THE RFQ INJECTOR FOR THE RADIOACTIVE ION BEAM OF SPES PROJECT

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Abstract

A Continuous Wave Radio Frequency Quadrupole Accelerator has been designed for the Radioactive Ion Beam of SPES Project to be used as an Injector of the ALPI Linac. The RFQ frequency is 80 MHz for an input energy of 40 keV, with output energy of 5 MeV and ion ratio q/A<= 1/7. Particular care has been put in the design phase to include an internal bunching section able to reduce the longitudinal output emittance. The details of the RF study of such a cavity are included as well.

BEAM DYNAMICS

Within the project SPES laboratory a new injection line will be built at INFN LNL to transport and match the RIB to the existing ALPI superconducting linac [1].

This line includes a new RFQ (see Tab. 1) that will operate in a CW mode (100% duty factor) at a resonant frequency of 80MHz. This frequency is the same of the lowest energy ALPI superconducting structures. The injection energy of ions was set to 5.7 keV/u. This choice is a compromise between the desire to reduce the ion energy to simplify the LEBT and the RFQ bunching section design and the need to increase the injection energy to increase the beam rigidity in the spectrometer and to reduce space charge effects. The extraction energy was set to 727 keV/u (respect to the 588 keV/u of the present SRFQ), to optimize the beam dynamics of the SRF ALPI linac.

Table 1: Principal RFQ Parameters

Parameter (units)	**Value**
Operational mode	CW
Frequency (MHz)	80.
Injection Energy (keV/u)	5.7 (β=0.0035)
Output Energy (keV/u)	727 (β=0.0395)
Accelerated beam current (μA)	100
Charge states of accelerated ions (Q/A)	7 – 3
Internal bunching section	Yes

The design goals were to minimize the longitudinal and transverse emittances growth and to optimize the RF losses and transmission of the RFQ structure. The RFQ cells were created using the program CORTO, used for the design of CERN linac3 RFQ [2,3], PARMTEQ code package and Toutatis in an iterative cell-by-cell procedure. With this design the RF power consumption is minimized, while a variable voltage profile, like the IFMIF RFQ [4], allows accelerating the beam more effectively at higher velocities and achieving higher output energy. A transition cell was used at both the entrance and exit of the RFQ. At the exit side, a radial matching section with an appropriate length after the transition cell was also used so that the output beam has the same Twiss parameters in both the horizontal and vertical planes. Table 2 and Figure 1 show the main parameters of the RFQ. The RFQ transmission is more than 95% of accelerated particles, the final longitudinal RMS emittance is 0.15 nskeV/u. The 99% longitudinal emittance is 1.2 nskeV/u , see Figures 2, 3 and 4.

Table 2: RFQ Design Parameters

Parameter (units)	Design 1
Inter-vane voltage V (kV, A/q=7)	63.8 – 120
Vane length L (m)	5.97
Average radius R_0 (mm)	5.03 – 9.574
Vane radius ρ to average radius ratio	0.8
Modulation factor m	1.0 – 3.16
Total number of cells	303
Synchronous phase (deg.)	-90 – -20
Focusing strength B	5.28 – 2.8
Peak field (Kilpatrick units)	1.7

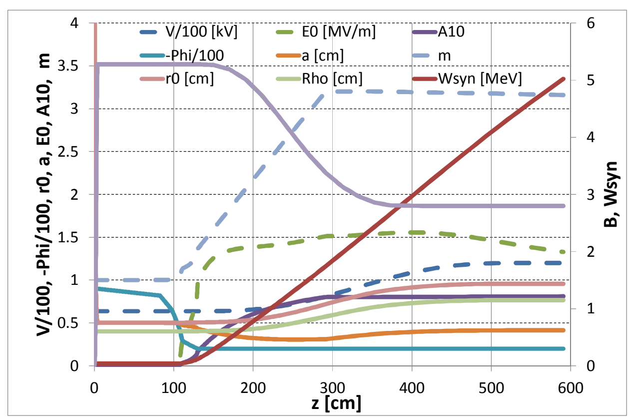

Figure 1: the main RFQ parameters vs. length as for beam dynamics outcomes.

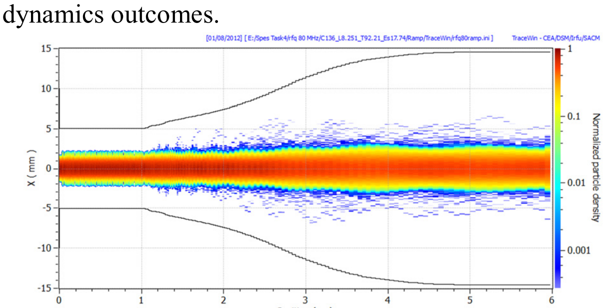

Figure 2: X envelope along the RFQ.

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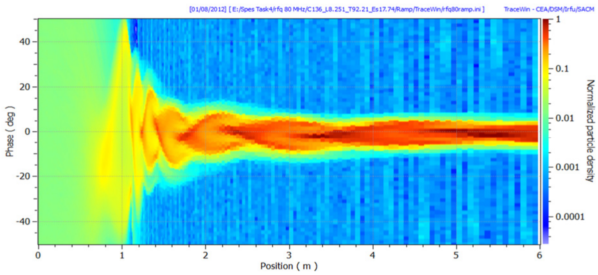

Figure 3: Phase density along the RFQ.

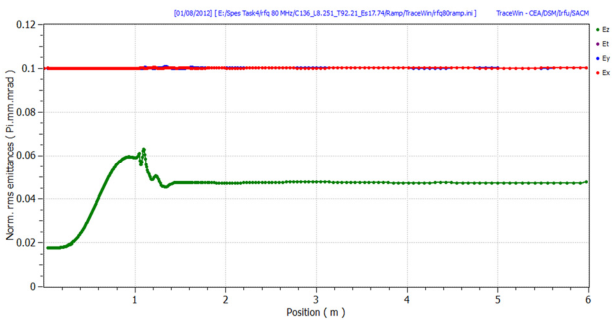

Figure 4: RMS emittance along the RFQ.

CONSTRUCTION CONCEPT

A nc cw four vane RFQ at similar dimensions and is being built for SPIRAL2 project [5].

The construction considered for SPES RFQ is a four vane structure, divided in 6 modules of approximately equal length. The cylindrical tank (800 mm diameter) is in copper plated iron properly annealed. The electrodes are built out of OFE copper and 316LN stainless steel; brazing under vacuum is used to build the cooling channels and the interface reference surfaces between electrode and tank.

The electrode modulation is milled to final value after brazing, and as the last operation the electrodes are positioned, aligned and bolted to their final position in the tank. Vacuum tightness is guaranteed at electrode bases by circular gaskets, that can be inspected and substituted without removing the electrode. The RF joint is at the electrode bases, with a current limited to about 22 A/cm even in the undercut region (see later).

RF STUDY

The choice of a four-vane structure with variable R_0 and voltage profile requires an accurate tuning of the 2D section of the RFQ in order to compensate for local TE_{21} cut-off frequency f(z) variation Δf(z) due both to voltage and aperture variation. In the first case such frequency variation is related to the 2^{nd} derivative of the voltage, according to the relationship

$$\Delta f(z) = \frac{1}{2f_0}\left(\frac{c}{2\pi}\right)^2 \frac{V''(z)}{V(z)}$$

while, in the second case, the cross section tuning process had to compensate the R_0 variation along the cells. The desired Cross Section Frequency is obtained by varying the Vane Base Width 2•W1 along the RFQ. This first optimization has been accomplished by performing simulations with HFSS (parametric mode) code both and then confirmed by SUPERFISH. The results of the two agree within 0.15%. In particular, in the given range of variation of the parameters, the function $f(W_b, R_0)$ can be approximated as

$$f(W_b, R_0) = (a_1 R_0 + a_0) W_b^2 +$$
$$+ (b_1 R_0 + b_0) W_b + c_2 R_0^2 + c_1 R_0 + c_0$$

where the coefficients were obtained by fitting the simulations data obtained by varying W_b and R_0. From this relationship, given the voltage law and the initial cut-off frequency f(0), it is possible to determine the $W_b(z)$ law directly.

In Figure 5 the variation of the W1 as a function of z and in Figure 6 the cross sections of the cavity corresponding to the Low Energy and High Energy Sides are shown. It is possible to notice that the minimum value of the Wb is about 3.5 cm and the maximum value is 10 cm. It should be noticed that the maximum current density at the RF joint is 22 A/cm

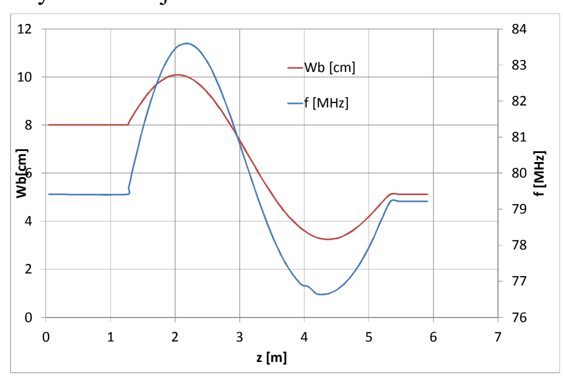

Figure 5: the local cut-off frequency and the Wb as a function of length.

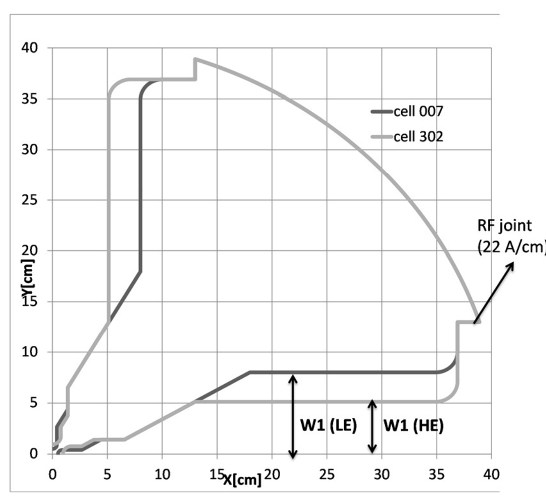

Figure 6: The low energy and High Energy cross sections of the RFQ.

As for power consumption calculations is concerned, it has to be pointed out that the total power P_{RF} is related to

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the 2D power calculated by SUPERFISH, PSF, by means of the relationship

$$P_{RF} = P_{SF}\alpha_{3D}\alpha_{RF}$$

where α_{3D}=1.3 is a factor that takes into account the 3D losses, α_{RF} = 1.2 takes into account the margins for RF System (losses in the lines and in the circulator, finite bandwidth of the amplifier etc). In the following table the main RF parameters are shown.

Table 3: Main RF Parameters

Shunt Impedance (SF)	400-635	kΩ·m
Q0 (SF)	17500-21500	
Copper power (SF)	100	kW
Stored Energy	3.7	J
Max H field (2D)	2200	A/m
Max Power Density (2D)	0.56	W/cm^2
Max Power Density (3D)	20	W/cm^2
Total Power	156	kW

The RF power will be fed by a single amplifier unit based on a TH535 tube (180 kW max power in CW).

The vane terminations and undercuts correspond to the maximum power density, and have to be properly cooled. Moreover with bolted electrodes one has to be careful about the maximum current across the RF joint at the bases of the electrode. The design proposed (Fig.6) is such to keep the current density always below the value of 2d cross section.

HFSS simulations showed that, actually, on the electrode base, where the RF joint is foreseen to be inserted, the maximum current is equal to 22 A/cm (Figures 7 and 8)

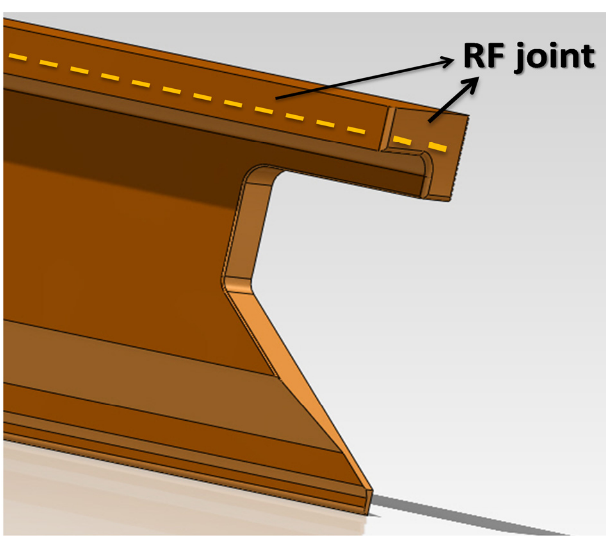

Figure 7: detail of the electrode on the High Energy Side of the RFQ, with the location of the RF joint.

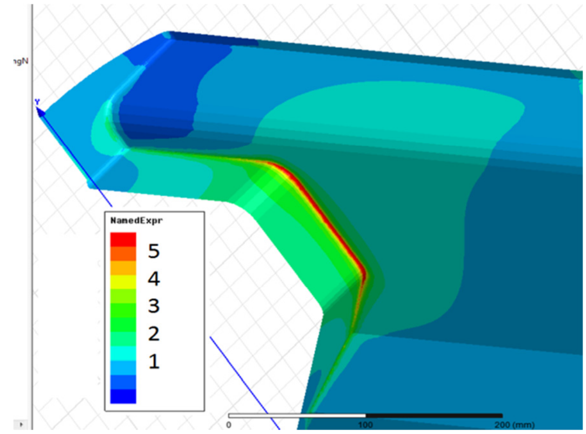

Figure 8: Current density on the undercut normalized to the 2D value (22 A/cm).

Some comments have to be made on the tuning range of the structure, related to the construction and alignment tolerances. The sensitivity with respect to geometrical errors was numerically addressed, and it was found that the maximum [minimum] sensitivity χ_{R0} is located in the initial [final] section of the RFQ, where $\partial f/\partial R0$=3.6 MHz/mm [2.2MHz/mm]. This means that a 0.2 mm misalignment of the electrodes provokes a frequency shift of 720 kHz [440 kHz]. Therefore, in order to allow the positioning of the electrodes with ±0.2 mm precision, an (average) tuning range of ± 600 kHz is needed. For this reason, the frequency f_0 was chosen to be equal to 79.4 MHz. . It has also to be pointed out that, due to the favourable L/λ ratio of this RFQ, the 1st upper quadrupole mode is about 3.8 MHz away from the fundamental one, and the attainment of a dipole-free region of ± 2 MHz is feasible. Therefore in this case the tuning range can be used mainly for compensation of misalignments. In order to allow the tuning of the structure a system of slug tuners has to be foreseen. In the present design, it is foreseen to use 24 tuners of 9 cm diameter. In this way, the working frequency can be reached by inserting all the slugs to a 50 mm penetration inside the cavity. The high value of the shunt impedance*length for such a structure and the power capability of the RF source allows the implementation of such a huge tuning range.

REFERENCES

[1] M. Comunian, et al. "Beam Dynamics of the Linac ALPI-PIAVE in view of possible upgrades scenario for the SPES Project", this conference.
[2] M. Comunian, "DINAMICA DEL FASCIO NELL'RFQ DEL NUOVO INIETTORE DIIONI PIOMBO AL CERN", degree thesis, Padua University, 1994 (in italian)
[3] G. Amendola et al, EPAC 92, p. 973
[4] M. Comunian, et al. "Beam Dynamics of the IFMIF-EVEDA RFQ", EPAC08 Genova.
[5] R. Ferdinand et al, EPAC 2006.

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