POWER CONVERTERS FOR ELECTROMAGNETS IN FAIR: INDIAN IN-KIND CONTRIBUTION

Mangesh B. Borage, RRCAT, Indore

on behalf of:

B. M. Barapatre, BARC, Mumbai, S. K. Thakur, VECC, Kolkata and ECIL, Hyderabad colleagues

Gratitude:

Shri Debashis Das; Dr. S. Chattopadhyay; members of TCMC, Executive Council BI-IFCC, …

FAIR – Facility for Antiproton and Ion Research

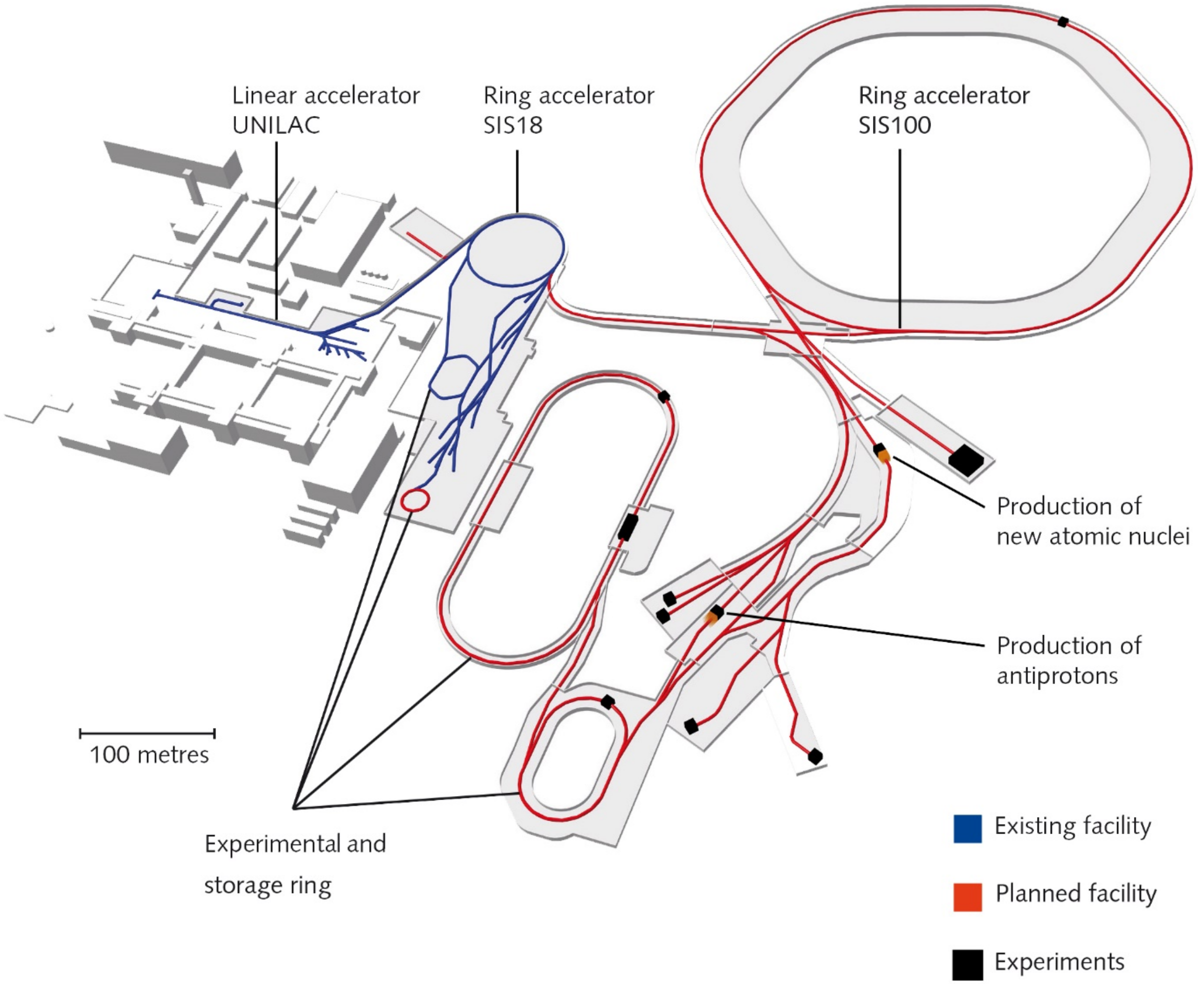
FAIR — Facility for Antiproton and Ion Research in Europe

- Partner Countries:

Finland, France, Germany, **India**, Poland, Romania, Russia, Slovenia and Sweden.

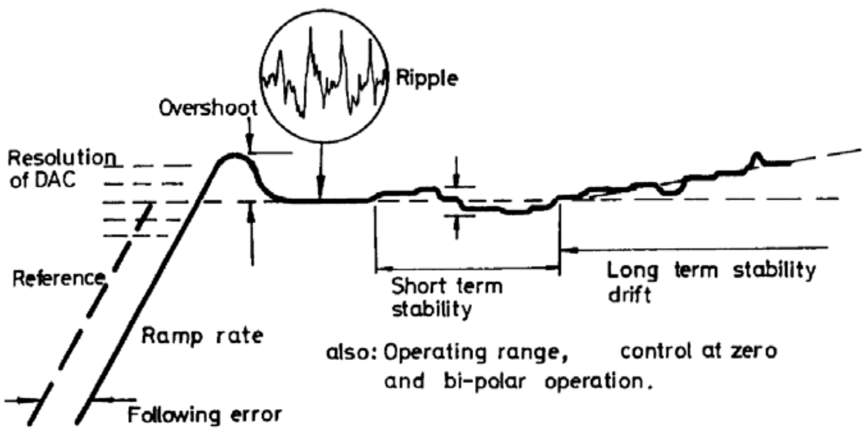
- The United Kingdom is associated.
- The Czech Republic is aspirant partner.

FAIR – Facility for Antiproton and Ion Research



POWERING (ELECTRO)MAGNETS

- The magnetic field depends on the current flowing through its coils.
- For stable/precisely controllable magnetic field, the current must be stable/precisely controllable.



Ref: Proc. CAS on Power Converters for Particle Accelerators, 1990

$$Stability = \frac{\Delta I}{I} \times 10^6 \ \ [\text{ppm}]$$

POWER CONVERTERS FOR (ELECTRO)MAGNETS

SPECIALITIES…

- Load is inductive
  - Only slow changes in load resistance due to temperature
  - Load inductance helps to attenuate ripple in current
  - If di/dt is high, voltage required increases
  - Slow system – proper design of control loops



Dipole, quadrupole and sextupole magnets in Indus Accelerator Complex at RRCAT, Indore

POWER CONVERTERS FOR (ELECTRO)MAGNETS

SPECIALITIES…

- **Stable current sensing device**
- **Shunt**
  - Low TCR alloy (e.g. Zeranin – an alloy of copper, manganese and germanium).
  - TCR 3 ppm/Deg. C

- **DCCT**
  - Special (and proprietary component)
  - Stability of output voltage is typically 1 ppm/Deg. C

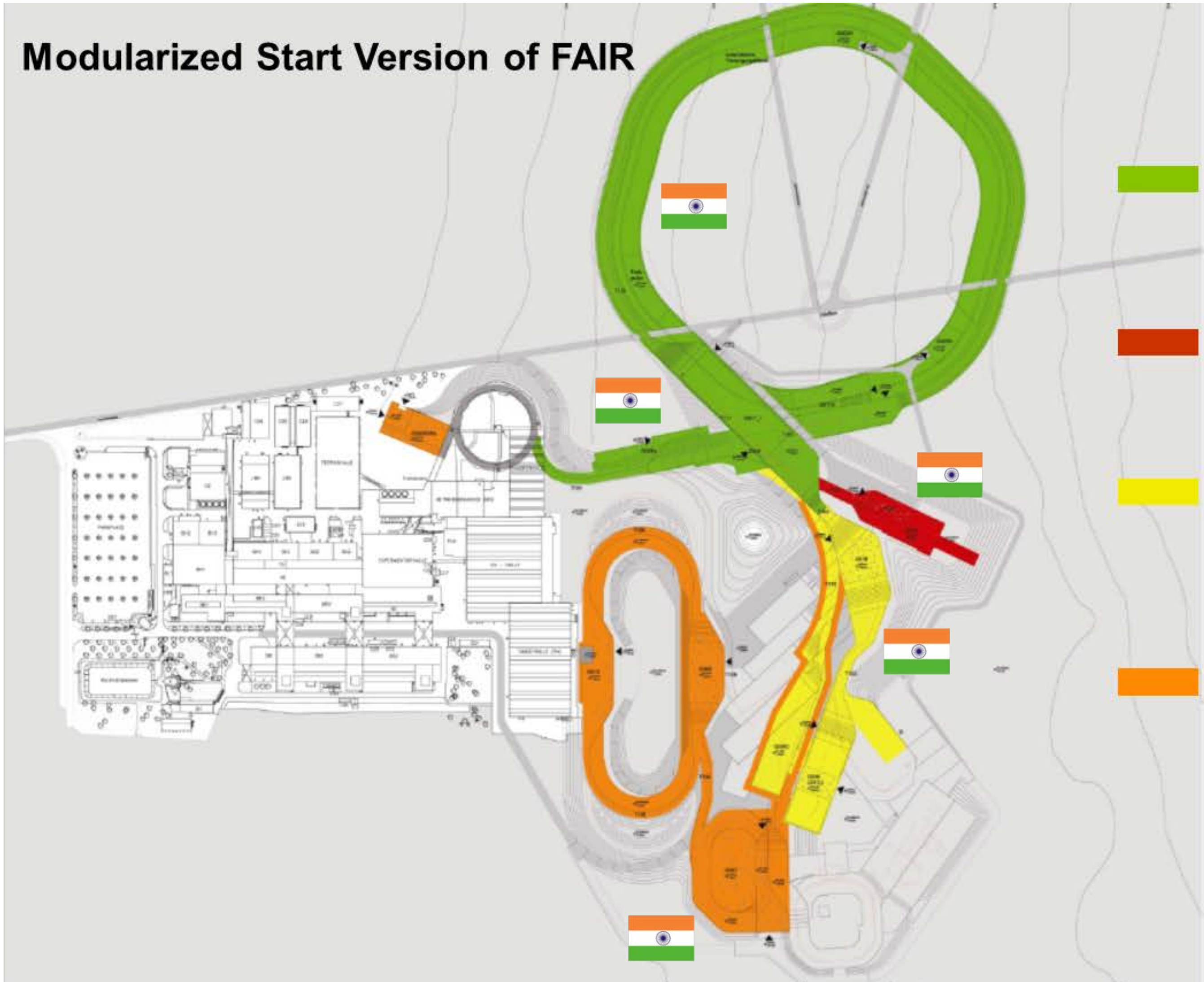
POWER CONVERTERS FOR (ELECTRO)MAGNETS

SPECIALITIES…

- Wide setting range of output current
  - From nearly zero to maximum, still maintaining the performance
- Different operational requirements
  - Cycling, ramping, steady – state at injection/intermediate/final energy

- Few watts to few 100's of kilowatts (even MWs!)
  - Different schemes, circuits and layouts

INDIAN POWER CONVERTERS IN FAIR ACCELERATORS



Module 0

SIS 100 with connection to GSI accelerators

Module 1

SIS 100 experiments areas

Module 2

SFRS

Module 3

p-linac, antiproton targert, CR, HESR

Modules 4 (**NESR**) and 5 (**RESR**) are not marked

INDIAN POWER CONVERTERS IN FAIR ACCELERATORS

- Magnet Power Converters @ FAIR

  Total ≈1700

  Module 0-3 ≈ 1200
- Expression-of-Interest (EoI) from India ≈ 533
  - Covered types / ratings = 29 (HEBT, SIS100, SFRS, CR)

    With outputs typically in the range:

    { 100 A to 850 A; 8 V to 420 V; 1 kW to 360 kW }

    Total cumulative power rating ≈ 14 MW

    'Total deviation' in output current: 100 ppm

    DC/pulsed mode; One, Two- and Four-Quadrant Operation
- In-kind contracts for 196 units (IKC-I and IKC-II)
- EoI for 140 more units (2014) and 15 more units (2019)
- **Total Power Converters ~ 700**

INDIAN POWER CONVERTERS IN FAIR ACCELERATORS

S.No.	PSP Code	Facility	PC Type	Topology	Rated Current [A]	Maximum Current [A]	Flat top Voltage [V]	Maximum Voltage [V]	Quantity	Covered under IKC
2	2.8.3.3.1.1		Error Comp. Quadrupole		250	300	10	38	12	Draft IKC-III
3	2.8.3.3.3.1		Error Comp.Sextupole		250	300	10	38	12	Draft IKC-III
4	2.8.3.3.5.1		1S.C4		775	850	76.16	427.52	6	
5	2.8.3.3.2.1		1S.C3		250	300	10	38	12	Draft IKC-III
6	2.8.3.4.2.1		1S.C8		250	300	10	38	166	Draft IKC-III
7	2.4.3.1.2.1		Dipol 2		246		22	138	1	
8	2.4.3.1.3.1		Dipol 3		246		18	121	7	
9	2.4.3.1.4.1		Dipol 4		200		7	215	1	
10	2.4.3.2.3.1	SuperFRS	Quadrupole 3	SM_4	292		7	69	36	
11	2.4.3.2.4.1		Quadrupole 4		292		7	100	21	
12	2.4.3.2.5.1		Quadrupole 5		292		7	69	4	
13	2.4.3.2.6.1		Quadrupole 6		292		7	100	1	
14	2.4.3.3.2.1		Sextupole 2		171		5	8	39	
15	2.3.3.2.16.1		HB.Q1.FBL	SM_4	271	300	87.9	142.78	6	Draft IKC-III
16	2.3.3.2.18.1		PCHBQ11	SM_4	467	525	53.55	53.55	1	Draft IKC-III
17	2.3.3.4.4.1		HB.S1.FBL	SM_4	93	100	38.7	38.7	4	Draft IKC-III
18	2.3.3.4.6.1		PCHBS2 HED	SM_4	400	400	61.2	87.9	4	Draft IKC-III
19	2.3.3.4.2.1		HB.C2	SM_4	400	400	61.2	87.9	41	Draft IKC-III
20	2.3.3.1.1.1		HB.D1	SM_1	535		90	98	3	
21	2.3.3.1.2.1		HB.D2	SM_4	535		173	210	2	
22	2.3.3.1.7.1		HB.D7	SM_4	535		200	250	1	
23	2.3.3.1.19.1		HB.D19	SM_2	535		55	167	1	
24	2.3.3.2.1.1	HEBT	HB.Q1	SM_4	271	300	87.9	142.78	23	IKC-I
25	2.3.3.2.2.1		HB.Q2	SM_2	271	300	87.9	142.78	50	
26	2.3.3.2.7.1		HB.Q7	SM_1	292		2	151	2	
27	2.3.3.2.8.1		HB.Q8	SM_1	292		2	187	9	
28	2.3.3.2.10.1		HB.Q10(*)	SM_2	455	500	51	90.53	28	
29	2.3.3.2.11.1		HB.Q11	SM_4	467	525	53.55	53.55	35	
30	2.3.3.2.12.1		HB.Q12	SM_2	455	500	89	173.84	1	
31	2.3.3.2.13.1		HB.Q13	SM_1	455	500	91.5	91.5	5	IKC-II
32	2.3.3.2.14.1		HB.Q14	SM_4	425	500	48.25	178.86	6	
33	2.3.3.4.1.1		HB.C1	SM_4	93	100	38.7	38.7	44	
34	2.3.3.2.15.1		HB.Q15(#)	SM_2	271	300	158.1	204.45	4	IKC-I
35	2.5.3.3.1.1	CR	Wide Sextupole	SM_4	116		210	212	7	
36	2.3.3.1.1.4	HEBT	HB.D1 Zero Field Control	SM_1	535		80.6	97.8	1	
37	2.3.3.1.6.1		HB.D6	SM_4	535		107	132	4	
38	2.8.3.3.4.1	SIS100	1S.C2	SM_4	250		95	490	7	
40	2.8.3.5.3.1		1.S.S3	SM_1	547		25.3	30.55	1	Additional EoI
41	2.4.3.3.5.1		FR.C4	SM_4	300		16.3	16.4	36	
42	2.4.3.4.1.1	SuperFRS	FR.C6	SM_4	300		16.3	16.4	14	
43	2.4.3.5.2.1		FR.C8	SM_4	12.3		17.2	19.2	3	
44	2.4.3.5.3.1		FR.C9	SM_4	12.3		18.7	20.42	21	

IKC-I	77
IKC-II	119
IKC-III	258

POWER CONVERTERS – WORK FLOW


Quality Management | General Specification | F-GS-F-01e | Q-FO-QM-0001 | Date: 13.03.2014 | Page 1 of 1

Title:	General Specification (General Specification for the FAIR Accelerator Facility Project)
Purpose:	Common rules and definitions
Organizational unit:	– FAIR@GSI Project Coordination – Configuration Management (PCCM) – FAIR Technical Division
Valid for:	FAIR Accelerator Facility Project
Key performance indicators:	

EDMS Id: 1365092 v.1

Document History:


GSI Helmholtzzentrum für Schwerionenforschung GmbH

FAIR GSI

Common Specification on Power Converters

F-CS-PC-01e Power Converters v1.03

2012-06-13

Abstract

The document describes Common Specifications for the Power Converters for the FAIR Accelerator Project.

GSI-B-EET

H.Ramakers, H.Welker


Quality Management | FAIR GSI | Detailed Specification | F-DS-PC-13e | Q-FO-QM-0005 | Date: 15.02.2017 | Page 1 of 21

Document Title:	Power Converters for SIS100 Steering Magnets
Description:	This document describes detailed specifications of power converters for SIS100 Steering Magnets
Division/ Organization:	GSI-EPS
Field of Application:	Project FAIR@GSI

Document History:

General Specs.

Legal Requirements

Standards

Internal Regulations

Quality Control

Safety

Guidelines

Common Specs.

Electrical conditions

Environmental conditions

Definitions

Design Principles

Reliability

Factory Acceptance Tests

Site Acceptance Tests

Transportation

Documentation

Detailed Specs.

Scope

Content of delivery

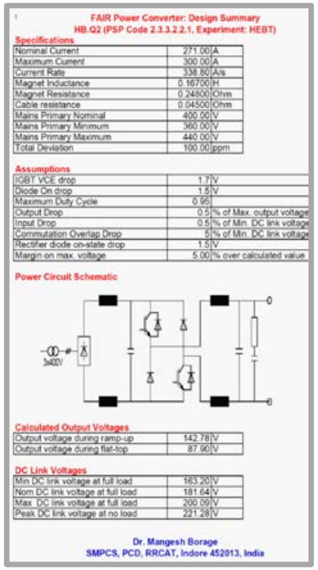
Technical specs.

Spares

Interfaces

Documentation

POWER CONVERTERS – WORK FLOW



FAIR Power Converter: Design Summary
HB.Q2 (PSP Code 2.3.3.2.2.1, Experiment: HEBT)

Specifications

Nominal Current	271.00	A
Maximum Current	300.00	A
Current Rate	338.80	A/s
Magnet Inductance	0.16700	H
Magnet Resistance	0.24800	Ohm
Cable resistance	0.04500	Ohm
Mains Primary Nominal	400.00	V
Mains Primary Minimum	360.00	V
Mains Primary Maximum	440.00	V
Total Deviation	100.00	ppm

Assumptions

IGBT VCE drop	1.7	V
Diode On drop	1.5	V
Maximum Duty Cycle	0.95	
Output Drop	0.5	% of Max. output voltage
Input Drop	0.5	% of Min. DC link voltage
Commutation Overlap Drop	5	% of Min. DC link voltage
Rectifier diode on-state drop	1.5	V
Margin on max. voltage	5.00	% over calculated value

Power Circuit Schematic

3x400V

Calculated Output Voltages

Output voltage during ramp-up	142.78	V
Output voltage during flat-top	87.90	V

DC Link Voltages

Min DC link voltage at full load	163.20	V
Nom DC link voltage at full load	181.64	V
Max DC link voltage at full load	200.09	V
Peak DC link voltage at no load	221.28	V

Dr. Mangesh Borage
SMPCS, PCD, RRCAT, Indore 452013, India

Baseline Design

Preliminary design for simulations and studies

RRCAT, Indore

BARC, Mumbai

VECC, Kolkata

Pre-prototype Development

Proof-of-principle

Document Title: Concept Design Document - Power Converter HB.Q2 (2.3.3.2.2.1) for FAIR

ELECTRONICS CORPORATION OF INDIA LIMITED
A Govt. Of India (Dept. Of Atomic Energy) Enterprise
Control & Automation Division, Control Systems Group
ECIL P.O., Hyderabad – 500 062, India

FAIR POWER CONVERTER
CONCEPT DESIGN DOCUMENT
HB.Q2 (2.3.3.2.2.1)

ABSTRACT

This document summarizes design calculations of the HB.Q2 power converter (2.3.3.2.2.1) for FAIR, which is a two quadrant converter rated for 300 A maximum current.

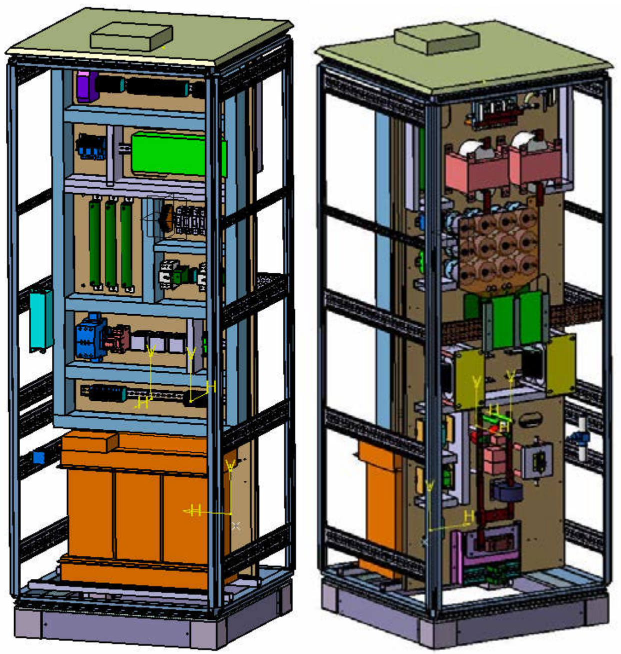
	ECIL			TCC / FAIR		
	Name	Date	Signature	Name	Date	Signature
Prepared	Balaramkumar. S, Engineer, CAD	15/11/2014				
Checked	Manjula. A, DGM, CAD	18/11/2014				
Approved	Asifulla Baig, SDGM, CAD	20/11/2014		Horst Welker	27.11.2014	

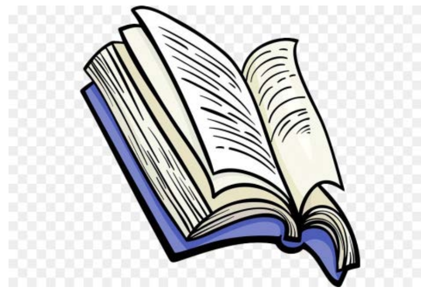
Document No: FAIR/ECIL/PS/2.3.3.2.2.1 (HB.Q2)/PROTO/CDR v1.1 | Page 1 of 44

Conceptual Design Report (CDR)

1. Functional description of all the components;
2. Explanation of design criteria according to Sec. 8.5 of [2];
3. Technical data;
4. Block diagrams;
5. Manufacturer/type of all main components;
6. Description of interface (control interfaces and interfaces to the environment);
7. Simulation of the operation modes given in the corresponding detailed specification;
8. Draft version of the production plan;
9. Test concept to ensure testability during FAT and SAT;
10. Definition of the critical components which are operated on the verge of or beyond to their specification limits;
11. Draft version of the Risk / Hazard Assessment.

POWER CONVERTERS – WORK FLOW





First-of-Series (FoS) Prototype

Final Design Review (FDR)

1. A description of the complete power converter;
2. Detailed specification of all main components (technical and mechanical data) (i.e. Cabinet, transformer, inductor, capacitor bank, arrangement of semiconductors, placement of DCCT-head);
3. Drawings or preferably 3D-models of the physical configuration of the complete power converter (components placement inside the cabinet);
4. Block diagrams and schematics of the control loops;
5. Complete schematics of all the electrical circuits;
6. Complete specification of all the interfaces (electrical, mechanical, building, media, software, etc.);
7. List of recommended spare parts;
8. Provision of design and production documents (production plan, quality plans, work instructions and test instructions);
9. Test plans and templates of test protocols for FAT and SAT;

Engineering Design

RRCAT, Indore

BARC, Mumbai

VECC, Kolkata

In collaboration with

ECIL, Hyderabad

POWER CONVERTERS – WORK FLOW

Factory Acceptance Test (FAT) of FoS Prototype

&

Clearance for Batch Production

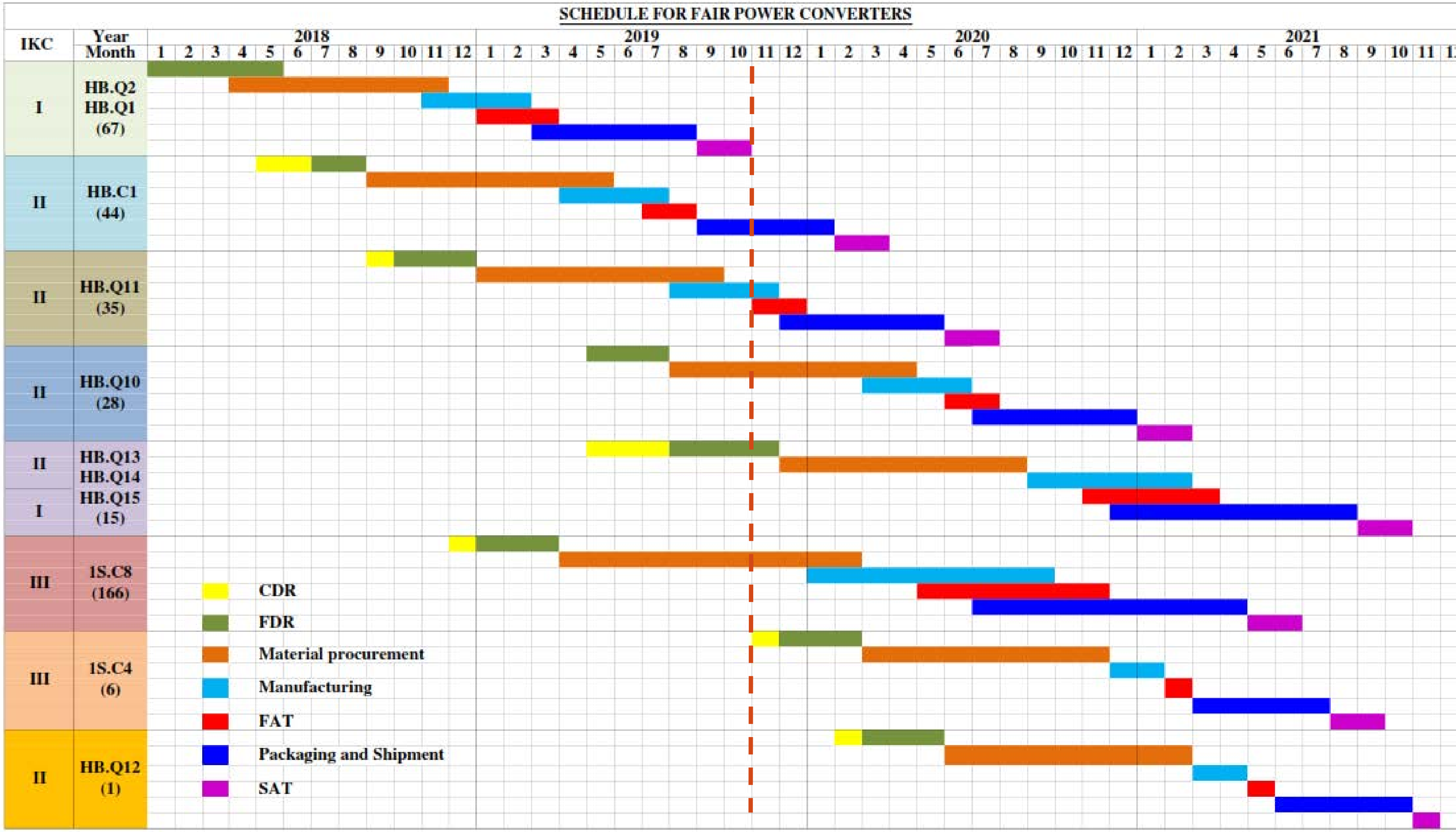
Production & FAT

POWER CONVERTERS – WORK FLOW

Installation and Commissioning
Site Acceptance Test (SAT)

Dispatch and Transportation

POWER CONVERTERS – TIGHT SCHEDULE!

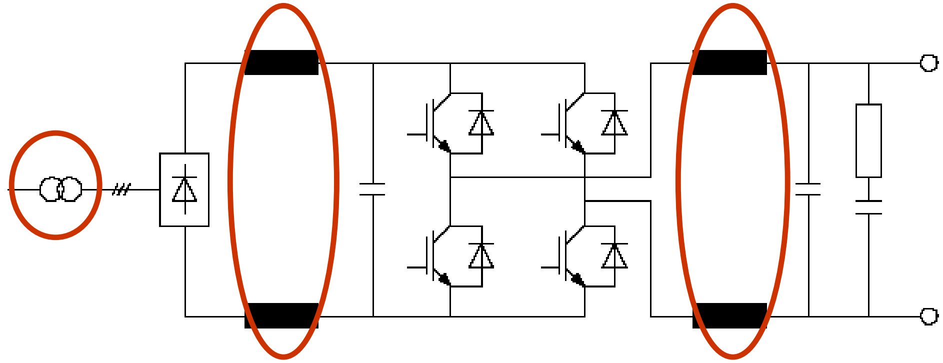


POWER CONVERTERS – CHALLENGES

- A large number of high-power converters
  - Live and dynamic systems
  - Operating continuously
  - Direct implication on the delivery of beam

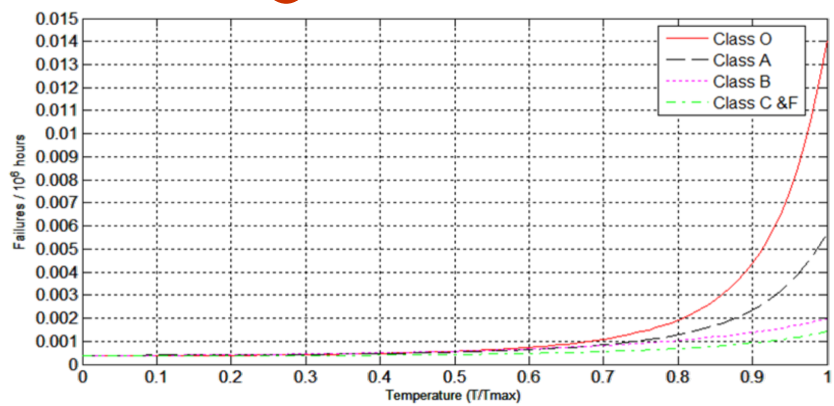
1. High reliability
2. Easy maintainability
3. Standardization (less variety in inventory)
4. Quality manufacturing
5. Extensive testing
6. Conformance to various regulatory standards
7. Tight deadlines

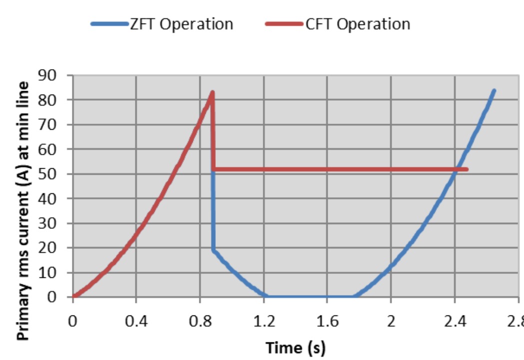
POWER CONVERTERS – CHALLENGES



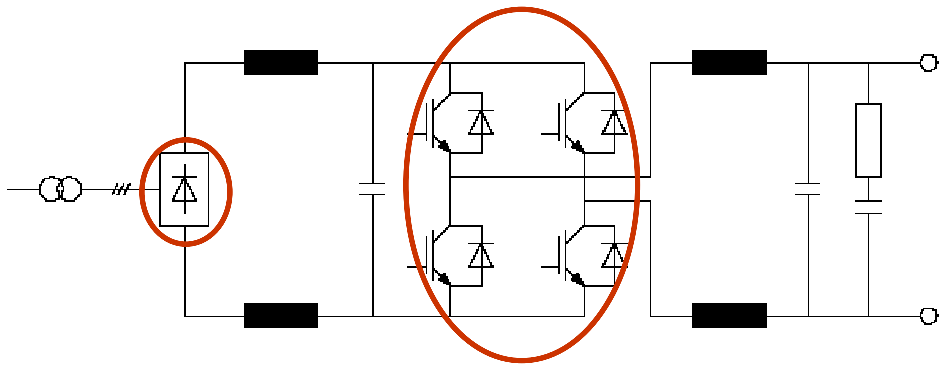
- **Magnetic Components**

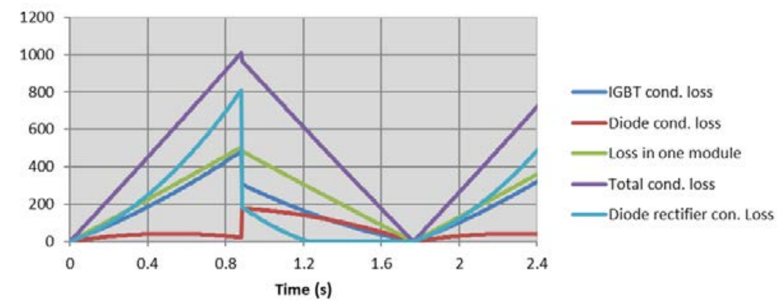
1. Operational life > 20 years
   - Small size (cabinet size is fixed)
   - Limit maximum temperature rise
2. Different load cycles
   - Judicious choice of ratings
3. CE compliance
4. Quality manufacturing
   - Tight manufacturing tolerances





POWER CONVERTERS – CHALLENGES

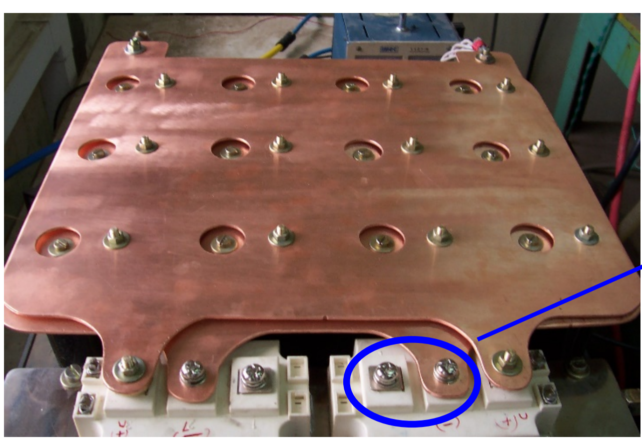


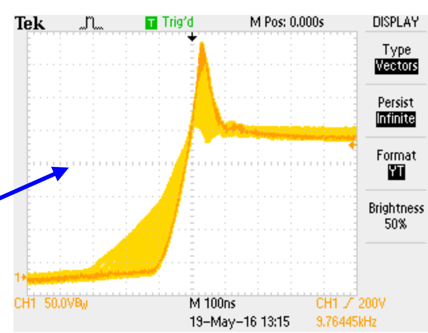


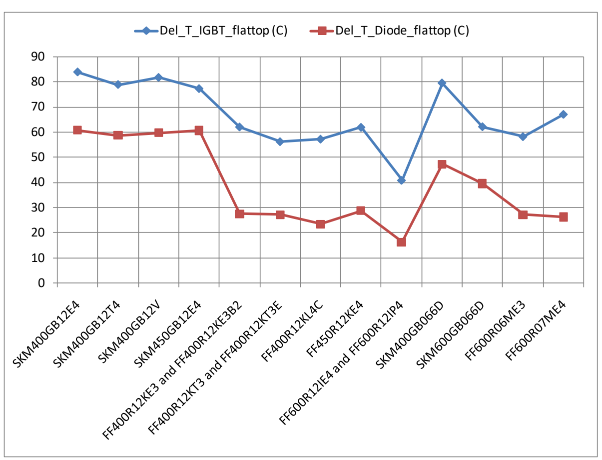
- **Power Semiconductors**

1. Losses / Junction Temperature

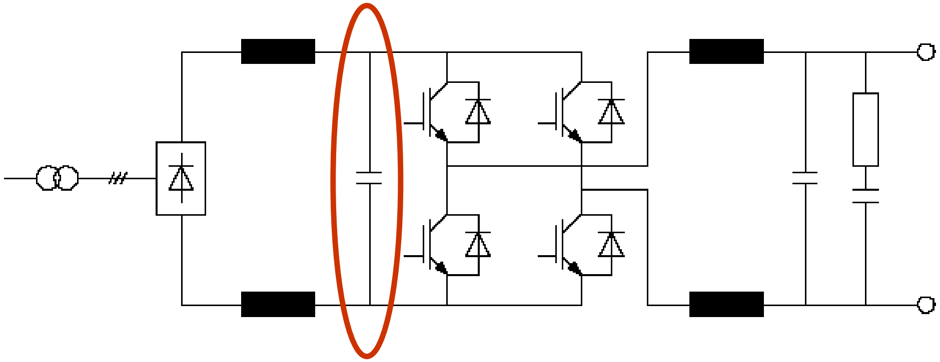
2. Peak Stresses
   - Minimize stray inductance







POWER CONVERTERS – CHALLENGES

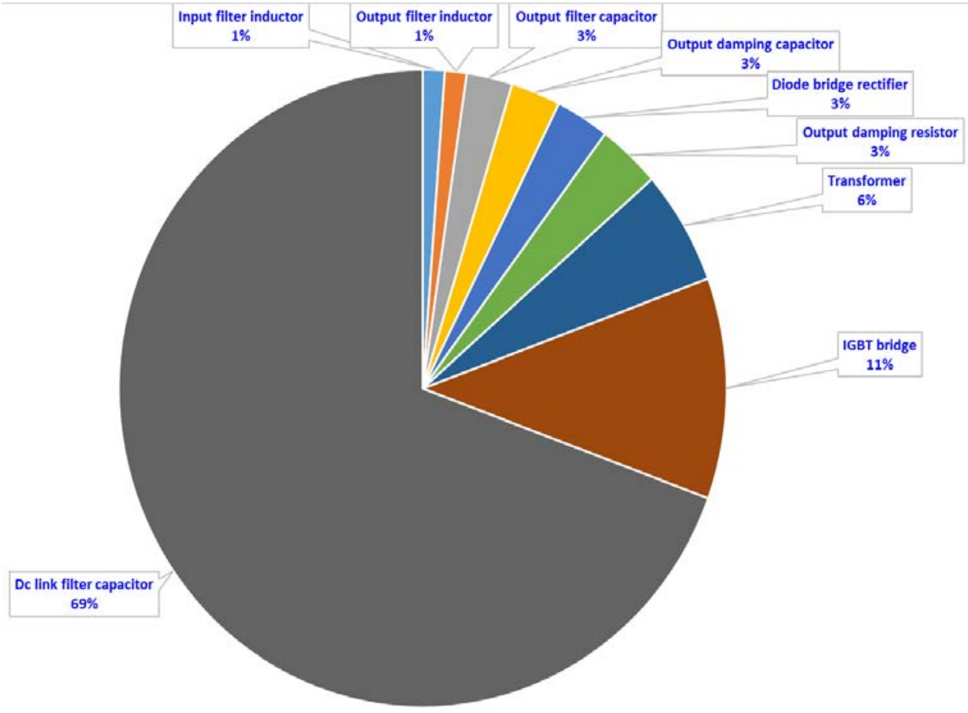


- **Electrolytic Capacitors**

1. Component with least life (and unfortunately they are many in a power converter!)

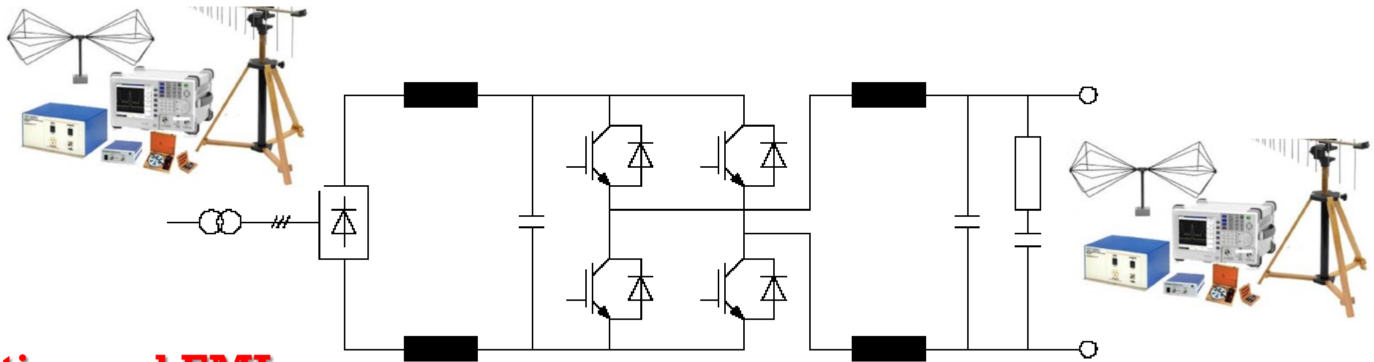
2. Proper design and de-rating

3. Multiple functions:
   - Filtering
   - Absorb magnet energy



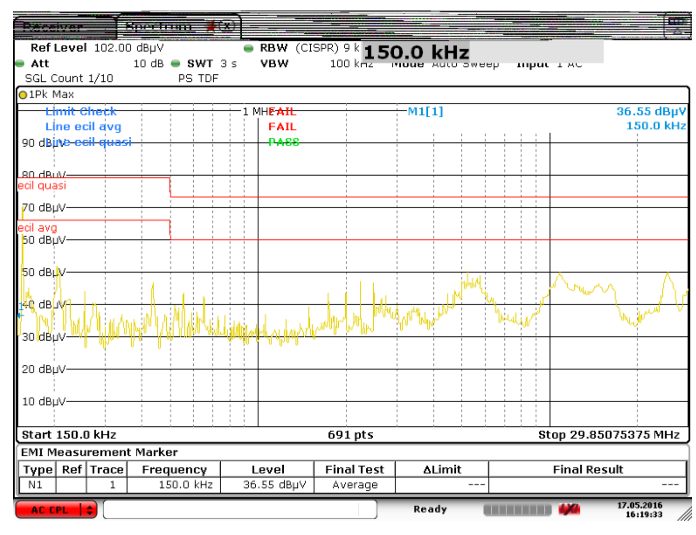
Example of failure rate distribution

POWER CONVERTERS – CHALLENGES



- **Harmonic pollution and EMI**

1. Rectifier is a non-linear load – generates line frequency harmonics, which need to be kept below a prescribed limit
2. Switching circuits → EMI
   → need to be kept below a prescribed limit
3. Special measures



POWER CONVERTERS – CHALLENGES

- **Maintaining Manufacturing Quality**

1. A detailed manufacturing document (~ 150 pages)
   - 12 manufacturing stages
   - Minutest details (e.g. wire routes, types of hardware, tightening toques etc.)
   - Procedures and precautions
2. Training of the working team
3. 100% inward inspection of components
4. Stage-wise inspection and reporting
5. Final quality check and reporting
6. Standard test templates
7. Automated testing and report generation with minimum operator intervention
8. Burn-in test of 100% units to thermal stabilization
9. Special type tests on 10% of the quantity
10. Detailed archive of test results (power converters and components)

Prototype

Product

POWER CONVERTERS – STATUS

Power converters for HB.Q2 and HB.Q1 magnets (HEBT) @ FAIR



Specifications		
Nominal Current	271.00	A
Maximum Current	300.00	A
Current Rate	338.80	A/s
Magnet Inductance	0.16700	H
Magnet Resistance	0.24800	Ohm
Cable resistance	0.04500	Ohm
Mains Primary Nominal	400.00	V
Mains Primary Minimum	360.00	V
Mains Primary Maximum	440.00	V
Total Deviation	100.00	ppm

73 Nos.

- Designed and pre-prototype developed at RRCAT, Indore
- Series Production at ECIL, Hyderabad
- Delivered !

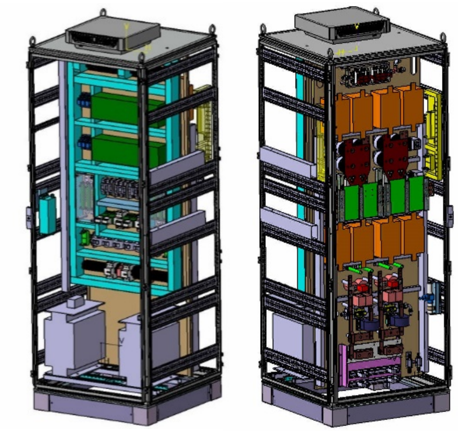
First in-kind contribution to FAIR from India

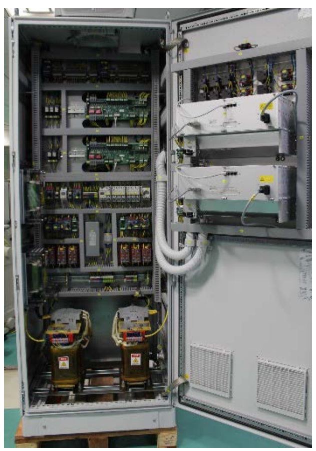
POWER CONVERTERS – STATUS

Power converters for HB.C1 magnets (HEBT) @ FAIR

Specifications		
Nominal Current	93.00	A
Maximum Current	100.00	A
Current Rate	232.5000	A/s
Magnet Inductance	0.0510	H
Magnet Resistance	0.2520	Ohm
Cable resistance	0.1350	Ohm
Mains Primary Nominal	400.00	V
Mains Primary Minimum	360.00	V
Mains Primary Maximum	440.00	V
Total Deviation	100.00	ppm

48 Nos.





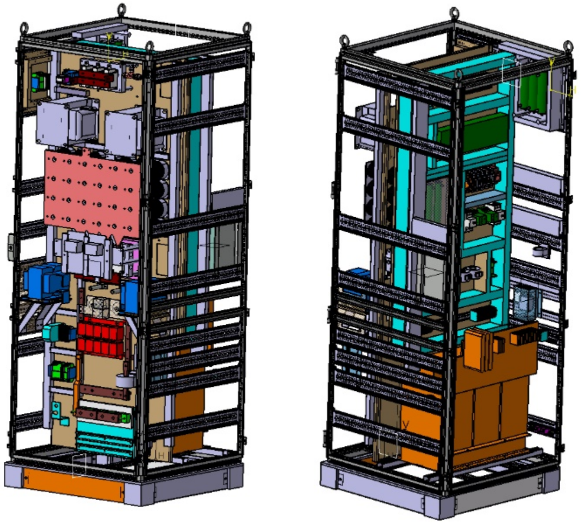
- Designed and pre-prototype developed at RRCAT, Indore
- Series production and testing progressing well ECIL, Hyderabad
- Completion expected in mid-November

POWER CONVERTERS – STATUS

Power converters for HB.Q11 magnets (HEBT) @ FAIR

Specifications		
Nominal Current	467.00	A
Maximum Current	525.00	A
Current Rate	50.0000	A/s
Magnet Inductance	0.0910	H
Magnet Resistance	0.0810	Ohm
Cable resistance	0.0210	Ohm
Mains Primary Nominal	400.00	V
Mains Primary Minimum	360.00	V
Mains Primary Maximum	440.00	V
Total Deviation	100.00	ppm

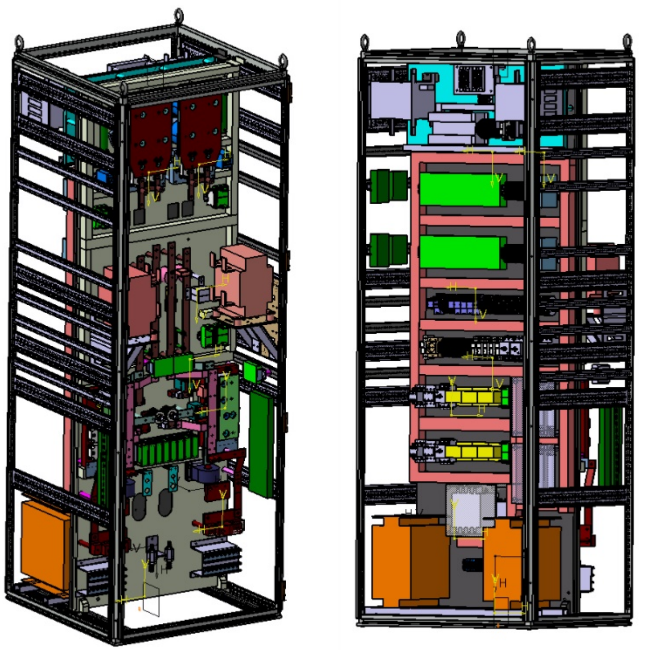
36 Nos.



- Designed at BARC, Mumbai
- First-of-series prototype manufactured and tested at ECIL, Hyderabad
- Series production to commence soon

POWER CONVERTERS – STATUS

Power converters for 1S.C8 magnets (SIS100) @ FAIR



202 Nos.

Nominal Current	250.00	A
Maximum Current	300.00	A
Current Rate	1250.0000	A/s
Magnet Inductance	0.0220	H
Magnet Resistance	0.0000	Ohm
Cable resistance	0.0420	Ohm
Mains Primary Nominal	400.00	V
Mains Primary Minimum	360.00	V
Mains Primary Maximum	440.00	V
Total Deviation	100.00	ppm

- Designed at VECC, Kolkata
- Manufacturing of first-of-series prototype to commence at ECIL, Hyderabad

OPPORTUNITIES FOR INDUSTRIES

- Manufacturing possibilities
  - High power magnetic components
  - Precisely machined mechanical items (bus plates, heat sinks, special connectors for coaxial power cables, etc.)
  - Cabinets
  - Electrical / electronics components
  - PCBs, component assembly
  - …

- Participate in FAIR Call for Tenders
  - FAIR website https://fair-center.eu/en/fair-gmbh/in-kind-procurement
  - BI-IFCC website http://www.jcbose.ac.in/bifcc-announcement

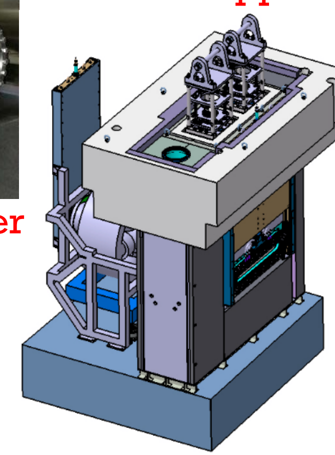
IN-KIND COMPONENTS FROM INDIA

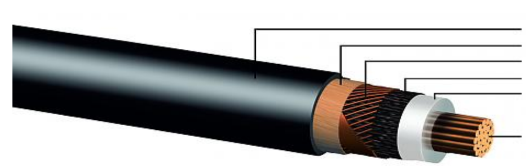
- Accelerator components
  - Power converters (~700 nos.)
  - UHV Chambers (~100 nos.)
  - Beam stoppers (~ 3 nos.)
  - Coaxial power cable (~180 km)
  - SC magnets for LEB
- Detector Components
  - Spectrometer
  - Neutron detector
  - Ion-trap
  - Muon chambers

Power converter

Vacuum Chamber

Beam Stopper





Coaxial Cable

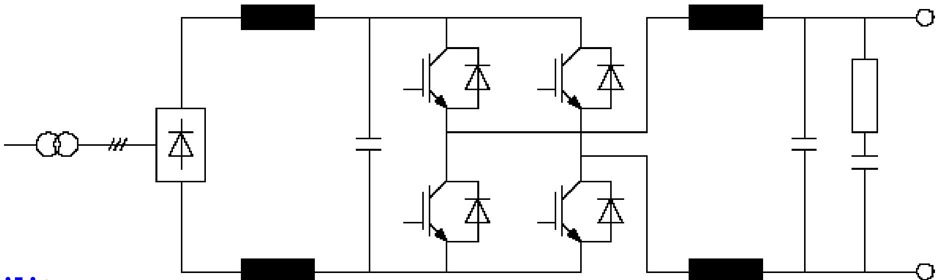
Ref: S. Chattopadhyay, Indian Industry in FAIR', Vigyan Samagam, Mumbai

SUMMARY

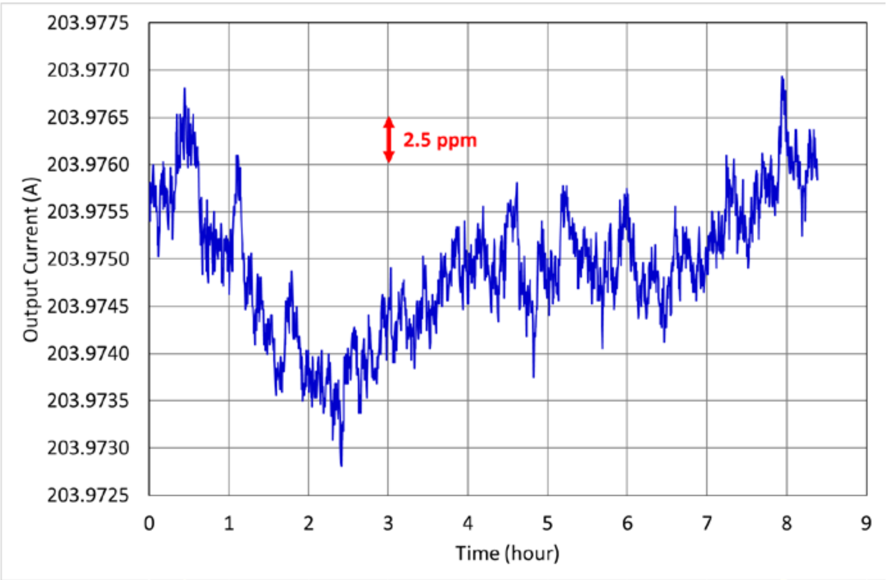
- A new technological avenue has opened up at FAIR for Indian industries
- All Indian in-kind items are being developed and built in India
- Indian industries participating for in-kind items – urge to explore the non in-kind items also.
  - Build/strengthen manufacturing capabilities
  - Contributions towards upcoming mega-projects in India
- Power converters for electromagnets is one of the major in-kind contribution for FAIR
  - Delivery started
  - Presents opportunities for many industries

THANK YOU!

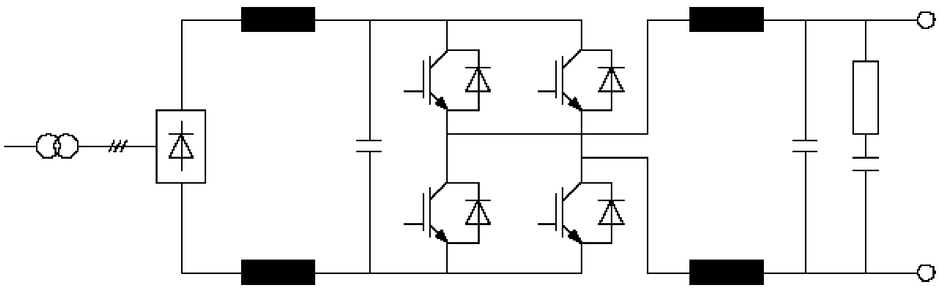
POWER CONVERTERS – CHALLENGES



- Output Current Stability



POWER CONVERTERS – CHALLENGES



- Cooling the Semiconductors

1. Water cooling!
2. Tight mechanical specifications (surface finish and flatness)
3. Durable assembly
4. Extensive thermal simulations