Electron Cooling of Highly Charged Ions in Traps

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- The HITRAP project at GSI
- Electron cooling in traps[1]
  - Features and challenges
  - Numerical calculations of the cooling process
  - Cooling times and losses by recombination
- Future tasks and open questions

- Coworkers

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[1] supported by BMBF and GSI

HITRAP @ GSI

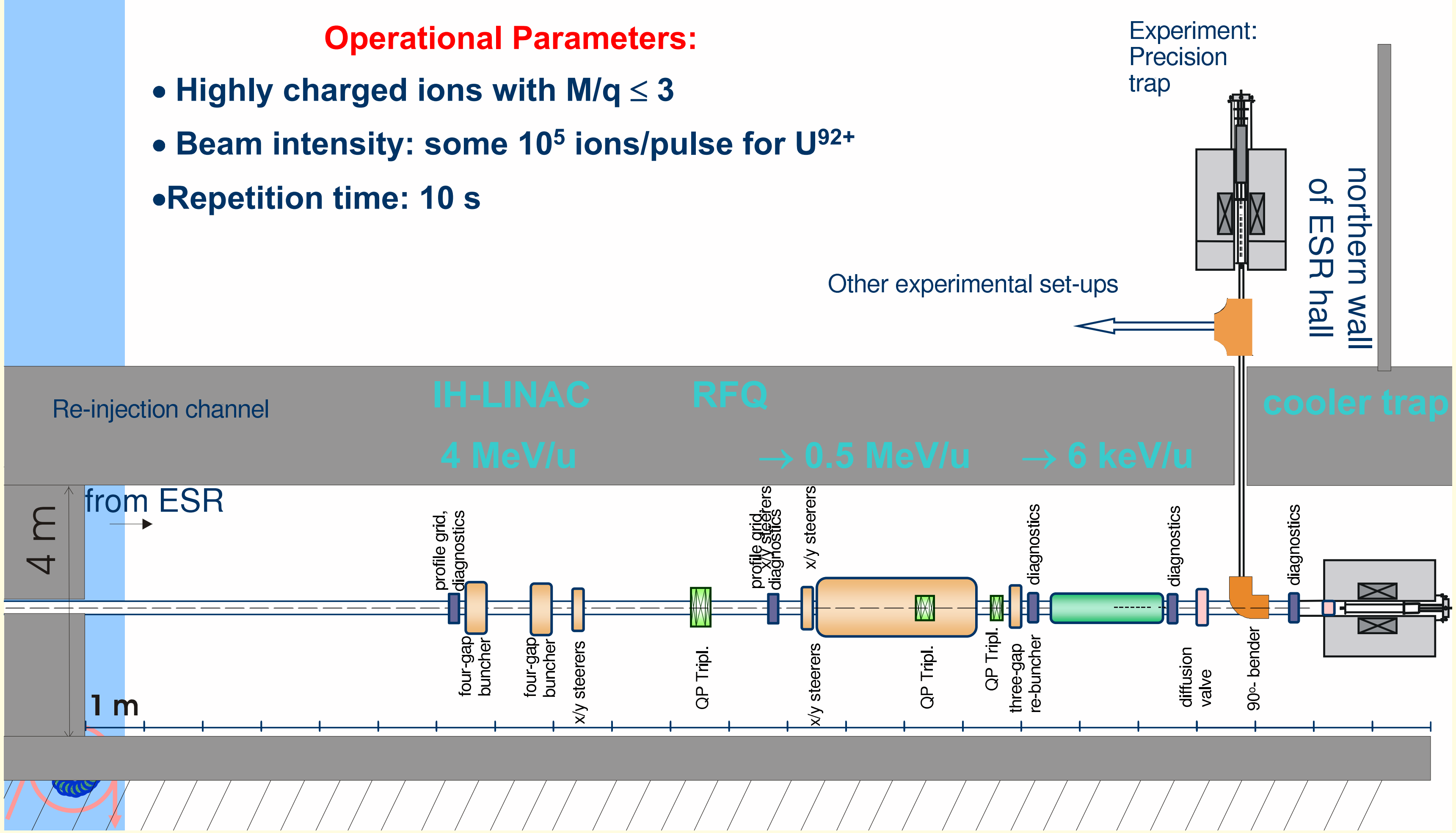
EXPERIMENTS WITH HIGHLY CHARGED IONS AT EXTREMELY LOW ENERGIES:

- **collisions at very low velocities ultra-accurate**
- **surface studies and hollow-atom spectroscopy**
- **laser and x-ray spectroscopy**
- **g-factor measurements (tests of QED)**
- **mass measurements**

HITRAP

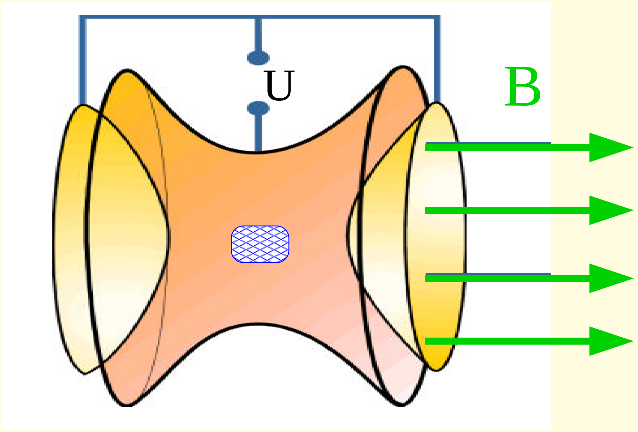
Operational Parameters:

- **Highly charged ions with M/q ≤ 3**
- **Beam intensity: some 10^5 ions/pulse for U^{92+}**
- **Repetition time: 10 s**



Electron Cooling in a Penning Trap

Principle of a Penning Trap:

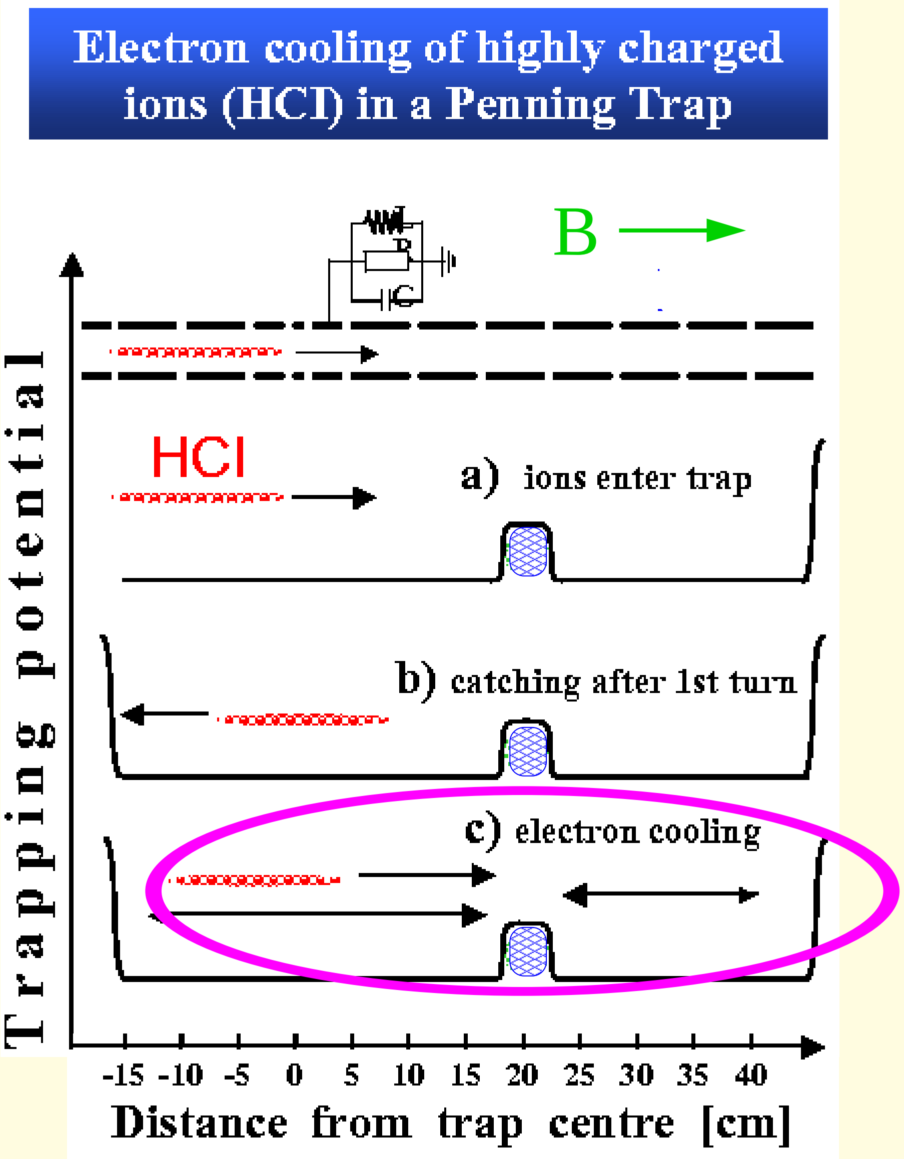


radial confinement by a strong homogeneous magnetic field

axial confinement by an electrostatic field

Typical parameters:

- $Z = -1, 1 \ldots 92$
- $B \lesssim 6$ T
- $T_{e,0} \approx 4$ K
- $n_e \approx 10^7$ cm^{-3}
- $N_e \approx 10^8 \ldots 10^{10}$
- $N_i \approx 10^5$



Electron cooling in traps

- Special features and requirements (HITRAP):
  - Cooling must be sufficiently fast to enable an operation cycle of 10 s (loading of the trap with electrons, catching of the ions, electron cooling, resistive cooling, extraction of the ions)
  - Heating of electrons by the ions, cooling of electrons by synchrotron radiation (strong fast heating of electrons $T_e(0) \sim meV$ to $T_e \sim eV$)
  - Cooling must be fast compared to recombination losses (for HCI!) (after electron cooling is completed the electrons are removed from the trap)

- Challenge for the theoretical description: cooling forces
  - Different and complementary theoretical approaches are employed (Poster P18)
  - Analytical: perturbative treatment of binary collisions (BC) and dielectric linear response (LR)
  - Simulations: Classical Trajectory Monte Carlo (CTMC), Particle-In-Cell (PIC)

Electron cooling of ions in a trap: A simplified model*

- Deceleration of the ions by collisions with magnetized electrons

$$M\frac{d\vec{V}_\mu}{dt} = \vec{F}[n_e, T_e, B, \vec{V}_\mu(t)]$$

- Energy loss of ions and transfer of the energy to the trapped electrons

$$\sum_\mu^{N_i}\frac{dE_\mu}{dt} = \sum_\mu^{N_i} M\vec{V}_\mu\cdot\frac{d\vec{V}_\mu}{dt} = -\frac{dE_e}{dt} \overset{!}{=} \frac{3}{2}N_e k_B\frac{dT_e}{dt}$$

- Heating of the electrons and cooling by synchrotron radiation ($\tau \approx 0.1s$) to $T_0 (= 4K)$

$$\frac{dT_e}{dt}(t) = -\frac{2}{3k_B N_e}\sum_\mu^{N_i}\frac{dE_\mu}{dt}(t) \; - \; \frac{1}{\tau}(T_e - T_0)$$

- Assumptions
  - Ions move in an infinitely extented electron plasma

$$\Rightarrow \quad \frac{N_i}{N_e} \leftrightarrow \frac{n_i}{n_e}$$

  - Electric fields in the trap not (yet) included
  - Ion energy instantaneously transfered into electron temperature

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* See also:

J. Bernard et al., NIMA **532**, 224 (2004).

S.L. Rolston, G. Gabrielse, Hyp.Int. **44**, 233 (1988).

Recombination

- Calculation of the actual radiative recombination rate $\nu_{RR}(t)$ for each ion:
  - Ion-electron RR-cross section (e.g. M. Pajeck, R. Schuch, NIMB **93**, 241 (1994).):

$$\sigma_{\mathrm{RR}} = \sigma_0 \left(\frac{0.161}{\tilde{v}_r^2} - \frac{\ln \tilde{v}_r}{\tilde{v}_r^2} + \frac{0.518}{\tilde{v}_r^{4/3}} + \frac{0.074}{\tilde{v}_r^{2/3}} + 0.046 \ln \tilde{v}_r + 0.068 \right)$$

with $\sigma_0 = 2.1 \cdot 10^{-22}$ cm^2 , $\tilde{v}_r^2 = \dfrac{m_e v_r^2}{2Z^2 13.6\mathrm{eV}}$ and $\vec{v}_r = \vec{V} - \vec{v}_e$

- ▶ Actual recombination rate using $V(t)$ and $T_e(t)$:

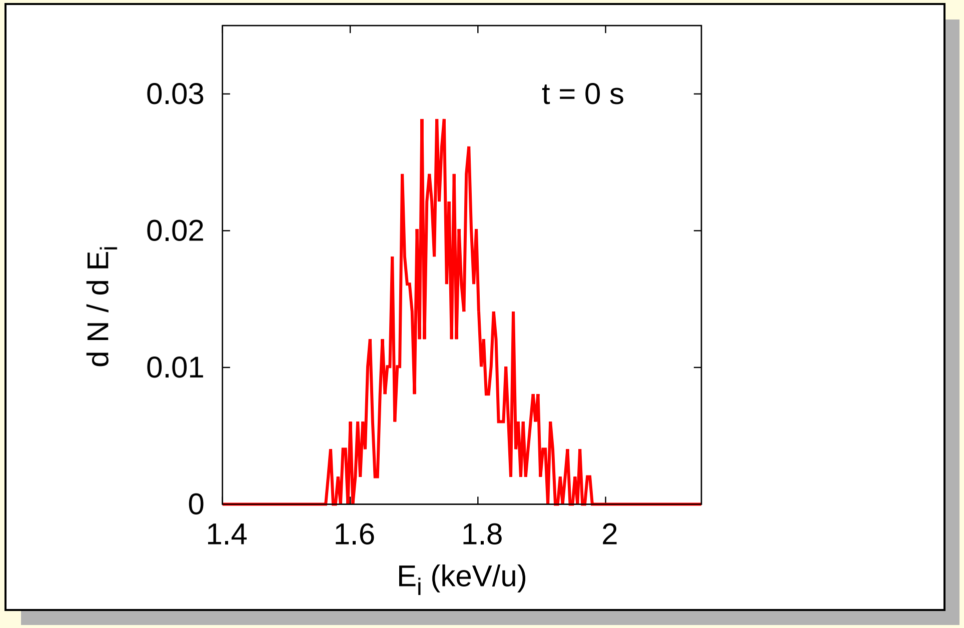
$$\nu_{\mathrm{RR}}(t) = n_e \int d^3 v_e \; v_r(t) \; \sigma_{\mathrm{RR}}(v_r(t)) \; \left(\frac{m_e}{2\pi k_B T_e(t)} \right)^{3/2} \exp \left(- \frac{m_e v_e^2}{2 k_B T_e(t)} \right)$$

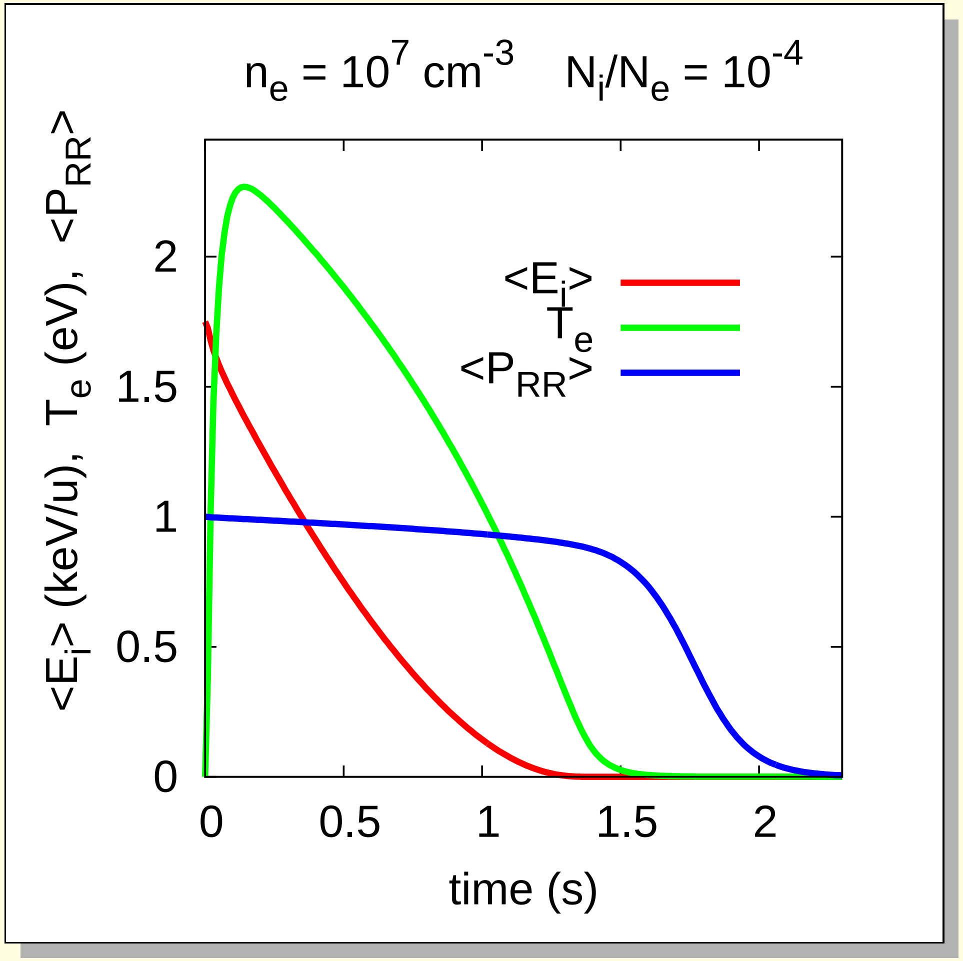
- ▶ Surviving probability (probability for remaining in the initial charge state):

$$P_{\mathrm{RR}}(t) = \exp \left(- \int_0^t dt' \nu_{\mathrm{RR}}(t') \right)$$

Cooling of U^{92+} and heating of electrons

- U^{92+}, $T_e(0) = 4$ K, $B = 6$T
- Initial ion distribution with $N_i = 500$ ions as obtained from ion optics simulations of the injection into the cooler trap for the HITRAP setup*





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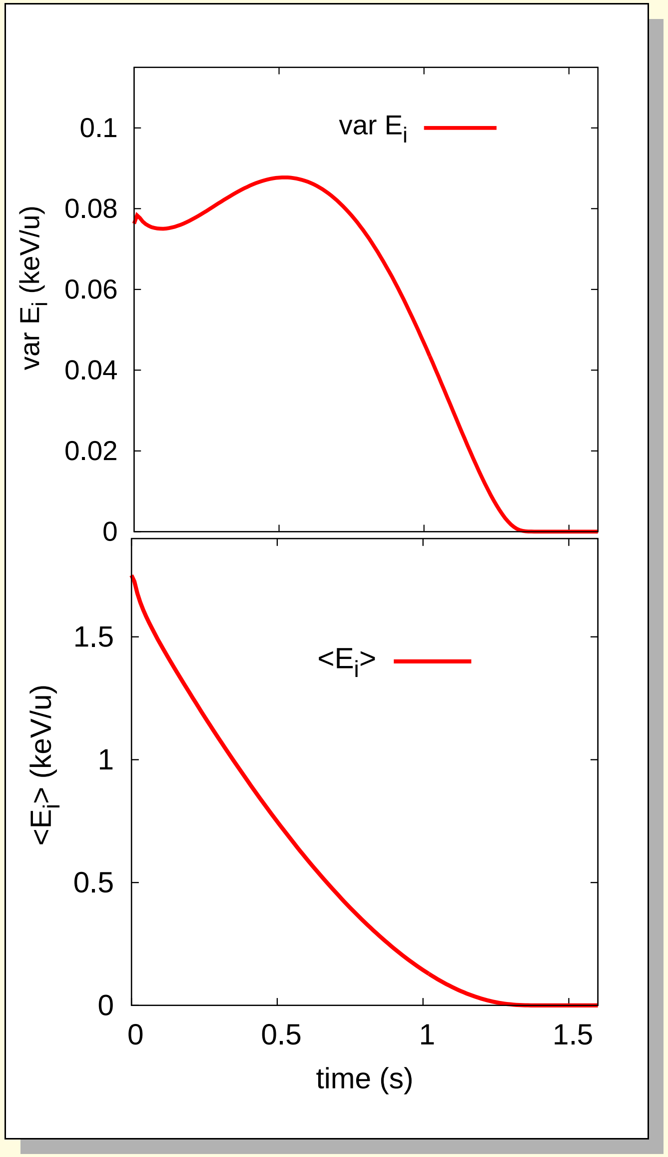
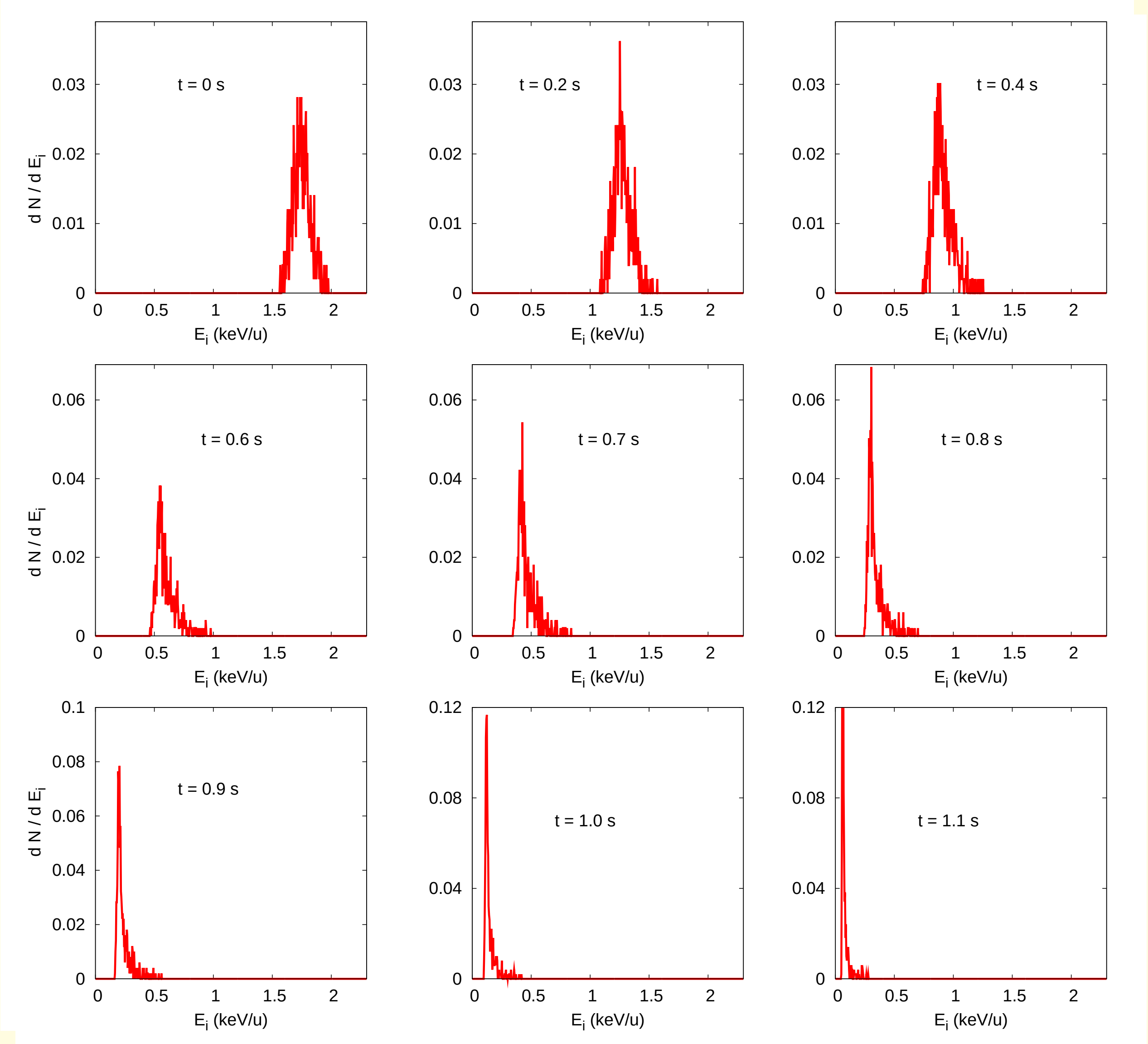
*F. Herfurth, private communications

Time evolution of the ion distribution

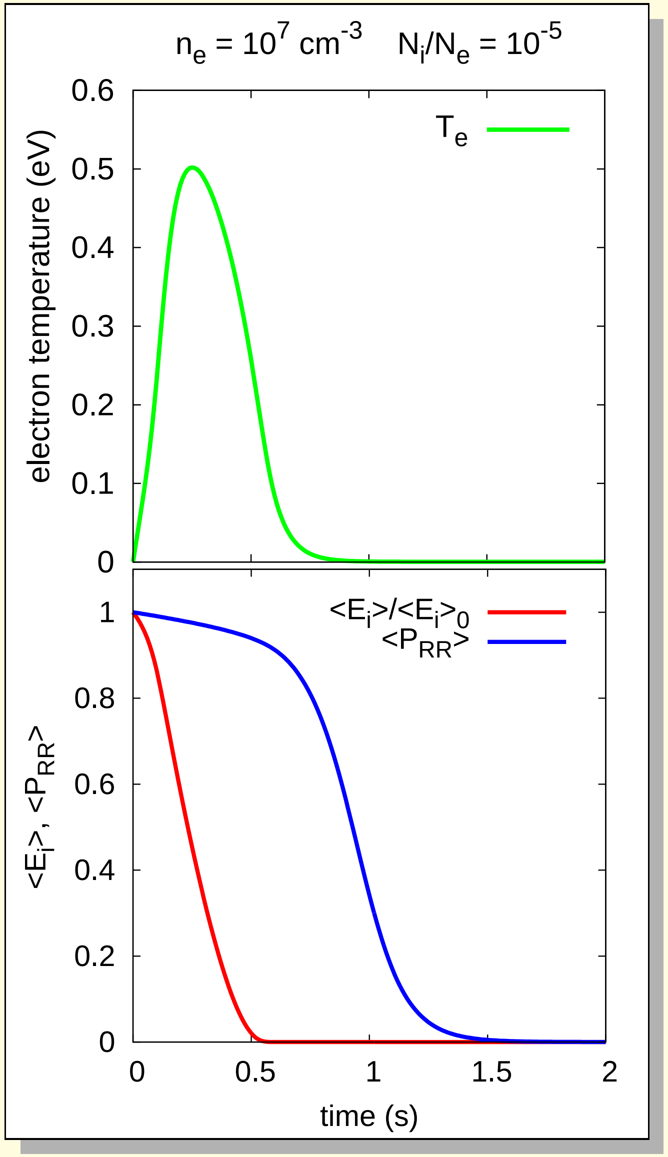
- $\mathrm{U}^{92+},\ T_e(0) = 4\ \mathrm{K},\ B = 6\mathrm{T},\ n_e = 10^7\mathrm{cm}^{-3},\ N_i/N_e = 10^{-4}$

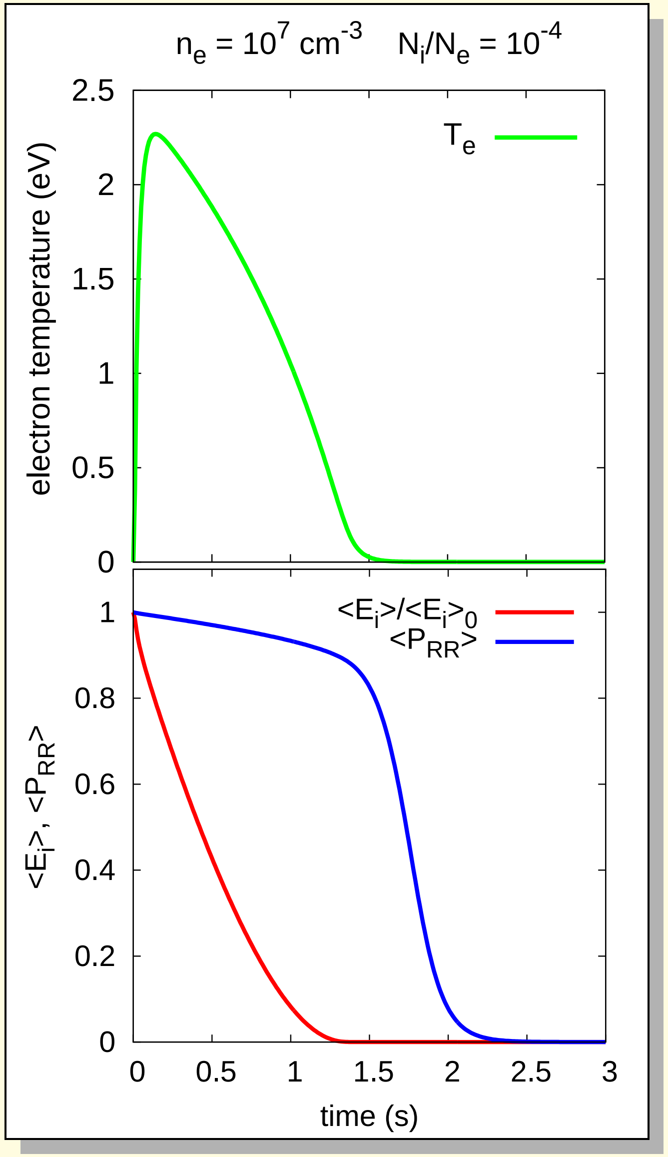


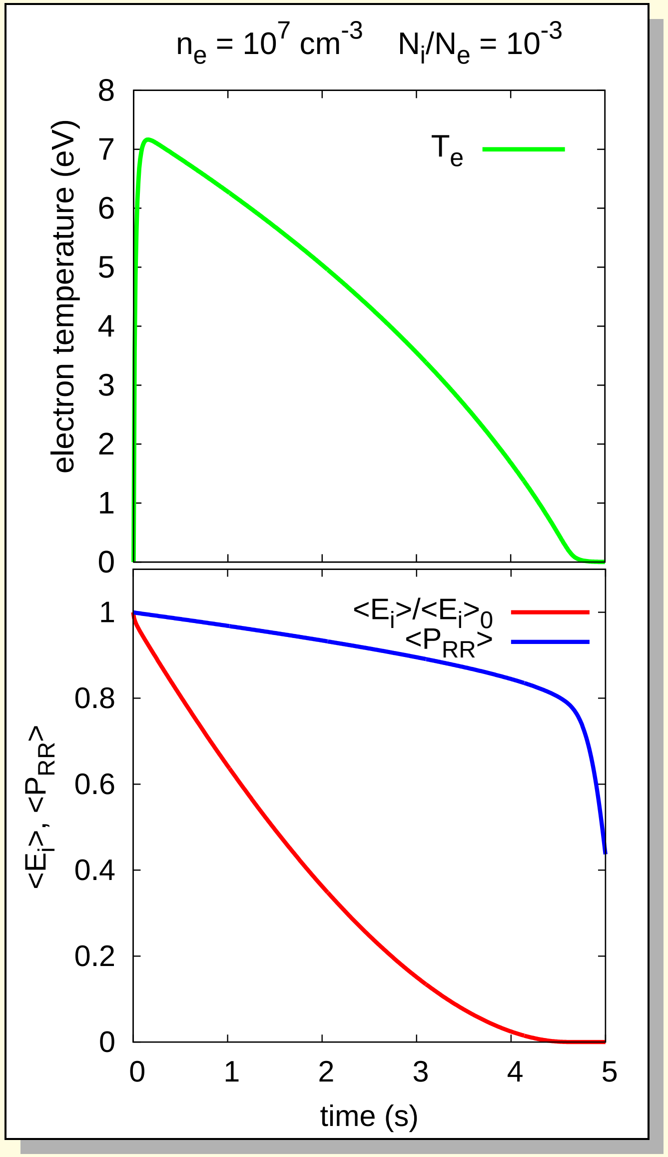


U^{92+}: electron temperature T_e, ion energy $\langle E_i \rangle$, surviving probability $\langle P_{\mathrm{RR}} \rangle$

for an increasing number of ions N_i at given electron number N_e and density $n_e = 10^7\ \mathrm{cm}^{-3}$







■ U^{92+}: electron temperature T_e, ion energy $\langle E_i \rangle$, surviving probability $\langle P_{\mathrm{RR}} \rangle$

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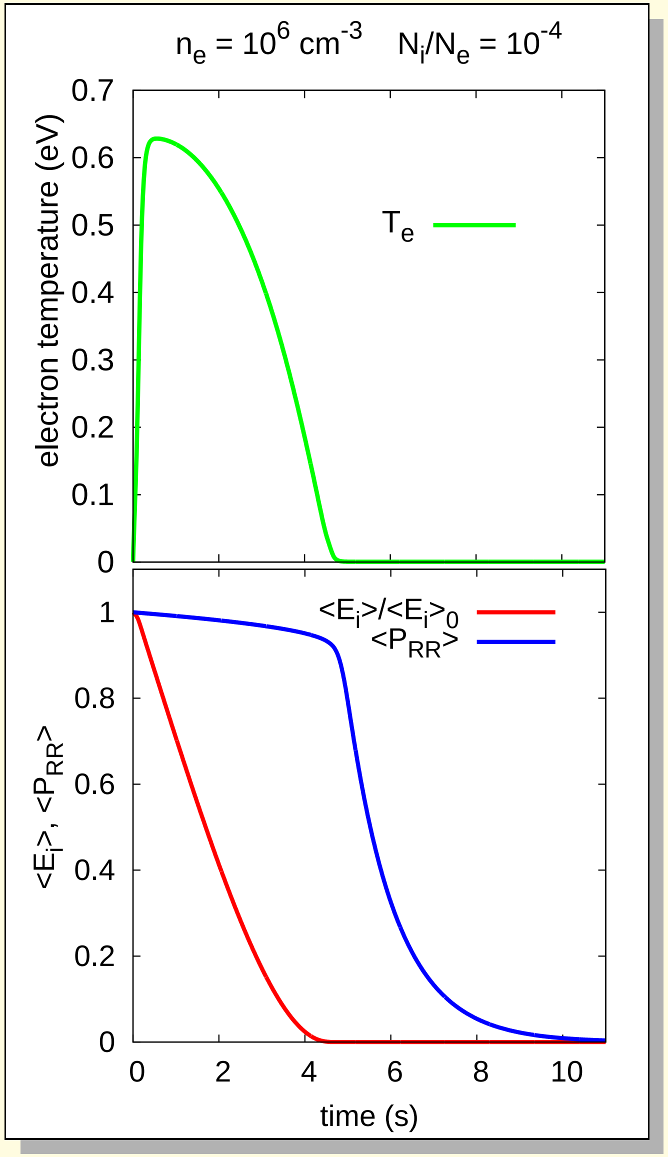
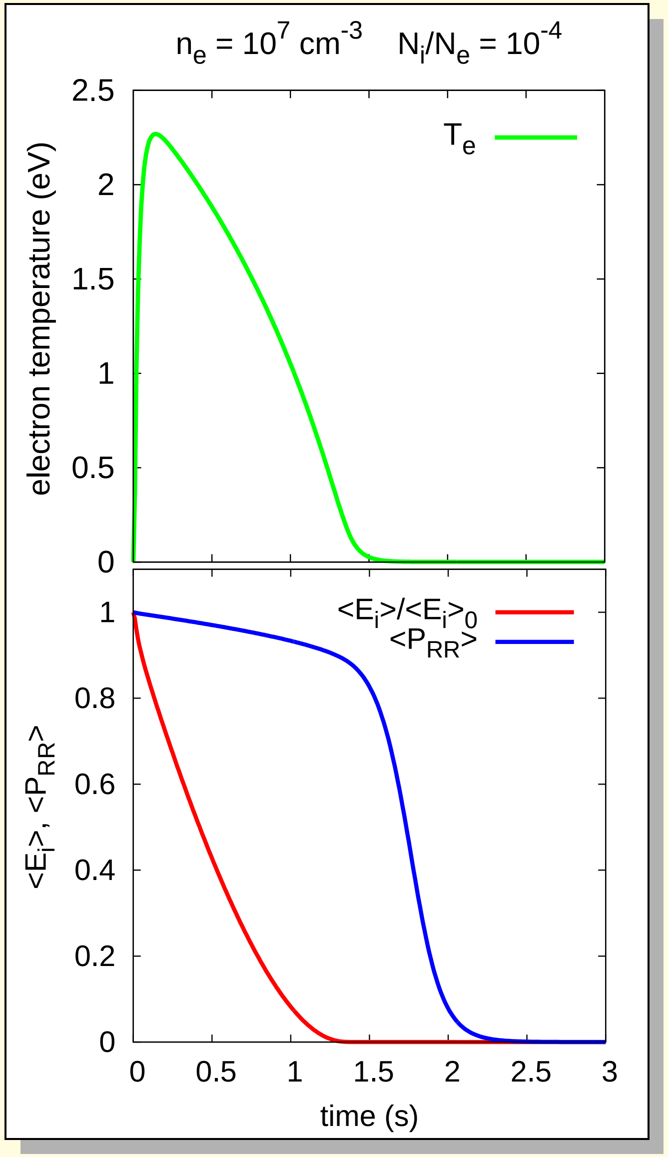
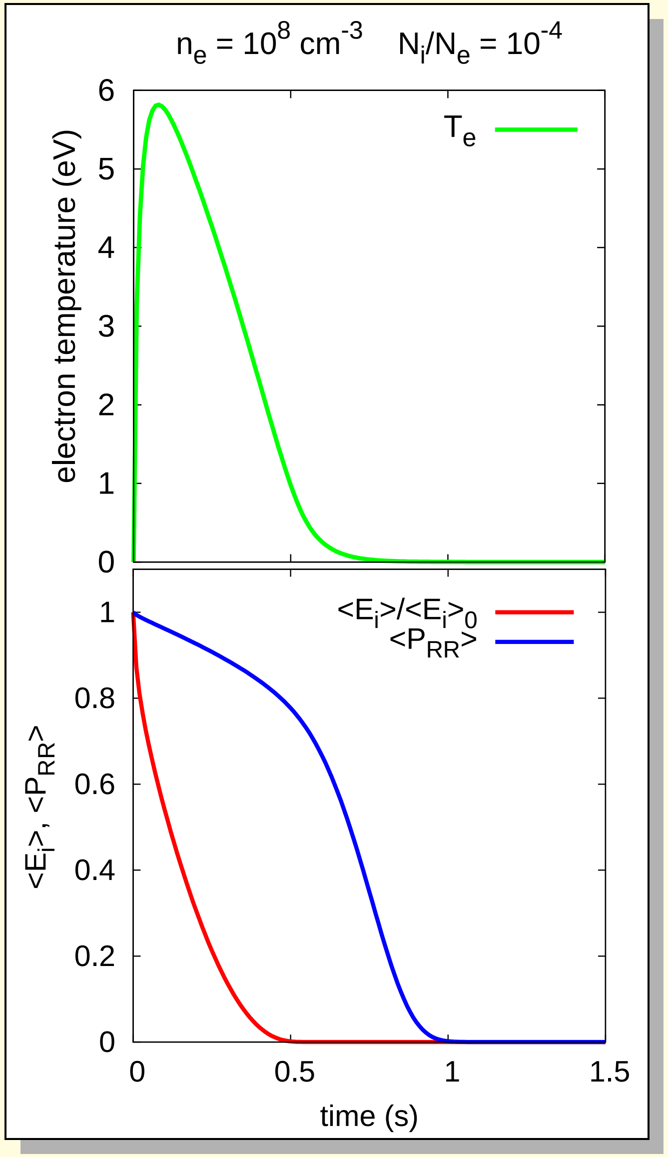
for increasing electron density n_e at fixed N_i, N_e, $N_i/N_e = 10^{-4}$







Summary and Outlook

- Cooling times and recombination losses strongly depend on N_i/N_e, n_e, and an intricate feedback between electron heating and the cooling force
  - ▶ Various options for optimization
  - ▶ Cooling times < 1 s and RR-losses $< 10\%$ seem feasible for U^{92+}

- Work in progress, open questions
  - Further improvement of the underlying cooling forces
  - Time evolution of the ions bunch including the local electron density $n_e(\vec{r})$ and the electric potential $\Phi(\vec{r})$ (external and space charge) in the trap

$$\frac{d\vec{r}_\mu}{dt} = \vec{V}_\mu \, , \; M\frac{d\vec{V}_\mu}{dt} = \vec{F}[n_e(\vec{r}_\mu), T_{e,\perp}, T_{e,\parallel}, B, \vec{V}_\mu(t)] + Ze\left(-\vec{\nabla}\Phi(\vec{r}_\mu) \; + \; \vec{V}_\mu \times \vec{B}\right)$$

  - 3-body-recombination?, B-field influence on recombination?, Anisotropic energy transfer and electron heating ↔ $T_{e,\perp}, T_{e,\parallel}$?