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# FAIR SIS100 LASER COOLING PILOT FACILITY

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*Abstract*

Ion beam cooling techniques are indispensable for generating high-quality ion beams and are, therefore, of great importance for accelerator research and fundamental physics experiments. For these reasons, ion beam cooling will play a major role in the accelerators of the Facility for Antiproton and Ion Research (FAIR), which is currently under construction in Darmstadt, Germany. The heavy-ion synchrotron SIS100 is the heart of FAIR and stores, accelerates and delivers high intensity ion beams at relativistic energies to the rest of the facility [1]. Since the highest charge states of heavy ions (*e.g.* $^{238}U^{92+}$) can only be produced by passing through a stripper foil at sufficiently high energies, the SIS100 accepts ion beams with a longitudinal momentum spread $\Delta p/p$ of the order of $10^{-3}$. For experiments with extracted ion beams (*e.g.* for the generation of high energy density in matter) from the SIS100, it would be better to have a much lower value, *i.e.* $\Delta p/p \approx 10^{-6}$, which could be achieved by laser cooling of bunched heavy ion beams [2]. Therefore, a special working group was formed to develop and establish the SIS100 laser cooling pilot facility for FAIR [4]. This group consists of scientists and accelerator experts from GSI and the collaborating partner universities and research centers in Dresden-Rossendorf, Darmstadt, Jena, Münster, and Lanzhou (China) [5].

It will be world-wide unique and also the first time to demonstrate laser cooling of bunched ion beams in such a large and modern machine as the SIS100. The planned novel scheme of using three independent laser systems (cw and pulsed) to cool the intense heavy ion beams, which can have very high charge states (*e.g.* up to $Xe^{51+}$) at highly relativistic energies ($\gamma$ up to 12), is therefore quite ambitious. But the expected improvement of the ion beam quality and especially the short ion pulses that could be created, offer unrivled possibilities for ion bunches extracted from the SIS100. Even without laser cooling, the bunch length in the SIS100 could already be as short as 50 ns, using the advanced bunch compression technique. Laser cooling could improve on that and first estimations show that bunch lengths down to about 10 ns, for cooling times of only a few seconds, could be achieved. The final longitudinal $\Delta p/p$ would then be on the level of $\approx 10^{-6}$ [3]. Such very cold and very short highly relativistic ion bunches could be used to generate high energy densities on a fixed target or serve a future secondary ion beam facility.

Laser cooling is based on the resonant absorption of laser photons (momentum & energy) in the longitudinal direction and the subsequent spontaneous random emission (fluorescence & ion recoil) by the ions, combined with a moderate bunching of the ion beam. Since the fluorescence emission occurs in a random direction, the recoil momenta average out to zero, leaving a net decelerating force on the ions. However, the ion beam must be cooled, not decelerated, which means it should "only" obtain a low $\Delta p/p$ value, keeping the ion revolution velocity in the accelerator constant (at $\beta \approx 1$). Therefore, a counteracting force to the laser force is required, which can be provided by an RF-bucket. This concept is thus also referred to as "bunched beam laser cooling".

The construction of the SIS100 tunnels is progressing well and a first important component for the laser cooling pilot facility (≈20 m underground) was already installed in January 2021. This component is part of the complete laser beamline, which will run from the SIS100 laser lab to the accelerator, crossing the gap between two tunnels (see 1). The complete laser beamline (length 25 m, diameter 20 cm) will be made out of stainless steel vacuum tubes. The vacuum has the advantage that laser light covering a very broad spectrum can be transported, ranging from the IR ($\lambda \approx \mu$m) down to the XUV range ($\lambda \approx$nm). GSI will provide the required infrastructure for the laser cooling pilot facility at FAIR, which includes a complete laser lab (180 m$^2$), a detector cave (45 m$^2$) in which special detector systems for x-ray measurements can be installed, the full laser beamline (including all components), special vacuum chambers for detectors and to couple the laser light in and out of the SIS100, scrapers for beam alignment (spatial overlap ≈25 m), control and data acquisition systems, etc. The Technical University of Darmstadt and the Helmholtz-Centre Dresden-Rossendorf contribute in total three laser systems, one cw and two pulsed systems. They can be operated either in the UV-range, at 257 nm with up to 250 mW (pulsed) and 600 mW (cw) of power, or in the visible range, at 514 nm with up to 23 W (pulsed) or 11 W (cw) of power. In the future, all three laser systems will be spatially, timely and spectrally overlapped to achieve a broad and a strong cooling force to address the full range of ion velocities [7]. For the detection of the strongly forward boosted fluorescence at the SIS100, the WWU Münster is currently developing and constructing an *in vacuo* xuv/soft x-ray detection system, which can be used as a fluorescence detector or as a spectrometer.

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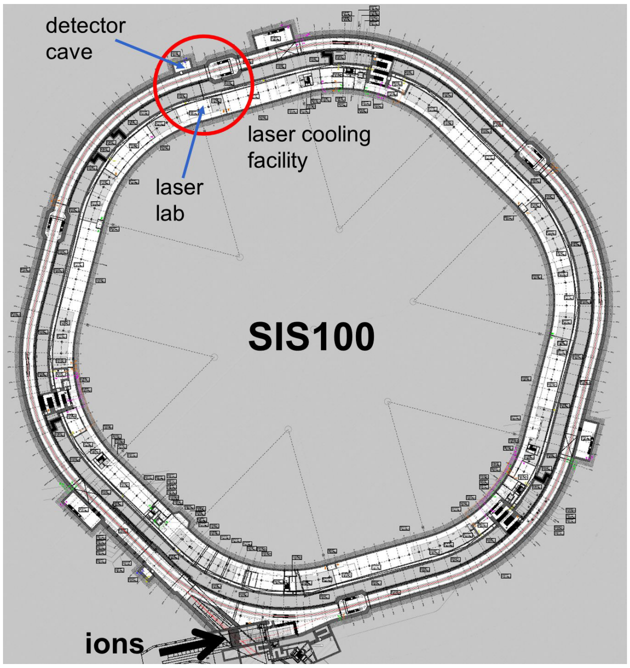


Figure 1: The FAIR heavy-ion synchrotron SIS100. The planned laser cooling pilot facility is indicated by the red circle [6].

In 2021, GSI offered the laser cooling collaboration the opportunity to evaluate the new high repetition rate pulsed UV laser system (TU Darmstadt) as well as the improved XUV fluorescence detection system ( WWU Münster) during a beam experiment at the ESR. For the first time, we could demonstrate bunched ion beam laser cooling with a powerful pulsed high repetition rate (~10 MHz) laser system at 47% of the speed of light. The data analysis is still ongoing and the results will be published soon.

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