PARAMETER DESIGN AND BEAM DYNAMICS SIMULATIONS FOR THE IFMIF-EVEDA ACCELERATORS

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Abstract

One major system of IFMIF (International Fusion Materials Irradiation Facility) is its accelerator facility, consisting of two 175 MHz CW accelerators, each accelerating a deuteron beam of 125 mA to the energy of 40 MeV. This high power beam, 10 MW, induces challenging issues that lead to plan a first phase called EVEDA (Engineering Validation and Engineering Design Activity), where only the portion up to 9 MeV of one accelerator will be constructed and tested. For these accelerators, the Parameter Design phase is about to be completed. Particular efforts have been dedicated to minimise the space charge effect that can strongly increase the beam size via the halo, and the losses that can prohibit the requested hand-on maintenance. This paper presents the status of these studies.

INTRODUCTION

In the future Fusion Demonstration Reactor (DEMO), the materials surrounding the plasma will be submitted to a very intense neutron flux, so that their atoms can be displaced up to hundreds of times more than with those of present fusion materials. In order to test and qualify the material behaviour under such severe irradiations, the International Fusion Materials Irradiation Facility (IFMIF) is planned, with the purpose of delivering an intense neutron flux, generated by the impact of an accelerated deuteron beam on a liquid lithium target. One major system of IFMIF is its accelerator facility, consisting of two 175 MHz CW accelerators, each accelerating a deuteron beam of 125 mA to the energy of 40 MeV. The total power delivered at the target is 10 MW. One important challenging specification of these accelerators is therefore their very high intensity, which must nevertheless be reconciled with the requested hands-on maintenance imperative. That is why a first phase called Engineering Validation and Engineering Design Activity (EVEDA) is now starting, where a prototype accelerator will be constructed and tested, consisting of only the portion up to 9 MeV of one IFMIF accelerator. For these accelerators, the parameter design and beam dynamics simulations are now well engaged. Two topics have been particularly scrutinised: characterisation and minimisation of the space-charge effect, very critical in the low energy part, and of the losses, very critical in the high energy part. Different solutions have been studied, and the choices between them are either done or underway. In this paper, after having given the general layout, the status of those studies is presented for each accelerator section.

LAYOUT & CHALLENGING ISSUES

The layout and general parameters of IFMIF and EVEDA accelerators are given in Fig.1. D+ particles are extracted from the ion source at 100 keV, then properly focused by the LEBT in order to be injected into the RFQ where they are bunched and accelerated to 5 MeV. The MEBT matches the RFQ output beam in transverse and longitudinal to that required by the superconducting HWR-Linac. Composed of 4 cryomodules housing solenoids and accelerating cavities, the Linac accelerates particles to the final energy of 40 MeV, where the HEBT transports the beam to the lithium target while giving it the required dimensions and homogeneity. For the prototype accelerator, only the first cryomodule will be constructed, and a special HEBT sends the resulting 9 MeV beam with the right dimensions to a beam dump, while allowing to measure its characteristics.

For Beam dynamics studies, the TraceWin package code(including PARTRAN and TOUTATIS) [1] is used as the common code between the different sections, where multiparticle trackings are performed under a strong space charge regime. Given the very high

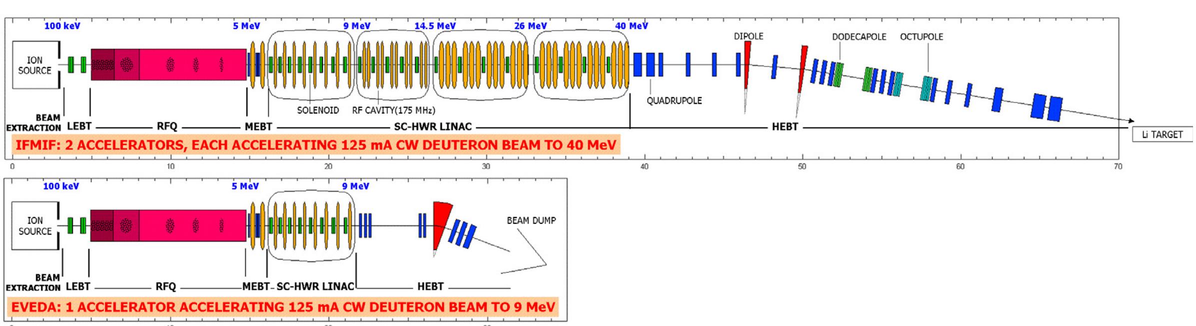

Figure1: General layout of the IFMIF-EVEDA accelerators.

intensity involved, any linear calculation is even useless. Indeed, space charge forces always overtake magnetic forces. The tune depression parameter is 0.4-0.5 in the RFQ, and 0.2-0.5 in the HWR-Linac. It results a high compactness for the accelerator so that available space for beam equipments and diagnostics has been dramatically reduced.

The high intensity impacts also strongly on beam losses considerations. To allow hands-on maintenance, losses should not exceed 1W/m for particles at energies beyond 5 MeV. Table 1 lists the beam power at different positions along the accelerator and the corresponding beam fraction per meter allowed to be lost. We can see that it concerns a really tiny part of the beam. Let us consider for example the 23 m long HWR-Linac. If we adopt an accepted loss average current of 100 nA/m, it means that, no more than 2 10^{-5} of the beam can be lost for the whole Linac. This demonstrates how carefully should be considered the beam loss problem for IFMIF. In particular, beam dynamics studies must be made with 10^6 macroparticles downstream the LEBT, and total losses of more than two dozens of macroparticles should be avoided. Losses in case of errors, tunings or accidents should also be precisely examined.

Table 1: Beam Energy, Beam Power and Allowed loss/m (Beam Fraction or Current) at Different Locations

End of	Energy (MeV)	Power (MW)	Allowed loss (fraction/m)	Allowed loss (nA/m)
RFQ	5.0	0.625	1.6 10^{-6}	200
1^{rst} Cryo	9.0	1.125	9.0 10^{-7}	100
2^{nd} Cryo	14.5	1.813	5.5 10^{-7}	70
3^{rd} Cryo	26.0	3.250	3.1 10^{-7}	38
4^{th} Cryo	40.0	5.000	2.0 10^{-7}	25

BEAM EXTRACTION

The beam extraction system is designed following that of the SILHI source [2]. To extract a higher flux from the ion source, the diameter of the plasma electrode hole is enlarged from 10 to 12 mm. To reduce the space charge effects, the overall length of extraction electrodes has been shortened by reducing their number from 5 to 4. Their spacing has been adjusted to keep a maximum electric field not exceeding too much 100 kV/cm. As a result, the extracted beam emittance is 0.06 πmm.mrad (normalised RMS), at the current of 140 mA (D+) in anticipation of some losses in the low energy sections. The beam distribution is not Gaussian. The density is rather flat, except on a thin part near the edge where it is higher. This is due to the beam size, in the very first extraction steps, which spreads into non linear focusing zones so that the external part is folded toward interior. For a same emittance, this distribution is more compact than a Gaussian one and should not be unfavourable.

LEBT

In this low energy section, the strong space charge is partially compensated by residual gas electrons. A fine calculation of the resulting space charge potential is thus necessary, and it has been performed with a home made code [3], taken into account the ionisation and the dynamics of ions and electrons. It has been found with this code that the space charge is better compensated within a quadrupole than within a solenoid. But for this line, quadrupoles induce more emittance growth because the distance source-quadrupole is so huge that a bigger beam enveloppe is induced than with solenoids that focus in both planes at the same time. For solutions with two solenoids, it has also been noted that a strong focusing scheme (with a waist in between them) leads to a stronger emittance growth. Finally, a configuration with 2 solenoids has been adopted in the weak focusing scheme. The 2.1m total length can admit various technical equipments and diagnostics, of which an emittance measurement. No beam loss occurs in this section, excepting the neutralisation induced by the addition of Krypton gas aiming at producing a more linear space charge. Nevertheless, the output emittance is higher than expected. This value can be lowered as first further optimisations have shown. Otherwise, either higher Krypton pressure has to be added, or the distance between the solenoids has to be reduced. The matching of the output beam to the RFQ channel is being performed by means of the TraceWin code.

RFQ

From this section, calculations begin to be made with 10^6 macroparticles, and losses should begin to be carefully managed. For that, the design [4] 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 energy. On the contrary, in the last third of the RFQ all parameters are let unchanged to avoid losses at an energy approaching 5 MeV. Therefore, losses are concentrated in the first part and concern mainly particles at low energy around 100 keV. Notice that only 3 particles out of 10^6 with energies between 3.5 and 4.5 MeV are not bunched and will be lost in the next sections. These calculations have been made with the PARMTEQM code [5], cross-checked with the TOUTATIS code. The overall transmission of the 9.78 m long RFQ depends on the beam current, emittance, and distribution type at input. We can remember that for 130 mA, 0.25 πmm.mrad at input, the transmission is 95.7 % for a Gaussian distribution, and 99.1% for a Waterbag one. The emittance growth is insignificant because here the tiny lengths of focusing lattices forbid any space charge manifestation.

MEBT

This section has been re-designed from the initial IFMIF Conceptual Design Report, in order to reach a more realistic 1.36 m long section, in which can be now installed essential beam diagnostics along with 3 quadrupoles and 2 buncher cavities. These last elements must have enough focalisation strength in transverse and longitudinal to be capable to match the beam from a very short focusing lattice (cm) of the RFQ to a much longer one (m) of the HWR-Linac.

HWR-LINAC

The design of the superconducting HWR-Linac has been performed under many constraints of energy, length, RF power, feasibility, and more particularly of emittance growth and beam losses [6]. The beam dimensions, in transverse as well as in longitudinal, have to be kept as small and regular as possible along the 22.8 m long Linac. To further improve the transition between consecutive cryomodules, the lattice lengths in each cryomodule have been progressively made longer. But these considerations about 3RMS beam size are not enough. A precise examination of the beam halo is necessary to prevent particle losses. For that, the very external fringe of the beam has to be considered. We arrive then to a solution where there is no loss over 10^6 macroparticles, and where the contour line encircling 100% of particles occupies 60-80% of the aperture, with a comfortable room in longitudinal acceptance. This result remains to be further improved. On the other hand, the emittance growth is not negligible; it reaches 50%, of which 40% occurs at the MEBT and the first meter of the first cryomodule.

The aim now is to keep this no-loss result in the presence of errors which remain to be simulated. While errors of the HWR-Linac alone could be not critical, errors combined from the ion source down to the accelerator end could enhance losses. Re-tuning of the Linac could be necessary in real operation. The point is that the above described tuning allowing to avoid losses is based on the knowledge of beam sizes. But in order to limit emittance and halo growths, focusing lattices need to be the shortest possible, and thus no place is available for beam size measurements. Therefore this question of managing losses in the real machine has to be addressed and simulated.

A possible solution that can help is the use of quadrupoles instead of solenoids. Thanks to the now different horizontal-vertical sizes, and provided that Beam Position Monitors can be installed inside the quadrupoles, difference of squared transverse sizes can be measured, and would be useful to match the beam [7]. That is why a Linac configuration with quadrupoles has also been simulated, and it gives equivalent results than with solenoids. The choice of the final configuration will depend on current feasibility studies of SC quadrupoles with BPM inside.

HEBT-EVEDA

For the prototype accelerator, the HEBT line transports the 9 MeV beam output from the first Linac cryomodule to a beam dump [8]. At this point, the beam is expanded at optimised size and divergence in order to spread the energy deposition. Another goal is to allow beam characterisation by a 3m long diagnostic plate. Given the high space-charge regime, the beam is very quickly debunched, and the use of a buncher is necessary for any longitudinal measurement. For the same reason, the transverse emittance measurement by varying quadrupole strengths is no longer possible by linear calculations. A minimisation code remains to be made, calling the multiparticle TraceWin code. For the moment, we have verified that variations of horizontal and vertical beam sizes by a factor of 6 and 3 are possible without any loss. Simulations along the 10m long HEBT have also shown that 100% of the beam occupies 50-70% of the aperture.

HEBT-IFMIF

For the IFMIF accelerator, the HEBT line has to guide the 5 MW beam to the target with precise specified dimensions and homogeneity. Until now, only a feasibility study has verified that with the beam output from the above HWR-Linac, it is possible to obtain roughly a beam footprint of 5x20 cm as required, with relatively hard edges and good homogeneity. All that with a ~40m long line containing quadrupoles, octupoles and dodecapoles. But it seems that results are very sensitive to the input beam. More detailed studies remain to be done.

CONCLUSIONS

The design and simulations of the IFMIF-EVEDA accelerators are challenging due to its very high beam power. A true competition between focusing and space-charge forces has to be managed. A detailed examination of each particle loss is necessary to allow the required hands-on maintenance. This paper has summarised the status of these studies, by pointing out the specific hot topics for each section, and the choices made or to be made to solve them.

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