THREE-BEAM LASER COOLING OF RELATIVISTIC ION BEAMS AT THE FAIR SIS100

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Abstract

How to "cool" intense beams of relativistic heavy ions? This is a very challenging task, especially when established ion beam cooling techniques have profound difficulties under such conditions. At the heavy-ion synchrotron SIS100 of the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, we will apply "bunched beam laser cooling" with a novel 3-beam concept, where laser beams from three complementary laser systems (1x cw and 2x pulsed) will be overlapped in space, time and energy to interact simultaneously with a very broad ion velocity range in order to maximize the cooling efficiency. We will present this project, including the facility and the laser and detector systems, and show new results from our simulations.

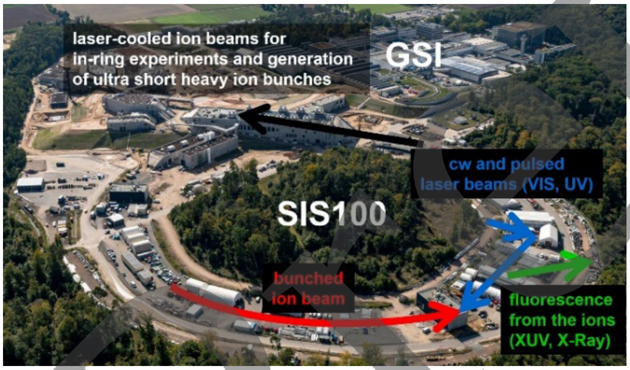

Figure 1: Laser cooling of bunched ion beams (red) at the SIS100 at FAIR will be performed using 3 independent laser beams (blue). The cold and ultra-short ion bunches will then be extracted towards experiments.

INTRODUCTION

Future accelerator facilities, such as FAIR in Darmstadt, Germany [1] and HIAF in Huizhou, China [2], will provide intense, high-energy, heavy-ion beams for fundamental research. Many of the experiments planned at these facilities, will greatly benefit from ion beams with small relative longitudinal momentum spreads ($\Delta p/p$). Electron cooling and stochastic cooling are the most frequently applied methods to obtain “cooled” ion beams. However, for highly relativistic (>1 GeV/u) and very intense ($>10^{10}$ ions) beams, these methods become less effective, see *e.g.* [3]. Laser cooling is an alternative method and should be much better suited for such ion beams, see *e.g.* [4].

THE SIS100

The heavy-ion synchrotron SIS100 will have a circumference of 1084 m, a maximum magnetic rigidity of 100 Tm, a vacuum pressure in the low 10^{-11} mbar range, and will be located in a tunnel 16 m below the surface. Figure 1 shows a recent photograph in which the beams are indicated. Beams of heavy-ions from the existing GSI facility will be injected and accumulated in the SIS100 and will then be accelerated to highly relativistic energies in order to provide extracted intense ion beams for FAIR experiments. Laser cooling will be the only ion beam cooling method available at the SIS100. The dedicated laser cooling facility, which is currently being built in the SIS100 tunnels, will be worldwide unique [5].

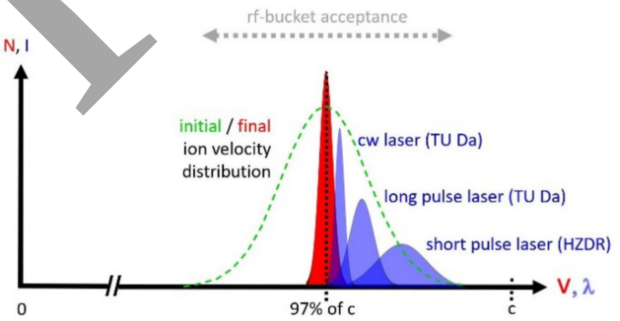

Figure 2: The 3-beam laser cooling scheme for the SIS100 at FAIR. The initial and final distributions are shown in green and red, respectively. According to simulations, $\Delta p/p$ could be reduced from 10^{-3} to 10^{-7} in only a few seconds.

THE 3-BEAM CONCEPT

The idea underlying the simultaneous application of three independent laser beams, can be seen in Fig. 2. The initial $\Delta p/p$ of the ion beams injected into the SIS100 is expected to be 10^{-4} up to 10^{-3}. This is very broad and cannot be efficiently covered by a single laser system only. However, by using a combination of two pulsed laser systems, *i.e.* one with a longer (~100 ps) and one with a shorter (~10

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ps) pulse duration, and a continuous wave (cw) laser system, the combined spectral width of the 3 laser beams is so broad that simultaneous interaction with all velocity classes of the ions is possible. Combined with the restoring force of the rf-bucket, this will lead to strong cooling, meaning short cooling times (Δt~10 s) and low relative longitudinal momentum spreads ($\Delta p/p$~10^{-7}) for highly relativistic heavy-ion beams.

The 3 laser beams must be overlapped in space, time and energy. The overlap in energy can be understood from Fig. 2, where the horizontal axis represents the ion velocity (v)and also the laser wavelength (λ). The overlap in time comes from the fact that the ion beam is bunched and that 2 of the 3 laser systems are pulsed. The laser repetition rate must match the ion bunching frequency, which are of the order of MHz, and the laser pulses must be synchronized with the ion bunches. Finally, the overlap is space comes from the fact that both the ion beam and the laser beams have diameters of ~10 mm and these – in total – 4 beams must be so-called "anti-collinear". This means that they must be parallel and lie exactly on top of each other. Since the dimensions at the SIS100 are large, the laser beams must travel up to 60 m. The spatial overlap region for laser and ion beams has a length of just over 20 m. In Fig. 3, the results from an "overlap" experiment, using 3 UV laser beams are shown [6]. The 3 laser beams were first combined and then propagated over ~60m.

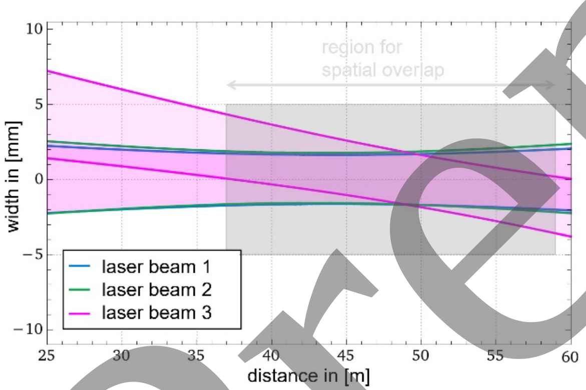

Figure 3: Experimental demonstration of the spatial overlap of three UV laser beams. The width of each laser beam was measured as a function of the distance from the laser system. (The UV power was about 2 W.)

SIMULATION RESULTS

Simulations of laser-cooled ion beams have been performed, using an updated Cython code [7]. (Original code by [8].) The candidate ion for these studies was chosen to be $^{48}\text{Ti}^{19+}$ at a velocity of $\beta=v/c=0.995$ ($\gamma=9.937$), or equivalently, an energy of ~8.3 GeV/u. The $2s_{1/2}$ - $2p_{3/2}$ transition wavelength of 25.93 nm can be excited using anti-collinear laser light at a wavelength of 514 nm. The laser power used was ~18 W for the cw laser and about 35 W for each pulsed laser. The SIS100 will be routinely operated using 10 rf-buckets (h=10), of which 8 are filled. (The 2 empty rf-buckets are required for the "emergency-kicker".) However, the influences of the bunching frequency (h) and the rf-bucket amplitude (U_0) have been studied in some detail. The results are shown in Fig. 4. For all simulations the initial $\Delta p/p$ was $4.6\text{x}10^{-4}$ and the laser power was the same. Simulations were done for three values of U_0 and for seven values of h. It was found that slightly better cooling results can be obtained for higher h and for higher U_0. The sudden increase at larger h is because the rf-bucket force is no longer matched to the laser force [7].

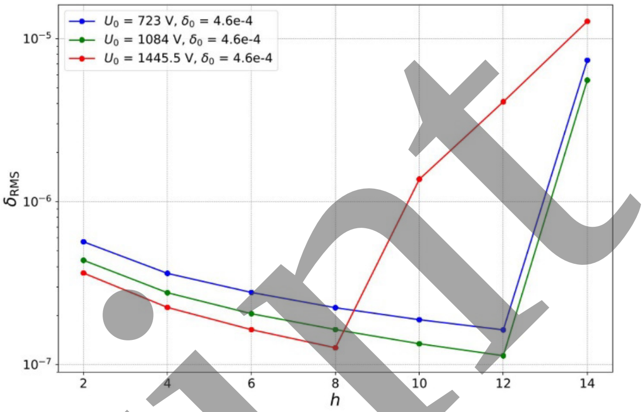

Figure 4: Simulation results for laser cooling of $^{48}\text{Ti}^{19+}$ at a velocity of 99.5% of c. Here, only a scanning CW laser was used. Higher h and larger U_0 lead to slightly colder ion beams.

Simulations were also performed to study space-charge (SC) and intra-beam scattering (IBS) effects, using two pulsed laser beams. Before the start of these simulations, the relative detuning of the two pulsed laser wavelengths was optimized. In the code [7,8], the routines for SC and IBS could independently be switched ON or OFF, allowing to simulate 4 cases. The results are shown in Fig. 5. It should be noted that the time required to cool down from $\Delta p/p$~$5\text{x}10^{-4}$ to below 10^{-6} (1000x reduction) is only ~10 s.

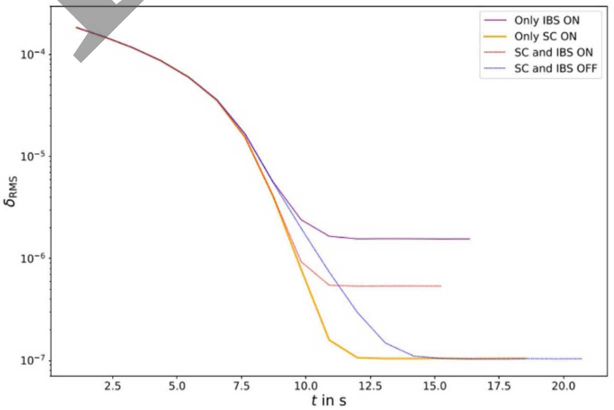

Figure 5: Simulation results for laser cooling of $^{48}\text{Ti}^{19+}$ showing the effects of space-charge (SC) and intra-beam scattering (IBS). Clear differences become apparent only for rather cold ion beams at the end of the cooling process.

LASER COOLING FACILITY

The laser cooling facility at the SIS100 is making good progress. In September 2025 the 2nd part of the laser beamline was installed in the accelerator tunnel, see Fig. 6. Also, two vacuum chambers, which will be part of the accelerator beamline, were transported to and installed in the accelerator tunnel. The construction of the laser lab (within the maintenance tunnel) was started in November 2025, see Fig. 7. The laser lab should be ready by the end of August 2026. The laser systems from TU Darmstadt and HZDR Dresden should be ready by July 2027.

Figure 6: The 2nd part of the laser beamline.

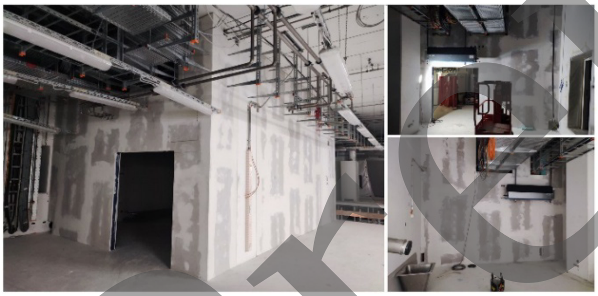

Figure 7: The laser lab at the SIS100.

CONCLUSIONS

Three-beam laser cooling is a very promising new method and should yield short cooling times and low longitudinal momentum spreads for intense, relativistic, heavy-ion beams at the FAIR SIS100. Our latest simulations take into account intra-beam scattering and space-charge effects, and show that relative tuning of the laser wavelengths is crucial for obtaining strong cooling.

The three laser beams (from 3 independent, but time-synchronized laser systems) offer great tunability and a lot of power. However, it will be a challenge to create a good and stable spatial overlap of all 3 laser beams with the ion beam. The laser cooling facility, which is currently being built at the SIS100, is making good progress. The vacuum chambers are already positioned in the accelerator and the laser beamline and the laser lab are close to being finished. A first ion beam in the SIS100 is expected not before the end of 2028.

ACKNOWLEDGEMENT

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