THE ESS RFQ BEAM DYNAMICS DESIGN

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Abstract

The European Spallation Source (ESS), to be built in Lund, Sweden, will use a high current proton linear accelerator (linac) required for generating high flux of pulsed neutrons by the spallation process. The linac will deliver proton beams of 50 mA and 2.5 GeV onto the 5 MW neutron production target. The Radio-Frequency Quadrupole (RFQ) will bunch the continuous beam, coming from the ion souce [1] and transported through the dual solenoid Low Energy Beam Transfer (LEBT) line [2] at 352.21 MHz, focalize and accelerate it from 75 keV to 3 MeV. The current design is a 4-vane RFQ composed of 4 segments of 1 m each. This new RFQ is 1 m shorter than the previous 2011 design. However very similar performances are foreseen. The paper reports the motivations of such a change and presents also the beam dynamics study of the current 4 m RFQ.

MOTIVATIONS FOR A SHORTER RFQ

Previous and current performance requirements

The previous RFQ 2011 design was, in part, based on the following performance requirements:

- initial operation at peak current of 50 mA but upgradable to 75 mA;
- beam loss above 2 MeV is limited to 1 W/m;
- both transverse and longitudinal emittances are minimized to reduce the potential for subsequent halo development;
- there should be no longitudinal tails as they are known to translate into transverse halo.

Beam dynamics studies showed that a long structure was needed to fulfill these requirements. The 2010 RFQ was then composed of 5 one-meter segments [3]. Since the latter design has been achieved, the benefits of having such a long structure and the associated potential risks have been deeply analyzed. In particular, the proton beam induced activation of the linac has been evaluated [4] and the beam loss criterion has been relaxed consequently. Moreover the design intensity has been revised. The reflection has finally led to recommand the following updated requirements:

- peak operational beam current will not exceed 50 mA;
- no limit to allowable beam loss below 3 MeV;
- halo development and beam loss in the high energy linac section traceable to the RFQ are minimized;
- no longitudinal tails as they are known to translate into transverse halo;
- phase advances are matched to adjacent sections.

To reach the requirements a 4 m RFQ has been designed. The latter includes less cells in the bunching section and performs a better rate of acceleration while keeping high performance beam dynamics.

Consequences on the designs

Taking into account the above-mentioned relaxation of the performance requirements, the design study results in a 1 m shorter RFQ. We have shortened the *pure* bunching section [1] from 160 to 55 cells. More losses of high energy protons have then been observed but very similar performances in terms of transmission and emittances are foreseen. Particle tracking have also been performed through the linac from the RFQ output to the end of the superconducting (sc) section and no hazardous losses have occurred. Full integration of the RFQ in the ESS linac has also been improved by matching the phase advances to the subsequent Drift Tube Linac (DTL) [5]. Moreover, the RFQ ouput beam orientation and size have been selected in order to facilitate the transport and matching in the Medium Energy Beam Transport (MEBT) line.

Benefits of a shorter RFQ

Shortening the RFQ has reduced the potential fabrication and operational risks since less tuners and vacuum and RF seals as well as vacuum pumps are required. The construction cost will also be lower as machining and brazing are known to impact significantly the overall cost of the RFQ. Less power dissipated in copper will as well reduce the cost in operation. Removing one segment will finally ease the alignment procedure

BEAM DYNAMICS

Geometry

The main geometry paramaters of the current 4 m RFQ are presented in Fig. 1. It can be observed that the minimal aperture is always greater than 3 mm and the modulation factor stays below 2.4. For more flexibility and in order to reduce sparking problems, the Kilpatrick limit [6] does

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[1] Non accelerating section where the synchronous phase is set to zero.

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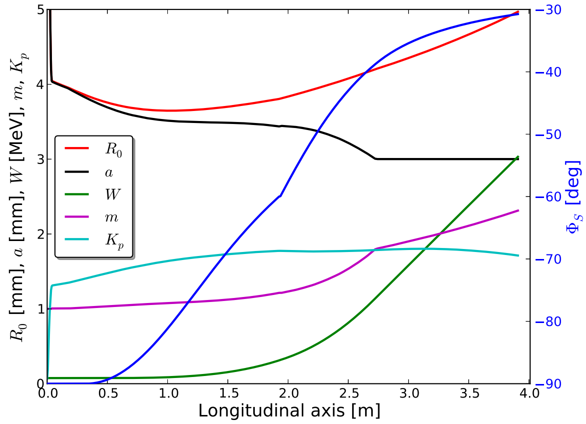

Figure 1: Main geometry parameters.

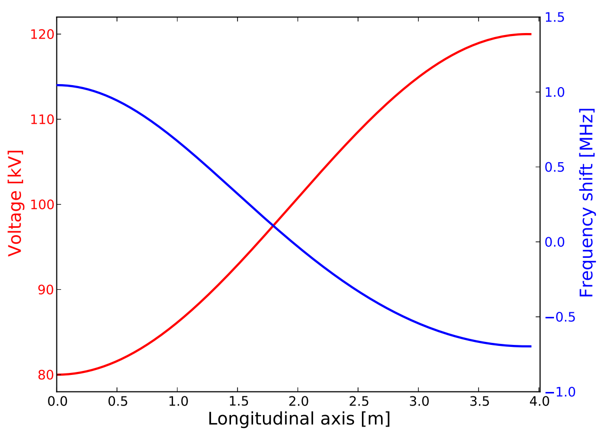

Figure 2: Voltage and 2 D frequency shift.

not exceed 1.8. The choice of varying the inter-vane voltage ranging from 80 kV to 120 kV has strongly influenced the geometry parameters generation. The voltage follows a sine function which cancells the derivative with respect to z (longidudinal position) at both extremities resulting in the abscence of circulating currents and potential additional losses. The choice of a sine function leads to a small extension range of the 2 D frequency as can be seen in Fig. 2. Finally it is important to mention that the radius of curvature is kept constant ($\rho = 3$ mm) along the z axis due to machining considerations. The latter two points illustrate the fact that the beam dynamics design has integrated in an early stage the mechanical and RF designs.

Matched phase advances to adjacent sections

In order to integrate the RFQ design inside the design of the ESS linac, phases advances at the RFQ exit have been matched to those of the DTL. Moreover, the opening of the has been increased as compared to the previous RFQ version thus facilitating the beam maching into the RFQ.

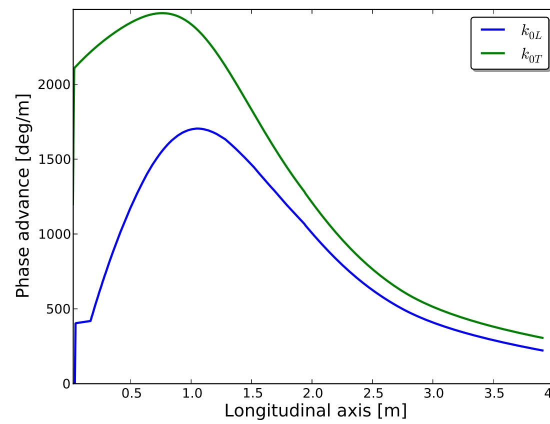

Figure 3: Phase advances.

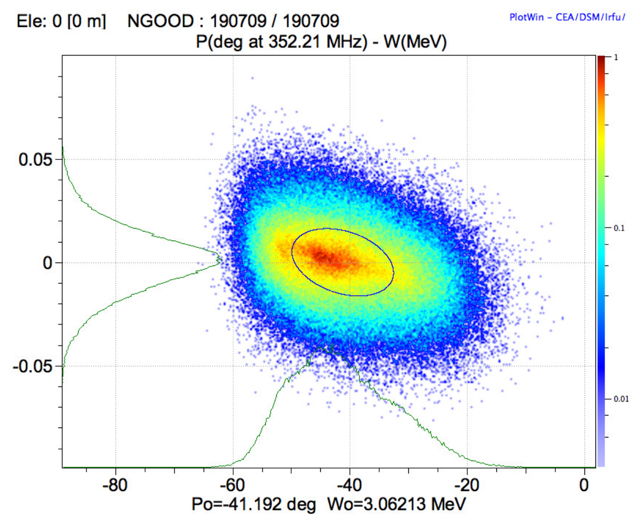

Figure 4: Beam portrait in longitudinal phase space.

Evolution of the phase advances along the longitudinal axis can be observed in Fig. 3.

Emittances and transmission

The ESS 4 m RFQ beam dynamics results have been performed with the Toutatis code [7] for 50 mA beams and a gaussian distribution (truncated at $4\,\sigma$) with $0.20\,\pi$.mm.mrad as input RMS transverse emittance. Results are presented in Tab. 1. Resonable transverse emittance growth is experienced and the transmission of the particles inside the longitudinal acceptance is better than 95 %.

Special cares have been taken to produce high quality beams. In particular no longitudinal tails as they may induce losses at high energy if translated into transverse halo have been formed in the RFQ during the bunching and acceleration phases. Figure 4 shows that no longitudinal tails are observed in the output longitudinal phase space.

Table 1: Output emittances and transmission.

Current (mA)	Distribution	Output tanvs. em. RMS (π.deg.MeV)	Output long. em. RMS (π.mm.mrad)	Transmission (%)
50	Gaussian	0.13	0.23	> 95

Fringe Field Section (FFS) length optimization

The vanes end with a FFS which makes a smooth transition between the focusing region and the field free region. The choice of the FFS length impacts the orientation of the bunches in the transverse phases spaces as well as their sizes out of the RFQ. Figures 5 and 6 show respectively the evolution at the RFQ ouput of the beam size and the tranverse divergences (in terms of the Twiss parameter α) as functions of the FFS length. A Medium Energy Beam Transport (MEBT) line [8] is foreseen after the RFQ and before the DTL section. The line includes bunching cavities, magnetic quadrupoles, collimator as well as a fast chopper and it is fully equipped by intrumentation for optimal characterization of the beam. The resulting 3.5 m long MEBT line might induce beam degradation as the periodic focusing is broken and the space charge forces are very high at this energy. Halo generation may occur and induce hazardous losses at higher energy. This is why three different output distibutions are being considered: minimal x size, same transverse orientation and same beam size in both transverse planes. First simulations seem to favor the second above-mentioned option [9].

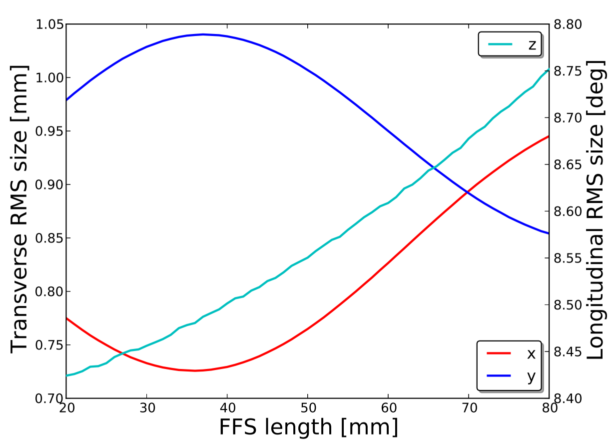

Figure 5: Beam size as a function of the FFS length.

CONCLUSIONS

The current ESS 352.21 MHz 4-vane RFQ is composed of 4 segments of 1 m each. It is one meter shorter than the previous 2011 design. The reduction ine length is, in part, due to the relaxation of the loss criterion and to the limitation of the operational peak current at 50 mA. From a beam dynamics point of view, apart from the losses which remain

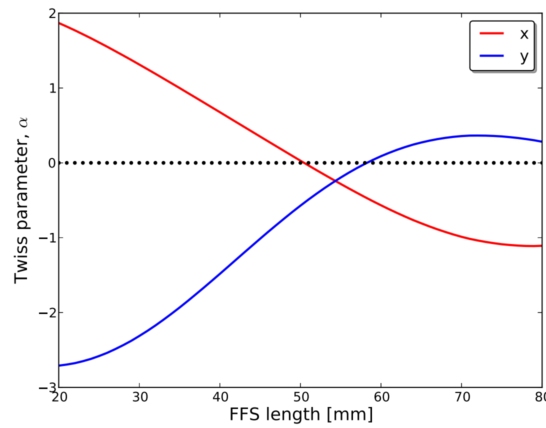

Figure 6: Twiss parameter α as a function of the FFS length.

nonetheless very low, simulations have not indicated any degradation. The transmission is very high and the longitudinal distribution is tailless. Significant improvements in the integration of the RFQ design have also been achieved in parallel with the consolidation of the ESS linac physical design. Not only the new RFQ design is fulfilling all the updated performance requirements but the fabrication and operational risks as well as the cost have also been lowered substantially.

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