Electron Accelerator Development Program at BARC

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Outline

1. High power electron linac program in BARC
2. Technology status
3. Project of setting up experimental neutron facility with electron accelerators.

Electron accelerator programme objectives

High power electron accelerator programme focused on

1. **Industrial accelerator for electron irradiation**
2. **X-ray and photoneutron sources**

- **New and innovative technology solutions**
- **Build facilities for scientific research and industrial trials**
- **Diffuse electron accelerator technology in India**
- **Promote utilisation of electron irradiation in the country**
- **Economic solution with competitive costs**

Summary of work of

The high power electron accelerator group of BARC

Electron linac technology development for next 5 years

10 MeV, 10 kW Linac (at EBC, Kharghar) Utilization and Upgradation of Facility	2856 MHz	0.9 m
Compact Linac 9 MeV, 6/3 MeV X-Ray source for cargo scanning, research accelerators- productionization at ECIL	2856 MHz	0.9 m and 0.6 m
30 MeV, 7 kW neutron generator for shielding & nuclear physics (n-TOF) studies (IGCAR, Kalpakkam)	2856 MHz	2.5 m
100 MeV, 100 kW neutron generator for ADS and material related studies	2856 MHz	11 m
Superconducting linac	1497/ 1300 MHz	9 cavity cells

Electron Beam Utilization of 10 MeV RF Linac

- Polyethylene o-rings for use up to 250ºC
- Reverse recovery time (trr) of Diodes reduced from 15 us to 7μs (BHEL production trials)
- Potato irradiation trials (Food Technology Division, BARC)
- Cross-linking of heat shrinkable rubber (Raychem)

- Gelation of Polyvinyl acetate (Pidilite Industries)
- Measurement of Delayed neutron from photofission for Fissile material detection (BARC)
- Photofission data for Mo-99 (BARC)
- Several other research projects of Universities

Electron Accelerators as Drivers for ADS

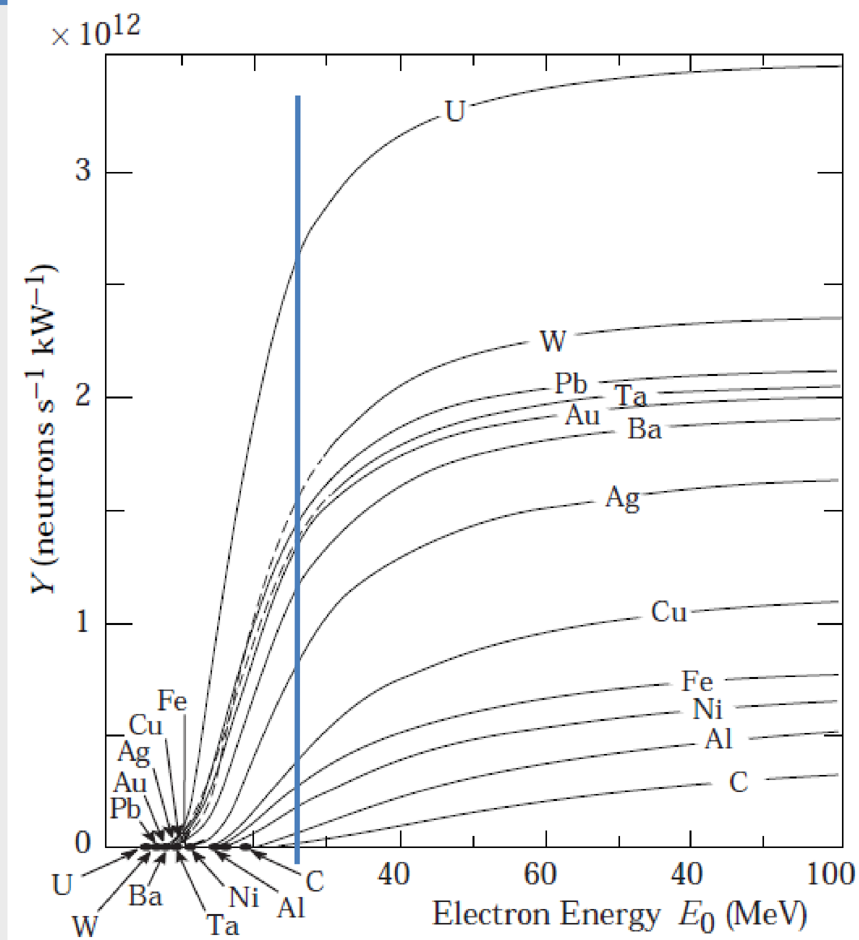
1. Electron accelerator technology is a mature technology
2. Easily used for Bremsstrahlung / photoneutron source
3. Isotope production for medical diagnosis and therapy
4. Nuclear physics studies related to ADS spallation, higher energy neutron reactions
5. Less efficient than proton machines in neutron production but has lower capital cost and comparable energy cost
6. ADS application is reliable because of less beam trips

A thorough evaluation is required for ADS application on a larger scale;

its suitability for experimental ADS studies is generally accepted.

Electron Beam as a neutron source

- neutrons are generated via **photonuclear and photo fission reactions** from Bremsstrahlung photons.
- In the photon energy range from threshold (few MeV) to about 30 MeV, neutron production is via the **Giant Dipole Resonance (GDR)** mechanism.
- For 5 MW, 100 MeV e- beam, in a dual zone reactor, power increases by 12 times for k=0.98
- Output Power will be ~ 5 x 12 = ~ 60 MW.



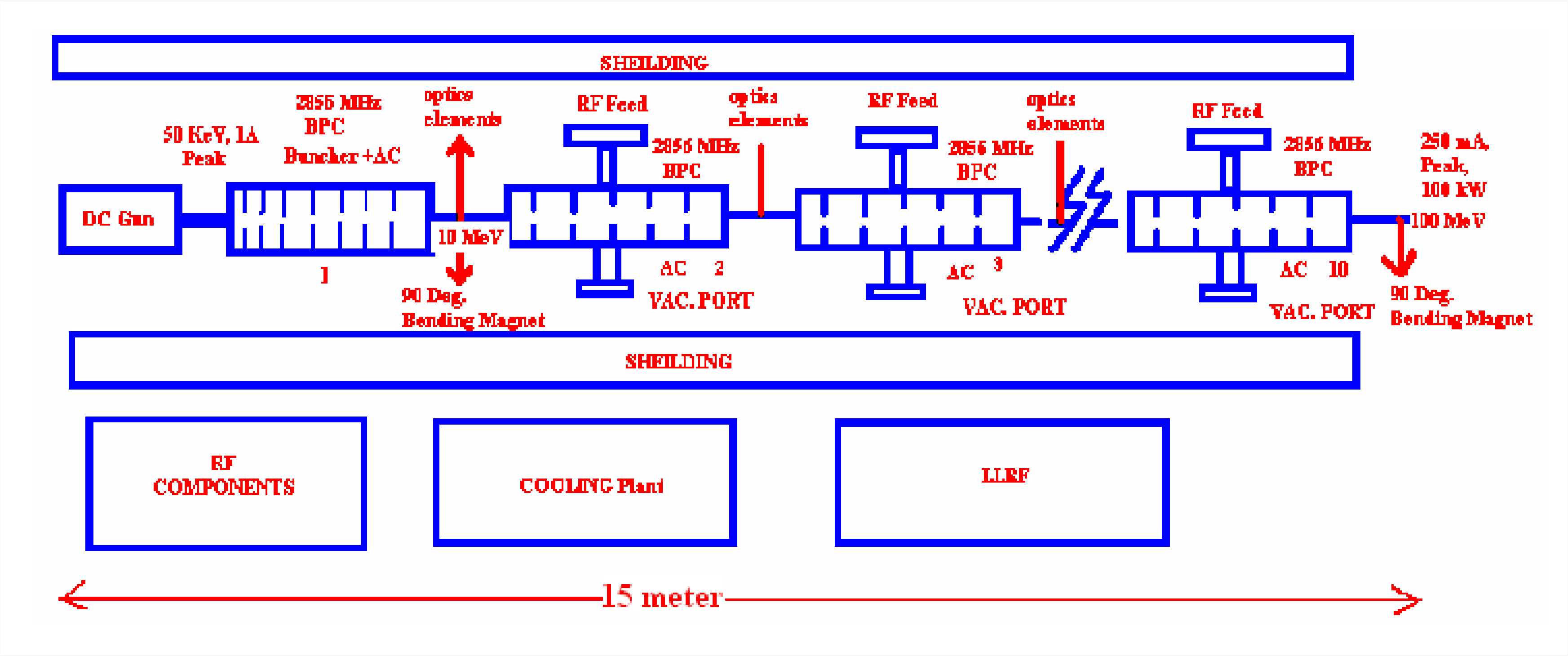
Ref:Swanson, IAEA Tech Rep 188 (1979)

Beam Energy (MeV)	Neutron Yeild (n s^{-1} kW^{-1})	Beam Current (mA)	Beam Power (MW)	Neutron Flux (n/s)
100 (U – Target)	$3.25X10^{12}$	50-100	5-10	$1.625\text{-}3.2X10^{16}$
100 (W –Target)	$2.17X10^{12}$	50-100	5-10	$1.085\text{-}2.17X10^{16}$
100 (Pb – Taget)	$1.97X10^{12}$	50-100	5-10	$0.985\text{-}1.97X10^{16}$
100 (Ta–Target)	$1.91X10^{12}$	50-100	5-10	$0.955\text{-}1.91X10^{16}$

RF Electron Linac for Neutron Generation

PHASE I:

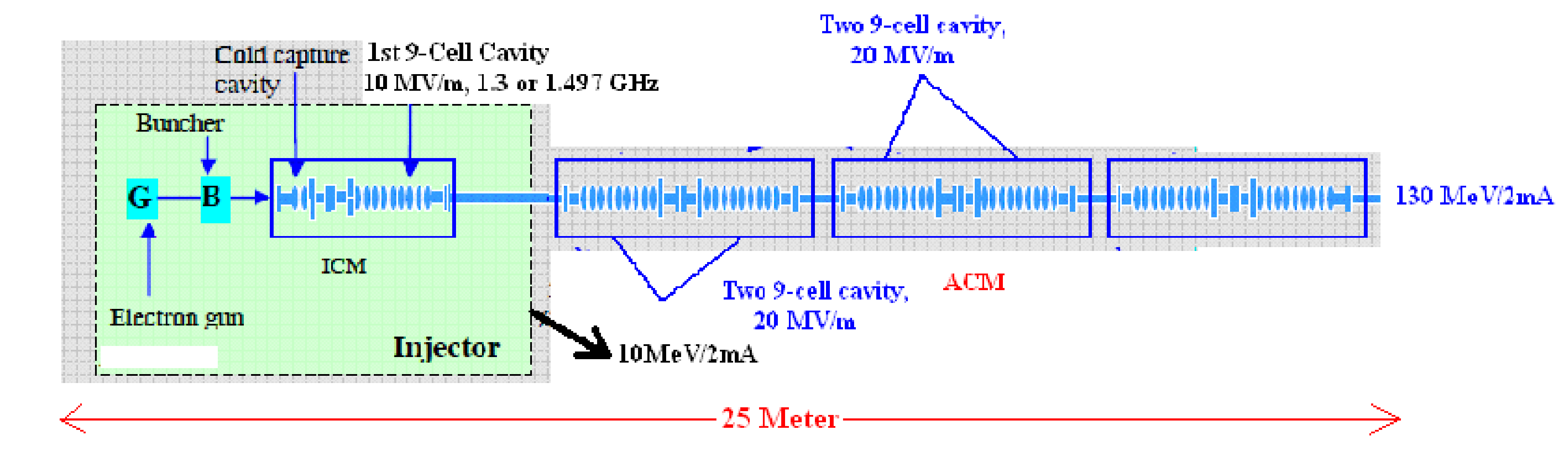
100MeV, 100 kW, pulsed normal conducting Linac (S-band, f = 2856 MHz), avg. neutron flux ~ 10^{13} n/cm^2/s



RF Electron Linac for Neutron Generation -2 contd

PHASE II

150MeV, 200-300 kW, cw -superconducting Linac (L-band), neutron flux ~ 10^{15} n/cm^2/s



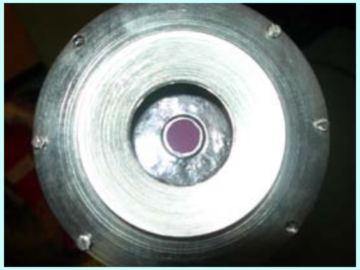
Main components of 100 MeV/100 kW e-accelerator

1	Electron Gun 1 A / 85 keV	Developed
2	RF Cavities (10 Modules of ~ 10 MeV) (33 Cells, 900 mm long)	Developed
3	Klystrons and Klystron Modulators 10 Nos. Each (5 MW peak, 36 kW Av.)	Klystrons development at CEERI, Pilani. Line type modulator developed. Solid State modulator under development
4	Focussing Devices (Solenoid, Quadrupole Magnets……)	Experience exists
5	Photo neutron Targets	Design in progress
6	Controls and Instrumentation	Developed for 10 MeV/ 9 MeV/ 6 MeV
7	Super conducting Cavities (Phase – II)	Development in progress

Development of Electron guns

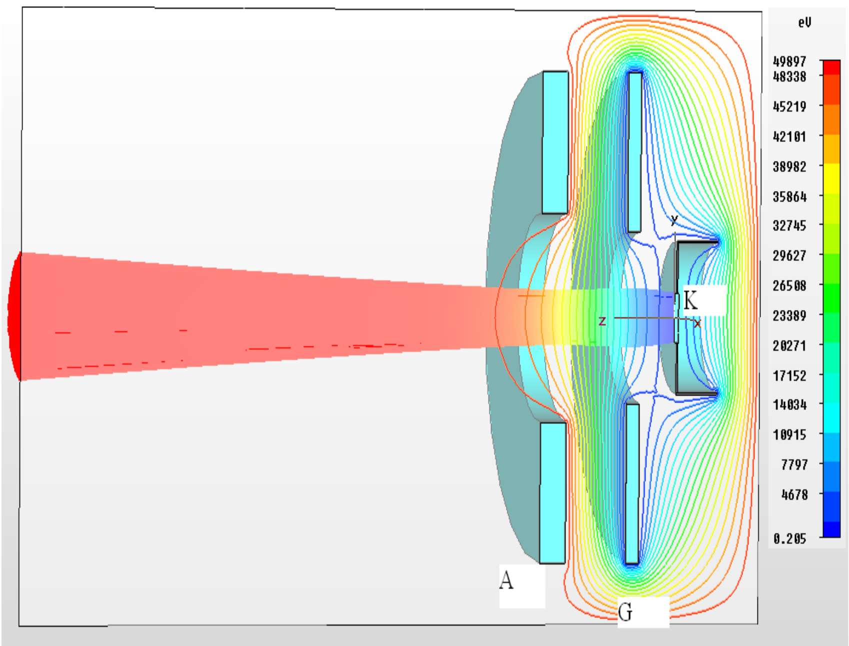
Electron gun of 10 MeV Industrial linac

Electron gun of 6/3 MeV compact linac

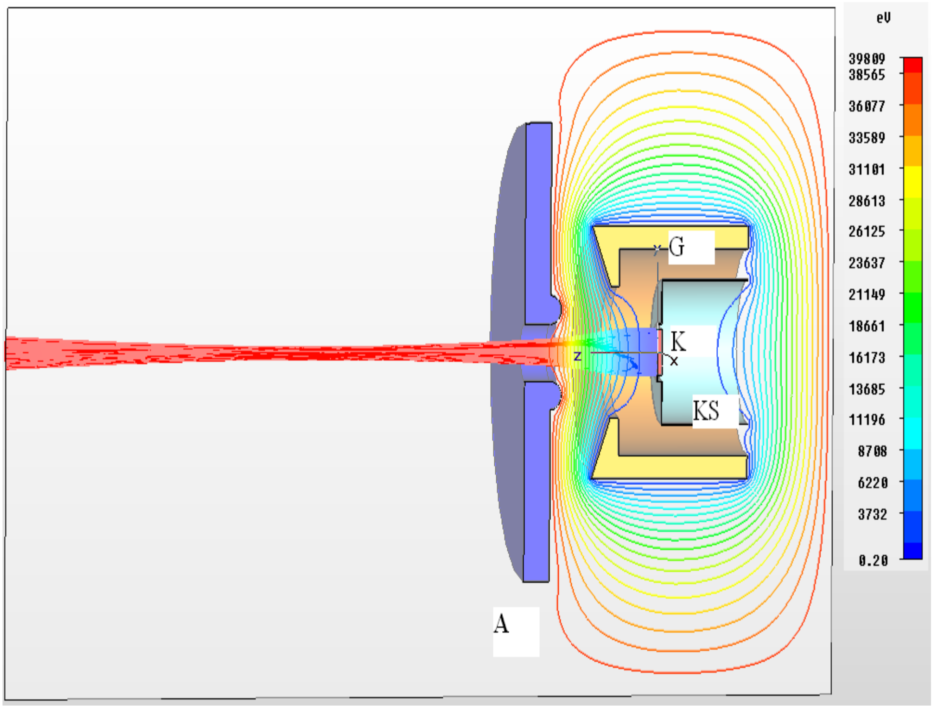


Components of Electron gun

Modelling & Simulation of Electron Guns

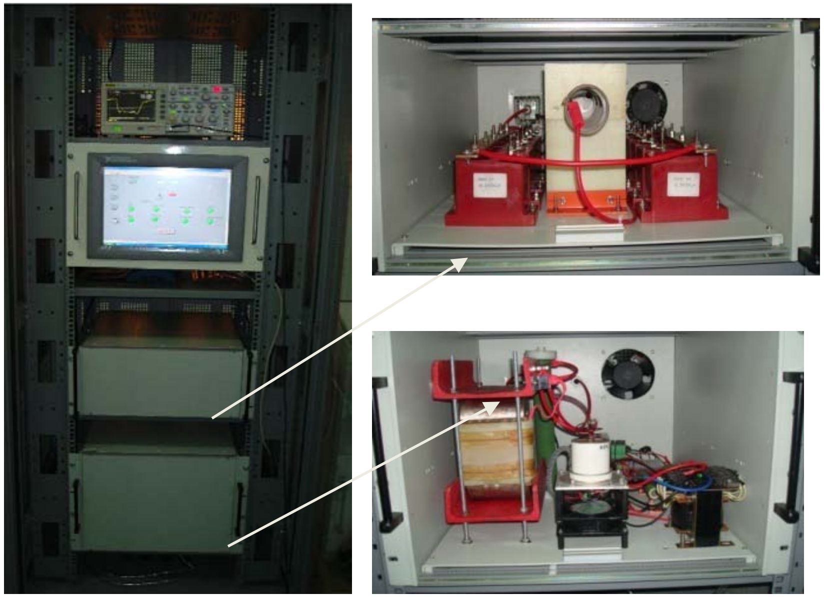


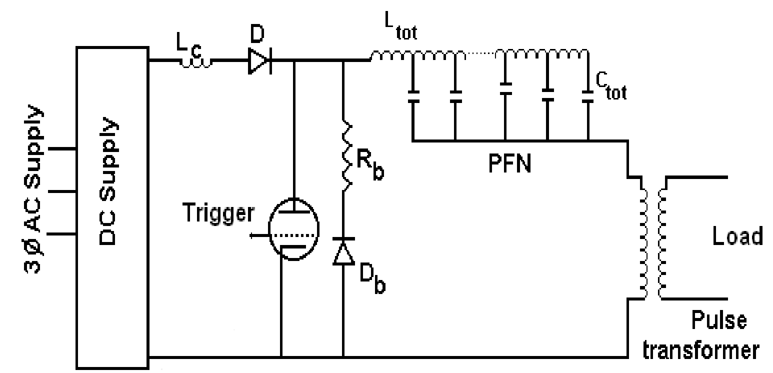
Equipotential and Trajectory plot of Planar Geometry Electron Gun



Equipotential and Trajectory plot of Pierce Geometry Electron Gun

Gun modulator (line-type)





Gun modulator of 6 MeV compact linac

Gun modulator of 10 MeV industrial linac

Specifications

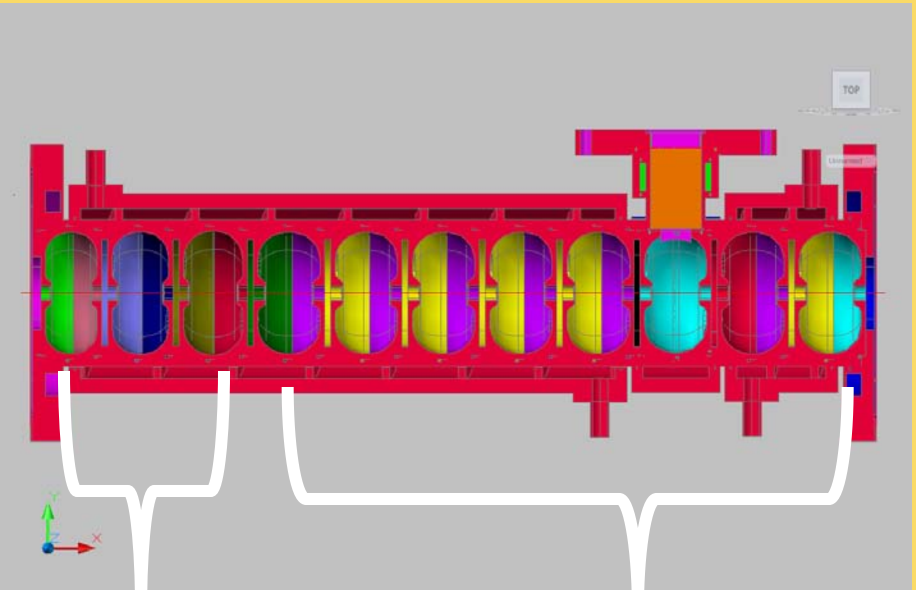
Voltage : 50 – 100 kV

Peak beam current: 0.5 – 1 A

Pulse width : 5 – 10 μs

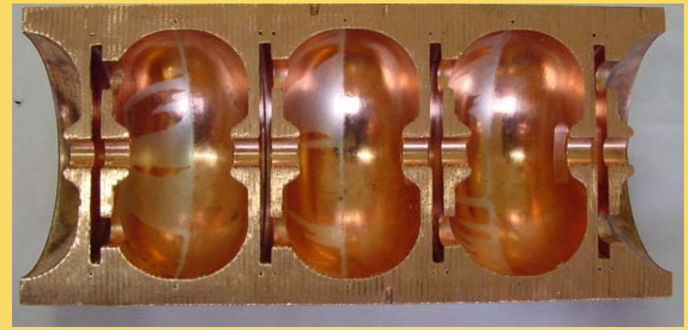
Rep.rate: 10 – 400 Hz

RF Structure - Compact Linac 6/3 MeV (21 Cells)



3 Buncher cavities (45, 48 , 50 mm)

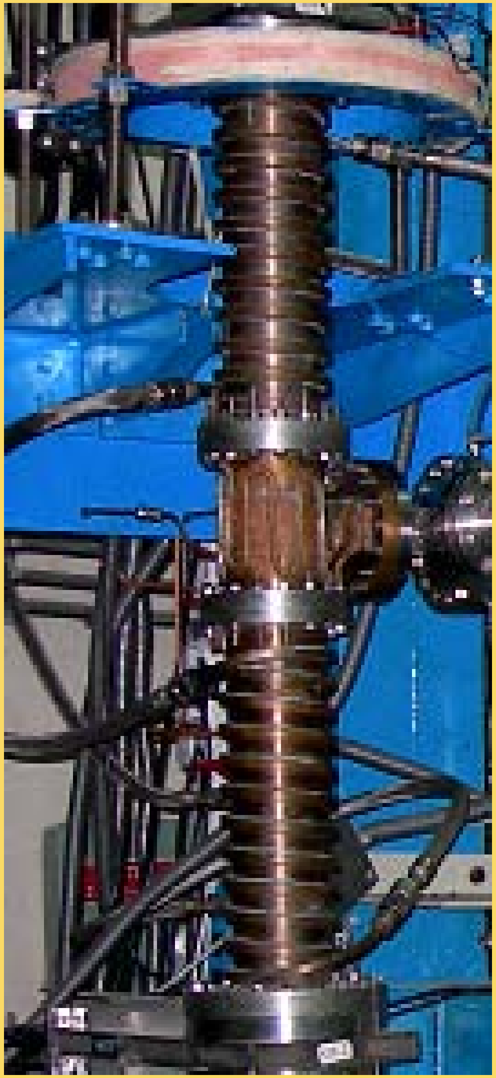
Accelerator Section (52 mm cell)



9 cell Brazed Assembly

Parameters	Designed	Measured
Q0	13,500	~ 13,000
Z_s (MOhms/m)	~ 80-90	~ 85
E_{accc} (MeV)	~ 10	~ 10
Beam Transmission Efficiency %	72	60
RF Power Transfer to Beam %	55	38

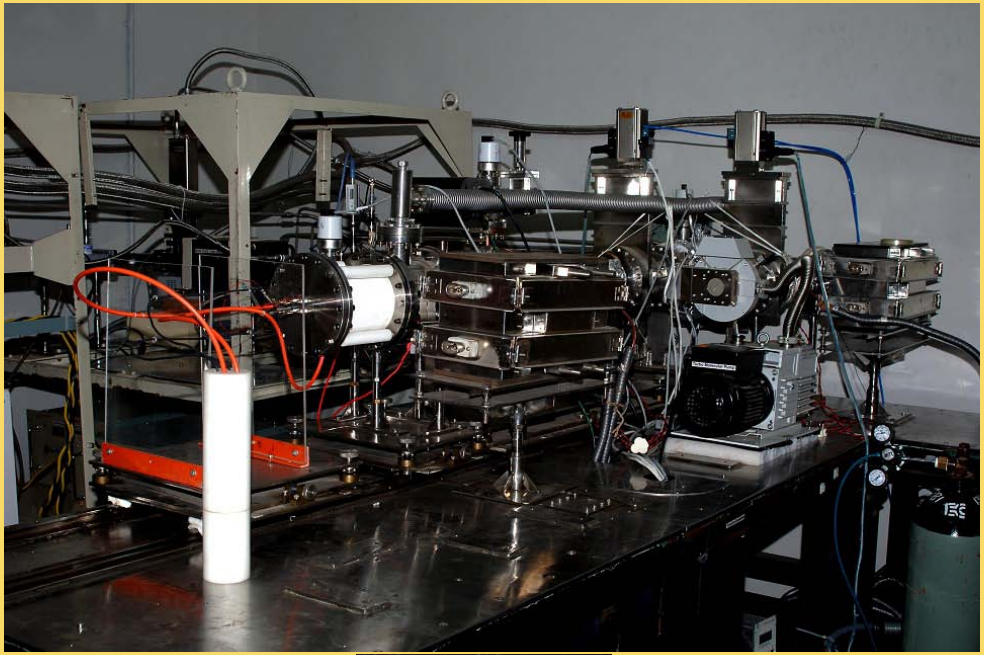
RF Structure



10 MeV linac

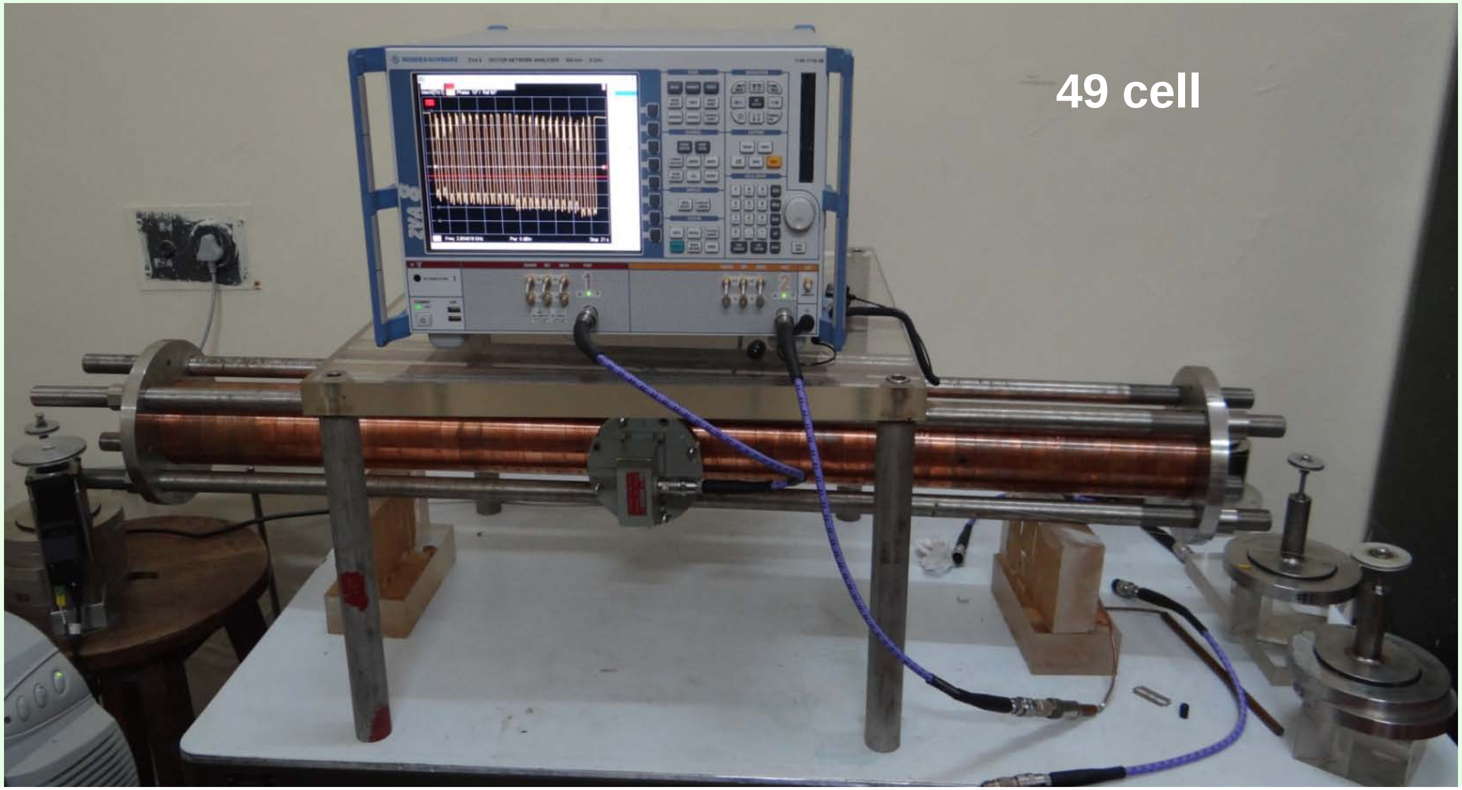
6/3 MeV linac

9 MeV linac



X-ray Spot diameter ~ 2.5 mm
Measured X-ray dose = 24 Gy/min/m

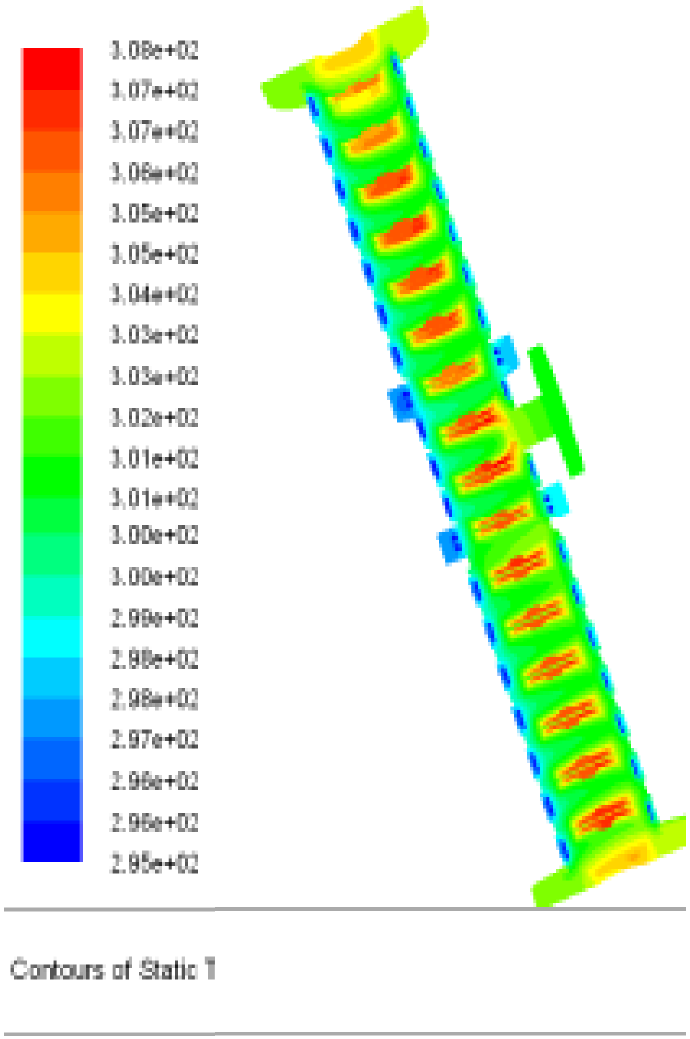
30 MeV linac Neutron generator
RF Measurements on 49 cell and 45 cell Structures

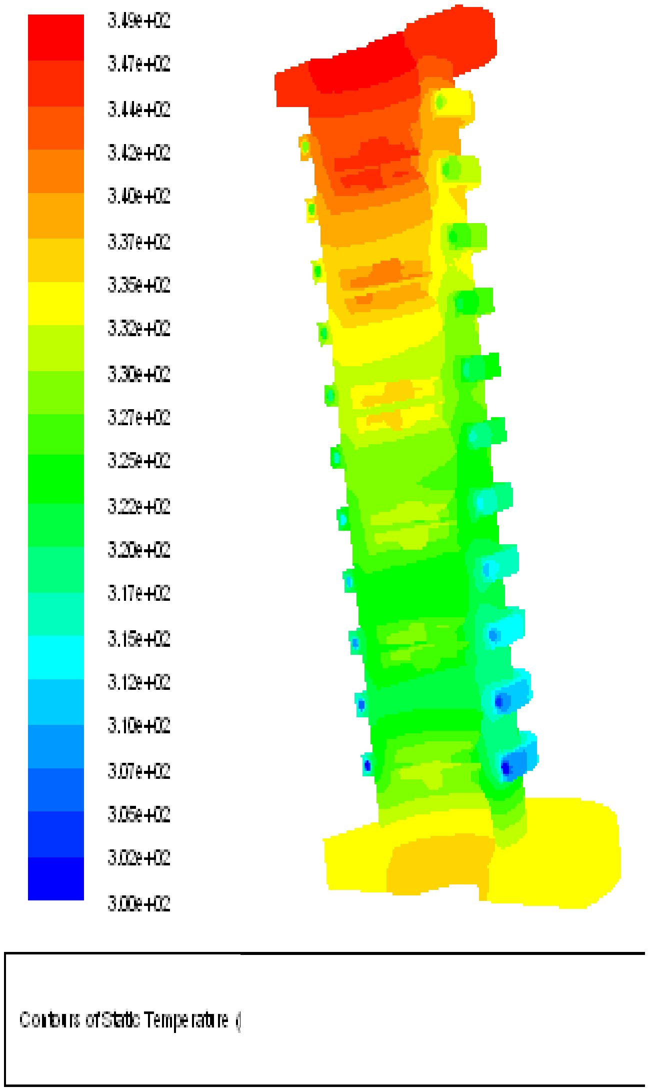


VNA shows the Electric Field Uniformity along the Accelerator Length

Measured Freq. – 2855.0 MHz, Q_0 ~ 10000 and Z_s ~ 80 – 90 MΩ

Thermal modelling of 10 MeV Electron Linac

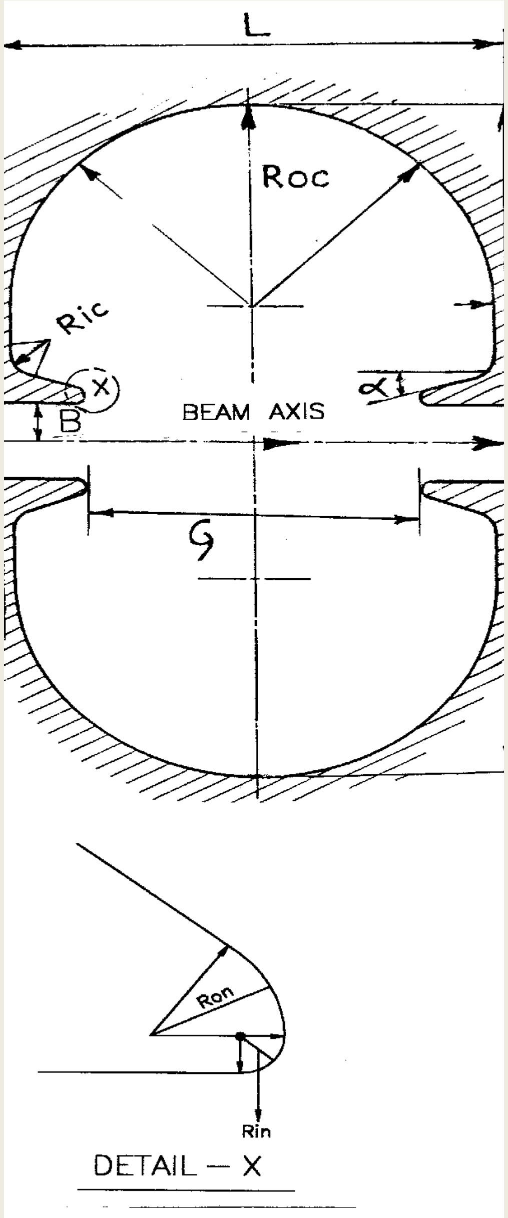




Design tolerances

Achieved during machining of cells

Sl. No.	Parameter	Change in frequency
1.	D	- 34 kHz / μ
2.	B	- 13 kHz / μ
3	L	- 25 kHz / μ
4	T	+ 25 kHz / μ
5	G	+ 22 kHz / μ
6	α	- 106 kHz / deg.
7	R_{in}	- 16 kHz / μ
8	R_{on}	- 7 kHz / μ
9	R_{ic}	+ 0.1 kHz / μ
10	R_{oc}	+ 24 kHz / μ



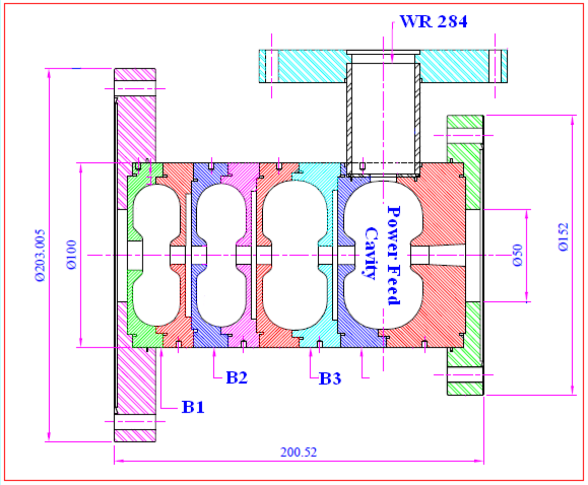
The RF measurements of Resonant Frequency before and after vacuum brazing has been observed within ~ 0.25 MHz

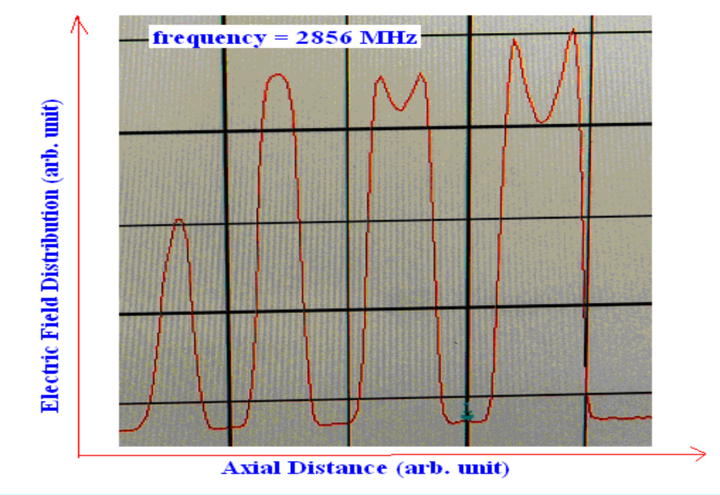
40 kV Autofocussing Buncher

- β = 0.66, 0.68, 0.84.
- Autofocussing by electrostatic lens

Aluminum Buncher Model

Schematic of 40 KV Buncher



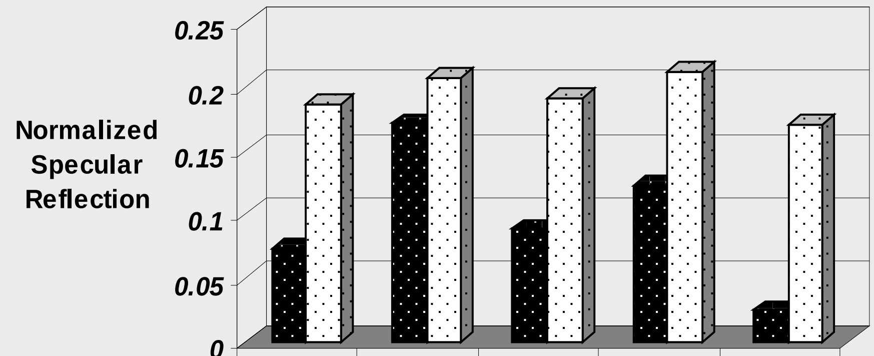


$\pi/2$ mode = 2856.4 MHz

Development of Copper Cavity Surface Treatment Process

SURFACE TREATMENT STEPS

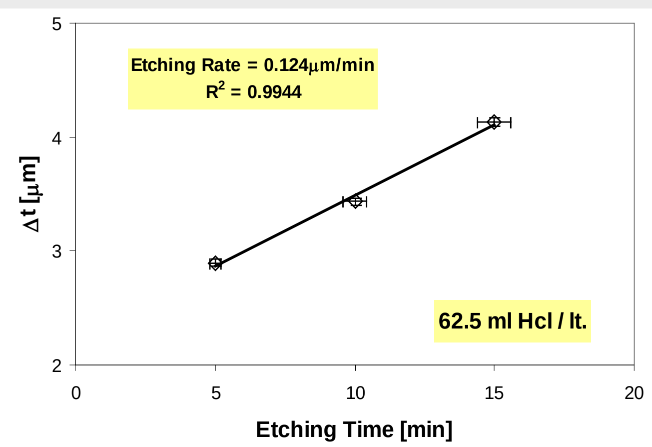
1. Sample cleaning by ultrasonic in HPLC grade Isopropyl alcohol – 10 mins
2. DM water (0.75 µS)
3. Ultrasonic in alkaline soln. pH 9.7 for 10 mins
4. DM water rinse
5. Acid pickling ~ 5% HCl 5 – 15 mins
6. DM water rinse
7. Passivation in CrO3 80g/l and 3cc/l H2SO4 at 523K for 1 min



	S1	S2	S3	S4	S5
Before Cleaning	0.073529	0.171569	0.088235	0.122549	0.02451
After Cleaning	0.186325	0.206838	0.191228	0.212281	0.170175

Evaluation by specular reflection

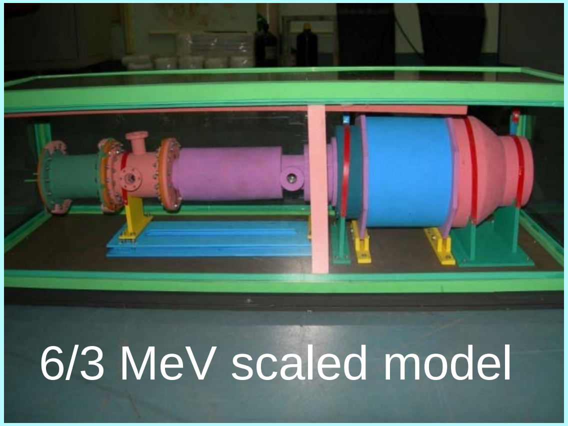
- **5% HCl for 6 min pickling shows best surface roughness – Sample S-4**
- **Passivation did not contribute**



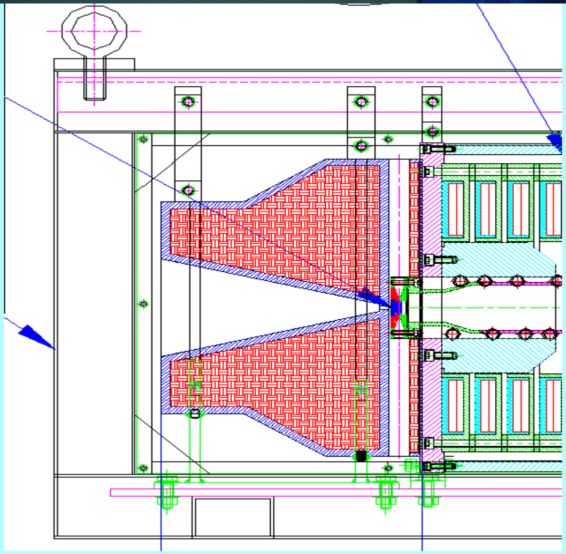
Development to achieve surface with low field emission

Prototype Dual Energy (6/3 MeV) Compact linac for material discrimination - Assembly & Testing

X-RAY TARGET



COLLIMATOR

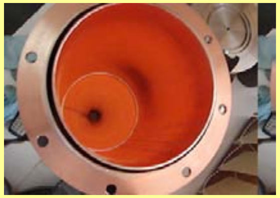


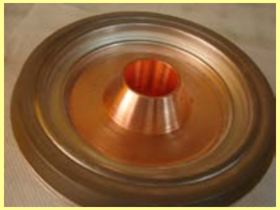
Klystron development at CEERI, Pilani

Gun Collector Test Module

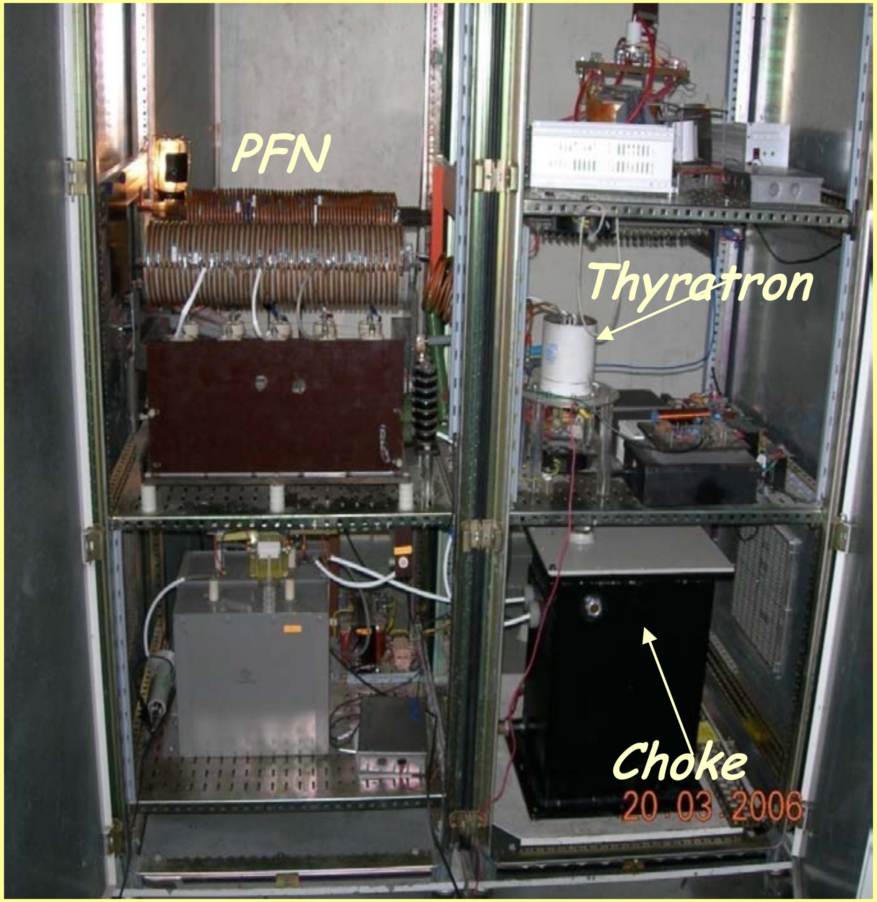
Specifications
Frequency : 2856 ± 10 MHz
Peak Output Power : 6 MW
Avg.Output Power : 24 kW
Beam Voltage : 140 – 165 kV
Peak beam current: 90-120 A
Pulse width : 5 – 10 μs
Rep.rate: 10 – 415 Hz

RF Section

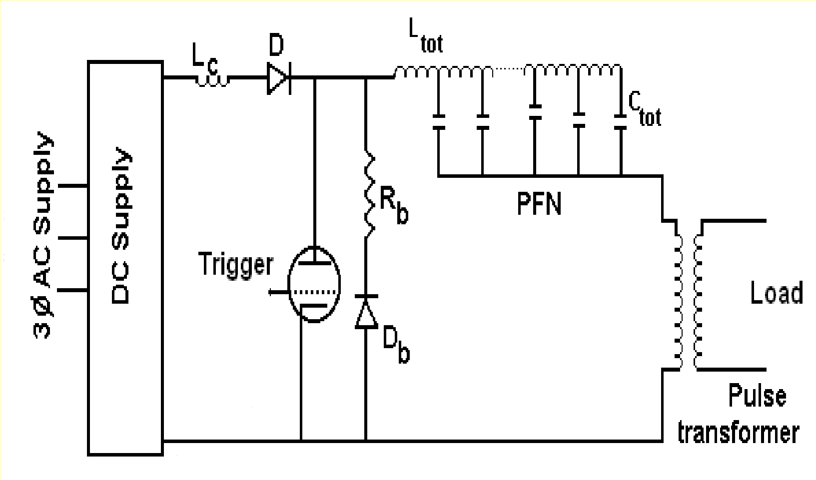




Klystron modulator development



Line-type (55 kV, 270 A, 10 μs, 400 Hz) in collaboration with SAMEER, Mumbai



Line-type (150 kV, 110A, 10 μs, 400 Hz)

Superconducting Vs Normal Conducting RF Cavities

Normal Conducting	Superconducting
• OFHC Copper	Niobium
• Q ~ 10,000	Q ~ $10^8 – 10^9$
• Room Temp	Liquid He Temp.
• High Power RF	Low power RF
• Electric Field ~ 10 MV/m	30-40 MV/m

SCRF Leads to Compact Linac Development

With additional cost of Cryogenics

Ingot Niobium SCRF Cavity Development

β = 0.49, f_0 = 1050 MHz large grain niobium cavity electron beam welded.

Parameters	Simulated	Measured
f [MHz]	1036.856	1036.507
Q	17032	8076
Rsh [MΩ/m]	4.711	3.61

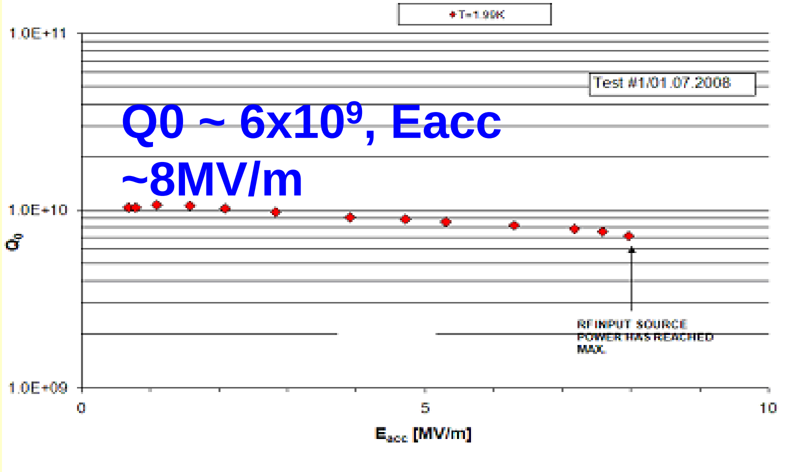
Design parameter of the β = 1.0, f0 = 1050 MHz cavity

Parameter	Value
Cavity diameter	255.4 mm
Cavity length	14.276 mm
Bore radius	43 mm
Accelerating Gradient	25 MV/m

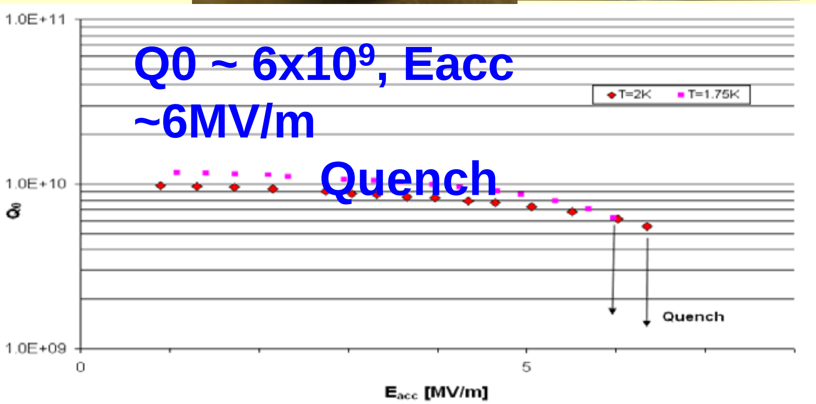
β=0.49, f =1050 MHz Niobium Cavity Test Results at 2K
(Courtesy: G. R. Myneni, in collaboration with JLab)

Polycrystalline Cavity, RRR>250

Large Grain Cavity, RRR>150



Q0 ~ 6x10^9, Eacc ~8MV/m



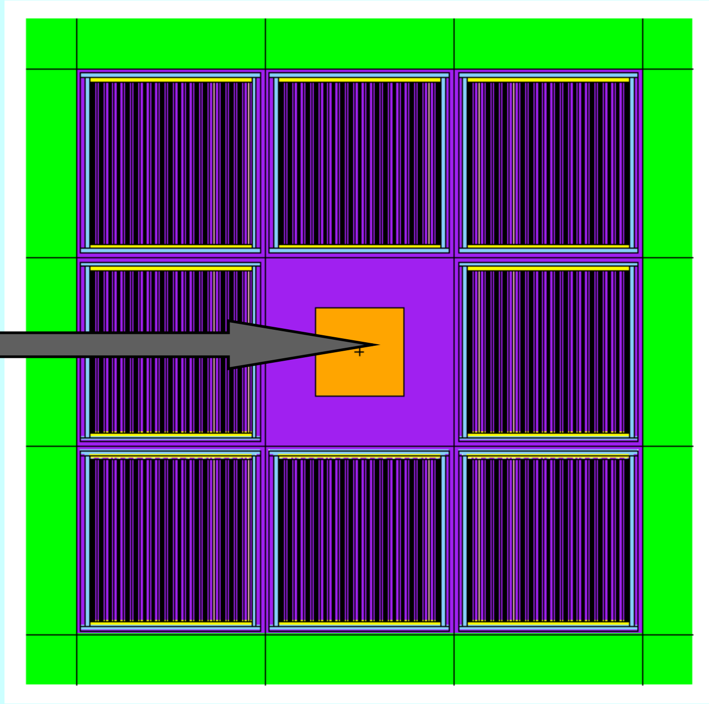
Q0 ~ 6x10^9, Eacc ~6MV/m

Quench

Neutron Multiplier

Solid fuel core layout
25.5x25.5x(30-60) cm

Target



Maximum neutron flux is
~5e12 at Keff of ~0.975 for
Tantalum target

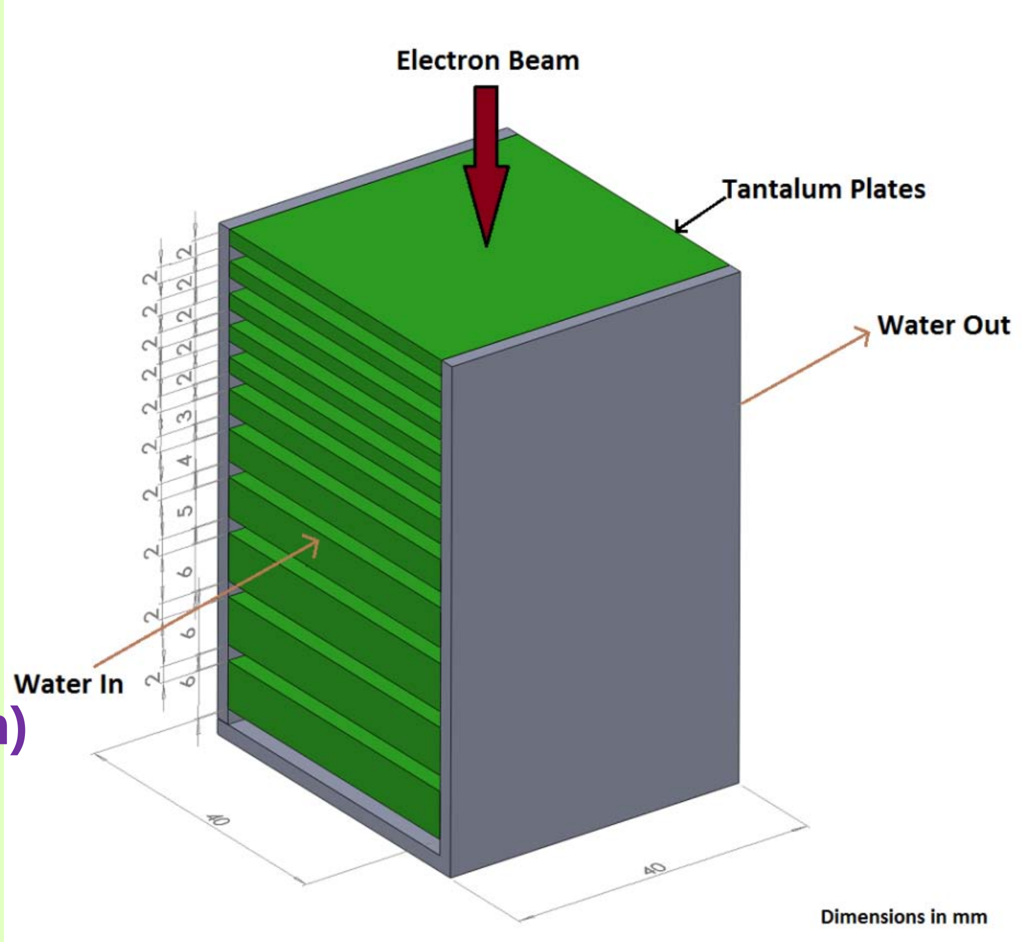
Target Configuration

Beam Parameters:

- **Beam Dia: 30 mm**
- **Beam Energy 100 MeV**
- **Beam power: 100 kW**
- **Duty cycle: 400 Hz**
- **Pulse duration: 10 µs.**

Target Geometry:

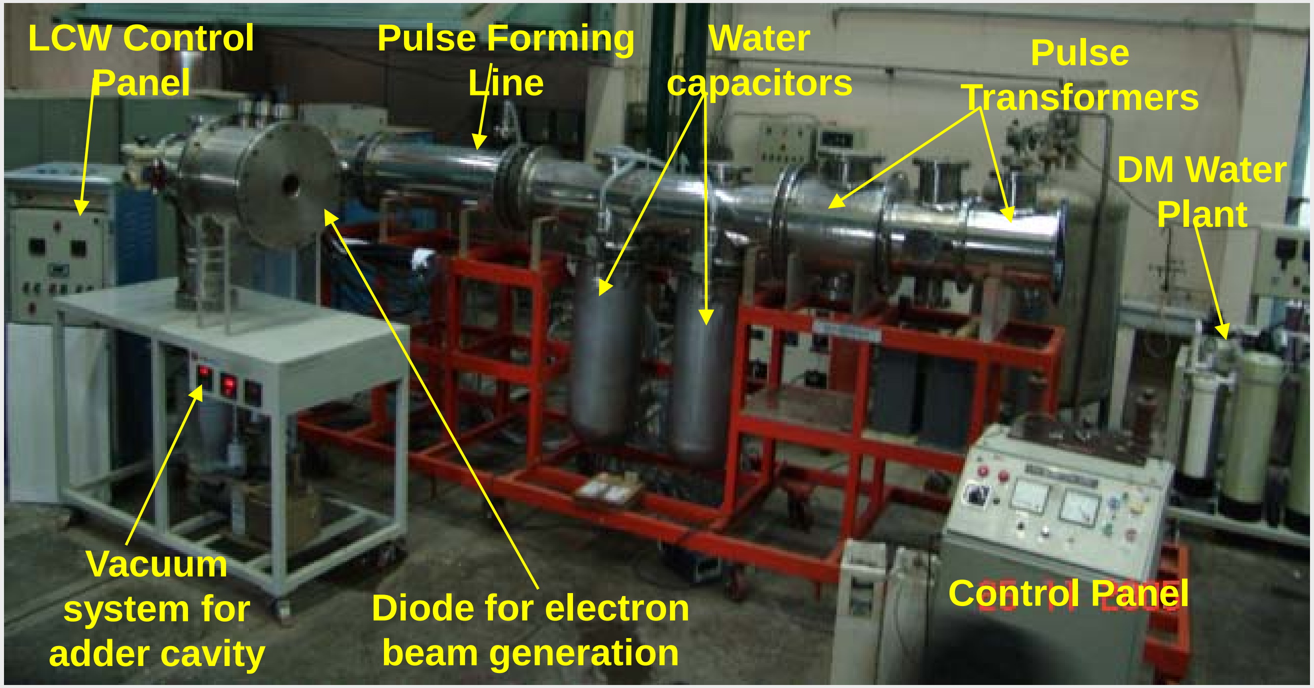
- **Rectangular plates (4 cm×4cm)**
- **Number of plates: 11**
- **Thickness : 0.2 – 0.6 cm**
- **Water channel width: 0.2 cm**

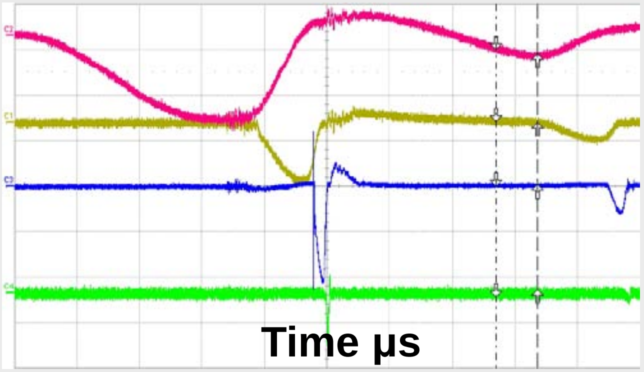


Schematic of Target configuration

Linear Induction Accelerator (LIA-200) as electron source

200keV, 5kA, 50ns, 10-100Hz as a possible injector for linac photoneutron source for nuclear physics experiments





15 µs

120 ns

- ❖ Short Pulse duration (10 – 100 ns)
- ❖ High Peak Current (10 – 50 A)
- ❖ Low Rep Rate (10 – 40 Hz)

Design issues of Beam tube

Beam tube delivers the beam from accelerator window to the target vault

- Diameter & divergence of the output beam of 100 MeV accelerator ~ 6mm and 5 mrad resp.

- Sizing of beam tube

- Bending of beam tube through the shielding wall

- Optics for beam expansion

- Beam diagnostics and correction optics

- Minimum loss beam transmission

- Isolation window and linac window design optimization

- Low radiation damage window

Control & Instrumentation

Main Control loops

1. RF peak power control to set power output
2. Automatic Frequency Control (AFC)
3. Phase Control for synchronization between linac stages
4. Output current control for beam power output
5. Pulse Rep rate depending upon application of linac
6. Temperature control for frequency stability

Analog Inputs (AI) /Analog output (AO) ~ 50
Digital Inputs (DI) /Digital outputs (DO) ~ 500
Sensors are developed for most parameters

Remote Handling Tasks

1. Fuel assembly replacement
2. Target replacement and assembly
3. Linac window repair and replacement
4. Handling of cooling lines of target and neutron multiplier
5. Shielding plugs handling
6. Handling of contaminated and activated components for replacement
7. Manual interventions for maintenance

Engineered Safety Aspects

1. Safety of neutron multipliers (Philosophy of reactor safety)
2. Neutron & x-ray Radiation shielding & monitoring
3. DM Cooling water & interlocks with beam
4. Vacuum integrity & interlock with fast closing valves
5. Helium cooled isolation windows
6. Use of low-activation alloys
7. Remote maintenance requirements
8. Ozone monitoring & safety
9. Safety Stack
10. Interlock of steering magnets with beam
11. Interlock of beam expansion optics with beam
12. High power RF and HV safety features
13. Low-level radioactive waste management

SUMMARY

High power electron accelerator is a focused program for developing enabling technologies and technology partners

Productionisation of the industrial accelerators will help attain technology maturity and develop infrastructure

Development plan for 100 MeV, 100 kW and later cw linac of 250 kW will pave the way for experimental facilities

Engineering design and safety issues are identified

Gratefully acknowledge

V. T. Nimje

Kavita P. Dixit

Jayanta Mandal

For inputs in preparing this talk


Thank you
For
Your kind attention