PRESERVING BEAM QUALITY IN LONG RFQS ON THE RF SIDE: VOLTAGE STABILIZATION AND TUNING

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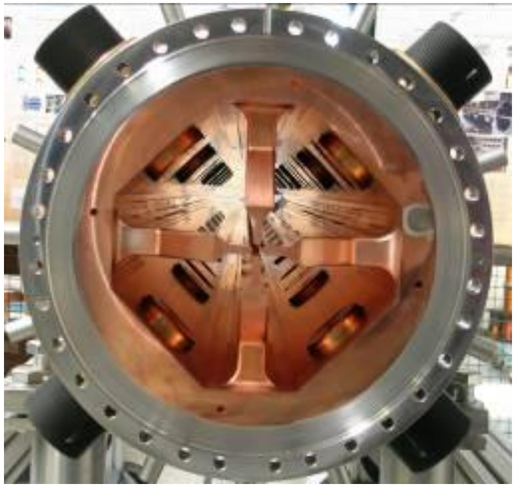
Contents

The RFQs developed at LNL: TRASCO

	TRASCO
status	Constructed
particle	p
f [MHz]	352.2
l [m]	7.13
l/λ	8.4
R_0[mm]	2.93-3.07
ρ/R_0	1
Ib [mA]	30
V[kV]	68
W [MeV/u]	5
E.M. segments	3
Mech. modules	6
$\delta V/V$ range	±1%(Q), ±2%(D),
Q_0	8000 (20% margin)
RF power [kW]	800 (20% margin)

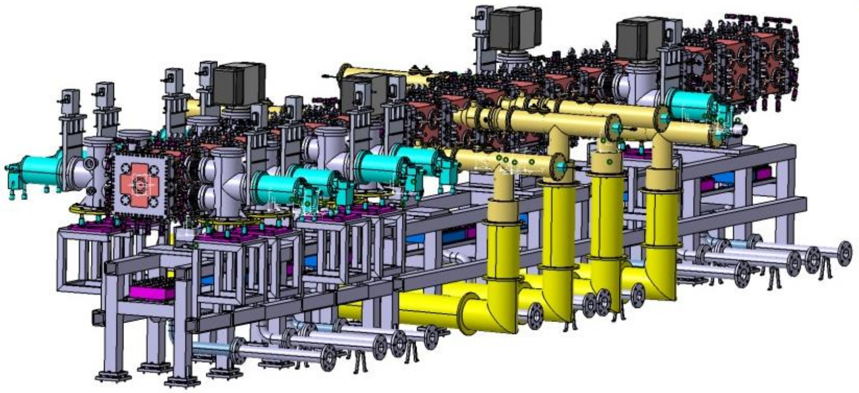
Completed modules of the RFQ



RFQ Inside view: the bulk is in OFE Copper, and the flange in LN316 SS

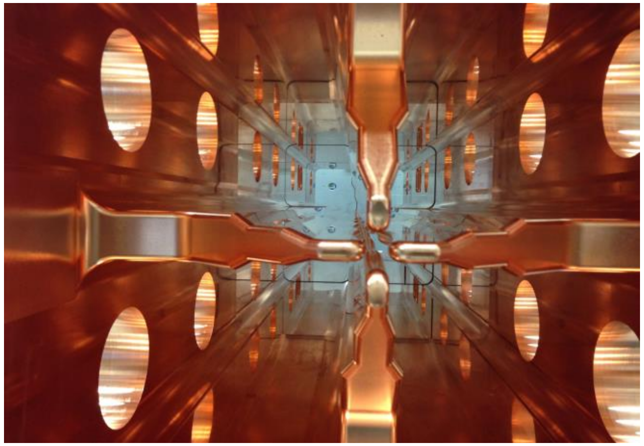
RFQ during High Power Tests @ Saclay (France)

The RFQs developed at LNL: IMFIF

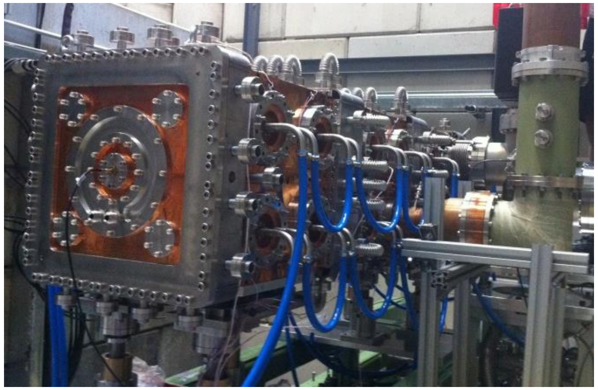


RFQ Layout with ancillaries

	IFMIF
Status	Construction in progress
Particle	d
f [MHz]	175
l [m]	9.8
l/λ	5.7
R_0[mm]	4.13-7.10
ρ/R_0	0.75
Ib [mA]	125
V[kV]	79-132
W [MeV/u]	5
E.M. segments	1
Mech. modules	18
$\delta V/V$ range	±2% (Q and D)
Q_0	12000 (25% margin)
RF power [kW]	1250(25% margin)

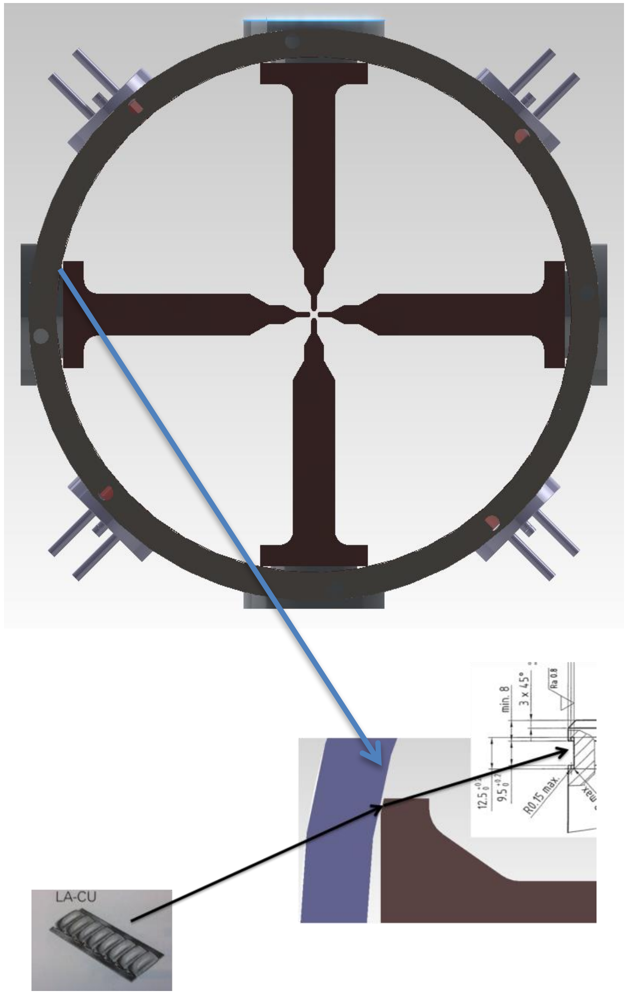


RFQ Inside view: the bulk is in OFE Copper, and the flanges are in LN316 SS



RFQ ready for High Power Tests @ LNL

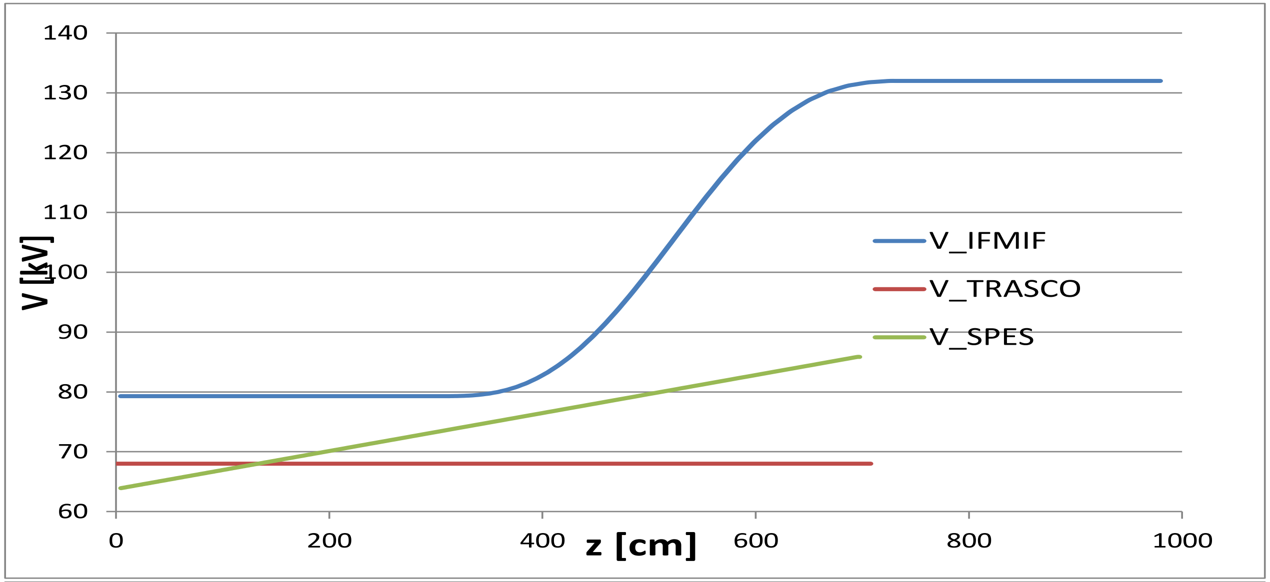
The RFQs developed at LNL: SPES

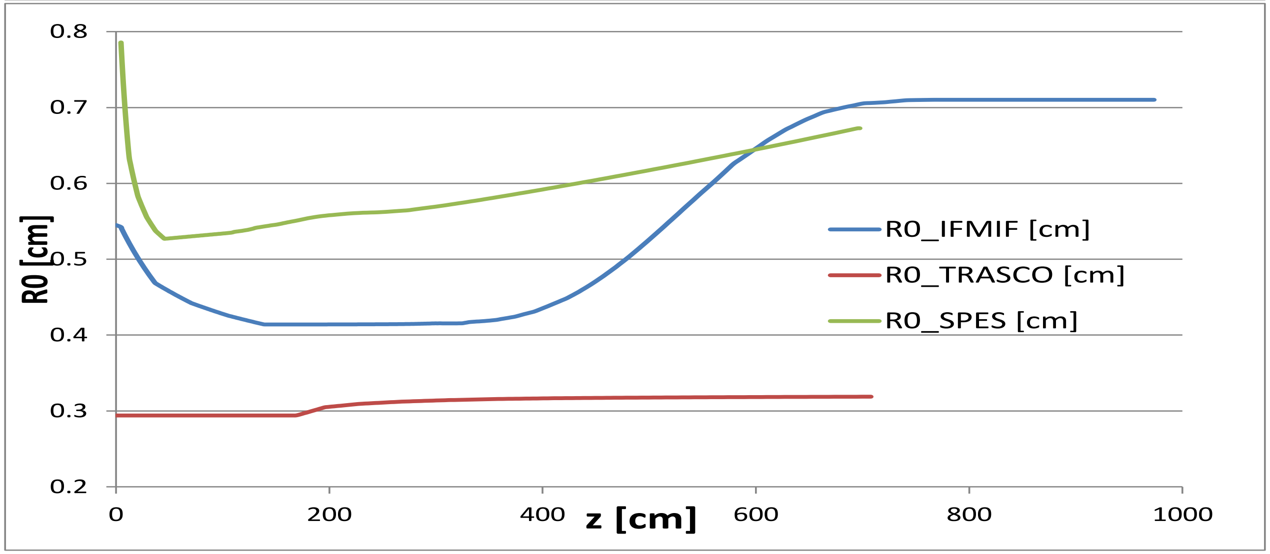


	SPES
status	Developing
particle	Heavy Ions
f [MHz]	80
l [m]	6.95
l/λ	1.9
R_0[mm]	5.27-7.86
ρ/R_0	0.76
Ib [mA]	1e-6
V[kV]	64-86
W [MeV/u]	0.727
E.M. segments	1
Mech. modules	6
$\delta V/V$ range	±3% (Q and D)
Q_0	16000 (20% margin)
RF power [kW]	120(20% margin)

RFQ Inside view: the Tank is in SS (with CU deposition) and the electrodes are in OFE Copper. The electrodes are bolted to the tank and a spring contact is inserted as RF joint.

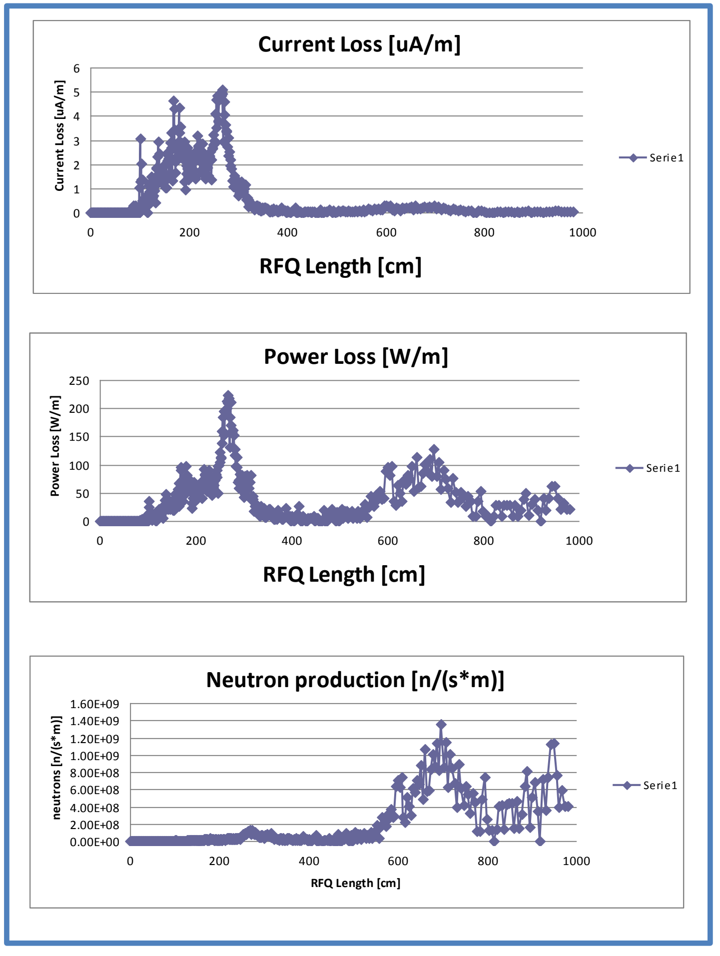
The RFQs developed at LNL: Voltage and R_0 comparisons





Introduction: What do these RFQ have in common?

- They are all NC four-vane structures
- They all need to achieve a beam transmission higher than 95%

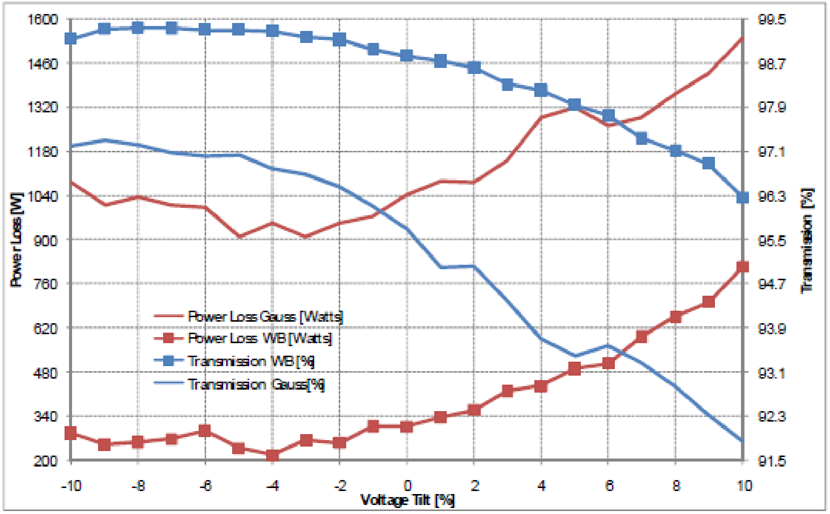


Losses for the IFMIF RFQ

- In p and d machines, the high space charge at low energy induces beam losses giving rise to the activation of the structure with the production of neutrons, (p-Cu and d-d reactions), and their control has to be compliant with an hands-on maintenance of the machine. Therefore the achievement of Beam losses concentrated in the low energy part is very important since neutron production is proportional to W^{2}.
- In heavy ion machines, the RIB current loss can jeopardize the quality of the outcomes of the Nuclear Physics experiments, on the other hand lost RIBs in the RFQ can beget high-lifetime decay products
- These circumstances call for the adoptions of some adjustments in beam dynamics design and some stricter constraints on the mechanical and electromagnetic parameters. One of them is…

Introduction (2): Voltage errors vs z can affect RFQ performances

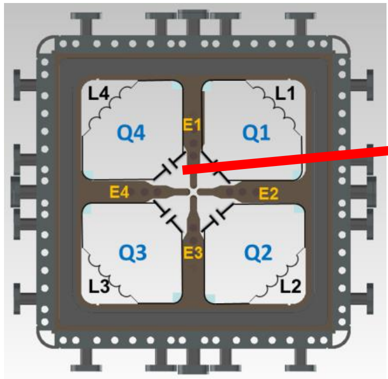
The longitudinal behavior of the inter-vane voltage along the four quadrants of the structure has to be accurately controlled and voltage dis-uniformities among the quadrants whose deviations from the nominal values shall not exceed a few %.
Therefore the understanding and this issue is one of the key aspects for proper RFQ performances.

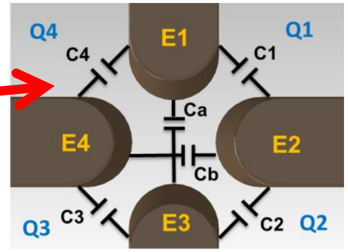


Key statement: These voltage errors depends on geometric errors on the RFQ (e.g. due to mechanical errors and/or misalignments) => perturbations
If the RFQ is regarded as a resonant cavity, these errors cause a mixing of the operating TE_{210} mode (Quadrupole mode) with neighboring quadrupole TE_{21n} and TE_{11n} dipole modes. Now, if the overall length l of the RFQ is significantly greater than the wavelength λ, the eigenfrequencies f_n of the neighbouring modes can be very close to the operational one f_0, thus enhancing the effect of perturbations. Therefore an analytical tool is needed in order to

- Foresee the effect of geometric errors on RFQ voltage (**Perturbation Analysis**)
- Correct the above-mentioned voltage errors (**Tuning and Stabilization**)

Circuit modeling of a four-vane RFQ: Multiconductor Transmission line





U =inter-vane voltages

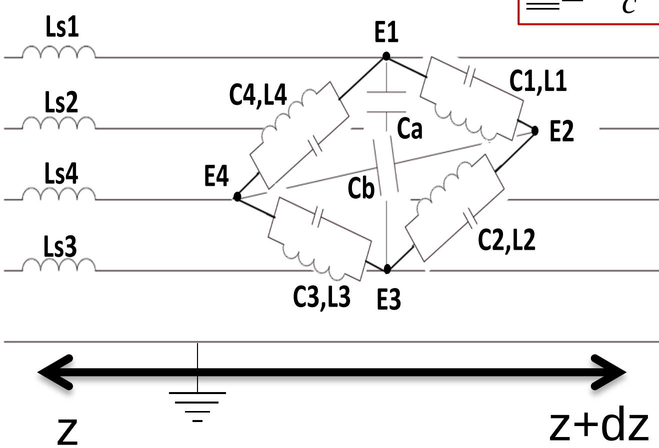
I = currents

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

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

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

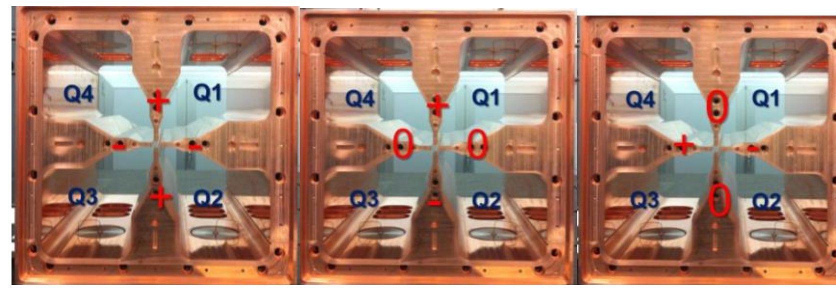
$$\boxed{\underline{\underline{\mathbf{L}}}_s \underline{\underline{\mathbf{C}}} = \frac{1}{c^2}\underline{\underline{\mathbf{I}}}_4}$$



Ideal RFQ (C_i=C, L_i=L and C_a=C_b, i=1,..,4)

$$\omega_0^2 = 1/LC \qquad h = C_a / C$$

$$\underline{\underline{\mathbf{S}}}^{-1}\underline{\underline{\mathbf{C}}}^{-1}\underline{\underline{\mathbf{L}}}\underline{\underline{\mathbf{S}}} = \underline{\underline{\mathbf{k}}}^2 \qquad \underline{\underline{\mathbf{k}}}^2 = c^{-2}\omega_0^2 diag(1,0,1/(1+h),1/(1+h))$$



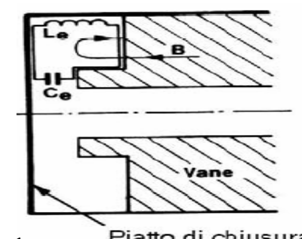
TE_{21}mode (Q)

$$f_q = f_0$$

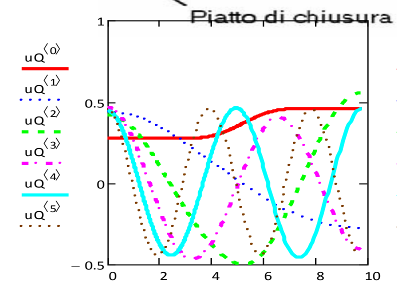
TE_{11}modes (D) (degenerate in an ideal RFQ)

$$f_d = f_0 / \sqrt{1+h}$$

Boundary conditions U'(0)=U'(l)=0 @f=,f_{q0} via a resonant lumped LC element (End-cell) and, if any, at coupling cell locations



Q & D eigenfrequencies f_{q0}, f_{q1},…f_{qn},… f_{d0}, f_{d1}, …f_{dn},… and eigenfunctions,ϕ_{q0},, ϕ_{q1},…ϕ_{qn},… ϕ_{d0}, ϕ_{d1}, …ϕ_{dn},…



Modeling geometry perturbations in a RFQ

Deviations from nominal RFQ geometry can be due to
1) Construction errors
2) Electrode displacement
3) Thermal-induced deformatiions

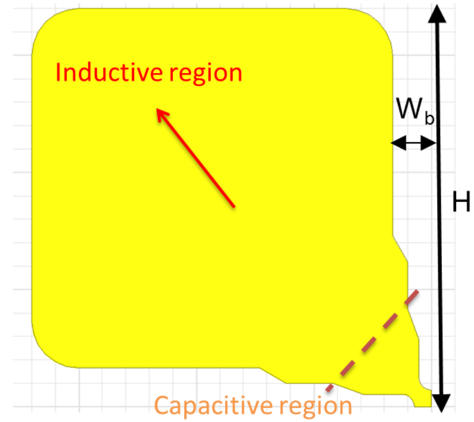
Variation of geometric parameters R_0, ρ, W_b, H => δR_0, $\delta\rho$, δW_b, δH

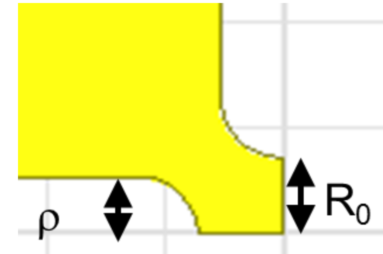
Variation of circuit paramaters L, C, f0 => δL_i, δCi, δf_0

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

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

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





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

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

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

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

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

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

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

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

Perturbative Development

Geometry perturbations in a RFQ: consequences

$\delta C_i = \alpha_{R0}\delta R_0 + \alpha_\rho \delta\rho$ $\delta L_i = \alpha_H \delta H + \alpha_{Wb}\delta W_b$.

$\delta f_0 = \chi_{R0}\delta R0 + \chi_\rho \delta\rho + \chi_H \delta H + \chi_{Wb}\delta W_b$

χ_ρ => construction accuracy (±(10-20) μm)

χ_{R0} => electrode positioning (errors of ± 100 μm can occur), due to alignment and/or brazing.

χ_H and χ_{Wb} : one order of magnitude lower

R_0 errors are dominant

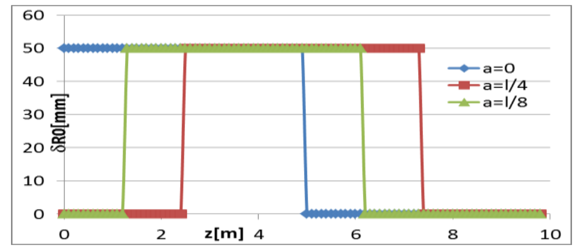
	TRASCO	IFMIF	SPES
χ_{R0} [MHz/mm]	40	7.6 to11.8	2.7 to 3.5
χ_ρ [MHz/mm]	-30	-3.6 to7-5.3	-3.2 to -2.2
χ_H [MHz/mm]	-3.2	-0.9	-0.13
χ_{Wb}[MHz/mm]	2.0	0.55	0.16

Comparison between mechanical and RF Measurements (i.e. IFMIF RFQ modules) confirmed that almost all the frequency shifts is due to R_0 shifts as well.

TEST CASE: 0.05 mm misalignment of one electrode in half l= 9.9 m unsegmented RFQ (ideal BC for Q and D modes), no dipole stabilizers needed.

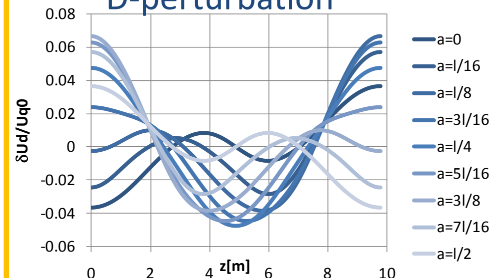
constant U and R_0 f= 175 MHz

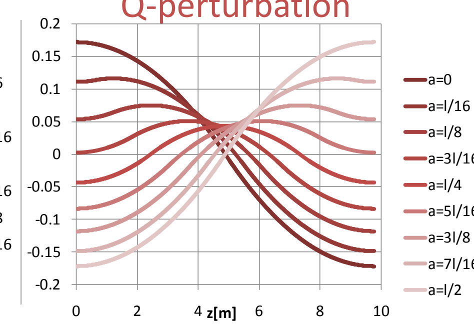
χ_{R0}=7.6 MHz/mm.



$$\frac{\delta\phi}{\phi_0} = \left(\frac{\ell}{\lambda}\right)^2 \frac{8\chi_{R0}\delta R_0}{f_0} \sum_{n=1}^{\infty} \frac{[\sin(\frac{n\pi}{2}+\frac{n\pi a}{\ell}) - \sin(\frac{n\pi a}{\ell})]\cos(\frac{n\pi z}{\ell})}{n^3\pi}\,\hat{\mathbf{e}}_1 +$$

$$-\frac{\sqrt{2}}{2}\frac{\chi_{R0}\delta R_0}{f_0}\sum_{n=1}^{\infty}\frac{\alpha_n[\sin(\frac{n\pi}{2}+\frac{n\pi a}{\ell}) - \sin(\frac{n\pi a}{\ell})]\cos(\frac{n\pi z}{\ell})}{n\pi\left[h-(1+h)(n\lambda/2\ell)^2\right]}(\hat{\mathbf{e}}_3+\hat{\mathbf{e}}_4)$$





Tenths of μm perturbation cause out-of-specification voltage variations=>need of corrective actions (STABILIZATION AND TUNING)

Stabilization and Tuning (definitions)

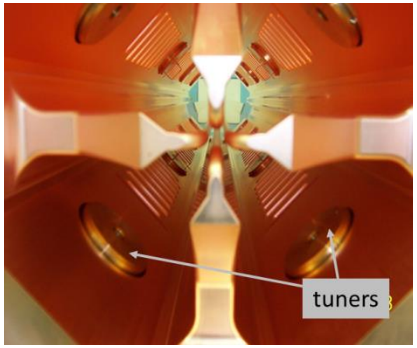
RFQ stabilization: voltage error mitigating actions that can be taken before knowing the actual RFQ voltage profile

1. Resonant coupling: This method consists in dividing the RFQ in N resonantly coupled segments and has the advantage of increasing the frequency spacing between the f_0 and the frequencies of the other quadrupole modes (LEDA, IPHI, TRASCO).
2. Dipole stabilization or DSRs: this method consists in inserting longitudinal bars in the RFQ volume in correspondence of the end-cells and coupling cells, which do not perturbate the quadrupole mode, but shift the dipole frequencies and create a "dipole-free region in the neighbourhood of the f_0 frequency.

These methods cause a reduction of the perturbed voltage but, in general, they are not sufficient themselves to get the voltage specifications

RFQ tuning: actions that, starting from the actual knowledge of the voltage along z, and of the frequency in the real RFQ (typically by measurements), allow the attainment of the voltage specifications at the target frequency.

Tuners: NT metallic cylinders of radius a and depth h in the cavity volume, which compensate the geometric variation in capacitive region with corresponding variations in the inductive region



A tuner placed in the position z_i (i=1,..,NT) varies:

- the local cut-off frequency fq_0 for any z in the interval $[z_i-a, z_i+a]$ $\delta fq_0(z) = \chi_{t2D} h_i$
- The global resonant frequency $\delta f_0 = \chi_{3D} h$

If $\delta fq_{0j}(z) \approx -+1/2\ \delta C_j(z)/C$, (j=1,..,4) is known, by setting the h_i in such a way that $\delta L_j(z_i) = -(L/C)\ \delta C_j(z_i)$ it is possible to compensate the capacitance and therefore the voltage perturbation.

The concept of Tuning Range (TR)

The **tuning range** is the maximum frequency /height interval Δf_{TR} /[0, h1+h2] that can be spanned by the tuners and should correct frequency (local and global) shifts induced by the maximum δR_0 error to be expected.

$$\delta f_{TR(2D)}=\chi_{2D}h1 , \quad \delta f_{TR(3D)}=\chi_{3D}h2 \qquad \Delta f_{TR}=\chi_{3D}(h1+h2)\ NT$$

. The choice of the tuning range establishes:

1. The choice of the 2D cut-off frequency f_{q0}, since the resonant frequency of the RFQ lies in the middle of TR.
2. The amount of extra power ΔP dissipated by the tuners, to be considered in dimensioning the RF system $\Delta P=k(R_s/2)H^2 2\pi a N_T(h1+h2)$, with k=margin for power dissipated on the tuners (k=2 in our cases), R_s =surface resistance, H= magnetic field in the tuner location

	TRASCO	IFMIF	SPES
NT	96	88	96
a [mm]	24.5	44.5	44.5
ΔR0 range[mm]	±0.05	±0.1	±0.2
Δf range[MHz]	±1	±1	±0.5
h1+h2 range[mm]	[-10, 10]	[-15, 30]	[0,80]
ΔP/P0 [%]	4	7	8

Perturbation Synthesis

1. U_1, U_2, U_3, U_4=>$\delta\phi_q$, $\delta\phi_{qd1}$, $\delta\phi_{qd2}$
2. The coefficients a_{qn}, a_{d1n}, a_{d2n} are determined from measured data (Fourier sum of $\delta\phi_q$, $\delta\phi_{qd1}$, $\delta\phi_{qd2}$)

$$a_{qn} = \int_0^l \delta\phi\varphi_{qn}dz, n \in \mathbb{N},\ a_{d1n} = \int_0^l \delta\phi_{qd1}\varphi_{dn}dz, n \in \mathbb{N}_0, a_{d2n} = \int_0^l \delta\phi_{qd2}\varphi_{dn}dz, n \in \mathbb{N}_0$$

3. The capacitance perturbations are spanned as a sum of RFQ eigenfunctions for a finite number of harmonics

$$\delta C_{QQ} = \sum_{m=1}^{NQ} b_{qm}\varphi_{qm}, \delta C_{Qd1} = \sum_{m=0}^{Nd1} b_{d1m}\varphi_{dm}, \delta C_{Qd2} = \sum_{m=0}^{Nd2} b_{d2m}\varphi_{dm}$$

4. The unknown coefficients ''b'' are determined by substituting the δC's in the perturbative sum

$$\mathbf{C^{(q)}b_q = a_q, C^{(d)}b_{d1} = a_{d1}, C^{(d)}b_{d2} = a_{d2}}$$

$$C_{nm}^{(q)} = \frac{\omega_0^2}{4C(\omega_0^2 - \omega_{qn}^2)}\int_0^l \varphi_{q0}(z)\varphi_{qn}(z)\varphi_{qm}(z)dz$$

$$C_{nm}^{(d)} = \frac{\omega_0^2}{4C(\omega_0^2 - \omega_{dn}^2)}\int_0^l \varphi_{q0}(z)\varphi_{dn}(z)\varphi_{dm}(z)dz$$

$$\begin{cases} \frac{\delta L_{QQ}}{L} = -\frac{\delta C_{QQ}}{C} \\ \frac{\delta L_{monopole}}{L} = 0 \\ \frac{\delta L_{Qd1}}{L} = -\frac{\delta C_{Qd1}}{C} \\ \frac{\delta L_{Qd2}}{L} = -\frac{\delta C_{Qd2}}{C} \end{cases} \Rightarrow \begin{cases} \frac{\delta L_1}{L} = -\frac{1}{4}\frac{\delta C_{QQ}}{C} - \frac{\sqrt{2}}{4(1+h)}\frac{\delta C_{Qd1}}{C} \\ \frac{\delta L_2}{L} = -\frac{1}{4}\frac{\delta C_{QQ}}{C} + \frac{\sqrt{2}}{4(1+h)}\frac{\delta C_{Qd2}}{C} \\ \frac{\delta L_3}{L} = -\frac{1}{4}\frac{\delta C_{QQ}}{C} + \frac{\sqrt{2}}{4(1+h)}\frac{\delta C_{Qd1}}{C} \\ \frac{\delta L_4}{L} = -\frac{1}{4}\frac{\delta C_{QQ}}{C} - \frac{\sqrt{2}}{4(1+h)}\frac{\delta C_{Qd2}}{C} \end{cases}$$

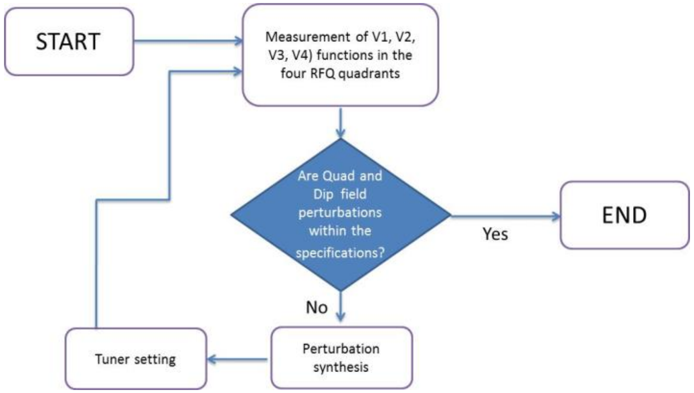
Inductance variations to be applied in tuner positions to compensate the capacitance ones (h1)

$$\delta f_0 = -N_T\chi_{3D}h2_0$$

Resonant frequency shift compensation

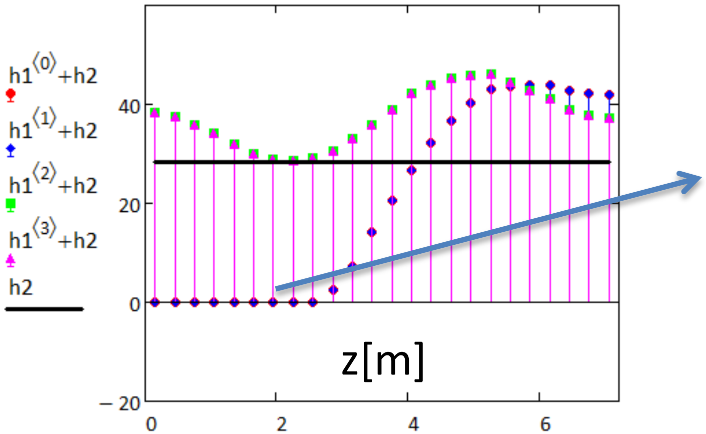
Perturbation Synthesis and Tuning Algorithm

TUNING ALGORITHM FLOWCHART



An example of usage for the SPES RFQ case: tuning range estimation

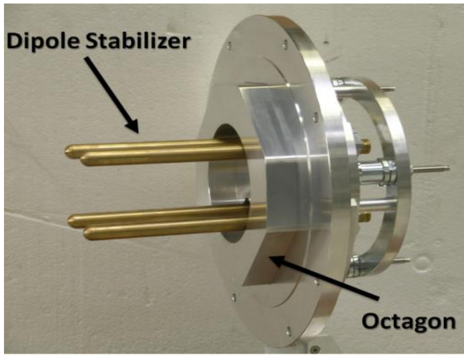
Two adjacent electrodes displaced of δR0=0.2 mm (δf0=150 kHz) for z in the interval [0,l/2]. Q [D] perturbations on nominal voltage of ±10% [±20%]. NT=96, a=44.5 mm, TR=[0 mm, 80 mm]



Tuning with NQ=4 and ND=3 .The tuner range is saturating for z<2.5 m: this is an indication that all tuning range is being employed. This sets the relationship between the maximum δR0 and the maximum h1+h2 (in this case h2=28 mm).
Results are worsened if tuner periodicity is broken (vacuum ports, couplers,…).

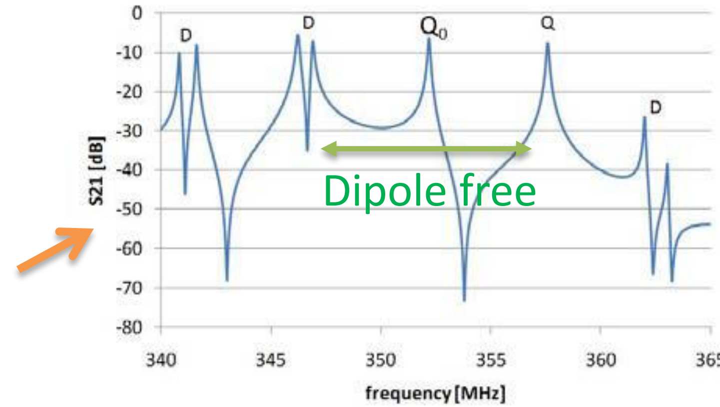
General comment: The usage of coupling elements is advisable if these «test perturbations» cannot be tuned and/or if the $\Delta P/P_0$ becomes too high (i.e >10%). In some cases the usage of a real-scale mock-up is very helpful in determining the choice.

Experimental results: TRASCO RFQ High PowerTest



Dummy End-Plate

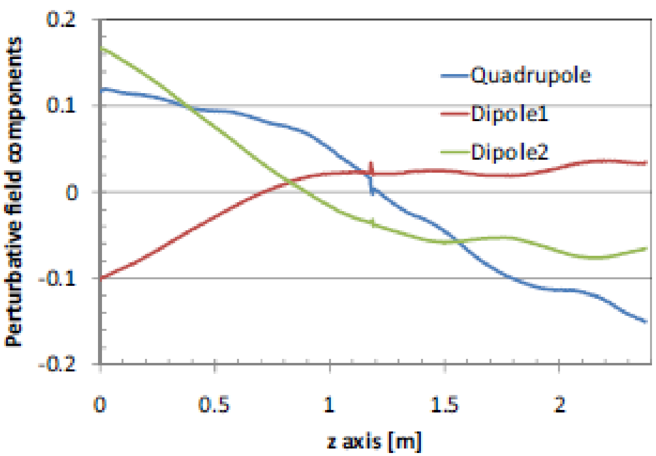
Final End-Plate



Mode Spectra $|S_{21}|$ vs frequency after Dipole Stabilizer optimization

l=2.37 m (2.8 λ), NT=32, almost uniform spacing

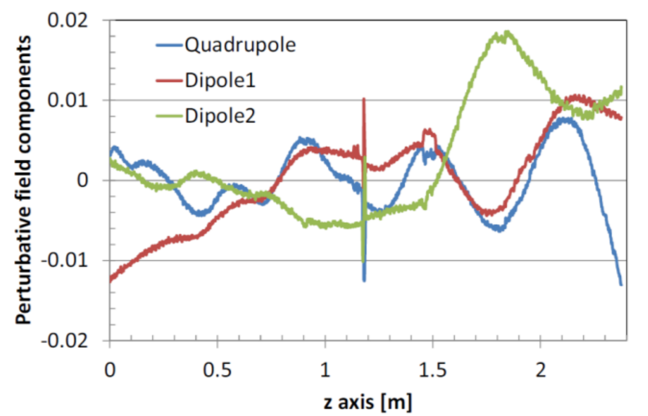
Before tuning



Tuner range
[-4.8 mm,11.5 mm]

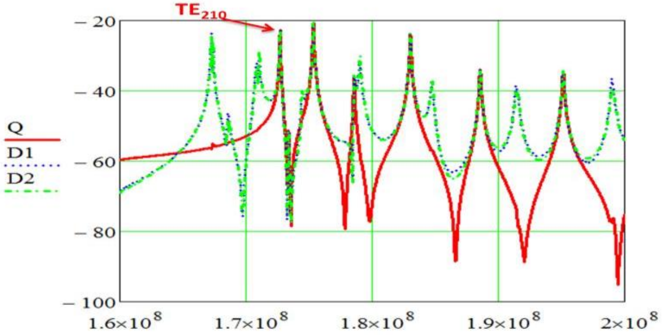
	TRASCO
NT	96
a [mm]	24.5
DR0 range[mm]	±0.05
Df range[MHz]	±1
h1+h2 range[mm]	[-10, 10]
DP/P0 [%]	4

After tuning

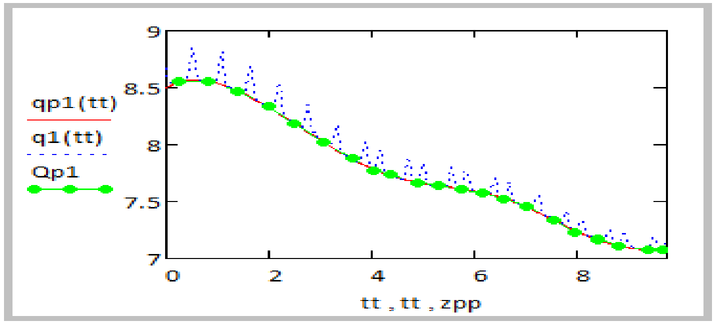


Experimental results(2): IFMIF RFQ Al model

l=9.9 m (5.7 λ), NT=88, No Coupling cells, no Dipole Stabilizers

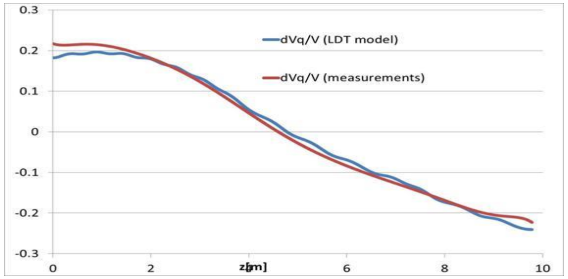


Mode Spectra $|S_{21}|$: f_{q0}= 172.7 MHz, Dipole free =±2 MHz

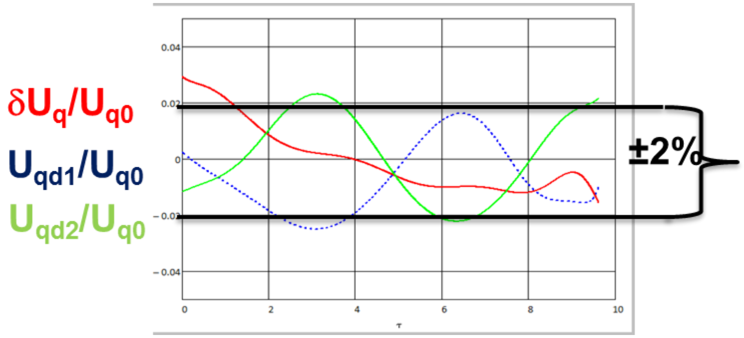


Raw phase data (beadpull) and their interpolation (Q1)

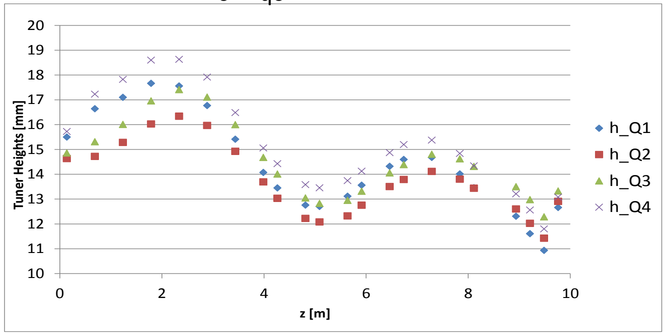
	IFMIF
NT	88
a [mm]	44.5
DR0 range[mm]	±0.1
Df range[MHz]	±1
h1+h2 range[mm]	[-15, 30]
DP/P0 [%]	7



Measured and calculated $\delta U_q/U_0$(all tuners @h=15 mm=(h1+h2)/2) => $f_0=f_{q0}$+1 MHz

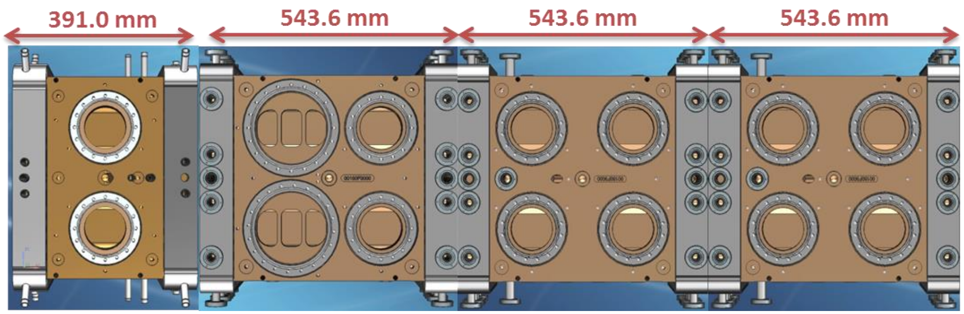


Tuned results (1 tuning step), $f=f_0$



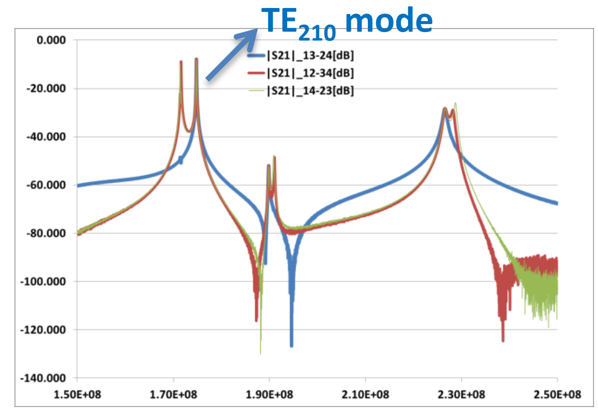
Tuner heights vs z in the range

Experimental results(3): IFMIF RFQ High Power Test

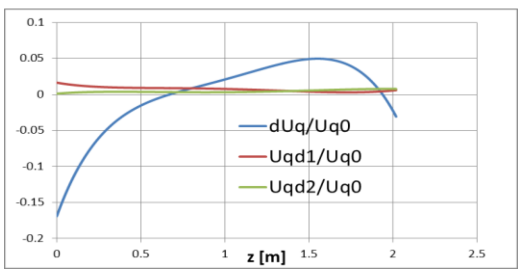


RF plug Mod 16 Mod 17 Mod 18

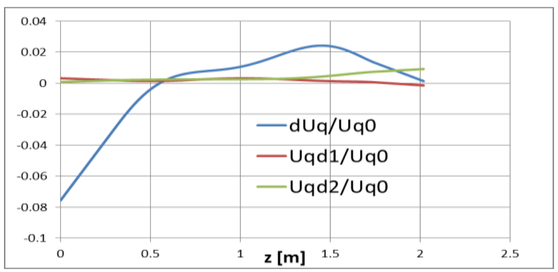
- NT=20, l=2 m (1.2 λ), No Dipole Stabilizers
- RF plug detuned (Δf(plug)=1 MHz) => initial tuner settings h=4.6 mm



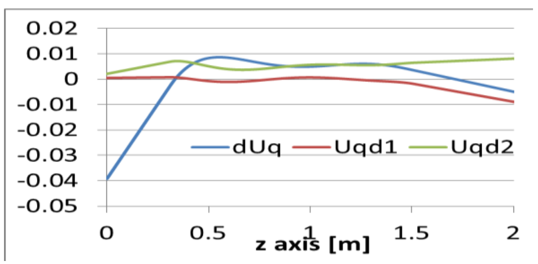
Mode spectra ($|S_{21}|$) with tuner flush (f_0=174.7 MHz)



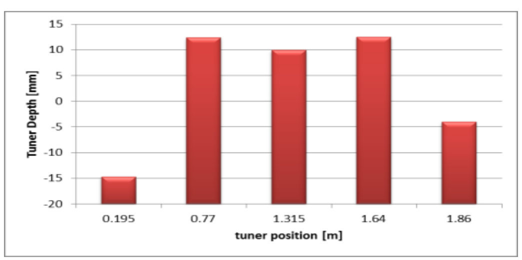
Initial measurement



End Plate optimization



After tuning



Tuner settings

Brazed Cu Tuners

a [mm]	44.5
DR0 range[mm]	±0.1
Df range[MHz]	±1
h1+h2 range[mm]	[-15, 30]
DP/P0 [%]	7

Conclusions and Perspectives

- The analysis proved useful in the design phase of the RFQ (relationships between e.m. specifications and geometric quantities
- The identification of the needed tuning margins and experimental results confirmed the adopted approach.
- The next steps include the tuning of the final structures considered in this presentation and the analysis on the effects of "real" RFQ voltage profile on beam dynamics parameters.

Acknowledgments

Only a few of these results would have been possible without the help and the support of the RFQ group, mainly namely Dr. Andrea Pisent, Dr. Michele Comunian, Dr. Enrico Fagotti, Dr. Francesco Grespan, and all the engineers and technicians of INFN-LNL, INFN-Padua and INFN-Turin who arranged the setup and made the RF measurements possible.