Heavy Ion Superconducting Accelerators: International Scenario

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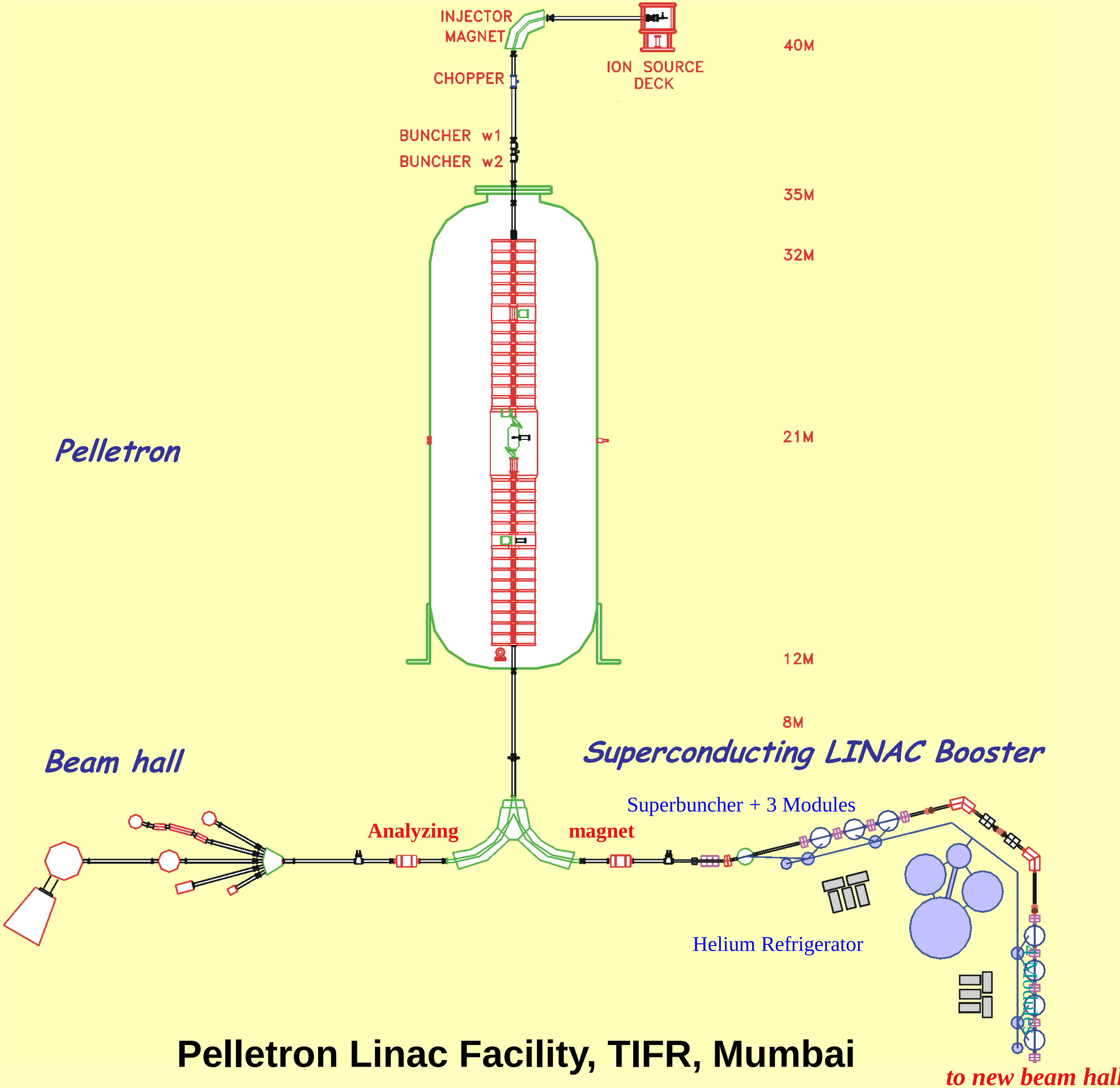
Heavy Ion Accelerators

Configuration

- For low energy Nuclear Physics
  - Physics close to the Coulomb Barrier
  - E/A ~ 5-20 MeV/u → v ~ 10-20 % c
- For H & He – like ions for Atomic Physics
- Accelerating elements (SLINAC)
  - Independently Phased Superconducting cavities
  - β (v/c) ~ 0.05, 0.10, 0.20
- Pre-accelerator
  - Tandem, RFQ, SRFQ, DTL, ultra-low beta S-Cavities



Pelletron Linac Facility, TIFR, Mumbai

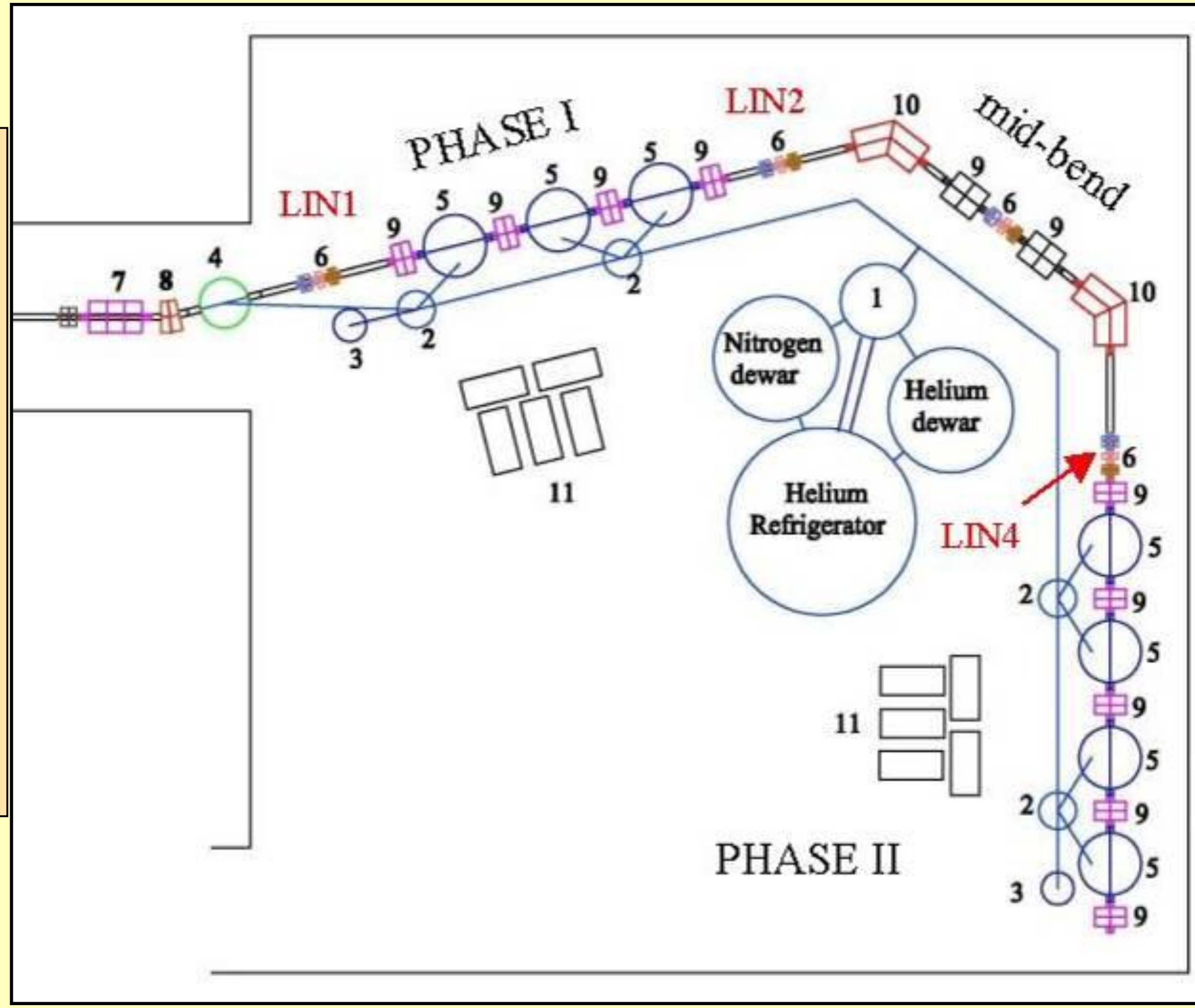
Joint TIFR – BARC Facility

Specifications

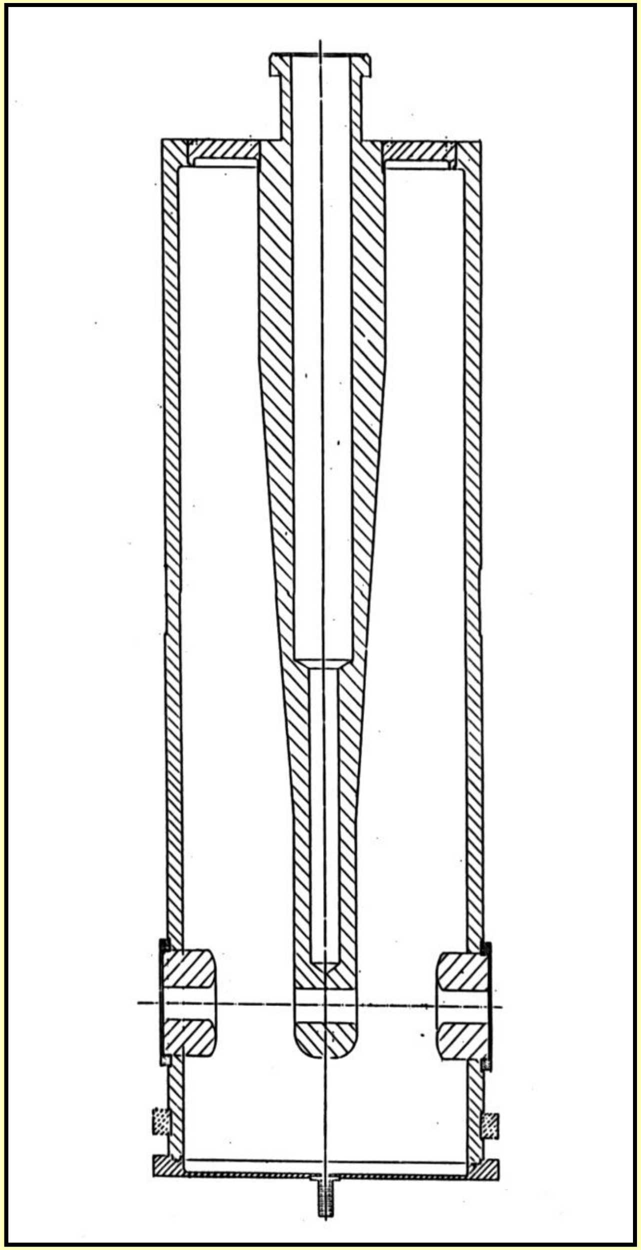
Heavy ions upto A~80
E/A~5-12 MeV

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

Bunch width ~200 ps
Beam Intensity 0.1-10 pnA

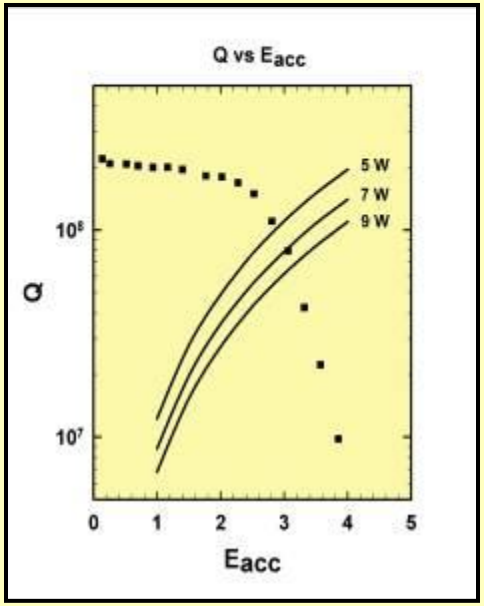


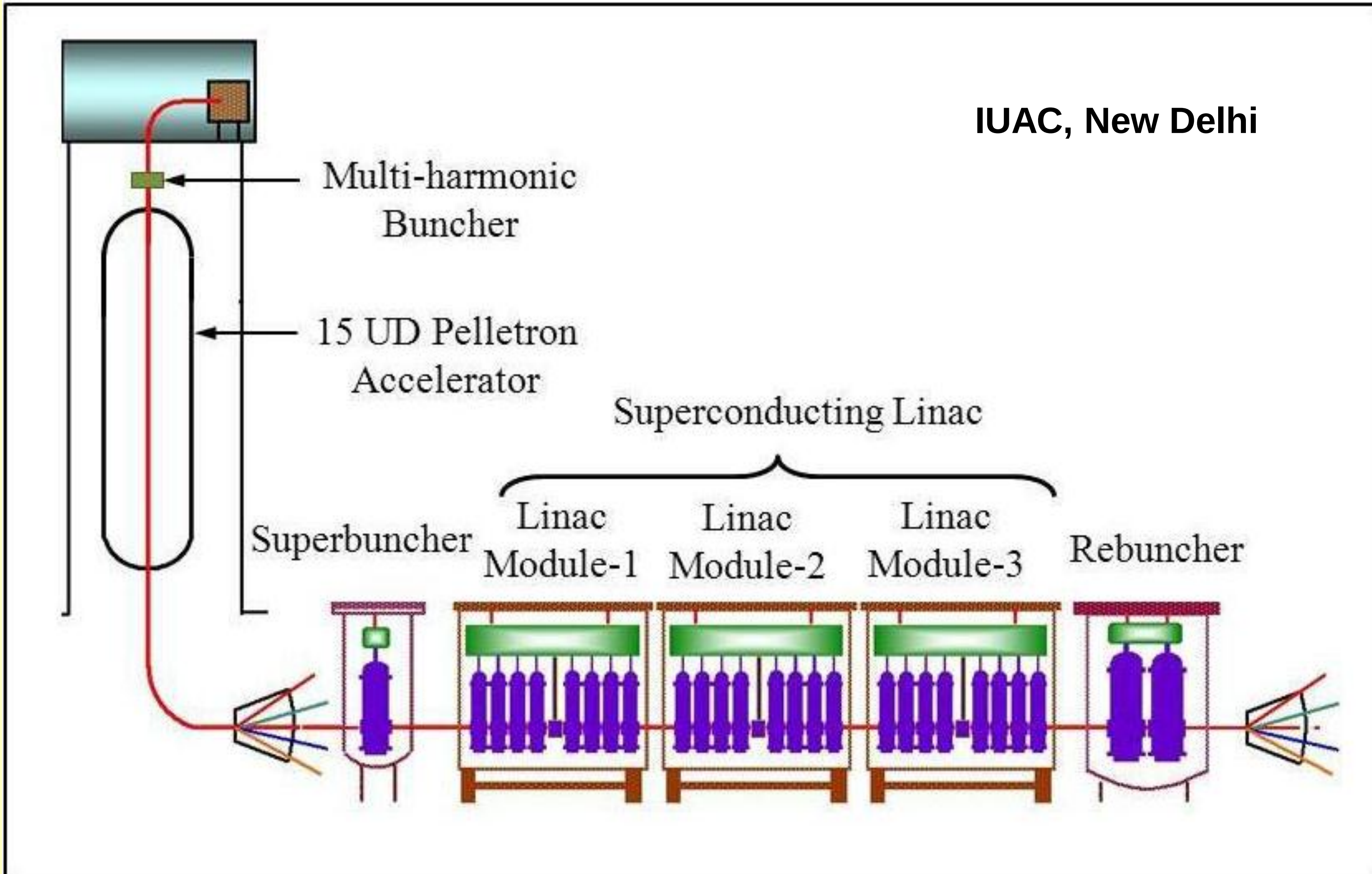
Phase I commissioned on September 22nd, 2002
Phase II commissioned on July 9th, 2007
LINAC dedicated to users on Nov. 28th, 2007



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




IUAC, New Delhi
Multi-harmonic Buncher
15 UD Pelletron Accelerator
Superconducting Linac
Superbuncher
Linac Module-1
Linac Module-2
Linac Module-3
Rebuncher

Nb QWR cavities development

IUAC New Delhi

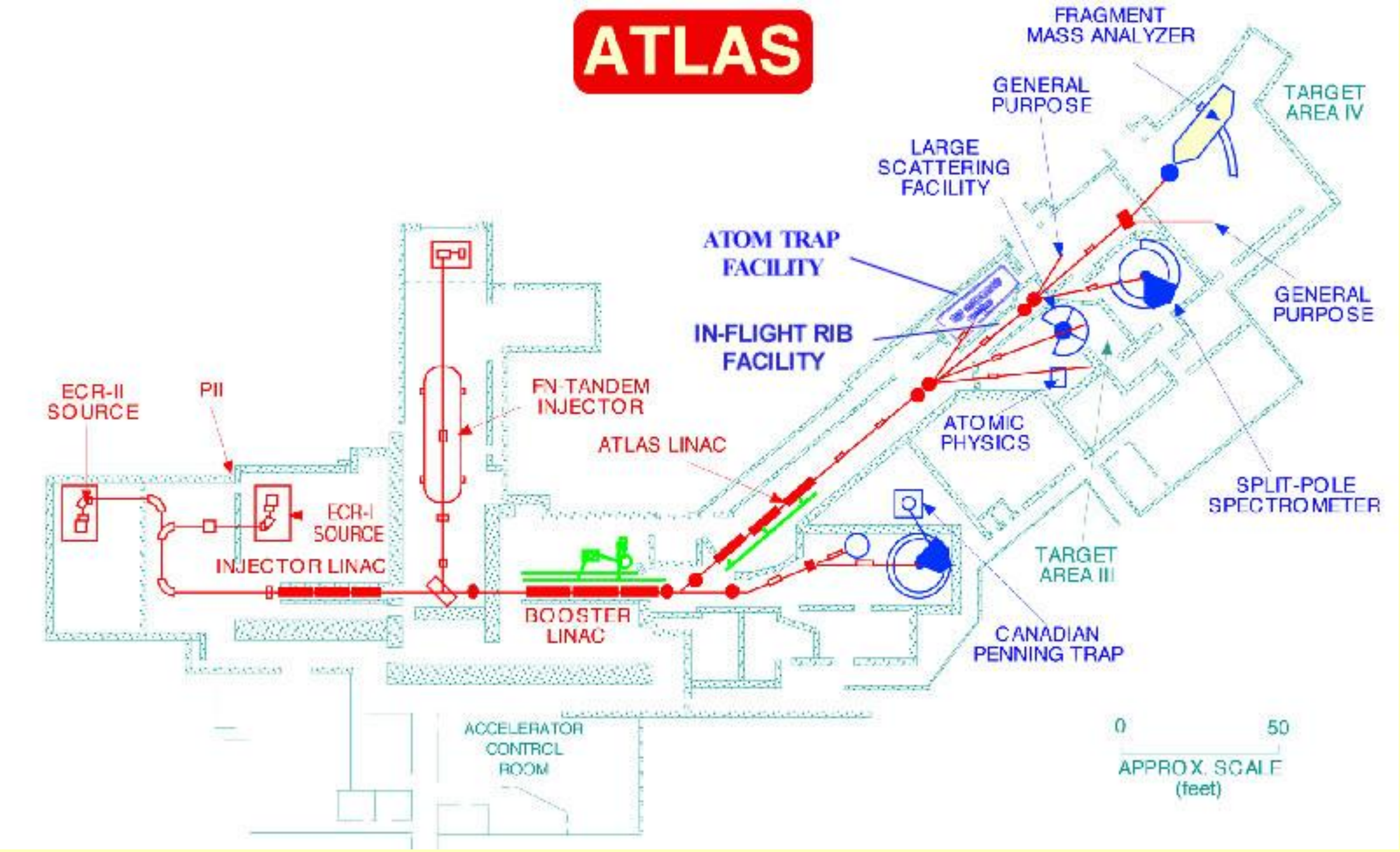
IUAC Linac module with

8 QWRs

Superbuncher cavity

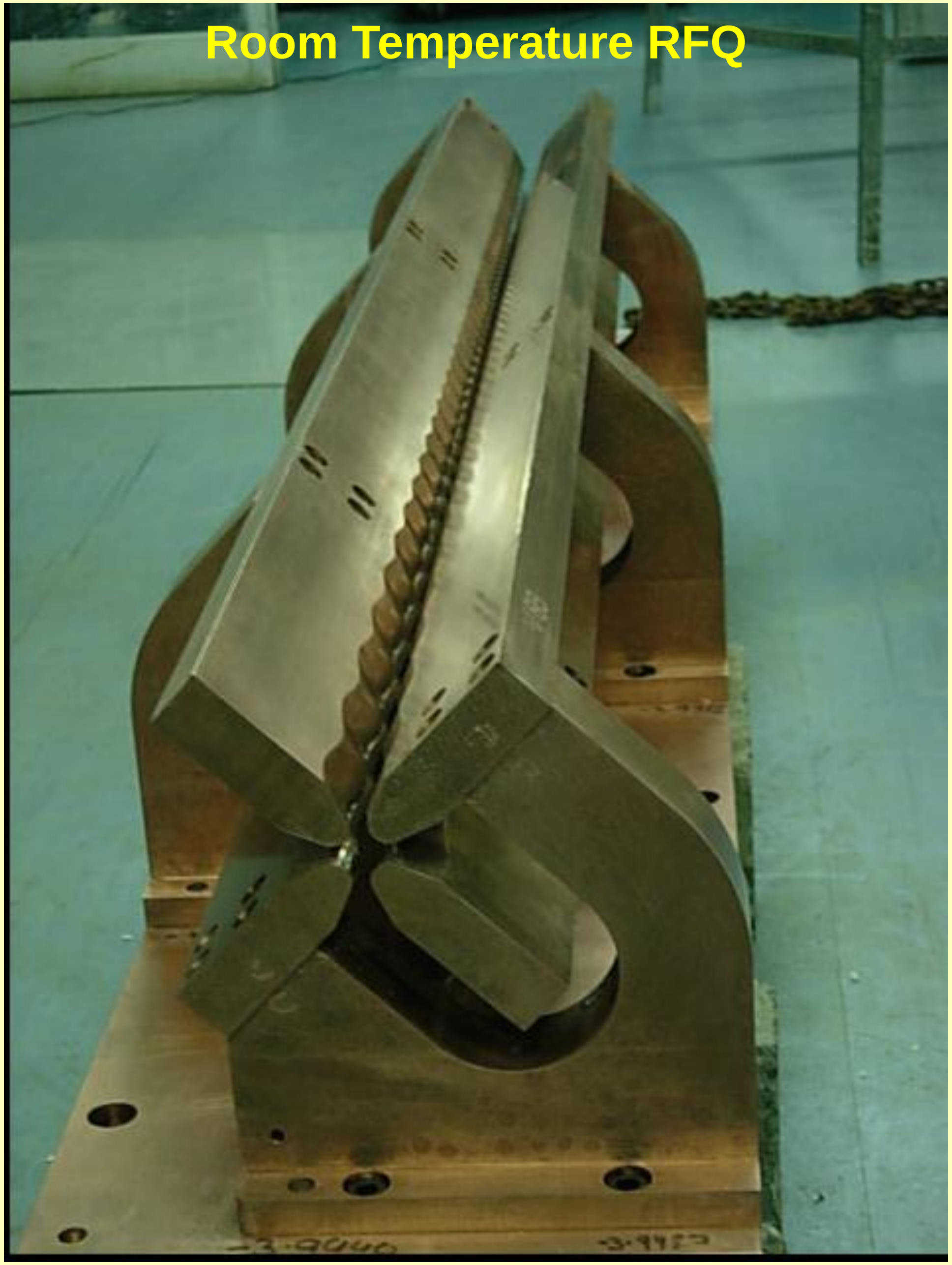
Before Plating

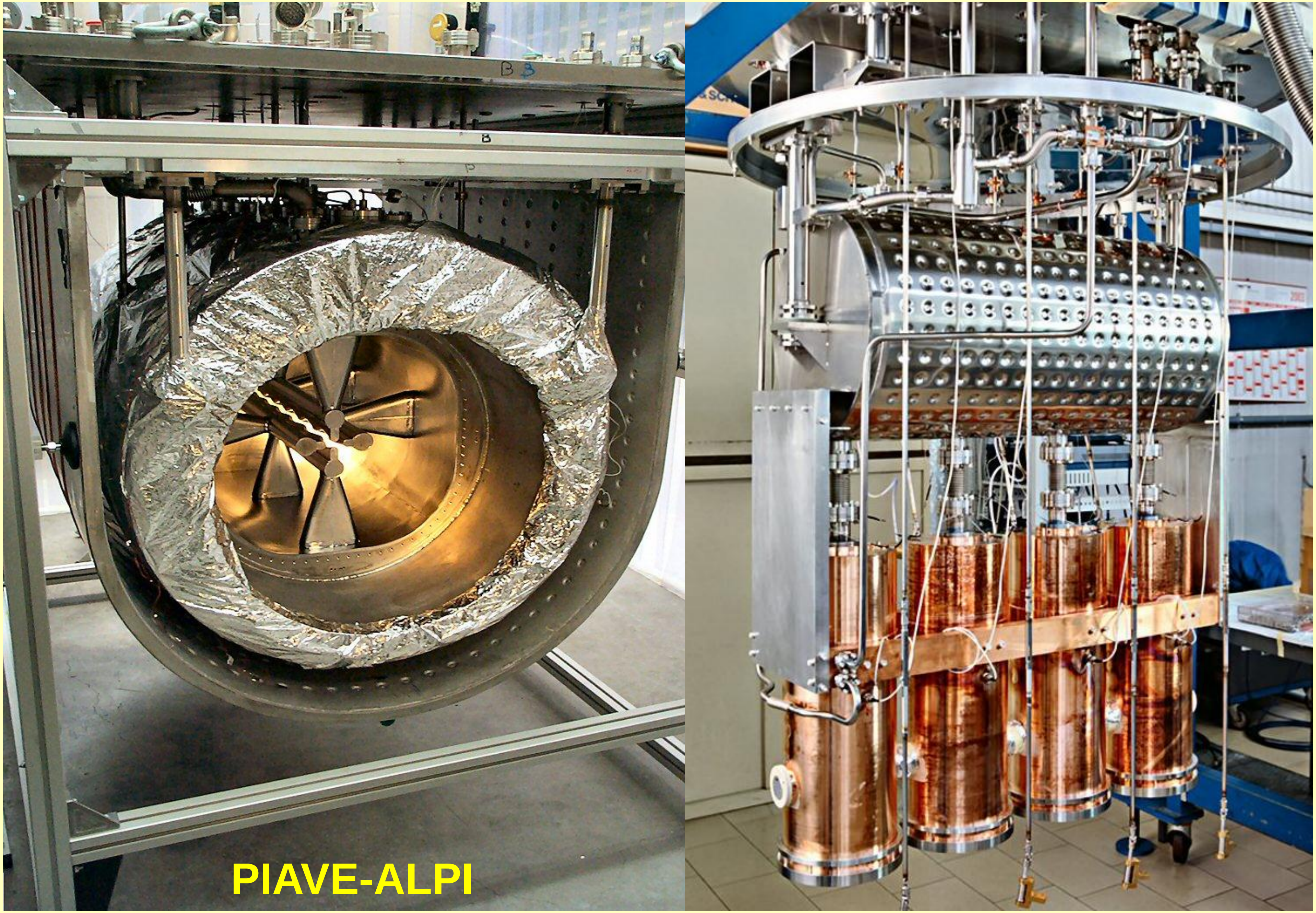
After Lead Plating



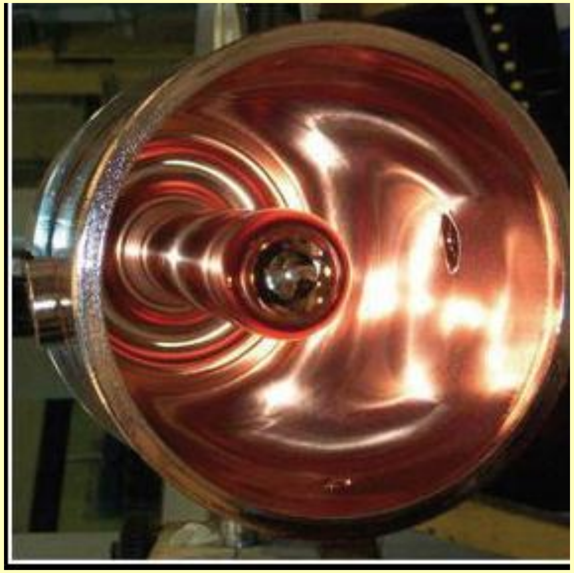
Pre-accelerator inter-digital ultra-low beta cavities
Main LINAC bulk-Nb Split-loop resonators

Room Temperature RFQ




PIAVE-ALPI

Nb Sputtered QWR
LNL, Legnaro



Rounded surfaces for better deposition

Heavy Ion Accelerators
(Superconducting LINAC)

Existing Facilities (partial listing)

USA:
ATLAS ANL
Canada:
ISAC, TRIUMF
Europe:
ALPI, INFN-LNL
ISOLDE, CERN
Japan:
JAERI, Tokai
India:
IUAC, New Delhi
TIFR, Mumbai

New Projects for Heavy Ions & RIBs

Israel, China, Spain, France, USA, India, …

Design Considerations

- Efficiency of acceleration
  - Operating point (E_{acc} vs P_{diss})
  - High Shunt Impedance
- RF Control
  - Stability (amplitude & phase)
  - Low Stored Energy
- Beam Dynamics - Phase Space
  - Longitudinal & Transverse evolution
  - Phase matching between sections
  - Bunching
  - Phase setting of Superconducting cavities
  - Pre-accelerator

TIFR-BARC Accelerator Facility

Pelletron accelerator

– E/A ~ 3-7 MeV, β ~ 0.08-0.12

– Heavy ions reactions upto A ~ 40

Superconducting Linac booster

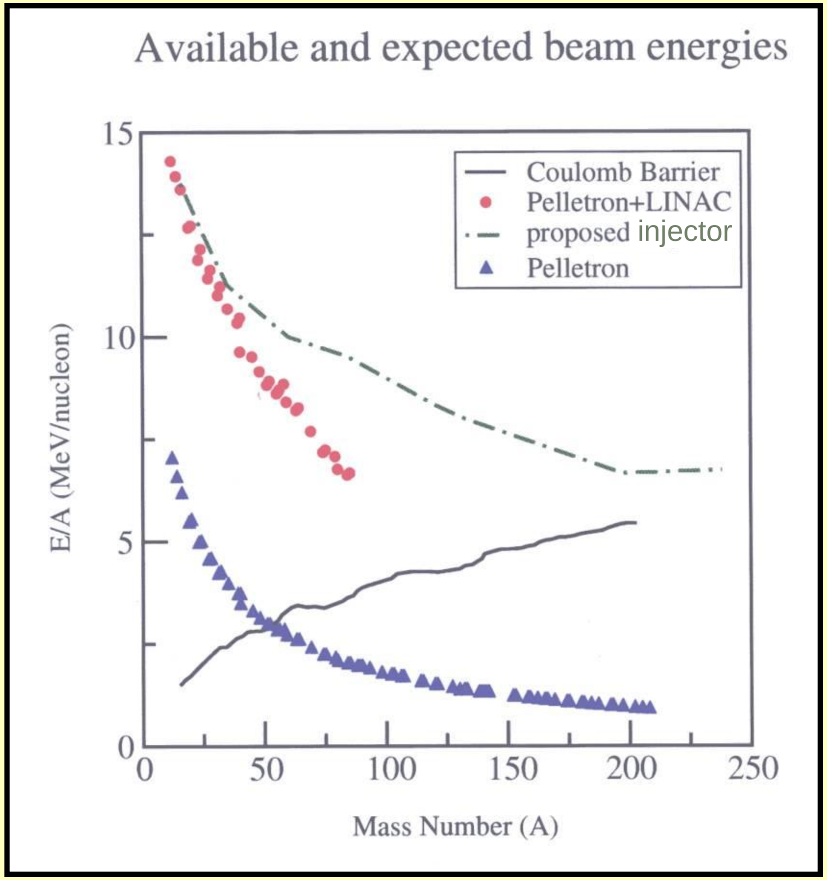
– E/A ~ 5-12 MeV, β ~ 0.10-0.15

– Heavy ions reactions upto A ~ 80

(limited by pre-accelerator)

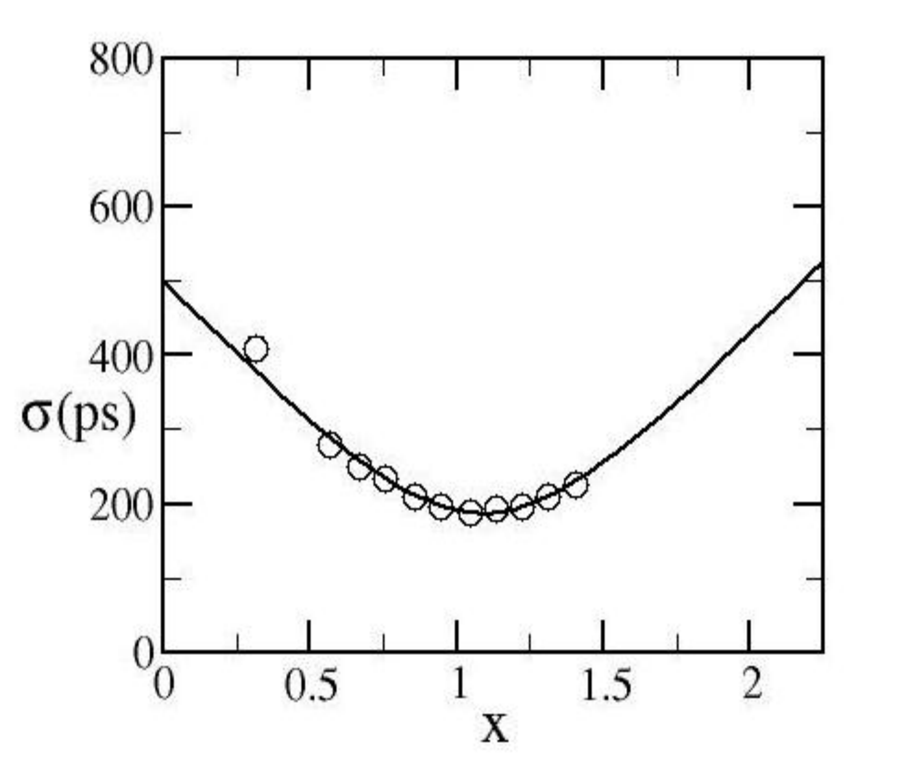
– Beam intensity: 0.1-10 pnA (10^{9-11} p/s)

(limited by ion source)



Beam Transport in LINAC

- Longitudinal Phase Space
  - bunching
  - matching and stability
- Transverse Phase Space
  - periodic focusing
- Magnetic Bend
  - achromatic and isochronous

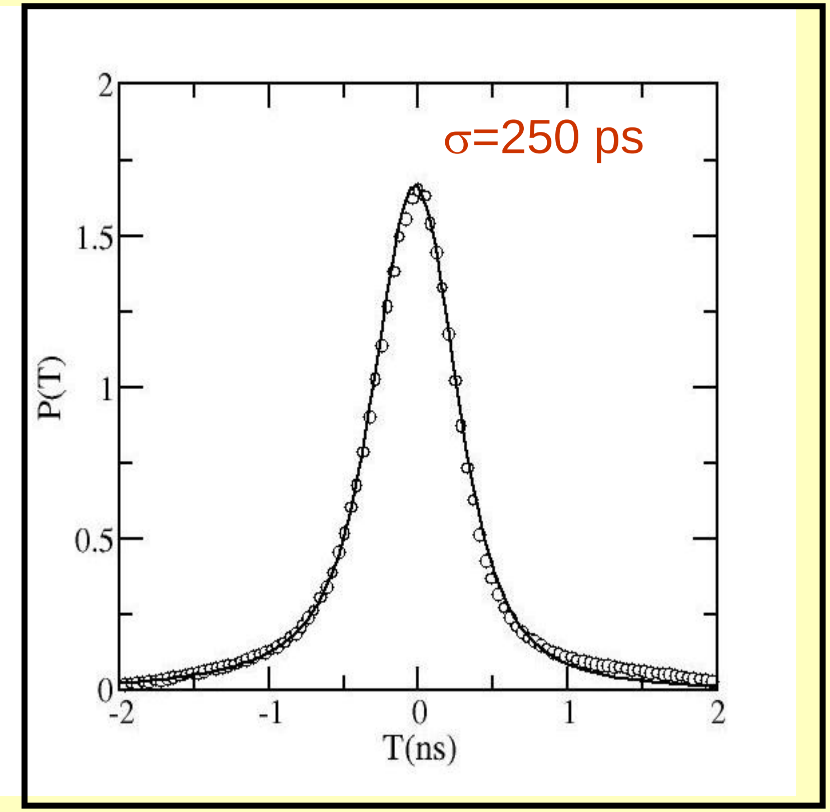


σ(ps) as a function of dimensionless scaled variable $x=\omega L E_B/2\beta c E$.

The solid line is the fit to the data.

E and β are the energy and velocity of the incident beam,

E_B and ω are the amplitude of energy gain and angular frequency.



The electron spectrum observed with MSP

If the low energy buncher beam width is not sufficiently narrow, then at the superbuncher the incident beam experiences the nonlinear part of the sinusoidal RF field and this results in a non-gaussian peak shape.

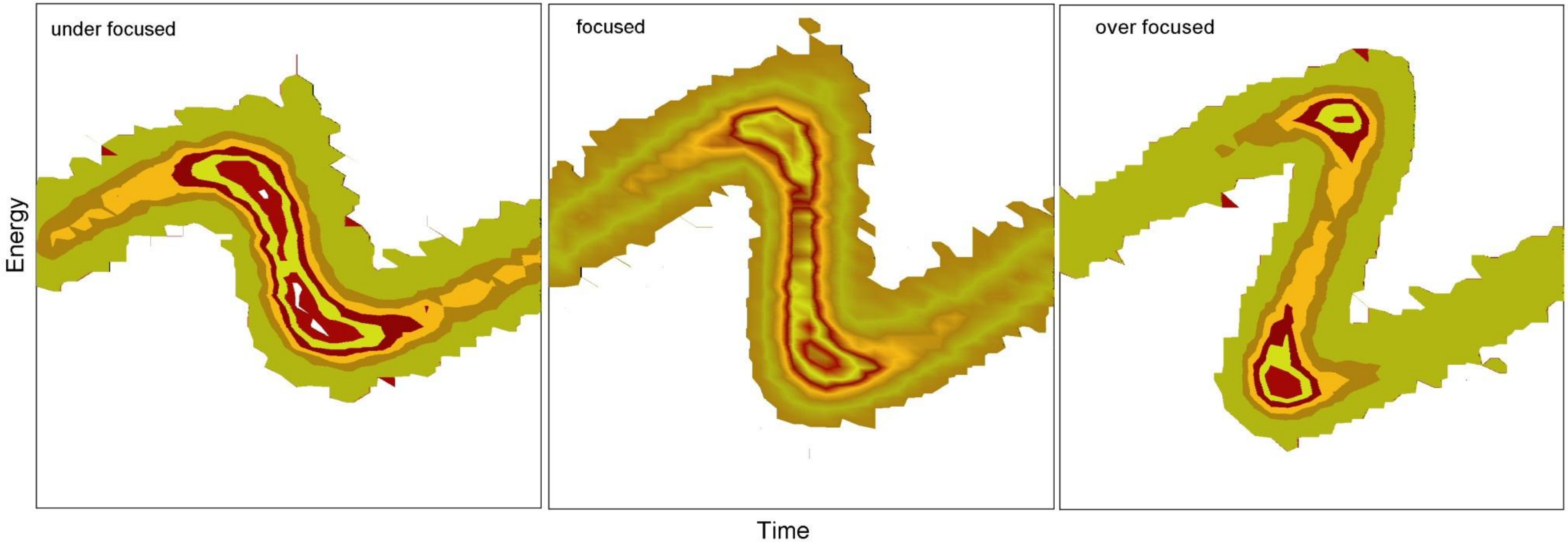


Fig. 1: Longitudinal phase space after superbuncher with DC-beam

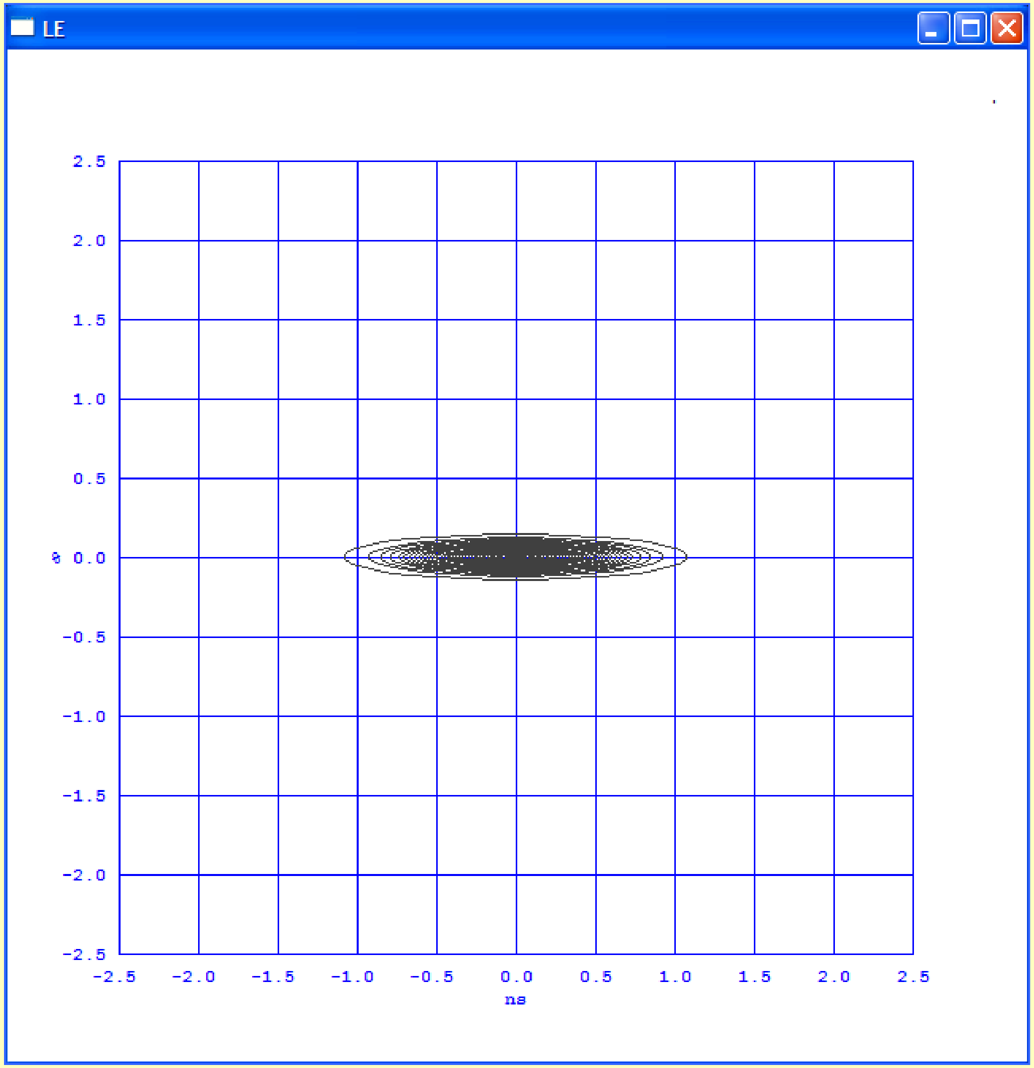
Evolution of longitudinal phase space

- Optimization of Beam quality at target
  transmission, energy spread and time structure

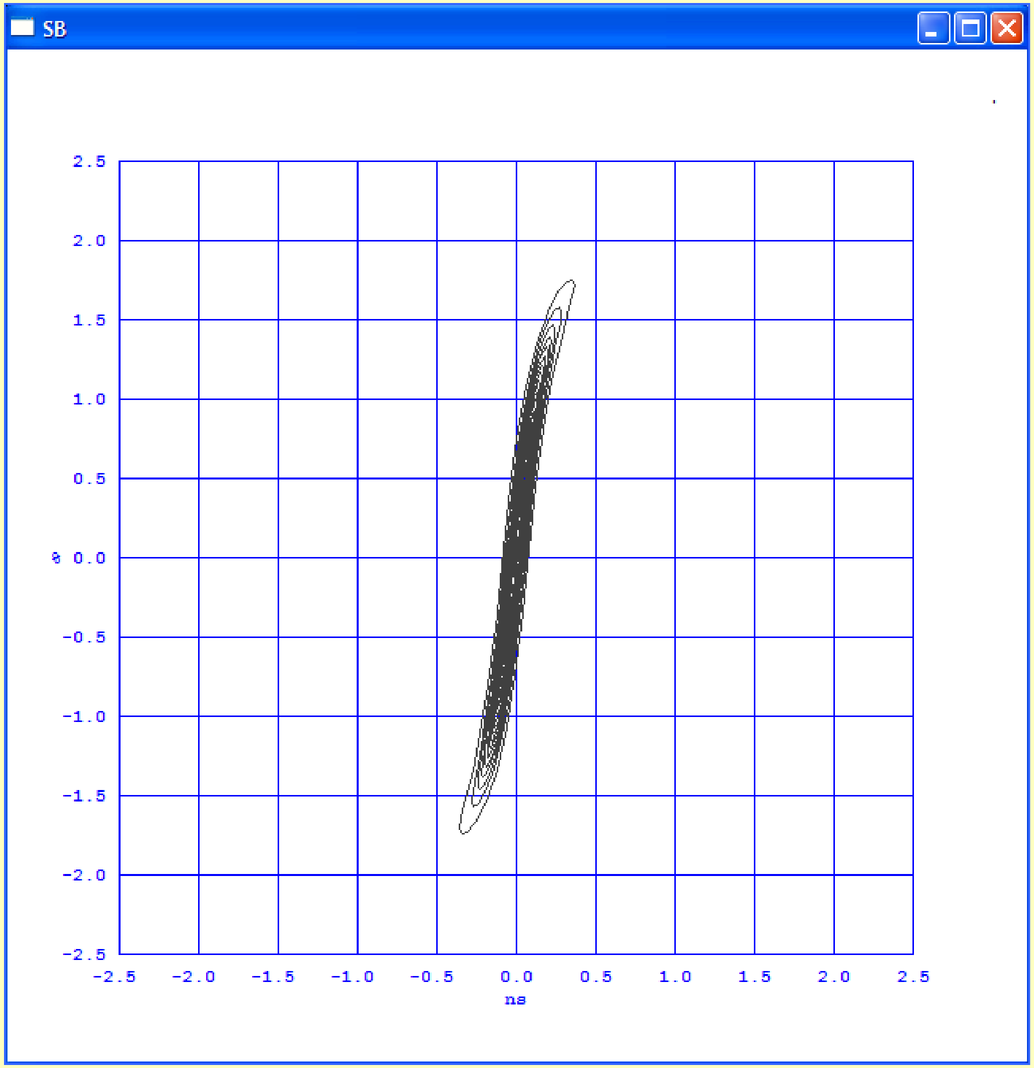
- Pre-compute synchronous phase settings (Φ_{res}) for 2^N configurations
  measured resonator field values
  time focusing (-20°) or time de-focusing (+20°)

- For any given set of Φ_{res} ,

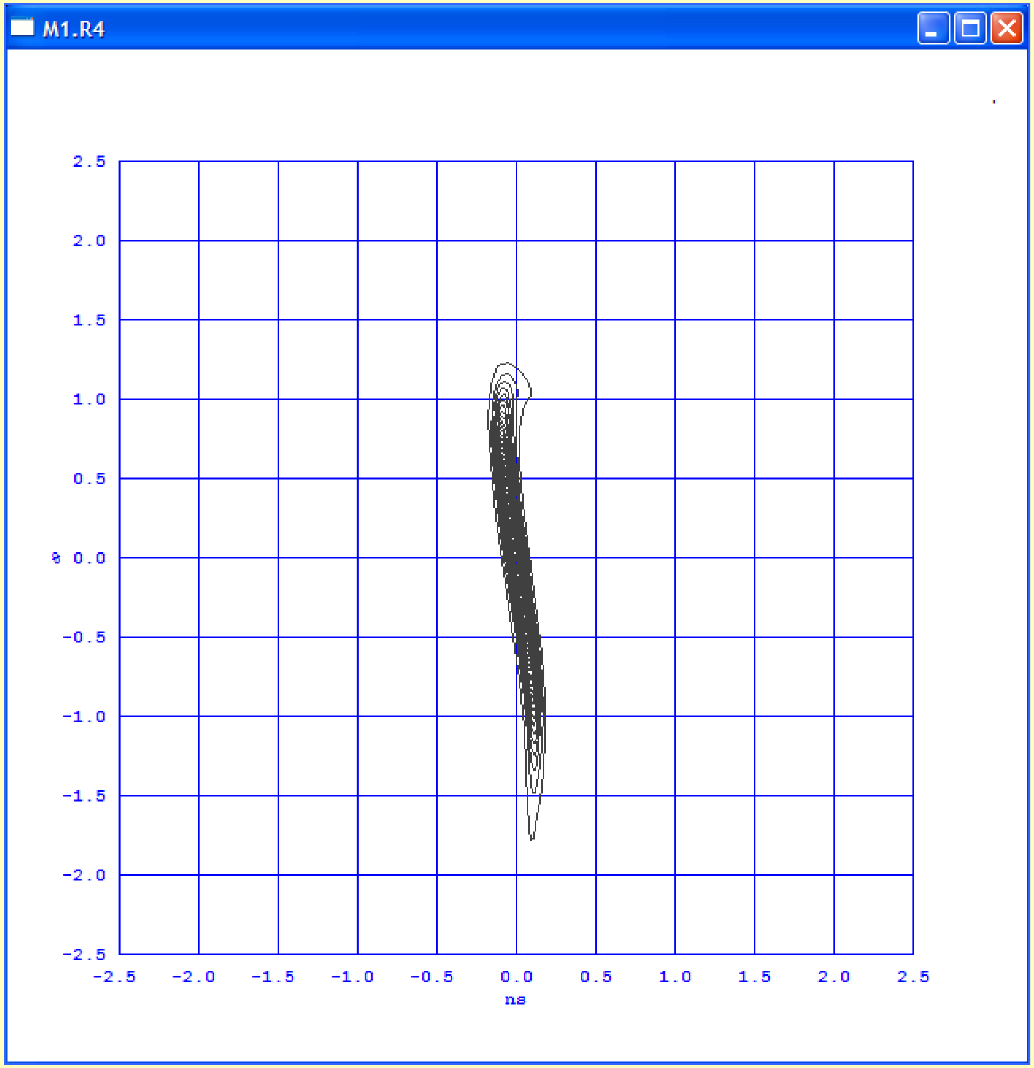
$$\Phi_{REF}\,(k+1) = \Phi_{REF}\,(k) + \Delta\Phi_0\,(k+1,\,k) - \Delta\,\Phi_{res}\,(k+1,k) - \omega(t_{k+1} - t_k)$$



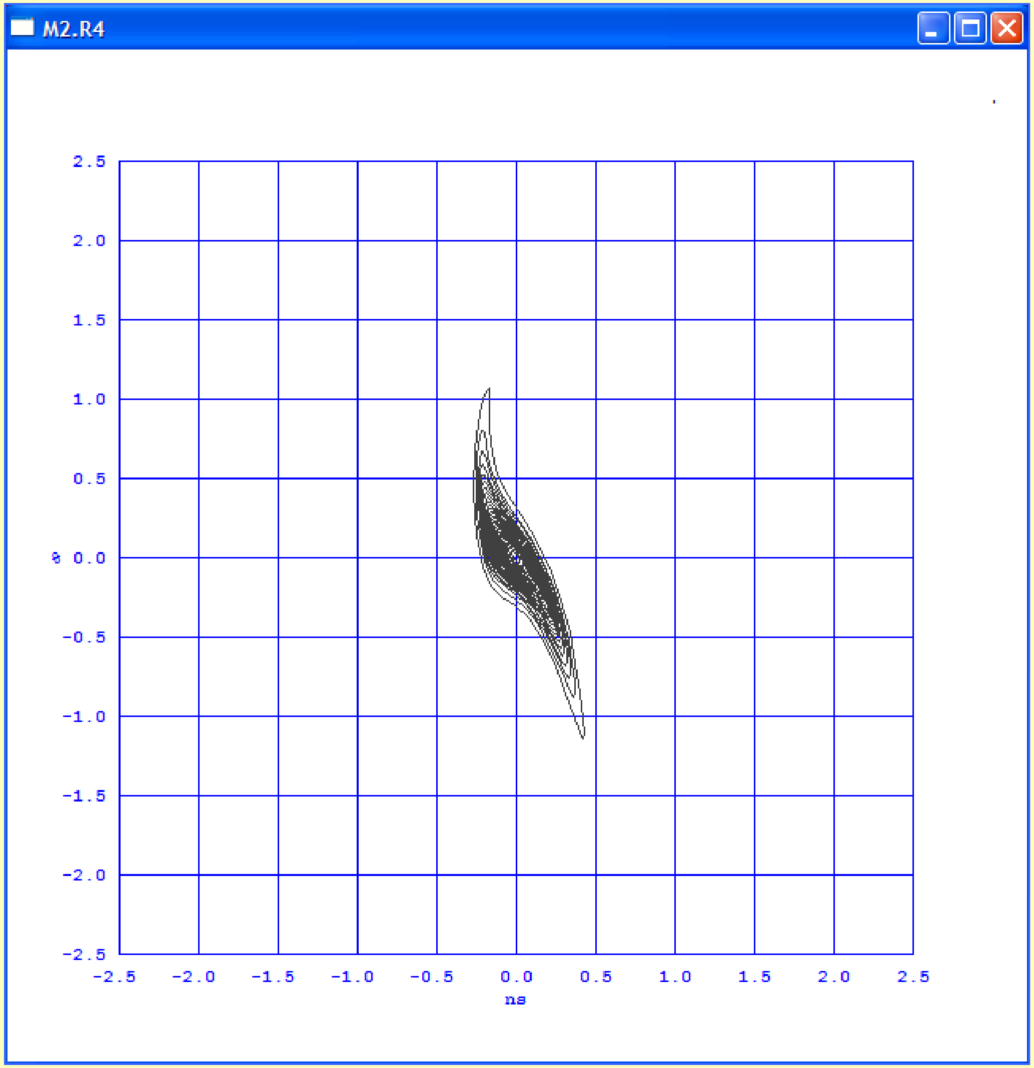
LE
2.5
2.0
1.5
1.0
0.5
δ 0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
ns



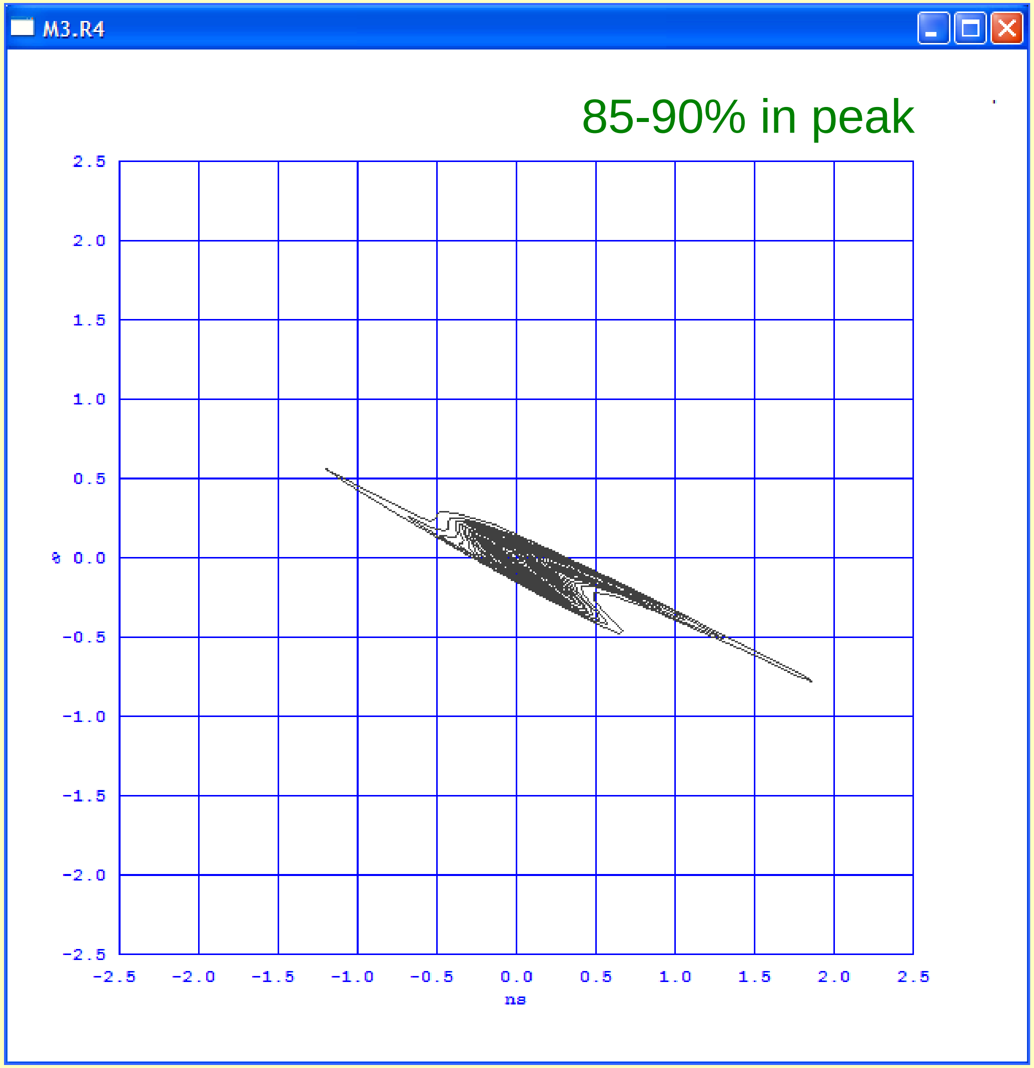
SB
2.5
2.0
1.5
1.0
0.5
δ 0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
ns



M1.R4
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
ns

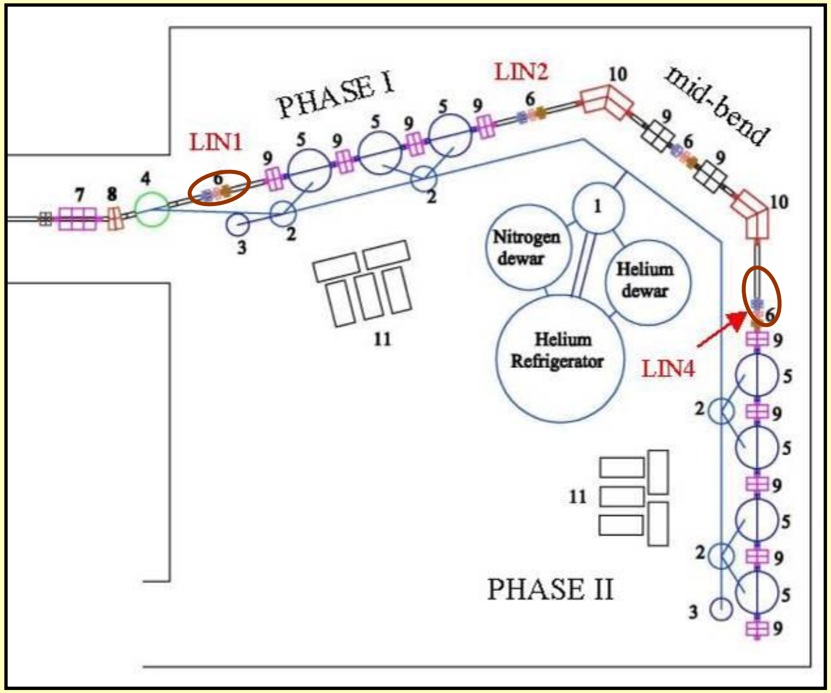


M2.R4
2.5
2.0
1.5
1.0
0.5
δ 0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
ns


M3.R4
85-90% in peak
2.5
2.0
1.5
1.0
0.5
δ 0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-2.5 -2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
ns

Evolution of longitudinal phase space

Final configuration corresponding to an optimal phase space at target determined by measurement of the transmission and the time structure.



Timing Detector (1” BaF_2)

@LIN1 : entrance of Phase I

@LIN4 : entrance of Phase II

@LIN7 : after switching magnet

@target position

Cavity in-beam performance

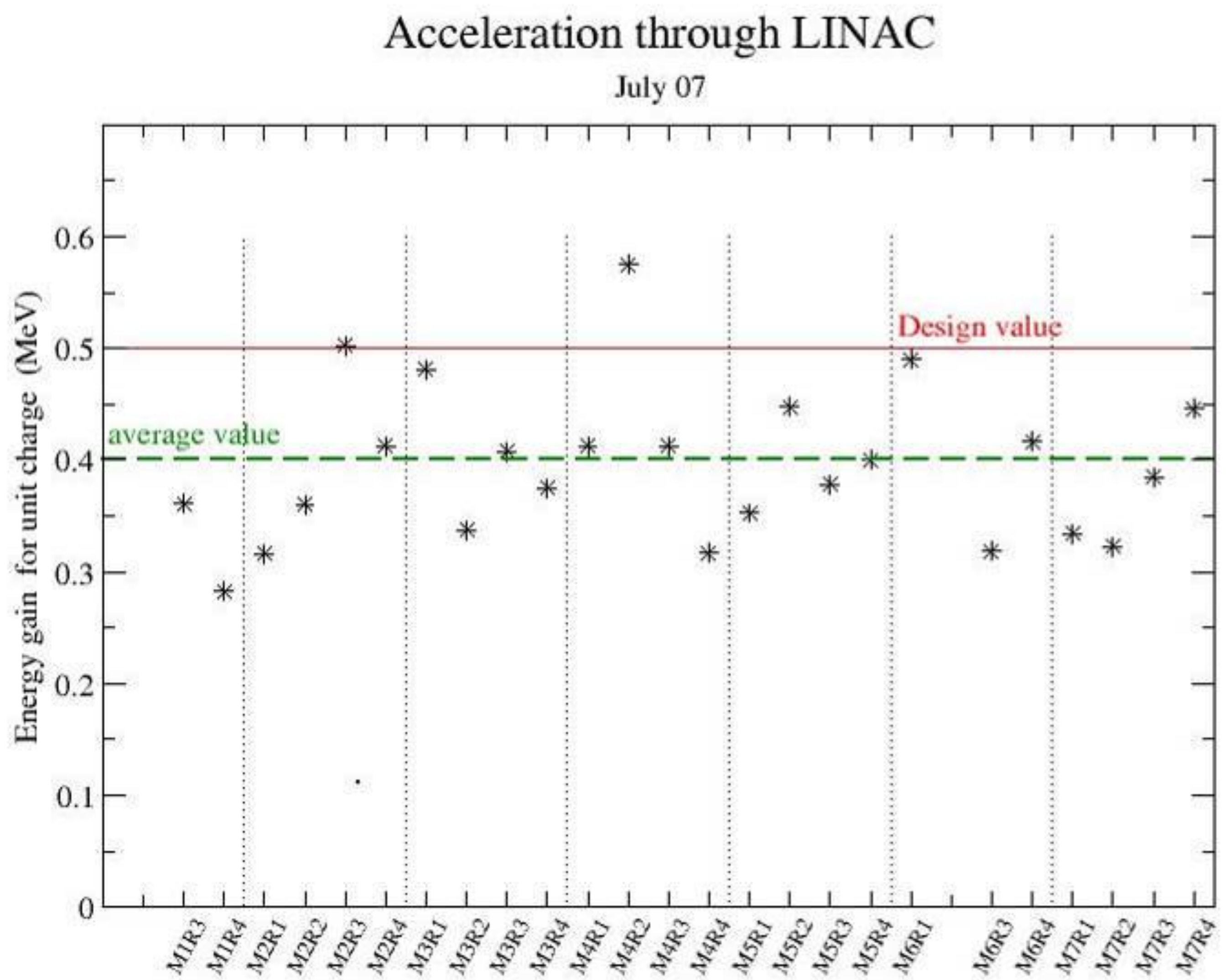
- Frequency Stability
  - Mechanical design vs Cooling
  - Mechanical vibrational modes
  - Radiation Pressure induced
  - Liquid Helium boiling induced

- Limits the in-beam performance
  - Determines RF power requirements
  - Determines cryogenic requirements

- RF Coupler, pickup and Frequency tuner

Full LINAC Test (July 07)

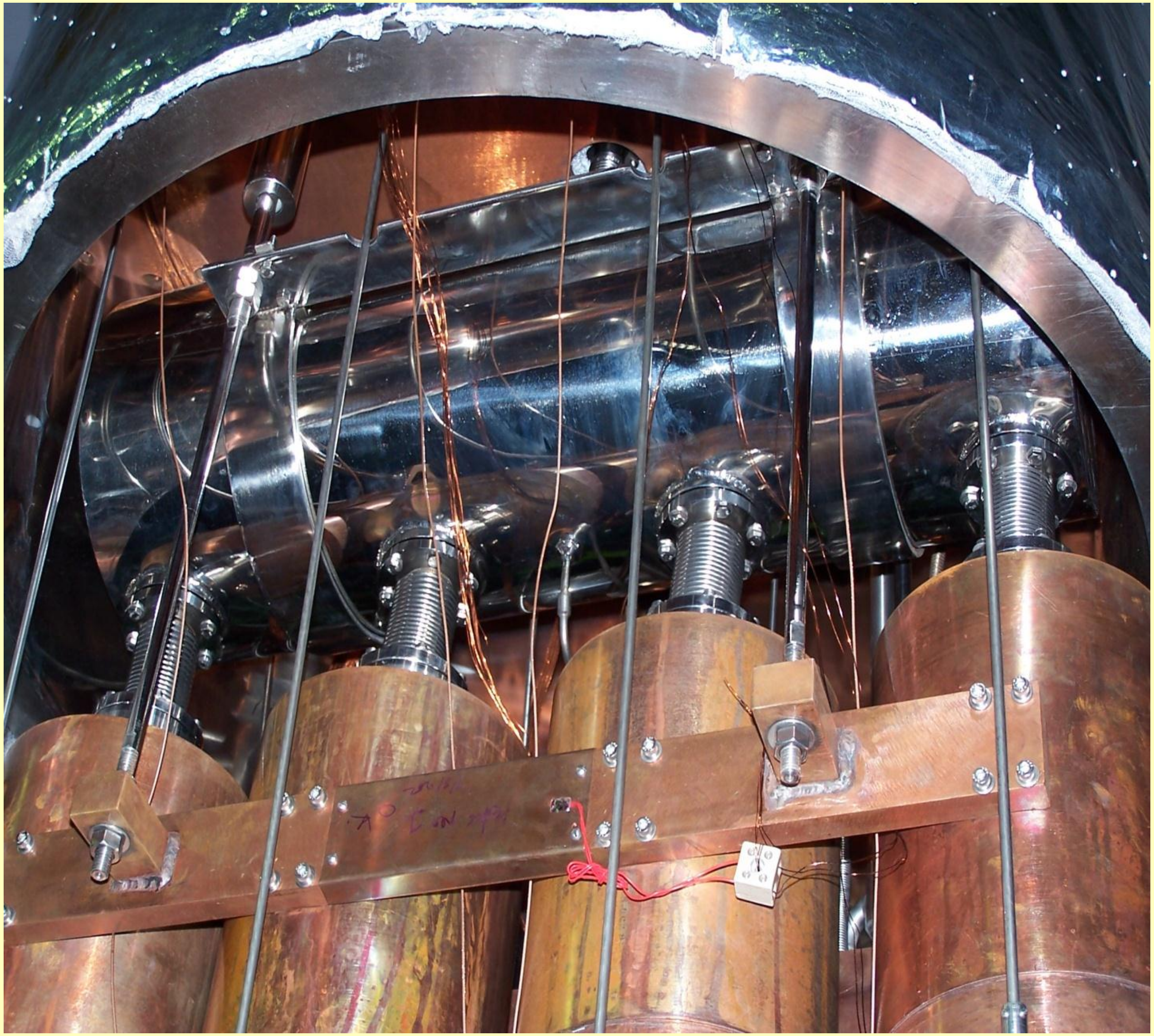
$^{28}Si^{13+}$



Cryogenics

Module Cryostat

Top view of the module



40 ltr. liq. He vessel
60 ltr. liq. N_2 vessel

Four QWRs Assembly in Cryostat

Cryogenics for the Linac

Linde TCF50S

Al Plate Fin Heat Exchangers
Two stage Turbine Expansion Engines
Two stage JT Expansion
250 KW Screw Compressor, 62 g/s

	Refrigeration at 4.5 K,	Liquification
Without LN_2	300 W,	50 l/hr
With LN_2 pre-cooling	450 W,	120 l/hr

Linde TCF50S Liquefier/Refrigerator Upgrade

- TCF50S commissioned in 1998

  Two turbo expanders

  50 litres/hour; 300 Watts @ 4.5K w/o LN_2

  Compressor 200 kW; 13 Bara; 62 g/s

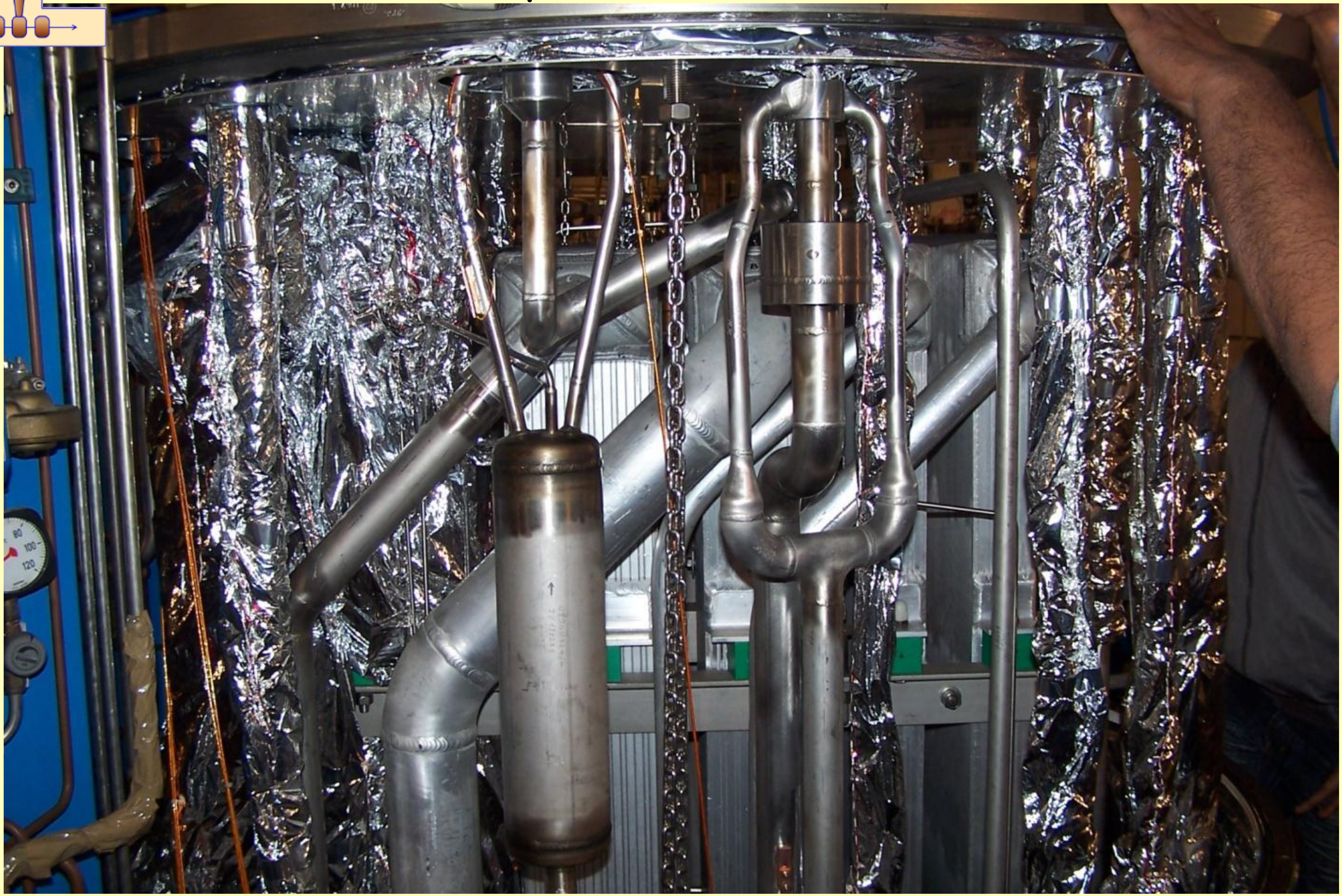
- 1st stage Turbine & Turbine housing changed
- 2nd stage Turbine modified
- New Compressor installed

  250 kW; 13 Bara; 80 g/s

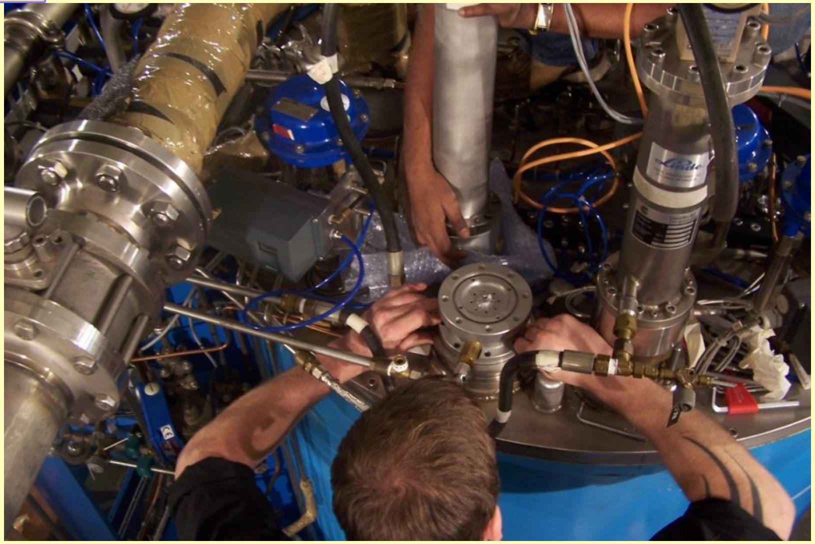
  80 litres/hour; ~450 Watts

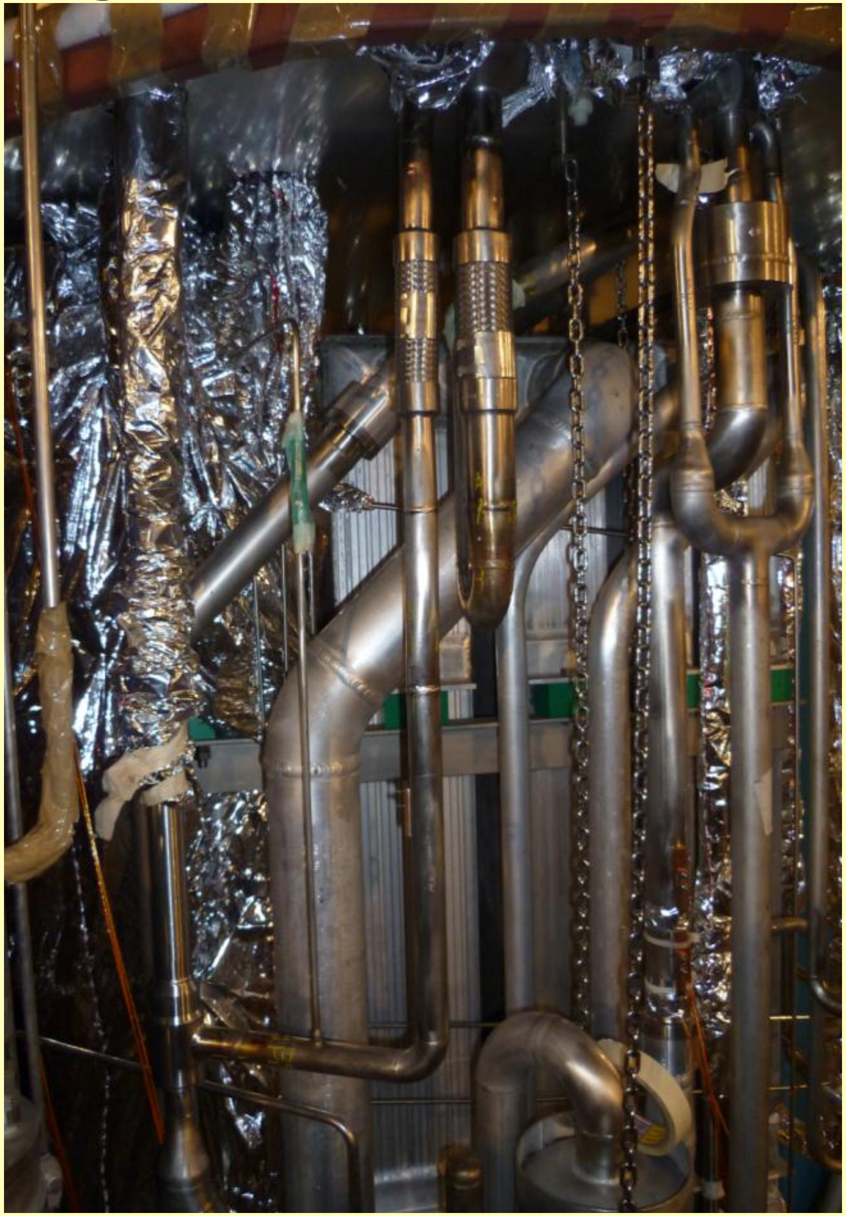
Cold Box Opened for Modifications

Cold Box Opened for Modifications

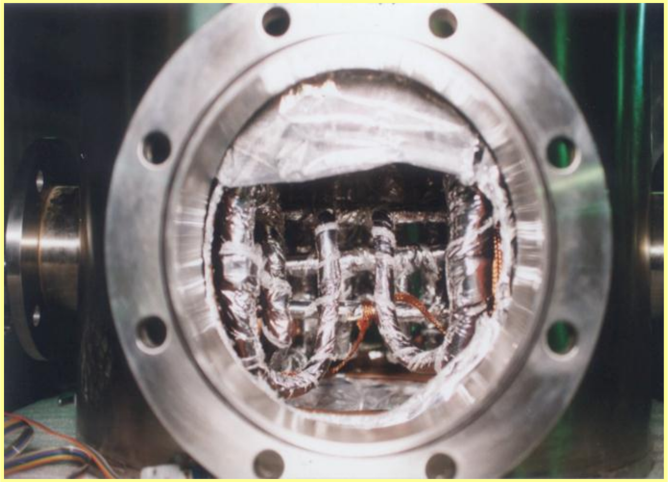


New Turbine Housing Installed





Junction Box

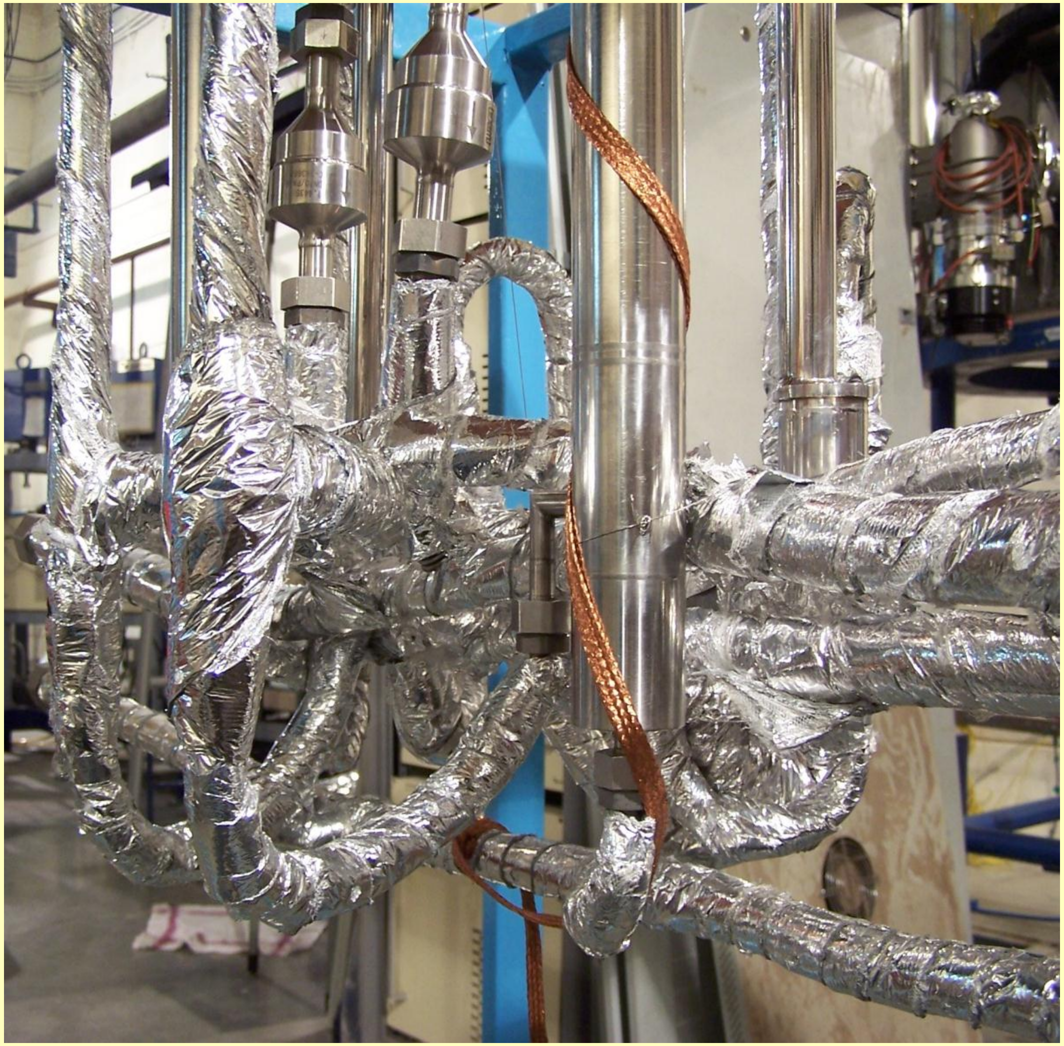


Inside View of Junction Box

The entire cryogenic distribution system was fabricated and assembled on-site.

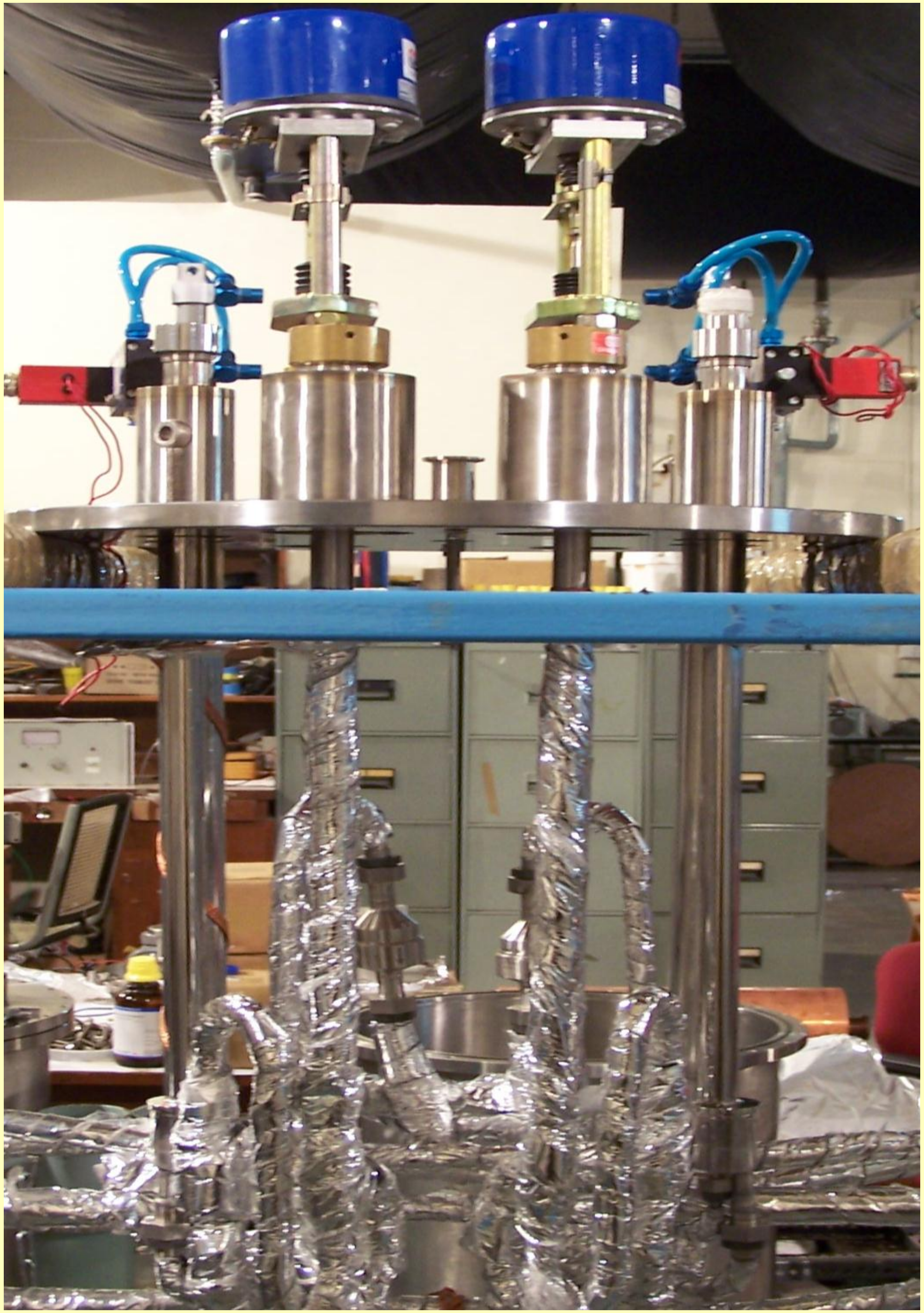
Junction Box

- LHe valves with ac motor actuators and position read-back
- Electro-pneumatic valves for LN_2 batch filling
- Tri-axial transfer tube ports



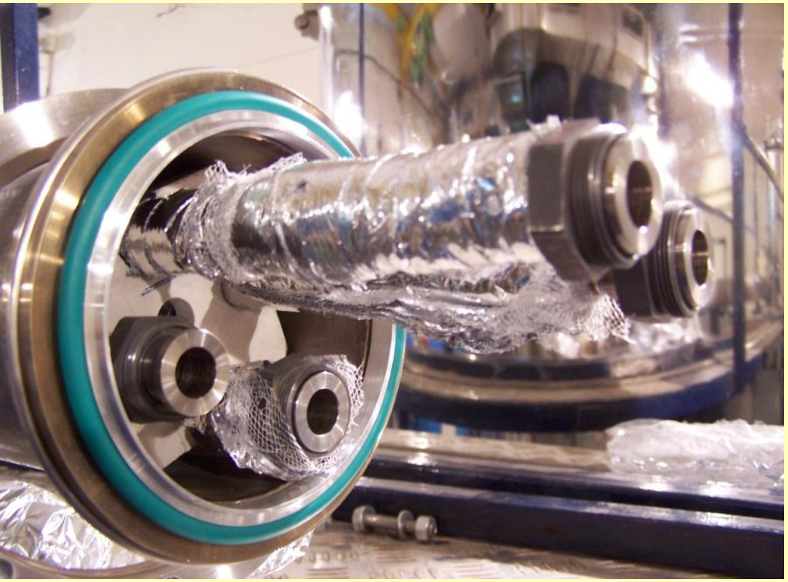
Junction Box

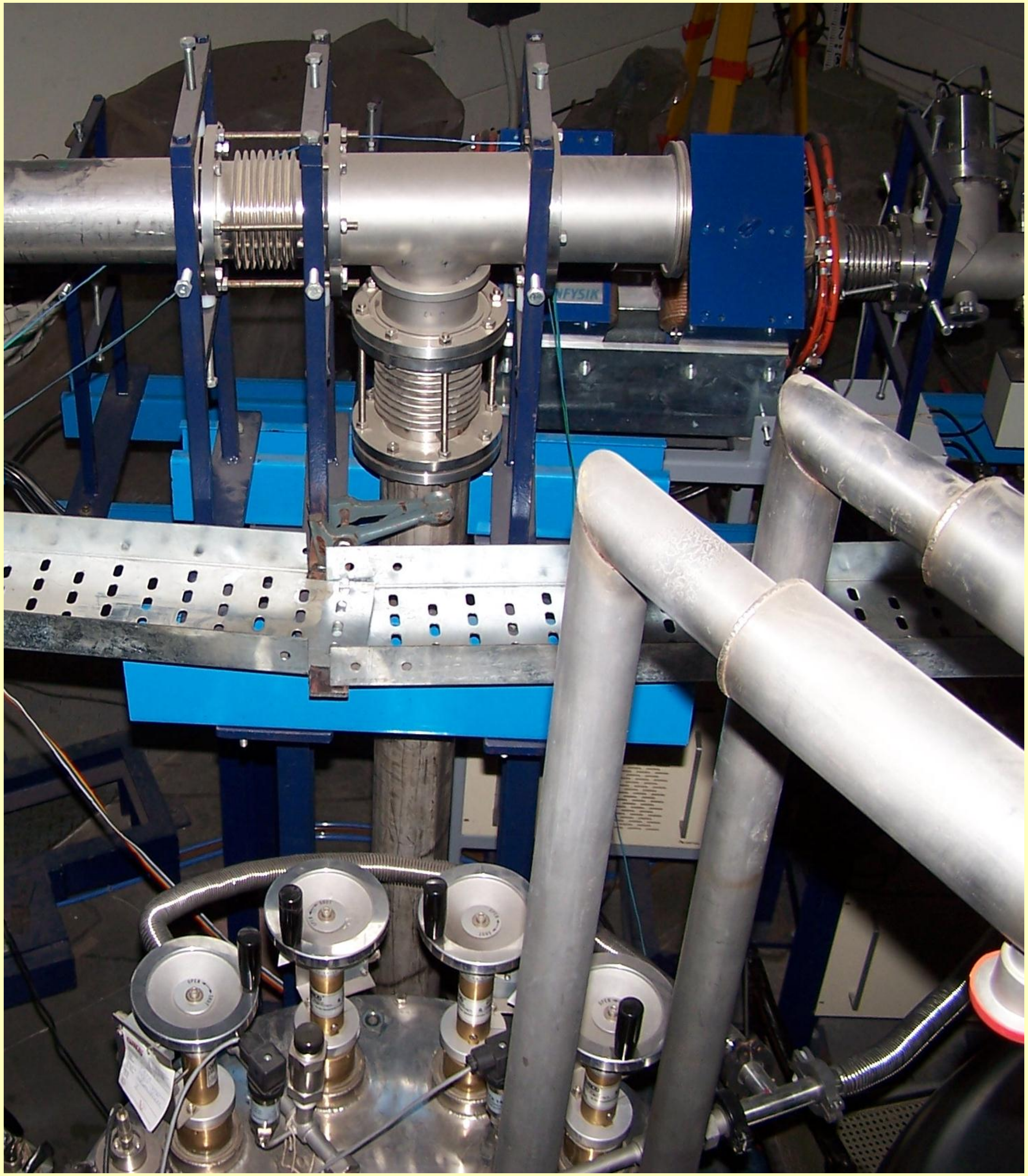
- WEKA make cryogenic valves for LHe
- WEKA make Transfer tube Bayonet for LHe
- WEKA make Cryogenic check valves
- Indigenously developed valves and bayonet for LN_2



Trunk Line

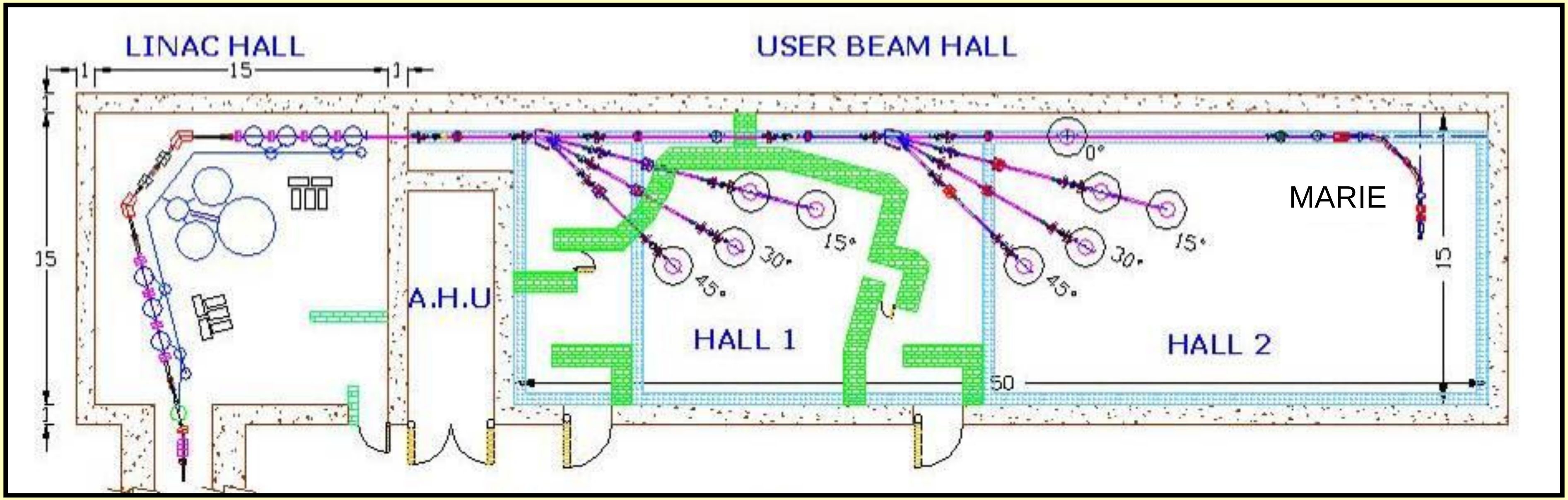
- Vacuum insulated trunk line 100mm dia with four tubes
- Made in separate sections with kennol fittings supported by Glass fibre loaded teflon spacers
- ~100mW/m





Beam lines & Diagnostic elements

LINAC & Experimental Beam Halls



Hall 1

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

Hall 2

- General Purpose/ Irradiation line
- HPGe Spectrometer (INGA)
- Charged particle ball
- **M**omentum **A**chromat for **R**adioactive **I**on **E**xperiments

Beam Transport to Experiments

- Mid-Bend system
  - Achromatic & Isochronous
  - Beam Loss (85-90% transmission)
- Switching Magnets
  - Dispersive
  - Beam Loss (85-90% transmission)
- Beam Diagnostics
  - X-Y slits
  - Beam Profile monitors (rotating wire)
  - Faraday Cups
  - Timing detectors (BaF_2 , MSP & Diamond)

Beam line components

Hall I

Hall II

Faraday cup control station

- **Design Concept**

1) FC Current read-back on PC with auto gain selection

2) 8 Local FC inputs

- **Parameters controlled & monitored**

1) Selection of desired FC and its signal

2) IN/OUT operation of selected FC

3) A/D conversion of beam current using 12-bit ADC

4) Pre-amplifier auto-gain selection (x1 & x3)

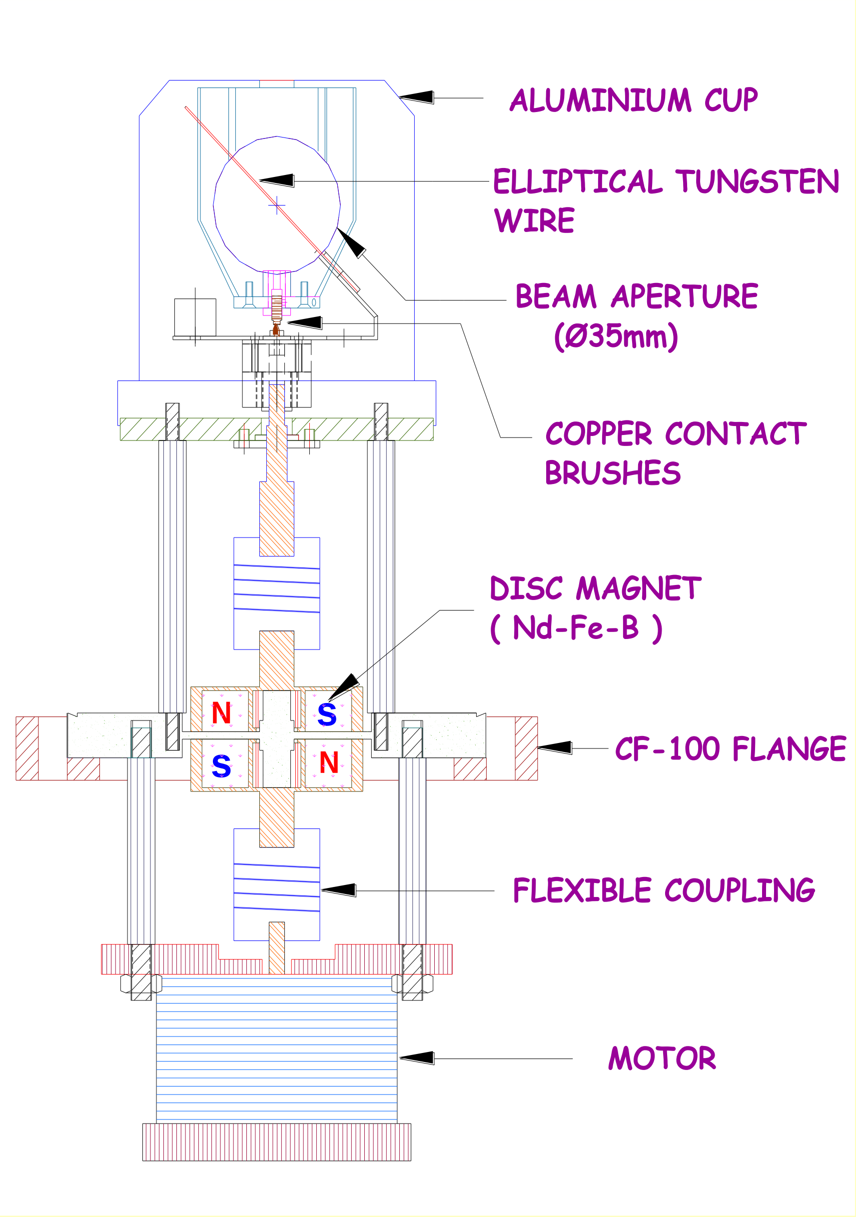
5) PC Interface via RS-232

Beam Profile Monitor (BPM)

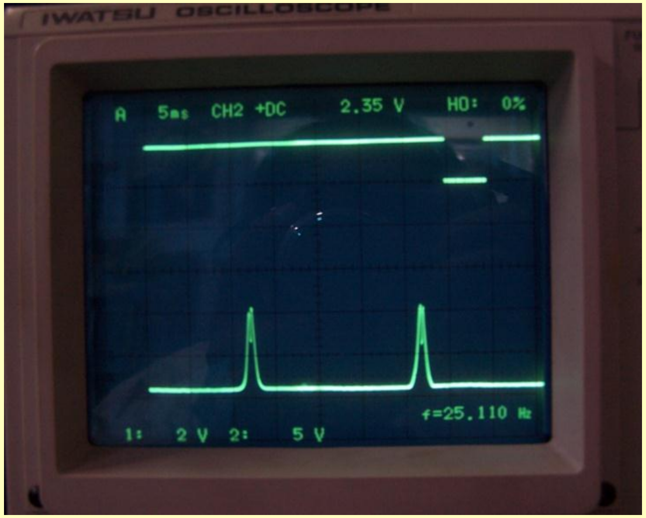
- Diagnostic tool
  (concept design based on Danfysik BPM)
- Contains an ***elliptical shaped wire***
- Scans beam in X & Y axis
- A 3 phase DC motor rotates this wire
- Developed at TIFR Central Workshop
- There are more than 20 BPM’s in the beam line

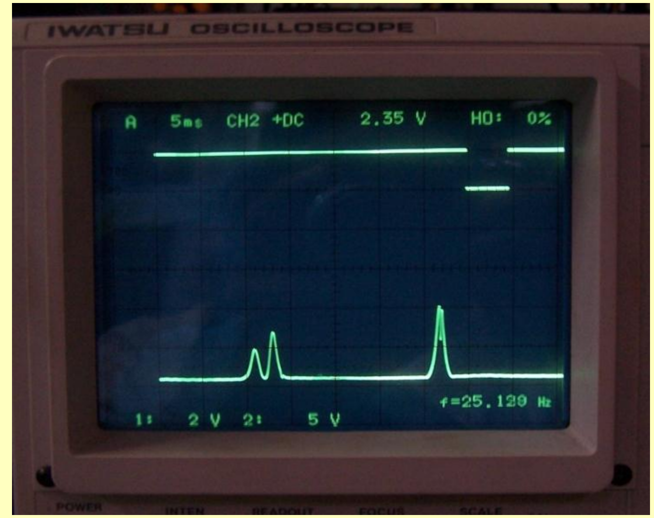
BPM fabricated @ TIFR

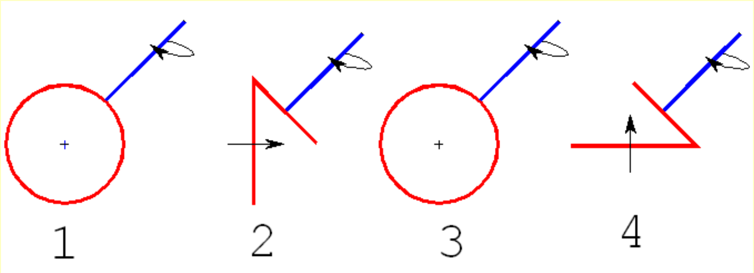
Design drawing



Beam profiles as seen on the oscilloscope







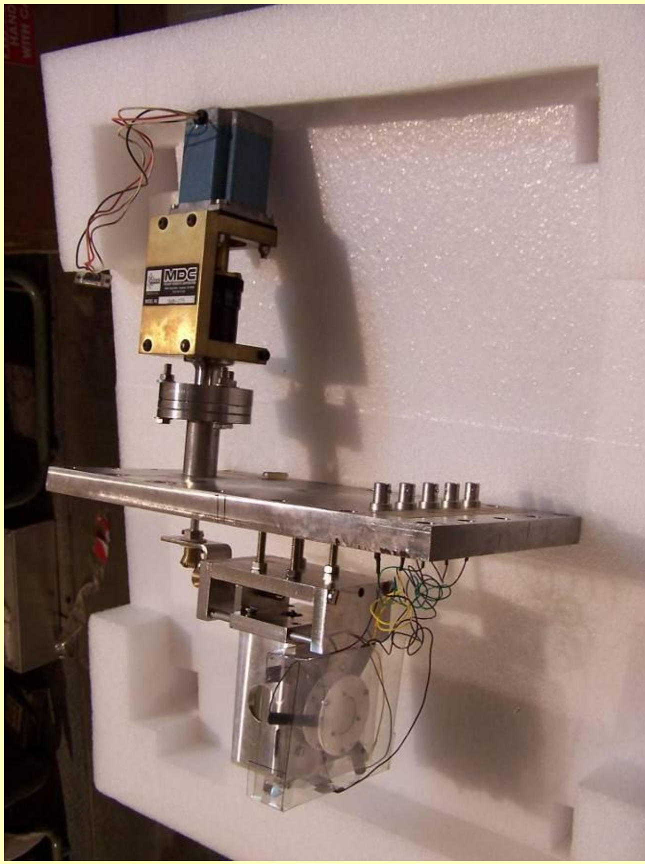
Position 1 : Wire loop appears as a circle

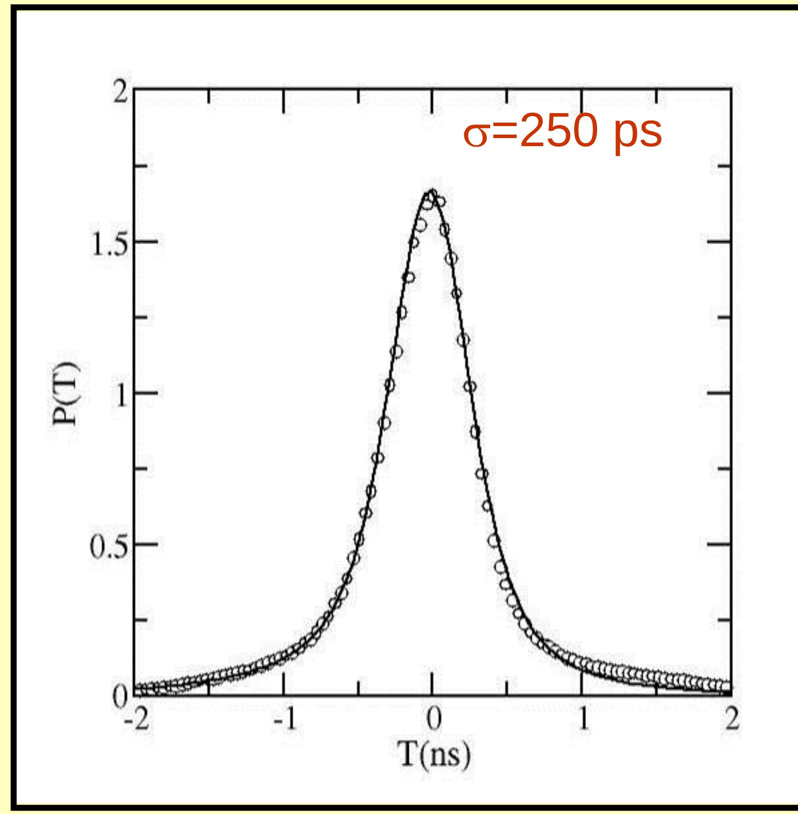
Position 2 : Wire loop collapses to a vertical line giving rise to the X profile.

Position 3 : Wire loop expands to a circle again.

Position 4 : Wire loop collapses to a horizontal line giving rise to the Y profile.

Micro-sphere Plate detector for timing

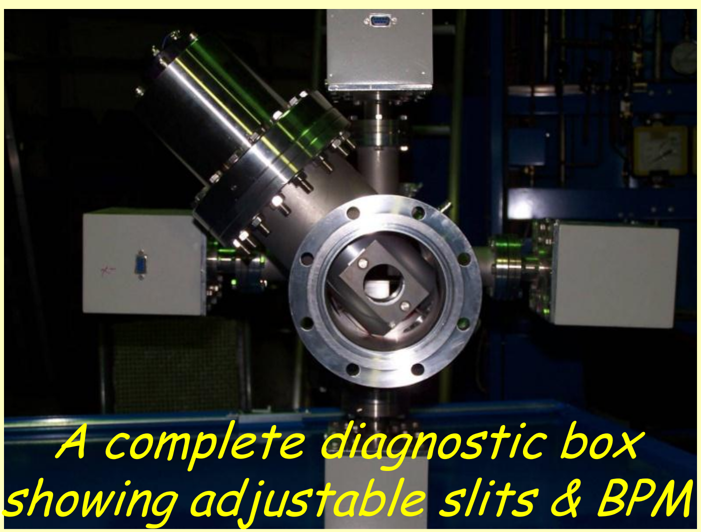




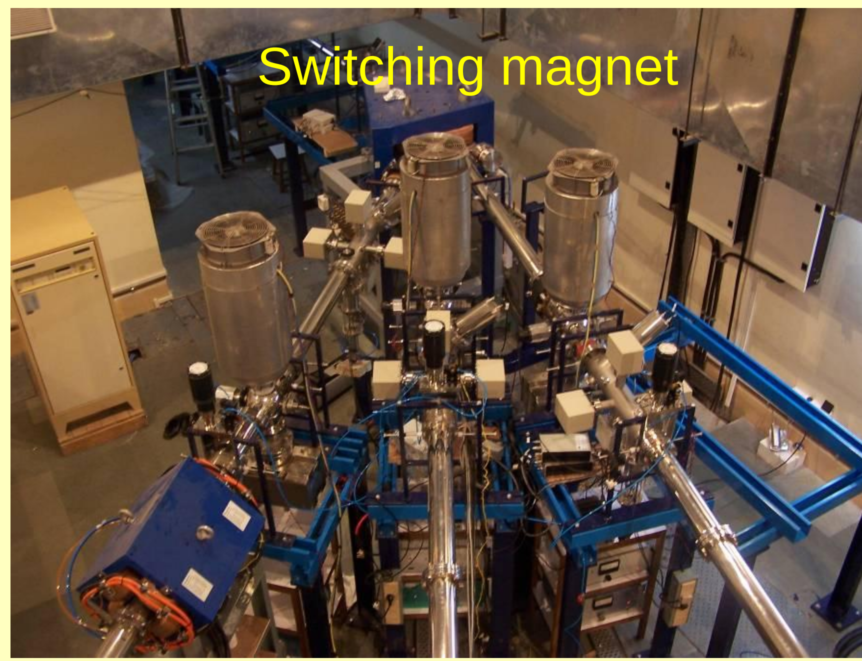
Development of Beamline components & Diagnostic elements

Ion pump and Sublimator pump

BPM & Faraday Cup



A complete diagnostic box showing adjustable slits & BPM



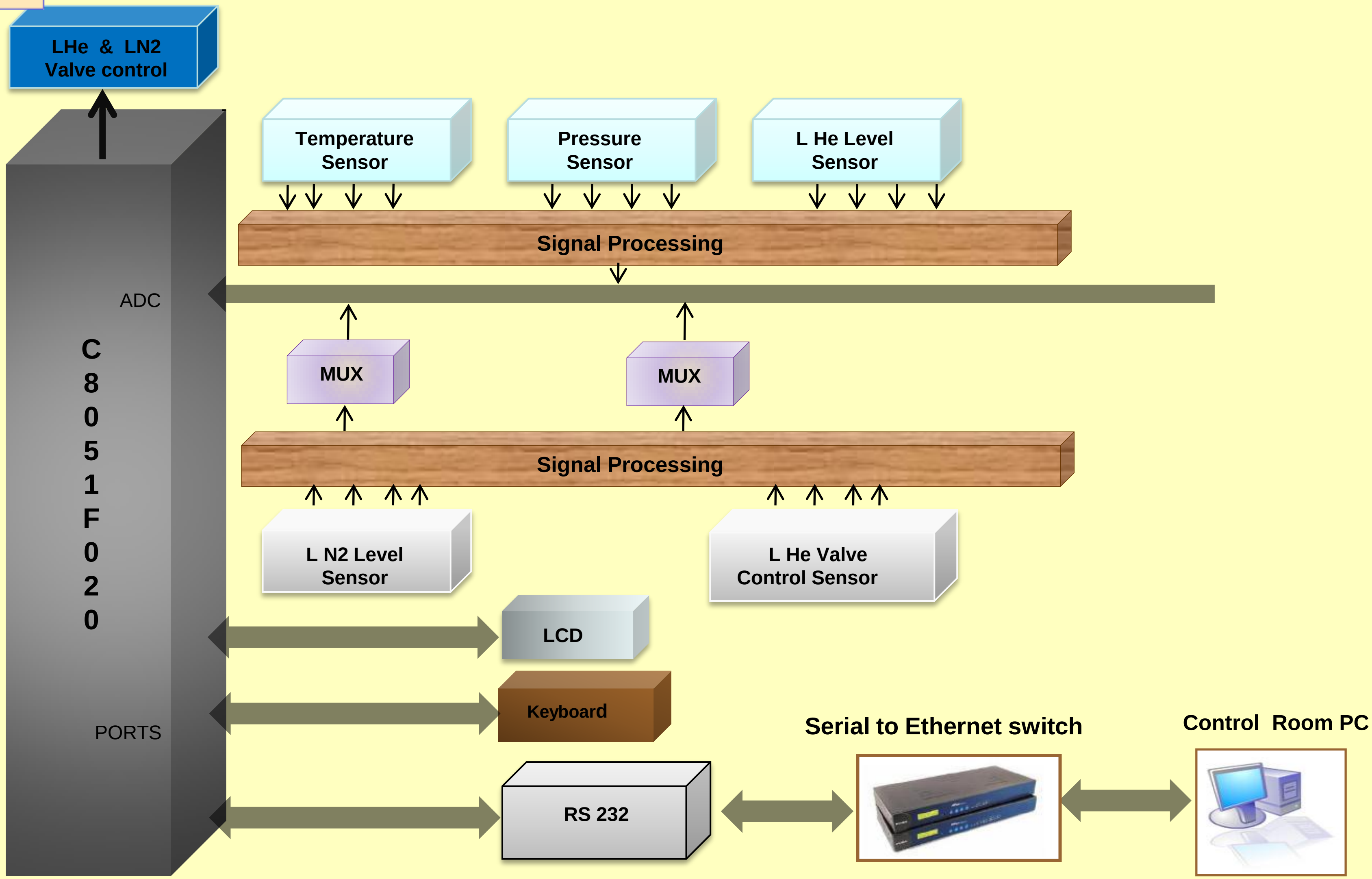
Switching magnet

Instrumentation & Control system

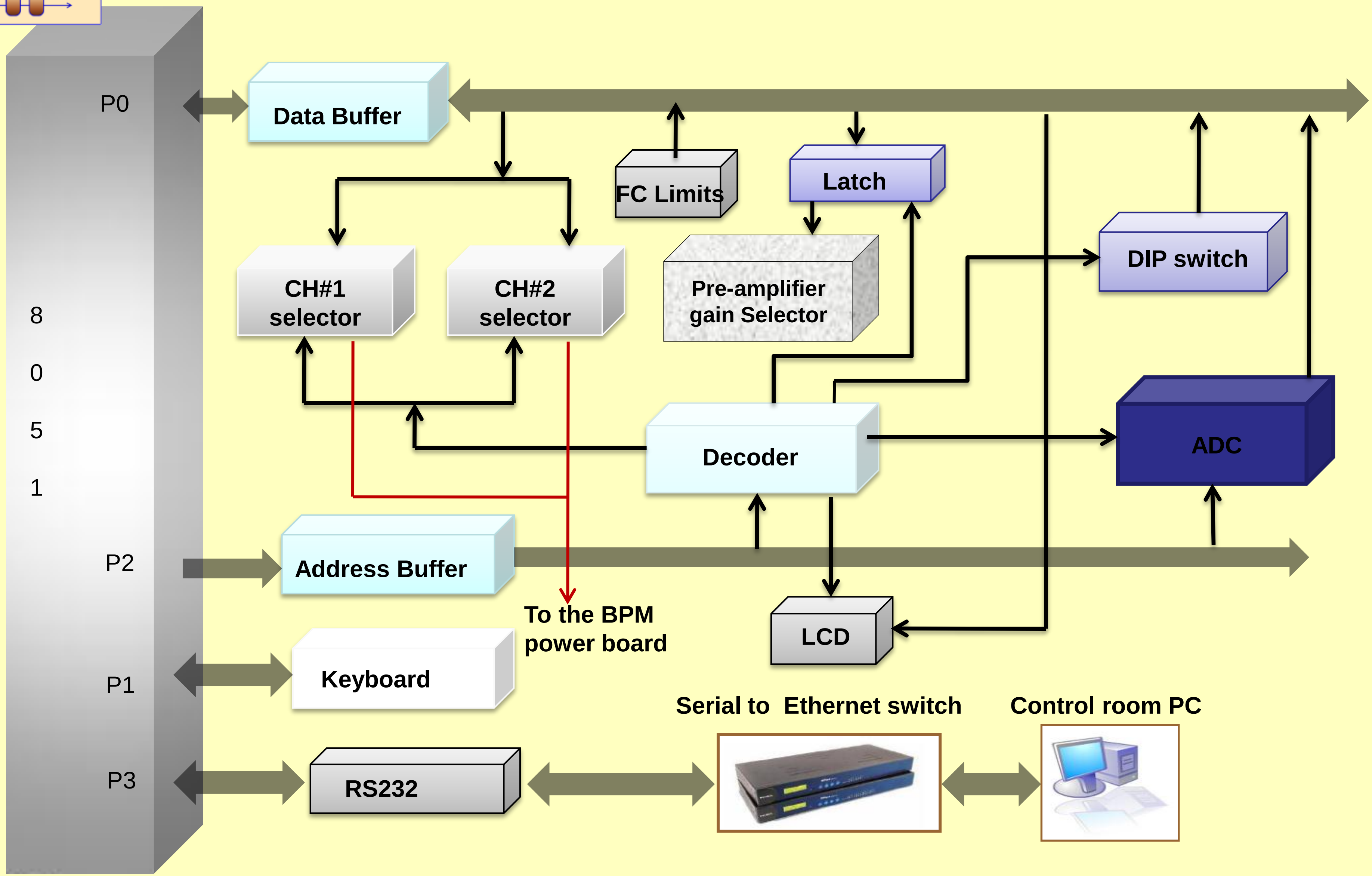
Instrumentation for the Heavy ion LINAC

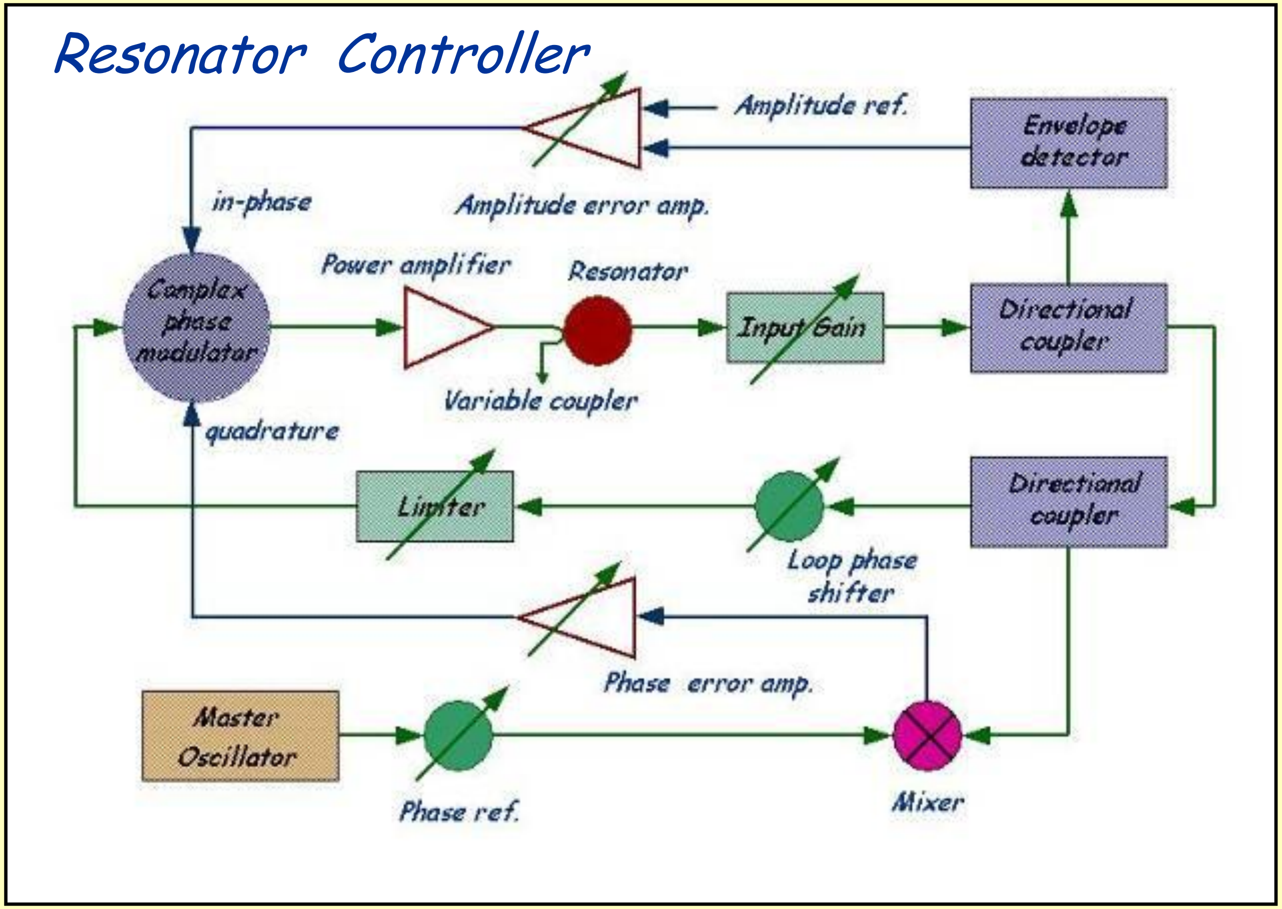
- Cryogenic monitor & control
- RF Cavities
  - RF phase & amplitude control
- Beam Transport & Diagnostic
- Beam Lines
  - Vacuum

Cryogenic control station Block diagram



FC/BPM controller block diagram





Based on a Self-excited Loop with Amplitude and Phase corrections

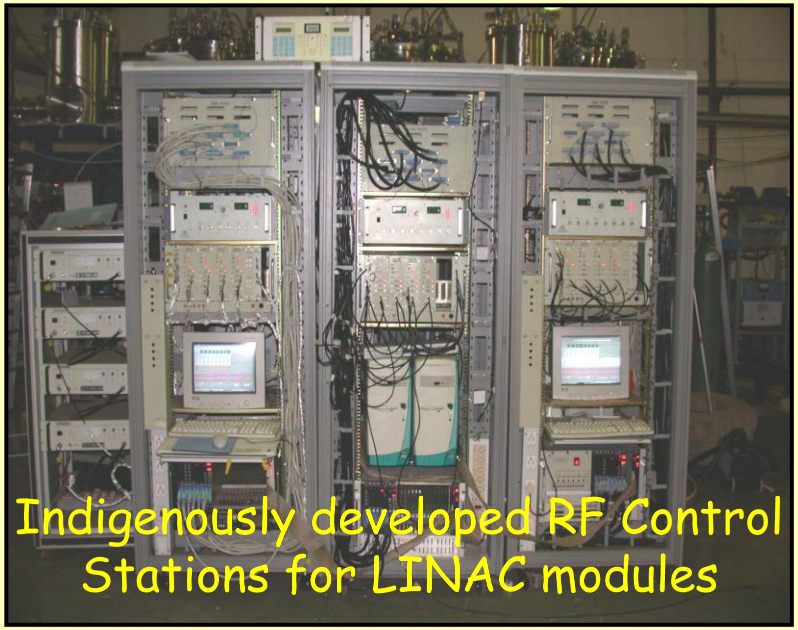
Intrinsic resonator bandwidth ~1Hz @ 150MHz

Cavity resonant frequency variations ~±25Hz

Field level set by limiter and variable coupler

RF Electronics and LINAC Control System

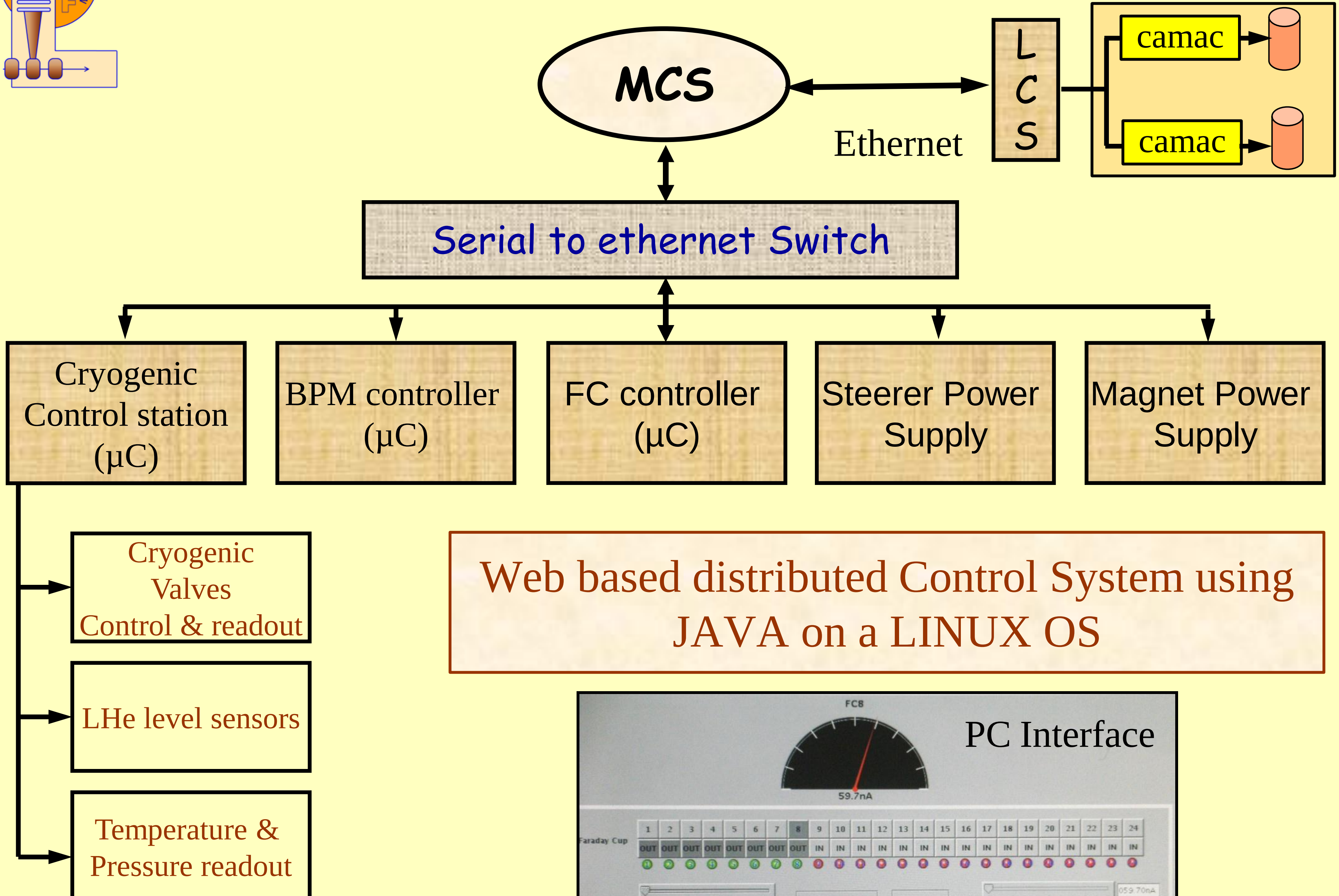
- Resonator controller and CAMAC system
    - *In house development using Indigenous/easily available RF modules*
    - *150 Watts, 150 MHz RF Power Amplifiers*
- LINUX based Operating system with JAVA
- Web based distributed control system (master + local stations)



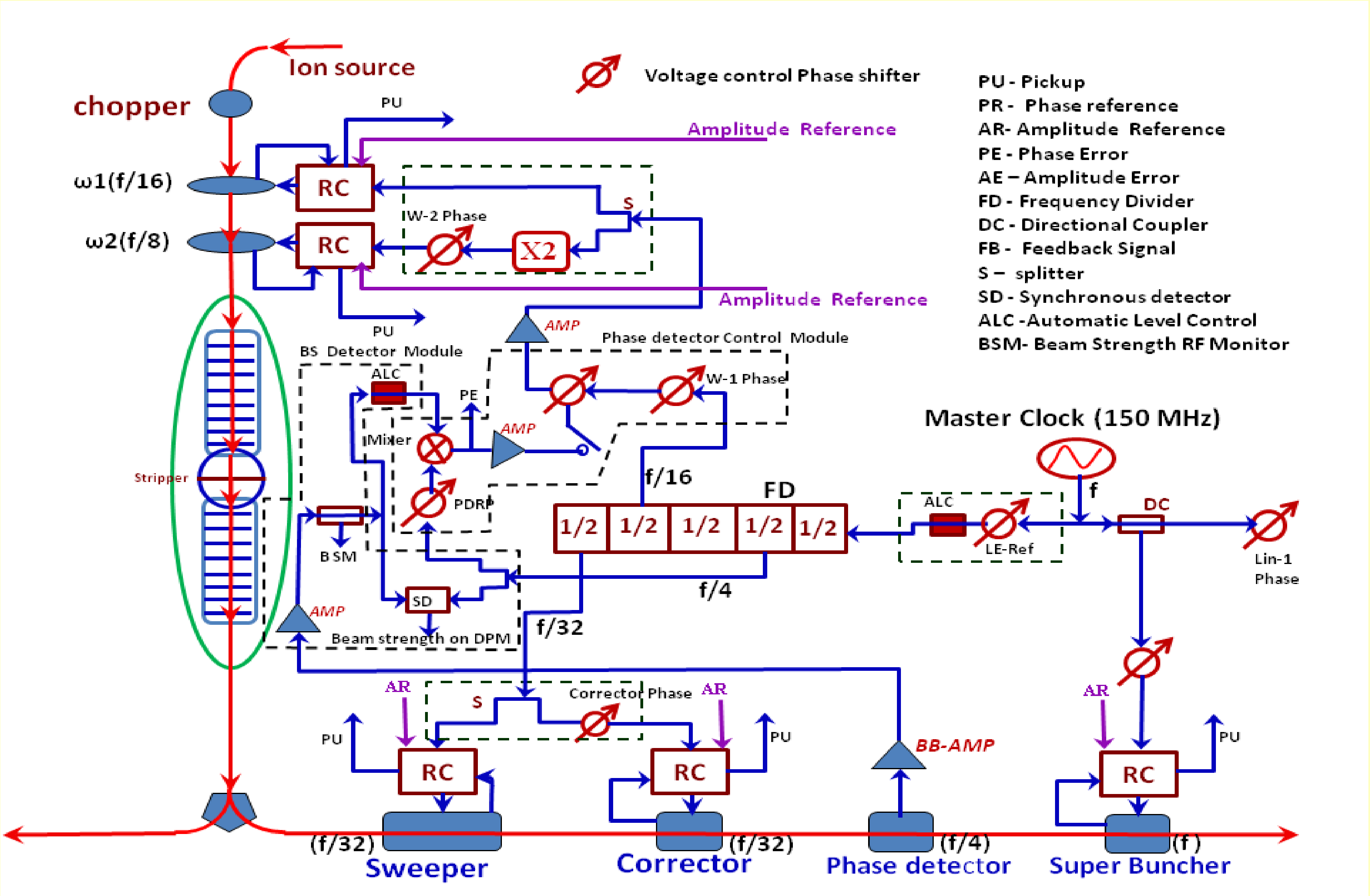
Indigenously developed RF Control Stations for LINAC modules

150 Watt, 150 MHz RF Amplifiers

Control & Operator Interface

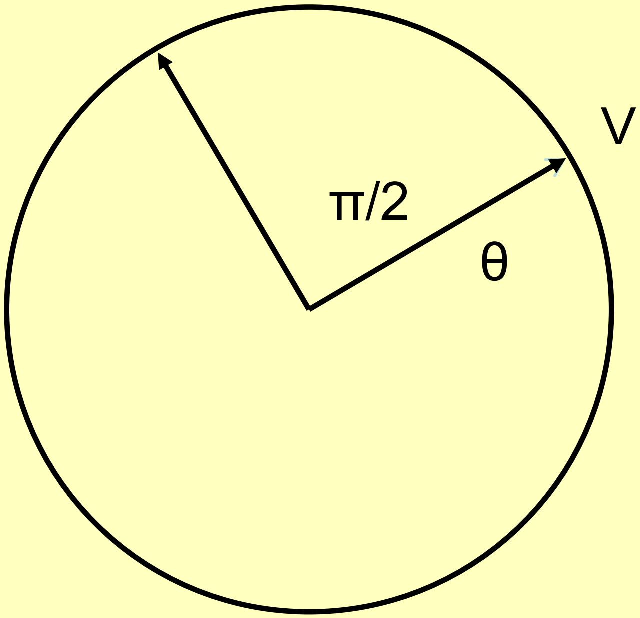


RF distribution and control in the PLF



New Developments

Using under-sampling



+V Cos(θ)
- V Sin(θ)
- V Cos(θ)
+V Sin(θ)

Choice of sampling period
$(n+1/4)*2\pi$

$(13/4)*2\pi=\pi/2$

Under sample with 4/13 of reference frequency (150 MHz)

Reconstruction – DAC at 8/13 of reference frequency

Digital RF Control of the Linac

- A digital implementation
  - Inherently free from the limitations of analog implementation:
    - DC off-sets
    - Drift
    - Gain Imbalance
    - Impedance mismatch, etc.
  - Besides it has:
    - Flexibility
    - Ability to execute complex algorithms

- With the availability of fast, high resolution data-converters and DSP/FPGA’s, modern digital hardware is able to satisfy the requirements of RF control applications

We are developing RF control based on digital techniques

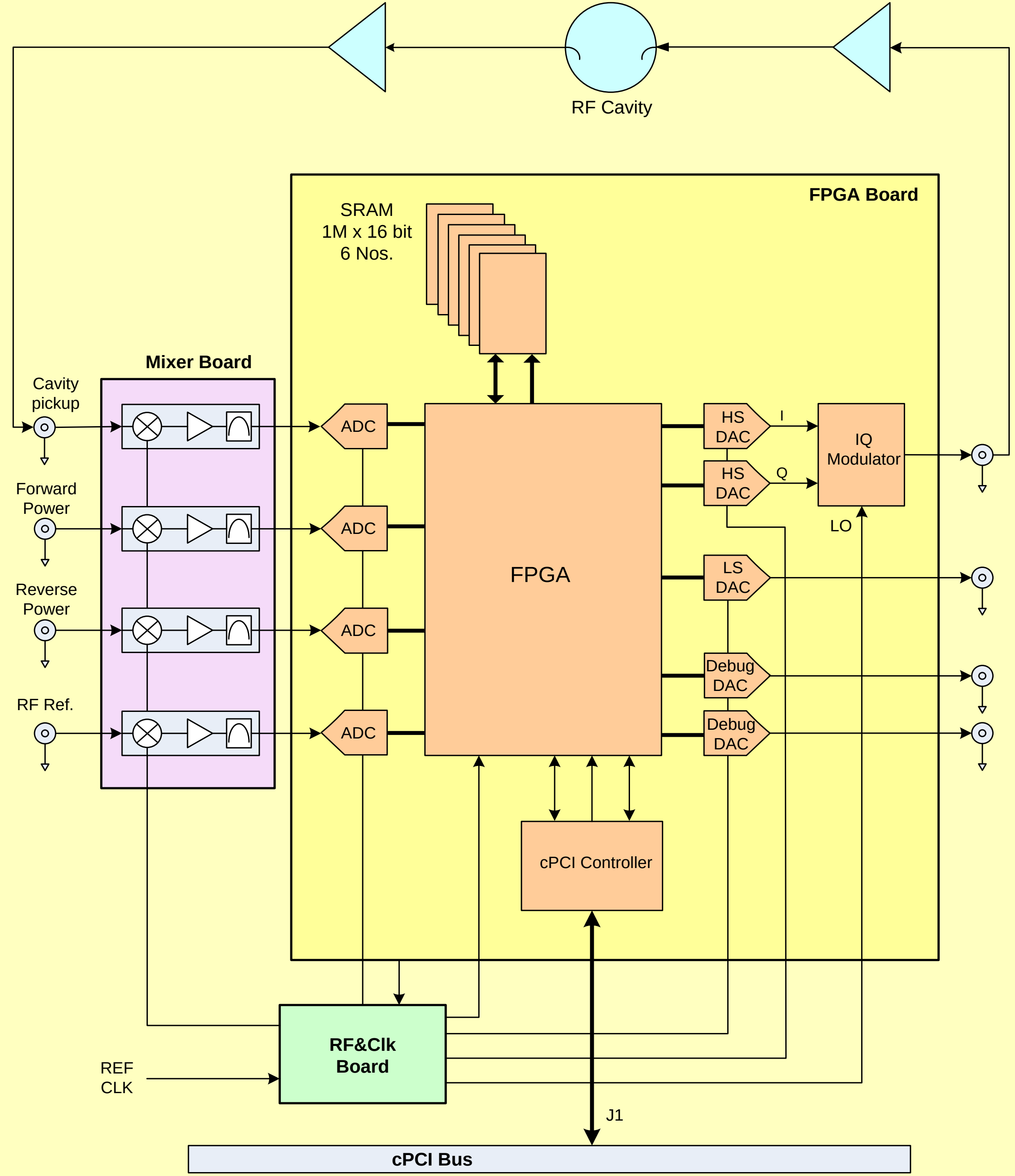
Typical Architecture of Digital RF Control:

Three sub-systems:

Digital Card:
ADC, DAC, FPGA, Memory, Modulator, cPCI interface

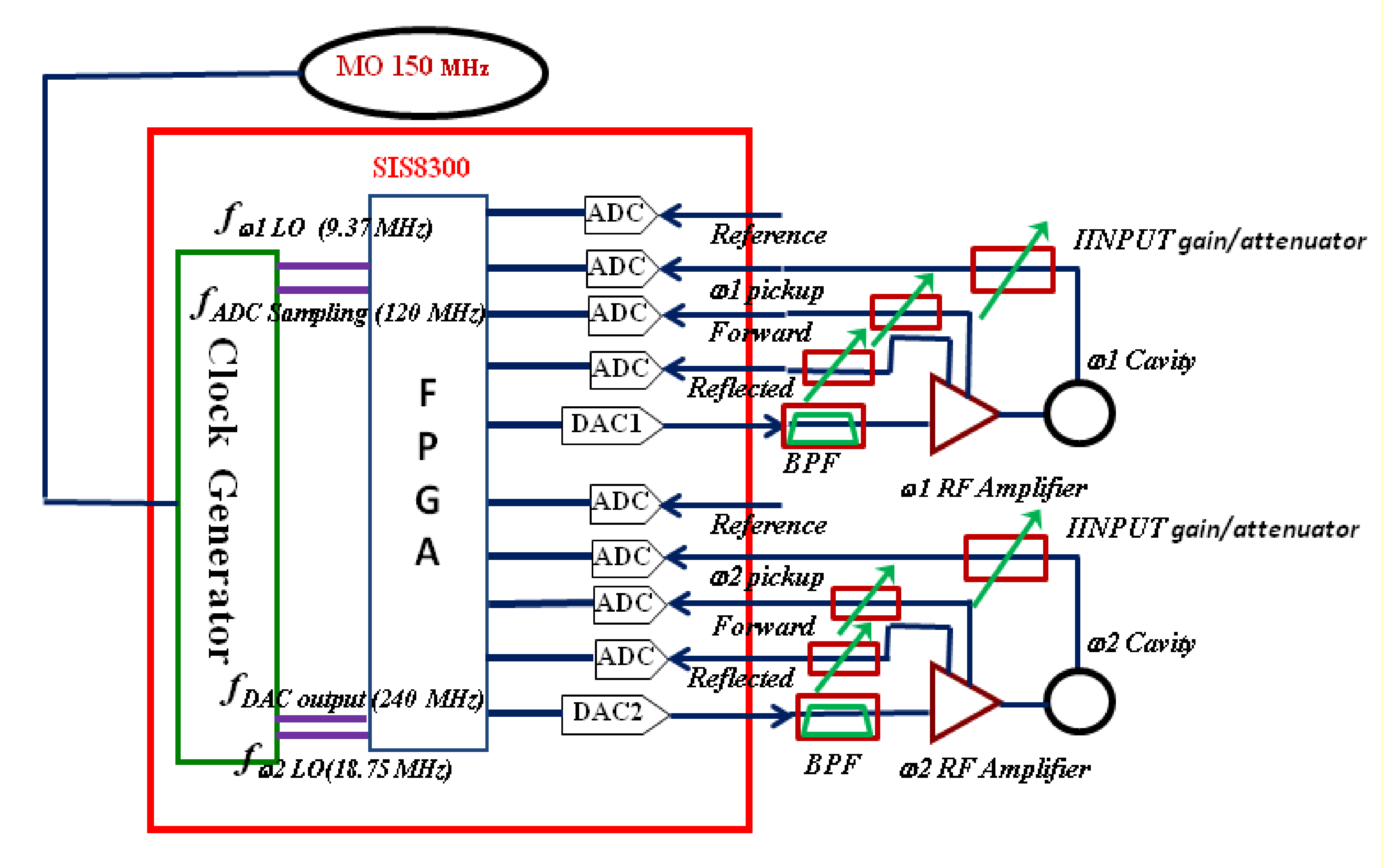
Clock Card:
Clock signals for ADC, DAC. FPGA, Down Converter

Mixer Board:
Down Converter, Filters



Digital LLRF Control System

A proposed scheme for digital RF control of LEB system

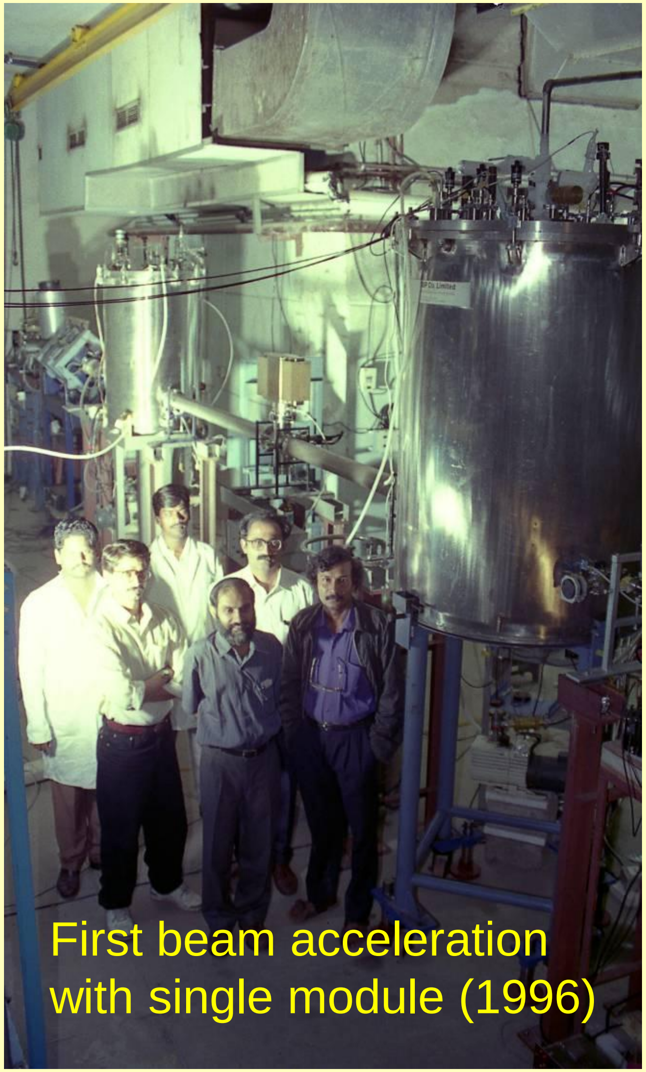


TIFR & BARC

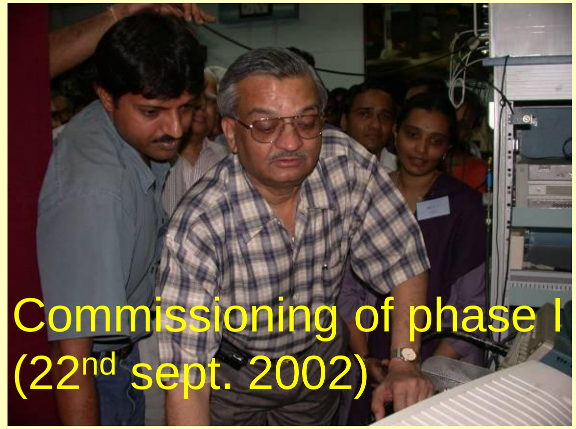
Critical components of LINAC booster have been designed, developed and fabricated indigenously.

Thank you

Some Milestones …



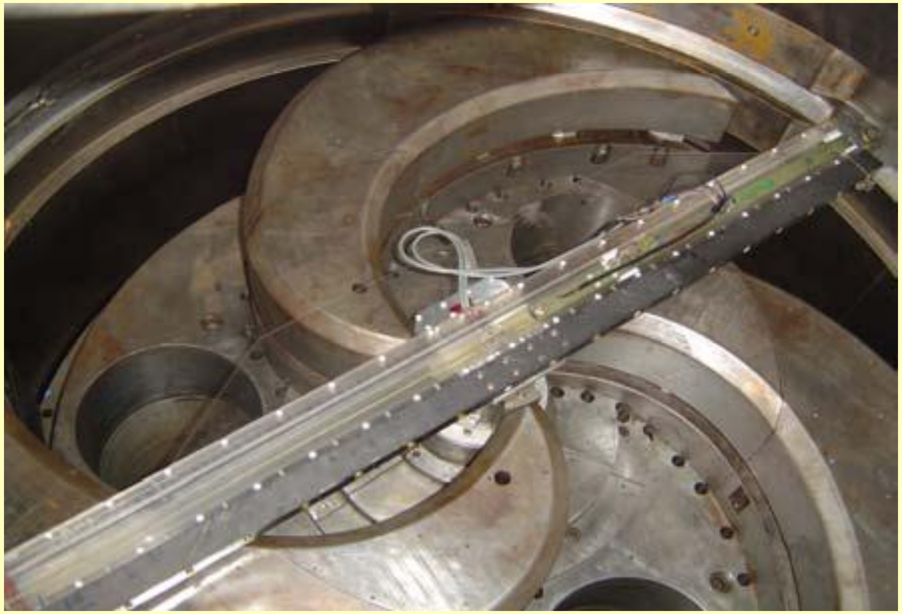
First beam acceleration with single module (1996)



Commissioning of phase I (22^{nd} sept. 2002)

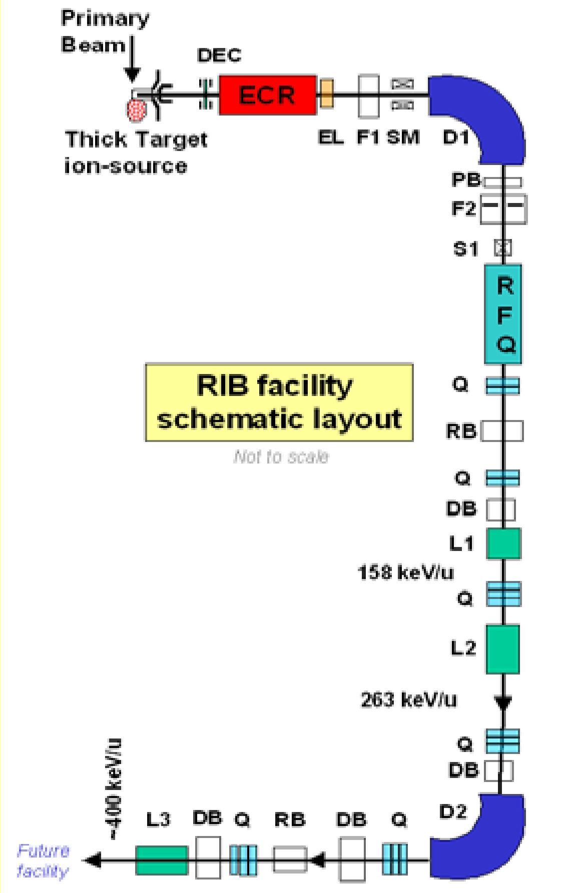
First LINAC experiment begins on 16th April 2003

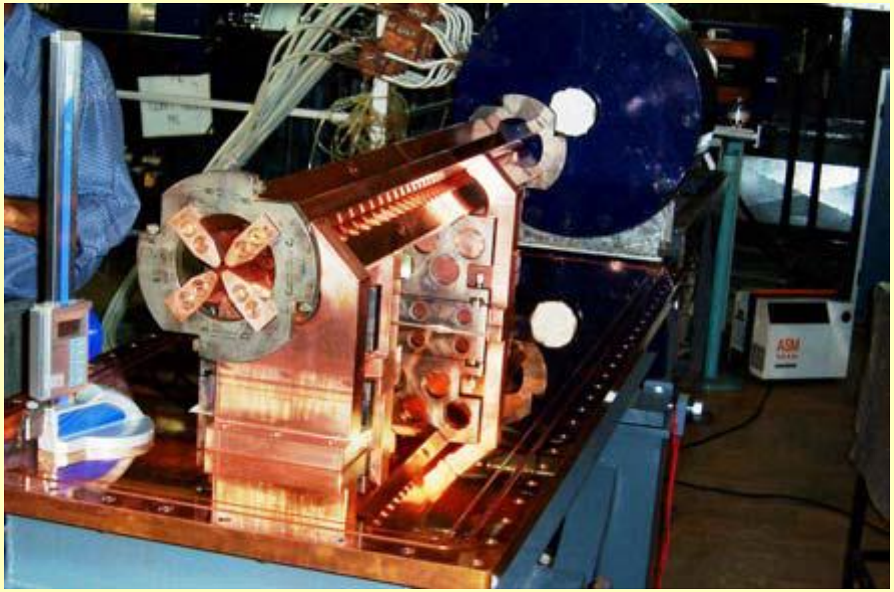
Dedicated to Users on November 28^{th}, 2007



Superconducting Cyclotron

VECC Kolkata





Low Energy RIB

VECC Kolkata

Nb QWR cavities development
IUAC New Delhi

IUAC Linac module with
8 QWRs