USING STEP-LIKE NONLINEAR MAGNETS FOR BEAM UNIFORMIZATION AT IFMIF TARGET*

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Abstract

Uniform beam distribution and minimum beam halo on target are often required in high intensity beam applications to prolong the target lifetime, ease cooling and obtain better irradiation effect. In this report, step-like nonlinear magnets instead of standard multipole magnets have been studied for the application at IFMIF. Although the preliminary results are still below the very critical requirement of spot uniformity at the IFMIF target, they are quite permissive. The method demonstrates significant advantages over the conventional combination of octupole and duodecapole on very low beam loss, better uniformity and very low cost. Further studies are needed to fully meet the IFMIF specifications.

INTRODUCTION

For high power hadron beam applications such as spallation neutron sources, material-irradiation studies, and accelerator-driven subcritical system etc., it is important to produce a beam spot at target as uniform as possible to prolong the lifetime of the targets as well as beam windows separating the target environment from the vacuum in the beam transport lines. In a hadron accelerator, there is still a very important halo part in beam distribution which can not be neglected. To produce a uniform spot distribution at target, only methods using non-linear magnets can be considered as other methods such as the scattering method and the scanning method used in hadron therapy are ruled out due to either too large beam loss or harmful time structure.

The SIEEV Department at CEA-Saclay (IRFU/SIIEV) is working on the accelerator design of the IFMIF (International Fusion Materials Irradiation Facility) accelerator. In this typical application based on two high power deuteron beams of 125 mA and 40 MeV, it is important to produce a uniform beam spot at the target as mentioned above. In earlier preliminary studies, a combination of non-linear magnets such as octupoles and dodecapoles has been considered for this purpose.

In this study, step-like field magnets are used to meet the very strict requirements at the IFMIF target. Step-like field magnets were initially proposed for the beam spot uniformization at the ESS targets [1]. They were also applied to the China Spallation Neutron Source [2] and China-ADS project for the same purpose. They are considered to be more effective and cheaper than conventional standard multipole magnets in this kind of applications.

BASICS

In some cases, the original distribution is not regular, so standard multipole magnets are not effective in the transformation to obtain a uniform beam spot at target. Step-like nonlinear magnets were proposed here to tackle the problem. Instead of twisting the distribution by higher order forces (standard multipole magnets or combined-function magnets) in phase space, the nonlinear magnets of step-like fields (see Fig. 1 and Fig. 2) are used to translate parts of the distribution. This method has a better control over outmost particles, thus is effective to carry out distribution transformation in the case of large beam halo. An example of such magnet with one step is shown in Fig. 2. Multi-step field can be produced by two or three adjoining magnets of one-step.

The step rising in the field of a step-like field magnet can be represented by an approximation:

$$B(x) = \frac{F_S / L}{1 + e^{-b(x - x_0)}} \quad (1)$$

B, x0 are the parameters for fitting; the field factor f and the distance x0 between the mid-rising and the beam center as well the field sharpness b can be used for the optimization. To improve the sharpness of the step field, another pair of irons and coils with reverse magnetic flux can be nested

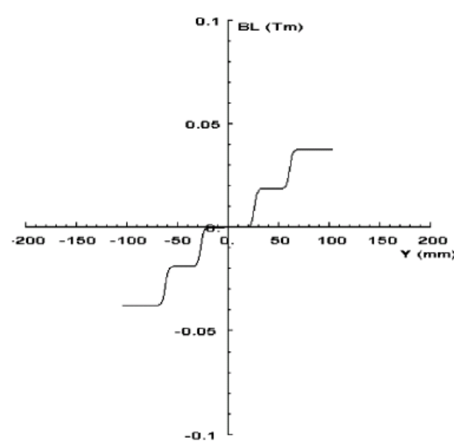

Figure 1: Multi-step magnetic field for the distribution transformation.

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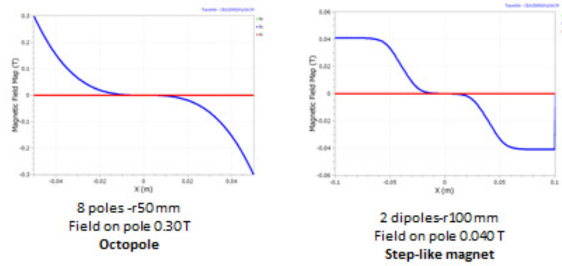

Figure 2: Field map of octupole and the step-like magnet.

A prototype of step-like field magnet was made at IHEP (see Fig.3). The field measurements confirm the three-dimensional magnetic field calculation [2].

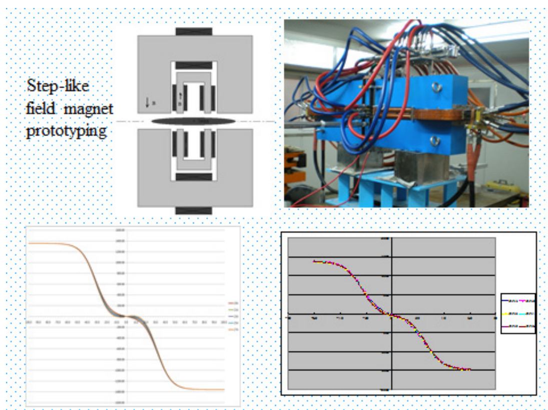

Figure 3: Field map and photo of the testing step-like field magnet.

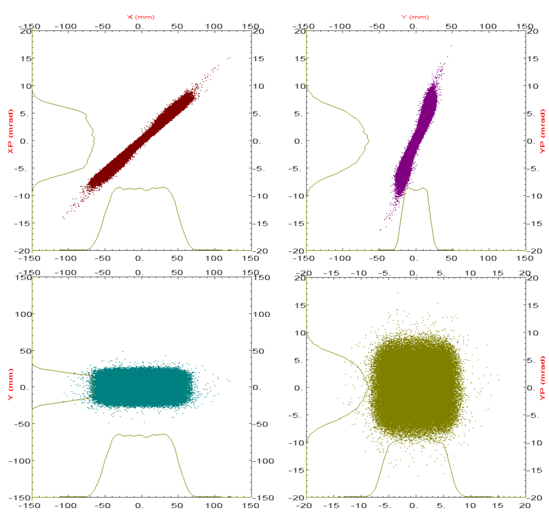

Figure 4: Beam distributions in the four projection phase spaces at the CSNS target after applying the step-like field magnets. One pair of SFM-X and SFM-Y magnets are used.

In order to show the practical effectiveness of step-like field magnets, we have tried to apply the magnets for the uniformization of beam spot distribution at the target of CSNS (China Spallation Neutron Source) and C-ADS (China Accelerator Driven Subcritical System), see Fig. 4 and Fig.5. We use the code TRANSPORT [3] and TURTLE [4] to finish the calculation. In the calculation the step-like field magnets can significantly reduce the maxim beam density and the beam halo.

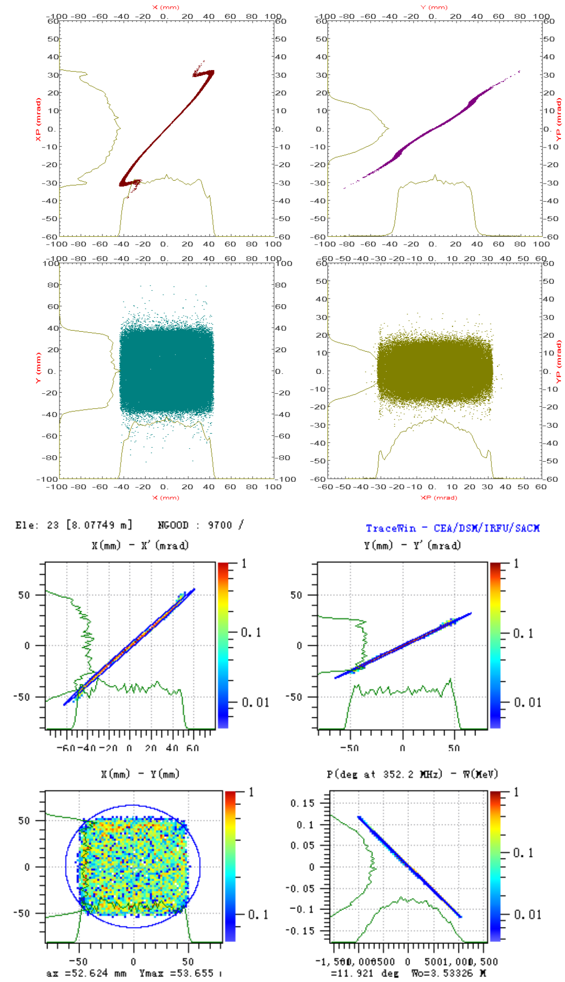

Figure 5: Beam distributions in the four projection phase spaces at the ADS-RFQ beam dump after applying the step-like field magnets. (Without and with the influence of space charge effect).

APPLICATIONS AT THE IFMIF TARGET

The IFMIF-EVEDA project takes place in the context of international research on energy production by thermonuclear fusion. The present international roadmap of fusion includes ITER (International Thermonuclear Experimental Reactor) that aims at demonstrating scientific and technical feasibilities, and DEMO (Fusion Demonstration Reactor) that aims at proving the industrial feasibility. In those reactors, the materials covering the internal wall will undergo intense radiation produced by 14 MeV neutrons coming from the fusion plasma. The damages induced are characterized by the number of dpa (displacements per atom) due to collisions with neutrons. While a damage of 3 dpa is estimated for the whole

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lifetime of ITER, the damage will amount to 30 dpa per year in DEMO [5].

An essential stage in the design of DEMO consists in testing and studying the materials capable of undergoing such strong neutron flux over a long period. That is the purpose of the IFMIF project, an accelerator based intense neutron source.

Requirements and Former Studies

IFMIF will be the world most intense neutron source capable of producing a flux 10^{17} neutrons/s at 14 MeV. It is composed of two accelerators driving two Deuteron particle beams at 40 MeV to the liquid Lithium Target, which will deliver the neutron flux to materials in the Test Cells. The radiation level should be enough to induce 20 to 50 dpa per year in the high flux Test Cell. [5]

The objective of the IFMIF HEBT line is to transport and properly focus the 40 MeV beam coming out from the SRF-Linac in order to achieve a beam footprint at the liquid-Lithium target following stringent constraints of dimension and homogeneity.

-The beam footprint has a rectangular shape, 20 cm (H) x 5 cm (V) on the flat top

-The beam density across the flat top is uniform (±5%)

-Beyond ±11 cm in horizontal, the beam density must be lower than 0.5 A/cm^2

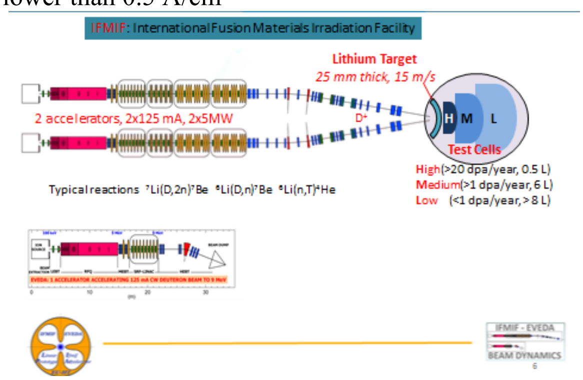

Figure 6: General layout of the IFMIF-EVEDA accelerators.

These very challenging specifications are currently under discussion to be re-defined. Concern about the input beam distribution (see Fig.7), non-linear magnets are needed to be used for the spot uniformaziton.

The general layout of the "classical" HEBT structure is given in Fig.8. Its total length is 45.177 m, and is composed of 2 dipoles, 19 quadrupoles, 2 octupoles and 2 duodecapoles. The 2 dipoles form an achromat of total angle 9°, aiming at minimising the backward radiation from the target. The first section including those dipoles is used to match the beam to the next section where are installed the octupoles and duodecapoles. The role of those magnetic multipoles is to fold the beam tail toward interior in order to obtain a squared beam profile. They are placed at a beam waist in one plane to act on the beam only in the other plane. The tuning of the two transverse planes are then roughly uncoupled. The last section allows expanding the beam to the proper size at the target [1].

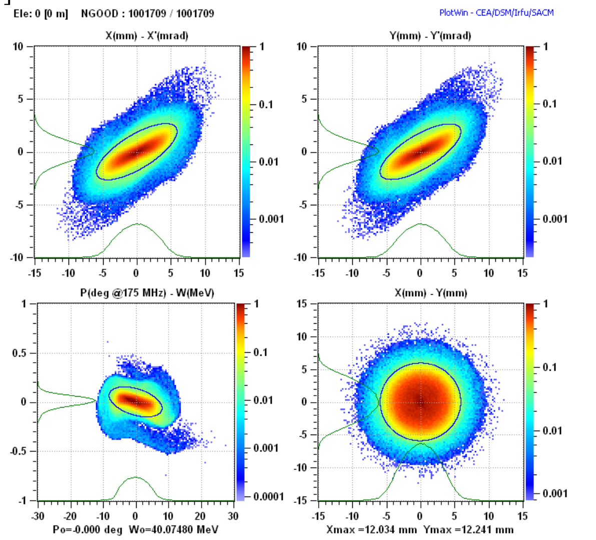

Figure 7: Beam distributions in the four projection phase spaces at the beginning of IFMIF-HEBT.

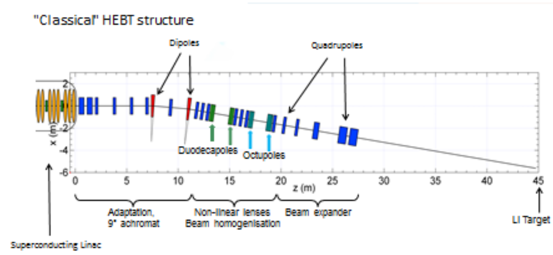

Figure 8: General layout of the "classical" HEBT structure.

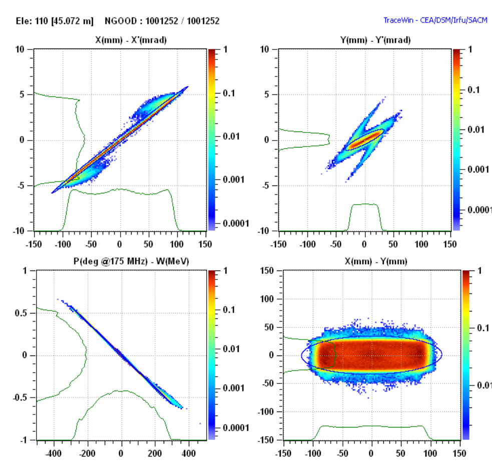

Figure 9: Beam distributions in the four projection phase spaces at the beam target after applying standard multipoles.

The resulting beam density distribution at the Lithium target is given in Fig.9. The transverse phase spaces (x, x') and (y, y') clearly result from the folding action of the multipolar lenses. The beam footprint can be seen in the

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real space (x, y). It does not fulfil the former requirements, especially on the part of beam halo.

Beam Spot Uniformization with Step-like Field Magnets

By keeping the original optics design unchanged, only combinations of the standard octupoles and duodecapoles magnets are replaced by step-like field magnets. The layout of the new HEBT structure is shown in Fig. 10. The beam spot distribution at the target after applying step-like field magnets and the beam loss along the HEBT is shown in Fig. 11. Multi-particle simulations are performed by using TRACEWIN code (Ref). From the beam footprint we can see that the beam halo has been controlled in a very low level while the uniform of the flat top is still need to improve. The result shows that step-like field magnets can do the uniformity gymnastics at least as well as the multipoles do. The parameters of the step-like field magnets are given in Table 1.

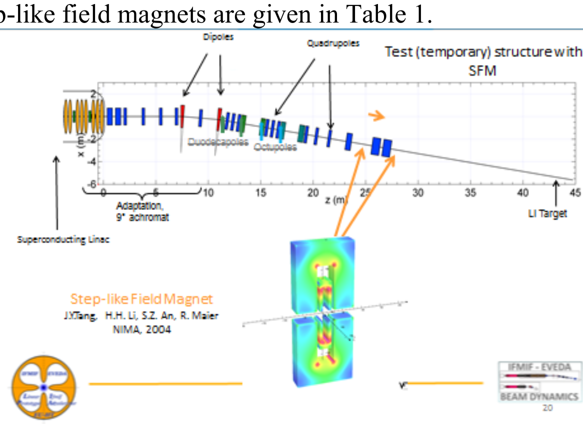

Figure 10: General layout of the new IFMIF HEBT.

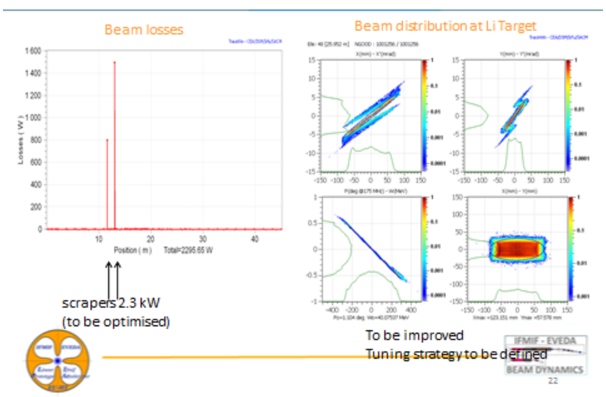

Figure 11: Beam distributions in the four projection phase spaces at the beam target after applying the step-like field magnets.

Table 1: Parameters of the Step-like Magnets Used in IFMIF-HEBT Line

	B (T)	L (m)	x0 (mm)	b (1/mm)	gap (mm)
SFM-Y1	0.002	0.25	23.46	0.23	25
SFM-Y2	0.022	0.25	56.58	0.15	25
SFM-X1	0.006	0.25	21.6	0.23	25
SFM-X2	0.1	0.25	46.8	0.22	25

Encouraged by the previous work, we changed the optics layout by removing a quadrupole triplet and changing the locations of the other quadrupoles and the step-like field magnets. The collimators have also been removed. The whole length of the HEBT is shortened to 5.5 m. In order to obtain a better control on beam halo, we put the third step-like field magnet in each direction. The layout of the the new HEBT structure is shown in Fig. 12. The beam spot distribution at the target after applying the step-like field magnets and the beam loss along the HEBT is shown in Fig. 13.

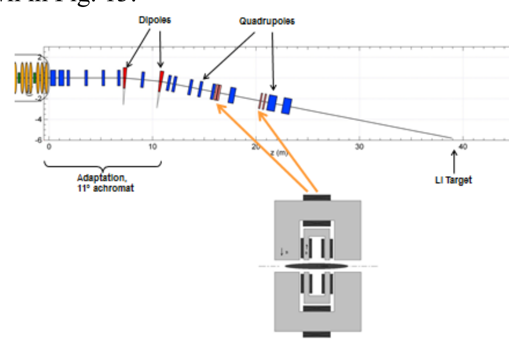

Figure 12: General layout of the new HEBT with step-like field magnets.

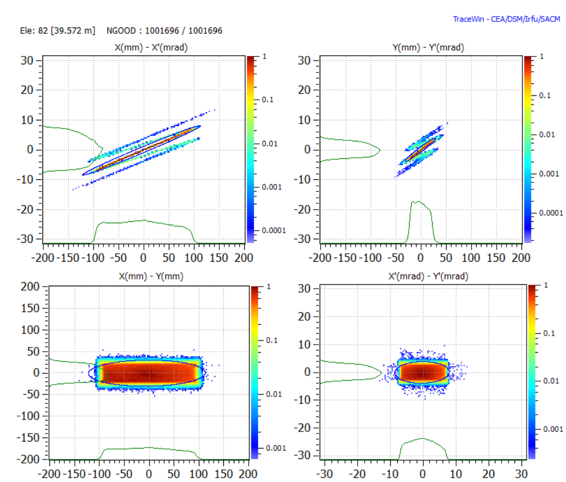

Figure 13: Beam distributions in the four projection phase spaces at the beam target after applying the step-like field magnets.

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The parameters of the step-like field magnets can be seen in Table 2. There is completely no beam loss in the HEBT, which is considered very important. From the beam footprint we can see that the amount of the Beam halo and the uniform of the flat top are both better than the result of not changing the optical structure. But there is still a large distance between the result we get now and the IFMIF's request.

Table 2: Parameters of the Step-Like Magnets Used in the New IFMIF-HEBT Line

	B (T)	L (m)	x0 (mm)	b (1/mm)	gap (mm)
SFM-Y1	0.018	0.25	28.0	0.19	20
SFM-Y2	0.068	0.25	51.2	0.17	20
SFM-Y3	0.032	0.15	68.0	0.19	20
SFM-X1	0.012	0.125	27.06	0.19	25
SFM-X2	0.069	0.125	52.48	0.20	28
SFM-X3	0.041	0.100	71.70	0.20	30

Table 3 shows the analysis on the simulated distribution of the beam spot at the IFMIF target. We can see that the design with step-like field magnets, especially the new design that changed the optic structure can get a very little beam halo and uniform beam density on the target.

Table 3: Analysis on the Simulated Distribution of the Beam Spot at the IFMIF Target. Here NLM Represents Combinations of Step-Like Field Magnets.

	Without NLM	With NLM	New design
Particles out of the footprint (200 mm × 50 mm)	2.7%	0.006%	0.0004%
The uniform of beam density across the flat top		18%	13%

From the Table 3, we can find that it is easy to obtain a clear beam spot with very little halo when the step-like field magnets are used. However, the uniformity across the flat top is still behind fulfilling the requirement by IFMIF. Because step-like field magnets have nonlinear magnetic fields, usually one looks for a good solution or a set of the magnet parameters by the trial and error method. It should improve the efficiency if one can make the optimization automatically by a computer code. For this purpose, the TraceWin code has been modified to include step-like field magnets and perform optimization on spot uniformity. For the optimization, only ideal SFMs represented by four parameters (L, B, b and X0) are used. However, a 2D or 3D field map can be read for more realistic tracking.

The error studies at IFMIF have also been carried out by using the TRACEWIN code. The results show that there is no beam loss in the beam transfer line if we design the apertures appropriately. As the gaps of the step-like field magnets are quite small, one should take care about the possible beam loss there.

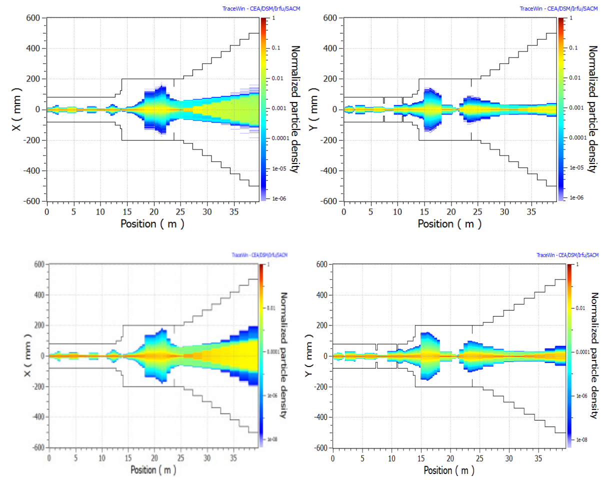

Figure 14: Simulation result with errors in IFMIF-HEBT.

CONCLUSIONS

Although there is still more work to be done, step like field magnets have been proved a good solution to achieve or approach the very strict requirements on beam spot uniformity and halo control at the IFMIF target. Through the further collaboration between CEA-Saclay and IHEP, we hope that we can reach the final goal at IFMIF, and at the same time make step like field magnets really work in practical applications.

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