Combined Traps

Francis Robicheaux
Auburn University

Single Particle Properties
Plasma Properties

Support from DOE and NSF

Combined Trap References

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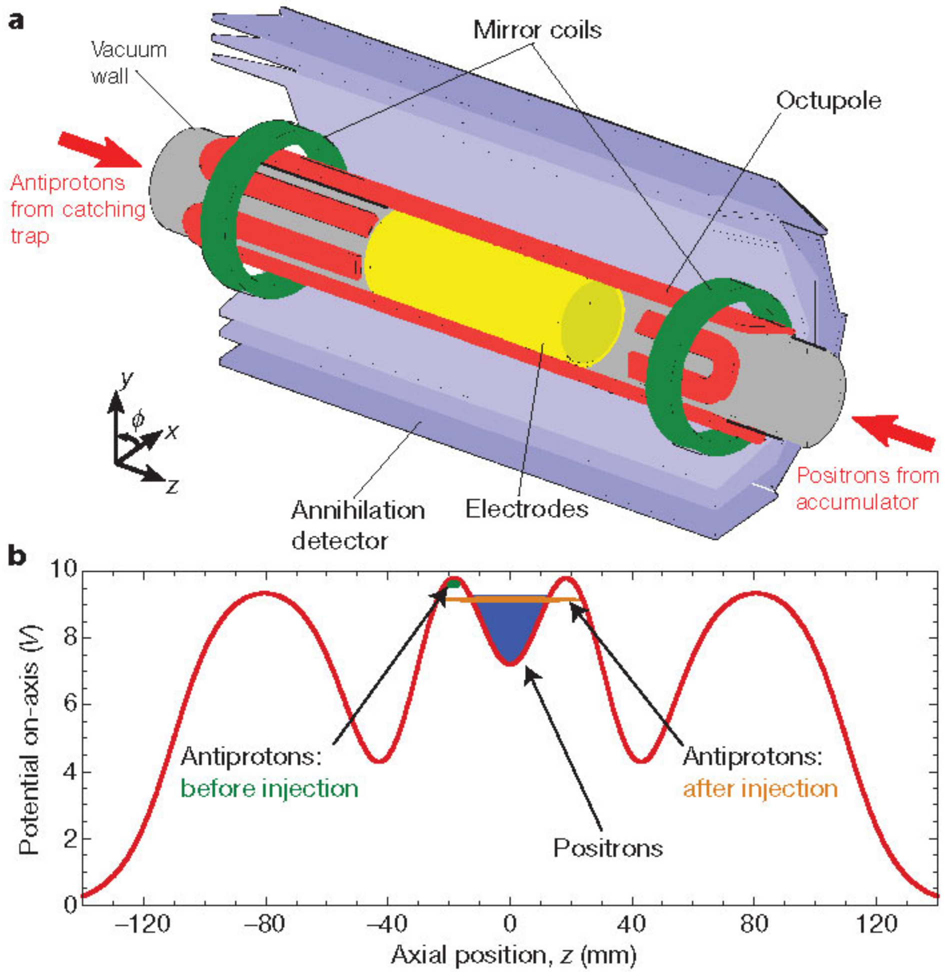
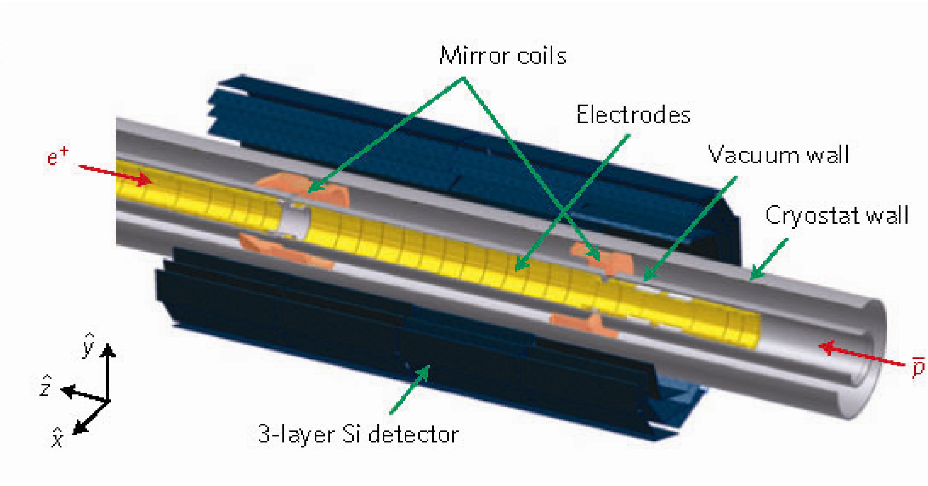
Generic Combined Trap

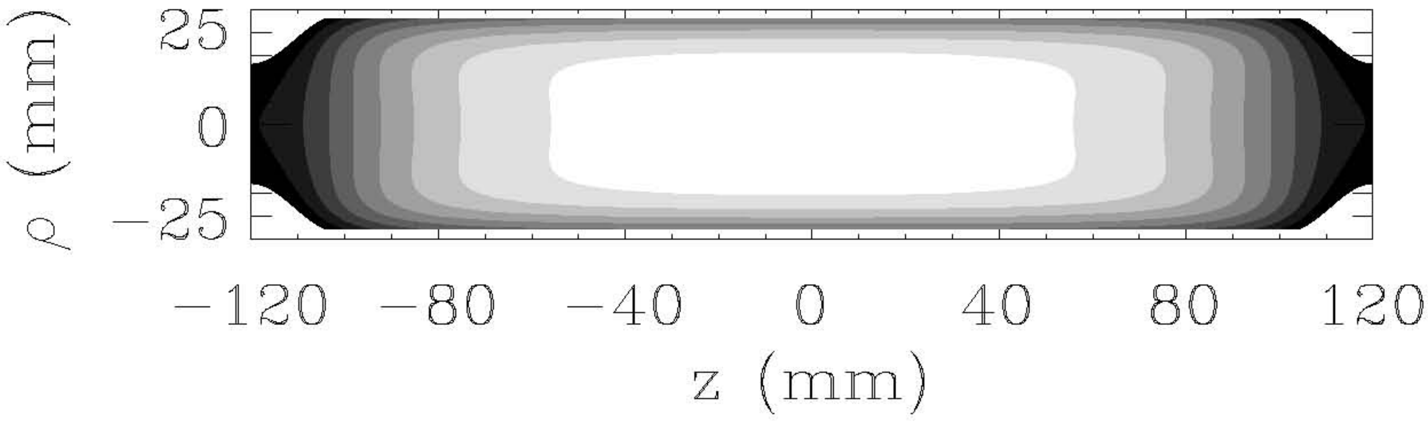


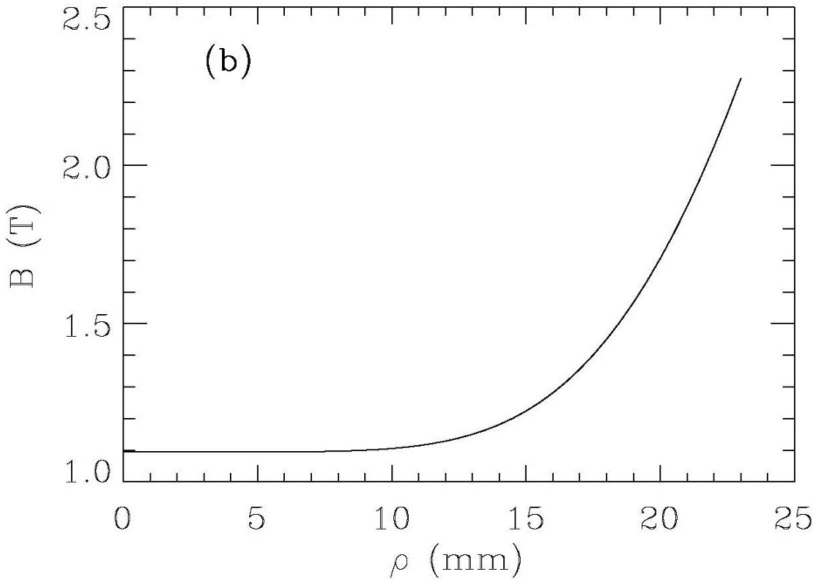


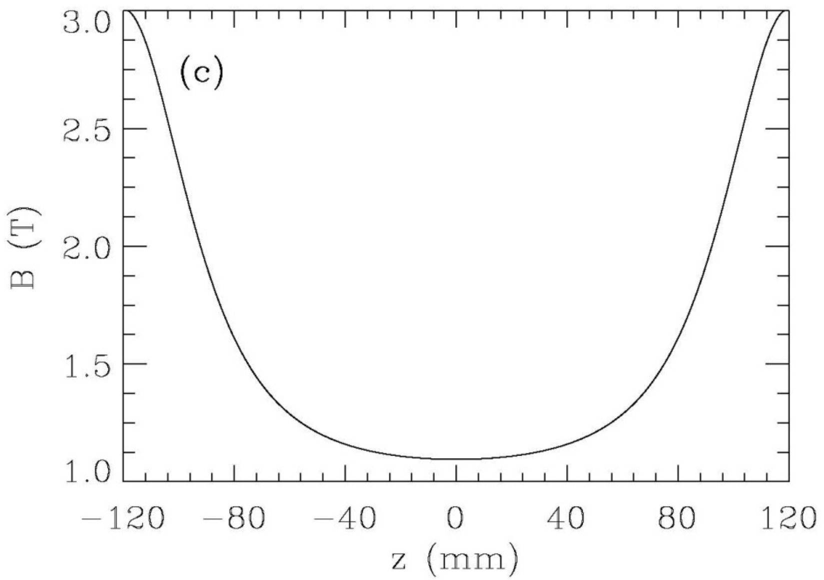
Trapping of charged particles

Axial electric potential well + axial B-field

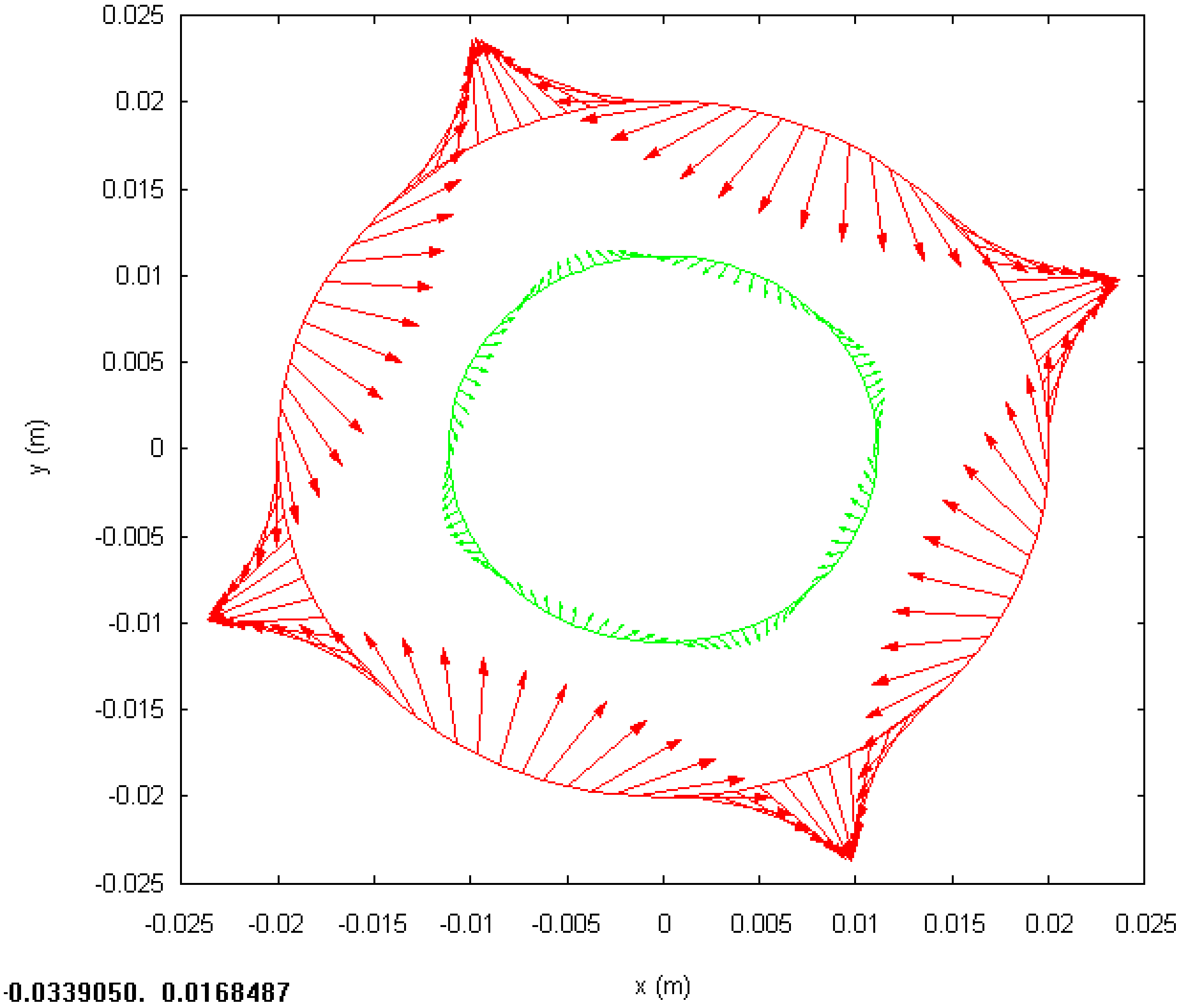
Trap For Neutral Atom







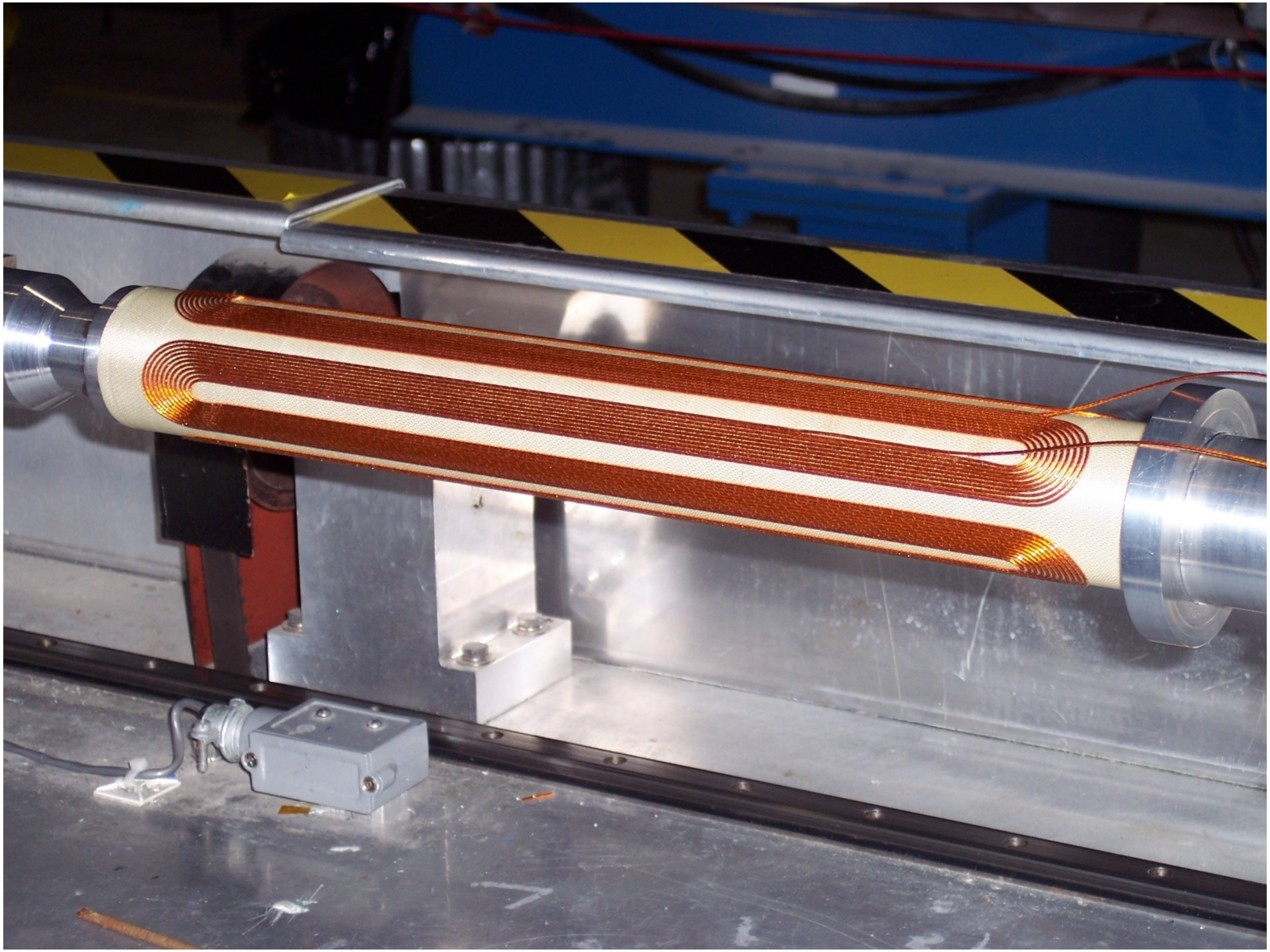
Octupole B-field



Decreases very rapidly as r goes to 0

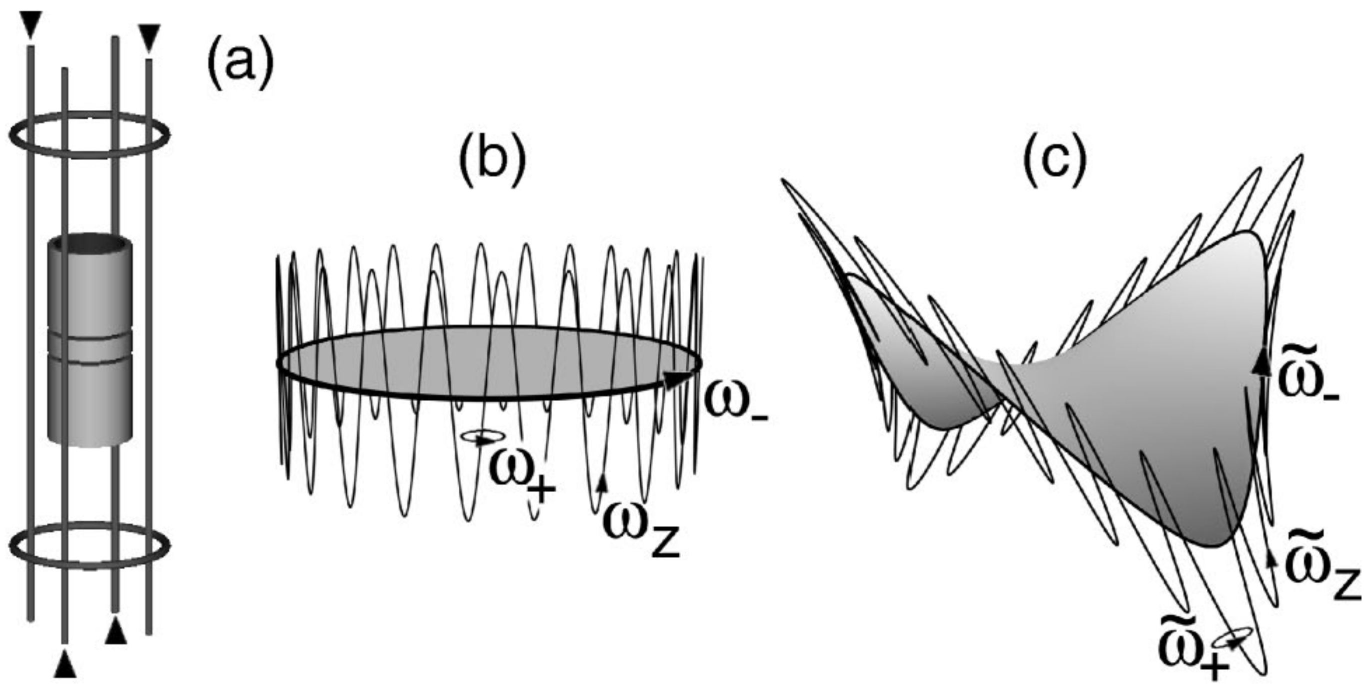
red = 0.9 r_w
green = 0.5 r_w

Actual Magnets: Octupole



Stability of a Charged Particle in a Combined Penning-Ioffe Trap

T. M. Squires, P. Yesley, and G. Gabrielse
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 January 2001)



Simplified quadrupole case

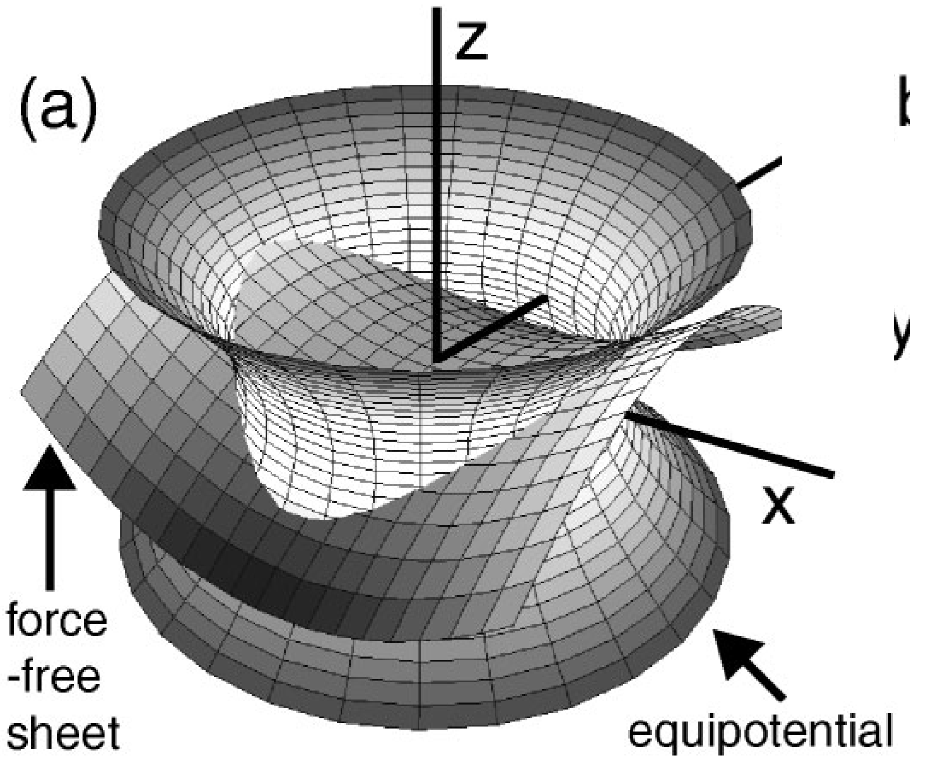
Restoring region

$PE = \frac{1}{2}\, m\, \omega_z\, (z^2 - r^2/2)$

$B = (x/R_0, -y/R_0, 1)\, B_0$

Edge of restoring region defined by F dot B = 0

$z = \frac{1}{2}\,(x^2 - y^2)/R_0$



Adiabatic Invariants

Fastest motion is cyclotron motion: not in xy plane because B is tilted

Next fastest motion is axial motion (not purely z)

Last is magnetron motion

Avoid resonances then trapped for exponentially long time

PHYSICS OF PLASMAS **15**, 032108 (2008)

Critical loss radius in a Penning trap subject to multipole fields

J. Fajans,[1,a)] N. Madsen,[2] and F. Robicheaux[3]
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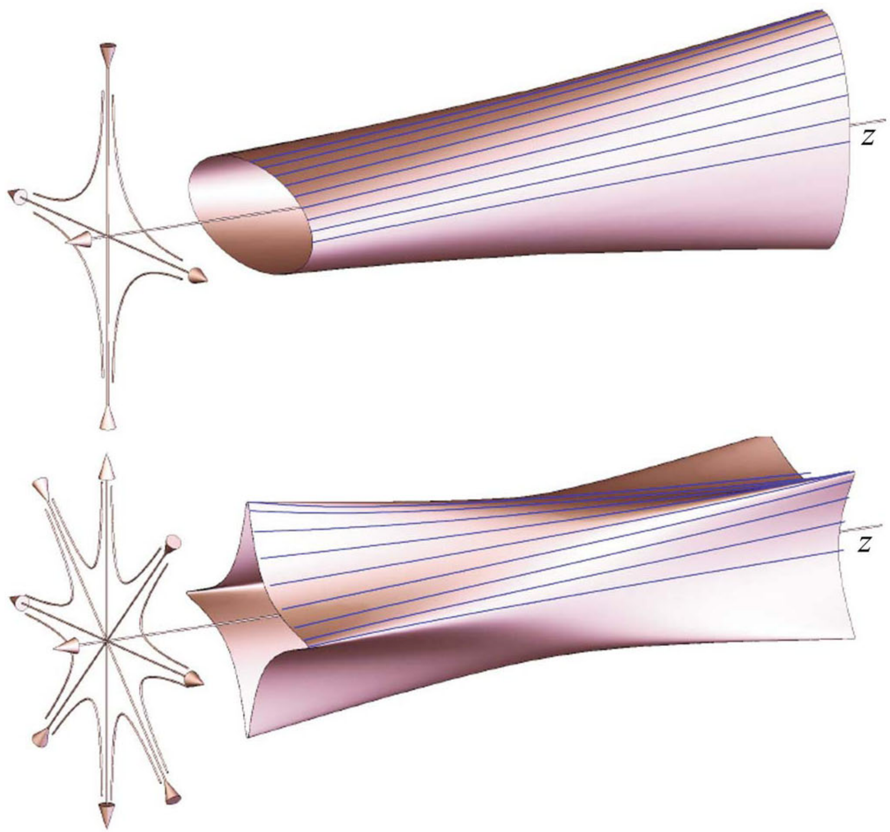
[3]*Department of Physics, Auburn University, Auburn, Alabama 36849-5311, USA*

(Received 17 December 2007; accepted 28 February 2008; published online 31 March 2008)



Initial circle following field lines to left and right for quadrupole and octupole

Single particle calculations

Distance z >> r

Radius vs. Initial Angle

Define scaled length

$L = B_w z / (B_z R_w)$

B_w = B at wall

B_z = axial B

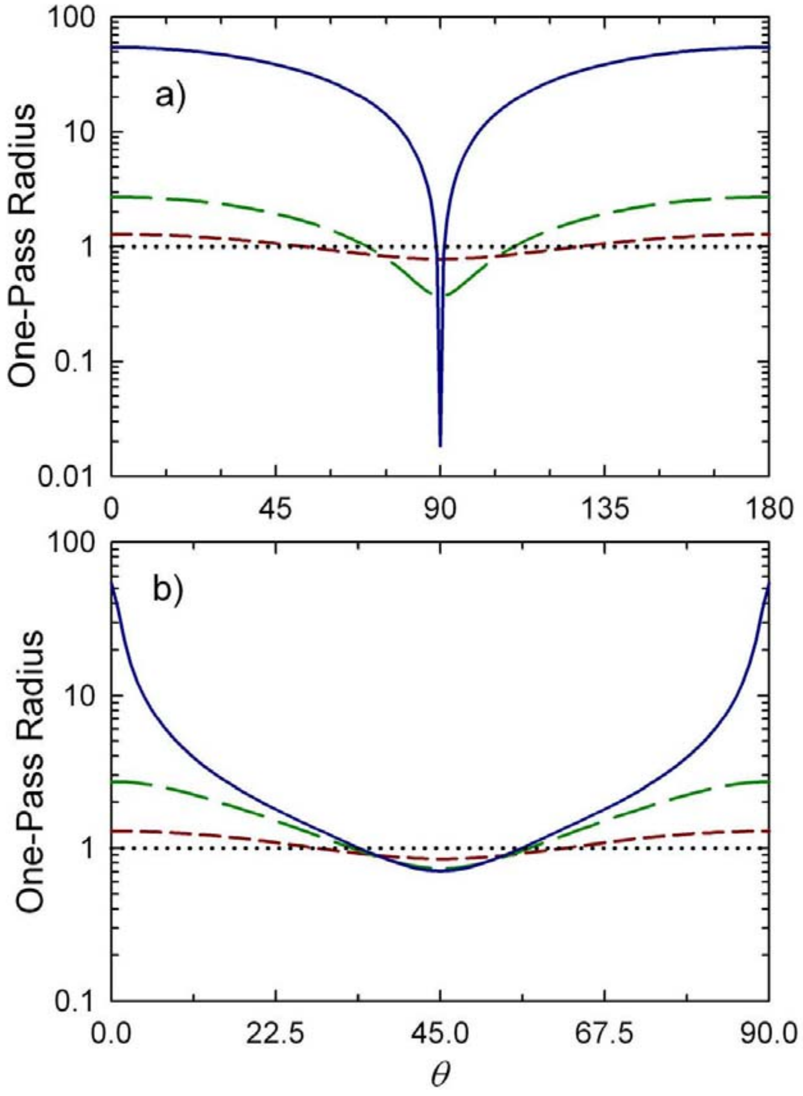
R_w = radius of wall

Quadrupole

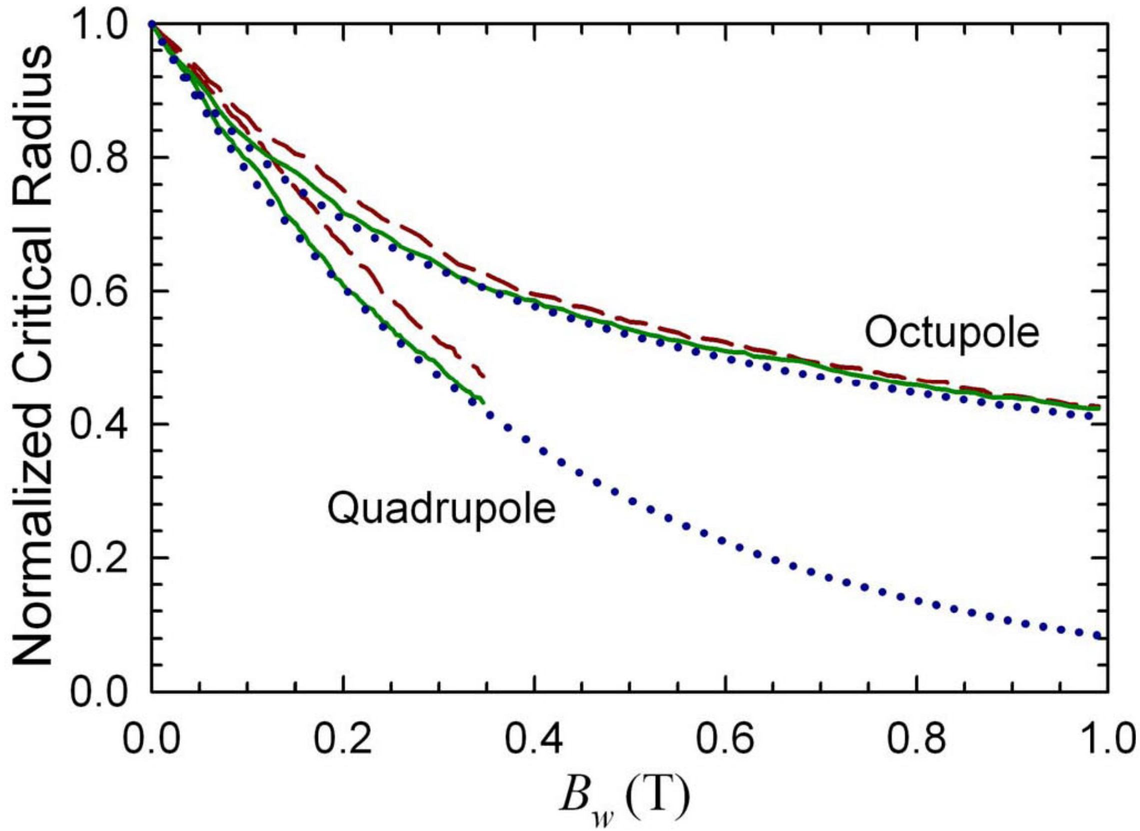
$r = r_0 \exp(L/2)$

Octupole

$r = r_0 / \mathrm{sqrt}[1 - 2 L (r_0 / R_w)^2]$



Critical Radius vs. B_w

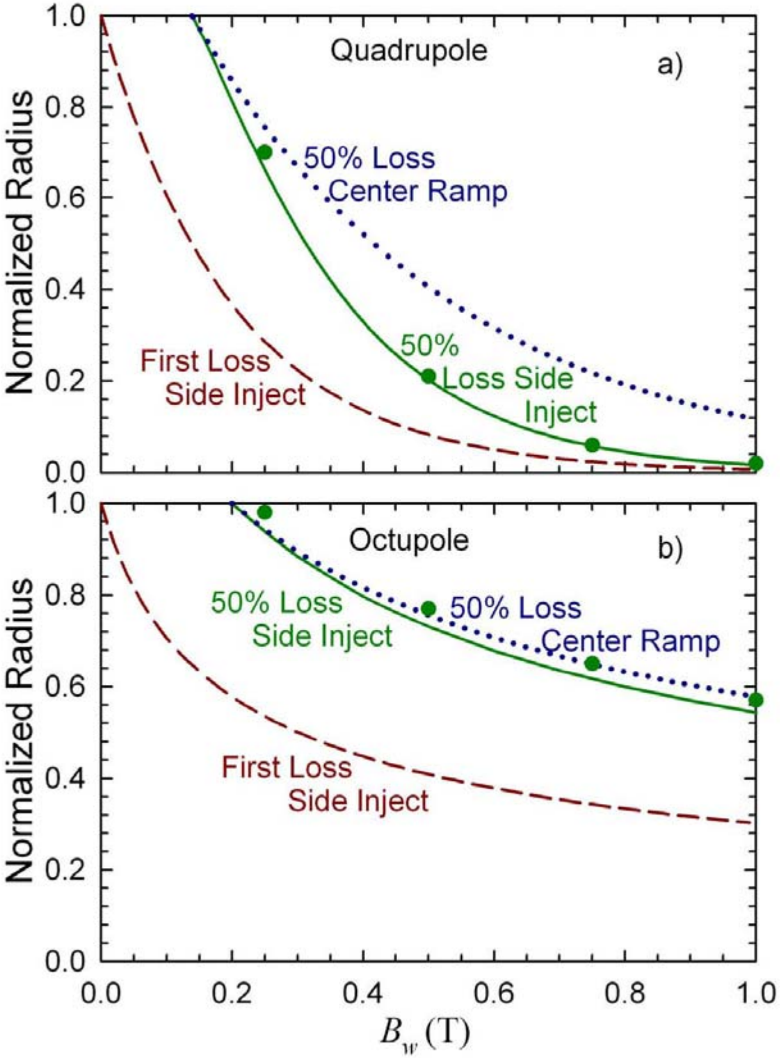


Dotted blue from inverting previous equation

Green line (numerical)

Red dashed (numerical no rotation)

Comparison of Loss vs. B_w



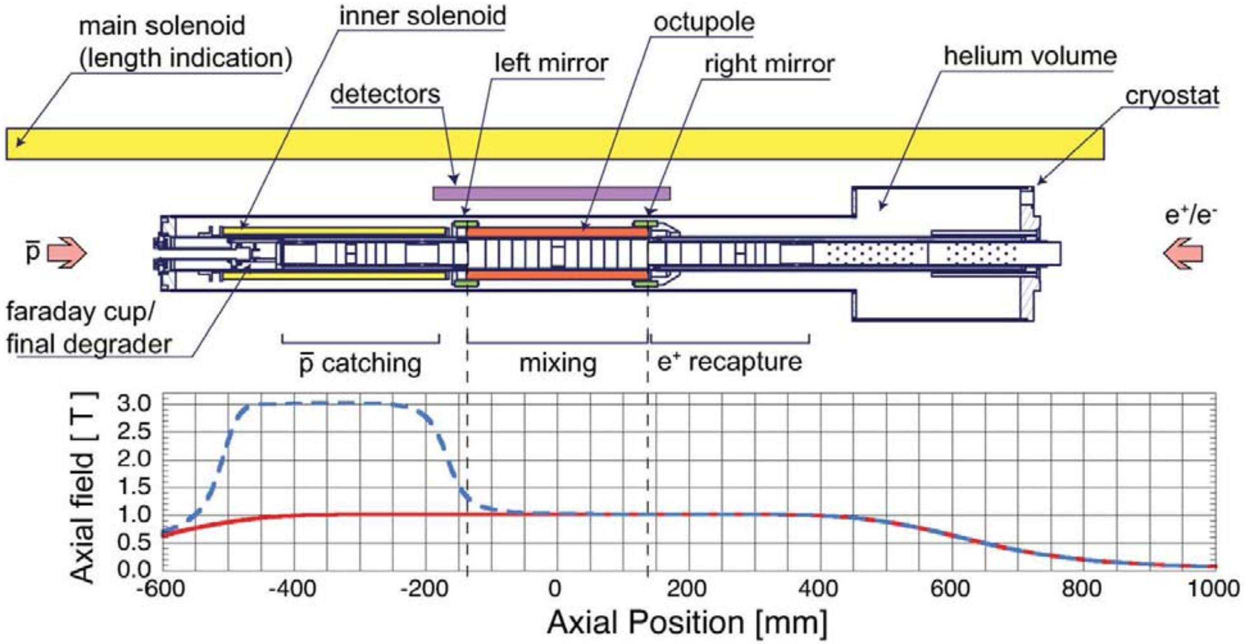
No collisions

What fraction of trajectories hit walls for quadrupole and octupole fields

PHYSICS OF PLASMAS **15**, 032107 (2008)

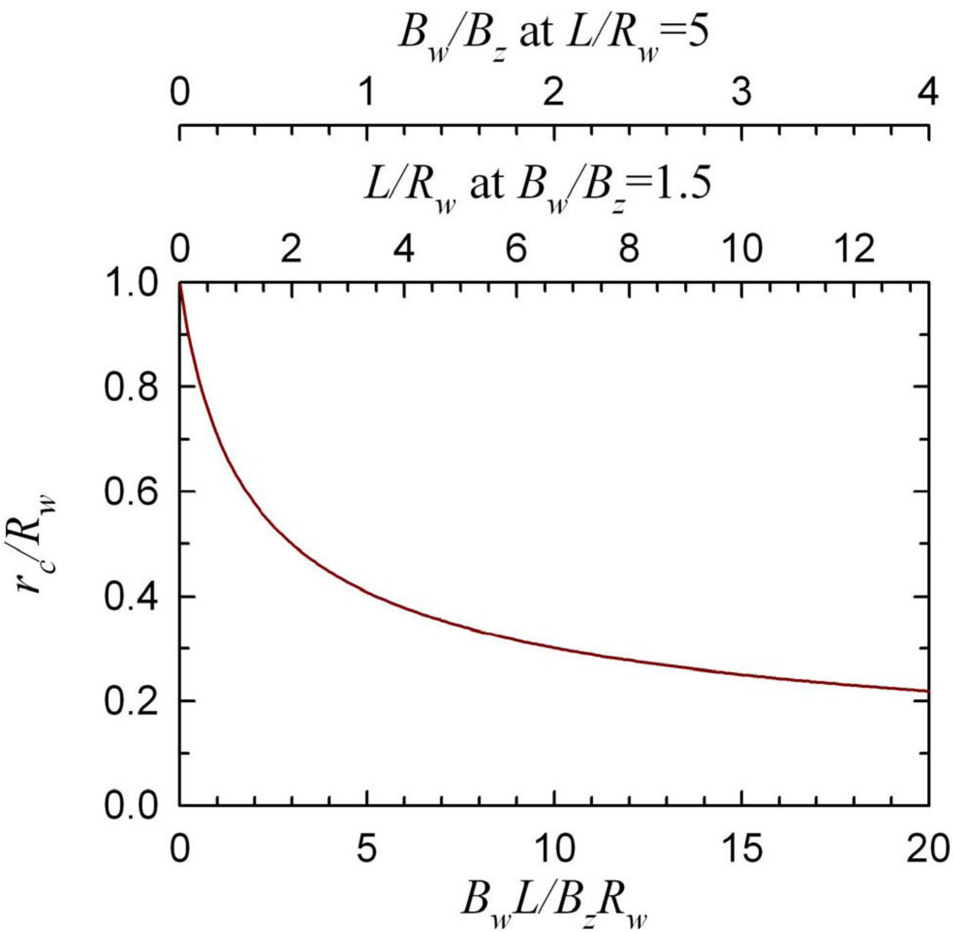
A novel antiproton radial diagnostic based on octupole induced ballistic loss

G. B. Andresen,[1] W. Bertsche,[2] P. D. Bowe,[1] C. C. Bray,[3] E. Butler,[2] C. L. Cesar,[4] S. Chapman,[3] M. Charlton,[2] J. Fajans,[3] M. C. Fujiwara,[5] R. Funakoshi,[6] D. R. Gill,[5] J. S. Hangst,[1] W. N. Hardy,[7] R. S. Hayano,[6] M. E. Hayden,[8] A. J. Humphries,[2] R. Hydomako,[9] M. J. Jenkins,[2] L. V. Jørgensen,[2] L. Kurchaninov,[5] R. Lambo,[4] N. Madsen,[2] P. Nolan,[10] K. Olchanski,[5] A. Olin,[5] R. D. Page,[10] A. Povilus,[3] P. Pusa,[10] F. Robicheaux,[11] E. Sarid,[12] S. Seif El Nasr,[7] D. M. Silveira,[4] J. W. Storey,[5] R. I. Thompson,[9] D. P. van der Werf,[2] J. S. Wurtele,[3] and Y. Yamazaki[13]



Increase octupole strength to shave off antiprotons!

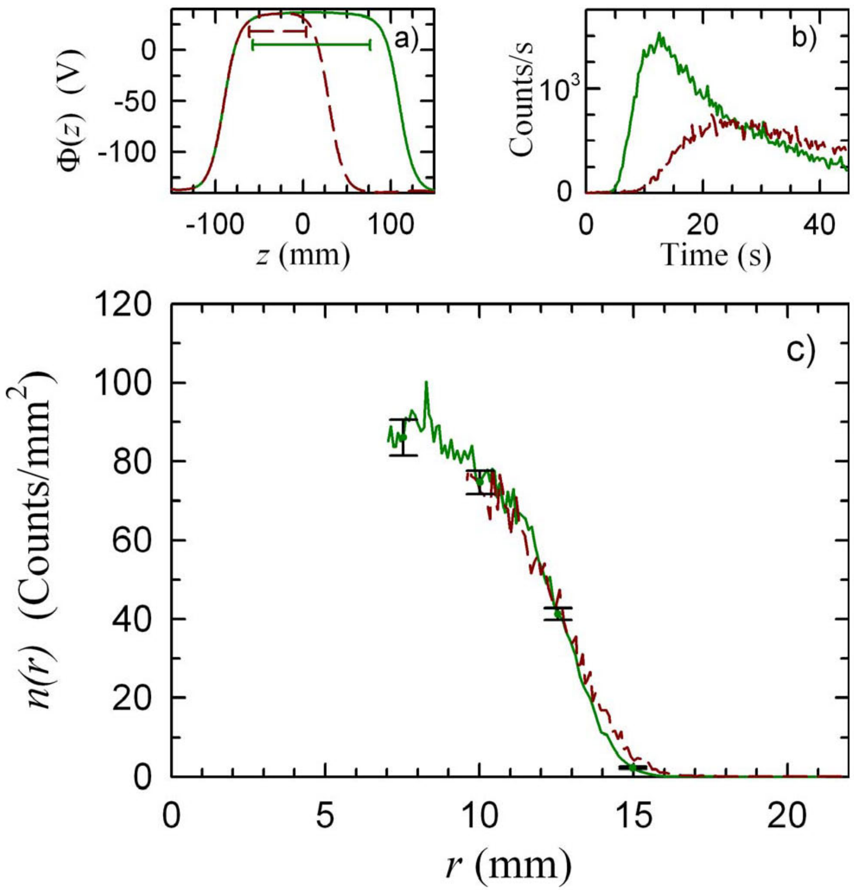
Critical Radius



Critical radius depends on length of plasma, axial B, octupole B at wall, and wall radius

Increase octupole B with time and use wall hits vs time to extract radial distribution

Application to Radial Density

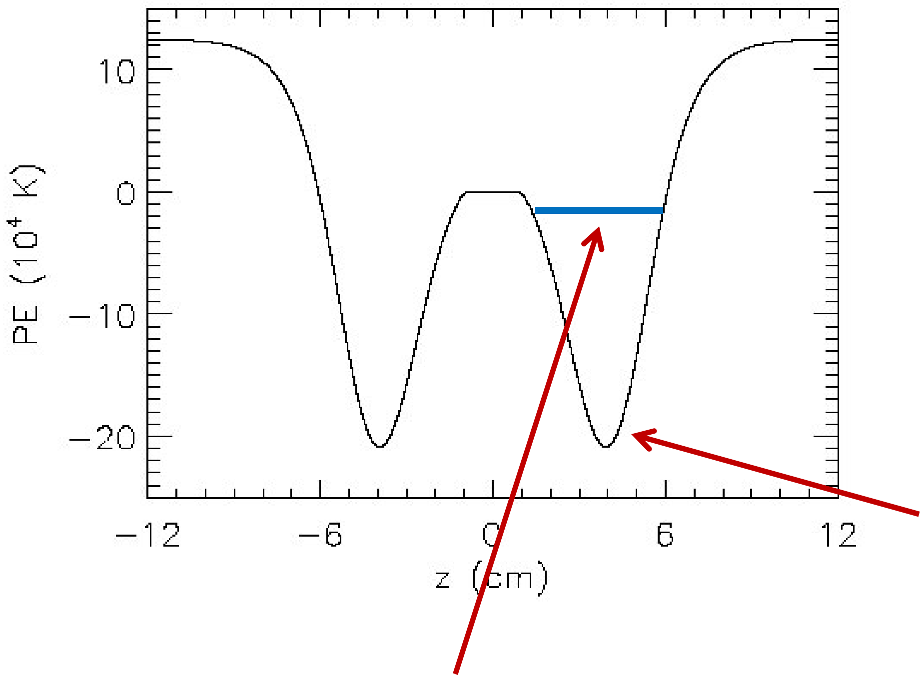


a) potentials
b) counts vs time
c) convert to density vs radius

Although different time dependence of hits get same reconstructed density

Limitation: there is minimum r can extract

What Happens When Mix



Mixing antiprotons that start out below the positron plasma

Slowly raise the bottom of the PE

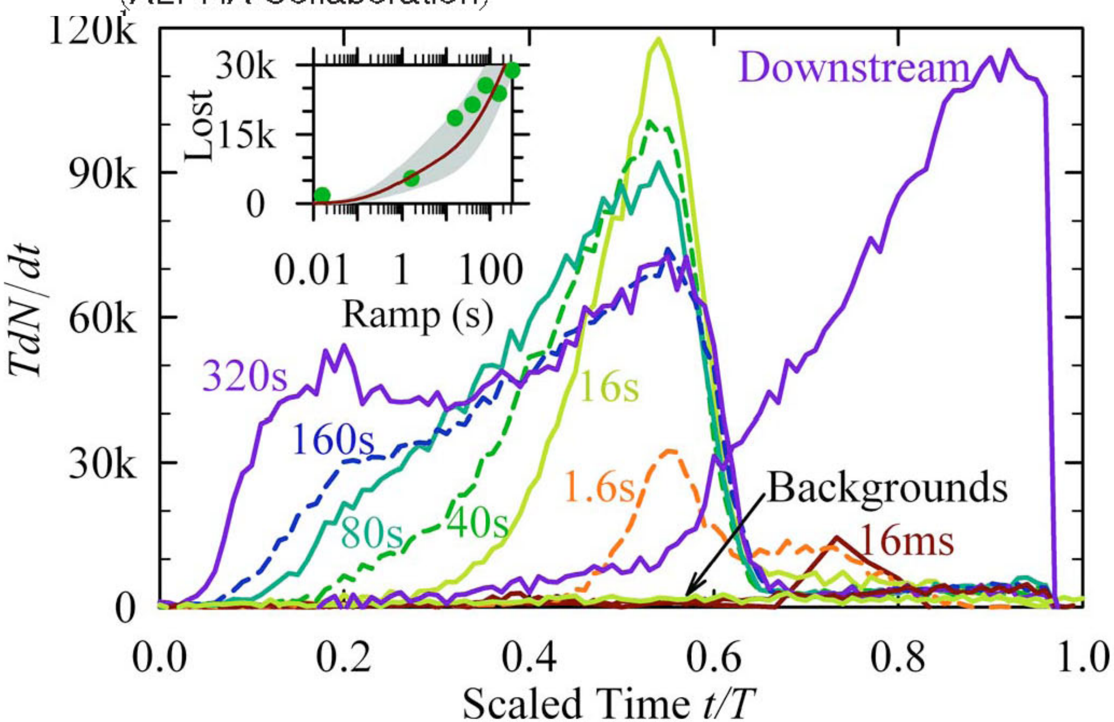
antiprotons

Small radius antiprotons should be stable

PHYSICS OF PLASMAS **16**, 100702 (2009)

Magnetic multipole induced zero-rotation frequency bounce-resonant loss in a Penning–Malmberg trap used for antihydrogen trapping

G. B. Andresen,[1] W. Bertsche,[2] C. C. Bray,[3] E. Butler,[2] C. L. Cesar,[4] S. Chapman,[3] M. Charlton,[2] J. Fajans,[3] M. C. Fujiwara,[5] D. R. Gill,[5] W. N. Hardy,[6] R. S. Hayano,[7] M. E. Hayden,[8] A. J. Humphries,[2] R. Hydomako,[9] L. V. Jørgensen,[2] S. J. Kerrigan,[2] J. Keller,[3] L. Kurchaninov,[5] R. Lambo,[4] N. Madsen,[2] P. Nolan,[10] K. Olchanski,[5] A. Olin,[5] A. Povilus,[3] P. Pusa,[10] F. Robicheaux,[11] E. Sarid,[12] S. Seif El Nasr,[6] D. M. Silveira,[7,13] J. W. Storey,[5] R. I. Thompson,[9] D. P. van der Werf,[2] J. S. Wurtele,[3] and Y. Yamazaki[13]
(ALPHA Collaboration)



Loss to walls

“Mysterious” loss of antiprotons when mixing the antiprotons with e^+

More loss when ramp slower

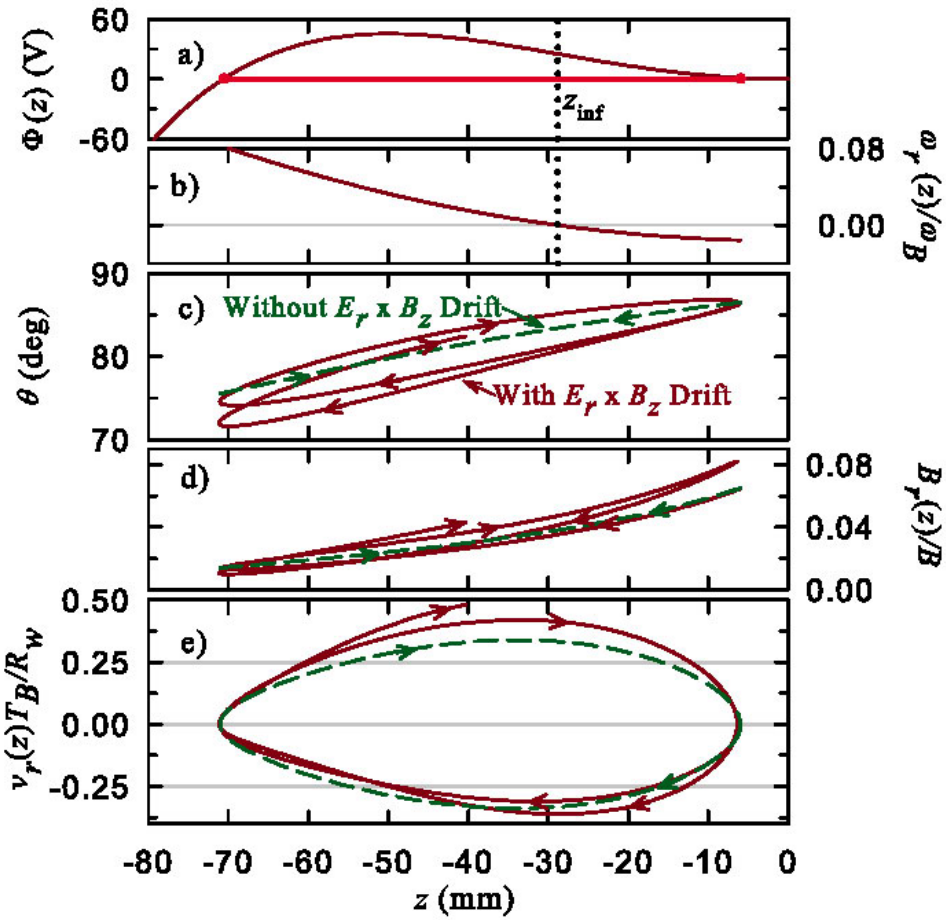
Why a Mystery?

Radius of antiprotons should have been small enough to have almost all with less than critical radius.

Time scale too fast for collisions.

Time scale too slow for immediate transport.

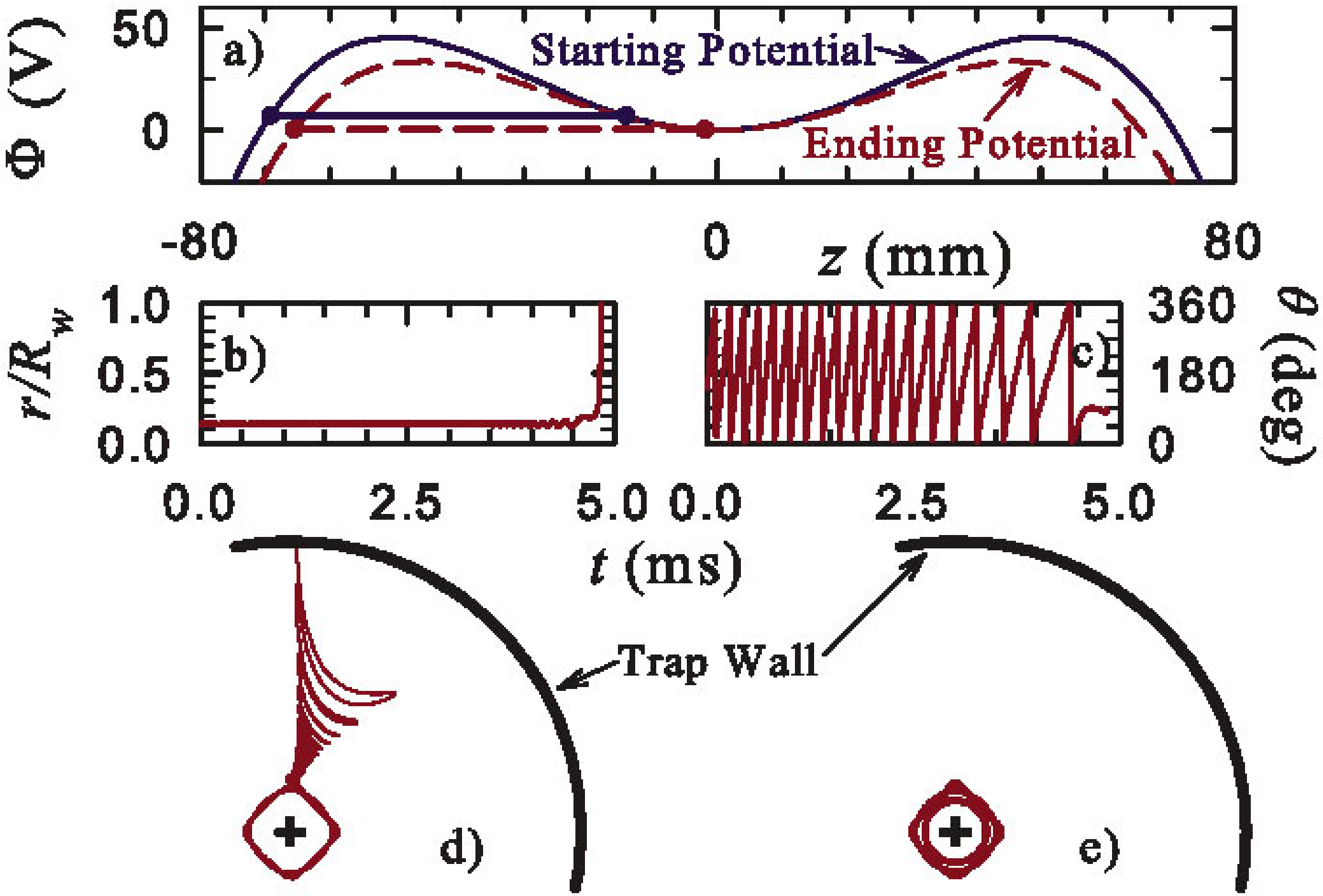
Rotation Around Axis Stalls



As the electric potential is elongated, the rotation direction around axis changes sign.

As t changes, reach condition where 0 rotation => leads to resonance loss.

Example Trajectory



Plots b-d are for same trajectory. Plot e has slightly different initial conditions and isn't lost.

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **40** (2007) 1019–1033 doi:10.1088/0953-4075/40/5/016

Regular and chaotic motion of anti-protons through a nested Penning trap with multipole magnetic fields

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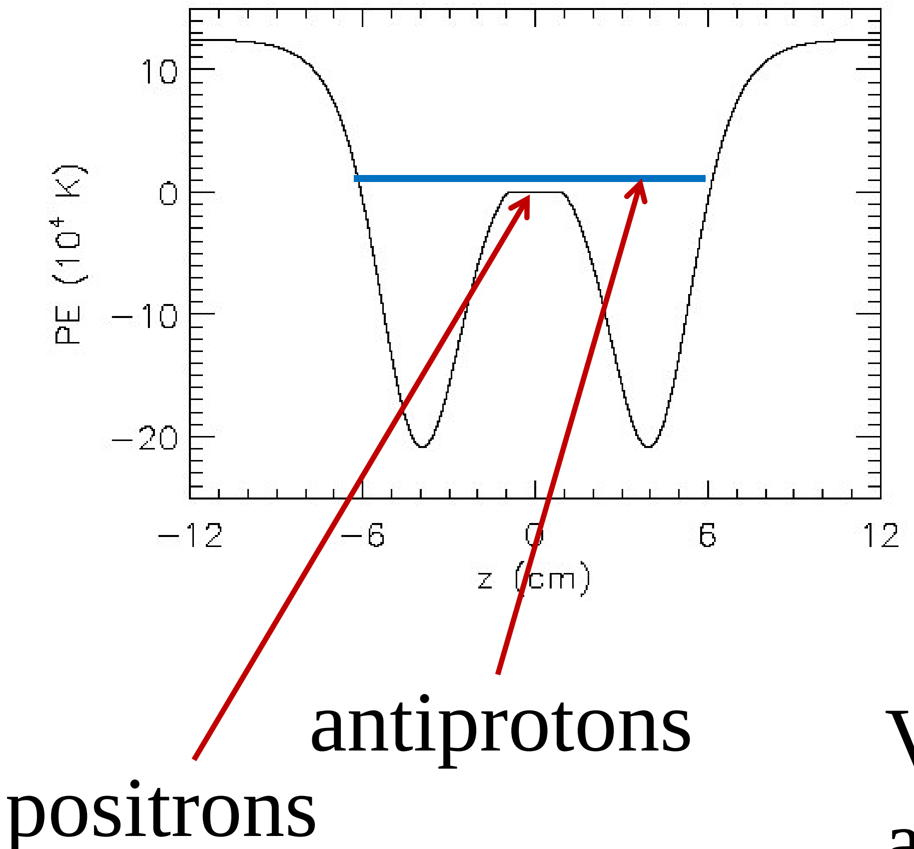
Received 13 November 2006, in final form 29 December 2006
Published 19 February 2007

What does the antiproton trajectory look like when they are just above the level of the positrons.

Antiproton Motion When Above

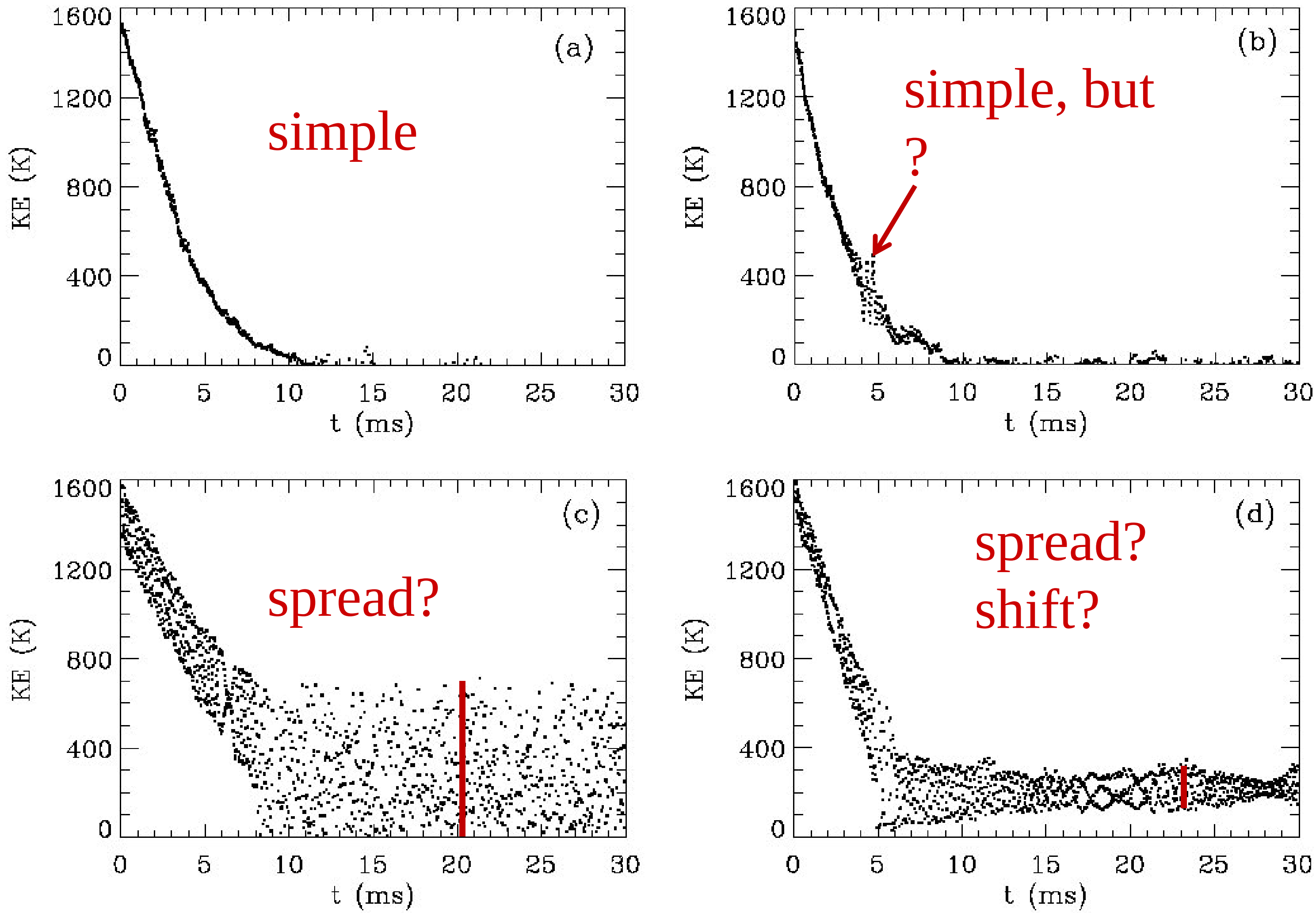


Antiprotons lose energy to the positrons by collisions/waves

Anything strange happens?

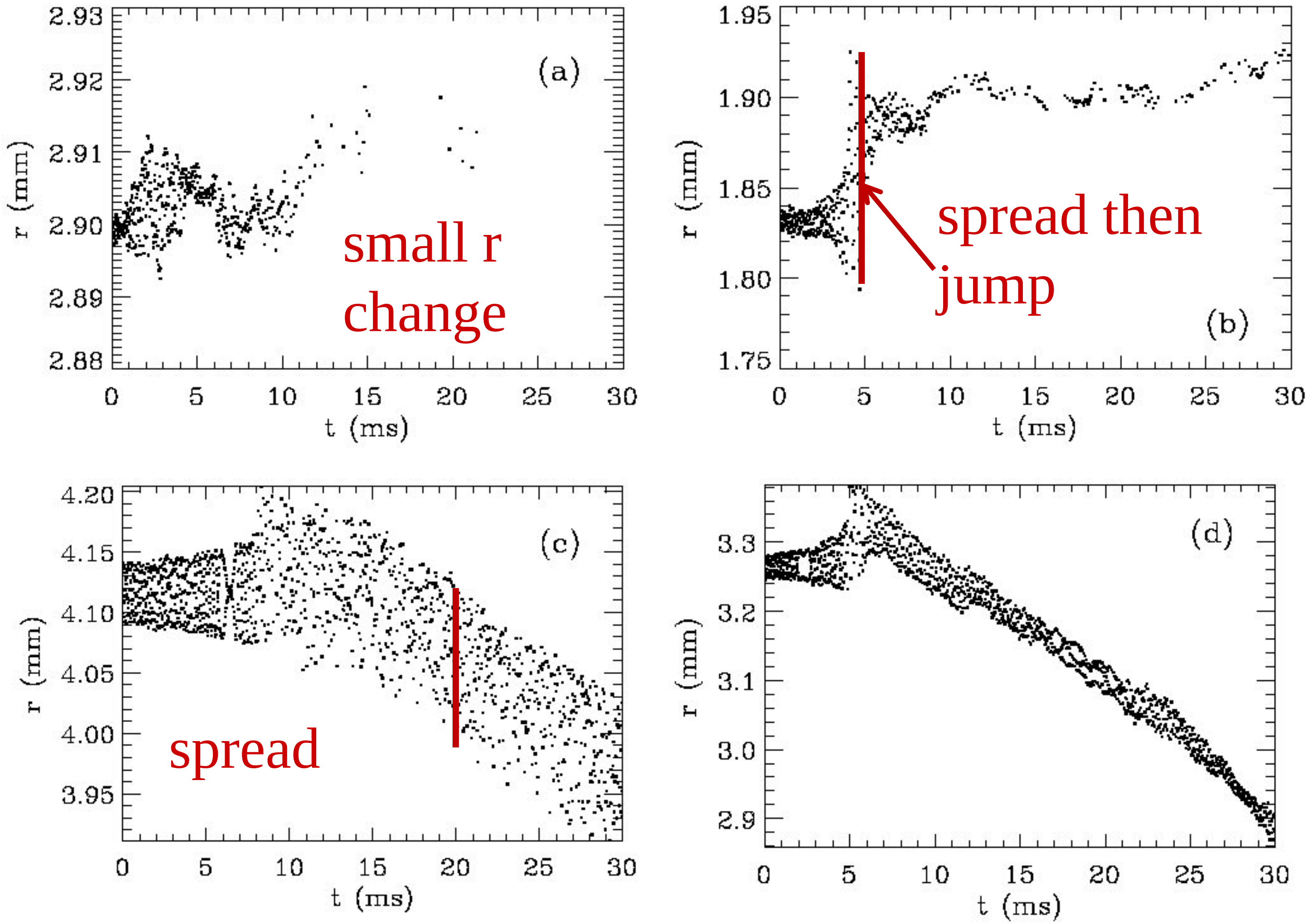
Very small radius so antiprotons motion should be simple

KE at z=0 vs. t



4 different trajectories

r at z=0 vs. t

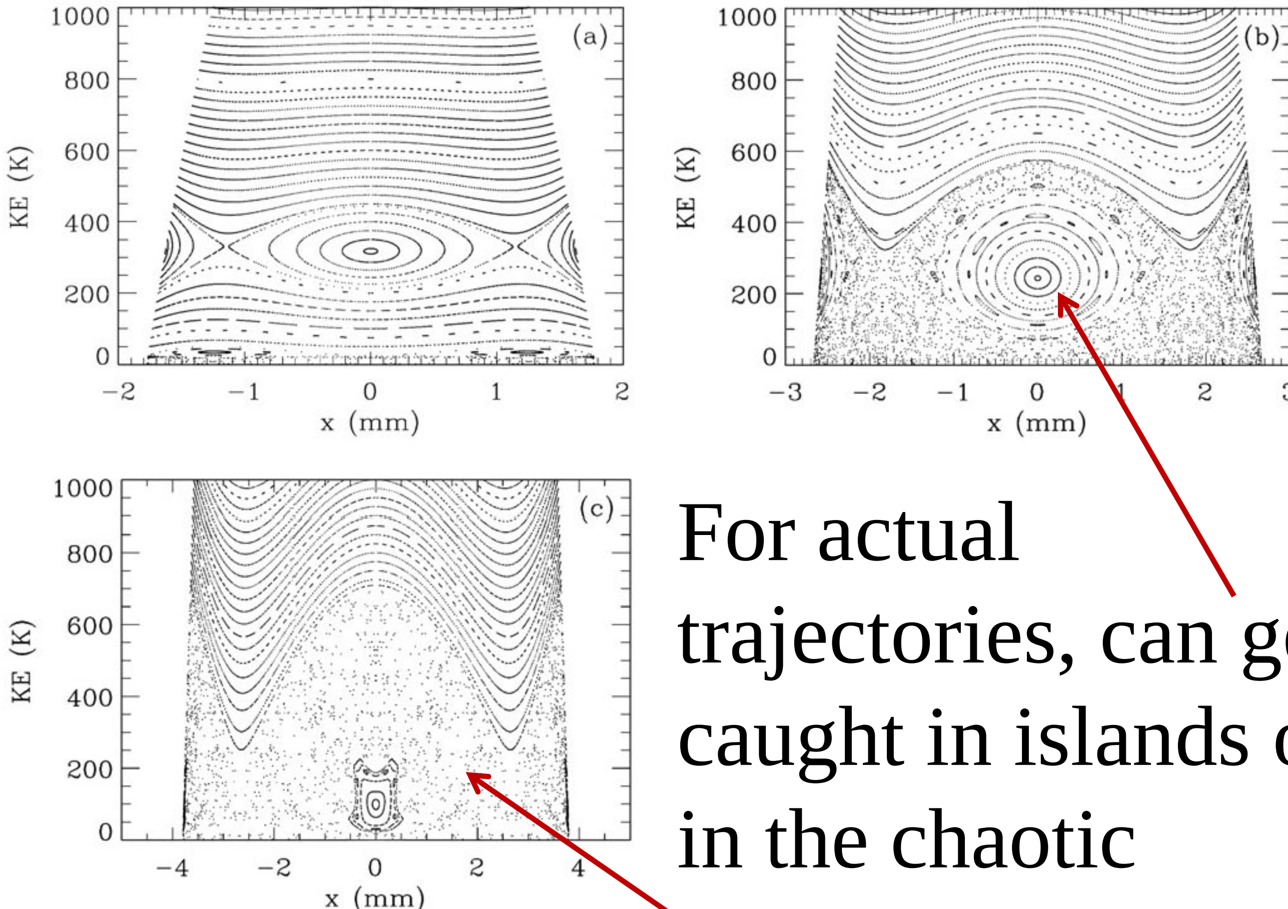


same 4 trajectories

Poincare Surface of Section

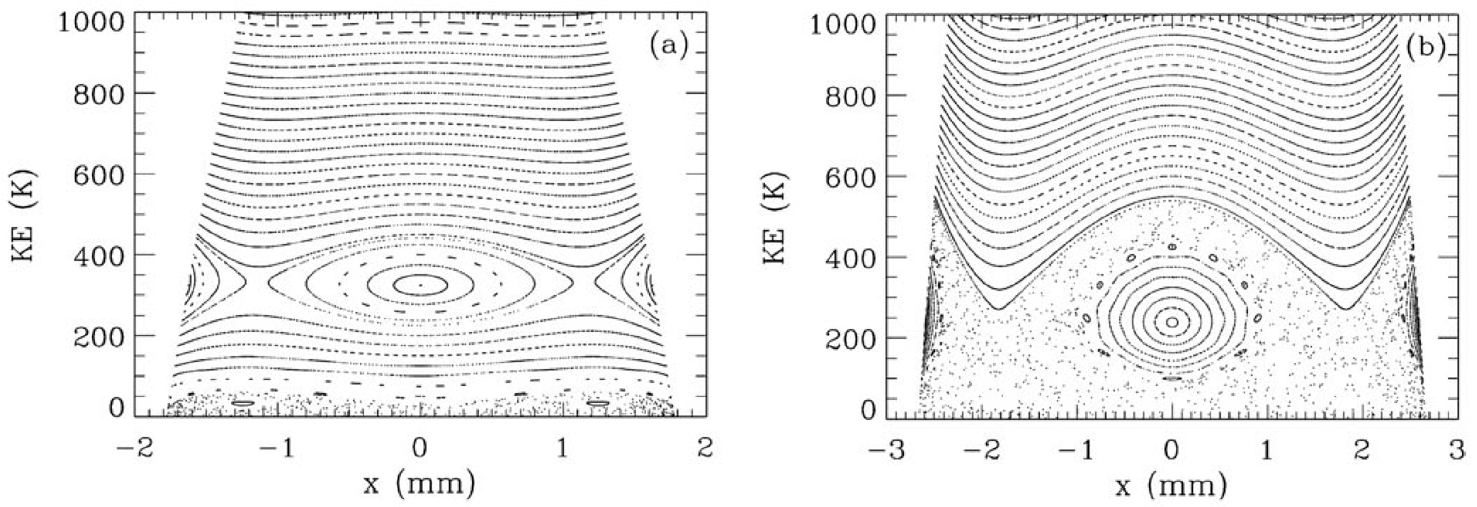
No KE loss to positrons

a to c is increasing radius



For actual trajectories, can get caught in islands or in the chaotic region

Simple Map



Envelope is due to conservation of E (PE changes with r)
Large KE only small rotation in each axial bounce
Main island from rotation in positron ~1/4
Size of chaotic region increases with r because variation of PE larger as r increases

End of 1 Particle Motion

Plasmas Change Things

Mirror magnets don’t introduce qualitative changes because cylindrical symmetry

Collisions and waves give problems for holding plasmas with multipole fields because break cylindrical symmetry

VOLUME 90, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2003

Quadrupole-Induced Resonant-Particle Transport in a Pure Electron Plasma

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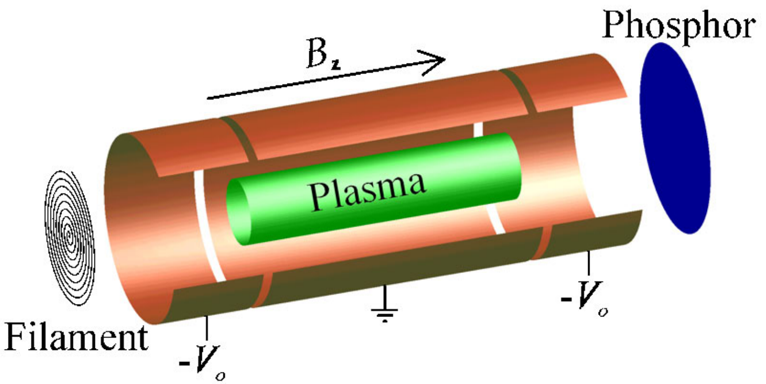
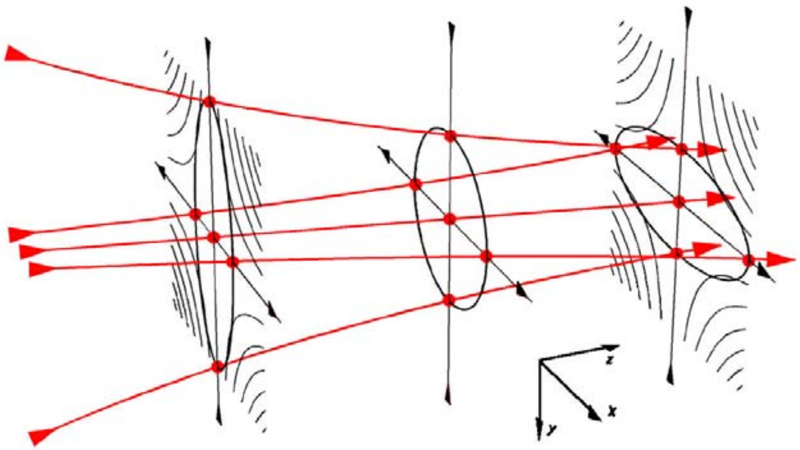
Department of Physics, University of California, Berkeley, California 94720

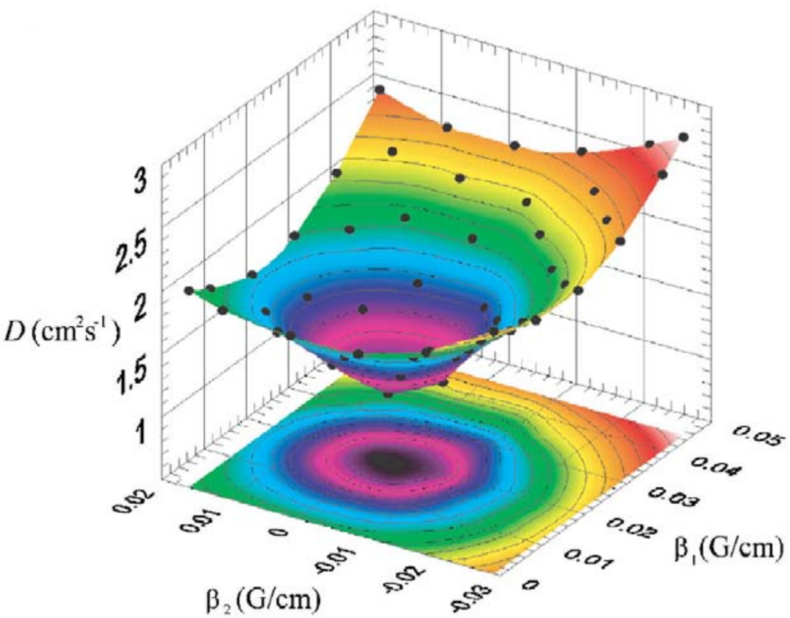
(Received 12 August 2002; revised manuscript received 28 October 2002; published 8 January 2003)

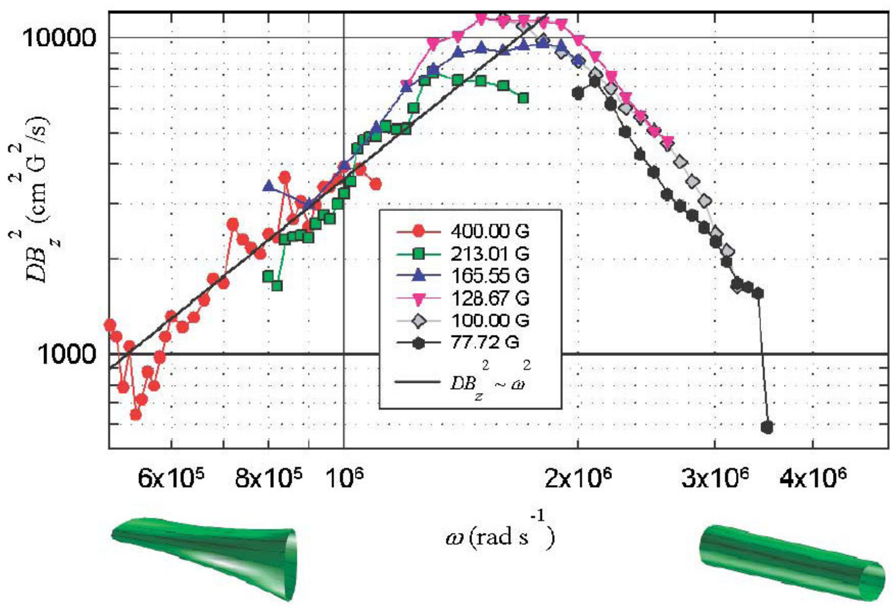


Look at transport in pure electron plasma vs quadrupole strength



Diffusion With Quadrupole

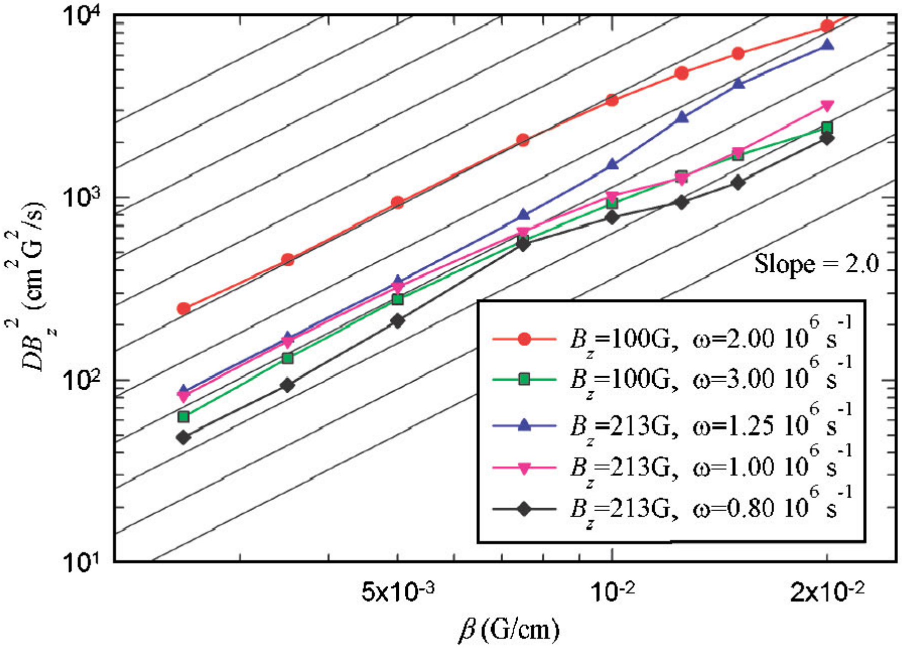




Diffusion as the quadrupole strength increases

Scaled diffusion vs plasma rotation frequency

Scaling of Diffusion



Diffusion scales as square of quadrupole strength

PHYSICS OF PLASMAS VOLUME 6, NUMBER 7 JULY 1999

Theory of asymmetry-induced transport in a non-neutral plasma

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(Received 19 January 1999; accepted 29 March 1999)

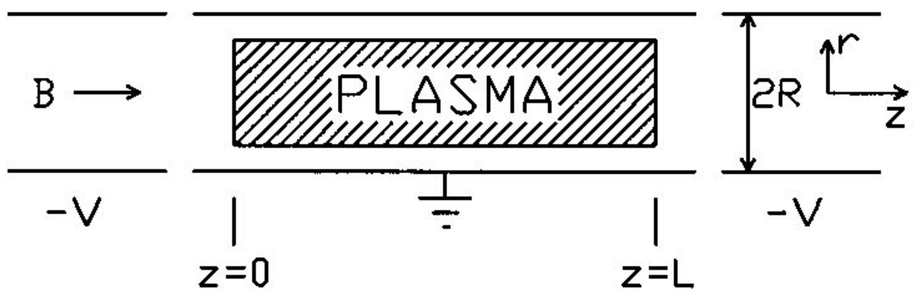

FIG. 1. Schematic of the plasma model used for this theory. The plasma is assumed to have flat ends and be of length L.

Transport dominated by particles that move in resonance with asymmetry

Agreement with experiment???

D. L. Eggleston, Phys. Plasmas **17**, 042304 (2010).

PRL **95,** 155001 (2005) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2005

Effects of Extreme Magnetic Quadrupole Fields on Penning Traps and the Consequences for Antihydrogen Trapping

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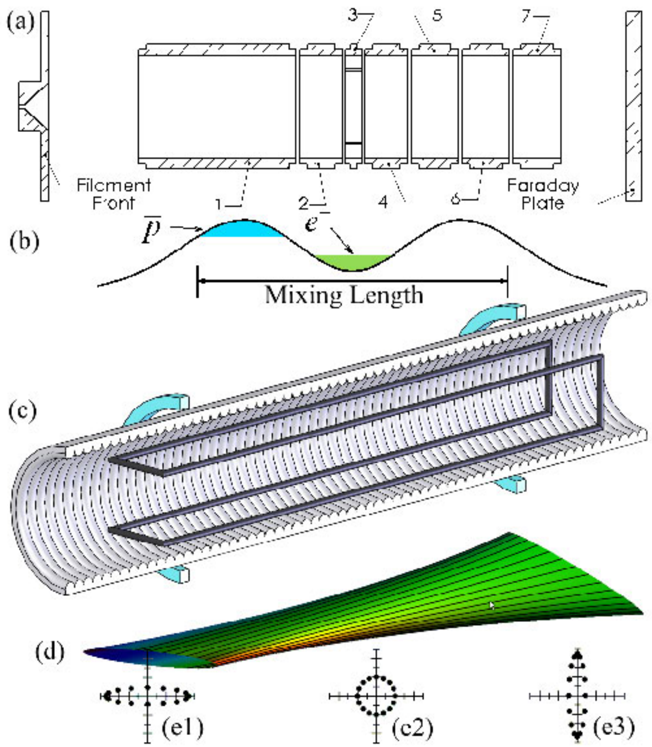
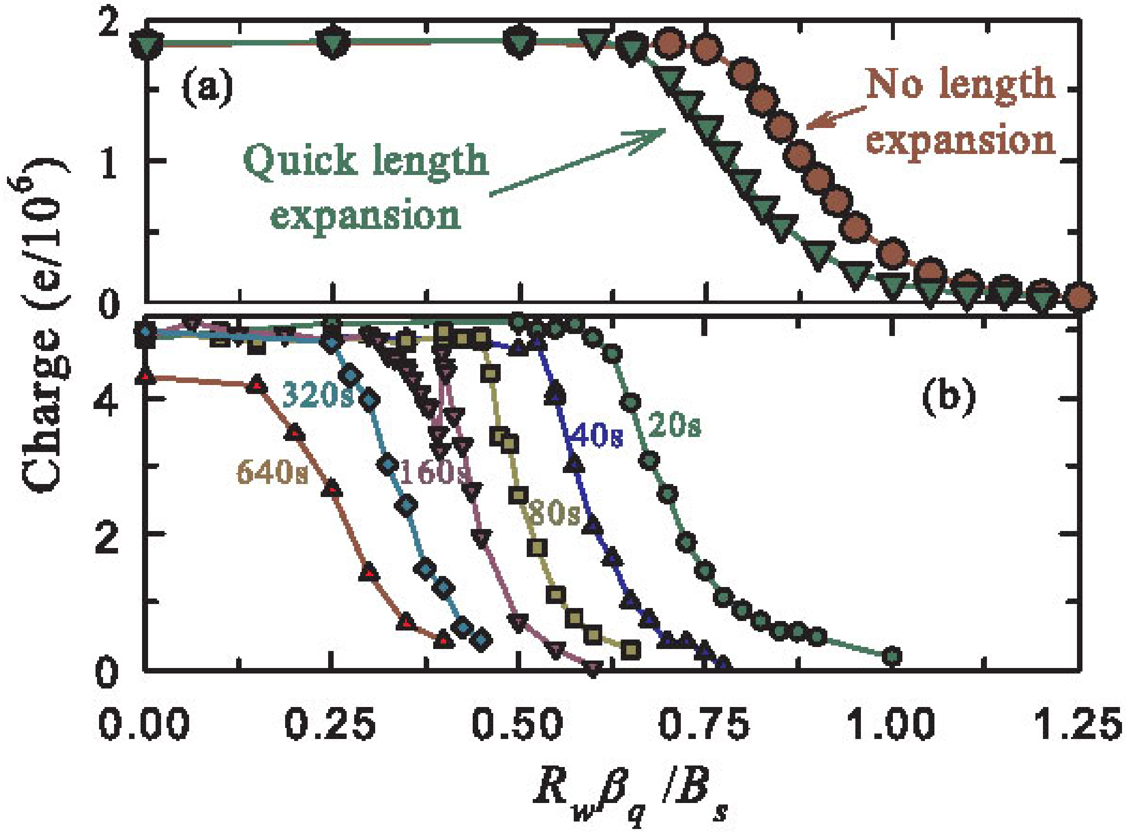
[2]*Department of Physics, University of Wales Swansea, Singleton Park SA2 8PP, United Kingdom*
(Received 16 November 2004; published 4 October 2005)



Immediate and diffusive transport to walls

"…suggest quadrupoles cannot be used to trap antihydrogen."

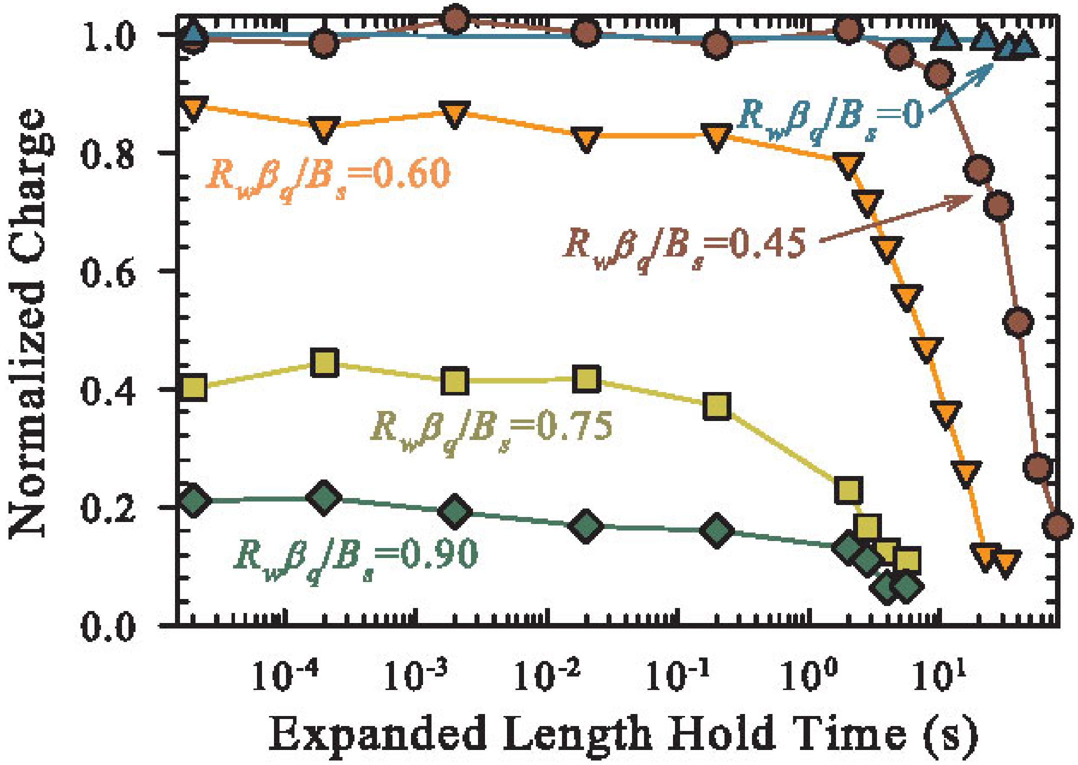
Charge Remaining



Expand from 1 to 4 cm

Remaining as a function of quadrupole strength: different hold times (2 cm)

Charge Remaining



Remaining as a function of hold time: different quadrupole strengths (4 cm)

Antimatter Plasmas in a Multipole Trap for Antihydrogen

G. Andresen,[1] W. Bertsche,[2] A. Boston,[3] P. D. Bowe,[1] C. L. Cesar,[4] S. Chapman,[2] M. Charlton,[5] M. Chartier,[3] A. Deutsch,[2] J. Fajans,[2] M. C. Fujiwara,[6] R. Funakoshi,[7] D. R. Gill,[6] K. Gomberoff,[2,8] J. S. Hangst,[1] R. S. Hayano,[7] R. Hydomako,[9] M. J. Jenkins,[5] L. V. Jørgensen,[5] L. Kurchaninov,[6] N. Madsen,[5] P. Nolan,[3] K. Olchanski,[6] A. Olin,[6] A. Povilus,[2] F. Robicheaux,[10] E. Sarid,[11] D. M. Silveira,[4] J. W. Storey,[6] H. H. Telle,[5] R. I. Thompson,[9] D. P. van der Werf,[5] J. S. Wurtele,[2] and Y. Yamazaki[12]

(ALPHA Collaboration)

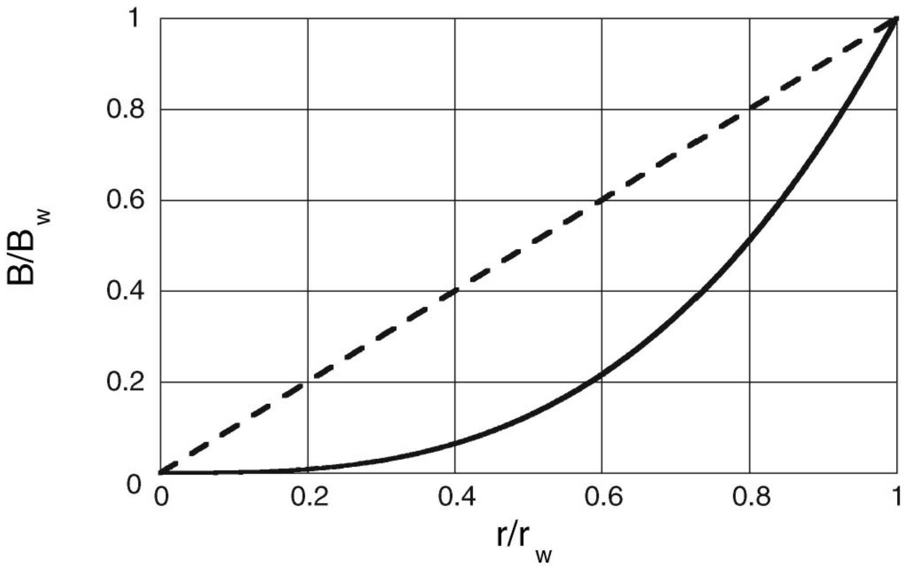
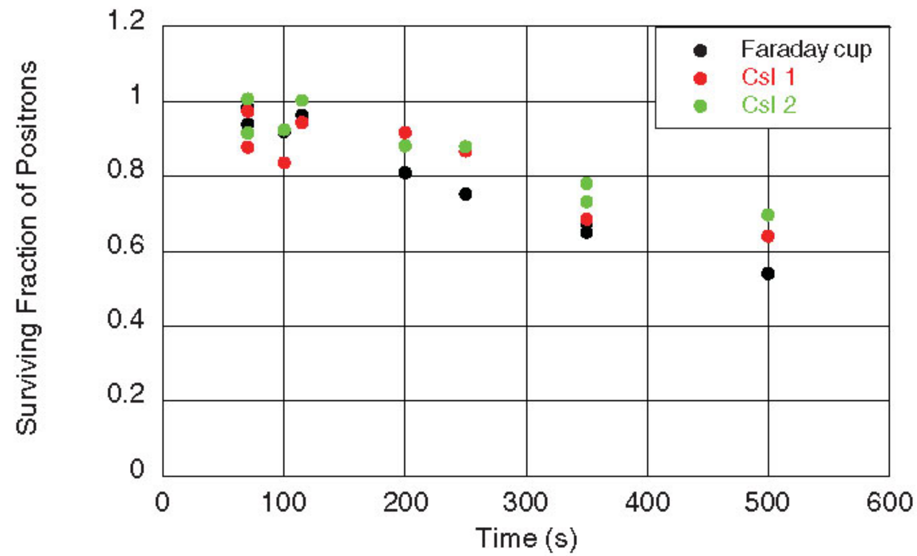


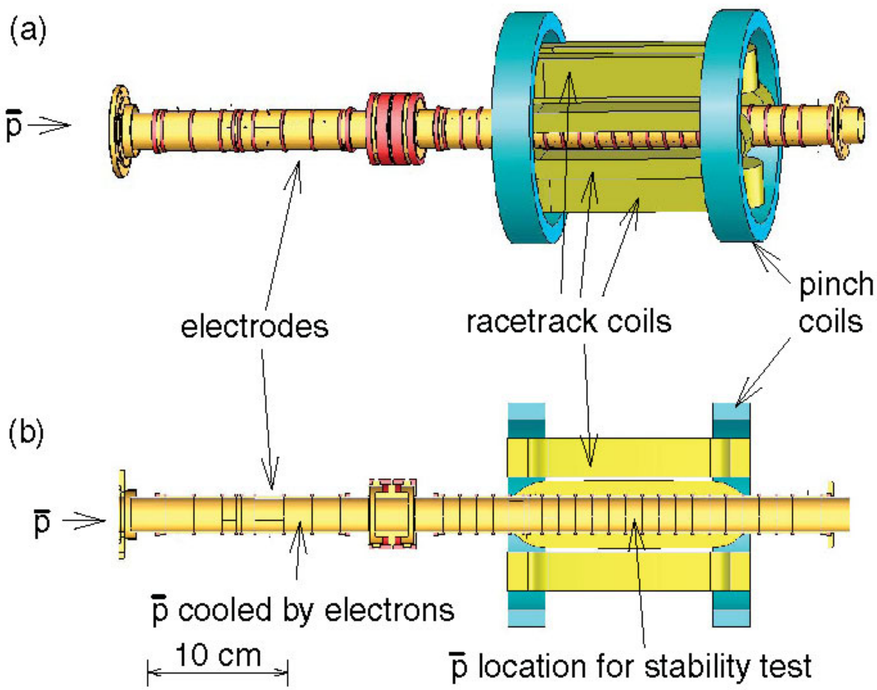
FIG. 2. Magnetic field strength versus radius for an ideal quadrupole (dashed line) and an ideal octupole (solid line). B_w is the field at the inner wall (radius r_w) of the Penning trap.

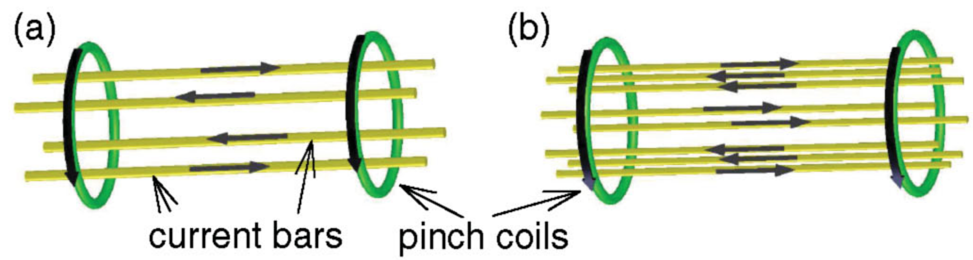


Antiproton Confinement in a Penning-Ioffe Trap for Antihydrogen

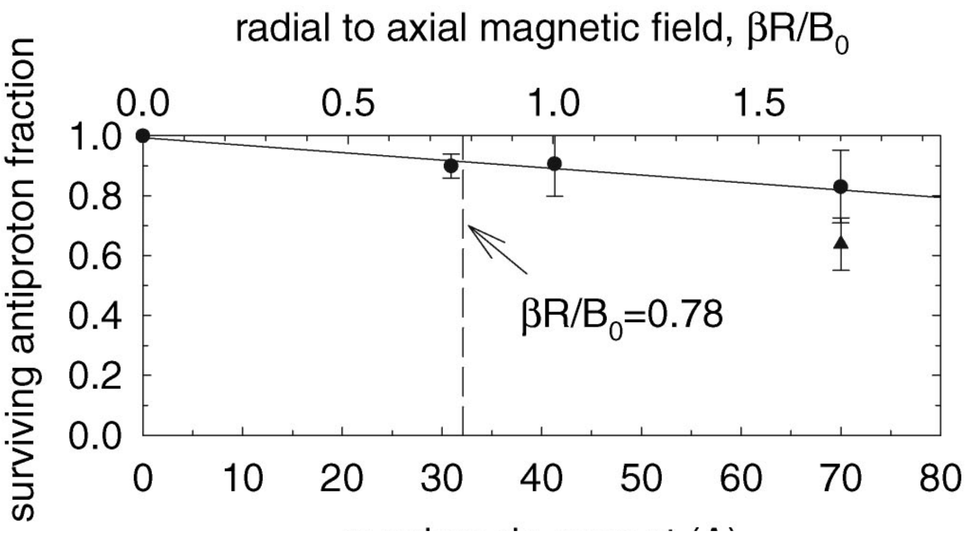
G. Gabrielse,[1,*] P. Larochelle,[1] D. Le Sage,[1] B. Levitt,[1] W. S. Kolthammer,[1] I. Kuljanishvili,[1] R. McConnell,[1] J. Wrubel,[1] F. M. Esser,[2] H. Glückler,[2] D. Grzonka,[3] G. Hansen,[2] S. Martin,[3] W. Oelert,[3] J. Schillings,[2] M. Schmitt,[2] T. Sefzick,[3] H. Soltner,[2] Z. Zhang,[3] D. Comeau,[4] M. C. George,[4] E. A. Hessels,[4] C. H. Storry,[4] M. Weel,[4] A. Speck,[5] F. Nillius,[6] J. Walz,[6] and T. W. Hänsch[7,8]

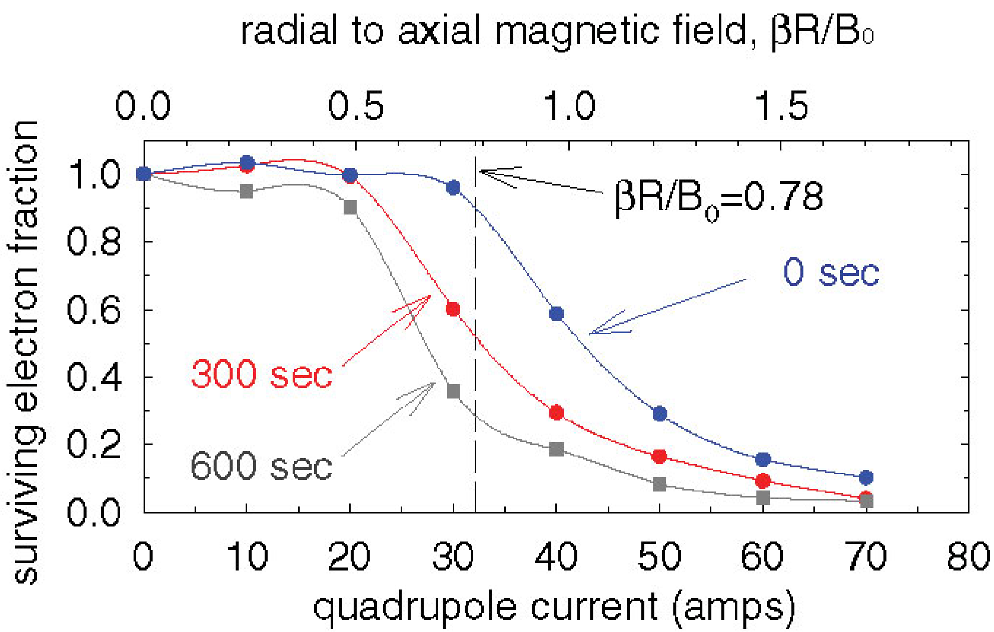
(ATRAP Collaboration)





Results





Trap depth is 375 mK for ground state H when $\beta R/B_0 = 0.78$

Fraction of trapped antiH scales like trap depth$^{3/2}$

Abstract & Conclusion

"This first demonstration with antiprotons suggests that quadrupole Ioffe traps can be superimposed upon antiproton and positron traps to attempt to capture antihydrogen atoms as they form, *contrary to conclusions of previous analyses.*"

"Quadrupole Ioffe traps thus seem to have a role to play for antihydrogen formed by charge exchange, *in spite of earlier claims to the contrary*."

(emphasis added)

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Simulations of plasma confinement in an antihydrogen trap

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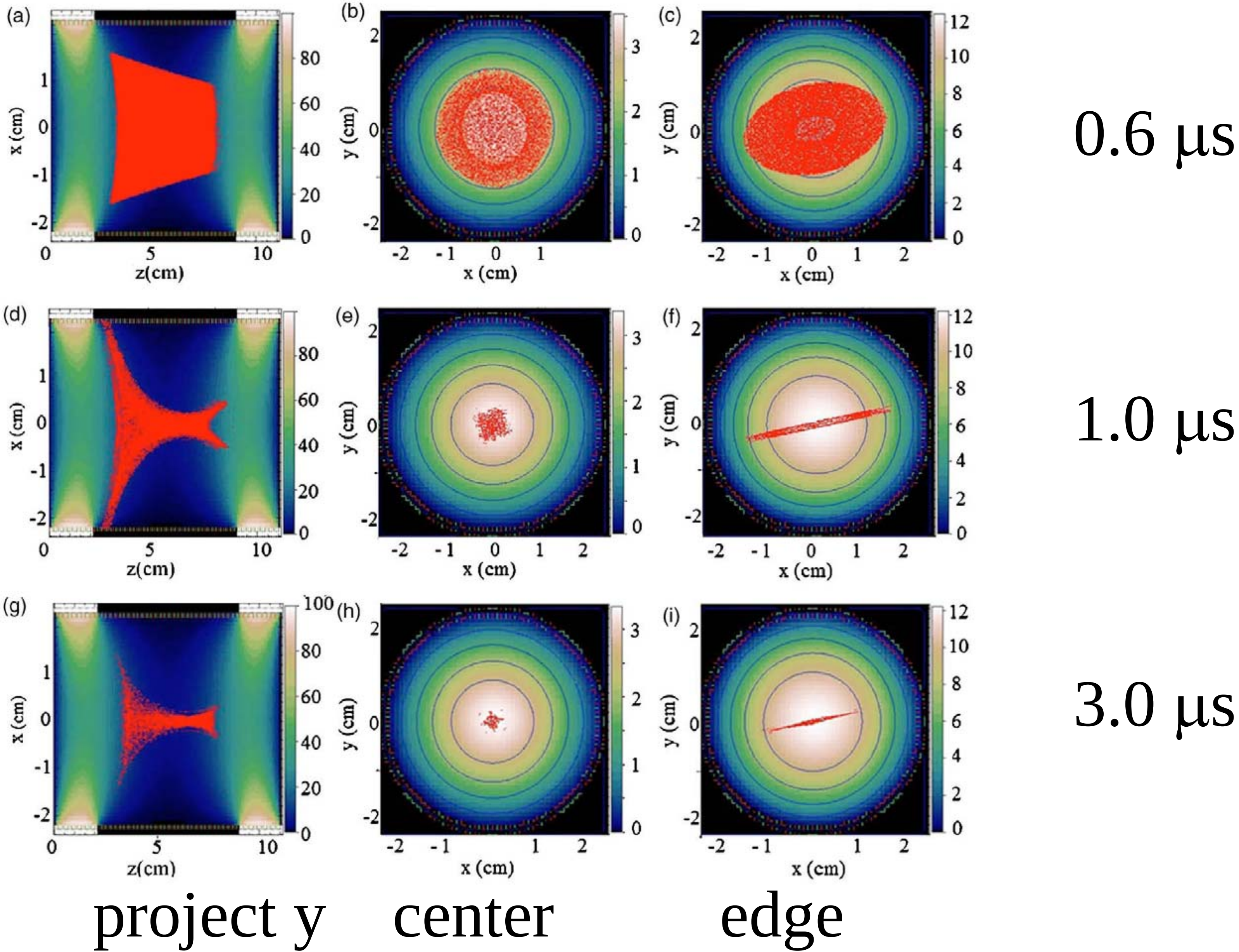
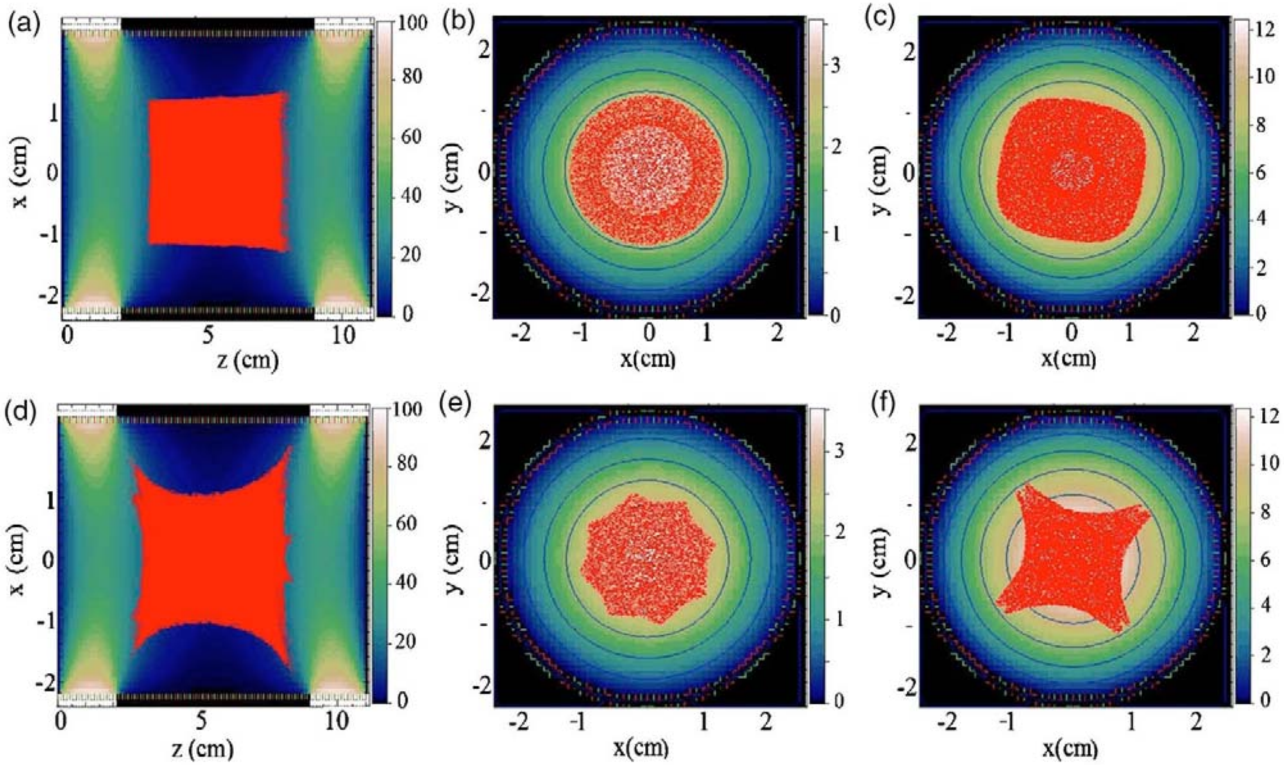
Quadrupole



Octupole



0.6 μs

3.0 μs

project y   center   edge

Survival vs. time