Radiofrequency Quadrupole Accelerators for the RIA Facility

- Beam Dynamics Analysis
- RFQs design and Beam Dynamics Simulations
- Design of Resonant structures

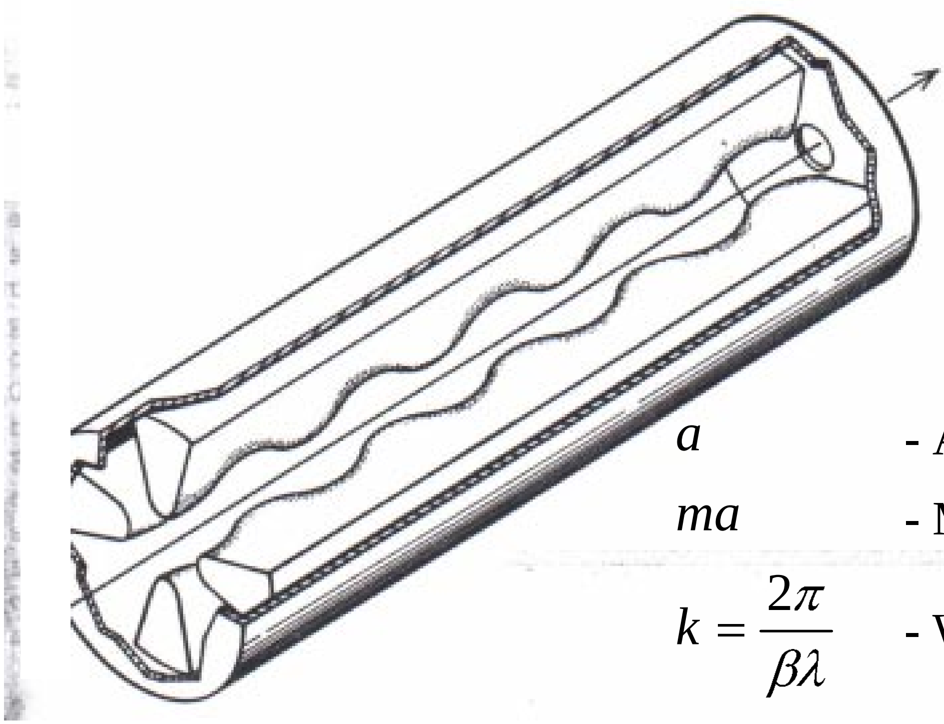
RFQs for RIA Linacs

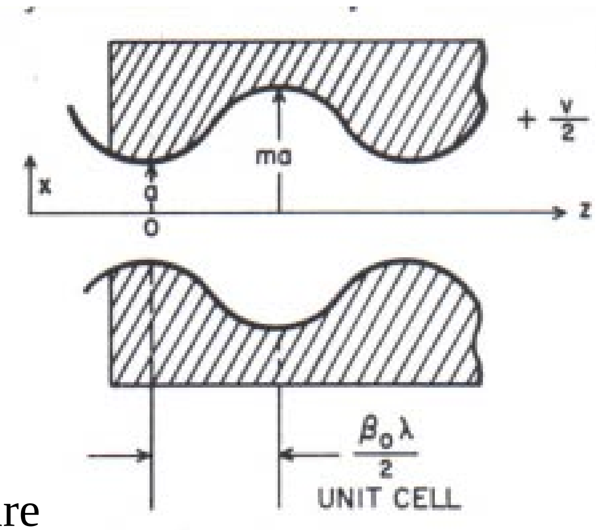
	β_{in}	β_{out}	**Frequency**	**A/q**
Driver linac RFQ	0.0051	0.021	57.5 MHz	1 – 8.351
RIB linac RFQ-1	0.0021	0.0039	12.125 MHz	6 - 240
RIB linac RFQ-2	0.0039	0.0066	12.125 MHz	6 - 240
RIB linac RFQ-3	0.0066	0.012	24.5 MHz	6 - 66

Non-Standard Features of the Driver RFQ

- CW regime over a wide range of voltages for acceleration of various ion species needed for the RIA operation.
- Capture of externally bunched beam with high efficiency
- Simultaneous acceleration of two charge states of uranium ions with minimum perturbation of their parameters.
- Formation at the RFQ output as small longitudinal emittance as possible.
- Large acceptance 3 times of expected input transverse emittance.

Main Characteristics of RFQ Electrodes





a - Aperture

ma - Maximum distance from axis to electrodes

$$k = \frac{2\pi}{\beta\lambda}$$ - Wave number

$$R_0 = \frac{2a}{m+1}$$ - Average distance from axis to electrodes

$$L_c = \frac{\beta\lambda}{2}$$ - Length of accelerating cell

Field in RFQ Working Area

$$U(r,\vartheta,z)=\frac{U_l}{2}\left[F_0(r,\theta)+\sum_{n=1}^{\infty}F_{2n}(r,\vartheta)\cdot\cos 2nkz+\sum_{n=1}^{\infty}F_{2n-1}(r,\theta)\cdot\cos(2n-1)kz\right]$$

$$F_0(r,\theta)=\sum_{m=0}^{\infty}A_{0,2m+1}\left(\frac{r}{R_0}\right)^{2(2m+1)}\cdot\cos 2(2m+1)\theta$$

$$F_{2n}(r,\theta)=\sum_{m=0}^{\infty}A_{2n,2m+1}\cdot I_{2(2m+1)}(2nkr)\cdot\cos 2(2m+1)\theta$$

$$F_{2n-1}(r,\theta)=\sum_{m=0}^{\infty}A_{2n-1,2m}\cdot I_{4m}[(2n-1)kr]\cdot\cos 4m\vartheta$$

$T=\frac{\pi}{4}\cdot A_{10}$ - Accelerating efficiency

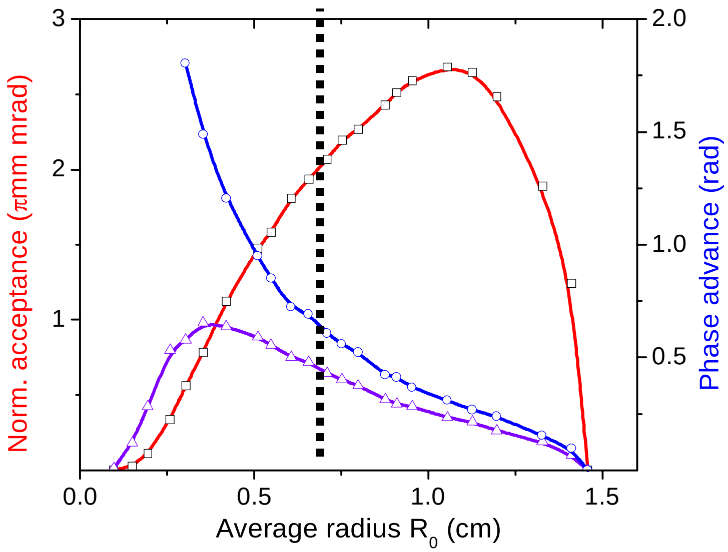
$K^2=\frac{eU_l}{4m_0c^2}\cdot\left(\frac{\lambda}{R_0}\right)^2 A_{01}$ - Focusing efficiency

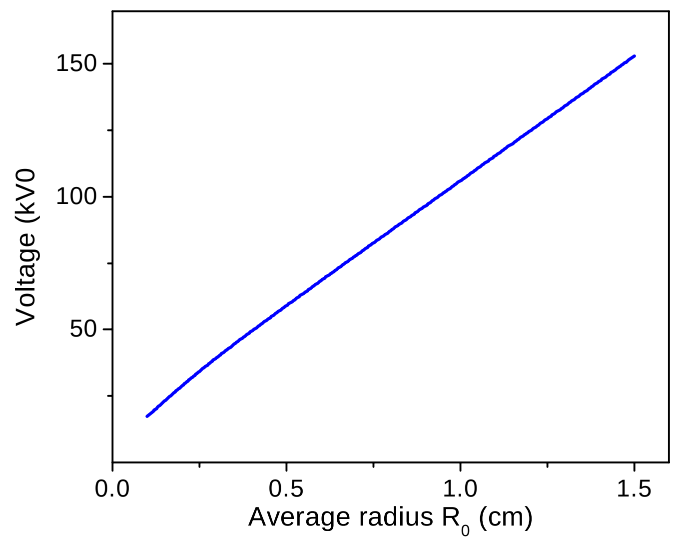
Maximum field at electrode surface

- Choice of peak field is most important for stable operation in CW mode
- The closest prototype - 35 MHz RFQ (TRIUMF) has been successfully tested at E_{max} = 1.35 Kilpatrick unit (141 kV/cm)
- CW RFQ with operating frequency 352 MHz (LEDA, Los Alamos) was tested at E_{max} = 1.8 Kilpatrick unit (340 kV/cm)
- For RIA Driver RFQ a conservative value 1.25 Kilpatrick units has been chosen

Transverse Motion Parameters

Peak field determines main RFQ parameters. The plots below are calculated for E_{max} – 1.25 Kilpatrick units

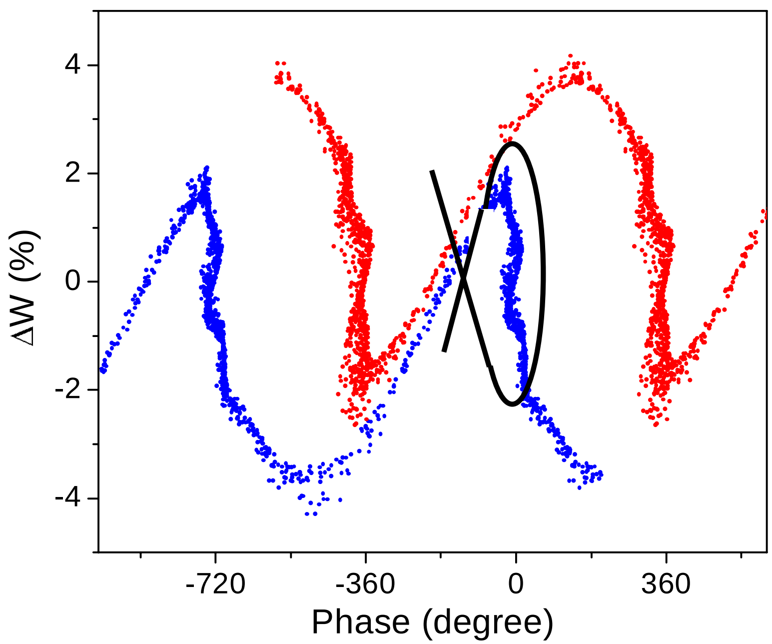


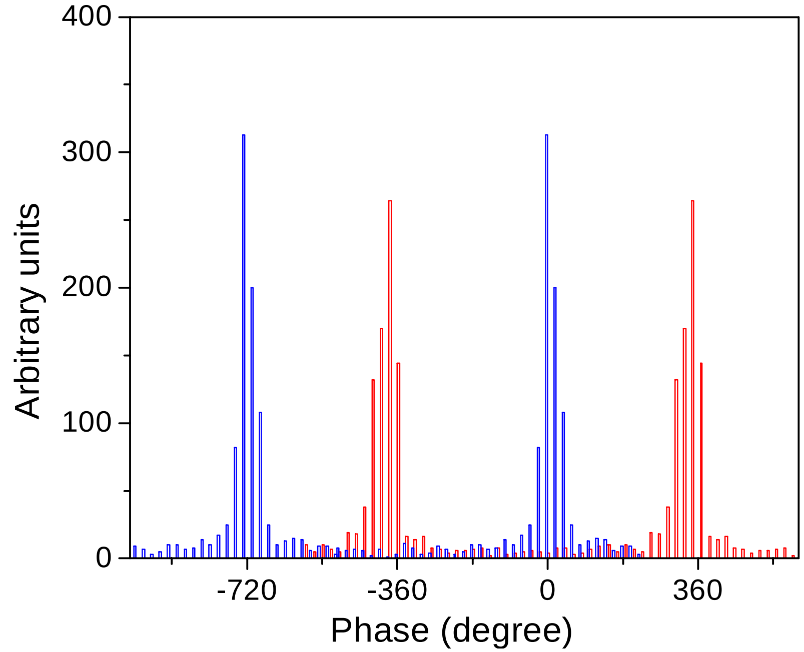


Red – normalized transverse acceptance
Blue – phase advance of transverse oscillations
Violet –$1/\rho^2$, ρ - maximum value of Floucket function module

Voltage between adjacent electrodes

Particle Distribution at the Entrance of the RFQ





In each bunch 80% particles are within phase width $\pm 25^0$

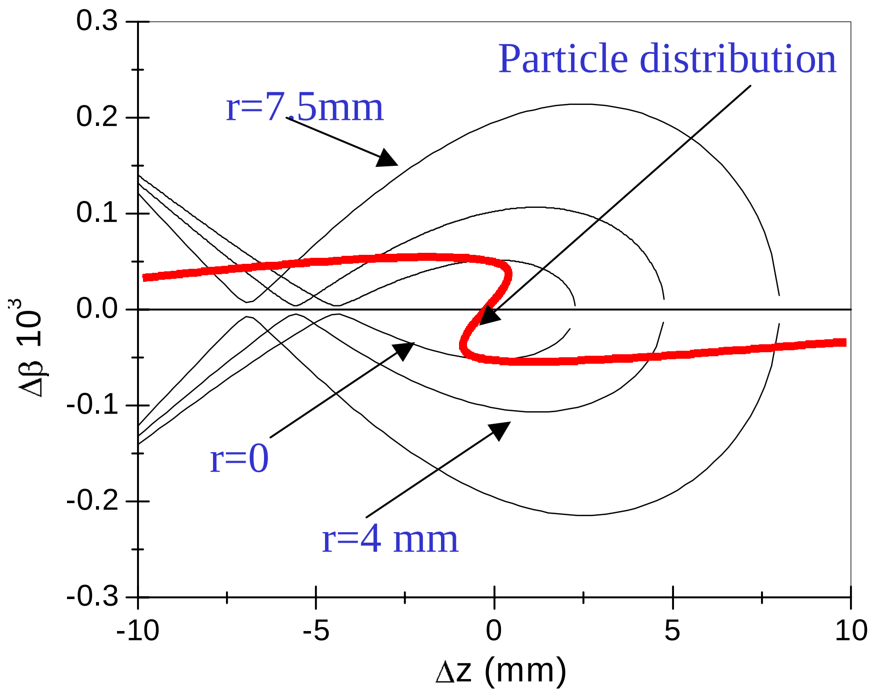
Coupling of transverse and longitudinal motion

$$H(\Delta z,\Delta\beta)=\frac{c\Delta\beta^2}{2}+\frac{ZeU_0T}{\pi AW_0}\left(k\Delta z\cos\varphi_s-I_0(kr)\sin(k\Delta z-\varphi_s)\right)$$

$\Delta\beta=\beta-\beta_s$ Difference between particle velocity and synchronous value

$\Delta z = z - z_c$ The corresponding difference between longitudinal coordinates

Separatrix of longitudinal oscillations calculated for the beginning of RFQ (k=2.38)



- Halo of longitudinal emittance is formed by particles from tails of the longitudinal distribution with high amplitudes of transverse motion.
- To decrease halo:
  - decrease $k=2\pi/\beta\lambda$
  - decrease r

Choice of Initial Parameters

- $R_0 = 6$ mm to ensure required transverse acceptance
- Frequency $f_0 = 57.5$ is determined by the following accelerating structures.
- $\varphi_s = -25^0$ is determined by phase width of initial particle distribution
- Initial $T = 36\ 10^{-2}$ corresponds to energy spread of initial longitudinal particle distribution.
- $U_l = 68{,}5$ kV corresponds chosen peak field for given R_0.
- R_0, U_l and φ_s are constant along axis.

Choice of Initial Parameters

- $T(\beta)$ has to ensure adiabatic longitudinal motion

$$\frac{T \sin \varphi_s}{\beta^2} = const$$

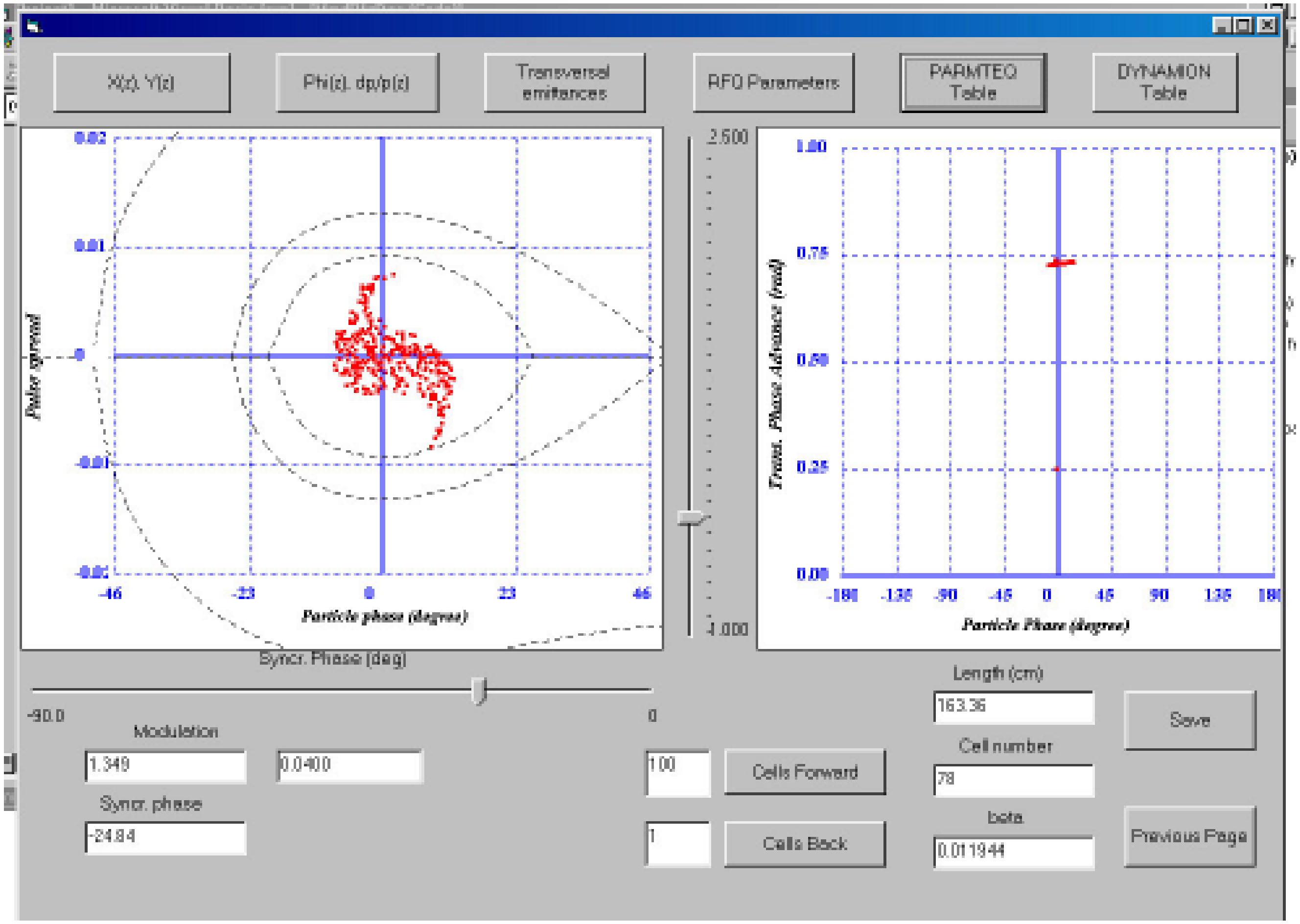
- Width of flat electrodes is $2R_e = 9$ mm
- 6 cell input radial matching section is used.
- Length of last cell is chosen from condition that beam has crossover at RFQ output

Design of Electrode Geometry

Code DESRFQ was used to design electrode geometry. The features of the code are:

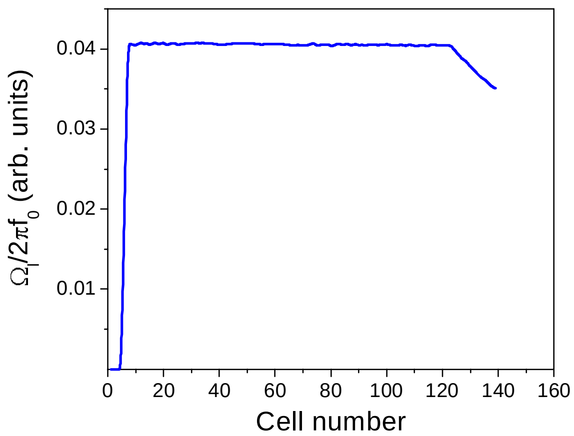
- Code use time as independent variable;
- It calculates 8 components of the potential in the current cell during each iteration;
- It calculates the length of cells along RFQ to satisfy the required laws ***m(n)*** and $\varphi_s(n)$;
- Calculation includes particle transversal motion.
- Space charge forces can be included into calculation.

Main Window of DESRFQ Code

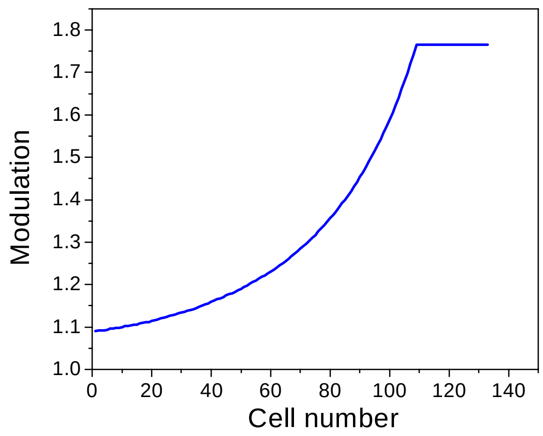


RFQ Main Parameters

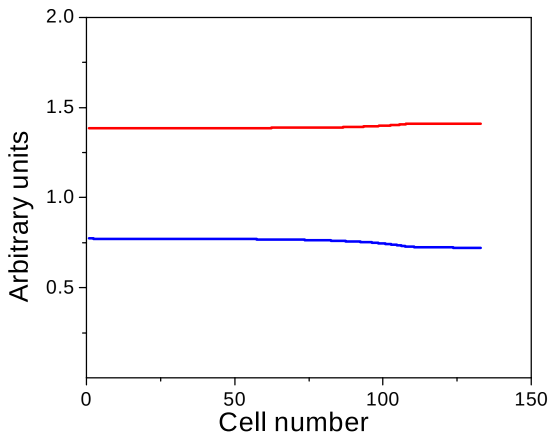
Norm. longitudinal frequency



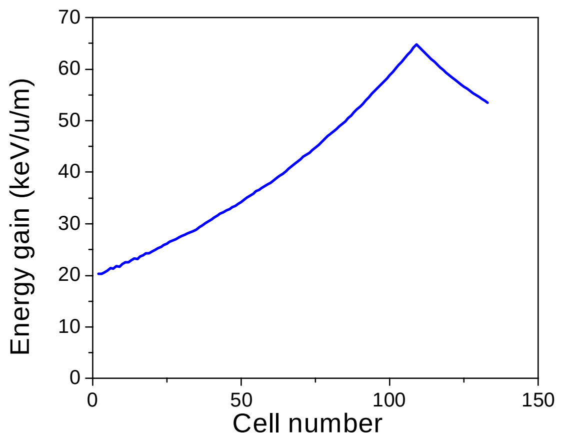
Modulation factor



Phase advance and module Floucket function



Energy gain



Main Parameters of the Driver RFQ

Initial parameters	
Operating frequency $\mathbf{f_0}$	57.5 MHz
Maximum voltage at electrode surface (Kilpartic units)	1.25
Structure length **L**	397
Relative electrode width $\mathbf{R_e/R_0}$	0.75
Calculated by DESRFQ parameters	
Average distance between opposite electrodes $\mathbf{R_0}$	0.6 cm
Aperture **a**	0.4 cm
Maximum voltage at electrode surface $\mathbf{E_{maxl}}$	141.3 kV/cm
Normalized transverse acceptance $\mathbf{A_n}$	1.51 π mm mrad
Simulations results	
Voltage between adjacent electrodes $\mathbf{U_l}$	68.47 kV
Phase advance of transverse oscillations	$44.3 – 39.6^0$
Output energy $\mathbf{W_{out}}$	206.4 keV/u
Longitudinal emittance ε_l calculated for bunched input beam and ε_t 0.5 π mm mrad	1.29 π kev/u nsec

Simulation of the Particle Motion in RFQ

Code DYNAMION was used for simulation of beam dynamics in the RFQ . The features of the code are:

•Time is used as independent variable.

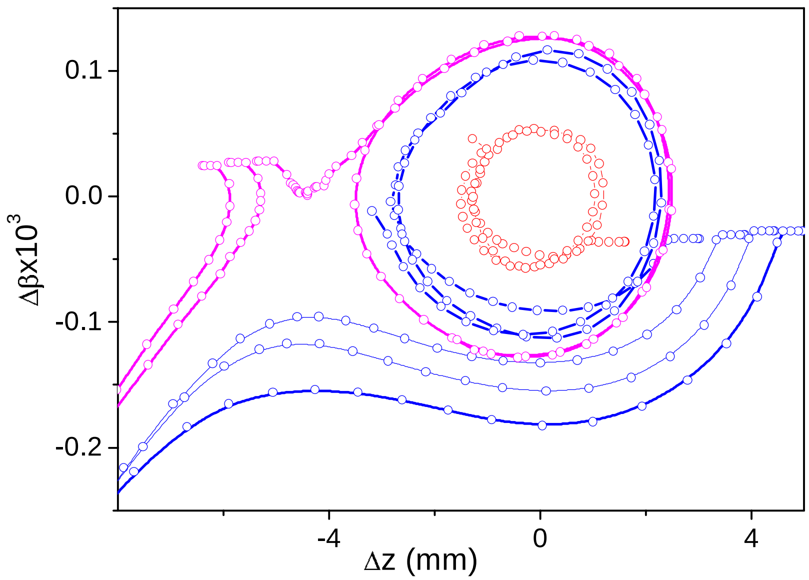
•DYNAMION uses motion equation in the most common type without any approximations that is especially important for low energy beam.

•Analytical expressions, results of external simulations or results of measurements can be used for 3D electric and magnetic field representation.

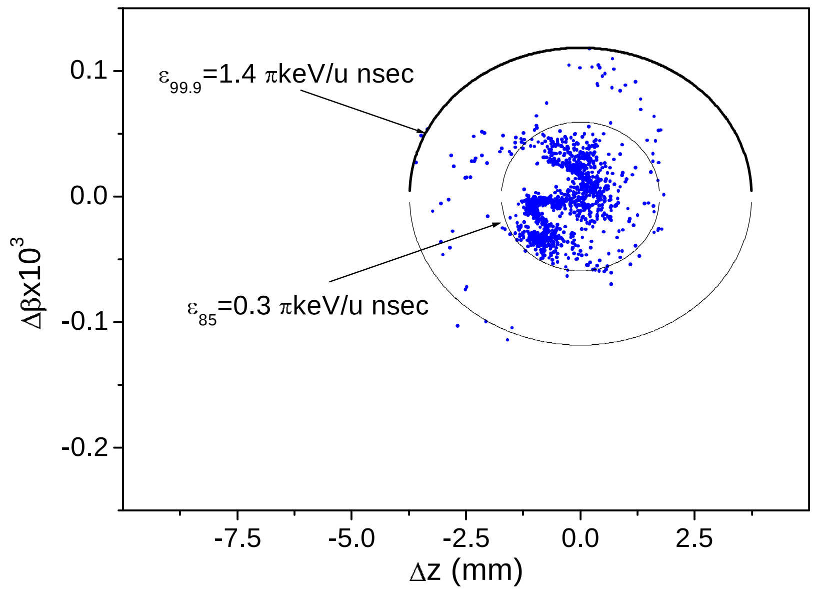
•Beam with different charge states of the particles can be simulated simultaneously.

Simulation
Formation of Longitudinal Emittance

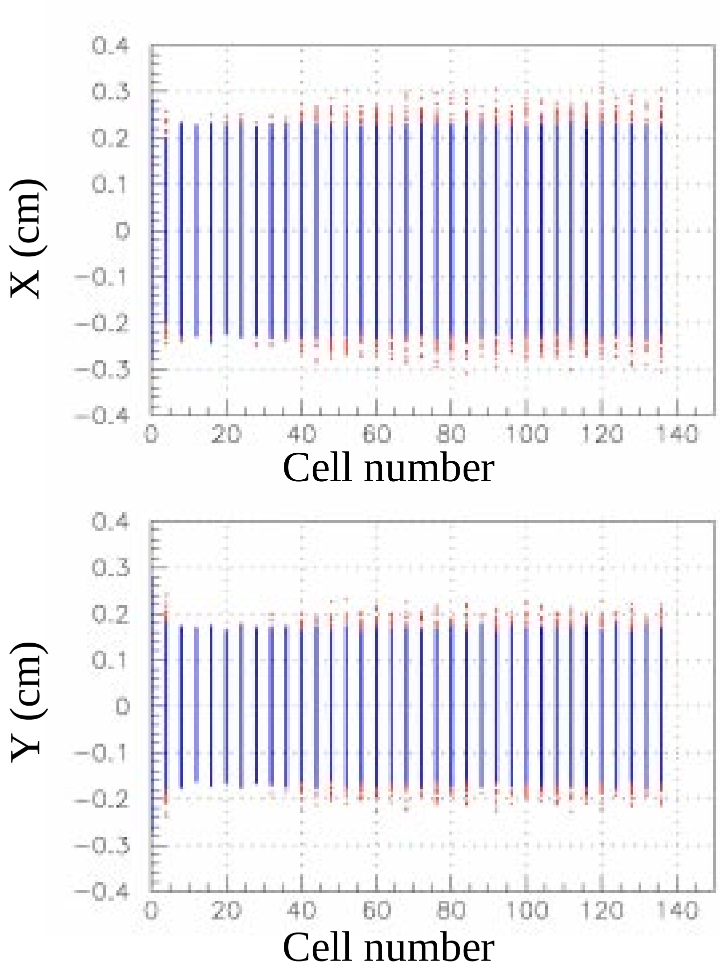
Some particle trajectories in longitudinal phase space



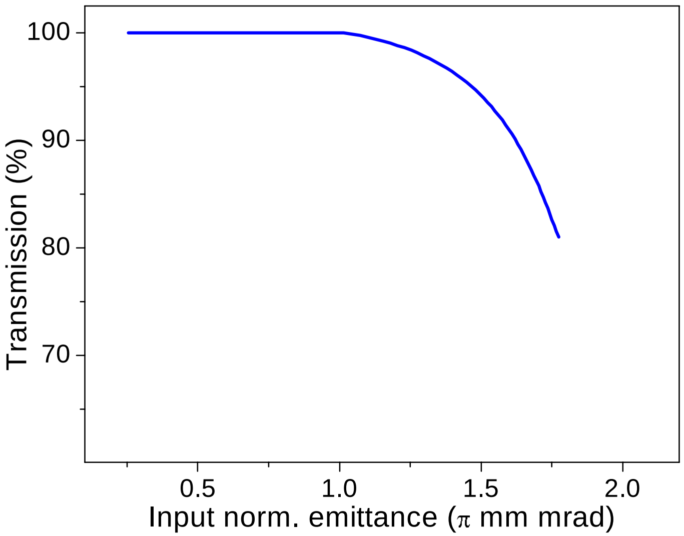
Longitudinal emittance at RFQ output



Simulations.
Transverse Motion

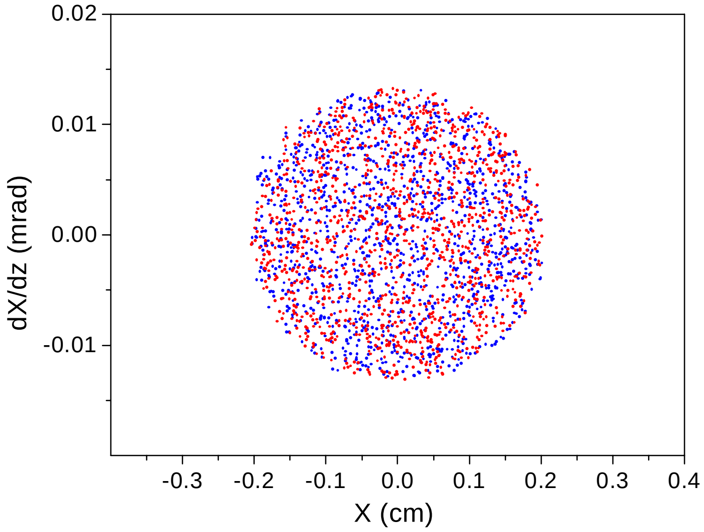


Transmission as a function of input emittance (all particles)

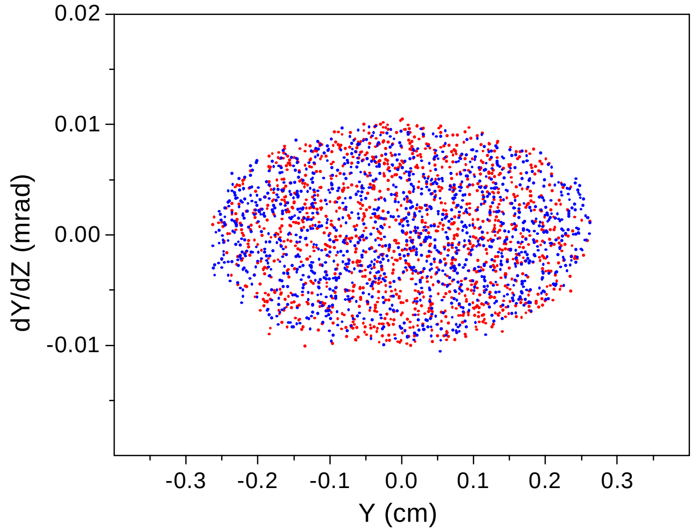


Simulations. Output Emittances

X plane



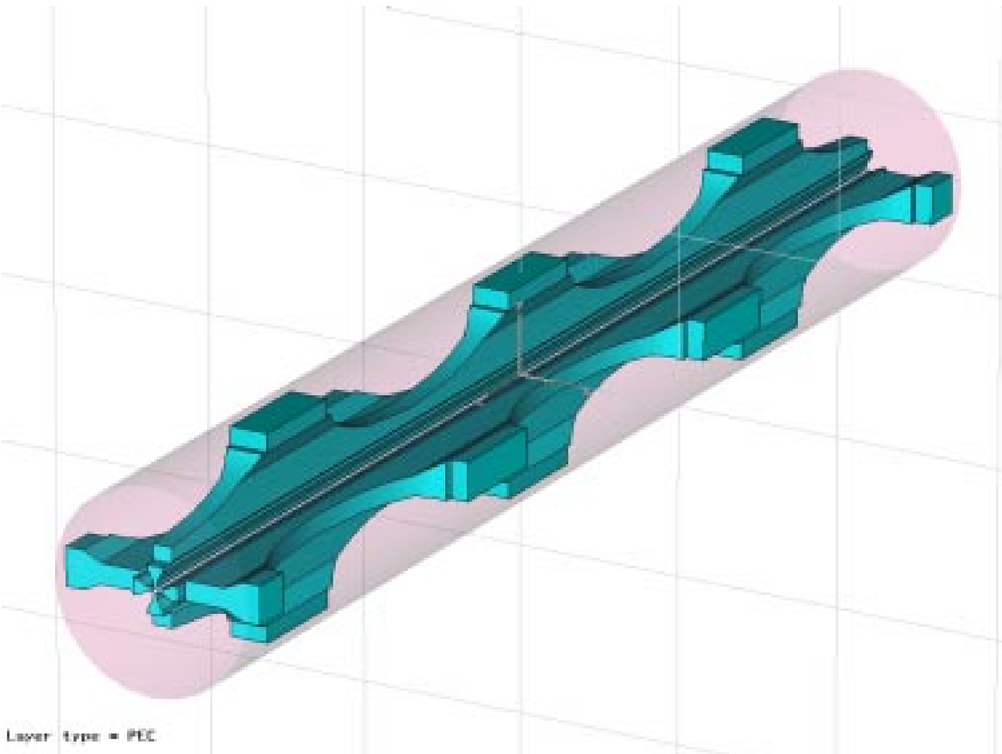
Y plane



Requirements to Resonant Structure

- The reliable CW operation.High shunt impedance.
- Stable field distribution along structure.
- Efficient water cooling of all parts of the resonant cavity.
- Mechanical stability of the construction together with precise alignment ability.
- Reliable rf contacts.
- Fine tuning of the resonant frequency during operation.

Resonant Structure



The resonant structure was proposed in ITEP and developed in collaboration with ANL and ITEP.

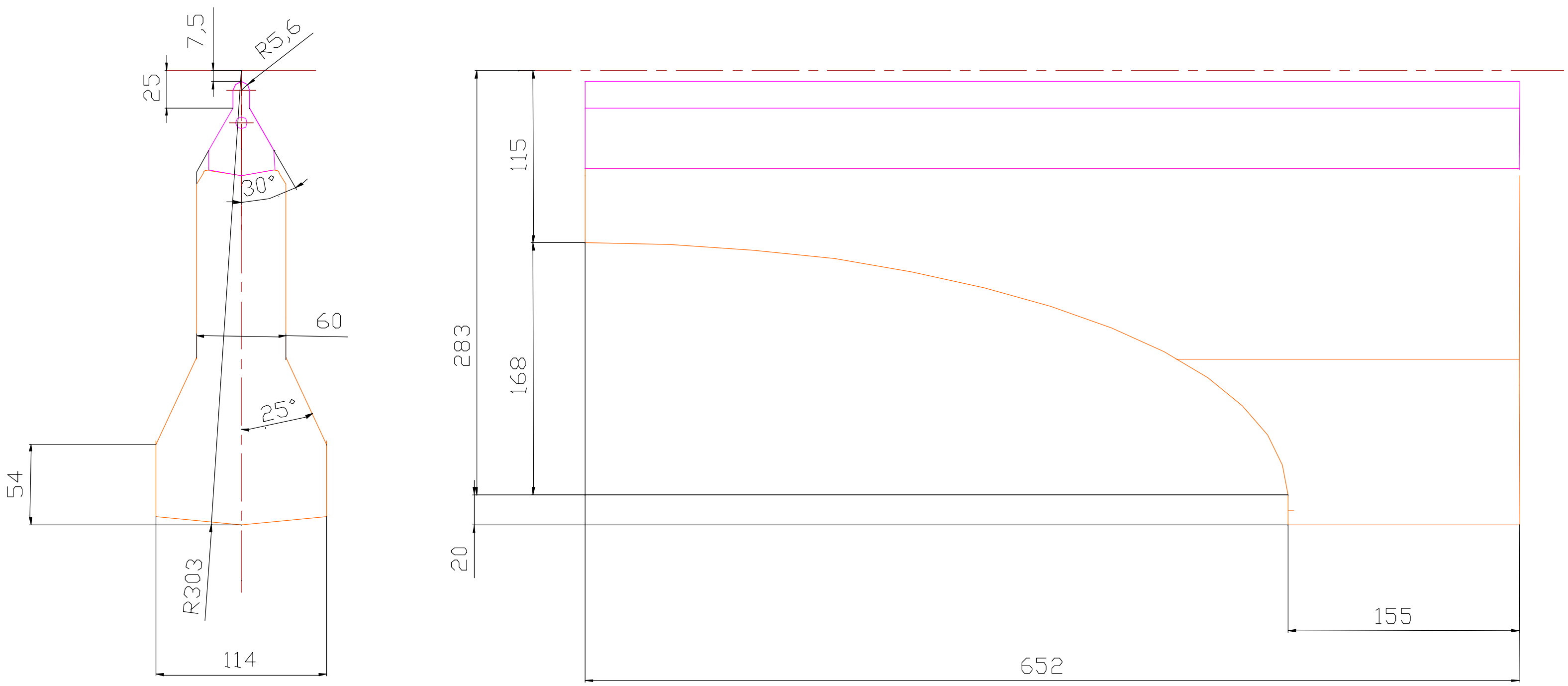
It can be considered:
•as four vane structure with periodically placed coupling windows, or
•as chain of split coaxial cavities.
It combines merits of both these structures.

Length of the structure half period is 652 mm.

Cavity diameter is 606 mm

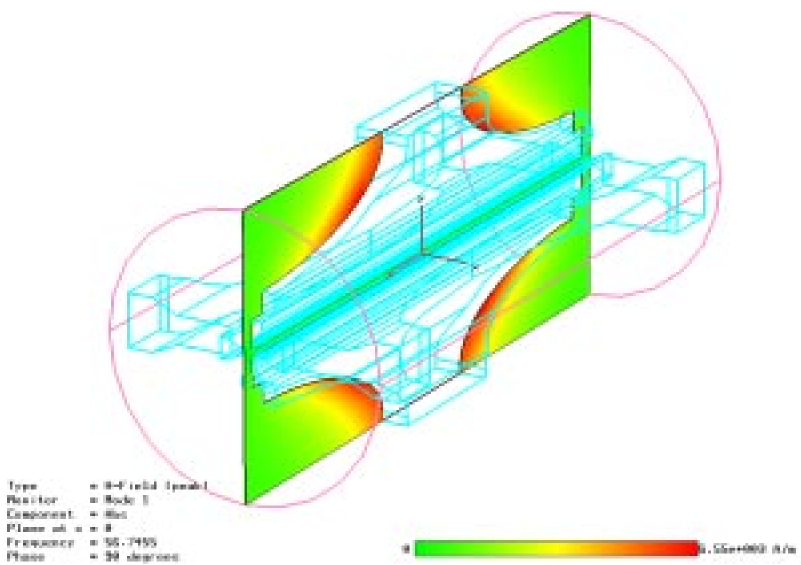
It consists of 6 half periods

Vane Geometry

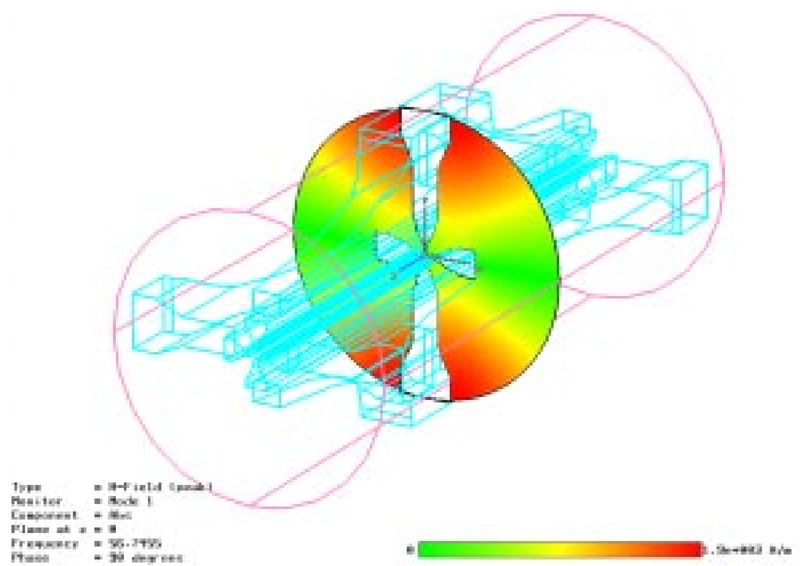


Magnetic Field in RFQ Cavity

YZ Plane

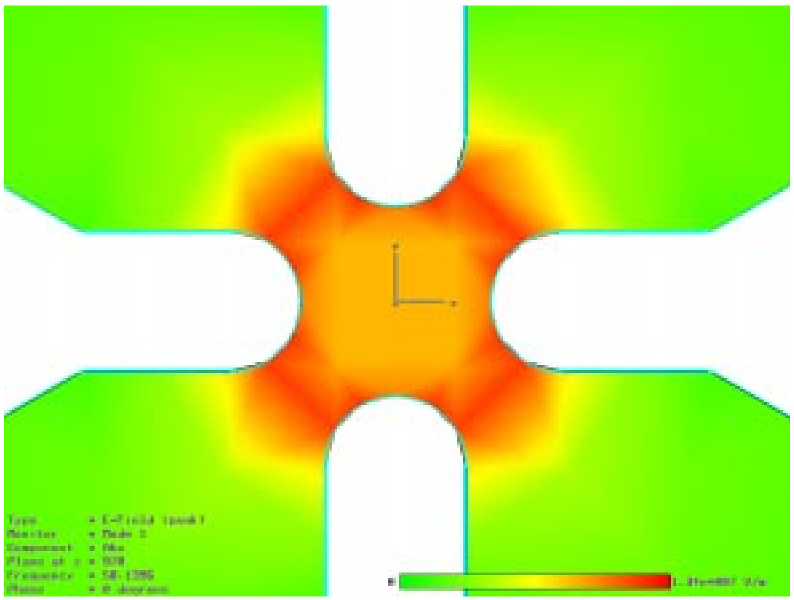


XY Plane

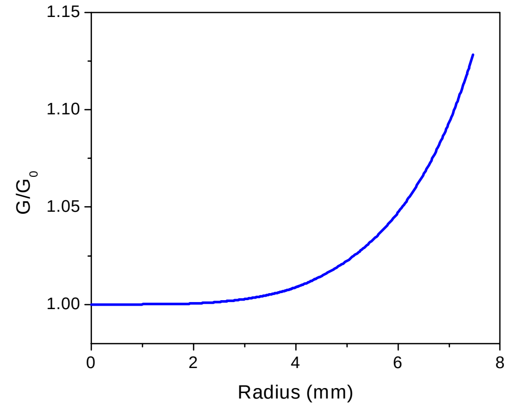


Electric Field in RFQ Cavity

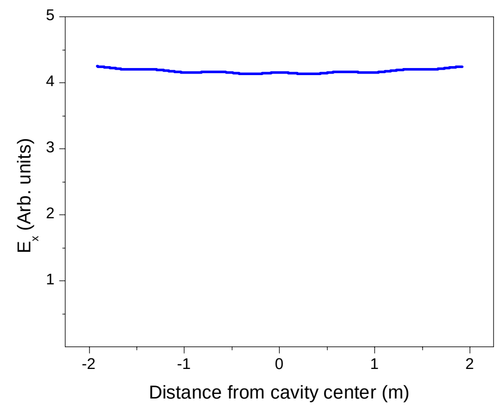
Electric field between electrodes



Gradient of electric field as a function of radius



Electric field along cavity

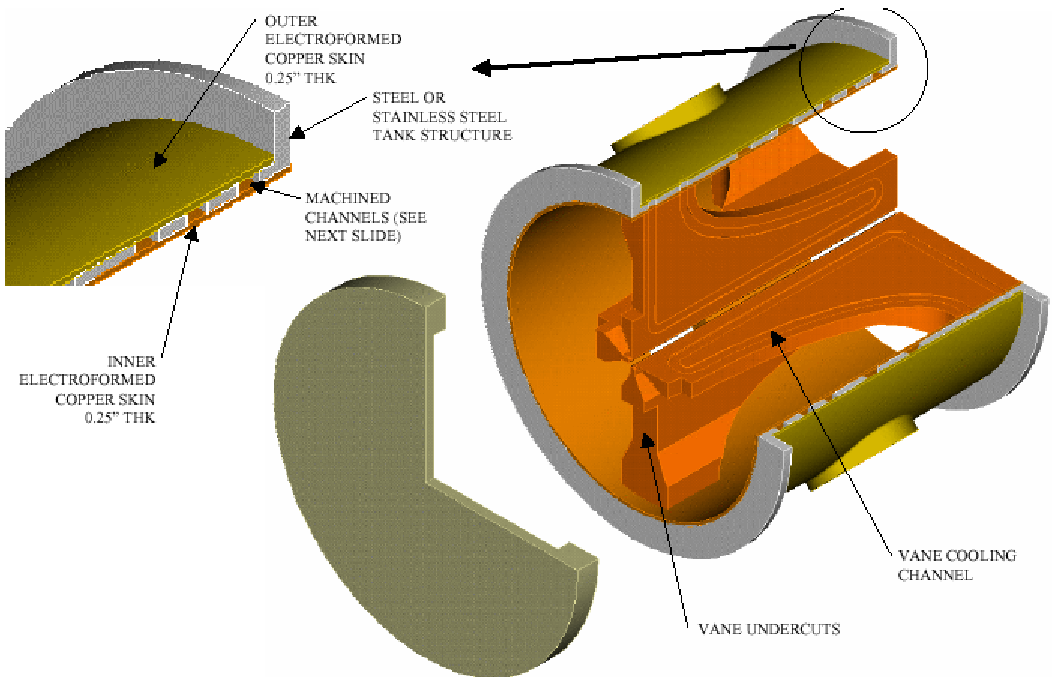


Calculated by MWS Parameters of the Resonant Structure

Frequency of operating mode	57.5 MHz
Frequency of the first nearest mode	68.4 MHz
Frequency of the second nearest mode	93.5 MHz
Q-factor	14000
Total rf power losses	48 kW
Specific rf power losses	12.3 kW/m

Mechanical Design Based on Electroforming Technology

ITEP concept revised by ANL/AES



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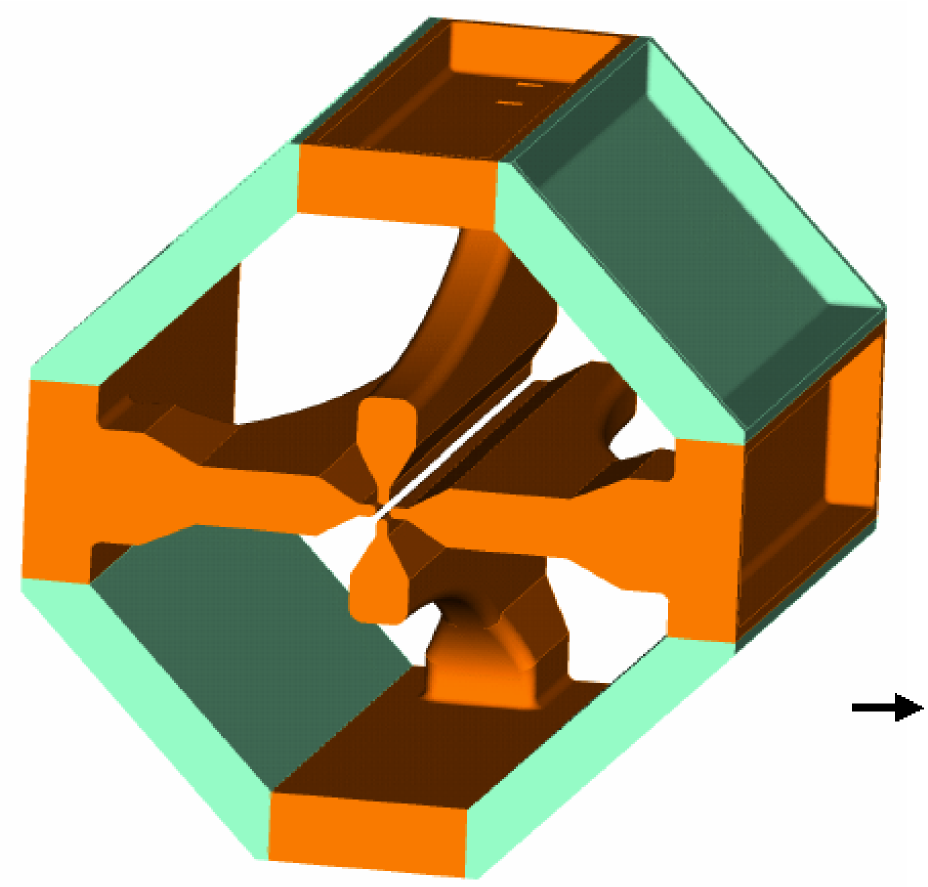
ANL/AES Alternate Concept



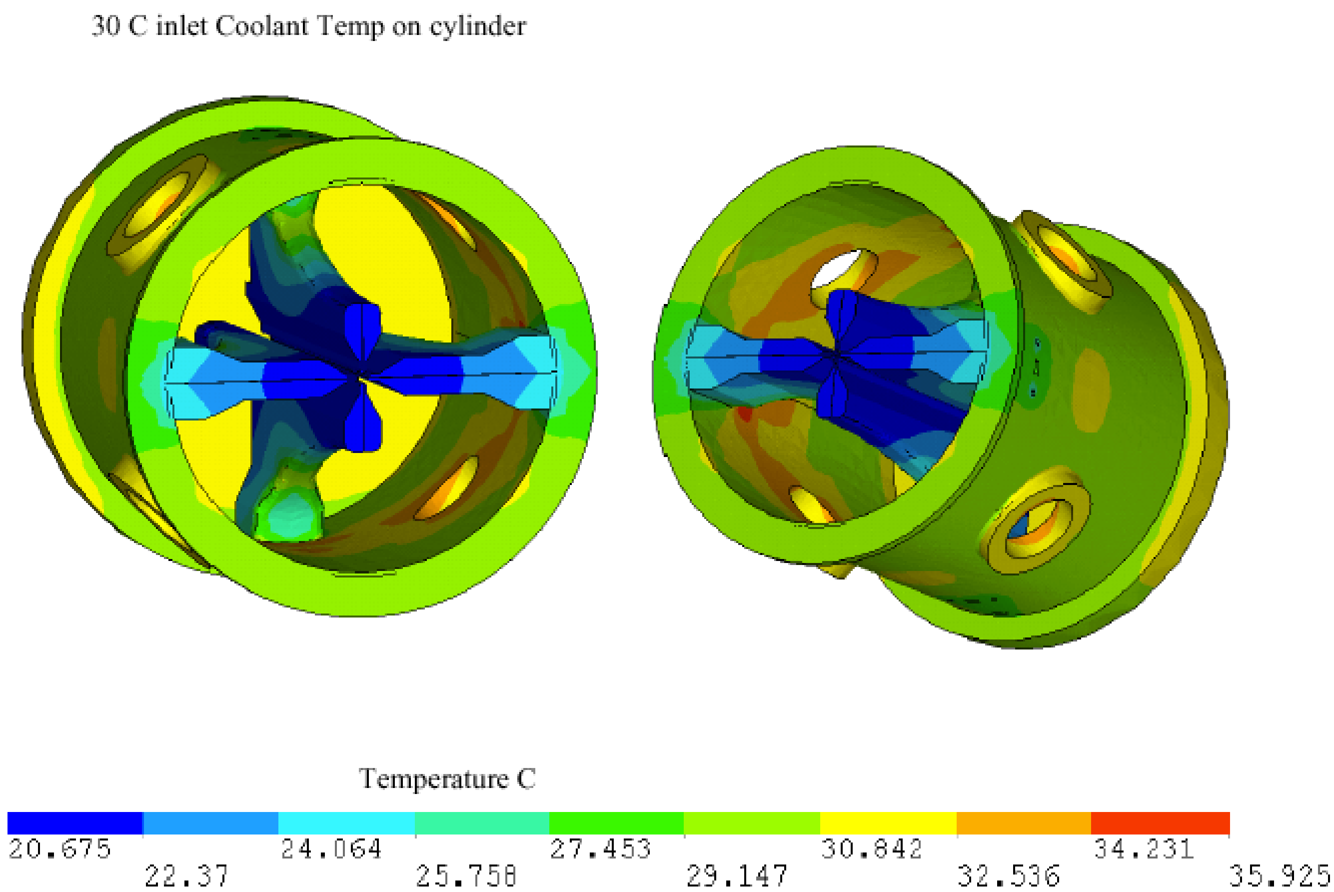
Assembly Options:

1. Bolted with Mechanical RF Seals
   - Done for GTA RFQ at 2% D.F. (LANL)
   - Done for many commercial low duty factor RFQ's
   - Requires vacuum vessel

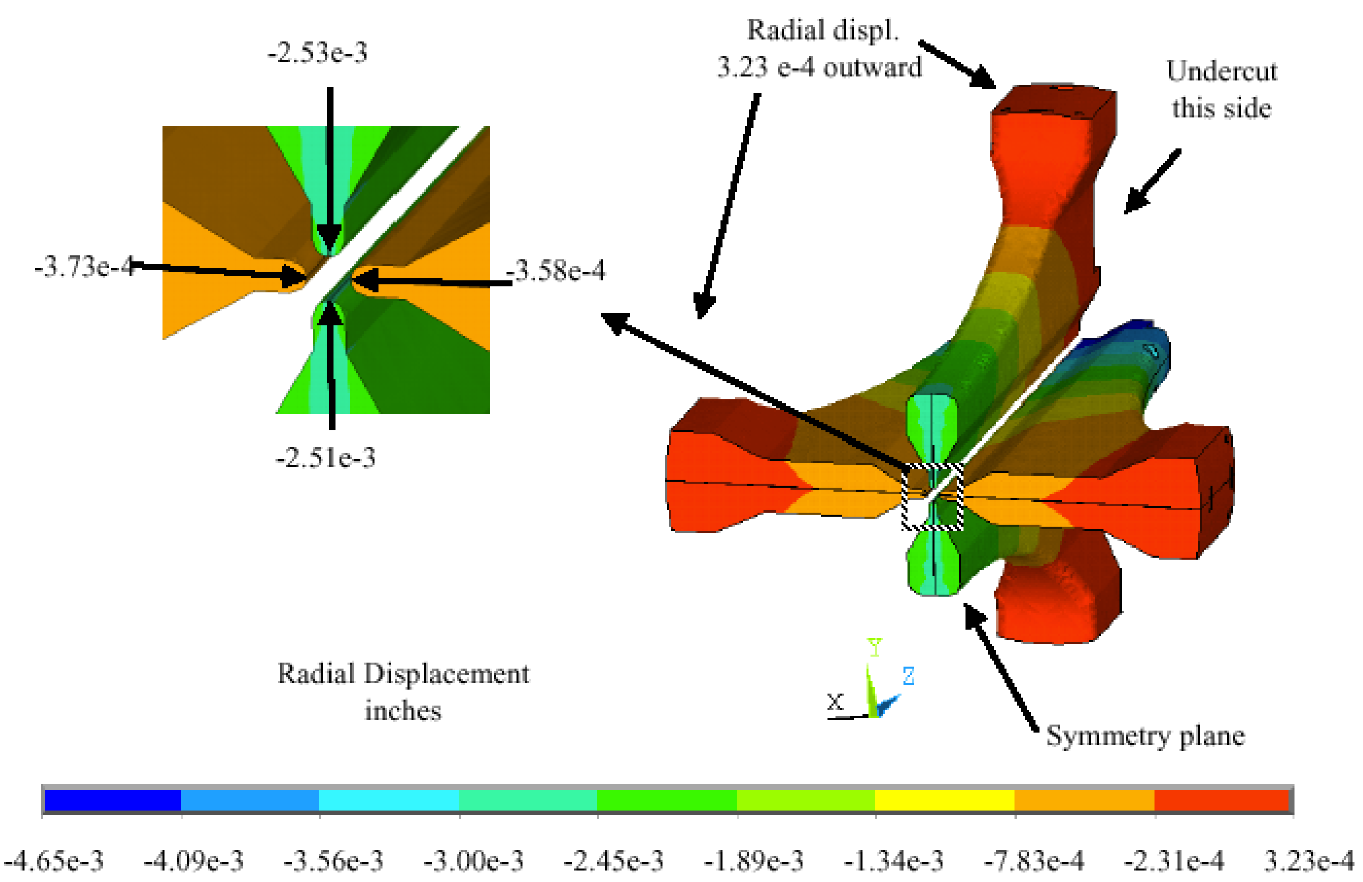
2. Electroformed Assembly
   - Done for BEAR, CWDD, and SSC RFQ's (up to CW)
   - Room temperature process - Maintains excellent alignment
   - Time Consuming Process (many weeks)
   - Expensive ?

→ 3. Brazed Assembly
   - Done for APT/LEDA RFQ - CW
   - Being used for SNS and Korean RFQ

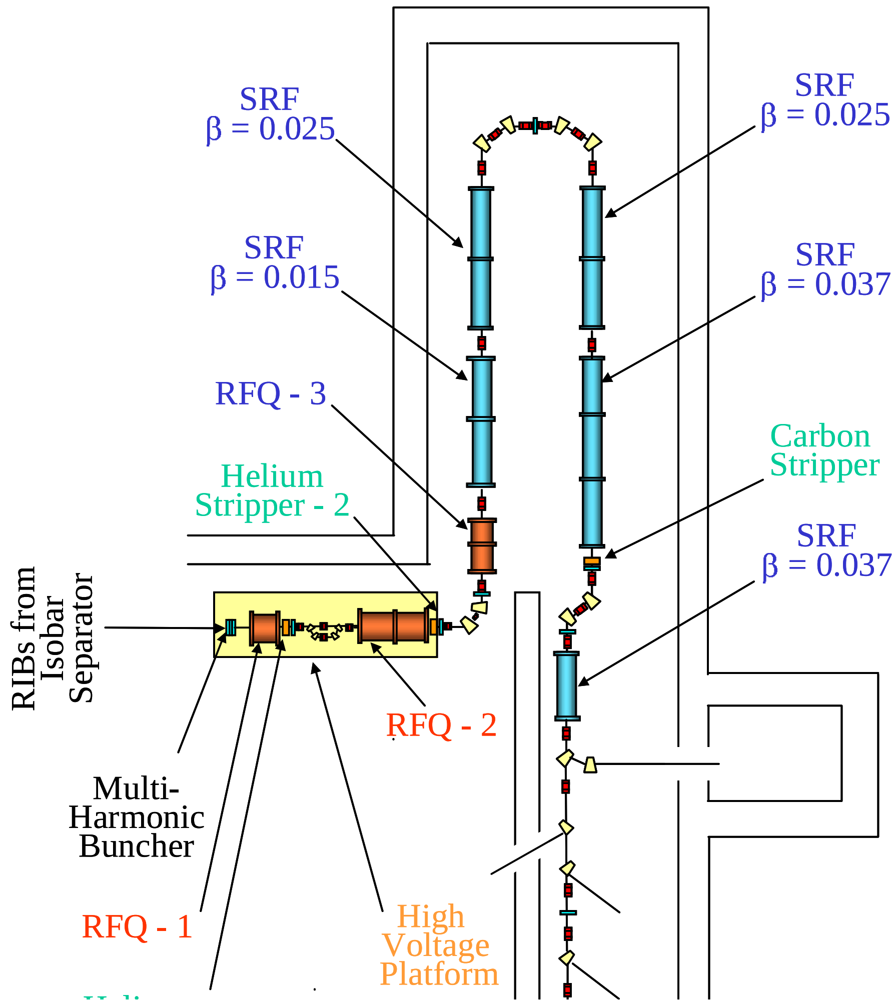
RFQ Section Temperature Distribution. AES Simulation Result



Radial displacement of Vanes.
AES Simulation Result



RIB Layout


SRF
β = 0.025
SRF
β = 0.015
RFQ - 3
Helium
Stripper - 2
RIBs from
Isobar
Separator
Multi-
Harmonic
Buncher
RFQ - 1
High
Voltage
Platform
RFQ - 2
SRF
β = 0.025
SRF
β = 0.037
Carbon
Stripper
SRF
β = 0.037

RFQ-1 for RIB

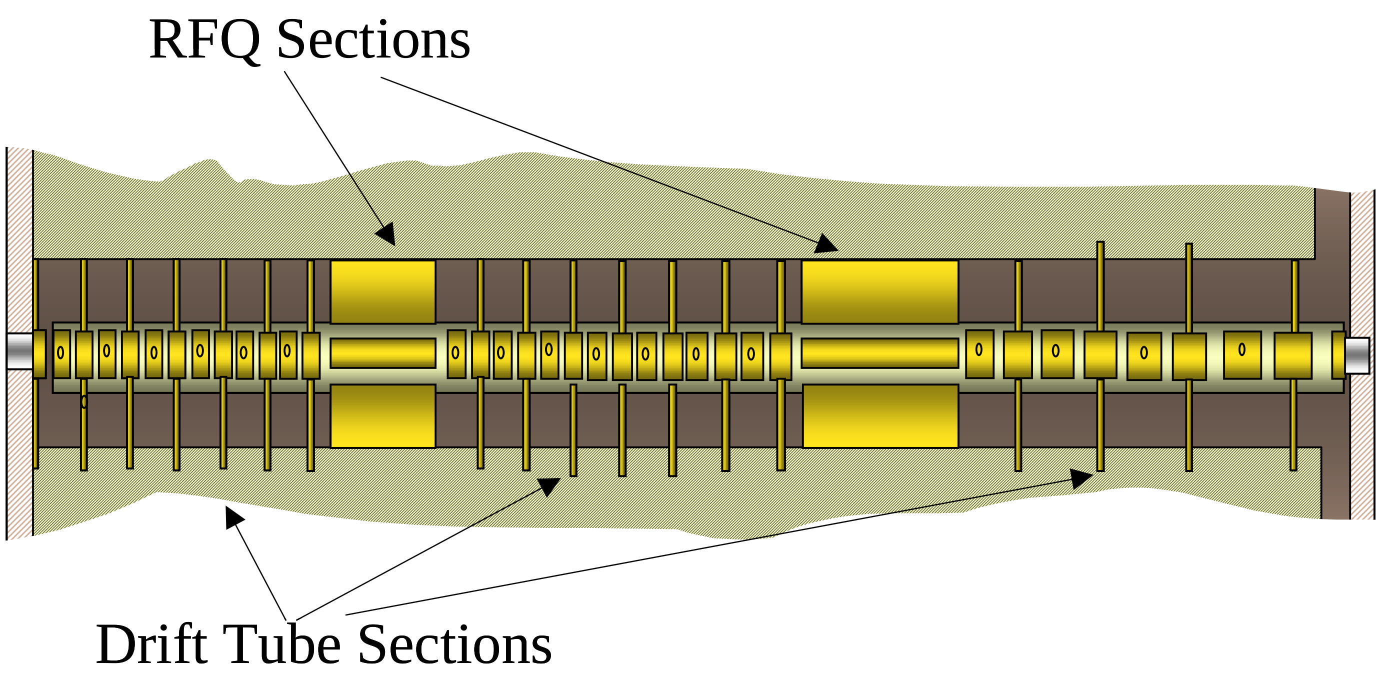
The existing 12 MHz split coaxial RFQ can be used at first stage with minimum modifications :

•Electrodes must be redesigned for 1/240 mass-to-charge ratio.
•Maximum field at electrode must be lower than 1.25 Kilpatrick units
•Output energy must be 7 keV/u for maximum stripping efficiency in the first gas stripper

Main Parameters of Redesigned 12 MHz Split-Coaxial RFQ

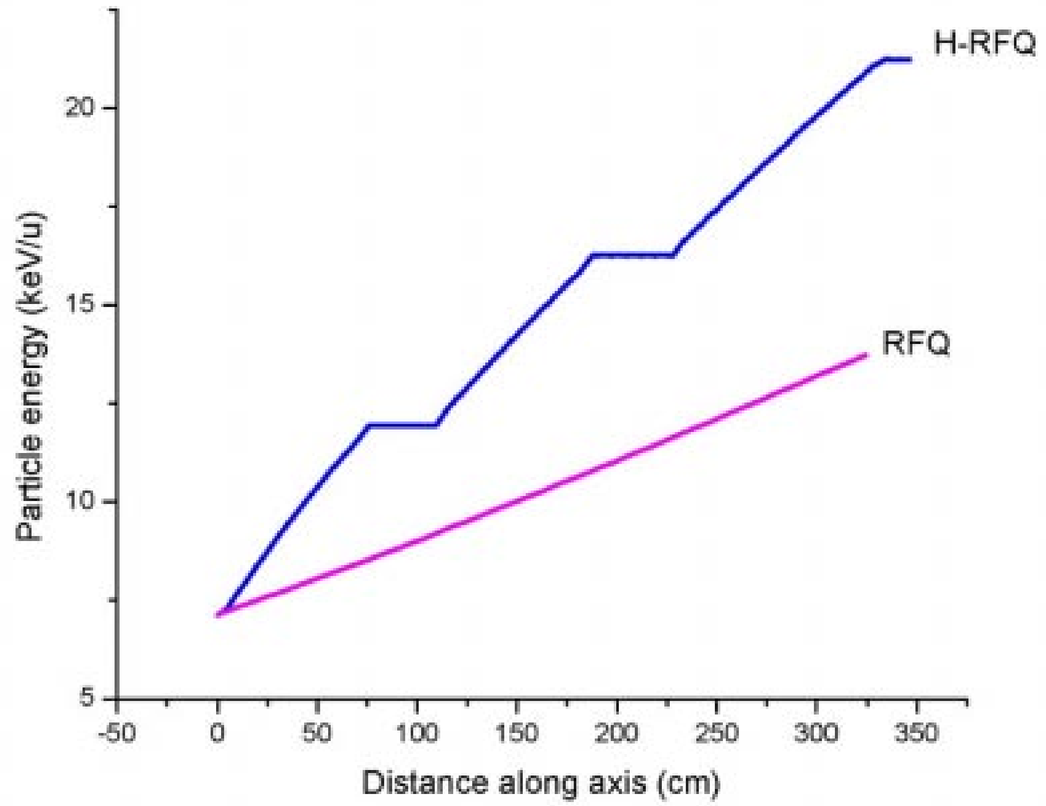
Initial parameters	
Operating frequency $\mathbf{f_0}$	12.125 MHz
Structure length **L**	220
Maximum voltage at electrode surface (Kilpartic units)	1.25
Relative electrode width $\mathbf{R_e/R_0}$	0.75
Calculated by DESRFQ parameters	
Average distance between opposite electrodes $\mathbf{R_0}$	0.6 cm
Aperture **a**	0.43 cm
Maximum voltage at electrode surface $\mathbf{E_{maxl}}$	139 kV/cm
Voltage between adjacent electrodes $\mathbf{U_l}$	67.5 kV
Normalized transverse acceptance $\mathbf{A_n}$	0.31 π mm mrad
Simulations results	
Output energy $\mathbf{W_{out}}$	7.1 keV/u
Phase advance of transverse oscillations	$33.0 – 31.3^0$
Transmission at nominal input emittance $\varepsilon_t = 0.1\ \pi$ mm mrad	100%
Longitudinal emittance ε_l at bunched input beam and $\varepsilon_t = 0.1\ \pi$ mm mrad	0.87 π kev/u nsec

Concept of the RFQ-2 (Hybrid RFQ)

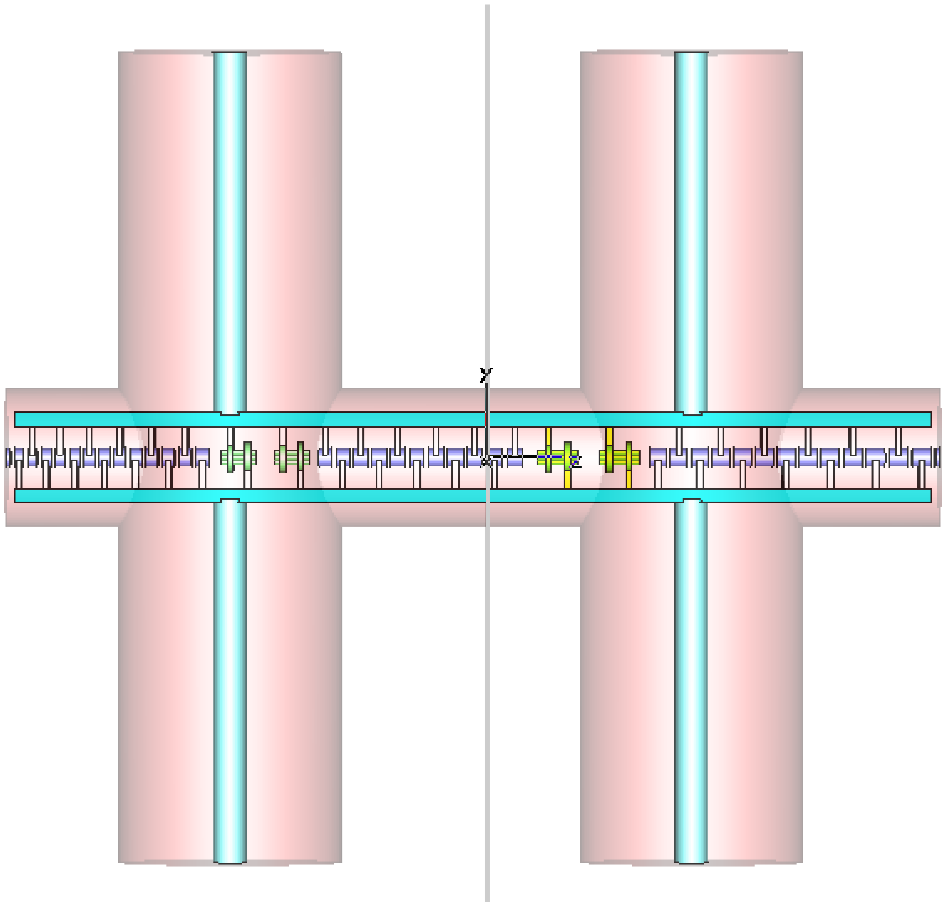


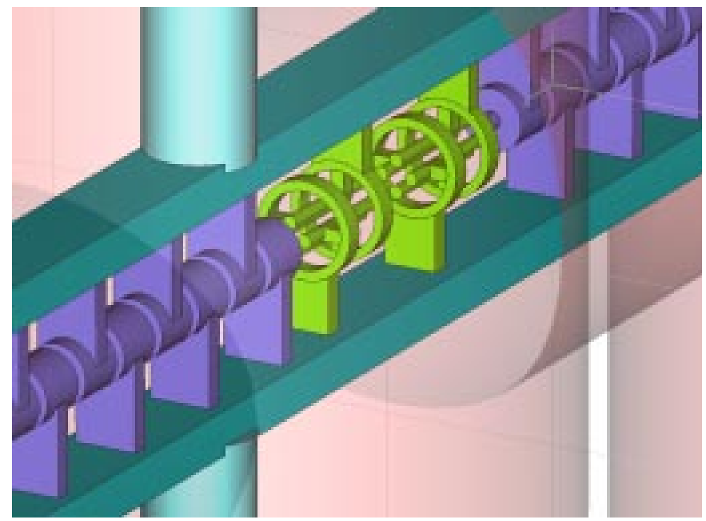
Energy Gain in Conventional and Hybrid RFQ

Maximum fields at electrode surface are the same for both structures



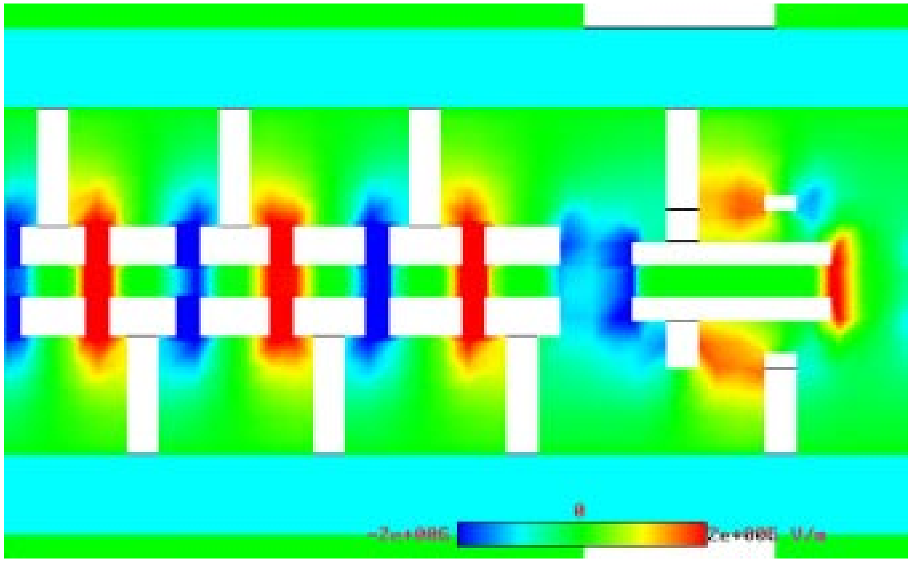
Full Length Model of H-RFQ Structure





MWS Simulation Results

Distribution of longitudinal electric field in DT and RFQ sections calculated by the MWS code



Calculated parameters of the structure

Frequency of operating mode	12.1 MHz
Frequency of nearest mode	24.4 MHz
Total rf power losses	11.6 kW
Specific rf power losses	3.6 kW/m
Q factor	10840

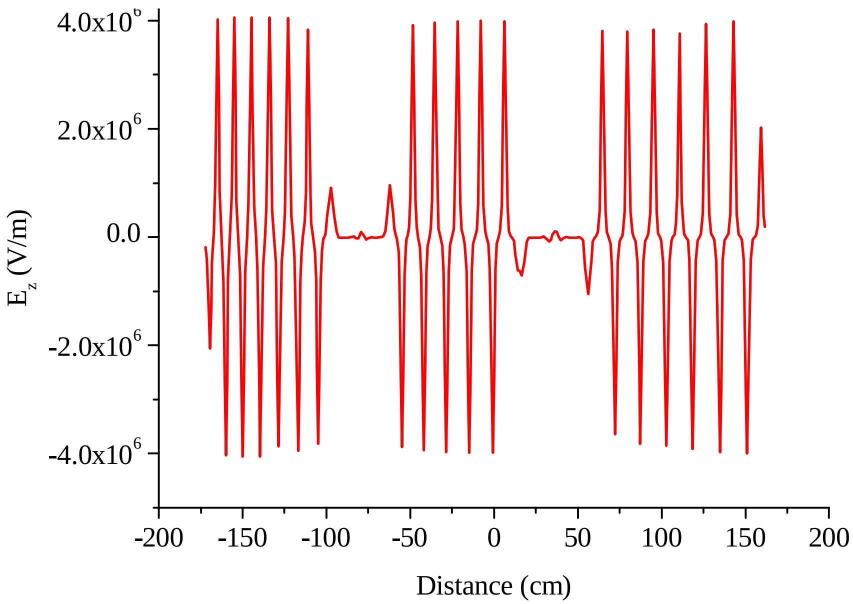
Initial Parameters for HRFQ Design

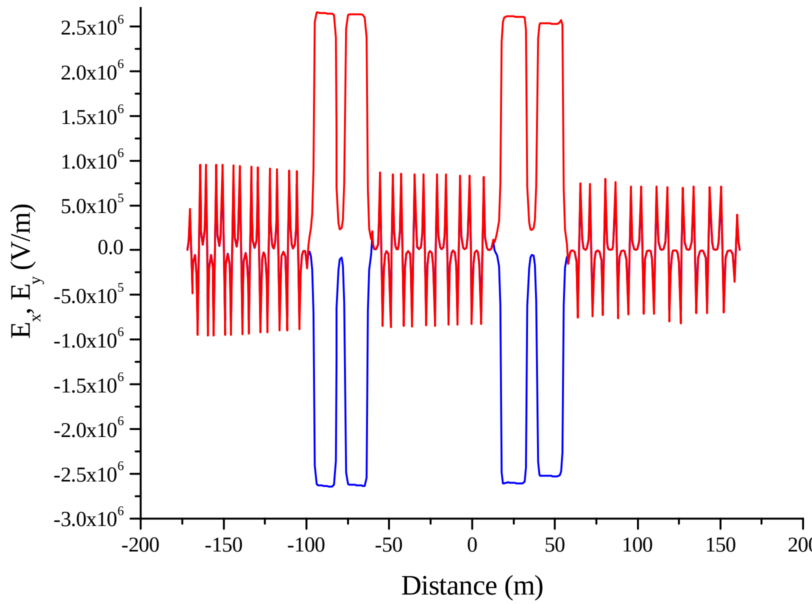
Frequency (MHz)	**12.125**
Charge-to-mass ratio	**1/240**
Total length (mm)	**3340**
Input energy (keV/u)	**7.12**
Output energy (keV/u)	**20.3**
Inter-electrode voltage (kV)	**100.0**
Norm. transverse acceptance (π mm mrad)	**0.2**

Parameters of the H-RFQ Sections

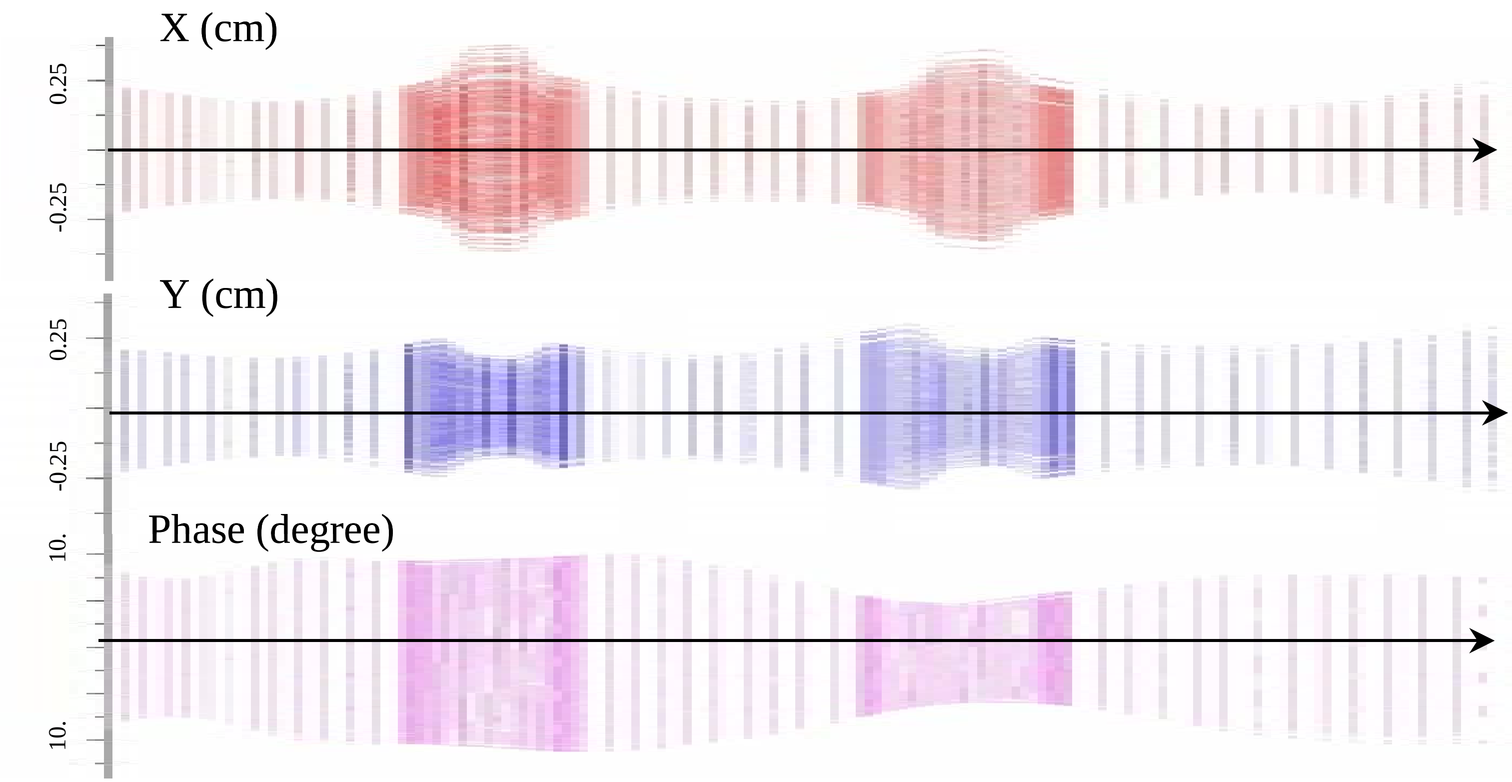
DT-1	**Number of gaps**	**13**
	Gap length (mm)	**15.0**
	Peak surface field (kV/cm)	**≈90.0**
	Synchronous phase (degree)	**0.**
RFQ-1	**Section length (mm)**	**250.6**
	Min. distance between opposite electrodes (mm)	**22.8**
	Peak surface field (kV/cm)	**118.**
DT-2	**Number of gaps**	**10**
	Gap length (mm)	**15.0**
	Peak surface field (kV/cm)	**≈90.0**
	Synchronous phase (degree)	**-20.0**
RFQ-2	**Section length (mm)**	**289.1**
	Min. distance between opposite electrodes (mm)	**22.8**
	Peak surface field (kV/cm)	**≈118.**
DT-3	**Number of gaps**	13
	Gap length (mm)	15.0
	Peak surface field (kV/cm)	**≈90.0**
	Synchronous phase (degree)	-20.0

Fields in H-RFQ Simulated by MWS



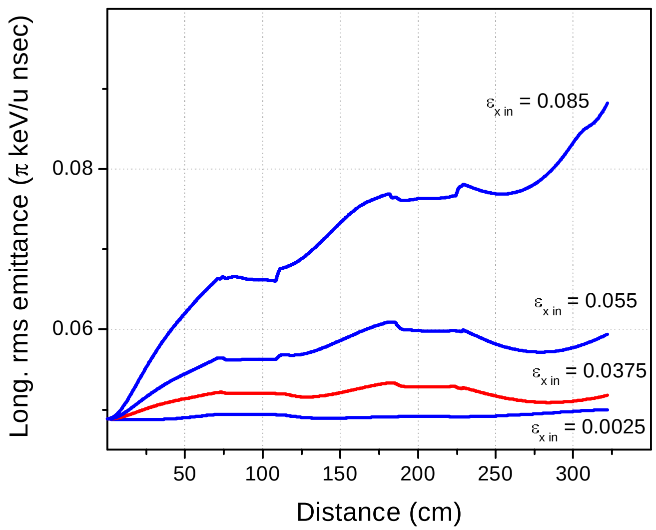


Simulation Results. Envelopes in HRFQ

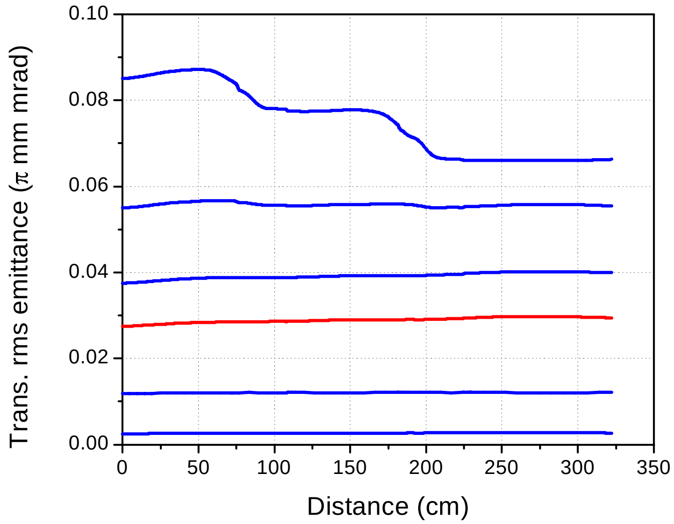


Coupling of Longitudinal and Transverse Motion in HRFQ

Long. emittance along the structure. The parameter is transverse rms emittance (π mm mrad).



Trans. emittance along the structure.



Conclusion

Beam dynamics design of all RFQs are satisfy initial requirements on formation longitudinal emittances, acceptances, emittance growths.

Original developed for 57.5 MHz RFQ resonant structure is a good compromise providing high shunt impedance, simple and stable mechanical design well suitable for efficient water cooling and perfect frequency separation of the modes. Initial thermal/ structural analysis indicate that good performance should be achievable across the full range of operating parameters.

The developed original hybrid RFQ has the following innovative features compared to conventional RFQs with similar parameters:
twice higher accelerating gradient;
lower rf power consumption per unit length;
lower peak surface electric fields at the same voltage between electrodes
less surface area at high electric field.