Nonlinear effects and anomalous transport in RF plasmas

Francis F. Chen

UCLA

2005 Workshop on Nonlocal, Collisionless Electron Transport in Plasmas
Princeton PPL, August 2-4, 2005

Selected examples

1. Anomalous skin depth in ICPs

J.D. Evans and F.F. Chen, Phys. Rev. Lett. **86**, 5502 (2001).

2. Anomalous transport in helicon discharges

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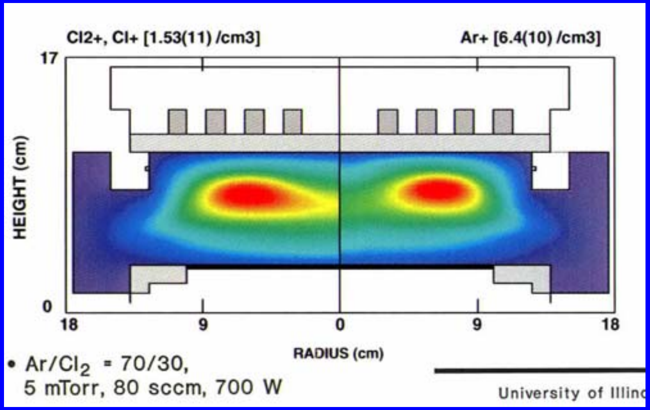
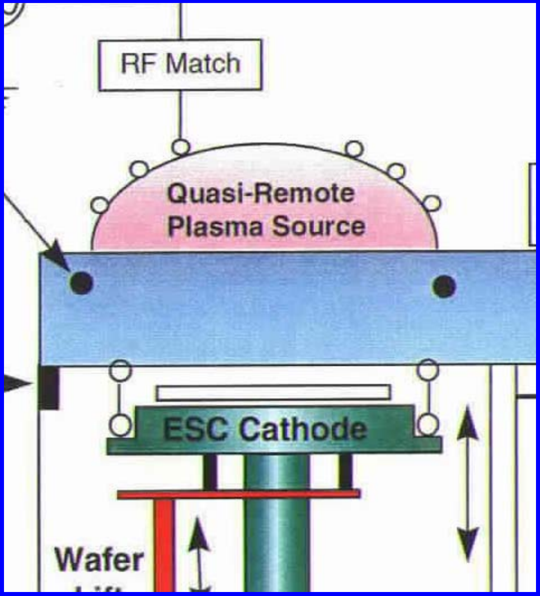
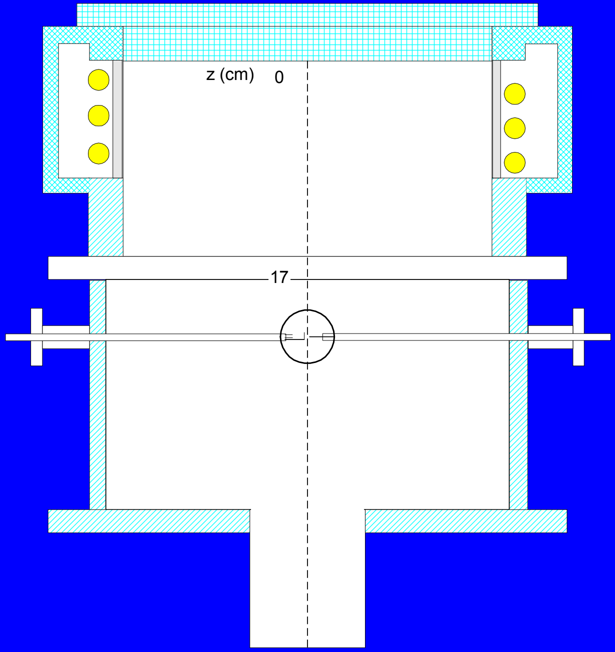
M. Krämer et al., Proc. EPS Conf. on Plasma Phys. and Control. Fusion, Montreux (2002) **26B**, O4.08.
B. Lorenz, M. Krämer, V.L. Selenin, and Yu.M. Aliev, Plasma Sources Sci. Technol. **14**, ??? (2005).

Three types of ICPs*



- Ar/Cl_2 = 70/30, 5 mTorr, 80 sccm, 700 W





*ICP = Inductively Coupled Plasma

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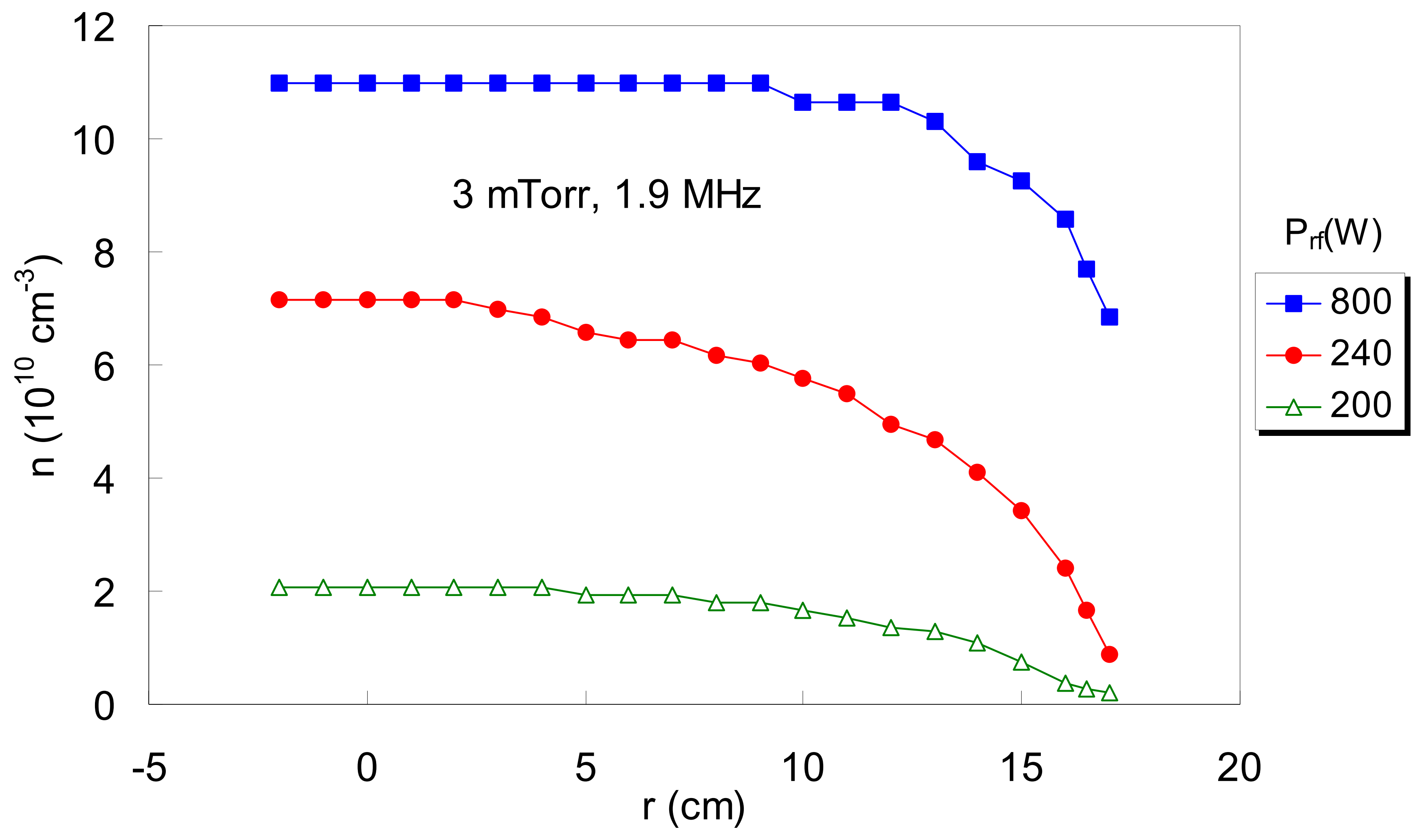
Density uniformity in a commercial ICP



Data by John Evans

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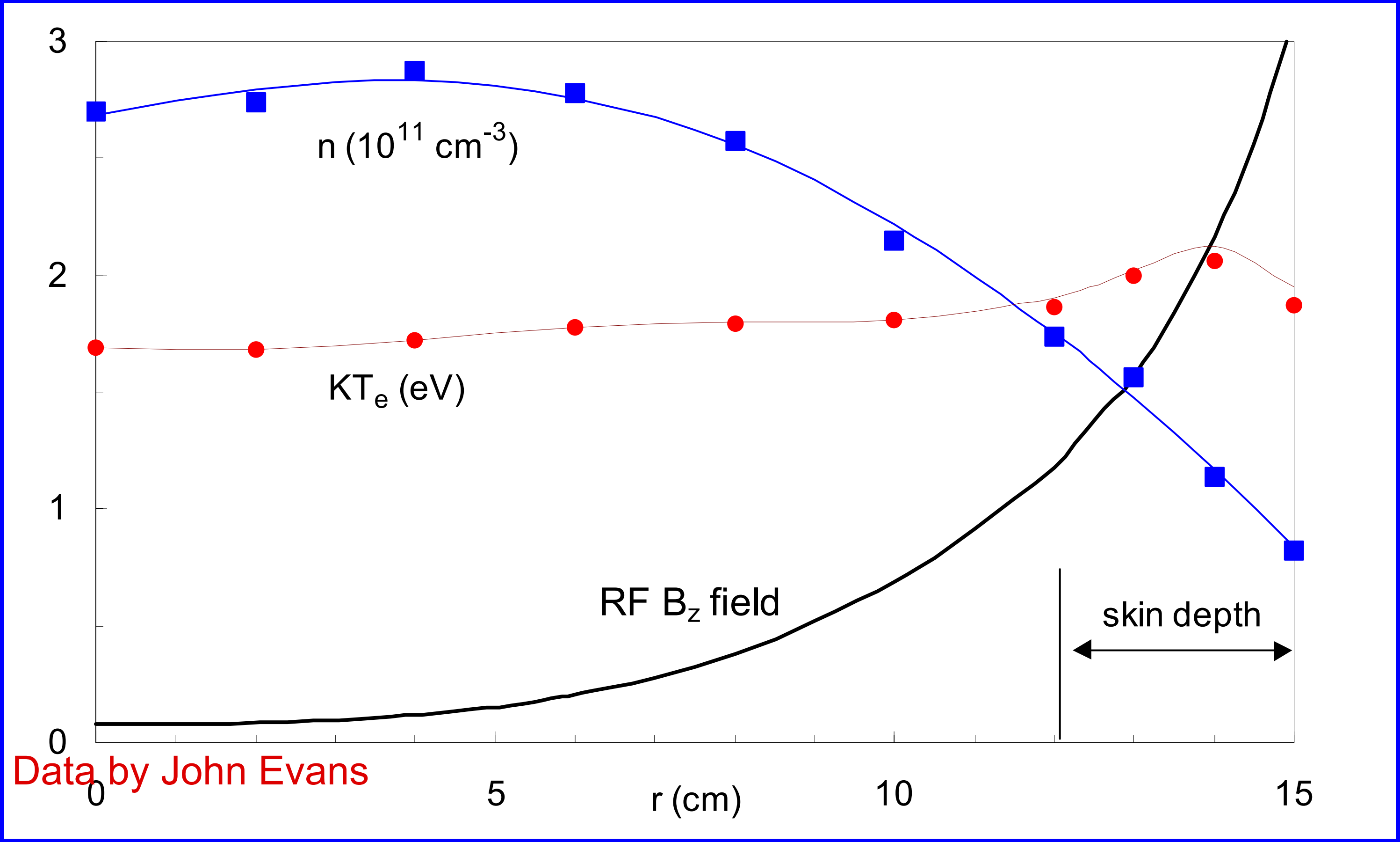
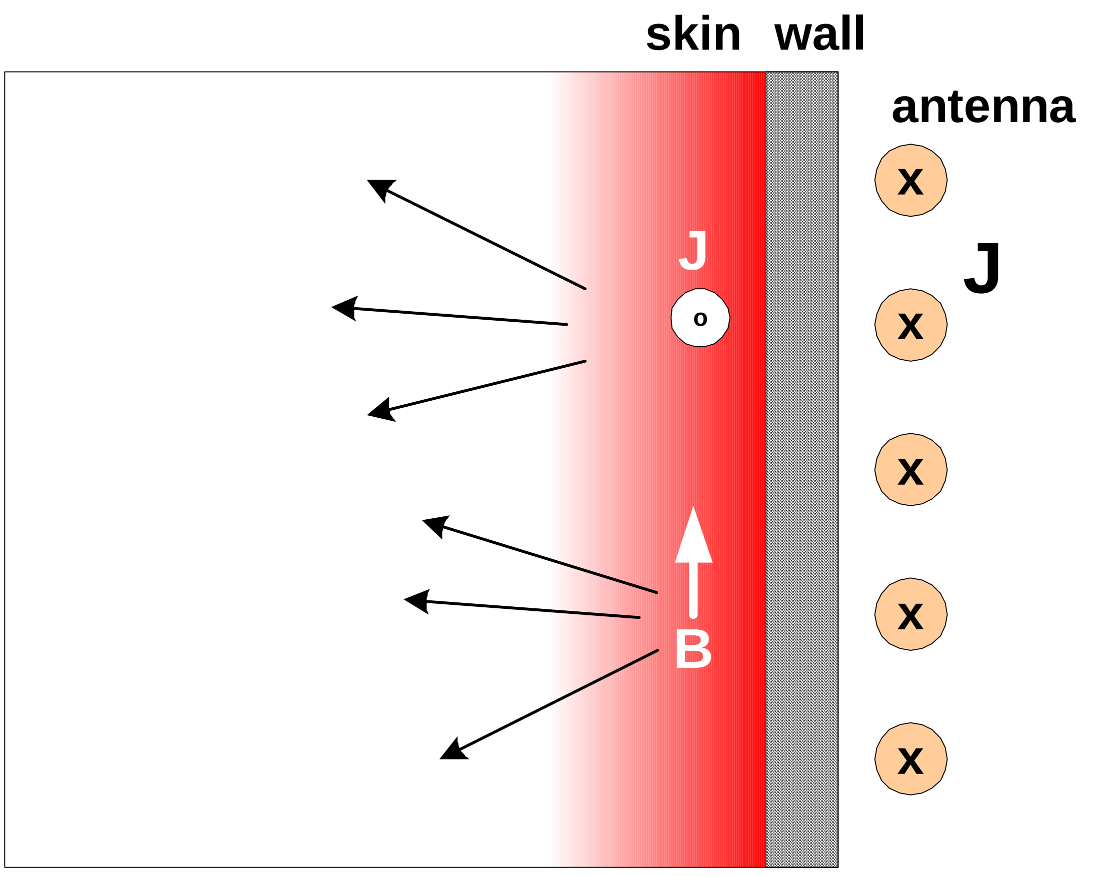
In the plane of the antenna, the density peaks well outside the classical skin layer



Data by John Evans

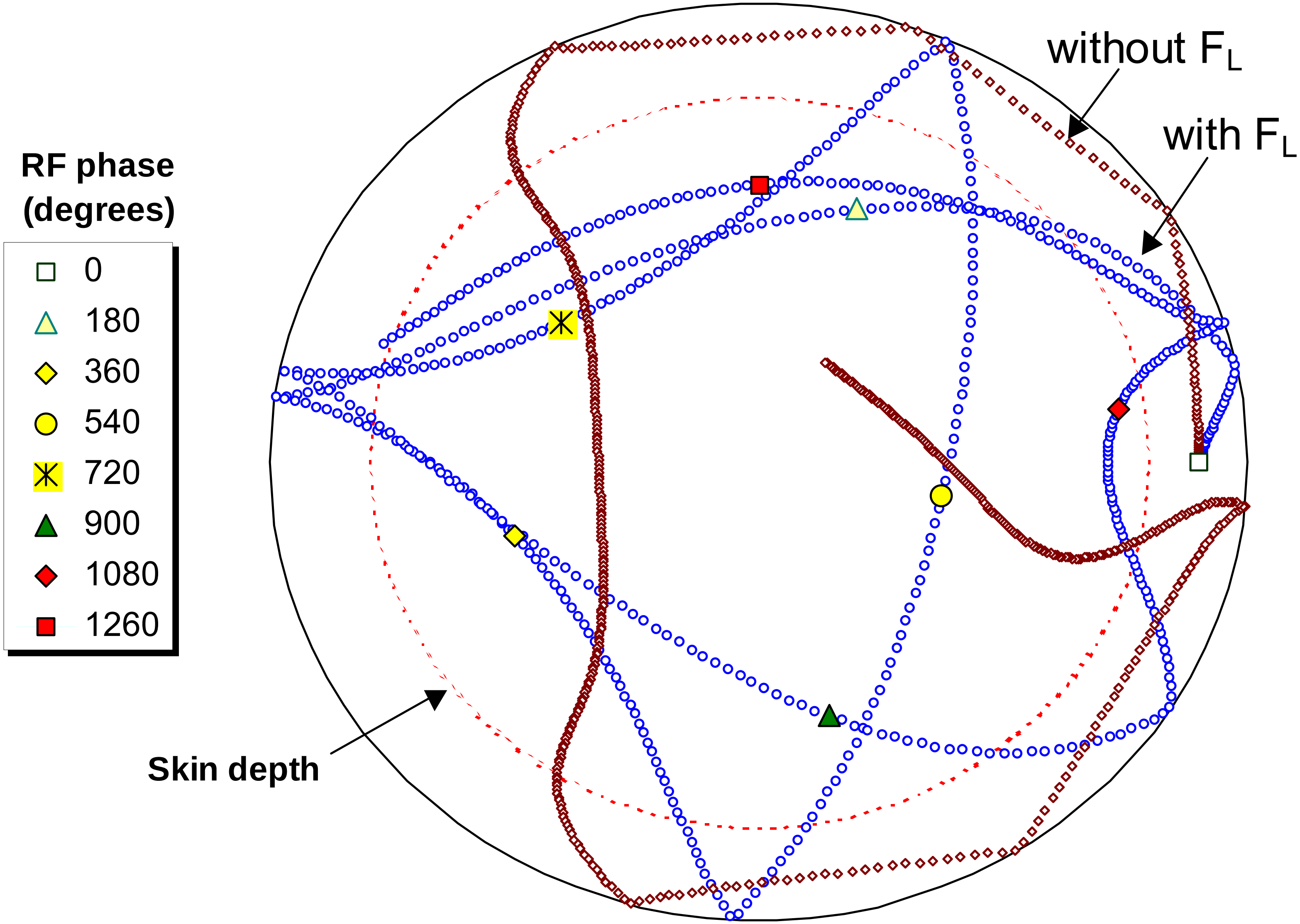
Thermal diffusion of fast electrons



Consider the nonlinear effect of the Lorentz force on the motion of an electron in an RF field E_θ

$$m\frac{d\mathbf{v}}{dt} = -e\left(\tilde{\mathbf{E}} + \underset{\substack{\nearrow \\ \mathbf{F}_L}}{\mathbf{v}\times\tilde{\mathbf{B}}}\right)$$

An electron trajectory over four RF cycles with and without the Lorentz force F_L



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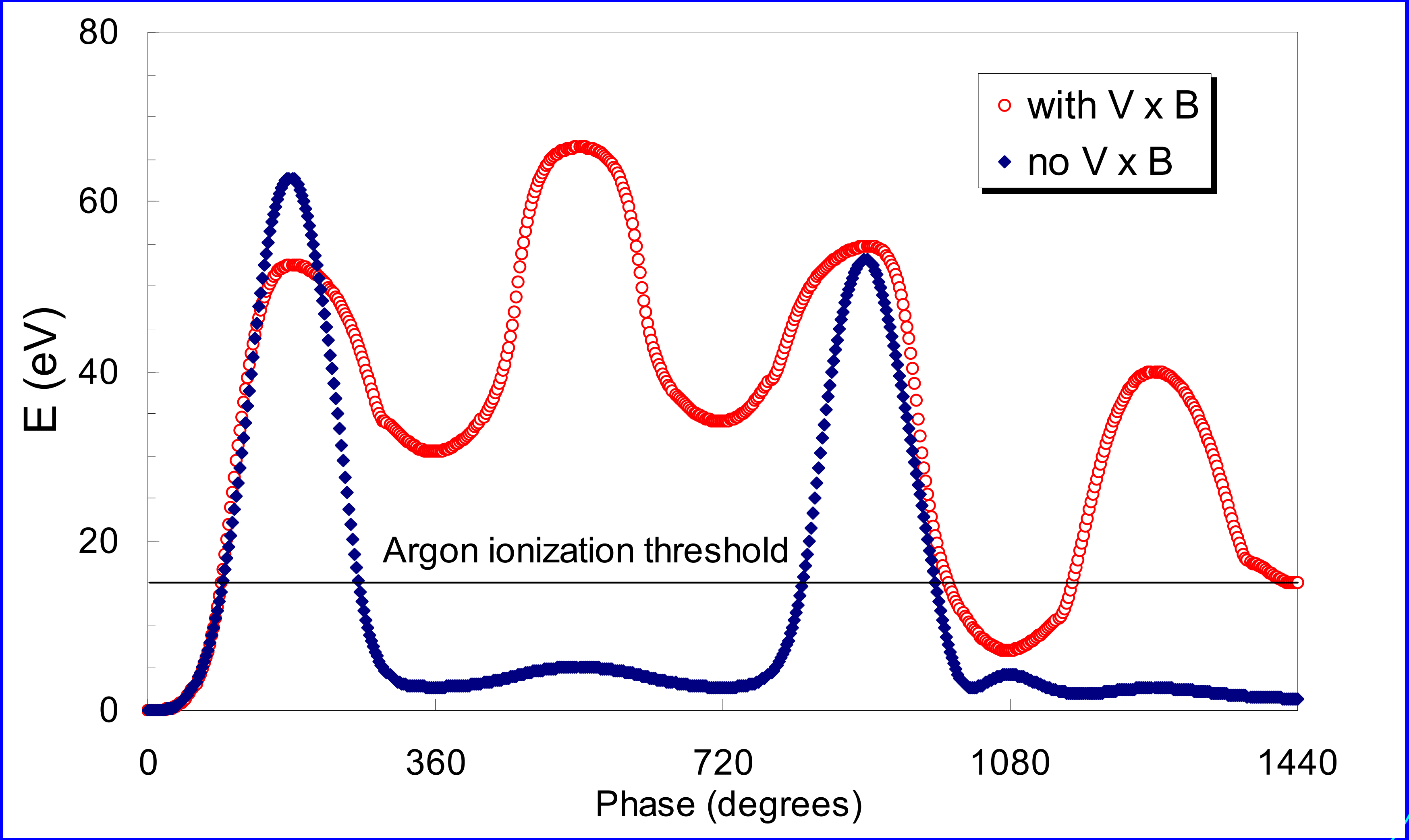
The electron's energy is large only inside the skin, if the Lorentz force is neglected



The effect of the Lorentz force is to push the electrons in the radial direction, causing them to bounce off the wall at a steep angle, so that they reach the central region before losing their energy in the next half cycle.

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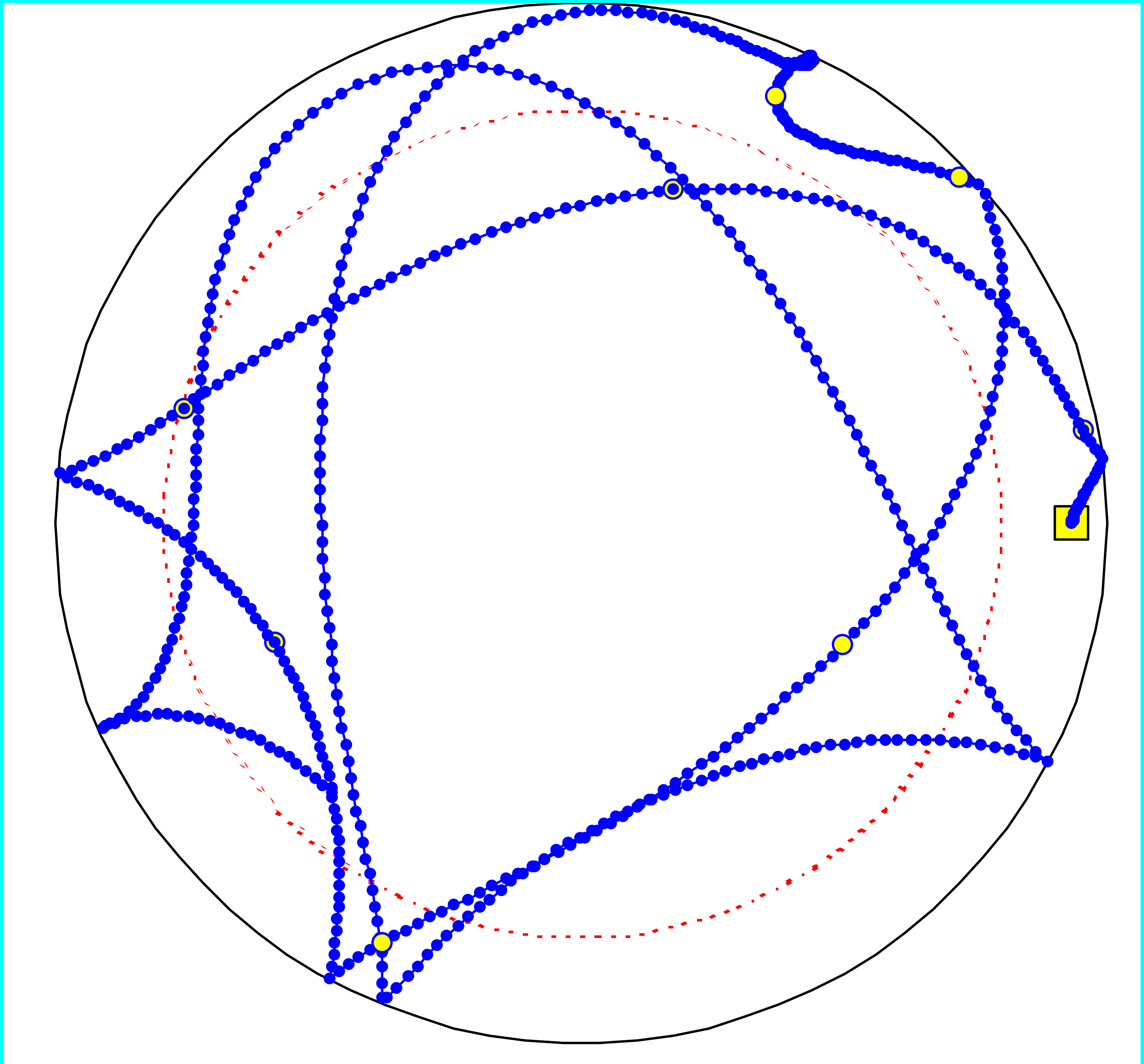

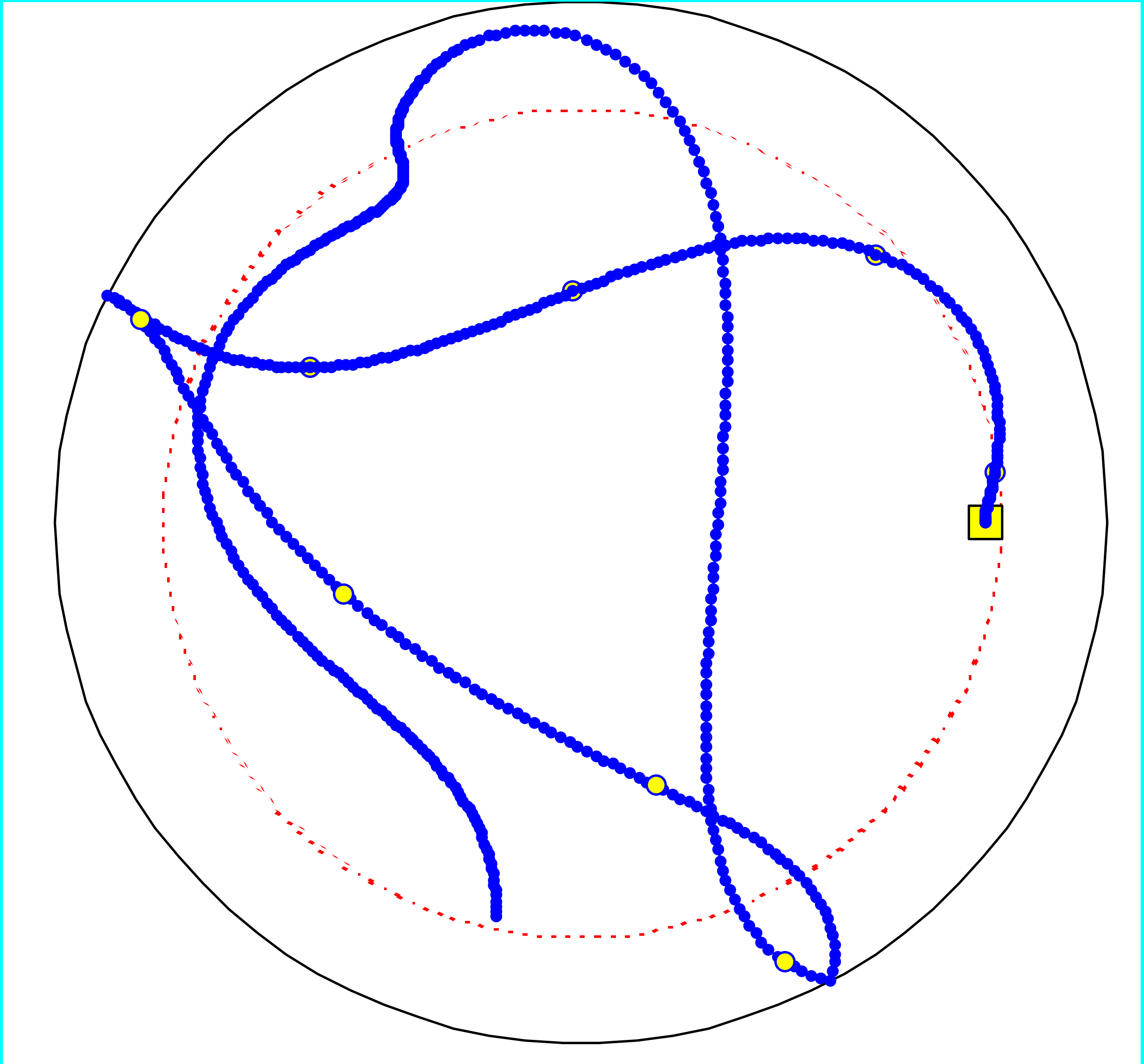

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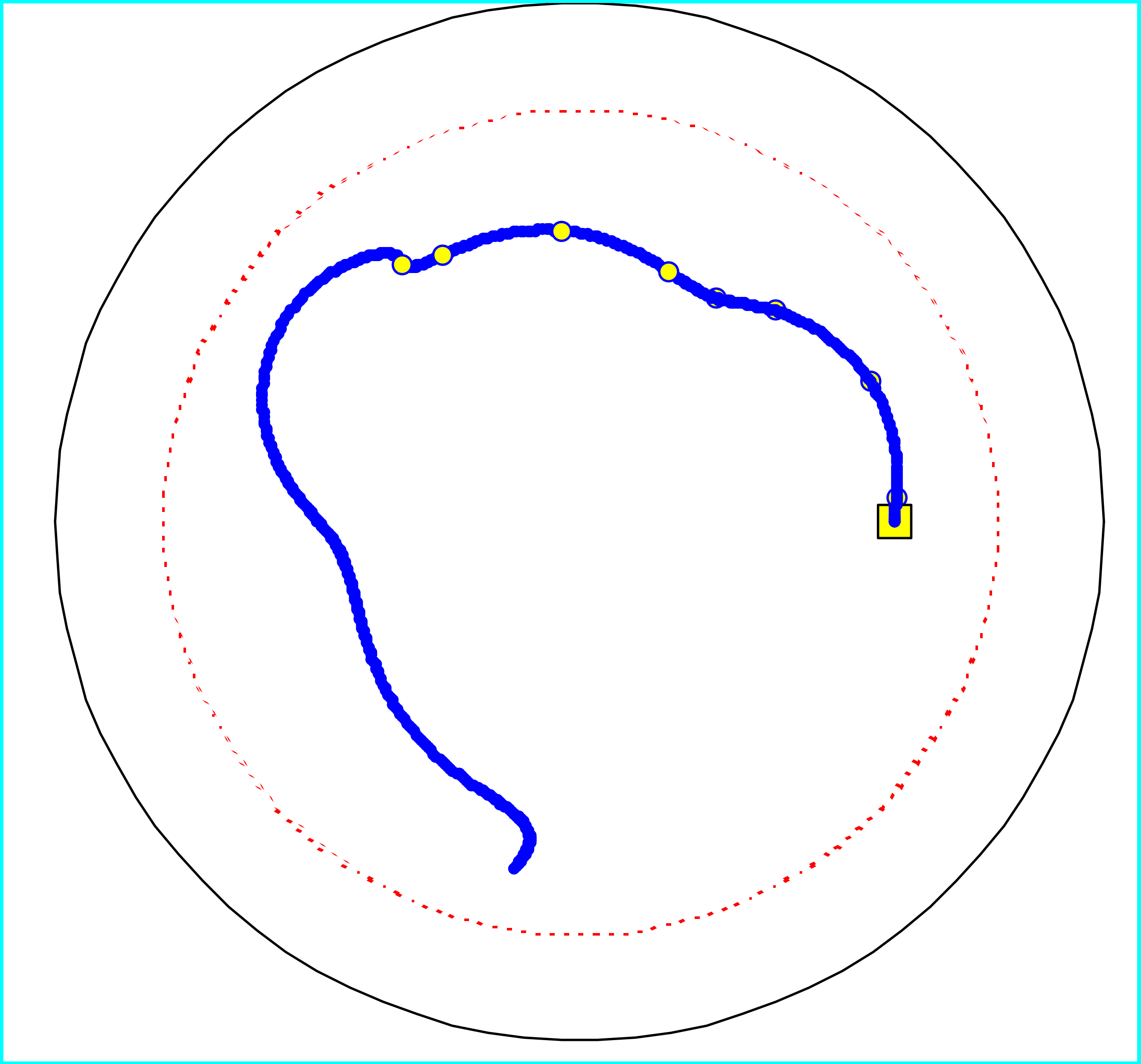
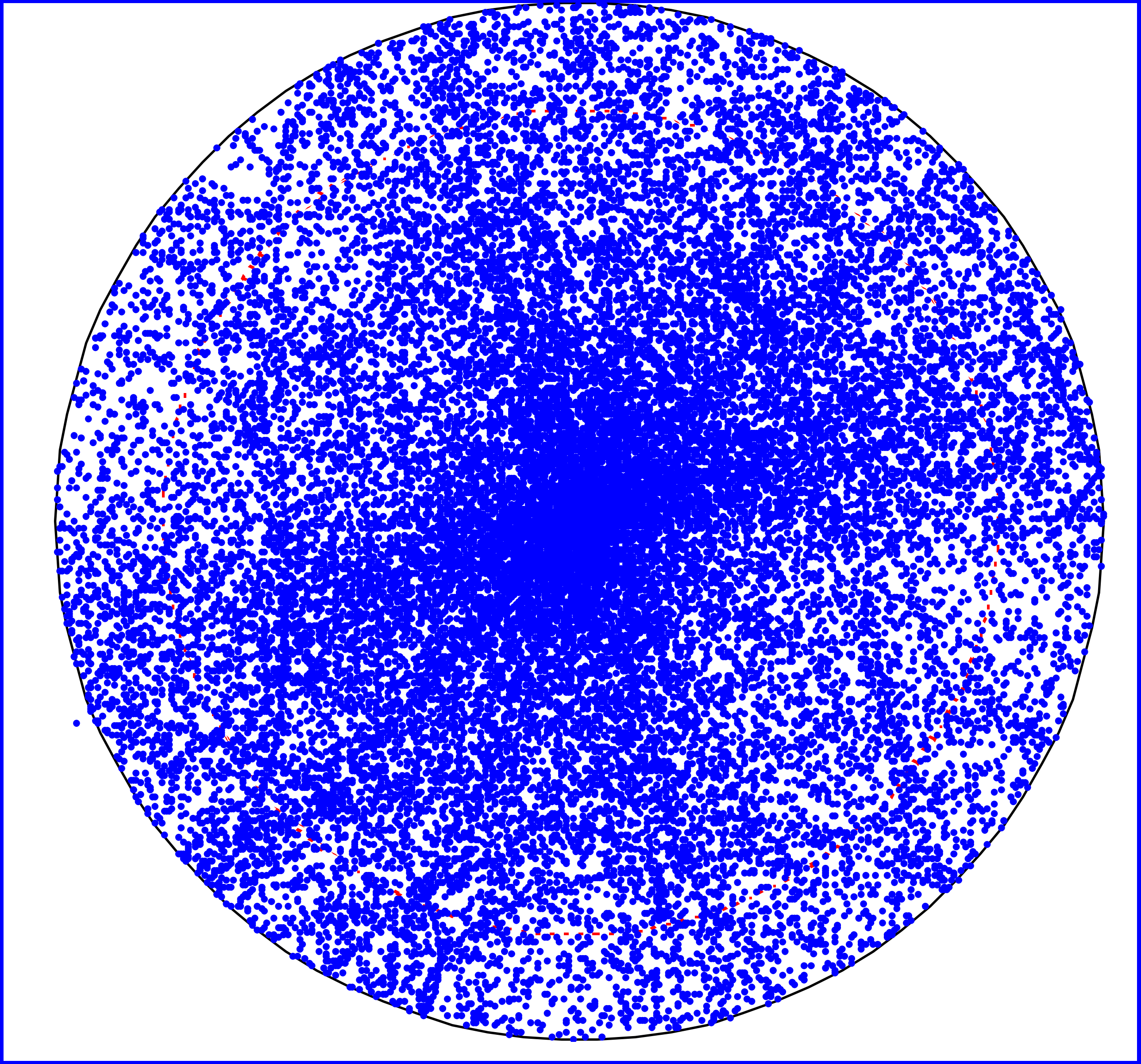


Electron positions after 32,000 time steps



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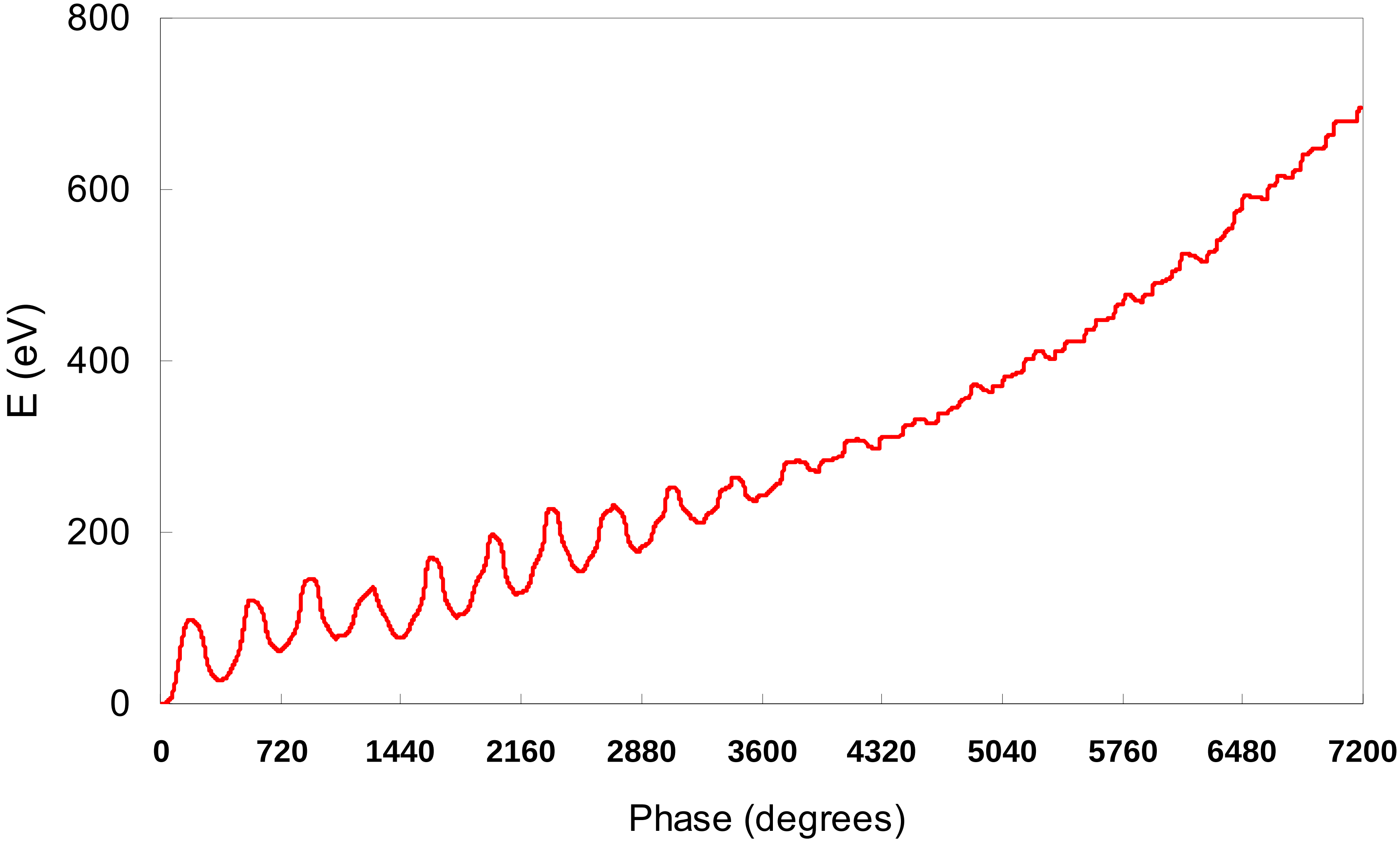
With no losses, the electron energy would just keep rising



Effects included in realistic calculations

- Elastic and inelastic collisions with neutrals (w. probability at given p_0 and local electron velocity)

- Losses through the wall sheath (prescribed sheath drop)

- Regeneration of electrons at an arbitrary position with an arbitrary velocity according to a Maxwellian distribution at chosen KT_e.

- Exact skin layer field with collisions and cylindrical geometry included.

Neglected: Motions and gradients in the z direction

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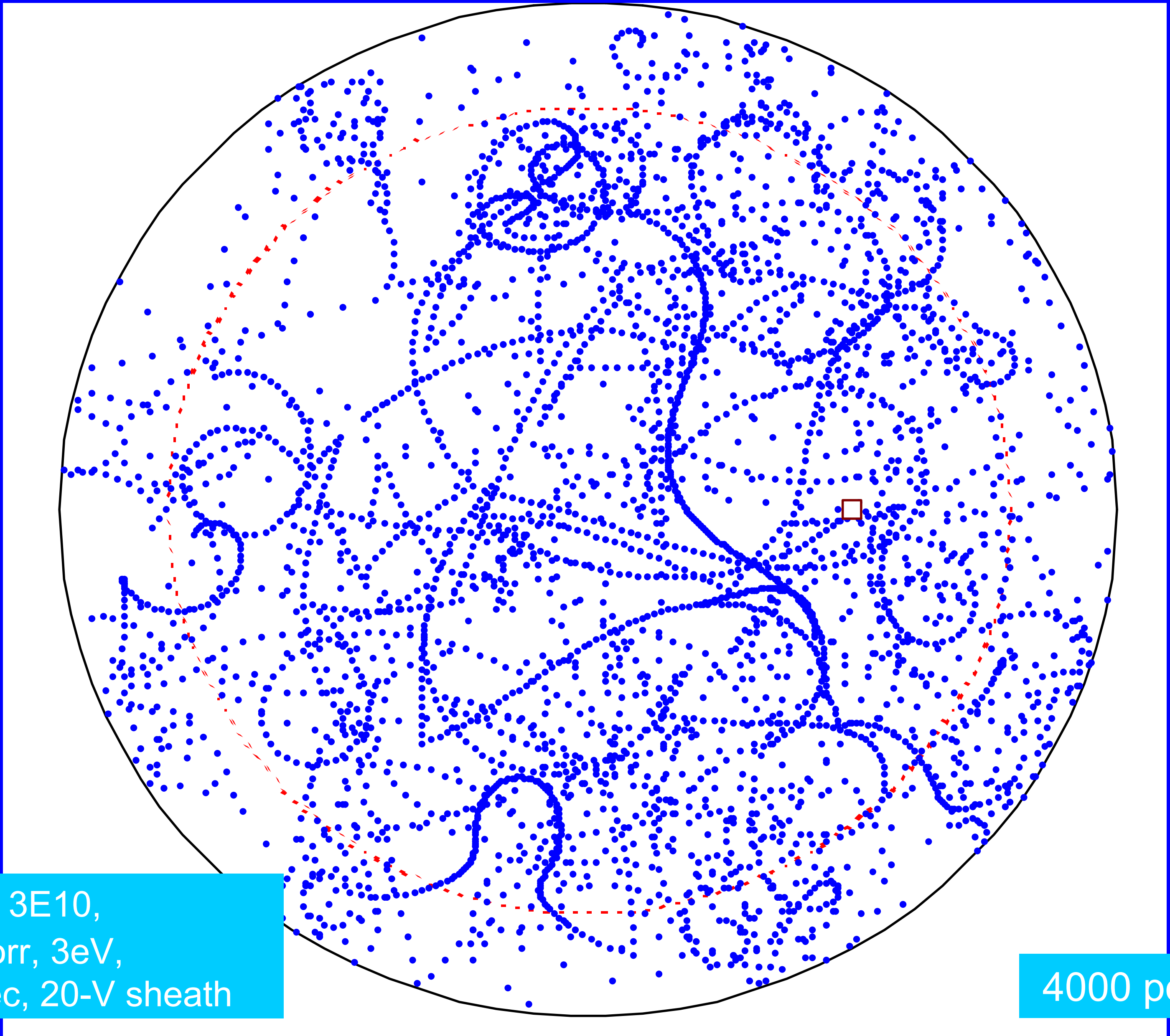

2 MHz, 3E10,
10 mTorr, 3eV,
2.5 nsec, 20-V sheath

4000 points

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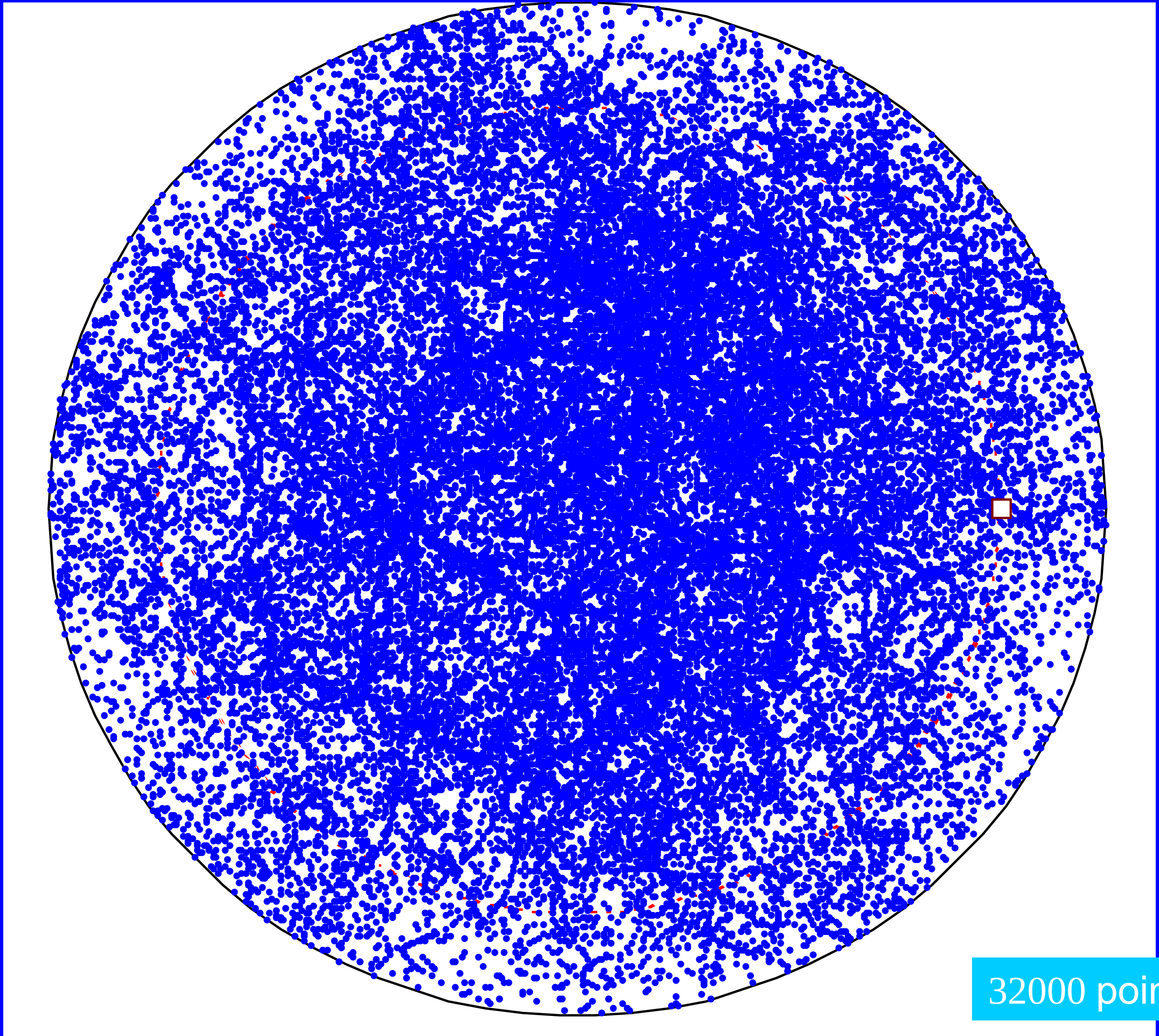

32000 points

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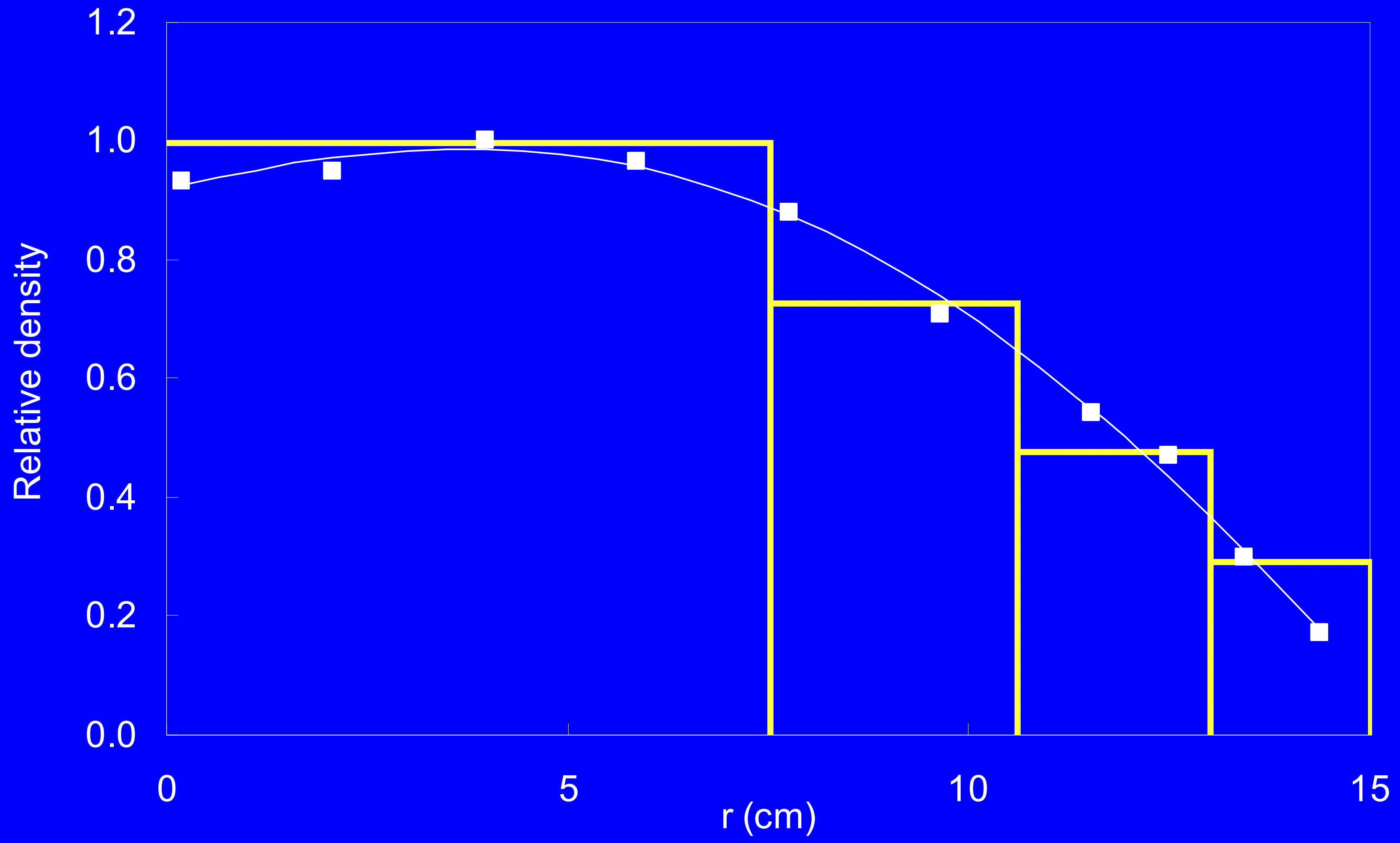
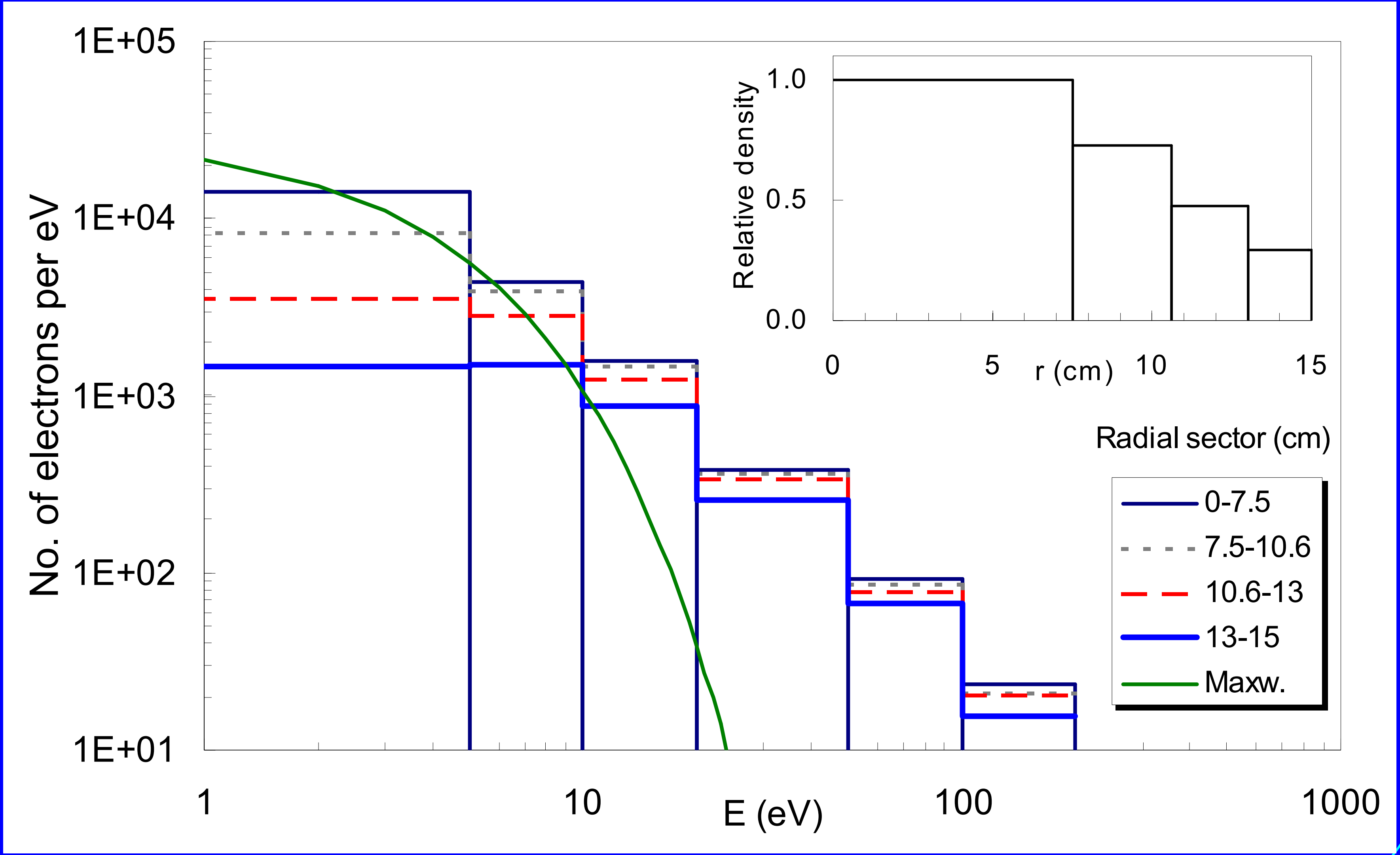
Density profile in four sectors of equal area



The number of ionizing electrons is largest in the central region

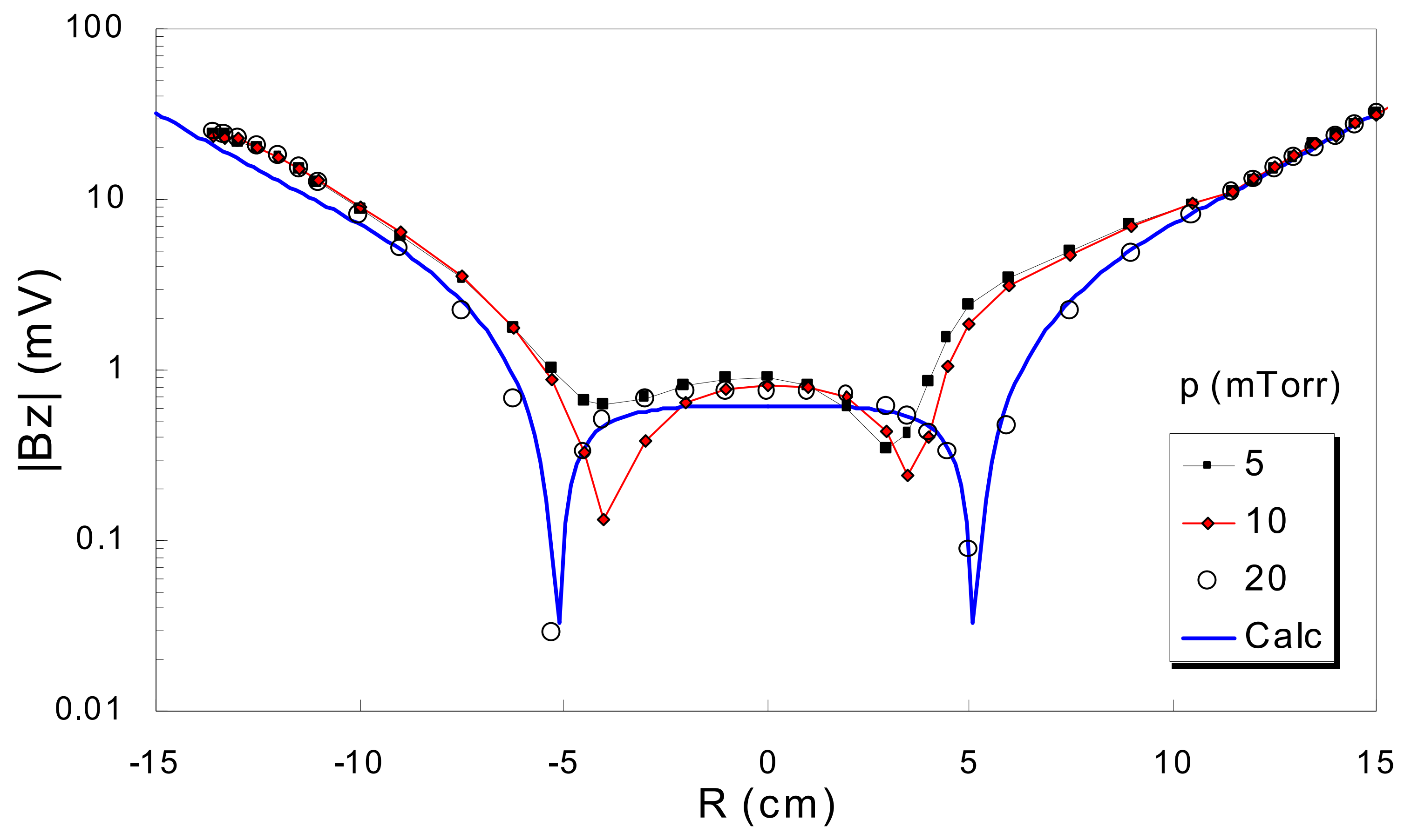


CONCLUSIONS

1. Ionizing electrons are created throughout the discharge, even outside the classical skin layer
2. This population must be treated kinetically, including the nonlinear Lorentz force.
3. Density tends to peak on axis because of the long residence time of slow electrons created there.
4. To achieve uniform density,

IT IS NOT NECESSARY TO HAVE ANTENNA ELEMENTS NEAR THE AXIS!

The "standing wave" effect



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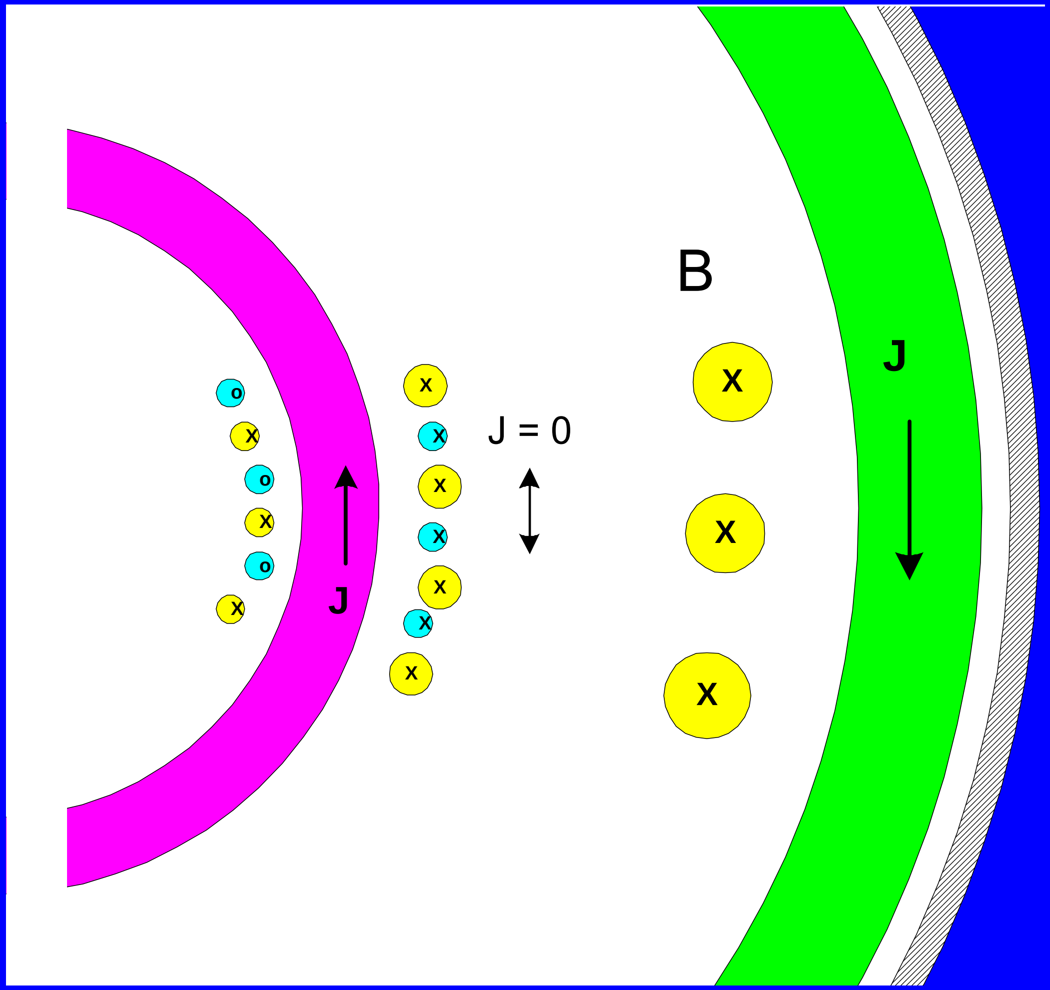
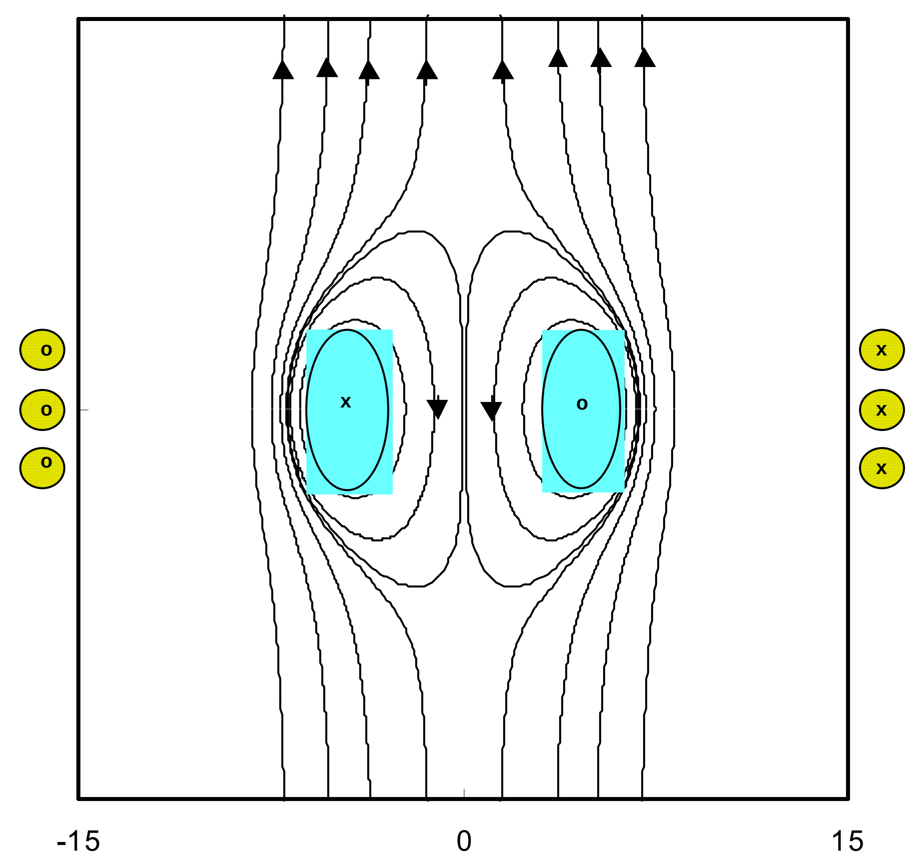
A detached current layer



The field of a detached current ring



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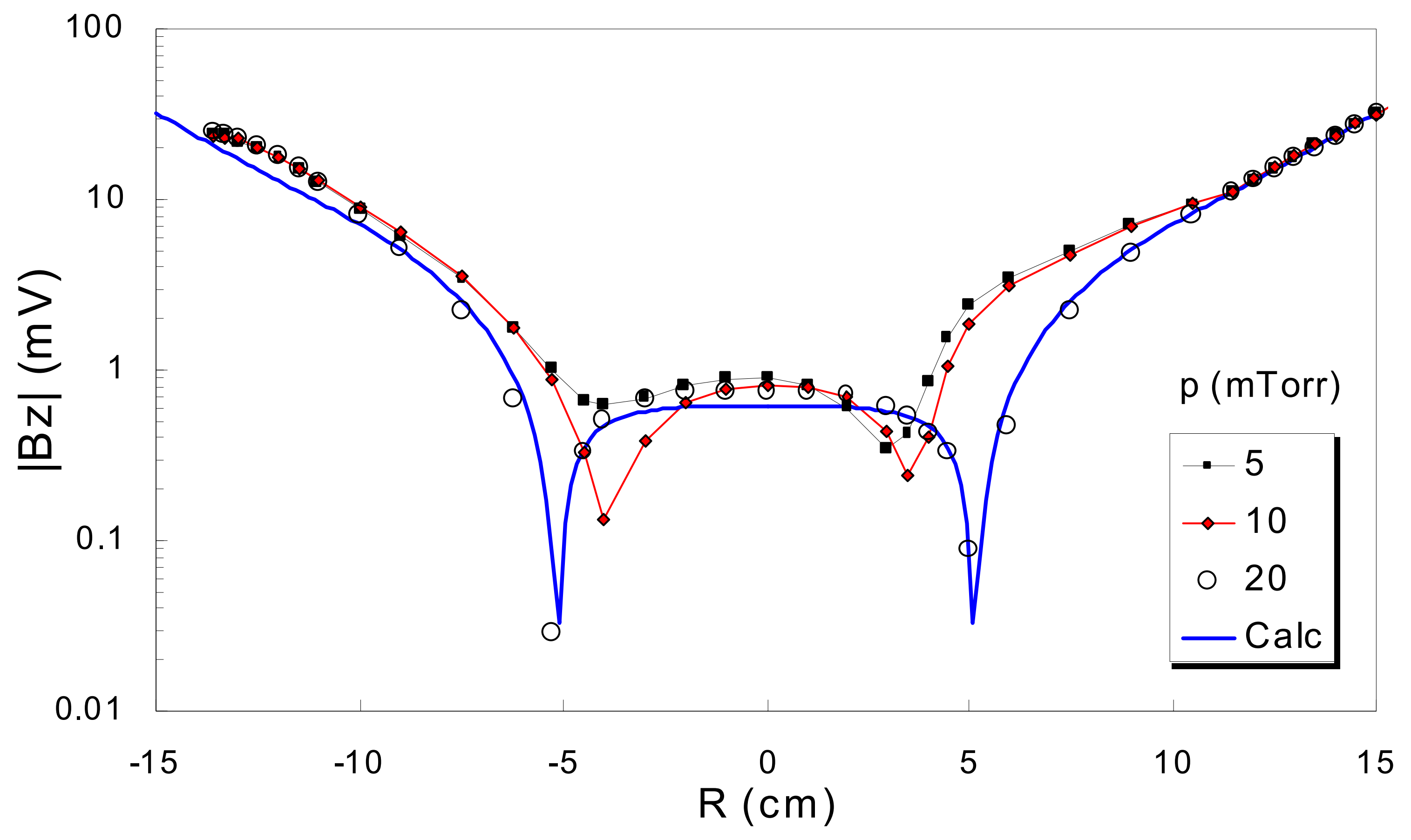

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G.R. Tynan et al, Plasma Phys. Control. Fusion **46**, A373 (2004).

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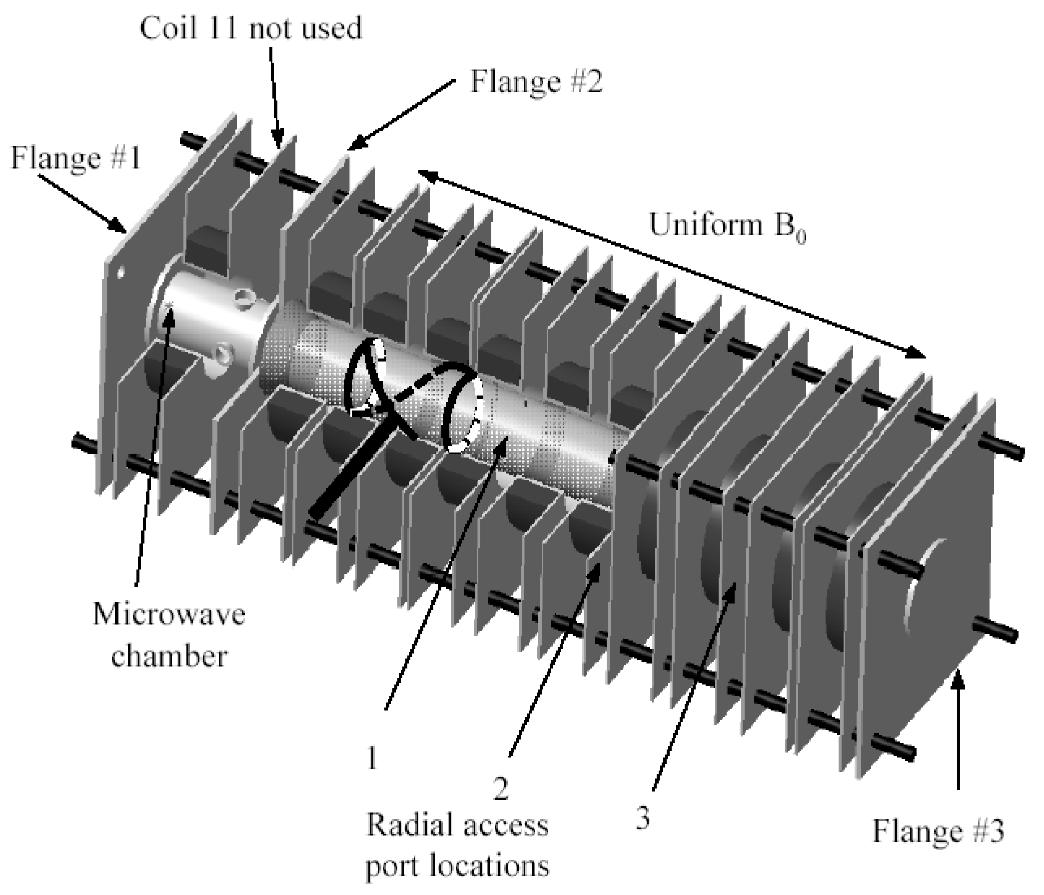
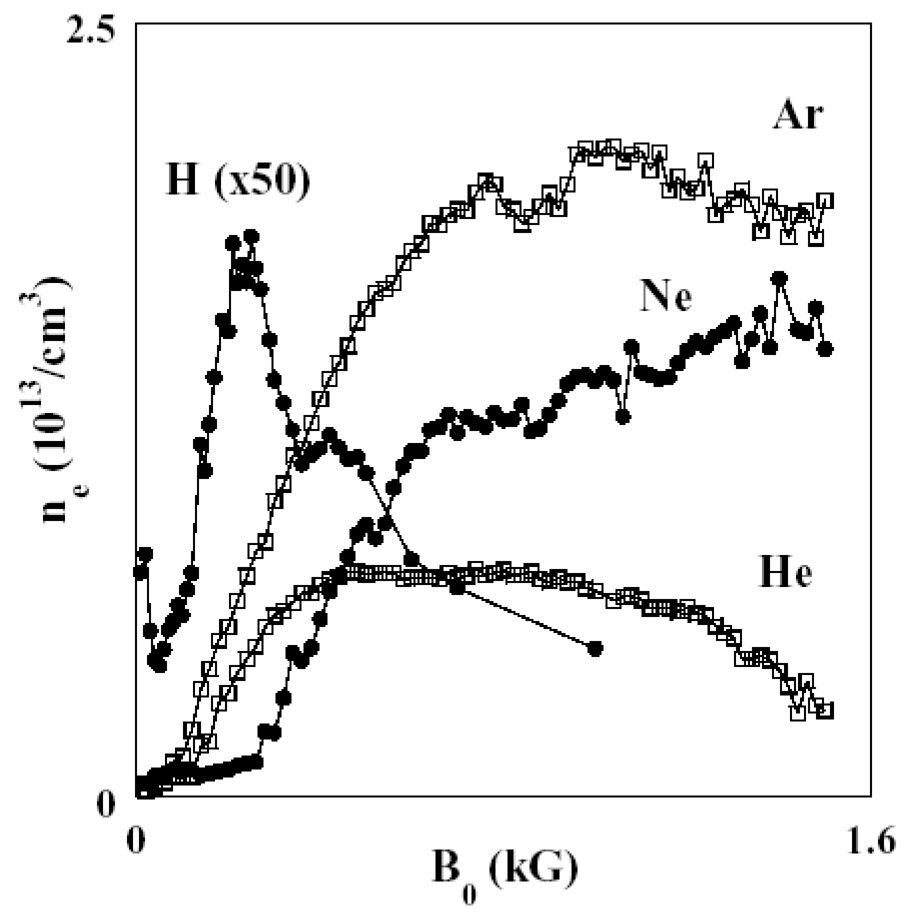
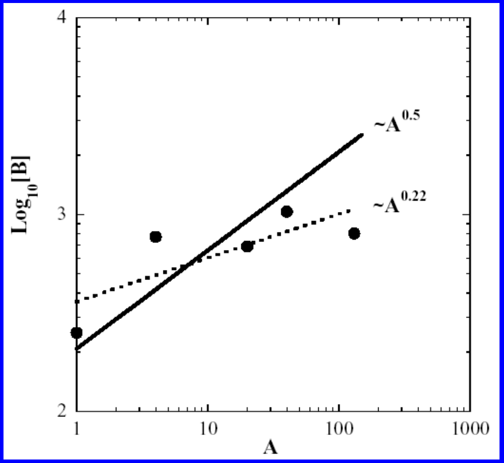
Max Light's helicon source at LANL



Density vs. B_0 for various gases



n(B_0) saturates or peaks at a critical field B_{crit} that increases with ion mass. Linear theory predicts n to grow linearly with B_0.



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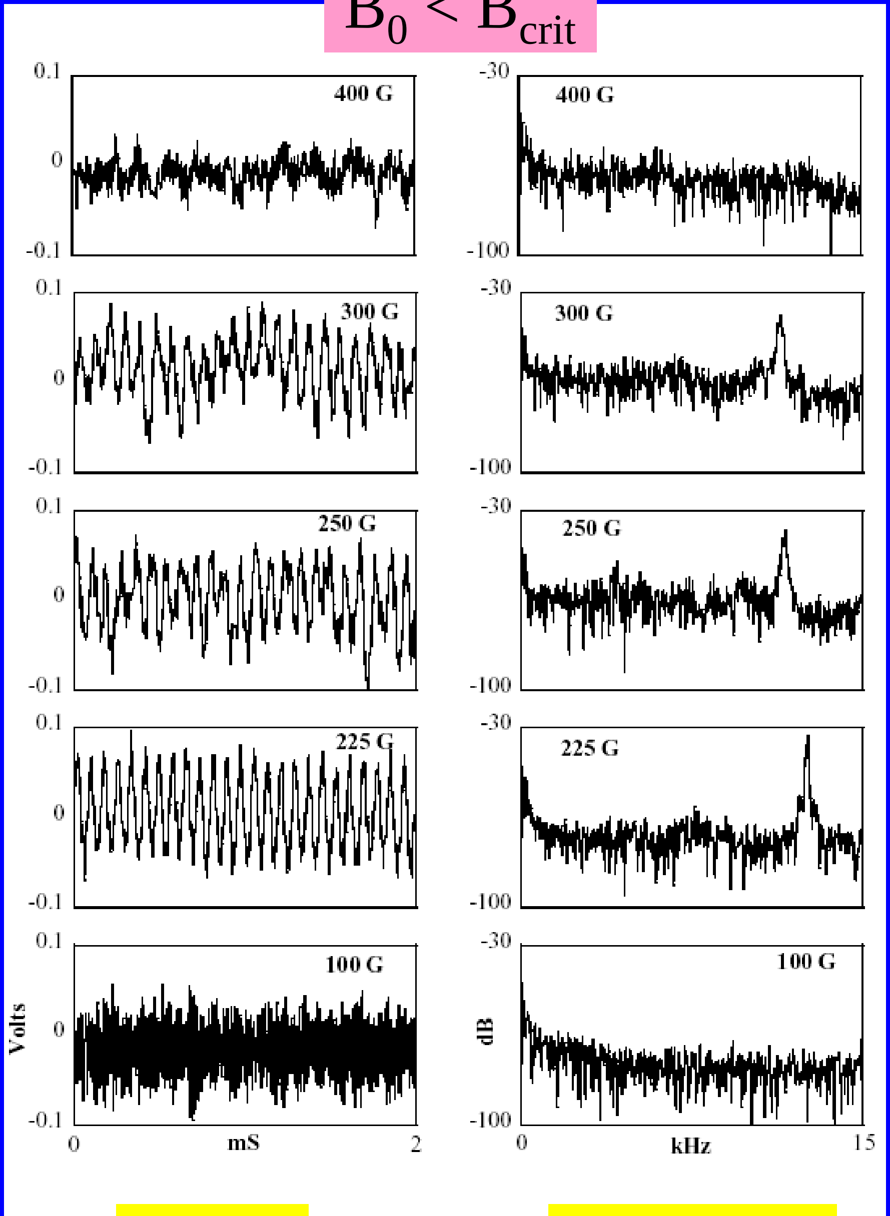
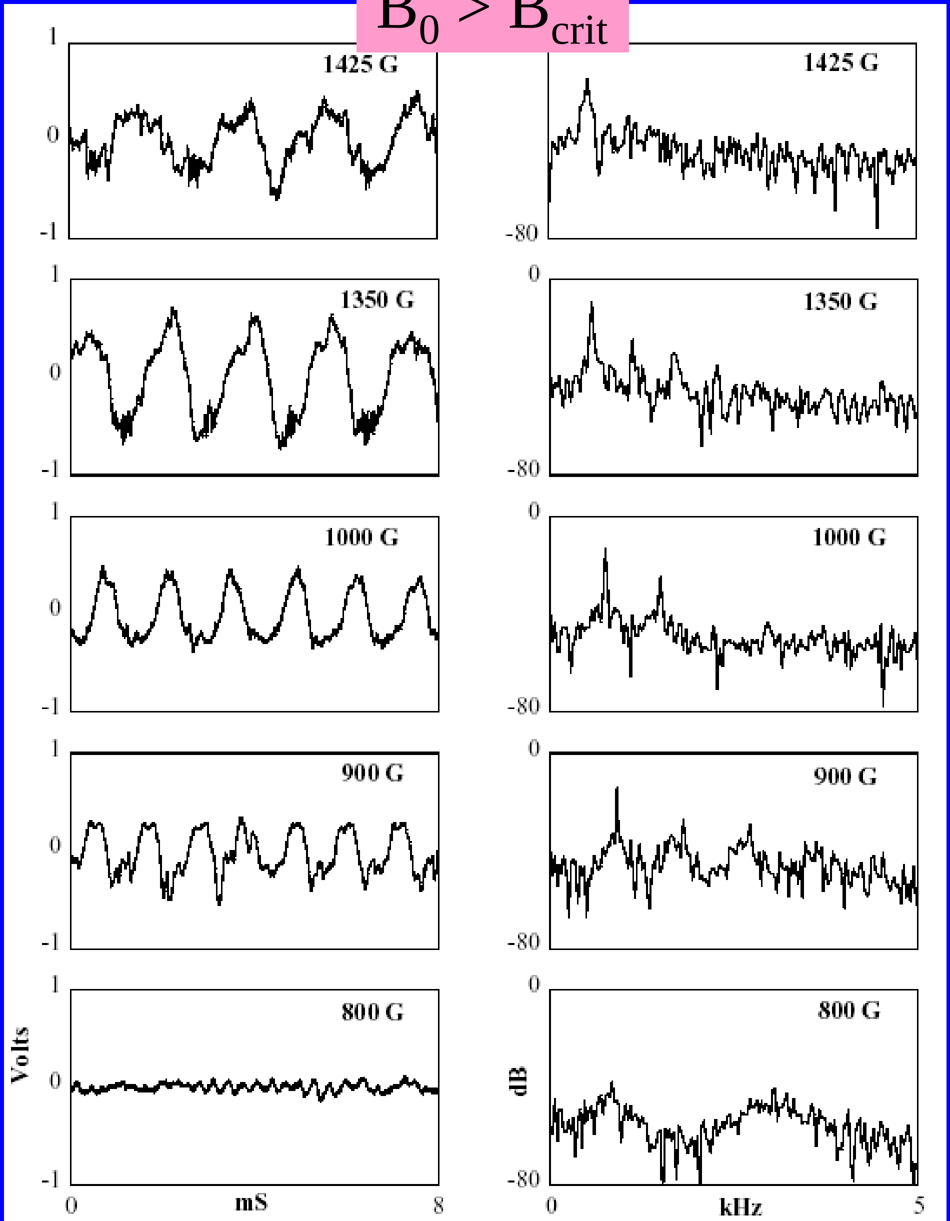
$B_0 < B_{crit}$



Time

Spectrum

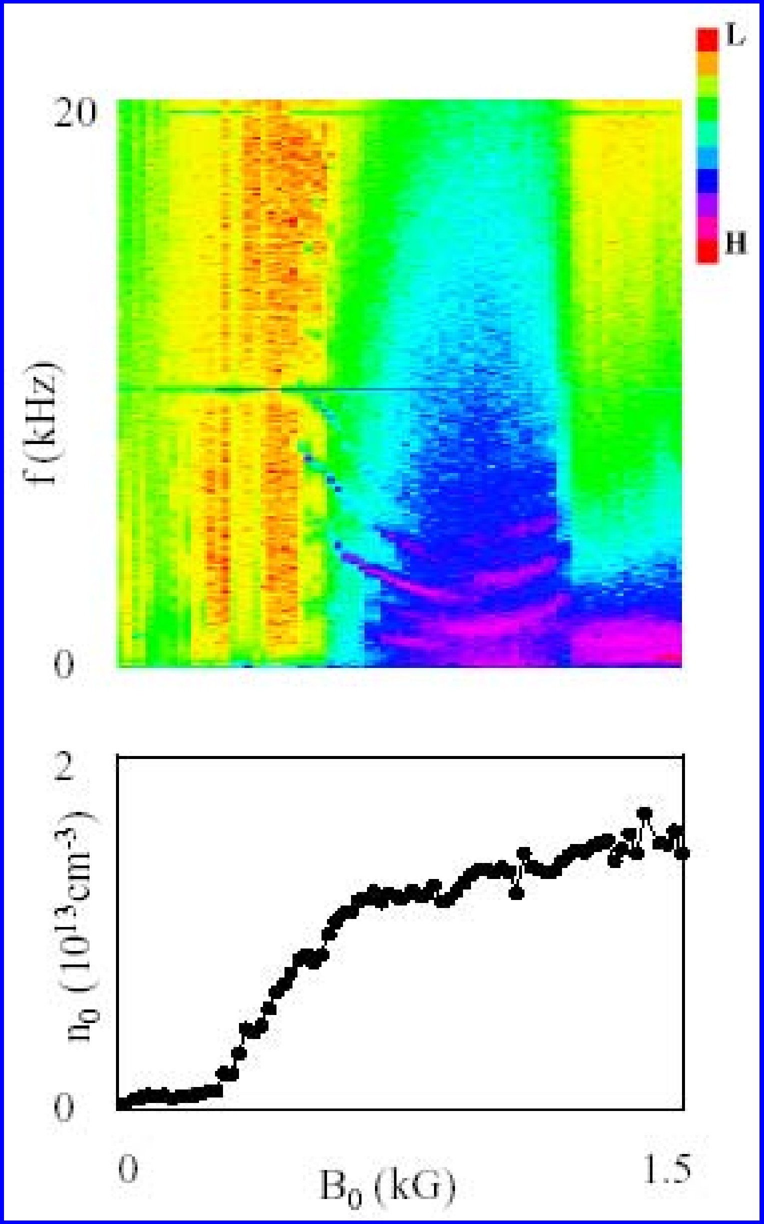
$B_0 > B_{crit}$



Time

Spectrum

Density saturates when instability starts



It is a combined drift and Kelvin-Helmholtz instability

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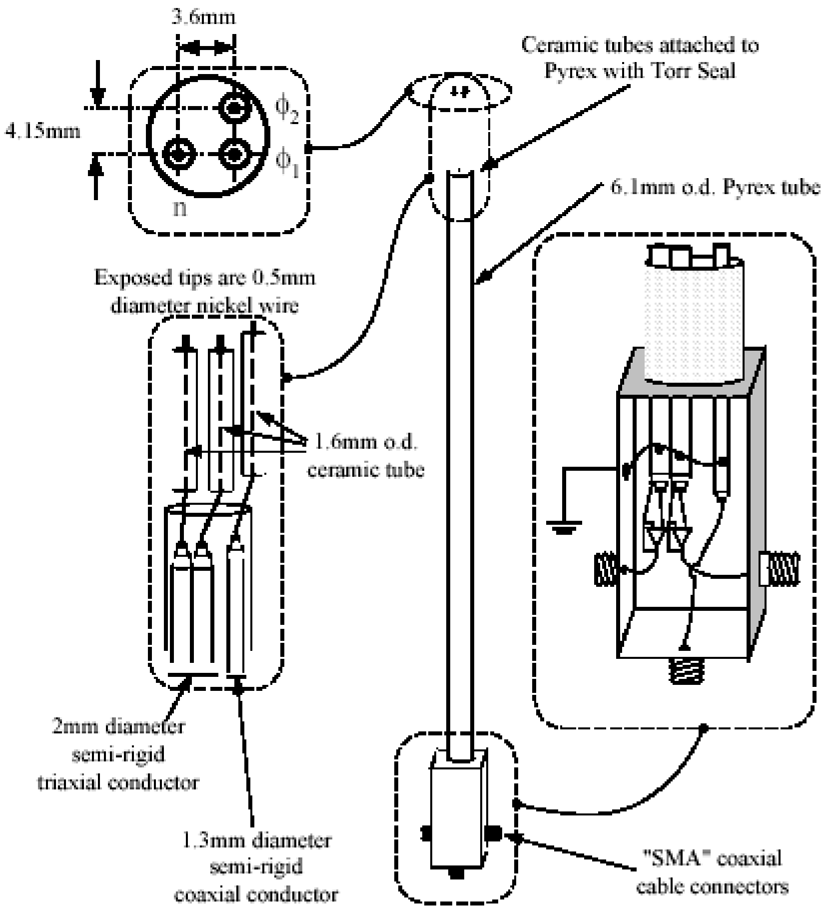
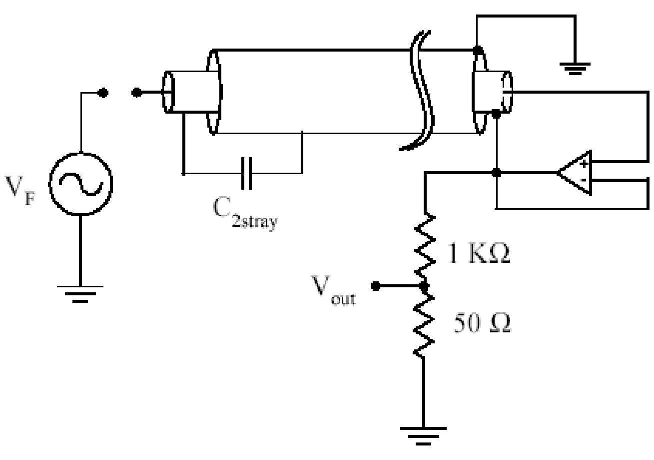
Diagnostics

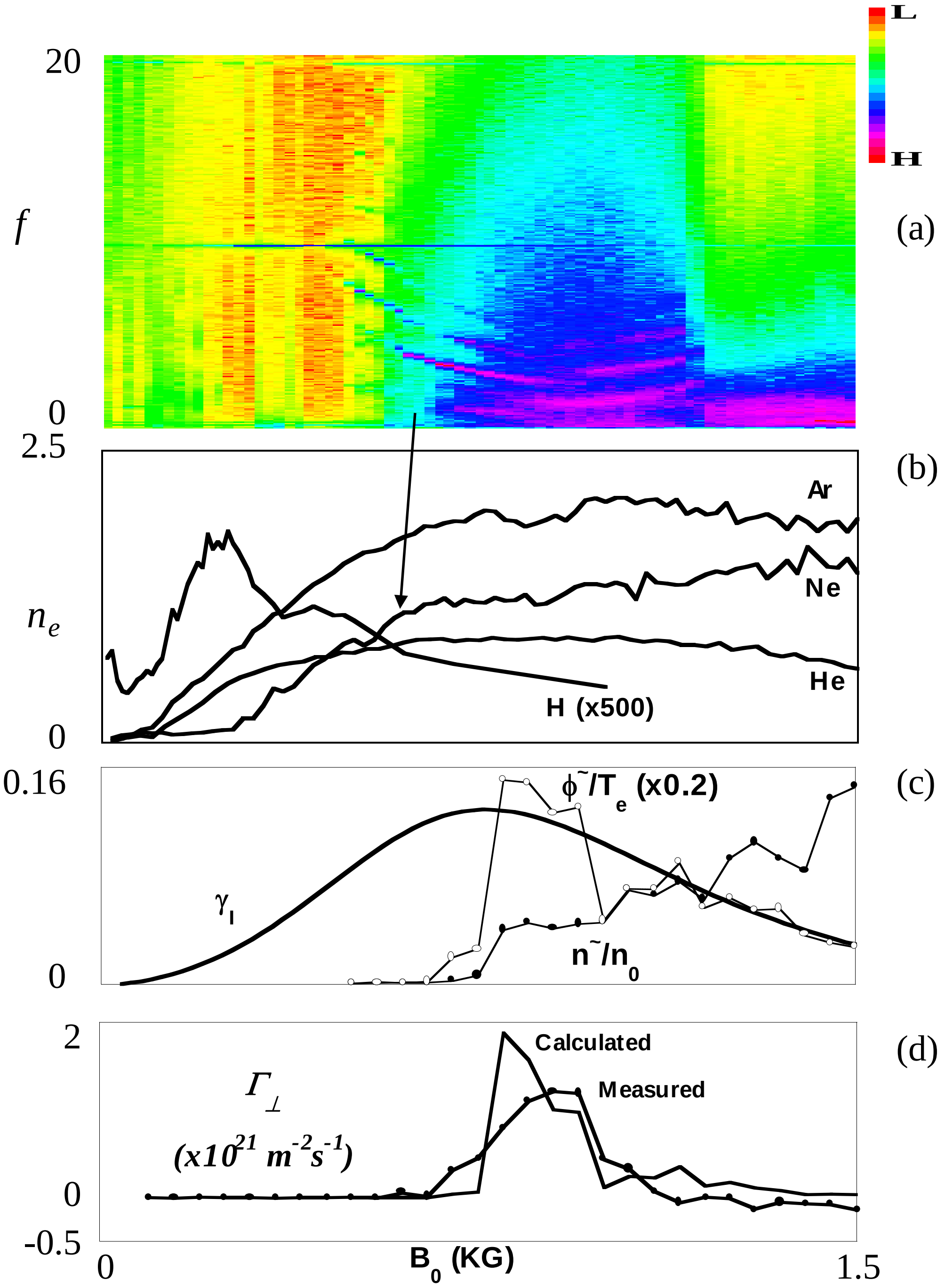


Triple probe for measuring $\tilde{n}$ and $\tilde{E}$



Capacitance neutralization is used to float two probes for measuring potential oscillations. This is for getting the anomalous $\langle n\phi \rangle$ transport.

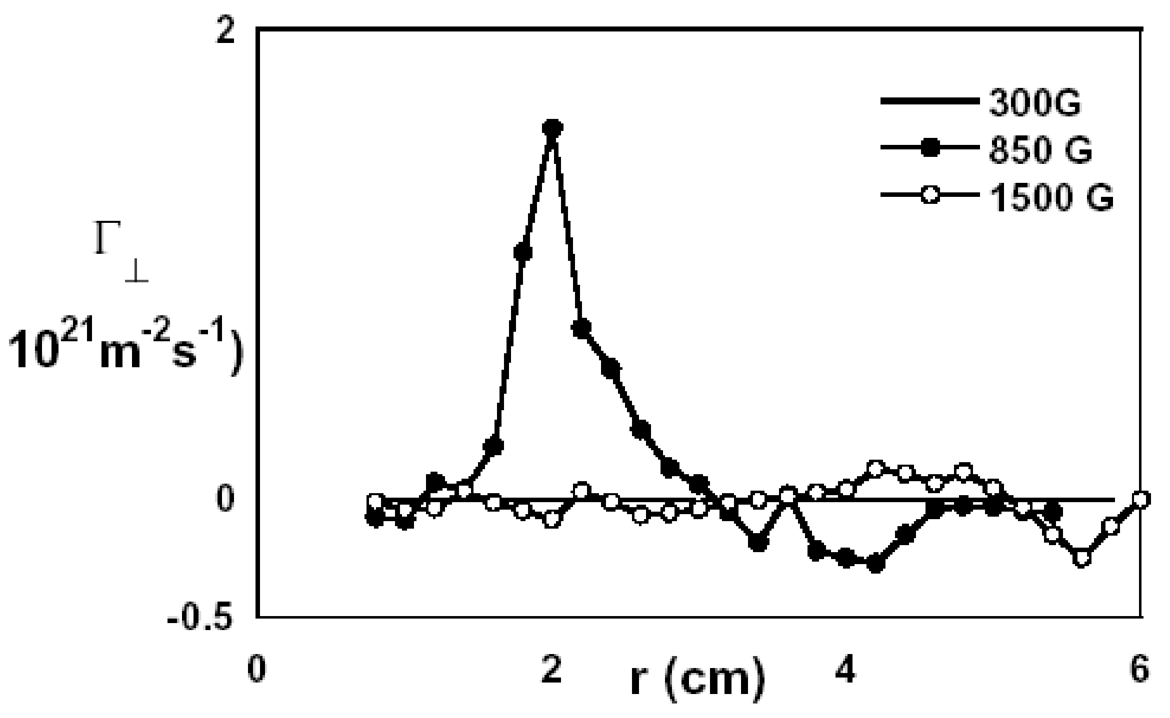
This is for neon.



The onset agrees with the maximum theor. growth rate.

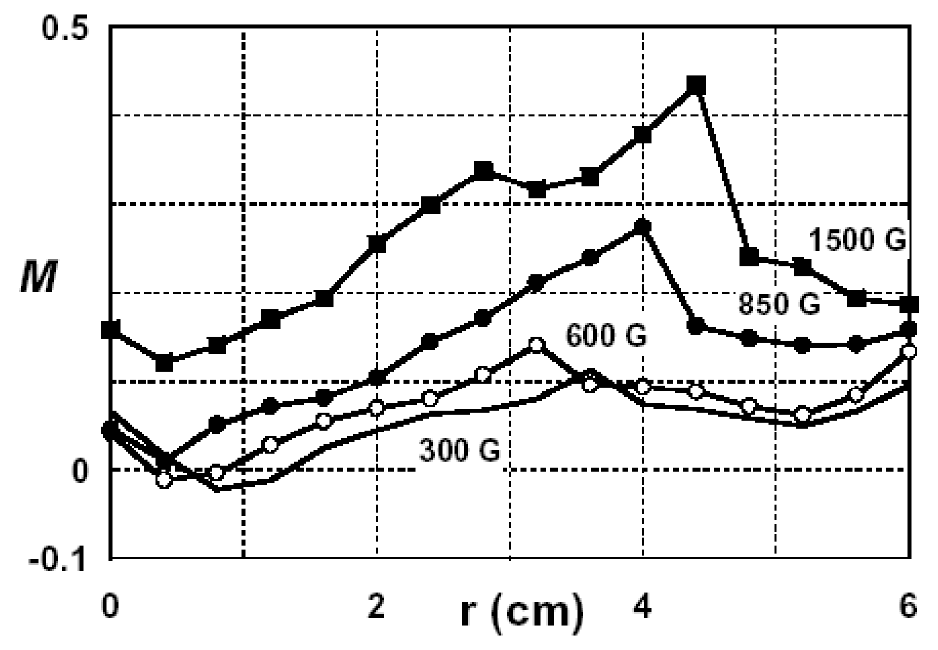
But the radial $\langle n\phi \rangle$ flux stops at high B_0.

The radial transport stops before reaching the edge



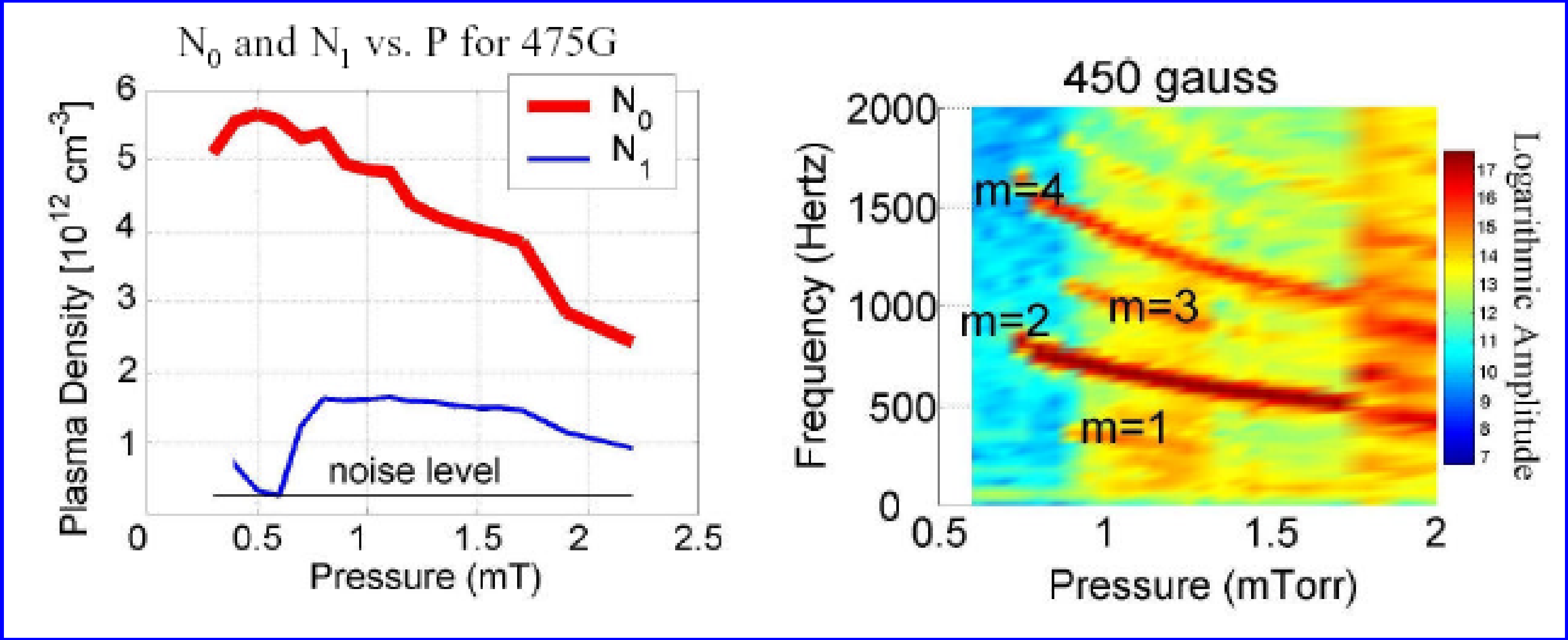
How does the plasma get out?

Axial ion flow with a Mach probe



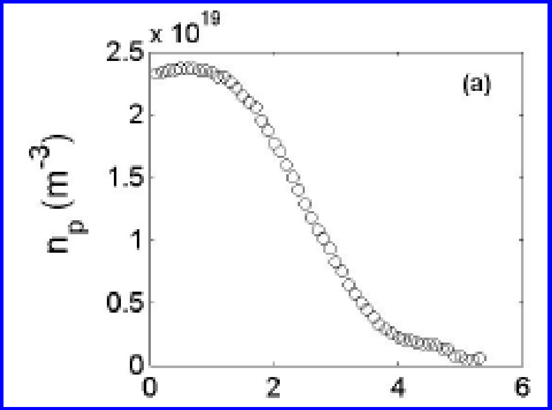
The plasma is oscillation-driven to the outside half, where it is then mainly lost by axial flow. This complicated loss mechanism is not entirely understood.

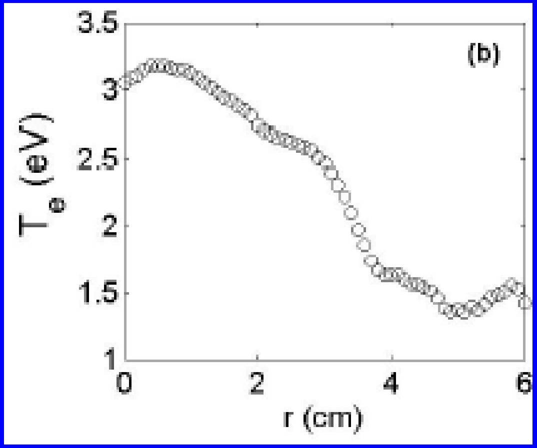
Similar effects were also seen by Tynan et al.*

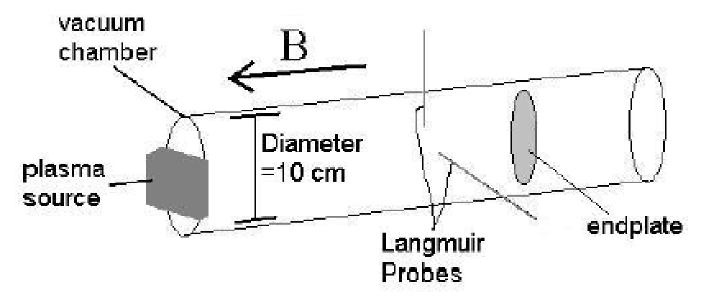


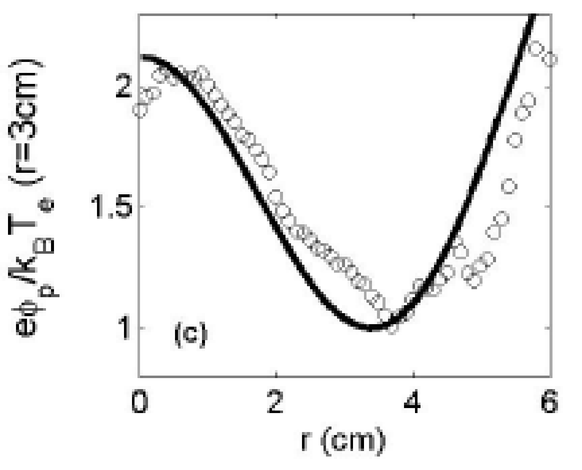
*J. George, Ph.D. Thesis, UCSD, G.R. Tynan et al, Plasma Phys. Control. Fusion **46**, A373 (2004).
M.J. Burin, G.R. Tynan, G.Y. Antar, N.A. Crocker, and C. Holland, Phys. Plasmas **12**, 052320 (2005)

A region of large electric field shear









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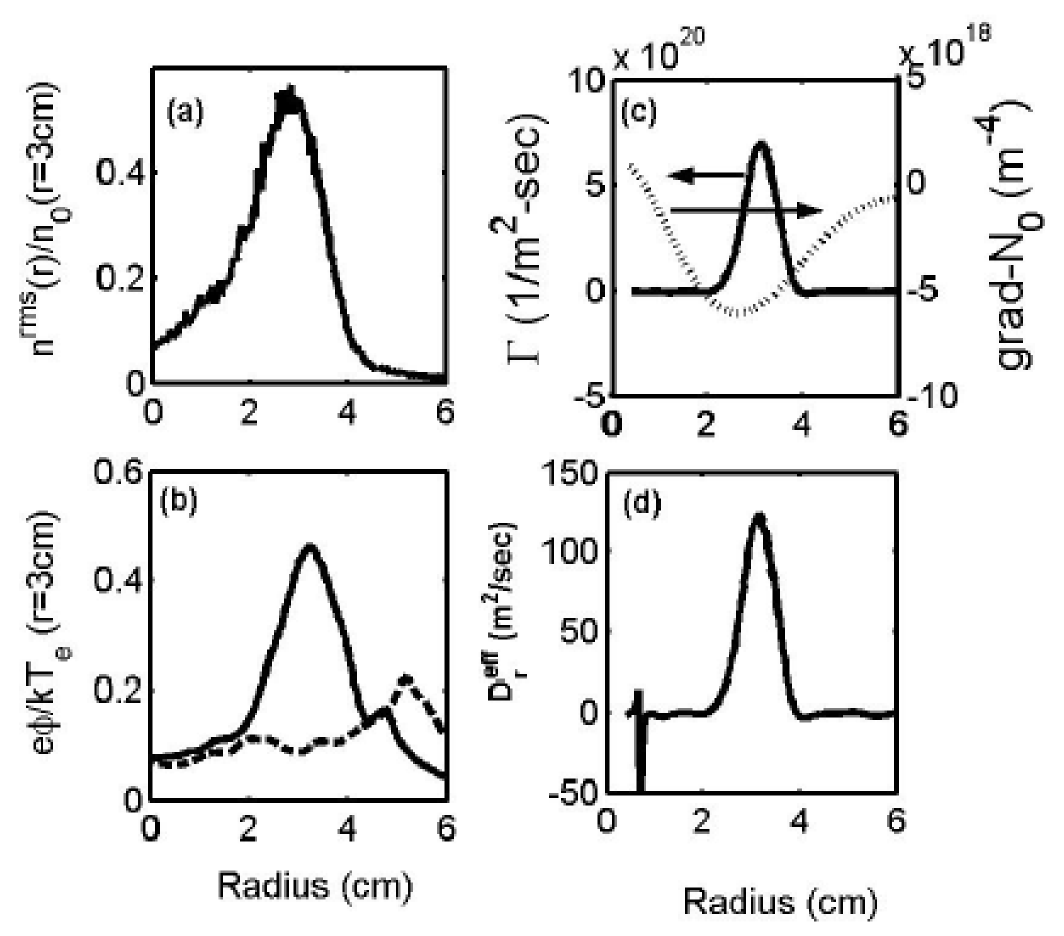
Fluctuations do not extend to radial wall



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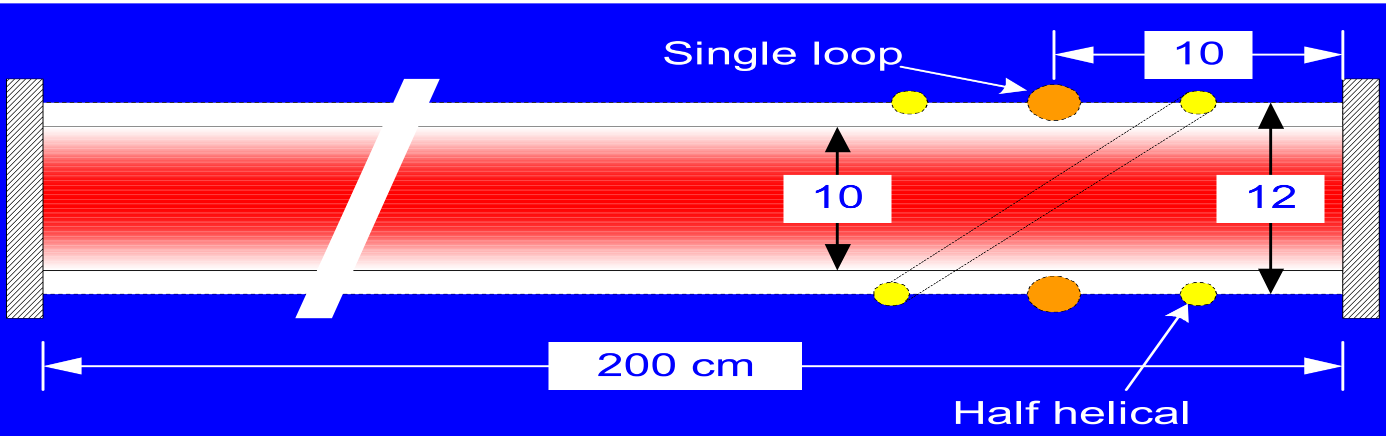
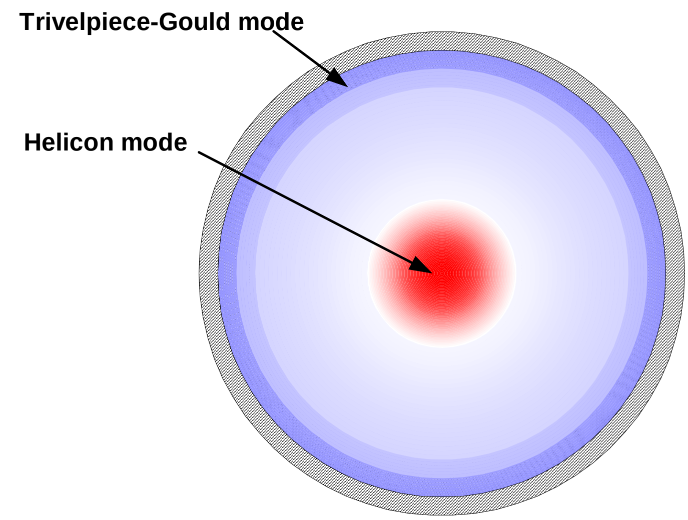
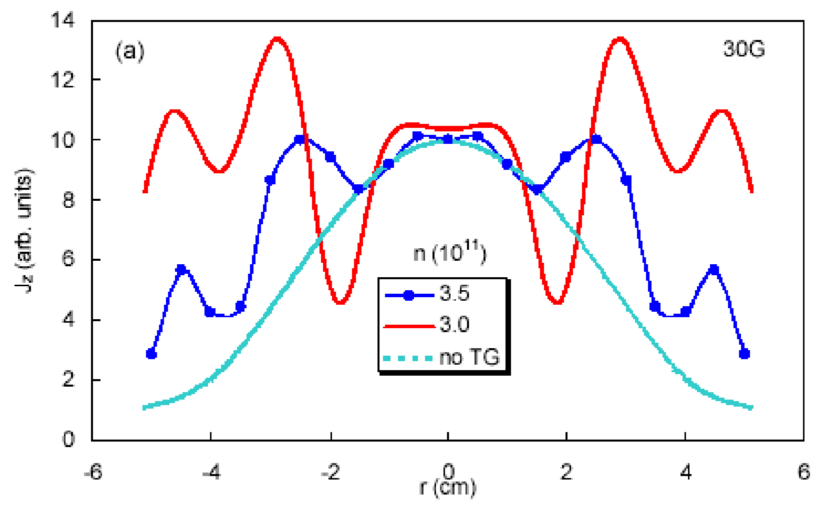
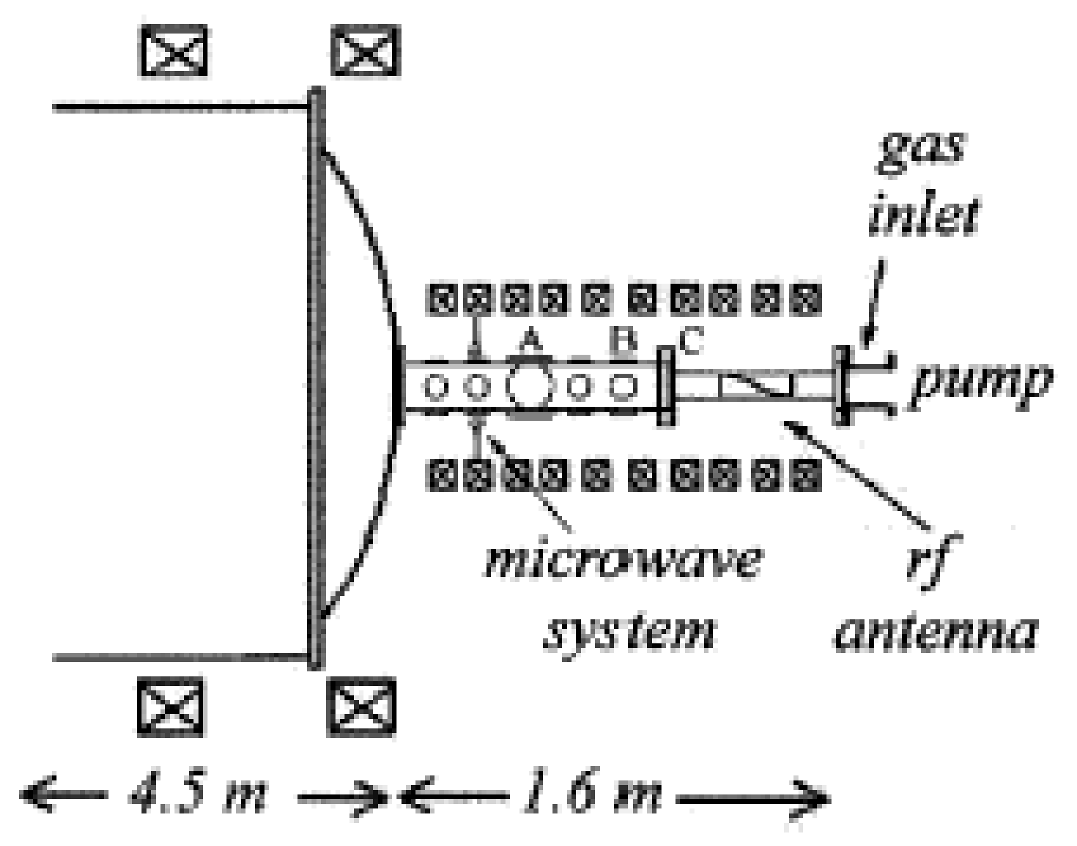
Introduction to energy coupling in helicons







Detection of parametric instabilities in helicons



Scime's helicon machine at West Virginia

J.L. Kline and E.E. Scime, Phys. Plasmas **10**, 135 (2003).

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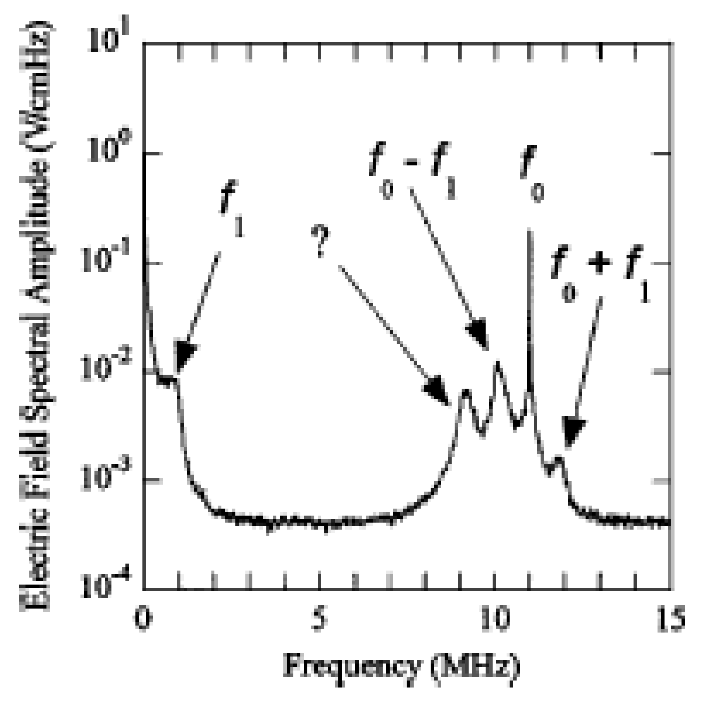
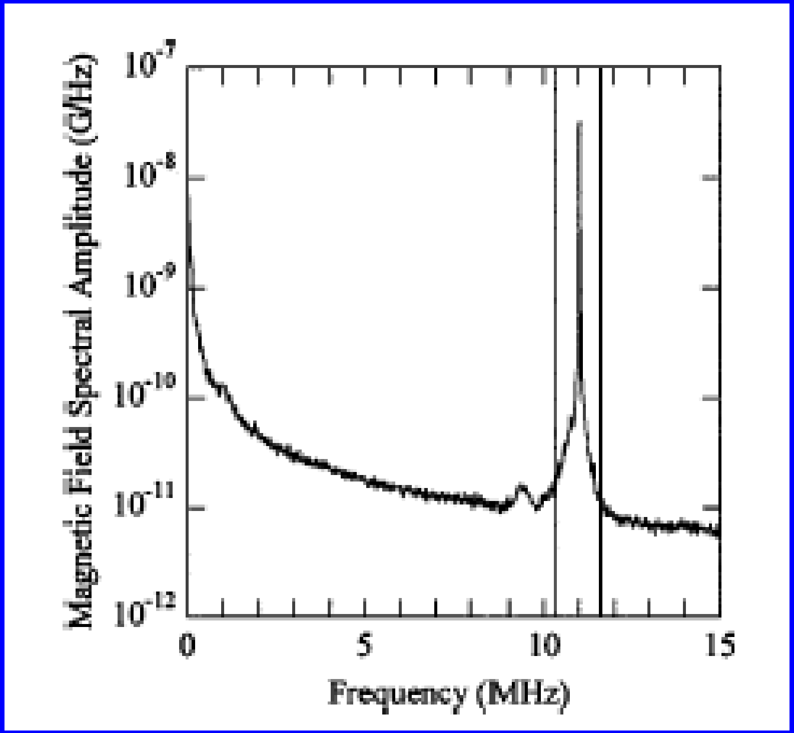
Fluctuation spectra downstream



Electrostatic signal



Magnetic signal

f_0 = 11 MHz, $f_{LH} \approx$ 9 MHz, $f_{LF} \approx$ 1 MHz

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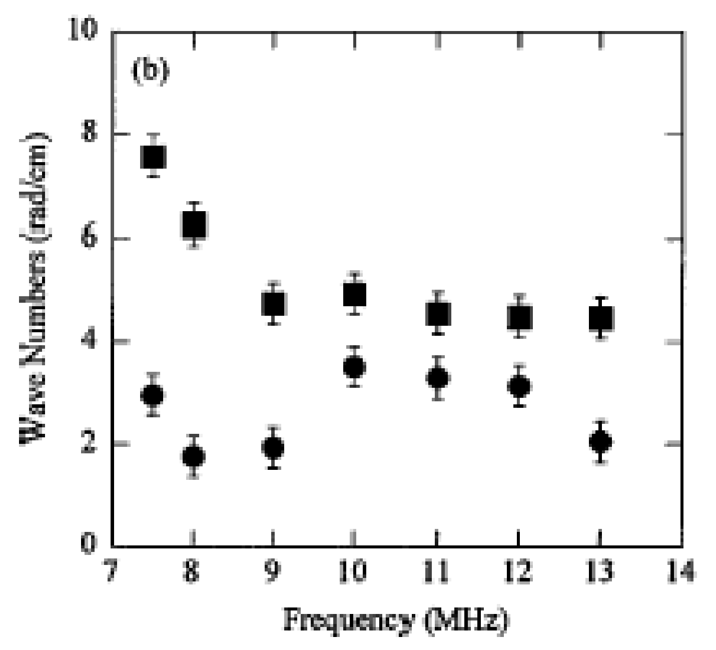
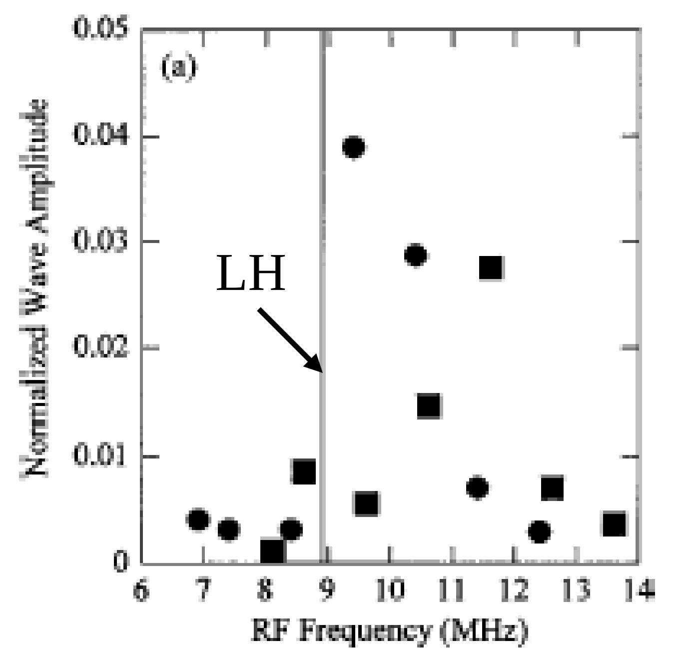
Relation to the lower hybrid frequency



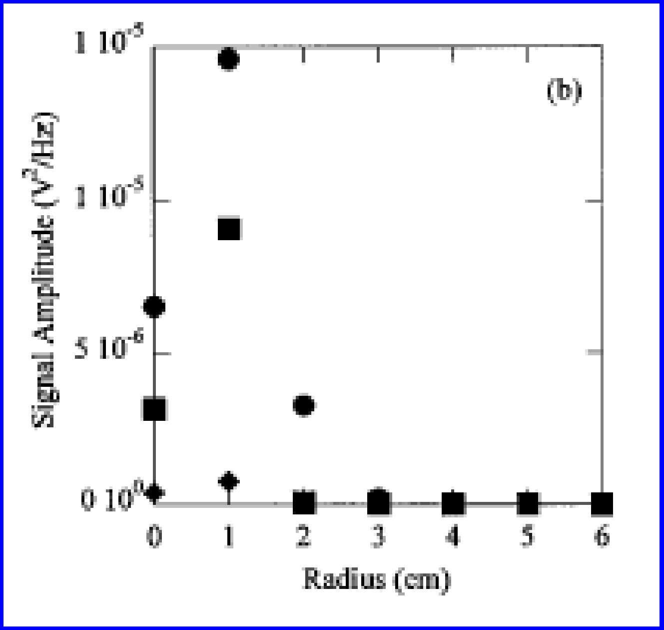
k_θ (■) and k_z(●) of LF wave



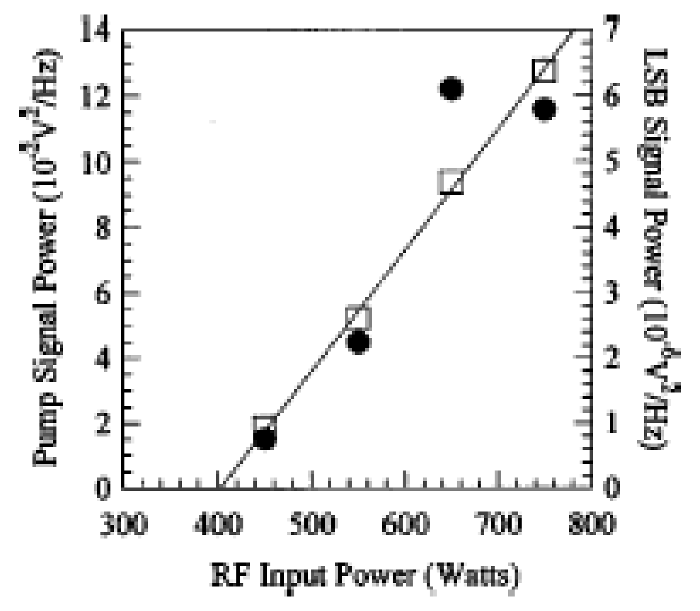
Amplitudes of the lower and upper sideband waves

Something happens just above the LH frequency

Other data



The waves are located near the axis



Amplitude of the sideband (❍) grows linearly with the pump (●). This shows that the sideband is NOT from parametric decay.

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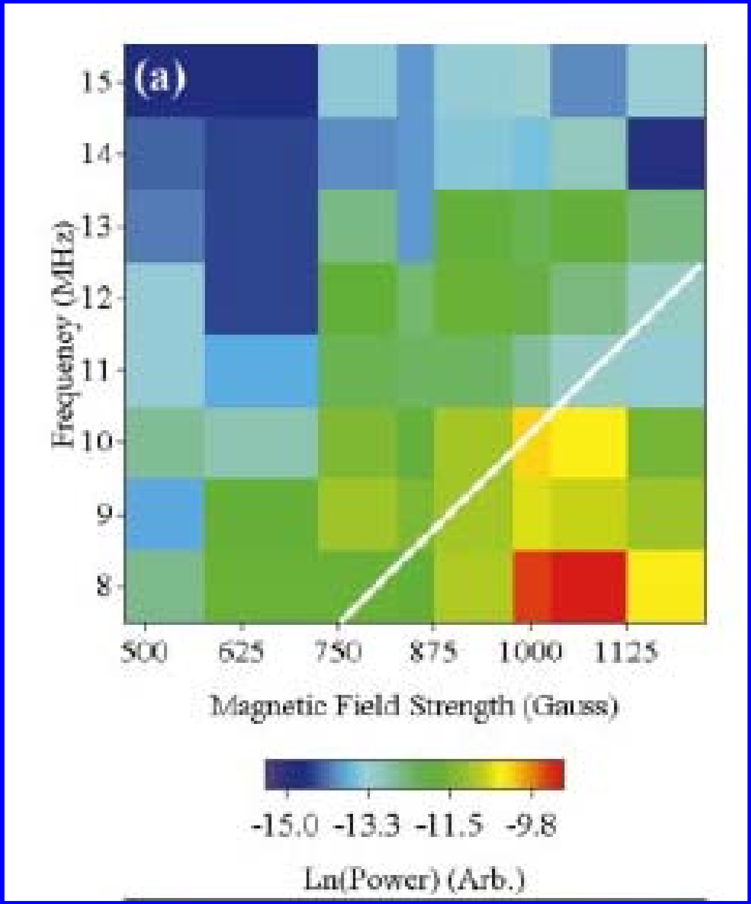
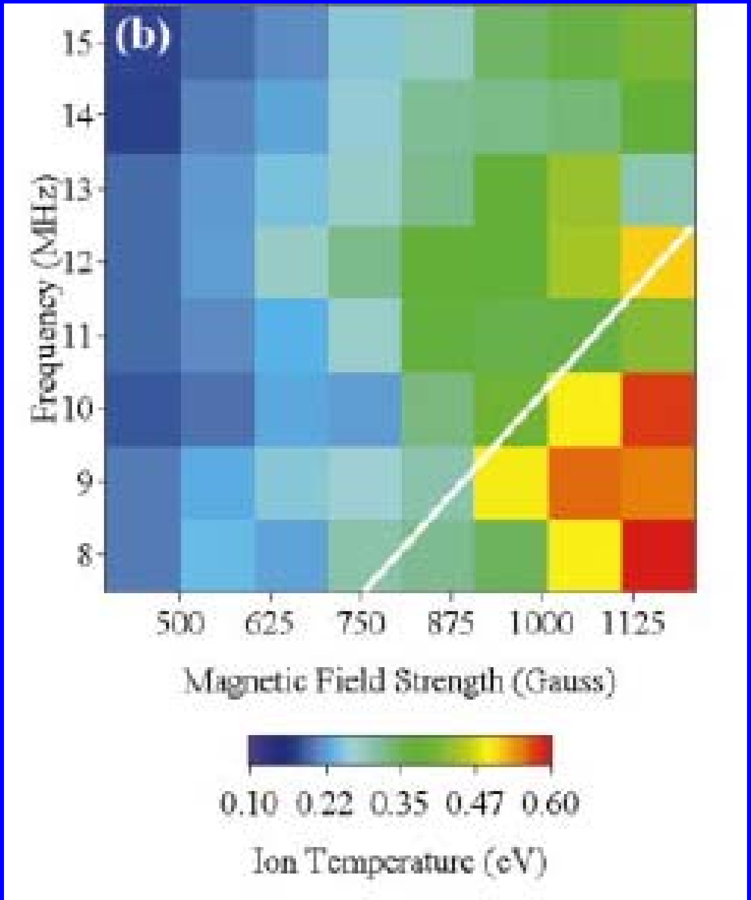
Relation to anomalous ion $T_\perp$'s



Power in LF wave



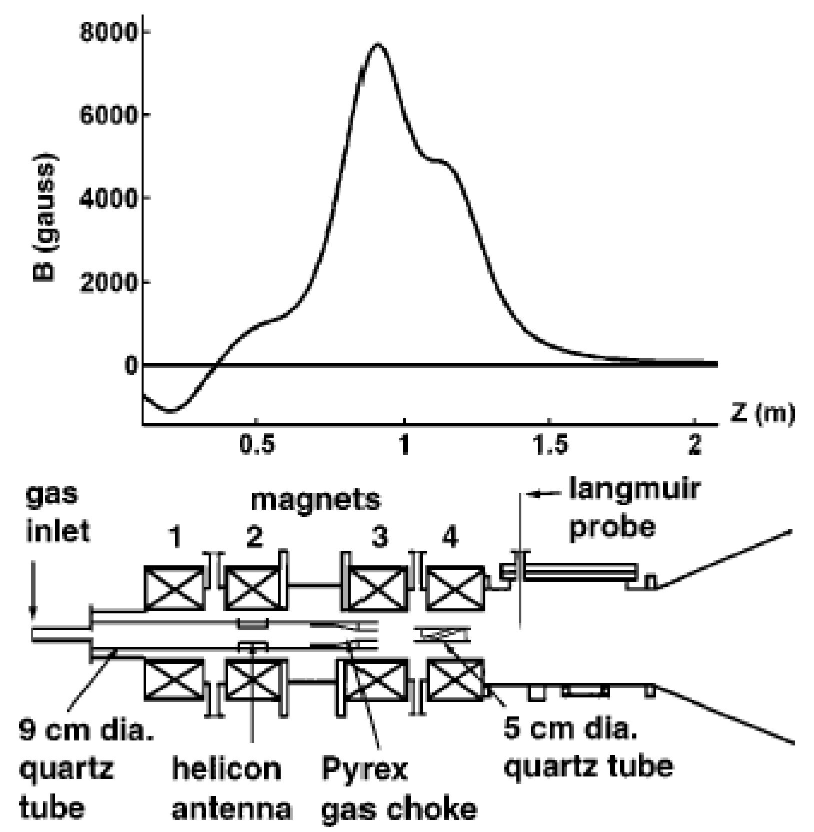
Perpendicular ion temperature

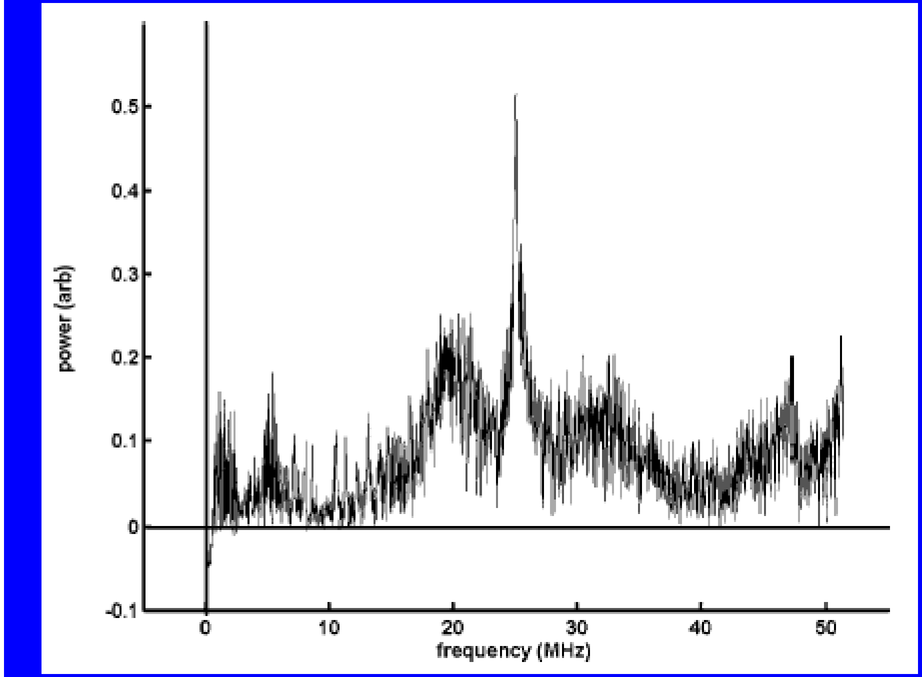
Parametric excitation of LH waves could cause the high ion $T_\perp$'s. This happens for pump frequency BELOW ω_{LH} at center, but near ω_{LH} at the edge.

Bottom line

The Kline-Scime experiment was the first to detect daughter waves from some sort of parametric decay, but their interpretation of the data was probably wrong. A wave near the LH frequency was seen, but it did not fit into a parametric decay scheme.

Sidebands were seen in the VASIMR space thruster



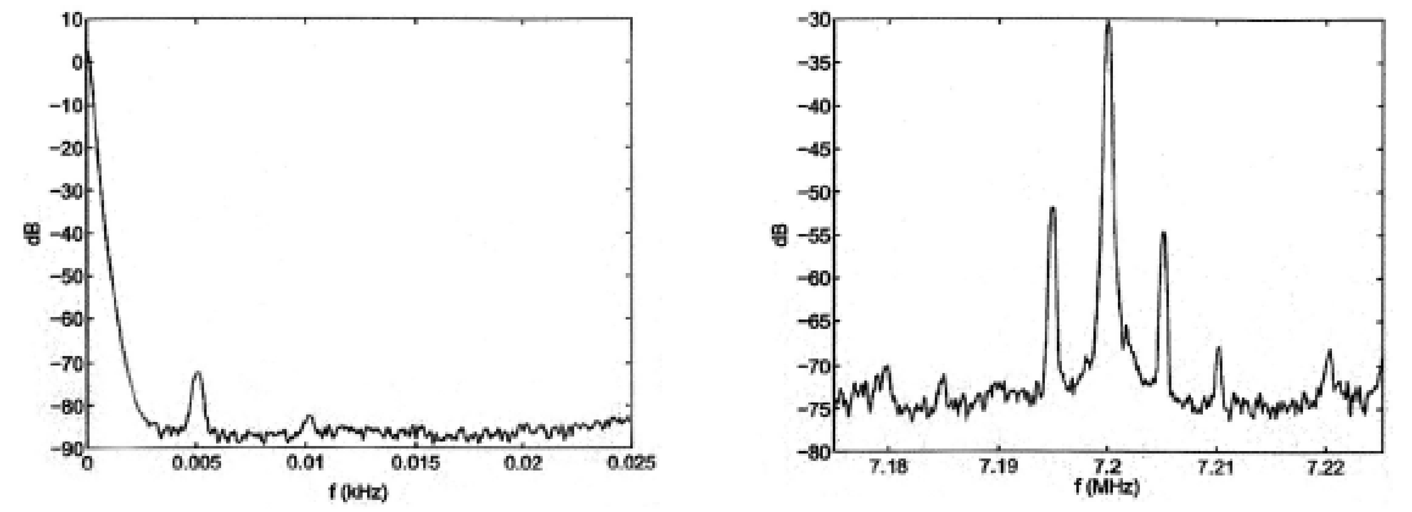


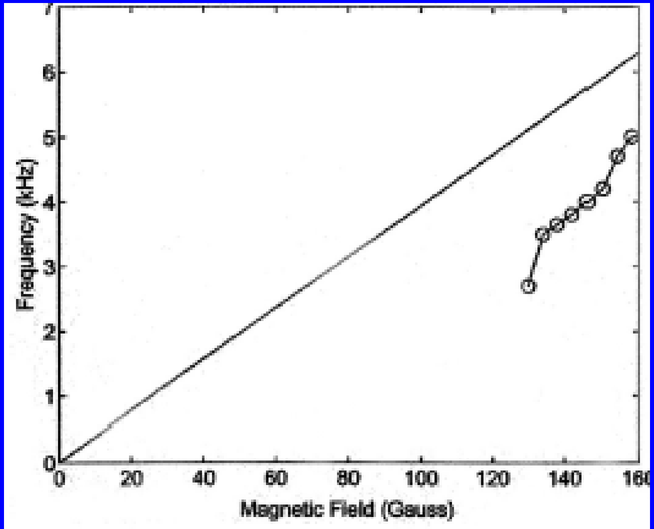
Pump: 25 MHz; gas: He

The B-field was very non-uniform, so no definite conclusions were possible.

Boswell, Sutherland, Charles, Squire, Chang-Diaz, Glover, Jacobson, Chavers, Bengtson, Bering, Goulding, and Light, Phys. Plasmas **11**, 5125 (2004).

Decay into ion cyclotron waves





Sutherland et al. saw EICW waves and explained them by a complicated 4-wave process involving filamentation of the helicon pump.

O. Sutherland, M. Giles, and R. Boswell, Phys. Rev. Lett. **94**, 205002 (2005).

A more definitive experiment on parametric instabilities in helicon discharges

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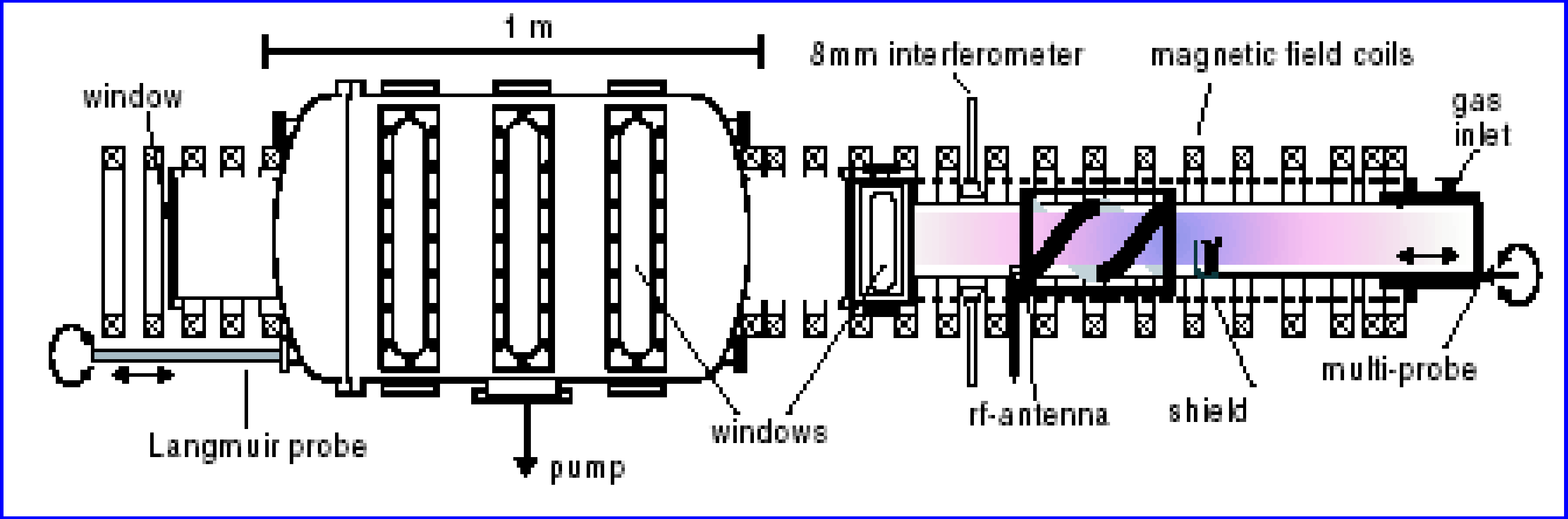
Lorenz, Krämer, Selenin, and Aliev* used:

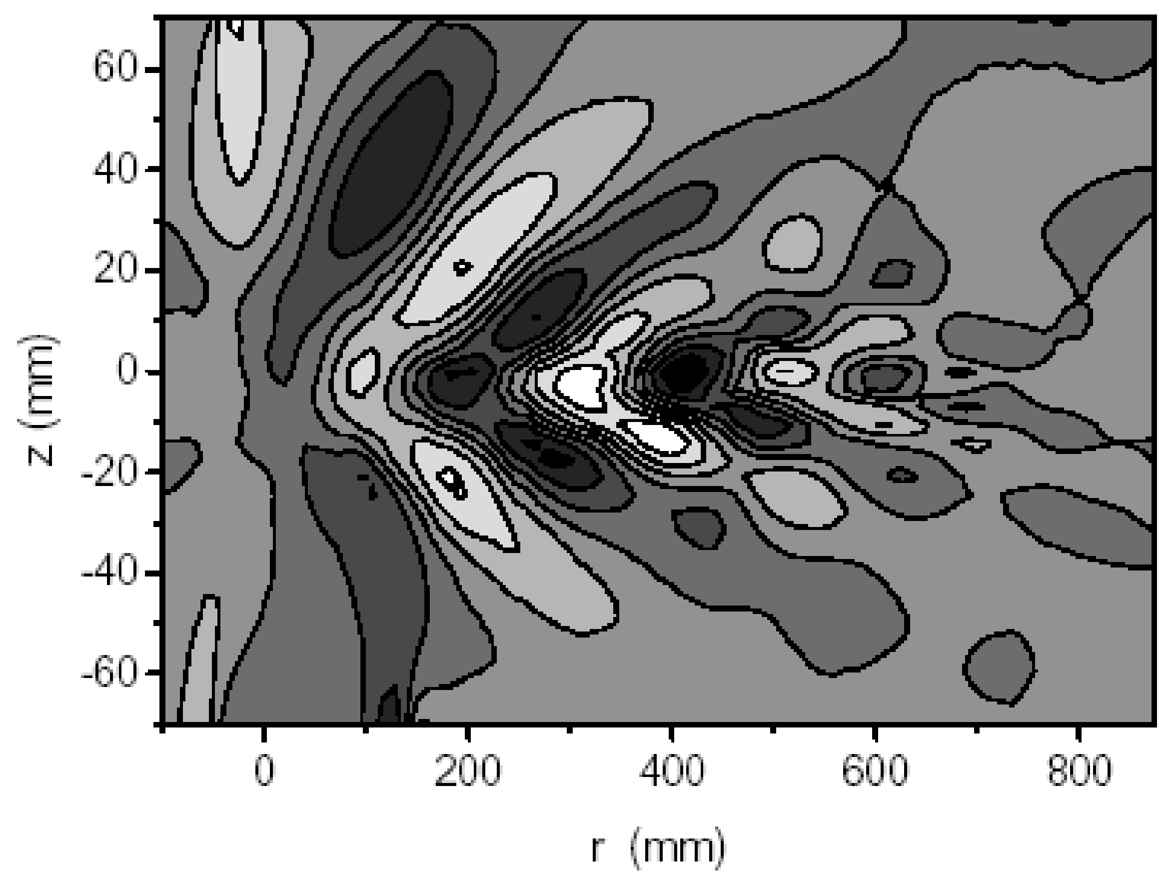
1. Test waves in a pre-formed plasma
2. An electrostatic probe array for ion oscillations
3. Capacitive probes for potential oscillations
4. Microwave backscatter on fluctuations
5. Correlation techniques to bring data out of noise

*B. Lorenz, M. Krämer, V.L. Selenin, and Yu.M. Aliev, Plasma Sources Sci.Technol. **14** (2005).

Krämer's machine

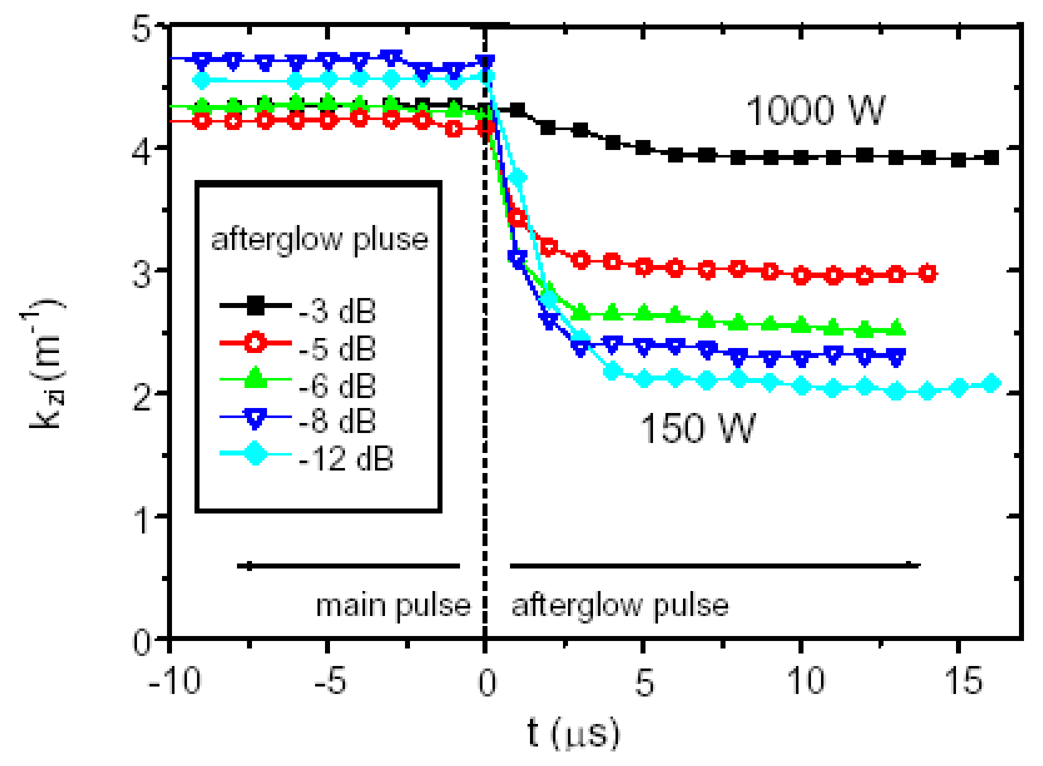


A helicon wave at one instant of time



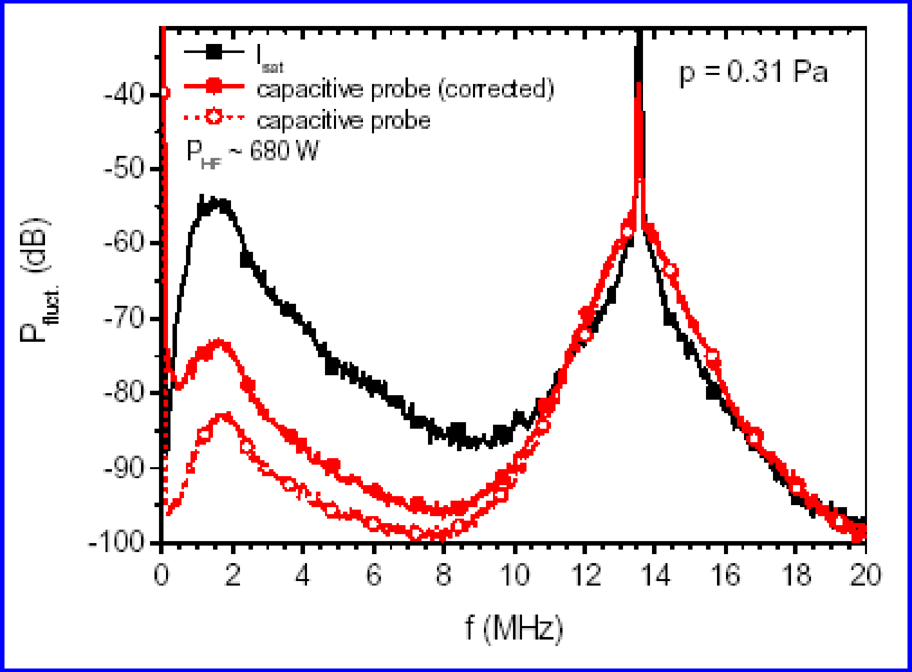
Note that the scales are very different!

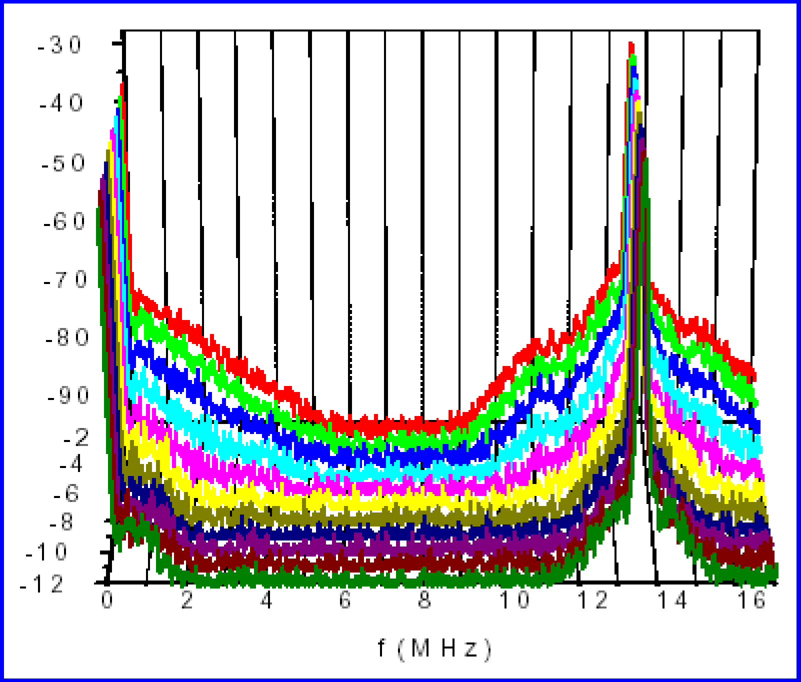
Damping rate in the helicon afterglow



The damping rate increases with P_{rf}, showing the existence of a nonlinear damping mechanism.

Excitation of a low-frequency wave





The LF wave is larger with the e.s. probe than with the capacitive probe, showing that the wave is electrostatic.

As P_{rf} is raised, the sidebands get larger due to the growth of the LF wave.

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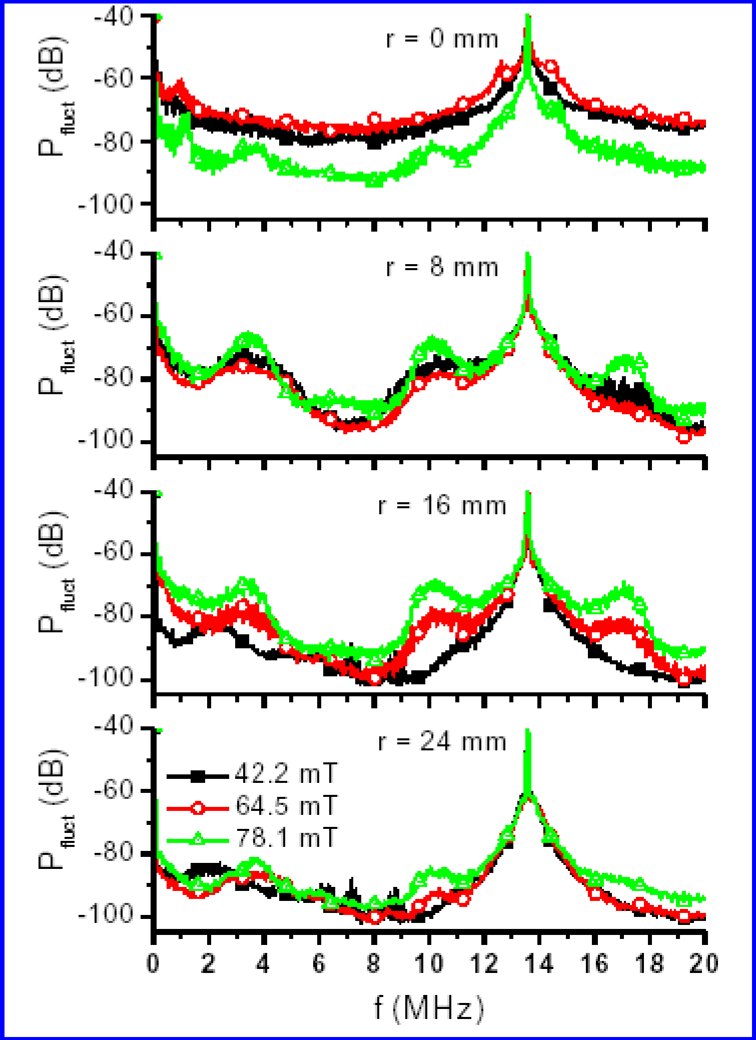
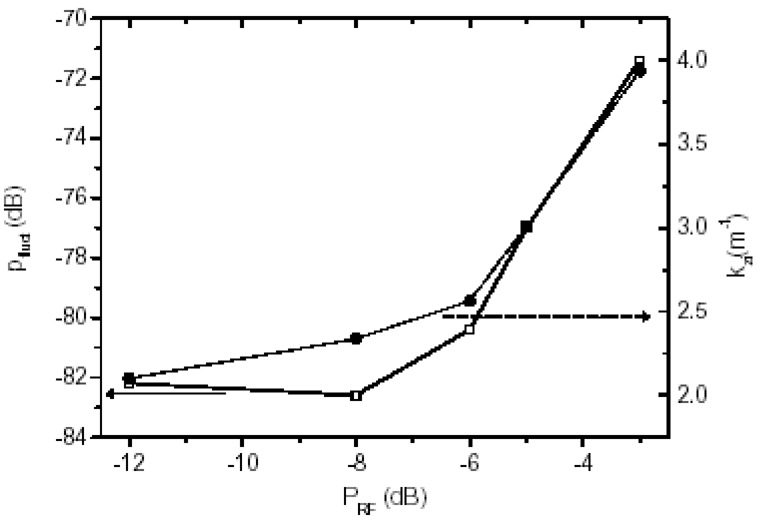
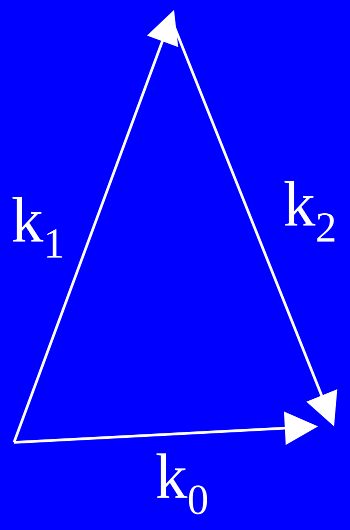
Oscillations are localized in radius and B-field





The fluctuation power and the helicon damping rate both increase nonlinearly with rf power.

Proposed parametric matching conditions



$$\omega_0 = \omega_1 + \omega_2$$

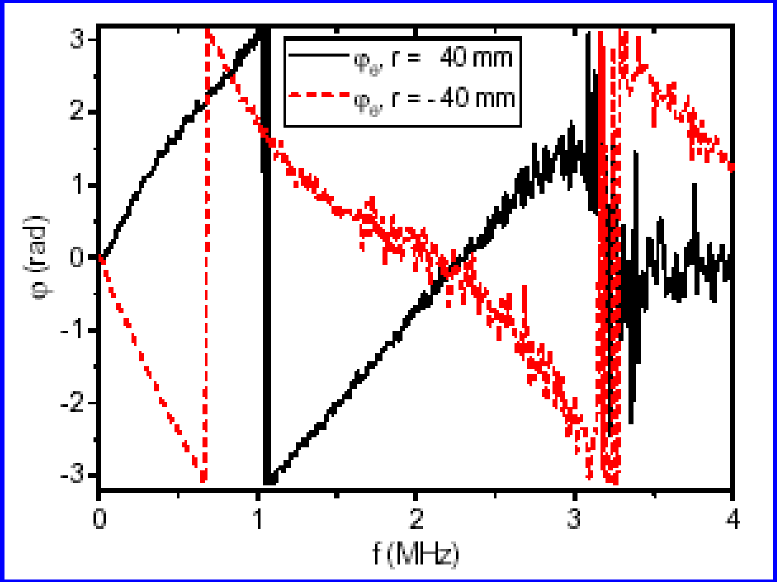
$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$$

$$\mathbf{k}_{\perp 0} = \mathbf{k}_{\perp 1} + \mathbf{k}_{\perp 2} \approx 0, \quad \mathbf{k}_{\perp 1} \approx -\mathbf{k}_{\perp 2}$$

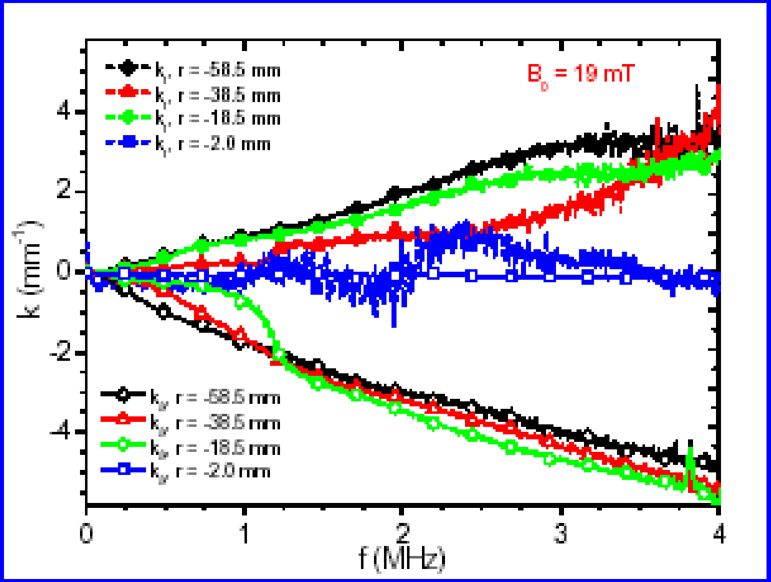
k_0 = helicon wave, k_1 = ion acoustic wave
k_2 = Trivelpiece-Gould mode

This was verified experimentally.

Evidence for m = 1 ion acoustic wave



The cross phase between two azimuthal probes reverses on opposite sides of the plasma.



k_θ is larger than k_r, and both increase linearly with frequency.

From the slope one can calculate the ion acoustic velocity, which yields T_e = 2.8 eV, agreeing with 3 eV from probe measurements.

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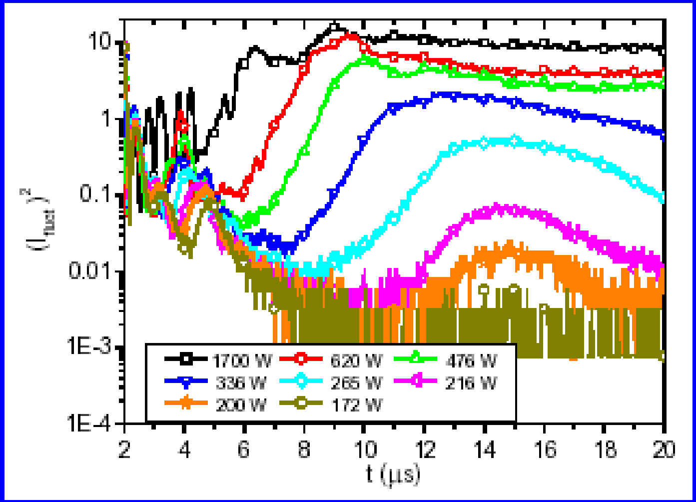
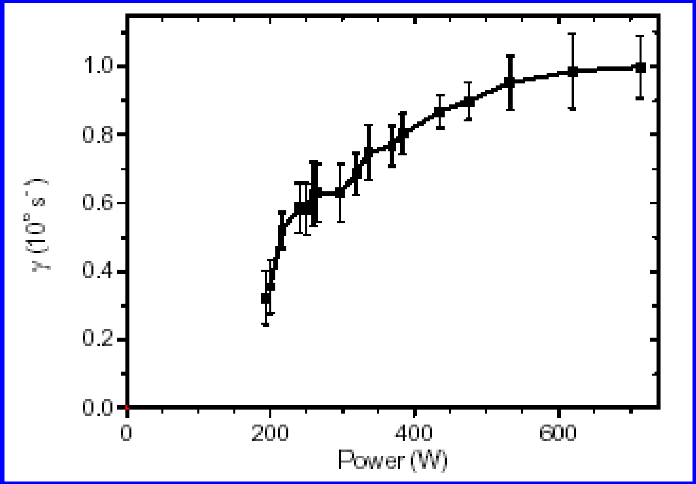
With a test pulse, the growth rate can be seen directly

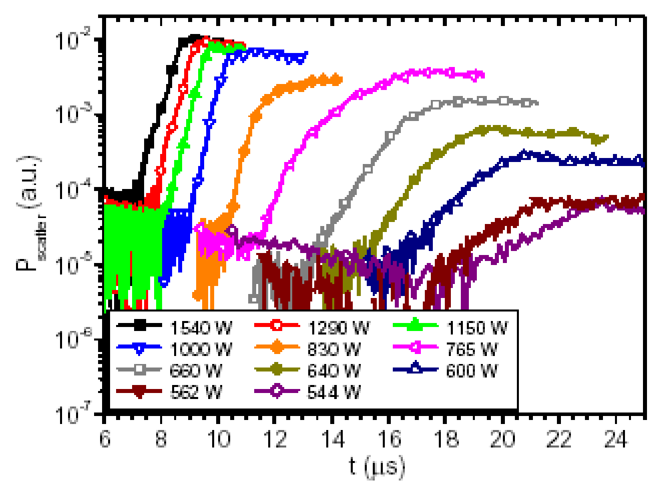
From probe data

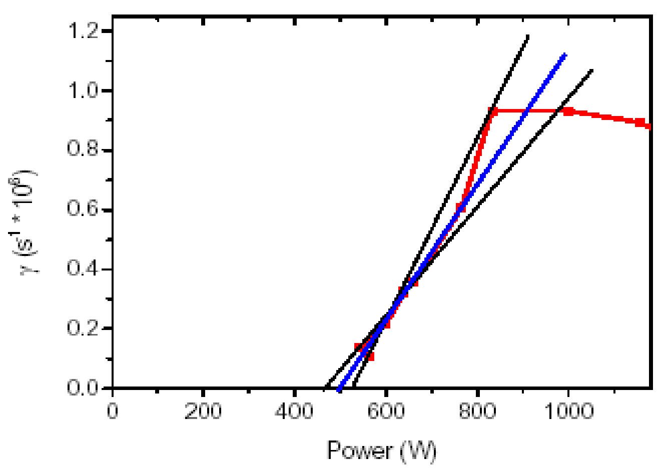




Growth rate vs. power

From μwave backscatter





Growth rate vs. power

Conclusion on parametric instabilities

Kramer et al. showed definitively that damping of helicon waves by parametric decay occurs near the axis. They identified the decay waves, checked the energy balance, and even checked the calculated instability threshold and growth rate.

However, this process is too small to be the major source of energy transfer from the antenna to the plasma. It is still unknown what happens under the antenna, where it is difficult to measure. It could be that the waves observed were actually created under the antenna but measured downstream.

Conclusion on nonlinear effects in low-temperature plasma physics

We have given three examples of interesting, fundamental plasma physics problems that occur in partially ionized plasmas. Connection is made with concepts learned from high-temperature, fusion-type plasmas. Low-temperature plasma physics does not have to be dirty science; there are clean, challenging problems to be solved.

The End