150 YEARS OF CELEBRATING THE MAHATMA

Exhibition schedule & venue

MUMBAI 8th May to 7th July, 2019 10 AM - 6 PM	NEHRU SCIENCE CENTRE Dr E Moses Road, Worli, Mumbai - 400 018 Phone: (022) 24932667 / 24920482 Email: director@nehrusciencecentre.gov.in www.nehrusciencecentre.gov.in
BENGALURU 29th July to 28th Sep., 2019 10 AM - 6 PM	VISVESVARAYA INDUSTRIAL & TECHNOLOGICAL MUSEUM Kasturba Road, Bengaluru - 560 001 Phone: (080) 2286 6200 Email: vitmuseum@gmail.com www.vismuseum.gov.in
KOLKATA 4th Nov. to 31st Dec., 2019 11 AM - 7 PM	SCIENCE CITY J B S Haldane Avenue Kolkata - 700 046 Phone: (033) 22854343 / 2607, 23432569 Email: sciencecity.kol@gmail.com www.sciencecitykolkata.org.in
DELHI 21st Jan. to 20th Mar., 2020 9:30 AM - 6 PM	NATIONAL SCIENCE CENTRE Pragati Maidan, Near Gate No.1 Bhairon Road, New Delhi - 110 001 Phone: (011) 23371893 / 23371945 Email: nscdl01@gmail.com www.nscd.gov.in

Website Facebook Twitter YouTube Instagram

Designed by
Visvesvaraya Industrial & Technological Museum, Bengaluru
National Council of Science Museums, Ministry of Culture, Govt. of India

परमाणु ऊर्जा विभाग
Department of Atomic Energy

विज्ञान एवं प्रौद्योगिकी विभाग
Department of Science & Technology

राष्ट्रीय विज्ञान संग्रहालय परिषद्
National Council of Science Museums

अणु-तरंग

Particle-Wave

VIGYAN SAMAGAM

PUSHING THE FRONTIERS OF SCIENCE

CERN FAIR INO iter LIGO INDIA SKA India TMT

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अणु-तरंग

Particle-Wave

VIGYAN SAMAGAM

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Organised by:

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National Council of Science Museums

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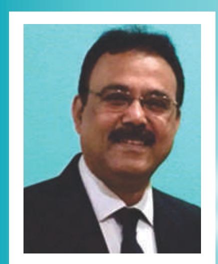
Chairman



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(NCSM)

Amritesh Srivastava
(NPCIL)

Contents

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Dilshad Sulaiman (ITER) | Anupreeta More (LIGO) | Debades Bandyopadhyay (SKA)
Prasanna Deshmukh (TMT) | Praveer Asthana (DST)

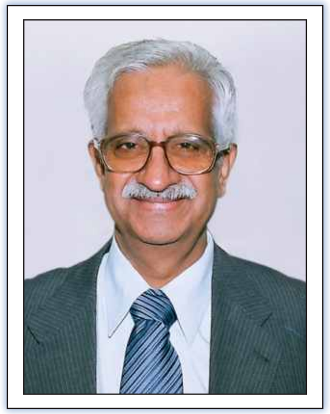
Messages

Dr Anil Kakodkar
Member, AEC &
Chairman, RGSTC, Mumbai

Understanding of Universe has been one of the most important research challenges and has necessitated development of custom designed very large and complex experimental tools. Such facilities by their very nature require co-operative and coordinated efforts of multiple institutions having interest and requisite capability in the specific area. Investments required for such efforts are often very large and call for international collaborations. For a large country like India, participation in such international mega-science projects presents interesting opportunities in a number of ways. Analysts can make important contributions to shaping global ideas for such efforts and improve our understanding based on experimental results, experimenters can contribute to making sophisticated hardware and a large number of young researchers can be exposed and initiated in contemporary front line research. Further, such facilities usually involve futuristic technologies and Indian industry can be exposed to valuable experience on mastering these technologies on a large scale. It is also a fact that such high tech equipment can be made in India at very competitive prices and that becomes a win-win opportunity both for us and the projects. Industry exposure to such futuristic technologies could also have many spin off benefits. As long as we can enable participation of adequately large number of young scientists in such efforts and our contribution is mostly in kind by way of supply of hardware made in India, mega - science projects, in my view, constitute excellent platforms for enhancing competitive scientific and technological edge of the country. The Department of Atomic Energy (DAE) and the Department of Science and Technology (DST) have been jointly promoting such efforts for quite some time now.

In order to spread the awareness of the role such mega-science projects play in furthering human understanding at a global level and benefiting national scientific and technological capability and to catalyse engagement of more students, researchers and industry, it is absolutely necessary to highlight the value and impact of such programs to a broad cross-section of society. I congratulate the Department of Atomic Energy (DAE), the Department of Science & Technology (DST) and the National Council of Science Museums (NCSM) for bringing mega-science activities in which our country is playing an active role, a step closer to society in the form of Vigyan Samagam exhibition. Anu-Tarang, the compendium of general and technical information related to Vigyan Samagam, would be beneficial for both the general and scientifically inclined readers alike.
I wish Vigyan Samagam all success.

Anil Kakodkar



Prof V S Ramamurthy

Emeritus Professor, NIAS
Bengaluru

I am happy to note that the Indian Department of Atomic Energy (DAE) and Department of Science and Technology (DST) are jointly organizing a multi-venue exhibition, VIGYAN SAMAGAM, showcasing India's contributions to International efforts in pushing the frontiers of science and technology beyond known frontiers.

Scientific research at the cutting edge today is highly dependent on expensive instruments and is often the collective effort of many people and organizations. It is not surprising that collaborations amongst scientists and institutions cutting across national boundaries are becoming more common.

In the recent decades, India has demonstrated unequivocally that it has the scientific and technological capabilities to contribute to such collaborations and the political willingness to commit the required resource.

I am confident that the present exhibition will attract the attention of every one to appreciate the challenge of carrying out research at the frontiers and encourage some of the students to opt for careers in research.

It is appropriate that the exhibitions are being hosted in the venues of National Council for Science Museums (NCSM) in different cities.

V. S. Ramamurthy

VIGYAN SAMAGAM
PUSHING THE FRONTIERS OF SCIENCE

Vigyan Samagam

Vigyan Samagam is a multi-venue mega-science exhibition showcasing India's contribution to international collaborations on fundamental science and research. It provides a common platform for all the Mega-Science Projects.

Mega-Science collaborations proposed to be showcased in Vigyan Samagam are:

- European Organization for Nuclear Research (CERN)
- Facility for Antiproton and Ion Research (FAIR)
- India-based Neutrino Observatory (INO)
- International Thermonuclear Experimental Reactor (ITER)
- Laser Interferometer Gravitational-Wave Observatory (LIGO)
- Square Kilometre Array (SKA)
- Thirty Meter Telescope (TMT)

Vigyan Samagam exhibition will showcase India's contribution in fundamental science and research, and provide an interactive platform for all mega-science Projects with students, academia and industry. All these Projects work on cutting-edge technologies which our Indian institutions would be exposed to and will develop industrial capacity. Presence in Mega-Science Projects with multi-national participation keeps us on the same platform as other developed countries. Indian participation in these Projects is based on its scientific and engineering capabilities.

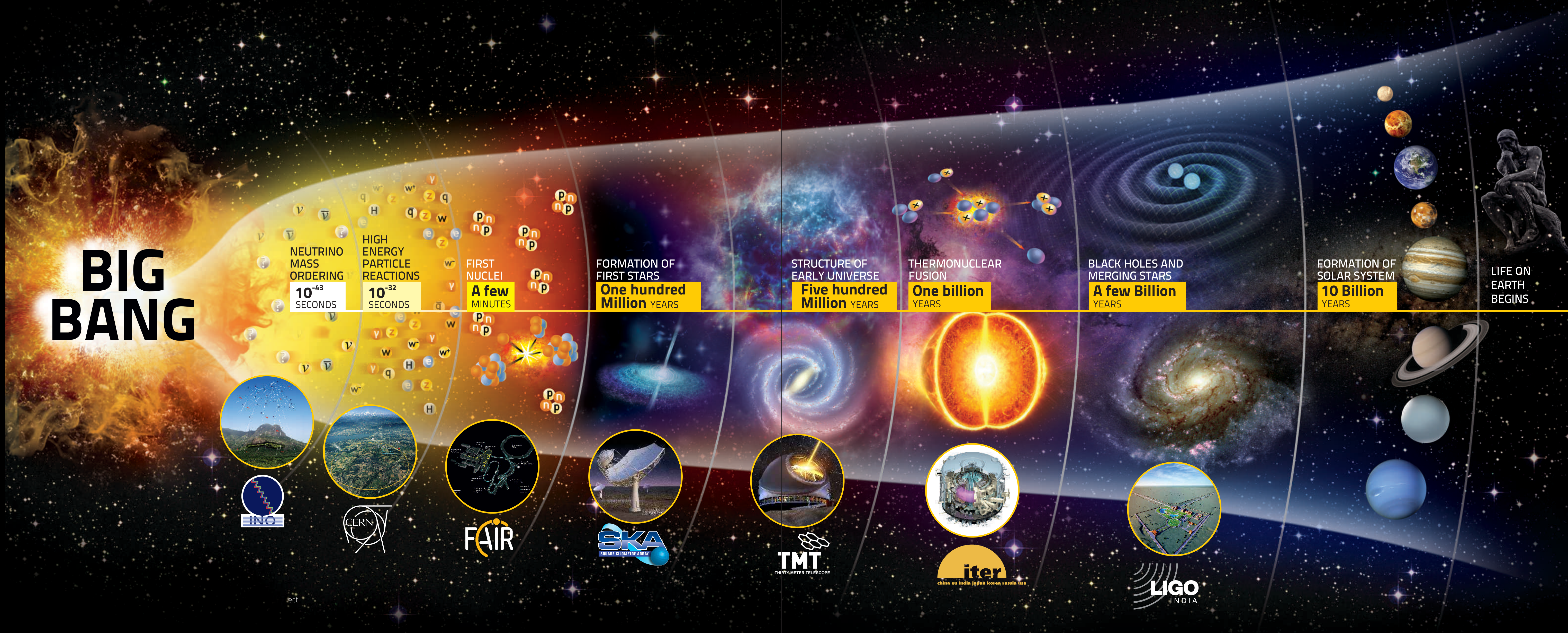
Vigyan Samagam will be a science communication platform for policy-makers, representatives of print and electronic media along with members of civil society. The exhibition will also usher youngsters to strong career options. Such a spectrum of audience is expected to pave the way for a greater interaction between all stakeholders, resulting in cross-fertilisation of ideas.

A first-of-its-kind exhibition, Vigyan Samagam will be hosted in a caravan mode at four cities – Mumbai, Bengaluru, Kolkata and Delhi – from May 2019 to March 2020. At each of the four locations, apart from the themed galleries of posters, models and exhibits, informative audio-visual content and interactive kiosks will be set up. Concurrent with the launch of the event, a 2-day scientific event shall be held at each venue. Weeklong activities consisting of science talks, demos, quiz programmes shall be conducted by all the Projects.

To know more, visit www.vigyansamagam.in or download the mobile app. You can also follow Vigyan Samagam on Facebook, Twitter, Instagram and YouTube.

From micro to macro:

Understanding the universe through mega science projects



An artist's impression of the evolution of the universe, showing one key area of science for each proj

परमाणु ऊर्जा विभाग
Department of Atomic Energy

Department of Atomic Energy

The Department of Atomic Energy (DAE) has been engaged in the development of nuclear power technology, applications of radiation technologies in the fields of agriculture, medicine, industry and basic research. In 1954, under the farsighted leadership of Dr. Homi Jehangir Bhabha, the Department started its journey with a promise of ushering India to a brighter future. Moving from strength to strength, the Department added several nuclear power plants, R&D centres, healthcare management units, fundamental research and higher education institutions, and industrial services. Environmental stewardship and community development are intrinsic to the programmes of the Department.

DAE proactively collaborates with several national and international institutions engaged in mega-science activities and fundamental research.

The Department of Atomic Energy comprises of six R&D centres, three Industrial Organisations, five Public Sector Undertakings and three Service Organisations. It also has under its aegis two boards for promoting and funding extra-mural research in nuclear & allied fields and mathematics and a national institute. It supports nine institutes of international repute engaged in research in basic sciences, astronomy, astrophysics, cancer research and education. It also has an educational society that provides educational facilities for children of DAE employees stationed across more than 60 locations in the country. It also has a deemed University which helps in in-house career development of its scientists and engineers.

Today India stands tall and proud in the world nuclear community due to deliveries achieved through entirely self-reliant and sustainable strategies of DAE.

To know more, please visit www.dae.gov.in or follow us at www.facebook.com/dae.connect and www.twitter.com/daeindia

विज्ञान एवं प्रौद्योगिकी विभाग
Department of Science & Technology

सत्यमेव जयते

Department of Science and Technology

The Department of Science and Technology (DST) was established in May 1971 with the objective of promoting new areas of Science & Technology (S&T) and to play the role of a nodal department for organizing, coordinating and promoting S&T activities in the country.

DST, ever since its creation, has led the policy formulation exercise for science and technology at the national level. DST regularly brings out S&T Statistics summarizing the state of S&T in the country.

DST has played the coordination role in the S&T sector quite actively and effectively over the years – with other Central Government Departments/Ministries, State Governments, industry, practising researchers and so on–so that all segments of country's scientific enterprise contribute effectively and make Science, Technology, and Innovation (STI) a key driver of national development. DST is also the nodal department for International S&T Cooperation.

The other hallmark of DST is capacity building and promotion of STI in the country. DST is the single-largest extramural research funding agency and helps sustain the research activities of a very large number of scientists and technologists in the country. It has significantly upgraded the research infrastructure of the higher educational institutions. It has programmes aimed at attracting, nurturing and promoting the study of science and practice of scientific research, right from the school level to practising researchers, including specially designed programmes for women. DST also supports innovation, entrepreneurship, technology development and commercialization covering all stages of the innovation cycle. DST promotes R&D on wide range of topics of scientific, technological and societal relevance without disciplinary and institutional boundaries.

DST has some of country's oldest and finest scientific organizations within its family. DST institutions have formidable research portfolio in areas such as astronomy and astrophysics, materials and nano science and technology and chemistry.

Further details may be found at www.dst.gov.in

राष्ट्रीय विज्ञान संग्रहालय परिषद्
National Council of Science Museums

National Council of Science Museums

National Council of Science Museums (NCSM), an autonomous scientific society under the Ministry of Culture, Government of India, was formed on April 4, 1978. Today, it administers 25 Science Centres/Museums/Planetariums spread all over India. Science City, Kolkata, Birla Industrial and Technological Museum (BITM), Kolkata, Nehru Science Centre, Mumbai, Visvesvaraya Industrial and Technological Museum (VITM), Bengaluru, National Science Centre, Delhi and Central Research & Training Laboratory (CRTL), Kolkata are National level centres of NCSM. Each of these centres/museums has its Regional Level Centres and District Level Centres called Satellite Units (SUs). CRTL is the Council's central hub for professional training, research and development. NCSM has developed Science Centres/museums for different States and Union Territories of India. It also has developed several centres and galleries for different Government and nongovernmental organisations such as ONGC, BEL, ICAR, and also collaborated internationally for development of Museums/Science Centres or for galleries such as Rajiv Gandhi Science Centre, Mauritius, "India gallery on Buddhism" at International Buddhist Museum, Sri Lanka etc. NCSM also has developed the National Museum of Indian Cinema at Mumbai. NCSM is one of the largest networks of science centres and museums in the world. The Council also collects, documents, restores and preserves important historical objects, which represent landmarks in the development of science, technology and industry. The Council is engaged in imparting scientific temper among the masses in general and students in particular and in enhancing the understanding of science among students. Annually millions of people visit the science centres under NCSM.

Visvesvaraya Industrial & Technological Museum Bengaluru

Visvesvaraya Industrial & Technological Museum, Bengaluru is the largest science museum in South India that began in 1965 and is the second science museum under National Council of Science Museums (NCSM). VITM is the southern regional headquarters of NCSM and it administers three other science centres in Southern region viz: Regional Science Centre, Tirupati, District Science Centre, Gulbarga, & District Science Centre, Tirunelveli. VITM is recognized as the hub of science popularization activities in the southern region and organizes several outreach programmes in the southern states. VITM has set up new science centres for the State Governments at Dharwad & Pilikula in Karnataka, Coimbatore in Tamilnadu & Puducherry. The museum is known for its pioneering activities in science and is well known worldwide as a tourist destination in Bengaluru. The museum receives over 10 lakh visitors a year and has proved itself as a non-formal science education resource centre especially for school students.

European Organization for Nuclear Research

Accelerating Science

India, an Associate Member (since 2016) of CERN–the world's largest accelerator laboratory is a proud partner of the Large Hadron Collider (LHC) project from the beginning. Indian scientists and engineers have contributed significantly to both science and technology of LHC. Indians have participated in the construction, commissioning and operation of LHC and of the two large experiments at LHC viz., ALICE (A Large Ion Collider Experiment) and CMS (Compact Muon Solenoid). India has established and is running two tier-2 grid computing centres in the country for LHC data analysis. Indian scientists have significantly contributed towards major discoveries reported from LHC, viz. the discovery of the Higgs boson (that is responsible for mass of elementary particles) in 2012, that led to the awarding of the Nobel Prize in Physics in 2013 and formation of Quark Gluon Pasma (QGP), a deconfined state of quarks and gluons in strongly interacting matter at under extreme temperatures.

LHC, located between Switzerland and France and housed in a tunnel of 27 km circumference, 100 m below the earth's surface is used for colliding protons and lead ions at centre-of-mass energies of 13 TeV and 5.7 TeV respectively creating controlled physical conditions that would have existed soon after the Big Bang. The Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, served as the nodal institute for India's participation in the building of the LHC and the CERN-India collaboration now constitutes a large number of universities and R&D institutes being jointly funded by DAE and DST.

In addition to exploration of science at the LHC, this Collaboration enables (a) participation of Indian industries in advanced technologies; (b) access to several challenging technologies; (c) human resource development by way of training and exposure of our young scientists and engineers at CERN; and (d) capacity building that helps in India's in-house accelerator projects. Prominent examples include four sets of 1MW CW klystrons, 1MW Circulators, wave-guide components and RF hardware for Indian proton accelerators at BARC and RRCAT. Beyond LHC, India has contributed towards design, development, tests and installation of accelerator components for Linac 4 (front-end of new injector for the luminosity upgrade program of LHC) and Compact Linear Collider (CLIC) Test Facility (CTF3).

Contributions to the ALICE detector

Presently, 12 Indian institutes/universities are participating in the ALICE experiment at LHC. Two major detectors, viz., the Photon Multiplicity Detector (PMD) for measurement of photons at forward rapidity and a Cathode Pad Chamber for muon measurements in the ALICE experiment, were fully conceptualized and fabricated by Indian collaborators and are being operated by them. A 16-channel readout ASIC, named MANAS, was developed in India and supplied to CERN for use in ALICE detectors. A state-of-the-art high-speed FPGA based PCIe40 read-out card is being fabricated in India for the ALICE-upgrade. As a part of further upgrade, prototypes of an electromagnetic calorimeter are being built using tungsten as absorber and radiation-hard silicon-pads for readout.

Contributions to the CMS detector

India has made significant contributions towards fabrication, assembly, installation, commissioning as well as operation and upgrade of several components of the CMS detector, notably the Hadron Outer Calorimeter (1100 units), electronics upgrade of the hadronic calorimeter (more than 900 multi-layer and high-end electronics boards and peripherals produced and characterized), mechanical casing of these electronics (100 housings), silicon-strip sensors for the electromagnetic pre-shower detector (more than 1000 units), Resistive Plate Chambers (RPCs) for the muon spectrometer system (50 RPCs and 200 copper-cooling sets for the RPC upgrade). Future hardware participation from India includes several high-technology subsystems of CMS experiment, meant for HL-LHC operation: silicon-based tracker as well as high granularity calorimeter, gas electron multiplier (GEM) detectors and custom-made trigger electronics employing state-of-the-art FPGAs.

Contributions to Worldwide LHC Computing GRID (WLCG)

GRID is the natural evolution of the internet technology (World Wide Web was invented at CERN). India has played significant role in the development of GRID technology involving tens of petabytes of data generated every year which involves sharing and monitoring of computing/storage resources worldwide via high-speed (multi-Gbps) internet. India hosts two Tier-2 GRID Computing Centres: at TIFR Mumbai for CMS experiment and at VECC, Kolkata for ALICE experiment.

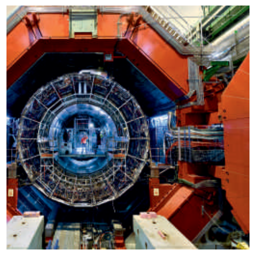
Collaborating Institutes in India

		Raja Ramanna Centre for Advanced Technology Indore	Bhabha Atomic Research Centre Mumbai	Variable Energy Cyclotron Centre Kolkata
Tata Insittute of Fundamental Research, Mumbai	Saha Institute of Nuclear Physics Kolkata	Indian Institute of Technology Bombay Mumbai	NISER Bhubaneswar	Delhi University Delhi
Panjab University Chandigarh	Aligarh Muslim University Aligarh	Rajasthan University Jaipur	Jammu University Jammu	Visva Bharati Santiniketan
Indian Institute of Science Education & Research, Pune	IIT Bhubaneswar	Indian Institute of Technology Madras Chennai	Bose Institute Kolkata	IISc, Bangalore
IIT Indore	University of Hyderabad	Gauhati University Guwahati	Institute of Physics Bhubaneswar	University of Calcutta Kolkata

Technology developed

LHC /Linac 4/CLIC: India contributed significantly towards LHC construction by developing and producing large numbers of a variety of high-technology components with active participation of the Indian industry, such as, high-precision jacks (7080), superconducting corrector magnets (1146MCS+616MCDO), quench heater power supplies (5500), local protection units (1435) etc. India also contributed towards software development including the JMT-II software, slow control, superconducting dipole magnet measurements (100 man years) and survey systems for LHC. Subsequently for advanced accelerators like Linac-4 and CLIC (CTF3) also, several technologies were developed and supplied. For Linac-4, our contributions included 100kV/20A state-of-the-art solid-state bouncer modulator, development of prototype waveguide components and copper-coated SS power couplers for DTL, CCDTL and commissioning support. For CTF3, our contributions included dipole magnets for TL2, vacuum chambers for TL2, optics design / simulation / analysis and results for TL 2, expert support for commissioning, operation of controls, prototype 12GHz power extraction and transfer structures, 20kW broad-b and solid-state amplifier for sub-harmonic buncher for CLIC linac.

ALICE



A Large Ion Collider Experiment ALICE Detector

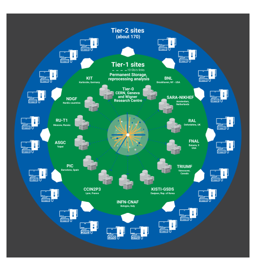
Technologies that have been developed/employed by India for the ALICE experiment are briefly mentioned below: (a) large volume gaseous proportional chambers with 220K readout channels employing extended cathode technology; (b) world's largest cathode pad chamber for muon measurement; (c) a 16-channel multiplexed readout ASIC called MANAS with challenging analog signal readout; (d)fabrication of a thick graphite absorber as hadron absorber in the muon detection system; (e) fabrication of Common Readout Unit (CRU), an FPGA-based data segregation system for handling huge data volume coming out of ALICE in higher luminosity operation; and (f) silicon-tungsten calorimeter for detection of electromagnetic particles in the forward region of ALICE.

CMS

Compact Muon Solenoid (CMS) Experiment

Starting with scintillator-based detectors, Indian scientists contributed towards silicon based as well as gas-ionization based detectors. The next phase is marked by production of complex electronics and GEM detectors to match high-data rates at LHC. The challenges of HL-LHC operation will be dealt with silicon based detectors where India will contribute significantly. The development of silicon sensors, as well as custom-made electronics, are some of the other ventures that will enable participation in cutting-edge technologies being used in LHC experiments.

GRID



World Wide LHC Computing Grid: WLCG

Our contributions to the LHC Computing Grid include: Grid View monitoring and visualisation tool; My WLCG, a personalized Grid Monitoring software; Cloudman, a high-level resource management tool to provide a central place to configure resource in a computer centre at an abstract level; Cloud Accounting Project; Distributed Quota Management; Open stack Quota Management; establishment and operation of Tier2 centres for ALICE and CMS experiments that provide the backbones for success of the computing efforts. One of the recent highlights include opportunistic use of cloud computing for CMS experiment from India and development of related middleware.

LHC

Indian industries involved

Electronics Corporation of India Ltd. | Hyderabad; Avasarala, Bangalore | MSME Indo-German Tool Room, Indore | Mann Aluminium, Pithampur, Indore | Semi-Conductor Laboratory (formerly Semiconductor Complex Limited), Chandigarh | Smile Electronics Limited, Bengaluru | Central Tool Room, Ludhiana | Bharat Electronics Limited (BEL), Bengaluru | Hi-Tech Industries, Mumbai | Micropack, Bengaluru | Peninsula Electronics, Bengaluru | Eata Plast Fabrics, Rabale, Mumbai | Alpha Pneumatics, Mumbai | PDR Videotronics, Mumbai | Amit Electronics | HiQ Electronics | Keithley/Tektronix | MPI | Micro-Epsilon India Private Limited, Bangalore | KAF International, New Delhi | Ameliorate Solutions, Bangalore | Nordson-EFD, Bangalore | HDR Holding India Pvt. Ltd, Kolkata

Contact person/Spokesperson

LHC/Accelerators:

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ALICE:

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CMS:

Prof. Brajesh Chandra Choudhary
Department of Physics and Astrophysics
University of Delhi, Delhi 110 007, Email: brajesh@fnal.gov

Superconducting corrector magnets for LHC

Website

http://www.rrcat.gov.in, http://india.web.cern.ch/india/

India-CERN Collaboration: Particle Accelerators

Indian Participation in construction and commissioning of accelerators (LHC, SPL-(Linac4), CLIC(CTF3) at CERN

Department of Atomic Energy, DAE, entered into a co-operation agreement with CERN on 28th March 1991, followed by a protocol for collaboration in Large Hadron Collider (LHC) on 29th March 1996 to make 'in-kind" contributions in which half of European Cost of an item is taken as Indian contribution, and the other half is credited by CERN to Indian Fund, set up at CERN, to support the visits of Indian scientists. Raja Ramanna Centre for Advanced Technology, RRCAT, India was identified as DAE's nodal institute for this collaboration.

During the construction phase of LHC, India contributed significantly by developing a variety of high technology components and equipment produced in the Indian industries, under the supervision of RRCAT, such as high-precision jacks, superconducting corrector magnets, quench heater power supplies, local protections units etc. Indian engineers also contributed in accelerator software development like, JMT-II software, slow control, Superconducting magnet measurement system, Survey systems for LHC. Table-1 illustrates contributions to LHC & Annexure- 1 contains some corresponding photos.

CERN invited India to participate in construction/commissioning of Advanced Accelerators under Novel Accelerator Technology Protocol, NAT, (signed in 2006) viz., Linac 4 (160MeV front end accelerator) for luminosity upgrade as a front end of Superconducting Proton Accelerator, SPL and Compact Linder Collider Test Facility, CTF3 as demonstration for Compact Linear Collider, CLIC. Some of these high technology items have been fully designed, developed and tested in India and installed at CERN. Table-2 illustrates contributions to NAT- Linac4 & CLIC-CTF3. Annexure- 2 contains some corresponding photos.

The participation in the accelerator technology proved highly beneficial for India as, (a) it enabled participation of our industry in projects requiring highest standard, challenges and monitoring as well as building infrastructure to produce the required high tech components (b) it enabled access to the know-how of several more challenging technologies that has helped in capacity building and promoted in-house applications (c) our young scientists and engineers were provided with a chance to learn many of these technologies, as well as, aspects of accelerator design and commissioning while contributing to various CERN projects. Indians being involved in all stages of the design, development and production along with the CERN teams, has contributed to in-house developments in the areas of beam-optics and related accelerator physics for example, in RRCAT accelerator projects at RRCAT and BARC.

Benefits of the DAE CERN collaboration in accelerators:

With the continuation of the collaborative efforts, access to the challenging technologies, equipment and its supply from CERN to India has continued. Prominent examples are testing and supply of four sets of 1MW CW klystrons, 1MW Circulators, waveguide components and RF hardware which are crucial for capacity building and initial testing of proton accelerators at RRCAT and BARC. Three klystrons, three circulators and one set of waveguide hardware have been supplied to BARC for its LEHIPA project. One set is kept at RRCAT as a test stand.

Participation of Indian cryogenics experts and young engineers provided ample opportunities and experience to work in the superconducting technology development and commissioning aspects at CERN. This has been very important for Indian SCRF program.

Thus, participation in LHC and Linac 4 accelerator development, commissioning and testing as well as building high-tech items has been beneficial to the Indian ADS, SNS, projects as it enhanc ed our experience and hands on working on high energy accelerator machines for both protons as well as electrons. Involved personnel had extensively participated in physics and engineering level design & development in several programmes depicted in the tables 1 and 2.

Further opportunities for the benefit of Indian Accelerator program:

1) Hardware for High Luminosity LHC, 2) Prototyping for Future Circular Collider (100 km circumference, 100 TeV. There is a possibility for partnership in the development of accelerators and components for applications for societal benefits and medical applications. It is the appropriate time to rapidly extend the participation so that technologies developed at CERN can be utilised for the benefit of the Indian accelerator community and society.

Table 1: Participation in LHC protocol for LHC accelerator construction/commissioning

Sr.	Description	Qty
1	Liquid Nitrogen tanks 50000 litres capacity	2
2	Superconducting corrector magnets : Sextupole, Decapole and Octupole	1146 616
3	Precision Magnet Positioning System (PMPS) Jacks	7080
4	Quench Heater Power Supplies, QHPS	5500
5	Integration of QHPS units into racks	6200
6	Control electronics for circuit breakers of energy extraction system	70
7	Local protection units (LPU)	1435
8	SC Dipole magnet measurements, expert support. Eq. man-years	100
9	LHC commissioning: Cryogenics, Controls, Converters, protections, man-years	20
10	Software development for LHC subsystems, eq. man-years	41

Table 2: Participation in NAT protocol for construction of [CLIC(CTF3)/SPL(LINAC4):

1	Design, development, magnetic tests of dipole magnets for TL2 of CTF 3	5
2	Design, Development, vacuum tests of Dipole vacuum chambers, for CTF3	64
3	Optics design, simulations, analysis and results for TL 2 of CTF 3, eq man months	9
4	Expert support for commissioning, operation of controls for CTF3, man months	41
5	Expert support for the commissioning of the subsystems of Linac 4, man months	25
6	100kV, 20A solid state modulator for CERN LINAC 4	1
7	20kW Broad Band solid state amplifier for harmonic buncher forCLIC linac	1
8	Development, supply of prototype components for Linac 4	6
9	Development, supply of copper coated SS power couplers for DTL for Linac 4	4
10	Tests and supply by CERN: 1MW CW 352.2 MHz klystrons, 1MW CW circulators, waveguide hardware, four sets each, LEP eq. for DAE's SNS/ADS	4 sets

LHC: Large Hadron Collider, SPL: Superconducting Proton Linac, CLIC: Compact Linear Collider, TL2:Transport Line 2, CTF3:Compact Linder Collider Test Facility,

Annexure 1 Photographs of components for LHC:


1) SC corrector magnets 2) PMPS jacks 3) QHPS power supplies


4) PMPS/QHPS in LHC 5) SC dipole Magnetic measurements 6) Local protection units

Annexure 2 Photographs of components for CLIC(CTF3) and SPL(Linac4):




1) Dipole magnets 2)Vacuum chambers(TL2), 3)20kW SSPA- CLIC 4)100kV modulator- Linac4



5)1MW klystron test stand at RRCAT 6) 1MW klystron/ circulators for LEHIPA, BARC



7)Copper coated SS Power Couplers developed at RRCAT & Installed in Linac 4 at CERN

ALICE

ALICE is the acronym for ALarge Ion Collider Experiment, one of the detector experiments at the Large Hadron Collider (LHC) at CERN, devoted to research in the physics of matter at an infinitely small scale. Specifically, the ALICE Experiment searches answers to fundamental questions, using the extraordinary tools provided by the LHC:

- What happens to matter when it is heated to 100,000 times the temperature at the centre of the Sun?
- Why do protons and neutrons weigh 100 times more than the quarks they are made of?
- Can the quarks inside the protons and neutrons be freed?

ALICE is very different in both design and purpose from the other experiments at the LHC. Its main aim is to study the head-on collisions between heavy nuclei, mainly Lead on Lead collisions at the top energy of the LHC. Note that the collisions of Lead nuclei are 100 times more energetic than those of protons. In these collisions, the enormous energy density heats up the matter in the collision zone to a temperature which is 100,000 times higher than the temperature in the core of the sun. At such high temperatures, nuclei and nucleons melt into their elementary constituents, quarks and gluons, to form the quark-gluon plasma for a very very short time. This primordial matter filled the universe a few microseconds after the Big Bang. Worldwide, experimental search for de-confined state of quarks and gluons are being performed in heavy-ion collisions in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and thereafter in the Large Hadron Collider (LHC) at CERN. The hot reaction zone formed in high energy heavy ion collisions expands at almost the speed of light and in the process cools and condenses back into ordinary, composite matter particles. In each collision, called 'little bangs", several thousands of particles are created. The ALICE detector measures as many as possible of the escaping particles, and records their number, type, mass, energy, momentum and direction. These observables are then used to infer the existence and properties of matter under the extreme conditions created during the instance of the collision. ALICE also takes data with proton-proton collisions in order to compare them with the heavy ion results. Thus, the ALICE detector experiment can characterise the global event structure of heavy ion collisions as well as proton reactions with its distinct and complementary set of detectors.

The ALICE collaboration has more than 1800 physicists, engineers and technicians from 176 institutes in 41 countries across the world. Indians have been participating in ALICE from its inception and have roles in design, development, fabrication, installation, commissioning and data taking. So far about 35 students from 12 Indian institutes have obtained PhD degree from the ALICE experiment. So far, India has built two major subsystems in ALICE, Photon Multiplicity Detector (PMD) for measurement of photons coming in a direction close to the beam direction and muon chambers meant to measure muons, an undisturbed messenger of the history of the collision zone. At present about 65 students are involved in ALICE experimental activities like hardware, data analysis.

ALICE as shown in Fig. 1 recorded data from the first Lead-Lead collisions at the LHC in 2010. Data sets taken during heavy-ion periods in 2010 and 2011 as well as data from 2013 and 2016 have provided an excellent basis for an in-depth look at the physics of quark–gluon plasma.

ALICE detector measures 26m long,16m high and 16m wide, with a total weight of approximately 10,000 tonne. It is situated in a vast cavern 56m below the ground on the border of St. Genis Pouilly in France. The detector is designed to measure the particles produced in the collision to reconstruct and study the evolution of the system during these collisions. To study the production of hadrons, electrons, muons, and photons produced in the collision of heavy nuclei, the experiment consist of 18 different sub-detectors, each of these detector systems has its own specific technology choice and design constraints that are motivated by the physics requirements and the experimental conditions expected at LHC. The different subsystems are designed to provide high-momentum resolution and excellent Particle Identification (PID) over a broad range in momentum, up to the highest multiplicities predicted for LHC.

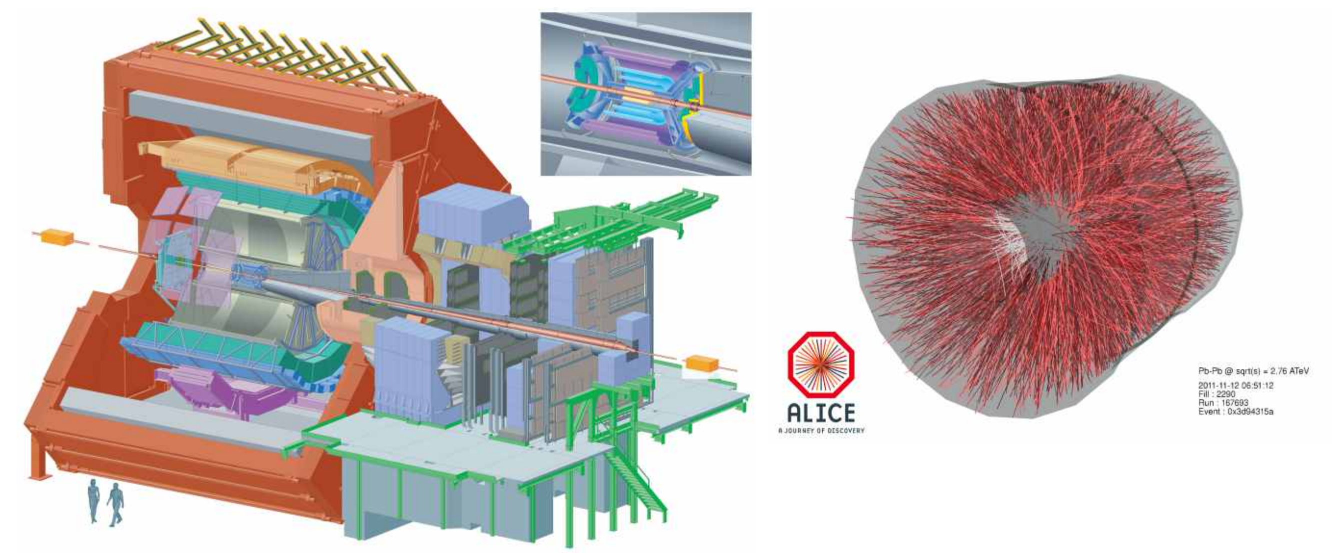


Fig. 1 (left) ALICE experimental setup
(right) image of one Pb-Pb collision

Key findings from ALICE so far are listed below:

1. In heavy-ion collisions at the LHC, ALICE has found that the hot matter created in the collisions behaves like a perfect, friction less fluid with almost zero viscosity.

2. ALICE also measured the size and lifetime of the fireball created in heavy-ion collisions with a technique called Bose-Einstein or HBT Interferometry and found that fireball formed in heavy-ion collisions at the LHC is hotter, lives longer and expands to a larger size than at lower energies.

3. Radiation of 'thermal photons' is one of the classic signals of formation of QGP with their spectrum reflecting the temperature of the system. ALICE data on photons produced in Lead-Lead collisions were in agreement with theoretical models which assume the formation of a quark–gluon plasma with a temperature of about 5 trillion degrees. The ALICE measurement also indicates that the LHC has produced the highest temperature ever formed in a laboratory and thus holds a record in Guinness world records.

4. An enhancement in the production of particles with strange quarks has long been thought to be a signature of extra degrees of freedom available in the QGP. In its recent results ALICE has observed strangeness enhancement in high multiplicity proton-proton and proton-Lead collisions.

5. The Quarkonia are bound states of heavy flavour quarks (charm or bottom) and their antiquarks. The first ALICE results for charm hadrons indicate strong in-medium energy loss for charm and strange quarks which is an indication of the formation of the hot medium of QGP. In addition the suppression of charmonium states was also observed in proton-Lead collisions at the LHC, in which Quark Gluon Plasma is not expected to be formed. This suggests that the observed suppression in proton-nucleus collisions originates from cold nuclear matter effects.

Writeup on CMS and India-CMS

Particle physics experiments at the colliders address the deepest mysteries of nature by querying nature via high-energy probes. The Large Hadron Collider at CERN, Geneva creates the conditions prevalent immediately after the Big Bang by colliding protons or Lead ions at several Terra Electron Volts (TeV) concentrated within distances smaller than the size of a proton (femtometer). The CMS (Compact Muon Solenoid) experiment is designed to take a snapshot of a billion mini Big Bangs created by the LHC every second. It identifies and stores results of interesting collisions relevant to the study the following aspects of fundamental interactions and the properties of the elementary particles:

1. Origin of the Universe: Big Bang or Primordial Plasma
2. Origin of Mass: The Discovery of Higgs boson marks an incredible success of the LHC, the CMS and the Standard Model of elementary particles
3. Why the universe is as it is? Precision stress-tests of the Standard Model predictions
4. Quantum nature of the Dark Matter: Searches for Super-Symmetric particles and direct production of dark matter particles
5. Einstein's Space-Time: Searches for Large Extra-Dimensions and Black Holes
6. On the way to the present form of the Universe: Why there is more matter than anti-matter in today's universe?

The CMS experiment consists of about 1900 PhD Physicists, ~1000 Physics PhD students, ~1100 undergraduate students, ~1000 Engineers and ~280 Technicians from 229 Institutions in 51 countries from Asia, Europe, Africa, North and South America. Indian participation in CMS consists of about 50 PhD physicists, ~80 PhD students, several engineers and technicians from 15 institutions across the country. India is the 9th largest group in CMS and the largest one outside Europe and the USA.

The Indian collaboration started in mid-1990s with four institutions namely, University of Delhi, Delhi; Panjab University, Chandigarh; TIFR, Mumbai and BARC, Mumbai. With time it has grown into a truly national collaboration with participation from SINP, Kolkata; IIT-Bombay; Mumbai, IIT-Madras, Chennai; IIT-Bhubaneswar; IOP-Bhubaneswar; NISER-Bhubaneswar; IISER-Pune; IISc-Bangalore; Visva Bharati-Santiniketan; University of Hyderabad, Hyderabad; UIET-PU, Chandigarh and Khalsa College-Ludhiana.

The Indian groups have helped with building and upgrading the CMS detector, the software development and physics analysis. Initially Indian students and faculty participated in construction of the following detectors:

1. Hadron Barrel Calorimeter Outer (HO) for measurement of jet and missing transverse energy and further replacing Hybrid Photo Diodes (HPD) with more efficient Silicon Photo-Multipliers for better efficiency.

2. Silicon strip based pre-shower detector for separating photons from neutral pions, which was crucial for the discovery of the Higgs boson in the diphoton channel.

3. Resistive Plate Chambers for the CMS muon system for fast timing and triggering needed to trigger on muons and to reject unnecessary background so that new particles could be discovered.

Having developed a substantive part of the detector, Indian scientists, engineers and students helped operate the experiment, collect and analyze the data from the very beginning and participated in the full physics spectrum of the experiment including to resolve the issue of electroweak symmetry breaking by leading in the discovery of Higgs Boson as a resonance of mass of 125 GeV.

Further Indian physicists and students played key rolesin understanding the nature of Higgs Boson by searching for Higgs beyond the Standard Model, measuring its coupling to other fermions and bosons including ttH coupling, searches for Supersymmetry, Extra-dimensions, leptoquarks, heavy-gauge bosons, Dark Matter, Compositeness, New resonances, detailed study of top quark properties and its precision mass measurement, EW symmetry breaking, various topics in beauty physics, forward and small x-physics, heavy-ion physics and the precision measurements within the standard model physics.

Indian groups further contributed with the upgrade of the CMS detector by

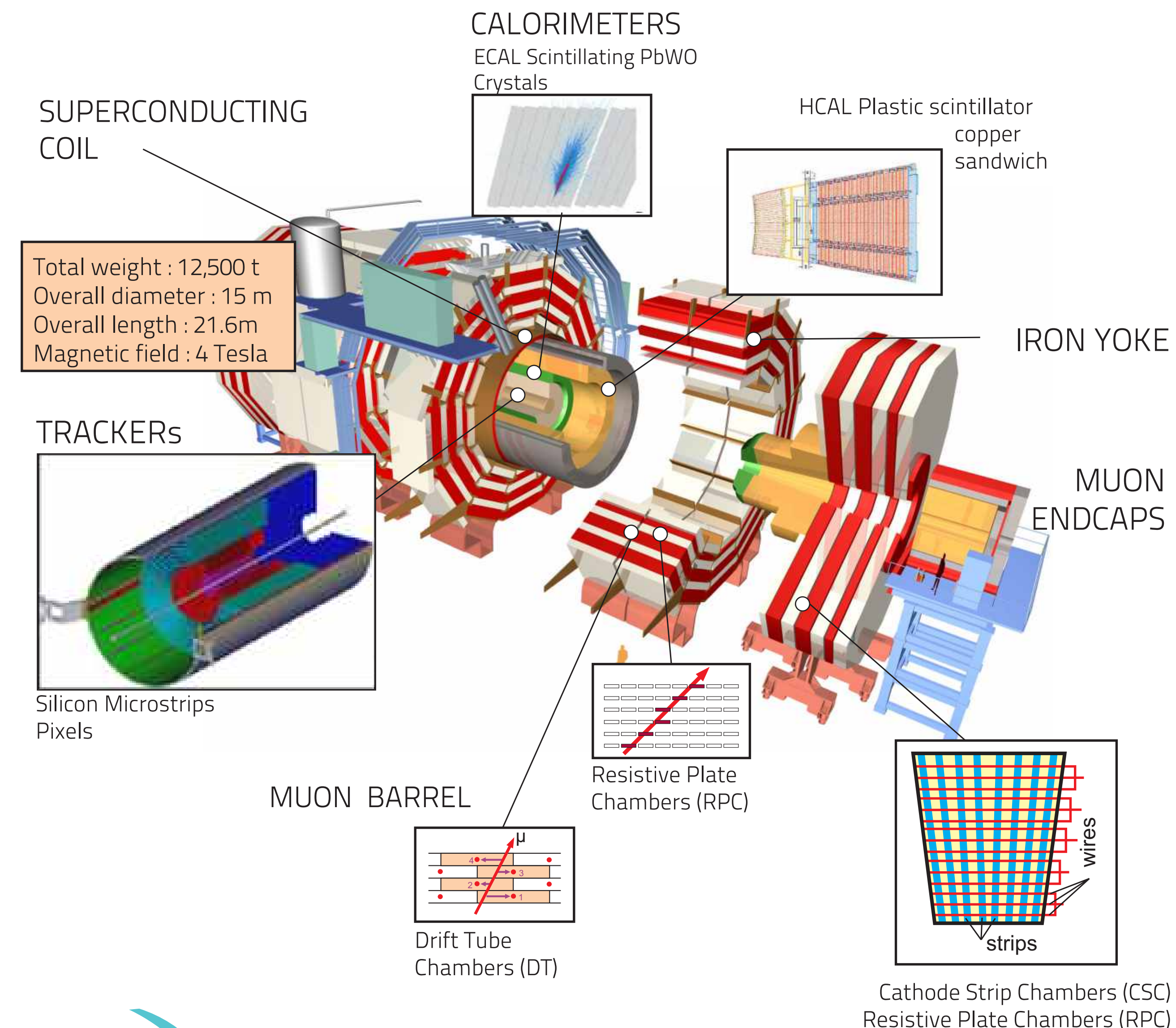
1. Building the GEM GE1/1 muon chambers, and
2. HCAL front-end and back-end electronics upgrade.

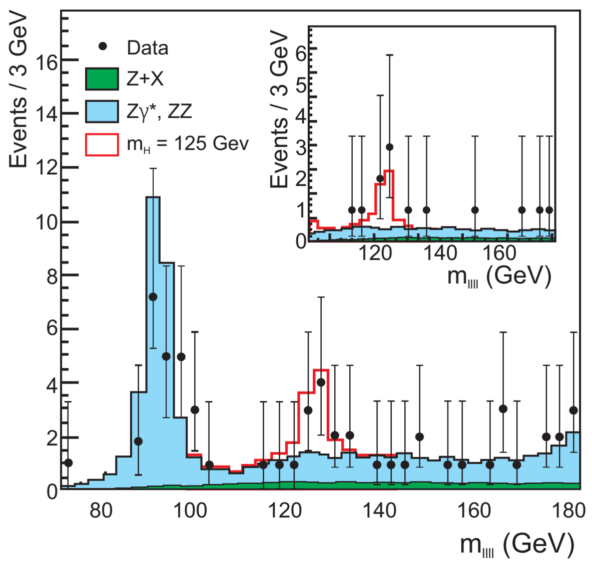
Indian groups are also participating actively and have a leading role in the future upgrade of the CMS detector by building part of its:

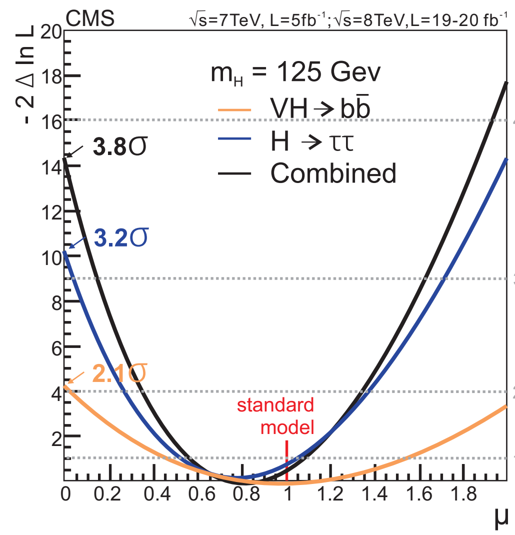
1. Endcap Calorimeter (HGCAL),
2. Outer Silicon Tracker system,
3. GEM GE2/1 and ME0 muon system and
4. Trigger system.

India-CMS has graduated about 70 PhD students, and has published several hundred papers in peer-reviewed journals, and India-CMS members have represented the CMS collaboration across the world by giving talks and presenting posters.

The Compact Muon Solenoid (CMS)





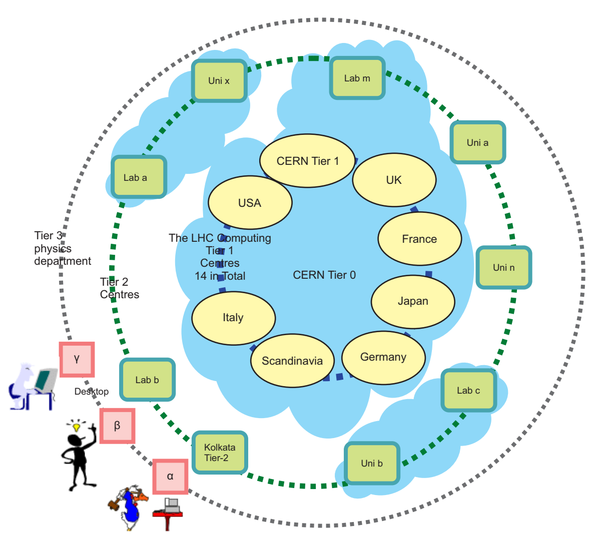


Science 338 (2012) 1569 -1575
The invariant mass of the four-lepton system shows epic at 125GeV. The same peak is also seen epic in the Two-photon invariant mass, signaling the discovery of the higgs boson.

Nature Physics 10(2014), 557-560
shows the first evidence for the Higgs boson decaying to a pair of spin-1/2 particles (b-quarks and tau-leptons)

GRID COMPUTING

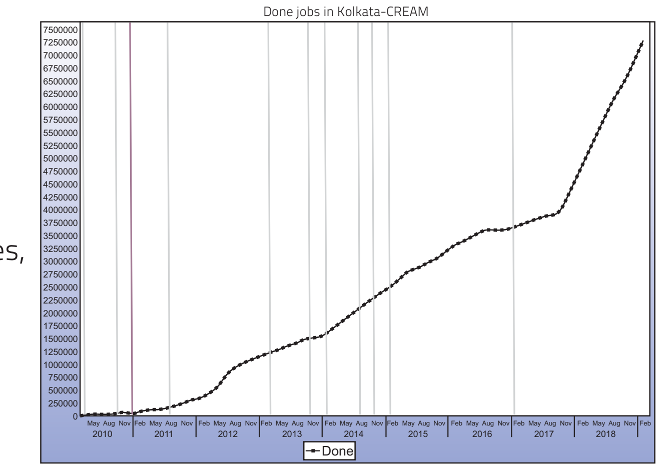
- Based on electric grid concept,
- Provides resources transparently and seamlessly,
- An amalgamation of cluster of computers and storage,
- Distributed across the different geographical locations,
- A common computing goal using common internet,
- Uses middleware to coordinate disparate IT resources across the network,
- Functions as a virtual whole.



WLCG

(Worldwide LHC Computing Grid) is realization of GRID computing concept which provides seamless access and storage to all involved in the LHC Project at CERN across the globe.Itis a global collaboration of more than 170 computing centres in 42 countries, linking up national and international grid infrastructures. There are four virtual organization (VO), named after four experiments (ALICE, ATLAS, CMS, LHCb) at LHC machine, under WLCG. Grid computing f acility at Kolkata is the only Tier-2 centre in India dedicatedly running for ALICE VOsince its inception in 2002-2003.

Online MonaLisa Repository for ALICE Grid sites shown Kolkata site with data transfer and active jobs.



Grid Computing Facility at VECC Kolkata:-

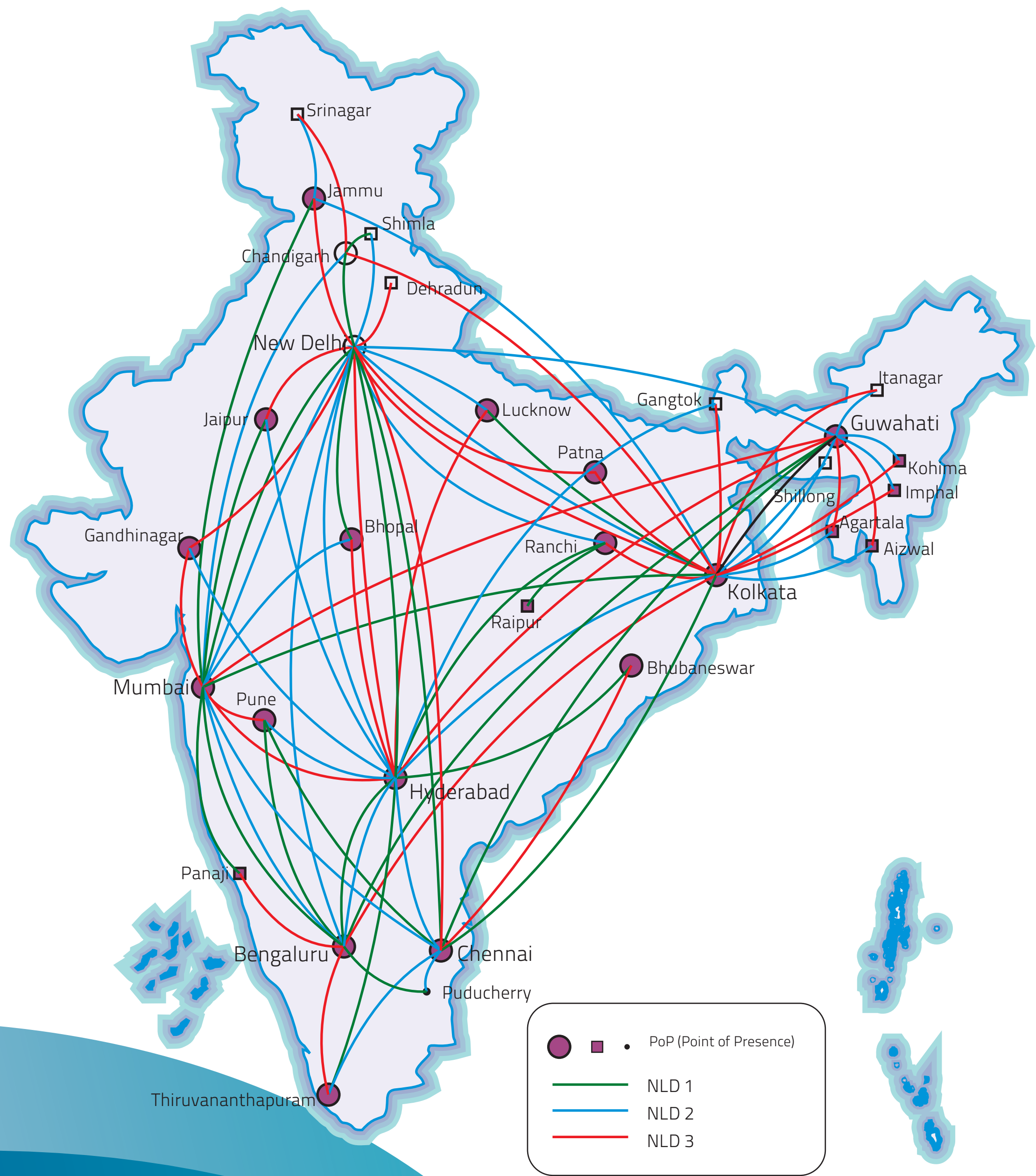
- 2 big computing clusters,
  - a) Kolkata tier-2 @ ALICE
  - b) Grid-peer tier-3 cluster for Indian collaborators,
- Pan India collaboration with 13 universities,
- 4000 cores of computing,
- 1.5 Petabytes of storage,
- 10Gbps global network connectivity provided by NKN,
- Redundant, reliable and high throughput backbone network to ensure no single point of failure,
- Backbone network comprises4 * 48 port low latencylayer-3fiber switches and 40Gigabit per second inter-switch connectivity,
- Grid Middleware:- UMD-3 on Scientific Linux CERN(SLC) OS,
- 8 Million ALICE Jobs successfully completed till Feb 2019.
- Consistently running round-the-clock for last 14 years.

Kolkata Tier-2 listed in the top Supercomputers in India:-

- Published in Jan, July 2018 and Jan 2019 list http://topsc.cdacb.in/jsps/feb2018/index.html
- 48 nodes cluster comprising 2688 HT Cores,
- 12 * 2U form factor dense enclosures,
- 4 hot swappable servers in each enclosure,
- Each servercontains2*2.40GHz (14 core) processors, 128GB RAM, 960GB SSD and dual 10Gb network interfaces,
- Rpeak per server = 2x2.4x14x16 Gigaflop = 1.0752 Teraflop (TF) (Single Server)
- Rpeak for cluster =1.0752 x 48 TF = 51.6096 TF
- Rmax for cluster = 43.105.8 TF (using Intel Parallel studio)

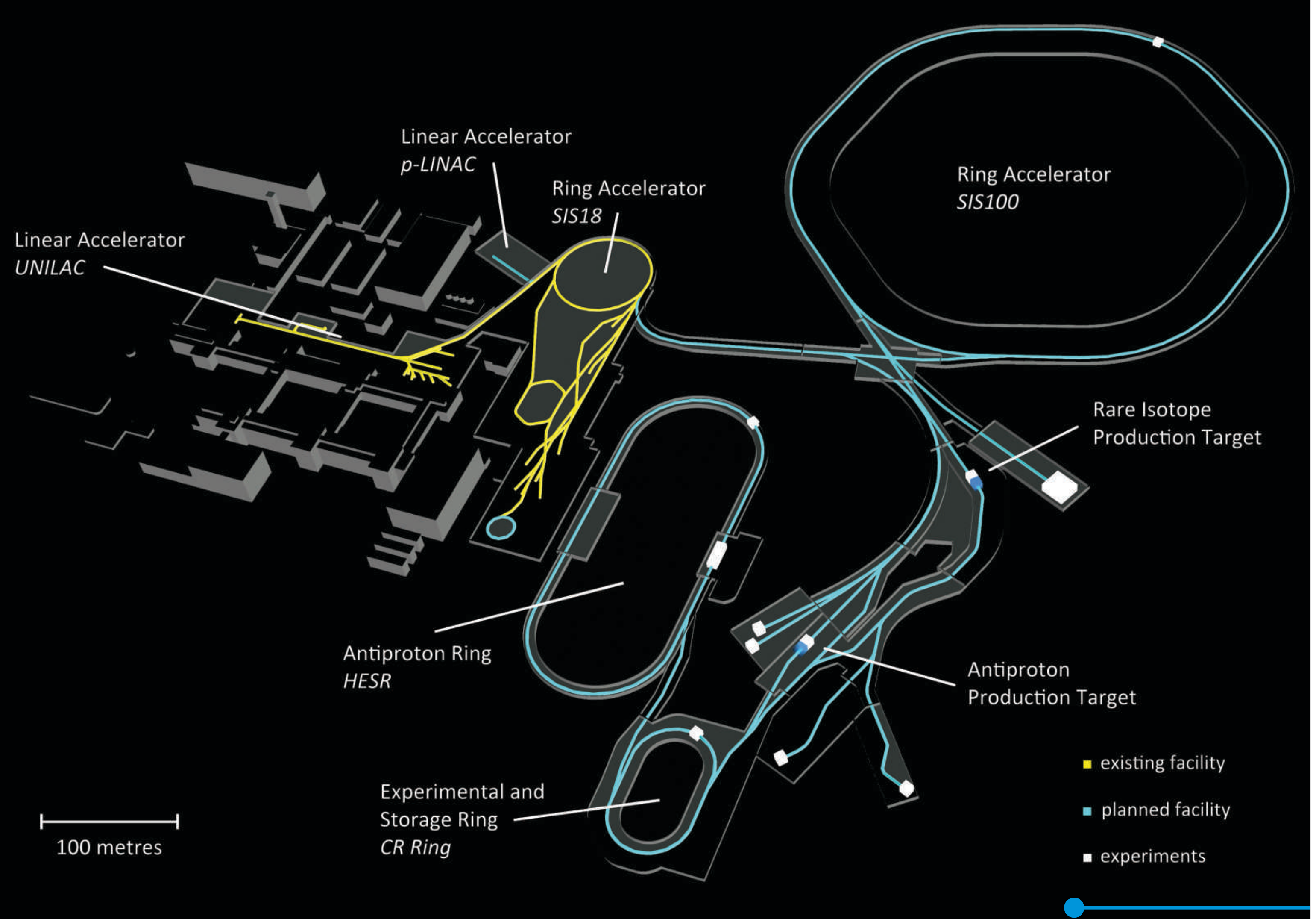
National Knowledge Network in India:

- A state-of-the-art multi-gigabit pan-India network,
- Provides a unified ultra-high speed network backbone for all institutions in the country,
- Supports a multitude of applications in a secure manner,
- Enables knowledge and information sharing among India,
- Providing redundant and reliable connectivity for WLCG project in India.



FAIR

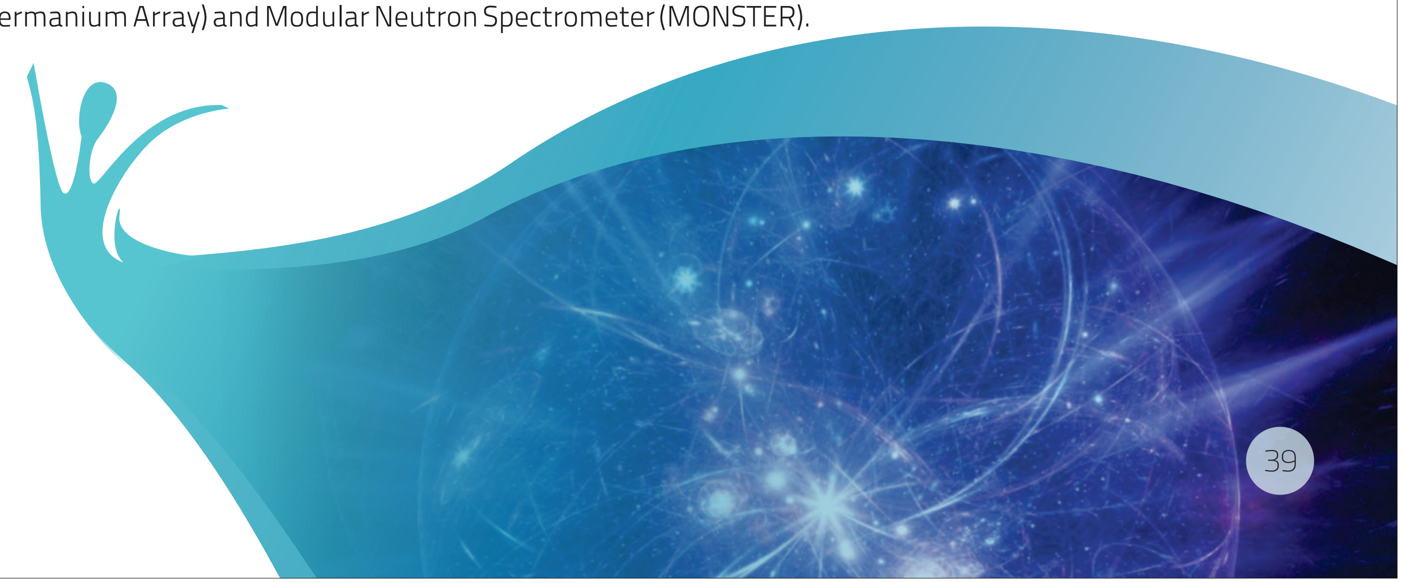
Facility for Antiproton and Ion Research



India is a founder country in World's biggest basic science accelerator project in the next decade.

The Universe in the Lab

The Facility for Antiproton and Ion Research (FAIR), that will be one of the largest international research facilities in the world, is coming up at Darmstadt, Germany. About 3000 scientists from 50 countires will study the structure of matter and evolution of the Universe from the Big Bang to the present using this facility. All the research activities at FAIR have been subdivided into four experimental programs, namely, Compressed Baryonic Matter (CBM), Nuclear Structure, Astrophysics and Reactions (NUSTAR), Atomic, Plasma Physics and Applications (APPA) and Antiproton Annihilation at Darmstadt (PANDA). The civil construction for the state-of-the-art ring accelerator of 1,100 m circumference as well as the experimental and computational facilities is in full swing on 20 hectares of land. India is the third largest contributor among nine countries (others are Finland, France, Germany, Poland, Romania, Russia, Slovenia and Sweden) that are working as partners to build this facility. India has major responsibilities in building FAIR. Indian companies will design and supply critical items such as ultra-stable power converters, co-axial power cables for powering the magnets, beam stoppers, ultra-high vacuum chambers and superconducting magnets for the FAIR accelerator system. Indian scientists are also working for participation in CBM and NUSTAR experiments. In CBM, the major responsibiliy of Indian scientists is to build a muon detection system based on Gas Electron Multiplier (GEM) technology. In the NUSTAR experiment, Indians are involved in building high resolution gamma-ray spectrometer (DESPEC Germanium Array) and Modular Neutron Spectrometer (MONSTER).

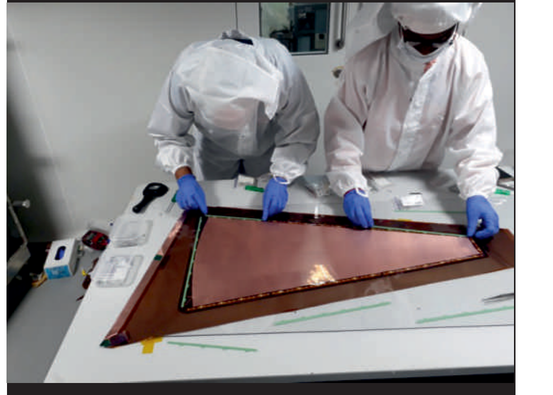


Collaborating Institutes in India

Variable Energy Cyclotron Centre Kolkata	Raja Ramanna Centre for Advanced Technology Indore	CSIR-Central Mechanical Engineering Research Institute Durgapur	Bose Institute Kolkata
Tata Institute of Fundamental Research Mumbai	Inter-University Accelerator Centre New Delhi	Aligarh Muslim University Aligarh	Panjab University Chandigarh
Rajasthan University Jaipur	University of Kashmir Srinagar	University of Calcutta Kolkata	Banaras Hindu University Varanasi
IIT, Indore	Bhabha Atomic Research Centre Mumbai	Saha Institute of Nuclear Physics Kolkata	IIT-Bombay
University of Delhi Delhi	IIT-Guwahati	National Institute of Science Education and Research Bhubaneswar	University of North Bengal Siliguri
IIT-Roorkee	Gauhati University Guwahati	Pune University, Pune	South Gujarat University Surat
National Institute of Technology Jalandhar	MSUniversity Vadodara	Magadh University Bodh Gaya	

Technology developed

- Ultra High Vacuum Chambers for housing beam diagnostic equipment at FAIR. The challenges involved are very thin walls and upto seven flanges.
- Superconducting Magnets with very high accuracy: large size magnets (dipoles and multipoles) have been designed by Indian engineers
- Beam stoppers: stop very high intensity Uranium beams in an absorber equipped with proper cooling arrangements. It has been designed in India and will be built by an Indian company.
- Power Converters: These are the devices that energize the superconducting magnets of the accelerator. They need to be ultra stable in voltage and current.
- Gas Electron Multiplier (GEM)-based muon detection system.



GEM prototype fabrication at VECC

Power converter

Indian industries involved

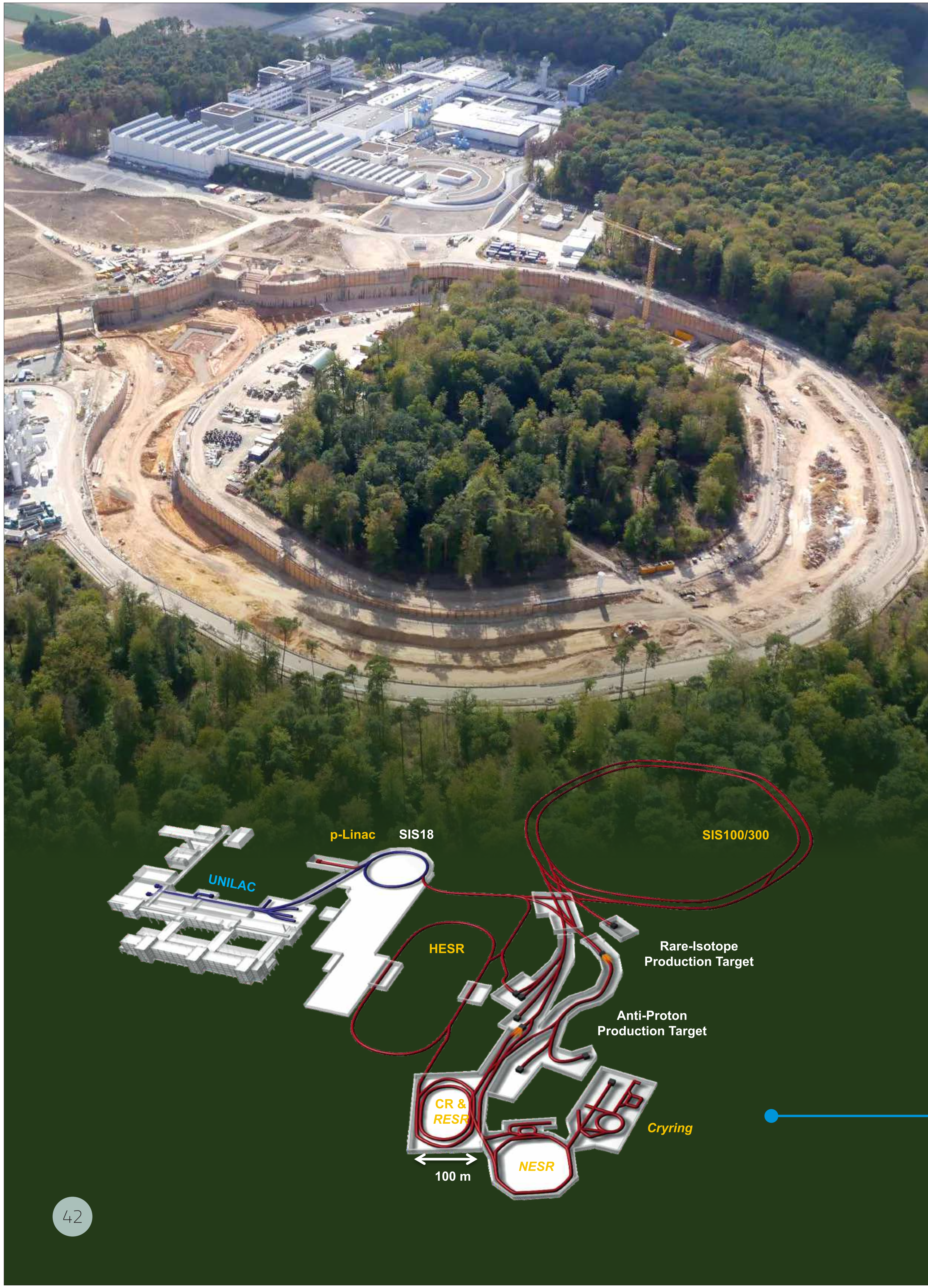
- Electronics Corporation of India Limited (ECIL), Hyderabad
- iDesign, Pune
- Cadillac Filters Private Limited, Kolkata
- Avasarala Industries, Bangalore
- Godrej Industries, Mumbai
- RPG Industries,Mysore
- Vacuum Techniques Pvt. Ltd, Bangalore

Contact person/Spokesperson

Dr. Subhasis Chattopadhyay
Variable Energy Cyclotron Centre
1/AF, Bidhan Nagar, Kolkata 700064, Email : sub@vecc.gov.in

Website

https://fair-center.eu



Facility for Antiproton and Ion Research

The Facility for Antiproton and Ion Research (FAIR) coming up at Darmstadt-Germany is arguably the largest upcoming basic science facility in the world. GSI, a German nuclear physics laboratory discovered several elements (e,g, Darmstadtium, Hessium etc) in the periodic table with pioneering contributions in the field of nuclear physics research over decades. It was decided that GSI be upgraded as an International facility with wide ranging physics exploration potential. On 4th October 2010, FAIR-GmbH was formed with India as the 3rd largest contributor after Germany and Russia. The main accelerator ring of FAIR is a synchrotron of 1.1 km circumference, 60 m wide and of 100 Tm rigidity. A few major features of this facility are (a) providing beams concurrently to four major fields of physics research and applications (b) high intensity beams for both stable and rare-ion species, the intensity for rare ion beams goes upto 10000 times higher compared to the existing GSI availability (c) acceleration of protons to Uranium ions and antiprotons (d) energy range from few MeV to 45 GeV/A, varying with ion species. Fig.1 shows a schematic view of the FAIR facility, showing the extension of existing GSI facility at left to the new FAIR facility shown by colored lines.

Fig.1: Schematic view of the FAIR facility. GSI is shown at the left. Beams from GSI will be injected to the main SIS100 ring and after acceleration will cater to four physics pillars. The switching building after SIS100 is crucial in delivering beams to different research facilities in parallel.

Unlike many such large projects, FAIR is to cater to the interests of four major research communities i.e., High Energy Nuclear physics, Nuclear Reactions, Structures and Astrophysics, Atomic & Plasma physics and Hadron physics using antiprotons. A varying science interest makes this facility attractive to a large international community including Indian researchers. Fig.2 shows schematically the regions of evolution of universe that FAIR physics programme will explore.

The evolution of the universe

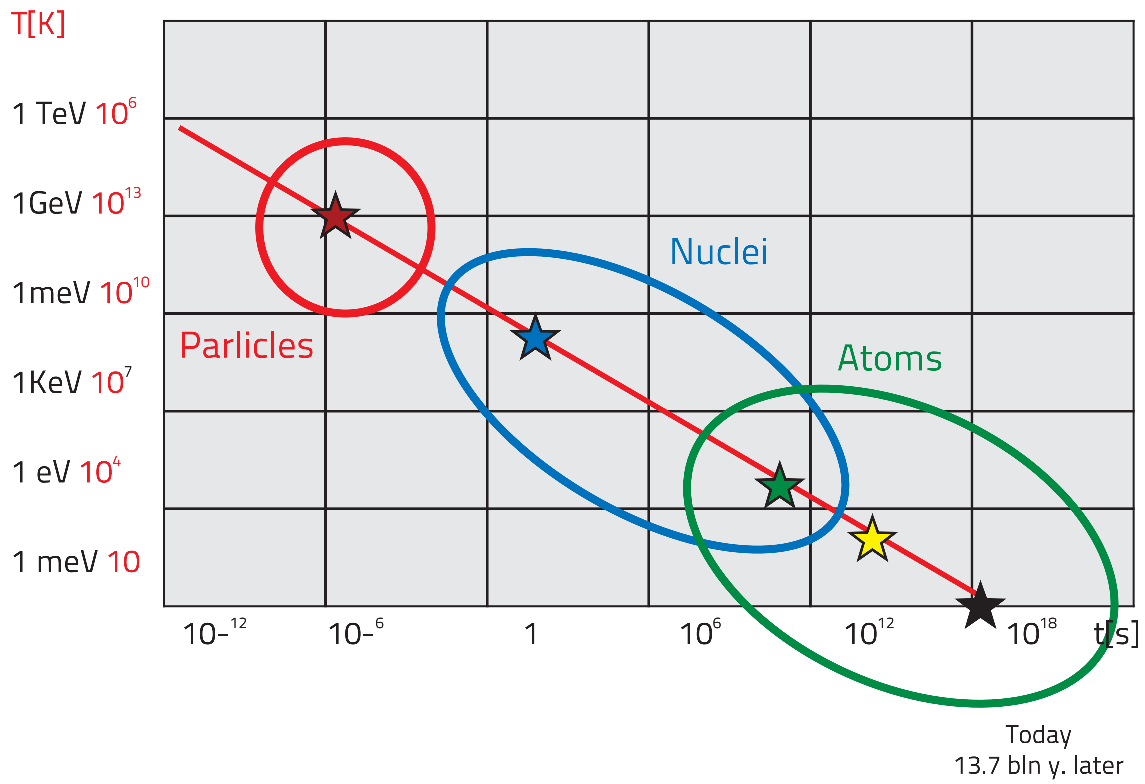


Fig.2: Regions shown in the evolution of the universe that are to be explored by FAIR such as high energy nuclear physics will explore microsecond-old universe, nuclear physics about a second after the Big B and atomic physics in the later part as shown above.

The project has made significant progress so far both in civil construction, accelerator components and experiment facilities. Fig.3 shows a snapshot of the civil construction showing the building of a portion of the tunnel.

Fig.3: A part of the SIS100 tunnel.

Some of the main features of the accelerator equipment are as follows:

1. Rapid-cycling magnets
2. Dynamic vacuum
3. High energy electron cooling

Physics programme of FAIR:

Some of the major science questions to be answered by FAIR are as follows:

- Why do we not observe individual quarks, the basic building blocks of strongly interacting matter?
- What is the origin of the masses of strongly interacting matter called hadrons. Note that the Higgs mechanism cannot explain the total mass of hadrons.
- What is the origin of elements?
- What is the structure of neutron stars?
- Can we ignite the solar fire on earth?
- Does matter differ from antimatter?

Below is a brief description of each of the experiments covering four pillars in the physics explored by FAIR

(a) Nuclear Structure Astrophysics and Reaction (NUSTAR): This setup, mainly facilitated by the super-proton synchrotron (Super-FRS) at FAIR, uses stable proton and neutron-rich rare ion beams (RIB) that explore the formation of nuclei and their structures. Exotic states of nuclear physics with non-conventional shapes and sizes such as, pigmy-resonances, are to be produced and studied at FAIR. It also studies the nuclei which are far from stability (stable nuclei have similar proton and neutron number) and formation of heavy elements in stars and supernovae. Major experimental setups like DESPEC/HISPEC and R3B will be installed to study the short-lived nuclei and their reactions.

(b) Pbar ANnihilations at DArmstadt (PANDA): This experiment will use antiproton beams to bombard various targets and produce short-lived states that will decay to reveal various features of hadron structures. This experiment will also explore the production of theoretically allowed but so far unobserved states like glueballs multiquark states among others. The uniqueness of PANDA is to employ very high quality beam particles in their studies.

(c) Compressed Baryonic Matter (CBM): This experiment that studies compressed baryonic matter will produce a medium similar to that at the core of the neutron star and of a density several times the nuclear matter density. At such a high density, nuclear matter is said to undergo a transition to a phase consisting of free quarks and gluons, the basic constituents of strongly interacting matter. The medium created in the collisions of accelerating ions with various targets would be studied using a set of observables to test the production of such a free state of quarks and gluons. The uniqueness of the experimental setup is to be equipped with detector systems that can detect particles coming out of the initial state of the collision. Such rare and penetrating probes allow unambiguous study of the system .

(d) Atomic, Plasma Physics and Applications (APPA): This setup studies atomic and plasma physics at FAIR. Beams with extreme electric field like Uranium beams with only one electron are examples of testing ground of Quantum ElectroDynamics (QED) at extreme conditions. High power lasers are used to perform spectroscopy. High intensity beams, when stopped in a thick cylindrical target produce ionic plasma of high density, which can be studied. FAIR beams can also be used to simulate radiation effects in space and effect on biological specimens among others.

India's role at FAIR:

India is a founder member of FAIR committed to contribute about 3% of the construction cost of 1.2 BEuro project. India's contribution is mostly in terms of contributing accelerator equipment and detectors as in-kind contributions.The equipments that have been identified so far to be built in India for FAIR are given below.

1.Power converter: A large fraction of magnets (at room temperature and superconducting) that will be used for FAIR accelerator will be powered by power converters being built by ECIL-Hyderabad, India. These devices will give required voltage with sufficient current capacity to energise the magnets. In total, it will be about 750 power converters to be built in India. A prominent feature of these devices is voltage and current stability of the order of 100 ppm. After several rounds of R&D in collaboration with FAIR engineers, ECIL has got clearances to ship 67 power converters. The procurement and production for next sets of power converters are underway.

2.Ultra-high vacuum chamber: About 70 vacuum chambers will be provided as Indian contribution. These chambers, to be installed in FAIR beam lines, will house the beam-diagnostic equipment. These chambers are to maintain vacuum level of 10-9 mili-bar pressure. Production of these chambers need to overcome several challenging features: special quality of steel to be used as materials, the quality of welding and other manufacturing process require special handling, multistep cleaning to ensure vacuum quality. Major challenge is to weld upto 7 cylindrical pipes on a barrel and finally to maintain mechanical tolerances at the level of tens of micrometers. The technology demands extreme care and quality control.

3.Beam stoppers: Uniqueness of FAIR is its high intensity beams of different species. The nuclear physics research programme requires rare ion beams that are produced by bombarding high energy Uranium ion beams on a thick target. The products and primary beam are stopped except the selected beam particle. The stopping of primary and secondary products requires special techniques of cooling and materials to withstand the power absorption. A team from Central Mechanical Engineering Research Institute (CMERI)-CSIR, Durgapur has completed the design work of this special device which has been cleared by the FAIR team. Efforts are underway to build such a device from this design.

4.Superconducting magnets: FAIR is mostly a superconducting accelerator using magnets of various size and strength. Indian designers have completed the design of a set of superconducting magnets each weighing about 90 ton. These magnets are to be installed in the low-energy nuclear physics research beamline. The design has been cleared by FAIR and has been credited to the Indian team.

5.Power cable: Indian industry is working to produce about 180 km co-axial cables to be used to connect the magnets with the power converters. Samples built by the Indian industry have been cleared by FAIR.

Apart from accelerator equipment, Indian researchers are also involved in building advanced detectors for the FAIR experiments. Even though about 40 groups expressed interest in performing the experiment at FAIR, presently Indian researchers are working on detector development for two physics pillars, namely, CBM and NUSTAR.

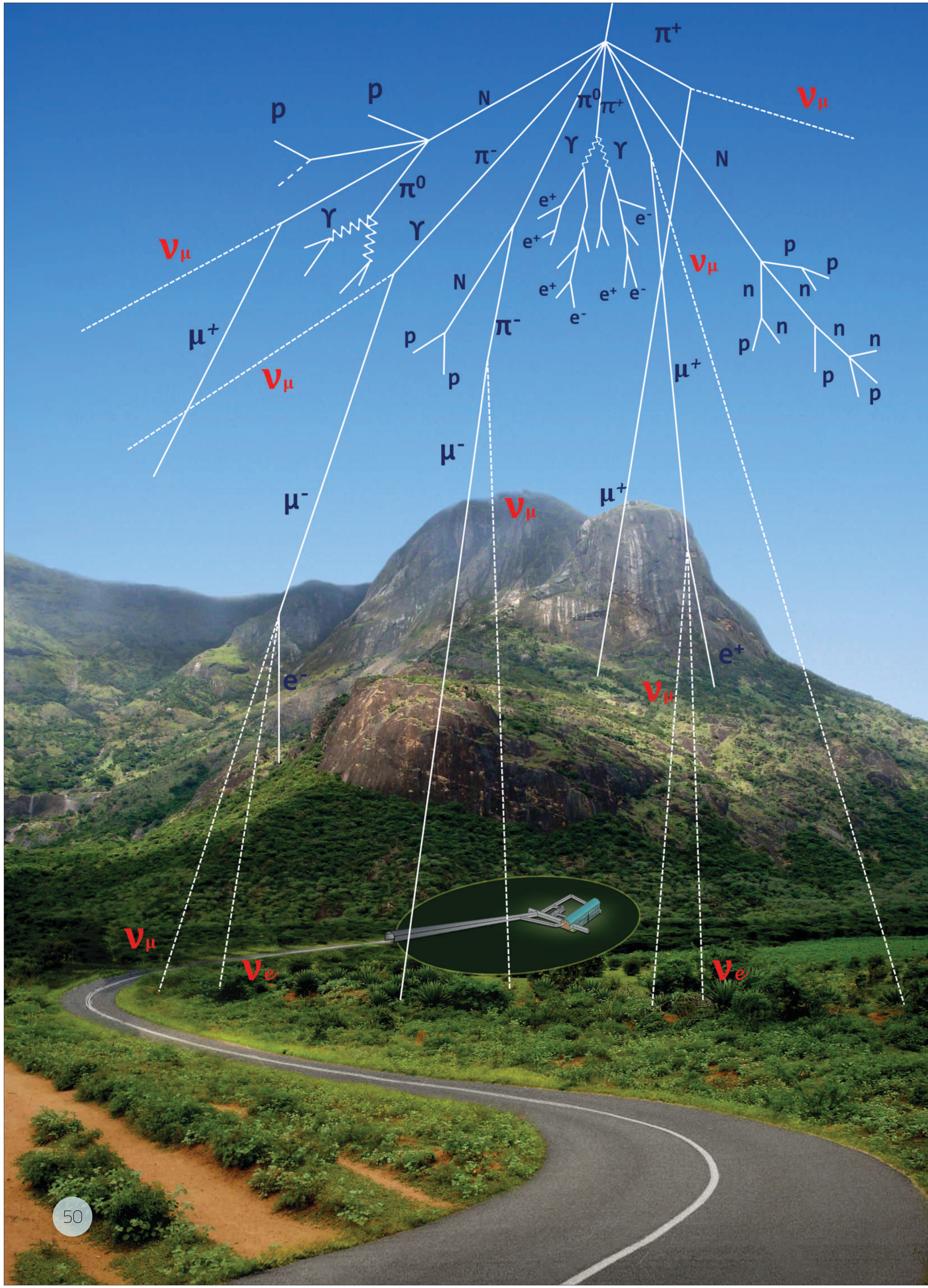
CBM experiment explores strongly interacting matter at high net-baryon density created in heavy ion collisions at FAIR energy. The debris from these collisions are to be detected for inferring details of the medium created. Emphasis of the CBM setup is to detect the particles created at the beginning of the collision. These particles will carry information on the initial state of the medium. One of the most interesting physics goals of CBM is to study the creation/modification of masses of hadrons. This can be studied by detecting particles that remain unaltered throughout the evolution of the collision zone. One such probe is muon-pairs that remain unaffected by the surrounding medium. Indian researchers are involved in development and building of detectors for muons. These detectors work on a principle of using a thick absorber segmented into several slices with detector medium like gas/silicon placed in between slices. Muons being weakly interacting pass through the absorber slices and leave signals in the detectors while passing through them. Other particles like pions that are strongly interacting interact with the absorber material and stop at an intermediate stage. The path of these penetrating muons will help obtain its momenta. One challenge for such detectors is to cope with very high interaction rate due to the high intensity beams. The detector and readout electronics therefore needs to be radiation hard and capable to handle high particle rate. Indians are working on a technology based on gaseous detector called Gas Electron Multiplier (GEM). These wireless gaseous detectors built by Indian researchers have been found to handle particle rate upto 3 MHz/cm2. Two large size (80 cm x 40 cm) sector-shaped GEM chambers have recently taken data in the phase-0 programme of FAIR.

NUSTAR experiment aims to study the nuclear physics far from stability line i.e., nuclei that have large asymmetry in proton and neutron number (N/Z ratio). These rare beams can be used to perform experiments producing exotic states and explain the production of different types of nuclei. In this setup, either the spectroscopy of the decay products from the compound formed by collision of the beam with target nuclei (DESPEC) is carried out, or in-beam spectroscopy with high intensity beams (HISPEC) is performed. Indian researchers are involved in building neutron and gamma detectors for the DESPEC setup. High resolution setup will make use of precision mechanical setup for holding the crystals for gamma spectroscopy. For neutron detectors, specially designed liquid scintillators are used to capture neutrons and discriminate them from gamma rays.

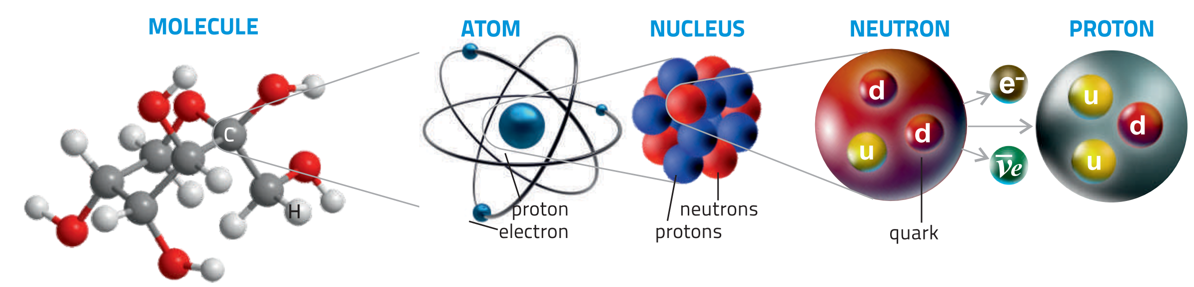
Fig. 4: (left) Two GEM chambers are ready to take data at GSI-Germany (right) a GEM chamber being assembled at VECC-Kolkata

Industry involvement in FAIR: FAIR is a technology marvel and will use the most advanced technologies in various fields like power converter, superconductivity, computing with low power consumption, high speed data acquisition and transfer, online data processing, ASIC development among others. Indian industries are involved in several challenging technological products as mentioned earlier. Several industry meets have been held for discussions with industry partners on various accelerator equipment. Presently, all industrial activities are being performed in collaboration with FAIR engineers thereby helping to improve the product quality control.

Human Resource Development (HRD): There are two types of HRD in this project, first one is development of technologists capable of handling front-ranking products for FAIR and science students trained and involved in front-ranking research, detector technology and discovery science. In India, about 40 groups shown interest in FAIR science and so far six students have obtained their PhD degrees even in the development phase.



India-based Neutrino Observatory



Hunting the elusive neutrino

The India-based Neutrino Observatory (INO) project is an ambitious basic science project aimed at studying the properties and interactions of the elusive elementary particle called neutrino. The Government approved the INO project in January 2015. This included the construction of an underground laboratory at Bodi West Hills (BWH) in Theni district, Tamil Nadu, setting up the flagship Iron Calorimeter (ICAL) detector there and the Inter-Institutional Centre for High Energy Physics (IICHEP) in Madurai. IICHEP would be the nodal centre for Research & Development of the associated detector technology and would run the underground laboratory in Theni. The key advantage of constructing a laboratory in a cavern in a mountain accessed by a 2km tunnel, with an all-round rock cover of about 1000m, is that it offers a low cosmic ray background environment (since the cosmic rays and secondary particles produced in their interaction with the upper atmosphere are filtered by the rock cover above the laboratory cavern). This is necessary for specialised experiments making measurements with neutrinos which interact very rarely with the detector material. In particular, ICAL will detect and measure atmospheric neutrinos to study the neutrino properties, including the mass ordering of the three tiny neutrino masses using matter enhanced neutrino oscillations. The ICAL detector can also be used to search for evidence of long-range interactions between neutrinos and matter, dark matter annihilation occurring in the sun, primordial magnetic monopoles and evidence for or against the anomalous events found by the proton decay detector in Kolar Gold Fields. Finally, the underground laboratory will also provide a conducive environment for other experiments. For example, a collaboration led by a TIFR group is working towards search for neutrinoless double beta decay in tin-124 using a cryogenic bolometer. Similarly, a collaboration led by SINP is planning to set up an experiment to search for Dark Matter using a cryogenic scintillator. The initial background studies have begun in a laboratory at -550m level in the Jaduguda mines.

Collaborating Institutes in India

		Aligarh Muslim University Aligarh	American College Madurai	Banaras Hindu University Varanasi
Bhabha Atomic Research Center Mumbai	Central Univ. of Karnataka Gulbarga	Delhi University Delhi	Harish Chandra Research Institute Allahabad	Indian Institute of Science Education & Research Mohali
Indian Institute of Technology Bombay Mumbai	Indian Institute of Technology Bombay Gandhinagar	Indian Institute of Technology Madras Chennai	Institute of Physics Bhubaneswar	Institute of Mathematical Sciences Chennai
Jammu University Jammu	Jawaharlal Nehru University New Delhi	Lucknow University Lucknow	Panjab University Chandigarh	Physical Research Laboratory Ahmedabad
Saha Institute of Nuclear Physics Kolkata	Tata Institute of Fundamental Research, Mumbai	Tezpur University Tezpur	University of Calcutta Kolkata	University of Calicut, Calicut
Univ. of Hyderabad, Hyderabad	Univ. of Kashmir Srinagar	Univ. of Mysore, Mysore	Utkal University Bhubaneswar	Variable Energy Cyclotron Center Kolkata

Technologies developed

Extruded polycarbonate side spacers and spacer buttons for RPCs; 1m x 1m, 2m x 2m Glass Resistive Plate Chambers with resistive graphite coating; front-end electronics; in-house developed boards for Data Acquisition, Trigger Module and Time Calibration. High-permeability low-carbon soft iron steel for ICAL; Layered Electro-Magnet (85 ton mini-ICAL module); induction heating based copper joint brazing technology; inductive proximity sensor based system for continuous gap measurement between two iron plate layers; magnetic measurements system with multiple search coil pickup loops (for magnetic flux) and arrays of Hall probes based measurements (for B-field strength in inter-plate gaps); closed loop chilled water system for cooling current carrying coils in mini-ICAL and associated DC power supply; RPC trolley (8m high) to place and remove 2m x 2m RPC from ICAL.

Iron calorimeter (ICAL) prototype

Indian industries/agencies involved

Consultancy : Tata Consulting Engineers, Mumbai (ICAL magnet DPR); Tamil Nadu Electricity Board, Chennai (INO DPR); Mitcon Consultancy & Engineering Services Ltd, Pune (MoEF & CC clearance); Pro Designa Consultants, Madurai (Civil works approval for IICHEP, INO site civil construction); Walch and Technology Group, Pune (Project Report for RPC manufacture).

RPC glass gaps : St. Gobain (Sriperumbudur); Asahi-India (Taloja); Cybernetic Instruments (Pune).

Closed loop gas system : Alpha Pneumatics (Mumbai); Shriram Automation (Mumbai).

Resistive coating of graphite paint on glass : Kansai-Nerolac (Mumbai).

Paint booth: Green Glory Technologies, Chennai.

RPC trays and pickup panels : Honeycomb International Inc. (Bengaluru); Nexgen Plastics (Mumbai); S. M. Enterprises (Pune); Fibre Reinforced Industry Ltd. (Pune).

Polycarbonate spacers for glass gaps : Ashwin Plastics (Mumbai); Studio CNC (Mumbai).

Low carbon magnetic grade steel plates : Steel Authority of India Ltd. (Bhilai); Essar Steel (Hazira).

Electronics boards of many types : Rangsons (Bengaluru); Dexcel (Bengaluru); PCB Power Circuit Systems India Ltd. (Gandhinagar).

RPC handling equipment, mini-ICAL assembly : Jalaram Industries (Mumbai); P Chandru Machine Tools (Vellore); Green & Green Engineering Solution (Coimbatore).

Magnet Power Reversal switch and gap measurement system - M/S Integrated systems Pvt. Ltd. (Mumbai).

Magnet coil support G-10 material : Autoelectrical & Mechanical works (Mumbai).

Soft iron plate and SS Spacer-Pin machining : Bhilai Engineering Corporation (Bhilai).

Magnet coil forming and fabrication : Centre for Design & Manufacturing, BARC (Mumbai).

Special Induction based brazing machine : Microtech Industries (Mumbai).

Low conductivity cooling water system: Entech industries (Bengaluru).

Magnetic Measurement Systems : Ferrite India (Pune).

Contact person/Spokesperson

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vivek.datar@gmail.com

Website

www.ino.tifr.res.in

The INO project – Hunting the Elusive Neutrino

Introduction

All of the matter that we see around us is composed of atoms, whose constituents are electrons, protons and neutrons. Protons and neutrons are not "elementary" particles but are made up of quarks. As of now, electrons and quarks are not believed to be subdivided any further. These elementary particles are members of a larger family of quarks and leptons that interact with one another through the exchange of "force carrier" particles: photons (electromagnetic interactions, responsible for holding the atom together, for example), "$W^{\pm}$ and Z^{0}" (weak interactions, responsible for beta decay, for example) and gluons (strong interactions, binding the quarks in neutrons and protons, for example). There are 3 families of quarks and leptons and each have their own anti-particles (except perhaps for neutrinos, who could be their own anti-particles). The Higgs boson, discovered experimentally in 2012, endows masses to these particles and completes our present understanding in terms of the Standard Model (SM) of particle physics.

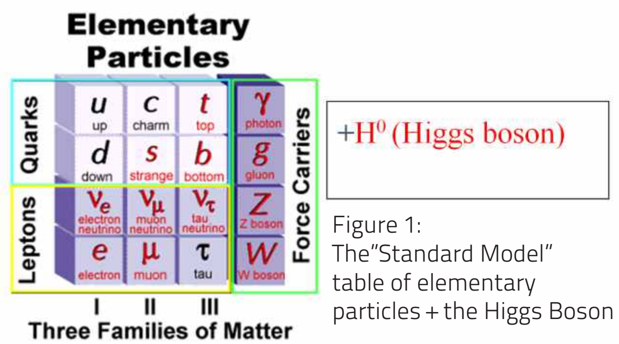


Figure 1: The "Standard Model" table of elementary particles + the Higgs Boson

(image courtesy: http://www2.slac.stanford.edu /wc/theory/fundamental.html)

The neutrino is one of the most enigmatic of the fundamental particles that we know [1]. It was proposed by Pauli in 1930 to explain the continuous energy spectra of electrons in beta decay. Soon after, Fermi wrote down the quantum theory for beta decay, on the lines of Dirac's quantum theory for the interaction of light and matter. The interaction probability of neutrinos was estimated by Bethe and Peierls to be so tiny that it would be "impossible to detect".

The Standard Model of particle physics has been very successful in understanding almost all that we know about particles and their interactions (electro-weak and strong) except the gravitational interaction. The last building block in this theory, the Higgs boson, was discovered recently and led to a Nobel prize in Physics in 2013. In the SM, whose predictions have been extensively verified, there are three kinds of neutrinos, one each associated with the electron, muon and tau lepton families and have zero masses. The phenomenon of transformation of neutrinos from one type to another, called neutrino oscillation, goes beyond the SM. It was confirmed experimentally by the Super-Kamiokande collaboration (1998) measuring atmospheric neutrinos and by the Sudbury Neutrino Observatory (2002) measuring solar neutrinos. Neutrino oscillations require neutrinos to possess a non-zero mass and non-conservation of flavour number.

Neutrinos can be described in terms of their 'flavour states" (electron, muon, or tau) or non-conservation of terms of their "mass states" just as in geometry a point can be described in terms of Cartesian coordinates (x,y,z) or polar coordinates (r,θ,φ). While the latter two descriptions are connected by a 3×3 matrix with real numbers, the neutrino states are connected by a 3×3 complex matrix. If we discover one or more species of sterile neutrinos then this matrix would have to be suitably expanded. Presently, efforts are being made throughout the world in order to pin down the parameters constituting this matrix, which are the three 'mixing angles" (symbols used are θ_{12}, θ_{13}, θ_{23}), three masses (m_1, m_2, m_3) and a CP phase angle (which increases to three angles if the neutrino is its own antiparticle). If neutrinos do not behave the same way as anti-neutrinos (that is, if there is particle-antiparticle asymmetry) this angle cannot be 0^{0} or 180^{0}. Experiments addressing neutrino oscillations measure the differences in the squared masses. The results of solar neutrino experiments can be understood when matter effects on the electron neutrinos, propagating outward from the core of the sun, are considered. This fixes the ordering of the masses of the m_1 and m_2 mass eigenstates, namely, $m_2 > m_1$. Data from accelerator experiments result in a value for $|m_3^2 - m_2^2|$. Since this is about 30 times larger than the corresponding difference for m_1 and m_2, the mass of third neutrino m_3 could be larger or smaller than m_1 and m_2. These situations correspond to the normal and inverted mass hierarchies.

Why is it important to know which of these hierarchies is followed in nature? Accelerator based experiments measuring neutrinos at long baselines usually have a hierarchy - CP phase ambiguity. A clear answer on the mass hierarchy could help measure unambiguously a possible CP violation in the neutrino sector. If it turns out to be sufficiently large it could help solve the matter-antimatter asymmetry in the universe, one of the most important problems in science.

The India-based Neutrino Observatory (INO)

Experimental evidence for atmospheric neutrinos was found in a deep mine at Kolar Gold Fields (KGF) by the TIFR-Osaka-Durham collaboration and almost simultaneously by a team led by Reines working at a gold mine in South Africa. However, building larger detectors in the mine, especially at the deepest level which is the ideal location, was not possible. Also the KGF became economically less competitive compared to other gold mines and were eventually closed down. Meanwhile, in the late 90's an effort began to revive the culture of underground experiments in India, focusing on neutrino experiments. Building such a lab at the end of a tunnel, such as at Kamioka in Japan and Gran Sasso in Italy, was a better option for housing large detectors. At around this time, the field of neutrino physics was becoming very interesting in view of results from the Kamiokande-I, Irvine-Michigan-Brookhaven and later Super-Kamiokande experiments, which turned the background event data for proton decay (for whose lifetime only upper bounds could be placed) measurements into a signal for atmospheric neutrino oscillations !

The idea of building an underground laboratory in India began with the signing of an MoU by the directors of six institutes of the Department of Atomic Energy (DAE) in 2002. Early on, it was decided that we would build a 50-100 kton magnetized iron calorimeter (ICAL) to study atmospheric muon neutrinos. This would be unique in that it would have the capability of distinguishing between neutrino and anti-neutrino induced events using the so called charged current interactions which produce muons of opposite charge, respectively. A similar proposal, MONOLITH, had been considered by an Italian group with a somewhat smaller, 32 kton detector. Simultaneously, R&D was started on simulations (both for neutrino detection and the magnet) and the active detector element. The choice for the latter fell on the glass Resistive Plate Chamber (RPC) which is a position sensitive, fast gas detector. The first document was prepared in May 2006 and the most recent information may be found in a white paper on the physics capability of ICAL at INO. There are about 25 national labs and universities collaborating in the INO project. The funding for the project, of about 1600 crore rupees (approx. $ 230M), was approved by the central government as a joint DAE-Department of Science and Technology project in December 2014. One of the important goals of INO is to contribute to human resource development in the area of Experimental High Energy Physics and Nuclear Physics. Presently the INO Graduate Training Programme, under the Homi Bhabha National Institute (through one of its constituent institutions, namely, Bhabha Atomic Research Centre) is in its 11^{th} year and has already led to about 15 PhD theses. Apart from the INO GTP, there are several students who have completed their PhDs at various collaborating Universities and IITs. While INO is the largest project of its kind in India when proposed in 2006, it aims to set up a world class laboratory dedicated to cutting edge research primarily in the area of neutrinos but also providing possibilities to other areas that benefit from the low cosmic ray background in underground caverns.

INO is a proposed underground laboratory located in the southern Indian state of Tamil Nadu at Pottipuram in Theni District. The experimental halls are proposed to be constructed at the end of a two km long tunnel in a hill, with about one km rock cover all round the hall. This will reduce the cosmic ray background by about a factor of a million, enabling low background experiments to be carried out. While the ICAL detector for measuring atmospheric muon neutrinos will be the largest in the underground laboratory, there are at least two other experiments which make use of the low cosmic background to search for neutrino-less double beta decay in ^{124}Sn (an isotope of the tin, the metal) and a scintillating cryogenic bolometer for directly detecting dark matter particles.

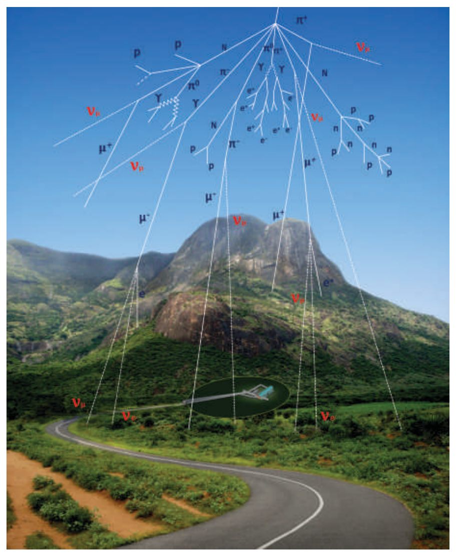


Fig. 2: Graphic of the proposed INO Lab tunnel complex under the mountain at Pottipuram, Theni district of Tamil Nadu.

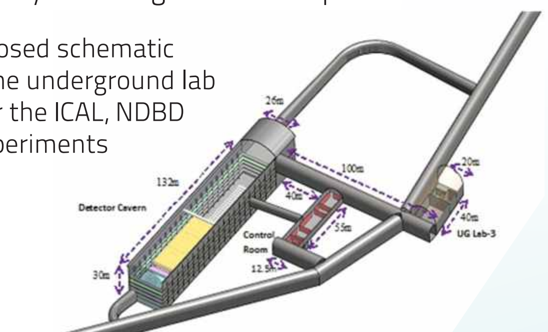


Fig. 3: Proposed schematic details of the underground lab complex for the ICAL, NDBD and DM experiments

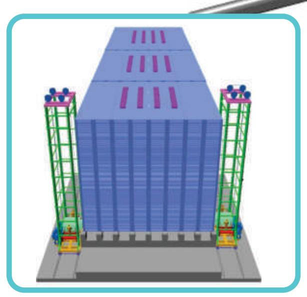


Fig. 4: Schematic of the three modules of the ICAL. Also shown are the two trolley lifts that will be used to access higher parts of the ICAL

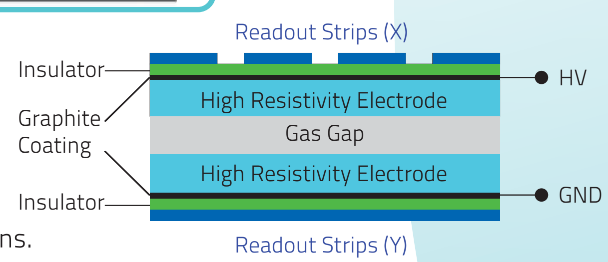


Fig. 5: Schematic of a Resistive Plate Chamber (RPC) that will detect charged particles such as muons.

Some of the important scientific goals of the ICAL experiment are (i) the determination of the ordering of neutrino masses, known as the mass hierarchy problem viz. whether $m_3 > m_2 > m_1$ (normal hierarchy) or $m_2 > m_1 > m_3$ (inverted hierarchy); (ii) a more precise measurement of the mixing parameters θ_{23} and Δm_{23}^2; and (iii) together with long baseline accelerator experiments, address the very fundamental problem of the predominance of matter over antimatter in the universe. The ICAL detector is best suited for such measurements because of its ability to distinguish between muon neutrinos and muon anti-neutrinos by identifying the μ^- and μ^+, respectively, resulting from neutrino interactions with iron, through the opposite curvature of tracks for a given direction.

The hierarchy sensitivity of the ICAL detector has its origin in the 'matter effect" where the effective neutrino mass and mixing angles change when neutrinos propagate through any material such as the earth. The change is different for neutrinos and antineutrinos, something which can be used in measurements that can discriminate between the two such as those with

the magnetic calorimeter ICAL. The large range of energies (1-10 GeV) and propagation distances (1-13000 km) of atmospheric neutrinos and the ability of ICAL to separately measure neutrinos and antineutrinos gives it an edge over other large detectors that do not have this ability. Other goals of ICAL include searches for exotic particles.

In addition, ICAL could search for non-standard neutrino interactions, sterile neutrinos, dark matter annihilation in the sun's core, anomalous events observed during the course of the proton decay experiments at Kolar Gold Fields, primordial magnetic monopoles with a better sensitivity than the best experiments and also use matter effects to probe the earth's interior.

There are also other experiments at the INO for which R&D or feasibility studies are ongoing. The first group aims to measure neutrino-less double beta decay in ^{124}Sn using a tin bolometer cooled to a temperature of ~10 milli-Kelvin. The first thermal signals from a small sample of natural tin have been observed. Another group is aiming to build a cryogenic scintillating bolometer to study dark matter. Initial R&D has commnenced at the -550m level in Jaduguda mine in Jharkhand. Finally, there is interest from university groups to set up a low energy accelerator facility to measure cross sections of interest to nuclear astrophysics.

Fig. 6: Cryogen free dilution refrigerator (CFDR) at TIFR

Figure 7: Tin Bolometer for NDBD experiment

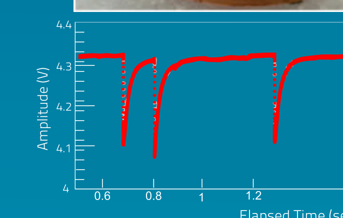


Fig 8: The slow pulses from the Tin Bolometer

In order to gain experience, several smaller efforts were undertaken that would help in the construction of the massive 51 kton ICAL detector. A 12 detector stack of 1m×1m glass RPC detectors was set up at TIFR measuring cosmic ray muons. It allowed a study their long term behaviour as also in the design, trouble-shooting and improvement of several other sub-systems viz. gas system, analog and digital front end electronics, high voltage module, trigger module, data acquisition board etc. Next, a stack using 2m×2m glass RPC was set up at the transit campus of INO at Madurai. A little prior to this, an 11 layer 2.3m×2.5m magnet was set up at the Variable Energy Cyclotron Centre at Kolkata and was useful in identifying problems in magnet construction and detector electronics including ElectroMagnetic Interference (EMI) issues.

An 85 ton, 4m×4m×1.2m size, 11 layer mini-ICAL detector was planned for the transit INO campus at Madurai to address issues of (a) construction of the magnet using 56mm thick low carbon, magnetic grade steel (b) magnetic field measurement systems of two kinds (using Hall probes in intentional 3mm gaps between plates and pick-up loops sensing ramp-up and ramp-down of magnet current in 3 layers) and exploration of a third method using muon spin rotation using stopped cosmic muons (c) long term performance of 2m×2m glass RPCs using a closed loop gas system (d) performance of electronics in RPC detector module in presence of fringe magnetic field and EMI (e) low conductivity chilled water system for cooling current carrying coils in mini-ICAL magnet (f) measurements of cosmic ray muons and comparison with simulations and (g) prototyping a cosmic muon veto detector surrounding mini-ICAL. Mini-ICAL and its ancillary systems were put together over a period of about 3 months by INO collaborators, including engineers from BARC, TIFR and VECC, and students. It has been functioning since June 2018 with 10 nos of 2m×2m glass RPCs placed at the centre, in the region of near homogeneous magnetic field in adjoining iron plates (see Fig. 4). This exercise has brought out some strengths and a few weaknesses that will be very useful in constructing the 600 ton, 8m×8m×2m, 21 layer engineering ICAL detector (e-ICAL) in the next 2 years. This will also serve as a test bench for the RPC detectors which are required in large numbers. A cosmic muon veto detector is also planned for the mini-ICAL detector and (e-ICAL)

Fig 9: mini-ICAL coil and magnet assembly in progress, using a gantry crane

Fig. 10: Induction brazing of the upper C-section to the U-Sections of 30mm x 30mm OFHC copper conductor of 17mm bore through which cooling water will be pumped.

Fig. 11: Assembly of RPC detectors prior to insertion into the mini-ICAL magnet (left) and students testing various electronics (right)

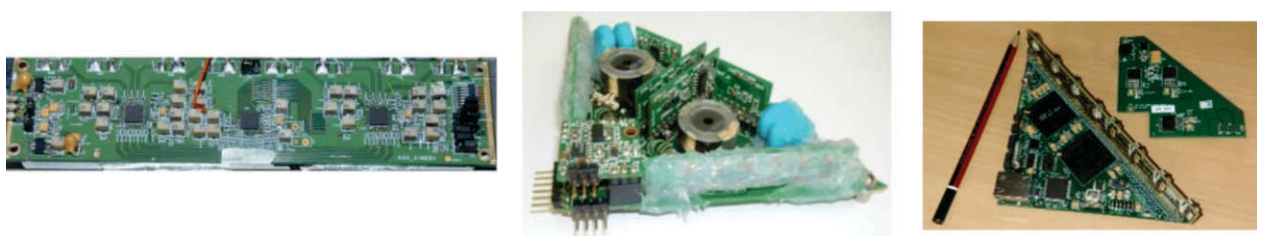
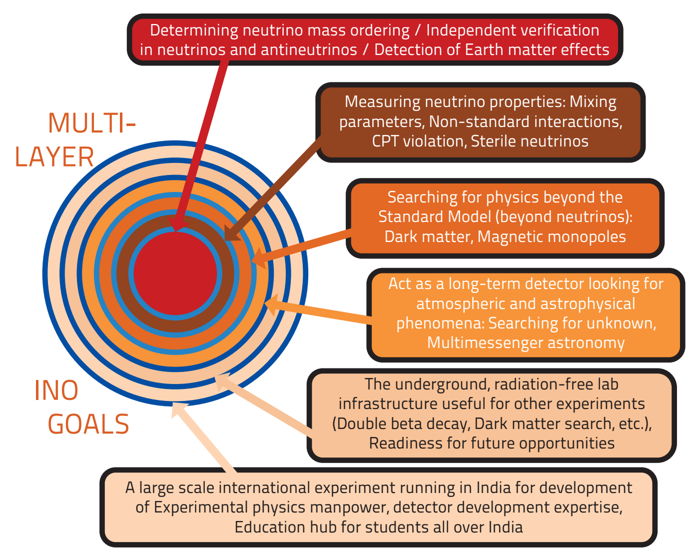


Fig: 12: (L to R) Front-end electronics board with 8-channel amplifier and discriminator, ±5kV DC module, DAQ board. All developed in house.

Fig 13: Low conductivity chilled water system for cooling the current carrying coils of the mini-ICAL magnet (left) and a view of the assembled mini-ICAL (right)



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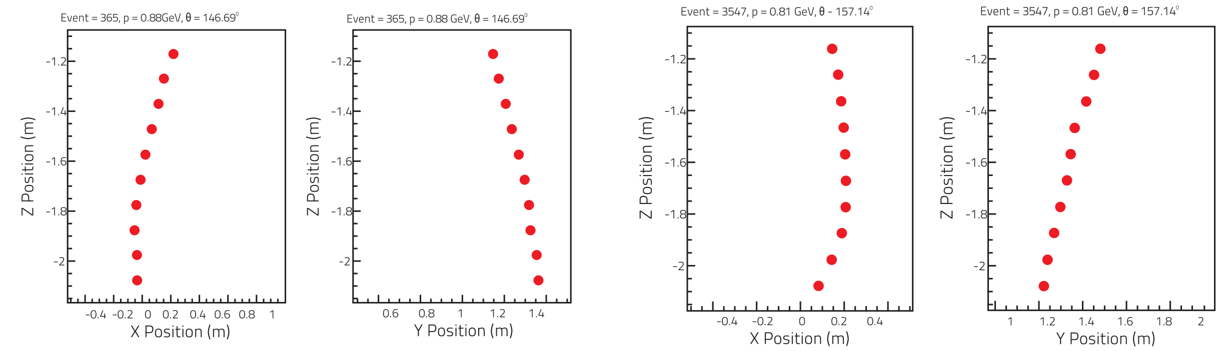

Fig. 14: Examples of cosmic muons, of either charge, firing various layers of the RPC's (at various Z positions) caused by their traversing the mini-ICAL detectors from top to bottom. The bending can be seen in the X-positions but essentially no bending in the Y-positions.

Successful industry interface

The INO project has incubated various cutting edge technologies for building a large underground research facility, the world's largest and massive 50 kton electromagnet, 30,000 fast and highly sensitive particle detectors called RPCs covering an active area of 100,000 m^2, an on-line multi-gas mixing, distribution and purification system for supplying 200,000 litre of gas mixture to the RPCs, sophisticated ASIC and FPGA based signal processing electronics, trigger and data acquisition systems, etc. The entire R & D efforts for the project were carried out in-house at various participating institutions using locally available materials and components to the extent possible. A conscious and consistent effort at developing local solutions for needs as diverse as raw materials like glass and bakelite, electronics, gas-mixing units, and RPC fabrication, has been made. A successful INO-Industry interface was developed because of the large scale of experimental science activity involved. Local industries are already key partners in building the ICAL detector and other laboratory infrastructure. About 100 local industries were roped in to work on upscaling lab R&D to industrial production and all the way to installation of the detectors.

Figure 15: A view of the RPC gap making procedure at the Saint-Gobain glass factory near Chennai

Current Status of the Project

The current status of the project is that the Environmental Clearance has been obtained and the Wildlife, Building construction and Pollution Control Board clearances are awaited.

In summary, the India-based Neutrino Laboratory is poised for building an underground laboratory in Pottipuram, Tamil Nadu in the southern part of India. The flagship experiment aims to address the neutrino hierarchy problem using a 51 kiloton iron calorimetric detector. The underground lab will also house other experiments that benefit from the low cosmic ray background.

References

[1] For a popular introduction to neutrinos visit http://www.ino.tifr.res.in/populararticles/

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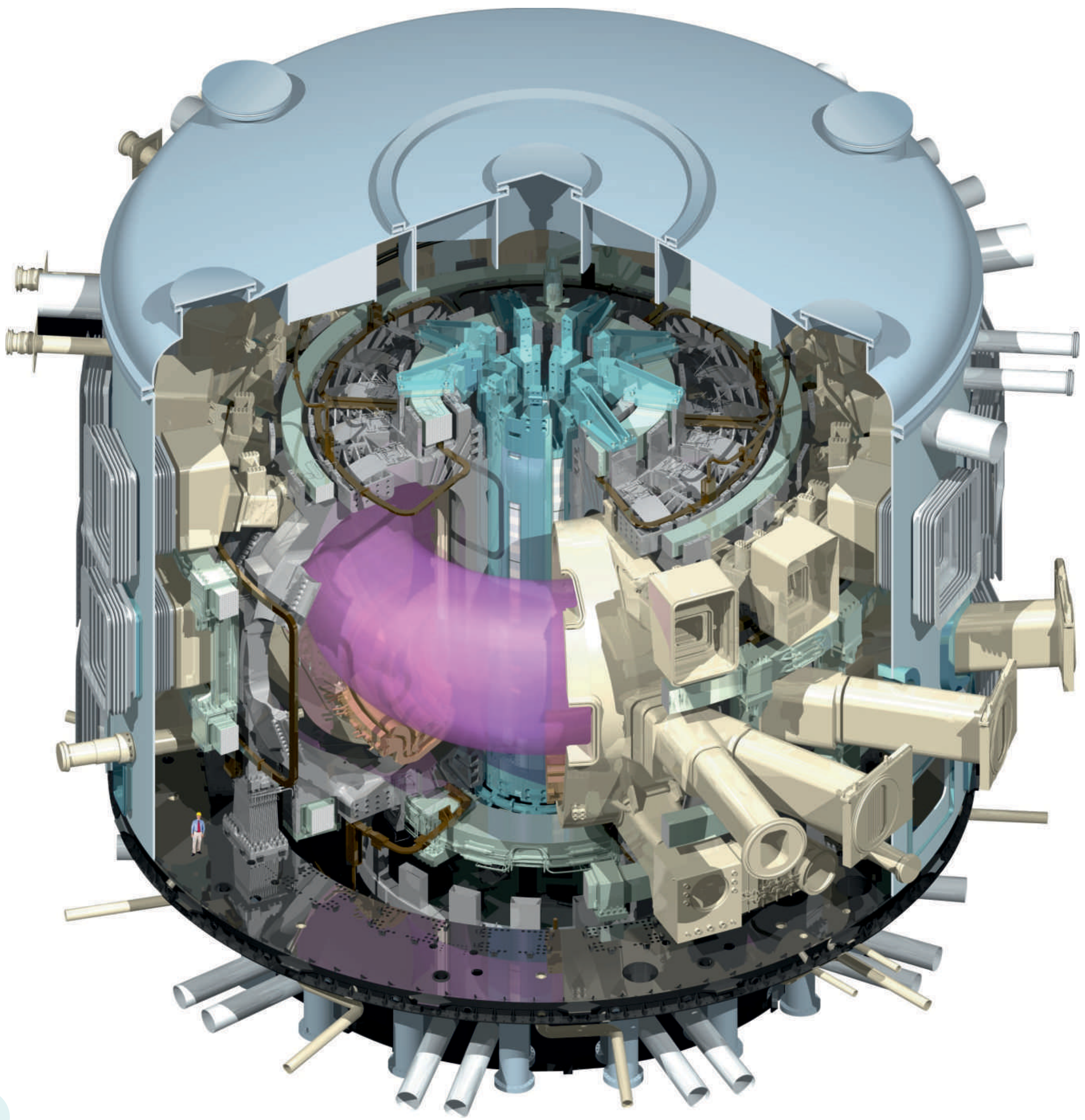
china eu india japan korea russia usa

International Thermonuclear Experimental Reactor

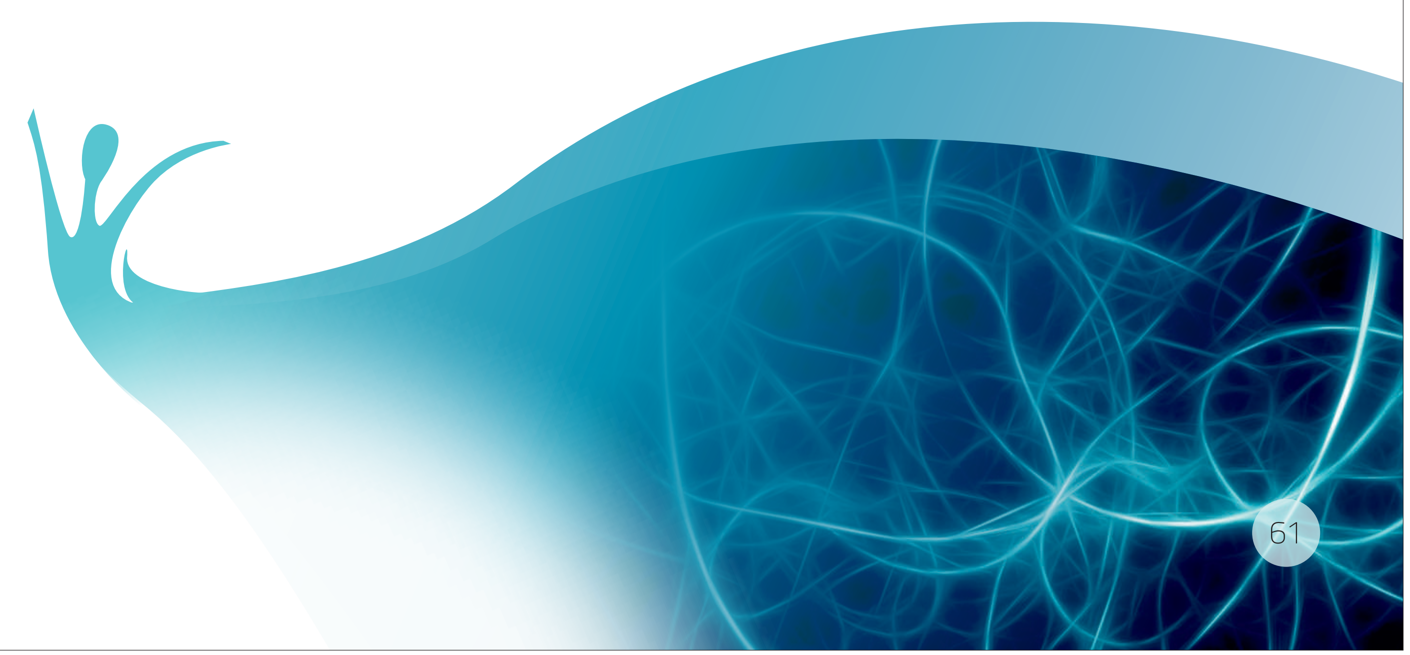


The Way to New Energy

ITER is an experimental fusion reactor facility under construction in Cadarache, in southern part of France to prove the feasibility of nuclear fusion as a future source of energy. ITER will work on the "Tokamak" concept where the reaction of hydrogen isotopes Deuterium and Tritium produce energy by the mass-energy conversion principle, thereby proving to be a source of unlimited energy. ITER partners are the European Union, China, India, Japan, South Korea, Russia and the United States of America. European Union, being the host party, contributes 45% and the other contribute 9% each. Most of these contributions are through 'in-kind' procurement of ITER components. India formally joined the ITER Project in 2005 and the ITER Agreement between the partners was signed in 2006. ITER Organization (IO) is the central team responsible for construction at site and operation, while the ITER partners have created their own domestic agencies to deliver their commitments to ITER. ITER-India is the Indian domestic agency, a specially-empowered project of the Institute for Plasma Research (IPR), an aided organization under the Department of Atomic Energy (DAE). ITER-India is responsible for delivery of the following ITER packages: Cryostat, In-wall Shielding, Cooling Water System, Cryogenic System, Ion-Cyclotron RF Heating System, Electron Cyclotron RF Heating System, Diagnostic Neutral Beam System, Power Supplies and some Diagnostics. Additionally, related R&D and experimental activities are being carried out at the ITER-India laboratory in Gandhinagar, Gujarat.

Collaborating Institutes in India

Institute for Plasma Research (IPR)
Bhat, Gandhinagar



Technologies developed/being developed

Cryostat:

30 m high and 30 m diameter Outer vacuum shell of ITER

Power supplies for DNB, ICRF and ECRF systems:

DNB: 10 kV, 140 A Extraction PS

90 kV, 70 A Acceleration PS

ICRH Driver Stage: 8-18 kV, 250 kW, End Stage : 27 kV, 2.8 MW

ECRH : 55 kV, 5.5 MW

Cryolines and cryo distribution system: 4 km cryolines, 7 km warm lines and 7 cryo distribution boxes for ITER cryo-plants of capacities 75 kW at 4.5K, 1 MW at 80K and their supply

In wall shielding: ~80% volume between the two shells of vacuum vessel is filled with borated steel (SS304B4, SS304B7) and ferritic steel for neutron shielding and reducing toroidal field ripple. Requires ~9000 blocks from 70,000 precision cut plates.

ECRH:

2 gyrotron sources: 1 MW power

Diagnostics: Essential to monitor plasma impurities and emission. Ports are needed to house the Diagnostic systems in position and act as shielding from neutrons.

- **X-Ray Crystal Spectroscopy (XRCS):** Set of spectrometers (X-ray crystals, Detectors, Vacuum Chamber).
- **Electron Cyclotron Emission (ECE):** Set of Michelson Interferometers and Radiometers, Polarization Splitter Unit, Transmission lines
- **CXRS:** Optical Fibres, Detectors, Visible Spectrometers, Opto-mechanical components like filters, mounts, I&C.

ITER – Water Cooling and Heat Rejection System: **10 cells of Cooling Tower:** Avg. 510 MW :Highest heat rejection capacity – Peak ~ 1.2 GW.

14 Plate type Heat Exchanger: 70 MW each: possibly at the highest range of design.

6 Air-cooled Chillers: 450 kW each: first, with requirement of seismic qualification for nuclear site.

Special material development

CuCrZr with % compositions controlled to Cr: 0.6 – 0.8%; Zr: 0.07% to 0.15% ; Cd: 0.01%; Co: 0.05% ; total impurities not to exceed 0.1%.

ICRF source system:

9 RF sources: 2.5 MW at VSWR 2.0/35-65MHz/CW or 3.0 MW at VSWR 1.5/40-55MHz/CW

Diagnostic neutral beam system: Detect He ash during D-T phase of ITER plasma and plasma diagnostics using 100 keV 20 A H neutral beam @ 20.7 m from the ion source. This requires extracting and accelerating 100 keV 60 A H- beam from the ion source at an extracted current density of 35 mA/cm2.

Indian industries involved

Larsen & Toubro	Avasarala Technologies Limited	INOXCVA	Kirloskar Group	kelvion India pvt.Ltd
Ratnamani Metals & Tubes Limited	Gemmo SpA	CARPENTER	Air Liquide Worldwide	PVA TePla
Amtech Electronics India Limited	Nonferrous Materials Technology Development Centre	Vacuum Techniques Pvt. Ltd.	SOLCON The Global Experts In Motor Controls	Research Instruments GmbH
Forbes Marshall Pvt. Ltd.		Blue Sky Spectroscopy Inc	Silver Touch Technologies Limited	Industeel
Continental Electronics Corporation	Transformers & Rectifiers(Indian)ltd.	MAN Diesel & Turbo Man Energy Solutions	THALES	Xylem Inc
Veeral Controls P. Ltd	Linde India Limited	CSIR-Central Electronics Engineering Research Institute	Nuclear Power Corporation of India Limited	

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Meeting ITER Challenges; the ITER–India way

ITER is one of the most ambitious energy projects in the world today. It is the world's largest tokamak, a magnetic fusion device, designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy based on the same principle that powers our Sun and stars.It is located in south of France 70 kms from the city of Marseille which is also a port city. ITER is presently under construction with an active collaboration and participation from 7 member states, China, European Union, India, Japan, Korea, Russia and the United States of America. While European Union contributes ~45% to the total cost of ITER, the remaining contributing nations share ~9% each of the total cost.

India joined the ITER project in 2005. The Institute for Plasma Research (IPR, an aided institute of the DAE) at Gandhinagar was entrusted by the government of India for the job of managing India's participation in ITER. ITER India thus came into existence as a specially empowered body created out of IPR in November, 2007, with 50 personnel joining initially from IPR. With time as the activities leaped forward at a fast pace, additional recruitments were made, the strength of ITER India today stands at 35 staff members seconded from IPR and 107 staff members recruited specially for ITER-India Project.

The main mandate of ITER India since its inception is not only to ensure a timely delivery of the in-kind contributions to ITER machine but also develop capabilities within the country for fusion related technologies. The Indian contributions to ITER are in the form of 9 procurement packages which include the following:

- A 30 m high and 30 m wide cryostat which is basically a jacket to ensure ultra-cool environment for the machine
- In-wall shields for neutron shielding and contributing to plasma performance by limiting perturbations from the magnetic field ripple.
- Various components of the ITER cooling water system which include cooling towers, plate type heat exchangers, air cooled chillers and about 20 km of piping of various lengths and diameters in form of 4500 spools.
- Cryoline and cryo-distribution system which includes various components of the ITER cryogenic system viz. 4 km of cryolines, 7 kms of warm lines and 7 cryodistribution boxes
- RF based plasma heating systems which includes the supply of 9 RF sources for the Ion cyclotron resonance based heating system (ICRH) and 2 gyrotron sources for electron cyclotron resonance based heating system (ECRH)
- A diagnostic neutral beam injector capable of delivering 100 keV ~20 A neutral hydrogen beams into the ITER plasma for He ash diagnostic purposes using charge exchange recombination spectroscopy technique (CXRS).
- Multi mega watt power supplies for the RF based heating systems and for the diagnostic neutral beam injector

- Various plasma diagnostics which include x-ray crystal spectroscopy, edge CXRS and electron cyclotron emission based spectroscopy.

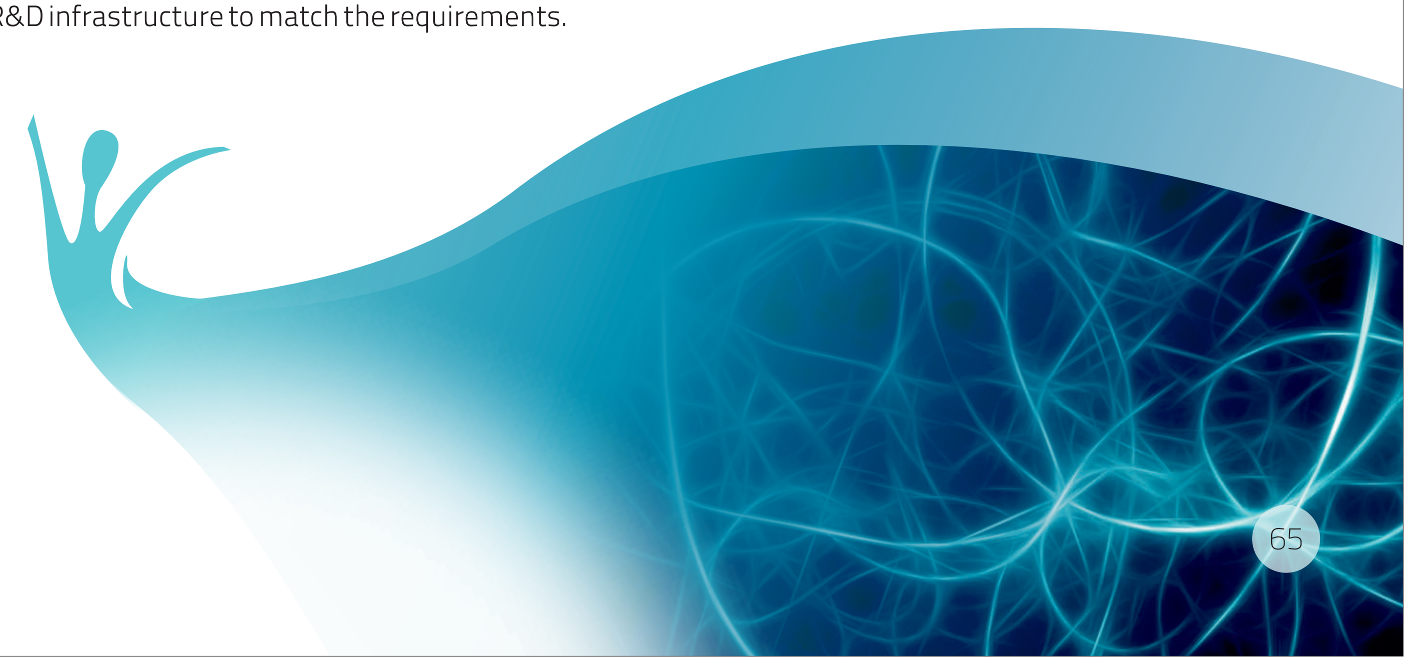
Each of the systems mentioned above are multi component systems and include a mix of precision, heavy, R&D intensive and interface intensive systems, under built-to-print and functional systems category. In addition many of these are unique from the perspective of their

- size
- being first of their kind
- have special ITER requirements to ensure their adaptability and functionality under harsh radiative environment for the life time of ITER. These special requirements include materials, manufacturing technologies and special jointing techniques defined in the various codes and standards and in ITER hand books which are compatible to French regulations for nuclear safety under various accidental scenarios.

It may be noted that the build to print category corresponds to those components where the components have to be manufactured as per the design provided by ITER. Post manufacturing the performance of the system as per ITER specifications or any improvements/design modifications and managing cost and schedule of such changes is ITER's responsibility. On the other hand the functional systems category involves those components where the performance specifications are generated by ITER and it is the responsibility of the country (domestic agency) supplying the component to design, manufacture and demonstrate the desired functional specifications. For the case of Indian packages like DNB, in-wall shields etc fall under the category of build to print while cryoline and cryodistribution systems, power supplies, water supply components fall under the category of functional specifications.

In order to meet these challenges and also to ensure India's readiness for hosting fusion machines post the success of ITER demonstrating its goals and objectives, ITER-India adopted a dual objective of propelling research to the frontier areas of fusion science and technology and to establish manufacturing processes, procedures and practices in the industries that are compliant with the requirements of an international nuclear facility.

A detailed analysis of the various areas which needed to be addressed to fulfill the above objectives lead to the conclusion that the situation is a challenging one. Survey of the various industries and existing laboratories within the country revealed that none had ever done or encountered such a scale-up either in size/volume, capacity, precision etc. and neither did anyone have the desired R&D infrastructure to match the requirements.



In order to mitigate the risks and ensure that the supply objectives were met with the desired stringent quality requirements the developed road map included the following:

- Developing an R&D program in the relevant areas of fusion technology
- Interact with the academia and the Indian industry to help develop the R&D
- Focus on areas of quality development and documentation
- Work with Indian industry to develop state of the art facilities
- Develop test beds for different areas of R&D in ITER – India lab at IPR
- Follow parallel path of development with Indian academia and industry for future requirements

It was believed that such a multi-pronged approach will help develop the desired facilities in Indian industries and institutesneeded to build and demonstrate the integrated and functional performance of many of the first if its kind and R&D intensive systems.Alignment of the knowledge database of the experts from academia, various institutes and industry will also provide industry with the unique opportunity to align their production process and assimilate the learning experience from the manufacturing activities for ITER deliverables, to application areas that blend technologies with stringent quality controls. Further by demonstrating its capability to deliver, the Indian industry will be able to leapfrog into aninternational competitive frame of deliveries related to technology products which meet all requirements of international quality standard.

Based on the above analysis and foresight several R&D programs have been launched on a national level with the various Indian industries sincethe start of ITER-India.Also under a specially funded program, several centers for excellence have been invited to participate and submit projects on areas of mutual benefit. Such an approach has also helped in developing several areas of fusion related R&D which include

- development of special ITER grade materials for components such as the Cryostat, in-wall shields and high heat flux facing DNB components,

- developing prototypes of various scales including full scale models to establish and ensure routes of manufacturing related to heavy and precision machining, similar and dis-similar metal jointing, multi-pipe multi-layer insulated cryolines, pipes, cold circulators, RF sources, power supplies and diagnostic systems.

- facilities with state of art testing equipment to qualify the produced prototypes as per stringent quality requirements both in the industry and at ITER India

- a 5,761 sq.mt ITER India laboratory (Figure 1), has been set up in institute for plasma research (IPR) Gandhinagar. The laboratory hosts test beds for test of the cryolines, the RF sources under matched and mismatched load conditions, the neutral beam test bed which is a prototype DNB line with a unique 21 m beam transport path to help establish the much desired data base for ITER diagnosticians involved with CXRS measurements, testing and development of various diagnostics and testing and development of power supplies in various topologies.

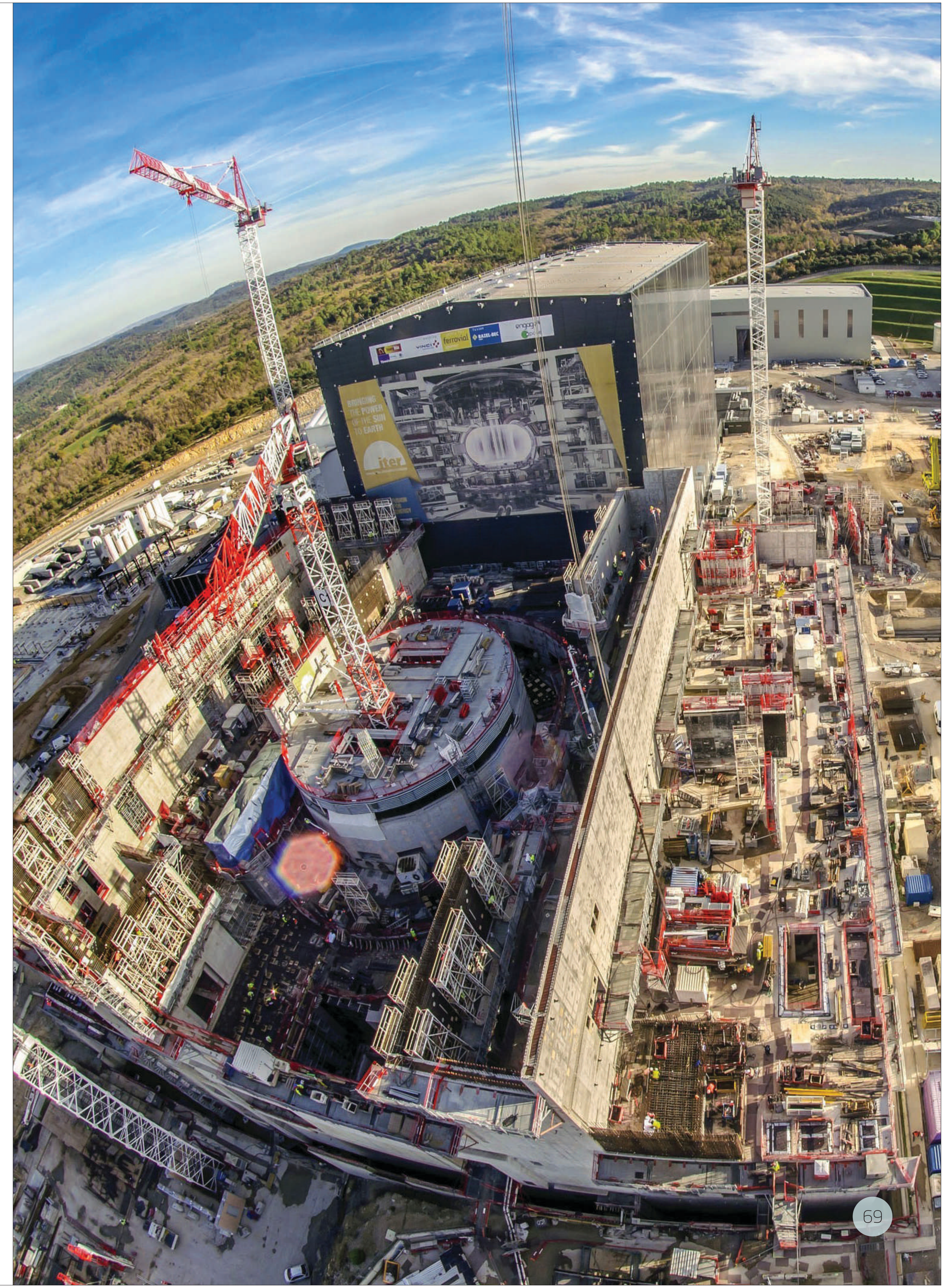
Cryoline test bed | **RF test bed with matched and mismatched loads** | **Neutral beam test bed (INTF)**

Figure 1 : The ITER India laboratory in IPR with various test beds

The vision and execution of the vision has been successful to a large extentFigure 2. It has helped to deliver several of the major components related to the (1) Cryostat (a gigantic vacuum chamber with the size of a 10-storeyed building), (2) water cooling systems (which include about 20 km of piping, chiller systemsthat are first of a kind 450 kW each with seismic qualification for nuclear site); cooling towers capable of handling an average heat load of 510 MW and a peak load of 1.2 GW; Plate type heat exchangers of 70 MW capacity which are possibly the highest in the range of design, pumps, electrical panels and interconnecting piping network, (3) about 60,000 plates of the in-wall shielding for preventing escape of nuclear radiation; and (4) 65-70% of the cryolineswith multi process pipes rated for heat in-leaks of 1.2 W/m @ 4.5 K and 4.2 W/m @ 80 K.

Multi megawatt power supplies of different ratings have been developed and tested successfully as per ITER requirements. A 100 kV, 7.2 MW accelerating power supply coupled to the SPIDER test source facility in Padova has been used to extract the first beams. A 4.5 m diameter 10 m long vacuum vessel with top opening and double o ring seal mechanism coupled to drift tubes to provide the 21 m path length for 100 kV diagnostic neutral beam production (INTF facility), characterization and transport has been fabricated and successfully installed at the ITER India laboratory. Several prototype development of the various neutral beam components have resulted in the present stage where all the full scale components are under manufacture which is expected to be completed by the end of 2019. These systems/equipment have been made in India by the Indian industries. A few other systems that being manufactured abroad have been designed by our engineers and are being tested in India by unique test-facilities that do not exist anywhere else. For example, 1.5 MW RF source prototypes based on two different tube technologies have been tested under matched and mismatched load conditions for the desired specification of 1.5 MW, 36-65 MHz, VSWR 2:1 and efforts are underway to establish the first of its kind amplifier chain using 2 of the above RF sources to meet the ITER requirement of 3 MW, 36-65 MHZ, VSWR 2:1.

Figure 2 : A collage of various prototypes and actual components manufactured by Indian industries for various Indian packages for ITER

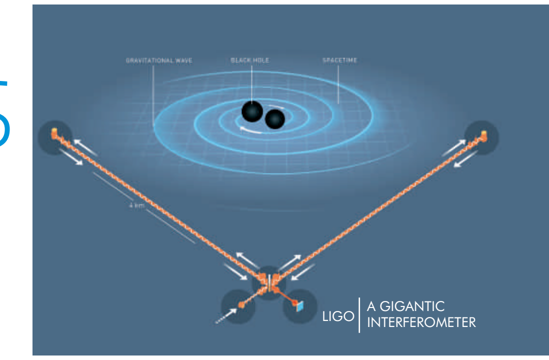


Laser Interferometer Gravitational-wave Observatory

LIGO INDIA

An Indian astronomy mega-science venture in joint collaboration with LIGO Laboratories, USA.

Sensing ripples in Space-Time



LIGO is a world-leading observatory designed to detect gravitational waves from the most violent events in the Universe. LIGO and the associated collaboration, involving 37 researchers from 9 Indian institutions, is known for the first direct detection of Gravitational Waves. This opened a completely new window with which scientists are starting to probe hitherto unexplored phenomena such as the formation of black holes, exploding neutron stars, witnessing the birth of our Universe and so on. This enriches multi-messenger astronomy complementing the conventional means of observing and studying the Universe with telescopes using light. The physical measurements required for gravitational wave detection are arguably the most precise ever made, and they involve cutting-edge technologies that have many day-to-day applications. LIGO-India, an ongoing enterprise to set up a new gravitational wave detector on Indian soil, is a mega-science project jointly funded by the DAE and DST. With this addition to the existing network of detectors globally, we will dramatically increase the sensitivity and positional accuracy with which gravitational events will be detected. India will provide the site, vacuum system and other infrastructure required to house and operate the interferometer and manpower, materials and supplies for installation, commissioning and operations. Presence of such a world-leading facility in India will inspire and attract generations of students to pursue challenging careers in science, technology and innovation.

DAE: Departments of Atomic Energy

DST: Department of Science and Technology

Collaborating Institutes in India

Chennai Mathematical Institute (CMI), Chennai	Directorate of Construction Services & Estate Management Mumbai *	Indian Institute of Science Education & Research Kolkata	Indian Institute of Science Education & Research Pune	Indian Institute of Technology (IIT)- Bombay Mumbai
Indian Institute of Technology (IIT) Gandhinagar	Indian Institute of Technology (IIT) Hyderabad	Indian Institute of Technology (IIT) - Madras Chennai	Institute of Advanced Research (IAR) Gandhinagar	Institute for Plasma Research (IPR) Gandhinagar *
International Centre of Theoretical Sciences (ICTS) Bengaluru	Inter-University Centre of Astronomy & Astrophysics Pune *	Raja Ramanna Centre of Advanced Technology Indore *	Tata Institute of Fundamental Research (TIFR), Mumbai	*Lead institutions responsible for the construction, commissioning and operation of LIGO-India

LIGO-India Observatory at the Aundha site. Aerial view as seen from the Corner Station (Artistic rendering by the DCSEM, DAE);

Technology developed

During its development, LIGO has already spawned innovative technologies in diverse areas as described below

Technology category	**Technology advanced or invented by LIGO**
High-performance optics and optical metrology	Photo-thermal interferometer
Optical components	Adaptive laser beam shaping
Lasers	Diode-pumped laser
Ultrahigh vacuum components and techniques	Vacuum cable clamp
Sensor technology	Interferometric displacement sensor
Materials engineering	Oxide bonding techniques
Computation and time-series data analysis	Fast chirp transform
Distributed computing	Distributed identity management

Source: Advanced LIGO webpage (https://www.ligo.caltech.edu/page/technology-transfer-case-studies)

A short description of some of the technologies listed above can be found below

Nonlinear optical materials used in the area of high-performance optics and optical metrology require precise measurement of properties such as absorption losses and damage thresholds. One of the most successful approaches developed in Advanced LIGO (aLIGO) to characterize these materials is the Photothermal Common Path Interferometry.

Adaptive beam shaping of the high-power laser beams had to be developed due to the extreme sensitivity to wavefront distortions encountered in LIGO. The thermal compensation system developed for correcting these distortions uses ring-heaters on the outer barrel of the mirrors to correct their radius of curvature and a CO2 laser to heat a transparent compensation plate.

LIGO uses a variant of 'silicate bonding" technique to fabricate the quasi-monolithic fused silica suspensions now being used for Advanced LIGO. This technique was selected for use in ground-based gravitational wave detectors because of its high strength obtained with very thin bonding layers, which results in low mechanical loss and leads to low thermal noise.

LIGO is leading the effort to bring the benefits of federated identity management to large scientific research organizations and projects. This will also give scientists the power to quickly create their own virtual groups and to manage user access to web pages, wikis, email lists, software repositories and other tools needed to support their projects.

Indian industries/companies involved

Indian institutions such as IUCAA, RRCAT, IPR, and DCSEM are in the process of discussing with industries/companies and identifying them which will help in developing the technological capability needed for building detector for LIGO-India.

Contact person/Spokesperson

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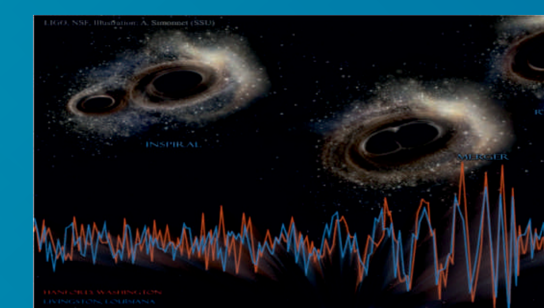
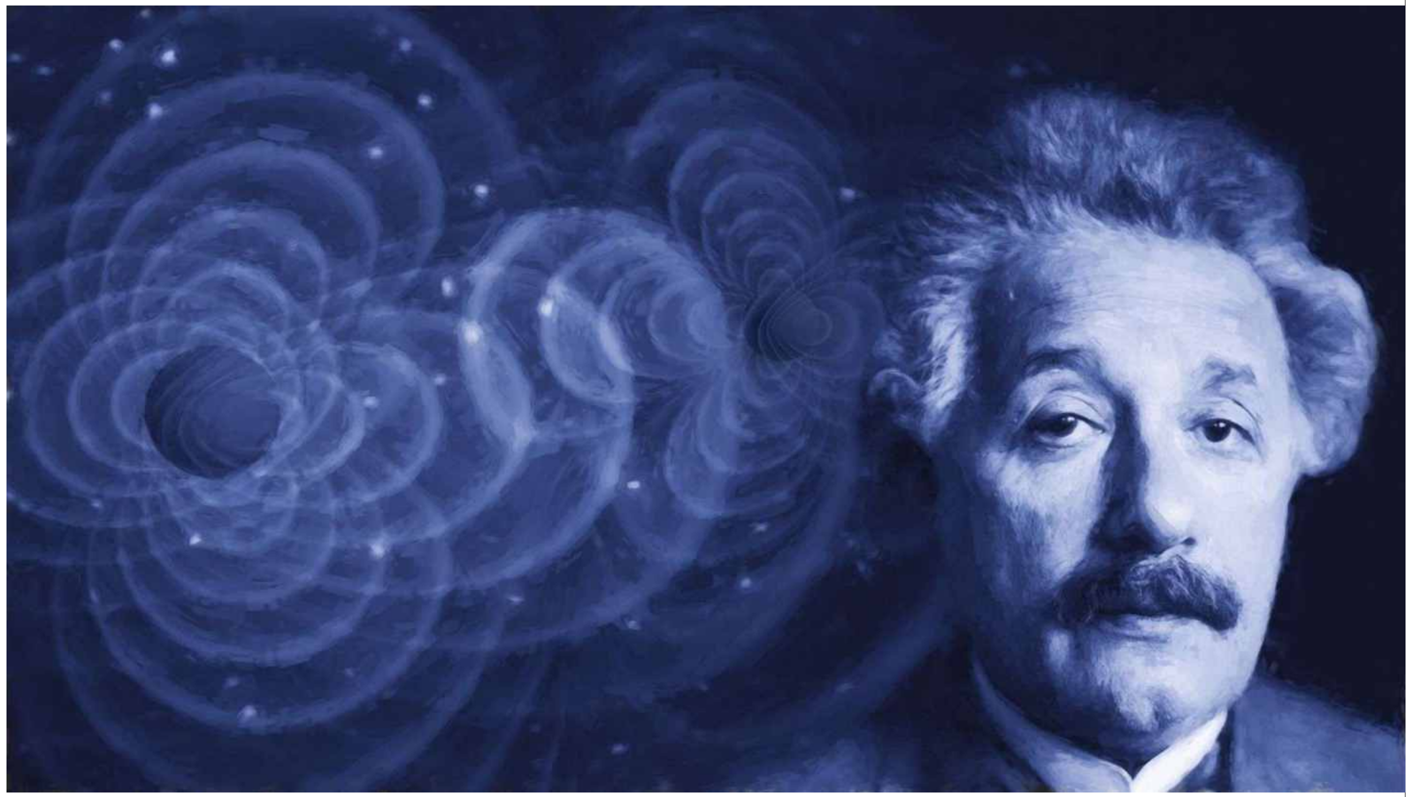


Gravitational waves were first detected on 14th September 2015 by Laser Interferometer Gravitational-wave Observatory (LIGO) based in Hanford and Livingston. Two black holes of masses 36 and 29 solar masses merged a billion light-years away to form a 62 solar mass black hole and the rest of the mass was released as energy in Gravitational Waves. A simulated picture of the merger event and the signals received in the two LIGO detectors are shown in the above image.

Gravitational Waves: How it all started in India

Background

The discovery of gravitational waves was announced on the 11th of February 2016. The LIGO detectors of the US had directly observed gravitational waves from a merger of two black holes on 14th September 2015. This was a historic moment since Einstein's prediction made a century ago in 1916 had been realised. Einstein had presented his theory of gravitation – the general theory of relativity – a year before, in 1915 and a spectacular prediction of this theory was gravitational waves.



Credits: NASA/IMAGNO/GETTY IMAGES

It took however a century before this prediction could be experimentally verified. Why did it take a century? This is because the interaction of gravity with matter is very weak – gravity weakly couples to matter – it is the weakest force among the four forces that we know of. Even astrophysically produced gravitational waves by massive or highly dense objects, carrying large amounts of energy, affect test particles quite feebly. A convenient measure of their strength is their strain amplitude denoted by h. This is a typical component of the metric perturbation, a mathematical concept of distance (Einstein's theory is a metric theory of gravity.)

For a typical source such as the binary black hole that was first discovered, $h \sim 10^{-21}$. The amplitude h can be easily visualised by observing the effect of a gravitational wave on test particles, which are just masses. Consider two test particles a distance L apart, and a gravitational wave with amplitude h is incident upon them. Then their separation changes by the amount $\delta L \sim h L$. So if $h \sim 10^{-21}$ then $\delta L \sim 10^{-21} L$. If one were to attempt this measurement with a table top interferometer say of arm length L ~ 1 metre, one would have to measure distances of the order of 10^{-21} metres! This is awfully small and an impossible task! Therefore it is a good idea to make L as large as is practically possible. The current interferometers have arm-lengths in kilometres – for the LIGO detectors L ~ 4 km. Even then one must measure distances of the order of 10^{-18} metres - 1/1000th the size of a proton - to get to $h \sim 10^{-22}$! This requires an incredible feat in technology. Technology has taken great strides during the past 100 years and this level of technology has been reached only in recent times.

In the 1960's Joe Weber made the first attempt to detect gravitational waves. He was the pioneer who started the field of the experimental detection and observation of gravitational waves. His detector was a resonant aluminium bar with a length of about 2 metres.

Credits: Special Collections and University Archives, University of Maryland Libraries

Joe Weber with the bar detector

However, it was soon realised that an interferometric arrangement was a better design (R. Forward, R. Weiss) – it was scalable, broadband and tuned to the quadrupolar nature of the waves. Soon groups employing the interferometric design sprang up in Europe in the '70's with the detectors having arm lengths of tens of metres. There was a 10 metre prototype detector at Glasgow, UK, a 30 metre at Munich, Germany. Also a 40 metre prototype was built in Caltech, USA

Given this backdrop of activity in the experimental detection of gravitational waves, in the late '80s and early 90's Bernard Schutz at Cardiff, UK and Kip Thorne at Caltech, USA thought that it was also time to start thinking about the data analysis aspect of gravitational wave detection. This was because, as mentioned above, in spite of the efforts put in by experimentalists to make the detectors extremely sensitive, the expected gravitational wave signals are so weak that they would be buried in the detector's noisy data. Sophisticated methods would be required to dig the signal out of the noise. It was at this early, but highly promising epoch, that Sanjeev Dhurandhar visited Bernard Schutz at Cardiff as a senior visiting fellow during 1987-88. The visit was a huge success and several foundational papers were an outcome of that visit. More importantly, a strong bond was established between the persons and their respective institutes. It was soon realised by Sanjeev Dhurandhar that employing sophisticated mathematical and statistical techniques would be most important for analysing gravitational wave data.

Gravitational waves enter India

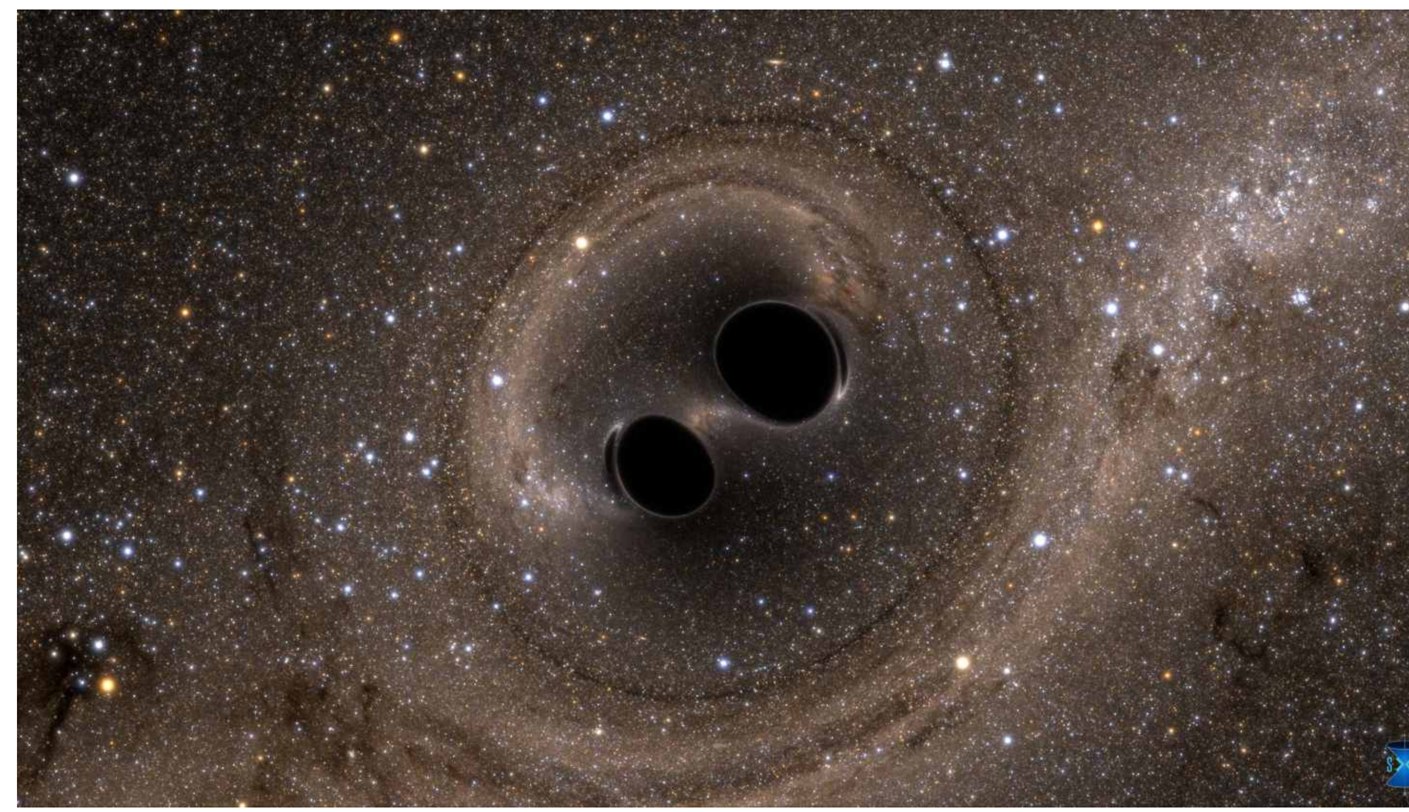
Sanjeev Dhurandhar returned to India in 1988 and was fortunate enough to join Inter-University Centre for Astronomy and Astrophysics (IUCAA) in 1989. He soon convinced his seniors, notably the director Jayant Narlikar (who had also been his thesis supervisor in the late 70's), that gravitational waves was the way to go - a strong activity in this field was a must for IUCAA, India and the world. This was a fertile field which was begging to be explored and promised rich dividends. The detection of gravitational waves would not only benefit fundamental physics, but also give rise to the birth of a new astronomy – Gravitational Wave Astronomy. A Nobel prize was obviously hanging in the background and was, in fact, realized in 2017 – the Nobel prize in physics 2017 was awarded for the discovery of gravitational waves.

Accordingly, a proposal to build a gravitational wave detector was made to the Department of Science and Technology (DST), India in 1989 by IUCAA. The DST advised that established experimentalists should be involved in the project and a workshop be held to discuss the details of the proposal. A workshop, therefore, was held at the Centre of Advanced Technology (CAT – now RRCAT), Indore, with full support and encouragement from Dr. D. Bhawalkar, the then director of CAT. Experts in the field from abroad were invited to the workshop. The recommendation of the workshop was that a 100 metre detector – a detector with the longest arm-length at that time – should be the goal and built in India. A proposal was then written by Sanjeev Dhurandhar (IUCAA), P. K. Gupta (CAT), A. S. Rajarao (CAT) mainly, and sent to the DST. However, the proposal did not meet with success for various reasons. The general advice given by the DST was to develop the data analysis aspect of the experiment at IUCAA for which there was evidence of expertise.

It is evident that, building and running such powerful machines represents an enormous enterprise. However, analysing the large amount of data and digging out with high confidence astrophysical signals from the noise which severely corrupts the data, presents its own challenges. In fact, a new field, that of gravitational wave data analysis emerged and it is now a key aspect for the successful detection and observation of gravitational waves.

From 1989 onwards with the able assistance of the postdocs B. S. Sathyaprakash and Patrick Dasgupta, Sanjeev Dhurandhar formed a group – the gravitational wave group – at IUCAA. In due course, many students joined the group and the group made several important contributions to the data analysis of gravitational waves. The thrust of the group was on developing algorithms for extracting gravitational wave signals produced by coalescing binaries – more appropriately the inspiral waveform – from detector noise. Sathyaprakash and Dhurandhar developed an efficient algorithm in 1991, exploiting the symmetries of the model and employing template banks which densely covered the parameter space. The discovery paper refers to this work – a quarter century had elapsed ! The current methods used are refinements of this algorithm conceived early on.

The compact coalescing binary source was the focus of the IUCAA group, because this source was considered to be the most promising source for laser interferometric detectors (Kip Thorne in 300 years of Gravitation, edited by Hawking & Israel, 1986) – one reason being their broadband sensitivity to kHz. And now we see that all the 11 gravitational wave events detected by the LIGO and Virgo detectors are in this category – binary black holes, or neutron stars !



An artist's conception of a pair of merging black holes
Credits: The SXS (Simulating eXtreme Spacetimes) Project

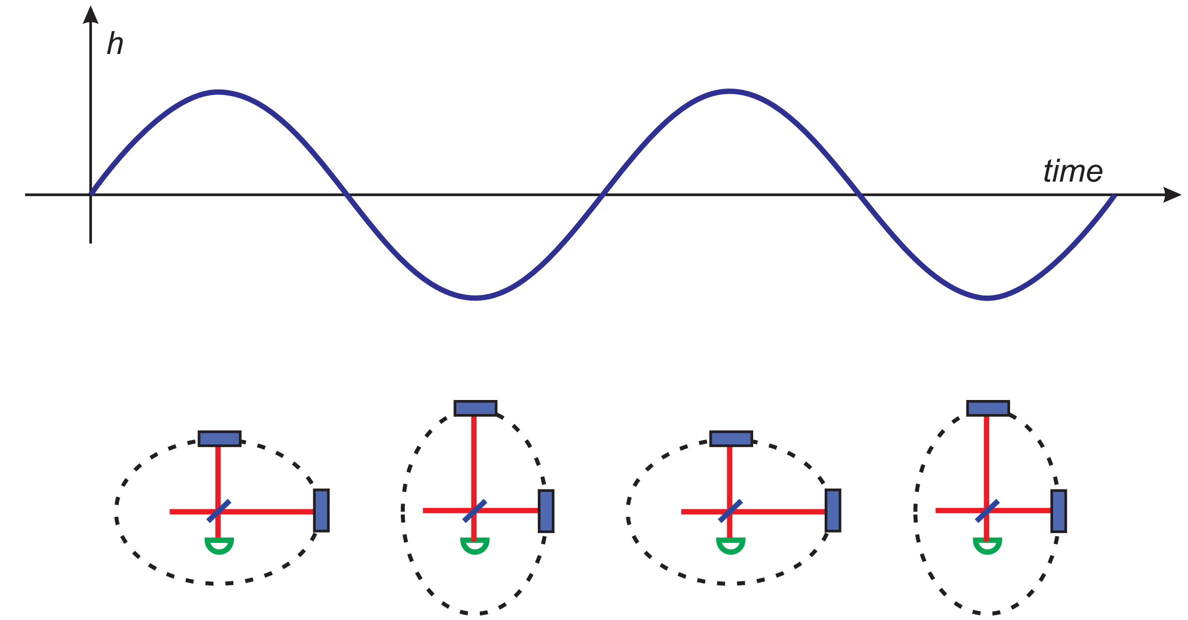
Kudos to Kip! This source was also a focal point for Kip Thorne's group at Caltech and foundational work was done by both the groups at IUCAA and Caltech. A most important observation from the Caltech group was that the waveform obtained from the quadrupole formula was woefully inadequate not only to estimate the parameters of the gravitational wave signal but even, more crucially, to detect it – the phasing was inaccurate so that the signal based on the approximate 'Newtonian' waveform would go undetected! One had to resort to higher order approximations – the post-Newtonian – and these had to be worked out. This was first time that it had happened that, in general relativity, experiment was driving theory! A few groups in the world started to compute these higher order terms in the post-Newtonian expansion – notably the French led by Thibault Damour, Luc Blanchet and others. From the Indian side Bala Iyer at RRI, Bangalore built up a strong collaboration with the French in this endeavour. He and his group made notable contributions to this worldwide effort. It must be remarked that these computations are extremely tedious and require a lot of skill.

Perhaps, the most important benefit to India from these activities was manpower development. The students and postdocs trained in these two groups are now holding key faculty positions in India and abroad. They have now nucleated their own groups and there are now 40-50 young people hungry to analyse data from detectors – especially from LIGO-India. It is now that the experimental effort is being launched DCSEM, RRCAT, IPR and IUCAA are taking the lead and other premier institutions have joined in the effort.

The physics of gravitational wave detection

The key to gravitational wave detection is the very precise measurement of small changes in distance. For laser interferometers, this is the distance between pairs of mirrors hanging at either end of two long, mutually perpendicular, vacuum tubes. Gravitational waves passing through the instrument will shorten one arm while lengthening the other. By using an interferometer design, the relative change in length of the two arms can be measured, thus signalling the passage of a gravitational wave at the detector. Long arm lengths, high laser power, and extremely well-controlled laser stability are essential to reach the requisite sensitivity. Gravitational wave detectors produce an enormous volume of output consisting mainly of noise from a host of sources both environmental and intrinsic to the detector. Buried in this noise will be the gravitational wave signature from an astrophysical source. Sophisticated data analysis techniques are needed to optimally extract physical data.

General relativity tells us that gravitational waves travel with the speed of light, are transverse and have two polarisations. The effect of a gravitational wave on test particles is that of a shear. The shearing effect can be conveniently seen on a circular ring of test particles - it deforms into an ellipse. This is shown in the figure below



Effect of a passing gravitational wave on the L shaped arms of an interferometer

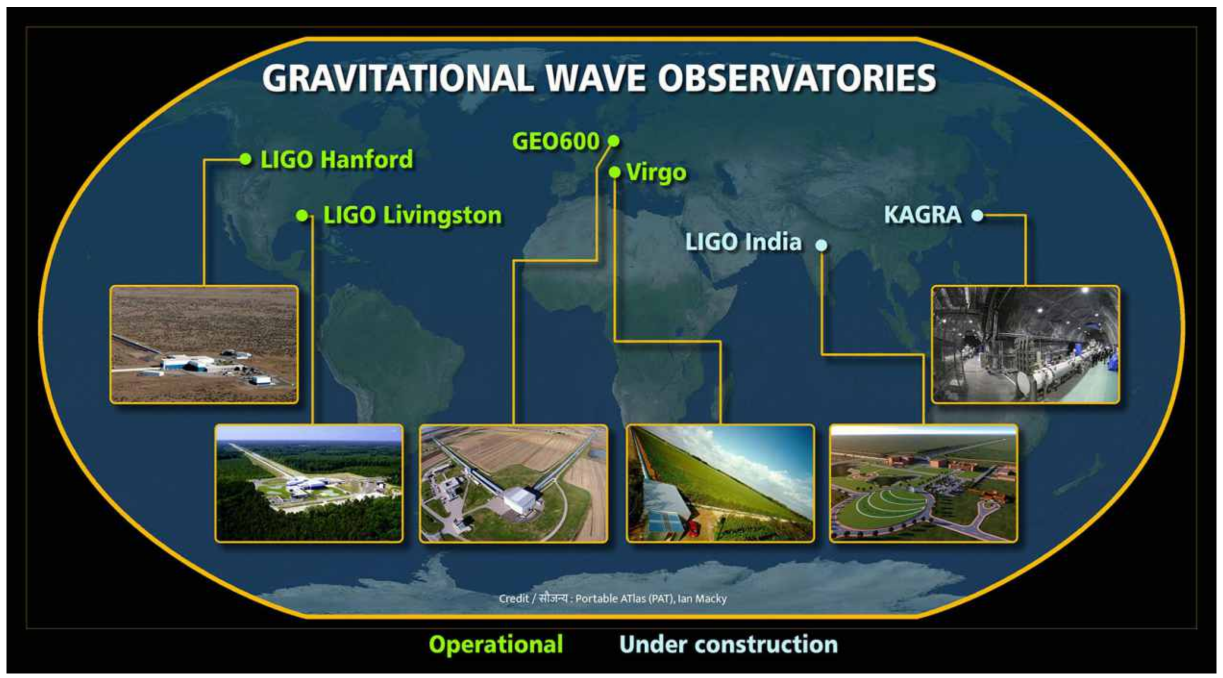
If we select two masses on this ring at right angles and monitor their distance with respect to the centre of the ring (the reference point) then during one half cycle of the wave one arm shortens while the other arm elongates. In the next half cycle of the wave the opposite happens. By using a laser interferometric arrangement, a passing gravitational wave will produce a time-varying path difference which can be detected on a photodiode. This is the principle of the detection of gravitational waves.

There is a catch, however! The changes in distances are exceedingly small for astrophysical sources. For example, a neutron star binary located a 100 million light years away - a typical distance to a source - will produce a differential length change of 10-16 cm for test masses kept few kilometres apart, which is the typical length of the arm of a large scale ground-based interferometric detector! For an astrophysical gravitational wave source, the strain h is given by the well-known Landau-Lifshitz quadrupole formula. If we consider solar mass objects which are compact and moving with speeds comparable to the speed of light and at a distance ranging from the galactic scale to a billion light years, then h ~ 10-17 to 10-22. These numbers then set the scale for the sensitivities at which the detectors must operate.

LIGO-India: The Road Ahead

The laser interferometric detector is essentially a quadrupole with almost a omni-directional antenna pattern (the analogue of a dipole in electromagnetism). A single detector therefore cannot determine the direction of a source – a widely separated network of detectors is needed to triangulate a source. So far among the kilometre scale detectors, there are the two LIGO detectors of the US at Hanford and Livingston, the French-Italian Virgo detector at Pisa, Italy, and the Japanese detector KAGRA which will soon come online. There is also a 0.6 km arm-length detector in Germany which is useful for developing advanced techniques like light squeezing, etc.

The longer the baseline, the better determination of the direction to the source. This is the main advantage of building LIGO-India - it is located almost on the diametrically opposite side of the earth with respect to the LIGO detectors in US, thus furnishing almost the longest possible baseline on Earth - 39 milliseconds of light (or more appropriately gravitational waves) travel time. It is also very far from the other detectors, namely, Virgo and KAGRA. With the addition of LIGO-India, the accuracy of locating objects in the sky will be increased by 10 to 100 times compared to existing detector network. Also LIGO-India will improve the sky coverage because of its very different orientation. Moreover, a different orientation has the further advantage of measuring a different polarisation, thus improving the estimate of the orientation of the source.



Global network of gravitational wave detectors including LIGO-India

It appears likely that the astrophysical stochastic background from hundreds of distant merging black holes and/or neutron stars will reveal itself within the next decade. One would then expect that LIGO-India along with other detectors will help in unravelling this very important new kind of gravitational wave source. There is also the possibility of discovering astrophysical sources not already discovered by electromagnetic astronomy – this will indeed be a big surprise! In general, the addition of LIGO-India to the global network of detectors will make gravitational wave astronomy a reality and India a major player in this field.

LIGO – India Education and Public Outreach (L I E P O)

The LIGO-India project has an Education and Public Outreach (EPO) team to go hand in hand with the progress of the project.
Following are the activities undertaken by the LIEPO team:

Outreach near the Site
1.GW science and astronomy workshops for schools and colleges.

- Toys from trashed inspired by Arvind Gupta used to explain concepts of GW science and physics to school children.
- Students are given exposure to astronomy by conducting star gazing sessions, by giving various live demonstrations (like working of telescopes etc) and videos.
- Starting from last few months, LIEPO team has reached to approximately more than 4000+ school students in different schools from near the site and other regions near Hingoli,Parbhani,Nanded and Latur.

Workshops at ZP schools in villages near the site:

Workshops in Hingoli:

Workshops near Nanded:

Workshops in Parbhani:

Workshops in Latur:

2. Forming local amateur astronomy clubs and conducting club activities.
   - LIEPO team got in touch with the local teachers and they motivated the group of teachers to form amateur astronomy groups.
   - 100 local teachers showed interest to become a member of the amateur astronomy club which was formed on 21st May 2018 in Hingoli.

3. Stargazing programs for public
   - Hingoli is a place where people don't have any access to telescopes. Many of them have not even seen/seen through a telescope.
   - LIEPO organizes sky watch sessions along with some GW activity in Hingoli and Basmat regions where the people are very curious and these events have got a huge response.

4. GW talks in local colleges in Maharashtra
   - LIEPO team organizes GW talks for the college students from various colleges in the areas like Hingoli, Nanded, Parbhani, and Latur.

Reaching colleges/universities across India

1. Conducting GW Talks and Workshops in various colleges.

2. Active participation in national-level technology exhibitions and college tech-fests.

Science Congress 2019 - Pride of India Exhibition (Technology Expo)

IIST - Conscientia Techfest 2019

IIT-Bombay Techfest 2018

Laser Interferometer Gravitational-wave Observatory

Exploring the Universe with the world's largest radio telescope

The Square Kilometre Array (SKA) will be an array of telescopes, spread over hundreds of kilometres. There will eventually be hundreds of dishes and hundreds of thousands of low frequency antennas that will monitor the sky in unprecedented detail. Both South Africa's Karoo region and Western Australia's Murchison Shire are chosen as co-hosting locations based on the characteristics of the atmosphere above the sites and their radio quietness, which comes from being some of the most remote yet accessible locations on the Earth.

The unprecedented sensitivity of the SKA's receivers will allow insights into the formation and evolution of the first stars and galaxies after the Big Bang, the role of cosmic magnetism, the nature of gravity, and possibly even life beyond Earth. Indian scientists are involved in many of the SKA's Science Working Groups, and co-chair the Solar physics WG.

The SKA will push several areas of technology to the next level, spanning antenna design, radio frequency electronics and optical fibre technologies, low-power electronic, signal processing, high performance computing, as well as complex system management software. Some of the most challenging innovations will be in the area of software and computing, making it a truly 'IT telescope".

Whilst 14 member nations including India are currently funding the SKA, around 100 organisations across about 20 countries representing over 1,000 scientists and engineers are participating in the design and development of the SKA. The National Centre for Radio Astrophysics of Tata Institute of Fundamental Research in Pune is leading India's participation in the SKA and the Telescope Manager consortium designing the SKA's software. India's activity is funded by the Deparment of Atomic Energy and Department of Science and Technology, Government of India. SKA-related initiatives in India are overseen by the SKA-India Consortium (SKAIC) which has almost twenty member organisations from all over the country.

with all the other elements to run the Observatory. The complex software to be used for the end-to-end management of the entire Observatory has been developed leveraging the expertise of Indian IT industries and utilizing next generation tools and ideas to tackle the complex problem. Indian institutions and industry have also been involved in technology and science with the SKA precursor and pathfinder facilities such as Murchison Widefield Array (MWA) Observatory in Australia and the Giant Metrewave Radio Telescope (GMRT) Observatory in India.

Collaborating Institutes in India

National Centre for Radio Astrophysics Pune	Raman Research Institute (RRI) Bengaluru	Inter-University Centre for Astronomy & Astrophysics Pune	Saha Institute of Nuclear Physics Kolkata	Physical Research Laboratory (PRL) Ahmedabad
IIT Indore	IIT Kanpur	IIT Kharagpur	Indian Institute of Science Education & Research Mohali	Indian Statistical Institute (ISI) Kolkata
Jamia Millia Islamia New Delhi	Presidency University Kolkata	Birla Institute of Technology and Science (BITS), Goa	Tata Institute of Fundamental Research (TIFR), Mumbai	IISc Bengaluru
Indian Institute of Space Science & Technology Thiruvananthapuram	M.G. University Kottayam	St. Thomas College Kozhencherry	Savitribai Phule Pune University	

Technologies developed

1. Telescope Manager: end-to-end observatory management system, with sophisticated algorithms and software, suitable for management of any complex, distributed system. Prototype version being deployed at NCRA's GMRT observatory, which is SKA pathfinder facility.

2. Wideband radio frequency and optical fibre systems: these have been developed by the teams from NCRA as part of the upgrade of the GMRT, a SKA pathfinder facility.

3. High speed digital signal processing modules: these have been developed by RRI for the MWA project – a SKA precursor facility, and also by NCRA for the upgraded GMRT – a SKA pathfinder facility.

Indian industries involved

1. Tata Consultancy Services, Pune
2. Persistent Systems Limited, Pune
3. NVIDIA India, Pune
4. HiQ Electronics, Hosur
5. Smile Electronics, Bengaluru
6. Kamal Electronics, Bengaluru

Low frequency antennas

Contact person / Spokesperson

Prof. Yashwant Gupta
NCRA, Pune, Email : skaindia@ncra.tifr.res.in

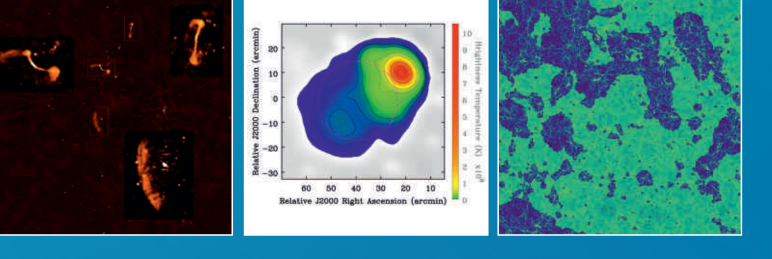
Website

http://www.ncra.tifr.res.in/ncra/skaindia

Sample SKA related science activities in India

Indian astronomers are using different SKA precursors and pathfinders to prepare for SKA science. The picture on the left shows an example, viz., a detailed map of a galaxy cluster (Abel521) made using GMRT (a SKA pathfinder facility), revealing interesting new features. Indian astronomers also use the SKA precursors MeerKAT and MWA observatories for cutting-edge science; for example, the picture in the middle shows one of the most detailed images of the Sun ever in radio band made using MWA data. One of the large survey projects at the MeerKAT is being led by astronomers from India. Scientists are also carrying out theoretical simulations which help in interpreting the data, for example, the picture on the right shows simulations of ionized bubbles produced by the first stars in our Universe.

Abell 521 with the uGMRT Band 4 RMS 10^{-5} Jy/beam



An international telescope for radio astronomy

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Abstract

The successful design of 45-m diameter dishes for the Giant Metrewave Radio Telescope (GMRT) at a relatively modest cost using the SMART concept, which incorporates stretched mesh attached to rope trusses to form the reflecting surface, gives us sufficient confidence to project the possibility of a much larger International Telescope for Radio Astronomy (ITRA), consisting of about 160 dishes of about 75 m diameter each, for investigating a variety of outstanding astrophysical problems. Some of these problems can only be studied in the decimetre and metre-wavelength region of the electromagnetic spectrum. ITRA could be located at a suitable site that has low winds, no snow and low man-made radio-frequency interference, in South America, Africa or Australia.

OVER the last few decades, many dramatic improvements have been made in the capabilities of radio telescopes, which have increased our knowledge about the Universe a great deal. However, while the angular resolutions of the radio telescopes have increased a million-fold, there has hardly been any significant increase in their collecting area.

Any major breakthrough in the development of a new scientific instrument takes place generally due to a pressing scientific need, e.g. desire to solve important astronomical issues. We believe that this is the case now: a radio telescope operating in the decimetre- and metre-wave region with a sensitivity about 30 to 50 times higher than GMRT. Arecibo1 or VLA2 will provide vital clues concerning the origin of the Universe, and the growth of density perturbations in the Universe that give rise to the formation of galaxies. Such a powerful telescope is also likely to result in many unforeseen discoveries.

In this paper, I discuss the scientific objectives, design considerations and estimated cost of a radio telescope with a collecting area about 15 times that of GMRT. Its system temperature can be about 1.5 and 3 times lower than that of GMRT at frequencies of 600 and 1420 MHz respectively, owing to higher efficiencies of the antennas and the use of cooled receivers. A multi frequency feed system could provide a near continuous frequency coverage, from about 25 to 1700 MHz, with additional feeds operating in the 2.2-and 2.7 GHz bands. The 2.7-GHz band could be the upper limit of the operation of the telescope at ~30% efficiency. We may call the proposed instrument 'The International Telescope for Radio Astronomy' (ITRA) (itra means perfume or essence in Hindustani, and is derived from attar in Persian).

Scientific Objectives

Two of the most important astrophysical objectives of GMRT are (i) the detection of the 21-cm radiation of the neutral hydrogen in the early stages of the Universe before the formation of galaxies, and (ii) the detection of primordial gravitational radiation through accurate timing measurements of rapidly rotating pulsars. Even if GMRT succeeds in finding answers to these questions, a much more sensitive instrument would be required to unravel the mysteries of the Universe in greater detail. For this reason, and also to search for extraterrestrial intelligence (SETI), I proposed, in 1988, the possible construction of 1000 numbers of GMRT-type 45-m-diameter dishes3. Recently Wilkinson4 has proposed the 'hydrogen array' consisting of 100 antennas of 113-m diameter to get a collecting area of 1 km2 for a detailed study of neutral hydrogen clouds in nearby galaxies as well as in distant parts of the Universe. As noted by him, the 'encyclopedia of the Universe is written in the small (weak) 21-cm typescript, to read which one requires a very sensitive telescope'. Such a telescope will allow detailed mapping of both continuum and line radiations from galaxies located up to a redshift of about one. Studies of the intergalactic clouds, interacting galaxies, radio galaxies, quasars, deuterium line and recombination line emission, pulsars, stellar radio emission, supernova remnants, H II regions and our solar system are also likely to yield many new and exciting results.

Array configuration and antenna system

To satisfy the requirement of some of the major scientific objectives of ITRA, e.g. study of diffuse features in our galaxy and in radio galaxies, studies of HI emission or absorption lines in galaxies and search for protoclusters and protogalaxies, we need to achieve quite a high sensitivity but a relatively modest resolution, say a few arcmin at 327 MHz or ~20 arcsec at 1420 MHz. For many other programmes resolutions of up to 0.1 arcsec are required. Therefore it may be preferable to place 60, 15, 15 and 10% of the antennas within about 2, 10, 25 and 200 km respectively. The central 2-km array may be chosen to be a random circular array in order to provide nearly uniform coverage of spatial frequencies. The outer array may consist of 3 arms in the form of a 'Y'. A Y-shaped array provides a reasonably good spatial frequency coverage and, further, the optical-fibre links can be used economically to interconnect all the antennas. However, the arms need not lie along straight lines and can deviate appreciably to suit existing terrain and approach roads.

Since the maximum frequency of ITRA will be about 2 GHz, it will be sufficient to use wire mesh for the reflector surface of the antenna, which will minimize wind loads on the antenna. For the 45-m dishes of GMRT, the SMART (stretched mesh attached to rope trusses) concept has been adopted to minimize the cost of the antennas. The dish is placed on a 3.6-m-diametre slew ring bearing, which is mounted on a reinforced concrete tower. The reflecting surface consists of 960 plain facets. The expected weighted r.m.s. error of the surface is about 1 cm. The basic concept of this design seems to be well suited for the antennas of the proposed ITRA. However, for improving the efficiency of the antennas at 21 cm and for the sake of economy, the design could be further optimized in several respects, such as (i) by adopting the homologous principle for the back-up structure and also optimization of its shape and design; (ii) a more elaborate rope-truss system to allow a better approximation to the curved surface: (iii) using a wire mesh made of half-hard stainless steel wires instead of the annealed wires used for the GMRT wire mesh, so that a smaller spacing of wire mesh can be used to cut down the leakage of the radio waves through the wire mesh; and (iv) using a wheel-and-track mount which would be economical.

What it will cost

Since the cost of a parabolic dish of diametre d is proportional to dk, where k is 2.5 to 2.7, its cost increases rapidly with the diameter. But a larger antenna has a narrower field of view, which is of considerable advantage at the longer wavelengths, since the ionospheric variations are smaller across the field of view of the antenna. On the other hand, smaller antennas will require more complex electronics. Hence the number and diameter of the dishes must be optimized suitably. We may estimate the cost of n dishes of ITRA of diameter d, including the associated electronics, by extrapolating the cost of 30 number of 45-m-diameter dishes of GMRT as follows:

$$\text{Cost} = K_1(n/30)(d/45)^{25}(v/vo)^2 + K_2(n/30) + K_3(n/30)^2 + K_4 + K_5 + K_6$$

where K_1.....K^6 are the cost of 30 parabolic dishes, associated electronics system including FFT engines of a FX-correlator, cross-multipliers and integrators, computer system, array operation centre, and salaries of technical and administrative staff including overheads respectively. For GMRT $K_1=14$, $K_2\approx3$, $K_3\approx0.2$, $K_4=2$, $K_5=2.5$ and $K_6=2.3$ million US dollars at the prevalent (1990) cost in India. The design wind velocity vo for a wind of 50-year return period at the GMRT site is 140 kmph at 10-m height. We assume v=vo for the ITRA site. For ITRA, we assume ($K_4+K_5+K_6$) to be about 20% of the cost of n antennas and associated electronics, which will be of the order of $70 to $80 million and seems to be a fair estimate taking into account the higher labour cost in the Western countries than in India. An exponent k=2.5 is used because of the likely improvements in the design of the ITRA antennas. In Table 1 are given the estimated cost of ITRA at 1990 prices for several choices of dish diameters, assuming the total collecting area of ITRA antennas to be 15 times that of GMRT. It is seen that

Table 1. Approximate cost estimate of ITRA with total collecting area of about 700.000 m^2

d(m)	45	60	75	90	105
Number of dishes	450	253	162	113	83
Cost (US$, millions)	360	338	352	373	397

cost is nearly the same for dishes with diameter d in the range of about 50 to 75 m. Considering various factors, about 160 numbers of 75-m-diameter dishes may be a reasonable choice of ITRA. The detailed design would entail many trade-offs, e.g. the steerability of the dish may be restricted, particularly because wind speeds are appreciably higher at a height of 100 m than at 50m. In any case, it seems desirable to achieve a steerability of at least ±60o, preferably ±70o , from the zenith.

Conclusion

The proposed ITRA will be an extremely valuable instrument for investigating a variety of outstanding astrophysical problems. It is likely to yield many exciting discoveries. A suitable site, with low radiofrequency interference, low winds and no snow, is likely to exist in South America, Africa or Australia. The estimated cost of ITRA is about $350 million at 1990 prices, which is relatively modest considering its tremendous scientific potential. I hope that the project can be initiated as an international collaborative effort, particularly by the European nations, starting from 1992, which has been declared as the International Space Year, the 500th year since the great voyage of Columbus. It would be a fitting tribute to the fraternity of the new European federation and its international outlook.

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Finding the finance

In 1963 four Indian astronomers then in USA wrote to Bhabha, D S Kothari (Chairman of UGC) and Hussain Zaheer enquiring whether any opportunity existed for beginning construction of some experimental facilities. Only Bhabha replied. Later two of the group actually arrived due to his encouragement (after Bhabha had ascertained that the members of the group had considerable original work and were of sufficient maturity to be able to work on their own in India) The group began with a small field station at Kalyan, utilizing a gift of 32 parabolic dishes from CSIRO of Australia lying unpacked for several years at NPL, New Delhi. A site for a big telescope was then chosen in 1965, at Ootacumund, where TIFR had long maintained a laboratory for studies of extensive air showers at 6000 feet altitude. Bhabha hopefully predicted the telescope would be operating in 1968, but it was ready only in 1970 after overcoming engineering problems of great difficulty. Bhabha had been advised by Swarup (the group leader) to expect a cost of approximately Rs 3 million. However, Bhabha discovered that such expenditure could be included only in the Fourth Five Year Plan of the Government of India. 'Until I arrived in Bombay, and until we had done something with the Kalyani dish. I didn't know what I'd do But I was sitting in the library, saw an interesting paper, began thinking of Arecibo and Greenbank, and then I began to get concrete technical ideas.' Bhabha solved this problem by searching in the provisions of the Third Plan for possible loopholes. He found an adequate yet untouched sum under the heading 'inter-university centres'. The ultimate cost of the telescope was about ten times and amount suggested as a memorial to Saha in 1957. That was not only the solution to financial problems (to avoid waiting) but also the beginning of the idea of a facility which would be shared among surrounding universities, as would be done in Calcutta with the VEC accelerator.

From Robert S Anderson, Building Scientific Institutions in India Saha and Bhabha Occasional Paper Series, No 11, Centre for Developing Area Studies, McGill University, Montreal, 1975.

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The Square Kilometre Array

The Square Kilometre Array (SKA) will be an array of telescopes, spread over hundreds of kilometres, located in radio quiet regions in two continents (Australia and Africa), with a central headquarters located in the United Kingdom. There will eventually be hundreds of dishes (part of the SKA-Mid telescope) and hundreds of thousands of low frequency antennas (part of the SKA-Low telescope), backed with state of the art electonics, signal transport, signal processing, computing and software systems, that will monitor the sky in unprecedented detail. Both South Africa's Karoo region (for SKA-Mid) and Western Australia's Murchison Shire (for SKA-Low) are chosen as co-hosting locations based on the characteristics of the atmosphere above the sites and their radio quietness, which comes from being some of the most remote yet accessible locations on the Earth.

The first ideas for the concept that is today the SKA, were mooted a few decades ago, and have since been refined and improved over time. The accompanying article by Professor Govind Swarup of NCRA-TIFR in 1991, is one of the early proposals justifying the need, and laying down the basic ideas, for a large next generation international radio observatory, called ITRA, which has now metamorphosed to the SKA.

The unprecedented sensitivity of the SKA's receivers will allow insights into the formation and evolution of the first stars and galaxies after the Big Bang, the role of cosmic magnetism, the nature of gravity, and possibly even life beyond Earth. Further, the role of serendipitous discoveries with such a powerful facility that is at least ten time better than the best existing radio observatories, brings additional promise to the aleady vast canvas of the SKA science case. Indian scientists are involved in many of the SKA's Science Working Groups, and presently co-chair the Solar physics Working Group.

The SKA will push several areas of technology to the next level, spanning antenna design, low-noise cryogenic radio frequency electronics and optical fibre technologies, low-power electronics, signal processing, high performance computing, as well as complex system management software. Some of the most challenging innovations will be in the area of software and computing, making it a truly "IT telescope".

Whilst 134 member nations including India are presently funding the SKA, around 100 organisations across about 20 countries representing over 1,000 scientists and engineers are participating currently in the design and development of the SKA. The National Centre for Radio Astrophysics of Tata Institute of Fundamental Research in Pune is leading India's participation in the SKA and the Telescope Manager consortium designing the SKA's software. India's activity is funded by the Deparment of Atomic Energy and Department of Science and Technology, Government of India. SKA-related initiatives in India are overseen by the SKA-India Consortium (SKAIC) which has almost twenty member organisations from all over the country.

SKA dishes, antenna arrays and low noise electronics

The SKA's dishes in the SKA-Mid telescope, one of the two types of receivers that will be used (the other one being the low-frequency aperture array dipole antennas in the SKA-Low telescope), will be built and deployed on a scale never seen before, using new and ground breaking techniques.

The SKA-Mid telescope, using multiple 15 metre wide dishes as an interferometer, will exceed the single dish sensitivity and capabilities of telescopes such as Arecibo in Puerto Rico, even though the individual they dishes are much smaller. It will also exceed the sensitivity and resolution provided by current world-class dish based interferometer observatories, such as the Giant Metrewave Radio Telescope (GMRT) in India. The combination of several hundreds of these "smaller" 15 metre wide dishes will form a substantial part of the SKA (the SKA-Mid in Australia), giving the telescope its high frequency capability. The high frequency dishes will be fully steerable, with an offset cassegrain aperture to give maximum sensitivity without any blockage of the aperture.

Many aspects of the SKA dish-design challenge are without precedentunprecedented, not only because of the large numbers of dishes required, and the engineering accuracy that entails, bBut also because of the huge sensitivity and the amounts of data that will result need tobe handled from this vast collecting area. Current radio telescope arrays like the VLBA in New Mexico use telescope dotted all over the United States for example, but the amount of data these generate will be dwarfed by the SKA.

The dishes for the SKA will be made from a mix of materials, including carbon fibre composites, with an accuracy and sensitivity figure (the shape) unrivalled in radio astronomy. Capable of withstanding high winds, and all sorts of intense thermal and environmental stresses, the SKA's dishes will be unique in the world of radio astronomy. The SKA-Mid dish antennas will be backed up with cryogenically cooled low noise electronics which will further enhance the sensitivity of the SKA-Mid to detect extremely weak signals coming from the distant reaches of the Cosmos.

A small number of large dishes could also provide high sensitivity but many smaller dishes with larger field of view also offer the prospect of faster surveys of the sky. This trade-off has resulted in the adoption of dishes with a diameter of 15 metres to give both a good field of view whilst also allowing high sensitivity at a suitable cost to enable the SKA-Mid to come instay within its target budget.

Although sensitivity is a strong driver of the SKA-Mid system design, there is also a need to carry out surveys of large regions of the sky, something the SKA will be able to conduct thousands of times faster than any previous radio telescope. As part of the dish design process, many factors such as imaging dynamic range, design for mass manufacture, feed flexibility, sensitivity per dish, rapid installation are to be taken into consideration.

Figure 1 :
Artist's impression of the central core area of the SKA-Mid telescope array showing a large number of the SKA dishes, to be located in the Karoo region of South Africa.

The antennas in the SKA-Low telescope (to be located in Australia) will use a different concept from dish antennas : aperture arrays formed from a collection of basic dipole antennas spread out on the ground. An aperture array is a large number of small, fixed antenna elements coupled to appropriate receiver systems which can be arranged in a regular or random pattern on the ground. Whereas with a traditional radio telescope radio signals bounce off the surface of a dish and are then captured at the focus, with aperture arrays the radio signals are captured when they first hit the receptor on the ground. The signals from all the elements are then added together electronically, in phase, to synthesise reception beams, and the result is a fast and flexible system. Multiple signal 'beams" can be formed and steered by combining all the received signals after appropriate time delays have been introduced to align the phases of the signals coming from a particular direction.

Innovative, efficient and low cost, aperture array antennas provide a large field of view and are capable of observing more than one part of the sky at once. By simultaneously using different sets of timing delays, this 'beam forming" can be repeated many times to create multiple independent beams, yielding an enormous total field of view. The ability to configure numerous beams will permit the system to look at multiple regions of the sky simultaneously, massively increasing the survey speed of the SKA-Low telescope. The number of useful beams produced, or total field of view, is essentially limited by signal processing, data comunications and computing capacity. The SKA from the outset is challenging industry and technology to the limits, with concepts and designs that, as with the Apollo program in the 1960s and 70s simply did not exist at the time of inception.

Aperture arrays using substantial digital processing systems are inherently very flexible since the system can 'trade off' between the field of view and bandwidth and hence provide an instrument that can be matched to that required by the experiment it is set to work on. This approach which uses essentially no moving parts is key to the design concept for the SKA-Low telescope, allowing rapid deployment and, hopefully, lower maintenance requirements. The SKA-Low dipole antennas will be backed-up with ambient temperature low noise electronics, as cyrogenic cooled receivers are neither practical nor required, for such dipole antenna arrays working at low frequencies.

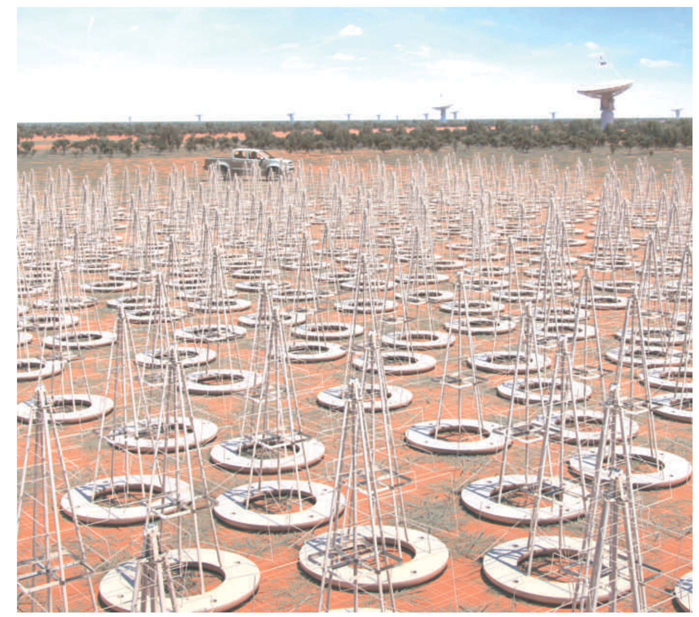


Figure 2 :
Artist's impression illustrating the concept for the Low Frequency Aperture Array of SKA-Low telescope, to be located in western Australiaabove1. The telescope is arranged in 'stations" with each station consisting of a cluster of individual wide-band dipole antennas. In this artist's illustration, the antennas of the ASKAP telescope – a co-located SKA precursor facility – can be seen in the background.

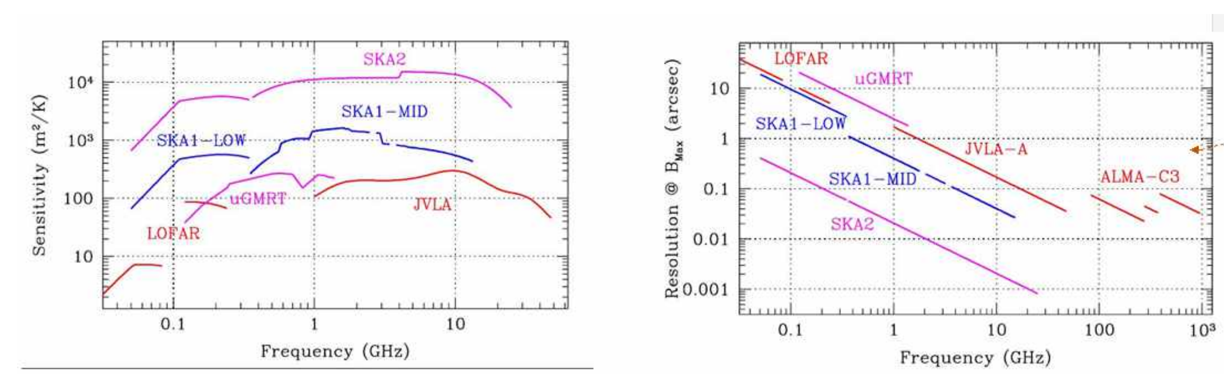


Figure 3 : Comparison of the sensitivity (left panel) and resolution (right panel) of the SKA with some of the major existing and upcoming facilities in the world, including India's upgraded Giant Metrewave Radio Telescope (uGMRT). Curves are shown for the first phase of the SKA (labeled SKA1) and for the full SKA (labeled SKA2), for both the Low and Mid telescopes of the SKA. As can be seen the SKA will be truly transformational compared to all existing facilities, when it comes these two important parameters for a radio telescope.

Figure 4 : A view of the recently completed SKA Headquarters at Jodrell Bank observatory near Mancheter, in the United Kingdom.

Signal Transport and Data Networks for the SKA

Signal transport and networks will be the backbone of the SKA telescope; they will interface with almost every aspect of the system and will ultimately represent the largest and most challenging network system in large science projects. An average of 8 Terabits per second of data will be transmitted both from the dishes and from the low-frequency aperture array to central processors at the sites in South Africa and Australia, respectively. This is a rate 100,000 times faster than the projected global average broadband speed in 2022 (source: CISCO; November 2018). The physical network infrastructure will primarily use optical fibre cable. The ability of optical fibres to carry large amounts of data over long distances at high speed can increase the sensitivity of the radio telescope because it maximises the volume of data transmitted from the receptors to the signal processing correlators located at each site. This means that distant galaxies, only glimpsed by extended observations today, will routinely be observed in a fraction of the time, giving astronomers using the SKA more sensitive data than has ever been available in the history of radio astronomy. The huge distances that the spiral SKA configuration will span means that the SKA will need enormous quantities of optical fibre, enough in fact, to wrap twice around the Earth !

Signal transport and networks are also essential for the operation of the SKA as it works as an interferometer. The functions of these transport networks will include timing and synchronisation, monitoring and control, the transmission of data from the receptors to the correlator as well as data connectivity externally for users across the world. Timing and the arrival of signals will form the backbone of how these vast interferometric networks will function.

Signal Processing and Computing for the SKA

Signal processing is an integral part of the radio astronomy process. It is used for pre-processing data for specific science requirements in preparation for making the stunning high-resolution radio images that the SKA will eventually produce. Signal processing also handles the complex operation of beam-forming, which enables the radio signals to initially be received from across the sky from any direction, and with the SKA, in multiple directions at the same time. Beam forming is a signal processing technique that is used in radio astronomy to observe radio signals from specific regions of the sky.

Data from all the antennas (dishes for SKA-Mid telescope and stations of dipole arrays for SKA-Low telescope) will be sent to the central correlators, which will house high-speed electronics and computeres designed to combined the signals from multiple antennas. These correlators will be situated near the core of the array, where the data will be combined and synchronised. Filters will be used to separate the radio frequency signals required for astronomy from any interfering radio frequency signal that would contaminate the data. This is one reason why the SKA locations have to be as radio quiet as possible.

The SKA will use advanced signal processing concepts to make high quality images of the various Cosmic sources, and also to automatically detect the repetitive pulsed signals from objects such as pulsars. In addition to such studies, the SKA will automatically detect transient events. These unexpected and unpredictable astronomical events include supernovae, gamma-ray bursts and micro-lensing events (which can temporarily brighten objects in the far reaches of the Universe, due to the gravity of a foreground object acting as a lens). Advanced auto-detection techniques requiring data with high time and frequency resolution will be employed.

The SKA will stretch signal processing algorithm development in two vital areas. Faster and better ways will be developed to make the high dynamic rangeA images required for SKA science. Effective radio interference (RFI) mitigation algorithms will also be needed to enable observations across wide segments of the radio spectrum. The algorithms used will need to be as efficient as possible, to process the huge amounts of data coming through the system. There is significant scope of machine learing and artiifical intelligence based algorithms in the complex signal processing domain of the SKA.

SKA signal processing has considerable requirements for signal transport, low-power processing electronics and back-end supercomputing facilities, due to the sheer size of the problem, with thousands of antennas providing data simultaneously at both locations. The signal processing will require exceptionally high-speed computer systems, that must meet budget, processing and thermal requirements. Processing the vast quantities of data produced by the SKA will require two (one in South Africa, one in Australia) very high-performance central supercomputers capable of in excess of 100 petaflops (one hundred thousand million million floating point operations per second of raw processing power), which is equivalent to the fastest supercomputer on Earth at the present time (Source: Top500; November 2018). In total, these two supercomputers will archive 600 Petabytes of data per year. To store this data on an average 500 GB laptop, you would need more than a million of them every year.

Telescope Manager and Indian participation in SKA

The endo-to-end control and management of a large, distributed and complex facility like the SKA observatory requires a very sophisticated telescope management system. For the SKA, this system – called the 'Telescope Manager" – is envisaged to provide such a functionality, all the way from genertion and submission of proposals for observations, to the actual preparation of the obsrerving plan and real-time execution of the same (including interfaces with the telescope operators and the maintenance engineers), all the way upto completion of the data analysis and communication to the user about the outcome of the same.

The Telescope Manager (TM) element includes all hardware and software necessary to control the telescope and associated infrastructure. The TM includes the co-ordination of the systems at observatory level and the software necessary for scheduling the telescope operations. It also includes the central monitoring of key performance metrics and the provision of central co-ordination of safety signals generated by Elements of the SKA. The TM provides physical and software access to, and at, remote locations for transmission of diagnostic data and local control. The TM does not include local control, whether hardware or embedded software, of units (e.g. individual dishes, beam formers, building control systems). It does not include either the generation of local metrics (e.g. tracking stability of dish, power consumption of LFAA).

In summary, the TM is responsible for the management of all astronomical observations, management of all the telescope hardware and software systems that perform the observations and facilitating communication across the primary stakeholders, in addition to ensuring safety. In the above process, the TM interacts with ever Element of the SKA, and is effectively the brain and nervous system of the observatory.

The work on this complex Telescope Manager system has been led by India, which has contributed extensively to the design of this Element, and hopes to lead the development of the various parts of this system during the construction phase of the SKA. The work in India, led by NCRA-TIFR, leverages the expertise of Indian IT industries, utilising next generation tools and ideas to tackle the complex problem. As a result, a successful model for industry interactions for SKA (and similar large projects) has been evolved in India, which can be leveraged for larger involvement of Indian industry in large, international science projects.

The TM Consortium of the SKA was led by Yashwant Gupta from NCRA-TIFR. The Consortium had a successful Critical Design Review (CDR) of the TM design in 2018 and was one of the first ones in the SKA community to complete the process.

In addition to the TM system, India is aiming ot participate in the development of the SKA signal processing and electronics systems for both the SKA-Low and SKA-Mid telescopes, leveraging the state-of-the-art experience gained from building and running the Giant Metrewave Radio Telescope (GMRT) – a SKA pathfinder facility located in India -- and participating in the international Muchinson Widefield Array (MWA) radio observatory – a SKA precursor facility located in Australia. In particular, the recent uprade of the GMRT carried out by NCRA-TIFR has several synergies with new technologies and science projects relevant to the SKA. Similarly, the design, implementation and successful delivery of the digital receiver systems for the MWA observatory by the team from the Raman Research Institute (RRI) in Bengaluru, sets the stage for Indian academia and industry to work together for similar, but larger scale, contributions to the SKA.

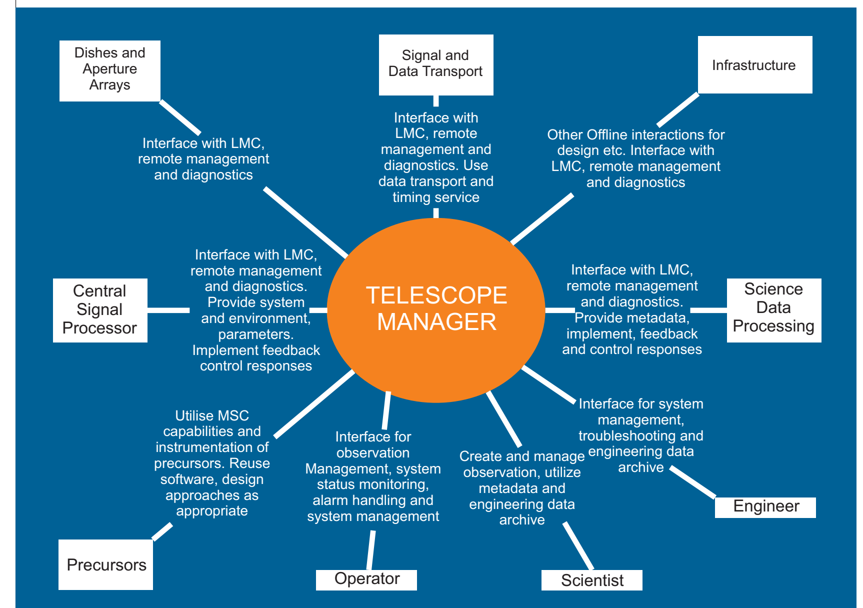


Figure 5 : Illustrating the central nature of the SKA Telescope Manager, as the brain nd nervous system of the entire SKA Observatory.

Figure 6 : The India led SKA TM team alongwith the SKAO staff and TM CDR review panel members, on the occasion of the SKA TM Critical Design Review meeting in April 2018 at the SKA HQ in Jodrell Bank, UK

Artist's view of TMT Observatory on Mauna Kea, Hawaii

A New Window to the Universe

Our view of the Universe was largely constrained by the unaided vision of our eyes before Galileo Galilei first adapted a telescope to look at the skies over four hundred years ago. Telescopes built till today have led to many fascinating and intriguing discoveries in astronomy, like the discovery of planets around other stars, evidence of accelerating expansion of the Universe, existence of dark matter and dark energy, monitoring of asteroids/comets that could pose a serious threat to the inhabitants of the Earth. The upcoming Thirty Meter Telescope (TMT) will be one of the world's most advanced and capable ground-based optical and infrared telescopes to probe unknown cosmos. An international consortium of scientific institutions and organizations in Canada, China, India, Japan and the USA is building TMT. In India, to efficiently manage India's contributions to TMT, the Department of Science and Technology (DST) and the Department of Atomic Energy (DAE), Government of India have jointly formed an India-TMT Coordination Centre (ITCC) at the Indian Institute of Astrophysics (IIA), Bengaluru. TMT will involve the latest innovations in technology at the heart of the telescope is a segmented mirror, made up of 492 individual hexagonal segments which will work as a single reflective surface of 30m diameter providing unprecedented light gathering capability and an advanced Adaptive Optics (AO) system which will provide superbly high resolution images as if the TMT were in space. India's in-kind contributions to the TMT project include Segment Polishing, Segment Support Assemblies, Actuators, Edge Sensors, Software development for the observatory and design and development of science instruments. TMT, enabled with these technologies will make ground-breaking advances in answering a wide range of fundamental and important scientific questions.

Thirty Meter Telescope (TMT) Project:

India's participation in the TMT project will provide Indian astronomers an opportunity to carry out frontline research in astronomy. Another major reason to participate in this scientific endeavour which integrates latest innovations in segmented mirror design, precision control and adaptive optics, is to bring home some of these engineering expertise through international collaboration.

Primary mirrors (M1) Segments are the most critical components for the TMT project. There are 574 (including 82 spares) segments of 1.44 m diameter each with a thickness of 45 mm. All the segments need to be hexagonally cut and polished to the roughness of about 22 Å RMS or to about 20 nm peak-to-valley (PV), and without any subsurface damage. All the segments are off-axis and aspheric. Asphericity is of the order of a few microns for the innermost segments to 220 microns for the outermost segments. Challenge is to produce at least two fully polished segments per week over the duration of TMT construction starting from 2019 to 2030. Clearly, no single optics facility will be able to provide such large numbers within the time frame of the telescope construction, necessitating the use of more than one optics laboratory. Japan, India, China and USA agreed to provide number of polished segments proportional to their share in the project. Thus, India as a 10% partner in the project is obligated to provide about 84 polished segments to the project. As a first step, India has to demonstrate segment polishing capability in the country. Efforts are on to develop the required technology and infrastructure for segment polishing using the stress mirror polishing (SMP) method.

In order to achieve very high spatial resolution as well as sensitivity, all the 492 hexagonal mirror segments of the TMT must be precisely positioned with respect to each other to form a 30-meter hyperboloid primary mirror as if it is made up of a single monolithic mirror. The M1CS is responsible for maintaining the overall shape of the segmented M1 mirror despite deformations of the telescope structure caused by temperature, gravity and disturbances from wind and vibrations (observatory generated and seismic). The M1 control system (M1CS) performs this task, with the help of segment support assembly (SSA), actuators and Edge sensors.

The TMT will host a set of back-end instruments for science observations like Wide Field Optical Spectrograph (WFOS) and Infra-Red Imaging Spectrograph (IRIS) on first light. All the near Infra-red back-end instruments will be assisted by a Mulit-Conjugate Adaptive Optics (MCAO) system called Near Field Infra-Red Adaptive Optics System (NFIRAOS). India is responsible for the end-to-end performance analysis of the optics design and software development for WFOS. India is also the leading P.I. country for the development of one of the second generation instrument called High Resolution Optical Spectrograph (HROS).

ITCC Activities:

Actuators

In order to achieve very high spatial resolution as well as sensitivity, all the 492 hexagonal mirror segments of the TMT must be precisely positioned with respect to each other to form a 30-meter hyperboloid primary mirror. The M1 control system (M1CS) performs this task, with the help of actuators that corrects for the segments' tip-tilt and piston errors measured by edge sensors. Actuator corrections are critical to retain the shape of the mirror that are otherwise disturbed due to wind and vibrations. Each mirror segment will be driven by three actuators, and altogether 1,476 actuators are required to keep all the segments aligned. Each of these actuators are made up of several precision manufactured components put together to act as a soft actuator working to nanometric accuracies and can provide tip, tilt and piston to each mirror segment with an accuracy of 4 nanometers. In 2018, 20 such prototype actuators have been manufactured at 4 Indian industries (Indo Danish Tool Room (IDTR), Jamshedpur., Southern Electronics, Bangalore., Tamboli Engineers Pvt. Ltd., Pune., Amado Tools, Bangalore.) and currently they are undergoing lifetime test at Jet Propulsion Laboratory (JPL) in Pasadena, USA.

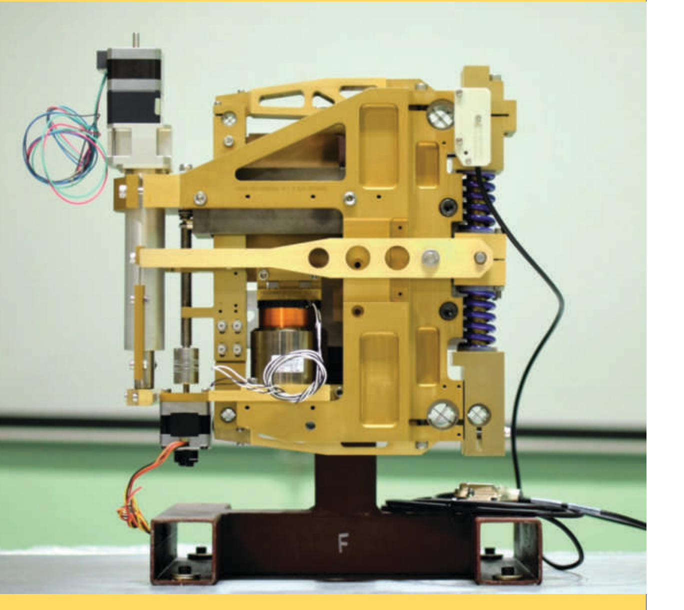


Figure1: **Prototype Actuator** fabricated in India. (Photo credits: IIA/ITCC/ Prasanna Deshmukh).

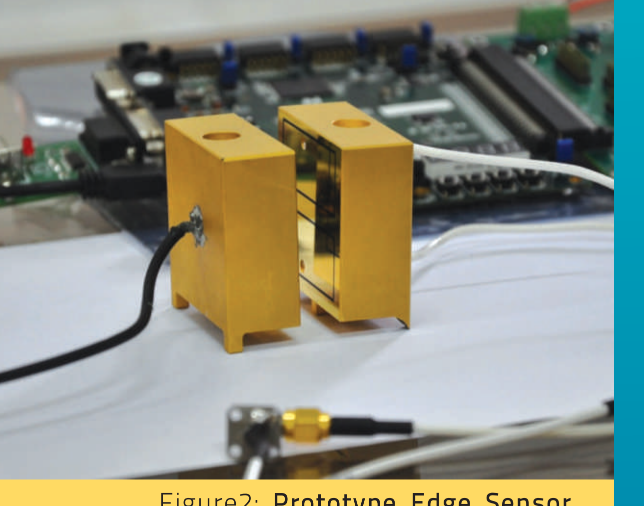


Figure2: **Prototype Edge Sensor** fabricated in India. (Photo credits: IIA/ITCC/ Prasanna Deshmukh).

Edge Sensors

During the course of science operations, segments may get displaced relative to each other due to varying gravity and thermal loads which degrades image quality. Thus, all the 492 segments must be actively co-phased to maintain the correct surface shape to produce sharpest possible images and, in the case of Adaptive Optics (AO) mode, diffraction limited images. Edge sensors would measure relative displacement, tip, and tilt of the segments which would then be relayed to Actuators. The current TMT design requires six edge sensors per segment, which is a total of about 2772 edge sensors. Sensors are critical to the operation of segmented mirror telescope technology by allowing the individual segments to adjust in controlled manner so as to form a single reflecting optical surface. Each of these sensors can measure relative displacement of mirror segments to an accuracy of 5 nanometers. Till now India-TMT with the help of General Optics Asia Ltd (GOAL), Pondicherry manufactured 12 capacitive edge sensor prototypes, that have successfully gone through the detailed testing at Jet Propulsion Lab (JPL, USA).

Segment Support Assemblies (SSAs)

Each mirror segment is mounted on a support called the Segment support assembly (SSA).

One Segment support assembly (SSA) is required per mirror segment. There are 82 types of mirror segments and hence TMT needs 82 types of SSAs, each customized for a specific type of segment. Each SSA in turn has several subcomponents that are to be manufactured separately, integrated and tested. Total 492 SSAs are required in the TMT that will be manufactured in India. Presently contract is placed with Larsen & Toubro (L&T) for manufacturing of 100 SSAs.

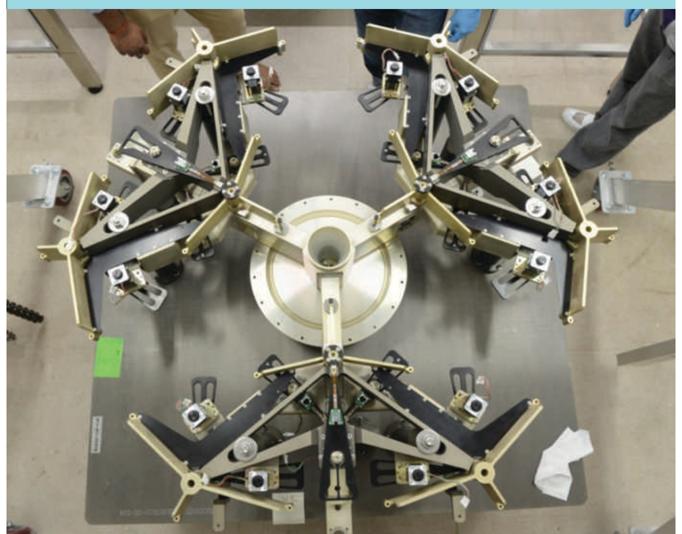


Figure3: **Prototype SSA** fabricated in India (Credits: IIA/ITCC/ Fred

Segment polishing:

Providing primary mirror segments to the TMT is one of the major challenges to India-TMT. As a first step towards this, India is in the process of demonstrating segment polishing capability by using Stress Mirror Polishing (SMP) technique which acquires a polishing roughness of about 22 Å RMS without any subsurface damage. Total 84 primary mirror segments will be fabricated in a special facility constructed by the Indian Institute of Astrophysics (IIA), India-TMT Optics Fabrication Facility (ITOFF), in Hoskote, near Bengaluru, India.

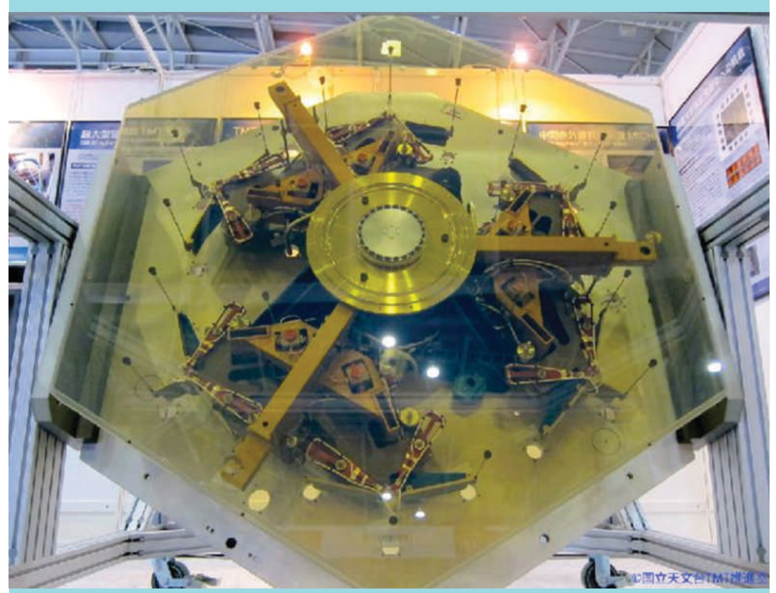


Figure 4: **TMT Primary Mirror Segment** (Credits: NAOJ)

Figure5: **India TMT optics fabrication facility (ITOFF)**
(Credits: IIA/ITCC/ Alikhan Basheer)

Software:

India is responsible for providing much of the software support system to the observatory. The important ones among them being the Observatory Software (OSW) and the Telescope Control Software (TCS):

India-TMT is responsible for developing and delivering some of the principal software systems on-site. Of these, the OSW provides the software architecture support and infrastructure that integrates all TMT software to form one cohesive system. OSW is responsible for providing the end-to-end observing software system, to capture and access all science and engineering data, synchronized operation of all the sub-systems and to enable high-level science operations from proposal preparation to observation execution.

TCS is responsible for the coordination and control of the various subsystems that make up the telescope as well as responding to commands received from the OSW and from expert user interfaces. It will provide high-level control of the mount, the mirrors, and the enclosure. It will enable precise pointing and tracking of observing targets. It will also help control the position and shape of the mirrors. Several adaptors to be developed will provide ways for external systems and hardware to be integrated into the TMT software system. Thought Works and Honeywell software companies, Pune, are contributing to these two major activities.

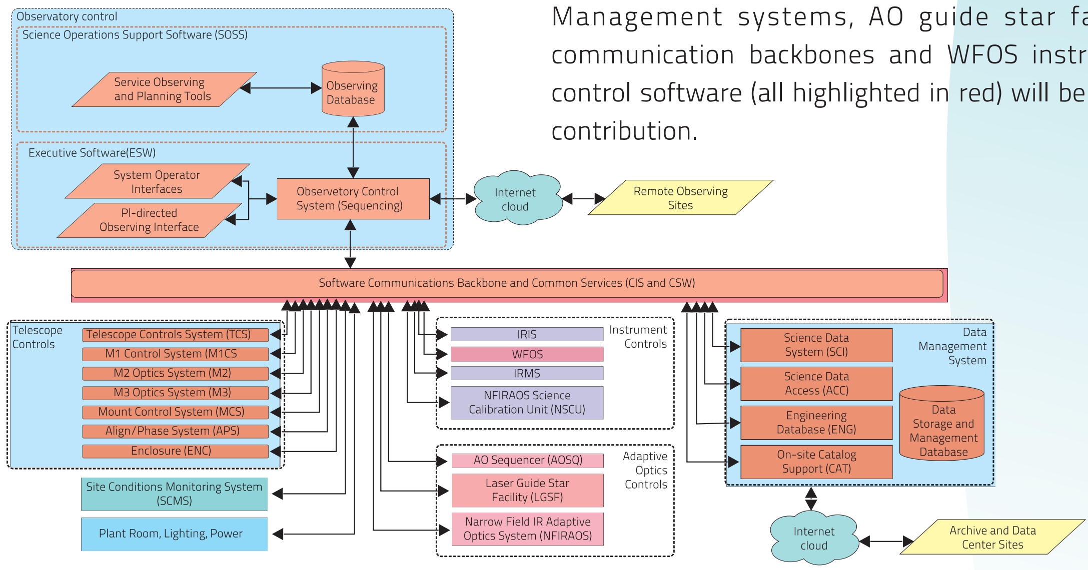


Figure 6: Complete Software Architecture of the TMT. Observatory controls, Telescope controls, Data Management systems, AO guide star facility, communication backbones and WFOS instrument control software (all highlighted in red) will be India's contribution.

Science Instruments:

Wide Field Optical Spectrograph (WFOS)

WFOS will probe galaxies and stars in the visible wavelength range to understand their birth and evolution from the past 10 billion years through powerful imaging and spectroscopy. WFOS will

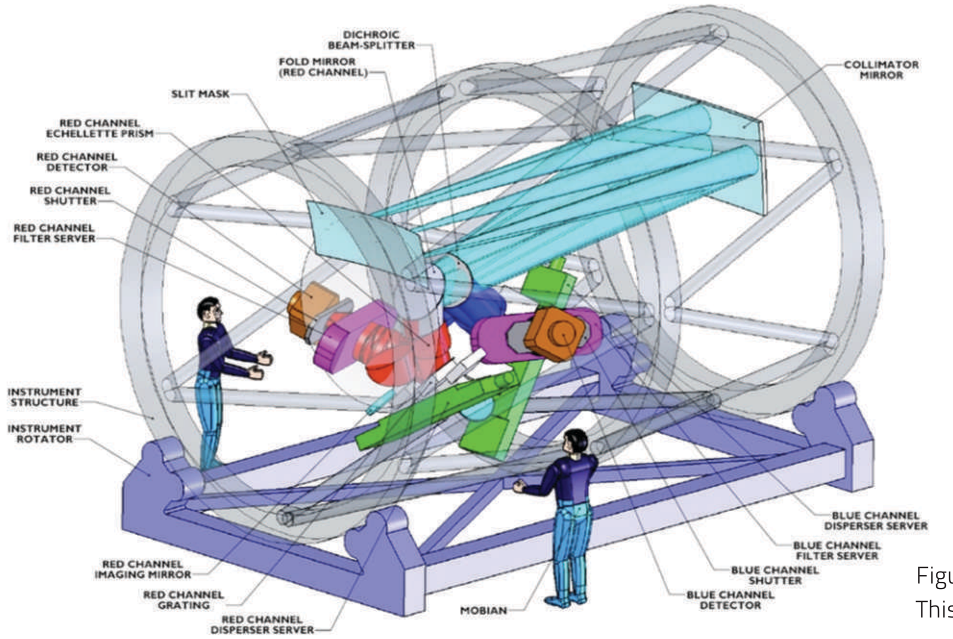


Figure 7: Internal design of WFOS. This is going to be one of the two workhorse instrument of TMT.

enable key discoveries in the field of Early universe, to understand how first stars and galaxies formed, the nature and composition of our Universe, to understand the exotic dark energy and accelerating universe through measurements of distant supernovae, and many more. India-TMT is an integral part of the team building WFOS. India will be performing the end-to-end analysis of the opto-mechanical design of the WFOS instrument. India will also be designing and constructing the Instrument Control Software for the WFOS.

InfraRed Imaging Spectrograph (IRIS)

IRIS is an InfraRed diffraction limited integral field spectrograph and imager operational on first light. Some of key science areas that IRIS will make significant contributions are in exoplanet science, to measure important bio-markers (like H20, CH4, O2, O3, etc.) present, if any, in these exoplanets. To understand our own solar system objects like Kuiper belts which hosts icy bodies that hold clues to how our own solar system formed. It will achieve an angular resolution 12 times better than images from the Hubble Space Telescope (HST) producing sharper images with finer details.

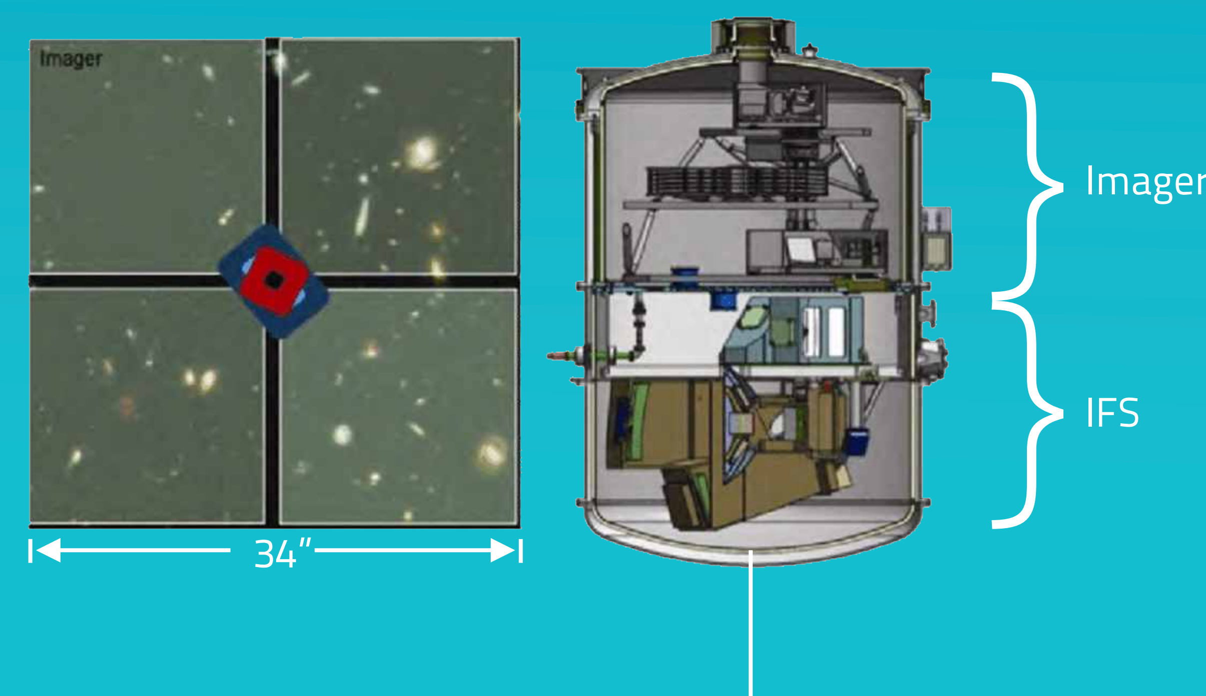


Figure8: (Left) The IRIS field of view. Four 4k x 4k detectors are used for the diffraction-limited imager. The coloured rectangles in the centre represent the four options for the field of view of the integral field spectrograph (IFS). (Right) The two-part design of the science instrument with light entering from above. The imager and IFS are being built separately and will be integrated before the instrument is sent to the telescope site.

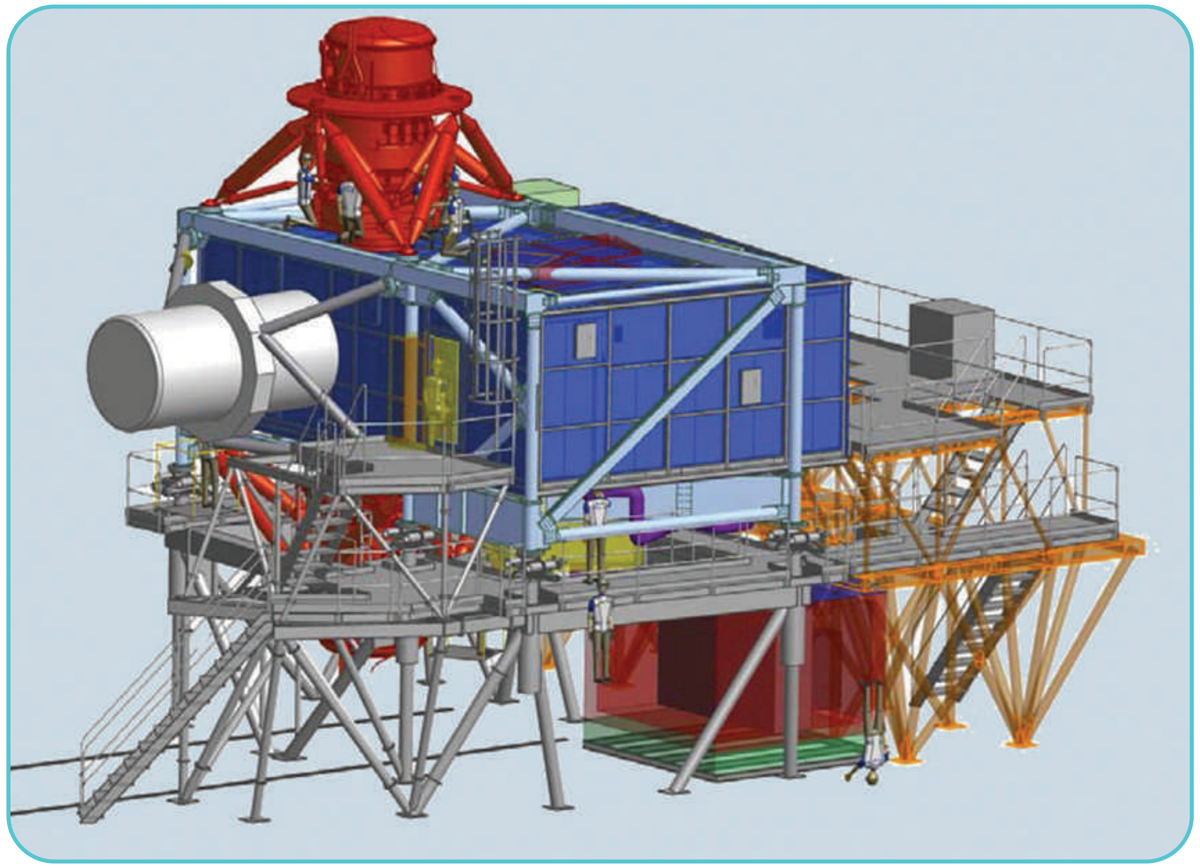


Figure 9: Internal design of NFIRAOS. The three potential instrument output ports are seen.

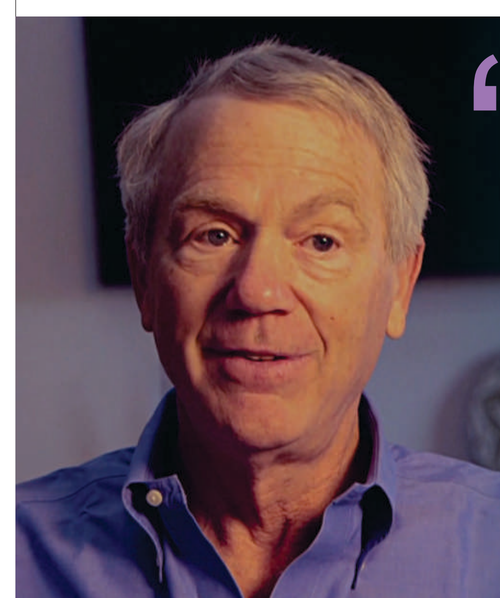
Near-infrared (NIR)

The near-infrared (NIR) observing instruments in TMT will be assisted by a multi conjugate adaptive optics (MCAO) system called NFIRAOS (Near Field Infrared Adaptive Optics System). The light will be fed to IRIS from NFIRAOS. NFIRAOS is the adaptive optics system that corrects for the effects of the atmospheric turbulence. A NIR catalogue of stars is highly essential to perform these corrections and India-TMT team is leading the creation of the final catalogue.

Interview excerpts :

"TIO is the amalgamation of five countries. Among these are top-notch laboratories and also good research groups. At present in India we have few 2-m class telescopes and one 3.5-m telescope which is the largest aperture optical and IR telescope. So jumping from 2-4 m class telescopes to TMT (a 30-m diameter telescope) is a great challenge as well as an opportunity."

B. Eswar Reddy, Professor in Astronomy & Astrophysics, IIA &Programme Director of India-TMT Coordination Centre.



"A big telescope lets you separate the image of a planet from the image of its host star. And it gives you the opportunity to measure quickly what's going on when the planet is passing in front of the star; to make measurements when the planet's in back of the star: by subtracting those two, you can figure out what the planet is doing to the light from the star. This will reveal the chemistry of its atmosphere and maybe even detect a signature of life."

Robert Kirshner, Clowes Research Professor of Astronomy at Harvard University & Chief Program Officer for Science at the Gordon and Betty Moore Foundation

Interview excerpts :

“We expect there could be transformative science, and eventually TMT will change the way astronomers and even non-astronomers understand our Universe.”

Suijian Xue, Deputy Director- General of the National Astronomical Observatories of Chinese Academy of Sciences

“TMT, by virtue of its larger aperture, will be able to push deeper into the Universe. We will be able to see, in far more detail, how structures in the Universe is assembled, how galaxies themselves are assembled and how the chemical evolution of the Universe has proceeded almost from the beginning of the modern era, which would be at the end of the so called Dark Ages. Very high redshift objects going right back to the aftermath of the Big Bang will be an important topic of TMT research.”

Gregory Fahlman, General Manager of Hertzberg Astronomy and Astrophysics at the National Research Council of Canada

Meetings and Events:

- TMT-India Science and Instrumentation Workshop, at Indian Institute of Space Science and Technology (IIST), Thiruvananthapuram 11 – 13 June 2015.
- TMT Science and Instrument Workshop, at IUCAA Pune, 10-12 December 2012.
- Planning for science with TMT: challenges and capabilities workshop, at ARIES Nainital. 05-06 November 2014.
- TMT-India Science and Instrumentation Workshop, at Tezpur University, 01 - 03 December 2015.
- India TMT Activities Workshop, at IIA Bangalore, 12th April 2013.
- TMT: Beyond First Light - TMT Science Forum at Mysore, India. 7-9 November 2017.
- India-TMT science and training workshop: Maximising the Indian participation, at XXXVII Meeting of Astronomical Society of India, Christ (Deemed to be University), Bengaluru,18 - 22 February 2019.

Outreach Actvities:

- **"The Thirty Meter Telescope Project"**, seminar at AstroComm Meet 2019, Jawaharlal Nehru Planetarium, Bengaluru. Mr. Prasanna Deshmukh. 17th February, 2019.
- **The Thirty Meter Telescope International Observatory (TIO) :** A new window to the Universe: Delhi University visitor Programme, Delhi Univ. Delhi. Dr. Eswar Reddy. 31st March, 2016.
- **"Thirty Meter Telescope"**, popular talk at the Jawaharlal Nehru Planetarium, Bengaluru. Dr. G. C. Anupama. 9th August 2015.
- **"Thirty Meter Telescope:** An India Perspective", seminar at LEOS, ISRO, Bengaluru. Dr. G. C. Anupama. 7th August 2015.
- **"The Thirty Meter Telescope International Observatory (TIO) :** A new window to the Universe", seminar at Karnataka State Science and Technology workshop at DavanagereUniversity, Davanagere. Dr. Eswar Reddy. 15th March, 2015.
- **"The Thirty Meter Telescope International Observatory (TIO):** A new window to the Universe", 500th ASET Forum, TIFR, Mumbai. Dr. Eswar Reddy. 13th March, 2015.
- **"India's Participation in The Thirty Meter Telescope International Observatory (TIO) Project"**, invited talk, 33rd ASI, NCRA, Pune. Dr. Eswar Reddy. 19th Feb, 2015.
- **"Thirty Meter Telescope:** An India Perspective", Invited talk during the APRIM-2014. Dr. G. C. Anupama. 18th August, 2014.

Coordinating Institutes in India:

Aryabhatta Research Institute of Observational Sciences (ARIES) Nainital	Indian Institute of Astrophysics (IIA) Bengaluru	Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune

International Partners

Caltech California Institute of Technology	University of California	National Research Council Canada	National Astronomical Observatory of Japan	National Astronomical Observatory of China

Collaborating Indian institutes & industries

			Delhi University, New Delhi	Indian Institute of Science, Bengaluru.	Indian Institute of Space Science and Technology, Thiruvananthapuram.
Physical Research Laboratory, Ahmedabad	Pt.Ravishankar Shukla University, Raipur	Raja Ramanna Centre for Advanced Technology, Indore	Tata Institute of Fundamental Research, Mumbai	Tezpur University, Tezpur	Amado Tools Bengaluru
Accurate Engineering Company Pvt. Ltd. Pune	Avasarala Technologies Limited Bengaluru	Center for Development of Advanced Computing Bengaluru	Central Manufacturing Technology Institute Bengaluru	Central Tool Room & Training Centre Bengaluru	Elite Metrology Bengaluru
International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad	Future Tech Engineering Pvt. Ltd. Bengaluru	General Optics (Asia) Limited Pondicherry	Godrej, Mumbai	Honeywell Automation India Limited, Pune	Indo Danish Tool Room Jamshedpur
National Centre for Aerospace Innovation and Research, IIT, Mumbai	IPA Private Limited Bengaluru	Lakshmi Tech & Engineering Industries Ltd. Coimbatore	Larsen & Toubro Coimbatore	Magma Machining Pvt. Ltd. Ahmedabad	Mechvac India Ltd. Mumbai
Sahajanand Laser Technology Ltd., Ahmedabad	Nucon Aerospace Pvt. Ltd. Hyderabad	Optics and Allied Engineering Pvt. Ltd. Bengaluru	Plan Measuring Services, Bengaluru	National Aerospace Laboratories, Bengaluru	SGS India Pvt. Ltd. Bengaluru
TÜV Rheinland, Bengaluru	Silvergrey Engineers Bengaluru	Southern Electronics Pvt. Ltd., Bengaluru	Tamboli Engineers Pvt. Ltd., Pune	Techno Tools Precision Engineering Bengaluru	ThoughtWorks Technologies Pune

Contact person/Spokesperson

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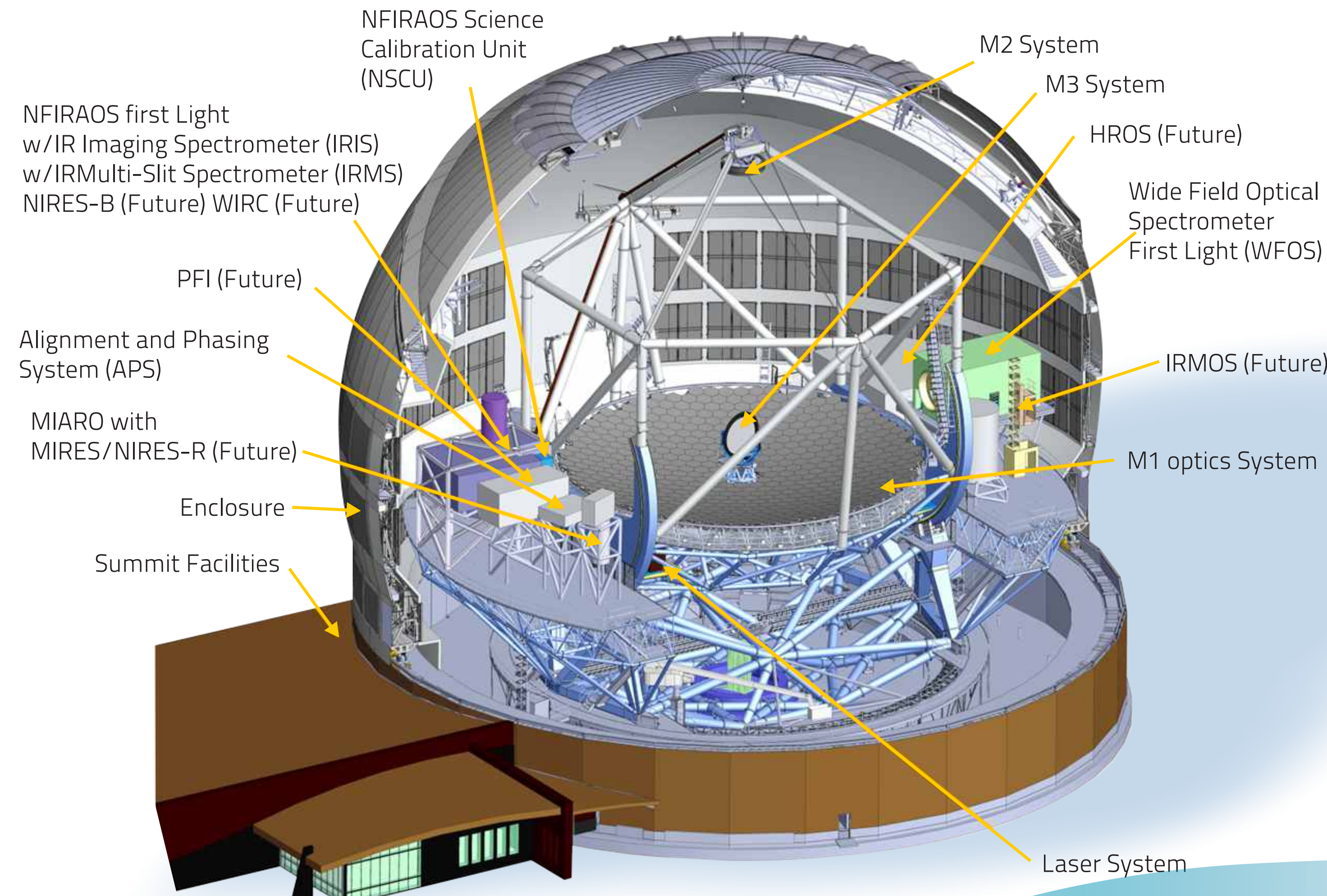
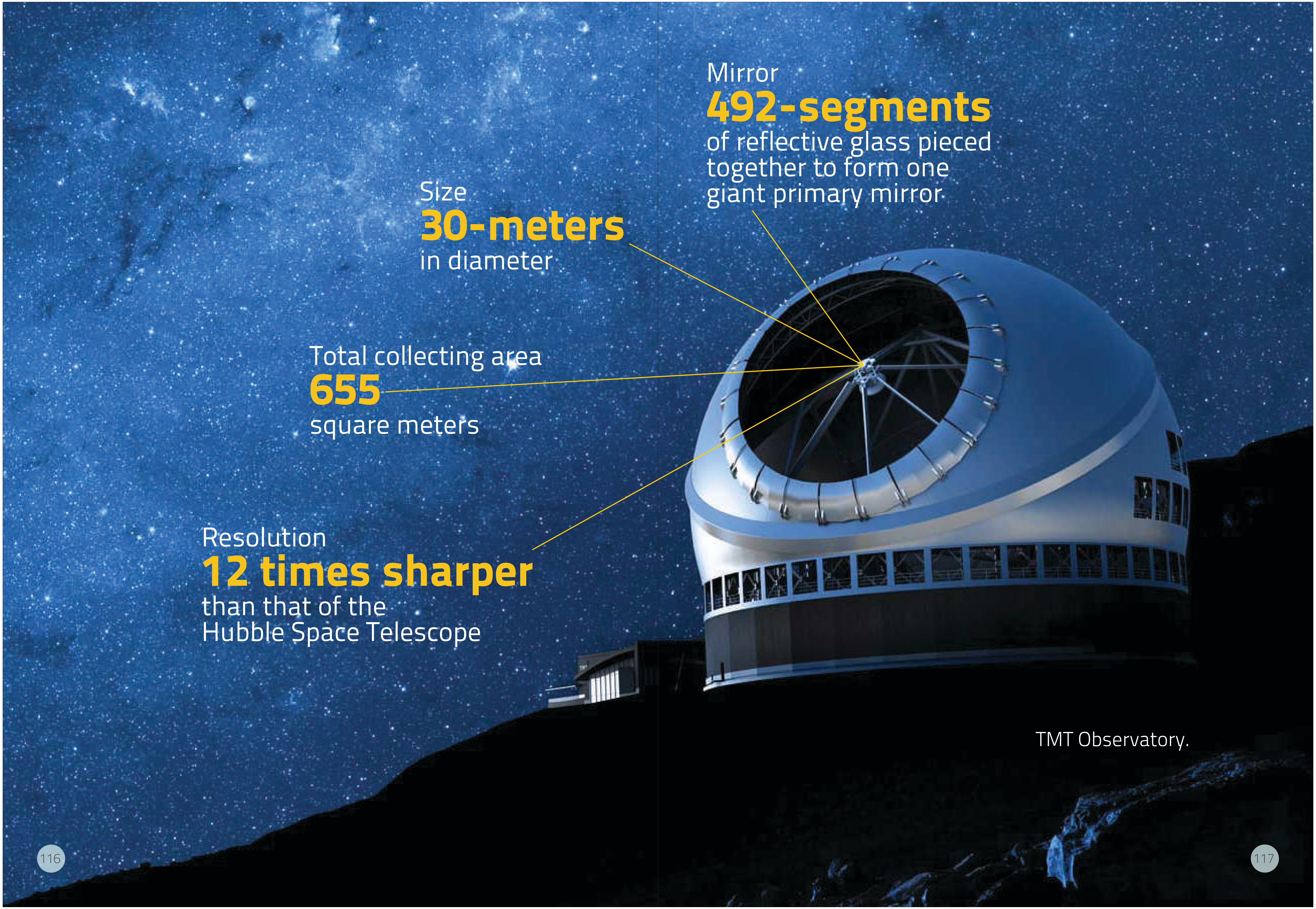


TMT Observatory.



TMT Observatory.

MACE Gamma-Ray Telescope

(Project of DAE)

(HiGRO collaboration -- BARC, TIFR and IIA)

Abstract : A large imaging atmospheric Cherenkov telescope MACE is being installed at the high altitude astronomical site at Hanle in the Ladakh region of North India. The MACE telescope deploys a 21 m diameter quasi-parabolic light collector on an altitude-azimuth tracking structure. The light collector comprises 356 mirror panels measuring 984 mm x 984 mm where each panel consists of 4 diamond turned spherical aluminium honeycomb mirror facets. The photomultiplier tubes based imaging camera of the telescope employs 1088 pixels and covers a field of view of 4.3° x 4.0° with a resolution of 0.125°. Designed to operate at a trigger threshold energy ~ 20 GeV, the telescope will play an important role in understanding very high energy processes in the Universe.

Key words : Gamma-ray astronomy, Imaging atmospheric Cherenkov telescope,

Introduction:

Exploring the gamma-ray sky at energies above 10 GeV (1 GeV= 10^9 eV, i.e., a billion electron-Volt) with low energy threshold ground-based imaging atmospheric Cherenkov telescopes is expected to lead to a potentially rich harvest of astrophysical discoveries, as has been already demonstrated by the MAGIC [1], VERITAS [2] and HESS [3] telescopes at gamma–ray energies above 100 GeV. Although the satellite- based Fermi observatory has detection capability up to 300 GeV, its sensitivity beyond 10 GeV is limited because of its small detection area of about ~1 m^2. Since the detailed temporal and spectral studies of highly variable sources like blazars are limited by the sensitivity constraints of the Fermi detector, exploring the gamma-ray sky in the 10s of GeV energy range with low threshold ground-based imaging atmospheric Cherenkov telescopes continues to be a challenging research area. The detection of pulsed gamma ray emission above 20 GeV from Vela pulsar [4] opens up another interesting area of understanding the nature of pulsars at GeV energies with ground-based gamma-ray telescopes. Furthermore, one can also search for dark matter by looking for gamma-ray signals produced in annihilation and/ or decay of dark matter particles.

In order to address the unexplored energy region above 20 GeV the Himalayan Gamma Ray Observatory (HiGRO) collaboration comprising BARC, TIFR and IIA is setting up a large area imaging atmospheric Cherenkov telescope MACE (Major Atmospheric Cherenkov Experiment) at Hanle (32.8° N, 78.9° E, 4270 m asl) in the Ladakh region of North India. The responsibility of manufacturing and installation of the telescope has been entrusted to ECIL. Hanle is a high altitude dark astronomical site which offers an annual average of about 260 uniformly distributed spectroscopic nights, leading to a year round sky coverage of sources with different right ascension values. The location also has the advantage of extending the longitudinal coverage of atmospheric Cherenkov telescopes in the northern hemisphere by filling the gap between the MAGIC and VERITAS telescopes. The reduced atmospheric attenuation effects at higher altitudes combined with the geometrical aspects of atmospheric Cherenkov light contribute substantially to lower the gamma-ray trigger threshold of the MACE telescope to ~20 GeV. The overall design concept of the telescope was evolved with the main target of lowering the trigger energy threshold to ~ 20 GeV with indigenous design and development. The three major subsystems of the telescope are the mechanical structure including its altitude-azimuth drive system, light collector optics and the multi-pixel camera along with its data acquisition system.

Imaging atmospheric Cherenkov technique :

The atmospheric mantle around the Earth does not permit gamma-rays to reach the Earth's surface. However, using atmospheric Cherenkov technique, one can detect very high energy (VHE) gamma-rays indirectly from the ground. A VHE gamma-ray from a celestial source, generates electron-positron in the Earth's atmosphere, which through a series of Bremsstrahlung and pair-production interactions, give rise to laterally extended shower of ultrarelativistic electrons/positrons. These ultrarelativistic particles in turn generate Cherenkov light in the atmosphere in a cone, whose axis is aligned in the direction of the primary gamma-ray. The large diameter of Cherenkov light pool implies an effective detection area several orders of magnitude greater than the physical size of a typical detector, offsetting thereby the limitations imposed by the usually low gamma-ray flux levels of gamma-ray sources encountered at energies above 10s of GeV.

A Cherenkov imaging telescope records the spatial distribution of the photons in the image plane (called the Cherenkov image) and a close-packed array of fast photomultiplier tubes (PMTs) is used for recording this distribution (also called the imaging camera with individual PMTs as its pixels). The appearance of the recorded image depends upon a number of factors like the nature and the energy of the incident particle, the arrival direction and the impact point of the particle trajectory on the ground. Segregation of VHE gamma-ray events from their cosmic ray counterpart is achieved by exploiting the subtle differences that exist in the two-dimensional Cherenkov image characteristics (shape, size and orientation) of the two event species. Gamma-ray events give rise to shower images which are preferentially oriented towards the source position in the image plane. Apart from being narrow and compact in shape, these images have a cometary shape with their light distribution skewed towards the source position in the image plane and become more elongated as the impact parameter increases. On the other hand, hadronic events give rise to images that are, on an average, broader and longer. Furthermore, Cherenkov images resulting from hadronic showers are randomly oriented within the field of view of the camera because of their isotropic nature. The differences in the images produced by gamma-ray and cosmic ray showers are caused by the physical processes responsible for their development in the atmosphere. TheCherenkov imaging technique was applied for the first time in 1988–1989 by the Whipple Collaboration to detect steady gamma-ray emission from the Crab Nebula using a 10m reflector with 37-pixel PMT camera.

Mechanical structure and drive system:

The MACE telescope deploys a 21m diameter quasi-parabolic light collector on an altitude-azimuth tracking structure. In order to ensure stability of the structure, a 'track and wheel' design is followed for the azimuth movement. The 180 ton telescope is supported on uniformly spaced 6 x 60cm diameter and 100mm wide wheels on a 27 m diameter circular track. Mild steel of EN-24 grade was chosen as the main structural material for the telescope. This material retains good impact strength at low temperatures of -30°C experienced at Hanle during the winter months. The first layer of the alidade structure connects the 6 wheels and the central pintle bearing housing. Two diametrically opposite A-frame structures rise to a height of 15 m to support the 2 elevation brackets which house the spherical roller bearings of 148 mm inner diameter. These brackets in turn support the 23 m diameter Stiffening Ring (SR) from which the mirror basket is suspended. The SR also supports the 4 planer booms which in turn hold the 1.5 ton camera assembly at a distance of 25 m from the mirror surface. The 2-layer mirror basket follows a 'rod and knot' design and has a square pitch of 1008 mm on the front surface where the 984 mm x 984 mm mirror assemblies are installed. Two azimuth drive-wheels are coupled to 3 phase, permanent magnet brushless AC servo motors through multi-stage gearboxes for providing azimuth movement. The elevation movement is provided through a gearbox coupled to the 13 section bull-gear assembly of ~11.6m radius. All the drives have counter torque capability to avoid gear back-lash errors. The motors are driven by pulse width modulated drive amplifiers powered by 480V DC derived from a solar photovoltaic array based power station. The positions of the two axes are monitored by 25 bit absolute optical encoders with 20 arc-sec accuracy. Both the azimuth and elevation gearboxes have also been provided with high speed options to move the telescope at 3o s-1 to quickly point in the direction of interest on receipt of a satellite alert for events like a gamma-ray burst. The drive system can ensure tracking accuracy of better than 1 arc-minute in wind speeds of up to 30 kmh-1. At sustained wind speed exceeding 40 kmh-1 the telescope is automatically brought to the parking position. The telescope structure is designed for survival at wind speeds of 150 kmh-1.

Light collector optics :

The 21m diameter mirror basket of the telescope has 356 square mirror panels of size 984 mm x 984 mm fixed on it. Each mirror panel comprises four indigenously developed diamond turned aluminium honeycomb mirror facets of size 488 mm x 488 mm. The individual spherical mirror facets on a panel are pre-aligned to give a spot size of less than 4mm diameter at its focus for a parallel beam of on-axis light. After characterisation and acceptance of the mirror facet for use on the telescope a protective layer of SiO_2 of about 100 nm thickness is deposited on its reflecting surface. The reflectivity of the mirror facets has been determined experimentally to be ~ 85% at a wavelength of around 400 nm. The photograph of one mirror panel comprising 4 aligned spherical mirror facets is shown in Fig.1. The reflection coefficient or a test sample of 8 mirror facets is shown in Fig.2. In order to ensure that the integrated spot size of the 21m diameter light collector is less than 27 mm diameter (1/2 of the pixel diameter), mirrors with increasing focal length of 25.00 m to 26.25 m are deployed from the centre of the mirror basket to its periphery. Each of the mirror panels is supported on 3 ball joints. Two of these are provided with motorised linear actuators with a travel range of within 25 mm for the purpose of aligning the individual mirror panels to form an integrated quasi-parabolic light collector surface. The mirror alignment system uses 712 brushless DC motors and their drive electronics is controlled by an elaborate algorithm to ensure reliability.

Imaging camera and data acquisition system:

The imaging camera of the MACE telescope employs 1088 PMTs (ETE, UK make 9117 WSB) for the detection of the few nanosecond duration Cherenkov light flashes. The camera has a resolution of 0.125° and covers a field of view of 4.3° x 4.0°. The PMTs, having a diameter of 38mm, are arranged at a triangular pitch of 55 mm. The PMTs are provided with hexagonal front coated light concentrators for enhancing their light collection efficiency by collecting the photons thatfall in the dead space between adjacent PMTs. The light collection efficiency of these light concentrators has been determined experimentally to be ~85% in the wavelength range of 300-650 nm. The camera is modular in design and comprises 68 camera integrated modules (CIMs) of 16 channels each. In order to overcome the problem of signal attenuation through long lengths of coaxial cables all the signal processing electronics are housed at the focal plane of the telescope with only power and data cables going to the control room. A fully assembled CIM, shown in Fig.3, houses the PMTs, high voltage generators, signal processing electronics, first level trigger generation logic and signal digitisation circuitry for 16 channels. The partially assembled camera and its power supply rack are shown in Fig.4. An analog switched capacitor array DRS-4 is being used at 1 GHz speed for continuous digitization of the PMT signals. The amplitude discriminator output of each channel is used for monitoring its single channel rate and also for generating the first level trigger from an individual CIM. The first level triggers from all the modules are collated in a second level trigger generator where proximity of the triggered pixels in adjacent CIMs is checked. After the generation of the second level trigger the data from all the 68 modules is collated by the Data Concentrator which in turn sends it to the data acquisition computer in the control room through optical fibres. The innermost 576 pixels (24x24) are used for generating this trigger as per predefined logic. The topological trigger scheme uses close cluster nearest neighbour patterns which are predefined for nearest pairs, triplets, quadruplets etc.

Fig.1 Photograph of one mirror panel comprising 4 aligned spherical mirror facets.

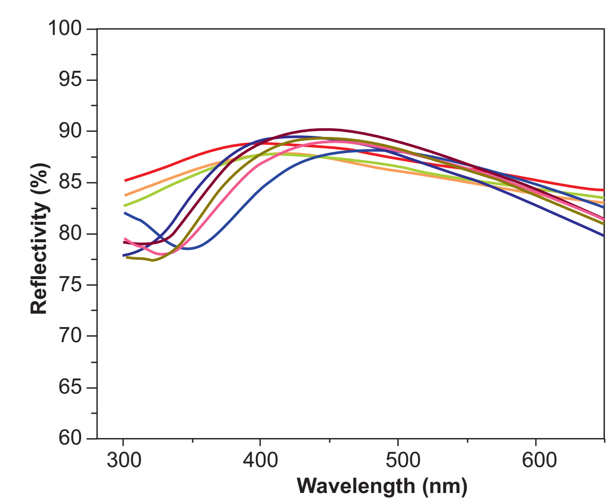


Fig.2 Plot of reflectivity as a function of wavelength for a test sample of 8 mirror facets.

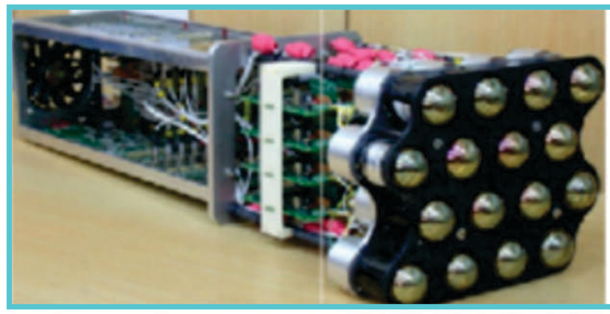


Fig.3 A fully assembled 16 channel Camera integrated module of MACE telescope.

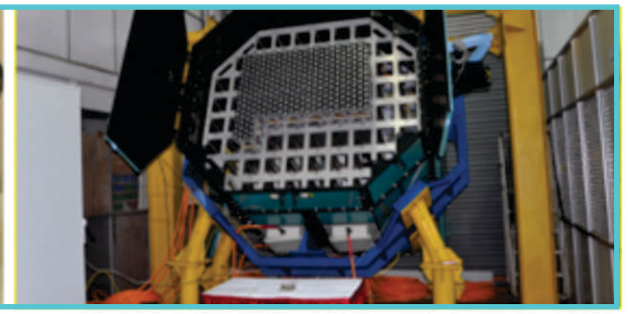


Fig.4 Partially assembled imaging camera of the MACE telescope at ECIL, Hyderabad.

About 40GB of data will be stored during every hour of observation. Quick look algorithms will carry out a preliminary analysis of the data and archive it. A copy of the data will also be archived in a data centre at BARC, Mumbai. The data acquisition and archiving system along with the telescope drive control system have been designed for internet based remote operation.

Simulation studies:

After defining the main specifications of the MACE telescope detailed simulation studies were carried out with the CORSIKAv6.735 (Cosmic Ray Simulations for KAscade) simulation package to understand its expected performance [6]. A database of a million showers each for gamma-rays, protons, electrons and alpha particles at each of the zenith angles of 0°, 20°, 40° and 60° was used for the study. A total of 16 million showers in the energy range of 5 GeV to 10 TeV (1 TeV= 1000 GeV) were generated for the simulation study. Various close cluster nearest neighbour (CCNN) trigger schemes were also investigated and it was determined that the best performance is obtained with 4 CCNN trigger along with a single pixel threshold of 9 photoelectrons. The sensitivity estimates of the telescope based on Random Forest technique suggest a 5 detection of a source with 2.7% Crab Nebula flux in 50h of observation. The angular resolution of the MACE telescope has been estimated to be ~ 0.21° at about 30 GeV. This value improves to about 0.06° at energies above 1.8 TeV. The energy of the primary gamma-rays has been estimated using the regressive Random Forest method and the energy resolution has been found to be ~40% at 30 GeV which improves to around 20% at energies above 1.8 TeV. The bias in estimating the primary energy of the gamma-rays is found to be about 36% at 30 GeV which improves to about - 0.2% at energies above 1.8 TeV. More details of the simulation studies are given in [7,8].

Implementation status :

The full mechanical structure of the MACE telescope has been installed at Hanle. Photograph of the telescope, with 225 mirror panels, depicting the present status of the MACE telescope, is shown in Fig. 5. A photograph of the drive control unit of the telescope is shown in Fig.6.

The altitude and azimuth drive systems of the telescope have been extensively tested. The elaborate software for data acquisition and archiving has also been tested extensively. Engineering trial runs of the telescope with 50 mirror panels and 64 CIMs have been performed recently by recording data for about 40 hours from various dark regions of the sky. The results obtained so far indicate satisfactory performance of various subsystems of the telescope.

Subsequently with the installation of all 356 mirror panels and the imaging camera with 68 CIMs, commissioning trials will start towards the end of 2019. It is proposed to observe the Crab Nebula during the commissioning trials for checking the integrity of the complex hardware and software of the telescope.

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Fig.5 A photograph of the telescope with 225 mirror panels, depicting the present status of the MACE telescope.

Fig.6 A photograph of the drive control unit of the telescope.

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