Driving the Electron-Cloud Instability by an Electron Cooler

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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 further information on the electron cloud instability, including 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

Gas ionization and/or photoemission combined with electron multiplication due to the secondary emission process on the inner side of the beam pipe may induce the build up of an electron cloud, which can significantly degrade the performance of rings operating with closely spaced proton or positron bunches. The undesired electron cloud causes pressure rise and beam instability when the parameters are pushed above certain thresholds [1].

The single-bunch instabilities driven by an electron cloud 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]. In this code, the interaction between a bunch of macro-particles and an electron cloud modeled with macro-electrons concentrated at one or more locations along the ring is simulated over successive turns. The application of the HEADTAIL to a number of existing machines where the electron cloud has been observed or to future rings where it will potentially be a limiting factor, has 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. If this were possible, the dependence of the electron cloud instability on chromaticity and/or bunch length could also 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 circulating inside a ring (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 produce 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 determined in the bunch by the passage through the quasi-stationary electrons can take place and moreover be 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

To understand the single bunch instabilities due to the electron cloud and the dependence on bunch length and chromaticity, the use of an electron cooler at the GSI heavy ion synchrotron SIS could provide definite experimental answers. The idea is to generate through the cooler a controlled electron cloud, very well localized and with known features, whose effects on the beam could then be easily monitored and analyzed. Contrary to what happens in a cooling process, an electron beam used for simulating an electron cloud must be strongly detuned with respect to the high energy ion beam. A list of essential simulation parameters for the electron cooler experiment are summarized in Table I.

Protons or D^+ ions are preferred in this experiment because of their light masses. The reason why the choice would rather fall on D^+ ions than on protons lies in the fact that a high current D^+ beam can be produced much more easily from the GSI ion sources. Through multi-turn injection into the SIS, intensities up to 1 to 2 $\times 10^{11}$ D^+/beam or about 10^{10} protons/beam can be achieved. The factor 10 to 20 in current compared with the factor 2 in particle masses obviously renders the option of using a D^+ beam more attractive. Such a beam can 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 $\beta_\mathrm{e} = 0.145$ and $\gamma_\mathrm{e} = 1.106$, whereas the ions have $\gamma_\mathrm{e} = 3.129$ 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),

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

where I_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. Currents are easy to relate to the electron volume densities via

$$n_\mathrm{e} = \frac{I_\mathrm{e}}{(\pi r_{be}^2)\mathrm{e}\beta_\mathrm{e}\mathrm{c}} \quad .$$

The radius of the cross section of the electron beam r_{be} can be equal to the radius of the cathode ($r_c = 1.27$ cm), 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 ($I_\mathrm{e} = 1.75$ A, $r_{be} = r_c$). These values yield $n_\mathrm{e}^{\max} = 4.25 \times 10^{14}$ m^{-3}. As the electron cooler stretches only over $\Delta s_\mathrm{cool} = 3$ m out of $C = 216$ m ring length, the simulated density integrates the potential effect of an electron cloud uniformly distributed along the ring and having reduced equivalent density $n_\mathrm{e}^{\max-\mathrm{eq}} = n_\mathrm{e}^{\max} \frac{\Delta s_\mathrm{cool}}{C} = 6 \times 10^{12}$ m^{-3}. Unfortunately the high density also requires a quite strong solenoid field to be confined, which can be evaluated using Eq. (1): $B^{\max} = 9.5$ 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 ($I_\mathrm{e} = 0.35$ A, $r_{be} = \sqrt{3} r_c$): $B^{\min} = 2.6$ mT. Densities corresponding to this value are $n_\mathrm{e}^{\min} = 3.3 \times 10^{13}$ m^{-3} and $n_\mathrm{e}^{\min-\mathrm{eq}} = 5 \times 10^{11}$ m^{-3}. In the simulations described in the next Section an intermediate case with $n_\mathrm{e} = 10^{12}$ and $B = 6.7$ mT will be examined.

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
Alpha's at the cooler ($\alpha_{x,y}$)	-0.66/-0.28
Dispersion at the cooler ($D_{x,y}$)	2.08/0 m
Mom. compaction (α)	0.0356
Rms-energy spread ($\delta p/p_0$)	5.2 to 21×10^{-4}
Chromaticities ($\xi_{x,y}$)	corrected
Cooler length (ΔL_cool)	3 m
Cooler cathode radius (r_c)	1.27 cm
Electron current (I_e)	0.35 to 1.5 A
Electron relat. β_e	0.145

3 SIMULATION OF THE TWO-STREAM INSTABILITY INDUCED BY THE ELECTRON BEAM IN THE COOLER

The code HEADTAIL has been used to simulate the effect of the electrons from a cooler on the D^+ ions of a bunch 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), when we come to 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 in the machine head and tail are not coupled by the cooler (the wake field has a shorter range than the whole bunch longitudinal extension). In the code, we require that after N_{sl} slices only a fraction $f = (1 + \Delta L_b/\Delta L_{\rm cool})\beta_e/\beta_i$ of the N_{me} macroelectrons must have memory. The effect can be achieved if at each slice $N_{me}/(f \times N_{sl})$ electrons are regenerated anew.

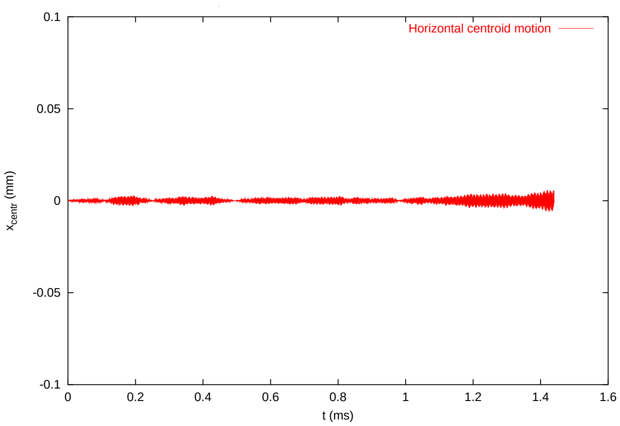

Figure 1: Horizontal centroid motion of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

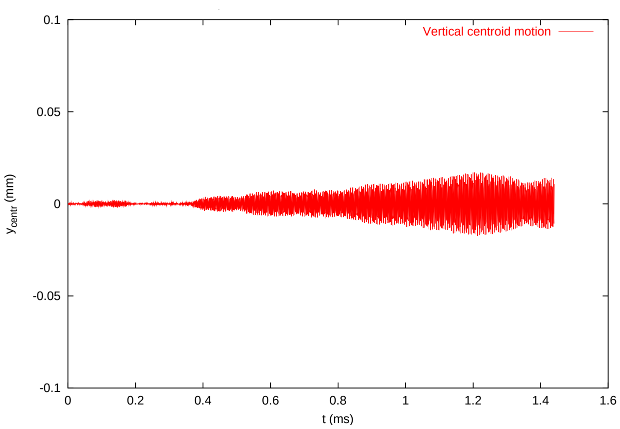

Figure 2: Vertical centroid motion of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

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 as 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. Figures 3 and 4 show that also the bunch rms-sizes remain stable over 2000 turns.

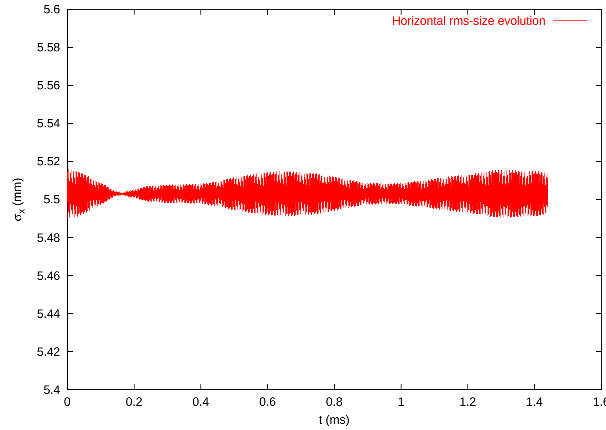

Figure 3: Horizontal rms-size evolution of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

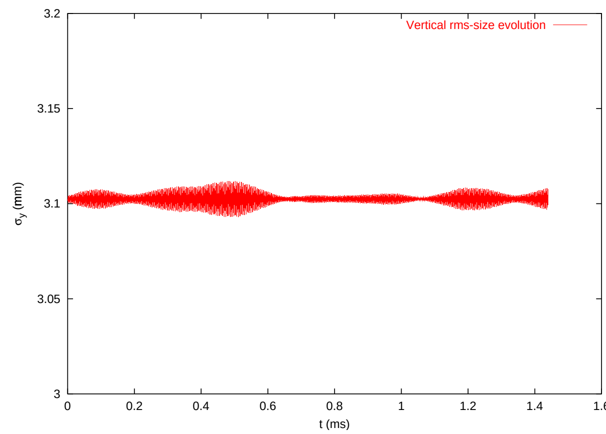

Figure 4: Vertical rms-size evolution of an SIS bunch when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 6.7$ mT.

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. Horizontal and vertical emittance growths relative to this case are plotted in Figs. 5 and 6.

- 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. Horizontal and vertical centroid motions are plotted in Figs. 7 and 8, and relative emittance blow-ups in Figs. 9 and 10.

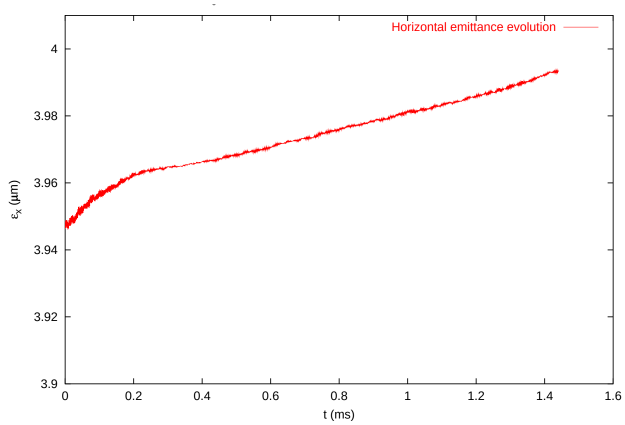

Figure 5: Emittance growth of an SIS bunch when the cooler parameters are $n_e = 6 \times 10^{13}$ m^{-3} and $B = 9.5$ mT.

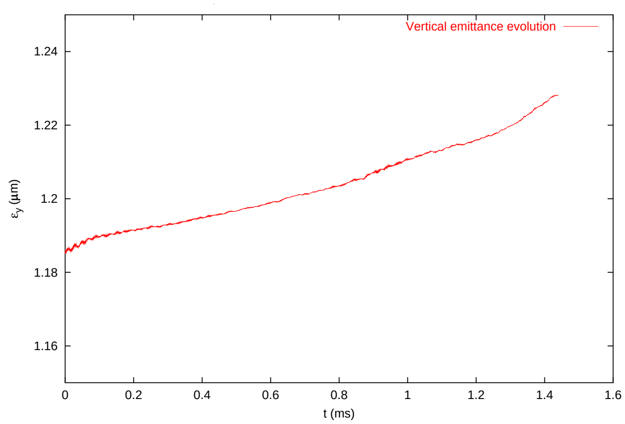

Figure 6: Emittance growth of an SIS bunch when the cooler parameters are $n_e = 6 \times 10^{13}$ m^{-3} and $B = 9.5$ mT.

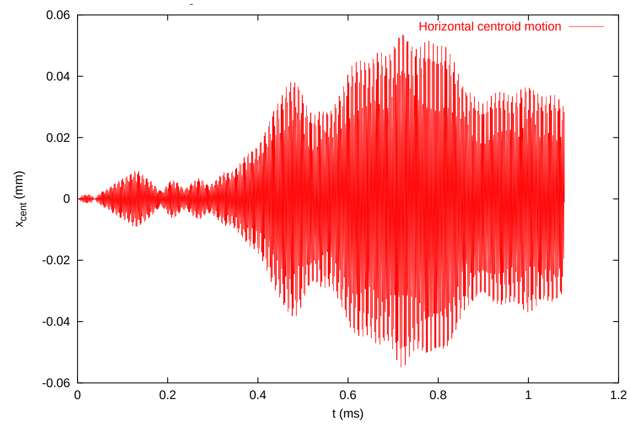

Figure 7: Horizontal centroid motion of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

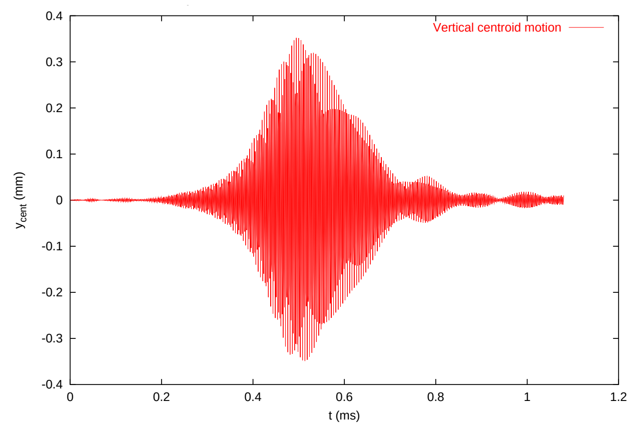

Figure 8: Vertical centroid motion of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

4 CONCLUSIONS AND OUTLOOK

In conclusion, we have studied possible beam-machine configurations which would allow us to excite an instability on a proton or ion beam by means of the electron cooler. The feasibility of this experiment would provide an invaluable tool to benchmark simulation outputs from the electron cloud instability codes against real data obtained under controlled conditions.

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 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. Work and inter-lab activity is underway to study in detail this and diverse further proposed options (use of the CERN-AD or the e-cooler at the FNAL).

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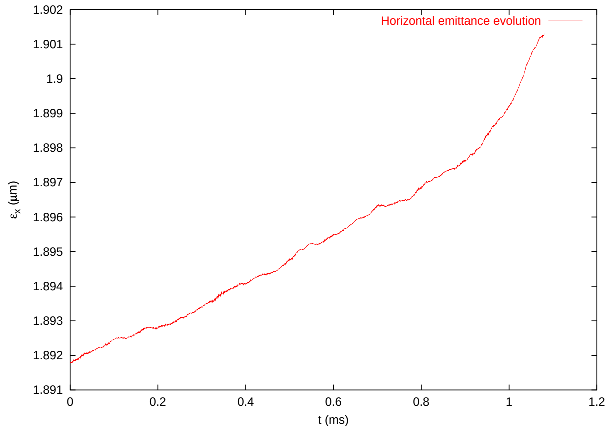

Figure 9: Emittance growth of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

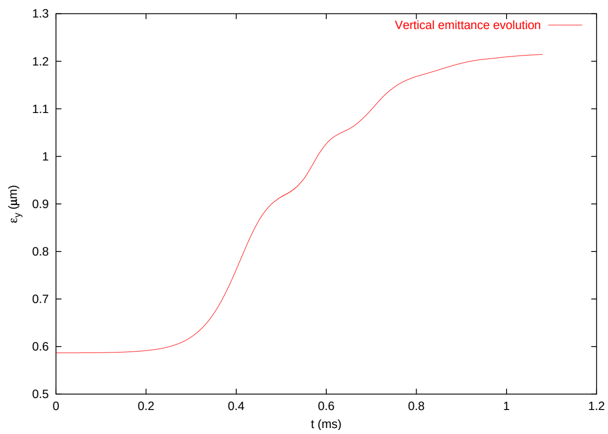

Figure 10: Emittance growth of an SIS bunch (single bunch configuration) when the cooler parameters are $n_e = 10^{12}$ m^{-3} and $B = 0.67$ mT.

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