# β ~ 1, magnetized plasmas in the laboratory

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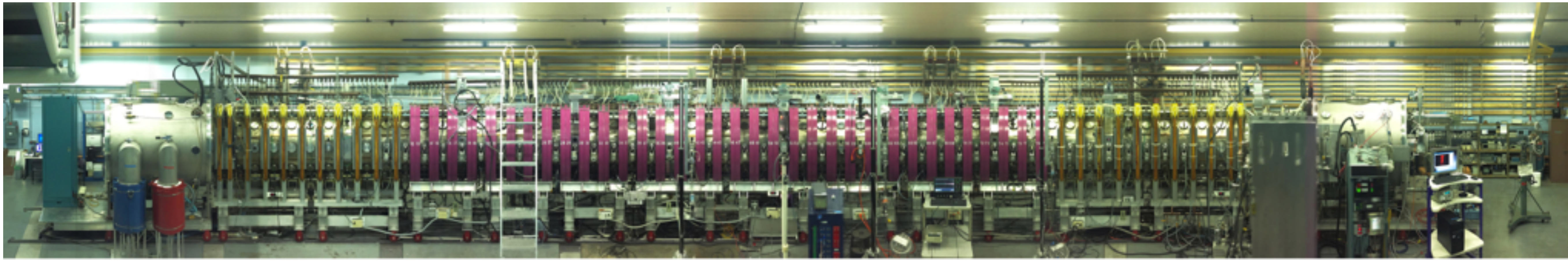
# Summary/Outline

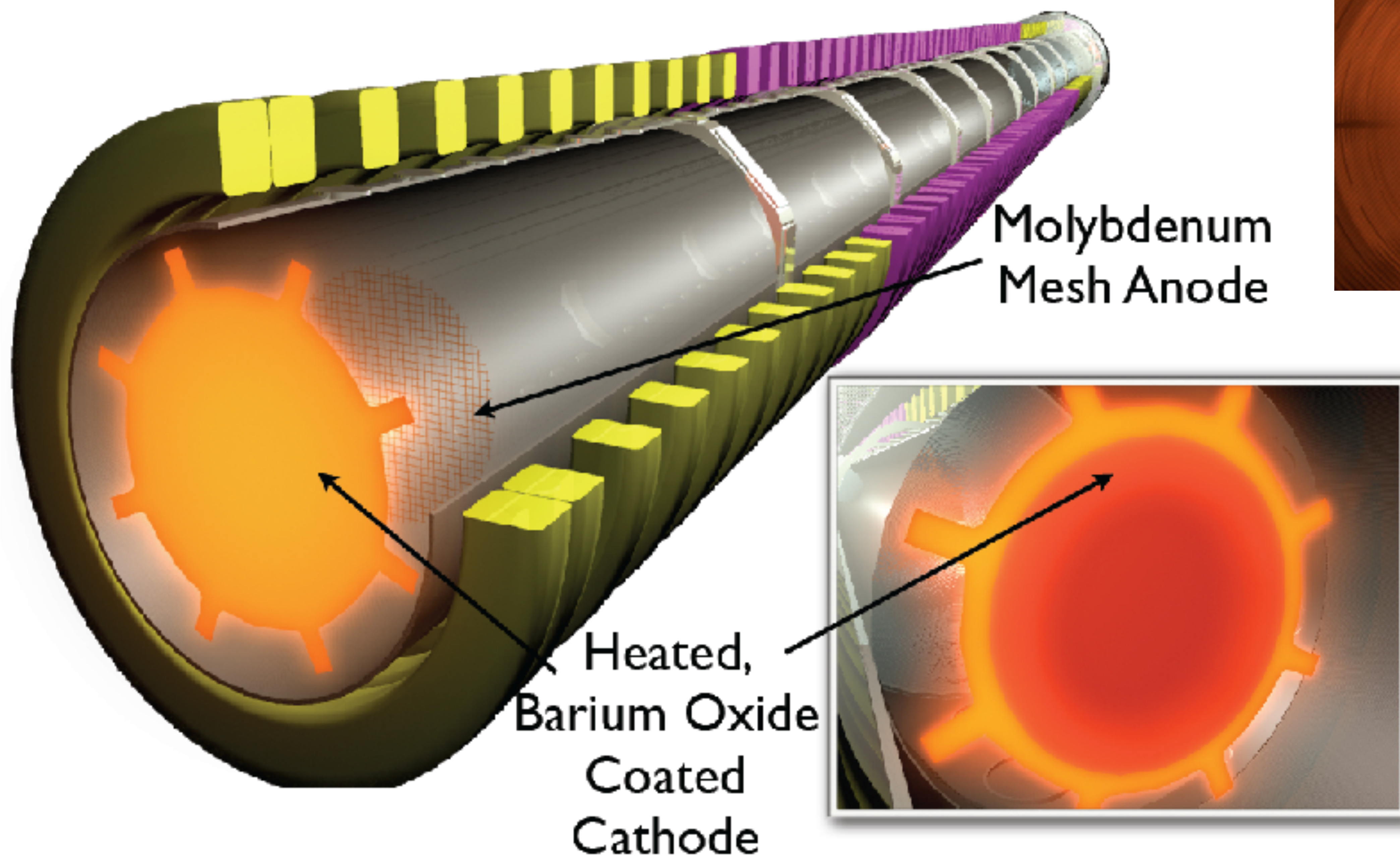
- Large Plasma Device (LAPD) at UCLA: Upgraded plasma source: LaB6 cathode provides up to 100x increase in plasma pressure + warm ions; with lowered B, $\beta \sim 1$
- Modification of pressure-gradient-driven turbulence and transport with increasing $\beta$
  - Magnetic fluctuations increase, with parallel magnetic fluctuations dominant (2x $\tilde{B}_\perp$ at highest $\beta$); Observations consistent with Gradient Driven Coupling (GDC) instability: favorable comparisons with GENE simulations
- Opportunities to study processes relevant to space/astrophysical plasmas in LAPD and new device ETPD
  - Linear and nonlinear physics of Alfvén waves, MHD turbulence in $\beta \sim 1$ plasmas
  - Pressure anisotropy: can mirror and firehose instabilities be studied in the laboratory?

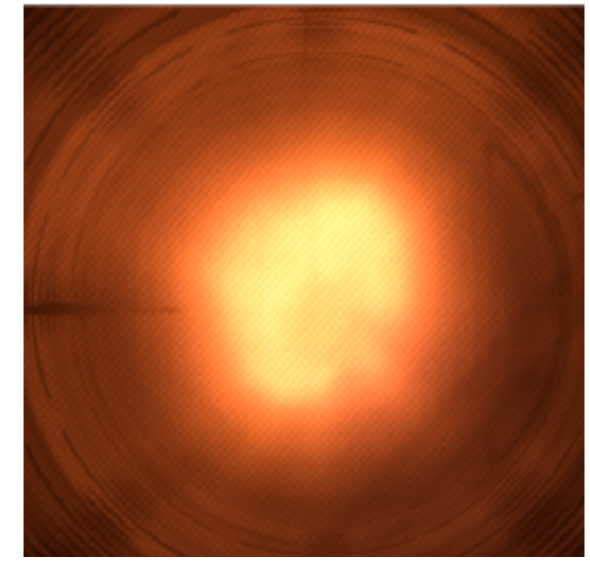
# The LArge Plasma Device (LAPD) at UCLA



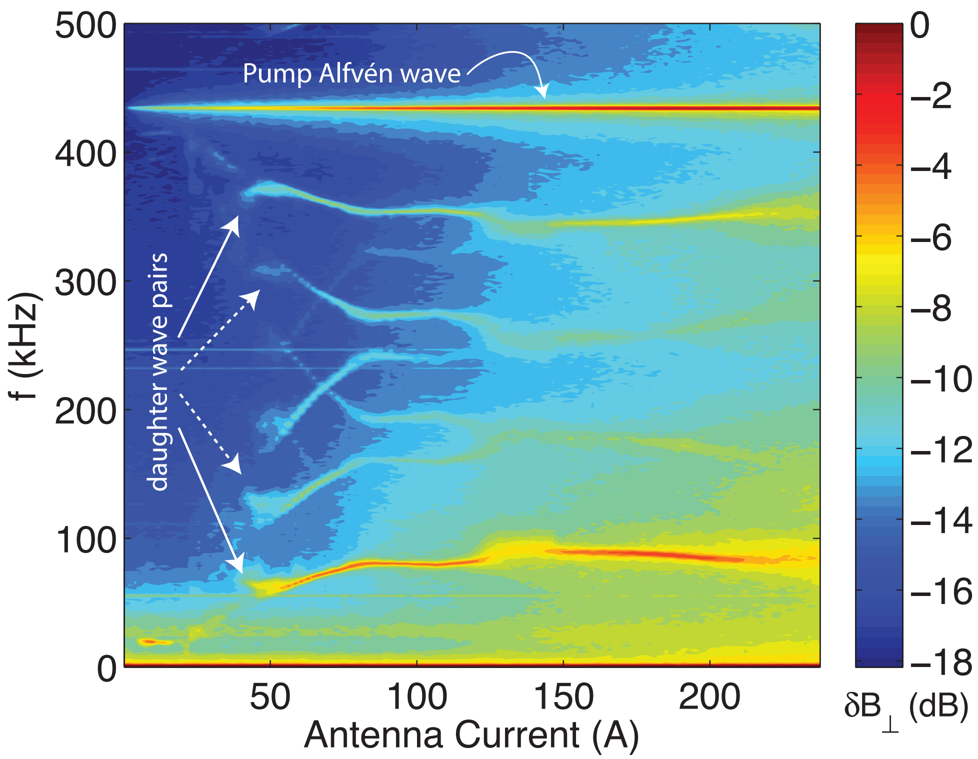
- Solenoidal magnetic field, cathode discharge plasma (BaO and $LaB_6$)
- BaO Cathode: n ~ $10^{12}$ $cm^{-3}$, $T_e$ ~ 5-10 eV, $T_i \lesssim$ 1 eV
- $LaB_6$ Cathode: n ~ $5 \times 10^{13}$ $cm^{-3}$, $T_e$ ~ 10-15 eV, $T_i$ ~ 6-10 eV
- B up to 2.5kG (with control of axial field profile)
- Large plasma size, 18m long, D~60cm (BaO) (1kG: ~300 $\rho_i$, ~100 $\rho_s$); D ~ 20cm ($LaB_6$ prototype)
- High repetition rate: 1 Hz
- US DOE/NSF user facility for basic plasma science: the Basic Plasma Science Facility or BaPSF (international users are welcome!)

# LAPD BaO Plasma source

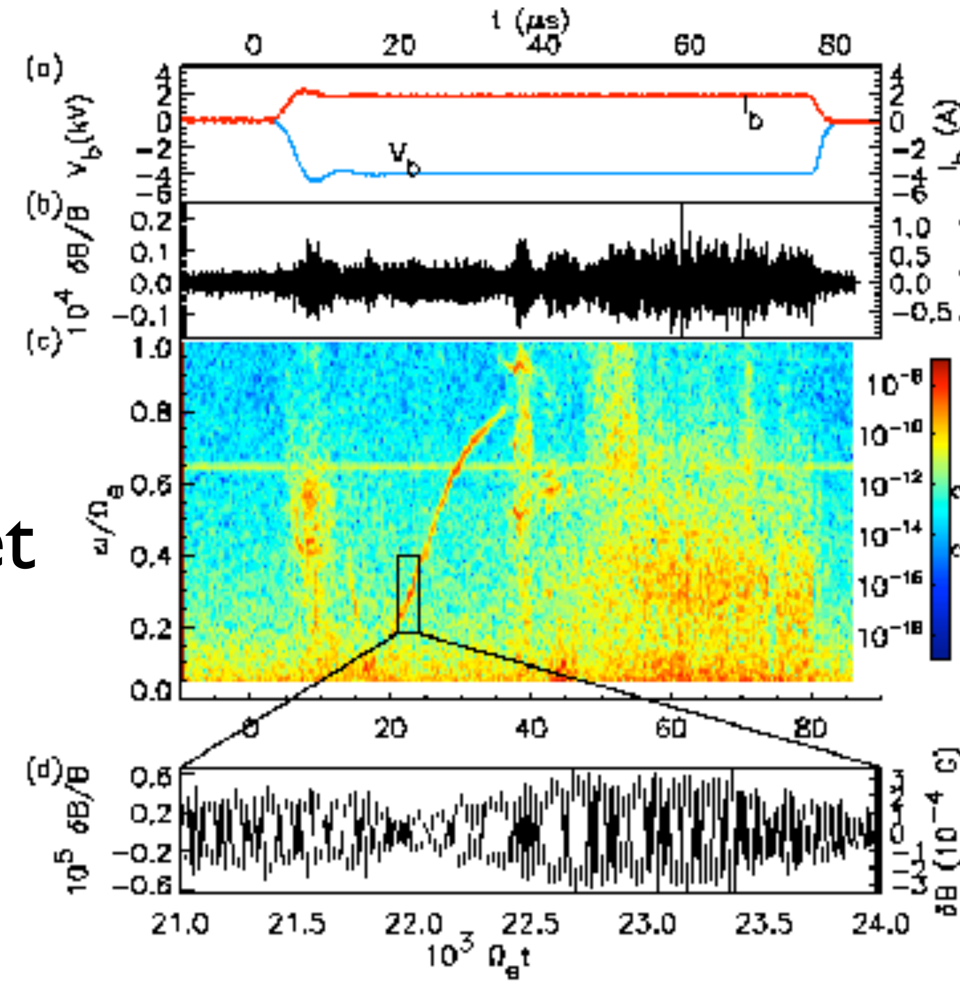


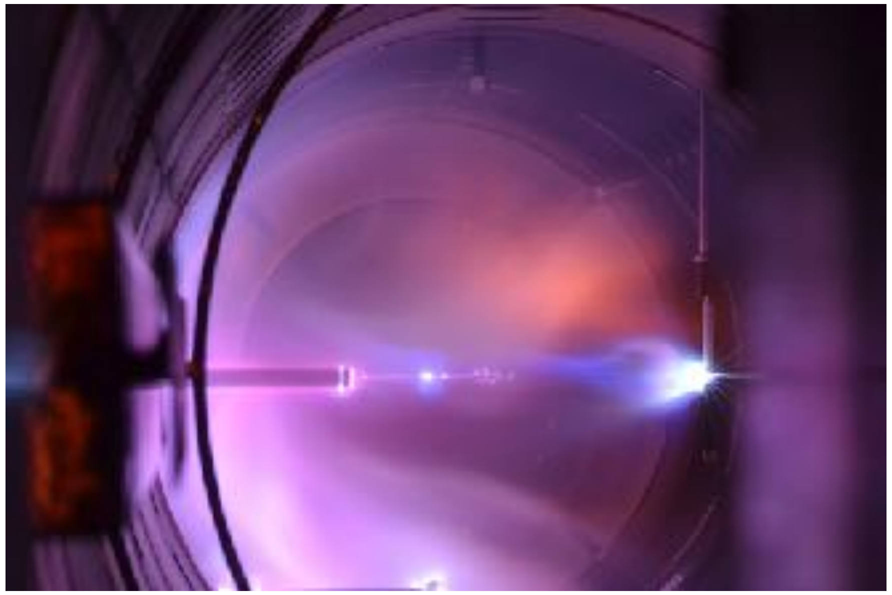
# Examples of recent research using BaPSF/LAPD




- Decay instabilities of large amplitude shear Alfvén waves [Dorfman & Carter, PRL 116, 195002 (2016)]

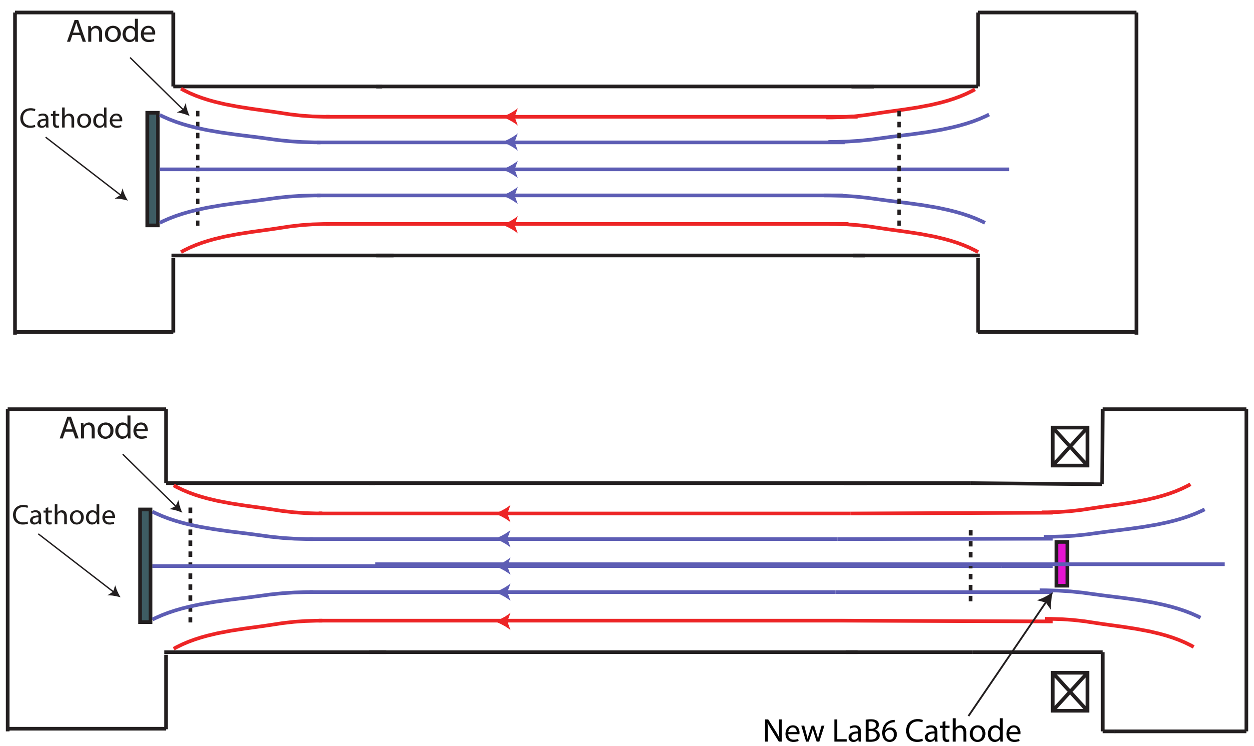


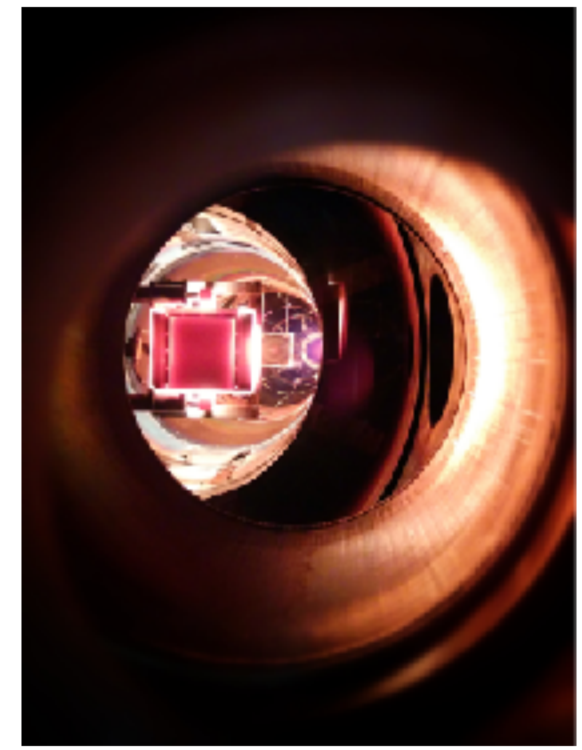

- Excitation of chirping whistler waves by energetic electrons [Van Compernolle, et al., PRL 114, 245002 (2015)]



- Laser-driven magnetized collisionless shocks [Bondarenko, et al., Nat. Phys. (2017)]

# LAPD prototype $LaB_6$ Cathode



- LaB6 cathode (operates at 1800C) 20cm square prototype cathode installed (larger version in development)
- Much better emissivity leads to 50x higher electron density, up to a factor of ~2 higher electron temperature, factor of ~10 higher ion temperature
- With reduced magnetic field, high $\beta$ (order unity) achievable with magnetized ions (marginally so at $\beta \sim 1$)

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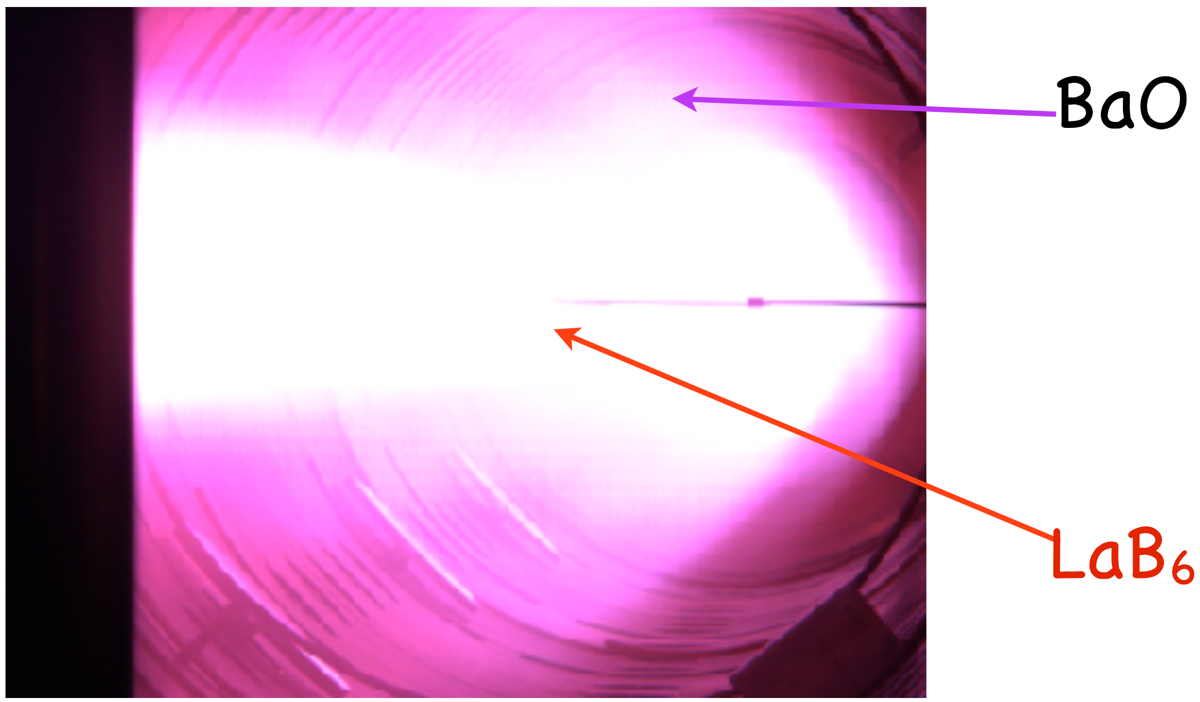


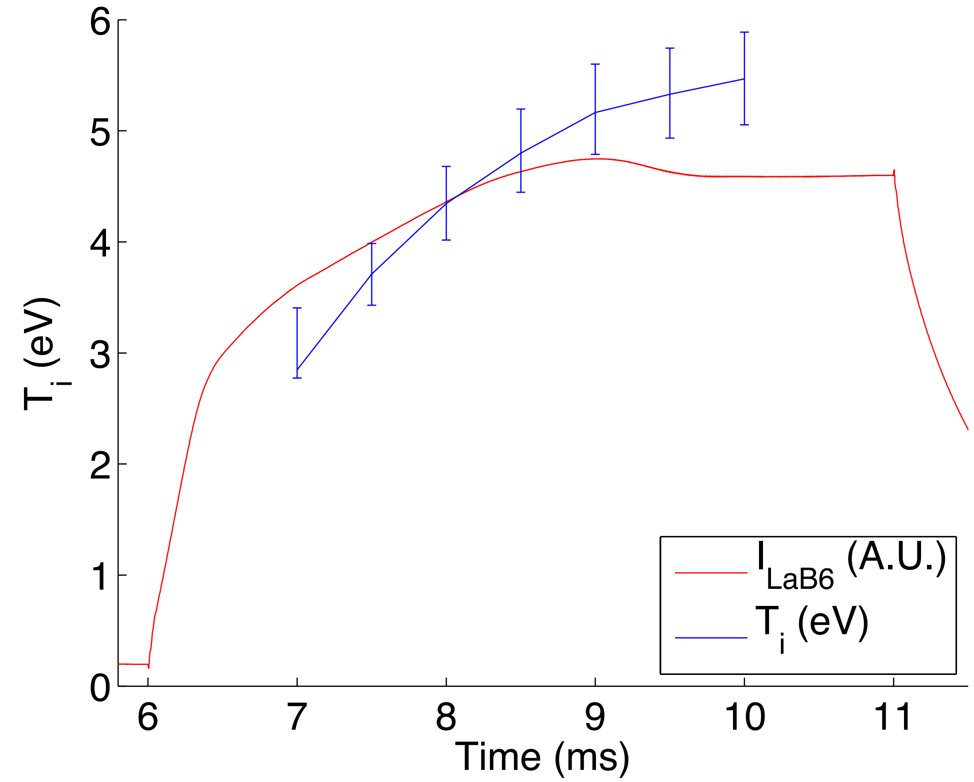


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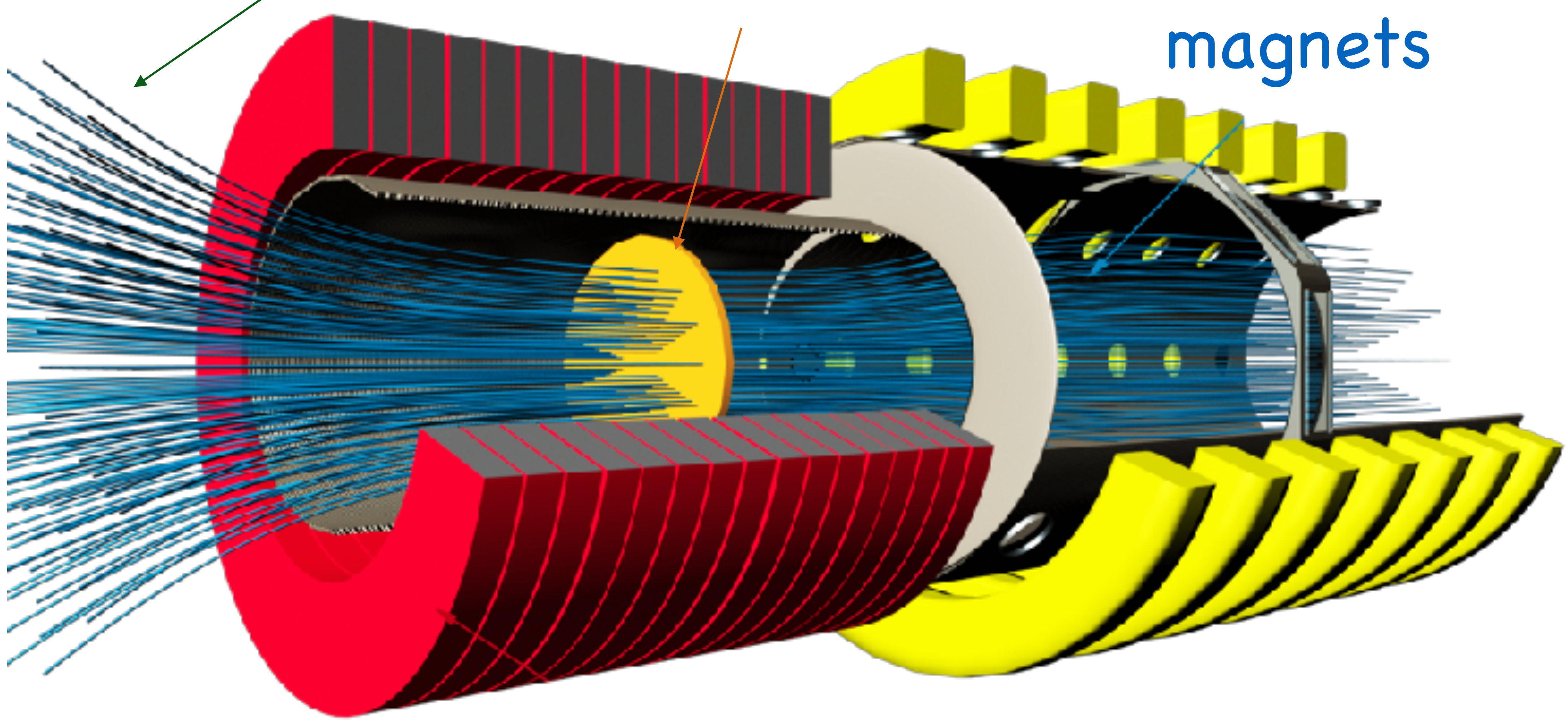
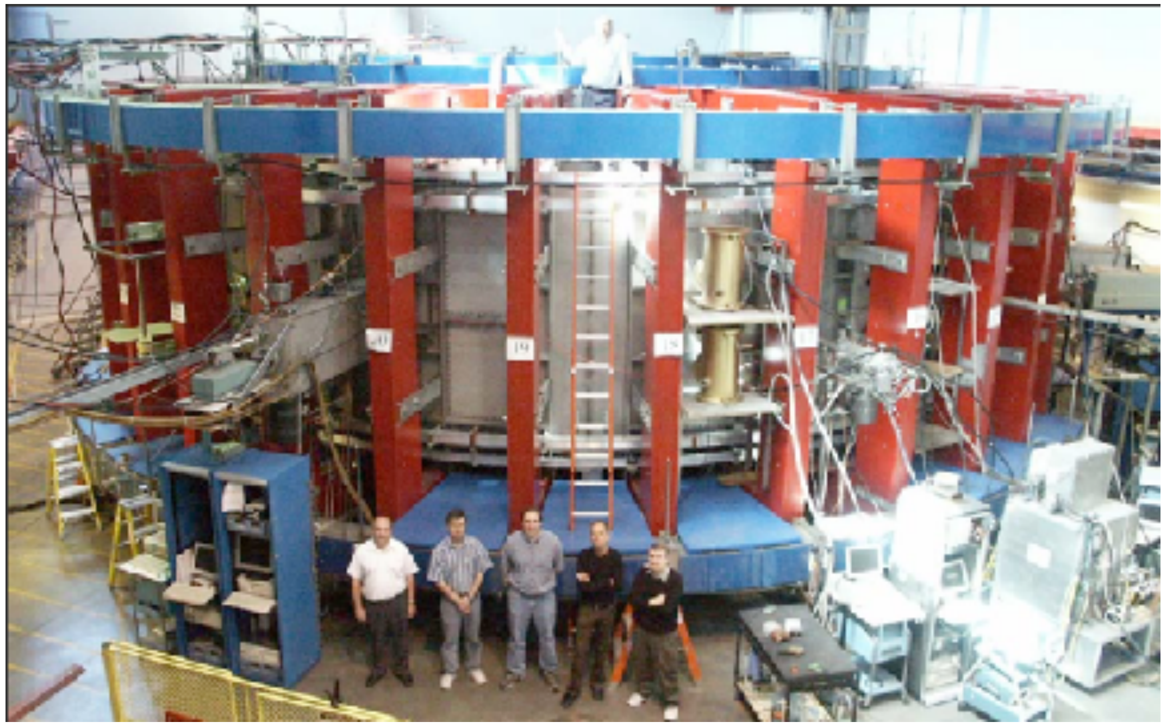
# Upcoming major upgrade: replace primary BaO cathode with large $LaB_6$ cathode source

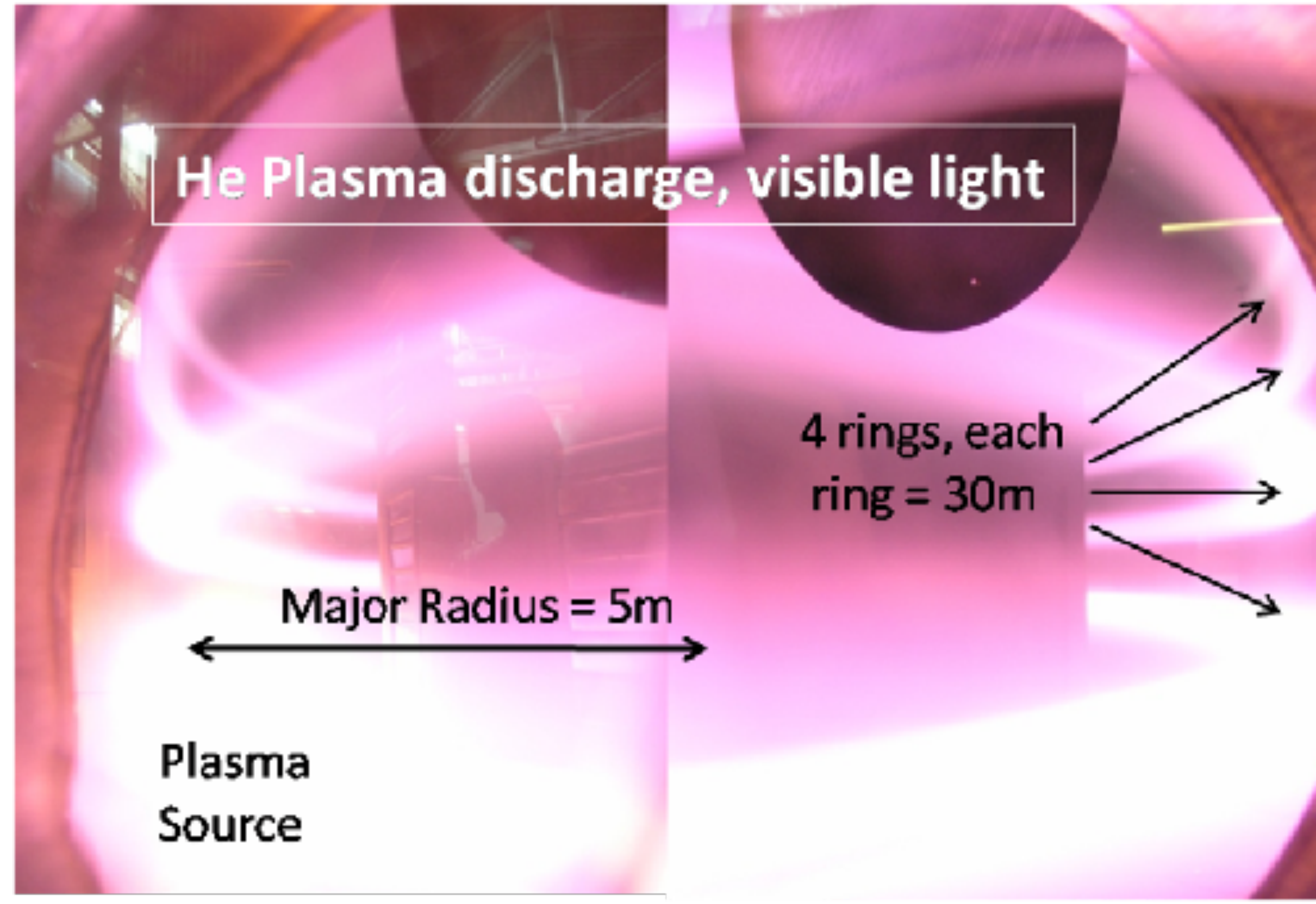



Will provide larger area (up to 80cm diameter)

$\beta \sim 1$ plasmas

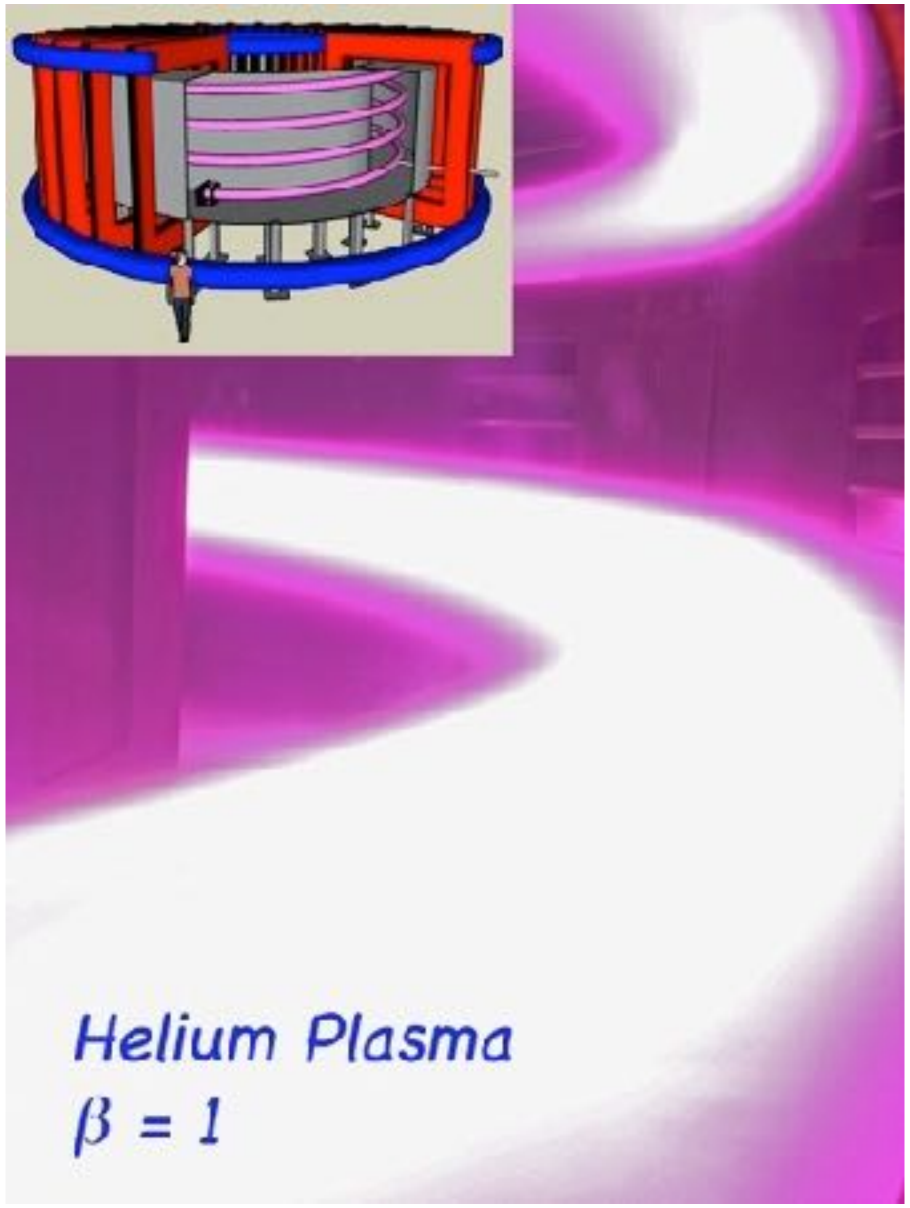
# Enormous Toroidal Plasma Device at UCLA

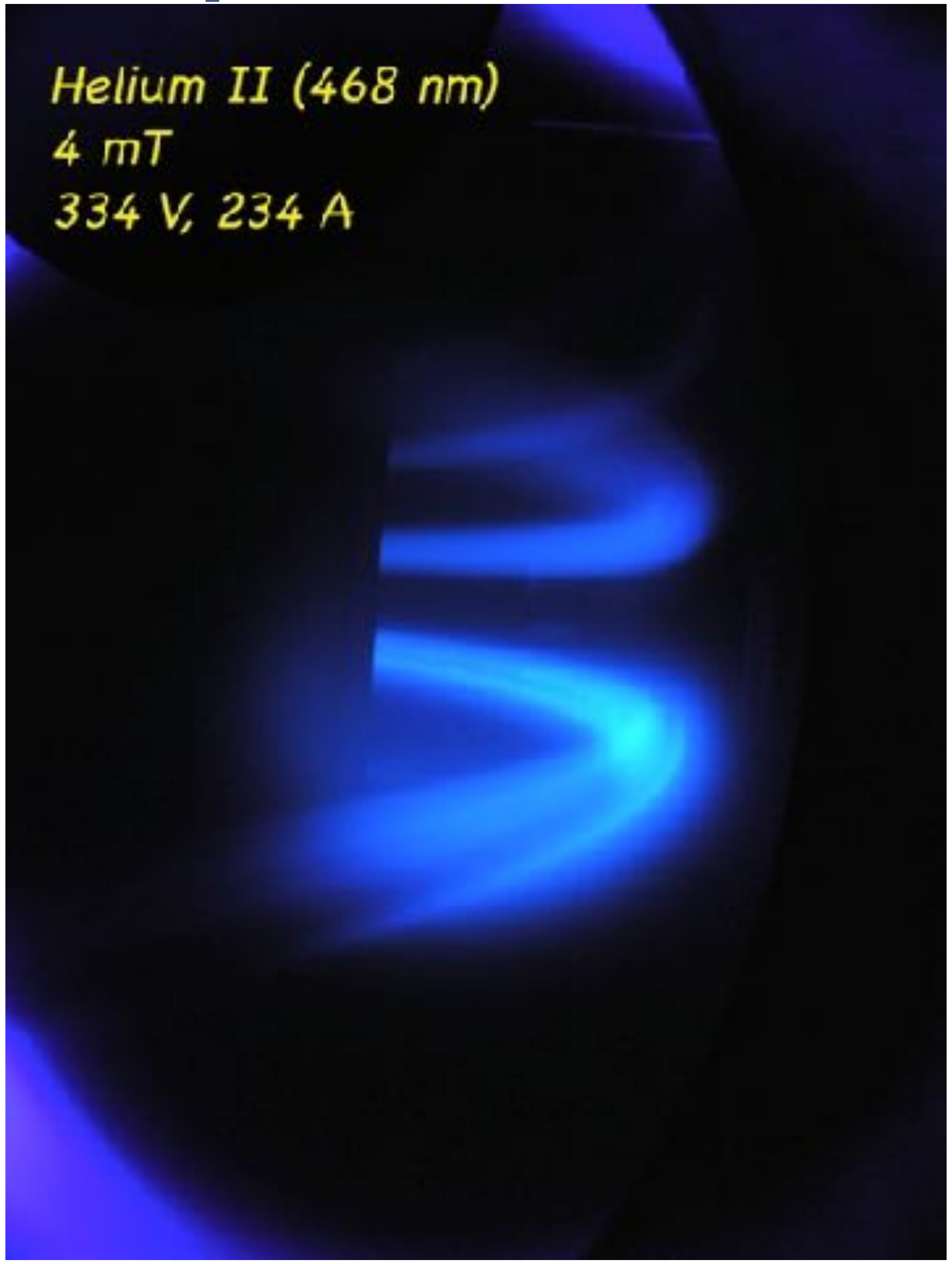





- Former Electric Tokamak, (5m major radius, 1m minor radius)
- Operating now with $LaB_6$ cathode discharge into toroidal+vertical field
- Produces ~120m long, magnetized, high beta plasma (up to ~$5\times10^{13}$ cm$^{-3}$, Te, Ti ~ 15-30eV, B~200G, $\beta$ ~ 1).

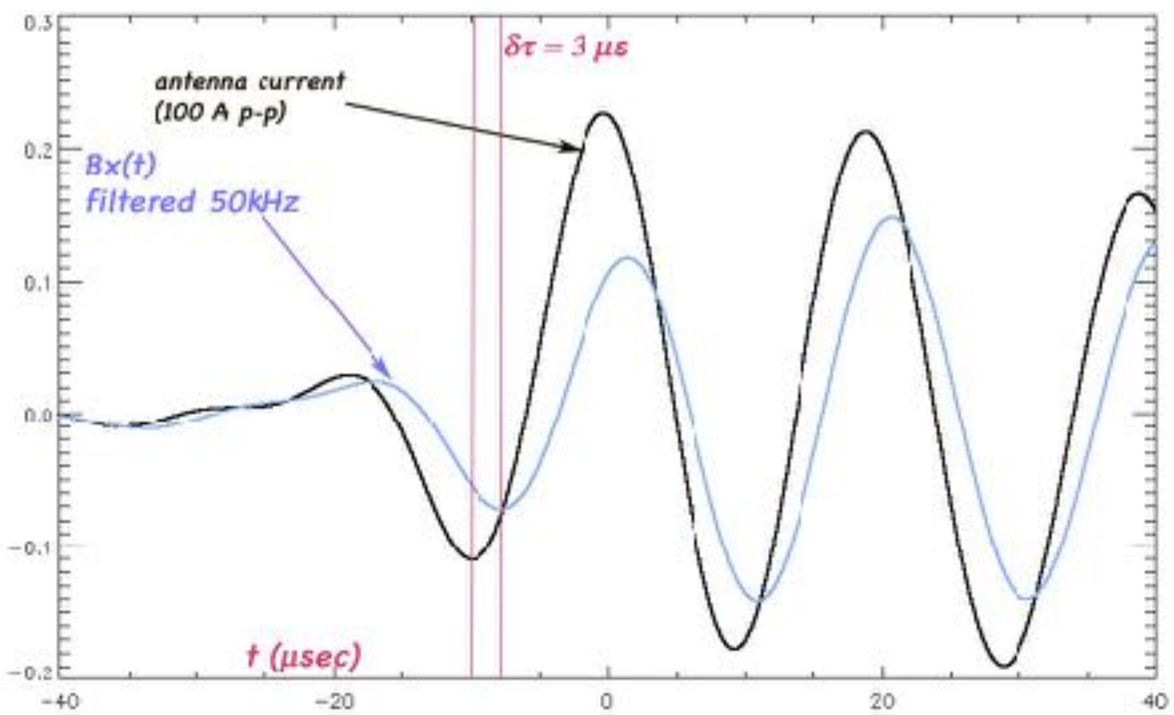
# High beta, hot ion plasmas in ETPD

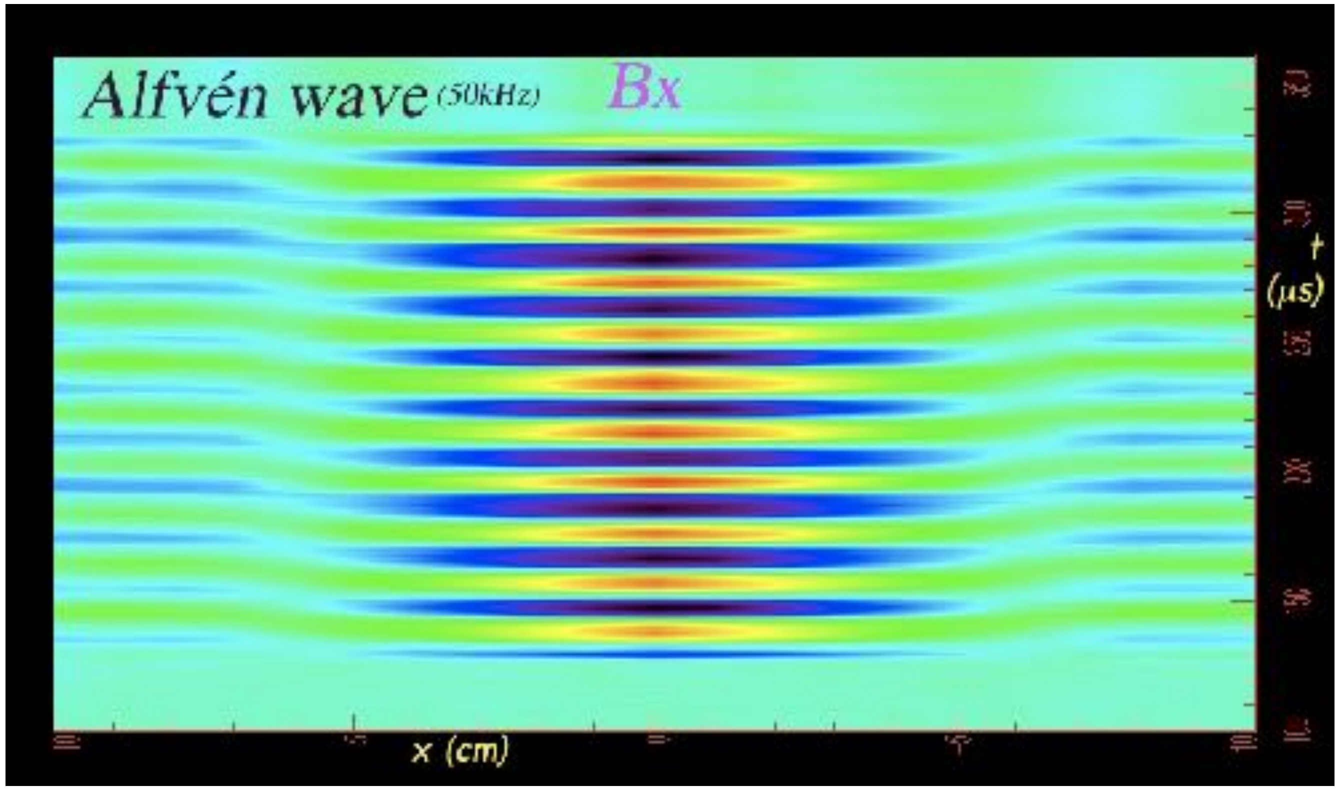



- $T_e \sim T_i \sim 20$ eV measured (passive spectroscopy of He II 4686 line).
- With B~250G, plasma beta of order unity is achieved

# 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

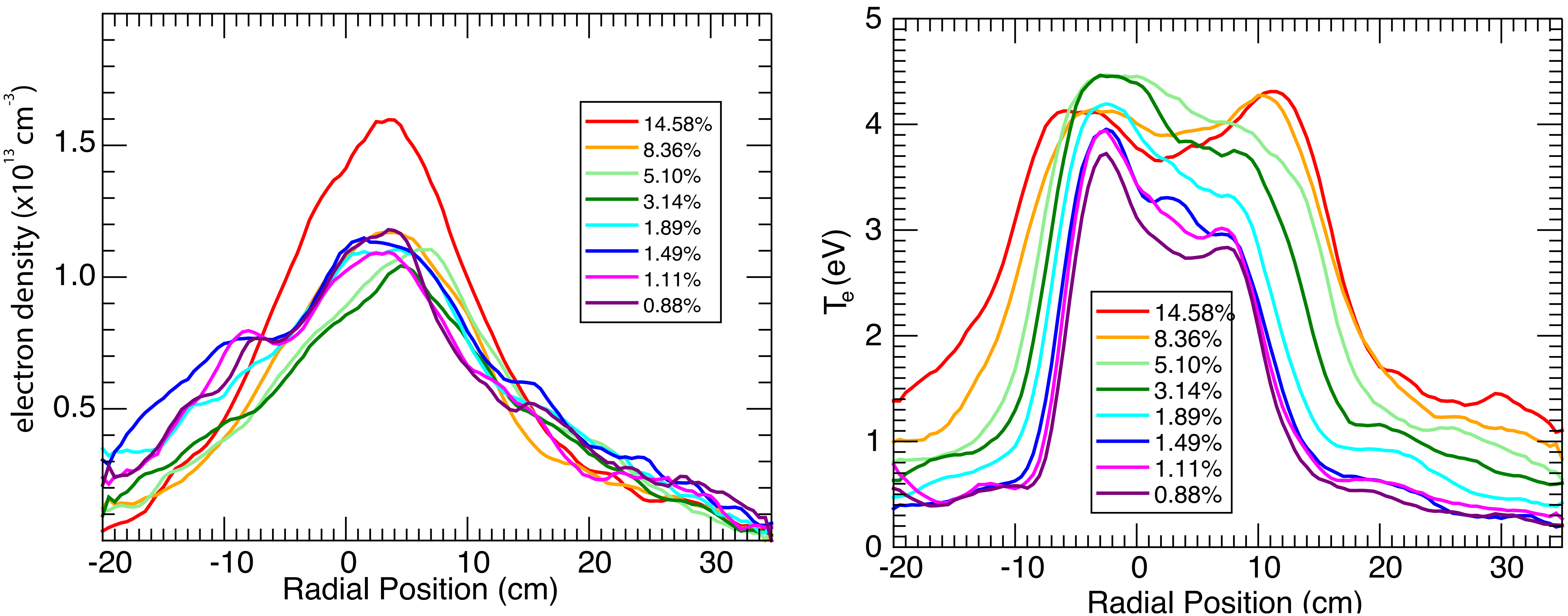
- Mirror/firehose: Drive anisotropy, higher beta through expansion (drive plasma into low field region)

- Reconnection, Shock physics

# Why does β matter for pressure-gradient-driven turbulence and transport?

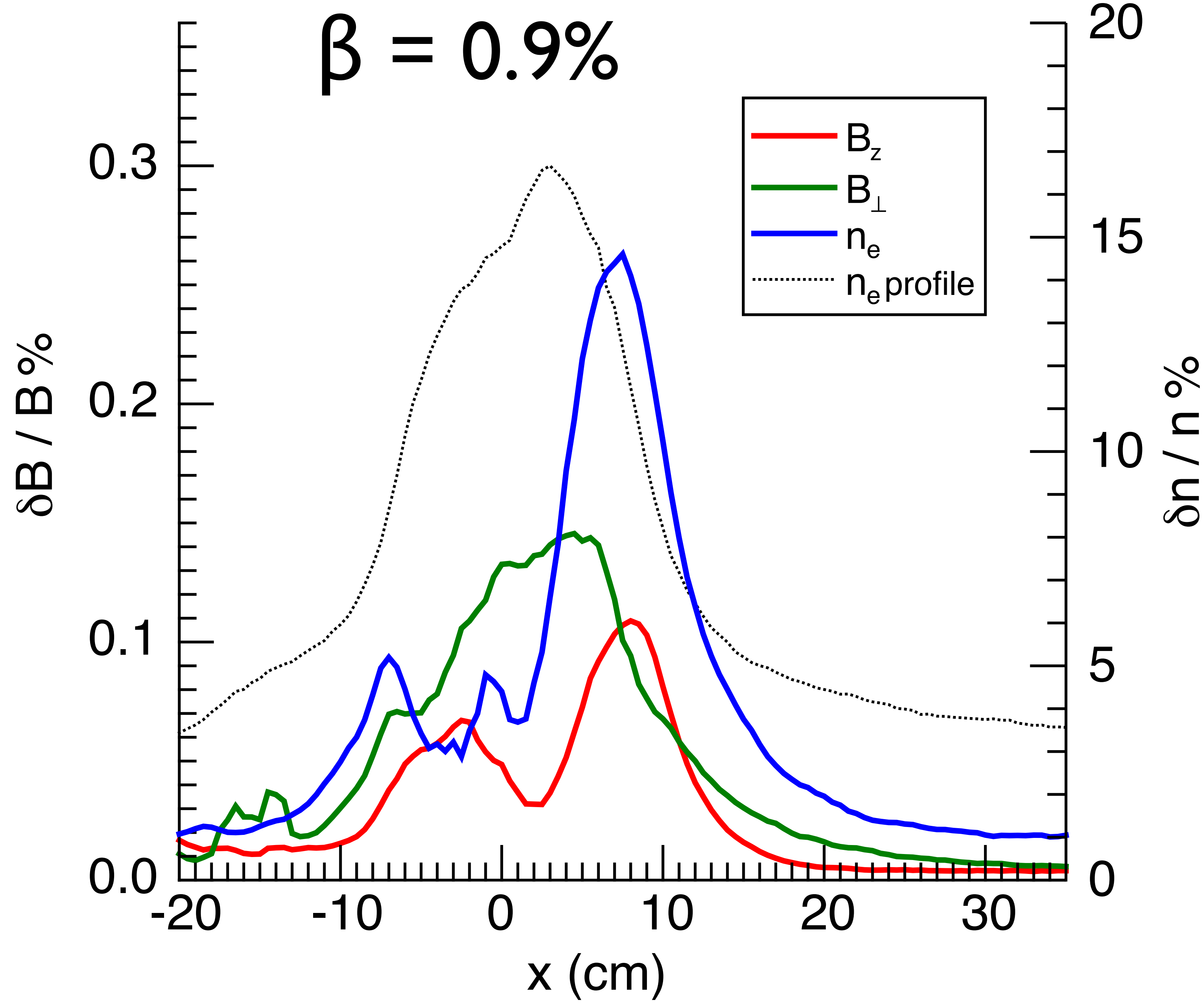
- Modifications to drift instabilities at finite β
  - Drift-Alfvén wave coupling at low β (mass ratio): leads to magnetic fluctuations ($\delta A_\parallel$ or $\delta B_\perp$) (seen in low β LAPD discharges)
  - ITG stabilization with increasing β
- Electromagnetic transport, e.g. magnetic flutter-transport arises with $B_\perp$ fluctuations (Rechester, 1978)
- New instabilities may develop at finite β
  - Kinetic ballooning, etc.
  - Gradient-driven drift-coupling mode (GDC)
    - Couples to collisionless tearing modes and drives faster magnetic reconnection rates (Pueschel, 2015)

# LAPD: β up to 15% produced with magnetic field scan




- Magnetic field varied from 1kG to 175G, $0.1\% \lesssim \beta \lesssim 15\%$ in the core
- $\rho_i$ varies from ~3mm to ~2.5cm; marginal magnetization at highest β ($\rho_i/L_n \sim 4$; FLR effects likely important)

# Fluctuation profiles: $\delta n$, $\delta B_{\parallel}$ peak on gradient; $\delta B_{\perp}$ core localized



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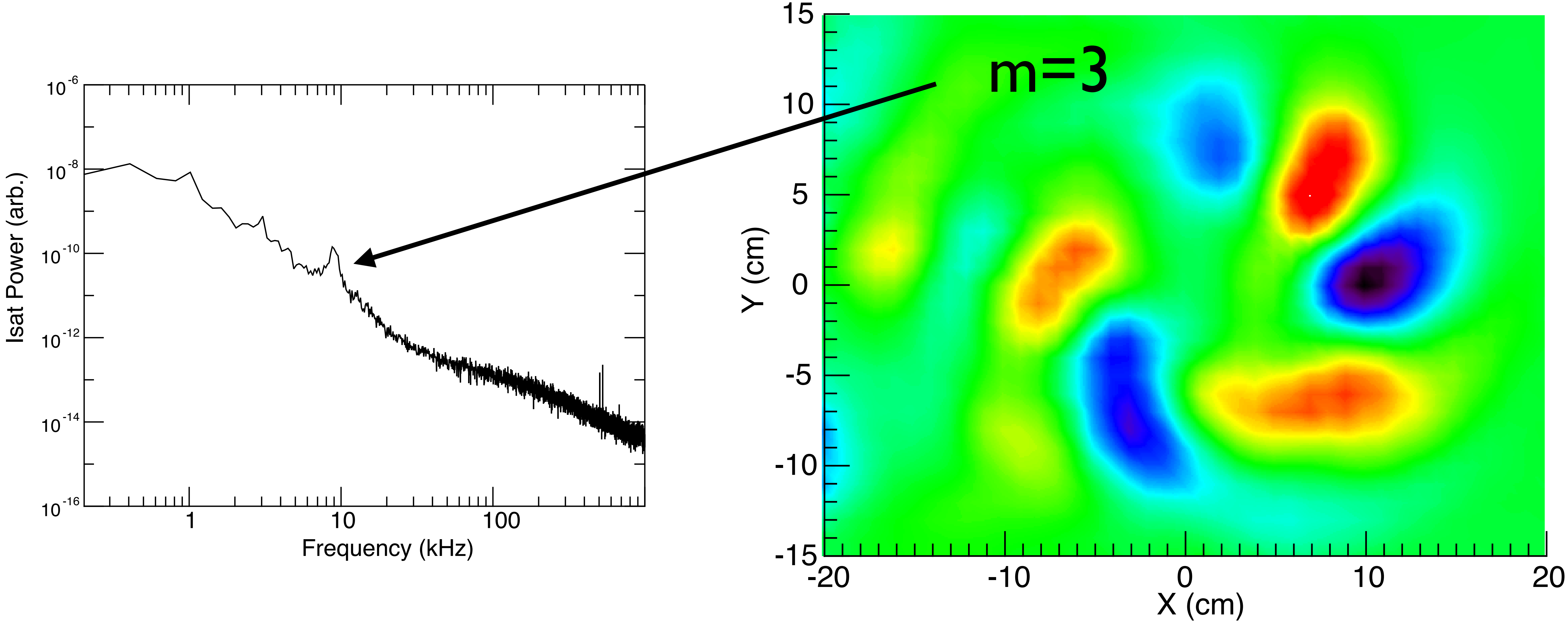
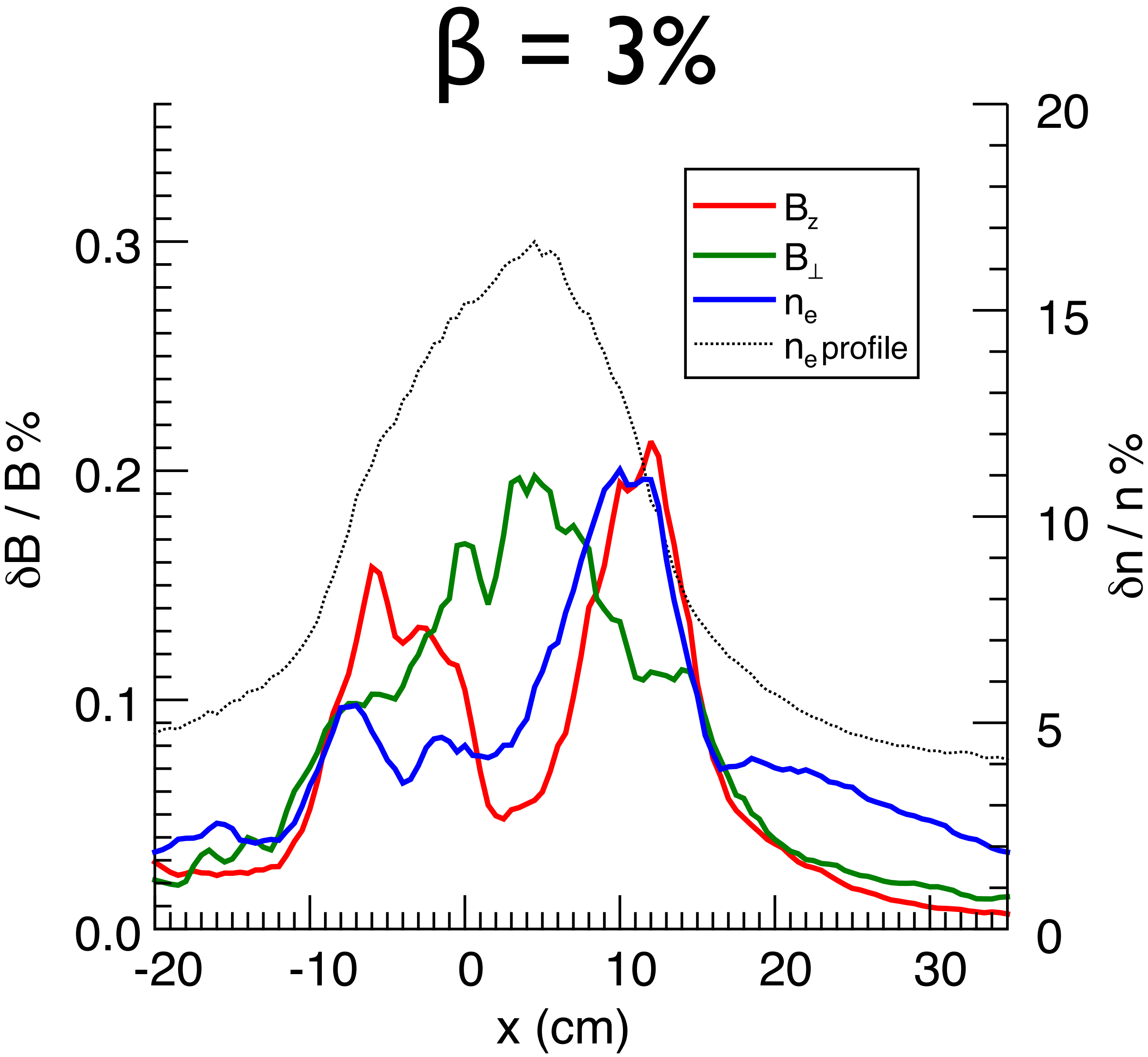
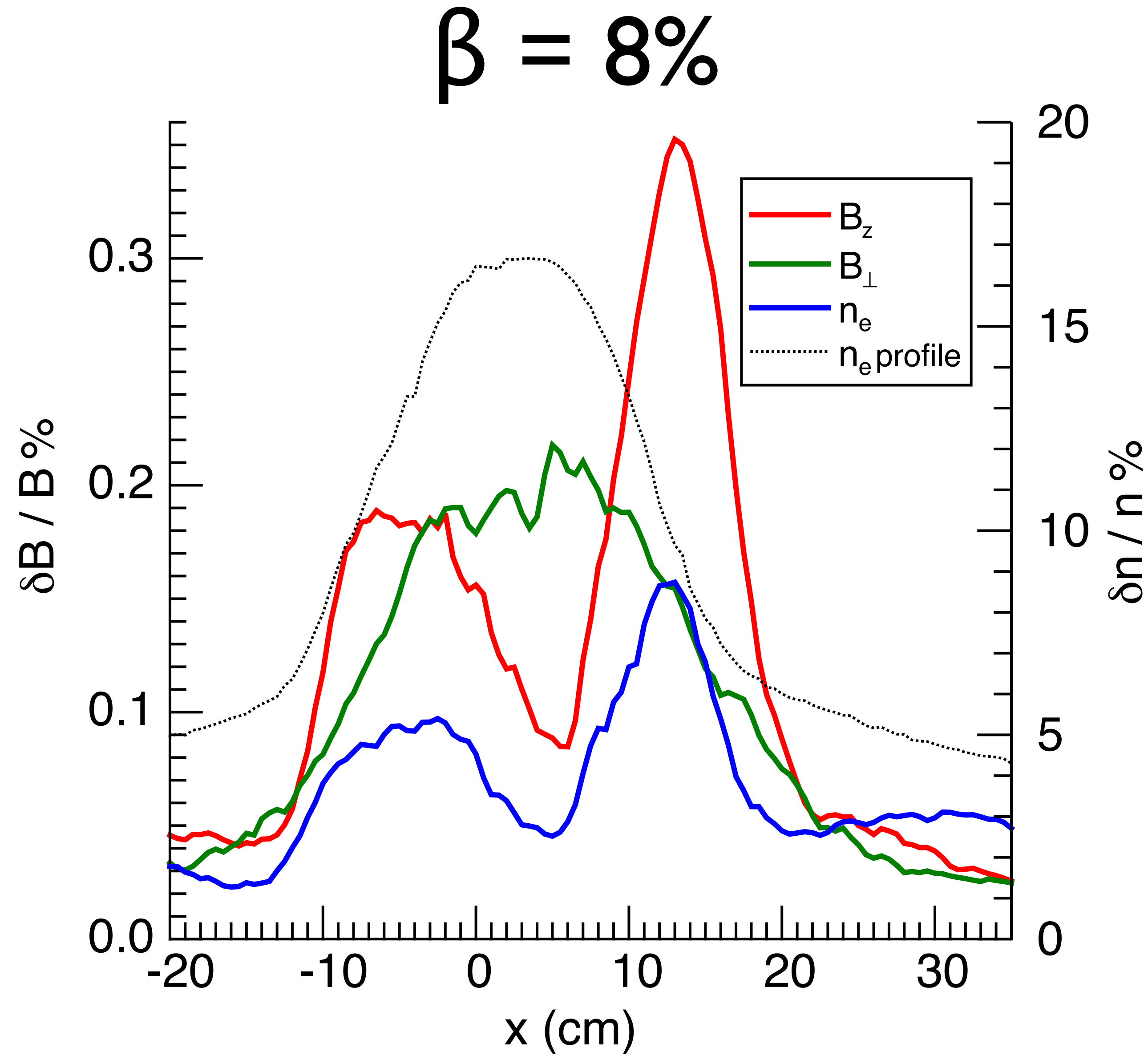


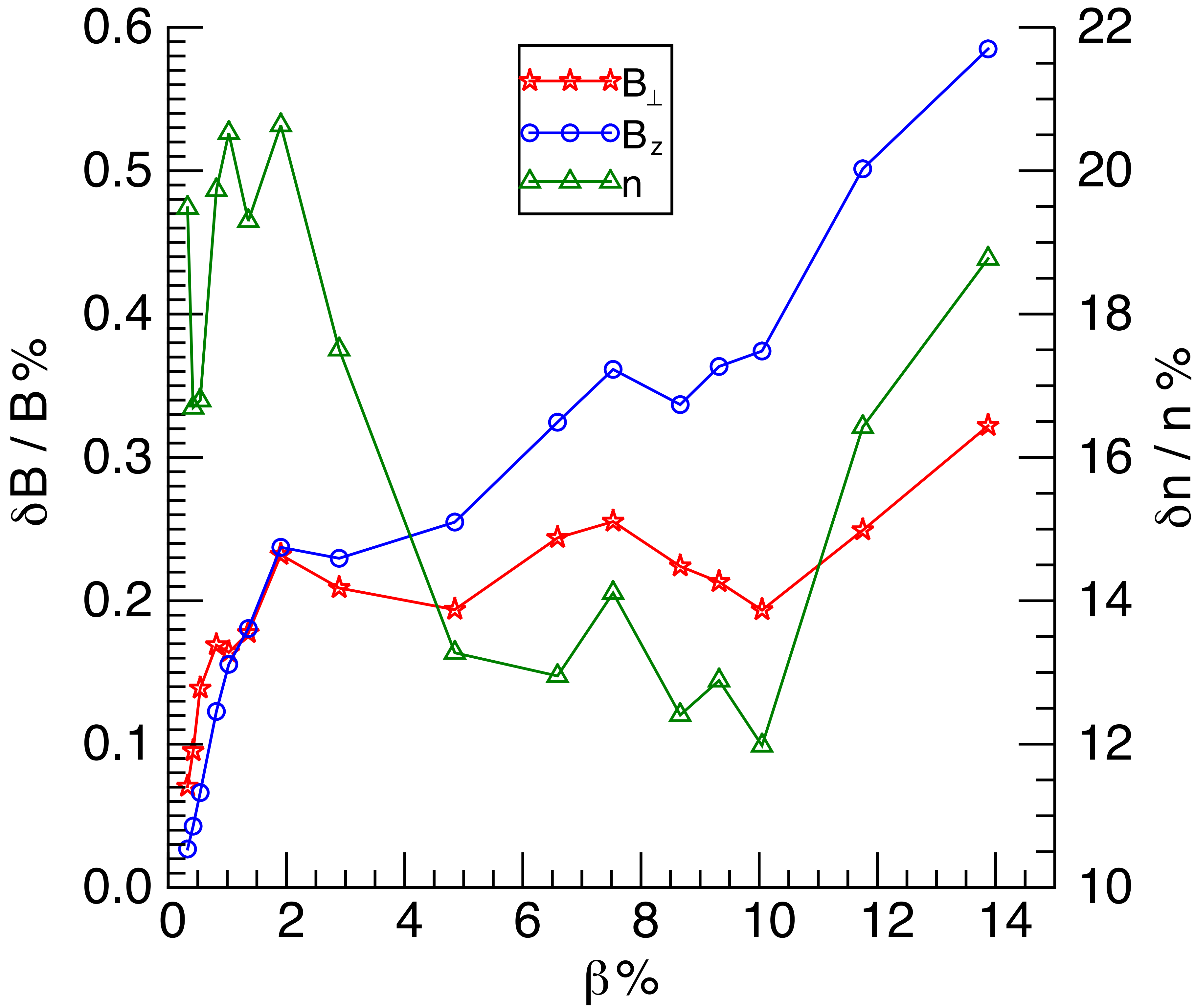

$\delta B_{\perp}$ profile consistent with dominance of low-m modes

# Magnetic fluctuations increase with β; surprise is that $\delta B_\parallel$ dominates

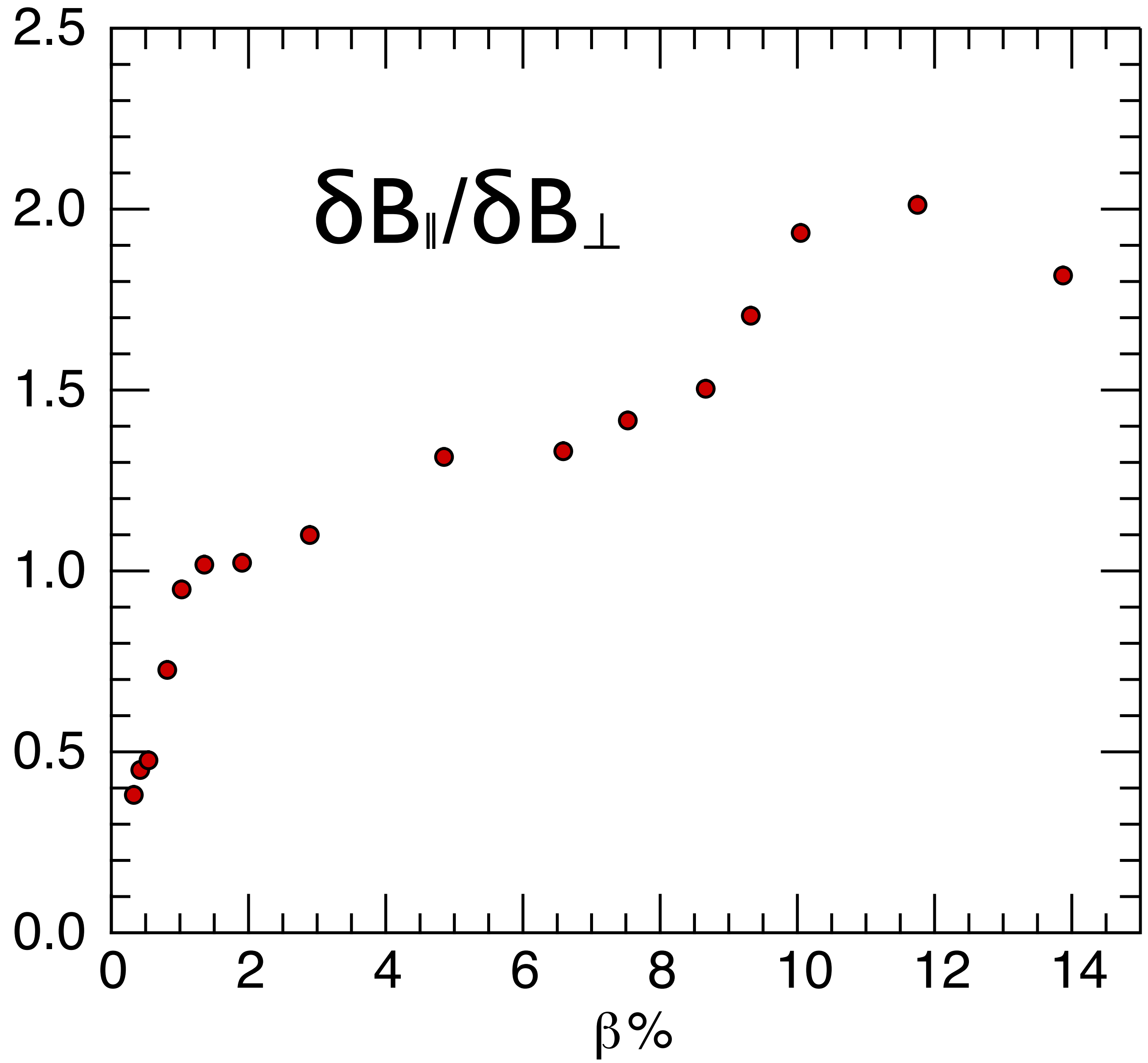


# Magnetic fluctuations increase with $\beta$, density fluctuations somewhat reduced



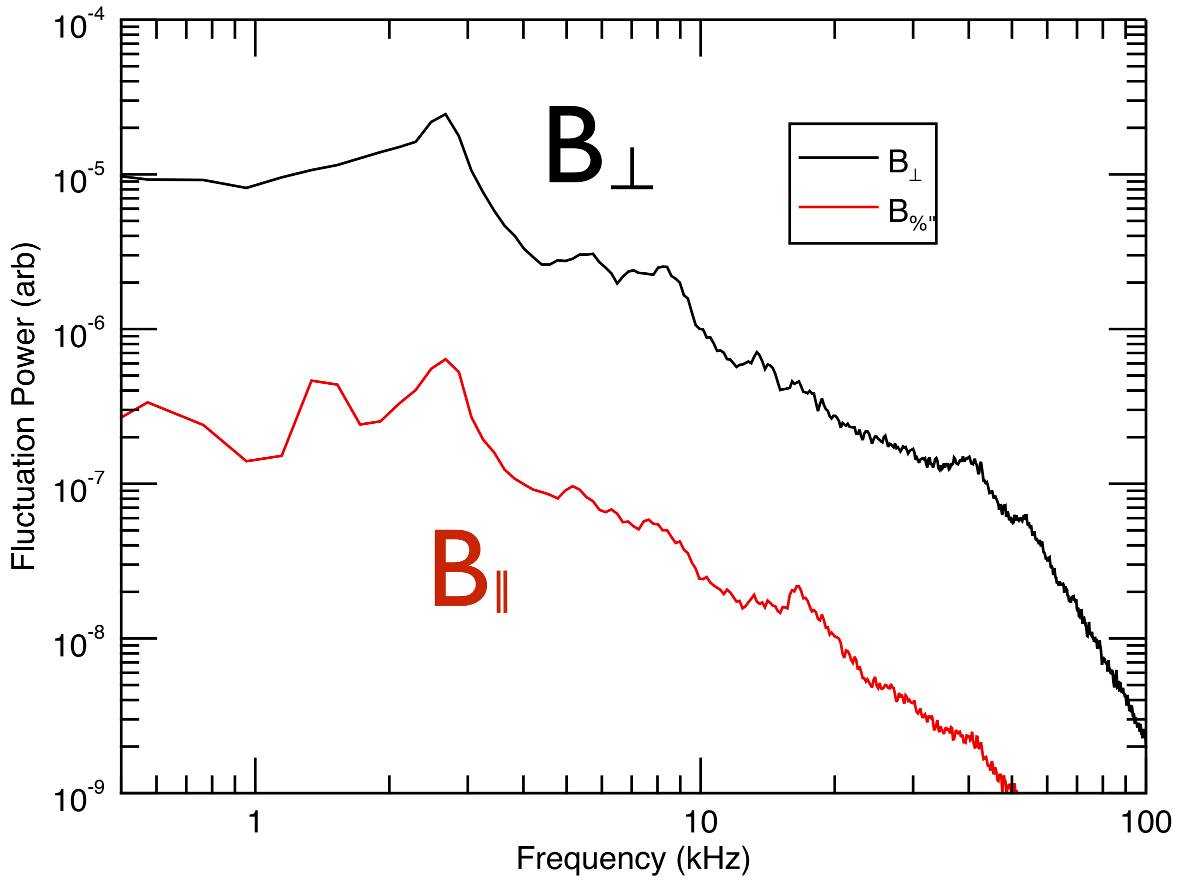
# Strong parallel magnetic field fluctuations seen as β is increased



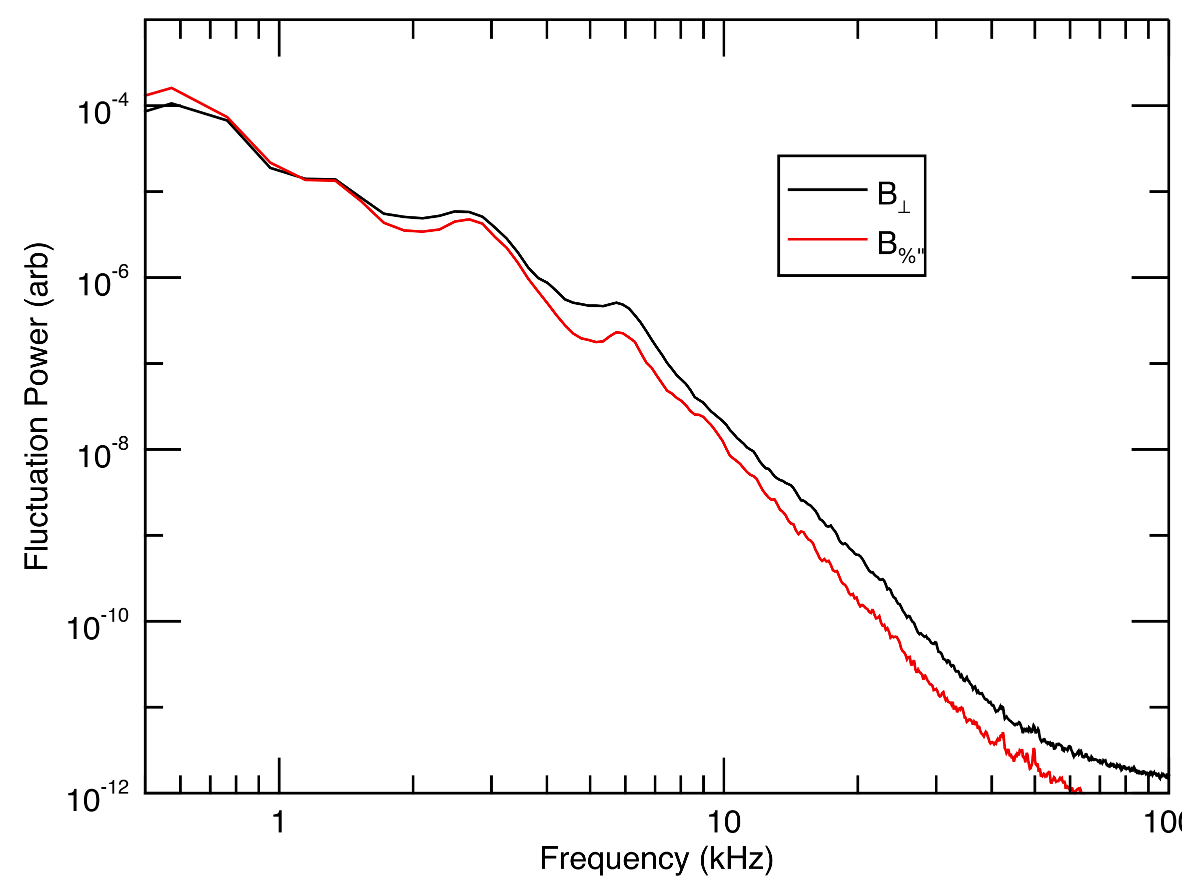

- Surprisingly, $B_\parallel$ fluctuations dominate above β ~ 1%
- Evidence for emergence of new instability?

# Strong parallel magnetic field fluctuations seen as β is increased

1kG, β~0.3%

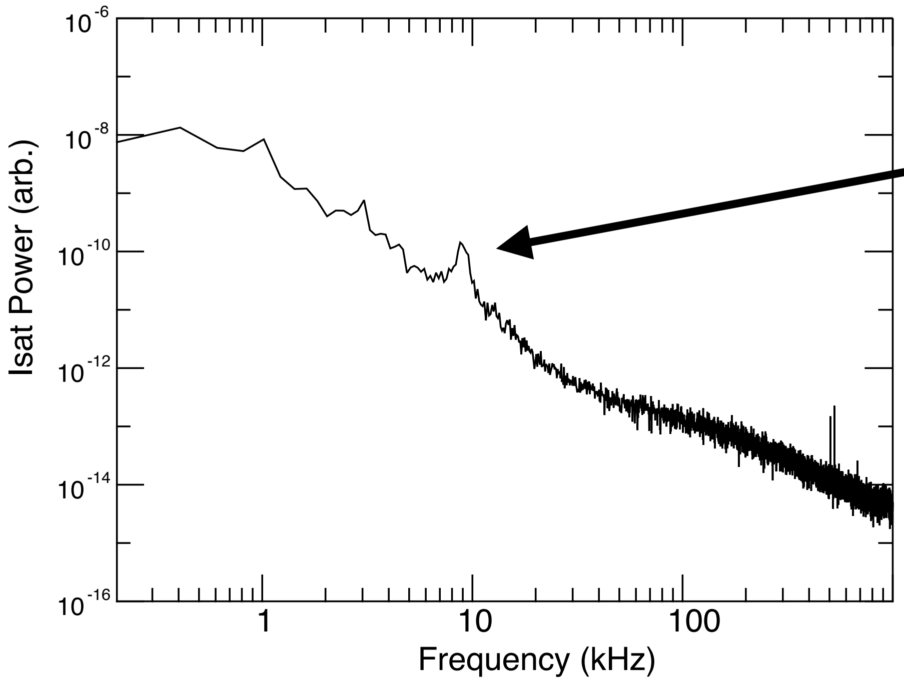


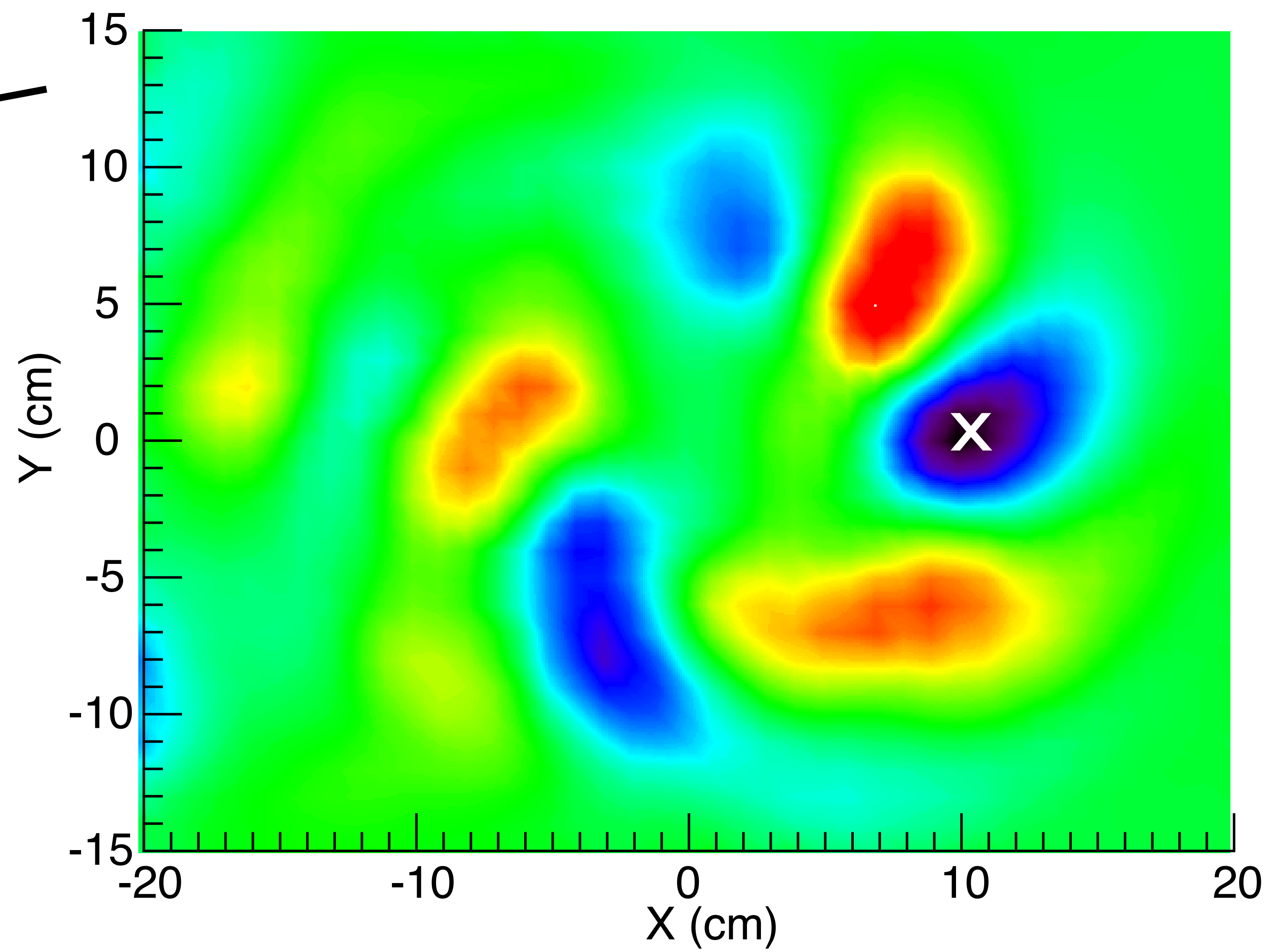

175G, β~15%




- Surprisingly, $B_\parallel$ fluctuations dominate above $\beta \sim 1\%$
- Evidence for emergence of new instability?

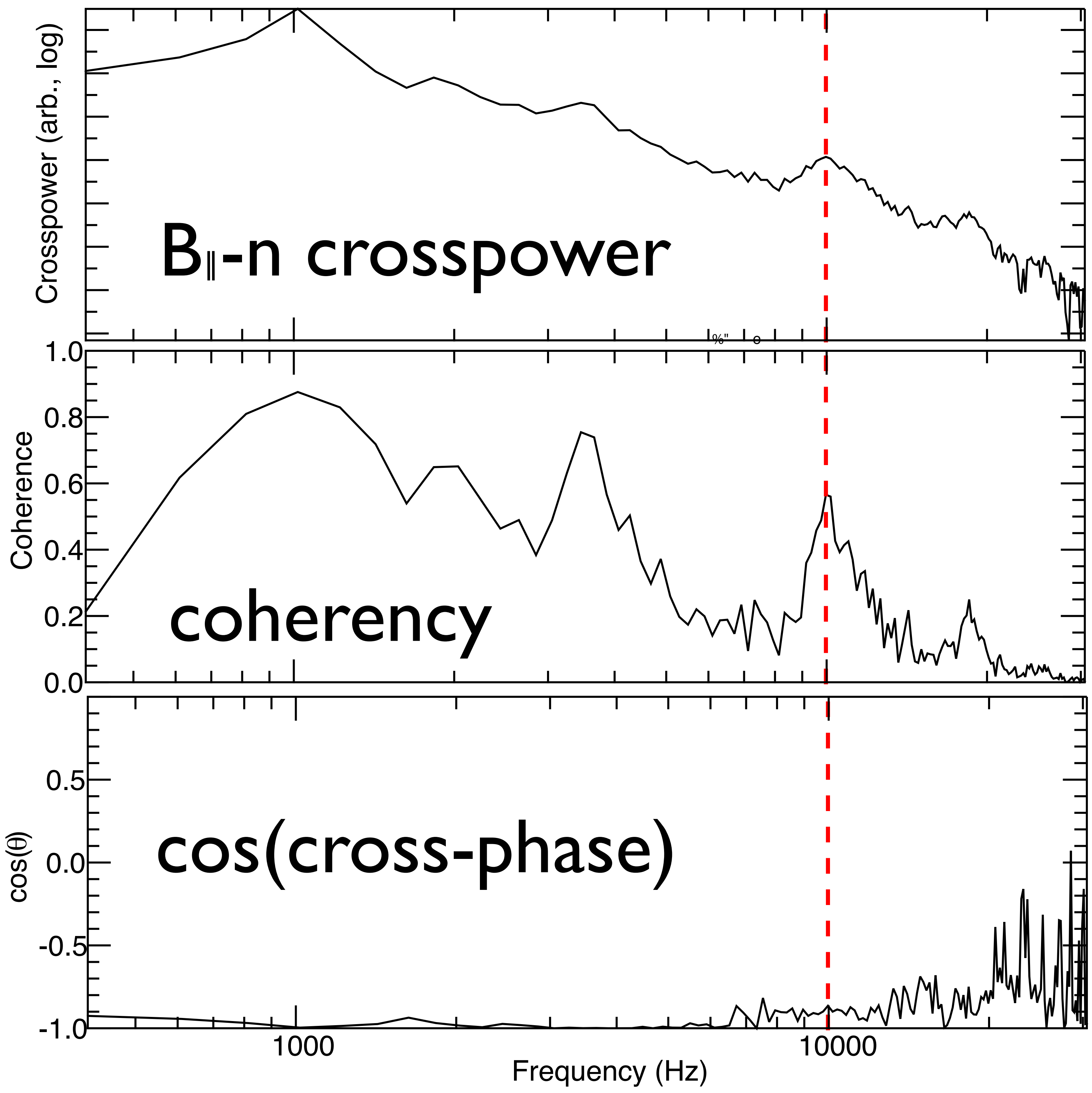
# Cross-correlation measurements reveal low-m structure and anti-correlation between $\tilde{n}_e$ and $\tilde{B}_\parallel$



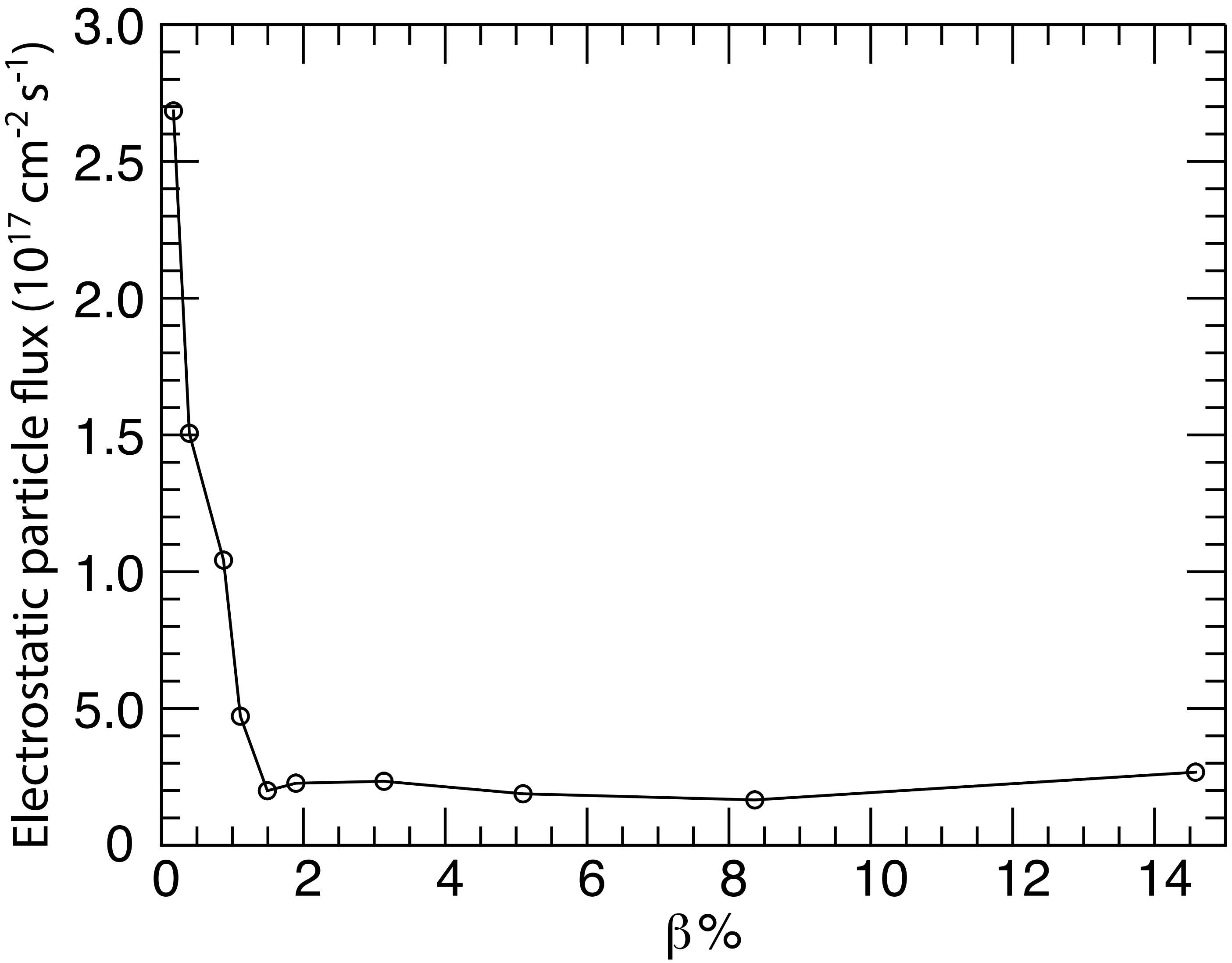




- Most fluctuation power in azimuthal modes m=1 to m=3
- Cross-correlation between density (Isat) and magnetic field fluctuations: two fields are ~π out of phase

# Cross-correlation measurements reveal low-m structure and anti-correlation between $\tilde{n}_e$ and $\tilde{B}_\parallel$



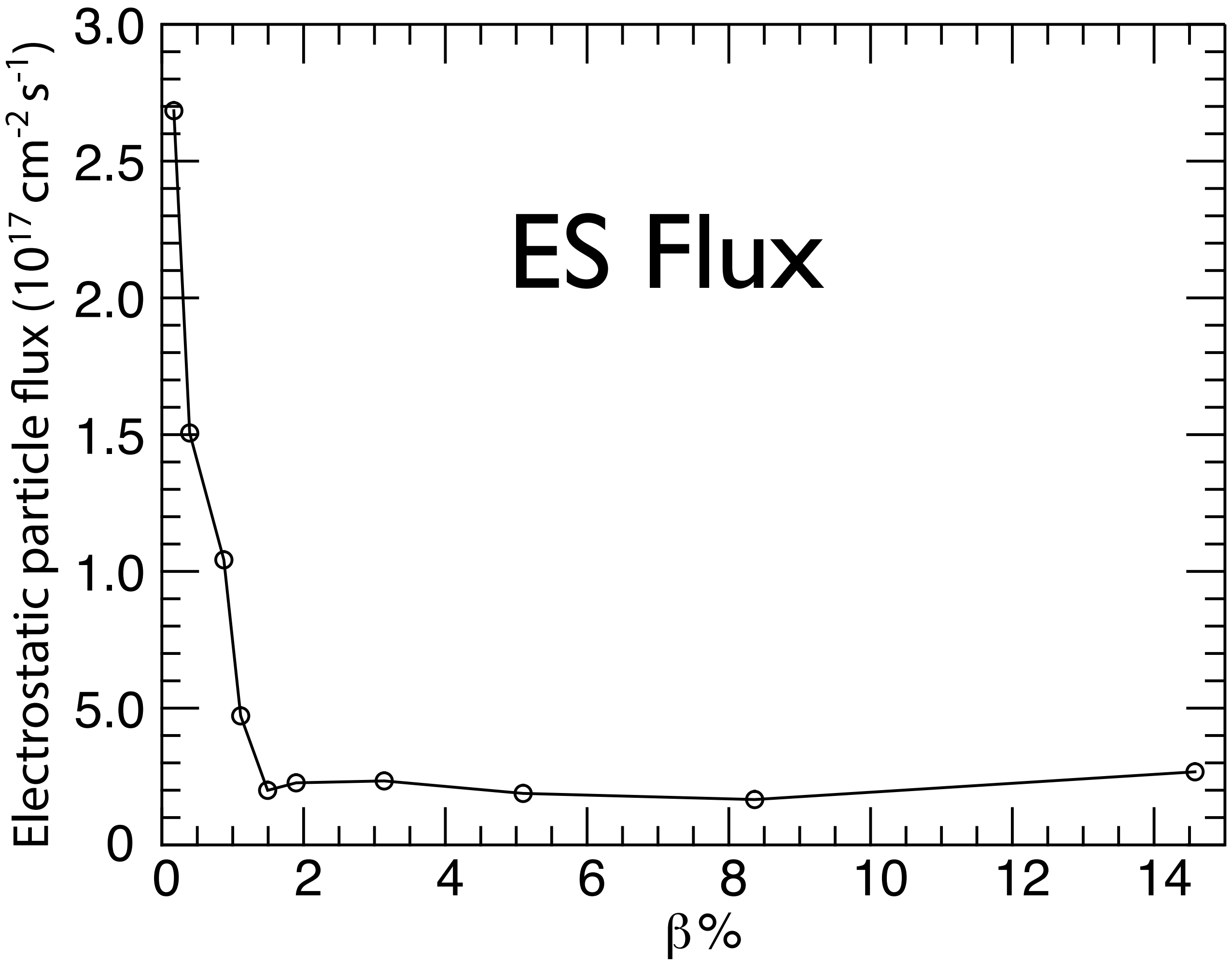
# Electrostatic particle flux decreases with increasing β

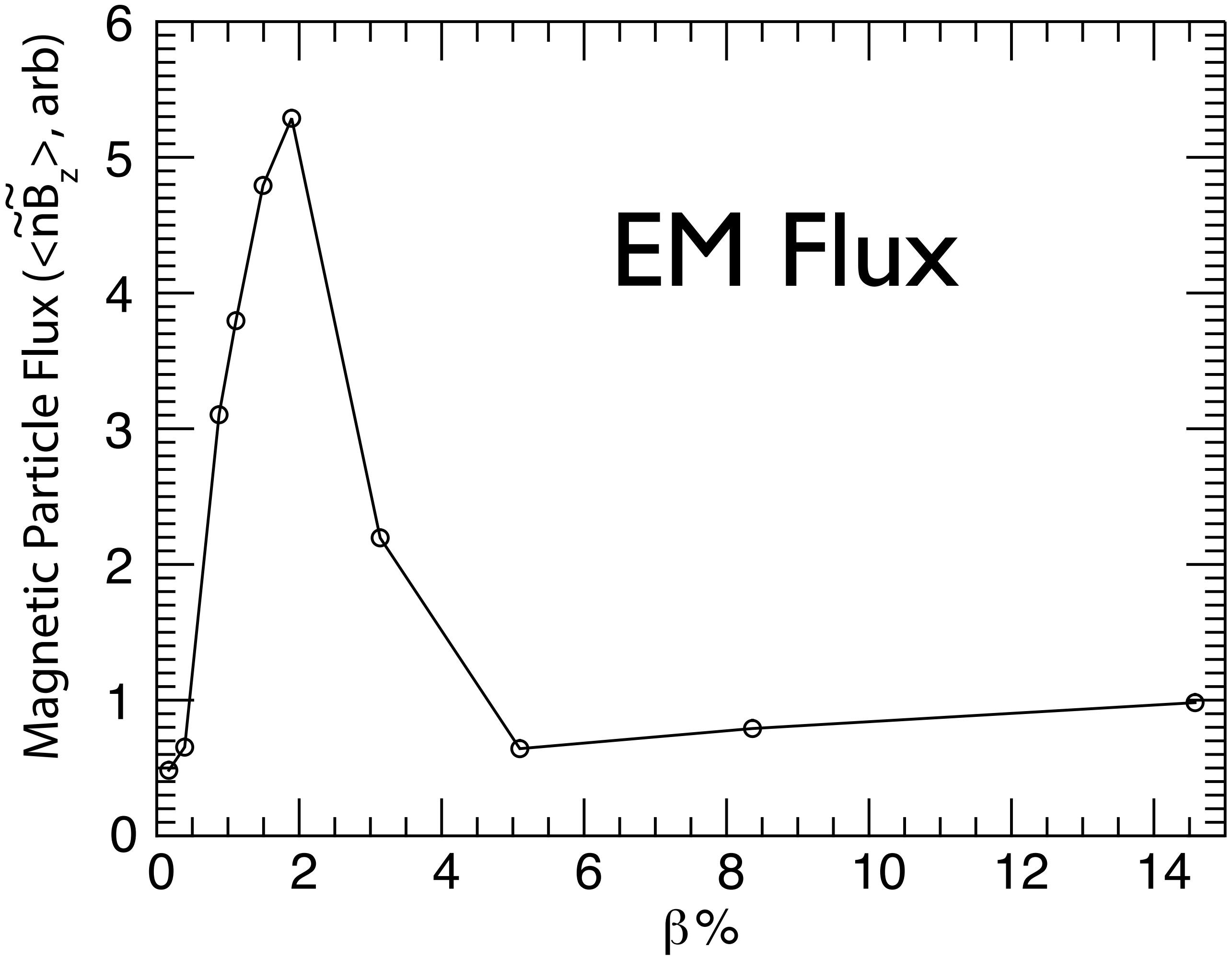



$$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle \propto \left\langle \tilde{n}\tilde{E}_\phi \right\rangle$$

- Peak ES particle flux decreases with β, primarily due to decreased density and electric field fluctuation amplitudes

# Electromagnetic transport?




- Initial magnetic flux estimate from $\Gamma \sim \tilde{n}\, \tilde{v}_{\nabla B} \propto \tilde{n}\, \tilde{B}_{\parallel}$
- Decrease at higher $\beta$ due to ion FLR? More work needed here (e.g. global particle balance, measurement of magnetic flutter transport)

# Observations are consistent with newly* predicted instability, the Gradient Drift Coupling (GDC) instability

- GDC recently discovered in the context of magnetic reconnection in high-$\beta$ current sheets [Pueschel, et al. PoP 2015]
  - Linear and nonlinear calculations show that it should be active in these LAPD experiments
  - Not likely to be excited in tokamaks due to magnetic shear, but expected in space/astro plasmas
- Similar to universal instability/interchange instability but relies on $B_{\parallel}$ perturbations that arise with density fluctuations in finite beta plasmas and the associated $\nabla B$ drifts in the perturbed fields
  - Predicts density, parallel magnetic fluctuations have $\pi$ phase shift

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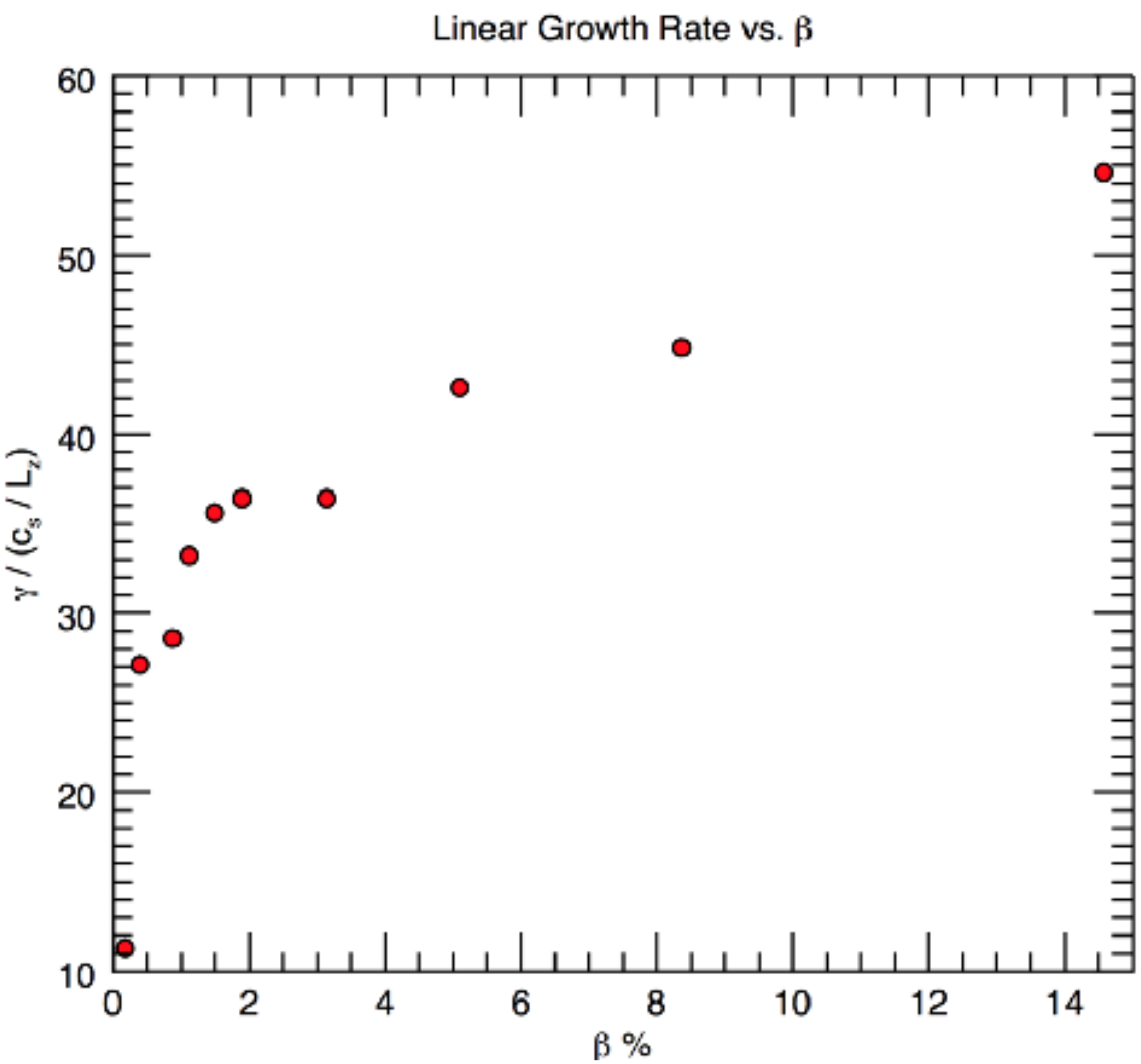
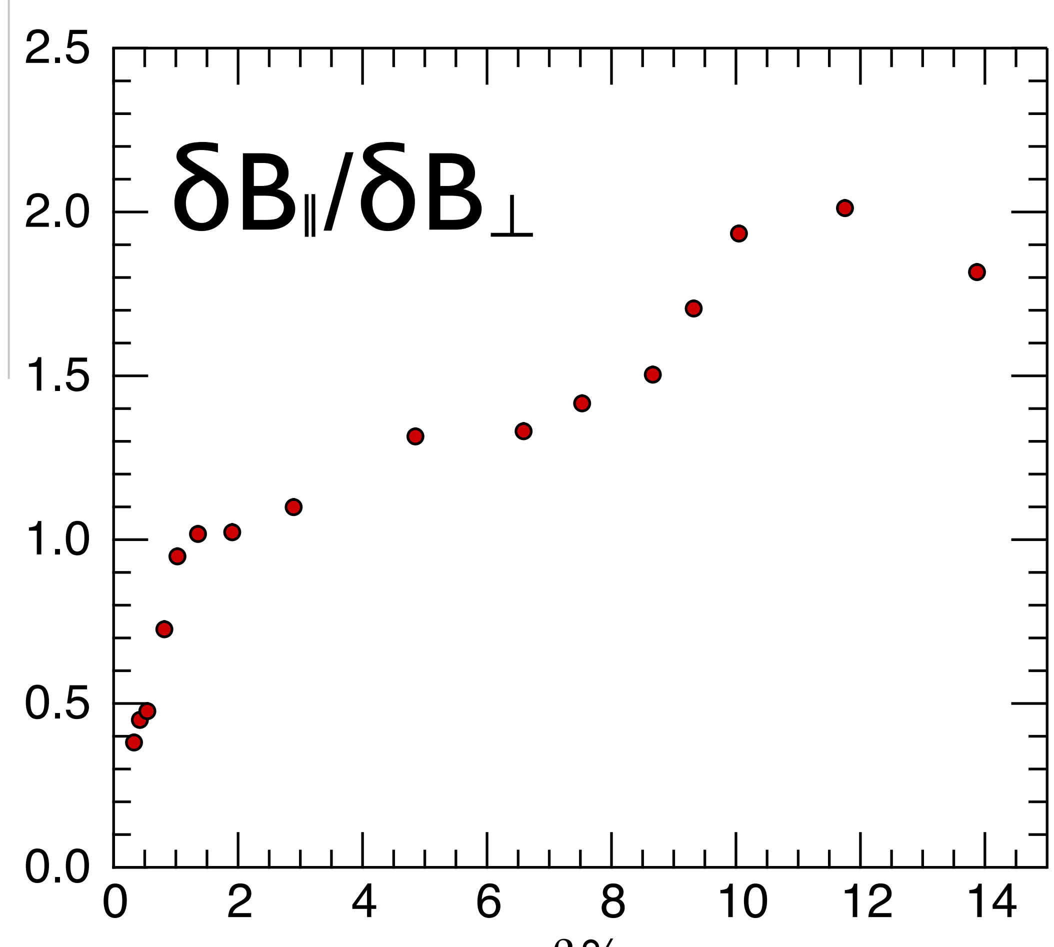



GDC linear growth rate from GENE, using experimental parameters: growing, and trend reminiscent of trends in saturated amplitudes



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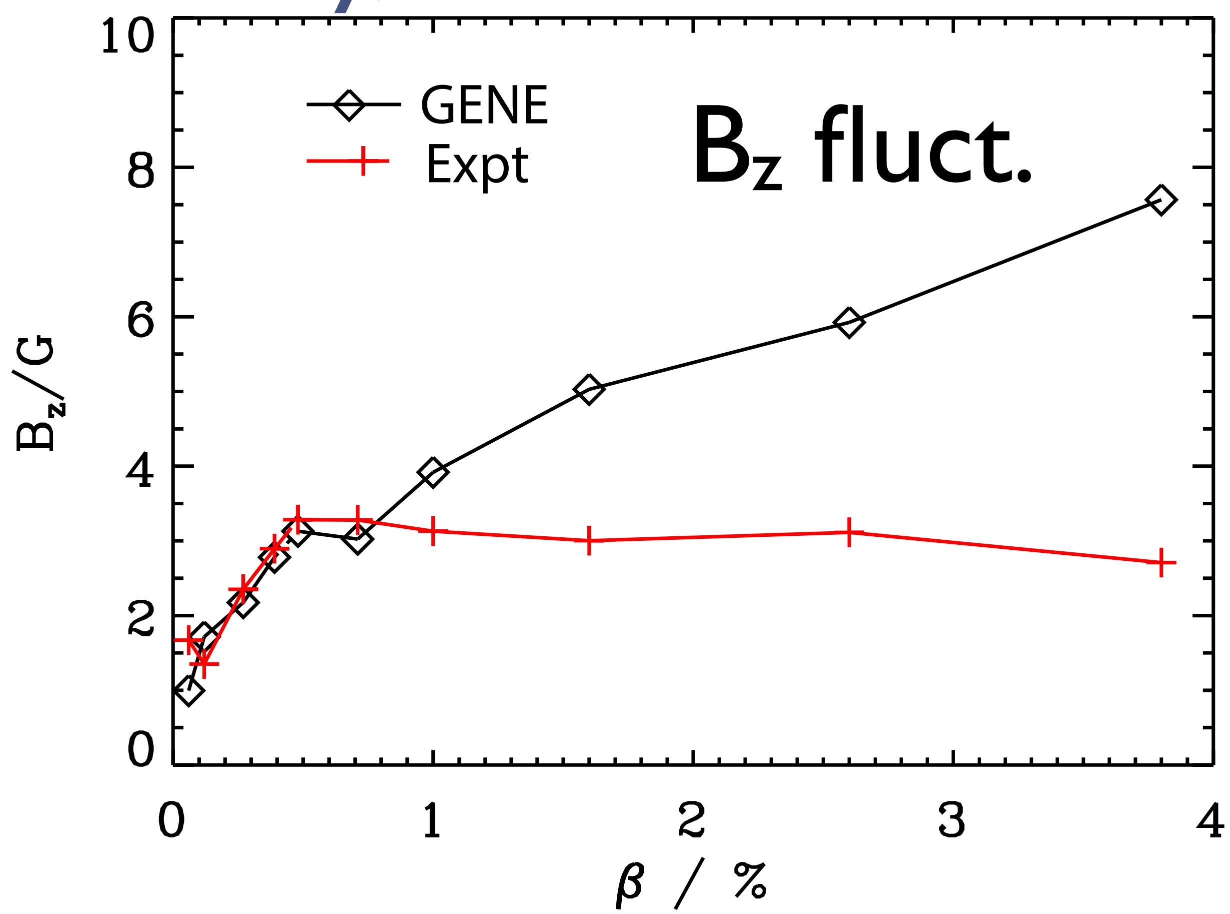
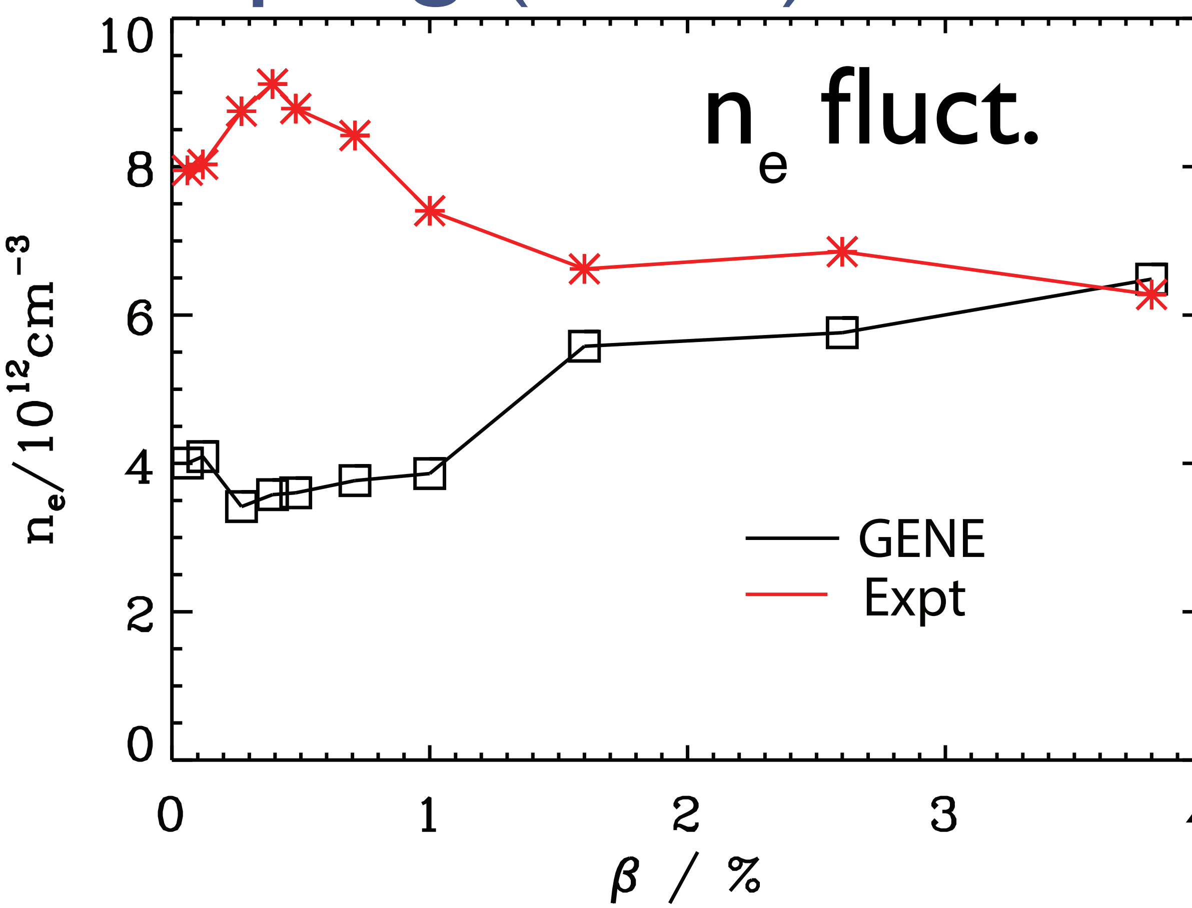
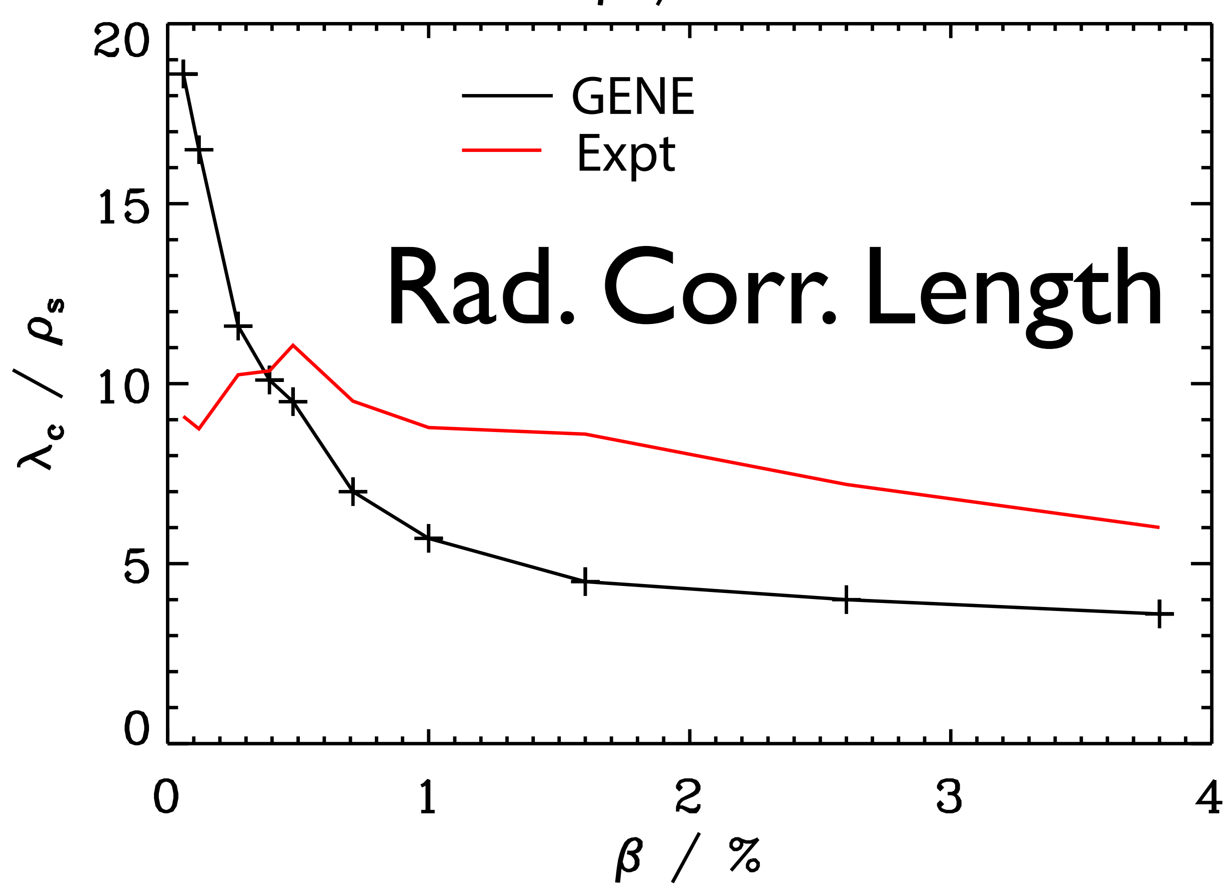



Nonlinear simulations: reasonable agreement on saturated amplitudes, radial correlation lengths

Pueschel at al., PPCF (2017)

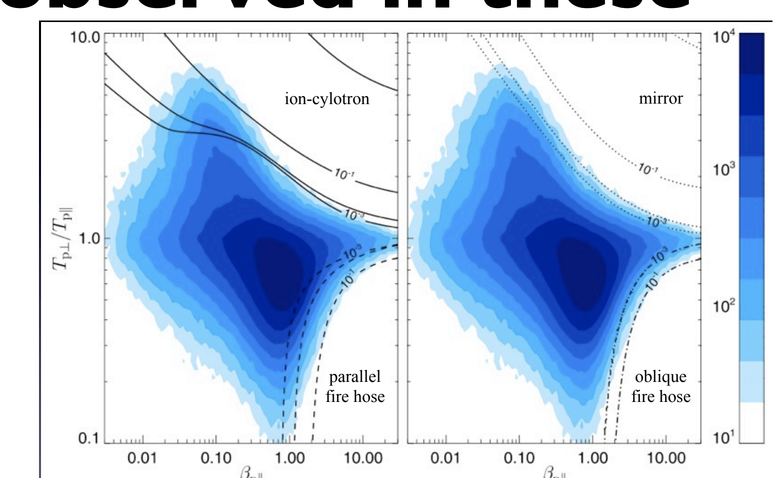
# Solar wind campaign: physics of $\beta \sim 1$, warm ion plasmas

- Kinetic instabilities, waves and turbulence at high plasma beta ($v_A \sim v_{th,i}$) with warm ions

- Warm ions provide opportunity to study ion kinetic effects in waves and instabilities: e.g. **ion FLR effects on Alfvén wave propagation; ion cyclotron absorption; modification to nonlinear Alfven wave interactions; MHD turbulence**

- 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 temperature anisotropy driven instabilities (mirror and firehose) be observed in these plasmas?**

Campaign Leader: Greg Howes (U. Iowa)

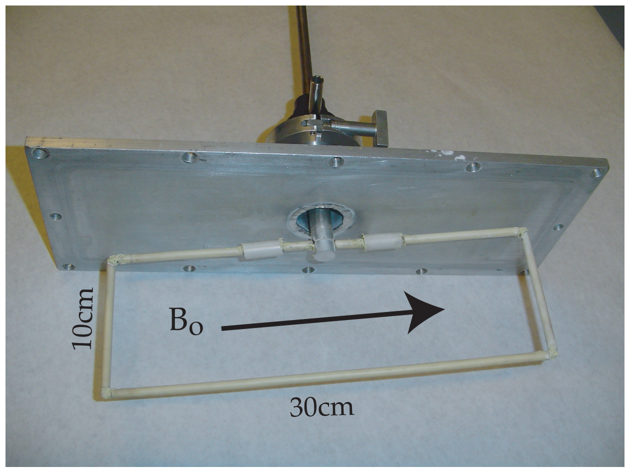


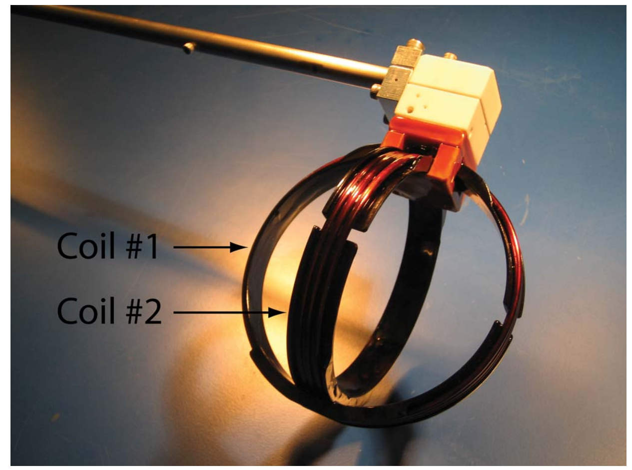

Hellinger, et al., 2006

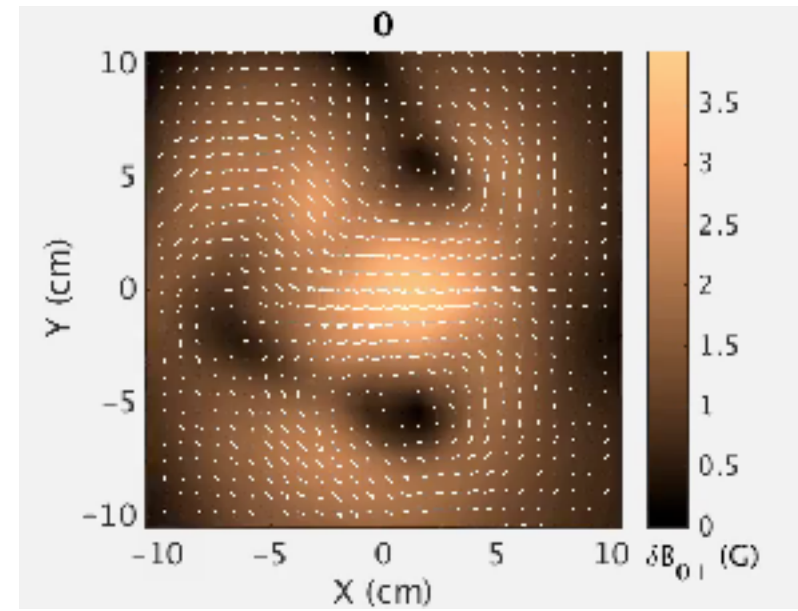
# Previous studies of nonlinear Alfvén waves in LAPD

- Series of experiments exploring three-wave interactions and decay instabilities. Motivations include studying Alfvénic turbulence in the lab
- Collision of two antenna-launched shear Alfvén waves:
    - Two co-propagating AWs produce a quasimode [Carter, et al., PRL, 96, 155001 (2006)]
    - Two co-propagating KAWs drive drift waves, lead to control/suppression of unstable modes (in favor of driven stable mode) [Auerbach, et al., PRL, 105, 135005 (2010)]
    - Two counter-propagating AWs, one long wavelength ($k_\parallel \approx 0$), produce daughter AW (building block of MHD turbulent cascade) [Howes, et al., PRL, 109, 255001 (2012)]
    - Two counter-propagating AWs nonlinearly excite an ion acoustic wave [Dorfman & Carter, PRL, 110, 195001 (2013)]
- Parametric instability of single large-amplitude shear wave [Dorfman & Carter, PRL, 116, 195002 (2016)]

# Large amplitude Alfvén wave generation



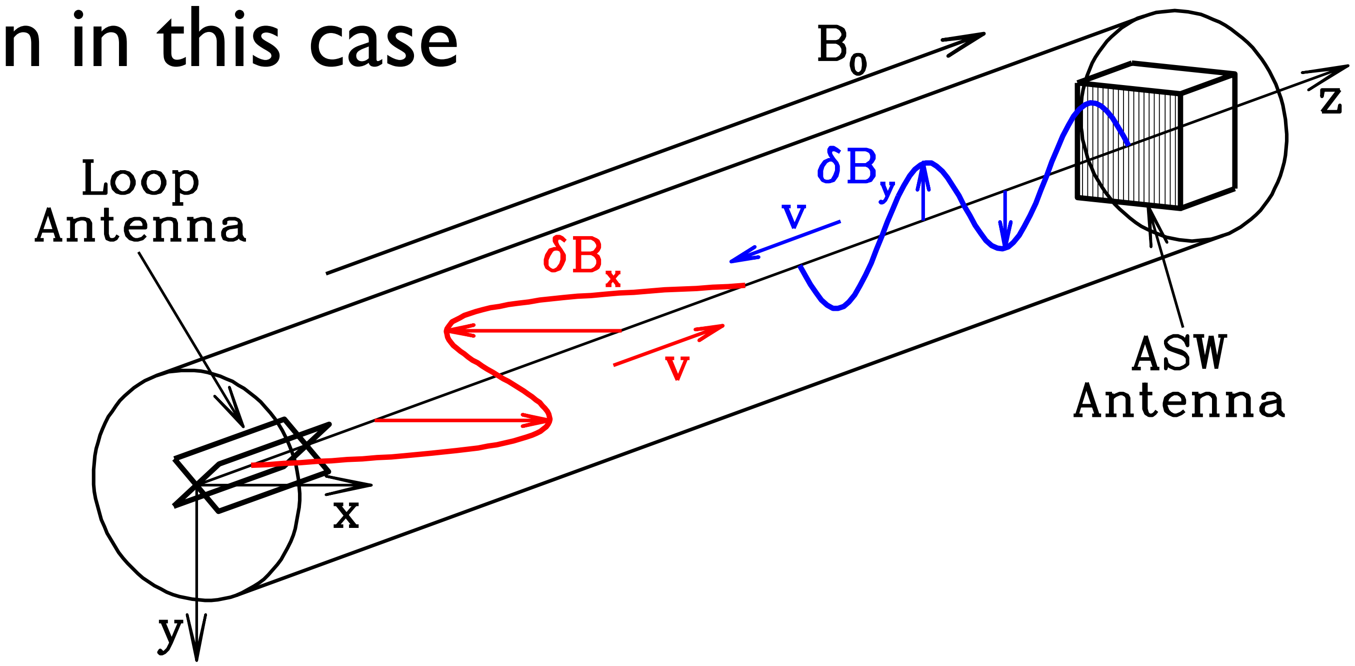




- Antennas can generate AWs with δB/B ~ 1% (~10G or 1mT); large amplitude from several points of view:
  - Wave beta is of order unity $\beta_w = \dfrac{2\mu_o p}{\langle \delta B^2 \rangle} \approx 1$
  - Wave Poynting flux ~ 200 kW/m$^2$, same as discharge heating power density
  - From GS theory: stronger nonlinearity for anisotropic waves; here $k_{||}/k_{\perp}$ ~ δB/B

# MHD-cascade relevant collisions: AW+AW → AW

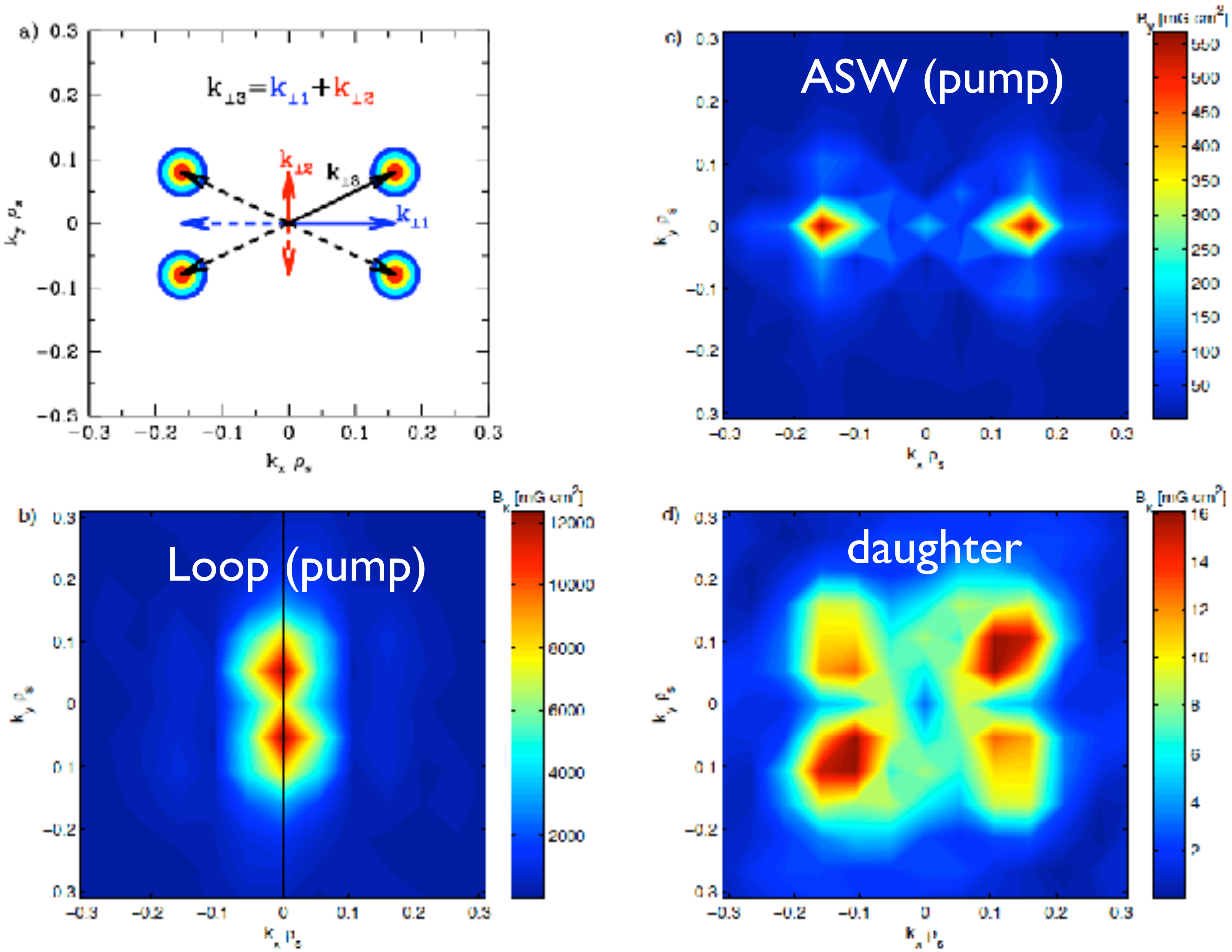
- Initial attempts in LAPD (Carter, Boldyrev, et al.): no strong evidence for daughter wave production/cascade (instead see beat waves, heating, harmonic generation, etc). Used local interaction, trying to look for perp. cascade.

- 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



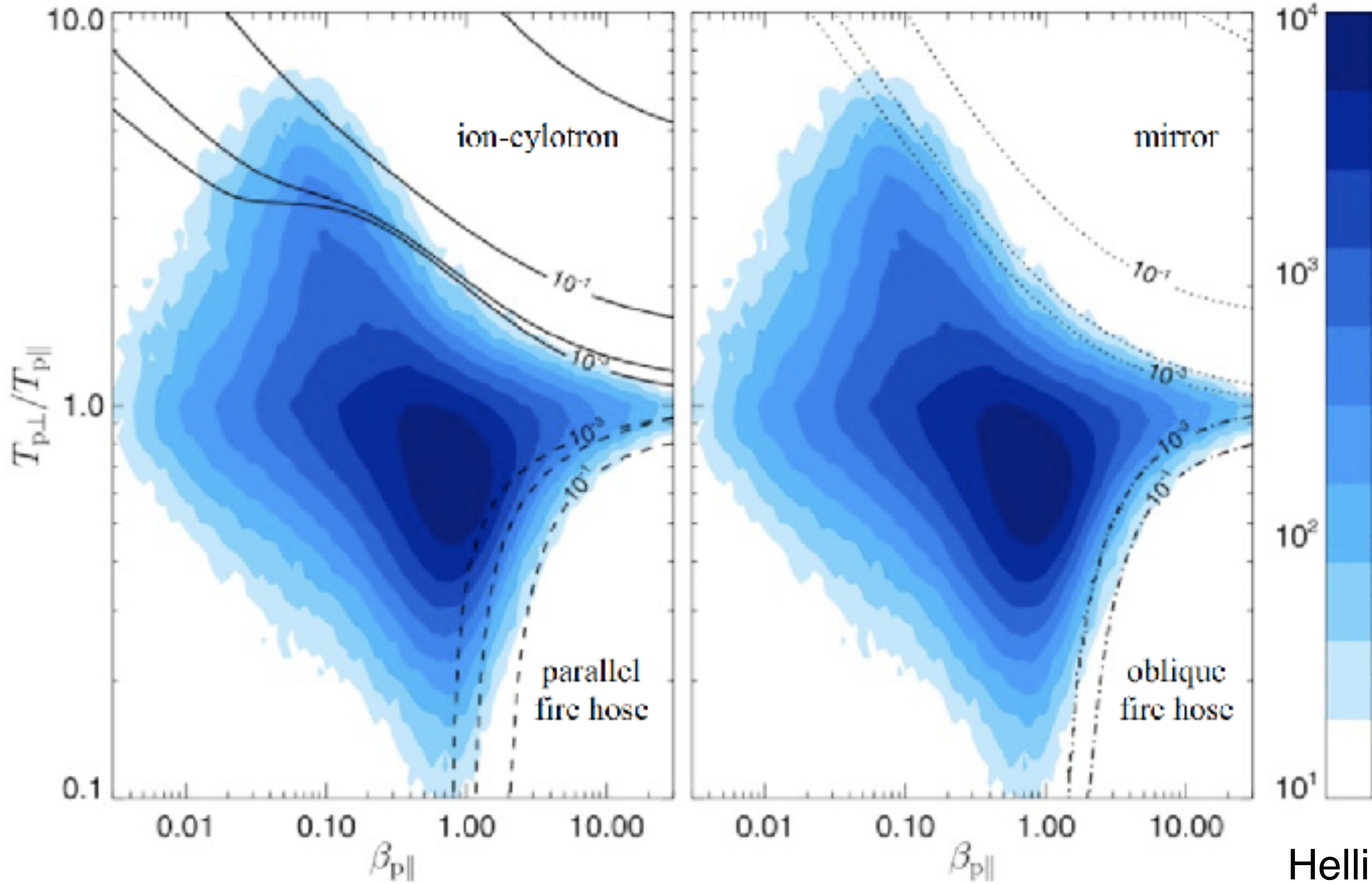

Howes et al., PRL 109, 255001 (2012)

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

# How do we achieve an MHD turbulent cascade in the lab?

- Have studied interesting AW interactions, but no success yet in LAPD in getting multiple collisions/development of inertial range
  - Two issues: (1) LAPD is long, but not long enough (not enough space for multiple collisions to occur/need to reflect waves, get a second pass) (2) Damping of pump wave is significant (we are near dissipation scale with pump)
  - Possible remedies: (1) new LAPD regime with higher beta, higher density (effective LAPD length gets longer, c/wpi smaller; lowered damping?) (2) Use ETPD to get much longer plasma length?
- Another approach: cascade driven by instabilities? One possibility: EM pressure gradient driven instabilities to act as stirring for cascade?

# Goal: Can we excite temperature-anisotropy-driven modes in the lab: mirror and firehose instabilities




Hellinger

- 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?

- MHD threshold for firehose: $\beta_{||} - \beta_{\perp} \geq 2$
- Resonant mirror/firehose can be triggered below the MHD threshold, but not far below; need high beta [Hellinger]
- Need to operate at low field to get high beta, but need magnetized ions. Also, typical scale size of firehose instability is $c/\omega_{pi}$, 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.

# Firehose in LAPD/ETPD?

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

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

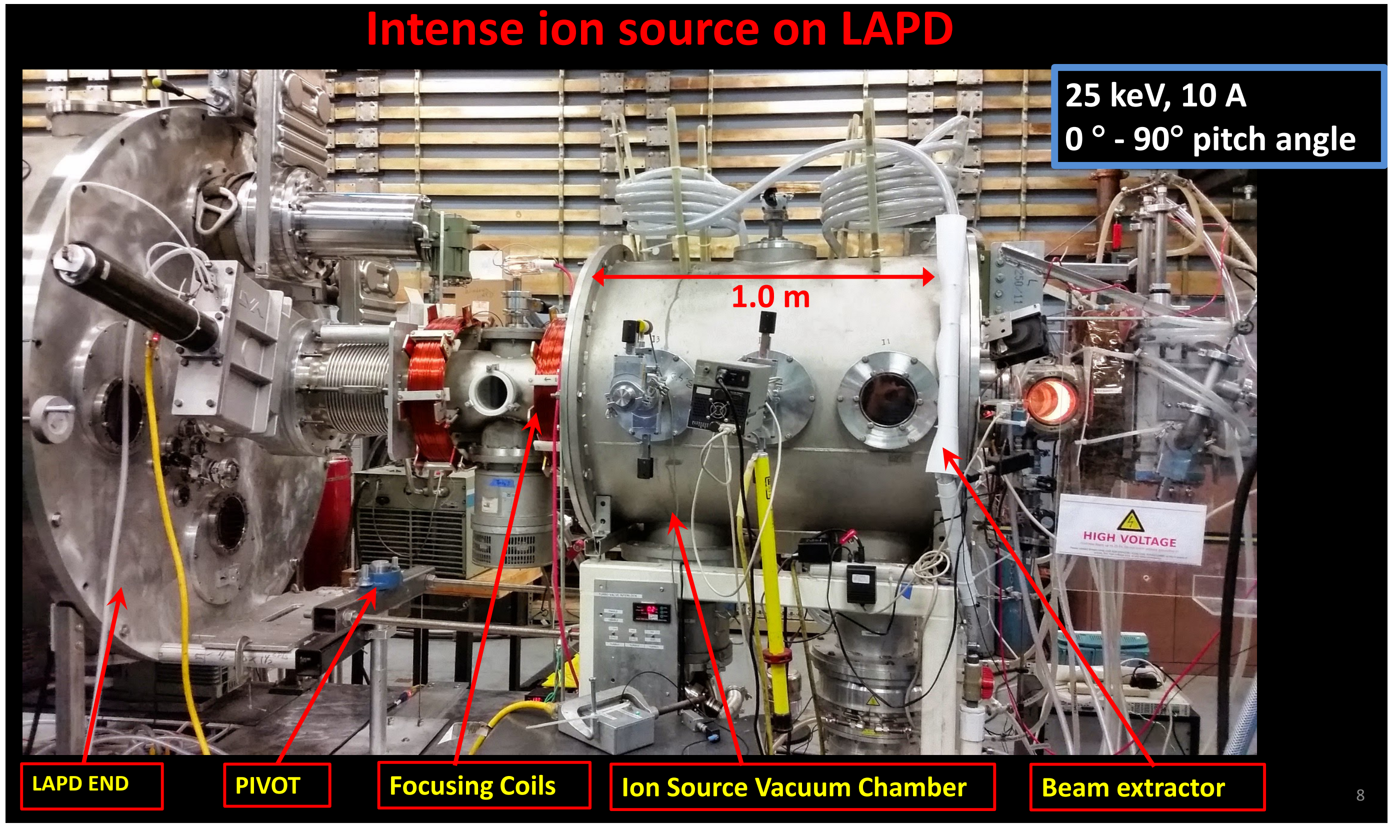
Need $Mv_A^2$ to be low enough (10 eV)?

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

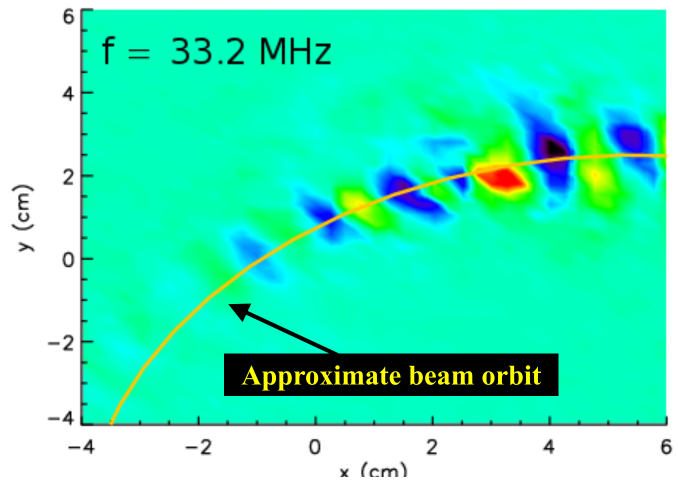
| Helium | Hydrogen |
|---|---|
| $T_i \sim 20\mathrm{eV}$ | $T_i \sim 20\mathrm{eV}$ |
| $\nu_{ii} \sim 13\mathrm{kHz}$ | $\nu_{ii} \sim 26\mathrm{kHz}$ |
| $f_{ci} \sim 20\mathrm{kHz}$ | $f_{ci} \sim 76\mathrm{kHz}$ |
| $\rho_i \sim 18\mathrm{cm}$ | $\rho_i \sim 9\mathrm{cm}$ |

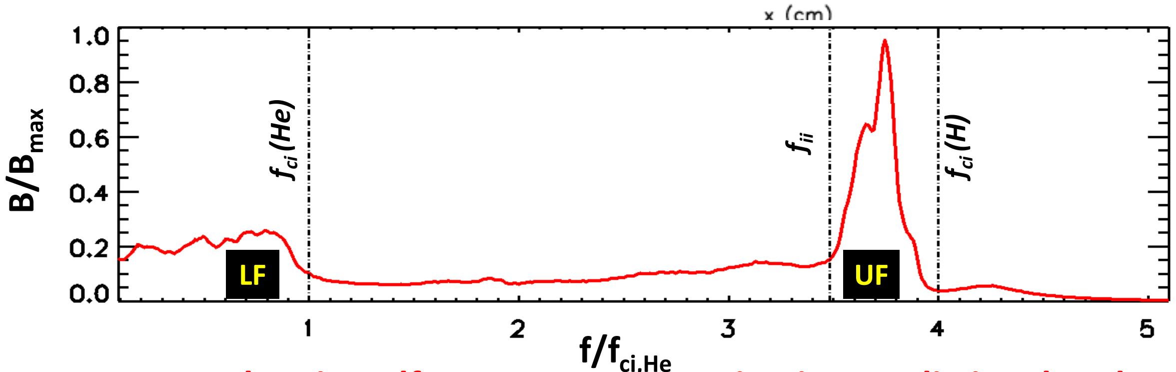
- Difficult, but may be possible to get to these conditions; need a large plasma to have magnetized ions (need ETPD?)

# One idea: use beam populations to drive anisotropy




**intense ion beam**

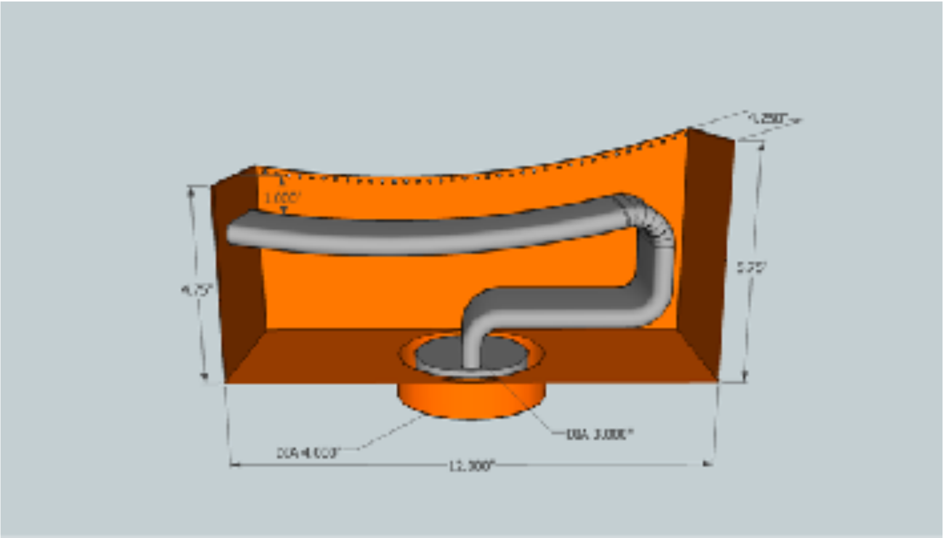


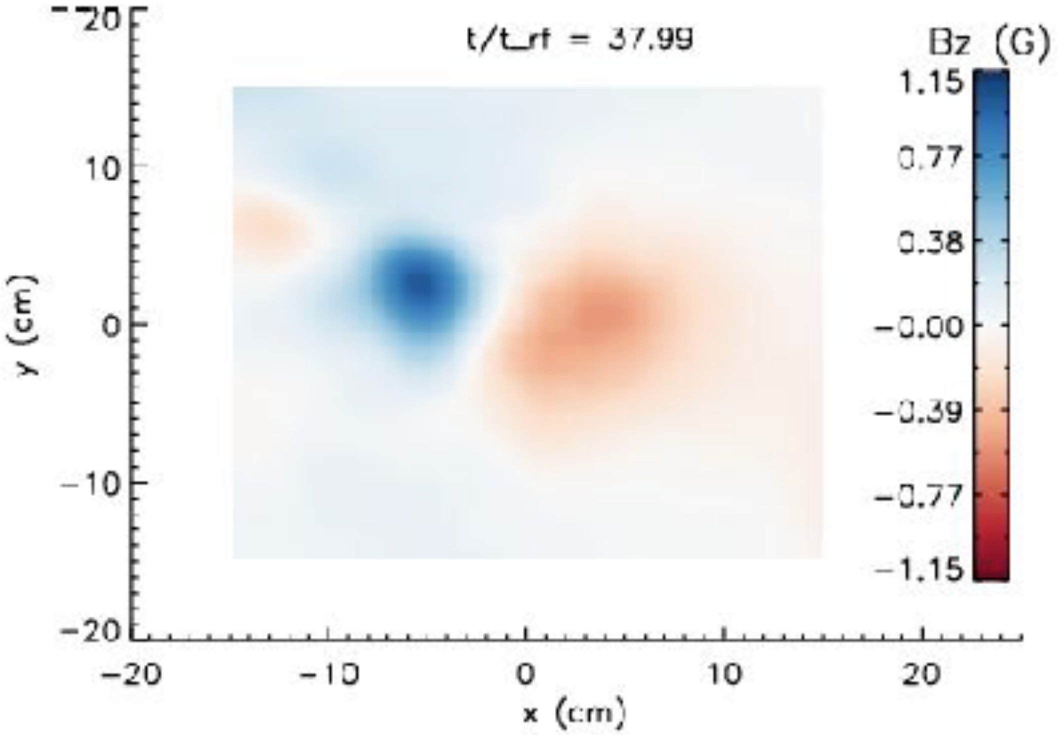




Spectrum showing Alfven wave propagation in two distinct bands

- 25 keV, 10A beam of H or He ions can be produced using existing beam
  - **Beam β large enough to reach firehose threshold at low B (~100G) [following Chen, et al., Astrophys. J. Lett. 825 L26 (2016)]**
  - Excitation of shear & fast Alfvén waves via Doppler-shifted IC resonance observed in low β plasmas

# Ion Cyclotron Resonance Heating for generation of energetic ions






**fast wave antenna**

- High power (~200 kW) RF driver and fast wave antenna available.
- Initial experiments: good coupling (~30G wave amplitude), some evidence of perpendicular ion heating via fundamental minority resonance (H in He plasma). **Can we generate an energetic tail, excite mirror instability?**

# Summary/Outline

- Large Plasma Device (LAPD) at UCLA: Upgraded plasma source: LaB6 cathode provides up to 100x increase in plasma pressure + warm ions; with lowered B, $\beta \sim 1$

- Modification of pressure-gradient-driven turbulence and transport with increasing $\beta$

    - Magnetic fluctuations increase, with parallel magnetic fluctuations dominant (2x $\tilde{B}_\perp$ at highest $\beta$); Observations consistent with Gradient Driven Coupling (GDC) instability: favorable comparisons with GENE simulations

- Opportunities to study processes relevant to space/astrophysical plasmas in LAPD and new device ETPD

    - Linear and nonlinear physics of Alfvén waves, MHD turbulence in $\beta \sim 1$ plasmas

    - Pressure anisotropy: can mirror and firehose instabilities be studied in the laboratory?