BEAM DYNAMICS DESIGN OF A SUPERCONDUCTING 175 MHZ CH-LINAC FOR IFMIF

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Abstract

In the IFMIF (International Fusion Material Irradiation Facility) project the generation of a 125 mA, 40 MeV D^+ beam is required to produce very high neutron fluxes from a liquid Li target to test appropriate wall materials for fusion reactor chambers. The linac design consists of a RFQ accelerator as first part (0.1 - 5 MeV) followed by a drift tube linac from 5 to 40 MeV. The required cw operation favours a superconducting approach with shorter length, high efficiency and larger aperture, which gives a higher safety margin against possible particle losses and resulting structure activation. One well suited candidate may be the CH-structure, which combines high acceleration efficiency with comparatively small geometrical dimensions. In a first attempt a beam dynamics design has been studied: a combination of a normal-conducting IH-cavity followed by a superconducting 175 MHz CH-section, which fulfils the IFMIF requirements. The DTL length is about 11 m only. Results of multiparticle simulations shows smooth beam behaviour and will be discussed together with the main structure parameters.

1 INTRODUCTION

For the acceleration of ions at low and medium particle velocities the most common superconducting structures are quarter wave and spoke type cavities with two or for gaps. With a chain of these resonators a high flexibility in the acceleration of different ion species and charge to mass ratios can be achieved by individual phase tuning in each resonator. In the IFMIF DTL only one ion species with a fixed velocity profile has to be accelerated, in this case multigap structures are more appropriate as e.g. H-type cavities. The room temperature IH-structure serves already successfully in the field of light and heavy ion acceleration in the energy range directly following the RFQ-accelerators up to 20 MeV/u with operating frequencies between 30 and 300 MHz. Together with the KONUS beam dynamics concept, which allows to built drift tubes without quadrupoles and concentrates the transverse focusing in separate quadrupole triplets, compact and highly efficient linacs can be designed and constructed, which can compete in efficiency to sc structures. For higher energies higher frequencies are required for efficient acceleration, which is met by the CH (crossbar H-mode) cavities [1]. Fig. 1 gives a principal view of the CH-structure. Due to the larger diameter compared to the IH structures frequencies up to 700 MHz and energies up to 150 MeV/u can be reached: thus the CH structure shows a large potential for rt as sc designs. CH-cavities show high mechanical and thermal robustness, which is provided by the crossed stems construction. The transverse dimensions are rather small compared to quarter wave or spoke type cavities operated at the same frequency. For the required cw operation the structure power losses are low and large drift tube apertures can be chosen to reduce the probability of particle losses. For the IFMIF DTL a combination of a room temperature IH tank with internal quadrupole triplet for the low energy part followed by a chain of superconducting CH-cavities with inter tank focusing has been designed and multi particle beam dynamics calculations have been performed to check the beam behaviour.

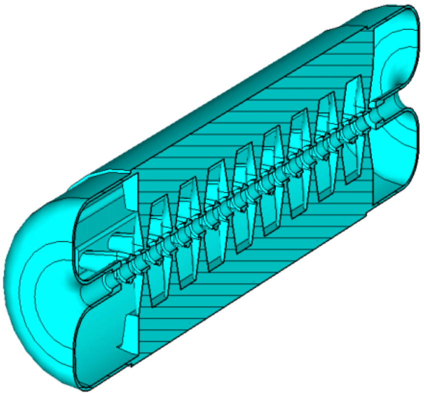

Fig. 1: Sectional view of a superconducting CH-cavity.

2 GENERAL LAYOUT

Fig. 2 is a schematic layout of a sc CH cavity chain which is used in the design study for the IFMIF case.

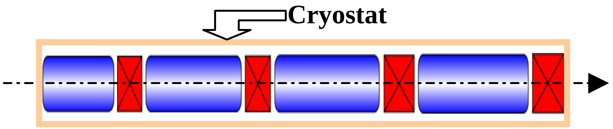

Fig. 2: Scheme of a chain of sc CH cavities (blue), inter tank quadrupole tripletts (red) and cryostat (brown).

The blue rectangles symbolize the sc CH cavities out of pure welded Niobium operated at 2 or 4.2 Kelvin which house several cells of length $\beta\lambda/2$. Typical cell numbers are 15 to 25 cells per tank. Longer tanks with more cells are preferable because they have a better gap field distribution, lower gap voltages which leads to reduced electric surface fields at the drift tubes ends and on the stems. Furthermore the area and the total strength of the dangerous magnetic surface fields at the tank end walls shrink in a long tank with more cells. Besides the most gaps operate at a synchronous phase of 0° as required by the special KONUS beam dynamics takes place with a combination of longitudinal focusing and maximum acceleration efficiency. To focus the beam in transverse phase space a quadrupole triplet is positioned between the tanks. In the superconducting case the coils are on the same temperature like the CH tanks and have iron yokes which limits the maximum magnetic surface field to 1.3 T. This allows to put the magnetic lenses inside the cryostat together with the CH tanks [2]. Therefore we have only one long cryostat which eases the facility plannings.

3 MULTI PARTICLE SIMULATIONS

A beam dynamics design for the IFMIF case has been studied for a combination of a room temperature IH-section followed by a chain of superconducting 175 MHz CH-sections. Fig. 3 shows a schematic layout of this IFMIF linac. Due to beam dynamics reasons a magnetic lens is integrated in the tank 1 (green colour) which has to be operated at room temperature then, the other four tanks (blue colour) are superconducting with external lenses in between (red colours). Table 1 shows the structure parameter of the linac generated with the multi particle program LORASR [3].

Table 1: Parameter of a IH+CH DTL design for IFMIF.

STRUCTURE PARAMETER	**IH+CH-DTL**	
A/q	2 (D^+)	
I_{design}	125.0	mA
f_{rf}	175.0	MHz
Lattice	FDF - DFD	
N_T	5 (1NC+4SC)	
L_T range	1.0 – 2.0	m
$P_{tot/T}$	NC:690.0 SC:740.0	kW
W_{in}	5.0	MeV
W_{out}	40.0	MeV
$W_{tot/L}$	3.24	MeV/m
N_{cell}	73	
L_{tot}	10.80	m
E_oT	NC:1.95 SC:4.1	MV/m
r_o	NC:1.5 SC:2.4 - 4.0	cm
G_{max} Quads	6.40	kG/cm
B_{max} Quads	1.28	T
b	1.00	

One important design restriction was the maximum total average rf power per tank needed in the sc part. It shouldn't exceed more than 800 kW in average due to rf amplifier and coupler power limits. Therefore the effective field amplitude E_{eff} was limited to 4.1 MV/m. The cw operation mode of the IFMIF facility and the use of deuterons require large safety margins in the bore sizes of the accelerators to avoid losses which lead to structure activation. Therefore we increased the bore radius of the drift tubes in the sc part from 2.4 cm up to 4.0 cm. Such a large increase of the linac aperture is only possible in a sc layout without a dramatic decrease in efficiency. Furthermore we reduced the maximum gap voltage to V_{gap} (max) ≤ 1.0 MV to avoid sparking and to reduce the critical electric surface fields E_C.

The next Figs. show the results of multi particle simulations with the program LORASR applying the KONUS beam dynamics. Space charge forces are calculated by the particle-in-cell technique PIC. Each run was made with 10,000 macroparticle. As starting distribution we used an ellipsoid with constant charge density in 3d phase space.

Fig. 3 shows the full beam sizes of the linac in horizontal and vertical plane along the linac. No particle hits the structure and by the increasing bore radius with increasing beam energy the safety margins in the high beta region of the accelerator are sufficiently large. In Figs. 4 and 5 the longitudinal 100 % beam envelopes along the linac are plotted. There are no longitudinal losses which indicates well confined particle bunches. The plots show the beam envelopes with respect to the synchronous particle of each structure section. Finally Fig. 6 displays the transverse and longitudinal RMS normalized emittances along the linac.

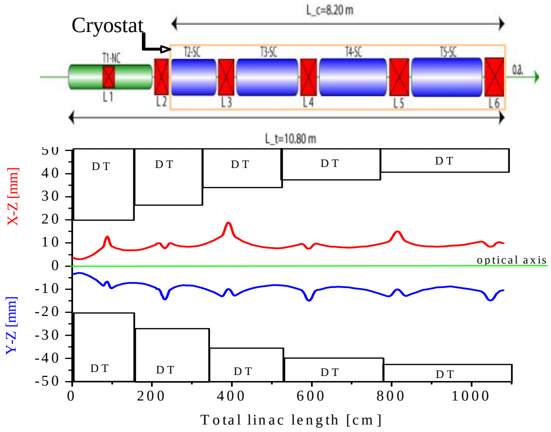

Fig. 3: Schematic layout of the DTL together with full transverse beam envelopes of the linac from Table 1: red line X-Z plane, blue line Y-Z plane. The rectangles inside the graph indicate the drift tube bore sizes.

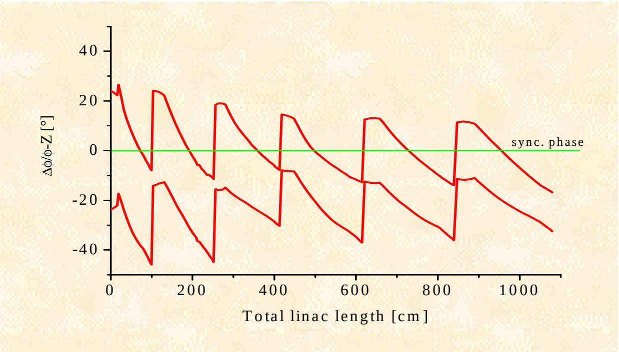

Fig. 4: 100 % effective phase profile along the linac.

In the Figs 7 to 9 the output distributions of the linac in every phase space are displayed.

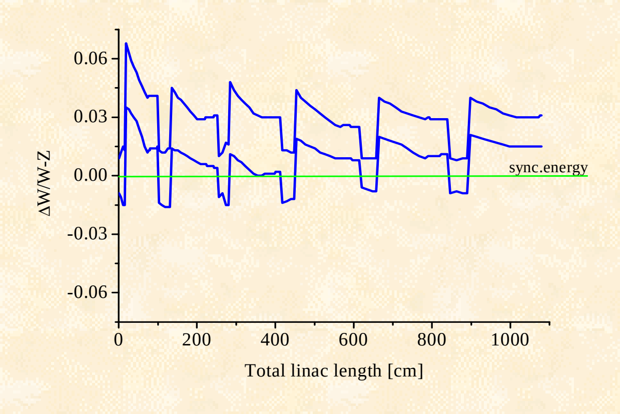

Fig. 5: 100 % effective energy profile along the linac.

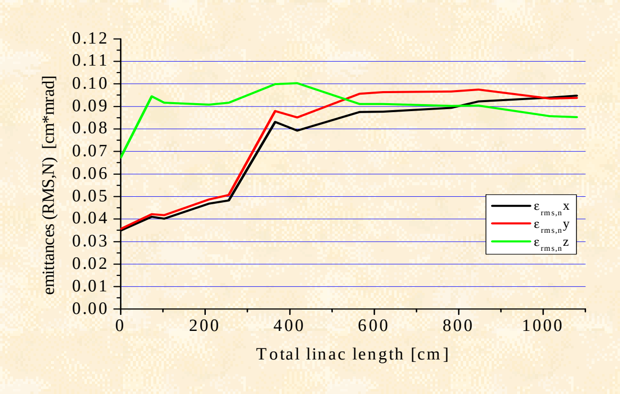

Fig. 6: Evolution of the RMS normalized emittances along the linac.

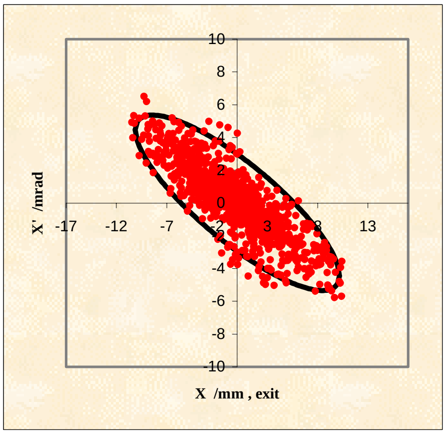

Fig. 7: Output beam distribution of the linac in the X-X' plane with 95 % emittance ellipse drawn.

4 CONCLUSION

A design for a combination of a rt IH structure and a chain of sc CH resonators with inter tank focusing has been found which fulfils the requirements for a high current IFMIF DTL. The sc CH DTL part provides very high rf and acceleration efficiency and due to its special cell geometry high mechanical robustness. The drift tube linac has a total length of ≈ 11 m only, the cryostat length is ≈ 8 m.

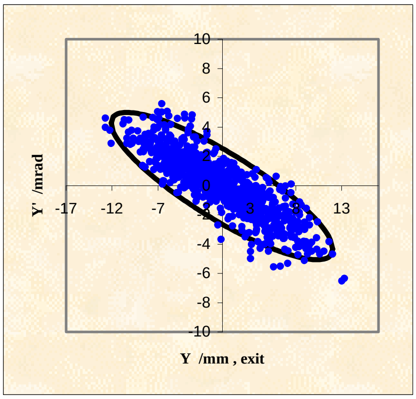

Fig. 8: Output beam distribution of the linac in the Y-Y' plane with 95 % emittance ellipse drawn.

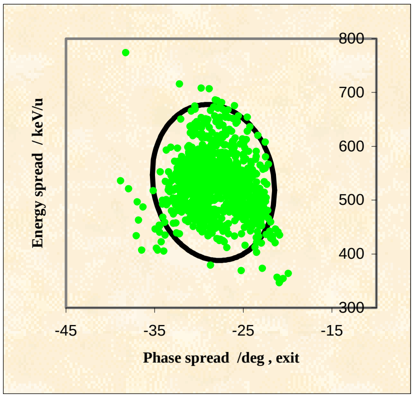

Fig. 9: Output beam distribution of the linac in the ΔW-Δϕ plane with 95 % emittance ellipse drawn.

The estimated total rf power of this design study is ≈ 4.1 MW, which demonstrates the high rf efficiency of the sc CH modules. In addition large drift tube apertures lower the risk of particle losses in the sc part. By variation of the field amplitude in the last two tanks the required variation of the linac end energy can be achieved. First calculations showed also a low sensitivity of the beam behaviour against statistic errors [4]. All results of particle dynamics calculations demonstrate the capability of the IH/CH structure to handle high current beams without losses.

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**Work performed in the EFDA/IFMIF collaboration*