# IFMIF-EVEDA ACCELERATORS: STRATEGIES AND CHOICES FOR OPTICS AND BEAM MEASUREMENTS

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## *Abstract*

The two IFMIF (International Fusion Materials Irradiation Facility) accelerators will each have to deliver 125mA, 5 MW of deuteron beam at 40 MeV. To validate the conceptual design, a prototype, consisting of one 9 MeV accelerator called EVEDA (Engineering Validation and Engineering Design Activity), is being constructed. Beam dynamics studies are entering the final phase for the whole EVEDA and for the accelerating part of IFMIF. The challenging points are the very high intensity and the very high power to be delivered. At energies up to 5 MeV, difficulties are to reach the requested intensity under a very strong space charge / compensation regime. Over 5 MeV, difficulties are to make sure that beam losses can be maintained well below $10^{-6}$ of the beam in order to meet hands-on maintenance requirements. This paper will report the strategies and choices adopted in the optics design and the beam measurement proposal.

## INTRODUCTION

The Fusion Broader Approach signed by Japan and Europe has launched the IFMIF project (International Fusion Materials Irradiation Facility) for studying future fusion materials which must resist to very intense neutron radiations ($10^{17}$ neutrons/s of 14 MeV). Such intense neutron fluxes are foreseen to be produced by two linear accelerators, each delivering continuously 125 mA of 40 MeV deuterons to a lithium target. The total power on target is thus 2x5 MW. These accelerators cumulate two very challenging issues: very high intensity and very high power. That is why in a first phase called EVEDA (Engineering Validation and Engineering Design Activity), a full scale prototype accelerating 125 mA deuterons up to 9 MeV, 1.1 MW is being studied and constructed in Europe, to be installed in Japan. For this last accelerator and the accelerating part of the final IFMIF accelerator, beam dynamics studies are entering the final phase. In the following, the updated layouts of these accelerators are presented, then the challenging issues are highlighted, and finally the adopted solutions are presented.

## LAYOUTS

The updated layouts of the IFMIF-EVEDA accelerators are given in Fig.1. Compared to the layouts presented in [1], the LEBT has been rearranged, the MEBT has been lengthened with more quadrupoles. We will see in the next paragraphs that this has induced consistent improvements allowing to fulfil the required specifications. This shows the importance of matching sections in the presence of strong space charge regime. One of the consequences is that optics elements within the cryomodules can now be distributed regularly. The other general features remain unchanged: injection at 100 keV, RFQ accelerating particles up to 5 MeV, SC-HWR Linac composed of 4 cryomodules accelerating respectively to 9, 14.5, 26 and 40 MeV. Only the first cryomodule will be used for EVEDA, where the design of the HEBT line driving the beam to a beam dump has been adopted. For IFMIF, the final HEBT line remains to be further studied.

## SPACE CHARGE ISSUE

Such very high power, very high intensity accelerators are submitted to a very strong space charge regime. Indeed, electric space charge forces often dominate over magnetic focusing forces. It can be seen by looking at the tune depression coefficient giving the ratio between adapted tunes without and with space charge. Fig. 2 shows the tune depression which is only 0.4-0.7 in the RFQ and 0.2-0.25 in the SC-HWR Linac, the two periodical structures along the EVEDA accelerator.

Another way to appreciate the space charge importance

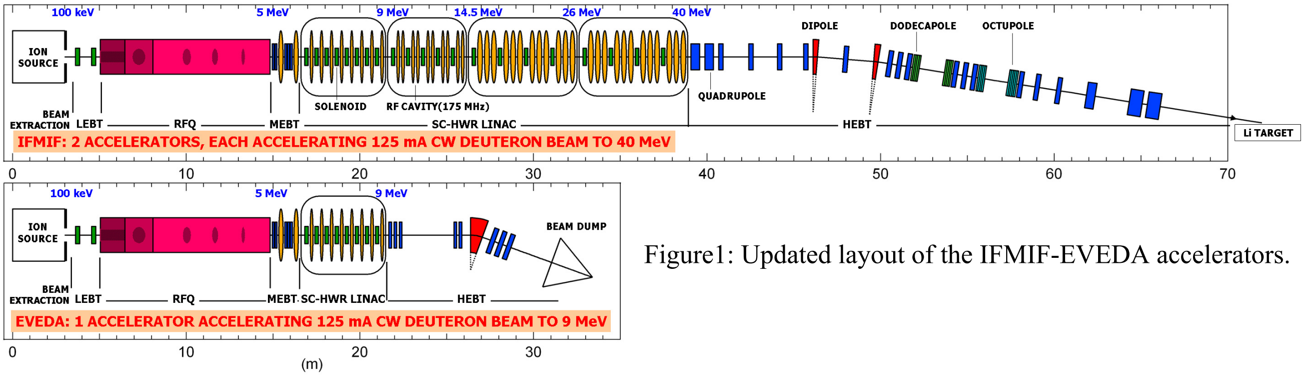

Figure1: Updated layout of the IFMIF-EVEDA accelerators.

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is to look at the two competing terms of the RMS envelope equation in the simplified case of a continuous elliptical beam [2]:

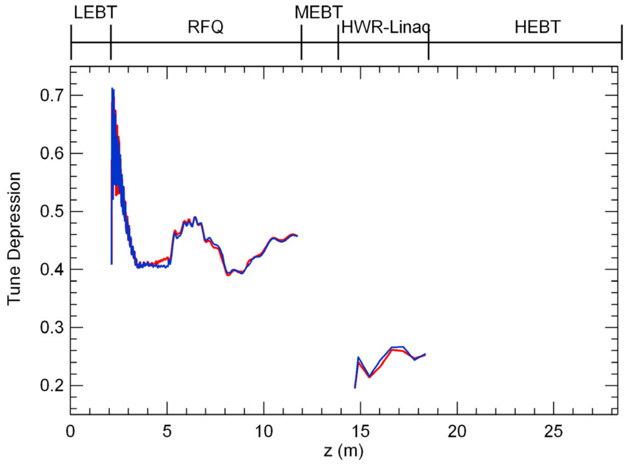

Figure 2: Tune depression in horizontal (red) and vertical (blue) planes.

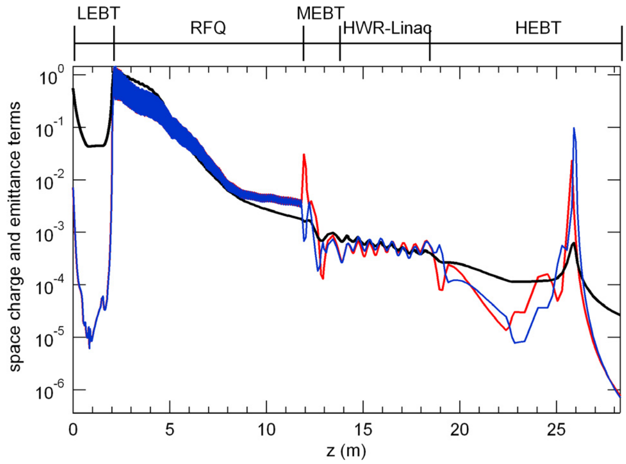

Figure 3: Space charge term (black) and emittance terms in horizontal (red) and vertical (blue) planes. See text for the definition of these terms.

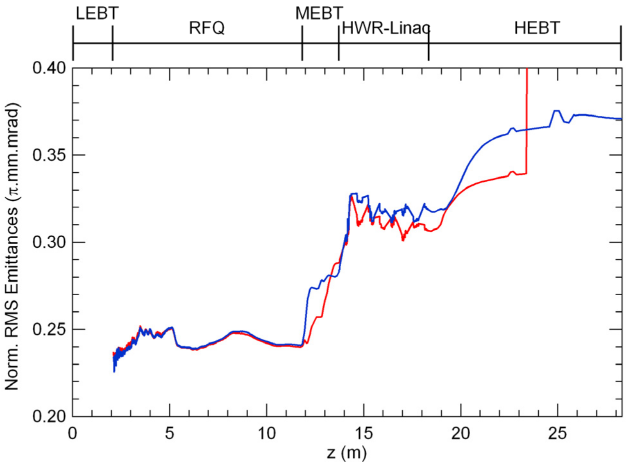

Figure 4: Normalised emittances in horizontal (red) and vertical (blue) planes.

- The space charge term $K/2(a_x+a_y)$, where $a_x$ and $a_y$ are the rms beam transverse sizes, K is the generalised perveance which is proportional to the beam current and inversely proportional to $\gamma^3$, $\gamma$ being the relativistic coefficient.
- The emittance terms $\varepsilon_x^2/\ a_x^3$, or $\varepsilon_y^2/\ a_y^3$ where $\varepsilon$ is the transverse emittance.

When the first term is larger, the beam is space charge dominated, and when the second terms are larger, the beam is emittance dominated.

Figure 3 shows that these terms globally decrease along the accelerator as energy increases, and are significantly larger at low energy as expected. When looking at Fig. 4 that gives in parallel the emittance evolution, one can notice that whenever the space charge term is larger than one of the two emittance terms, the transverse emittances will grow up to inverse this trend. This happens at every section transition, except for the HEBT where effects of large beam size variations have prevailed. That means that at these structure entrances, space charge forces are so strong over magnetic forces that they induce emittance growth, and that beam dynamics optimisations must be particularly careful there. Another consequence is the need to reduce the distance between magnetic elements in order to constantly maintain focusing forces, leading to a high structure compactness which prevents the installation of equipments and diagnostics.

We have therefore to face several critical issues. On the one hand, strong space charge implies delicate optimisations, high sensitive tunings, and strong non linear calculations. Aside the difficulties of these tasks, all that strongly suggests that theoretical optics found could be noticeably different from the right settings for the real machine. Machine tunings based on beam diagnostics seem to be crucial. But on the other hand, the high compactness due to strong space charge also consequently limits space for beam measurements installation. The problem is then to perform beam dynamics optimisations in the way that could be reproduced on the real machine, according to the few possible beam measurements, or to propose the appropriate beam measurements likely to allow tuning the accelerator similarly to theoretical optimisations.

These principles are illustrated in more concrete terms in the two following paragraphs, for energies lower than 5 MeV, then larger than 5 MeV, where additional issues will be evoked, due respectively to the high beam current then the high beam power.

## ISSUES AND CHOICES FOR E < 5 MEV

This low energy part concerns the source extraction, the LEBT and the RFQ, where losses are relatively important, of the order of some % of the beam. The main challenging point is thus to minimise these losses in order to reach the required current of 125 mA. First of all, the extraction must be designed to extract a high enough current at 100 keV from the source [3] and the RFQ must be optimised to drastically reduce losses while bunching and accelerating the beam to 5 MeV [4]. For that, on the first side, the higher the current, the larger the extraction hole must be, provoking a larger beam size, and due to the very strong space charge, the beam divergence is also larger. On the other side at the RFQ, the stronger the space charge term, the more the emittance term must balance, and the smaller must be the beam size.

Between the two, the LEBT task is expected to be hard, all the more since strong space charge forces efficiently prevent from focusing the beam [5]. Fortunately at this energy, electrons coming from the residual gas partly compensate the $D^+$ space charge. But this effect still has to be calculated precisely because seen the importance of the involved forces, a small advantage of one of the competitors will lead to drastically different results. This is done by a home made code [6] which calculates a potential map taking into account the dynamics of electrons and ions.

Usual tricks employed to enhance the compensation are simulated: injection of a heavy residual gas to increase the electron density, installation of an electron repeller to avoid electron leaking toward the RFQ. Although the best injection into the RFQ leading to minimum losses consists in obtaining the matched emittance and Twiss parameters at the RFQ entrance, we have chosen instead to optimise the current transmission through the RFQ. Because this kind of optimisation can be performed with simply a current measurement at the RFQ output, while there is no room at the RFQ entrance for emittance or Twiss parameter measurements. The obtaining of these matched parameters is verified a posteriori to make sure that the best injection is reached. The final result is a very compact structure of 2 solenoids and 1 electron repeller, at the limit of the technical feasibility (see [5]).

## ISSUES AND CHOICES FOR E > 5 MEV

Over the energy of 5 MeV, material activations become significant. But the hands-on maintenance is required for the IFMIF accelerators, implying that losses must be maintained well less than 1W/m. Considering that for a CW current of 125 mA, the beam power is 0.6, 1.1, 5 MW at respectively 5, 9, 40 MeV, i.e. at the RFQ, 1st and 4th cryomodule exits, the losses must be maintained in this second part of the accelerator well less then $10^{-6}$ of the beam. The main challenging point is thus to prevent micro-losses in order to meet the hands-on maintenance constraint.

For that, the very external limit of the beam must be carefully scrutinized. But the space charge regime is so strong that the halo is significant and irregular, so that there is no close relation between the RMS beam size and the external beam limit. A regular RMS envelope for example does not mean a regular external beam size. Thus envelope calculations are not meaningful, multiparticle simulations are mandatory, with at least $10^6$ macro-particles, and ultimately 10 or 100 times more, which means that beam dynamics optimisations are very time consuming. Optimisation procedures have been established aiming at minimising the external beam limit in the HWR-Linac. Here also, the role of the transition section, the MEBT, is crucial in correctly matching the beam between the RFQ and the HWR-Linac. A satisfying configuration of the MEBT and the Linac is finally obtained, with a total beam occupancy well regular and smooth, even in the presence of very conservative structure errors [7].

But these theoretical results in the presence of such non-linear forces and at these degrees of precision have probably little chance to be totally realistic. These optimisation procedures only make sense if they can be performed in the same way on the real machine. That is why we propose to have devices installed the closest to the focusing solenoid chambers, capable of detecting the micro-losses that will mainly occur there. Tunings aiming at minimising these micro-losses are equivalent to the theoretical procedures used above.

## CONCLUSION

The IFMIF accelerator design has to face important challenges related to its very high intensity at low energy and to its very high power at higher energy. The unusually strong space charge regime imposes specific difficulties that have been overcome, at least theoretically. We have deliberately chosen optimisation procedures and corresponding beam measurements so that they can be reproduced on the real machine.

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