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CHALLENGES FOR THE SIS100 EMERGENCY BEAM DUMP SYSTEM

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Abstract

The heavy ion synchrotron SIS100 is the flagship accelerator of the Facility for Antiproton and Ion Research (FAIR) currently under construction at GSI, Darmstadt. It will provide high intensity beams of particles ranging from protons to uranium ions at beam rigidities up to 100 Tm. Part of the machine protection system is an emergency beam dump that is partly inside the vacuum system and partly outside. Due to the beam dump's tight integration with the beam extraction system, there is little flexibility for the design of the dump or beam optics defining the shape of the impacting beam. High energy deposition densities and the wide range of accelerated ions pose unique challenges to the survival of the dump. In this paper we identify the most demanding beam impact scenarios for the different dump components that will consequently guide choices for materials and design.

INTRODUCTION

During nominal operation of the SIS100 the accelerated beams are extracted at rigidities ranging from 27 Tm to 100 Tm and guided towards the experiments via a high energy beam transport (HEBT) line. Along this line is a beam dump to be used e.g. during commissioning. The HEBT is not ramped and the extraction channel apertures of the septum magnets are laid out to accommodate beams of 27 Tm rigidity or higher. Hence, for the case of an emergency at arbitrary energy, a more closely integrated beam dump is necessary. Lacking space for a dedicated beam extraction line, the emergency beam dump reuses the existing extraction kicker system but with opposite kicker polarity. Consequently, the emergency beam dump is located below the third (last) extraction septum, opposite of the extraction channel. The tight integration means there is little space for the dump and the reuse of the preloaded extraction kicker system leaves no room for ion optical measures to dilute the dumped beam. Initial studies showed that the dump will be exposed to challenging beam impact scenarios, hence the decision to have parts of the dump in air for easier maintenance and a lower probability to contaminate the vacuum with potentially ejected material.

A model of the emergency beam dump is shown in Fig. 1. The design is governed by the unique challenges posed by the high dE/dx of heavy ions. Two 15 cm long blocks of carbon material are installed to stop high-Z ions and scatter or break up medium-Z ions inside the vacuum system. This is necessary in order to protect the vacuum vessel wall made of steel as the high interaction cross section of those ions would result in energy deposition densities far beyond the damage limit. Outside the vacuum vessel tungsten blocks are placed to catch low-Z ions –in particular protons– as well as secondaries in order to keep the energy deposition in the superconducting coils of the downstream quadrupole below the quench limit.

We expect that U^{28+} at injection energy to be the most challenging beam impact scenario for the first carbon block, owing to its high intensity and nuclear charge Z, which leads to high dE/dx and a sharp Bragg peak. For the tungsten blocks outside the vacuum, the proton beam at highest energy is expected to be the most straining option as it has high intensity, low emittance and little scattering in the carbon blocks. For the second carbon block and the vacuum vessel wall no such prediction is possible a priori due to the complex interactions of the ions on their way to the Bragg peak depth (e.g. fragmentation of ions smearing out the Bragg peak). Thus, we decided to perform a Monte Carlo simulation campaign scanning likely ions species and energy ranges. For the simulation of particle-matter interactions we chose the FLUKA Monte Carlo code [1–3] with DPMJET-3 and rQMD-2.4 event generators [4–7].

BEAMS IN SIS100

SIS100 was designed with proton and U^{28+} beams as reference beams. In order to obtain realistic worst case intensities for other ion species we assume the injector SIS18 is operating at the space charge limit. This has been experimentally achieved for N^{7+} reaching an intensity of 2×10^{11} ions. The intensity of the space charge limited N^{7+} beam is then scaled with A/Q^2 for the respective ion beam and multiplied with a stacking factor of 4 from SIS18. It should be noted that the beam intensity obtained for U^{28+} in this way is about 1.7 times higher than the reference intensity. For the sake of better comparison, we will use the scaled intensity in this paper unless stated otherwise.

Like the intensities, the emittances of the beams are defined by the injector chain. The injection into SIS18 is considered the bottleneck in terms of transverse emittances with an acceptance of 150 mm mrad in the horizontal and 50 mm mrad in the vertical plane. This acceptance is assumed to correspond to 2.6 σ of the Gaussian transverse beam distribution.

The beam energy at injection into SIS18 is 11.4 MeV/u for all ion species, regardless of mass or charge state, due to the Alvarez structure of the UNILAC injector. The energy and acceptance lead to the normalized emittances of the beam and thus to the emittances at the respective beam energies in SIS100. Proton beams are a special case both in terms of intensity and emittance scaling as they will be injected into the SIS18 synchrotron from a new injector, pLINAC, injecting protons at 70 MeV into SIS18. The normalized emittances are calculated accordingly while the intensity is set to the design intensity of 2.5×10^{13} protons.

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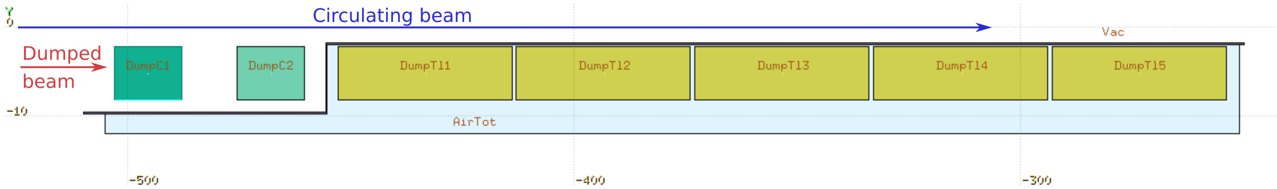

Figure 1: FLUKA model of the SIS100 beam dump [8]. The nominal beam is circulating at $Y = 0$. The dumped beam will be deflected downwards by kicker magnets located upstream and enter the carbon dump block (green) from the left. Low Z ion beams will exit the vacuum vessel (gray) and enter the DENSIMET® 185 blocks (yellow) situated in air (blue).

The ion species considered in this study are a collection of ions and charge states that have been accelerated in SIS18 in the past years. The list is not necessarily complete but should be representative enough to find the most critical scenarios. Figure 2 shows the assumed intensities vs. the ions represented by their nuclear charge Z. The two arms in Fig. 2 are due to the option to accelerate partially stripped (upper arm) or (almost) fully stripped ions (lower arm).

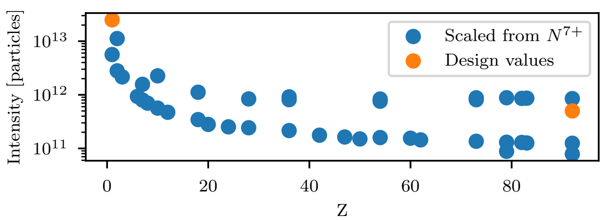

Figure 2: Beam intensities assumed in this study vs. respective ion species represented by their Z. The two arms are due to different charge states.

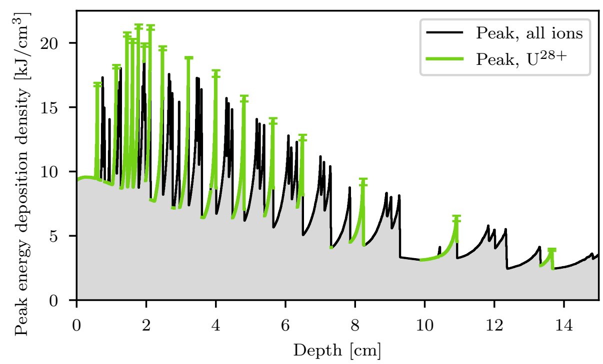

Figure 3: Energy deposition in the first carbon block. The black line denotes the highest energy deposition overall, the green line shows where U^{28+} is the worst case. Note that the data was obtained by scanning steps in the energy, so the worst case for each depth must be thought of as the envelope created by the various Bragg peaks of each ion. For better visualization, error bars are only shown for the U^{28+} peaks.

Lastly the transverse beam size is defined by the optics of SIS100. Currently four optics settings are foreseen: two for ion beams (fast and slow extraction) and two for protons beams with significantly different vertical tunes. For this study the optics with the lowest Twiss β functions at the dump were used as they will result in the smallest beam and highest energy deposition densities in the dump.

CARBON BLOCKS

Figure 3 shows the highest energy deposition densities per depth found in this study, as well as the regions where the highest energy is deposited by U^{28+} beams of varying energies. As can be seen, U^{28+} is in fact the worst case, as expected. The highest peaks occur at energies around 350 to 400 MeV/u where the Bragg peak depth is about 1.7 cm. Only at higher energies and greater Bragg peak depth is the envelope of U^{28+} overtaken by Au^{25+}, but this is far from the highest energy deposition and thus irrelevant. It should be noted that the highest energy deposition density in the first ~ 0.5 cm is caused by U^{28+} at 2.7 GeV/u, corresponding to highest energy and thus smallest beam size.

The significant reduction of energy deposition in the deeper half of the first carbon absorber block opens up the possibility to make parts of this block –which is planned to be constructed of thinner slices of 3D-C/C anyway– denser, increasing scattering and absorption and protecting the downstream components of the dump system even more.

The peak energy deposition densities in the second, more dense carbon absorber block are plotted in Fig. 4. Here, Au^{25+} and Pb^{26+} represent the worst cases. However since the energy deposition is significantly lower than in the first block, while similar mechanical material parameters can be expected, the second carbon block is non-critical for the beam dump design: if the first block can survive, the second one will as well.

VACUUM VESSEL WALL

Since the vacuum vessel wall has a thickness of just 2 mm, the longitudinal binning was kept low, just enough to discern a Bragg peak in the material. Of the five ions with highest energy deposition shown in Fig. 5, only Xe^{21+} at 2.52 GeV/u causes a Bragg peak below 100 Tm beam rigidity. The other four cases merely correspond to the highest beam energy –i.e. smallest beam size– of the respective ions. The Bragg peak of Xe^{21+} is only about 20 % above the background of secondaries and fragments so the longitudinal gradient is not expected to create a problem. Hence we regard Ta^{25+} as the worst case for the vacuum vessel wall.

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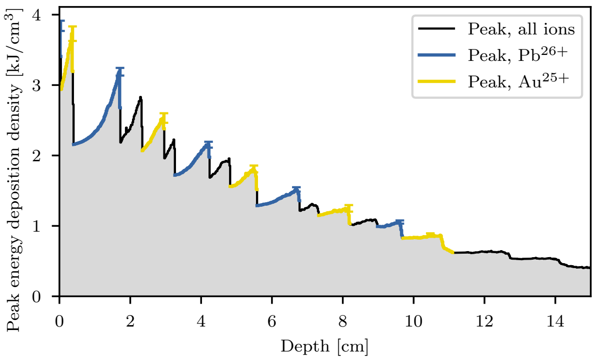

Figure 4: Energy deposition in the second carbon block. Peak energy deposition densities are significantly lower than in the first block.

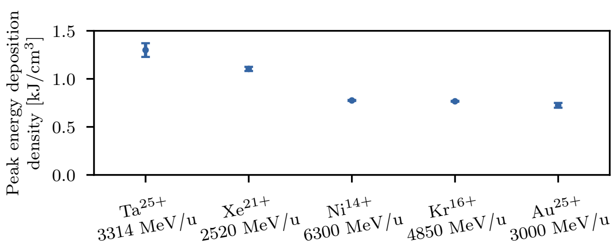

Figure 5: The five ions with the highest energy deposition density in the steel vacuum vessel wall.

TUNGSTEN BLOCKS

Lastly the first tungsten block is analyzed. The energy deposition curves of the three worst cases are shown in Fig. 6. Ta^{25+} and Xe^{21+} being among them is unsurprising as they also are the worst cases in the vacuum vessel wall immediately before the tungsten block. The worst case is however protons due to their high intensity and low cross section in the preceding materials. Unlike the heavier ions, protons have their peak deposition not at the surface but about 5 cm inside the material. From the deposition curves it is immediately clear that only the first of the five tungsten blocks will experience significant strain.

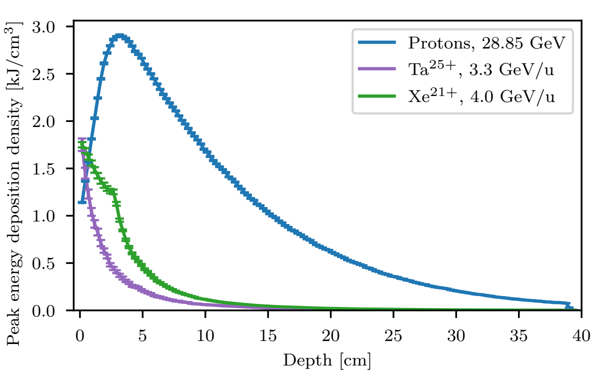

Figure 6: Energy deposition in the first tungsten block for the three worst cases.

DEGRADER

Early thermomechanical simulations of the carbon blocks resulted in peak temperatures far beyond the sublimation temperatures of known carbon materials. Consequently the peak energy deposition even in the first absorber of the dump system must be significantly reduced. We were advised to implement a degrader, a thin carbon foil to scatter ions before they enter the carbon block, thus spreading out the energy deposition. A viable position for the degrader was found 3.54 m upstream of the beam dump. The degrader must not be exposed to a Bragg peak, otherwise the problems will just be shifted to a different element. This gives the maximum thickness of the degrader which we calculated as 0.825 g/cm^2 avoiding the Bragg peak of 200 MeV/u U^{28+}. The effect of the degrader is demonstrated in Fig. 7. The long drift between degrader and first carbon block gives enough leverage to reduce the peak energy deposition by about ~ 50 %. Thus the degrader has proven quite effective and is henceforth included in the simulations for thermomechanical studies [9].

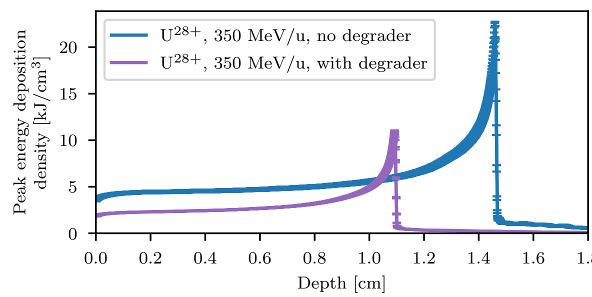

Figure 7: Reduction of energy deposition density for 350 MeV/u U^{28+} in the first carbon block with a degrader of 0.825 g/cm^2 thickness.

SUMMARY

The SIS100 emergency beam dump is a essential and challenging device that needs to withstand a wide variety of beam impact scenarios. We observed that partially charged ions are more problematic due to the higher achievable beam intensities. We identified the worst case scenarios for the various emergency beam dump components to be U^{28+} at energies around 400 MeV/u for the carbon blocks, Ta^{25+} at 3.3 GeV/u for the vacuum vessel wall and 28.85 GeV protons for the tungsten absorber blocks. These ions will be used as references for simulations of the thermomechanical responses of the respective components [9].

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