TECHNOLOGIES FOR STABILIZING THE DYNAMIC VACUUM AND CHARGE RELATED BEAM LOSS IN HEAVY ION SYNCHROTRONS

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Abstract

Increasing the intensities of beams of highly charged heavy ions in synchrotrons is limited by various space charge and current driven effects. Lowering the charge state is therefore the most effective and finally the only measures to overcome these limitations and to generate ultimate intensity heavy ion beams. Although the acceleration of heavy ion beams in synchrotrons has always required excellent vacuum conditions, operation with high intensity intermediate or low charge state heavy ions drives these requirements to the limit of reachability. Ultimate intensities of beams of intermediate charge state heavy ions shall be accelerated in the FAIR synchrotrons SIS18 and SIS100. Therefore, a unique and tremendous effort had to be taken to minimize the static residual gas pressure and to control desorption driven pressure dynamics and thereby generated beam loss by ionization.

INTRODUCTION

SIS18 and SIS100 are the main accelerators for primary beams of the FAIR project. Both synchrotrons shall accelerate high intensity Proton and heavy ion beams. Acceleration of intense Proton beams does not generate specific requirements exceeding those of other world wide existing synchrotrons of comparable size and energy as the PS, AGS or the JPARC main ring. However, acceleration of more than 10^{11}, up to 10^{12} Uranium ions per cycle has required a new synchrotron concept and a unique UHV system design. In order to exceed the presently existing space charge limits in SIS18 and to reach the desired intensities in SIS100, the charge state of Uranium beams had to be lowered from the presently used charge state 73^+, down to charge state 28^+ for the future FAIR operation. The outstanding challenge of acceleration of such high intensity, intermediate charge state heavy ion beams is caused by their significantly enhanced cross section for ionization and their high potential for generating ion desorption driven vacuum instabilities. The challenge of a perfect control over the dynamic vacuum has dominated the main system decision of SIS100, namely to make use of superconducting magnets to enable extended cryogenic pumping. The goal of the overall UHV system layout is to keep the ionization beam loss below 3%.

For the normal conducting SIS18, which acts as the booster synchrotron for SIS100, an extended upgrade program has been defined in 2005 and completed [1]. The upgrade program was focused on the dynamics vacuum and ionization beam loss. In the course of the upgrade program the intensity of accelerated intermediate charge state heavy ions could be increased by two orders of magnitude. The SIS18 machine developments have provided the foundation for the understanding of these phenomena and enabled GSI to develop an appropriate system design for SIS100.

SIS100 LATTICE DESIGN AND PATTERN OF IONIZATION BEAM LOSS

The strong focusing SIS100 lattice has been optimized for providing a peaked distribution of ionization beam loss.

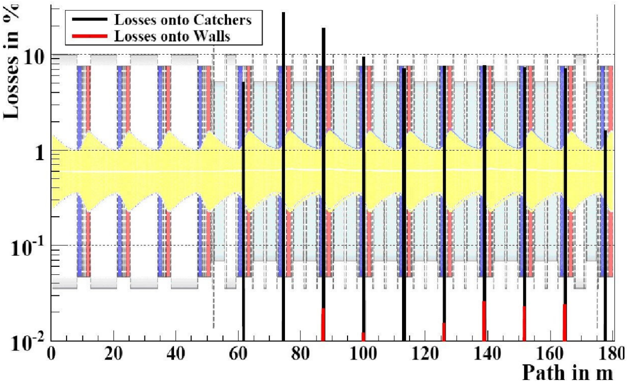

Figure 1: Peaked loss pattern of ionization beam loss.

The peaked loss distribution enables a control over the primary U28+ ions, which underwent a further single or multiple ionization (29^+, 30^+, . . .) by collisions with residual gas atoms. This perfect control is essential to prevent these ions from desorbing gas molecules from the surface of impact and thereby initiating a vacuum instability. A vacuum instability is generated by a local pressure bump which further amplifies ionization beam loss and thereby creates new pressure bumps downstream the starting point. Such a consecutive process may develop over the full circumference and may lead to complete loss of the heavy ion beam. The SIS100 doublet lattice provides a strongly peaked pattern of incident for single ionized U^{28+} ions (Fig. 1). By means of ion catchers installed at these pronounced positions in each lattice cell of the arc, almost 100% of the lost ions can be controlled. The SIS18 lattice has never been optimized for generating a peaked loss distribution at operation with U^{28+}-ions. However, the triplet lattice does also provide a loss distribution which enables the control of 68% of ionized particles. Due to their alternating beta function, typical FODO lattices are not suited at all for the control of ionization beam loss.

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CROSS SECTIONS FOR CHARGE EXCHANGE

The cross sections for ionization and electron capture have been calculated for different beam energies and for various residual gas components (Fig. 2) [2]. The cross sections for ionization of U^{28+}-ions at collisions with heavy residual gas components, e.g. Argon is about 100 times higher than for light residual gas atoms like Hydrogen. Therefore, it is most important to generate an initial residual gas spectrum, before beam injection, free of any impurities with heavy residual gas components. During beam operation, the initial static mass spectrum is significantly modified by desorption processes. The dynamic vacuum is continuously changing its total pressure, its partial pressures and its pressure distribution around the machine. The UHV system has to assure that the dynamic pressure of each residual gas components, multiplied with its cross section, does not exceed certain thresholds during the overall machine cycle. For the simulation of dynamic vacuum and the charge exchange processes the STRAHLSIM code has been developed at GSI [3]. The code is able to predict the time and space resolved evolution of total and partial pressures over a machine cycle and calculates the amount of charge exchange processes in this dynamic vacuum environment.

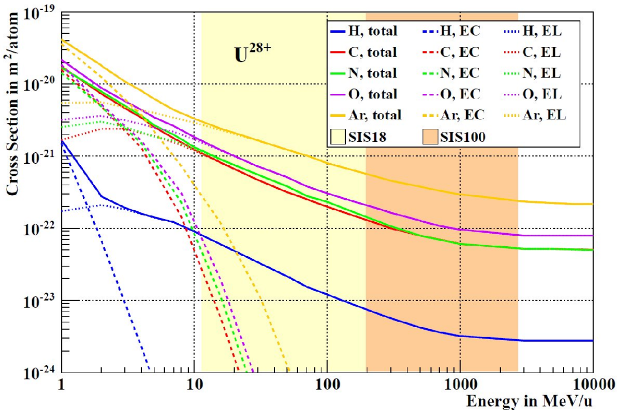

Figure 2: Ionization and electron capture cross sections for U^{28+} as a function of beam energy for various residual gas components.

CRYOGENIC ION CATCHER SYSTEMS

The special SIS100 lattice assures that charge exchanged ions are lost at well-defined positions, namely on the cryocatchers situated in between the two main lattice quadrupoles. Dynamic vacuum effects are suppressed effectively by means of a special low desorption surface used in the cryocatcher. The cryocatcher unit consists of the actual cryocatcher, which is a Gold coated Copper block, a support structure and a cryogenic UHV chamber. The surrounding vacuum chamber acts as a cryopump operated at temperatures below 10 K and is directly linked to the He supply line of the magnet cryostat. To keep the desorption rate low, in contrast to the cryocatcher chamber, freezing out of gases has to be avoided on the cryocatcher block itself. Therefore, the cryocatcher block has to be stabilized on a higher temperature than the chamber. This is achieved by its special support structure, which allows connecting the cryocatcher block thermally to the radiation shield of the cryostat (about 60 K). To keep the desorption yield low, the cryocatcher block provides a perpendicular surface of incidence for lost ions. A prototype cryocatcher has already been designed, manufactured, and tested at GSI (Fig. 3) [4].

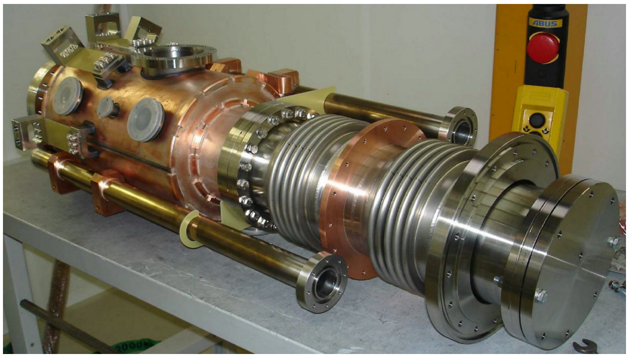

Figure 3: Prototype SIS100 cryocatcher unit.

The ion catcher concept has already been successfully tested in SIS18. A system of ten room temperature charge catchers has been installed. Different to the SIS100 catcher system which consists only of one block, two blocks are installed in each catcher of SIS18. The block on the inner side covers ions after further ionization and the block on the outer side dumps ions after electron capture. At the SIS18 injection energy of 11.4 MeV/u, cross sections for electron capture are still high (see Fig. 1). Thus, over the SIS18 acceleration cycle, depending on their energy, both sides of the ion catchers are hit by a relevant fraction of charge exchanged ions.

LHe COOLED, CRYOGENIC VACUUM CHAMBERS

The SIS100 dipole and quadrupole vacuum chambers are equipped with supplementary cooling tubes and will be mechanically integrated in the cold iron yokes of the fast-ramped superconducting dipole and quadrupole magnets. Due to the fast field variation, eddy current effects are considerable, especially in the SIS100 dipole chambers, and contribute significantly to the overall heat load of the cold mass. In order to keep the heat load for the cryogenic system at an acceptable level, the wall thickness of the dipole vacuum chambers must be 0.3 mm only. To obtain the necessary mechanical stability a strengthening by transverse stiffing ribs will be used (Fig. 4). The inner surface of the cold beam pipe will be used as a distributed cryopump. This means that the residual gas molecules will be effectively frozen out on the inner surface of the chamber wall. In order to preserve the effectiveness of cryopumping, the wall temperature of the beam pipe must be in a range $T \leq 15$ K. At these temperatures, all residual gas species except helium are pumped by the cold chamber walls. Assuming no external or internal leaks, the static residual gas pressure in the cold beam pipe will be in the order of some 10^{-12} mbar (at cryogenic temperatures).

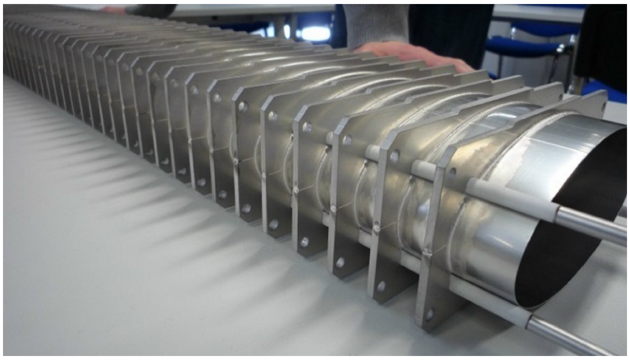

Figure 4: First of series thin wall, rib reinforced and actively LHe cooled dipole vacuum chamber.

With exceeding a critical wall temperature, previously pumped gas desorbs from the walls and increases the pressure during ramping. Therefore, a cooling of the vacuum chamber with four insulated LHe cooling tubes is required to keep the wall temperature during operation below 15 K. The insulation is required to minimize the induced eddy currents and to maintain a proper field quality at fast ramping. The heat transfer from the chamber surface to the cooling pipes of the first of series vacuum chamber has been provided by a ceramics filler (Ceramacoat 503-VFG-C). In a pure triangular magnet cycle a surface temperature of 17.5 K could be reached. In order to develop a more efficient bonding technology of the cooling pipes to the chamber ribs and surface and to further lower the surface temperature, six experimental chambers have been developed and tested under cryogenic conditions. The following bonding technologies have been manufactured and tested: 1-Metalized sapphire feed coating, 2-metalized segmented Al_2O_3 ceramics feed coating, 3-metalized segmented Al_2O_3/ZrO ceramics coating, 4-direct soldering of cooling tubes on chamber (insufficient field quality expected), 5-epoxy coating plus epoxy/silver filler, 6-epoxy glass fiber taping.

CRYO-ADSORPTION PUMPS

The cryogenic vacuum system of SIS100 will be operated at temperatures between 5 and 15 K and at pressures below 5×10^{-12} mbar (pressure value is related to cryogenic temperatures). At these temperatures, the bare cold chamber walls have a limited pumping capacity for H_2 and almost no pumping power for He. Therefore, additional pumping speed for these both gas species is of crucial importance for low and long-term stable vacuum pressures. For this reason cryoadsorption pumps will be installed in the cryogenic sections of SIS100 as auxiliary pumps providing additional pumping speed for He and H_2 (Fig. 5). Ten cryoadsorption pumps will be distributed per cryogenic arc of SIS100. The pumps will be installed in intervals of 13 m between each s.c. dipole pair as well as in the s.c. quadrupole doublets located on the straight beam lines of the ring. In total, 85 series cryoadsorption pumps will be installed in SIS100. The installation between the dipole magnets enables a stabilization of the H and He partial pressure in this conductance limited section of the machine. The H2 and He pumping speed of the dipole- and quadrupole chambers may suffer from increased surface temperatures at strong eddy current heating (depending on the accelerator cycles). In such cases, the cryoadsorption pumps between the dipole magnets and the cryocatcher in between the quadrupole magnet chamber will stabilize the H_2 and He partial pressures below the critical value.

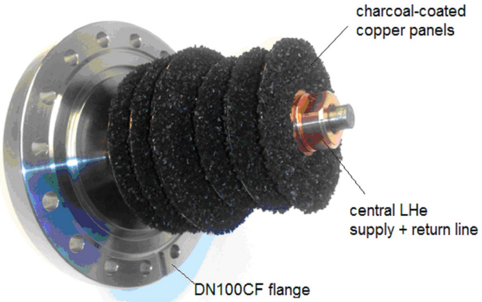

Figure 5: SIS100 cryo adsorption pump.

EXTREMES OF CONVENTIONAL UHV SYSTEM DESIGN

By design, the pressure peaks over the four warm straight cells in each of the six straights of SIS100 will finally define the beam life time. In order to minimize the pressure peaks in the warm cells, all warm accelerator components in SIS18 and SIS100 are equipped with a bake-out system enabling thermal cycles of up to 300 °C. Most of the vacuum chambers of the warm devices in the SIS100 straights will be NEG coated or make use of NEG panels in conductance limited sections. Large injection- and extraction devices are equipped with powerful systems of conventional IGP pumps as well as IGP/NEG combination pumps. E.g. the 5 m long electrostatic extraction septum will be pumped by 20 NEG modules and 4 ion getter pumps. Thereby, the maximum total pressure in the warm SIS100 cells will be kept below 10^{-11} mbar.

ACKNOWLEDGMENTS

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