STUDY OF A HIGH-CURRENT 176 MHZ RFQ AS A DEUTERON INJECTOR FOR THE SPES PROJECT

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Abstract

The SPES project[1], aimed at the construction of a RIB facility at LNL, is based on the use of a primary beam of protons, and foresees a further development based on the acceleration of deuterons and light ions. In this article we report about the preliminary study of a 176 MHz RFQ to be used as an injector for such kind of beams. The structure explored foresees a "four ladder" symmetric resonator, built in brazed copper. In particular beam dynamics, electrodynamics design and preliminary thermo-structural analysis of the cavity is presented.

INTRODUCTION

In the ISOL production method chosen for the LNL facility, the number of fission reactions producing exotic species can be increased of about an order of magnitude by using deuterium ions instead of protons.

On the other hand, the transmission is a very important parameter for a deuteron RFQ. Indeed the D-D fusion reaction d(d,^{3}He)n, that has no threshold, happens when an accelerated particle hits a deuteron condensed on the electrode surface. As a consequence losses are dangerous at any energy.

Our primary goal was to design a CW mode normal conductive RFQ able to accelerate more than 99% of the deuterons at the entrance of the structure in order to minimize activation problems.

Besides we were interested to conceive a structure whose length does not exceed 8 m, with the aim of containing manufacturing and maintenance costs.

Indeed such structure were to keep relatively low global power consumption (less than 500 kW), and a realistic local power dissipation (maximum value less than 20 W/cm^2).

BEAM DYNAMICS

The primary goal was reached by optimizing the dynamics of the RFQ whose main parameter are listed in table 1.

Table 1. RFQ main parameters

Mass (A)	3
Charge state (q)	1
Current (I)	9 mA
Voltage (V)	70.4÷82.4 kV
Inject/Final energy	0.023/1.7 MeV/u
Frequency ν_0	176 MHz
Peak surface electric field	<25.3 MV/m (1.8 Kp)
ε_{RMS} normalized	0.25 mm·mrad
Max RF dissipated power	<500 kW

Since external forces scale as $(q/A)\cdot V$ and internal forces according to $(q/A)\cdot I$, the beam dynamics is exactly the same for deuterons with a beam current of 6 mA and a inter vane voltage of $2/3$ of the nominal case. Moreover, to improve the deuteron transmission, there is the possibility to increase the voltage and the surface field to 1.8 Kilpatrick.

Simulations show that high transmission, more than 90%, required the focusing force, represented by the B focusing parameter, takes more than 40% of the overall electric field; this is important above all in the shaper and bunching sections. We know that the higher is B the lower is the accelerating force, represented by A accelerating parameter, which influences the RFQ length.

Using LANL codes (PARI and PARMTEQM) we could reach a 98.9% simulated transmission for ions with mass equal to 3. Transmission reaches 99.8% for deuteron beam with the maximum voltage; this means that inside the RFQ structure we lose 12 μA of deuterons, which is an acceptable value.

The RFQ length was contained in 7.5 m; this result was possible by optimizing the accelerating section of the RFQ. In fact in this section less focusing force is necessary to maintain stable beam. So we could reduce B parameter by increasing A one (figure 1).

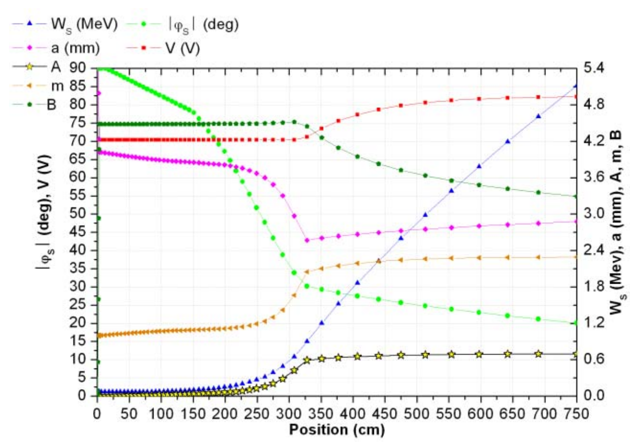

Figure 1: RFQ dynamics parameters.

The optimization was carried out by calculating RFQ parameter cell by cell for the accelerating section, starting from the parameter given by RFQUICK code for the shaper and bunching sections, and substituting them into the control file for the PARI and PARTEQM codes.

In particular we have seen that the acceptance in the accelerating section was larger than necessary; this allowed to reduce acceptance, without having beam losses. This was done by increasing the minimum aperture a between electrodes.

Moreover the voltage between electrodes is ramped along the RFQ without exceeding the 1.8 Kilpatrick limit.

Error studies were done checking the transmission dependence on the displacement along transverse direction (δx), change in emittance (ε_{RMS}), in current (I) and fluctuation of the electric field (Drop). In this last case we simulated an oscillating trend with displacement of some per cent from the nominal value. Results are plotted in figure 2. The main parameters are listed in table 2.

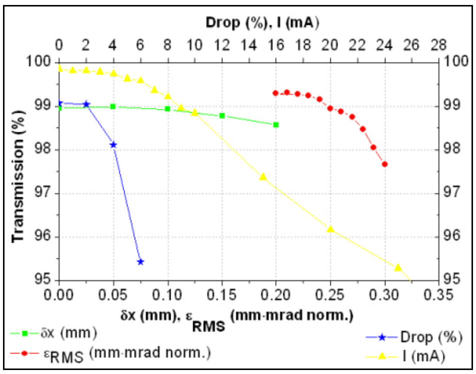

Figure 2: Transmission variation for different errors.

Table 2. Dynamics results

Transmission (simulated)	98.9 % (99.8 % for deuterons)
Length	7.5 m
Peak surface electric field	24.84 MV/m (1.77 Kp)
Mean aperture r_0	4.01 mm
Modulation factor m	1÷2.4

RF RESONANT CAVITY

Our starting point was the TRASCO RFQ[2] geometry in which opening in the windows have been made, in order to lower resonant frequency. Thus we have obtained a kind of "four ladder" structure as represented in figure 3. We can use 5 flanged modules of 5 cells each to get the total RFQ length. Every single segment can be brazed from 4 pieces in a fashion similar to the TRASCO project.

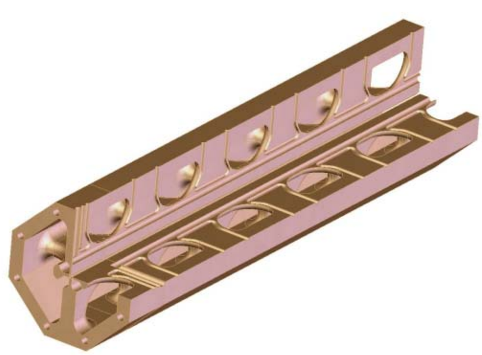

Figure 3. Geometry of one RFQ module (1.5 m long).

We established two main goals in our RF design. First we have imposed to have an overall RF dissipated power lower than 500 kW; in particular structure development showed that a power density lower than 20 W/cm^2 was necessary to allow a feasible cooling channel system. Second, we have imposed to keep the first dipole mode at least 5 MHz above the operating mode, in order to avoid any presence of dipole modes in the neighbourhood of the quadrupole mode.

Therefore simulations with HFSS 8.0 code have been performed varying the parameters L, R_T and R_L. The quantity W has been chosen in order to get the correct 176 MHz quadrupole frequency (Figure 4). For symmetry reasons only one quarter of the cell has been taken into account.

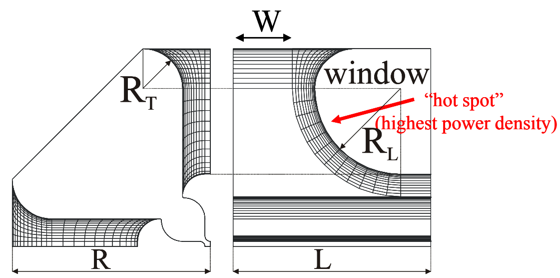

Figure 4: Profiles of the elementary cell of the RFQ.

First of all we have found that shorter is the length L the lower is the power density. Therefore we decided to keep L equal to 300 mm, such value both being a sub multiple of the entire length of the RFQ and allowing us a realistic starting point in order to reduce power dissipations on the stems.

Then we have varied the R_T and R_L radii in order to reach power density lower than 20 W/cm^2, by varying at the same time the window area , by changing W, in order to keep frequency to the design value. As a final result we have obtained a geometry with a power density equal to 18 W/cm^2 and with a dipole frequency 5.5 MHz higher than quadrupole frequency.

Figure 5 shows the power density of the cavity $p = \frac{1}{2\sigma\delta}\left|\mathbf{i_n} \times \mathbf{H}\right|^2$ σ being the electrical conductivity of copper and δ the skin depth: its peak value is about 18 W/cm^2 and it is located in the stems. Deformation of this region causes light frequency shift; if radius R_L or R_T varies, frequency change is about 10 kHz/0.01 mm.

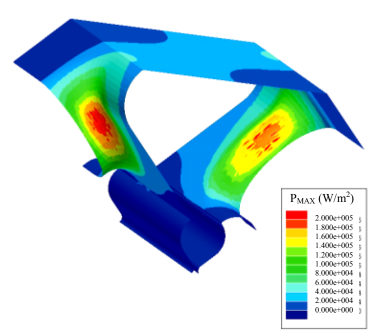

Figure 5. Power density distribution.

In the following table the main quantities determined by the RF study are reported.

R	150 mm
L	300 mm
N_C (number of cells)	25
$R_T \div R_L$	30 ÷ 65 mm
Quadrupole frequency n_0 (simulated)	176.07 MHz
Dipole frequency n_{D0} (simulated)	181.56 MHz
Power density	18 W/cm^2
Total dissipated power	444 kW
Q value (simulated)	9547

The nearest higher-order mode of the 7.5 m cavity is the 1st superior quadrupole mode, whose frequency is 1.1 MHz higher than the operational one. This result has been obtained making use of the dispersion relationships $\nu_p = \nu_0\sqrt{1+(p\lambda_0/2l)^2}$, $p \in N$ l= 7.5 m being the length of the cavity. Such relationship, formally equal as for the four-vane RFQ, has been validated by simulating 5 and 10 cells of the structure. In this way we have verified that the frequencies corresponding to the indexes p multiple of 5 given by the above equation and the corresponding simulated frequencies agree within 0.1%. The longitudinal field variation V(z) along the 5-cells simulated structure is reported in Figure 6. The uniformity is kept below ±1% and the bumps on the V(z) function are due to the presence of the apertures.

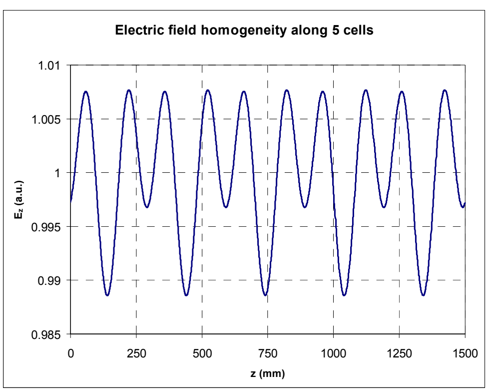

Figure 6: longitudinal V(z) variation along 5 cells.

PRELIMINARY THERMO STRUCTURAL ANALYSIS

In order to study the thermal and structural behaviour of the structure we have performed ANSYS simulations on one RF cell. As an input we have considered the RF power density as indicated in figure 5. A preliminary solution that we have found foresees the use of cooling water channels disposed as in figure 3: four cooling channels of radius 10 mm are drilled close to the vane tips: eight channels with the same radius are drilled on the octagonal tank, four near the electrode and four on the lateral side. The channels with radius 6 mm that follow the window profile can be dug from the outside part with a milling machine, and refilled with brazed pieces. The water velocity is assumed to be 4.5 m/s @ 19 ^{o}C. The channel geometry at the transition between modules is schematically indicated in figure 3.

The results are reported in figure 7.

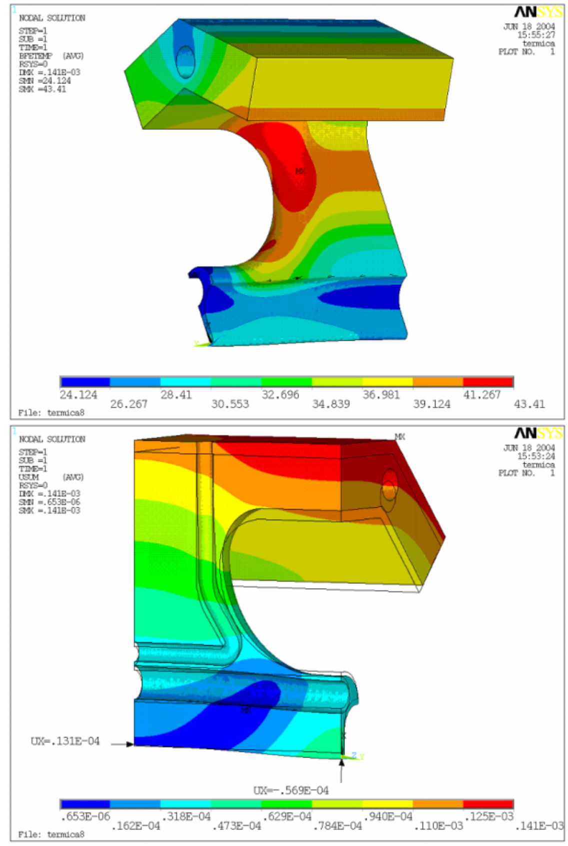

Figure 7: Temperature in ^{o}C and deformations in meters.

The maximum temperature on the structure is 43 ^{o}C, the maximum deformation near the pole tip is 57 µm, and the maximum Von Mises stress is about 90 MPa. The water temperature increase after 1 meter on the long drilled channels is about 2.5 ^{o}C. The total water flow on the full section is 19 Liter/sec.

CONCLUSIONS

The preliminary study of the 176 MHz deuteron accelerator has been carried out. The next steps in the design of the RFQ foresee the implementation of the voltage ramping law by properly varying the area of the apertures in each cell and the study of the RF feed line.

REFERENCES

[1] INFN-LNL Rep. 181/02

[2] A. Pisent et al. LINAC 2000 Conference Monterey (USA), page 902.