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ADVANCED CONCEPTS AND TECHNOLOGIES FOR HEAVY ION SYNCHROTRONS

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Abstract

New concepts and technologies, relevant for a new generation of heavy ion synchrotrons with novel features, are developed and studied at GSI. To reach the intensity goals for heavy ions of the FAIR project [1], several of these approaches had to be implemented already in the FAIR synchrotrons SIS18 and SIS100. Other technical advances were achieved in the FAIR preparatory phase in preparation of the heavy ion synchrotron SIS300. Beyond these new concepts and technologies realized in the FAIR synchrotrons, new advanced accelerator R&D is conducted with the potential of a major impact on several large synchrotrons world-wide.

DYNAMIC VACUUM AND INTERMEDIATE CHARGE STATE HEAVY ION BEAMS

During operation with intermediate charge state heavy ions, the main intensity limitation is determined by charge exchange process in collisions with residual gas atoms and molecules [2]. Beam loss originated by such processes starts to dominate the overall loss budget significantly earlier than any space charge or current dominated phaenomena. The cross section for ionization of intermediate charge state heavy ions in the energy range of SIS100 [3], is about a factor of Hundred higher than for highly charged heavy ions. The issue with charge exchange driven loss becomes significant and develops into an instability as the residual gas pressure in the machine is no longer static but becomes strongly dynamic with local variations of up to two orders of magnitude. The main driver for the vacuum dynamics is the beam itself. Systematic processes (e.g. injection/extraction processes, Rf capture losses etc.) and especially in case of intermediate charge state heavy ion operation, charge exchange processes, are the initiators of a strong residual gas pressure dynamics. A single ion impact on the surface of an accelerator component is able to release up to 104 bound atoms and molecules. In order to be able to conduct self-consistent simulations of the spatial and time resolved development of the pressure evolution and charge exchange processes in circular accelerators, the STRAHLSIM code [4] has been developed. STRAHLSIM accounts for the following features: the machine lattice, the machine cycles, the atomic physics cross sections for projectile ionization and capture, the cross sections for target ionization, the properties of the conventional UHV system, the desorption yields of different materials, and the pumping properties of NEG and cryogenic surfaces.

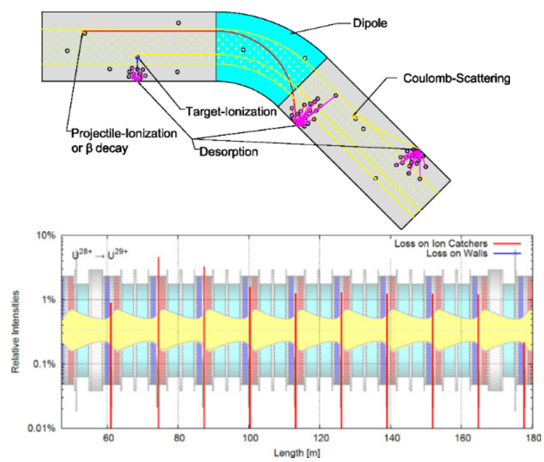

Figure 1: Top: Charge exchange processes at collisions with residual gas particles drive local pressure bumps. Bottom: The SIS100 charge separator lattice provides a peaked loss distribution for ionized projectiles with peaks in the middle of each doublet group (red lines). This loss distribution enables a control of the desorbed gases.

The control and stabilization of the dynamic vacuum and the minimization of beam loss by charge exchange processes are key developments for the FAIR synchrotrons SIS18 and SIS100 [5]. In SIS100, the main technical approach for stabilizing the dynamic vacuum is the charge separator lattice (Fig. 1) coupled with the application of cryo-pumping. The usage of superconducting magnets in SIS100 is mostly driven by the need for a cryogenic UHV system which acts as a super-pump and stabilizes the dynamics of the residual gas pressure. Besides the superconducting magnets themselves, there is a number of devices making use of the LHe as coolant. All magnet chambers are actively cooled with LHe (Fig. 2).

Figure 2: Thin wall, rib reinforced, LHe cooled quadrupole chamber.

Even during fast ramping and corresponding inductive heating by the changing magnetic field, their surface temperature has to be kept at 10 K. The chambers are cooled via separate process lines, connected to an

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individual auxiliary supply header. The decoupling of the UHV system cooling from the magnet cooling, enables independent thermal cycles, e.g. to recover the UHV system from condensed and adsorbed gases.

In addition to the cryogenic magnet chambers and with the purpose of providing sufficient pumping power for light atoms, e.g. for H_2 and He, a large number of cryosorption pumps is foreseen (Fig. 3). The cryosorption pump uses a LHe cooled charcoal to provide large pumping power for light residual gas atoms. In order to minimize and control the pressure bump generated at the main loss positions for ionized projectiles, special cryo ion catchers [6, 7] have been developed (Fig. 3).

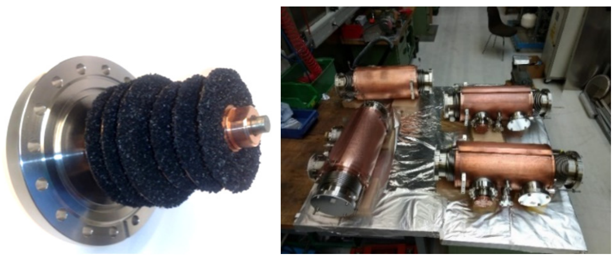

Figure 3: Left: Cryosorption pump using charcoal for H2 and He-pumping. Right: Series cryogenic ion catchers with included low desorption beam absorbers.

The cryo ion catchers contain a block which dumps the ionized projectiles outside the machine acceptance, surrounded by a cryogenic surface. To minimize the release of particles, the Cu-blocks have a low desorption yield Au-coating. The block is kept on an intermediate temperature by means of its connection to the shield cooling system. This assures that the block itself does not act as a cryopump and no residual gas molecules stick to its surface. The surrounding vacuum vessel provides a cryogenic surface with a stable temperature of 4.5 K free from inductive heating by the field of the neighbouring quadrupole magnets.

FAST RAMPED SUPERCONDUCTING MAGNETS

For SIS100, fast ramped superferric dipole magnets providing a field of 1.9 T with a maximum cycle frequency of 1 Hz and a ramp rate of 4 T/s have been developed [8]. The magnets are operated at 4.5 K and use a Nuclotron type cable. In this cable the superconducting NbTi-strands are wrapped around a tube which is cooled by a two phase forced helium flow. The coil is hold mechanically tight by the cold iron yoke and cooled in series with the yoke. The magnets create heat when they are ramped due to hysteresis and eddy current effects. With respect to the original Nuklotron magnets, the AC loss could be significantly reduced. In order to enable continuous operation with triangular cycles, a curved, single layer coil dipole has been developed. The coil is made of a high current cable with lower hydraulic resistivity and reduced AC losses using new NbTi strands with a Cu-Mn interfilamentary matrix. The curved 3 m long magnet has a bending angle of 3 1/3°.

For the planned second stage synchrotron SIS300, a first full size prototype of a curved dipole has been developed at INFN and tested at LASA in Milan, Italy [9]. The 7 m long magnet provides a magnet field of 4.5 T and is ramped with 1 T/s. This challenging magnet has also the particular characteristic to be geometrically curved with a radius of curvature of 66.67 m and a Sagitta of 114 mm. A second enhanced collared coil has been built in the frame of the European CRISP project. The R&D program included: a) the development of low loss superconducting wires and cables, b) the construction of a curved dipole coil winding and c) the construction of the complete dipole. At IHEP in Protvino, Russia, corresponding fast ramped SIS300 prototype quadrupole magnets with enhanced low loss cable has been built and successfully tested. In order to further advance the technologies for fast ramped s.c. magnets, in the frame of the EU IFAST program, GSI and others aim for the development of a new multi-layer HTS cable in conduit. This cable shall deliver the performance needed for a fast ramped SIS400 dipole magnet.

FLEXIBLE OPERATION AND HEAT LOAD MANAGEMENT

Since SIS100 shall be operated similar to a normal conducting synchrotron, special concepts had to be developed to assure a stable cooling of the magnet string and an efficient operation of the central cryogenic facility. The heat load to the cryogenics system varies significantly between the different operation modes, e.g. pure triangular cycle and cycles with long extraction plateau for slow extraction. Three independent electrical systems power the dipole and three quadrupole families with different current cycles, generating different heat loads in the corresponding units of each family. The individual and parallel magnet cooling circuits of each unit, are hydraulically adjusted to each other by means of mass flow restrictors with reference to a selected high load cycle [10]. Nevertheless, due to operation with quite different cycles and the fact, that each quadrupole circuit is in general performing a different ramp, the goal of reaching 100 % of gaseous He in the return header cannot always be reached. Therefore, in order to maintain an efficient operation of the cryogenic system, it is planned to adapt the supply header pressure according to the mean load value of the upcoming cycles. Furthermore, liquid Helium pumps are foreseen in the feed boxes to pump remaining liquid from the return header to the supply line. Furthermore, each of the parallel hydraulic magnet circuits is equipped with heaters, which provide auxiliary heat to the different parallel cryogenic circuits and act as valve in low loss cycles or during transition phases.

LASER COOLING OF HEAVY ION BEAMS

High-quality ion beams can be obtained by means of electron cooling and/or stochastic cooling. At intermediate kinetic energies these methods work very well. But at very

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high kinetic energies (γ>5), they become less effective. As first synchrotron world-wide, the SIS100 will be equipped with a laser cooling facility [11]. Several ion-charge state combinations (for Z<=54) have been identified as candidates suitable for laser cooling at relativistic energies. Laser cooling will also provi de very short ion bunches at final energy just before fast extraction. The laser lab, which will host 3 laser systems (1 cw and 2 pulsed systems), will be situated in the parallel supply tunnel of SIS100. The laser beam will be guided from the laser lab, through a dedicated (evacuated) laser beam line consisting of high-reflectivity UV mirrors, to the accelerator tunnel where a special vacuum chamber will be used to couple-in the laser light. Once inside the accelerator vacuum, the laser beam will be overlapped with the ion beam, using two sets of scrapers. To enable a long interaction region, a horizontal closed orbit distortion is generated by means of the steerer magnets, which tilts the beam axis over almost a full straight section of SIS100. The principle of laser cooling is as follows: The \`classical´ laser force results from the scattering (i.e. absorption and subsequent emission) of laser photons from an ion via a fast atomic transition, which is typically a fast electric dipole (E1) transition. The absorbed laser photons, and thus their momentum, always come from a single direction and their wavelength must match the Doppler-shifted cooling transition in the ion. Fluorescence emission, and thus recoil, occurs in all directions and averages out to zero, leaving a net cooling force in the direction of the laser light. In this anti-collinear geometry, the required laser wavelength scales extremely favourable with the Lorentz factor (γ). However, to achieve cooling, there must also be ‘counteracting´ force to the laser force. This is provided by the Rf-bucket force, which is also used for bunching the ion beam. Due to the bunching, the ions will also perform synchrotron motions inside the Rf-bucket, having different amplitudes depending on the relative velocities of the ions. By detuning the laser wavelength to the red side of the spectrum, i.e. to slightly lower photon energies, only ions that are a bit too fast will feel the laser force and will be slightly decelerated. By using two different (broadband) laser pulses and a scanning cw laser beam, even ion beams with an initially large momentum spread (dp/p ~10^{-3}) can be captured by the laser light and be cooled down to dp/p ~10^{-7} within only a few seconds. Thereby, also very short ion bunches are generated, e.g. for the generation of high energy density in matter which serves the investigation of the physics of dense plasma.

ELECTRON LENSES FOR SPACE CHARGE COMPENSATION

Space charge represents a major intensity limitation in synchrotrons operating at low or medium energies. The limitation arises due to the space charge induced tune spread and its overlap with incoherent, nonlinear resonances. For SIS100, detailed predictions for the space charge induced beam loss were presented in [12]. Losses below a few percent during the accumulation plateau of 1 second can be tolerated and determine the space charge limit in SIS100. Any means to further decrease the losses and increase the space charge limit would be very important for future experimental programs. Pulsed electron lenses represent a potential FAIR intensity upgrade measure [13, 14]. For space charge compensation, the electron current profile has to match exactly the longitudinal profile of the circulating ion bunch. In order to minimize the number of lenses, which will be less than the super period of the synchrotrons, the electron beam's transverse profile should be homogeneous in order to provide a linear focusing force. This reduces nonlinear error resonances induced by the lenses.

For the FAIR synchrotrons with typically long bunches compared to the length of an electron lens, the matching of the electron current profile with the ion bunch profile using a pulsed electron gun is possible. The GSI heavy-ion synchrotron SIS18 will be used as a testbed for the space charge compensation scheme using a pulsed electron lens. The demonstrator electron lens for SIS18 is presently being designed at GSI. The evolution of RF frequency f_{Rf} and (full) bunch length τ during the SIS18 cycle, determines the frequency and bandwidth requirements for the electron lens modulator. The RF modulated electron gun for the space charge compensation demonstrator is presently built as a Joint Research Activity within the ARIES EU-program by a collaboration among GSI, University of Frankfurt (UF), Riga Technical University (RTU), and CERN.

For the SIS100, first simulation results already show that such a concept based on only three lenses and a correctly adjusted partial space charge compensation substantially increases the low-loss areas in the working point diagram.

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