THE BEAM EXPANDER SYSTEM FOR THE EUROPEAN SPALLATION SOURCE

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Abstract

At the European Spallation Source (ESS), neutrons are produced by high energy (2.5 GeV) protons impinging on a target. The lifetime of the target is highly dependent on the beam footprint. In general, the lower the average current density, the longer the lifetime of the target will be. A detailed study of two different expander systems suggested to be used to obtain the desired beam footprint has been undertaken. For reference, a system of quadrupole defocusing is used. The two systems under study are expansion of the beam by magnetic multipoles and raster scanning (painting) of the narrow linac beam pulse over the target area. The designs, specifications, and comparative risks of the three systems will be described.

INTRODUCTION

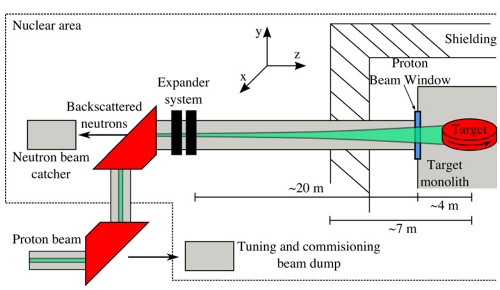

Figure 1: A sketch of the last part of the HEBT and target.

At the ESS [1], a few beam line elements will inevitably be exposed to the full average beam power of 5 MW (125 MW during the 2.86 ms pulse). Besides the target, the proton beam window, isolating the vacuum of the linac from the target section, will be traversed by the beam, cf. Fig. 1. For the given set of high level parameters, the beam impact on these critical elements can advantageously be reduced by broadening the transverse beam distribution of a pulse, *i.e.* expanding the beam upstream. The final part of the ESS High Energy Beam Transport (HEBT) will thus include a beam expander system; cf. [2] for a description of the full ESS HEBT.

PROTON BEAM WINDOW AND TARGET

In general, locally large transverse current densities will augment material damage which could affect reliability of the exposed element (proton beam window or target).

The exposed element will contain a restriction as to the extent of the transverse area available for the beam. Disregarding the nature of the region beyond this, it will be referred to as a "sensitive" region. The area available for the beam to traverse will be referred to as the "design" region. The current density within the design region is minimized by choosing a broad beam distribution with only negligible current in the sensitive region. Considering only the minimization of the current density, a 2D top-hat distribution extending to the border of the sensitive region would seem optimal. However, since large beam profile gradients can cause thermal stress in an element due to large local differences in beam heat deposit, a sharply edged distribution should be avoided. Flattening of the beam profile while avoiding sharp edges and reducing beam tails is thus advisable. Temporal variation of the local intensity will also affect the lifetime of the exposed elements, as large temporal current density variation will cause thermal fatigue in the element material. The beam and proton beam window/target are thus best left in a steady-state demanding a high Mean Time Between Failures (MTBF) or reliability of the facility, including the expander system.

EXPANDER SYSTEMS

In the following, three candidate systems for diluting the beam pulse density on the target surface will be discussed: 1) a system of magnetic quadrupoles, 2) multipoles, or 3) deflecting dipoles sweeping the narrow pulse on the target surface.

As an input beam distribution to the expander system, we shall assume a 2D Gaussian in the transverse plane, although the real distribution is expected to be a central Gaussian with a halo distribution. For simplicity, most principles will be explained considering only 1D distributions. We define a transverse extent x_t within which 99% of the beam should strike. The parameter x_t thus marks the onset of the sensitive region. To verify beam distribution on the target, a diagnostics tool (like a camera looking indirectly at a fluorescent coating on the target surface) is necessary.

Quadrupole Expansion

An expander system based on quadrupoles conserves the Gaussian transverse shape, but increases the xy root mean square (RMS) σ_x and σ_y, thus lowering the maximum current density value for a fixed total current (50 mA during an ESS pulse). As the current distribution shape is not improved, this linear expander system is considered the base-

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line. A Gaussian distribution has only modest gradients, and expanding to $3\sigma_x = x_t$ keeps 99.7% of the beam within the design region. A set of few (4–6) quadrupole magnets has been found sufficient to prepare the footprint, while still retaining flexibility. In order to further decrease the maximum current density while respecting the sensitive region, the particle distribution must effectively be changed.

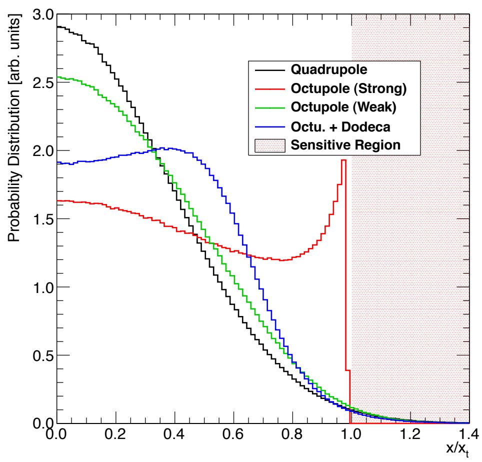

Figure 2: Normalized transverse distributions on the proton beam window/target for various expander systems. In all cases, the sensitive region is struck by less than 1% of the particles.

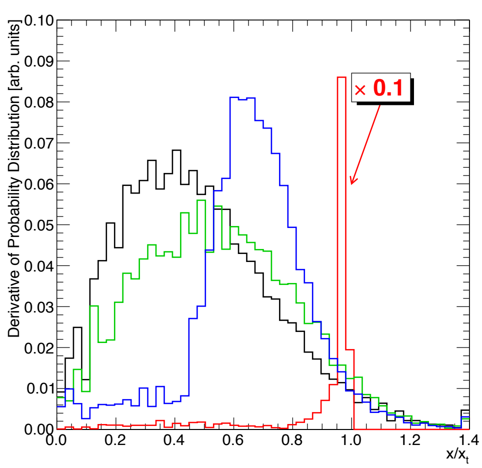

Figure 3: The bin-by-bin derivatives of the distributions of Fig. 2. The same legend applies. Notice that the curve corresponding to a strong octupole field has been scaled by 0.1 to put the curves on the same scale!

Multipole Expansion

Flattening high-power ion beams using a nonlinear lens system consisting of magnetic quadrupoles *and* magnetic multipoles ($2n$ pole elements with $n \geq 3$, *i.e.* sextupoles, octupoles, *etc*.) has long been studied [3] and is considered as the baseline for *e.g.* the IFMIF facility [4].

Considering an elliptical distribution in (x, x') phase space, a properly applied octupole magnetic field will symmetrically fold the tails towards the center, leaving the projected x distribution somewhat flatter. This inherent tail reduction allows for further broadening of the distribution, while still respecting the sensitive region.

Fig. 2 shows a comparison of normalized 1D particle distributions for various expander systems. The multipole Monte Carlo simulations are based on the Eq. (11) from [3]. In each case, the feasibility of constructing the expander system, *i.e.* field strengths vs. apertures and magnetic lengths, is disregarded for now. Here, the magnet parameters are freely tuned to flatten the distribution while respecting the sensitive region and avoiding large distribution gradients. Whereas strong octupole fields are seen to lower the local peak levels considerably, the distribution suffers from strongly spiked fringe peaks ('ears') near the distribution edge. Fig. 3 shows the gradients of the distributions in Fig. 2. In case of a misaligned octupole, the distribution will be skewed, thus enhancing one of the fringe peaks. Any higher- and even-order multipoles ($n = 6, 8, \ldots$) can be used to compensate the undesirable fringe peaks. In Fig. 2, combining an octupole and dodecapole field is seen to remedy the fringe peaks, while still lowering the peak levels to $\simeq 70\%$ in 1D; the gain can of course be squared when applying to both transverse dimensions. At the very best, the peak current density could be reduced by close to $\simeq 60\%$ (or $\simeq 36\%$ in 2D) compared to the Gaussian value. A more uniform distribution can thus be obtained by combining octupoles and dodecapoles, possibly in a combined-function magnet.

At ESS's average beam power level of 5 MW, beam distribution tails corresponding to even tiny fractions of the beam could be harmful to the machine. An even more attractive feature of a multipole system is thus its efficient tail reduction. Using weak octupoles, the tails are clearly reduced compared to the peak. Apart from the strong octupoles, all systems have comparable current density gradients, cf. Fig. 3.

For feasible 2D flattening, uncoupled adjustment of the x and y multipoles is preferable. By setting a large beam size aspect ratio—a waist ($|\sigma_y/\sigma_x| \ll 1$ in the x multipole)—coupling can be efficiently avoided. To accomplish this, a 2D multipole expander system comprises 1) a section to prepare the first waist (quadrupoles), 2) the first (*e.g.* horizontal) multipole, 3) a section to prepare the second waist, 4) the vertical multipole, 5) the final active expander elements (quadrupoles) before a long drift section. Such a system thus necessitates considerable longitudinal space, several tens of meters. Designing the octupoles also involves the trade-off between having a large impact on the beam—the integrated octupole strength is inversely proportional to the aperture cubed—while retaining sufficiently large apertures to avoid beam losses. This balance becomes increasingly difficult with a very rigid beam.

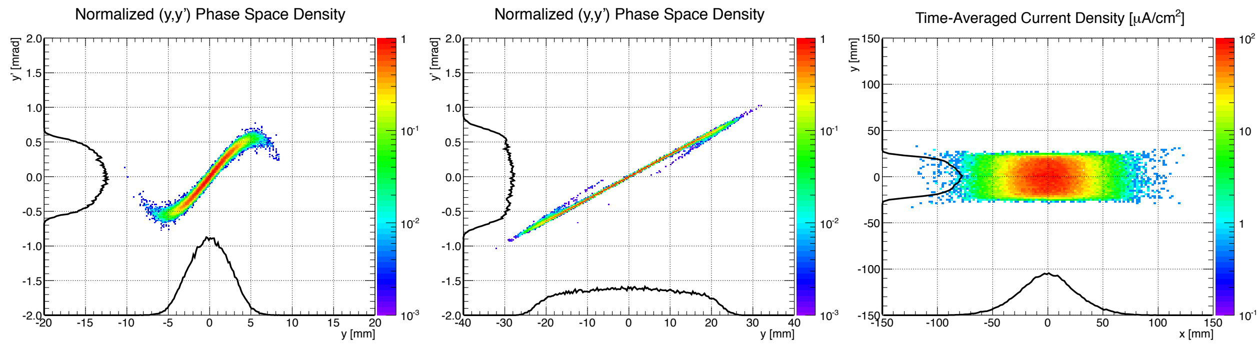

Figure 4: TraceWin [5] simulations based on transporting 10^5 particles. Left Panel: the (y, y') phase space distribution at the exit of the octupole, $s = 0.8$ m. Middle panel: the (y, y') phase space distribution at target, $s = 34.7$ m. Right panel: the (x, y) distribution on target has a Gaussian horizontal profile and an almost uniform vertical profile.

The ESS Case Since the primary ESS target candidate is a horizontally rotating disc, the demands for the x distribution are lowered, and horizontal quadrupole expansion could suffice. As a baseline distribution, we have aimed for a horizontal Gaussian profile with $x_t = \pm 70$ mm and a vertical tophat with $y_t = \pm 25$ mm. This footprint is likely to change as the target design is frozen. Using 4 quadrupoles and a single Ø50 mm octupole of 800 mm magnetic length and $d^3B/dx^3 = 22.4\,\mathrm{kT/m^3}$ (0.35 T pole tip field), a suitable distribution can be obtained. This octupole appears feasible from initial 2D field calculations. Fig. 4 shows not only how the octupole affects the (y, y') phase space, but also the (x, y) distribution on the target surface. In the example, the expansion system takes up 4.9 m and the beam passively expands during a 30.8 m drift to the target. The octupole ensures a very efficient tail reduction.

From the simulation, the maximum current density on the target is found to be $\simeq 100\ \mu\mathrm{A/cm^2}$. The single octupole thus reduces the maximum current density to 63% of the corresponding value for a 2D Gaussian with the same (x_t, y_t), $\simeq 160\ \mu\mathrm{A/cm^2}$.

Raster Scanning ('Painting')

Beam painting is a technique where a uniform beam distribution of any arbitrary shape can be obtained by painting an only slightly expanded beam over a larger surface using at least two sweeping dipoles. For the ESS, where a flat rectangular footprint is preferred, a similar scheme is in principle possible. However, due to the target's thermal constraints, the beam footprint should be fully illuminated within on pulse period. This means that the sweeping magnets have to be extremely fast, which in turn sets large requirements on the power supplies. Having several parallel sweeps in each direction is clearly excluded, while a circular pattern is more feasible through sinusoidal currents in the sweeping magnets. This sets a limit to the degree of maximum current density reduction.

A major concern with this method is failure of the scanning supply, causing a full pulse to impact at the same small target spot, "target burning". The AC components clearly require a more complex, redundant, fail-safe design and monitoring of component failure to avoid target burning. With DC multipole elements, monitoring is more straightforward. Machine commissioning will take place with a low power beam, most likely by reducing the pulse duration considerably. Since painting has an inherent time structure, this expander scheme cannot be fully tested using a shorter pulse. The effect of multipole expansion is independent of the pulse duration.

CONCLUSION

The existence of an efficient expander system in the ESS HEBT has been justified. Using schemes beyond linear focusing can lower the maximum current density by altering the transverse beam distribution within the requested target area. Using octupoles seems most promising, especially due to the method's efficient tail reduction. A feasible octupole design relevant to the ESS HEBT was presented. The stability and error sensitivity of the systems are yet to be studied.

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