DEVELOPMENT OF A NEUTRONICS FACILITY USING RADIO FREQUENCY QUADRUPOLE FOR CHARACTERIZATION OF FUSION GRADE MATERIALS

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Abstract

Qualification of the materials is among the important challenges for a fusion reactor. Working in tandem with the present need that recognizes the value of evaluating fusion reactor materials, Institute for Plasma Research has initiated the "Development of RFQ for Accelerators" project, which will provide a neutronics facility for material qualification in a relatively larger scale. The facility will consist of a high intensity ECR ion (H+/D+) source coupled to Radio Frequency Quadrupole (RFQ) Accelerator through a LEBT system to produce 5 MeV, 40 mA deuterium ions to fulfil the objectives. Further upgrade in the beam energy and current is also foreseen to suit the facility requirement. A four vane type copper RFQ @352.2 MHz frequency with transmission efficiency of ≈ 96% has been designed to accelerate deuterons upto 1 MeV energy as a demonstration of the RFQ functioning and controls. Through LEBT system, deuterons are then focused into RFQ using weak beam focalization method. The harmonization of the vane tips design and manufacturing constraints has been part of the study to have a near realistic engineering design. Design and analysis of RFQ will be discussed.

INTRODUCTION

A compact accelerator-driven neutron source has several advantages over a large accelerator-driven neutron source in terms of low cost of construction, maintenance and flexible machine time. To promote the neutron utilization in various fields of sciences and technologies specially fusion material characterization it is necessary to develop a high performance compact accelerator based neutron source.

We, at IPR, have aimed to develop a Fusion Material Irradiation Facility for closely simulating the fusion neutron environment for Accelerator Driven Deuterium Beam (ADDB) with an ultimate target of generating 14 MeV neutron flux close to 10^{14} n/cm^2/s in a 500 cm^3 volume (equivalent wall loading of approx. 2.3 MW/m^2) for fusion reactor materials characterization, using a Radio Frequency Quadrupole (RFQ) accelerator as front end injector to accelerate the ion beam. The Schematics of the facility is shown in the Fig. 1.

RADIO FREQUENCY QUADRUPOLE

RFQ accelerator, proposed by I. M. Kapchinsky and V. A.Teplyakov in 1970, can simultaneously focus, bunch and accelerate low energy beam extracted from ion source directly, based on the radio frequency electrical field of a modulated quadrupole transport channel [1,2]. With proper selection of the parameters, a high beam transmission (>90%) can be achieved easily in RFQ. At present, RFQs can provide high current (up to hundreds of mA) ion beams at energy level of MeV over the mass range from Hydrogen to Uranium and the 5 MHz to 500 MHz frequency range.

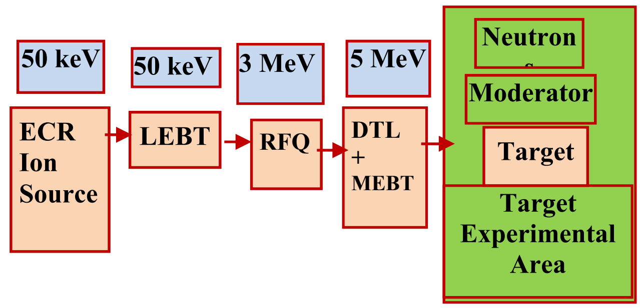

Figure 1: Schematics of the Neutronics facility.

RFQ is the main component of the neutronics facility to be developed using ion irradiation followed by generation of a comparable neutron flux and fluence which in turn will be produced by accelerating 40 mA beam current of D^+ particle at 50 KeV from ion source to 5 MeV.

As a intial step, a Prototype 4 vane type copper RFQ has been designed to establish the proof of Principle. The parameters of the prototype are listed in Table 1.

BEAM DYNAMICS DESIGN

Conventional design scheme proposed by LANL, where RFQ is divided into four sections, namely Radial matcher (RM), shaper (SH), gentle buncher (GB) and accelerator (AC) sections, has been adopted for the beam dynamics design of RFQ. The beam dynamics of the RFQ has been carried out using the simulation codes RFQGEN [3] and TOUTATIS [4]. The vane voltage 'V' and the focusing factor 'B' are kept constant at 56 KV and 4.25 respectively to limit the peak surface electric field to less than 1.8 times the Kilpatrick criteria [5].

Some modifications in the accelerator section have reduced the concentration of the beam loss in the high energy section of RFQ and increased the transmission of the beam through RFQ. The RFQ parameters along the length of RFQ are listed in Table 2 and the beam ellipse plots for 95.3% transmission as obtained in beam

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dynamics studies using RFQGEN code are shown in Fig. 2.

Table 1: Parameters of the Prototype RFQ

S.No.	Parameters	Value
1.	Frequency	352.2 MHz
2.	Type	4 Vane Type
3.	Injection Energy	50 KeV
4.	Output Energy	1 MeV
5.	Beam Current	1 mA
6.	Norm. r.m.s Emittance	0.25 pi.mm.mrad
7.	Ions	D^+
8.	Operation	Pulsed
9.	Duty Cycle	1%

Table 2: Optimized Parameters of the RFQ

S.No.	Parameters	Value
1.	Vane Voltage	56 KV
2.	Peak Field	32.8 MV/m
3.	Transmission	95.3 %
4.	Max. Modulation	1.6
5.	Focussing Factor	4.25
6.	Length	1.81 m

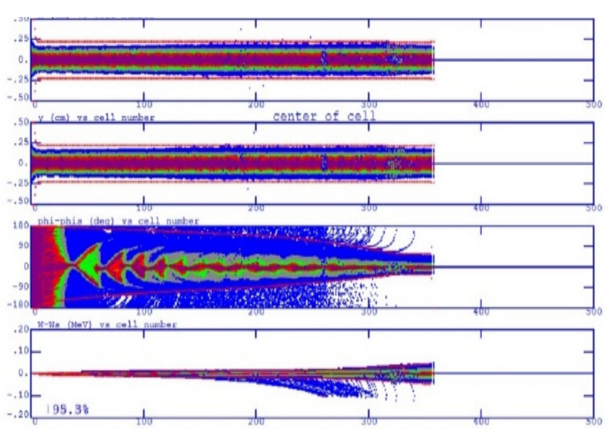

Figure 2: Beam ellipse plots through RFQ.

EM DESIGN

An attempt has been made to incorporate the real physical features of the RFQ in the 3D model for EM simulations. These specific features e.g., modulated tip, radial matching section, and fringe field section etc. require a dedicated designing tool which can not only handle the complex modulating curve, shown in Fig. 3, to model the vane tip but also has parametric behaviour so that the vane profile can be edited at any point during optimization. Having advantage of importing thousands of points all together for creating smooth modulation curve in addition to its user friendly GUI, design tool "SOLIDWORKS" provided the edge over the other tools and thus is selected to generate intricate sections of RFQ. The RFQ model, thus produced with these features is shown in Fig. 4.

This model is then exported to CST MWS for the quadrupole and dipole mode frequency determination with the Eigen-mode solver. The meshing plays a vital role in producing accurate and repeatable results and hence special attention has been paid towards this aspect by constructing fine local mesh on the vane tips. Constructing fine meshing ≈ 6-10 μm at the vane tips, helped in bringing operating quadrupole mode frequency near to that obtained from 2D model i.e., 350.6 MHz.

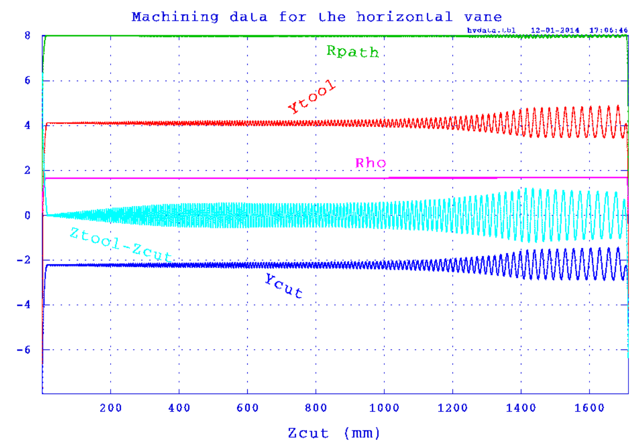

Figure 3: Vane tip modulation curve for Horizontal Vane.

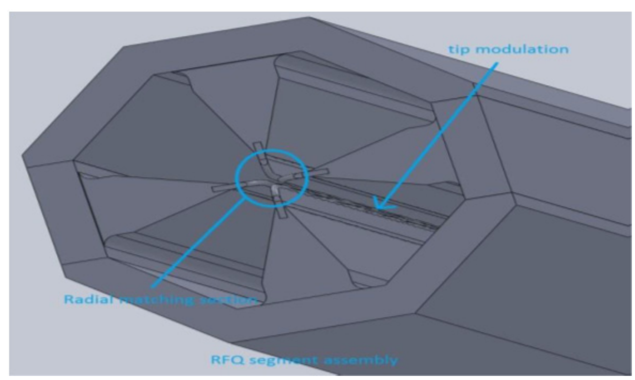

Figure 4: RFQ model in SOLIDWORKS representing vane tip modulation and other sections of RFQ

VANE UNDERCUT DESIGN

On the basis of the whole cavity profile, the design of the undercut is necessary in order to approach the designed field distribution of the operating mode. The local frequency is particularly high without undercut near the vane ends. By removing the metal material in the undercut region, the local frequency is lowered effectively. The parameters of the undercuts are optimized such that the inter-vane voltage distribution approaches the designed curve and the magnetic field turn round the undercuts to satisfy the desired boundary conditions.

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According to the Slater perturbation theory [2], the specific shape of undercut is not very important. We have adopted trapezoid-shape-like undercut to maintain the cooling convenience. The schematic of vane undercut is shown in Fig. 5.

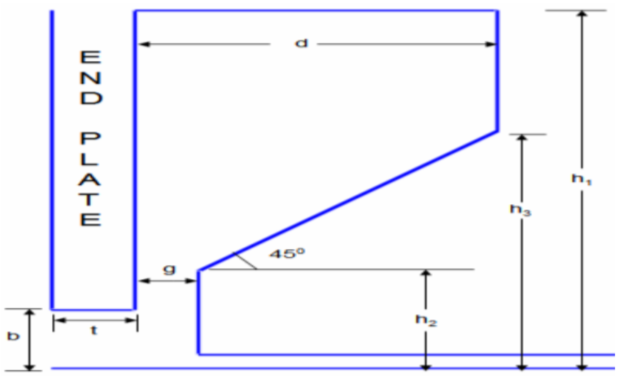

Figure 5: Cutback dimensions at the entrance and exit of RFQ.

The parameters of end cuts are optimized such that these end cells resonate at the quadrupole frequency of 350.8 MHz. The optimized parameters of the BC and EC are shown in Table 3.

Table 3: Optimized Parameters of End Cells

S.No.	Parameters	BC(cm)	EC(cm)
1.	Height (h_1)	9.610	9.610
2.	Height (h_3)	5.610	5.610
3.	Height (h_2)	3.610	3.610
4.	Depth (d)	4.596	3.686
5.	Vane Gap (g)	2.459	2.868
6.	Thickness (t)	2.5	2.5

THERMAL DESIGN

The structural stability of a CW RFQ is the main concern of the thermal engineering design. 1.8 m long RFQ is planned to be fabricated into 2 segments of ~1 m each. RFQ cavity is most sensitive at the vane tip region and has tolerances of order of ≈ 50 μm only in this region, hence appropriate precautions have been taken in deciding the locations and size of the cooling passages. Also minimum wall of 4 mm is maintained for the fabrication feasibility of cooling channels. A total of 24 channels in 3 different set of diameters of 6, 8 and 10 mm are designed to compensate the steady state load of 120 kW. The optimized arrangement of cooling distribution is shown in the Fig. 6.

Table 4 summarizes the 2D design parameters of the RFQ cavity.

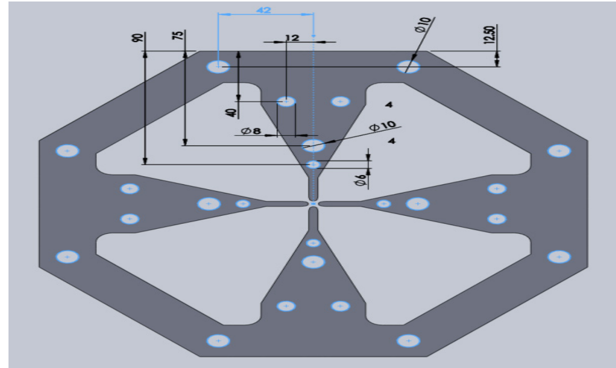

Figure 6: Optimized location of cooling channels.

Table 4: Two-dimensional Design Parameters of RFQ

S.No.	Parameters	Value
1.	Resonant Frequency	350.8
2.	Dipole Mode Frequency	345.4
3.	Total Structure Power Loss	112 kW
4.	Beam Power	1 kW
6.	Quality Factor	10080
7.	Material of Fabrication	OFHC Cu

The temperature profile yielded by ANSYS Workbench is shown in Fig 7. A maximum deformation of 6 μm at the vane-tip has been observed in the analysis.

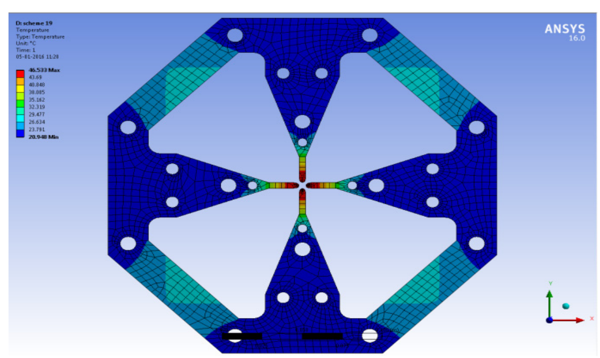

Figure7: Temperature profile with optimized water cooling.

CONCLUSION

A four Vane Type copper prototype RFQ for 352.2 MHz frequency and 1 mA beam current has been designed to accelerate the deuteron beam to 1 MeV energies. The physics, mechanical and thermal design for the CW operation of the RFQ have been completed. The engineering design is in progress.

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