ACCELERATOR ACTIVITIES AT MUMBAI & DELHI

NUCLEAR PHYSICS RESEARCH

S.KAILAS (Bhabha Atomic Research Centre,Mumbai)
A.ROY(Inter University Accelerator Centre,Delhi)

MUMBAI

DELHI

Albert Einstein, Hideki Yukawa,   John Archibald Wheeler, H. J. Bhabha

Credit line: Princeton University,
Courtesy AIP Emilio Segre Visual Archives, Yukawa Collection

ACCELERATOR FACILITIES

DETECTORS & INSTRUMENTATION

NUCLEAR PHYSICS RESEARCH

GROWTH OF ACCELERATORS IN INDIA
For Nuclear Physics Research

LEHIPA at BARC
ECR + SC LINAC at Delhi,Mumbai
SCC at VECC
RIB at VECC
FRENA at SINP

FOTIA at BARC
SC LINAC at Delhi, Mumbai
14 MV Mumbai Pelletron
15 MV Delhi Pelletron
3 MV IOP Pelletron

K =130 VEC

2 MV VDG – IIT(K)
Cyclotron PU
Cyclotron SINP

5. 5 MV VDG - BARC
1 MV Cascade Gen - TIFR

BARC Accelerators

Ion

6 MV Folded Tandem Ion Accelerator (BARC)

- 14 MV Pelletron (BARC- TIFR)
- SC Linac booster at Mumbai (Pb)-(BARC-TIFR)
- 3 MV Tandem (NCCCM,BARC)

Electron

- 10 MeV, 10 kW Linac (EBC,BARC)
- 7 MeV Electron accelerator (BARC)
- 2 MeV, 20 kW ILU6 electron machine (BARC,BRIT)
- 500 keV electron accelerator(BARC,BRIT)

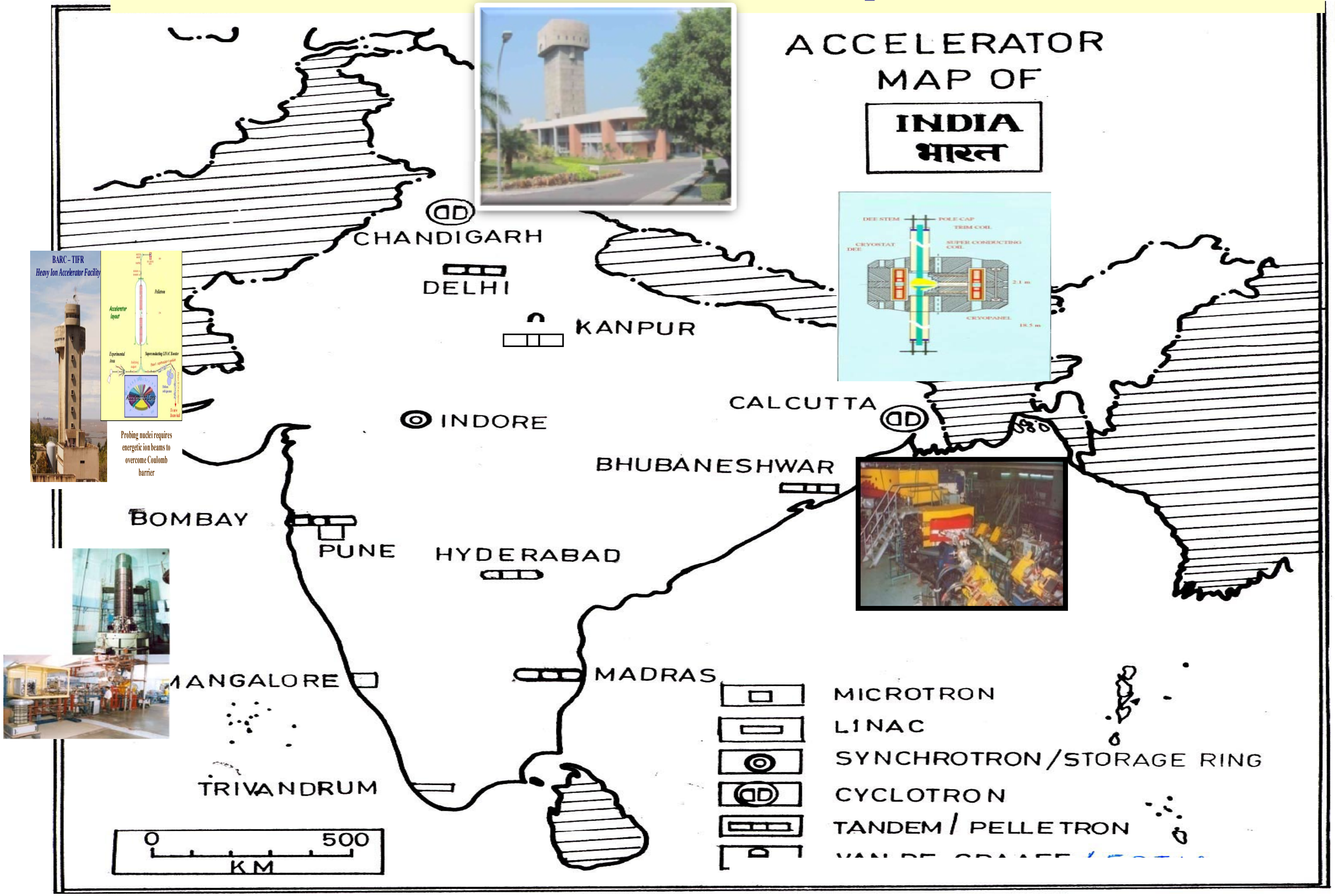
Neutrons

- D + D from 400 keV PURNIMA facility(BARC)
- (p,n) reactions at 6 m level at Pelletron(BARC-TIFR)

Major ongoing projects

- ✓ 20 MeV High Intensity Proton Accelerator)- BARC
- ✓ ECR injector based heavy ion SC Linac (BARC-TIFR)
- ✓ 3 MeV electron accelerator(EBC,BARC),30 MeV at Vizag

ION Accelerator Map of India



Goal: Establish an accelerator system for providing a wide a range of stable heavy ions with good energy and time resolution. To carry out Nuclear Physics & multidisciplinary research

1989 : 14 UD NEC Pelletron installed at TIFR

Development of Pb plated Cu cavity based Linac booster. Designed Cavity (in collaboration with SUNY, USA). Commissioned in 2007.

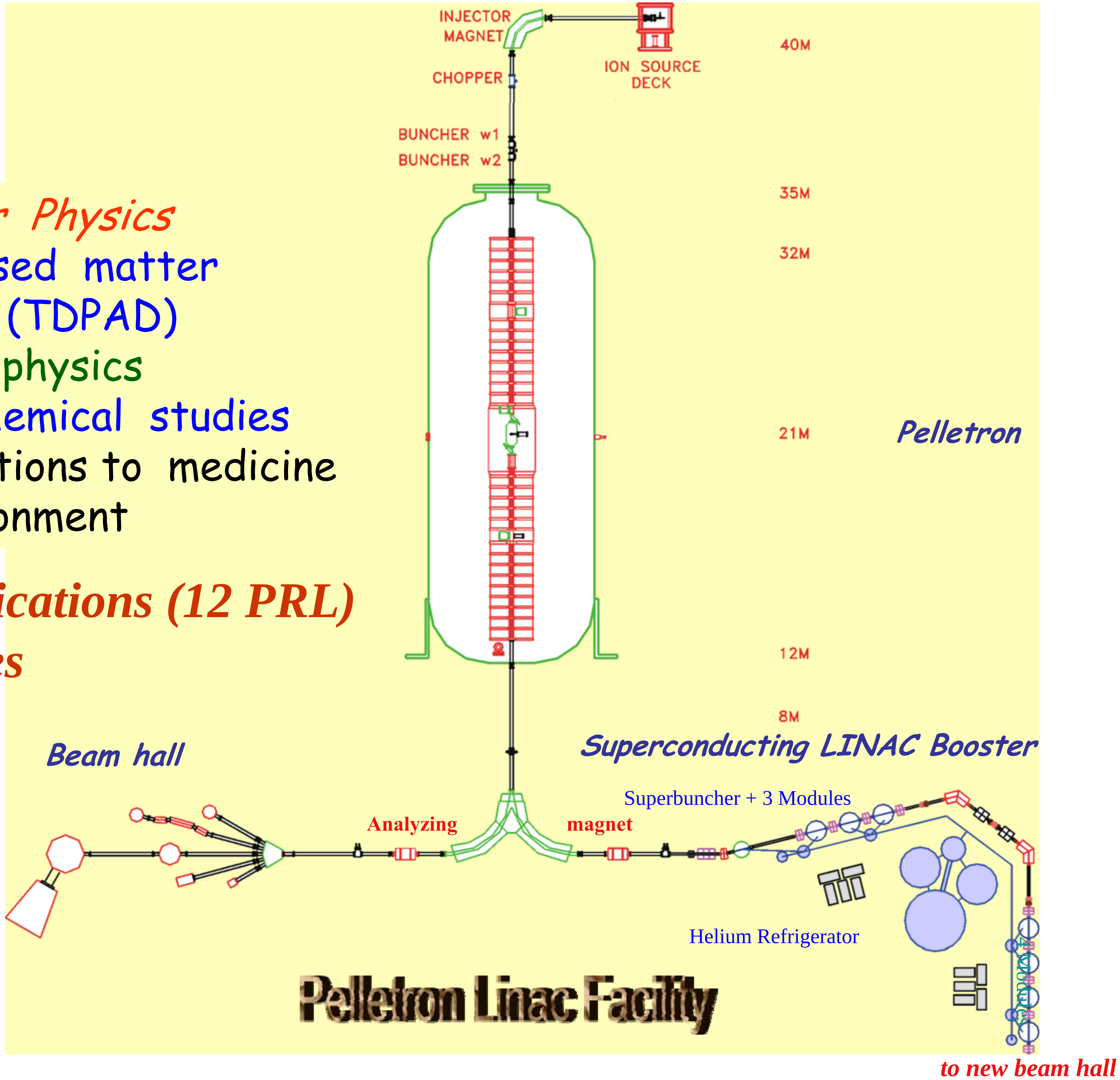
1990: 15 UD NEC Pelletron installed at IUAC

Development of of bulk Nb cavity based Linac booster. New design of QWR cavity (in collaboration with ANL, USA) Partially commissioned in 2009.

- *Nuclear Physics*
- Condensed matter physics (TDPAD)
- Atomic physics
- Radiochemical studies
- Applications to medicine & environment

458 Publications (12 PRL)

77 Theses



Superconducting LINAC Booster

Joint TIFR – BARC Project

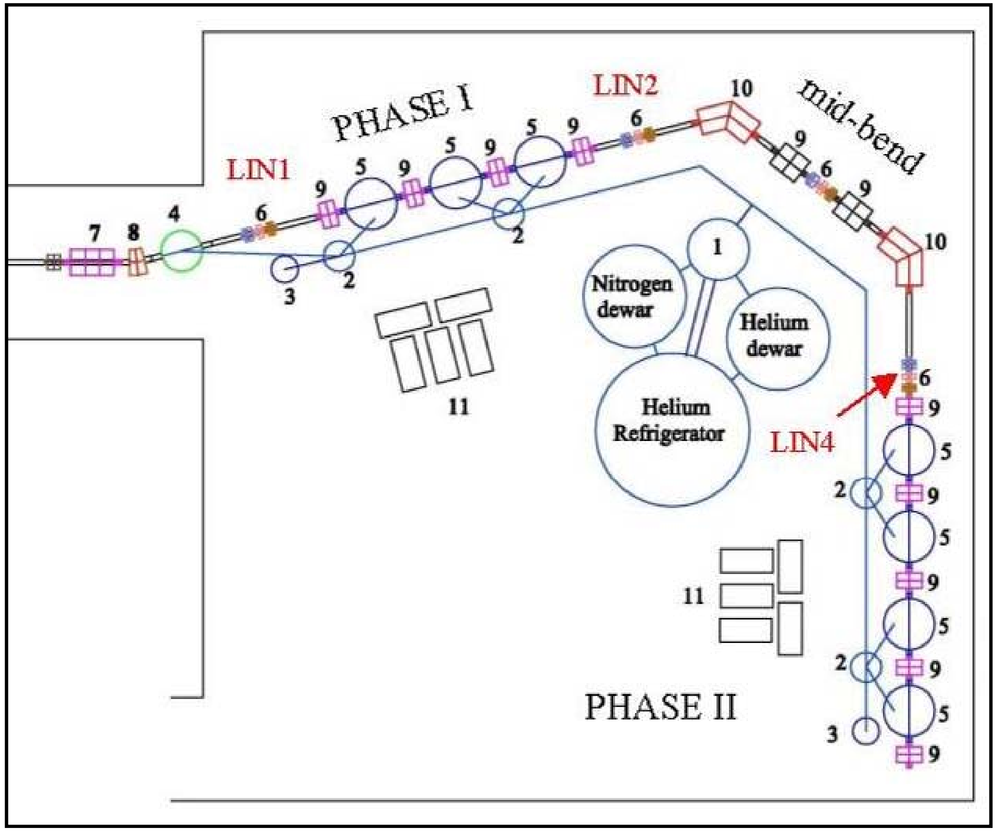
Dept of Atomic Energy, India

Specifications

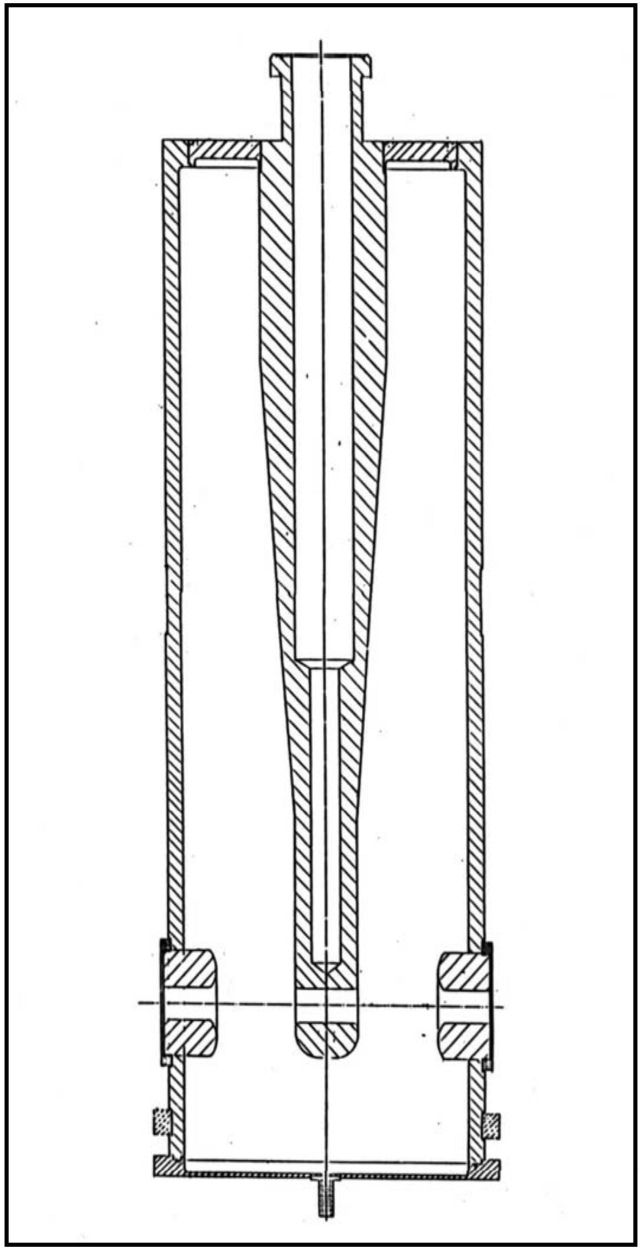
Heavy ions upto A~80
E/A~5-12 MeV

Energy gain 14MV/q
Module 7 nos
Resonators 28 nos

Bunch width ~200 ps
Beam Intensity 0.1-10 pnA

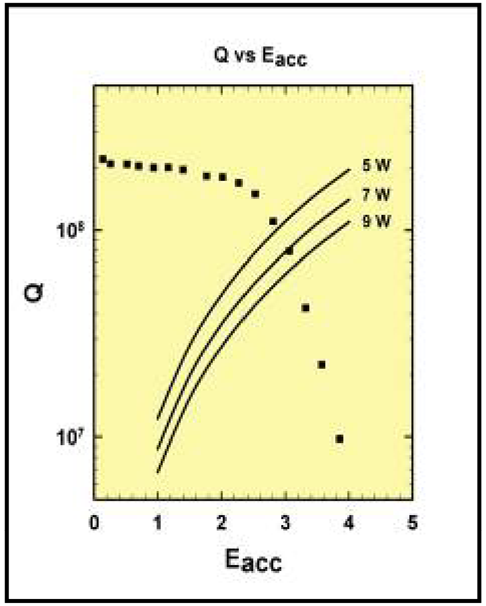


Phase I commissioned on September 22nd, 2002
Phase II commissioned on July 9th, 2007
LINAC dedicated to users on Nov. 28, 2007



Quarter Wave Resonators

Material	OFHC Cu
Superconducting surface	2 μm thick. Pb
Frequency	150 MHz
Cavity Length	64 cm
Cavity Diameter	20 cm
Optimum velocity	β=0.1
Design goal	2.5 to 3 MV/m
	@ 6 to 9 Watts

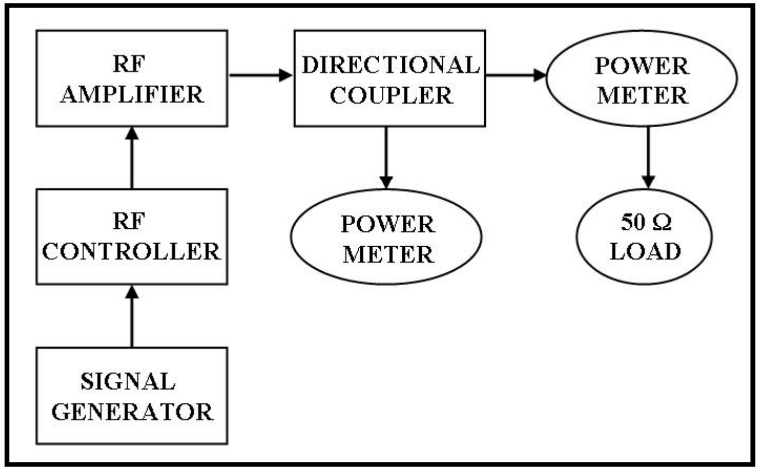


Cryogenics ...

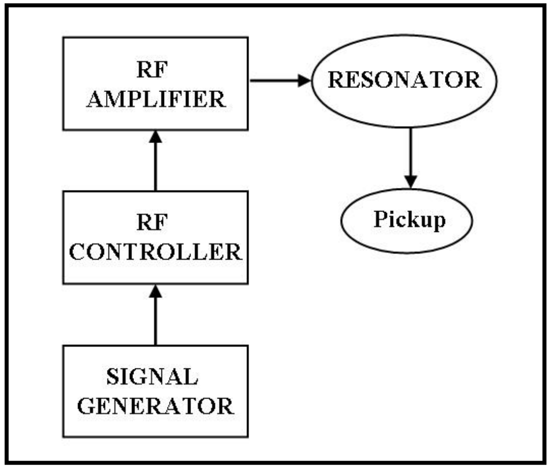
	Estimated Heat Load		Actual Heat Load
	Phase I	Phase II	
Distribution box, main box and trunk line	16W	16W	50W
Transfer tube and cryostat, 12W each	4x12W=48W	4x12W=48W	130W
QWR @6W each and Superbuncher @4W	12x6W=72W 1 x 4W =4W	16x6W=96W	172W
Total (Phase I + II)	300W		352W

The entire cryogenic distribution was fabricated and assembled on-site and has performed very well.

Resonator Power settings & Field measurement

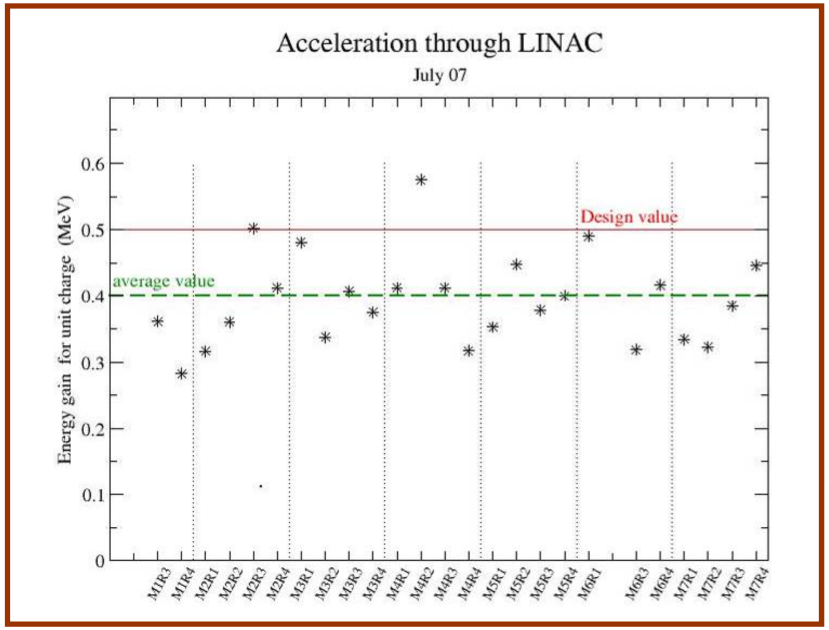


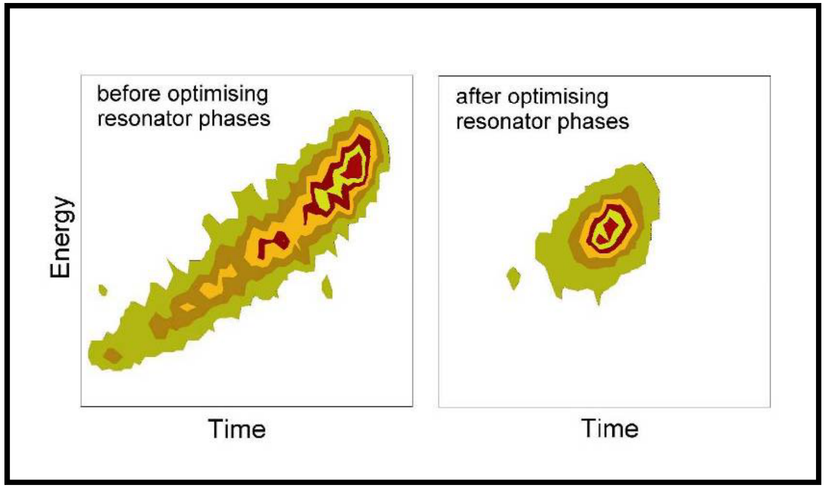
Calibration of controller card



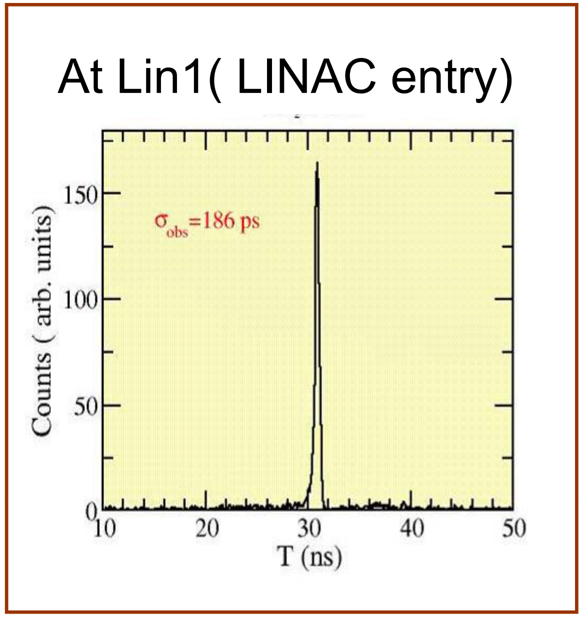
Set @ equal power levels (6W)

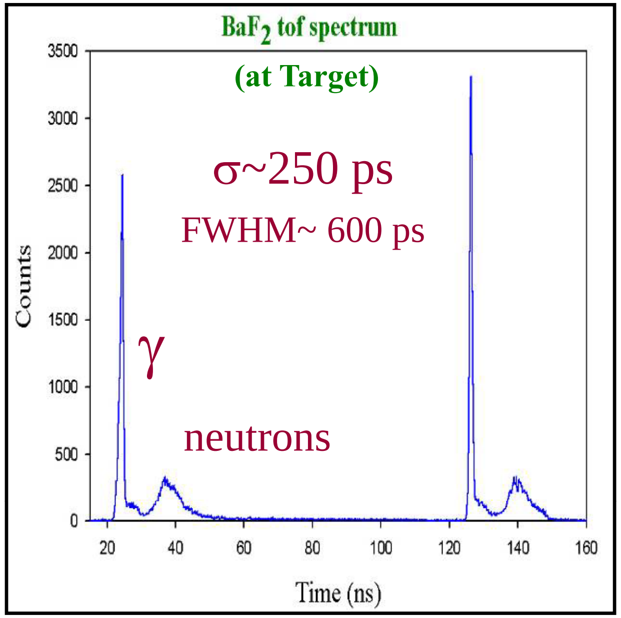
- Calibrate controller by measuring output power
- Set resonators at 6W and measure energy gain with DC beam to get resonator fields
- Set QP at 50W and restore field amplitude (6W pickup) by over-coupling





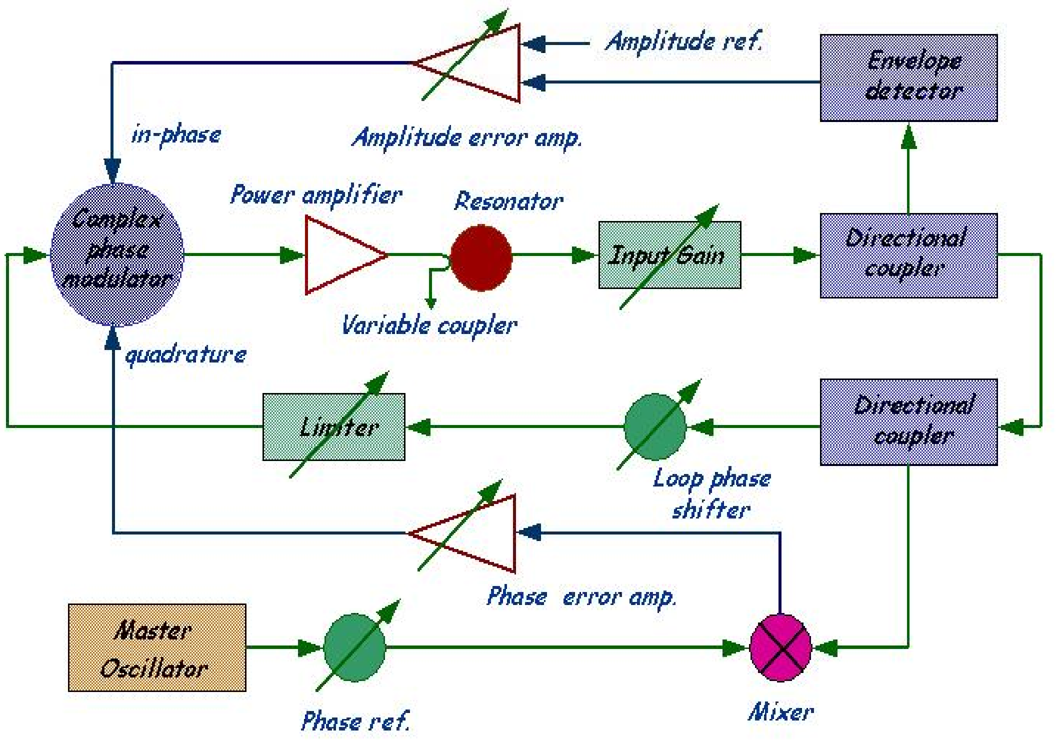
Longitudinal phase space after mid-bend (E-T measurement)





RF Electronics for Superconducting Resonators

In house development, uses either indigenous or easily available RF modules



RF Controller (schematic)

Variable RF coupler

Also delivered to ANU Canberra, IUAC New Delhi

Experiments with LINAC

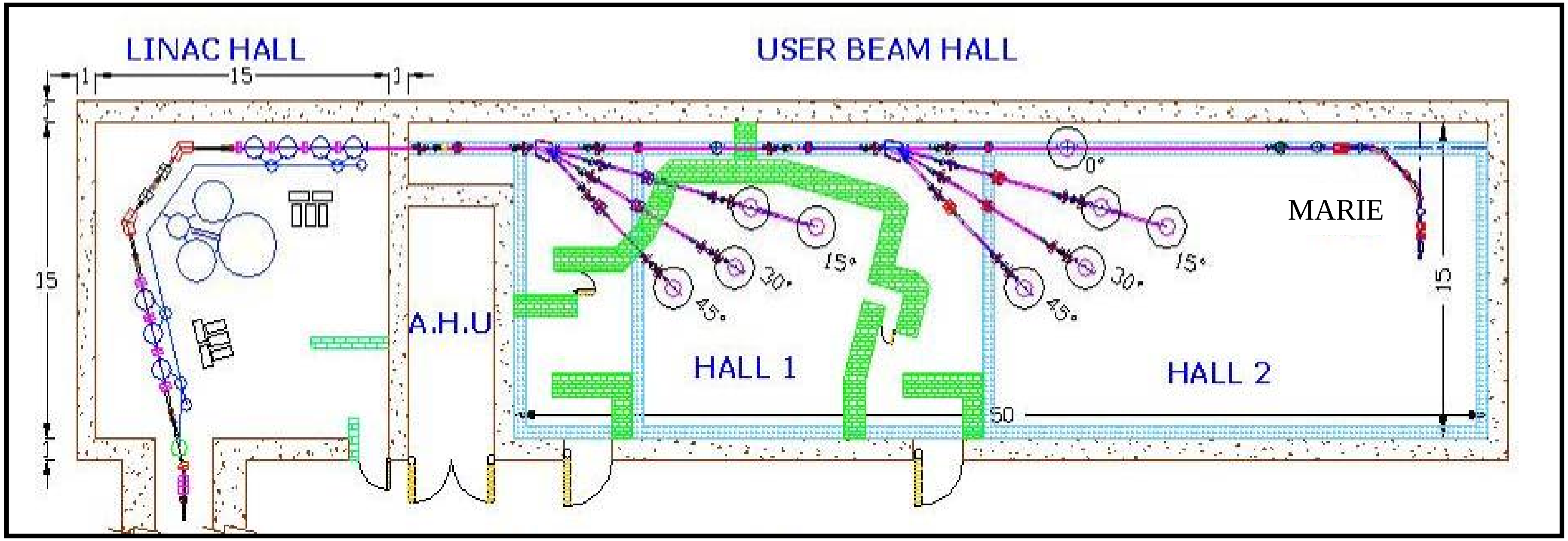
Nov.07, July08, Jan.09

Beam	E_{pell} (MeV) Pelletron	E_{LINAC} (MeV) LINAC	E_{total} (MeV) Total
^{12}C	82.5	37.5	120.0
^{16}O	93.6	22.1	115.7
^{19}F	94.0	50.2	144.2
^{28}Si	90-100	48-109	138-209

Typical tuning time 6-8 hours

Beam transmission through LINAC 80 to 85 %

Experimental Facilities



Hall 1

- General Purpose Scattering Chamber
- Condensed Matter Physics (7 T Magnet) & Atomic, Molecular & Cluster Physics
- High energy gamma ray & neutron wall

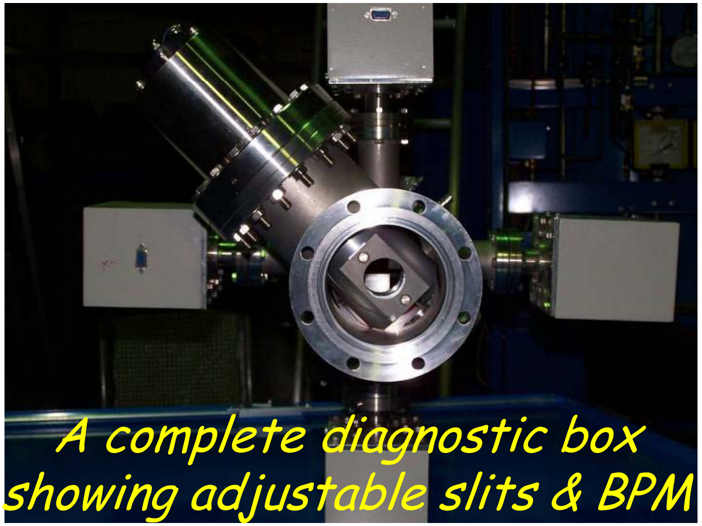
Hall 2

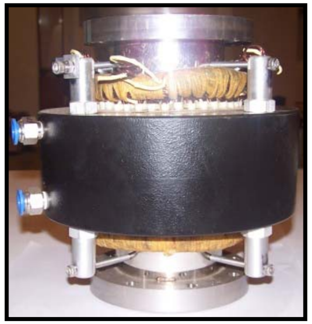
- General Purpose/ Irradiation line
- HPGe Spectrometer (INGA)
- Charged particle ball
- Momentum Achromat for Radioactive Ion Experiments

Beam Diagnostic devices

BPM developed at TIFR

Faraday cup

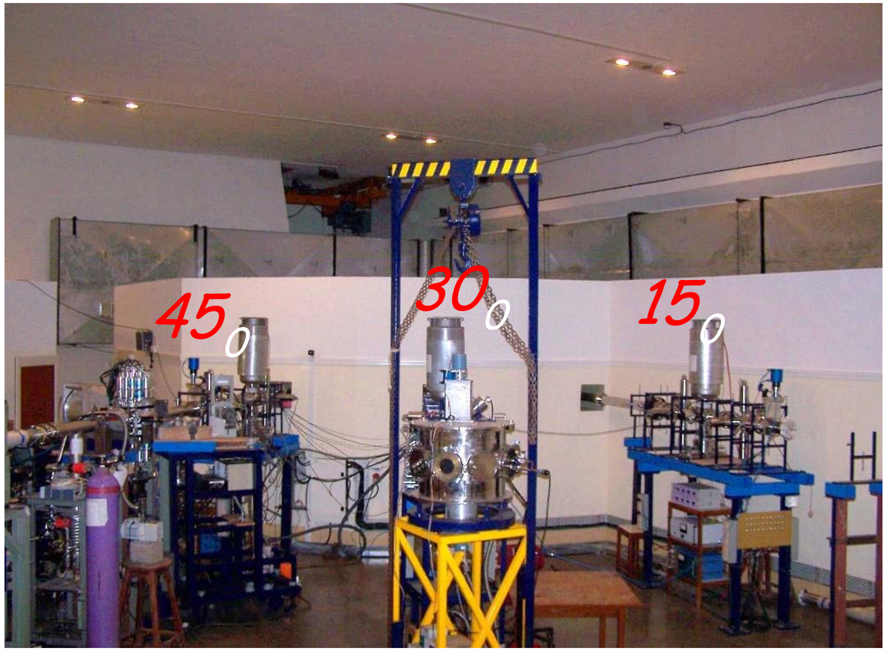




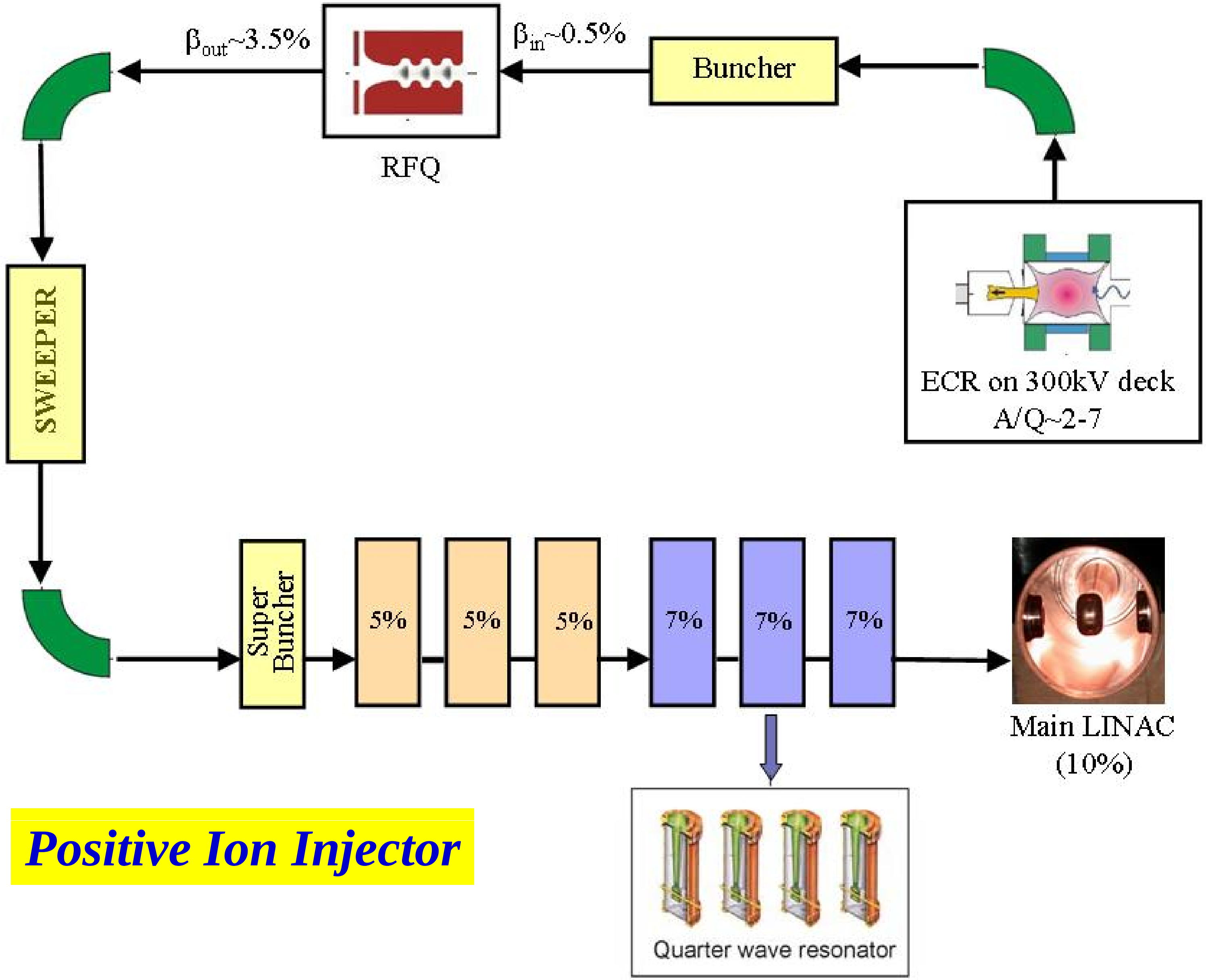
Magnetic Steerer

User beam Hall

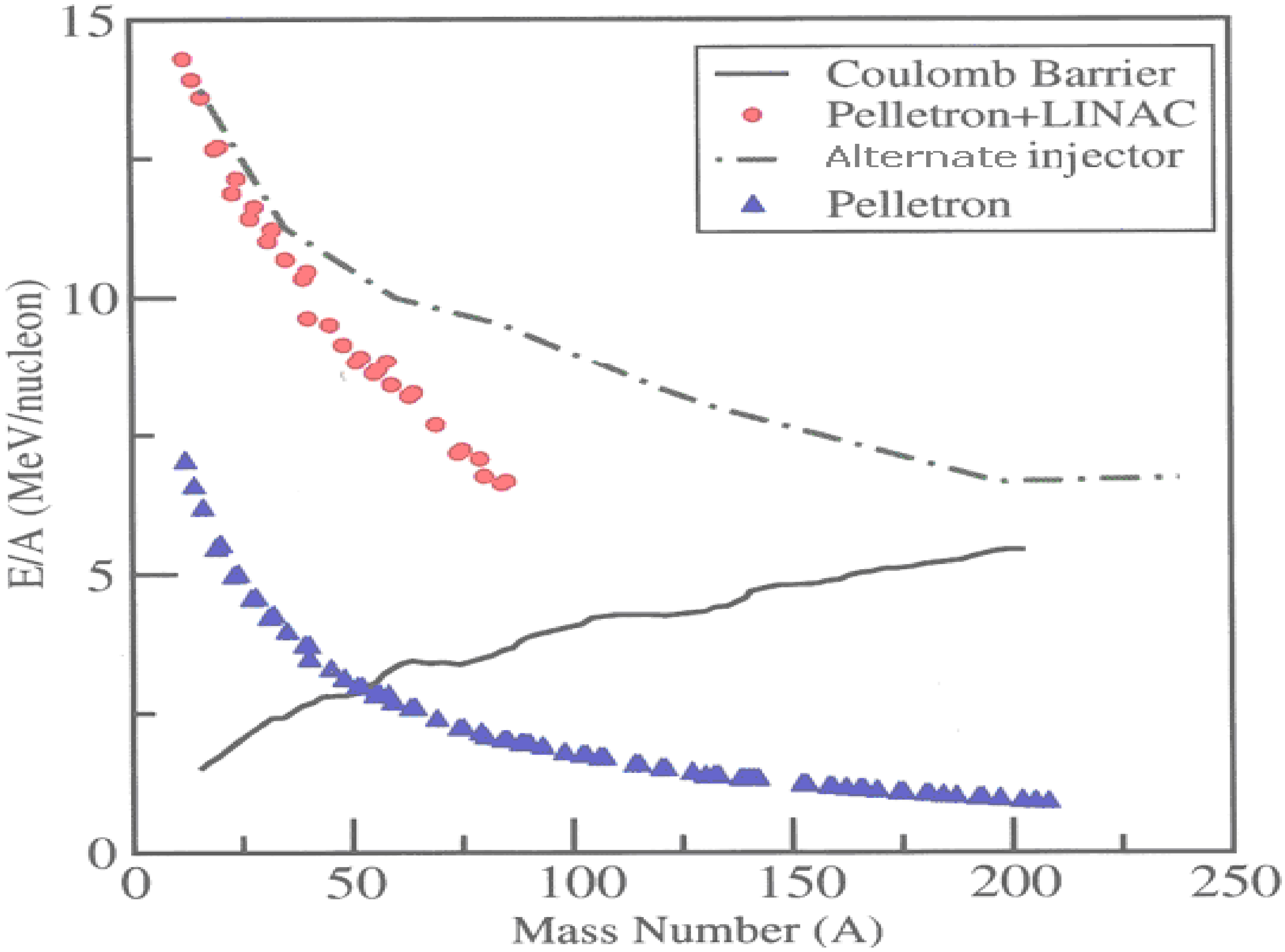
Hall I Experimental stations



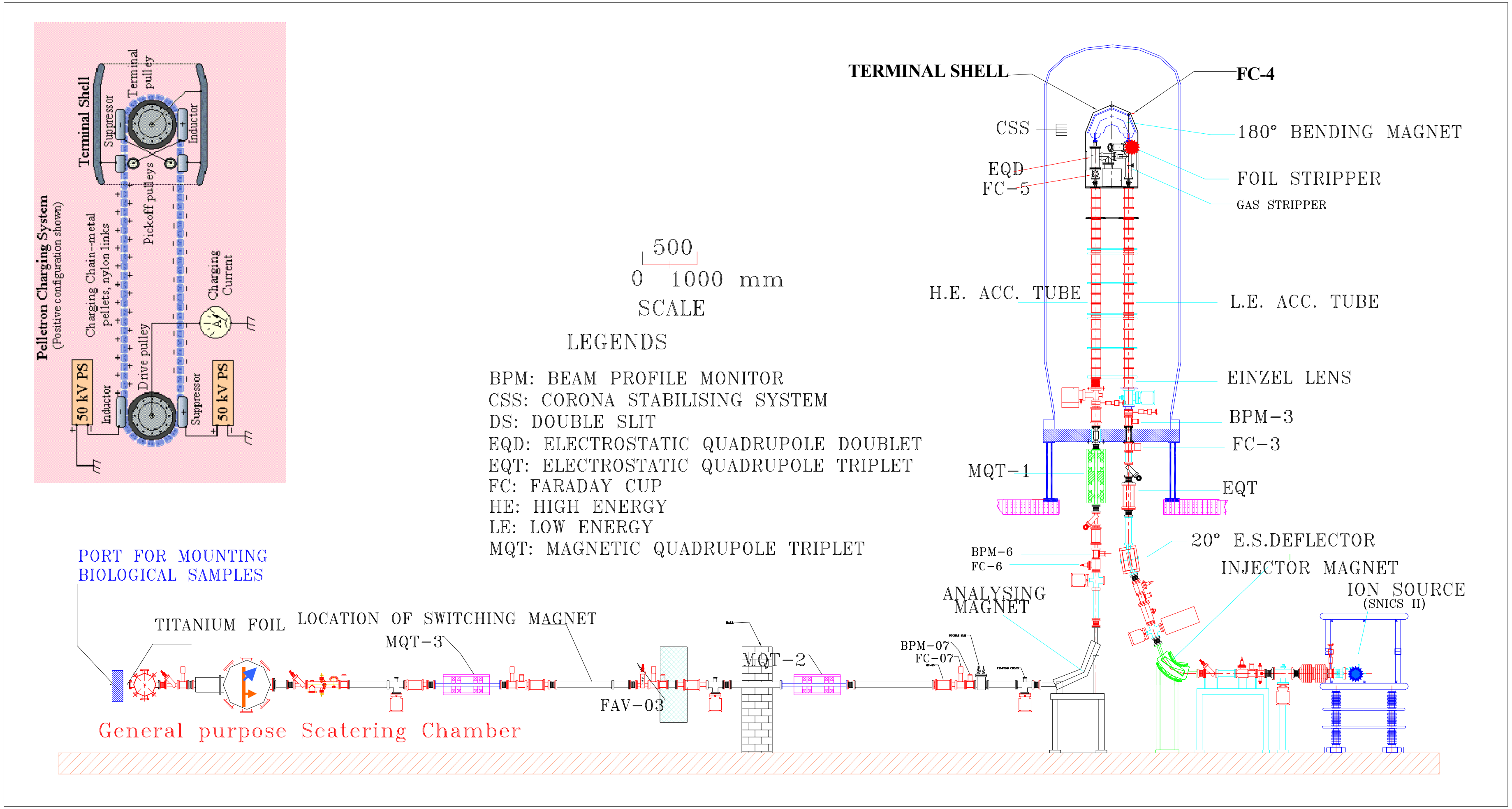
Hall II Experimental stations

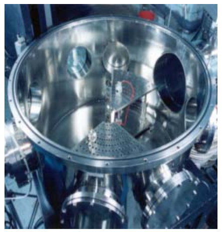


β_{out}~3.5%
RFQ
β_{in}~0.5%
Buncher
ECR on 300kV deck
A/Q~2-7
SWEEPER
Super Buncher
5%
5%
5%
7%
7%
7%
Main LINAC
(10%)
Quarter wave resonator
Positive Ion Injector



Coulomb Barrier
Pelletron+LINAC
Alternate injector
Pelletron
E/A (MeV/nucleon)
Mass Number (A)
0
5
10
15
0
50
100
150
200
250





Scattering chamber

Switching Magnet

90^0 Magnet

180^0 Magnet

70^0 Magnet

SNICS II ion Source

Medical Cyclotron

Features of PETtrace® Medical Cyclotron

•Unshielded - placed in concrete vault with entry through a maze

•Fixed Beam Energy variable current

•16.5 MeV (H-), 75 µA single beam, 40 µA dual beam

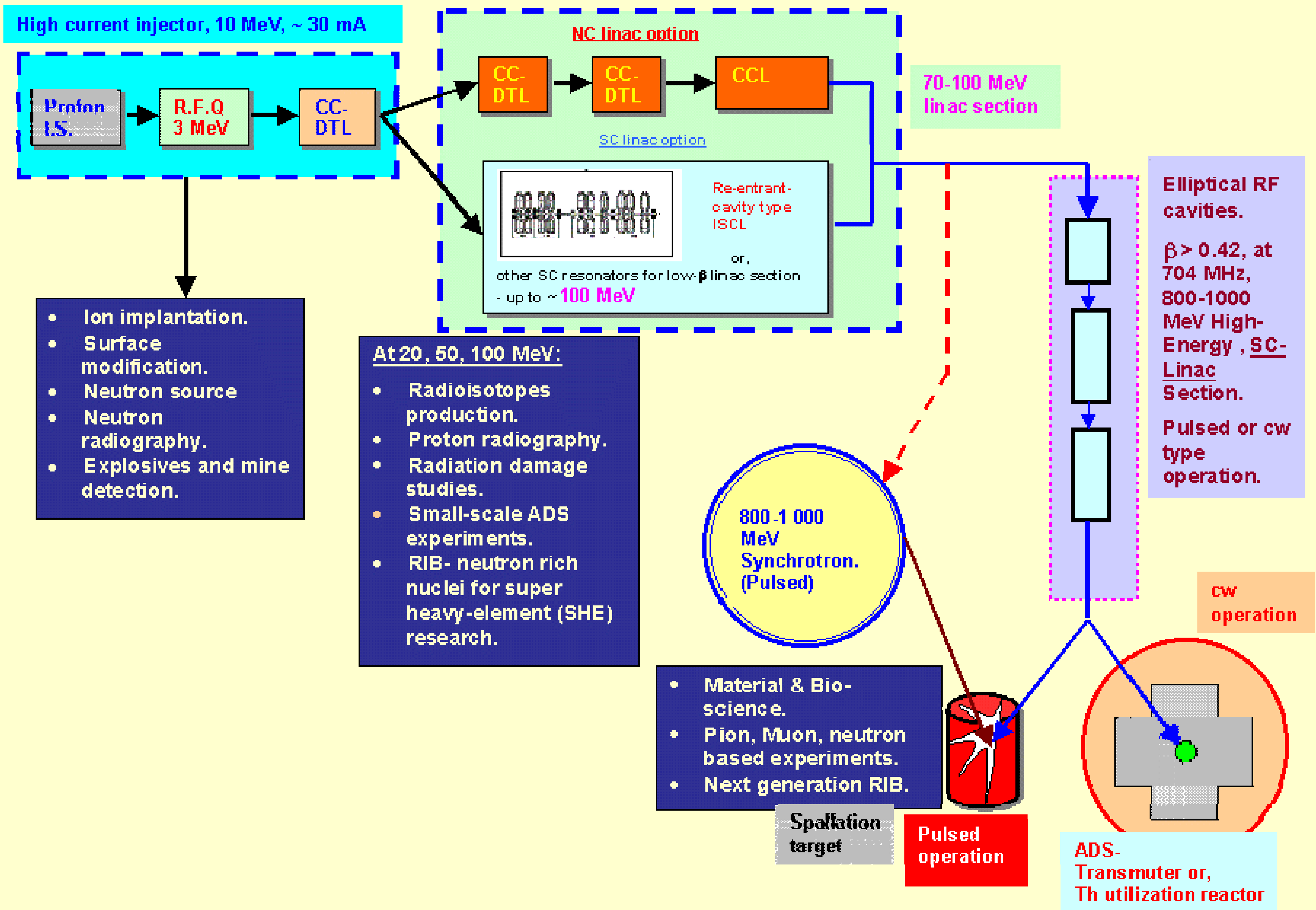
•4 MeV (D-) 60 µA single beam, 30 µA dual beam

•Target: 6 Ports - liquid - 3, gas – 3

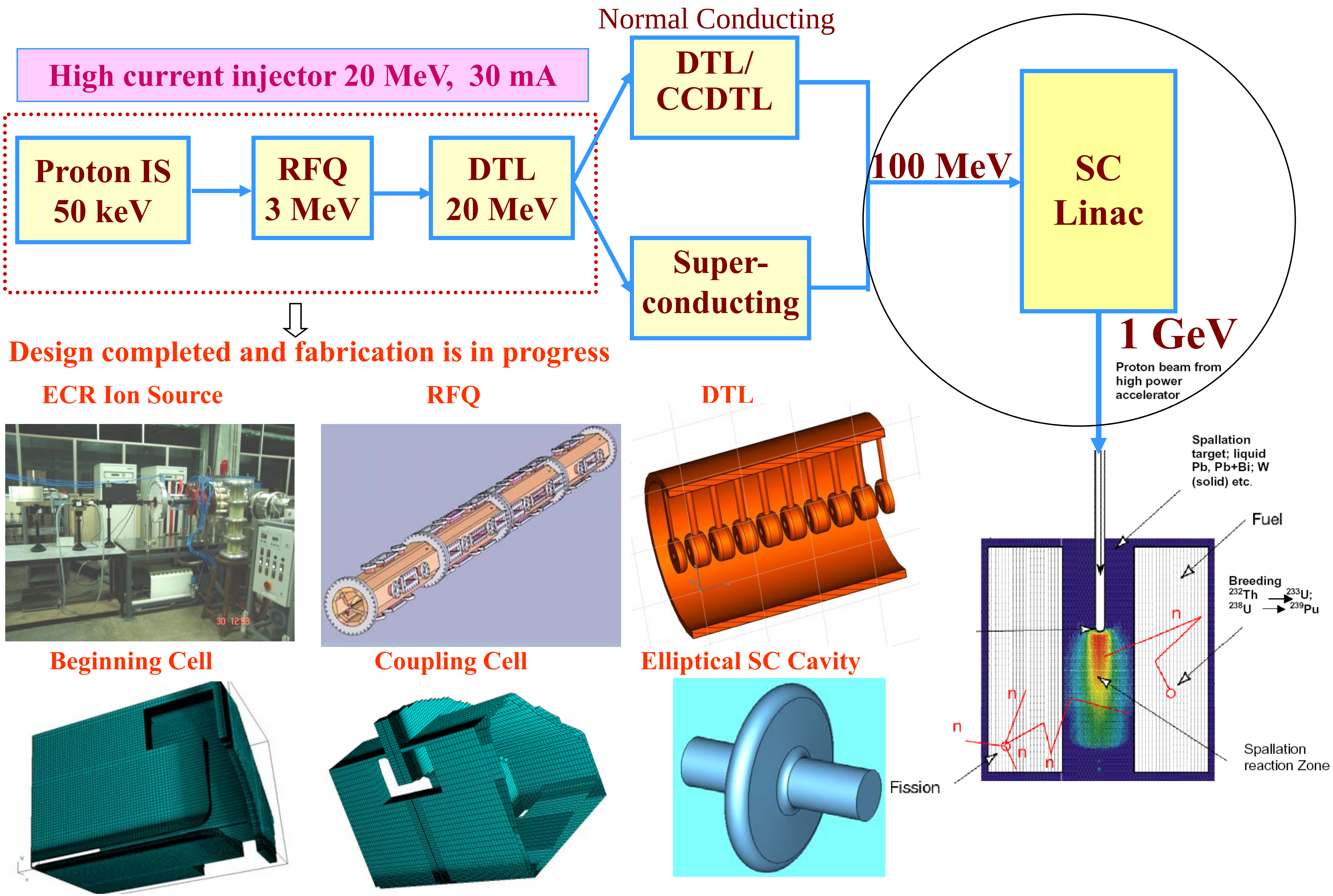
•Radionuclides that can be Produced - 18F, 11C, 13N & 15O

BGO Array is used for imaging
The PET

Development of Key Technologies for Accelerator-Driven Sub-critical System (ADSS)



Scheme for Accelerator Development for Indian ADS Program



Accelerator Augmentation at IUAC

Superconducting Linac booster

Complete indigenous technology development

Resonator fabrication facility set-up

Large Cryogenic system

RF electronics, synergy with National laboratories and industry

Beam Transport systems

High Current Injector

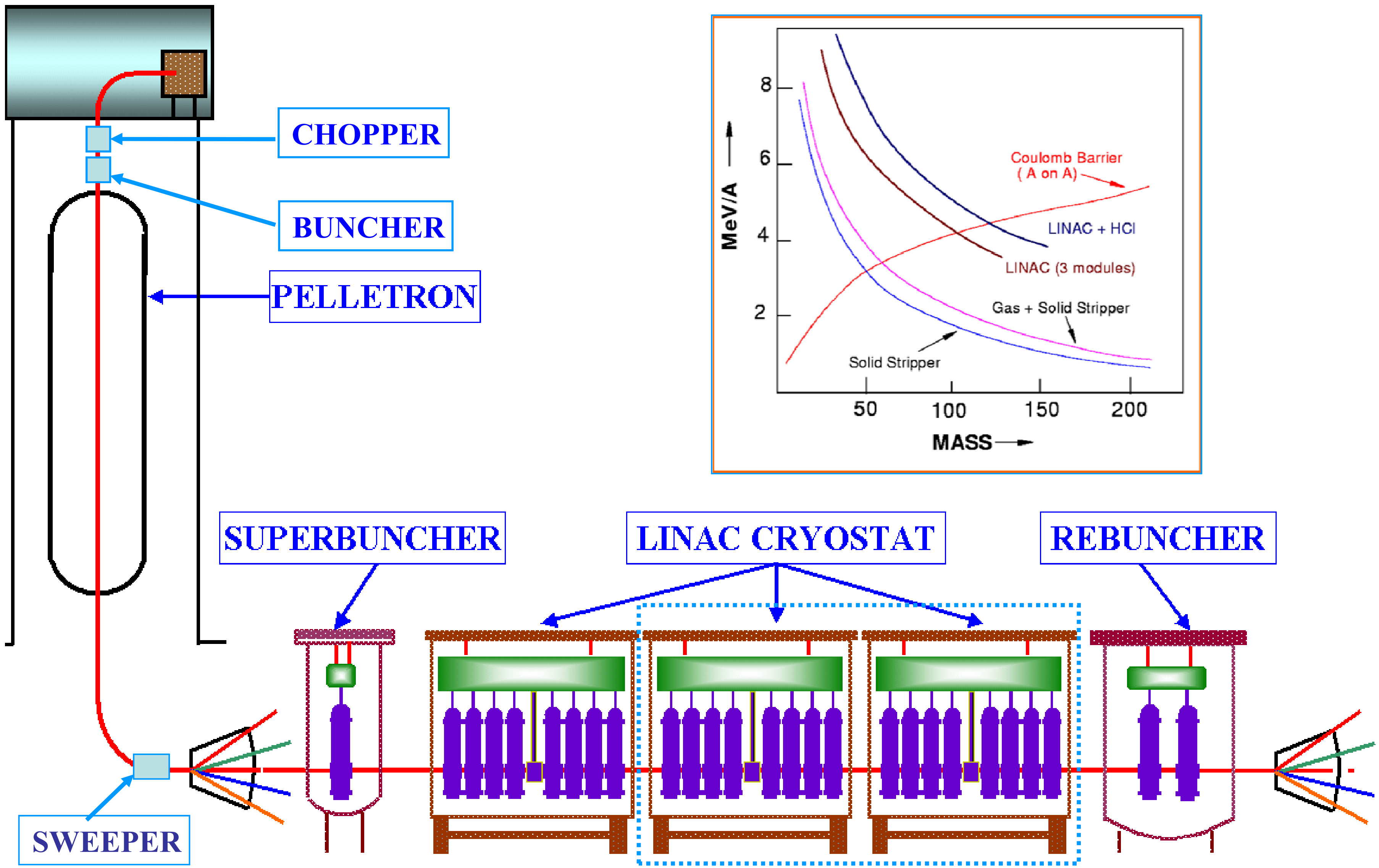
Novel Electron Cyclotron Resonance ion source using high Tc superconductor.

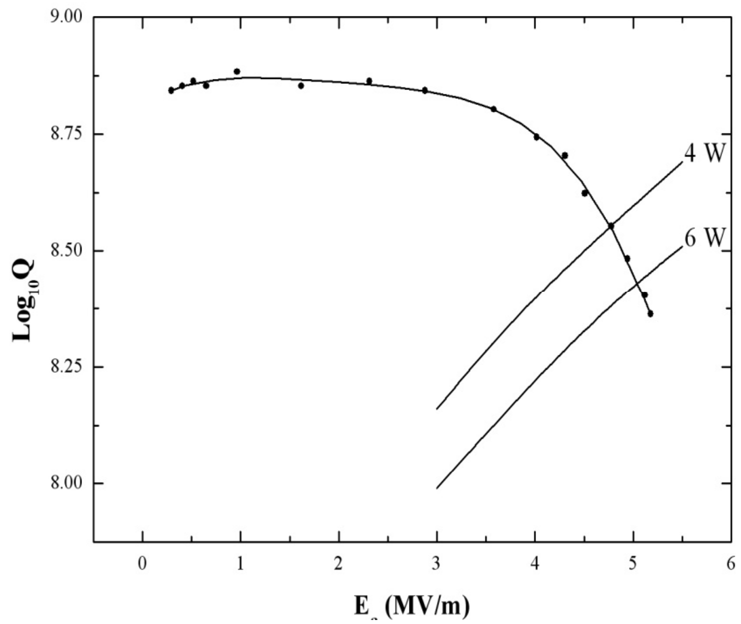
Radio frequency quadrupole accelerator

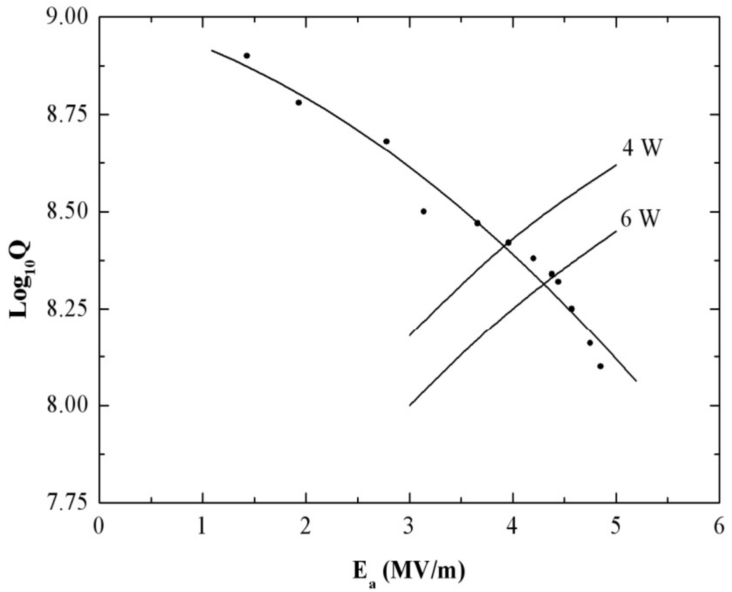
Drift Tube Linac

Low beta cavity module

Layout of Pelletron and Superconducting Linac Booster

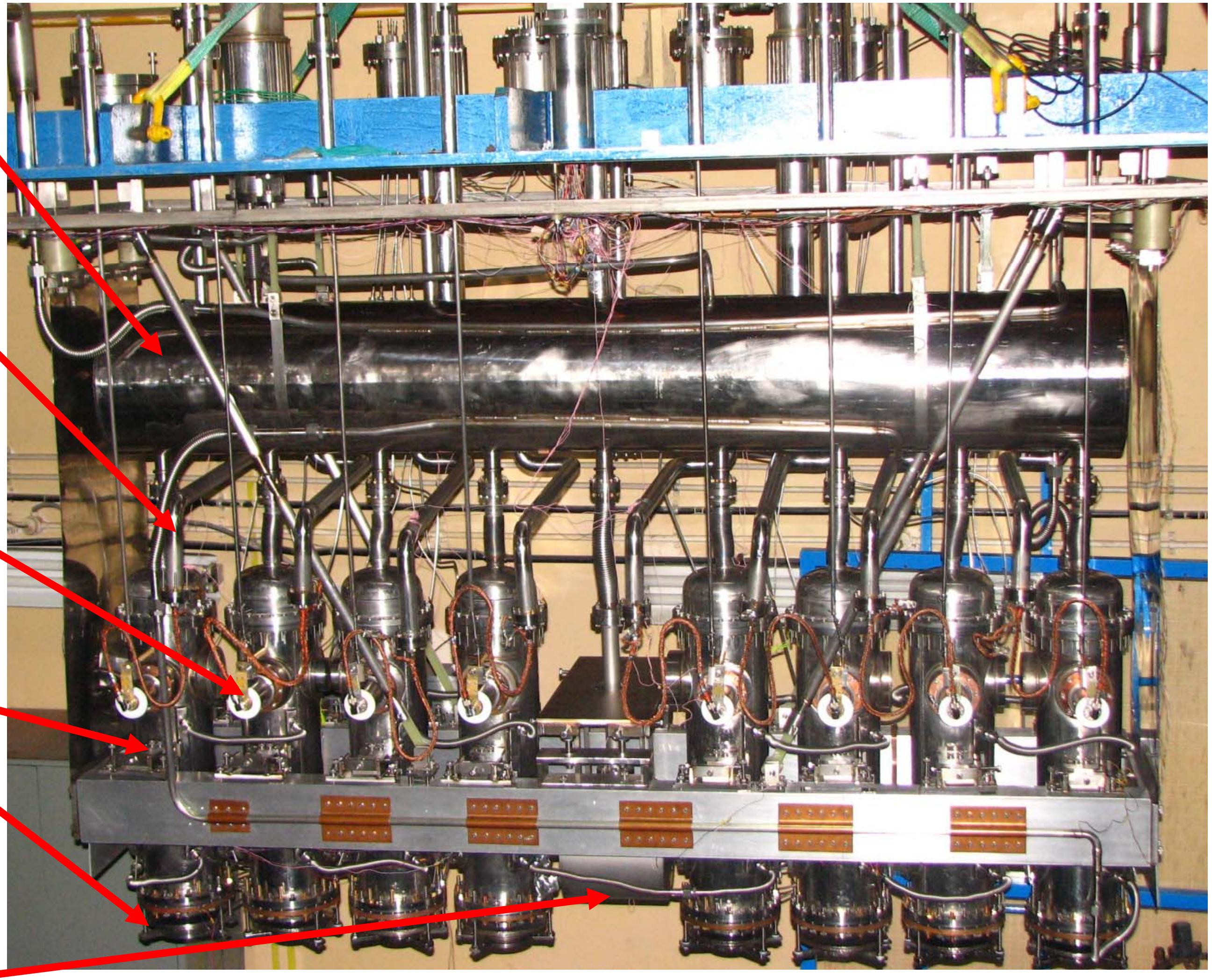






Resonant Frequency	**97MHz**
Synchronous velocity	**0.08c**
Drift tube Voltage	**85kV**
Energy Content	**110 mJ**
Peak Magnetic field	**106 G**
Peak Electric field	**3.9MV/m**
Geometric factor	**17.3**
Active length	**15.9 cm**

A complete Linac cryostat with eight resonators and a solenoid magnet



Liquid He-vessel

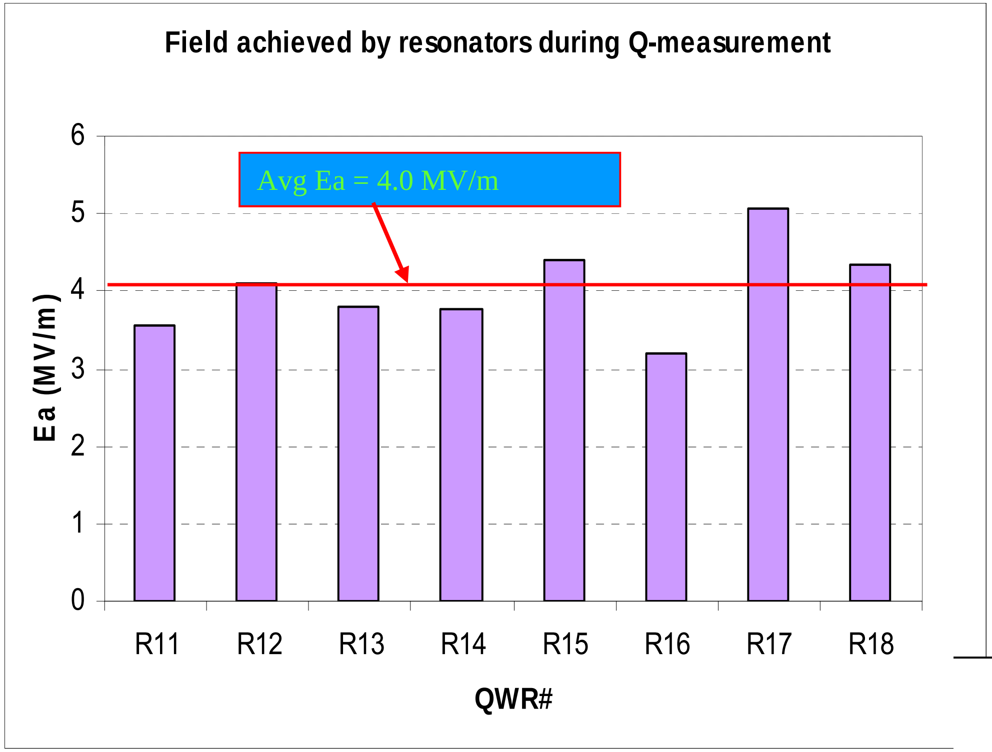
LN2 manifold to cool Power cable

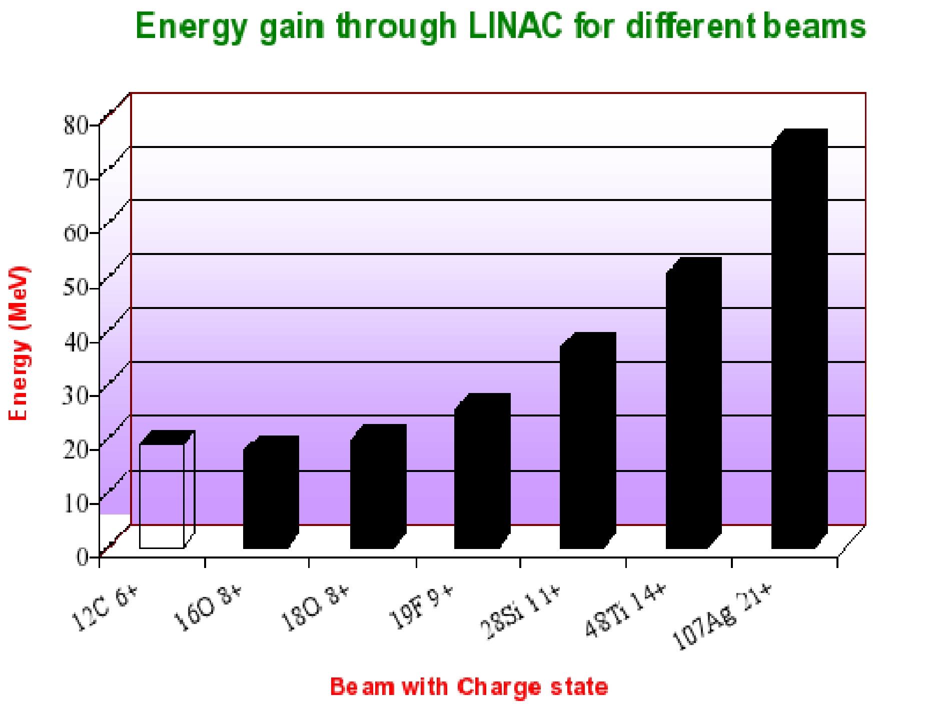
Drive coupler

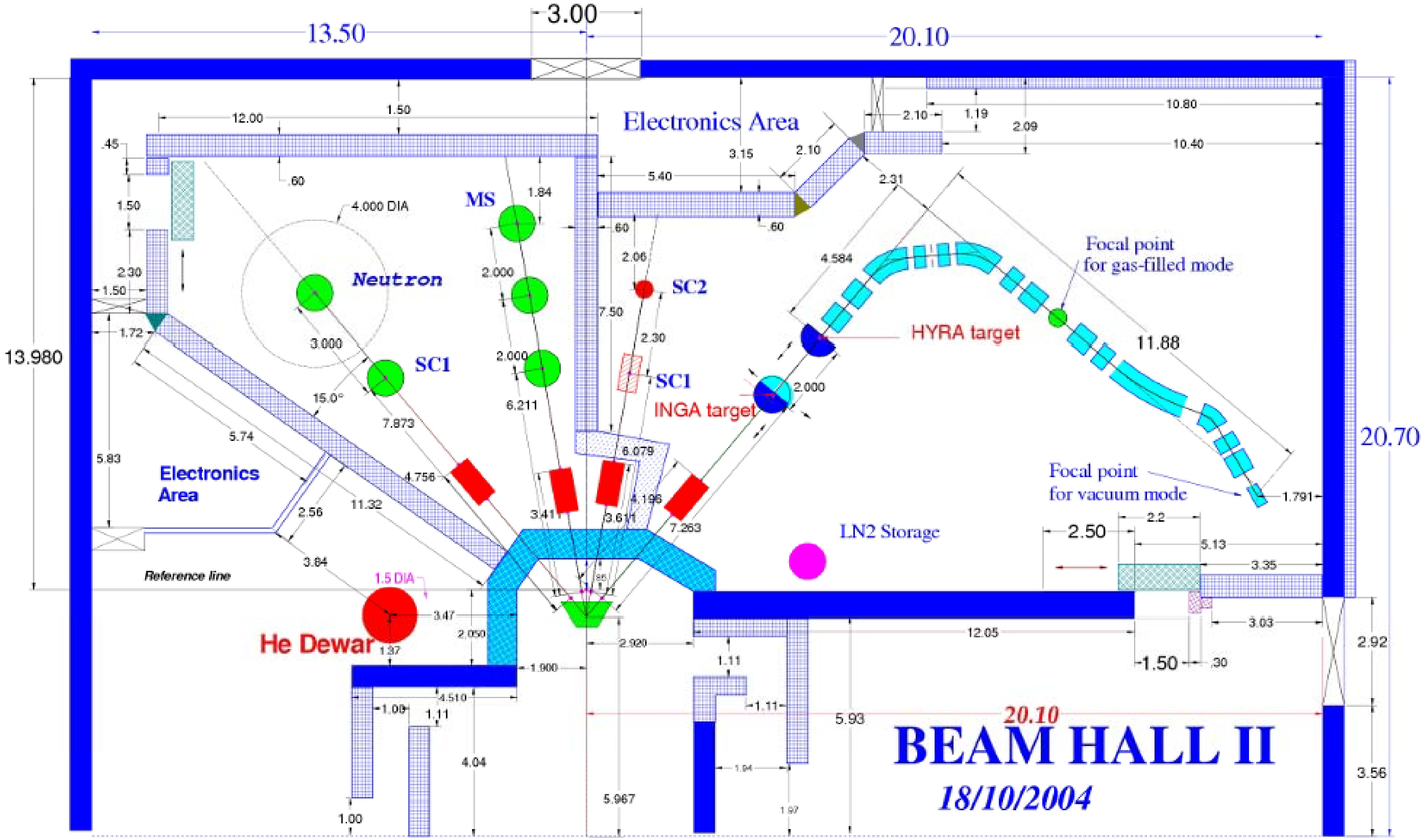
Resonators

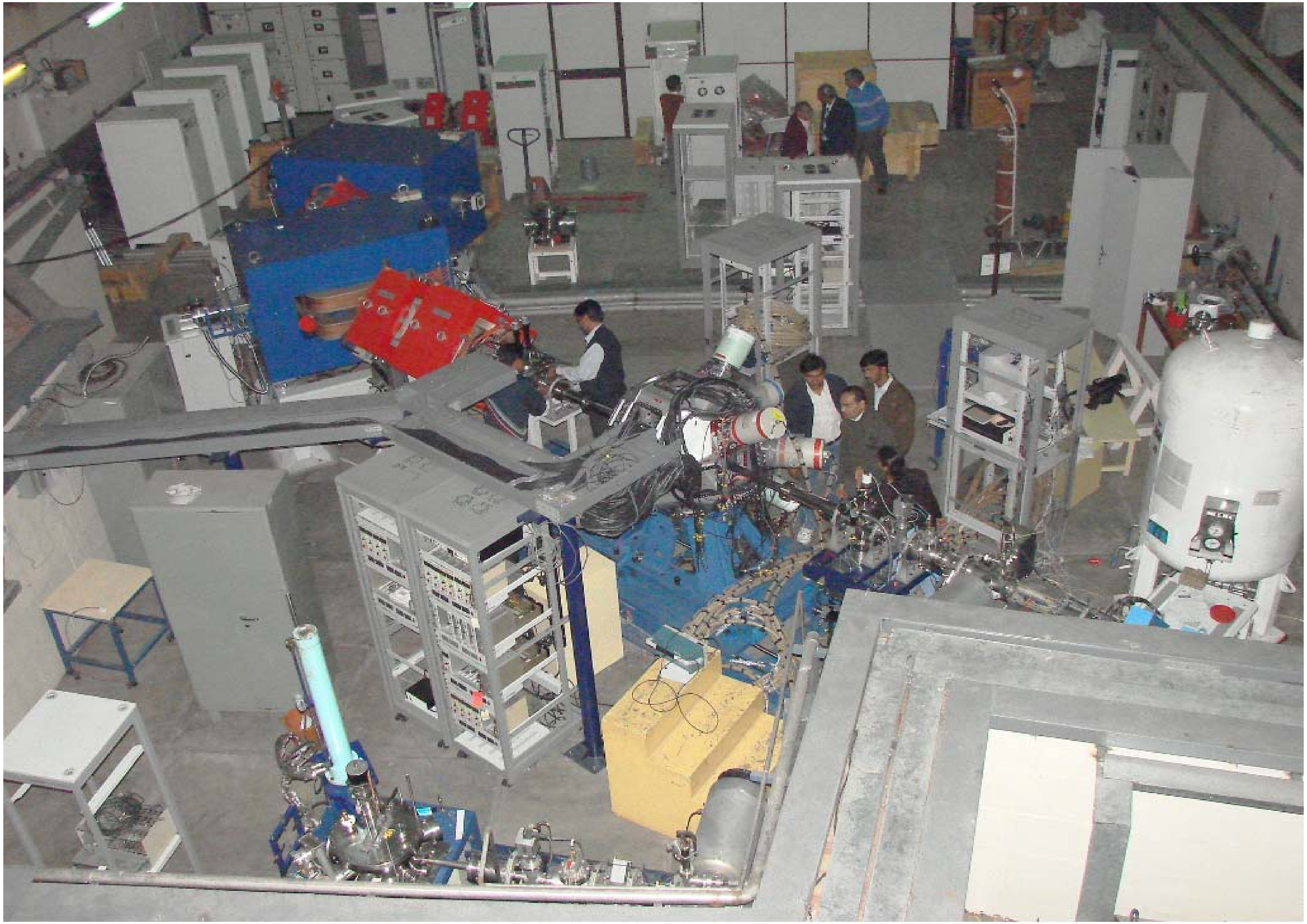
Mechanical Tuner

Solenoid


Field achieved by resonators during Q-measurement
Avg Ea = 4.0 MV/m
Ea (MV/m)
0
1
2
3
4
5
6
R11
R12
R13
R14
R15
R16
R17
R18
QWR#


Energy gain through LINAC for different beams
Energy (MeV)
0
10
20
30
40
50
60
70
80
12C 6+
16O 8+
18O 8+
19F 9+
28Si 11+
48Ti 14+
107Ag 21+
Beam with Charge state


BEAM HALL II
18/10/2004
Electronics Area
Electronics Area
Neutron
MS
SC1
SC1
SC2
4.000 DIA
HYRA target
INGA target
Focal point for gas-filled mode
Focal point for vacuum mode
LN2 Storage
He Dewar
1.5 DIA
Reference line
13.50
3.00
20.10
20.70
13.980
11.88
20.10

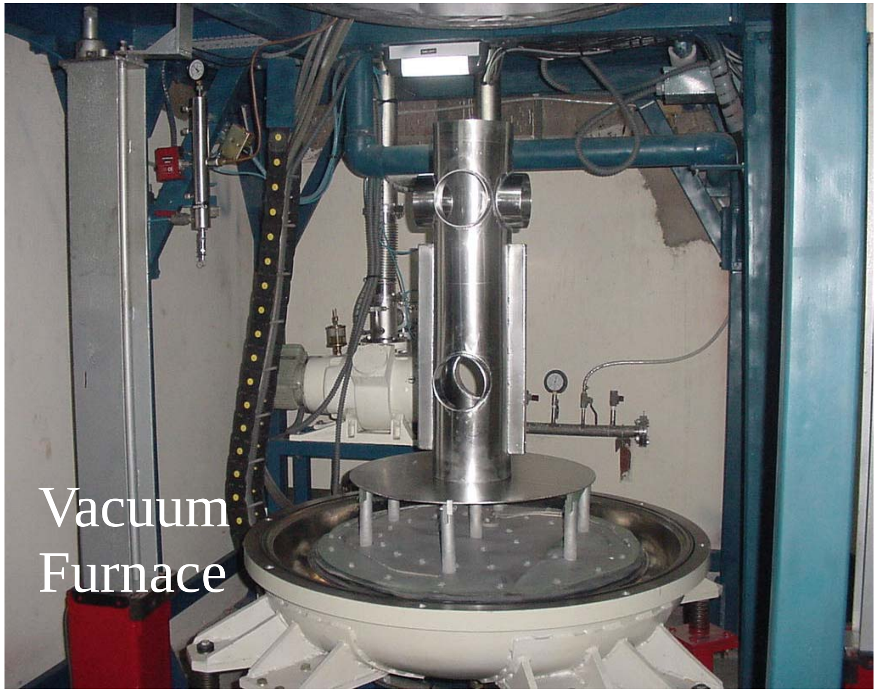


INGA + HYRA in Beam Hall-II

Electron Beam Welding Machine

Superconducting Resonator Fabrication Facility

Electropolishing Set-up

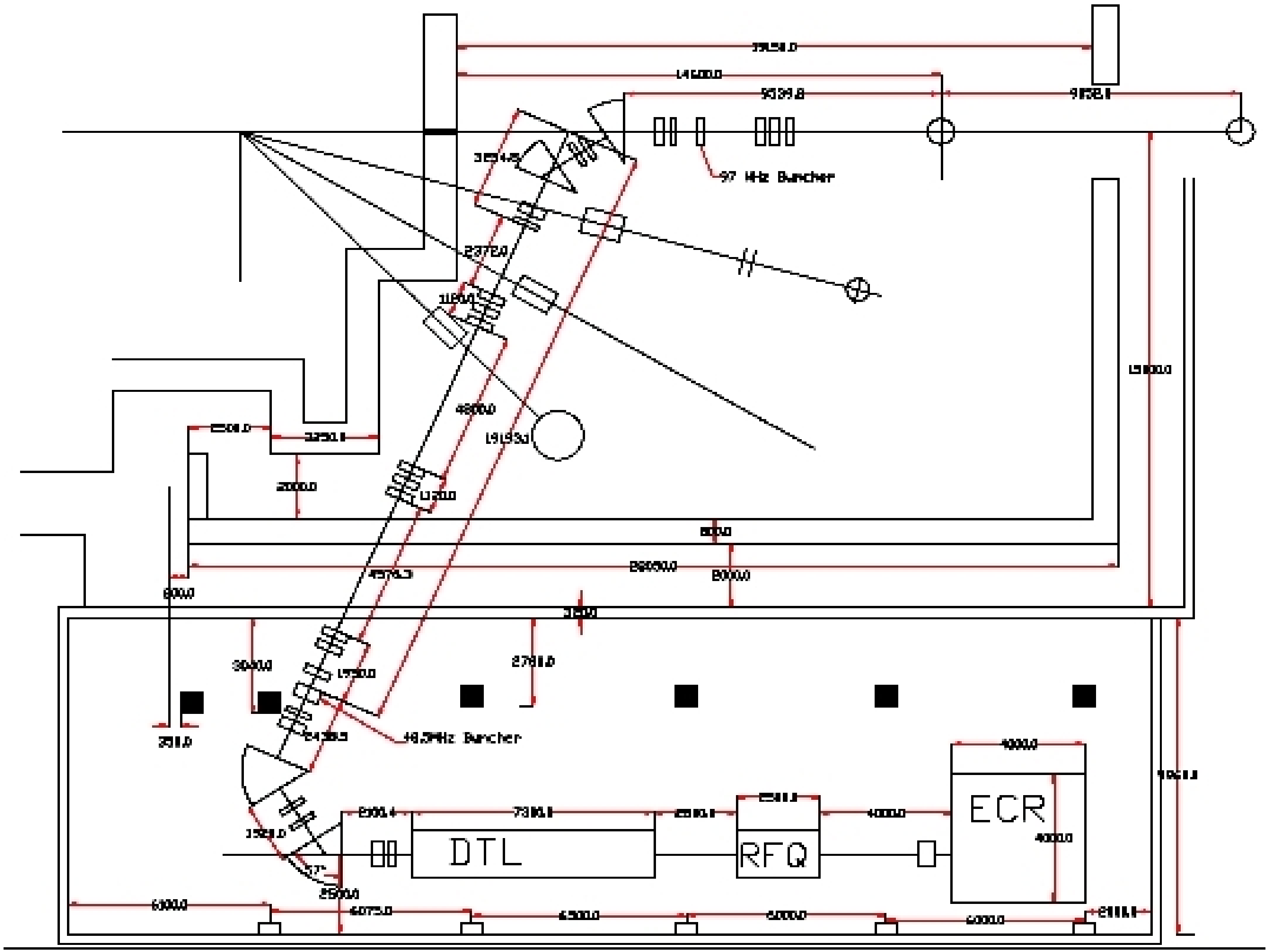


Vacuum Furnace

- Successful control of LINAC using Dynamic Phase Control, Resonator Controller developed in synergy with Electronics Div, BARC.
- 400 Watt 97 MHz Power Amplifier developed in-house
- Monitoring of output & reflected power
- Technologyof RF Amplifier transferred to BEL for, used in BARC-TIFR Linac

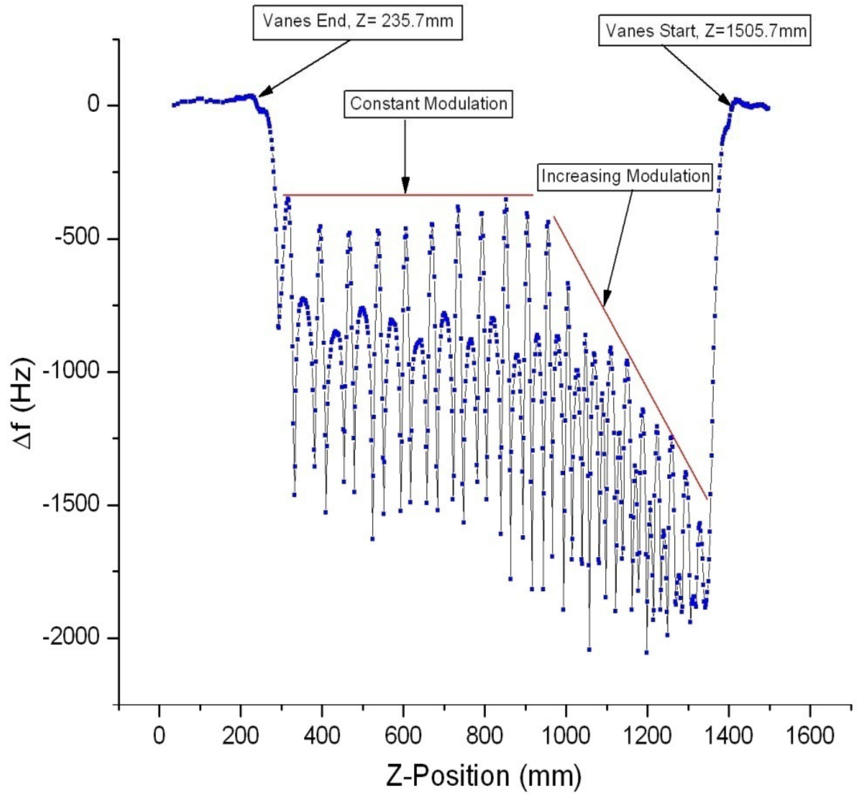
400 WATT , 97 MHz RF POWER AMPLIFIER

ECR based High Current Injector for LINAC

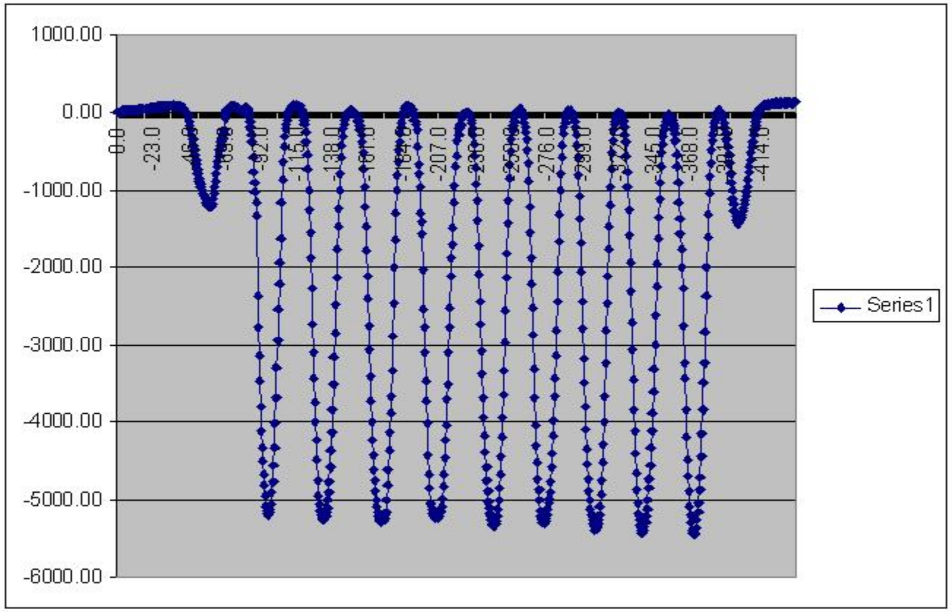


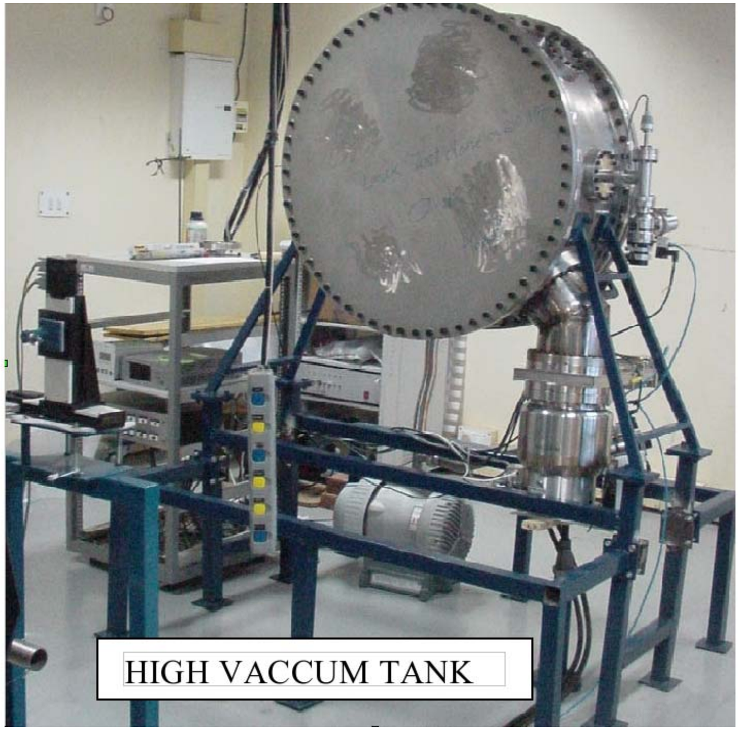
World's first High Tc Superconductor based ECR source, PKDELIS

General Assembly of the 1.17m modulated RFQ, A/q = 7, E_{in} = 8keV/u.



Drift Tube Linac prototype





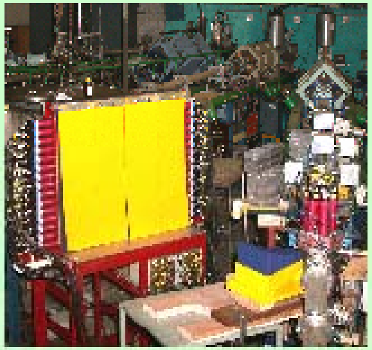
DETECTOR ARRAYS

Gas Detectors of different types

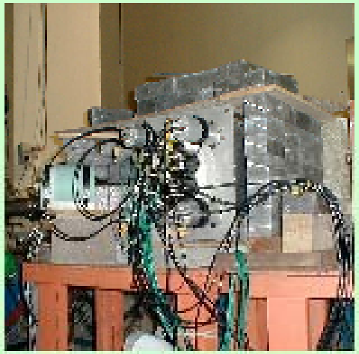
Charged Particle Array=silicon,CsI,gas
Neutron detector array= NE213 based
Gamma detector array =BGO, BaF2 arrays

INGA - 24 HPGe with anti-compton
Recoil Mass Separator = HYRA
MARIE =

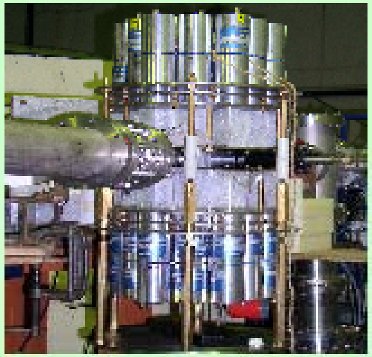
Neutron Array



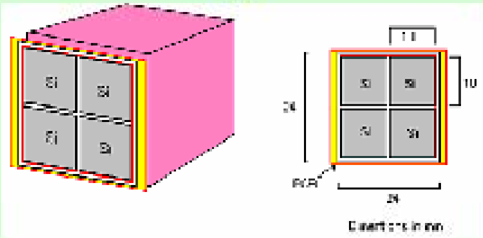
BaF_2 Array

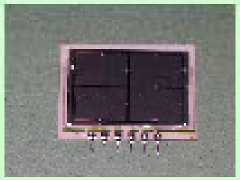


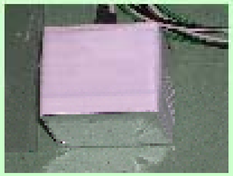
BGO-Mult. Array



A unit of Charged Particle Array

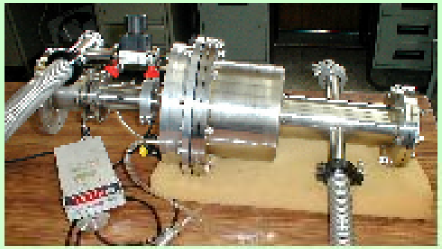




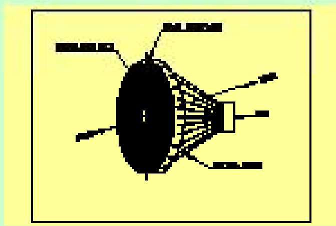


Si pad detector **CsI detector**

Residue Detectors



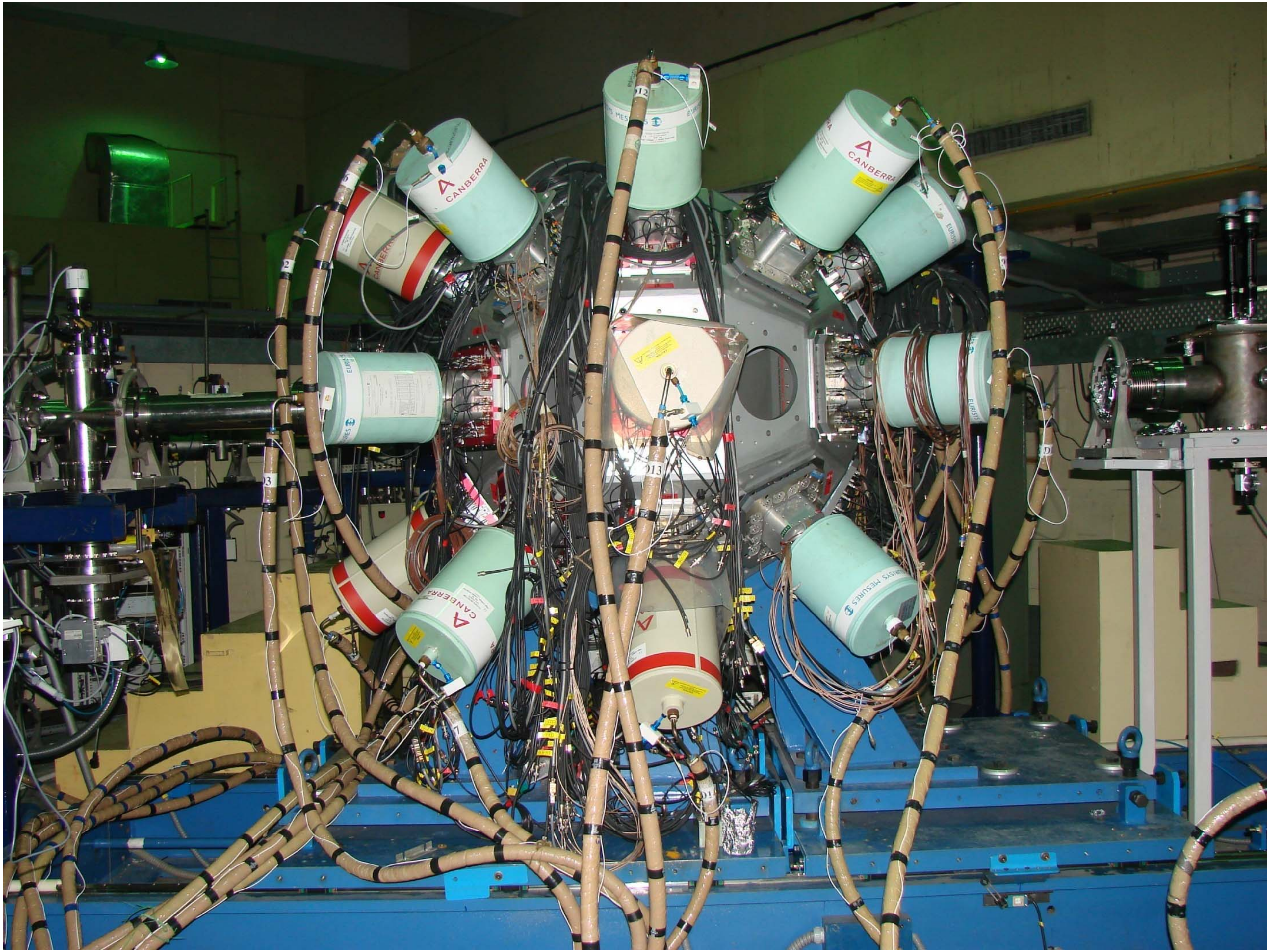
Annular PPAC



Thin-film detector

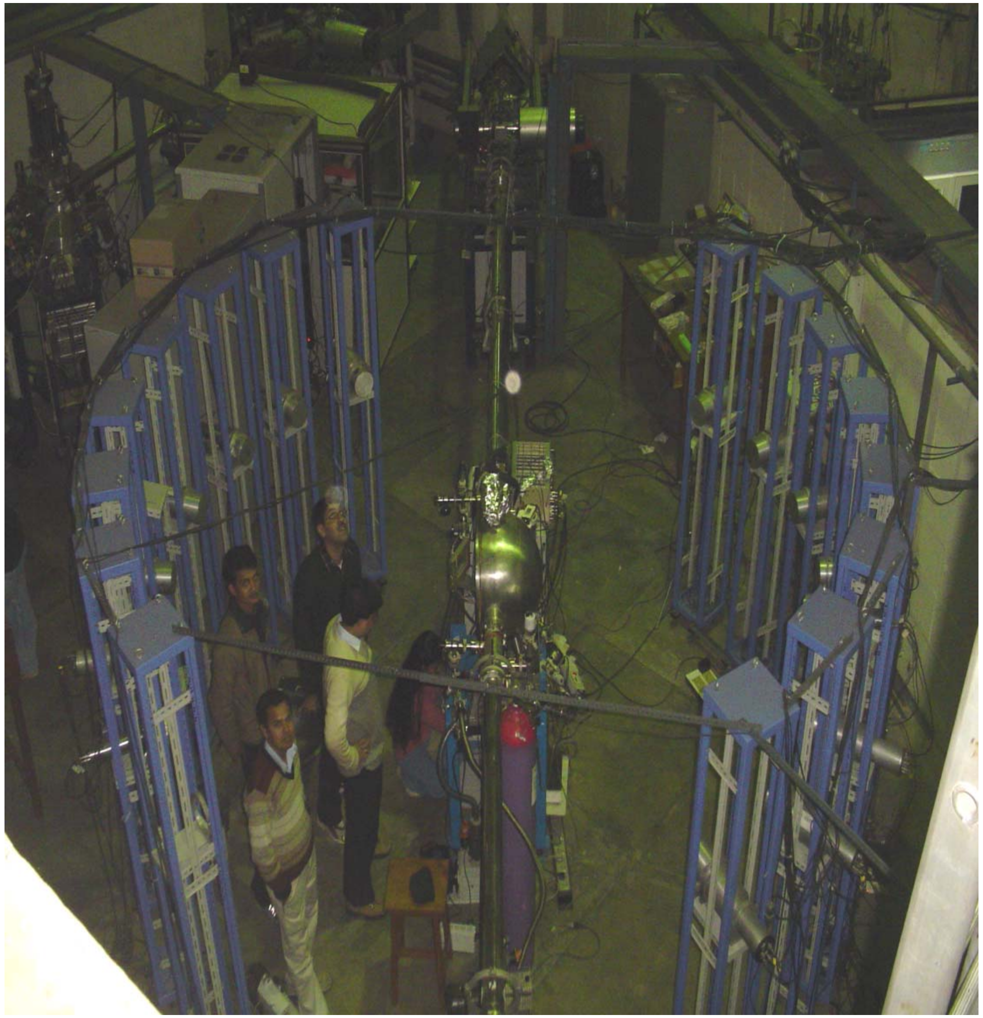
Specifications of INGA

- Solid angle 25 % of 4π
- Photo peak efficiency ~ 5 % with Clover Ge
- Detector 24 Clover, and 6 LEPS
- Detector to Target distance 24 cm
- Clover 89% HPGe Volume
- Plunger device to be added
- INGA (16 Clover) + HYRA in 2011


CANBERRA

National Array of Neutron Detectors (NAND)

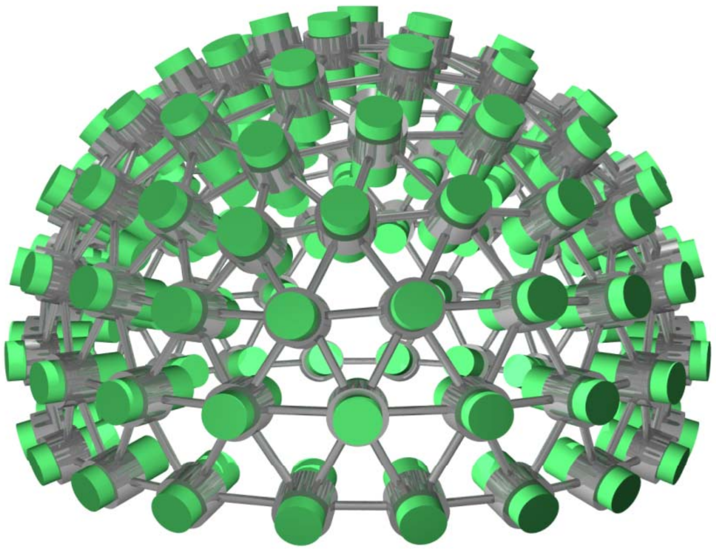
For fusion-fission dynamics studies



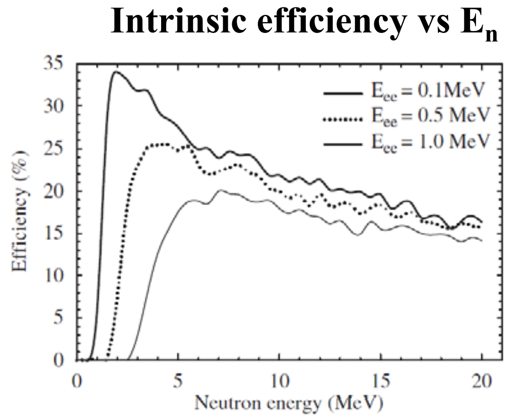
Salient features

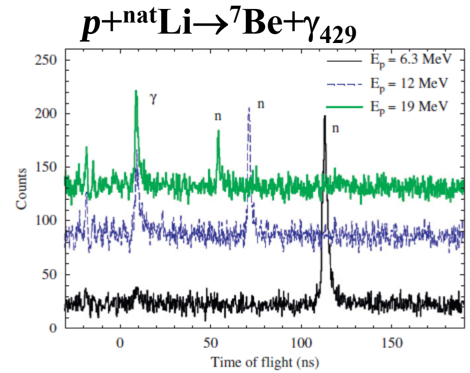
100 detectors at 1meter distance
5" × 5" BC501 liquid scintillators
Total solid angle coverage ~ 10 %

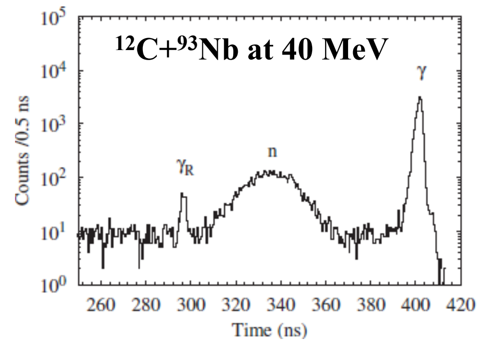
Angle between nearest detectors: ~15o
Eight 5" × 3" MWPCs for Fission Detection



Neutron detector array for TOF measurements





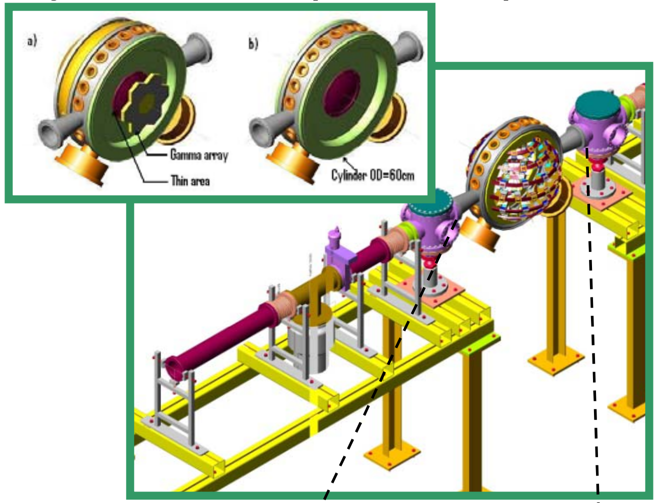


16 nos. fast plastic scintillators (6 cm × 6 cm × 100 cm) with PMTs at either end (1 m^2 area)
ΔTOF~1.2 nsec at Eee ~100-300 keV, Δx ~ 20 cm

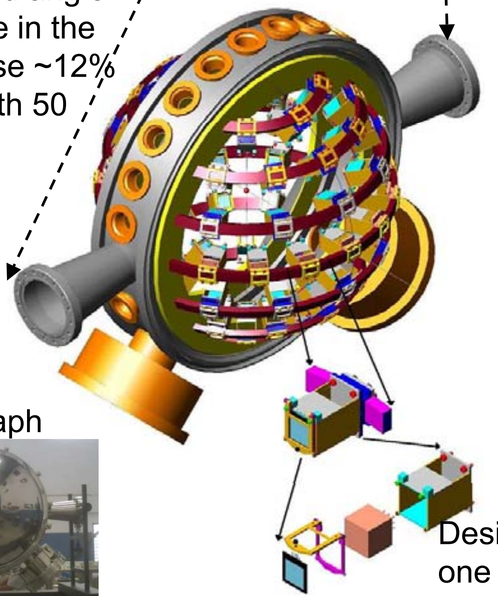
*Rout et al., NIM A**598, 5**26 (2009)*

Charged Particle Detector Array

A scattering chamber that can be configured in compact cylindrical, hemi-spherical or spherical shapes



Total solid angle coverage in the first phase ~12% of 4π with 50 detector modules



Photograph

Design of one detector module

50 Si-CsI detector telescopes for Z and energy information of heavy ion reaction products

Field of study:

(i) Fusion-fission dynamics

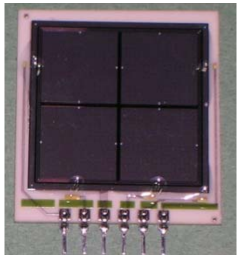
(ii) Nuclear structure at elevated temperatures and angular momenta

(iii) Nuclear clustering

and related fields

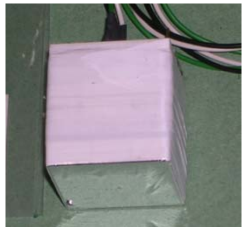
Detector specifications and test results

Ion implanted silicon pad detectors (BARC make)



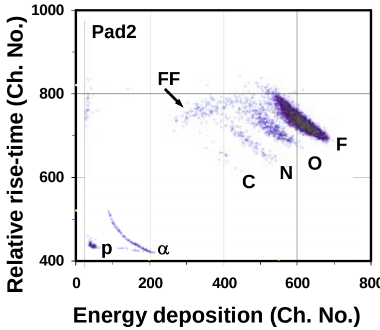
300 μm thick wafer, four pads 10x10 mm

CsI(Tl) detectors (SCIONIX make)



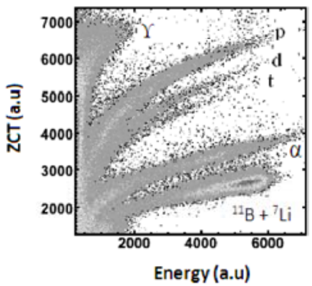
10 mm thick crystal PIN diode readout

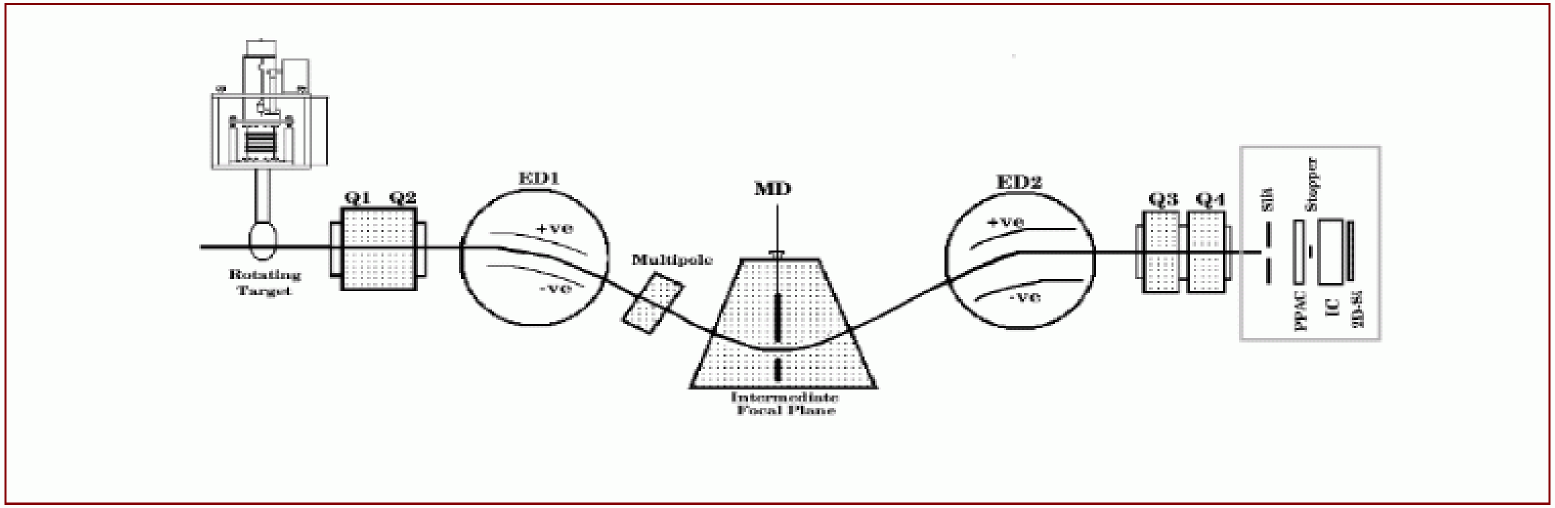
PSD for ion identification



Test results from typical reactions

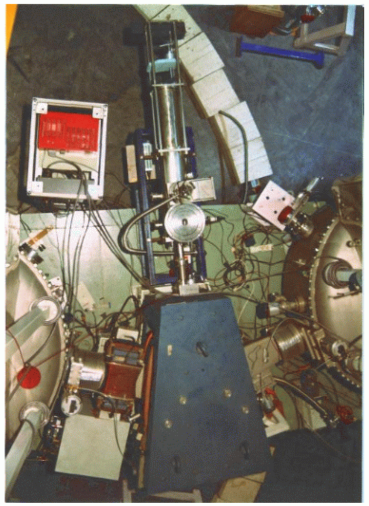
PSD for LCP identification





Heavy Ion Reaction Analyzer (HIRA) set up in 1991

Beam rejection > 1012 (best)
Heaviest CN ~ 203Bi (recent)
Highest voltage on EDs ~ 188 kV
Largest angle ~ 25 degrees
Calibration of NMR for energy



^{7}Be RIB parameters:

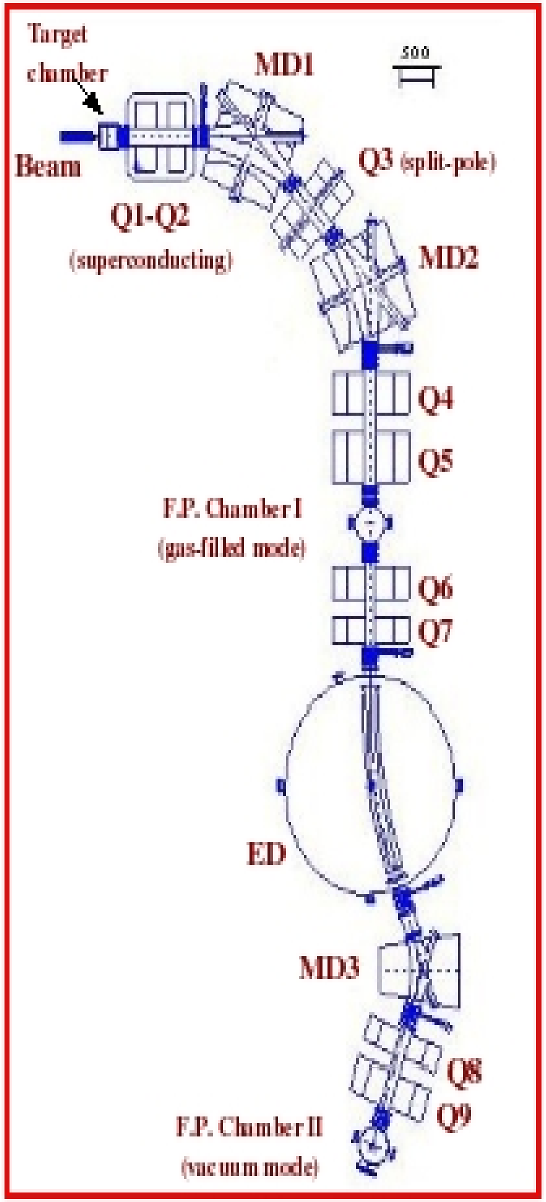
Method: p(^{7}Li,^{7}Be)n
Inverse Kinematics
Purity > 99 %
Energy ~ 12 to 21 MeV
(1 MeV spread)
Intensity ~ 10^{3} – 10^{4} pps
Spatial ~ 4 mm (FWHM)
Angular ~ +/- 30 mrad

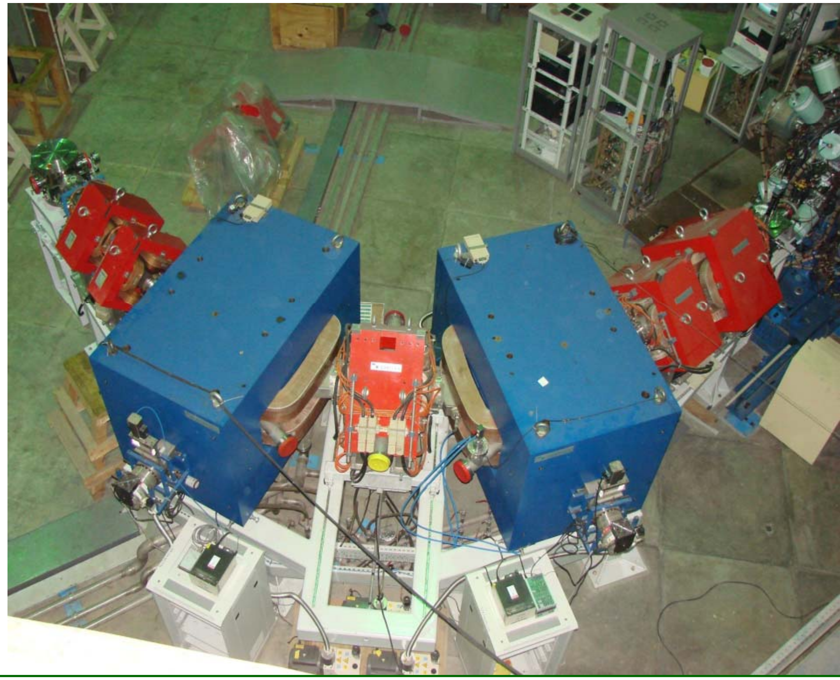
Dual Mode Operation of HYRA-HYbrid Recoil mass Analyser

- **Gas-Filled Mode:** (First stage)
- For A > 200 amu
- Normal Kinematics
- Good Collection Efficiency (q, v focus)
- Z, A identification using recoil decay technique

- **Vacuum Mode:** (Both stages)
- For N ~ Z (~ 100 amu)
- Inverse Kinematics
- Good primary beam rejection (two stage)
- Z, A identification using X, ΔE, E measurement

HYRA spectrometer (Gas-Filled Separator / Vacuum Mode RMS)
(Funded by DST,Govt. of India





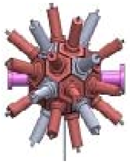
Heavy Fusion Residues
With large eff along beam direction in gas filled mode

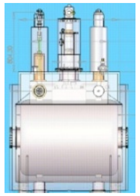
Secondary Radioactive Beams in momentum Achromat (vacuum)mode

Selection of medium mass evaporation residues with large eff Along beam direction In inverse kinematics

FUTURE PLANS - HYRA

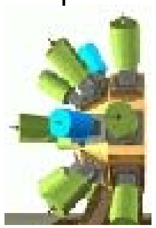
TIFR Spin Spectrometer



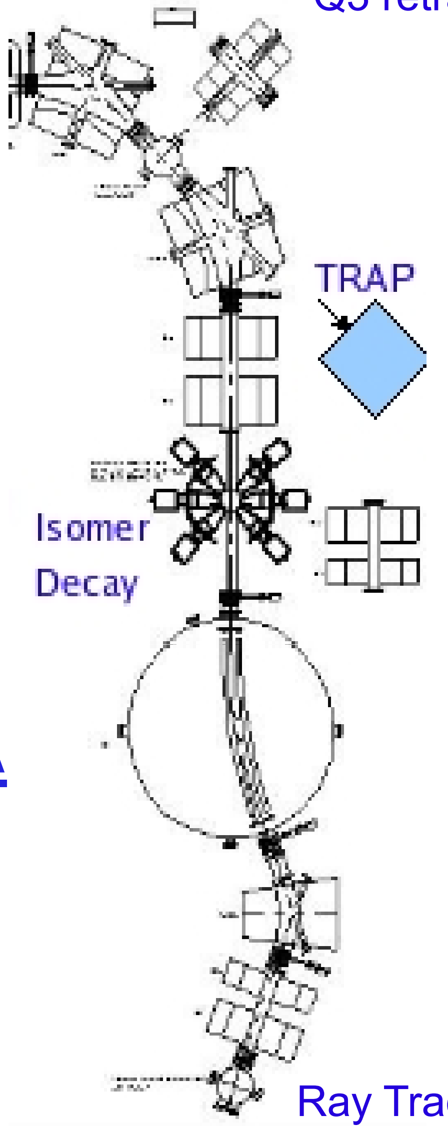


Superconducting Q1Q2

Indian National Gamma Array



Q3 retracted



Q6Q7 retracted

Ray Tracing (vacuum mode)

Momentum Achromat for light Radioactive Ion Experiments

For light nuclei : (p,n), (d,n), (p,d) reactions

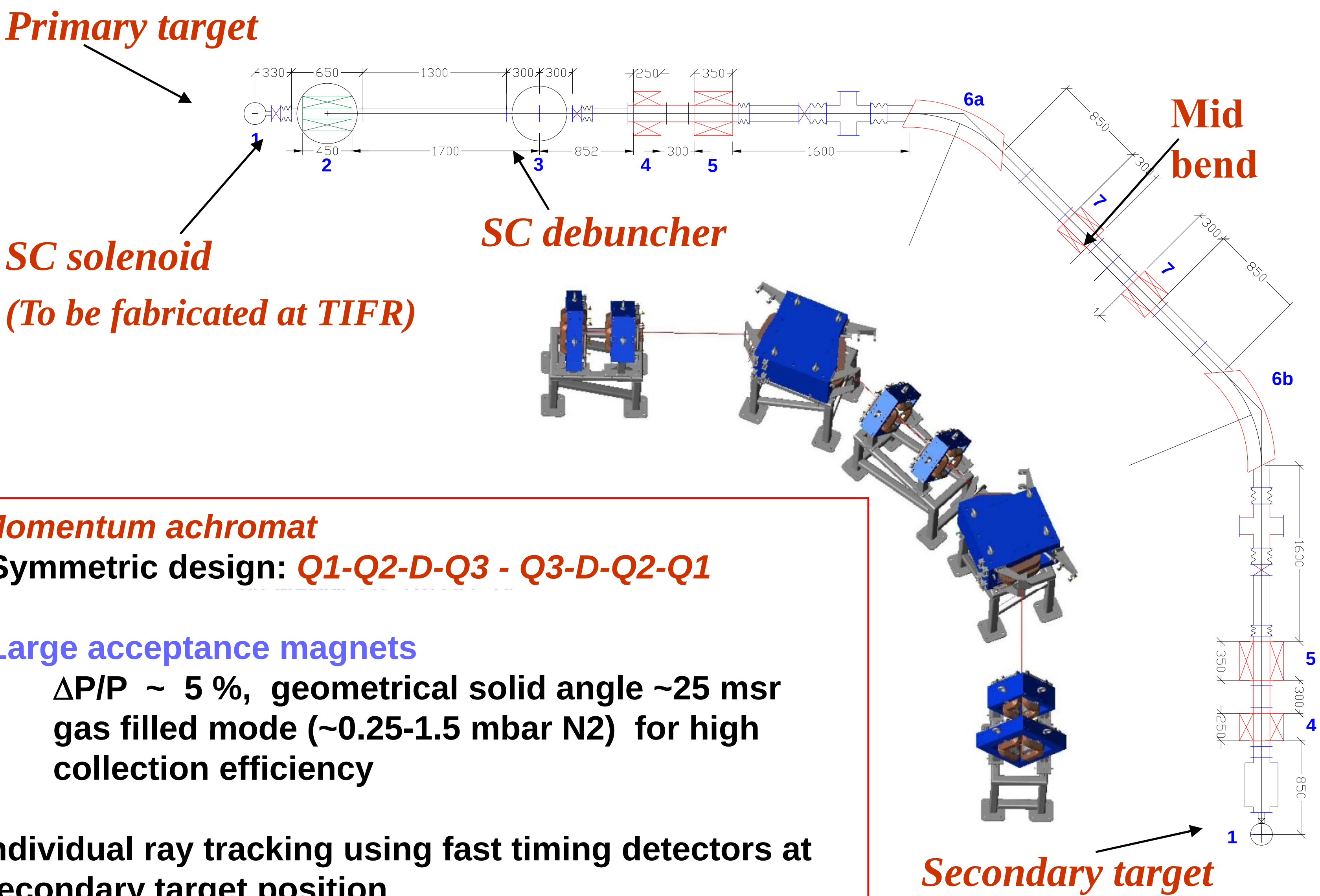
A primary target should be able to handle large beam current and introduce as little straggling as possible.
Small beam spot and good timing at primary target spot essential.
Identification and characterization of secondary beam

- **Magnetic field setting (hall probe measurement) –Br**
- **TOF w.r.t. RF**
- **a thin degrader foil at half point**

Primary Beam rejection
For light ions change in q is large
Dipole chambers have Ta lining on inner sides
Gas filled mode will also be helpful for isobaric separation
Adjustable stoppers at mid bend

Residue tagging in normal kinematics is also possible for heavy ions
- enable separation of CF/ICF/beam like events.

Magnetic Separator for RIB



Momentum achromat

Symmetric design: ***Q1-Q2-D-Q3 - Q3-D-Q2-Q1***

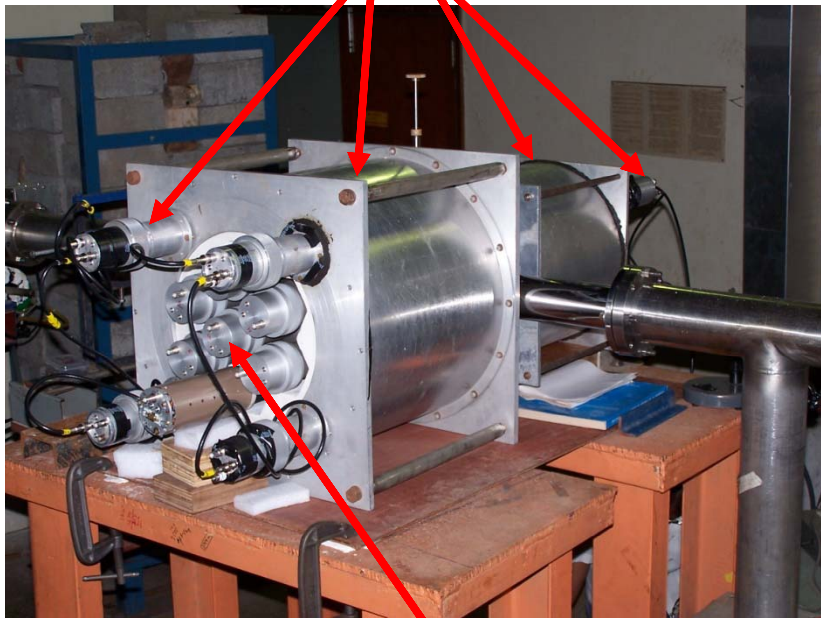
Large acceptance magnets

ΔP/P ~ 5 %, geometrical solid angle ~25 msr
gas filled mode (~0.25-1.5 mbar N2) for high collection efficiency

Individual ray tracking using fast timing detectors at secondary target position

BaF_2 detector Arrays
For High Energy Gamma Rays

Cylindrical Plastic Scintillator Shield For Cosmic Ray rejection and its PMT

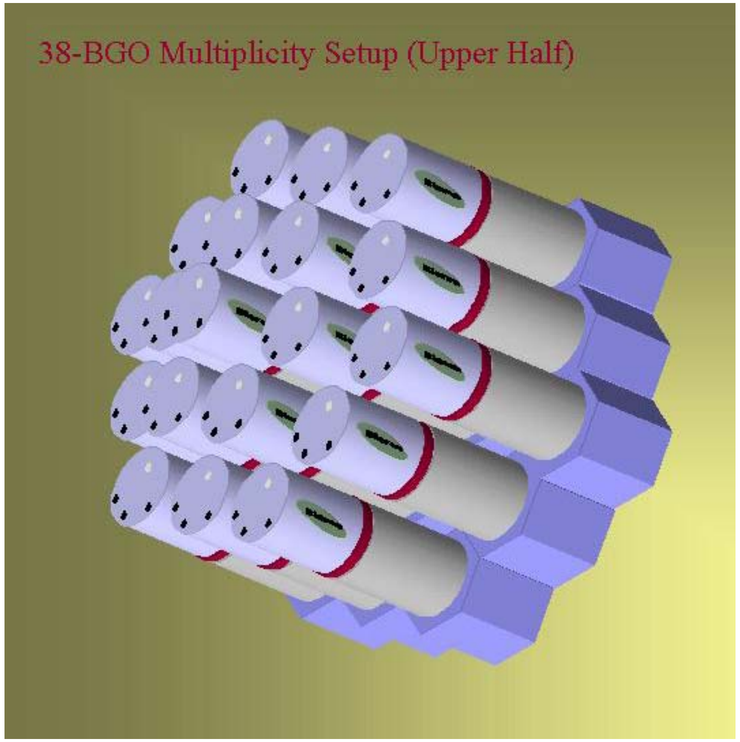


BaF_2's PMT

Each array has 7 closed packed detectors
Length: 20 cm (of each type)
Hexagonal cross section height: 9 cm
" " (small array): 6 cm

Timing: FWHM ~ 1 ns
TOF was used to discriminate the neutron

38-BGO multiplicity set-up
For Angular Momentum measurement



Efficiency ~ 70%

Light & Heavy Ions For Nuclear Physics Research

LIGHT & HEAVY IONS

VERY LOW E 1 to - 5.5 MeV	1 MV (CG) TIFR 5.5 MV(VDG) BARC PU cyclotron IIT(Kanpur)	Isobaric Analogue Resonances Nuclear Spectroscopy of Low Lying States Coulomb ex Nuclear Optical Model at Sub-Coulomb energies CP,n-fission
LOW E 30 MeV p 80 MeV α	K = 130 (VEC) VECC	Quasi Molecular Resonances High Energy Gammas Nuclear Fission
MEDIUM E 1 - 7 MeV/A	14 MV(Pellet) (TIFR) 15MV(Pellet) (IUAC) HI (VEC) VECC IOP,FOTIA	Sub-Barrier Fusion &Pre-Equilibrium Fission High Spin Spectroscopy GDR IMF Breakup Orbiting Pheno.
HIGH E 10 -50 MeV/A	SC Linac (TIFR,IUAC) SCC (VECC) ECR + SC Linac	DIC & QF Weakly Bound Proj. Multifragmentation LGP PEQ Spectroscopy of HN & LN RIB Nuclei at Extreme Ex, J , T & A

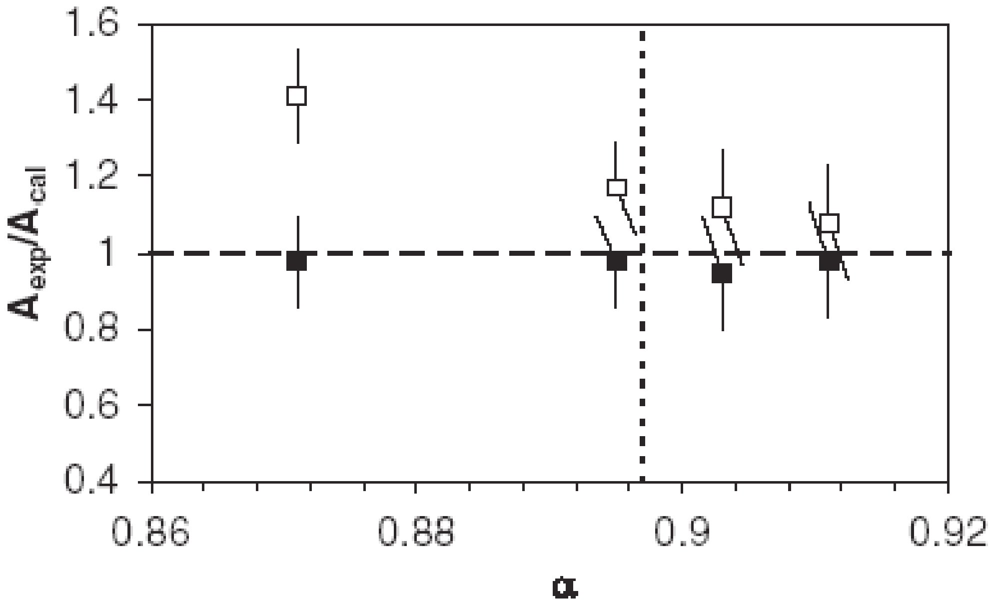
Entrance Channel Dependence of Fission Fragment Anisotropy
$^{11}B+^{237}Np$, $^{12}C+^{236}U$, $^{13}C+^{235}U$, and $^{16}O+^{232}Th$.

α	0.911	0.903	0.895	0.871

$\alpha = (A_T - A_P) / (A_T + A_P)$

Phys.Rev.C

77, 021601(R) (2008)



Ratio of experimental and calculated anisotropy (A_{exp}/A_{cal}) versus entrance channel mass asymmetry α. The open squares are the results when A_{exp} are compared with A_{cal} obtained using the SSPM (only CN fission). The filled squares are obtained when A_{exp} are compared with A_{cal} obtained using the prescription of Thomas *et al.* [15] (both CN fission and PEF). The vertical dotted line represents the α_{BG} boundary.

Temperature and angular momentum dependence of giant dipole resonance in nuclei with A~150

The contribution of thermal shape fluctuation and collissional damping to the GDR width is an open question. The T-dependence of the width has different forms in the two processes, the latter being more steeply varying.

A systematic study for a given compound system at widely different excitation energies and covering a broad range of angular momentum can address the issue better.

The present work constitutes such measurements.

Experimental features

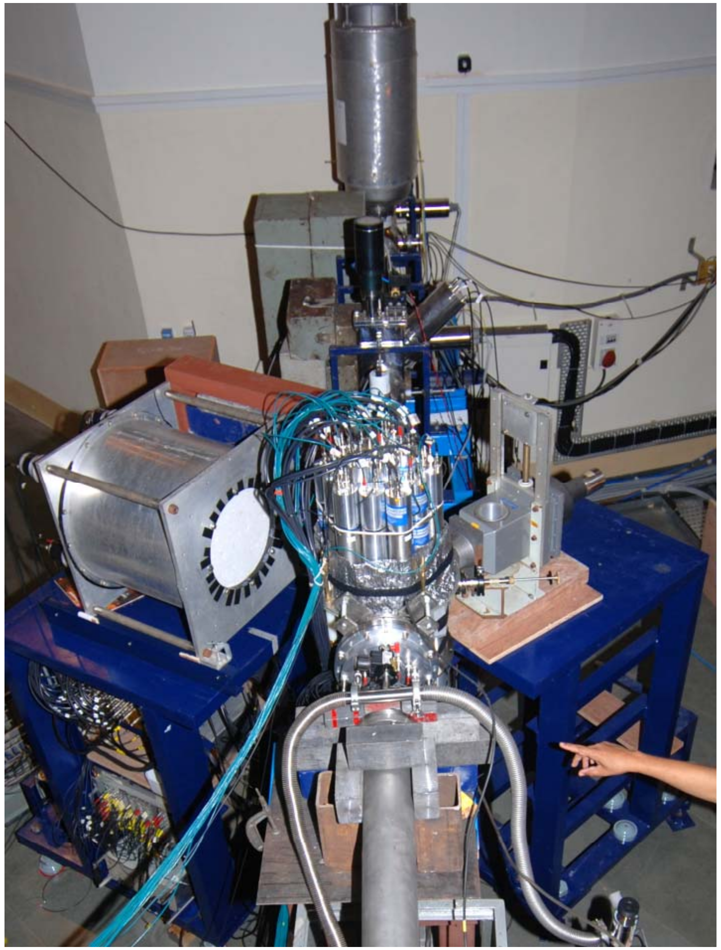
$^{28}Si + ^{124}Sn$ at $E(^{28}Si)$ = 149 and 185 MeV

^{28}Si beam from PLF, Mumbai

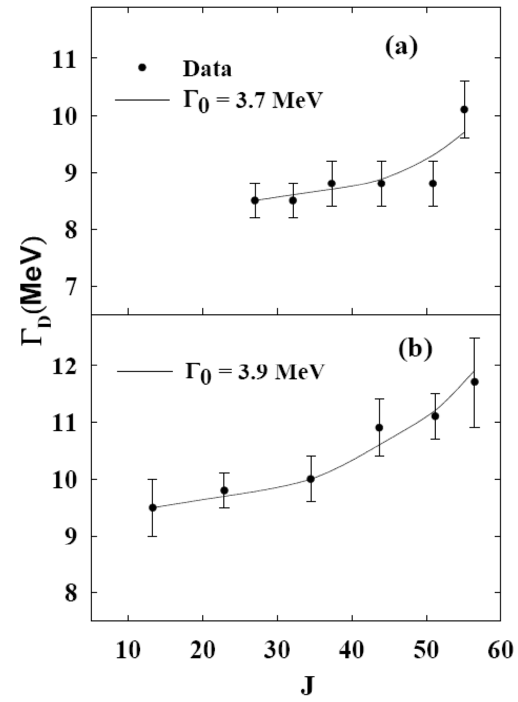
Exclusive high energy gamma spectra with low-energy gamma multiplicity gating.
Fusion residue gating at the higher energy.

Statistical model analysis with simulated Monte-Carlo CASCADE code

T and J dependence explicitly included at every step of GDR gamma emission in the code. The procedure is free of the uncertainty in defining average T and J for various multiplicity gates while comparing with a calculation.

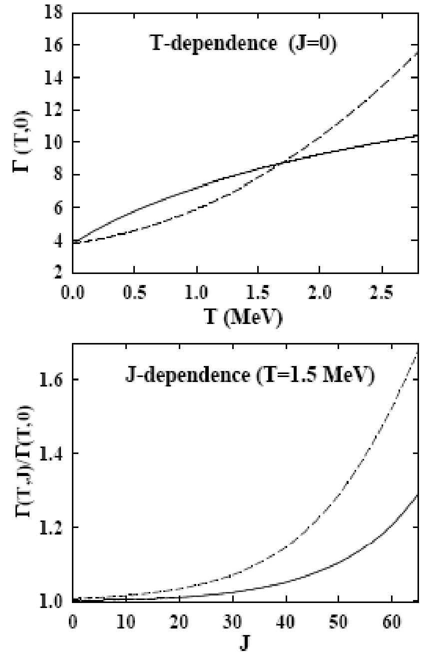


Final Results



Experimental GDR width for various multiplicity windows plotted against the representative J-values

Solid lines – calculated using the (T,J) dependence described by the dashed lines in the adjacent figure



Dashed lines: T and J dependence of GDR width needed to explain data

Solid lines : Global thermal shape fluctuation model calculation

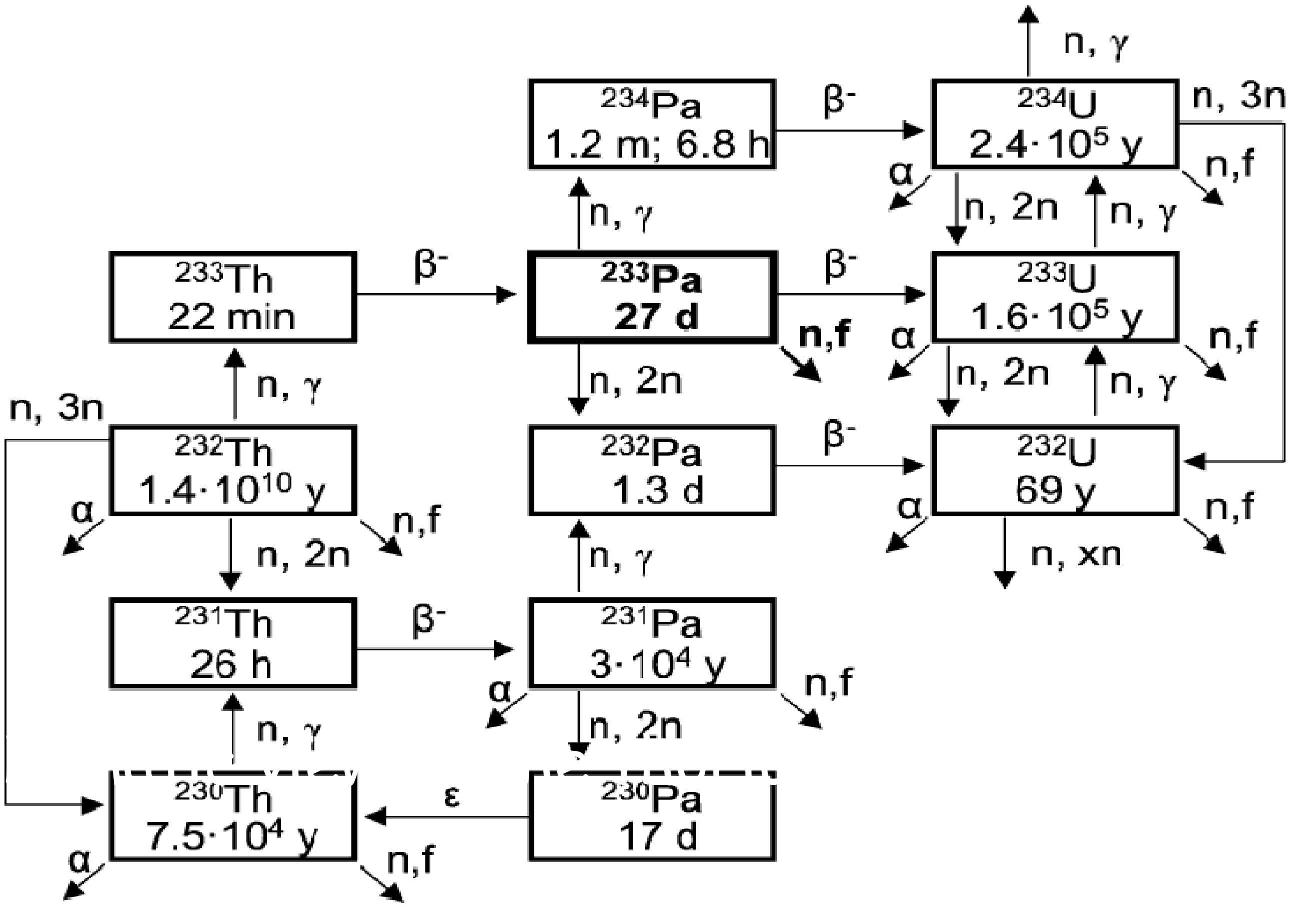
Conclusions:

1)Global TSFM calculation cannot explain the data

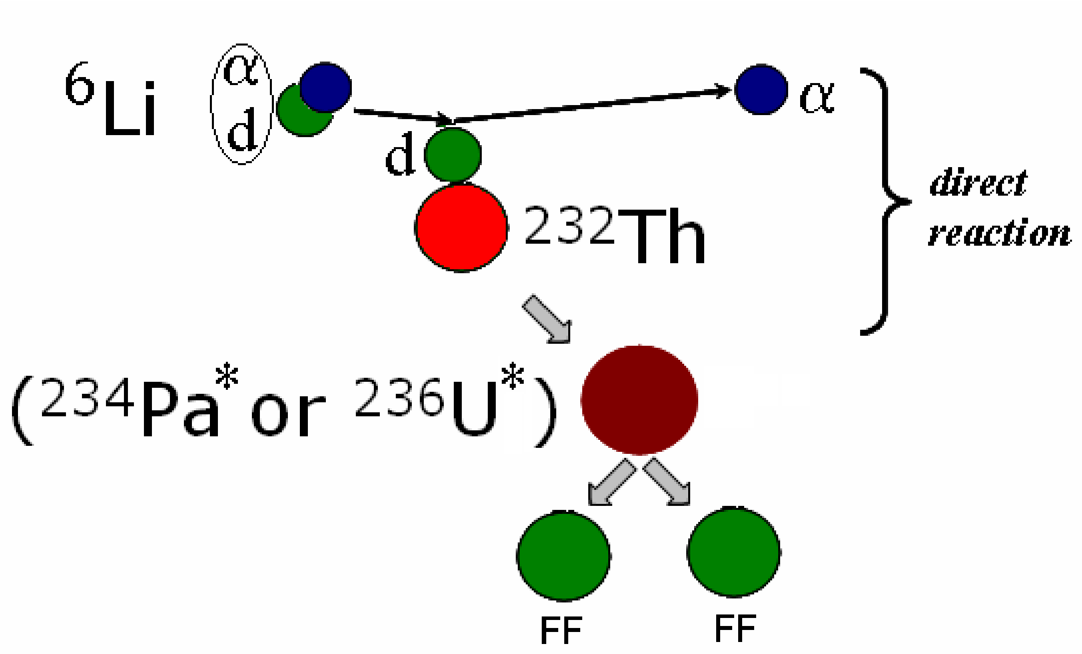
2)T-dependence has contribution from collisional damping also.

3) The J-dependence is steeper than the TSFM results

Isotopes in the Th-U fuel cycle



$^{6}Li + ^{232}Th$ transfer reaction (as the Hybrid Surrogate reaction)



By carrying out PLF-FF coincidence measurement, we can determine the decay probability of the compound residues.

$^{6}Li+^{232}Th$ transfer reaction

$^{232}Th(^{6}Li, \alpha)\rightarrow^{234}Pa$

$Q_{gg}=6.769$ MeV

$^{232}Th(^{6}Li, d)\rightarrow^{236}U$

$Q_{gg}=-6.047$ MeV

$Q_{opt}= [(Z_f/Z_i)-1)]E_{c.m.}$

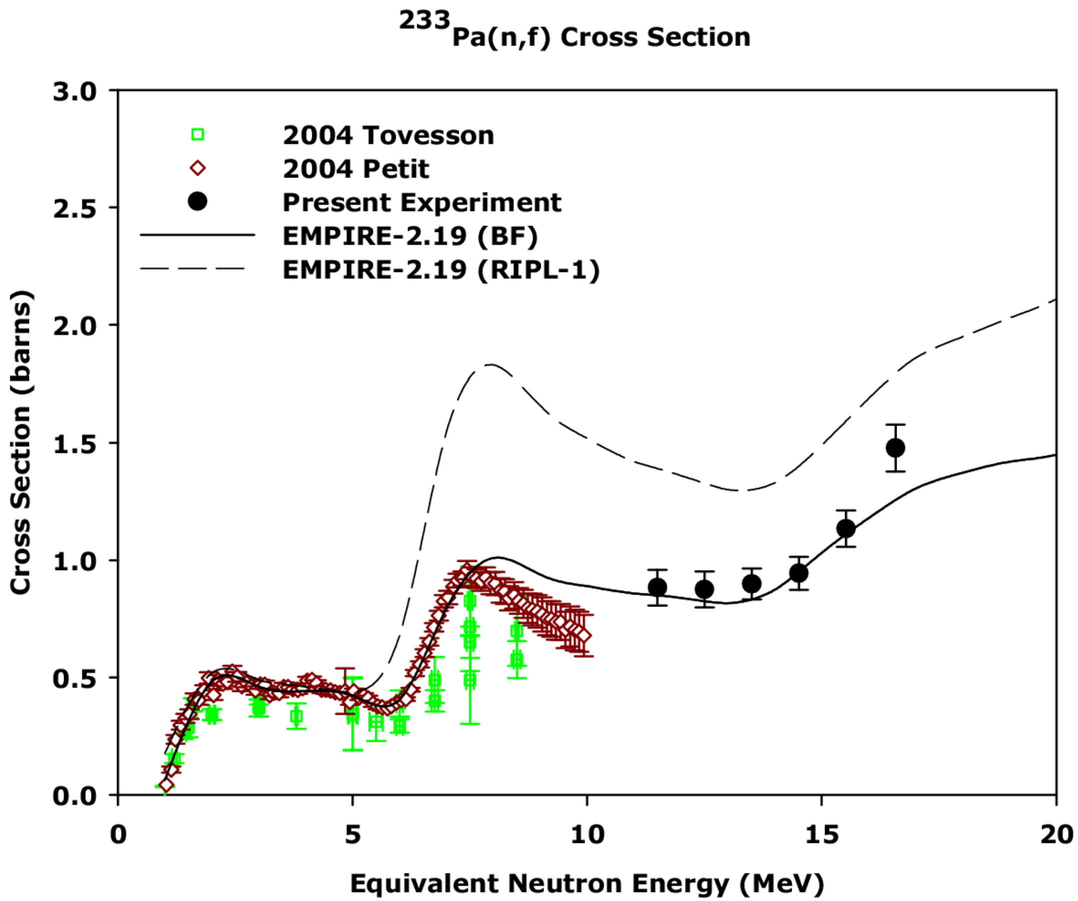
$E_x=Q_{gg}+Q_{opt}$

At $E_{lab}=$ 38.0 MeV

($^{234}Pa^*$) α -peak = 19.0 MeV

($^{236}U^*$) d-peak = 18.5 MeV

Determination of the ^{233}Pa(n, f) reaction cross-section from 11.5 to 16.5 MeV neutron energy by hybrid surrogate ratio approach



232Th+6Li

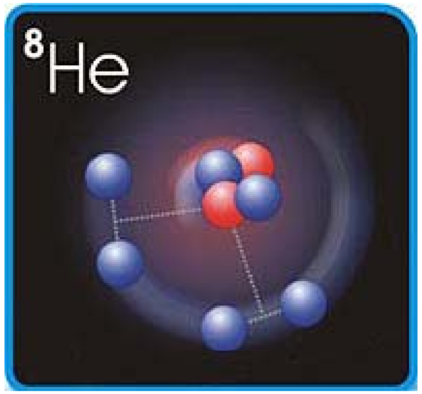
232Th+4He (235U+n)

232Th+2H (233Pa+n)

B.K.Nayak(Phys Rev. C (2009)rapid

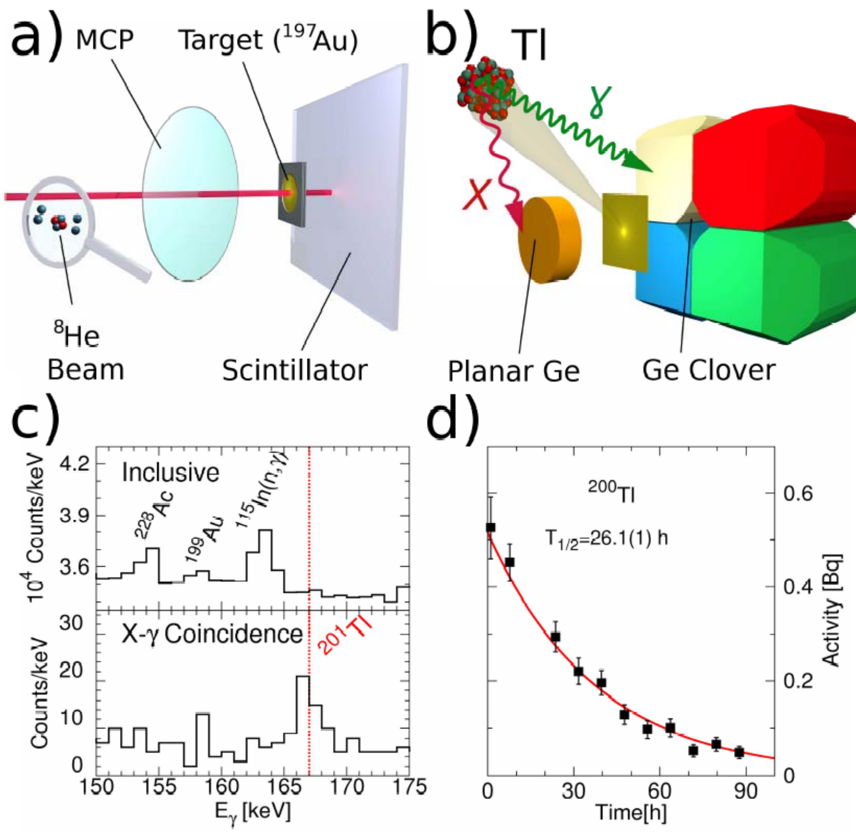
Tunneling of the most neutron-rich nucleus (@ Ganil)

^{8}He: largest N/Z ratio, strong di-neutron correlations
interesting case to study tunneling probability

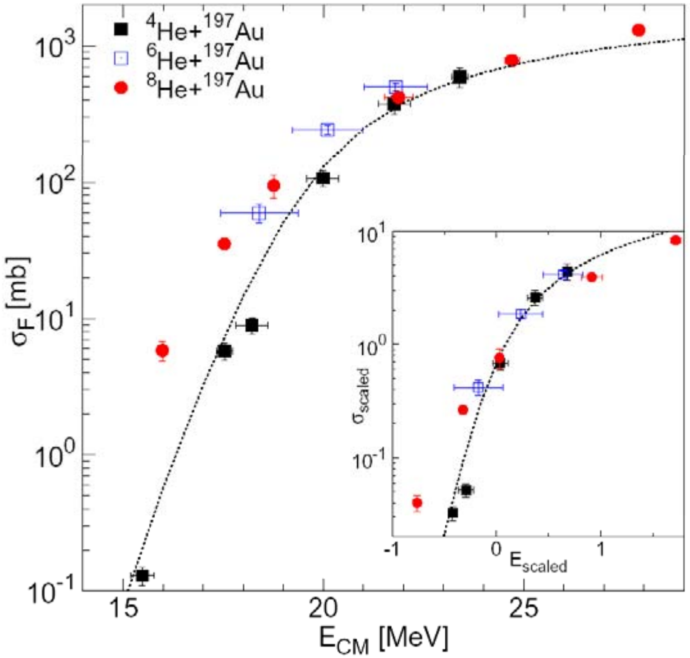


sensitive off beam technique

4x10^{5}pps



Comparison of tunneling in He isotopes



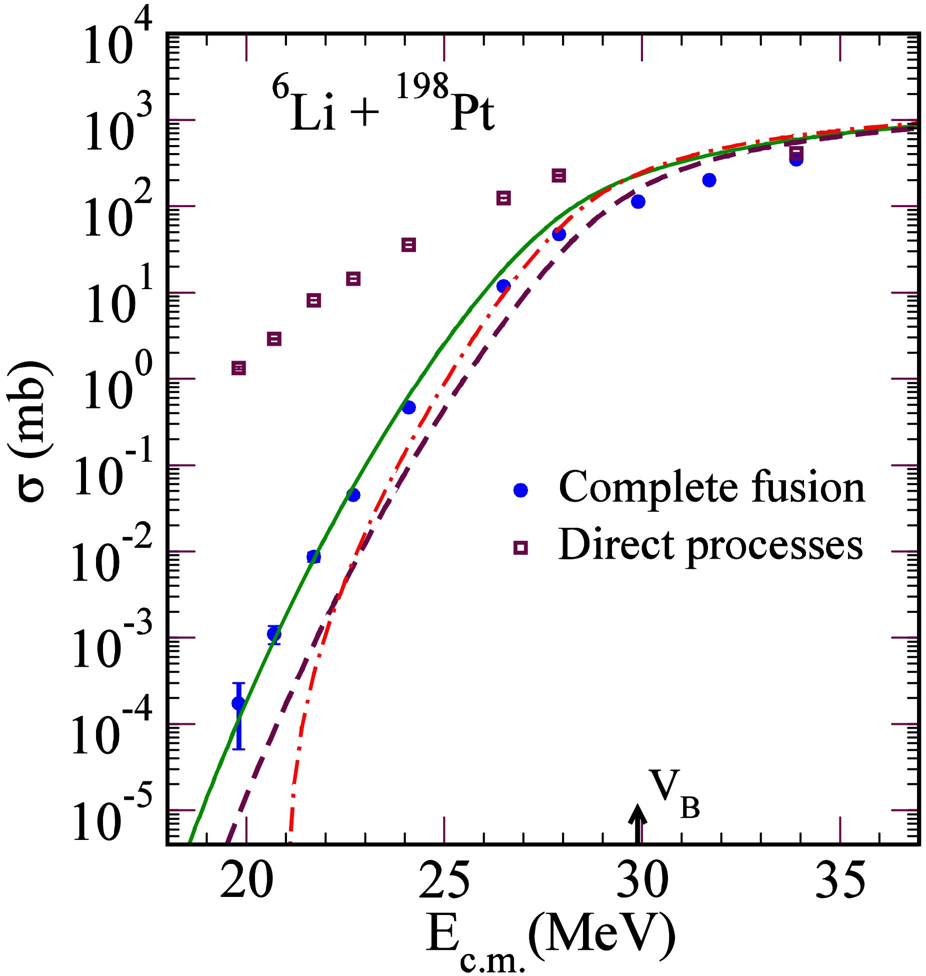
σ_{fus}(^{6,8}He > σ_{fus}(^{4}He) expected
σ_{fus} (^{6}He) ~ σ_{fus}(^{8}He) unexpected

Unusual behavior of tunneling of ^{8}He compared to lighter helium

PRL 103, 232701 (2009)

Fusion cross-sections

A.Shrivastava et al. (PRL(2009)Dec)



Coupled channels calculations
CCFULL (WS potential)
Solid curve: with coupling to 198Pt and 6Li inelastic states
Dashed curve: no coupling

Single channels calculations
M3Y+rep core – dashed dot line

Coupled channels explain data over entire energy range
No fusion hindrance observed
Transition to Adiabatic from sudden!

Nuclear Physics Programmes

- **Low Energy Nuclear Physics with national accelerator facilities**
- **SHE research with INFN**
- **RIB research with GANIL**
- **Intermediate energy nuclear physics- hadron physics at COSY**
- **Relativistic Heavy In Collisions – BNL, LHC**
- **GSI------**

India -International Collaborations

CERN - LHC India has Observer Status

FAIR, Germany- India is a member

ITER – India is a member

IAEA, Vienna- NDS

MOU with Fermi lab, USA,

GANIL, CEA, ILL, France

RIKEN, KEK,Japan

IBA, Belgium,TRIUMF, Canada

BESSY,Germany,RAL,UK,……

Acknowledgements

- **Thank colleagues**
- **From Mumbai and Delhi Pelletrons**

- **R.G.Pillay**
- **V.Nanal**
- **N.Madhavan**
- **S.Muralithar**
- **D.R.Chakrabarty**
- **V.M.Datar**

B.V.John
B.K.Nayak
P.V.Bhagwat
A.Shrivastava
K.S.Golda
Suresh Kumar