DRIVING THE ELECTRON-CLOUD INSTABILITY BY AN ELECTRON COOLER

G. Rumolo, F. Zimmermann, SL/AP, CERN, Geneva, Switzerland
O. Boine-Frankenheim, I. Hofmann, HSBP, GSI, Darmstadt, Germany

Abstract

We have studied the possibility to detune an electron cooler in order to have a high-current single bunch go through a controlled electron cloud of known density. This experiment could provide information on the electron cloud instability like its dependence on chromaticity, beam size, beam energy, and bunch length, and permit a calibration of the simulation code. We present simulation results for the SIS (Heavy-Ion Synchrotron) ring of GSI, equipped with electron cooler, and explore for which parameter combinations of beam intensity, bunch length, solenoid field, and electron current an instability might occur.

1 INTRODUCTION AND MOTIVATIONS

The single-bunch instabilities driven by an electron cloud [1] are currently studied by means of analytical approaches [2] as well as of multi-particle simulations carried out with the HEADTAIL code developed at CERN [3]. Simulation campaigns for a number of existing machines where the electron cloud has been observed or for future rings where it will potentially be a limiting factor, have highlighted a series of common features of this type of instability: it appears above a certain threshold (in bunch intensity or cloud density), it gets damped by positive values of chromaticity in machines operating above transition, it is more severe for long bunches, it may be easily suppressed by weak solenoid fields present along the ring, and it is expected to be only vertical in rings where the electron cloud mainly builds up in dipole regions.

The goal of this paper is to discuss a way to benchmark the results of the code against experimental data acquired in a situation where the electron cloud is known in detail and controlled. When instability is generated, its dependence on chromaticity and/or bunch length could be experimentally investigated and assessed. The electron cooler appears to be a very promising tool to be used for this purpose. The electron cooler generates a beam of electrons, which overlaps with the main beam stored inside a ring (and usually made of positive ions), along a small straight fraction of the whole circumference. In standard operation, the electron beam has the same mean velocity as the ion beam in order to effect its cooling by means of thermal exchange through collisions. For the experiment that we propose, we need an electron beam much slower than the ion beam (or moving in opposite direction), such that the head-tail coupling in the bunch due to the passage through the quasi-stationary electrons can take place. The electrons are produced afresh at each turn. For the set of parameters and tunability that it offers, the heavy ion synchrotron SIS at GSI-Darmstadt seems a suitable candidate to conduct this study. In Sec. II we will describe the experiment that we have conceived at the SIS in its details and discuss ranges within which parameters can be varied in order to optimize the chances of success. Section III will be devoted to the results of simulations from the adequately modified HEADTAIL code for some sample cases worked out in Sec. II. In Sec. IV conclusions are drawn.

2 EXPERIMENTAL STUDY OF THE ELECTRON CLOUD INSTABILITY AT THE SIS

A list of essential simulation parameters for the electron cooler experiment are summarized in Table I.

Through multi-turn injection into the SIS, intensities up to 1 to 2 $\times 10^{11}$ D^+/beam are accumulated. The beam can then be accelerated up to 2 GeV/u inside the SIS. It can be split into 4 bunches with an intensity of 2.5 to 5 $\times 10^{10}$ ions each and 5 to 10 m long (in total), as is required for the accelerating process, or the 4 bunches can be optionally merged into one single bunch 10 to 20 m long. Maximum detuning of the electron beam with respect to the ion beam can be achieved by tuning the electron beam on the ions at injection energy (10 MeV/u). This means that we can dispose of an electron beam having relativistic factors $\beta_{\rm e} = 0.145$ and $\gamma_{\rm e} = 1.106$, whereas the ions have $\gamma_{\rm e} = 3.129$ after acceleration. Because of the non-negligible longitudinal motion of the electrons, a modification to the ordinary HEADTAIL code has been implemented to take into account a "sliding" effect: each bunch slice sees mostly the previously deformed electron cloud but also a small fraction of newly generated electrons in substitution of those collected to the anode in the Δt between two subsequent slices.

The electrons in the cooler are guided by a solenoid field, whose minimum intensity (known as Brillouin field [4]) is proportional to the square root of the electron current density (and therefore to the electron volume density, too),

$$B = \sqrt{\frac{2{\rm m_e} I_{\rm e} \gamma_{\rm e}}{\epsilon_0 {\rm e} \beta_{\rm e} {\rm c} (\pi r_{be}^2)}} \ , \qquad (1)$$

where $I_{\rm e}$ is the electron current and r_{be} is the radius of the cross section of the electron beam. Available electron currents at the SIS cooler are in the range 0.35–1.5 A ($n_{\rm e} \propto I_{\rm e}$). The radius of the cross section of the electron beam r_{be} can be equal to the radius of the cathode, or can be expanded by a factor as large as $\sqrt{3}$ (namely a factor 3 in the cross section) [4]. Maximum density is obtained with maximum current and minimum cross section expansion ($I_{\rm e} = 1.75$ A, $r_{be} = r_c$). These values yield $n_{\rm e}^{\rm max} = 4.25 \times 10^{14}$ m^{-3}. Unfortunately the high density also requires a quite strong solenoid field to be confined, which can be evaluated using Eq. (1): $B^{\rm max} = 9.5$ mT. Strong solenoid fields are not desirable in this context, because they are known to have a stabilizing action and therefore push the instability thresholds higher [5], making the regime in which we are interested more difficult to reach. Minimum solenoid field is associated with minimum current and maximum cross section expansion ($I_{\rm e} = 0.35$ A, $r_{be} = \sqrt{3} r_c$): $B^{\rm min} = 2.6$ mT. The density corresponding to this value is $n_{\rm e}^{\rm min} = 3.3 \times 10^{13}$ m^{-3}. In the simulations described in the next Section an intermediate case with $n_{\rm e} = 10^{14}$ and $B = 6.7$ mT will be examined. The average density around the ring is 10^{12} m^{-3}.

Table 1: SIS parameters used for the simulations.

Circumference	216 m
Relativistic γ	3.129
Number of bunches	1 to 4
Bunch population (N_b)	2.5×10^{10} to 10^{11} D^+
Emittances ($\epsilon_{x,y}$)	$3.75/1.25$ μm
Tunes ($Q_{x,y,s}$)	4.308/3.29/4.8$\times 10^{-4}$
Bunch rms-length (σ_z)	1.25 m to 5 m
Beta's at the cooler ($\beta_{x,y}$)	7.67/8.12 m
Mom. compaction (α)	0.0356
Rms-energy spread ($\delta p/p_0$)	5.2 to 21 $\times$ 10^{-4}
Cooler length ($\Delta L_{\rm cool}$)	3 m
Cooler cathode radius (r_c)	1.27 cm
Electron current (I_e)	0.35 to 1.5 A
Electron relat. $\beta_{\rm e}$	0.145

3 SIMULATION OF THE TWO-STREAM INSTABILITY

The code HEADTAIL has been used to simulate the effect of the electrons from a cooler on the bunched D^+ ions circulating in the SIS. For this purpose two major modifications of the original code were needed. First, a solenoid field acting on the electrons has been added. Recent studies on the wake functions due to the electron cloud have shown that a solenoid field can lower by one or two orders of magnitude the trailing field induced by a displaced bunch head as the rest of the bunch goes through an electron cloud [3, 5]. Therefore the presence of a solenoid, which is necessary in the cooler to keep the electron stream confined, is expected to play an important role that should not be neglected in a realistic study. Second, the electrons in the cooler, even if they are slow with respect to the ions in the beam, have a high longitudinal velocity (about 0.145c), which causes a small fraction of electrons to be lost to the anode during the bunch slice passage time Δt_{sl} and to be replaced by newly incoming electrons. In most cases, this is a significant effect since we can easily check that, for the short bunches ($\approx$ 5 m), at the very end of the bunch between 1/3 and 1/2 of the electrons have been regenerated during the bunch passage and thus do not carry any memory of the bunch head. This effect becomes worse yet for longer bunches. In quantitative terms, we could say that the longitudinal motion of the electrons introduces a sort of *interaction length* above which any possible coupling along the bunch disappears: $\Delta l_{int} = \Delta L_{\rm cool}(\beta_i/\beta_e - 1)$. SIS numbers yield $\Delta l_{int} \approx 18$ m, which means that in the case of the single long bunch head and tail are not coupled by the cooler (the wake field has a shorter range than the whole bunch longitudinal extension).

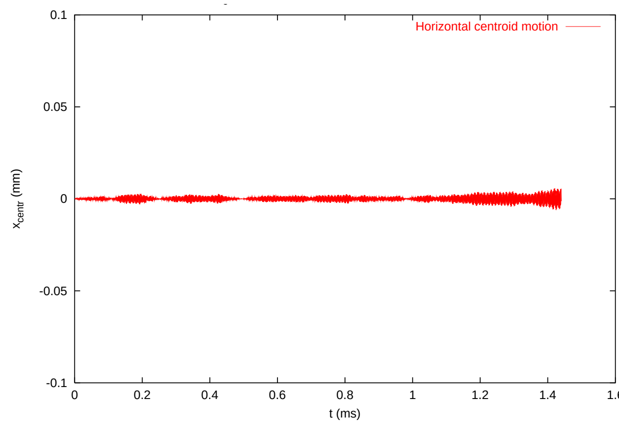

Figure 1: Horizontal centroid motion of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

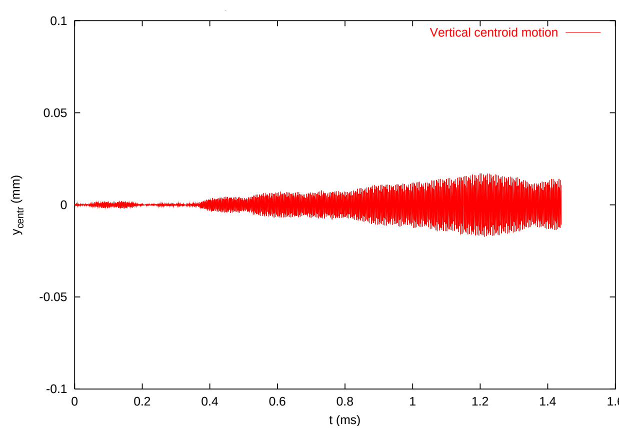

Figure 2: Vertical centroid motion of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

Both the solenoid field and the interaction length tend to have a stabilizing effect on the beam.
Results from HEADTAIL simulations show that using the sets of nominal parameters found in the previous section, the bunch never becomes unstable because of the cooler. For instance, Figs. 1 and 2 show the centroid motion for the intermediate case $n_e = 10^{12}$ m^{-3} and solenoid field $B = 6.7$ mT (4 bunches in the SIS). The single bunch does not exhibit any significant unstable dipole oscillation over 2000 turns.

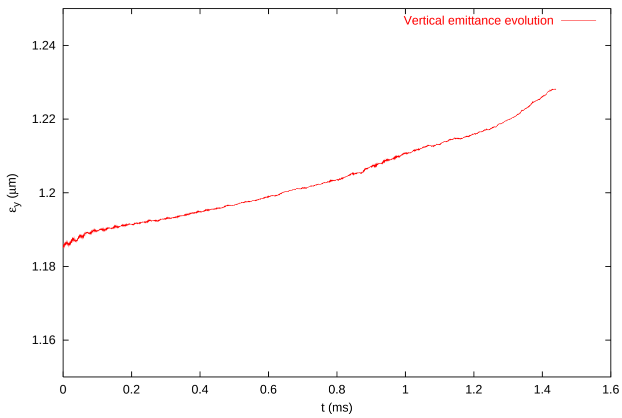

Figure 3: Emittance growth of an SIS bunch when the cooler parameters are $n_e = 6 \times 10^{13}$ m^{-3} and $B = 9.5$ mT.

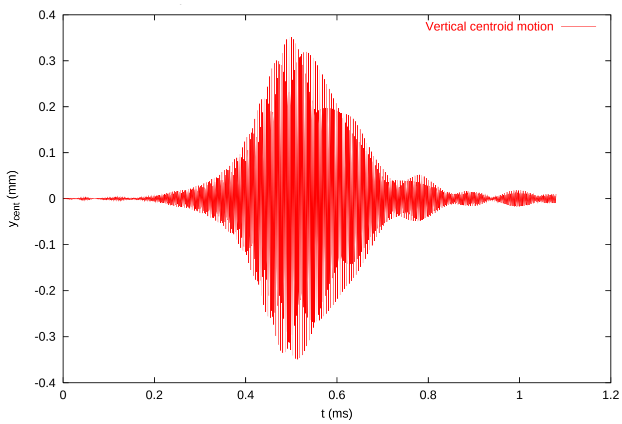

Figure 4: Vertical centroid motion of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

If we move parameters away from the nominal setting, we can easily cross the stability boundary. As examples of instability driven by the electron cooler we present:

- 4 bunches configuration, solenoid field about 0.01 T, electron beam density $n_e = 6 \times 10^{13}$ m^{-3}, which is about a factor 10 higher than thought to be achievable at the SIS cooler. The vertical emittance growth for this case is plotted in Fig. 3.
- Single bunch configuration, electron beam density $n_e = 10^{12}$ m^{-3}, solenoid field $B = 0.67$ mT, namely ten times lower than required to keep the electron beam stable in the SIS cooler. The vertical centroid motions is plotted in Fig. 4, and relative emittance blow-ups in Fig. 5.

4 CONCLUSIONS AND OUTLOOK

Simulations carried out using the parameters for the SIS synchrotron indicate that the instability cannot be driven in this particular ring under standard working conditions. Possible solutions would be to push the current to higher

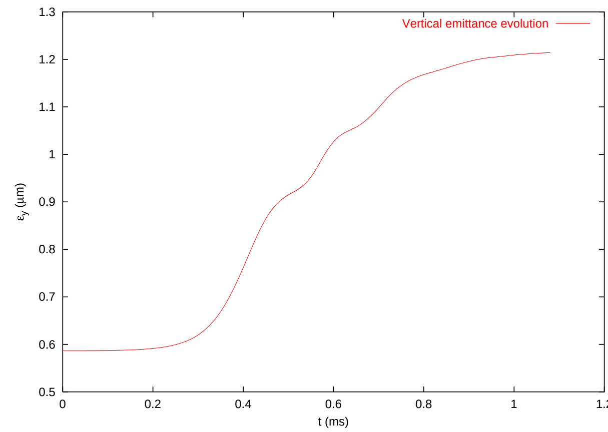

Figure 5: Emittance growth of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

values and/or have a transversely smaller beam at the cooler section and/or decrease Q_s. Another possibility to be explored is the excitation of a regular head-tail instability instead of a TMCI by setting the chromaticity to appropriate positive values (as we are below transition).
Simulations have anyway proven that by pushing the parameters sufficiently above some SIS thresholds, the strong head-tail instability can be triggered. This means that the use of machines other than the SIS should be taken into consideration, where a more favourable ratio between cooler section and ring circumference and/or higher proton currents could be available. Presently, the idea of using the ESR at GSI in isochronous mode (bunches are longitudinally frozen) appears especially promising.

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