# DYNAMICS OF THE IFMIF VERY HIGH-INTENSITY BEAM

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## *Abstract*

For the purpose of material studies for future nuclear fusion reactors, the IFMIF deuteron beams present a simultaneous combination of unprecedentedly high intensity (2x125 mA CW), power (2 x5 MW) and space charge. Special considerations and new concepts have been developed in order to overcome these challenges. The global strategy for beam dynamics design in the 40 MeV IFMIF accelerators is presented, stressing on the control of micro-losses, and the possibility of on-line fine tuning. The obtained results are then analysed in terms of beam halo and emittance growth.

## INTRODUCTION

Set in the Fusion Broader Approach agreement between Europe and Japan, IFMIF (International Fusion Materials Irradiation Facility) will be the world's most intense neutron source dedicated to study materials covering internal walls of the future fusion reactors. It will include two identical linear accelerators accelerating 2x125 mA of CW deuteron beams to the energy of 40 MeV, resulting in a total beam power of 2x5 MW [1]. In a first phase currently in progress, a full scale prototype accelerator up to 9 MeV – 1.1 MW is being studied and constructed in Europe, to be installed in Japan.

In this paper, the global parameters of IFMIF are compared to those of other high-power accelerators. This reveals the simultaneous combination of unprecedented characteristics to be achieved. The induced challenges in beam dynamics design are pointed out, and the strategies to overcome them are outlined. Finally, the obtained results are analysed in terms of beam halo and emittance growth, and possible ways for improvement discussed.

## GLOBAL PARAMETERS

Due to the very high CW beam intensity required, the $D^+$ beam power becomes significant from the earliest acceleration stages where the beam energy is still low. The average power is 18 kW at the ion source extraction, 0.6 MW at the RFQ exit, 1.1 MW after the first SRF-Linac's cryomodule, and finally 5 MW after the 4 cryomodules. This corresponds respectively to the energies of 100 keV, 5, 9 and 40 MeV, where space-charge effects are still dominant.

This situation is unique when compared to worldwide linear accelerators in operation or planned. Fig.1 shows the average beam power as a function of beam energy for the most powerful accelerators, while Fig. 2 gives for the same accelerators the generalised perveance K, relevant for judging space-charge forces. In addition to IFMIF are carried forward the proton linacs ESS (Lund, Sweden), Linac4 (CERN, Switzerland), JPARC (Tokai, Japan), SNS (ORNL, USA), ProjectX (FNL, USA).

We can see that for a given energy, IFMIF-EVEDA has the highest beam power and the highest space-charge regime. When considering power absolute values, IFMIF can be ranked second. But unlike any other accelerator, even for the most powerful, when the beam power becomes critical from the point of view of losses, let us say for example from 1 MW, IFMIF has by far the highest space-charge importance. As indicated on Fig.1, 2, IFMIF perveance K is higher by at least two or three orders of magnitude. It means that when the beam power becomes so high that it should be very precisely controlled, because even tiny losses as low as $10^{-6}$ of the beam must be avoided, the beam behaviour is still very difficult to control due to the importance of space-charge effects.

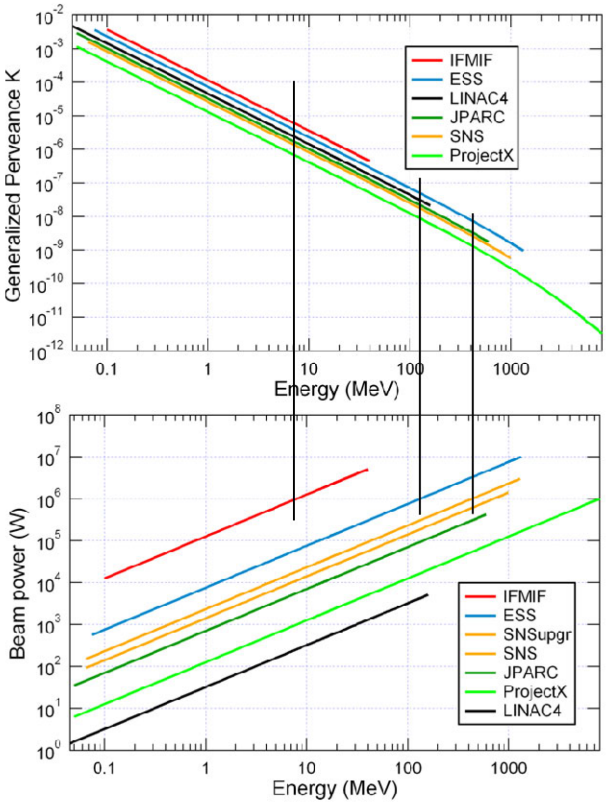

Figure 1 and 2: Generalise perveance K and beam power as functions of energy 2.

As the space-charge effect decreases with energy, particles must be accelerated by the RFQ to high enough energy before being accelerated more efficiently by separated cavities and focusing elements. That is why in IFMIF, the RFQ must accelerate particles to the energy as high as 5 MeV, and is the longest RFQ ever constructed.

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The space-charge effect can also be seen by the tune depression that indicates the focusing deficit experienced by the beam within the periodical structures. Fig. 3 shows that this tune depression in the transverse plane is very low, between 0.4 and 0.6 in the RFQ, and between only 0.2 and 0.6 along the four cryomodules of the SRF-Linac.

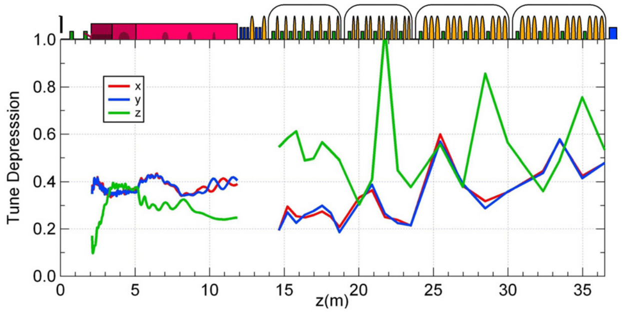

Figure 3: Tune depression in the RFQ and the SRF-Linac

## GENERAL STRATEGY

The unprecedented high beam intensity induces the simultaneous combination of two other unprecedented challenges: high beam power and high space charge. That leads to numerous issues, often conflicting, which ask for a general strategy that can be summarised as follows (see details in [2] and references therein):

- For E < 5 MeV, i.e. for the ion source Extraction, the LEBT and the RFQ, beam losses are still significant (~ % of the beam), the global aim is to be able to obtain the required 125 mA. At these low energies, the conflicting issue comes from the emittance that can explode due to the strong space charge, but must be low enough to be injected into the RFQ. All the efforts must therefore be dedicated to work around the space-charge effects: enlarge extraction aperture, shorten as much as possible source extraction and RFQ injection lengths where there is poor space-charge compensation, enhance this compensation in the LEBT by injecting heavy ion gas and installing electron repellers at entrance and exit, increase extraction field and RFQ focusing field to the limit of electric breakdown. A crucial point too is to calculate precisely the resulting space-charge potential map in the LEBT taking into account all the above ingredients.

- For E > 5 MeV, i.e. for the MEBT, the SRF- Linac and the HEBT, losses can cause harmful material activation and must be maintained much less than 1W/m. As simultaneously the beam power is in the MW class, the global aim is to maintain micro-losses much less than $10^{-6}$ of the beam. This very limiting constraint is made furthermore difficult by the presence of strong space-charge forces, so that every tuning is distribution dependent. As a result, considerations of RMS beam characteristics are no more enough, multiparticle simulations with more than $10^6$ macroparticles are mandatory, which are very time consuming. An uncommon procedure has been adopted then: beam dynamics optimisations aim to optimise the extent of the very external beam border, rather than emittance or beta values. We can speak about "halo matching" rather than "envelope matching".

Another concern for very high-intensity accelerators is the need of possibly frequent in-situ fine tunings, because they strongly depend on the initial beam distribution characteristics. That is conflicting with the lack of diagnostics imposed by the compactness necessary for reducing space-charge effects. For IFMIF, we have adopted the rule to only carry out beam dynamics optimisations that can be later applied online. For the LEBT, the focalisation setting has been established by searching to maximise the RFQ transition, which can be reproduced online by maximising the beam current at RFQ exit. The online tuning is furthermore crucial at higher energies because the needed precision of $10^{-6}$ or even better is hard to ensure with theoretical calculations or machine reproducibility. The "halo matching" mentioned above can be applied in situ at the condition that enough microloss detectors are available along the SRF-Linac cryomodules, close enough to the beam pipe so that the loss distribution can be known with good enough spatial resolution. For that, neutron detectors by Chemical Vapour Deposition diamond is being evaluated in CEA-Saclay [3]. It is important to stress that these detectors, as well as the beam current monitor at RFQ exit should be used daily for fine tuning, and should be considered as "essential" as the classical beam position monitors for example.

## RESULTS AND DISCUSSIONS

Separate beam dynamics optimisations for individual sections allow to find out the tunings where there is no loss in the LEBT, no microloss after the RFQ, while losses in the RFQ are mainly limited to low energy particles not correctly bunched nor accelerated. With $10^6$ macroparticles, the beam very external border is regular, far enough from the pipe wall. Start-to-end simulations without and with errors have been performed for the prototype accelerator [4].

Efforts have also been devoted to understand the physics of such high-intensity beams. It has been observed for example that once the external beam limit is perfectly minimised and regular along the MEBT and SRF-Linac, the emittance can sometimes literally blow up. A compromise is often necessary between halo and emittance minimisations. After careful examination, the emittance growths can be attributed to different mechanisms.

At the MEBT and the first cryomodule entrance, (see Fig. 4, top) whenever the space-charge term is larger than the emittance term (resp. SC and $E_x$, $E_y$, see [2] for the definitions), meaning that the beam is space charge dominant, the emittance grows in the corresponding plane. We can also see at each time that the growing distance is about 0.90 m, which corresponds to the average length covered by the beam during a quarter of the plasma oscillating time. This is typical of the classical mechanism of charge redistribution when the beam leaves a strong focusing environment for a less strong one. Here, it occurs at the transition from the RFQ to the MEBT, then at the long transition without transverse focusing between the last MEBT quadrupole and the first cryomodule solenoid.

This mechanism can also be clearly seen in the x-y beam density (Fig. 4, bottom) when looking at the importance of the maximum density (red area), or the projections in x and y (green line). When the beam has a large tail in a given plane, typical of a space charge dominated beam, that leads to emittance growth. When the beam has a much more compact profile, due to rapid charge redistribution providing shielding to the external focusing field, typical of an emittance dominated beam, the emittance growth is stopped.

The emittance growths downstream do not present such behaviours. Coupling mechanisms should rather be invoked. Fig. 5 shows that whenever the x and z tune numbers are close to each other, there is transfer of horizontal emittance to vertical one. In [5], this resonance mechanism is studied in more details, and propositions for improvement are made.

## CONCLUSION

In the study of very high-intensity IFMIF accelerators, new concepts have emerged like microlosses, halo matching, essential diagnostics. Every beam dynamics optimisation are carried out so that they can be reproduced online, in order to enhance the chance to obtain real performances as theoretically expected. IFMIF, with its record beam intensity, beam power, space-charge regime and RFQ length, provides a tremendous opportunity for studying High Intensity Beam Physics in its most extreme limit.

## REFERENCES

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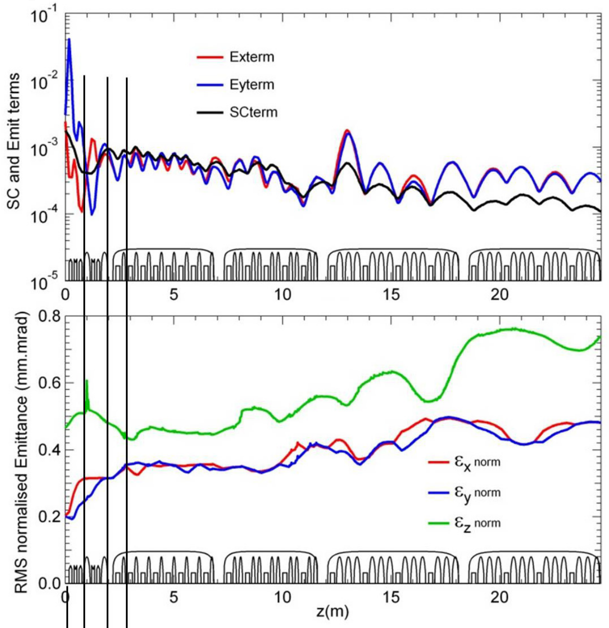

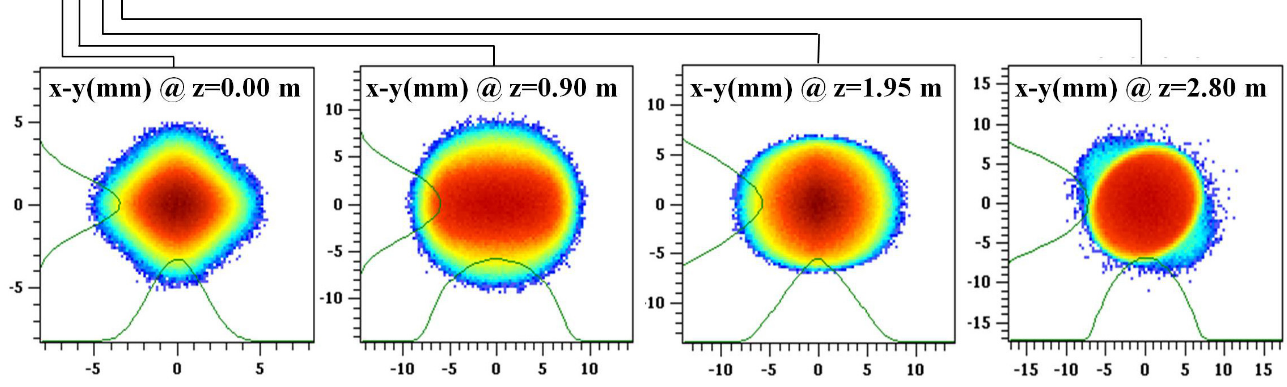

Figure 4: Variation of $E_{x,y}$ and *SC* terms along the MEBT and the four cryomodules of the SRF-Linac (Top). The corresponding variation of emittance is also given (Centre). The beam presents remarkable behaviours (see text) at the positions z = 0.90, 1.95, 2.80 m. Beam density in the x-y space, and its projection in x and y (green line), are given for z = 0 and those positions. Red is the densest and blue the less dense (Bottom).

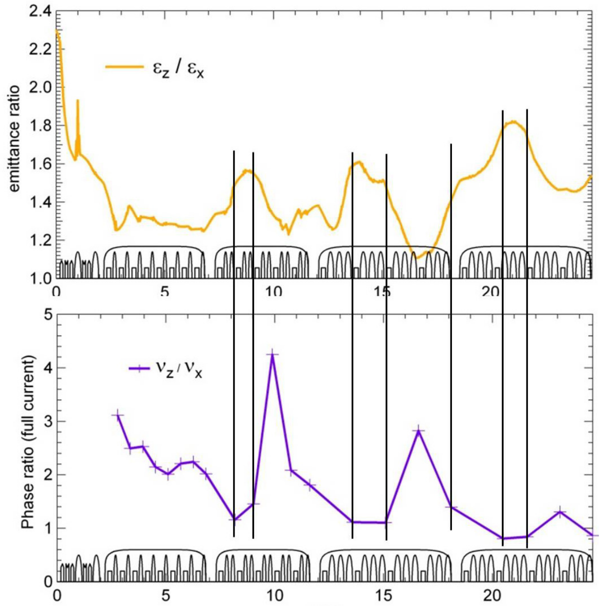

Figure 5: Variation of emittance ratio and tune ratio along the MEBT and the 4 cryomodules of the SRF-Linac