

# OPTIMIZATION RESULTS OF BEAM DYNAMICS SIMULATIONS FOR THE SUPERCONDUCTING HWR IFMIF LINAC

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## Abstract

The 250 mA, 40 MeV cw deuteron beam required for the International Fusion Materials Irradiation Facility (IFMIF) will be provided by two 125 mA linacs. In order to accelerate the beam from 5 MeV to 40 MeV, a superconducting (SC) linac, housed in four cryomodules, is proposed. The design is based on two beta families ( $\beta=0.094$  and  $\beta=0.166$ ) of half-wave resonators (HWR) at 175 MHz. The transverse focusing is achieved using one solenoid coil per focusing period. This paper presents the extensive multi-particle beam dynamics simulations that have been performed to adapt the beam along the SC-HWR structure in such a high space charge regime. As one of the constraints of the IFMIF linac is hands-on maintenance, specific optimizations have been done to minimize the beam occupancy in the line (halo). A Monte Carlo error analysis has also been carried out to study the effects of misalignments or field imperfections.

## INTRODUCTION

The International Fusion Materials Irradiation Facility will produce a high flux ( $10^{18}\text{n.m}^{-2}\text{s}^{-1}$ ) of 14 MeV neutron dedicated to characterization and study of candidate materials for future fusion reactors. To reach such a challenging goal, a solution based on two high power cw accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to a liquid lithium target, is foreseen [1].

In a previous work [3], the feasibility of the superconducting option, using low- $\beta$  half-wave resonators at 175 MHz to accelerate the deuteron beam from 5 MeV to 40 MeV, has been investigated. Further studies, in particular on the design of the MEBT and on beam dynamics optimizations, were necessary to validate the final design of the HWR cavities linac.

## MEBT AND LINAC DESIGN

In the framework of the IFMIF Engineering Validation and Engineering Design Activities (EVEDA), it is planned to build and test a demonstrator accelerator at full beam current at 9 MeV. As a result, the output energy of the first section (i.e. first cryomodule) of the IFMIF linac has to 9 MeV, which adds a constraint on the design.

## MEBT

The MEBT section is designed to transport the beam from the RFQ exit and to adapt it for its injection into the SC HWR linac. Former beam dynamics studies have led to a first version of the MEBT with 2 bunchers and 3 quadrupoles [3] but it appears that the matching capabilities were not satisfying. This is the reason why a new design has been proposed, with 2 bunchers cavities ( $\beta=0.073$ ) at 175 MHz and 5 magnetic quadrupoles. Five quadrupole are needed to match the beam size and divergence and to control its extent MEBT as well. The MEBT length is now around 1.9 m.

## HWR Cavities

The acceleration of high-intensity beams pushes for both large beam pipe aperture and conservative accelerating field, in order to minimize beam losses and to reduce the R.F. power. So, a gradient of  $4.5\text{ MV/m}$  and apertures in the 40-50 mm range were chosen for the SC resonators. Two HWR families, with different geometric  $\beta$ -values, are enough to cover the acceleration from the RFQ exit (5 MeV) to the final energy (40 MeV).

The GenLinWin code [4] has been used to generate the shortest linac with the fewest cavities while meeting the IFMIF (and the EVEDA) requirements with the optimal set of geometric cavity  $\beta$ -values, transition energies and number of resonators per period.

As a result, the SC linac needs four cryomodules:

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

Assuming an inter-cryomodule spacing of 0.35 m, the total SC linac length is 22 m. The design of the linac lattice has been made as safe as possible, with a large longitudinal acceptance and without any structure instability. At low energy, the synchronous phase has been set to  $-50^\circ$  while letting it grow linearly with the beam energy until  $-30^\circ$ . Given the beam intensity of 125 mA, the maximum R.F. power per cavity is 75 kW for the low- $\beta$  resonators and 150 kW for the high- $\beta$  resonators.

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## Transverse Focusing

Concerning the transverse focusing, two different lattices have been initially studied: one based on a Focusing-Defocusing (FDO) lattice with quadrupole doublet and, another one, with one solenoid (FO). The preliminary beam dynamics simulations showed comparable results for the two solutions.

At first, the quadrupole doublet solution seemed interesting as it would allow to match the beam transversally using the quadrupolar moments from Beam Position Monitors (BPM) measurements. However, the integration of quadrupoles in the cryomodules appeared to be more complicated and more expensive than solenoids; then, the requested gradients were difficult to reach with superferric quadrupoles, without losing field linearity.

For the SC solenoid lattice, it is assumed that the beam transverse tuning can be based on beam loss monitors. The axial field is kept 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 BPMs for orbit correction. Consequently, the design based on SC solenoids for transverse focusing has been chosen for the IFMIF HWR linac.

## BEAM DYNAMICS SIMULATIONS

### Simulation Conditions

The beam distribution taken as the input of the simulations is the output distribution coming from the latest design of the RFQ, achieved by INFN-LNL [2]. The transport in the RFQ has been simulated with Toutatis [4].

The half-wave resonators were modeled by a Bessel development of the theoretical field on axis. For the solenoid coils, axisymmetrical field maps have been calculated by finite elements method.

### Optimization Methods

All the beam dynamics numerical simulations reported in this paper have been performed with TraceWin [4].

In the longitudinal plane, only the buncher cavities of the MEBT are used to adapt the beam in the HWR channel whereas in the transverse plane it is necessary to adjust the MEBT quadrupoles and all the solenoids of the linac.

A first optimization is done in order to obtain a smooth RMS size (transversally and longitudinally) at each period of the HWR structure. As we are in very strong space charge regime, this method doesn't lead to a minimum halo, and the beam extent could be important. By doing so, beam losses, incompatible with the IFMIF hands-on maintenance requirements, could be induced. This is particularly true for the cryomodules 3 and 4, where the transverse focusing period becomes longer.

As a second step, other optimization studies has been carried on for cryomodules 3 and 4, to minimize the beam

extent. These optimizations have been performed in multi-particle mode with  $6 \times 10^5$  particles.

Another interesting aspect of this approach is that it could be used to tune the machine. In the IFMIF SC linac, no RMS beam size measurement are available because of lack of space, but beam loss monitors can be used instead. Minimization of the beam extent in simulations is similar to beam loss minimization in operation.

## BEAM DYNAMICS RESULTS

### Beam Envelope and Beam Occupancy

Figure 1 presents the beam envelope at 3-RMS size through the SC linac optimized with the "RMS size" method. The smoothness of the envelopes shows correct matchings between the cryomodules.

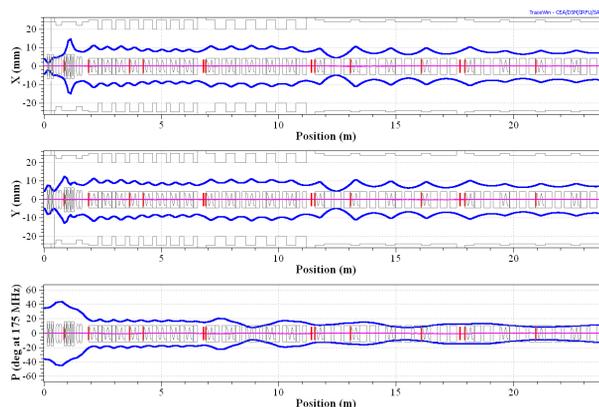


Figure 1: Beam envelope at 3 RMS in the HWR structure.

In Fig. 2, a comparison of the results obtained with the two optimization methods is shown. Even if the beam envelope is smoother in the case of the RMS size optimization, it can be observed that the beam occupancy is lower in the beam extent optimization. This shows that in a high space charge regime with significant beam halo, the RMS dimensions are no longer relevant parameters to minimize the beam occupancy in the beam pipe.

### Emittance Growth

The emittance growths through the SC linac are 64% and 40% in the transverse and longitudinal planes, in the RMS size optimization case. With the beam extent optimization, the emittance growths are 82% and 12%, respectively. As the beam envelope is less smooth in this later case, the transverse emittance growth is higher and an emittance transfer between the transverse and the longitudinal plane is observed.

### Error Study

In order to study the effect of static errors along the linac, a Monte-Carlo simulation method has been carried out by tracking  $1.3 \times 10^6$  particles through 500 different

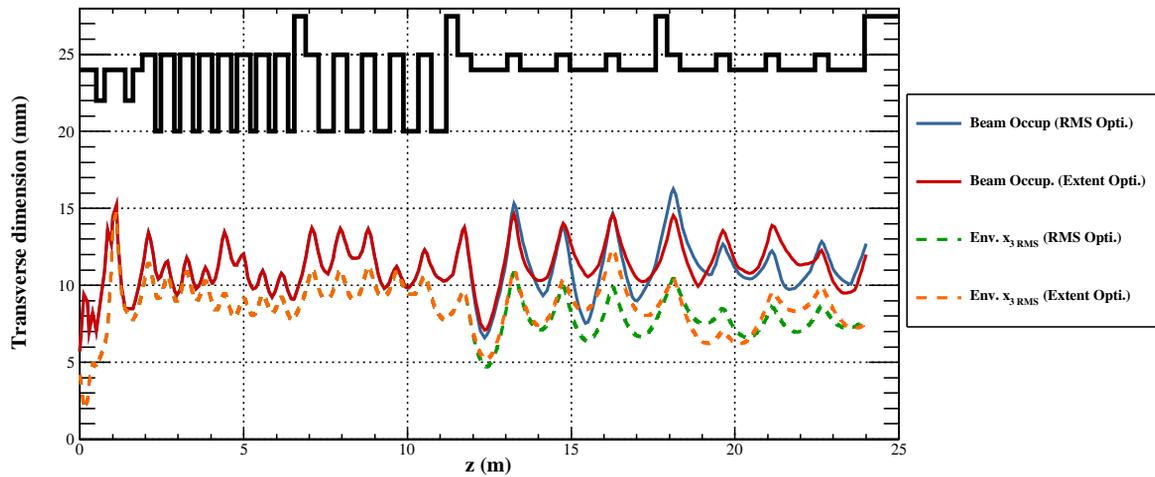


Figure 2: Beam occupancy (solid lines) and beam envelope at 3 RMS (dashed lines) for the two optimization methods. The simulations are made with  $1.3 \times 10^6$  particles.

linacs, each with different random errors. The errors are uniformly distributed in the ranges presented in Table 1.

Table 1: Errors Distribution

Error Type	Error range
<b>Resonator</b>	
Misalignment [x,y]	$\pm 2$ mm
Tilt [ $\varphi_x, \varphi_y$ ]	$\pm 20$ mrad
Field amplitude (static)	$\pm 1$ %
Field phase (static)	$\pm 1$ deg
<b>Solenoids</b>	
Misalignment [x,y]	$\pm 1$ mm
Tilt [ $\varphi_x, \varphi_y$ ]	$\pm 10$ mrad
Field amplitude	$\pm 1$ %
<b>Beam Position Monitor</b>	
Measurement accuracy	$\pm 0.25$ mm

The correction scheme relies on steering coils (H and V) associated with the downstream beam position monitors (H and V) located at every solenoid package. This one-to-one correction scheme maintain the RMS beam orbit displacement below 0.4 mm while keeping the maximum deviation below 1 mm.

The particle density in the beam pipe, calculated under these conditions, is shown on Fig. 3 and is close to the one simulated without errors, giving a reasonable safety margin between the beam extent and the pipe aperture (around 8 cm at least).

### CONCLUSION

Beam dynamics simulations show that the proposed SC half-wave resonator structure can accelerate from 5 MeV

#### Beam Dynamics and Electromagnetic Fields

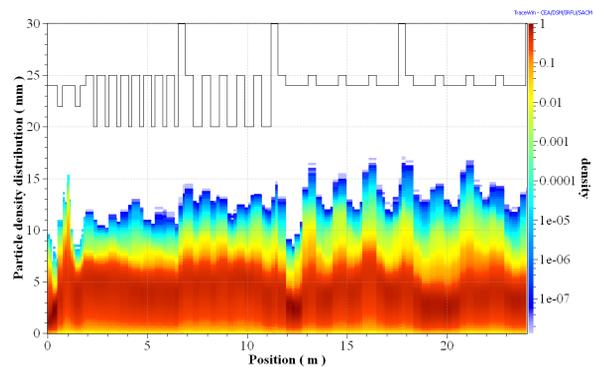


Figure 3: Density plot for 500 runs (with errors), with  $1.3 \times 10^6$  particles each.

to 40 MeV a high intensity (125 mA) deuteron beam for the IFMIF accelerator. The MEBT and first HWR section (up to 9 MeV) of the present design have been adopted for the EVEDA project and are now under detailed mechanical studies.

Furthermore, the optimization based on the beam extent minimization appears to be a relevant method, transposed in operation to beam loss minimization. This technique is then proposed for the IFMIF tuning procedure.

### REFERENCES

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- [4] <http://irfu.cea.fr/Sacm/logiciels/index.php>.