Recombination Enhancement in Electron Coolers

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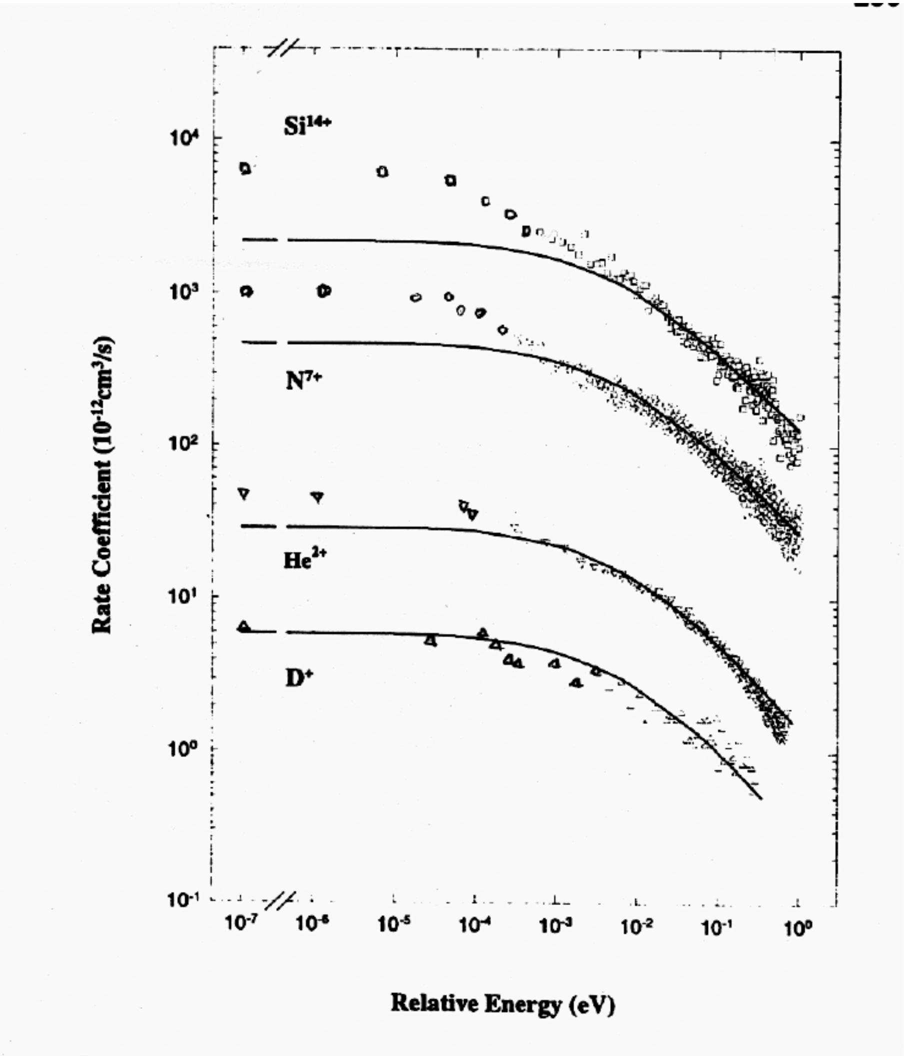
Experiments

- Ion-electron recombination is observed in electron coolers.
- Experimental recombination rate is greater than predicted by standard theory.
  “recombination enhancement”
- Experiments with bare ions or rare gas electron configurations
  ⇒ radiative recombination



H. Gao, R. Schuch, et al., J. Phys. B 30 (1997) L499.

The physics of radiative recombination

Measurement:

- Rate R_{det} counts ions that recombine to a state below n_{cut} per time interval.
- Rate coefficient $\alpha_{\mathsf{exp}} = \gamma^2 \frac{L}{N_{\mathsf{i}}\, l} \frac{R_{\mathsf{det}}}{n_{0,\mathsf{e}}}$ is normalized to the bulk density $n_{0,\mathsf{e}}$.

Theories:

- Stobbe:
  overlap $\langle \psi_{\mathsf{f}} | \mathbf{r} | \psi_{\mathsf{i}} \rangle$
  in flux-normalized basis
- Bethe/Salpeter:
  analogy to photoionization
  corrected by Gaunt factors

Approximations:

- nonrelativistic quantum mechanics
- Radiation is weak disturbance
- dipole approximation
- electrons asymptotically free

Enhancement factor

- Only free electrons are accounted for in standard theory.
- Additionally, electrons get captured in Rydberg states when ion and electron beam are merged.
- Transitions from Rydberg states to levels below n_{cut} are possible

$$\Rightarrow \quad \alpha^{\mathrm{RR}} = \alpha^{\mathrm{RR}}_{\mathrm{free}} + \alpha^{\mathrm{RR}}_{\mathrm{bound}}$$

- Transition rate of free and bound states is steady at the continuum limit.
- Enhancement factor $\epsilon := \dfrac{\alpha^{\mathrm{RR}}}{\alpha^{\mathrm{RR}}_{\mathrm{free}}} \approx \dfrac{\langle n_{\mathrm{free}} + n_{\mathrm{bound}} \rangle}{\langle n_{\mathrm{free}} \rangle}$
- Above quantity is averaged over cylinder of cyclotron radius.

Vlasov Poisson equation in axial symmetry

- Vlasov Poisson equation for a collisionless plasma in 6-dim. phase space

$$\frac{\partial f}{\partial t} + \mathbf{p} \cdot \frac{\partial f}{\partial \mathbf{r}} + \left(\mathbf{F}^{\text{ext}} + \mathbf{E}^{\text{mf}}\right) \cdot \frac{\partial f}{\partial \mathbf{p}} = 0 \,, \qquad \boldsymbol{\nabla} \cdot \mathbf{E}^{\text{mf}} = \int \mathrm{d}^3 p \, f \; - \; 1$$

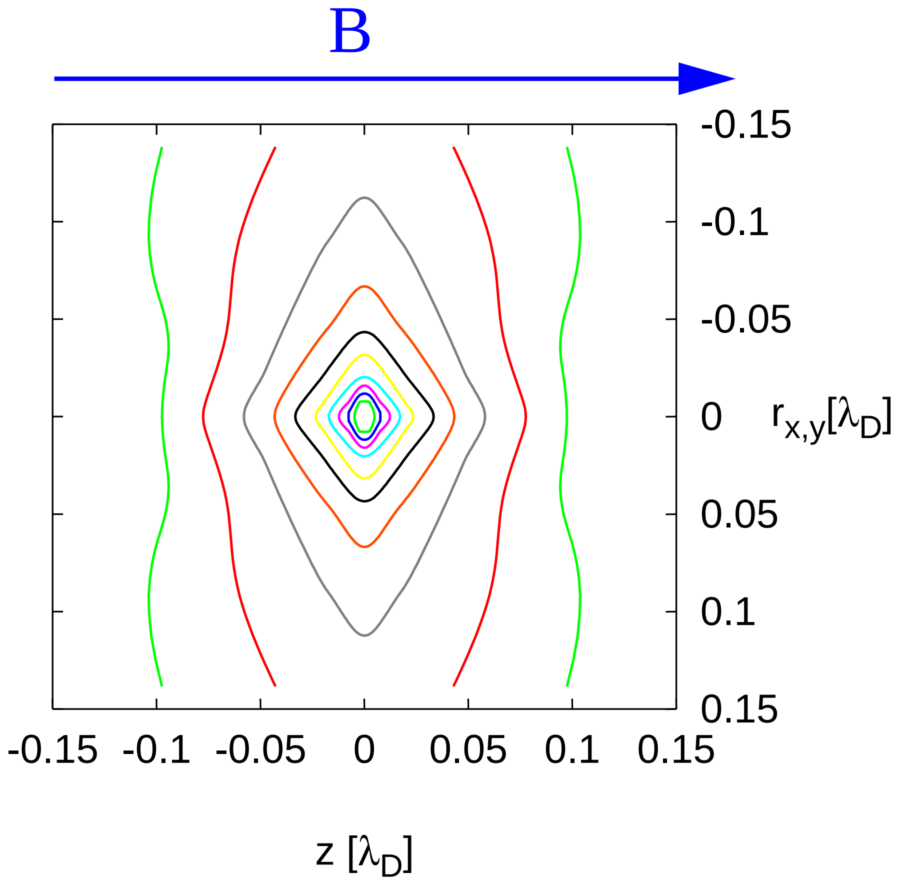
- Axial symmetry of electron density around magnetic field (z-direction)
Invariants under z-rotation:
$r_\perp$, $v_\perp$, $(\mathbf{r} \cdot \mathbf{v})$; z, v_z $\Rightarrow$ **5 independent coordinates**

- Vlasov equation becomes

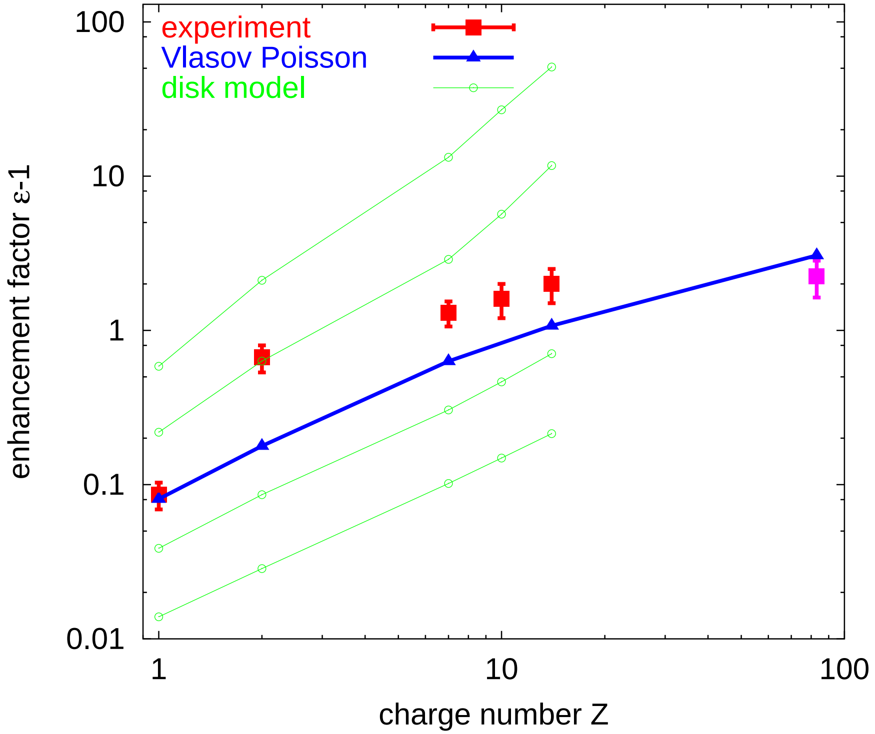
$$\frac{\partial f}{\partial t} + v_\perp \frac{\partial f}{\partial r_\perp} + \left(\frac{l_0^2}{r_\perp^3} + B \frac{l_0}{r_\perp} + E_\perp \right) \frac{\partial f}{\partial v_\perp} \; + \; v_z \frac{\partial f}{\partial z} + E_z \frac{\partial f}{\partial v_z} \; = \; 0$$

with $f = f(l, r_\perp, v_\perp, z, v_z)$. $\qquad l = l_0 + \frac{1}{2} B r_\perp^2$ is conserved.

Enhancement: dependency on ionic charge



Iso-contour plot of electron density around a Si ion at the exit of the cooler.



Enhancement factor as a function of ion charge.

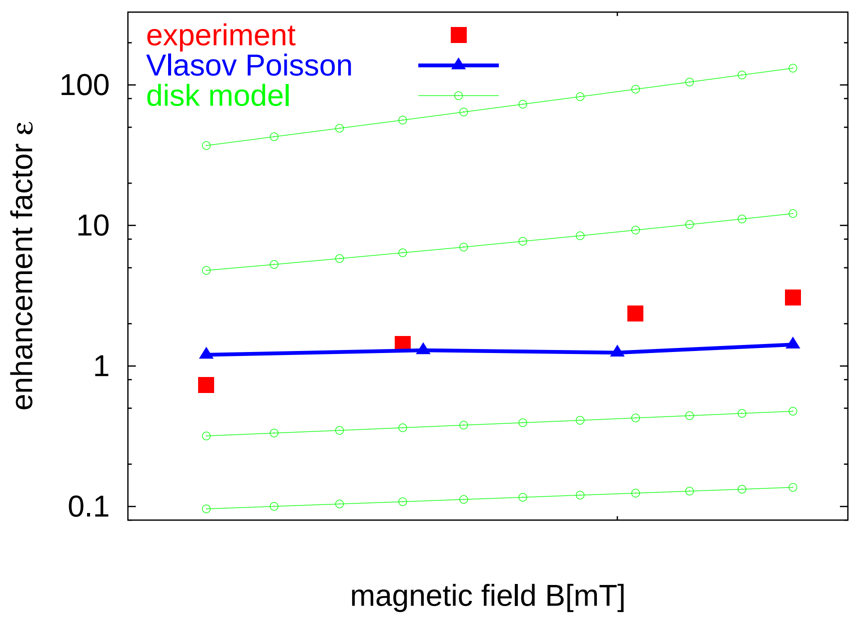
H. Gao, R. Schuch, et al., J. Phys. B 30 (1997) L499.

A. Hoffknecht, T. Bartsch, et al., EAS 20 (1999) 37.

Q. Spreiter, C. Toepffer, J.Phys B 33 (2000) 2347.

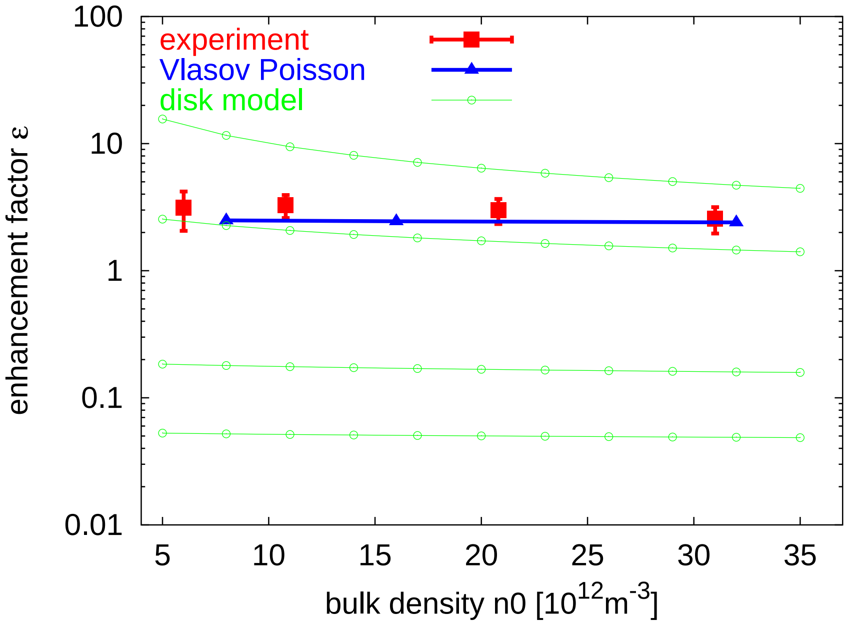
Enhancement: dependency on B and n_0

Au^{25+} ions:



A. Hoffknecht, et al., J. Phys. B 31 (1998) 2415.

Ne^{10+} ions:



H. Gao, et al, Hyperfine Interactions 99 (1996) 301.

Experimental data

quantity		value[1]	value[2]	value[3]	unit
$T^{\parallel}$	$=$	1.4	11.6	1.74	K
	$=$	0.121	1.0	0.15	meV
$T^{\perp}$	$=$	116	1160	232	K
	$=$	10.0	100	20.0	meV
$\lambda_{\mathrm{D}}^{\parallel}$	$=$	18.3	12.9	16.1	10^{-6}m
$\lambda_{\mathrm{D}}^{\perp}$	$=$	166	129	186	10^{-6}m
n_0	$=$	20	330	5..35	10^{12}m^{-3}
ω_{p}	$=$	2.52	10.2	3.19	10^{8}s^{-1}
Z	$=$	1,2,7,10,14	25	10	
B	$=$	30	240..330	30	mT
Q	$=$	0.0079..0.11	0.0278	0.022..0.045	
Ω	$=$	20.9	41.19..56.63	16.5..33.1	
α	$=$	0.101	0.10	0.866	

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[1] H. Gao, R. Schuch, et al., J. Phys. B 30 (1997) L499.

[2] A. Hoffknecht, O. Uwira, et al. , J. Phys. B 31 (1998) 2415.

[3] H. Gao, S. Asp, et al, Hyperfine Interactions 99 (1996) 301.

Conclusion

Summary

- Radiative recombination is enhanced in electron coolers.
- Density enhancement may be modeled numerically by the Vlasov Poisson equation.
- Density enhancement drives the recombination enhancement.
- The proposed measures describe the experimental results at reasonable quality.

Outlook

- Systematic study of various physical parameter sets
- Realistic simulation of beam merging
- Additional ion velocity
- Better understanding how to derive a recombination rate from classical simulations