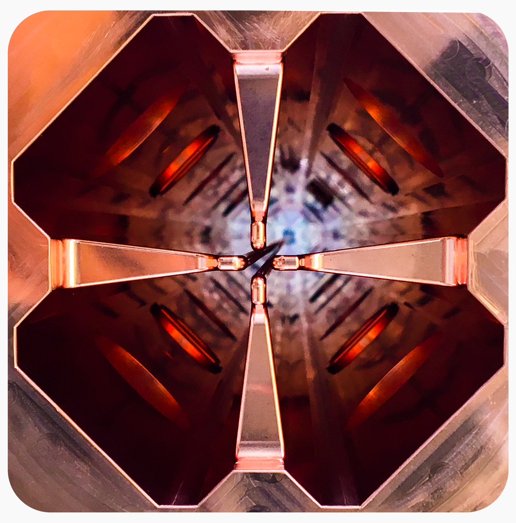
Tuning of the CERN 750 MHz RFQ for Medical Applications



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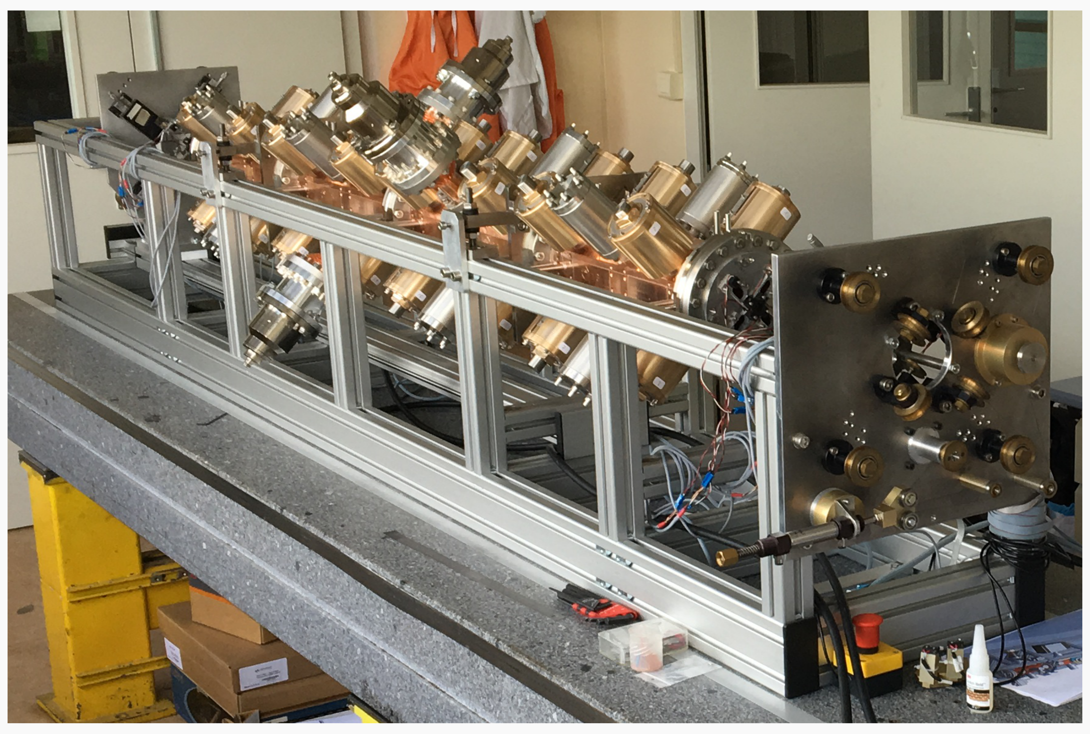
Abstract

CERN has built a compact 750 MHz RFQ as an injector for a hadron therapy linac. This RFQ was designed to accelerate protons to an energy of 5 MeV within only 2 m length. It is divided into four segments and equipped with 32 tuners in total. The RFQ length corresponds to 5λ which is considered to be close to the limit for simple field adjustment using tuners. Nevertheless the high frequency results in a sensitive structure and requires careful tuning by means of the alignment of the pumping ports and fixed tuners. This paper gives an overview of the tuning procedure and bead pull measurements of the RFQ.

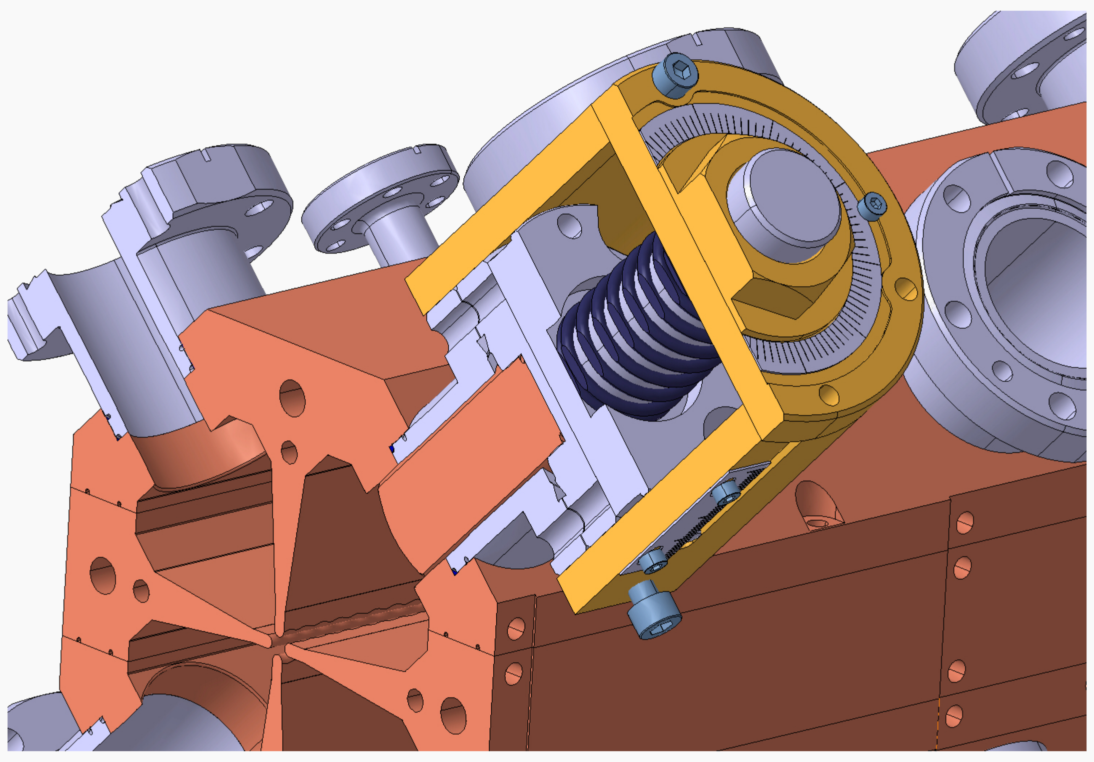
Introduction

The HF-RFQ (High Frequency - RFQ) will be used as an injector for the LIGHT project, a linac based proton therapy facility. It accelerates protons from 50 keV to 5 MeV within 2 m and is designed to minimize beam losses above 1 MeV. From an RF point of view the very compact 4-vane structure operates at about twice the frequency of existing RFQs. It consists of four modules with a length of about half a meter. The dipolar modes are detuned by means of dipole stabilizer rods at the end plates. The electrode voltage is designed to be constant along the RFQ that corresponds to a constant longitudinal field distribution in terms of tuning. In order to compensate construction errors the structure is equipped with 32 tuners. 12 pumping ports also could be used as additional tuning devices if necessary. The 4 power couplers are placed at the two middle segments of the RFQ, one in each quadrant. Each power coupler will be fed by a 100 kW Inductive Output Tube (IOT) in order to maintain a nominal voltage of 68kV. The Q-factor due to losses in copper is about 6500 according to 3D RF design simulations. The operation frequency is set to 749.48 MHz.

Bead Pull System

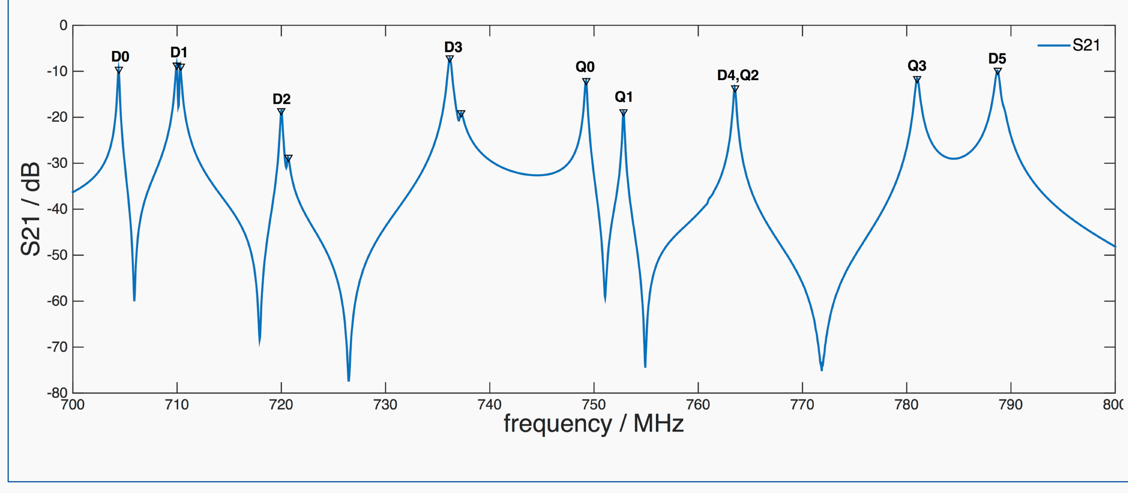


- measurement system from LINAC4 RFQ
- aluminum bead
- closed loop of wire to measure all 4 quadrants
- cone shaped tuner design
  - minimization RF losses
  - adequate tuning range and sensitivity
- special tool for tuner alignment
  - accurate tuner alignment during tuning
  - proper tuner positioning after cutting



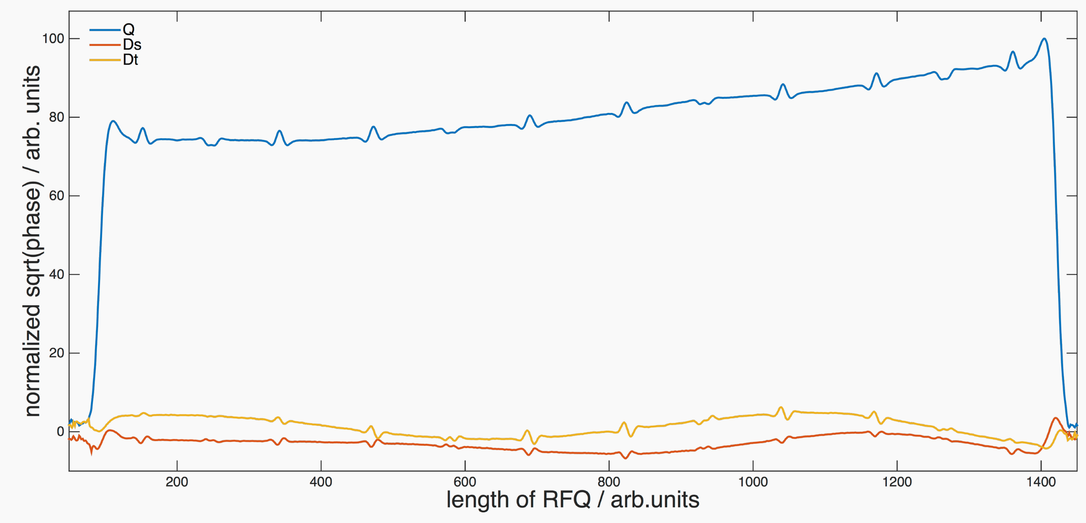
RF Measurements

The objective of tuning is to provide a proper field distribution according to the beam dynamics requirements and also to adjust the operation frequency. All RF measurements have been done at the defined operating temperature of the RFQ at 24°C. For precise frequency adjustment the cavity was filled with dry nitrogen to avoid any influence of the air humidity.



Definition of Quadrupole and Dipole Components

$$
\begin{aligned}
Q &= (B_1 - B_2 + B_3 - B_4)/4 \\
Ds &= (B_1 - B_3)/2 \\
Dt &= (B_2 - B_4)/2
\end{aligned}
$$



Tuning Algorithm

The tuning algorithm is based on calculating a response matrix that describes the influence of every single tuner on the field components at every longitudinal location.

$$
M = \begin{bmatrix}
\frac{\partial Q_1}{\partial T_1} & \frac{\partial Q_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Q_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\frac{\partial Q_i}{\partial T_1} & \frac{\partial Q_i}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Q_i}{\partial T_{32}} \\
\frac{\partial Ds_1}{\partial T_1} & \frac{\partial Ds_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Ds_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\frac{\partial Dt_1}{\partial T_1} & \frac{\partial Dt_1}{\partial T_2} & \cdots & \cdots & \cdots & \frac{\partial Dt_1}{\partial T_{32}} \\
\vdots & \ddots & \ddots & \ddots & \ddots & \vdots
\end{bmatrix}
$$

The relation between the field locations and the tuner positions can be described by

$$V = \mathbf{M} \cdot T$$

By inverting matrix M a tuner setting can be found

$$T = \mathbf{M}^{-1} \cdot V$$

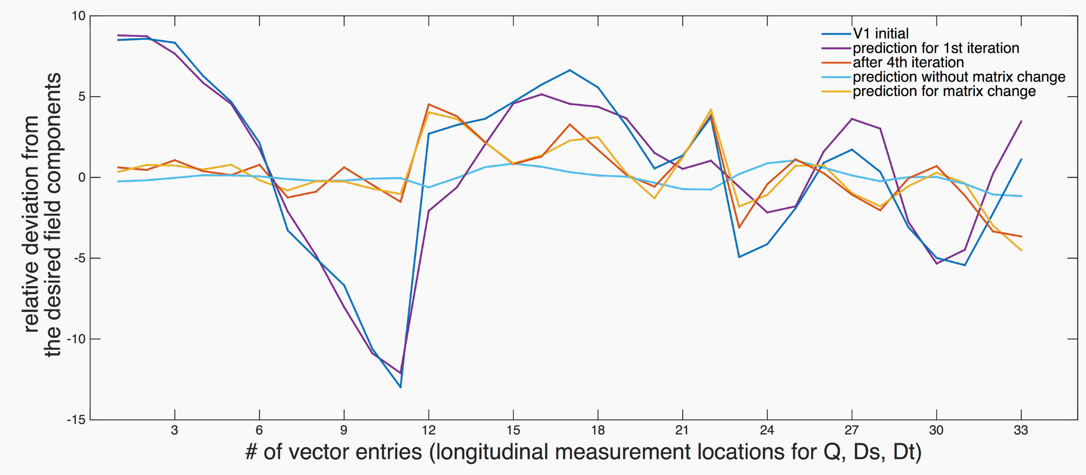
For inversion of matrix M, singular value decomposition (SVD) was used. The SVD allows one to invert a non-square and even ill-conditioned matrix

$$
\begin{aligned}
\mathbf{M} &= [U \cdot S \cdot V^T] \\
\mathbf{M}^{-1} &= [V \cdot S^{-1} \cdot U^T]
\end{aligned}
$$

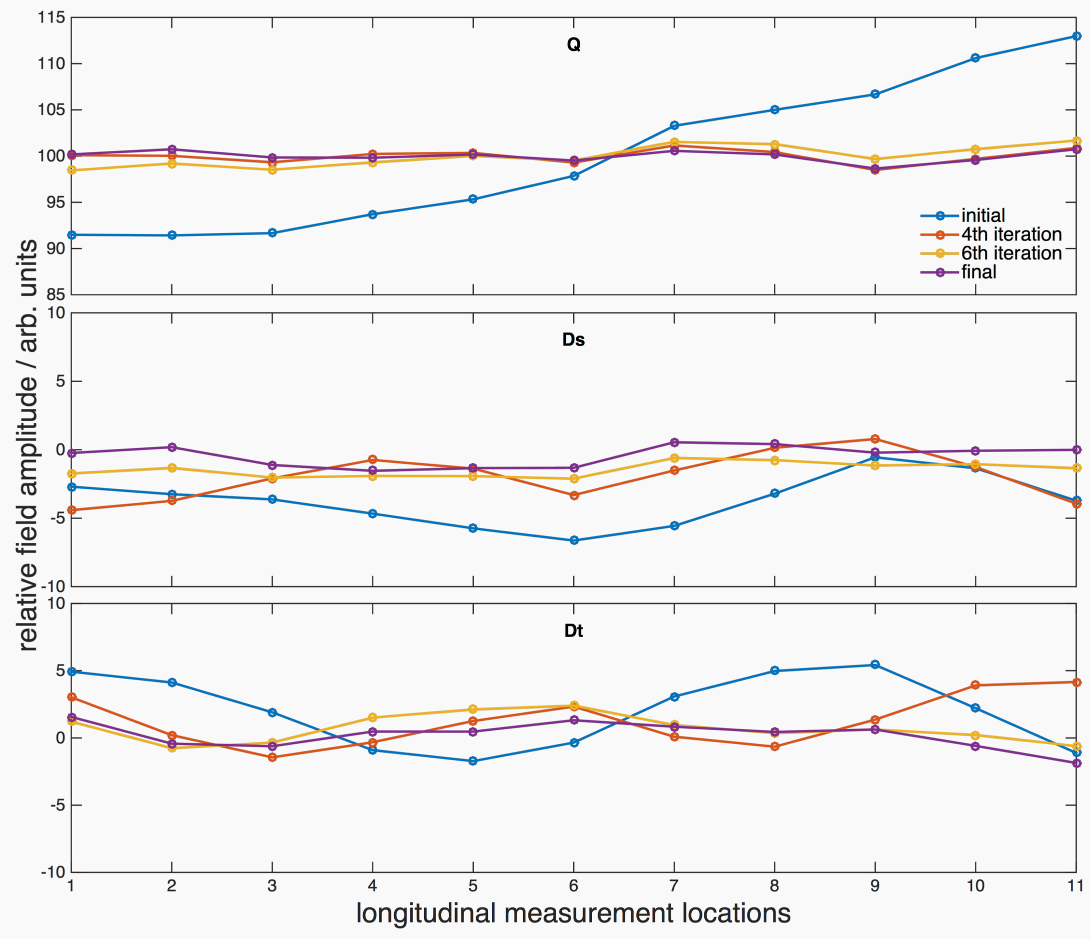
Since the matrix was ill-conditioned and non-square the singular values have been modified. This enables one to find various solutions for T and also to calculate predictions for the tuner settings.

$$
\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & M & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}
=
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & U & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}
\begin{bmatrix} \sigma_1 & & \\ & \sigma_2 & \\ & & \sigma_3 \end{bmatrix}
\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & V^T & \cdot \end{bmatrix}
$$

Tuning



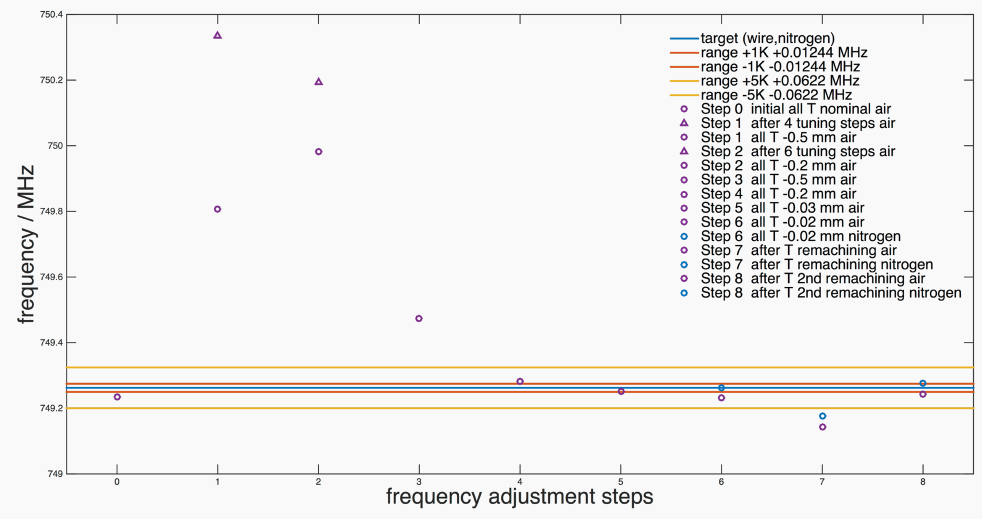
The goal of tuning is to find a mechanical setting for each tuner that provides a constant longitudinal field distribution for the quadrupole mode (Q). The dipolar components (Ds, Dt), should be zero or minimized to a small fraction of the quadrupole component.



Component	Initial	Final
Q	±10.8 %	±1.0 %
Ds	±3.0 %	±1.0 %
Dt	±3.6 %	±1.7 %

Frequency Adjustment

For frequency adjustment all tuners have been moved the same amount to approach the target frequency of 749.48 MHz. This has been done in several steps in dry nitrogen for proper scaling.



Measurement of Q-Factors

Q-factors have been designed to provide enough margin for RF losses with an 18 % over-coupling. This results still in a slight over-coupled case after field and frequency tuning.

	Design	Measurements
Q_0	6440	6570
Q_{ext_1}	21900	26060
Q_{ext_2}		27878
Q_{ext_3}		27878
Q_{ext_4}		21410
Q_{ext_eff}	5475	6376
β	1.18	1.03

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