PHASE-SPACE TRANSFORMATION FOR A UNIFORM TARGET IRRADIATION AT DONES*

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Abstract

In the framework of the EU Roadmap, a DEMO Oriented Neutron Source (DONES) [1] has been proposed to provide a high neutron intense neutron source with a suitable neutron spectrum to understand the degradation of advanced materials under DEMO and future fusion plants irradiation conditions. DONES will be based on the International Fusion Materials Irradiation Facility IFMIF [2], being only one accelerator considered. The HEBT will be devoted to the transport, bending and shaping of the 40 MeV, 125 mA CW deuteron beam to the free surface of the rapidly flowing lithium target. To produce a forward peaked source of fusion-like neutrons, which stream through the target into the test cell, a rectangular uniform distribution across the flat top of the beam profile is required, being the footprint tailored in both the vertical and horizontal directions according to the target design. Different methods for beam uniformization in IFMIF accelerator has been proposed in the past [3]. Two main concerns in DONES will be the minimization of particle losses over the whole HEBT and the effect of the different shaping techniques on such strong space charge regime, especially on the beam halo modulation. A review of the different methods for the beam shaping of the high power, high space charge DONES HEBT beam will be depicted. A final solution will be proposed.

DONES HEBT REQUIREMENTS

The need of a rectangular flat top beam profile on the liquid-Lithium target determines the design of the High Energy Beam Transport (HEBT) line between the superconducting linac and the Liquid Lithium target. Two beam size configurations (20x5 cm2, 10x5 cm2) with 5% top density uniformity are demanded at the Lithium surface. Additionally constraints in the beam tails (to avoid a sudden increase in the deposited power in the Lithium target as well to eliminate heating of the adjacent structure) are imposed. A sketch of the required horizontal and vertical beam profile at target is shown in Fig. 1.

The high space charge, high power beam imposes two additional concerns in the HEBT design: the minimization and safe control from the radioprotection point of view of losses as well the space requirement for beam diagnostics [4].

BEAM SHAPING

Different techniques of providing an arbitrary spatial beam distribution starting from a given input beam can be found. Active techniques based on pencil beam scanning, used in some other projects as ESS [5], have been shown to be not an option for DONES given the possible disruption of the liquid Lithium by the pressure waves [6].

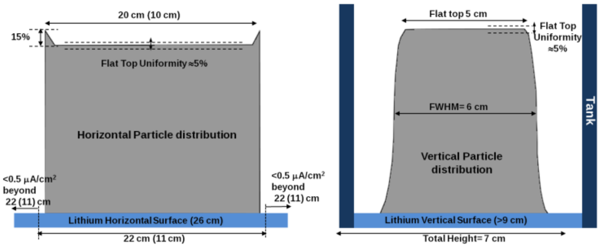

Figure 1: DONES horizontal (left) and vertical (right) beam requirements at the Lithium target.

The use of non-linear magnetic fields to shape the beam to a required beam profile has been considered the best option [7]. Although previous studies showed the advantage of using special dipoles, called "step-like field magnets" [8], which remove the scrapers and their associated shielding, the need of a magnet prototype and the impact on the DONES timeline has pushed to the traditional non-linear magnet solution.

The use of standard high order multipoles to obtain a uniform beam has been well documented and used in several facilities [9, 10]. Whereas particles in the center of the beam distribution are unaffected by the non-linear magnets, the divergence of particles far from the center is modified such, after the subsequent transport, the beam edges are folded into the core.

The lowest-order non-linear magnets are desirable to reduce the magnet aperture and technology difficulties as well possible beam losses. However, octupoles optimized to improve the beam uniformity would have an undesirable large effect on the particles in the very far beam tail, which will be excessively folded, producing losses downstream the octupole. To counteract this effect, critical in DONES given the halo produced by the high space charge, duodecapoles nee to be introduced. With both type of multipoles, the beam uniformity will be almost controlled by the octupoles whereas the maximum beam extension (and the minimum pipe aperture) will be limited by the duodecapoles.

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HEBT LAYOUT

Figure 2 presents a general layout of the DONES HEBT design. A quasi-achromatic 9º bending system has been considered for minimum upstream machine activation due to neutron back-streaming from the target.

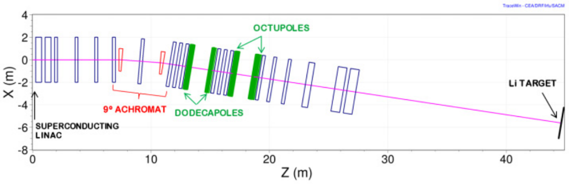

Figure 2: Reference layout of the DONES HEBT.

Two duodecapoles and two octupoles are used to shape the beam in both transverse directions, whereas 19 quadrupoles are placed to transport properly the beam, to ensure optical conditions at the non-linear magnets location to reduce the x-y coupling as to expand the beam to the required size at the target. Fig. 3 shows the rms beam sizes along the HEBT for both x and y direction.

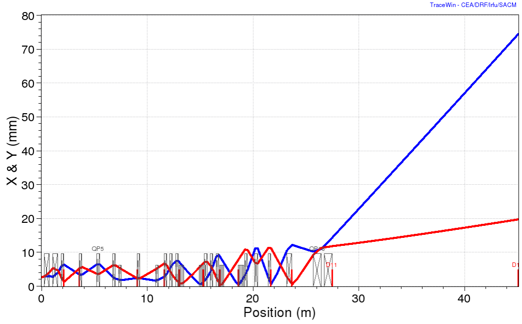

Figure 3: Horizontal (blue line) and vertical (red line) RMS beam size along the HEBT.

PHASE ADVANCE

Different analytical approaches have been developed to provide the optimum multipole strength required for beam uniformization. For a Gaussian beam, the octupole strength can be expressed as [11]:

$$K_8\left(\frac{1}{m^3}\right) = \frac{1}{\varepsilon\beta^2 \tan\varphi}. \qquad (1)$$

where ε and β are, respectively, the emittance and Twiss parameter at the octupole and φ the betatron phase advance from the octupole to the target. Although the DONES strong space charge beam will differ from a Gaussian beam, a qualitative analysis of the impact of phase advance on the shaping method can be made.

The phase advance in optical sections designed to expand the beam size at the target is, typically, close to $n\pi$, being n a integer. From Eq. (1) it can be deduced that phase advances very close to $n\pi$ would require very strong octupoles to obtain a flat beam. On the other hand, solutions with slight deviations from $n\pi$, (±10º), would demand much weaker octupoles to obtain a uniform beam. Fig. 4 shows beam distributions at target for two different phase advance values between the horizontal octupole and the Li target. Only the last six quadrupoles have been slightly modified. The required octupole strength to get a flat beam is much lower in the lower phase advance (1600 T/m^3) than in the close to $n\pi$ configuration (2400 T/m^3).

Although a solution demanding weak octupoles will be highly desirable from the magnet fabrication point of view, the lower phase advance would result in a higher contribution of particle divergence at the octupole (*xx'* transfer matrix element, M_{12}, proportional to $\sin\varphi$) which will affect to the target beam distribution. Basically the main effects are two: firstly, a loss of sharpness and secondly, a smoother beam profile top as particles with the same position but with different divergence will be spread out across the beam distribution (see Fig. 5).

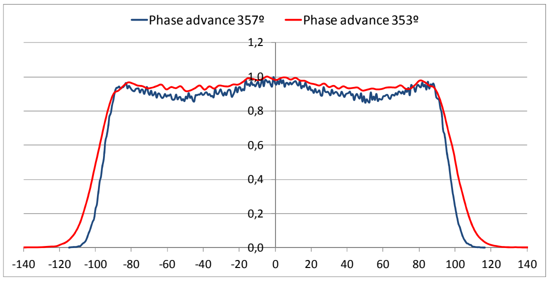

Figure 4: Horizontal beam profile at Li target for quadrupole tuning with different phase advances. Red line: φ_x=353º (K_8=1600T/m3); Blue line=φ_x=357º (K_8=2400T/m3).

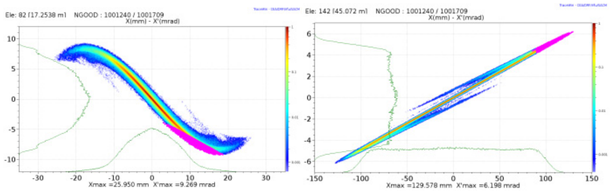

Figure 5: Beam distribution at the octupole location (left) and at the target entrance for φ_x=353º. Selected particles, in pink, illustrate how particles with large *x'* at octupole location contribute, given the strong term M_{12}, to the target beam tails.

It can therefore be concluded that a balance between sharp edges (phase advance very close to $n\pi$, strong octupoles) and configurations with weaker octupoles but smoother edges has to be made according to target and neutron irradiation requirements. Anyway, note the even in the close to nπ configuration, there is a residual beam tails contribution from the strong space charge

The strong dependence of target beam shape on the phase advance leads to a cumbersome beam tuning procedure. Concerning beam dynamics simulations, the last HEBT six quadrupoles, which strongly modify the phase advance, have been matched according to a developed diagnostic which optimize beam uniformity, edge sharpness and maximum beam extension. During commissioning and operation, quadrupole tuning based on some kind of accelerator virtual tool would be very helpful to find the optimum beam shape. Note the additional difficulties present in DONES, as the beam distribution, strongly dependent on the space charge and therefore on the beam current, and the lack of a beam dump (only at the beginning of the HEBT) to validate the beam shape before sending it to the target.

DONES SIMULATIONS

Simulations have been performed with TraceWin code [12], using the CETA-CIEMAT cluster resources§, to analyze the sensitive to octupole and duodecapole strength. Fig. 6 shows the dependence of the *x* beam distribution at the target on the strength of the octupole. Weak octupoles modify only the far fringes whereas as the octupole strength increases the central part of the distribution becomes flatter. However, very strong octupole results in large spikes at the distribution tails.

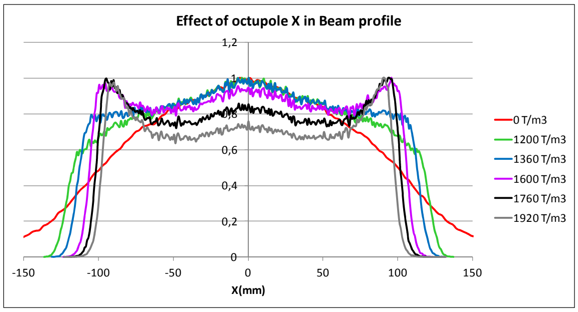

Figure 6: Modification of target beam distribution by different octupole strength.

The influence of octupoles on the beam uniformity and on peak edges is shown in Fig. 7. The formation of beam spikes at edges reduces the uniform region.

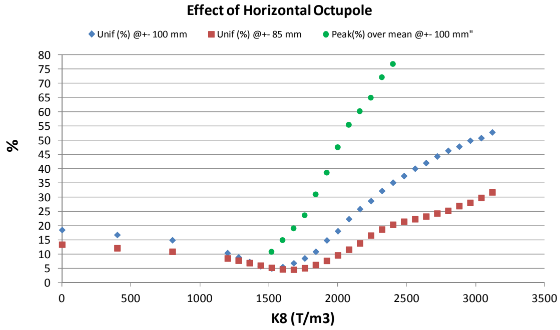

Figure 7: Beam uniformity (at two different regions: ±100mm, red square, and ± 85 mm, blue diamonds) and the relative peak height (green circles) for different octupole strength.

As duodecapoles will only affect the insignificantly populated far beam fringes, they will have negligible effect on the target beam core. Stronger duodecapoles will result in unacceptable losses between the duodecapoles and octupoles. A combined octupole-duodecapole magnet would avoid this problem, but its feasibility still needs to be proven.

Figure 8 illustrates the impact of both duodecapoles and octupoles in both transverse directions on the target beam. Note the presence of large y particles as result of the *XY* coupling, not yet optimized.

CONCLUSION

The application to DONES of the beam shaping method with non-linear magnets has been shown, being highlighted the strong impact of the phase advance on the optimum magnet tuning procedure.

Future simulations will include an optimization of the phase advance, minimization of x-y coupling and analysis of the 10x5 cm^2 beam configuration. Additionally, of particular importance are the error studies to define magnets tolerances and analysis of the space charge.

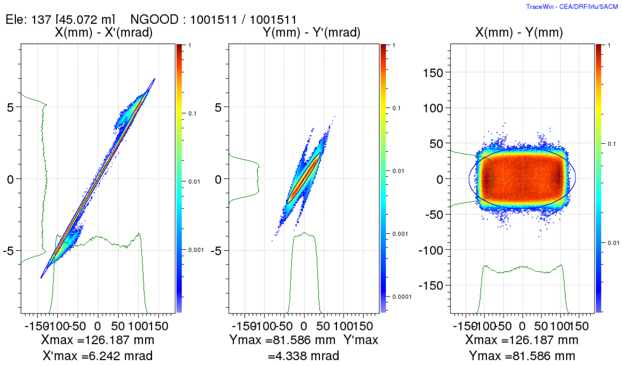

Figure 8: Target beam phase space distribution.

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