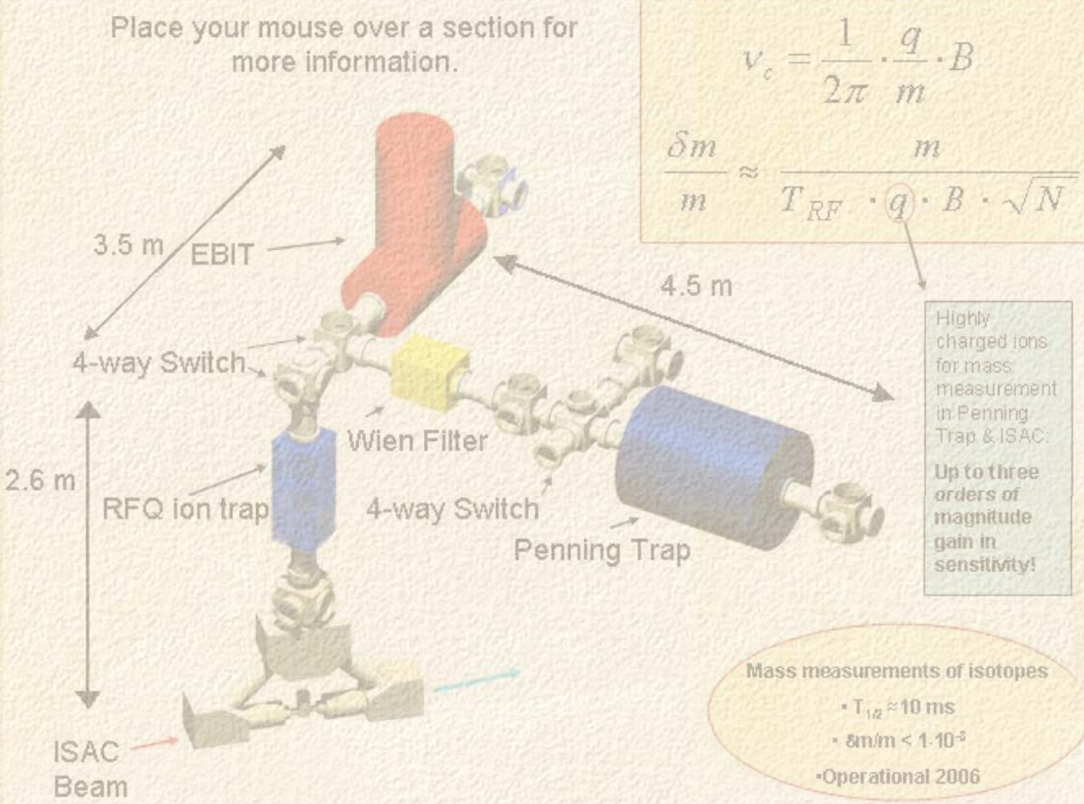
Cooling of Highly Charged Ions
at
TITAN

Gerald Gwinner
University of Manitoba

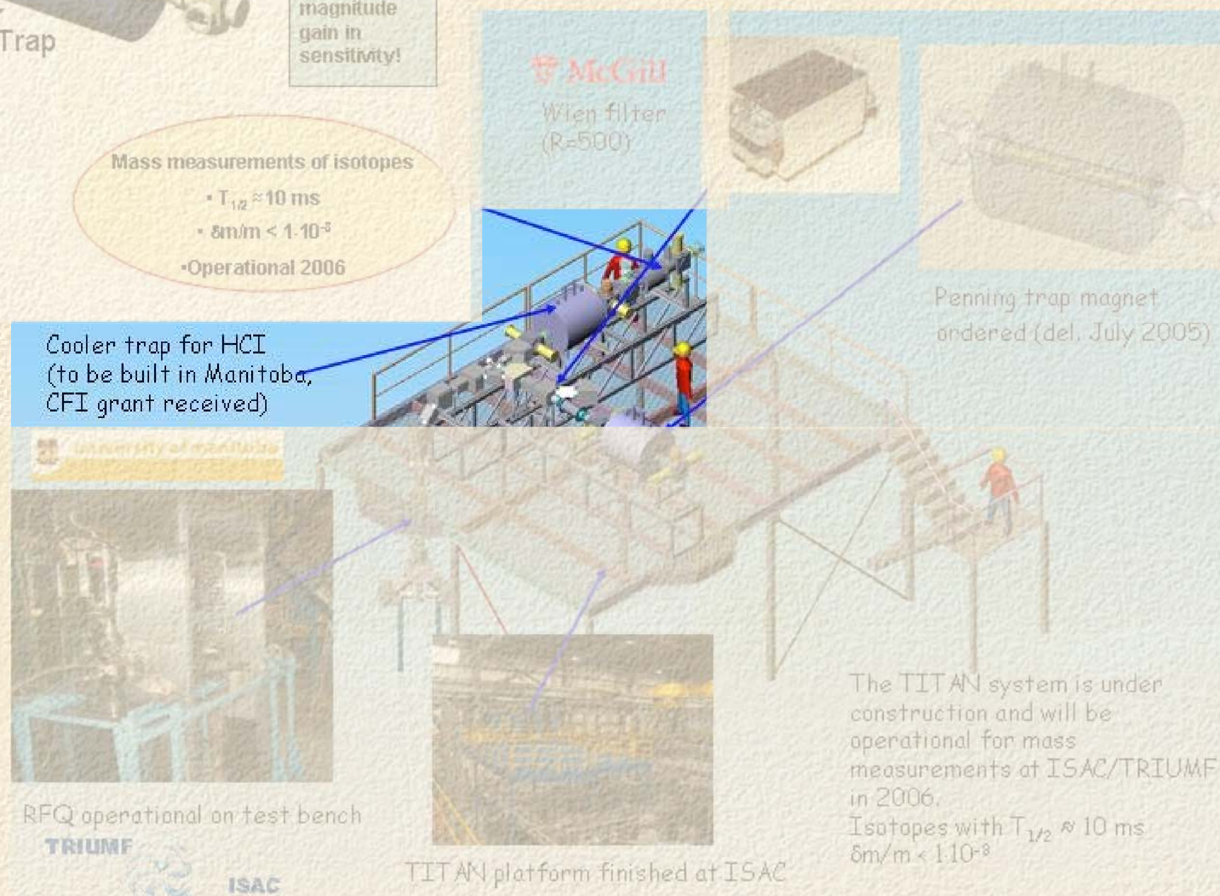
in collaboration with Jens Dilling, Zunjian Ke, Peter Grothkopp, and Vladimir Ryjkov

TITAN collaboration meeting, June 10 & 11, 2005, TRIUMF

original layout



current layout



What is different ?

A cooler trap for HCI

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 ?

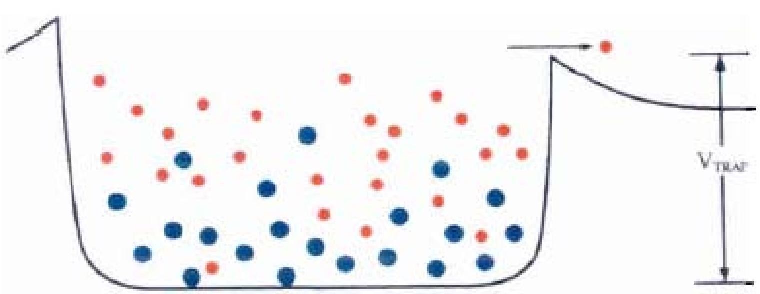
- REXEBIS: few 10 eV/q
- Oshima et al.: EBIS/ECRIS ”generally” > 10 eV/q
- Dresden EBIT: $T_i q = 3 - 6$ eV/q measured for Ar^{16+} but low j_e and E_e
- Livermore, evaporative cooling inside EBIT: $10 - 20$ eV/q for Dy^{66+} (no data ?) Penetrante et al.
- Livermore, evaporative cooling & self-cooling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

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

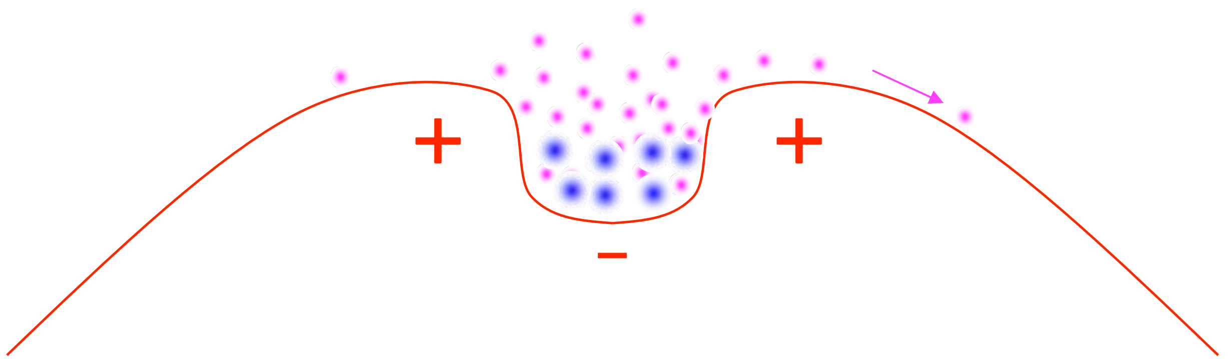


- Controlled injection and evaporation of low-Z ions compensates for electron beam heating of high-q ions
- Thermal equilibrium $\Rightarrow T_i \approx 0.1qeV_{trap}$
- Self cooling during extraction can produce a dramatic reduction in ion temperature

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

Evaporative cooling

- collisions with beam electrons heat up ion ensemble
- light, less tightly trapped ions (e.g. Ne^{10+}) evaporate removing thermal energy



- heavy, highly charged ions (e.g. Ba^{53+}) remain trapped

Ion temperatures from 1000 eV to 30 eV

↓

Doppler width $\Delta\lambda/\lambda \approx 1/20.000$ (Ba^{53+})

↓

High resolution spectroscopy

AFAIK, not demonstrated yet

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

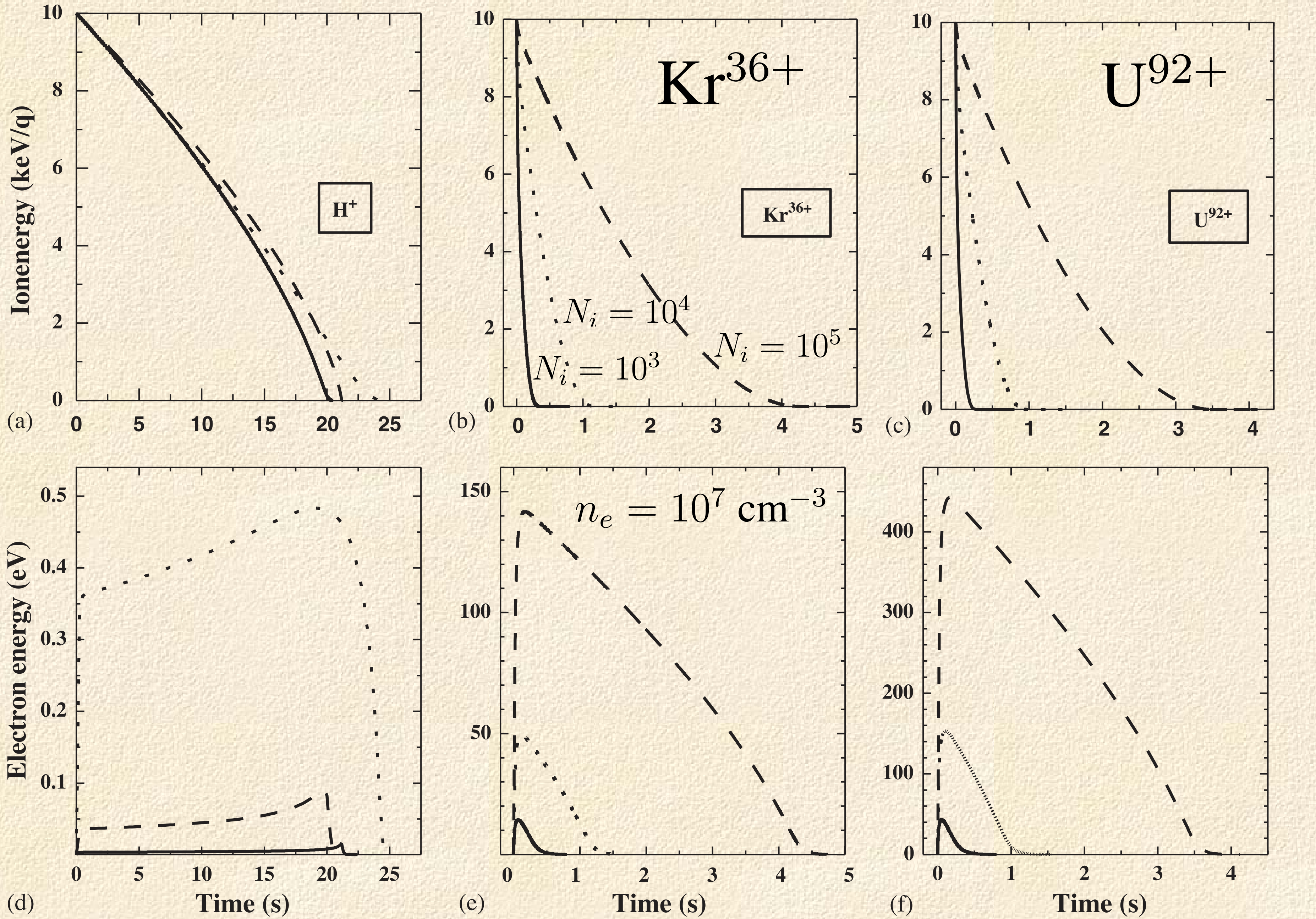
- electron self-cool via synchrotron radiation
  - for $B = 6\ \mathrm{T} \ \rightarrow \ \gamma_c \approx 0.1\ \mathrm{s}$

$$\gamma_{\mathrm{c}} = \frac{1}{\tau_{\mathrm{e}}} = \frac{4e^2\omega_{\mathrm{c}}^2}{3m_{\mathrm{e}}c^3} \qquad \omega_{\mathrm{c}} = eB/m$$

- Spitzer formula for equilibration time:
  - need to take into account continuing electron self-cooling

$$\tau_{\mathrm{i}} = \frac{3m_{\mathrm{e}}m_{\mathrm{i}}c^3}{8\sqrt{2\pi}n_{\mathrm{e}}Z^2e^4\ln(\Lambda)}\left(\frac{kT_{\mathrm{i}}}{m_{\mathrm{i}}c^2} + \frac{kT_{\mathrm{e}}}{m_{\mathrm{e}}c^2}\right)^{\frac{3}{2}} \qquad \ln(\Lambda) = \ln\left(\frac{b_{\max}}{b_{\min}}\right)$$

J. Bernard et al. / Nuclear Instruments and Methods in Physics Research A 532 (2004) 224–228



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Problem: recombination

- radiative recombination
  - $\sigma \propto 1/E_r \;\rightarrow\;$ significant if electron and ion velocities *match*
  - for given electron temperature T_e, velocity match only for ion energies

$$K_i \lesssim \frac{m_i}{m_e} k T_e$$

  - $\star\; T_e = 4\,\mathrm{K} \;\rightarrow\; K_i \lesssim 1\,\mathrm{eV/q}$
  - $\star\; T_e = 300\,\mathrm{K} \;\rightarrow\; K_i \lesssim 100\,\mathrm{eV/q}$

- at higher energies, electron cooling is ‘safe’ from recombination

- at lower ion energies, recombination is essentially a function of the electron temperature

$$\Gamma_{\rm RR} \approx 6 \times 10^{-11} \frac{n_e}{T^{1/2}} {\rm s}^{-1} \times Z^2$$

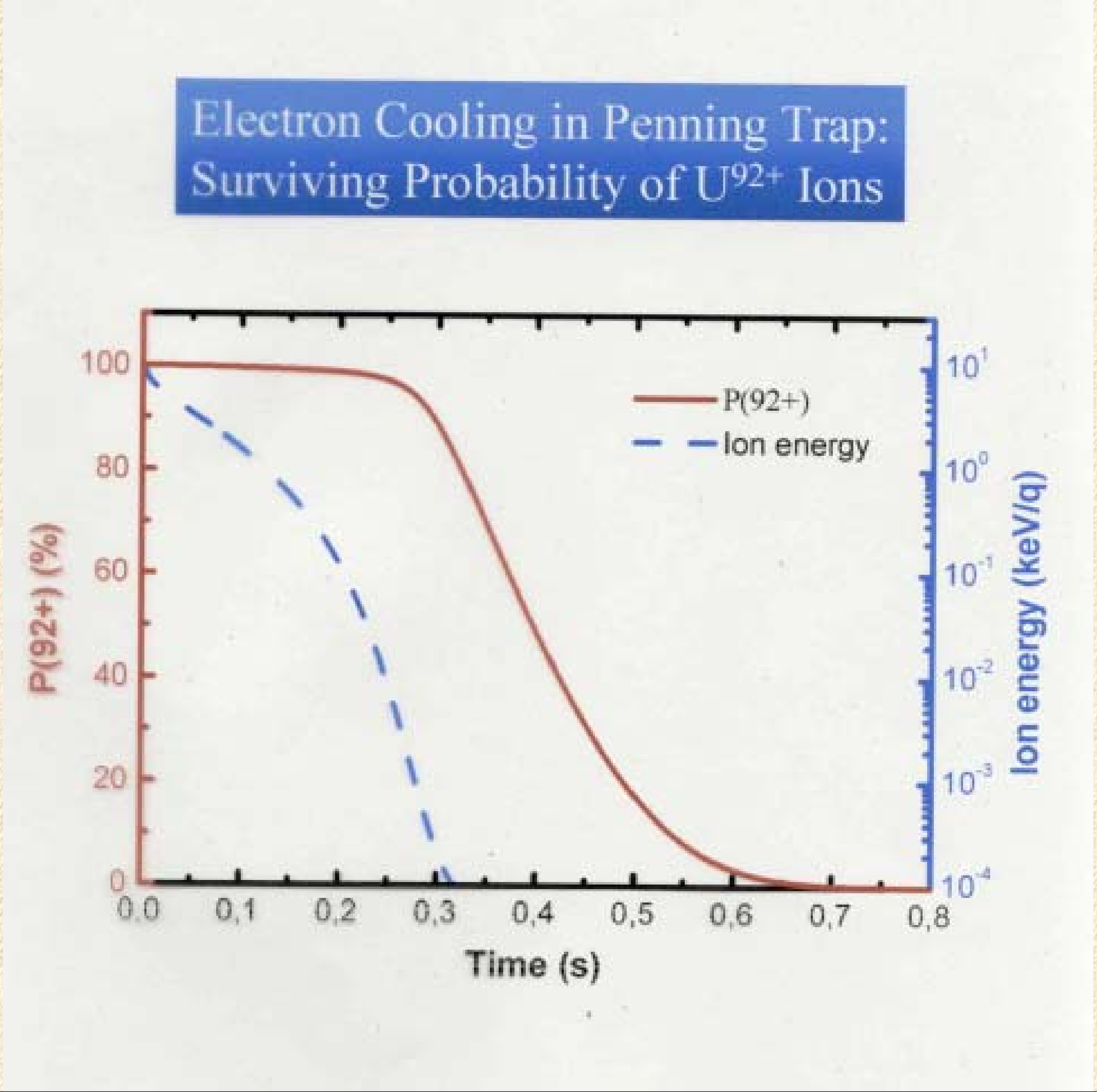
- with $n_e = 10^7$ cm^{-3}, $T_e = 300$ K, and $Z = 50$:

$$\Gamma_{\rm RR} \approx 0.09 \ {\rm s}^{-1}$$

- this looks feasible !

G. Werth, 2002 GSI HITRAP workshop

T = 4 K



Proton cooling of HCI

- similar to electron cooling, however no self-cooling of protons (or He^{2+}) → need initially cold sample
- Simulations by P. Grothkopp

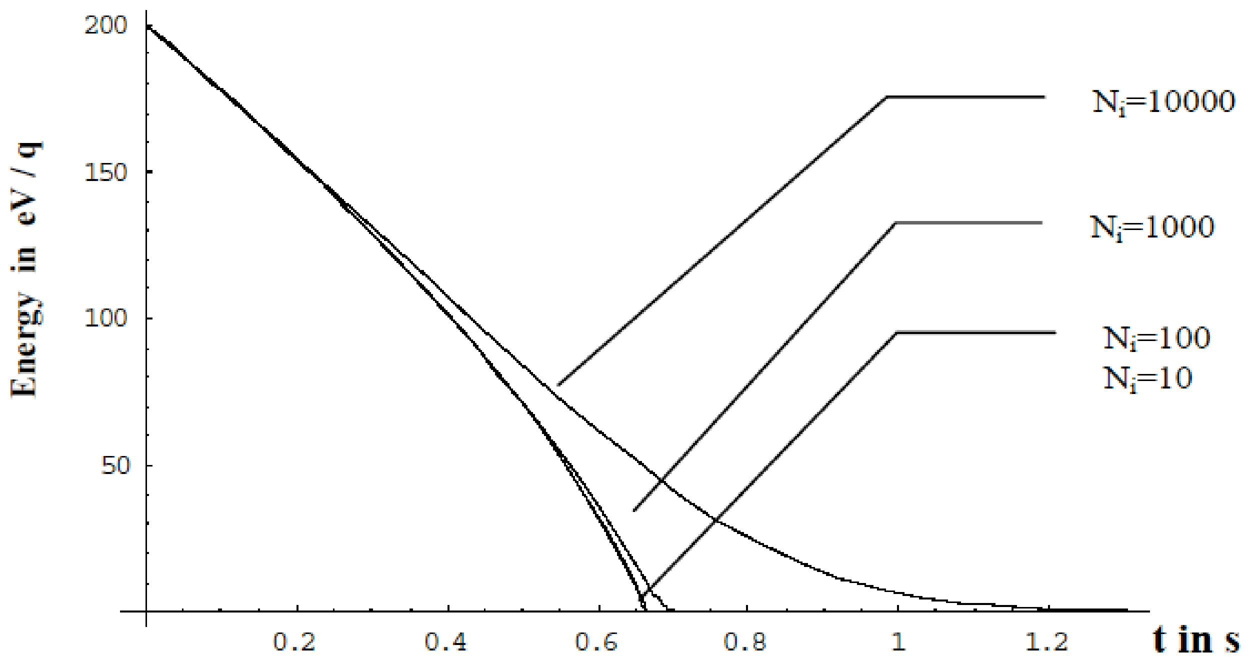


Fig. 2 Uranium (90+) with an initial energy of 200 eV/q and different numbers of injecting ions from 10 to 10^4. Cooled by protons with a density of $n = 10^7 \text{cm}^{-3}$ and a number of $N = 10^7$.

At the Brillouin limit, cooling could be really fast!

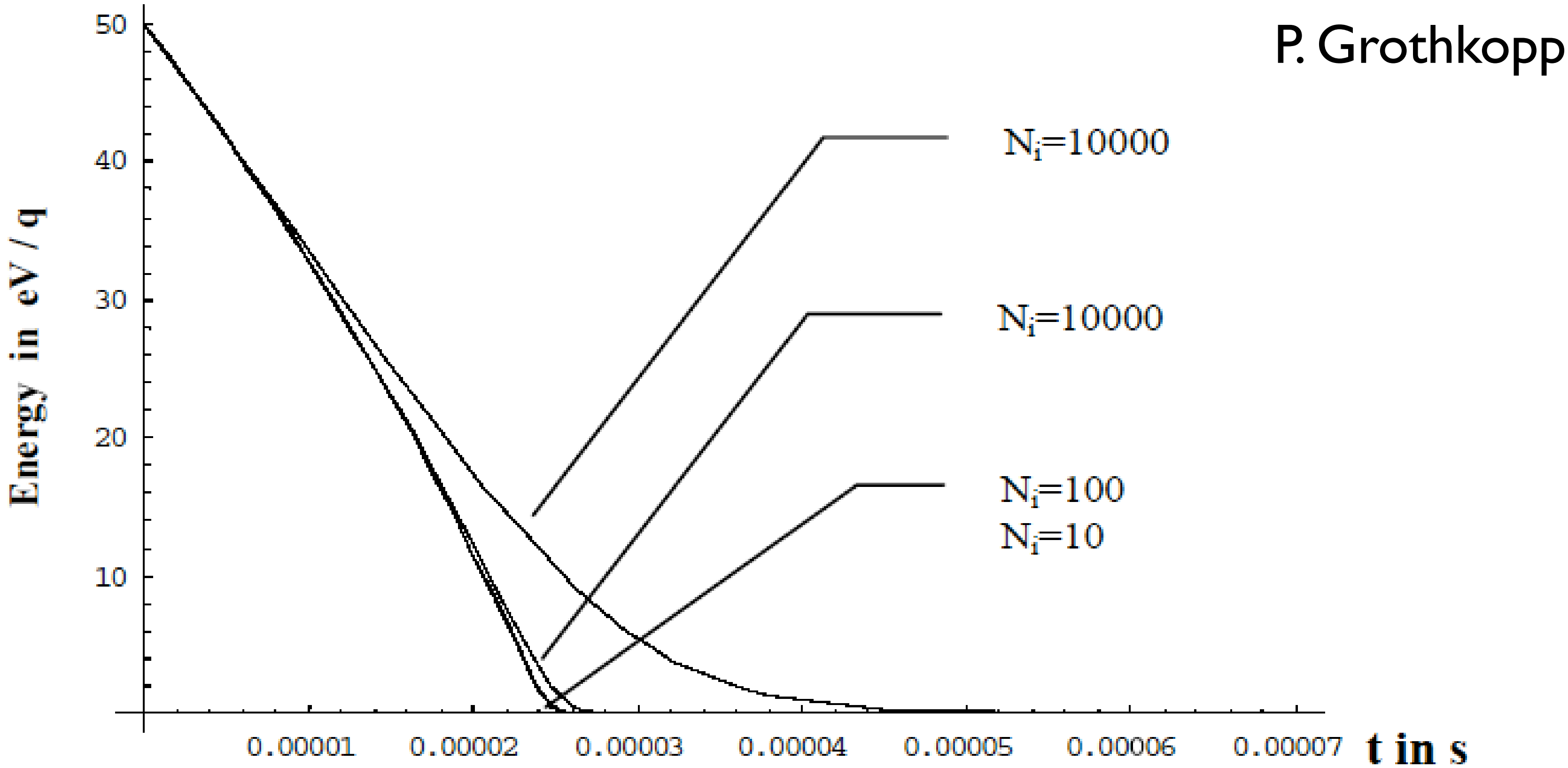


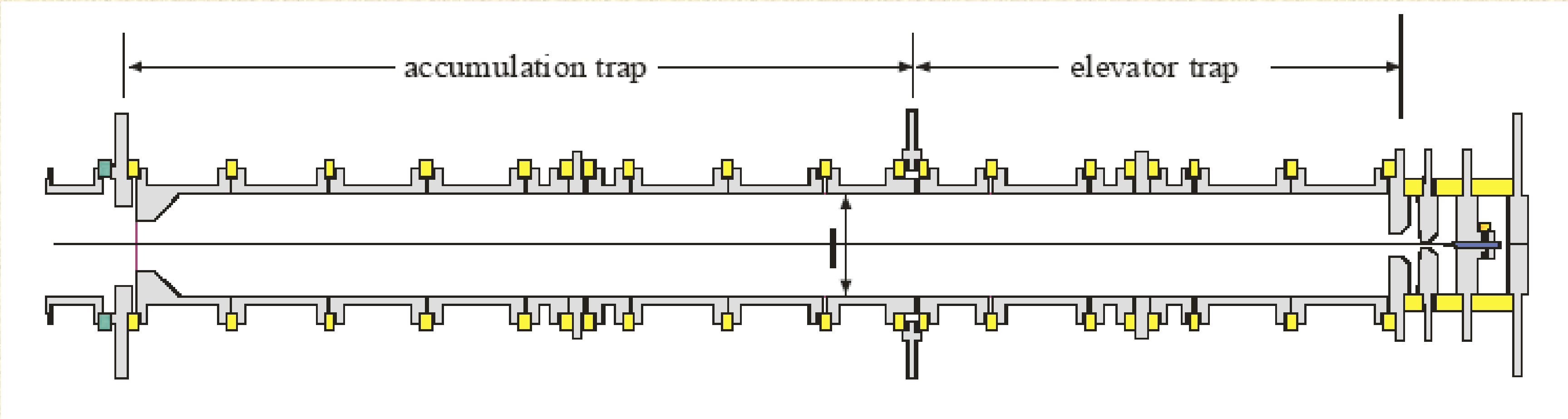
Fig. 5 Uranium (90+) with an initial energy of 50 eV/q and different numbers of injecting ions from 10 to 10^4. Cooled by protons with a density of $n = 4.23 * 10^{10}$ cm^{-3} and a number of $N = 10^7$ cool ions.

- no self-cooling $\Rightarrow$ $T_{\mathrm{eq}} \approx T_{\mathrm{coolant}}$ only for $N_{\mathrm{HCI}} \ll N_{\mathrm{p}}$

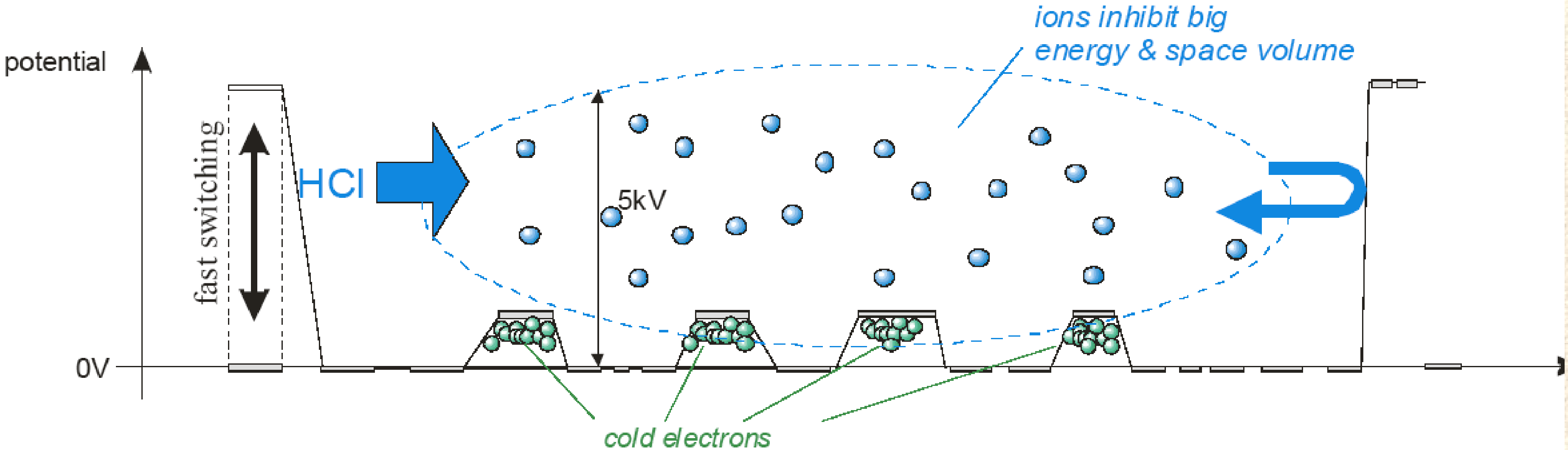
Design of a HCI cooler trap

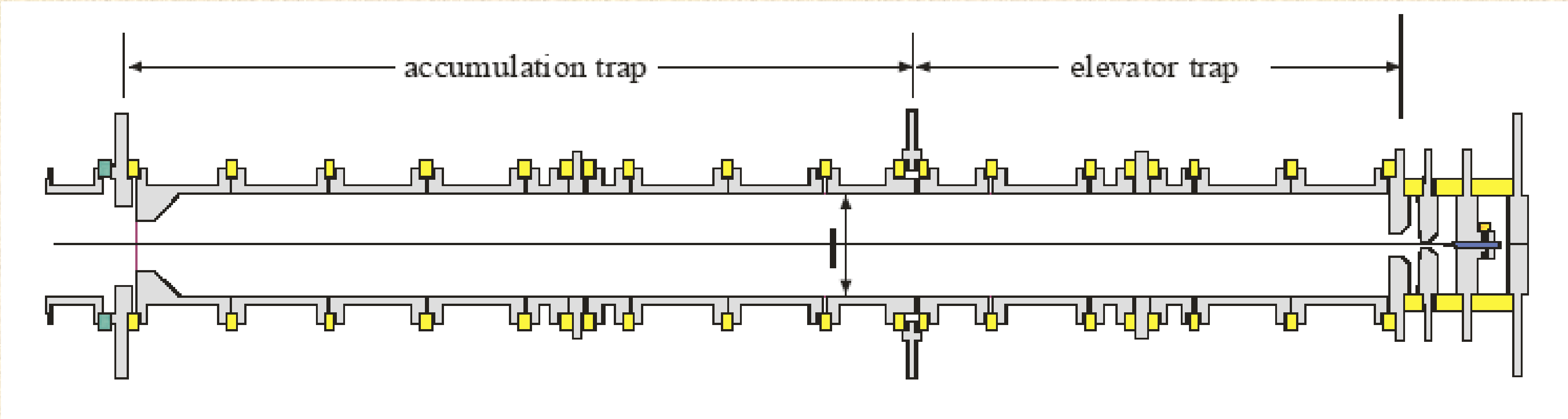
- what has been done in this field so far ?
  - nested Penning trap for (anti)proton cooling with electrons / positrons (Gabrielse et al., also ATHENA)
  - cooler Penning trap for HITRAP project at GSI
  - RIKEN HCI cooler trap for surface studies

The HITRAP cooler trap at GSI (under development)

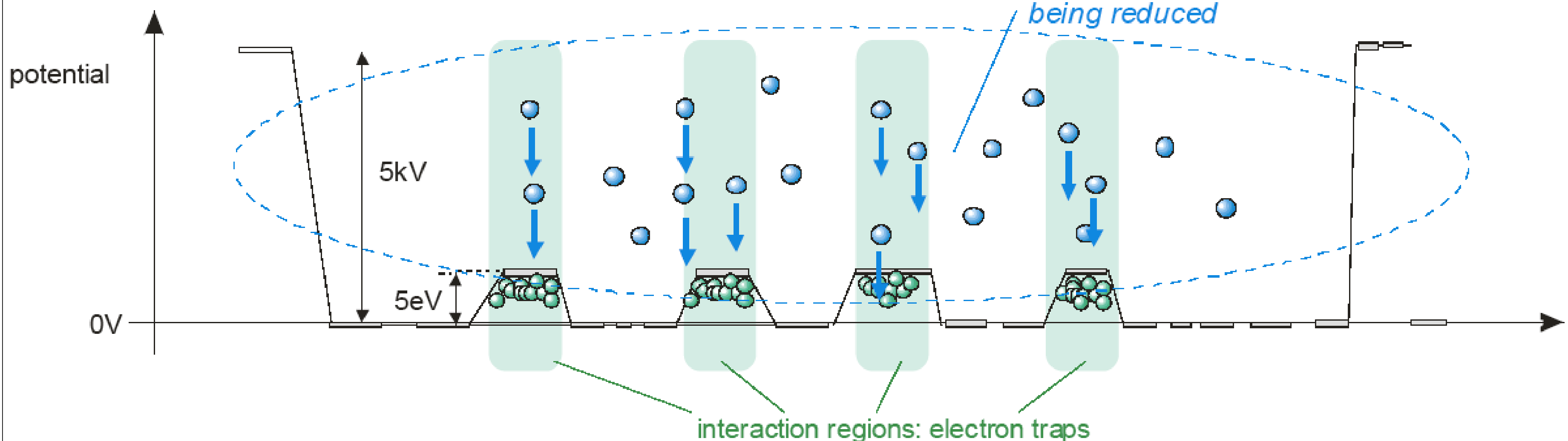


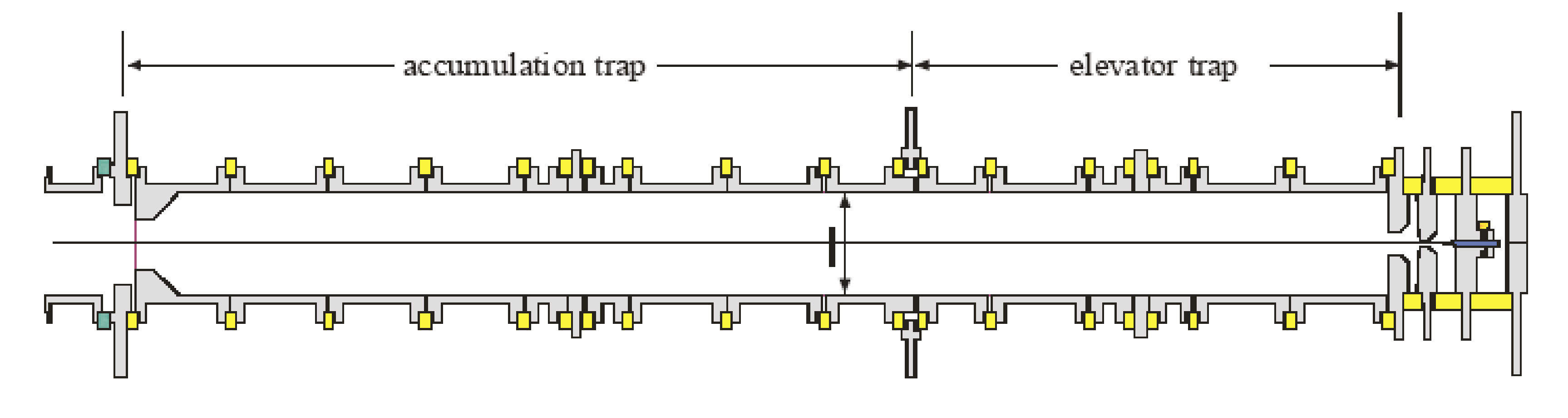
Step 1 : capture deccelerated "hot" ions (5keV / q) into whole trap structure (2 µs)



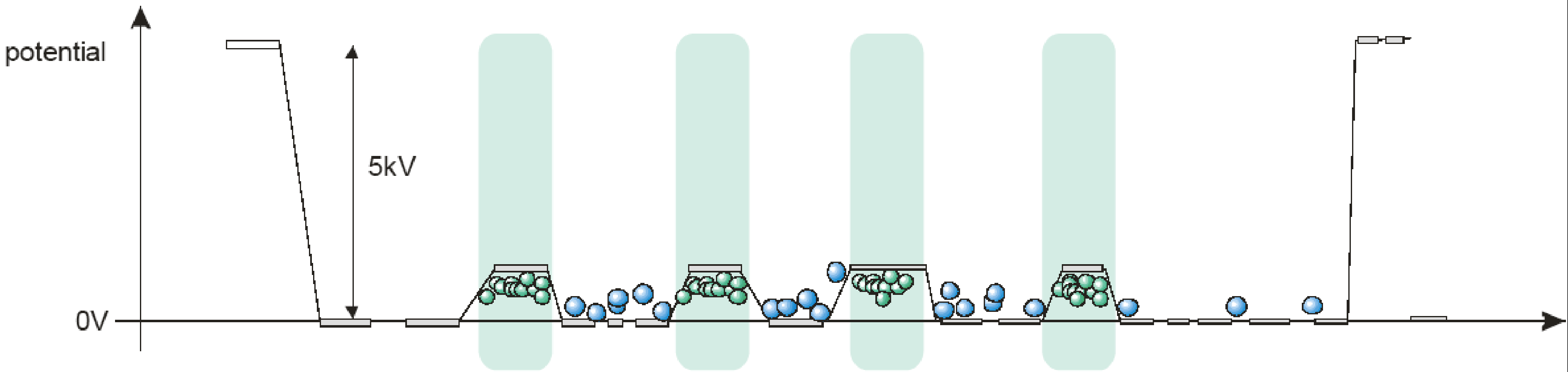


Step 2 : electron-ion interaction: cooling process as soon as the ions cross the electron traps region (duration: 2s)

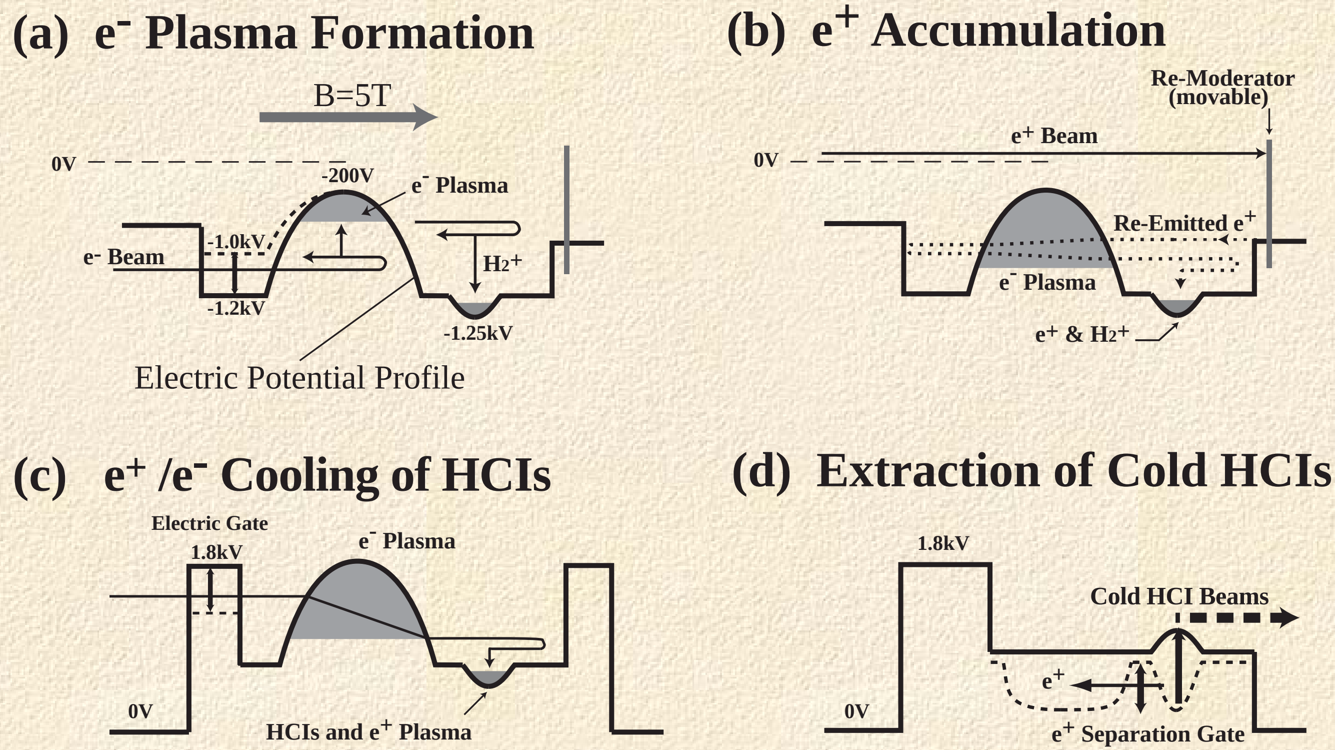


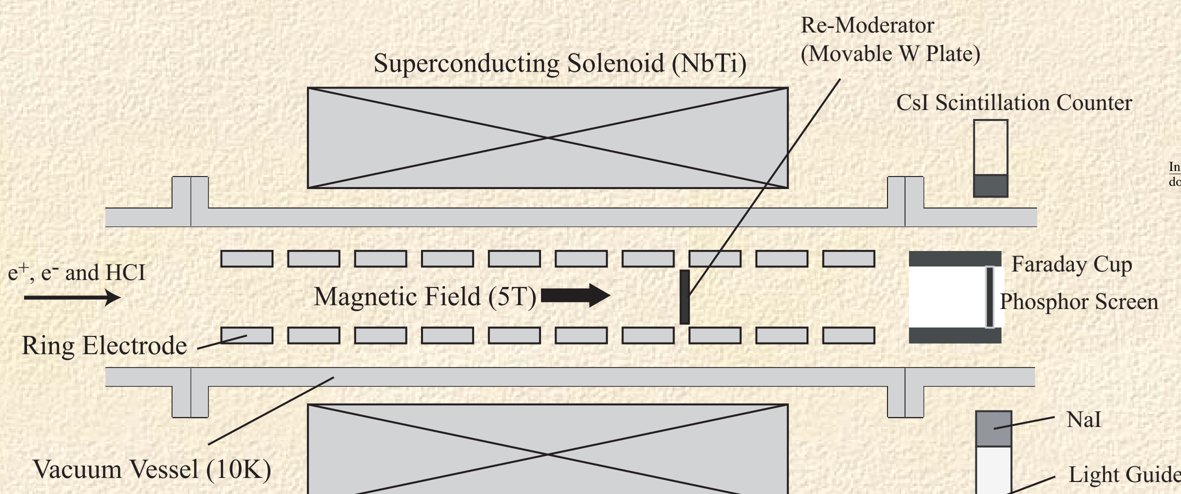


Step 3 : spatial separation after cooling to several eV



continue with resistive cooling to go to 4K





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Project to Produce Cold Highly Charged Ions using Positron and Electron Cooling Techniques

Nagayasu Oshima*, Megumi Niigaki*†, Masato Inoue†, Takao M. Kojima*, Akihiro Mohri*, Yasuyuki Kanai*, Yoichi Nakai*, Ken-ichiro Komaki† and Yasunori Yamazaki*†

**Atomic Physics Lboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
†Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

Propose to build a cooler trap capable of electron cooling and light-ion cooling

- design principles can be very similar to HITRAP and RIKEN cooler traps
  - long trap structure ($\approx$ 50 cm)
    - ⋆ accommodate ion bunches from EBIT (25 cm long)
    - ⋆ form multiple nested potentials
    - ⋆ large diameter ($\gtrsim$ 1")
  - current design: shoot through cooler trap
    - ⋆ off-axis insertion of electrons/protons (RIKEN trap)

- 6 T magnet for electron cooling
  - 10 ppm magnet, 4-5" warm bore
  - 1 ppm or better for addt'l applications ?
- TITAN Penning trap at room temperature
  - make system cryo-ready, resistive cooling etc. to 4K
- integrate 'mini-EBIT' for offline tests of cooling ?

... finally the sad part

update, June 20, 2005:
finally the good news ....
the CFI proposal has been approved by the province !