OBSERVATION OF A STRONG DIOCOTRON INSTABILITY IN AN ANTIPROTON PLASMA RING AND “TAILORING” OF PURE ELECTRON PLASMAS IN THE STRONG DRIVE REGIME

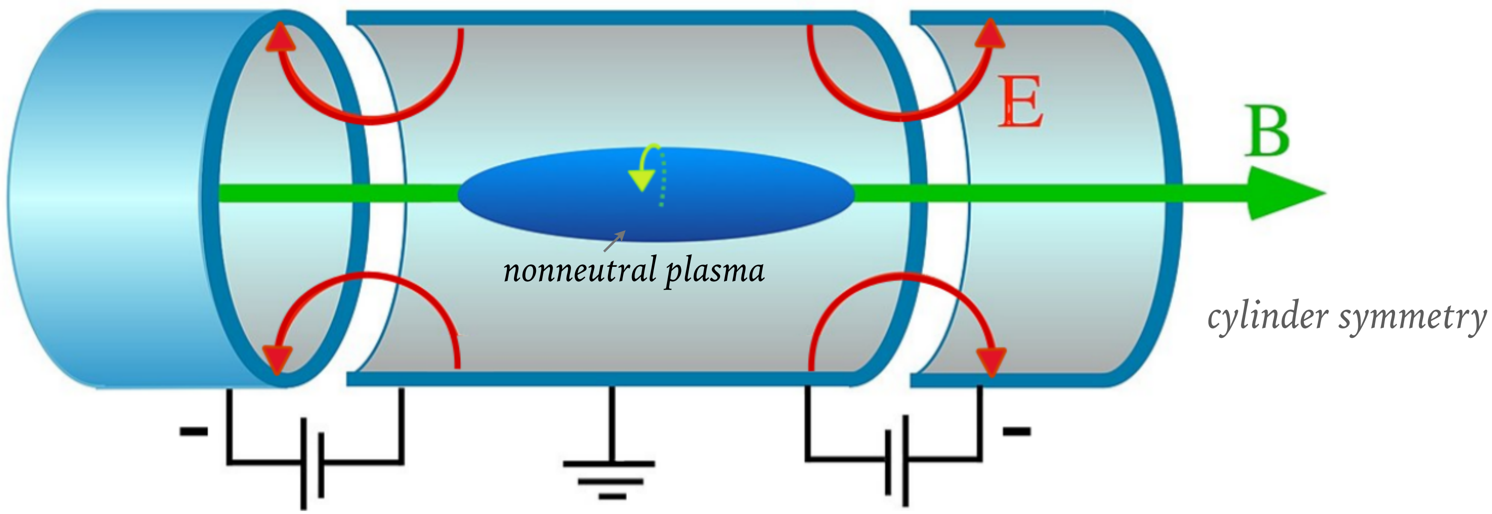
Ingmari Tietje (TU Berlin)
On behalf of the AEgIS collaboration (CERN)

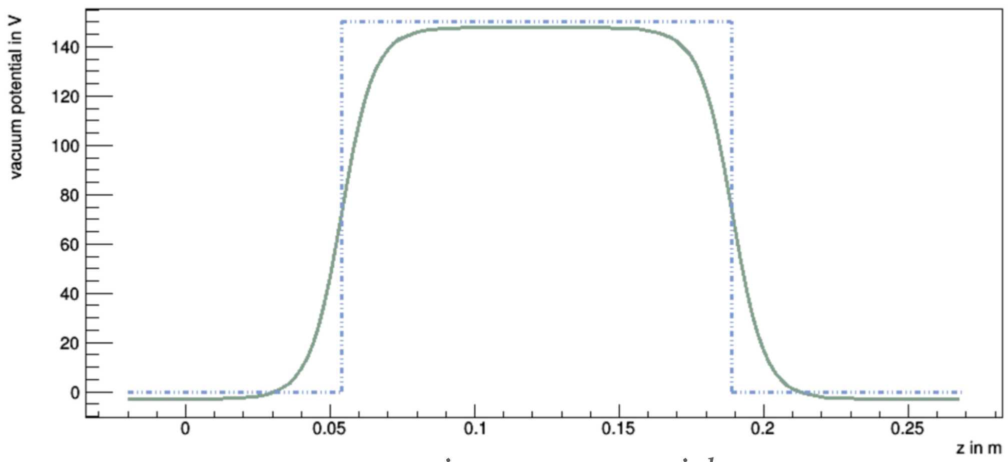
OUTLINE

- Properties of nonneutral plasmas.
- Strong DRive EVaporative Cooling (SDREVC) of electron plasmas (pioneered by the ALPHA collaboration)
  - Strong drive.
  - Strong drive + simultaneous evaporation of electrons.
- Diocotron instability
  - Fluid analogy of nonneutral plasma physics.
  - Hollow antiproton ring diocotron evolution.
- Plasma fluctuations.
- Summary & Outlook.

NONNEUTRAL PLASMAS

PENNING-MALMBERG TRAP



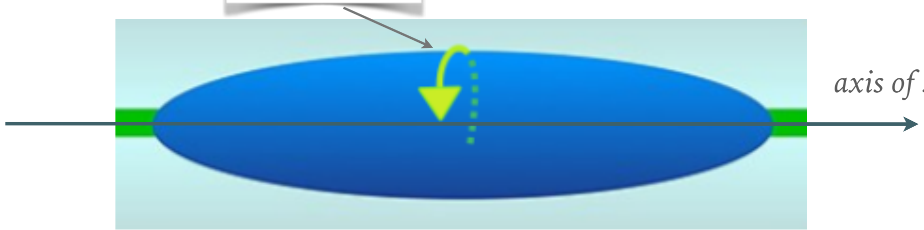


on-axis vacuum potential

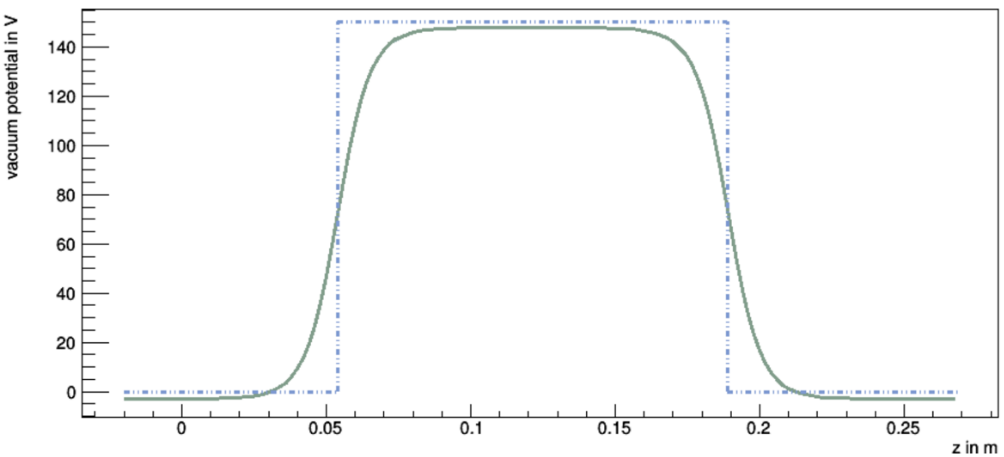
NONNEUTRAL PLASMAS

$$f_E = \frac{nq}{4\pi\epsilon_0 B}$$

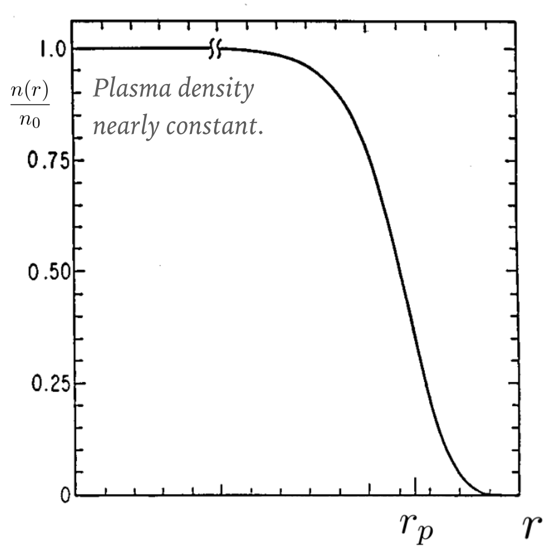
rotation frequency



axis of symmetry z



on-axis vacuum potential



Rapid drop-off over a Debye length.

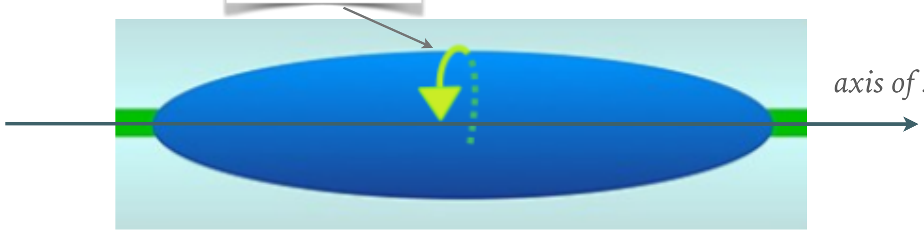
$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{nq^2}}$$

adapted from D. H. E. Dubin and T. M. O'Neil, Rev. Mod. Phys. 71, 87–172 (1999)

NONNEUTRAL PLASMAS

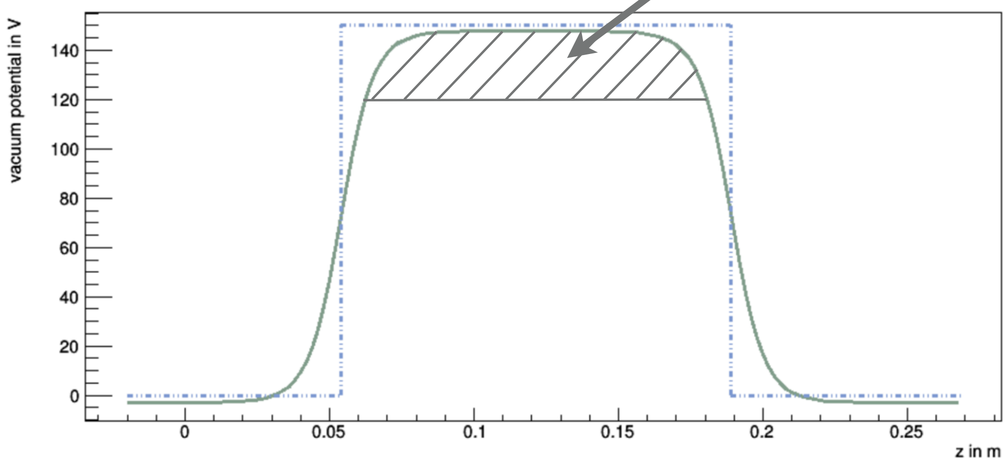
$$f_E = \frac{nq}{4\pi\epsilon_0 B}$$

rotation frequency

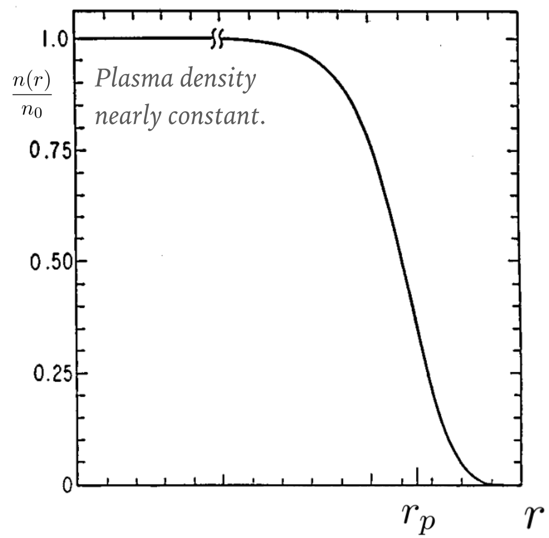


axis of symmetry z

space charge!!!



on-axis vacuum potential



Rapid drop-off over a Debye length.

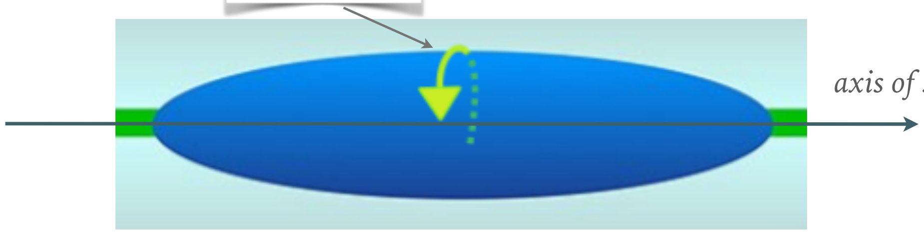
$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{nq^2}}$$

adapted from D. H. E. Dubin and T. M. O'Neil, Rev. Mod. Phys. 71, 87–172 (1999)

NONNEUTRAL PLASMAS

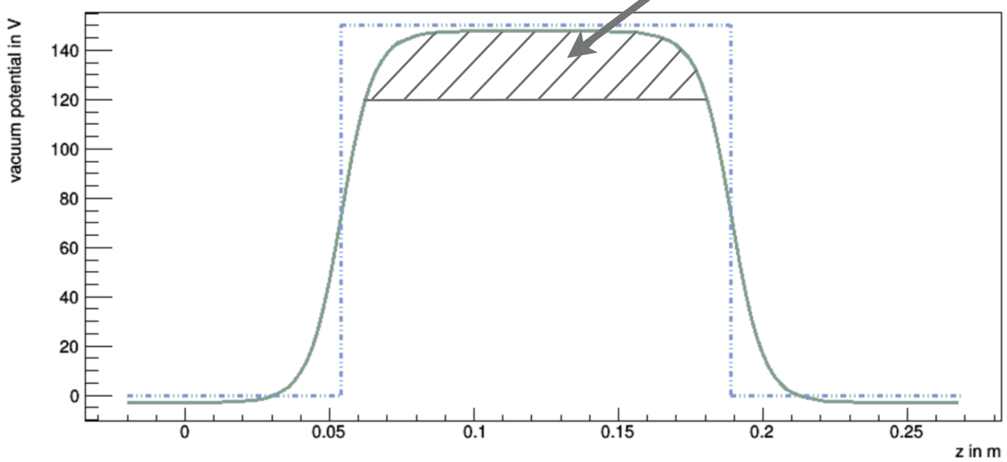
$$f_E = \frac{nq}{4\pi\epsilon_0 B}$$

rotation frequency



axis of symmetry z

space charge!!!



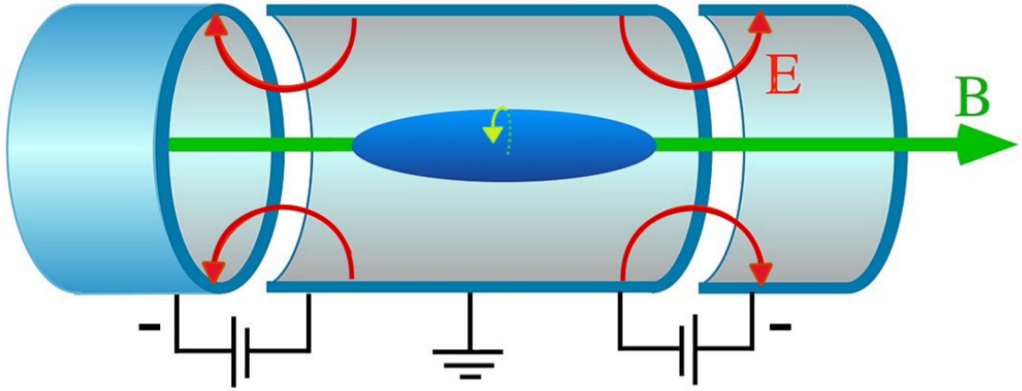
on-axis vacuum potential

AEgIS experiment mostly operates in the regime of:

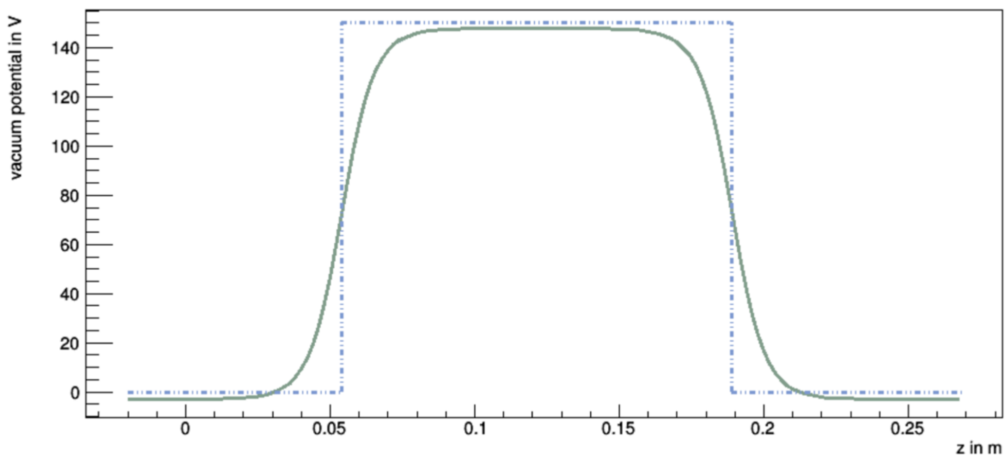
Cold-fluid guiding-center approximation!

$$\frac{\omega_p^2(r)}{\omega_c^2} = \frac{4\pi n_0(r) mc^2}{B_0} \ll 1$$

PROPERTIES OF NONNEUTRAL PLASMAS



Penning-Malmberg trap



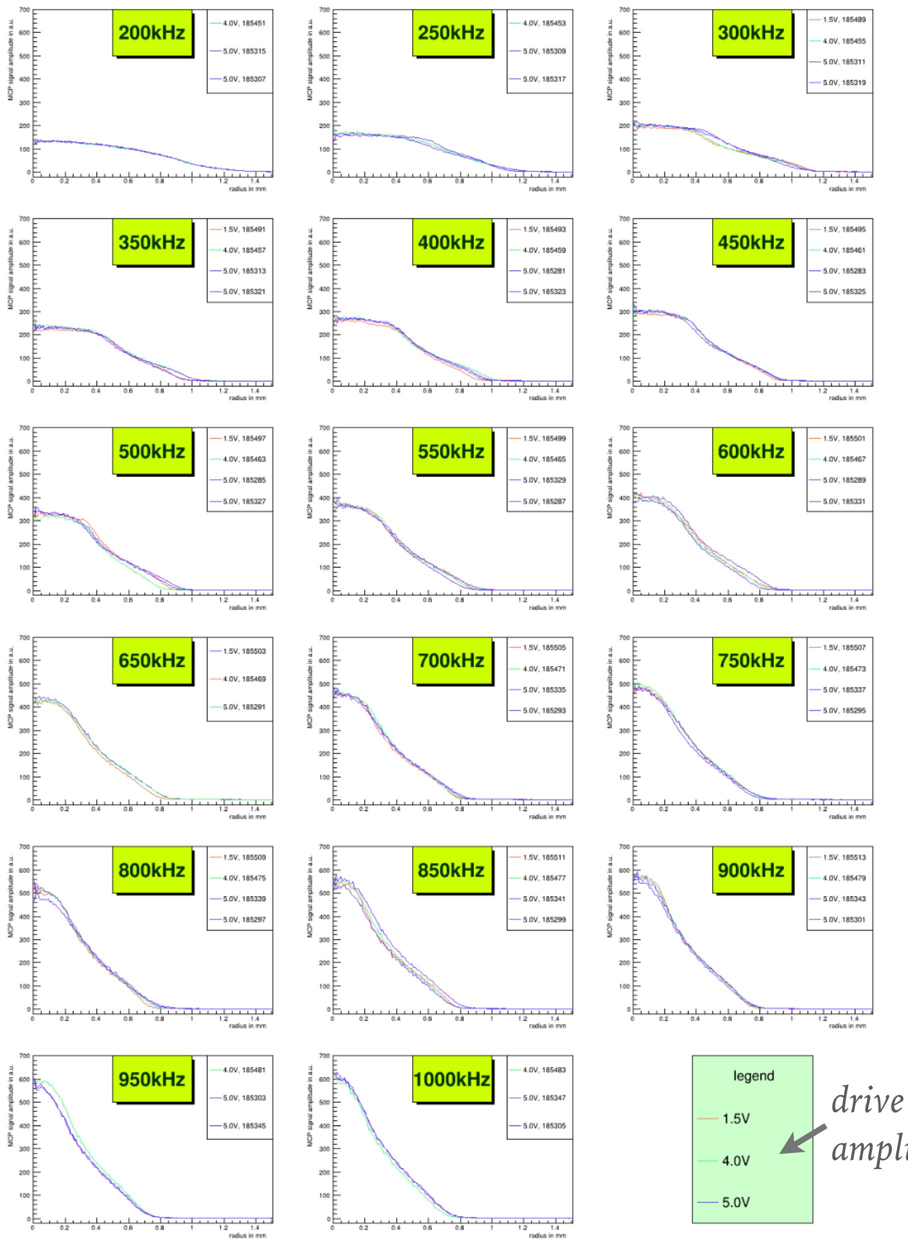
on-axis vacuum potential

- A nonneutral plasma ...
  - ... significantly alters the vacuum potential of the confining trap.
  - ... self-shields over the order of a Debye length: $\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{n q^2}}$
  - ... rotates at a uniform rate about the z-axis of the trap, when in thermal equilibrium.
  - ... assumes a density, which is proportional to the frequency it is rotating at. $f_E = \frac{nq}{4\pi\epsilon_0 B}$
- The regime AEgIS is working in can be adequately described within the cold-fluid guiding-center approximation.

$$\frac{\omega_p^2(r)}{\omega_c^2} = \frac{4\pi n_0(r) m c^2}{B_0} \ll 1$$

STRONG DRIVE EVAPORATIVE COOLING

of electron plasmas



drive amplitude

STRONG DRIVE

$$f_{\mathbf{rw}} \equiv f_E = \frac{nq}{4\pi\epsilon_0 B}$$

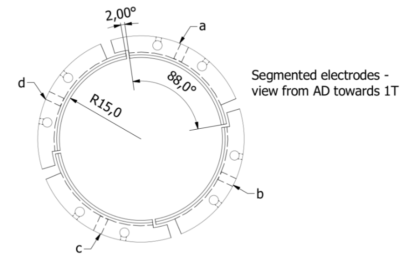
- A strongly driven nonneutral plasma `locks' to its drive frequency. Plasma density proportional to applied drive frequency.

  → *Plasma compression.*

  J. R. Danielson and C. M. Surko, Phys. Rev. Lett. ***94****, 035001 (2005).*

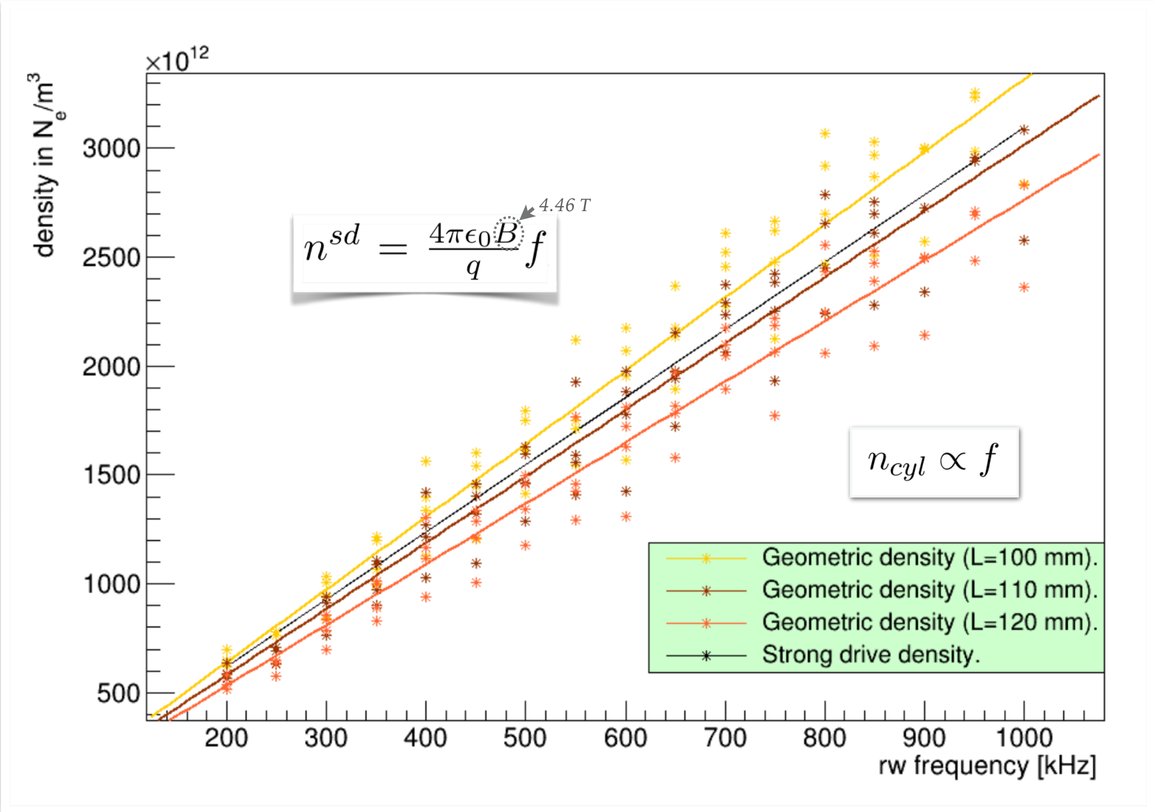
  J.R. Danielson and C. M. Surko, Physics of Plasmas ***13****, 055706 (2006)*

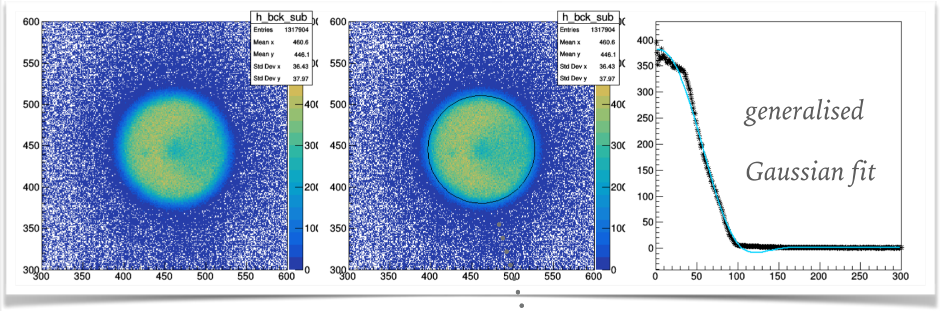
- The rotating wall technique provides the drive.



$$\phi_j(\theta, t) = a_{rw}\cos[m_\theta(\theta_j - 2\pi f_{rw}t)], \theta_j - \frac{\Delta\theta}{2} < \theta < \theta_j + \frac{\Delta\theta}{2}$$

STRONG DRIVE





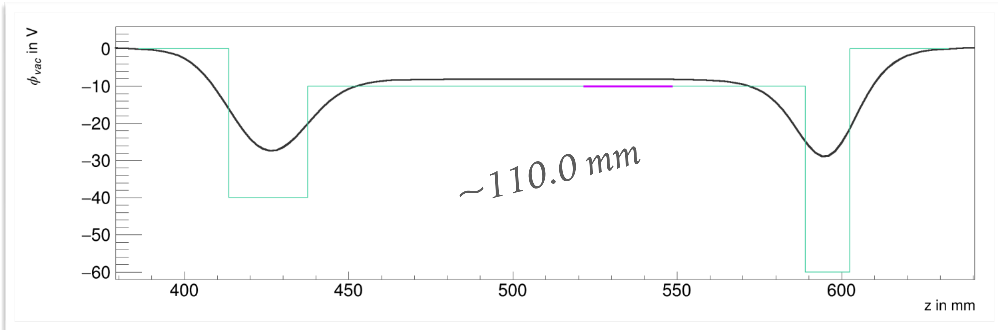
MCP image

Each image is generated by a destructive projection of a plasma onto a MCP located in the 1 T region of the experiment.

electron number measured by Faraday cup

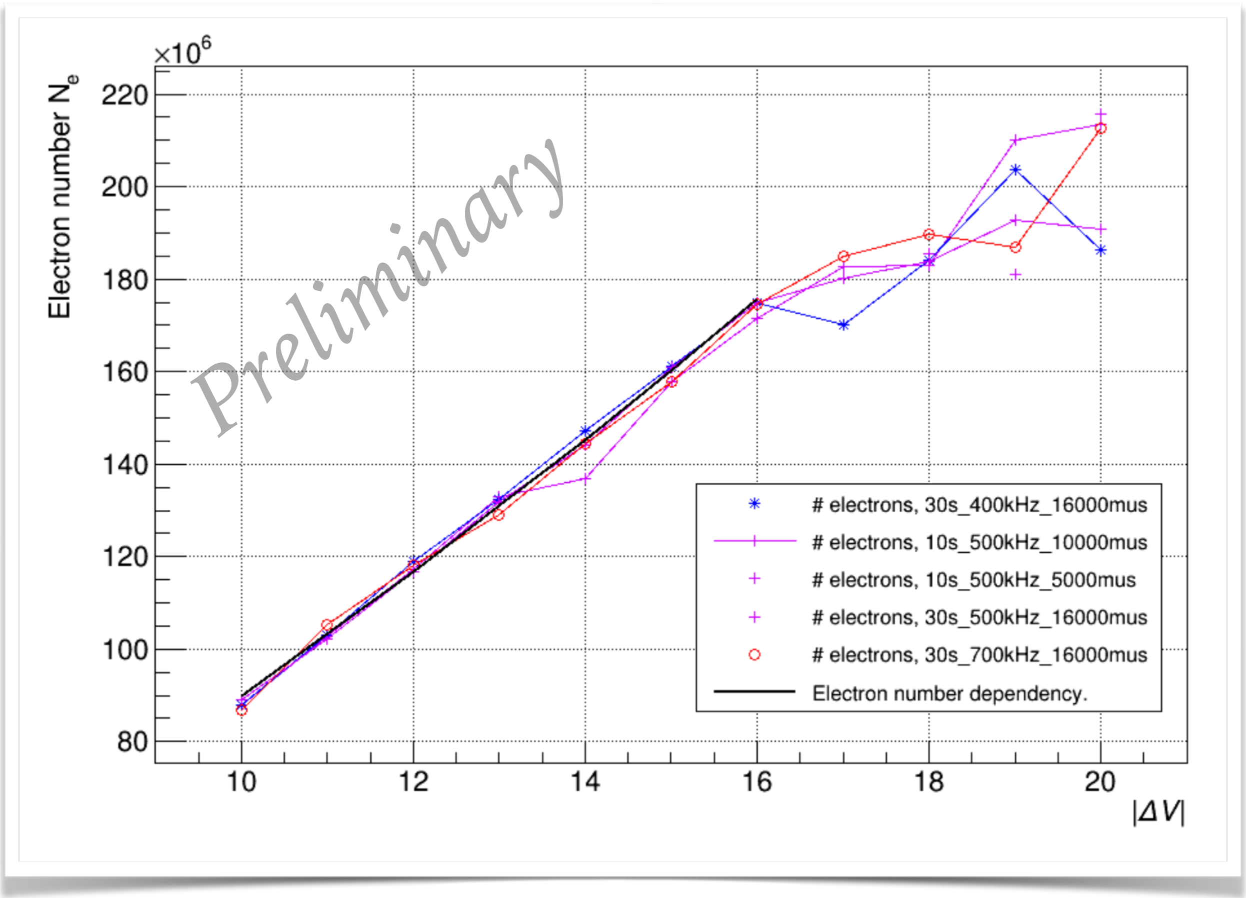
$$n_{cyl} = \frac{N_e}{\pi \cdot r_p^2 \cdot L}$$

trap length estimates



The density inferred from measurement clearly indicates, that the plasma is strongly driven.

STRONG DRIVE EVAPORATIVE COOLING



PHYSICAL REVIEW LETTERS **120**, 025001 (2018)

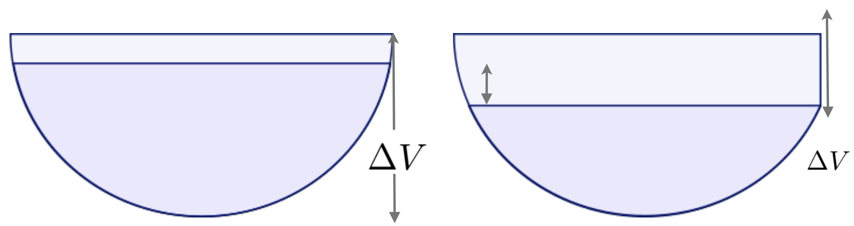
Editors' Suggestion

Enhanced Control and Reproducibility of Non-Neutral Plasmas

M. Ahmadi,[1] B. X. R. Alves,[2] C. J. Baker,[3] W. Bertsche,[4,5] A. Capra,[6] C. Carruth,[7,*] C. L. Cesar,[8] M. Charlton,[3] S. Cohen,[9] R. Collister,[6] S. Eriksson,[3] A. Evans,[10] N. Evetts,[11] J. Fajans,[7] T. Friesen,[2] M. C. Fujiwara,[6] D. R. Gill,[6] J. S. Hangst,[2] W. N. Hardy,[11] M. E. Hayden,[12] C. A. Isaac,[3] M. A. Johnson,[4] S. A. Jones,[2,3] S. Jonsell,[13] L. Kurchaninov,[6] N. Madsen,[3] M. Mathers,[14] D. Maxwell,[3] J. T. K. McKenna,[6] S. Menary,[14] T. Momose,[15] J. J. Munich,[12] K. Olchanski,[6] A. Olin,[6,16] P. Pusa,[1] C. Ø. Rasmussen,[2] F. Robicheaux,[17] R. L. Sacramento,[8] M. Sameed,[3,4] E. Sarid,[18] D. M. Silveira,[8] C. So,[6,10] G. Stutter,[2] T. D. Tharp,[19] J. E. Thompson,[14] R. I. Thompson,[6,10] D. P. van der Werf,[3,20] and J. S. Wurtele[7]

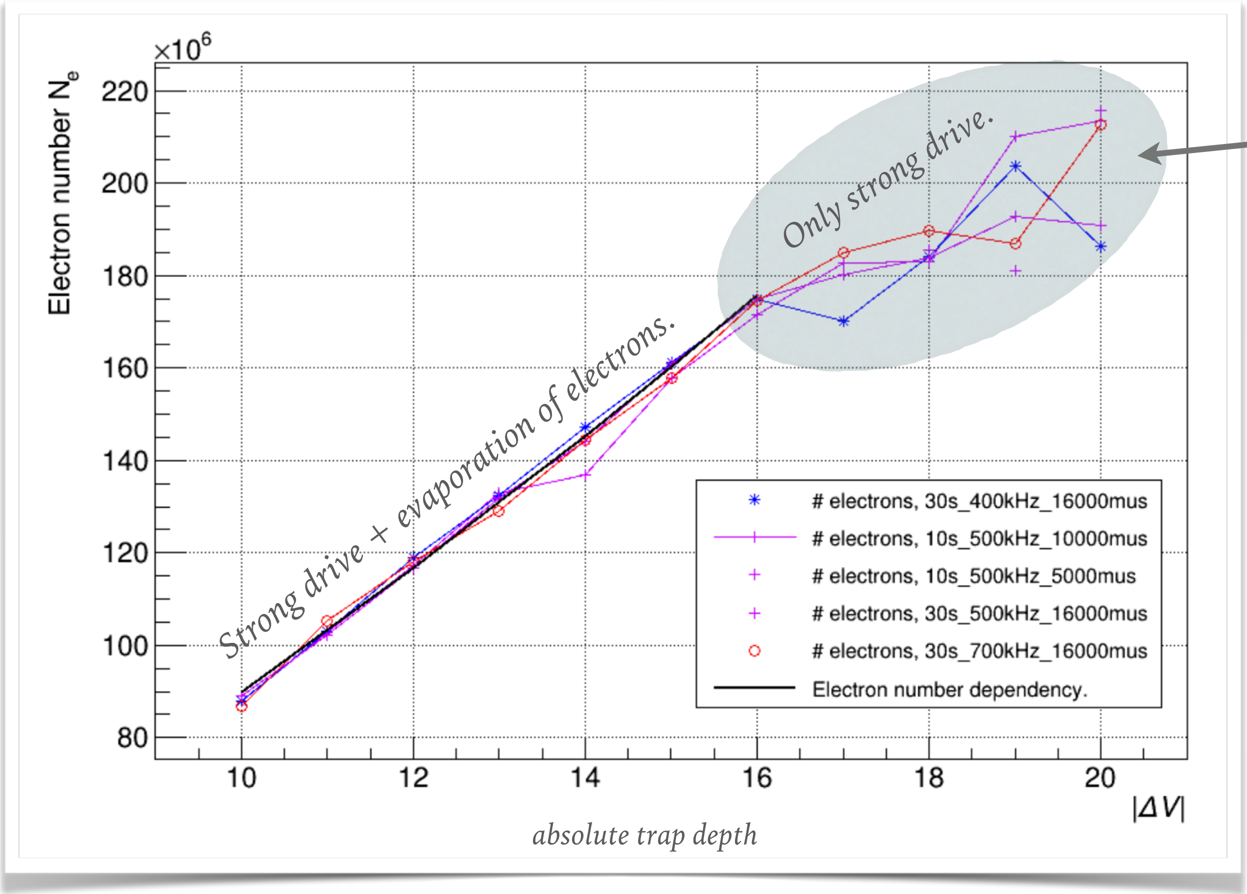
(ALPHA Collaboration)

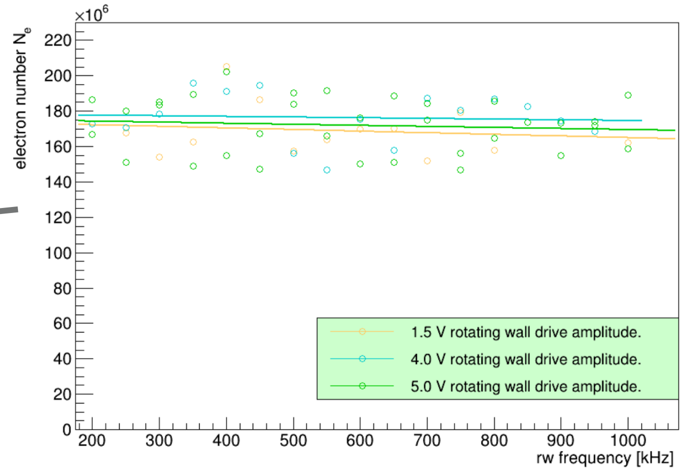
C. Carruth, "Methods for plasma stabilization and control to improve antihydrogen production.", PhD thesis (UC Berkeley, 2018)

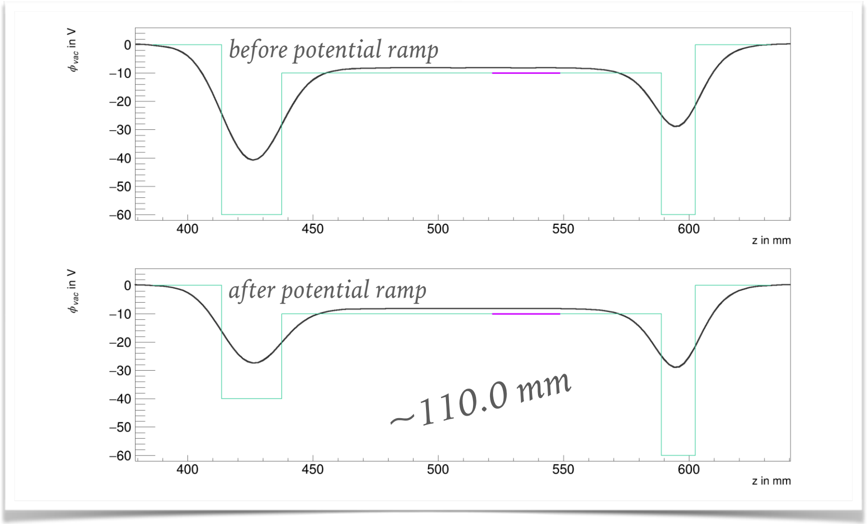


$$\frac{mv_\parallel^2}{2} - e\phi > -e\Delta V$$

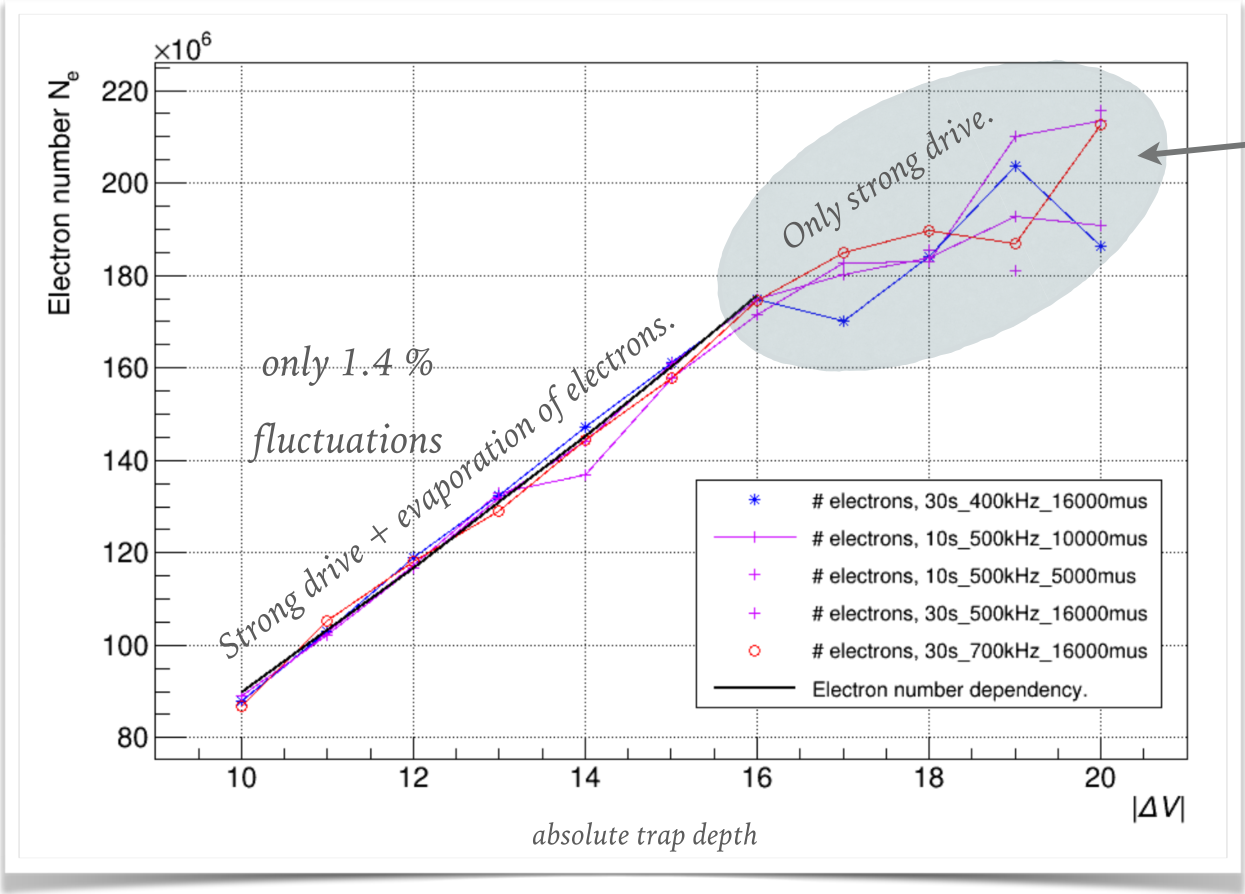
STRONG DRIVE EVAPORATIVE COOLING

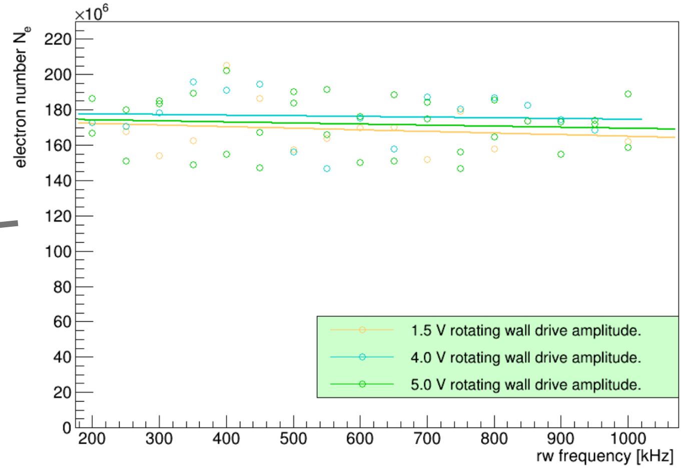






STRONG DRIVE EVAPORATIVE COOLING

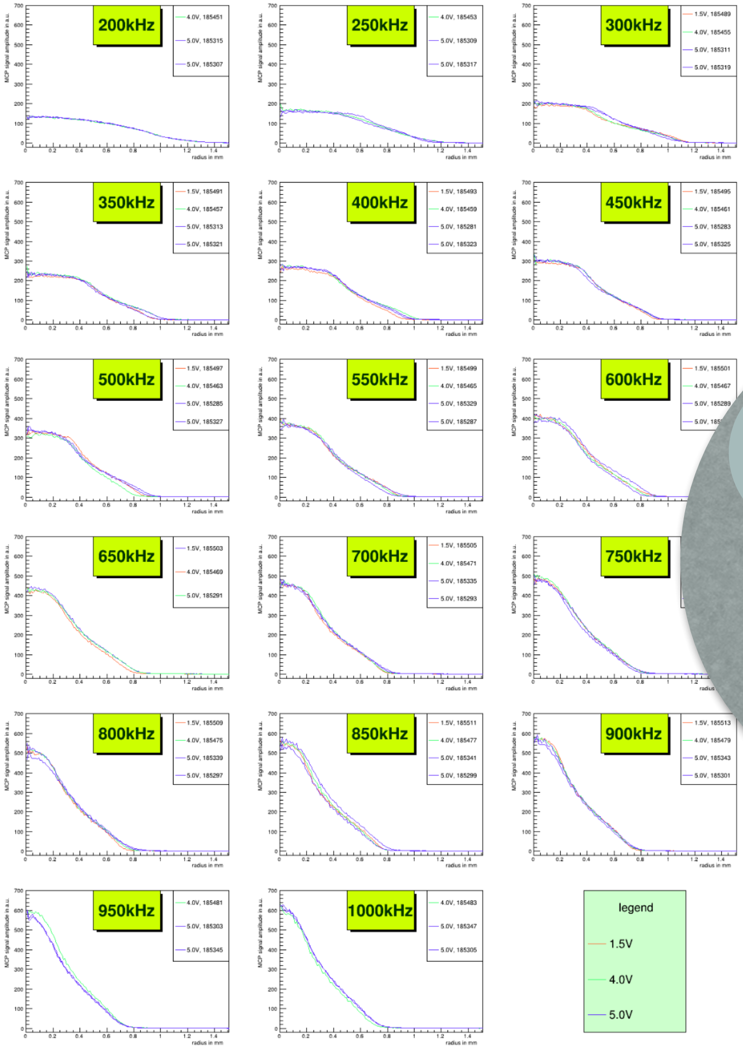




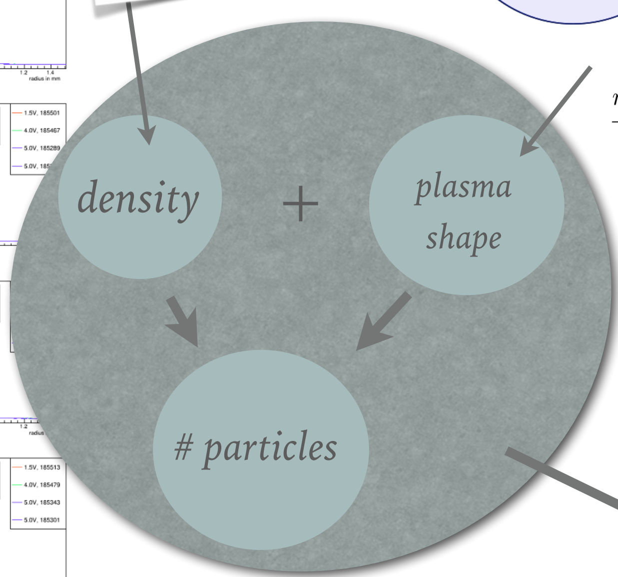
$$N = \frac{N_0}{\phi^0_{sc}} \cdot \frac{L_0}{L} \cdot \phi_{sc}$$

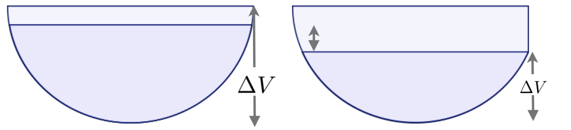
$$\begin{aligned} N_0 &= \pi r_{p0}^2 \cdot L_0 \cdot \frac{4\pi\epsilon_0 B}{q} \cdot \cancel{f} \cdot \frac{f_0}{\cancel{f}} \\ &= \pi r_{p0}^2 \cdot L_0 \cdot \frac{4\pi\epsilon_0 B}{q} \cdot f_0 \, , \end{aligned}$$

STRONG DRIVE EVAPORATIVE COOLING



$$f_{\mathbf{rw}} \equiv f_E = \frac{nq}{4\pi\epsilon_0 B}$$



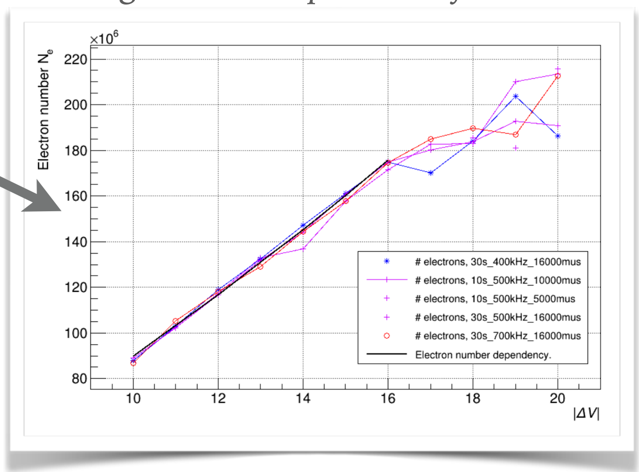


$$\frac{mv_\parallel^2}{2} - e\phi > -e\Delta V \quad \textit{(Spilling condition)}$$

Plasma shape unique in given trap geometry.

S. A. Prasad and T. M. O'Neil, Phys. Fluids 22, 278–281 (1979).

Strong drive + evaporation of electrons.



only 1.4 % fluctuations in particle number

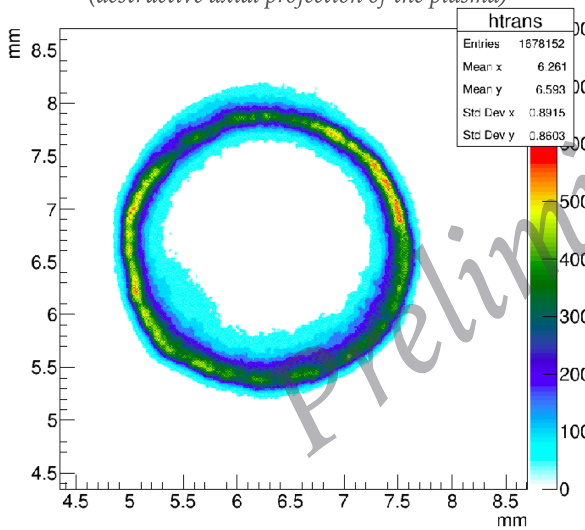
DIOCOTRON INSTABILITY

(Kelvin-Helmholtz like instability)

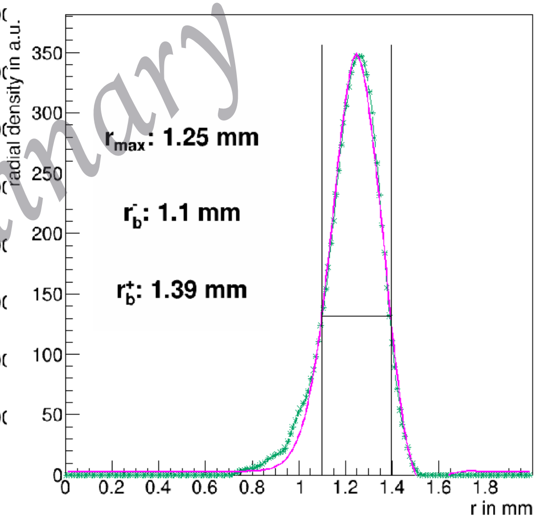
INITIAL DENSITY PROFILE

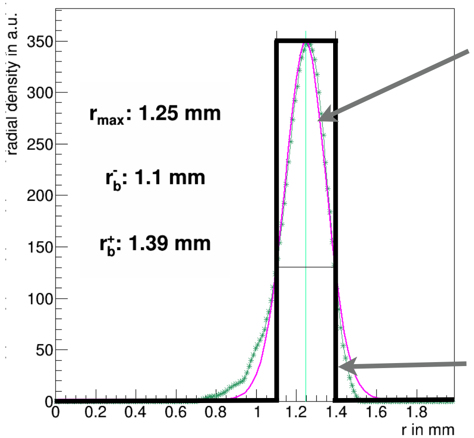
processed MCP image

(destructive axial projection of the plasma)



radial projection of plasma





Generalised Gaussian fit.

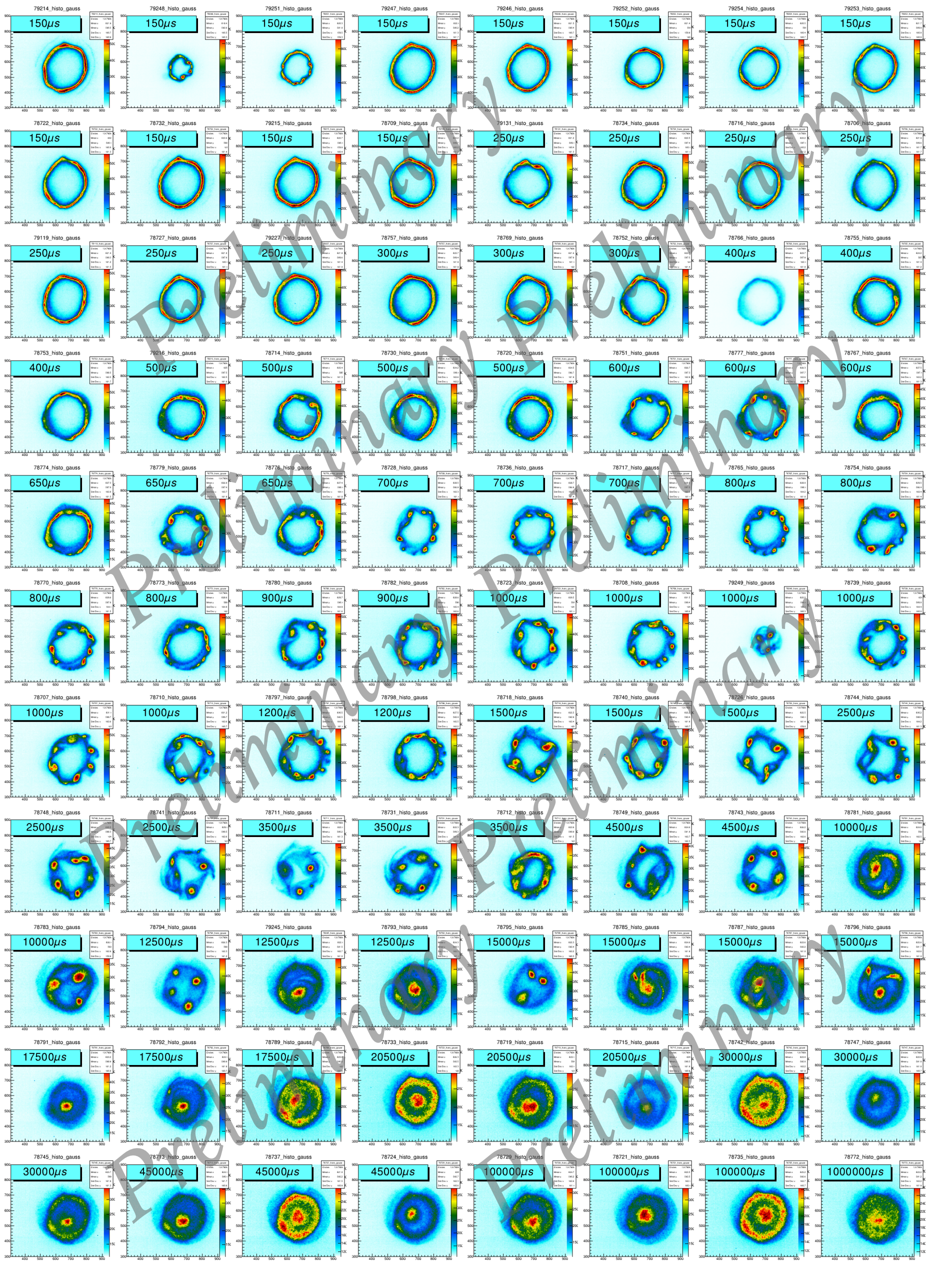
Step-profile approximation.

$$n^0(r) = \begin{cases} 0 & a \le r < r_b^- \\ \hat{n_0} = const. & r_b^- < r < r_b^+ \\ 0 & r_b^+ < r < r_w \end{cases}$$

Antiproton ring rotates at all times!

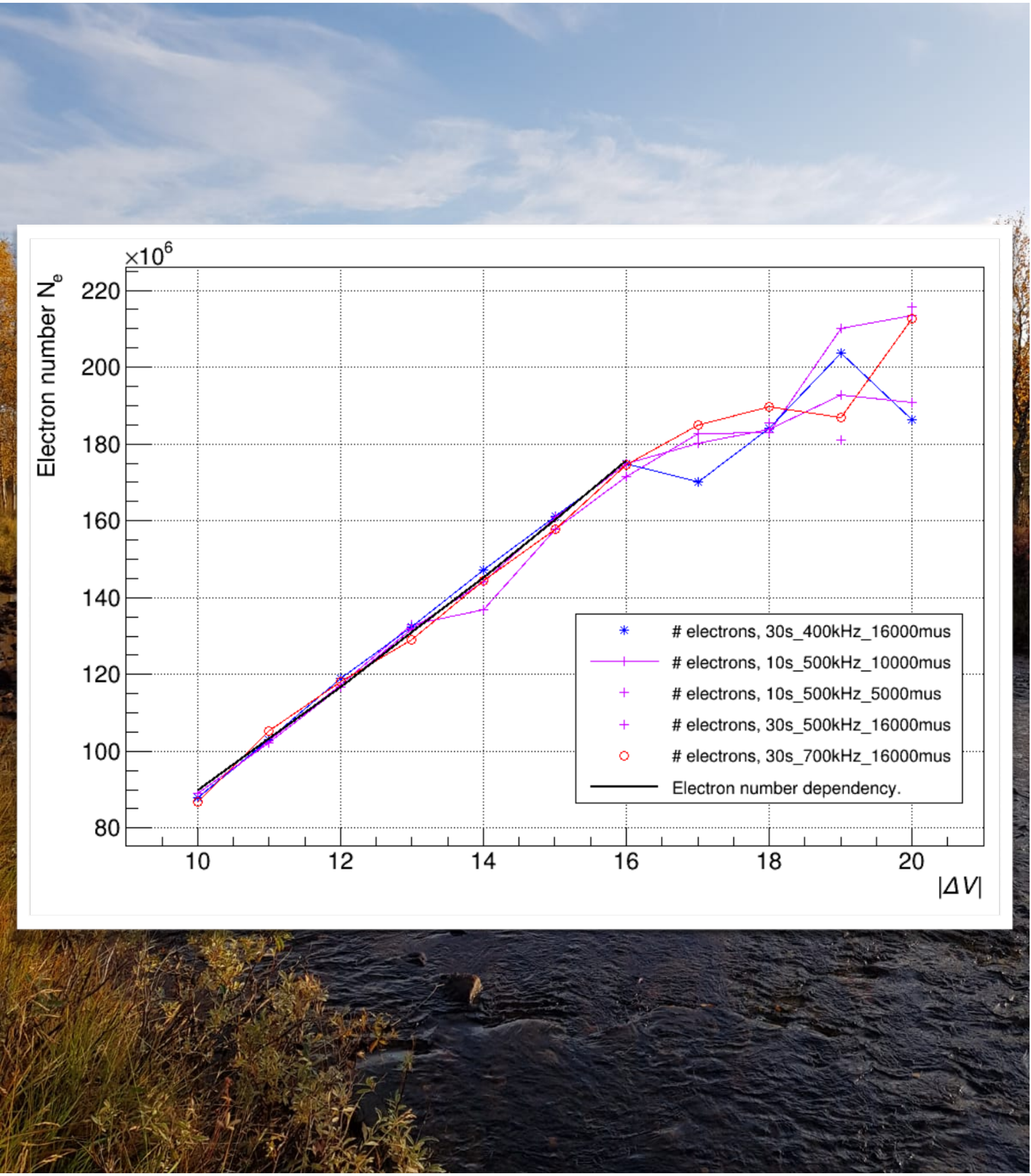
$$f_E = \frac{nq}{4\pi\epsilon_0 B}$$

Shear in velocities!



DIOCOTRON INSTABILITY IN AN ANTIPROTON RING

- Stages of the evolution:
  - Linear Stage.
    - Growth of instabilities.
      - Fastest growing mode determines the number of vortices.
  - Vortex formation = end of the linear stage.
  - Nonlinear Stage.
    - Radial transport of plasma bulk material through nonlinear dynamics.
      - Vortex interaction.
      - Filamentation.
      - Vortex mergers.
  - Final stage.
    - Stable density distribution.



FLUCTUATIONS

- Fluctuations in antiproton ring size.
    - Due to fluctuations in electron number and density as well as antiproton number fluctuations in the antiproton decelerator cycle.
    - The electron plasma fluctuations affect the antiproton ring size, since the antiproton rings are created through centrifugal separation and ejection of the electron core.
- Fluctuations can be minimized by the SDREVC technique (Strong Drive EVaporative Cooling) in the future.
    - The shallow potential wells of Penning-Malmberg traps permit the precise control of electron plasma particle number by strongly driving the plasma whilst evaporating particles through ramping the potential well.

SUMMARY & OUTLOOK

- Summary:
  - Successful implementation of the SDREVC technique into the AEgIS apparatus.
  - Experimental observation of the temporal evolution of a step-profile-like annular antiproton layer.
- Outlook:
  - Incorporation of the SDREVC technique into the regular AEgIS protocols.
    - Stabilisation of charged particle transfers from the trapping to the antihydrogen production region:
      - e.g. the ballistic transfer of antiprotons from the 5T trap region to the antihydrogen production trap.
    - Stabilisation of antiproton ring radii for diocotron instability investigations.


THANK YOU VERY MUCH FOR YOUR ATTENTION!