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ANALYSIS OF LOSSES AND PROTECTION OF THE ELECTROSTATIC SEPTUM ANODE WIRES IN SIS18

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Abstract

The synchrotron SIS18 at GSI uses resonant extraction for slow beam extraction. Recently it was discovered that about 50% of the anode wires of the electrostatic extraction septum were broken during beam operation. In this paper, we present the analysis of the possible loss scenario that led to the anode wire damage and suggest machine protection measures to prevent future damage. The investigations revealed the importance of having access to stored data representing machine parameter settings and their changes as well as signals from devices and beam instrumentation to be able to analyse the events leading to losses. Relevant signals include beam current, beam loss monitor signals, and vacuum pressure. Systems for logging and archiving such data are under development for FAIR, but are not yet routinely available.

INTRODUCTION

The synchrotron SIS18 at GSI uses resonant extraction for slow beam extraction, with an electrostatic extraction septum (ES) [1], designed for a deflection angle of 2.5 mrad at a maximum electric field of 90 kV/cm, see Fig. 1. The anode consists of an array of $W_{0.75}Re_{0.25}$ wires of diameter 100 µm, spaced 2 mm apart. The anode wires are suspended from mechanical springs with a pre-tension force of 2 N to keep the wires straight, counteracting the transverse electrostatic force between cathode and anode. See Table 1 for a summary of the septum parameters.

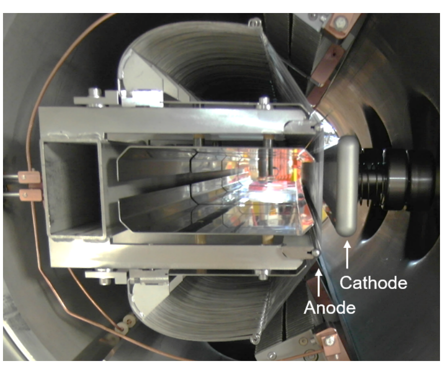

Figure 1: The electrostatic extraction septum in the beam direction with anode wires and pre-tension springs.

In May 2022, the anode wires were damaged to about half the length during beam operation. This was discovered indirectly, since the voltage of the ES needed to be increased significantly from the nominal value, to achieve good extraction. Further investigations to confirm the damage were performed in June 2022, among those a measurement of the ES deflection angle, an observed dependence of the beam's tune on the ES voltage, indicating penetration of the electric field into the circulating beam area, and a visual inspection of the anode wires through a view-port.[1] It should also be noted that wire damage is rare and no major damage of the anode wires has taken place since 2002 [2].

Table 1: Parameters of the Electrostatic Extraction Septum

Cathode length	1.5	m
Anode wire thickness	100	µm
Wire spring force	2	N
Maximum voltage	160	kV
Max. electric field	90	kV/cm
Deflection angle	2.5	mrad

When the ES was finally disassembled in January 2023, it was found that in total 356 out of 751 wires were broken for a length of 0.71 m. In Fig. 2, the ES with the broken wires is shown.

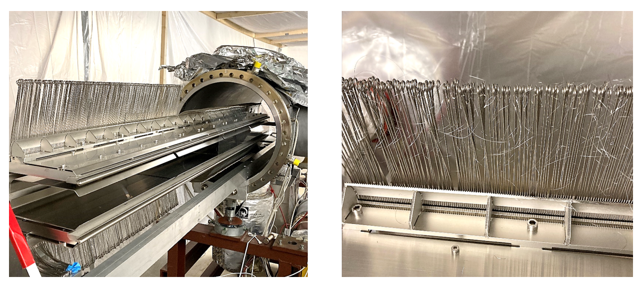

Figure 2: Disassembled ES: anode wire springs have retracted in the positions where the wires are broken (left); detailed view of broken wires (right).

In the present contribution we analyse the beam loss conditions leading to the damage of the wires, with the help of archived data of ring vacuum and beam instrumentation data such as beam current. This is important to understand why the damage to the anode wires occurred and to take mitigation measures to prevent anode wire damage in the future.

ANALYSIS OF BEAM LOSS

In SIS18, a detection system for broken anode wires in the ES is not available. Therefore, it is difficult to be certain about the exact time when wires were damaged. By contrast, for the electrostatic septa in SIS100 [3] a system for detection of broken wires by electrical contact of the spring has been

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[1] However, by end of April 2022 a NEG panel inside the ES was discovered to have a shortage, which is a sign that at least one wire had broken earlier, but without significant impact on the extraction performance.

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included in the design [4]. Lacking such direct diagnostics, vacuum and beam instrumentation data, most importantly beam current traces, have been used to analyse the events leading to the broken anode wires, post-mortem.

Vacuum Pressure Indicating Beam Loss

Machine experiments with high intensities of U^{28+} beam in the beginning of May were suspected as the main cause of ES wire damage due to significant vacuum pressure increase in S04, the sector of SIS18 where the ES is located (see Fig. 3). The base pressure in this sector is in the range of 10^{-10} mbar, and vacuum peaks related to discharges at the ES normally are in the 10^{-9} mbar range. Vacuum peaks in the range of 10^{-8} mbar, as observed, are unusually high. They are interpreted as signals from beam loss leading to gas desorption and/or evaporation of material, and hence as potential indication of broken anode wires.

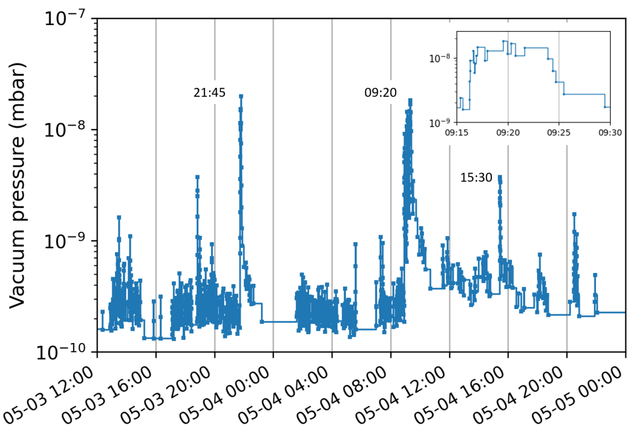

Figure 3: Vacuum pressure on gauge GS04VM2, close to the ES, where pressure peaks are indications of beam loss. Marked with times are those peaks which have been analysed further. Inset: zoom-in around the 09:20 peak.

Beam Current Analysis

The control system for the GSI accelerators contains a prototype of the archiving system, designed for the future FAIR facility, which is logging various beam instrumentation signals. With the help of this, the vacuum peaks marked in Fig. 3 were investigated further. Analysing the beam current signals from the DC transformer (DCT) in SIS18, GS09DT, it was found that the vacuum peaks at the ES are clearly correlated to high beam loss. Figure 4 shows the beam current signal around the time of the vacuum peak 09:20, sampled at 1 kHz. For U^{28+} ions at the injection energy of 11.5 MeV/u, the maximum current of 20 mA corresponds to 2×10^{10} ions. In the beam current trace one clearly sees high losses, which in fact occur at the beginning of acceleration, when the dipole magnets start ramping.

A more detailed analysis show that the losses take place over a time of 10–20 ms, corresponding to 2000–4000 turns. The total number of cycles with high losses for the peaks at 21:45, 9:20 and 15:30 in Fig. 3 were more than 1000, with losses at the beginning of the acceleration ranging from 0.5–2.5 × 10^{10} particles per cycle.

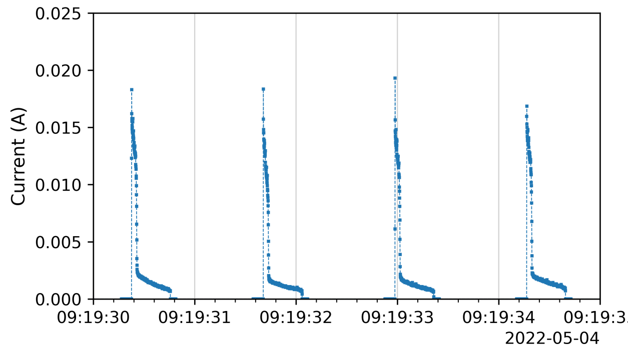

Figure 4: Beam current on DCT GS09DT around the pressure peak at 09:20. High losses at the beginning of the magnet ramp are seen.

Underlying Reasons for Beam Loss

Losses at the beginning of the acceleration ramp, as seen in Fig. 4, are a typical sign of particles not being bunched, which do not get accelerated and therefore lose synchronization to the ramping magnetic field. In SIS18, these particles move to the inside of the ring until they eventually get lost at the closest aperture limitation. Principal reasons for such dispersive losses are faulty RF-voltage, mismatch of timing between RF and magnet ramping, or bad longitudinal injection matching. As the ES electrodes are situated at the inside of the ring in SIS18, the anode wires are a potential location for this type of losses. Beam optics calculations confirmed that dispersive losses would indeed occur on the ES anode wires, if not protected properly by a movable scraper upstream the ES. Since U^{28+} has a high specific energy deposition in W-Re at injection energy, dispersive loss is the most likely explanation for the observed damage.

In order to find the cause of the suspected losses, the settings stored in the settings database were searched for changes in machine parameters that could generate dispersive losses. In at least two of the vacuum peaks seen in Fig. 3, at 21:45 and 15:30, losses could be traced back to changes of RF-cavity settings together with a calibration error resulting in significanly lower RF-voltage than required. For the case 09:20, shown in Fig. 4 above, the reason is not entirely clear, though, because only insignificant changes to injection parameters were found in the settings database. Most probably the injector linac had a technical problem during this time which led to an injected beam with a large momentum offset or spread.

ENERGY LOSS AND WIRE DAMAGE

In the following the energy loss needed to break an anode wire is discussed, assuming it is heated by beam loss to a temperature where the tensile strength is reduced to a critical value. Due to the large horizontal size of the injected beam, this requires the dispersive motion of the beam to be slow enough that the whole beam is essentially dumped into a single anode wire. Analysis shows that this condition is fulfilled when losses occur over a few thousand turns, or

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several milliseconds. Fast losses, where the beam is lost over just a few turns, have a much smaller potential of damaging the wires.

A U^{28+} ion at the injection energy of 11.5 MeV/u has a high specific energy loss in $W_{0.75}Re_{0.25}$, close to the maximum, and its range in this material is a mere 35 µm [5]. This means that, for an anode wire of 100 µm diameter, the ion will deposit its entire energy in the first wire being hit, unless the collision is very peripheral.

The force applied to the wire from the springs is 2 N, resulting in a tension of 254 MPa. The tensile strength of $W_{0.75}Re_{0.25}$ is relatively high compared to pure W, but it still decreases with temperature and is about 250 MPa [6] at 1700 K, meaning that the wire will break if this temperature is exceeded. The heat capacity of the wires, C_p, has an approximately linear temperature dependence up to 1700 K, and interpolating gives an average of $C_p = 0.150\,\mathrm{J/(g\,K)}$ [7], so the energy required to raise the wire temperature from room temperature to 1700 K is $dU/dm = 210\,\mathrm{J/g}$.

At injection energy, the vertical beta function at the ES is 6.7 m. Assuming the vertical acceptance of 50 mm·mrad to be filled, the beam full height at the ES is 37 mm. Taking into account the density 19.7 g/cm^3 of the wires [6], this means that the mass of the wire hit by the beam is 5.7 mg. Assuming further that the beam is distributed uniformly, or at least that the temperature is distributed equally over the beam height, we then obtain the energy needed to reach 1700 K as $\Delta U = 1.2\,\mathrm{J}$.

For $^{238}U^{28+}$, the kinetic energy per ion at injection is 2.7 GeV, or 4.35×10^{-10} J, meaning that a loss of 2.7×10^9 ions is needed to break one wire. Thus, a beam loss of 10^{10} particles per cycle, as in Fig. 4, has actually the potential of breaking three wires.

In this analysis, radiation and heat conduction have been neglected. This can be justified by the fast nature of the process. A beam loss of 4 J in 20 ms corresponds to a power of 200 W, while heat radiation at 1700 K, assuming an emissivity of 0.25 for the wires, gives a radiative cooling of 2 W. Cooling through heat conduction is even smaller, about 0.1 W.

Preliminary microscope observations also support the hypothesis of damage by temperature-induced reduction of tensile strength, since the broken wires show signs of elongation. However, the mechanism of the damage is not yet fully understood. In particular, the total number of cycles with dispersive losses of about 10^{10} particles, found by analysing the current traces, is about 1000 and since each such event has the potential of damaging at least one wire, it means all the 751 septum potentially could have been destroyed and not only 356. One possible explanation for this discrepancy is that the beam loss position may have changed from the ES to some other, less critical, location owing to the relatively large angle of 7.5 mrad of the anode with respect to the beam axis. Alternatively, the assumption that the lost particles are dumped in the first wire may be wrong. If only a fraction of the losses goes to the first wire, while the rest is lost elsewhere, it might take several cycles to increase temperature above the critical value in the wire. Further analysis is required to answer those open questions.

SUMMARY AND DISCUSSION

Damage of anode wires of the ES took place during beam operation in 2022. By help of the archived vacuum pressure and beam current traces, the most likely cause of the wire damage was, post-mortem, found to be dispersive beam loss at the beginning of the ramp due to non-bunched ions. The cause of the observed dispersive losses is not yet clear for all cases of high beam loss encountered, but insufficient RF-voltage due to a calibration error has been identified as one major factor. The investigations revealed the importance of having access to stored machine parameter settings as well as signals from devices and beam instrumentation.

Since high intensity beam operation with heavy ions, especially uranium, has shown the potential to damage machine components due to the high specific energy loss, it is important to have proper machine protection systems in place during such operation. In SIS18, establishing the correct position of a protective scraper is essential to prevent damage to the ES. Unfortunately, this scraper has not routinely been set to a position where it protects the ES, although this was the intention.

Further studies will be performed to resolve the observed discrepancy between the damage potential of the beam loss observed and the number of broken wires. To this end, beam optics simulations will be compared to the archived traces of beam loss monitors around the ring. More refined investigations of the broken wires will be performed aiming at a determination of the maximum temperature reached before breaking. A detailed quantitative understanding of the behavior of anode wires under these conditions is also very important for operation of the future SIS100 with slow extraction of high intensity heavy ion beams.

In future machine studies, the proper position of the protective scraper in sector 3 for preventing dispersive losses on the ES will be established.

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Data for pure W was used due to lack of data for $W_{0.75}Re_{0.25}$