SYNCHROTRON OPERATION WITH INTERMEDIATE CHARGE STATE HEAVY ION BEAMS

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Abstract

Increasing the intensity of heavy ion beams in synchrotrons, especially in the low and intermediate energy range, requires a decrease of the charge state. The FAIR project [1,2] at GSI is aiming for highest heavy ion beam intensities with an increase of two orders of magnitude compared to the present intensity levels. Space charge limits and significant beam loss in stripper stages disable a continuation of the present high charge state operation. The presently achieved level of heavy ion beam intensities is in the order of 10^9 and 10^{10} heavy ions per cycle (e.g. with U^{73+}or Ta^{61+} ions). The FAIR intensities of 10^{11} to 10^{12} heavy ions per cycle can only be reached by reducing the charge states, e.g. with acceleration of U^{28+}-ions instead of U^{73+}-ions. As an extreme example of the general tendency to lower charge states with increasing intensity, the Heavy Ion Fusion (HIF) driver studies HIBALL I/II and HIDIF can be taken, which have been conducted at GSI. For reaching ignition of the fusion pellet, about 10^{15} Bismut ions with charge state 1+ are required. With high rigidity heavy ion synchrotrons, like the planned FAIR synchrotron SIS300 and low charge state heavy ions like U^{4+}, intensity values in the middle of the presently achieved and the fusion driver intensities may be generated.

DYNAMIC VACUUM AND CHARGE CHANGING PROCESSES

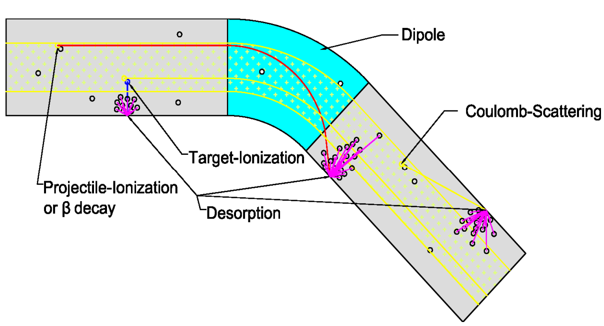

Figure 1: Electron capture or ionization processes at collisions with residual gas atoms and molecules change the charge state of the beam ions. Gas desorption drives a pressure bump at the impact position after dispersive elements.

Completely neglected in the fusion driver studies, however the main loss mechanism at heavy ion operation with low charge states in circular accelerators is ionization (or at low energies electron capture) due to collisions of the projectiles with residual gas atoms (see Figure 1). Ions with changed charge states and thereby large deviations form the reference rigidity are lost at positions with sufficient dispersion.

Local pressure bumps at these impact positions, generated by ion desorption processes, drive a strong vacuum dynamics. Thus, a very low static, initial pressure (in the range of $<10^{-11}$ mbar) is important but not sufficient and suitable to prevent a strong residual gas pressure dynamics and consequently major beam loss.

In the collision process, the charge state of an ion tends to approach the equilibrium charge state at the relevant beam energy. Depending on the energy range, the dominating processes may even face a transition from electron capture to ionization during the acceleration process (Table 1).

The problem arises especially since the injectors linacs are most often not well matched to the equilibrium charge state at the injection energy. The charge state of the injected beam is typically determined by the stripper system of the linac and depends on the equilibrium charge state at the energy of the stripping process. Thus, in existing facilities the charge state for injection can not easily be changed.

Table 1: Injected and equilibrium charge states in SIS18 at injection and extraction energy for different ions. With respect to ionization beam loss 59+ would be the best charge state for injection into SIS18.

Ion	Injected charge with/without stripper	Equilibrium charge state at injection	Equilibrium charge state at extraction
Ne	7+ /10+	10+	10+
Ar	10+/18+	17+	18+
Ni	14+/26+	25+	28+
Kr	16+/34+	31+	36+
Xe	21+/48+	42+	54+
Ta	24+/61+	51+	73+
Au	24+/64+	54+	79+
U	28+/73+	59+	92+

Electron Capture

The resulting charge state from electron capture processes can be estimated by the Schlachter formula [3]. Although at collisions with heavy elements (e.g. Ar), deviations from measured cross section values are known, qualitatively the energy dependence is well described. Figure 2 shows the cross sections for U^{28+} in the energy range of SIS18 and SIS100.

Electron Loss

At collisions with residual gas atoms, the beam ions may loose one or more electrons. Multiple ionisations may occur in a single or in multiple events. Actually, there is no empirical formula for the electron loss process which describes the cross sections with sufficient precision. In order to extent the experimental data basis for ionisation cross section, a number of machine experiments have been conducted in the GSI Experimental Storage Ring (ESR). By means of the internal gas jet target, the interaction rate can be controlled with high precision. For higher, non-relativistic energies, Olson has developed a cross section model following the n-CTMC (classical trajectory Monte-Carlo method) for single- and multiple ionization [4]. For the calculation of the total ionization cross sections in the relativistic energy range, Shevelko has developed the relativistic LOSS-R-Code [5]. However, the n-CTMC approach enables the treatment of individual ionization channels (degrees).

Figure 2 shows the loss cross section calculated with the LOSS-R-Code and the capture cross sections for different target atoms which are typically constituents of the residual gas spectrum. As can be seen, in the energy range of SIS18 and SIS100 electron capture has a minor importance.

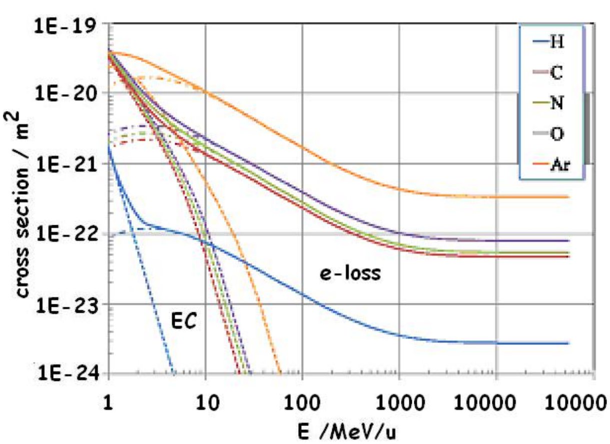

Figure 2: Electron capture cross section (short dashed lines), loss cross sections (long dashed lines) and total cross section (solid line) for charge change of U^{28+}as a function of the beam energy.

The GSI atomic physics group has provided the cross sections of various ion species and charge states used for the design studies of SIS18 and SIS100 [6]. Generally, the cross sections increase with the atomic number and decrease with the charge state. Therefore, dynamic vacuum driven beam loss is a challenge especially for the operation with the most heavy ions. In order to determine the trajectories of the beam ions after the collisions and to predict the loss distribution over the circumference, cross sections are needed for each ionization degree. Therefore, the total cross sections calculated by the LOSS-R-code have been split into the different ionization channels.

Figure 3 shows the probability for multiple ionization of U^{28+} up to 200 MeV/u calculated by Olson.

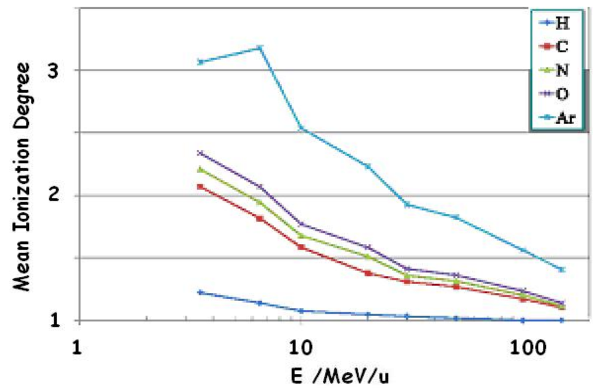

Figure 3: Mean ionisation degree increase for U^{28+} as a function of the beam energy.

Applying this scaling, the probability for each ionization degree can be calculated for the different residual gas components. Figure 4 and 5 show the cross sections for different ionization degrees at collisions with H (light) and Ar (heavy) atoms.

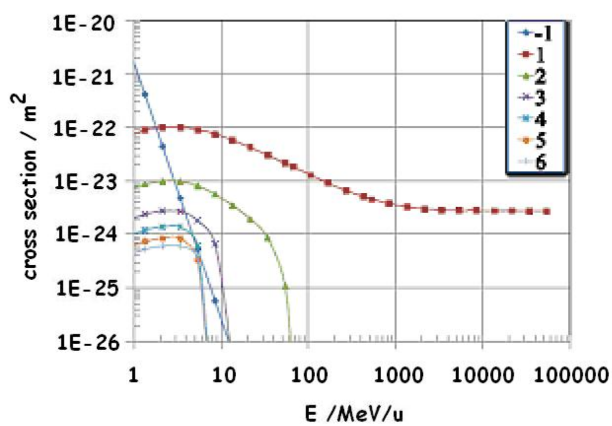

Figure 4: Cross section for different degrees of ionisation in H.

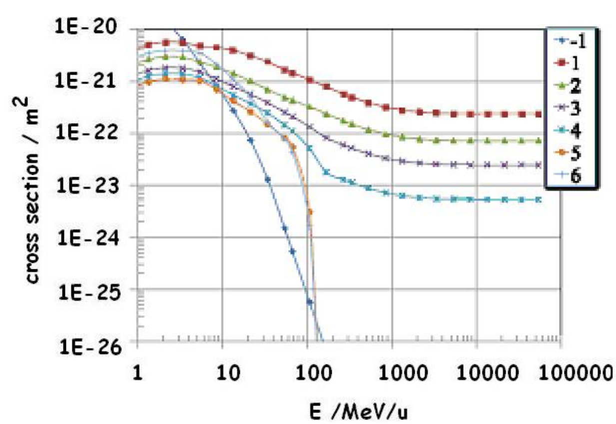

Figure 5: Cross section for different degrees of ionisation in Argon.

As can be seen, the cross sections for Hydrogen are almost two orders of magnitude lower than for Argon. Although in the dynamic case the residual gas spectrum is determined by the desorbed CO and CO_2 molecules, the fraction of heavy constituents in the initial static residual gas should be minimized.

STRAHLSIM DYNAMIC VACUUM CODE

For the simulation of dynamic vacuum effects and beam loss due to a charge change of the projectiles, the program STRAHLSIM has been developed [7]. The accuracy of the predictions for ionization beam loss in the energy range of SIS100 could be continuously improved and has been benchmarked with SIS18 machine experiments. The new cross sections, as well as a new scaling law for the desorption yield according to the specific energy deposition $(dE/dx)^2$ [8] were implemented. However, experimental studies are still missing, supporting the scaling to high energies. Furthermore, the beam scrubbing effect and the dependence of the pumping speed of NEG-coated and cryogenic surfaces as a function of the number of mono-layers adsorbed gases are accounted. Thereby, long term simulations and predictions on the ionization beam loss and dynamic pressure have been enabled.

SIS18 AND SIS100 FOR FAIR

In the frame of the SIS18upgrade program [9,10] the following recipe has been developed for the acceleration of intermediate charge state heavy ions:

- Minimization of systematic beam loss and control of unavoidable loss by means of dedicated, low desorption yield catchers, especially at the beginning of the cycle, at injection or the RF capture process to avoid initial pressure bumps.
- Fast magnet ramping for a fast reduction of the cross sections with energy.
- Short cycle times to minimize the interaction time.
- Minimization of the average initial static pressure and avoidance of local pressure peaks in a conductance limited UHV system by means of a strong distributed pumping system.
- Limited number of cycles in an injection batch to enable a recovery of the residual gas pressure.
- Control of ionization beam loss by means of a dedicated low desorption yield catcher system with locally increased pumping power.

According to these rules, an extended upgrade program has been defined to prepare SIS18 for the FAIR booster operation. The upgrade program involves most of the technical systems and is dedicated to the stabilization and control of the dynamic vacuum at very high U^{28+} intensities with $1.5x10^{11}$ per cycle. In the frame of the upgrade program which is presently realized, significant progress has been achieved in the acceleration of intermediate charge state heavy ions (Figure 6).

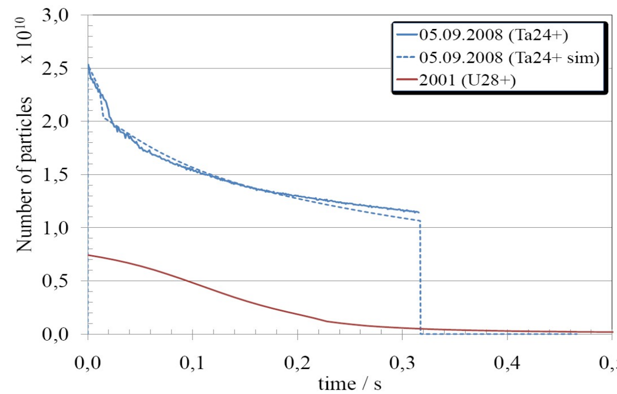

Figure 6: Time dependent intensity of intermediate charge state heavy ions (Ta^{24+} and U^{28+}) in a SIS18 cycle. The significant amount of beam loss is due to charge changing processes – mainly ionization. The progress as indicated by the two intensity curves has been made in the frame of the SIS18upgrade program.

In parallel, for reaching the FAIR intensity goals, a new synchrotron design concept had to be developed for SIS100 with the goal to minimize the beam-residual gas interaction and consequently the beam loss by charge change: SIS100 is the first synchrotron which has been optimised for the acceleration of high intensity, intermediate charge state, heavy ions [11]. Ionisation beam loss, desorption processes and pressure stabilization were the driving issues for the chosen general system layout and for several technological approaches. The SIS100 lattice structure (charge separator lattice) has been optimised with respect to the efficiency of a charge catcher system, consisting of six times eleven catchers situated in the arcs of SIS100. Each lattice cell acts as a charge separator providing a peaked distribution of ionisation beam loss along the circumference. The peaked loss distribution enables the control of ionisation beam loss by means of a specially developed catcher system which assures a very low effective desorption yield.

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