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Notes on the Bead-Pull System Design for PXIE RFQ

D. Bazyl, I.V. Gonin, T.N. Khabiboulline, V.V. Poloubotko, G.V. Romanov

Fermilab, Batavia, Illinois

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One of the key components of Project X Injector Experiment facility is CW Radio-Frequency Quadrupole (RFQ) for beam acceleration from 30 keV to 2.5 MeV. The RFQ is to be built by the end of 2014. The bead-pull measurements will be used to verify manufacturing quality of the RFQ parts and to perform RF tuning of the complete RFQ before commissioning. The SRF Development Department of Technical division is responsible for the bead-pull system design and development. This technical note presents conceptual design solutions.

Contents

1 Introduction

The Project X Injector Experiment (PXIE) will be a prototype front end of the Project X multi-MW CW proton accelerator proposed by Fermilab [1]. PXIE will consist of an H- ion source, a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ) accelerator, a medium-energy beam transport (MEBT) and a section of superconducting cryomodules and will accelerate the beam from 30 keV to 30 MeV [2]. Lawrence Berkeley National Laboratory (LBNL) with a support from Fermilab has developed an RFQ design for PXIE with fabrication scheduled to begin before the end of CY 2012. A general view of the RFQ is shown in Fig.1.

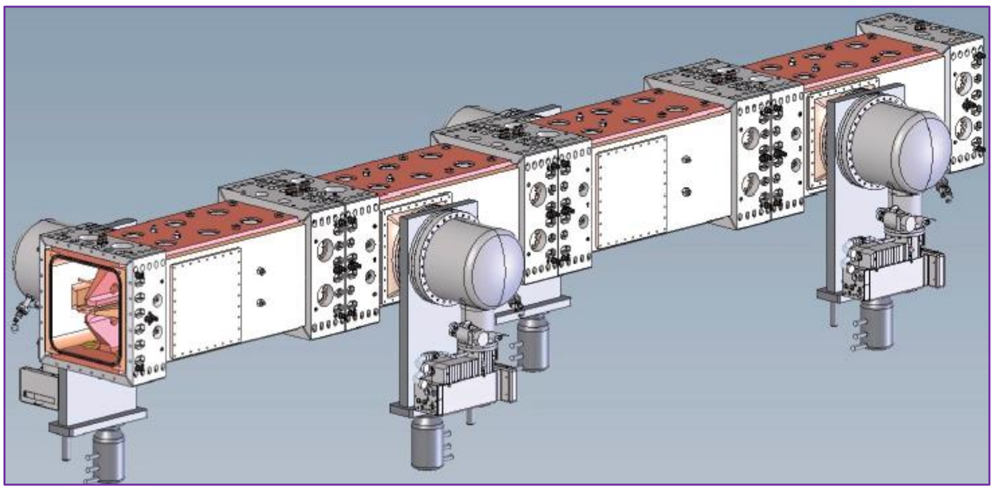


Fig.1: CAD model of the full four-module RFQ

The radio frequency (RF) parameters of RFQ cavities, especially field distribution, are very sensitive to the manufacturing errors and to the field perturbations caused by different elements like power couplers. Practically it is impossible to include all RFQ elements in the simulations and to model exact RFQ geometry with high accuracy. As a rule the pretty much simplified RFQ models are used for RF design that provide rather idealized picture. Also it is impossible to tighten further tolerances for machining, which are already at the edge of achievable. As a result all RFQ cavities have to be tuned before operation to obtain design RF parameters even in case of perfect manufacturing.

Tuning procedure includes measurements of field distribution in RFQ, which are performed with the use of bead-pull technique. Fermilab is responsible for the design and manufacturing of the bead-pull system for PXIE RFQ tuning. This technical note describes our approach to the problem of field distribution measurements as well as preliminary design of the bead-pull system.

2 General layout

Bead-pull is a commonly used RF field measurement technique. RF field measurements play an important role in qualifying any RF cavity. These field measurements are also used in the tuning of the cavities to obtain the required field flatness. The bead-pull method is based on the classical Slater formula, which states that, if any resonant cavity is perturbed by a “small” deformation or “small” body, its resonant frequency shifts from the original frequency. This frequency shift induced by such “small” perturbation (small enough to neglect changes in field distribution) is proportional to the combination of the squared amplitudes of the electrical and magnetic fields at the location of the bead. This relationship is given by equation:

$$\frac{\Delta\omega_0}{\omega_0} \approx \frac{\int_{\Delta V} (\mu_0 \mu_r |\mathbf{H}|^2 - \varepsilon_0 \varepsilon_r |\mathbf{E}|^2) dV}{\int_V (\mu |\mathbf{H}|^2 + \varepsilon |\mathbf{E}|^2) dV} = \frac{\int_{\Delta V} (\mu_0 \mu_r |\mathbf{H}|^2 - \varepsilon_0 \varepsilon_r |\mathbf{E}|^2) dV}{W_{total}} , \qquad (1)$$

where $\Delta\omega_0$ and ω_0 are the frequency shift and the original resonant frequency respectively, μ is permeability constant and ε is permittivity constant of media that fills cavity (presumably air), ε_o is the permittivity of free space and μ_0 is the permeability of free space, ε_r and μ_r are the relative permittivity and permeability of the perturbation material respectively, V and ΔV are the cavity volume and the volume of "small" perturbation respectively, W is the energy stored in the cavity while **E** and **H** are the electric and magnetic field amplitudes respectively.

From this equation the relative electromagnetic field levels can be evaluated basing on the change of resonant frequency.

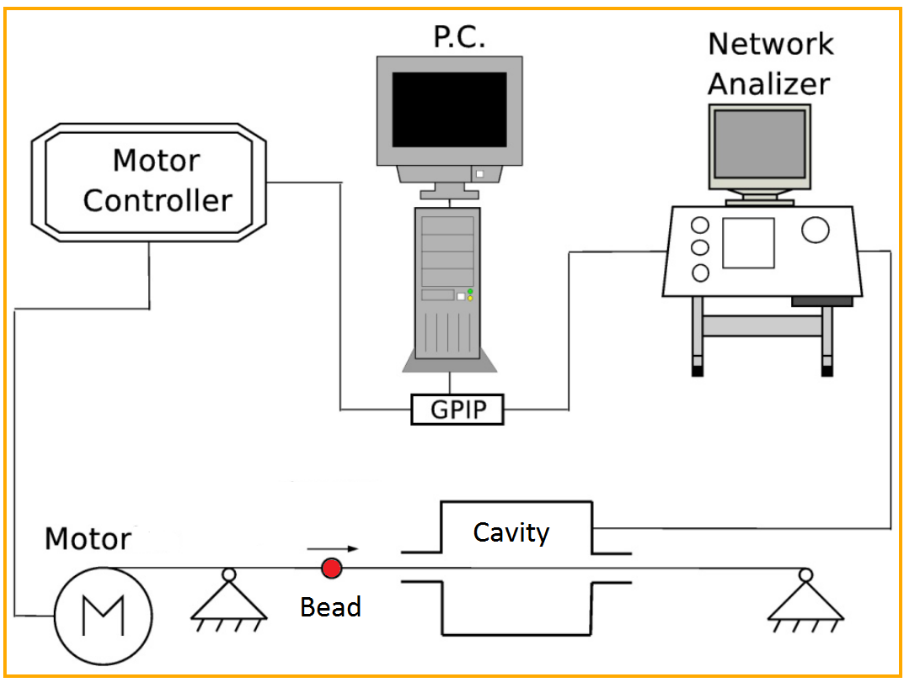


Fig.2: Typical schematic block diagram of bead-pull system.

Practically bead-pull measurement system consists of a small dielectric or metallic bead (sphere or cylinder) being pulled through a cavity while frequency measurements on the cavity are taken (see Fig.2). A step motor and a pulley system guide the motion of the bead attached to a thin thread through the cavity, while a Network Analyzer is used to take the RF measurements. PC is used to control the hardware of the whole bead pull system. The software will coordinate the step motor's movement, acquire data via the Network Analyzer and process the data as required. In the design under consideration the software will also control positioning of the bead-pull line in the plane transverse to the cavity axes – this is essentially a new feature of the bead-pull system.

The PXIE RFQ is so called four-vane RFQ by design. The four-vane RFQ cavities have four chambers (see Fig.3), and the field measurements must be done in each chamber separately. Because of that the bead-pull systems for four-vane RFQ cavities are somewhat specific – normally they have four threads and four beads, i.e. one thread and one bead per chamber (see Fig.4). The main reason is that the balance of fields in the chambers is very sensitive to the perturbation in any single chamber. So, even a very thin thread together with a bead in a single chamber can change field balance between chambers beyond acceptable limit. Such sensitivity can make the machining tolerances very tight and RFQ tuning very sophisticated.

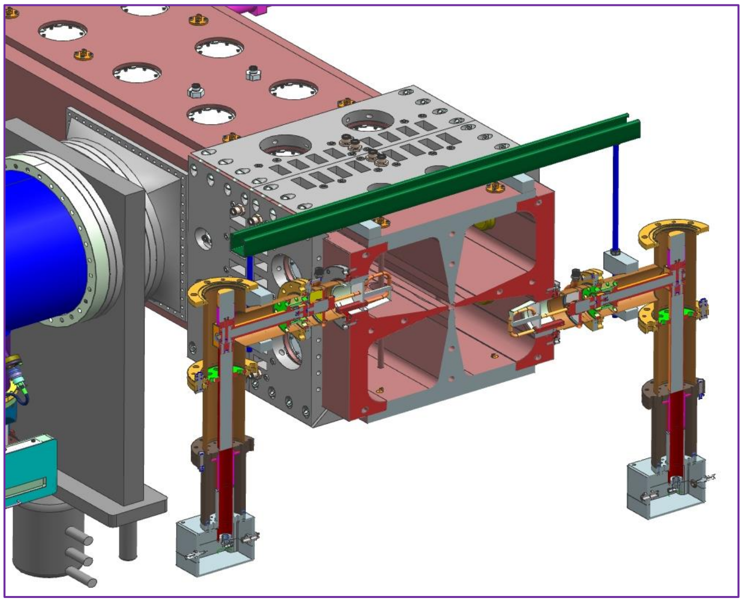


Fig.3: Cross-sectional view of the four-vane PXIE RFQ

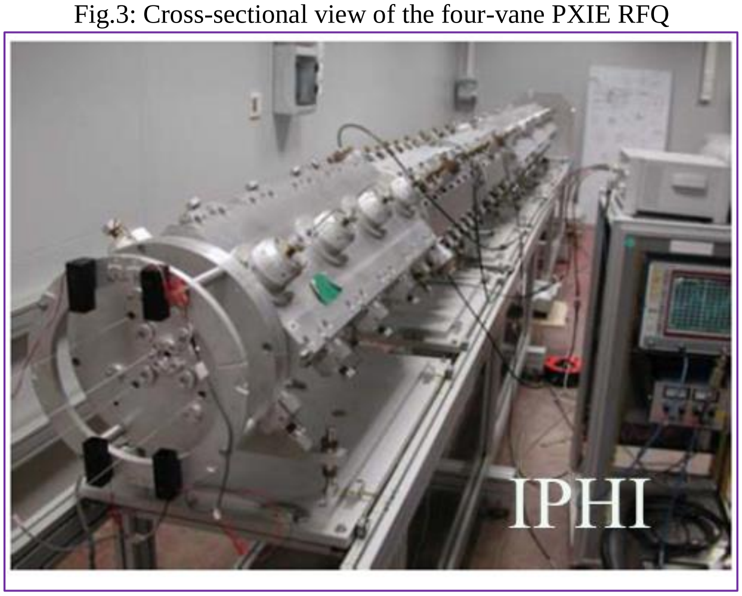


Fig.4: IPHI bead-pull system. Four threads are clearly seen on the left.

The special field stabilizers are used in the cases when azimuthal field stability (balance between chambers) is more important than power effectiveness or mechanical complexity. The PXIE RFQ is such stabilized structure. It uses very effective stabilizers, so called Pi-Mode

Stabilizing Loops – PISL. The PISLs eliminate the azimuthal instability almost completely – detuning of one chamber by 400 kHz creates chamber-to-chamber disbalance of ±1.1% only. Frequency detuning of one chamber by thread and bead together is expected less than 10 kHz, therefore azimuthal field stability is not a problem for RFQ with PISLs. But even for stabilized RFQ the four thread systems were used because alignment of threads in fixed positions is simpler [3]. A single thread has to be moved from chamber to chamber and aligned strictly symmetrically in each chamber. Years ago it was not easy and cheap to develop such bead-pull system. Since then the modern progress in positioning systems was significant (see for example [4]). Therefore we decided to design and develop a single thread bead-pull system with fully automated thread positioning, bead motion control, data processing and generating of recommendations for RFQ tuning.

3 Temporary end terminations.

Mechanically PXIE RFQ consists of four ≈ 1 meter long modules which will be manufactured one by one with 1-2 months delay. At least first module will be measured using bead-pull technique to verify RF parameters and mechanical design. This test will allow correcting possible errors before manufacturing the rest of modules.

A technical problem with these planned measurements is that the central modules do not have proper end terminations at all, while first and fourth modules have input and output terminations respectively. Without proper end terminations the operating quadrupole mode cannot be excited in RFQ structure. To make the bead-pull measurements on the separate module possible, LBNL designed the temporary end terminations (see Fig.5), which emulate the output vane cut-backs [5].

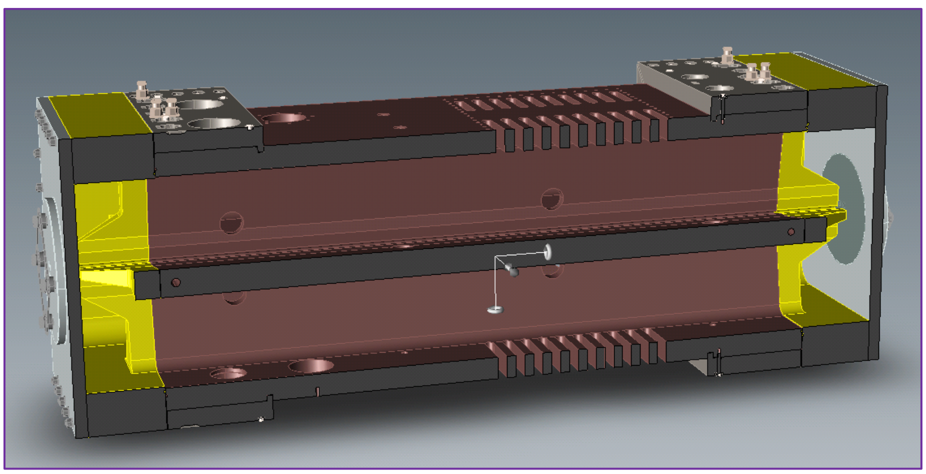


Fig.5: Sectional view of Module 3 assembled with the temporary end terminations (highlighted).

The CST model of Module 3 with the temporary end terminations was built to verify the termination design (see Fig.6). The simulations show practically undisturbed field distribution, and this confirms correct geometry of the temporary terminations. Though, the frequency of the 162.672 MHz is higher than design value by almost 200 kHz. But this frequency rise is not due to the terminations design. Simply the temporary terminations increase regular length of the module, while the number of PISLs, which are main contributors to frequency decrease, remains the same. The depth of vane modulation also changes cavity frequency. Since the depth of modulation is different in the modules, the simulations should be done for each of them to get a reference frequency, if it would be decided to measure all modules separately.

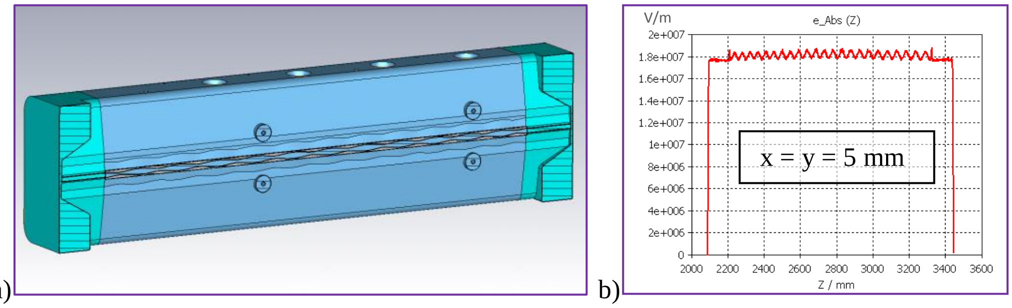


Fig.5: a) The CST model of Module 3 with temporary end-walls. The vanes are modulated. b) Electric field magnitude in the gap between vane tips (x=y=5 mm) as a function of z.

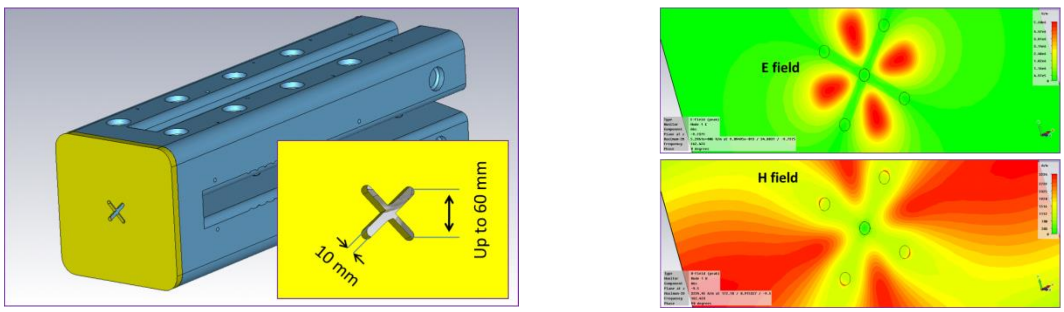


Fig.6: Crossed slots on the end plate for passing thread and bead. Field distributions on the inner wall of the end plate are shown on the right.

We chose a central position for thread and bead by the reasons explained below. Therefore the plates, which cover the end terminations, must have crossed slots to allow repositioning of the single thread from one cavity chamber to another. The proposed dimensions and orientation of the slots are shown in Fig.6. There was a concern about possible field perturbation by the slots. But the simulations showed that due to the quadrupole symmetry of operating mode the slots are placed in the zero electromagnetic fields, and this perturbation is absolutely negligible.

4 Radial position of the bead

Though accelerating and focusing field in RFQs is between vane tips, this area is not suitable for bead-pulling. Typically there is not enough room between vane tips for safe bead-pulling, high fields and strong gradients create perturbation and alignment problems, it is not easy to extract information on azimuthal symmetry of the field distribution. So, without any exclusion the bead-pulling is performed in the RFQ chambers. It was proved theoretically and practically that the field distributions in the chambers provide correct information about the paraxial accelerating fields. A position of bead (or line along which a bead will be pulled) should provide sufficient frequency shift. There are two such areas in RFQ cross-section: closer to axis, where electric field dominates; and closer to the RFQ walls, where magnetic field dominates (see Fig.7 a) and b)). In between a bead-pull has low sensitivity in general, and it is simply unavailable because of PISLs in case of PXIE RFQ.

For JPARC 325 MHz RFQ that also has PISLs the peripheral bead position was chosen (see Fig.7 c)), probably, because the transverse dimensions of the RFQ cavity is smaller. We found that the longitudinal magnetic field distribution between PISLs and RFQ walls is too nonuniform because of PISLs, tuners and pick-up loops (see Fig.8). That makes estimation of actual field flatness very difficult. The magnetic field is much smoother between PISLs and RFQ axis, though impact of PISLs is still significant. The longitudinal electric field distribution is very uniform between PISLs and RFQ axis, practically field distribution non-uniformity due to the vane tip modulation is seen in the gap between electrodes.

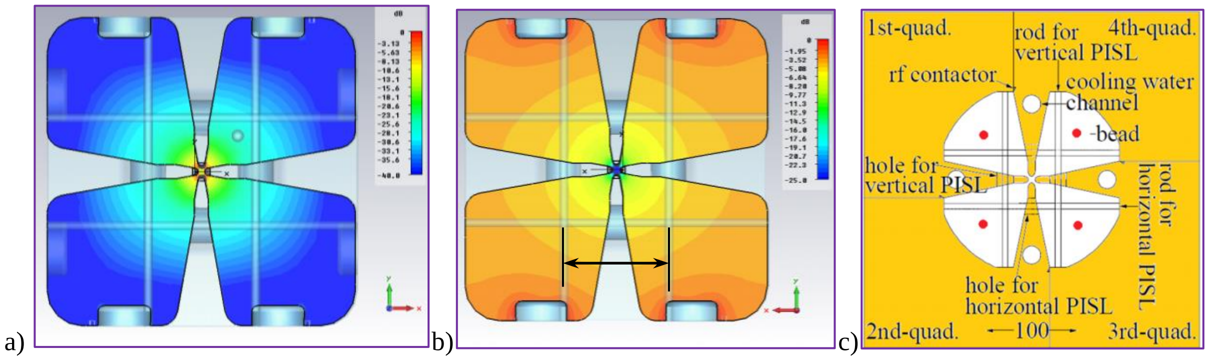


Fig.7: a) Electric field distribution in PXIE RFQ cross-section, possible position of bead is shown b) Magnetic field distribution in PXIE RFQ cross-section, c) Choice of bead positions for JPARC, 325 MHz RFQ.

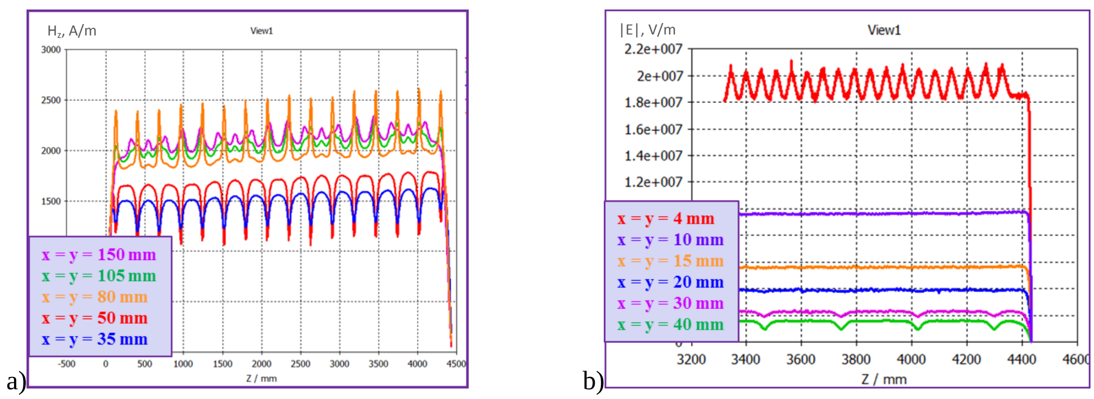


Fig.8: a) Magnetic field distributions in the full length model of PXIE RFQ at different distances from the axis. b) Electric field distributions in the model of Module 4 at different distances from the axis.

Taking into account the importance of field distribution uniformity it was decided to perform bead-pull measurements between PISLs and the gap between vanes, as shown in Fig.7 a).

5 Size and material of the bead

The choice of material and size of the bead is not trivial for measurements of 4 m long RFQ. The bead must be big enough to provide sufficient frequency shift, on the other hand it should be very light to avoid thread sag or excessive thread tension.

Actually the choice of material is not very broad – it can be either dielectric with high permittivity or it can be metal. For these materials the frequency shifts derived from (1) are:

For a dielectric sphere with radius ***r*** - $$\frac{\Delta\omega_0}{\omega_0} = -\frac{\pi r^3}{W_{total}}\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\varepsilon_0 E^2 \quad ; \qquad (2)$$

For diamagnetic metal with radius ***r*** - $$\frac{\Delta\omega_0}{\omega_0} = -\frac{\pi r^3}{W_{total}}(\varepsilon_0 E^2 - \mu_0\frac{H^2}{2}) \quad , \qquad (3)$$

where ε_o is the permittivity of free space, ε_r is the relative permittivity of the sphere and μ_0 is the permeability of free space.

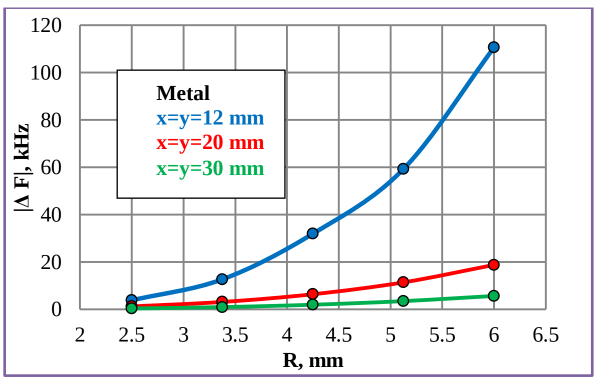
According to the formulas a dielectric bead is effective in strong electric fields, while a metal bead is effective in areas where either electric or magnetic field dominates. It turned out that for particular field distribution between axis and the PISLs in the PXIE RFQ practically both materials are equally effective, assuming that dielectric has $\varepsilon_r > 9$. The frequency shift vs bead radius for different radial positions of the bead calculated for a single module are summarized in the tables below, and the corresponding plots are shown in Fig.9.

Metal bead

Bead radius R, mm	|ΔF|, kHz		
	x=y=12 mm	x=y=20 mm	x=y=30 mm
2.5	3.876	1.2825	0.405
3.375	12.725	3.175	0.9975
4.25	31.995	6.4325	2
5.125	59.325	11.4425	3.525
6	110.65	18.81	5.695

Dielectric bead (ε_r = 10.5)

Bead radius R, mm	|ΔF|, kHz		
	x=y=12 mm	x=y=20 mm	x=y=30 mm
2.5	3.87	1	0.345
3.375	9.88	2.475	0.8525
4.25	20.91	5.0025	1.705
5.125	40.4125	8.88	3.005
6	76.055	14.5325	4.8475



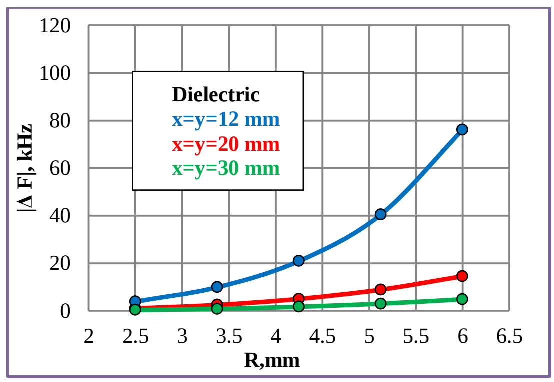


Fig.9: Frequency shift vs bead radius for different radial positions of the bead simulated with CST MWS. The simulations were performed for a single 1 meter long module.

Finally the bead size and its material will depend on the particular choices. For example, if it will be decided to pull the bead without touching the RFQ vanes, then a metal bead is preferable. It can be made as a hollow sphere and therefore will be lighter than solid dielectric bead. If the RFQ vanes will be used as a guide rail and a bead will touch them, then a dielectric bead should be used to avoid surface scratching and additional instability due to electric current between bead and RFQ walls. The bead size will depend on its radial position and on the cavity length. Probably it would be necessary to use bigger beads to measure full length RFQ, since the frequency shift drops linearly with the length of cavity.

6 Bead alignment

A bead-pull system with single thread will require frequent repositioning of the bead from one RFQ chamber to another. This repositioning should be done with high accuracy and be repeatable. The bead repositioning is not a trivial task, if the vanes are not used as a guide rail, which is not a current approach. The bead-pull system under development will have a fully automated positioning capability to deal with this problem. Such automated positioning requires a precise reference point to assure required accuracy. For RFQ cavity such natural reference is its electromagnetic axis.

To find the coordinates of the electromagnetic axis in the RFQ the bead-pulling in radial direction is supposed to be used as shown in Fig. 10, a). The approach is based on the fact the electric field is zero in the center of RFQ (Fig.10, b)). A series of crisscross measurements will provide a number of points that will be used to locate the electric field minimum and define its coordinate. The measurements have to be done in several positions along the cavity. It does not seem to be a quick procedure, but it will be needed to be done only once after bead-pull system is mounted on the cavity.

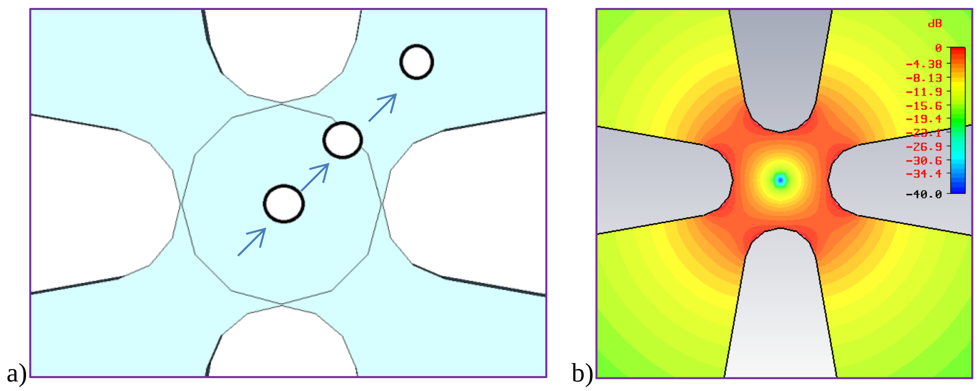


Fig.10: a) The bead-pulling across RFQ to locate electromagnetic axis. b) Magnitude of electric field in central area of RFQ.

The electric field in the RFQ center absolutely dominates and it is very strong, so both materials are of equal worth. The bead size is more critical –it should be smaller than the gap between the vane tips and at the same time it should provide sufficient frequency shift without field distortion.

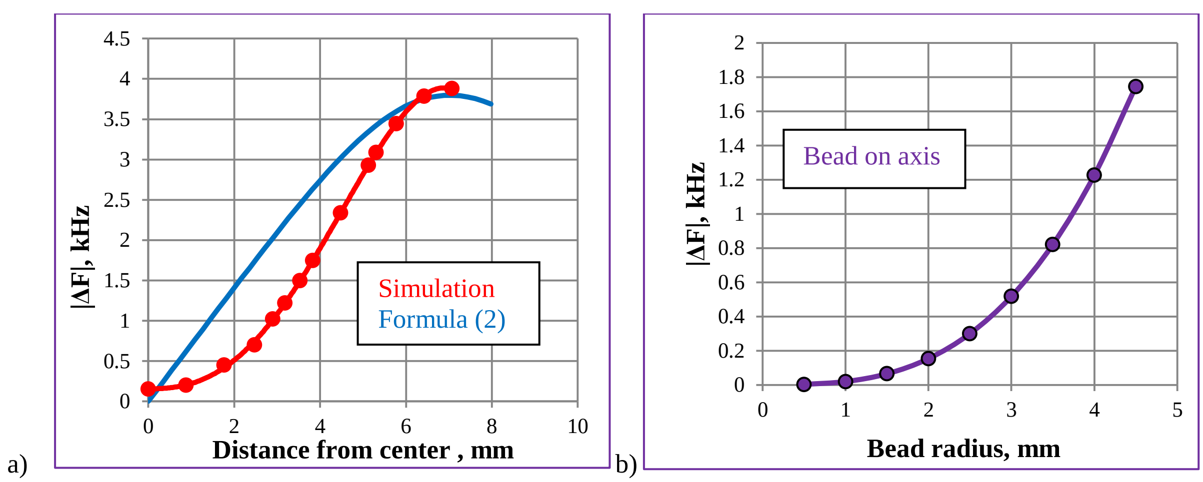


Fig.11: a) Frequency shift vs bead position, dielectric bead, ε_r = 10.5, radius - 2 mm; b) Frequency shift vs bead radius. The frequency shifts correspond to 4 meter long RFQ model for both plots.

Frequency shifts as the functions of bead size and its radial position are plotted in Fig.11. Since the bead alignment is more important for measurements of full RFQ, the simulations were performed with 4 meter long model with flat vane tips (no modulation since exact field distribution is not important). It seems that the bead radius of 2 mm is an optimal size.

The Fig.11 a) shows that a violation of "small perturbation" principle is big, so such measurements would be not acceptable for field distribution evaluation. But what is needed to be determined is a location of electromagnetic axis, which corresponds to minimal frequency shift, not exact field profile. Direct measurements of this minimum cannot be accurate enough, since it is very shallow and very small absolute frequency shift around it is hard to indicate. Apparently the linear part of curve $|\Delta F|(r)$ will be measured, and then it will be elongated to low field area.

Next step of the bead alignment is moving the bead to chosen point inside RFQ chamber. The choice of operating bead position is dictated by two contradicting factors – frequency shift and accuracy of positioning. Plot of radial distribution of electric field (we may neglect magnetic field, its contribution is not big) in Fig.12 points out that the bead position that is closer to the RFQ center provides larger frequency shift, but makes the accuracy of bead positioning very demanding due to the strong field gradient.

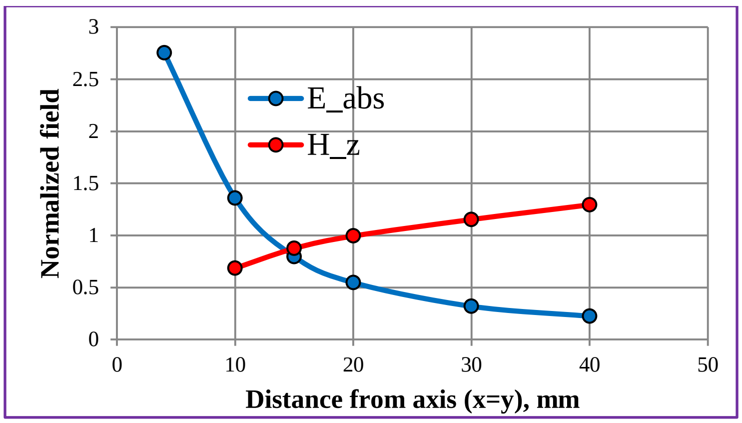


Fig.12: Normalized field distributions between RFQ axis and PISls. In absolute values electric field heavily dominates – for metal bead contribution of magnetic field to frequency shift does not exceed 10%.

Simple estimations of alignment accuracy for two extreme locations, made on the base of simulated field gradients, are given in the table below:

Distance from axis , x=y in mm	40	15
Alignment sensitivity, % of field/mm	1.6	8.1
Alignment accuracy for ±1% of field, mm	±0.63	±0.12

Depending on the field distribution flatness requirement, accuracy of the bead-pull system mechanics and accuracy of measurements an optimal choice of bead size and bead transverse position will have to be done. It is very likely that the final establishing of the bead-pull procedure will require certain experiments and tests.

7 Conceptual design of the bead-pull system

Taking into account the considerations stated above a mechanical design of the bead-pull system has to be very flexible.

The main feature of the system will be the operation with a single thread. To allow quick and precise repositioning of the bead, the system will have a capability of PC controlled alignment of the bead in transverse plane as shown in Fig.13. Two pairs of actuators will move the thread and the bead in horizontal and vertical planes independently.

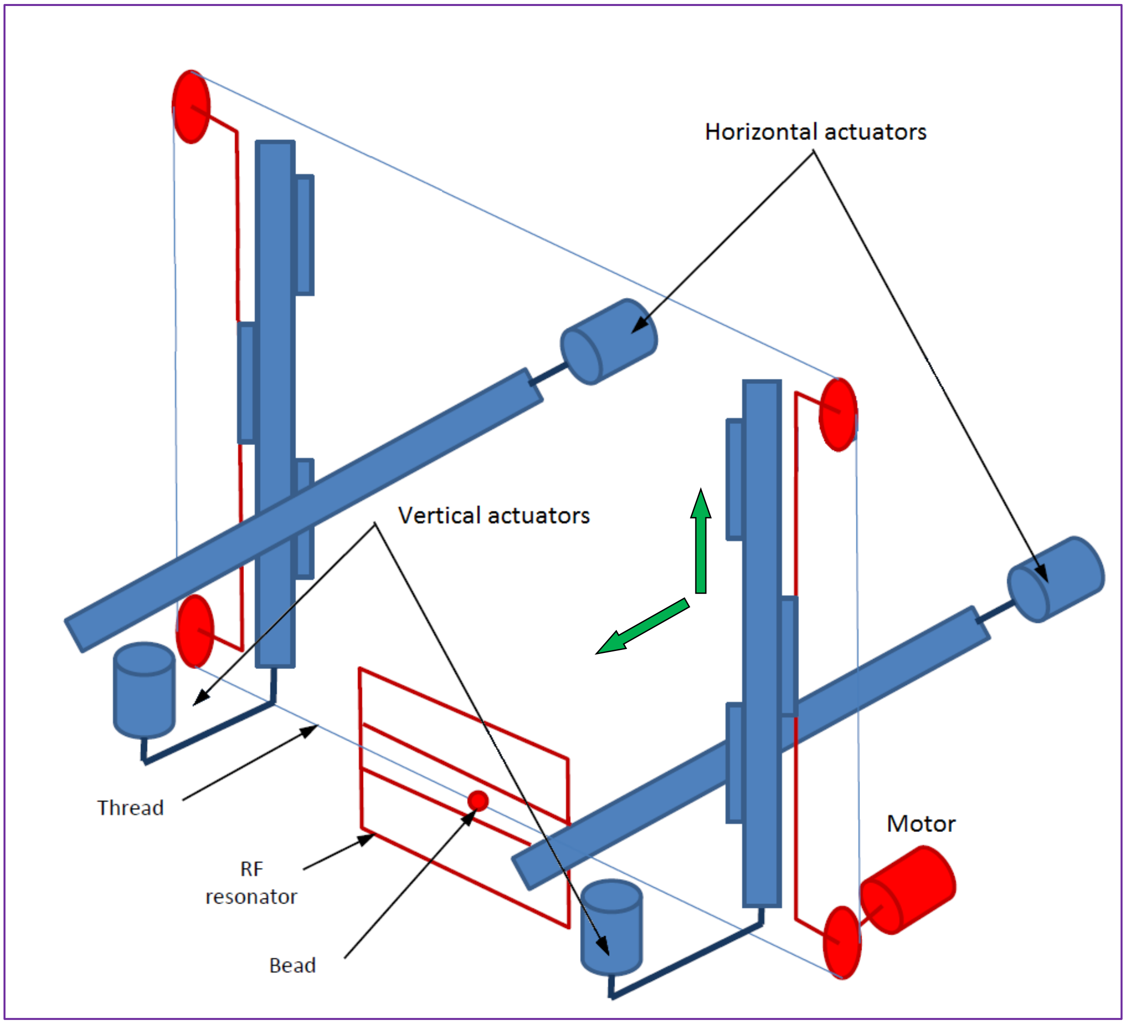


Fig. 13: Kinematic diagram of the proposed bead-pull system. The main feature of the system is PC controlled alignment of the bead in transverse plane, indicated by green arrows in the sketch.

A general scheme of driving and passive rollers, and a tension roller controlled by a load cell, is typical and shown in Fig 13, a). All rollers, driving motor, actuators and rails are mounted on a platform (Fig.13, b). The platform in its turn is mounted on the temporary end plates (Fig.13, c) and stands motionless, while the whole system can be moved along the rails. The front and back bead-pull assemblies are identical, except one of them does not have driving motor.

The Kevlar thread is supposed to be used because it is non-elastic and very strong, though some tests are planned to make a final choice. The set of spherical beads of different diameters will be manufactures to cover all possible needs.

A PC will control bead alignment and movement, collect and process data from Network analyzer, taking into account frequency drift and thread sag, and finally generates the recommendations for RFQ tuning.

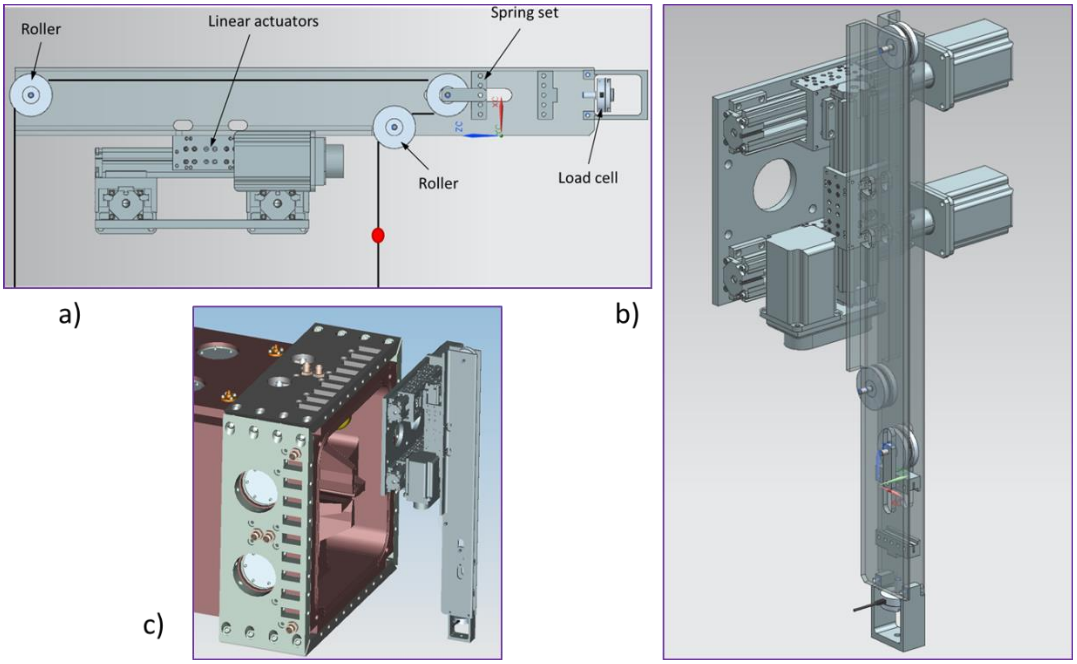


Fig.14: a) Scheme of bead-pulling; b) General view of the front bead-pull assembly. c) Position of the bead-pull assembly relatively to the RFQ (the temporary end plate is not shown)

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