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BEAM DYNAMICS AND COLLIMATION 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, where beam energy is recovered by decelerating the beam in linac cryomodules and transferring kinetic energy to the RF. The ERL mode provides the opportunity to operate experiments at peak energy with thin targets, combining high luminosities typical for storage rings and high beam brightness typical for linacs. The MESA Internal Gas Target Experiment (MAGIX) aims to operate jet targets at high luminosities with different gases up to Xenon. As scattering effects in the beam rise with the atomic number, investigations on the impact of the target on beam dynamics and beam losses are required for machine safety. The goal of this work is to understand target induced halo, track halo particles through downstream sections and protect the machine with a suitable collimation system and shielding from direct and indirect damage through beam losses and radiation. The present status of the investigations is presented.

MESA

An overview of MESA is given in [1]. MESA will supply the P2 experiment in external beam (EB) mode with a beam current of 150 µA at 155 MeV [1,2]. In EB mode, the whole beam is dumped after interaction with the target. A second beamline is set up for the ERL mode, where the beam passes the MAGIX target and is then phase shifted 180° with respect to the RF and recirculated through the cryomodules for energy recovery. MESA will maintain a 1 mA beam current in the first stage and 10 mA after upgrade at 105 MeV.

MAGIX

ERL operation is possible since MAGIX provides a low density target and only a small fraction of the beam actually interacts with the gas. The target is designed as a gas jet of nearly homogenous density. The jet is of cylindrical shape with 4 mm in height and diameter [3] and is produced by accelerating gas to supersonic speeds in a Laval nozzle perpendicular to the beam axis. A gas catcher is set up opposite to the Laval nozzle to collect the major part of the injected gas in order to keep vacuum conditions at a tolerable level. MAGIX is designed to operate with various gases (H, He, O, Ar, Xe, CH_4) for fundamental physics experiments, e.g. the search for the dark photon as well as investigations on the proton form- and astrophysical S-factor [4]. The setup is shown in Fig. 1.

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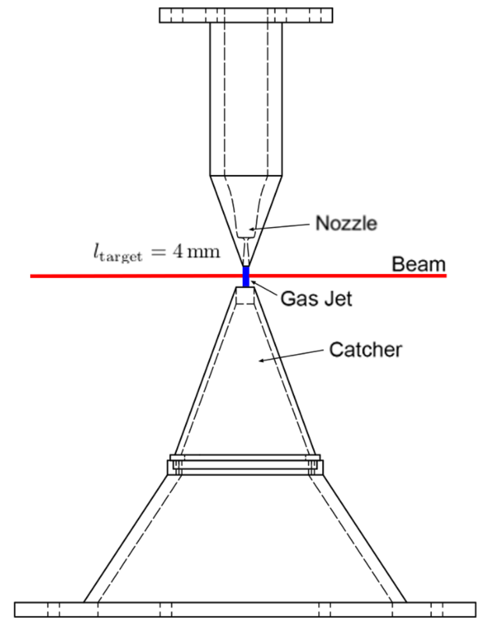

Figure 1: Schematic drawing of the MAGIX gas target [5].

Luminosity Limit Estimation

Target scattering and beam optics limit the luminosity of targets in ERL operation. Luminosity and target density limits for MAGIX can be estimated as presented in [6]. The luminosity limit then depends on beam and target properties. The necessities of radiation protection simultaneously set a limit to beam power losses outside adequately shielded areas. It is therefore important to examine these parameters to ensure reliable ERL operation.

TARGET INDUCED HALO

Scattering on the gas target widens the angle and energy distribution of the electron beam in a way that a halo forms around the original beam cross-sectional area as shown in Fig. 2. The halo is therefore called "Target Induced Halo" (TAIL). TAIL might cause malicious beam dynamical behavior when passing the cryomodules, such as inducing Higher Order Modes (HOMs) in the cavity, or directly damage machine parts when electrons get dumped in the cavities and beam pipes. Radiation produced by dumping electrons may further lead to damage especially to electronic components and generate background noise in the detectors of the experiments reducing measurement precision. It is therefore crucial to carefully investigate on the effects originating from the beam passage of MAGIX and formulate a collimation approach downstream the target to encounter impacts on machine operation safety and reliability.

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SIMULATION OF TAIL AT MAGIX

Statistical scattering models such as the Moliere distribution in practice quickly get complicated to evaluate owing to the degree of idealization on which these models are based. Simulating the target hence is a key part in understanding the formation of the TAIL. The Open Source simulation toolkit Geant4 is used for this purpose since it offers the greatest flexibility, high precision and high performance in simulating passage of particles through matter. The gas target is modeled with a particle density of 10^{19} cm^{-2} of the above mentioned gases. The beam transverse profile is modeled as an rotationally symmetrical 2-dimensional gaussian. Beam energy and angle distributions are gaussian with $E = 105$ MeV, $\sigma_E = 100$ keV and $\sigma_\theta = 2.5$ mrad respectively. Assuming a beam current of 1 mA as considered for the first stage of MESA, the corresponding luminosity is 6.2×10^{34} cm^{-2} s^{-1}.

Angle Distribution

The impact of target passage on the angle distribution is shown in Fig. 2. The region outside 15 mrad is identified with the TAIL region. A mentionable broadening of the distribution is visible to higher angles. These effects enlarge with higher mass target gases. H, He and CH_4 targets lead to TAIL intensities below 1 W and are therefore assumed to be technical manageable without greater impacts, whereas heavier gas targets greatly increase TAIL power up to 200 W with Xe and therefore have to be handled carefully.

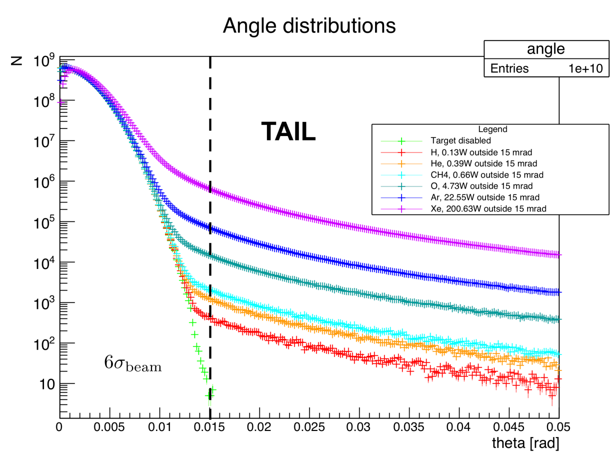

Figure 2: Geant4 simulation of the angle distributions with and without a gas targets as designed for MAGIX. All target gases are modeled with a particle density of 10^{19} cm^{-2} and the beam current is assumed to be 1 mA. TAIL region starts at 15 mrad, corresponding to $6\sigma_{\text{beam}}$.

Energy Distribution

Energy distributions before and after target passage have been extracted to investigate on the effects on the energy distribution. The distributions yield no net widening of energy deviation in the region of the initial beam design energy. The scattering process yet produces low energy electrons as shown in Fig. 3, potentially reaching downstream accelerator sections. These electrons are expected to be dumped after the first dipole magnet, since their energy is much lower than the magnet design value. The amount of low energy halo is again increasing with higher target masses.

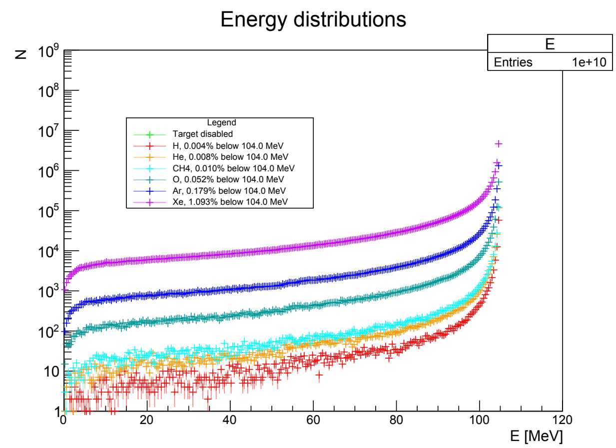

Figure 3: Electron energy spectrum after target passage. Beam mean energy remains virtually untouched, while few low energy particles are produced through scattering.

Bunch Elongation

Scattering processes may result in longer pathlengths of electrons passing the MAGIX target and thus temporal delay of single electrons. An electron bunch may therefore elongate and occupy larger phase intervals when decelerated as for acceleration. However, simulations indicate that this effect is not significant and therefore negligible for the deceleration process.

TAIL TRACKING

The previously generated halo is tracked through the following section to determine where beam losses occur and to estimate their intensity. BDSIM is used for this purpose, as it utilizes Geant4 physics precision and greatly enhances workflow for accelerator design-related simulations [7]. The modelled lattice section is starting at the MAGIX gas jet and ends at the building wall, after which the beam is directed back to the cryomodules. The TAIL resulting from a Xenon target is used as starting distribution for tracking studies, as it reveals the largest angle spread and is therefore considered to be computationally cheapest for beam loss simulations. Working with this worst case scenario, the effects of other mentioned target gases on beam loss are considered to be less severe.

Beam Pipe Material

The accelerator layout uses commercially available beam pipes. These beam pipes consist of aluminium or stainless steel, depending on their desired properties regarding magnetic permeability or their ability to be baked out. The beam pipe is first considered to have the smallest practical aperture

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with a diameter of 40 mm to acquire the greatest statistic of beam loss. The wall thickness is chosen to be 3 mm. Two simulations are conducted, one with aluminium and one with stainless steel beam pipes, to estimate radiation safety related advantages. The results are shown in Fig. 4 and indicate that stainless steel stops incident electrons more effective than aluminium due to the higher atomic number and density of iron. Electrons are therefore partly passing aluminium pipe walls and are stopped in the magnet yokes. However, this effect results in reduced energy deposition in aluminium in the drift section directly after the MAGIX target and thus is preferable regarding detector noise. The following considerations therefore use aluminium beam pipes.

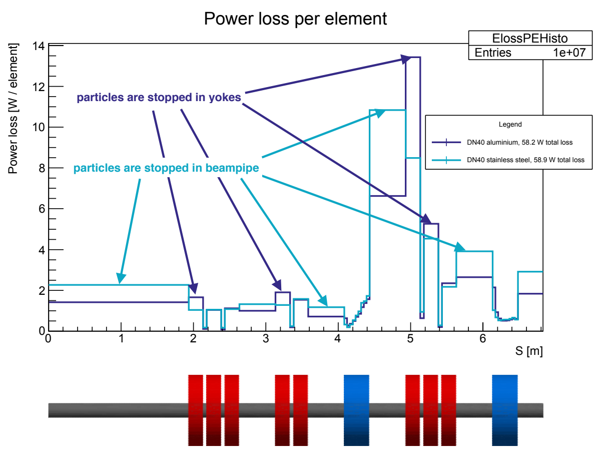

Figure 4: BDSIM halo tracking simulation with DN40 aluminium and stainless steel beam pipes. Drift sections are gray in the lattice plot, quadrupoles red and dipoles blue.

Beam Pipe Aperture

Energy loss is also depending on the aperture size as larger apertures allow more space for the halo to be transported. Figure 5 shows results of energy loss simulations for aluminium pipes with different commercially available DN pipes from 40 mm to 100 mm diameter. Choosing a diameter of 100 mm for the section downstream from MAGIX seems favorable to transport the largest part of TAIL to a collimator, where halo can be lost in a controlled manner.

COLLIMATION STRATEGY

As visible in Fig. 5, the highest loss powers are located following the first dipole magnet, especially in the quadrupole triplet. This is due to low energy electrons in the TAIL, resulting in smaller bending radii compared to design and finally wrong exit angles. Taking this into account, it is convenient to replace the quadrupole triplet with a collimator and surround it with proper shielding to keep energy losses and radiation locally confined.

CONCLUSION

Simulations on TAIL properties were conducted to quantify effects of using an internal gas jet target. The simulations

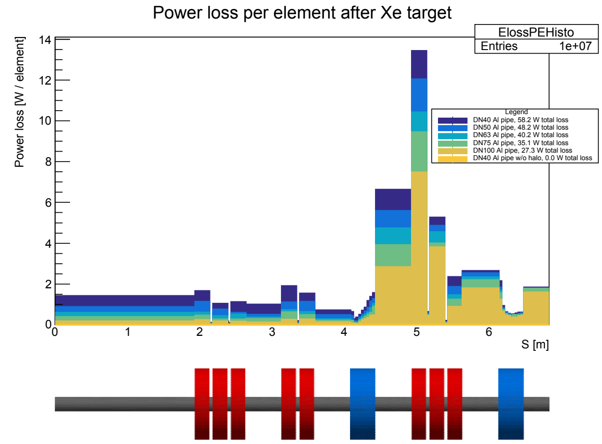

Figure 5: BDSIM halo tracking simulation with aluminium beam pipes of different diameters. The most power is deposited after the first dipole magnet.

show that it is possible to operate such a target in ERL mode, however aiming to operate the target with gases of higher atomic number reduces the maximum reachable luminosity as relative beam loss is rising unavoidably. To counteract uncontrolled beam loss, the losses are now localized and therefore a suitable collimation location found. Current studies are focusing on collimator layout as well as radiation generated by electron losses and its impact on detectors and radiation safety.

ACKNOWLEDGEMENT

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