Trapped non neutral plasma: introduction

G. Testera – INFN (Genoa, IT)

AVA School on low energy antimatter physics
June 2018, CERN

Summary

- Space charge
- Non Neutral plasma rotation
- Equilibrium distributions
- T=0 limit in the harmonic trap

  - Collision rate
  - Getting a plasma in the trap
  - Centrifugal separation
  - Plasma modes
  - Rotating Wall

Energy equipartition rate & collision rate

Coulomb collisions re-distribuite energy
Transport to thermal equilibrium is due to Coulomb collisions

B=0

- Spitzer self-collision time: time necessary to eliminate any anisotropy in the temperature distribution
- More precisely: time necessary to rotate the velocity by 90 through Coulomb Collisions
- Test particle
- Change of velocity due to collisions
- Integral over the impact parameters: bmin bmax

B

Collisions with exchange of velocity parallel and perp. to B are less efficient
adiabatic invariants…

Cyclotron radius calculated with the thermal velocity $\overline{r}_c = \frac{v_t}{\Omega_c}$ $\frac{1}{2} m v_t^2 = KT$ ⟷ Debye lenght

$\overline{r}_c >> \lambda_D$ The magnetic field does not influence the collision rate

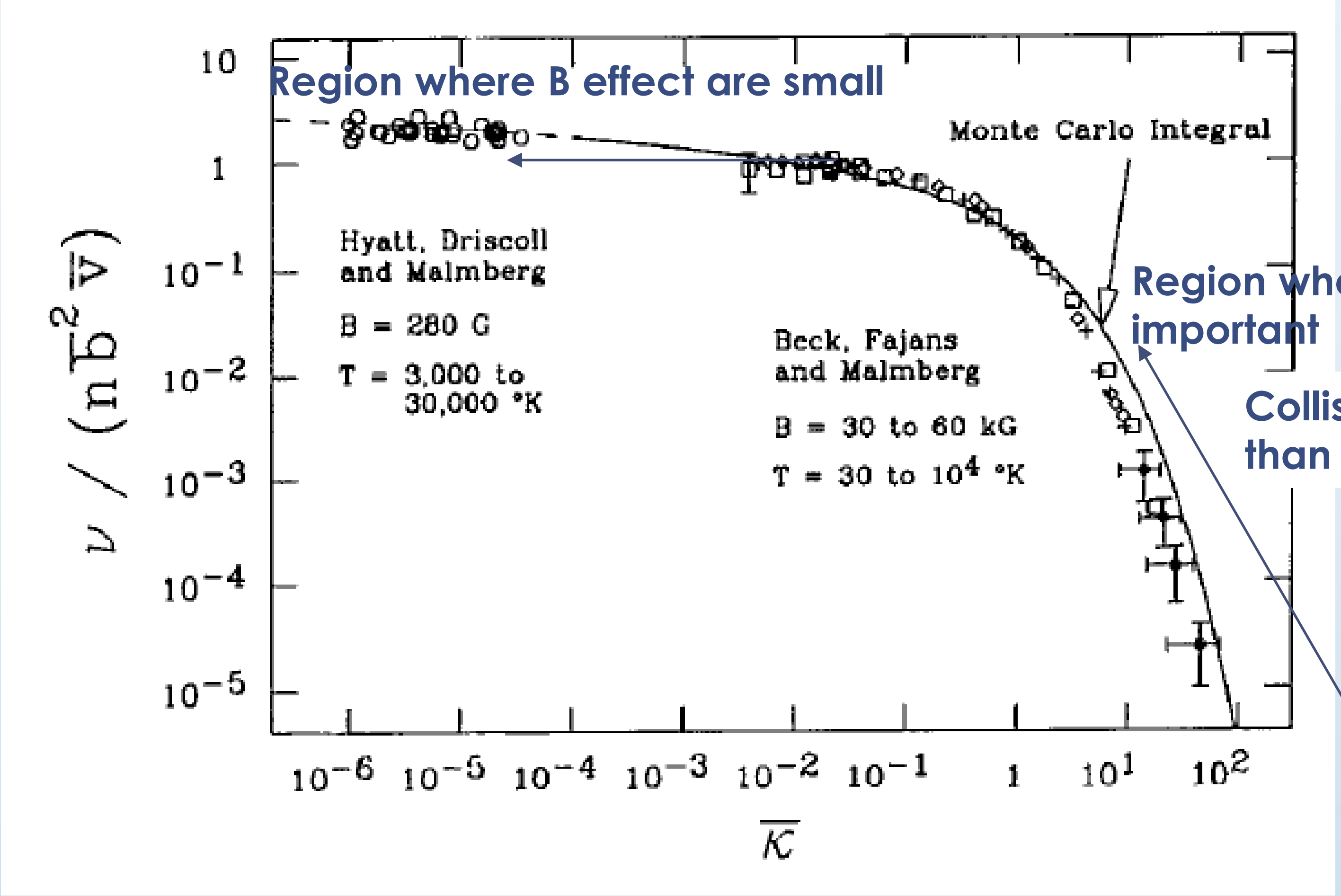
$\overline{r}_c << \lambda_D$ The magnetic field strongly influences the collision rate

Distance of closest approach $\overline{b} = 2 \frac{1}{4\pi\varepsilon_0} \frac{q^2}{KT}$

$\kappa = \overline{b} / \overline{r}_c$

Collision rate

$$\upsilon_c = n \overline{v_t}\, \overline{b}^2\, I(\kappa)$$



$$\upsilon_c = n\overline{v_t}\,\overline{b}^2\, I(\kappa)$$

Collision rate high, time to establish equilibrium $(1/\nu_c)$short

$$\upsilon_c \propto n\sqrt{\frac{1}{m}}\frac{1}{(KT)^{3/2}} I\left(\ldots\ldots\frac{B}{\sqrt{m}(KT)^{3/2}}\right)$$

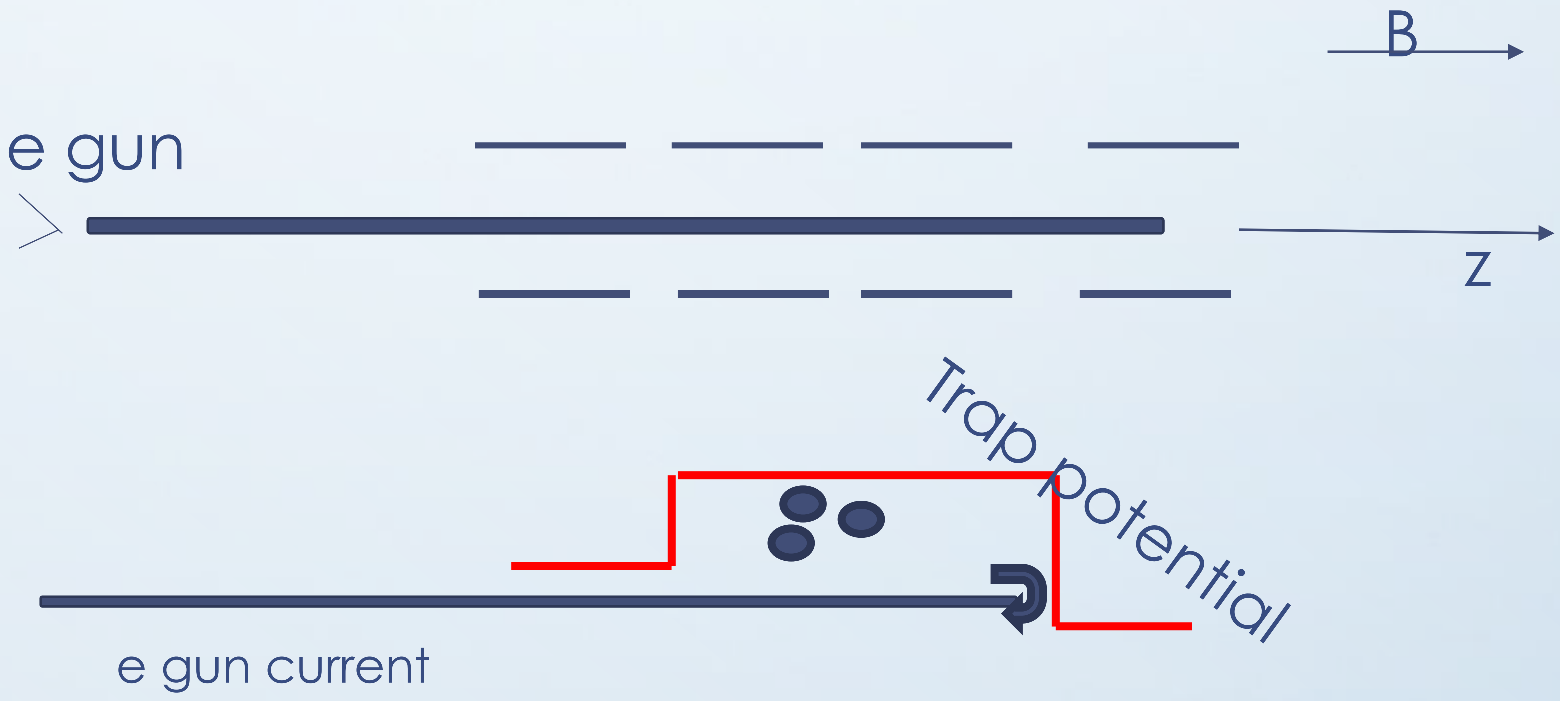
Collision suppressed if the argument is big
Large B, low T

Ex with e-
$10^9 cm^{-3}$ B=5T 10K 30 ms
$10^9 cm^{-3}$ B=1T 10K few μs

Phys. Fluids B, Vol. 4, No. 5, May 1992

Creating the e- plasma

- Trap in high magnetic field
- E gun: Cathode (similar to the one of G. Tranquille)
- emission current; several μA
- Located in the fringe field



It is needed an energy loss mechnism during the passage in the trap
Collisions within the beam current…

Detectors (antimatter plasma)

1) Faraday cup (e-,e+ number)

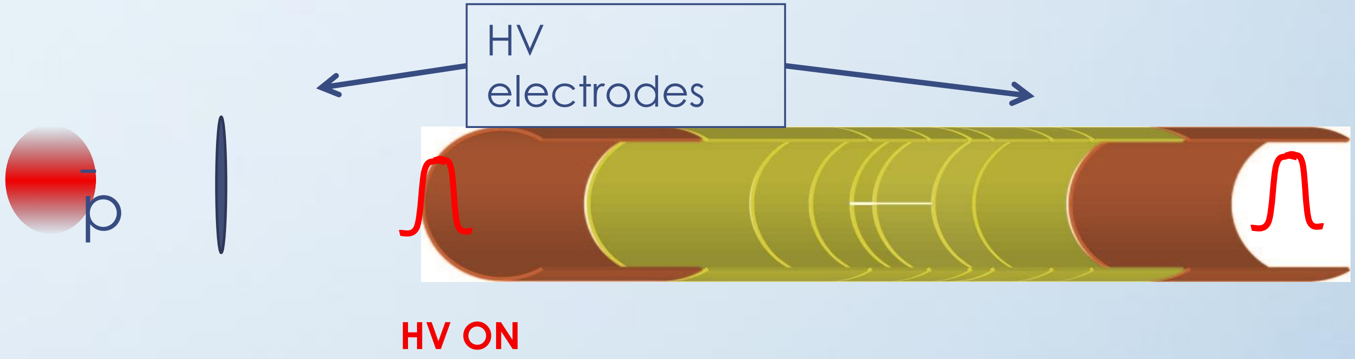
2) Imaging system (MCP+Phosphor+CCD, z integrated radial profile)

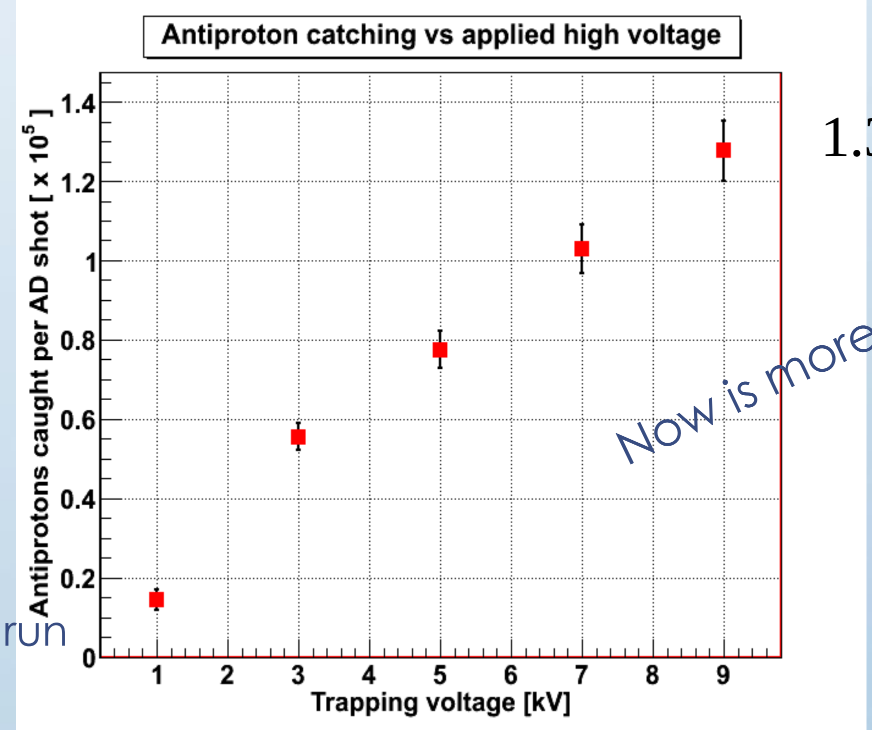
3) Scintillators (pbar annihilations, e+ annihilations)

4) Induced charge on the electrodes (plasma modes, suitable pickup electrodes) also tuned circuits

Antiproton catching : from 5 MeV to 9 KeV (AEgIS) (similar in all AD experiment except ASACUSA)

- About 3 10^7 antiproton/shot
- about 150 ns lenght
- every 100 sec
- 5 MeV kinetic energy
- $\Delta p/p = 10^{-4}$
- catch in flight after deceleration through material foils of proper thickness



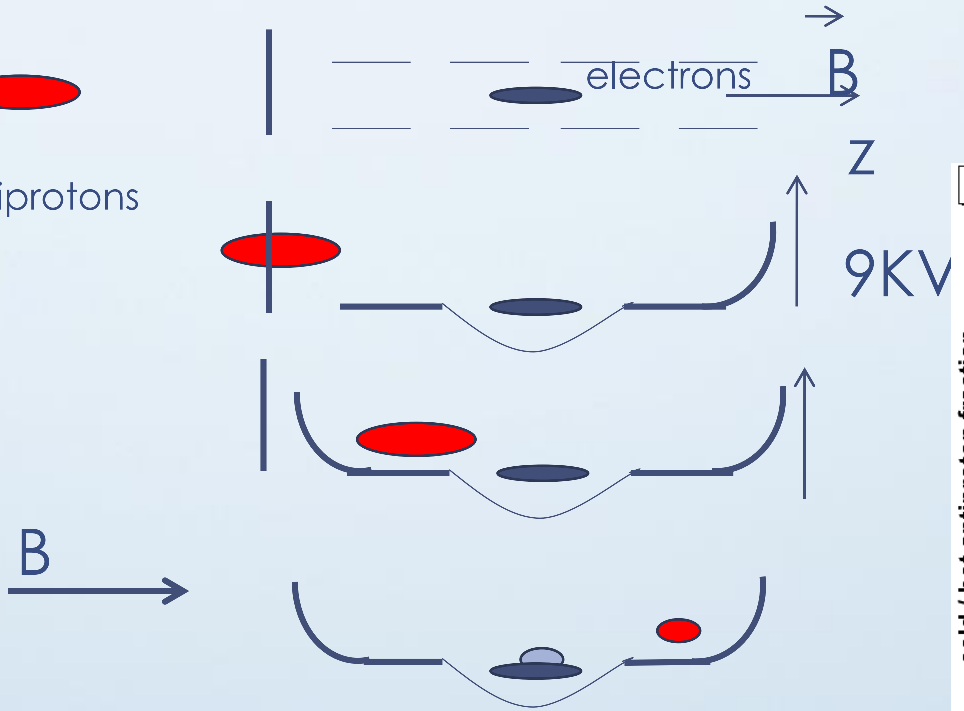


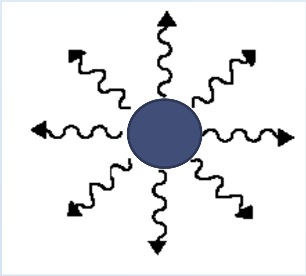
$1.3\,10^5\ \bar{p}/shot$

Now is more then 2 times higher

First AEgIS results
May-Dec2012 antiproton run

Antiproton cooling



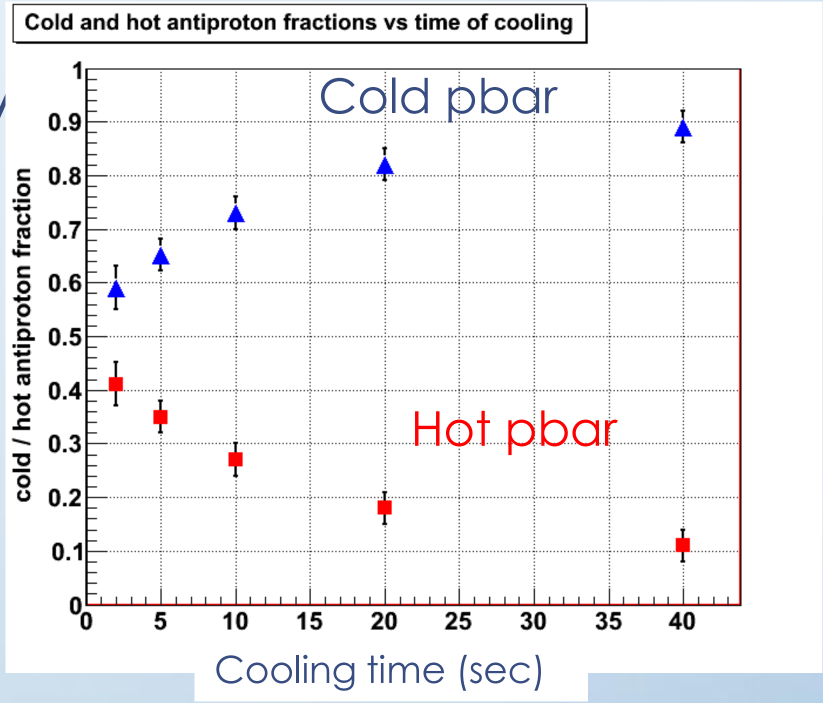


e- (and also positrons)
Radiation in high magnetic field (cyclotron cooling)

$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap} + \ldots.$$

$$\tau_{rad} \propto \frac{m^3}{B^2}$$

e^-, e^+	$\tau_{rad} \cong 0.1 \sec @ 5T$
$\bar{p}$	$\tau_{rad} \cong 10^9 \sec @ 5T$



Cyclotron radiation + Coulomb collisions
= thermal equilibrium for e- and pbar

Multispecies plasma: centrifugal separation

- plasma made of particles with different mass and same charge (e-, pbar or different ions)
- Trapped together
- Particle distribution function??

Density in the trap center

$$n_1(r,z) = n_{01} e^{\Psi_1(r,z)}$$
$$n_2(r,z) = n_{02} e^{\Psi_2(r,z)}$$

1 electrons
2 pbar

$$\Psi_{1,2} = -\left(\frac{1}{KT}\right)\left(m_{1,2}\,\omega \frac{r^2}{2}\left(\Omega_{c1,2} - \omega\right) + q\,\Phi_{trap}(r,z) + q\,\Phi_p(r,z) - q\,\Phi(0,0)\right)^2$$

What is the ratio of the density at some r away from the center??

$$\frac{n_2(r,z)}{n_1(r,z)} = \ldots\ldots = \frac{n_{02}}{n_{01}} e^{\frac{(m_2 - m_1)\,\omega^2 r^2}{2KT}}$$

The density ratio is not constant, it depends on r

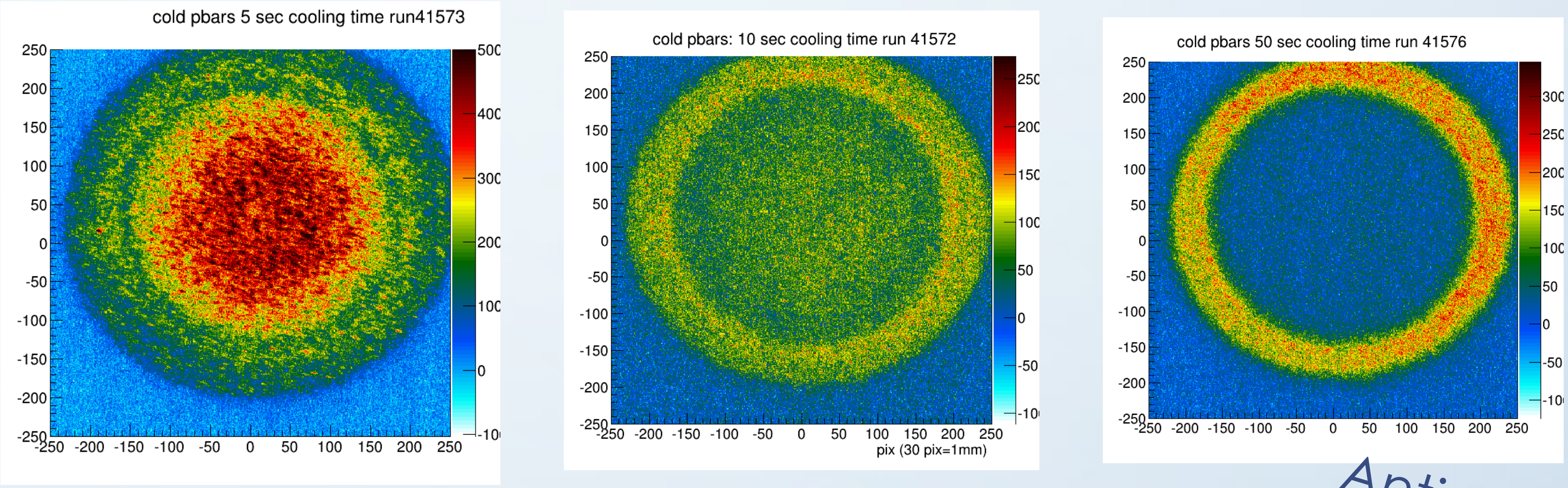
If $\frac{(m_2 - m_1)\,\omega^2 r^2}{2KT} >> 1$ then the density of the type 2 is much higher than that of type1

Centrifugal separation: $\frac{1}{2} m_2 \omega^2 r^2 >> KT$

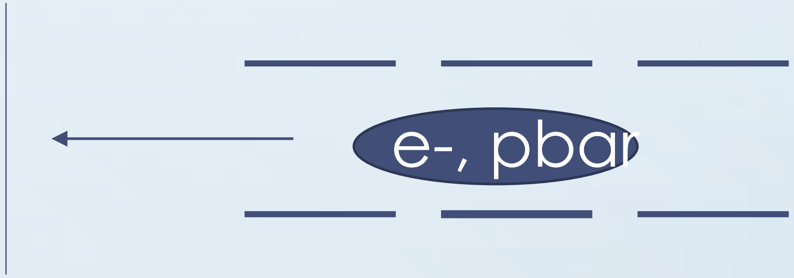
Rotation energy of the heavy species larger than KT

Centrifugal separation of pbar and e- (AEgIS)

See also ALPHA,ATRAP



Antiproton images
Fast e- dump
Then pbar dump



MCP+Phosph+CCD

Plasma modes

Perturbation from the equilibrium

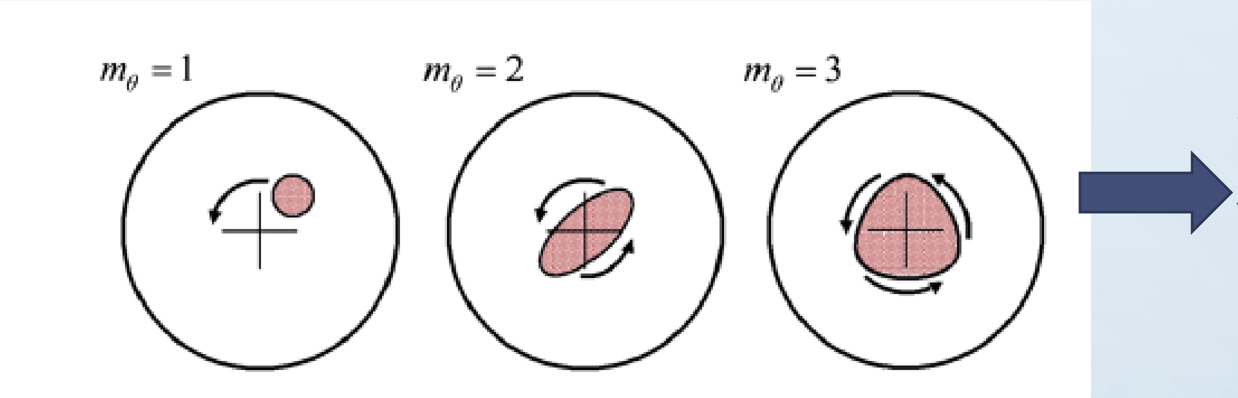
δΦ and n oscillates with proper frequencies

$$\delta\phi(\mathbf{r}, t) = J_{m_\theta}(k_\perp r)\exp(im_\theta\theta - i\omega t)\cos(k_z z),$$

Example: diocotron modes

Low frequency, z independent, azimuthal distorsions in long plasma

$$\delta\phi(\mathbf{r}, t) = C r^{m_\theta}\exp(im_\theta\theta - i\omega t).$$



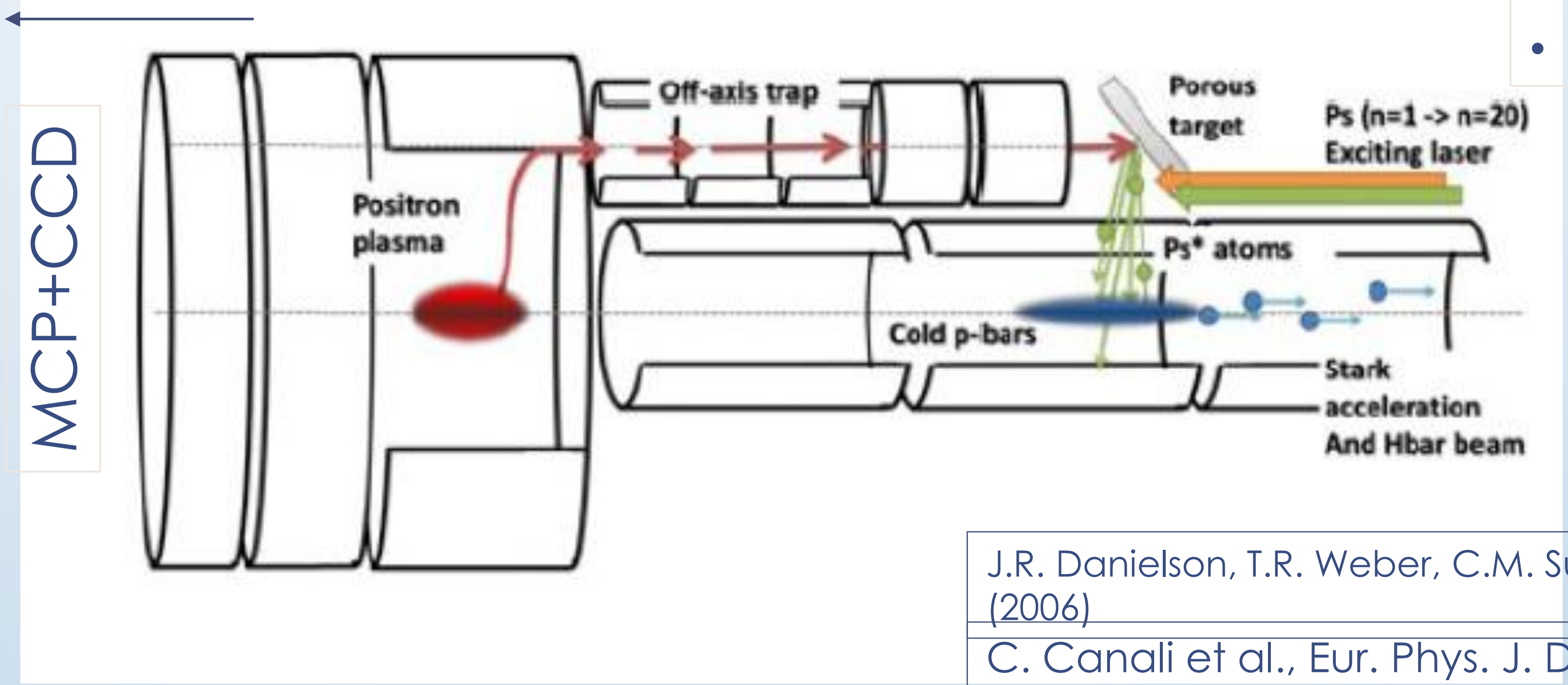
Detection of current due to
Variation of the induced charges
Signal at the mode frequency

Excitation with RF close to the mode frequency

m=1 Diocotron mode excitation in AEgIS : move plasma off axis

- Detection with a Faraday cup (in place of the e+ target)
- Detection with MCP+CCD

MCP+CCD



J.R. Danielson, T.R. Weber, C.M. Surko, Phys. Plasmas **13**, 123502 (2006)

C. Canali et al., Eur. Phys. J. D **65 (3)** 499-504 (2011)

- **RF excitation, non linear oscillator (frequency depends on the amplitude)**
- **Presently we inject e+ on target using another method (direct injection from the accumulator)**

AEgIS: diocotron excitation of electrons (mimic e+)

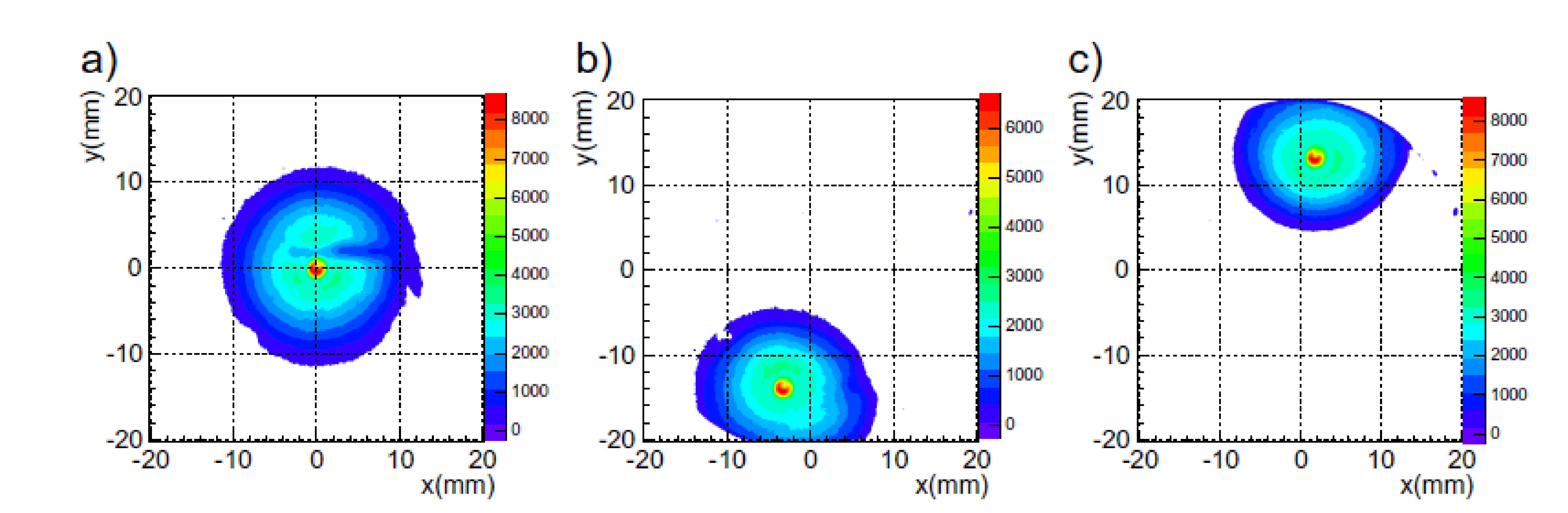


Fig. 3 Excitation of the diocotron mode of electrons. **a** no excitation; **b**, **c** displacement of the plasma with controlled phase. The amplitude D = 1.5 cm is consistent with that necessary to reach the nanoporous target. The radius of the big trap is 2.2 cm

Hyperfine Interact (2015) 233:13–20

Axial mode of a spheroidal plasma

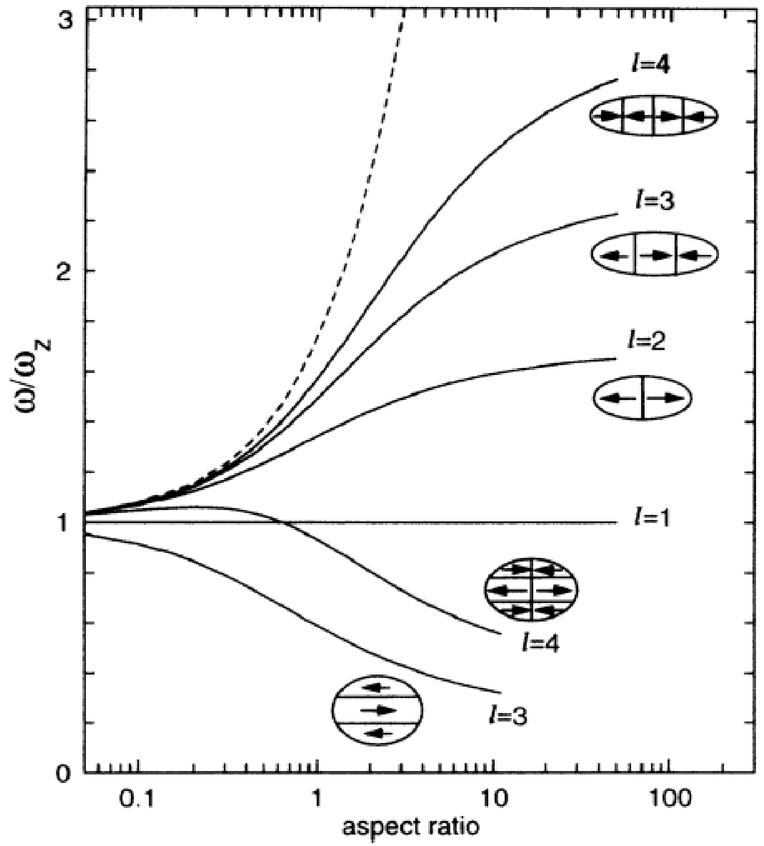


FIG. 5. Dispersion relation for $m_\theta = 0$ modes in spheroidal plasmas [Eq. (55)]. Only the lowest-order azimuthally symmetric modes are shown; the dashed line is the plasma frequency. For the $l = 3$ and $l = 4$ modes, there are two branches. The sketches indicate the fluid motion for each mode. From Tinkle *et al.*, 1994.

Exact expression at T=0
Corrections for T not null

Non destructive diagnostic

$$\omega_1 \ \omega_2 \ N$$

→ Assume T=0
We get z_p, r_p, n
(closed system)

→ More frequencies
to get cross check

l=2 quadrupole mode
T
Used a diagnostic for T changes
(ATHENA, ALPHA)

Quadrupole mode and Temperature

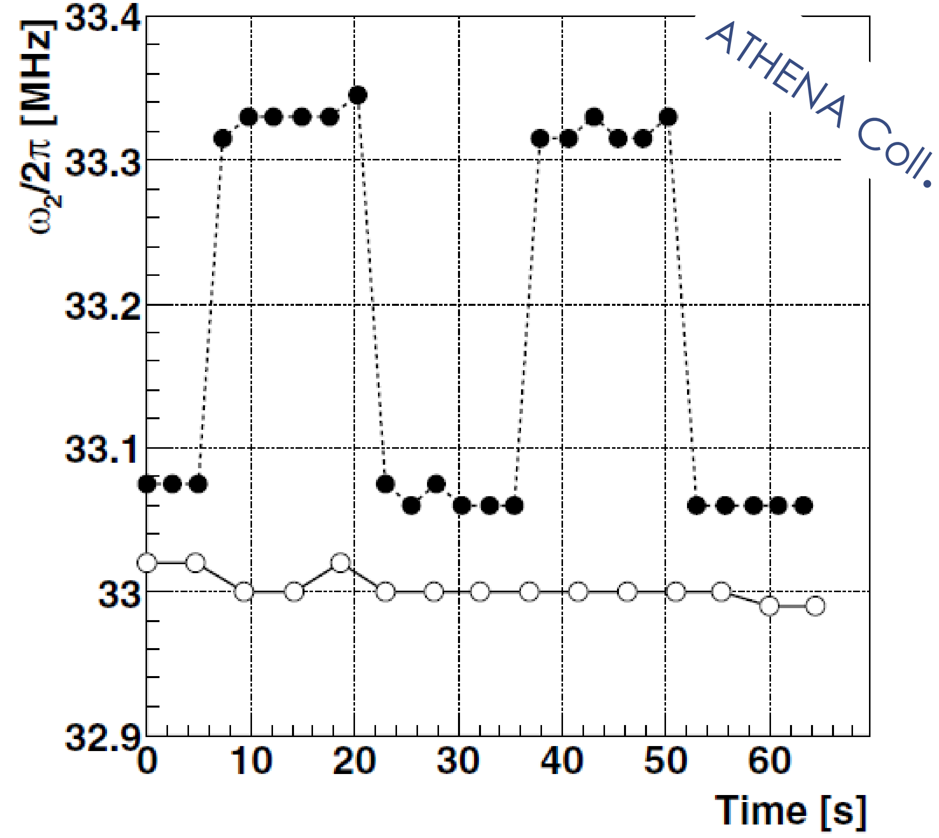


FIG. 3. The quadrupole mode frequency versus time for normal evolution (○) and for two heat off-on cycles (●). The frequency shift corresponds to an increase of the plasma temperature of about 150 meV.

$$(\omega_2')^2 - (\omega_2)^2 = 20\left(3 - \frac{\alpha^2}{2}\frac{\omega_p^2}{(\omega_2^c)^2}\frac{\partial^2 f(\alpha)}{\partial\alpha^2}\right)\frac{k_B \Delta T}{mL^2},$$

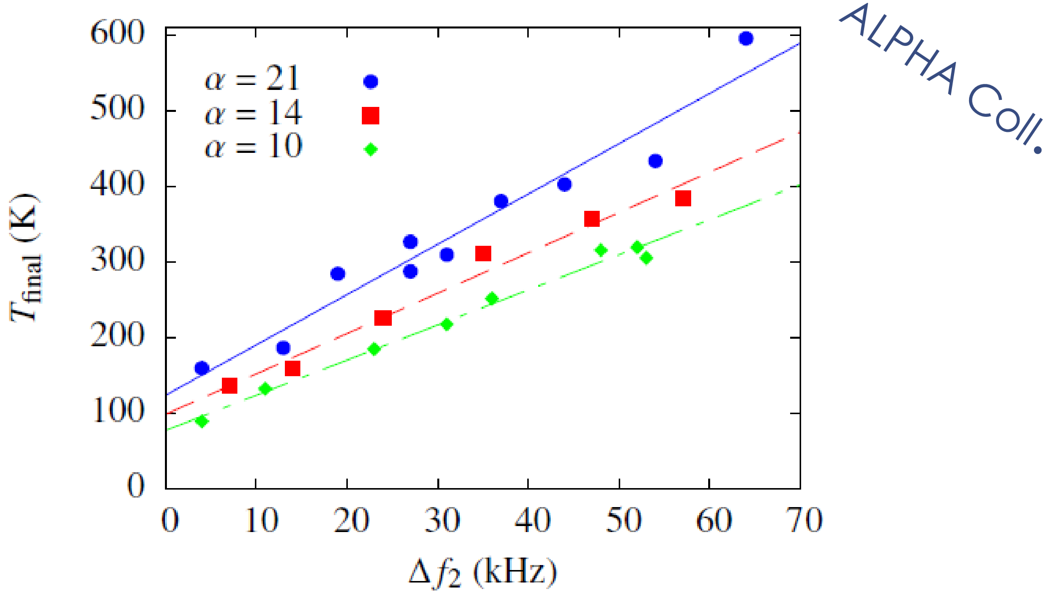
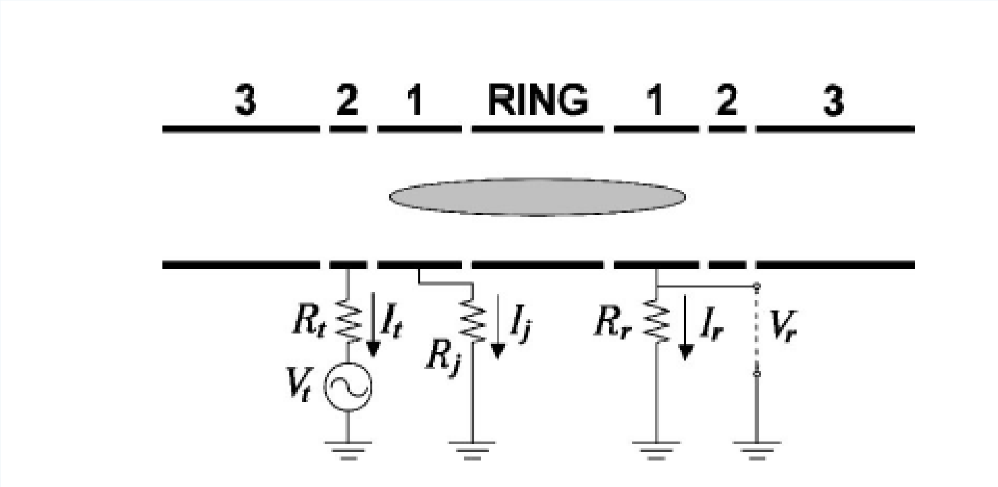
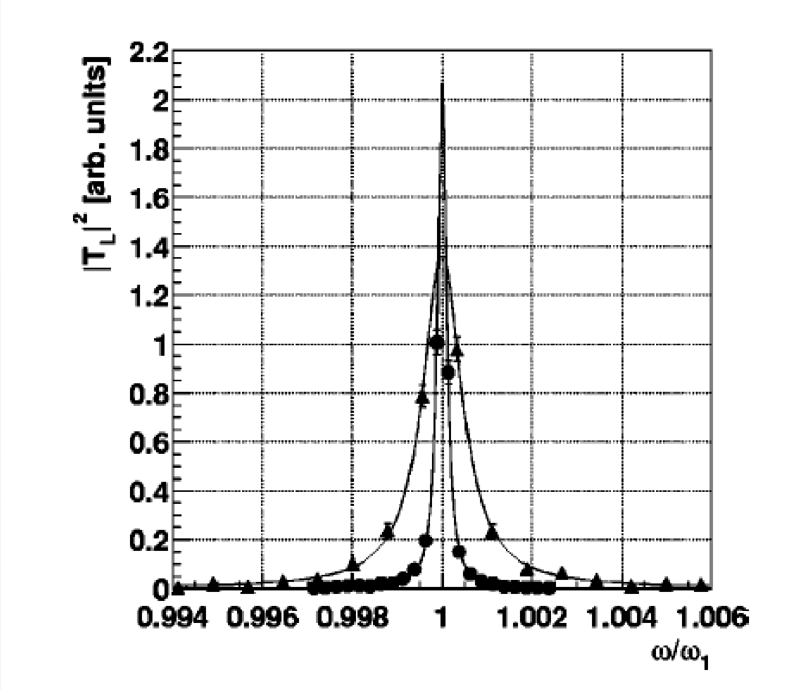


FIGURE 4. Final plasma temperature versus the corresponding quadrupole mode frequency shift for plasmas with three different aspect ratios.

PRL91 5 (2003) Ath, Coll

Complete non destructive diagnostic using spheroidal plasma modes





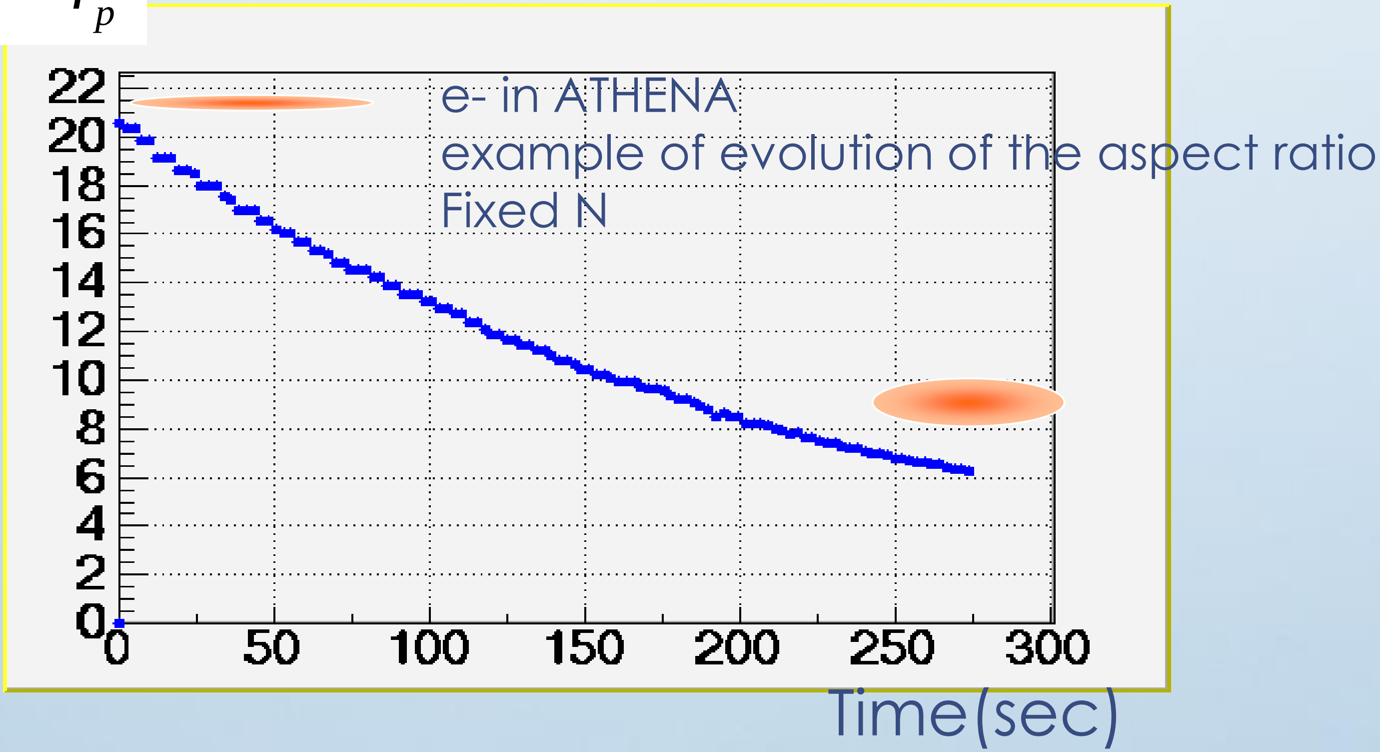
- Mode excitation at various frequency
- Developed a model to describe the lineshape
- Include effects due to the plasma shape
- Know the gain of system
- Get N fitting the lineshape

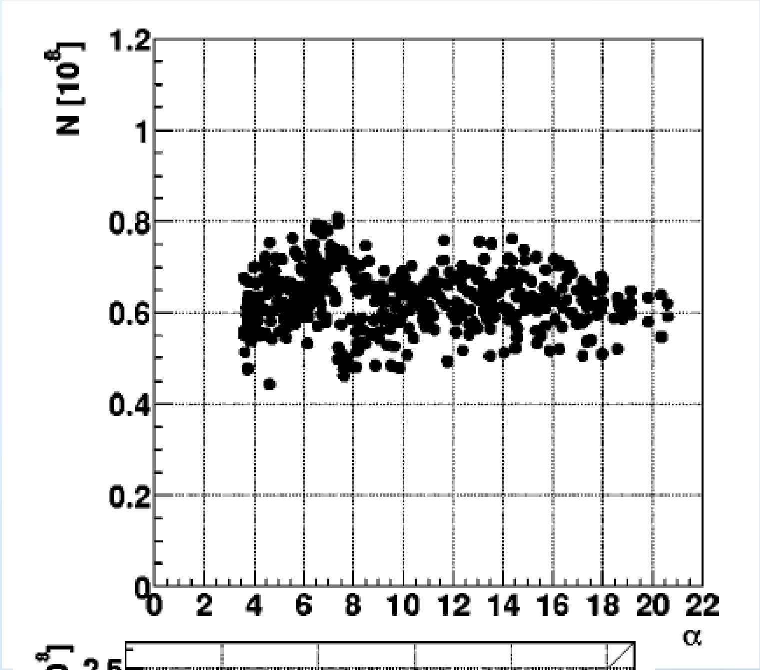
Athena Coll.

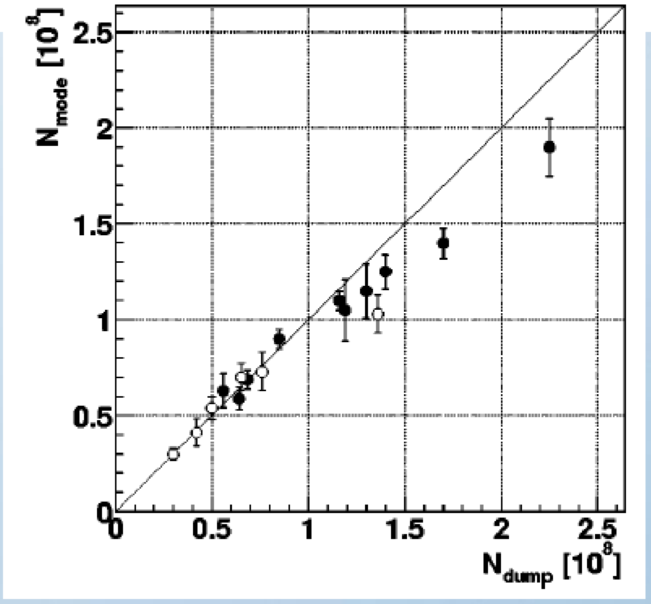
Phys. Plasmas, Vol. 10, No. 8, August 2003

N obtained through plasma mode

$$\alpha = \frac{z_p}{r_p}$$

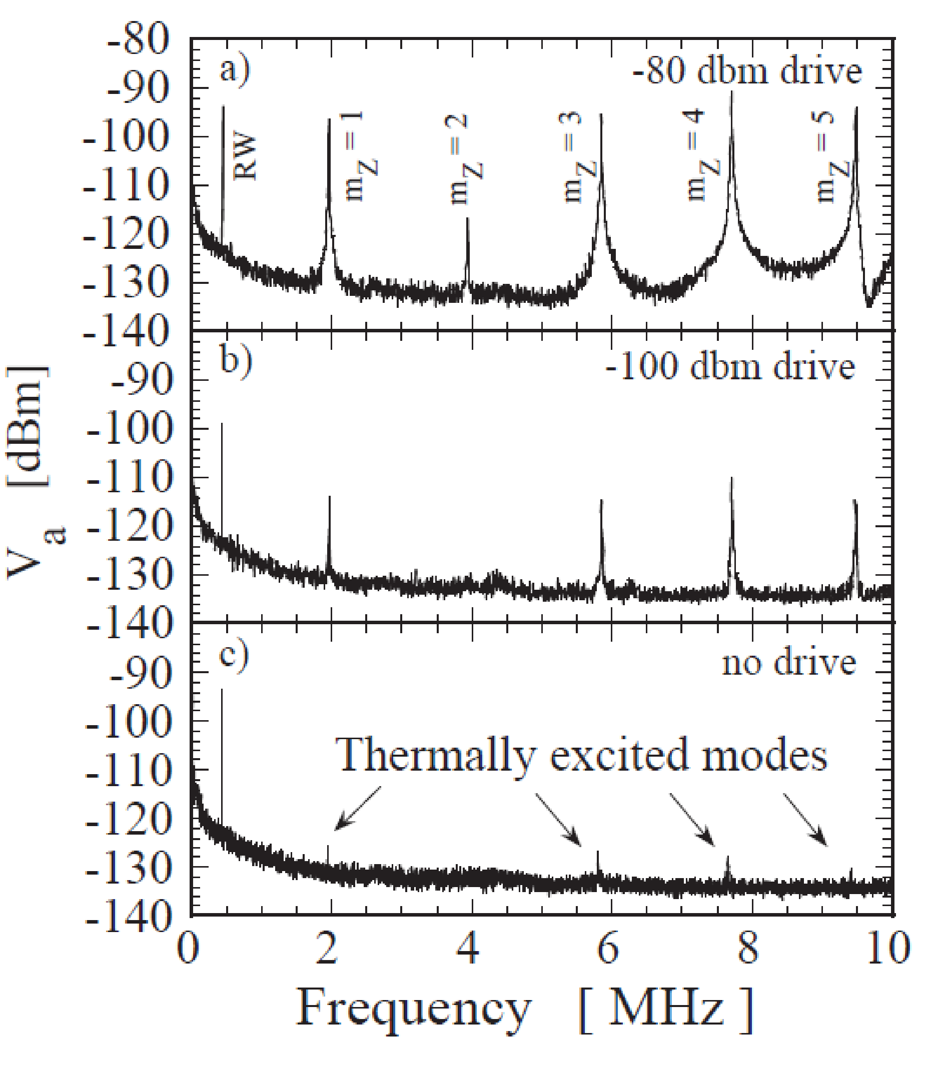






○ e+
● e-

Thermally excited mode (Trivelpiece-Gould) in a long plasma



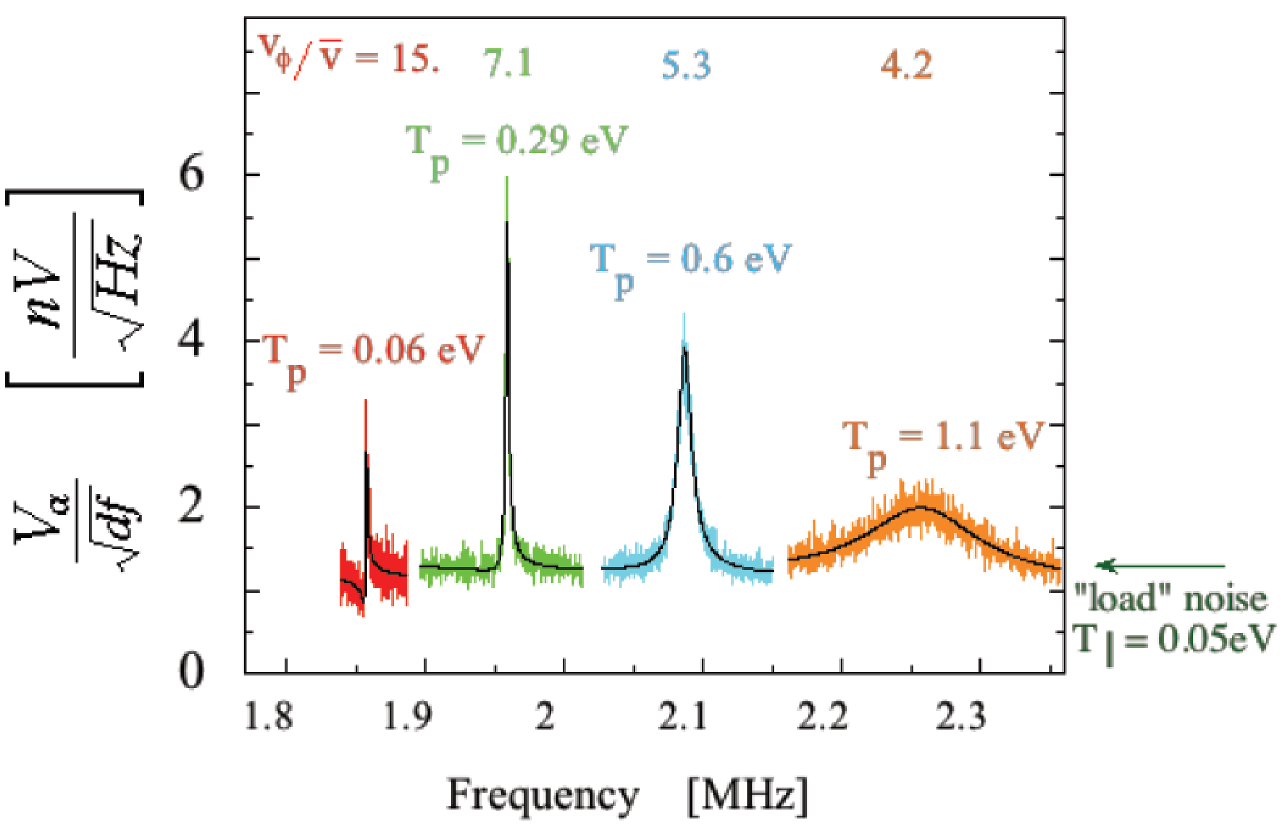


FIGURE 7. Thermal spectrum of the m_z=1 mode for 4 different plasma temperatures.

T. O'Neil AIP Conf. Proc 1721(2016)

Angular momentum conservation and infinite trapping time

How long can I confine a non neutral plasma??

- Assume good vacuum
- Neglect collisions with background gas
- No heating sources, so KT<< trap potential well,no way to gain energy
- Radial drift, expansion and losses toward the wall
- Can I trap the plasma forever??

Total angular momentum constant

$$r \ z \ \vartheta$$

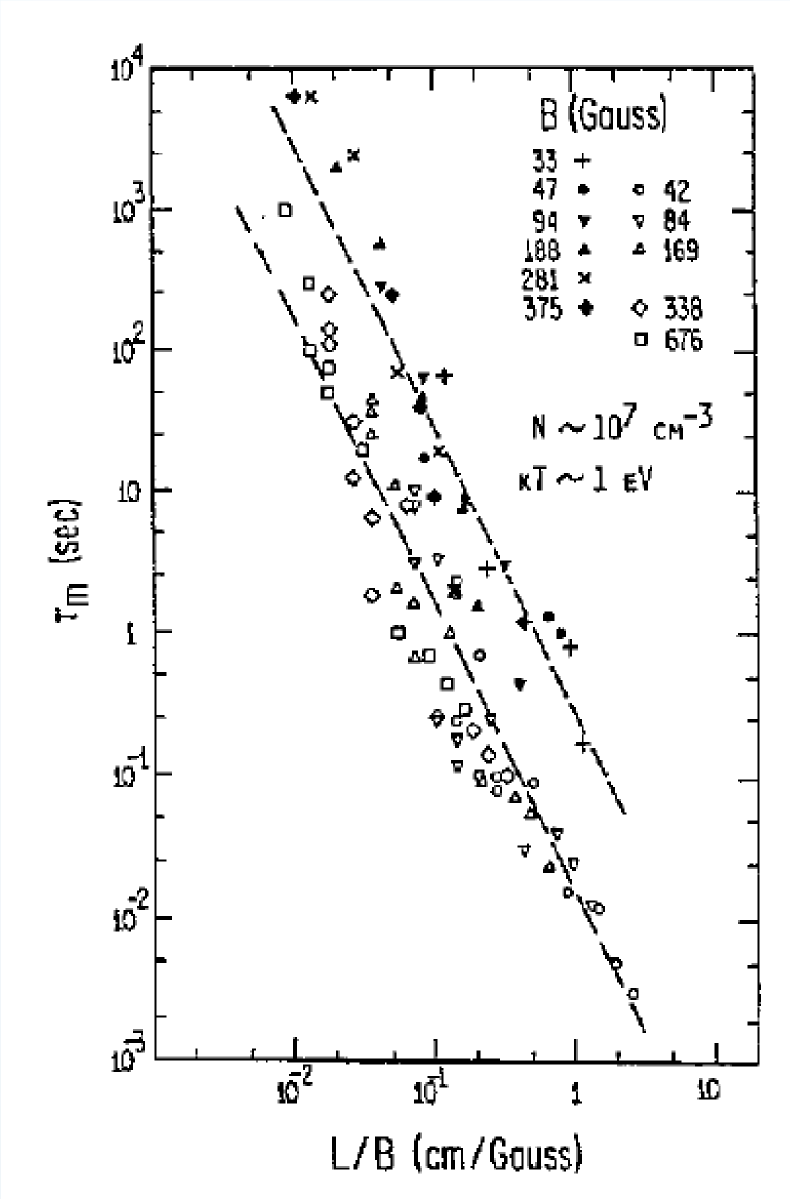
$$p_r \ p_z \ p_\vartheta$$

$$P_\vartheta = \sum (p_\vartheta)_i = \sum m r_i^2 \dot{\theta}_i + qB\frac{r_i^2}{2} \Longrightarrow P_\vartheta = \sum (p_\vartheta)_i \approx \sum qB\frac{r_i^2}{2}$$

This is limiting the possibility to expand

Real plasma: expansion due to collisions with gas, asymmetries, non ideal halo….

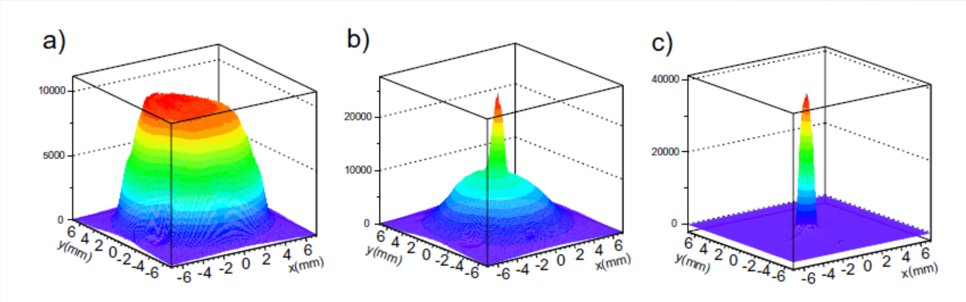
Plasma losses due to asymmeteries



PRL 50, 167 1983

- One of the first results (some time ago)
- Transport depends on B and L (L/B)
- A lot of experimental and theorethical work
- Result qualitatively still true
- Details of the scaling depend on the apparatus
- Different scaling found by others people

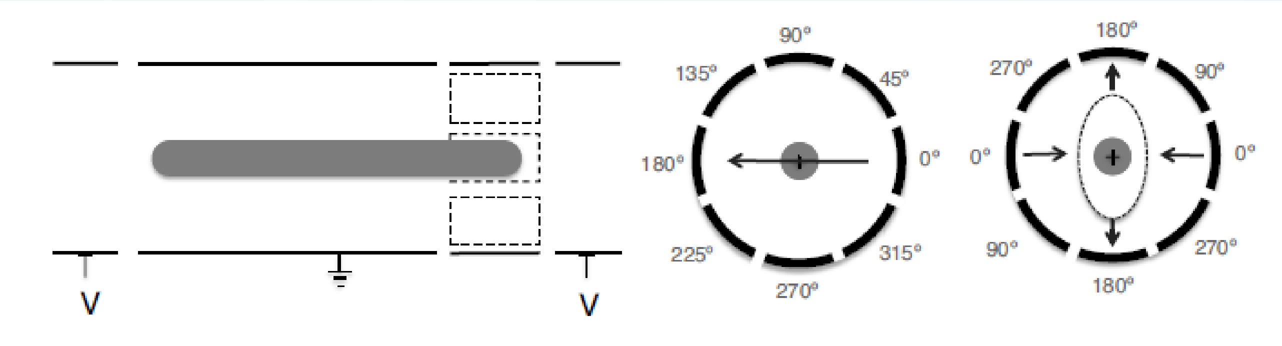
Rotating wall



Example of e- image (AEgIS)
With RW applied with fixed amplitude and freq
for different time

Single particle: Axialization (reduce the magnetron radius)
couple magnetron to z (example)
cool z and then reduce the magnetron radius
coupling: RF field a frequency

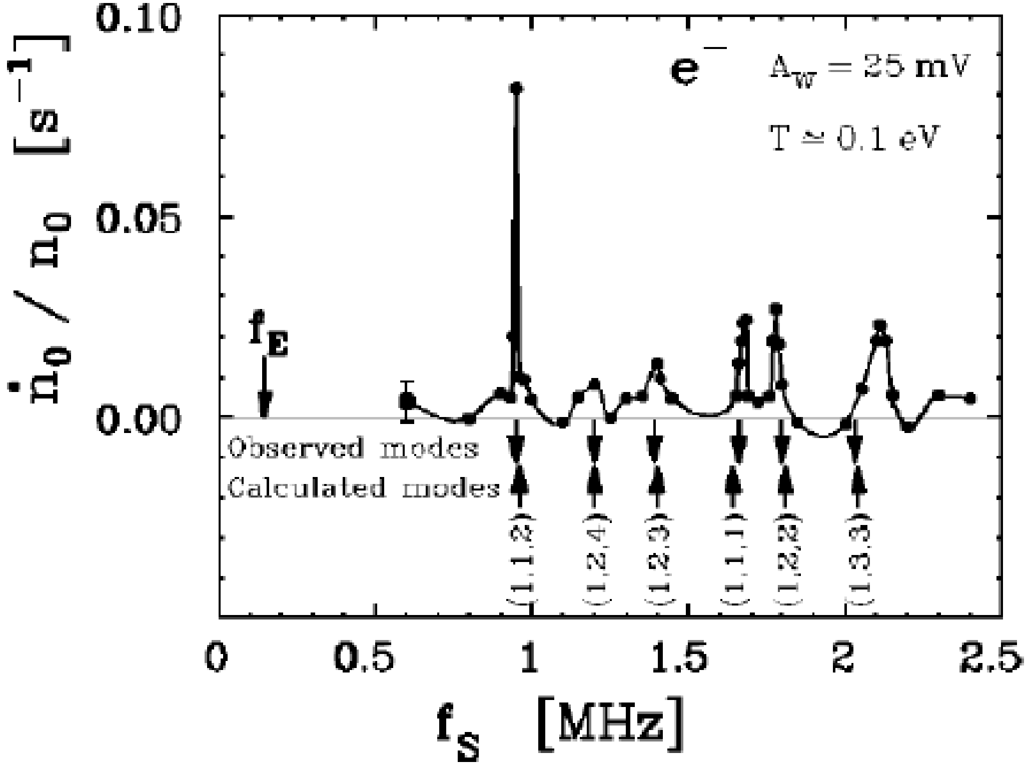
Plasma: change angular momentum with rotating electric field



Need cooling

Rotating wall: coupling to plasma modes

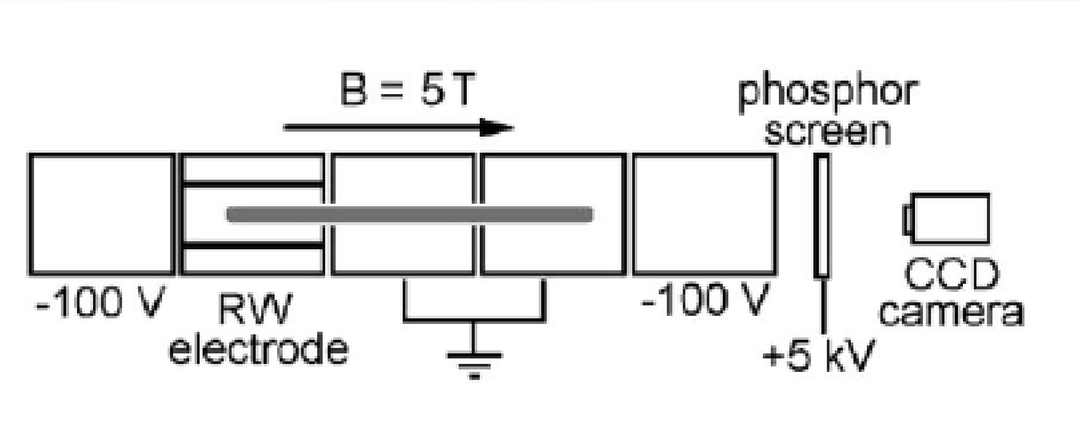
Central density compression by RW coupling to modes

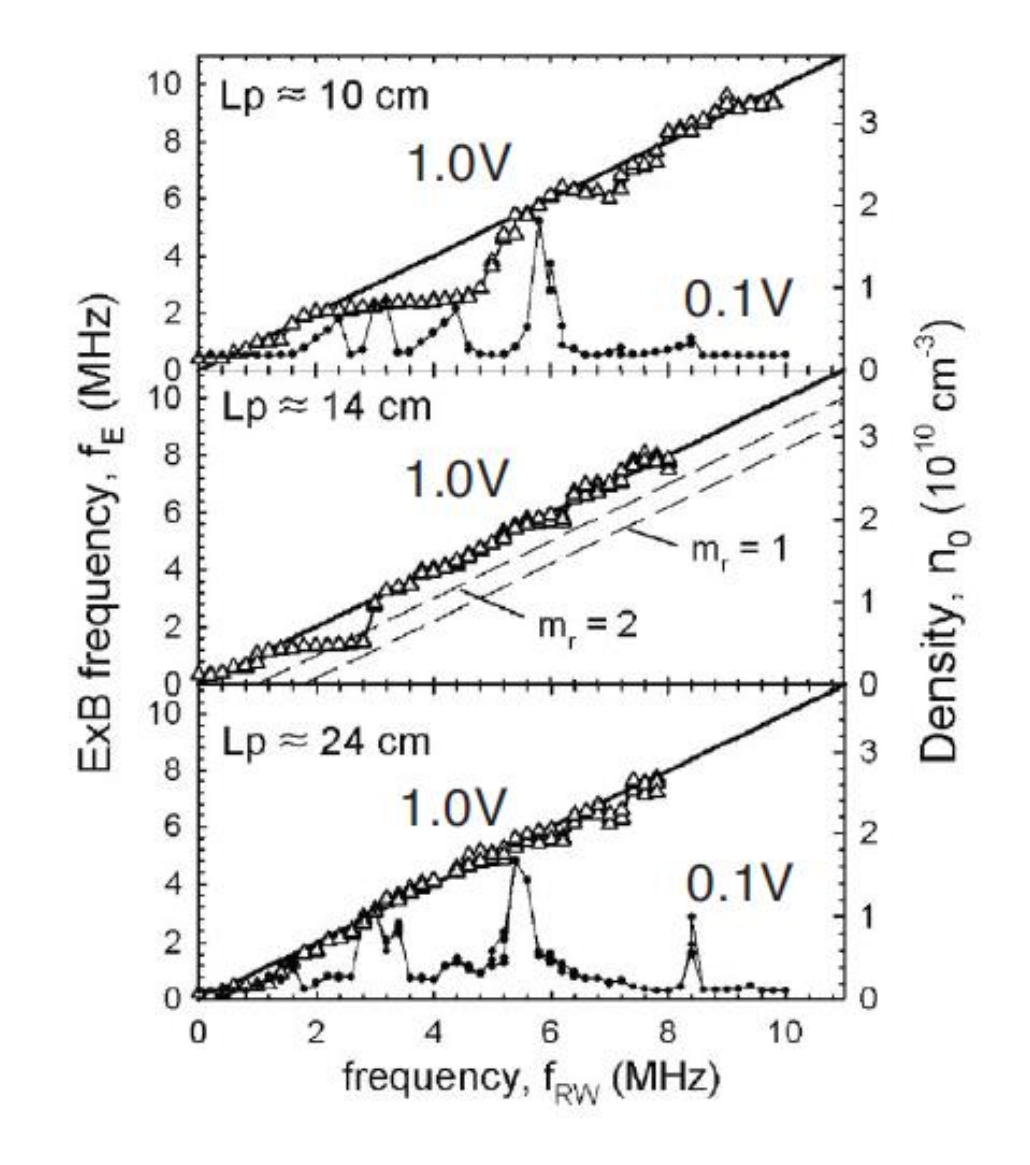


UCSD Mg^+ and e^- experiments

PRL **78**, 875 (1997); PRL **81**, 4875 (1998); POP **7**, 2776 (2000)

Rotating Wall: the strong drive regime





Low amplitude: coupling to plasma modes
High Amplitude: compression at all the frequency
No slip
Plasma rotate at the rw frequency
We can set the density

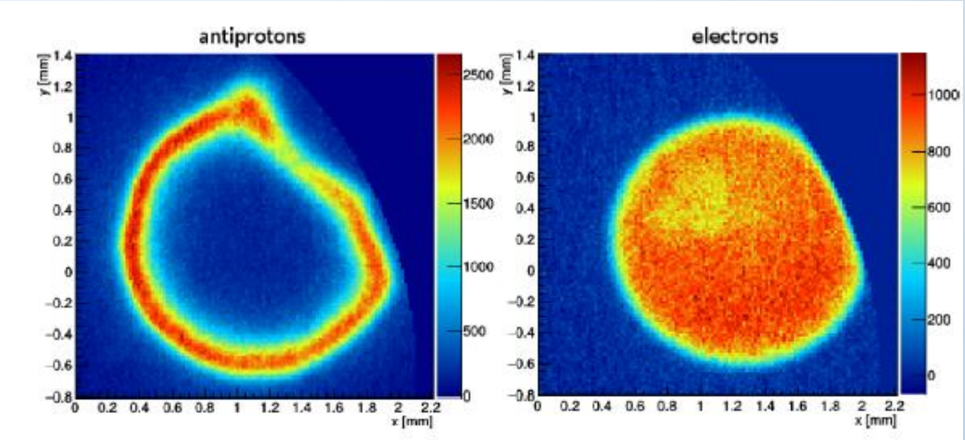
Danielson/Surko strong drive regime
PRL **94**, 035001 (2005); POP **13**, 055706 (2006); PRL **99**, 135005 (2007)

Compression of mixed pbar and e-plasma

AEgIS coll.

- First results published by ALPHA, ASACUSA
- More recent results from AEgIS
- Continuos development

Eur. Phys. J. D (2018) 72: 76



- Avoid centrifugal separation
- Use large number of e- during pbar cooling
- Reduce the number of e- for compression
- without centrifugal separation
- Pay attention to compress the plama tails..(non ideal)

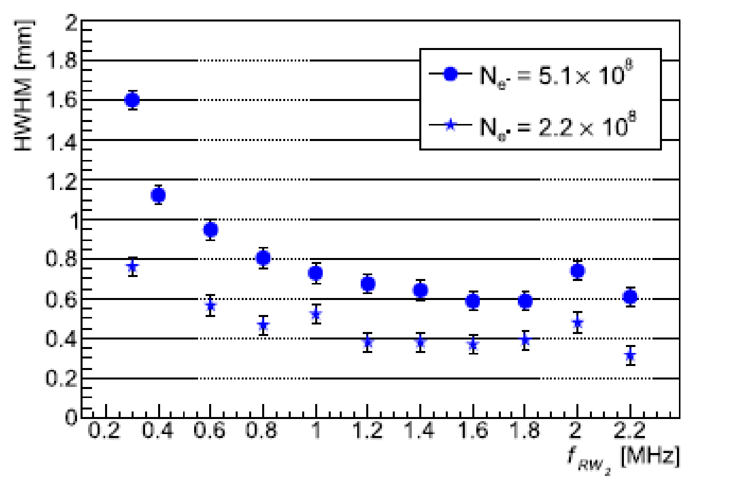


Fig. 5. Electron cloud radii (HWHM) vs. applied RW_2 frequency in a two step compression procedure in the absence of antiprotons. The two data sets differ in the initial electron loading conditions.

Less e- are better compressed…..

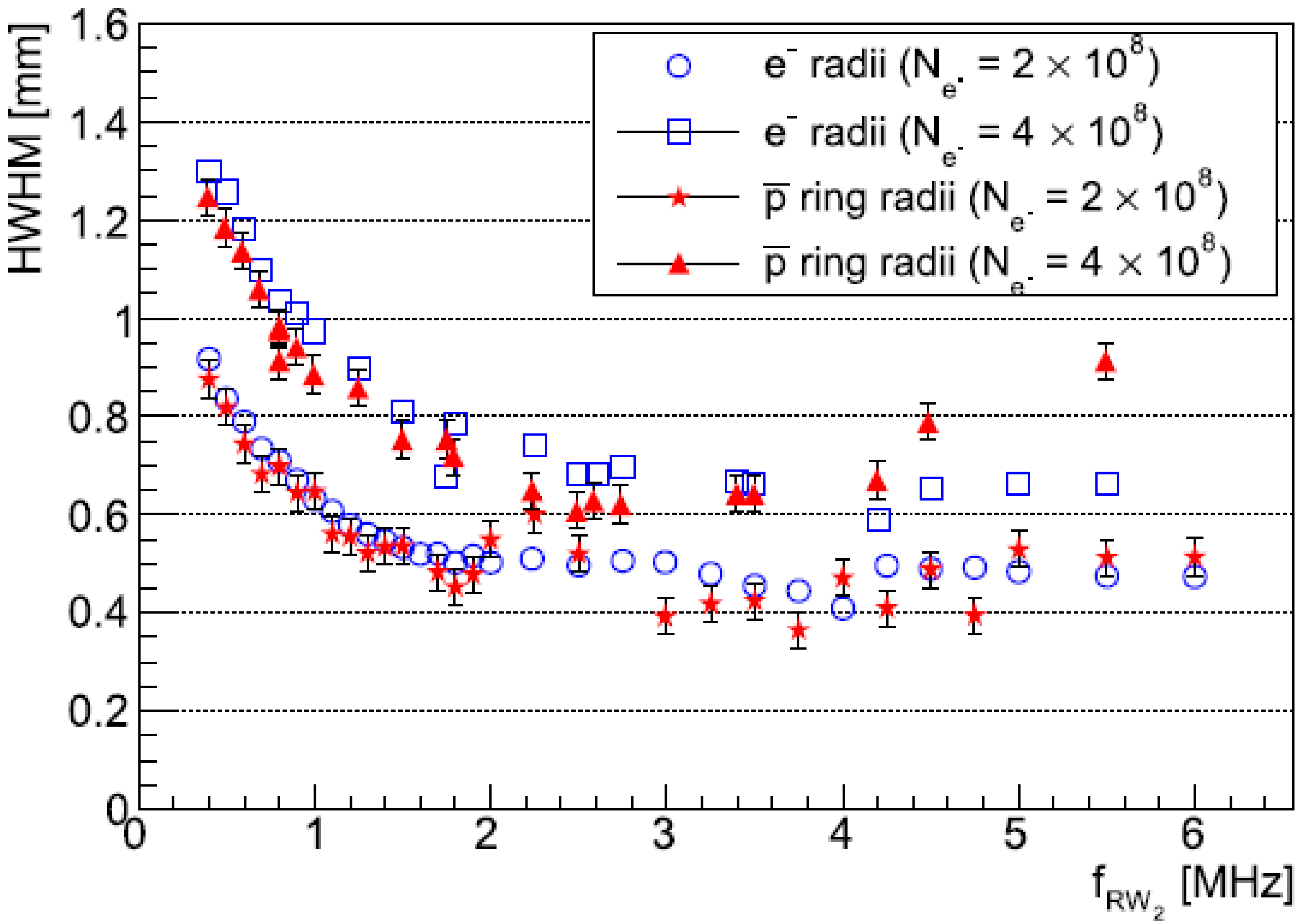


Fig. 7. Single step $\bar{p}$ RW compression. Electron and antiproton radii are plotted as a function of f_{RW_2} for two e^- loading conditions.

Pbar and e- Compression

Eur. Phys. J. D (2018) 72: 76

Multistep compression of mixed pbar and e-

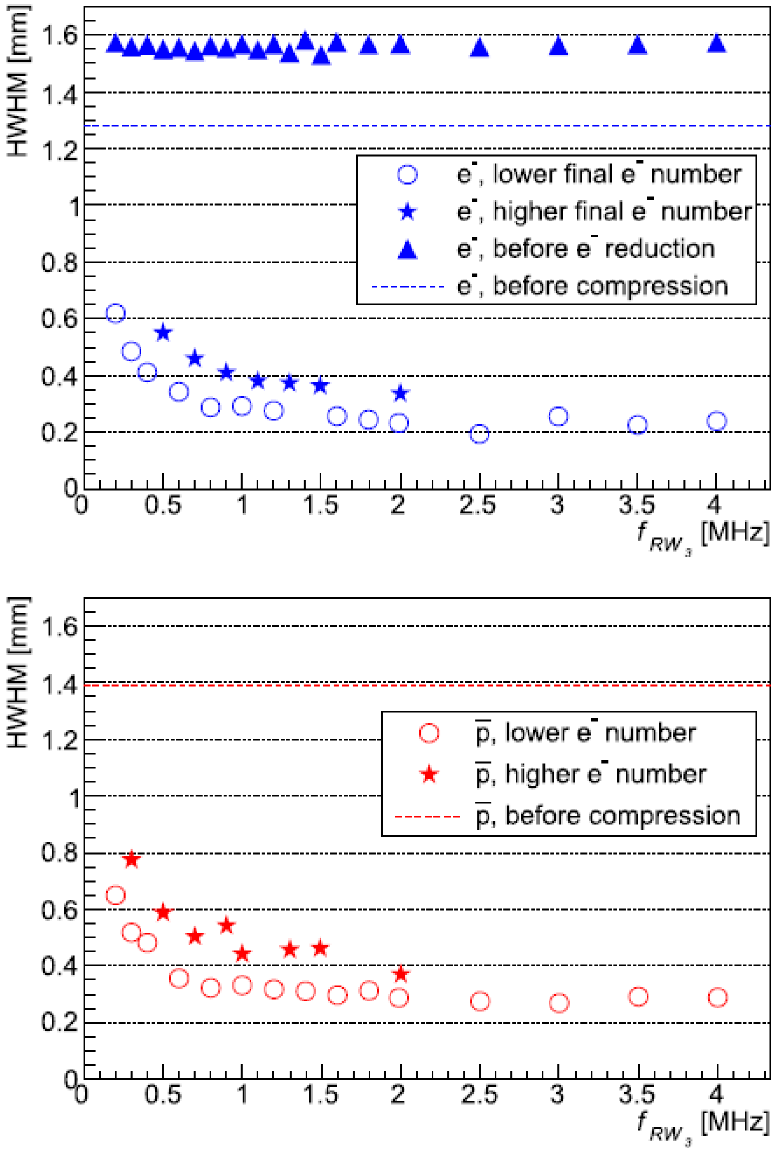


Fig. 10. HWHM of electrons (top panel) and antiprotons (bottom panel) vs. f_{RW_3} during the two-step $\bar{p}$ RW compression procedure. When more electrons remain in the trap after the partial e^- removal (stars) compression is less pronounced. The dotted lines indicate the particle cloud radius after the e^- reduction before turning on the RW drive.

compression of mixed pbar and e-

Pbar shapes follow e- shape

Importance of tail compression

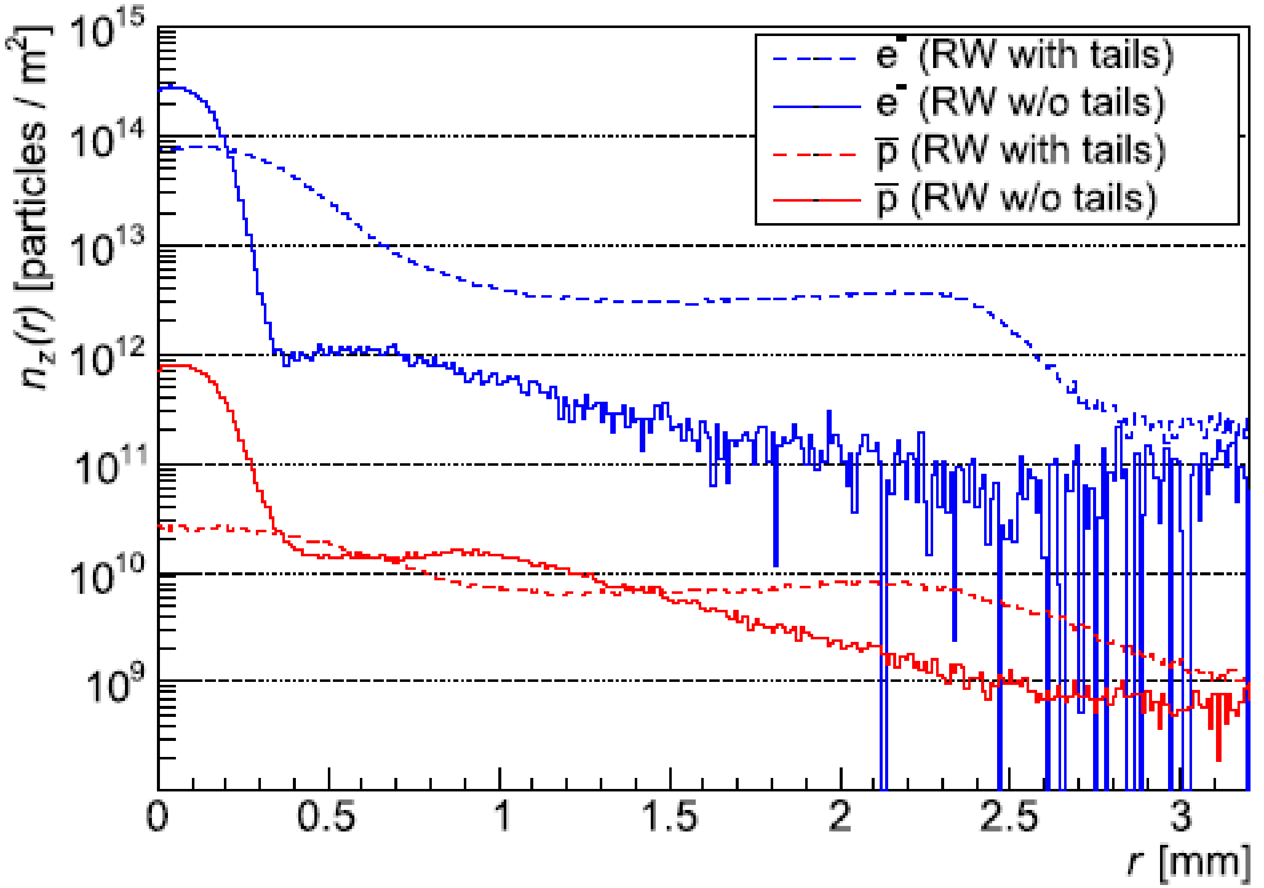


Fig. 12. Radial density profile of e^- and $\bar{p}$ after two cases of RW compression. Dotted lines show unsuccessful compression while the full lines show the high-density $\bar{p}$ compression example. Because of the limited dynamic range of the MCP, the high-density electron curves show higher noise at large radii with respect to the lower density $\bar{p}$ profiles.

Eur. Phys. J. D (2018) 72: 76