IMPACT OF THE MAGNET ALIGNMENT AND FIELD ERRORS ON THE OUTPUT UNIFORM BEAM AT THE DONES HEBT LINE*

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Abstract

IFMIF-DONES will be a facility devoted to study the degradation of advanced materials for operation of fusion reactors. Motivated by the need of optimizing the neutron irradiation to the materials samples, the HEBT line of the deuteron DONES (DEMO Oriented Neutron Source) accelerator is based on non-linear magnetic fields. By using octupoles and dodecapoles magnets, it is possible to shape the beam profile to achieve the demanded rectangular uniform distribution across the flat top of the beam profile, with high edge peaks in the horizontal direction. Special optics conditions are obtained with a proper setting of quadrupole magnets to minimize the x-y coupling. Additionally, the high beam power (5 MW, for a 125 mA, 40 MeV deuteron beam) in conjunction with the huge space charge makes challenging the HEBT line design to avoid non-controlled losses, except in the devoted scrapers. A comprehensive beam dynamics analysis has been made using TraceWin code. It includes extensive error studies to define tolerances and verify the robustness of the design with respect to magnet misalignment, power supply instabilities and injection parameters.

DONES ACCELERATOR

The European Roadmap sets as priority the development of a high-intense fusion-like neutron source to allow a better understanding of the radiation damage and the qualification of the suitable materials to be used in the future DEMO and commercial fusion reactors. Based on the design of the International Fusion Materials Irradiation Facility IFMIF [1], DONES, a DEMO Oriented Neutron Source [2], has been proposed as a neutron source through the interaction of high intensity deuteron beam on a Lithium target.

The ultimate goal of the DONES project requires cutting-edge technology [3] to transport and accelerate the 40 MeV, 125 mA CW deuteron beam. The huge beam power (5 MW) in continuous mode conditions the design of the accelerator as minimum beam losses below <1 W/m are required, except those safety controlled in devoted structures (scrapers and collimators). A challenging feature of DONES accelerator is the space charge regime, being the strongest space charge accelerator in the world [4], demanding a carefully design to keep the halo production under control.

HEBT

The High Energy Beam Transport (HEBT) line aims at the transport, bending and shaping of the 40 MeV, 125 mA CW deuteron beam from the SRF accelerating cavities to the free surface of the rapidly flowing liquid Lithium target. The final goal of producing an intense forward peaked source of fusion-like neutrons demands a very specific beam profile at the target location. A rectangular uniform distribution across the flat top of the beam profile is required, with peak edges in the horizontal direction (Fig. 1). Variable beam size configurations between 10-20 cm in horizontal plane and 5 cm in vertical one are considered.

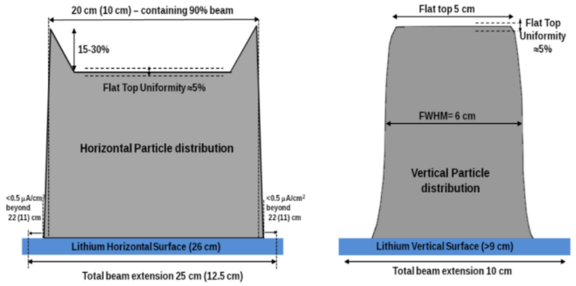

Figure 1: DONES horizontal (left) and vertical (right) beam requirements at the Lithium target.

The HEBT configuration is fully driven by different issues:

- Strong space charge regime: the unprecedented space charge forces require a strong focusing scheme to avoid emittance and beam halo growth.
- Huge beam power: The halo growth and the tails induced by non-linear magnets may induce some losses along the HEBT which would be unacceptable given the high beam power. A careful design has been performed to avoid losses in the line, except those allowed in the devoted scrapers and collimators, which include shielding and remote handling maintenance.
- Beam shaping: Although different methods for beam uniformization have been proposed in the past [5], the high beam power makes the use of non-linear magnets as the appropriate technique to achieve the required beam profile. Both octupole and dodecapole fields have been chosen to fold the beam tails into the core, being octupoles in charge of the uniformity and peak

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* This work has been carried out within the framework of the EURO fusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No. 633053 and No. 870186. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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edges whereas dodecapoles are more devoted to control the particles in the beam tails to avoid losses.

- Beam diagnostics needs: The technique for the beam shaping requires a very good characterization of the beam properties, allowing an optimum magnet tuning. Of special importance is the measurement of the so different beam sizes at the multipole location as well the beam centering. Those, in conjunction with the high beam power continuous conditions, impose the need of a suitable set of beam diagnostics along the line, with the consequent impact on the required room for their installation [6].

General Layout

Figure 2 represents the DONES HEBT line [7] from the SRF output to the final target, consisting of eighteen quadrupoles, two 4.5° and one 30° bending magnets, two pairs of octupoles and two pairs of dodecapoles. Six pairs of horizontal and vertical steerers are placed along the HEBT line for the beam centering at the beam position monitors.

- In the section S1, six quadrupoles are needed to adapt the beam coming from the SRF and to transport it through the two 4.5° bending magnets, allowing a total 9° main line beam deviation for a minimum component activation due to neutron back-streaming from the target. Among the two bending magnets, a 30° dipole bends the beam towards a beam dump through the Beam Dump Transport Line, BDTL. The beam dump is foreseen to be used during accelerator commissioning and tuning.
- The HEBT section S2 is devoted to match the beam to the optical conditions required for the use of non-linear magnets. A quadrupole triplet is required for each pair of dodecapoles and octupoles, producing a decoupled beam evolution where the beam size at the multipole location is very large in one direction and as small as possible in the opposite one (zoom in Fig. 3), minimizing the possible x-y coupling introduced by the non-linear fields.
- Finally, the third HEBT section, S3, produces the suitable phase advance between the multipoles and target, as well to expand the beam according to the target beam requirements. As it was explained in [8], the value of the phase advance is critical, being values very close to $n\pi$ the optimum ones for a sharp profile but with the drawback of demanding stronger multipoles, which in turn would add stronger x-y coupling and larger beam size evolution. A trade-off has been made taking into account the beam emittance, the phase advance and the final beam size configurations.

To avoid undesirable losses along the HEBT and to enable the use of the optimum values of octupoles and dodecapoles required to achieve the target beam requirements, an x-y movable scraper, with limited power deposition, is placed among the dodecapoles. Furthermore, a specific collimator at the end of the line ensures no losses in the TIR and Test Cell rooms.

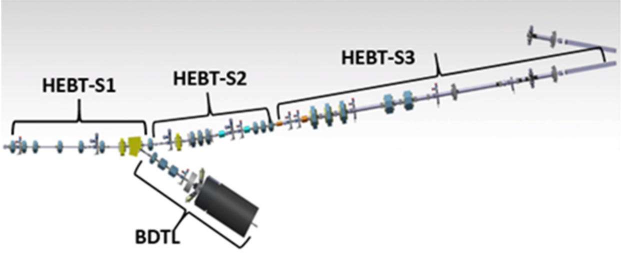

Figure 2: DONES HEBT.

ERROR SIMULATIONS

Given the specific features of the HEBT beam line, with the use of non-linear magnets, a comprehensive analysis of beam dynamics is required. Nominal simulations have been carried out obtaining the final beam requirements and optimum beam transport along the line. The beam envelopes (3 RMS beam size) in both transverse directions along the HEBT are shown in Fig. 3.

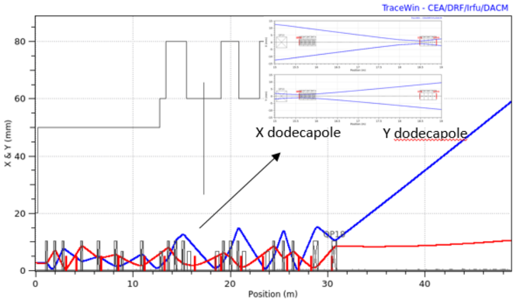

Figure 3: Horizontal (blue line) and vertical (red line) RMS beam size along the HEBT. A zoom illustrates the different beam size configuration at the multipoles.

However, real conditions during acceleration should be taken into account in this design phase to avoid any distortion in the beam profile or non-acceptable losses. The target beam profile uniformity and the height of the peak edges are determined by the multipole strength, which in turn is proportional to the beam size at such non-linear magnets. On the other hand, any modification of the beam at the multipole magnets far from the ideal one (large size in one direction, small in the other) would add x-y coupling, distorting the final beam profile and increasing the probability of losses. Additionally, the phase advance modification due to beam size variation would affect the sharpness, uniformity and edge peak height of the beam profile. Beyond the possible beam misalignment at the target location, of relevance given the beam power and the stringent positioning requirements, the beam centering at the multipoles is critical. Given the non-linear nature of such dodecapoles or octupoles field distribution, beam deviations in such magnets would introduce a notable beam asymmetry in the final beam profile.

To address and analyse all these effects, comprehensive error studies have been carried out, including alignment, rotation and power supply errors of the different magnets in both transverse directions. Two types of errors have been considered, static and dynamic errors. Static errors, that are, very slow errors have been corrected by using steerers, whereas the effect of very fast dynamic errors, such power supply ripple or magnet vibration are considered without any possible correction. From the simulations, a set of error values (Table 1) is considered as the maximum values ensuring a safe transport and minimum beam profile distortion.

Table 1: Magnet Errors

	Type of Error	Static Errors	Dynamic Errors
Quad	Displacement (x,y) (mm)	±0.1	±0.005
	Rotation (x,y) (°)	±0.3	±0.03
	Rotation (z) (°)	±0.15	±0.015
	Field (%)	-	±0.1
Dipole	Displacement (x,y) (mm)	±2	±0.25
	Rotation (x,y,z) (°)	±1.5	±0.25
	Field (%)	±0.2	±0.1
Multipoles	Displacement (x,y) (mm)	±0.1	±0.05
	Rotation (x,y) (°)	±0.3	±0.1
	Rotation (z) (°)	±0.15	±0.1
	Field (%)	-	±0.1

Results

600 linacs with different combination of both static and dynamic errors have been simulated with Tracewin code [9]. A beam distribution of approximately 10 million of particles has been considered for each linac. Figure 4 shows the particle density probabilities in both transverse directions. The cumulated beam density distribution at the Lithium target with errors is given in Fig. 5. Only 50 simulated linacs are represented due to computing issues.

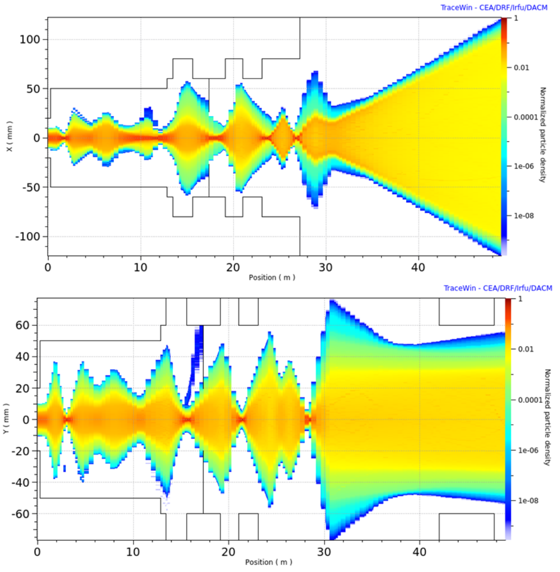

Figure 4: Beam density along the DONES HEBT (20x5 cm^2 configuration).

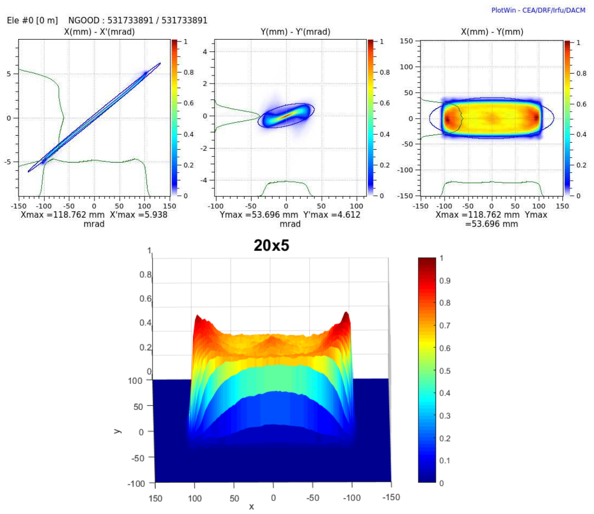

Figure 5: Phase space (up) and 3D distribution (bottom) of the beam at target entrance (20x5 cm^2 configuration).

CONCLUSION

The challenging goals of the DONES HEBT have required a comprehensive analysis of the beam dynamics, with special attention to the minimization of beam losses and the beam shape manipulation to obtain the final target beam for homogenous neutron irradiation field. Extensive error simulations have shown the fulfilment of the main requirements where magnet misalignments and power supply ripple are considered.

REFERENCES

[1] IFMIF International Team 2004, “IFMIF Comprehensive Design Report”, IFMIF/EVEDA, Rokkasho, Japan, 2004.

[2] A. Ibarra *et al.*, "The European approach to the fusion-like neutron source: the IFMIF-DONES project", *Nucl. Fus.*, vol. 59, no. 6, 2019. `doi:10.1088/1741-4326/ab0d57`

[3] I. Podadera *et al.*, "The accelerator system of IFMIF-DONES multi-Mw facility", presented at IPAC’21, Campinas, Brazil, May 2021, paper TUPAB211, this conference.

[4] P.A.P. Nghiem *et al.*, Advanced concepts and methods for very high intensity accelerators, *Laser and part. Beams*, vol. 32, p. 639, 2014. `doi:10.1017/S0263034614000664`

[5] The IFMIF/EVEDA Integrated Project Team 2013, “IFMIF Intermediate Engineering Design Report”,IFMIF/EVEDA, Rokkasho, Japan, 2013.

[6] I. Podadera *et al.*, “Beam Diagnostics for the Multi-MW Hadron Linac IFMIF/DONES”, in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 111-114. `doi:10.18429/JACoW-IBIC2016-MOPG32`

[7] O. Nomen *et al.*, “Preliminary design of HEBT of IFMIF-DONES”, *Fus. Eng. Design*, vol. 153, p. 111515, 2020. `doi:10.1016/j.fusengdes.2020.111515`

[8] C. Oliver *et al.*, “Phase-Space Transformation for a Uniform Target Irradiation at DONES”, in *Proc. LINAC’16*, East Lansing, MI, USA, Sep. 2016, pp. 424–426. `doi:10.18429/JACoW-LINAC2016-TUPRC006`

[9] D. Uriot and N. Pichoff, “Status of TraceWin Code”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 92-94. `doi:10.18429/JACoW-IPAC2015-MOPWA008`