Ion Beam Neutralization

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Introduction

- It is more difficult to transport high-current ion beams than electron beams. Nonrelativistic ions move slower than electrons of equal kinetic energy. Therefore, an ion beam has higher space-charge electric fields than an electron beam of the same current. Also, magnetic focusing by beam-generated fields is ineffective for nonrelativistic beams.

- We must apply neutralization to create and to transport high-flux ion beams. The idea is to mix electrons with the ions to reduce the beam-generated electric field. The process is feasible because of the low mass of the electron. The mobile electrons rapidly enter the beam volume. Low-energy electrons can follow high-energy ions to neutralize a beam propagating into free space.

- [Plasma neutralization] We can direct the beam through a dense plasma. The plasma electrons shift in position to compensate for the added positive charge.

- [Vacuum neutralization] Sources located outside the vacuum beam transport region create the electrons. The electrons join the ions as needed. The resulting neutralized beam has an electron density approximately equal to the beam density. (1) Longitudinal neutralization (external electric field vs self-generating space-charge field) (2) Transverse neutralization (side injection using space-charge electric fields)

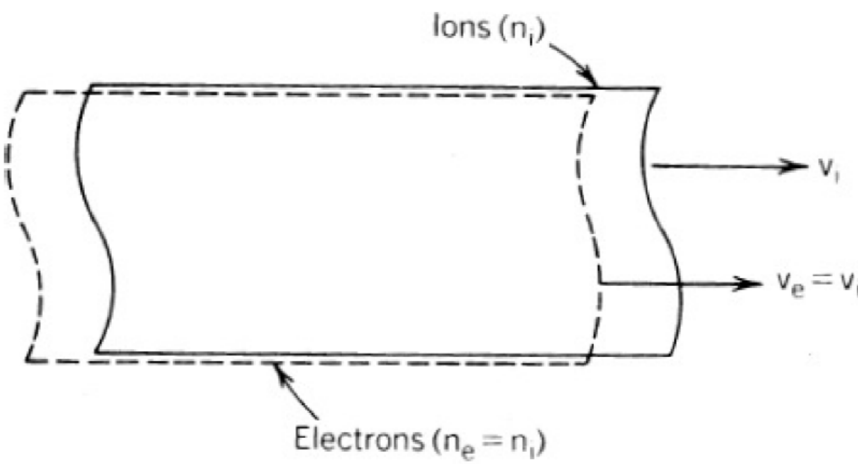
Neutralization by co-moving electrons: active neutralization

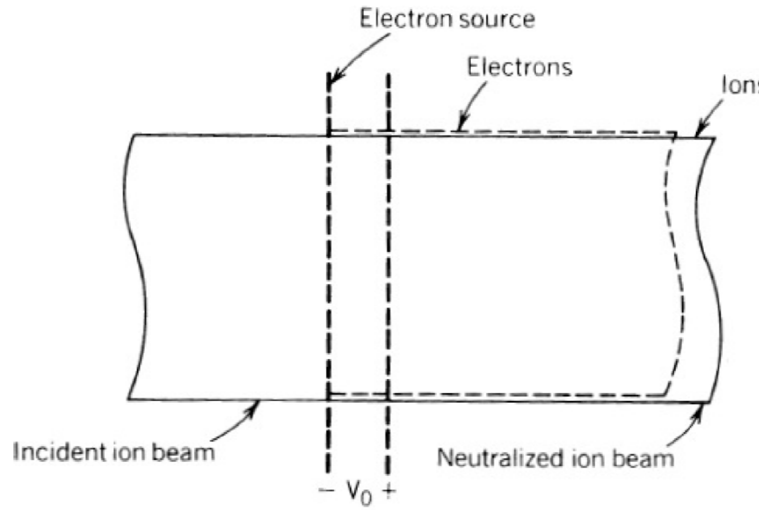
- The electron and ion densities are equal, so there is no beam-generated electric field. The electrons move at same velocity as the ions, $v_e = v_i$.
- [Active neutralization] To accelerate electrons to kinetic energy T_e and to combine them with the ion beam. The required electron kinetic energy is

$$T_e = \frac{1}{2} m_e v_i^2 = \left(\frac{m_e}{m_i}\right) T_i$$

- The voltage is

$$V_0 = \left(\frac{m_e}{m_i}\right) \frac{T_i}{e}$$





Electron current density for active neutralization

- The one-dimensional Poisson equation:

$$\frac{d^2\phi}{dx^2} = \frac{en_0}{\epsilon_0}\left[\left(\frac{V_0}{\phi}\right)^{1/2} - 1\right]$$

- The boundary conditions:

$$\phi(x=0) = 0 \qquad \phi(x=d) = V_0 \qquad \left.\frac{d\phi}{dx}\right|_{x=0} = 0 \qquad n_e(x=d) = n_0$$

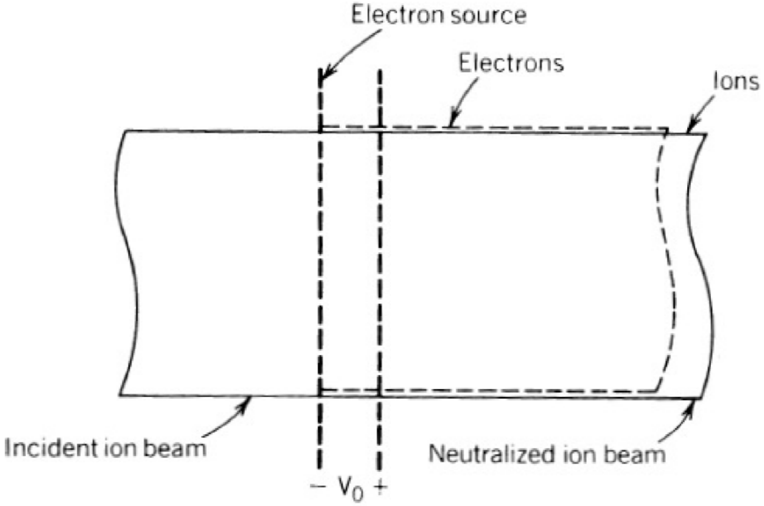
- The solution:

$$j_e = \frac{4\epsilon_0}{9}\left(\frac{2e}{m_e}\right)^{1/2}\frac{V_0^{3/2}}{d^2}\left[\frac{3}{2\sqrt{2}}\int_0^1 \frac{dX}{\sqrt{2X^{1/2} - X}}\right]^2$$

- Or simply:

$$j_e = 1.46\, j_{e,Child}$$

Due to ion space charge



Transverse neutralization

- Transverse neutralization is effective if electrons in the beam volume do not return to the boundary. If electrons are trapped in the beam volume, then additional electrons can enter from the boundaries until space-charge fields are completely canceled.
- Relaxing the constraint of one-dimensional motion allows electron trapping. If an electron suffers a deflection normal to the x direction, conservation of energy implies that it cannot return to the boundaries.

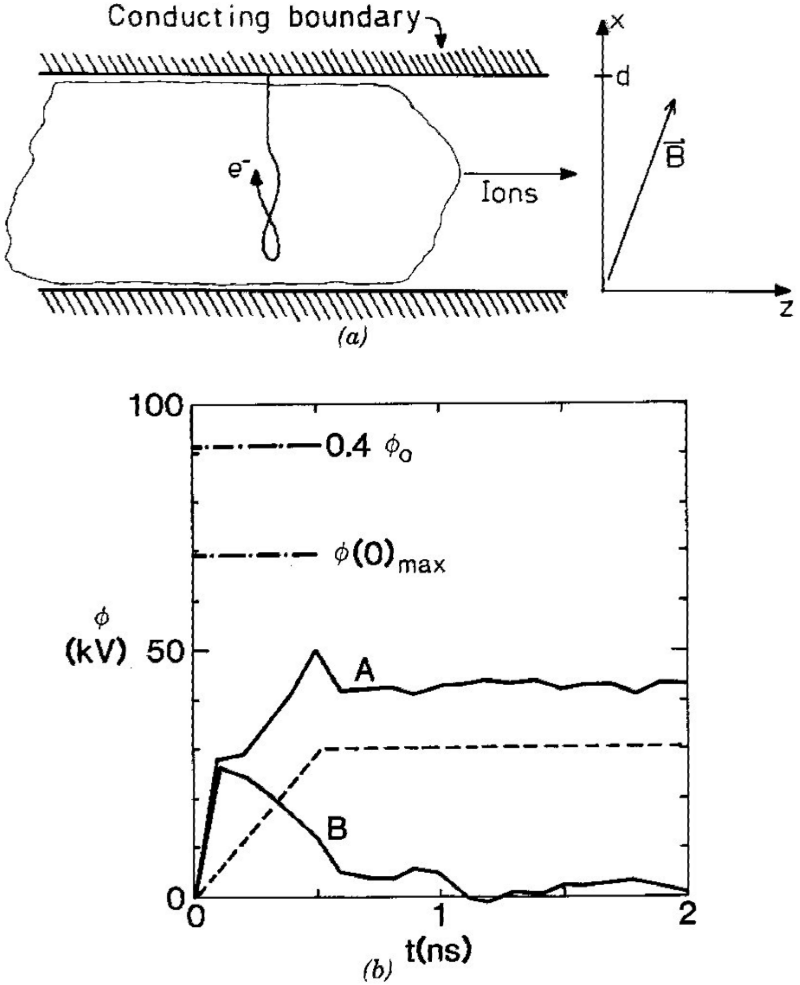
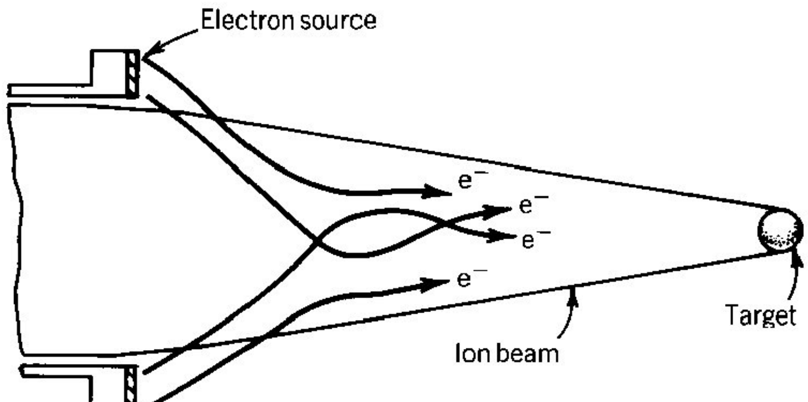


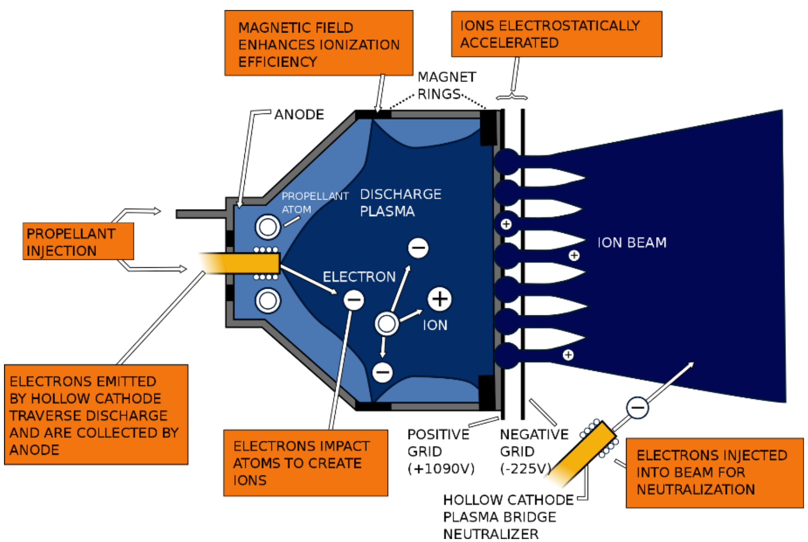
Figure 11.8. Particle-in-cell computer simulation of transverse neutralization. *a*) Simulation geometry – the ion density increases with time between grounded conducting electron emitters. The figure shows an electron orbit deflected by a skewed magnetic field. *b*) Simulation results - time-variation of electrostatic potential on the midplane. Dashed line shows variation of ion density with peak value $n_o = 10^{18}$ m^{-3}. Quantities $0.4\phi_o$ and $\phi(0)_{max}$ described in text. Curve *A*: magnetic field inclination angle: 0° - one-dimensional electron motion. Curve *B*: magnetic field inclination angle: 15°. (Courtesy, J. Poukey, Sandia National Laboratories).

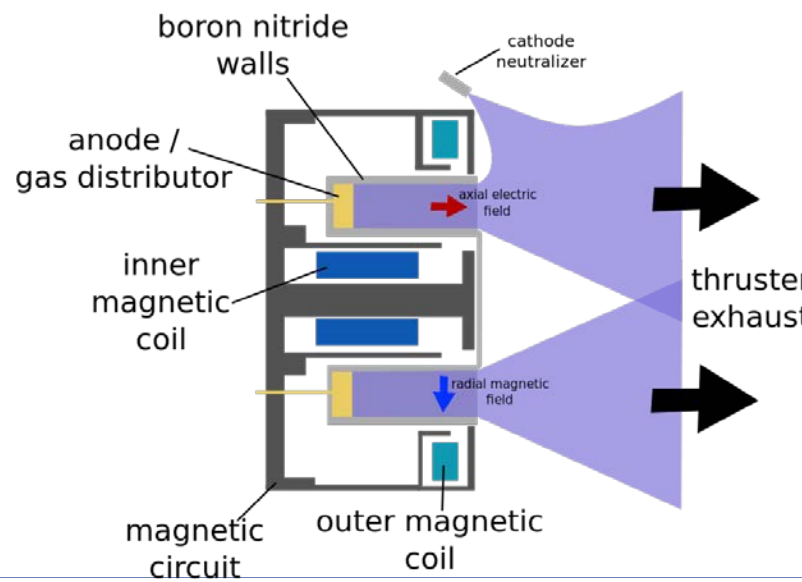
Current neutralization of ion beams by electron flow

- When a high-current ion beam moves into an infinite field-free volume, accompanying electrons provide both space-charge neutralization and current neutralization.



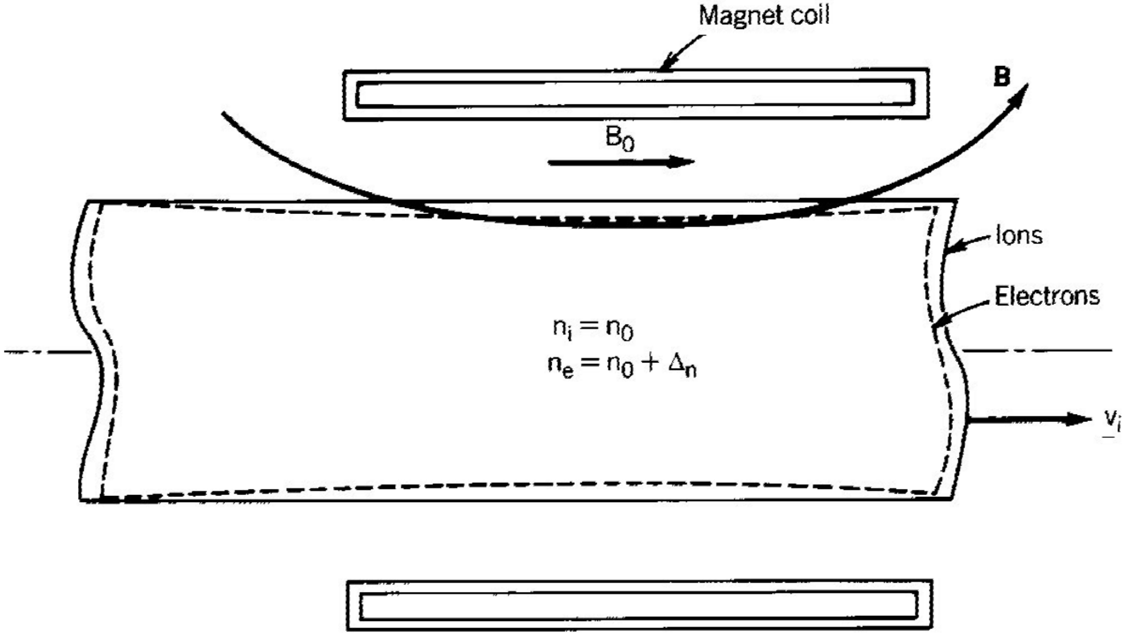
(a)





Transport of neutralized ion beams via space-charge lens

- The space-charge lens is used for collective focusing of neutralized ion beams. In contrast to the cusp transport system, the space-charge lens is an isolated solenoid lens with linear radial forces that focus a neutralized ion beam toward a point.

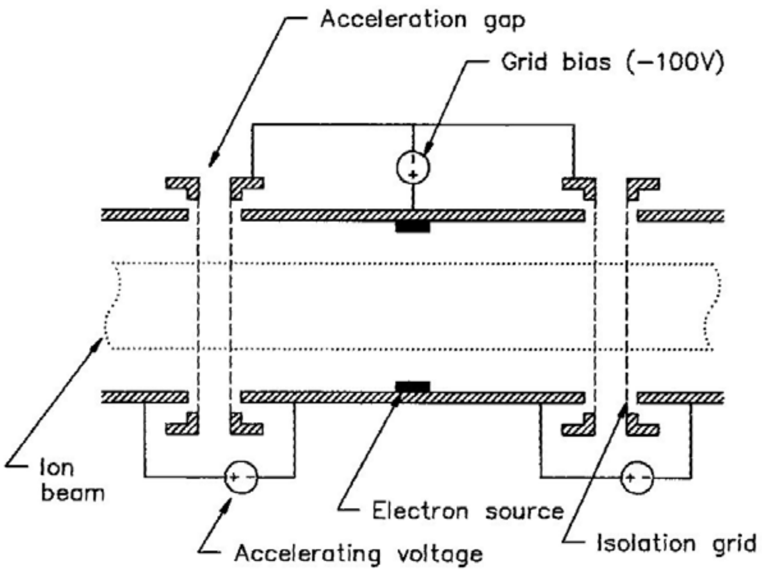


- Charge imbalance and the resulting radial electric field:

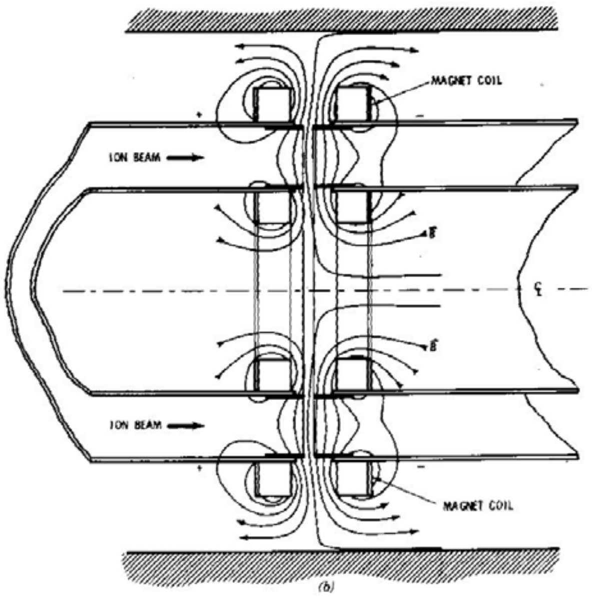
$$\Delta n = \left(\frac{eB_0}{2m_e}\right)^2 \frac{2\epsilon_0 m_e}{e^2} \quad \Rightarrow \quad E_r = -\frac{\omega_{g0}^2 m_e}{4e} r$$

Methods to accelerate high-current neutralized ion beams

- The challenge in a neutralized beam accelerator is control of electrons in the presence of strong axial electric fields.
- The electrons cannot cross acceleration gaps with the ions. The neutralizing electrons must be removed from the ion beam at the entrance to a gap and replaced at the downstream side. Also the drift regions between acceleration gaps must be electrically isolated from the gaps.



Bias grids prevent streaming of electrons into the acceleration gaps



Radial magnetic field inhibits electron streaming

Self-neutralization of ion beam by collisions with background neutrals

- Neutralization can be achieved by allowing the beam to pass through a background gas where the beam ions have ionizing and charge exchange collisions with the gas molecules.
  - Charge exchange (transfer)
    A^+ (fast) + X^0 (slow) → A^0 (fast) + X^+ (slow)
  - Ionization
    A^+ (fast) + X^0 (slow) → A^+ (fast) + X^+ (slow) + e

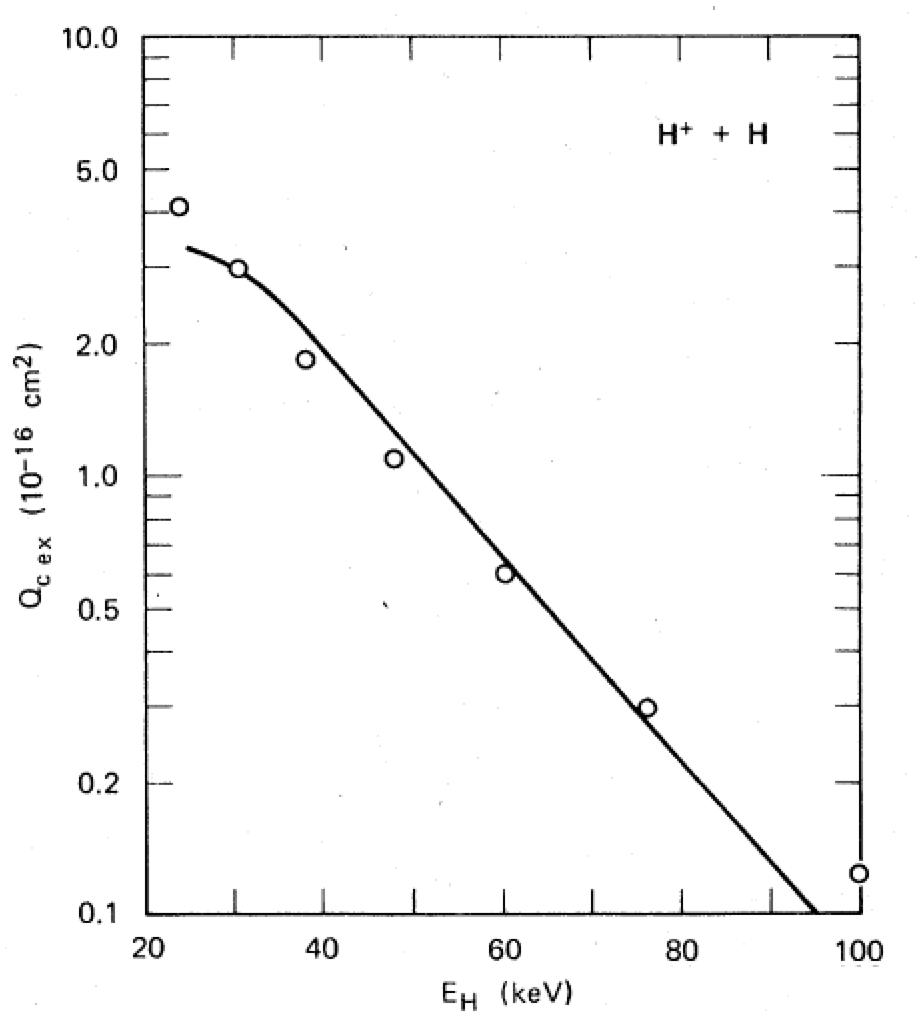
  → Slow positive ions and electrons are produced.

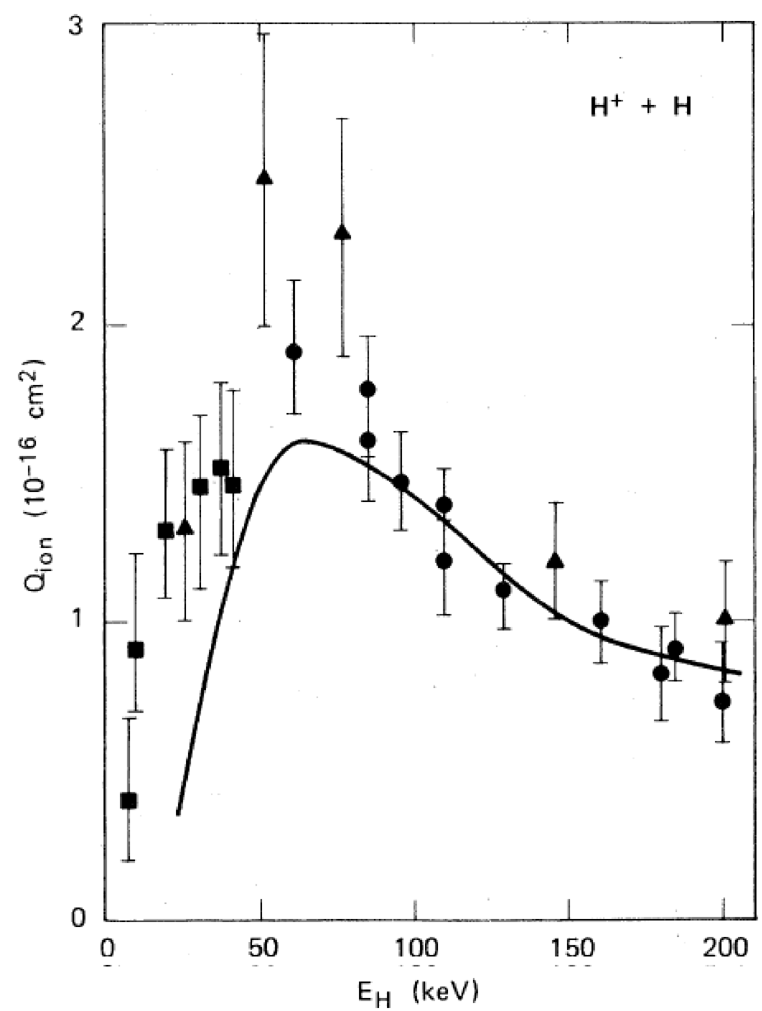
- Electrons, produced by ionization, are trapped within the beam by its own space charge, resulting in a decrease of the effective beam perveance, and hence space-charge expansion, to a value that is considerably less than that of the unneutralized beam.

- The slow positive ions are expelled from the beam by the radial electric field. Conversely, the electrons are captured within the beam.
- Poisson equation (complicated, solved by Holmes (PRA, 19, 389 (1979)):

$$\frac{d^2\phi}{dr^2} + \frac{1}{r}\frac{d\phi}{dr} = -\frac{e}{\epsilon_0}[n_b + n_i - n_e]$$

Cross-sections for ion-induced reactions





Olsen and Salop, PRA, 16, 531 (1977)

Numerical results (Holmes (PRA, 19, 389 (1979))

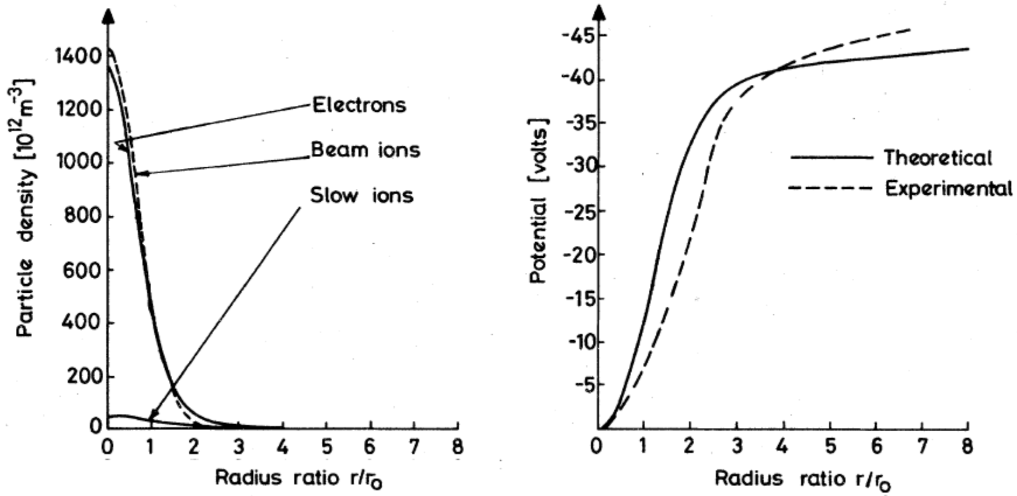


FIG. 4. Shape of the potential well and particle profiles at low pressure; beam energy 20-keV He$^+$, pressure 1.25×10^{-4} Torr, current 17.6 mA, radius 5 mm.

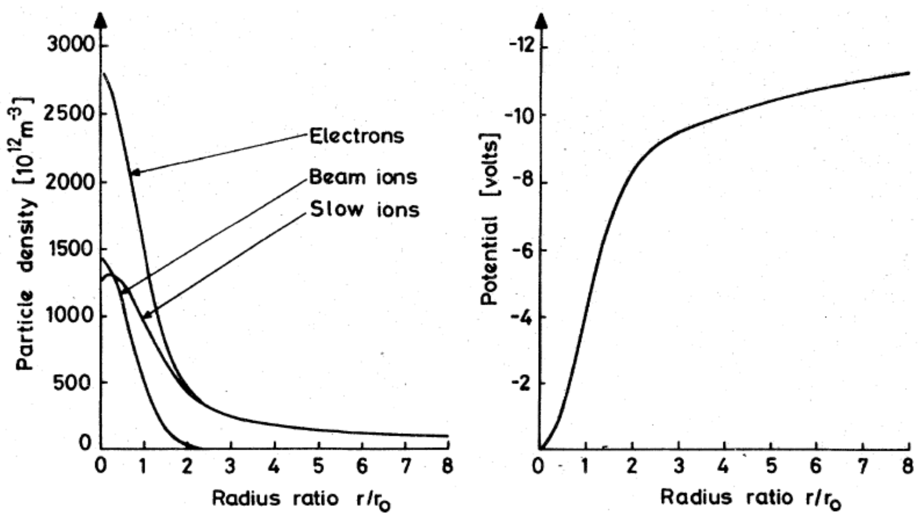


FIG. 5. Shape of the potential well and particle profiles at high pressure; beam energy 20-keV He$^+$, pressure 2×10^{-3} Torr, current 17.6 mA, radius 5 mm.

Numerical results (Holmes (PRA, 19, 389 (1979))