Electron Cooling of bare Uranium in HITRAP*

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Electron cooling in HITRAP [1] is an essential tool for providing cold ions required for planned experiments. We study the evolution of the energy distribution of the trapped ions within the following model (see also e.g. [2] and references therein) which takes into account: (i) the deceleration of the N_i ions ($\mu = 1, \ldots, N_i$) by collisions with magnetized electrons

$$M\frac{d\vec{V}_\mu}{dt} = \vec{F}_\mu = \vec{F}[n_e, T_e, B, \vec{V}_\mu(t)]\,, \qquad (1)$$

(ii) the transfer of the ionic energy ($E_{i,\mu} = MV_\mu^2/2$) to the electrons, which are trapped together with the ions

$$N_i\langle\frac{dE_i}{dt}\rangle(t) = \sum_{\mu}^{N_i} \vec{V}_\mu\cdot\vec{F}_\mu = -\frac{dE_e}{dt} \overset{!}{=} -\frac{3}{2}N_e k_B \frac{dT_e}{dt}\,. \qquad (2)$$

(iii) the heating of the N_e electrons and their cooling by synchrotron radiation (with a time constant τ)

$$\frac{dT_e}{dt}(t) = -\frac{2}{3k_B}\frac{N_i}{N_e}\langle\frac{dE_i}{dt}\rangle(t) \;-\; \frac{1}{\tau}\left(T_e(t) - T_0\right), \qquad (3)$$

where $\tau \approx 0.1$ s for $B = 6$ T, and $T_0 = 4$ K is the ambient temperature supplied by the cryostat. These coupled differential equations for the velocities $\vec{V}_\mu(t)$ and the electron temperature $T_e(t)$ are solved numerically. Simultaneously we calculate for each ion the radiative ion-electron recombination rate

$$\nu_{\mathrm{RR},\mu}(t) = n_e\!\int\! d^3v_e\; v_{r,\mu}\;\sigma_{\mathrm{RR}}(v_{r,\mu})\, f\left(v_e, T_e(t)\right) \qquad (4)$$

(with $\sigma_{\mathrm{RR}}(v_r)$ from [3], $v_{r,\mu}(t) = |\vec{V}_\mu(t) - \vec{v}_e|$, and $f(v_e)$ is a Maxwellian distribution), and the surviving probability $P_{\mathrm{RR},\mu}(t) = \exp\left(-\int_0^t dt'\nu_{\mathrm{RR},\mu}(t')\right)$. A similar treatment has already been applied, e.g. in [2]. There the energy loss dE_i/dt was, however, modeled by a rate equation for the ionic temperature, instead of the detailed description based on the cooling force $\vec{F}_\mu$ for individual ions as given by Eqs.(1) and (2).

Using this model we considered the case of bare Uranium, for an initial ($t = 0$) ion distribution of 500 ions which represents the ensemble of about 10^5 ions in the trap and which was obtained from a simulation of the injection into HITRAP [4]. For the cooling force $\vec{F}$ in Eq. (1) we employed here a linear response expression for strong magnetic fields, see [5]. Since the ions are only cooled when traveling through the electrons, the cooling force $\vec{F}$ was multiplied by a factor 0.4 (extension of the electron cloud/effective trap length). Fig. 1 shows the time evolution of $\langle E_i\rangle, T_e$ and $\langle P_{\mathrm{RR}}\rangle$ together with some snapshots of the energy distribution dN/dE_i for typical HITRAP conditions. The decrease of the average ion energy $\langle E_i\rangle$ indicates a cooling time of about one second. A strong heating of the electrons from initially $T_0 \approx 0.34$ meV to about $T_e = 2.2$ eV takes place. The recombination becomes only effective at late times with small E_i and T_e. In(de)creasing the electron density by a factor 10 results in roughly 0.5(4) seconds cooling time and a maximal T_e of about 6(0.6) eV, whereas the overall qualitative picture remains unchanged. Roughly the same values are observed for in(de)creasing N_e by a factor 10 (at fixed $n_e = 10^7$ cm^{-3}). Altogether this analysis clearly indicates that cooling times around a second at recombination losses of about 10% are feasible for electron cooling of bare Uranium in HITRAP.

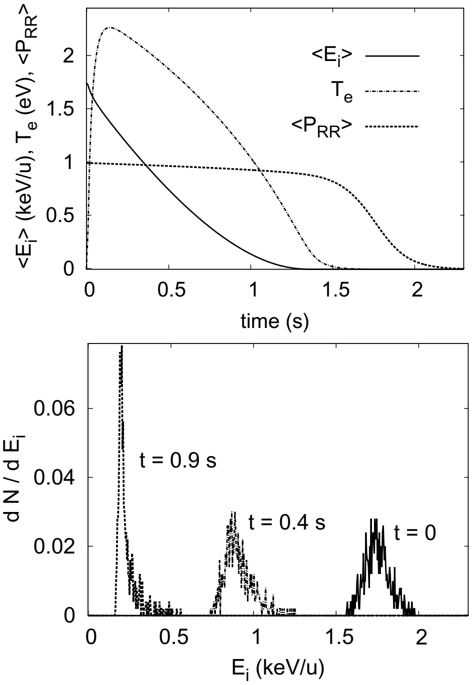

Figure 1: Top: Temporal evolution of $\langle E_i\rangle, T_e$ and $\langle P_{\mathrm{RR}}\rangle$ for U^{92+} ions at $B = 6$T, $n_e = 10^7$ cm^{-3}, $N_e = 10^4 N_i$. Bottom: some corresponding E_i-distributions.

References

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