Cooling of Highly Charged Ions
at
TITAN

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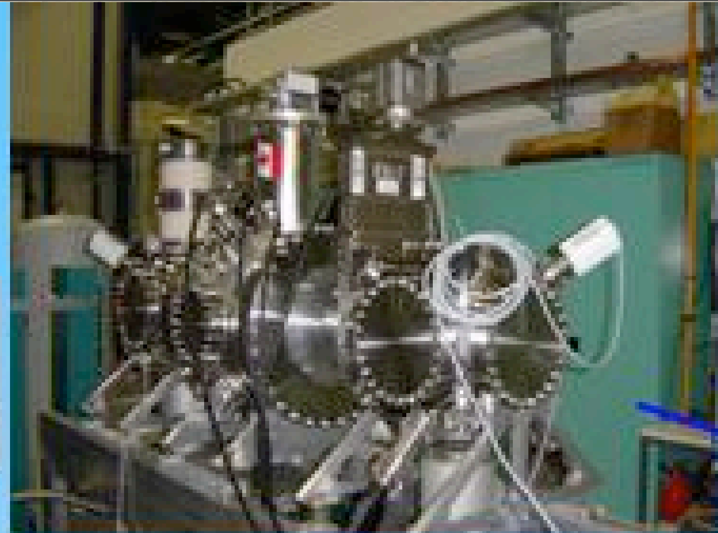
in collaboration with Zunjian Ke, Wei Shi, Steven Toews (UoM)
and Jens Dilling, Vladimir Ryjkov (TRIUMF)

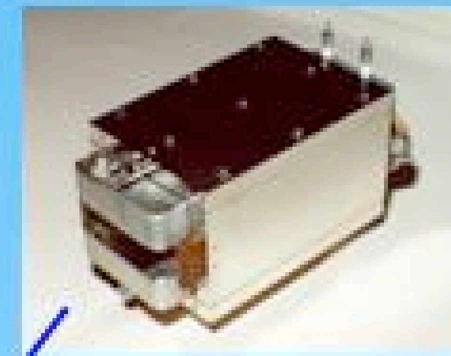
20 Years of EBIT, Berkeley, November 2006

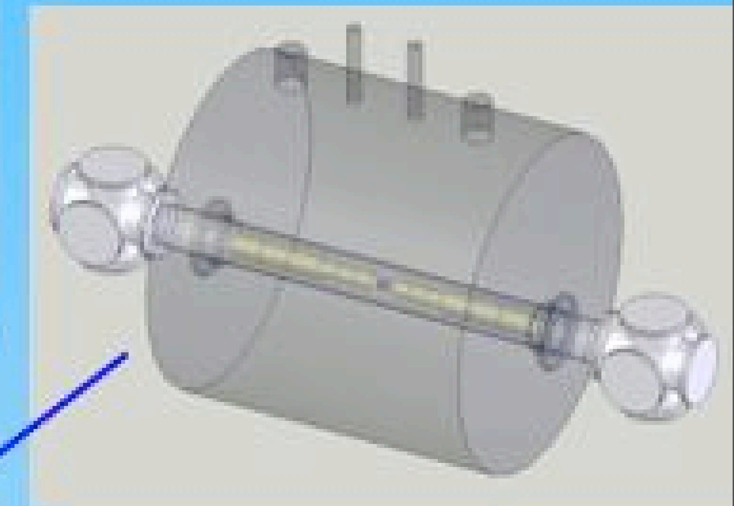


EBIT under testing at MPI-HD.
to TRIUMF July 2005.

McGill

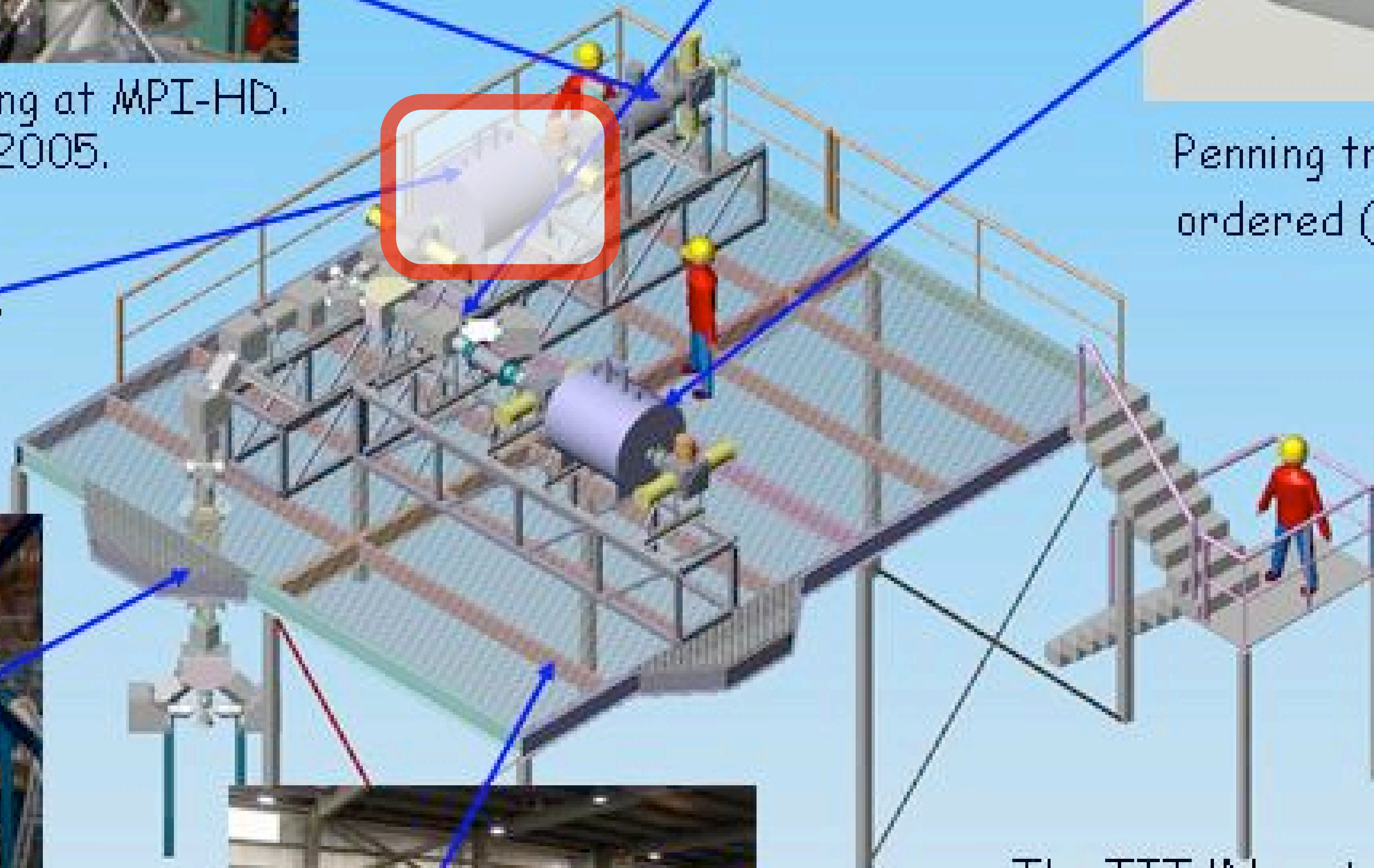
Wien filter
(R=500)



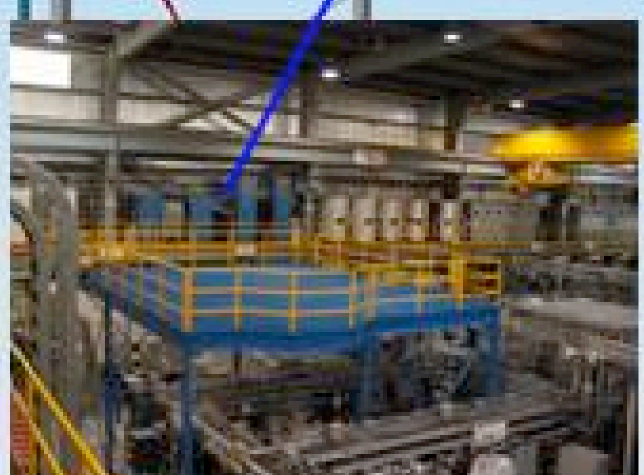


Penning trap magnet
ordered (del. July 2005)

Cooler trap for HCI
(to be built in Manitoba,
CFI grant received)



RFQ operational on test bench



TITAN platform finished at ISAC

The TITAN system is under construction and will be operational for mass measurements at ISAC/TRIUMF in 2006.
Isotopes with $T_{1/2} \approx 10$ ms
$\delta m/m < 1\cdot 10^{-8}$

Why do we need to cool HCI between the EBIT and the precision Penning trap ?

- ion temperature for mass measurement:

$$T_i \lesssim 1 \text{ eV/q}$$

- EBIT: $T_i \gg 1$ eV/q must be expected

What do we know about ion temperatures in EBITs ?

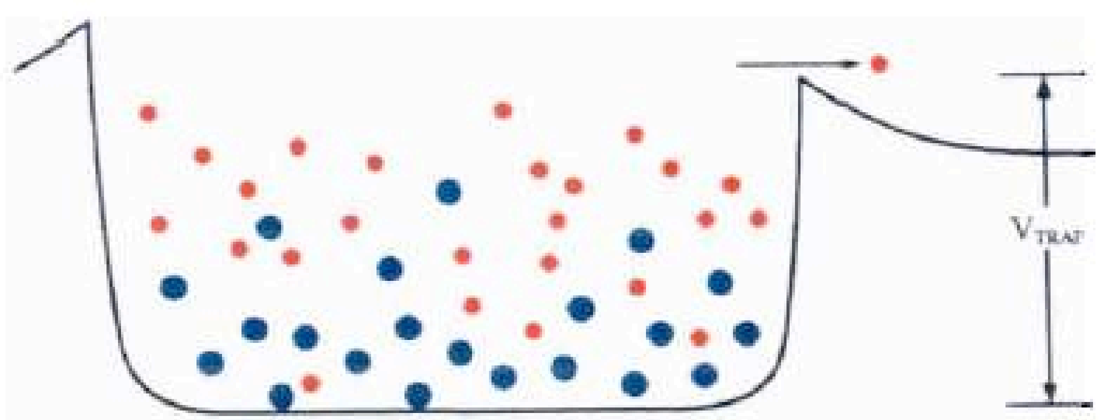
- REXEBIS: few 10 eV/q
- Oshima et al.: EBIS/ECRIS ”generally” $>$ 10 eV/q
- Dresden EBIT: $T_i = 3 - 6$ eV/q measured for Ar^{16+} but low j_e and E_e
- Livermore, evaporative cooling inside EBIT:
  $10 - 20$ eV/q for Dy^{66+} (no data ?)
  Penetrante et al.
- Livermore, evaporative cooling & self-cooling during extraction: $T_i \approx 0.1 qeV_{\text{trap}} \Rightarrow \approx 10 - 50$ eV/q
  Marrs, TITAN workshop 2002 (no data)

R. Marrs, 2002 TITAN workshop

Ion Heating and Cooling

- Ions are heated by Coulomb collisions with beam electrons
  - Heating rate per ion: $$H_i = \pi \frac{j_e}{e} \frac{q^2 e^4}{E_e} \frac{2m_e}{M_i} \lambda_{ie}$$
  - Example: $^{100}Sn^{40+}$ in an Intense EBIT, $H_i \approx 5q$ eV/ms
    (Note: beam space charge potential $\approx 450q$ eV)
- Evaporative ion cooling reduces ion temperature and emittance

evaporation rate $\propto e^{-qeV_{trap}/T_i}$
$\Rightarrow$ low-q ions are lost
$\Rightarrow$ high-q ions are trapped



- Controlled injection and evaporation of low-Z ions compensates for electron beam heating of high-q ions
- Thermal equilibrium
  $\Rightarrow T_i \approx 0.1qeV_{trap}$
- Self cooling during extraction can produce a dramatic reduction in ion temperature

- self-cooling requires slow (ms) spills — not suitable in our case

Ion temperature on extraction from EBIT

- actual data appears sparse
- no definite conclusions possible
- emittance/temperature measurements from TITAN EBIT will be necessary, and also interesting in general
- For now must assume that HCI have temperatures of 10...100 eV/q

$\Rightarrow$ additional cooling before precision trap most likely necessary

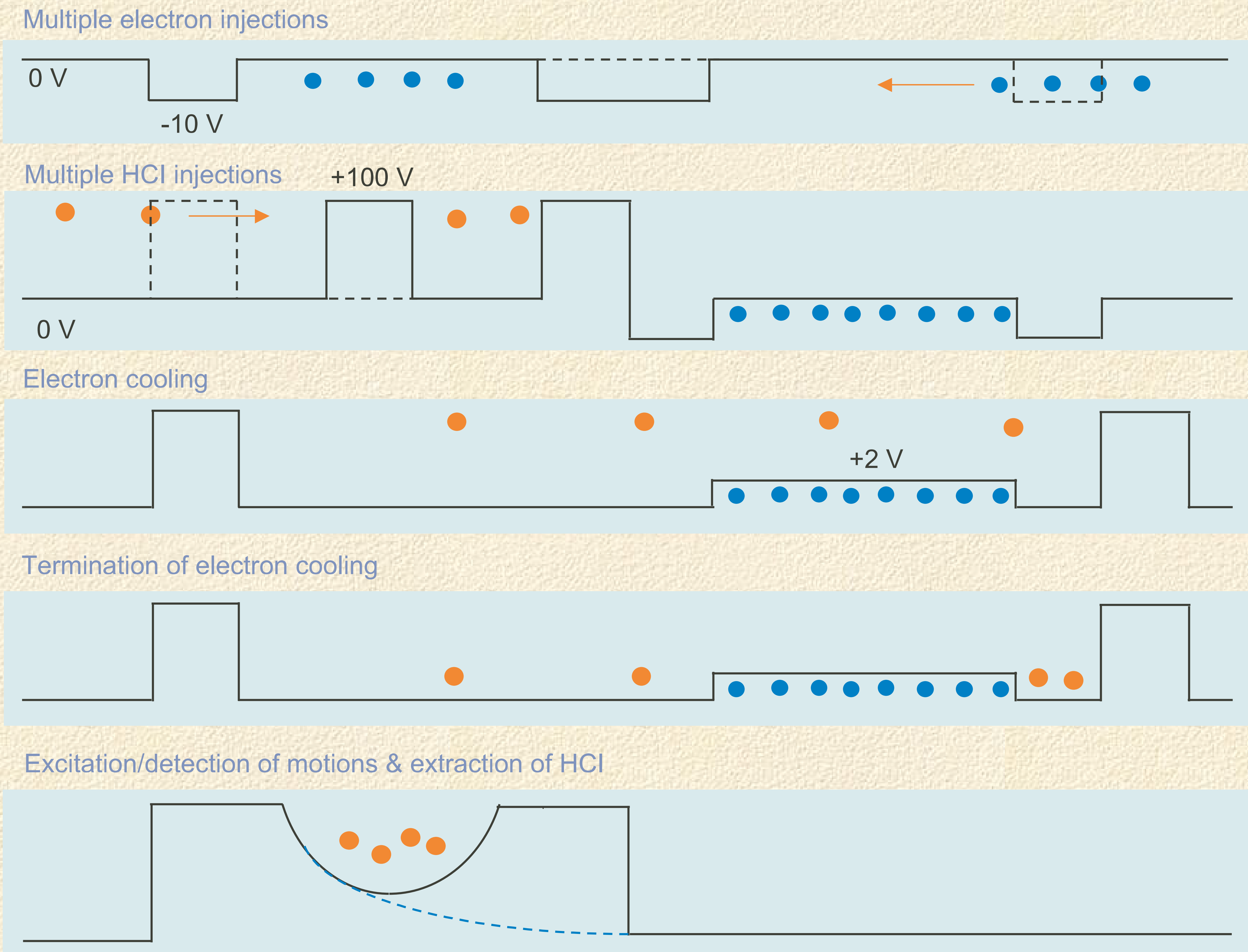
Techniques for ion cooling

- buffer gas cooling
  - well established method for SCI
    NO (charge exchange)
- resistive cooling
  - well established, fast enough — if Q high enough → would require cryogenic operation
  - ion specific tuning of resonant circuit required

- electron cooling
  - demonstrated for (anti)protons and HCI at $T_i \gtrsim$ few eV/q
  - advantage: electrons self-cool via synchrotron radiation
  - disadvantage: electron-ion recombination
- positron cooling
  - avoids recombination, but technically more involved (mCi level source)
- ion-ion cooling with light, cool ions (protons, He^{2+})
  - no recombination issues
  - but no synchrotron cooling, need initially cold light ions

laser cooling?

Electron Cooling Scheme



Simulations of Electron Cooling

- Ignore magnetic field
- simple two-component plasma model
    - Spitzer (1956), Rolston & Gabrielse (1989), Bernard *et al.* (2004)

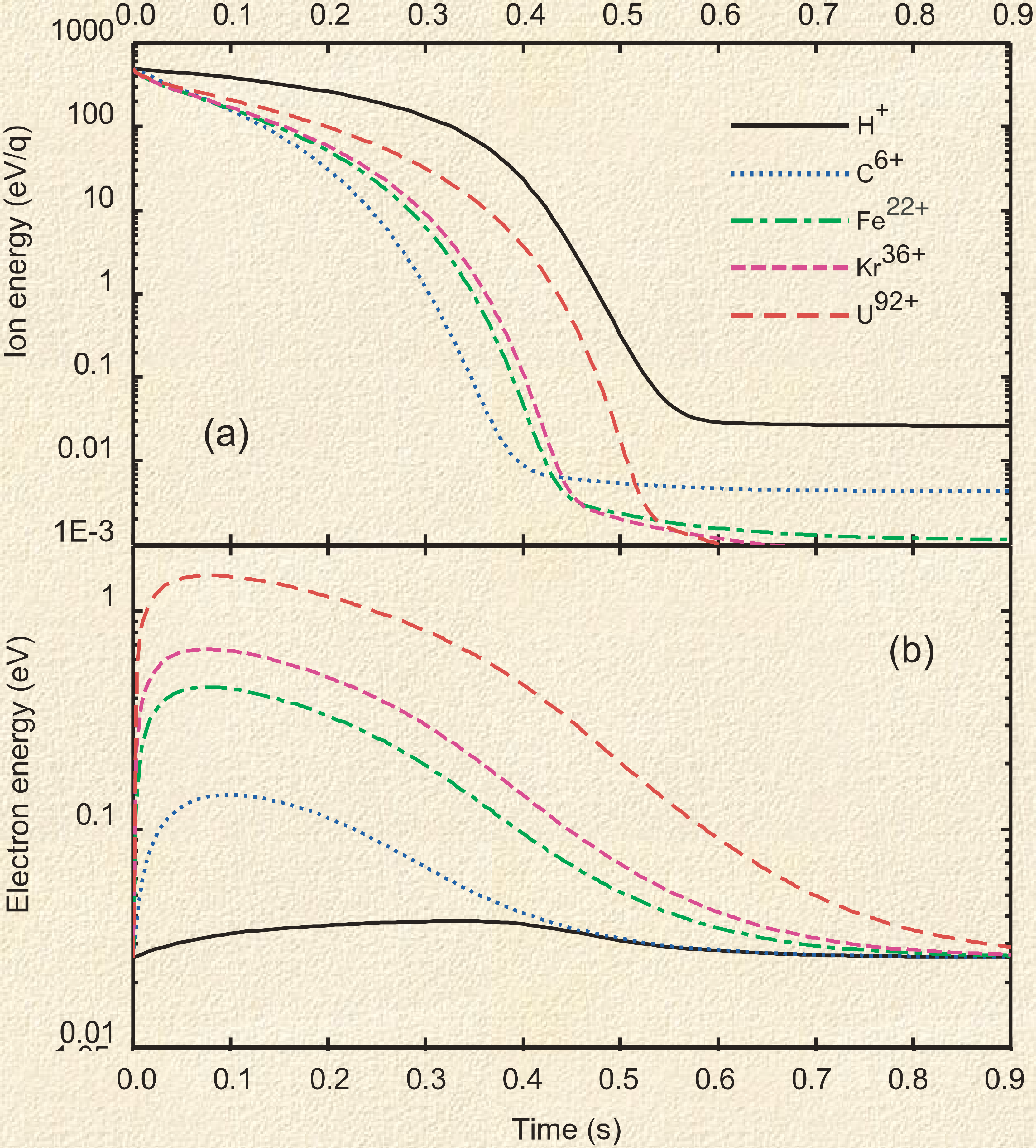
$$\frac{dT_e}{dt} = \frac{1}{\tau_i}\frac{N_i}{N_e}(T_i - T_e) - \frac{1}{\tau_e}(T_e - T_{res}),$$

$$\frac{dT_i}{dt} = -\frac{1}{\tau_i}(T_i - T_e),$$

$$\tau_i = \frac{3(4\pi\epsilon_0)^2 m_e m_i c^3}{8\sqrt{2\pi} n_e q^2 e^4 ln(\Lambda)}\left(\frac{kT_i}{m_i c^2} + \frac{kT_e}{m_e c^2}\right)^{\frac{3}{2}}$$

$$ln(\Lambda) = \ln\left(4\pi\left(\frac{\epsilon_0 k}{e^2}\right)^{\frac{3}{2}}\frac{1}{q}\sqrt{\frac{T_e}{n_e}}(T_e + \frac{m_e}{m_i}T_i + 2\sqrt{\frac{m_e}{m_i}}\sqrt{T_e T_i}\right)$$

Electron cooling I: Cooling

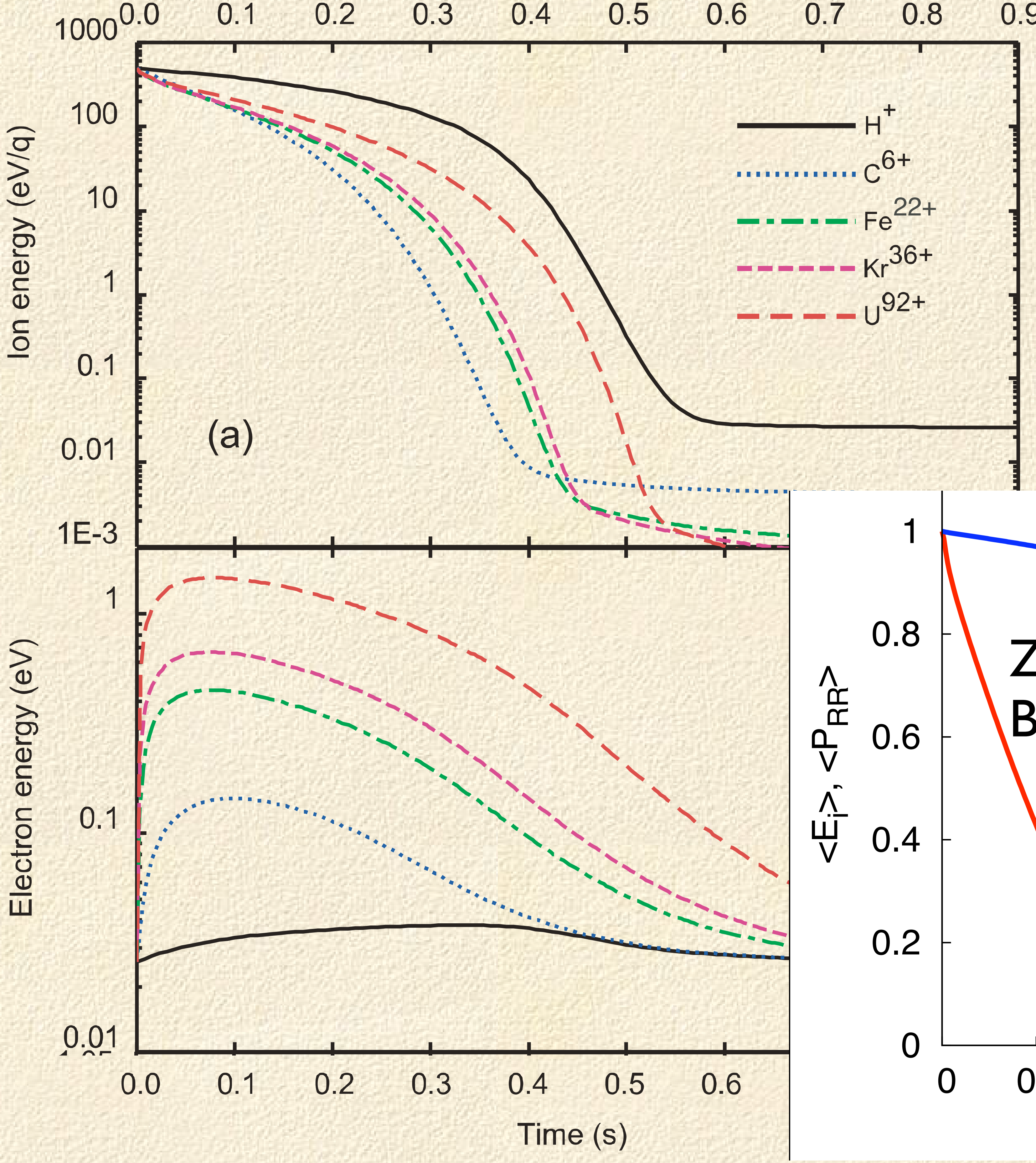


$n_e = 10^7 \text{ cm}^{-3}$

$N_i / N_e = 10^{-4}$

$T_{\text{res}} = 300K$

Electron cooling I: Cooling



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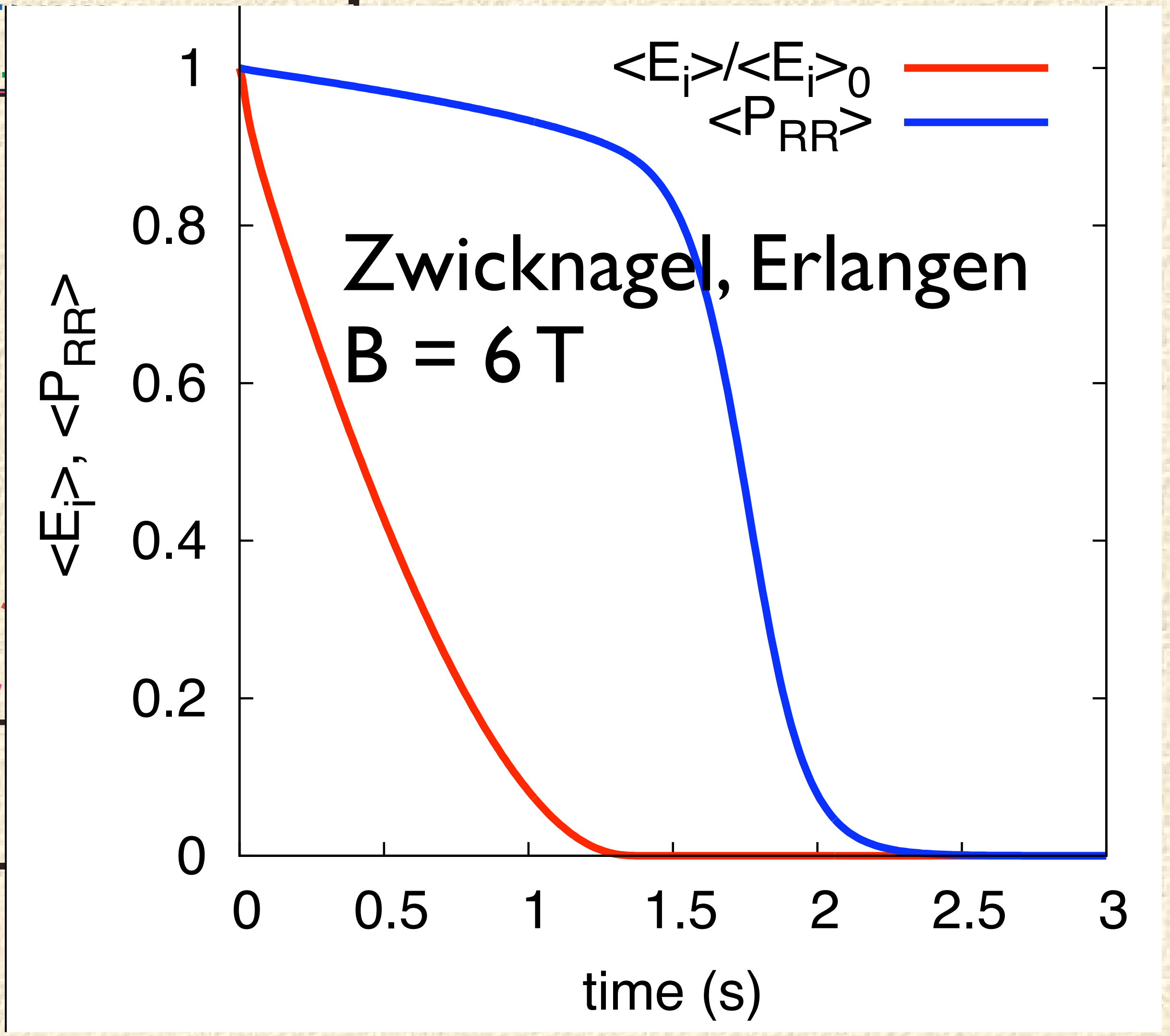


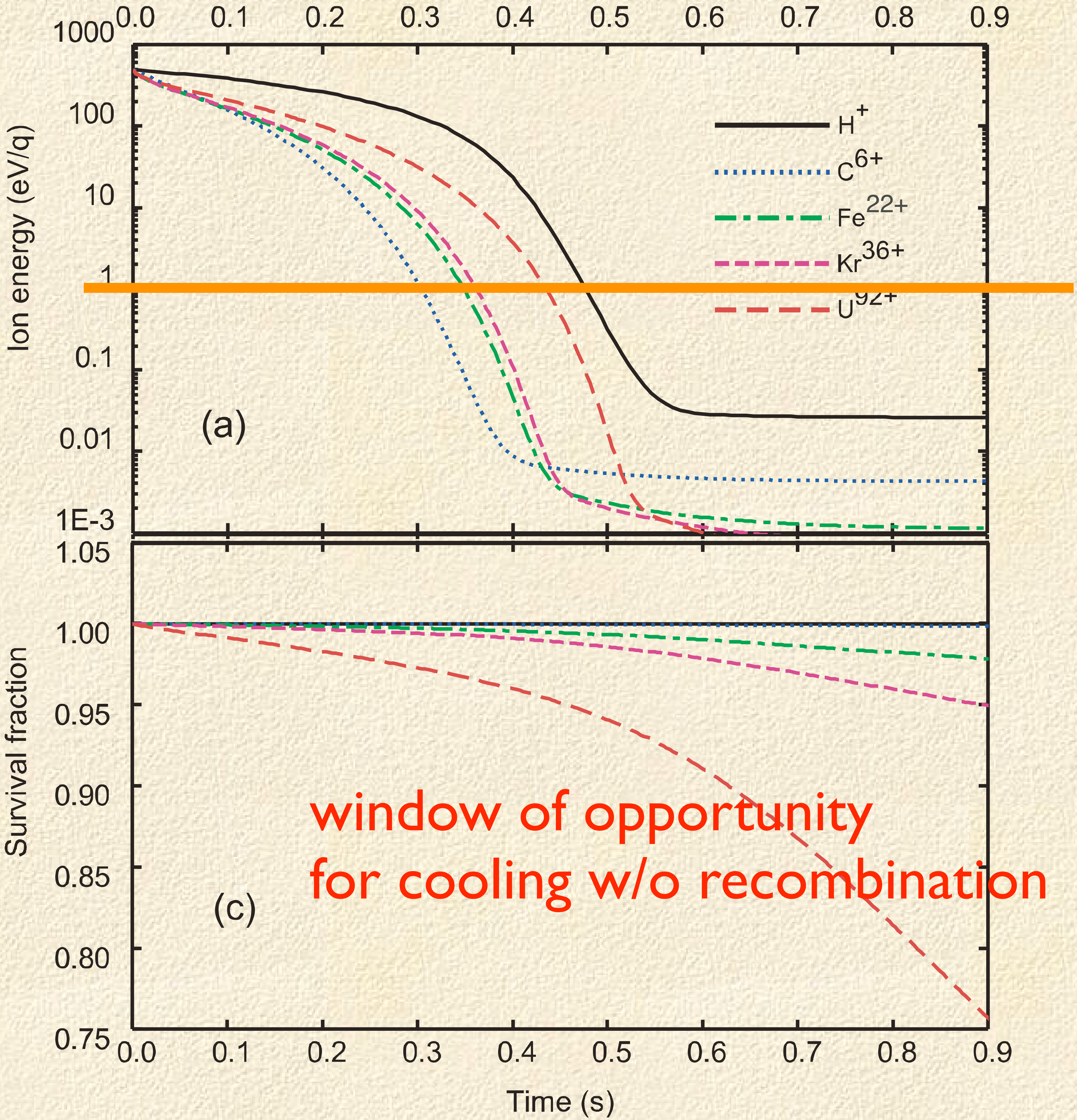
Electron cooling II: Recombination

$$\frac{dP}{dt} = (\alpha_{\rm RR} + \alpha_{\rm DR} + \alpha_{\rm TBR}) n_e$$

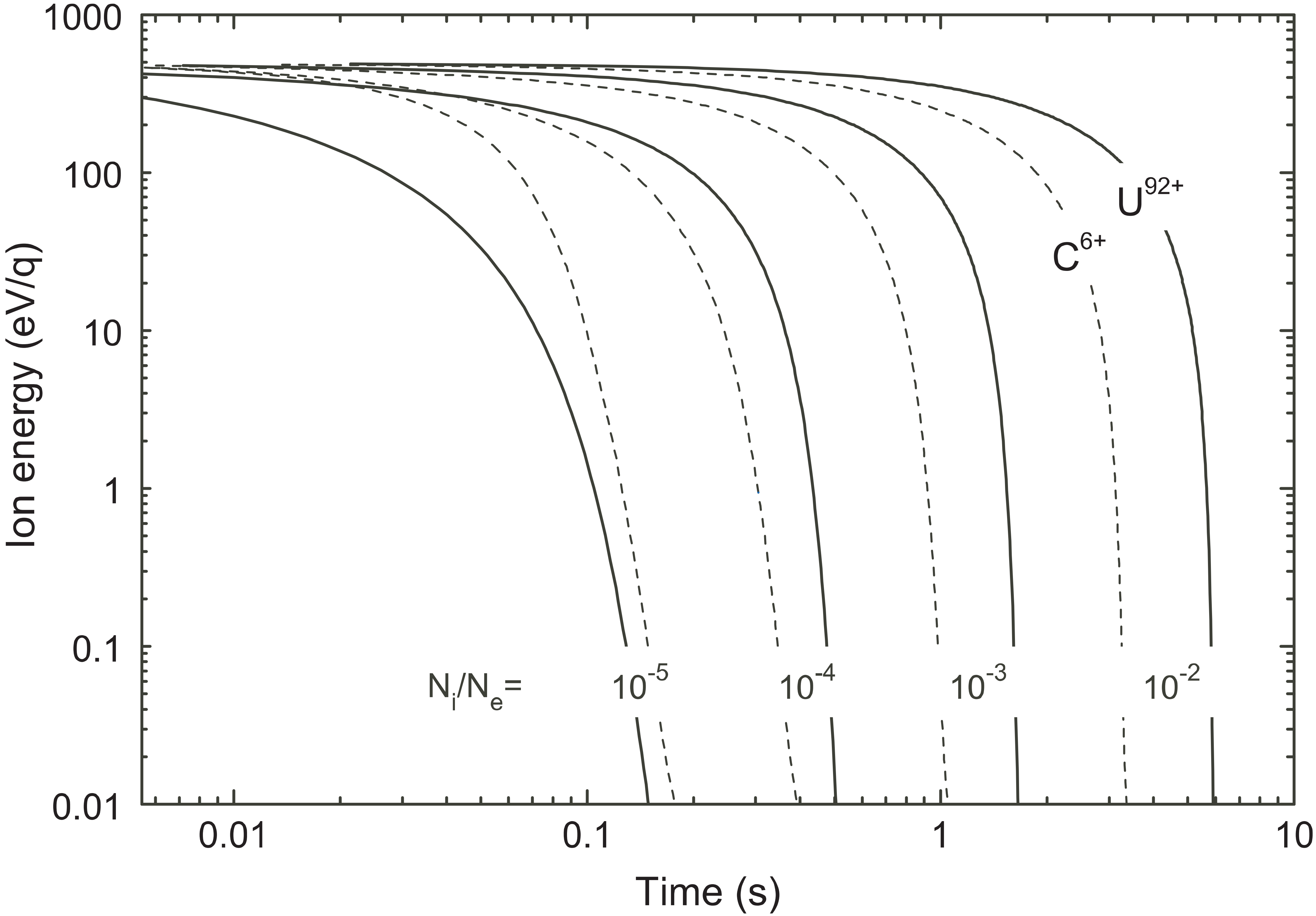
$$\alpha_{\rm RR} = 5.2 \times 10^{-14} Z_{\rm eff} \sqrt{\frac{E_\infty}{T_{\rm eff}}} \left(0.43 + \frac{1}{2} \ln\left(E_\infty / T_{\rm eff}\right) + 0.469 (E_\infty / T_{\rm eff})^{-1/3}\right) \text{ cm}^3 \text{ s}^{-1}$$

$$\alpha_{\rm TBR} = [2.0 \times 10^{-27} \text{ cm}^6 \text{ s}^{-1}]\, q^3\, T_{\rm eff}^{-4.5} n_e$$

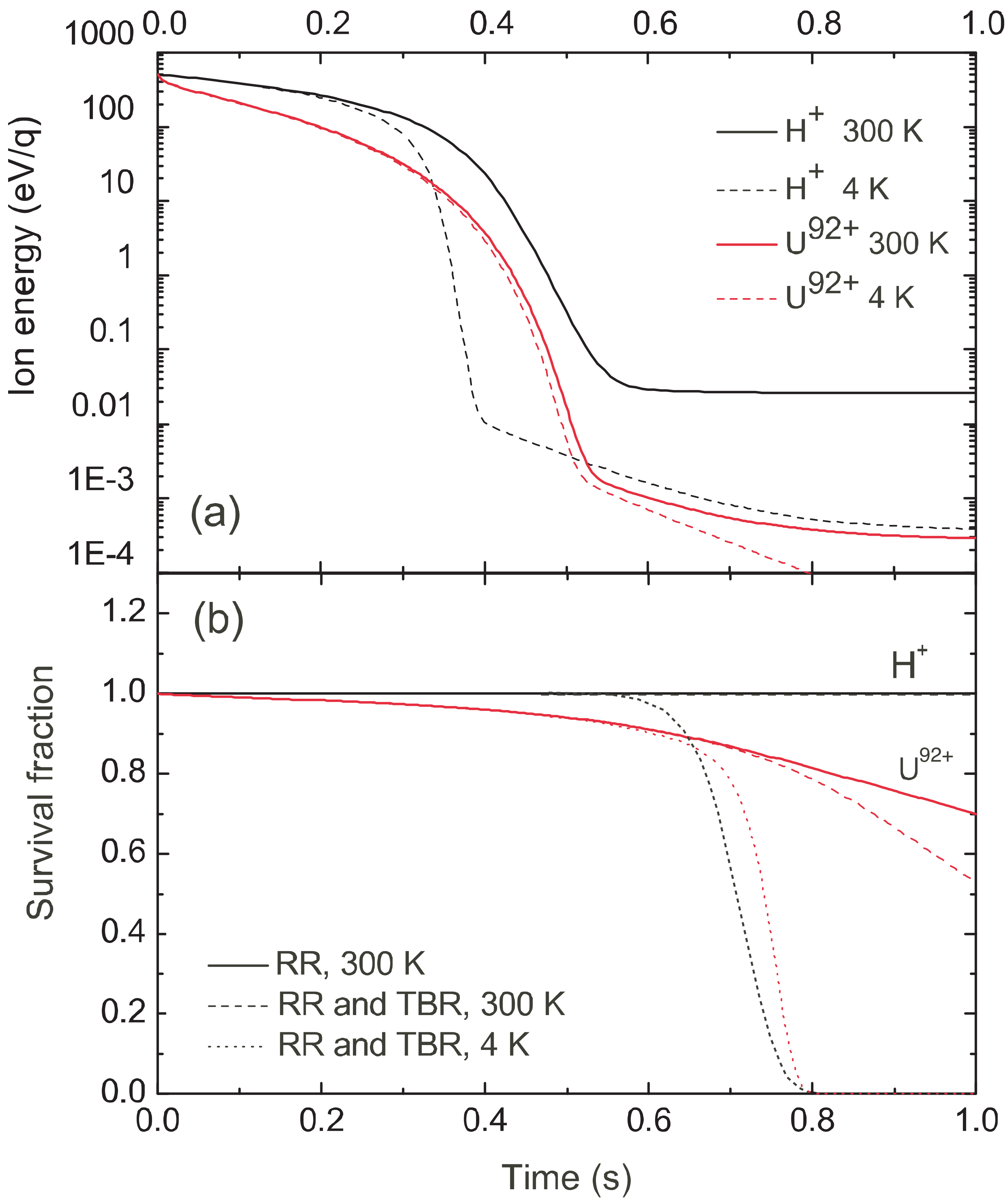
Electron cooling II: Recombination



Cooling speed as a function of N_i/N_e

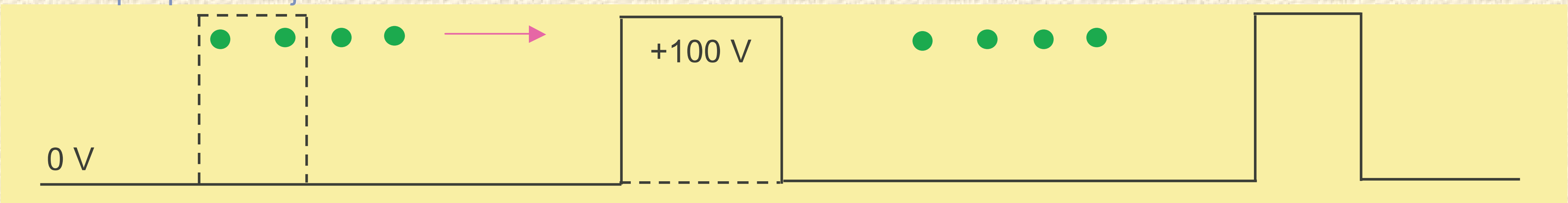


Influence of three-body recombination

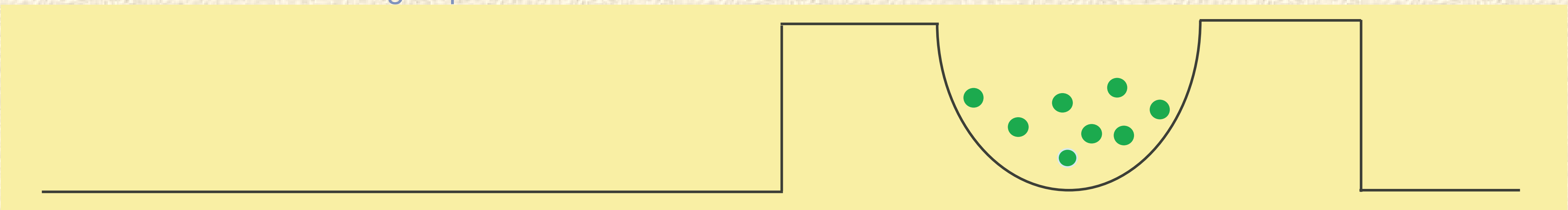


Proton Cooling Scheme

Multiple proton injections

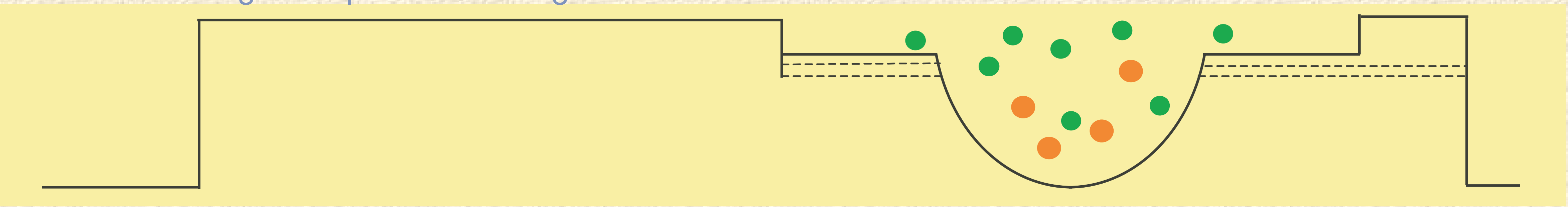


Possible resistive cooling of protons

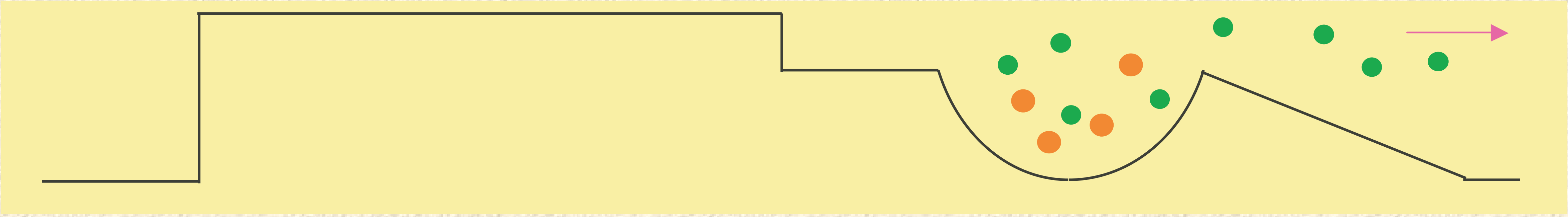


Multiple HCI injections

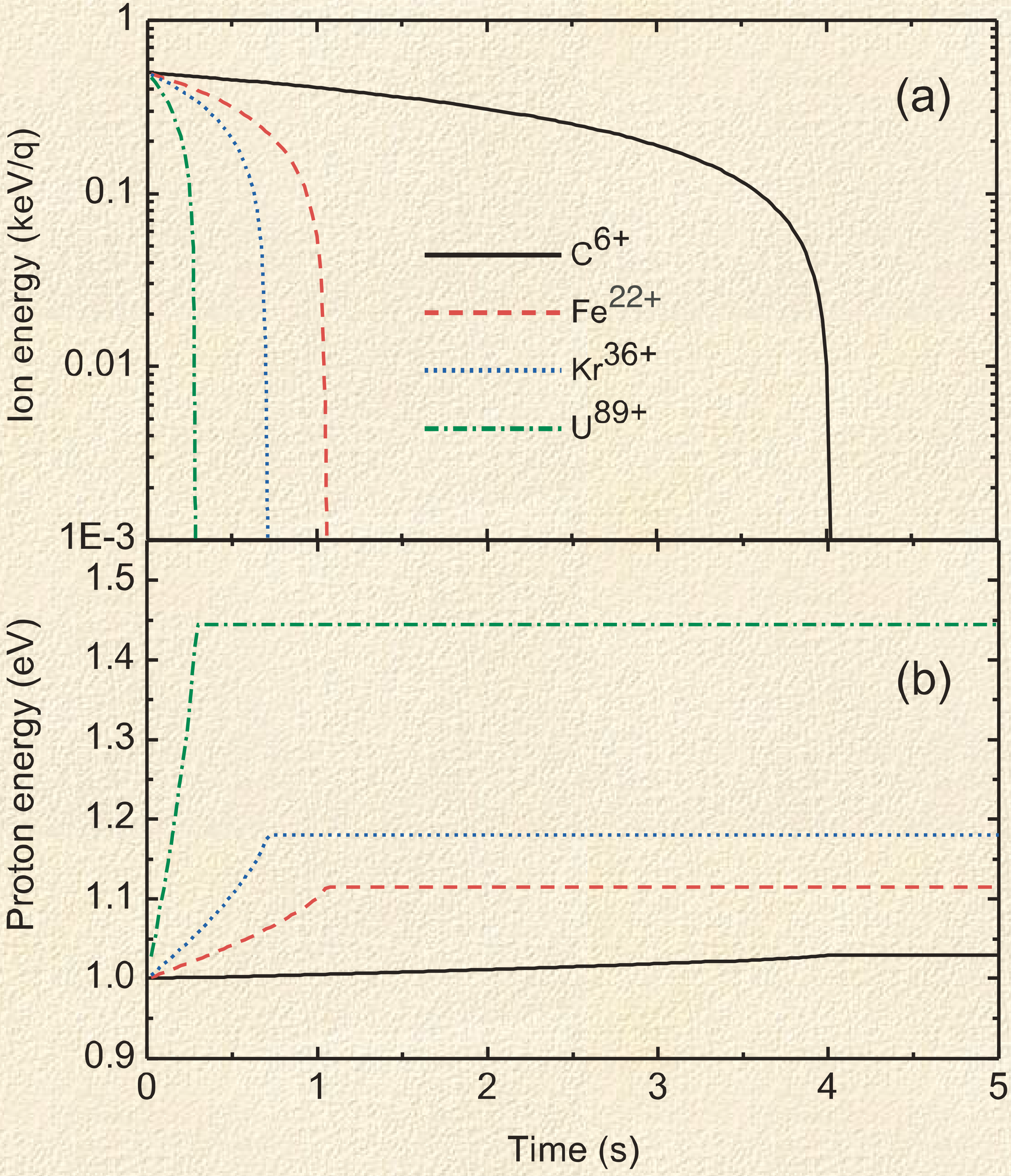
Proton cooling & evaporative cooling



Resonant/non-resonant proton expelling

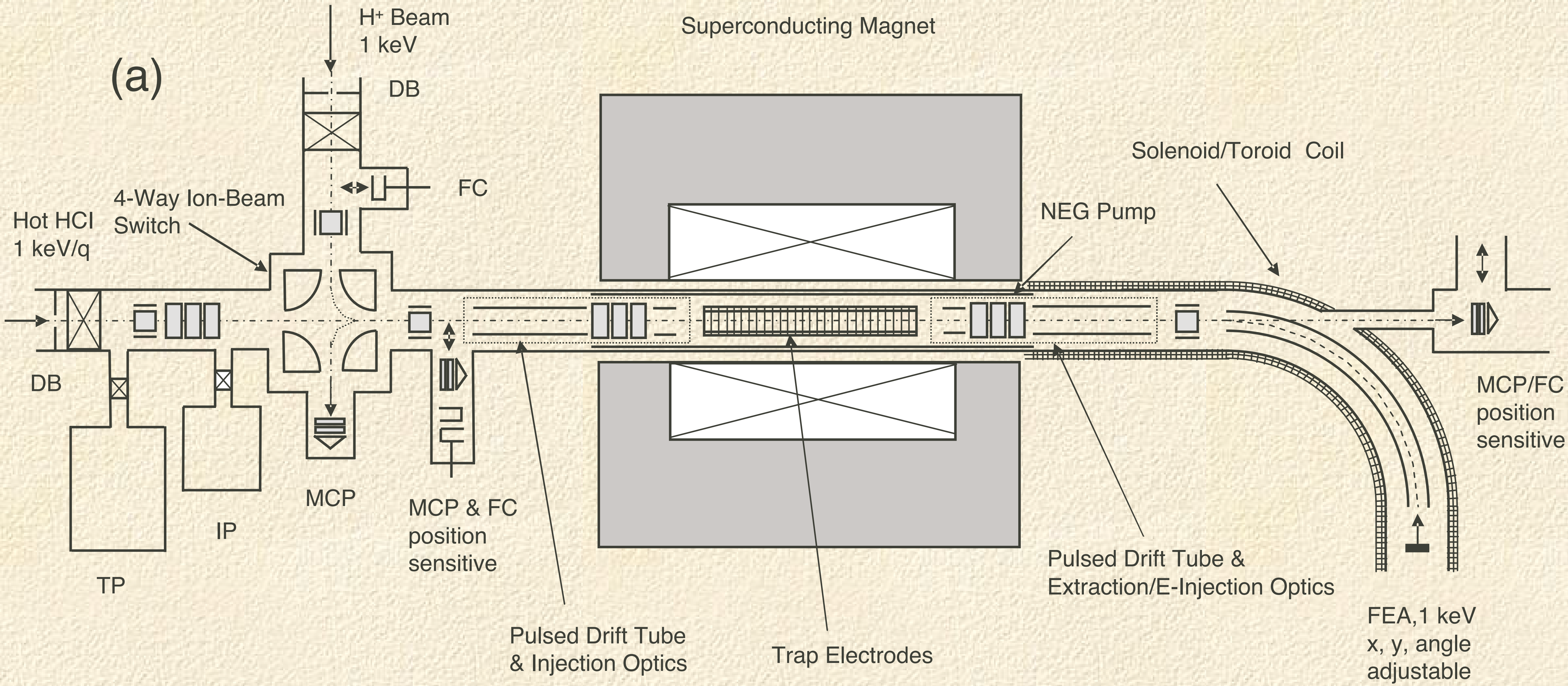


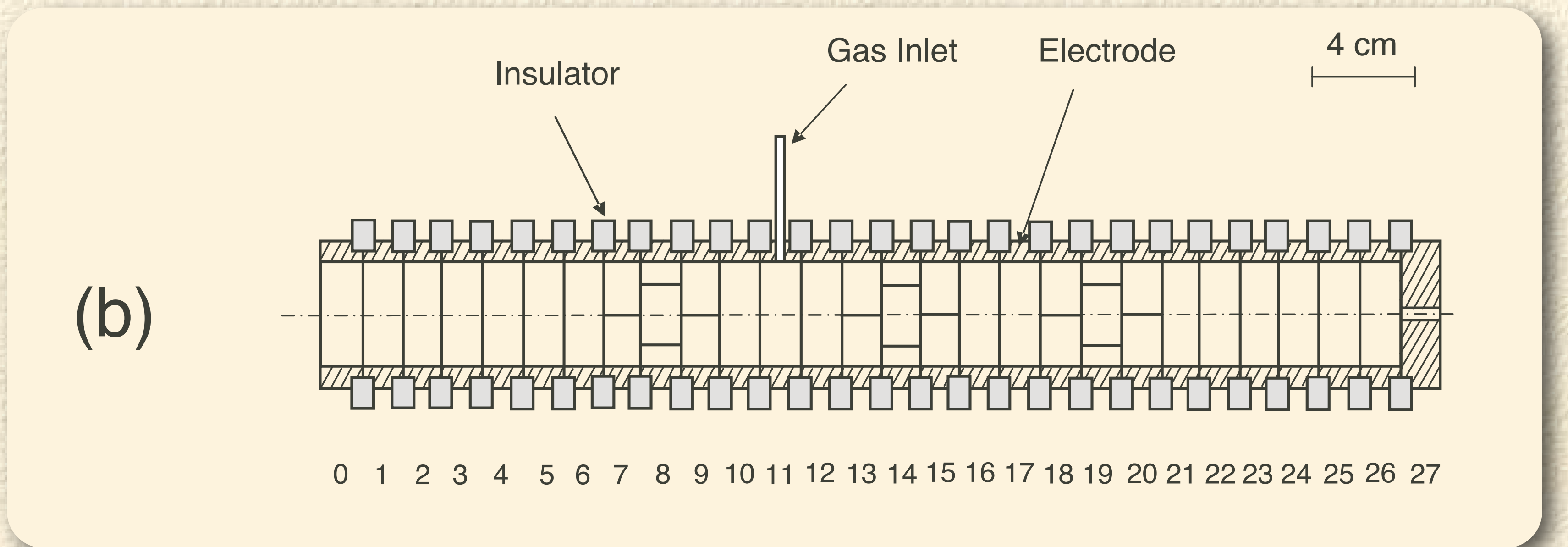
Proton cooling



$$n_p = 10^8 \text{ cm}^{-3}$$
$$N_i / N_p = 10^{-5}$$

Design currently under way





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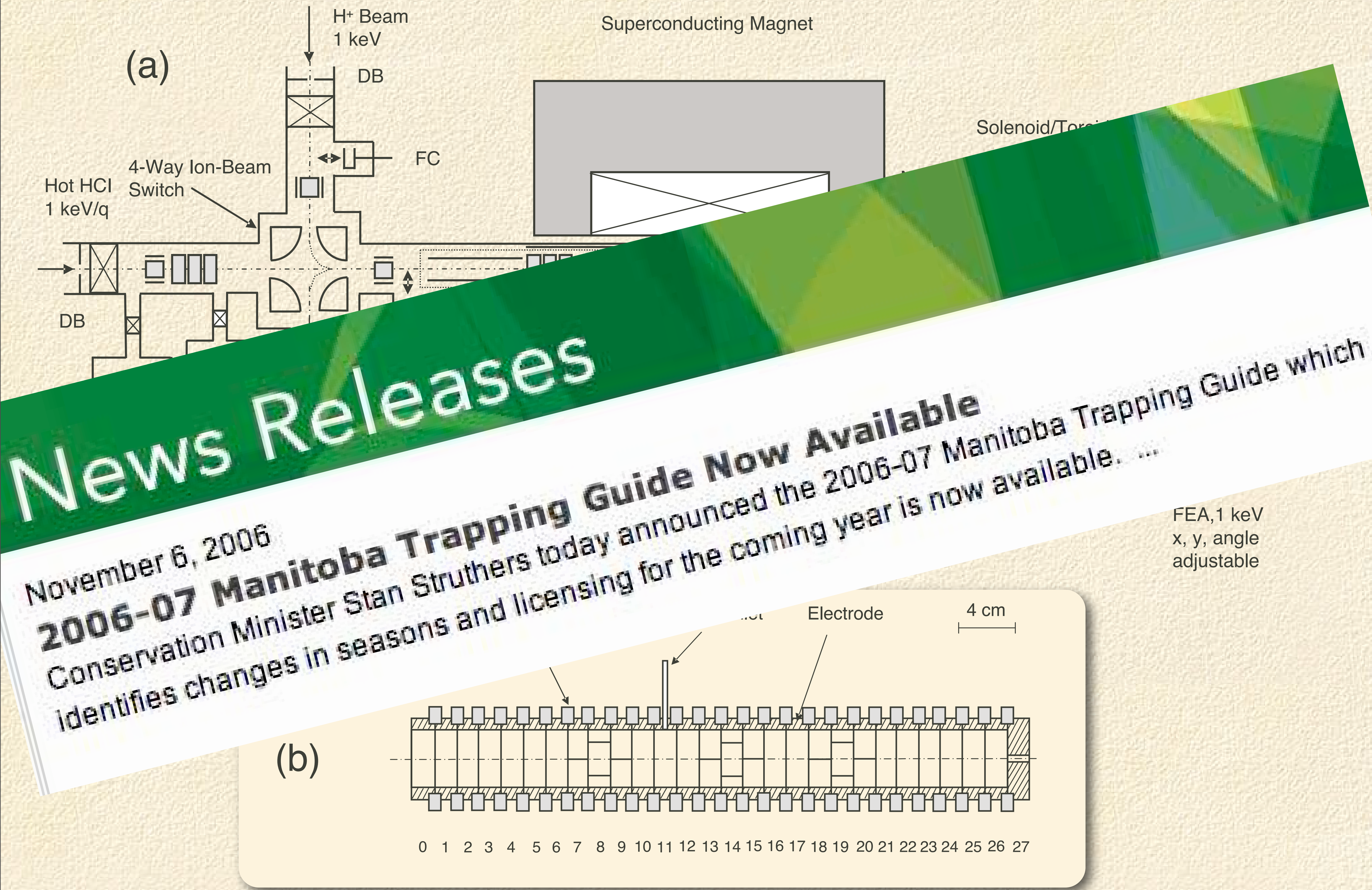

News Releases

November 6, 2006

2006-07 Manitoba Trapping Guide Now Available

Conservation Minister Stan Struthers today announced the 2006-07 Manitoba Trapping Guide which identifies changes in seasons and licensing for the coming year is now available. ...