IONIZATION LOSS AND DYNAMIC VACUUM IN HEAVY ION SYNCHROTRONS

L. Bozyk[*], P. Spiller, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

Dynamic vacuum effects, induced by charge exchange processes and ion impact driven gas desorption, generate an intensity limitation for high intensity heavy ion synchrotrons. In order to reach ultimate heavy ion intensities, medium charge state heavy ions are used. The cross sections for charge exchange in collisions with residual gas molecules for such beams are much higher, than for highly charged heavy ion beams. Therefore high pumping power is required to obtain a very low static residual gas pressure and to suppress vacuum dynamics during operation. In modern heavy ion synchrotrons different techniques are employed: NEG-coating, cryogenic pumping, and low-desorption ion-catcher. The unique StrahlSim code [1] allows the comparison of different design options for heavy ion synchrotrons.

Different aspects of dynamic vacuum limitations are summarized, such as the dependence on different injection parameter. A comparison between a room temperature and a cryogenic synchrotron from the vacuum point of view is given.

INTRODUCTION

Modern heavy ion synchrotrons are aiming for highest particles intensities. In order to reach these goals, medium charge states are used. Thereby, the space charge limit is shifted to higher number of particles and stripping losses are avoided. However, the cross sections for charge exchange in collisions with residual gas molecules are much higher, than for higher charge states. Ions, which lost or gained an electron, do not match the ion optical lattice any more. They are separated from the circulating beam and get lost. Ions hitting the vacuum chamber walls at an grazing angle produce a huge amount of gas via ion-impact stimulated gas desorption. This local gas production in turn increases the probability for further charge exchange and beam loss. This principle is sketched in Fig. 1. Above a certain threshold of beam intensity, a self-amplification develops, which can lead to complete beam loss and finally represents an intensity limitation.

The gas production is significantly reduced by placing low desorbing surfaces, so-called ion catchers, at the loss positions. The desorption rate can be reduced by two orders of magnitude, stabilizing the pressure and shifting the intensity limitation to higher number of particles. Since any kind of beam loss can cause ion-impact stimulated desorption, all systematic beam loss has to be avoided and reduced to the minimum. Since the charge exchange cross sections decrease with the projectile energy [2], losses during injection are especially serious. The whole acceleration cycle suffers from the gas production at the cycle start. Unnecessary storage times at low energies have to be avoided as well. It is necessary to reach high beam energies with low cross sections as fast as possible.

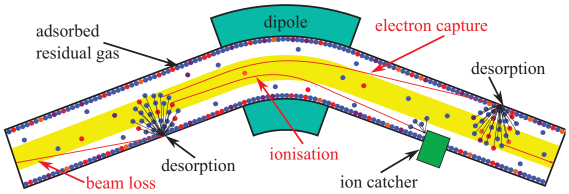

Figure 1: Principle of ionization loss and dynamic vacuum.

SIMULATION OF DYNAMIC VACUUM EFFECTS

In this paper some simulations of dynamic vacuum are shown, which compare the impact of different parameters of a heavy ion booster synchrotron. The relevant parameters of the accelerator are listed in Table 1. If some of these parameters are varied during the simulation, it is noted in the text. For the simulations the StrahlSim-code [1] has been used. It is based on the self-consistent simulation of longitudinal pressure profiles for each residual gas component. Energy dependent projectile charge exchange is calculated and particles are tracked in the system via linear ion optics. The impact of lost ions in target-elements yields in a time limited increase of the local outgasing rate, decreasing the local pressure. Such a feedback between vacuum system and heavy ion beams is established.

To characterize the dependency of the synchrotron on a specific parameters, the number of injected particles has been varied and the corresponding number of extracted particles is evaluated. Without ionization loss, the amount of extracted particles linearly depends on the number of injected particles. Due to dynamic vacuum effects, the transmission decreases with increasing intensity. Such a limit for the number of extractable particles arises. Above a specific number of injected particles the number of extracted particles drops.

INJECTION PARAMETER VARIATION

The transmission and maximum number of extractable particles strongly depends on the amount of injection loss. Also the influence of storage time, required for the injection process and the injection energy have been investigated.

Injection Losses

Figure 2 shows the number of extractable particles as a function of the injected intensity for different amounts of

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[*] L.Bozyk@gsi.de

Table 1: Main Parameter of the Heavy Ion Synchrotron Used for the Presented Simulations

Ion	U^{28+}
Injection energy	11.4 MeV/u
Extraction energy	200 MeV/u
Circumference	216 m
Fraction coated with NEG	61.2%
Ion catching efficiency	60%
Repetition rate	1 Hz
Cycle time	0.87 s
Ramping rate	4 T/s

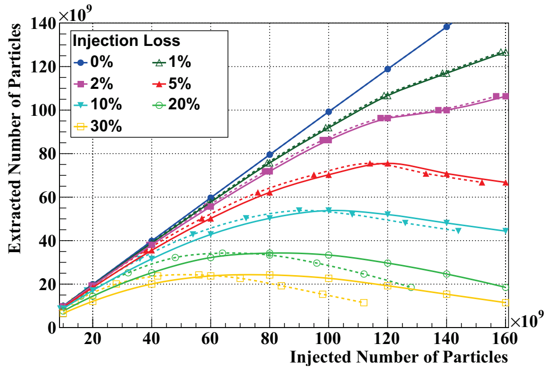

Figure 2: Number of extracted particles as a function of the number of injected particles for different amount of injection loss. The dashed lines represent the stored number of particles after injection, i.e. after the subtraction of injection loss.

injection loss. In the loss-free case, the vacuum system of the synchrotron is not destabilized, and the dependence is linear. But vacuum degradation by upcoming injection loss leads to increased ionization loss, decreasing the intensity at extraction and even yielding in a maximum number of extractable particles.

For the further analysis, shown in Fig. 3, the maximum number of extracted particles has been determined from Fig. 2. Additionally, the following cycles have been simulated, which suffer from the vacuum degradation from the previous cycle. The strong dependence on the injection loss is clearly visible. After several cycles an equilibrium between gas production due to ionization loss and pumping power develops. Therefore the curves approach each other for increasing cycle number.

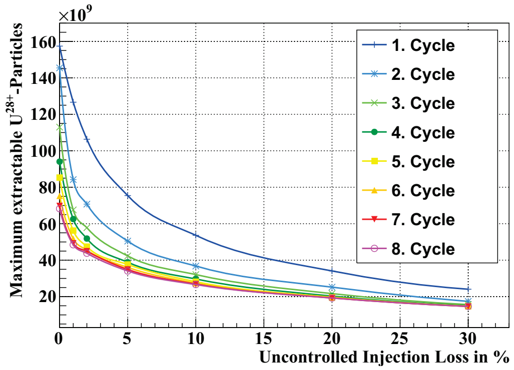

Figure 3: Evolution of the maximum extractable intensity for different amount of injection loss.

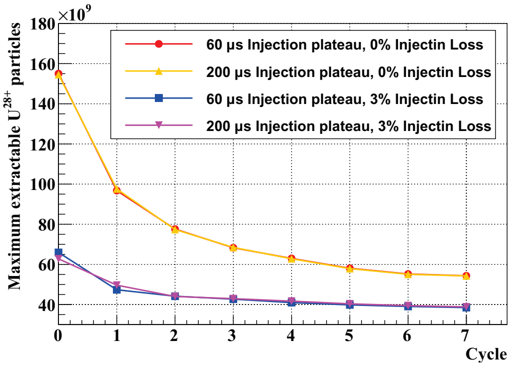

Figure 4: Dependency of the maximum extractable particles on the length of the injection plateau. This figure also represents a cut through Fig. 3 for 0% and 3% injection loss.

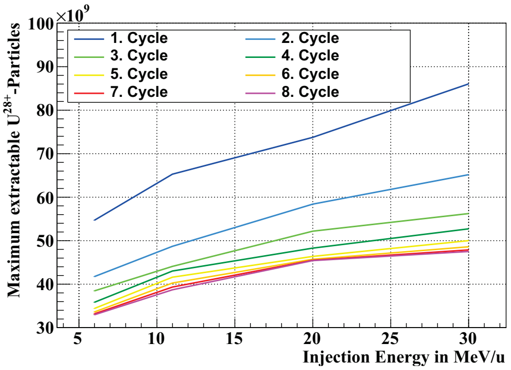

Figure 5: Dependency of the maximum extractable particles on the injection energy.

Injection Plateau Duration

In the next calculation, the storage time during multi-turn injection has been varied, see Fig. 4. The injection time has been increased by about a factor 3, and the loss-free case is compared to a scenario with 3% injection loss. It turns out, that the dependence on the injection plateau length can be neglected, compared to the amount of injection loss. If 200 µs are required for a lossless injection, the ionization loss does not increase compared to 60 µs injection time.

Figure 4 also represents a cut through Fig. 3 for 0% and 3% injection loss. The cycle dependent evolution of maximum extractable particles shows a saturation after several cycles. Here, the equilibrium between gas production and pumping speed has been reached.

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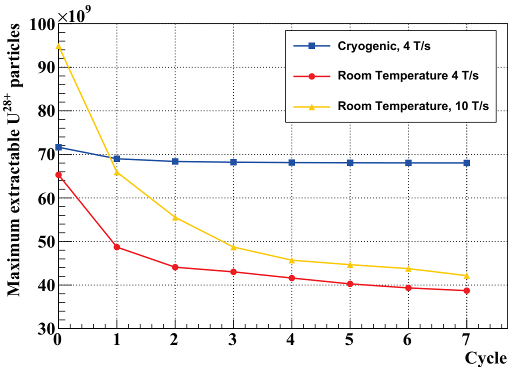

Figure 6: Comparison between a slow and a fast room temperature and a cryogenic heavy ion booster synchrotron from the dynamic vacuum point of view. 3% injection loss has been assumed.

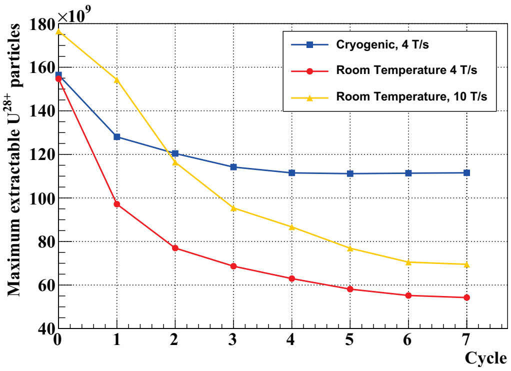

Figure 7: Comparison between a slow and a fast room temperature and a cryogenic heavy ion booster synchrotron from the dynamic vacuum point of view. No injection loss has been assumed.

Injection Energy

The injection energy has been varied for the simulations shown in Fig. 5. Here 3% injection loss are assumed. Again, the maximum intensity at extraction has been determined by assuming different injection intensities. The curves for different cycles approach as well, as an equilibrium between gas production and pumps is reached. The maximum intensity increases with injection energy, since the cross sections decrease with energy [2]. The dependency is not as strong as on the injection loss.

COMPARISON ROOM TEMPERATURE AND CRYOGENIC UHV SYSTEM

In the design phase of a high-intensity heavy ion synchrotron the decision has to be taken, if a room-temperature or a cryogenic vacuum system should be used. This question has been investigated from the dynamic vacuum point of view. Room-temperature magnets can safely be ramped up to 10 T/s. Here, distributed pumps are realized by NEG-coating, which does not provide pumping speed for all gas species [3, 4]. Superconducting/superferric magnets typically reach a ramping rate of about 4 T/s. But they offer the possibility of a cryogenic vacuum system. Cryogenic vacuum chamber walls in the temperature range of 5-15 K provide a reliable and high pumping speed for all residual gas species. In the given temperature range, Hydrogen gets pumped via cryoadsorption, a process which is limited in capacity. With a proper technical realization the capacity is sufficient for a reliable operation [5].

In the following simulations, the NEG coated magnet vacuum chambers assumed in the previous simulations have been replaced by cryogenic vacuum chambers. The straight sections between the magnet chambers remain at room temperature for any required installations. Now 58% of the circumference has a 15 K surface and only 9% is NEG-coated.

Figure 6 shows the comparison between a heavy ion synchrotron ramped with 4 T/s and 10 T/s, assuming 3% injection loss. The pumps from the faster synchrotron suffer from the injection loss and subsequent ionization loss, such that the maximum extractable intensity drops within few cycles to a low level. The slower cryogenic synchrotron is not able to extract as much ions as a fast room temperature synchrotron in the first cycle, but the intensity remains almost constant.

To compare the time-averaged extraction intensity, one has to consider, that the cycles with 10 T/s have a shorter cycle time by a factor of 2.1, than the 4 T/s cycles.

Fig. 7 shows the same simulation but without injection loss. As expected from Fig. 3, the maximum intensity strongly increases. All three synchrotron types do now require more cycles to reach an equilibrium, than in the case with injection loss. Vacuum degradation only happens via ionization loss in the residual gas atmosphere. The cryogenic and the slow room temperature synchrotron start with the same intensity and the fast room temperature synchrotron remains more cycles predominant.

SUMMARY

Ionization loss and dynamic vacuum effects represent an intensity simulation in high intensity heavy ion synchrotrons. The StrahlSim code enables a comparison of different design options and loss scenarios. The maximum extractable intensity strongly depends on the amount of injection loss. Because of high charge exchange cross sections at injection energies, the whole cycle suffers from this type of loss. The vacuum degradation, which builds up over several cycles, subsequently decreases the intensity. Injection energy and duration have been investigated in the same way. However, the dependency of the intensity is not as strong as from the injection loss.

The decision process, which arises in the design phase of a new high intensity-heavy ion synchrotron, concerning a room-temperature or a cryogenic vacuum system, has been investigated. The favourable solution depends on the requirements. But a cryogenic pumping system generally stabilizes the vacuum pressure at a lower pressure, than a room temperature system is able to.

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