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COMBINED MCNP/TURTLE SIMULATION OF THE SINQ BEAM LINE AT PSI-HIPA

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Abstract

With a nominal beam power of nearly 1.4 MW, the PSI High Intensity Proton Accelerator (HIPA) complex is currently at the forefront of the high intensity frontier of particle accelerators. A key issue of such facilities is the minimization of beam losses that could lead to excessive activation of beam line components. At HIPA, the SINQ beam line is particularly subject to relatively large losses since it receives the highly divergent beam scattered off a 40 or 60 mm thick muon production graphite target (TE). So far, for HIPA, beam line simulations have been carried out only by means of the matrix multiplication codes Transport and Turtle. Although very efficient, such tools do not allow a precise determination of beam losses whenever targets and collimators are substantially affecting the beam optics. A true understanding of how beam halo and the low momentum tail contribute to the measured losses can only be achieved by complementing the traditional simulations techniques by a tool that can transport beam particles in different materials and, at the same time, handle complex geometries like the ones of collimators situated in the beam line. Moreover, such an improved beam line simulation would give a significant contribution in evaluating the feasibility of the SINQ beam rotation system currently under study. In this paper we present a simulation of the SINQ beam line combining MCNP models of TE and collimator sections with the Turtle computation of the magnetic channel.

INTRODUCTION

The PSI high intensity proton accelerator (HIPA) generates a continuous wave 1.4 MW beam. Protons are brought to 590 MeV energy by an accelerator chain composed by a Cockcroft-Walton generator followed by an injector and a ring cyclotron [1]. After extraction, the beam is transported through the 60 m long “proton channel” provided with two graphite target stations, so-called TM and TE, located 18 m apart from each other. TM has a thickness of 5 mm, whereas TE is 40 or, alternatively, 60 mm thick (from now on, the two TE versions will be simply called TE40 and TE60). The highly divergent 570 MeV (560 MeV for TE60) beam fraction leaving TE is reshaped by a system of four copper collimators and delivered to the SINQ target through a 55 m beam line. In the proton channel, the beam current is measured by six 2nd harmonic resonators (MHC1-6) [2]. MHC1-3 are located upstream of TM, MHC4 in the section between TM and TE and MHC5-6 are installed in the SINQ beam line, downstream of TE. Although very fast, these monitors can only measure relative beam currents and need frequent recalibration. An absolute Bergoz® [3] current monitor (MHC2b), located upstream of the first target station TM, is available since 2009. A second Bergoz® Monitor (MHC6b) was installed in the SINQ beam line during the 2017 shutdown [4]. Prior to the installation of MHC6b, the calibration of the SINQ current monitors MHC5 and MHC6 was solely based on the simulation of the beam transmission through TE and its collimator system carried out using the software tool Turtle/Muscat [5]. Since 2017, the presence of the two absolute current monitors MHC6b and MHC2b has allowed the direct determination of the beam transmission through the two graphite targets along with their collimator systems. The delivered value shows that ~2.5% of beam is missing if compared to the prediction made by the Turtle/Muscat simulation (see Table 1) for both TE40 and TE60. For this reason, an improved SINQ beam line simulation has been conceived in which TE and its collimator system as well as the SINQ target collimators are modeled using the MCNPX software code. In MCNPX simulations were performed using the default INC and EVAP models by Bertini-Dresner [6].

THE SINQ BEAM LINE

Figure 1 shows 2σ envelope fits of the proton beam along the 55 m beam line between TE and the SINQ target (TSNQ) in case of a TE40 (black envelopes) as well as TE60 (red envelopes). The fit constraints are given by the beam widths measured by the profile monitors. The half aperture in both horizontal (upper) and vertical planes is 150 mm. The quadrupole magnets are depicted by the red rectangles. The location of the TE copper collimators (KHE0-3) as well as the three copper collimators protecting the SINQ target

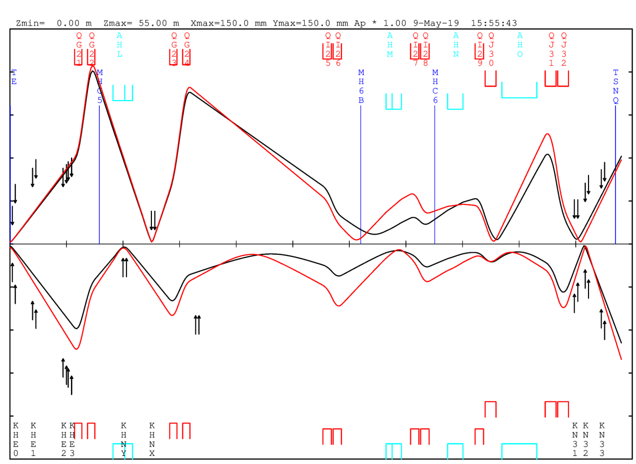

Figure 1: Beam envelope fit between TE and SINQ.

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(KHN31-33) are displayed by black arrows. Moreover, the picture shows the location of the current monitors MHC5-6 as well as the Bergoz® Monitor MHC6b. After passing through TE and the collimator system, the beam gets cut short in the horizontal plane (upper envelopes) by KHE2-3. Downstream of the first doublet, the beam is diverted downwards and then upwards by means of four dipole magnets (light blue rectangles) before being vertically dumped into the SINQ target. In the region between the last doublet and the SINQ target the beam optics has to follow the rather complicated shape of the KHN31-33 collimators.

BEAM LINE SIMULATIONS

So far, simulations of the HIPA proton channel, including the SINQ beam line have been carried out exclusively employing the Transport/Turtle computer codes [5]. Although very fast, these tools suffer severe limitations in the description of complex geometries. Conical collimators with elliptic cross section like SINQ KHNs can be implemented, but more complicated elements like collimators KHE2-3 (Fig. 2) have to be simplified with consequent loss of accuracy. Moreover, Turtle relies on the external code Muscat, which provides parameters for multiple scattering, nuclear elastic scattering and absorption but does not include inelastic scattering. Both issues can be tackled by using a more sophisticated tool like MCNPX [6]. In order to get some preliminary results in a reasonable amount of time it was decided, as a first step, to combine Turtle and MCNPX, using the latter only for the two beam line sections where TE and collimators, but no magnetic elements, are present. This way, it was possible to exploit both the computing speed of Turtle as well as the accuracy of MCNPX as far as the interaction between particles and matter is concerned. The simulation procedure starts with 10 millions protons at the upstream end of TM. The initial beam parameters are taken from an envelope fit making use of the available beam profile measurements. Turtle tracks particles to the upstream end of TE. The resulting distribution is then used as an input for MCNPX, which, in turn, simulates the beam line section between TE and the downstream end of KHE3 (the last of the four TE collimators). At this point Turtle takes over again, reading in the MCNPX output and tracking protons through the magnetic elements till the upstream end of KHN31 (the first out of three SINQ target collimators). MCNPX is then in charge of the very last part of the beam line, computing the losses through the SINQ collimators and dumping the beam distribution at the SINQ target entrance window. This procedure was carried out for both TE40 and TE60. In MCNPX the proton distribution was written out by the ptrac card on a surface without energy cut. The resulting horizontal (x) and vertical (y) distributions, compared to the ones obtained by the pure turtle simulation, are displayed in Fig. 3, whereas the corresponding beam transmissions are reported in Table 1. In the following analysis all percentages are relative to the initial sample of 10 millions particles. The upper plots of Fig. 3 display the situation at the downstream end of KHE3, i.e. after TE along with its four collimators. The MCNPX distributions show huge tails both in x and y, while the turtle distributions fall relatively fast towards zero. At this location, the beam transmission calculated by MCNPX is 4(5)% smaller than the one computed by Turtle for TE40(TE60). A deeper study has pointed out that the main difference between the two simulations happens in the collimator system KHE2-3, where for TE40(TE60) the beam absorption is around 22(30)% in MCNPX and only 15(20)% in Turtle. This huge discrepancy can be due to the simplified implemented collimator geometry as well as the absence of the inelastic scattering process in Turtle. When tracked through the beam line, the wider MCNPX distribution causes much larger losses than the Turtle one. At MHC6 the plots show that the MCNPX distribution is much wider than the Turtle one especially in the vertical plane and the difference in beam transmission becomes 6.4(7.3)% for TE40(TE60). At this location, the computed transmission can be compared to the one obtained by taking the ratio between the values measured by the two absolute current monitors MHC6b and MHC2b. The values reported in Table 1 were obtained tak-

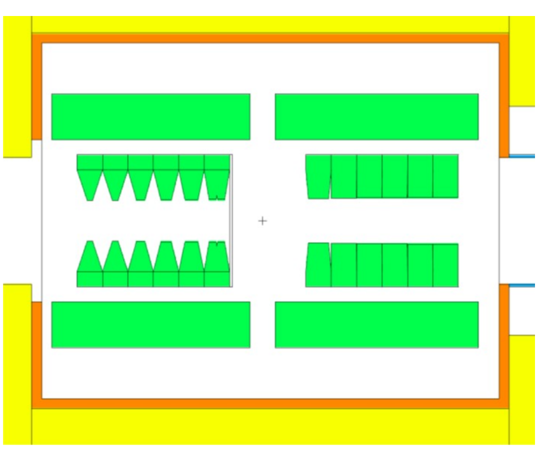

Figure 2: Cross section in the XZ-plane (top view) of the KHE2 (left) and KHE3 collimators. The beam enters from the left. The complex teeth structure of KHE2 is clearly visible.

Table 1: Compilation of beam transmission (in %) at different location of the TM-TE-SINQ beam line computed using pure Turtle as well as combined Turtle/MCNPX (MCNP in the column title) simulations for TE40 and TE60. The measured transmission MHC6b/MHC2b is also displayed for comparison.

Location	Beam Trans. (TE40)			Beam Trans. (TE60)		
	Turtle	MCNP	Meas.	Turtle	MCNP	Meas.
TM in	100	100	100	100	100	100
TE in	97.7	97.7		97.7	97.7	
KHE3 out	69.9	65.9		57.3	52.6	
MHC5	69.2	63.7		56.5	50.2	
MHC6	68.6	62.0	65.9	55.9	48.6	53.3
KHN31 in	68.6	62.0		55.9	48.6	
SINQ	68.4	61.1		55.7	47.4	

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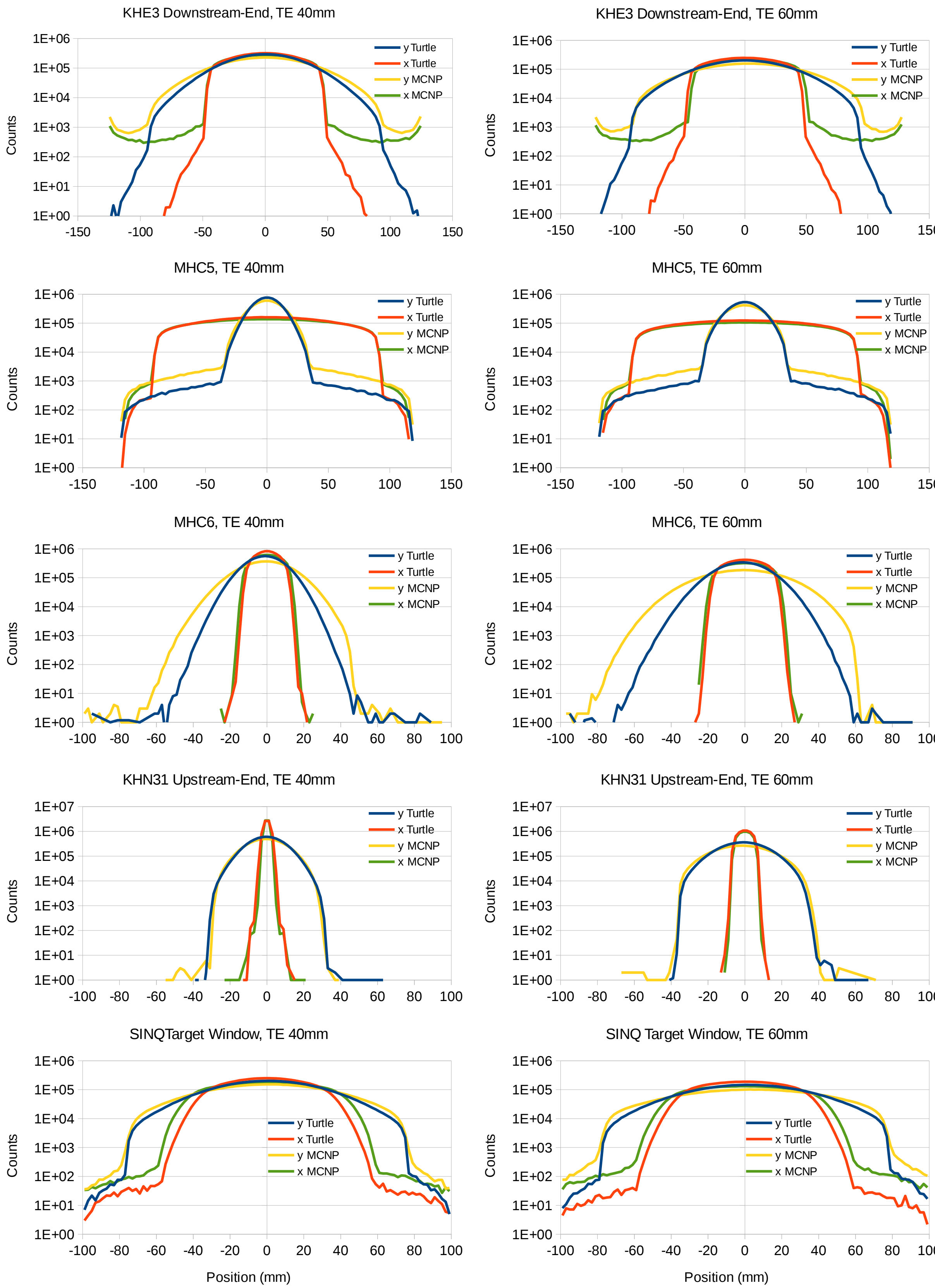

Figure 3: Proton beam distributions for TE40 and TE60 along the SINQ beam line obtained with pure Turtle as well as combined Turtle/MCNPX (MCNP in the legend) simulations.

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ing the average over the months of August 2017 for TE60 and August 2018 for TE40. It is interesting to note that the measured transmissions lie between the two computed values, i.e. none of the two simulation methods can reproduce the experimental results. Another, smaller, difference between Turtle and MCNPX is given by the estimated absorption through the KHNs collimators upstream of the SINQ target window. In this case for TE40(TE60) MCNPX predicts 1.0(1.2)% absorption, while Turtle only 0.2(0.2)%. At the location of the SINQ target, the MCNPX distribution matches very well the beam envelope fit (Fig. 1) in the horizontal plane (x), where the beam tails are largely shaped by the TE collimators. In the vertical plane (y), Turtle reproduces better the envelope fit, but only in case of TE40.

CONCLUSION

The comparison between the pure Turtle and the combined MCNPX/Turtle simulations of the SINQ beam line shows a clear discrepancy among them. The main source of difference is clearly coming from the scattering in the TE collimators KHE2 and KHE3. None of the two simulations is in agreement with the experimentally measured beam transmission. A deeper understanding of how the two tools differ in this respect is essential for the further development of this simulation study.

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