Simulation and code development plans for LS2

Andrea Latina

Acknowledgments and credits:

Nicolò Biancacci, Davide Gamba, Angela Saa Hernandez,
Michalis Zampetakis, Simon Hirlander. A.Frassier, G.Tranquille.
Javier Résta Lopez, Bianca Veglia (University of Liverpool)

E-beams meeting - 13-3-2019

Cooling at LEIR

The Electron Cooler is essential for LEIR operation, but it's complex and with limited diagnostics → instead characterized by studying the effects on ion beam

We want to use simulation tools and dedicated experiments to understand the performance limitations and overcome them.

Not many "simple" codes either… measurements to benchmark the newly developed Electron Cooling module of the code RF-Track.

NB, DG, ASH, MZ, BV, JRL and myself, started a series of meetings on "Beam Dynamics and Electron Cooling", now part of this project
https://indico.cern.ch/category/10717/

Outline of this presentation

1. Theory and simulations
   - New ideas, new code [AL]
   - Benchmark against other codes [BV]
   - Benchmark against measurements [AL, NB, DG]

2. New studies to be performed
   - Simulation work
   - Code development

3. Resources available

EC: Theory and simulation

Physics of electron cooling:

- Some good references are in my previous presentations

Two aspects are important:

1. Model of the binary cooling force: "single ion – many electrons"
2. Inclusion of the electrons' thermal effects

Example of "single ion – many electrons" cooling force:
V.V. Parkhomchuk: Nucl. Instrum. Meth. Phys. Res. A 441, 9 (2000)

$$F_{\parallel}(\boldsymbol{v}_i) = -\frac{4\pi n_e Z^2 e^4}{m} \frac{v_{i\parallel}}{(v_{i\parallel}^2 + v_{i\perp}^2 + v_{\mathrm{eff}}^2)^{3/2}} \ln\left(1 + \frac{\langle s_{\max}\rangle}{\langle s_{\min}\rangle + a_e}\right) \qquad (6.8)$$

The new code (RF-Track) implements:

- A sound theoretical model of the binary cooling force
- A virtually exact integration of the electrons' thermal effects

RF-Track simulation: Hybrid-Kinetic Model

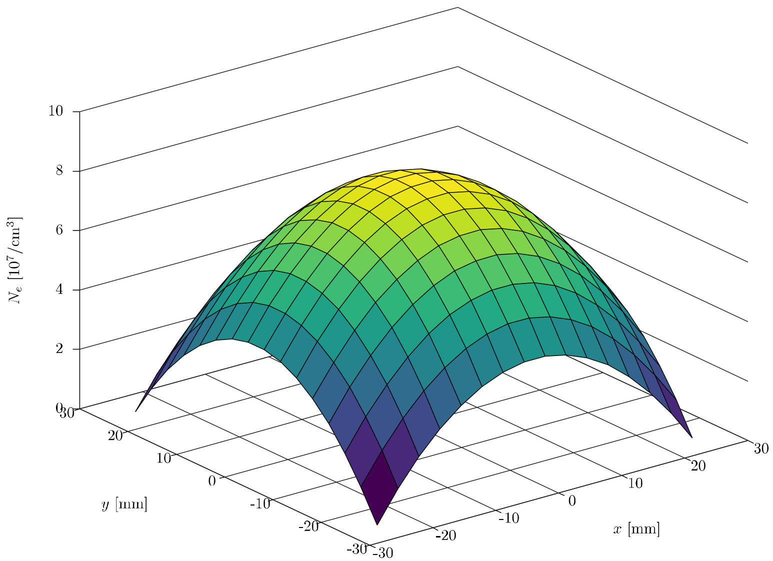
- Full 6D multi-particle ion simulation + electron plasma

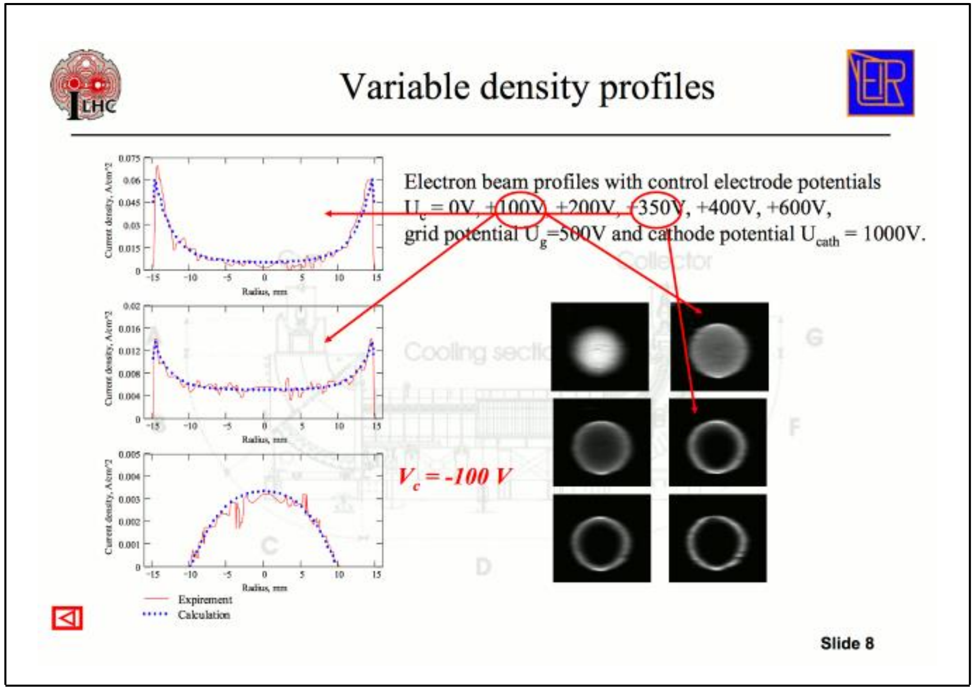
- The electrons' parameters are stored on a 3D grid mesh: each cell carries
  - Electron density and velocity
  - Local magnetic field

This enables the simulations of realistic conditions:

- Hollow / parabolic beams
- Misalignments ions / electrons / magnetic fields

RF-Track simulation: Hybrid-Kinetic Model





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

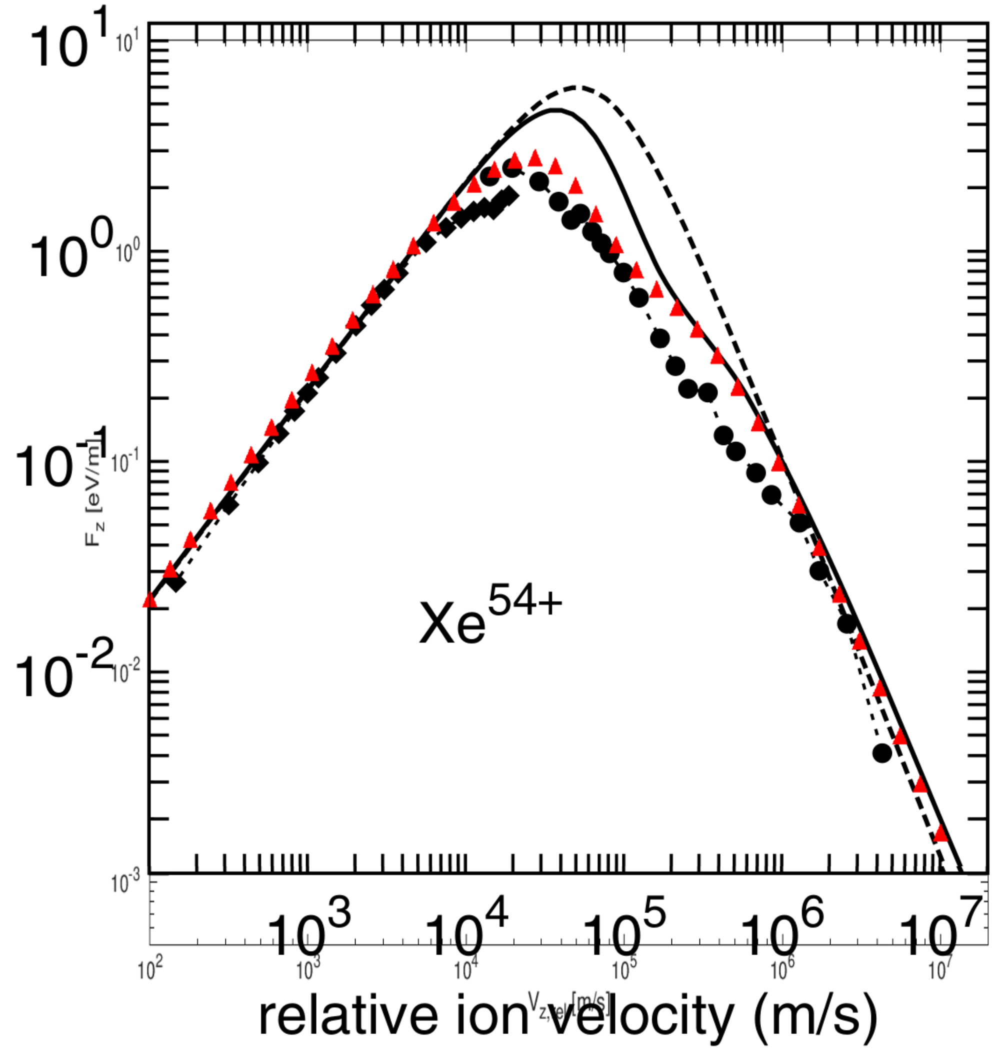
[Slide taken from Gerard Tranquille]

Benchmark against literature

ESR Ring (GSI):
Longitudinal cooling force for various fully stripped Xe^{54+} ions as function of the relative ion velocity with respect to the rest frame of the electron beam.

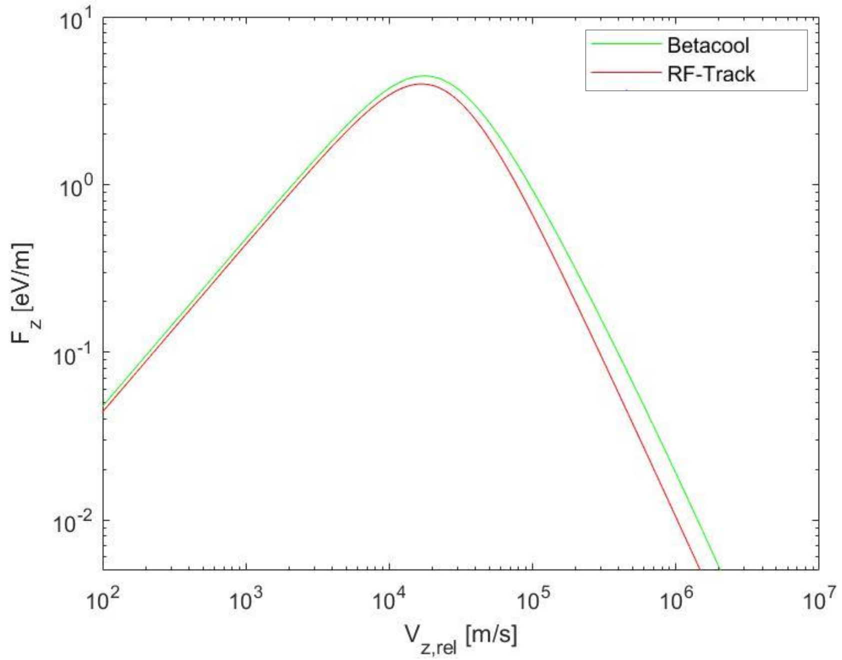
$$n_e = 10^{12}\ \mathrm{m}^{-3}$$
$$k_B T_\perp = 0.11\ \mathrm{eV}$$
$$k_B T_\perp = 0.1\ \mathrm{meV}$$
$$B = 0.1\ \mathrm{T}$$

Black marks: experimental data.
Solid curve: binary collision approximation.
Dashed curve: Parkhomchuk's empiric formula (BETACOOL).
Red triangles: RF-Track



“Single-ion” cooling force at ESR (GSI)

BETACOOL vs RF-Track Simulation



Ions:
A = 131.2 proton mass
(Xenon)
Q = 54^+

Electrons:
$N_e = 1 \times 10^{12}$ e/m^3
$T_\perp = 0.11$ eV

$T_\parallel = 0.001$ eV
B = 0.1 T

B. Veglia

Measurement of the cooling force

We measured the cooling force at LEIR, with Pb ions, $Q = 54^+$.

- The cooler was set with electron beam current 210 mA, with temperatures

  $k_B T_\perp = 0.1$ eV and

  $k_B T_{||} = 1$ meV,

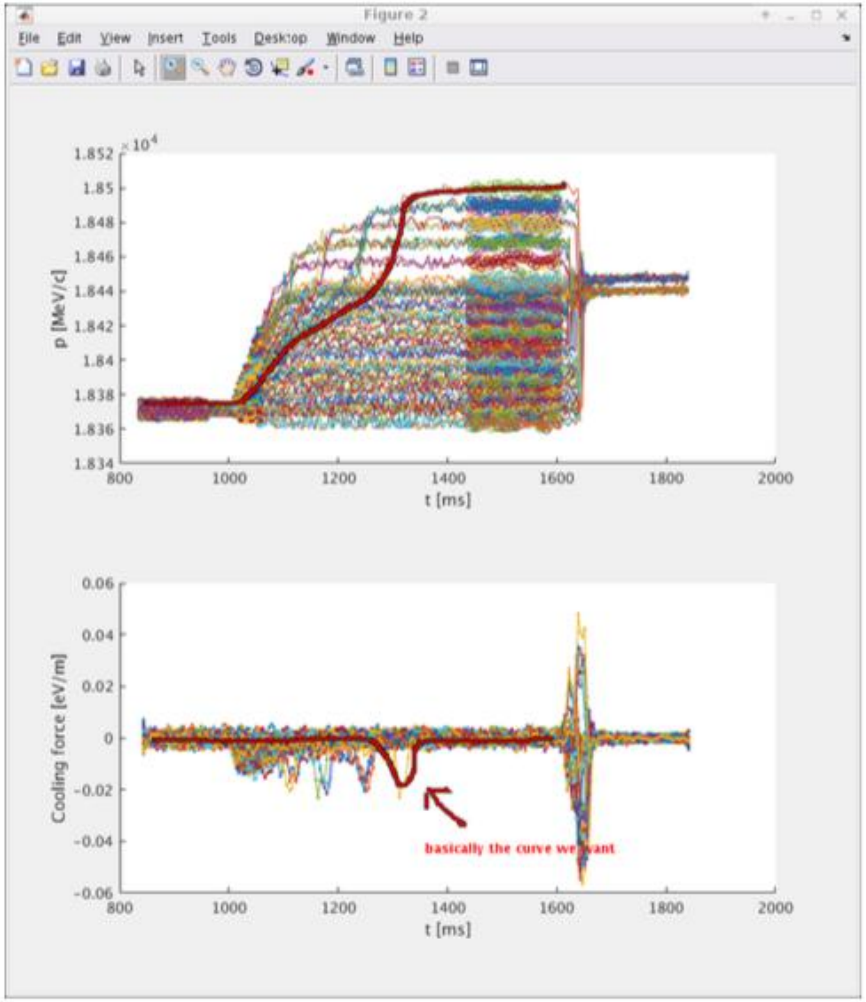
  in a solenoid magnetic field of $B = 0.07$ T

- We performed a velocity scan of the electrons, in order to evaluate the force at different

$$\Delta V = v_i - v_e$$

- The cooling force is computed as

$$F = \frac{\Delta P}{\Delta t}$$



Benchmark against measurements

Simulation setup:

Pb ions

Q = 54+

$\beta = 0.0943$; $\beta\gamma = 0.0947$

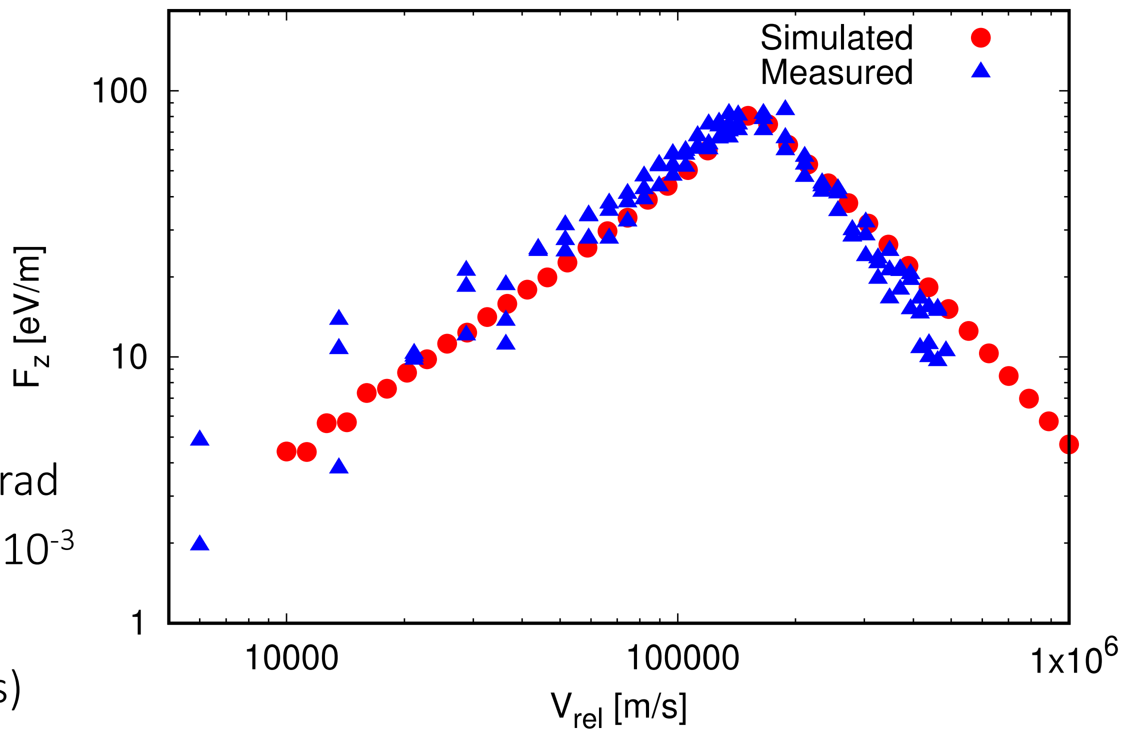
Initial geometric emittance = 7 mm.mrad

Initial P spread = Stacked gaussians, $\pm 10^{-3}$

Cooler (fitted to match measurements)

Ne = 4e13 e/m^3

$T_\perp = 0.01$ eV ; $T_\parallel = 0.001$ eV

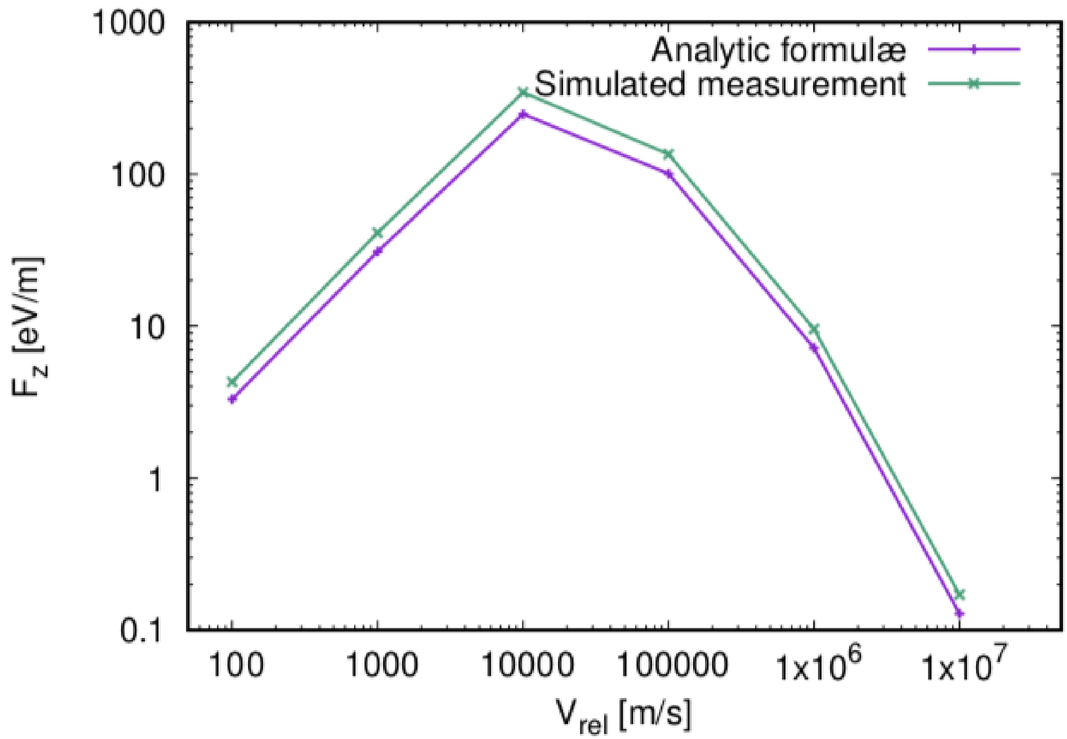


Note: the e$^-$ current depends on the electron beam size

Measurements performed with Nicolò B., Davide G.

Consistency check: Simulation of the measurement

A simulation of the measurement itself has been put in place (self-consistency test)

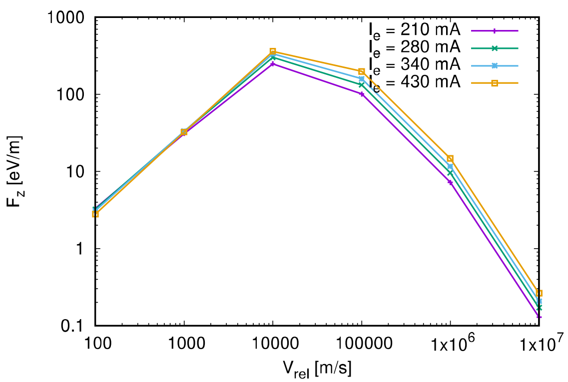


Analytic formulæ: Simulated force

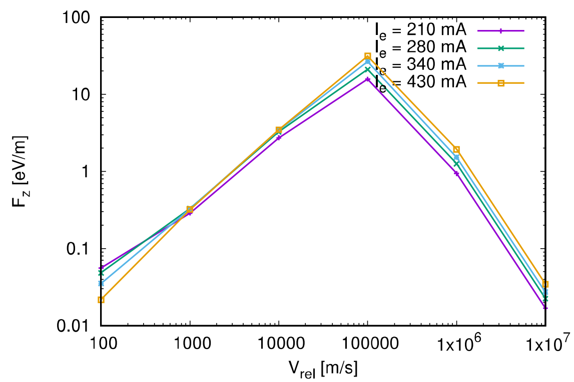
1. 50 ms of cooling before the electron velocity difference is excited
2. The estimate of the cooling force is computed considering the first 1 ms

Dependence from the electron current

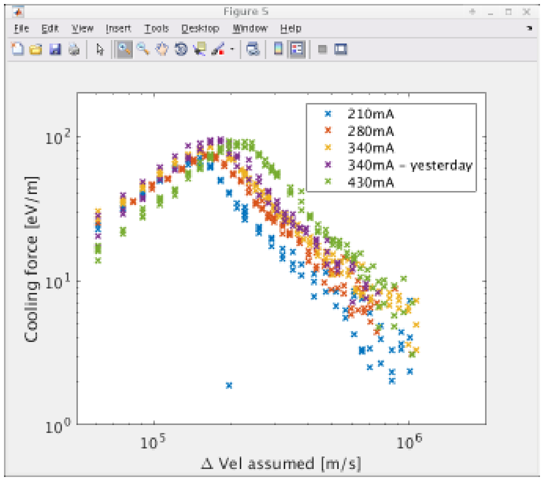
A simulation of the measurement was performed for different electron currents:



uniform distribution (simulation)



hollow distribution (simulation)



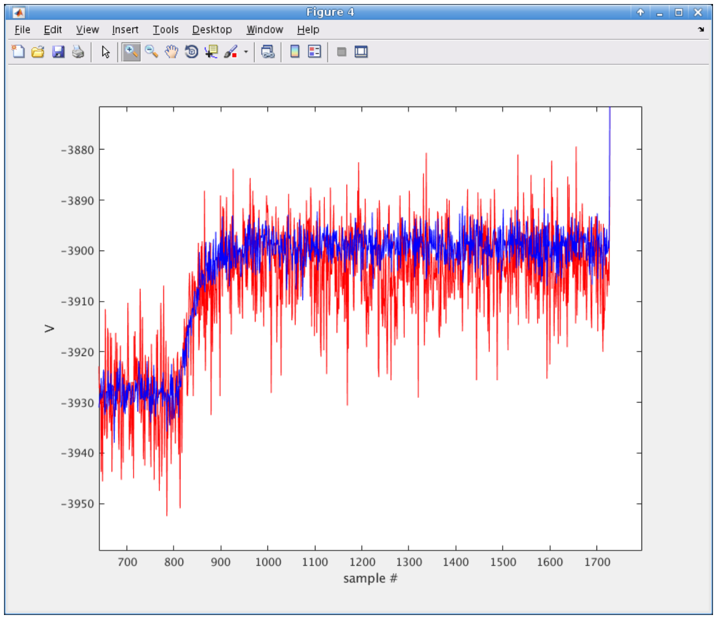
measurement

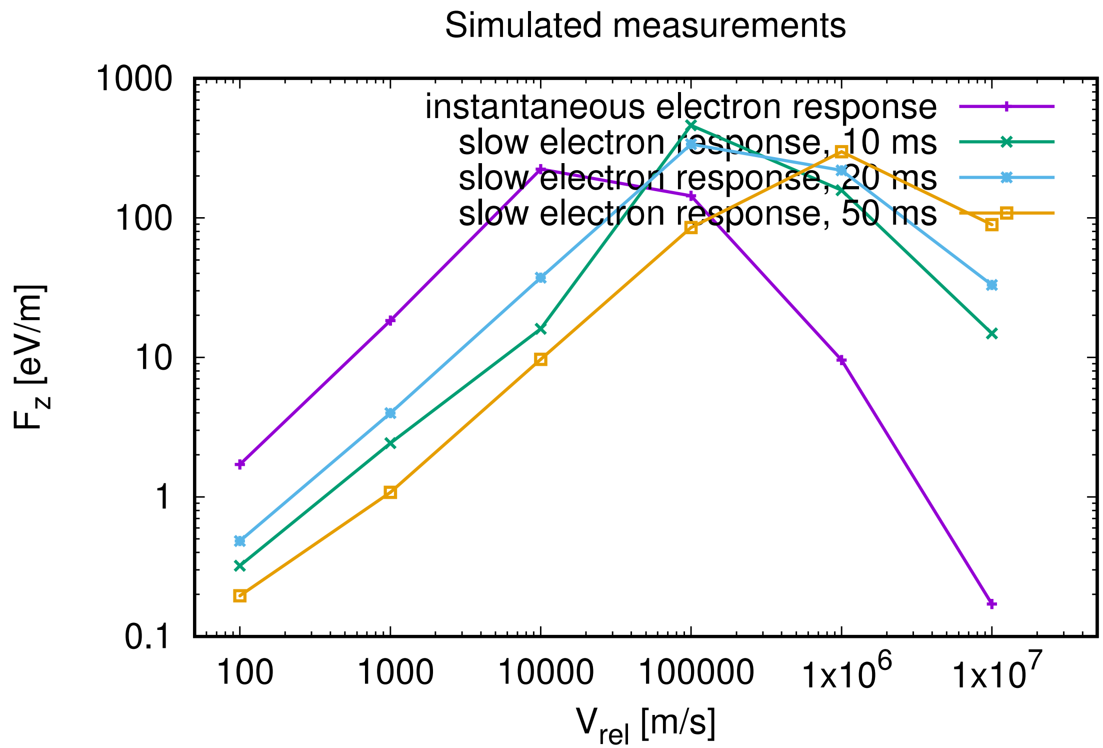
The fact that the peak shifts with the current, indicates that something more happens. E.g.

- Electron gun rise time?
- Electron beam profile?
- Other effects?

Measurements performed with Nicolò B., Davide G.

Effects of the electron gun rise time





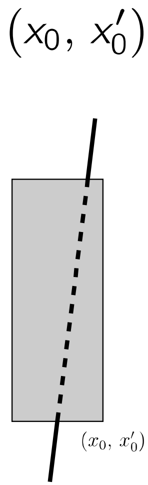
Measured rise time is of the order of 100 ms (one sample every ms in the LHS plot) (eLogBook: 14/05/2018)

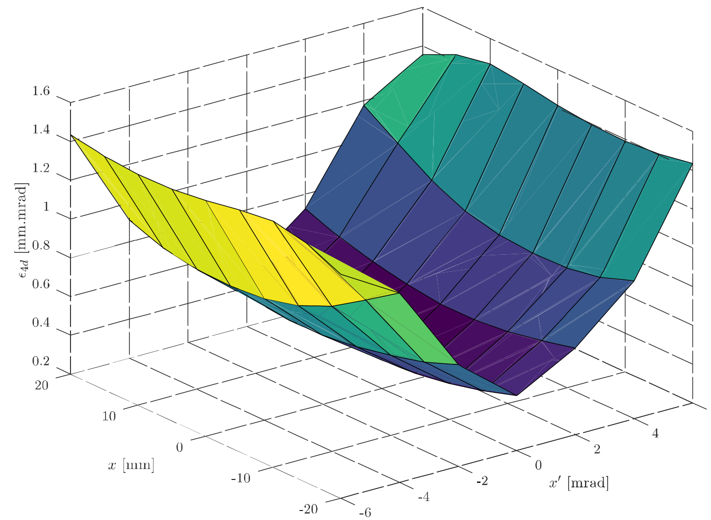
Conclusion: we need to feed the simulation with a reasonable rise time and then estimate the cooler parameters

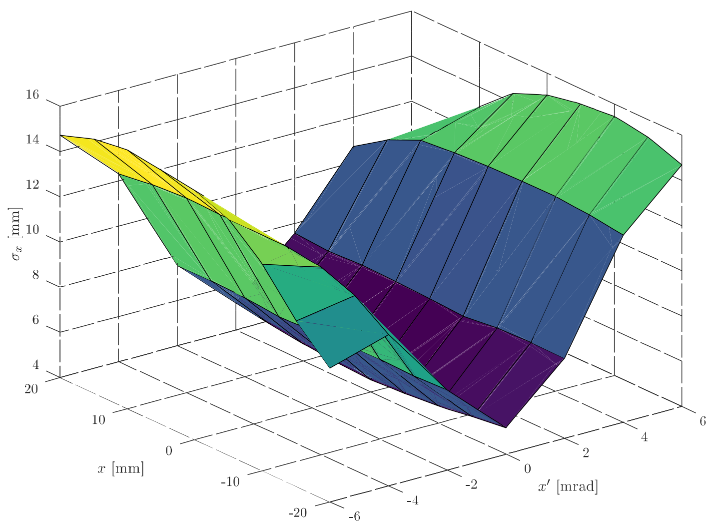
Studies of equilibrium values

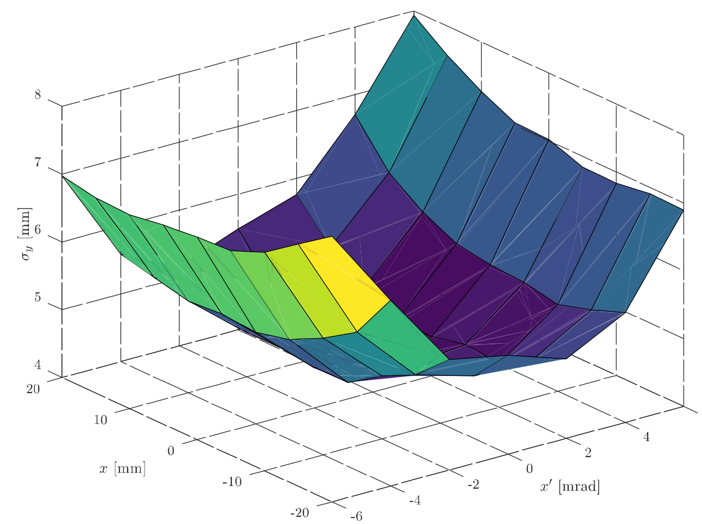
[Simulation]

Closed orbit scan at the cooler entrance









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

On-going and new studies

Analysis of existing data and verification in simulation:

- E.g. Various electron currents, Emittance angle – position scans, bunched beams

Simulation studies:

- Interplay between cooling and heating
  - IBS, SC, Ion stripping [Michail, Bianca, Angela]
  - Impedance [Nicolò, Andrea]
- Impact of other machine parameters:
  - e.g. impedance, coupling, etc. [Nicolò, Andrea]
  - Bunched beam? [Michail, Angela]
- New studies:
  - Performance simulations and parameters optimisation for ELENA ?
  - Performance simulations and parameters optimisation for AD ?

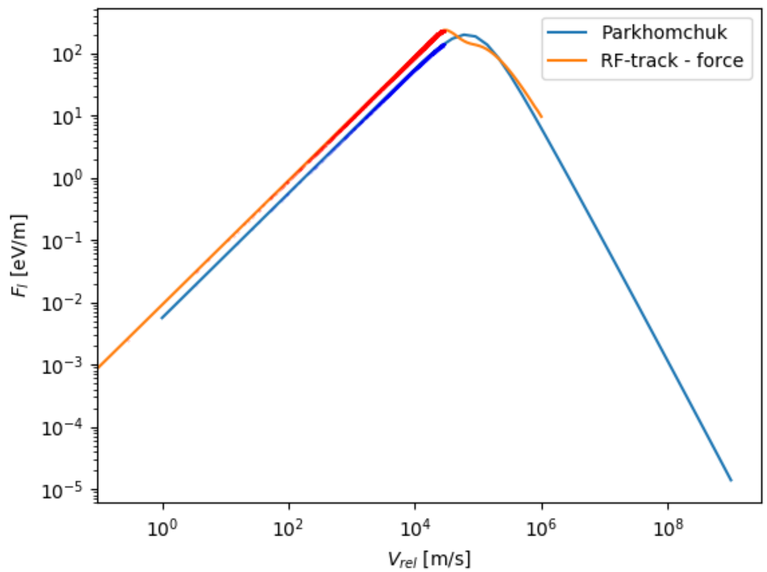
Code review and development:

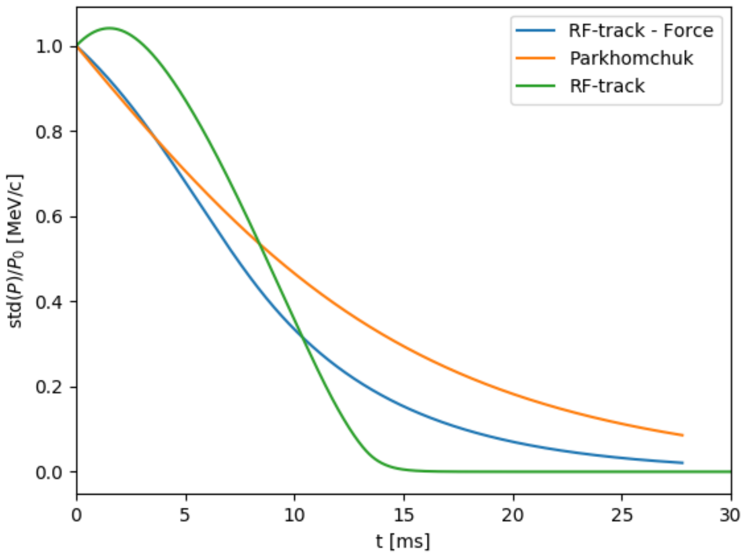
- Link: pyheadtail <-> RF-Track (EC),
  BLonD(*) <-> RF-Track (EC)
- Review of IBS models: SIRE, MAD-X, …
- Implementation of IBS (kinetic model) into RF-Track

(*) Longitudinal tracking code

Integration RF-Track - PyHEADTAIL

Very preliminary result, work ongoing
First step to the integration to pyheadtail





Credits: Nicolò B. and AL

From Electron-Cooling to Electron Lenses Simulation

- The EC simulation considers
  - Scattering ion-electrons (friction force)
  - Ions self-fields in free space
- It ignores:
  - Electrons self-fields
  - Electrons dynamics in plasma electrons are considered as rigid (i.e., their state parameters are constant)
- In order to simulate E-lens one should also consider
  - The self-fields created by the electrons (mostly magnetic)
    - Need to extend the electron plasma simulation (some work needed)
  - The effect of the ion bunch on the electron plasma
    - Implement the Euler's equations of fluid dynamics (some work needed)
  - To complete the picture: the shieling effect of the electrons on the ions self-fields (some work needed)
- Resource needed:
  - My time or the help of 1 person with good programming/simulation skills and good physics background

Resources for LEIR EC Studies

A fraction of:

- Andrea
- Nicolò
- Davide [ELENA, AD]

Post-Docs:

- Angela (not for long…)

Students:

- Michail [100%]
- Bianca Veglia (University of Liverpool, already half-way)
- New PhD student?

Conclusions and next steps

We have simulation tools that allow us to simulate electron coolers

Initial benchmarks give expected results. Detailed studies can start.

We have performed many different measurements, but most of them haven't yet been reproduced in simulations (mainly because of lack of resources).

Limited resources -> we'll need to prioritise studies, and possibly get some additional help.

We need to fully conclude on the cooler parameters that would best fit our observation (force, effect of currents, cooling maps, rise time), to be then safe to extrapolate to interesting cases (e.g. 150ms injection repetition rate vs 200ms presently used) .

The code can be used for ELENA and AD.

With some extensions, also for Electron lenses.