Recent High Power RFQ Development

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on behalf of

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Outline

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- RFQ Projects
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  - HLI for GSI in Darmstadt
  - FRANZ RFQ for the SGZ
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Introduction

High power (HP) means:

Maximization of Beam current resp. power → cw operation → high thermal load on structure, which shall be characterized by kW/m.

Fields of HP application:

•Heavy ion beams require high charge states for efficient acceleration. Production rates of highly charged ions are limited.

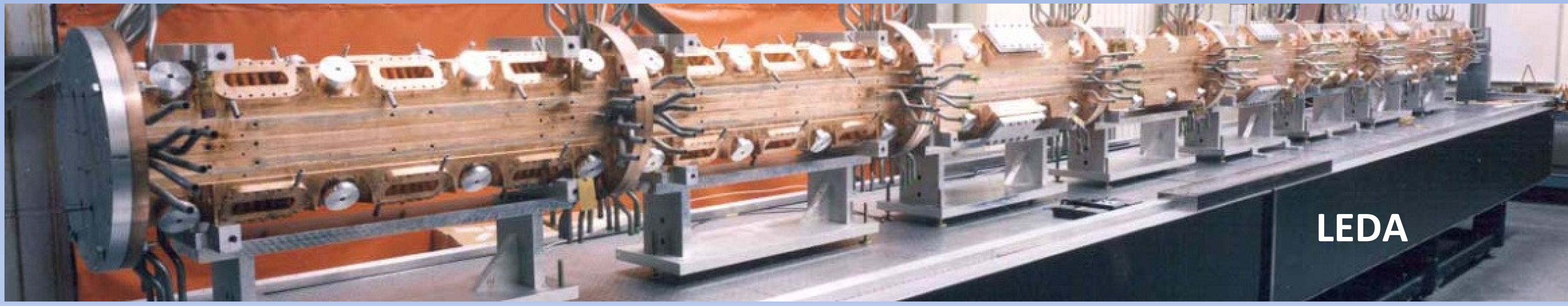
•Production of secondary particles → increase production rates.

•Post acceleration of RIBs due to low production rates.

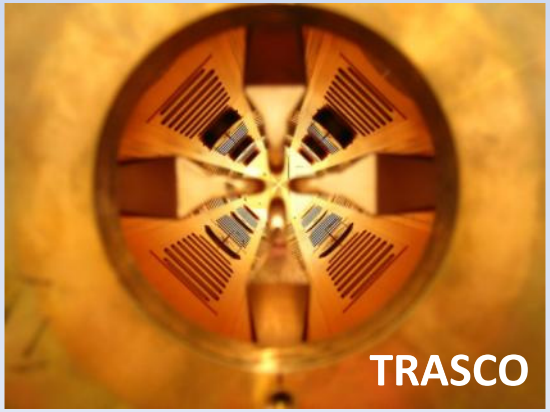
•Nuclear waste transmutation (20 MW beam power, 1 GeV p → 20 mA required for neutron spallation)

•Material research for e.g. future fusion reactors (SNS, IFMIF, PSI and others).

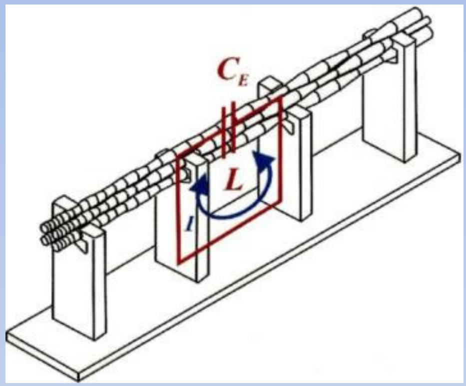
cw 4-vane-RFQs



	LEDA	*IPHI*	*SPIRAL2*	*TRASCO*
frequency [MHz]	350	352	88	352
mass to charge ratio	1	1	2 & 3	1
acceleration [MeV/u]	0.075 - 6.7	0.095 - 5	0.02 - 0.75	0.08 - 5
beam current [mA]	100	100	5 & 1	30
length [m]	8	8	5	7.1
inter vane voltage [kV]	66-120	87-123	100-113	68
thermal load[kW/m]	150	150	40	<113

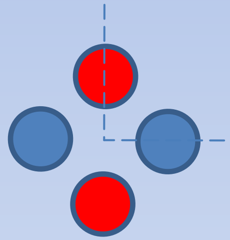


4-rod-RFQ Design

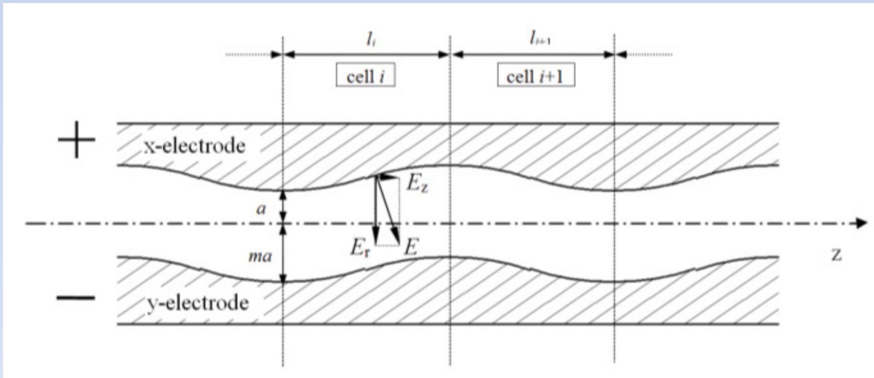


The main issue of the electrode design is the longitudinal aperture modulation characterized by three geometric parameters:

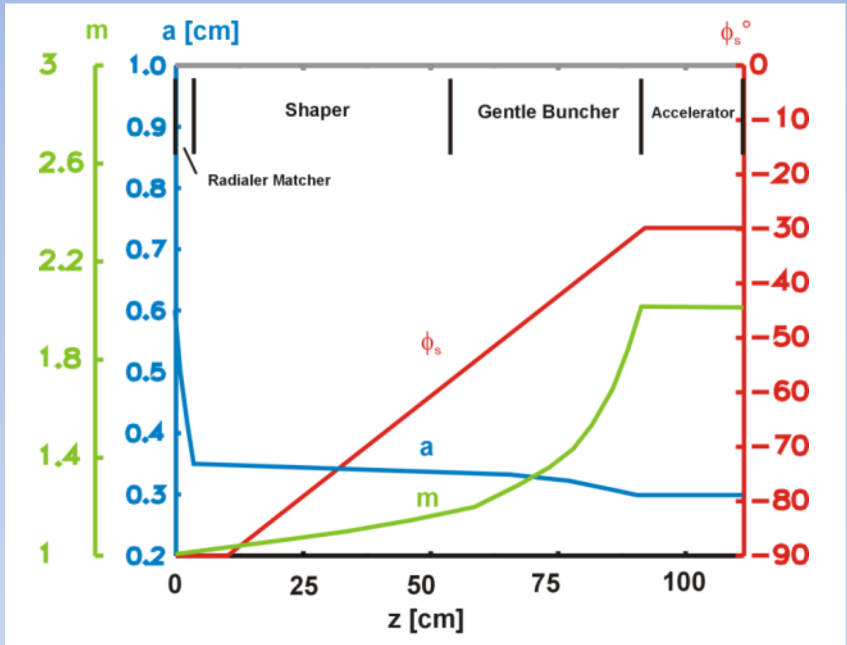
- *Modulation m*
- *Aperture a*
- *Cell length l*



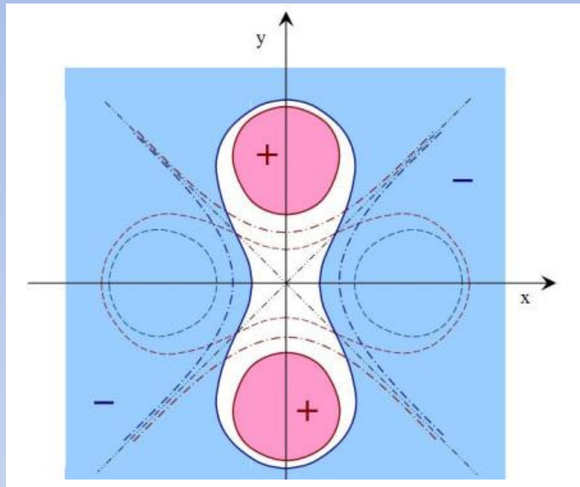
One resonating ground cell is formed by two adjacent stems with the conducting ground plate one side and the capacity of the electrodes on the other.



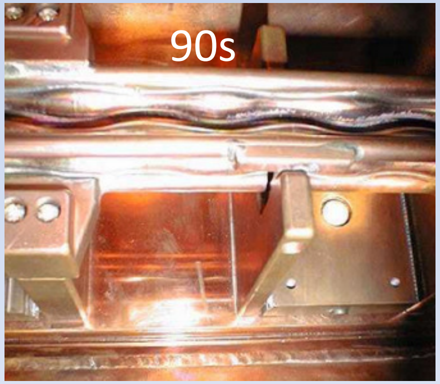
Electrode design

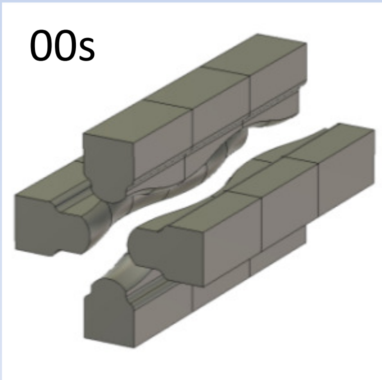


$$V(r,\varphi,z) = A_{0,1}\left(\frac{r}{a}\right)^2 \cos(2\varphi) + A_{1,0}\, I_0(kr)\cos(kz)$$



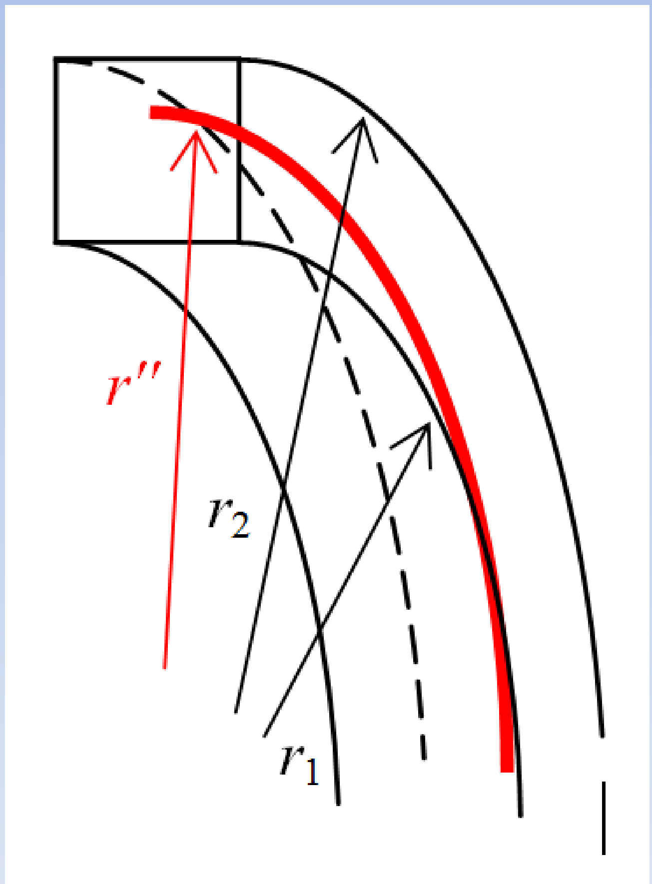
ideal after 2-term potential

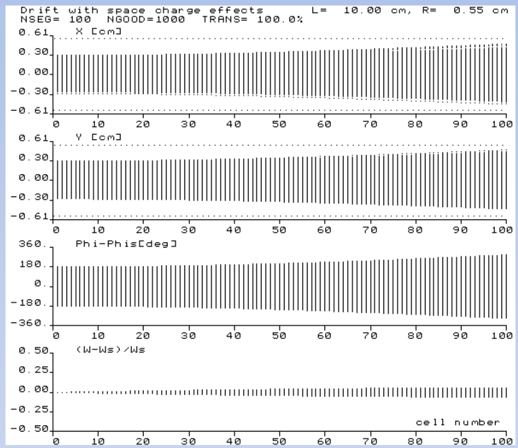


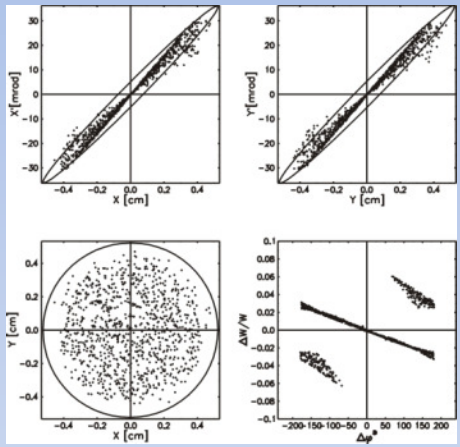


Real electrode shapes were following the constrains of available milling techniques.
They can also be treated analytically to a certain degree by e.g. using a Laplace-solver.

Space Charge at RFQsim





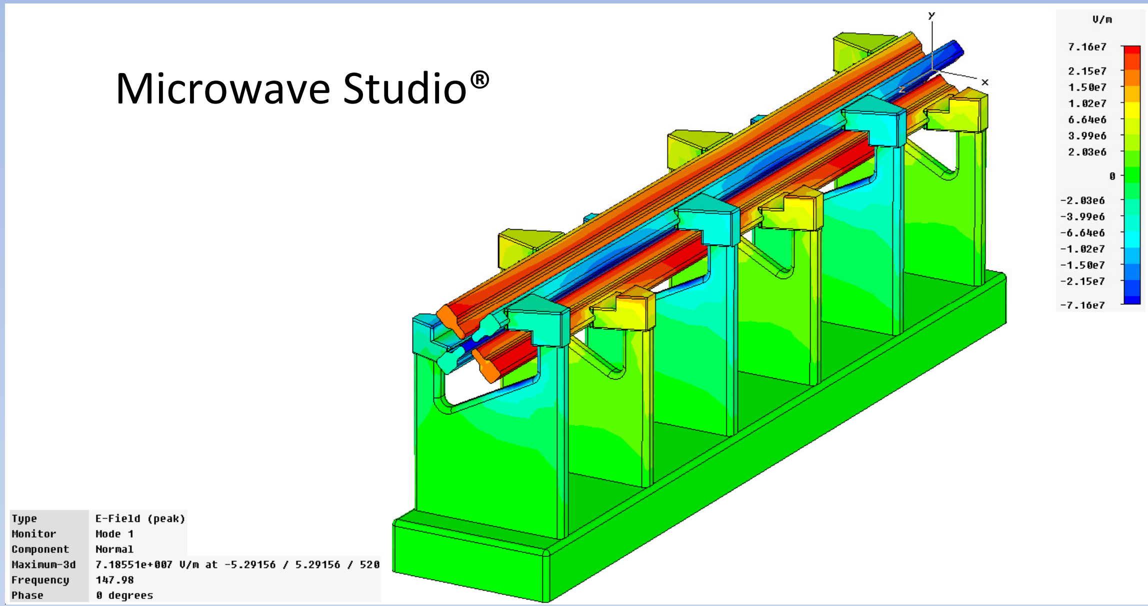


•Following the principle of "charged rings" ⟶ space charge forces applied in the middle of an RFQ cell where cylinder symmetry of the bunch is given.

•Checked by calculating spherical charge distribution, which can be treated analytically.

•Alternative: Poisson solver, solving Poisson equation on a grid ⟶ mirror charge. Takes a lot of computing power and time.

Resonator Design



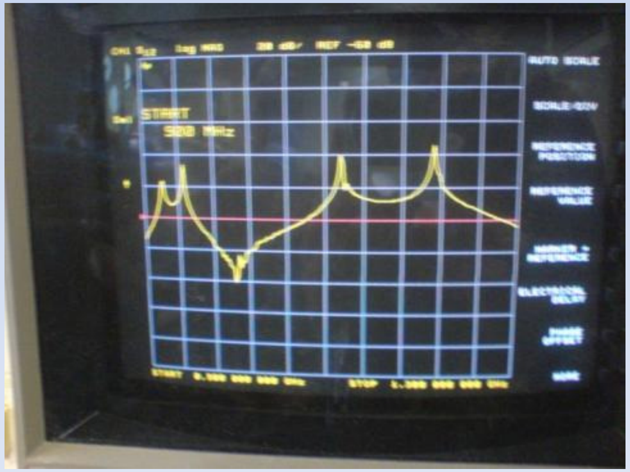
- Frequency
- HOM spectrum
- Power Consumption (R_p-value)
- Peak Fields
- Power dissipation on Parts
- Field distribution (introducing modulation)
- Feedback on electrode design to get balanced design.

Power density is 2-4 times higher than for 4-vane structures.

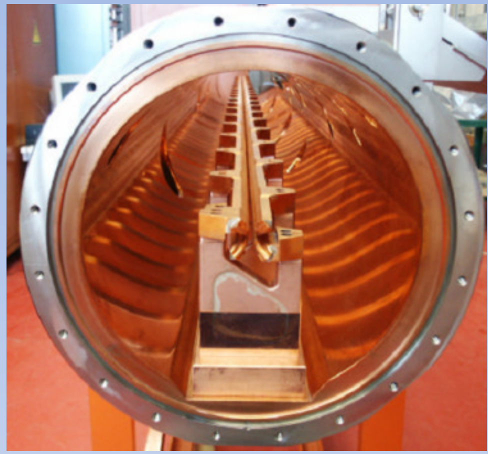
Simple stem and electrode cooling can compensate for that.

Stable operation at ΔT = 50 K is proven with only marginal effect on beam dynamics.

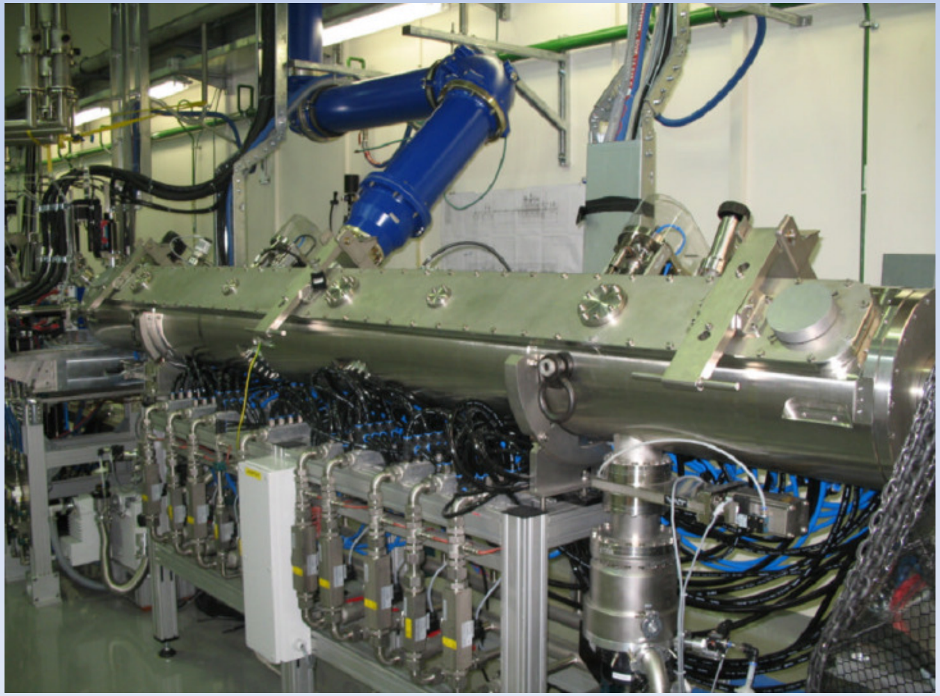
Modeling



SARAF RFQ at Soreq Israel

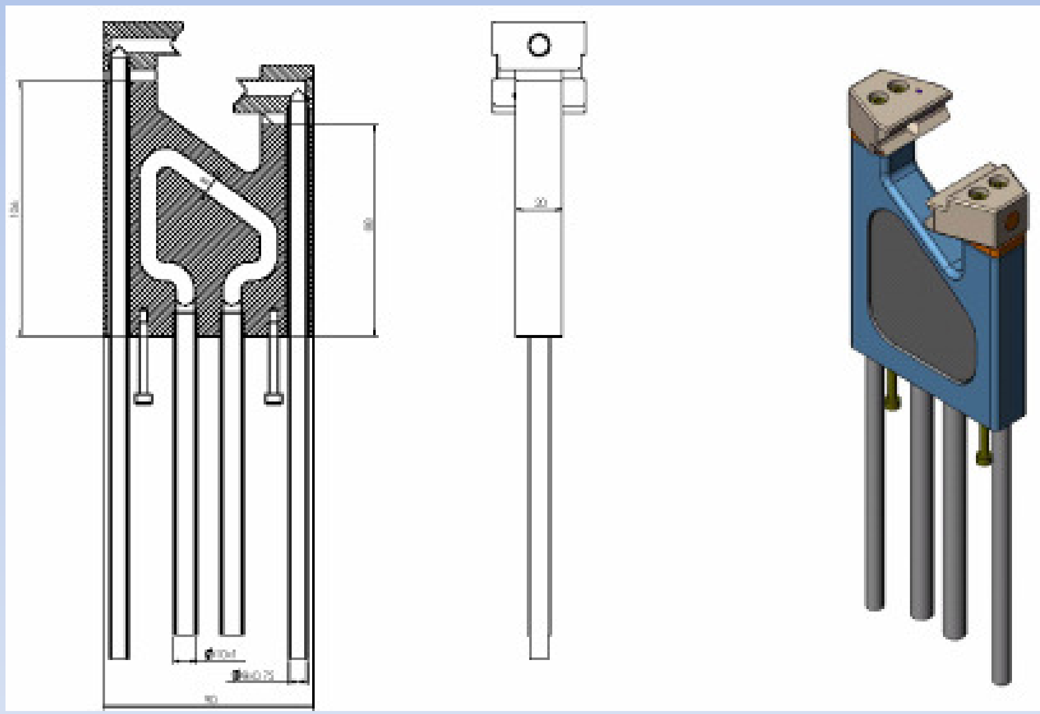


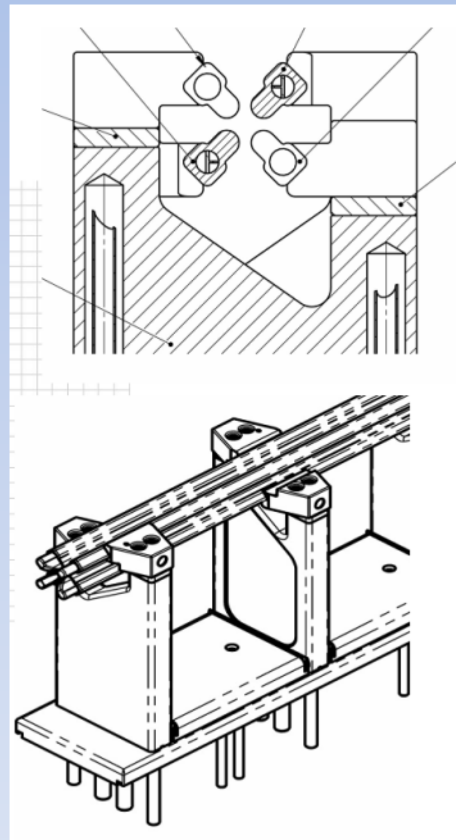
Parameter	Value
frequency f_0 [MHz]	176
input energy W_{in} [keV/u]	20
output energy W_{out} [keV/u]	1500
max. mass to charge ratio A/q	2
inter electrode voltage V_{el} [kV]	65
electrode length [cm]	390
duty factor [%]	100
thermal load [kW/m]	62.5



- Most recent high power 4-rod-RFQ in operation.
- Has proven stable operation at 47.5 kW/m (!), which already exceeds the ever reached thermal load on a 4-rod structure by a factor of 2.4
- 85% dc reached at 250 kW (spec.).
- will serve as a prototype for upcoming high power applications.

Cooling Concept at SARAF

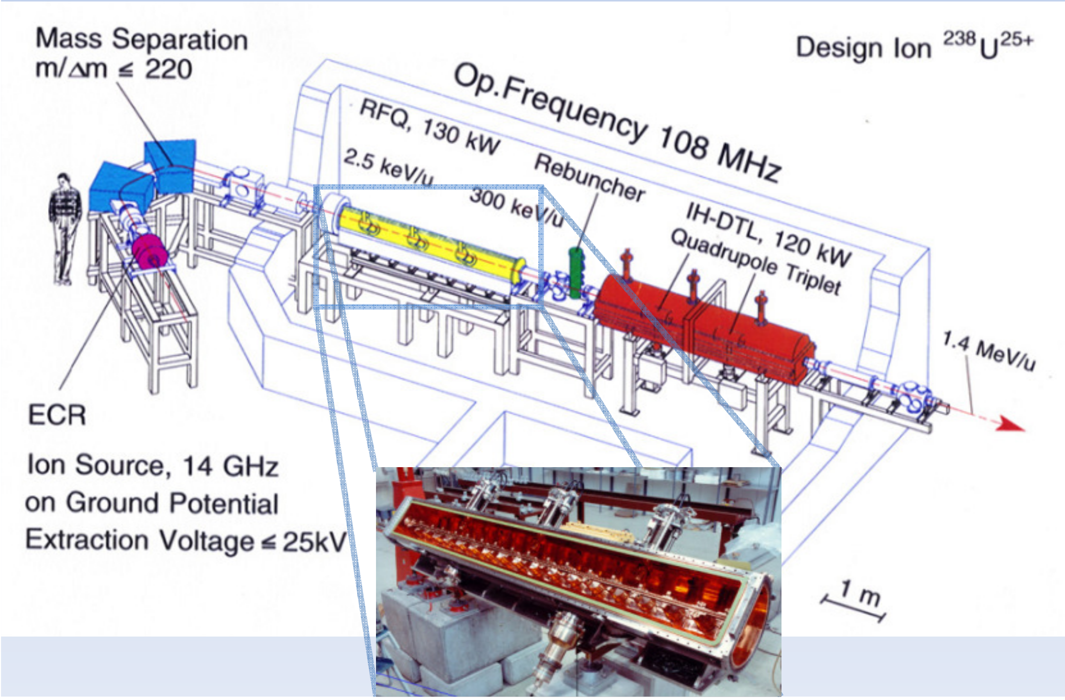


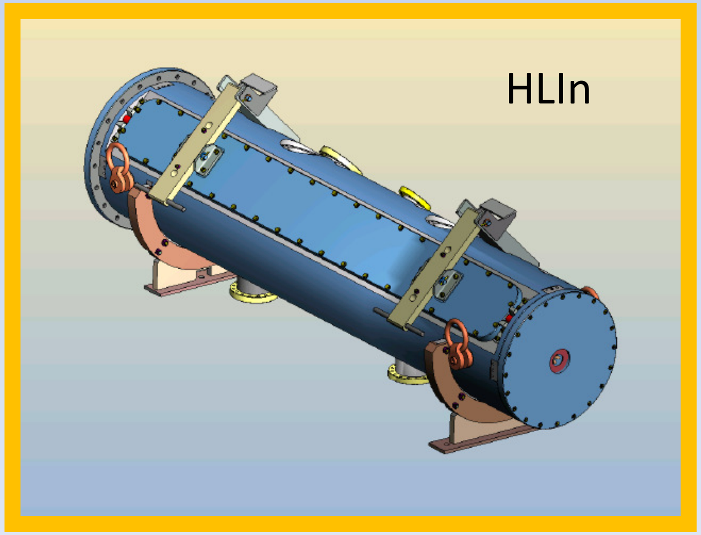


GSI HLI-RFQ

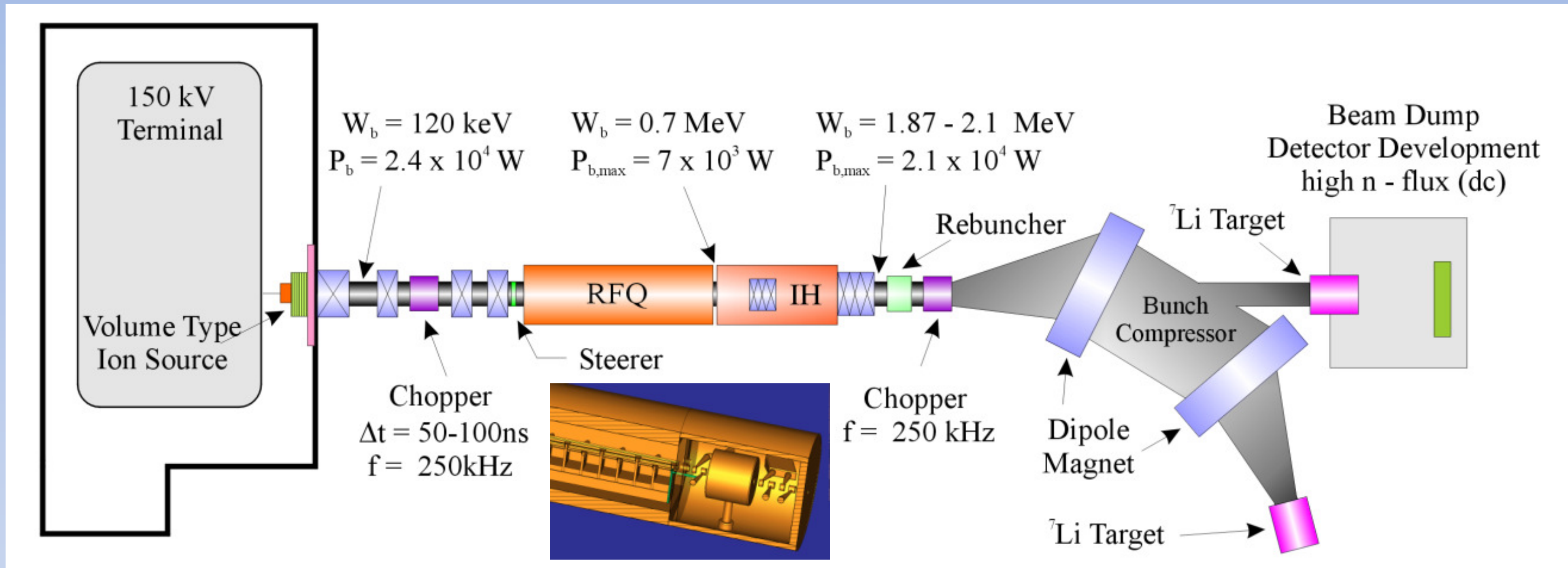
Parameter	*HLI*	*HLIn*
frequency f_0 [MHz]	108.48	108,48
input energy W_{in} [keV/u]	2.5	4
output energy W_{out} [keV/u]	300	300
max. mass to charge ratio A/q	8.5	6
inter electrode voltage V_{el} [kV]	85	55
input emittance $e_{rms,norm.,in}$ [mm mrad]	0.07	0.1
output emittance $e_{rms,norm.,out}$ [mm mrad]	0.12	0.1009
electrode length [cm]	305	199.5
duty factor [%]	25	100
thermal load [kW/m]	7	28

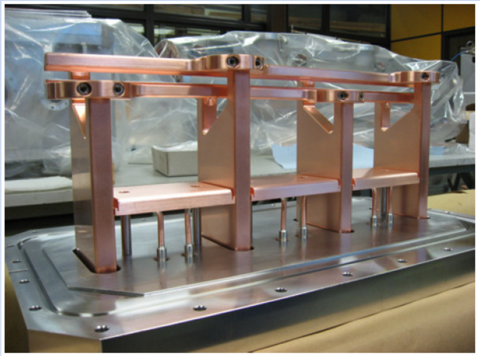
- In operation since 1991
- first ECR-RFQ-IH combination
- Prototype injector for the Lead Injector CERN, Medicine Injector Heidelberg,,,
- Problem: steep angle at injection due to low input energy.
- Upgrade: New ECR IS with e.g. higher output energy → reduction of matching problems.

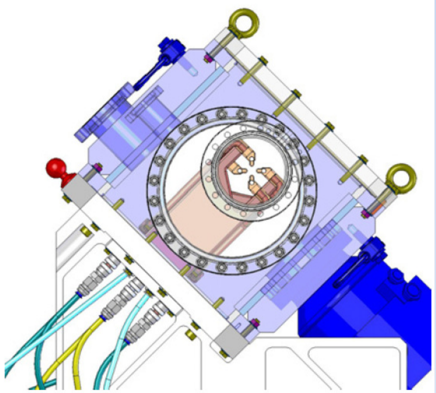




FRANZ RFQ

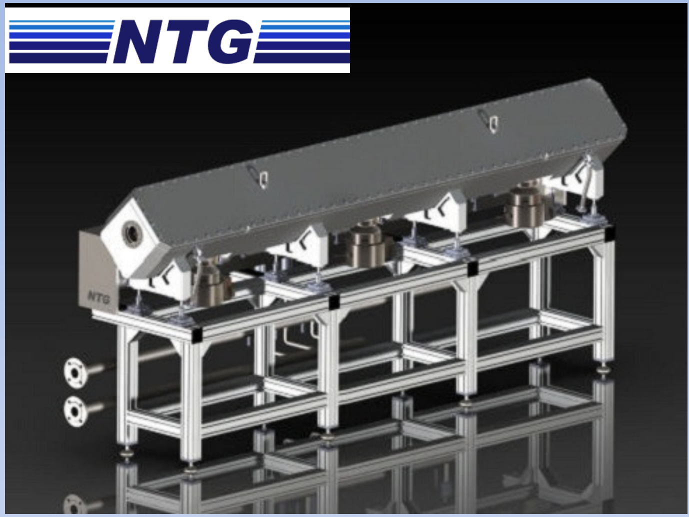


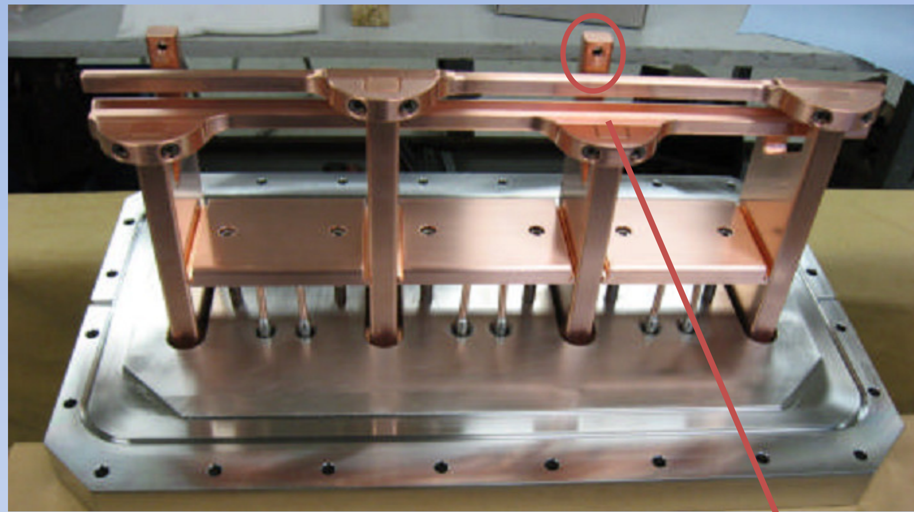


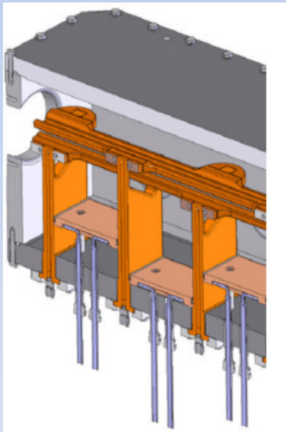


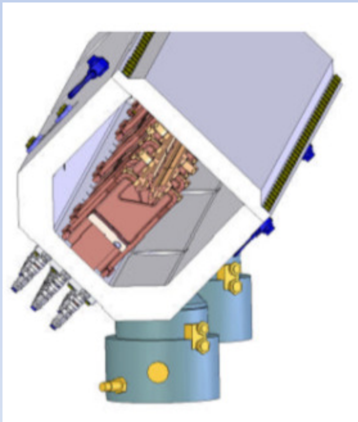
Parameter	Value
frequency f_0 [MHz]	175
input energy W_{in} [keV/u]	120
output energy W_{out} [keV/u]	700
max. mass to charge ratio A/q	1
inter electrode voltage V_{el} [kV]	75
electrode length [cm]	175
beam current [mA]	150-200
duty factor [%]	100
thermal load [kW/m]	65

New Prototyping







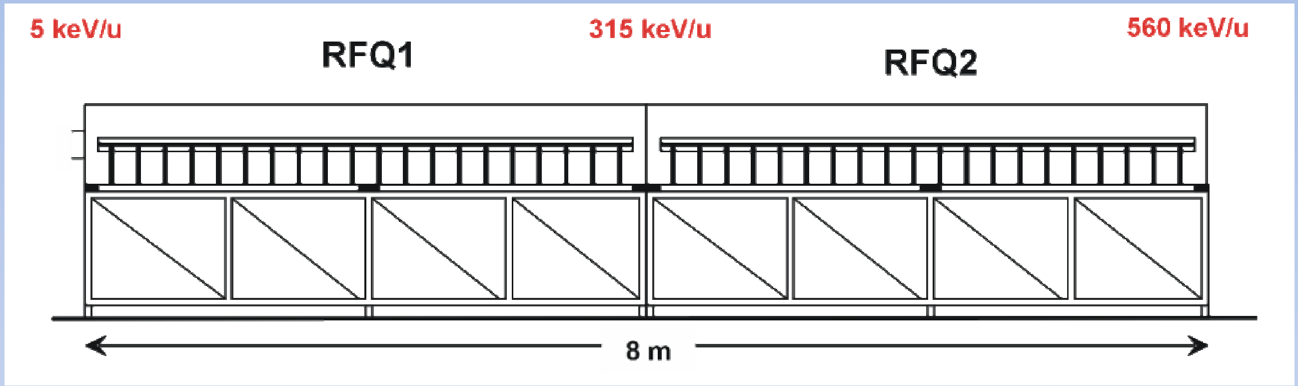


Parameter MSU-RFQ	*Value*
frequency f_0 [MHz]	80
input energy W_{in} [keV/u]	12
output energy W_{out} [keV/u]	600
max. mass to charge ratio A/q	5
inter electrode voltage V_{el} [kV]	87
electrode length [cm]	3.35
duty factor [%]	100

- Less complex
- No shims for excessive alignment (!) → alignment pin on electrode with tight fitting to stem whole.
- Al-cavity is considered to avoid cooper plating (R_p?)
- Block milling, st. steel Flanges, cooling tubes,,,

check at www.ntg.de

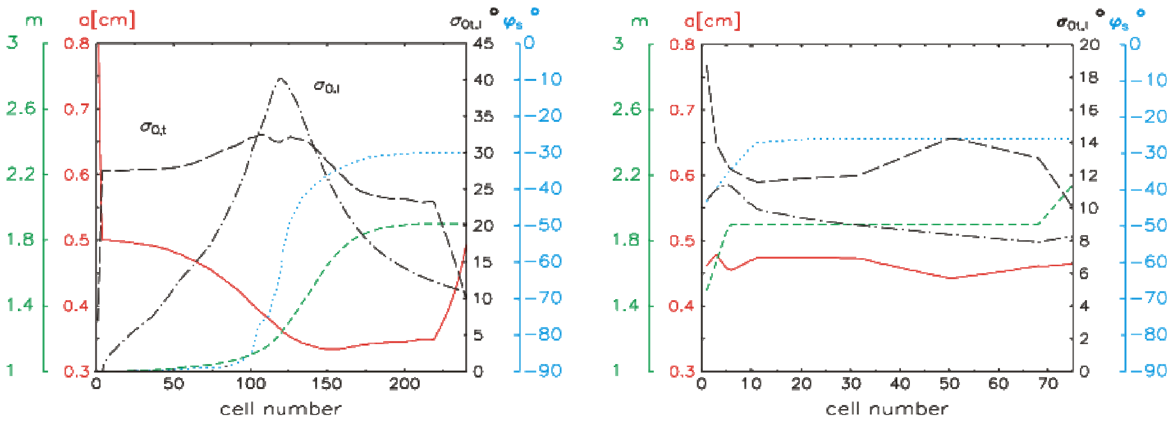
Normal conducting RFQ design for EURISOL post accelerator



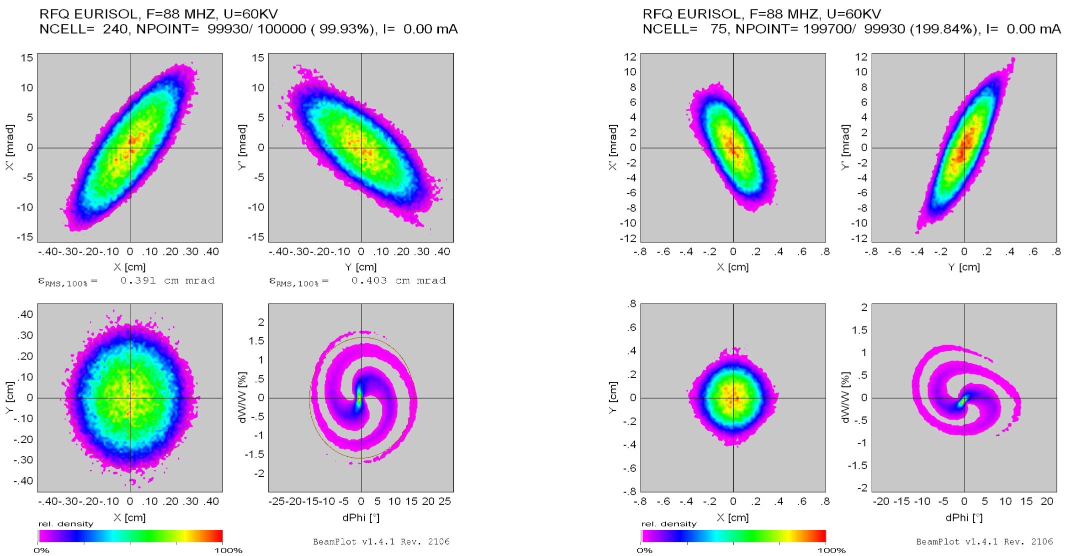
Parameter	*NC-RFQ1*	*NC-RFQ2*
electrode length l_{el}	391 cm	390 cm
frequency f_0	88 MHz	88 MHz
mass over charge A/q	7	7
input energy W_{in}	5 keV/u	319 keV/u
output energy W_{out}	319 keV/u	560 keV/u
minimum aperture a_{min}	3.3 mm	4.4 mm
electrode Voltage V_{el}	60 kV	60 kV
rf-power P_{rf}	120 kW	120 kW
duty cycle	cw	cw
input emittance $\varepsilon_{rms,n}$	0.1 mm mrad	0.105 mm mrad
Transmission	99.9 %	99.9 %
transversal emittance growth	5%	1%
energy spread ΔW	1.5 %	1.3%
phase spread $\Delta\varphi$	15°	15°
thermal load [kW/m]	30 kW/m	30 kW/m

- A/q = 7 tends to high inter vane voltages.
- Limitation to thermal load on structure restrict applicable voltage.
- 60 kV inter vane voltage provides 37% safety margin compared to stable operation reached at SARAF. → Headroom for even higher A/q values.
- 4-rod structure is foreseen, since there is no competitor with respect to maintenance and replacement of possibly activated parts.

Beam dynamics for EURISOL

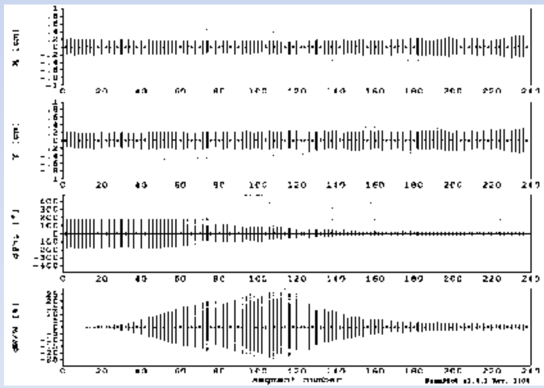


main design parameters along RFQ1 and RFQ2

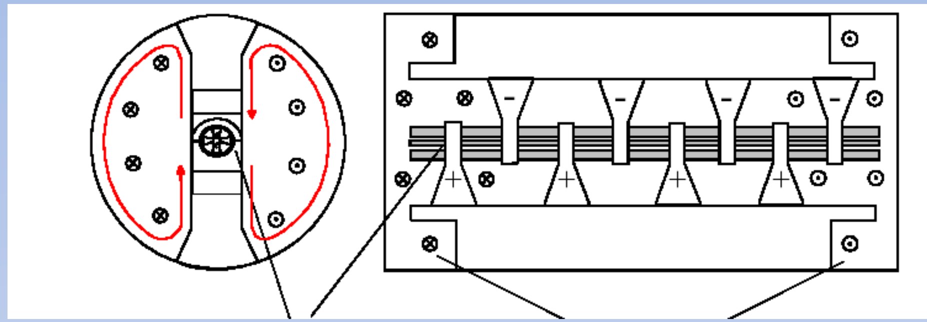


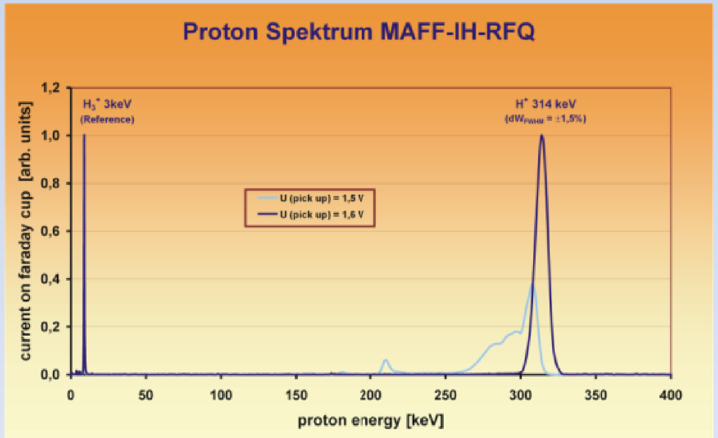
output distribution of RFQ1 and RFQ2

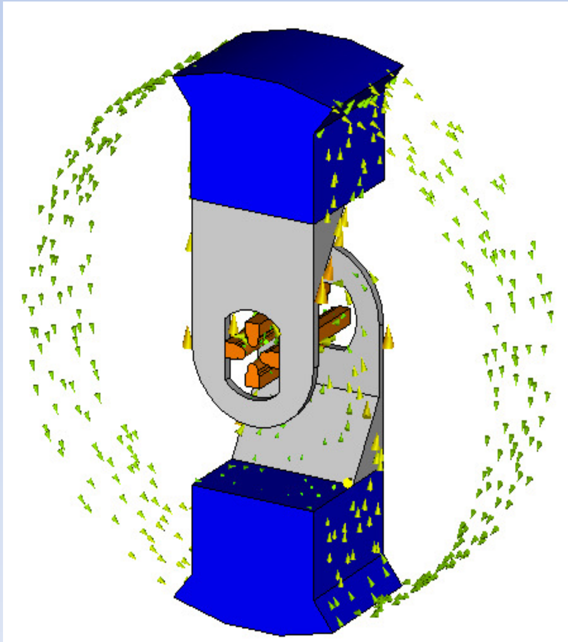
- Design provides loss free transition between RFQ1 and RFQ2.
- Only 5% transversal emittance growth.
- Used code: RFQsim.

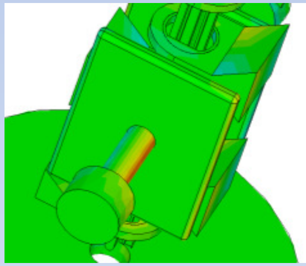


MAFF-IH-RFQ at 101 MHz



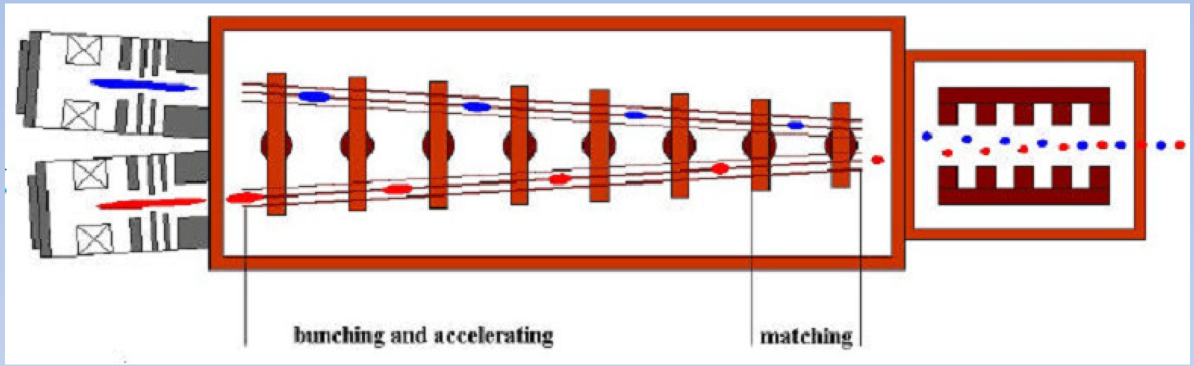


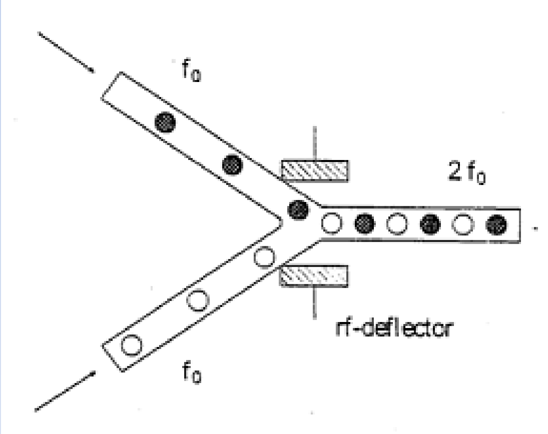




- R_p(IH) ≈ R_p(4-rod)
- Lack of tuning concept → losses on plunger stem.
- R&D in progress.

The Funneling Experiment at 54 MHz





- Limitations of ion sources. $\varepsilon_N \propto I_{beam}$
- Ideal: same emittance, twice the beam current
- Advantages: ε_N = const., higher currents at higher energies
- Experiment: $\Delta\varepsilon > 0$, Tr. < 1

Summary

- The 4-rod structure has proven its ability to withstand a thermal load of 47.5 kW/m, which opens up a new field of high power applications.

- New concepts are currently under investigation to push the limits.

Thanks!

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