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COLLIMATION OF TARGET INDUCED HALO FOLLOWING MAGIX AT MESA

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Abstract

The Mainz Energy-recovering Superconducting Accelerator (MESA) will be an electron accelerator allowing operation in energy-recovery linac (ERL) mode. It provides the opportunity to operate scattering experiments at energies of ~ 100 MeV with thin gas-targets. The MESA Internal Gas Target Experiment (MAGIX) aims to operate windowless jet targets and different gases up to Xenon to search for possible dark photon interactions, to precisely measure the magnetic proton radius and astrophysical S-factors. Investigations on the impact of the target on beam dynamics and beam losses are required for machine safety and to examine limits to ERL operation. The goal of this work is to understand target induced halo in the different experimental setups, track halo particles through downstream sections to examine beam losses and include a suitable collimation system and shielding into the accelerator layout to protect the machine from direct and indirect damage through beam losses and radiation. The present status of the investigations is presented.

MESA

A brief overview of MESA and its beam line is provided in [1, 2]. This paper continues studies presented in [3] and focuses on the ERL mode for MAGIX, for which a beam line is set up so that the beam phase at peak energy can be shifted 180° with respect to the cryomodule RF. MESA provides an electron beam of 1 mA with up to 105 MeV in ERL mode. After passing the MAGIX target, the beam is recirculated into the cryomodules for energy recovery down to the injector energy of $E_{\text{Rec}} = 5$ MeV before being dumped. It is of fundamental importance to restrict the fraction of lost beam power to a reasonable amount to effectively utilize the advantages of energy recovery. This work is therefore dedicated to the design of suitable collimator setups for MESA ERL mode.

MAGIX

A short overview of MAGIX is given in [4, 5]. MAGIX will operate a windowless gas jet target. The gas jet is generated in a pressure head and vertically accelerated to supersonic speeds through a Laval nozzle. A gas catcher on the opposite side collects the majority of the gas, ensuring as good as possible vacuum conditions in the interaction section. The target can reach particle area densities of 10^{19} cm^{-2} [4]. Starting with Hydrogen targets, MAGIX aims to operate with various gases with higher nuclear charges Z up to Xenon.

TARGET INDUCED HALO (TAIL)

Operating at the MESA beam current of > 1 mA, MAGIX will achieve a luminosity $L \sim 10^{35}$ cm^{-2} s^{-1} which will allow a wide range of experiments. Due to interaction with the target, inevitable beam losses are induced since particles are scattered into regions of the phase space which are outside of both the acceptance of the experiment and of the accelerator. The main loss mechanism is elastic Coulomb scattering under small angles. Due to the form of the cross section, the number of such particles will be proportional to Z^2. Since the signal rate in most of the experiments also scales with this factor, the "effective" luminosity is almost constant. In some of the simulations presented below it proved advantageous to use high Z target materials since stronger interaction leads to statistically significant results in shorter simulation time. The actual range of the losses is determined by the experimental arrangement of MESA and MAGIX, for instance beta function at the target, aperture sizes and maximum beta function during the deceleration process. The simulations presented below take the actual conditions into account. They indicate that for the mentioned effective luminosity, losses of several Watts are expected until the first decelerating cryomodule. This is only ~ 10^{-4} of the total beam intensity of 105 kW at the target or 2×10^{-3} of the beam power after energy recovery $P_{\text{Rec}} = 5$ kW. Losses after deceleration still have to be simulated, but are expected to be smaller. A luminosity limit can be defined based on the fact that power losses should remain about an order of magnitude smaller than the beam power after recovery, leading to:

$$\mathcal{L}_{\max} = \frac{1}{Z^2} \times 5 \times 10^{36}\,\text{cm}^{-2}\,\text{s}^{-1}$$

for MAGIX in the present arrangement. For a hydrogen target of the density mentioned above, this is still well above the luminosities that could be achieved at MESA-stage 2, which will operate with 10 mA of beam current. Power losses of "only" a few Watts may seem tolerable, but since they happen more or less continuously over the whole length of the deceleration beam line, the induced radiation may lead to remanent radioactivity, damage to sensitive electronics and/or background in the experiment. Moreover, beam losses in the cryomodules should be minimized. The purpose of the following investigation is to make realistic simulations of

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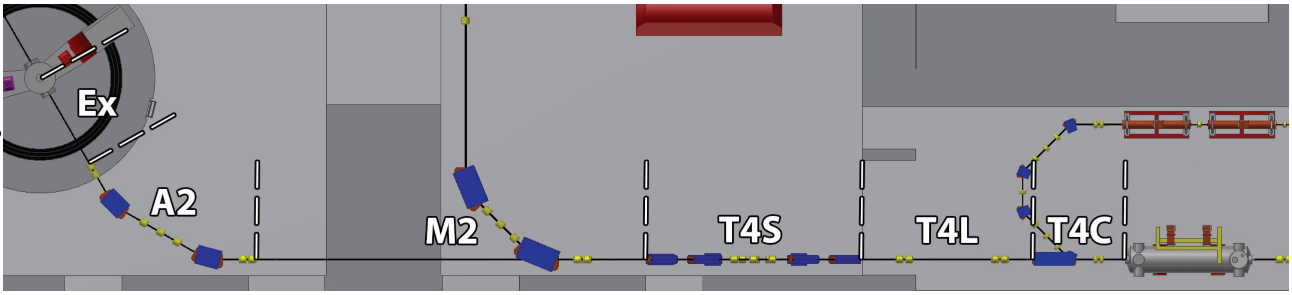

Figure 1: Lattice used for tracking with dedicated sections used for beam loss evaluation. MAGIX is located at the most left in the spectrometer circle, the next downstream cryomodule is illustrated on the right. Quadrupoles are drawn in yellow, dipoles in blue. The beamline in section M2 partially runs through a wall (dark grey).

the losses. Moreover, an arrangement of collimators is simulated which could allow to confine a larger fraction of losses to a small region. Such a small region can be shielded effectively so that the above-mentioned problems will be reduced in proportion to the collimation efficiency.

TAIL GENERATION IN MAGIX

Detailed information about halo shape, beam loss fractions and beam loss locations is needed for machine protection purposes. It is therefore necessary to simulate the process of TAIL generation and to conduct halo tracking studies. The beam-target scattering at MESA is simulated in Geant4 [6] to extract transverse and longitudinal halo as presented in [3], the outcoming beam is tracked downstream in BDSIM [7] to obtain beam losses and their locations in the accelerator. An overview of the parameters used in the following sections, unless otherwise noted, is given in Table 1.

Table 1: Simulation Parameters. Parameters Refer to Values at the Target.

Parameter	Description	Value
$\varepsilon_{\mathrm{n,rms}}$	Norm. Emittance	1.5 mm mrad
E	Beam Energy	105 MeV
σ_E	Energy Spread	10.5 keV
$\sigma_{p,*}$	Transv. Ang. Spread	156 µrad
I	Beam Current	1 mA
P	Beam Power	105 kW
β_*	β (Twiss)	30 cm
α_*	α (Twiss)	0
a	Aperture	40 mm
L	Target Length	4 mm
ϱ	Target Part. Density	10^{19} cm^{-2}
$\mathcal{L}$	Luminosity	6×10^{34} cm^{-2} s^{-1}
Z	Target Nucl. Charge	54 (Xe)

TAIL TRACKING

Previously generated transverse and longitudinal beam particle distributions reveal the impact of an internal target on the beam shape, distorting it to be non-gaussian. As the transport of such a beam can neither easily be handled with linear beam dynamics models nor can the impact of the distortion be neglected, tracking simulations are needed to investigate on further effects. Previous results are therefore used as input for BDSIM to identify loss locations and amounts. The beam is tracked through the lattice until the next downstream cryomodule. The accelerator layout is divided into sections as shown in Fig. 1, for each of which losses are integrated.

Influence of Target Thickness

The halo distributions as generated before are tracked downstream, beam losses are evaluated and shown in Fig. 2. The total losses approach quadratic behavior for $Z > 10$, the behavior of losses with lower Z requires further investigations. Losses in particular sections show a behavior similar to the total losses, except for the subsequent sections A2 and M2, where losses seem to be redistributed to the former when going to higher Z. An aperture of 40 mm is sufficient to keep losses directly behind MAGIX below 100 mW even for thick targets and are therefore not expected to interfere to an unreasonable extent with the MAGIX instrumentation, while the amount of power lost in downstream sections demands a collimation concept to counteract uncontrolled beam loss.

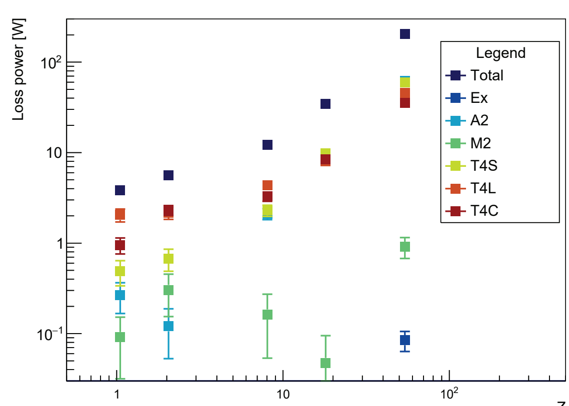

Figure 2: BDSIM simulation of energy losses for different target gases with a particle area density of 10^{19} cm^{-2}.

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HALO COLLIMATION

To counteract uncontrolled beam losses following MAGIX, collimator pairs for transverse x- and y-directions with rectangular aperture are introduced in section A2. The first triplet quadrupole is replaced by 1 cm long Be halo spreaders, which are low density collimators to widen and separate the halo further from the core and reduce the halo's power density instead of stopping halo directly. The last triplet quadrupole is replaced by 10 cm long collimators made of Be, Graphite, Cu and W to absorb the widened halo and section A2 is subdivided as shown in Fig. 3.

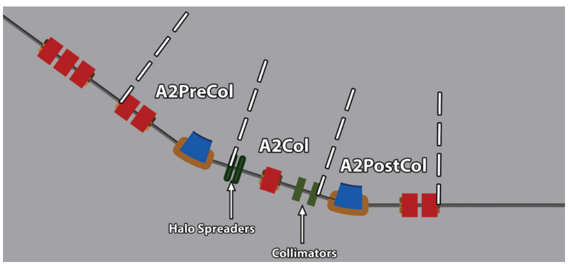

Figure 3: Detailed view of section A2 with introduced halo spreaders and collimators. The section is split into one part A2Col containing the new elements and the parts preceding (A2PreCol) and following (A2PostCol). Quadrupoles are drawn in red, dipoles in blue and spreaders and collimators in green. Magnet coils are illustrated in brown.

Apertures are chosen to be $10\sigma_{\text{beam}}$ of the corresponding direction at the respective locations. As the replaced quadrupoles are not used in the present MESA lattice design, the optics are not changed by the introduction of collimators.

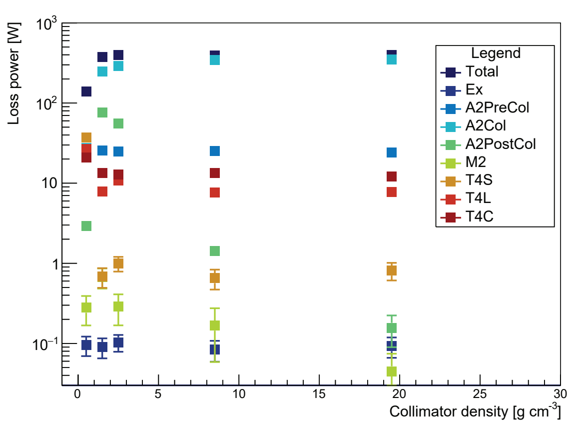

Figure 4: BDSIM simulation of uncollimated losses and different collimator materials used in section A2.

Figure 4 shows that most losses now appear in the collimator section, catching the majority of halo particles. The fraction of collimated particles rises for denser materials in comparison with Be as the stopping power for electrons and photons is sufficient to stop the hitting particles completely. Using denser collimator materials, the losses in the following sections A2 and M2 are significantly reduced to regions of 1 W and below and demonstrates that power losses in the section following MAGIX can be significantly reduced through the use of collimators. However, it is noteworthy that the sections T4L and T4C directly before the cryomodule still experience losses in the region of 10 W and consequently have to be guarded by additional measures. Figure 5 shows ratios of collimated and uncollimated losses and reveals the effect of collimation with efficiencies of $\sim 30\,\%$ to $\sim 100\,\%$ for most sections after the collimators. Total losses are almost doubled since the collimators are able to stop more halo particles, which is expected to reduce losses after the cryomodule. Collimator apertures in A2 can be further reduced to stop larger amounts of halo directly on the cost of collimating core beam. It is therefore preferable to introduce additional collimators in downstream sections to collimate halo with more precision.

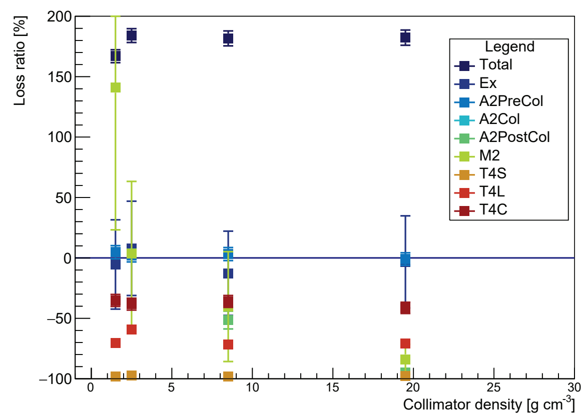

Figure 5: Ratios of collimated and uncollimated power losses for different collimator materials.

CONCLUSION

Considerations regarding impacts of operating an internal target at MESA on beam losses are presented. Detailed halo particle distributions are generated with Geant4, tracked downstream with BDSIM and reveal severe effects of distorted beam from beam-target interaction on beam losses. These TAIL effects put operational limits on internal targets in ERLs and have to be integrated in machine protection considerations. Simulations show that collimation in a suitable location is an effective way of controlling beam loss for the operation of MESA in ERL mode. However, results also suggest that several collimators have to be included into the accelerator layout to have sufficient flexibility in controlling power losses emerging from nonlinear beam dynamical behavior induced by MAGIX. Future investigations will focus on a more detailed description of TAIL effects and elaborated proposals of extended countermeasures.

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