Parallel Temperature Diagnostic

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Winter School on Physics with Trapped Charged Particles
9-20 January 2012

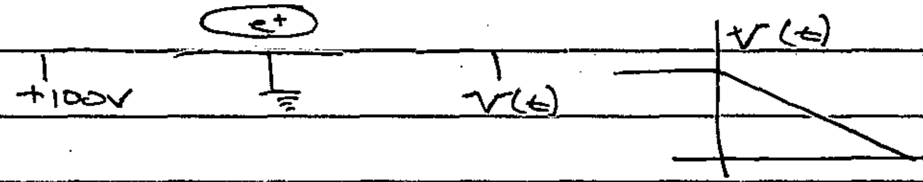
Ecole de Physique des Houches

D. L. Eggleston, C. F. Driscoll, B. R. Beck, A. W. Hyatt, and J. H. Malmberg, Parallel energy analyzer for pure electron plasma devices, Phys. Fluids B **4**, 3432 (1992).

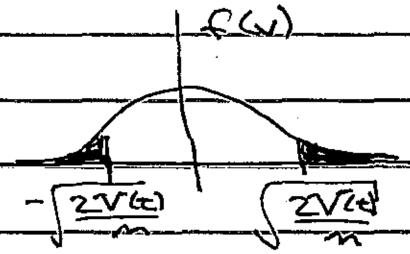
B. R. Beck, Measurement of the magnetic and temperature dependence of the electron-electron anisotropic temperature relaxation rate, Ph.D Thesis, UCSD, 1990.

Parallel Temperature Diagnostic

1) Penning Malmberg trap - positrons



2) Calculate how many charges have escaped when the potential is at V(t)



$$Q_{esc} = 2\int_{\sqrt{\frac{2V(t)}{m}}}^{\infty} dv\, f(v)$$

3) Dropping all constants

$$Q_{esc} = N\int_{\sqrt{V}}^{\infty} dv\, e^{-v^2/T}$$ N = # charges in plasma

$$u = v/\sqrt{T}$$

$$= N\sqrt{T}\int_{\sqrt{V/T}}^{\infty} du\, e^{-u^2}$$ complementary error function

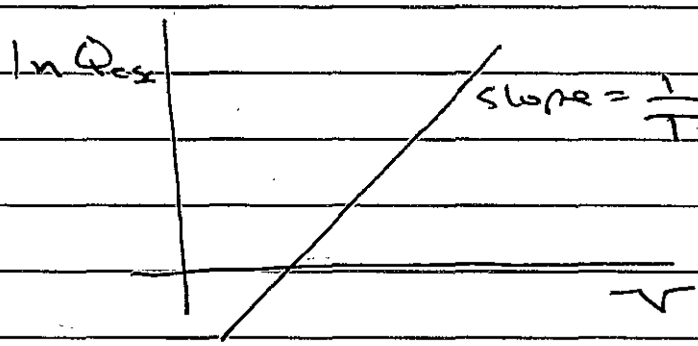
$$\frac{dQ_{esc}}{dV} = N\sqrt{T}\, e^{-V/T}\frac{1}{\sqrt{VT}} = \frac{N e^{-V/T}}{\sqrt{V}}$$

$$Q_{esc} = N\sqrt{T}\frac{e^{-V/T}}{\sqrt{V/T}}$$ $$\int_{\sqrt{x}}^{\infty} du\, e^{-u^2} \simeq \frac{e^{-x}}{2\sqrt{x}}$$

$$= \frac{NT}{\sqrt{V}}e^{-V/T}$$

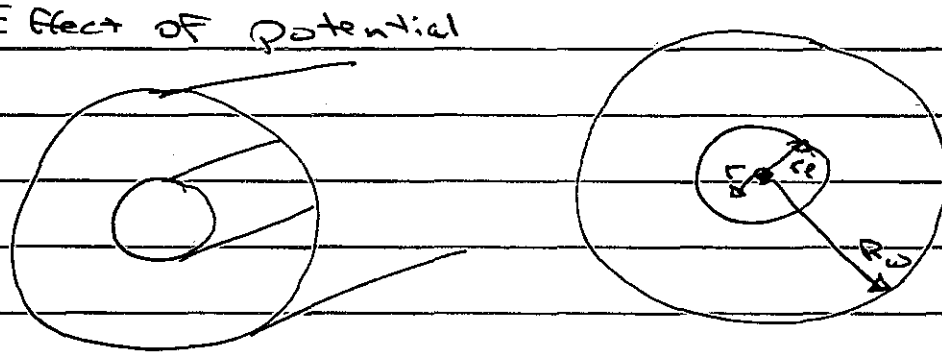
$$\frac{d \ln Q_{esc}}{dV} = \frac{1}{Q_{esc}} \frac{d Q_{esc}}{dV} = \frac{\sqrt{V}}{NT} e^{+V/T} \frac{N}{\sqrt{V}} e^{-V/T}$$

$$\boxed{\frac{d \ln Q_{esc}}{dV} = \frac{1}{T}}$$



Correct and complete if space charge isn't important $\Rightarrow$ not a plasma

4) Effect of potential



$$\Phi(r) = \frac{n_0 e}{4\epsilon_0}\left[1 - \frac{r_p^2}{R_w^2} + 2 \ln \frac{R_w}{r_p}\right] r_p^2$$

4a $T = 0$ limit

$$\Phi(r) = \Phi_0 - \frac{n e}{4\epsilon_0} r^2$$

$$V(t) = V_0 - \Delta V = \Phi_0 - \Delta V$$

Charge escapes if $\Phi(r) > V(t)$

escapes out to r — for simplicity, choose $V_0 = \Phi_0$

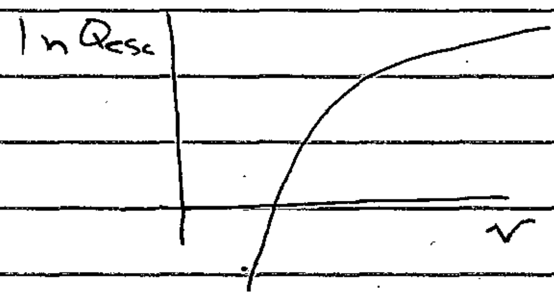
$$\Phi_0 - \frac{ne}{4\epsilon_0} r^2 = \Phi_0 - \Delta V$$

4a cont $\qquad \dfrac{ne}{4\epsilon_0} r^2 = \Delta V$

$$r^2 = \frac{4\epsilon_0 \Delta V}{ne} \qquad L \equiv \text{plume Length}$$

$$Q_{esc} = L n \pi r^2 = L n \pi \frac{4\epsilon_0 \Delta V}{ne}$$

$$Q_{esc} = \frac{4\pi L \epsilon_0}{e} \Delta V$$



No temperature dependence, obviously

Need to reconcile this curve with previous curve

4b Lets assume that at $T=0$, charge is just starting to escape at $r=0$

i.e $V(t) = \Phi_0$

Will charge escape off the axis?
Yes, if $T \neq 0$

How far off the axis?

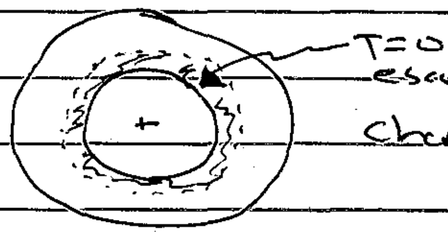
$$V(t) - \Phi(r) \lesssim kT/e$$

$$\frac{ne}{4\epsilon_0} r^2 \simeq kT/e$$

$$r^2 = 4\frac{kT\epsilon_0}{ne^2} \simeq \lambda_D^2$$

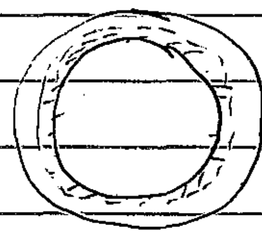
Postrons out to a radius of a few Debye lengths will escape

What about when many positrons have escaped?

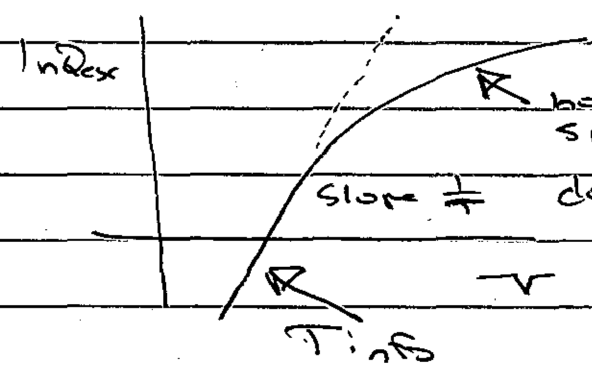


charge escapes from bulked region

a bit later



Plasma is basically unfolding from the center ... not density, only space charge info



5) How much charge contains practical T info

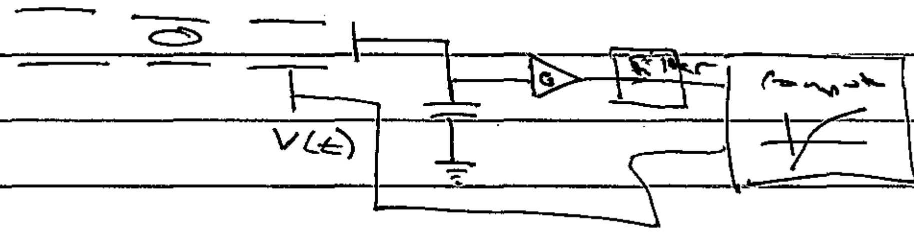
$$Q_{useful} = n\pi r^2 L = n\pi\lambda_D^2 L$$

$$= \pi n L \frac{kT\epsilon_0}{ne} = \pi L \frac{kT\epsilon_0}{e}$$

$$\boxed{Q_{useful} \propto LT}$$

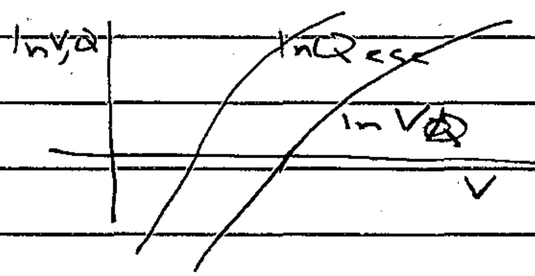
independent of n!

6) Practical implementation



$V_Q = \frac{Q_{esc}}{C} G$ what about G, C?

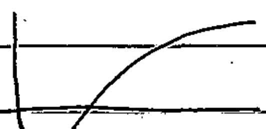
$\ln V_Q = \ln Q_{esc} + \ln \frac{G}{C}$ → just an offset



G and C have no interesting effects

Filters leave signal unchanged.

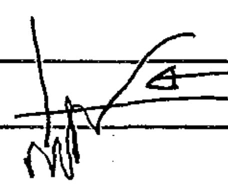
7) Effects of Noise...



← How far down does this go?

Quantization one limit... not important for leptons important for p̄

Noise



← Need at least a decade of straight line to find T

Upper limit

Q_{useful} dT gets harder and harder at low temperatures

7) cont At $T = 100K$, and $L = 10$ mm

$Q_{esc} \approx 1000$ charges.

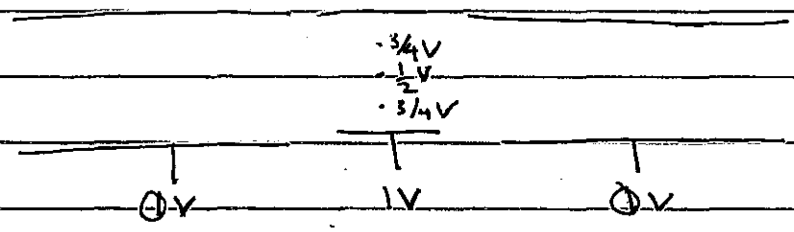
But this assumes everything is pulled out from the center. Approximation used for complementary error function breaks down.

$Q_{esc} \approx 100$.

7a) For long plasma, Bret Beck developed method incorporating info beyond straight line regions

8 Corrections

a) Finite length electrodes



Easy

b) Adiabatic Expansion

$$\frac{T_1}{T_0} = \left(\frac{L_0}{L_1}\right)^2, \quad \left(\frac{L_0}{L_1}\right)^{2/3}$$

1d

As the plasma is allowed to escape, it expands, temperature changes

c Subtle space charge effects

d ... Absolute factor of 2, roughly 20%

Example with Antiprotons

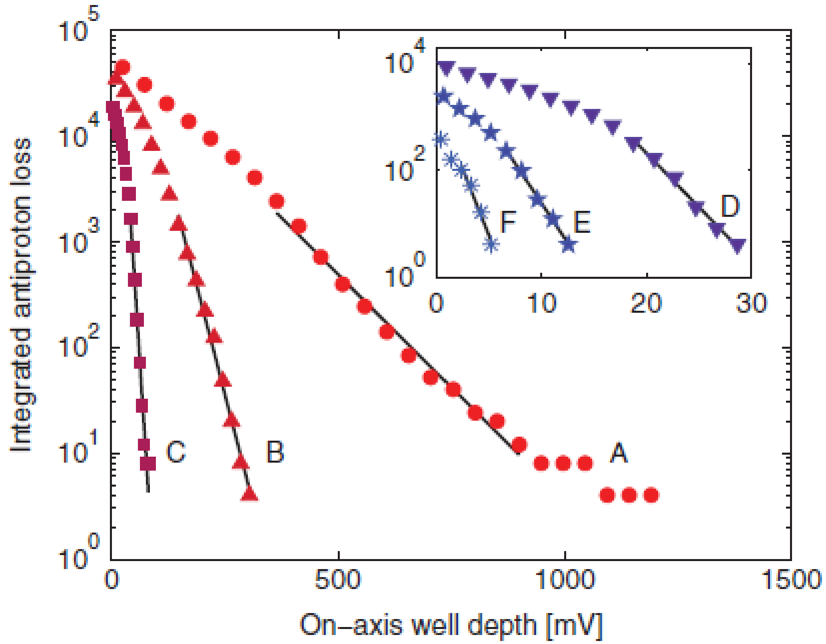
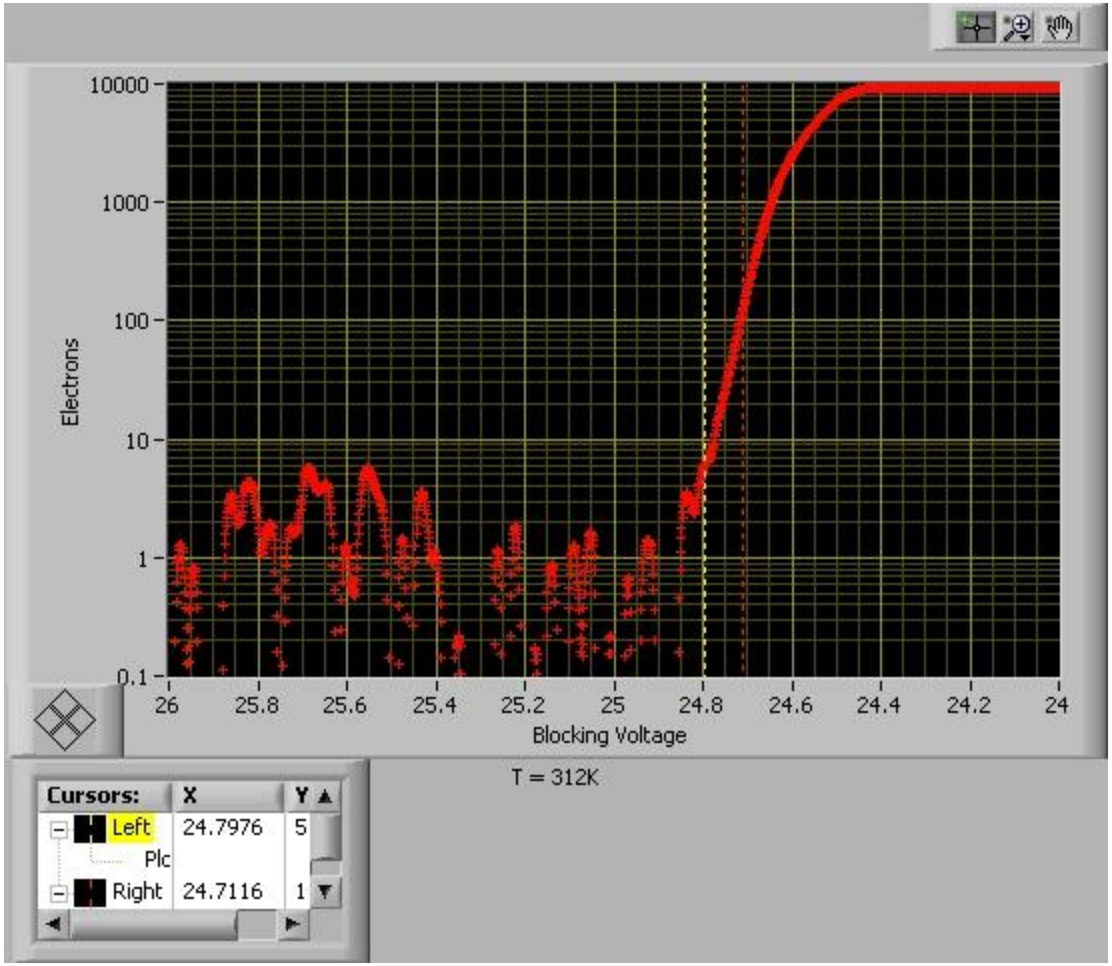


FIG. 2 (color). The number of antiprotons lost from the well as its depth is reduced is integrated over time and plotted against the well depth. The well depth is ramped from high to low; thus, time flows from right to left in the figure. The measured number is corrected for the 25% detection efficiency. The curves are labeled in decreasing order of the temperatures extracted from an exponential fit, shown as the solid lines. The temperatures (corrected as described in the text) are: A: 1040, B: 325, C: 57, D: 23, E: 19, and F: 9 K. As the antiprotons get colder, fewer can be used to determine their temperature, an effect described in Ref. [13].

Andresen et al (ALPHA Collaboration), Evaporative Cooling of Antiprotons to Cryogenic Temperatures, Phys. Rev. Lett., **105** 013003, 2010.

Example with Leptons



Example with Leptons