Electron Cooling of Highly Charged Ions and Antiprotons in Traps

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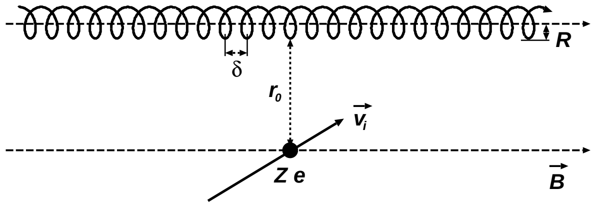
Two complementary approaches

- Binary collision model (BC): The drag on the ion is the accumulated result of many binary collisions between the ion and the electrons. The collective polarization of the electrons is only accounted for by shielding the Coulomb interaction at large distances.
- Dielectric linear response (LR): The drag on the ion is due to the polarization it creates in its wake. This continuum theory breaks down at small distances where hard collisions dominate and linear response is not sufficient.
- Observation: Without magnetic field both approaches agree.
- Question: What happens for a strong magnetic field (cyclotron radius $R \ll$ shielding length λ)?

Binary collision model

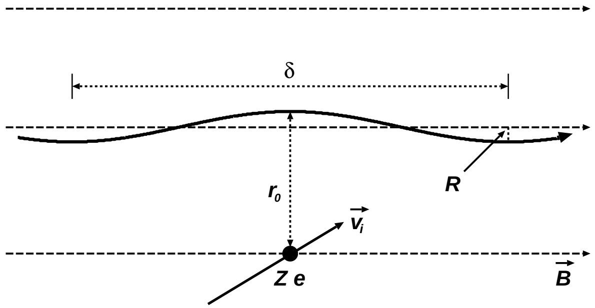
- Depending on the relative size of the parameters $r_0 =$ distance of closest approach, $R =$ cyclotron radius, $\delta =$ pitch of the helix, three regimes can be identified:

t: adiabatic
tight helices
$R < r_0, \delta < r_0$

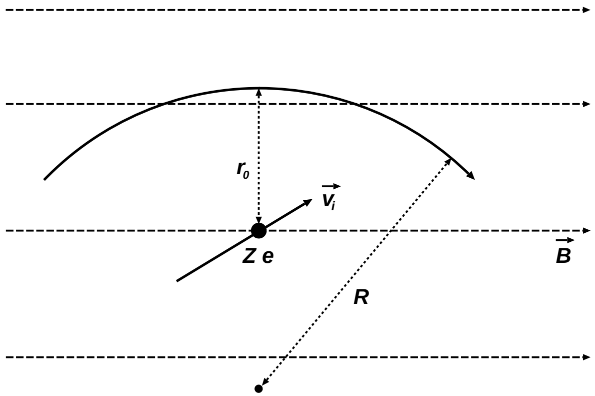


dominates for a
strong magnetic field
($R <$ shielding length λ)

s: adiabatic
stretched helices
$R < r_0, \delta > r_0$



c: weak magnetic field
Rutherford trajectories
$R > r_0$



LEIR parameters

B_0	$=0.06$	T
Ω	$=1.06 \cdot 10^{10}$	s^{-1}
$T_{\parallel}$	$=10^{-4}$	eV
$T_{\perp}$	$=0.1$	eV
$v_{\mathrm{th}\parallel}$	$=4.2 \cdot 10^{3}$	$\frac{\mathrm{m}}{\mathrm{s}}$
n_e	$=4.5 \cdot 10^{7}$	cm^{-3}
λ	$=2.8 \cdot 10^{-4}$	m
R	$=1.2 \cdot 10^{-5}$	m

Anisotropic velocity distribution !

Scales

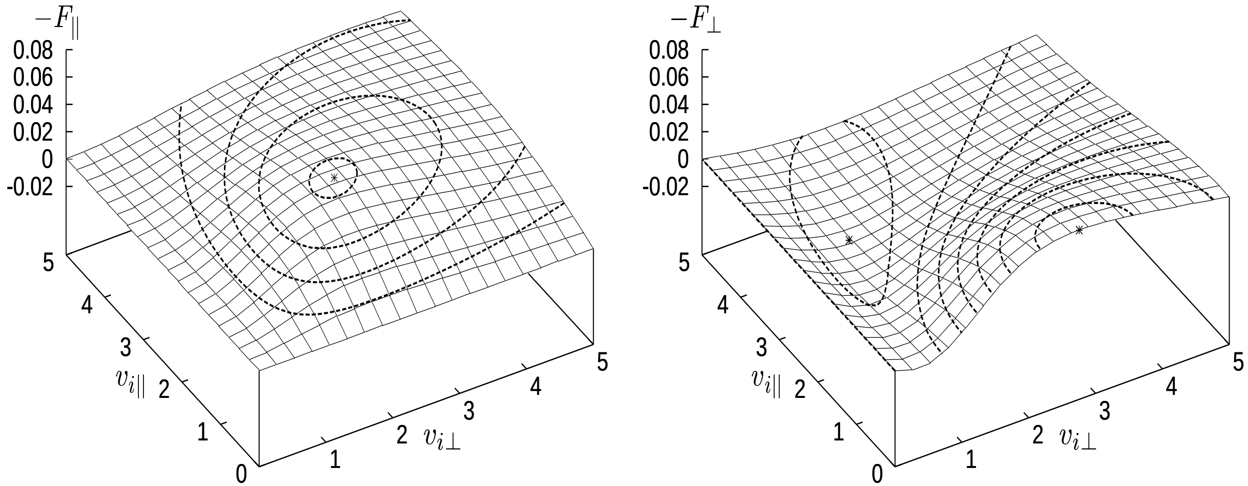
$$\frac{dE_i/ds}{\left(\frac{4\pi Z^2 \not{e}^4 n_e}{m v_{\mathrm{th}\parallel}^2}\right)} \rightarrow dE_i/ds$$

$$v_i/v_{\mathrm{th}\parallel} \rightarrow v_i$$

Drag force under LEIR conditions

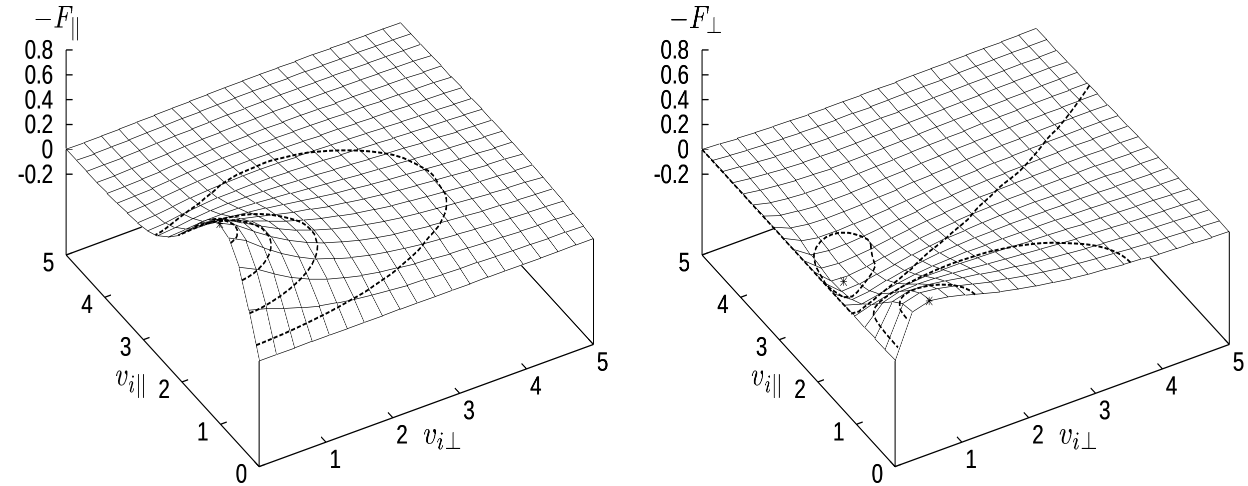
- For comoving ions ($v_{i\perp} \to 0$) the drag force vanishes for symmetry reasons in BC.

BC, Z=54



- In LR also collective response is included, but the drag is overestimated as linearization fails for $v_{i\perp} \to 0$.

LR, Z=54

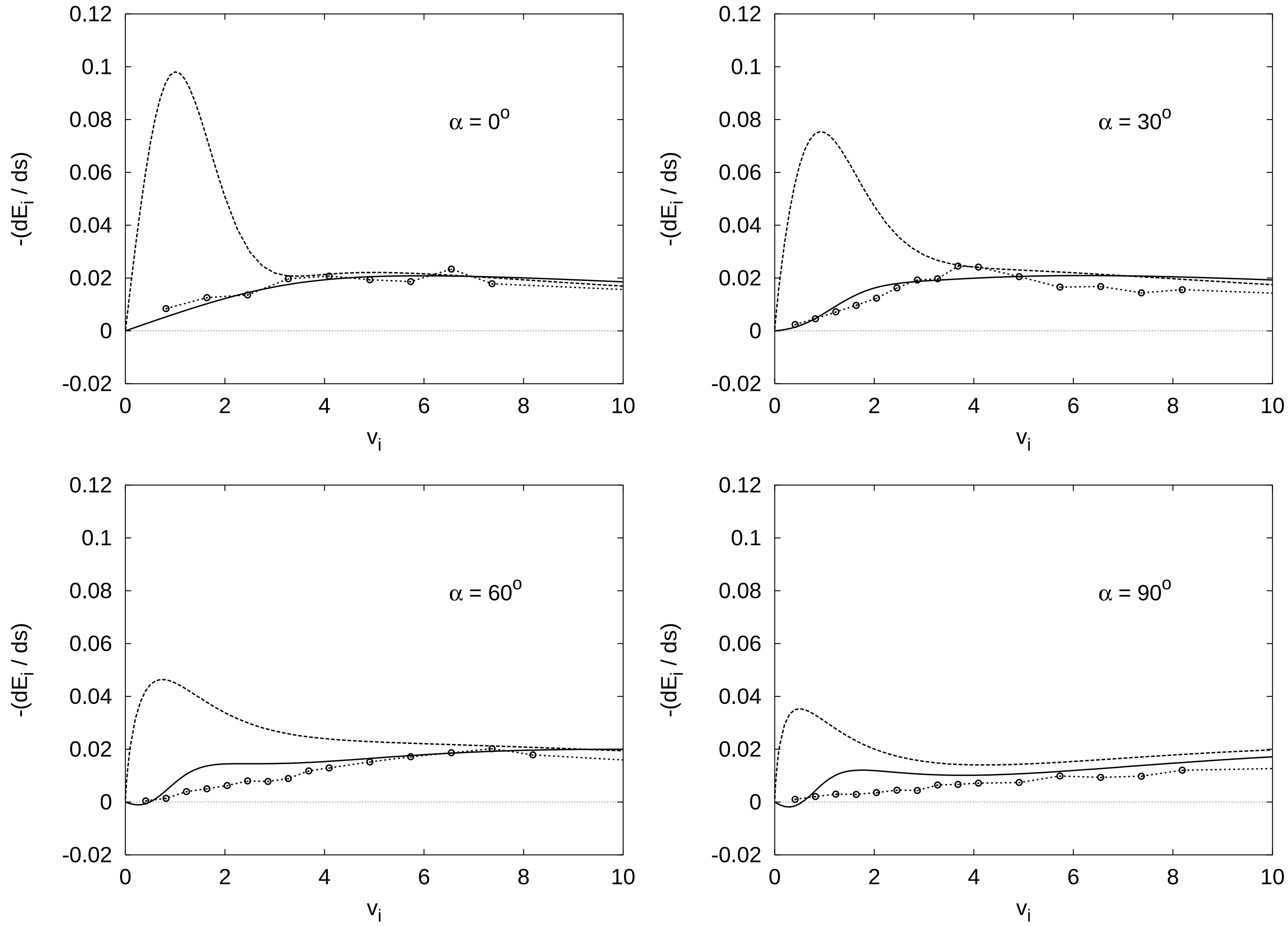


A numerical solution of the Vlasov-Poisson equation, including non-linear response and collectivity shows that the $v_i \to 0$ behavior of the linearized dielectric theory is unrealistic.

solid: BC

dashed: LR

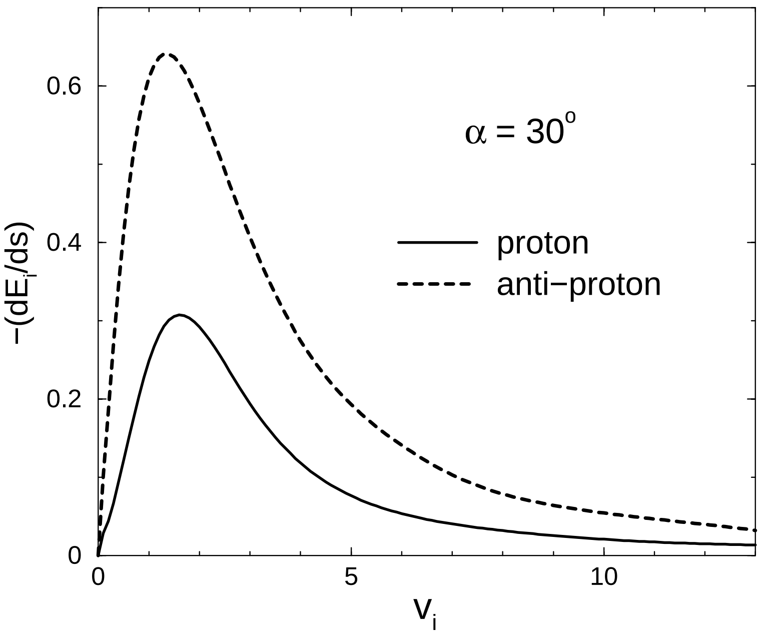
circles: nonlinear Vlasov-Poisson

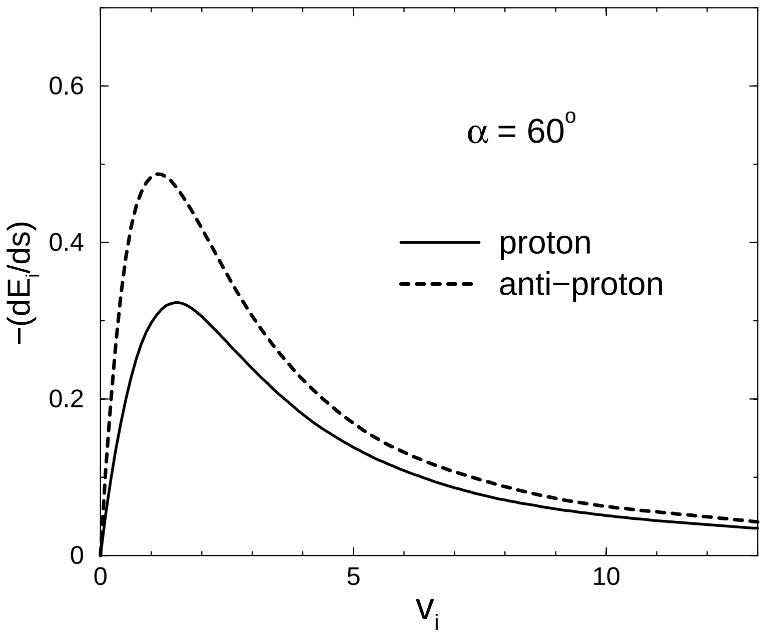


$Z = 10, T_{\parallel} = 10$ K, $T_{\perp} = 1000$ K, $n_e = 1.55 \cdot 10^{10}$cm^{-3} and $B = 0.04$ T

p vs. $\overline{p}$

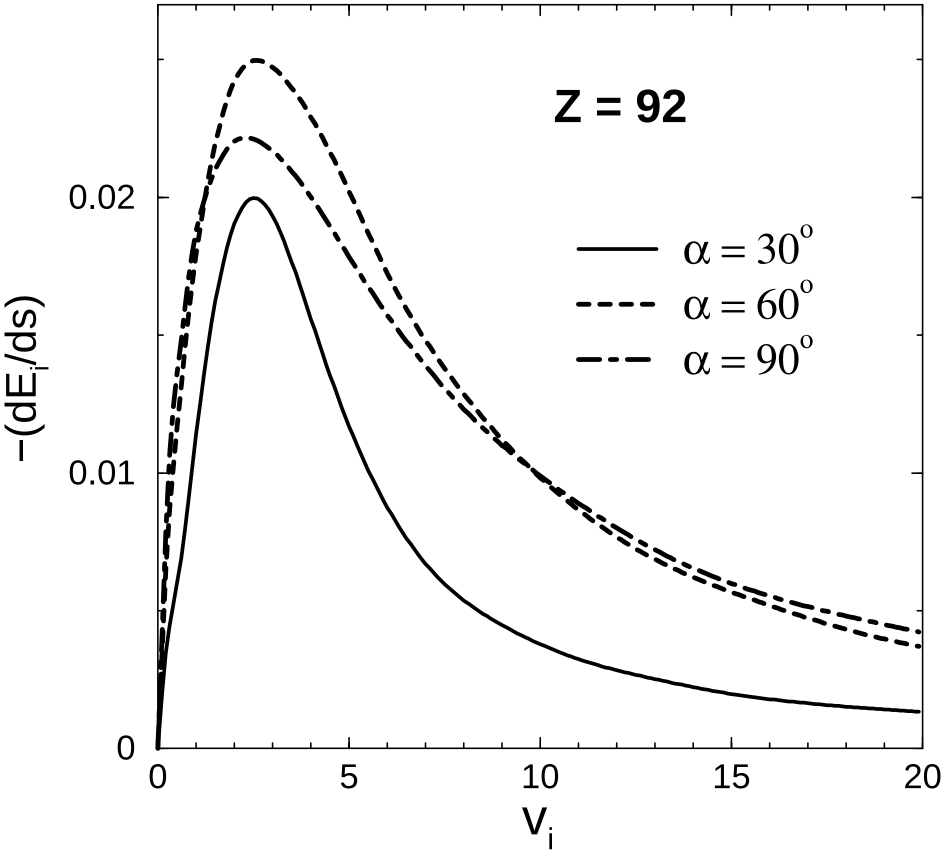
- In the limit of large magnetic fields ($R \ll \lambda$, well established for HITRAP, ATRAP, ATHENA) the electrons move along the field lines like beads on a wire.
- For comoving ($v_i \to 0$), positively charged ions (p) the drag vanishes for symmetry reasons.
- For negatively charged ions ($\overline{p}$) electrons are reflected. This cannot be accounted for by linearization or in a perturbation treatment.
- p vs. $\overline{p}$ under HITRAP conditions in CTMC (Classical Trajectory Monte Carlo) calculations of binary collisions (BC).

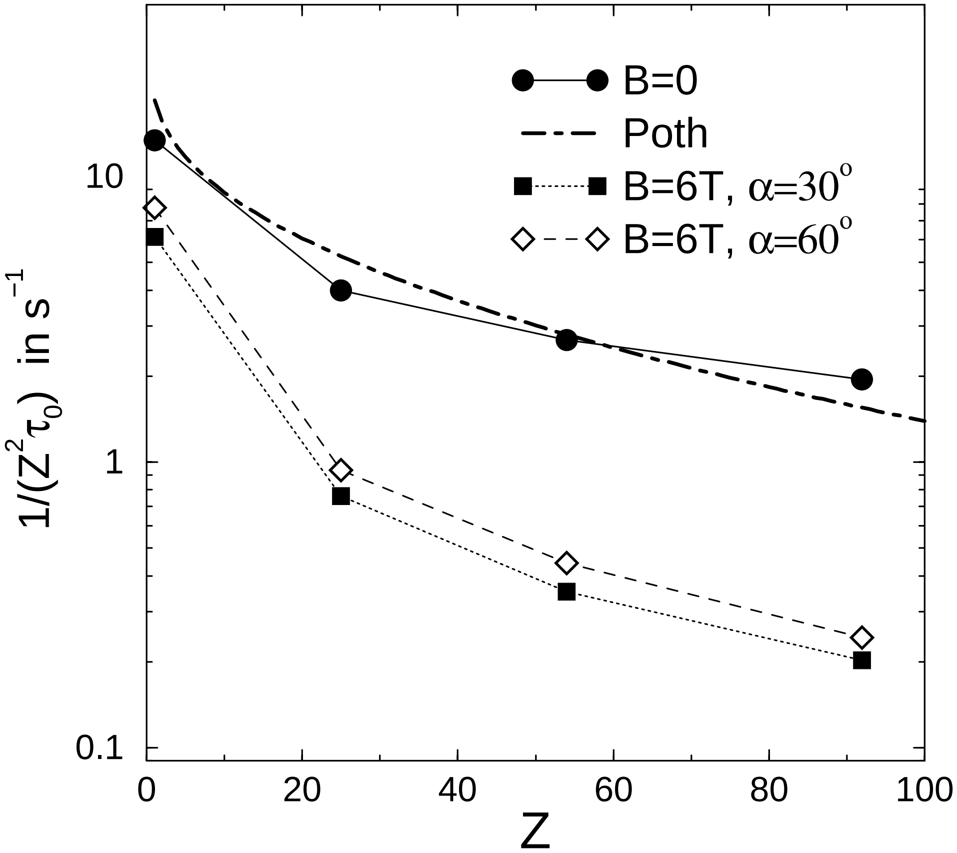




Estimate of cooling time

$$\tau \;\approx\; \frac{\tau_0}{3}\left[\left(\frac{v_{i,\mathrm{init}}}{v_{i,\mathrm{max}}}\right)^3 - 1\right]\;, \qquad\qquad \frac{1}{\tau_0} \;=\; \frac{1}{Mv_i}\frac{dE_i}{ds}(v_i)\Big|_{\mathrm{max}(dE_i/ds)}$$





The interaction between charged particles in a magnetic field is an interesting subject of research

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