Ion Heating and Cooling in an EBIT or EBIS

Ross Marrs

Lawrence Livermore National Laboratory

HIE-EBIS Workshop

CERN

16-17 October 2012

LLNL-PRES-590713

Three mechanisms for ion heating

(1) Electron beam heating by single-particle Coulomb collisions

$$\boxed{H_i = \pi \frac{j_e}{e} \frac{q^2 e^4}{E_e} \frac{2m_e}{M_i} \lambda_{ie} = 442 \frac{q^2 j_e}{E_e A} \lambda_{ie}} \quad \text{(eV/s)}$$

j_e [A/cm^2], E_e [eV],
A = mass number, λ_{ie} ~ 15

(2) Heating by radial contraction of the ion distribution

$$\boxed{\frac{dE_i}{dr_i} = -2\frac{T_i}{r_i}}$$

Example: 10% decrease in radius increases ion temperature by 20%

(Same equation as for compression of an ideal gas or conservation of emittance)

-Important for high-emittance ions injected at large radius

-Ion radius contracts with increasing charge state

-Not important for steady state (EBIT) operation

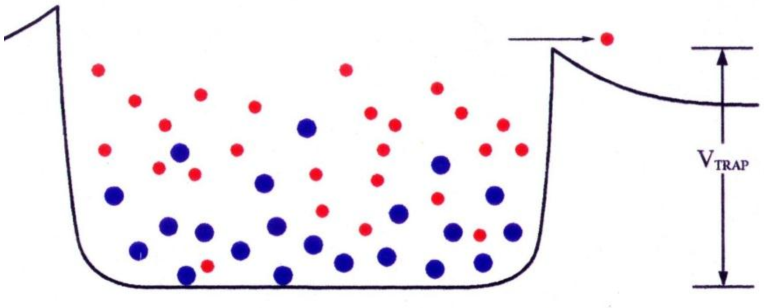
(3) Heating by plasma instabilities

- Dominant heating rate if it occurs

Ion heating requires ion cooling for high charge state production

- Electron beam heating rate $\sim q^2$ Ionization cross section $\sim 1/q^2$
- Ion temperature exceeds electron beam space-charge potential for high charge states
- Production of charge states of roughly 50+ or greater (depending on machine parameters) is impossible without ion cooling

Evaporative ion cooling is used (either by design or by accident) to achieve the production and retention of very high charge states



evaporation rate $\sim e^{-qeV_{trap}/T_i}$

$\Rightarrow$ low-q ions are lost

$\Rightarrow$ high-q ions are trapped

- Loss rate depends exponentially on ion charge
- Thermal equilibrium $\Rightarrow T_i \approx 0.1qeV_{trap}$
- The axial trap potential controls the ion temperature and radial distribution of ions within the electron beam

Ion-ion energy exchange

- Energy exchange among ions is determined by the ion-ion collision rate

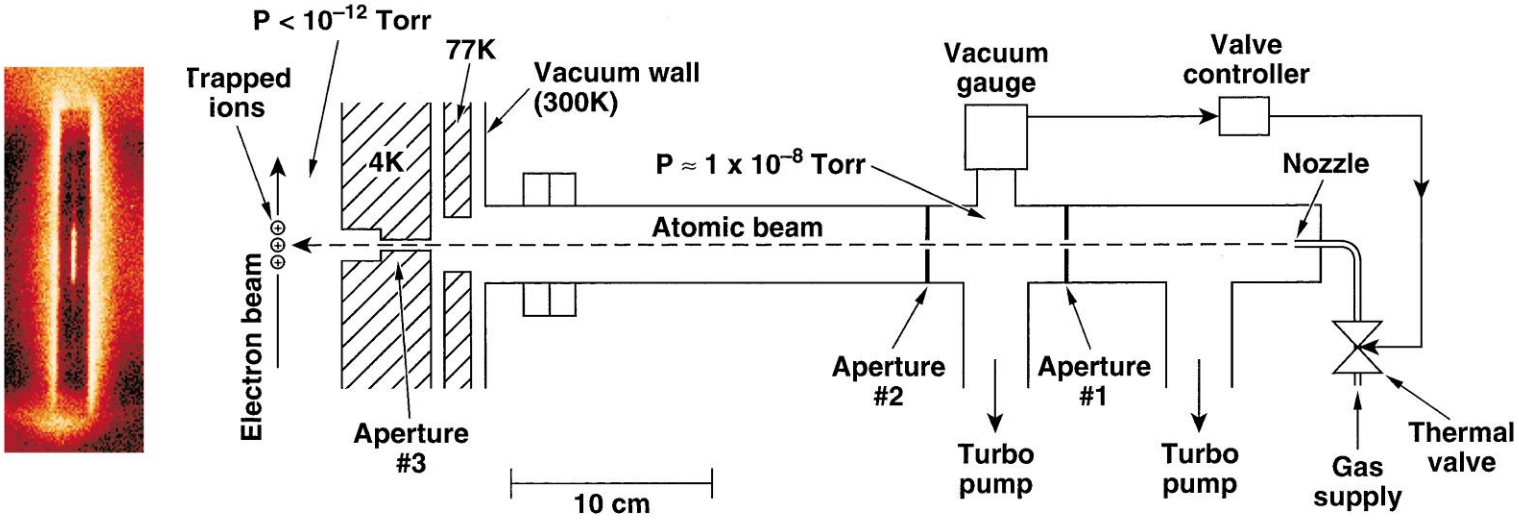
$$\nu_i = \sqrt{2}\,\pi\, n_i \frac{q^4 e^4}{\sqrt{M_i}\,T_i^{3/2}}\lambda_i \;=\; 9.0\times 10^{-8}\frac{n_i\, q^4}{\sqrt{A}\,T_i^{3/2}}\lambda_i \quad (\mathrm{s}^{-1})$$

n_i [cm^{-3}], T_i [eV],
A = mass number, λ_i ~ 9

- Ion-ion energy exchange is usually the fastest rate in the trap – faster than ion heating, ion evaporation, and high charge state production
    - Highly charged ions are all at the same temperature
    - Low charge ions gain energy quickly from highly charge ions and are not far behind in temperature

Rapid ion-ion energy exchange enables light-ion evaporative cooling of highly charged ions

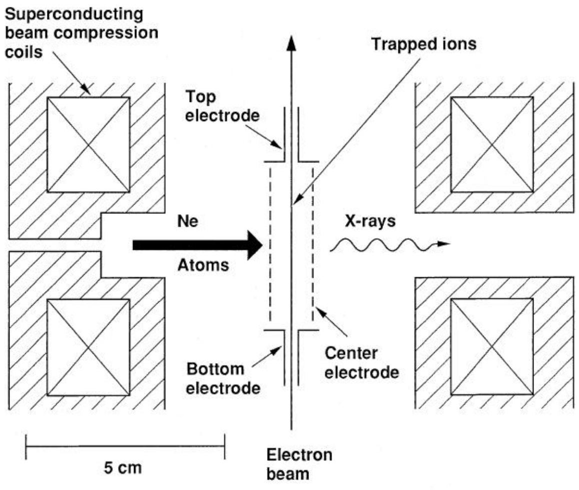
LLNL Super EBIT cooling-gas injector

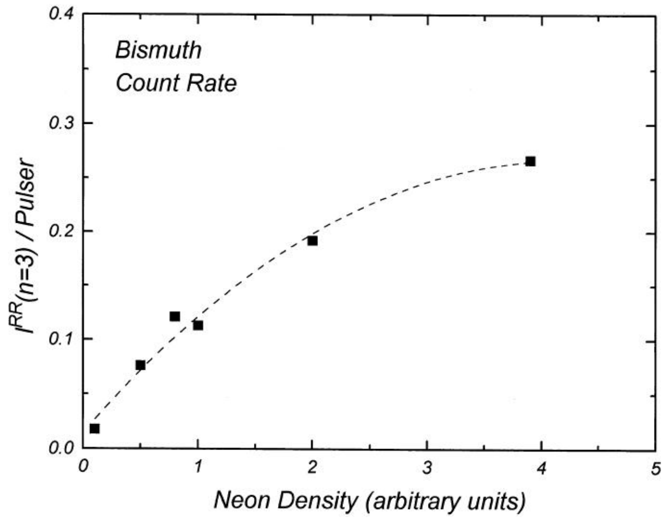


- A beam of neutral atoms (usually neon) is produced by differential pumping and collimation
- Neutral atomic beam crosses electron beam in trap center
- Best performance is achieved when all x-ray ports are covered by beryllium windows at 4 K to minimize background gas density in the trap

Neon is a good choice for cooling: atomic number is about right, chemically inert, small charge exchange recombination cross section

Injection of low-Z cooling gas controls high-Z ion inventories





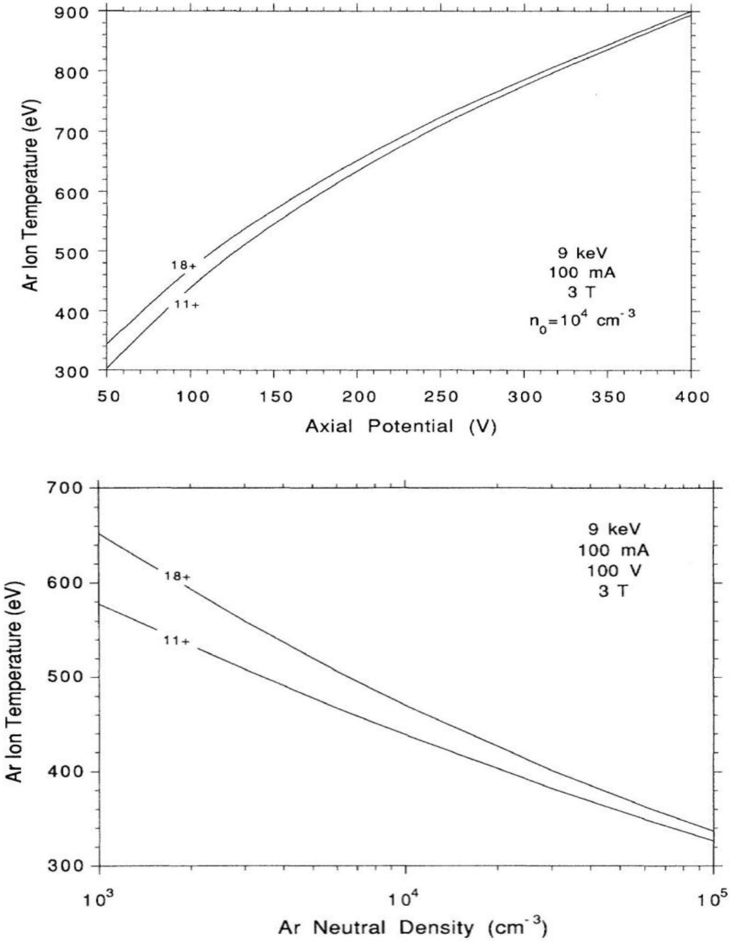
- Neutral neon atoms are injected radially through an aperture in the 4 K magnet bobbin
- Some neon atoms are ionized and captured in the electron beam

- The trap is filled with a single injection of low-charge bismuth
- The amount of highly charged bismuth retained in the trap is controlled by the amount of neon cooling

Data with a clean trap confirms that the number of high-charge ions retained in the EBIT electron beam is roughly proportional to the injection rate of low-Z cooling ions

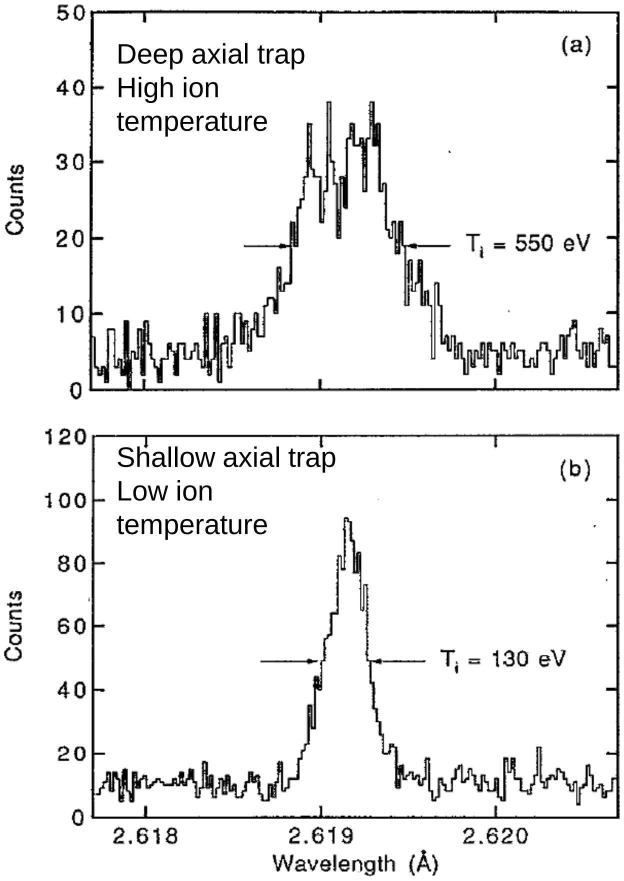
Measurements and detailed computer models support our understanding of ion thermal processes

Computer model of steady-state argon ion temperature



B. Penetrante et al., PRA **43**, 4861 (1991)

Measured He-like Ti^{20+} Doppler-broadened x-ray line width

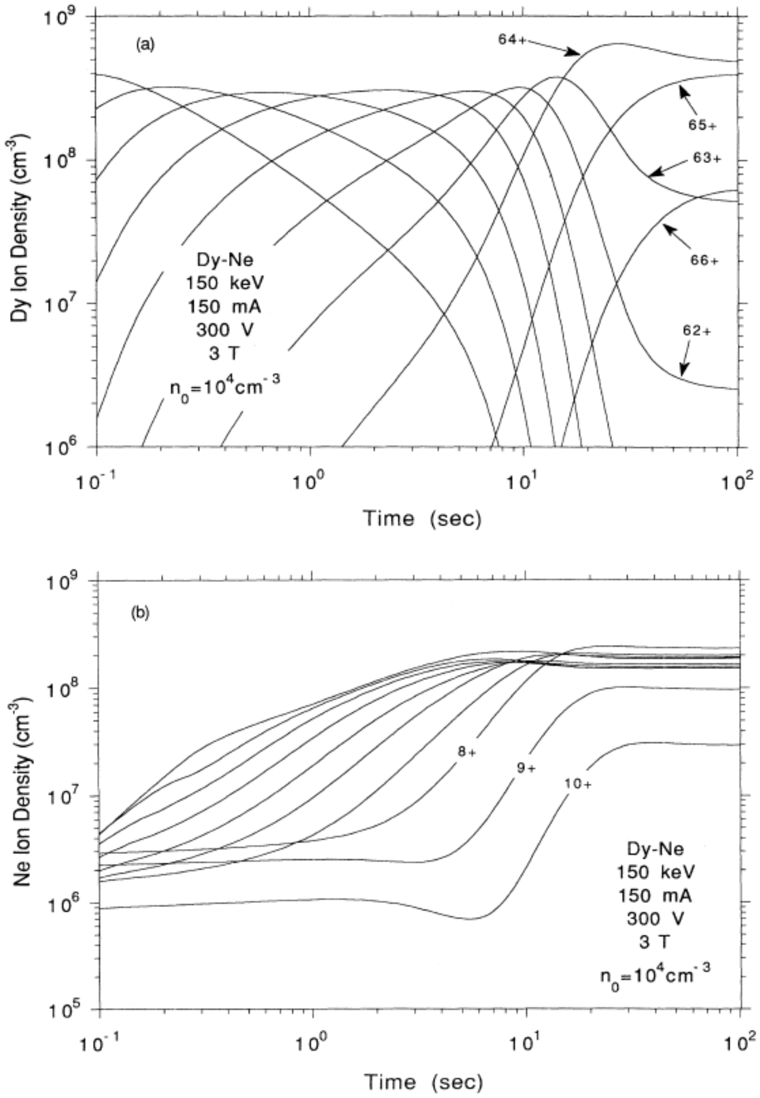


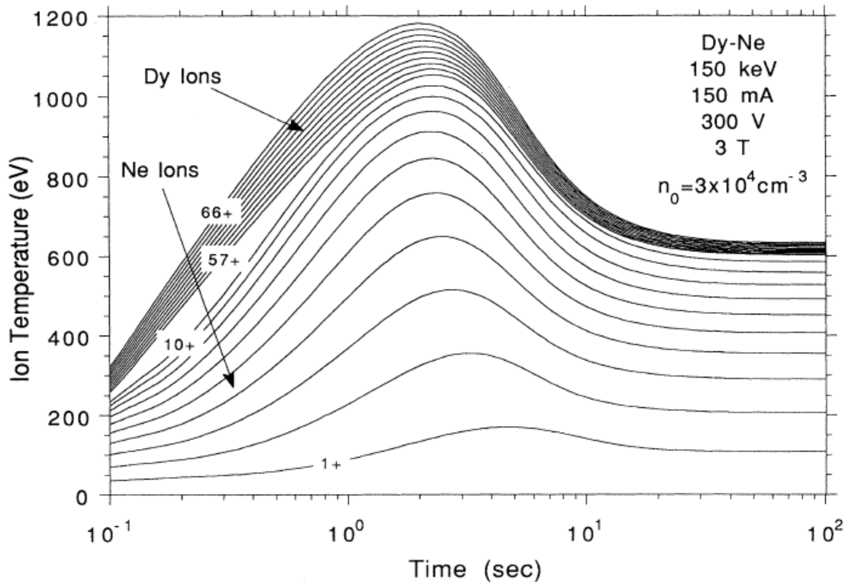
Deep axial trap
High ion
temperature

Shallow axial trap
Low ion
temperature

P. Beiersdorfer et al., RSI **66**, 303 (1995)

Computer model of charge-state evolution for neon-cooled dysprosium

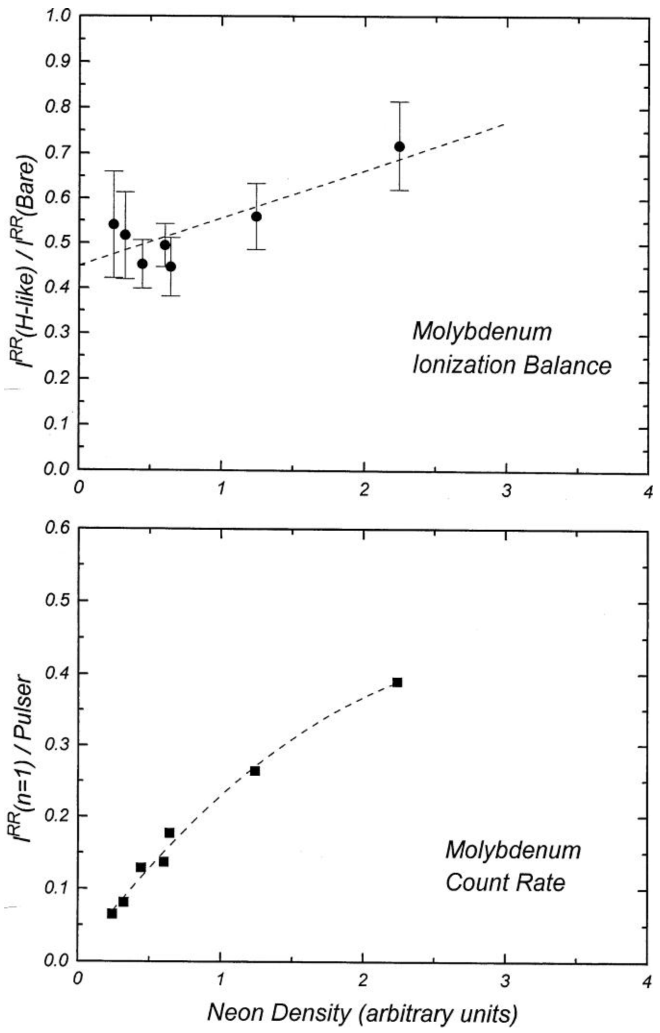




- Predicted evolution of charge states of Dy (Z=66) and Ne (Z=10) in the LLNL Super EBIT following injection of low-charge dysprosium ions
  - Calculation uses a 300-V axial trap potential that produces a hot ion distribution
- Calculation includes electron ionization and recombination, charge exchange recombination, ion heating, energy exchange, and escape

B. Penetrante et al., PRA **43**, 4873 (1991)

It is possible to have good cooling (i.e., high count rate) and good ionization balance at the same time



- Several operating parameters can be adjusted to optimize conditions for specific measurements
  - Cooling gas density
  - Axial trap potential
  - Electron beam current and density

- We are lucky that the ratio of cross sections for electron impact ionization and charge exchange recombination is sufficient for production of high-charge-state ions

$$\frac{N_{i+1}}{N_i} = \frac{\sigma^{ion}_{i\to i+1}}{\sigma^{RR}_{i+1\to i} + \left(\frac{e}{j_e}\right) n_0 \left\langle v_{ion}\sigma^{CX}_{i+1\to i}\right\rangle}$$

Strong self cooling during ion extraction

- Strong self cooling is enabled by a favorable ordering of the time scales for ion-ion energy exchange, ion evaporation, and ion extraction
  - Does not occur in all devices, but could be achieved in advanced charge breeders
  - Produces extremely low emittance and high brightness

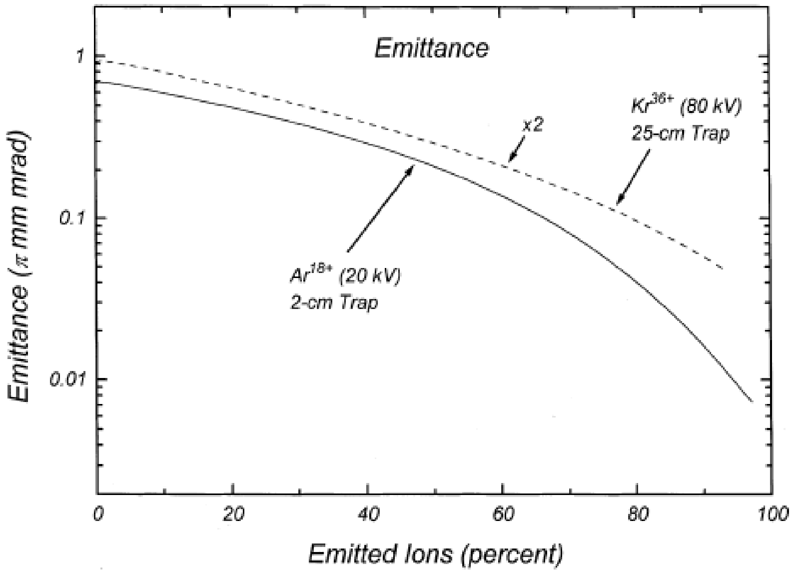


Fig. 4. Calculated absolute emittance for Ar^{18+} ions accelerated by a 20 kV potential and Kr^{36+} ions accelerated by a 80 kV potential. The Kr^{36+} curve has been multiplied by a factor of 2 for display purposes to compensate for the difference in acceleration potentials. From R. E. Marrs, NIM B **149**, 182 (1999)

Example: Kr^{36+} ions in an advanced breeder, extracted by lowering the axial barrier at a rate of 25 volts/ms

Time (ms)	Trap potential (V)	Remaining ions (10^8)	Emittance (π mm mrad)	Brightness (10^9 ions per mm^2 mrad^2 s)
-12	300	2.0	0.46	0.96
-1.2	30	0.87	0.12	6.0
-0.4	10	0.53	0.065	13
-0.12	3	0.28	0.036	22
-0.04	1	0.15	0.025	24
0	0	0	--	--

Electron-ion two stream instability: a possible big heating mechanism

- Effect of electron-ion two stream instability is to convert free energy of the electron beam into ion thermal energy
- Heating power is much greater than for single particle electron-ion collisions

Two-stream instability could prevent successful charge breeding if it occurs

- Growth rate calculated by: C. Litwin, M. C. Vella, and A. Sessler, NIM **198**, 189 (1982)

$$\gamma = \frac{\sqrt{3}}{2}\left[\frac{\omega_{pe}\omega_{pi}^{2}}{2}\right]^{1/3} = 5.6\times10^{-2}\left(f\,\phi\,\frac{q}{A}\right)^{1/3}\omega_{pe} \qquad \text{where} \quad \omega_{pe} = \sqrt{\frac{4\pi n_e e^{2}}{m_e}} = 3.25\times10^{9}\,\frac{j_e^{1/2}\left[A/cm^{2}\right]}{E_e^{1/4}\left[kV\right]}$$

(f = space charge neutralization fraction, φ = electron-ion overlap factor)

- Instability is avoided if either condition (1) or (2) holds

(1) $L < \frac{3v_{phase}}{\gamma} \approx \frac{v_e}{\gamma}$ $\longrightarrow$ $\boxed{j_e < 106\,\frac{E_e^{3/2}}{\left(f\,\phi\,\frac{q}{A}\right)^{2/3}L^{2}}}$ [A, keV, cm]

(trap length is less than
~3 growth lengths)

(2) $\lambda_D > r_b$ where $\lambda_D = \sqrt{\frac{T_e}{4\pi\, n_e\, e^{2}}}$ $\longrightarrow$ $\boxed{\frac{r_b}{\lambda_D} = 1.4\left(\frac{I_e}{T_e\sqrt{E_e}}\right)^{1/2} < 1}$ [A, keV]

(Debye length is larger than
electron beam radius)

Electron-ion two stream stability for a few devices

	Parameters						Stability criteria		
Device	I_e (A)	j_c (A/cm^2)	j_e (A/cm^2)	T_e (eV)	E_e (keV)	L (cm)	$\frac{j_e}{j_e\text{(max)}}$	r_b / λ_D	stable
LLNL EBIT	0.15	2.2	4 x 10^3	190	10	2	0.6	0.7	yes
LLNL Super EBIT	0.15	2.2	4 x 10^3	190	150	2	0.01	0.4	yes
REX-ISOLDE EBIS	0.2	10	200	2	5	80	140	9.3	no
RHIC EBIS	10	15	500	3.3	25	150	110	34	no
MSU EBIS	1.5	4	1 x 10^4	250	30	80	460	1.5	?
LLNL Intense EBIT	5	4	1 x 10^5	2500	30	25	450	0.8	?

T_e = 0.1 eV x j_e / j_c j_e (max) calculated for $f = 0.3$, $\varphi = 0.5$, $q/A = 0.3$

Short length, high electron energy, and high beam compression (i.e., electron temperature) are good for avoiding the electron-ion two stream instability

Summary

- Heating of trapped ions by single particle Coulomb collisions with beam electrons is proportional to q^2 and produces ion temperatures that exceed the space charge potential of the electron beam before the highest charge states can be produced

- Evaporative ion cooling (by design or accident) is required for the production, retention, and emittance reduction of very highly charged ions

- Successful ion cooling was achieved in the LLNL Super EBIT with:

  Low background gas density -- Drift tubes are at 4 K and have minimal openings that view room temperature surfaces

  Controlled crossed-beam injection of neutral neon atoms for evaporative cooling

  Use of the axial trap potential to adjust ion temperature and electron-ion overlap

Backup slides

Charge-exchange recombination with neutral gas destroys high charge states

- Destruction rate is $\frac{dN_i}{dt} = n_0 v_i \sigma^{cx}$
    - The cross section is enormous: $\sigma^{cx} \sim 2 \times 10^{-14}$ cm^2 for q = 50+ and neutral neon

- Neutral gas density must be very low ($\sim 10^{-12}$ Torr equivalent pressure or less) to avoid destruction of high charge states
- Several features of the EBIT design were chosen to minimize neutral gas in the trap
    - Trap electrodes at 4 K with small beam entrance and exit holes
    - Beryllium x-ray windows at 4 K
    - Collector cooled by liquid nitrogen

Strong self cooling during ion extraction

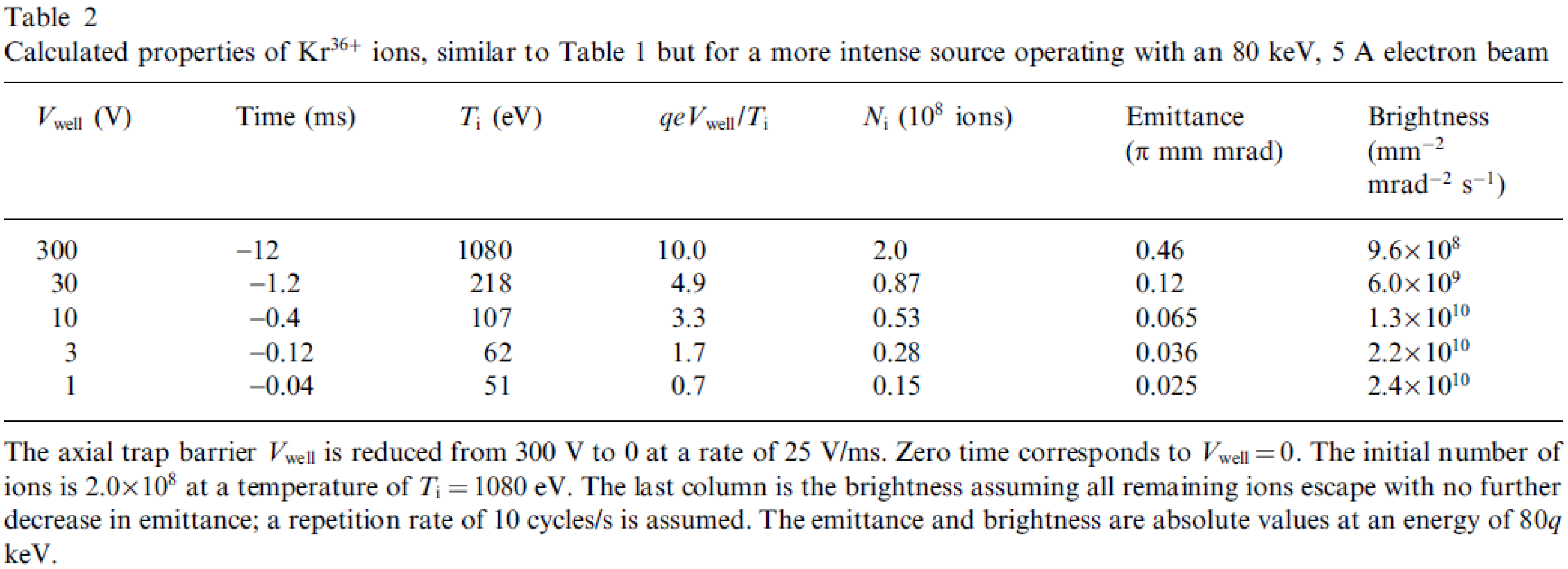


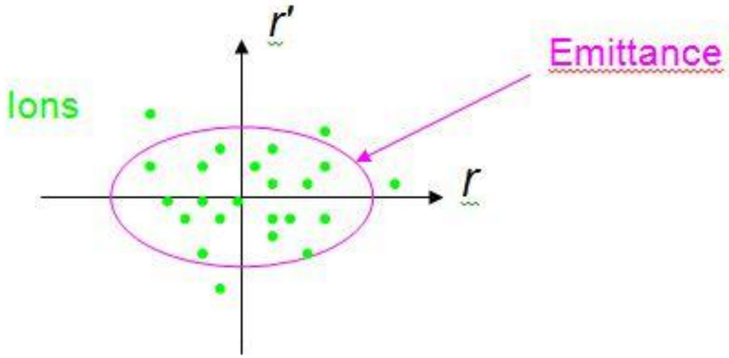
Table 2
Calculated properties of Kr^{36+} ions, similar to Table 1 but for a more intense source operating with an 80 keV, 5 A electron beam

V_{well} (V)	Time (ms)	T_{i} (eV)	$qeV_{\text{well}}/T_{\text{i}}$	N_{i} (10^8 ions)	Emittance (π mm mrad)	Brightness (mm^{-2} mrad^{-2} s^{-1})
300	−12	1080	10.0	2.0	0.46	9.6×10^8
30	−1.2	218	4.9	0.87	0.12	6.0×10^9
10	−0.4	107	3.3	0.53	0.065	1.3×10^{10}
3	−0.12	62	1.7	0.28	0.036	2.2×10^{10}
1	−0.04	51	0.7	0.15	0.025	2.4×10^{10}

The axial trap barrier V_{well} is reduced from 300 V to 0 at a rate of 25 V/ms. Zero time corresponds to $V_{\text{well}} = 0$. The initial number of ions is 2.0×10^8 at a temperature of $T_{\text{i}} = 1080$ eV. The last column is the brightness assuming all remaining ions escape with no further decrease in emittance; a repetition rate of 10 cycles/s is assumed. The emittance and brightness are absolute values at an energy of $80q$ keV.

Ion Acceptance and Emittance

- Acceptance and emittance have the same units -- phase space volume



- Phase space volume = $\pi\, r\, r'$ ← conserved

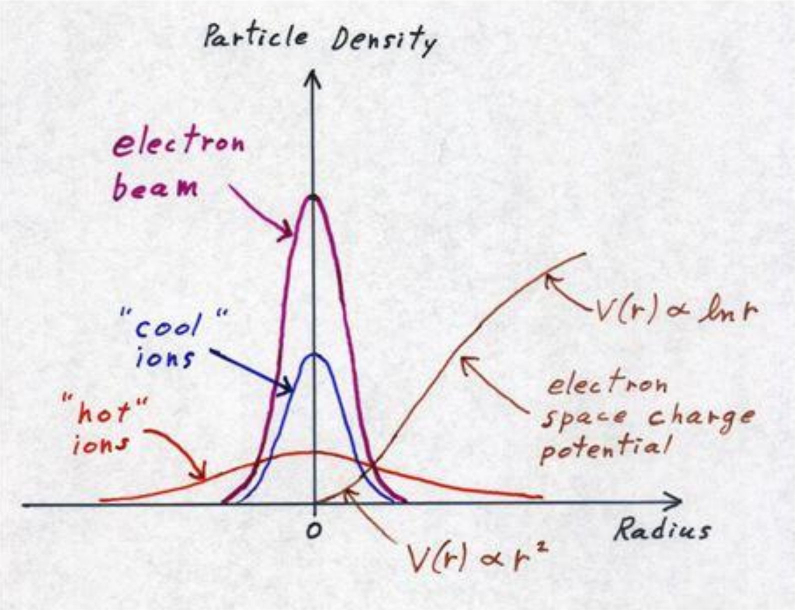
  ⇒ Relate emittance to temperature and radius of ions in the trap

- Absolute acceptance (emittance):

$$\varepsilon = \pi R_{80} \sqrt{\frac{T_i}{qeU}}$$

(*U* is acceleration potential)

Radial distribution of ions in an EBIT



Choosing the smallest possible electron beam radius always gives the best electron-ion overlap

- The Intense EBIT has a large space-charge potential

  $V(r)$ = 450 volts at beam edge ($r \approx 50\ \mu$m)

  $V(r)$ = 4.5 kV at drift tube radius (r = 5 mm)

- Acceptance (at U = 30 kV)

  $\varepsilon \approx 6\ \pi$ mm mrad for good beam overlap ($\sigma_i = \sigma_e$, T_i = 450 eV)

  $\varepsilon >> 6\ \pi$ mm mrad for capture into trap