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Verification of passive cooling techniques in the Super-FRS beam collimators

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Abstract. The Super FRagment Separator (Super-FRS) at the FAIR facility will be the largest in-flight separator of heavy ions in the world. One of the essential steps in the separation procedure is to stop the unwanted ions with beam collimators. In one of the most common situations, the heavy ions are produced by a fission reaction of a primary ^{238}U-beam (1.5 GeV/u) hitting a ^{12}C target (2.5 g/cm^2). In this situation, some of the produced ions are highly charged states of ^{238}U. These ions can reach the collimators with energies of up to 1.3 GeV/u and a power of up to 500 W. Under these conditions, a cooling system is required to prevent damage to the collimators and to the corresponding electronics. Due to the highly radioactive environment, both the collimators and the cooling system must be suitable for robot handling. Therefore, an active cooling system is undesirable because of the increased possibility of malfunctioning and other complications. By using thermal simulations (performed with NX9 of Siemens PLM), the possibility of passive cooling is explored. The validity of these simulations is tested by independent comparison with other simulation programs and by experimental verification. The experimental verification is still under analysis, but preliminary results indicate that the explored passive cooling option provides sufficient temperature reduction.

1. Introduction

The Super FRagment Separator (Super-FRS) will be the largest in-flight separator of exotic nuclei in the world [1]. It produces beams of exotic nuclei to be used by the experiments of the new FAIR accelerator facility [2]. All kinds of exotic nuclei up to uranium can be produced and separated [1].

To produce the exotic nuclei, a high-luminosity ^{238}U-beam is used. This beam is produced by the primary SIS-ring [2] with an energy of 1.5 GeV/u and is collided with a fixed ^{12}C target of 2.5 g/cm^2 to produce exotic nuclei by fission and fragmentation reactions [1]. The produced exotic nuclei are extracted from the target by their forward momentum and then guided through a series of dipole and quadrupole magnets and beam collimators to remove the unwanted ions.

Some of these exotic nuclei can hit the first beam collimator with an energy of up to 1.3 GeV/u and a power of up to 500 W [3]. These energies will activate the first collimators and their surroundings up to a level that is dangerous for humans, even when the beam is switched off [1]. After more unwanted ions are stopped by previous collimators, the incident power on the next collimator decreases and the activation is less severe. Hence, it is only dangerous for humans to be around the first few collimators. This area is called the pre-separator [1], where every action is handled by robots.

The next stage of the Super-FRS is called the main separator. Humans can safely enter this area when the beam is switched off [1]. After the main separator area, the fragment separator splits up into three different branches that can guide the exotic beam to different experimental areas [1]. A schematic overview of the different experimental areas in the Super-FRS is given in figure 1.

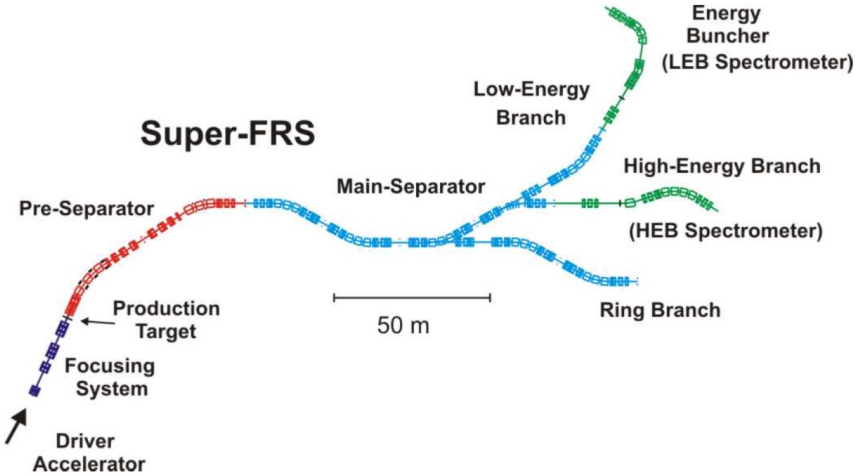

Figure 1. Schematic overview of the different experimental areas in the Super-FRS. The beam from the Driver accelerator is the ^{238}U-beam from the SIS-ring. The pre-separator area is drawn in red. The main separator area is drawn in blue [1].

Beam collimators that stop unwanted ions on the left and the right of the beam center are denoted as X-slits (since they move along the x-axis). Beam collimators that stop unwanted ions at the top and bottom of the beam center are denoted as Y-slits (since they move along the y-axis). In this paper, we focus on the thermal cooling of the first X-slit after the target. In the worst-case scenario this collimator receives $^{238}U^{90+}$ ions with an energy of 1.3 GeV/u and a power of 500 W [3]. All of these ions are stopped by the collimator. This means that the X-slit system should be sufficiently cooled to handle this 500 W.

2. Overview of the X-slit system

The actual collimation in the X-slit system is done by two blocks of Densimet. Densimet is an alloy of 97% Tungsten, 2% Nickel and 1% Iron [3]. These blocks are hanging in vacuum by two stainless steel rods. The movement of these blocks is controlled and read out by stepping motors and electronics located on the other side of the vacuum wall (in air). See figure 2.

On top of the X-slit system is a robot mount. This allows the robot to lift the entire X-slit system out of the beam line and replace it with a new one. This is a prerequisite, since some of the X-slit systems are located inside the pre-separator [1], [3]. Hence, replacement of the X-slit system must be possible in case of a malfunction. During the replacement procedure the Densimet blocks are disconnected by the robot and then reconnected to the new system.

3. Cooling options for the X-slit system

Our simulations (performed with Siemens NX 9.0 [4]) indicate that without cooling, the Densimet blocks can locally heat up to 700 °C. Due to conduction and radiation, the top flange of the X-slit system (part of the wall of the vacuum chamber) will then heat up to about 100 °C. This might cause malfunction in

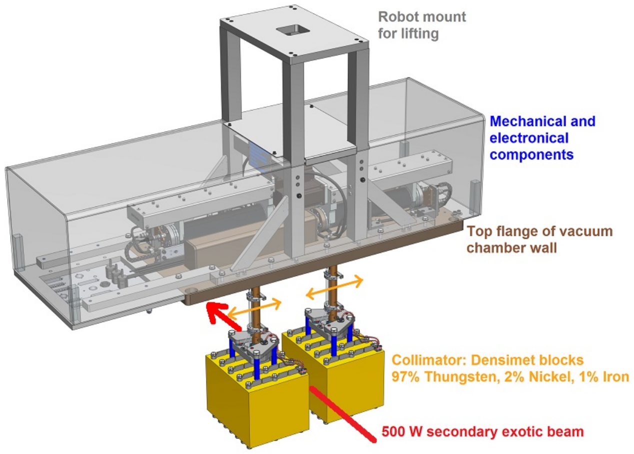

Figure 2. Computer drawing of the complete X-slit system with all of its components, as designed at KVI-CART.

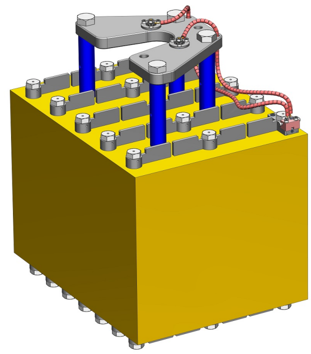

Figure 3. Computer drawing of a Densimet block of the X-slit system with stainless steel ribs on top. The dimensions of the block are 250 mm along the beam axis, see figure 2, 180 mm horizontal and 196 mm vertical.

the electronics located on the other side of the flange. Hence, cooling is required. For this cooling, one basically has two options: active cooling and passive cooling.

Our simulations also show that active water cooling on the Densimet blocks can easily reduce the temperature of the blocks from 700 °C to less then 200 °C and can, therefore, prevent the electronics from heating up too much. However, an active water cooling system adds a lot of complexity to the design of the X-slit system. Since this system has to run inside the pre-separator area where humans cannot enter, a complex system is undesirable since repair work as a result of a malfunction is extremely difficult, if not impossible. Especially (radioactive) water leaks can cause a lot of trouble since the pre-separator area is difficult to clean. Therefore, active cooling is undesirable.

Passive cooling means that one artificially increases the infrared emission of the Densimet blocks. Since tungsten has an emissivity below $\epsilon = 0.04$, [5], the emissivity of Densimet will also be very low. Hence, a lot of cooling can be done by increasing this emissivity. Our solution is to put ribs of stainless steel on the top and the bottom of the Densimet blocks (see figure 3). Since stainless steel has an emissivity of about $\epsilon = 0.65$ [4], [3], this provides an easy and effective cooling method without additional possibilities of malfunction.

Our simulations show that with the stainless steel ribs the Densimet will only heat up to 550 °C and the top flange of the X-slit system only heats up to about 35 °C [3]. This suggests that passive cooling with stainless steel ribs is enough to prevent damage to the mechanical and electronical components of the X-slit system (see figure 2). The question that then remains is how reliable our simulations are.

4. Simulation verification

In order to verify our simulation results, our procedure with Siemens NX 9.0 is compared to a simulation with Comsol [6]. For this comparison a simple test scenario is used where a plain Densimet block floats in the vacuum and is irradiated with a ^{238}U-beam of 500 W and 1.5 GeV/u. The beam profile is Gaussian with $\sigma = 5$ mm in both the x- and y-direction. The beam hits the block at 60 mm from the edge. A Densimet emissivity of $\epsilon = 0.07$ was used [3]. Results for a non-uniform triangular mesh of 0.3 mm around the beam spot are displayed in figures 4 - 5.

The overall difference between the temperature distributions produced by the NX and Comsol simulations is no more than 0.74 °C. This suggests that both simulation procedures can be regarded as reliable.

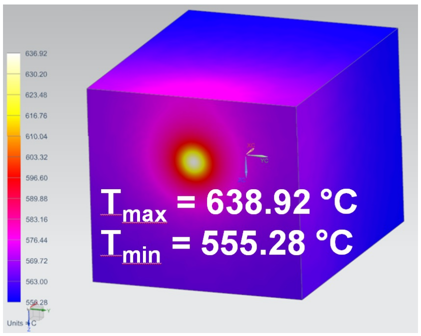

Figure 4. NX simulation results for the test scenario on a non-uniform triangular mesh.

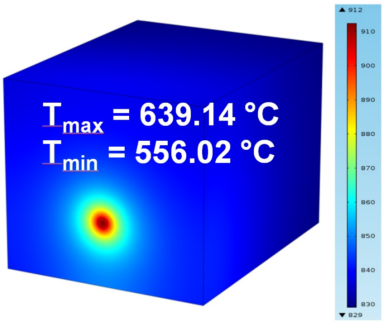

Figure 5. Comsol simulation results for the test scenario on a non-uniform triangular mesh.

5. Experimental verification

Our simulation results are further tested with an experimental verification. For this procedure a small test setup with Densimet blocks of $30 \times 30 \times 50$ mm^3 is used. The blocks are irradiated by a $^{20}Ne^{5+}$-beam of 30 MeV/u (21.6 W). The experiment is performed with the AGOR cyclotron at KVI-CART [7]. During irradiation, the temperatures of the Densimet blocks are measured with K-type thermocouples. An overview of the setup is given in figure 6.

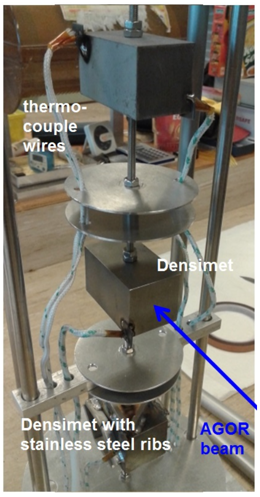

Figure 6. The constructed experimental setup used to verify the X-slit heat simulations.

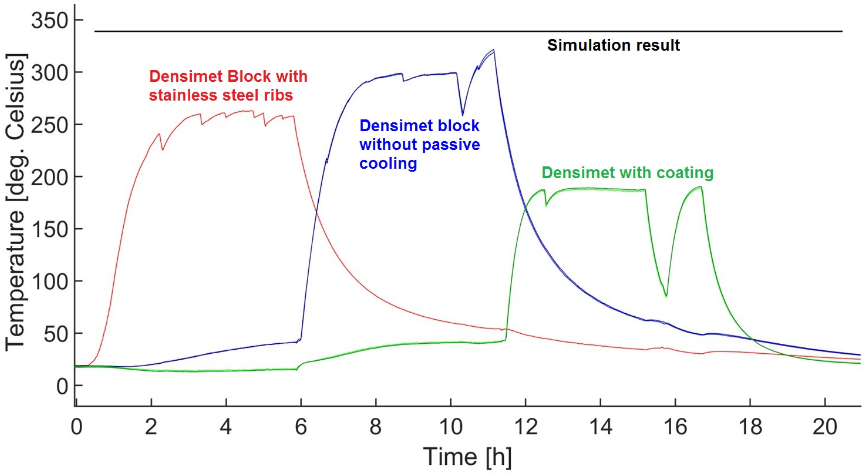

Figure 7. Temperature measurements of the Densimet blocks by two K-type thermocouples (linearly calibrated on the steam point and the ice point). The kinks in the graphs match the short beam failures. The high spike in the two blue graphs (two thermocouples) corresponds to a temporary increase of beam power to 30 W.

Three different Densimet blocks are irradiated one by one. One block is without any cooling (middle block in figure 6), another block is provided with passive cooling by stainless steel ribs (the bottom block) and the third block is provided with another type of passive cooling: a special coating with $\epsilon > 0.9$ [3]. This third block also had slightly different dimensions of $25 \times 25 \times 50$ mm^3. This allows us to both verify our simulation procedure and study the effect of passive cooling methods. The results are displayed in figure 7.

The black horizontal line in figure 7 corresponds to the temperature of the uncooled block in our latest NX simulation. So far, we have run only steady state simulations, but this work is still ongoing. So far,

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the difference between experiment and simulation is about 40 °C. We would like to point out that for any reasonable choice of parameters, the simulated results have always been higher than the experimental results.

It is also clear from figure 7 that the stainless steel ribs do provide passive cooling with respect to the uncooled block. The coating provides better passive cooling than the stainless steel ribs. However, after removing the setup from the beam-line, the coating sustained some damage while the stainless steel ribs appeared to be undamaged. Given the fact that the X-slit system should run inside the pre-separator area for many years, passive cooling by stainless steel ribbons does seem like the better option.

6. Conclusion

According to our results, passive cooling by connecting stainless steel ribs to the Densimet blocks seems to be the most suited cooling method for the X-slit system. Our NX simulations show that with this cooling the electrical and mechanical components will have a temperature below 35 °C (see section 3). Our simulation procedure has been tested against another simulation procedure and bench-marked by a measurement. The difference between our NX and Comsol simulation was no more then 0.74 °C, which suggests that our procedure is reliable. The steady state difference between our NX simulation and our experimental data is about 40 °C. This difference is still unresolved. The fact that each simulation shows a higher temperature than our experimental data might suggest that also in reality the electrical and mechanical components will have a temperature below 35 °C. However, the 40 °C difference should first be resolved and transient simulations should be run before any definitive statement can be made.

Acknowledgments

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