High beta, hot ion, magnetized laboratory plasmas in LAPD and ETPD: prospects for studying processes relevant to space and astrophysical plasmas

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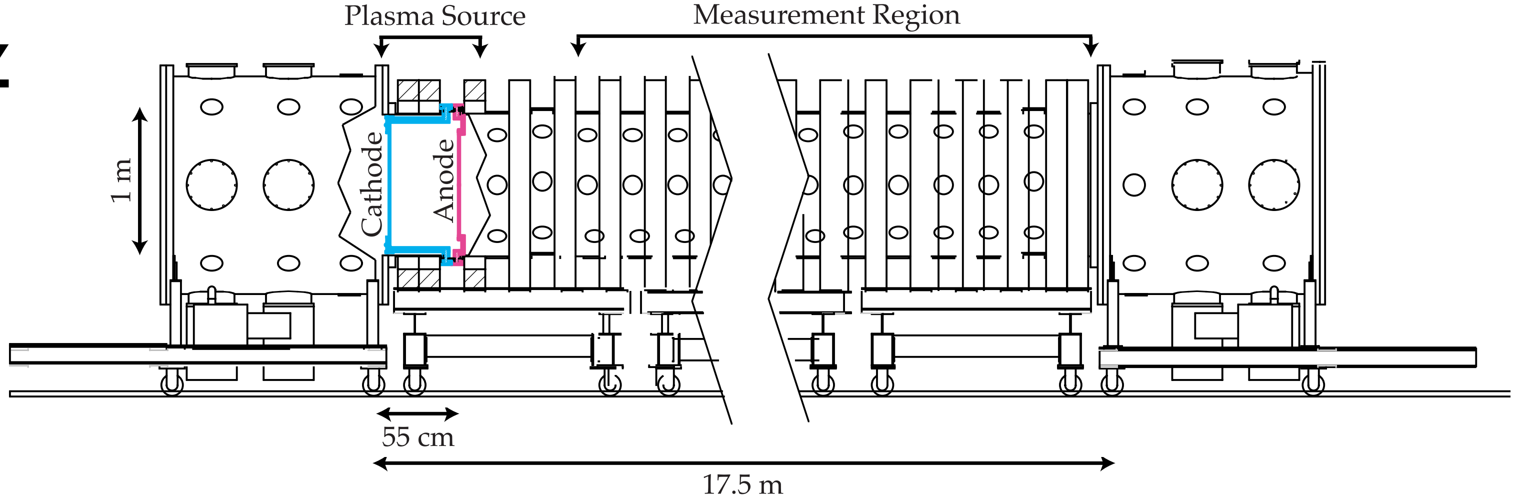
Summary/Outline

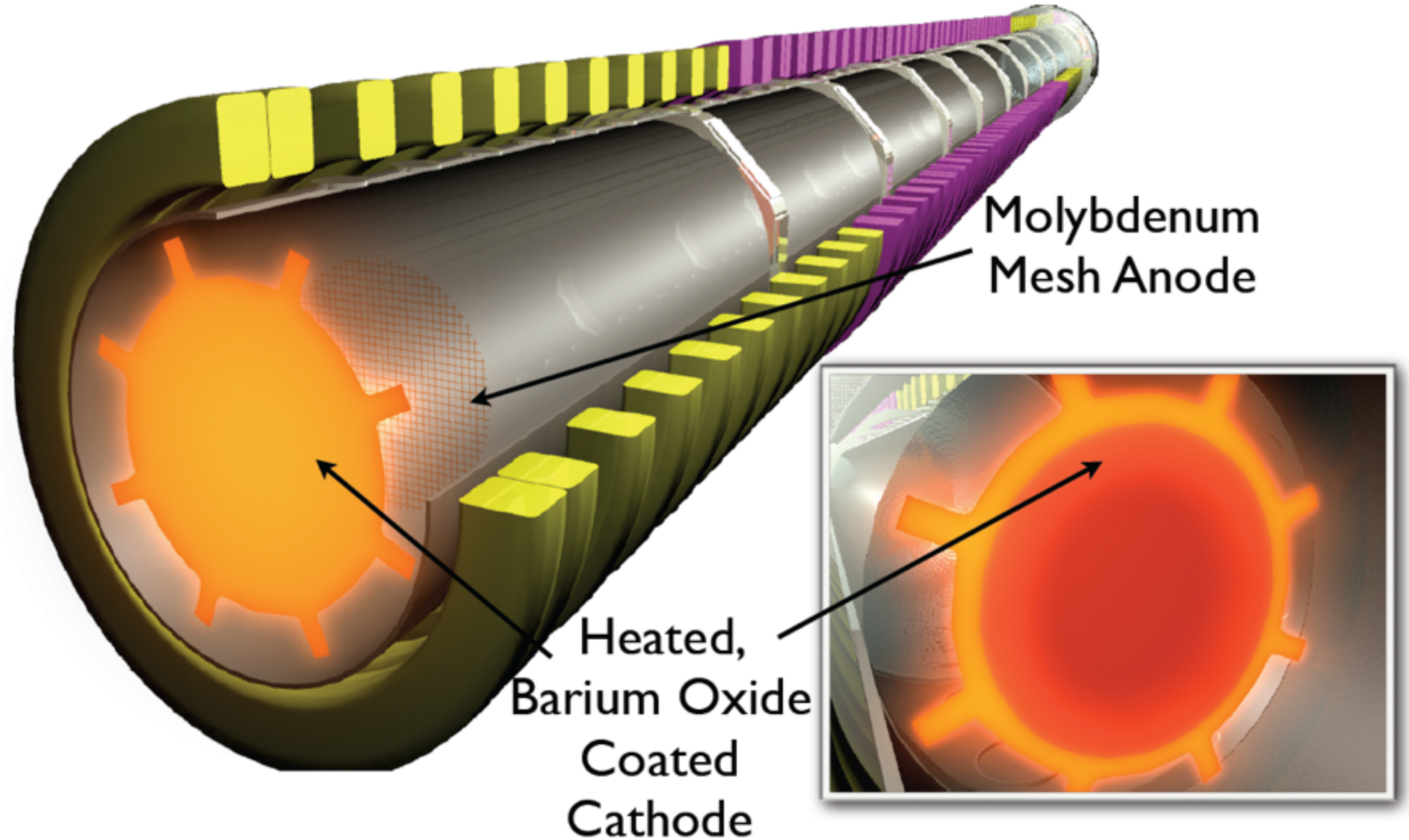
- Update on Nonlinear Alfven wave studies on LAPD (excitation of sound waves, evidence for decay instability)
- New LaB_6 cathode source added to LAPD; prototyped in the Enormous Toroidal Plasma Device
  - Order of magnitude increase in density, electron temperature increased by factor of 2, increased electron-ion coupling results in $T_i \sim T_e$
- Warm ions provides opportunity to study ion kinetic effects in waves and instabilities: e.g. FLR effects on Alfvén wave propagation; ion cyclotron absorption; modification to nonlinear Alfven wave interactions
- With lower field, plasma beta can be increased substantially to study, e.g., modifications to Alfvén wave dispersion and damping (e.g. ion Landau/Barnes damping). Can high-beta temperature anisotropy driven instabilities (mirror and firehose) be observed in these plasmas?

The LArge Plasma Device (LAPD) at UCLA

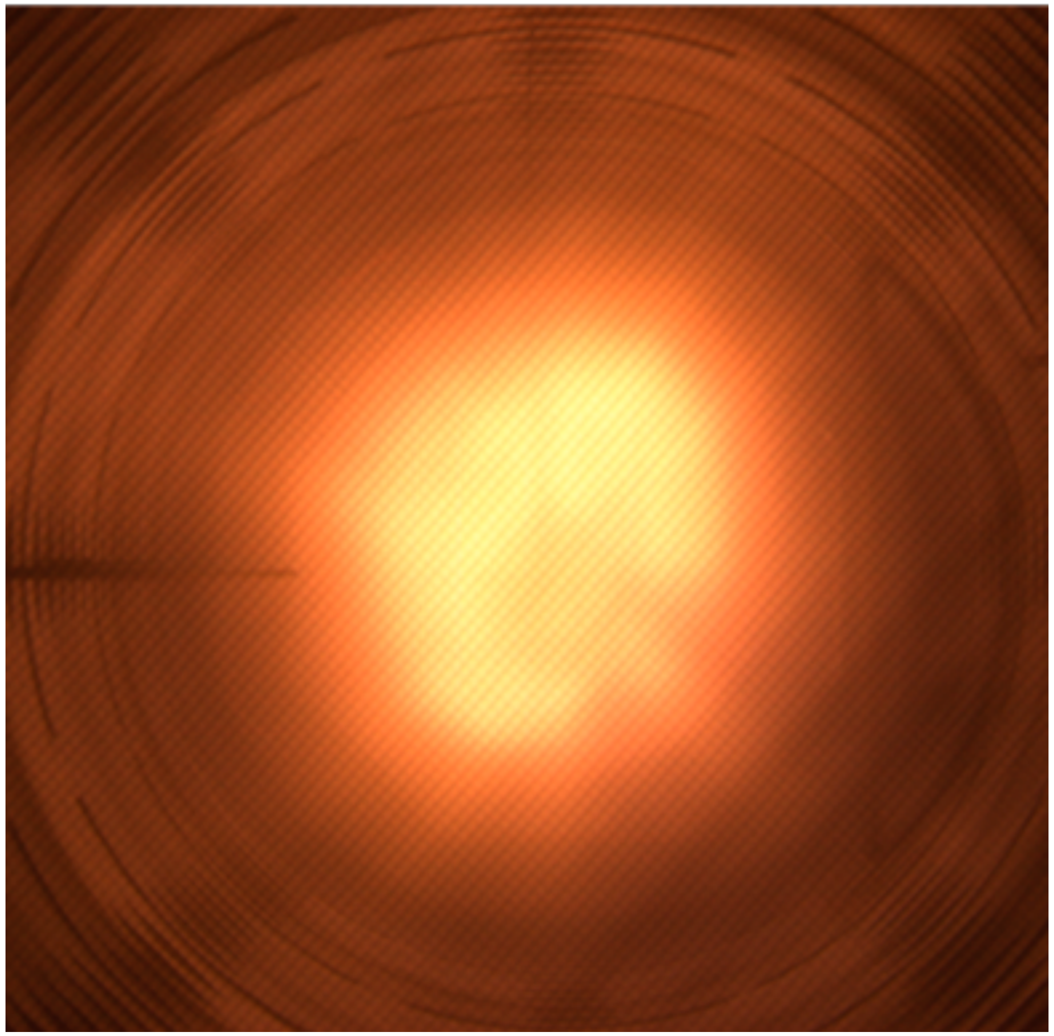
- US DOE/NSF sponsored user facility (http://plasma.physics.ucla.edu)
- Solenoidal magnetic field, cathode discharge plasma
- $0.5 < B < 2\,\mathrm{kG}, n_e \sim 10^{12}\,\mathrm{cm}^{-3}, T_e \sim 5\,\mathrm{eV}, T_i \sim 1\,\mathrm{eV}$
- Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz

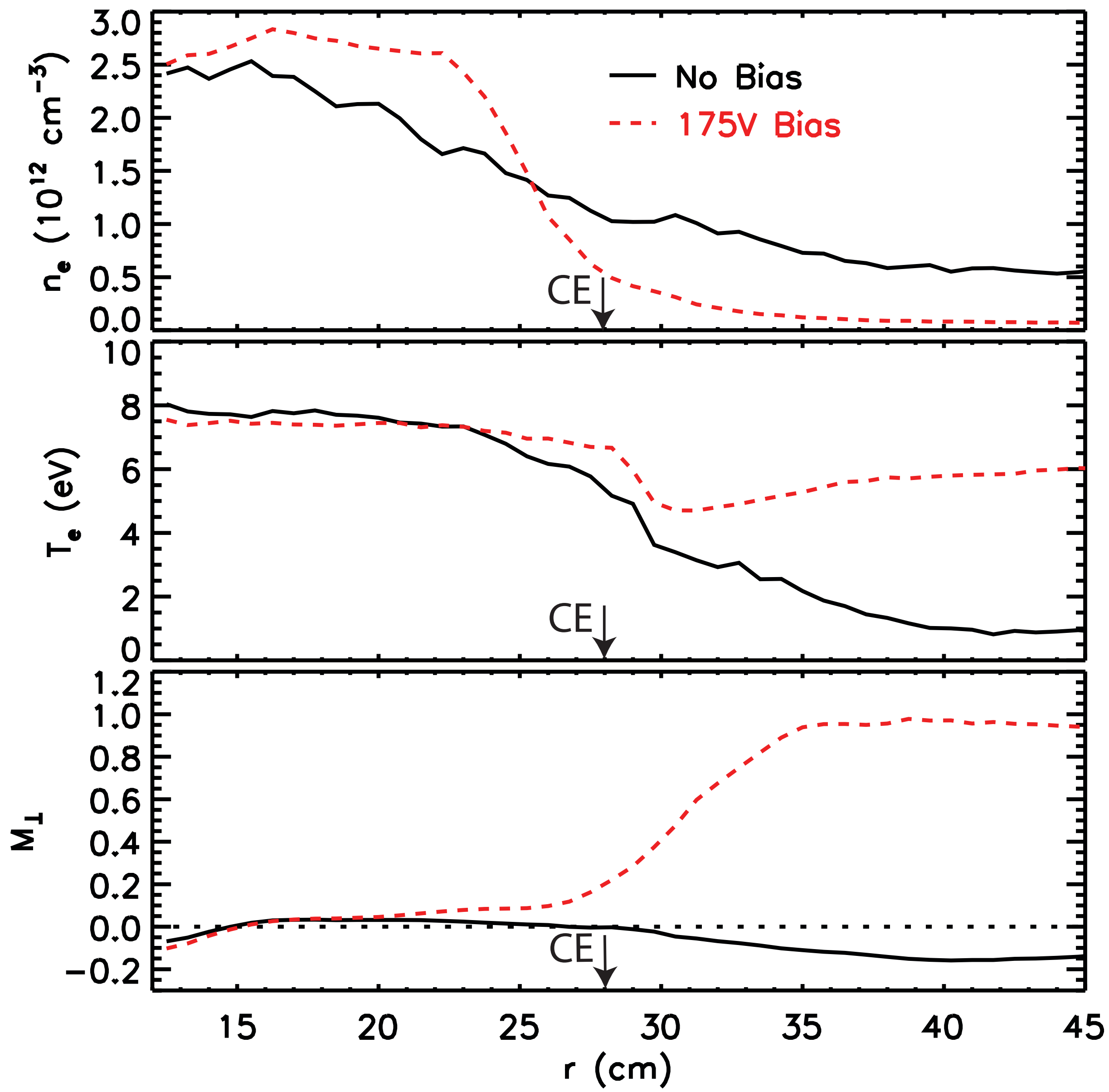


LAPD BaO Plasma source



BaO Cathode: LAPD Plasma Profiles





- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm
- Broadband turbulence generally observed in the edge region (localized to pressure gradient)

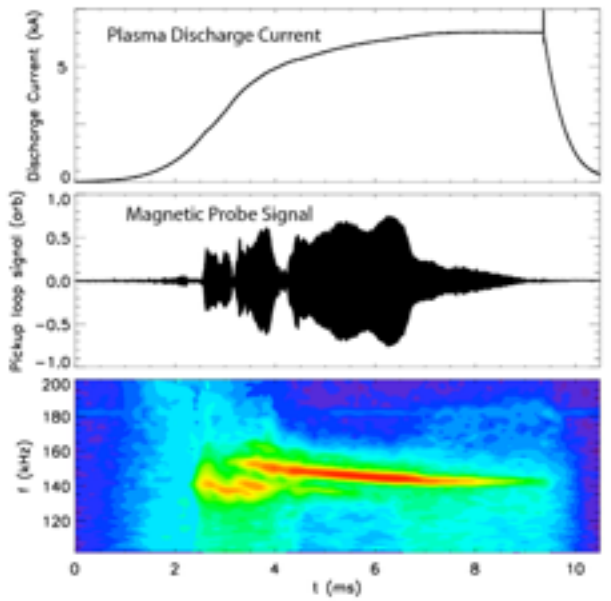
* Carter, et al, PoP 16, 012304 (2009)

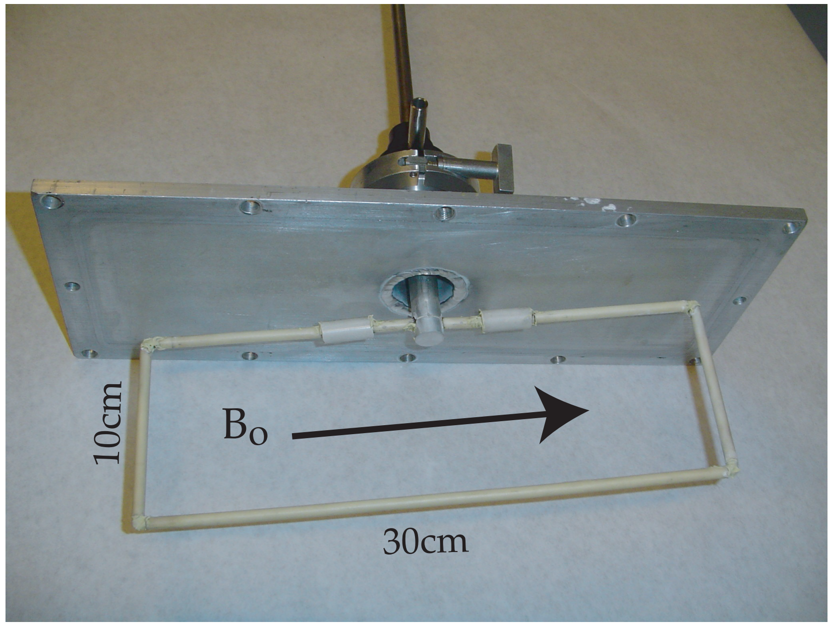
LAPD BaO Plasma Parameters: Collisional for long-wavelength modes, kinetic effects important for Alfvén waves

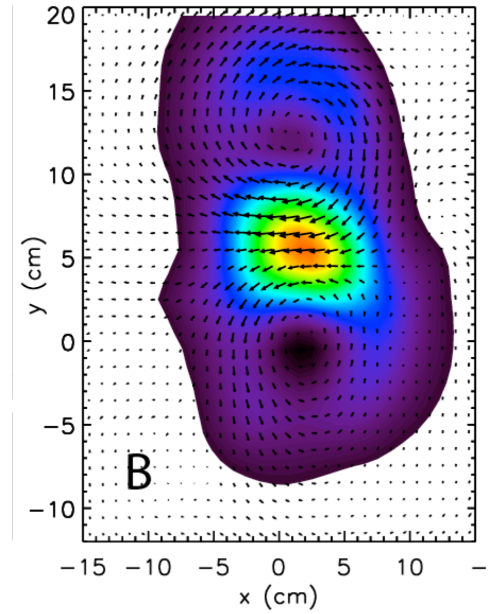
$$\Omega_i \sim 400\text{kHz}$$
$$\nu_{ei} \sim 3\text{MHz}$$
$$\nu_{ii} \sim 300\text{kHz}$$
$$\omega_\text{A} \sim 200\text{kHz}$$
$$L_\| \sim 18\text{m}$$
$$L_\perp \sim 50\text{cm}$$
$$\lambda_\text{mfp} \sim 20\text{cm}$$
$$\rho_i \sim 2\text{mm}$$
$$\rho_s \sim 5\text{mm}$$
$$\delta_e \sim 5\text{mm}$$
$$v_\text{th,e} \sim 1 \times 10^8\text{cm/s}$$
$$v_\text{A} \sim 1 \times 10^8\text{cm/s}$$
$$\beta \sim m_e/m_i \sim 1 \times 10^{-4}$$

- Coulomb collisionality dominates (50%+ ionized)
- Long-wavelength modes (drift-waves), $L_\|/\lambda_{mfp} \sim 100$: fluid theory should work well
- Short wavelength modes (e.g. Alfvén waves), collisionless effects important (Landau damping explains observed damping rate of kinetic Alfvén waves)

Nonlinear Alfvén wave interaction experiments in LAPD



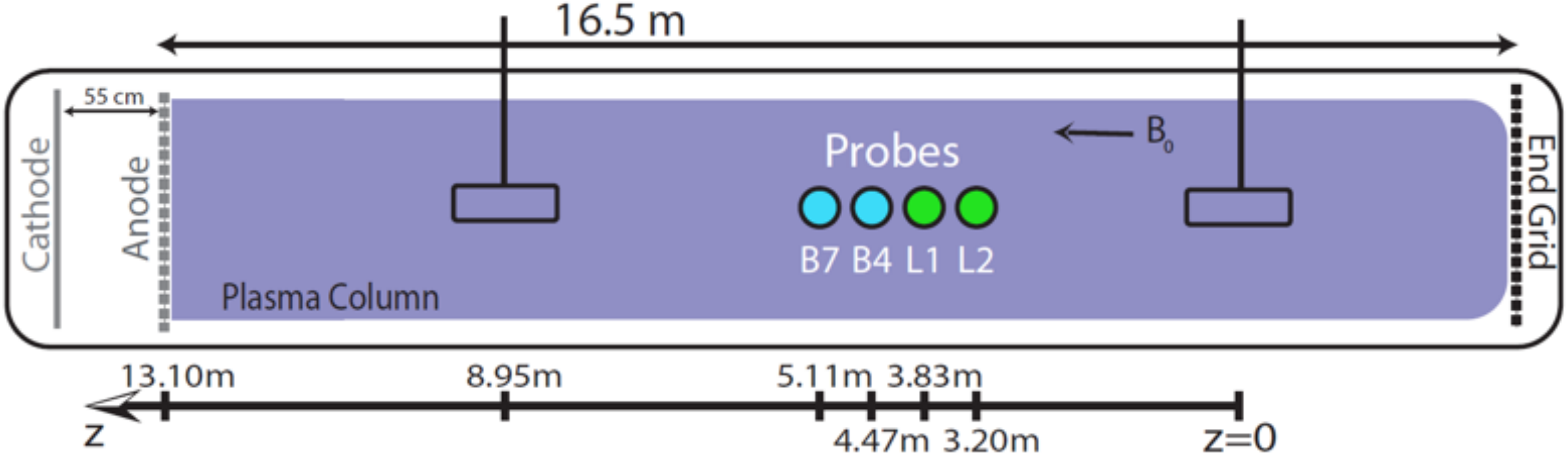




- Generate large amplitude Alfvén waves using antennas (& resonant cavities), study three-wave interactions
  - co-propagating waves interact to: drive quasimodes [Carter, et al. PRL 2006], excite/control drift-wave instabilities [Auerbach, et al., PRL 2010]
  - counter-propagating waves interact to generate daughter Alfvén waves [Howes, et al., PRL 2012], sound waves [Dorfman, et al., PRL 2013]

Nonlinear excitation of sound waves by AWs

- Study three-wave process at heart of parametric decay by interacting two slightly-detuned, counter-propagating AWs



[Dorfman & Carter, PRL 110, 195001 (2013)]

Nonlinear excitation of sound waves by AWs

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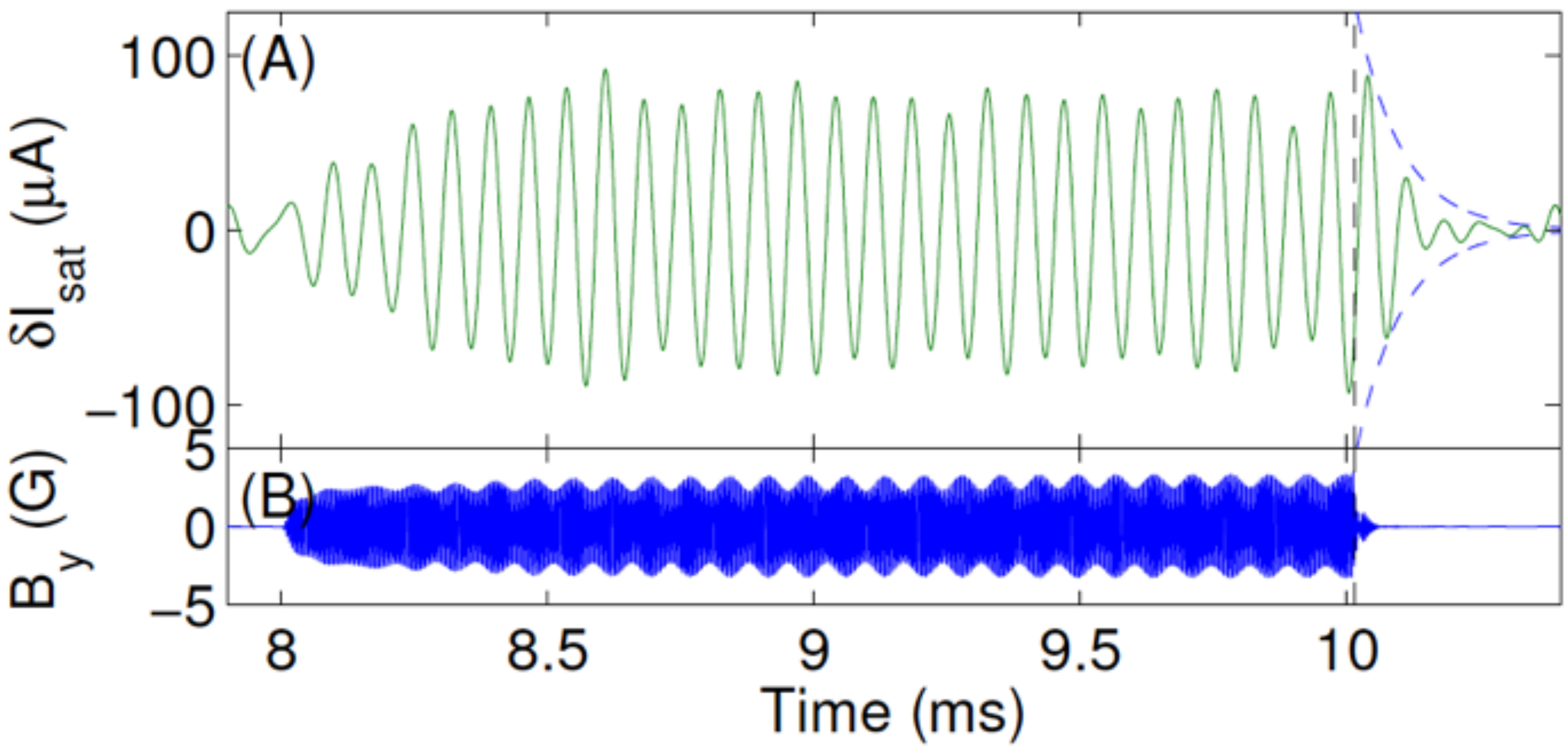
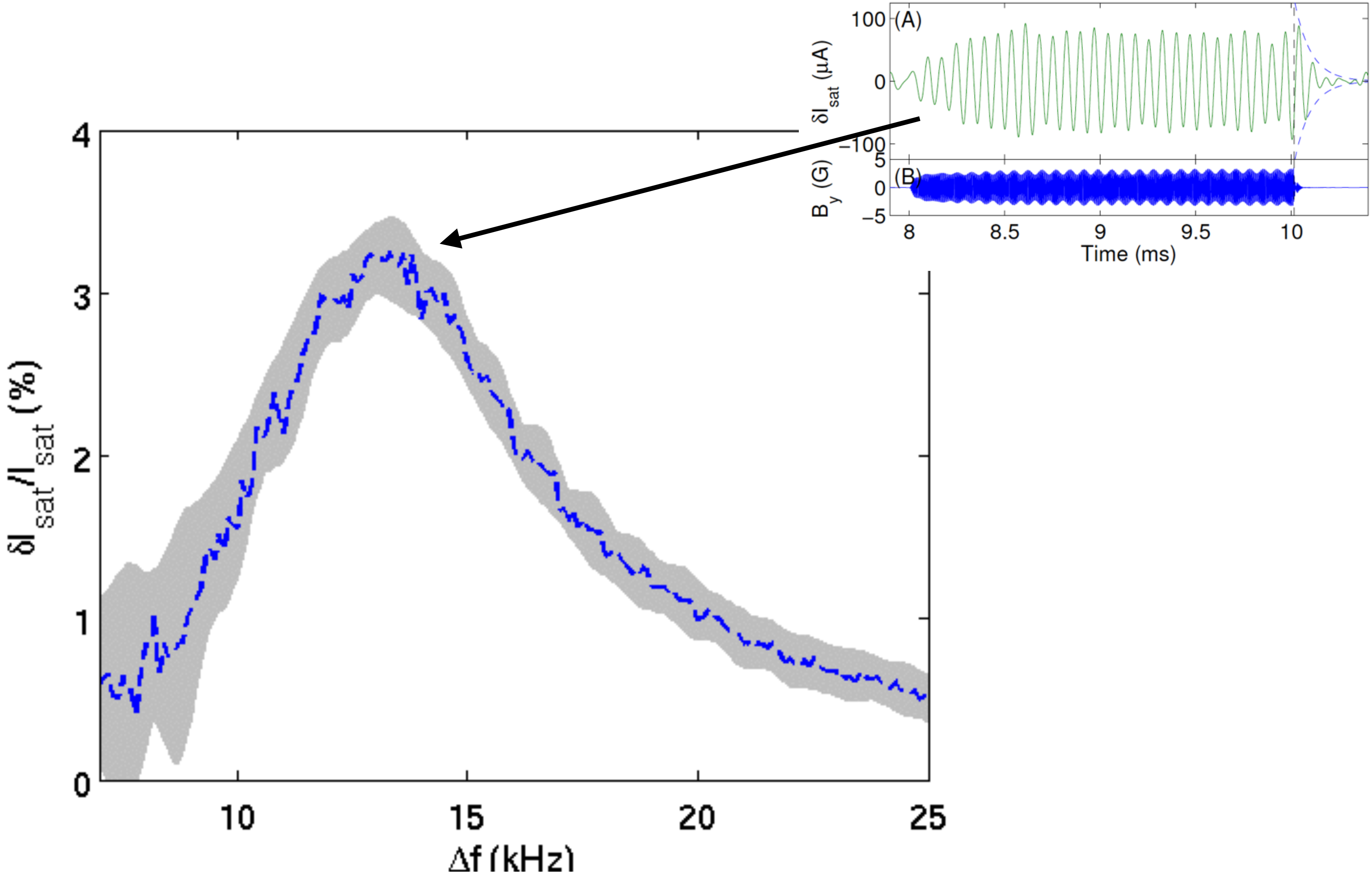


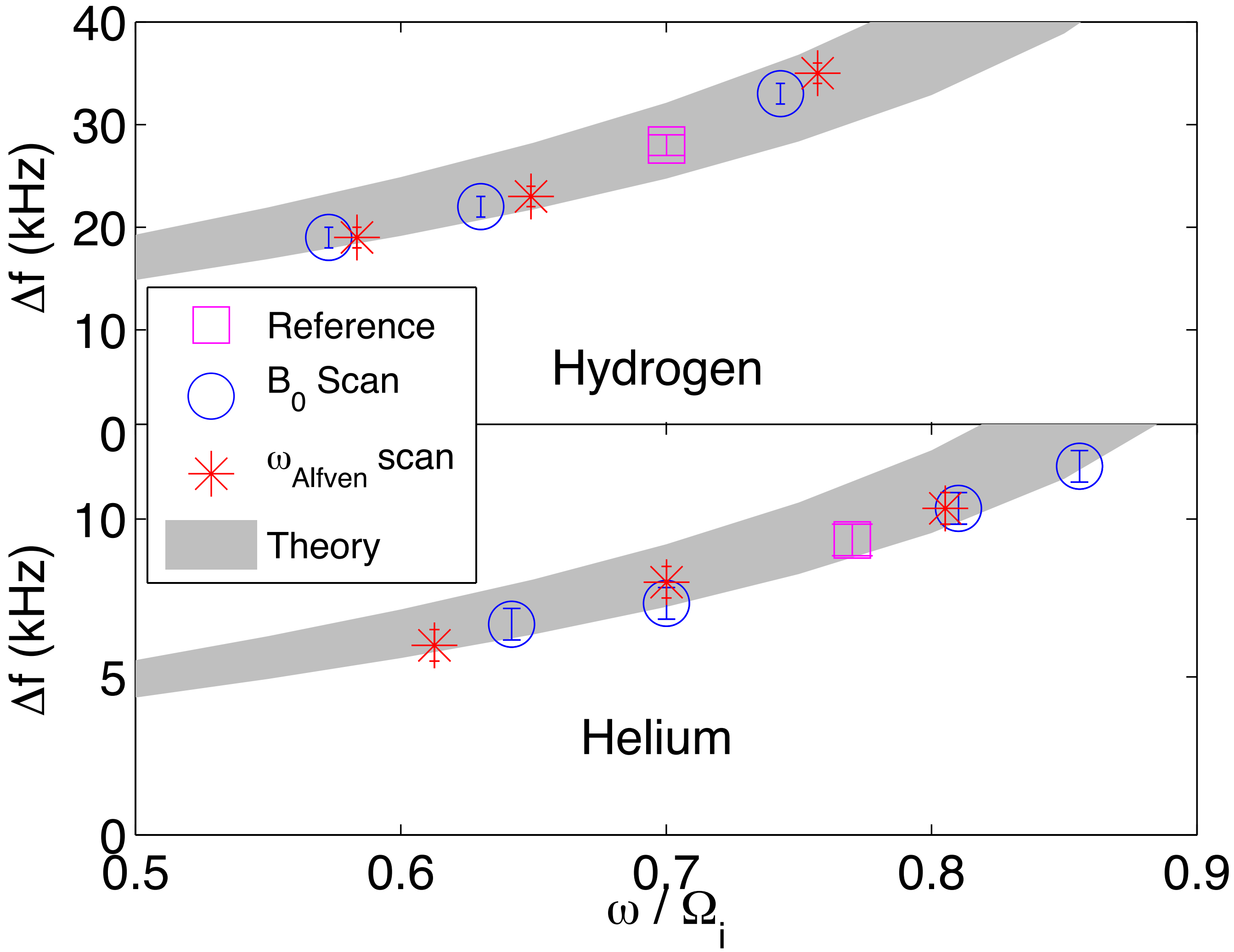
- Strong nonlinear response at beat frequency observed; response persists after nonlinear drive is turned off: evidence for excitation of damped linear wave

[Dorfman & Carter, PRL 110, 195001 (2013)]

Variation of nonlinear response with beat frequency: consistent with resonance with linear wave



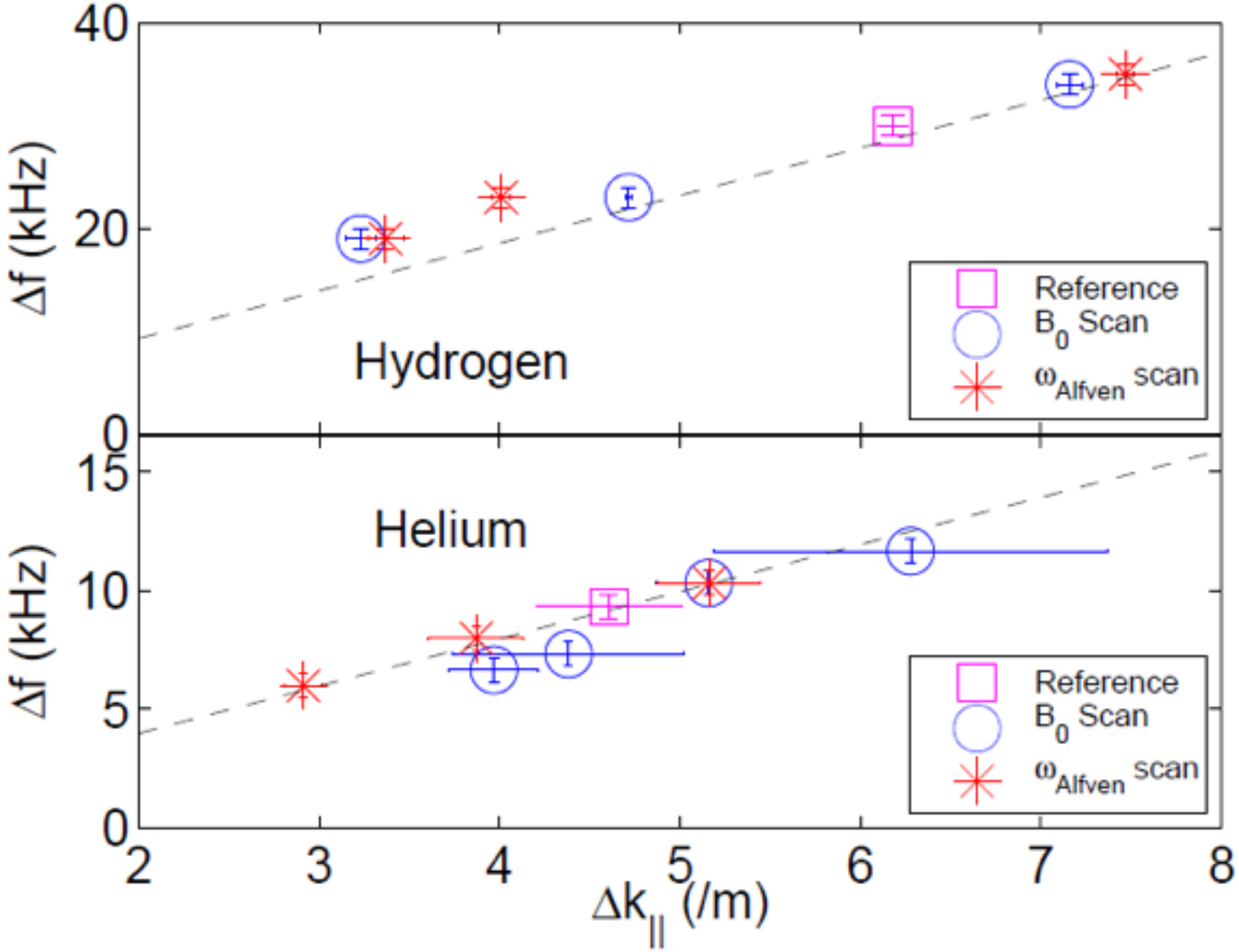
Variation in peak of resonant response consistent with nonlinear excitation of sound waves



$$\Delta\omega = \frac{2\omega\sqrt{\beta}}{\sqrt{1 + (k_\perp \rho_s)^2 - \left(\frac{\omega}{\Omega_i}\right)^2}}$$

- Beat-wave response peaks at beat frequency consistent with simple fluid model (three-wave matching KAW + KAW → Sound Wave)

Phase velocity/wavelength of nonlinearly driven response consistent with sound wave dispersion



$v_{ph} = 29.1 \pm 0.7$ km/s

Measured:
$T_e = 4.3 \pm 1.0$ eV

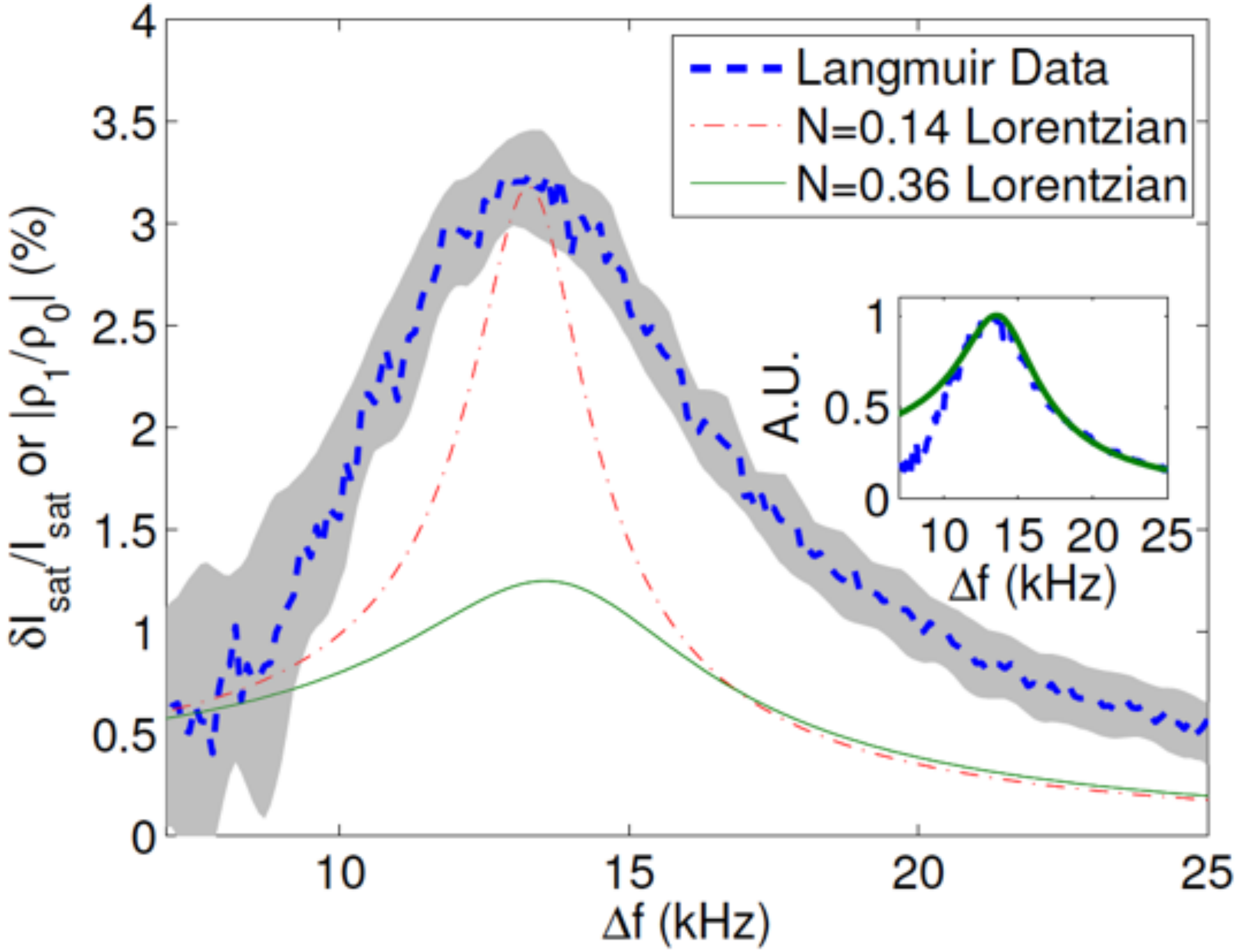
From v_{ph} (if $T_i = 2$ eV):
$T_e = 5.2 \pm 0.3$ eV

$v_{ph} = 12.5 \pm 0.3$ km/s

Measured:
$T_e = 4.3 \pm 0.9$ eV

From v_{ph} (if $T_i = 1$ eV):
$T_e = 4.4 \pm 0.3$ eV

Resonant response consistent with simple model (although damping not fully explained)

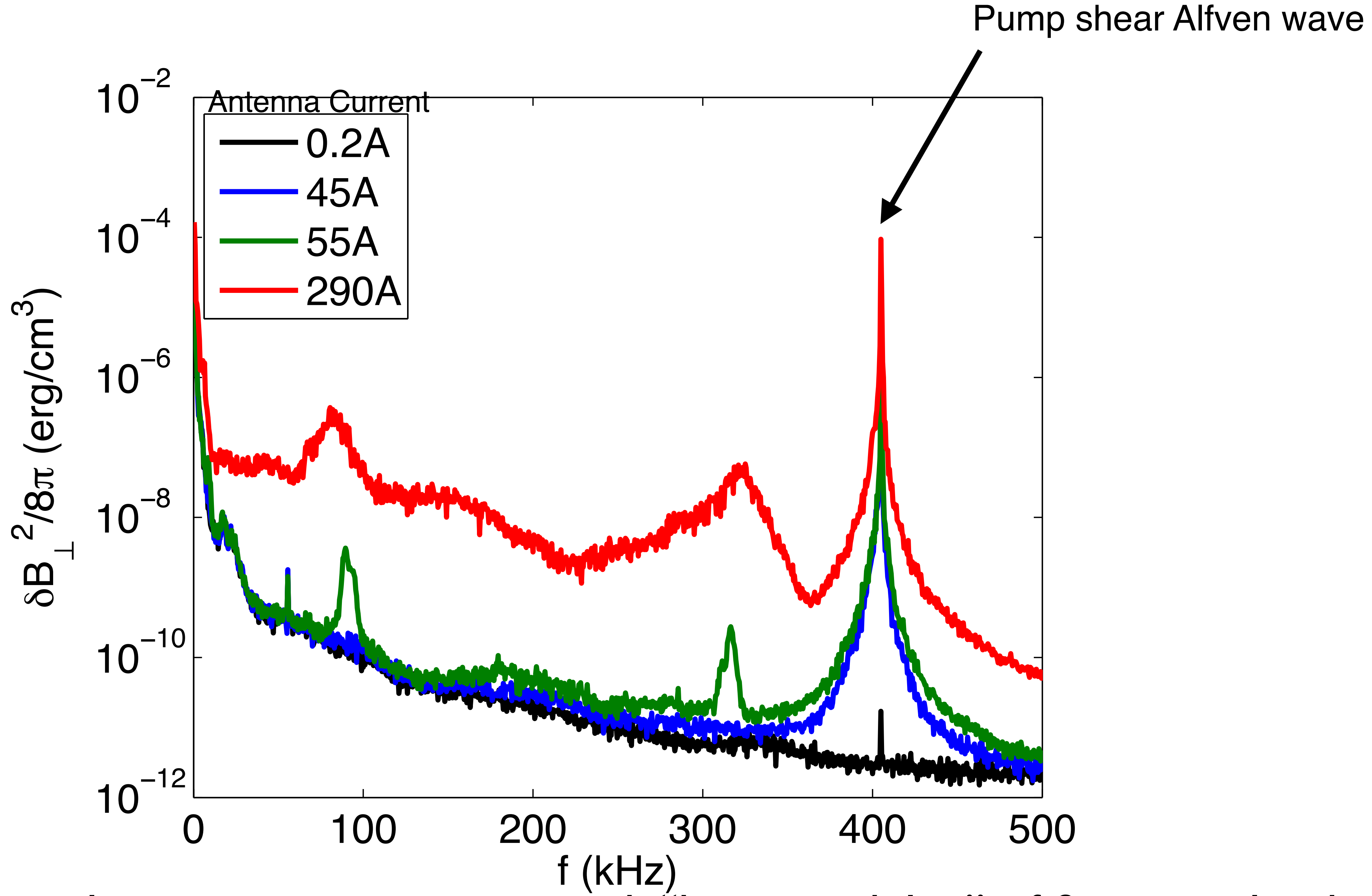


$$\frac{\partial^2 \rho}{\partial t^2} + \nu \frac{\partial \rho}{\partial t} - {C_s}^2 \frac{\partial^2 \rho}{\partial z^2} = \frac{\partial^2}{\partial z^2}\left[\frac{b_{\perp 1} \cdot b_{\perp 2}}{4\pi}\right]$$

$$\left|\frac{\rho_1}{\rho_D}\right| = \frac{1}{\sqrt{\left(1 - {\Omega_D}^2\right)^2 + N^2 {\Omega_D}^2}}$$

- Amplitude of peak predicted by theory (damping via ion-neutral collisions), but width not matched

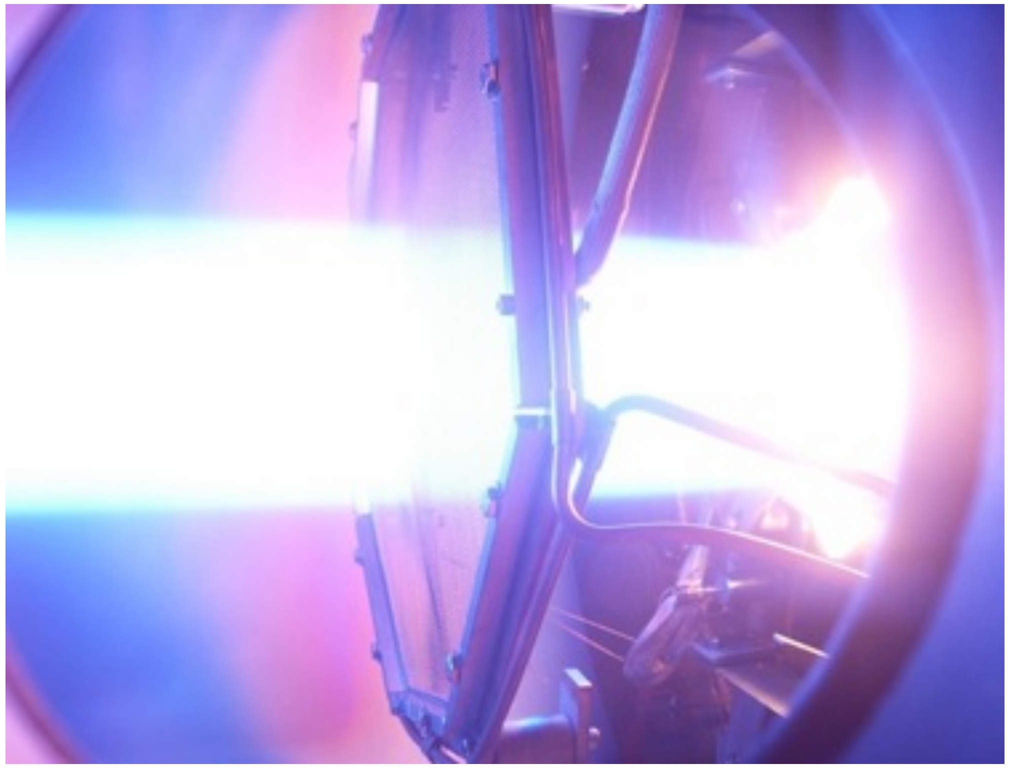
(Hot off the press) Possible evidence for decay instability : high frequency shear Alfvén waves in H plasmas with minority He

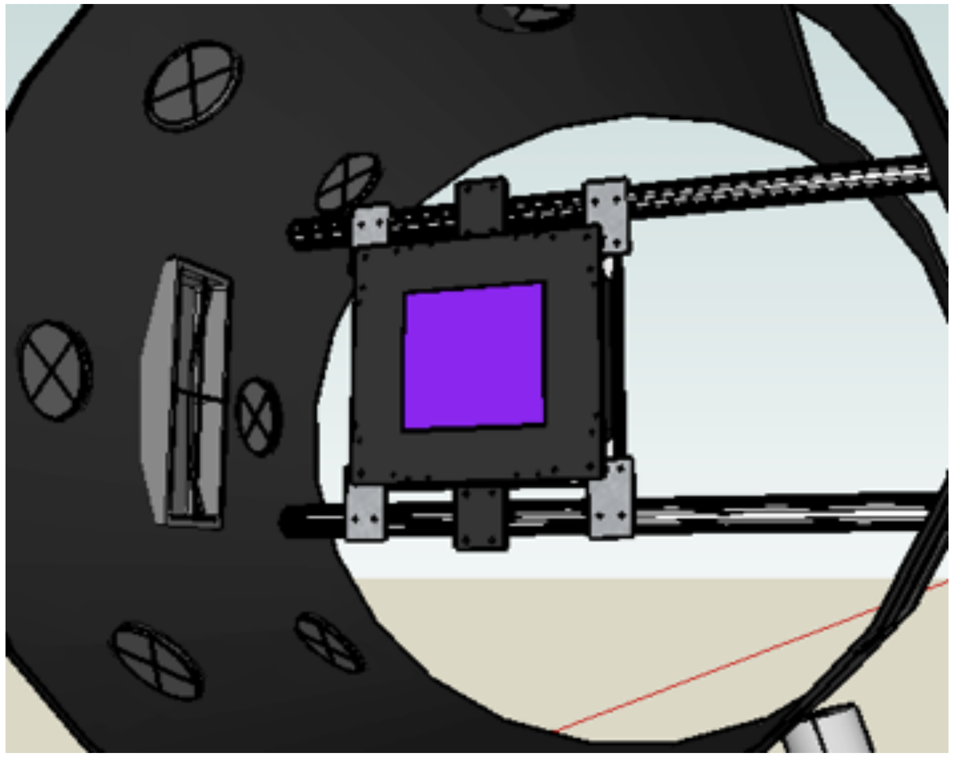


- At first glance, seems consistent with “beat instability” of finite amplitude shear waves (backward propagating lower sideband, quasimode at low frequency); See it at very high frequency (0.85*f_{ci})

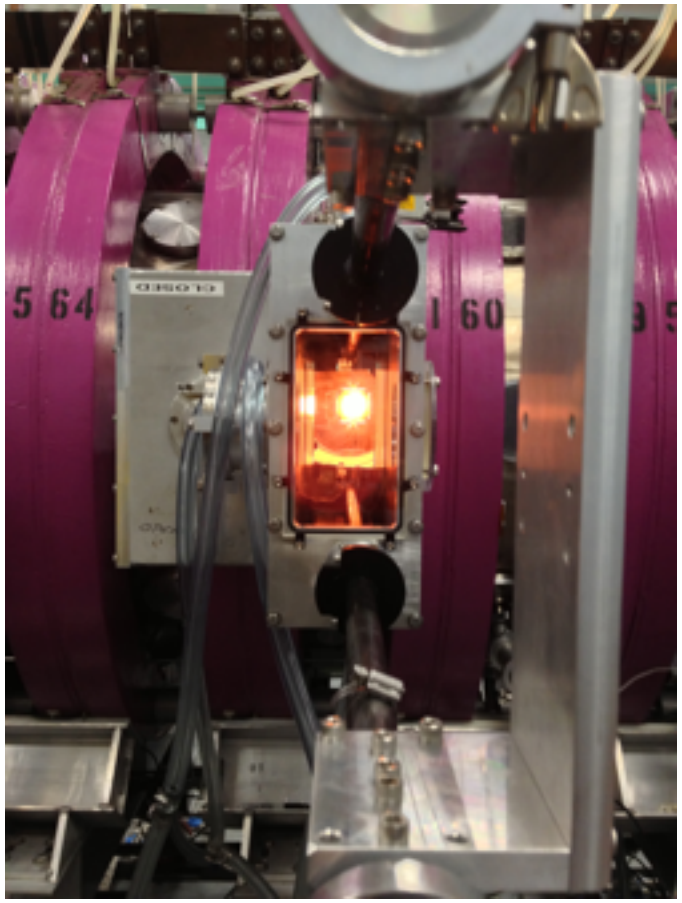
- Another possibility: low frequency wave is on He Alfvén wave branch in two-ion species plasma

New LAPD LaB_6 Cathode

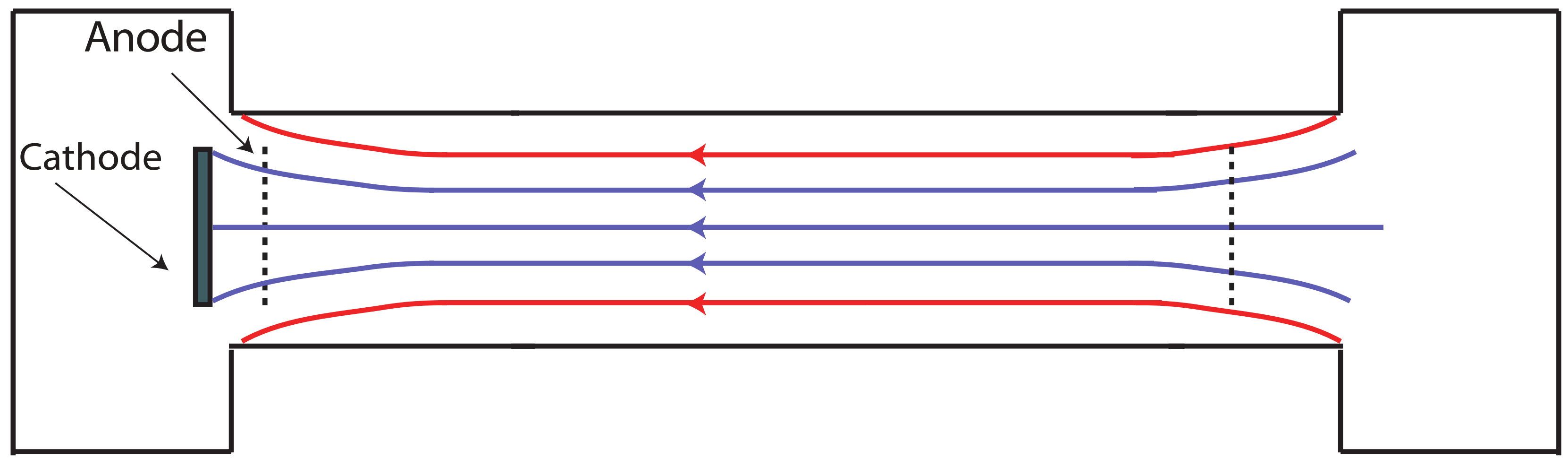


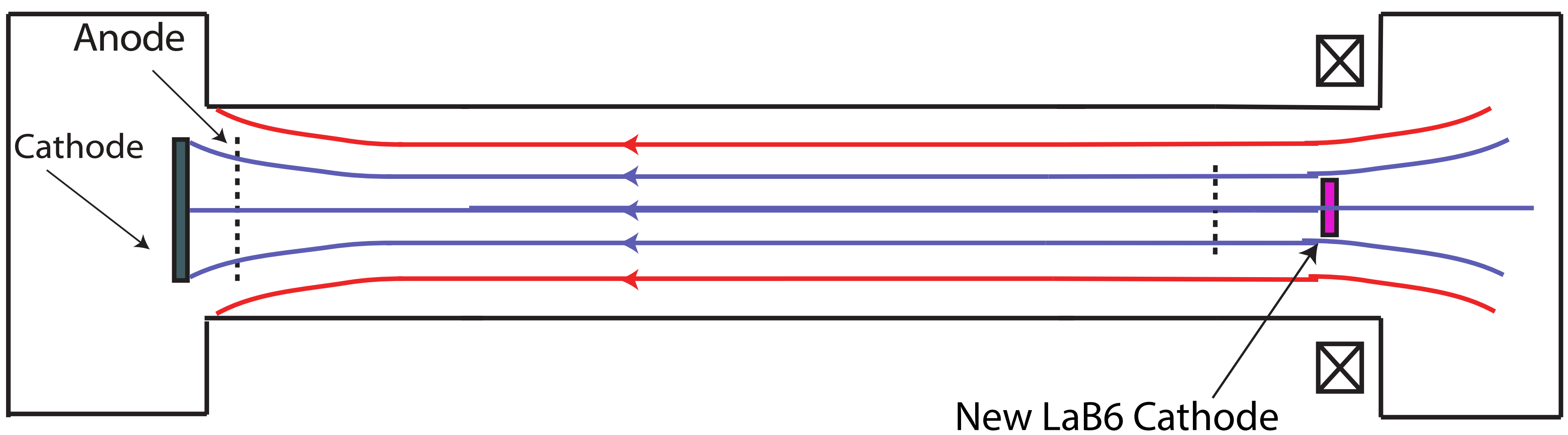


- Second plasma source added at south end; LaB6 cathode (1800K) much better electron emitter. 20cm square cathode.
- Operational as of Oct 2013.
- Order of magnitude increase in density, hotter electrons and ions



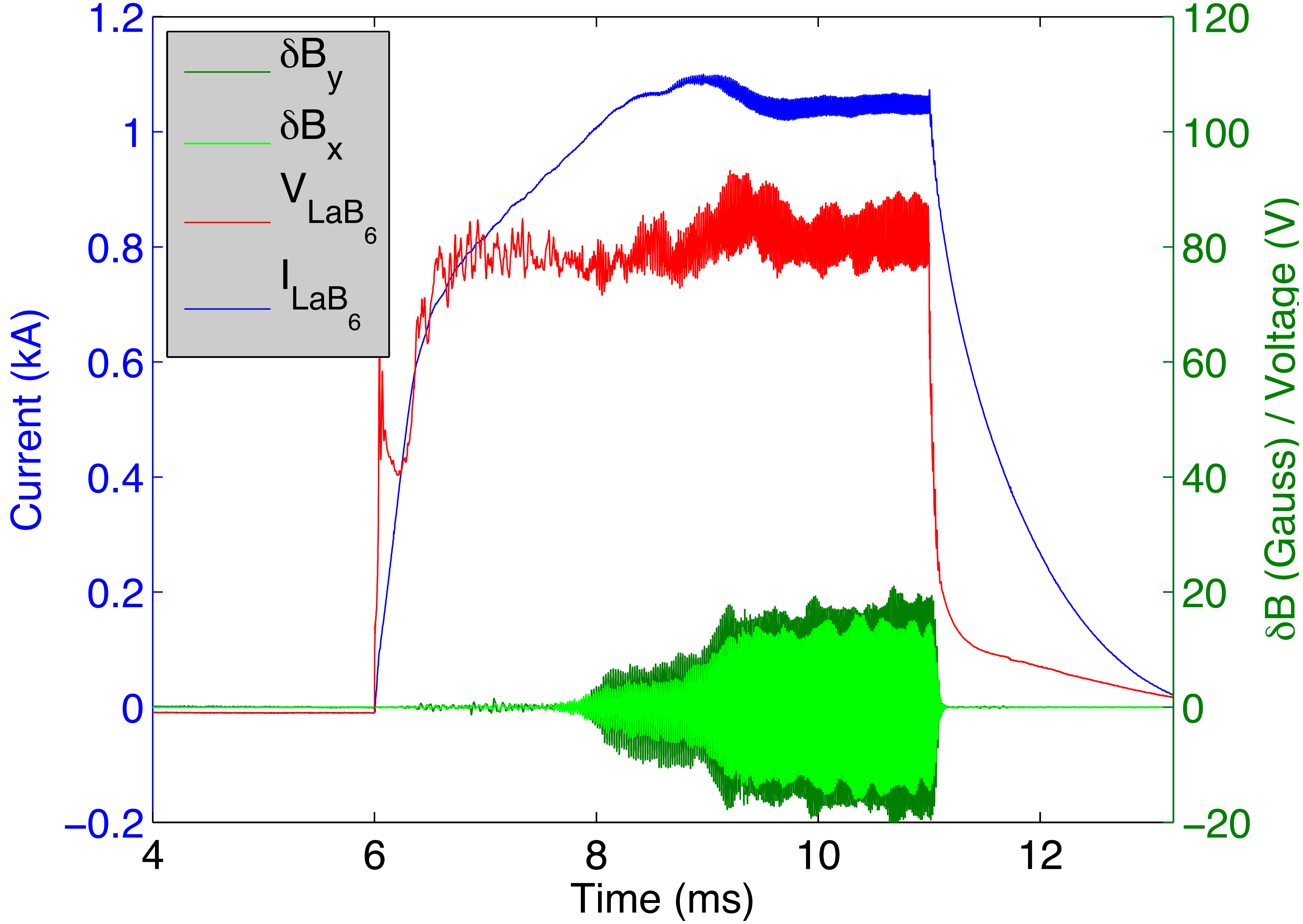
New LAPD LaB_6 Cathode





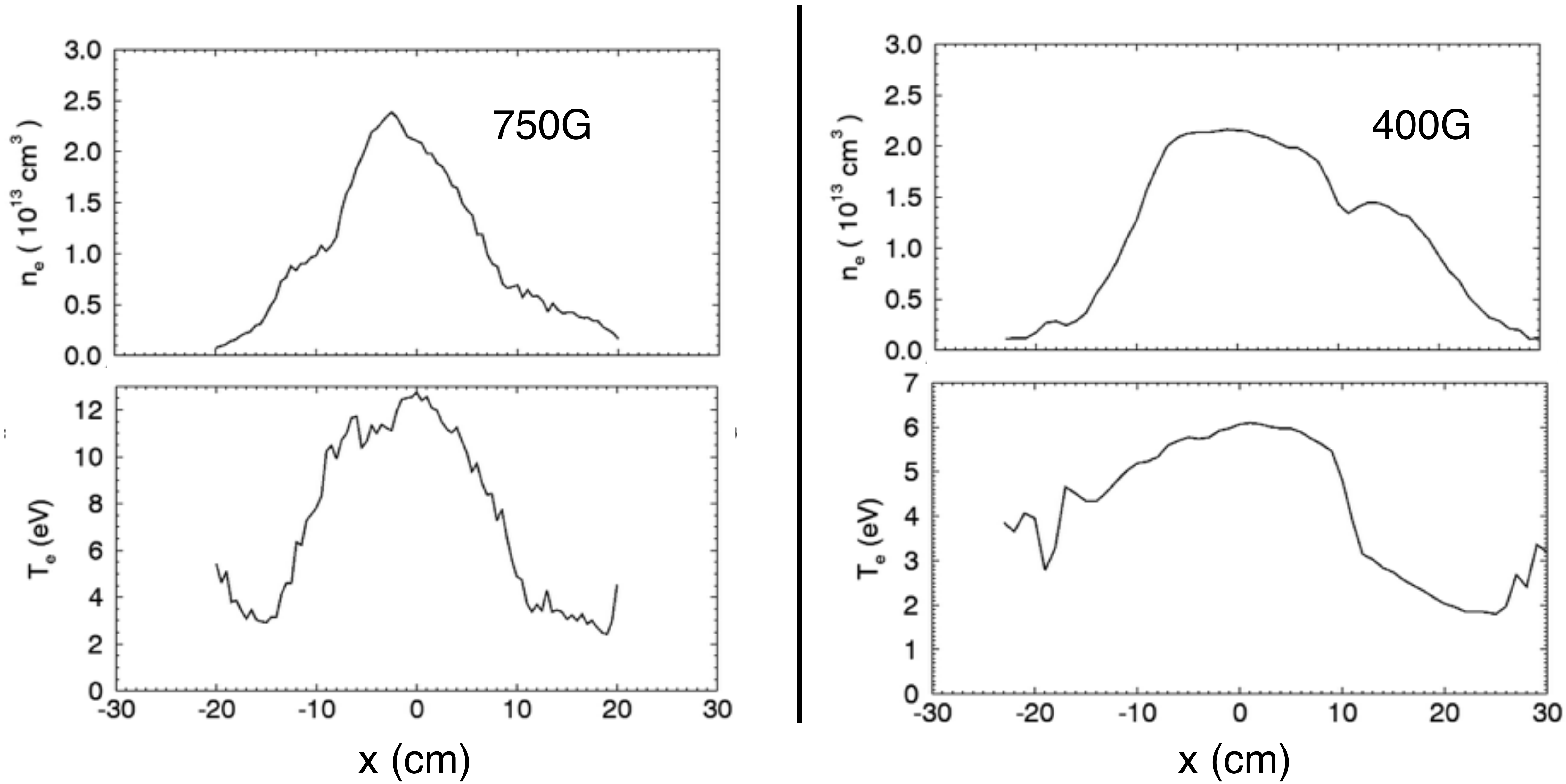
- ~50kW heating (graphite heater), Typical discharge: ~250V, 2kA (comparable power to BaO cathode)
- New coil installed to allow field control near cathode, also allows for expansion of plasma produced by new cathode

LaB6 discharge: high power density; Alfvén wave MASER observed



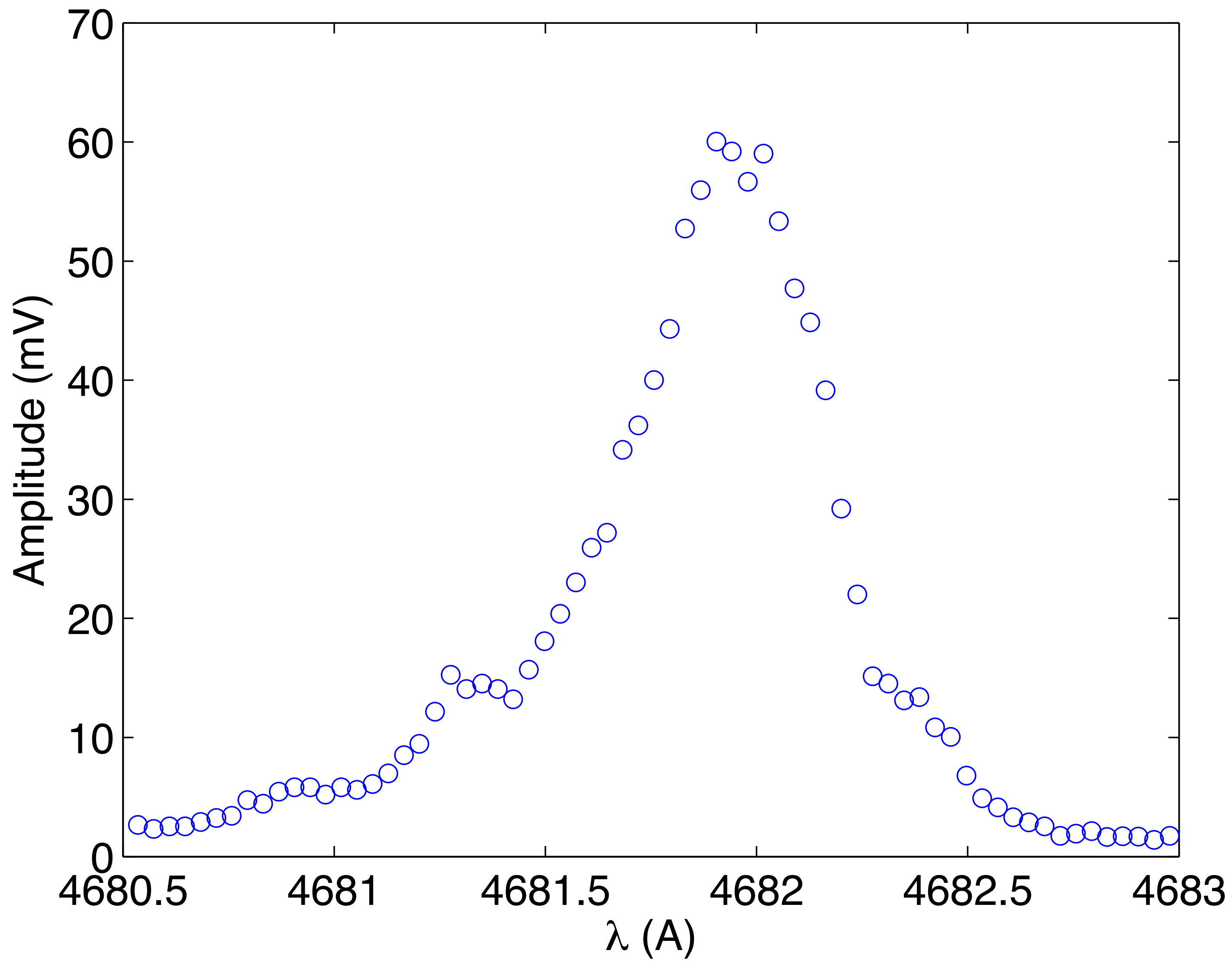
- Very large amplitude Alfvén wave spontaneously generated by source; consistent with excitation of fundamental shear wave in anode-cathode cavity

Hotter, denser plasmas with LaB_6 cathode in LAPD



- Density 10x BaO source, Temperature x2 (at higher field); plasma ~20cm wide
- Ion-electron coupling significantly increased, get warm ions (measured spectroscopically to be 6 eV+)

Hot off the press: spectroscopic measurement of He ion temperature in LAPD

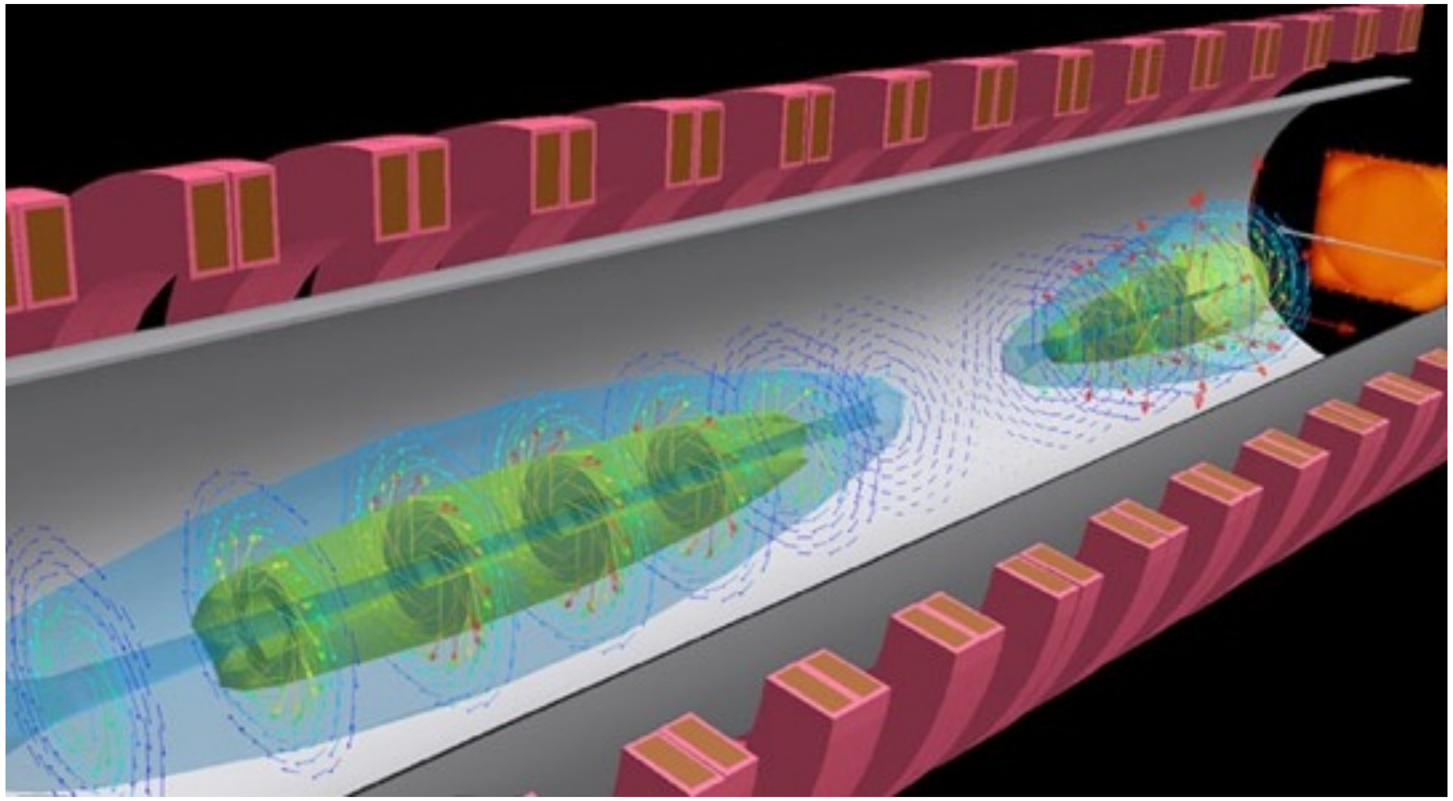


- 2m spectrometer; measurement of He II 4686Å line(s)
- Modeling/fitting underway, initial estimates are for T_i~6eV

LAPD LaB_6 Plasma Parameters: lower ion collisionality, higher plasma beta

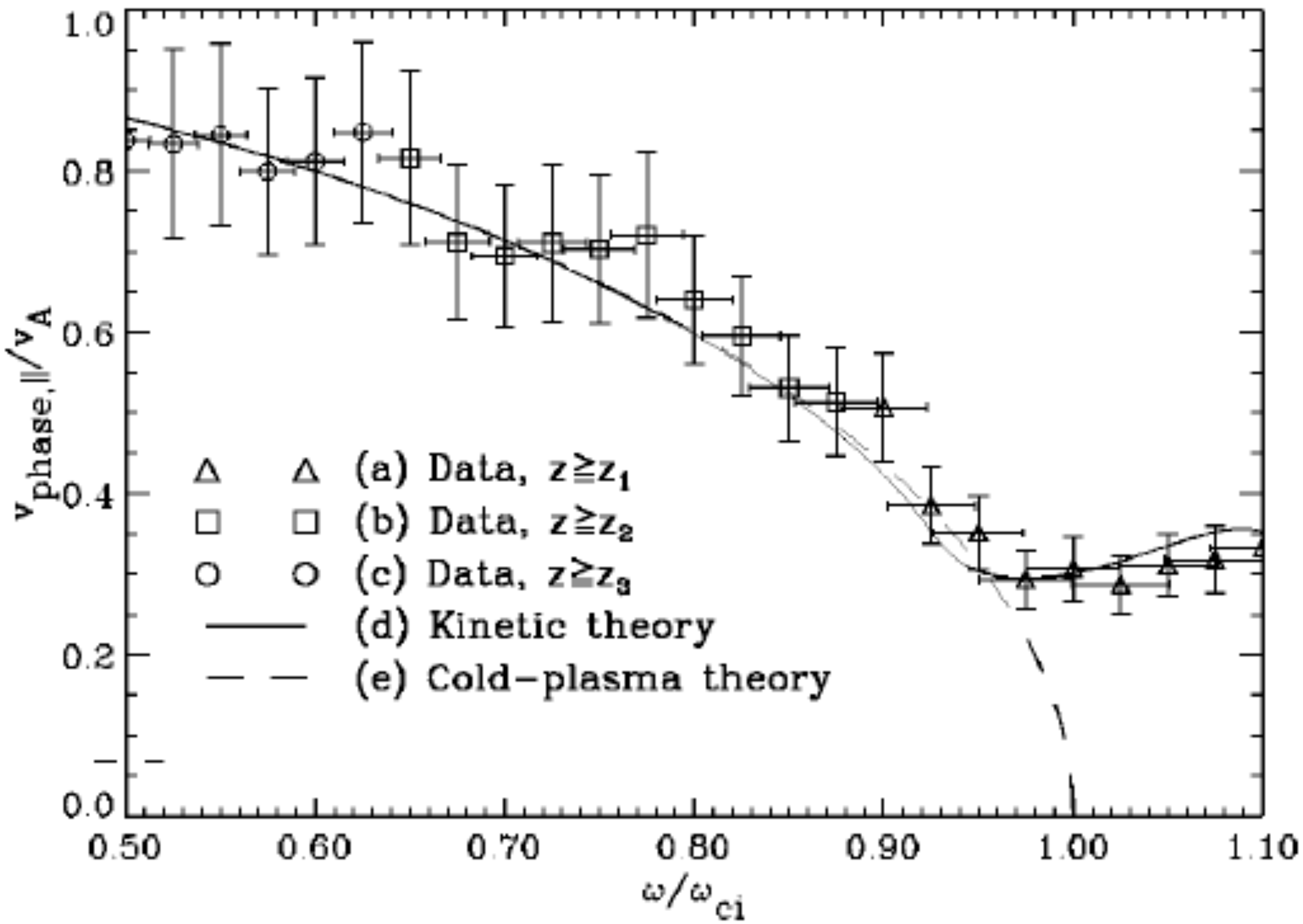
Parameter	BaO (1 kG)	LaB_6 (1 kG)	LaB_6 (400G)*	LaB_6 (125G)*
Density (cm^{-3})	2×10^{12}	2×10^{13}	2×10^{13}	2×10^{13}
Electron temperature (eV)	5-10	6-15	6-15	6-15
Ion temperature (eV)	<1	$\sim T_e$	$\sim T_e$	$\sim T_e$
Electron gyroradius (mm)	0.06	0.08	0.21	0.66
Ion gyroradius (cm)	0.2	0.7	1.8	5.7
Ion sound gyroradius (cm)	0.5	0.7	1.8	5.7
c/ω_{pe} (mm)	4	1	1	1
c/ω_{pi} (cm)	50	15	15	15
Ion cyclotron frequency (kHz)	380	380	152	48
Electron collision frequency (MHz)	3	10	10	10
Ion collision frequency (kHz)	300	100	100	100
Typical Alfvén wave frequency (kHz)	200	200	100	25
Plasma Beta	4×10^{-4}	1.6%	10%	~ 1

Alfven waves in hot ion, high beta plasmas



- Dispersion and damping of kinetic Alfven wave modified by ion FLR effects
- At unity beta, $v_A \sim v_{thi,i}$, get ion Landau damping and TTMP/Barnes damping

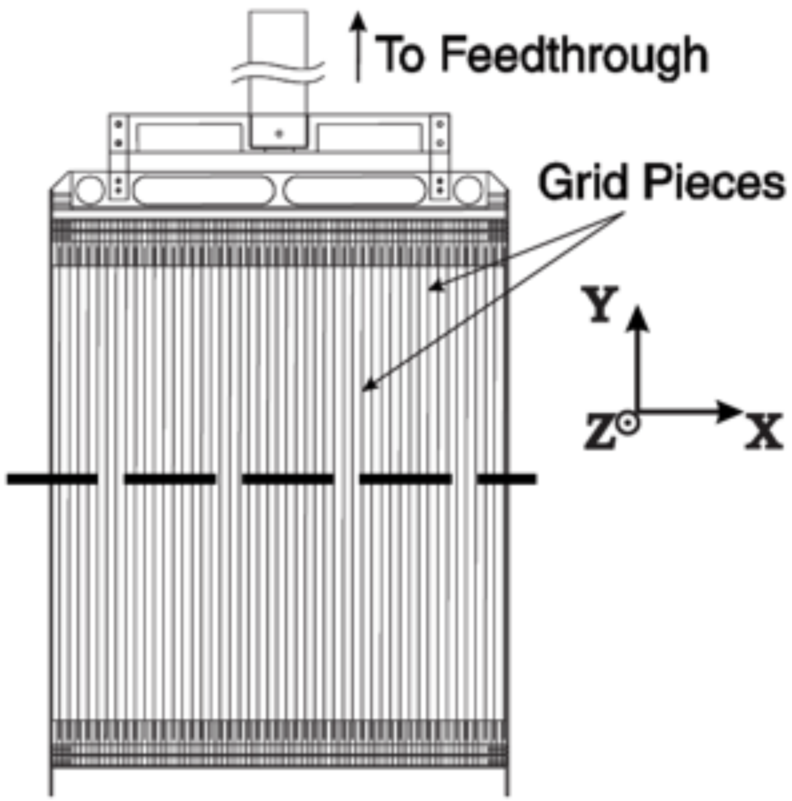
Magnetic beach experiment: variation in damping with hot ions, high beta

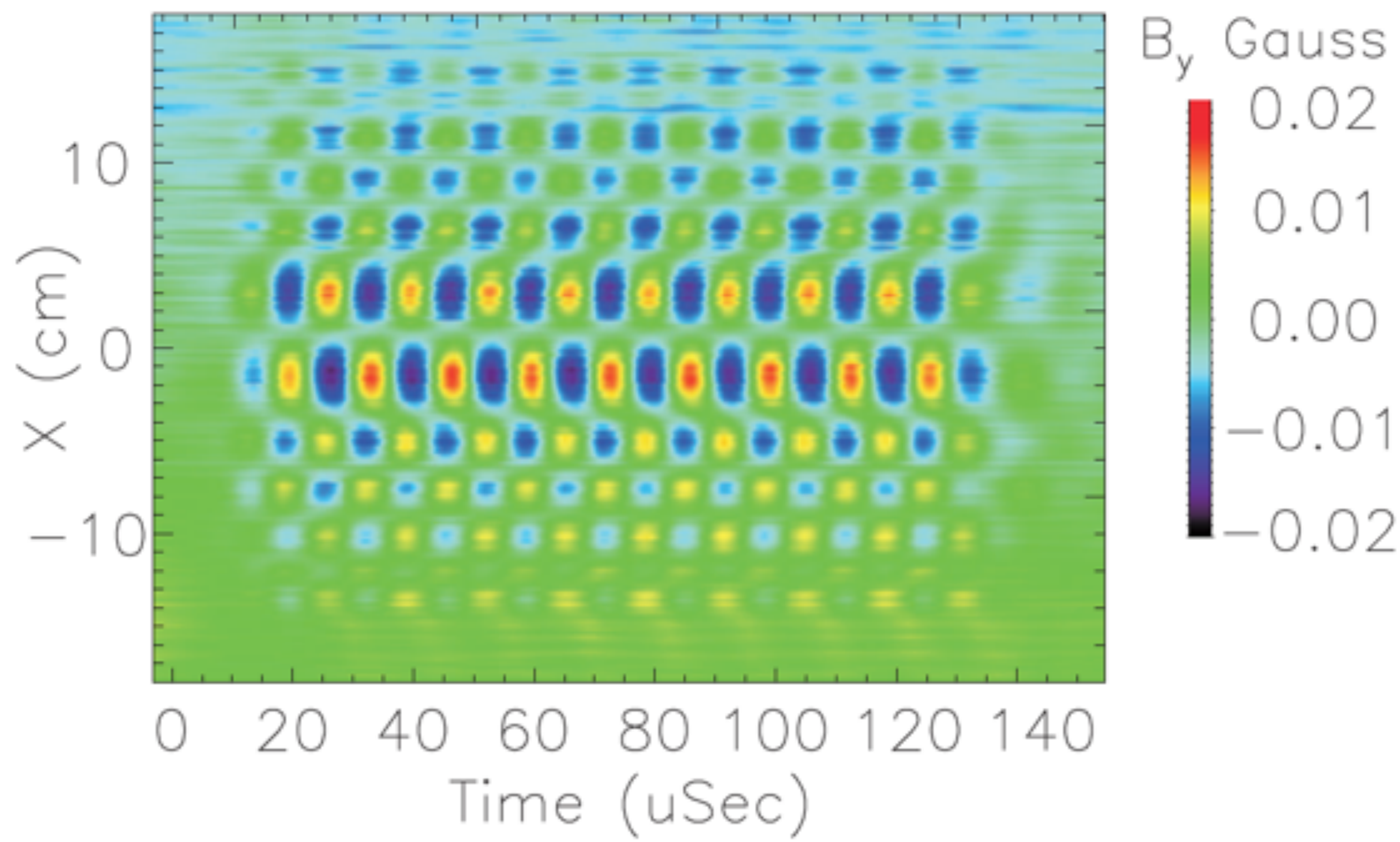


Vincena, et al. PoP 8, 3884 (2001)

- Low beta experiments: Need ion kinetic effects to explain observations around Ω_i
- Absorption of waves primarily due to collisional, electron Landau damping: How does this change with hot ions, high beta?

Study of IAW/KAW dispersion & damping



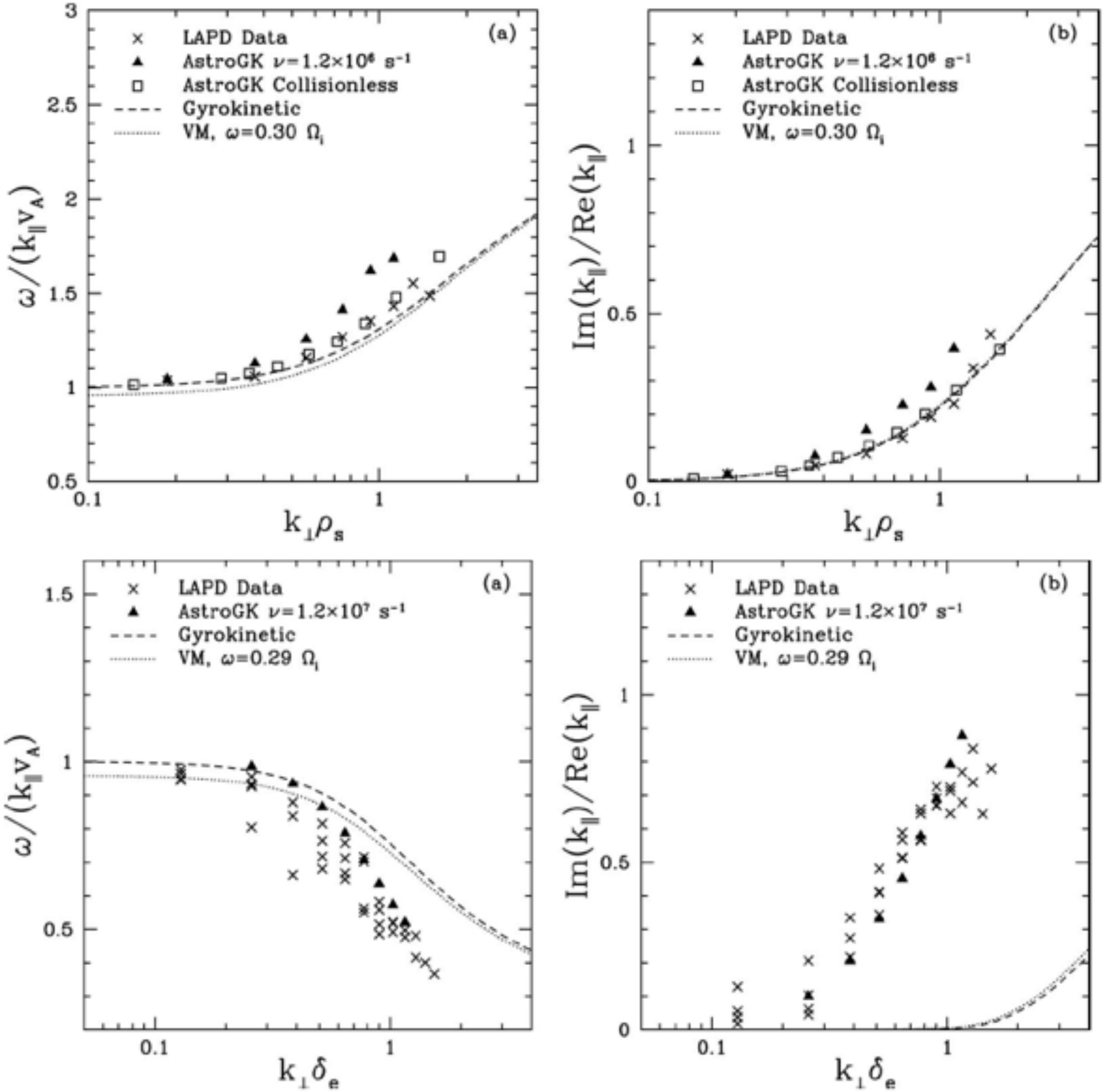


- Special antenna built to create plane-wave-like AWs with control over k to do detailed dispersion/damping measurements [U. Iowa group, Kletzing, Skiff + students]

Kletzing, et al, PRL 104, 095001 (2010)

Measured dispersion and damping, GK modeling; Extend to astrophysical relevant, hot ion, high beta plasmas

- Measurements compared to AstroGK simulations, including collisions (crucial to get inertial AW dispersion/damping right)



kinetic AW

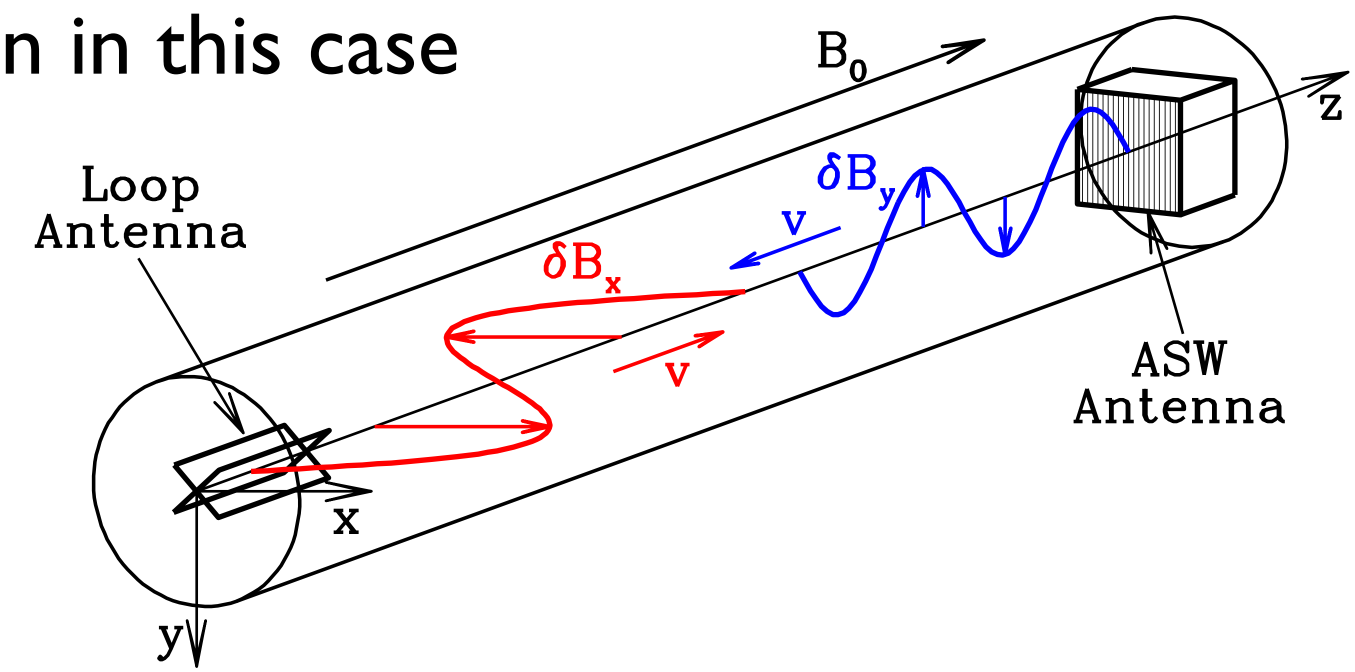
inertial AW

Nielson, Howes, et al, PoP **17**, 022105 (2010)

MHD-cascade relevant collisions: AW+AW → AW

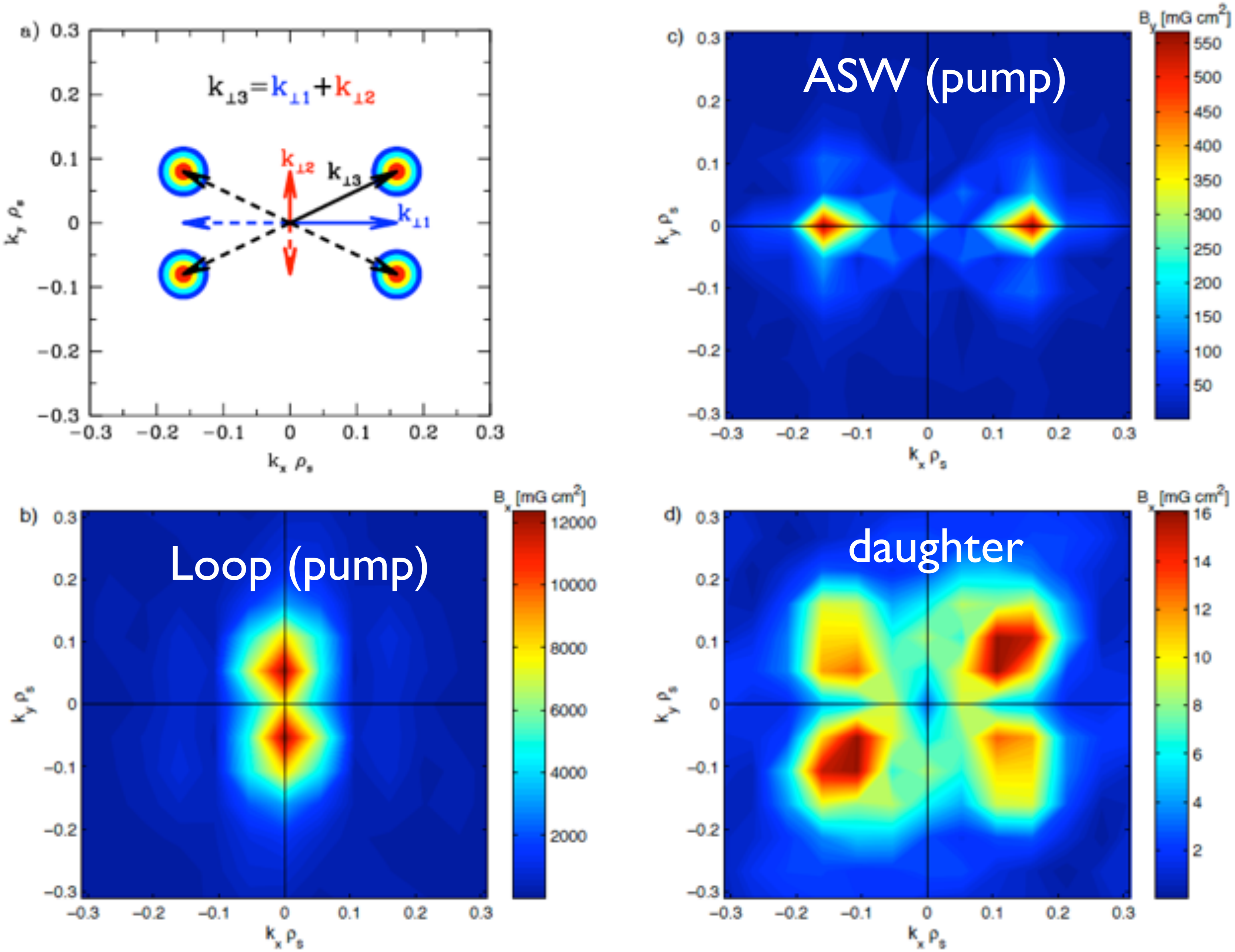
- Initial attempts in LAPD (Carter, Boldyrev, et al.): no strong evidence for daughter wave production/cascade (instead see beat waves, heating, harmonic generation, etc). Used local interaction, trying to look for perp. cascade.

- New idea (Howes): have one of the two interacting (pump) waves be $k_\parallel \approx 0$, theoretical prediction for stronger NL interaction in this case



- UCLA Loop antenna (large amplitude) versus U. Iowa ASW antenna (small amplitude but precise $k_\perp$ control)

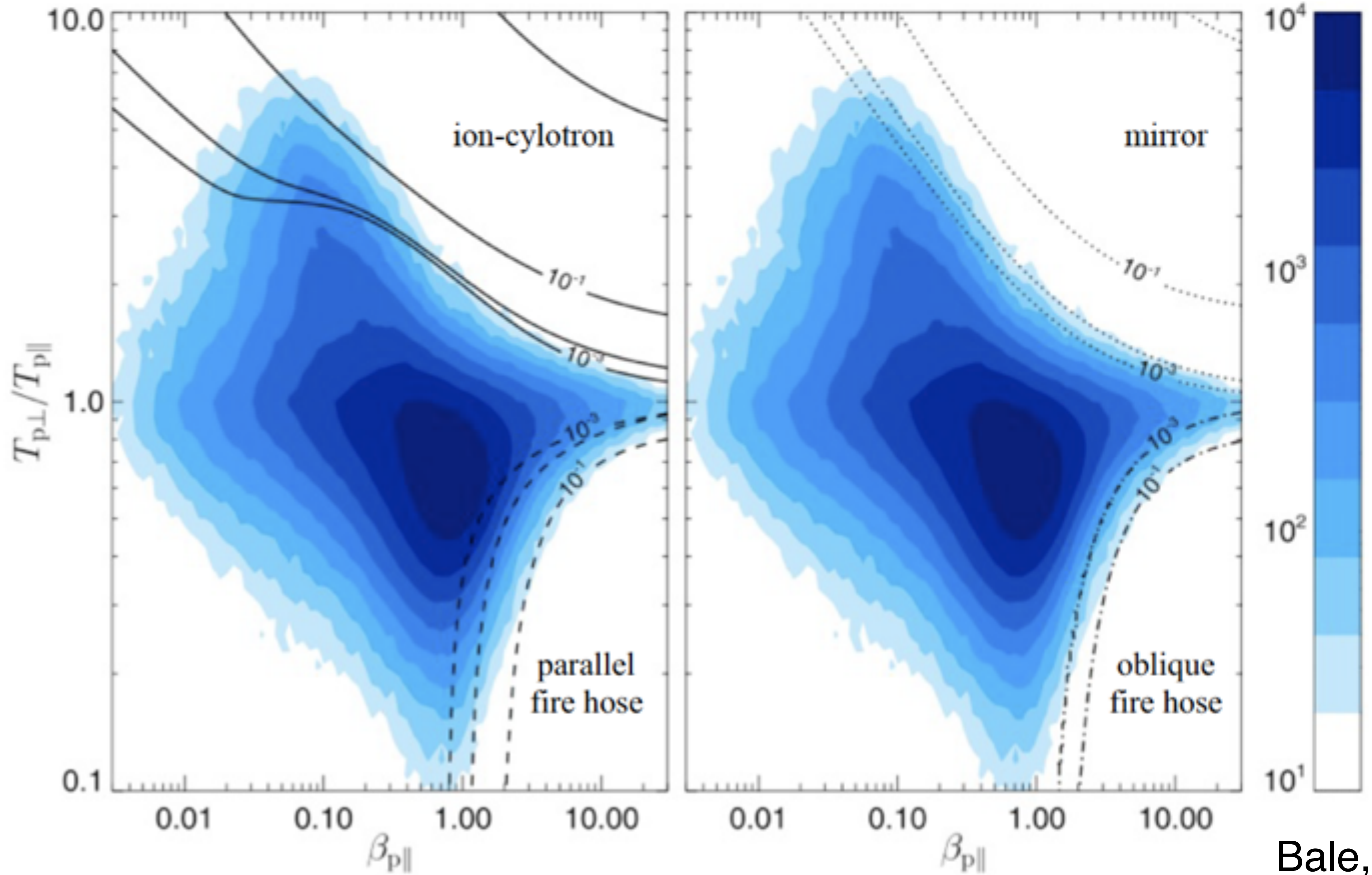
First laboratory observation of daughter AW production: consistent with weak turbulence theory



Howes et al., PRL 109, 255001 (2012)

- Perpendicular wavenumber spectrum consistent with three-wave matching ($k_1 + k_2 = k_3$)

Temperature-anisotropy-driven modes in high beta plasmas: mirror and firehose instabilities



Bale, et al., 2009

- Ion temperature anisotropy in the solar wind: limits explained by action of mirror and firehose modes
- Could play important role in solar wind thermodynamics; also thought to be important in other astrophysical plasmas, e.g. accretion disks

Mirror/Firehose in the laboratory?

- Need $\beta_i > 1$ with temperature anisotropy
- Need to operate at low field to get high beta, but need magnetized ions. Also, typical parallel scale of firehose instability is c/ω_{pi}, need large enough density to include this scale in the experiment
- Need low collisionality! Growth time for firehose can be ~ f_{ci}, need collisionality at least lower than this — tough when factoring in requirement for high density. Also limits achievable anisotropy
- Method for driving anisotropy?

MHD Firehose in LAPD?

$$\beta_{\|} - \beta_{\perp} \geq 2$$

$$k_B T_{\|} - k_B T_{\perp} \geq M v_A^2$$

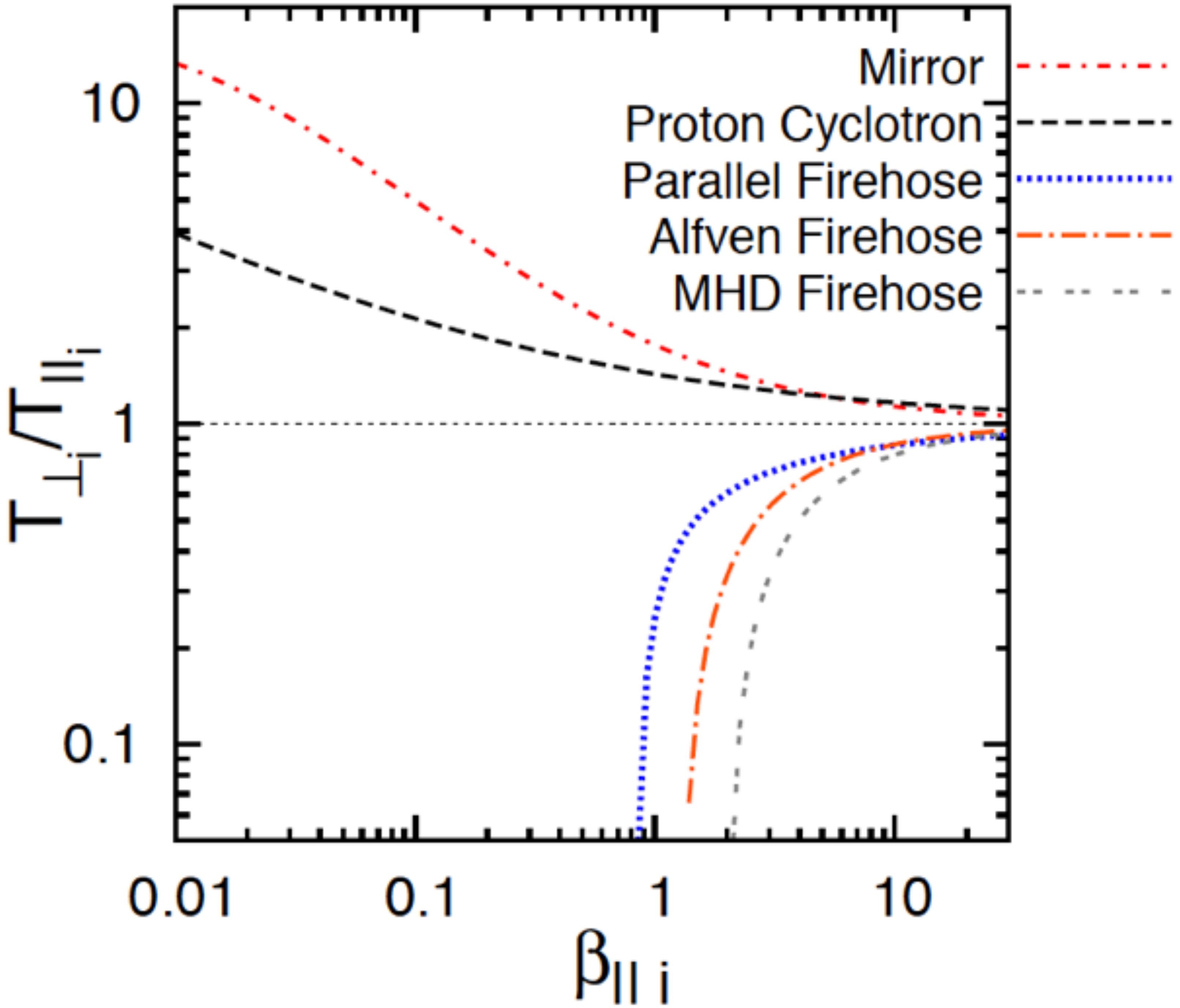
Need Mv_A^2 to be low enough (10 eV)?

- At LAPD/ETPD densities, this requires very low field: $n=10^{13}$ /cc, B=50G, Mv_A^2 ~ 12 eV (He)

Helium	Hydrogen
$T_i \sim 20\text{eV}$	$T_i \sim 20\text{eV}$
$\nu_{ii} \sim 13\text{kHz}$	$\nu_{ii} \sim 26\text{kHz}$
$f_{ci} \sim 20\text{kHz}$	$f_{ci} \sim 76\text{kHz}$
$\rho_i \sim 18\text{cm}$	$\rho_i \sim 9\text{cm}$

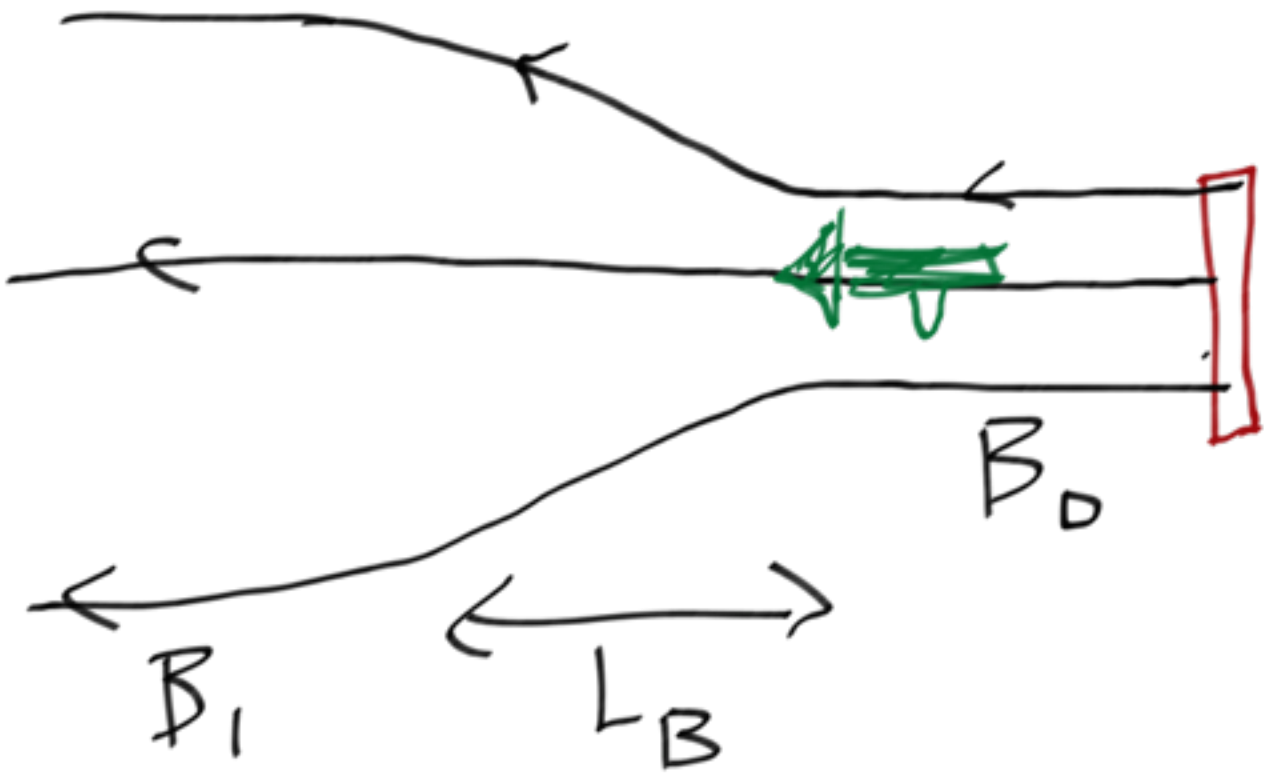
- Difficult, but may be possible to get to these conditions; need a large plasma to have magnetized ions (need ETPD?)

Parallel and oblique firehose have lower threshold than MHD Firehose



- Kinetic versions of firehose have lower thresholds; calculations done for LAPD parameters by K. Klein (U. Iowa)

Driving anisotropy: expanding plasmas for firehose?



- Firehose boundary could be reached in the same way as in the solar wind: flowing plasma into an expanding magnetic field
- Need collision time longer than transit time for ion through the expanding region
- Can Double Layers form in high beta, higher density plasmas (e.g. Charles, et al. 2004)? Supersonic ion beams could result (which could be unstable to firehose)

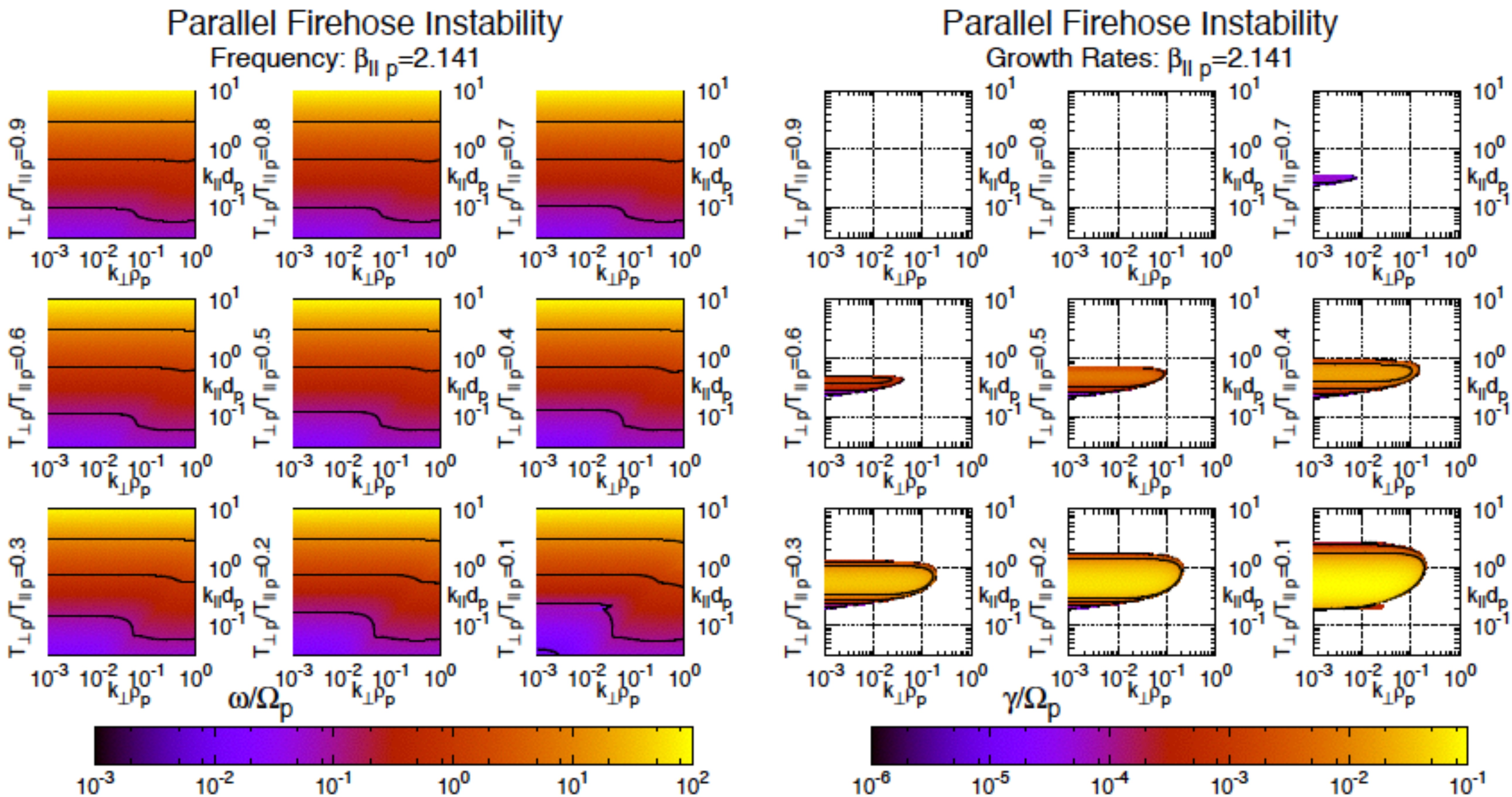
Target parameters for expanding plasma experiment

Species	H	H	H	H
T_i (eV)	15	15	12	15
T_e (eV)	15	15	12	15
B_1 (G)	100	75	75	50
n (10^{13} cm^{-3})	2	2	1	2
L_B (cm)	100	25	25	25
β_i	1.2	2.15	0.86	4.8
f_{ci} (kHz)	152	114	114	76
ν_{ii} (kHz)	177	177	126	177
$1/\tau_{\text{transit}}$ (kHz)	53.6	214	192	214
ρ_i (cm)	5.6	7.5	6.7	11.2

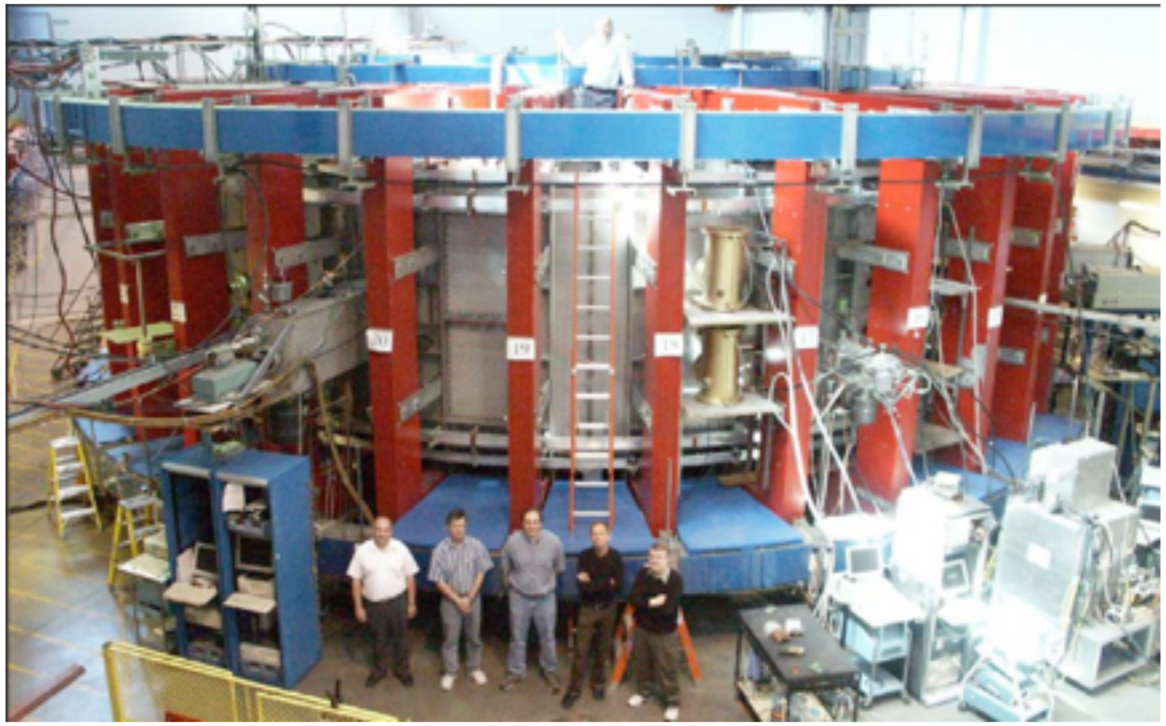
Calculated growth rates for firehose in target LAPD plasmas

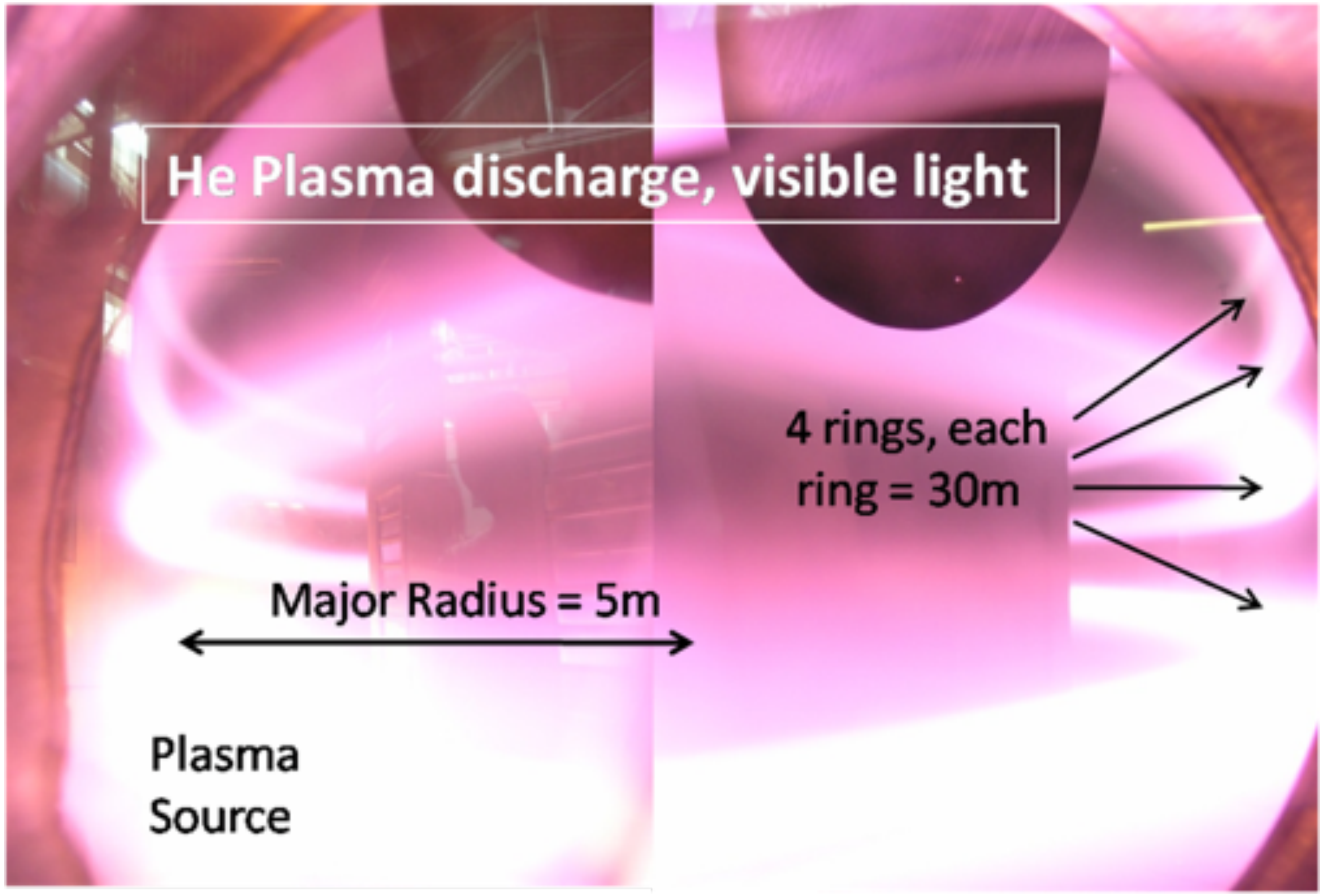
$T_{\perp p}/T_{\parallel p}$	$\beta_{\parallel p} = 0.859$		$\beta_{\parallel p} = 1.208$		$\beta_{\parallel p} = 2.1416$		$\beta_{\parallel p} = 4.832$	
1.0	ω/Ω_p $k_\perp \rho_p$	γ/Ω_p $k_\parallel \rho_p$	ω/Ω_p $k_\perp \rho_p$	γ/Ω_p $k_\parallel \rho_p$	ω/Ω_p $k_\perp \rho_p$	γ/Ω_p $k_\parallel \rho_p$	ω/Ω_p $k_\perp \rho_p$	γ/Ω_p $k_\parallel \rho_p$
0.9	X X	X X	X X	X X	X X	X X	X X	X X
0.8	X X	X X	X X	X X	X X	X X	2.30E-01 1.00E-03	1.87E-04 3.96E-01
0.7	X X	X X	X X	X X	3.86E-01 1.00E-03	6.72E-05 4.04E-01	3.05E-01 1.00E-03	1.25E-02 5.31E-01
0.6	X X	X X	5.62E-01 1.00E-03	2.00E-05 3.85E-01	5.24E-01 1.00E-03	1.47E-03 4.91E-01	2.15E-01 1.00E-03	6.59E-02 4.46E-01
0.5	8.38E-01 1.00E-03	1.29E-05 4.06E-01	7.86E-01 1.00E-03	2.44E-04 4.61E-01	6.40E-01 1.00E-03	7.29E-03 5.36E-01	2.27E-01 1.00E-03	1.18E-01 4.29E-01
0.4	1.06E+00 1.00E-03	7.91E-05 4.35E-01	9.90E-01 1.00E-03	9.87E-04 4.93E-01	6.96E-01 1.00E-03	1.95E-02 5.25E-01	2.88E-01 1.00E-03	1.60E-01 4.39E-01
0.3	1.27E+00 1.00E-03	2.27E-04 4.31E-01	1.10E+00 1.00E-03	2.39E-03 4.67E-01	6.63E-01 1.00E-03	3.89E-02 4.54E-01	3.87E-01 1.00E-03	1.97E-01 4.55E-01
0.2	1.43E+00 1.00E-03	4.48E-04 3.85E-01	1.52E+00 1.00E-03	3.97E-03 4.78E-01	5.86E-01 1.00E-03	6.56E-02 3.55E-01	4.16E-01 1.00E-03	2.33E-01 3.89E-01
0.1	1.52E+00 1.00E-03	7.22E-04 2.85E-01	1.31E+00 1.00E-03	7.01E-03 3.09E-01	5.19E-01 1.00E-03	9.85E-02 2.40E-01	4.47E-01 1.00E-03	2.66E-01 2.87E-01

Calculated growth rates for firehose in target LAPD plasmas



Enormous Toroidal Plasma Device at UCLA

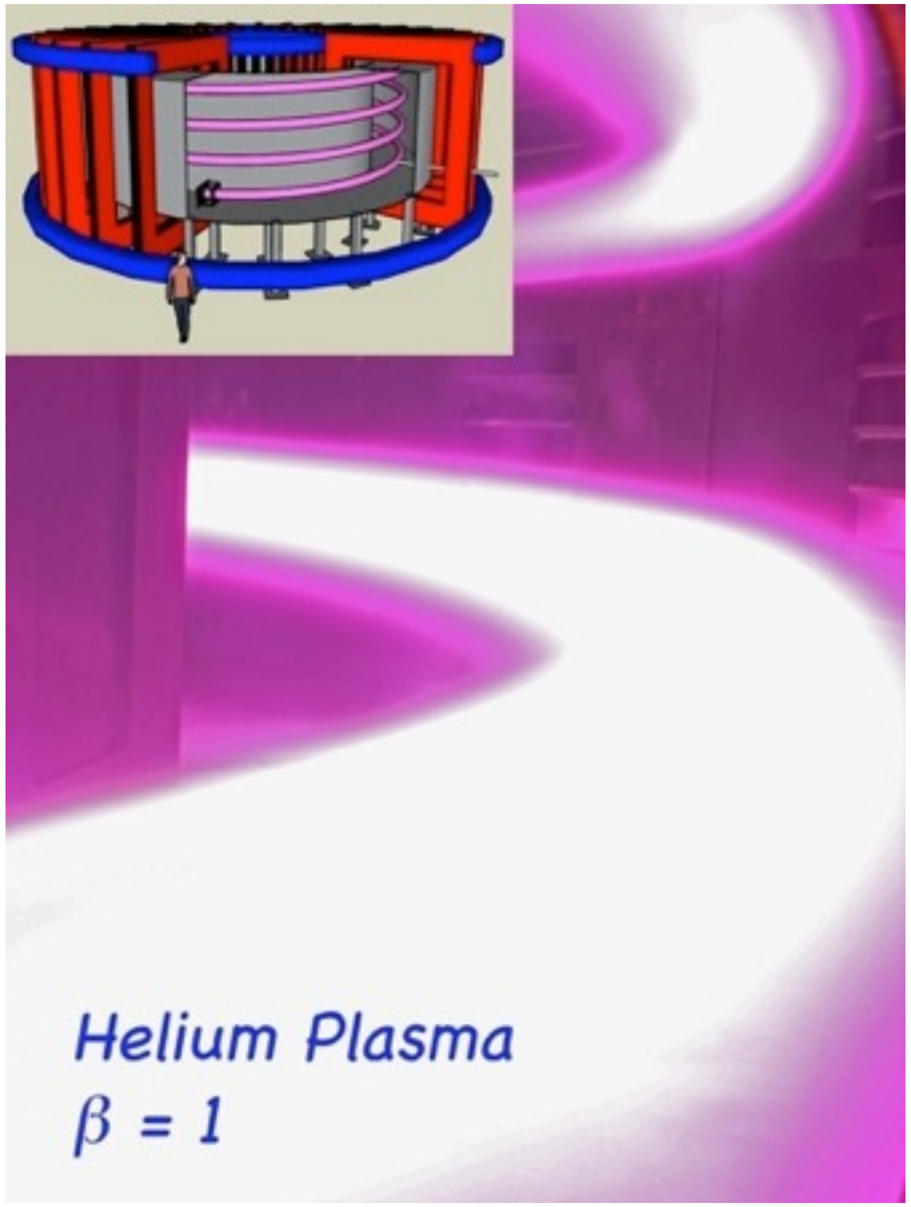


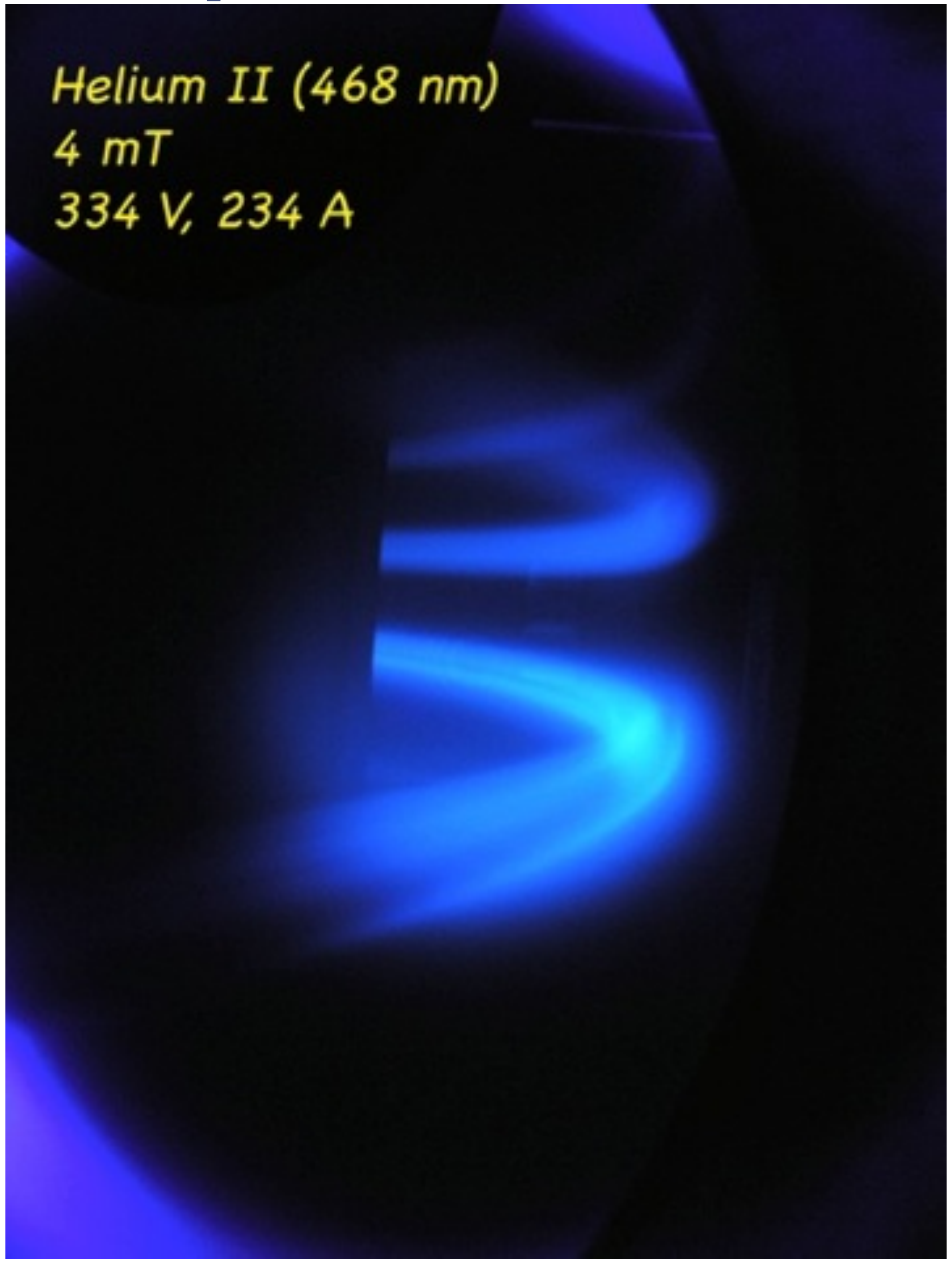


- Former Electric Tokamak, (5m major radius, 1m minor radius) operating now with LaB_6 cathode discharge into toroidal+vertical field

- Produces ~100m long, magnetized, high beta plasma (up to ~5×10^{13} cm^{-3}, Te, Ti ~ 15-30eV, B~200G, β ~ 1). Small (20cm) source operating presently, developing large area source (60cm wide plasma column planned).

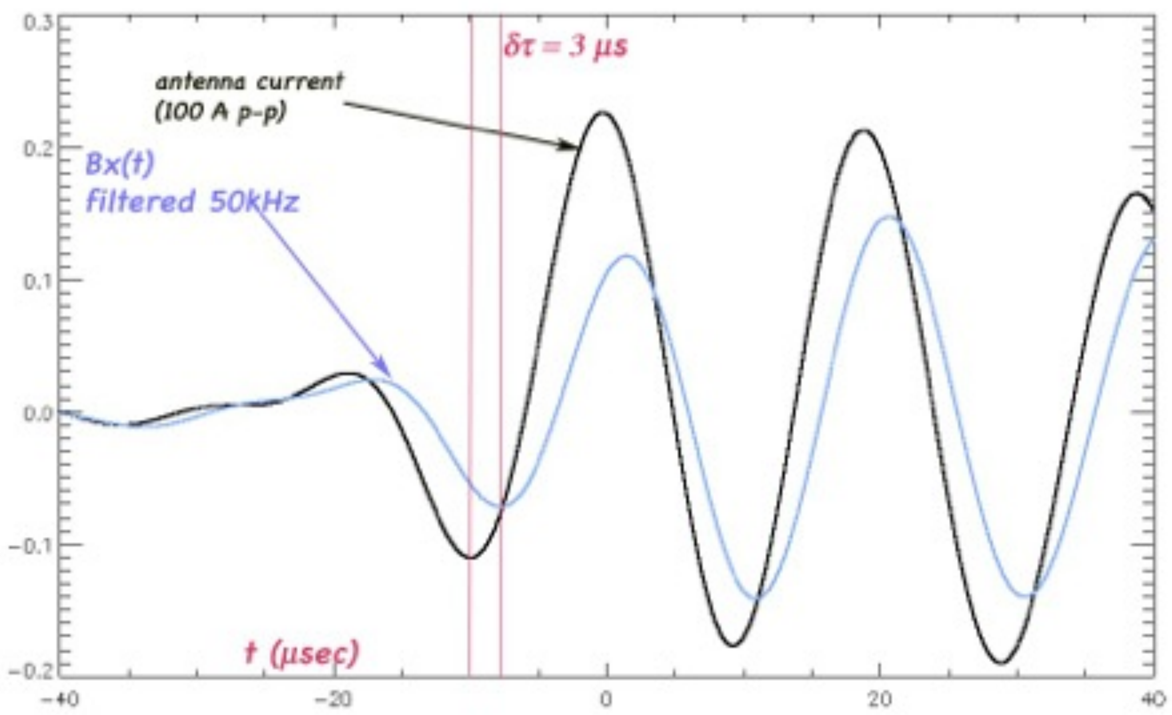
High beta, hot ion plasmas in ETPD

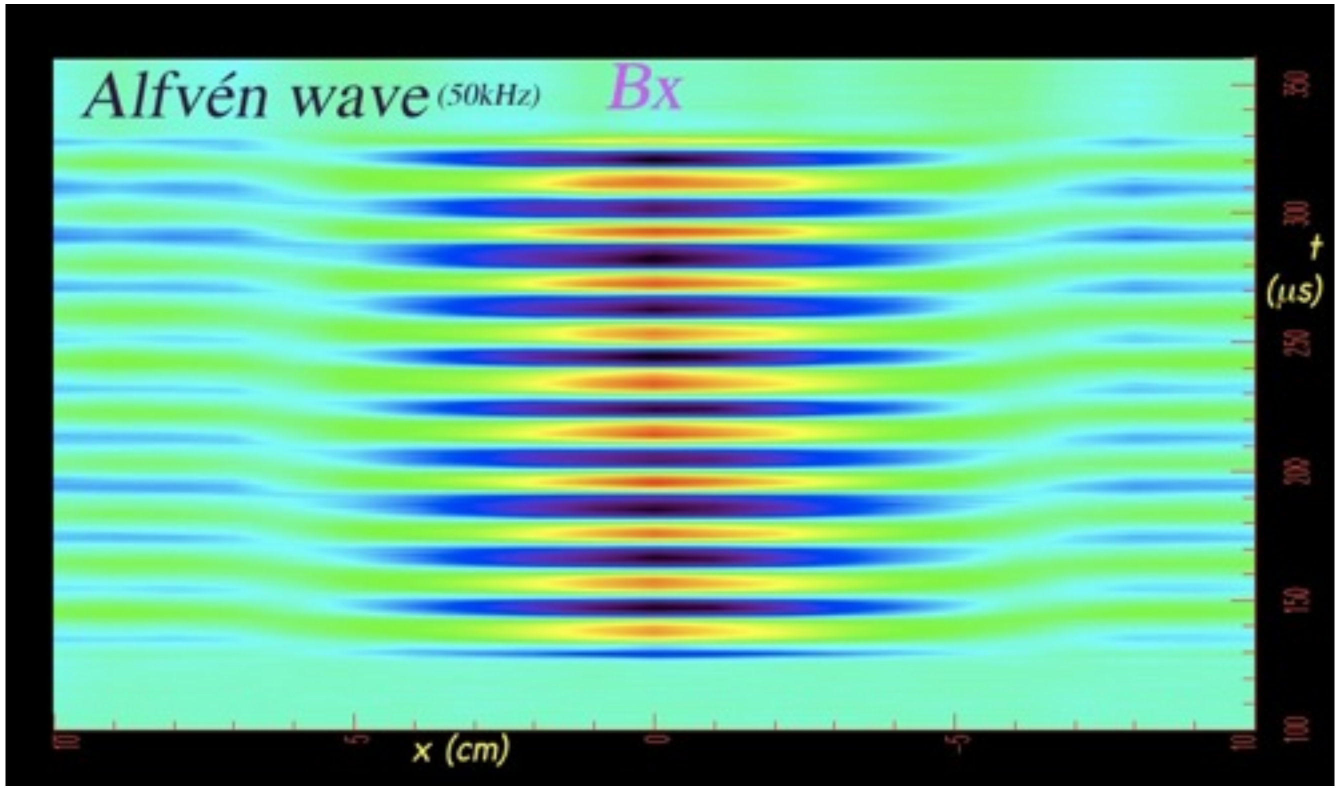




- $T_e \sim T_i \sim 20$ eV measured (passive spectroscopy of He II 4686 line).
- With B~250G, plasma beta of order unity is achieved

Possible studies in ETPD





- Alfvén waves, damping at β~1 (underway, data above), many (~100) Alfvén parallel wavelengths in device; Wave-wave interactions, driven Alfvénic cascade at β~1

- Gradient-driven/interchange turbulence at high β

- Mirror/firehose: Drive anisotropy, higher beta through expansion (drive plasma into low field region)

- Reconnection, Shock physics

Summary/Outline

- Update on Nonlinear Alfven wave studies on LAPD (excitation of sound waves, evidence for decay instability)
- New LaB_6 cathode source added to LAPD; prototyped in the Enormous Toroidal Plasma Device
  - Order of magnitude increase in density, electron temperature increased by factor of 2, increased electron-ion coupling results in $T_i \sim T_e$
- Warm ions provides opportunity to study ion kinetic effects in waves and instabilities: e.g. FLR effects on Alfvén wave propagation; ion cyclotron absorption; modification to nonlinear Alfven wave interactions
- With lower field, plasma beta can be increased substantially to study, e.g., modifications to Alfvén wave dispersion and damping (e.g. ion Landau/Barnes damping). Can high-beta temperature anisotropy driven instabilities (mirror and firehose) be observed in these plasmas?