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TECHNOLOGIES AND CONCEPTS FOR THE NEXT GENERATION OF HEAVY ION SYNCHROTRONS

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Abstract

For reaching the goals of the FAIR project, various new concepts and technologies have been developed and implemented. Especially the challenging operation with high intensity, low charge state heavy ions and their high sensitivity for charge exchange processes has been addressed. Combining the needs for fast ramping and higher energy efficiency, new low loss s.c. cables using HTS technology are under development. Beyond the challenges of FAIR, further innovations for the next generation heavy ion synchrotrons are under investigation. Approaching one of the most important performance limits of large-scale circular accelerators, the Laslett space charge tune shift, by means of an Rf modulated electron lens is as ambitious as the new laser cooling system under construction for the FAIR SIS100.

ELECTRON LENSES FOR SPACE CHARGE COMPENSATION

Space charge is the origin of a major intensity limitation in synchrotrons operating at low or medium beam energies. The incoherent space charge tune shift $\Delta Q_{x,y}$ indicates the maximum intensity in synchrotrons and storage rings.

$$\Delta Q_{\mathrm{x,y}} = -\frac{r_0}{\pi}\left(\frac{q^2}{A}\right)\frac{N}{\beta^2\gamma^3}\frac{F_{\mathrm{x,y}}G_{\mathrm{x,y}}}{B_{\mathrm{f}}}\frac{1}{E_{\mathrm{x,y}}\left(1+\sqrt{\frac{E_{\mathrm{y,x}}Q_{\mathrm{x,y}}}{E_{\mathrm{x,y}}Q_{\mathrm{y,x}}}}\right)}$$

With $F_{x,y}$: Laslett's form factor, $G_{x,y}$: form factor for transverse distribution, Bf: bunching factor, $E_{x,y}$: emittance in x- and y-plane. The limitation arises from 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 [1]. Losses below a few percent during the accumulation plateau of 1 second can be tolerated and determine the intensity 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 [2-4]. For space charge compensation, the electron current profile has to match the longitudinal profile of the circulating ion bunch. A minimum number of lenses is required to maintain the symmetry. However, the number of lenses can be less than the super-period of the synchrotrons. The electron beams 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 spacecharge compensation scheme using a pulsed electron lens (Fig. 1). The demonstrator lens is presently being designed for SIS18 at GSI [5]. 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. A prototype 10 A electron gun, Rf modulator, transport section and collector have been developed in a Joint Research Activity within the ARIES EU-program by a collaboration among GSI, University of Frankfurt, Riga Technical University and CERN.

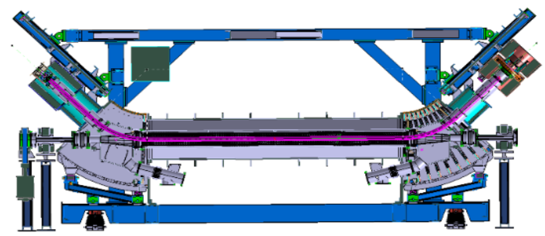

Figure 1: Design of an Rf modulated prototype electron lens for SIS18.

DYNAMIC VACUUM AND LOW CHARGE STATE HEAVY ION BEAMS

Space charge, beam current and impedances limit the maximum intensity of heavy ion beams in synchrotrons. Further increase of the beam intensity can be enabled by lowering the projectile charge state. However, at 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 [6]. Beam loss originated by such processes starts to dominate the overall loss budget significantly earlier than any space charge or current dominated phaenomena. Thus, lowering the charge state may at first generate more beam loss than any space charge related loss. Only if the charge exchange related beam loss is controlled by dedicated technical measures, a benefit for the intensity can be achieved. The cross section for ionization of intermediate charge state heavy ions in the energy range of SIS100, 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 for intermediate charge state heavy ion operation, charge exchange processes, are initiating a strong residual gas pressure dynamics. A single ion impact on the surface of an accelerator component is able to

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release up to 104 bound atoms and molecules. In order to predict the effect of technical modifications, the STRAHLSIM code [7] has been developed at GSI. It enables self-consistent simulations of the spatial and time resolved development of the pressure evolution and charge exchange processes in circular accelerators,. 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. 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 [8]. In SIS100, the main technical approach for stabilizing the dynamic vacuum is the charge separator lattice. The SIS100 charge separator lattice provides a peaked loss distribution for ionized projectiles with the peaks in the middle of each doublet group. This loss distribution enables a control of the desorbed gases by means of cryogenic ion catchers placed at these positions. 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 LHe as coolant. All magnet chambers are actively cooled with LHe. Even during fast ramping and corresponding inductive heating by the changing magnetic field, their surface temperature is kept below 10 K. In the first thermal cycle of the recently completed SIS100 string test, full functionality of the cryo-pumping concept in connected string of cryo-magnetic modules, forming a complete lattice cell, could be demonstrated. The chambers are cooled via a separate process line, connected to an 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 H2 and He, a large number of cryosorption pumps used. 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 [9, 10] have been developed. 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. It is planned to apply cryo-pumping concept as powerful tool for stabilizing the dynamics vacuum also in the room temperature SIS18. Experimental studies using prototype cryogenic inserts for the charge collimator system and for the thin wall magnet chambers have been completed (Fig. 2).

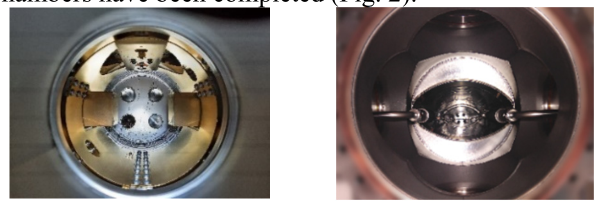

Figure 2: SIS18 ion catcher system (left) and thin wall magnet chamber (right) with cryogenic inserts.

FAST RAMPED LTS AND HTS SUPERCONDUCTING MAGNETS

Considering the requirements of FAIR and a potential next generation synchrotrons at GSI/FAIR, our R&D is focused onto the development of fast ramped superconducting magnets rather than of high field magnets. For SIS100, fast ramped super ferric 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 [11]. 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 CuNi 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. At fast ramping, AC loss in the magnets create heat dominated by hysteresis and eddy current effects in the yoke. By various modifications in the yoke (stainless steel end plates, smaller coil heads etc.) and cable, the AC loss could be significantly reduced in comparison with the original Nuclotron magnets. In order to enable continuous operation with triangular cycles, a curved, single layer coil dipole has been developed. The new coil is made of a high current cable with lower hydraulic resistance and reduced AC loss using small diameter NbTi filaments in a Cu-Mn interfilamentary matrix. The curved 3 m long magnet has a bending angle of 3 1/3°. In the frame of the EU IFAST program and in future as contribution to the EU MAHTS program, the know-how for technologies of fast ramped s.c. magnets and dedicate cables is further strengthened. GSI and its collaborators aim for the development of a new multi-layer HTS cable in conduit. The motivation for this development is the performance needed for the potential next generation FAIR synchrotron, SIS400, and its fast ramped magnets. The new general trend in using HTS technologies shall also serve the goal of enhancing the energy efficiency of the next generation of accelerators and thereby enable a more economic operation. Especially fast ramped s.c. synchrotrons, often used in high repetition operation or as injectors for larger synchrotrons or colliders, with their enormous amount of dynamic loss and heat induced into the cryogenic system determine the energy consumption of the cryoplant. JINR, Dubna is operating the superconducting Nuclotron synchrotron. JINR is planning a major modification of its LTS magnet

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system. In the frame of a largely completed R&D phase, JINR has developed a modified Nuclotron cable based on HTS tapes wound around the central cooling channel instead of the NbTi strands. Using HTS for the Nuclotron cable allows higher coolant temperatures and the use of other liquids and gases. Besides other options, the yokes of the new Nuclotron magnets will potentially be cooled by boiling N@80 K and the coil by gaseous He at 50 K. JINR has also explored ion beam treatment of HTS tapes and succeeded to enhance the critical current density. By exchanging all LTS magnets by the new HTS magnets, the energy cost for operating the cryoplant shall be reduced by more than ten times [12, 13]. The approach of developing HTS cable for the next generation of synchrotrons is also a core R&D activity at GSI. In collaboration with IEE Slovak Academy of Science, the ILK, Dresden and EMS University of Twente a round high current low AC loss ReBCO cable is under development. The application of the new cable in a future FAIR SIS400 dipole magnet has been used as starting point for its specification. The properties of cooling in axial and radial direction have been investigated separately. For the axial cooling parametric studies of mass flow, supply pressure, temperatures have been studied in dependence of cable length and diameter. The maximum length for different cable diameter depends on the AC loss. Winding tests have been conducted with different transposition twist pitch and winding directions to study e.g. the mechanical properties of the HTS tape under bending stress and different winding tensions (Fig. 3).

Figure 3: Winding test of a new HTS Nuclotron cable.

Electromagnetic models have been developed to estimate the magnetization in transverse AC field. Cable samples have been manufactured and measurements of AC loss and lateral cooling tests for various numbers of HTS layers were conducted. The AC loss in an HTS Nuclotron cable in an external magnetic field, e.g. in a coil of magnet is dominated by hysteresis loss. The hysteresis loss increase with the width of the tape.

$$Q_{hT} = \frac{2}{\pi cos\alpha} B_{max} I_c w$$

At the ramp rate needed for the SIS400 dipole cycle, with about 373 W/m, the AC loss would become inacceptable high. To lower hysteresis loss, several attempts have been performed in industry to substructure HTS tapes in smaller filaments, e.g. by laser cutting, mechanical cutting or etching. A new development of the company Supra for making striated HTS cables with filament widths of less than 0.1 mm may become a new opportunity to enable high ramp rates. Experimental studies applying the new striated HTS tapes to the HTS Nuclotron cable are in preparation. Furthermore, the application of such a new cable technology for energy transport in AC electric grids will be investigated.

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 high kinetic energies (γ>5), they become less effective. As first synchrotron world-wide, the SIS100 will be equipped with a laser cooling facility [14]. Several ion-charge state combinations (for Z<= 54) have been identified as candidates suitable for laser cooling at relativistic energies. The laser lab, which will host three 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 revolving heavy 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, the laser force will only act on the faster ions and will be slightly decelerated them. 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 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. Different to Rf bunching, bunch shorting by means of a laser cooler does not enlarge the longitudinal momentum spread, consequently no negative side effects of conventional Rf bunching appear such as beam size increase in dispersive sections or sections with large chromaticity or focusing systems with large chromatic aberrations.

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