Digital Signal Processing for Complete Spectroscopy of Rotating Nuclei

(with Large Compton Suppressed Clover Array)

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TIFR

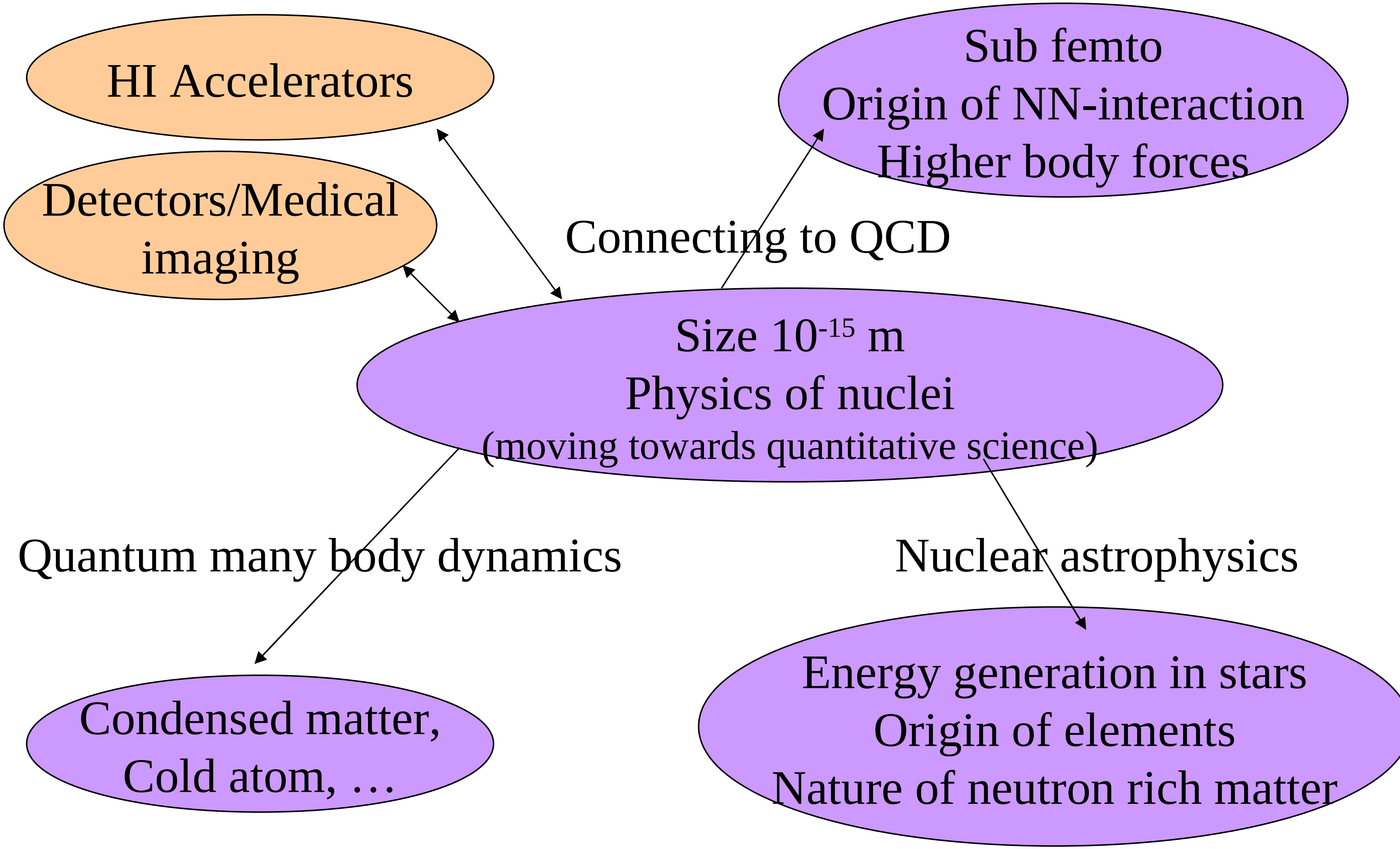
Outline

- 1. Scope of gamma spectroscopy for nuclear structure
- 2. Large Array of Detectors
- 3: Why digital?
- 4: INGA array at Pelletron LINAC facility
- 5: Application of these techniques in medical imaging

Outline

- 1. Scope of gamma spectroscopy for nuclear structure
  - Where is our field of nuclear structure going?
  - What is the role of gamma spectroscopy?
  - With few examples from previous experiments
- 2. Large Array of Detectors
- 3: Why digital?
- 4: INGA array at Pelletron LINAC facility
- 5: Application of these techniques in medical imaging

NUclear STructure and Reactions



NUclear STructure Astrophysics and Reactions

What are the limits for existence of nuclei? ★

Where are the proton and neutron drip lines situated?

Where does the nuclear chart end?

How does the nuclear force depend on varying proton-to-neutron ratios?

What is the isospin dependence of the spin-orbit force?

How does shell structure change far away from stability? ★

How to explain collective phenomena from individual motion?

What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system? ★

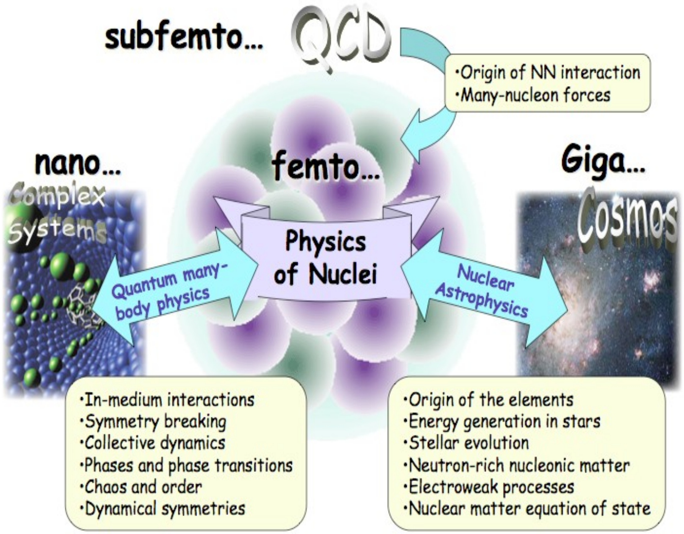
How are complex nuclei built from their basic constituents?

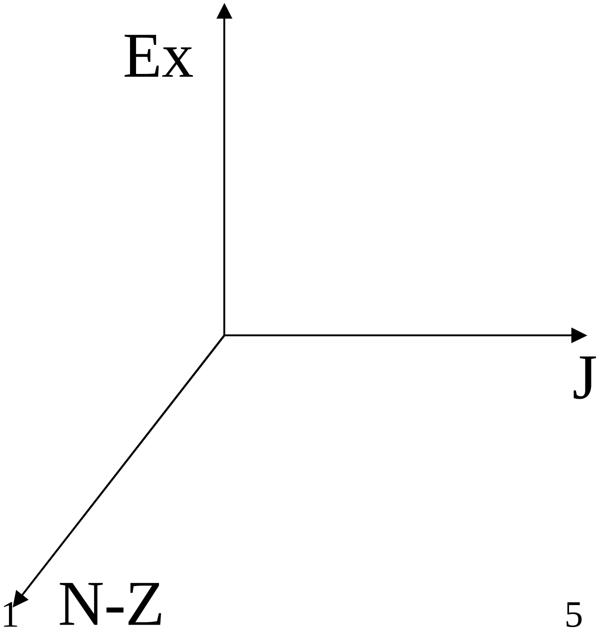
What is the effective nucleon-nucleon interaction?

How does QCD constrain its parameters?

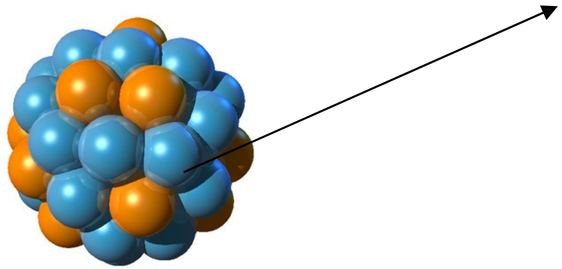
Which are the nuclei relevant for astrophysical processes and what are their properties? ★

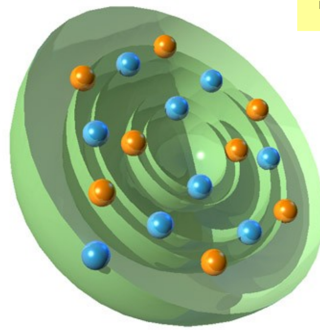
What is the origin of the heavy elements?





Low energy nuclear excitations are due to

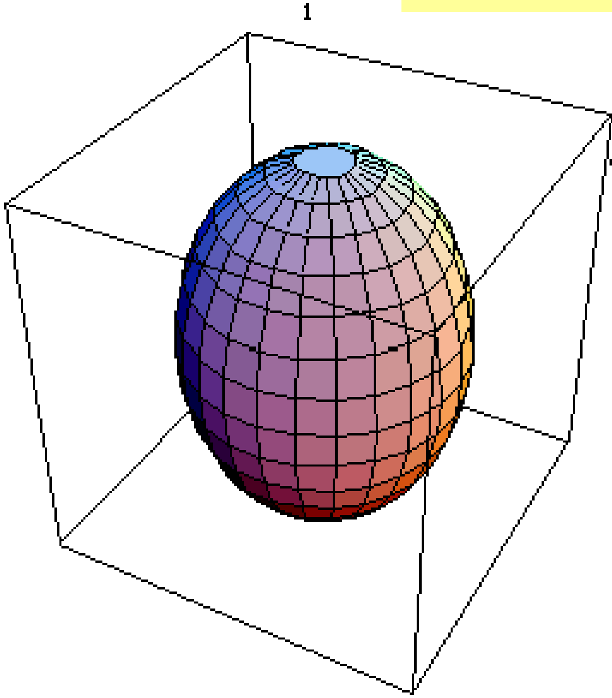


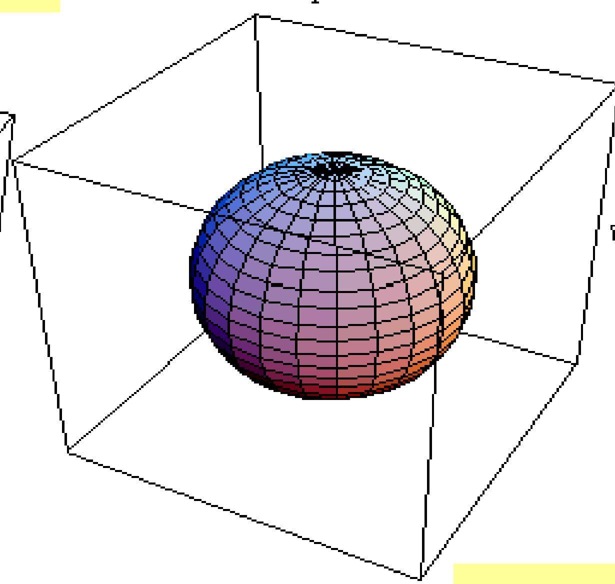


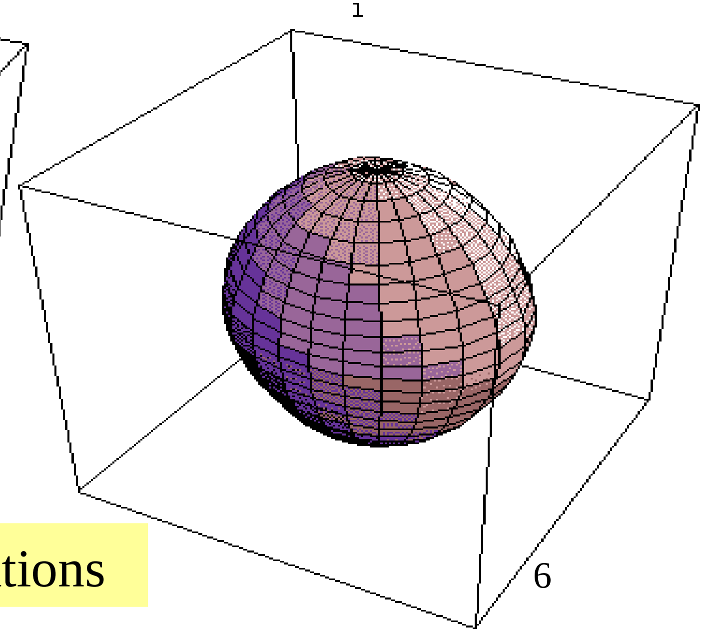
Single Particle Excitations

Coupling between the simple modes creates interesting pattern & provide shape informations

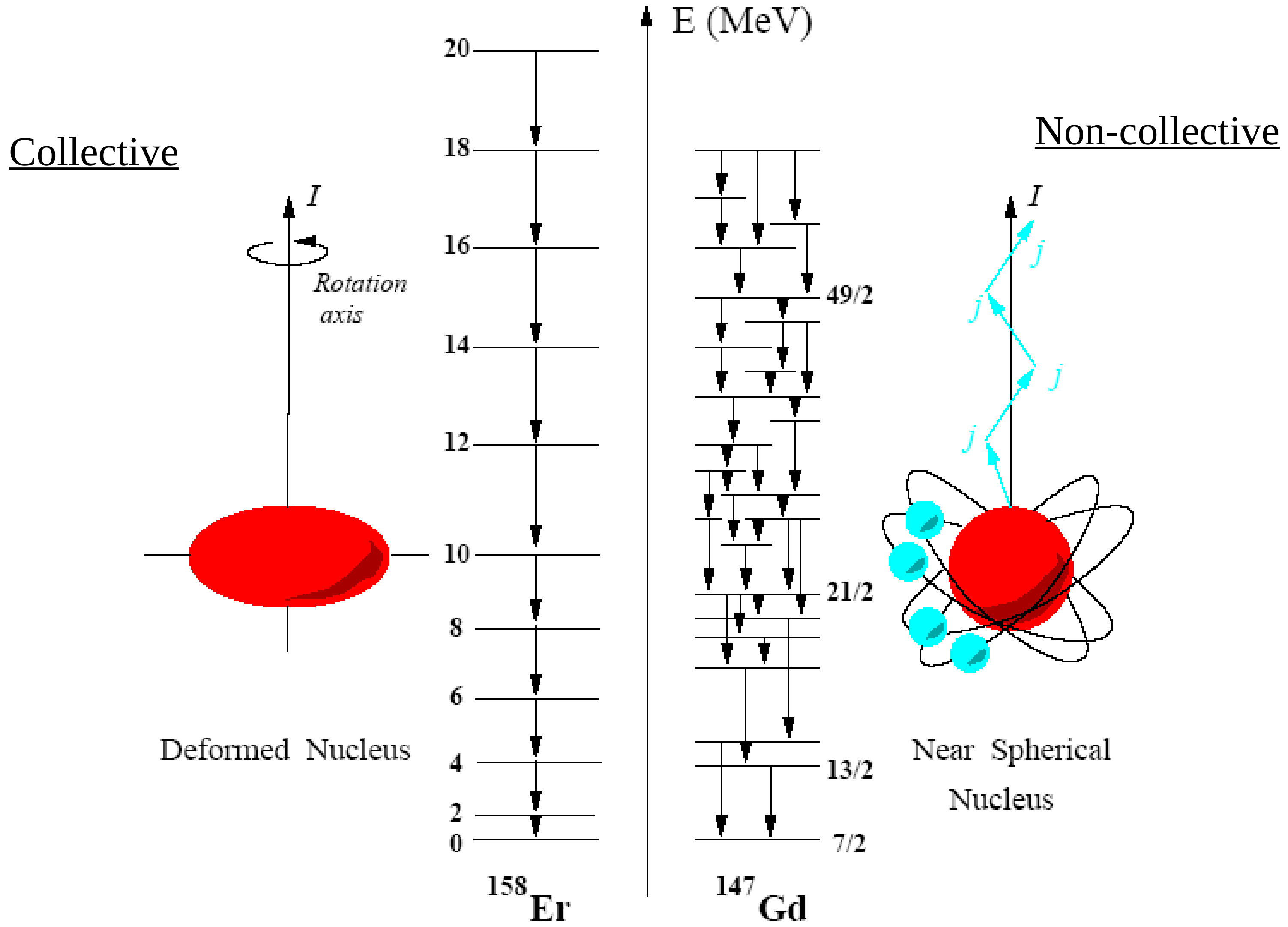
Rotations





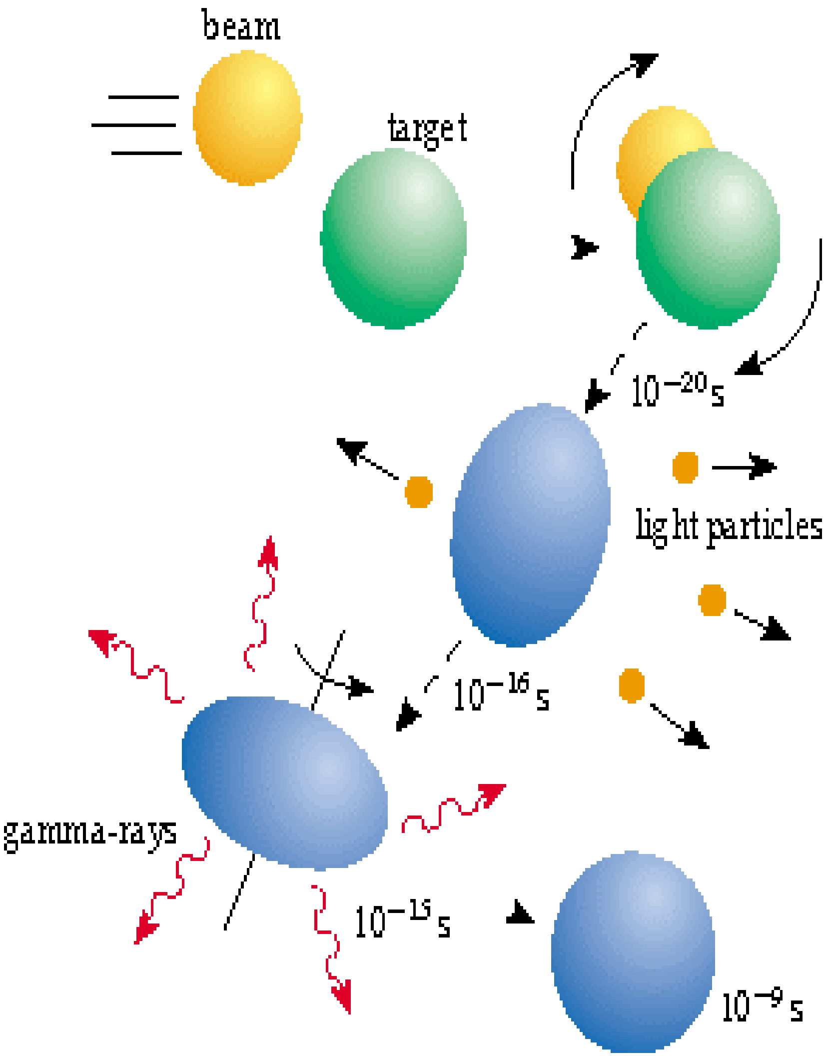


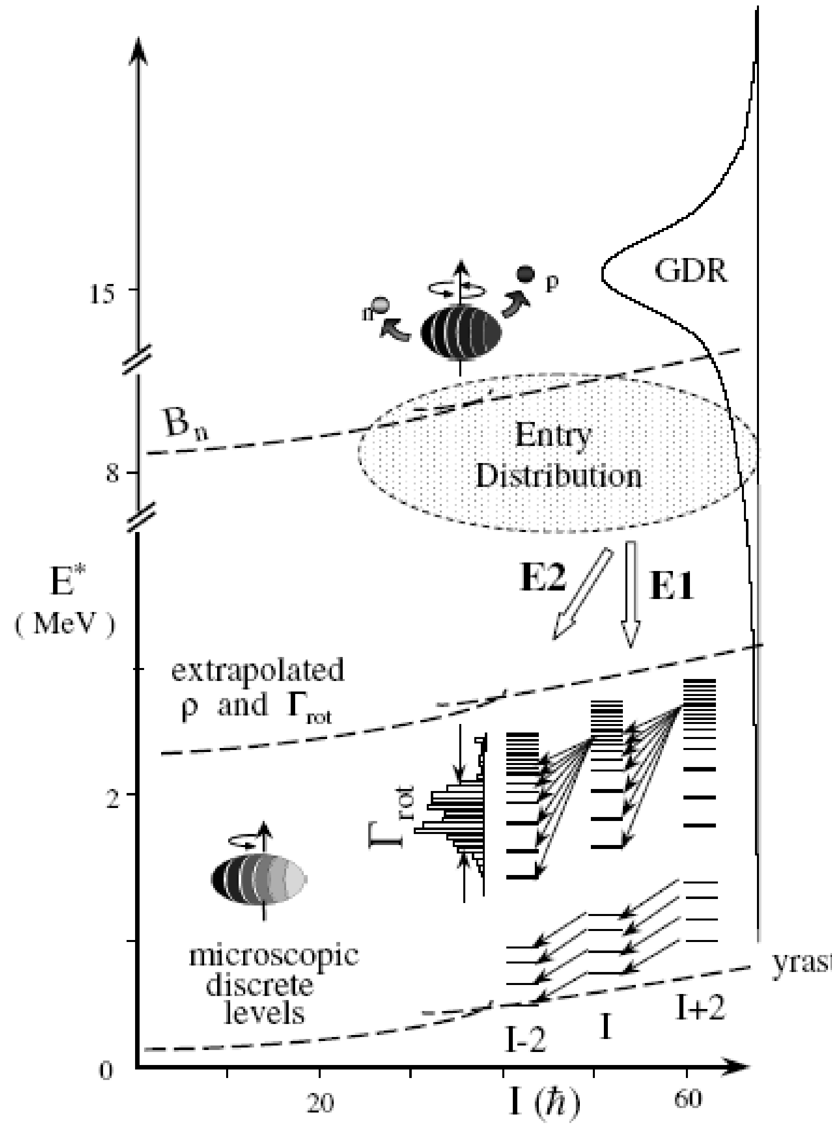
Vibrations



Energy scale of different modes comparable … rich interplay

How to produce the excited states?





How to Identify & Characterize them?

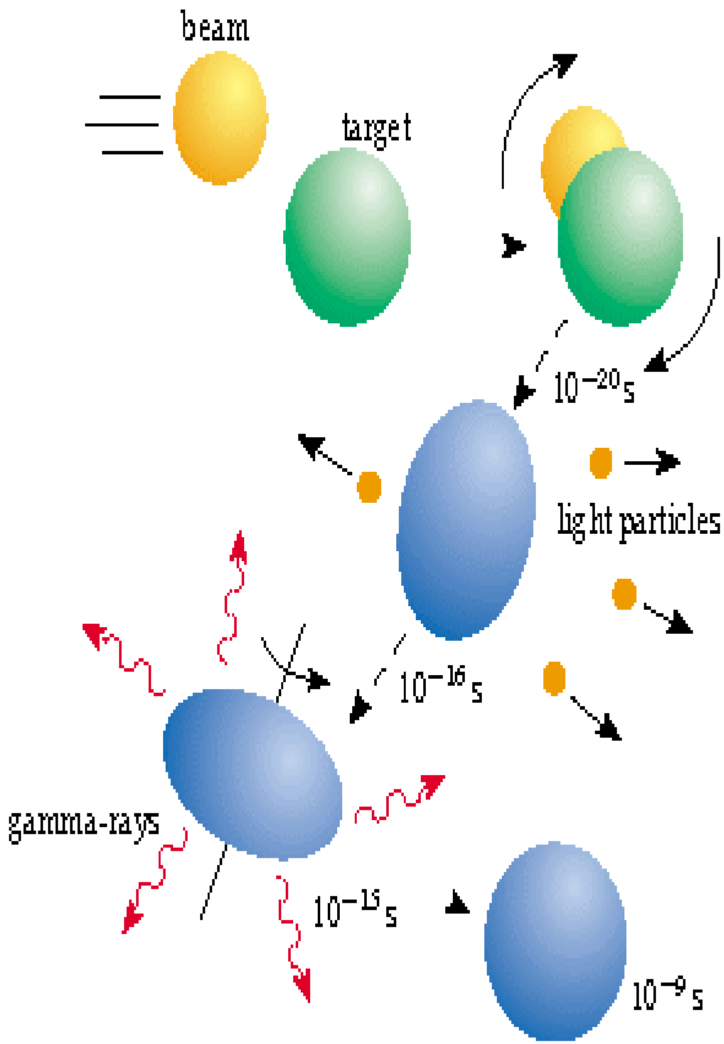
Identify the residue in a spectrometer

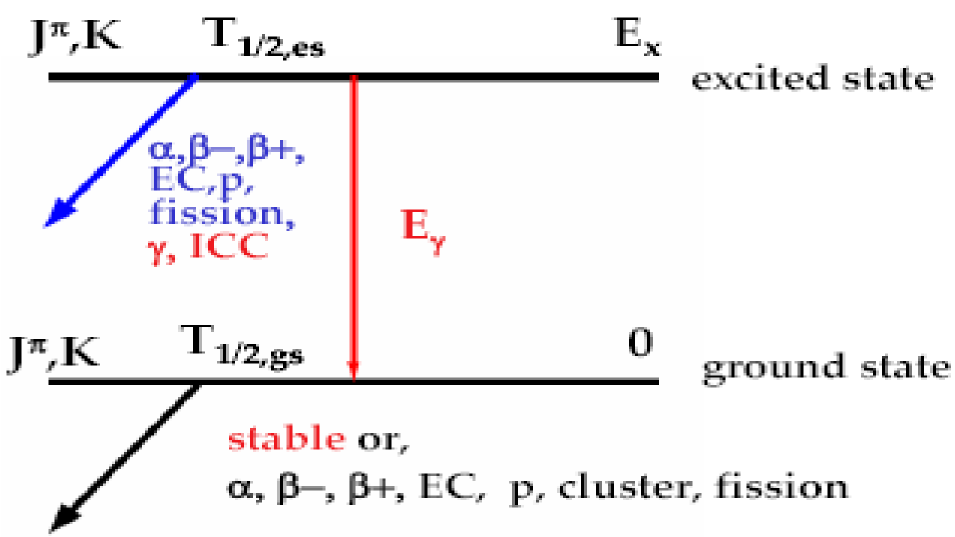
Measure the p,α,n multiplicity

Gamma coincidence, correlation & polarization measurements:

Excitation energy (E), Spin (J), Parity (π)*

Lifetime measurement by transition strength (wave function overlap)

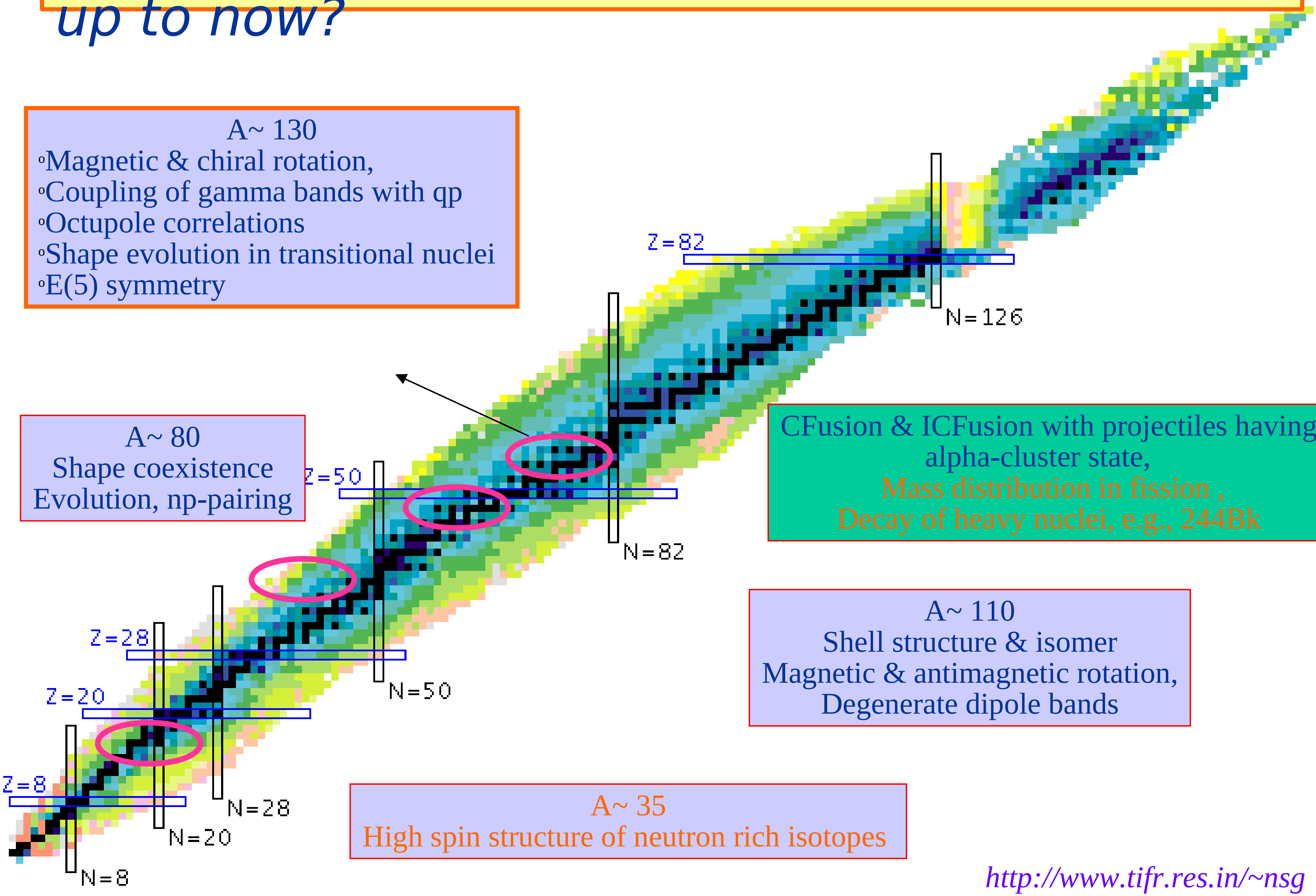




What have we studied with the array @TIFR up to now?

A~ 130
- Magnetic & chiral rotation,
- Coupling of gamma bands with qp
- Octupole correlations
- Shape evolution in transitional nuclei
- E(5) symmetry

A~ 80
Shape coexistence
Evolution, np-pairing



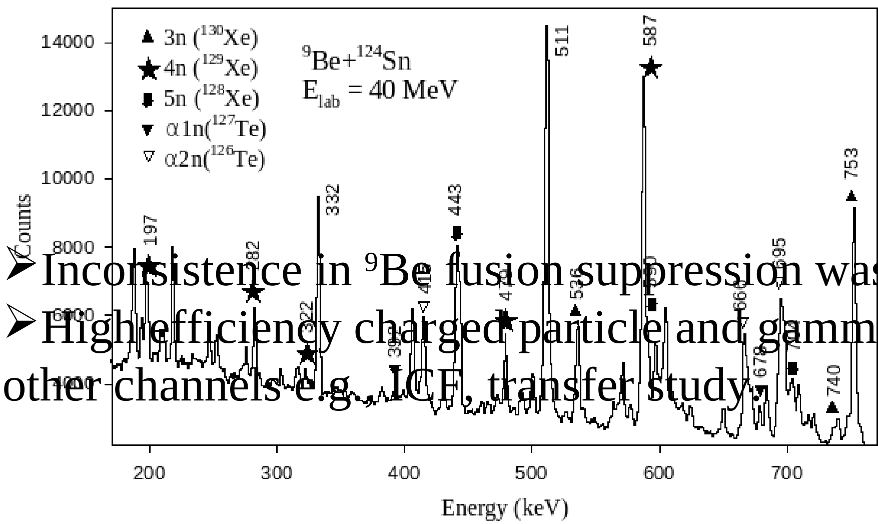
CFusion & ICFusion with projectiles having alpha-cluster state,
Mass distribution in fission ,
Decay of heavy nuclei, e.g., 244Bk

A~ 110
Shell structure & isomer
Magnetic & antimagnetic rotation,
Degenerate dipole bands

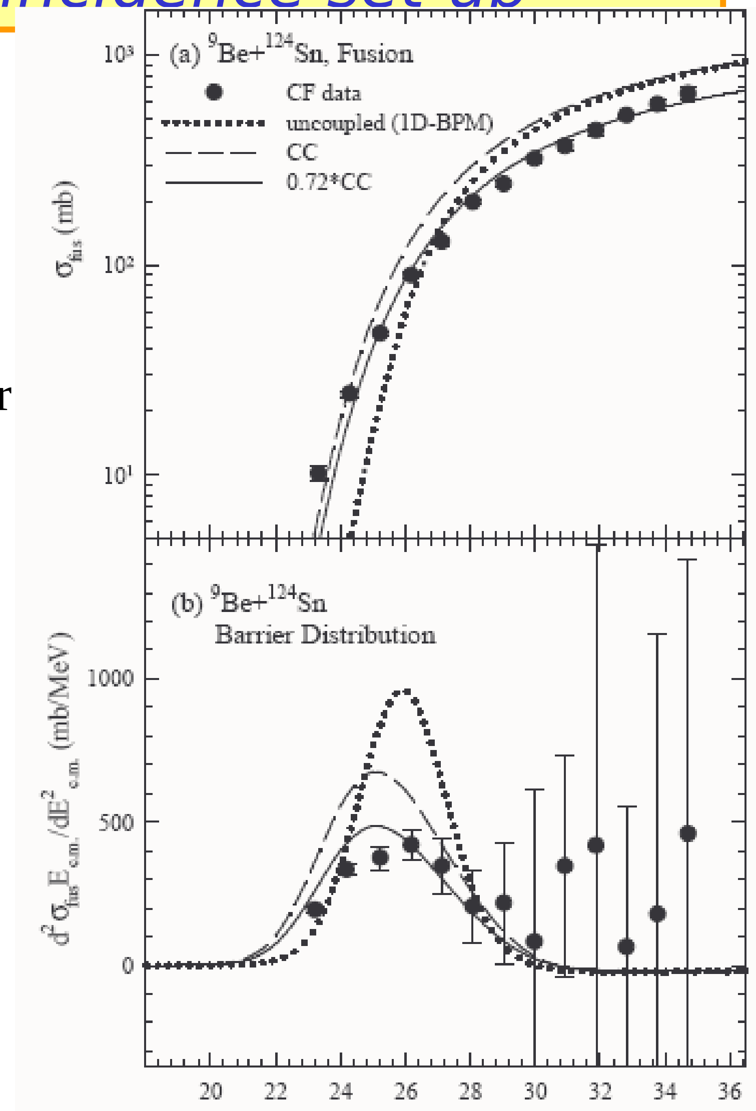
A~ 35
High spin structure of neutron rich isotopes

http://www.tifr.res.in/~nsg

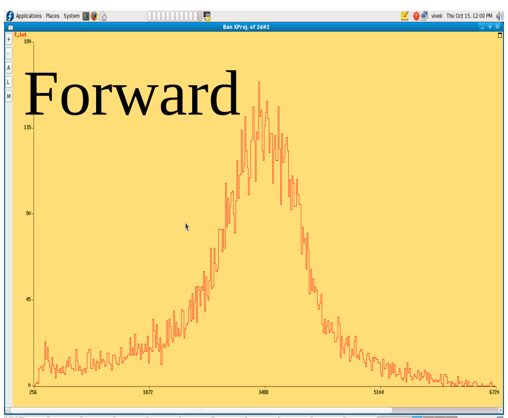
Complete and incomplete fusion cross-sections in $^{9}Be+^{124}Sn$ with particle-gamma coincidence set-up

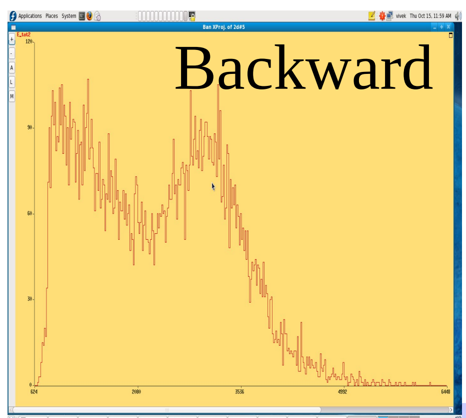


- Inconsistence in ^{9}Be fusion suppression was resolved.
- High efficiency charged particle and gamma set-up for other channels e.g. ICF, transfer study.



Alpha spectrum





V. Parkar, R. Palit, et al. PRC (2010).

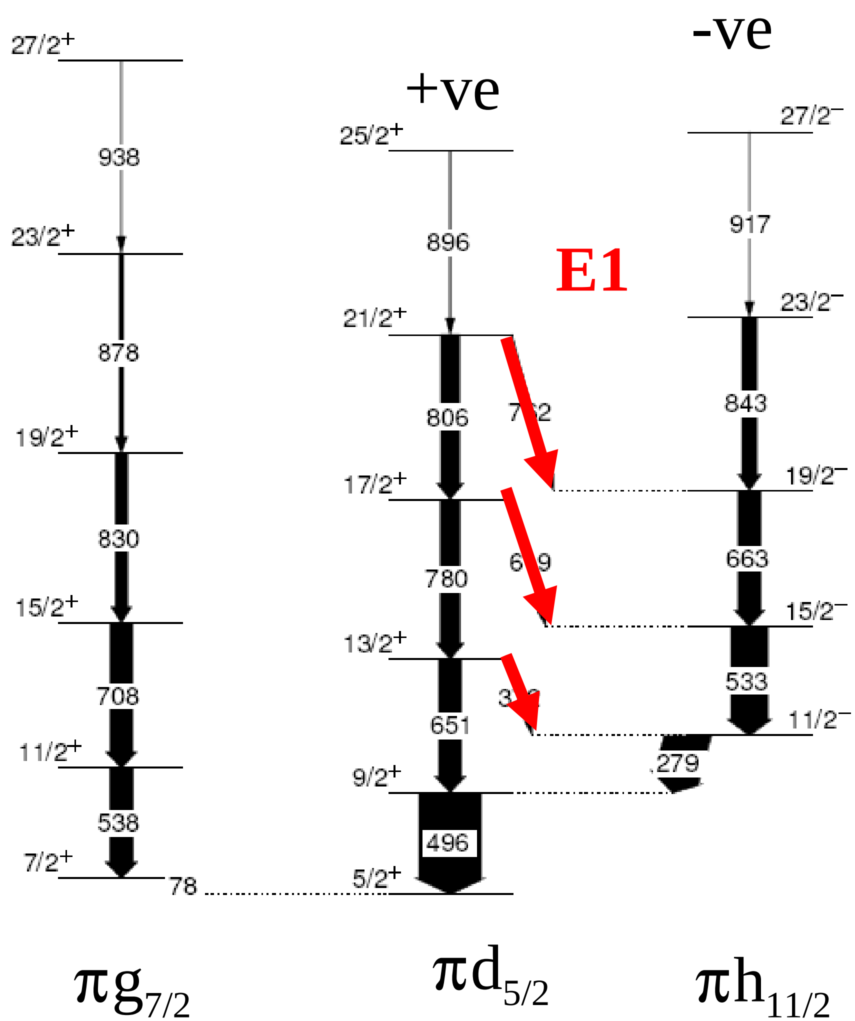
Octupole Correlations in ^{131}Cs

Opposite parity, Δl = 3 orbitals near Fermi surface

•Weak E1 transitions between $\pi d_{5/2}$ and $\pi h_{11/2}$ bands in ^{131}Cs has been observed.
(**0.3%** of the strong E2 transitions.)

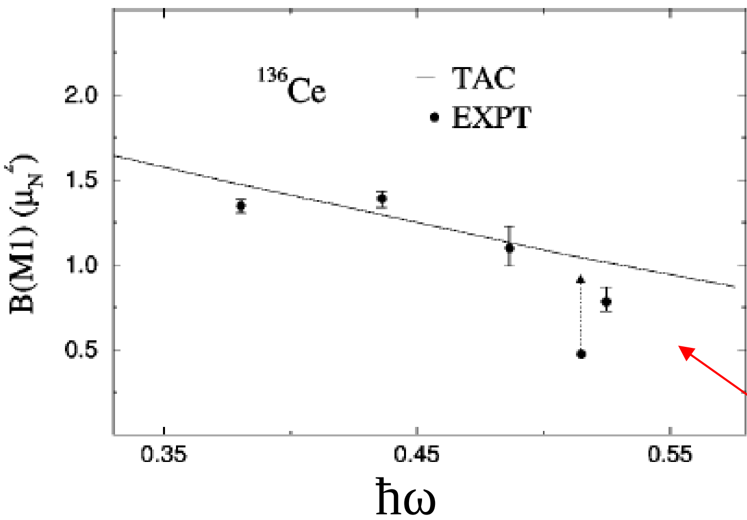
•Low Ω indicates highly localized wave functions thereby enhancing large octupole interaction matrix.

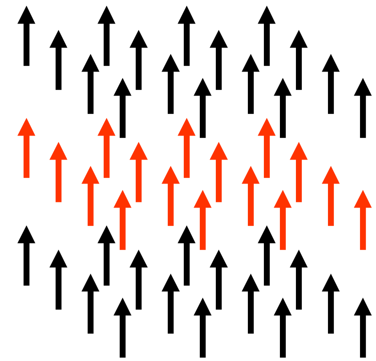
B(E1) ~ 6.0 x 10^{-5} W.u.
Comparable to Ba & Xe isotopes.



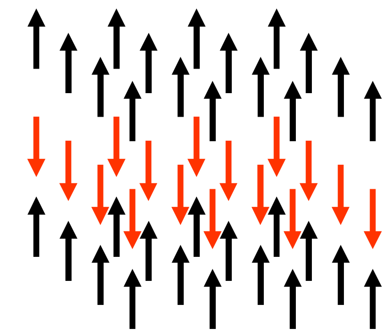
S. Sihotra, R. Palit, et. al. PRC78 (2008).

Magnetic & Antimagnetic Rotation



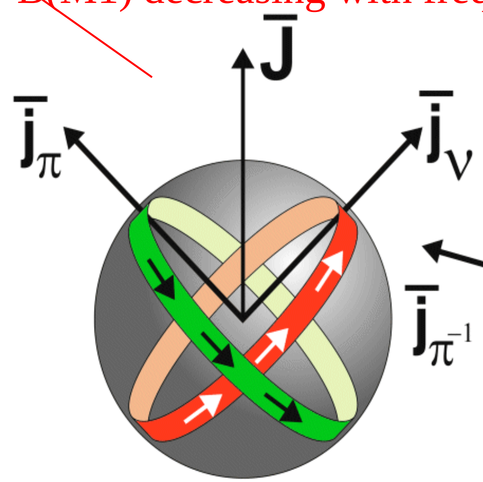


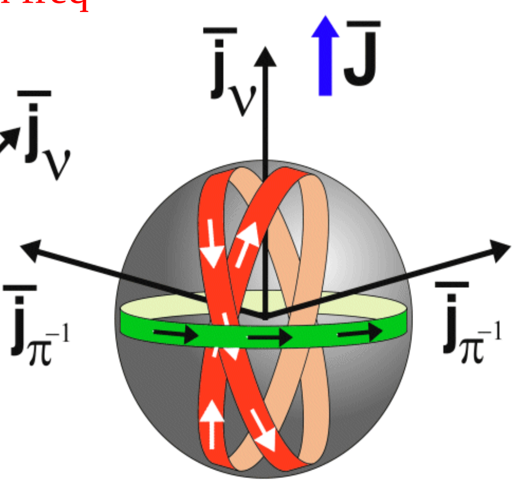
Ferromagnet



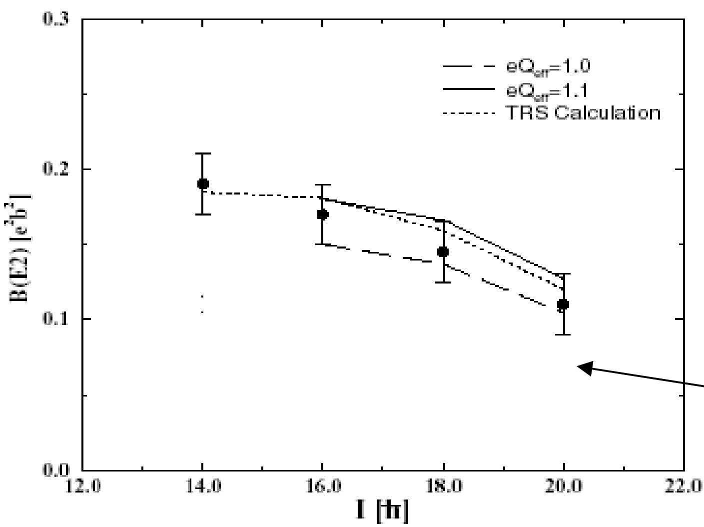
Anti-Ferromagnet

B(M1) decreasing with freq





B(E2) decreasing with spin



Magnetic rotor   Antimagnetic rotor

FIG. 2. $B(E2)$ rates vs spin for positive parity yrast band of ^{108}Cd.

References

Results

- Spectroscopy of Transitional Nuclei in A ~ 130

PRC 76, 014306 (2007), PRC 78, 034313 (2008)
PRC 81, 067304 (2010)

- Gamma vibrations & its coupling

Nucl Phys. A 824, 58(2009)

- Degenerate dipole bands & chirality

PRC 79, 067304 (2009), EPJ A 43, 45 (2010), NPA 834, 81c (2010)

- Reactions for population high spin states in transitional nuclei

PRC 82, 054601 (2010)

- INGA details & DSP

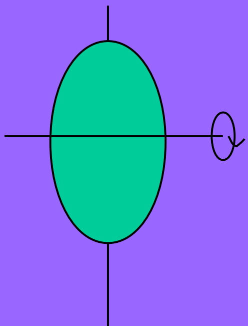
AIP, March (2011)

Outline

- 1. Scope of gamma spectroscopy for nuclear structure
- 2. Large Array of Detectors
  - Why do we need it?
  - Basic configurations & coupling with other Ancillary detectors
- 3: Why digital?
- 4: INGA array at Pelletron LINAC facility
- 5: Application of these techniques in medical imaging

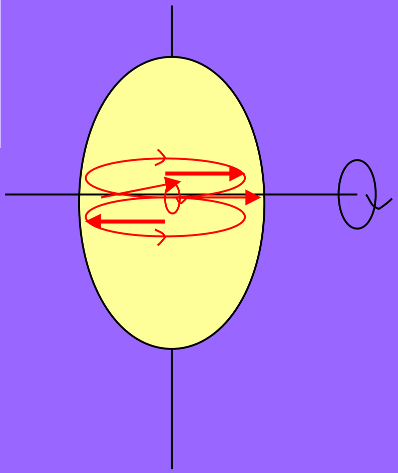
What do we need for investigation of rotating nuclei?

Decay spectroscopy
Single detector
1960..



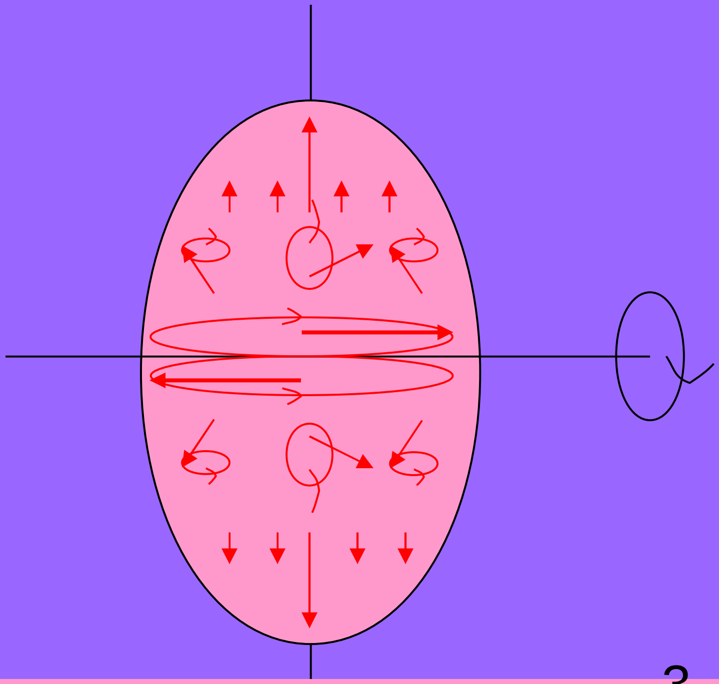
Collective rotation

HI induced reaction
Small array
1980..



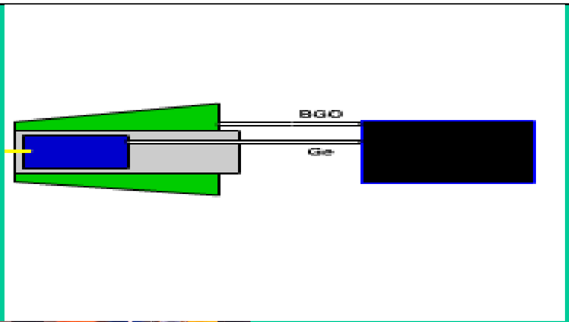
Interplay between collective and sp. degrees of freedom

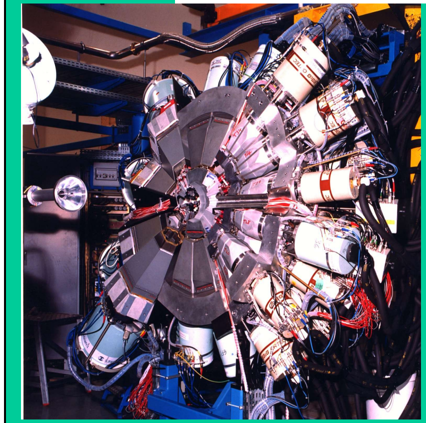
HI induced reaction
Large array, ancillary detectors, …
1990 … 2010



Exotic high spin phenomena arising from coupling of different shapes, spinning nucleons and weak yields

Large Gamma Arrays based on Compton Suppressed Spectrometers





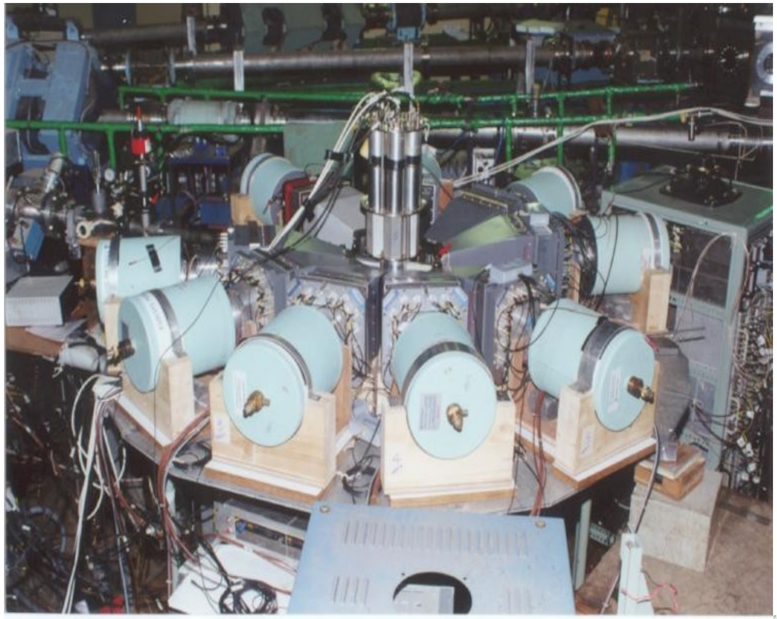
EUROBALL

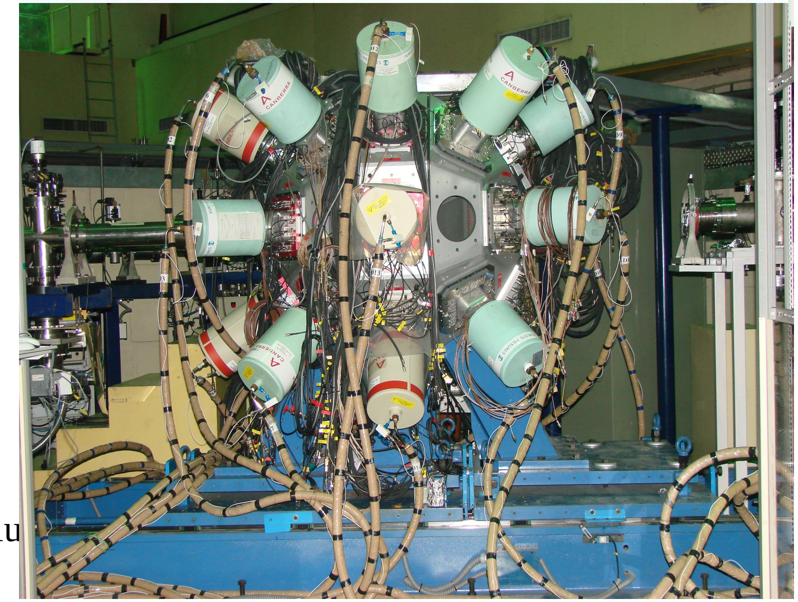
GAMMASPHERE

$\varepsilon \sim$ 10 — 5 %

(M_γ=1 — M_γ=30)

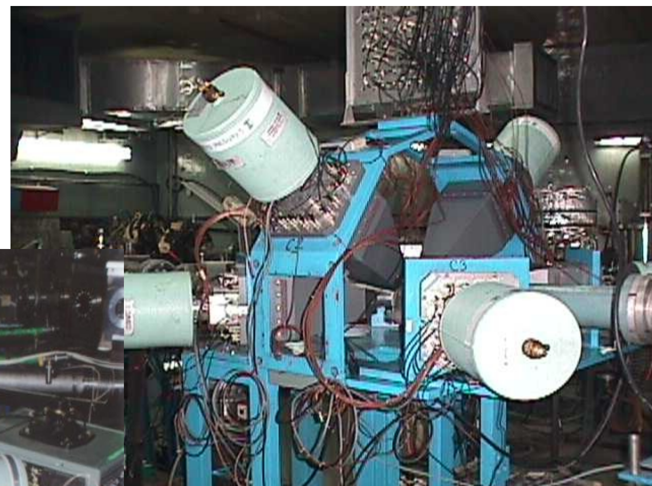
Ge Detectors within India

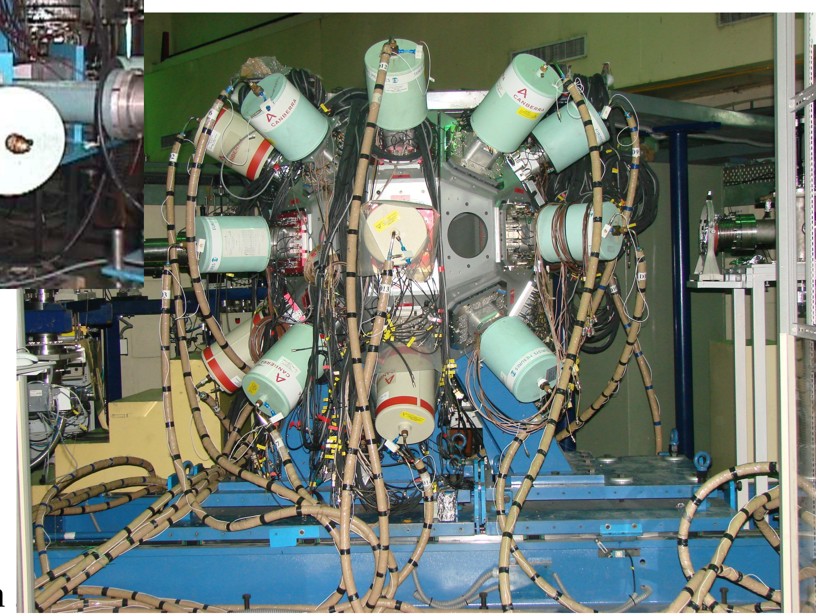




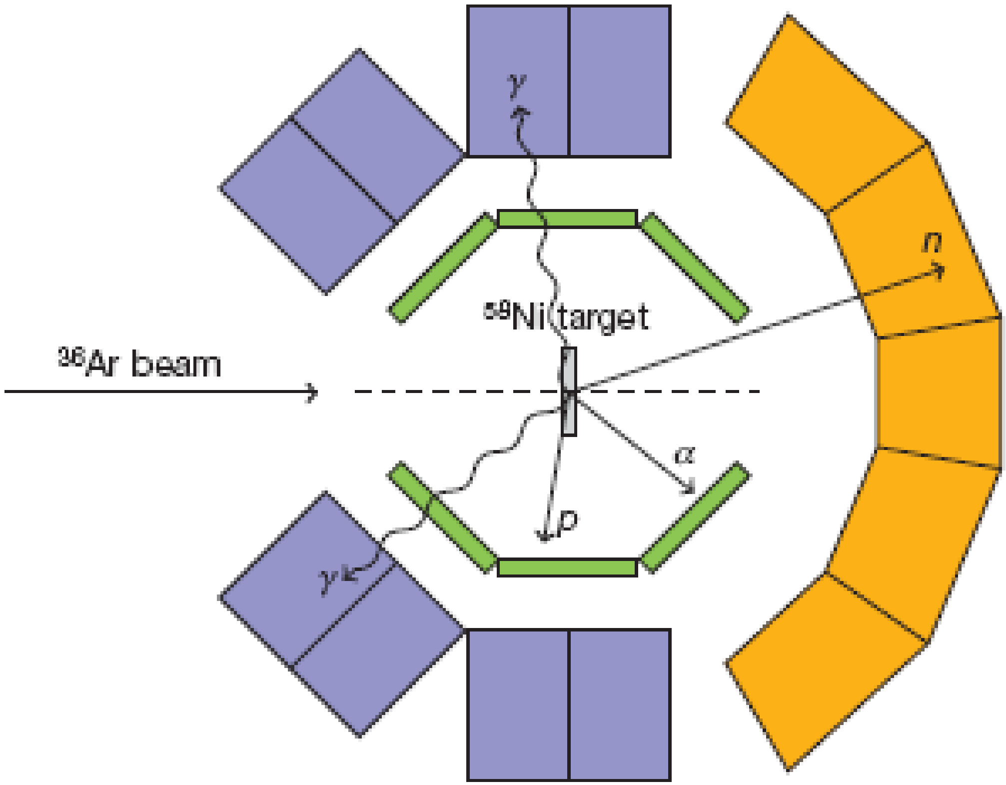
INGA campaigns at different accelerator facilities

INGA01	INGA03	INGA05	sINGA07-8	INGA08-9	INGA10-11
TIFR	NSC	VECC	TIFR	IUAC	TIFR

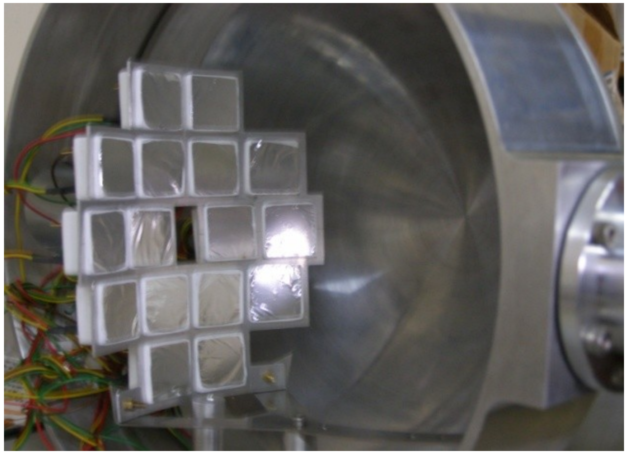




Typical requirement for the setup

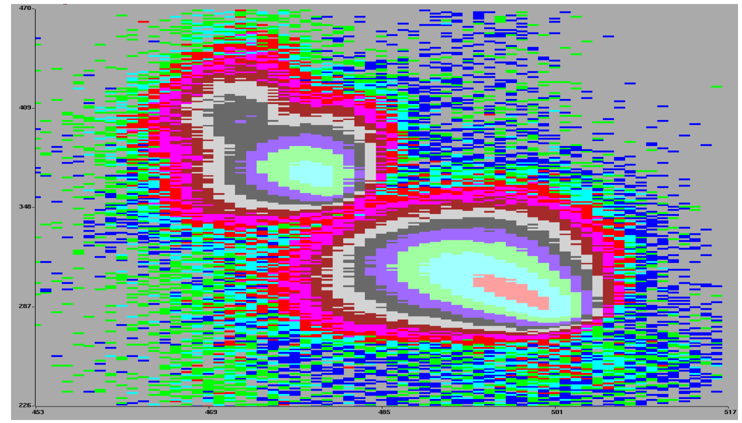


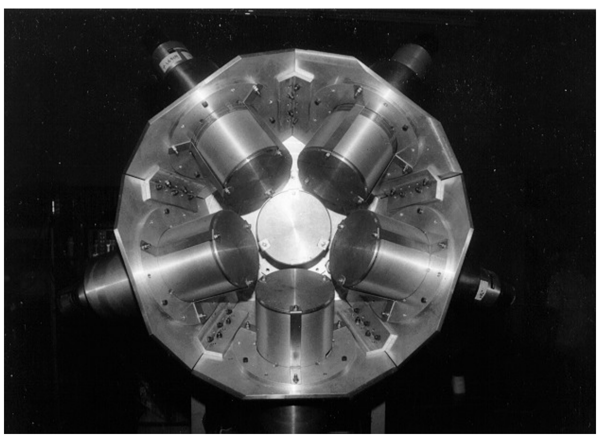
Ancillary detectors for Detection of Evaporation Particles *using pulse shape analysis*



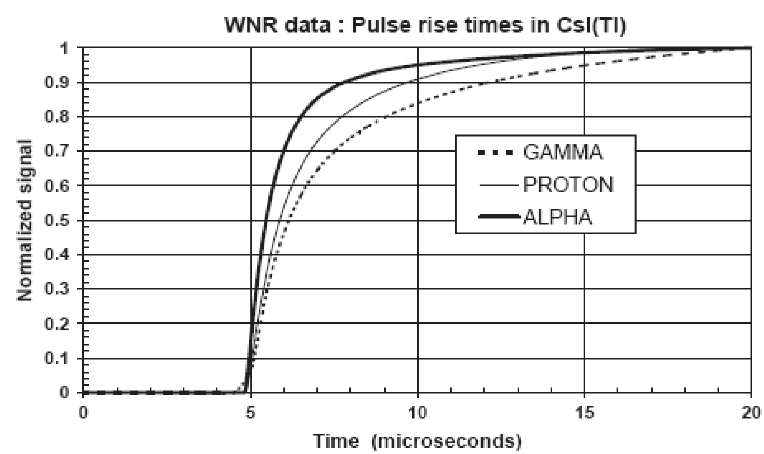
CsI(Tl) CPDA for charged particle tagging

2-dim plot of zero-crossover & ratio (PH_S/PH_L):





Neutron Detector Array @ TIFR
for neutron tagging



Radiation Protection Dosimetry 110, 219 (2004)

Neutron Multiplicity Filter

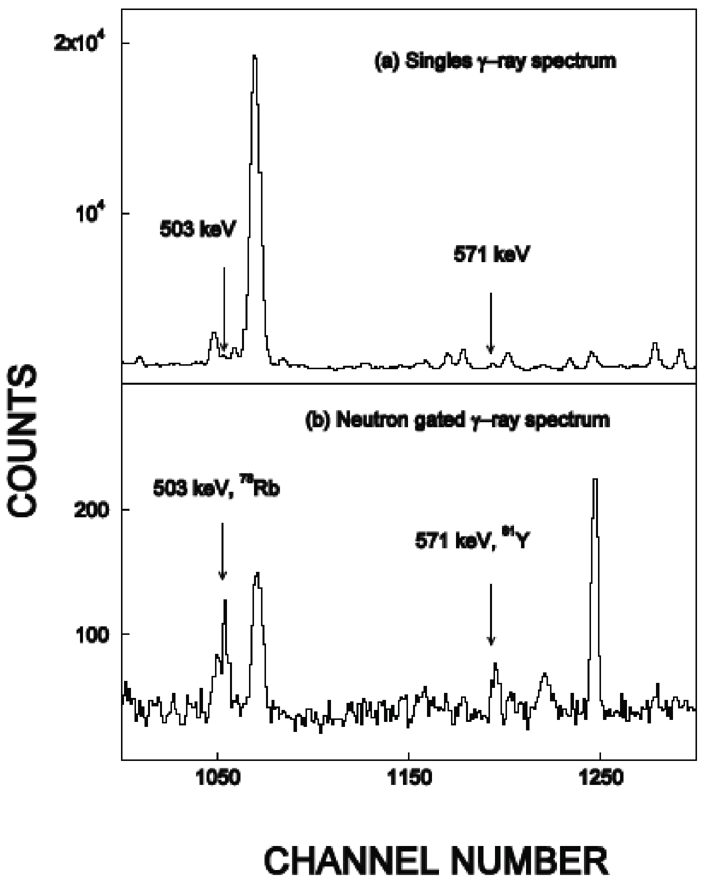
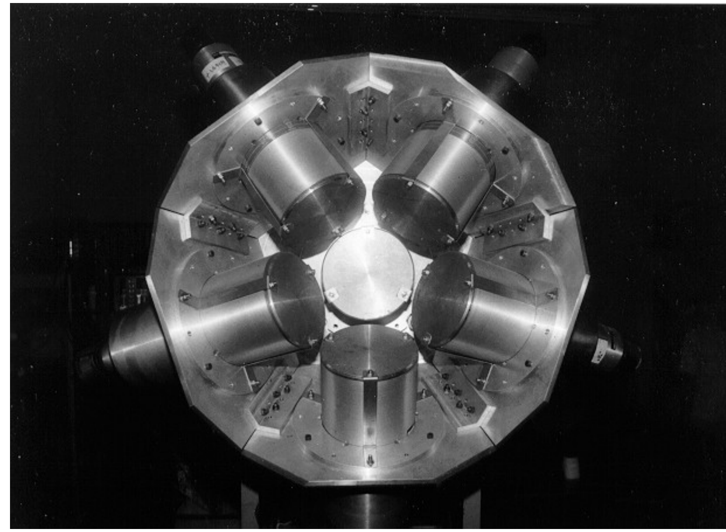
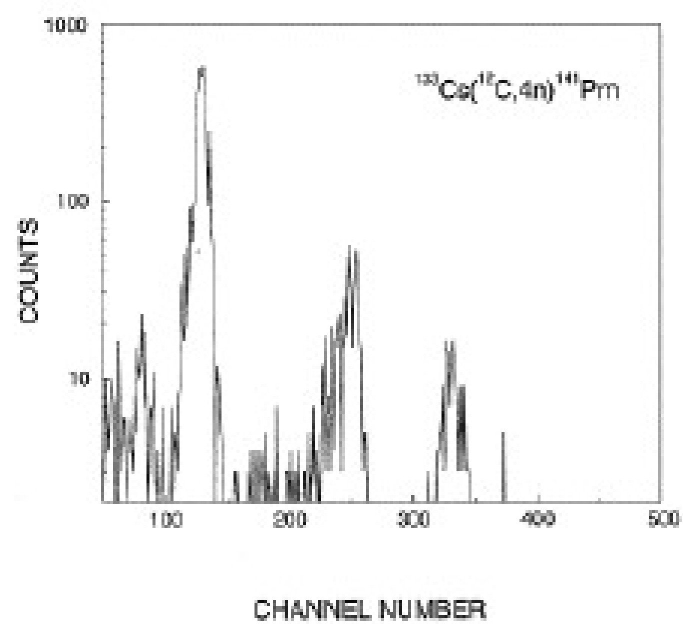


Fig 3. Comparison of neutron gated spectrum with singles spectrum





R.Palit, et al, NIM 443, 386

Charged particle array for identification of residual nuclei

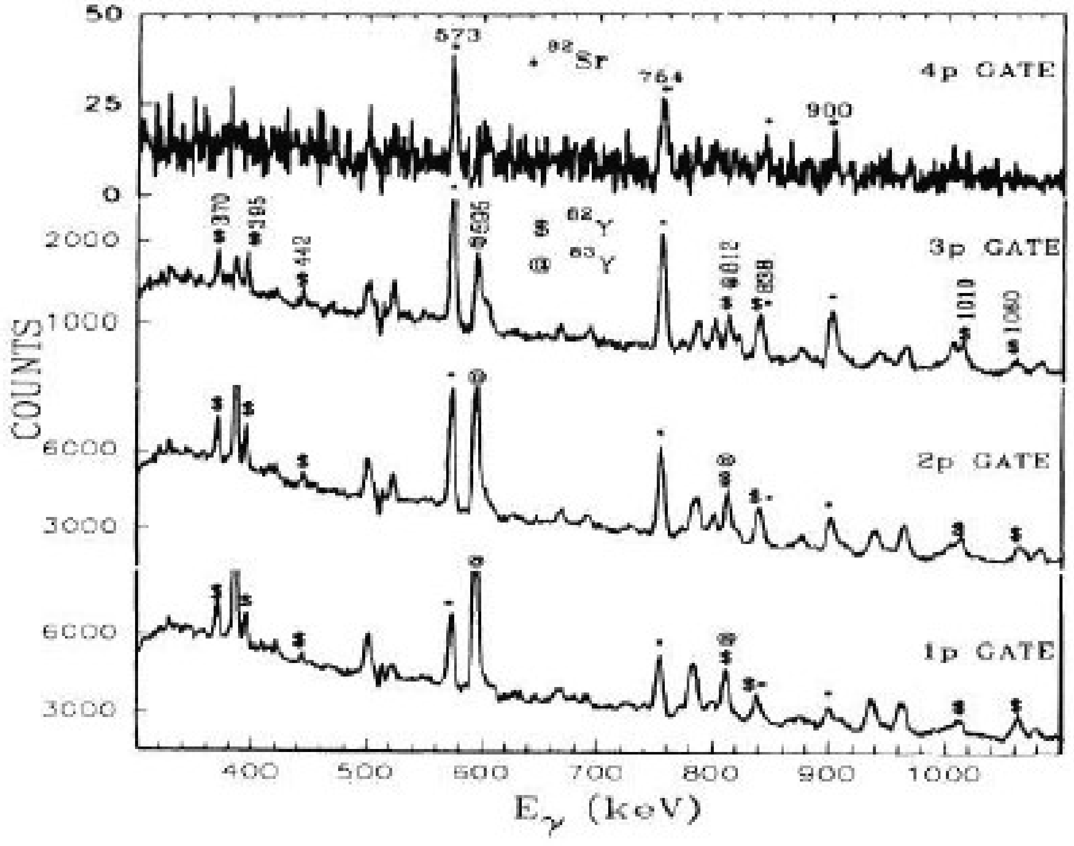


Fig. 4. 1p, 2p, 3p and 4p gated gamma spectra obtained with CPDA at TIFR coupled with 6 HPGe detectors.

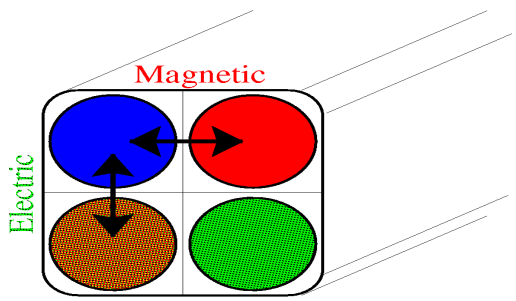
S.D. Paul, et al. PRC (1995)

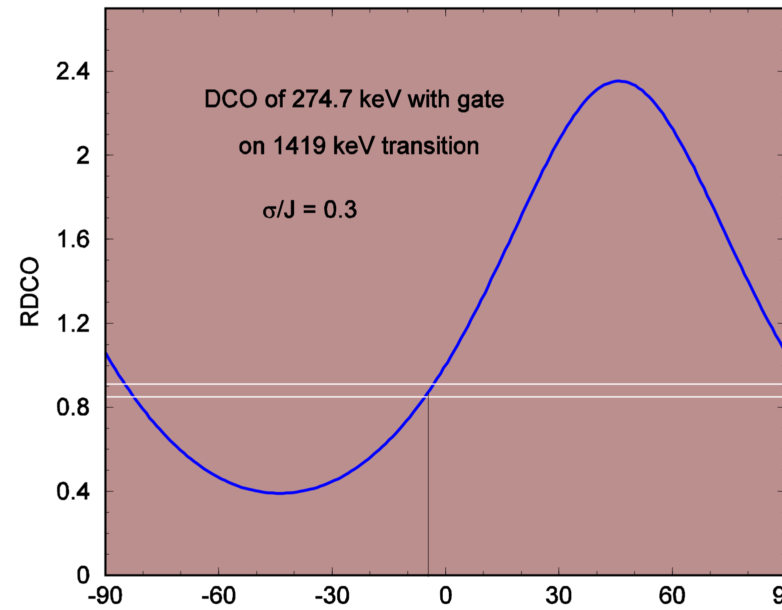
Clover detectors in INGA

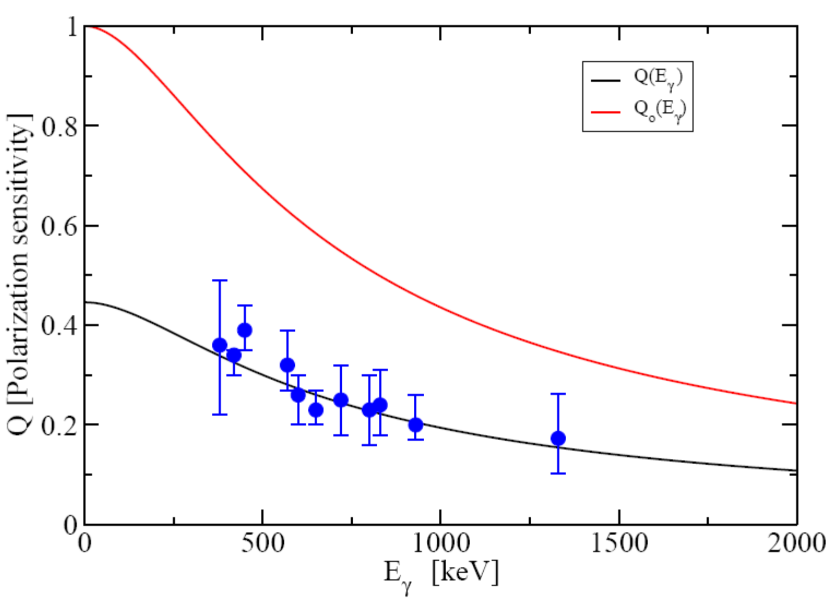
- Eurisys
- N-type
- Size per crystal: $50x50x70mm^3$
- Relative eff. :
  - per crystal: 20%
  - Add-back (total) : 120%
- Gain
  - 200mV/MeV

Measurements for intensity, DCO, **Polarization & $T_{1/2}$ for investigation of elaborate level structure of excited states of nuclei**

Measured quantities for complete spectroscopy
Polarization, DCO and Lineshape







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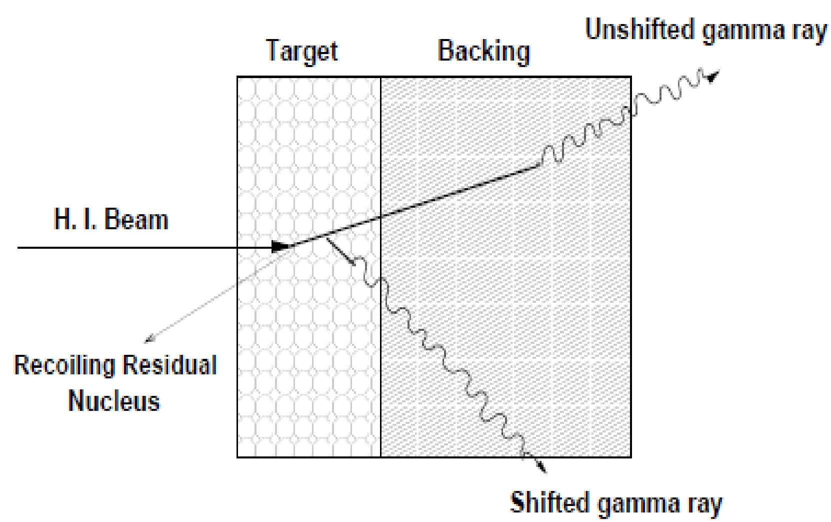
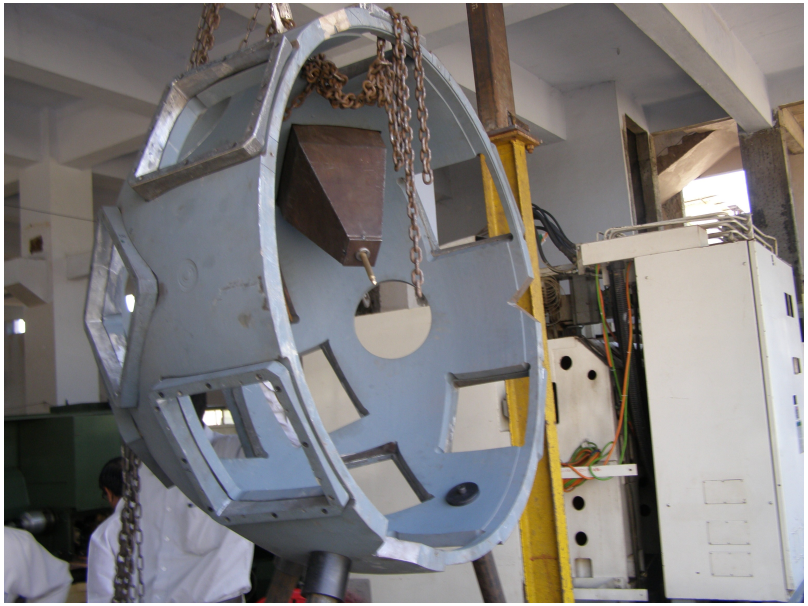
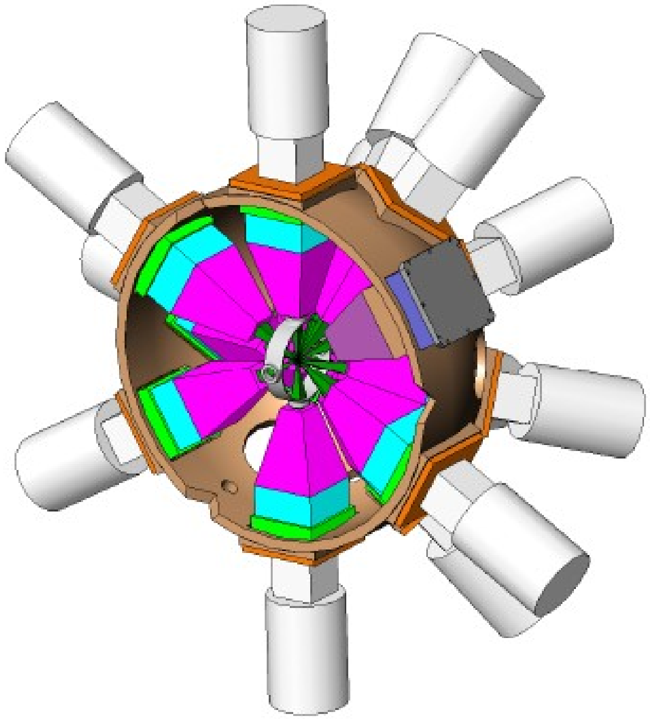
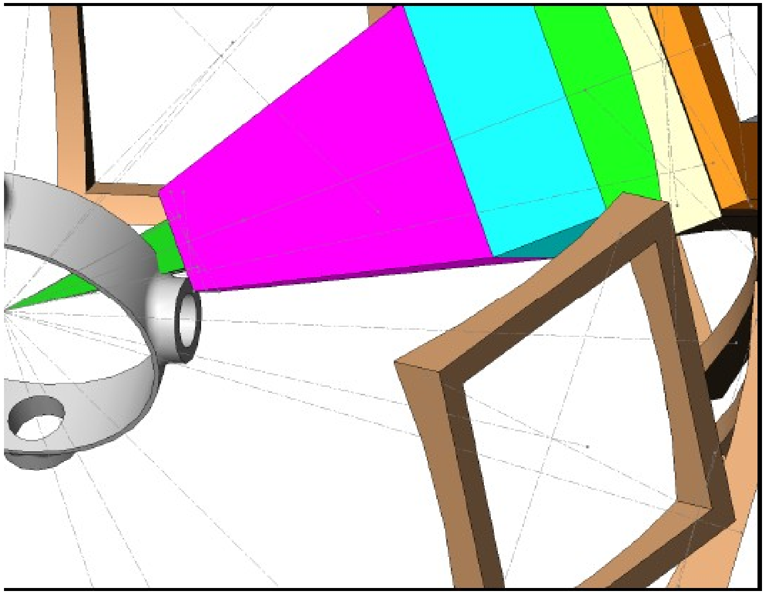


Clover array at TIFR

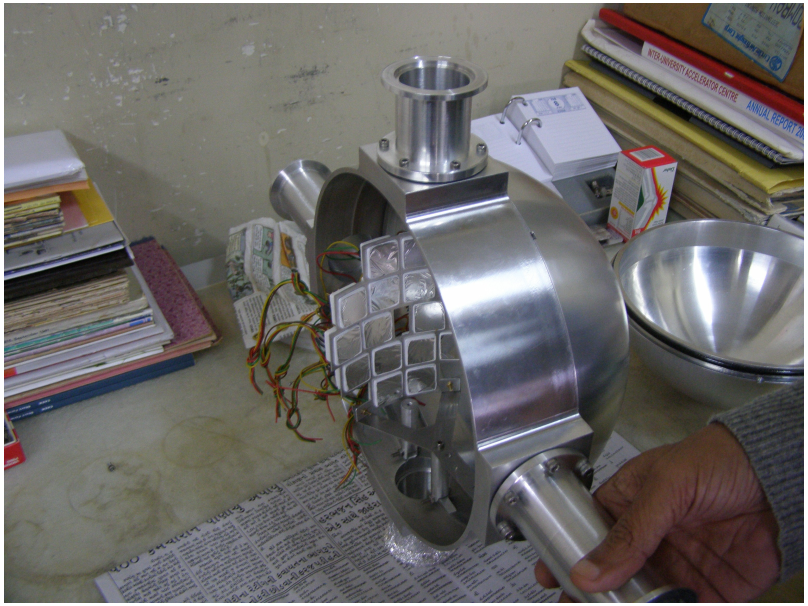


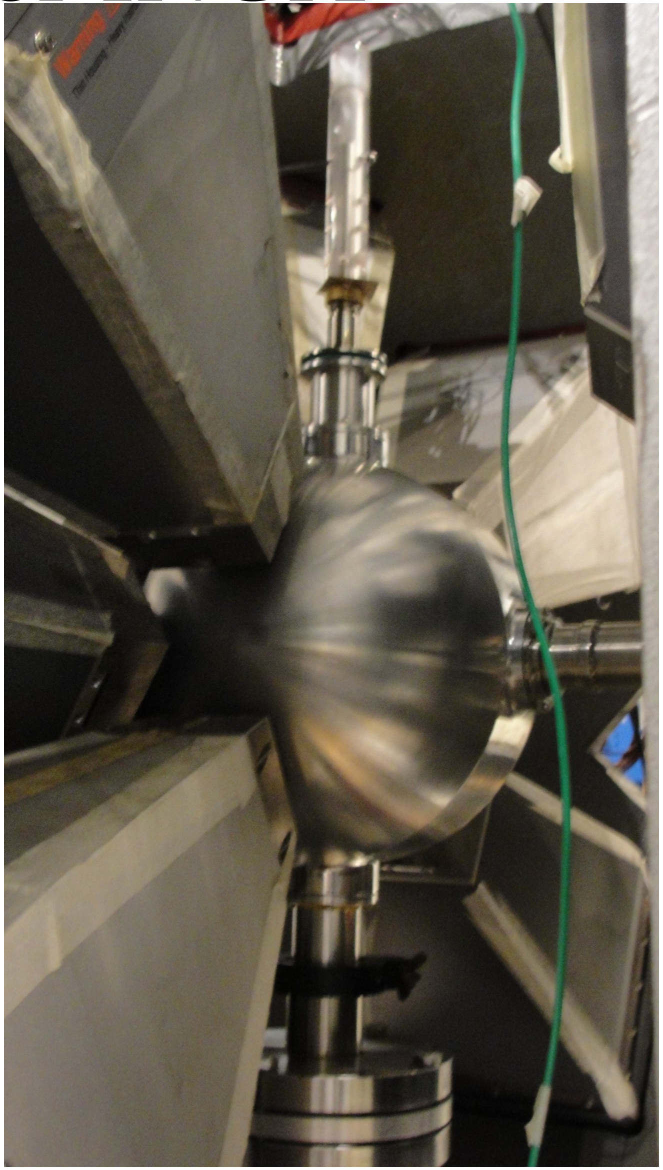
Clover array at TIFR





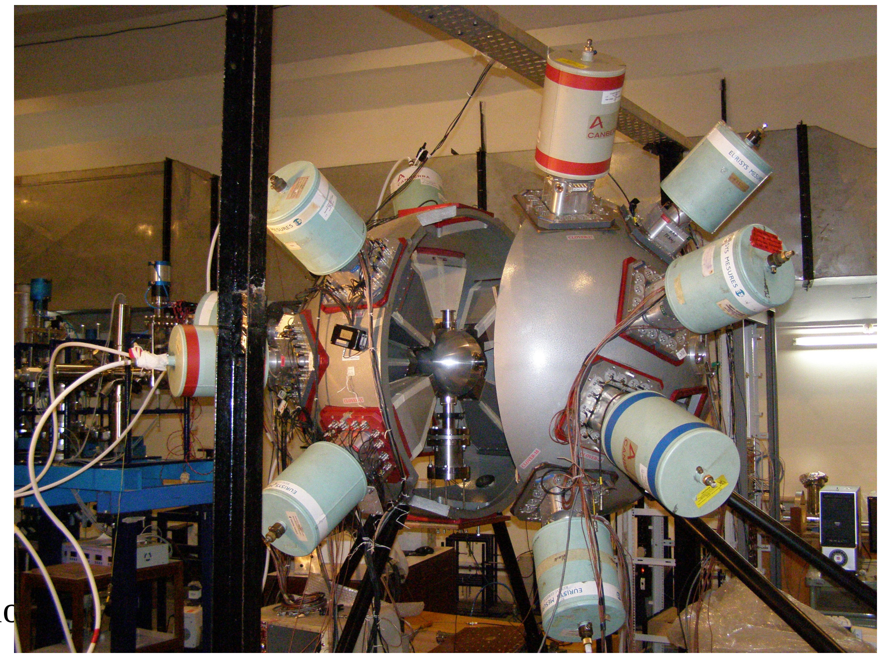
Target chamber for INGA





Basic Configuration at TIFR from 2010

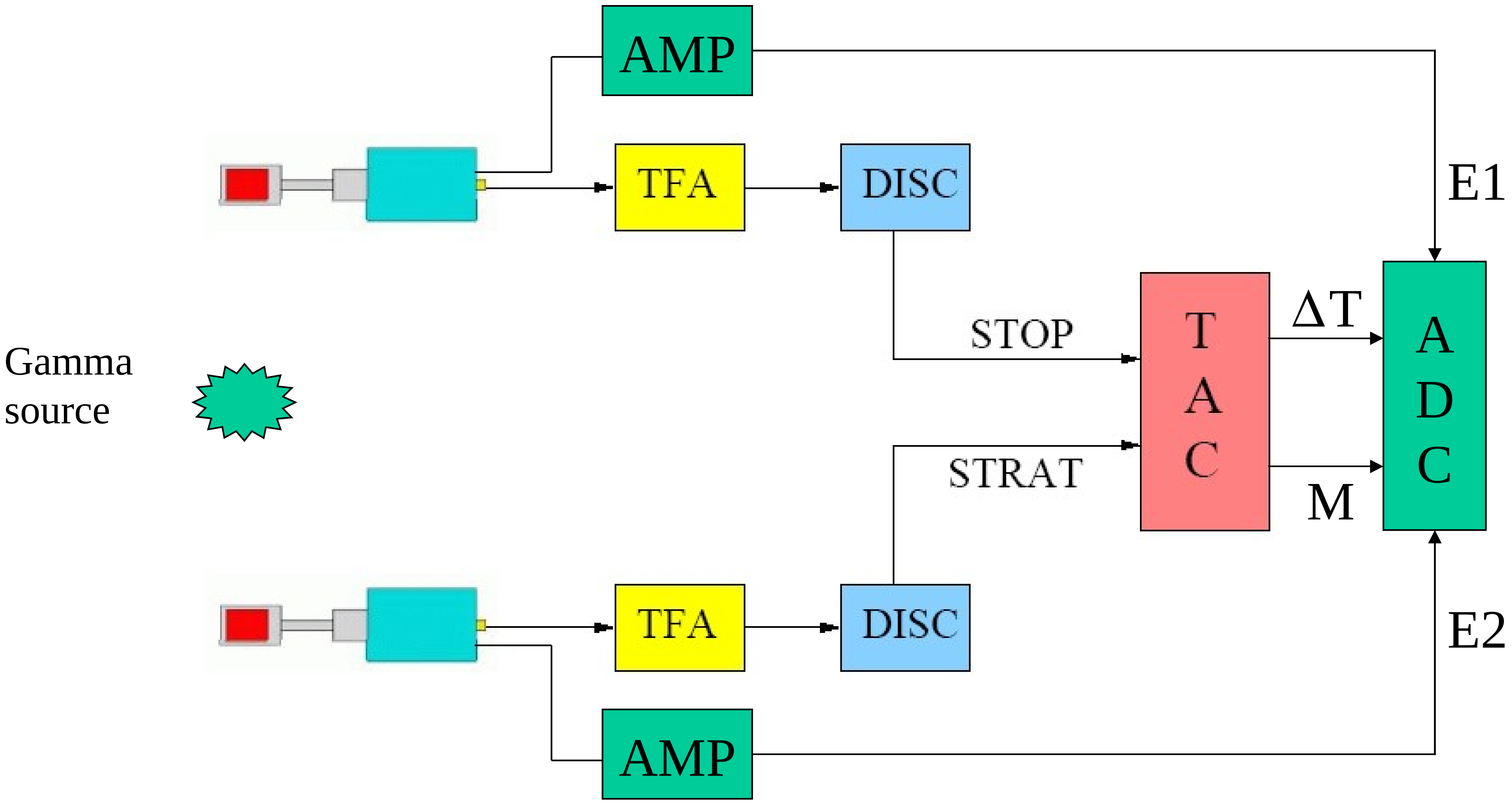
- Set up in Beam hall II of TIFR-BARC (LINAC beam hall)
- Mounting position for 24 Clovers (~5% ε_P)
- Movement on rails for precision alignment
- *Space for mounting Charged Particle Array*
- *3 at 23°, 40°, 65°, 115°, 140°, 157° and 6 at 90°*



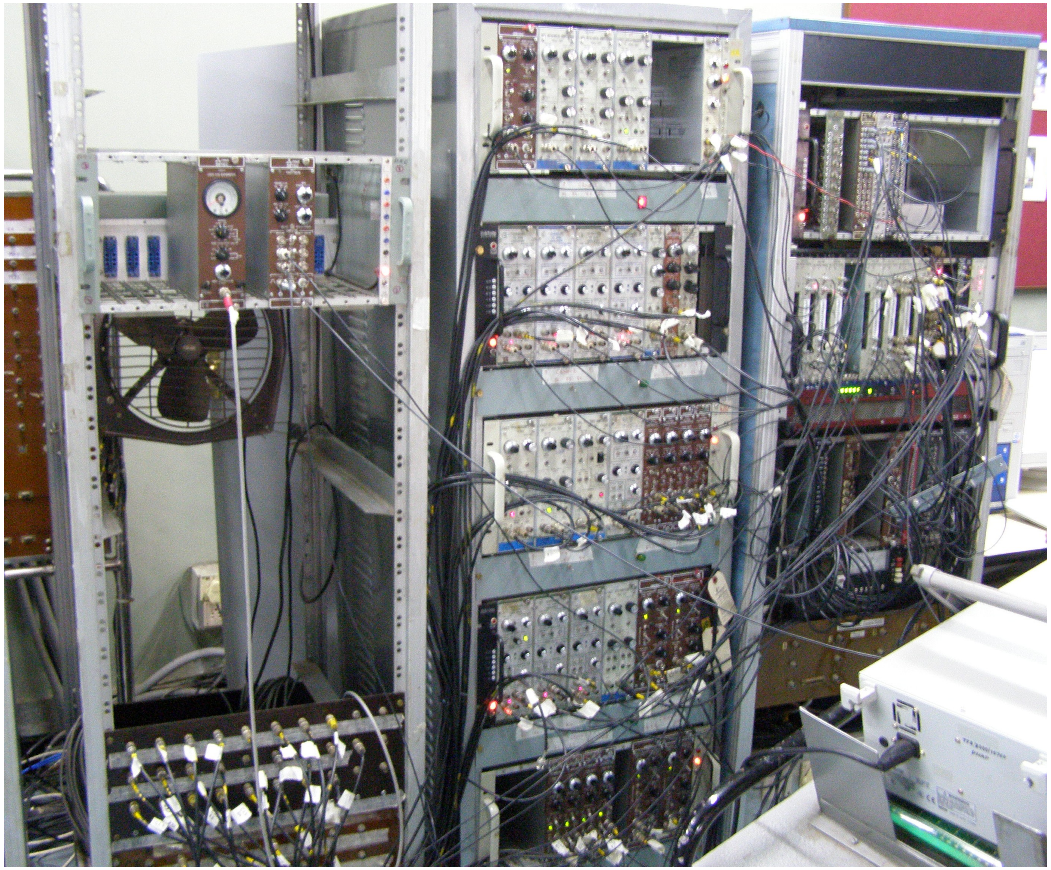
Outline

- 1. Scope of gamma spectroscopy for nuclear structure
- 2. Large Array of Detectors
- 3: Why digital?
  - Basic components
  - Comparison with analog systems
  - Implementation for different detectors
- 4: INGA array at Pelletron LINAC facility
- 5: Application of these techniques in medical imaging

Slow-Fast coincidence techniques: Old school



Too complicated most of the times … set up at TIFR during 2007



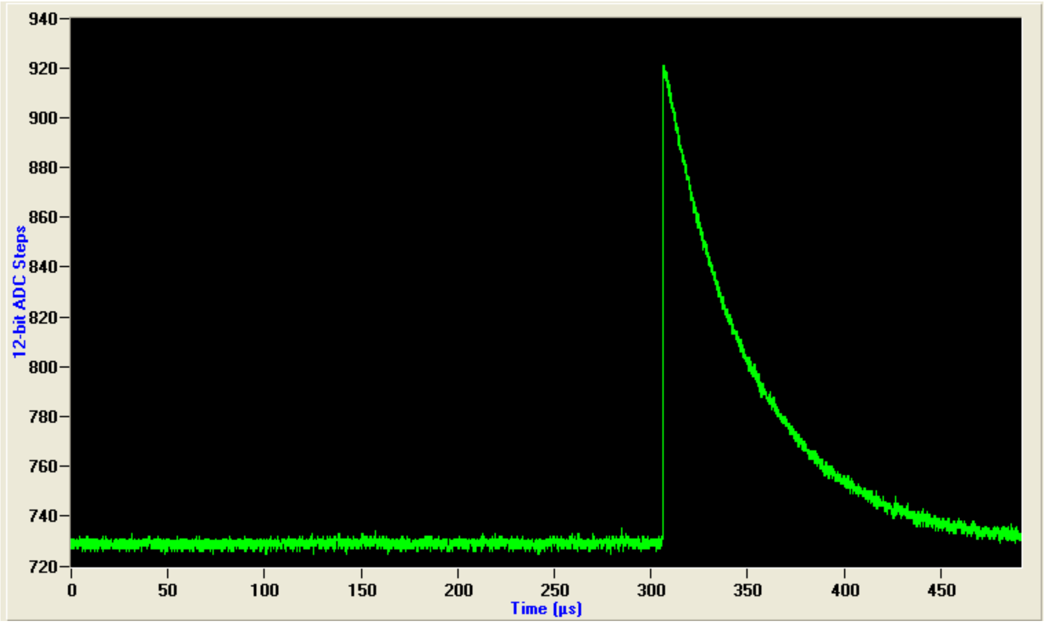
DSP based DAQ

(from view point of researchers in nuclear physics)

- DSP gives an elegant solution for signal processing of radiation detectors
- Digital data can be stored and retrieved
- Numerical algorithms can be optimized for different detectors with same hardware to give E, T, PID with good resolution
- Compact, robust, flexible and fast
- Time correlation of events in arbitrary time scale

Requirement for experiments

Digital Signal processing for radiation detectors



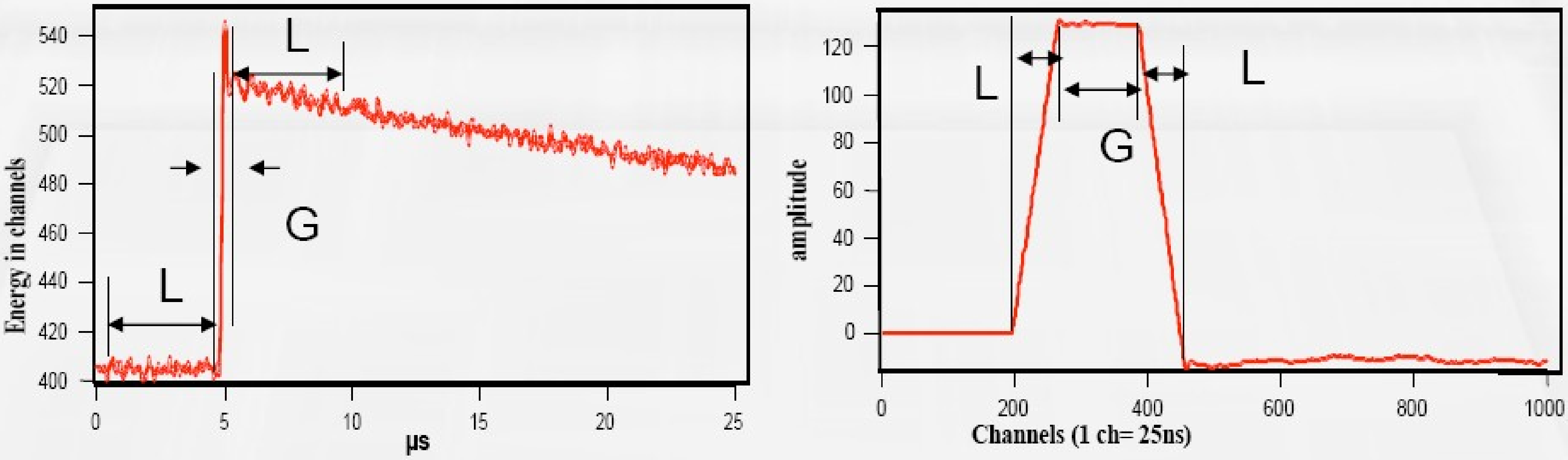
$$FF[i] = \sum_{j=i-(FL-1)}^{i} Trace[j] - \sum_{j=i-(2*FL+FG-1)}^{i-(FL+FG)} Trace[j]$$

Pulses involving time scale in 100 psec to 100 µsec

100 to 1000 channels for the typical experiments

100 Hz to 1MHz count rate for detectors

Pulse shape information MHz to GHz

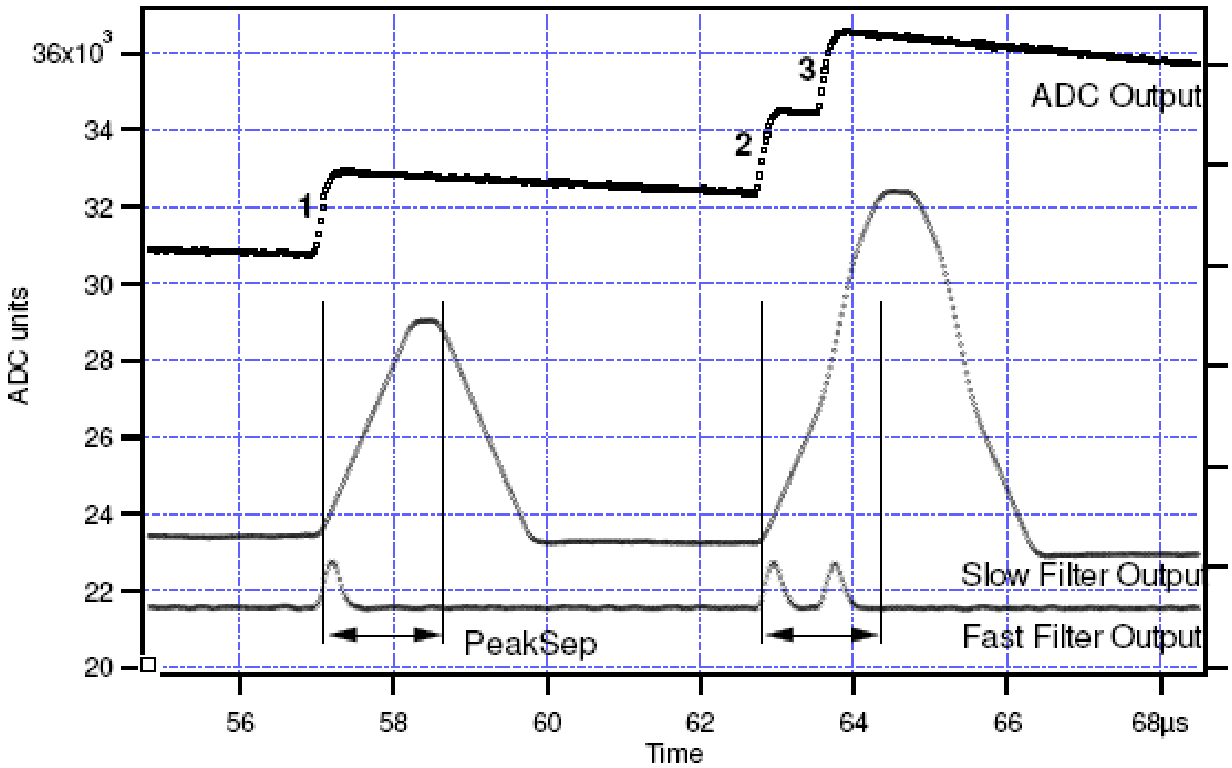


Detector pulse *Transformed pulse*

$$FF[i] = \sum_{j=i-(FL-1)}^{i} Trace[j] - \sum_{j=i-(2*FL+FG-1)}^{i-(FL+FG)} Trace[j]$$

$$CFD[i+D] = FF[i+D] - FF[i]/2^{(W+1)}$$

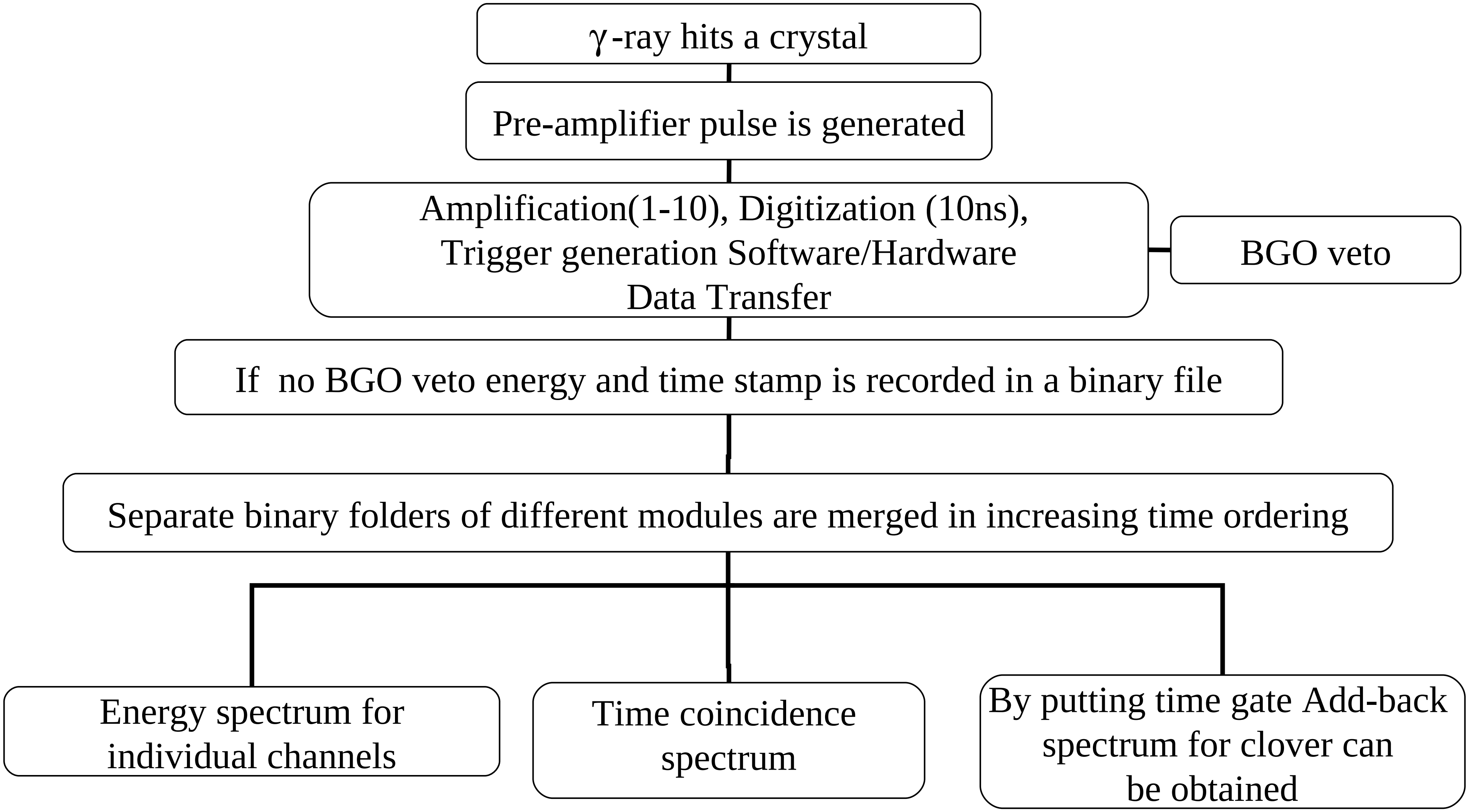
What happens with high count rate?



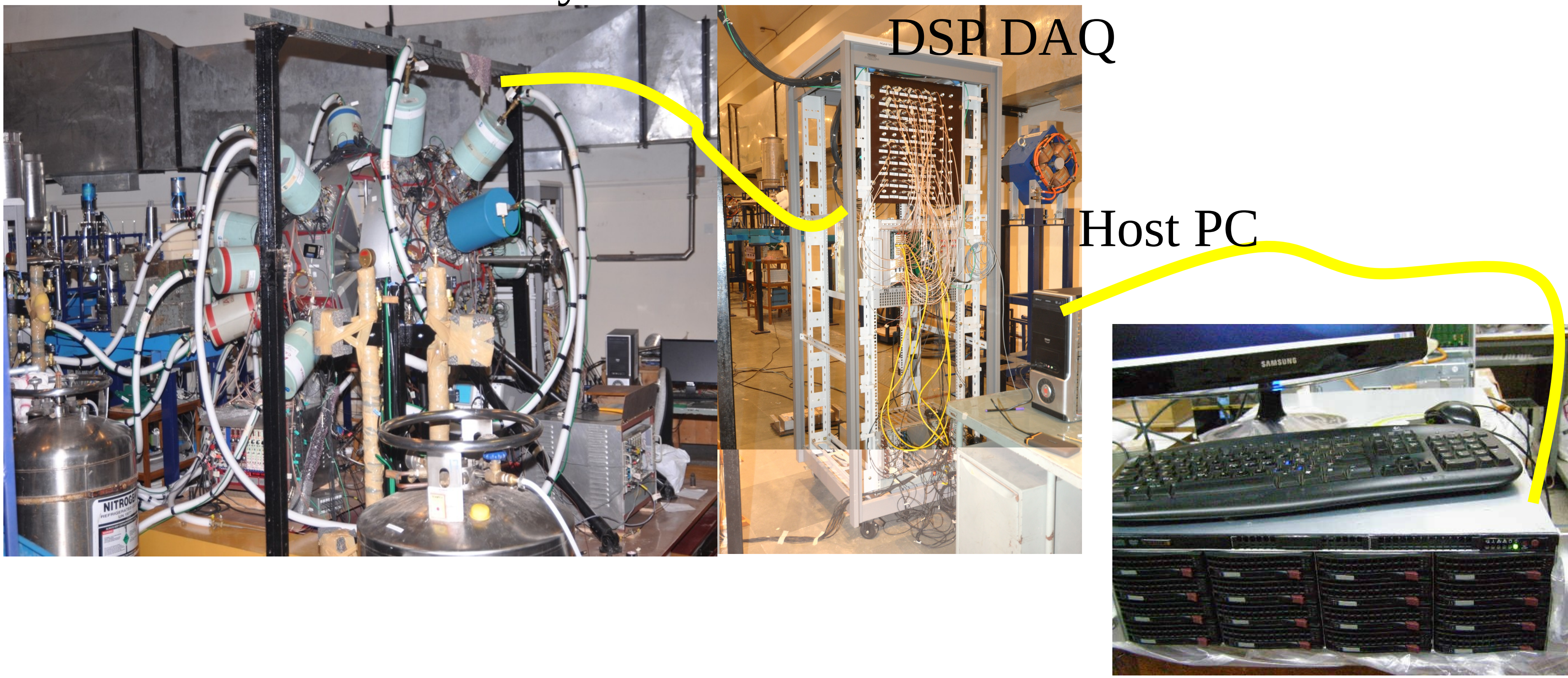
DSP based DAQ for 24 CS-Clovers and Ancillary detectors at TIFR

- 100 MHz & 12-bit ADC's
- Data rate: 80 MB/sec
- Handle high count rate with good E,T.
- Particle ID in CsI detectors using digital pulse shaping
- Trigger less system
- For in-beam Clover + CsI expts and off-line expts with planar detectors.

Signal processing with DDAQ

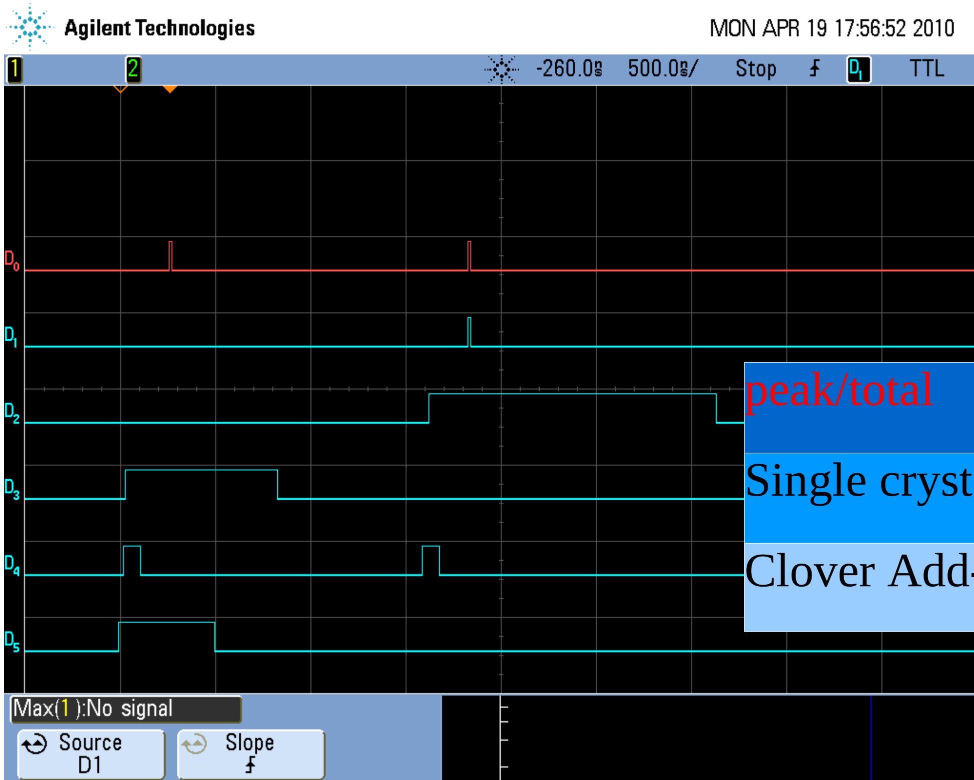


DDAQ with INGA

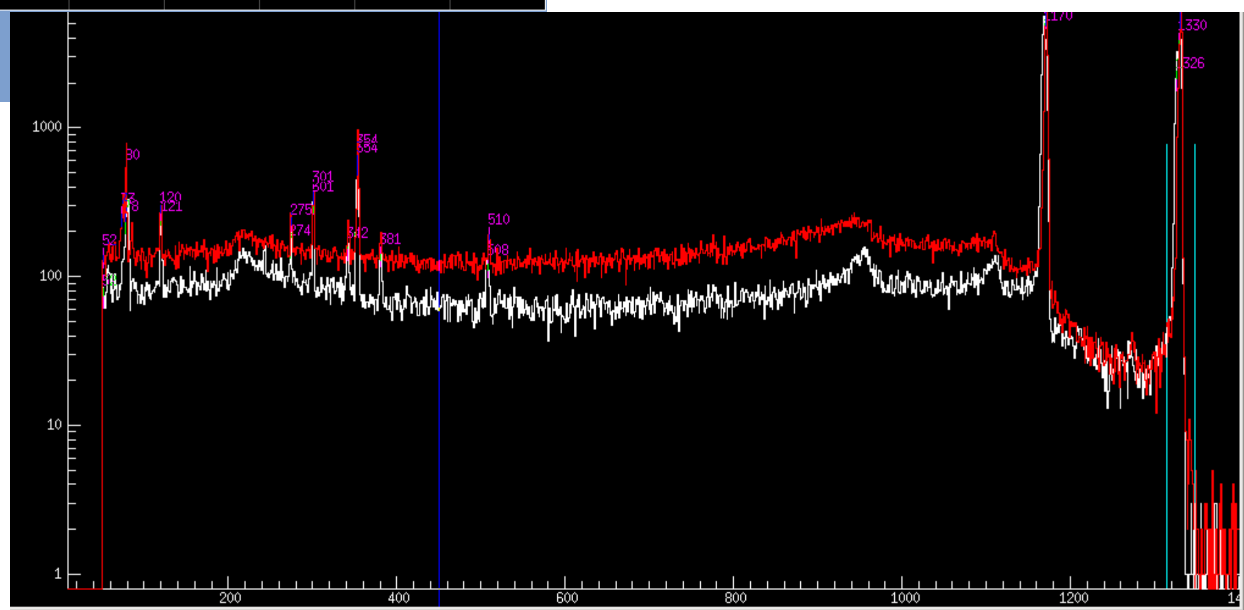


Detectors -> DSP cards -> PCI Bridge -> PC-> Gigabit -> PC

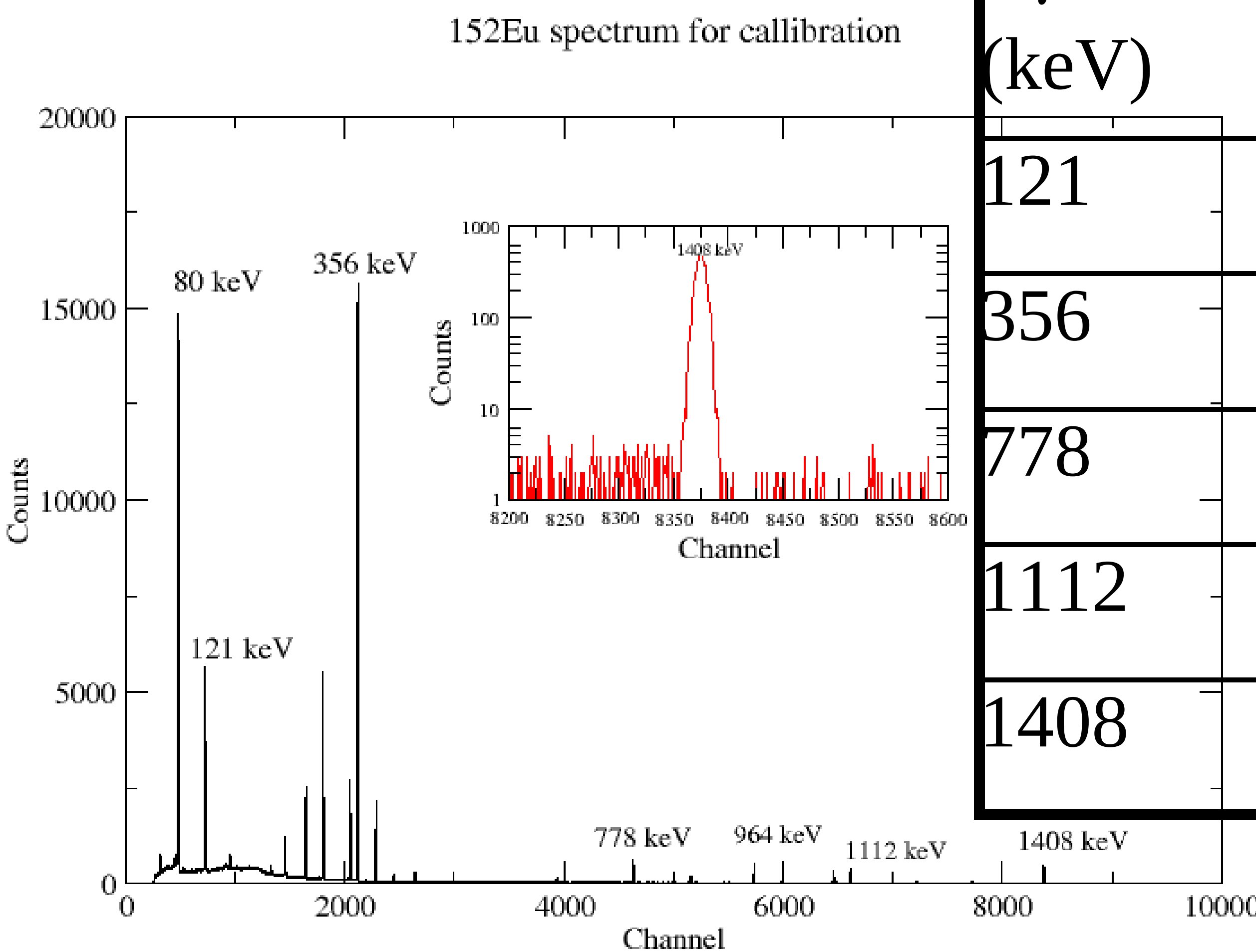
Compton suppression in Clover



peak/total	BGO off	BGO on
Single crystal of Clover	~ 10%	~ 15 %
Clover Add-back	~ 22%	~ 40%



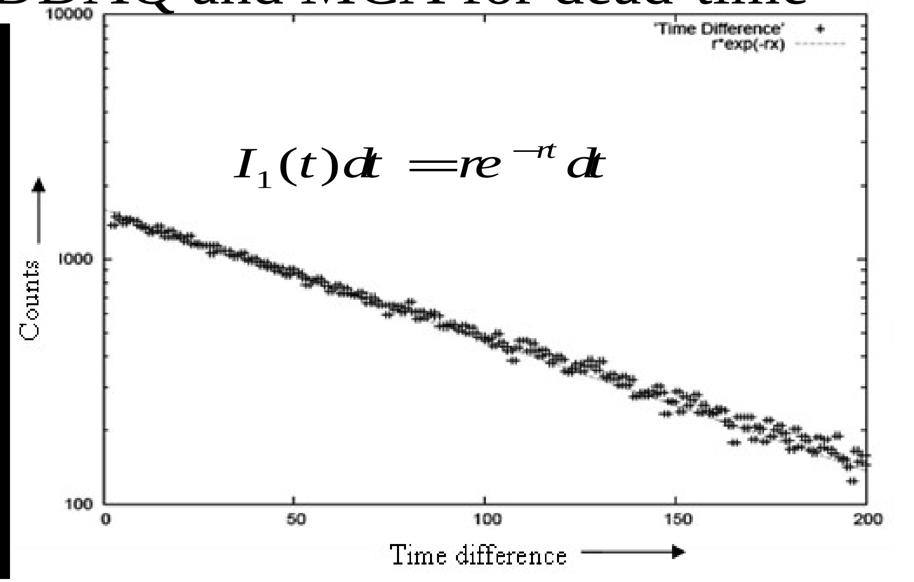
Energy: comparison with Analog system



Eγ (keV)	FWHM (keV)	FWHM (keV)
121	1.15	1.82
356	1.30	1.97
778	1.61	2.16
1112	1.82	2.33
1408	1.98	2.56

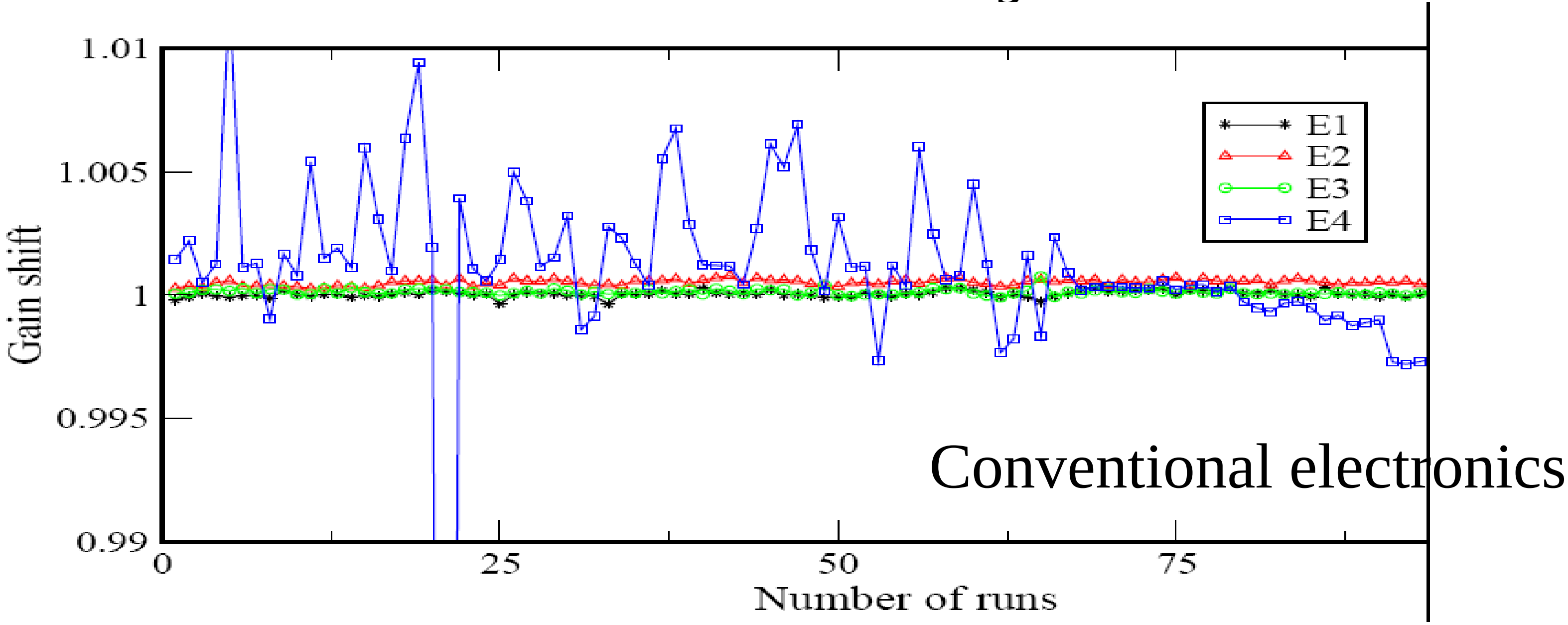
Comparison of count rates in DDAQ and MCA for dead-time

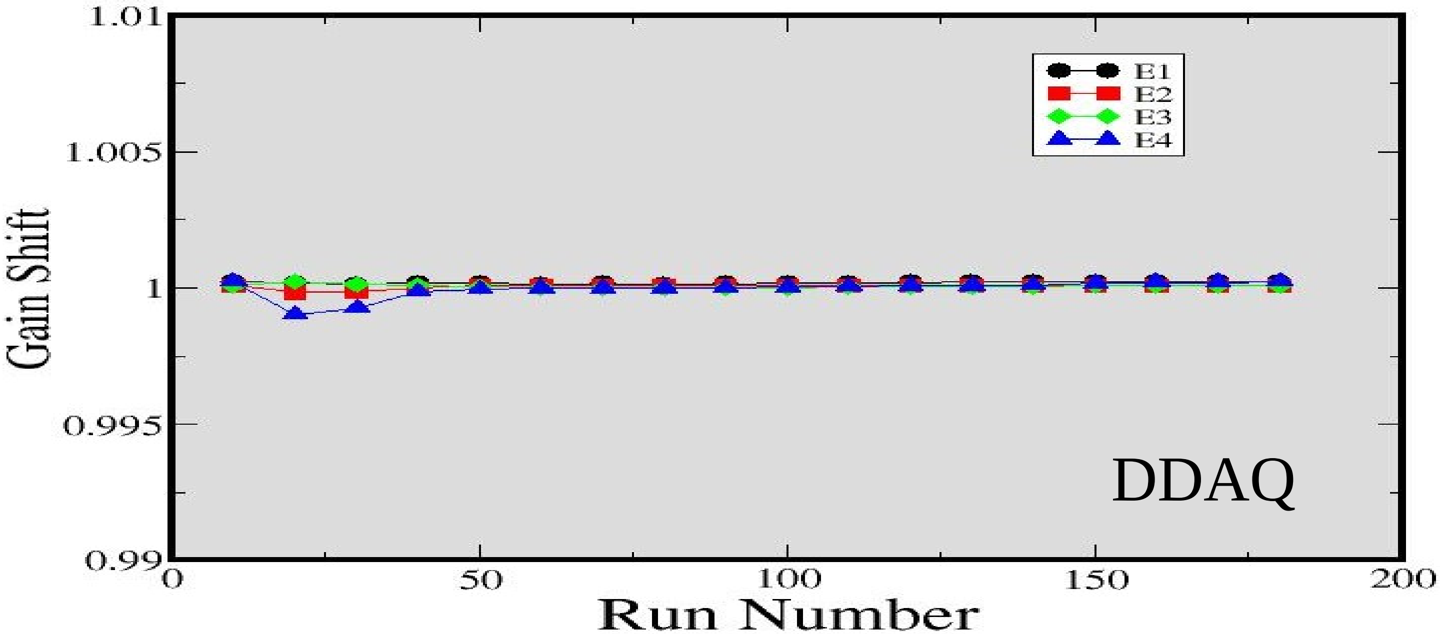
Eg (keV)	Area (DDAQ)	Area (MCA)
778	5604	5226
1112	4489	4583
1408	5849	5710



- ^{152}Eu-^{133}Ba source data taken for one hour with 46 channels are connected to DDAQ vs. 1channel connected to MCA.
- Analysis of time difference between consecutive events are shown in figure on right.

Better stability





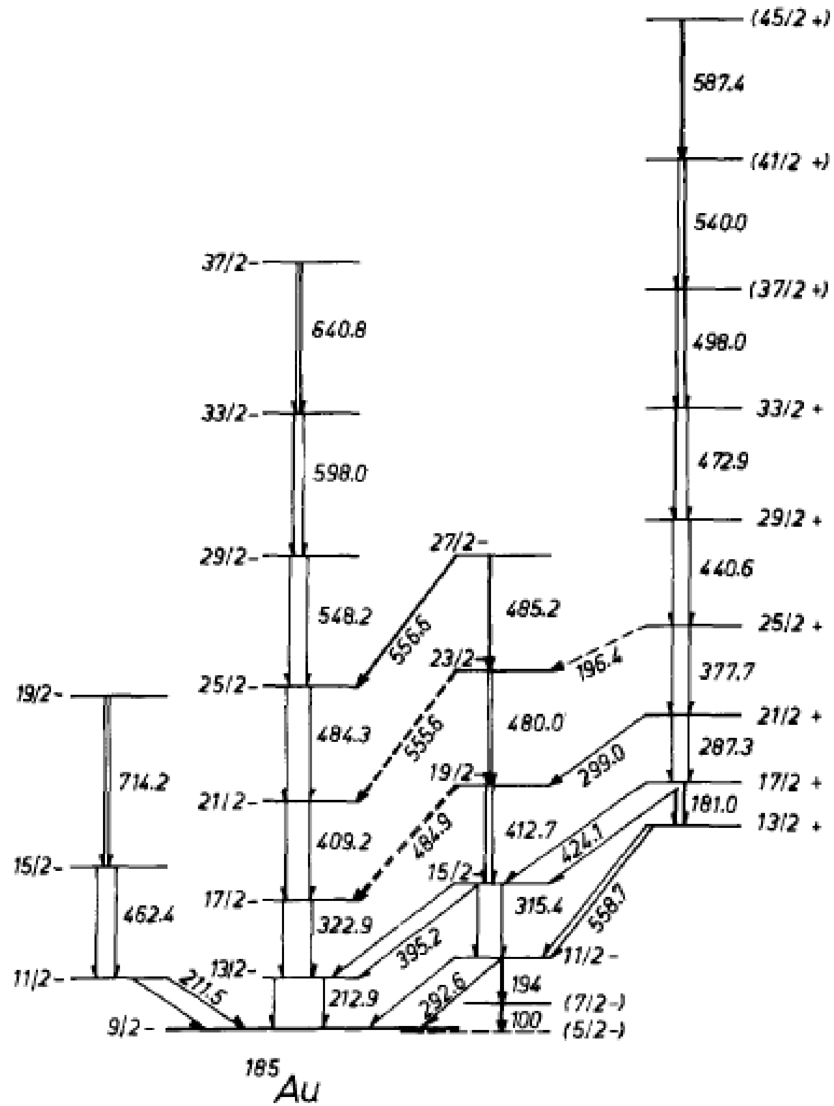
Generating coincidence events from time stamped data

7 -10 kHz per crystal
15 – 20 kHz 2-fold clover
3.5 – 5 kHz 3-fold clover
with 14 clovers

>10 kHz 3-fold with 24 clovers

TIFI

^{185}Au



Data Analysis

Each event is time stamped with the internal clock.

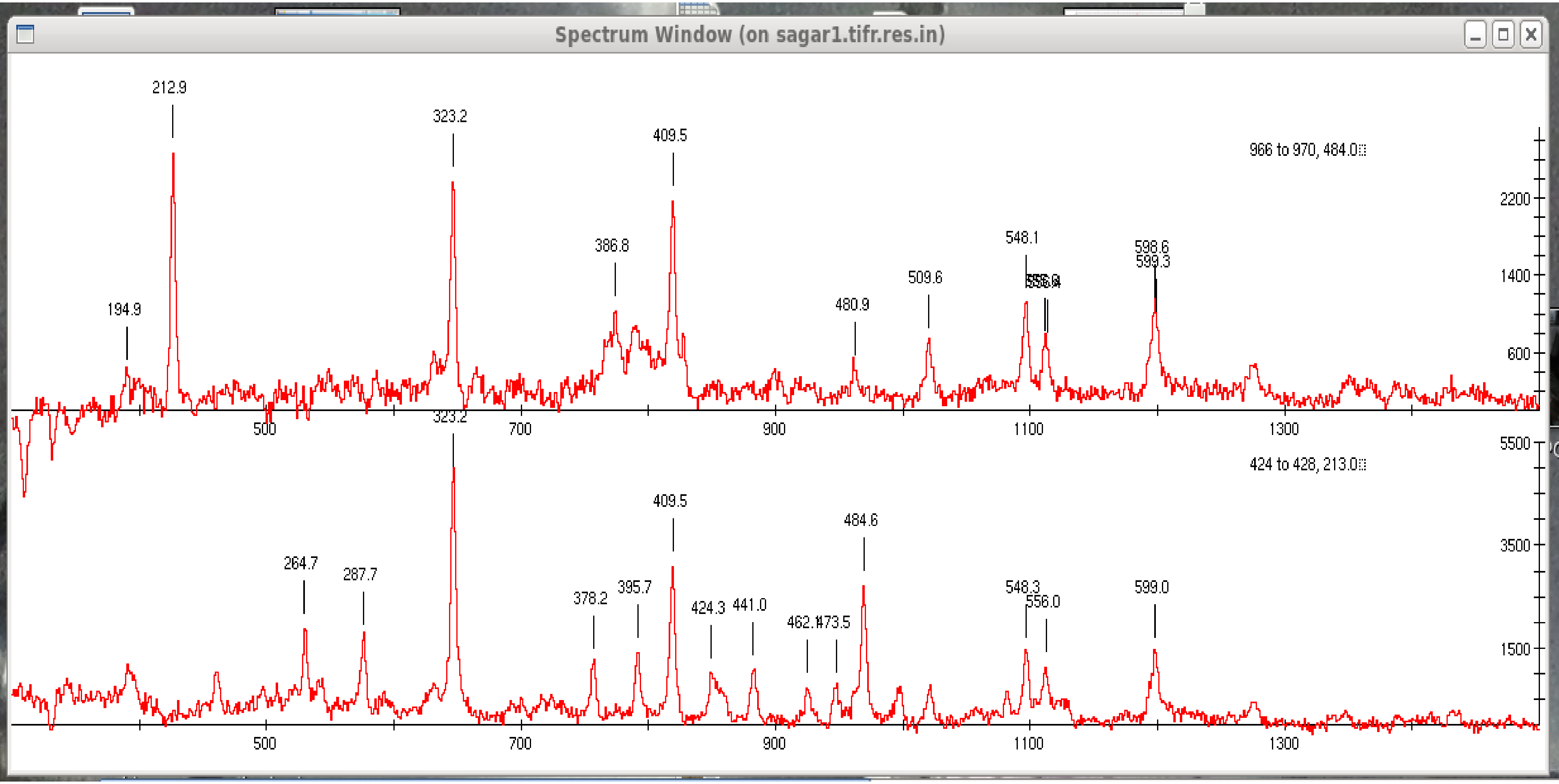
Coincidence events are generated from the time stamped list mode file.

Each experimental run generates 4 *.bin files.

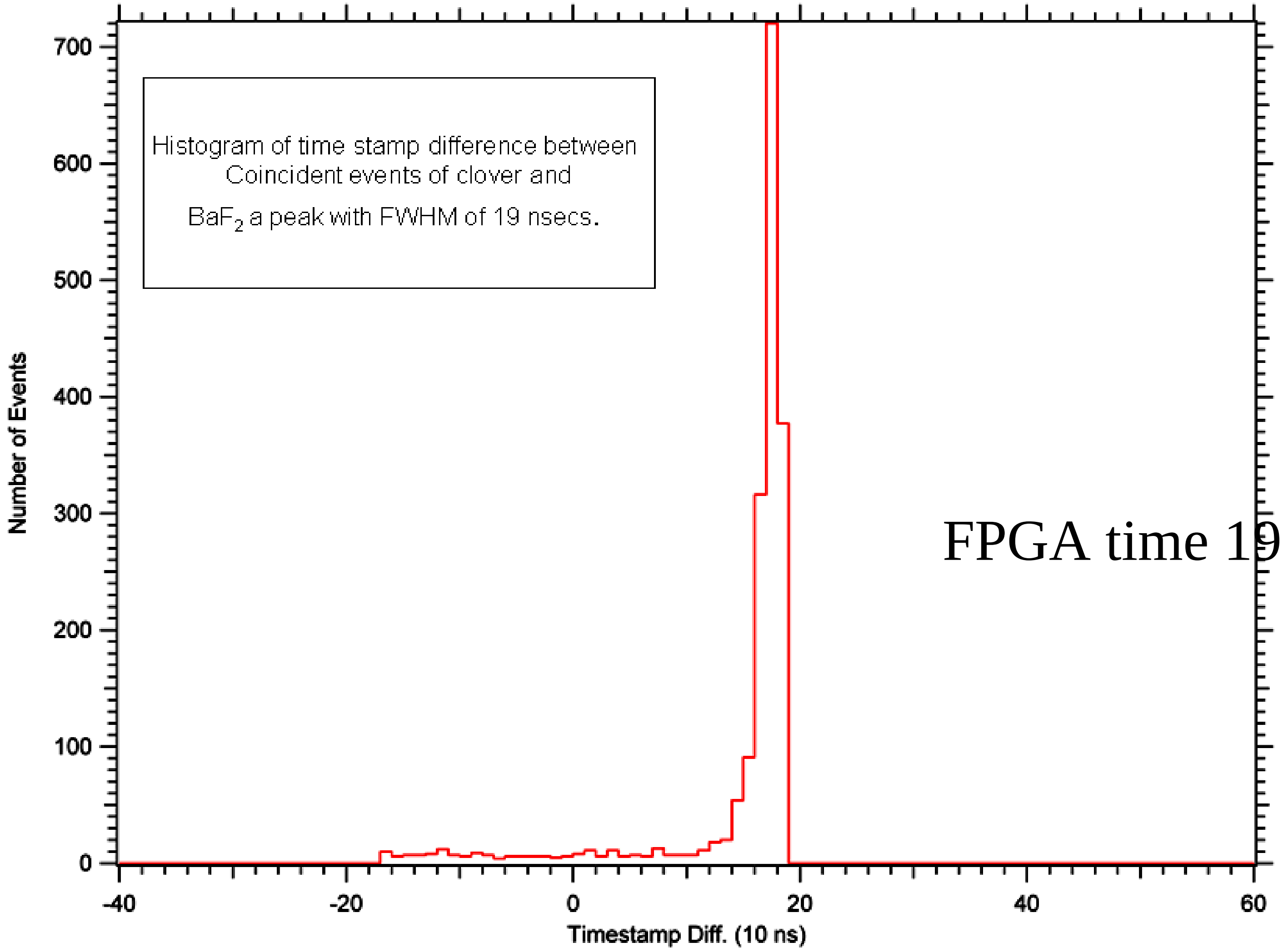
The program "timemerge4" combines the 4 files to generate one list mode file. This arranges the events as per increasing time.

The program "marcos" does the sorting of the data to generate (after gain matching) 1d-histogram, 2d-histogram (gamma-gamma), DCO/DSAM matrix, Polarization, cube and time spectra.

Coincident spectra for level scheme of ^{185}Au with New DDAQ

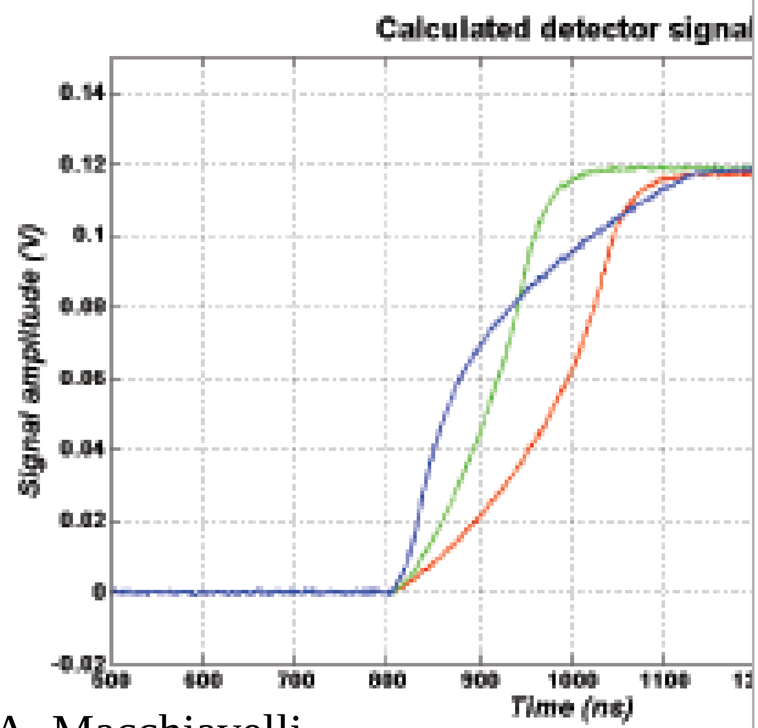


Good energy resolution. What about time measurement?

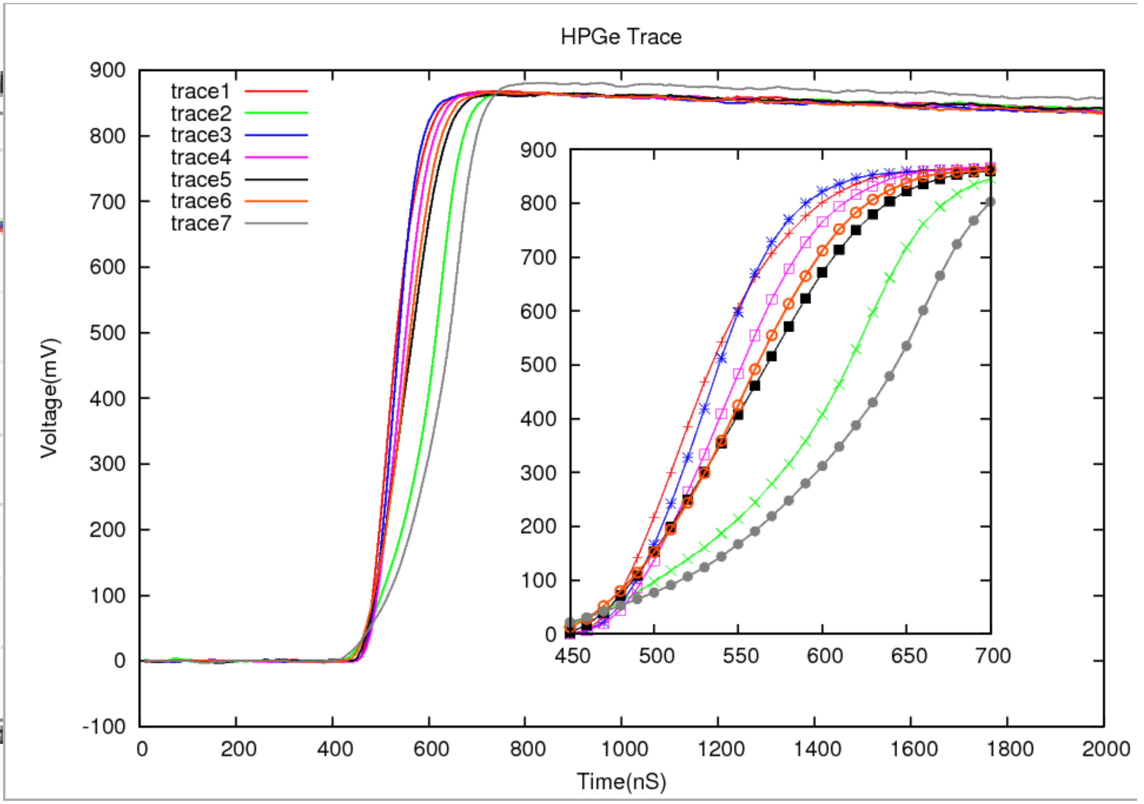


FPGA time 19 nsec!!!

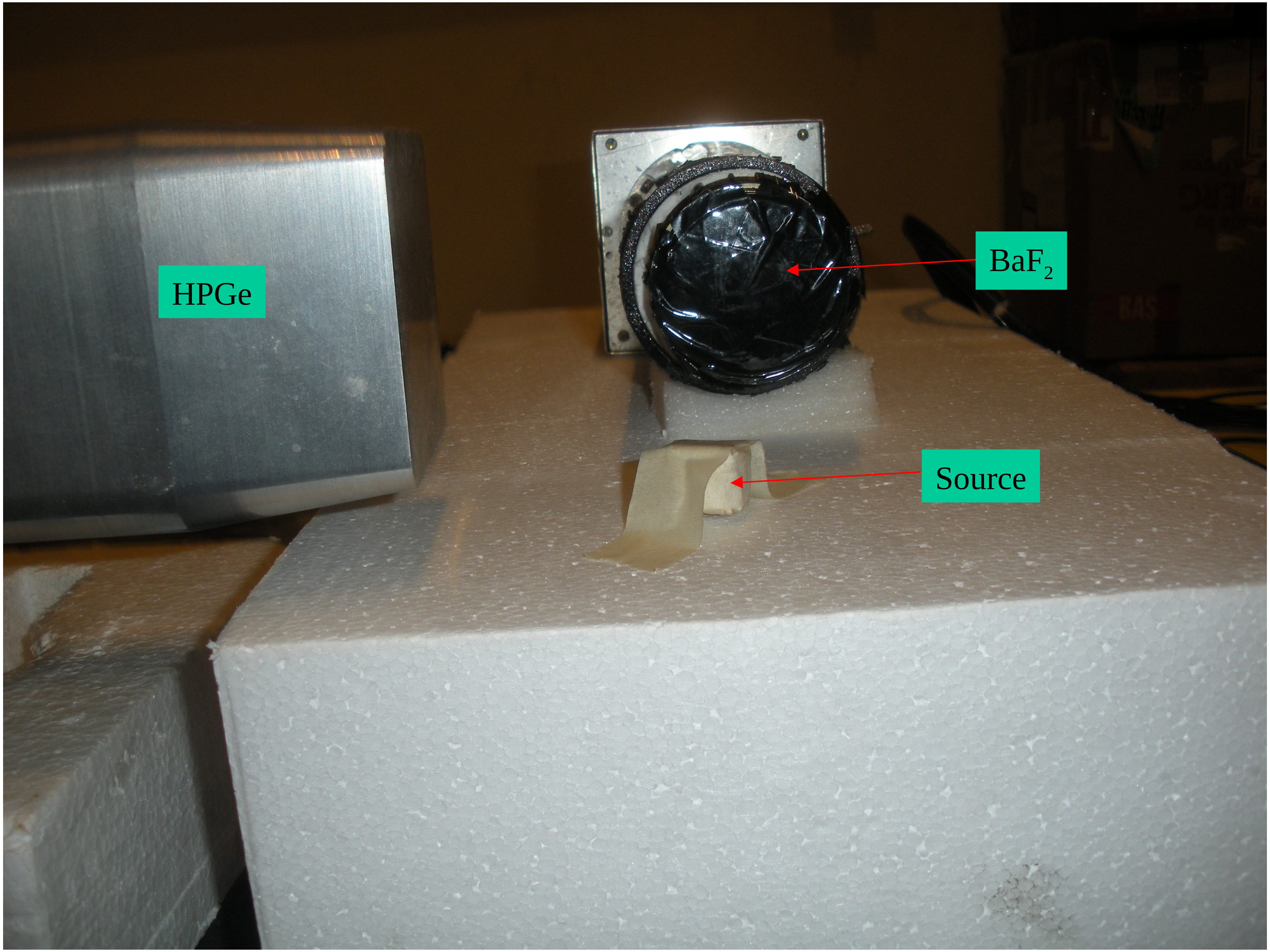
HPGe traces



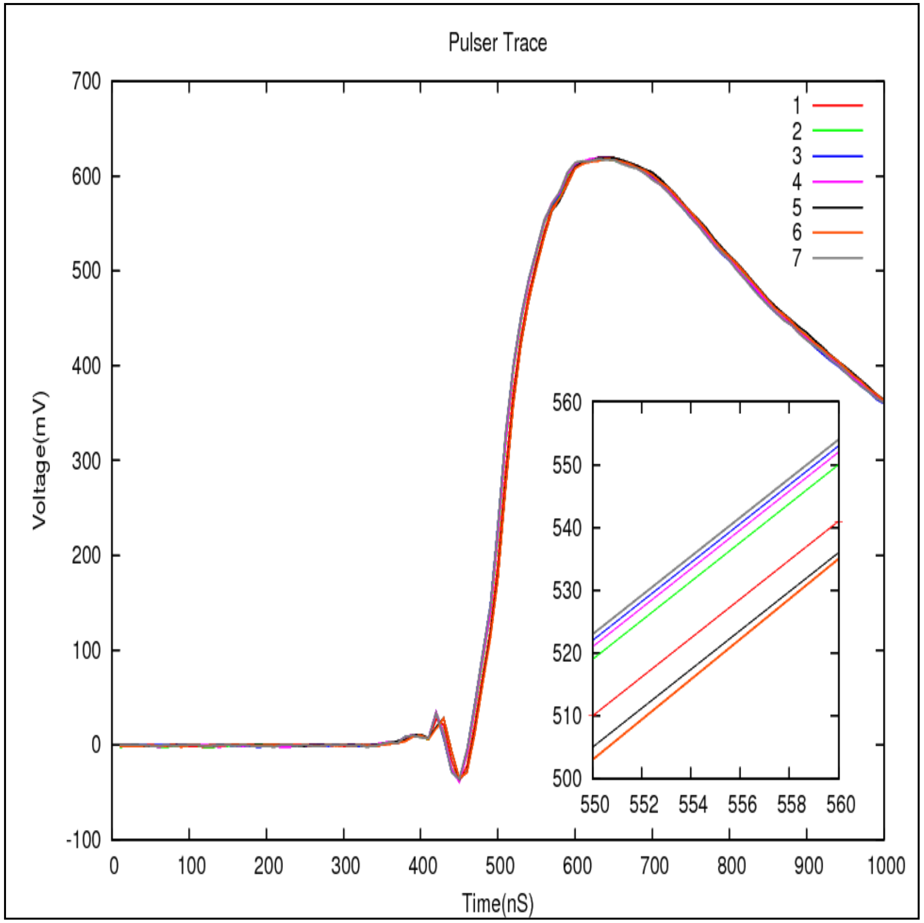
A. Macchiavelli



Measured pulse traces from clover


HPGe
BaF2
Source

Pulsar Trace

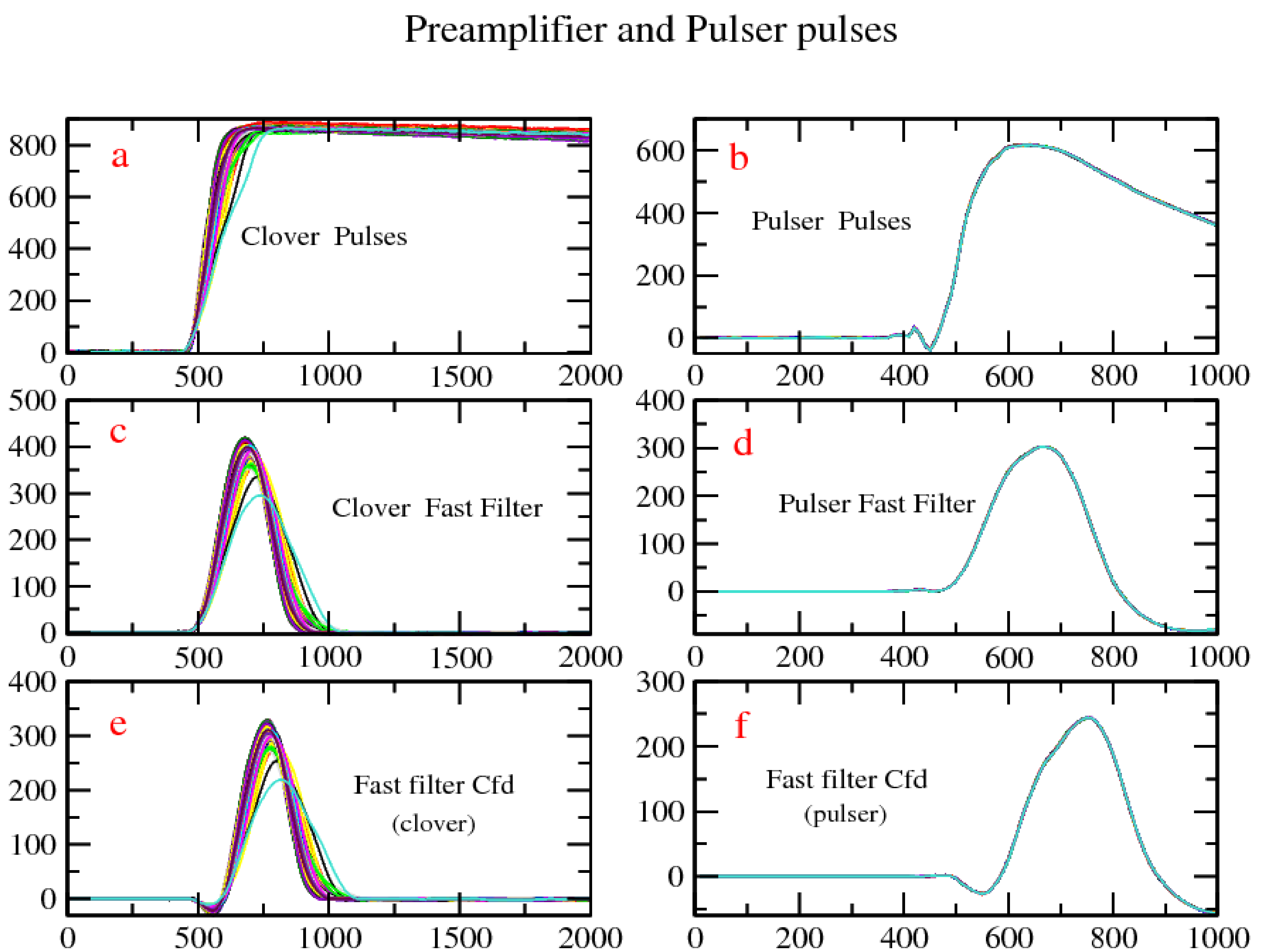


- BNC Pulsar generates preamplifier like pulses of identical shape.
- Due to quick timing response in BaF2 detector, the trigger pulses generated in BNC pulsar has a very narrow distribution compared to HPGe as shown in the fig inset.

Algorithm used for getting first filter pulse and CFD pulses

Fast Filter	FF[i]= $\sum_{j=i-(FL-1)}^{i} Trace[j] - \sum_{j=i-(2*FL+FG-1)}^{i-(FL+FG)} Trace[j]$
CFD	$CFD[i+D] = FF[i+D] - FF[i] \times f$

- The digitized waveform stream can be represented by a data series Trace[i],i=0,1,2,....
- In fast filter algorithm FL is called fast length and FG is called the fast gap of the digital trapezoidal filter.
- In CFD algorithm D is called CFD delay length and f is a fraction



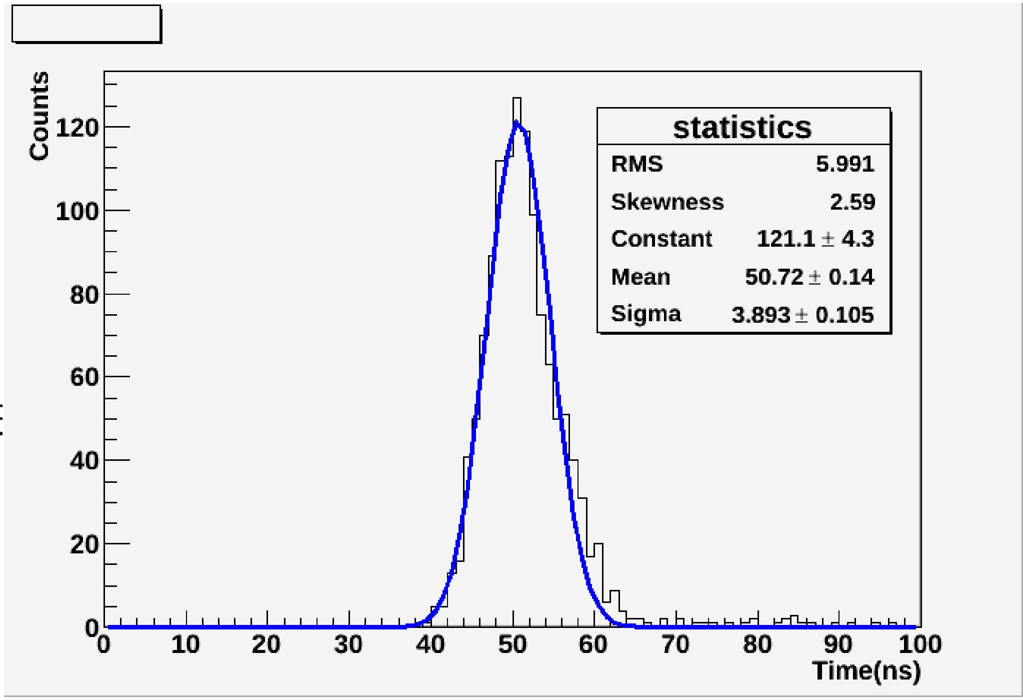
Preamplifier and Pulser pulses
a
Clover Pulses
0
200
400
600
800
0
500
1000
1500
2000
b
Pulser Pulses
0
200
400
600
0
200
400
600
800
1000
c
Clover Fast Filter
0
100
200
300
400
500
d
Pulser Fast Filter
0
100
200
300
400
e
Fast filter Cfd
(clover)
f
Fast filter Cfd
(pulser)

Timing Resolution with ^{60}Co

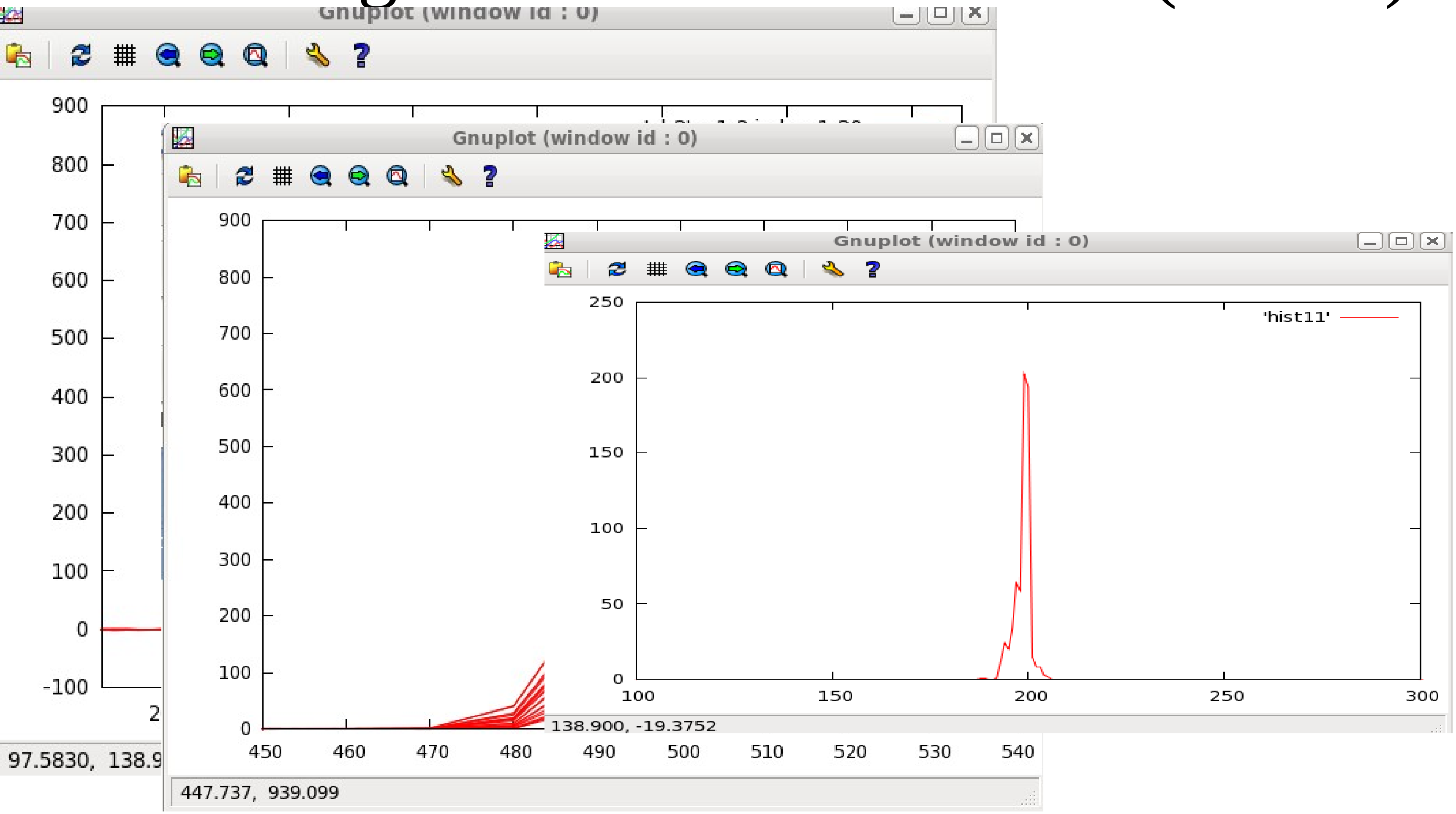
✓Digital CFD gives resolution ~ 9.1 nsec for individual clovers

➢Improving the timing by storing pulse shape (up to 1 msec)

➢Dynamic filter parameters for ke good energy resolution



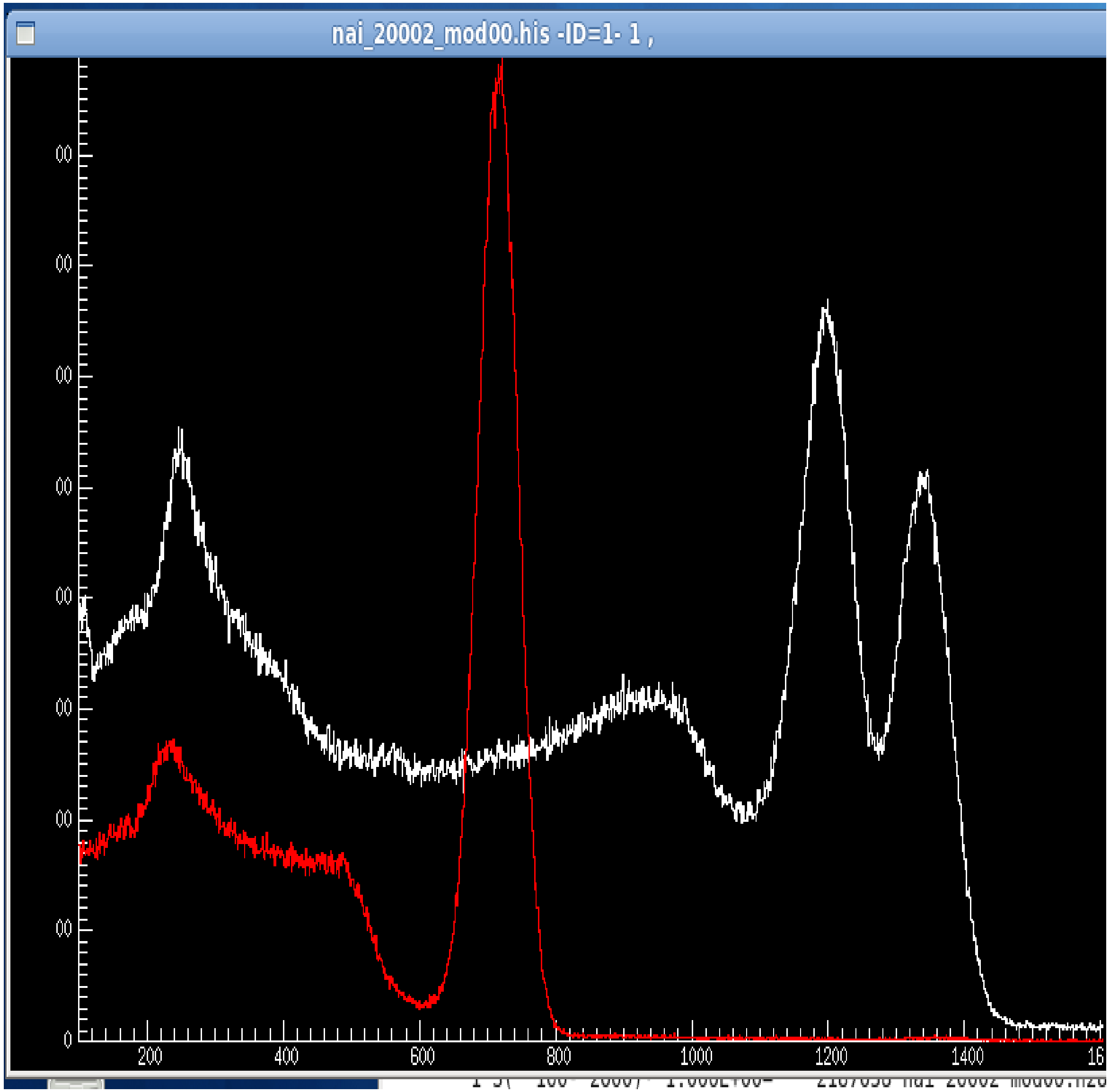
Timing with Fast Scintillators (LaBr3)



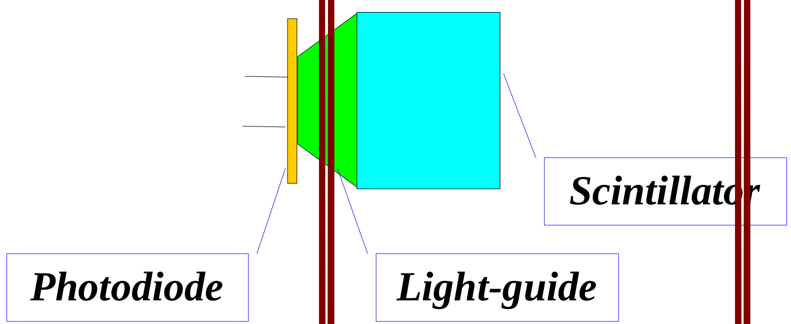
Fitting the pulses with function to get time resolution of 160 – 250 ps even at 100 MHz sampling

Preliminary result

Energy spectrum of NaI(Tl) multiplicity filter

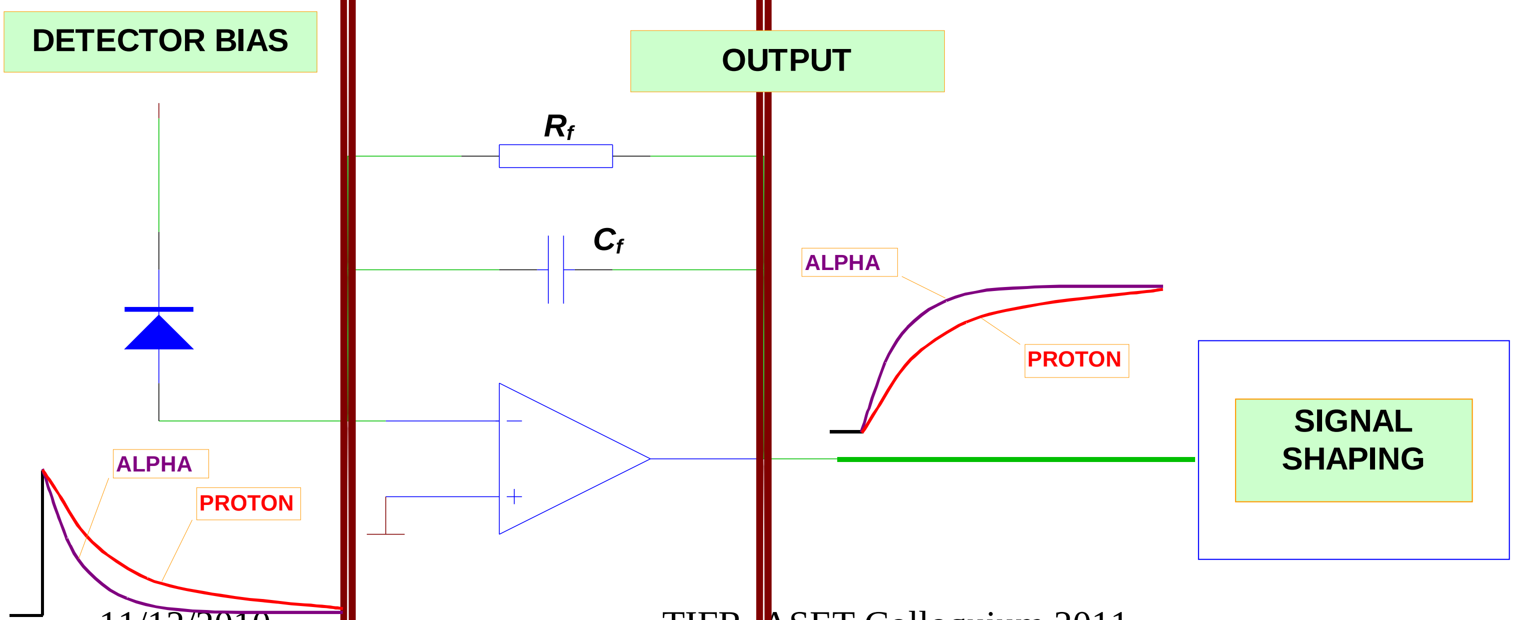


Scintillation detector for charged particle detection

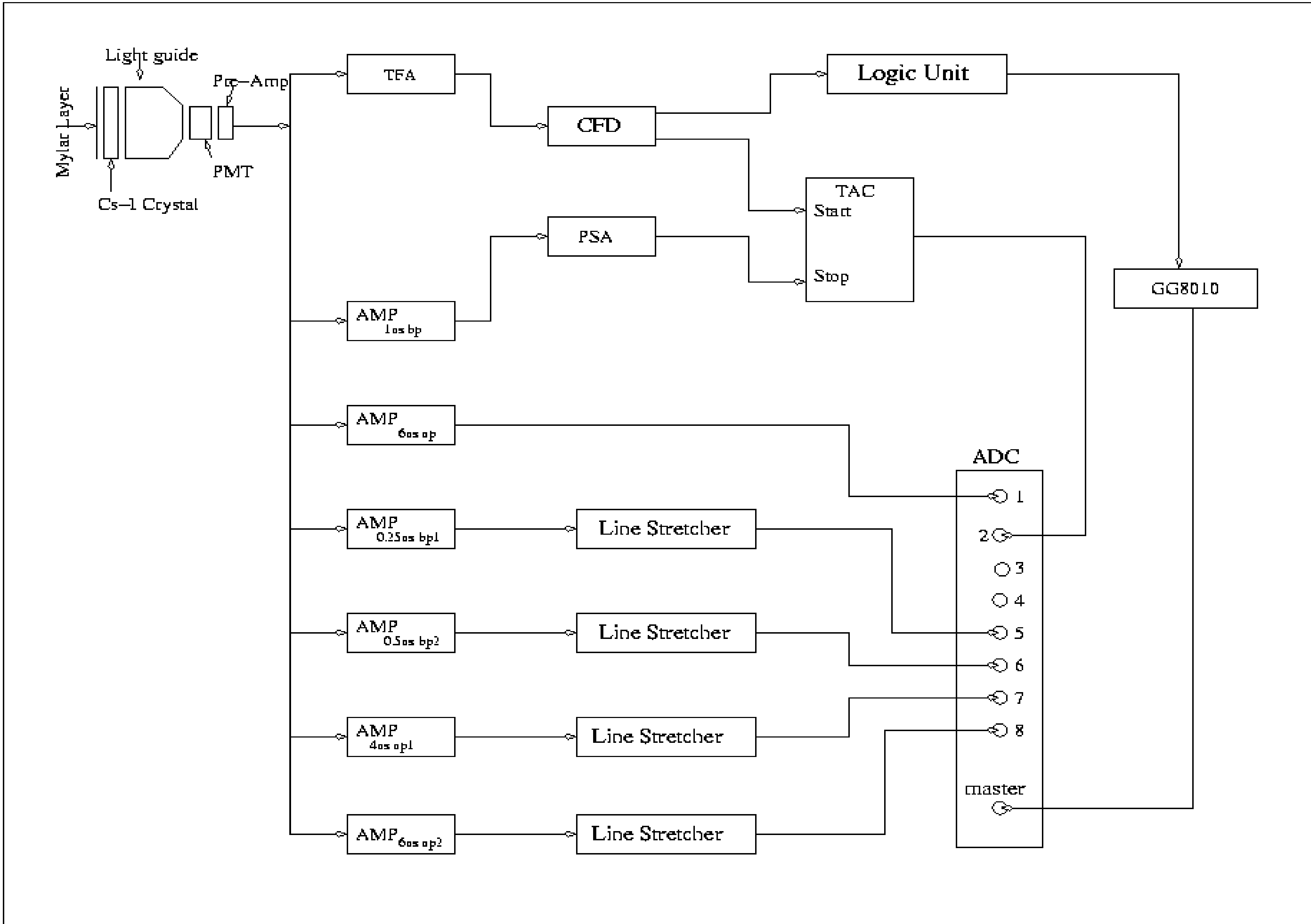


Decay time constant: *depends on the particle type*

alpha:	~720 ns
proton:	~1150 ns
electron:	~1540 ns

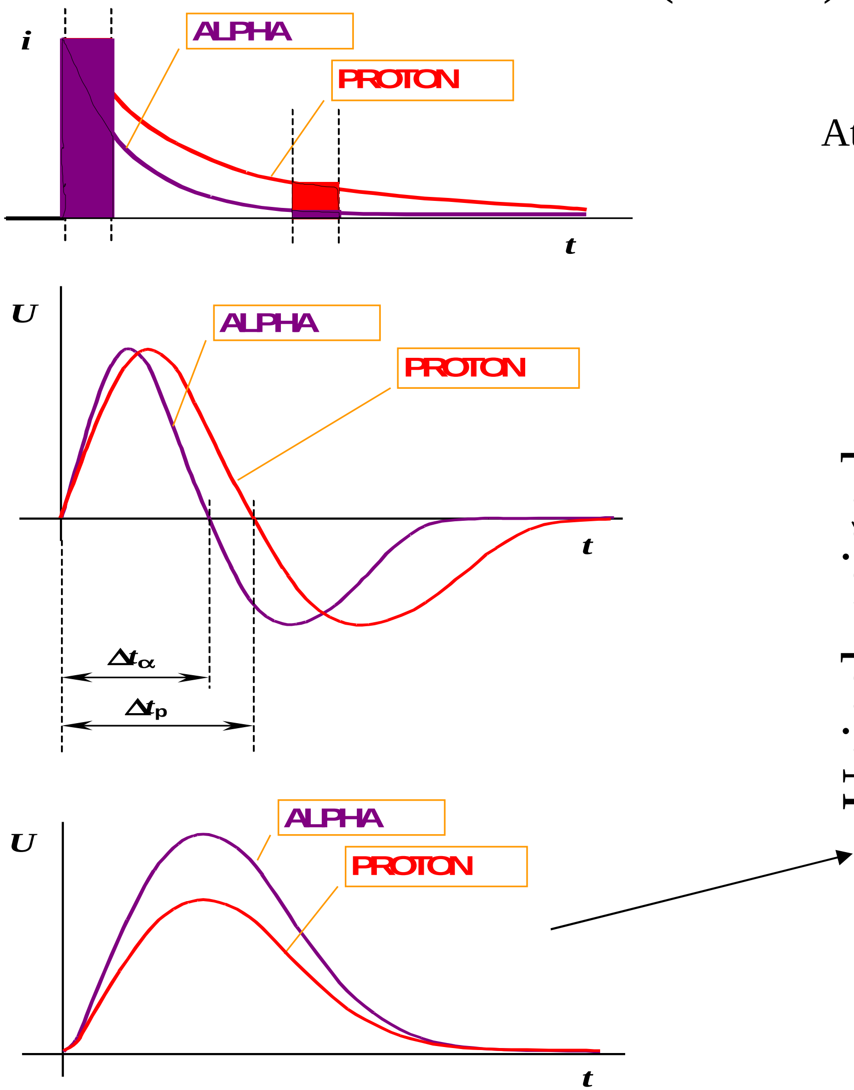


CIRCUIT DIAGRAM

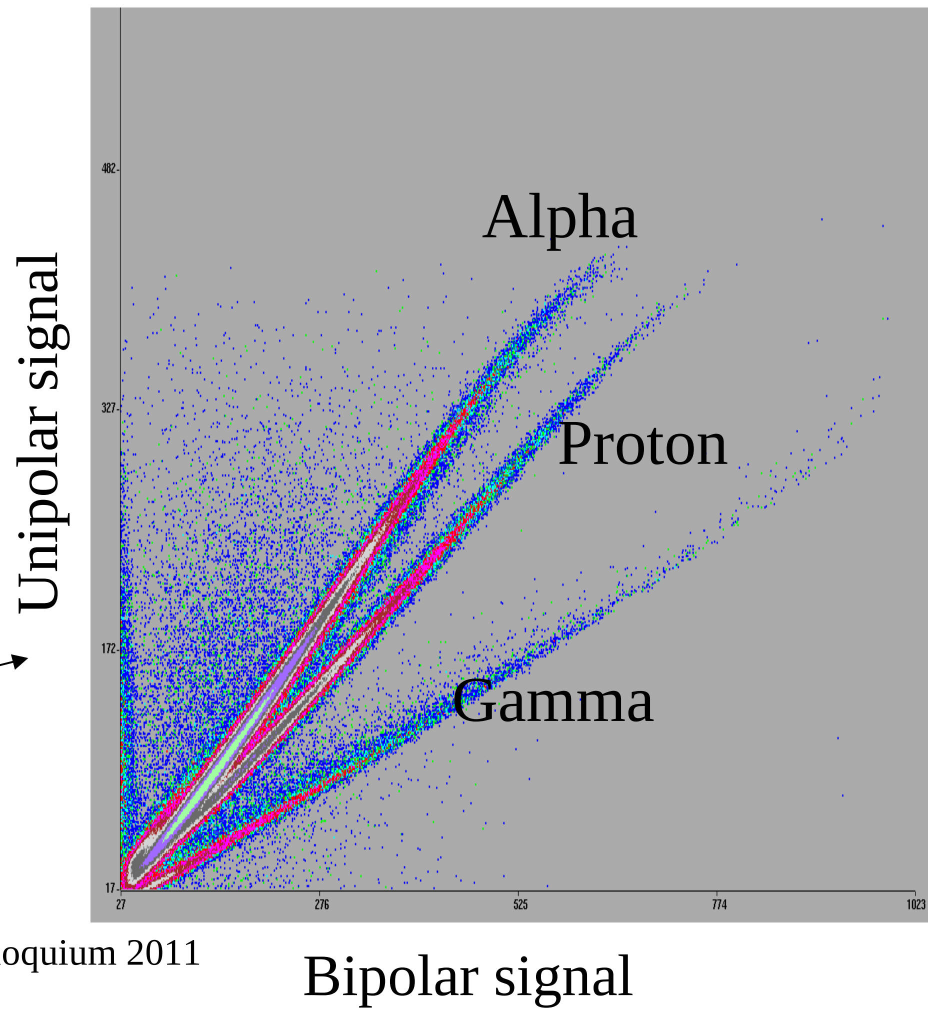


Unipolar signal Vs Bipolar signal in analog

^{19}F + Ni(natural) @ 75 MeV

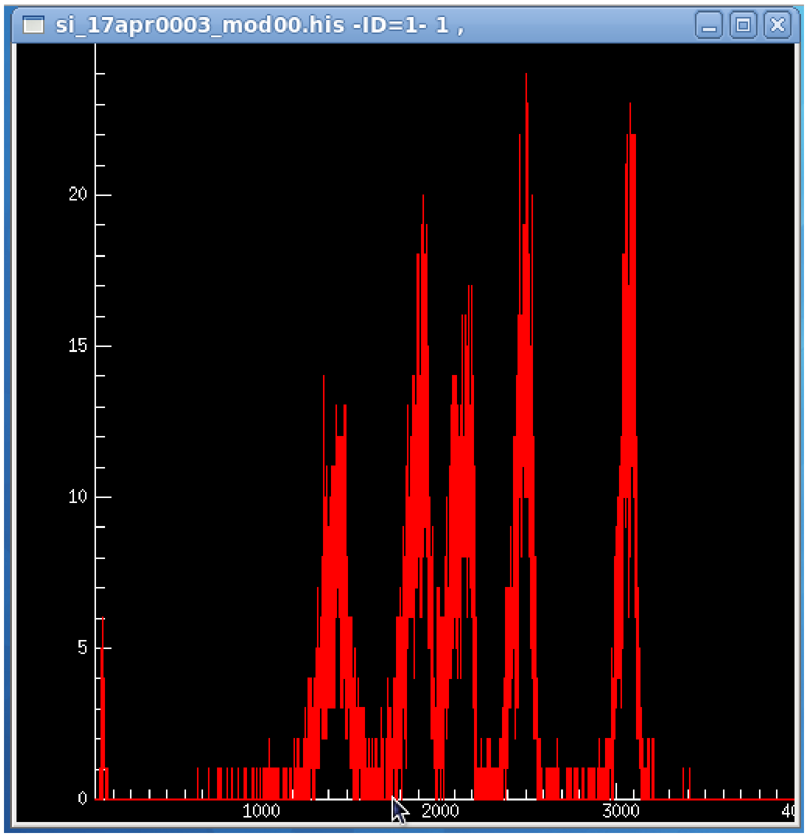


At backward angle 110° where Elastic are not observed

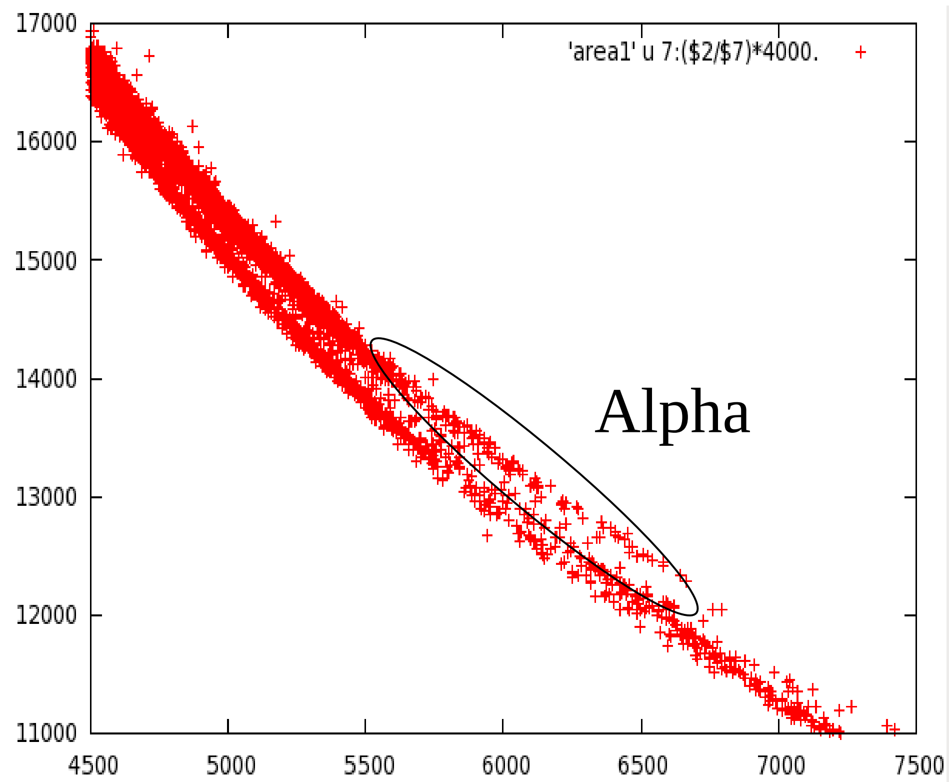


DSP test results with charged particle detectors

Alpha test with Si

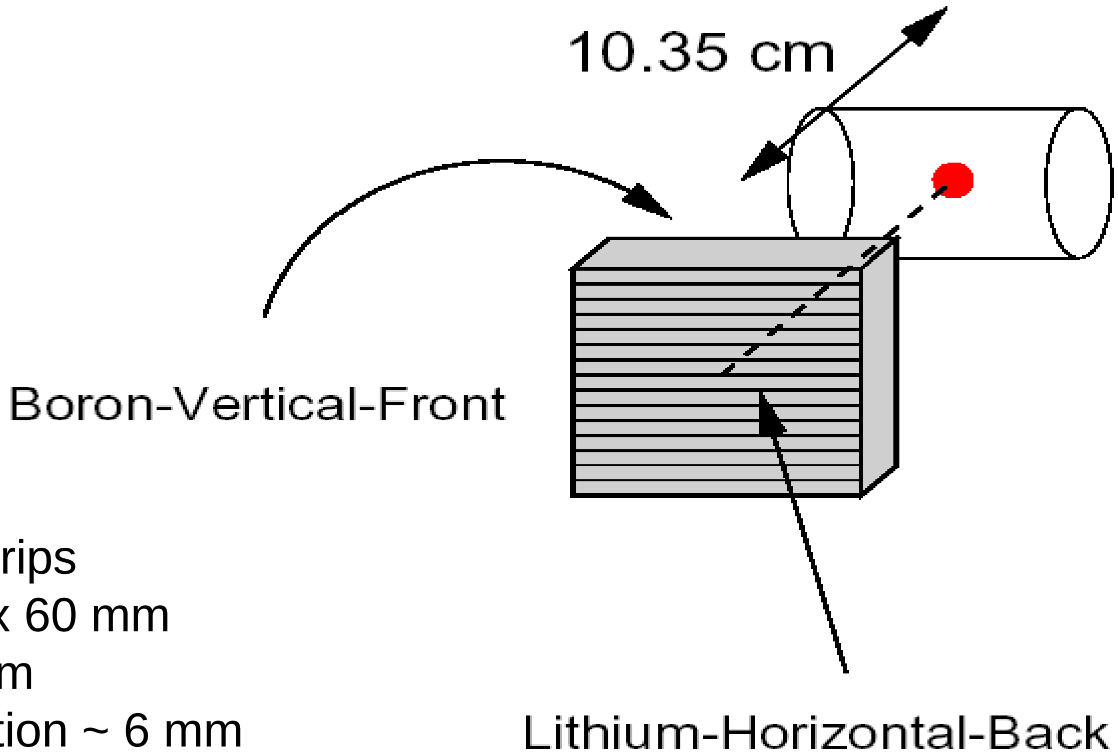


Preliminary result from beam test of CsI(Tl)



DSP: Energy threshold will reduce for PID

Planar Ge detector

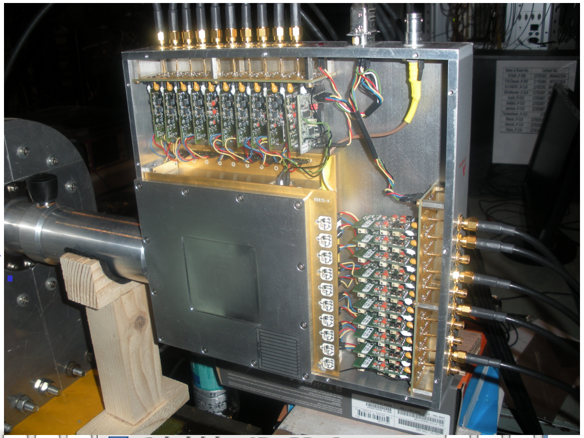


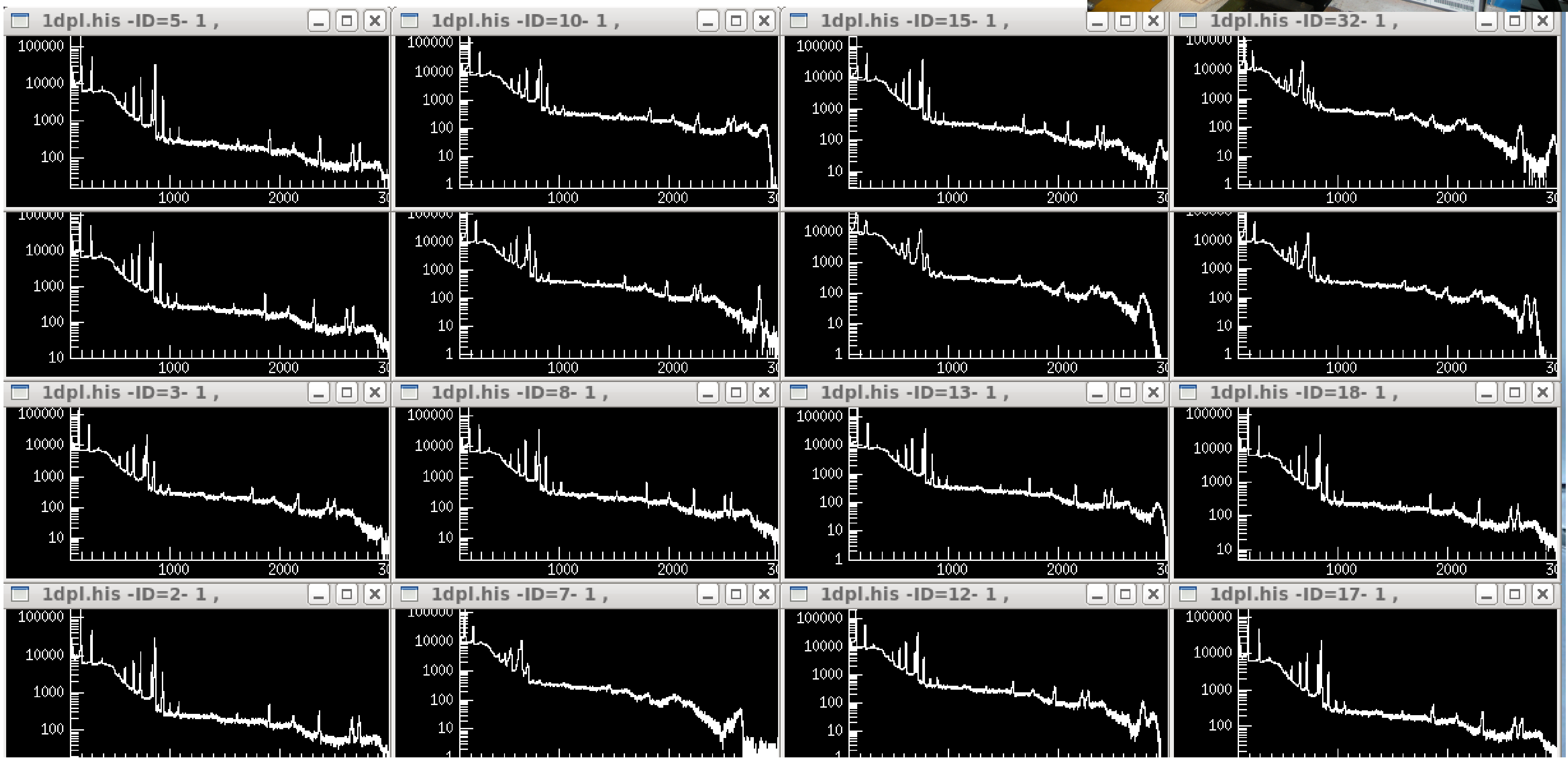
10 X and 10Y strips
One strip 6mm x 60 mm
Thickness 20 mm
Position Resolution ~ 6 mm

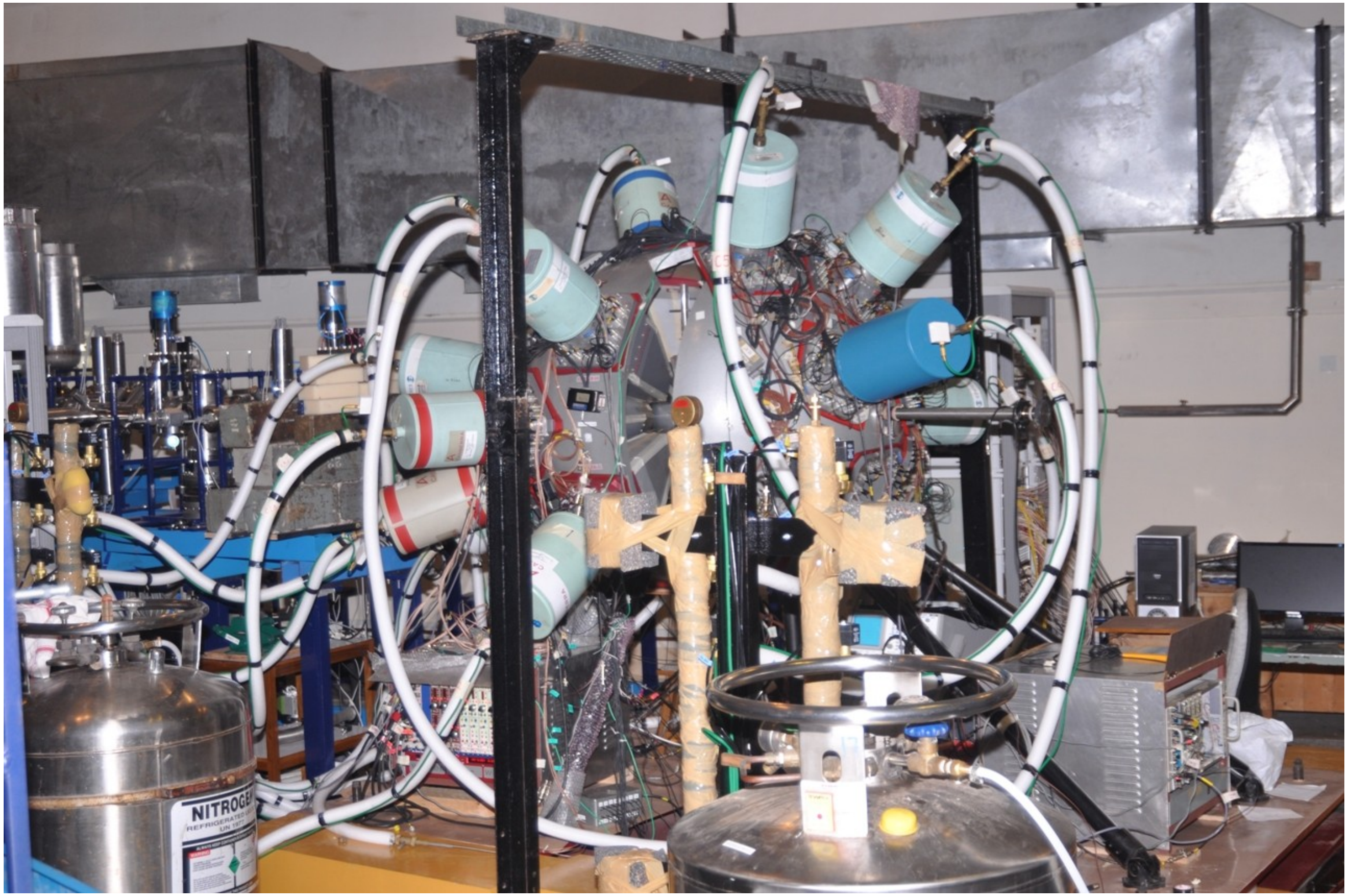
Position resolution can improve to 1 mm by gamma tracking by digital signal processing

Spectra from 10X-10Y detector

- ✓ Energy Characterization is completed.
- ➢ Imaging studies is planned using DSP.
- ➢ Study of heavy nuclei through decay spectroscopy.





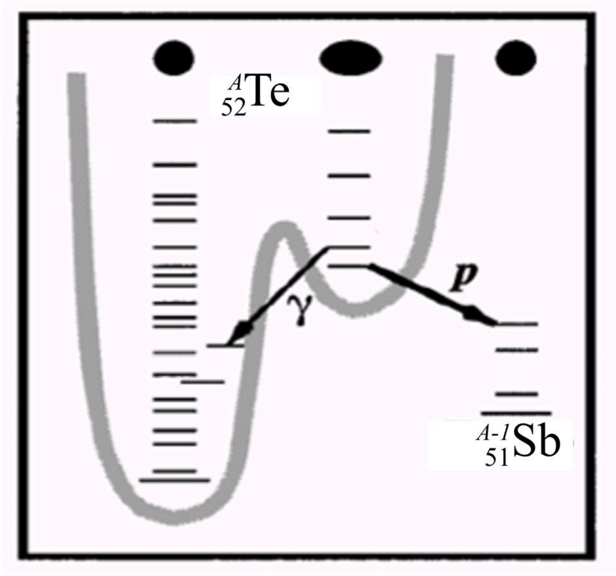


36 experiments are proposed for the current campaign by TIFR, IUAC, BARC, IUC-DAE-Kolkata, SINP, VECC, IITs, Univ. collaboration

Physics with the array

- Exotic nuclear shapes
  - **M1 bands, Anti-magnetic bands**
  - **Chiral bands**
  - **Tetrahedral, Oblate bands**
- Symmetries in medium mass nuclei near N~Z
- Spectroscopy of the heaviest nuclei
- Experiments with radioactive targets (e.g., ^{3}H and many others)
- Neutron-rich nuclei
  - **Towards neutron shell closure**
- *‘Horizontal growth’ of level scheme*

Some of the key future experiments with particle gamma coincidence



- Identify candidates for prompt proton emission outside of Z~28, N~28
  - Possibly neutron-deficient Te isotopes?
- Study astrophysically important nuclei around $N=Z$ line
- Heavy nuclei spectroscopy with tagging on fast particle emission
- Investigation of proton rich nuclei in light mass region
- Investigation of lifetime of states in quasi-continuum

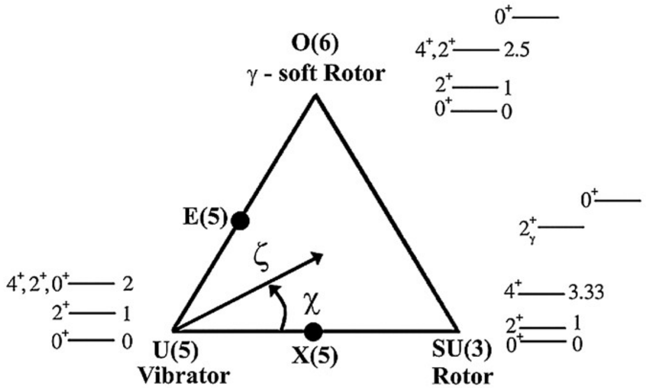
1

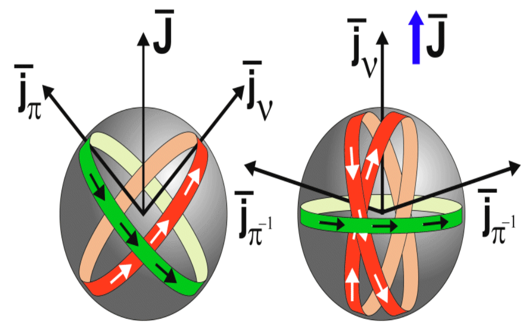
Summary

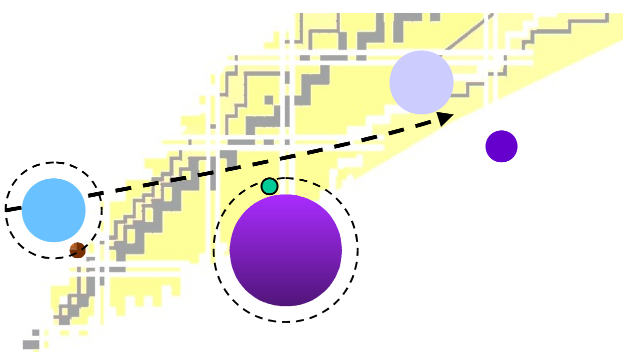
DSP is an efficient & vesatile option for gamma spectrocopy.

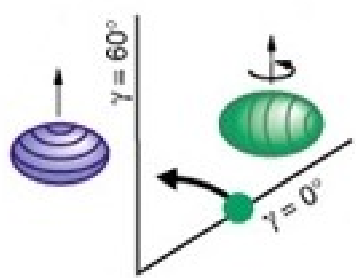
Nuclear Structure with varying J & T(N-Z) for probing

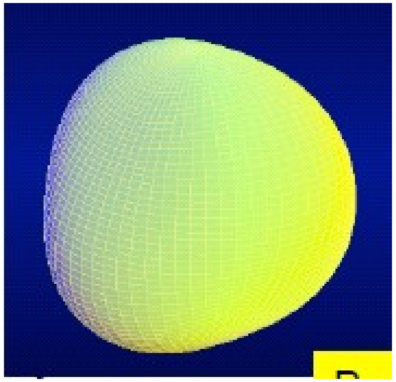
- Different phases, their coexistence & transitions
- Insight for shell structure and residual interactions
- Stable & RIB both are required for future experiment



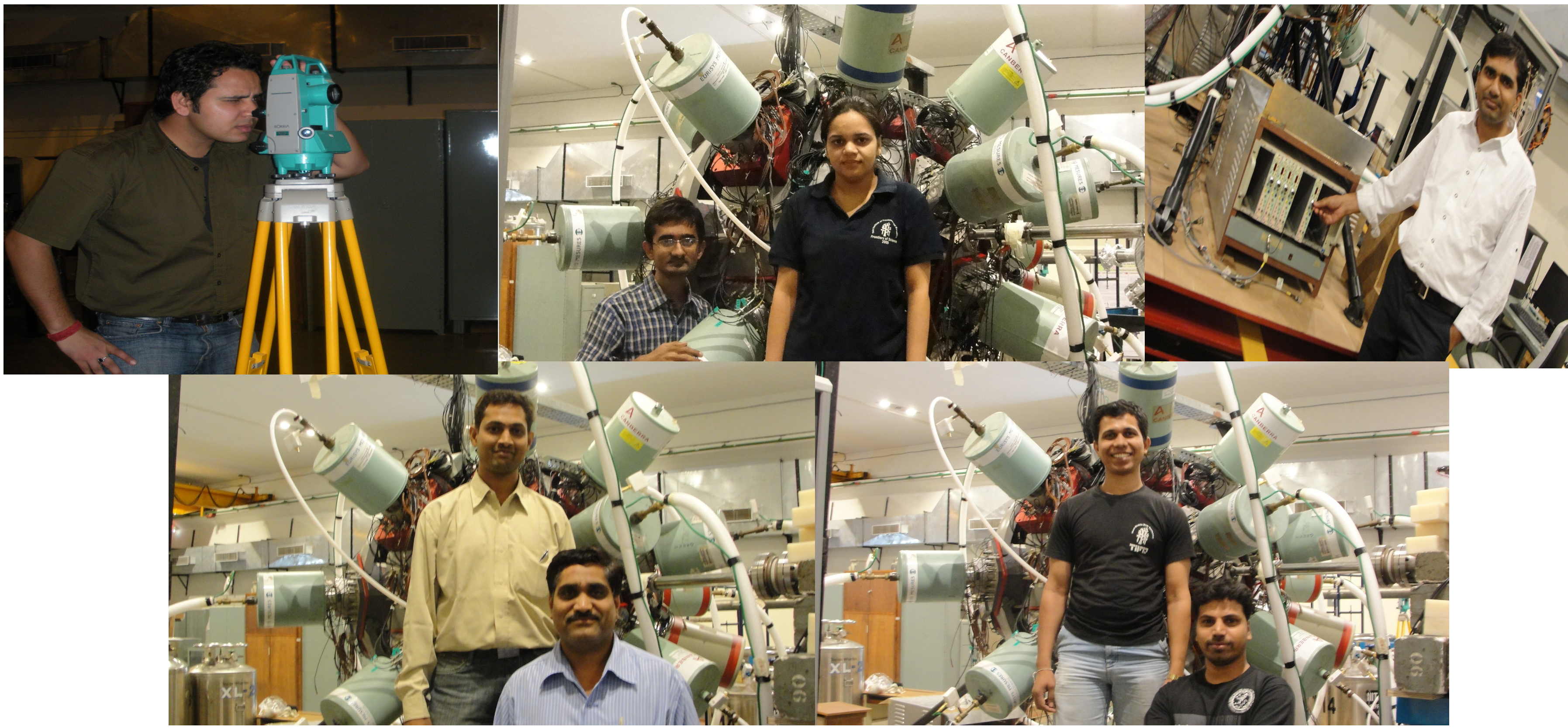








Collectivity!!!



And

INGA Collaboration

(TIFR-BARC-IUAC-IUC-SINP-VECC-Universities- IITs)

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