WP3 Capture ½-day

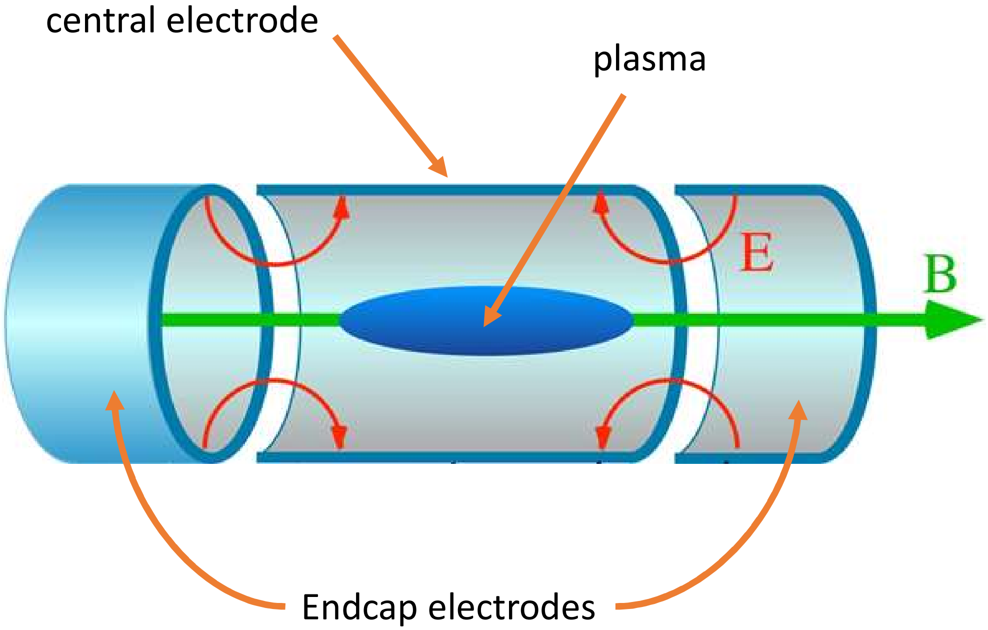
Non-neutral plasma approach

Christopher Baker

11th April 2022

Trap – Basic non-neutral plasma

- Cylindrical Penning, or Penning-Malmberg trap
- 3+ electrodes – 2x endcaps + electrodes (central, compensating, Rotating wall, …)
- All electrodes floating / ungrounded



Adapted from Capture meeting presentation 18th Jan 2022

Trap requirements / comparison

- Previous Gabor plasma

Primarily Nonnenmacher *et al.* Appl. Sci. **11** 4357 (2021) ref.'s [28-34]

  - B-field 0.01-0.5T
  - Electron density near Brillouin limit often modelled
    - Although 'Pozimski Factor' ~ 0.1-0.75 quoted
  - Plasma radius = Anode radius
  - Confining voltage 2-600kV

    = space-charge
  - Load via internal discharge
  - Lifetime/confinement time <1s
    - Dynamic equilibrium
  - Reload rate >Hz

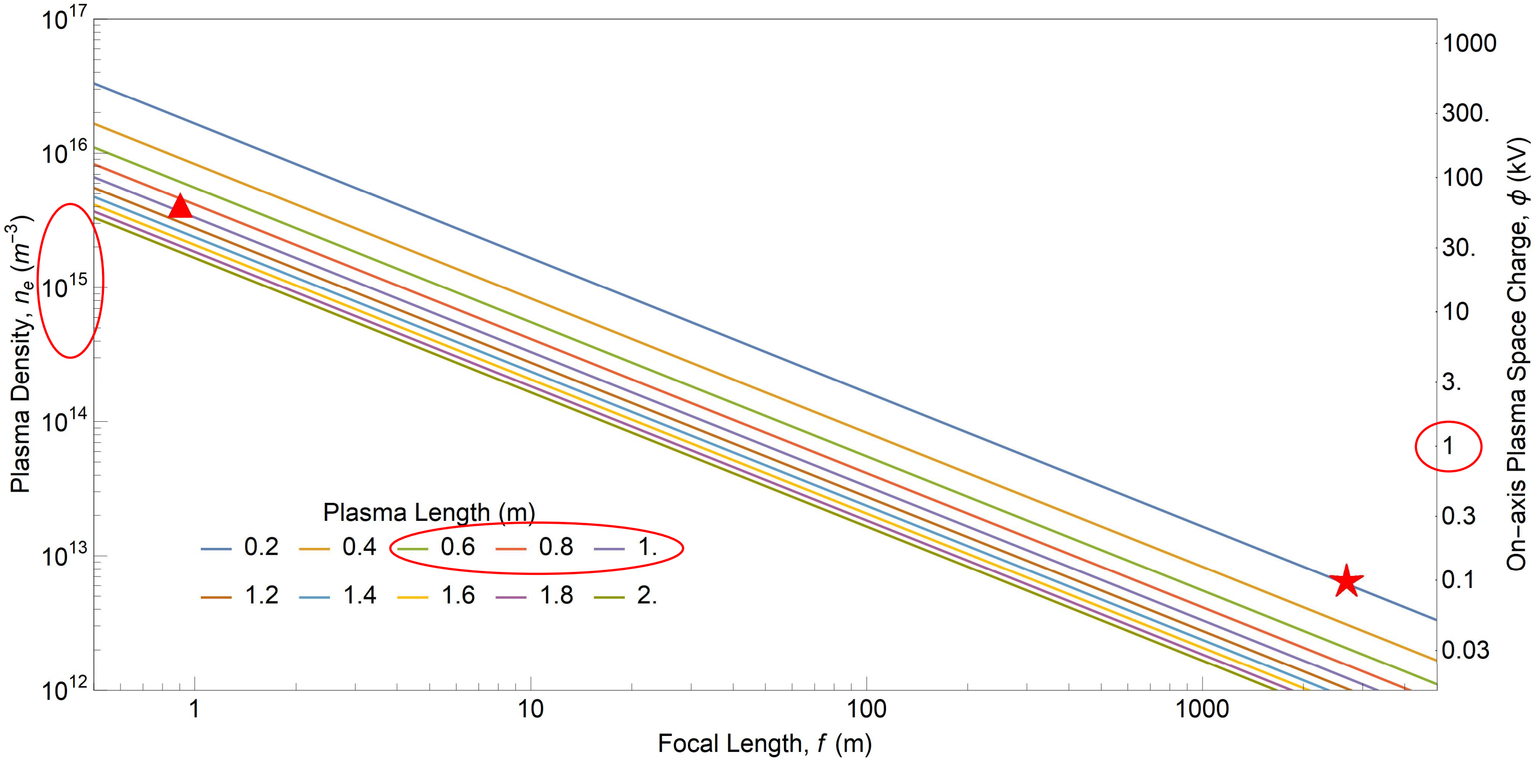
- Proposed plasma

to be experimentally determined

  - B-field ~0.1T
  - Electron density at 10-20% of Brillouin limit (i.e. 0.1-0.2 'Pozimski Factor')
  - Plasma radius ~ 0.3-0.5 electrode radius
  - Confining voltage ~ 60kV

    > Space charge
  - Load via ext. 'beam' source
  - Lifetime - ?
  - Reload rate - ?
  - Density ~ 10^{15} m^{-3}
  - Length ~ 1 m

Parameter space plot



Source (beam)

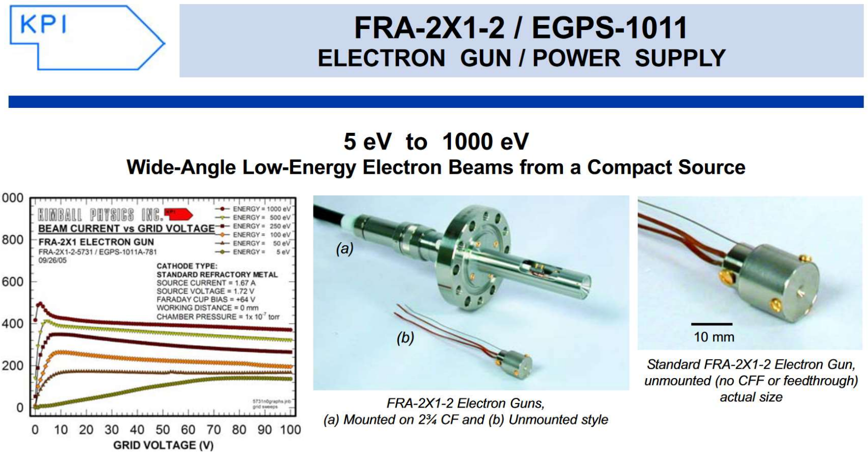
Hot (field assisted) cathode/filament (Thoriated tungsten) used to produce a beam

- Can be located in a low magnetic field, a fringe field, or a high (Tesla-level) field
  - Typically located on-axis
    - Fixed & ‘transparent’ to ion beam
    - Movable in/out of beam

Beam directed into trapping region (electrodes/anode)

Static particle trap (2-stream instability/collisions)

Dynamic particle trap (beam capture)



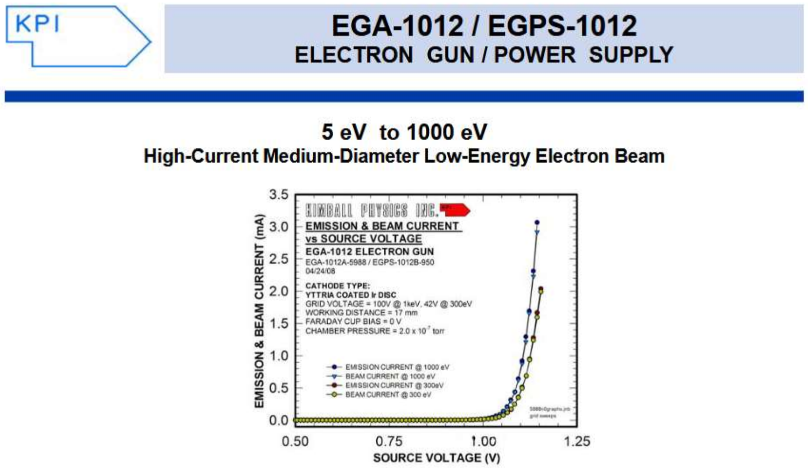
KPI

FRA-2X1-2 / EGPS-1011
ELECTRON GUN / POWER SUPPLY

5 eV to 1000 eV
Wide-Angle Low-Energy Electron Beams from a Compact Source

FRA-2X1-2 Electron Guns,
(a) Mounted on 2¾ CF and (b) Unmounted style

Standard FRA-2X1-2 Electron Gun, unmounted (no CFF or feedthrough) actual size

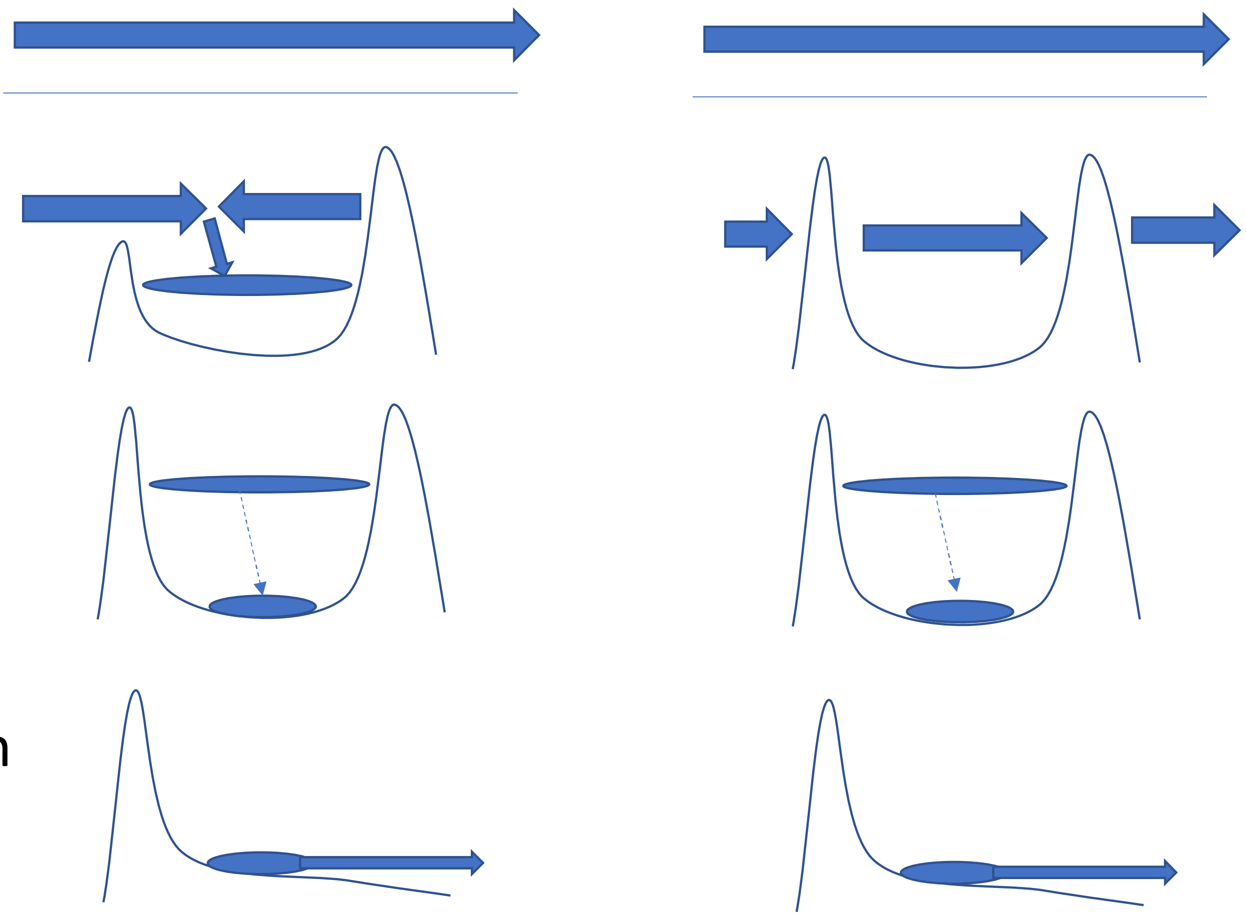


KPI

EGA-1012 / EGPS-1012
ELECTRON GUN / POWER SUPPLY

5 eV to 1000 eV
High-Current Medium-Diameter Low-Energy Electron Beam

Procedure



- Capture
  - μs – 10s
- Study/Storage
  - Times: μs – 10^6s
  - Cooling (0.1-10s)
- Eject to MCP/P-screen
  - μs - ms

Storage - I

PHYSICS OF PLASMAS **13**, 123502 (2006)

Plasma manipulation techniques for positron storage in a multicell trap

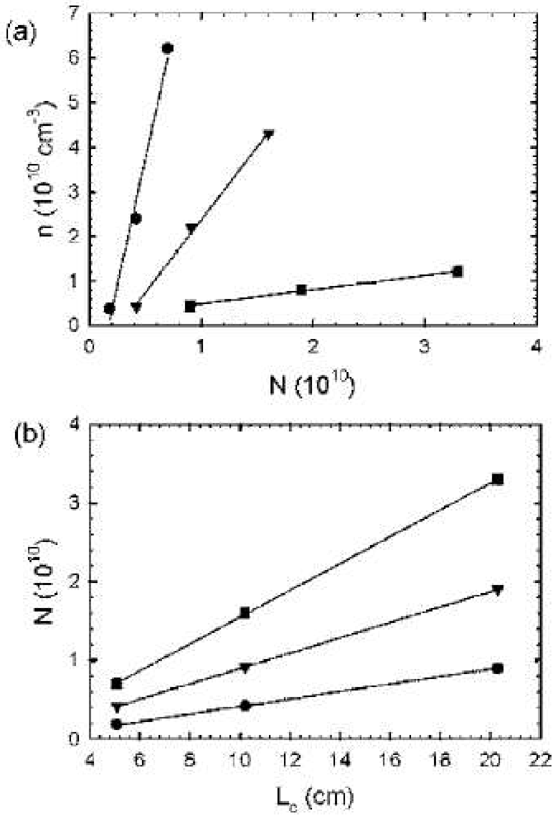
J. R. Danielson, T. R. Weber, and C. M. Surko

TABLE II. Summary of plasma parameters achieved for a 1000 V confinement potential, including the confinement length L_c, fill voltage V_f, total particle number N, plasma radius R_p, plasma length L_p, plasma density $\bar{n}$, and the space charge potential ϕ_o.

L_c (cm)	V_f (V)	N (10^{10})	R_p (cm)	L_p (cm)	$\bar{n}$ (cm^{-3})	ϕ_0 (V)
5.08	300	0.18	0.18	4.7	0.38	270
	600	0.42	0.10	5.5	2.4	670
	900	0.70	0.07	7.3	6.2	930
10.2	300	0.42	0.18	9.8	0.42	300
	600	0.91	0.11	10.8	2.2	715
	900	1.60	0.09	14.7	4.3	990
20.3	300	0.90	0.18	20.0	0.44	320
	600	1.90	0.19	20.6	0.81	640
	900	3.30	0.19	23.4	1.2	975

Rw = 1.27cm
(Rp/Rw<0.2)

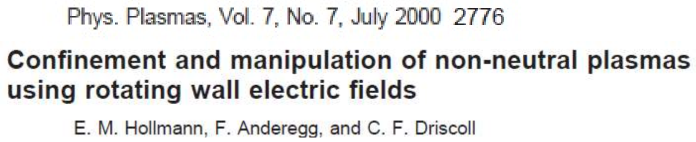
nique. Operation of the trap at confinement potentials of 1 kV was also demonstrated, resulting in the ability to store $\geqslant 10^{10}$ particles in a single cell. In other recent work, it has been shown that plasmas can be compressed radially and maintained for days using the rotating wall compression in the newly discovered strong-drive regime by application of a single, fixed RW frequency, thereby eliminating the need for



$10^{15} – 10^{16}$ m^{-3}

FIG. 5. (a) The dependence of plasma density on total number N for three different confinement lengths L_c of (●) 5.1, (▼) 10.2, and (■) 20.3 cm. (b) The dependence of N on L_c for three different fill voltages: V_f: (●) 300, (▼) 600, and (■) 900 V. For all experiments, the confinement voltage V_c=1.0 kV.

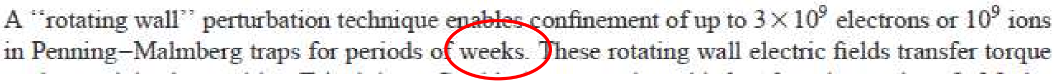
Storage - II



Phys. Plasmas, Vol. 7, No. 7, July 2000 2776

Confinement and manipulation of non-neutral plasmas using rotating wall electric fields

E. M. Hollmann, F. Anderegg, and C. F. Driscoll



A "rotating wall" perturbation technique enables confinement of up to 3×10^9 electrons or 10^9 ions in Penning–Malmberg traps for periods of weeks. These rotating wall electric fields transfer torque

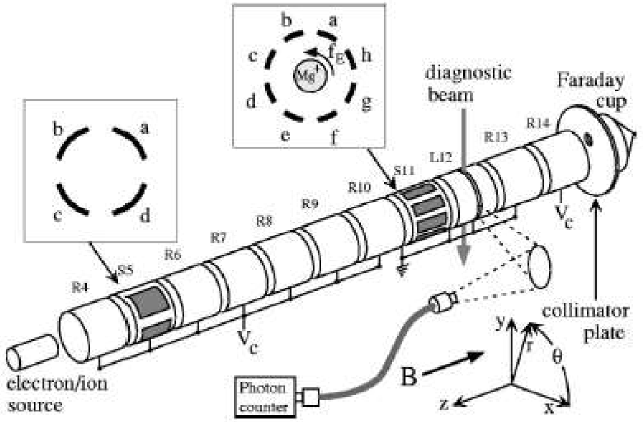
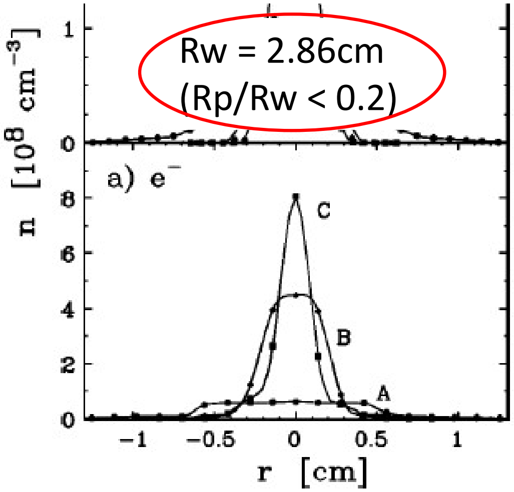


FIG. 1. Schematic of the IV Penning–Malmberg trap used for electron and ion plasma experiments. Electrons are typically confined in the region S5 → S11; Mg^+ ions (shown) are typically confined in the region S11 → R13. A laser diagnostic is used for ion plasmas; a collimator plate and Faraday cup diagnostic is used for electron plasmas. Azimuthally-dependent modes are driven and detected with sectored rings (S5 and S11).

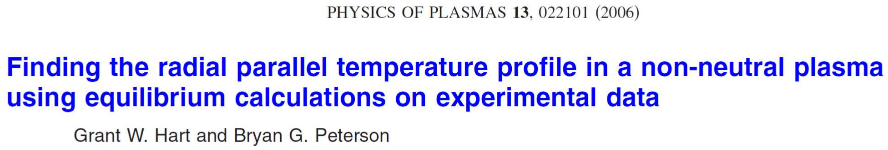


Rw = 2.86cm

(Rp/Rw < 0.2)

$10^{14} – 10^{15}\ \mathrm{m^{-3}}$

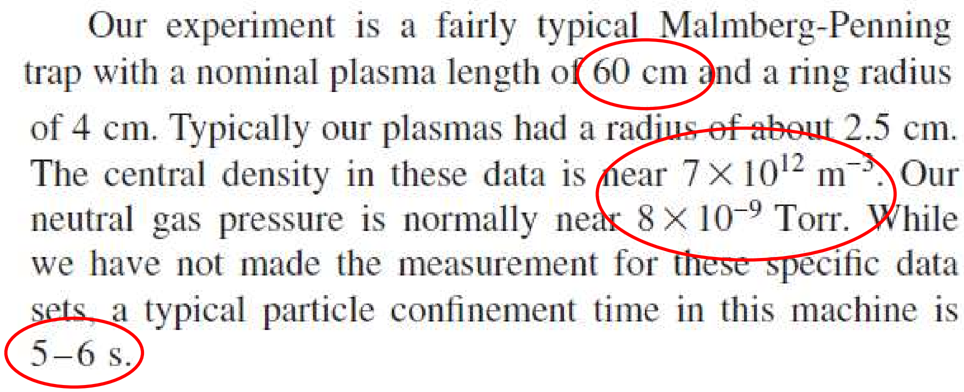
Storage - III



PHYSICS OF PLASMAS **13**, 022101 (2006)

Finding the radial parallel temperature profile in a non-neutral plasma using equilibrium calculations on experimental data

Grant W. Hart and Bryan G. Peterson



Our experiment is a fairly typical Malmberg-Penning trap with a nominal plasma length of 60 cm and a ring radius of 4 cm. Typically our plasmas had a radius of about 2.5 cm. The central density in these data is near $7 \times 10^{12}\ \mathrm{m}^{-3}$. Our neutral gas pressure is normally near 8×10^{-9} Torr. While we have not made the measurement for these specific data sets, a typical particle confinement time in this machine is 5–6 s.

B-field=? (original work 40-675gauss)

Rp/Rw ~0.6

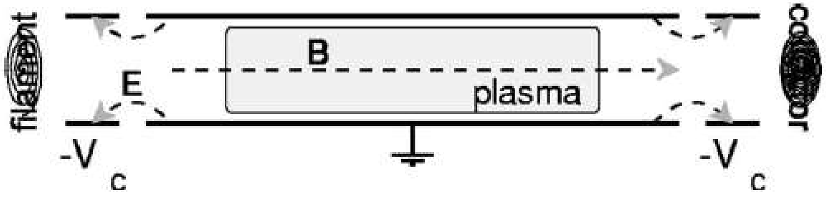


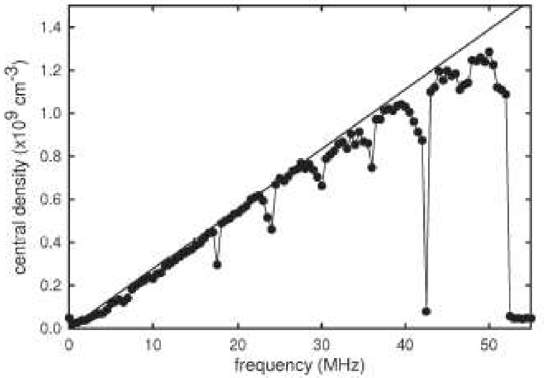
FIG. 1. Electric and magnetic fields in a Malmberg-Penning trap.

1. Notice large Archimedes spiral hot cathode filament
2. RW unused

Storage - IV

J. R. Danielson, D. H. E. Dubin, R. G. Greaves, and C. M. Surko
Rev. Mod. Phys. **87**, 247 – Published 17 March 2015

$10^{14} – 10^{15}$ m^{-3}



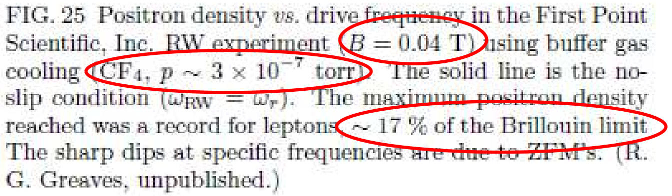
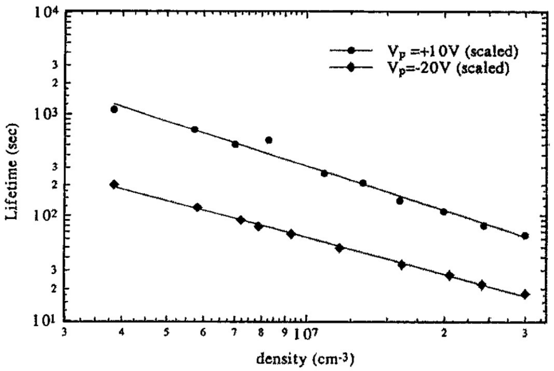
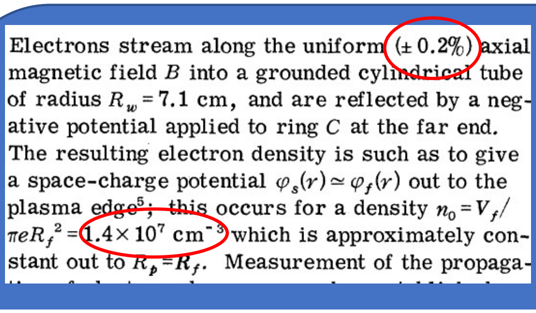


FIG. 25 Positron density *vs.* drive frequency in the First Point Scientific, Inc. RW experiment ($B = 0.04$ T) using buffer gas cooling (CF_4, $p \sim 3 \times 10^{-7}$ torr). The solid line is the no-slip condition ($\omega_{RW} = \omega_r$). The maximum positron density reached was a record for leptons, ~ 17 % of the Brillouin limit. The sharp dips at specific frequencies are due to ZFM's. (R. G. Greaves, unpublished.)

- Details difficult to come by due to commercial considerations
  - Lifetime likely annihilation limited (but 10s seconds)
  - Pressures not unlike that possible in Gabor lens

Lifetimes (static)





Electrons stream along the uniform (± 0.2%) axial magnetic field B into a grounded cylindrical tube of radius $R_w = 7.1$ cm, and are reflected by a negative potential applied to ring C at the far end. The resulting electron density is such as to give a space-charge potential $\varphi_s(r) \simeq \varphi_f(r)$ out to the plasma edge[5]; this occurs for a density $n_0 = V_f/\pi e R_f^{\,2} = 1.4\times 10^7\ \mathrm{cm}^{-3}$ which is approximately constant out to $R_p = R_f$. Measurement of the propaga-

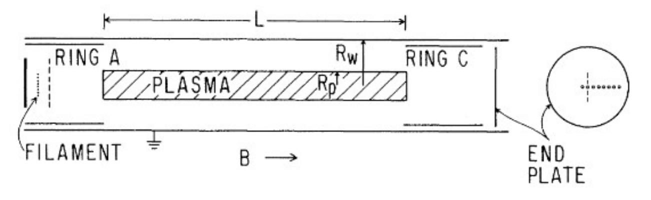
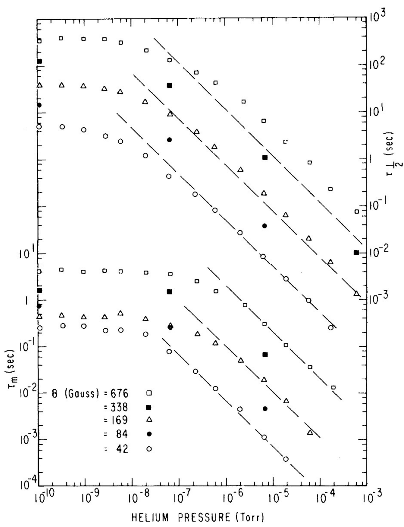


FIG. 1. The cylindrical confinement geometry.

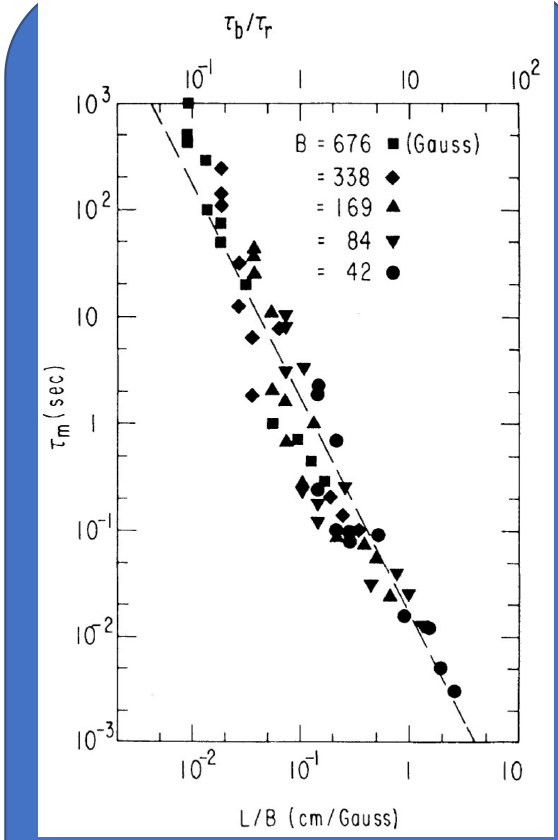


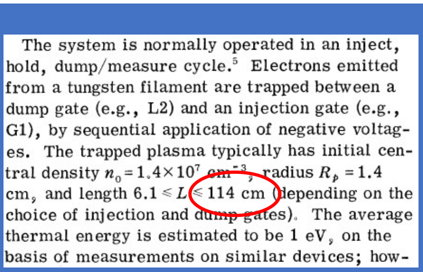
Phys. Rev. Lett. **50** 167 (1983)

Phys. Plasmas **1** 1123 (1994)

Phys. Rev. Lett. **44** 654 (1980)

Rp/Rw ~0.2





The system is normally operated in an inject, hold, dump/measure cycle.[5] Electrons emitted from a tungsten filament are trapped between a dump gate (e.g., L2) and an injection gate (e.g., G1), by sequential application of negative voltages. The trapped plasma typically has initial central density $n_0 = 1.4\times 10^7\ \mathrm{cm}^{-3}$, radius $R_p = 1.4$ cm, and length $6.1 \leqslant L \leqslant 114$ cm (depending on the choice of injection and dump gates). The average thermal energy is estimated to be 1 eV, on the basis of measurements on similar devices; how-

Some Equations

- Brillouin limit (number density): $n_B = \frac{B^2}{2\,\mu_0\, m\, c^2}$
- Space charge: $\phi = \frac{e\, n_e\, r_p^2}{4\,\epsilon_0}\left(1 + 2\ln\left(\frac{r_w}{r_p}\right) + \frac{r^2}{r_p^2}\right)$
- (inverse) Focal length: $\frac{1}{f} = \frac{e\, Z\, n_e\, l}{4\,\epsilon_0\, U}$

Adapted from Capture meeting presentation 18th Jan 2022

Focal length (focussing constant)

e.g. Pozimski and Meusel Rev. Sci. Instrum. 76 063308 (2005)

$$\frac{1}{f} = k\ l = \frac{e\ Z\ \rho_e\ l}{4\ \epsilon_0 E_k}$$

- Non-relativistic, short, weak, parallel, no space-charge lens approximation
  [identical to Aymar *et al.* fphy **08** 567738 (2020)]

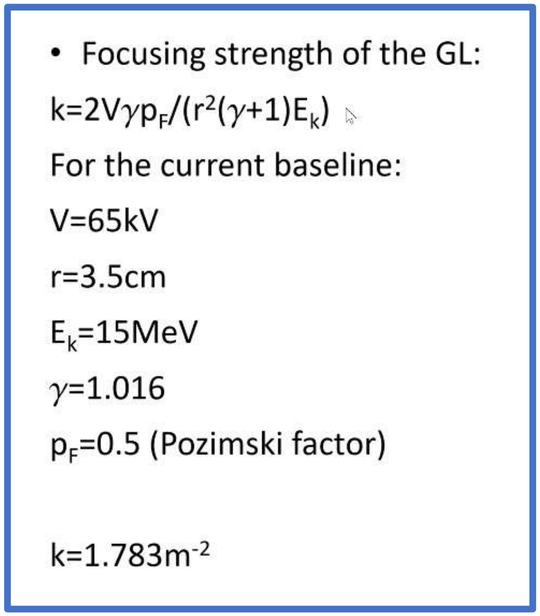
With expected plasma parameters:

l = plasma length (0.8-1 m)
ρ_e = plasma density [n_B] (5E15 m^{-3})
E_k = Ion Kinetic Energy (15 MeV)
e, ϵ_0 = physical constants

One finds
k = focussing constant (1.2-1.5 m^{-2})
f = focal length (0.8-0.7 m)

Also expecting:

r_p = plasma radius (3.5 cm)
r_A = anode radius (5-10 cm)
ϕ = space charge (50-85 kV)
V_A = Confining voltage (100 - 400 kV)
B = Confining magnetic field (0.1 T)
n_B = Broullion limit (~5E16)
P_F = ρ_e / n_B (~0.1)



- Focusing strength of the GL:

$k=2V\gamma p_F/(r^2(\gamma+1)E_k)$

For the current baseline:

V=65kV
r=3.5cm
E_k=15MeV
γ=1.016
p_F=0.5 (Pozimski factor)

k=1.783m^{-2}