BEAM DYNAMICS SIMULATION OF SUPERCONDUCTING HWR OPTION FOR THE IFMIF LINAC

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Abstract

One of the requirements of the International Fusion Materials Irradiation Facility (IFMIF) is a 250 mA, 40 MeV cw deuteron beam provided by two 125 mA accelerators. A superconducting (SC) option for the 5 to 40 MeV section could present some advantages. In this paper, a design based on SC-Half Wave Resonators and solenoids is presented. Multi particle beam dynamics simulations have been performed in order to validate the linac design in such a high charge space regime. A Monte Carlo error analysis has been carried out to study the effects of misalignments or field variations.

INTRODUCTION

The driver of the International Fusion Materials Irradiation Facility consists of two 125 mA, 40 MeV cw deuteron accelerators, providing a total of 10 MW beam power to the liquid lithium target. A superconducting solution for the 5 to 40 MeV accelerator section could offer some advantages compared to the copper Alvarez-type Drift Tube Linac of the reference design [1]: linac length reduction and significant plug power saving.

In this paper, the SC design using low-β half-wave resonators (HWR) at 175 MHz is presented. In order to assess the feasibility of this superconducting HWR option in a very high space charge regime of the IFMIF linac, beam dynamics calculations and error studies have been performed.

LINAC LAYOUT

Resonators

The acceleration of high-intensity beams pushes for both large beam pipe aperture and conservative accelerating field, in order to prevent any beam loss and to restrict the demands on the RF power. A larger aperture leads to a larger peak-to-accelerating fields ratio and then tends to decrease the accelerating gradient as well, in order to keep the peak surface field at an acceptable magnitude.

These considerations lead to the choice of a gradient of 4.5 MV/m and apertures in the 40-50 mm range were chosen for the SC resonators. Two resonator families, with different geometric β-values, are enough to cover the acceleration from the RFQ exit (5 MeV) to the final energy (40 MeV).

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Focusing Magnets

The transverse focusing is ensured by SC solenoids. The axial field is kept low enough (around 6 T) in order to use the classical NbTi technology for the coils.

The solenoid package includes bucking coils in order to cancel the fringe field at the cavity location and also steering coils, associated with button-type beam positions monitors (BPM) for orbit correction.

Linac Layout Optimization

Once accelerating gradients and realistic component dimensions and spacings are given, an optimization is done to achieve the shortest linac with the fewest cavities while meeting the IFMIF requirements. The GenLinWin code [2] has been used to find the optimal set of geometric cavity β-values, transition energies between the cavity families and number of resonators per period.

As a result, the SC linac needs a total of four cryomodules:

- the first cryomodule contains 8 periods of 1 solenoid and 1 resonator (β=0.094).
- the second cryomodule contains 5 periods of 1 solenoid and 2 resonators (β=0.094).
- the last two cryomodules contain 4 periods of 1 solenoid and 3 resonators(β=0.166).

In order to avoid dilution and beam losses, the phase advance per period has been kept lower than 90° and the beam has to be carefully matched in all planes (longitudinal and transverse) between cryomodule. This last statement favors a large number of resonators per cryomodule and lead to choose a solution with 3 different families of cryomodules.

Within the EVEDA (Engineering Validation Engineering Design Activities) phase of IFMIF, it is planned to build and test the accelerator prototype at full beam current, with this first stage of acceleration. As a result, the beam energy at the exit of the first cryomodule is 9 MeV, which is identical to the energy originally planned after the first tank of the room temperaure DTL.

Assuming an inter-cryomodule spacing of 40 cm, the total SC linac length is 22 m. It is shorter than the normal conducting Alvarez DTL of the reference design ($\sim$30 m). Table 1 summarizes the parameters of the cryomodules.

The design of the linac lattice has been made as safe as possible, in particular with a large longitudinal acceptance and without any structure instability. These features ensure

Table 1: Cryomodules parameters.

Cryomodules	1	2	3 & 4
Cavity β	0.094	0.094	0.166
Cavity length (mm)	180	180	280
Beam aperture (mm)	40	40	48
Nb cavities / period	1	2	3
Nb cavities / cryostat	1×8	2×5	3×4
Cryostat length (m)	4.64	4.30	6.03
Output energy (MeV)	9	14.5	26/40

minimum beam halo and losses that could be induced by machine imperfections or beam mismatch. At low energy, where the phase extension of the bunches is still large, the synchronous phase has been set to large negative values (-50°) while letting grow linearly with the beam energy (until -30°). The longitudinal phase advance, can be rather high at low energy and trigger the structure instability; the field is then reduced to lower the phase advance below 90° per period.

The resulting energy gain provided by the resonators is shown in Fig. 1. Given the beam intensity of 125 mA, the maximum R.F. power per cavity is 75 kW for the low-β resonators and 150 kW for the high-β resonators.

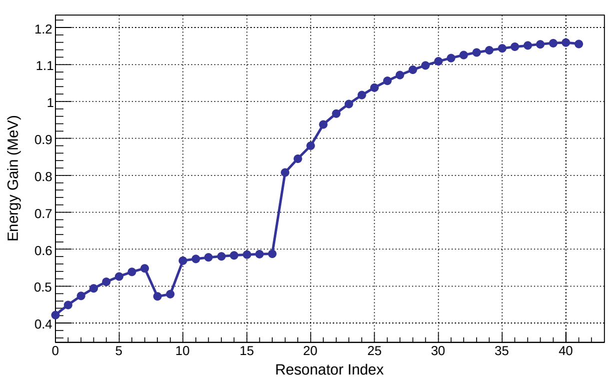

Figure 1: Energy gain in the resonators.

BEAM DYNAMICS

Intensive beam dynamics studies have been carried out to probe the linac design. The resonators were modeled by a Bessel development of the theoretical field on axis. Besides, axial and radial field maps of the solenoid coils, calculated by finite elements method, have been included in the simulations.

The numerical simulations have been performed with TraceWin[2]. This code has been benchmarked with other tracking codes used in the accelerator community for simulations of high-intensity linacs [3].

The beam distribution taken as the input of our simulations is the output distribution coming from a RFQ designed by INFN-LNL, in the framework of the IFMIF-EVEDA project. This RFQ has been simulated using Toutatis with 10^6 macro-particles generated in a 4D Gaussian distribution (with a 4σcut).

A matching section composed of 2 buncher cavities and 3 magnetic quadrupoles had been included in the simulations in order to adapt the beam coming from the RFQ into the SC linac.

Fig. 2 presents the beam envelope at 3-RMS size through the SC linac. The smoothness of the envelopes shows correct matchings between the cryomodules.

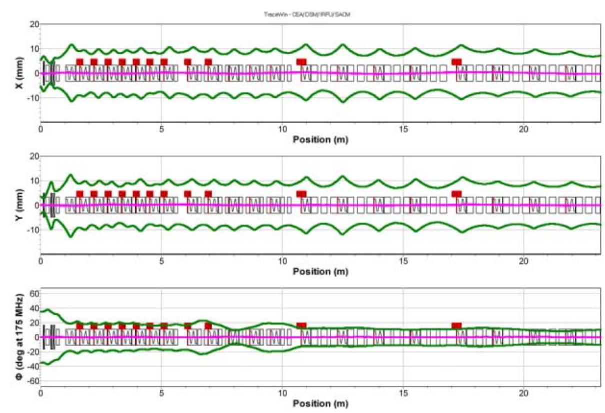

Figure 2: Beam envelope at 3 RMS in the HWR structure.

The emittance growths through the SC linac are 73% and 14% in the transverse and longitudinal planes (see Fig. 3).

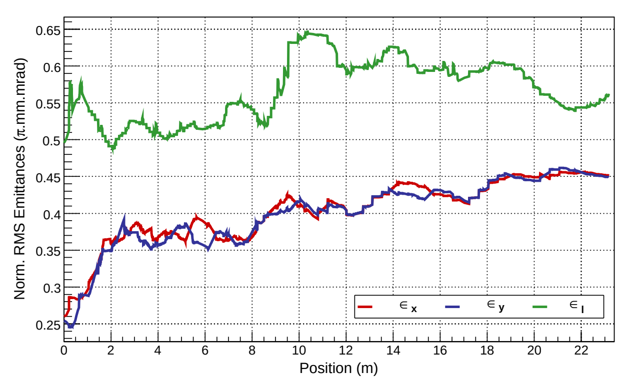

Figure 3: Normalized RMS emittances along the linac (green: longitudinal; red and blue: horizontal and vertical).

The beam phase space distribution at the exit of the linac is shown in Fig. 4. The beam transmission is equal to 100% and no beam loss is observed with the 10^6 particle beam distribution. The full beam envelope stays, at least, 6 cm far from the bore radius of the cavities. The safety margin, measured by the bore-to-beam radius ratio, is higher in the HWR scheme than in the Alvarez reference DTL [4].

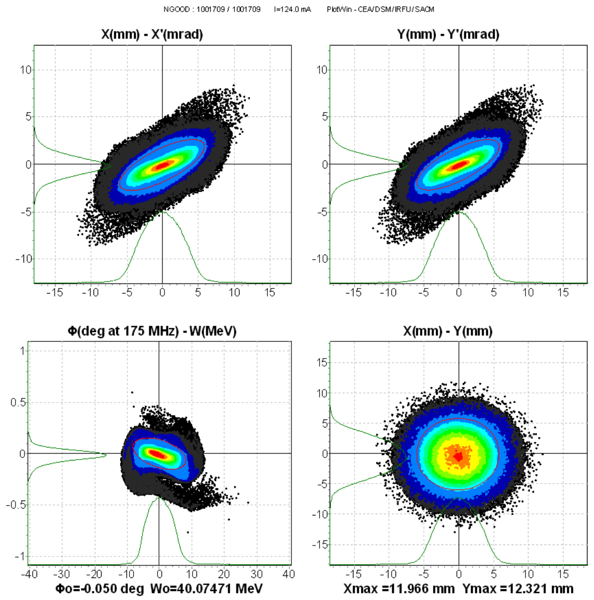

Figure 4: The beam space phase distribution at the linac exit.

ERROR ANALYSIS

In order to study the effect of random errors along the linac, a Monte-Carlo simulation method has been carried out by tracking 10^6 particles through 200 different linacs, each with different random errors. The errors are uniformly distributed in the ranges presented in Table 2.

Table 2: Errors distribution.

Error Type	Error range
Resonator	
Misalignment [x,y]	$\pm$1.0 mm
Tilt [φ_x,φ_y,φ_z]	$\pm$7.5 mrad
Field amplitude (static)	$\pm$1 %
Field phase (static)	$\pm$1 deg
Solenoids	
Misalignment [x,y]	$\pm$1.0 mm
Tilt [φ_x,φ_y]	$\pm$7.5 mrad
Field amplitude	$\pm$1 %
Beam Position Monitor	
Measurement accuracy	$\pm$0.25 mm

The error ranges (1 mm misalignment, for instance) have been intentionally chosen very conservative. The beam orbit spoiling stems mainly from the solenoid tilts. The correction scheme relies on the steering coils (H and V) associated with the downstream beam position monitors (H and V) located at every solenoid package. This simple one-to-one correction scheme limits the RMS beam displacement maintained below 0.5 mm while keeping the maximum deviation below 2 mm.

The particle distribution in the beam pipe, calculated with these loose tolerances and with the corrections made by steering coils, are shown on Fig. 5. The contour lines are close to those simulated without errors, giving a reasonable safety margin between the beam occupancy and the pipe aperture.

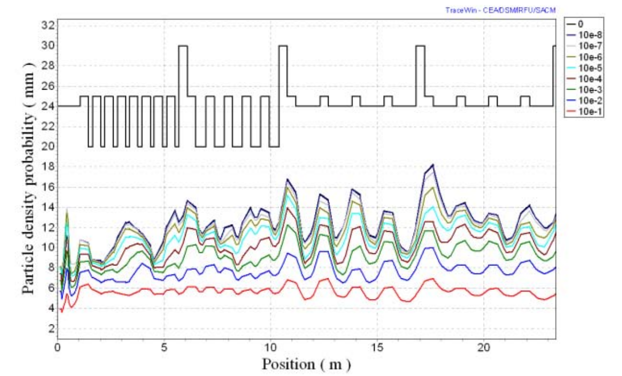

Figure 5: Plot of contour lines encircling 90% to 100% of particles (with errors).

CONCLUSIONS

This work shows that SC half-wave resonators can safely accelerate, up to 40 MeV, high-intensity beams like the 125 mA deuteron beam of the IFMIF linac. We have also checked that, by injecting the beam output from this SC solution in the IFMIF HEBT, the beam dimension and homogeneity on the liquid Li target are as satisfying as with the room temperature DTL reference design. The layout of the first accelerating section (up to 9 MeV) for the IFMIF-EVEDA project will be based on the present design.

However, more beam dynamics simulations have to be done to include a matching section with more realistic dimensions and an input beam distribution from the last RFQ design [5]. Furthermore, an alternative design, using quadrupole doublet for transverse focusing (FDO lattice) instead of solenoids, is presently under study.

REFERENCES

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