BEAM OPTICS FOR THE TARGET BEAM LINES OF THE EUROPEAN SPALLATION SOURCE

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Abstract

The beam optical design of the he target beam line complex of the European Spallation Source is discussed. These beam lines join beams from two 1.334 GeV accumulator rings and deliver the beam to a beam dump, a 1 MW target, a 5 MW target, and a transmission muon target in the beam line to the 5 MW target.

1 INTRODUCTION

The target beam line complex of the European Spallation Source (ESS) joins beams from both accumulator rings and delivers the beam (see Fig. 1) to a beam dump, a 1 MW target, a 5 MW target, and a transmission muon target in the beam line to the 5 MW target.

The previous beam optical design of the target beam lines [1] was based on modules made of quadrupole triplets, rather similar to those used in the accumulator rings. This, however, entails comparatively high quadrupole excitations and limited flexibility of tuning the beta functions and dispersion.

Here we start from an entirely different perspective [2]. As a basic building block of the beam line complex we use 90° and 60° FODO cells with a cell length of 8 m and 12 m, respectively. The former are used to limit the length of the beam line and the latter are only used in the long 10 Hz line to save magnets and reduce their excitation. FODO cells with 90° or 60° phase advance in both planes have rather nice beam optical properties:

- It is possible to use a large number of equally designed magnets, which reduces the cost.
- The horizontal and vertical beta functions are oscillating out of phase, i.e. β_x is large in focusing quadrupoles where β_y is small. This allows almost independent control of the horizontal and vertical plane and four consecutive quadrupoles allow to control $\beta_x, \alpha_x, \beta_y, \alpha_y$.
- Placing bending magnets with equal/opposite bending angle $180^\circ/360^\circ$ betatron phase apart cancels their contribution to the dispersion.
- Displacing a 180°-section longitudinally by making the drift space before the section a little longer and making the drift space following the section a little shorter generates beta beat inside the 180°-section only, but does not affect the beta functions outside.
- Powering two consecutive focusing quadrupoles in a 90° lattice equally only produces a local beta beat between the two quadrupoles, but does not affect the beta functions outside.[1] This feature can be exploited to tune non-zero dispersion without perturbing the beta functions.
- The required elliptic target spot size is easily achievable by letting the beam expand in a drift space following the last two quadrupoles which can be used to tune the spot size on target.

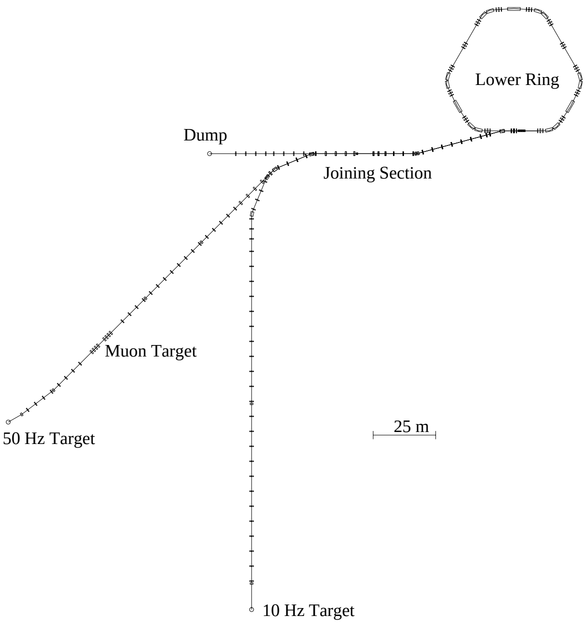

Figure 1: *Layout of the ESS Target Beam Lines.*

The beam delivered from the accumulator rings has a design emittance of $30\,10^{-6}\,\pi\,\mathrm{m\,rad}$. The aperture requirement throughout the ESS target beam line complex is set to

$$\mathrm{Aperture} > \sqrt{480\,10^{-6}\beta} + 6\,10^{-3}D + 3\,\mathrm{mm} \qquad (1)$$

where β is the beta function, D is the absolute value of the dispersion, and the 3 mm is the thickness of the vacuum chamber wall. Orbit errors and misalignment are absorbed in $480\,10^{-6}\pi$m rad.

2 BEAM OPTICS

After exiting the rings the beam must be matched into a 90° FODO line using 4 consecutive quadrupoles. Af-

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[1] This is correct for thin quadrupoles. Long quadrupoles generate aberrations proportional to higher order in the quadrupole excitation.

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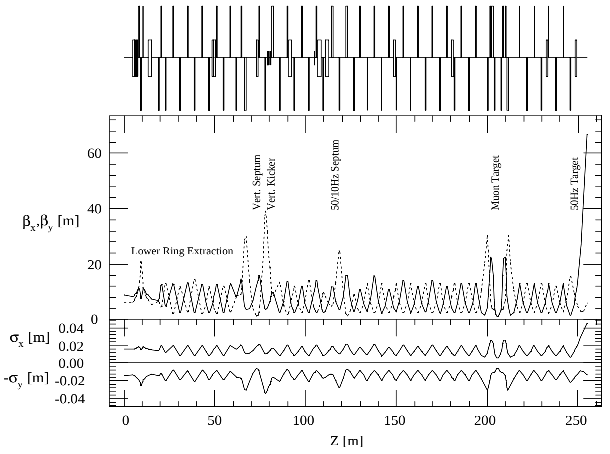

Figure 2: *Beam lines to the 50 Hz Target.*

ter cancelling the dispersion generated by the ring septum with two short 0.6 m long bending magnets and fine tuning the dispersion by the method explained above, the upper beam is bend downwards and joined with the beam from the lower ring in a vertical septum magnet and a kicker. The section leading the upper beam which is 2 m above the lower beam down is 15 m long and called the "elevator". The $360°$ vertical phase advance through the elevator that is needed to cancel the vertical dispersion is generated by a powerful quadrupole triplet (gradient = 8.5 T/m). The outermost quadrupole is 5.2 m away from the center of the vertical bending magnets and, taking the beam chamber radius into account results in a moderate half-height restriction of those magnets of 0.62 m. The magnets in the lower line a pushed away from the joining septum, resulting in a 0.8 m half-height restriction for the closest quadrupole in the lower line. After the joining septum the beam line is matched into a $90°$ FODO lattice.

Most of the magnets in the joining section have rather modest requirements with a few notable exception: (i) The triplet in the elevator has the cross section of the standard quadrupole, but is 50 % longer. (ii) The joining septum limits the aperture to 3 sigmas in order to allow sufficient blade thickness. (iii) The associated vertical kicker is about 15 % stronger than the ring extraction kicker. (iv) One non-standard quadrupole between between the kicker and the septum is required in order to accomodate the kicked orbit.

The next special area is the first switch yard which leads the beam to the dump target if the first $22.5°$ bending magnet is turned off. The beam enters the dump line through a zero degree port of the C-type bending magnet. The first four quadrupoles in the dump line are pushed away from the bending magnet by 0.8 m. This allows staggering of these quadrupoles with those in the 50 Hz line. The rest of the dump line consists of regular $90°$ quadrupoles. The rms beam spot size on the dump is 4.4 by 4.4 cm, but can be tuned easily with the last two quadrupoles, which are 10.28 m away from the dump and may have to be made radiation hard.

If the first $22.5°$ bending magnet is turned on the beam is bend into the 50 Hz line. This bending magnet generates dispersion of up to 1.5 m which is cancelled with a second $22.5°$ C-type bending magnet before the beam enters the second switch yard. There every fifth pulse is kicked into the the bending channel of two septum magnets that deflect the beam by $22.5°$ and lead it to the 10 Hz target. If the switching magnet is turned off, the beam enters the 50 Hz beam line where the first four quadrupoles are pushed away from the septum to allow staggering. After an initial matching section the beam is vertically elevated by 4.3 m to ground level and encounters the muon target where the beta functions are focused to 1 m. The interaction point is 1.5 m away from the face of the closest quadrupoles. The optics is designed to keep the maximum beta functions in the 30 m range and the gradients below 7.5 T/m such that standard quadrupoles can be used, even though they have to be radiation hard. The length of the muon target is chosen to be a multiple of the normal $90°$ cell length such that it can be substituted by regular FODO cells. After exiting the muon target the beam is bend by two $7.5°$ bending magnets onto the 50 Hz target that is 5.4 m after the final (possibly radiation hard) bending magnet. On target the rms beam size is 4.4 by 1.3 cm but can be tuned by the last two quadrupoles.

As already mentioned above every fifth pulse is directed into the deflecting channel of two septum magnets that bend the beam into the 10 Hz line. The orbit and beam sizes between the switching magnet and the septum are optimized such that standard quadrupoles can be used. The septum magnets generate dispersion which is cancelled in another $22.5°$ C-type bending magnet $180°$ phase advance downstream. Immediately following the last bending magnet the phase advance per cell is changed to $60°$ in order to reduce the number of quadrupoles in the long beam line to the 10 Hz target. Before the target the beam is brought up 4.3 m to ground level. In order to cancel the dispersion the two $3.4°$ bending magnets have to be 6 cells apart. The dis-

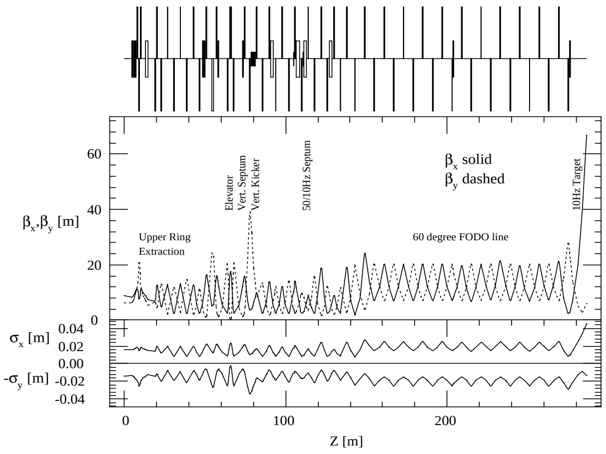

Figure 3: *Beam lines to the 10 Hz Target.*

tance between the last bending magnet and the 10 Hz target is 10.1 m in which the beam expands to 4.4 by 1.3 cm but can be tuned with the last two quadrupoles.

3 DIRECT LINAC BEAM TO 50 HZ TARGET

In order to allow the direct linac beam impinge on the 50 Hz target with its much reduced emittance of $0.6\,10^{-6}\pi$m rad, the regular 90° FODO quadrupoles after the muon target can be turned off and the muon target quads can be used to tune the spot size. With the reduced emittance we were able to produce rms beam sizes on the 50 Hz target of 4.4 by 1.3 cm without excessive quadrupole excitations. If the regular quadrupoles after the muon target are connected in series to their own power supply this feature will not incur any extra costs from the beam optics point of view. In this mode of operation one has to keep in mind the very large sensitivity of the target position on the quadrupole misalignment. The amplification factor is on the order of 200 for some quadrupoles such that 0.3 mm misalignment leads to 60 mm offset on the target which is about 1.5 rms beam sizes. Thus one has to carefully align the magnets between the muon target and the 50 Hz target.

4 MAGNETS

The large beam power of the 1.334 GeV proton beams and large emittances of $30\,10^{-6}\,\pi$ m rad together with the requirement for small beam losses implies to use large aperture magnets. We propose to mostly use two types of standard quadrupoles. The short .A quadrupoles are 0.40 m long and have standard radius 0.11 m. They are used in the 60° and 90° FODO lines. They should be designed for a maximum gradient of 75 kG/m. The long .B quadrupoles are 0.60 m long and have standard radius 0.14 m. They are used when the integrated gradient needs to be higher or the radius needs to be larger. They should be designed for maximum gradient 70 kG/m. A small number of special quadrupoles are also needed and will be discussed in the respective sections.

All bending magnets are rectangular bends (they do not focus in the bend plane, but in the other plane) and they come in two varieties: The .S bending magnets are 0.6 m long and the .L are 1.8 m long C-type magnets, which allow extracting beams through a zero-degree port. This feature is needed at the dump-line junction. Both .S and .L magnets are designed for a peak field of 16 kG.

5 MUON TARGET

The Muon Target section is designed such that it has a length that is a multiple of the normal FODO cell length, such that initially it can be replaced by standard FODO quads. The distance of the Interaction point and the final quad is 1.5 m and the minimum beta function is 1 m in both planes. These specifications are achieved by using a standard triplet optics that is matched into the 90° FODO line. The maximum beta functions are 30 m. The magnets in the Muon target area QD24.M.B,...,QD27.M.B must be constructed to withstand a high radiation dose.

6 TUNING AND DIAGNOSTIC

In order to correct the orbit we propose to use 26 horizontal and 26 vertical orbit correctors together with 45 beam position monitors at critical places in the target beam line complex. The correctors should provide 3.5 mrad kick angle and should be placed around beam pipes with 0.11 m and 0.14 m radius.

A total of 8 current monitors are needed. Two should be placed near the first quadrupole in the upper and lower ring extraction beam lines, one after the joining septum, one in the dump line, and one near the start and end of the 50 Hz and 10 Hz lines, respectively.

In order to match the beam properly into the respective beam lines a total of 30 beam size monitors (harps) are required. Half of them to measure the horizontal and half to measure the vertical beam size. In the dump, 50 Hz and 10 Hz line they should be arranged in groups of 4 in order to measure the complete incoming beam's matrix. To each of the beam size measuring section corresponds a tuning section of normally four quadrupoles on individual power supplies that allow to control the proper matching of the beam into the beam lines.

There will be 3 m long beam loss monitors placed every 4 m along the beam lines, resulting in a total number of 163. Information about the beam position on the targets will be generated by thermo-couplers on the target.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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