# Developmental Studies of High Current Linac for Indian ADS program


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**Mumbai, India**


**Plan of the talk:**

1. What is an Accelerator Driven sub-critical reactor System (ADS)
2. Why is ADS so important to us?
3. Accelerator Configuration
4. Developmental studies of high intensity proton linac (20 MeV LEHIPA)
5. Status of the project
6. Summary & conclusions.

- **At the present consumption level, known reserves for coal, oil and gas correspond to duration of:**

- **Coal: 230 yrs**

- **Oil: 45 yrs**

- **Gas: 65 yrs**

- **Nuclear Power appears to be an <u>inevitable option</u> as future energy source; but disposal of nuclear waste is an important issue of concern in harnessing nuclear energy through "<u>critical reactors</u>", which needs to be addressed satisfactorily.**

# Annual yield of Plutonium & Minor Actinides and (some) fission products in spent fuel from 1 GWe LWR plant operation.

| Isotope | Mass (kg/yr) | $T_{½}$ (year) | Fission Products |
|---|---|---|---|
| $^{238}Pu$ | 4 | 87.7 | |
| $^{239}Pu$ | 166 | 24110 | $^{89}Sr$ – $^{90}Y$…. Short-lived |
| $^{240}Pu$ | 76.7 | 6550 | $^{137}Cs$ .. $T_{½}$ ~ 30 years |
| $^{241}Pu$ | 25.4 | 14.4 | $^{99}Tc$ Truly Long-lived, |
| $^{242}Pu$ | 15.5 | $3.5x\ 10^5$ | $^{135}Cs$ $T_{½}$ ~ $10^4$-$10^6$ |
| $^{237}Np$ | 14.5 | $2.14x10^6$ | $^{129}I$ years |
| $^{241}Am$ | 16.6 | 432.6 | |
| $^{243}Am$ | 3 | 737 | Others are $^{93}Zr$, |
| $^{244}Cm$ | 0.6 | 18.1 | $^{107}Pd$ |

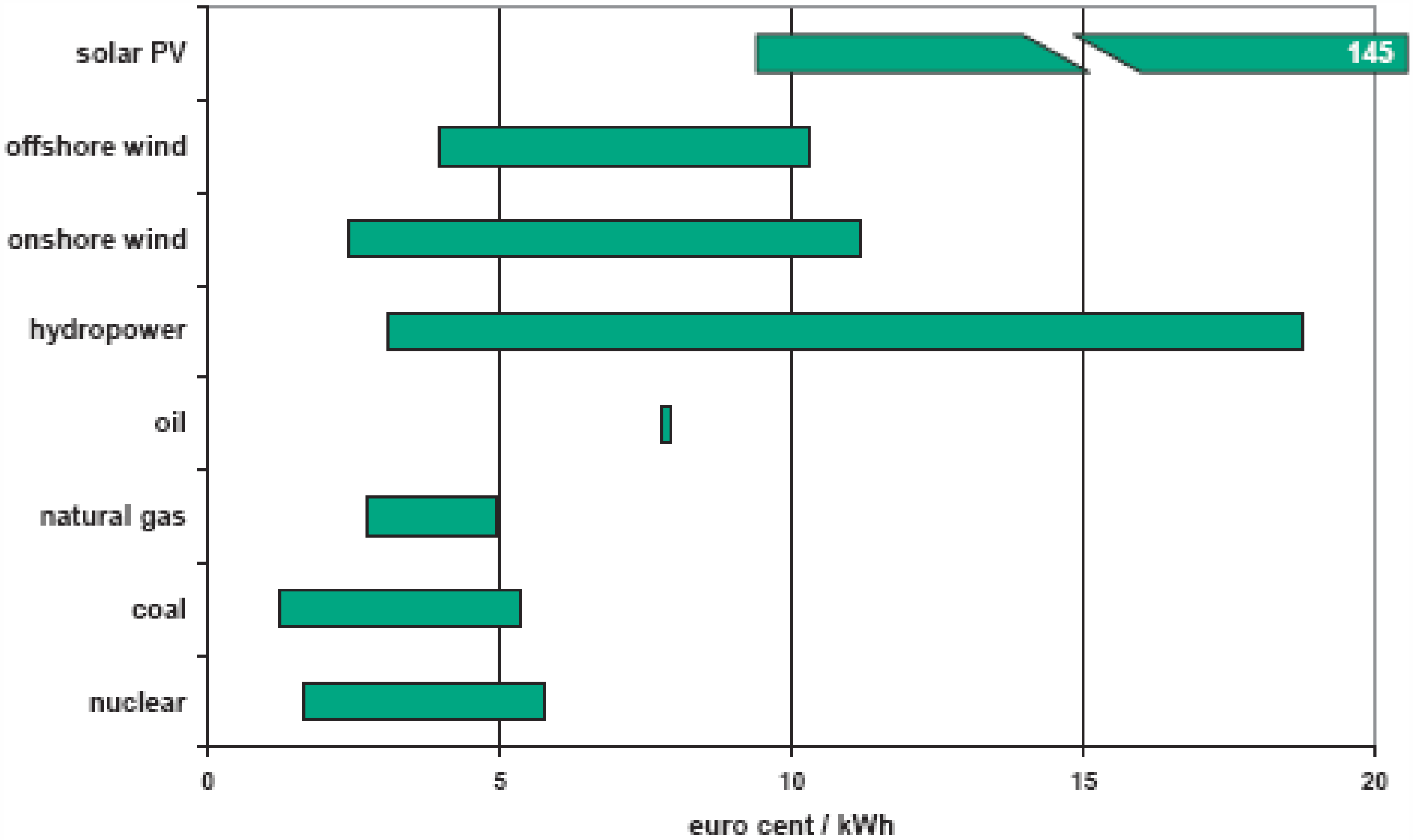



*FIG. A-3. The ranges of levelized costs associated with new construction as estimated in seven recent studies for electricity generating technologies in different countries (PV: photovoltaic).*

IAEA report-2006

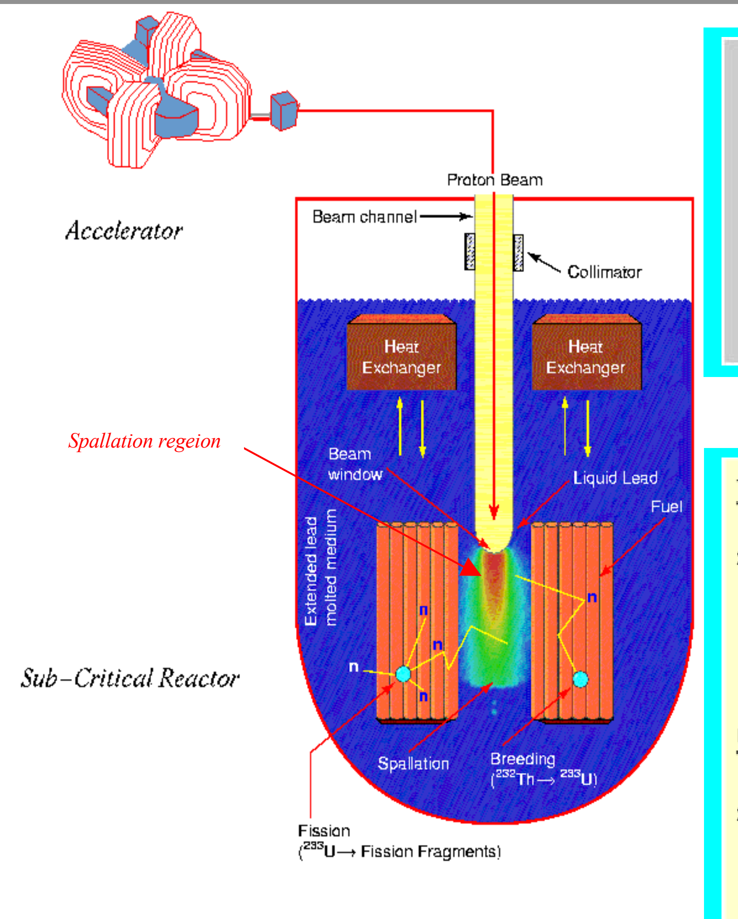
# World Thorium Resources

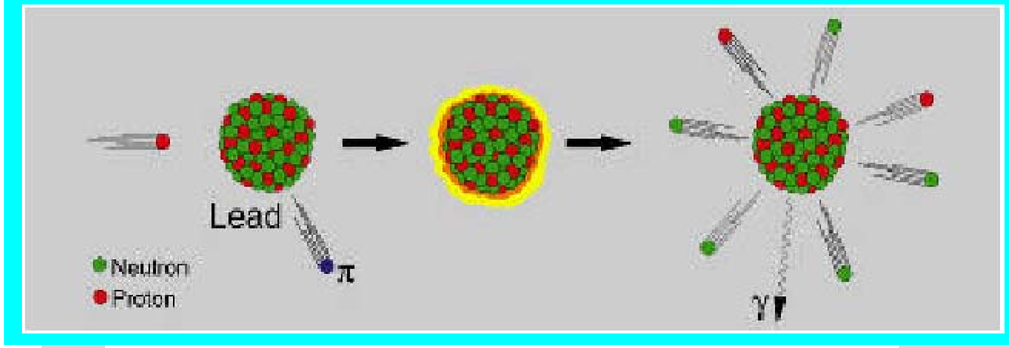
| Country | Reserves (tons) |
|---|---|
| Australia | 300,000 |
| India | 290,000 |
| Norway | 170,000 |
| USA | 160,000 |
| Canada | 100,000 |
| S. Africa | 35,000 |
| Brazil | 16,000 |
| Other Countries | 95,000 |
| World total | 1,200,000 |

# India needs a system which can…

- Produce Energy
- Transmute the high level long-lived radioactive waste
- Can use efficiently Thorium resources

# SCHEMATIC OF ACCELERATOR-DRIVEN SYSTEM




**Spallation reaction of high-enrgy proton with lead nucleus**

Thorium breeding into fissile uranium.

$^{232}$Th + n → (Neutron capture) → $^{233}$Th → β⁻ (beta decay, 22 min. half-life.) → $^{233}$Pa → β⁻ (beta decay, 27 days half-life.) → $^{233}$U (fissile isotope)

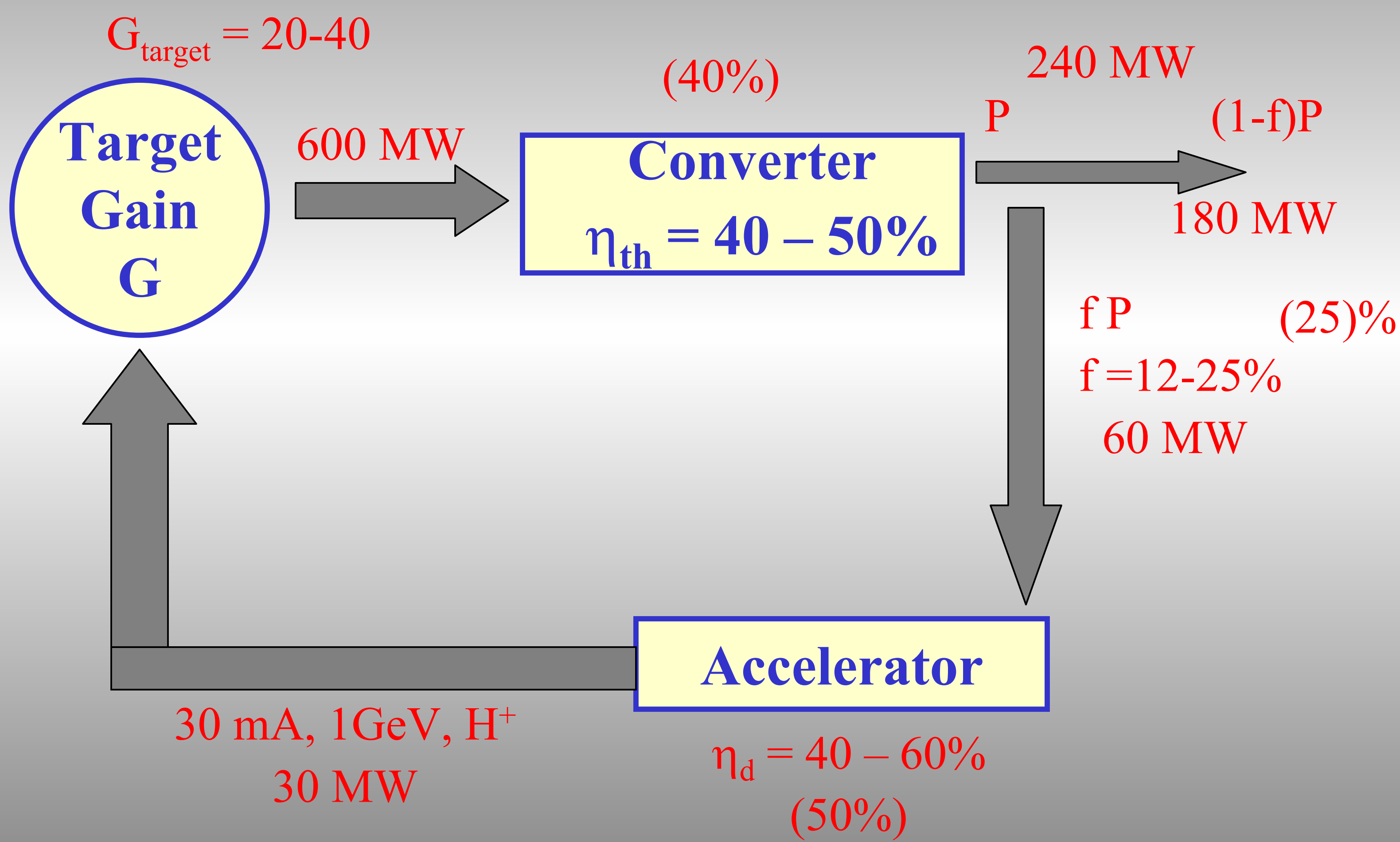
Uranium (bulk) $^{238}$U breeding into fissile plutonium.

$^{238}$U + n → (Neutron capture) → $^{239}$U → β⁻ (beta decay, 23 min. half-life.) → $^{239}$Np → β⁻ (beta decay, 2.3 days half-life.) → $^{239}$Pu (fissile isotope)

**Accelerator-Driven Sub-critical reactor can be used for:**

- **Generating nuclear power with Thorium as fuel,**
- **Transmutation of nuclear waste discharged from nuclear reactor of U-Pu fuel cycle.**

# ACCELERATOR DRIVEN ENERGY AMPLIFIER

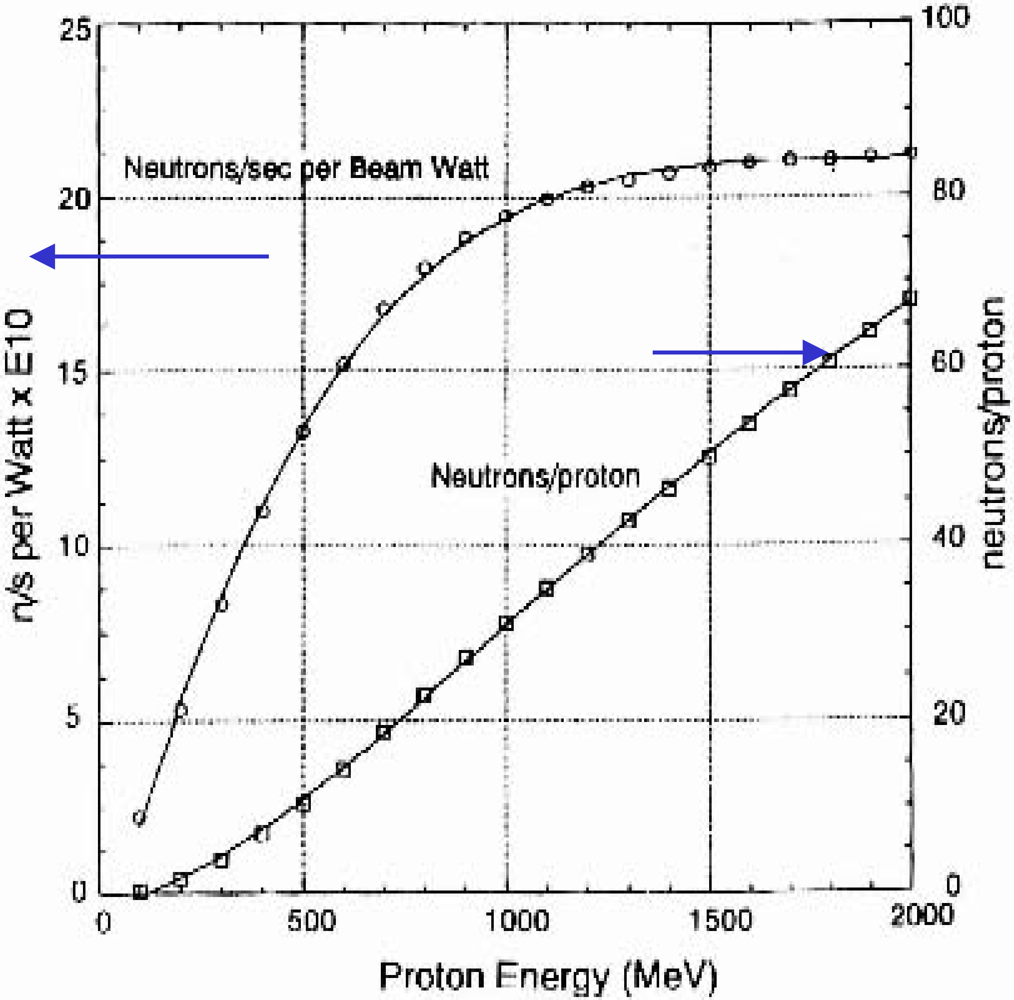



Carlo Rubia et al

# 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
$\nu_s$ = 25 neutrons/proton
$\nu$ = 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 |

# Some of the ADS Projects around the world

| | |
|---|---|
| JAPAN | Under its OMEGA (Option Making Extra Gains of Actinides and FP), that is extension of its earlier Actinides Burner Reactor (ABR). |
| KOREA | Under its HYPER (Hybrid Power Extraction Reactor) programme. |
| ITALY | Under its TRASCO (TRAnsmutazion SCOrie) Programme and, Industrial project undertaken by ANSALDO for EC. |
| CHINA | Proposed as CIAE+IHEP project but under an un-named ADS programme of Sino-Italian collaboration. |
| BELGIUM | Under MYRRHA project as extension of ADONIS (Accelerator-Driven Operated New Irradiation System) programme for radioisotope production. |
| FRANCE | Its CNRS/IN2P3 institutes are spearheading waste incineration R&D with spinoff of its TRISPAL activities for accelerator to ADS. |
| GERMANY | Activities under FZK in the yet un-named programme. |
| RUSSIA | Undertaken several study projects in ITEP/ISTC against the EC/US funding. |
| USA | Earlier as ATW. Now AAA (Advanced Accelerator Applications) aiming for having ADTF in 10 years from 2001. Full technological Demo in next 10 years. |

**The technologically most important and challenging part in ADS scheme is the High Power Proton Accelerator.**

## The main requirements from this accelerator are:-

- High Reliability
- High Beam Power
- CW Operating Mode
- High Conversion Efficiency
- Minimum Beam Loss
- Easy Maintenance & Serviceability

**The linac option seems attractive because higher beam current can be achieved.**

**The Linac is divided into three parts for convenience.**

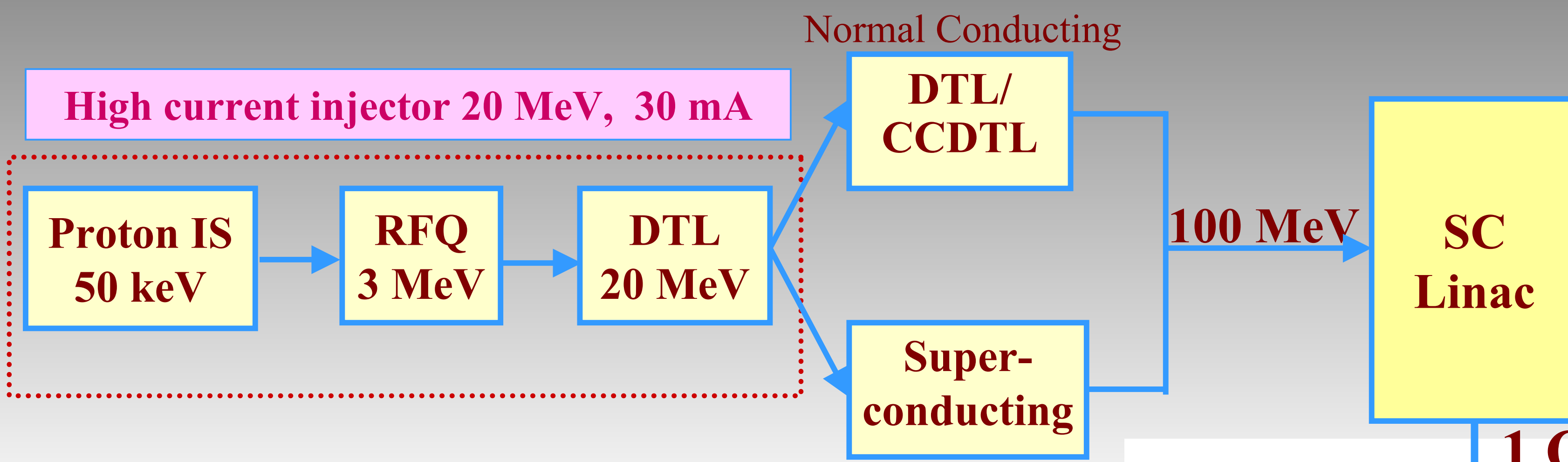
- Low Energy (upto 20 MeV)
- Medium Energy (20 MeV to 100 MeV)
- High Energy ( > 100 MeV )

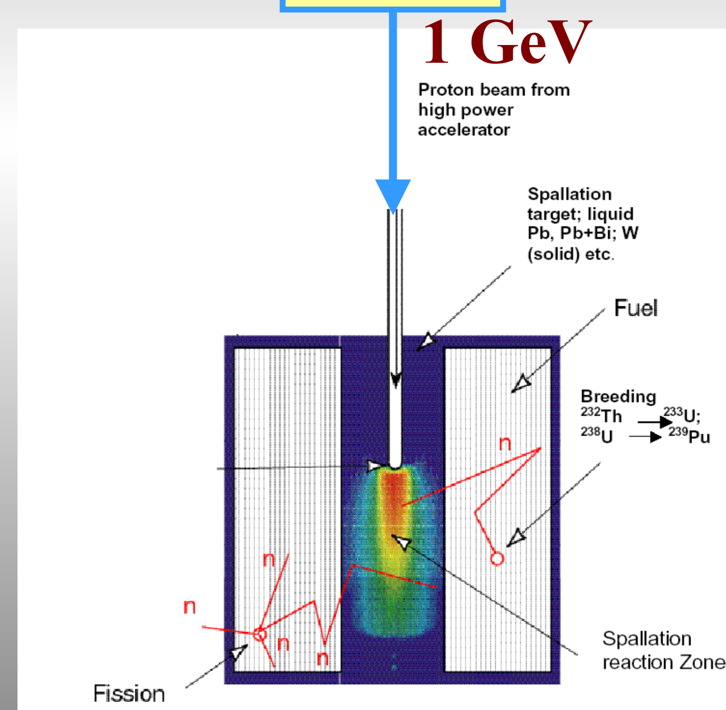
**The accelerating structures used at different energies are:-**

- Low Energy – RFQ, DTL/CCDTL /SDTL
- Medium Energy - CCDTL /SDTL
- High Energy – CCL, Superconducting structures

Main Design issue is beam loss control.
Space charge forces are strongest in the low energy end.
**So particular care must be taken to design this part.**

# Scheme for Indian ADS Programme

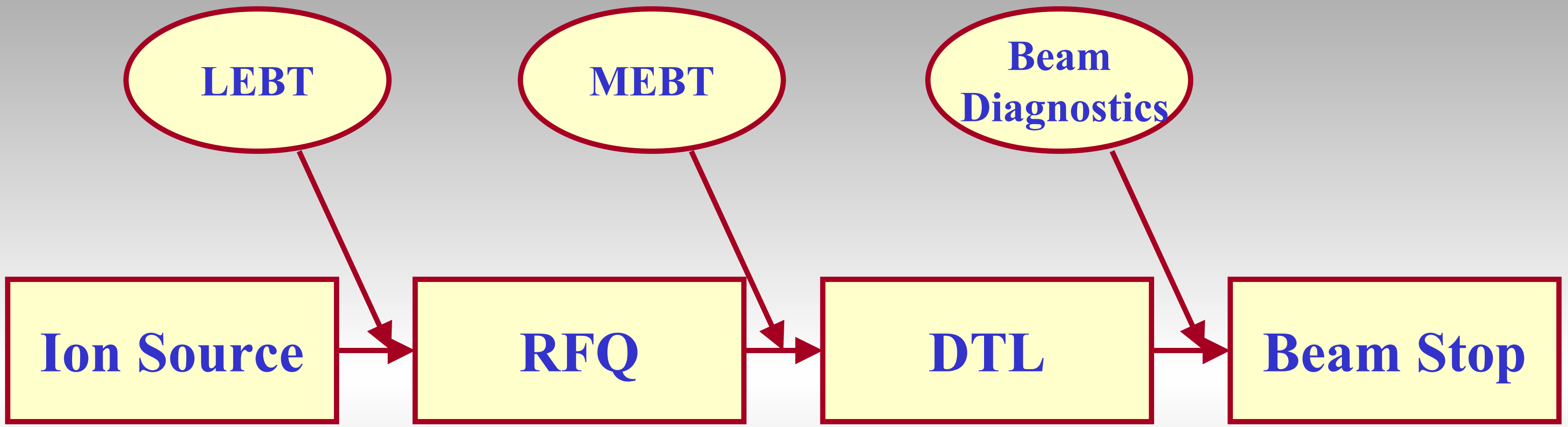



***Main design issue:***

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

# 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

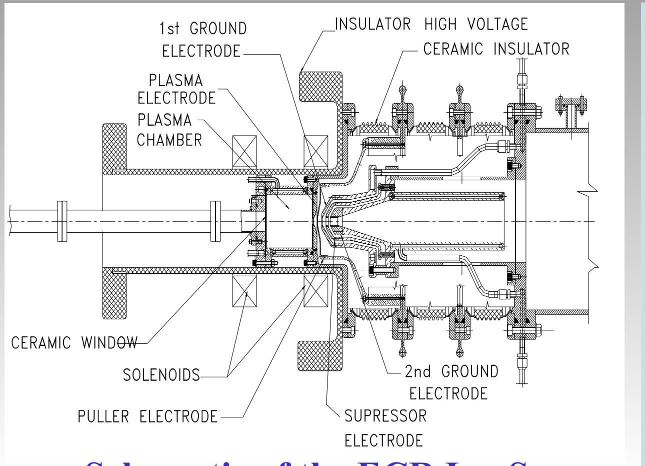
**MEBT** : Medium Energy Beam Transport System

**DTL** : Drift Tube Linac

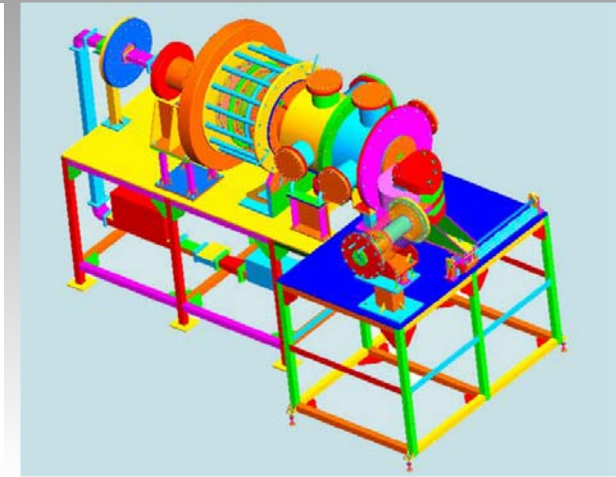
# ECR Ion Source

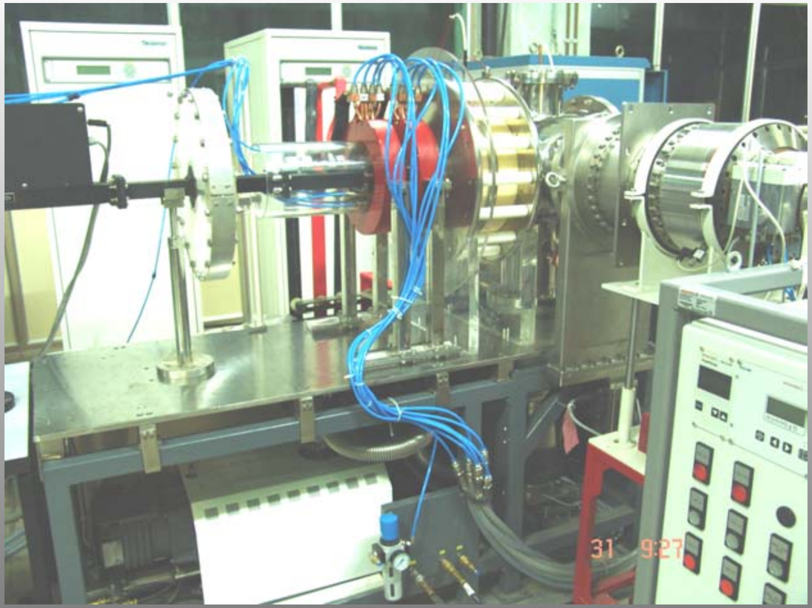
P. Roychowdhary et al, APPD, BARC

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




Schematic of the ECR Ion Source

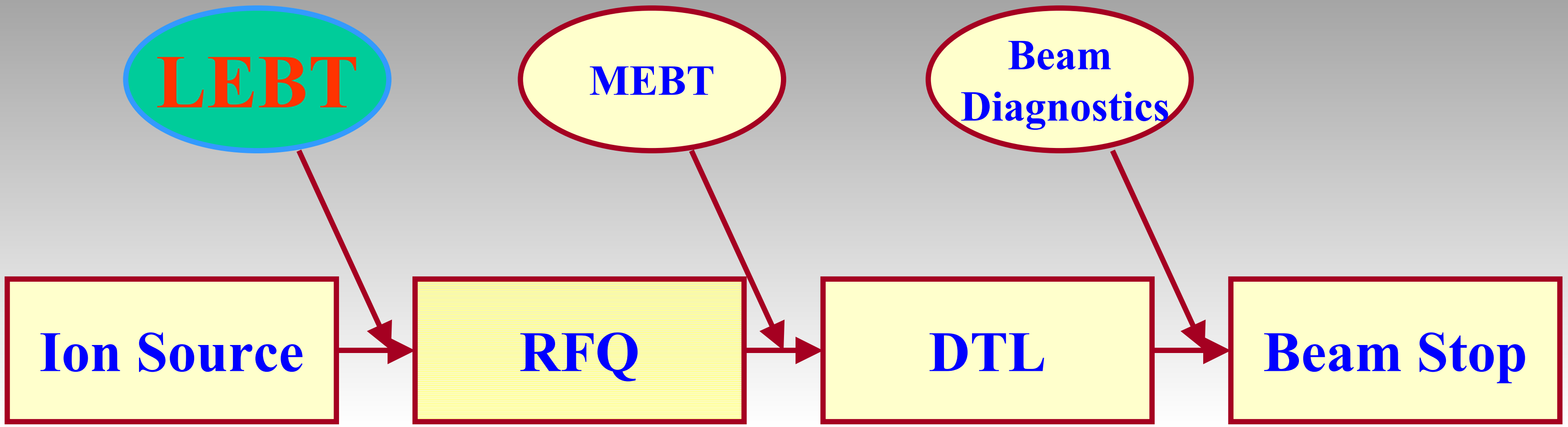






Testing in progress

# 20 MeV Linac: Transport Line LEBT




2.45 GHz
ECR Ion source
50 keV, 35mA.

352.21 MHz,
4-Vane type RFQ
3-MeV, 30 mA

352.21 MHz,
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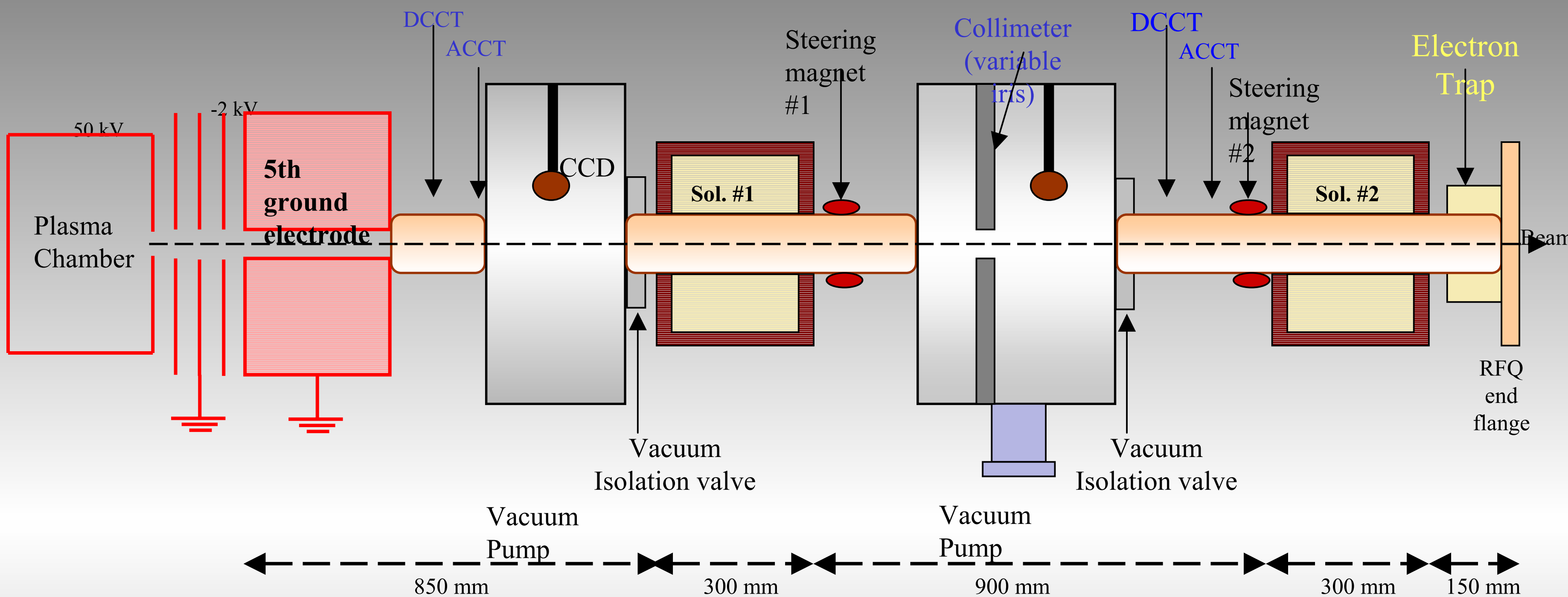
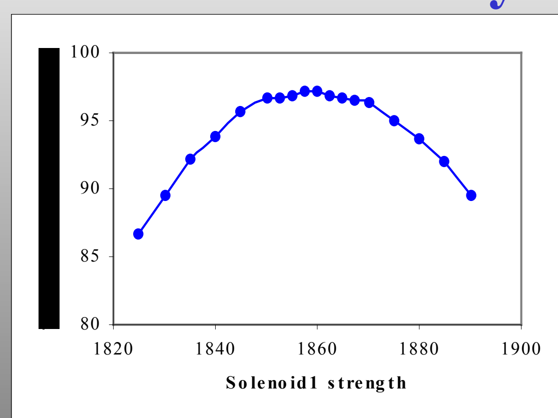
Alvarez type DTL

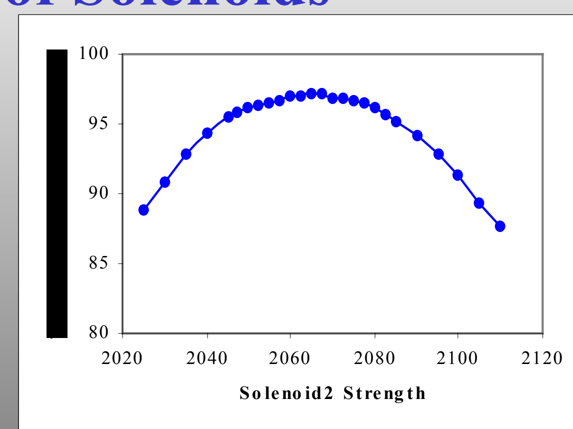
# Low Energy Beam Transport (LEBT) System




## Error Analysis of Solenoids

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




Tolerance on solenoid strength = ± 30 Gauss

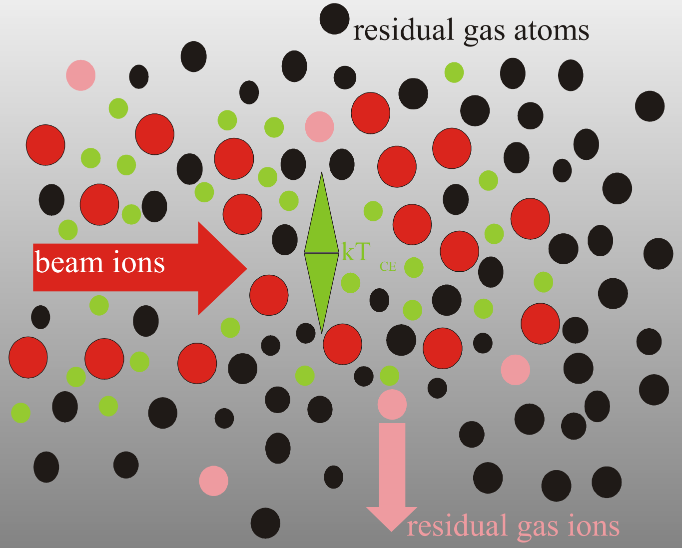
# Space Charge Compensation in LEBT

➲Beam transport in the LEBT is mostly determined by space charge forces

➲Space charge compensation can restrict increase in beam size and emittance growth significantly.

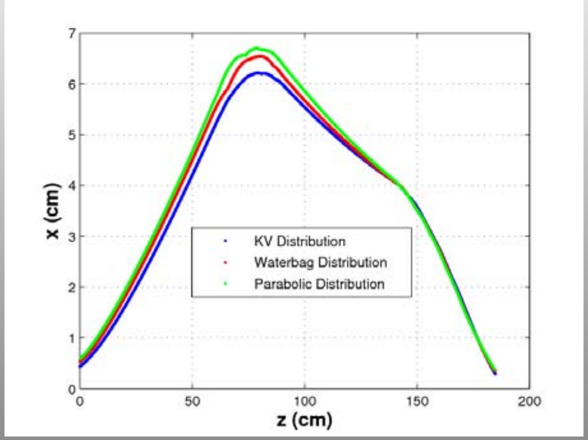
## How it is done?

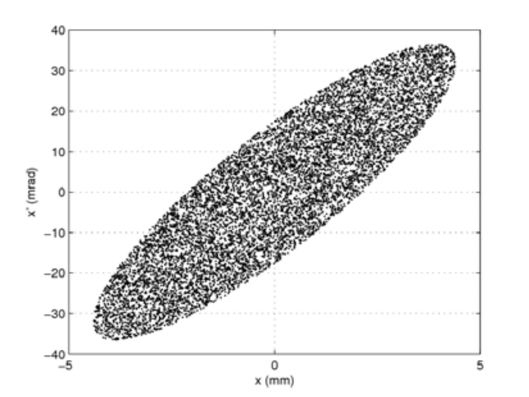
- Introduce a residual gas in the background.
- The beam ionizes the residual gas.
- **Electrons are trapped by the space charge potential of the beam.**
- So space charge is gradually reduced.

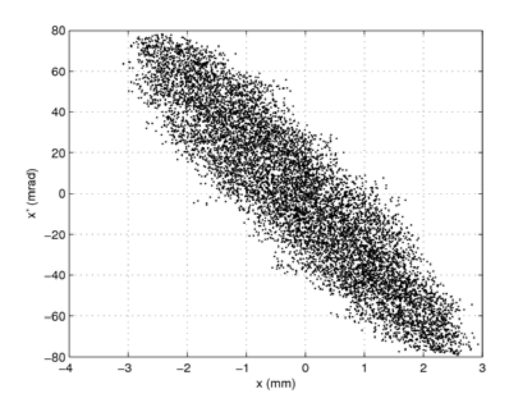


# Effect of Non-Linear space charge on beam dynamics in LEBT

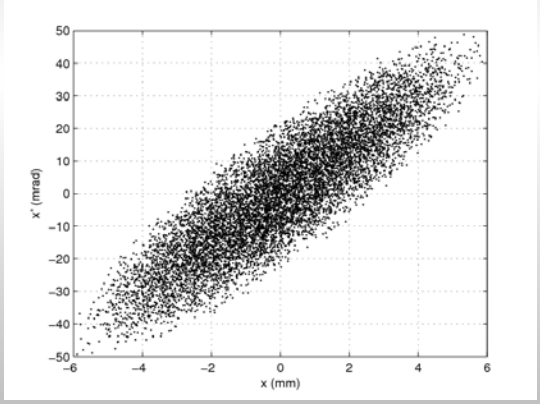
- KV distribution being uniform causes linear space charge forces.
- Any kind of non-uniformity in the density will give rise to non-linear space charge.
- Non-linearity of the space charge field reflects in emittance increase as well as in waist diameter.

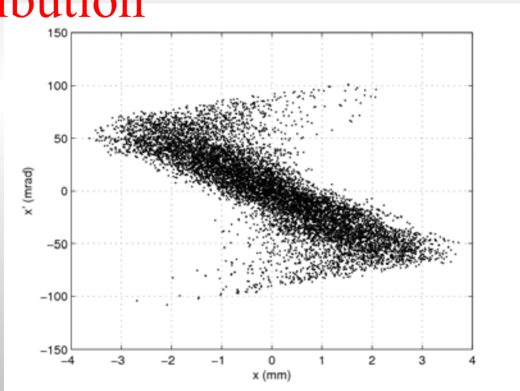



With KV- distribution




With Parabolic distribution

KV: Kapchinskij-Vladimirskij distribution

S.C.L. Srivastava, S.V.L.S. Rao and P. Singh., Pramana-J Phys <u>68</u>, 331 (2007)

# 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

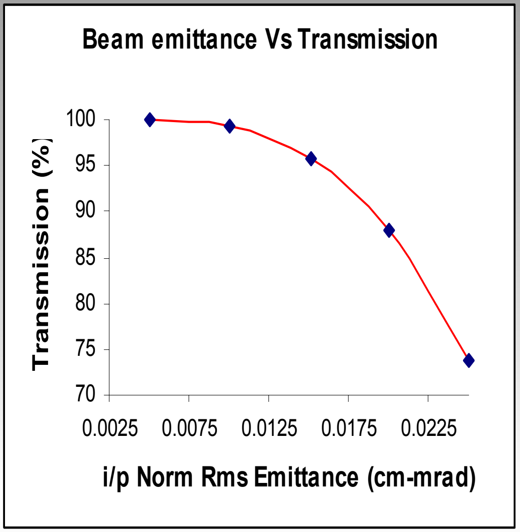
Max. beam size in the LEBT = 13 cm
Total length = 1.85 m.

## 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 |

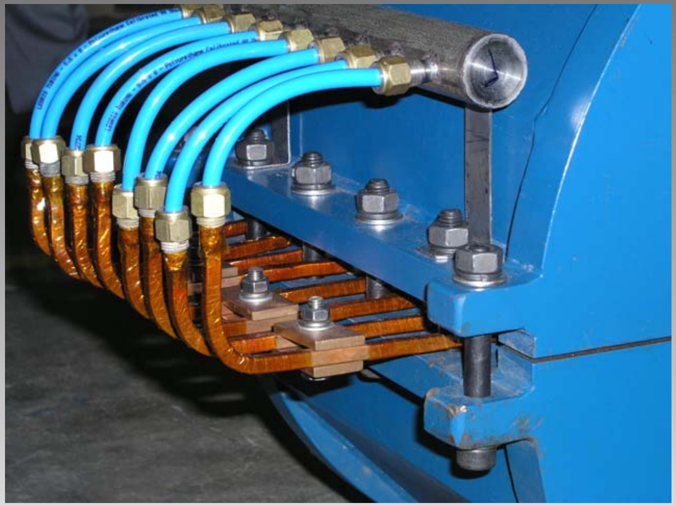
# Effect of Emittance on Transmission

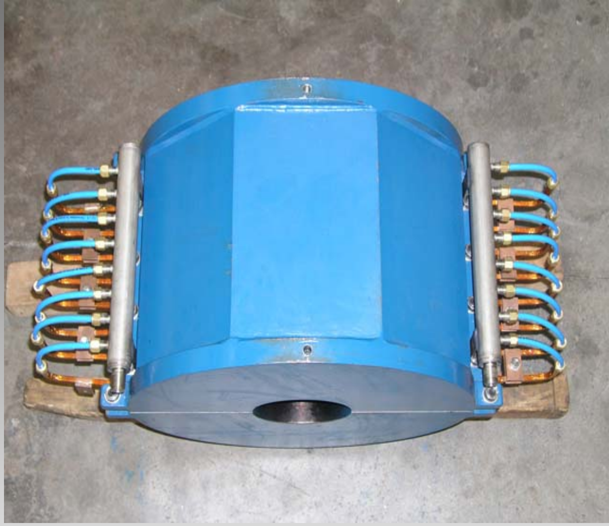
If the emittance of the input beam to the RFQ is more than the designed value the transmission drops drastically.

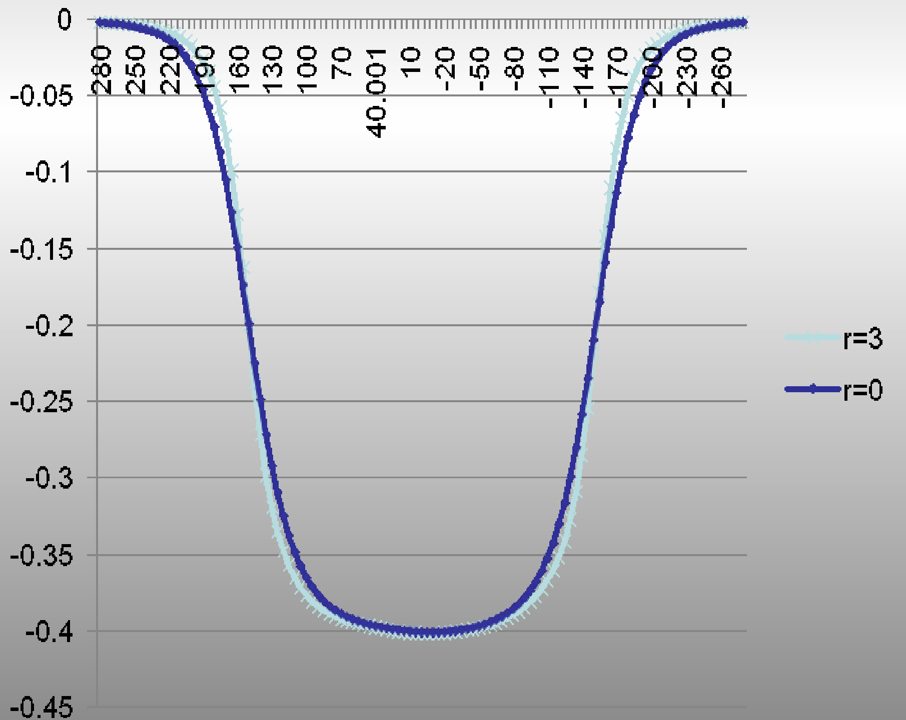



**Critical Input parameter for RFQ design:**

**rms emittance of the beam from the ion source**

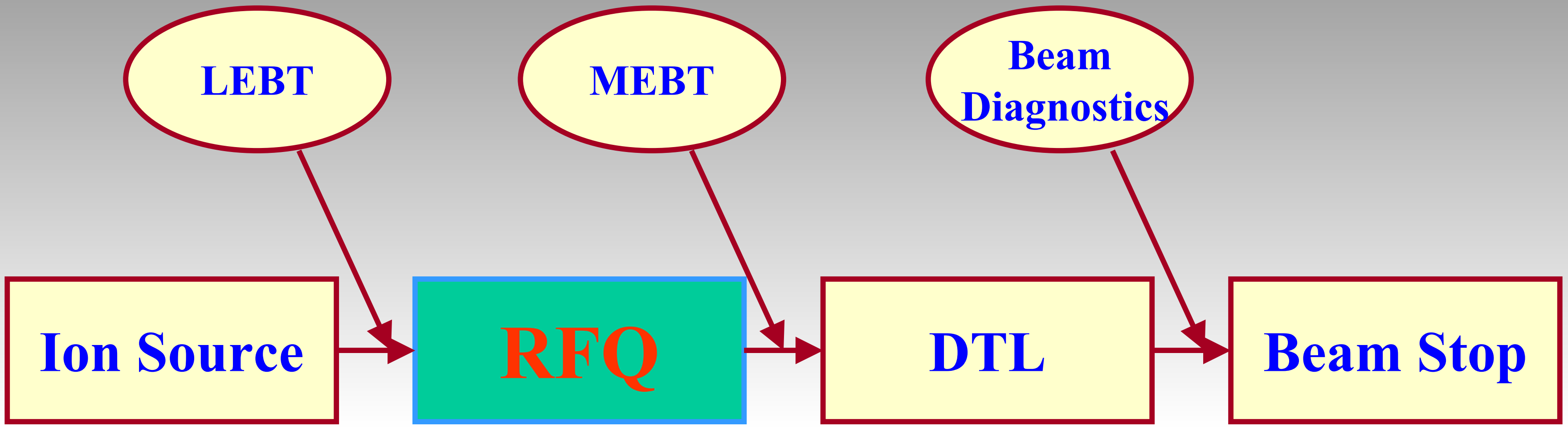






Fabricated & tested at RRCAT, Indore

# 20 MeV Linac: Accelerating Structure RFQ




2.45 GHz
ECR Ion source
50 keV, 35mA.

352.21 MHz,
4-Vane type RFQ
3-MeV, 30 mA

352.21 MHz,
20 MeV, 30 mA
Alvarez type DTL

# Principle of RFQ

Particles experience alternate gradient electric focusing which is stronger than magnetic focusing for low velocity particles.

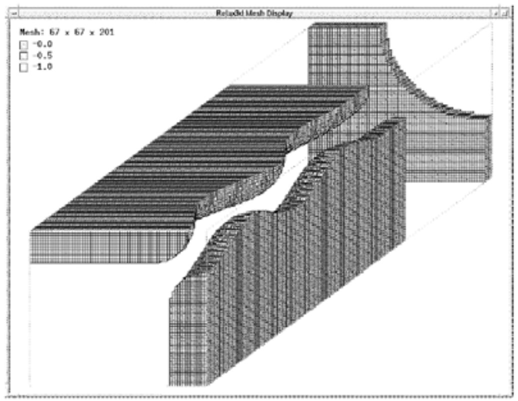
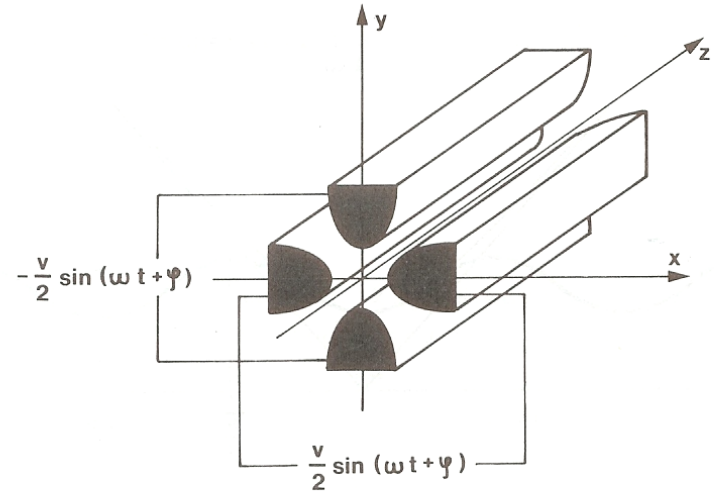
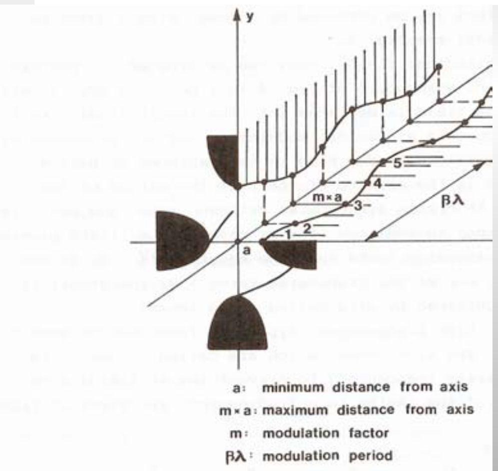
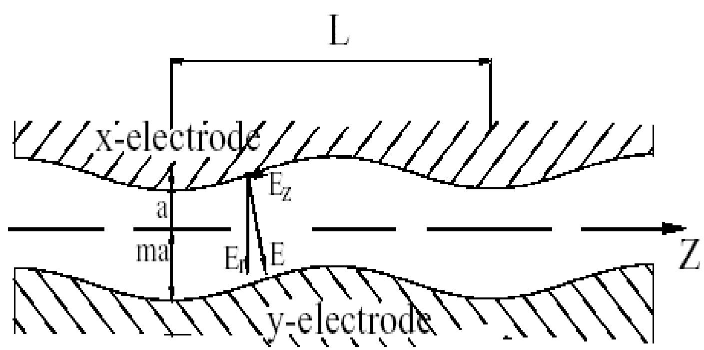
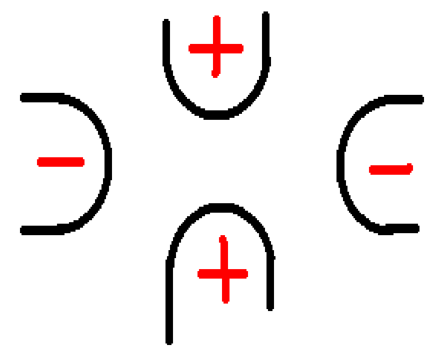


Figure 2: A RELAX3D model of the exit region showing three regular cells, a transition cell and a short unmodulated end section.



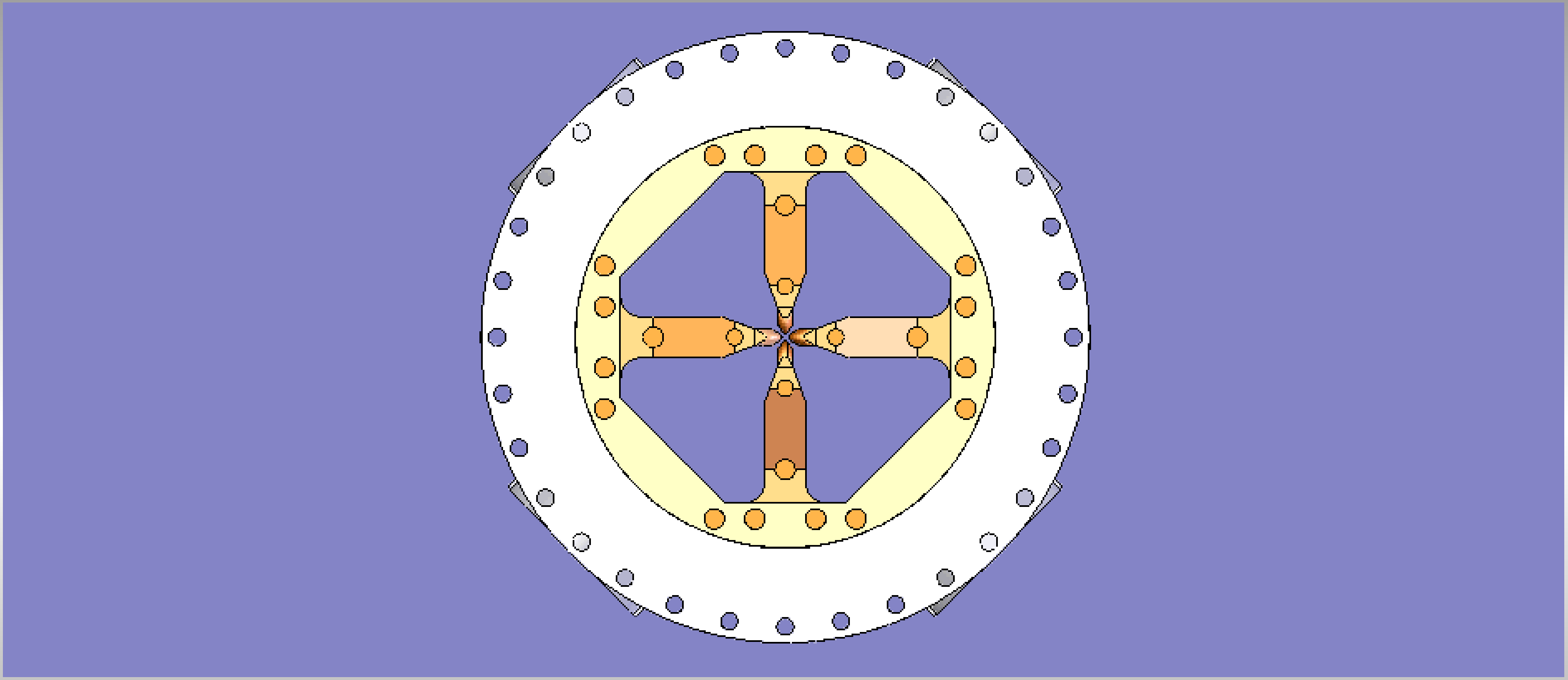




The longitudinal fields for acceleration are produced by modulating the electrodes longitudinally.

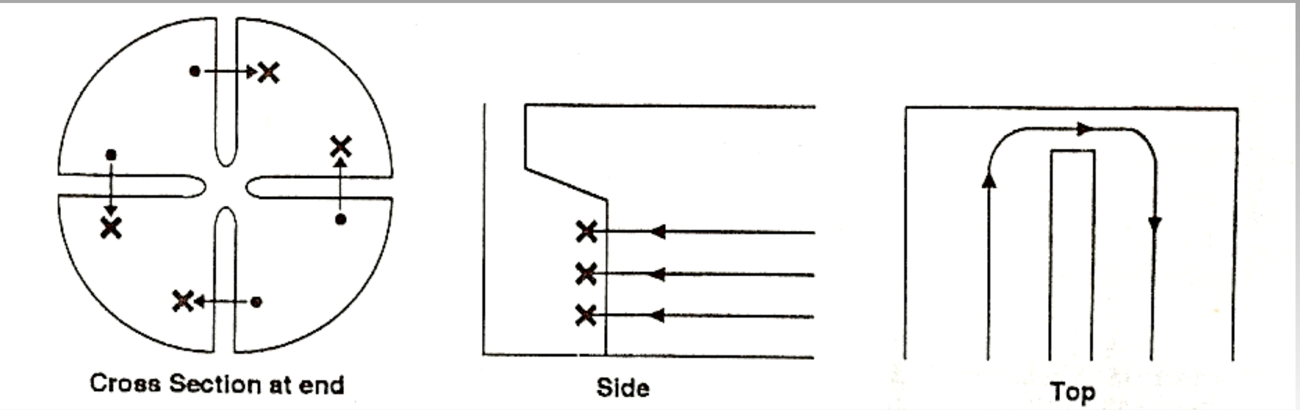
The RFQ simultaneously **Focuses**, **Bunches** and **Accelerates** the beam.

# Full 3D model of the RFQ



# RFQ Cavity design (3D)

## End Regions of the RFQ




Magnetic Field lines in Quadrupole mode at end

**Boundary conditions**

$E_p = 0$ $B_n = 0$

**The RFQ resonator has to be closed at both ends.The longitudinal magnetic field lines cannot be perpendicular to the end plate It must be parallel.**

**Vanes do not extend to the end plate and in addition are cut to facilitate turning of the magnetic field.**

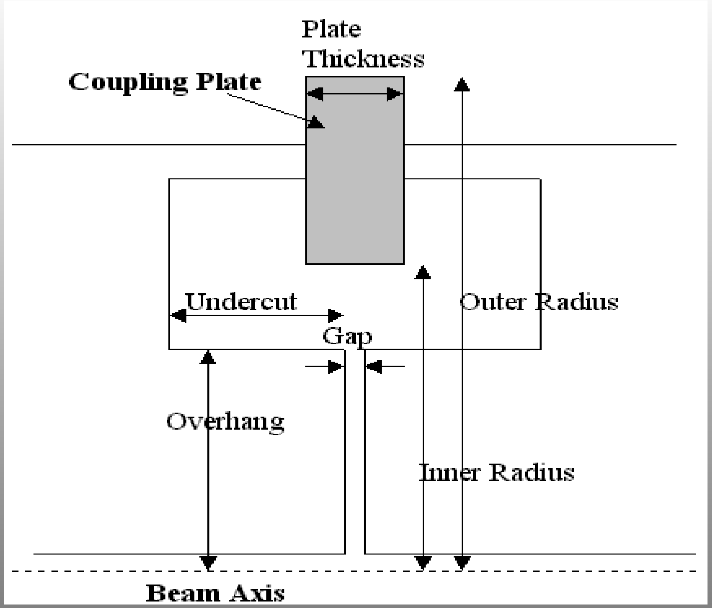
**Operating Mode: $TE_{210}$ like mode**

**Dominant modes**
$TE_{21}$- Quadrupole
$TE_{11}$ -Dipole

# Coupling Cell

- For smaller length the number of modes in a given frequency range is less.
- Field tilt effects can become important for structures with a length of few wavelengths.

The RFQ is 4 m long. For better stability it will be made in smaller sections which will be **resonantly coupled**.

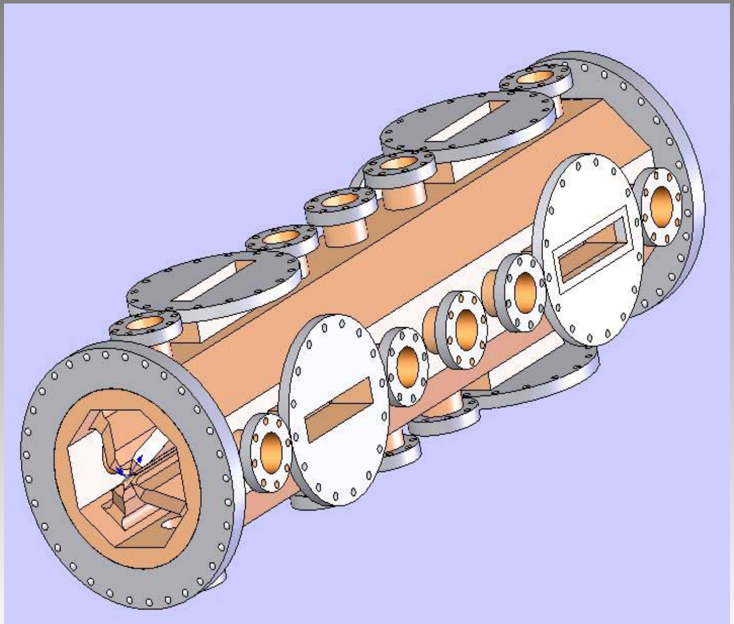


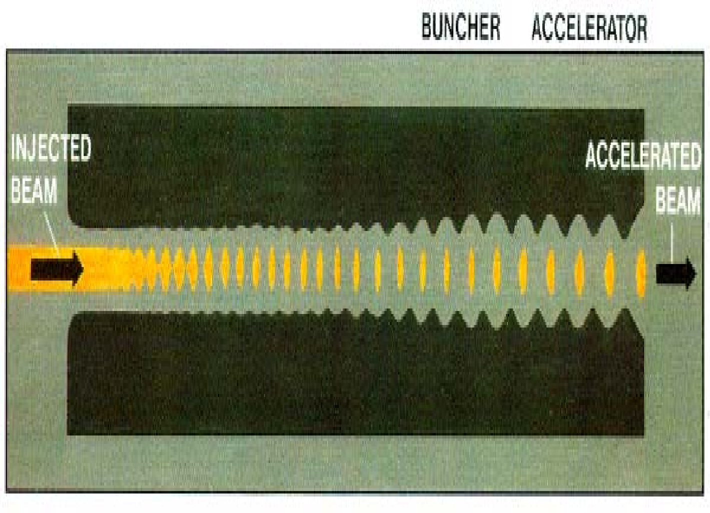

The coupling plates separate the segments and prevent the magnetic field lines from continuing from one segment to the next. The gap between the vanes provides capacitive coupling.

# RFQ Parameters

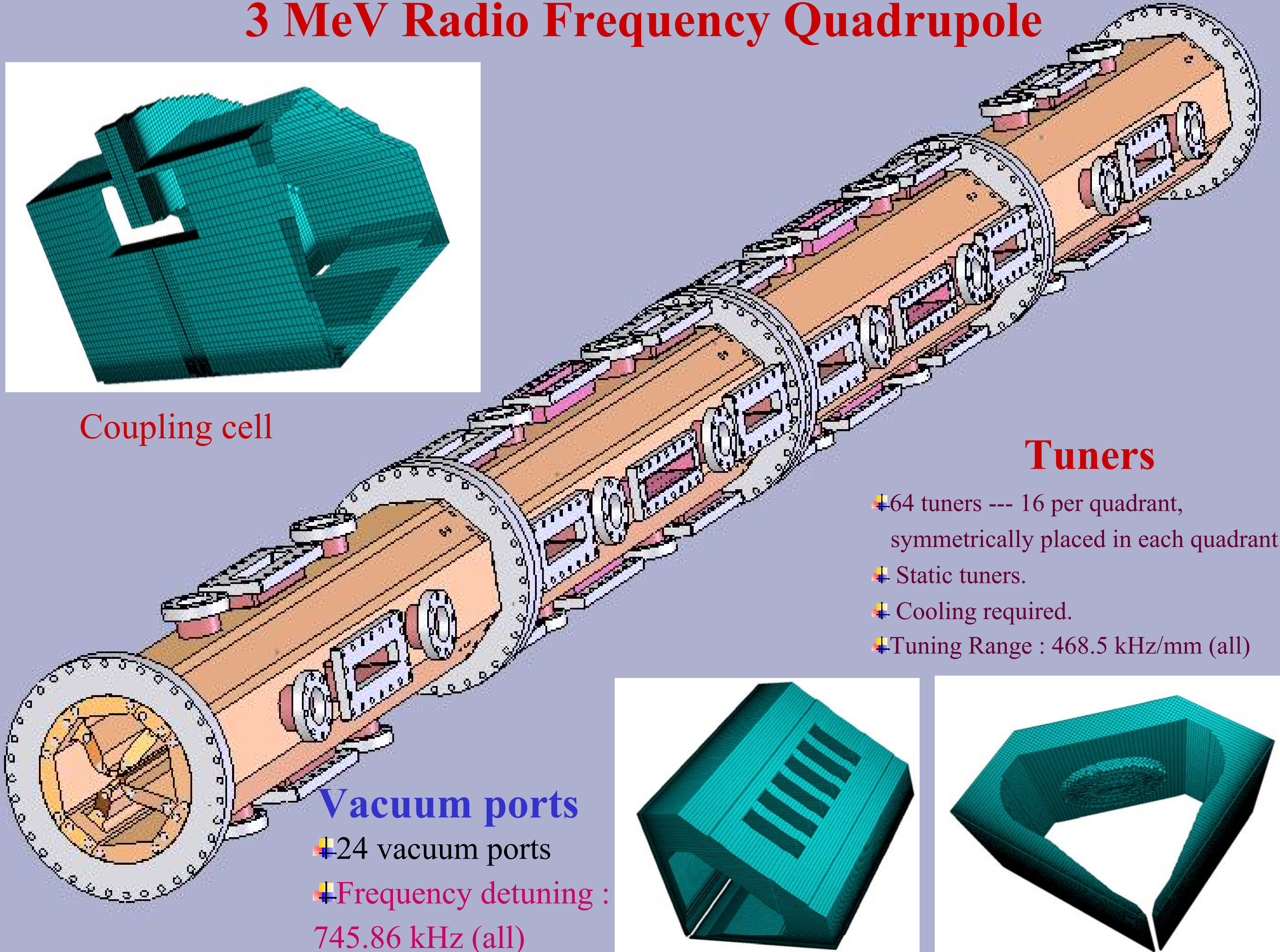
1. Bunching 2. Focusing 3. Acceleration

| | |
|---|---|
| Frequency | 352.21 MHz |
| Energy | 50 keV/ 3 MeV |
| Input current | 30 mA |
| Vane voltage | 80 kV |
| Avg. Aperture $R_0$ | 3.63-4.53 mm |
| Length | 4 m |
| Total RF power | 500 kW |
| **Transmission** | **98 %** |





# 3 MeV Radio Frequency Quadrupole



Coupling cell

## Tuners

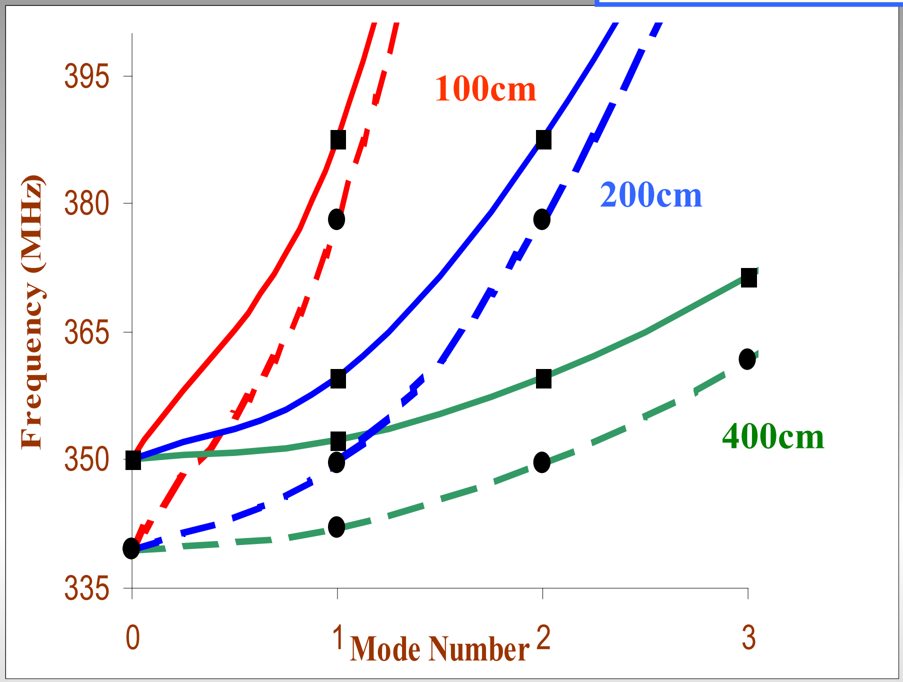
- 64 tuners --- 16 per quadrant, symmetrically placed in each quadrant
- Static tuners.
- Cooling required.
- Tuning Range : 468.5 kHz/mm (all)

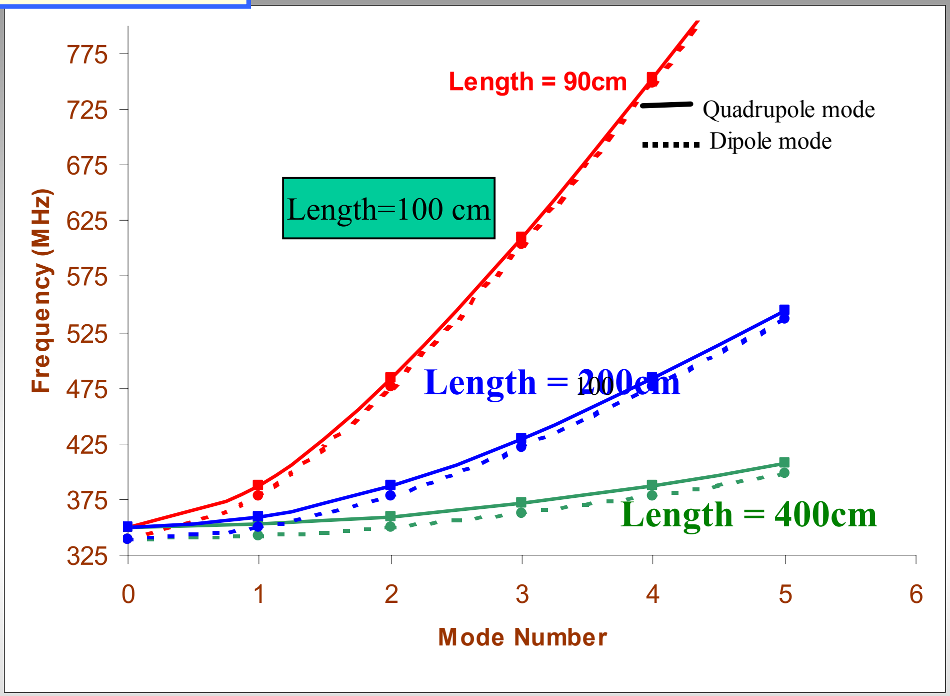
## Vacuum ports

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

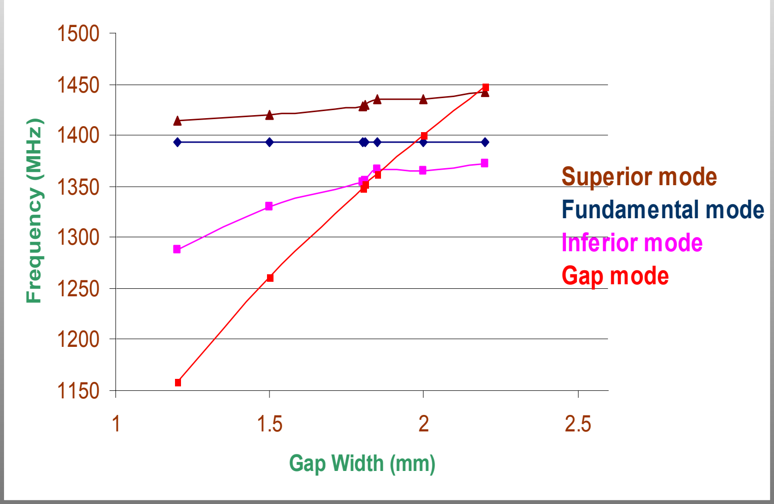
# Variation of dipolar and quadrupolar frequencies with RFQ length

**RFQ Length = 4 m**



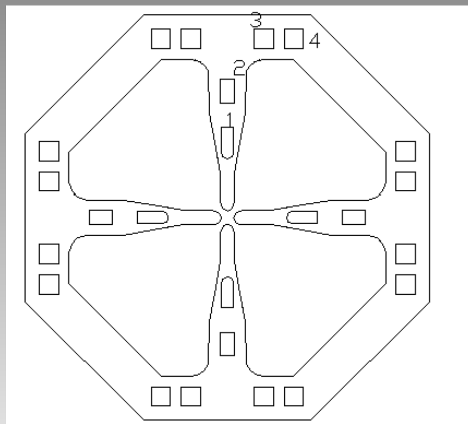

$$\omega_n^2 = \omega_0^2 + (n\pi c/L)^2$$




Boundary conditions

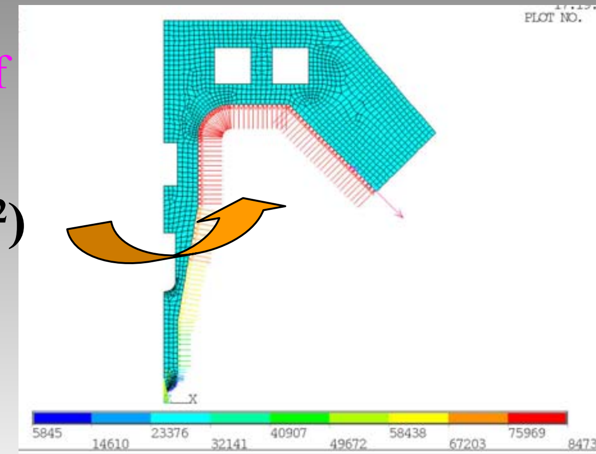
$E_p = 0 \qquad B_n = 0$

# Thermal Analysis of the RFQ

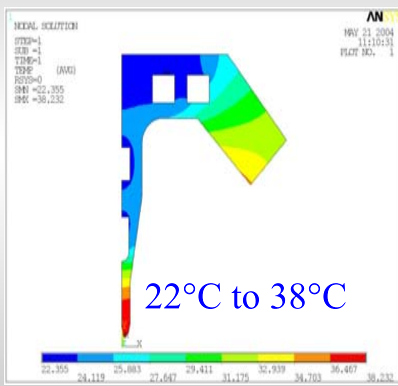


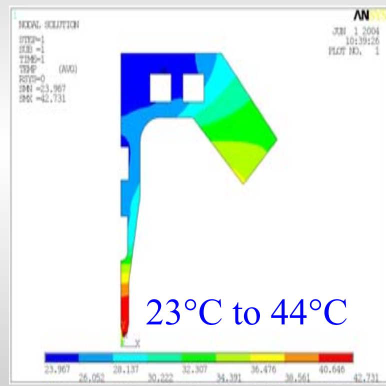
Heat flux on Cavity walls of the RFQ

**5845-84734 (W/m²)**



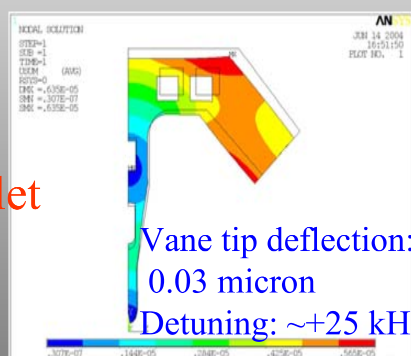

Temperature distribution at inlet and outlet

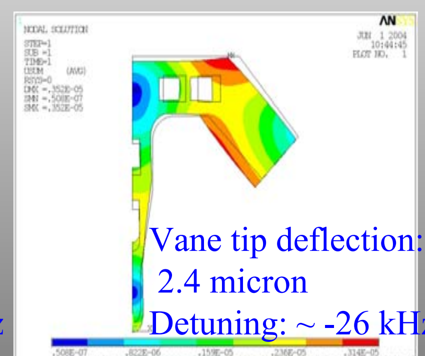


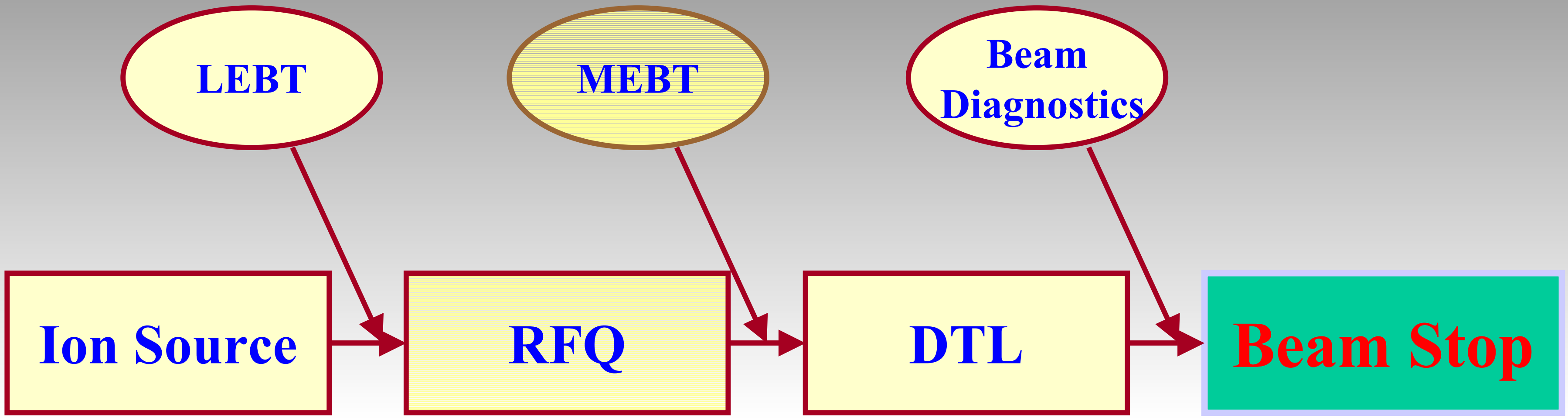

- ❖Coolant temperatures are 16⁰C in vane channels and 20⁰C in wall channels
- ❖Frequency sensitivity with vane water temperature is –46 kHz/⁰C
- ❖Frequency sensitivity with wall water temperature is +35 kHz/⁰C

Deflections at inlet and outlet



# 20 MeV Linac: Beam Stop

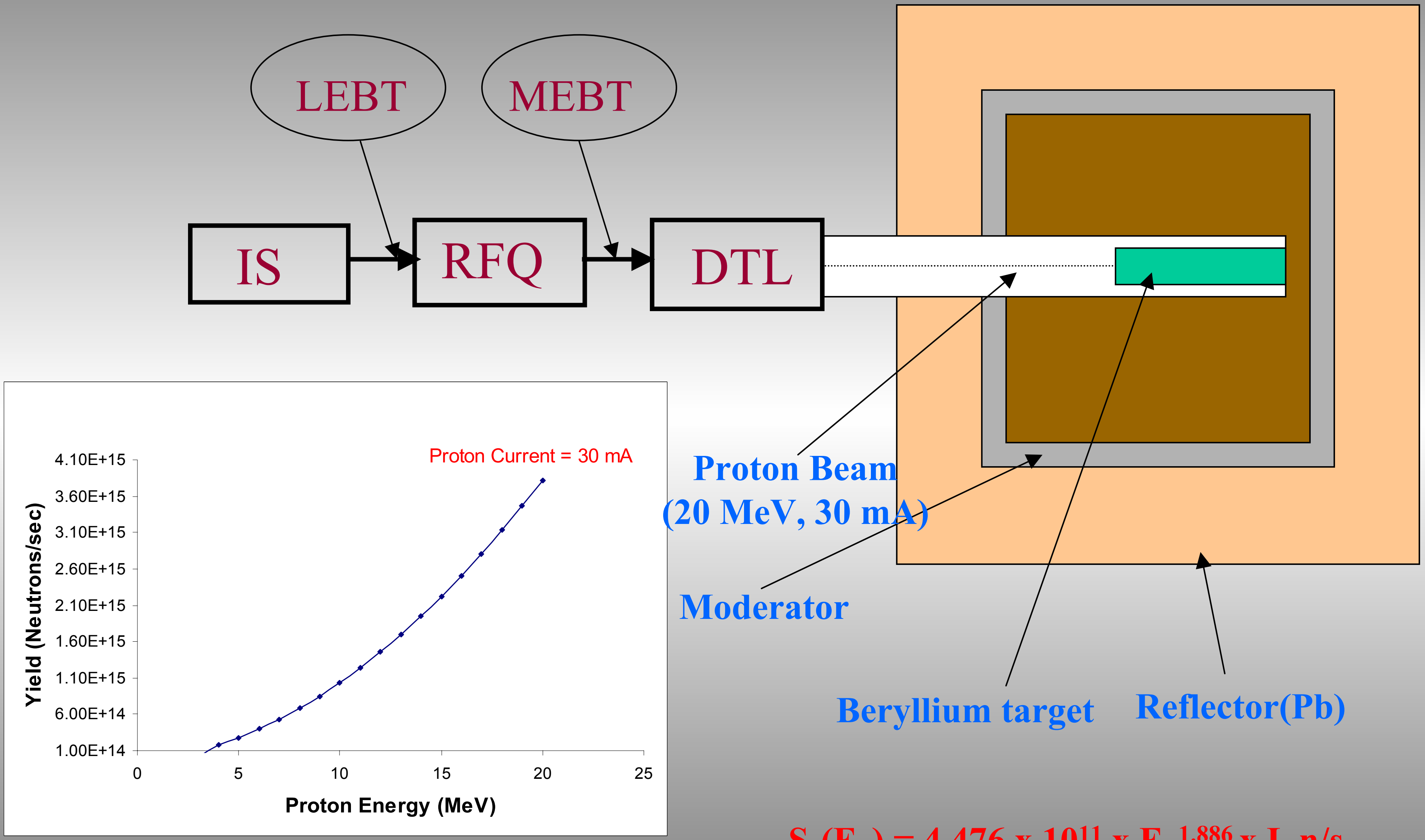



2.45 GHz
ECR Ion source
50 keV, 35mA.

352.21 MHz,
4-Vane type RFQ
3-MeV, 30 mA

352.21 MHz,
20 MeV, 30 mA
Alvarez type DTL

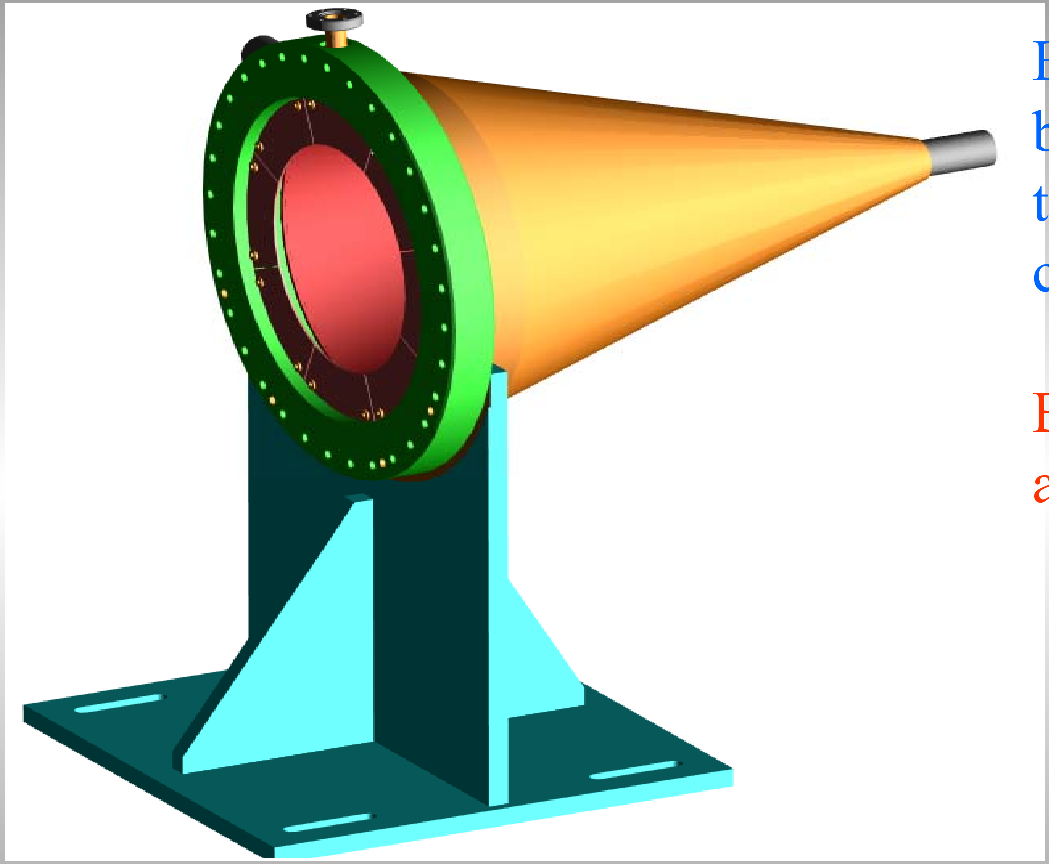
# High flux neutron Facility




Neutron Yield for Beryllium target

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

# Beam Stop



Conical target for beam dump.

Beam stop will be used to stop the beam of protons in order to test the quality of the beam during commissioning.

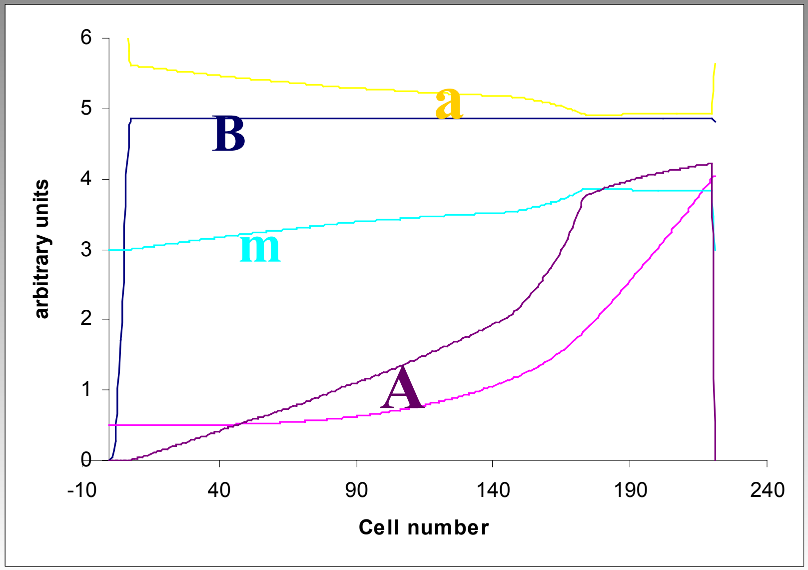
Beam will be under full power and continuous

- 20 MeV, 30 mA Beam
- Total power 600 kW

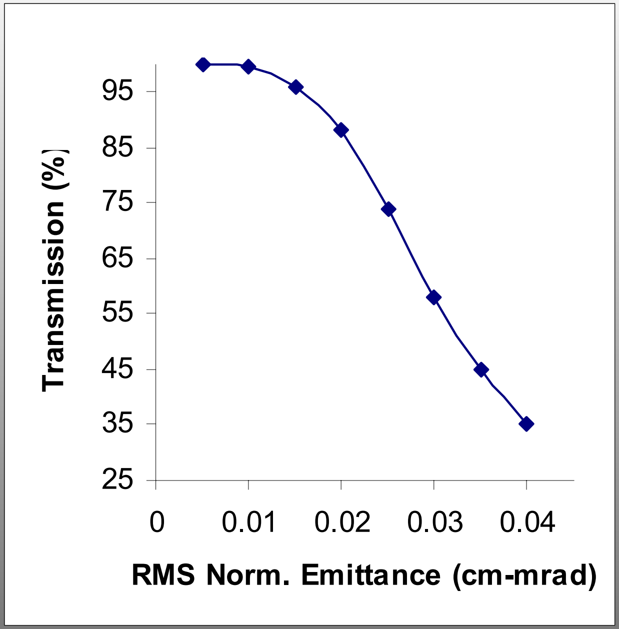
# 400 keV RFQ parameters

| 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 |

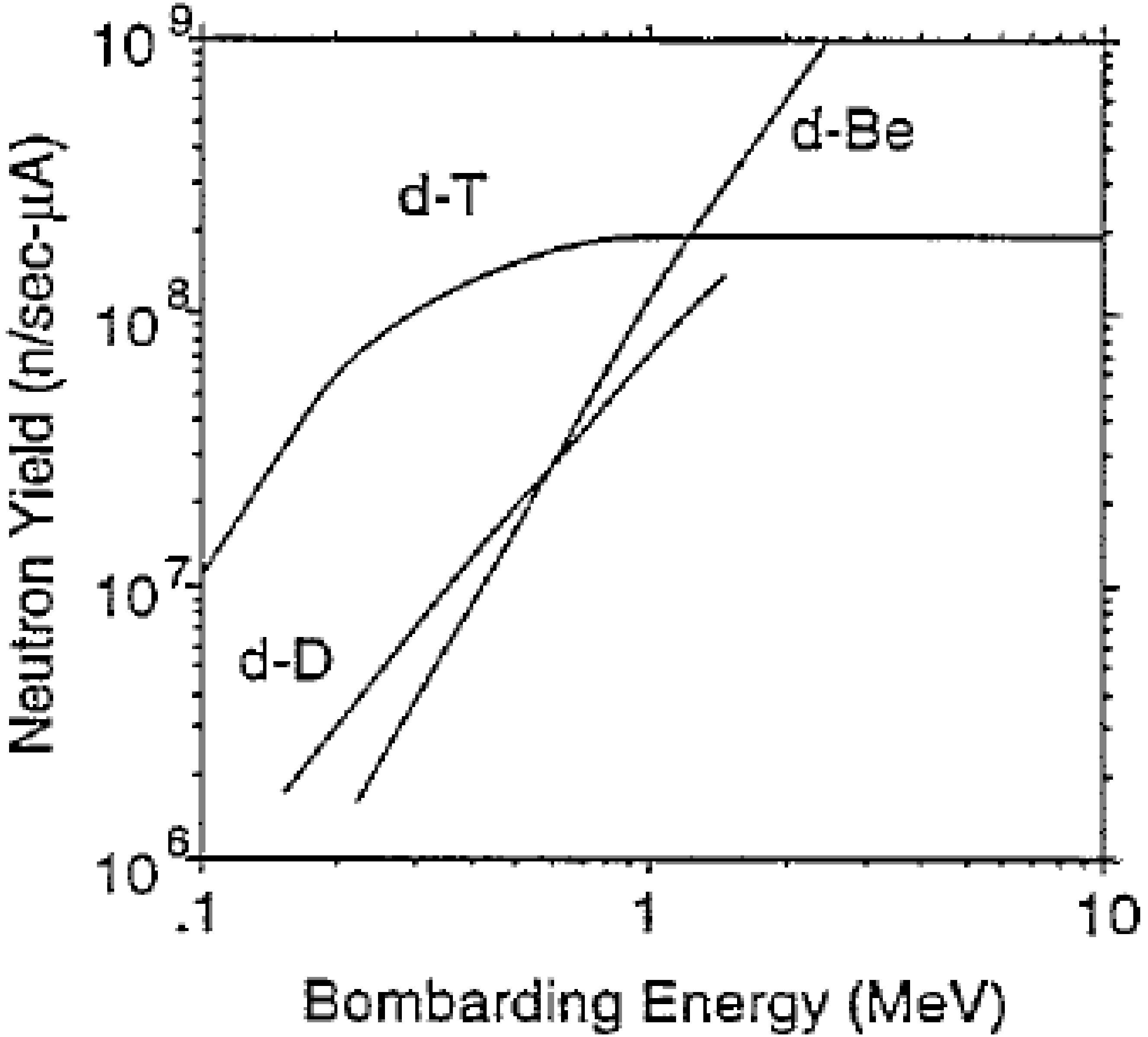
Transmission at the end of RFQ : 94.8%




Variation of RFQ parameters along the length.




If the emittance of the input beam to the RFQ is more than the designed value the transmission drops drastically.

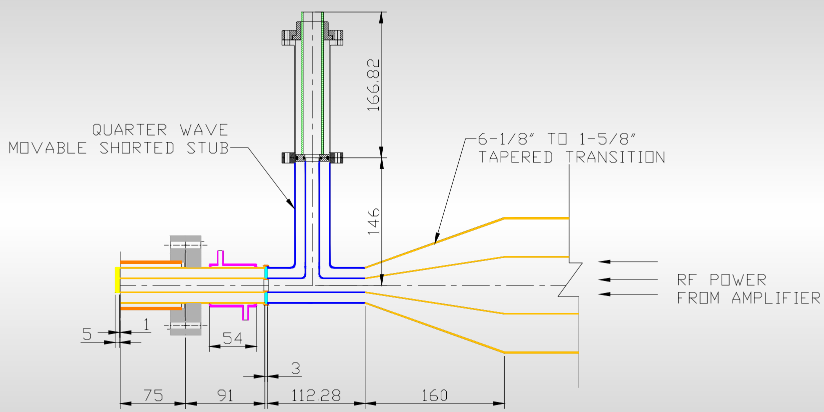


Neutron Yield (n/sec-µA)
10^9
10^8
10^7
10^6
d-Be
d-T
d-D
.1
1
10
Bombarding Energy (MeV)

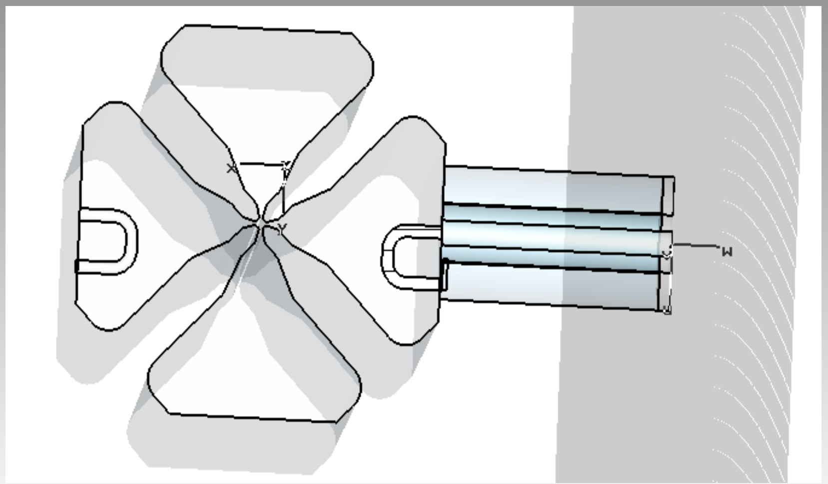
# RF Coupler design

## ◈ Coupler Dimensions:

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



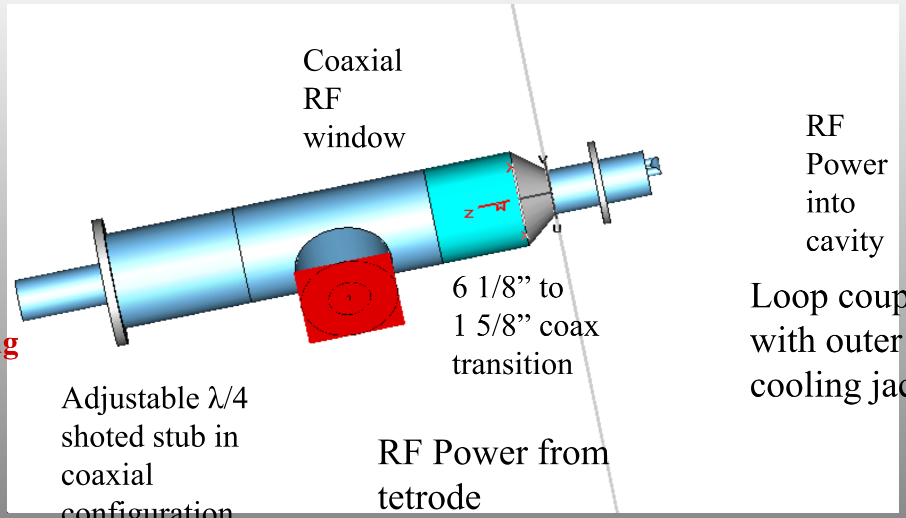

LAYOUT OF 50 kW RF COUPLER ASSEMBLY



**50 kW Coaxial Coupler specifications:**

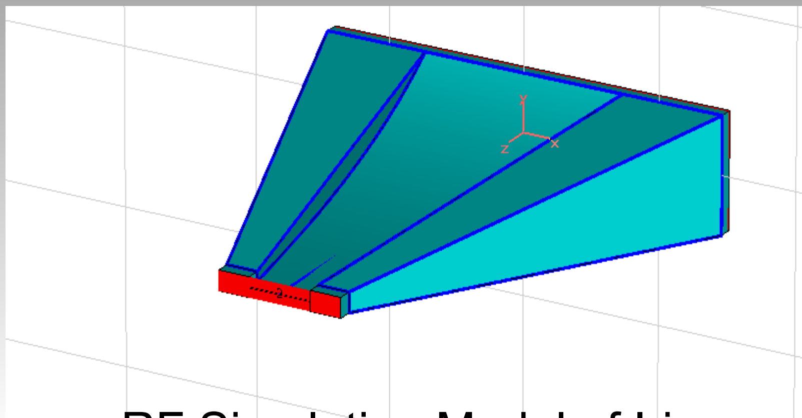
- Return Loss: Better than -25 db
- Coupling Coefficient: Variable from 1.2 to 0.7
- Max delta T on window: < 30°C
- Max. temperature on loop: 120°C
- Frequency Shift:  < 2 MHz

**Cooling water inlet**




Loop coupler with outer cooling jacket

# 250 kW, 352 MHz Iris Coupler Development



RF Simulation Model of Iris Coupler

- Ten No. Waveguide couplers required for 20 MeV LEHIPA
- WR2300 to Iris transition using double ridge waveguide
- Tapered transition with variable and constant ridge width has been studied.
- Thermo -Structural analysis and design in progress

| Length of iris (cm) | External Q |
|---|---|
| 8.15 | 30710.0 |
| 10.15 | 5844.0 |
| 10.72 | 4052.5 |
| 10.77 | 3895.1 |
| 12.15 | 1861.0 |
| 14.15 | 802.3 |
| 16.15 | 412.7 |

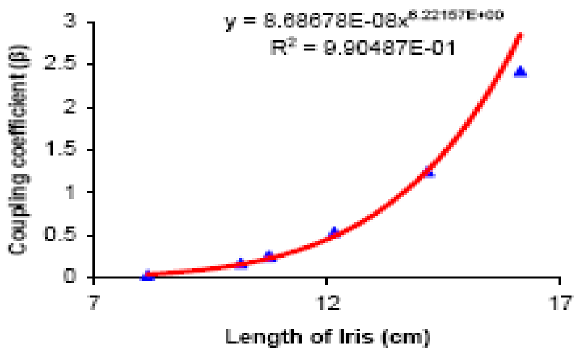
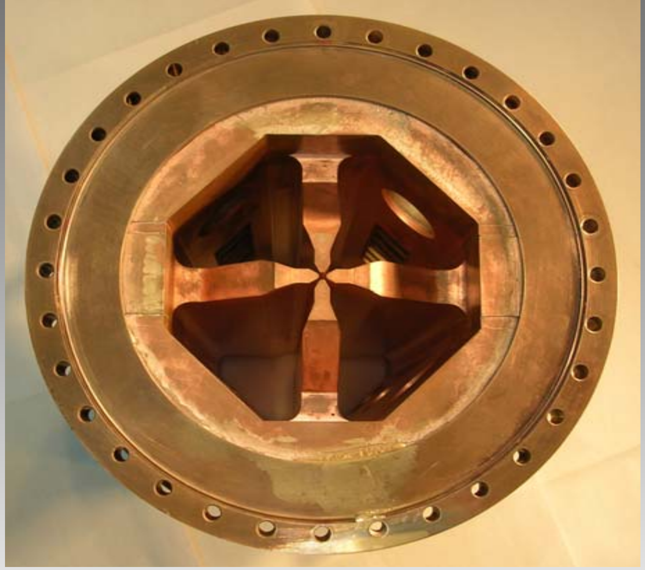
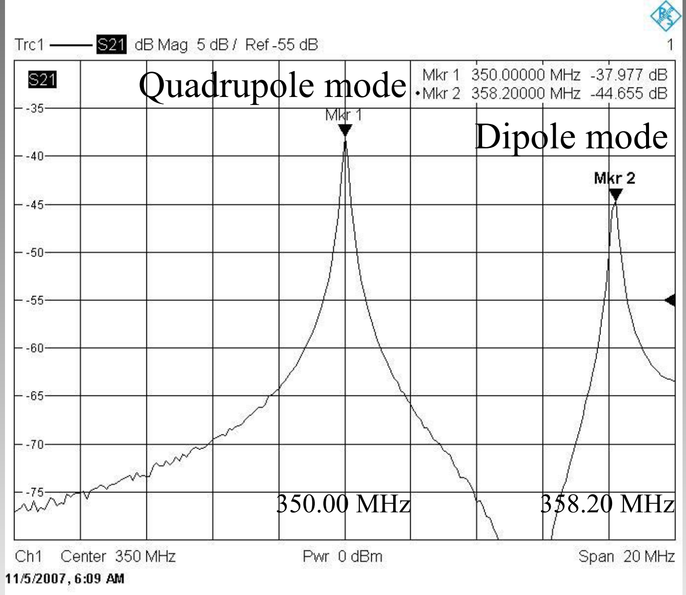
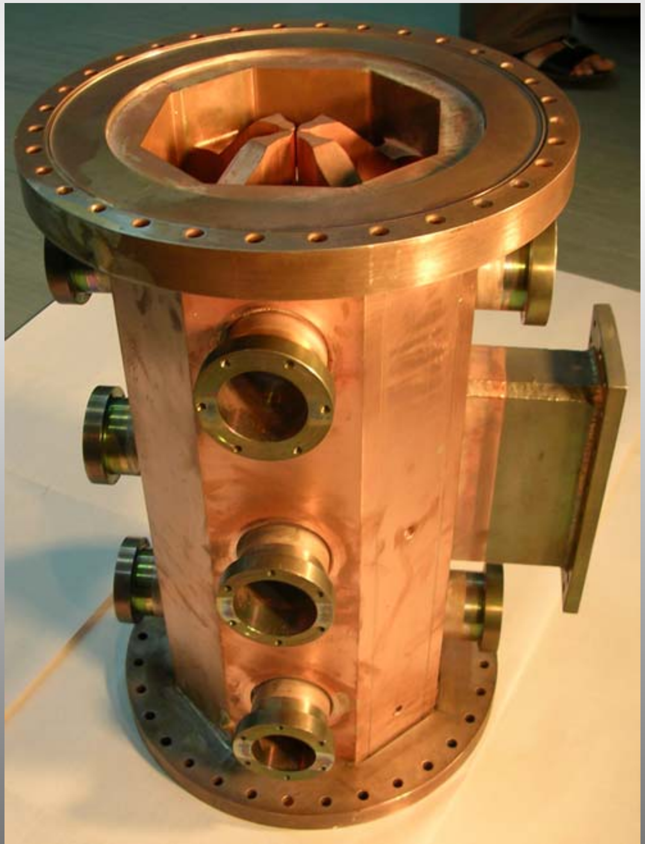


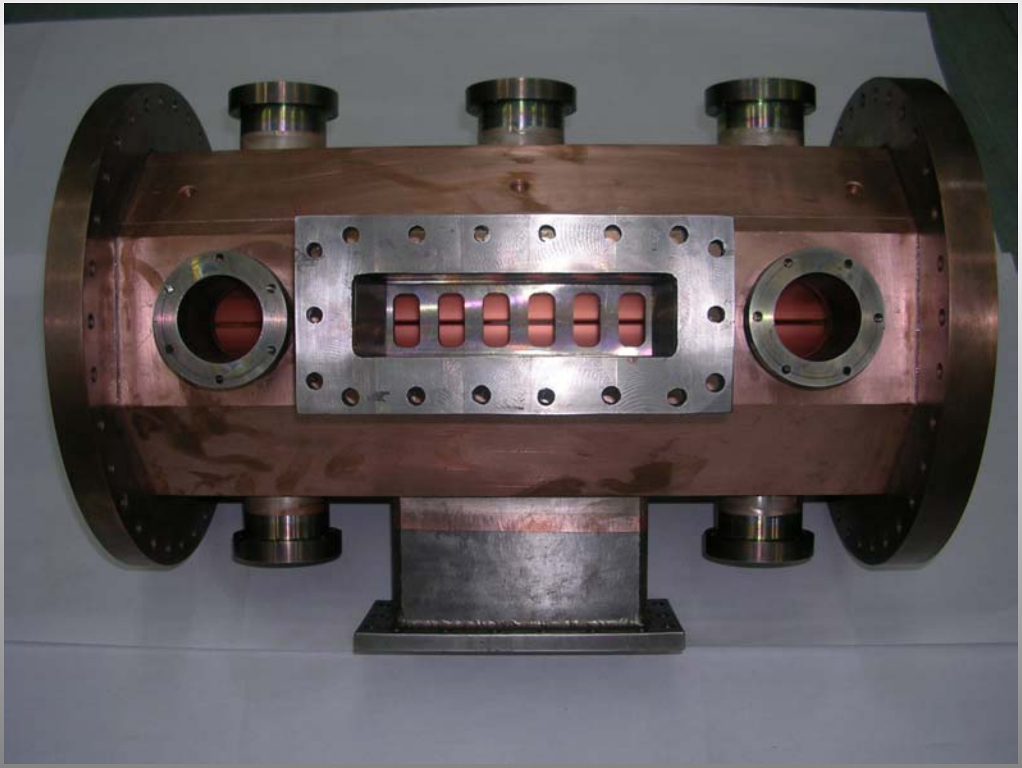

Fig 6. β vs length of the iris.

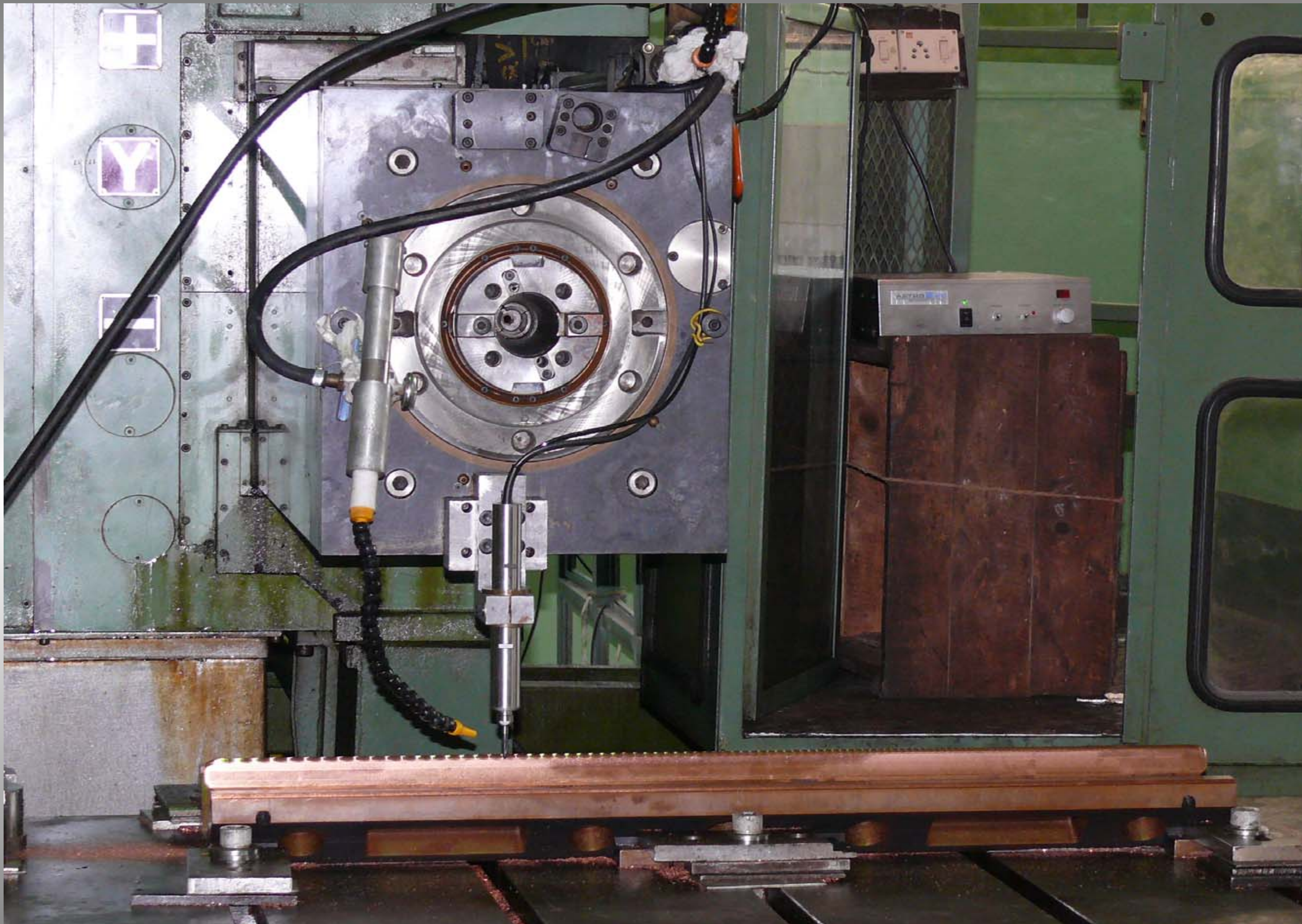
External Q and Coupling Coefficient variation with Iris length



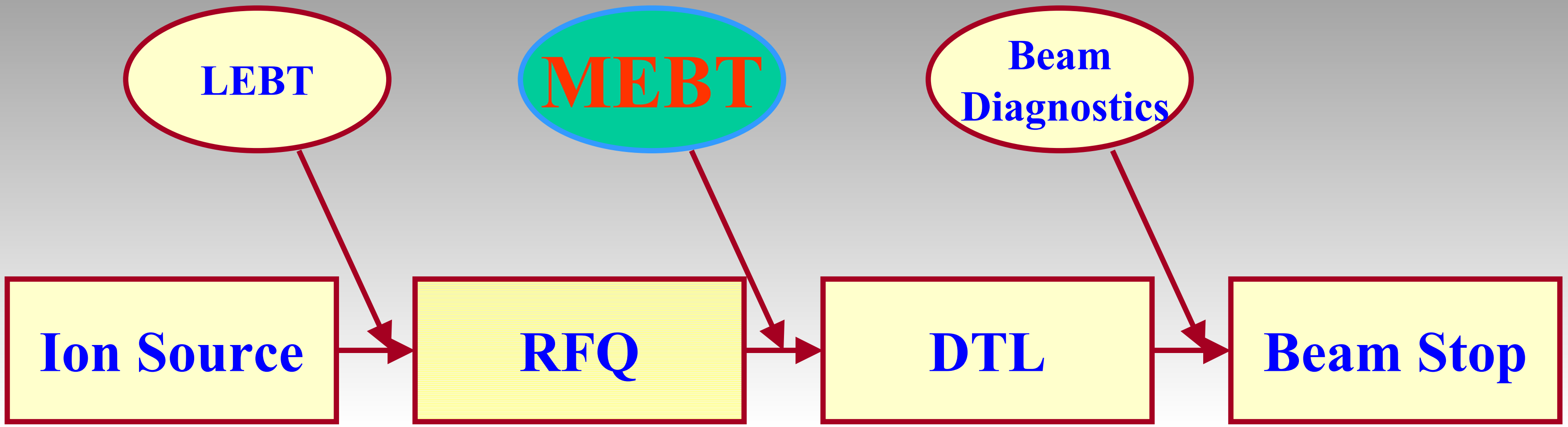

Trc1 S21 dB Mag 5 dB / Ref -55 dB
1
S21
Quadrupole mode
Mkr 1 350.00000 MHz -37.977 dB
•Mkr 2 358.20000 MHz -44.655 dB
Mkr 1
Dipole mode
Mkr 2
-35
-40
-45
-50
-55
-60
-65
-70
-75
350.00 MHz
358.20 MHz
Ch1 Center 350 MHz
Pwr 0 dBm
Span 20 MHz
11/5/2007, 6:09 AM






Y

# 20 MeV Linac: Transport Line MEBT



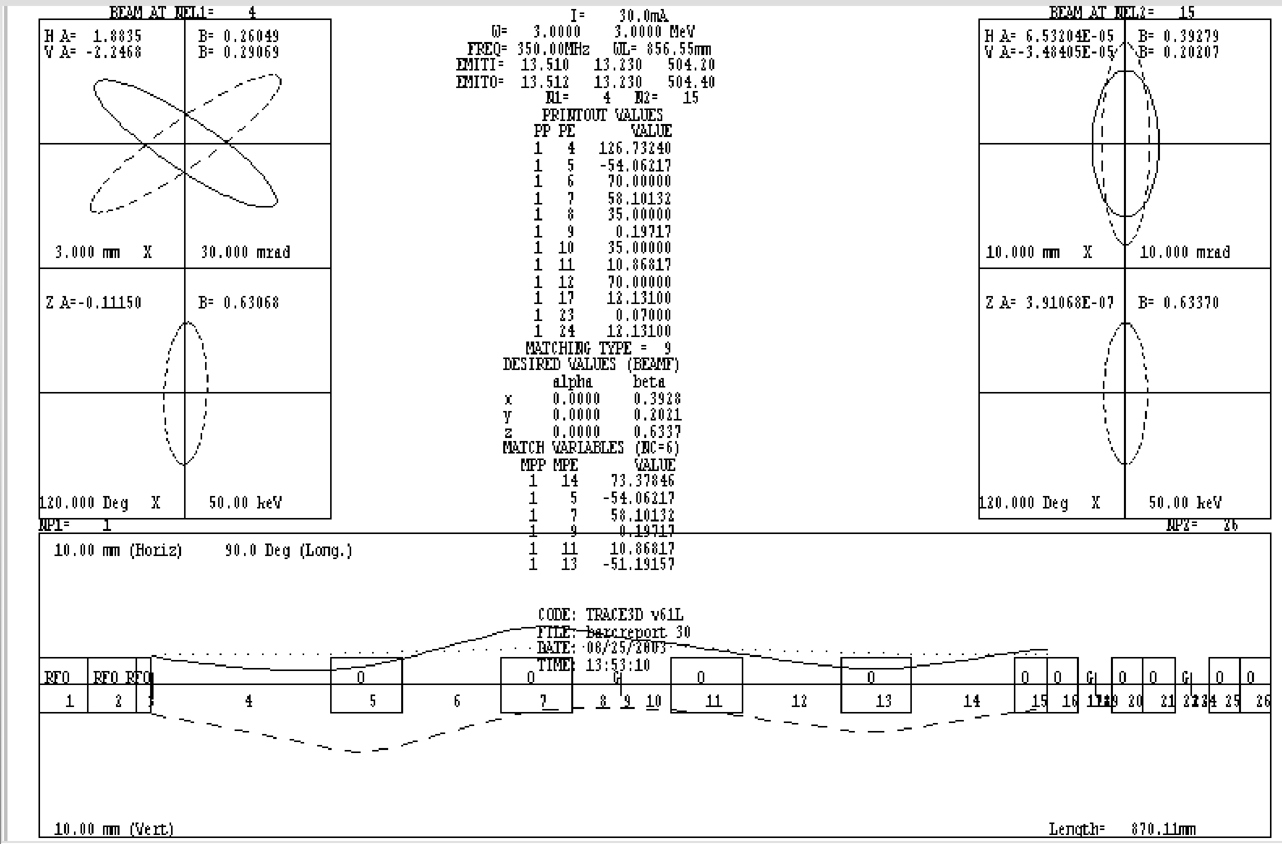

2.45 GHz
ECR Ion source
50 keV, 35mA.

352.21 MHz,
4-Vane type RFQ
3-MeV, 30 mA

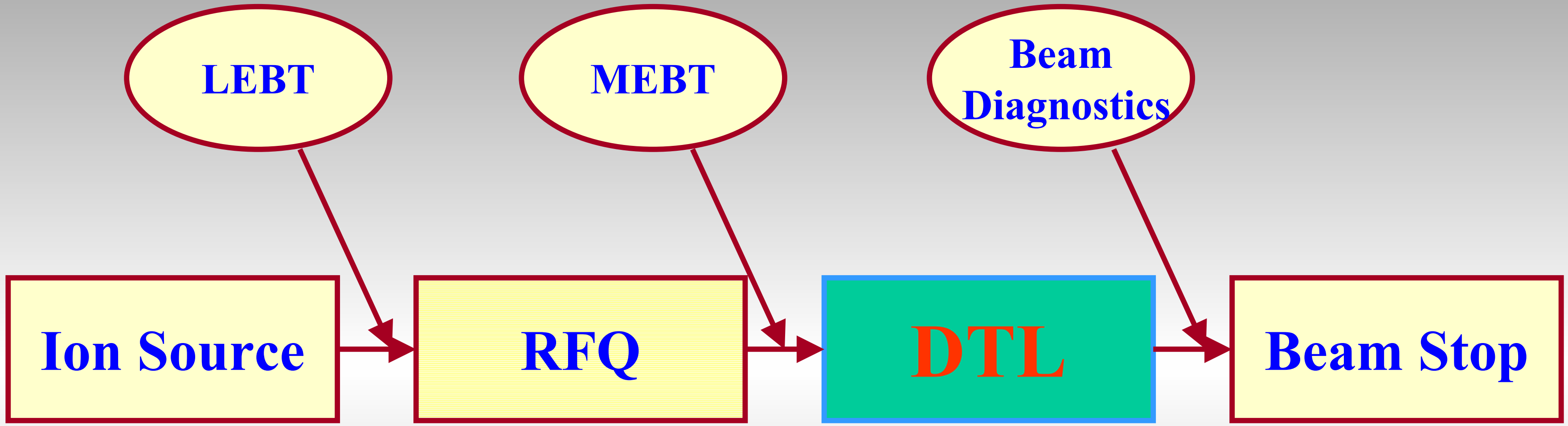
352.210 MHz,
20 MeV, 30 mA
Alvarez type DTL

# Medium Energy Beam Transport Line

- Beam from the ion source is not round and is pulsed.
- So now four transverse parameters of the beam have to be matched to the input of the DTL.
- The transverse matching is achieved by using 4 quadrupoles.
- RF buncher is used for longitudinal matching.



# 20 MeV Linac: Accelerating Structure DTL



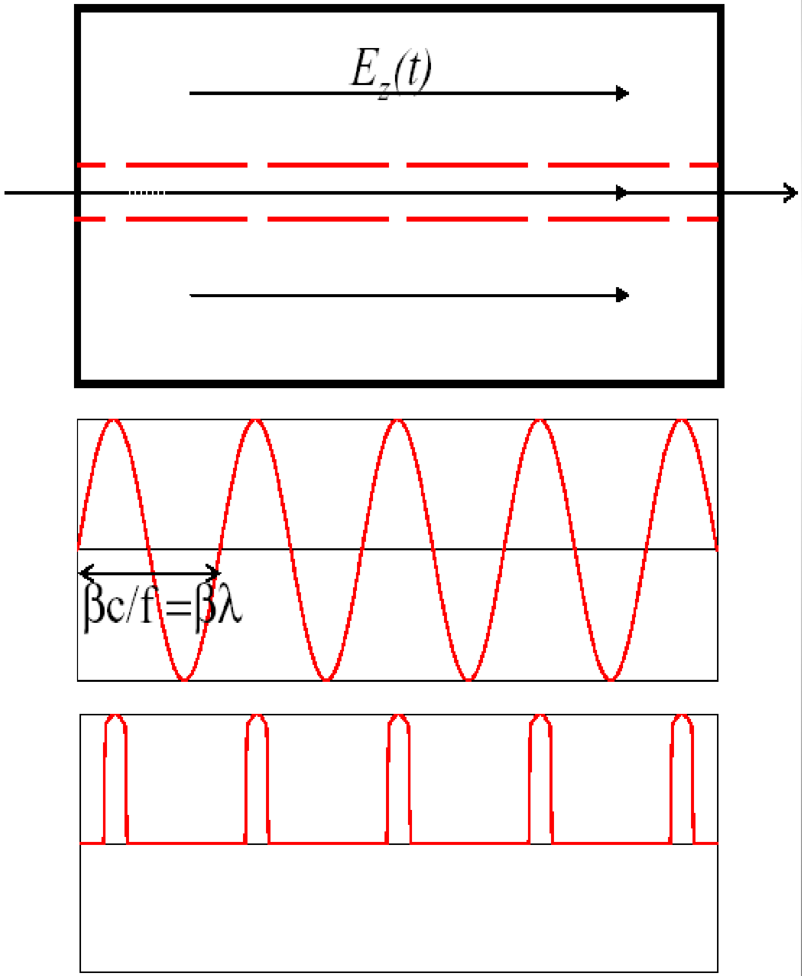

2.45 GHz
ECR Ion source
50 keV, 35mA.

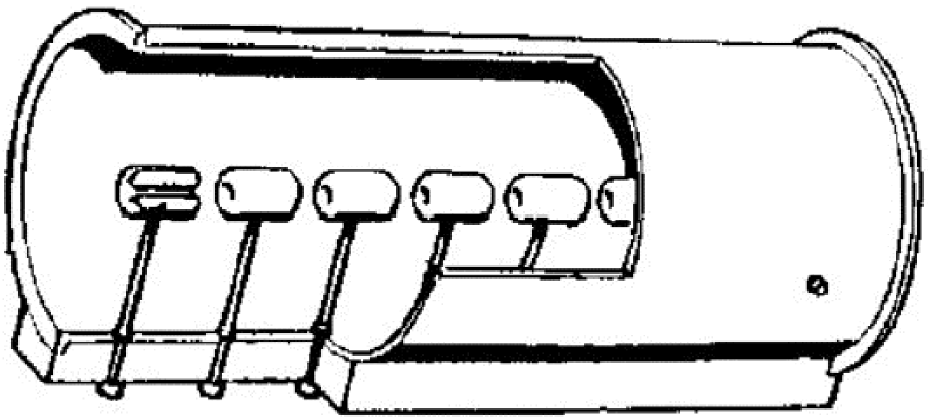
350 MHz,
4-Vane type RFQ
3-MeV, 30 mA

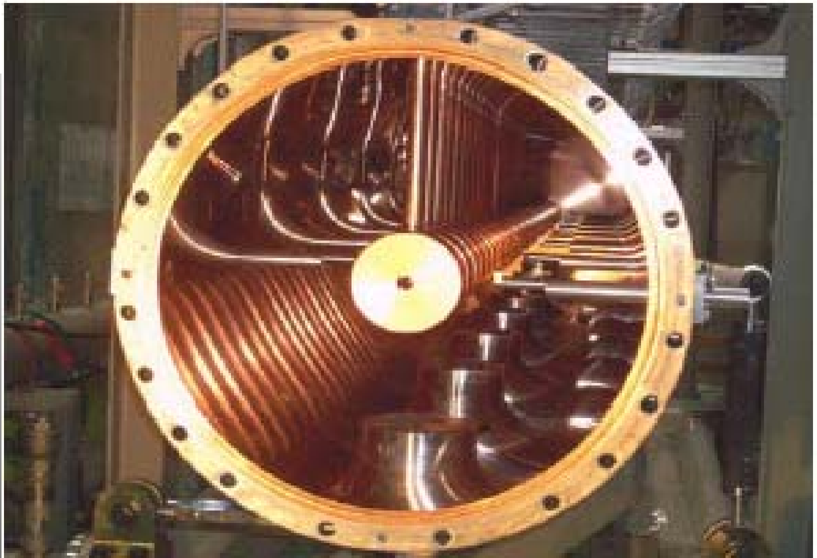
350 MHz,
20 MeV, 30 mA
Alvarez type DTL

# The Drift Tube Linac

- The DTL tank is a resonant cavity excited in the $TM_{010}$ mode.
- It consists of drift tubes connected to tank by stems separated by gaps.
- Quadrupoles are mounted in drift tubes for focusing.

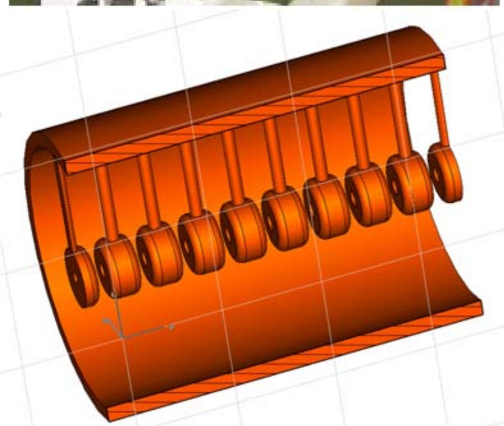


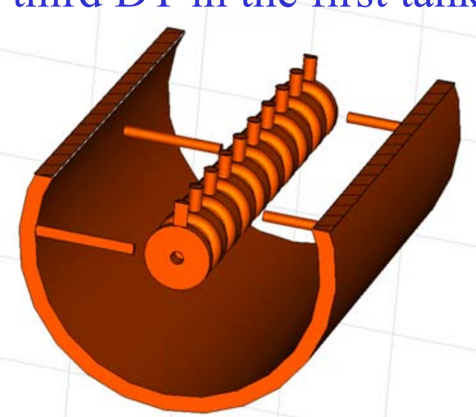


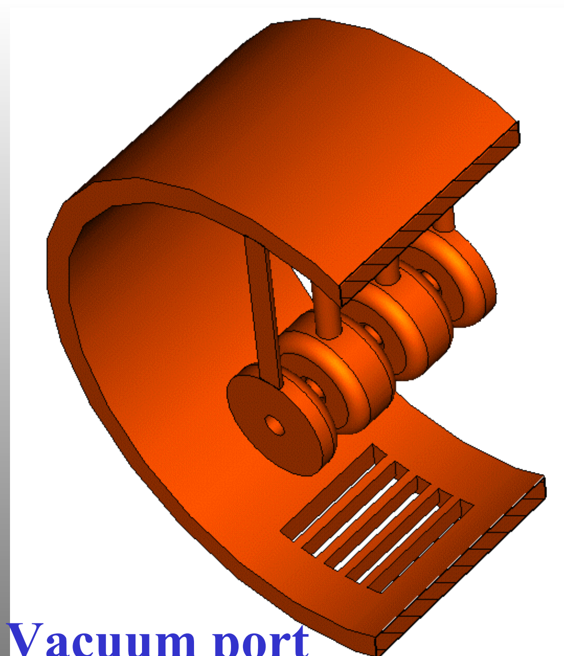
# DTL

Tuners



Post Couplers placed every third DT in the first tank





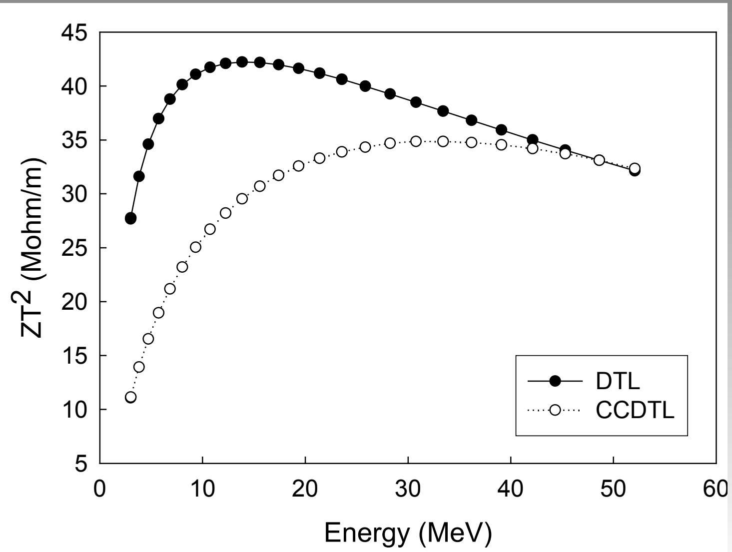
Vacuum port

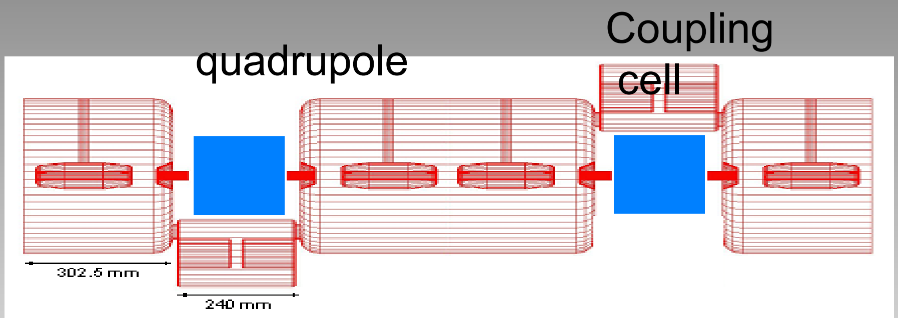
## Cavity Parameters

| | |
|---|---|
| Frequency (MHz) | 352.21 |
| Cavity Diameter (cm) | 52 |
| Drift tube diameter (cm) | 12 |
| Bore radius (cm) | 1.1 |
| Face Angle (deg) | 0 |
| Corner radius (cm) | 1.5 |
| Inner corner rad. (cm) | 0.5 |
| Outer corner rad. (cm) | 0.5 |

- 5 rectangular slots per vacuum port
- Slots orientation along the direction of surface current
- Port Conductance: 1400 l/s
- No. of vacuum ports in first tank: 2
- Frequency detuning due to the vacuum ports is negligible (13.39 kHz with both ports)

# Comparison of DTL and CCDTL

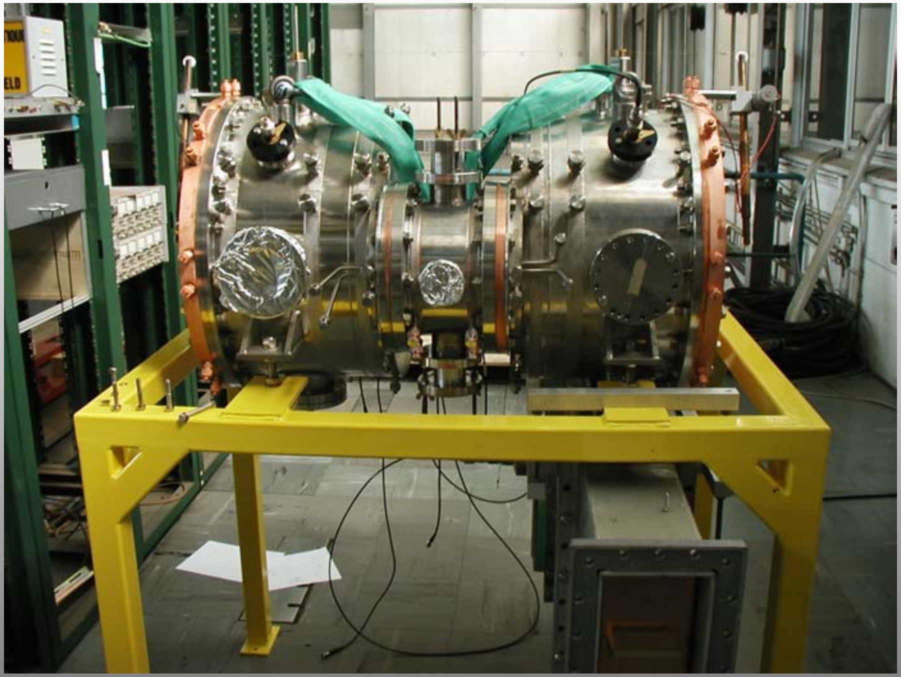



**40-100 MeV**

| **Parameter** | **DTL** | **CCDTL** |
|---|---|---|
| Energy Range (MeV) | 3-40 | 40-100.2 |
| Frequency (MHz) | 352.21 | 704.42 |
| Current (mA) | 29.3 | 29.3 |
| Quadrupole Gradient (T/m) | 43 | 62.4-19.5 |
| Eff. Length of Quad. (cm) | 4.72 | 8.0 |
| No. of Quadrupoles | 155 | 186 |
| Avg. Acc. Gradient (MV/m) | 2.5 | 1.37 |
| Aperture Radius (cm) | 1.0 | 1.2 |
| Total Length (m) | 24 | 70 |

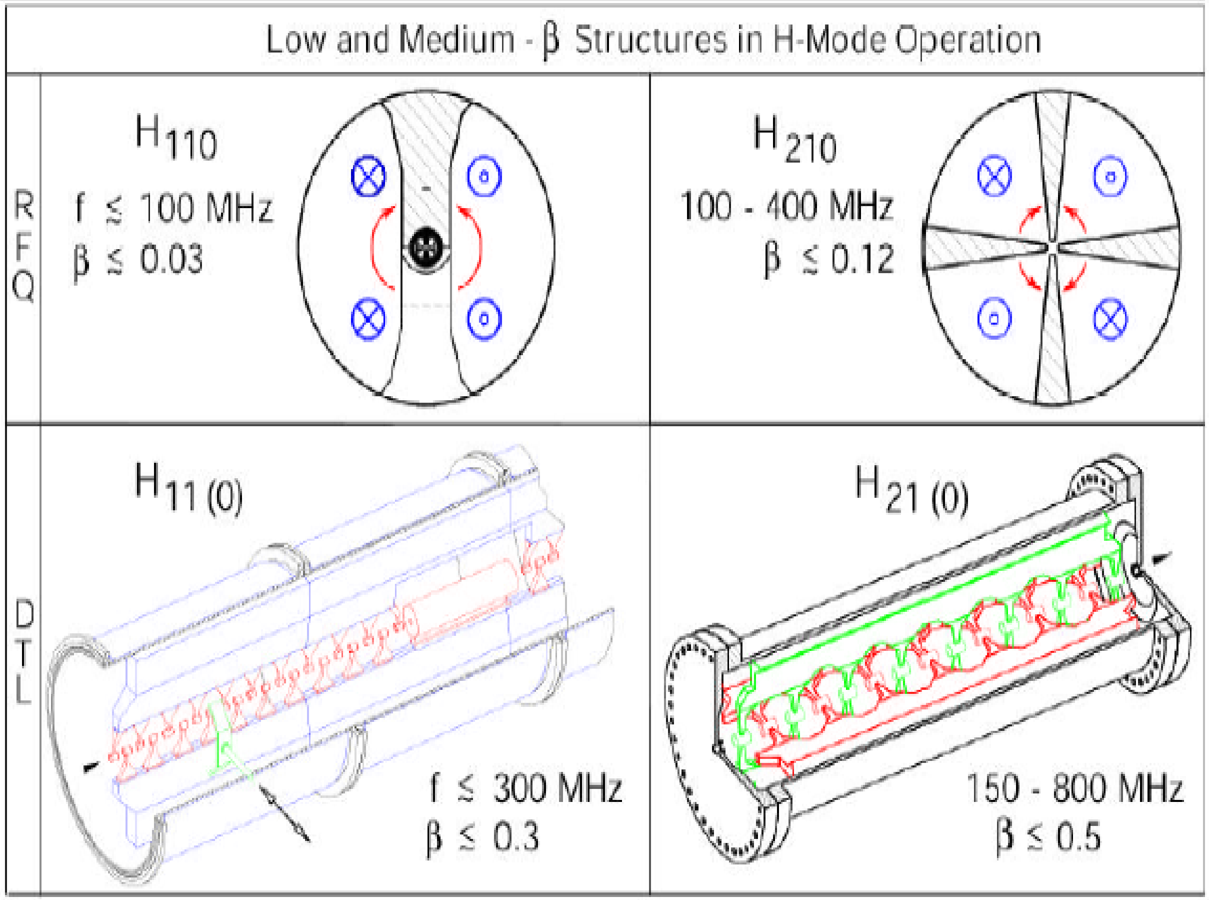
**CCDTL at CERN**



# The Family of H-Mode Resonators

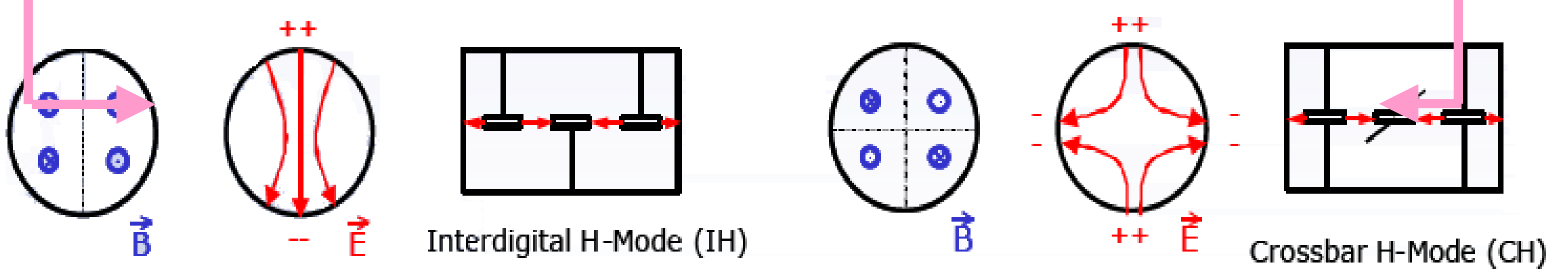
IH-RFQ

4-vane RFQ

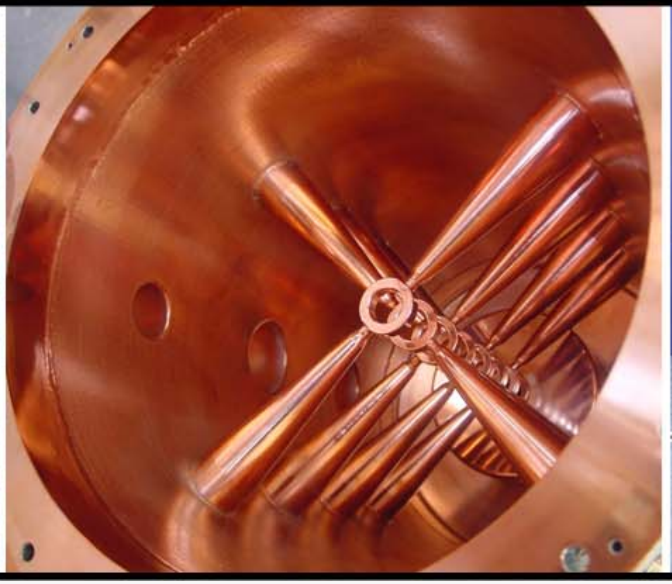
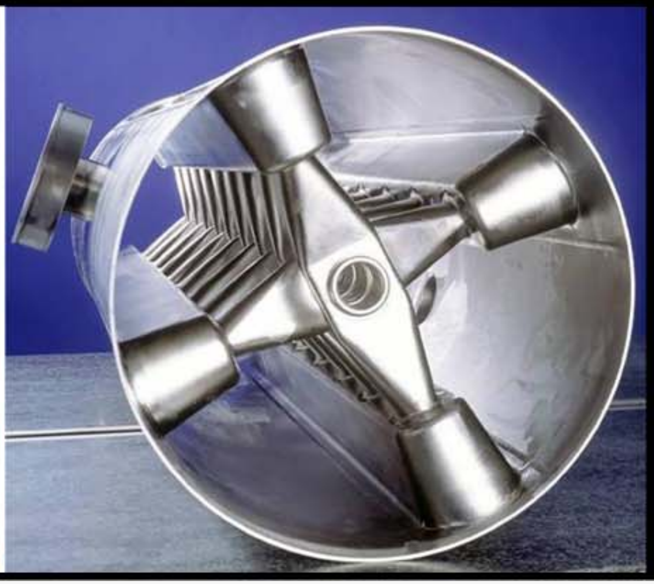



IH-Structure

CH-Structure



# H-type DTL's

r.t. IH-DTL
W < 30 MeV
30-250 MHz

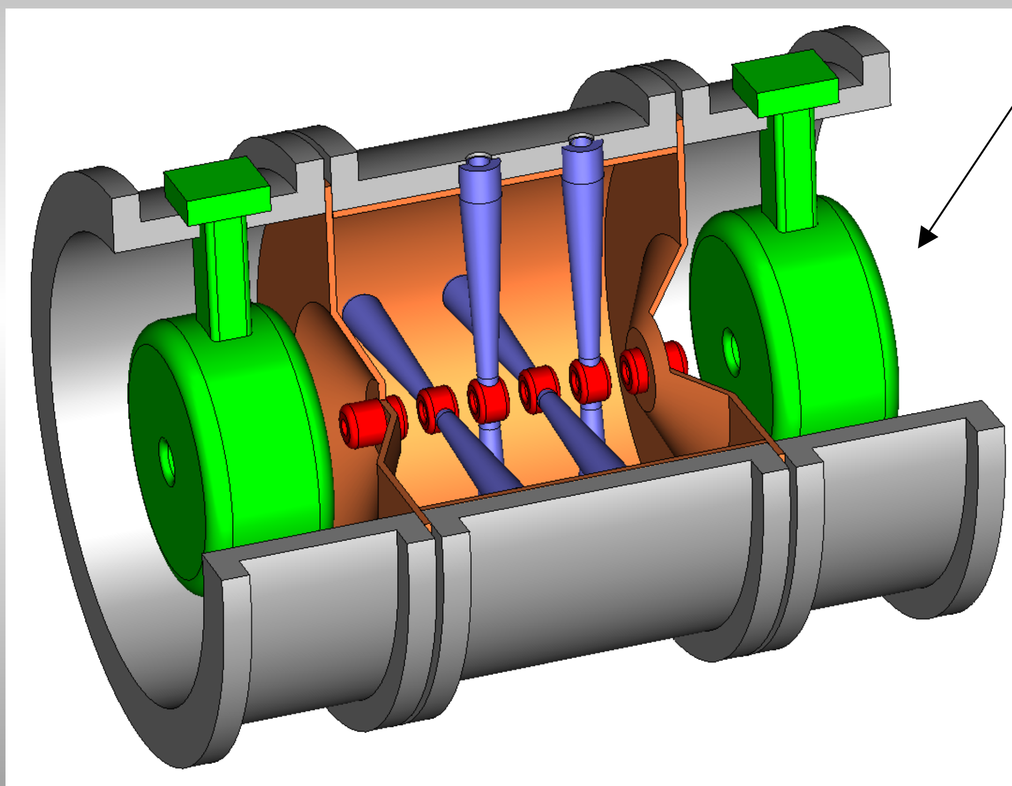
r.t. CH-DTL
W < 150 MeV
150-700 MHz

s.c. CH-DTL
W < 150 MeV
150-700 MHz
bulk niobium

copper plated steel

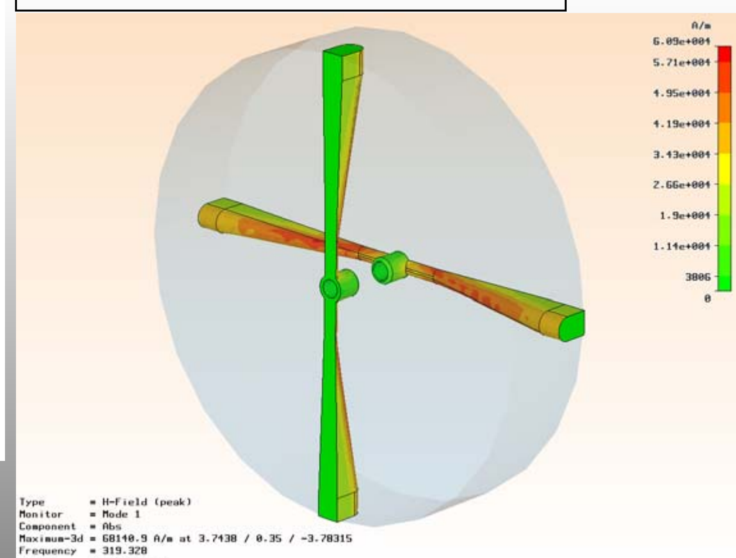
# RT SR section

Solution is Room Temperature Spoke Resonator (aka Cross-bar H-type resonators) section from 3 MeV to 15 MeV .



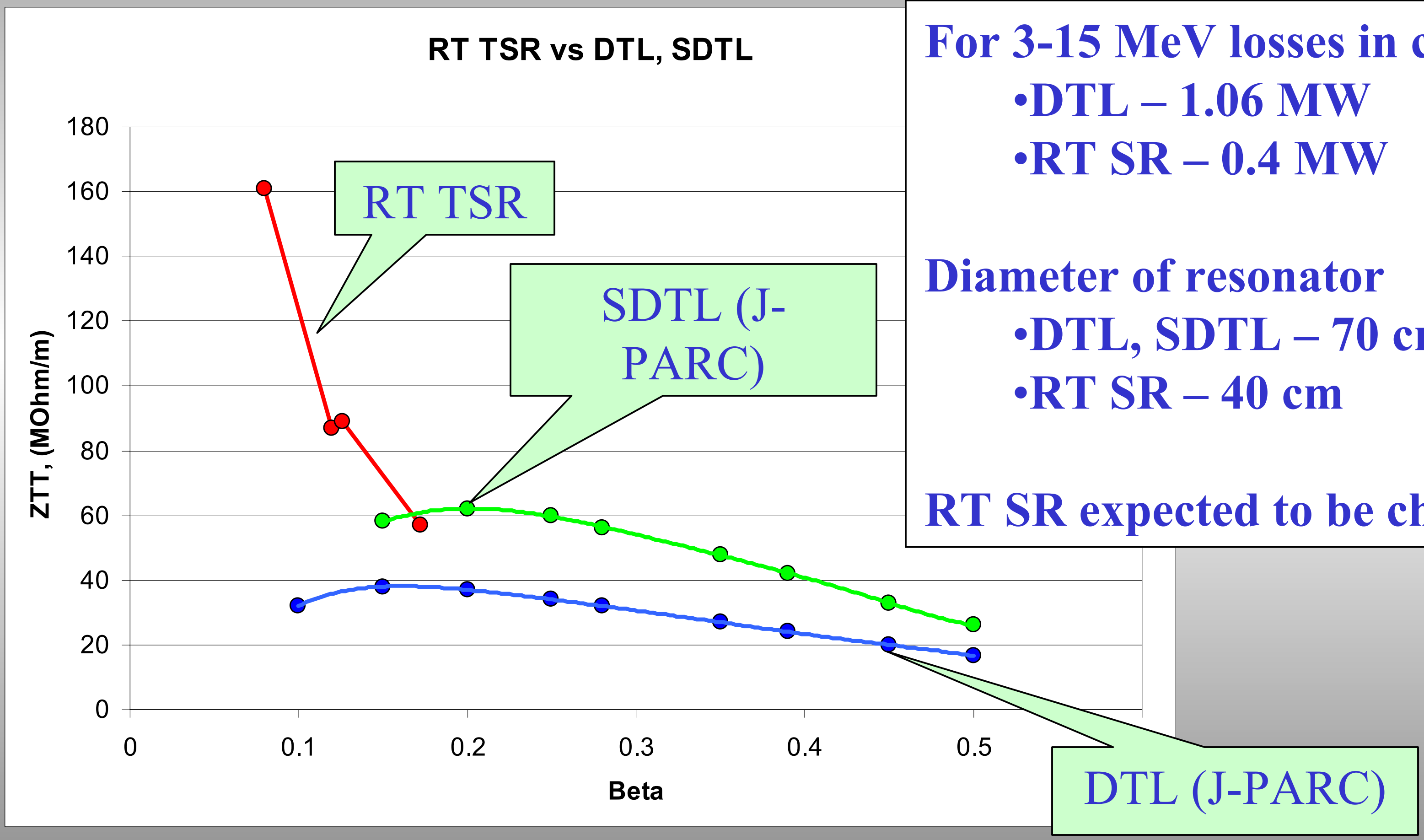
Solenoid in individual cryostat

Shape Optimization



# RT TSR section

The main advantage of RT SR is its high shunt




**For 3-15 MeV losses in copper:**

- **DTL – 1.06 MW**
- **RT SR – 0.4 MW**

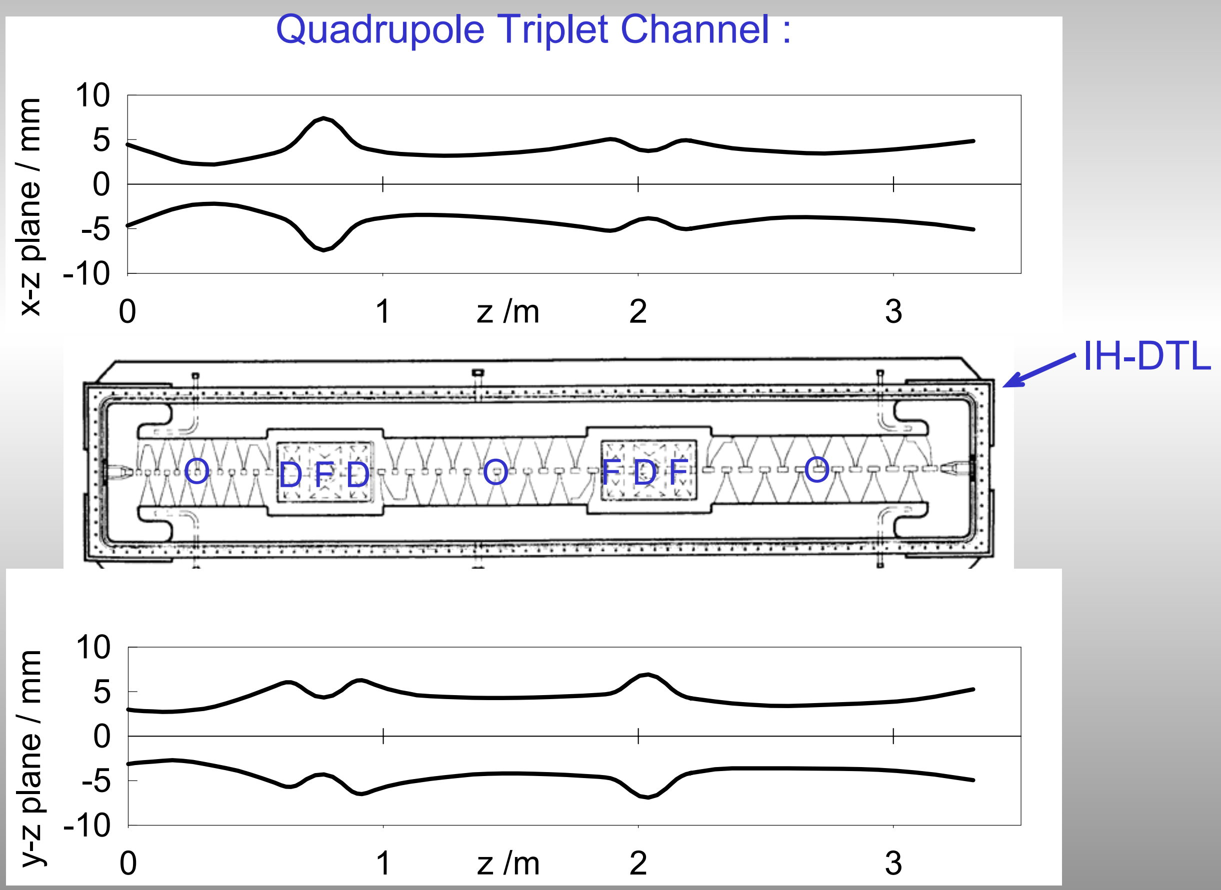
**Diameter of resonator**

- **DTL, SDTL – 70 cm**
- **RT SR – 40 cm**

**RT SR expected to be cheaper**

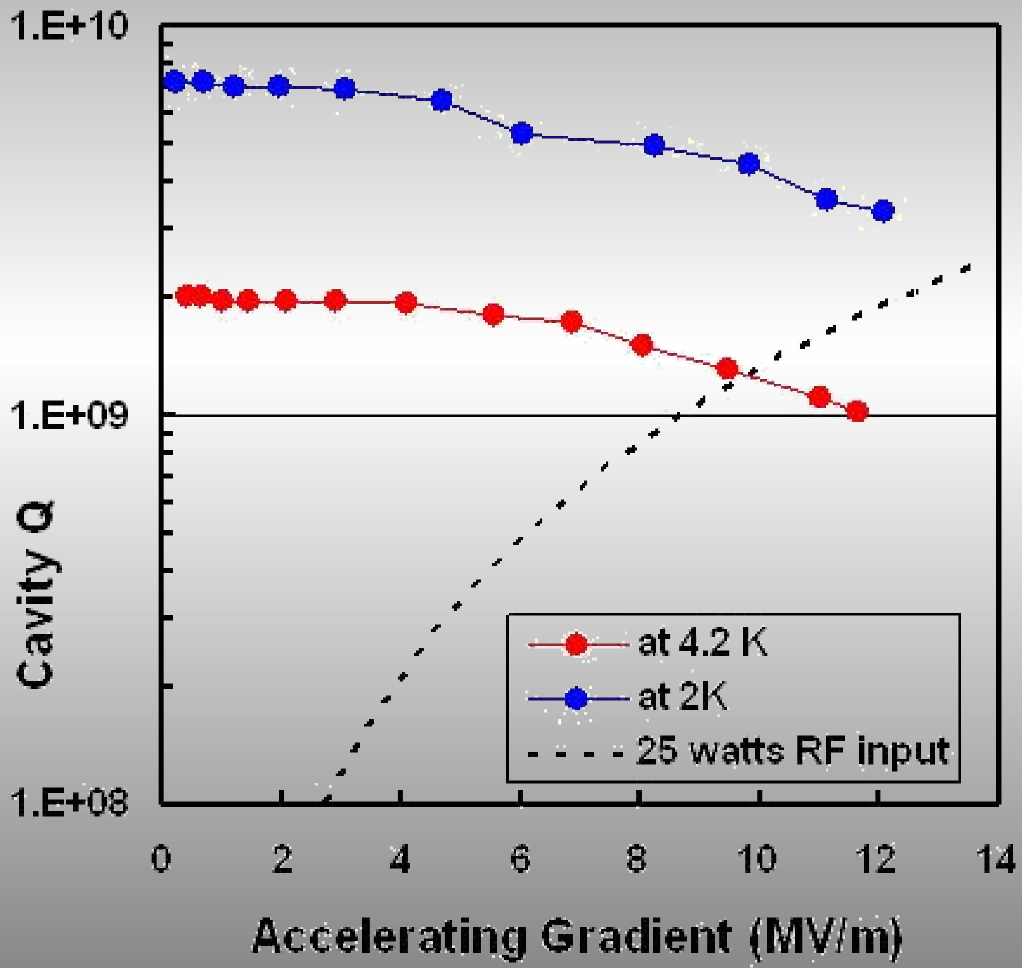
# H-type DTL's

**KONUS (Combined 0° Structure) beam dynamics**
**Example: GSI HLI IH cavity**

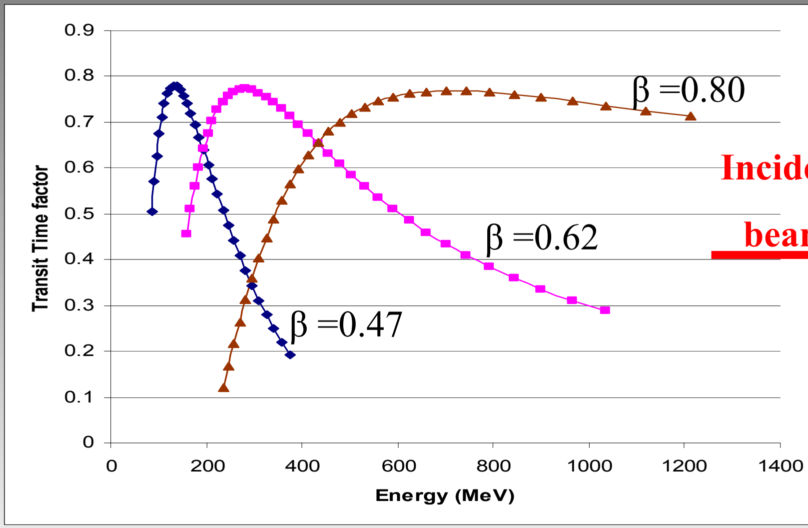


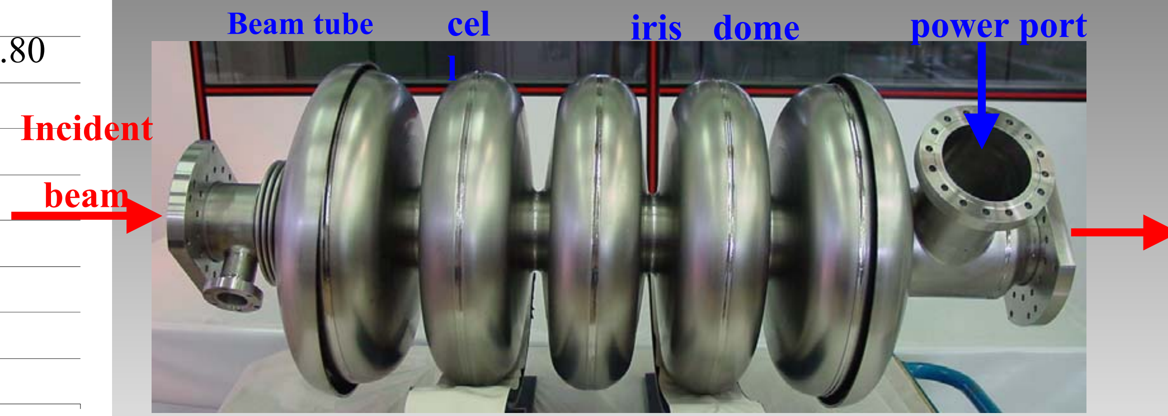
# SC Spoke Resonator

**Shepard, Kelly, Fuerst, presented at PAC 2003, SRF 2003**



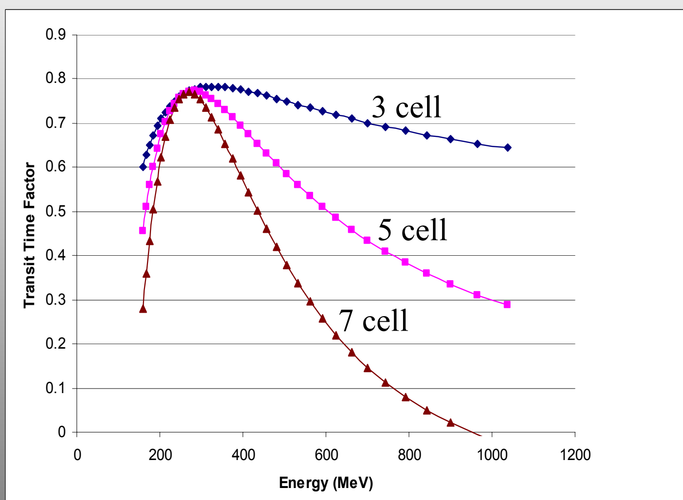

**The cavity can operate cw at gradients up to 12 MV/m, producing more than 4.5 MV of accelerating potential**



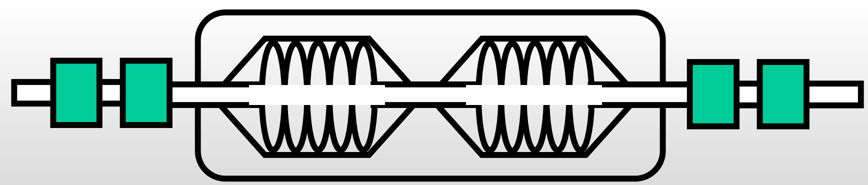




*Superconducting cavity (IPN Orsay) – 5 cells, 700 MHz, β=0,65*

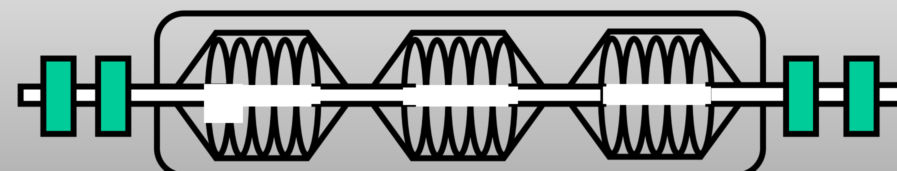
In order to efficiently design a linac it is necessary to divide it in sections, each using a different cavity geometry in an energy range.



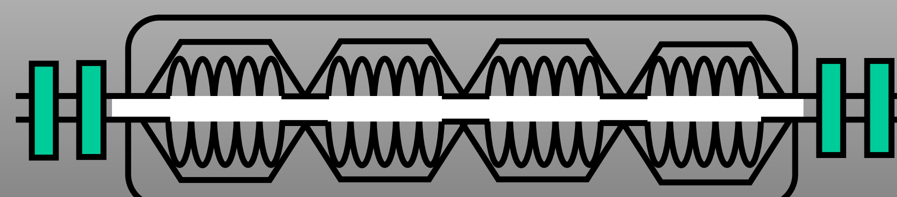

**$\beta_G$= 0.47**



**$\beta_G$= 0.62**

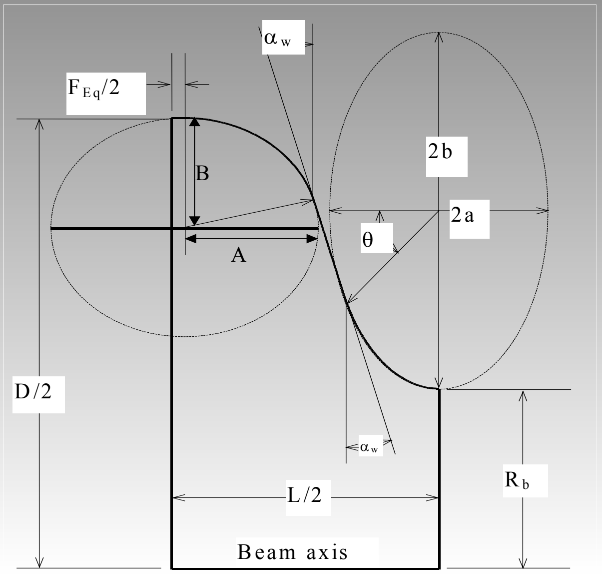


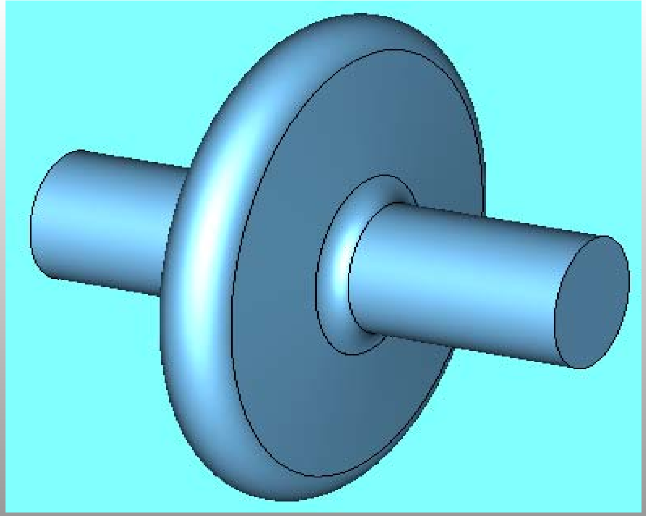
**$\beta_G$= 0.80**



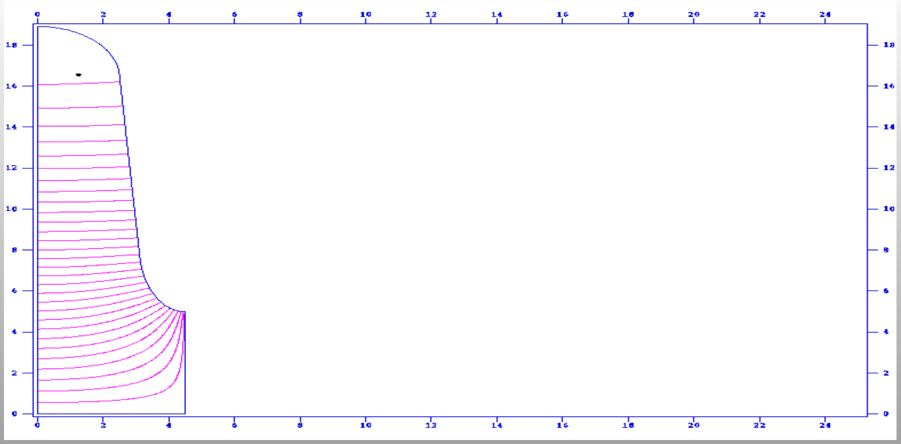
# Design of Superconducting Cavity

| Parameters | $\beta_G$=0.47 | $\beta_G$ = 0.62 | $\beta_G$ = 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 $\alpha_w$(deg) | 5 | 5 | 7 |
| Iris a/b | 1.2 | 1 | 0.5 |
| Bore Radius (cm) | 4 | 4 | 4 |



3-D view of the cavity at 700 MHz



SUPERFISH output plot showing electric field lines for single cell cavity without beam tube

# 100 MeV – 1 GeV SC Linac

## (Initial design with 5 MV/m gradient)

| Parameter | $\beta_G = 0.47$ | $\beta_G = 0.62$ | $\beta_G = 0.80$ |
|---|---|---|---|
| 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 ( 762 m) | 105.04 | 243.2 | 413.46 |
| Norm. Trans. Emitt. ($\pi$cm-mrad) $\varepsilon_x$<br>$\varepsilon_y$ | 0.024-0.025<br>0.024-0.025 | 0.025-0.029<br>0.025-0.028 | 0.029-0.030<br>0.028-0.027 |
| Norm. Long. Emitt. (MeV-deg) | 0.327-0.444 | 0.444-0.482 | 0.482-0.499 |

# Main parameters of the HINS (8GeV $H^-$ linac)

| Parameter | RFQ | RT Triple Spoke | Single-spoke | Double-spoke | Triple spoke | TESLA1 | TESLA2 |
|---|---|---|---|---|---|---|---|
| Frequency, MHz | 325 | 325 | 325 | 325 | 325 | 1300 | 1300 |
| Beta geometrical | | 0.08🕑0.18 | 0.21 | 0.4 | 0.61 | 0.81 | 1.0 |
| Number of accelerating gaps | | 4 | 2 | 3 | 4 | 8 | 9 |
| $E_{peak}$, MV/m | | TBD | 32 | 32 | 32 | 45 | 45 |
| $E_{acc}$, MV/m | | 2.3🕑3.7 | 10.67 | 10.67 | 10.67 | 20.5 | 22.5 |
| Cavity effective length, cm | | 15🕑32 | 13 | 36.9 | 85.8 | 74.7 | 103.8 |
| Number of resonators | | 21 | 16 | 28 | 42 | 56 | 322 |
| Synchronous phase, deg | | -40 (first 6), -40🕑-30 ramp | -30 | -30 | -30🕑-20 ramp | -30 | -16 |
| Input energy, MeV | 0.06 | 3.0 | 15.6 | 33 | 110 | 400 | 1120 |
| Output energy, MeV | 3.0 | 15.6 | 33 | 110 | 402 | 1120 | 8021 |
| Length of the section, m | 3.8 | 10.4 | 12.5 | 17.2 | 64 | 77 | 554 |
| Maximum coupler power, for 26 mA $H^-$ beam, kW | | 54 | (25.5) TBD | (102) TBD | (238) TBD | 398 | 607 |

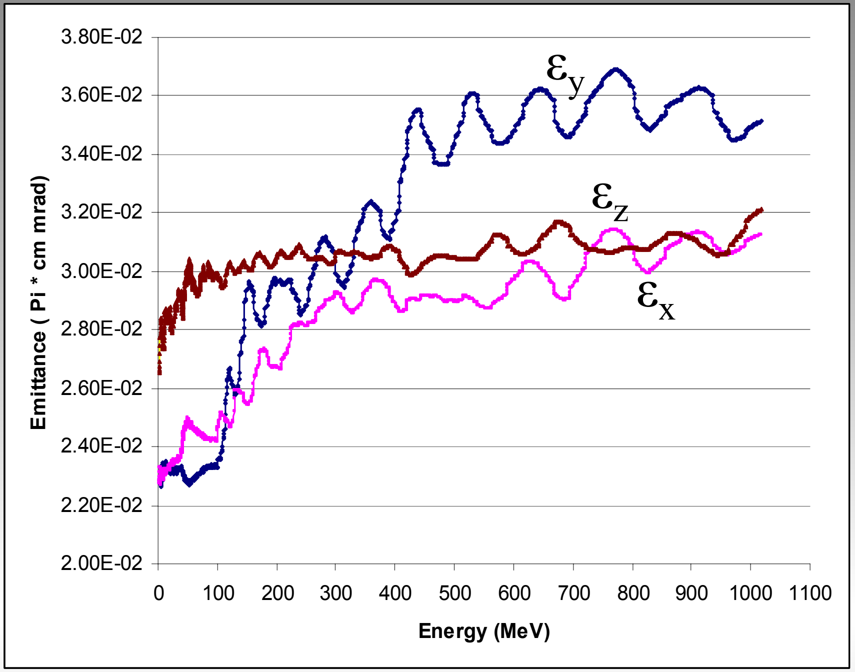
Global Accelerator Parameters for 500 GeV cms.

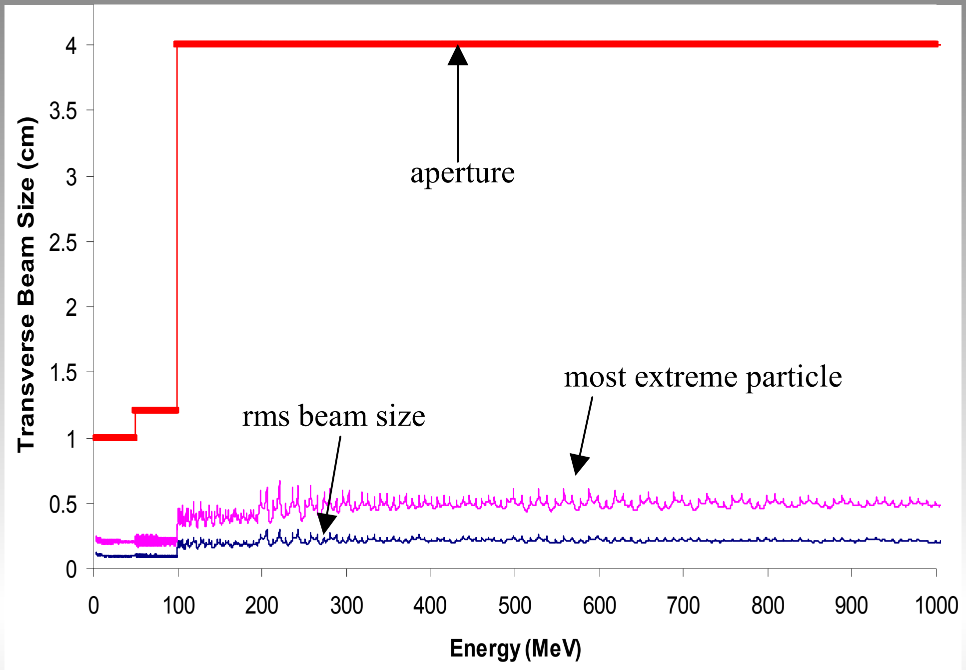
| Parameter | Value | Units |
|---|---|---|
| Center-of-mass energy | 500 | GeV |
| Peak luminosity | $2 \times 10^{34}$ | $cm^{-2}s^{-1}$ |
| Availability | 75 | % |
| Repetition rate | 5 | Hz |
| Duty cycle | 0.5 | % |
| Main Linacs | | |
| Average accelerating gradient in cavities | 31.5 | MV/m |
| Length of each Main Linac | 11 | km |
| Beam pulse length | 1 | ms |
| Average beam current in pulse | 9.0 | mA |
| Damping Rings | | |
| Beam energy | 5 | GeV |
| Circumference | 6.7 | km |
| Length of Beam Delivery section (2 beams) | 4.5 | km |
| Total site length | 31 | km |
| Total site power consumption | 230 | MW |
| Total installed power | ~300 | MW |

# Parameters of SC Linac (15 MV/m)

| **Parameter** | $\beta_G$= **0.49** | $\beta_G$= **0.62** | $\beta_G$= **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 (**306 m**) | **34.76** | **88.15** | **183.33** |
| Norm. Trans. Emitt. (πcm-mrad) $\varepsilon_x$ , $\varepsilon_y$ | 0.023-0.030<br>0.024-0.027 | 0.030-0.033<br>0.027-0.030 | 0.033-0.037<br>0.030-0.031 |
| Norm. Long. Emitt. (MeV-deg) | 0.237-0.241 | 0.241-0.240 | 0.240-0.257 |

# Beam Dynamics




•Aperture is more than 16 times the rms beam size in the SC Linac

• Emittance growth is very small

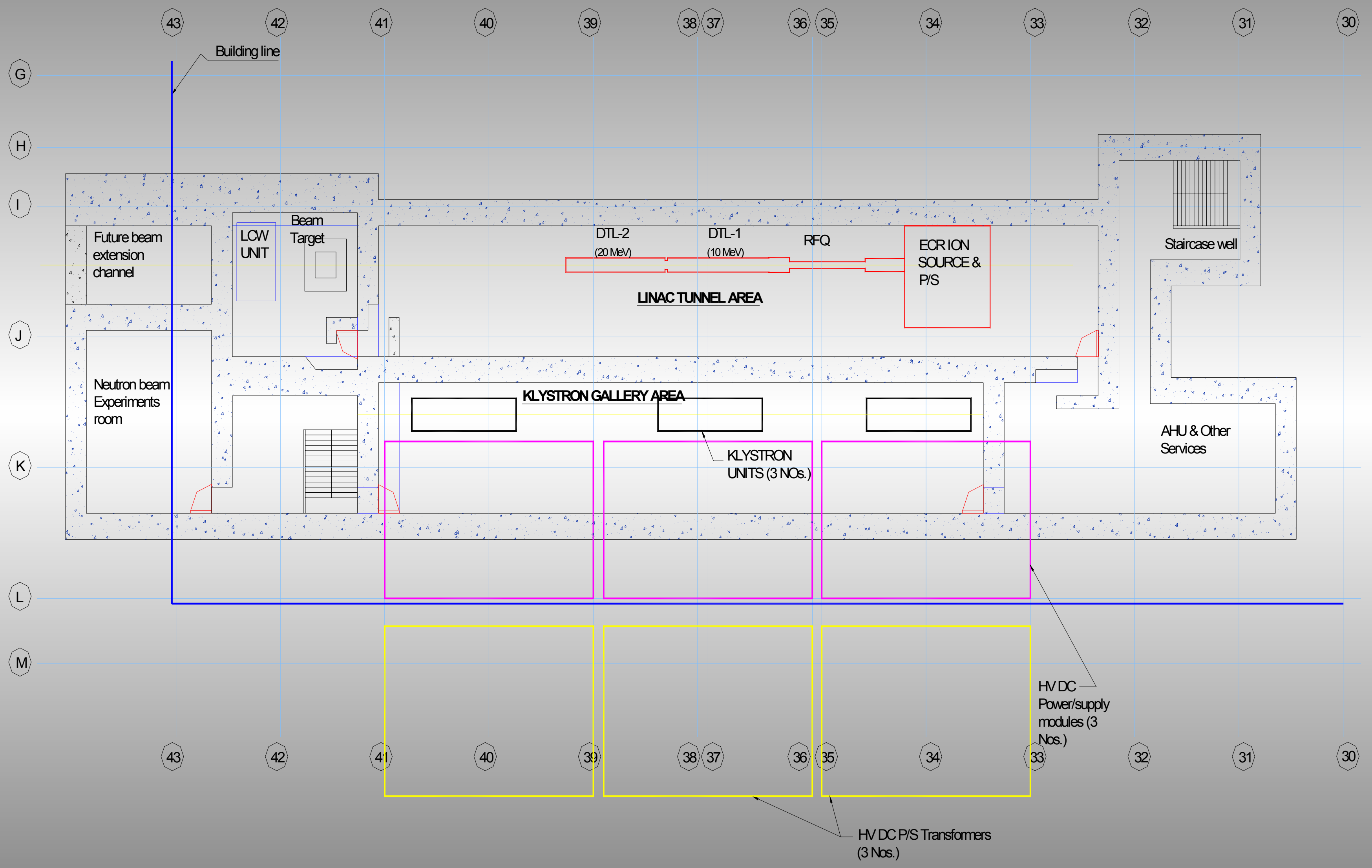
•Transmission through the linac = 100%.

# Accelerating Gradient in SC Linac

| | 5 MV/m | | | | 15 MV/m | | | |
|---|---|---|---|---|---|---|---|---|
| IS, LEBT, MEBT: | 1 | MW | 0.5 | MeV | 1.0 | MW | 0.5 | MeV |
| RFQ | :0.5 | MW | 3 | MeV | 0.5 | MW | 3 | MeV |
| DTL | : 4 | MW | 50 | MeV | 3.0 | MW | 40 | MeV |
| CCDTL | : 5 | MW | 100 | MeV | 6.4 | MW | 100 | MeV |
| SC Linac | : 27 | MW | 1 | GeV | 26.9 | MW | 1 | GeV |
| Total RF Power | : 38 | MW | | | 38 | MW | | |

| | 5 MV/m | 15 MV/m |
|---|---|---|
| Ion source | : 2.0 m | 2.0 m |
| LEBT | : 1.8 m | 1.8 m |
| RFQ | : 4.0 m | 4.0 m |
| MEBT | : 1.5 m | 1.5 m |
| DTL | : 28.0 m | 23.0 m (40 MeV) |
| CCDTL | : 75.0 m | 70.0 m |
| SC Linac | : 762.0 m | 306.0 m |
| Total Length | : 894.3 m | 408.3 m |

# Layout of LEHIPA Building



# Summary

- Physics Design of a 1 GeV, 30 mA Linac has been done
- 100-1000 MeV part will be superconducting
- In Phase I, 20 MeV, 30 mA Linac is being built
- Development of prototypes of different sub-systems is in progress
- Although work in progress but not covered in detail are RF power, Control systems, Diagnostics, Radiation safety, monitors, Cooling systems, Material development, Cryogenics, Vacuum systems, Shielding, Target and Reactor design
- We have made some progress but still miles to go………..

## 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)

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धन्यवाद

Thank You !