THE SPES RFQ:
AN OUTLINE OF THE RF ASPECTS

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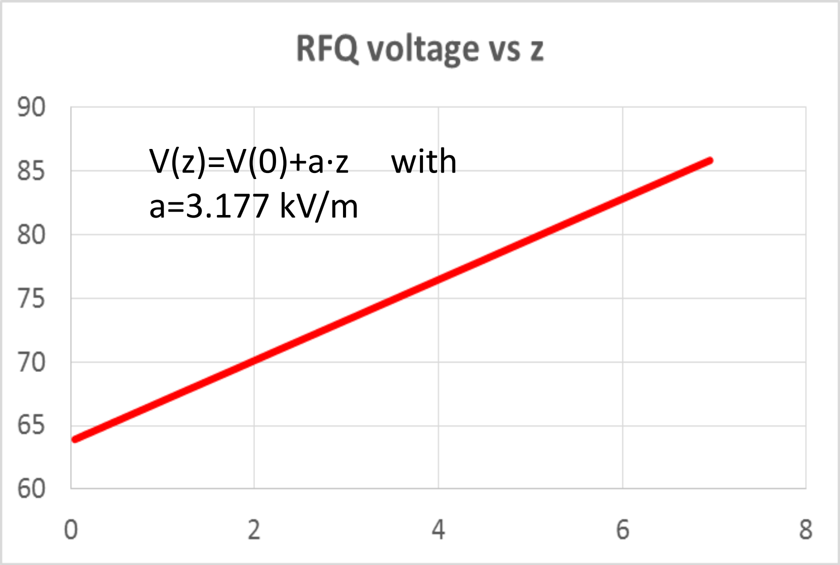
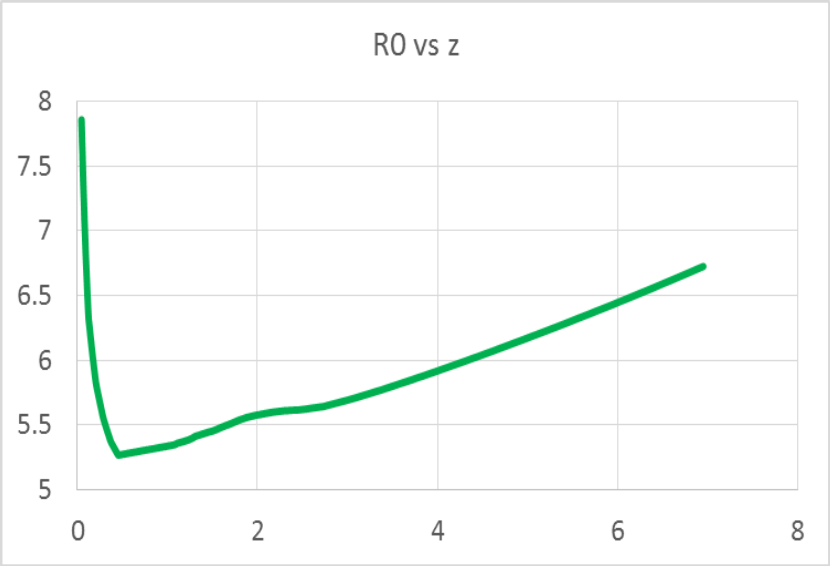
Outline

- RF Design input parameters
- RFQ transverse shape design
- Geometric errors and sensitivities
- RFQ modeling and perturbation analysis
- Tuning algorithm
- 3D aspects: End cell design
- RF joint
- Frequency regulation during operation: tuning with cooling water
- RF amplifier, tuner design, RF coupler design
- Conclusions

Input parameters

- Beam dynamics calculations outputs used as input for RF design, namely Voltage law, R0 law, r law for each RFQ cell. cavity length.

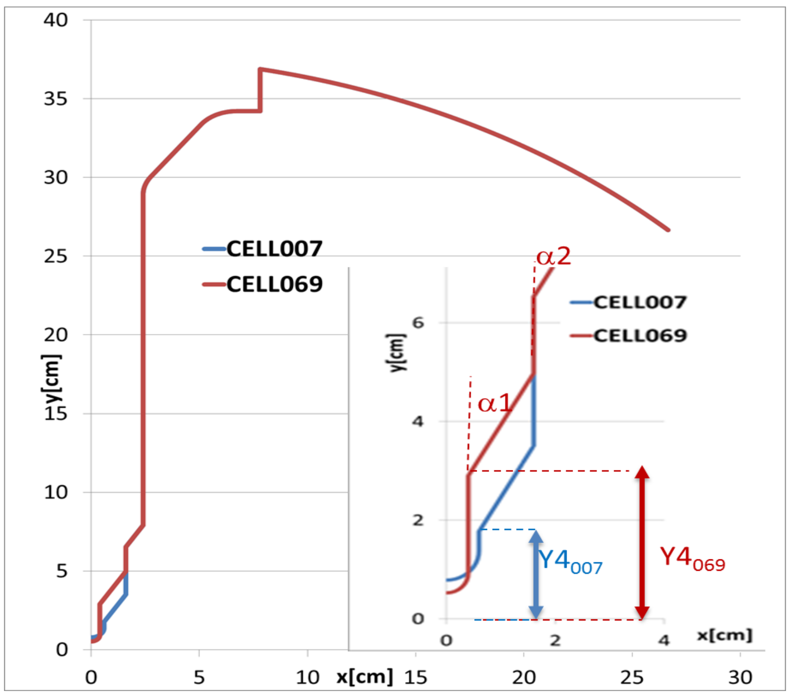




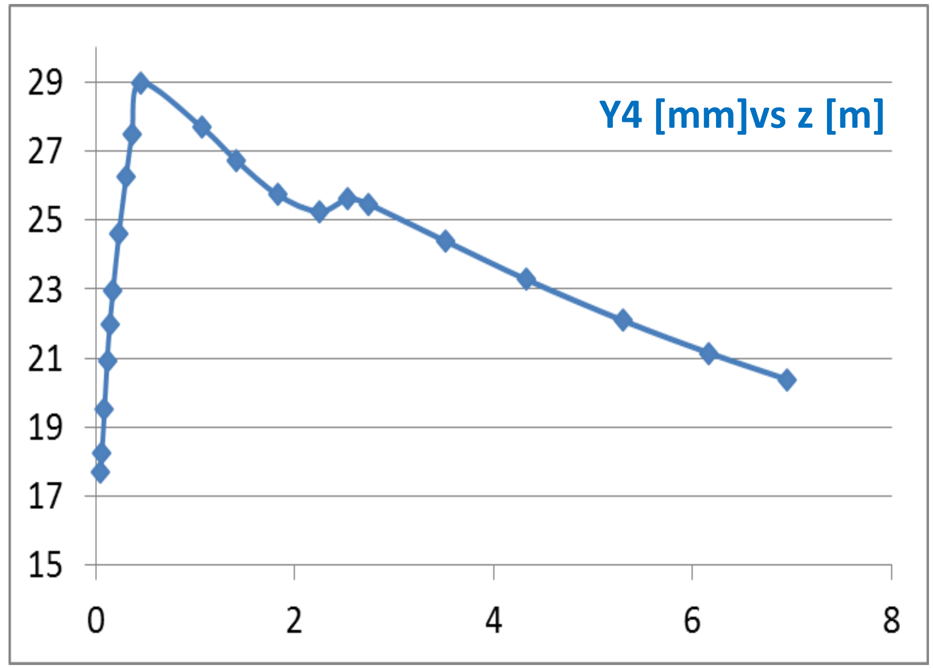
In order to implement V(z) all sections are designed with same constant TE_{21} cut-off frequency fc=79.5 MHz (see slides on the tuning) ; then by properly shaping the vane undercuts at the Low and High Energy Ends of the RFQ the desired voltage slope is obtained.

RFQ transverse section design

- In order to ease machining the capacitive region is varied along the RFQ. The electrode thickness is equal to 48 mm, the vane angles α1 and 2 are equal to 30° and the tank radius is equal to 377 mm.

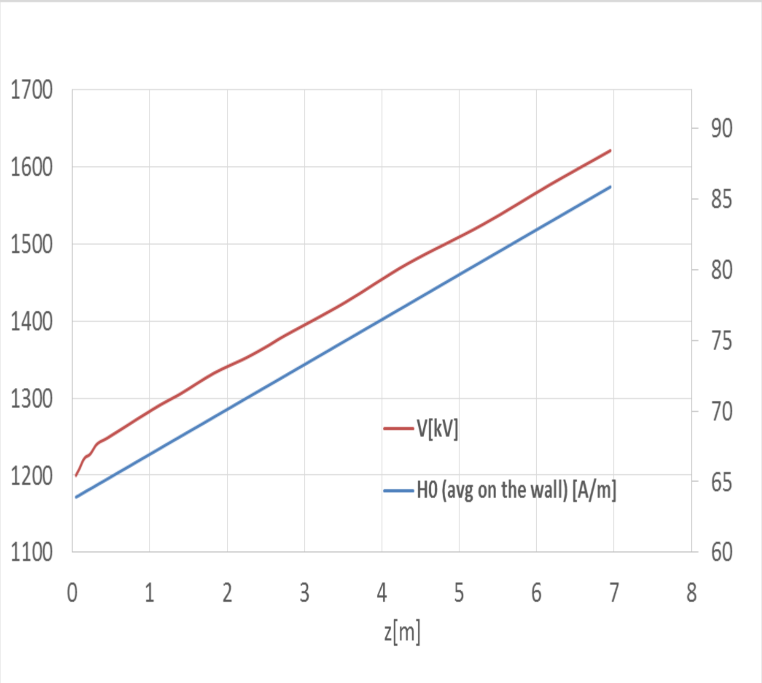


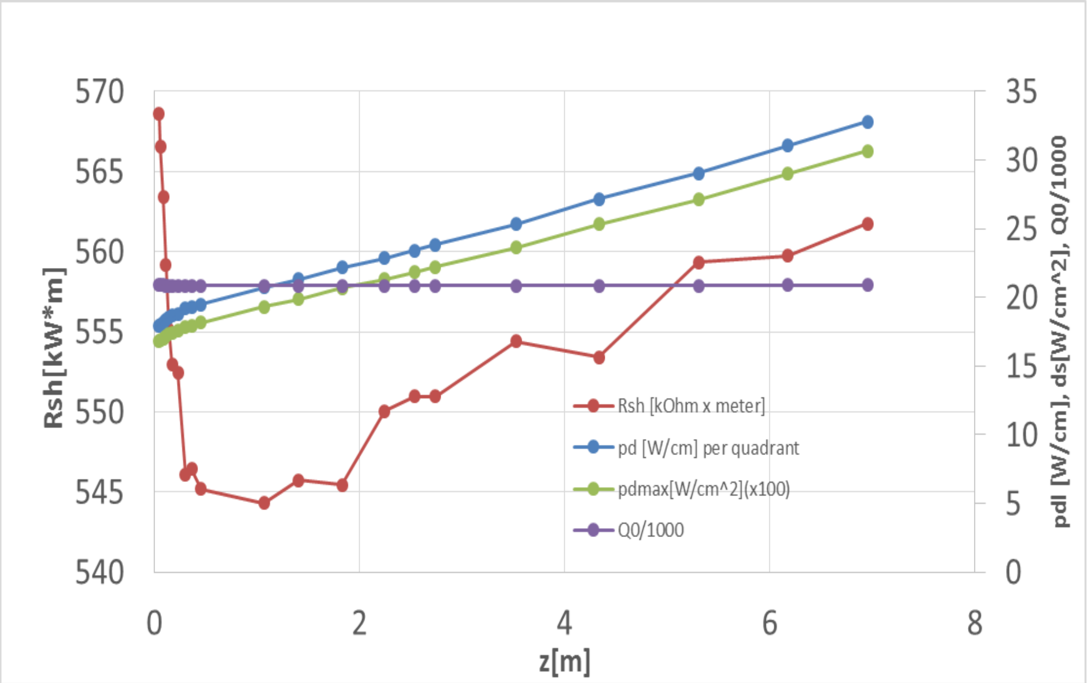
1/8 of RFQ with the capacitive tuning zone



Y4 (tuning height) vs z

RFQ transverse section design (2)





Voltage and magnetic field vs z (SFISH)

Shunt impedance and power densities (linear and surface) vs z (SFISH)

RFQ transverse section design (3)

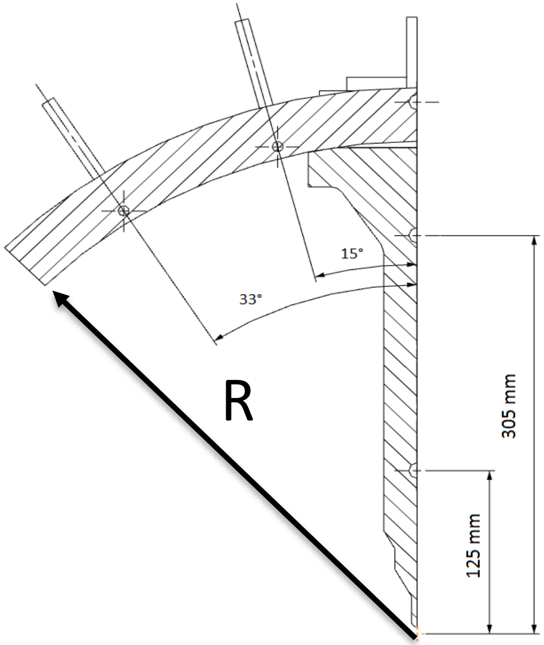
Summary of SUPERFISH Calculations

Paramater [units]	Design value
Frequency [MHz]	80
TE_{21}[TE_{11}] cut-off frequency [MHz]	79.5 [77.3]
$V_{intravane}$[kV]	63.76-85.85
R_0[mm]	5.29-7.58
Shunt impedance [kΩ*m]	545-569
Stored Energy [J]	2.87
RF Power [kW] (SF) (P_0)	74
Q_0 value (SF)	20900
Max power density [W/cm^2]	0.31

$$P_{RF}=P_0 \cdot \alpha_{RF}=P_0 \cdot \alpha_{RF} \cdot \alpha_{reg}=73\text{ kW}\cdot 1.3\cdot 1.2=73\text{ kW}\cdot 1.56=115\text{ kW}$$

α_{RF}= margin for 3D details and RF joint
α_{reg}= margin for LLRF regulation

Error sensitivity calculations



χ_R=-200 kHz/mm

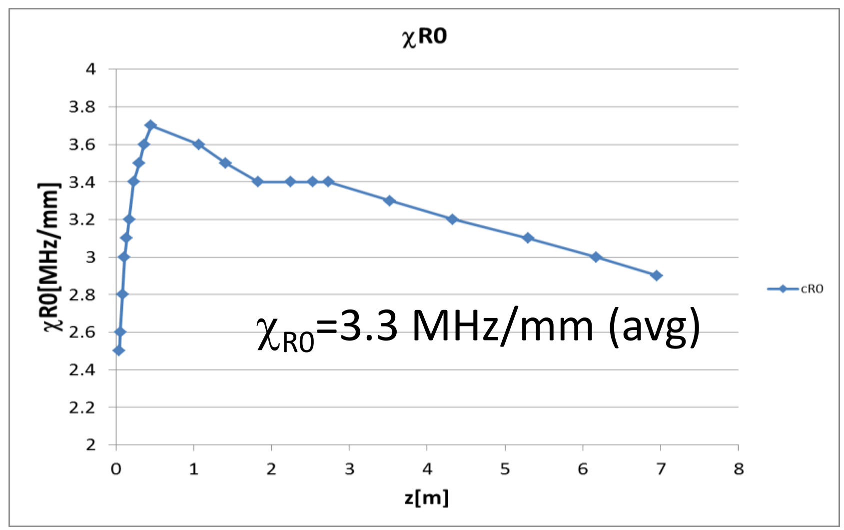
$$\delta f_0=\chi_{R0}\Delta R0+\chi_\rho\Delta\rho+\chi_R\Delta R$$

$\delta\rho$ => construction accuracy (±(10-20) μm)

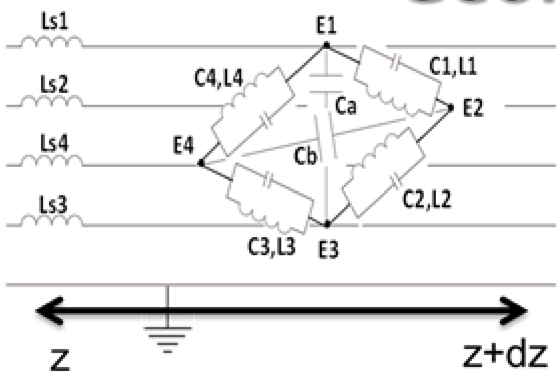
δR_0 => electrode positioning (errors of ± 100 μm can occur), due to alignment and/or brazing.

δR => tank machining errors ((errors of ± 100 μm can occur)

R_0 errors are dominant=> $\delta f_0 \approx \chi_{R0}\Delta R_0$



Geometric error modeling



$$\frac{d\underline{U}}{dz} = -j\omega \underline{\underline{L}}_s \underline{I}$$

$$\frac{d\underline{I}}{dz} = -\left(j\omega \underline{\underline{C}} + \frac{1}{j\omega}\underline{\underline{L}}\right)\underline{U}$$

$$\frac{d^2\underline{U}}{dz^2} = \left(-\frac{\omega^2}{c^2} + \frac{1}{c^2}\underline{\underline{C}}^{-1}\underline{\underline{L}}\right)\underline{U}$$

$$\underline{\underline{L}}_s \underline{\underline{C}} = \frac{1}{c^2}\underline{\underline{I}}_4$$

Variation of geometric parameters R_0, R=> δR_0, δR

Variation of circuit paramaters L, C, f0 => δL_i, δCi, δf_0

Perturbation of the d^2/dz^2-$\mathbf{C}^{-1}\mathbf{L}$ operator

$$c^{-2}\delta\left(\underline{\underline{C}}^{-1}\underline{\underline{L}}\right) = c^{-2}\left(\underline{\underline{C}}^{-1}\underline{\underline{\delta L}} - \underline{\underline{C}}^{-1}\underline{\underline{\delta C}}\,\underline{\underline{C}}^{-1}\underline{\underline{L}}\right)$$

$$\underline{\underline{\delta k}}^2 = c^{-2}\underline{\underline{S}}^{-1}\underline{\underline{C}}^{-1}\left(\underline{\underline{\delta L}} - \underline{\underline{\delta C}}\,\underline{\underline{C}}^{-1}\underline{\underline{L}}\right)\underline{\underline{S}}$$

Perturbative Development

$$\underline{\phi} = \underline{\phi}_{q0} + \delta\underline{\phi} = \underline{\phi}_{q0} + \sum_{n=1}^{\infty} a_{qn}\underline{\phi}_{qn} + \sum_{n=0}^{\infty} a_{d1n}\underline{\phi}_{d1n} + \sum_{n=0}^{\infty} a_{d2n}\underline{\phi}_{d2n}$$

$$a_{qn} = \frac{-\omega_0^2}{4(\omega_0^2 - \omega_{qn}^2)}\int_0^{\ell} \varphi_{q0}\varphi_{qn}\left(\frac{\delta C_{QQ}}{C} + \frac{\delta L_{QQ}}{L}\right)dz \quad n \in N$$

$$a_{d1n,d2n} = \frac{-\sqrt{2}\omega_0^2}{4(\omega_0^2 - \omega_{dn}^2)}\int_0^{\ell} \varphi_{q0}\varphi_{dn}\left(\frac{\delta C_{Qd1,Qd2}}{C} + \frac{\delta L_{Qd1,Qd2}}{L}\right)dz \quad n \in N_0$$

$$\delta C_{QQ}(z) = \delta C_1(z) + \delta C_2(z) + \delta C_3(z) + \delta C_4(z)$$

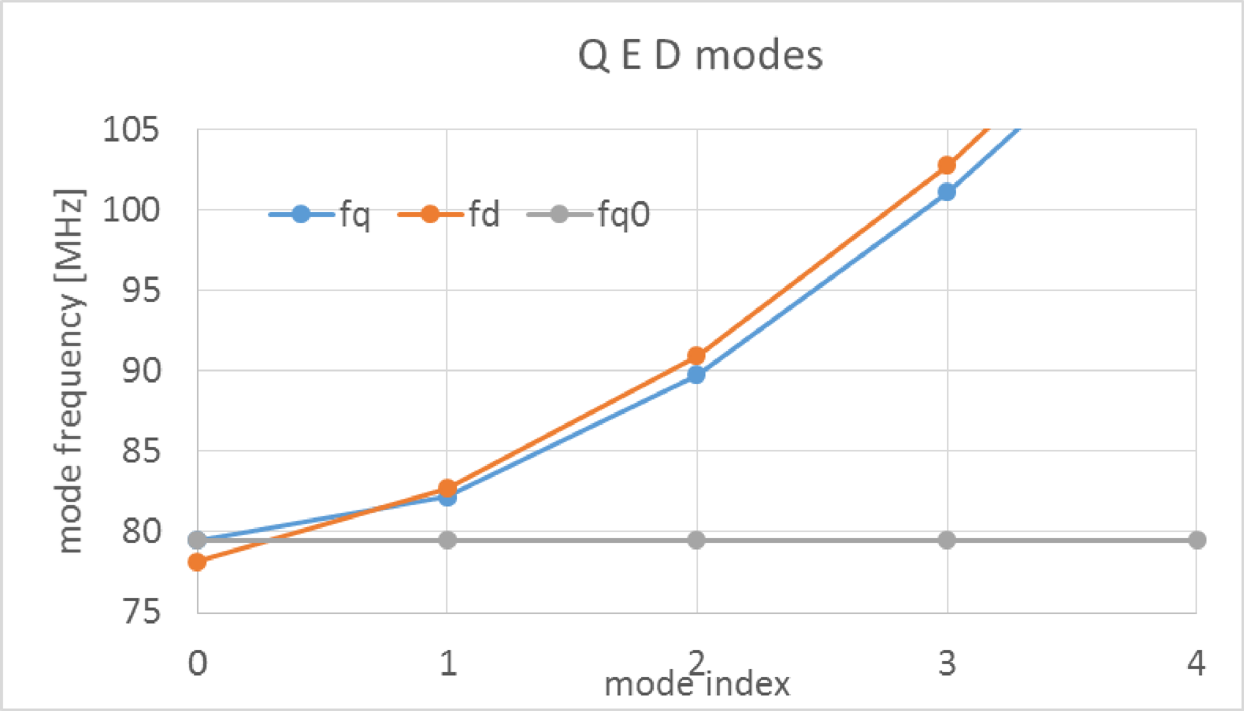
$$\delta L_{QQ}(z) = \delta L_1(z) + \delta L_2(z) + \delta L_3(z) + \delta L_4(z)$$

$$\delta C_{Qd1}(z) = \frac{\sqrt{2}(\delta C_1(z) - \delta C_3(z))}{(1+h)}, \delta C_{Qd2}(z) = \frac{\sqrt{2}(\delta C_4(z) - \delta C_2(z))}{(1+h)}$$

$$\delta L_{Qd1}(z) = \sqrt{2}(\delta L_1(z) - \delta L_3(z)), \delta L_{Qd2}(z) = \sqrt{2}(\delta L_4(z) - \delta L_2(z))$$

$$\delta\omega_0 \cong -c^2 / 2\omega_0 \left\langle \underline{\phi}_{q0} \middle| \underline{\underline{\delta k}}^2 \middle| \underline{\phi}_{q0} \right\rangle$$

Q & D modes



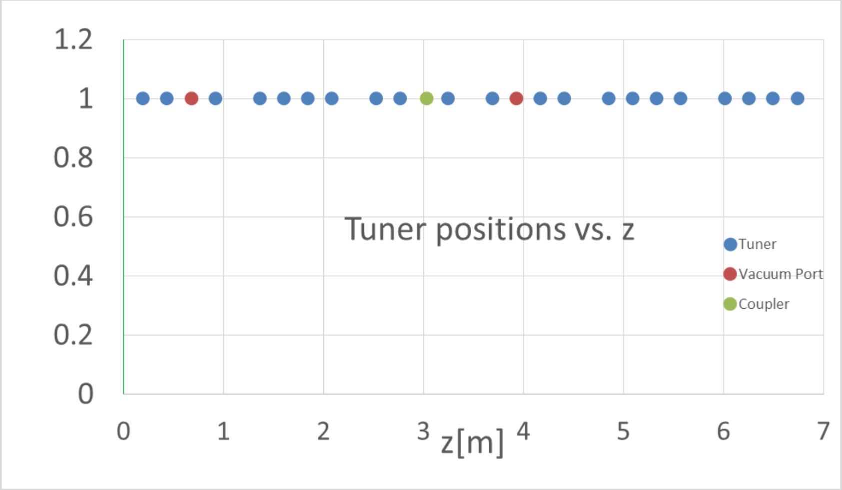
Dispersion relationship for the RFQ with tuned undercuts calculated with TL theory.

- The 1st upper quadrupole mode frequency is 2.7 MHz higher then the f_0 = 79.5 MHz
- The dipole free region is not symmetric with respect to f_0. In fact f_{d0}=78.14 MHz and f_{d2}= 81.49 MHz.

Tolerance budget and tuning range

- For the given R_0 sensitivity, the idea is to allow a maximum ΔR_0 variation of $\Delta R_{0,max}$ =±150 μm all along the RFQ. This determines the frequency tuning range

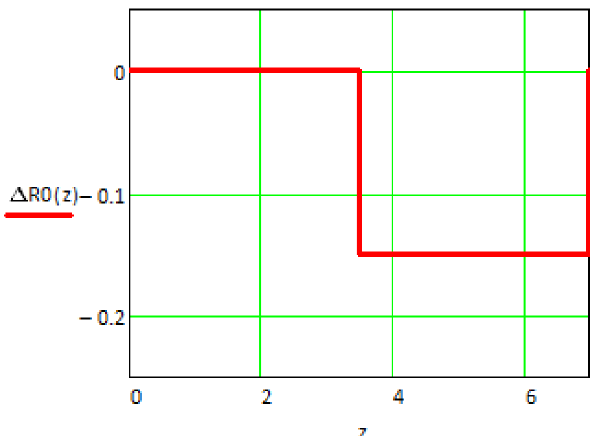
  $[f_0 - \chi_{R0}\Delta R_0+, f_0 + \chi_{R0}\Delta R_0]$ = [79.5MHz,80.5MHz]
- In order to keep the same design of IFMIF tuners, the tuner radius is equal to 44.5 mm.
- The number of tuners is N_T=84 (21 per quadrant): the average tuner sensitivity is equal to about χ_{tun}= 10 kHz/mm (all tuners). Therefore, the tuning range can be spanned with a range of tuner depths $h_t=[h_{tmin}, h_{tmax}]$= [0 mm, 100 mm], corresponding to a nominal tuner position of h_{t0}=50 mm.

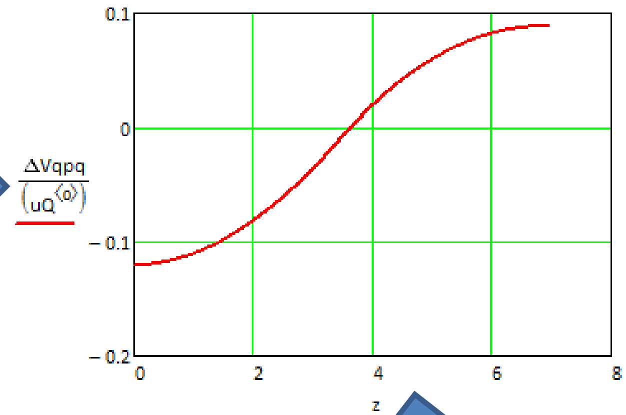


The amount of extra power ΔP dissipated by the tuners, is $\Delta P=(R_s/2)H^2 2\pi a N_T h_{tmax}$, R_s =surface resistance, H= magnetic field in the tuner location. In our case $\Delta P/P_0$ = 0.08

Application of the tuning algorithm

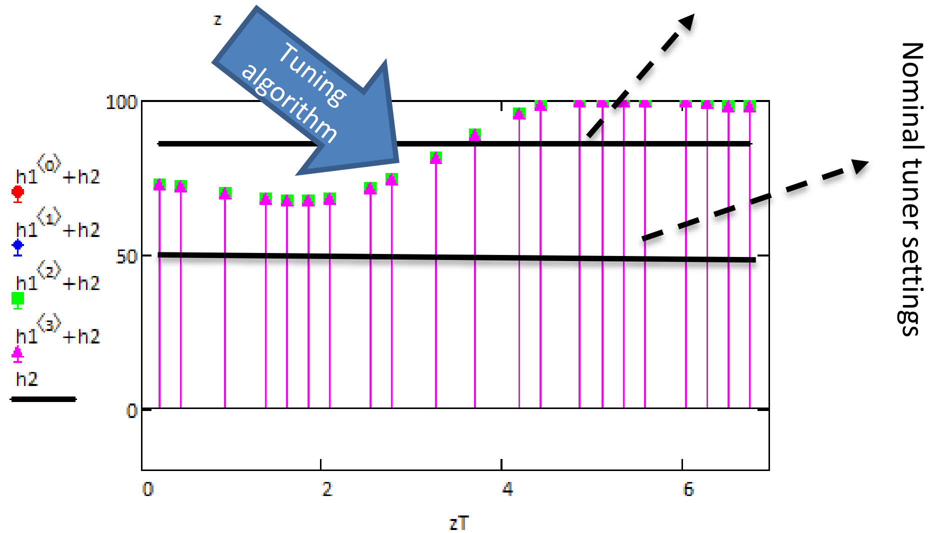
Test case: let us suppose to have a misaglinement of all four elctrodes of 150 mm towards the beam axis for the first 3 RFQ modules (half RFQ length). In this case vane undercut are present, but no Dipole stabilizers are used.

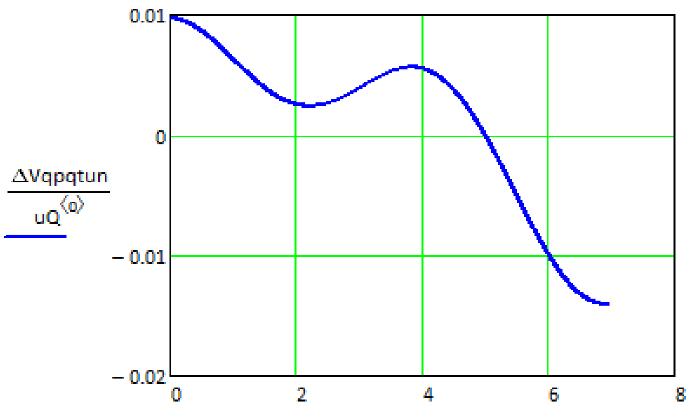




The effect is a ΔV/V=±10% volatge variation and a frequency shift of -280 kHz

Offset for frequency correction

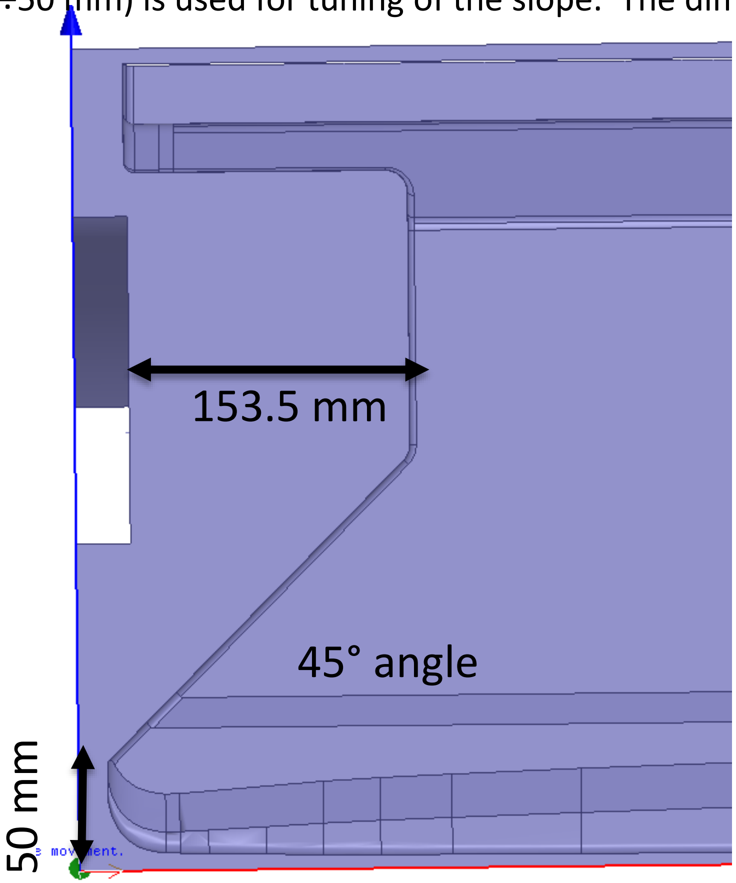




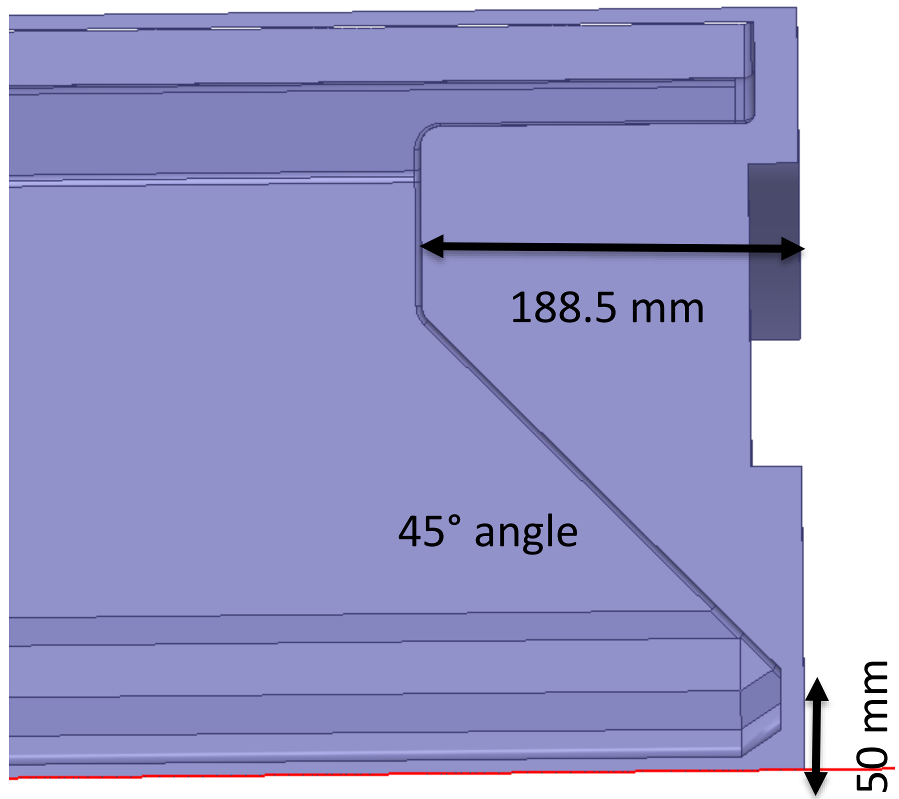
Tuned voltage ΔV/V=±1.5%

3D details: End cells

The end cells of the RFQ have to provide the proper value of the voltage slope at both RFQ ends, that is $s_a = V'(0)/V(0)$, $s_b = -V'\,(L)V(L)$ In general $s_{a,b} = \kappa({f_{EC}}^2 - f^2)$. Since all the RFQ sections have the same cut-off frequency, the end cell tuning is obtained by tuning the low [high] energy cell high [low] in frequency with respect to the RFQ. The dimensioning of the vane undercut is made with a 45° angle and a tuning ring (internal radius 150 mm, external radius 300 mm, thickness 0÷50 mm) is used for tuning of the slope. The dimensions of the undercuts were optimized with HFSS simulations.

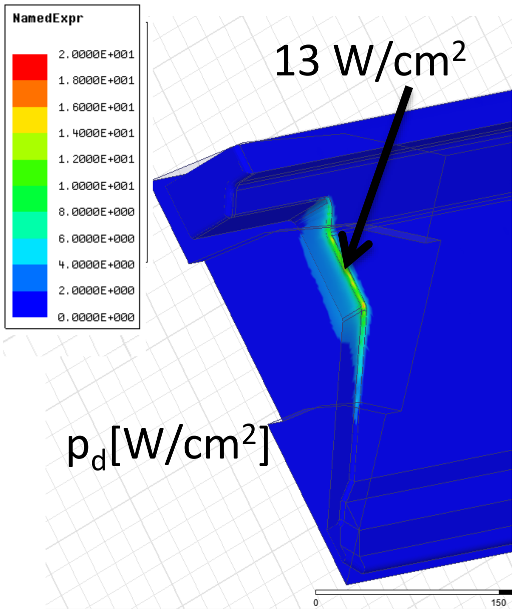


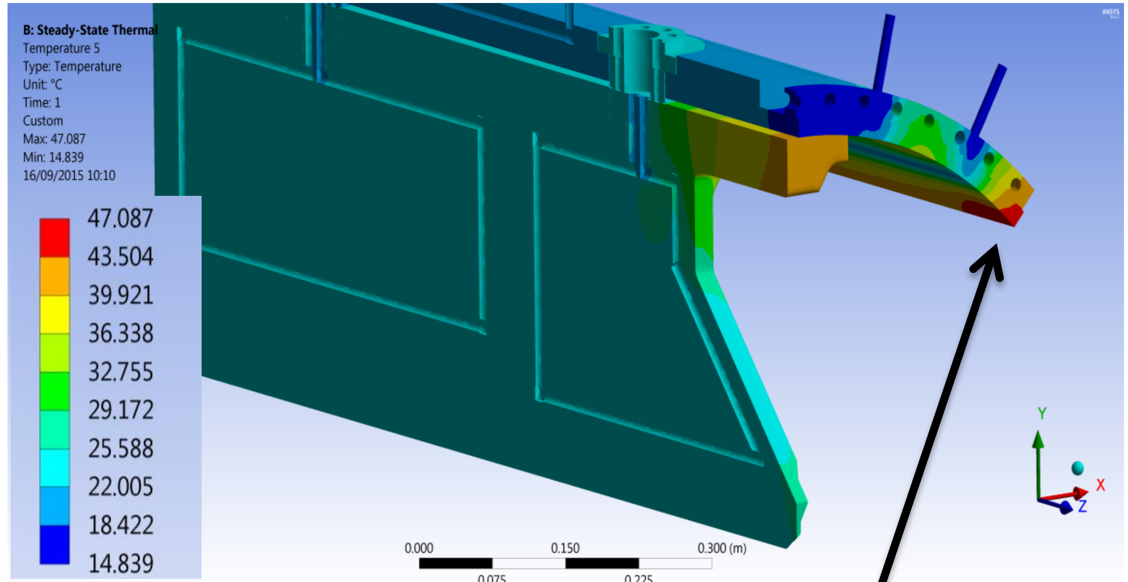
LE side



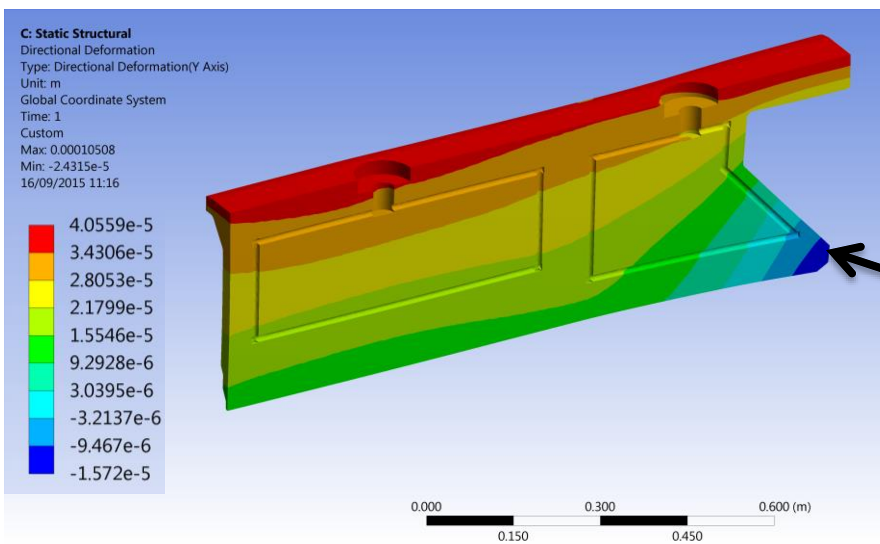
HE side

3D details: End cells (2)





Tmax = 47°C, v=3m/s



Power density, Temperature and deformations for the HE side

Maximum tip displacement 15 µm

The RF joint between electrode and tank

In order to allow proper operation of the RFQ, a RF joint must be placed longitudinally between the electrode and the tank. Moreover the electrical properties of the joint have to comply with the possibility of ±0.2 mm regulation of the electrode orthogonally with respect to beam axis.

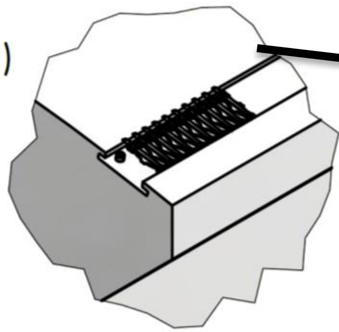
Contact main properties

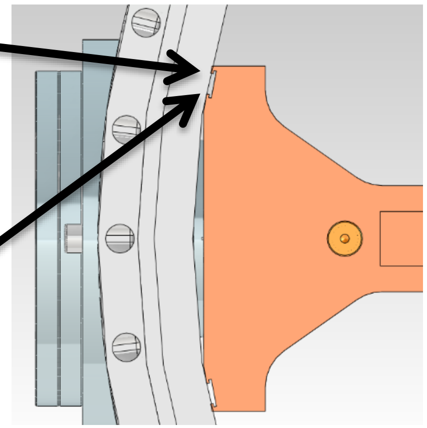
$I_{max} = H_{max} * L_{module} = 1650$ A/m*1.15 m =1900 A, T=40°C (operating temperature), P=10^{-7} mbar (operating pressure)

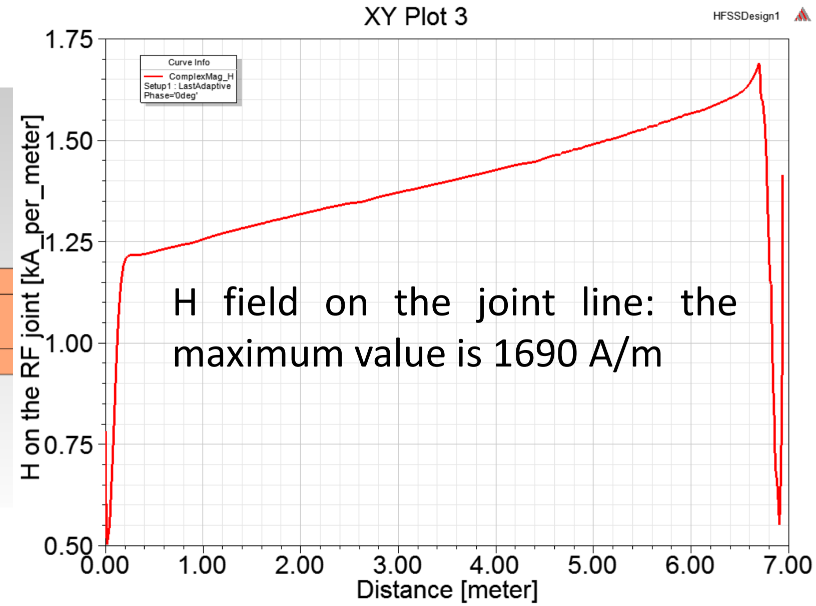
Solution: usage of a multi-louver reed-shaped spring joint Contact louvers in copper, silver-plated
and mounted on a stainless steel carrier., i.e. the LA-CUD/0,15/0/477ST joints,by Multi-Contact® (400 louvers/m), which guarantee (in particular the LA-CUD joint) a current capability of tenth of Amperes per louver, the required regulation (±0.6 mm, nominal) , and a shrinkage force in the range of (200 ÷320) kg per meter of spring joint . The variation of this force, connected with the positioning of the electrode, cause the contact resistance to vary accordingly.
The same type joint was used for the couplers of TRASCO and IFMIF RFQs.

Longitudinal currents: Since the RFQ voltage is not uniform along z-axis, in addition to the transversal current given by SuperFish a longitudinal component of Surface Current on cavity walls is to be expected.As for longitudinal currents is concerned, HFSS simulations showed that |Htransv|/|Hlong| is in the order of 0.1%.

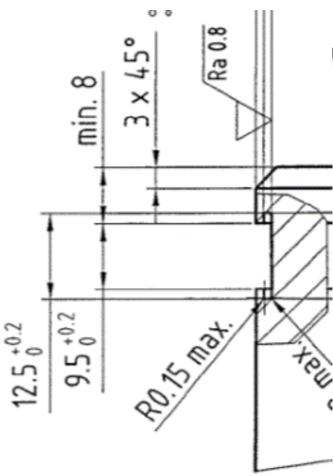
The RF joint between electrode and tank (2)



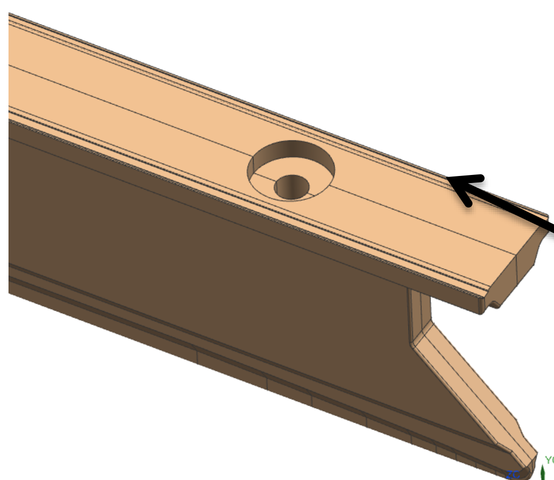


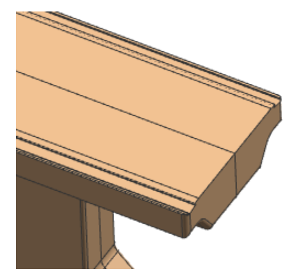


H field on the joint line: the maximum value is 1690 A/m



Detail of the groove for the spring joint



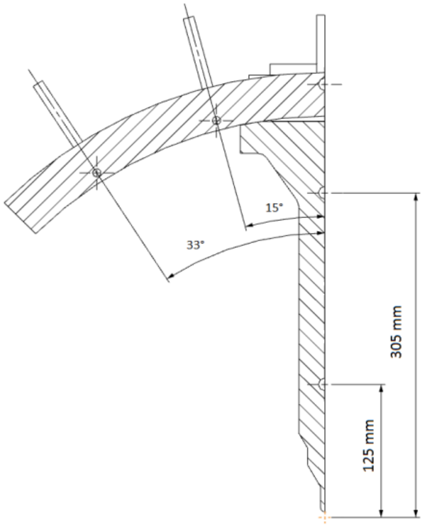


Longitudinal position of the groove and detail on the undercut region

RF regulation with water cooling

The RFQ Cooling system is designed to remove power and to finely tune the cavity resonant frequency during operation by temperature regulation. For such a purpose, it is necessary to have two independent water loops with two temperature set points: a “cold” circuit for the tank, and a “warm” one for the vanes. By mixing with a 3-way valve the cold inlet water with part of the warm water coming from the cavity, it is possible to vary the resonant frequency of the RFQ and to tune the cavity accordingly. Let us notice that

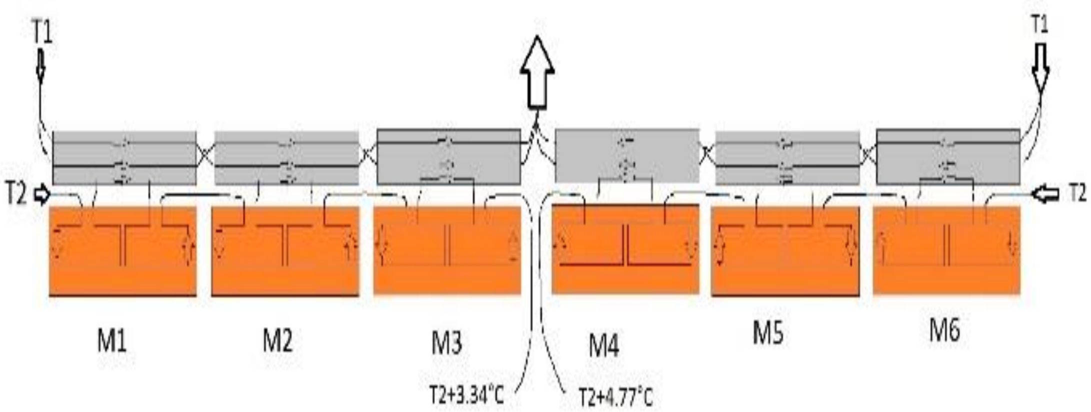
- the vane and the tank are thermally insulated
- the RF power balance is approximately 60% on the vanes (Cu) and 40% on the tank (SS).
- The channel radii are Rc_2= 6 mm on the vane and Rc_1=4 mm on the tank, the inlet water velocity is 3 m/s and consequently the heat convection coefficient h_c was chosen to be equal to 10000 $W/m^2 \cdot K$. For the reference case study the inlet vane temperature (T_2) is 20°C and the inlet tank temperature (T_1) is 15°C. The channel heights on the vane are 125 mm (90 mm for the 1st and 6th module) and 305 mm, while the channel angles on the tank with respect to the electrode symmetry plane are 15° and 33°
- In order to reduce the thermal stress on the adaptation piece between tank and electrode, an additional cooling channel on the tank is foreseen with same radius inlet temperature of the vane ones.



RF regulation with water cooling (2)

The vane and tank channels are connected in series from modules 1 to 3 and then from modules 6 to 4. As for the water temperature calculations to be used as input data for thermo-structural calculations, they were derived from the knowledge of the power per unit length $p_{d2}(z)$ [$p_{d1}(z)$] on the vane [tank] [W/m], given by SUPERFISH.

$$p_{d2}(z) = 0.6 \cdot p_d(z) = 0.6 \cdot \oint_{\gamma} p_{densSF}(z,s)\,ds \qquad p_{d1}(z) = 0.4 \cdot p_d(z) = 0.4 \cdot \oint_{\gamma} p_{densSF}(z,s)\,ds$$

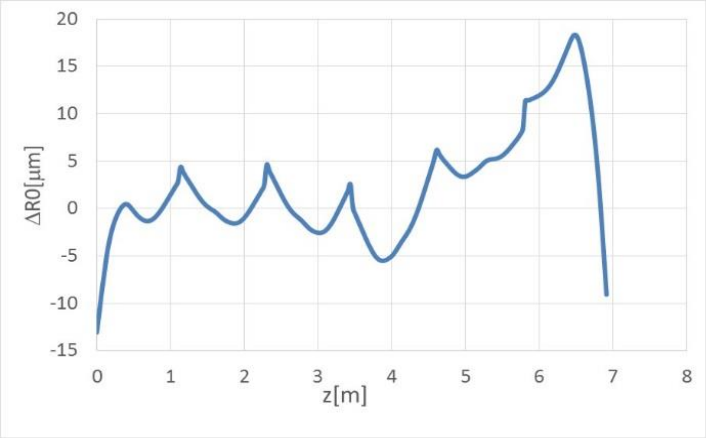


$$\mathrm{T}_{out1[2]} = \mathrm{T}_{in[2]} + (1/\dot{m}c_p)\int_{z_{in}}^{z_{out}} p_{d1[2]}(z)\,dz$$

Inputs for thermo-structural calculations:

- power density profiles from SUPERFISH (interoplated according to the voltage law)
- power densities from HFSS on the vane undercuts

RF regulation with water cooling (3)



Average aperture perturbation in the case T_1=15°C, T_2=20°C. The associated frequency shift is equal to 7 kHz and a voltage perturbation $|\Delta V(z)/V(z)|<0.005$, to be compared with the maximum admittable value of 0.03, as for beam dynamics specifications.

The frequency temperature sensitivity in this case was investigated as well. The vane temperature coefficient $\partial f/\partial T_2$ is equal to about -17 kHz/°C. Moreover the frequency shift Δf_{on-off} from maximum input power to zero input power is +85 kHz, and the vane+tank temperature coefficient $\partial f/\partial T_{1,2}$ (that is the frequency shift due to both T_1 and T_2 increase) is -2kHz/°C. Therefore a temperature tuning range of about ±85 kHz can be established for a T_2 variation in the range [15°C, 25°C]. Moreover, as power increases frequency increases, as well as water temperature. Nevertheless, since $\partial f/\partial T_{1,2}<0$, then a stabilizing mechanism is established and a thermal runaway is avoided.

The RF Amplifier

Parameter	Value	Unit	comment
Modes of operation	CW and pulsed		
Max Output forward power (CW)	200	kW	CW
Linearity	±1	dB	
Babdwidth (1 dB)	±1	MHz	
Harmonics	<-30	dBc	
Spurious	<-60	dBc	
Cooling type	Deionized water, forced air		
Power regulation	0-100 %		
Anode voltage	13	kV	
Input power	0	dBm	
Efficiency (RF power/Grid power)	>	50%	

The RF transmitter (DB Elettronica) is a tetrode amplifier based on the 220 kW TH781 tube and it is the same used for the IFMIF RFQ High Power Tests (175 MHz). In order to allow 80 MHz operation, the replacements of the driver amplifier, the RF combiners and the tube cavity will be performed

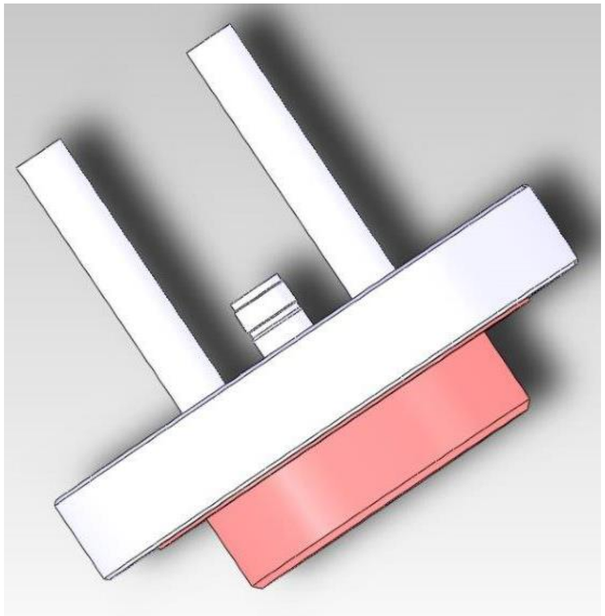
Distribution Board 630 KVA

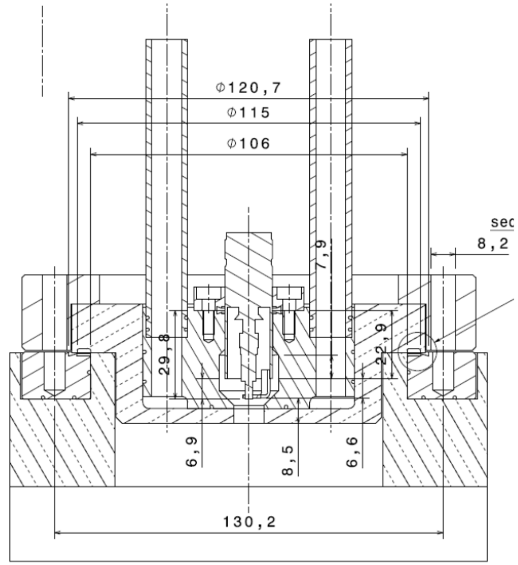
Power Supply 12 KV DC 28 A

RF Driver 16 kW

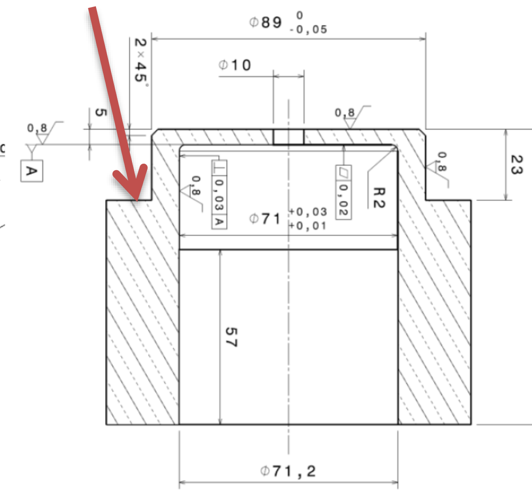
Tube and cavity

Other 3D aspects : tuner design



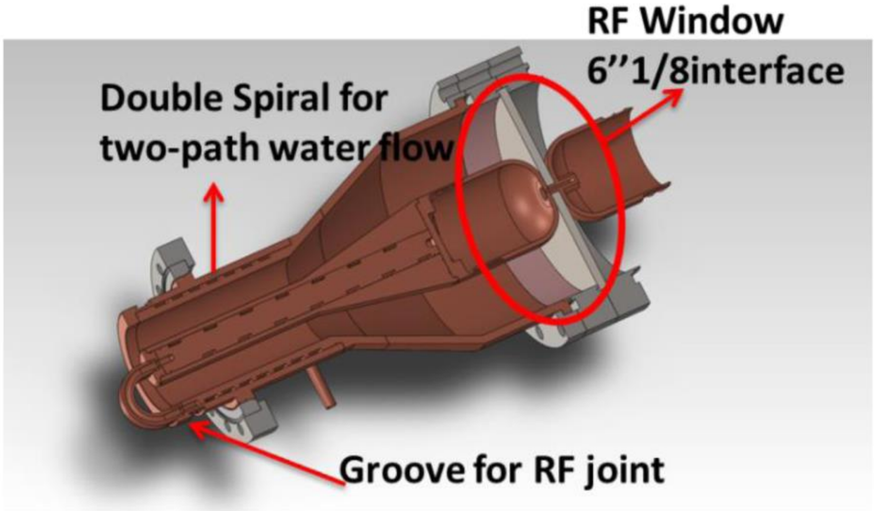


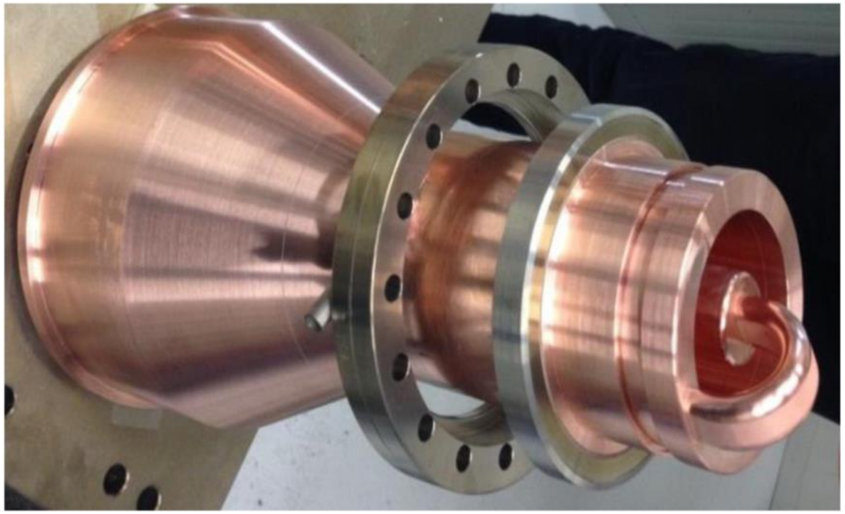
Part to be machined



This solution is the same used for the IFMIF RFQ. The semifinished copper piece is dimensioned in such a way to guarentee all the tuner penetration in the range [-20 mm, 100mm]. Such object is finished only in its inner part for the brazing of the SS bulk containing the cooling channels and the hole for the pick-up. Such hole is flared, in order to avoid contact with SS bulk. The flange is boosted and a Helicoflex® joint is used. After final RF measurements the external part of the SS-Copper assembly is set to the proper depth and finished.

Other 3D aspects : High Power Coupler





Also in this case solution is the same used for the IFMIF RFQ (200 kW CW). Therefore 1 coupler is foreseen. The construction procedure foresees three brazing steps. In the first step, the cooling spirals are brazed separately on inner and outer conductors and also the SS flange seats and the water tubes are brazed on the copper bulk. In the second step, the plugs are brazed at both ends of the inner conductor and the outer conductor with cooling spiral is brazed with the tapered coaxial. Finally, in the third step the inner and outer conductors are brazed to the loop, and the assembly is completed. After both the first and the second brazing step, machining is required and brazing defects can be eventually recovered. The RF window is a planar type window, The material to be used is Alumina 99% with 1.5 to 3 nm TiN coating, with nominal RL of 40 dB and Insertion Loss of less than 0.01 dB. A preliminary estimation of the area needed for optimum coupling gives the value of 35 cm^2. In order to correct possible loop-induced detuning (- 2kHz, preliminary estimation), tuners are placed in the other quadrants

Conclusions

The main issues of the RF design of the RFQ have been addressed, namely

- The 2D carachterization, including cell tuning
- The end cell design
- The error sensitivities, the tuning range and the tuning algorithm
- The RF joint was chosen
- The thermal behavior of the RFQ under various A/q scenarios was studied
- The maximum possible advantage from IFMIF experience (Tuner, coupler and amplifier) was exploited
- To be completed: vacuum grid and dipole stabilizer analysis.