THE IFMIF-EVEDA CHALLENGES AND THEIR TREATMENT

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Abstract

One major system of the IFMIF project (International Fusion Materials Irradiation Facility) is its two accelerators producing the neutron flux by accelerating Deuteron particles up to 40 MeV against a Lithium target. In a first phase called EVEDA (Engineering Validation and Engineering Design Activity), a full scale prototype accelerating particles up to 9 MeV is being studied and constructed in Europe, to be installed in Japan.

Two unprecedented performances are required for the IFMIF-EVEDA accelerators: the very high power of 5 MW and very high intensity of 125 mA CW. That leads to numerous unprecedented challenges: harmful losses even for those as low as 10^{-6} of the beam, non-linear dynamics induced by very strong space charge forces, difficulties for equipment and diagnostic implementations in the high compact structure, need of specific tuning strategies in this context.

These issues are highlighted in this article, and the ways they are addressed are detailed.

INTRODUCTION

The IFMIF project (International Fusion Materials Irradiation Facility) is set in the context of the Fusion Broader Approach signed between Japan and Europe, aiming at studying materials which must resist to very intense neutron radiations in future fusion reactors. One objective is to construct the world most intense neutron source capable of producing 10^{17} neutrons/s at 14 MeV. A major system of this project is its two accelerators producing the neutron flux by accelerating Deuteron particles up to 40 MeV against a Lithium target. In a first phase called EVEDA (Engineering Validation and Engineering Design Activity), a full scale prototype accelerating particles up to 9 MeV is being studied and constructed in Europe, to be installed in Japan.

To produce the neutron flux equivalent to that of future fusion reactors, the required Deuteron intensity in the accelerators is very high, 125 mA CW, which, combined with the required final energy, makes IFMIF-EVEDA the accelerators of the megawatt class at relatively low energy. This article points out how the simultaneous combination of these two very high intensity and very high power induces unprecedented challenges, but also provides exciting opportunity for HIB studies.

IFMIF MAIN FEATURES

The general layouts of the IFMIF-EVEDA accelerators are displayed in Fig. 1. In each of the two IFMIF accelerators, D^+ particles are first accelerated by the source extraction system, then by the long RFQ and finally the SRF-Linac composed of four cryomodules. The LEBT and MEBT have to focus and match the beam in the 6D phase space from an accelerating structure to another. The HEBT drives the beam to the Lithium target where, with the help of multipolar magnetic elements, the transverse beam density must be made flat in a well defined rectangle shape. The EVEDA accelerator is composed of exactly the same sections up to the first cryomodule, and a simplified HEBT which must properly expands the beam toward the Beam Dump.

In Fig. 1 are also indicated beam energies together with beam powers along the accelerators. Due to the very high beam intensity of 125 mA, the beam power is already 625 kW at the RFQ exit and 1.1 MW after the first cryomodule, to reach 5 MW after the 4th cryomodule. And that at relatively low energies of 5, 9 and 40 MeV, where space charge effects are still dominant.

That situation is unique when compared to worldwide linear accelerators in operation or planned. Figure 2 shows the beam power as a function of beam energy for the most powerful accelerators, while Fig. 3 gives for the same accelerators the generalised perveance K, relevant for judging space-charge forces. We can see that for a given energy, IFMIF-EVEDA has the highest beam power and the highest space charge regime. When considering beam power absolute values, IFMIF-EVEDA can be ranked second. But unlike any other accelerator, even for

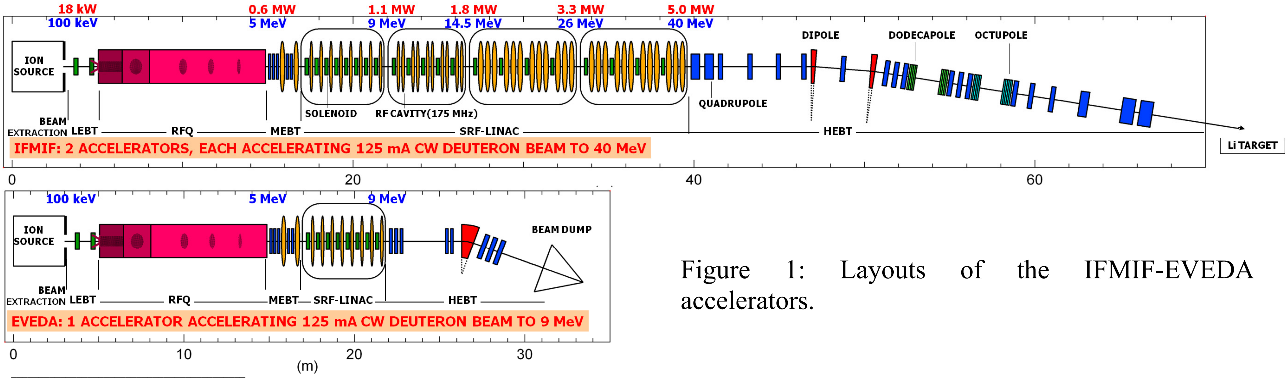

Figure 1: Layouts of the IFMIF-EVEDA accelerators.

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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-EVEDA has by far the highest space charge importance. That 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.

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

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. Figure 4 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 0.4 along the 4th cryomodules of the SRF-Linac.

CHALLENGES AND TREATMENT

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 that can be summarised as follows:

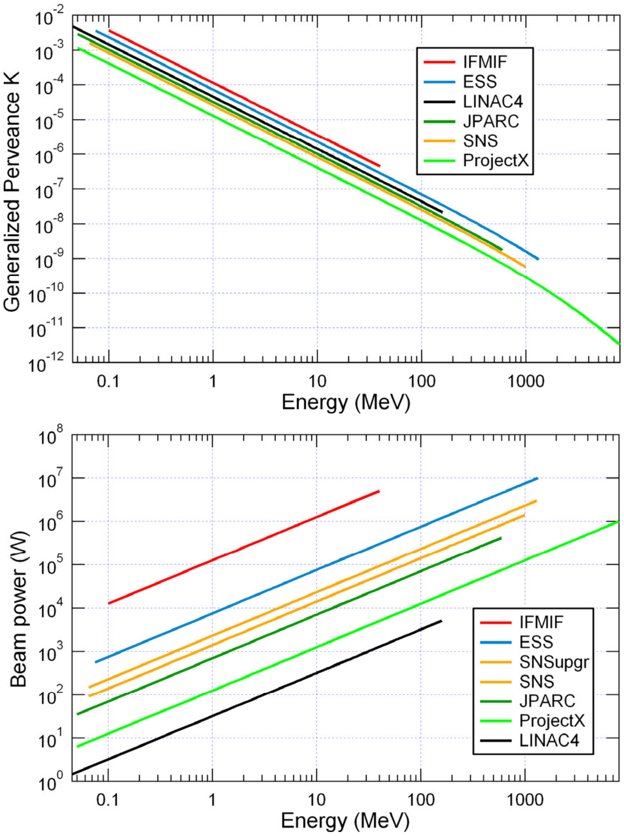
- For E < 5 MeV, i.e. for the Source Extraction, the LEBT and the RFQ, beam losses are still significant (~ % of the beam), the issue is to be able to obtain the required 125 mA.

- For E > 5 MeV, i.e. for the MEBT, the SRF- Linac and the HEBT, losses induce harmful material activation and must be maintained << 1W/m. As simultaneously the beam power is in the MW class, the issue is to avoid microlosses << 10^{-6} of the beam.

Those issues, of which a few are conflicting, are furthermore detailed in the following, and the ways foreseen to overcome them presented.

Source Extraction

In anticipation of possible important losses in the LEBT-RFQ sections, and of the undesirable species extracted, a total extracted current as high as 175 mA is required. Besides, the beam emittance must also be low enough, so that after passing through the LEBT, it must not exceed 0.30 πmm.mrad at the RFQ entrance, in order to stay in the range of the RFQ optimum transmission.



Figures 2 and 3: Generalized Perveance K and Beam Power as functions of energy.

High current and low emittance are generally conflicting requirements. A higher current means higher space charge forces, contributing strongly to increase the emittance. In order to limit the extracted emittance, it is then necessary to work around effects of space charge forces. The adopted solutions [1] are to enlarge as much as possible the extraction aperture, to increase the accelerating field but keeping it below 100 kV/cm to limit spark risks, and to shorten the extraction length, where there is no possible neutralisation, by reducing the number of extraction electrodes to four.

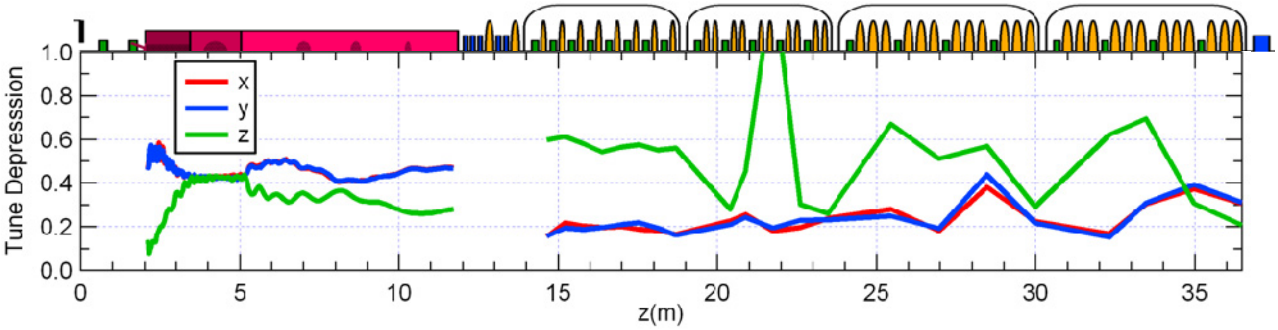


Figure 4: Tune depression in the RFQ and the SRF-Linac

LEBT

The high current implies an important space charge effect, but at this low energy, ionisation cross-section is still large, the D^+ beam will itself sufficiently ionise the residual gas so that released electrons can efficiently compensate its own charge. Those competing effects, the space charge and its neutralisation, must be finely studied because the resulting effect along with its detailed location, will significantly affect the beam dynamics.

The SolMaxP code [2] has been used to calculate the resulting radial and longitudinal space-charge potential profile, regarding collision and ionisation mechanisms. With that, it has been demonstrated that the targets are not reached, if all the usual tricks are not employed to enhance the space charge compensation, like additional residual heavy gas (Krypton), electron repellers at extraction exit and RFQ entrance. The space charge potential map must then correctly take into account all those equipments as well as the focusing fields.

The optimisation of the latter aims at obtaining the highest beam transmission at the RFQ exit [3]. It is then verified a posterior that the Twiss parameters at the RFQ entrance are within the theoretical optimum range. That optimisation method was deliberately chosen in order to ensure that it can be reproduced on-line by only looking at the RFQ output current. Indeed, the high compactness dictated by the high space charge regime does not allow implementing more appropriate beam measurements. Furthermore, we have to keep in mind that the real beam output from the ion source could be significantly different from the theoretical one studied here, and that can also change with time, making on-line fine tuning mandatory.

RFQ

First of all, the high space charge regime obliges to accelerate while focusing particles to energy as high as 5 MeV. That means a longer RFQ and in addition a higher beam power, which is furthermore in an energy range where particle losses begin to induce harmful material activation. Then the bunching task becomes particularly delicate. In addition to have to face strong longitudinal space charge, the bunching process must limit as much as possible losses, spread losses on a biggest length in order to lower lost power density, while limiting them to the lower energy part. All that will also induce a longer Gentle Buncher section.

To overcome those difficulties, the RFQ optimisation consists in limiting as far as possible the total length, the losses in high energy part, the maximum surface field, the power consumption [4]. The focusing strength B_0 is chosen to be weak at entrance [5] in order to ease beam injection from the LEBT. Then it grows very fast in order to compensate high space charge forces and to keep the beam in linear force fields. With the same purpose, the design has adopted a "2TERM" geometry type combined with a strong electric focusing to produce extremely linear transverse fields around the beam. At the end of the Gentle Buncher, about the first third of the RFQ, an abrupt decrease of the aperture is intended to loose out-of-energy particles that are not bunched, in order to prevent them from being accelerated to higher energies. On the contrary, in the last third of the RFQ all parameters are let unchanged to avoid losses at energies approaching 5 MeV.

MEBT and SRF-Linac

The MEBT basic mission would be to transport the 5 MeV beam output from the RFQ and match it for injection into the SRF-Linac. That would mean that the SRF-Linac is a channel with its well defined matched beam in terms of RMS values, to which the input beam has just to be adjusted. Then the tuning of the MEBT and the SRF-Linac are decoupled. The problem is in fact much more delicate.

It appears that RMS quantities are not enough relevant [6], so that the multiparticle aspect must always be considered. Indeed, on the one hand, as the beam is space-charge dominated, and as there are long transitions without focusing in the SRF-Linac, any change in the beam distribution will impact on the net forces acting on the particles, and change their trajectory. On the other hand, as the energy is over 5 MeV, loss-induced material activation becomes harmful and the hands-on maintenance imposes losses to be well less than 1 W/m, which means 10^{-6} of the beam. We call them micro-losses.

All that point out that every simulation or optimisation must be performed for the MEBT and SRF-Linac together, in multiparticle mode, with at least 10^6 macroparticles, and each macroparticle at the very external beam tail must be carefully examined. That makes optimisations very time consuming.

Furthermore, theoretical calculations have little chance to describe the reality at this degree of precision, as well as it is hard to assure this degree of machine reproducibility. Thus frequent fine tuning is expected in real life, and the numerical optimisation procedure employed to avoid micro-losses must have an on-line equivalent procedure, with the appropriate diagnostics.

To solve this very challenging objective, an uncommon procedure has been adopted. A first optimisation is done to match the beam in RMS envelope, then from this starting point, an extra optimisation is carried out, aiming at minimising the extent of macroparticles at the external border of the beam. After this step which is time consuming due to many multiparticle transports, the result is very satisfying: there are no micro-losses, and the beam very external border is regular, enough far from the beam pipe wall. On the contrary, the beam RMS envelope becomes less regular. Everything happens as if a “halo matching” has been performed, instead of the classical “beam matching”.

That second optimisation can be used for on-line tunings, at the condition that micro-loss detectors can be implemented along the cryomodules, the closest possible to the beam pipe. The device capable of measuring a fraction of W loss is under discussion and not yet decided. It could measure either the deposited heat, or deposited current, or the induced neutrons and/or gammas.

HEBT

The EVEDA HEBT has a double mission [7]:

- Drive the beam and carefully expand it as symmetrically as possible at the Beam Dump so that the power density does not exceed 300 W/cm^2.
- Adapt the beam size for beam measurements, in particular for a diagnostic plate of more than 2 m long.

Note that the HEBT is the only section of the accelerator where all the measurements for beam characterisation are planned, which will help to check the validity of beam dynamics calculations under very strong space charge regime, an important step in the validation mission of EVEDA for the final IFMIF.

Seen the beam power, the issues here are to avoid micro-losses while limiting beam power densities at the Beam Dump, as well for nominal conditions as for the different tunings necessary for example for the emittance measurement by the quadrupole variation method. Many multiparticle simulations are mandatory, and all of them are not yet finished up to now.

The IFMIF HEBT has for mission to drive the beam toward the liquid Lithium target where, with the help of multipolar magnetic elements, it must be expanded in a ‘perfect’ rectangular shape of 5 x 20 cm, with a ‘perfectly’ uniform density. For the moment, only preliminary studies have been performed to prove the feasibility of the present HEBT configuration. But, seen the beam power of 2x5 MW, any small deviation from the ideal situation could consistently bias results of physics experiments or strongly damage equipments. Many more studies remain to be performed in order to estimate the reliability, the reproducibility and the stability of such a beam, as well as to limit the backward radiation from the target.

A “LABORATORY” FOR HIB STUDIES

The above described procedures allow finding out immediate beam dynamics solutions for the challenging IFMIF objectives, but much remains to do in order to well understand the physics of its very high intensity beam. It has been observed for example that once the external beam limit is perfectly minimised and regular along the SRF-Linac, the emittance can sometimes literally blow up. A compromise is often necessary between halo and emittance minimisations.

In [8], the reason of emittance growth has been sought by looking at the two competing terms of the envelope equations, the emittance term and the space charge term [9], which are given by

$$E_{x,y} = \frac{\varepsilon_{x,y}^2}{\sigma_{x,y}^3} \qquad (1)$$

$$SC = \frac{K}{2(\sigma_x + \sigma_y)} \qquad (2)$$

where $\varepsilon_{x,y}$ is the horizontal, vertical non-normalised emittance, $\sigma_{x,y}$ is the corresponding RMS beam size and K the generalized perveance. But this SC term, although valid for all types of distribution with elliptical symmetry, is rather valid for a continuous beam. In case of bunched beams, it is more correct to use instead

$$SC_3 = \frac{3K_3(1-f)}{(\sigma_x + \sigma_y)\sigma_z} \qquad (3)$$

where f is a form factor given by [10], and K_3 the 3-D space-charge parameter [9]. The only problem is that K_3 depends on a coefficient that varies with the particle distribution type. To choose the appropriate coefficient corresponding to our case, we can remark that when the longitudinal dimension is much greater than the transversal ones, $f \to 0$ and $SC_3 = SC$. As at one location very close to the RFQ exit, the beam is in such a condition ($f \lesssim 0.1$), we can find out the coefficient in the K_3 expression by equalising SC_3 and SC there.

The comparative evolution of SC$_3$ and E$_{x,y}$ is given in Fig. 5 along the MEBT and the four cryomodules of the SRF-Linac. The corresponding emittance growth is also given in the same figure.

After careful examination, the first emittance growths till the SRF-Linac entrance look understandable. Whenever the SC term is larger than the E$_x$ or E$_y$ term, meaning that the beam is space charge dominant, the emittance grows in the corresponding plane. Right at the RFQ exit (z = 0 m), $SC_3 > E_x$, the horizontal emittance immediately grows, up to z~0.9 m where the situation is inversed. In the vertical plane, E_y is larger than SC_3 at z = 0 m, then progressively decreases below at z~0.9 m, that is why the vertical emittance grows after and slower than the horizontal one and continues to grow after 0.9 m, up to about z=1.90 m. But then, close to the MEBT end at z~1.95 m where the beam begins to get cylindrically symmetric, it is again in the condition where the horizontal and vertical emittances grow together up to z~2.80 m, where an equilibrium is reached.

We can 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, the first time is the transition from the RFQ to the MEBT, and the second one is due to 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. 5, bottom) when looking at the importance of the maximum density (red area), or the projections in x and y (green line). For x and y, at z = 0 m, as well as for only x, at z = 1.95 m, the beam has a large tail, typical of a space charge dominated beam, leading to emittance growth. On the contrary, for x and in a less extent for y, at z = 0.9 m, then for x and y, at z = 2.8m, the beam has a much more compact profile, due to rapid charge redistribution to provide shielding to the external focusing field. This is typical of an emittance dominated beam, stopping the emittance growth process.

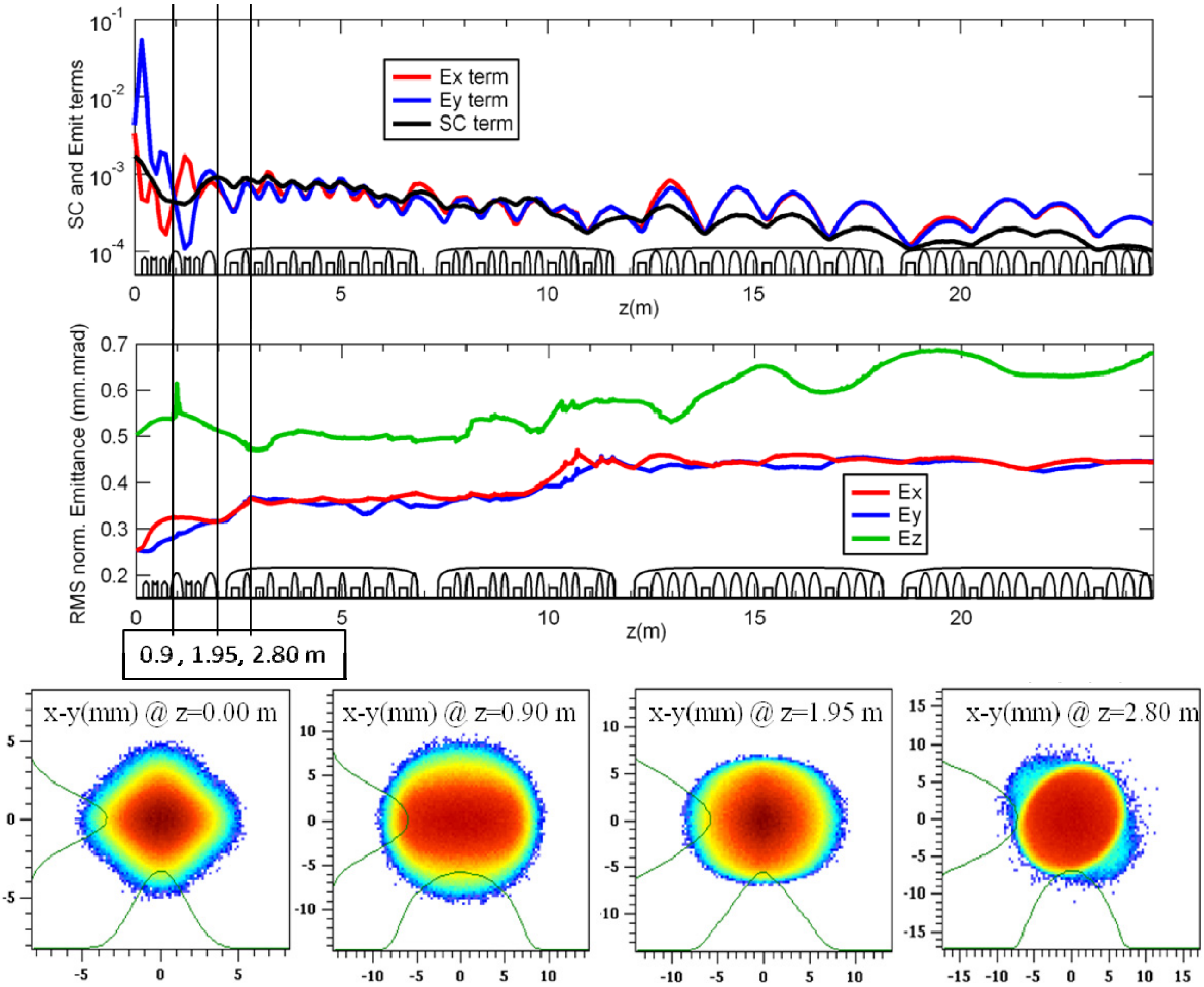


Figure 5: Variation of $E_{x,y}$ and SC_3 terms along the MEBT and the four cryomodules of the SRF-Linac (Top). The corresponding variation of emittance is also given (Centre). The beam presents remarkable behaviors (see text) at the positions z = 0.90, 1.95, 2.80 m. Beam density in the x-y space, and its projection in x and y(green line), are given for z = 0 and those positions. Red is the most dense and blue the less dense (Bottom).

However, the emittance growths in the next sections as well as in longitudinal cannot be explained by that mechanism. Resonance and/or coupling mechanisms should rather be invoked. Additional exciting studies should be carried out in order to better understand the processes leading to emittance and/or halo growths. From this point of view, we are in the presence of a true "laboratory" for High Intensity Beam studies.

CONCLUSION

The IFMIF-EVEDA record intensity, which induces simultaneously the highest beam power, the highest space charge and the longest RFQ, makes that unprecedented challenges have to be faced. But it provides also a tremendous opportunity for studying High Intensity Beam Physics.

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