Traps and Trap-Based Beams
New Tools for Positron Science

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C. M. Surko ICPA 18
8/19/2018

Theme of This Talk

Positrons are relatively scarce, and so it pays to make optimum use of them

If you want to manipulate and tailor collections of antparticles, keep them away from matter

Neutral antimatter is hard to confine

So the natural solution is to trap a **single-component plasma**

Accumulate antiparticles, tailor the plasma, then tailor the delivery for specific applications

References

Download from the **Summary and Review section** at

positrons.ucsd.edu

tutorial

Accumulation, storage and manipulation of positrons in traps
I – The Basics, C. M. Surko,
II – Selected Topics, C. M. Surko, J. R. Danielson, and T. R. Weber

(Chapters 4 and 5 in *Physics with Trapped Charged Particles*, M. Knoop, *et al*., eds. (Imperial College Press, 2014)

hard core

Plasma and Trap-based Techniques for Science with Positrons, J. R. Danielson, D. H. E. Dubin, R.G. Greaves, and C. M. Surko, *Rev. Mod. Phys*. **87**, p. 247 (2015).

History of Antimatter Trapping

Positrons, magnetic mirror, Gibson, Jordan, Lauer, 1960

Positrons, Penning trap,
Schwinberg, Van Dyck, Dehmelt, 1981

Antiprotons, Penning trap, Gabrielse, 1986

Positron plasma, Penning-Malmberg (PM) trap
Leventhal et al., 1989

Merged antiprotons & positrons, ATHENA, ATRAP, 2002

Positrons in magnetic dipole, Saitoh, 2013

Tailored Delivery of Positrons

large numbers **($N > 10^8$)**

electron-positron plasma
Ps_2 molecules / BEC Ps

short temporal pulses
($\Delta t < 1$ nsec)

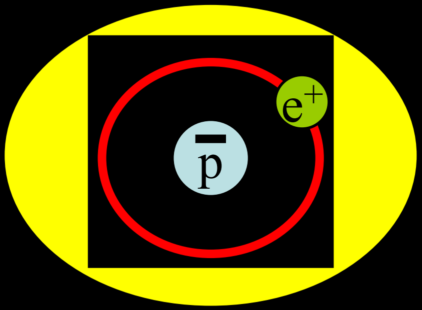
positron lifetime spectroscopy
Ps_2 molecules / BEC Ps

cold/narrow beams
($\Delta E < 25$ meV; $\Delta x < 50$ μm)

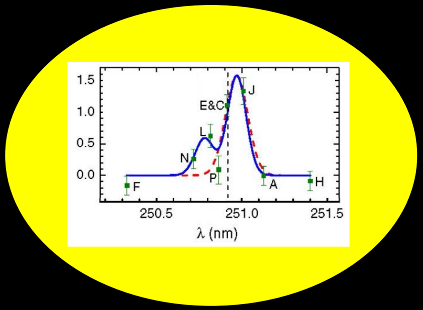
antihydrogen production
annihilation studies
microprobes / microscopes

electrostatic beams

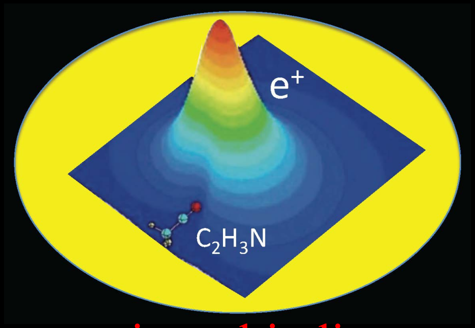
positron Auger spectroscopy
scattering studies



antihydrogen

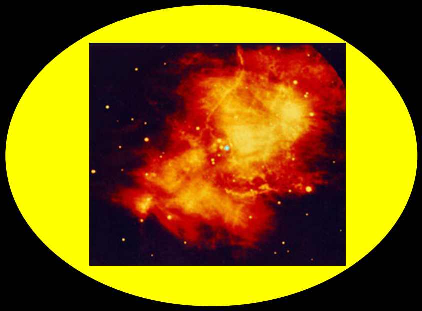


positronium physics (Ps, Ps_2)

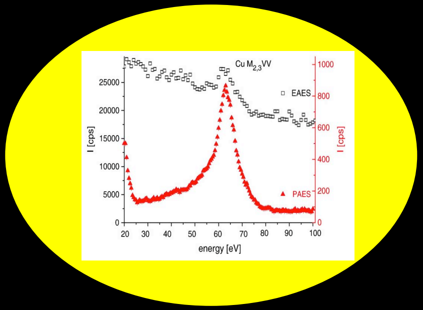


positron binding to matter

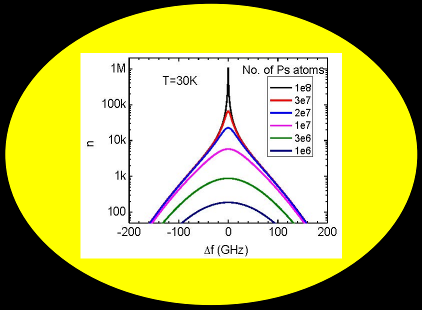
New Physics with Positron Traps and Beams



e^+- e^- (pair) plasmas



e^+- Auger spectroscopy



Ps-atom BEC

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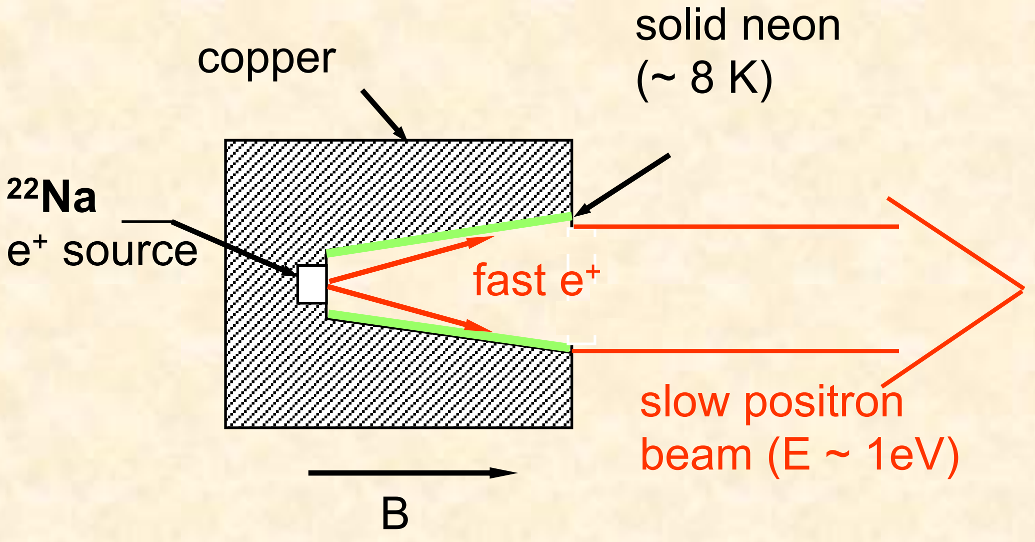
Start with Low-Energy Positrons

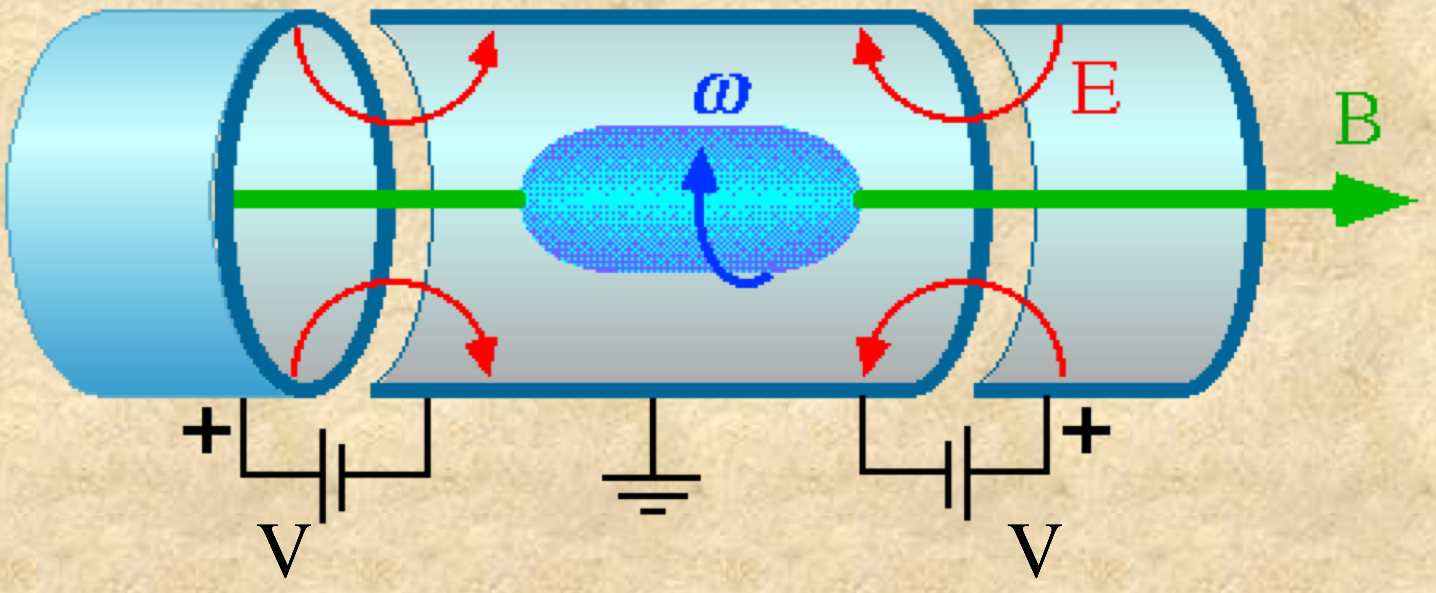
Use "moderators" 100's of keV → ~ 1 eV



Neon efficiency ~ 1%

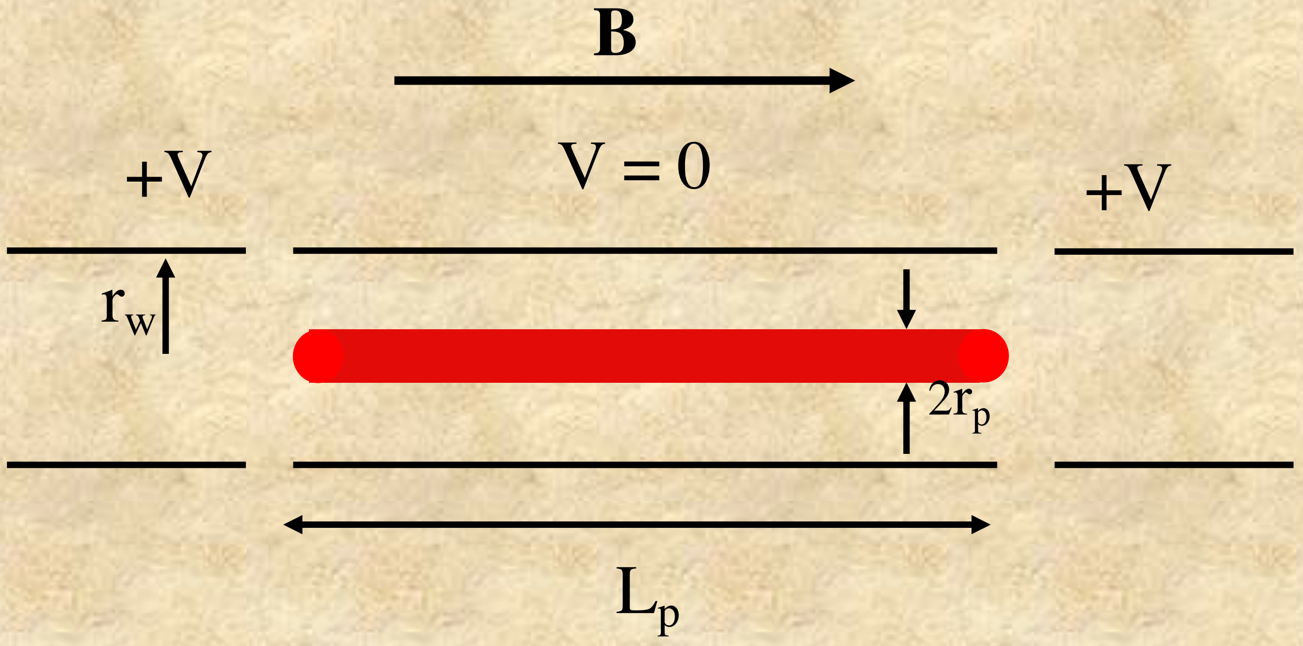
50 mCi ^{22}Na ~ 1 pA slow e$^+$

Penning/Penning-Malmberg Trap



Primer on Single-component Plasmas in Penning and Penning-Malmberg Traps

N particles in a cylindrical plasma of length L_p, and radius r_p in a grounded cylindrical electrode of radius $r_{w,}$ in a uniform magnetic field, B.



The Plasma Regime

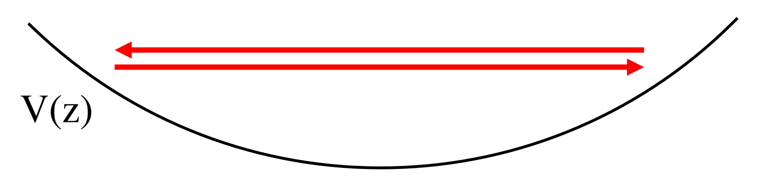
Debye screening

$$\lambda_D = v_T / \omega_p$$

$$\phi(r) = \frac{q}{r} e^{-\frac{r}{\lambda_D}}$$

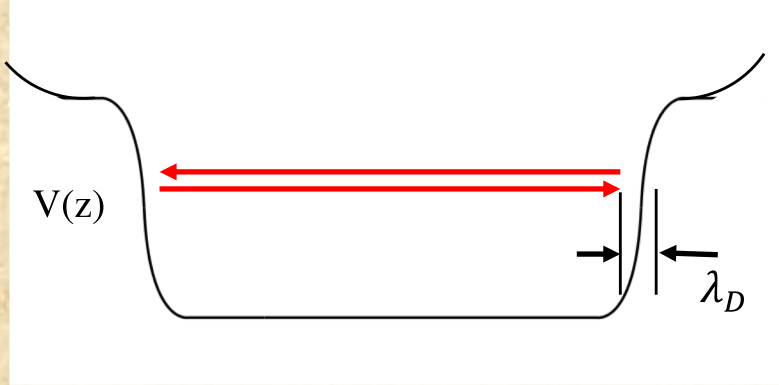
$L_p, r_p << \lambda_D$

single particle motion



$L_p, r_p >> \lambda_D$

plasma screening



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Plasma Parameters

density n

temperature T

(cgs units)

thermal velocity $v_T = \sqrt{T/m}$

frequencies

- cyclotron frequency $\omega_c = eB/mc$
- plasma frequency $\omega_p = (4\pi n e^2/m)^{1/2}$
- bounce frequency $f_b = v_T/2L_p$

lengths

- cyclotron radius $r_c = v_T/\,\omega_c$
- Debye screening $\lambda_D = v_T/\,\omega_p$

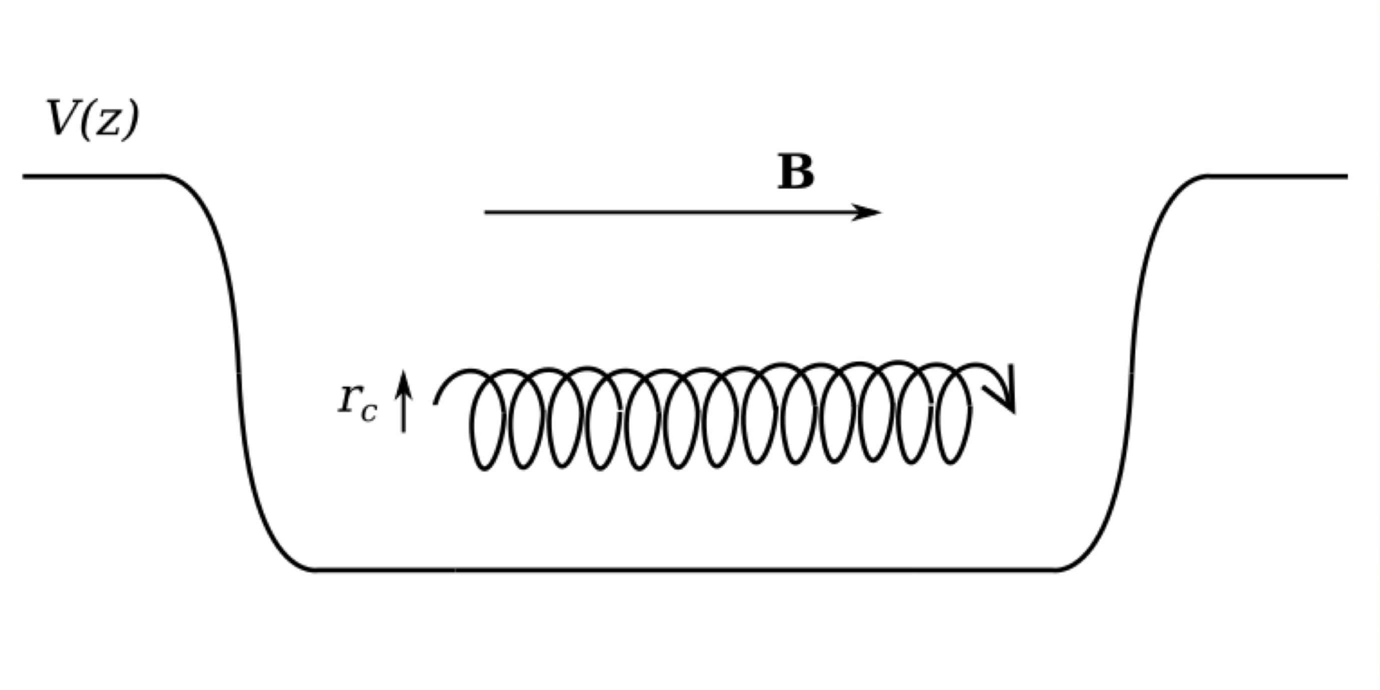
space charge potential

$$\varphi(r) = \frac{eN}{L_p}\left[1 - \left(\frac{r}{r_p}\right)^2 + 2ln(r_w/r_p)\right]$$

Coulomb collisions

$$\nu_{ee} \approx \frac{\sqrt{\pi}\, n e^4}{{v_T}^3 m^2} \ln(r_c T/e^2)$$

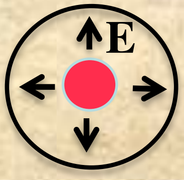
Particles spiral around field lines with gyroradius (cyclotron radius) r_c as they move along the field.



Typically, r_c is small compared to other distances (i.e., $r_c << \lambda_D, r_p$), so the particles are "tied to the field lines" - a strongly magnetized plasma.

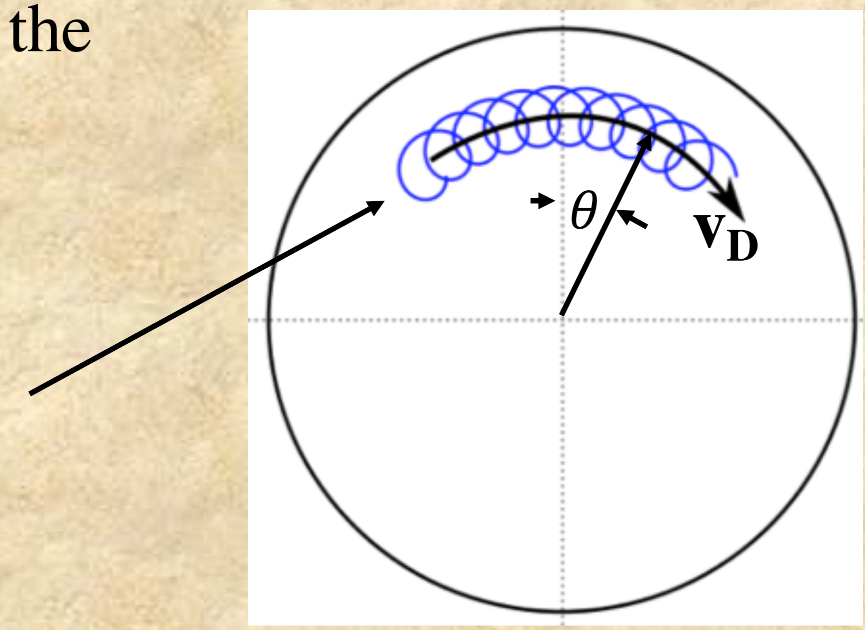
E x *B* Drift Velocity

A single-component plasma has a space-charge electric field. For a long plasma, $\vec{E} = E\,\hat{r}$



E perpendicular to *B* gives an *E* x *B* drift, $\vec{v}_D = c\,\frac{E}{B}\,\hat{\theta}$

Particles drift around the plasma center
with frequency f_{ExB}

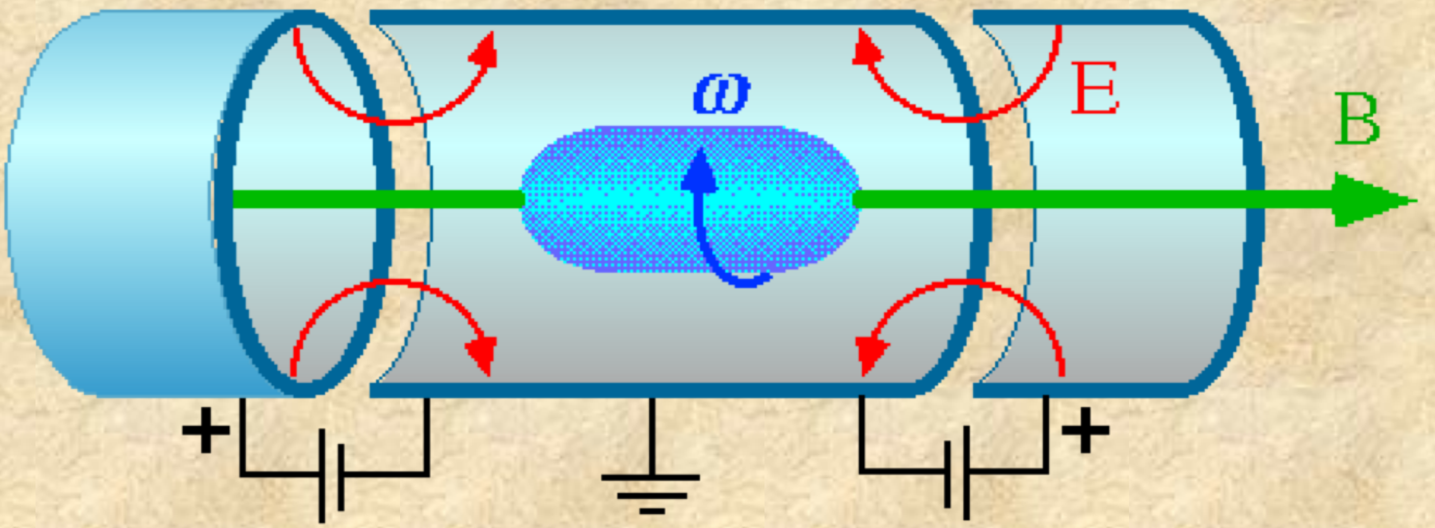


cyclotron orbit with superimposed drift

(B out of the page)

Plasma rotation reduces outward transport due to asymmetries

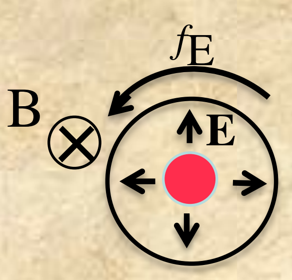
Radial Vacuum Fields in a Short Trap



For low density charge clouds ($\lambda_D \geq L_p$), the vacuum fields produce a beneficial *E* x *B* rotation (i.e., “magnetron motion”)

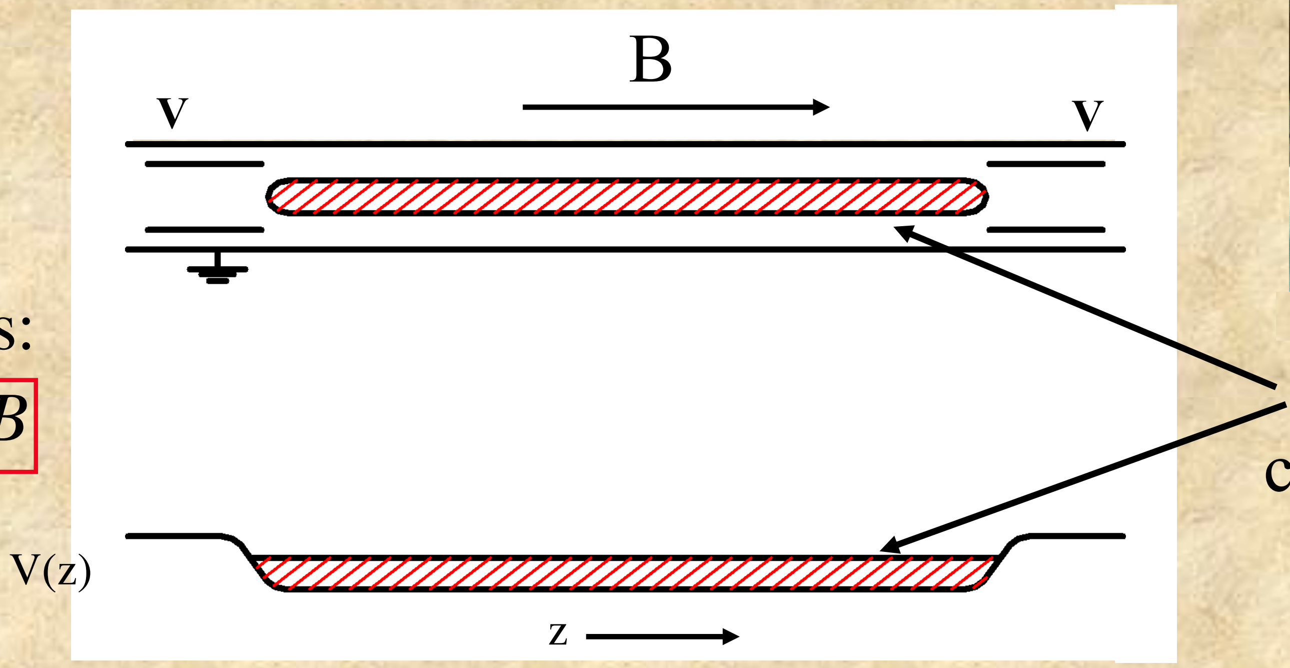
A Near-Perfect "Antimatter Bottle"

the Penning-Malmberg Trap



plasma rotates:

$$\boxed{f_E = cne/B}$$



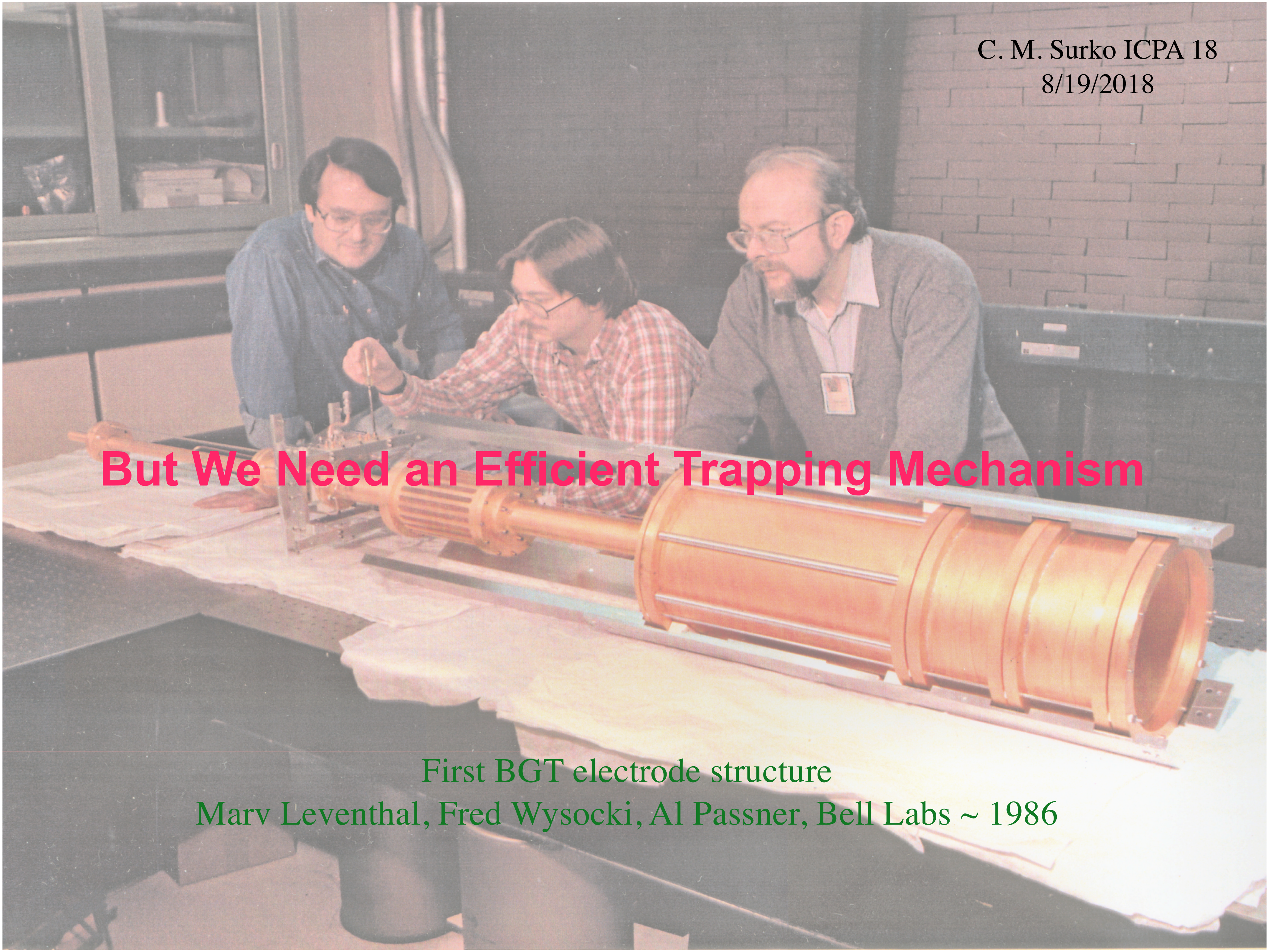
single-component plasma

Canonical angular momentum $L_z \approx \frac{m\omega_c}{2}\sum_j r_j^2$

No torques $\Rightarrow$ $\sum_j r_j^2$ is constant. No expansion!

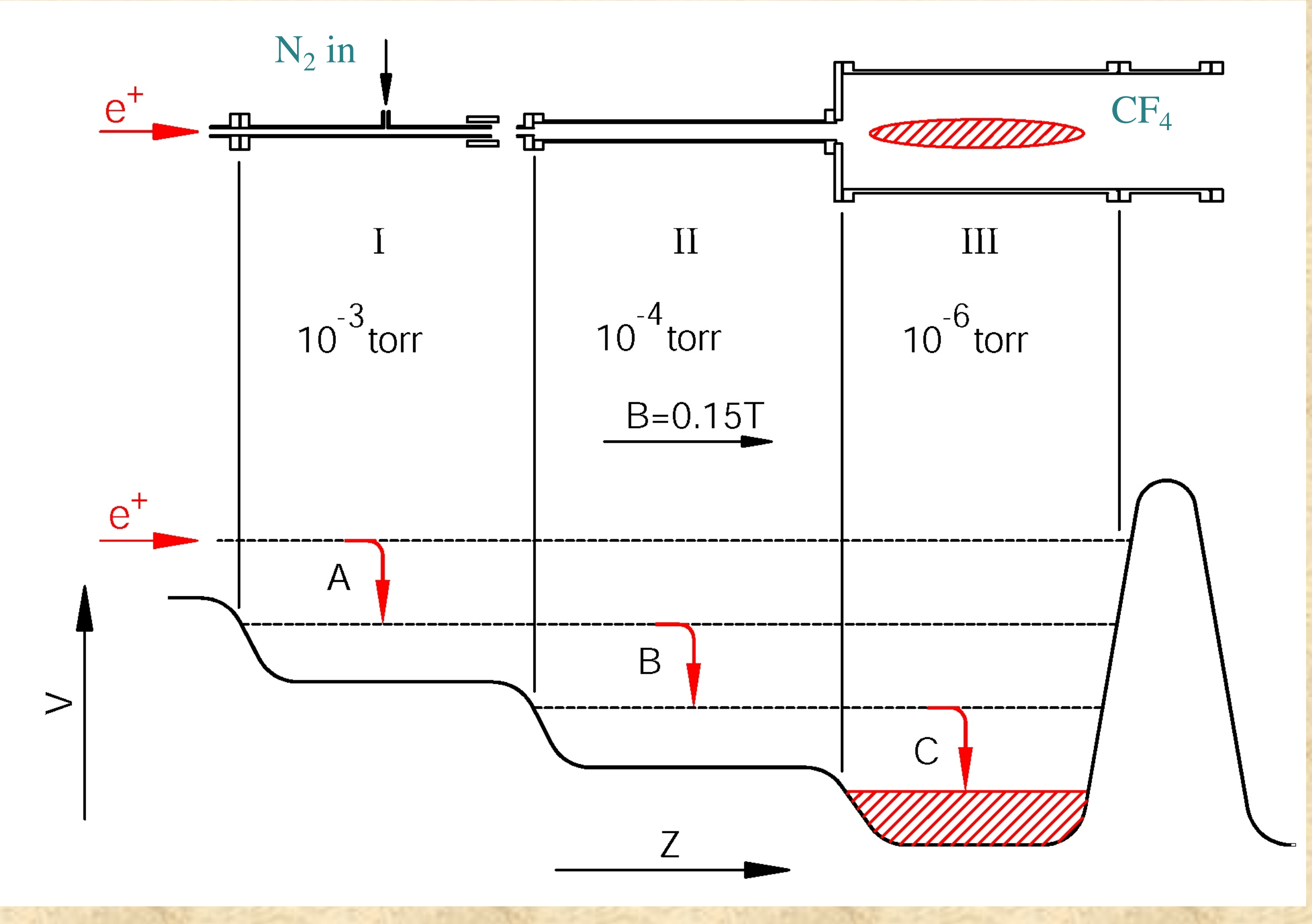
(Malmberg & deGrassie '75; O'Neil '80)

But We Need an Efficient Trapping Mechanism



First BGT electrode structure
Marv Leventhal, Fred Wysocki, Al Passner, Bell Labs ~ 1986

Buffer-Gas Positron Trap

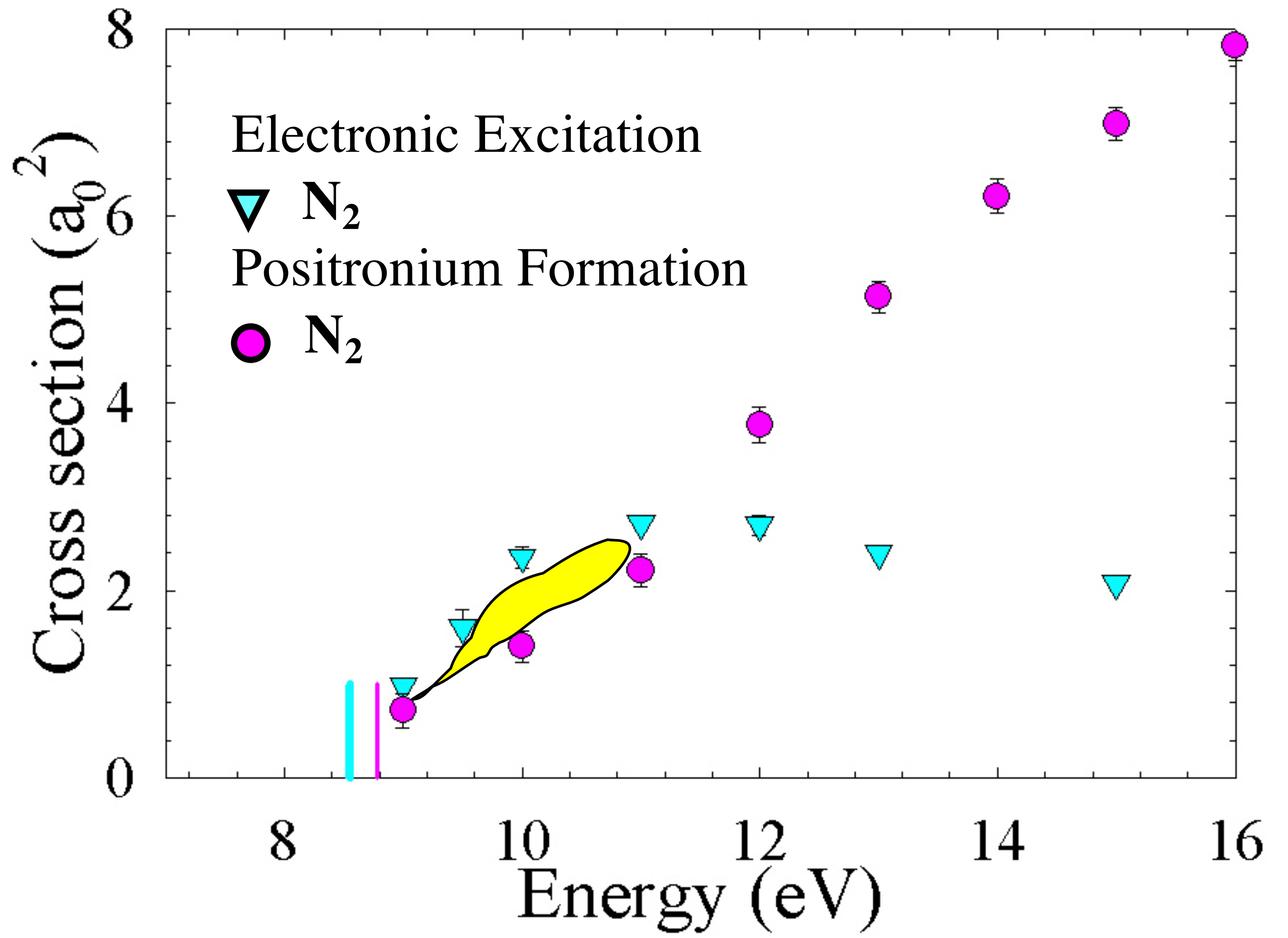


- Trap using electronic excitation of N$_2$
- Positrons cool to 300K on CF$_4$ in ~ 0.1s

<u>30% trapping efficiency</u>

Surko et al., PRL ‘88; Murphy et al., PR ‘92

N_2 is the Gas of Choice for Positron Trapping (electronic excitation > Ps formation)



Large EE cross section compared with Ps =>
N_2 is the buffer gas of choice.

Marler, et al., PRA 05

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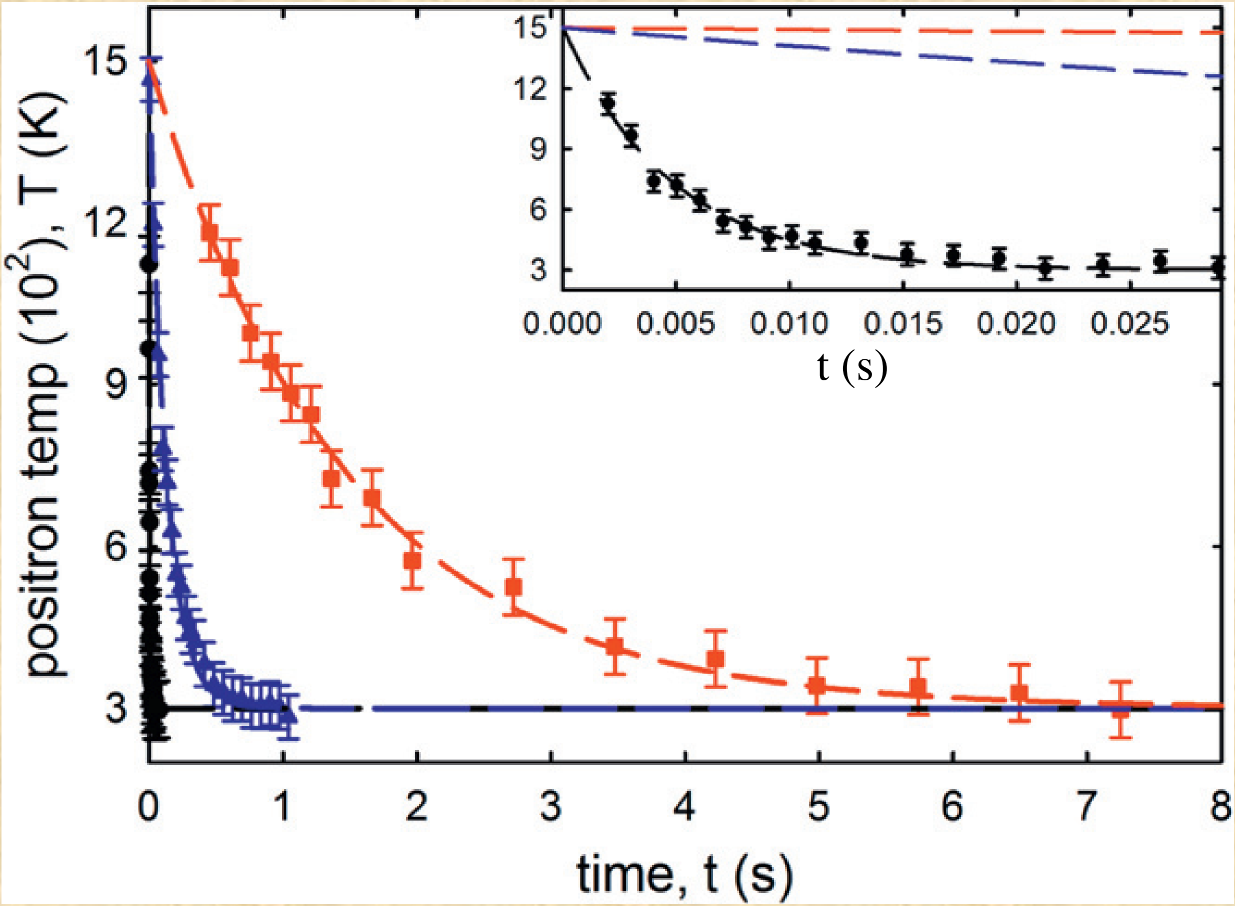
Cooling on a Buffer Gas



p = 10^{-6} torr

T = 300 K

Cooling can be on vibrational or rotational transitions; choice of gas depends on ambient temperature.

Natisin, et al., *J. Phys. B* (2014)

Positron Annihilation

Avoid Large Molecules!

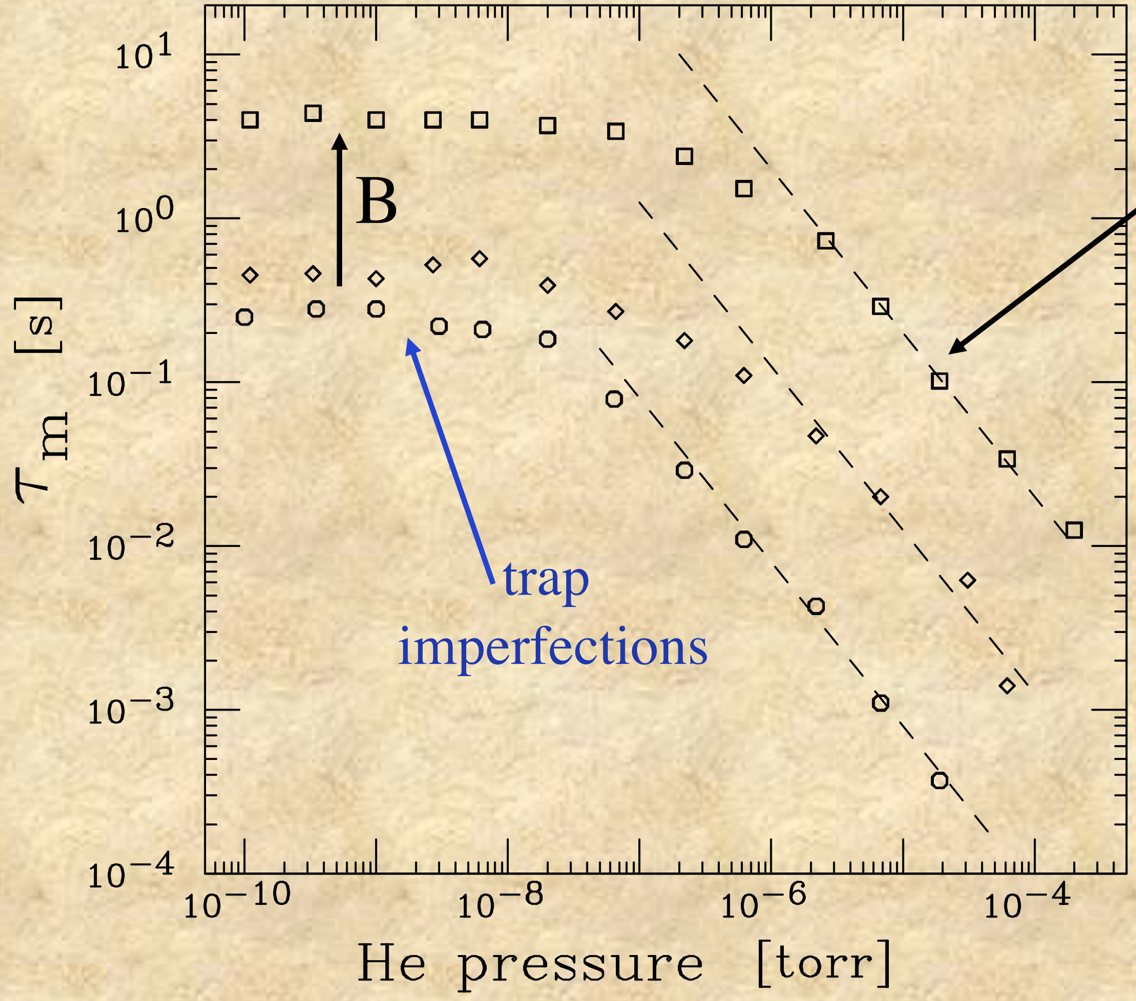
Molecule	formula	τ_a (s)
small molecules	N_2, CO, CF_4	$\geq 5 \times 10^4$
tetraethyl silane	$Si(C_2H_5)_4$	6.2
glycerol	$C_3H_8O_3$	2.2
dodecane	$C_{12}H_{26}$	1.8

$p = 10^{-9}$ torr

(diffusion pump oil C_xH_{2x+2} x ~ 15 – 40)

Positrons attach to all but the smallest molecules leading to much larger annihilation rates

Outward Transport



gas collisions

trap
imperfections

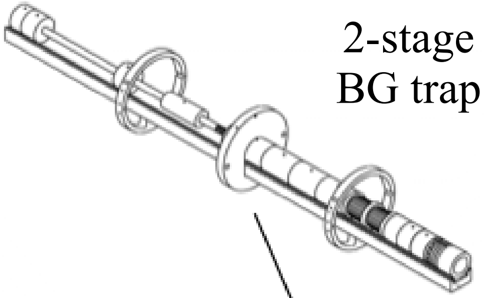
τ_m is central
density decay
time

There are two regimes of “diffusive” positron loss.
At low background gas pressures, imperfections dominate.

Malmberg & Driscoll, PRL (1980)

Commercial Buffer-gas Positron Traps

First Point Scientific, Inc. (R. G. Greaves)



2-stage
BG trap

Storage stage

Source

BG trap

source/moderator

Commercial & home-built
traps in the U. S.,Australia, China,
U. K., Russia & CERN (4)

two-stage trap

So We've Trapped Positrons, What's Next?

(ANU positron beamlines)

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Antimatter Plasma Control and Manipulation

Good particle cooling achieved with various techniques

Plasma compression with rotating electric fields

Trap-based beams from tailored plasmas

narrow energy spreads, time-compression, or finely focused beams

Merged plasmas (antiproton and positron) for antihydrogen

Antiparticle Cooling

Critical for Many Applications

Collisional cooling (positrons; excite rotations and vibrations in molecules) e.g, CF_4, SF_6; but annihilation loss

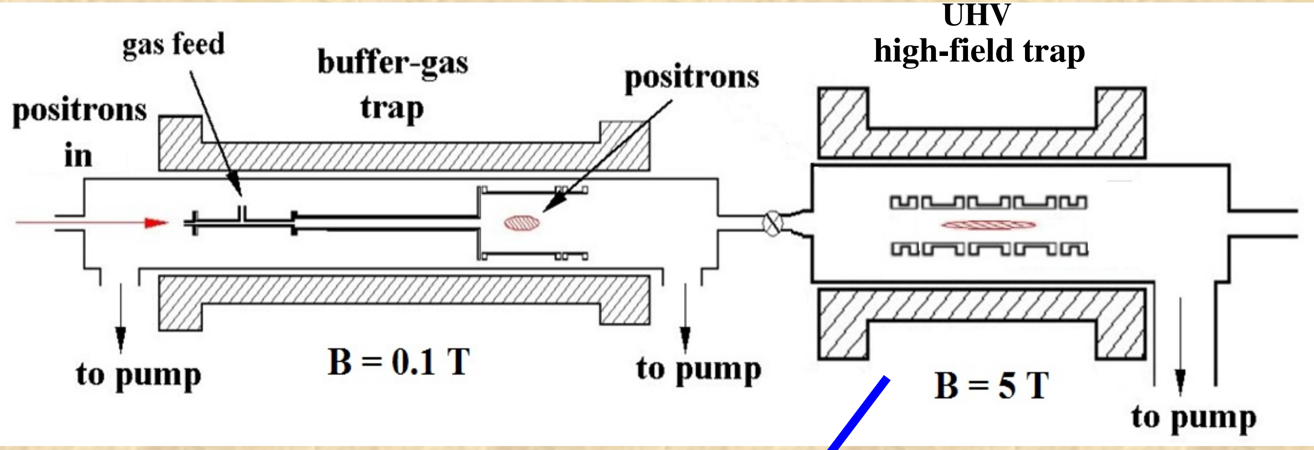
Cyclotron radiation (positrons, or antiprotons sympathetically using electrons; UHV compatible); need large B, not so fast

$$\tau_{cyc} = \frac{4}{B^2\ (\text{tesla})}\ (\text{s})$$

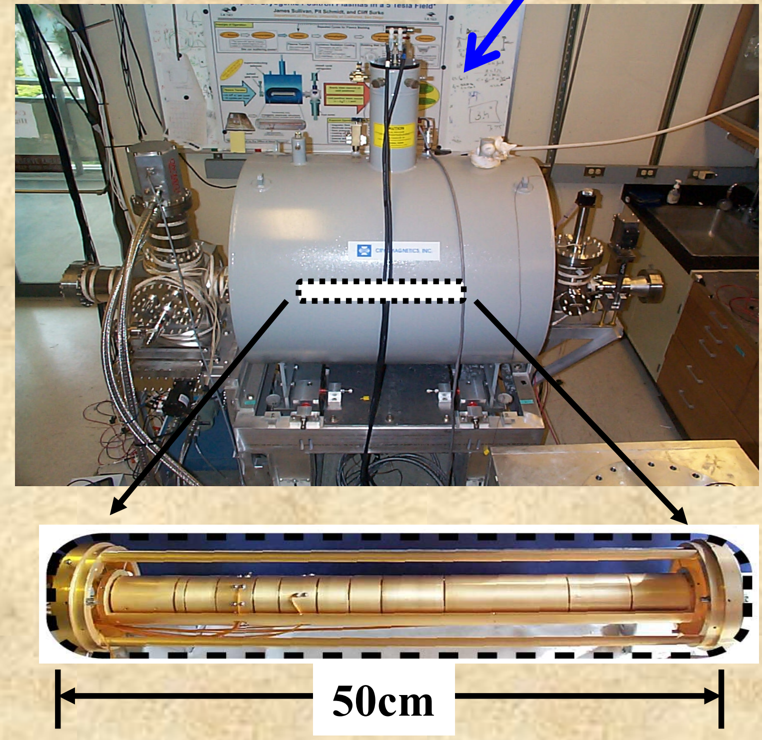
Laser cooling (cool Be^+ ions to cool positrons sympathetically); mK temperatures, but centrifugal separation

Evaporation (positrons or antiprotons); particle loss

Shuttle to UHV for Long Term Storage



$p < 10^{-9}$ torr
annihilation negligible



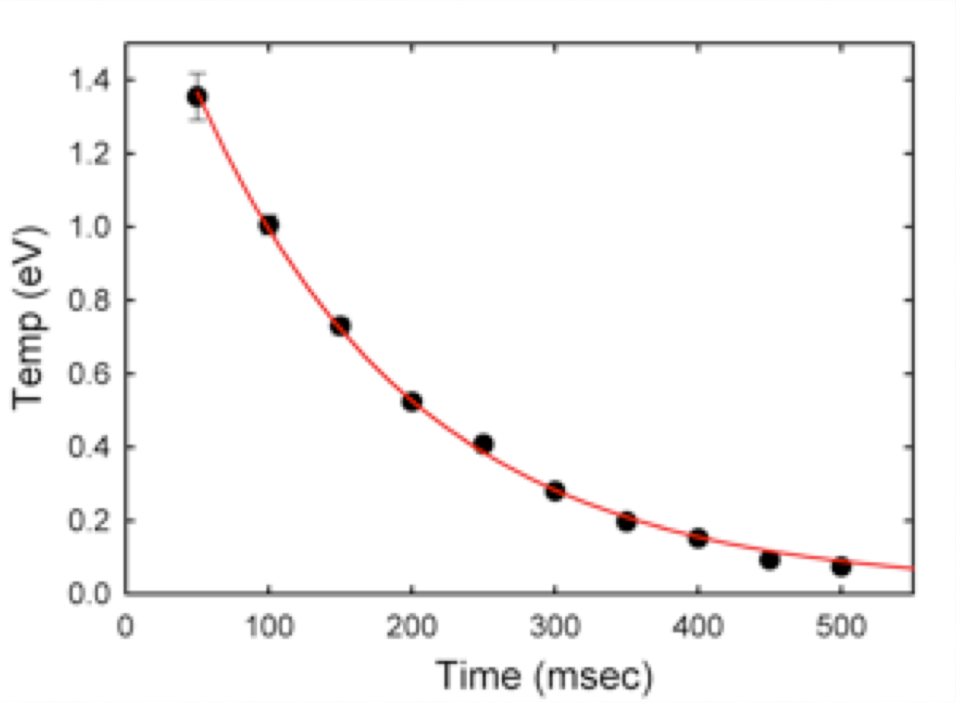
plasma cools by cyclotron radiation

(positrons or electrons)

Surko, Greaves, Charlton HI ‘97

Cyclotron Cooling in a Large B Field in UHV

B = 5 T



$$T(t) = T_0 + (T_1 - T_w)\exp(-\tau/\ \tau_c)$$

$$\boxed{\tau_c = 4/B^2 = 0.16\ \text{s}}$$

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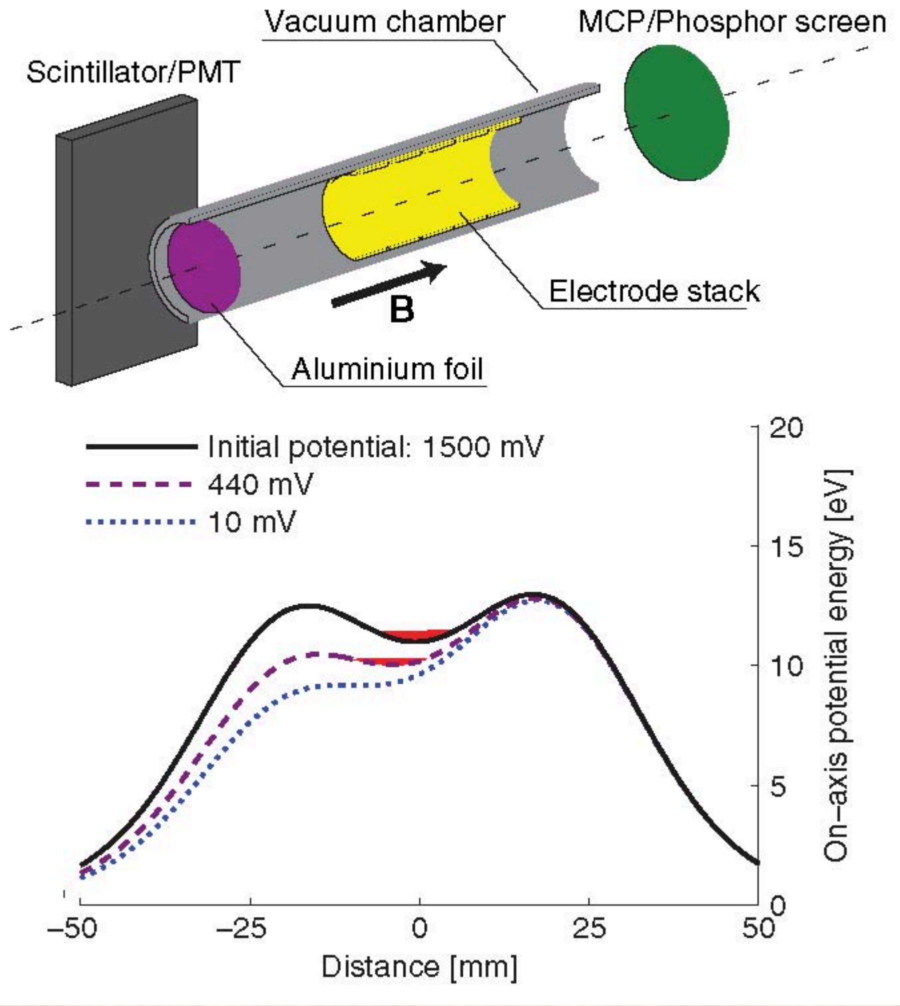
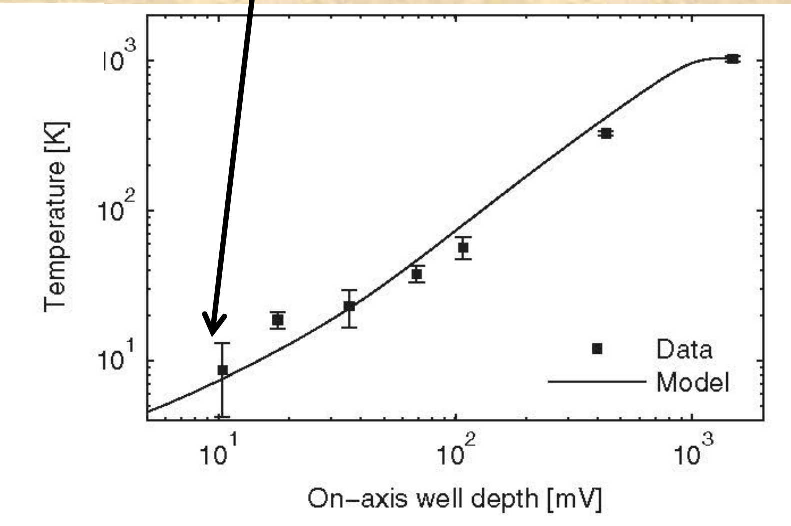
Evaporative Cooling of Antiprotons



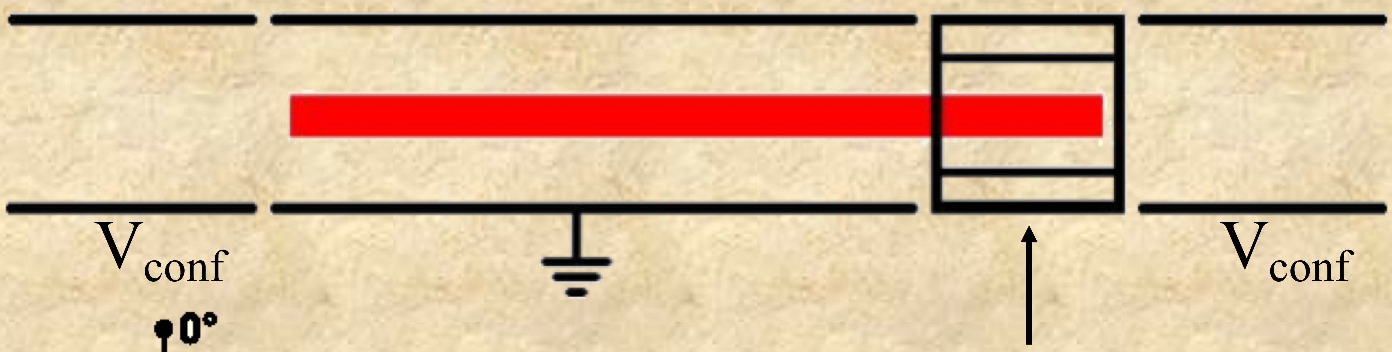
9 K (but > 90 % loss)

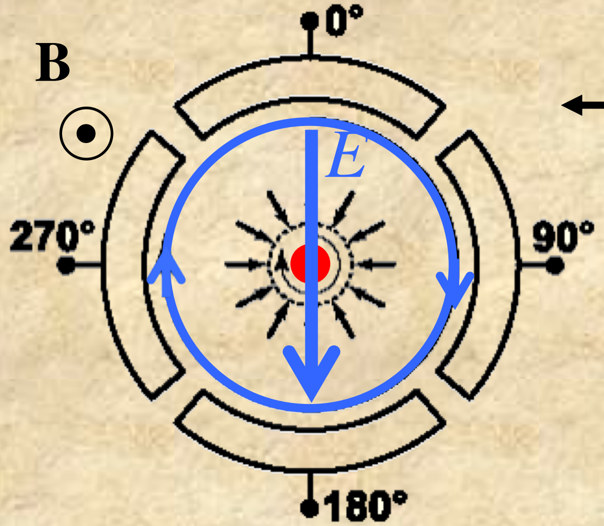


ALPHA; Andresen et al., PRL 2010

Increase Density by Radial Compression with Rotating Electric Fields

"The Rotating Wall Technique"





Apply a torque using a rotating electric field =>
radial compression for $f_{RW} > f_E$

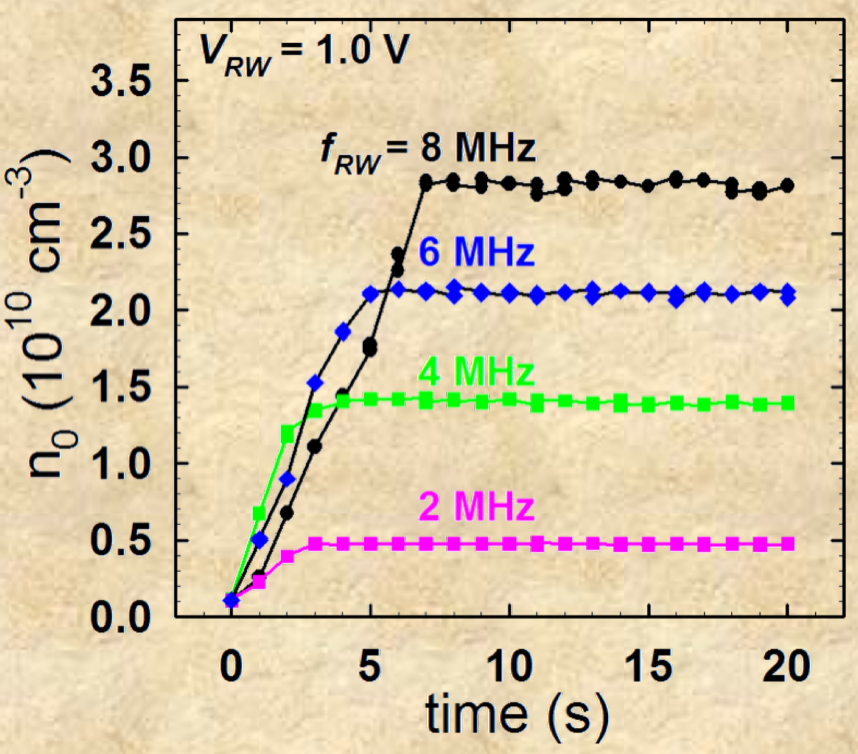
$$V = \mathbf{V_{RW}} \cos[(2\pi \boldsymbol{f}_{\mathbf{RW}})\, t + \phi]$$

(Huang, et al., Anderegg, et al., Hollmann, et al., Greaves et al., Danielson et al., 1997 - 2007)

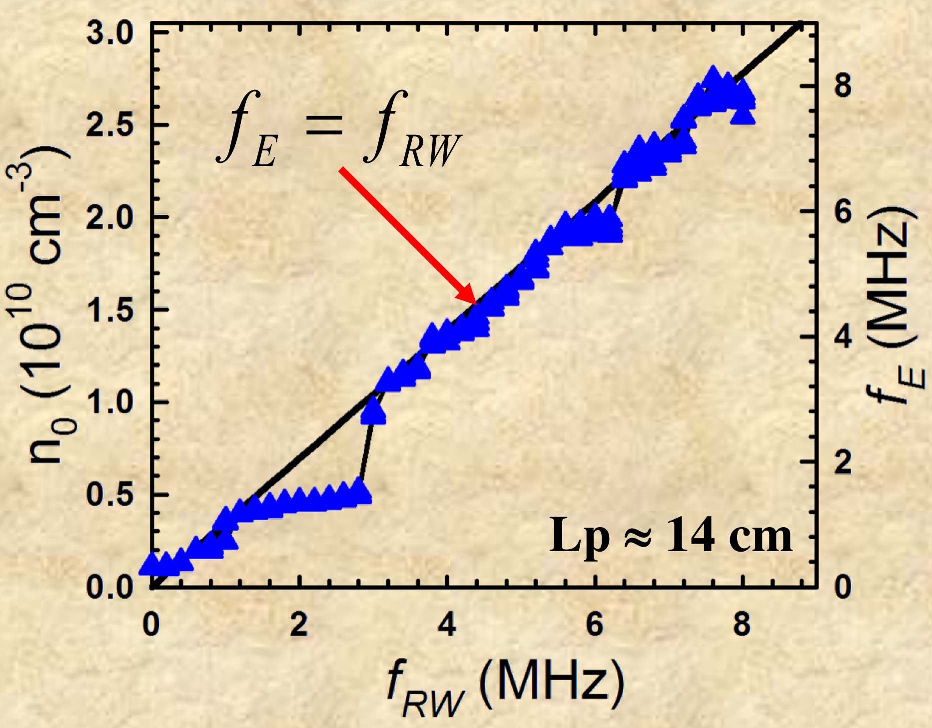
Radial Compression with Rotating Electric Fields

"The RW Strong-Drive Regime"

Density vs time for different f_{RW}



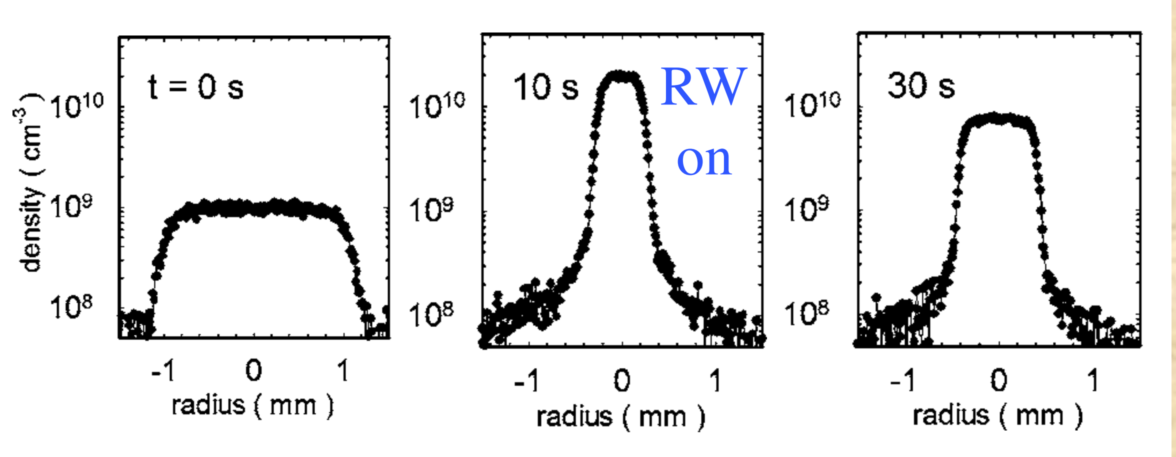
Steady-state density vs. f_{RW}



Danielson, et al., Phys. Plasmas 2006

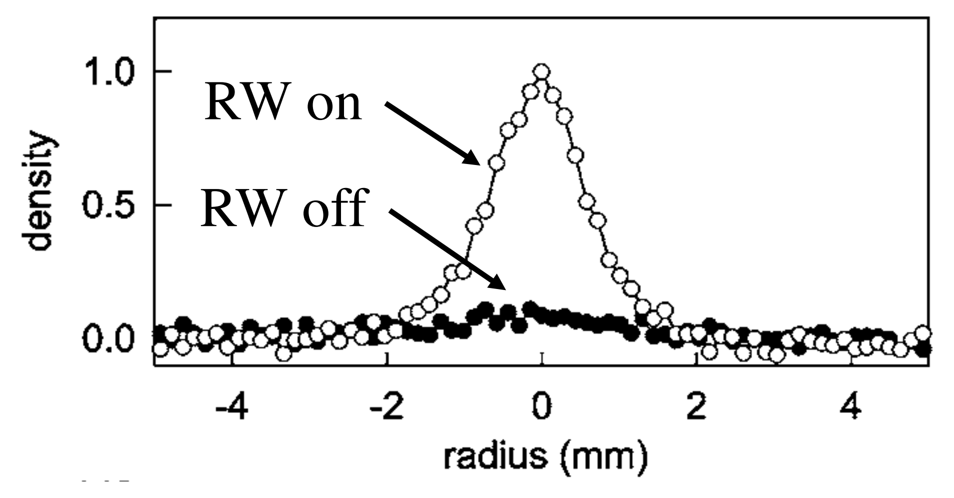
RW Compression

Cyclotron cooling at high n



Danielson et al.
PP (2006)

Buffer-gas cooling at low n

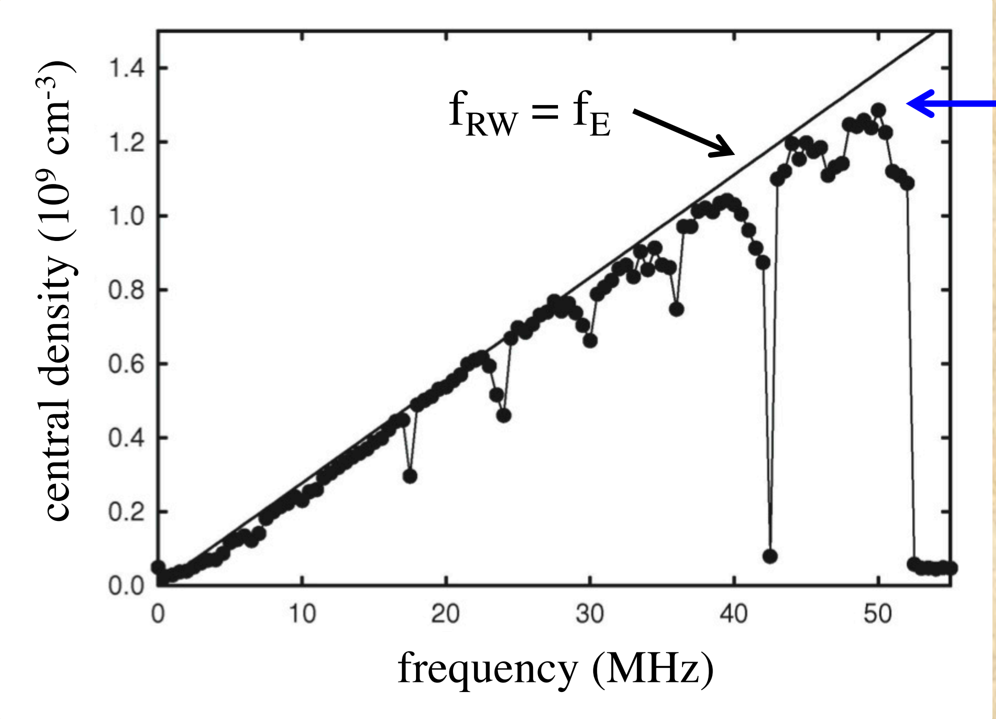


Cassidy et al.
RSI (2006)

Danielson, Phys. Plasmas 2006

Cassidy, RSI 2006

Density Control Using Rotating-wall Compression (buffer-gas cooling)



$n_0 \approx 17\%$ of the Brillouin limit, n_B

B = 400 G   positron plasma

Glitches due to trap imperfections

$$n_B = \frac{B^2}{8\pi mc^2}$$

At 5 T, $n_{max} \leq 10^{-3}\, n_B$ – this is not understood?

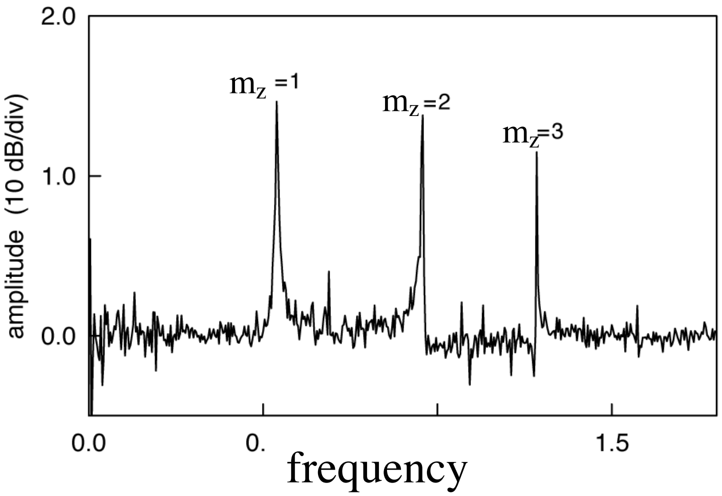
The Rotating Wall also works in the single-particle regime, but somewhat differently (i.e., as a “rotating particle-bounce” resonance)

(Danielson et al., RMP, 2015)

Positron Plasma Parameters

Magnetic field	10^{-2} – 5 tesla
Number	10^{4} - 10^{10}
Density	10^{5} - 10^{10} cm^{-3}
Space charge	10^{-3} – 10^{3} eV
Temperature	10^{-3} – 1 eV
Plasma length	1 – 30 cm
Plasma radius	0.5 – 10 mm
Debye length	10^{-2} – 1 cm
Confinement time	10^{2} – 10^{5} s

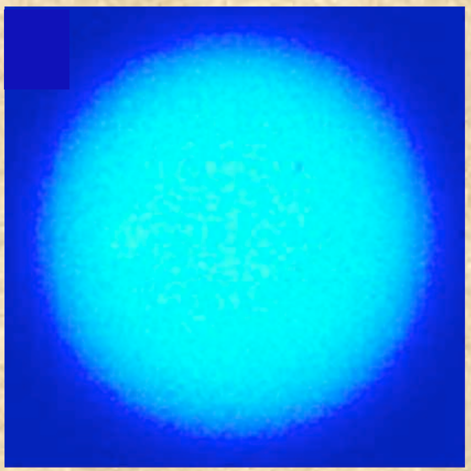
Trivelpiece-Gould modes*



Dubin PF ’93, Tinkle PP ‘94

Diagnostics:

Escaping particles to measure T; modes to measure N, n, T, & aspect ratio 2D CCD images



Surko AIP ‘99, Weber PP ‘08

Various Positron and Antiproton PM Trap Plasmas

	magnetic field (T)	length (cm)	r_p (mm)	temp. (eV)	density (10^8 cm^-3)	total number (10^8)	space charge potential (V)	confinement/ annihilation time (s)
UCSD	0.1	10	6	0.03	0.02	3	15	300
UCR	0.09	–	0.5	0.03	–	0.01	0.01	1
FPSI	0.04	–	0.5	0.05	12	–	10	1000
ALPHA pbars	1	2	1	0.01	0.2	0.0009	0.5	-
ALPHA e+	1	2	0.4	0.002	3	0.03	1.6	-
ATRAP	1	–	–	0.001	–	40	5 30	-

🟩	low B, buffer-gas cooling
🟦	high B, cyclotron cooling

Large-N e^- Plasma in High-B UHV Trap

$\underline{N = 1 \times 10^9}$

$T = 0.1$ eV

$r_p = 0.03$ cm

$L_p = 14$ cm

$B = 5$ tesla

$r_w = 1.2$ cm

$$\mathbf{f_c >> f_p >> f_{ExB} > \nu_{\varepsilon\varepsilon} > f_b}$$

$$\mathbf{r_w >> r_p >> \lambda_D >> r_c}$$

$$\mathbf{n\,\lambda_D^3 \sim 200 \text{ (i.e., } >> 1)}$$

The results:

$v_T = 10^7$ cm/s

$f_c = 140$ GHz

$f_p = 2$ GHz

$f_{ExB} = 8$ MHz

$f_b = 0.6$ MHz

$\lambda_D = 10^{-3}$ cm

$r_c = 10^{-5}$ cm

$\phi(r=0) = 80$ Volts

collision rate

$\nu_{ee} = 2$ MHz

cooling rate

$\nu_c = 6$ Hz

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Example of Plasma Control
Strong Drive Regime and Evaporative Cooling

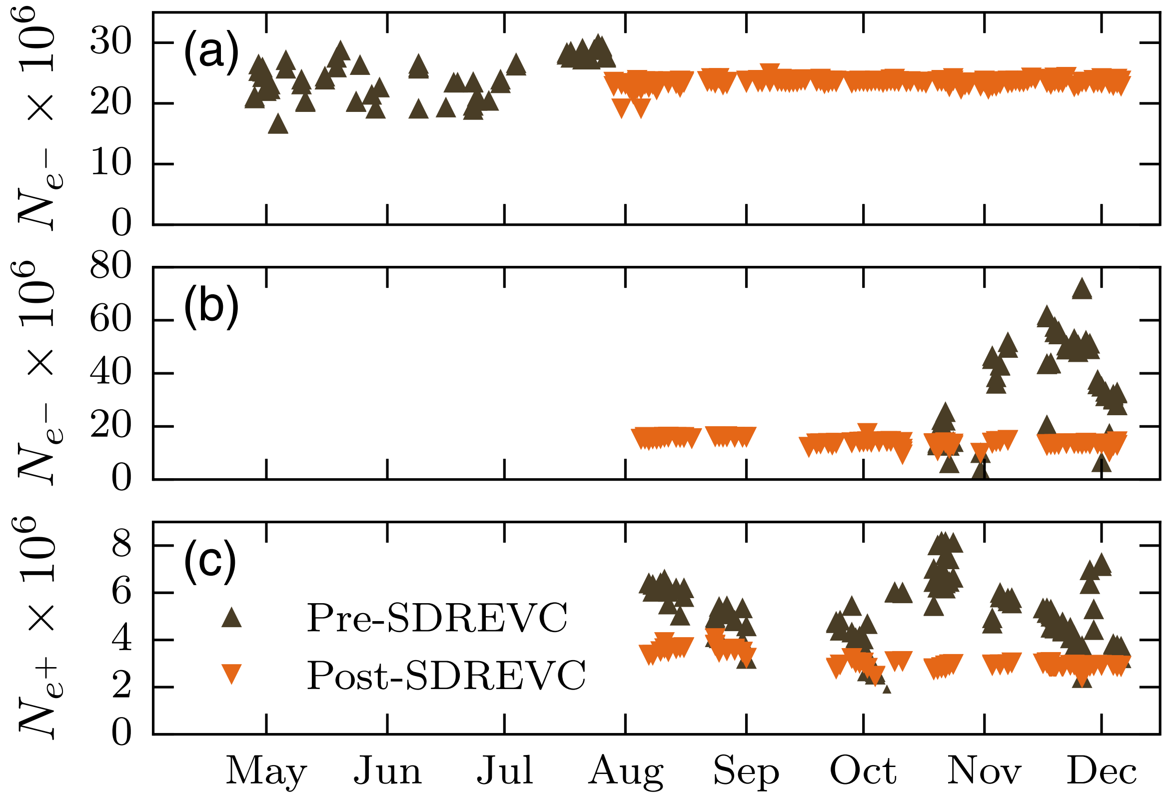
Fixes density, temperature, $r_{p,}$ and plasma potential
Results in unprecedented plasma control

Increased x > 10 rate of trappable antihydrogen production!

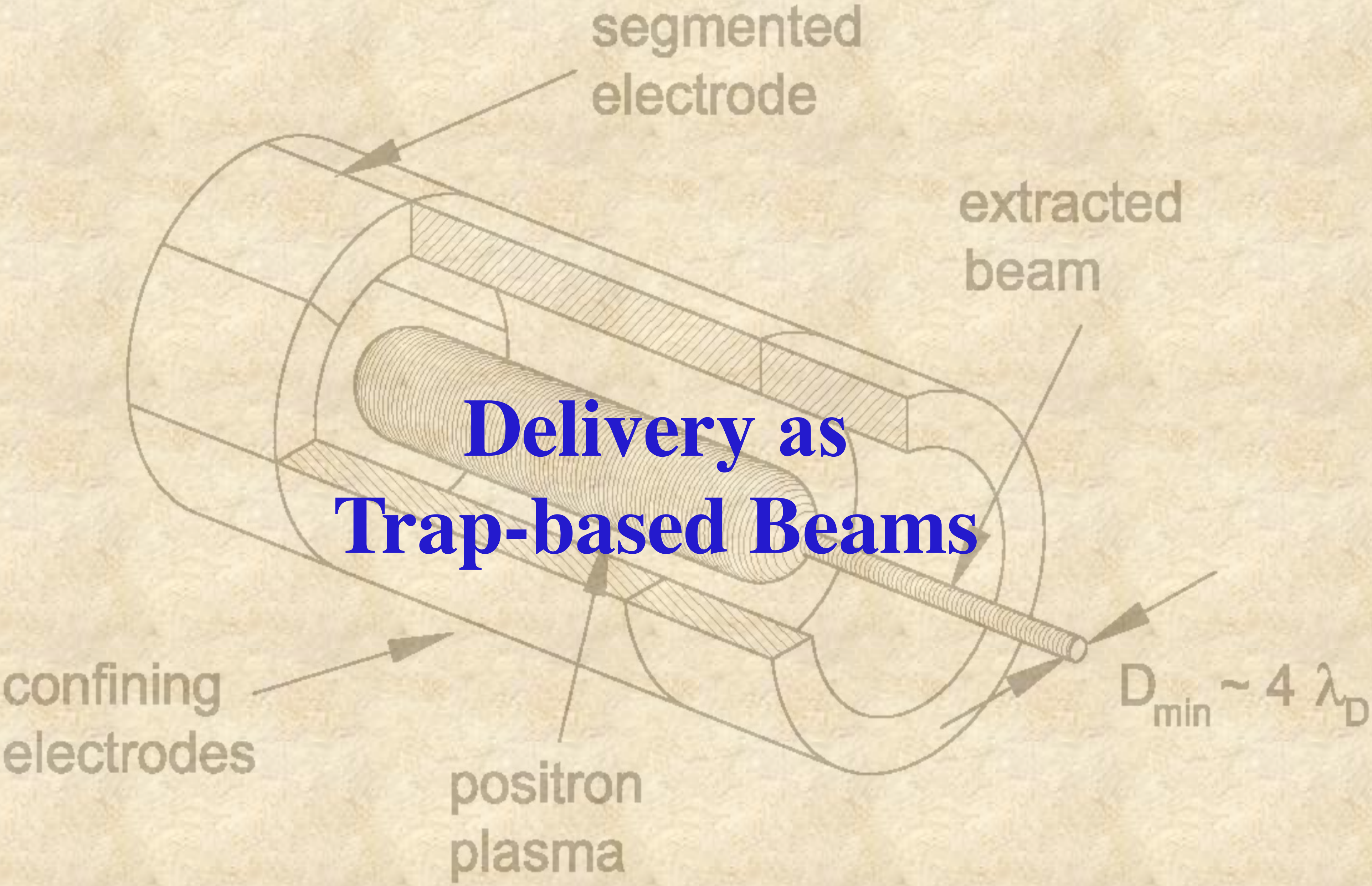
e^{-} pbar catching trap

e^{-} atom trap

e^{+} atom trap



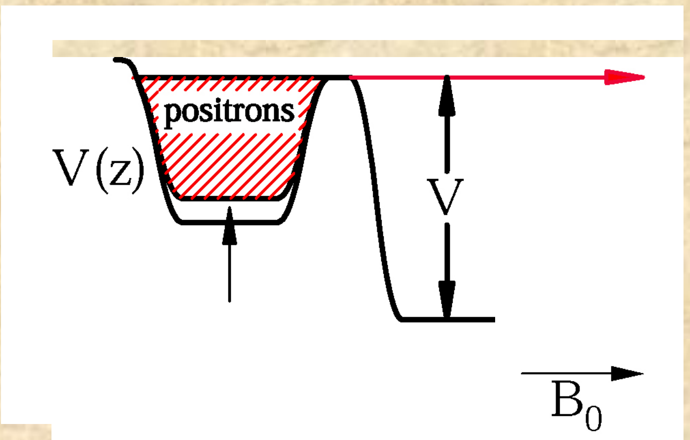
ALPHA collaboration, PRL **120**, 025001 (2018)



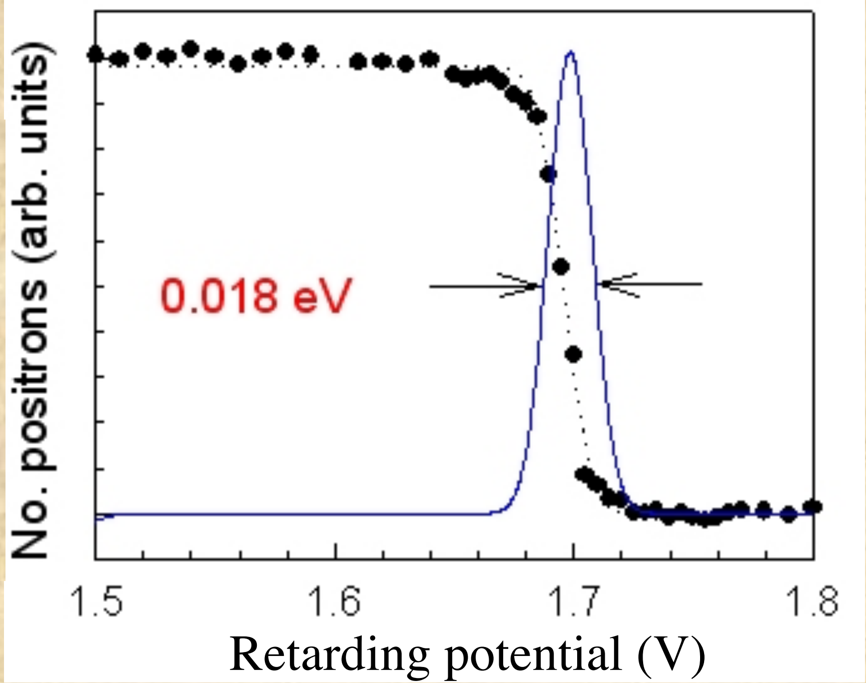
Delivery as Trap-based Beams

Trap-based Positron Beam
High Energy Resolution

Trap, cool and release:



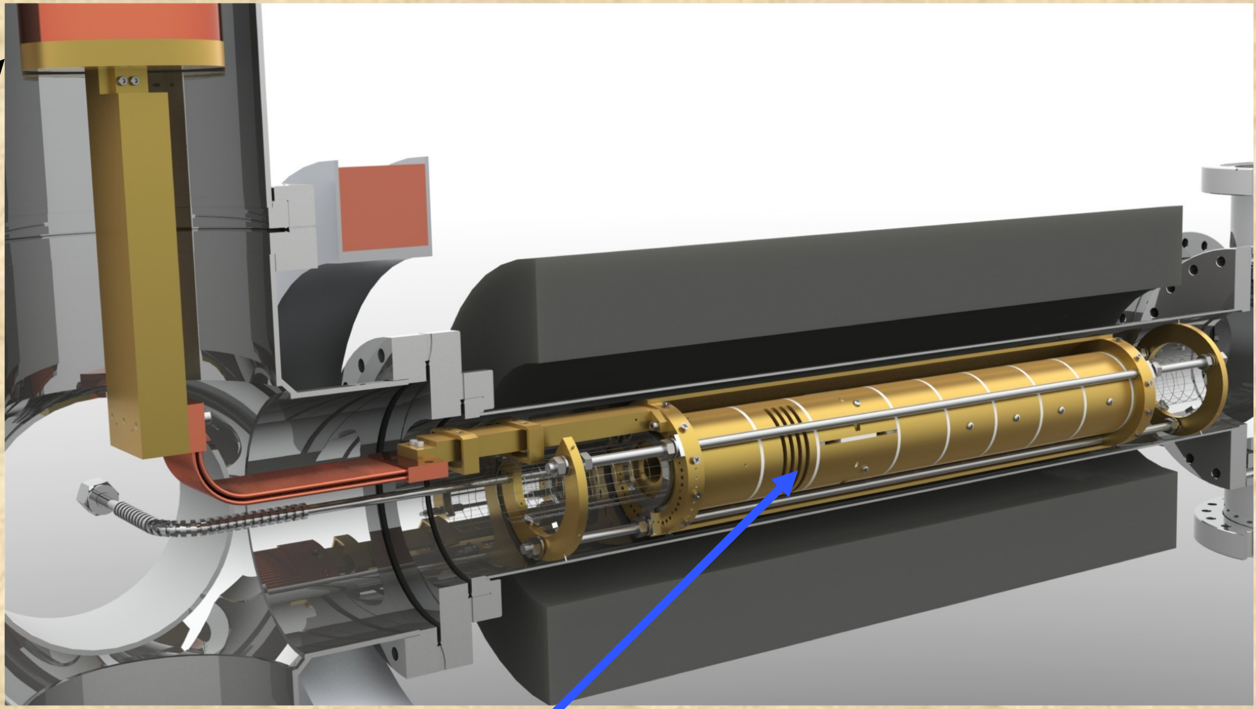
300 K buffer gas
(k_BT = 25 meV)



$\boxed{\Delta\varepsilon_{tot} \approx 40 - 45 \text{ meV}}$

Gilbert *et al*., APL (1997)

A 50 K Buffer-Gas Cooled Positron Beam



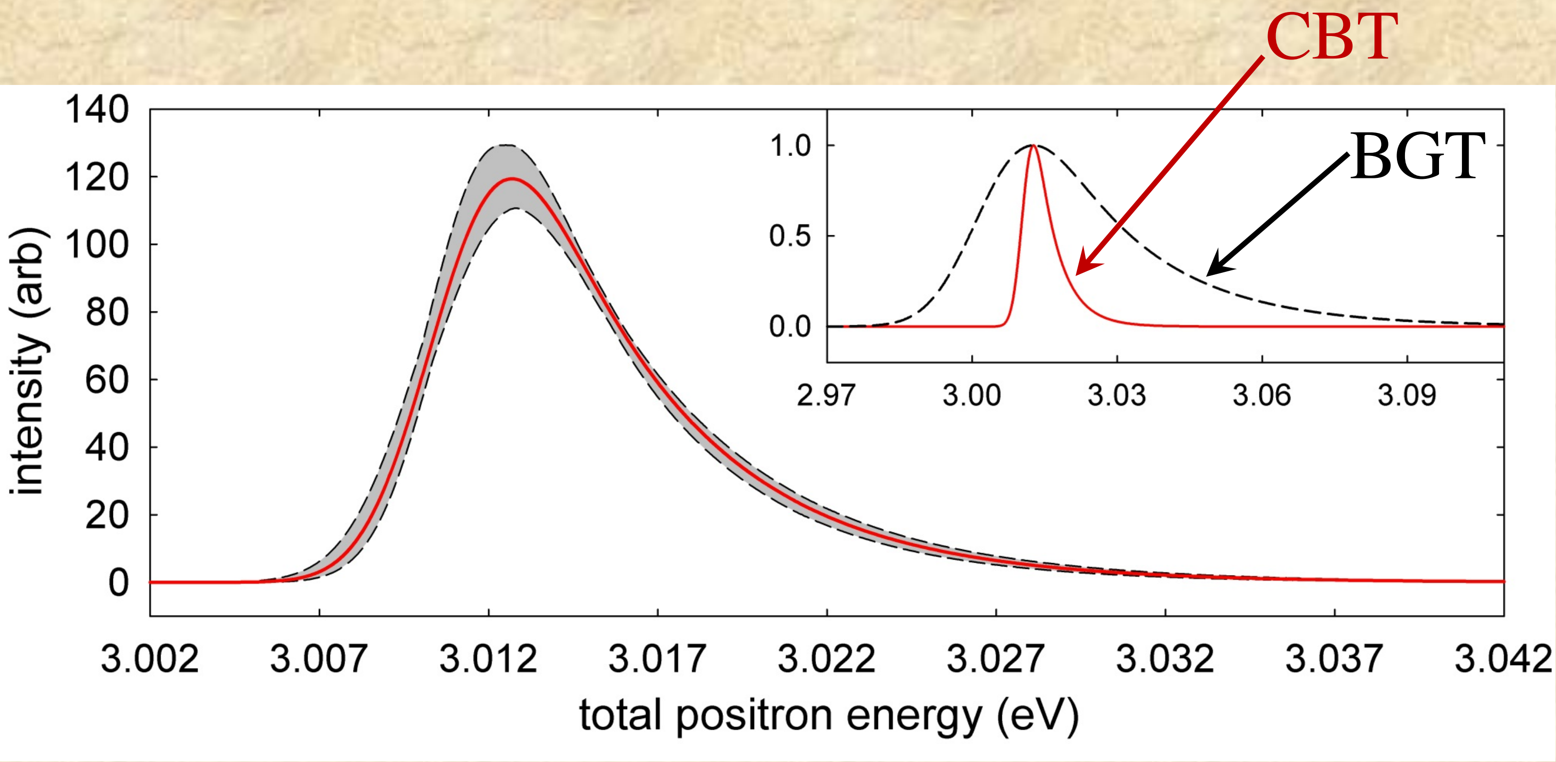
cryocooler

cooled electrodes
CO buffer gas at 50 K

M. R. Natisin, 2016

Cryogenic Buffer-Gas Trap (CBT)

Total Energy Distribution



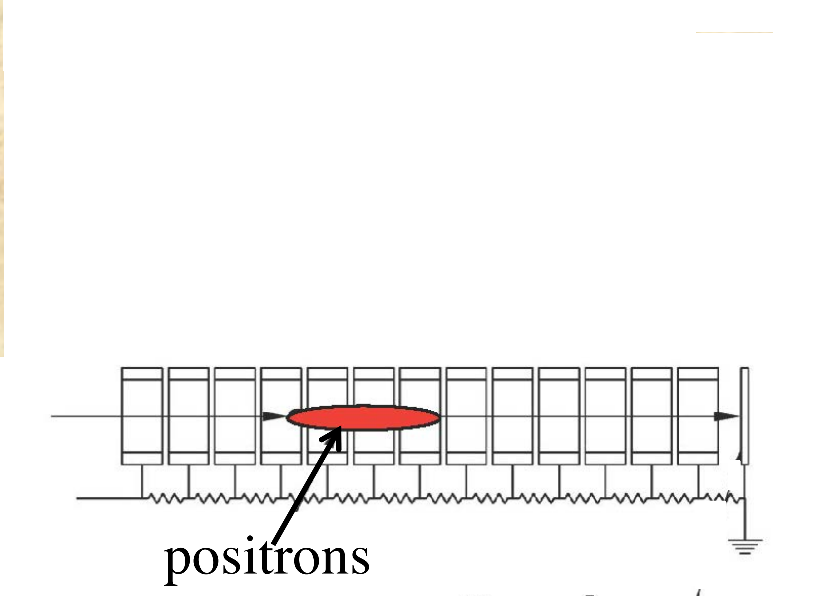
$$\Delta E_{tot} = 6.9 \pm 0.7 \text{ meV FWHM}$$
$$(\sigma_{tot} = 4.8 \pm 0.3 \text{ meV})$$

factor of ~5 better than previous state-of-the-art

M. R. Natisin, *et al.*, *Appl*. *Phys*. *Lett*. (2016)

Trap-based Beams – **Temporal Compression**

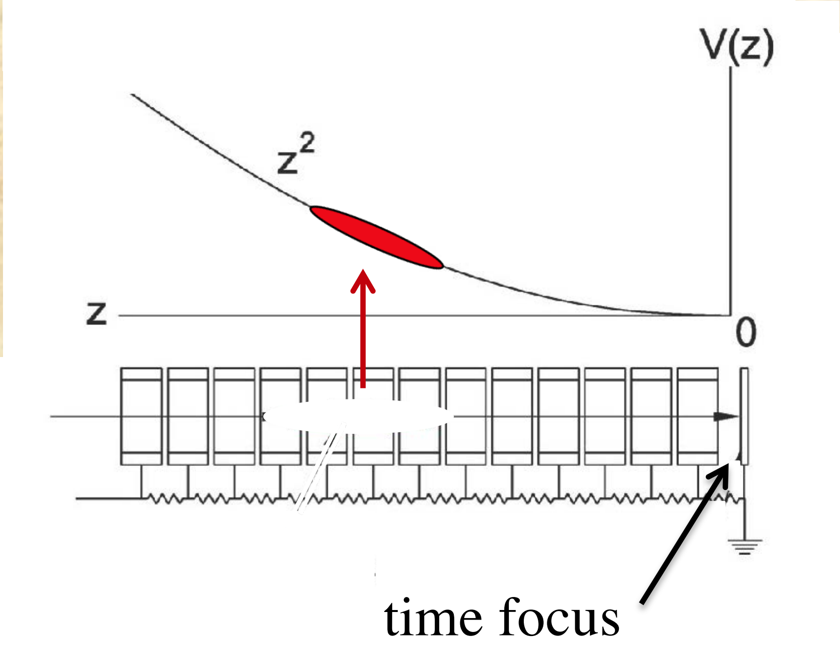
"harmonic bunching" using a parabolic potential



Cassidy et al., RSI 2006

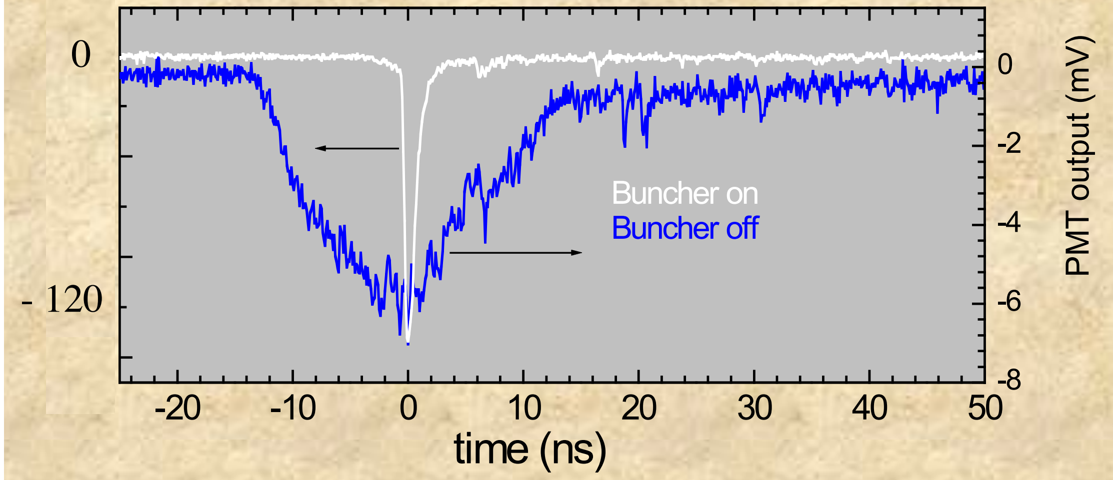
Trap-based Beams – **Temporal Compression**

“harmonic bunching” using a parabolic potential



time focus

positrons



15 ns pulse -> 1 ns pulse

Cassidy et al., RSI 2006

PM Traps Preserve Positron Spin Polarization from a ^{22}Na source
- critical for Ps$_2$ and BEC Ps experiments

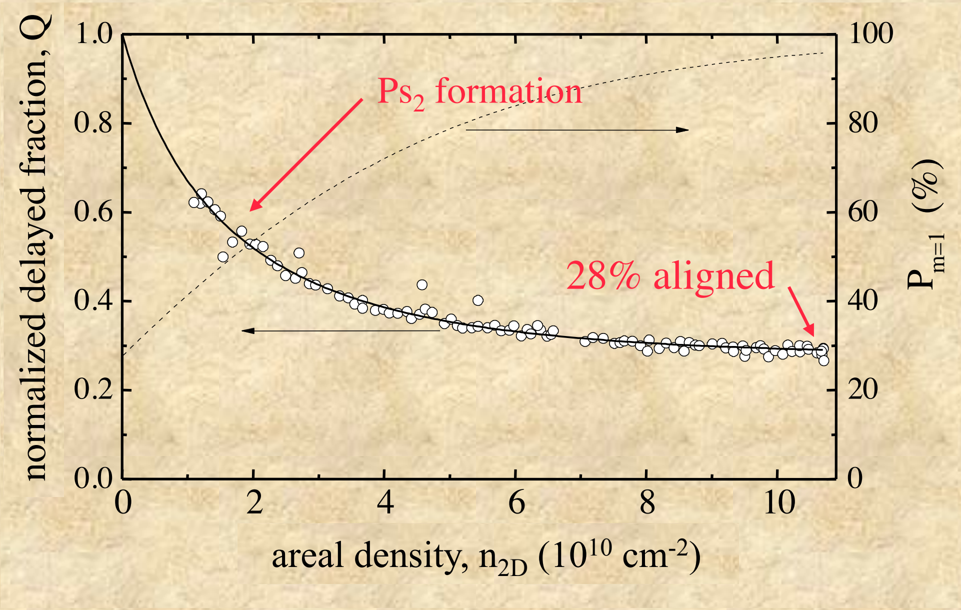
^{22}Na source produces e+ via weak interactions
⇒ spin oriented parallel to the momentum

BGT, storage in UHV, RW compression don't destroy this polarization!

28% aligned m = 1 Ps atoms

(would be no spin alignment
for LINAC sources)

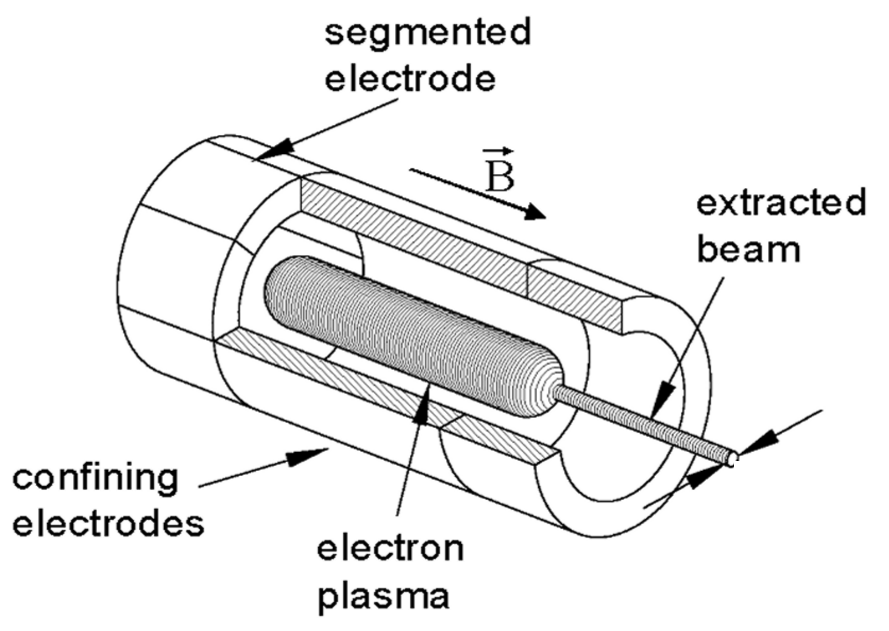
Cassidy et al., PRL '10



Extraction Beams of Narrow Spatial Extent from PM Traps
How narrow?
Multiple beams reproducible?

Basic idea: lower end-gate potential carefully - space charge pushes out particles near center first

- Goal to use efficiently all the trapped positrons
- Questions:
  - Does the plasma re-equilibrate?
  - Reproducible beams?
  - Time between extractions?



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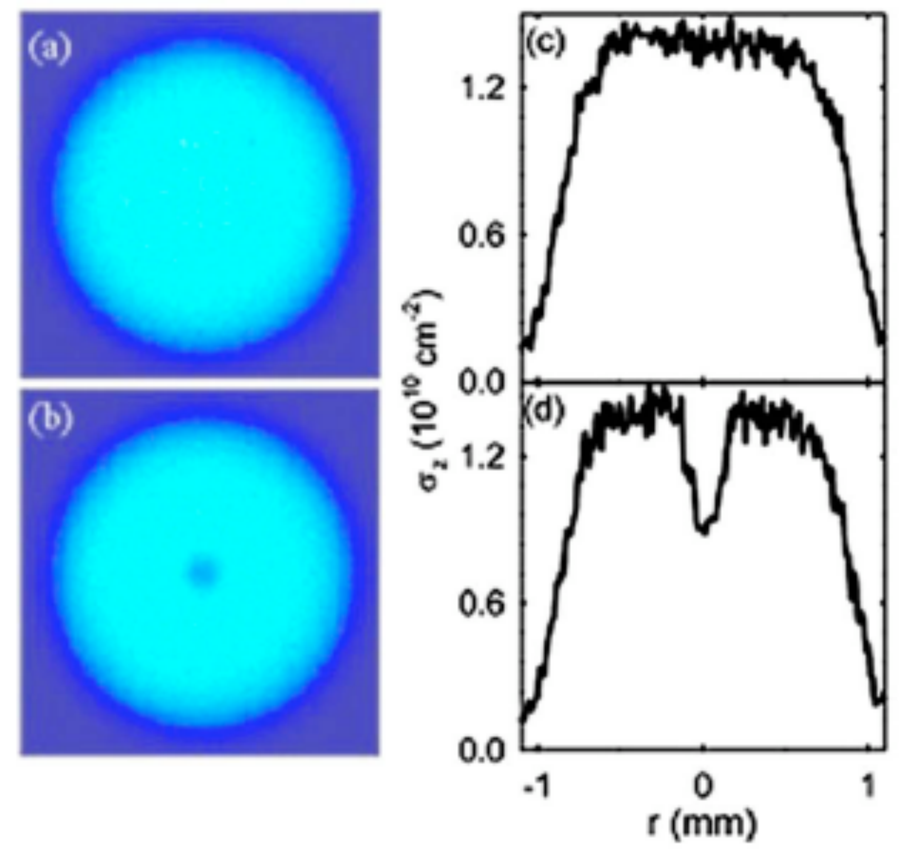
Pulsed beam extraction leaves a “hole” (10 μs pulse)

before

after



hole moves coherently to edge in ≤ 1 ms

Weber et al., PP 2008, 2009

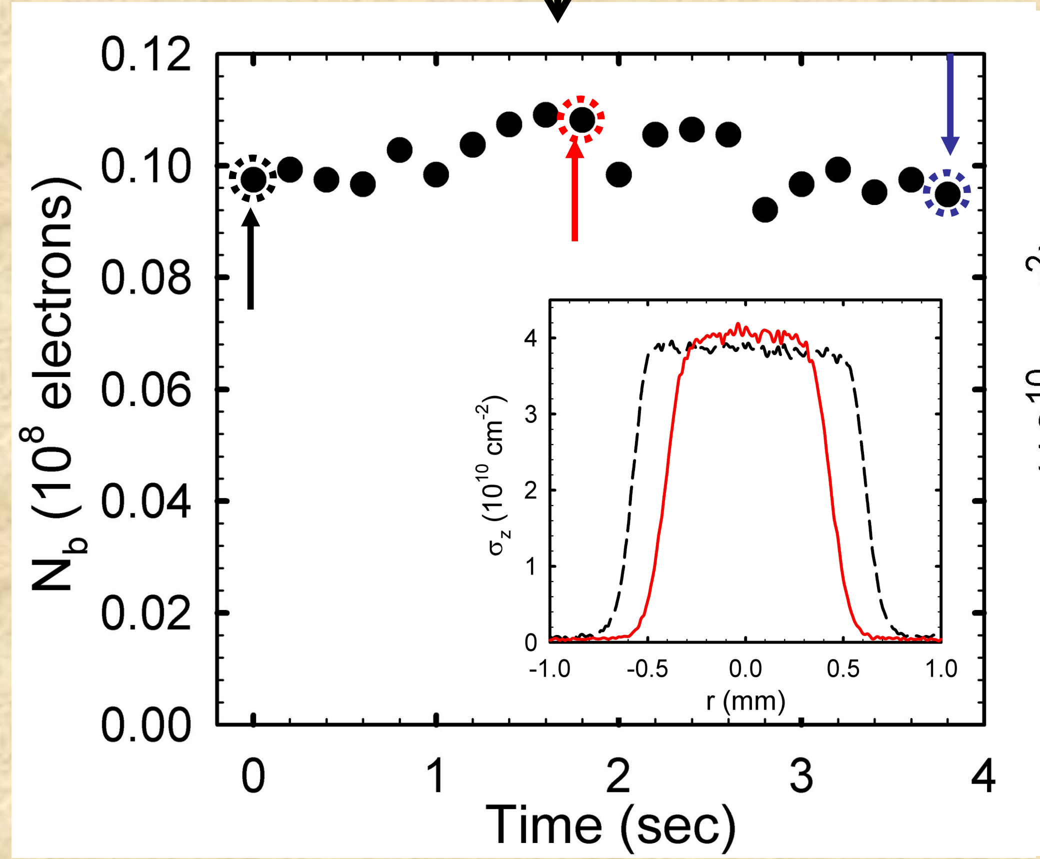
Multiple Beams from a Single Plasma

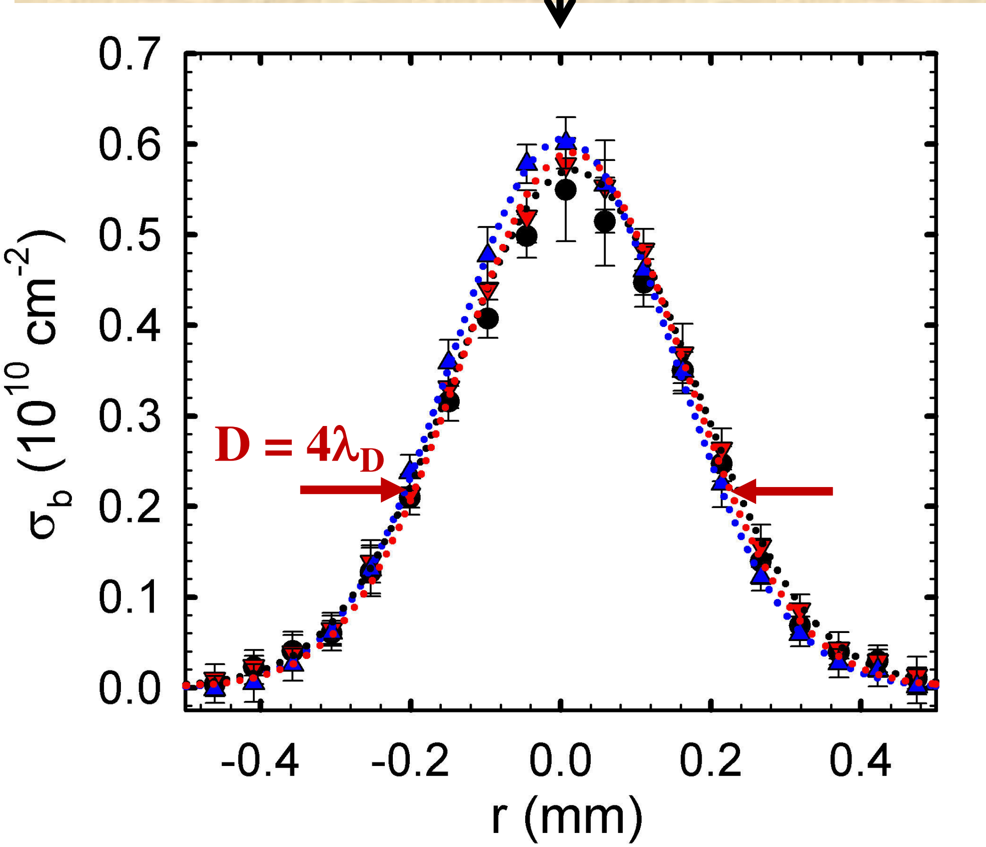
keep RW on

> 50% of plasma extracted

$\boxed{\lambda_D = v_T / \omega_p}$

1st, 10th, and 20th beam

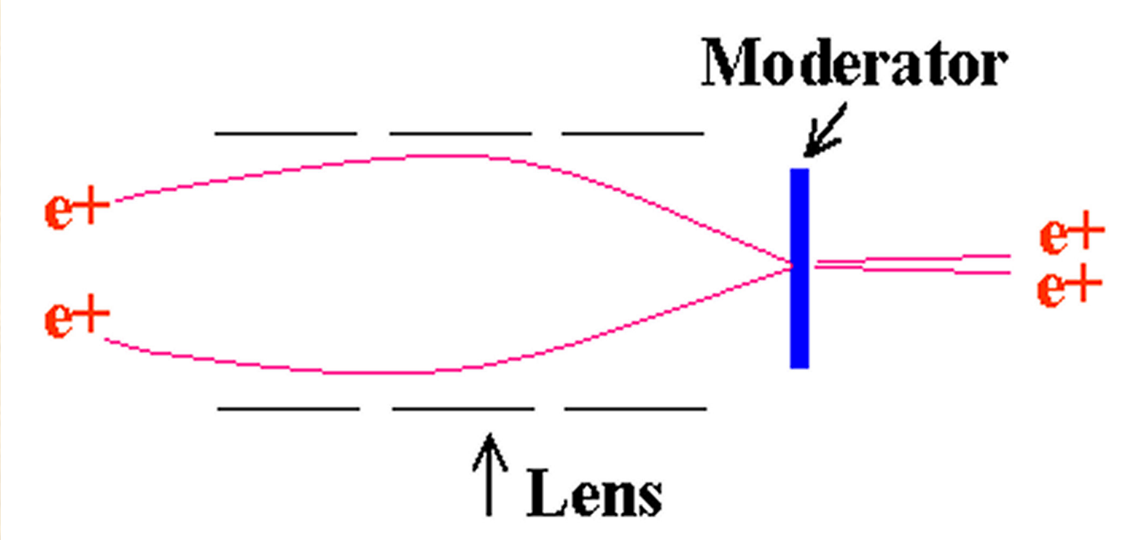




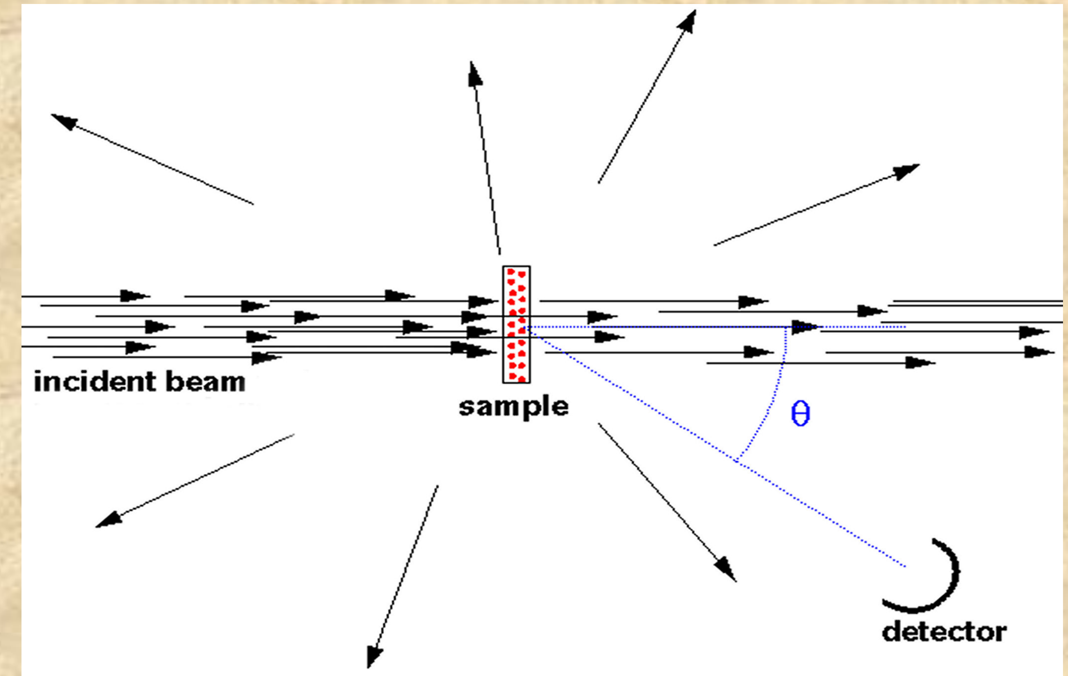
Weber et al., PP 2008, 2009

Electrostatic Beam Applications

- Microbeams through electrostatic focus and re-moderation



- Atomic physics scattering experiments



Weber et al., PP 2010

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Single Particle Motion

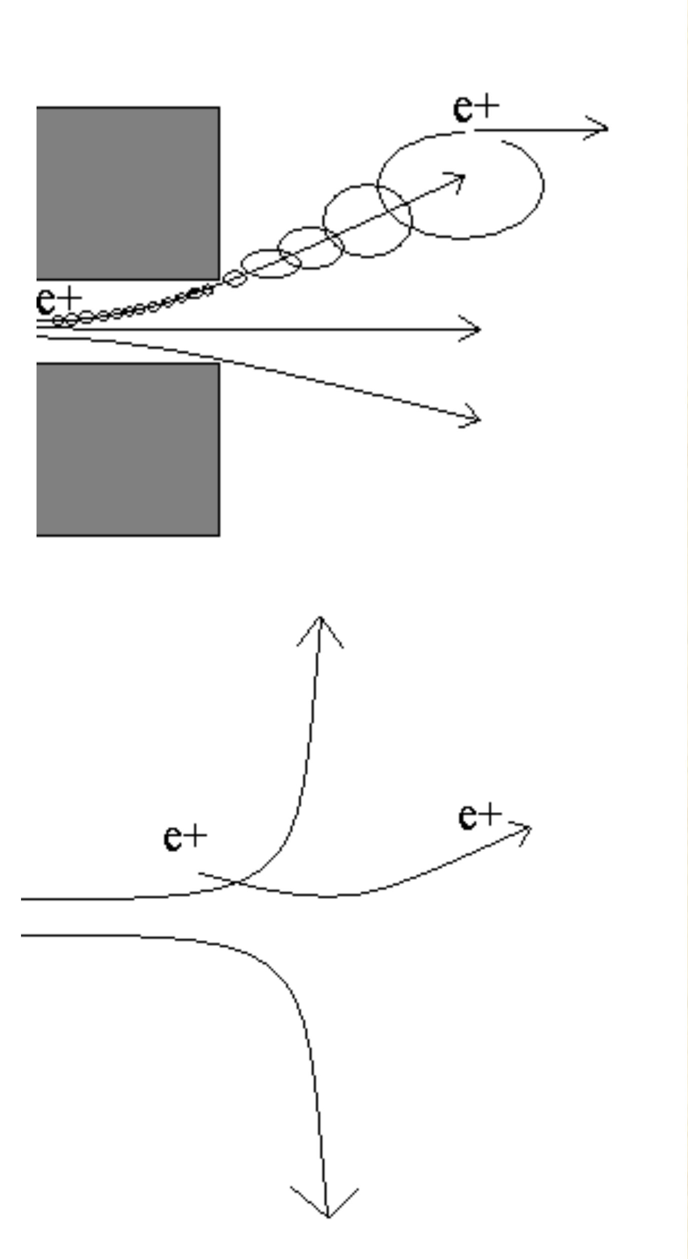
- For slow extraction, particles stayed "glued" to field lines and maintain adiabatic invariant

$$\frac{E_\perp}{B} = const.$$

- Fast extraction, particles leave field lines and conserve canonical angular momentum with θ "kick" δp_θ

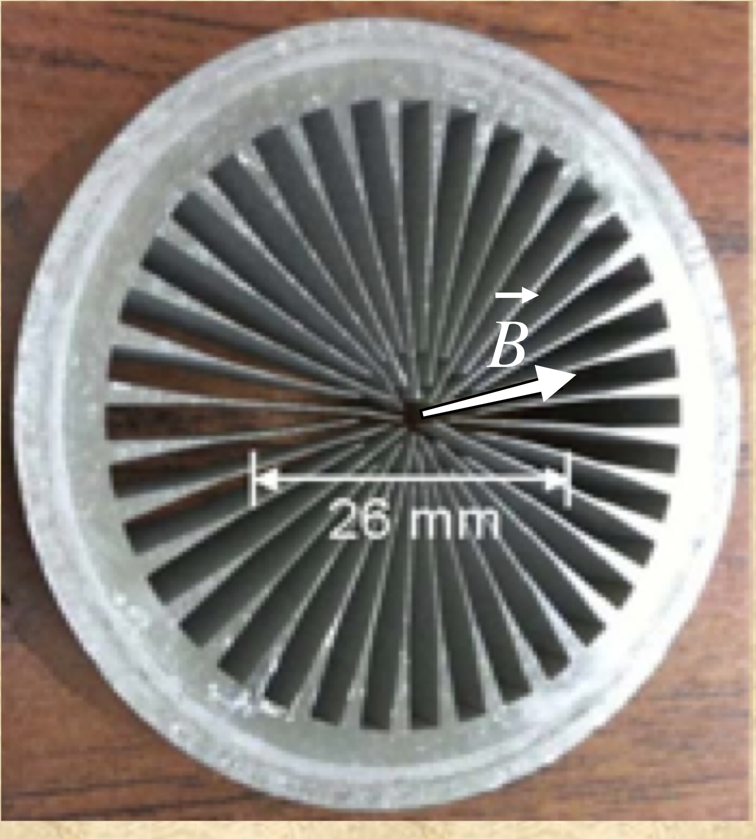
$$L_z = const. = rp_\theta + qrA_\theta$$

$$\delta p_\theta \sim m\omega_c r$$



Reduce Kick by Replacing Hole in Iron with High-permeability Alloy "Spider"*

reduced perpendicular kick in δp_θ by ≥ 5



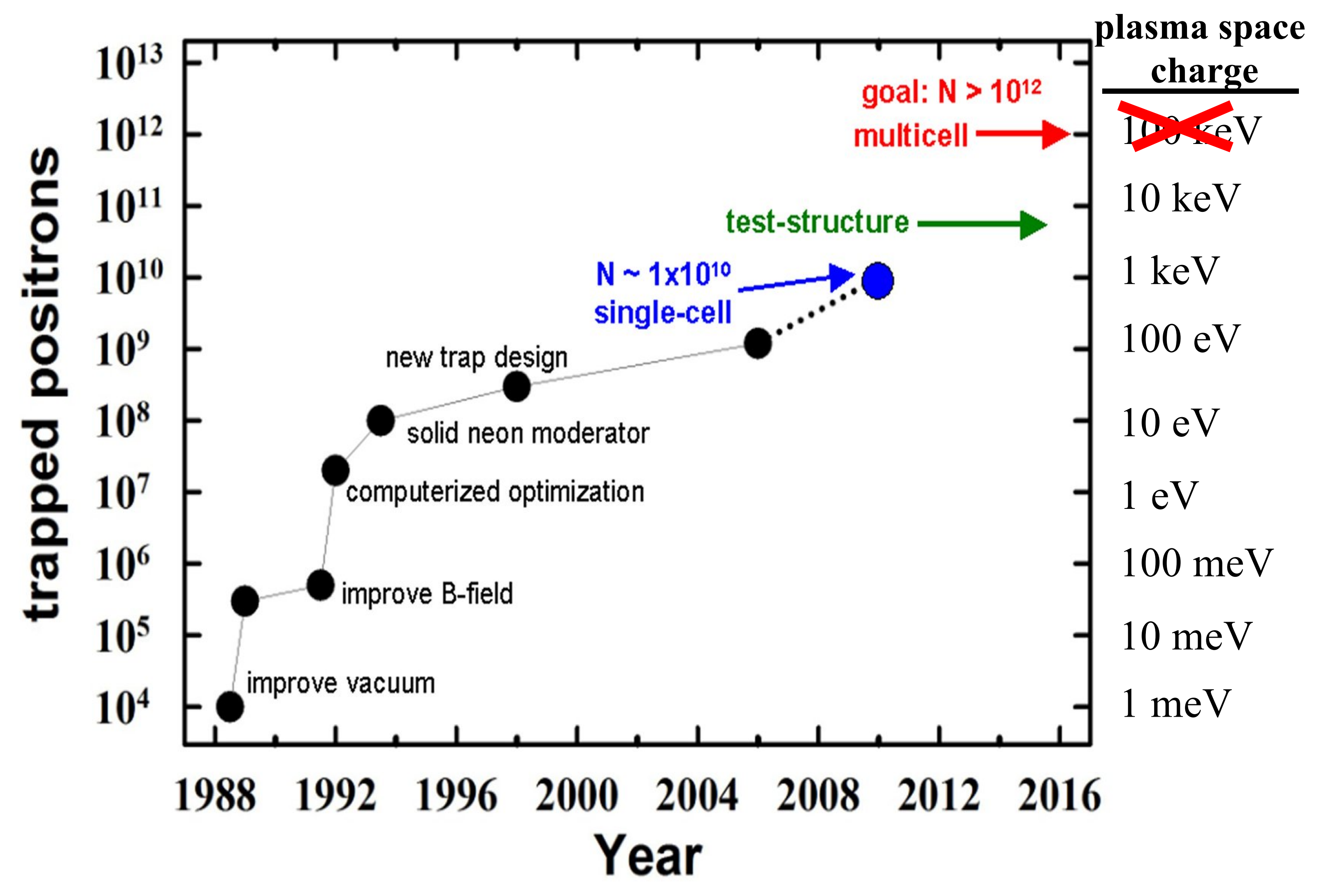
* W. Stoeffl, et al., Livermore National Laboratory

Latest result
$V_L = 3.4$ kV
≥ 40 % in
$r \leq 0.12$ cm

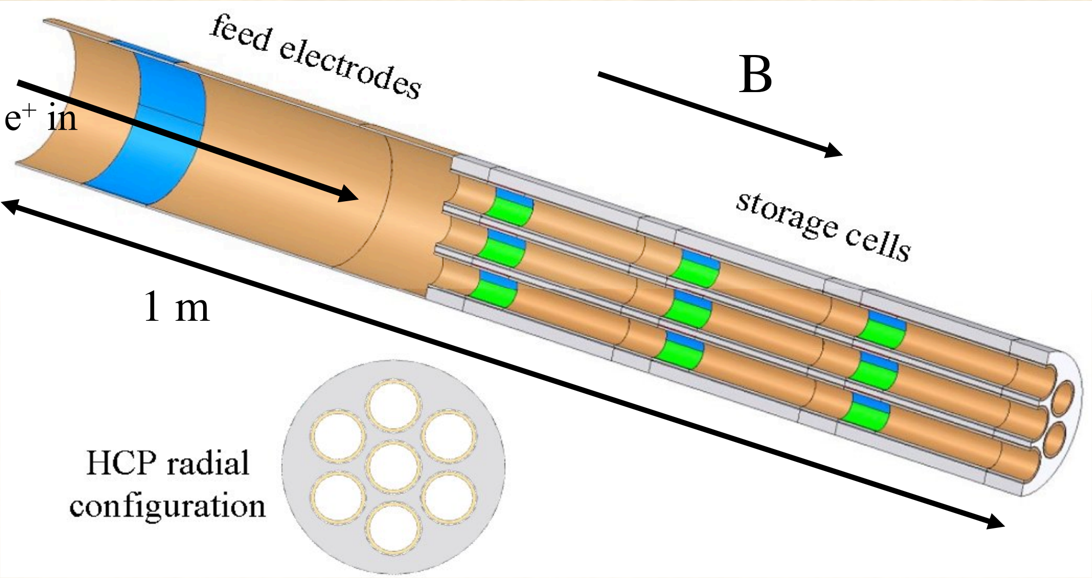
Weber et al., PP 2008, 2009

Larger Collections of Antimatter

For Single PM Traps, Space Charge Becomes Prohibitive



Solution: Shield Parallel Cells with Copper Electrodes – a multicell trap for 10^{12} positrons



3 banks of 7 cells with 5×10^{10} e^+ each

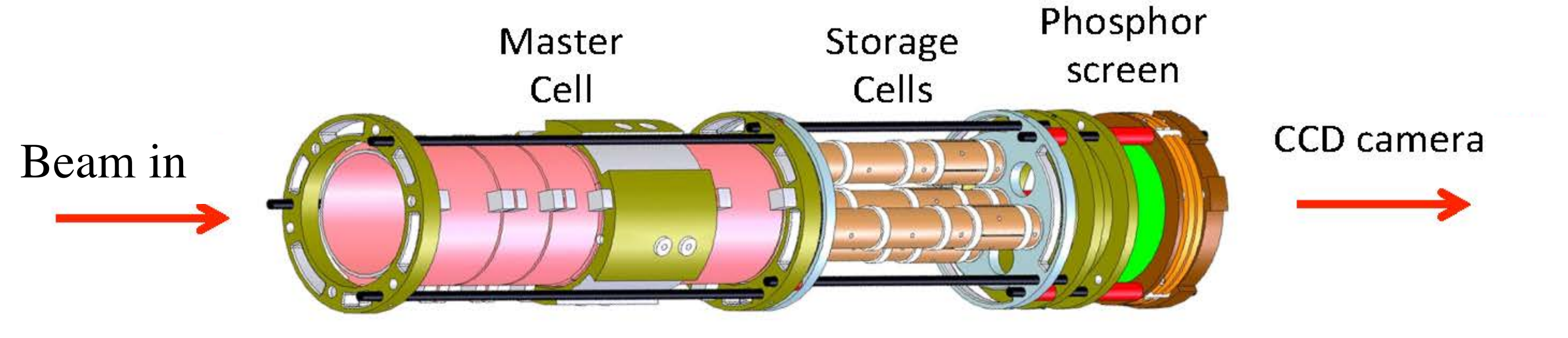
1 kV confinement potentials

Move plasma across *B* using autoresonant diocotron mode*

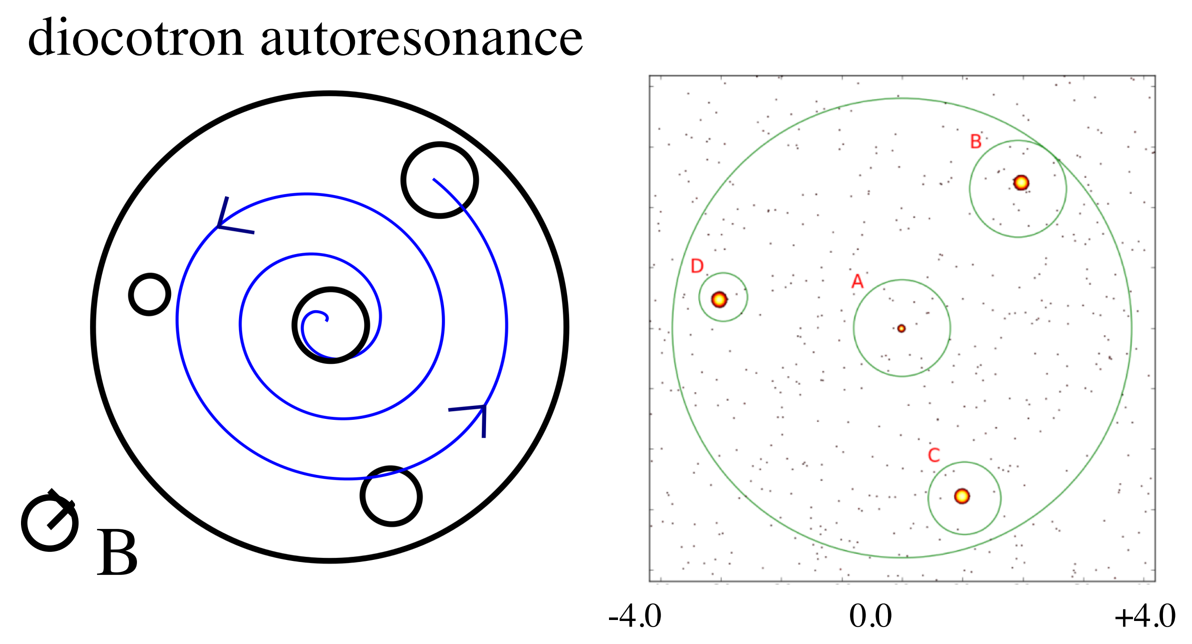
Surko, JRCP '03
Danielson, PP '06
Baker PP 15
* Fajans, '99 - '01

Multicell Trap Test Structure

3 off-axis cells

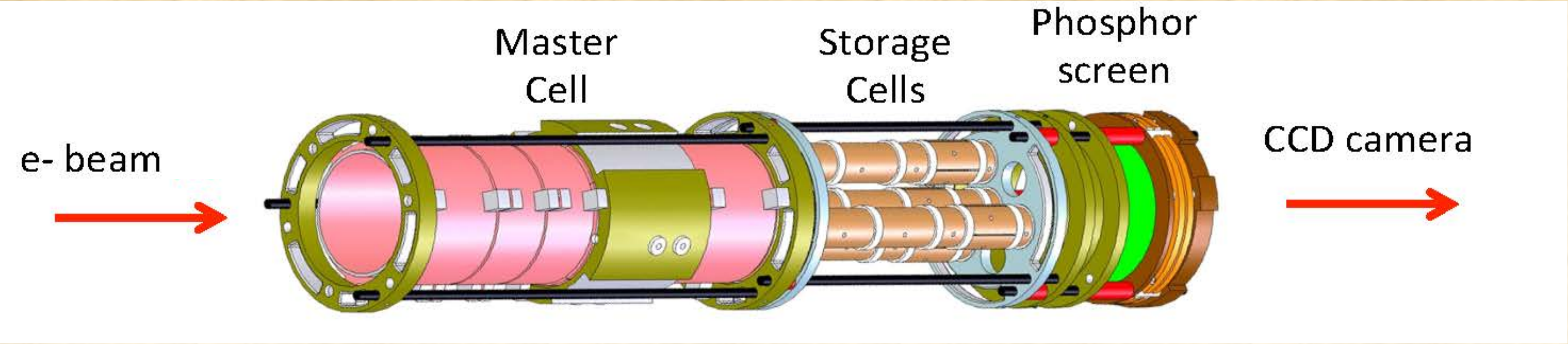


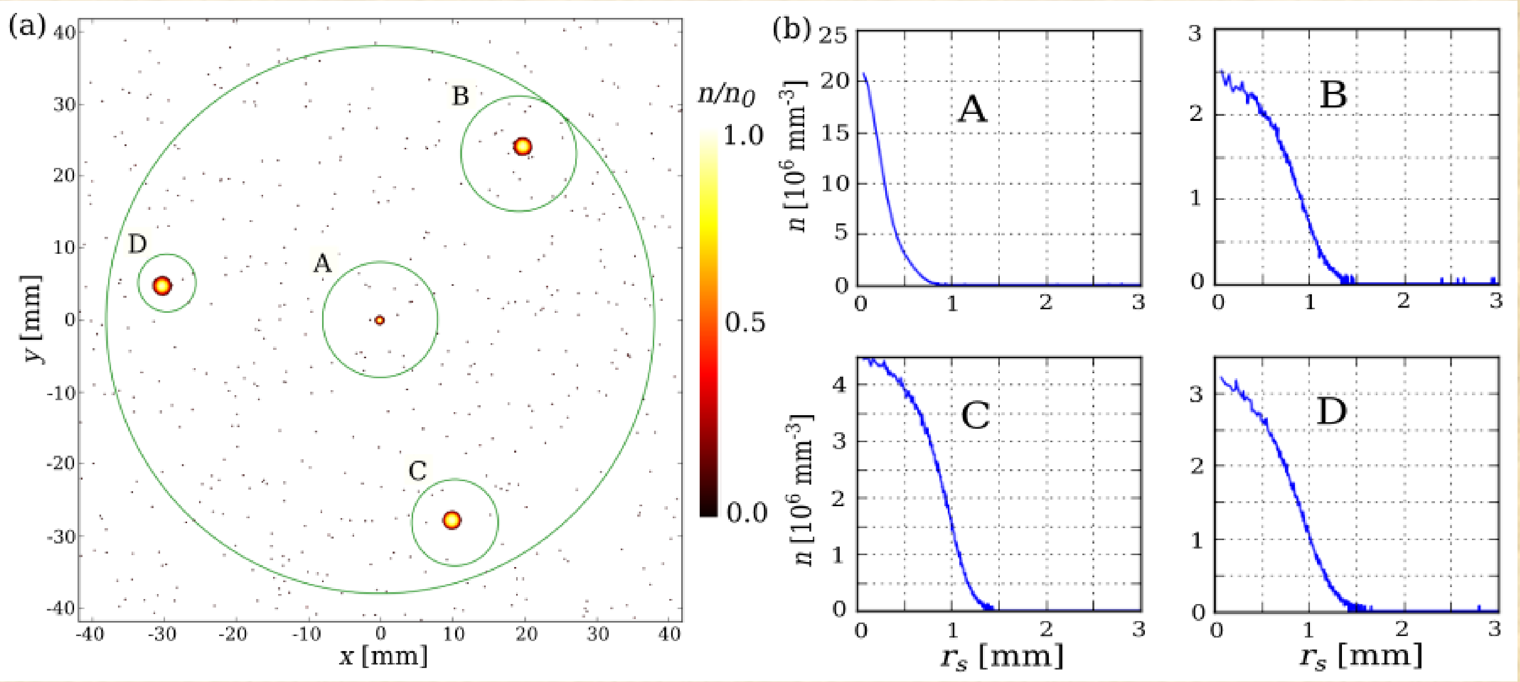
- ≥ 50% transfer efficiency
- Need to demonstrate confinement of kV space charge off axis


diocotron autoresonance

Hurst et al., PRL (2014)
Baker et al., PP (2015)

Plasmas Transferred Of Axis In the MCT





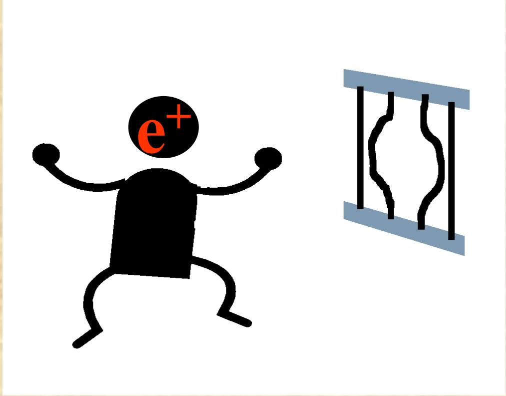
Baker et al., PP (2015)

Challenges

- Rotating Wall compression
  - Density limit at high B?
- Large Numbers of Positrons
  - Develop the multicell trap
- Short temporal pulses (≤ 100 ps)
  - Optimized fast electronics
- Portable antimatter traps??
  - Likely awaits improved magnet technology?

For references and links
to other work see:

positrons.ucsd.edu



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Plasma References

Download from the Summary and Review section at
http://positrons.ucsd.edu

tutorial

Accumulation, storage and manipulation of positrons in traps
I – The Basics, C. M. Surko,
II – Selected Topics, C. M. Surko, J. R. Danielson, and T. R. Weber

(Chapters 4 and 5 in *Physics with Trapped Charged Particles*,
M. Knoop, *et al*., eds. (Imperial College Press, 2014)

hard core

Plasma and Trap-based Techniques for Science with Positrons, J. R. Danielson, D. H. E. Dubin, R.G. Greaves, and C. M. Surko, *Rev. Mod. Phys.* **87**, p. 247 (2015).