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मेहिपा-I लिनॉक हेतु त्वरक संरचनाओं का विद्युत चुम्बकीय अभिकल्पन

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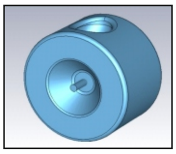

एसएसआर-बी गुहिका का 3डी मॉडल

सारांश

मेहिपा-1 चिकित्सा एवं अनुसंधान अनुप्रयोगों के लिए रेडियोसक्रिय आयन कणपुंज उत्पादन हेतु एक प्रस्तावित 40 MeV, 10 mA प्रोटॉन लिनॉक है, जिसमें 3 MeV RFQ, एक 3-10 MeV DTL और 10-40 MeV से अति-चालक एसएसआर-बी गुहिकाएं शामिल हैं। इस लेख में, इन त्वरक संरचनाओं का एक विस्तृत विद्युत चुम्बकीय अभिकल्पन प्रस्तुत किया गया है।

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Electromagnetic Design of Accelerating Structures for MEHIPA-1 linac

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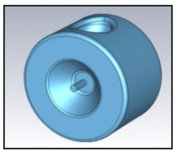

3D model of a SSR-B cavity

ABSTRACT

MEHIPA-1 is a proposed 40 MeV, 10 mA proton linac for radioactive ion beam production for medical and research applications, comprising a 3 MeV RFQ, a 3-10 MeV DTL, and superconducting SSR-B cavities from 10-40 MeV. A detailed electromagnetic design of these accelerating structures is presented in this article.

KEYWORDS: *MEHIPA, Proton linac, Radioactive ion*

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Introduction

The layout of MEHIPA-1 linac [1] is shown in Fig.1. All the accelerating structures will operate at a frequency of 325 MHz. The electromagnetic design details of the individual accelerating structures are presented in the following sections.

Radio Frequency Quadrupole (RFQ)

RFQs are widely used in the front end of linear accelerators for simultaneous beam focusing, bunching, and acceleration [2]. The cavity design and optimization of the MEHIPA-1 RFQ were carried out to achieve TE_{210} like operating mode at 325 MHz with low RF losses, accepted peak surface electric field and practical fabrication feasibility.

Electromagnetic Design

First, the transverse cross-section of the RFQ was optimized using SUPERFISH (SF) [3]. The optimized geometry was then modelled in CST MWS [4] to study the effects of asymmetric structures such as tuners, vacuum ports, end cells, coupling cells, and DSRs. Initially, a comparative study between 2D and 3D simulations was performed using a single quadrant 3D model of the RFQ with a length of 25 cm without any asymmetric structures. The parameters obtained from the 2D and 3D simulations show good agreement, as summarized in Table 1. International experience indicates that the achieved RFQ cavity Q is typically about 70-80% of the simulated value. With 70% of the simulated Q, the cavity RF power dissipation is estimated to be 292 kW.

Table 1: RF Parameters from 2D and 3D simulations.

Parameters	SF	MWS	Unit
Quadrupole Mode Frequency (f_0)	322.99	322.98	MHz
Dipole Mode Frequency(f_d)	313.19	313.17	MHz
Q Value	11326	11338	
Power Dissipation (P)	204	203.5	kW
Max Electric Field E_{max}	29.43	29.48	MV/m

Tuners: Adjustable cylindrical tuners (Fig.2 (a)) are installed along the cavity walls to fine-tune the resonant frequency and field distribution. A total of 64 tuners of radius 2.25 cm will be used in the 4-meter-long RFQ, providing an overall tuning range of 0.31 MHz/mm. To achieve a resonant frequency of 325 MHz, each tuner has to be inserted by 6.4 mm.

Beginning / End Cell and Coupling Cell: The TE_{210} -like mode cannot be sustained in an RFQ terminated by conducting end walls because the longitudinal magnetic field must vanish at the boundaries. Vane undercuts (Fig.2(b)) are therefore introduced to support the required field configuration, forming the beginning cell (BC) and end cell (EC), whose geometries were optimized using CST simulations.

Dipole and higher-order quadrupole modes close to the TE_{210} operating mode can degrade beam dynamics and longitudinal uniformity of TE_{210} mode. To suppress these effects, the RFQ is divided into shorter segments and resonantly coupled using an optimized coupling cell designed in CST MWS (Fig.2(c)).

Dipole Stabilizer Rods (DSRs): The operating field in the RFQ is stabilized against nearby dipole modes using DSRs [5], which are cylindrical rods mounted on the end flanges and

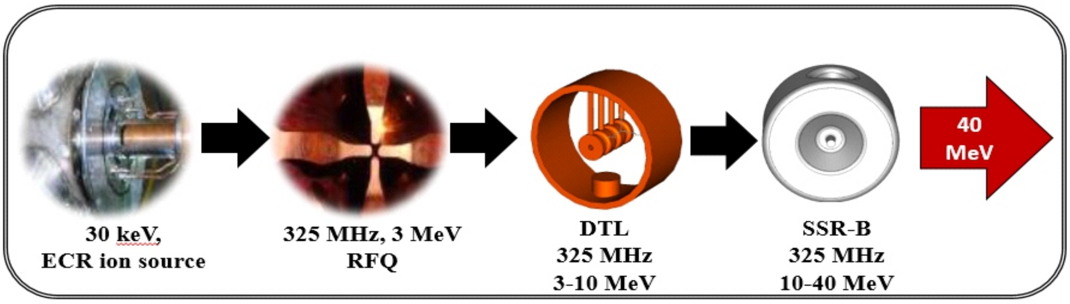

Fig.1: Layout of MEHIPA-1 linac.

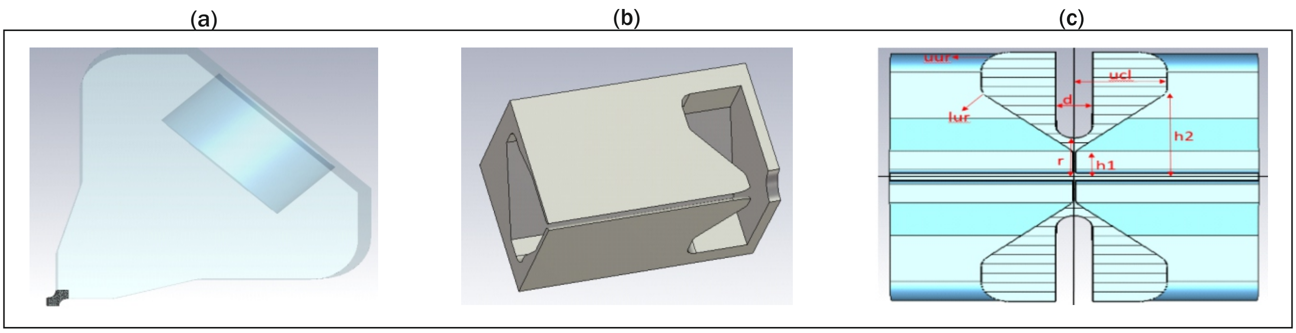

Fig.2: CST MWS model of RFQ with (a) Tuner (b)End cell (c) Coupling cell.

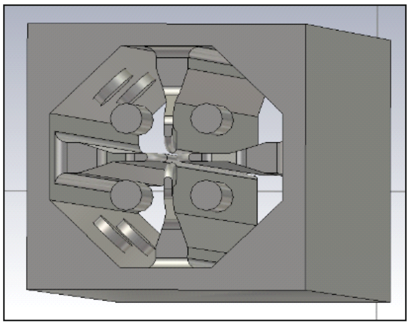

Fig.3: 3D CST model of RFQ with DSRs.

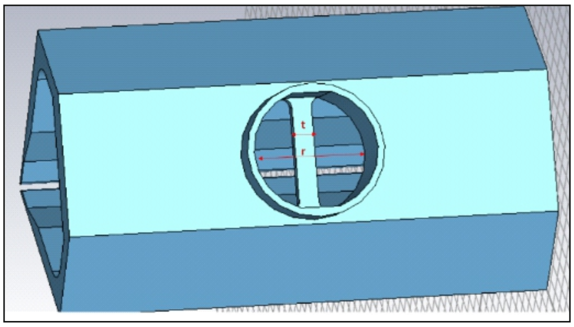

Fig.4: RFQ model with vacuum port.

either side of the coupling plate at suitable locations in all four quadrants of the RFQ. A 3D CST model of the RFQ, including vane undercuts and DSRs is shown in Fig.3. The optimized DSR diameter is 15 mm and length is 120 mm.

Vacuum ports: The RFQ is designed to operate at a vacuum level of approximately 10^{-7} Torr using circular pumping ports distributed across the cavity walls. A conducting bar is provided across each port aperture (Fig.4) to maintain surface current continuity and minimize degradation of the quality factor. An optimized port diameter of 6 cm ensures reasonable vacuum conductance while maintaining a 3.83 GHz cutoff frequency for rapid electromagnetic field decay.

Drift Tube Linac (DTL)

The DTL will be used to accelerate 10 mA proton beam from 3 MeV to 10 MeV. The DTL will be fabricated in two tanks of approximately 2.5 m length. Permanent magnet quadrupoles will be installed in the drift tubes for transverse focusing of the beam.

Electromagnetic Design

The program DTLFISH in the Poisson SUPERFISH [3] code distribution is used to design the cavity shape and compute fields, RF power losses, transit time factor and shunt impedance. The Quality Factor (Q) listed in Table 2 corresponds to 2D simulations performed using SF. Based on internationally reported results and experience from the LEHIPA project, the achieved Q is typically about 30% lower than the simulated value. Accordingly, the estimated power dissipation for the two tanks is 236 kW and 233 kW, respectively.

Table 2: Parameters of MEHIPA-1 DTL.

Parameters	Tank 1	Tank 2
Frequency (MHz)	325	325
Energy Range (MeV)	3-6.33	6.33-10
Tank Diameter (cm)	58.207	58.166
Quality factor	54157	57059
Bore Radius (cm)	1.2	1.2
Dissipated Power (kW)	165	163

DTL Cavity 3D design

In order to include features that break the 2D symmetry, a 3D design of the DTL tank was done using CST MWS. A 4-cell simulation model was used for computational ease with high number of mesh cells.

Stems and Tuners: The drift tubes are supported by stems attached to the tank surface, which introduce a shift in the cavity resonant frequency. In the CST MWS model (Fig.5) of the four-cell DTL, inclusion of 2.5 cm diameter stems shifted the TM_{010} mode frequency by 0.84 MHz for tank 1 and 0.71 MHz for tank 2, which was compensated by increasing the tank diameter.

Six tuners of 12 cm diameter will be installed uniformly along the length of each tank to provide frequency tuning. The total tuning range is ±1.1 MHz for tank 1 and ±1 MHz for tank 2, with maximum tuner depths of 13 cm and 12 cm, respectively. CST model of tuner is shown in Fig.6.

Postcoupler: Postcouplers are employed for field stabilization of the DTL. A total of 9 and 11 postcouplers will be used in tanks 1 and 2, respectively, with confluence achieved at postcoupler lengths of 18 cm and 17.8 cm. CST model of DTL tank 1 is shown in Fig.7.

Single Spoke Resonator (SSR)

For CW structures a lot of RF power is dissipated on the structures and removing this dissipated heat is a major challenge, besides being wasteful. Use of superconducting technology will make the linac compact and cost effective [6]. For the MEHIPA-1 project, after evaluating all options, we have decided to go ahead with superconducting single spoke resonators in the medium energy region from 10-40 MeV.

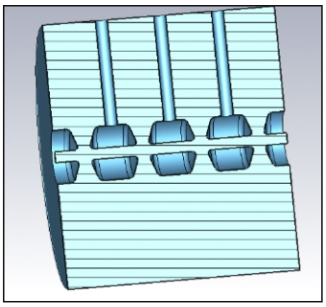

Fig.5: Four cell model of DTL.

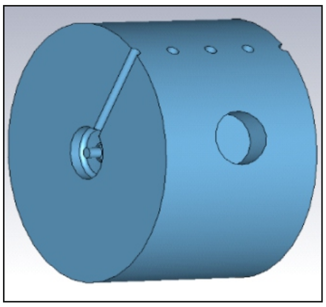

Fig.6: DTL model with tuner.

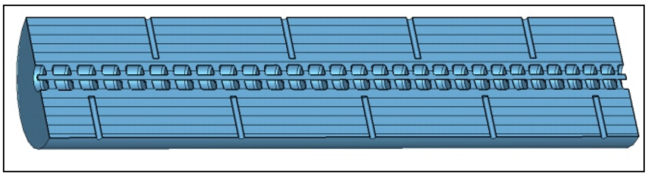

Fig.7: DTL model showing postcoupler location in tank 1.

Table 3: RF Parameters of SSR-B.

Parameters	Values
Frequency (MHz)	325
Beam Tube Radius (cm)	1.5
Cavity Length (cm)	30
Cavity Diameter (cm)	49.62
Average accelerating gradient, *Eacc* (MV/m)	10
Peak surface electric field, *Epeak*(MV/m)	37.6
Peak surface magnetic field, *Bpeak*(mT)	66.5
(R/Q) (Ω)	227.2
G (Ω)	98.9

Cavity Design

The geometry optimization for the SSR-B cavity (β_g =0.21) was performed using CST MWS. Fig.8 shows the vacuum model of a SSR-B cavity. One of the primary objectives of the RF design is to minimize the peak surface electric and magnetic fields through optimization of the cavity geometry in order to avoid field emission and prevent loss of superconductivity in the niobium spoke cavities. Secondly, the optimization aims at maximizing the R/Q and G (=R_sQ) of the cavity. The optimized parameters of the SSR-B cavity are listed in Table 3. Fig.9 shows the Transit Time Factor as a function of particle velocity, which is maximum for β_{opt} =0.2557.

Higher order mode

The calculated R/Q values for the dominant monopole, dipole, and quadrupole HOMs of the SSR-B cavity are negligibly

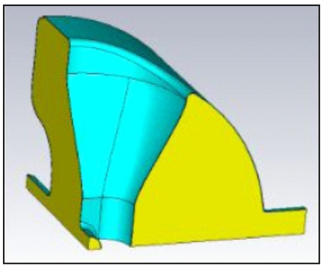

Fig.10: One-eighth cavity model.

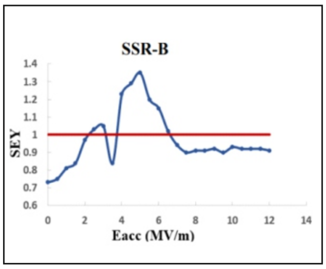

Fig.11: SEY vs accelerating gradient for SSR-B.

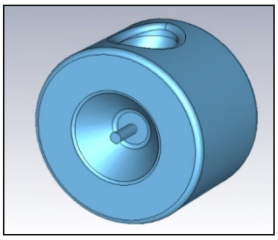

Fig.8: 3D model of a SSR-B cavity.

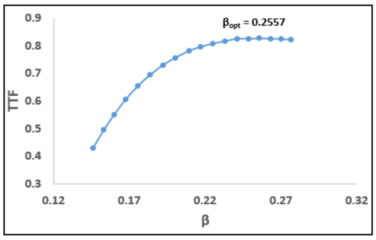

Fig.9: Transit Time Factor as a function of β.

small, indicating no significant risk of beam instability or additional cryogenic load.

Multipacting

Resonant amplification of secondary electron emission can cause RF power loss and localized heating, limiting accelerating fields and potentially causing quenching in superconducting cavities. Multipacting studies of the SSR-B cavity were therefore carried out using a one-eighth model (Fig.10) for computational efficiency. The variation of SEY with accelerating gradient is shown in Fig.11, revealing a pronounced multipacting barrier in the 4–6.5 MV/m range and no multipacting activity beyond 6.5 MV/m.

Conclusion

The electromagnetic design of the RFQ, DTL, and SSR structures for the MEHIPA-1 proton linac has been carried out using integrated 2D and 3D simulations. The optimized structures satisfy the required RF and operational constraints while maintaining fabrication feasibility. Studies of field stabilization, tuning, HOMs, and multipacting demonstrate the suitability of the proposed designs for reliable accelerator operation.

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