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LASER COOLING TAKEN TO THE EXTREME: COLD RELATIVISTIC INTENSE BEAMS OF HIGHLY-CHARGED HEAVY IONS

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Abstract

The Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, will deliver high-quality beams with high energies and high intensities for a broad range of new physics experiments. At the heart of FAIR is the heavy-ion synchrotron SIS100, which will accelerate intense beams of highly charged ions up to relativistic velocities. However, for such extreme ion beams (Lorentz factor γ up to 12), established cooling techniques, such as electron cooling and stochastic cooling, become rather expensive and difficult to implement, and have particular disadventages. Laser cooling of bunched ion beams was then considered the best solution for the SIS100. Therefore, a special project group was formed to specify, design, order, construct and test the SIS100 laser cooling facility for FAIR. (Work supported by POF IV, MT ARD.) The project group consists of scientists from GSI and the collaborating partner universities and research centers in Dresden-Rossendorf, Darmstadt, Jena, Münster, and Lanzhou (China). This group and the new facility will take laser cooling to the extreme.

SIS100 ACCELERATOR

The heavy-ion synchrotron SIS100 will have a circumference of 1084 m and will store ion beams with a magnetic rigidity between 9 and 100 Tm [1]. The SIS100 has been designed for the operation of highly relativistic ion beams with very high intensities [2, 3]. The ring will be quipped with more than 100 dipole magnets and over 80 quadrupole magnets, all of them being superconducting. The cryogenic infrastructure for these magnets is large and very impressive. The vacuum system is also very powerful and should provide for a pressure in the low 10^{-11} mbar range over the whole ring. Ion beam losses due to charge exchange should thus be strongly suppressed. To further improve the vacuum and the ion beam quality, a cryo-catcher system will be installed. The novel cavity systems of the SIS100 will enable powerful bunching capabilities and should also produce short ion

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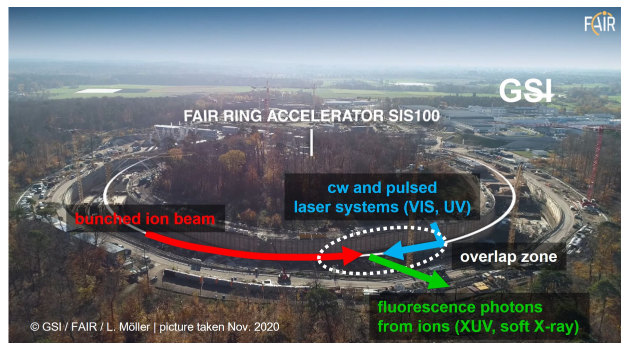

Figure 1: Photo of the SIS100 at FAIR. The dotted line roughly indicates the position of the laser cooling facility.

bunches (down to 50 ns). Fig. 1 shows a photo of the SIS100 tunnel at the FAIR building site, as seen from the north.

LASER COOLING AREA

The area where 'bunched beam laser cooling' will take place is indicated by the white dotted line in Fig. 1. The stored ion beam will orbit the SIS100 from left to right (red arrow), the laser beams (blue arrow) will counter-propagate the ion beam, and the fluorescence (green arrow) from the ions will be recorded [4]. A better impression of the laser cooling area can be obtained from Fig. 2. There, it can be seen that the SIS100 actually consists of two tunnels: the (outer) accelerator tunnel and the (inner) maintenance or supply tunnel, which are separated by several meters of concrete. The laser lab will be constructed in the maintenance tunnel. Overlap between ion and laser beams, as well as fluorescence detection, will occur in the accelerator tunnel. The laser beams need to cross the concrete wall between the tunnels, in order to reach the ion beam. This will be explained in the next sections.

ION AND LASER BEAMS OVERLAP

Because the SIS100 is a large accelerator, which is completely filled with components, is was challenging to find a good place for the laser cooling facility. For laser cooling

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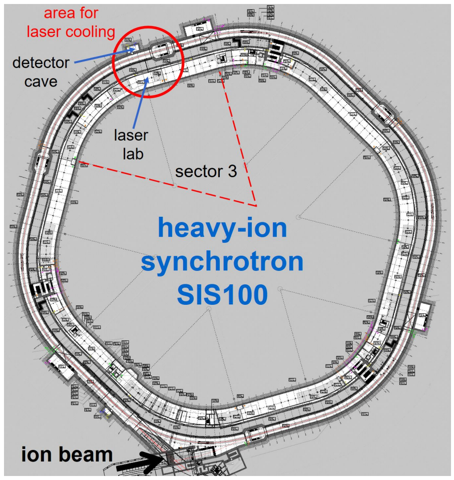

Figure 2: Schematic (topview) of the SIS100 accelerator. The laser cooling facility is indicated by the red circle. The ions will orbit the SIS100 in a counter-clockwise manner.

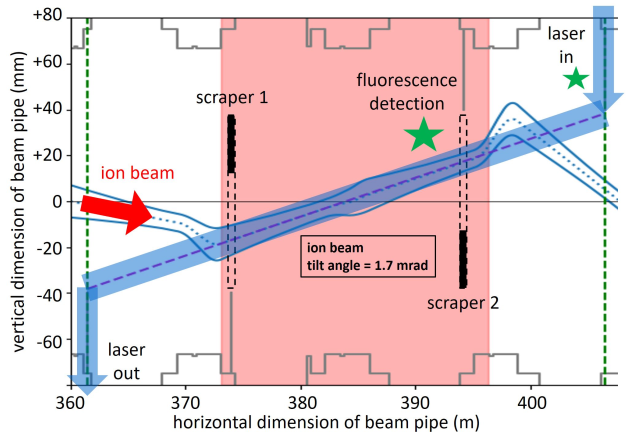

Figure 3: Dimensions of the setup at the SIS100 (sector 3). The simulated ion beam has been given a very small tilt to enable good spatial overlap with the laser beams. Overlap is checked by the scraper system. The stars mark the places where fluorescence will be detected.

it is crucial to have the best possible overlap between the ion beam and the laser beams. Therefore, a straight section of the SIS100 lattice is the best choice. In sector 3, several cavities will not be installed directly (MSV 0-3), which leaves space for the components required for laser cooling. However, to get laser beams in and out of the vacuum of the accelerator, a straight section is not so easy as a curved section. In a straight section, the light must enter and exit perpendicularly to the beampipe. Ergo, one mirror couples the laser light into the vacuum, then the laser light travels against the ion beam direction (*i.e.* anti-collinearly), and a second mirror couples the laser light out of the vacuum. The mirrors must be UHV compatible, *i.e.* they must be bakeable up to ~150 degrees Celcius. Since they will only be used for laser cooling, they should be fully retractable and thus move towards ('in') and away from ('out') the ion beam repeatedly, for which they must be robust. Because they should reflect high power (several Watts) laser light in the UV and visible range, the best material choice is highly-polished solid aluminium. The mirrors must also be large enough (2-inch diameter), else the laser beams will either not be fully reflected or cannot be moved over the mirror surface in order to optimize their position. Due to their size, the mirrors can only come fairly close to the ion beam and the laser beams must thus make an angle with respect to an ion beam 'on axis'. This would considerably reduce the effectiv overlap between ion and laser beams. Therefore, the idea came up to slightly tilt the ion beam locally, and thus increase the overlap range again. The tilt (1-2 mrad) will be made by a horizontal closed-orbit distortion. Fig. 3 shows a simulation of the orbit of a stored ion beam in the SIS100 in sector 3, which is where the laser cooling area is. The ion beam (as seen from above) is injected from the left, the laser beams enter from the top right. Please note the different scale of the two axes (mm and m). The total length the laser light travels inside the accelerator vacuum is about 45 m, the effective overlap of ion and laser beams is about 22 m.

The simulation is for a Li-like xenon ($^{132}Xe^{51+}$) ion beam with a kinetic energy of 10.66 GeV/u, which implies γ=12.4 and $B\rho$= 99.75 Tm. The tilt of the ion beam is only 1.7 mrad. Under these conditions, the two Al-mirrors can come close enough to the ion beam without being hit. The overlap between ion and laser beams will be checked and optimized using scraper 1 and scraper 2. Each scraper blade will have a width of 25 mm and the scraper can moved horizontally (by a manipulator) over ±25 mm, which is sufficient to fully cover the ion beam position and its diameter. Vertically, the scrapers can move over a range of 50 mm and can either fully cross the ion beam or be fully retracted. The positions of the scraper blades (inside the UHV) will be calibrated. For alignment, the scrapers will first be used to determine the positions (X_i,Y_i) and widths (δX_i,δY_i) of the ion beam at two positions (for i = 1, 2), separated by about 20 m (*i.e.* the distance between the two scrapers). For these measurements, the ion beam will have a very low intensity (also for safety). Since the ion beam current will be monitored all the time by the current transformer (DCCT) and the Schottky pick-up system of the SIS100, it will directly be observed (by a loss in signal) when a scraper 'touches' the ion beam. A first reduction of the signal implies that the scraper is at the outer diameter of the ion beam. When the signal is gone, the scraper is at the center of the ion beam. Position and size are thus determined. Then the ion beam will be dumped and the scrapers will be used to determine the positions and widths of the laser beams. When the results for ion and laser beams are too different, either of the two (or both) can be adjusted to improve the overlap. The overlap should have a maximum uncertainty of about 2 mm at the scraper positions. Also shown in Fig. 3, by the green stars, are the two positions where detection of the fluorescence from the laser-cooled ions will take place. There will be one detection system close to 'laser in', and there will be a special fluorescence detection and spectroscopy system close to scraper 2.

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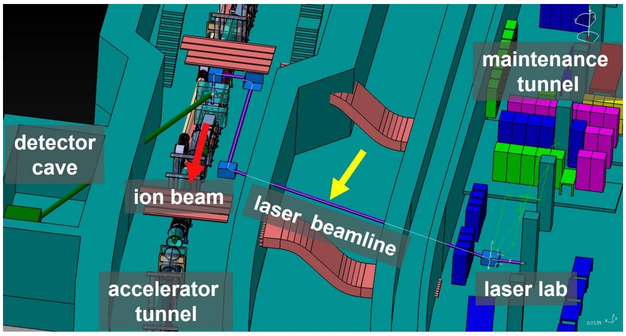

Figure 4: Illustration of the laser beamline at the SIS100. The laser lab and the detector cave are also indicated.

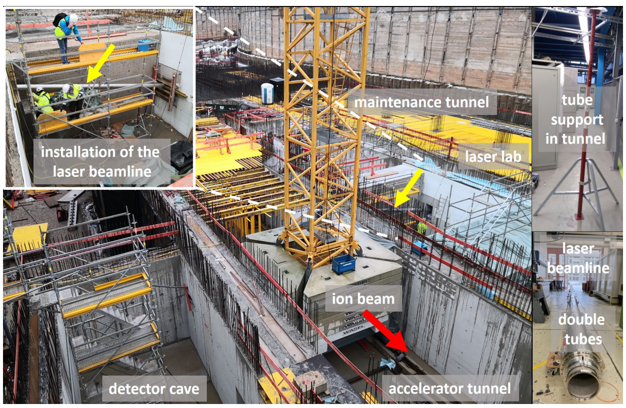

Figure 5: Photographs taken during the construction of the SIS100 tunnels. The inset shows the installation (in 2021) of the laser beamline, which can be seen on the lower right.

LASER BEAMLINE

As already stated above, the laser lab will not be located in the accelerator tunnel, but in the maintenance tunnel. This laser lab will be a controlled radiation safety area, which should allow us to normally work in the lab (during ion beam operation) and control the laser systems. The laser light must then be transported by a high-quality laser beamline to the accelerator tunnel, meaning that the laser light must travel a distance of about 25 m, of which almost 12 m run through the concrete wall between the two tunnels. Fig. 4 shows an illustration of the section of the SIS100 tunnels, which contains the laser lab, the laser beamline and the detector cave. To minimize radiation going through the hole for the beamline, the diameter of the hole was limited by 200 mm and the beamline hat to run from high to low (diagonally). The beamline is made out of two stainless steel tubes: an outer tube with DN200CF flanges, and an inner tube with DN160CF flanges. Stainless steel tubes, flanges and copper (OFHC) seals were chosen to have a robust, airtight and radiation-proof system. The outer tube acts as a spare/guard and allows for a possible repair/exchange of the inner tube. The laser light itself will only go through the inner tube. The beamline was mounted diagonally, fixed by supports, and then poured over with concrete. The photos in Fig. 5 were taken during the installation of the beamline, which occured simultaneously with the construction of the tunnels. Therefore, the laser beamline was also the first component of the SIS100 accelerator/experiment to be installed. The embedded part of the beamline is, however, only the first part of the complete beamline. When this part exits the wall of the accelerator tunnel, it will be connected to a second part, which will be almost 11 m long and will run along the ceiling to a point just above accelerator, where it will come down (see Fig. 4). The laser beams will then enter the SIS100 vacuum via a high-quality quarz viewport after which the previously mentioned aluminium mirror will reflect (>85%) the laser beams ‘upstream’ the ion beam (anti-collinear geometry). Part II of the laser beamline will contain several 90 degree bends, which will be made by small cubes containing highly-reflective (>99.5%) dichroic mirrors (257-266 nm and 514-532 nm). Part II will be suspended from the ceiling of the tunnel. The complete beamline will be closed on both ends by high-quality quartz viewports to block temperature and humidity drafts between the two tunnels (and also to prevent *e.g.* insects, spiders and mice from entering). The complete laser beam line will have its own vacuum system and will be pumped down by a forepump to a pressure in the low 10^{-2} mbar range. The vacuum is created to assure that the beamline is free of air, dust and humidity and will thus keep the dichroic mirrors clean.

LASER SYTEMS AND LASER LAB

A sophisticated combination of 3 newly developed UV/vis (257/514 nm) laser systems, together with modest rf-bunching, will allow for fast cooling of injected intense heavy-ion beams in the SIS100. There will be two powerful pulsed laser systems with MHz repetition rates and variable pulse duration (1-100 ps and 50-740 ps) and one powerful tunable cw laser system. The 1-100 ps pulsed laser system is built by the group in Dresden. The 50-740 ps pulsed laser system and the cw laser system are built by the group in Darmstadt. The picosecond laser pulses are broad in frequency and will enable fast cooling of the injected ion beam with a large initial longitudinal momentum spread. The cw laser can be quickly tuned over a large range and has high spectral power, creating a very cold ion beam [5]. This combination of 3 laser beams should be up for the challenge of suppressing intra-beam scattering and space charge effects. The scheme of using 3 independent, yet highly complementary, laser systems is completely new and very promising [6]. However, it comes with 3 challenges. Firstly, the 3 laser beams must be overlapped in space with each other and with the ion beam. This implies that all beams must follow the same path over a total length of about 65 m, including mirrors and lenses, and that the laser beam stabilization system is adapted to control these 3 independent laser beams. Secondly, the wavelengths and spectral widths of the laser beams must be adjusted such that they best match the velocity distribution of the stored and bunched ion beam. Thirdly, the two pulsed laser systems must be properly synchronized with

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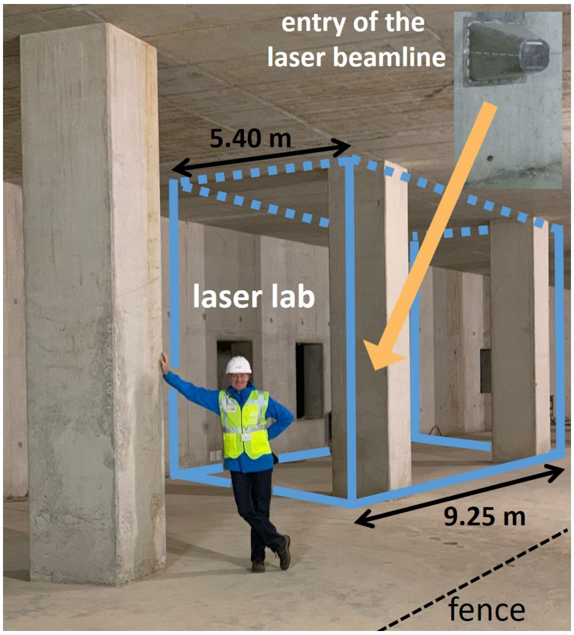

Figure 6: Artist photo of the future laser lab in the SIS100 maintenance tunnel. The entry of the laser beamline is also indicated (hidden behind the pillar). The lab will house 3 novel complementary laser systems (2 pulsed, 1 cw).

each other and with the ion bunches. Ergo, simultaneous overlap in space, time and energy is required.

The laser systems will be set up in a dedicated laser lab in the SIS100 maintenance tunnel. The 3 laser systems will be distributed over 2 optical tables. The laser power, control and cooling systems will be placed directly above and below the tables and there will be four 19-inch wide electronic racks inside the lab. The lab will have an air conditioning system and there will be laminar-flow boxes above the optical tables. The dimensions of the lab will be 9.25 m times 5.40 m, yielding an area of ~50 m^2. Fig. 6 shows an animated photo of the future laser lab. The laser light will exit the optical tables at a height of ~1 m and will then enter the laser beamline, which has a local height of ~1.3 m. (The height of the exit in the accelerator tunnel is ~3.8 m.)

DETECTOR CAVE

The last part of the laser cooling facility is the detector cave. Fig. 7 shows an animated photo of it. This cave was built at around the same time as part I of the laser beamline, and is located opposite to it. The dimensions of the detector cave are 10 m times 4.99 m, yielding also ~50 m^2. There will be five 19-ich wide electronic racks inside the cave. The cave will provide a shielded environment for sensitive detector systems and their control and power systems. The cave can only be accessed via a thick sliding radiation safety door and only during a shut-down of the SIS100 (after radiation levels have dropped). The entry of the fluorescence (white arrow) from the laser-cooled ions can also be seen in Fig. 7.

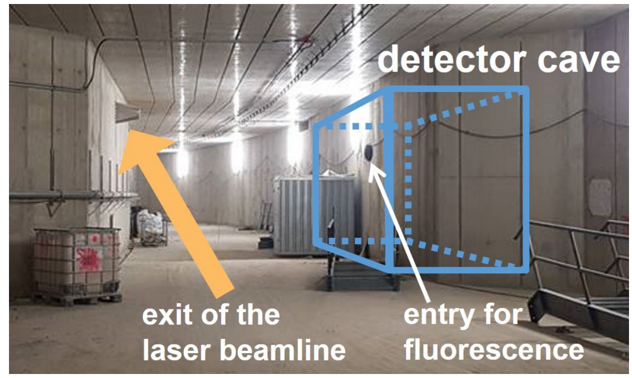

Figure 7: Artist photo of the detector cave in the SIS100 accelerator tunnel. (Photo was taken in the ion beam direction.) The exit of the laser beamline (part I) is also indicated.

The detector cave was designed for the full version of FAIR and could also be used for a possible future SIS300.

OUTLOOK

The civil construction of the SIS100 tunnels is practically finished. Currently, the technical infrastructure is being installed. From 2024 on, the installation of the first SIS100 accelerator components (sector 4) will start. Directly after, the components of sector 3 will be installed. The laser cooling facility will consist of 6 so-called ‘components along the beamline’. Five of these components will be installed in 5 vacuum chambers, the sixth is the laser beamline. The vacuum chambers contain, in order of appearance for the ion beam (cf. Fig. 3), the following components: laser out, scraper 1, fluorescence, scraper 2, laser in. The ‘laser in’ and ‘laser out’ chambers will contain the moveable aluminium mirrors. The ‘laser in’ chamber will also be equipped with a small fluorescence detector. The ‘scraper 1 & 2’ chambers will contain the two moveable scraper systems, which will be controlled by (X, Y) manipulators (Z is the ion beam direction). The ‘fluorescence’ chamber can be operated in two modes: (I) ‘counting mode’ and (II) ‘spectroscopy mode’. In mode (I) it simply detects the total amount of fluorescence from the laser-cooled ions. In mode (II) the fluorescence will be spectrally resolved, which is a really new and exciting feature. The latter will also strongly improve the possibility to perform precision laser spectroscopy of the ions. The complete fluorescence detection system is built by the group in Münster, with support from GSI.

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