FODO LATTICE DESIGN FOR BEAM HALO RESEARCH AT SNS

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Abstract

Beam halo is a big challenge for high intensity accelerators. Knowledge of the mechanisms of halo formation could help to prevent it. The Spallation Neutron Source (SNS) Beam Test Facility (BTF) is a functional duplicate of the SNS front end with enhanced diagnostics capable of accelerating 50 mA H- or protons to 2.5 MeV. To explore halo development in both matched and mismatched beams, a dedicated FODO lattice is being designed as an extension to the BTF. The FODO lattice will be 3.5 meters in length and is comprised of 16 quadrupole magnets, with dedicating matching magnets. Simulations of the design lattice show halo can be seen clearly in the phase space density plot when beam is mismatched. Details of the FODO design will be presented in the paper.

INTRODUCTION

Beam halo is a big challenge for high intensity and high power accelerators, because it will cause particle loss which can damage accelerator components and lead to unwanted radioactivity. To understand the mechanisms of halo formation, some experiments have been conducted at LANL (Los Alamos National Laboratory) in US [1] and at IHEP (Institute of High Energy Physics) in China [2]. But they all failed to accurately predict emittance growth and halo by using simulation codes for mismatched lattice case. The failures were not the codes are not sophisticated enough to reproduce the measured beam profile, but knowledge of the input Twiss parameters and emittances was not sufficient for predicting beam halo [3].

A similar experiment facility is being built at Spallation Neutron Source (SNS), which consists of the beam test facility (BTF) and a dedicated FODO lattice. The BTF is a functional duplicate of the SNS front end capable of accelerating 50 mA H- or protons to 2.5 MeV [4], and one of the main goals of it is to conduct the first direct 6D phase space measurement of a hadron beam with enhanced diagnostics [5]. The FODO lattice being designed will be an extension to BTF, it allows to explore halo development in both matched and mismatched beams by using the results of the direct 6D phase space measurement as inputs which is the main difference from the mentioned previous experiments. Design of the FODO lattice will be described in detail in this paper.

CHARACTERIZATION OF HALO [6]

Halo is a kind of beam distribution, it is far from the beam core and has a low particle density (10^{-6} to 10^{-4} relative to peak density), particles of it have a large oscillation amplitudes and can reach the aperture of beam line causing uncontrolled beam loss. Usually, a beam distribution in 2D phase space can be obtained easily by beam measurement, but it cannot easily tell whether a halo exists or not (as shown in Fig. 1 (a)). Therefore, the method of plotting phase space density vs. normalized radius is proposed to easily identify a halo in a beam distribution. The following procedures show how to transform a 2D phase space distribution into a phase space density plot:

a. Transform particle coordinates x, x' to normalized coordinates according to the following formula:

$$x_n = \frac{x}{\sqrt{\beta_{rms}}}$$

$$x_n' = \frac{\alpha_{rms} \cdot x}{\sqrt{\beta_{rms}}} + x'\sqrt{\beta_{rms}}$$

where α_{rms}, β_{rms} are the RMS Twiss parameters.

b. Calculate $r = \sqrt{x_n^2 + x_n'^2}$, count number of particles N_r within dr intervals.

c. Plot normalized particle numbers $n(r) = \frac{N_r}{2\pi r dr}$ vs. r using in semi log scale.

In order to identify a halo more conveniently the phase space density curve can be compared with its Guassion fit curve or the input particle density curve (as shown in Fig. 1 (d)), and deviation between them means a halo exists. Figure 1 shows the results of every transformation step.

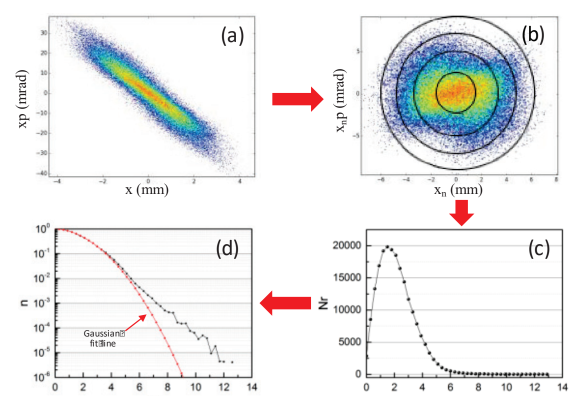

Figure 1: Transformation of a 2D phase space distribution into phase space density plot.

FODO LATTICE DESIGN

Figure 2 displays the lattice configuration of one FODO period. In the figure, Ld, Lq and D denote the drift length, quadrupole length and quadrupole spacing, respectively. Quadrupole Q1 and Q2 have equal but opposite gradients.

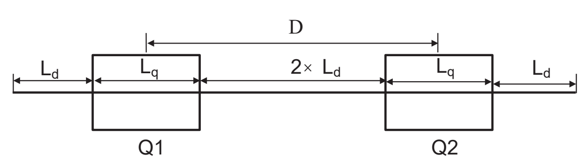

Figure 2: Lattice configuration of one FODO period.

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Figure 3 shows the phase space density plots of different zero current phase advance and FODO period when mismatch factor is 2, and in the plots C means FODO periods. It should be noted that mismatch factor equals 1 in the paper when beam and FODO lattice are matched.

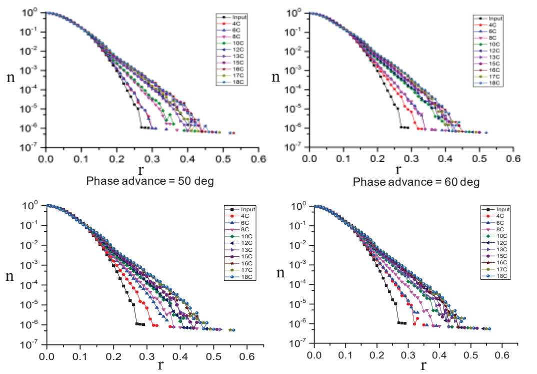

Figure 3: Phase space density plots of different phase advance and FODO periods.

Figure 3 indicates that, phase space density curves of particle distributions at the end of a FODO lattice deviate distinctly from the input particle density curve when FODO length is or bigger than 8 FODO periods, which means halo can be produced with 8 or more FODO periods. Our studies also show beam sizes are comparatively small when zero current phase advance is around 90 deg, which indicates the phase advance should not be small to get a small beam size. From beam dynamics theory we know phase advance is proportional to magnet gradient and spacing. Considering the requirements of the FODO lattice which include short length and small magnet gradients, it was determined the final FODO lattice is eight FODO periods long (3.52 meter, as shown in Fig. 5), quadrupole gradient is 20 T/m, quadrupole length and spacing are 75 mm and 220 mm, and the zero current phase advance is 78.7 deg. Figure 4 shows the phase space density plots of the final FODO lattice design, and it tells no halo is developed with matched beam and halo is developed for mismatched case, particles in halo can reach further with a bigger mismatch.

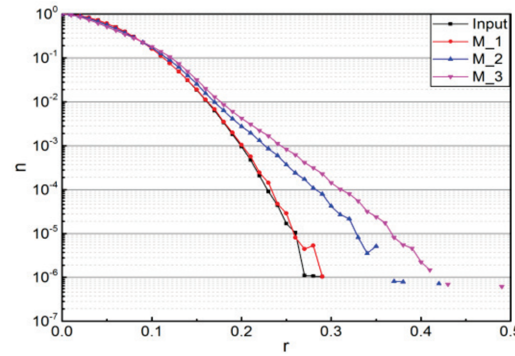

Figure 4: Phase space density plot at the end of the final FODO lattice.

DESIGN OF BENDING SECTION AND MATCHING SECTION

Figure 5 is the whole beam line layout of BTF and FODO lattice. Due to the limited space a bending section was designed to make the FODO lattice installed parallelly to the BTF line. A matching section was designed, too, to match the output beam of the bending section to the input requirements of the FODO lattice.

$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ 0 & 0 & 1 \end{bmatrix}$$

No dispersion is required when beam transmits through the bending section. Assuming M is the transfer matrix through one section of beam line containing bending magnets, and eliminating dispersion is achieved by making the dispersion term M_{13} and M_{23} equal zero. Other design requirements include short section length but having enough space to install diagnostics devices (such as

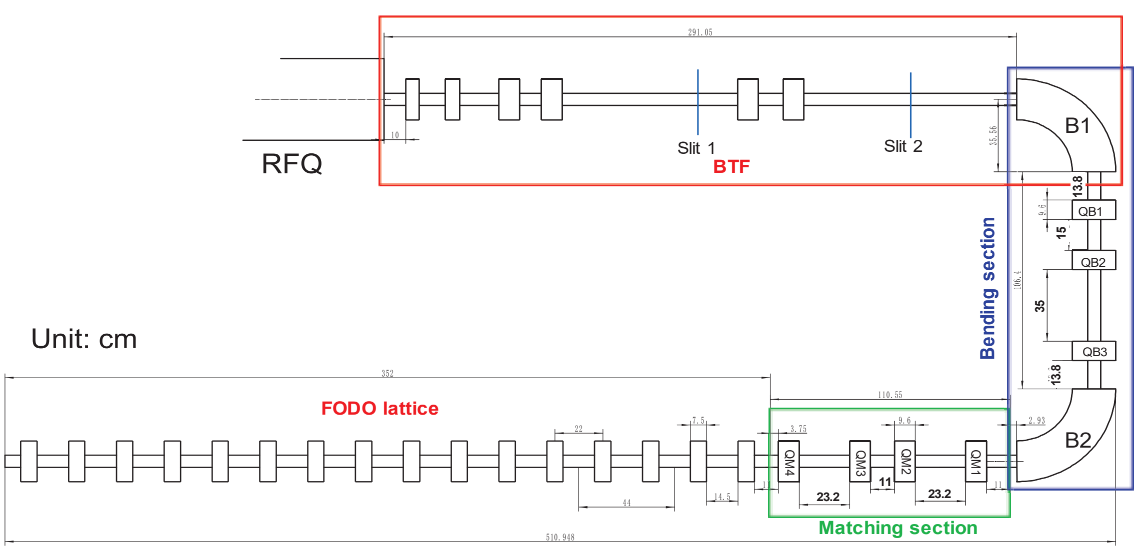

Figure 5: Whole beam line of BTF and FODO lattice.

bunch shape monitor, etc.), small beam sizes and not very high magnet gradients. Three quadrupoles are needed to meet requirements, and layout of the bending section is shown in Fig. 5. Gradients of the three quadrupoles are 5.5 T/m, 8.1 T/m and 1.1 T/m, respectively.

Matching section contains four quadrupoles, it must meet the requirements of mismatch factors of the FODO lattice. Quadrupole gradients are required not bigger than 20 T/m to utilize the existing quadrupoles at SNS. Layout of the matching section can be seen in Fig. 5.

SIMULATION OF WHOLE BEAM LINE

The whole beam line starting from RFQ exit was simulated by using the PIC (particle-in cell) simulation code PyORBIT which is developed at SNS [7]. The beam distribution at RFQ exit, calculated by measurements at BTF, was used as the input distribution for the simulation. Fig. 6 shows the particle phase space density plot in vertical plane at the end of the FODO lattice. From the plot we can see halo is developed when mismatch factor is 3, but halo is developed, too, when mismatch factor is 1. To figure out the problem beam distributions at different locations in the whole beam line were analysed, locations includes the end of bending section, location of slit 1 (see Fig. 5) and RFQ exit. Results indicate halo has already been developed at the location of slit 1, and zero current results show there is no halo at the same location, therefore, it can be concluded the halo at slit 1 is mainly caused by space charge forces other than mismatch.

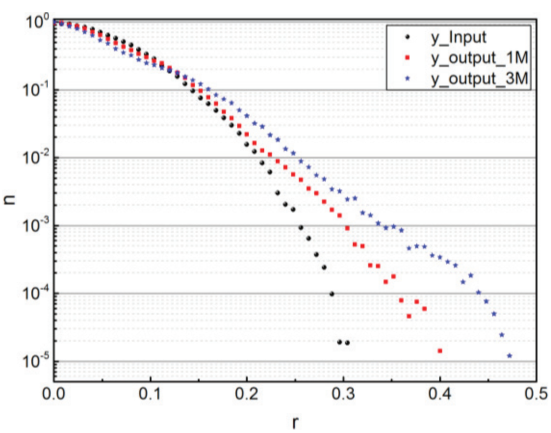

Figure 6: Phase space density plot at the end of whole beam line with measured input distribution.

CONCLUSION

A FODO lattice has been designed to study the mechanism of halo formation, and simulation results show there is no halo with matched beam and halo can be identified clearly with mismatched beam. Simulation of the whole beam line with the measured beam distribution shows halo has already been developed at the location of the first slit of BTF, therefore, the halo needs to be scrapped off before beam entering the FODO lattice to do the halo research.

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