Electron Cooling Simulations

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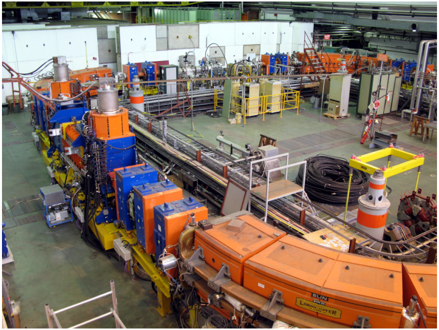
What is Electron Cooling

- EC is a method to shrink the emittance (size, divergence, and energy spread) of a charged particle beam without removing particles from the beam.

- Since the number of particles remains unchanged and the space coordinates and their derivatives (angles) are reduced, this means that the phase space occupied by the stored particles is compressed.



- It is equivalent to reducing the temperature of the beam:

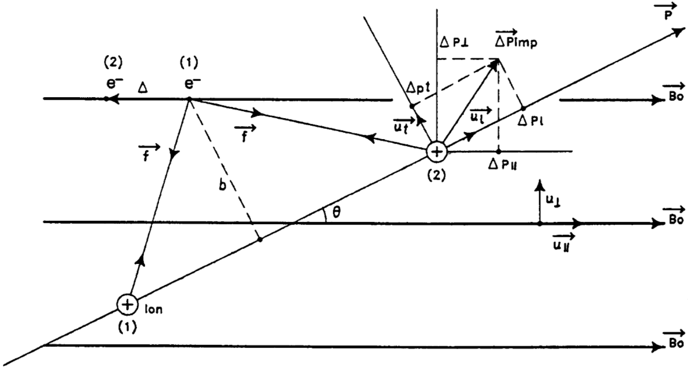
$$\frac{3}{2}k_B T = \frac{1}{2}m\left\langle v^{\star 2}\right\rangle$$

cooling is reached when

$$T_i \simeq T_e$$

Physics of Electron Cooling

- Ion traveling through a cold magnetised plasma of electrons.



[CERN 92-01 - CAS 1991 - J. Bosser, "Electron Cooling"]

- Electromagnetic interaction between ions and electrons causes the energy exchange.

"Hybrid" model: fluid electrons, kinetic ions

Electron Cooling has been implemented in RF-Track.

- The **ion beam** is represented as an ensemble of macro particles
  - full 6d phase space, e.g.
    $$(x, x', y, y', t, P)$$
    for accurate tracking and for capturing non linearities
  - integrate the effect of cooling force + solenoidal magnetic field, in Δs

- The **electron beam** is represented as a fluid on a 3d cartesian mesh
  - each cell (i, j, k) is characterised by

$n_{e,\ ijk}$	electron density $[\#/\mathrm{m}^3]$
$\vec{v_{ijk}}$	average electron velocity $[\mathrm{c}]$
$\Delta_{e\perp,\ ijk}$	electron transverse temperature
$\Delta_{e\parallel,\ ijk}$	electron longitudinal temperature

  - automatic tri-cubic interpolation of each quantities at any arbitrary location
  - it allows arbitrary electron density / velocity distributions
  - integrate the Euler equation of an incompressible fluid, in Δt (in progress)

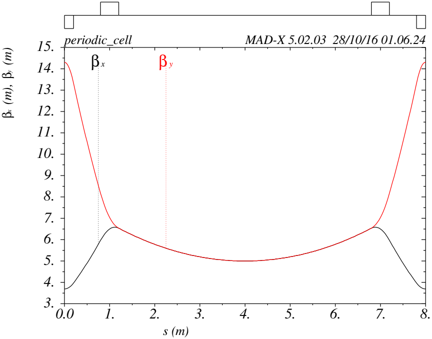
- Embedded in a solenoidal magnetic field (next step: use a measured / numerical field map)

Simulation Results

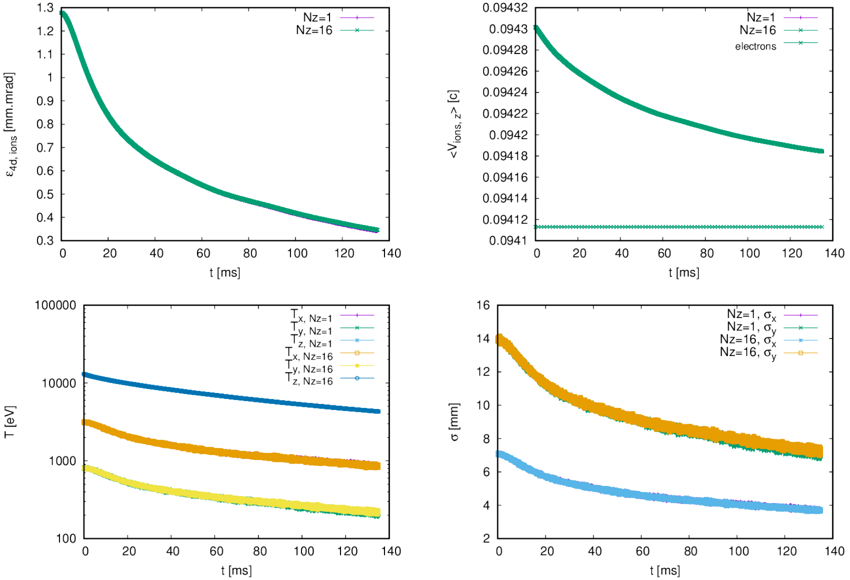
Simple periodic triplet with $\beta_{x,y} = 5$ m, with 2.7 m long cooling section in the middle

Simulation setup:

- Electron temperatures:
  $T_{e\perp} = 0.04$ eV;
  $T_{e||} = 1.7 \times 10^{-5}$ eV
- Average initial ion velocity is: 0.094302 c
- Electron velocity is: 0.094113 c (0.2% less than the ions' velocity)
- Measured cooling time: ~120 ms ($\approx$ 50′000 turns)
  - 1 turn: 2.7 μs

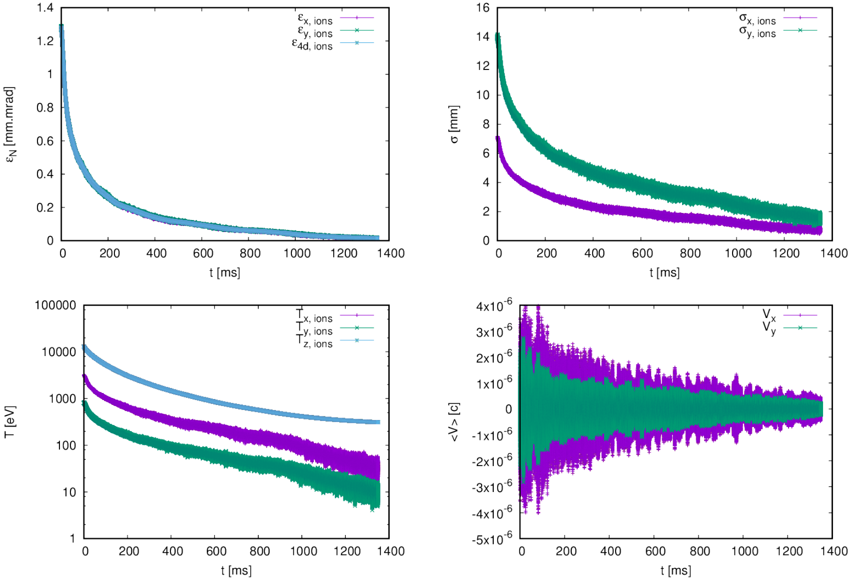


Convergence studies



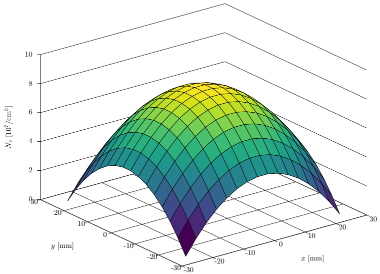
$$V_{\text{electrons}} = 0.998 \cdot V_{\text{ions}};\ \epsilon_{\text{geom, ions}} = 14\ \text{mm.mrad}$$

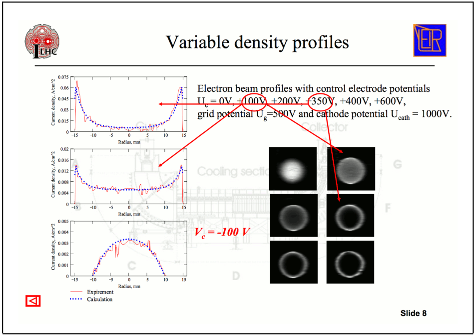
Long term tracking (500'000 turns)



$$V_{\text{electrons}} = 0.998 \cdot V_{\text{ions}};\ \epsilon_{\text{geom, ions}} = 14 \text{ mm.mrad}$$

Parabolic density profile for the electron beam





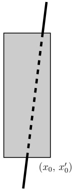
A 2d parabolic distribution has been simulated. Density peak at the nominal value, goes to zero at the four external vertexes.

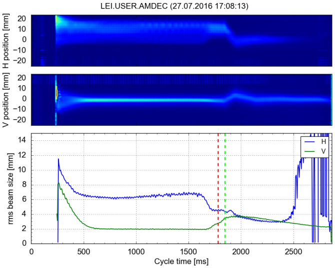
[Slide taken from Gerard Tranquille]

Ion beam tilt angle (simulated vs measured)

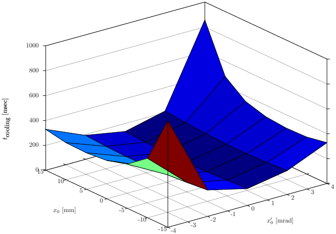
Closed orbit scan at the cooler entrance

$$(x_0,\ x_0')$$

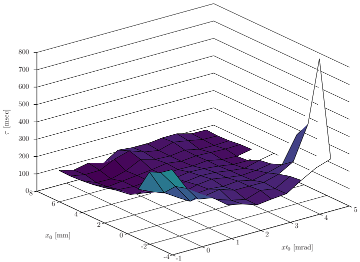




Simulated data:



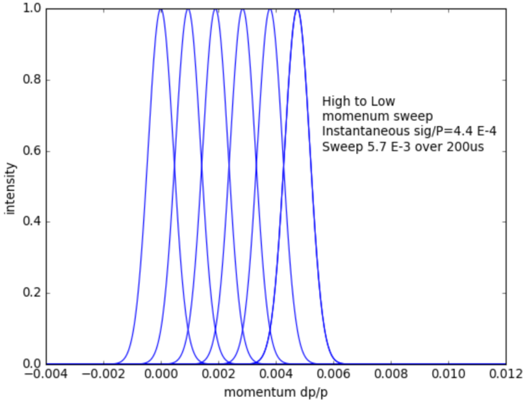
Measured data:



The measured cooling time is computed using the vertical axis information only.

Realistic Ions' longitudinal momentum profile

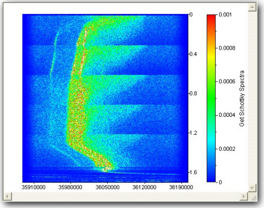
The actual ion's longitudinal momentum profile is:



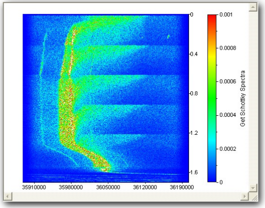
[Courtesy of R. Scrivens]

Ions multi injection and Schottky signal

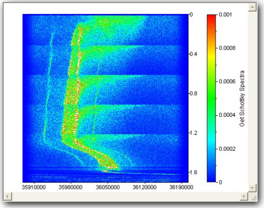
Ions are injected 7 times: ~200 ms (~75,000 turns) between two consecutive injections.



Ie = 291 mA, Vc/Vg = 0.94



Ie = 297 mA, Vc/Vg = 0.5

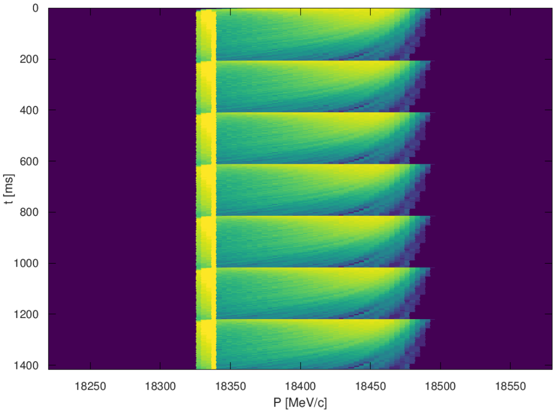


Ie = 294 mA, Vc/Vg = 0.197

[from Gerard A. Tranquille, "Electron cooling and IPM", LIU-IONS PS Injectors - Beam Performance Meeting, May 2 2017]

Simulated multi injection and Schottky signal

Ions are injected 7 times: ~200 ms (~75,000 turns) between two consecutive injections.



Conclusions and Outlook

- An Electron Cooling module has been implemented in RF-Track
  - It handles arbitrary electron distributions
  - It handles different optics
  - It handles misalignments
  - It simulates the full interaction ion-electrons, with a fair amount of realism

- It's being tested / benchmarked against measurements
  - Next measurements at end of June

- More feature could be implemented
  - Use of a realistic solenoid magnetic field map (see work in progress for ELENA)
  - Ion-ion space-charge effects / intra-beam scattering
  - ...