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ION TRAPPING AND INSTABILITIES IN SLS 2.0

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Abstract

Residual gas atoms, ionized by the electron beam, may create two effects in an electron accelerator. One is the trapping of ions in the beam channel by the Coulomb forces of the beam and the other is the fast beam ion instability, a dynamic mutual transverse oscillation between ions and electrons. While the strongly reduced beam emittance of the accelerator upgrade SLS 2.0 is helpful in that situation, it will not suppress ion related effects completely. To avoid ion trapping, a small ion clearing gap of 30 buckets is still required. Pressures of 10^{-9} mBar, expected during vacuum conditioning, may cause sufficient build up of ions during the passage of the bunch train to provoke fast beam ion instabilities, requiring damping by the bunch by bunch feedback system or multiple clearing gaps. At nominal conditions with 10^{-10} mBar, a stable operation is expected.

INTRODUCTION

In the beginning of 2025, the upgraded Swiss Light Source SLS 2.0 [1] will go in operation, featuring an advanced multibend optics with an improvement of more than fifty in the brilliance of the generated light and an enhanced power efficiency due to the use of permanent magnets solid state amplification in the main RF. Main parameters are listed in Table 1.

Table 1: Main Parameters of SLS 2.0

Parameter	Value
Circumference	288 m
Harmonic Number	480
Average Current	400 mA
Emittance	160 pmrad
Emittance coupling	6.6 %
Camshaft bunch	5 nC

In addition to wake fields and coherent synchrotron radiation, thin plasma generated by collisions between the beam and residual rest gas atoms may affect the stability and life time of the circulating beam. This may happen via two mechanisms.

Trapping of ions in the transverse potential well of the electron beam cause an increased rate of collision between beam and ions, which deteriorates the emittance and reduces the life time. The important parameters for this are the horizontal and vertical beam size throughout the machine, as determined by emittance and beta function, and the atomic weight of the gas molecules. The magnitude of the residual gas pressure only affects the speed of the accumulation of ions, but does not influence the principal effect. The occurence of this trapping is controlled by a sufficient length of the ion clearing gap in the fill pattern.

With suitably high ion densities, coupled oscillations between the ion cloud and the electron beam may appear leading to a fast beam ion instability (FBII). In the presence of an ion clearing gap, inhibiting the slow accumulation of trapped ions, this requires a certain minimum residual gas pressure. As the bunch train passes through a given segment of the machine, enough ions need to be generated to exceed the stability threshold towards the end of the train before they drift out and get lost in the clearing gap. The first bunches in the train typically are stable and will only ionize whereas the oscillation starts somewhere in the middle increasing towards the end of the train. A second condition for this instability is, that the oscillation frequency of the ions within the potential of the beam lies in the vicinity of one of the betratron side bands to be able to couple. So any coupling driving this instability happens only in those location of the ring, where the betatron and ion resonances cross.

TRAPPING

A first trapping analysis was performed already by Albin Wrulich for an early lattice version [2]. Using up to date lattice data, the same approach was also used here.

Approach

For small oscillation amplitudes, the kick experienced by an ion due to the Coulomb field of an electron bunch can be described in a thin lens approximation as:

$$\begin{bmatrix}\Delta x'\\ \Delta y'\end{bmatrix} = -\frac{2N_b r_p}{A}\left(\frac{1}{\sigma_x+\sigma_y}\right)\begin{bmatrix}x/\sigma_x\\ y/\sigma_y\end{bmatrix} = -\alpha\begin{bmatrix}x/\sigma_x\\ y/\sigma_y\end{bmatrix} \quad (1)$$

N_b is here the number of electrons per bunch, r_p the classical radius, $\sigma_{x,y}$ the rms beam size and A the ion mass in atomic units. Having been kicked by the bunch, the ion drifts freely until the next bunch arrives.

The ion motion can be described by the following optics matrices

$$M_d = \begin{bmatrix}1 & d\\ 0 & 1\end{bmatrix}, M_g = \begin{bmatrix}1 & Gd\\ 0 & 1\end{bmatrix}, M_b = \begin{bmatrix}1 & 0\\ -\alpha & 1\end{bmatrix},$$

where M_d models the drift along one bunch spacing d, M_g the drift along the ion clearing gap of length Gd, M_b the kick and N the harmonic number of the ring. With that, the dynamics of the ion oscillation during one full passage of the bunch train is described by the revolution matrix:

$$M_{rev} = (M_d M_b)^{N-G} M_g M_b \quad (2)$$

A trapped ion will follow a stable orbit, the kick experienced is small enough so that the motion is periodic. Mathematically, this corresponds to the absolute eigenvalues of M_{rev} being smaller equal to one, or - easier to compute - that the trace of the matrix is smaller equal to two.

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In physical terms, trapping happens with a higher probability for ions with a high atomic weight and at locations with large beam sizes/large beta function values. A suitably long ion clearing gap is the typical countermeasure used to destabilize the ion orbits.

Results

Figure 1 shows the beta functions over a good third of the ring. To examine trapping, three locations with high beta function were examined and are indicated in the plot. Location A corresponds to a function maximum inside the bend, B to the maximum situated in the quadrupole doublet in the medium straight and C to that in the doublet of the long straights. Exact coordinates and beta values are listed in Table 2.

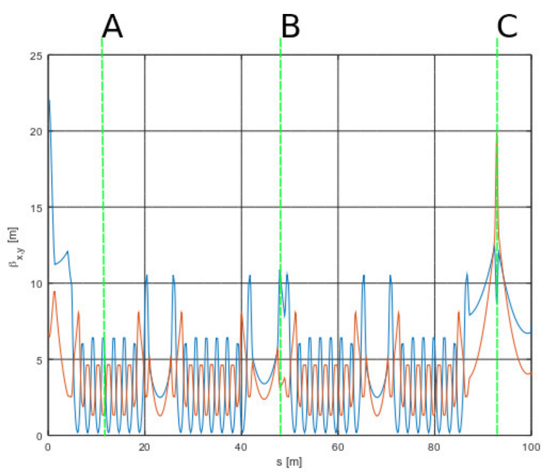

Figure 1: Beta function (blue:x, red: y) of a good third of the ring with test locations (A,B,C) examined in the analysis. The ring has threefold symmetry.

Table 2: Locations Suitable for Trapping

Name	S [m]	β_x [m]	β_y [m]
A	10.96	3.31	2.40
B	47.55	6.31	5.32
C	10.96	8.66	19.81

The nominal values (Table 1) were used for emittance and coupling factor. Figure 2 shows the trapping conditions without ion clearing gap. Atomic weights with instable oscillation conditions (no trapping) are marked in green, while trapping is shown in red. Also marked are ion types, we can expect (H_2, CH_4, H_2O, CO and CO_2). The heaviest ions are CO_2^+ ions with an atomic weight of 44. While hydrogen is always expelled by the kicks, the heavier species will get trapped, so that an ion clearing gap will be required.

Figures 3 and 4 show the situation with the nominal gap of 30 buckets with and without a camshaft bunch in the middle of the gap. While we see still one weight, where we may expect trapping (in principle harmless, since there are no ion species with that weight), a camshaft bunch of 5 nC destabilizes even that, so that we can expect stable operation.

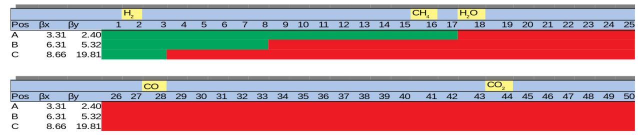

Figure 2: Trapping at various locations versus atomic weight for homogeneous filling

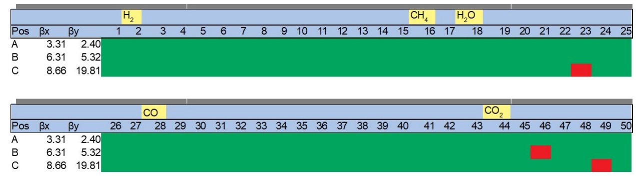

Figure 3: Trapping with ion clearing gap of 30 buckets

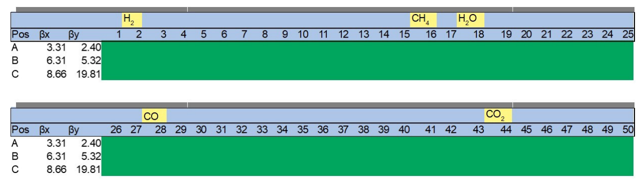

Figure 4: Trapping with 30 buckets gap and 5 nC camshaft bunch in the middle of the gap

FAST BEAM ION INSTABILITY

Approach

The fast beam ion instability is essentially caused by the coupled oscillation of two charged columns, the electron beam and the ions. Since the ion column is generated by the collision between electron and neutrals, it will have the same transverse dimensions as the electron beam. To analyze the dynamic behaviour, the approach by Bosch and Hsue [5, 6] was used here.

For a simple ring optics with a constant beta function and small amplitudes in the tranverse electron and ion offsets x_e, x_I, the dynamic of an individual bunch is given by the following coupled system:

$$\frac{d^2 x_I}{dt^2} = -\omega_I^2 (x_I - x_e) \tag{3}$$

$$\omega_I^2 = \frac{< N_e >}{M_I \sigma_y (\sigma_x + \sigma_y)} \tag{4}$$

$$\frac{d^2 x_e}{ds^2} + \frac{\omega_\beta^2}{c^2} x_e = -\omega_e^2 (x_e - x_I) \tag{5}$$

$$\omega_e^2 = \frac{< N_I >}{\gamma M_e \sigma_y (\sigma_x + \sigma_y)} \tag{6}$$

σ_x, σ_y are the transverse beam size, $< N_e >$, $< N_I >$ the number of electrons and ions, averaged over the ring circumference, M_e, M_I the electron and ion mass and γ the relativistic energy of the beam. For a coupled bunch motion, the ion resonance must overlapp with one of the synchrotron side bands $m\omega_0 + \omega_\beta$ (ω_0 is the revolution frequency). The

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instability growth rate α is:

$$\frac{\alpha}{\omega_0} = \frac{\omega_e}{2\omega_0}\sqrt{\frac{\omega_i}{m\omega_0 - \omega_i}} \tag{7}$$

In a real ring, the beta functions vary so that also also the ion resonance frequencies are not fixed, but are distributed with a density $f_I(\eta)$, which is given by the beta functions in the ring. Resonances and growth factors can be obtained with the following convolution:

$$-\Omega = \omega_\beta + \frac{\omega_e^2}{2\omega_\beta}$$

$$\left[1 + PV\int_0^\infty \frac{\eta^2 f_I(\eta)}{\omega_R^2 - \eta^2} d\eta - i\frac{\pi}{2}\omega_R f_I(\omega_R)\right] \tag{8}$$

$$\alpha = \frac{\pi\omega_e^2}{4\omega_\beta}\left|\omega_\beta + m\omega_0\right| f_I(\left|\omega_\beta + m\omega_0\right|) \tag{9}$$

Results

The residual gas in the vacuum system is expected to be dominated to equal parts by hydrogen and carbon monoxide. Hydrogen ion orbits are already instable over single bunch spacings (see also Fig. 2 and will not accumulate during the passage of the train. Only carbon monoxide ions need to be investigated as possible causes of FBII. The density distribution of the FBII resonances is shown for all modes in Fig. 5.

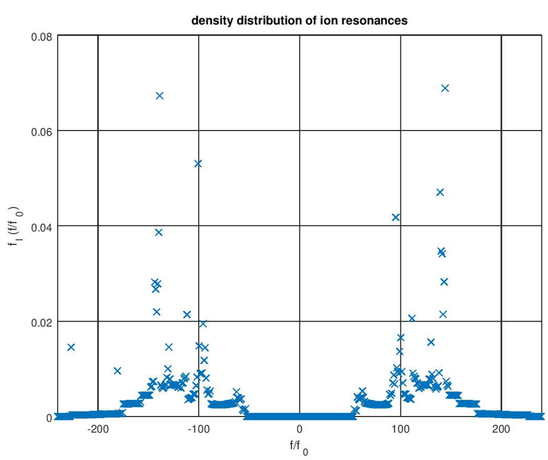

Figure 5: Ion resonances: density distribution for carbon monoxide versus normalized frequency

During the commissioning phase, we expect initial pressure of 10^{-9} mBar with the CO partial pressure half of that [7]. With 400 mA current in 450 bunches (nominal gap of 30) and assuming an ionization cross section of $\sigma_{CO} \sim 1.8\cdot$ 10-22 m^2 [8], the number of ions created per bunch and length turns out to be

$$N_I = \sigma_{CO}\rho_{CO}N_e = 12CO^+/m/bunch \tag{10}$$

where ρ_{CO} is the neutral gas density of CO. During the passage of the train, the ion density will increase from zero

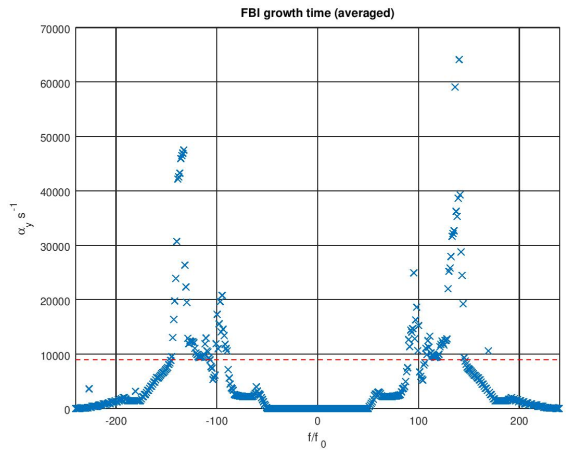

Figure 6: Ion resonances: growth time averaged over full train in the commissioning scenario with partial pressure $p_{CO} = 5\cdot 10^{-10}$ mBar (red line shows damping due to synchrotron and chromaticity)

for each bunch by this value reaching a peak before the gap clears out all accumulated ions.

The FBII growth time is proportional to the ion density; motion of the first bunch in the train will be damped by natural damping and it is only for following bunches, that an instability may form. Integrating damping and antidamping effects over the full bunch train gives an averaged growth time, which is shown for all coupled bunch modes in Fig. 6. In the commissioning scenario with large partial pressures of $p_{CO} = 5\cdot 10^{-10}$, growth rates for modes in the range $\pm 95\ldots 150$ exceed the combined effect of natural damping and chromaticity. But we still expect to be able to control any instabilities with the transverse bunch by bunch feedback system.

Standard operation is expected to happen at pressures lower by a factor 10. Here unconditional stability without external feedbacks is expected.

CONCLUSION

The new lattice of the upgraded SLS 2.0 will exhibit strongly reduced beta functions and smaller beam sizes. To avoid trapping of ions, it still requires an ion clearing gap in the ion fill pattern, which is now strongly reduced to 30 buckets from 90 in SLS. An analysis of fast beam ion instability predicts instable conditions at the elevated pressures of the commissioning phase. Under nominal operating conditions, no such effects are expected.

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