Experiments with nonneutral plasmas

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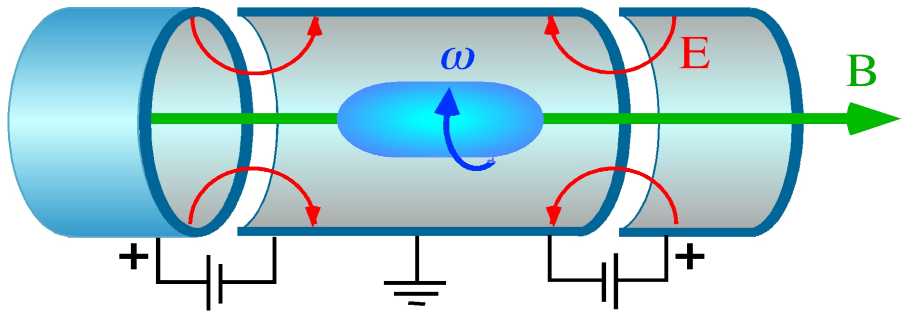
Malmberg-Pennning Trap



Confined thermal equilibrium

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

Potential well in rotating frame

$$e\varphi_{rot}(r,z) = e\varphi_{trap}(r,z) - m\omega^2 r^2/2 + \underbrace{\int_0^r eB(\overbrace{v_\vartheta(r)}^{\omega r}/c)dr}_{eB\omega r^2/2c}$$

Long lived quiescent confinement

Imaginary cylinder of uniform neutralizing negative charge

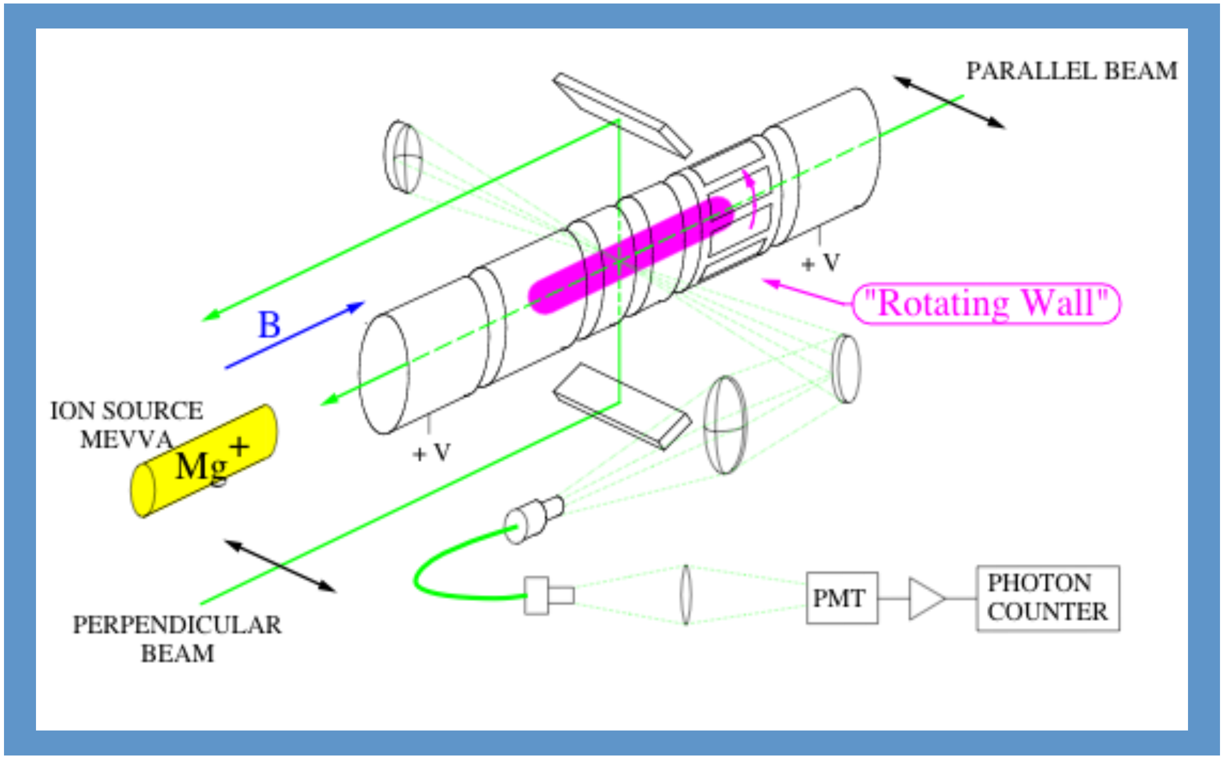
$$e\varphi_{rot}(r,z) = e\varphi_{trap}(r,z) + m\omega(\underbrace{\Omega_c}_{eB/mc} - \omega)r^2/2$$

The plasma matches its density to the density of the imaginary neutralizing negative charge out to some surface of revolution where the supply of plasma charges is exhausted, and there the plasma density drops off on scale of Debye length.

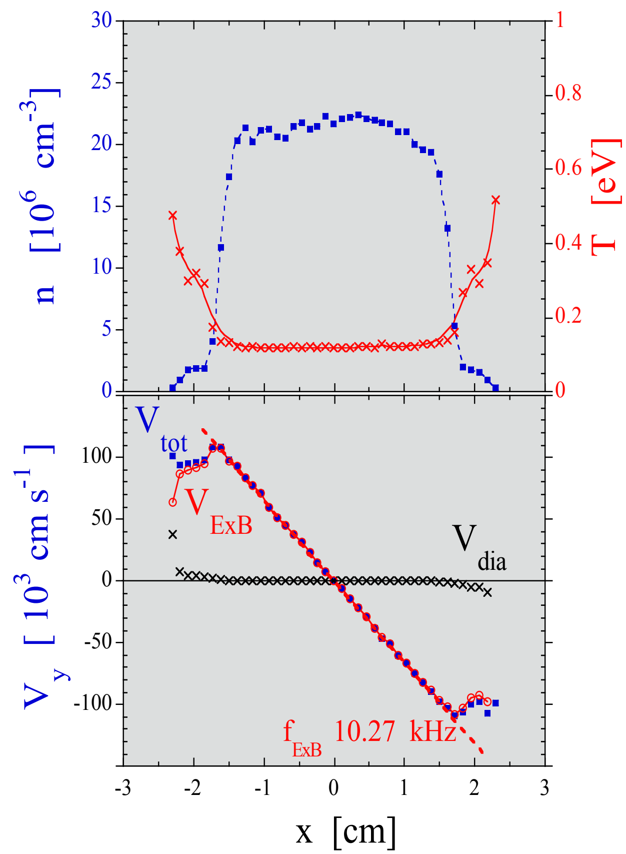
Signatures of thermal equilibrium:

- density = constant
- temperature = constant
- rotation frequency = constant

UCSD ion trap



18 hours old plasma



Relax to near-thermal equilibrium

F. Anderegg and C.F. Driscoll

Microscopic order

The Gibbs distribution for the magnetically confined plasma is the same as that for a plasma confined by a uniform cylinder of neutralizing negative charge.

Thus, the magnetically confined plasma is a simple laboratory realization of a well known theoretical model: the one component plasma (a system of classical point charges embedded in a uniform neutralizing background charge). The OCP was studied as a model for high density matter (e.g., degenerate star).

For an infinite homogeneous OCP, the correlation properties are determined by the coupling parameter: $\Gamma = e^2/akT$, where $4\pi a^3 n/3 = 1$.

$\Gamma << 1$ weakly correlated plasma

$\Gamma = 2$ liquid

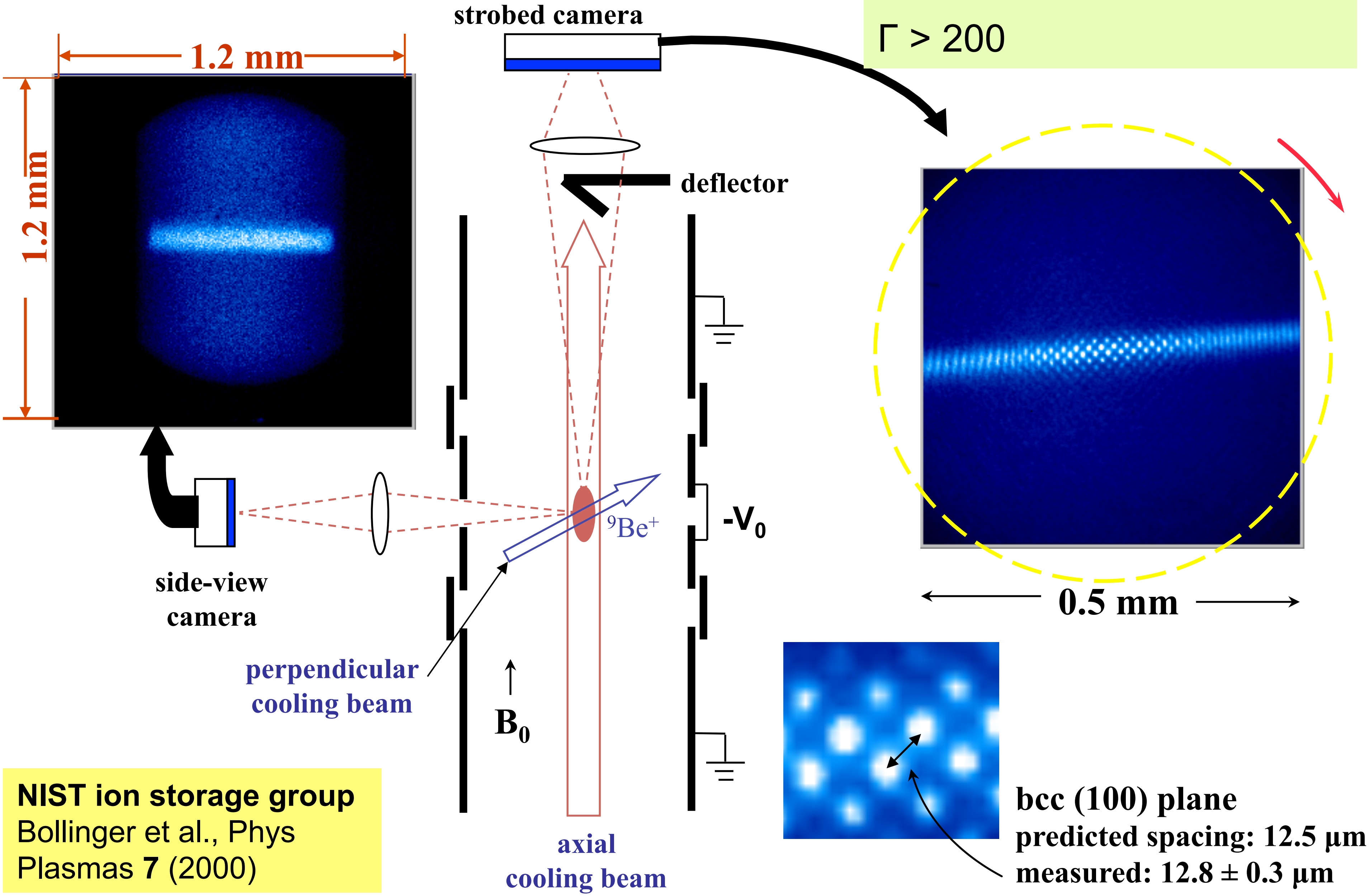
$\Gamma = 178$ bcc crystal

bcc crystal observations

1.8×10^5 Be^+ ions

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

$\Gamma > 200$



NIST ion storage group
Bollinger et al., Phys Plasmas **7** (2000)

Modeling fusion in dense matter

Salpeter enhancement factor for the thermonuclear fusion rate:

$$R_{fusion} = R_0 e^{\Gamma}.$$

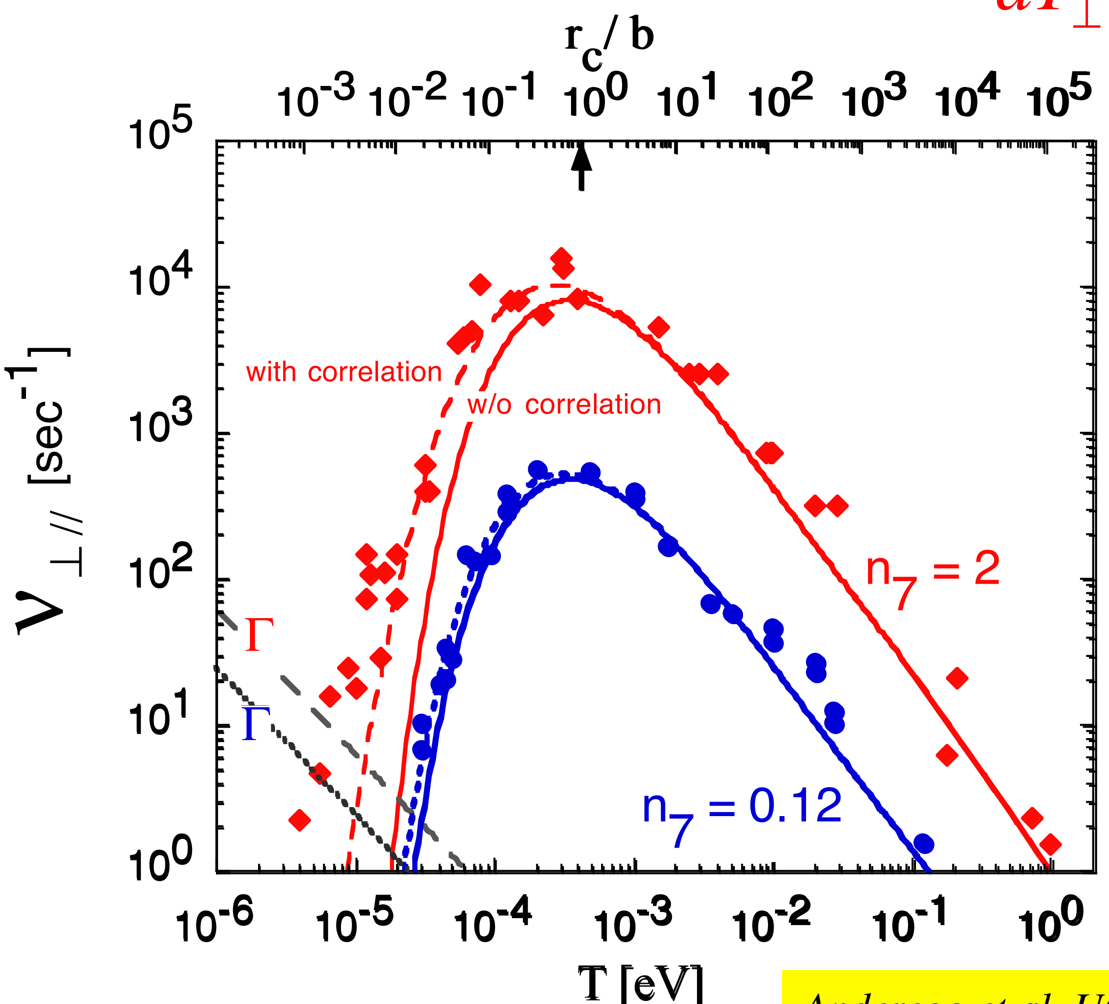
For a strongly magnetized plasma ($r_c << b = e^2/kT$) the cyclotron action is an adiabatic invariant that is broken only by close energetic collisions; there is an analogy to fusion, where nuclear energy is released only by close energetic collisions.

Dubin (Phys. Rev. Lett., 2005) showed that the analogy is quantitative:

$$\nu_{\perp||} = (\nu_{\perp||})_0 e^{\Gamma}, \text{ where } dT_\perp / dt = \nu_{\perp||}(T_{||} - T_\perp).$$

Measured collisional equipartition rate in a pure ion plasma

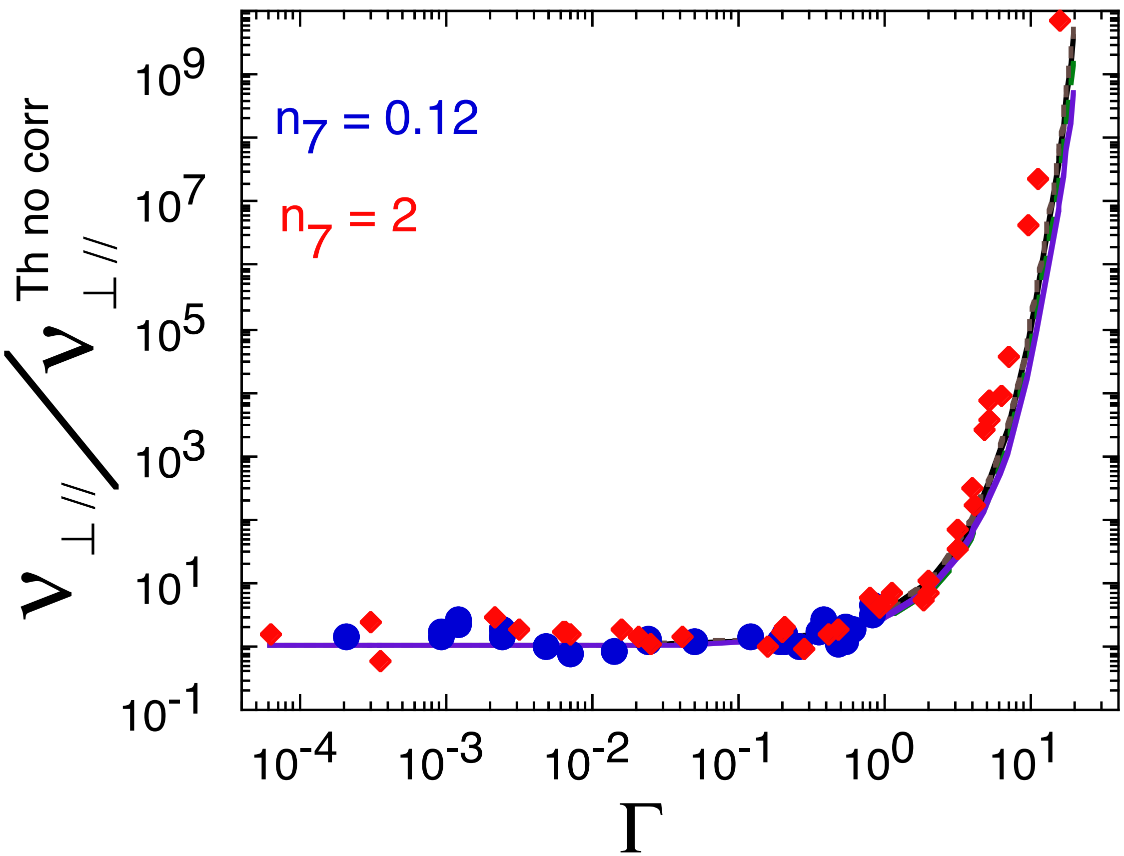
$$dT_\perp / dt = \nu_{\perp\|}(T_\| - T_\perp)$$



B = 3 Tesla

Anderegg et al. UCSD, Phys. Rev. Lett. (2009); Phys. Plasmas (2010)

Measured enhancement factor



Theories for enhancement factor:

$$e^{\Gamma}$$

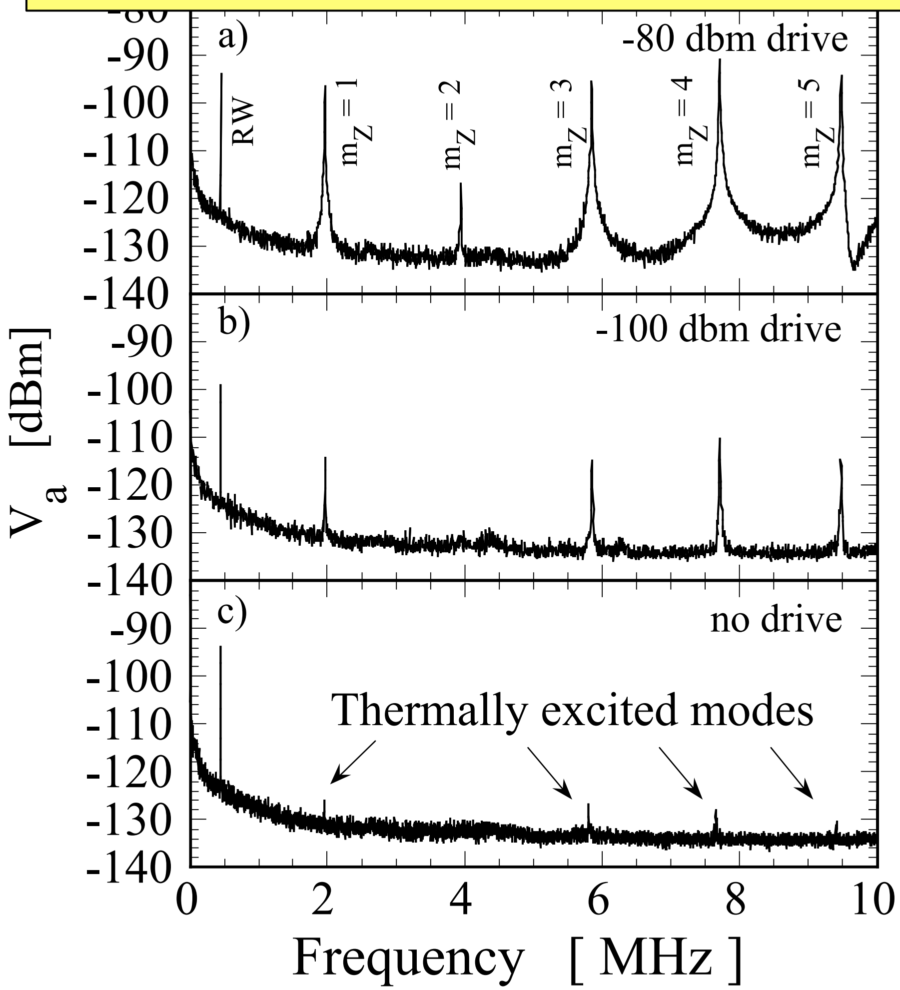
Ichimaru
Rev Mod Phys 65, 255, 1993

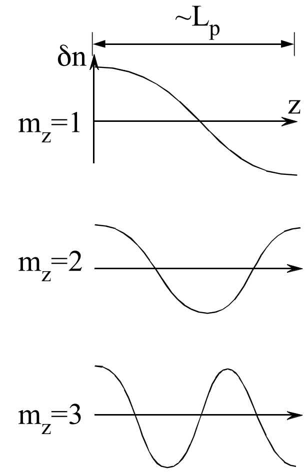
Ogata
Astrophys J 481, 883, 1997

DeWitt, Slattery
Contrib Plasma Phys 39, 97, 1999

Anderegg et al. UCSD, Phys. Rev. Lett. (2009); Phys. Plasmas (2010)

Plasma modes are easy to excite





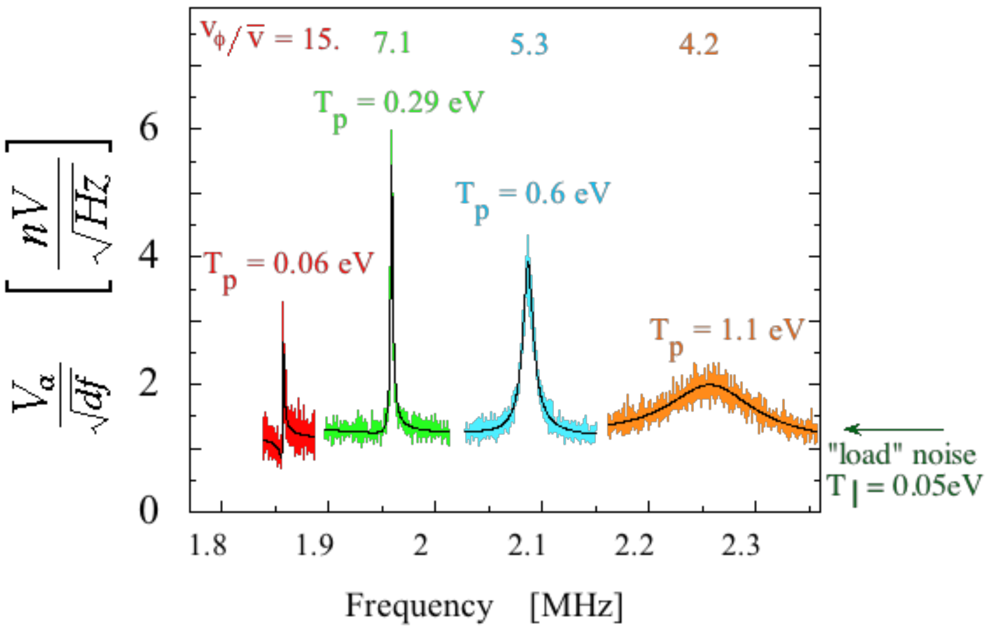
Higher m_z results in higher frequency

Plasma modes are excited at very low level by thermal fluctuations

Provide effective diagnostic tool.

F. Anderegg, N. Shiga, J.R. Danielson, D.H.E. Dubin, and C.F. Driscoll, R.W. Gould, Phys. Rev. Lett. **90**, 115001 (2003)

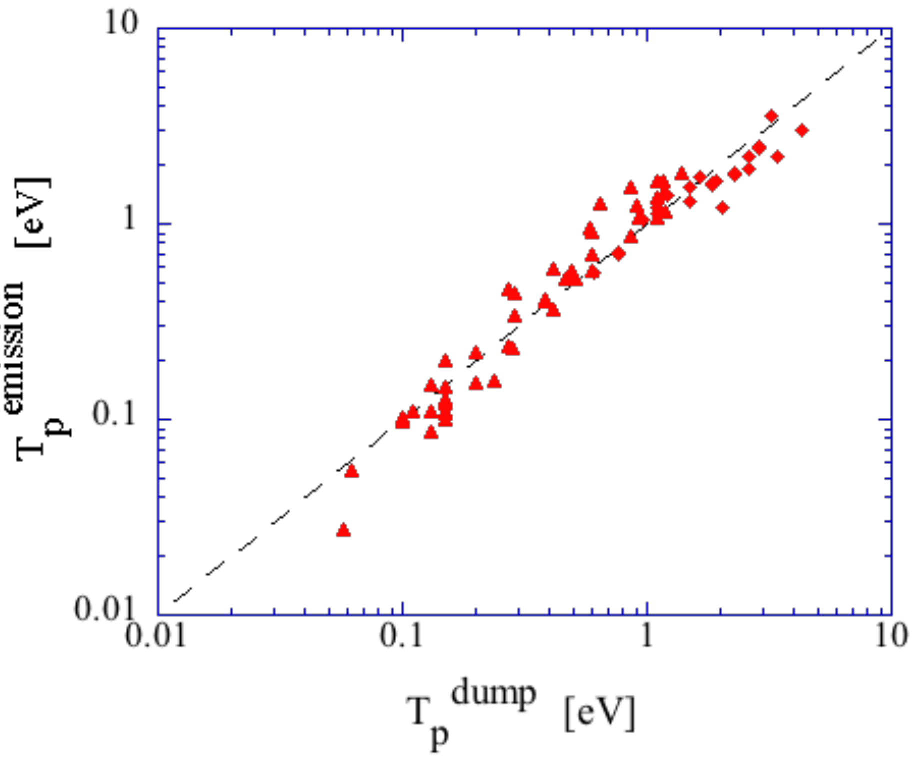
Thermally excited TG plasma modes



As the plasma temperature T_p increases:

- Mode frequency increases
- Landau damping increases and resonance width increases
- Area under the resonance curve increases

Plasma temperature from thermally excited mode

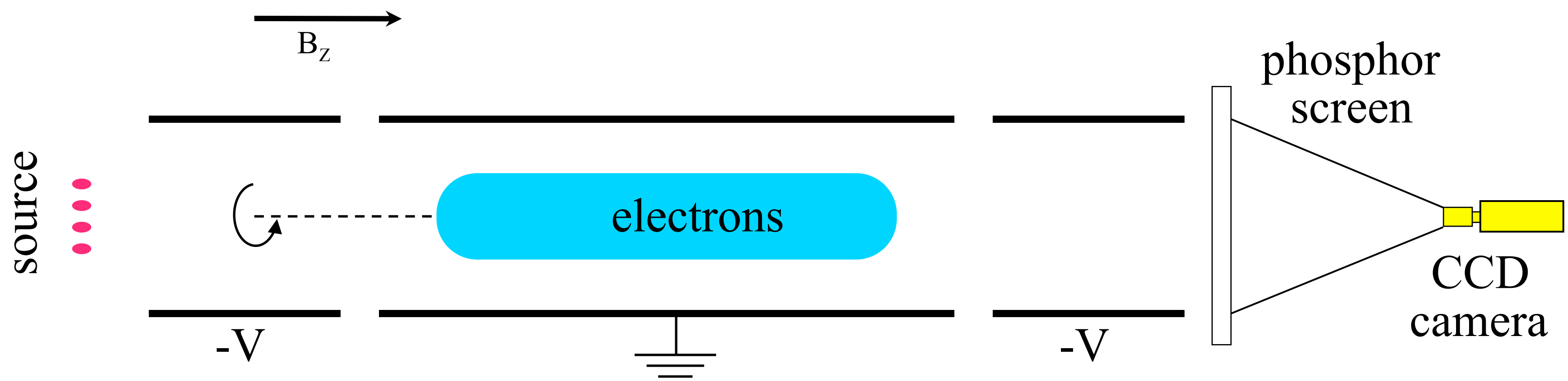


Use a room-temperature amplifier

The plasma temperature is non-destructively determined by ”listening” to plasma fluctuations.

F. Anderegg, N. Shiga, D.H.E. Dubin, and C.F. Driscoll, UCSD; and Roy Gould, Phys. Plas. 10, 1556 (2003)

Modeling 2D ideal flow with electron plasma *



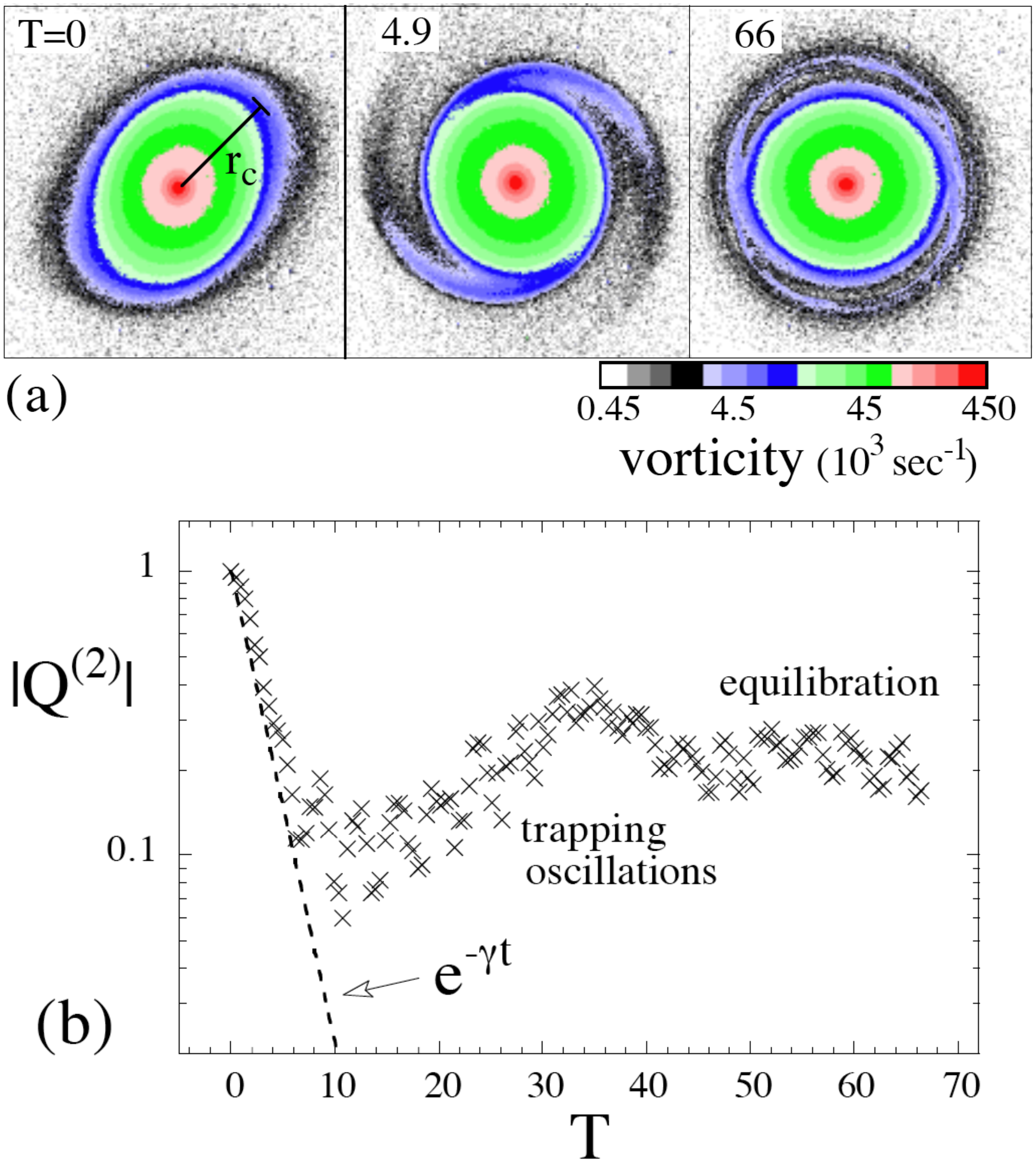
$$\Omega_c >> \omega_{bounce} >> \omega_{drift}$$

(2D ExB drift flow) ⟷ (2D Euler flow)

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

Advantages: image vorticity directly; extremely low viscosity ($R > 10^5$); no boundary layer at walls (free slip bc); and high shot to shot reproducibility.

* Driscoll et. al. UCSD

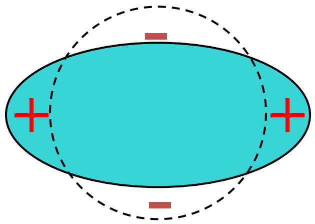


$j \sim e^{i(l\theta - \omega t)}$

Landau resonance

$\omega = l\, \omega_{drift}(r_c)$

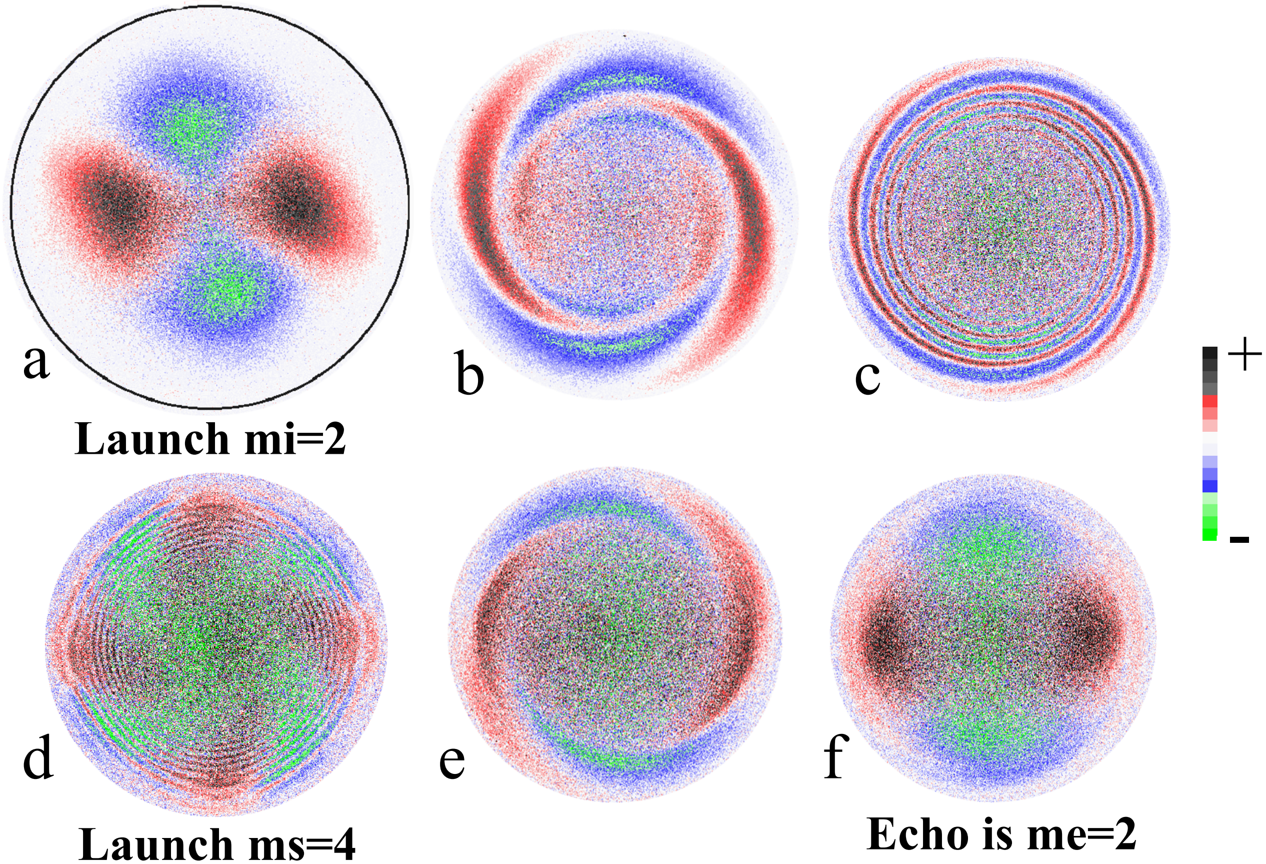
Driscoll et. al.
UCSD



$$\delta n(r,\theta,t) \equiv n(r,\theta,t) - n_o(r)$$

J. H. Yu, et. al., UCSD

Experimental
Density
Perturbation
Images



Measured Wall Signal