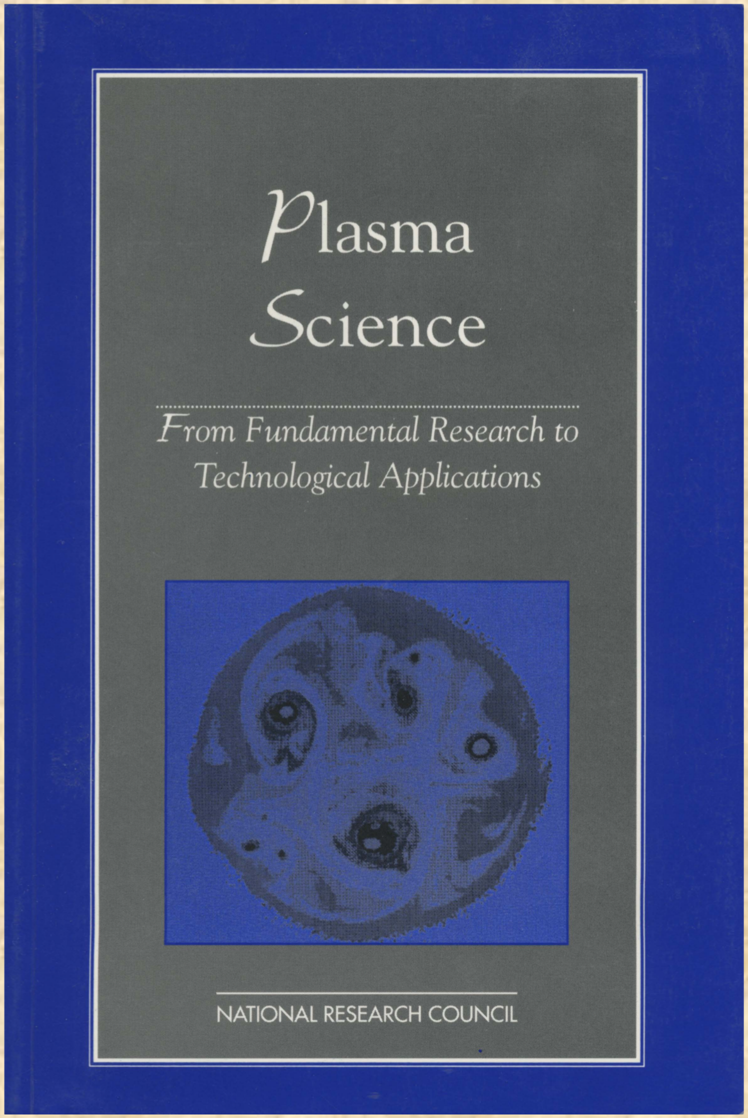
Reflections on the 1995 NRC Plasma Science Report

and

Progress and Promise in Nonneutral Plasmas
An Example of Basic Plasma Research

Clifford M. Surko
Department of Physics
University of California San Diego



1995 NRC Plasma Science Report

Clifford M. Surko*

University of California, San Diego

* Co-chair John Ahearne

1995 NRC Plasma Science Report

Chronology - the Long View

1986 - Brinkman report section on Plasmas and Fluids

1988 - Formation of a Plasma Science Committee at the National Research Council

1992 – Decadal Plasma Science Study commissioned

March 1995 Plasma Science Report (3 year delay is unusual)

(many things going on simultaneously)

December, 1996: the NSF/DOE Plasma Partnership began

Brinkman report on Fluids and Plasmas (1986)

(One of four general recommendations)

".....**we recommend a renewed commitment** by the federal government **to basic research** (in fluids and plasmas). An adequate level of basic research, …, should be established in order to provide the foundations for future scientific advances and new technologies."

Plasma Science 1995 Report

Emphasize the Unity of the Science

1. Overview

2. Topical Areas:

Low-temperature plasmas; nonneutral plasmas; inertial confinement fusion; magnetic confinement fusion; beams, accelerators, and coherent radiation sources; space plasmas; plasma astrophysics

3. Broad Areas of Plasma Science

Basic Plasma Experiment

Theoretical and Computational Plasma Science

Education in Plasma Physics

1995 NRC Report

(Six major recommendations, focused on university-scale science.)

1. **Emphasis should be placed on university-scale research programs**.

2. **The National Science Foundation should provide increased support for basic plasma science.**

3. **The Office of Basic Energy Sciences, with the cooperation of the Office of Fusion Energy, should provide increased support for basic experimental plasma science** (to) leverage the DOE's present investment and strengthen investigations in other energy-related areas of plasma science and technology.

1995 NRC Report

4. **Approximately $15 million per year for university-scale experiments should be provided and continued in future years to effectively redress the current lack of support for fundamental plasma science, which is a central concern of this report.**

5. **The agencies supporting plasma science should cooperate to coordinate plasma science policy and funding**

6. **Members of the plasma community in industry and academe should work aggressively for tenure-track recognition of plasma science as an academic discipline.**

Singling Out Basic Experiment?

The panel concluded that basic experiment was on life support. Compared to theory, …………… experiments take dedicated resources, including infrastructure and equipment.

Focus on Small-Scale Research?

That was the enterprise disappearing from the landscape. While basic research can be done at any scale, it is easier at smaller scales, where reconfiguring or building another experiment is less burdensome.

1995 – 1996

March 1996 – House Subcommittee on Energy and Environment of the Committee on Science.

FEAC and DOE indicated that there would be significant increase in funding for <u>plasma</u> <u>science</u> in the FY '97 budget.

December 1996: the NSF/DOE Plasma Partnership was formed

The DOE program became more science oriented.
(and U. S. withdrew from ITER in 1999)

Partnership Was Recognized in the DOE (FES) FY 1998 Budget Request

"A new initiative in general plasma science and engineering began in FY 1997, including a joint program with NSF targeted at university programs and a young investigators program providing research opportunities for tenure-track faculty in plasma science. In FY 1998, the plasma science initiative will be increased.

Thematic Questions Related to the Partnership

What is the outlook for US university faculty positions in plasma physics?

Definitely better with the Partnership than without it.

How could the Partnership facilitate an increase in the academic footprint in disciplines with limited university presence?

Continued emphasis on Early Career Awards, student and post doc support, and support for exciting aspects of the science.

What is the role of the Partnership among the multiple government agencies that support plasma science?

Historically, the Partnership is literally unique in being able to support basic plasma science as central to the agencies' missions.

NSF: “we support basic research and people to create knowledge that transforms the future.”

DOE FES: “Continued stewardship of discovery in plasma science ….will address frontier science issues underpinning great mysteries of the visible universe and help attract and retain a new generation of plasma/fusion science leaders.”

Some Thoughts Going Forward

Your Decadal Study is a critical vehicle to transmit the unity of Plasma Science. I encourage you to use this opportunity to aggressively promote the discipline.

Make sure all of the topical areas are well covered. What's new? What's important for the future, and why?

When asking for resources, prioritize.

Recognition of Plasma Physics

Plasma Physics is underrepresented in elite U. S. university Physics Departments (e.g., the top 10 or so).

The perceived underrepresentation of plasma physicists in the NAS is arguably related to this.

Exciting and emerging areas of plasma physics could be a vehicle to achieve higher recognition of plasma science (and hence further advance academic recognition of the field).

Progress in Nonneutral Plasma Research
– One Facet of Basic Plasma Research

"A hallmark of basic research is the ability to follow the internal logic of the problem."

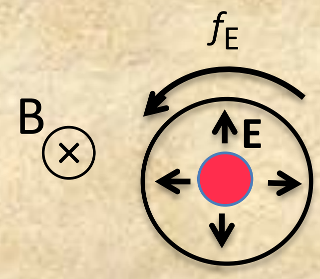
John H. Malmberg, *circa* 1988.

Smallest scale possible, flexible, investigator driven.

A Near-Perfect "Plasma Bottle"

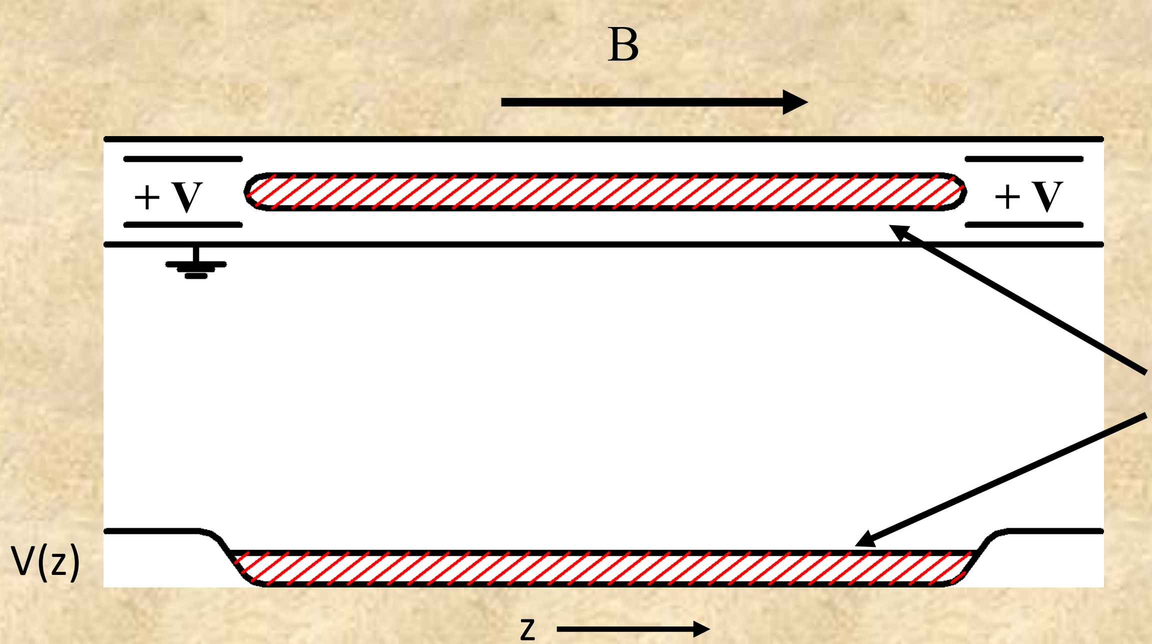
the Penning-Malmberg Trap

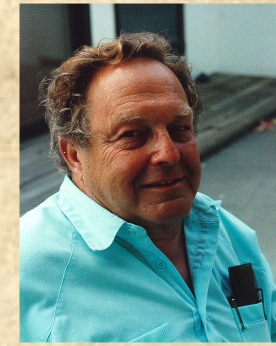
$$\boldsymbol{v_D} = c\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$



plasma rotates

$$f_E = cne/B$$





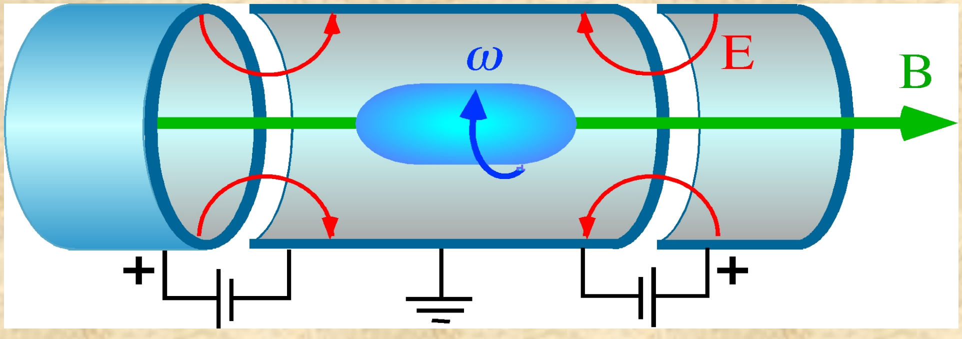
Canonical angular momentum $L_z \approx -\frac{m\omega_c}{2}\sum_j r_j^2$

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

C. Surko, NRC panel meeting, Irvine CA, Jan. 10, 2019

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

Penning-Malmberg Trap



$$f = C\exp(-H_{rot}/kT)$$

Plasmas reach thermal equilibrium

– long-lived, quiescent confinement

Signatures of the thermal equilibrium state:

constant density, temperature, and rotation frequency

Correlation in Single Component Plasmas

A magnetically confined single component plasma is equivalent to a system of classical point charges embedded in a neutralizing background charge.

Correlation parameter

$$\Gamma = \frac{e^2/\bar{r}}{k_B T}$$

where $\bar{r} = \left(\frac{3}{4\pi n}\right)^{1/3}$

$\Gamma < 1$ "classical" plasma

$\Gamma \approx 2$ liquid

$\Gamma \geq 178$ crystalline phases

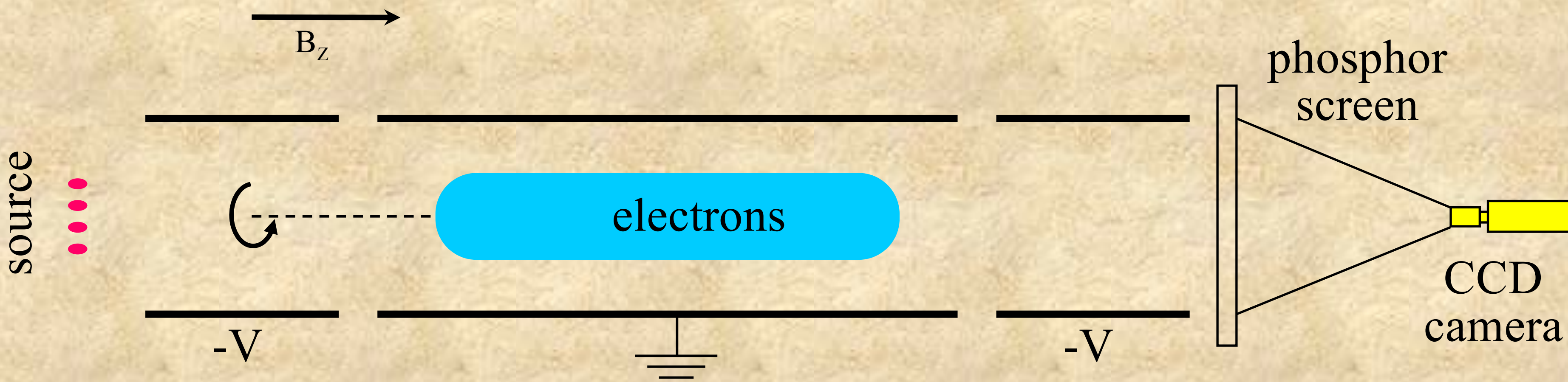
Examples of Emerging Physics with Single Component Plasmas

2D fluid dynamics

Exploiting crystalline order

Antimatter confinement and antihydrogen

Studying 2D Ideal Fluid Flows with Electron Plasmas



$$\Omega_c >> \omega_{bounce} >> \omega_{drift}$$

2D E x B drift flow ⟷ 2D Euler (inviscid fluid) flow

drift velocity	⟷	fluid velocity
electric potential	⟷	stream function
electron density	⟷	**vorticity**

Can image vorticity directly, extremely low viscosity (R > 10^5), and high shot-to-shot reproducibility.

C. F. Driscoll et al.

Examples of quasi-2D fluids

Electron plasma experimental results may be relevant to other related systems (natural and man-made) that follow quasi-2D fluid dynamics.

Geophysical fluids

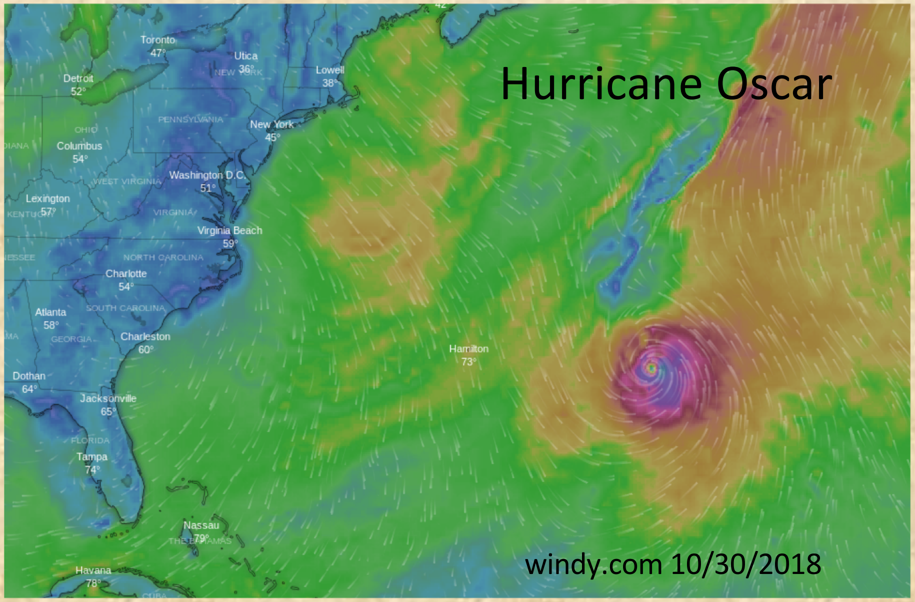
Atmospheres & oceans of Earth and other planets.

Astrophysical disks

Galaxies, accretion disks, etc.

Other magnetized plasmas

For example, toroidal fusion plasmas.



Non-2D & non-ideal effects: Density gradients, thermal forcing, rotation, topography

Free Vortex Relaxation in Electron Plasmas

Examples:

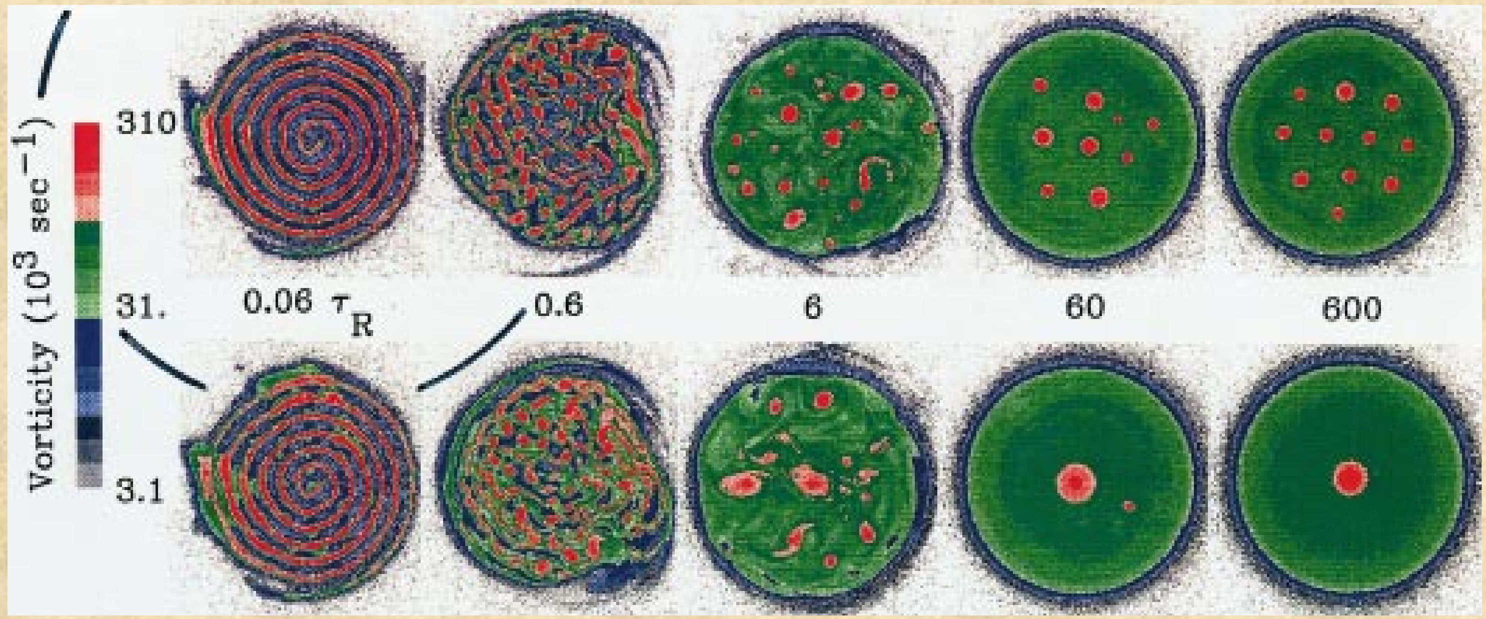
* Vortex merger

* Vortex crystals

* Turbulent cascades

* Vortex axisymmetrization

* Kelvin-Helmholtz instability

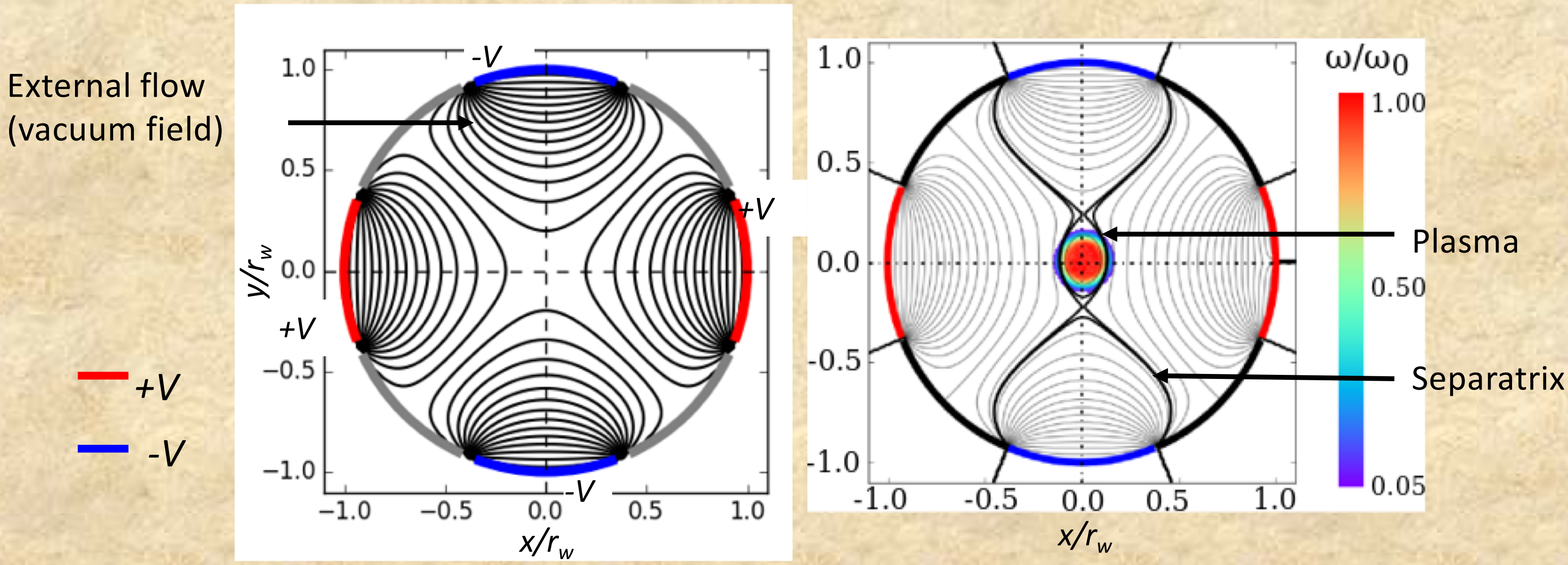


K. Fine, et al., PRL (1995)

Vortex Dynamics in External Strain Flows

$$\text{strain } \varepsilon = \frac{1}{2}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) \propto \text{applied voltage}$$

Simple strain flow with quadrupolar boundary conditions



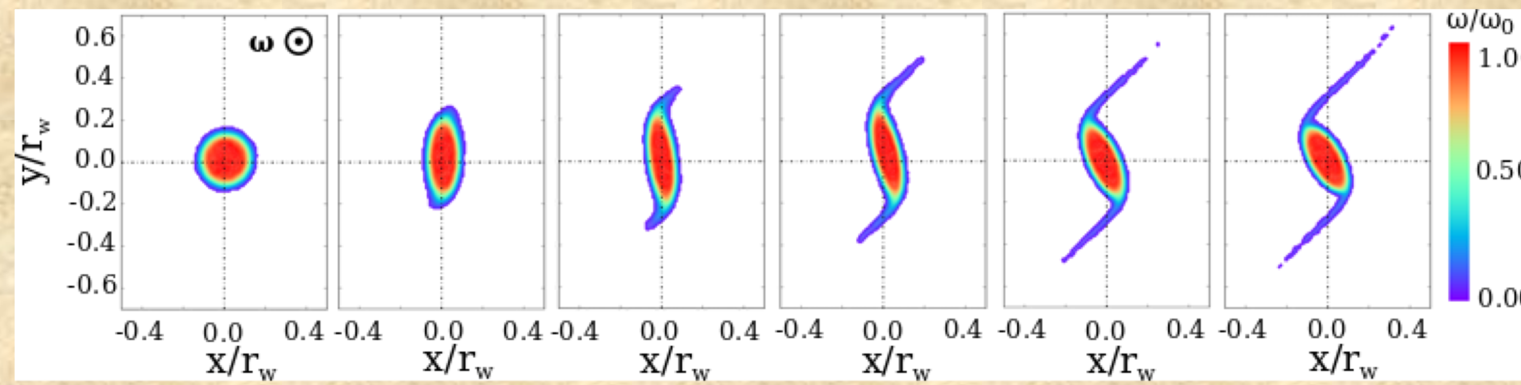
Diagnose e⁻ density (vorticity) with phosphor screen + CCD camera (right panel).

Solve Poisson equation numerically to find potential (stream function).

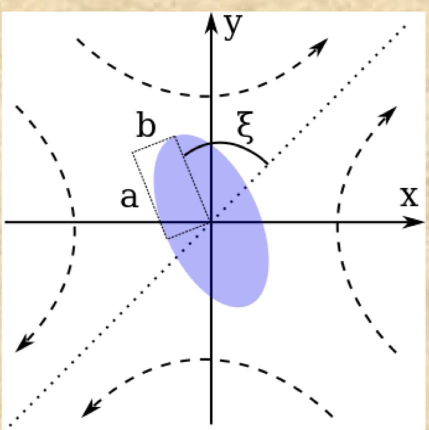
N. C. Hurst, et al., PRL (2016); JFM (2018)

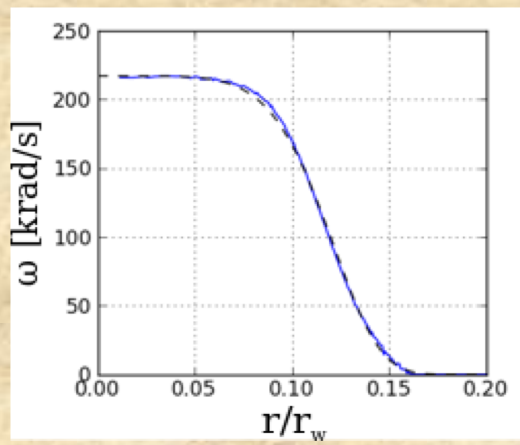
Electron Plasma Vortex Subject to Constant Strain

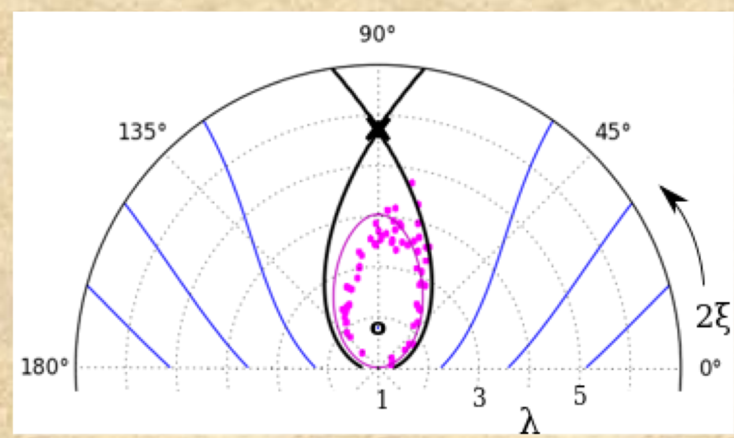
$\varepsilon^* = 0.116$



Flat-top Vortex







$\boldsymbol{\lambda}$ = a / b = aspect ratio

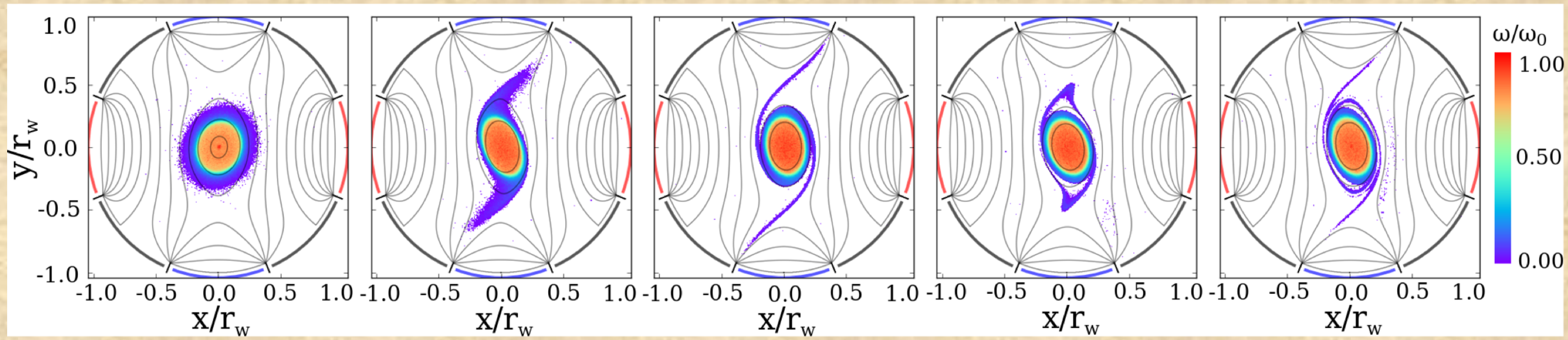
$\boldsymbol{\xi}$ = orientation

$\varepsilon^* = \varepsilon/\omega_0$ = strain to vorticity ratio

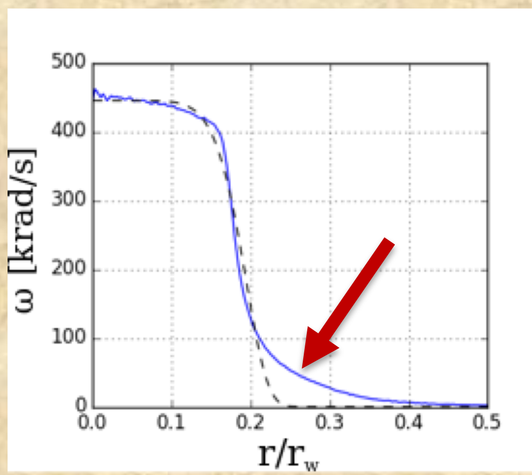
N. C. Hurst, et al.
Kida, JPSJ (1981)

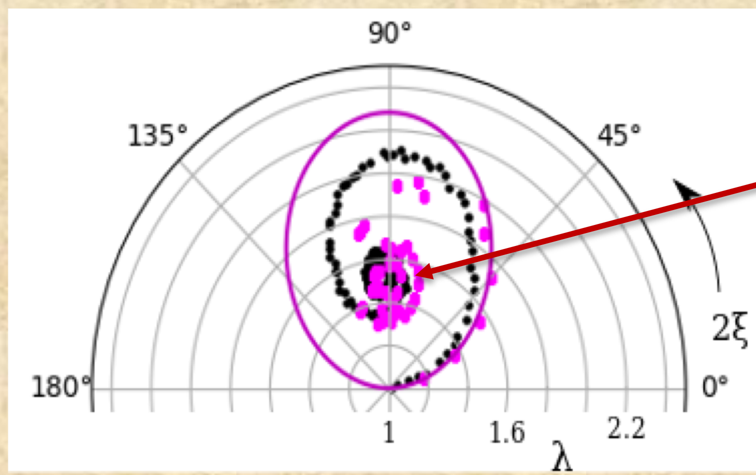
Collisionless Damping Due to Tail of the Vorticity Profile

$\varepsilon^* = 0.09$



Tail of Vorticity





Decay to a fixed point

N. C. Hurst, et al., PRL (2016); JFM (2018)

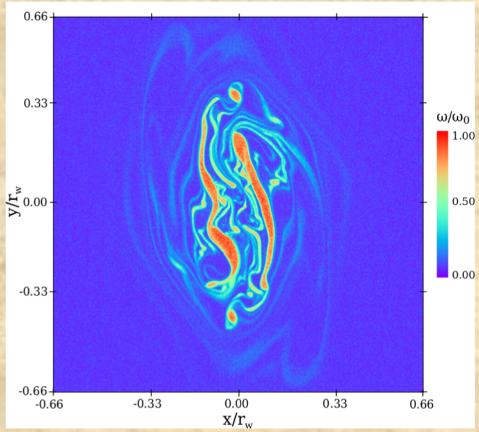
Future Electron Vortex Research

Studies of realistic vorticity profiles – filaments and damping

Study the transition from adiabatic to non-adiabatic behavior

Introduce 3D effects

Vortices in turbulent flows



6 cycles of
harmonic strain on an
axisymmetric vortex

Single Component Plasmas in the Strong Correlation Regime

$$\Gamma >> 1$$

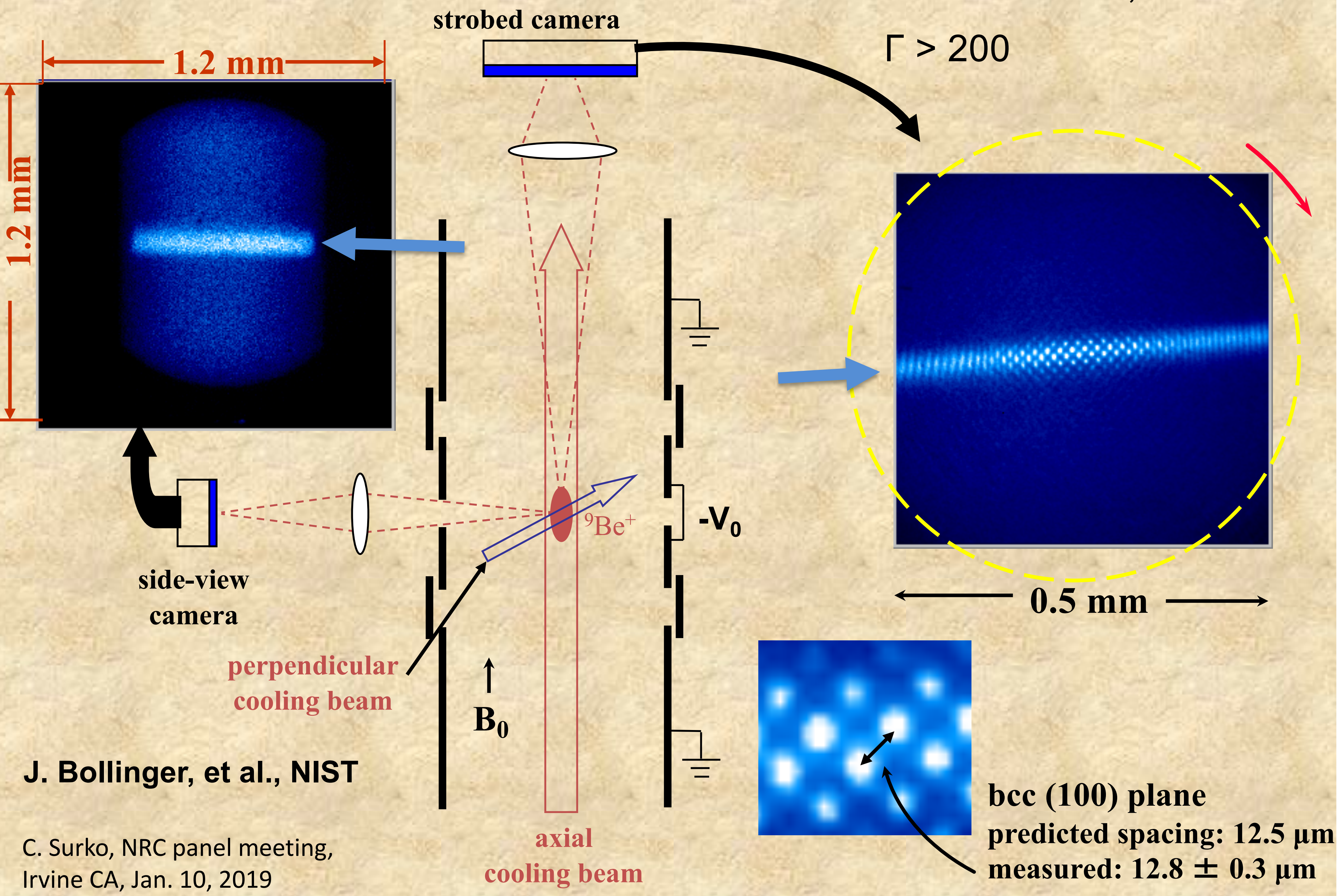
C. Surko, NRC panel meeting, Irvine CA, Jan. 10, 2019

Ion Crystals

1.8×10^5 Be^+ ions

$n = 4 \times 10^8$ cm^{-3}, **T< 10mK**

$\Gamma > 200$



J. Bollinger, et al., NIST

C. Surko, NRC panel meeting,
Irvine CA, Jan. 10, 2019

Applications of Strongly Correlated Single-Component Ion Plasmas, $\Gamma >> 1$

Quantum Simulation and Quantum Sensing**

- Large number of qubits
- Control system normal modes that couple the spin degrees of freedom

Probing Salpeter-like (fusion) enhancements*

$$R \propto e^{\Gamma}$$

- Used $v_{\parallel}$ to $v_{\perp}$ equilibration in a magnetized plasma. Tested scaling over a factor 10^9!

Transport in $\Gamma >> 1$ plasmas

* D. Dubin (2008), F. Anderegg et al.

** J. Bollinger et al. (preprint)

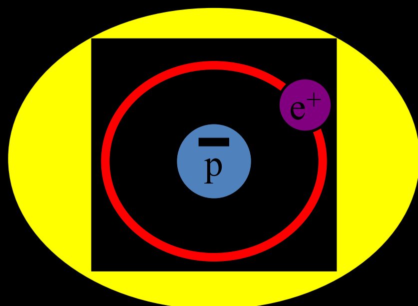
Antimatter and the Plasma Connection

If you want to keep antimatter around, keep it away from matter

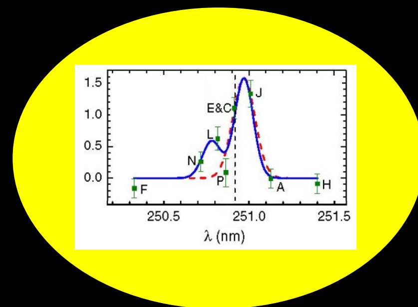
So store particles in a **single-component plasma**

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

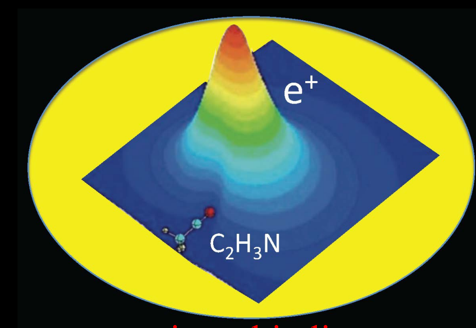
Antimatter - Exploiting the Plasma Connection



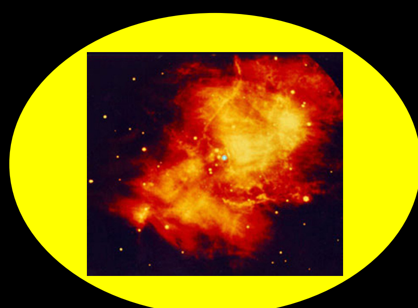
antihydrogen



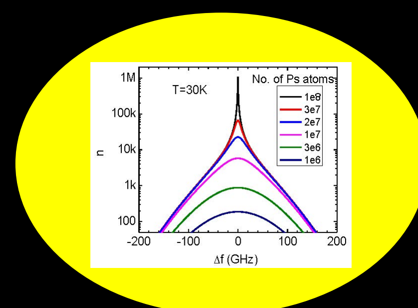
positronium physics (Ps, Ps_2)



positron binding to matter



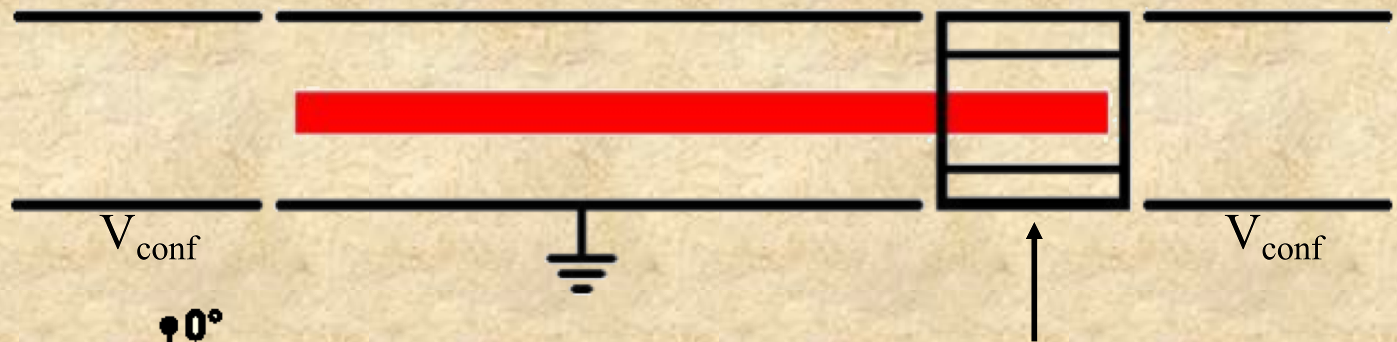
e^+- e^- (pair) plasmas



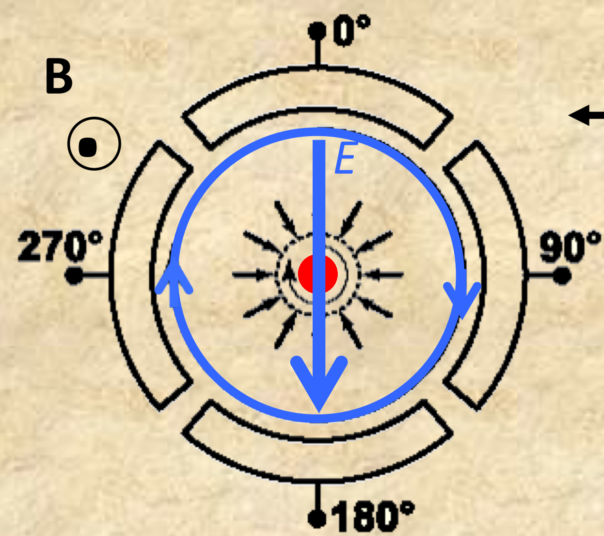
Ps-atom BEC

Increase and Control Density by Radial Compression with Rotating Electric Fields

"The Rotating Wall Technique"



segmented electrode



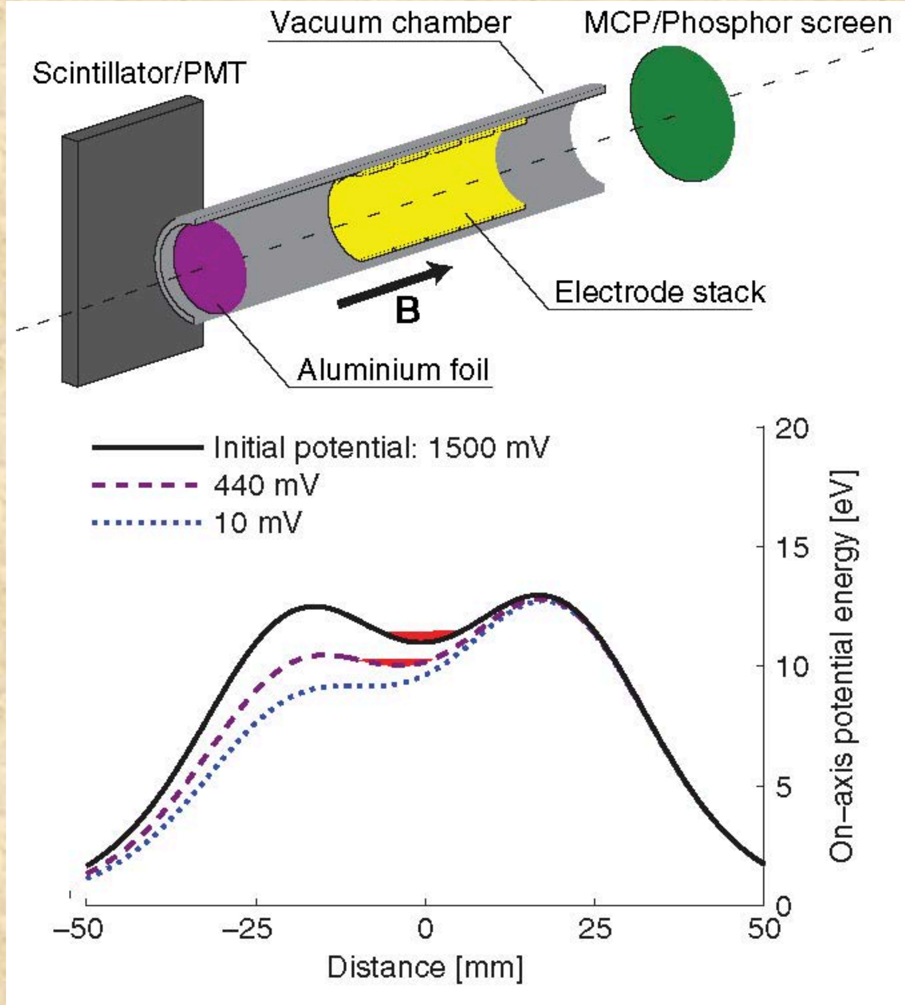
$V = \mathbf{V_{RW}} \cos[(2\pi \boldsymbol{f}_{\mathbf{RW}})\, t + \phi]$

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

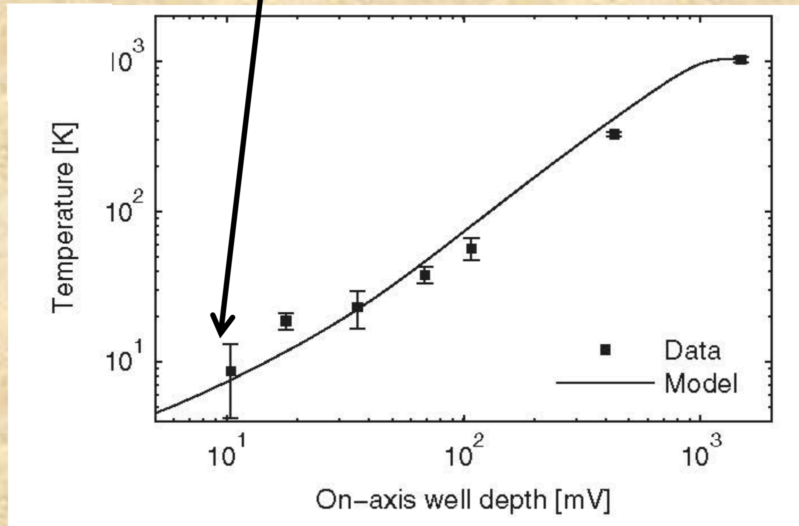
Strong drive: $f_E \to f_{RW}$

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

Evaporative Cooling (of Antiprotons)



9 K (but > 90 % loss)

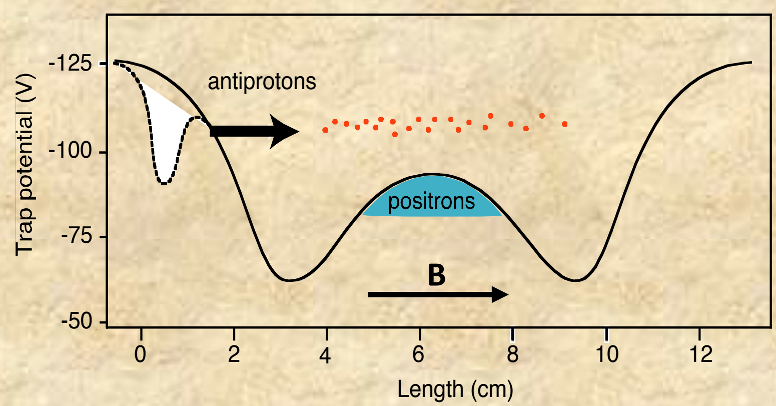


ALPHA; Andresen et al., PRL 2010

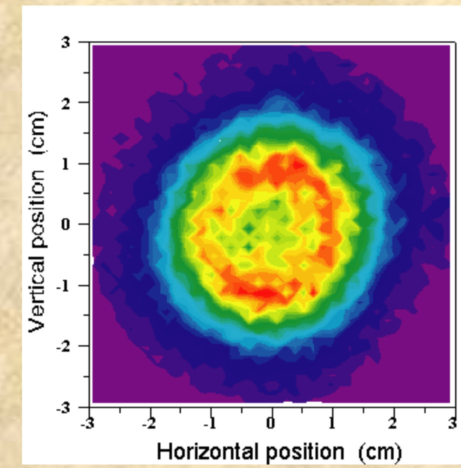
Antihydrogen Production

(one scenario)

Nested Penning traps



p, e^+ plasmas trapped, cooled, RW-compressed



~ 10^8 positrons

Launch ~ 10^4 antiprotons into mixing region

Mixing time 190 sec

$\bar{H}$ formed by three-body collisions: $\bar{p} + e^+ + e^+ = \bar{H} + e^+$

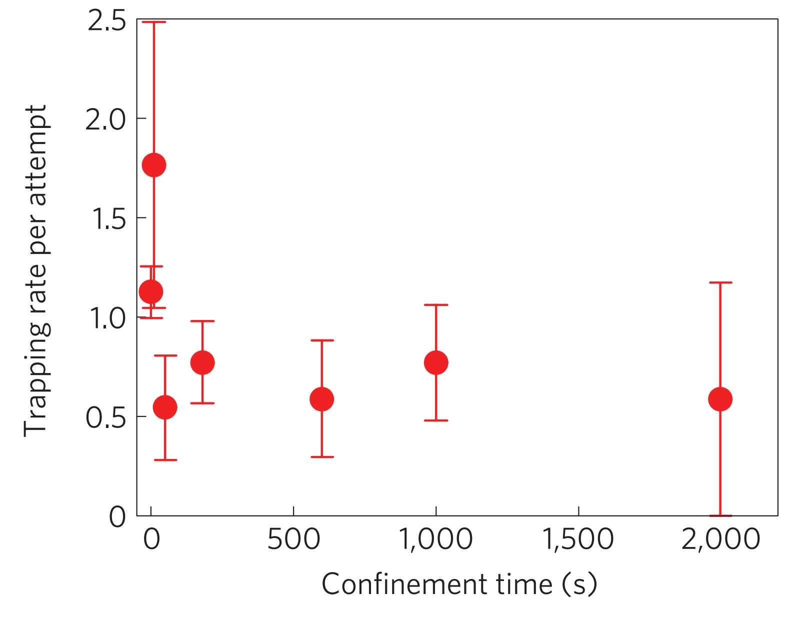
ATHENA
Amoretti et al., Nature 2002

ATRAP similar

Trapped Antihydrogen
The First Stable, Neutral Antimatter

Accumulate $\bar{H}$, then quench Ioffe trap to release.

99% reach the ground state in < 1 s



- ALPHA
- Andresen, Nature Physics (2011)

ATRAP similar, Gabrielse, PRL 2012

Example of Plasma Control
Strong Drive Regime and Evaporative Cooling

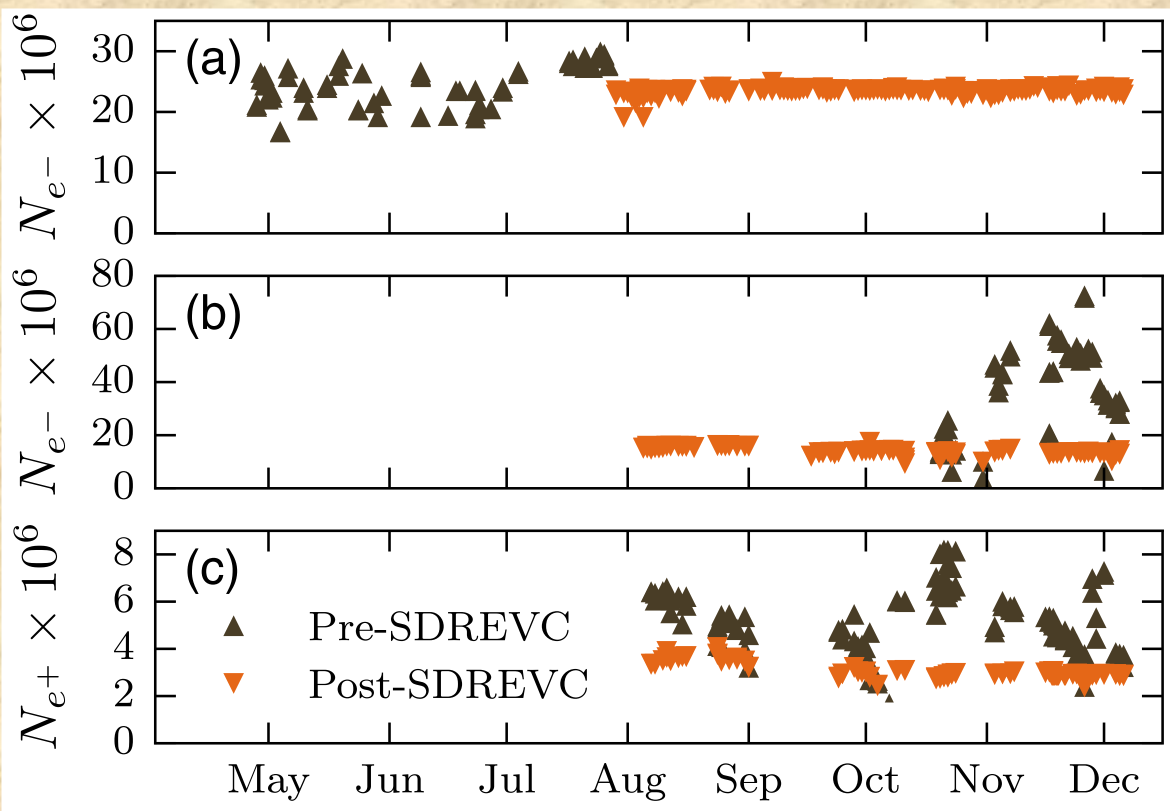
Fixes density, temperature, $r_{p,}$ and plasma potential
Results in unprecedented plasma control

Increased x > 10 rate of trappable antihydrogen production!

e^- pbar catching trap

e^- atom trap

e^+ atom trap



ALPHA collab.,
Ahmadi et al., PRL (2018)

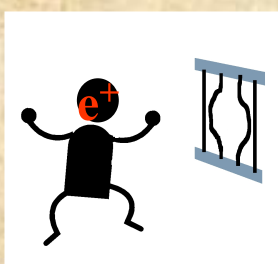
Precision Measurement of the 1S – 2S Transition in Antihydrogen

Used SDREVC to obtain fractional precision: 2×10^{-12}

ALPHA
Ahmadi, et al., *Nature* (2018)

Low-Energy Antimatter in the Laboratory
A Look to the Future

- Precision experiments with Antihydrogen
  - Tests of CPT and gravity in progress
- Positronium atom BEC
  - Higher areal density, short e^+ pulses, cold Ps
- Classical pair plasmas
  - Levitated magnetic dipole and a multicell positron trap
- Portable antimatter traps
  - Advances in multicell traps and magnet technology




Nonneutral Plasma studies are one example of Small-Scale, Basic Plasma Research.

There are also many other small-scale basic plasma research opportunities to create new knowledge and train new scientific leaders for tomorrow.