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RFQ NEWGAIN: RF AND THERMOMECHANICAL DESIGN*

P. Hamel†, N. Sellami, M. Desmons, O. Piquet, B. Prevet, CEA-IRFU, 91191 Gif-sur-Yvette, France

Abstract

A new injector called NEWGAIN will be added to the SPIRAL2 Linear Accelerator (LINAC) [1], in parallel with the existing one. It will be mainly composed of an ion source and a Radio Frequency Quadrupole (RFQ) connected to the superconductive LINAC of SPIRAL2. The new RFQ will accelerate at 88.05 MHz particles with charge-over-mass ratio (Q/A) between 1/3 and 1/7, from 10 keV/u up to 590 keV/u. It consists of a 4-vane resonant cavity with a total length of 7 m. It is a CW machine that has to show stable operation, provide the request availability, have the minimum losses in order to provide the highest current to the superconductive LINAC and show the best quality/cost ratio. This paper will present the preliminary RF design and the thermomechanical study for this RFQ.

INTRODUCTION

The purpose of the NEWGAIN project is to develop a new injector, consisting of an ion source (type: superconductive ECR) and a RFQ (A/q = 7), for the SPIRAL2 LINAC. It will enable GANIL to provide ion beams of worldwide highest intensities (from proton to uranium), thus opening up unprecedented opportunities for nuclear structure and reaction studies at the extremes of the chart of nuclides from N=Z nuclei at the proton dripline to super-heavy species, including the discovery of new elements, and the production of radioisotopes. It also makes it possible to extend the use of SPIRAL2 beams to interdisciplinary research as well as applications.

The NEWGAIN RFQ cavity RF is very close to the SPIRAL2 RFQ cavity, currently operating in GANIL as they both operate at the same frequency. The choice is made to assemble the cavity mechanically, the same as SPIRAL2, in order to skip the complex process of brazing of such large cavity sections. The RF design and thermomechanical study follow the procedure developed at CEA and presented in [2].

RF DESIGN

Beam Dynamic Specifications

The modulations of the RFQ vanes have been optimized using the TOUTATIS solver. At the end of this optimization, the Kilpatrick limit remains below 1.6 and the vane voltage is constant, at 70 kV, along the RFQ. The RFQ length, about 7 m, ensures a frequency distance of about 1 MHz between the accelerator mode and neighboring dipole modes which have to be avoided. This will guarantee stability during the operation.

Transmisson Line Model (TLM)

From a microwave point-of-view, a RFQ is merely a waveguide-based circuit, consisting of small 3D devices at the end regions, connected by multiple segments of waveguide with constant cross-section. Thus, this RF circuit is modeled as a transmission line model composed of capacitances and inductances as illustrated in Fig. 1:

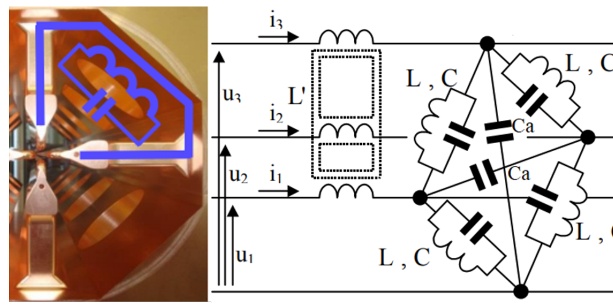

Figure 1: TLM. Left: electrical circuit corresponding to the geometry. Right: 4-wire line equivalent circuit.

Cross-section Design

The final RFQ will be made of seven 1-m long sections. Since the vane voltage has to be constant along the RFQ, the cutoff frequency of the cross-section has to be also constant. For an easier manufacturing process, the radius of the cavity has been set constant. Thus, the inductance, proportional to the surface cross-section, will also be constant. From these considerations, the capacitance has also to be constant. Despite the vane radius and the mean distance of the vane to the axis being constant along the RFQ, the sine shape of the modulation implies a modification of the vane from cell to cell, to adjust the capacitance. One geometrical parameter, called J1, has been selected for profile tuning taking into account ease of machining: this parameter is adjusted piecewise linearly to best fit the required voltage profile at a lower cost. The geometry cross-section and the J1 position are illustrated in Fig. 2:

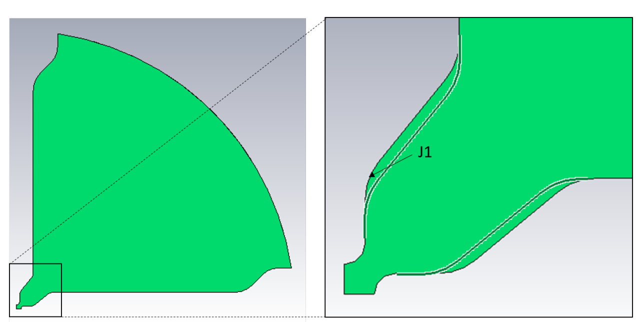

Figure 2: Cross-section geometry.

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† pierrick.hamel@cea.fr

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Capacitance Calculation

Each cell is simulated with CST and COMSOL eigenmode solvers. The magnetic flux $\vec{H}$ through the cross-section S is integrated and the capacitance C for a cell of length L_{cell}, is derived from the voltage V:

$$V = \int_S \omega \mu_0 \vec{H} d\vec{s} \tag{1}$$

and from the stored energy W:

$$C = \frac{2W}{V^2} = \frac{2W}{L_{cell}[\int_S \omega \mu_0 \vec{H} d\vec{s}]^2} \tag{2}$$

The resulting capacitance remains constant along the RFQ, about 37.3 $\mu F/m$. The comparison between COMSOL and CST depicted in Fig. 3 shows a good agreement, lower than 0.5%:

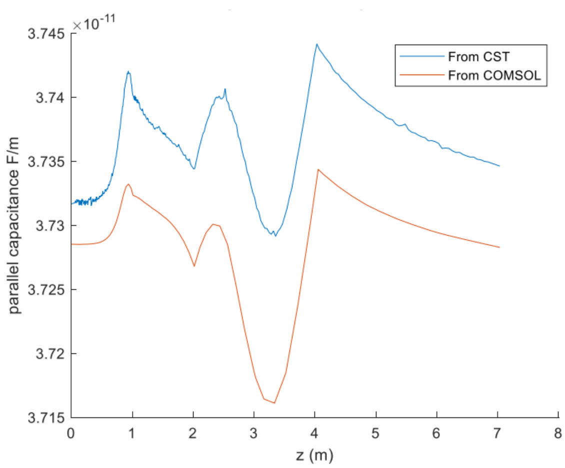

Figure 3: Parallel capacitance.

Tuner Considerations

Fine tuning process, described in [3], will be performed with standard stubs. The number of stubs, two per section per quadrant (4x2x7 in total), their spacing (502 mm) and their diameter (130 mm) are directly related to the manufacturing accuracy and final thermal losses. Tuner 2D inductance slopes required by TLM are derived from CST simulations and are presented in Fig. 4.

They exhibit a linear behavior and are roughly independent of tuner location. Bead-pull measurements are used to sense longitudinal magnetic field $Hz(x0, y0, z)$ vs. abscissa z at some transverse location $(x0, y0)$ in RFQ quadrants. This transverse location is set to get a minimum perturbation on the magnetic field for a 90 mm tuner insertion. On a field point located at z =125 mm from the tuner center the perturbation is lower than 0.5%.

Manifacturing Accuracy

Tuner position limits required to compensate for mechanical construction errors are derived from inter-vane capacitance errors. Tolerances on electrodes tips are defined by the two numbers t and δ :

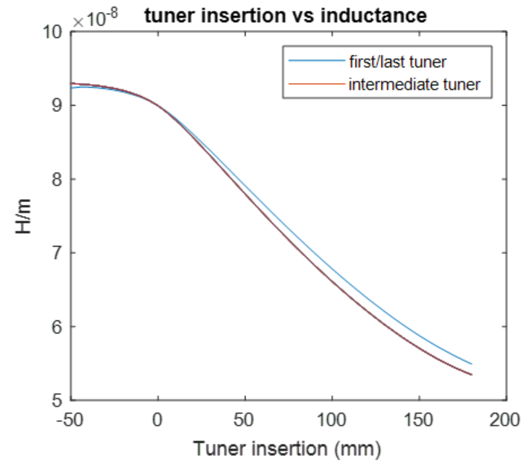

Figure 4: 2D inductance vs. tuner insertion.

- center of curvature of each electrode tip is located in a square with side $2t$, centered at its theoretical location;
- electrode tip radius error is bounded by $\pm\delta$.

Parameters t and δ are varied in the intervals [40 µm,60 µm] and [10 µm,30 µm] respectively. Each pair (t, δ) defines a capacitance relative error volume. Tuner position limits are then calculated according method described in [4], assuming constant inductance slope. A 30% safety margin is then added on either side of range, and results are corrected according to actual inductance slope. As shown in Table 1, tuner position limits approximately remain in a [−3 mm,91 mm] interval provided that $t + \delta$ is lower than 80 m.

Table 1: Tuner Position Limits in mm vs t and δ

	t = 40 m	t = 50 m	t = 60 m
δ = 10 m	[13 ; 77]	[7 ; 84]	[-2 ; 90]
δ = 20 m	[6 ; 84]	[-2 ; 91]	[-16 ; 97]
δ = 30 m	[-3 ; 91]	[-18 ; 98]	[-50 ; 104]

THERMOMECANICAL DESIGN

RF Optimization and Thermal Management

The RF power induces a heat deposit in the copper of the RFQ cavity that must be removed through a strategic positioning of the cooling channels. The main goal for optimizing the hydraulic system within the cavity and its components is to limit the structural deformation and hence control the shape and the frequency of the RFQ cavity.

2D coupled RF-thermomechanical calculations produced the final hydraulic distribution of the channels implemented in the RFQ cavity based on a similar strategy used for SPIRAL2. The 2D design optimized the deformation of the overall cavity so that under nominal operating conditions, the targeted frequency for the cavity is reached.

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3D Thermomechanical Model

The 3D model is constructed using a quarter geometry of the RFQ with 2-planes symmetry (Fig. 5). RF couplers, are not included in the model. Their impact should be limited only to the weight as they have their own cooling channels. Each vane is cooled thanks to 4 dip-tubes while the outer tube of the cavity is cooled using 2 channels per quadrant (8 channels for the tube per section) as represented in Fig. 5. Separately, 2 dip tubes serve to cool each tuner and a single duct is attached to each end plate.

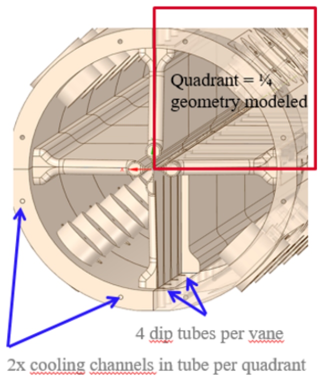

Figure 5: cooling channels within the cavity.

3D Thermal and Structural Results

The temperature distribution in the RFQ cavity and its components is illustrated in Fig. 6 for a heat deposit of 110kW (+20% margin) and a 20 °C water inlet temperature. The maximum temperature in the RFQ body is 38.5 °C and is located in the high power region at the upper vane undercut. The temperature does not exceed 31 °C for the tuners and 28 °C for the stabilizing rods mounted on the endplates.

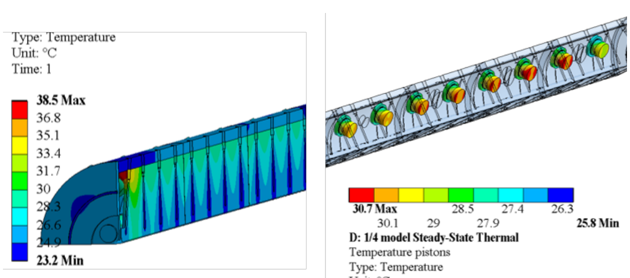

Figure 6: Temperature distribution. Left: body and vane. Right: tuner.

This thermal load induces the lengthening of the RFQ cavity by 0.6 mm as seen in Fig. 7 (±0.3 mm with a fixed point at the fourth section).

The deformation is overall under 10 m close to the vane tip toward the beam axis and around 20 m at the upper wall cavity away from the beam axis as presented on Fig. 8. In those proportions, the cavity deformation meets the targeted frequency as verified with the 2D computations. Locally, the vane undercut tip reaches 40 m deformation but the impact on the frequency shift is minimal.

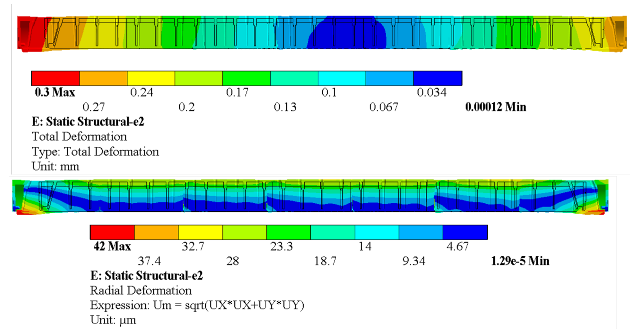

Figure 7: Longitudinal and radial displacement of the RFQ body.

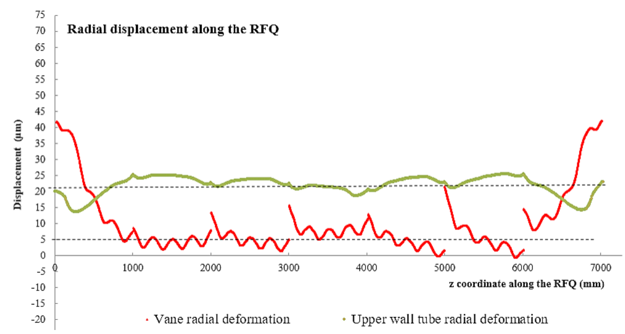

Figure 8: Radial displacement at the vane tip and the cavity upper wall.

CONCLUSION

From the beam dynamic specifications, the RF design has been presented, defining electrical model parameters such as capacitances and inductances. Slug tuners will be used to compensate manufacturing errors and to achieve the expected inter-vane voltage. The mechanical stress induced by RF heating is evaluated. Mechanical deformations are small enough and won't modify the cavity performances.

REFERENCES

[1] M. Di Giacomo *et al.*, "RF Commissioning of the SPIRAL2 RFQ in CW Mode and Beyond Nominal Field", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2804–2806. doi:10.18429/JACoW-IPAC2019-WEPRB007

[2] O. Piquet, "RFQ Developments at CEA-IRFU", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 42–44. doi:10.18429/JACoW-IPAC2016-MOOCA02

[3] P. Hamel *et al.*, "ESS RFQ: Installation and Tuning at Lund", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1372–1374. doi:10.18429/JACoW-IPAC2021-TUPAB016

[4] A. France, O. Delferriere, M. Desmons, and O. Piquet, "Design of Slug Tuners for the SPIRAL2 RFQ", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper TUPAN006, pp. 1398–1400.