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Driving the Electron Cloud Instability by an Electron Cooler

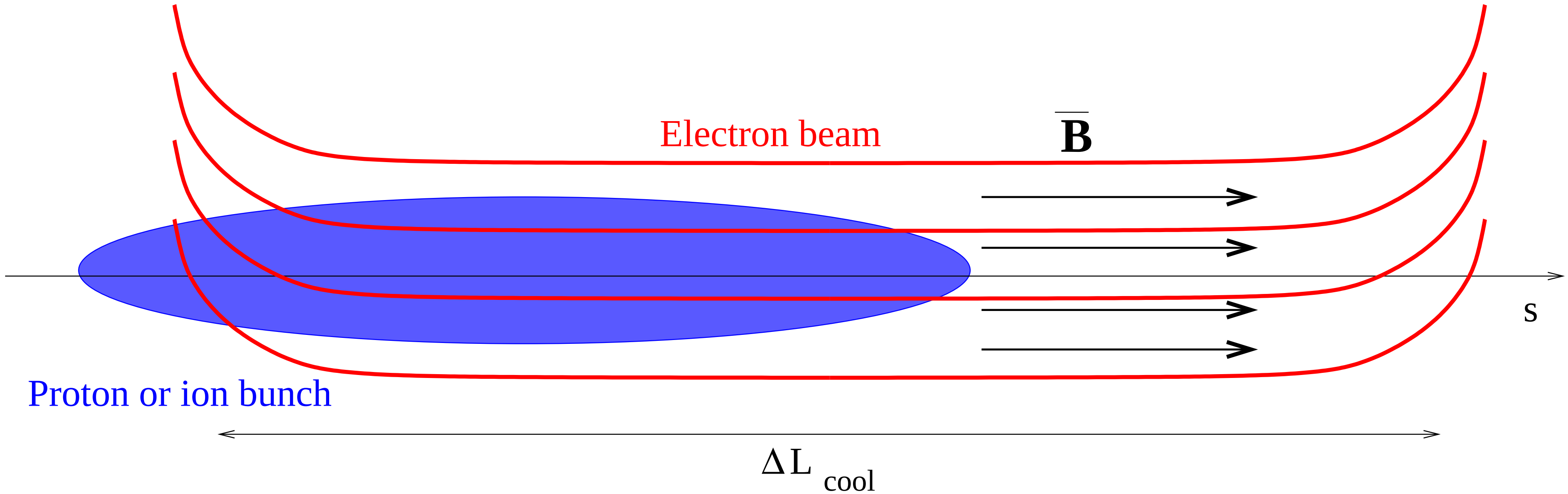
- Experiment: creating a controlled electron cloud with an electron cooler for the study of the e-cloud instability

- SIS parameters and their compatibility with the experiment needs

- Simulation of the experiment with the HEADTAIL code

- Summary and conclusions.

Schematic of an electron cooling device



IN STANDARD OPERATION:

$\bar{v}_e = \bar{v}_{i(p)} \Rightarrow$ cooling by means of thermal exchange through collisions.

FOR THE EXPERIMENT:

$\bar{v}_e \ll \bar{v}_{i(p)} \Rightarrow$ head-tail coupling induced in the bunch by the slow electrons can take place and be newly produced at each turn.

Goals of the experiment

- Observation of an electron cloud driven single bunch instability under controlled conditions.
- Benchmark the results of the HEADTAIL code against experimental data acquired in a situation where the electron cloud is known in detail.
- The dependence of the electron cloud instability on chromaticity and/or bunch length could also be experimentally investigated.

The use of the Heavy Ion Synchrotron SIS at GSI-Darmstadt is the option we have studied !!

Table 1: SIS parameters used for the simulations.

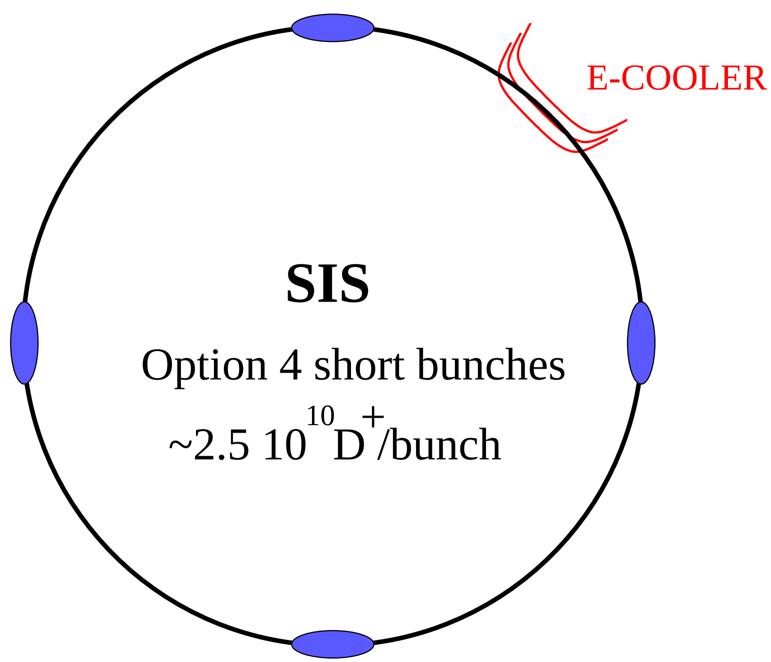
Circumference	216 m
Relativistic γ	3.129
Number of bunches	1 to 4
Bunch population (N_b)	2.5×10^{10} to 10^{11} D^+
Emittances ($\epsilon_{x,y}$)	3.75/1.25 μm
Tunes ($Q_{x,y,s}$)	4.308/3.29/4.8$\times 10^{-4}$
Bunch rms-length (σ_z)	1.25 m to 5 m
Beta's at the cooler ($\beta_{x,y}$)	7.67/8.12 m
Alpha's 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 $\times 10^{-4}$
Chromaticities ($\xi_{x,y}$)	corrected
Cooler cathode radius (r_c)	1.27 cm
Electron current (I_e)	0.35 to 1.5 A
Electron relat. β_e	0.145

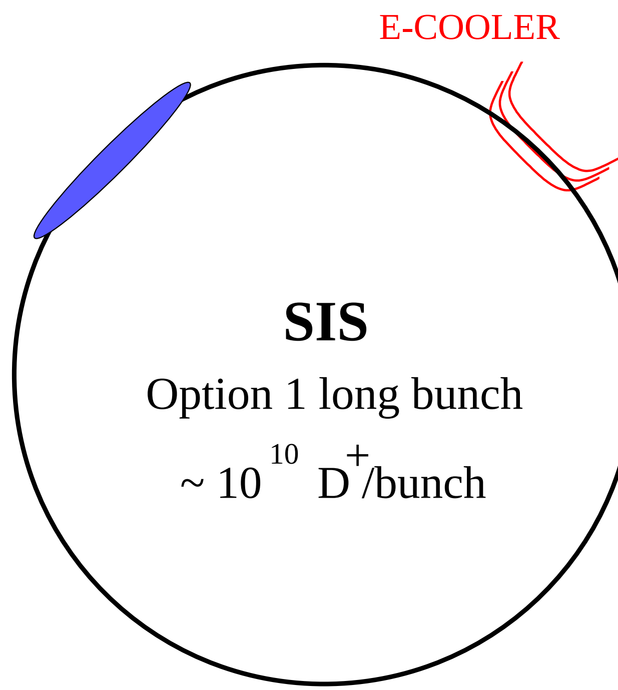
- protons or D^+ ?

  At the SIS a beam with $1 - 2 \times 10^{11}$ D^+ ions can be produced,

  with protons a current at least a factor 10 lower !!

- How many bunches ?





- D^+ ions can be accelerated in the SIS up to 2 GeV/u ($\gamma = 3.176$)
- Maximum detuning is obtained if the electrons are tuned on the ions at injection energy ($\approx$ 11 MeV/u $\longrightarrow$ 6.3 keV for the electrons, $\beta\mathrm{e} = 0.145$, $\gamma_\mathrm{e} = 1.01$)
- Electron currents in the range I_e =0.35–1.5 A
- Minimum solenoid field to keep the electron beam within a cross section of radius r_{be} is the Brillouin field:

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

Radius of the electron beam cross section r_{be} equal to cathode radius $r_c = 1.27$ cm (expansion possible to $r_{be} = \sqrt{3} r_c$) and current range

$$+$$

Formula for the minimum solenoid field

$$\Downarrow$$

Some realistic sets of parameters:

$$n_{\mathrm{e1}} = 4.25 \times 10^{14}\mathrm{m}^{-3} \Rightarrow \quad n_{\mathrm{e1}}^{\mathrm{eq}} = 6 \times 10^{12}\mathrm{m}^{-3} \quad B^{\mathrm{max}} = 9.5\mathrm{mT}$$

$$n_{\mathrm{e2}} = 3.3 \times 10^{13}\mathrm{m}^{-3} \Rightarrow \quad n_{\mathrm{e2}}^{\mathrm{eq}} = 5 \times 10^{11}\mathrm{m}^{-3} \quad B^{\mathrm{min}} = 2.6\mathrm{mT}$$

$$n_{\mathrm{e3}} = 7.2 \times 10^{13}\mathrm{m}^{-3} \Rightarrow \quad n_{\mathrm{e3}}^{\mathrm{eq}} = 10^{12}\mathrm{m}^{-3} \quad B = 6.7\mathrm{mT}$$

Simulations

Necessary modifications to the HEADTAIL code in order to simulate the bunch through a detuned electron cooler:

(1) The option of a solenoid field acting on the electrons has been implemented.

(2) The non-negligible longitudinal motion of the electrons. At the end of the interaction bunch-electrons only a fraction $(1 - \beta_e c \Delta t_b / \Delta L_{\mathrm{cool}})$ of the initial electrons keeps memory of the previous interaction.
$\Rightarrow$ IN THE CODE: Subsequent bunch slices couple mostly with the same electrons except for a small fraction which have been lost to the anode during the slice time Δt_{sl} and have been replaced by newly incoming electrons.

The longitudinal motion of the electrons causes the coupling within the bunch to be fading over a very well defined length that can even be shorter than the bunch !!

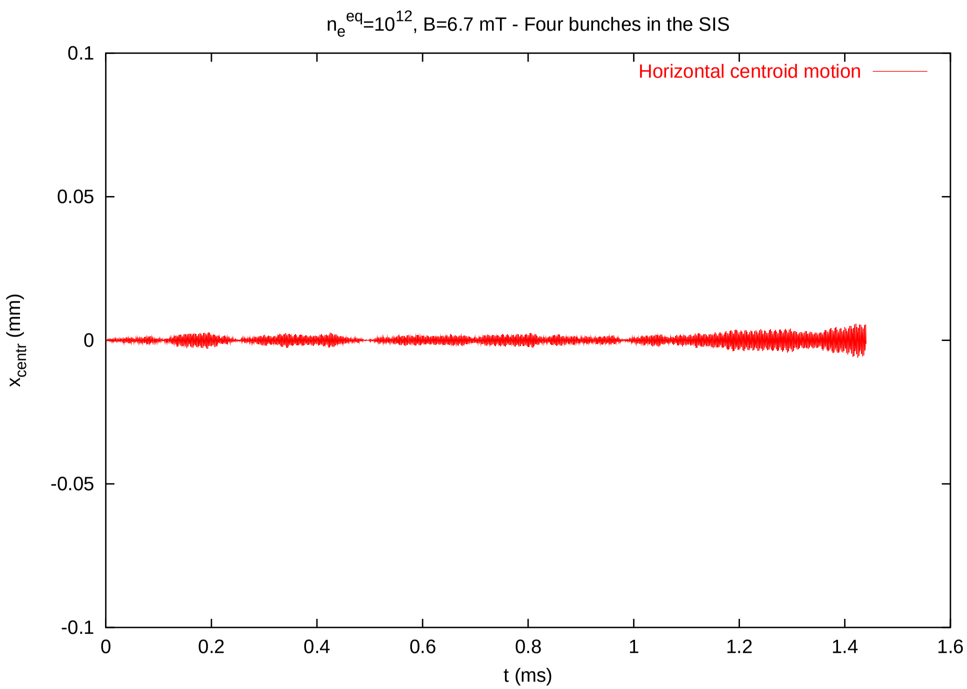
$\longrightarrow$ call it interaction length ΔL_{int}

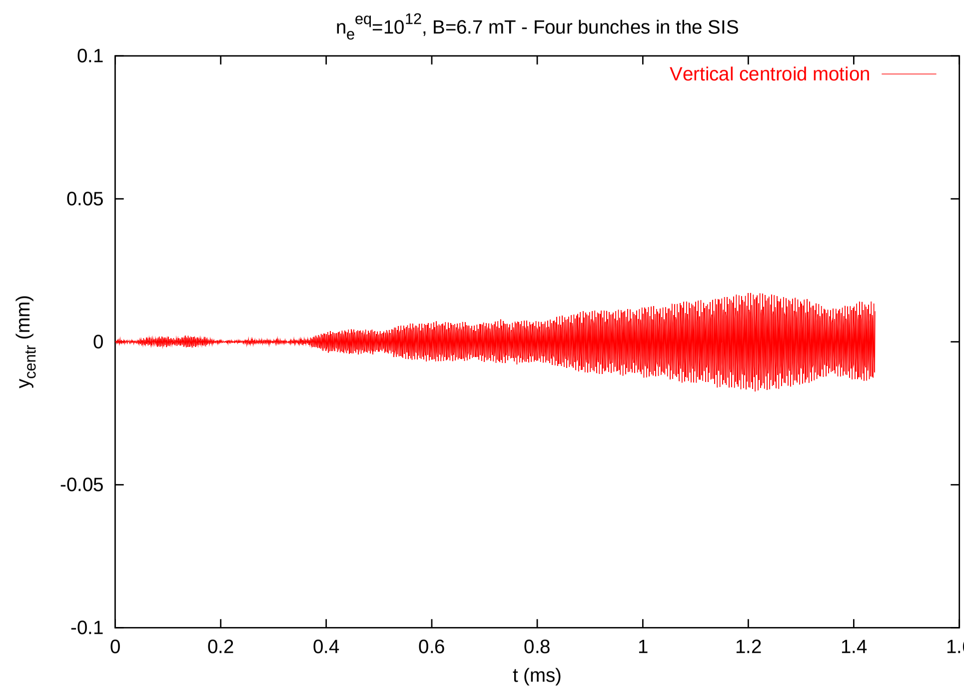
$$\Delta L_{\mathrm{int}} = \Delta L_{\mathrm{cool}} \left(\frac{\beta_i}{\beta_e} - 1 \right)$$

$\longrightarrow$ with SIS numbers $\Delta L_{\mathrm{int}} = 17.7\ \mathrm{m} \Rightarrow$ long bunches are at the limit.

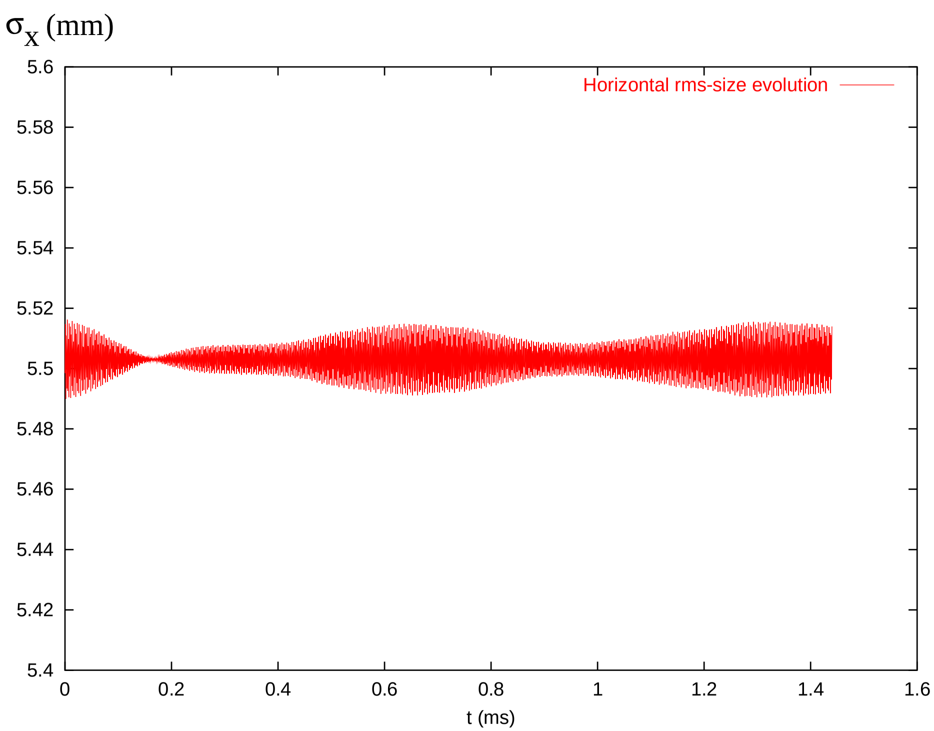
This effect also weakens the instability !!

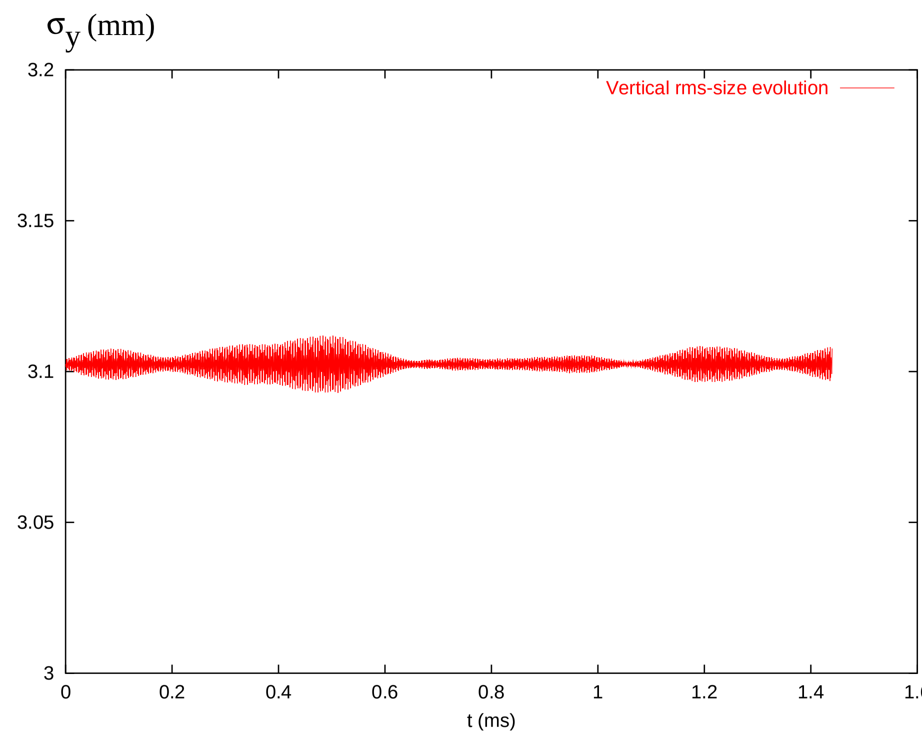
SIMULATION RESULTS



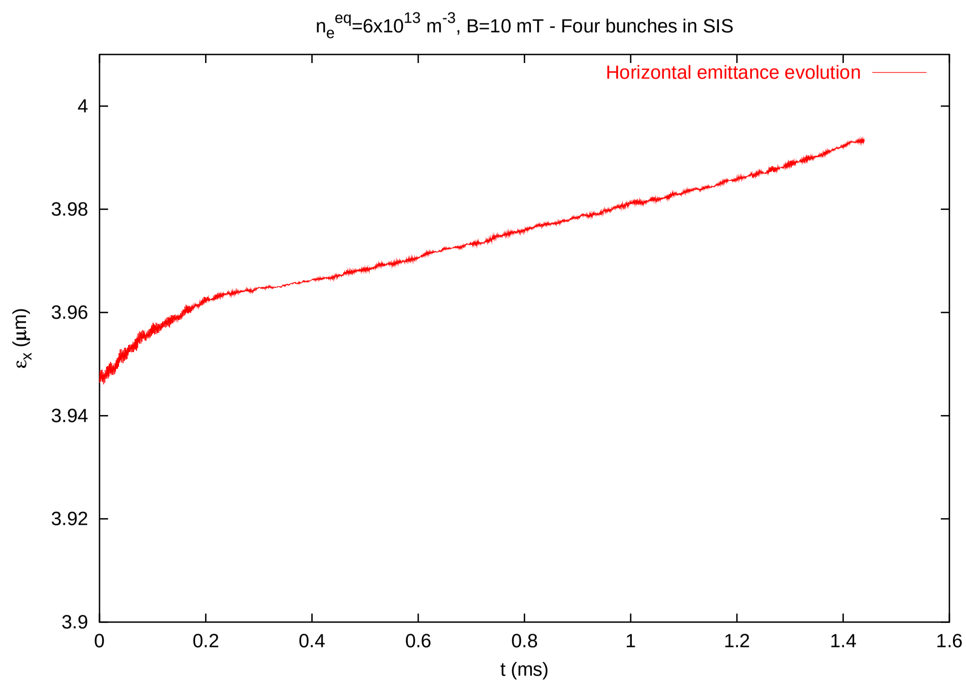


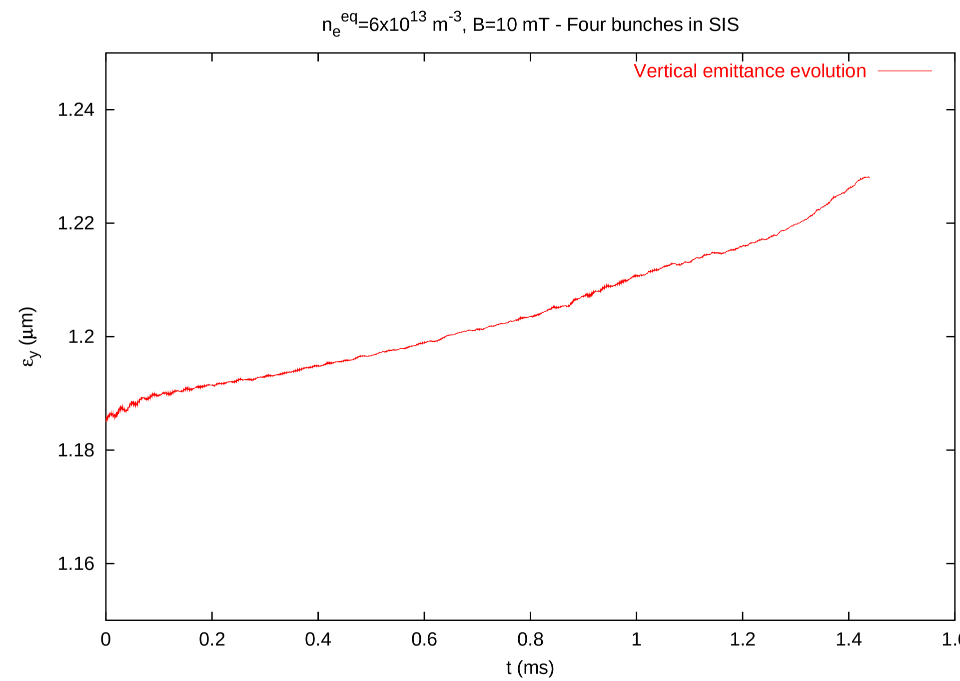
Combination of parameters electron density 10^{12} m^{-3} and solenoid field $B = 6.7$ mT. The bunch does not exhibit an unstable dipole oscillation over 2000 turns.



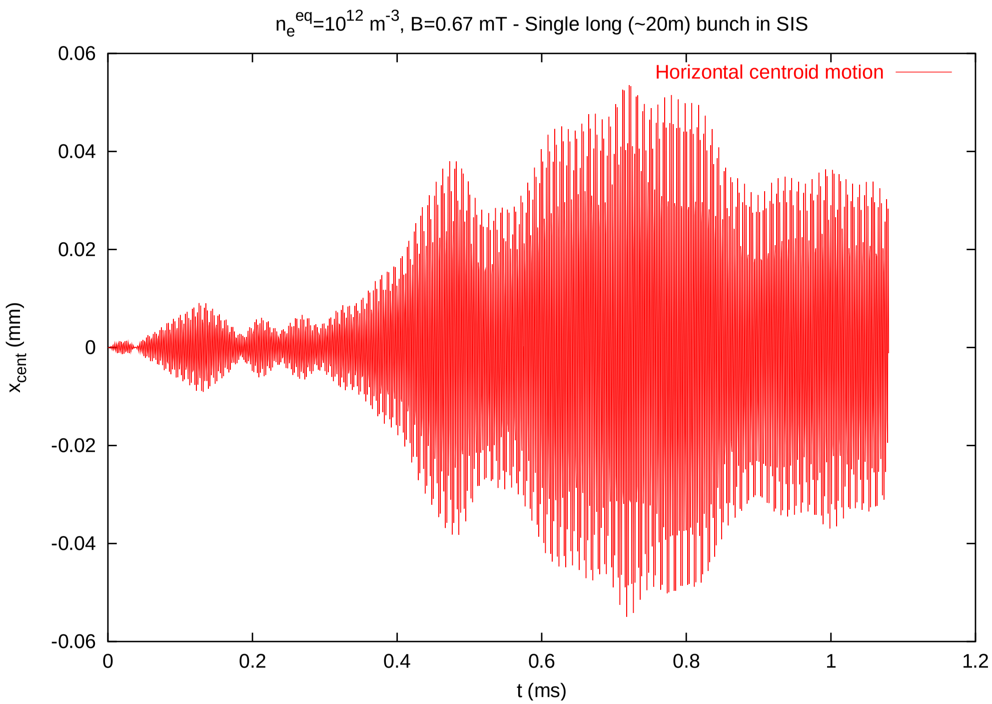


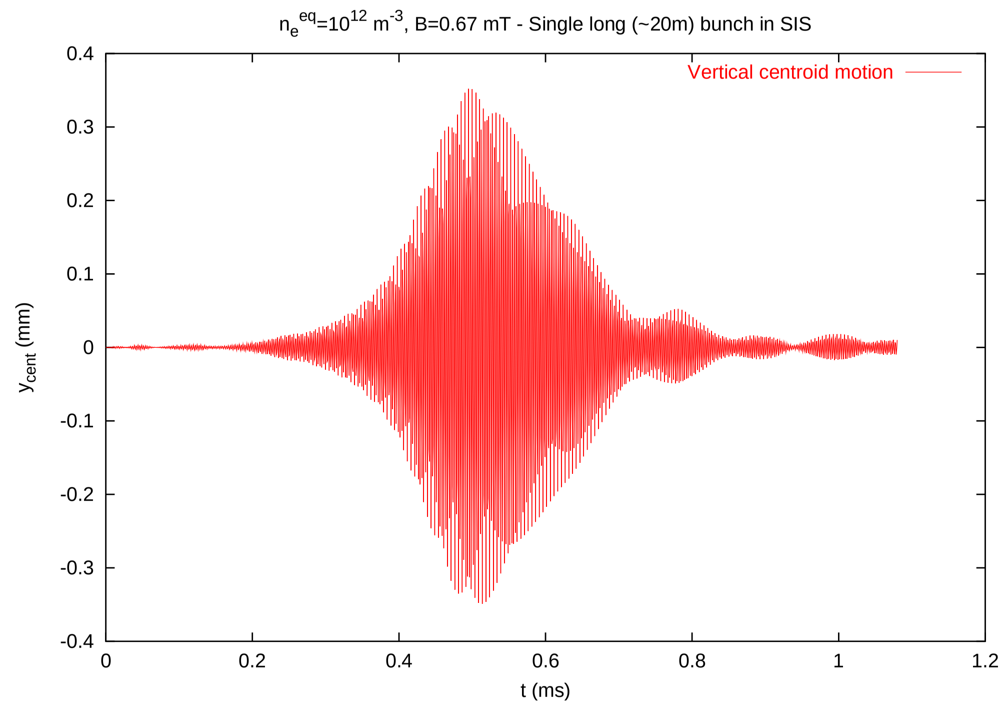
Combination of parameters electron density $10^{12}\ \mathrm{m}^{-3}$ and solenoid field $B = 6.7\ \mathrm{mT}$. The bunch rms-sizes also remain stable over 2000 turns.



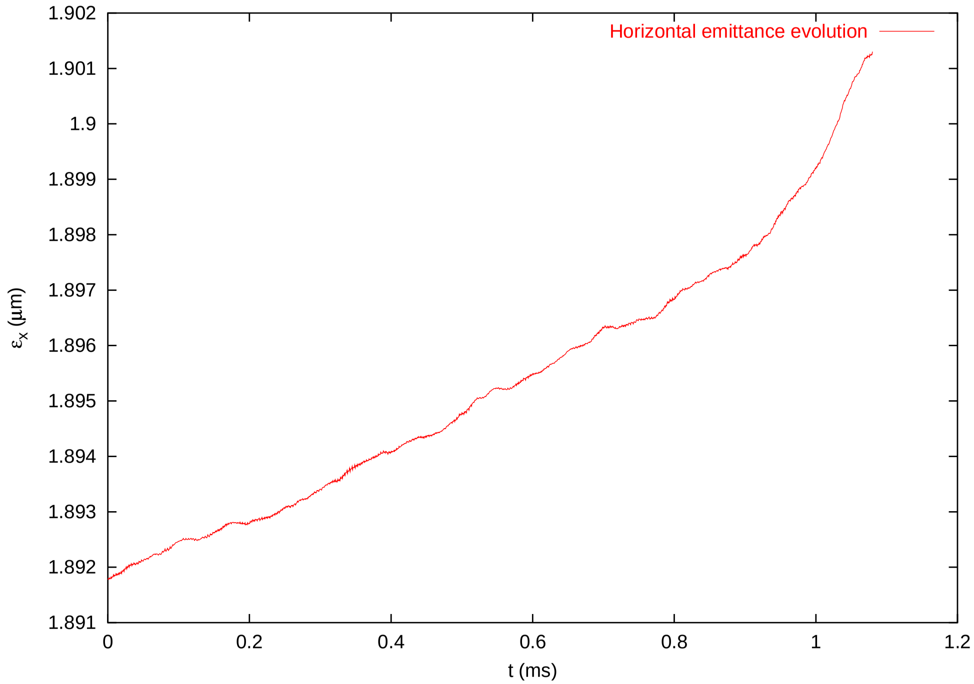


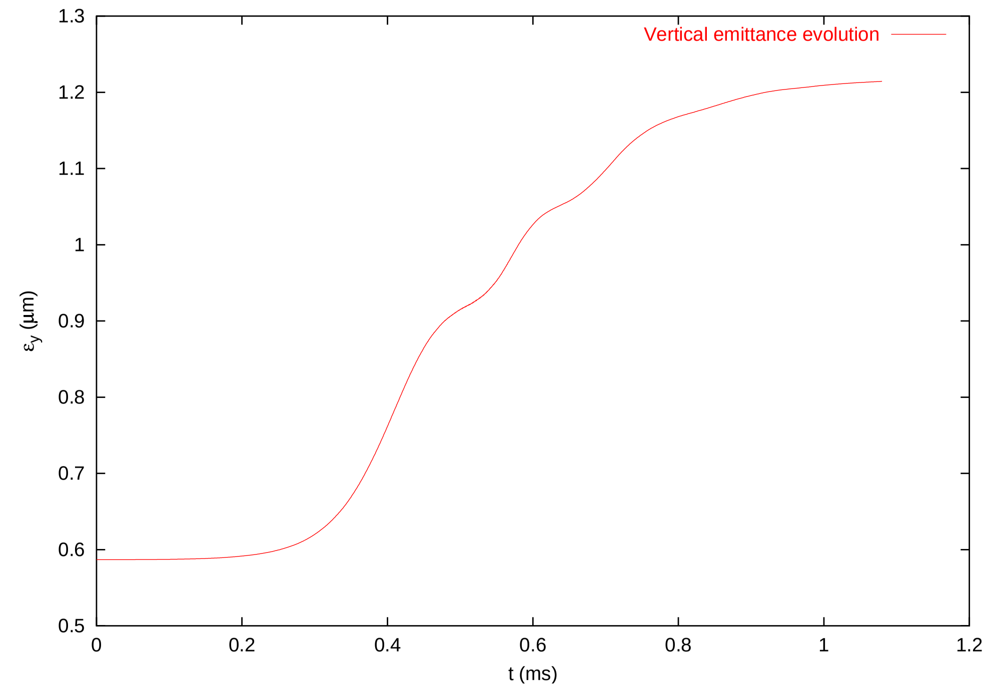
Emittance growth appears when we move away from the previous parameters. For the above plots we considered a configuration with maximum solenoid field, but electron density 10 times higher.





The single long bunch in the SIS would be very unstable if the solenoid field were assumed to be 10 times lower than required in our nominal parameter configuration.





Emittance growth for the single long bunch in the SIS due to the electron cooler if the delivered electron density was $n_e^{eq} = 10^{12}\ \mathrm{m}^{-3}$ but with a solenoid field $B = 0.67$ mT.

If possible...

1- Try to have different settings of the SIS parameters (i.e. push the current to higher values, have a transversely smaller beam at the cooler section, decrease Q_s, ...)

2- Instead of the TMCI, attempt to excite a regular head-tail instability by setting the chromaticity to positive values

3- Use a different machine with a longer cooler section and/or more cooling sections (maybe the ESR at GSI ?) and/or higher proton currents available...

4- More ideas are welcome !