MARS TRACKING SIMULATIONS FOR THE MU2E SLOW EXTRACTED PROTON BEAM*

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Abstract

Particle tracking taking into account interactions with fields and materials is necessary for proper evaluation of the resonant extraction losses and geometry optimization for the extraction beam line. This paper describes the tracking simulations for the Mu2e Resonant Extraction and discusses the geometry choices made based on these simulations.

INTRODUCTION

Mu2e experiment [1] uses the third integer resonant extraction from the Fermilab Delivery Ring to deliver the 8kW proton beam to the production target. Beam losses at the extraction location are a very serious concern of the design. Heavy in-tunnel shielding will be needed even for localized beam losses as low as 1% in order to keep prompt radiation dose levels on the surface within acceptable range and to reduce the residual doses in the tunnel to facilitate the machine maintenance. Another consequence of high beam losses is activation of hardware, which makes its servicing more difficult. Extraction channel geometry needs to be optimized for best extraction efficiency. We define the extraction channel here as the section of the beam line including two Electrostatic Septa (ESS) straddling a focusing quad Q203, defocusing quad Q204 and two magnetic septa straddling the large aperture quad Q205. The layout of this section is shown in Fig. 1. Extracted beam is separated from the circulating beam and deflected horizontally in the ESS and vertically in the Lambertson and the C-magnet. Quads Q204 and Q205 provide additional horizontal and vertical kicks outwards due to their defocusing and focusing functions correspondingly. The process of beam passage through the extraction channel and generation of losses in the ESS has been studied using tracking simulations with MARS program [2]. MARS provides a very detailed description of particle interaction with materials as well as tracking in the fields. Also MARS provides calculation of the prompt dose and residual activation maps, which are not discussed here.

MARS MODEL

Most of the beam line elements were described in the model using MARS “extended” and “nonstandard” types of geometry. Mixing these two types has to be done with care and should be avoided in volumes with thin objects. It is important that tracking in the ESS handles correctly transitions in and out the tiny foil strips, therefore only “extended” objects are used there. The volume recognition is verified in Fig. 2 that shows the proton beam crossing through the foil plane. Red dots on the plot indicate locations of the ends of steps along the particle path. The points are random outside the foil plane but in the plane they concentrate on the foil boundaries; this demonstrates that the volume transitions are properly recognized. The ESS planes are formed by the W/Re 50µ thick foils, of 1mm width, spaced at 2.6mm centre-centre. The foil shapes in Fig. 2 are exaggerated by the strong compression in z-direction along the beam path.

Particle samples for the MARS tracking have been provided from the resonant extraction simulation in the Delivery Ring made with the Synergia program [3,4]. The phase space of two such samples is shown in Fig. 3. The green sample (Sample 1) represents particles at the entrance of the ESS1 that arrive beyond the nominal position of the septum foil plane in X - these are the extracted particles. The red sample (Sample 2) represents the outmost parts of the beam that still circulate in the ring but will be extracted after the next 1, 2 and 3 turns.

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Figure 1: Extraction beam line, plan view. Extraction channel is marked by the red dashed line. Hatched yellow blocks are the in-tunnel shielding around the most activated elements.

Figure 2: Beam tracking through the foil plane. Red dots show stopping points between two consecutive steps of a particle. They “light up” the foil strips boundaries.

4: Hadron Accelerators
T12 - Beam Injection/Extraction and Transport
Beam losses

Beam scattering and losses are analysed in the detector placed behind the C-magnet. There is a deficit of protons in the detector due to the direct local losses in the extraction channel. There will be also distributed losses downstream in the ring and the extraction beam line because not all the remaining protons are contained within the machine acceptance. Figure 5 shows the phase space of the beam in extracted (green) and circulating (blue) regions. Scattered protons form the halo shown in red. Cyan ellipses are the 20 π-mm-mrad boundaries for the ring and extraction beam line acceptance.

Figure 5: Phase space of the beam at the C-magnet exit after scattering in the ESS foils.

We chose to use the fraction of scattered particles outside the cyan ellipses in Fig. 5 as a measure of total distributed losses downstream. The sum of local and distributed losses gives the total inefficiency of the extraction. It needs to be noted that similar scattering tails are observed in vertical plane as well. Besides, scattered particles also have deficit in energy. The numbers quoted below are obtained by counting outside particles in all three dimensions. However, this is not much different from counting horizontal plane only because the tails in Y-, ΔE- and X-distributions are correlated. For the case shown in Fig. 5 the local losses are 0.7% and distributed losses are 0.55% therefore total inefficiency is 1.25%.

Choice of Foils

Since relatively recently, the electrostatic septa made with foil ribbons instead of wires have become a preferred choice for slow extraction in the high energy machines due to better mechanical stability of the foils. Here we compare the performance of the foils and wires in their typical configurations. Performance is evaluated by modelling total and local losses dependent on the beam misalignment with septum plane (angle scans). Figure 6 presents such an angle scan for ESS1 with the septum plane made of 100µm diameter W/Re wires spaced with 2mm and that of 50µ thick W/Re foils of 1mm width spaced with 2.6mm centre-to-centre.

As expected, local losses for the wire plane are smaller. Not so obviously, total losses for the wire plane are larger than that of the foil plane. That is because the total losses are close to the geometrical losses, which are proportional to the full septum plane thickness. We conclude that wires
do not have an apparent advantage over the foils. This is also a conservative comparison because options of using the 25µ thick W/Re foils or Molybdenum foils are also available.

SEPTUM LENGTHS

Extracted beam starts to separate from the circulating beam in the ESS1 due to deflection in the electrostatic field. This separation becomes substantial in ESS2, so scattering in the ESS2 does not practically contribute to losses. The circulating beam in ESS1 remains close to the foil plane, continuing to contribute to losses due to its angular spread. This component of the losses can be minimized by reducing the length of ESS1 and increasing the ESS2 length so that the total kick remains unchanged. Figure 7 shows the total losses angle scan for different ESS1/ESS2 length combinations.

DIFFUSER

Particles that experience most scattering in the foils resulting in their loss predominantly travel substantial distance through the foil plane until multiple scattering deflects them away from this plane. A clever way to reduce scattering for these particles was proposed at CERN [5]. This is done with a plane of low density material of the same thickness as the foils placed in front and aligned with the ESS1 foil plane. This diffuser selectively pre-scatters particles most affected otherwise by foil plane scattering and helps them avoid this stronger scattering in the septum plane. An angle scan with a pre-scattering diffuser is shown in Fig. 8.

CONCLUSION

A possibility to achieve a low level of beam losses for slow extraction from the Delivery Ring has been demonstrated in the MARS tracking simulations. With a careful orbit control they could be at the level of 1.5% and about half of that are the local losses. The use of a low density diffuser can reduce losses by about half. Further improvement may be made by reducing the foil thickness down to 25µ and/or reconfiguring the machine optics.

REFERENCES