# START-TO-END BEAM DYNAMICS SIMULATIONS FOR THE PROTOTYPE ACCELERATOR OF THE IFMIF/EVEDA PROJECT

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*Abstract*

The EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF (International Fusion Materials Irradiation Facility) project consists in building, testing and operating a 125 mA/9 MeV prototype accelerator in Rokkasho-Mura (Japan).

Because of high beam intensity and power, the different sections of the accelerator (injector, RFQ, MEBT, Superconducting Radio-Frequency linac and HEBT) have been optimized with the twofold objective of minimizing losses along the machine and keeping a good beam quality. Extensive start-to-end multi-particles simulations have been performed to validate the prototype accelerator design. A Monte Carlo error analysis has been carried out to study the effects of misalignments and field variations. In this paper, the results of theses beam dynamics simulations, in terms of beam emittance, halo formation and beam losses, are presented.

## INTRODUCTION

The International Fusion Materials Irradiation Facility will produce a high flux ($10^{18}$n.m$^{-2}$.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 first phase, called Engineering Validation and Engineering Design Activities (EVEDA), it is planned to build and test a prototype accelerator at full beam current up to an energy of 9 MeV [1].

This paper describes briefly the general design of the different sections of the IFMIF/EVEDA prototype accelerator and will presents the start-to-end simulations that have been performed to validate it.

## IFMIF-EVEDA ACCELERATOR DESIGN

### *Issues and choices*

With such a high intensity, the beam is expected to be submitted to strong space charge forces which often dominate the focusing forces. Under these conditions, particle losses and emittance growth can occur. In order to limit space charge effects the whole design of the accelerator has been done with the objective of reducing as much as possible the distances between the focusing elements.

Beyond the energy of 5 MeV (i.e. after the RFQ), material activation induced by particle losses becomes significant. As one of the requirements of the IFMIF/EVEDA prototype is hands-on maintenance, beam losses must be maintained under 1W/m. Consequently, specific optimizations have to be performed to minimize the beam occupancy in the line (halo). Furthermore, as the beam power is in the mega-watt range, it is necessary to perform multi-particle simulations with at least $10^6$ macro-particles to have enough statistics to study the losses.

### *IFMIF/EVEDA Prototype Accelerator Sections*

A scheme of the IFMIF/EVEDA prototype accelerator is presented in Figure 1.

**Injector** The 140 mA cw $D^+$ beam which has to be delivered by the IFMIF/EVEDA injector is produced by a 2.45 GHz ECR ion source based on the SILHI design [2]. A four electrode extraction system has been optimize to extract the beam at 100 keV and to minimize its divergence. The low energy beam transfer line (LEBT) is based on a dual solenoid focusing system to transport the beam and to match it into the RFQ [3].

**RFQ** The RFQ strongly focuses the beam while bunching and accelerating it to the energy of 5 MeV. The first part of this RFQ has been recently modified to lower its focusing strength [4]. This modification allows to increase the acceptance and thus relax the input beam requirements at the end of the LEBT. The total RFQ length is 9.81 m which is the longest one ever constructed.

**MEBT** The MEBT section is designed to transport the beam from the RFQ exit and to adapt it for its injection into the superconducting radio-frequency (SRF) linac. It is composed by 2 beam scrappers (H and V), 2 bunchers cavities ($\beta$=0.073) at 175 MHz and 5 magnetic quadrupoles with a total length of 2.35 m [5]. Five quadrupoles are needed to match the beam size and divergence and to control its extent in the MEBT.

**SRF linac** The acceleration of high-intensity beams pushes for both large beam pipe aperture and conservative

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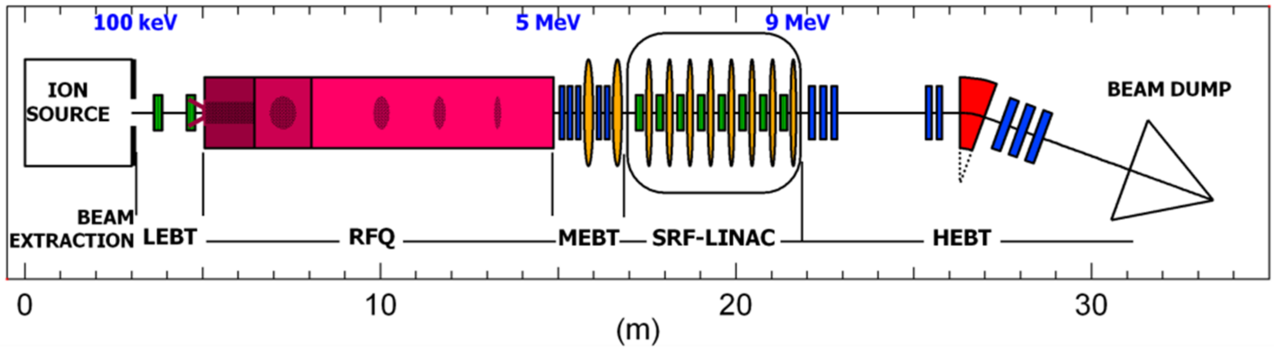


Figure 1: Scheme of the IFMIF-EVEDA prototype accelerator.

accelerating field in order to minimize beam losses and to reduce the R.F. power. So, a gradient of 4.5 MV/m and an aperture of 40 mm range were chosen for the superconducting Half-Wave Resonators (HWR). The transverse focusing is achieved with superconducting solenoids (maximum field ≈ 6T). Finally, the SC linac of the prototype accelerator needs one cryomodule containing 8 periods of 1 solenoid and 1 HWR cavity ($\beta$=0.094 at 175 MHz).

Although the IFMIF/EVEDA prototype accelerates the beam at 9 MeV it was necessary to study the whole IFMIF accelerator (up to 40 MeV) to guarantee that an optimal solution exists for the final IFMIF machine. The complete design and beam dynamic simulations of the IFMIF SC linac are detailed in reference [6].

**HEBT** The High Energy Beam Transport (HEBT) line drives the beam through a diagnostic plate toward a beam dump [7]. The 1.1 MW beam has to be expanded on the beam dump as symmetrically as possible to avoid local energy deposition higher than 300 W/cm2. The transport and the matching of the beam into the beam dump is done by two quadrupole triplets and one doublet. A 20° bending magnet has been inserted in the HEBT to reduce the back streamed neutron flux coming from the beam dump toward the linac; it can also be used as the spectrometer for the energy measurement. The total length of the HEBT is 9.64 m.

## BEAM DYNAMICS SIMULATIONS

### *Codes*

First, a modelling of the ECR source extraction system has been done with a commercial code: AXCEL-INP [8].

In order to achieve realistic beam transport simulations in the LEBT, it is necessary to take into account the space charge compensation of the beam on the residual gas. So, a particle-in-cell (PIC) code, called SOLMAXP [3], has been employed for this work.

Then, all the other section of the prototype accelerator have been simulated with the TraceWin code [9].

Except in the case of the HEBT quadrupoles and dipole (simulated by hard edge models), the fields maps of all the elements of the accelerator have been calculated by finite element methods. The following beam dynamics simulations have been performed with theses field maps.

### *Optimization*

In order to be as realistic as possible, the machine optimizations have been done using the beam diagnostics that will be available on the prototype accelerator. The LEBT solenoids have been optimized by maximizing the extracted beam intensity (i.e. the RFQ transmission). Concerning the MEBT and the SRF-Linac, an original procedure has been applied in order to minimize the excursion of particles at the beam edge. On the real machine, these sections will be tuned by minimizing the beam losses.

Finally, the HEBT was tuned in order to obtain the required beam size at the beam dump entrance while minimizing the beam extend through the line.

After optimization and study of each section separately, another important step is to perform start-to-end simulations to verify the global coherence of the accelerator.

### *Start-to-End Simulation Results*

In the present simulations, the starting point (z=0) is located 26 mm after the ion source plasma electrode.

The beam density through the accelerator, calculated with $10^7$ macro-particles is shown Figure 2. The beam halo is acceptable and for an energy higher than 5 MeV, local losses are everywhere lower than 0.5 W. The beam emittance values at the source extraction, at the end of the LEBT, after the RFQ and after the SRF linac are respectively: 0.06, 0.17, 0.22 and 0.36 $\pi$ mm.mrad.

## ERRORS STUDY

In order to study the effect of static errors along the linac, a Monte-Carlo simulation method has been carried out by tracking $1.1\times10^6$ particles through 110 different linacs, each with different random errors. The errors are uniformly distributed in the ranges presented in Table 1.

The correction scheme relies on steering coils (H and V) associated with downstream beam position monitors (H and V). In the LEBT, steerers are located inside the

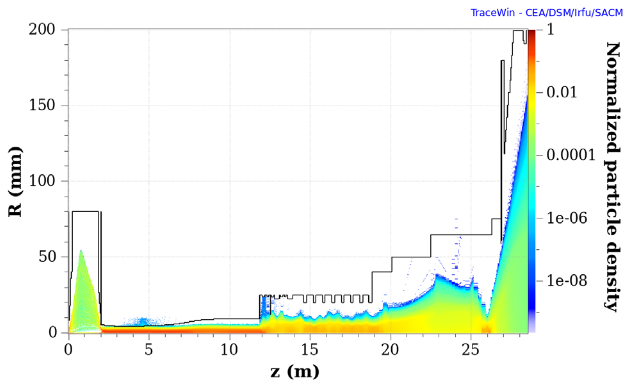


Figure 2: Beam density along the IFMIF/EVEDA prototype accelerator. Simulation performed with $10^7$ particles.

two solenoids. Then, 4 steerers and BPMs are located the MEBT, 8 in the SRF-linac (at each lattice) and 6 in the HEBT. This one-to-one correction scheme maintain the RMS beam orbit displacement below 0.5 mm while keeping the maximum deviation below 1 mm.

The cumulated particle density, calculated under these conditions, is shown Figure 3. Compared to the nominal case, more losses are observed, particularly at the beginning of the MEBT (scrappers position) and around z=24 m, where is located the bending magnet. The particles that are lost at these locations are extracted from the RFQ (with errors) with an energy or a phase significantly different from the adapted bunch. Nevertheless, in more than 99% of the cases, the beam losses remain less than 1 W/m (for a beam energy higher than 5 MeV).

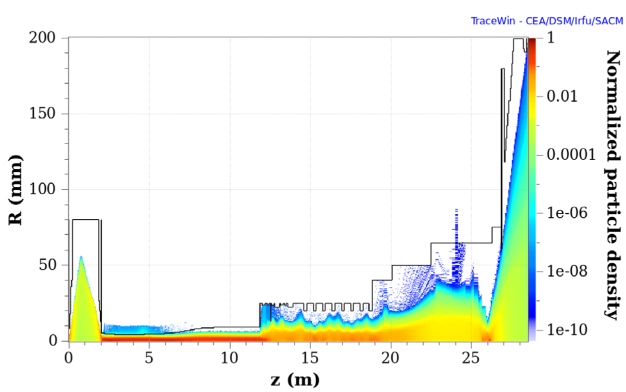


Figure 3: Cumulated densities for 150 runs (with errors), with $1.1\times10^6$particles each.

## CONCLUSION

Beam dynamics simulations show that the proposed design for the IFMIF/EVEDA prototype can accelerate safely a 125 mA $D^+$ continuous beam at 9 MeV. The injector is now under commissioning in Saclay and the other sections are under detailed mechanical studies or realization.

Table 1: Errors distribution.

| Error Type | Error range |
|---|---|
| **LEBT** | |
| Solenoids Misalignment [x,y] | $\pm$0.2 mm |
| Solenoids Tilt [$\varphi_x$,$\varphi_y$] | $\pm$3.5 mrad |
| **RFQ** | |
| RFQ Segment Misalignment [x,y] | $\pm$0.1 mm |
| RFQ Voltage (first harmonic shape) | $\pm$2 % |
| RFQ Mean Radius | $\pm$20 $\mu$m |
| RFQ Vane Radius | $\pm$20 $\mu$m |
| **MEBT** | |
| Quadrupoles Misalignment [x,y] | $\pm$0.2 mm |
| Quadrupoles Tilt [$\varphi_x$,$\varphi_y$] | $\pm$10 mrad |
| Buncher cavities Misalignment [x,y] | $\pm$1 mm |
| Buncher cavities Tilt [$\varphi_x$,$\varphi_y$] | $\pm$30 mrad |
| BPMs Measurement Accuracy | $\pm$0.1 mm |
| **SRF linac** | |
| Resonators Misalignment [x,y] | $\pm$2 mm |
| Resonators Tilt [$\varphi_x$,$\varphi_y$] | $\pm$20 mrad |
| Resonators Field amplitude | $\pm$1 % |
| Resonators Field phase | $\pm$1 deg |
| Solenoids Misalignment [x,y] | $\pm$1 mm |
| Solenoids Tilt [$\varphi_x$,$\varphi_y$] | $\pm$10 mrad |
| BPMs Measurement Accuracy | $\pm$0.25 mm |
| **HEBT** | |
| Quadrupoles Misalignment [x,y] | $\pm$0.2 mm |
| Quadrupoles Tilt [$\varphi_x$,$\varphi_y$] | $\pm$15 mrad |
| Quadrupoles Tilt [$\varphi_z$] | $\pm$3 mrad |
| Dipole Misalignment [x,y] | $\pm$1 mm |
| Dipole Tilt [$\varphi_x$,$\varphi_y$,$\varphi_z$] | $\pm$10 mrad |
| BPMs Measurement Accuracy | $\pm$0.1 mm |

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