Developmental Studies for High Current Proton Linac at BARC

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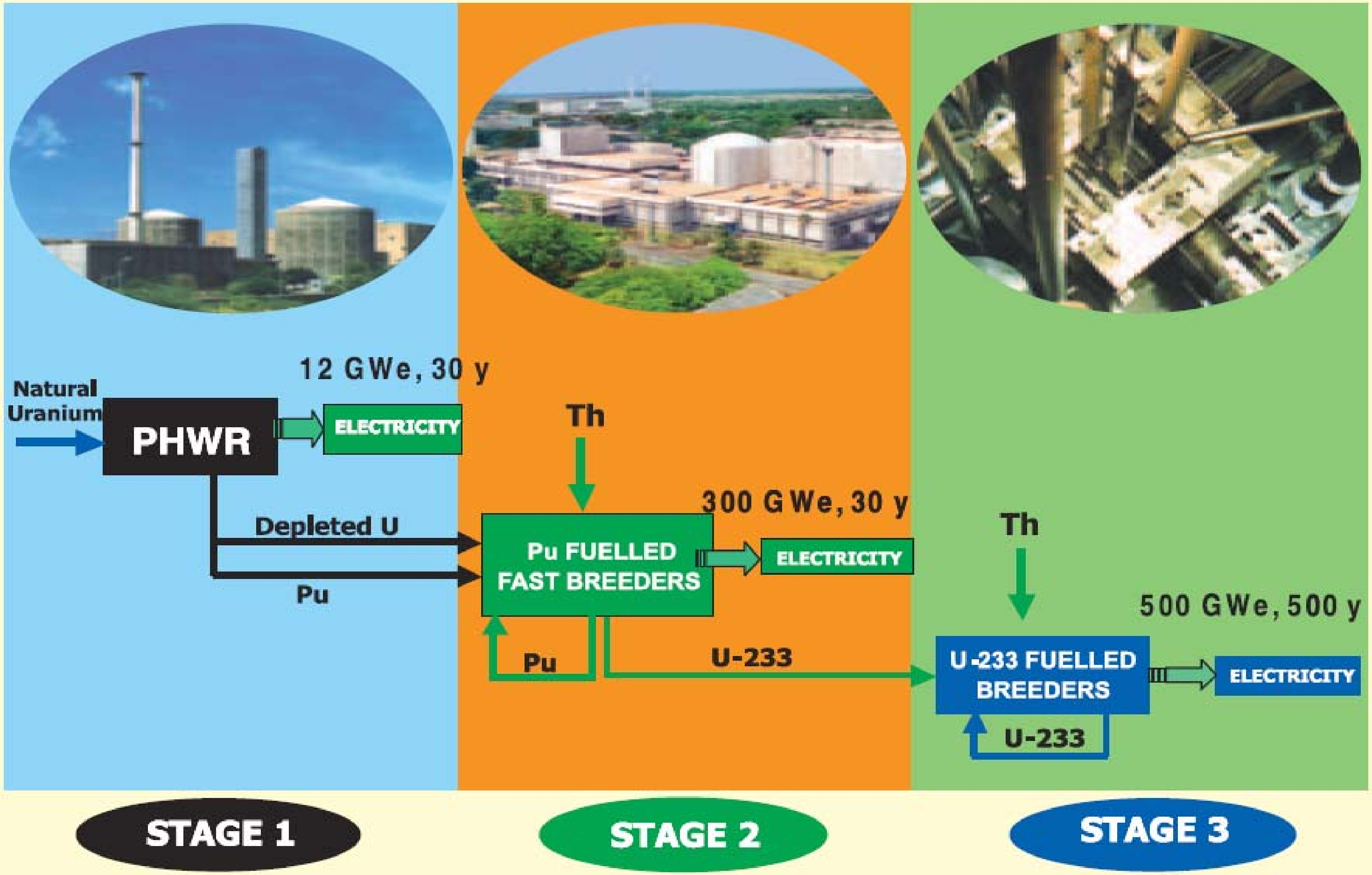
Three Stages of Indian Nuclear Power Programme



Kalpakkam has the unique distinction of being the only place in the world, where all the three fissile isotopes viz., U-235 [MAPS], Pu-239 [FBTR] & U-233 [KAMINI] are used as fuel in reactors.

Uranium reserves are limited and also Thorium offers a proliferation resistant fuel cycle

World Thorium Resources

Country	Reserves (tons)
Australia	300,000
India	290,000
Norway	170,000
USA	160,000
Canada	100,000
S. Africa	35,000
Brazil	16,000
Other Countries	95,000
World total	1,200,000

Why Thorium so important to us?

- **Thorium produces much less quantity of long-lived radioactive actinide wastes as compared to Uranium**

- **Large reserves available**

- **Cost is much less as compare to uranium**

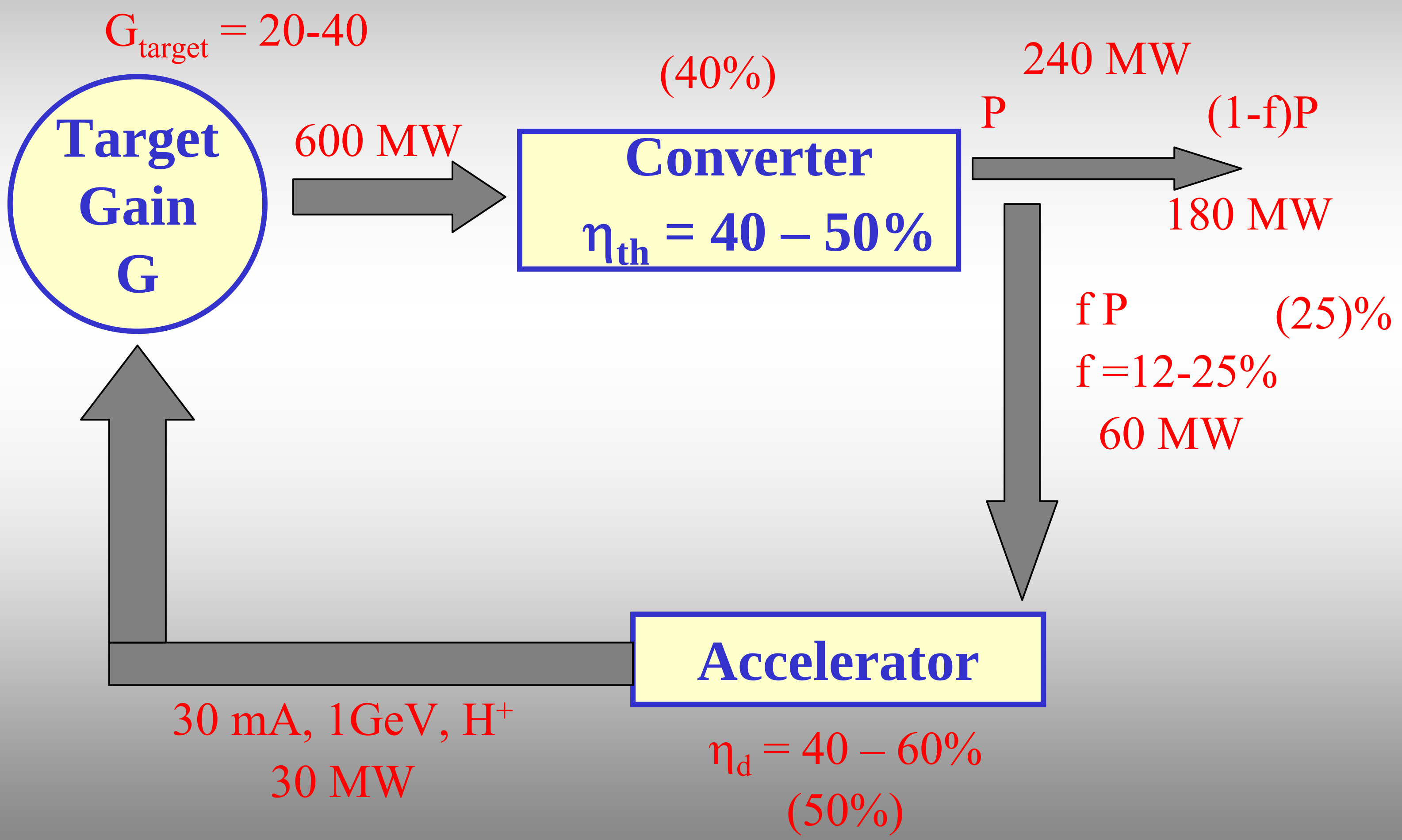
Accelerator Driven Sub-critical Reactor System (ADS)

A new type of fission reactor, where nuclear power (say, 500-1000 MWe) can be generated in a neutron multiplying core ($k_{eff} < 1.000$) without the need of criticality.

But, ADS has to be driven by an external neutron source

ACCELERATOR DRIVEN ENERGY AMPLIFIER

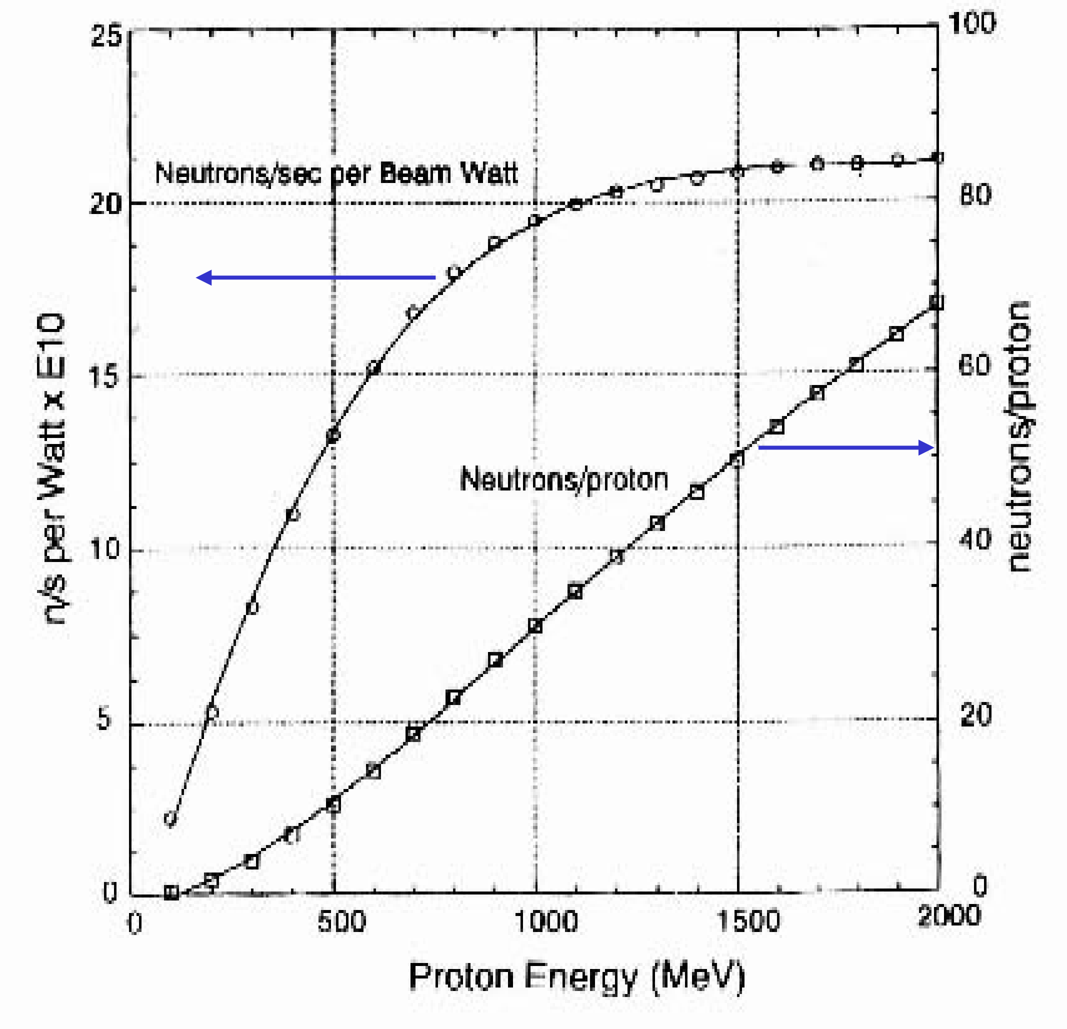
(Carlo Rubia)



Most cost effective way to produce neutrons

- By Spallation process with GeV energy protons striking on high Z target.

- Number of neutrons per proton per Watt of beam power reaches a plateau just above 1 GeV.

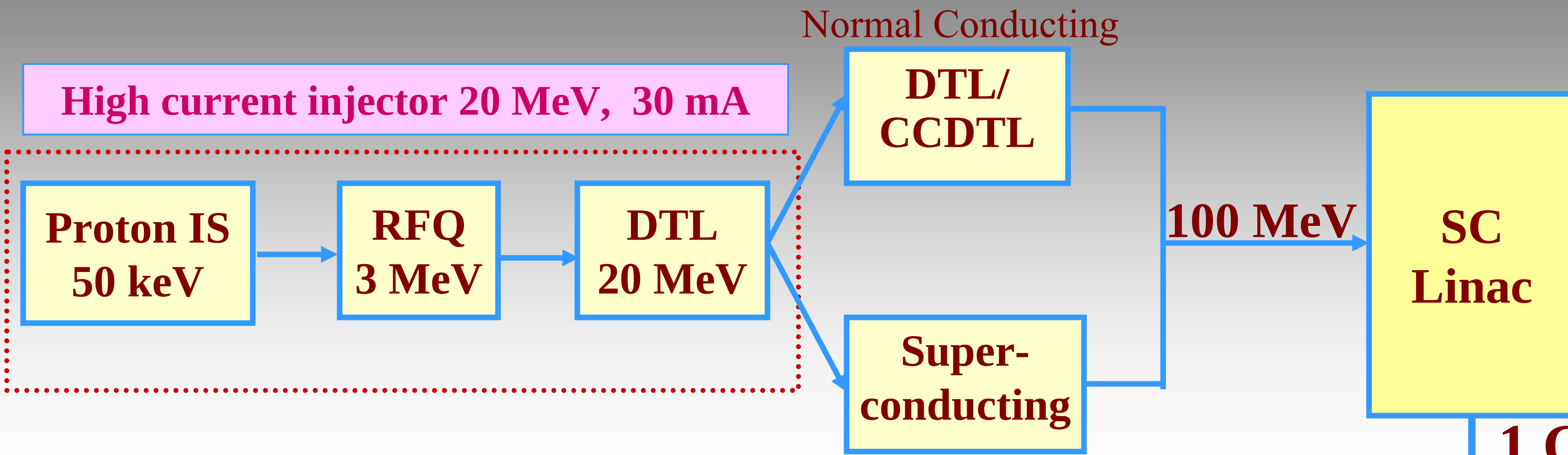


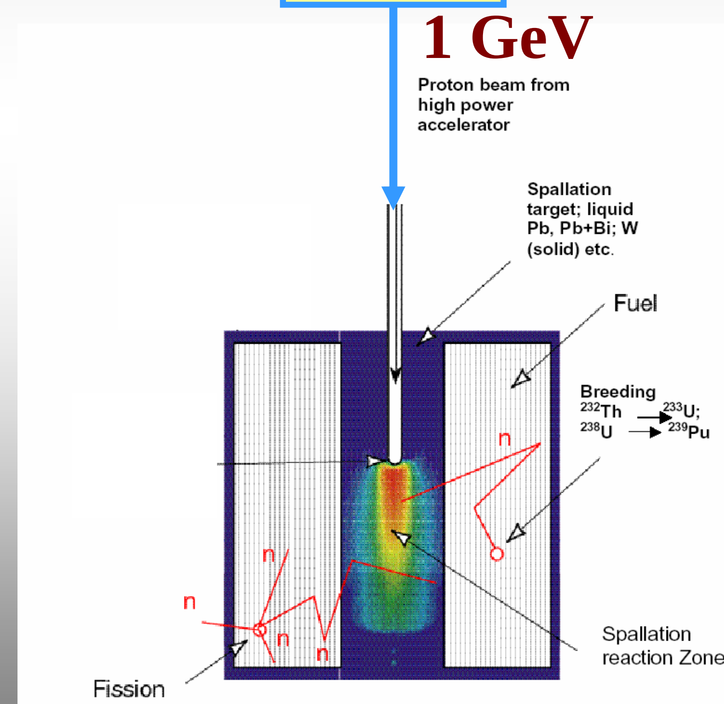
$$P_{thermal}(MW) = E_{fission}(MeV) I(A) \frac{\nu_s}{\nu} \frac{k}{1-k}$$

Proton Energy : 1 GeV
ν_s = 25 neutrons/proton
ν = 2.5 neutrons/fission
$P_{electrical}$ = 500 MW (1500 MW (th))
k = 0.95

$P_{thermal}$ (MW)	I (mA)
1000	29.2
1500	43.9
2000	58.5
2500	73.1
3000	87.7

Scheme for Indian ADS Programme



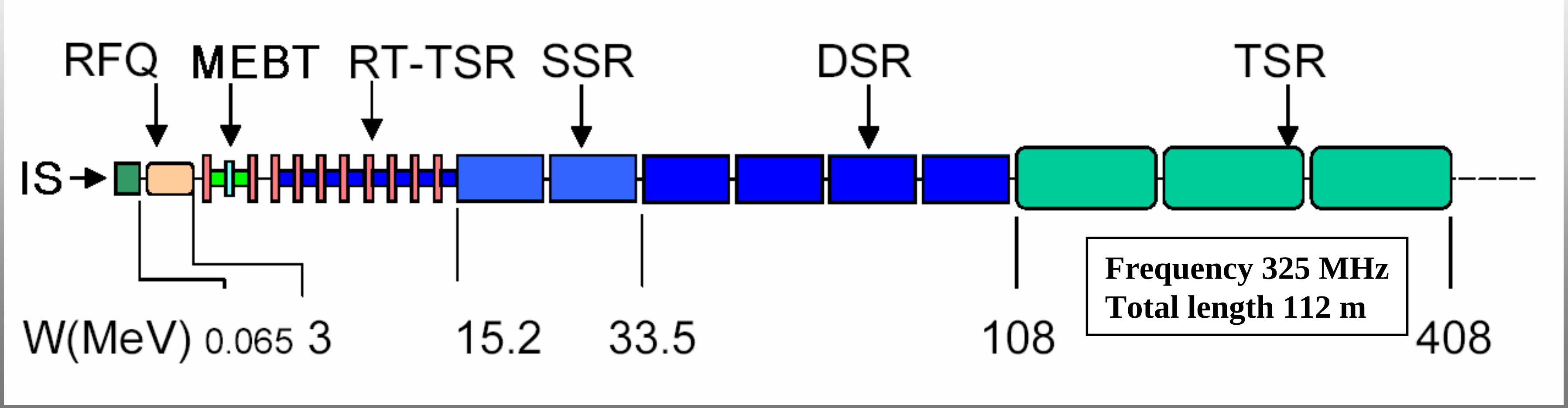


Main design issue:

- beam loss <1 Watt/m.
- Avoid halo formation

HINS Front end general layout

Ion source H^-, LEBT			0.065 MeV
Radio Frequency Quadrupole		4-5 m,	3 MeV
MEBT	(2 bunchers, 4 SC sol., chopper)	4 m	
RT TSR section	(21 resonators, 21 SC solenoid)	10 m	15.2 MeV
SSR section	(16 resonators, 16 SC solenoids)	12.5 m	33.5 MeV
DSR section	(28 resonators, 14 SC solenoids)	17 m	108 MeV
TSR section	(42 resonators, 42 quads)	64 m	408 MeV

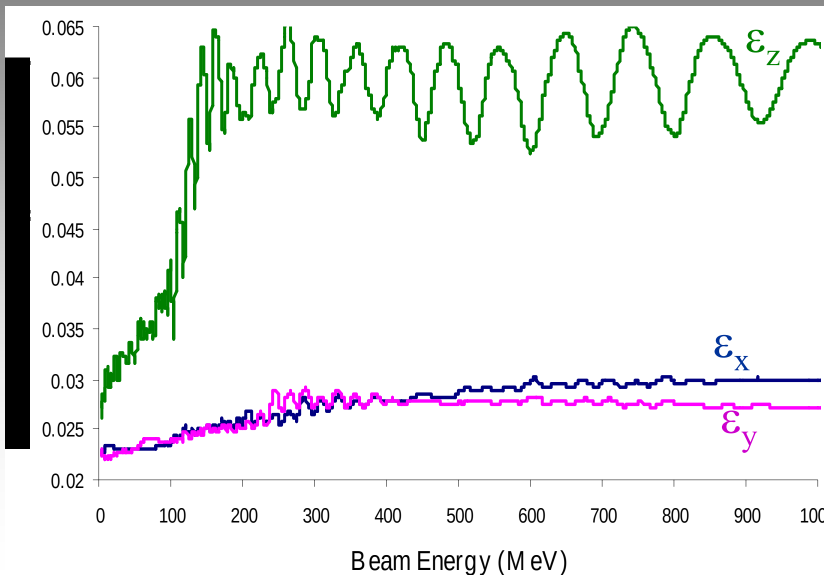


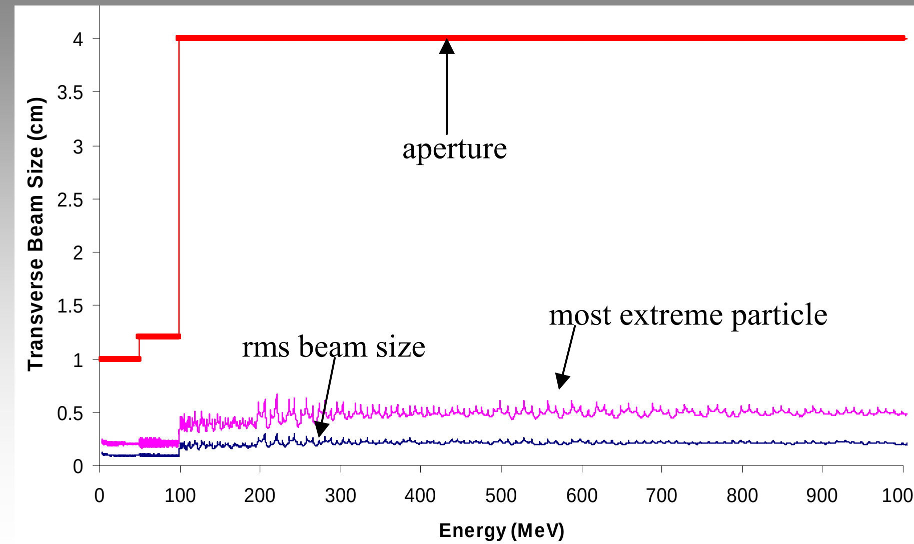
100 MeV – 1 GeV SC Linac

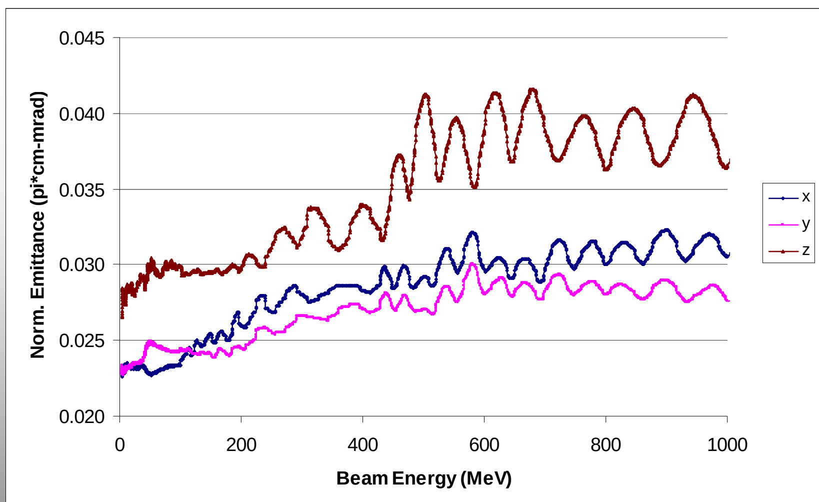
(Initial design with 5 MV/m gradient)

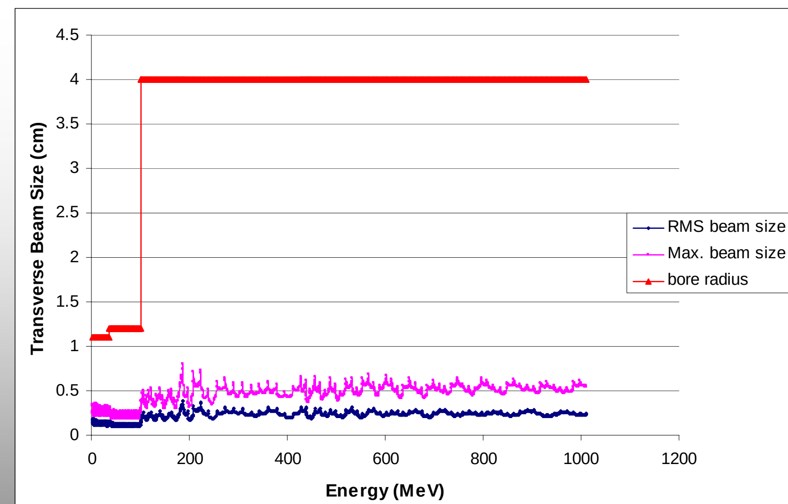
Parameter	β_G= 0.47	β_G= 0.62	β_G= 0.80
Energy Range (MeV)	**98.6-198.3**	**198.3-498.3**	**498.3-1008.3**
Frequency (MHz)	704.42	704.42	704.42
Current (mA)	29.3	29.3	29.3
Trans. Focusing lattice	Doublet	Doublet	Doublet
Lattice Period (cm)	300.1	608.0	810.7
Quadrupole gradient (T/m)	5.8-5.37	4.5	4.4
Eff. Length of Quad (cm)	35	40	45
Synch. Phase (degrees)	-30	-23.44	-23.44
Cavities/cryomodule	2	3	4
No. of Cryomodules	35	40	51
Aperture Radius (cm)	4.0	4.0	4.0
Total length (m)	105.04	243.2	413.46
Norm. Trans. Emitt. (πcm-mrad) ε_x ε_y	0.024-0.025 0.024-0.025	0.025-0.029 0.025-0.028	0.029-0.030 0.028-0.027
Norm. Long. Emitt. (MeV-deg)	0.327-0.444	0.444-0.482	0.482-0.499

Beam Dynamics









- Aperture is more than 16 times the rms beam size in the SC Linac.
- Aperture is 10-12 times the rms beam size in the NC Linac.
- Transmission through the linac = 100%.

Parameters of RFQ, DTL, CCDTL and SC Linac

RFQ

Frequency	352.21 MHz
Energy	50 keV/ 3 MeV
Input current	30 mA
Vane voltage	82-111 kV
Avg. Aperture R_0	3.63-4.53 mm
Length	3.45 m
Total RF power	500 kW
Transmission	97 %

DTL / CCDTL

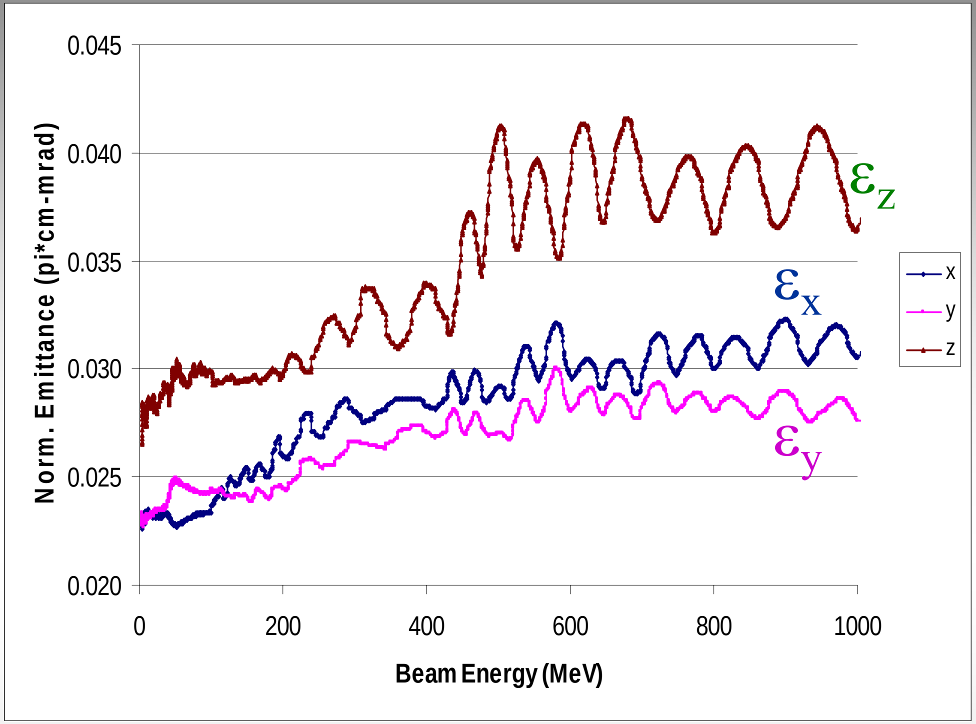
	DTL	CCDTL
Energy Range (MeV)	3-40.1	40.1-100.2
Frequency (MHz)	352.21	704.42
Current (mA)	29.3	29.3
Focusing Lattice	FFDD	FODO
Quadrupole Gradient (T/m)	43	62.4-19.5
Avg. Acc. Gradient (MV/m)	2.5	1.37
Total Length (m)	22.66	69.57
Norm. Trans. Emitt. (πcm-mrad) ε_x ε_y	0.022-0.0232 0.022-0.0236	0.0232-0.0233 0.0236-0.0242

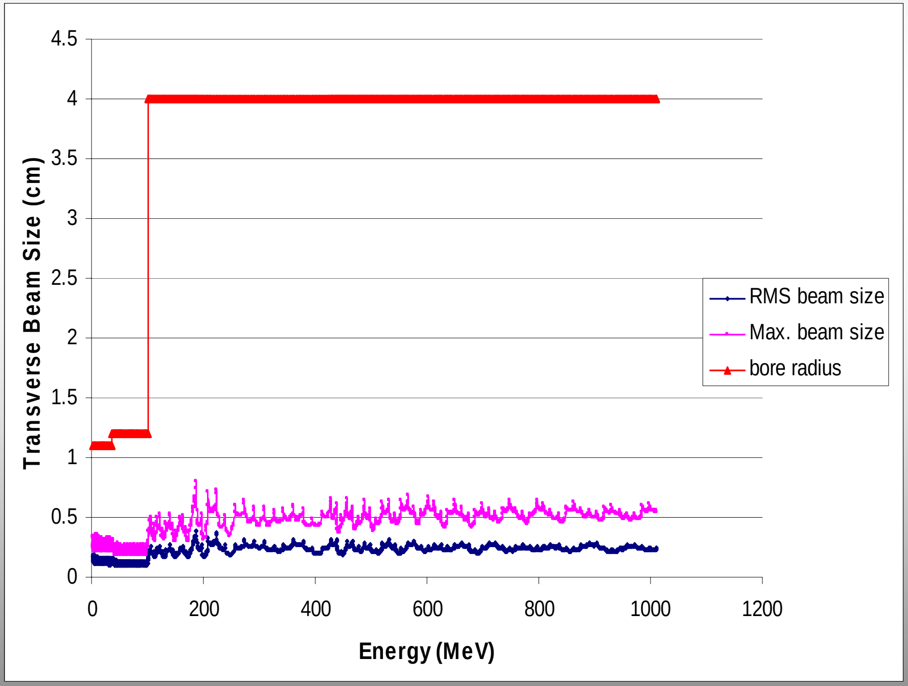
SC Linac (15 MV/m)

Parameter	β_G= 0.49	β_G= 0.62	β_G= 0.80
Energy Range (MeV)	100.2-197.2	197.2-421.3	421.3-1016.5
Frequency (MHz)	704.42	704.42	704.42
Current (mA)	29.3	29.3	29.3
Trans. Focusing lattice	Doublet	Doublet	Doublet
Lattice Period (cm)	304.27	607.90	810.47
Quadrupole gradient (T/m)	5.80-4.31	4.50-4.99	4.40
Eff. Length of Quad (cm)	35	40	45
Synch. Phase (degrees)	-30	-35.24	-34.37
Cavities/cryomodule	2	3	4
No. of Cryomodules	12	15	23
Aperture Radius (cm)	4.0	4.0	4.0
Total length (m)	34.76	88.15	183.33
Norm. Trans. Emitt. (πcm-mrad) ε_x , ε_y	0.023-0.030 0.024-0.027	0.030-0.033 0.027-0.030	0.033-0.037 0.030-0.031
Norm. Long. Emitt. (MeV-deg)	0.237-0.241	0.241-0.240	0.240-0.257

Transmission = 100% ; Total Length = 407 m (100.68 + 306.24)

Beam Dynamics





- Aperture is more than 16 times the rms beam size in the SC Linac.
- Aperture is 10-12 times the rms beam size in the NC Linac.
- Transmission through the linac = 100%.

Scheme for Accelerator Development for ADS

High current injector 20 MeV, 30 mA

Proton IS 50 keV → **RFQ 3 MeV** → **DTL 20 MeV**

Phase 1

Normal Conducting

DTL/ CCDTL

Phase II

Super-conducting

100 MeV →

Phase III

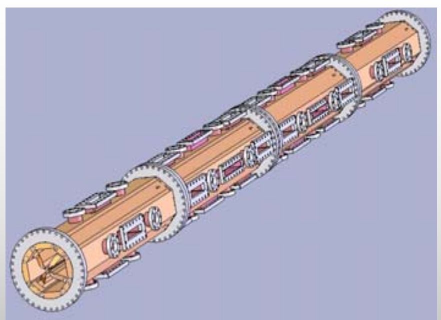
SC Linac

1 GeV

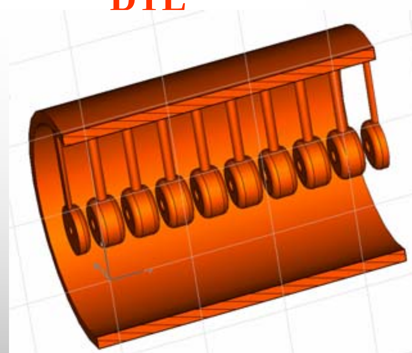
Design completed and fabrication is in progress

ECR Ion Source

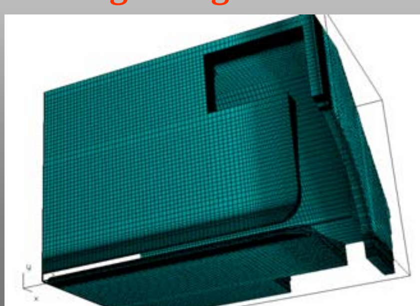
RFQ



DTL

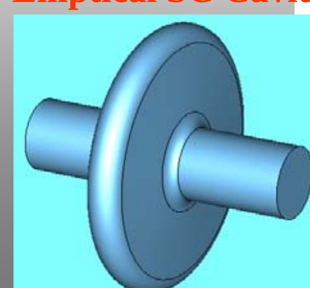


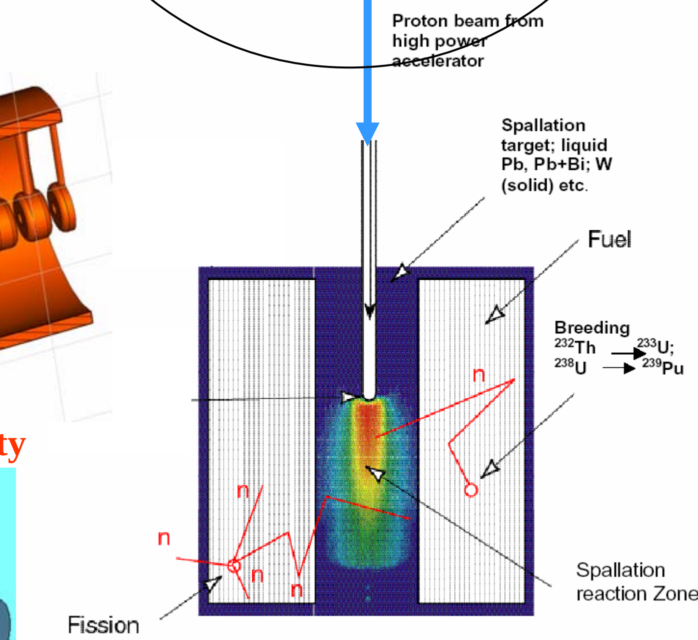
Beginning/End Cell



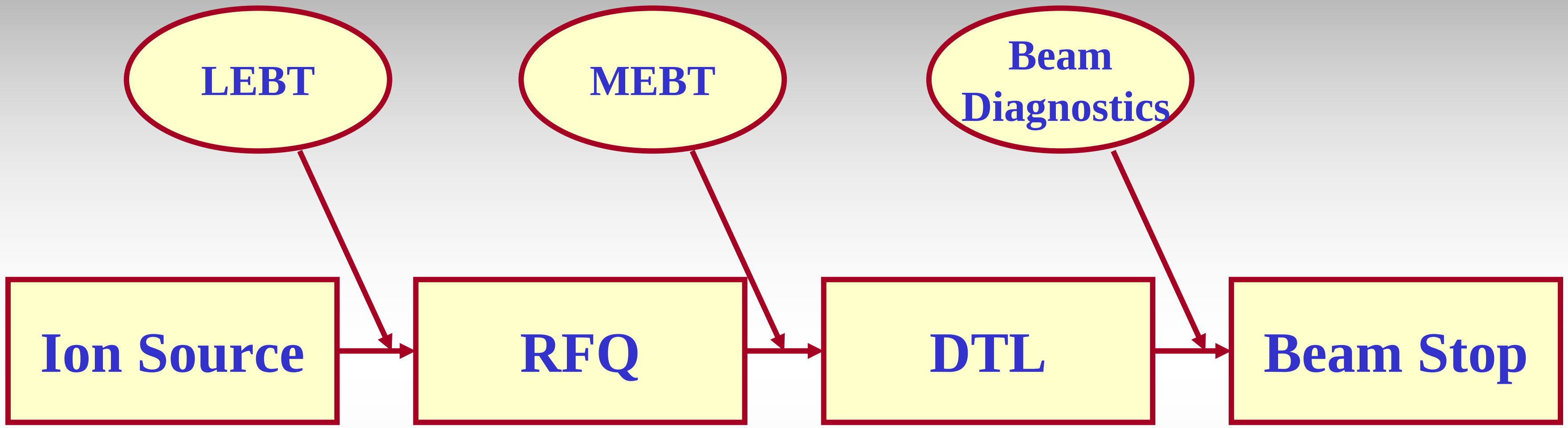
Coupling Cell

Elliptical SC Cavity





Phase I: Layout of 20 MeV Linac Section



ECR Ion source	RFQ 4 Vane type	20 MeV, 30 mA
50 keV, 35mA.	3MeV, 30 mA	Alvarez type DTL

LEBT : Low Energy Beam Transport System

RFQ : Radio Frequency Quadrupole

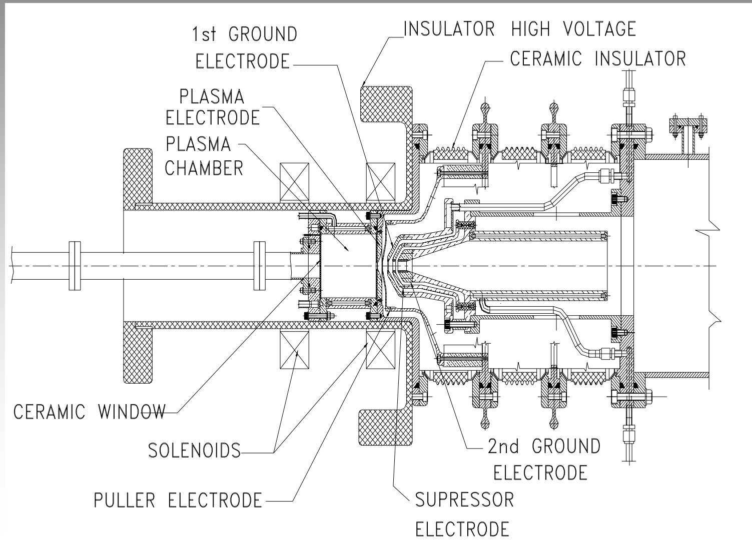
MEBT : Medium Energy Beam Transport System

DTL : Drift Tube Linac

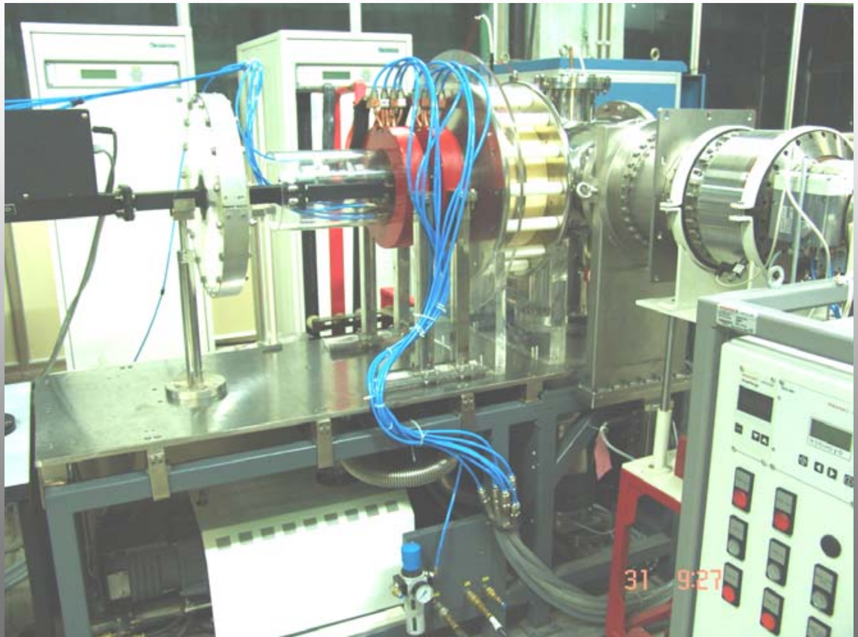
ECR Ion Source

(being developed by APPD, BARC)

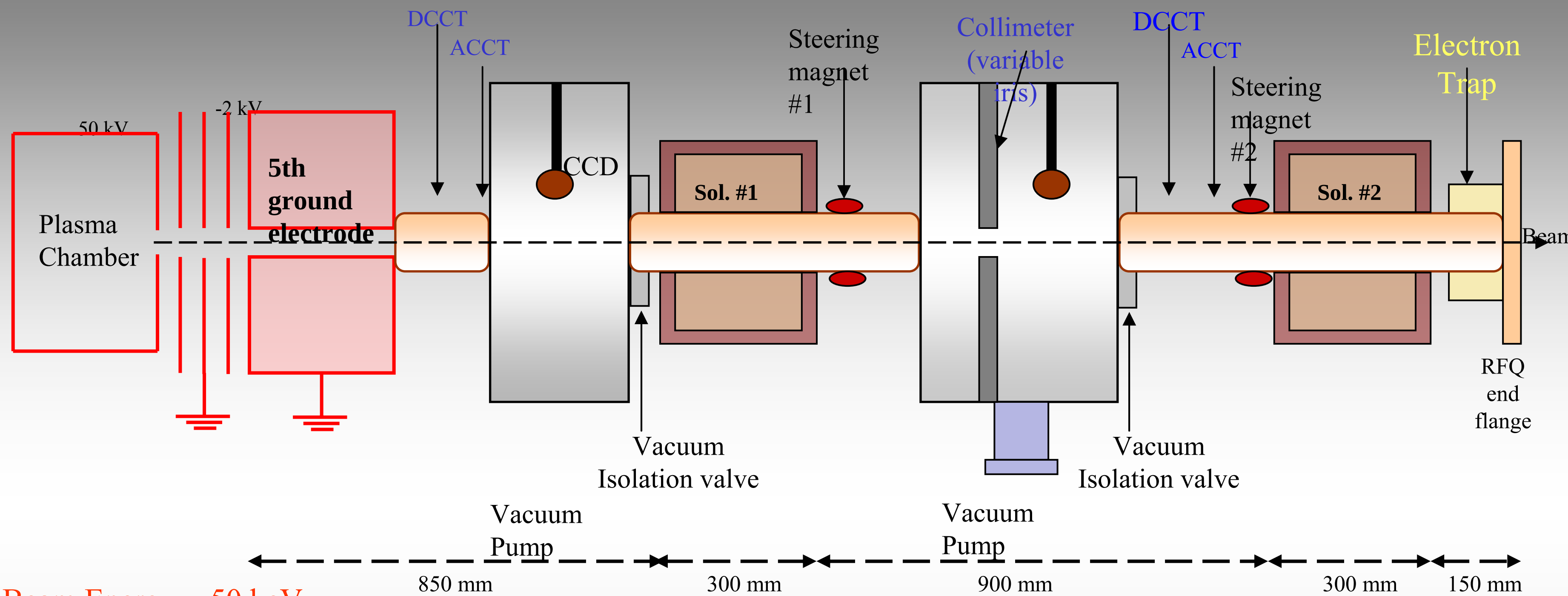
- Five electrodes
- 2.45 GHz
- 50 keV
- 50 mA
- 0.02 π cm-mrad



Schematic of the ECR Ion Source



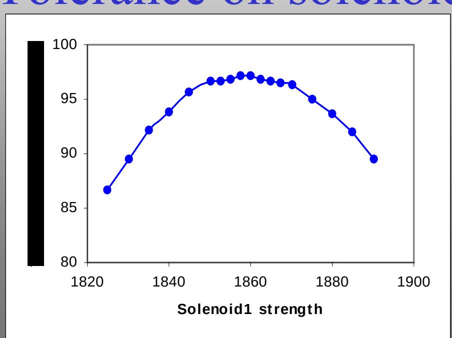
Low Energy Beam Transport (LEBT) System

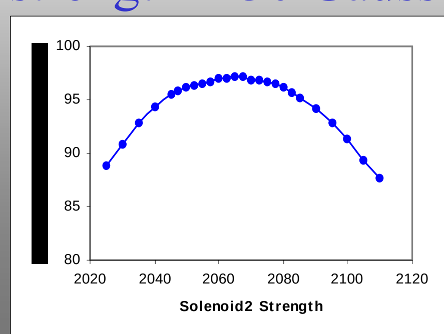


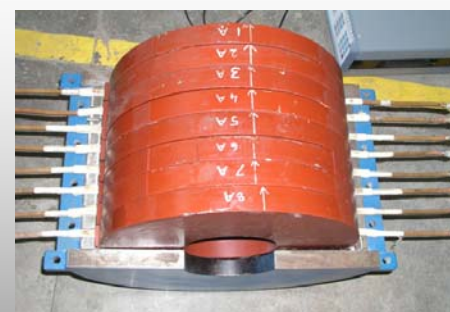
Beam Energy = 50 keV
Beam current = 30 mA
RMS Normalized Beam Emittance = 0.02 π cm mrad

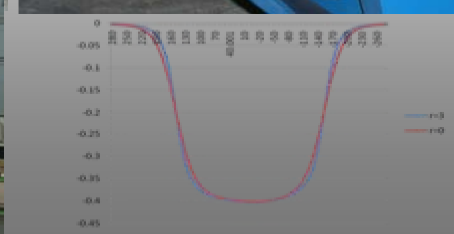
Error Analysis of Solenoids

Tolerance on solenoid strength=±30 Gauss









Low Energy Beam Transport Line

- Used to match the dc beam from the ion source to the RFQ.
- Two solenoids (~2 kG) are used.

Beam Energy = 50 keV
Beam current = 30 mA
RMS Norm. Emittance = 0.02π cm mrad

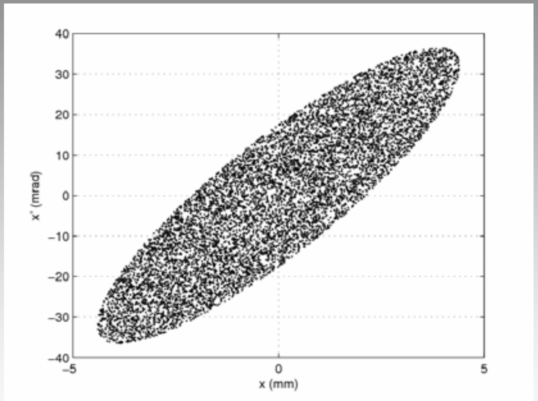
Max. beam size in the LEBT = 13 cm
Total length = 1.85 m.

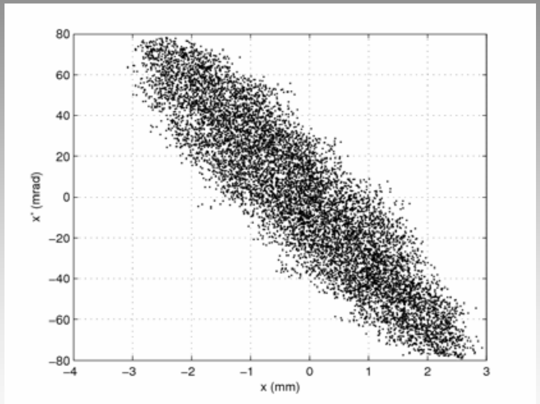
Effect of Space Charge Compensation on beam dynamics

Degree of Space Charge Compensation (%)	I_{eff} (mA)	Max. Beam size (cm)	Emit at end of LEBT (cm mrad)	Transmission through the RFQ (%)
0	30	13.0	0.02081	97.1
90	3.0	7.0	0.02003	96.0
95	1.5	6.8	0.02000	97.3
98	0.6	6.4	0.02000	97.4

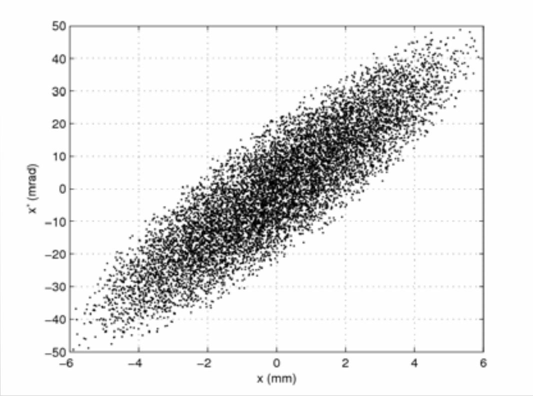
Effect of Non-Linear space charge on beam dynamics in LEBT

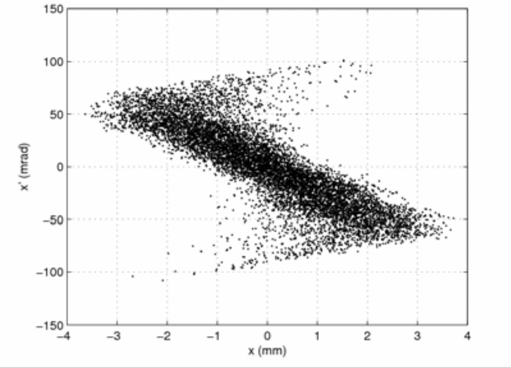
- KV distribution being uniform causes linear space charge forces.
- Any kind of non-uniformity in the density will give rise to non-linear space charge.
- Non-linearity of the space charge field reflects in emittance increase as well as in waist diameter.



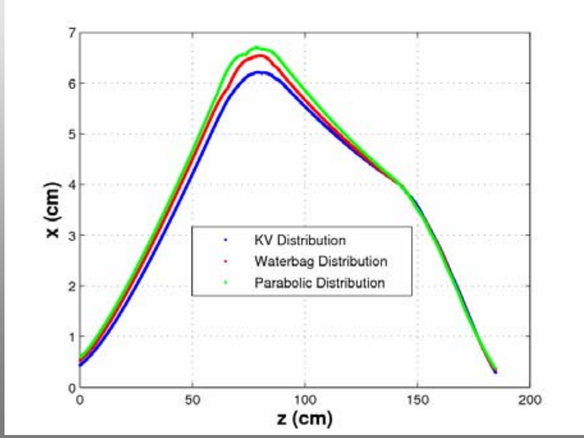


With KV- distribution





With Parabolic distribution



KV: Kapchinskij-Vladimirskij distribution

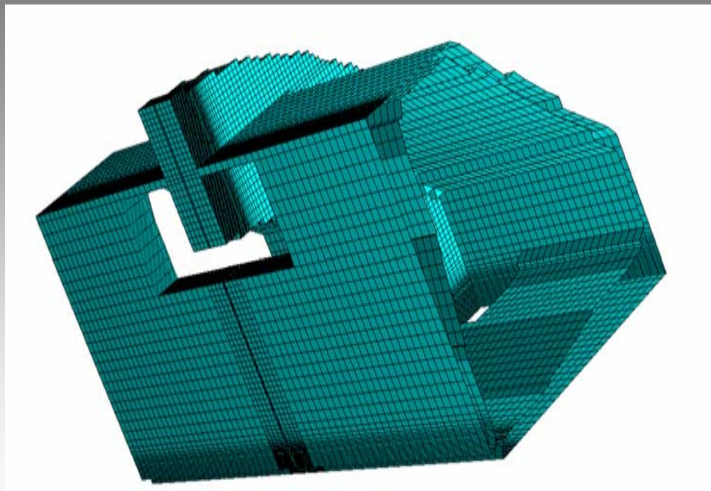
S.C.L. Srivastava, S.V.L.S. Rao and P. Singh, Pramana-J Phys. 69, 551(2007)

RFQ Parameters

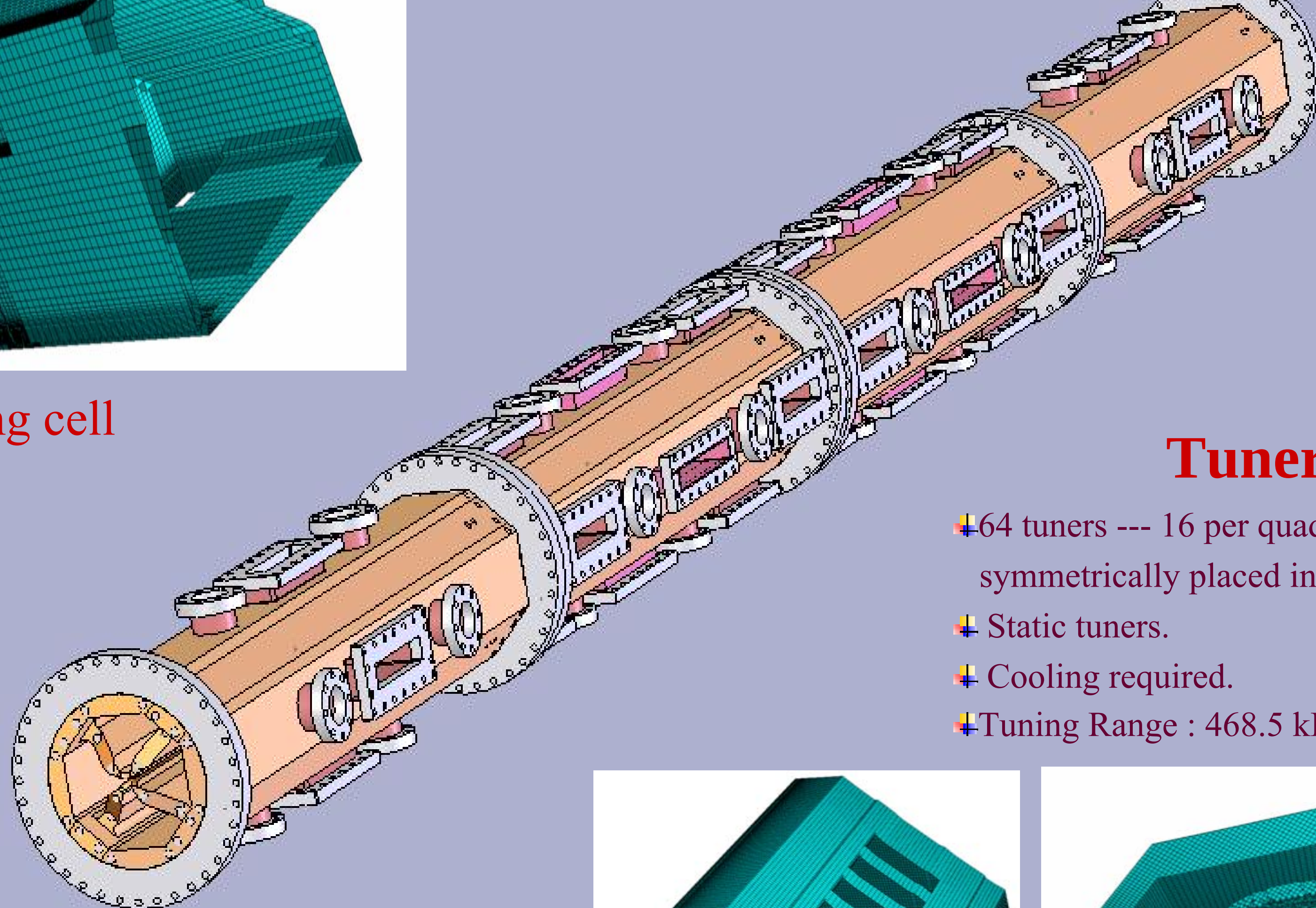
1. Bunching 2. Focusing 3. Acceleration

Frequency	352.21 MHz
Energy	50 keV/ 3 MeV
Input current	30 mA
Vane voltage	82-111 kV
Avg. Aperture R_0	3.63-4.53 mm
Length	3.45 m
Total RF power	500 kW
Transmission	97 %

3 MeV Radio Frequency Quadrupole



Coupling cell

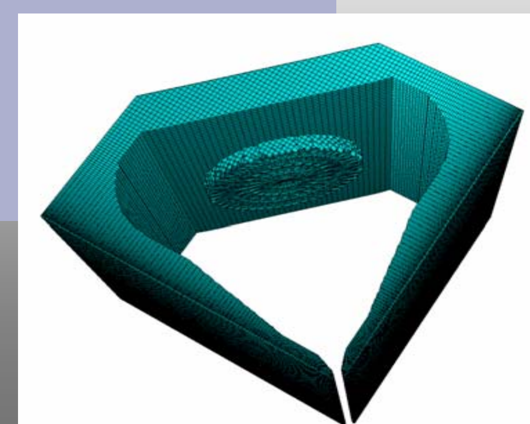


Tuners

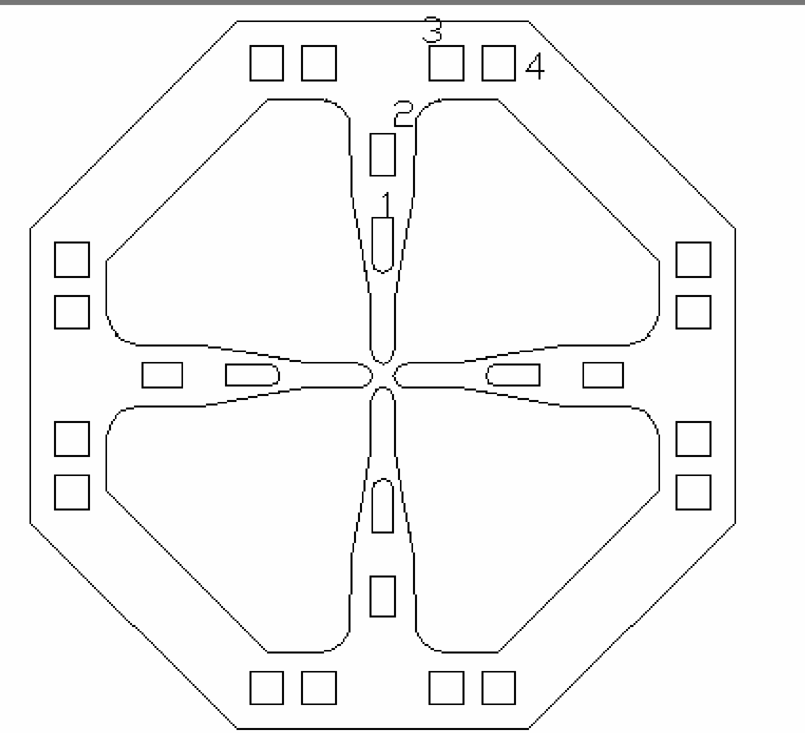
- 64 tuners --- 16 per quadrant, symmetrically placed in each quadrant
- Static tuners.
- Cooling required.
- Tuning Range : 468.5 kHz/mm (all)

Vacuum ports

- 24 vacuum ports
- Frequency detuning : 745.86 kHz (all)



Thermal Analysis



24 cooling channels

1,2-Vane channel

3,4-Wall channels

Coolant temperatures are 16 ^{0}C in vane channels and 20 ^{0}C in wall channels

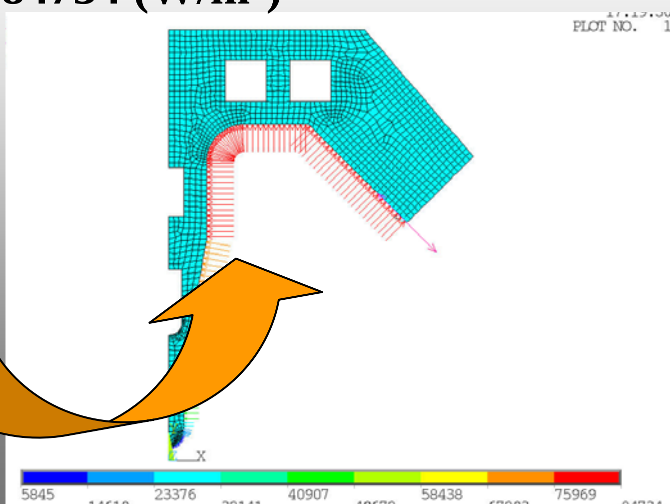
Water temp within ± 0.1^{o}C,

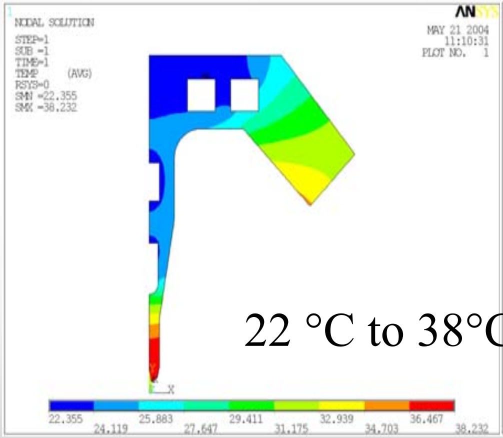
Already available within ± 0.05 ^{o}C at RRCAT

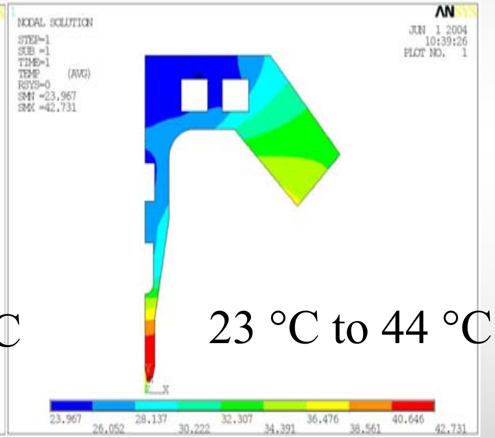
Heat flux on Cavity walls of the RFQ

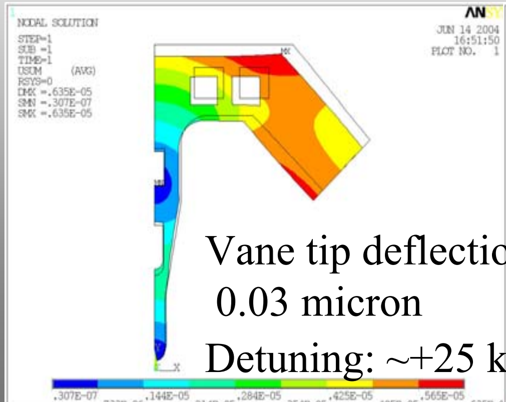
As calculated using SUPERFISH

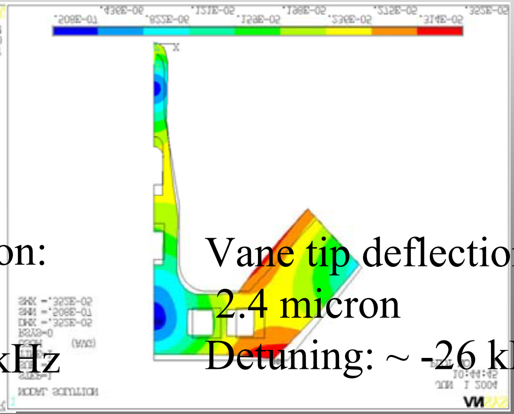
5845-84734 (W/m^2)







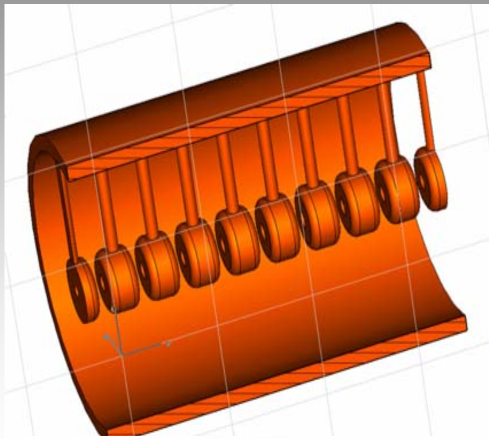


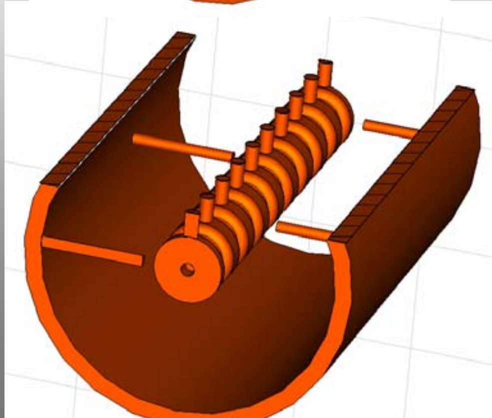


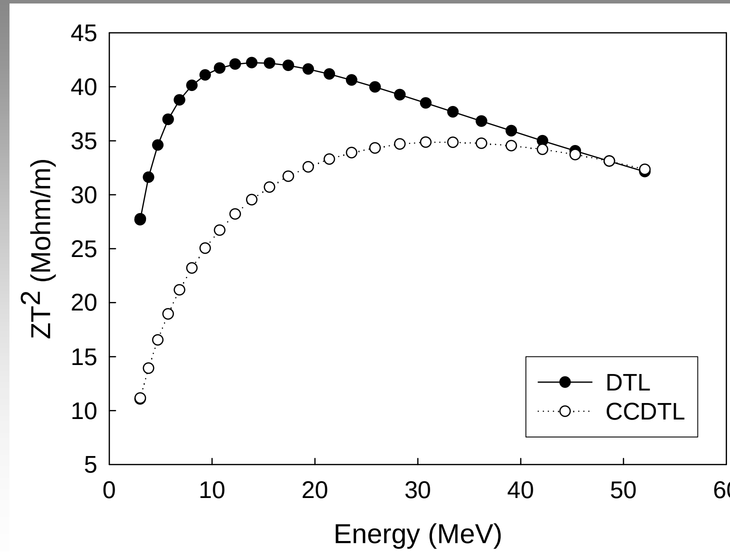
Phase II: DTL and CCDTL

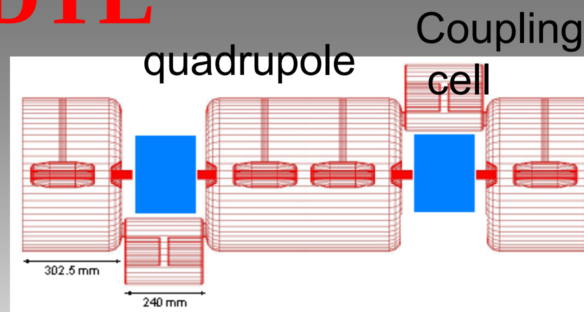
3-50 MeV

DTL



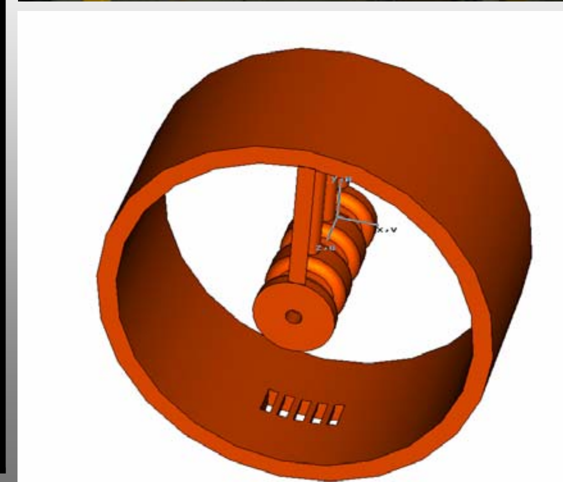






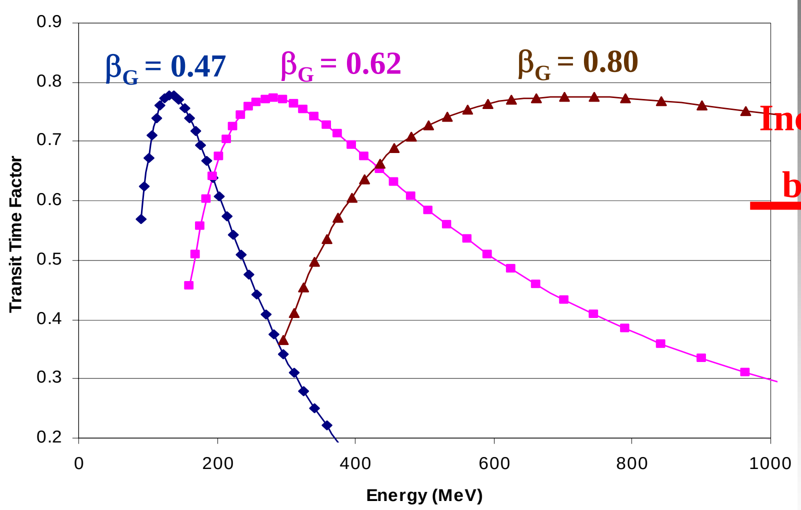
50-100 MeV

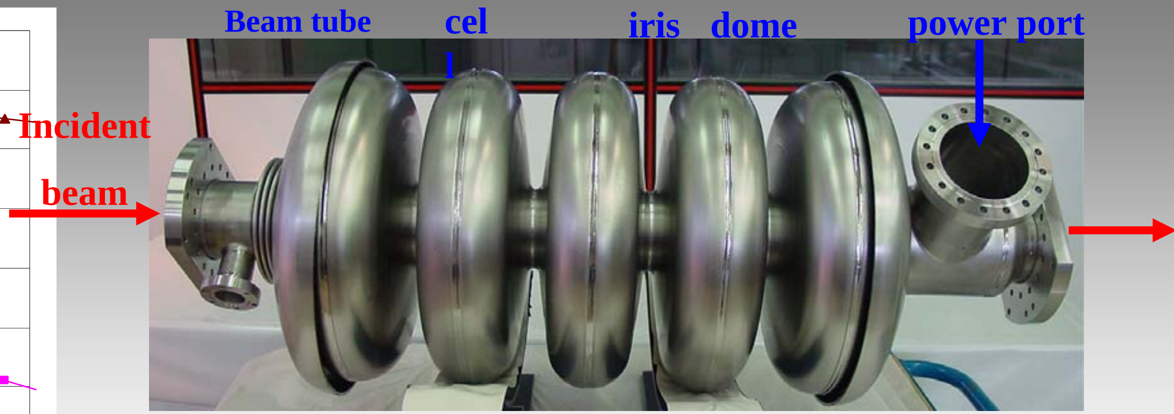
CCDTL at CERN



Parameter	DTL	CCDTL
Energy Range (MeV)	3-50	50-98.6
Frequency (MHz)	352.21	704.42
Current (mA)	29.3	29.3
Quadrupole Gradient (T/m)	100	58.2-19.6
Eff. Length of Quad. (cm)	4.72	8.0
No. of Quadrupoles	164	182
Avg. Acc. Gradient (MV/m)	2.58	1.6
Aperture Radius (cm)	1.0	1.2
Total Length (m)	28	75

Phase III: Design of Superconducting Cavity

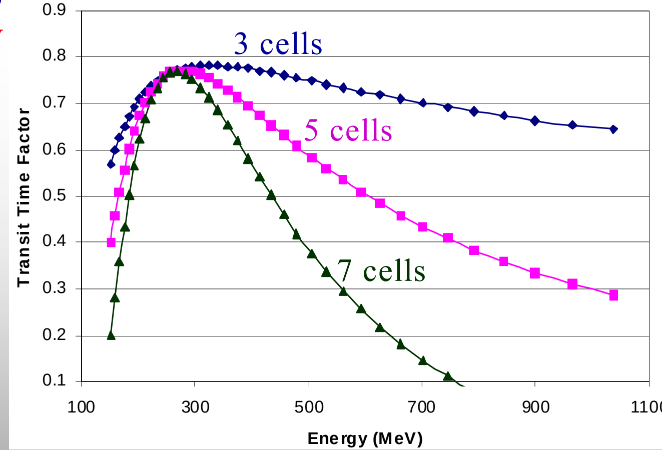


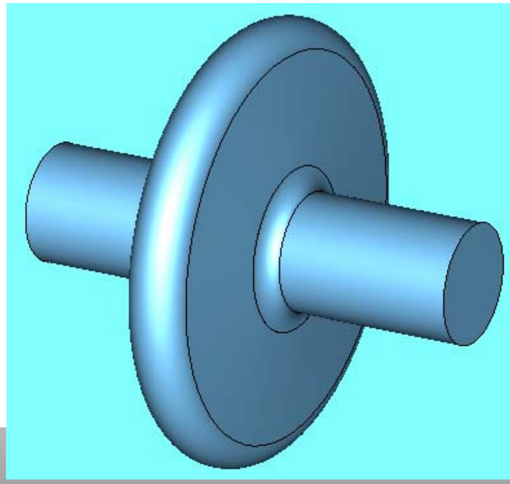


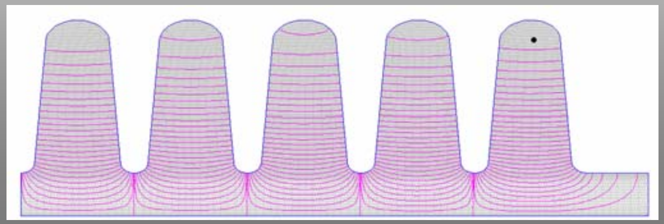
Superconducting cavity (IPN Orsay) – 5 cells, 700 MHz, β=0,65

In order to efficiently design a linac it is necessary to divide it in sections, each using a different cavity geometry in an energy range.

3-D view of the cavity





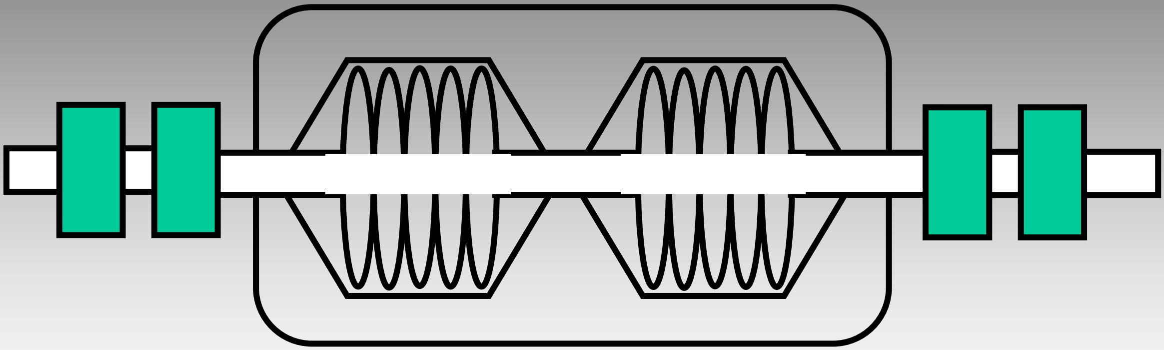


Single Cell Cavity in Copper is fabricated at APPD,BARC.

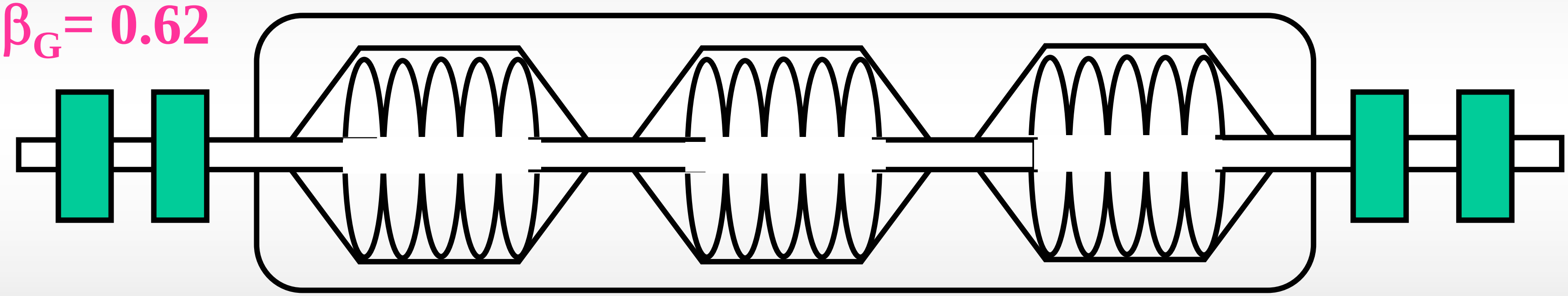
Parameters	β_G=0.47	β_G = 0.62	β_G = 0.8
No. of Cells	5	5	5
Diameter D (cm)	36.27	35.83	37.34
Dome B (cm)	2	3	5.5
Dome A/B	1.5	1.5	1
Wall Angle α_w(deg)	5	5	7
Iris a/b	1.2	1	0.5
Bore Radius (cm)	4	4	4

Cryomodules for Different Beta Sections

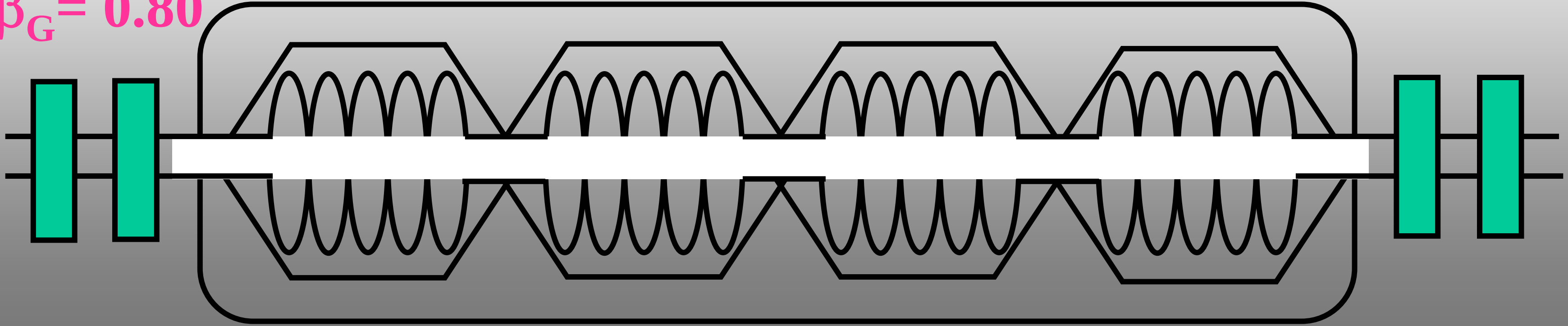
$\beta_G = 0.47$



$\beta_G = 0.62$



$\beta_G = 0.80$



Field in SC Linac: 5 MV/m 15 MV/m

	5 MV/m		15 MV/m	
RFQ	:0.5 MW	3 MeV	0.50 MW	3 MeV
DTL	: 4 MW	50 MeV	4 MW	50 MeV
CCDTL	: 5 MW	100 MeV	5 MW	100 MeV
SC Linac	: 27 MW	1 GeV	27 MW	1 GeV
Total RF Power	: 37 MW		37 MW	

	5 MV/m	15 MV/m
RFQ	: 3.5 m	3.5 m
DTL	: 28 m	23 m
CCDTL	: 75 m	70 m
SC Linac	: 762 m	306 m
Total Length	: 879 m	403 m

Experimental facility

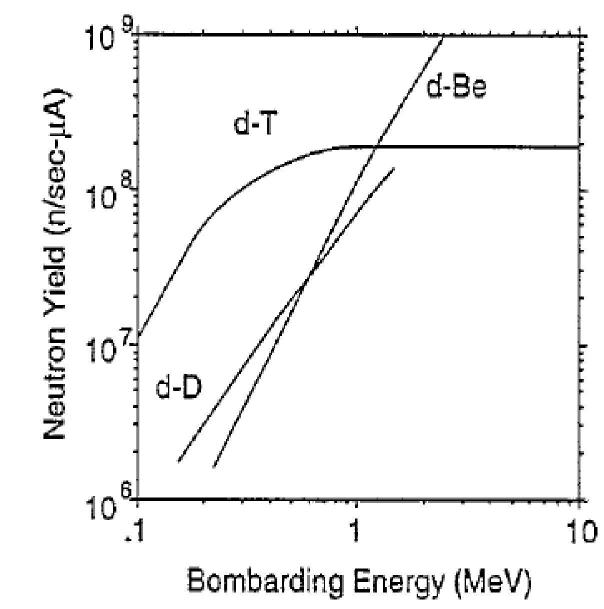
- ***Facility for carrying out experiments on physics of ADS and for testing the simulations is being set up. This will use 14 MeV neutrons produced through D+T reaction.***

- ***Simple sub-critical assembly (k_{eff}=0.87) of natural uranium and light water is chosen***

- ***Measurements of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out.***

- ***For this purpose a 400 keV RFQ is being built***

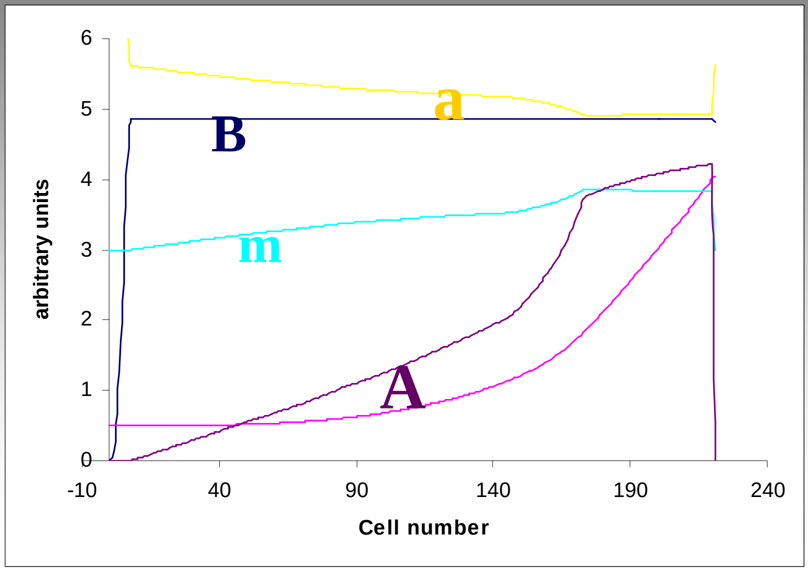
For deuteron current of 1mA at 400 keV, 14 MeV neutron yield is 1.0x 10^{11} n/s D+T reaction



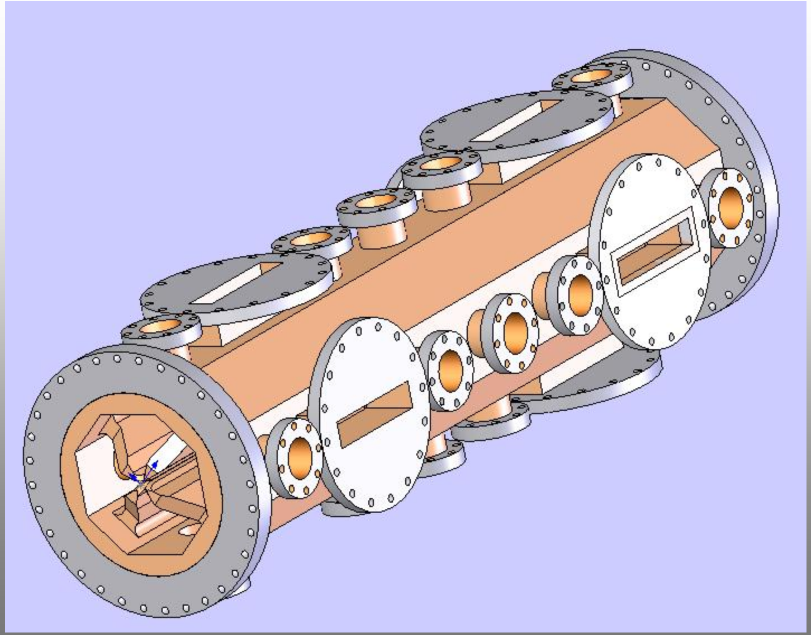
400 keV RFQ parameters

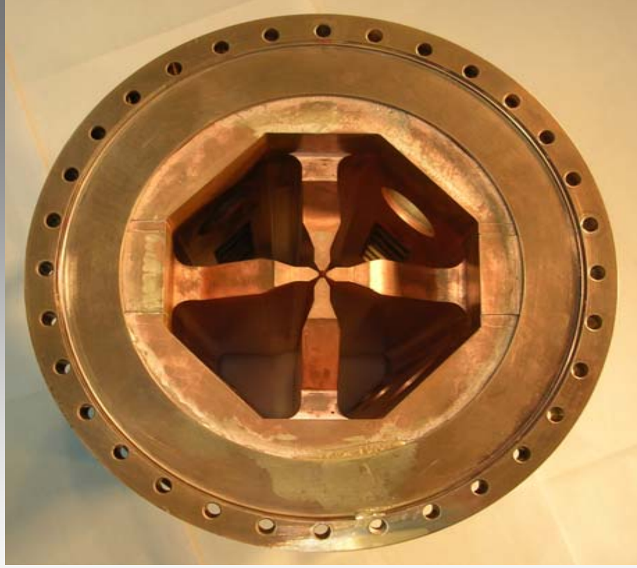
Parameters	Value
Frequency	350 MHz
Injection energy	50 keV
Final energy	400 keV
RFQ length	1.05 m
RF Power dissipated	68 kW
Beam current	1 mA
Norm. RMS emittance	0.015 π cm-mrad
Vane voltage	44 kV
Transmission efficiency	96 %
Peak surface field	32.9 MV/m
Average radius	1.873 cm
Maximum Modulation	1.287

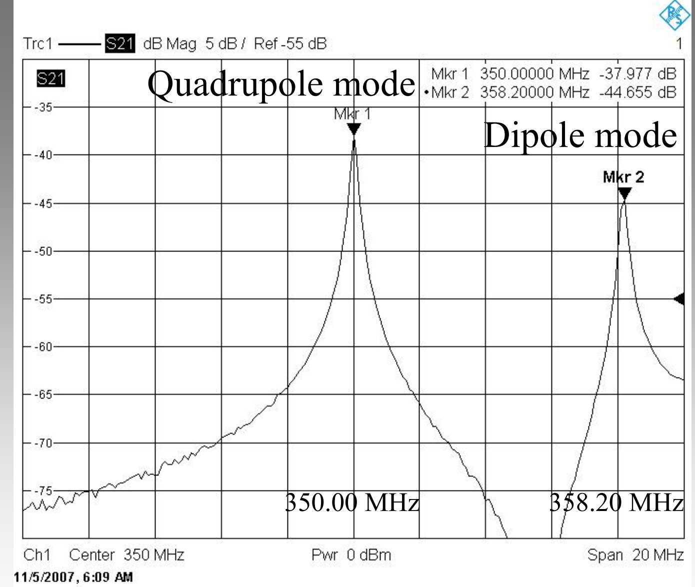
Transmission at the end of RFQ : 94.8%



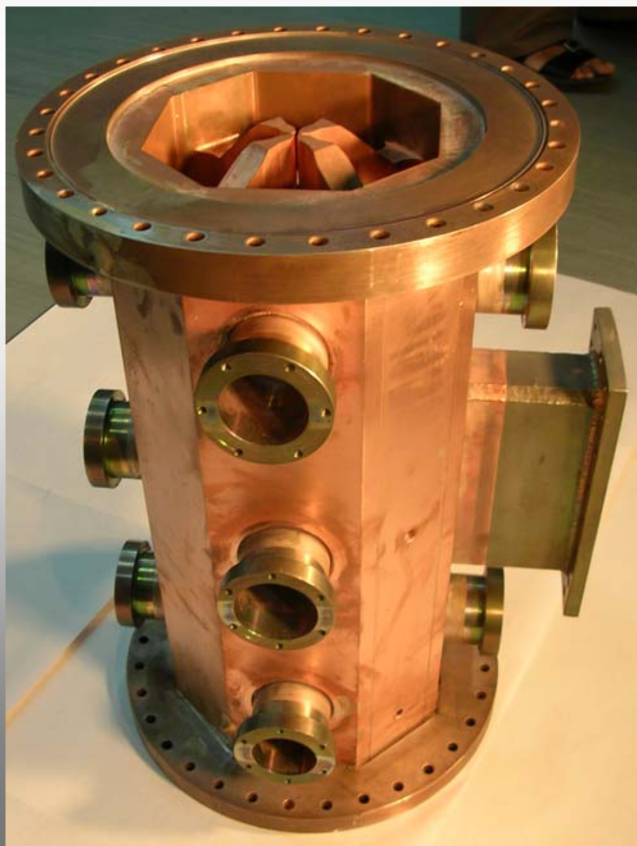
Variation of RFQ parameters along the length.

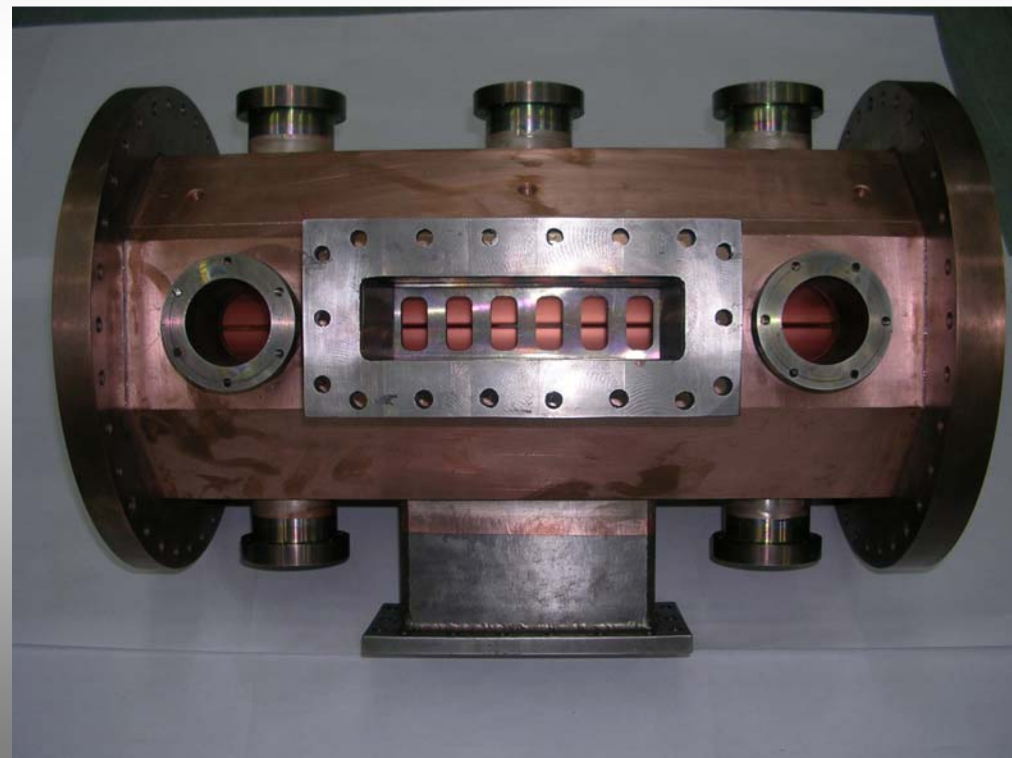


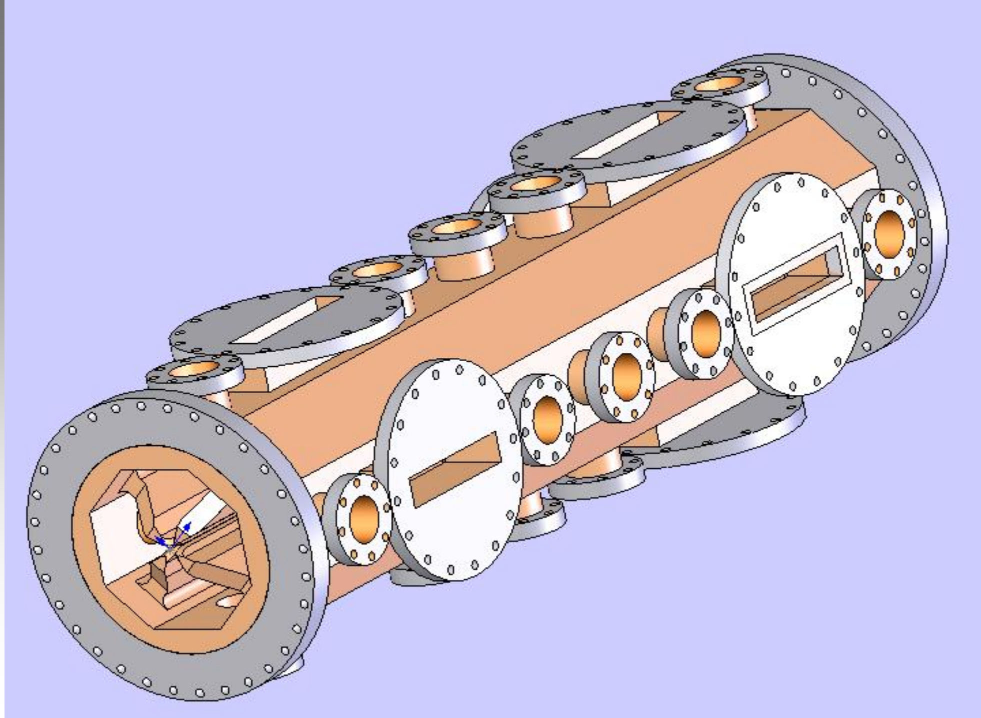




Trc1 S21 dB Mag 5 dB / Ref -55 dB 1
S21
Quadrupole mode
Mkr 1 350.00000 MHz -37.977 dB
•Mkr 2 358.20000 MHz -44.655 dB
Mkr 1
Dipole mode
Mkr 2
-35
-40
-45
-50
-55
-60
-65
-70
-75
350.00 MHz
358.20 MHz
Ch1 Center 350 MHz
Pwr 0 dBm
Span 20 MHz
11/5/2007, 6:09 AM



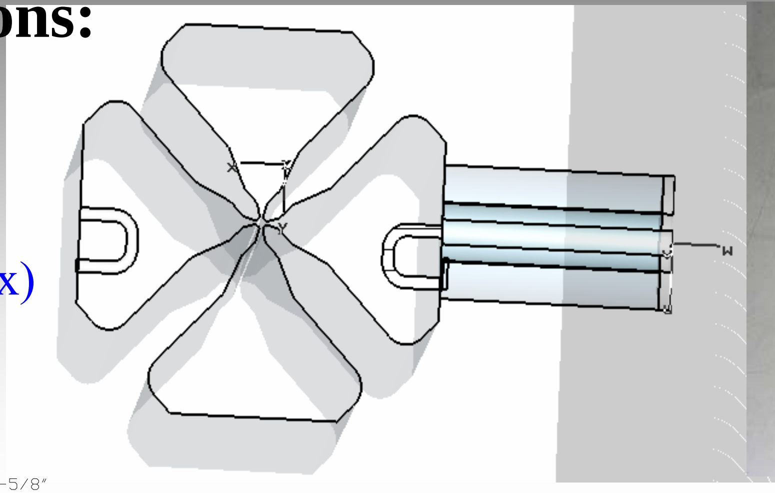


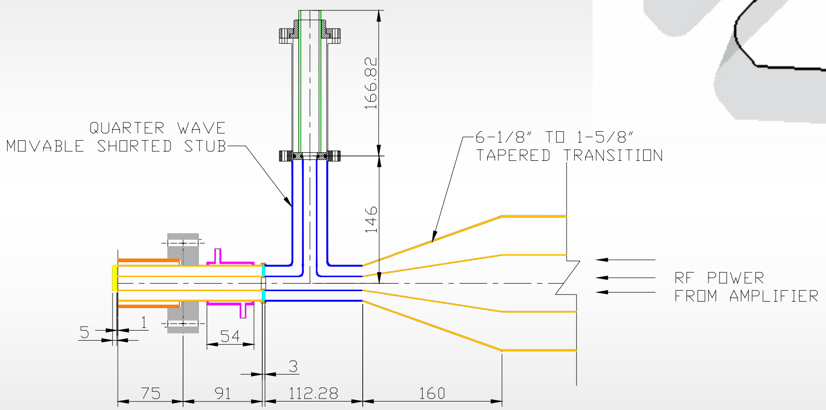


RF Coupler design

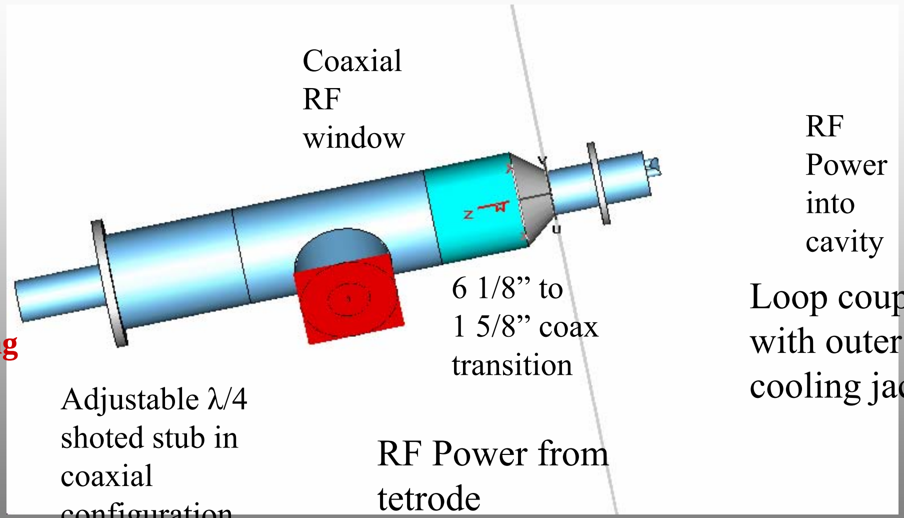
Coupler Dimensions:

Coax ID:	15 mm
Coax OD:	34.5mm
Loop Diameter:	10 mm
Loop Depth:	12 mm (max)





LAYOUT OF 50 kW RF COUPLER ASSEMBLY



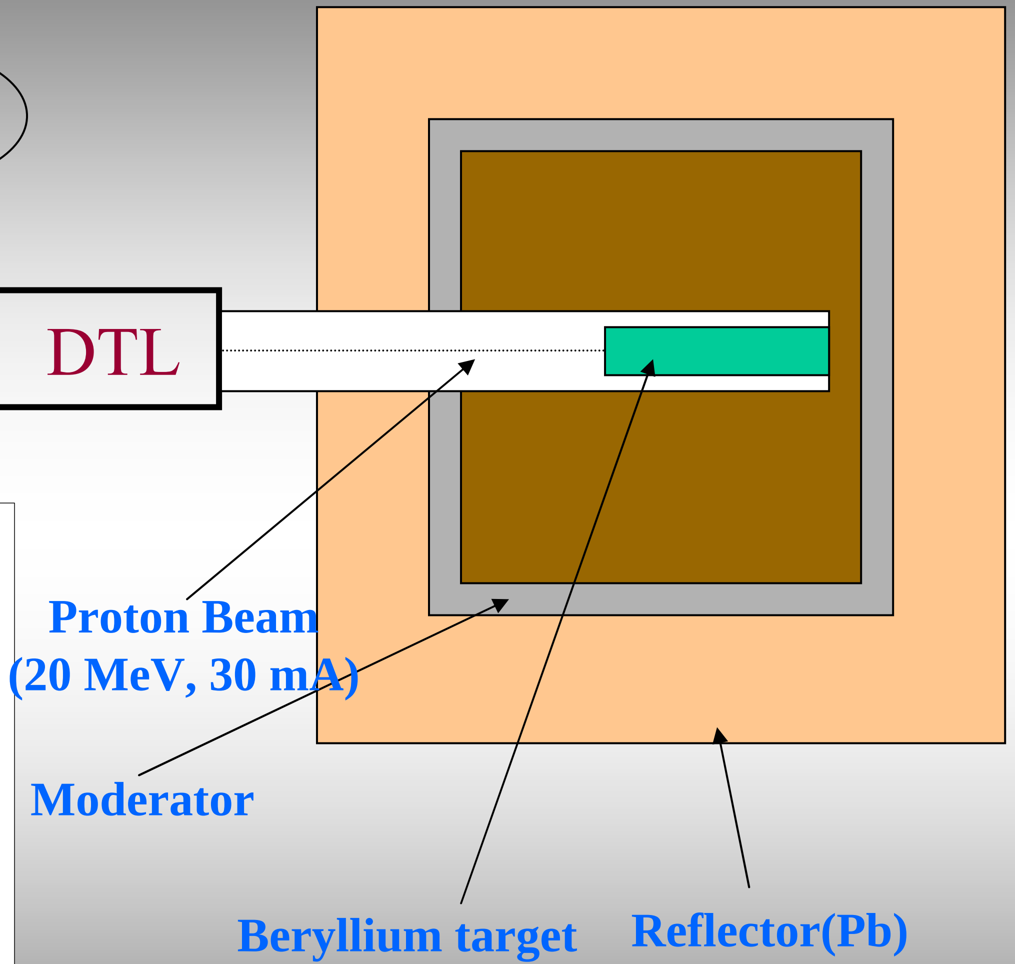
Loop coupler with outer cooling jacket

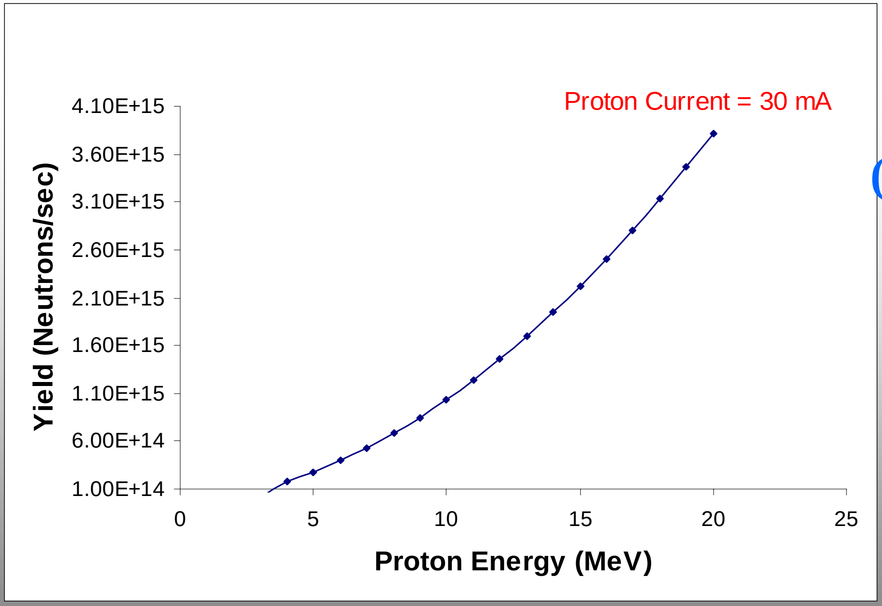
Cooling water inlet

50 kW Coaxial Coupler specifications:

- Return Loss: Better than -25 db
- Coupling Coefficient: Variable from 1.2 to 0.7
- Max delta T on window: < 30°C
- Max. temperature on loop: 120°C
- Frequency Shift: < 2 MHz

High flux neutron Facility

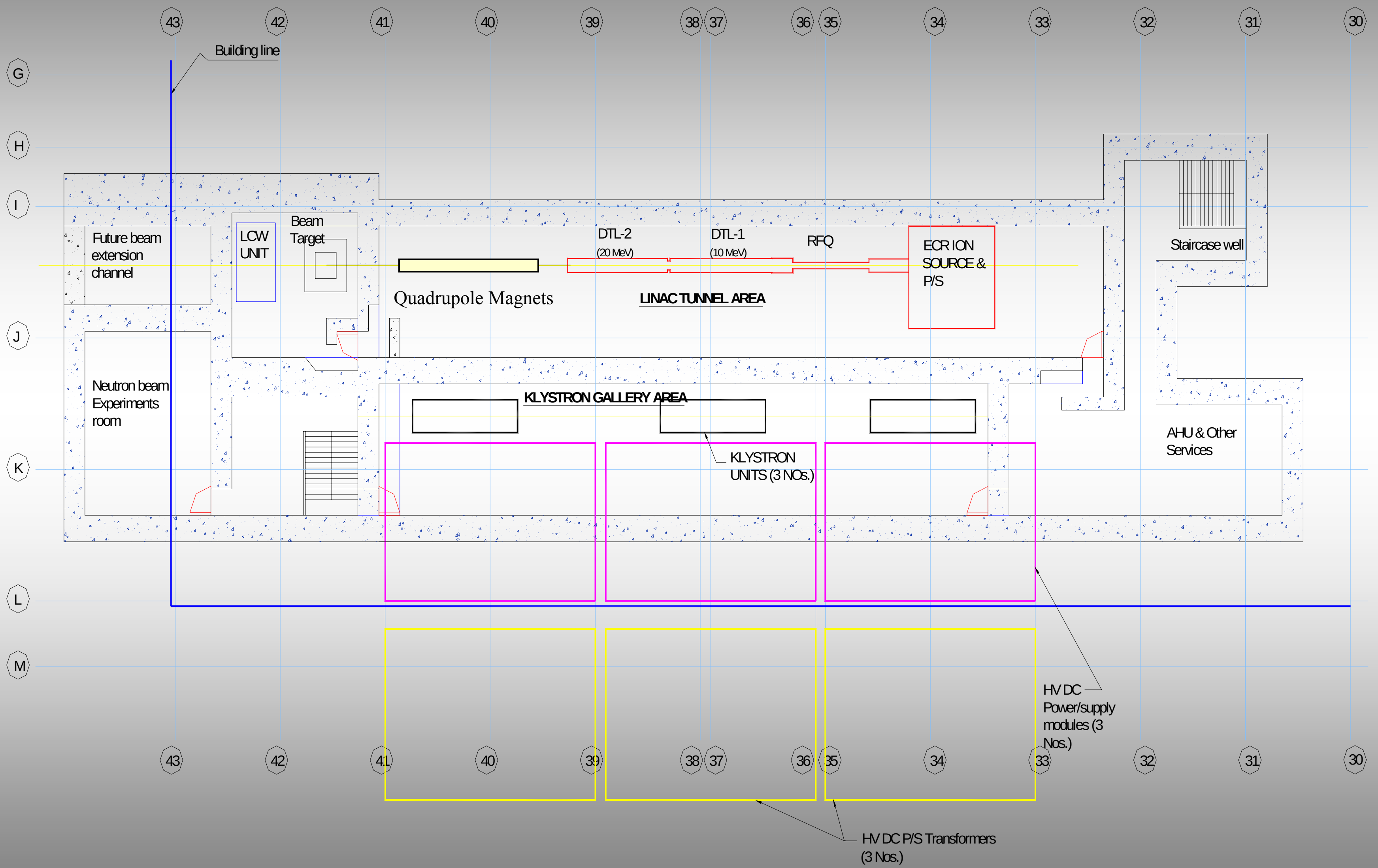




Neutron Yield for Beryllium target

$$S_0(E_P) = 4.476 \times 10^{11} \times E_P^{1.886} \times I \ \ \text{n/s}$$

Layout of LEHIPA Building



Summary

- **Physics Design of a 1 GeV, 30 mA Linac has been done and refinements are in progress.**
- **100-1000 MeV part will be superconducting**
- **In Phase I, 20 MeV, 30 mA Linac is being made**
- **Development of prototypes of different sub-systems is in progress**
- **Work on Control, RF, Cooling, diagnostics and other systems is in progress**
- **It is expected that 20 MeV beam will be available in 2012.**
- **Developmental work on SC cavities has been initiated at BARC**

PARTICIPATING DIVISIONS:

- ✓**Nuclear Physics Division (NPD)**
- ✓Vacuum Physics and Instrumentation Division (VPID)
- ✓Accelerator & Pulse Power Division (APPD)
- ✓Reactor Safety Division (RSD)
- ✓Centre for Design and Manufacture (CDM)
- ✓Research Reactor Design & Projects Division (RRDPD)
- ✓Technical Services Division (TSD)
- ✓Architecture & Civil Engineering Division (A&CED)
- ✓Laser and Neutron Physics Section (LNPS)
- ✓Control Instrumentation Division (CnID)
- ✓Radiation Safety & Systems Division (RSSD)
- ✓Electronics Division (ED)
- ✓Reactor Control Division (RCnD)
- ✓Reactor Projects Division (RPD)
- ✓Raja Ramanna Centre for Advanced Technology (RRCAT)

धन्यवाद

Thank You !