A COUPLED RFQ-IH-DTL CAVITY FOR FRANZ: A CHALLENGE FOR RF TECHNOLOGY AND BEAM DYNAMICS

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Abstract

For the 'Frankfurt Neutron Source at the Stern-Gerlach-Zentrum' (FRANZ) facility an inductively coupled combination of a 4-Rod-type Radio-Frequency-Quadrupole (4-Rod-RFQ) and an 8 gap interdigital H-type (IH-DTL) structure will provide the main acceleration of an intense proton beam from 120 keV to 2.0 MeV. The RFQ-IH combination with a total length of about 2.3 m will be operated at 175 MHz in cw mode. The expected total power need is around 200 kW. Due to the internal inductive coupling only one RF amplifier is needed, which significantly reduces the investment costs. At present the RFQ is installed separately in the beam line for conditioning up to the design rf power and for measuring the beam quality behind the RFQ. In parallel, the IH-DTL is rf tuned together with a dummy RFQ outside the FRANZ cave. This paper will present the status of the project with emphasis on key questions like beam dynamics constraints, rf tuning issues and technological challenges resulting from the high thermal load in cw operation.

INTRODUCTION

At the FRANZ facility on the campus of the Frankfurt University physics faculty, a 2 MeV proton primary beam will produce 1 – 200 keV neutrons by the ^{7}Li(p,n)^{7}Be reaction with a maximum neutron yield at 30 keV. For such lower neutron energies, the FRANZ facility will provide intensities by two to three orders of magnitude larger than from existing accel. driven intense neutron sources [1].

The facility will mainly serve to nuclear astrophysics experiments [2], namely:

- Measurement of the differential neutron capture cross sections dσ/dE, with relevance to the stellar nucleosynthesis (slow neutron capture process). For this purpose, time-of-flight (TOF) measurements are needed and the FRANZ facility has to deliver 1 ns short proton bunches with a repetition rate of 250 kHz. In the so called "compressor mode" it is aimed to produce a neutron flux of $1 \cdot 10^{7}$ /cm^2/s at the sample.
- Measurement of integrated neutron capture cross sections. In the so called "activation mode" the facility is designed to produce 10^{11} n/cm^2/s in cw operation.

In order to fulfil these ambitious specifications, an intense primary proton beam of several mA (for the activation mode) and up to 140 mA (for the compressor mode) must be accelerated to 2.1 MeV with an energy variation of ± 0.2 MeV. In the first operation phase of FRANZ, the maximum proton beam current will be limited to 50 mA. However, the in house developed filament driven source already delivered a 200 mA d. c. proton beam. The time structure needed for the TOF measurements will be applied by a chopper array integrated to the LEBT section, which will form macro pulses with a flat top of 50 ns and 250 kHz repetition rate. Behind the main linac, a Mobley type "bunch compressor" will merge 9 consecutive micro bunches as delivered by the linac and bunch the proton beam to the final length at target of around 1.1 ns.

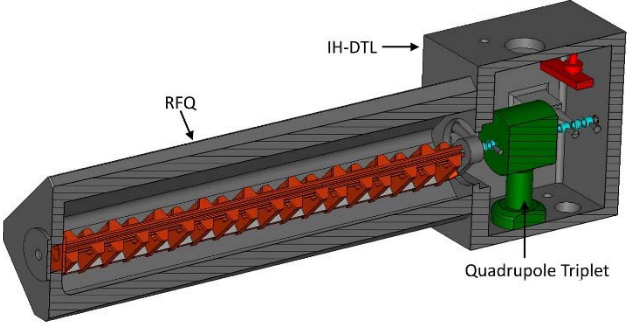

Figure 1: Coupled RFQ-IH-DTL cavity.

Table 1: Parameters of the Coupled Cavity

Parameter	**Value**	
f [MHz]	175	
I [mA]	50 (140)	
coupling factor k	0.004	
	4-Rod-RFQ	**IH-DTL**
energy range [MeV]	0.12 – 0.7	0.7 – 2.0
total length [m]	1.7	0.6
rf losses [kW]	95 (140)	60 (60)
4-Rod-RFQ		
electrode volt. [kV]	62 (75)	
R_p [kΩm]	70	
no. of stems	18	
IH-DTL		
eff. gap volt. [kV]	80 – 350 (80 - 350)	
$R_{shunt,eff.}$ [MΩ / m]	62	
no. of gaps	8	

This paper focuses on the discussion of all points of interest related to the main accelerator component, an inductively coupled 4-Rod-RFQ & IH-DTL combination (see Figure 1): from beam dynamics to rf tuning aspects and right up to mechanical design challenges due to the high thermal load on the cavities at cw operation.

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After a careful assessment of several alternatives (see next chapter), the inductive coupling was chosen because it helps reducing rf amplifier costs and utility space, but also minimizing the length of the inter tank section, which is an advantage in high current beam dynamics.

CAVITY COUPLING OPTIONS

The most natural solution would have been an RFQ resonator up to the end energy of 2 MeV. This cavity would be about 3 meters long and require a 300 kW amplifier. This is why, mainly for costs reasons, the more efficient combination of an RFQ up to 700 keV followed by the IH-DTL up to 2 MeV has been chosen. In this case, feeding each resonator cavity by its own amplifier unit is the natural solution with the highest degree of flexibility with respect to rf tuning and cavity control. However, in case of two independent cavities, two cw amplifiers would have been needed, in the power class between 100 kW (IH-DTL) and 200 kW (4-Rod-RFQ). This option has been rejected from the start, by lack of budget and of the needed utility space on site. This is why different alternative solutions have been carefully investigated [3], [4]. All alternatives described below have in common that only one amplifier in the power class of 250 kW would be needed.

Power Splitter

By using a splitter, the power from one amplifier can be divided according to the needed RFQ-DTL amplitude ratio as defined in advance. However, the power ratios are then fixed and cannot be easily rematched. The splitter itself would be an expensive, custom-made item. Moreover, one has to fight against reflections at the splitter unit and difficult phase matching between 4-Rod-RFQ and IH-DTL.

Phase Shifter

The full rf power is coupled into one of the cavities (e.g. the 4-Rod-RFQ), then partly out coupled and critically coupled to the second cavity (IH-DTL) by means of the phase shifter unit. The rf phase relation between both structures can be adjusted by length variation of the coaxial transmission line. However, the phase matching is rather sensitive.

Galvanic Internal Coupling

The full rf power is again coupled into the RFQ and then transferred to the IH-DTL by a bridge directly connected to the last RFQ and the first DTL stem. The positions of the connections to both stems basically define the voltage amplitude ratio U_{IH}/U_{RFQ}. This option has been investigated in detail and seriously considered in the early project phase [5]. However, it has been finally abandoned because of a missing technical solution for the sophisticated, coaxial water cooling system needed for absorbing the thermal losses along the coupling bridge.

Inductive Internal Coupling

The inductive coupling is accomplished by just opening the connection flange between both structures. Thus the magnetic field can penetrate through the coupling cell (see Figure 2) and can induce a common (i.e. coupled) resonance of both connected cavities. This concept allows for a flexible tuning of the resonance frequency and the RFQ-DTL amplitude ratio, and hence it was finally chosen for the FRANZ RFQ-DTL combination.

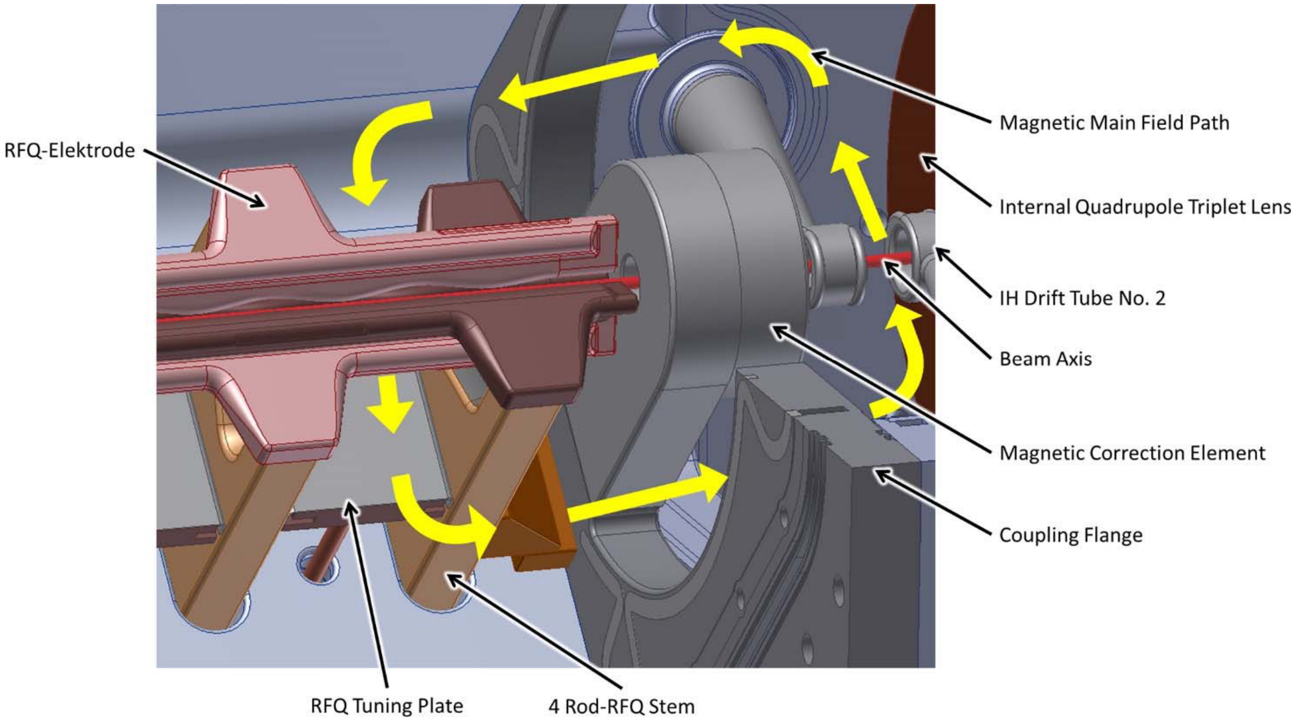

Figure 2: Detail view of the coupling flange between Four Rod RFQ and IH DTL. The qualitative pathway of the magnetic field lines (in yellow) in case of the zero mode is shown.

TUNING OF THE INDUCTIVE COUPLED RFQ-IH-DTL COMBINATION

The theory of eigenmodes in a series of n inductive coupled resonant circuits is described in many textbooks, e.g. by T.P. Wangler [6]. In our case the eigenvalue problem must be solved for only two coupled oscillators. Assuming that both cavities are independently tuned to the same resonance frequency f_0 before coupling, then after coupling the following two coupled resonances appear:

$$\omega_1 = \omega_0 \cdot \sqrt{\frac{1}{1+k}} \qquad \text{with } i_2 = i_1\text{, “zero mode”} \tag{1}$$

$$\omega_2 = \omega_0 \cdot \sqrt{\frac{1}{1-k}} \qquad \text{with } i_2 = -\, i_1\text{, “}\pi\text{ mode”} \tag{2}$$

The bandwidth is then given as follows:

$$\delta\omega = \omega_2 - \omega_1 \approx \omega_0 \cdot k \tag{3}$$

with k being the coupling factor ($k = M / L$).

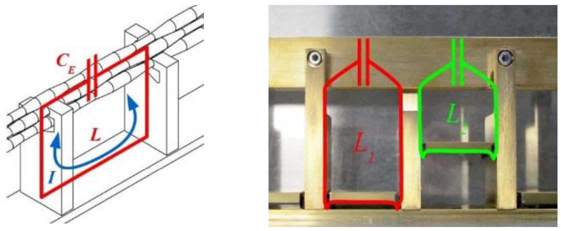

Figure 3: Adjusting the resonance of Four-Rod-RFQ cells by changing the tuning plates’ positions.

Based on these considerations, the tuning procedure of the coupled 4-Rod-RFQ IH-DTL combination has been performed in the following steps [3], [4], [7]:

- Tuning of the uncoupled cavities to the same resonance frequency f_0. The 4-Rod-RFQ can be described as a chain of coupled $\lambda/2$ resonators. The inductance of each cell can be tuned by changing the position of the contacting tuning plates (see Figure 3). By these means, the FRANZ RFQ has a tuning range of several MHz, limited only by the required field flatness. The IH-DTL has a tuning range of ± 2 MHz by static tuners, also limited by the voltage distribution.

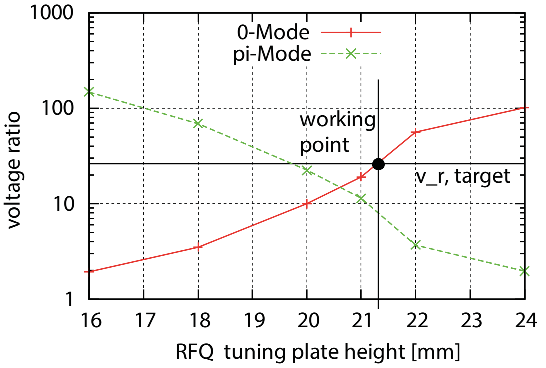

Figure 4: U_{IH}/U_{RFQ} adjustment by RFQ tuning plates.

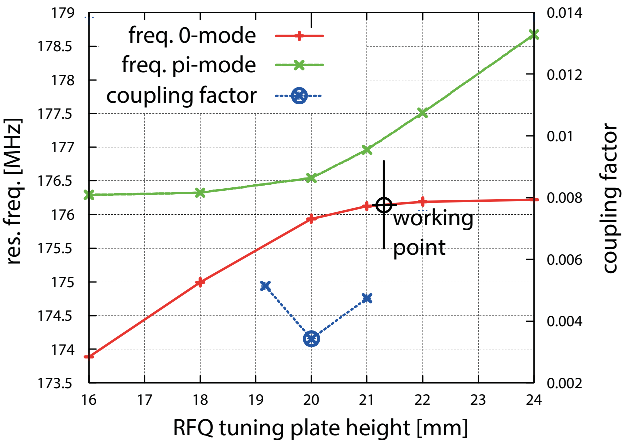

Figure 5: Mode separation and dependence of the coupling factor on the position of the last RFQ tuning plate.

- Couple the cavities and use the tuning knobs as described before for setting the desired U_{IH}/U_{RFQ} voltage ratio. The target value was 25.4. As seen from Figure 4, the voltage ratio can be matched effectively by only changing the position of the last RFQ tuning plate.
- Rebalance the field flatness in the RFQ and the voltage distribution in the IH-DTL and simultaneously adjust the coupled cavity resonance to f_1 = 175 MHz. This final step can be performed by using all RFQ tuning plates and the movable RFQ and DTL tuners (only small displacements needed for fine adjustment).

The described tuning procedure has been investigated on a cold model cavity. Key results are shown in Figure 4 and Figure 5 [3], [7]. Microwave Studio simulations would be too time consuming in this case, because of the complicated mesh and lack of symmetries. After optimization of the coupling parameters by measurements, CST MWS simulations were used for cross checking.

As shown in Figure 4 and Figure 5, the zero and the pi mode act in an opposite way, as expected from theory, and moreover they are separated by a minimum of 0.6 MHz and by about 1.0 MHz at the working point. Finally, the feasibility of the cavity coupling with good accuracy and high tuning ability could be demonstrated (see Figure 6).

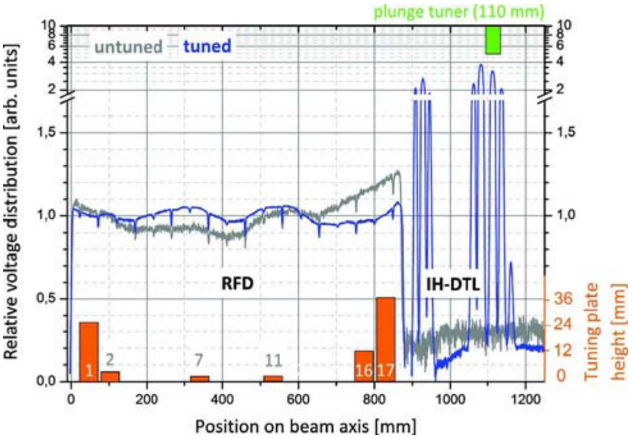

Figure 6: Demonstration of the successful inductive coupling (blue line) based on cold model measurements.

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STATUS OF THE RFQ AND IH-DTL STRUCTURES

A technological challenge for both the RFQ and the IH-DTL structure of the FRANZ project is given by the high thermal load due to cw operation. This is why extensive rf and thermal simulations were necessary in the design phase of both cavities. Based on the results, improved cooling and contacting techniques had to be developed, as for example: The RFQ cooling channels were done by electroforming technology; the contact pressure between the tuning plates and the stems was improved by using specially shaped shims instead of the conventional spring contacts.

For the validation of the new technology, a short (0.4 m long) prototype RFQ was built and power tested. Figure 7 shows the encouraging power test result: At the maximum power level of 46 kW (i.e. 115 kW/m, 2.5 times higher than ever achieved for cw operated 4-Rod-RFQs) the reflected power (in red) is still less than 1%. Long term stability was also demonstrated in a 200 hours run at 31 kW (i.e. 78 kW/m, which is the FRANZ 4-Rod-RFQ design value) [8].

For the IH-DTL, extensive simulations of the heat distribution were performed, resulting into max. surface field reduction and the development of a cavity walls and stems cooling concept [4], [9].

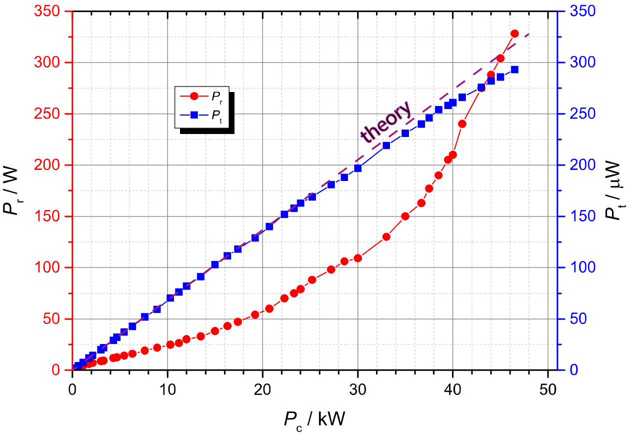

Figure 7: Power test results on the short RFQ prototype cavity. Pickup (P_t, blue) and reflected (P_r, red) power as function of the cavity power.

At present, both cavities and all subsidiary components (e.g. the coupling flange with integrated steering magnet unit) are ready for installation (see Figure 8). The 4-Rod-RFQ has been rf tuned as a "stand alone" cavity and is now under high power rf conditioning. For the IH-DTL rf tuning measurements are performed by using a RFQ dummy, in order to prepare the coupled mode operation. The final steps will be the coupling of both cavities, installation in the FRANZ cave and first tests with beam.

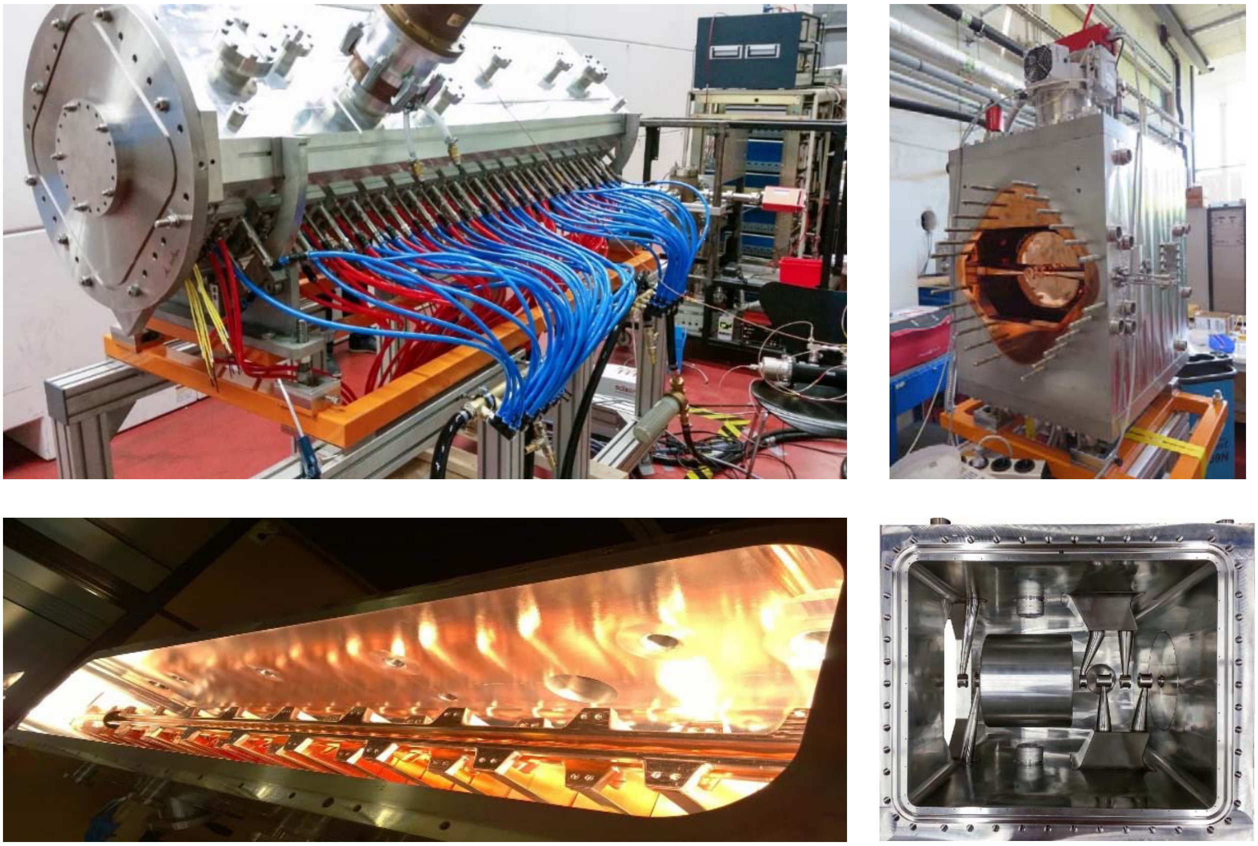

Figure 8: RFQ and IH-DTL ready for power testing and installation into the FRANZ cave.

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BEAM DYNAMICS ISSUES

The RFQ beam dynamics design has been performed with the PARMTEQ code (results not shown in this paper). The RFQ output distribution is used as an input for the DTL simulations performed with the in-house developed code LORASR. The results are shown in Figure 9 and Figure 10. In the simulations the subsequent quadrupole triplet lenses as well as the rebunching CH-type cavity are included. The transverse beam dynamics is defined by a quadrupole triplet channel, whereas the longitudinal motion is that of a separated function linac: a combination of main acceleration sections at $\phi_s = 0$ deg and rebunching gaps at negative synchronous phase.

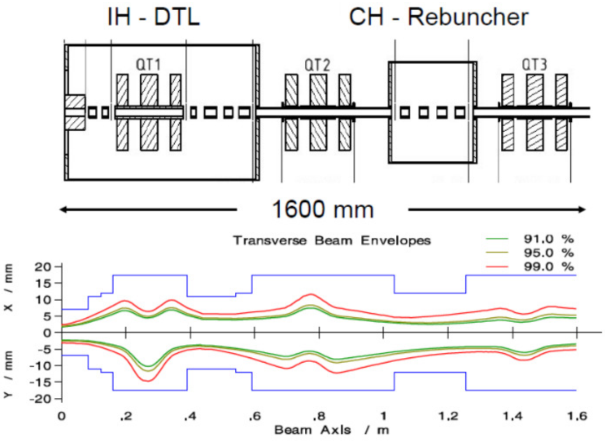

Figure 9: Transverse beam envelopes along the IH cavity and the subsequent transport and bunching section.

The major beam dynamics constraint to be considered is the fixed RFQ-DTL rf phase relation. This is why the drift between the RFQ electrode ends and the first DTL gap has to be matched with high precision. However, the RFQ output phase and beam energy might diverge, depending on the achievable coupled RFQ-DTL rf tuning accuracy.

This is why detailed error sensitivity simulations are necessary and can start as soon as the final coupled cavity rf tuning data will be available. First cross check simulations as shown in Figure 10 are very promising: The lattice shows high robustness with respect to very large offsets in phase (10 deg) and beam energy (5 %).

CONCLUSION

A novel, inductively coupled RFQ-IH-DTL combination will serve as the main linac component for the FRANZ project, accelerating a 50 mA proton beam from 120 keV to 2.0 MeV in cw operation. The basic structure parameters have been defined after detailed numerical simulations and measurements on a scaled model.

At present all components were delivered and are tuned and rf conditioned separately, in preparation for the coupled mode operation. An extended beam dynamics error study is under preparation in order to define the needed coupled cavity tuning accuracy.

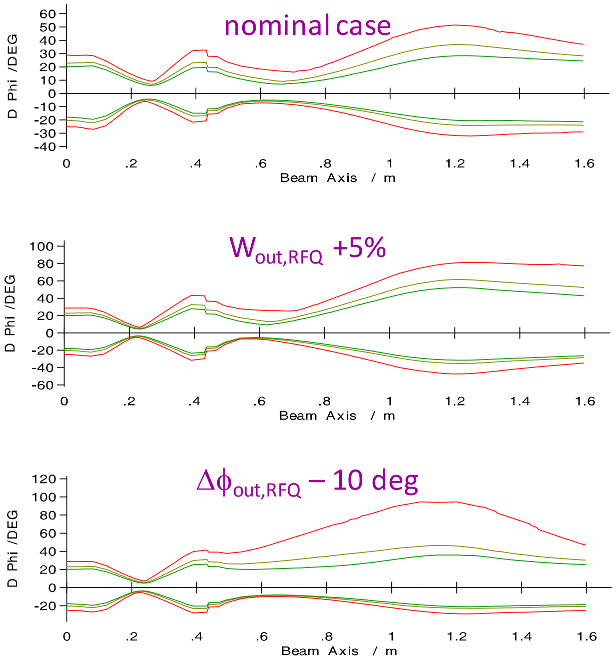

Figure 10: Error sensitivity of longitudinal beam dynamics with respect to starting phase and RFQ output energy variation.

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