Plasma wave studies using the Basic Plasma Science Facility

T.A. Carter[1,2], S. Dorfman[3], G. Bal[2], J. Larson[2], T. Look[2], Y. Wug[2], P. Travis[2], P. Pribyl[2], S. Vincena[2], S. Tripathi[2], M. Abler[2], J. Han[2], B. Van Compernolle[5], R. Pinsker[5]

1 Oak Ridge National Laboratory
2 Department of Physics and Astronomy, UCLA
3 Space Science Institute
4 Realta Fusion
5 General Atomics

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PSTI UCLA
Plasma Science and Technology Institute

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I'm wearing a new hat

UCLA

Professor of Physics (since 2002!)
Director of Basic Plasma Science Facility (since 2017)

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Oak Ridge National Laboratory

Director, Fusion Energy Division
(starting July 1, 2024)
(Leave of absence from UCLA)

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IPELS 1997 (Maui, USA)

IPELS 1999 (Kreuth, Germany)

IPELS 2017 (San Diego, USA)

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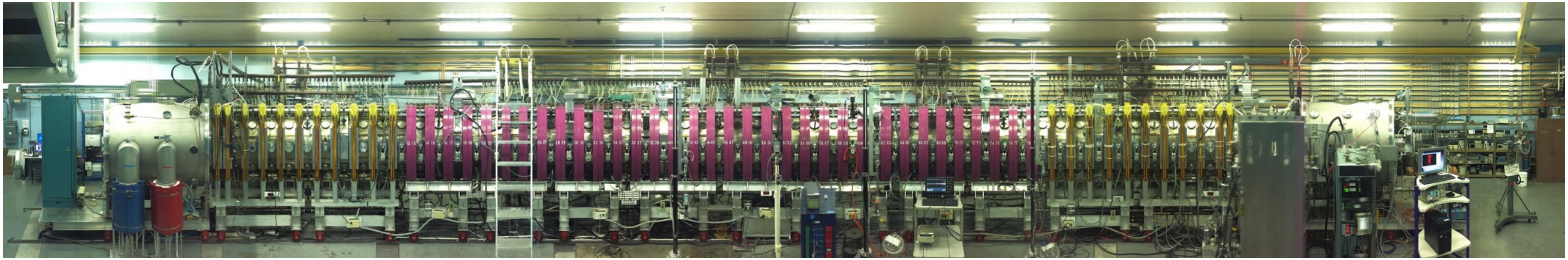
Prof. Emeritus Walter Gekelman will serve as Interim Director of BaPSF (planning search for new Director).
gekelman@physics.ucla.edu

Dep. Director: Dr. Steve Vincena (vincena@physics.ucla.edu)

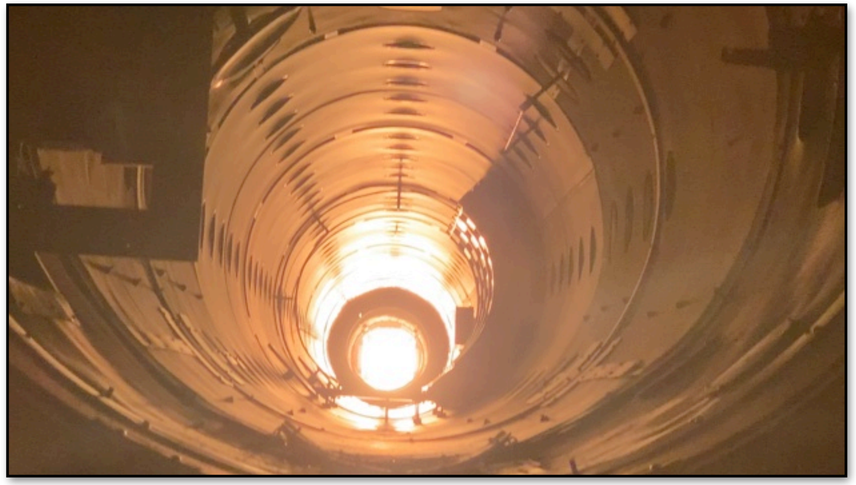
Summary

- Basic Plasma Science Facility: US DOE and NSF sponsored collaborative research facility for study of fundamental processes in magnetized plasmas. Primary device is Large Plasma Device (LAPD).
- Wide range of studies performed: waves, instabilities, turbulence & transport, shocks, reconnection. Will cover recent work on the linear and nonlinear physics of plasma waves:
  - **Parametric instabilities of Shear Alfvén waves:** Above an amplitude threshold, observe production of daughter waves consistent with Modulational decay instability [Dorfman & Carter, PRL 2016]
  - **Fast Waves/ICRF**: Scattering/Mode conversion of FW on density filaments, Mitigation of RF sheaths using insulating antenna enclosure [Bal et al., NF (2022)]

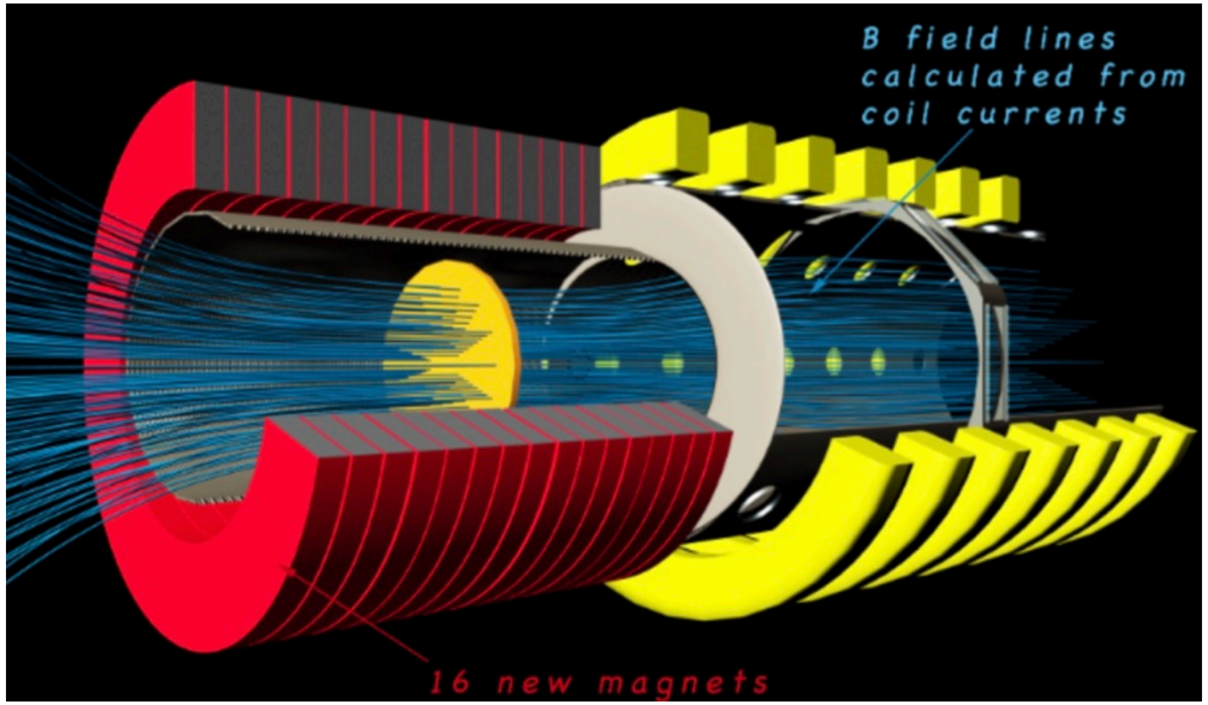
The Large Plasma Device (LAPD): a flexible experimental platform

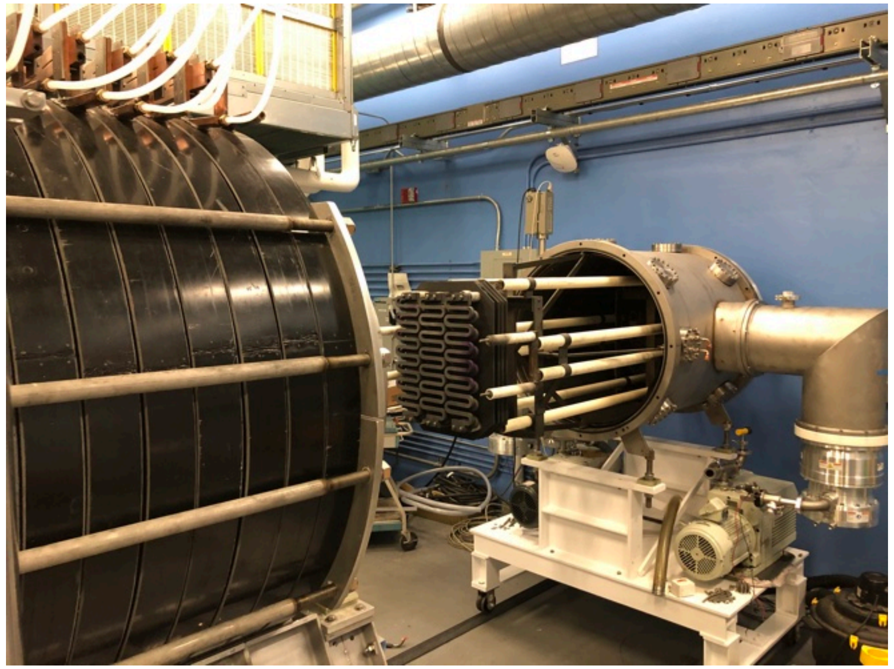


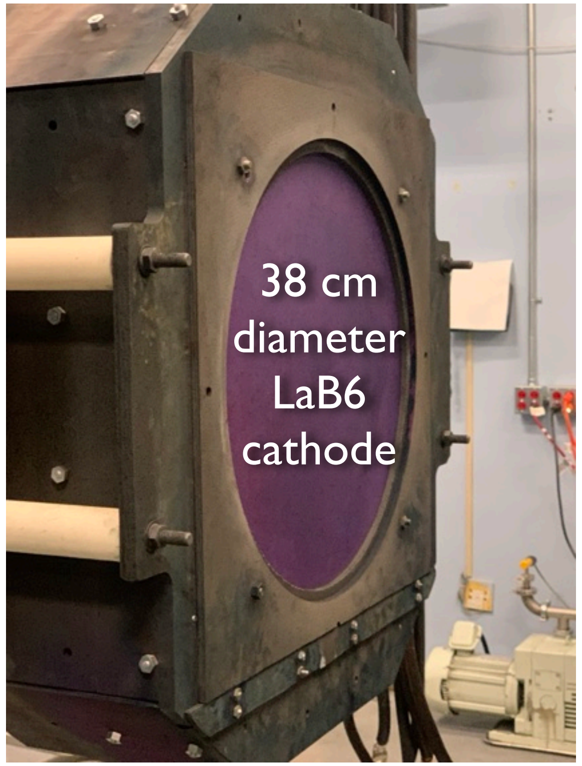
- 20m long, 1m diameter vacuum chamber; emissive cathode discharge
- LaB_6 Cathode: $n \sim 1 \times 10^{13}$ cm^{-3}, $T_e \sim 10\text{–}15$ eV, $T_i \sim 6\text{–}10$ eV
- B up to 3.5kG (with control of axial field profile)
- High repetition rate: 1 Hz
- US DOE & NSF Sponsored Collaborative Research Facility



Plasma Source Upgrade: large-area LaB_6



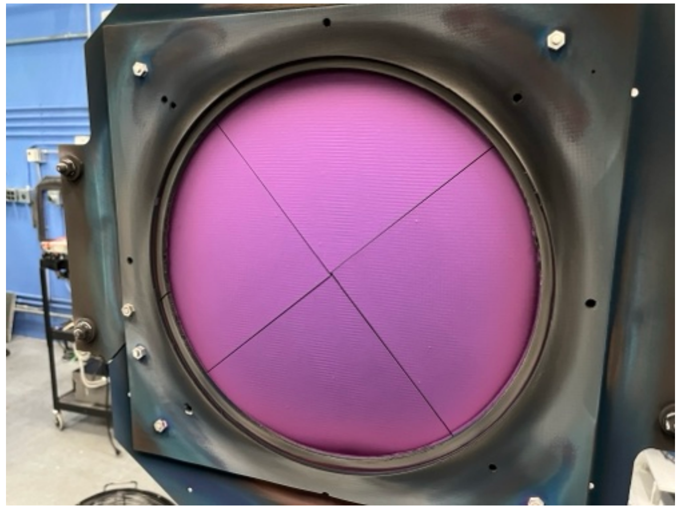




- New large-area LaB_6 emissive cathode source provides higher power density; access to higher density, higher pressure plasmas

- New magnet section, up to 0.9T, to allow magnetic expansion of plasma source region

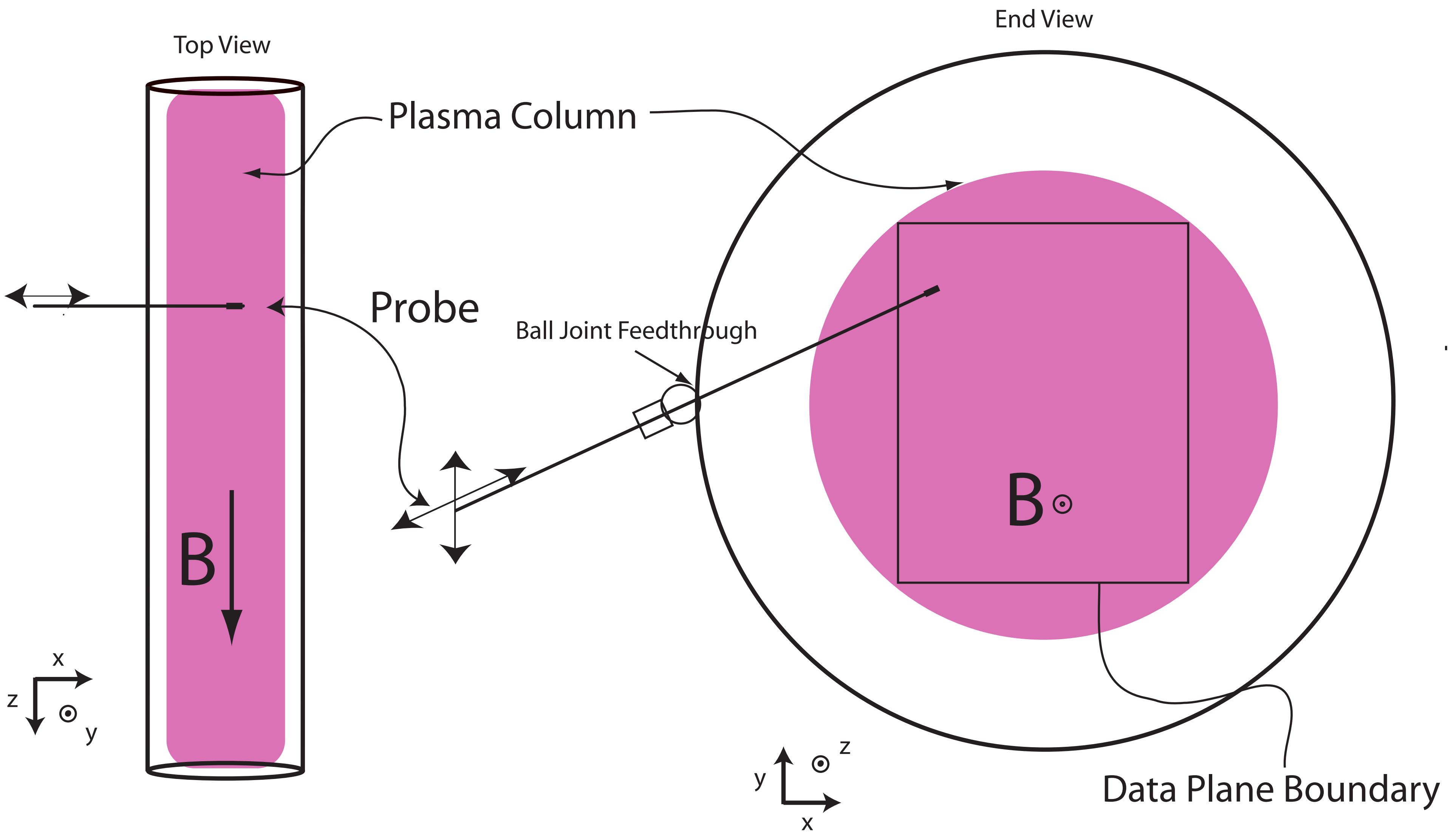
- Additionally, installed capability for gas-puffing to fuel discharge to access improved operational regimes



Y. Chen, et al., Rev Sci Instrum., 94, 085104 (2023)

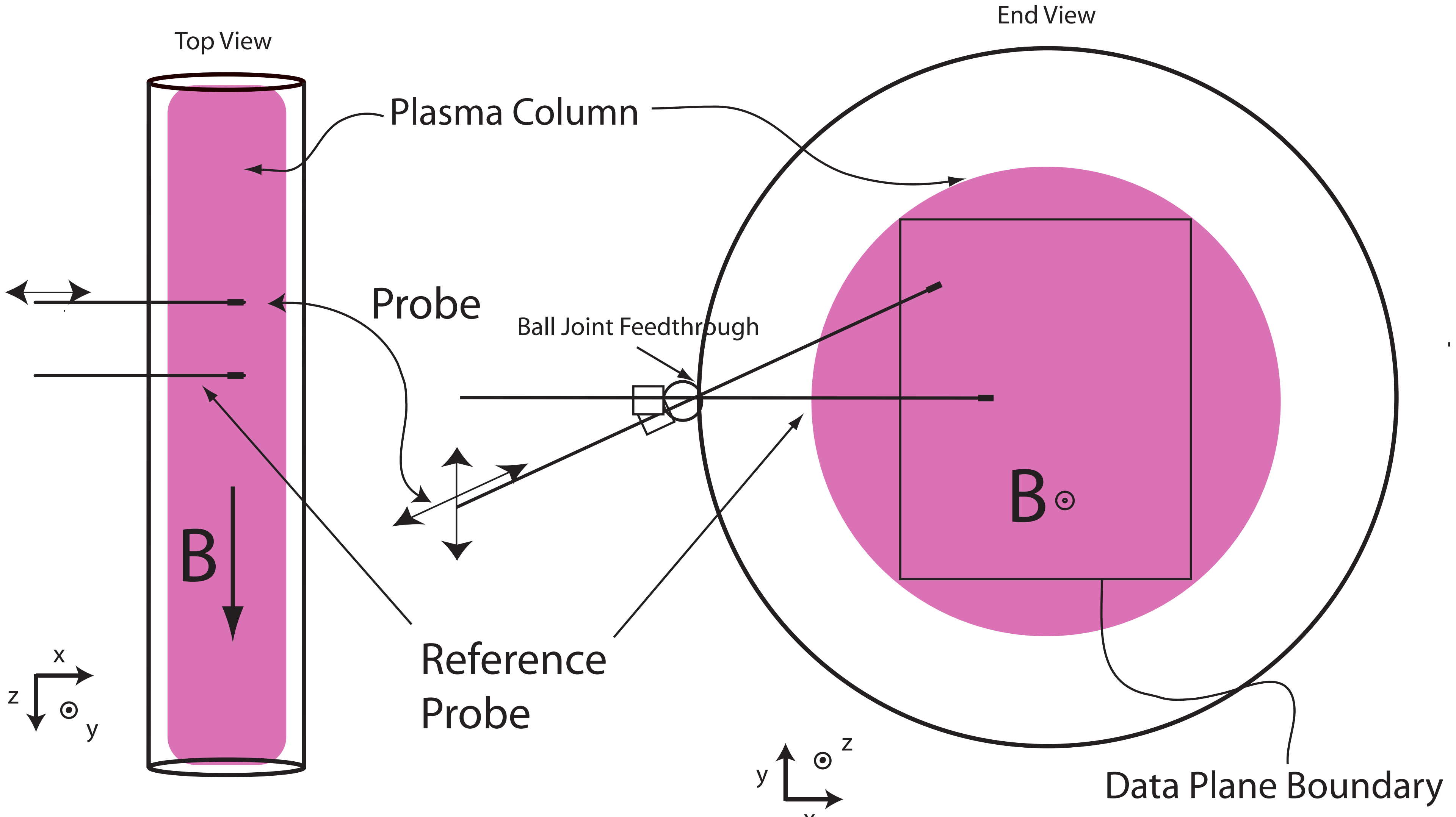
High rep-rate enables volumetric data acquisition in LAPD

- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles

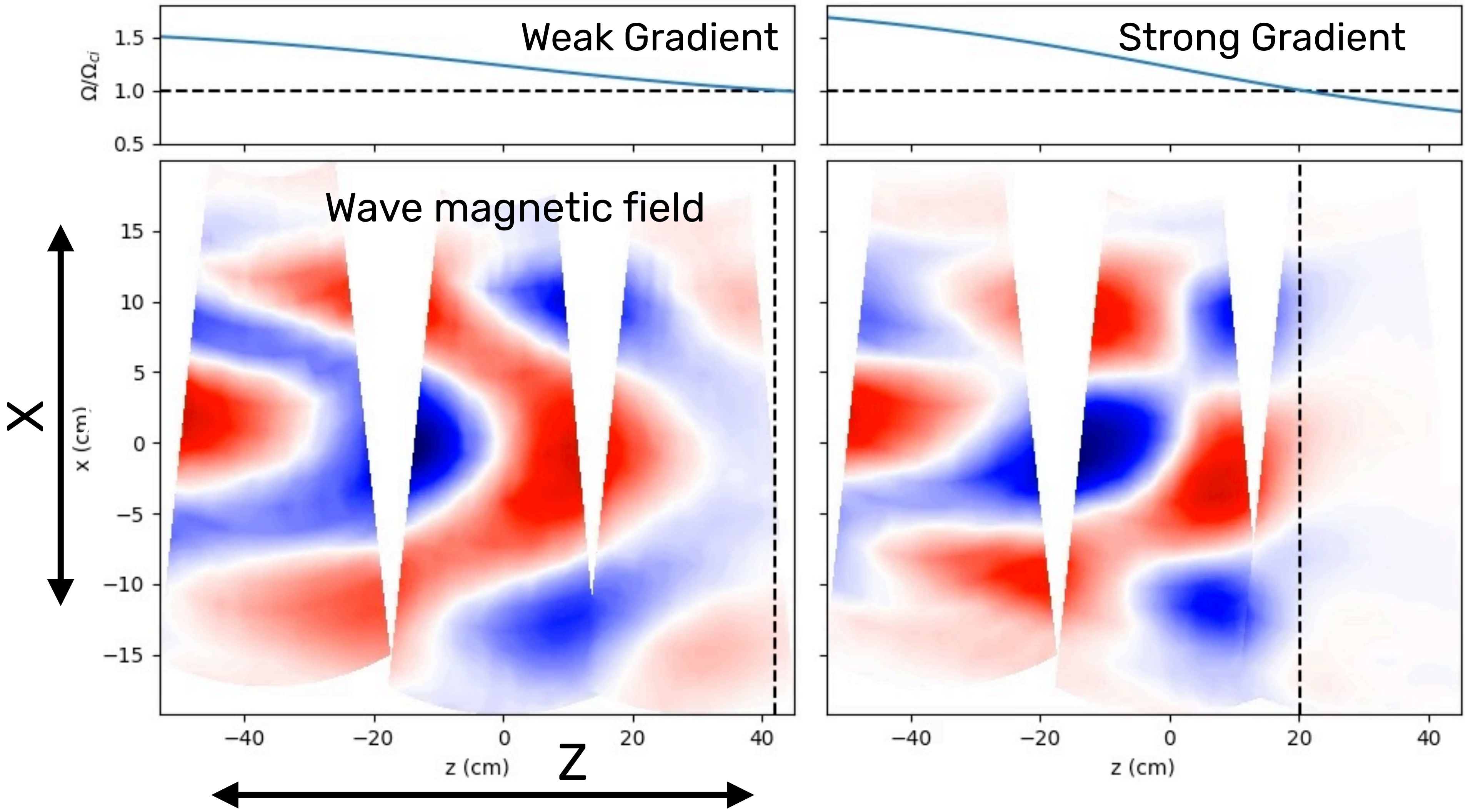


High rep-rate enables volumetric data acquisition in LAPD

- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles
- Add a second (reference) probe to use correlation techniques to make detailed statistical measurements of non-repeatable phenomena (e.g. turbulence)



Example data: Shear Alfvén wave absorption in strong field gradients



- Measured wave propagation & absorption to validate models of resonance broadening due to strong field gradients

S. Frank (Realta) + Y. Wug (UCLA)

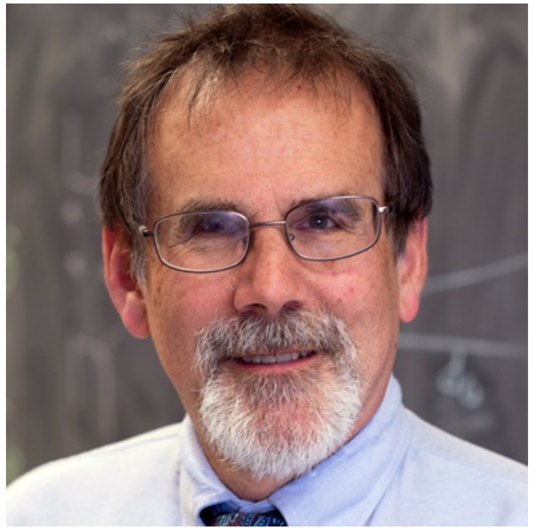
S. Frank, et al., AIP Conference Proceedings 2984, 130002 (2023)
D. Smithe, et al., Phys. Rev. Lett. 60, 801 (1988)

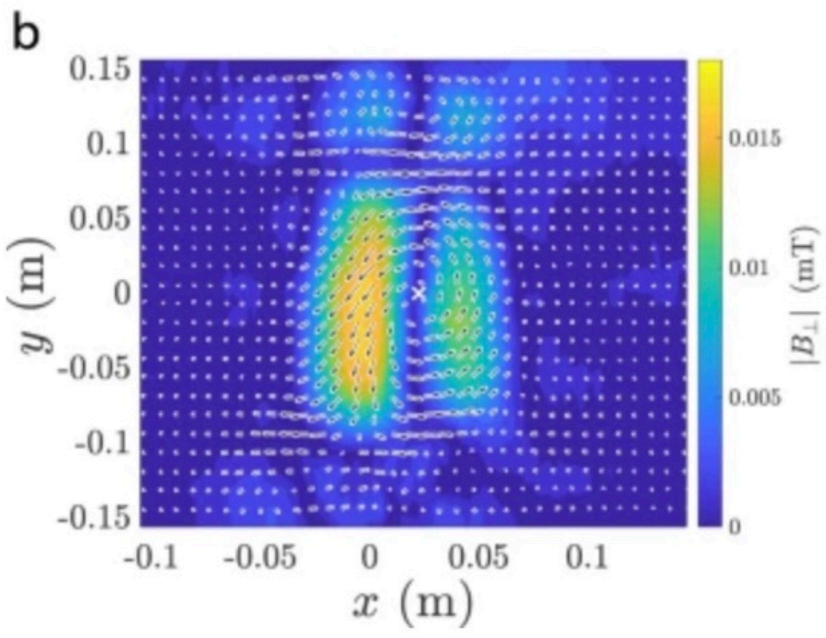
BaPSF is a collaborative research facility

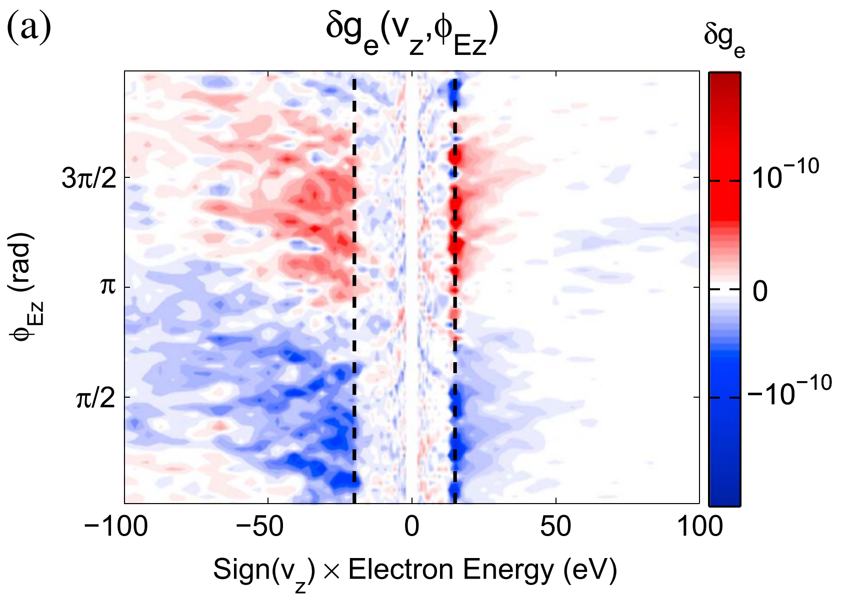
- 50% of LAPD operational time is offered to external users via a yearly call for runtime proposals
- Can handle ~10 external projects a year (2-3 weeks of runtime per project).
  - Foreign users/projects are welcome! (Have 3 currently - UK, France, Canada)
  - **No experimental/laboratory experience needed — BaPSF staff can assist with designing, executing, analyzing experiments. We have many users from the space community (theorists and observers!)**
  - Some users are here at the meeting presenting their work: Prof. Chris Chen, Dr. Sam Greess, Prof. Rick Sydora, Dr. Lucas Rovige, Dr. Mel Abler (now a BaPSF staff member!)
- Yearly call for proposals in the fall (usually announced by October, due January)

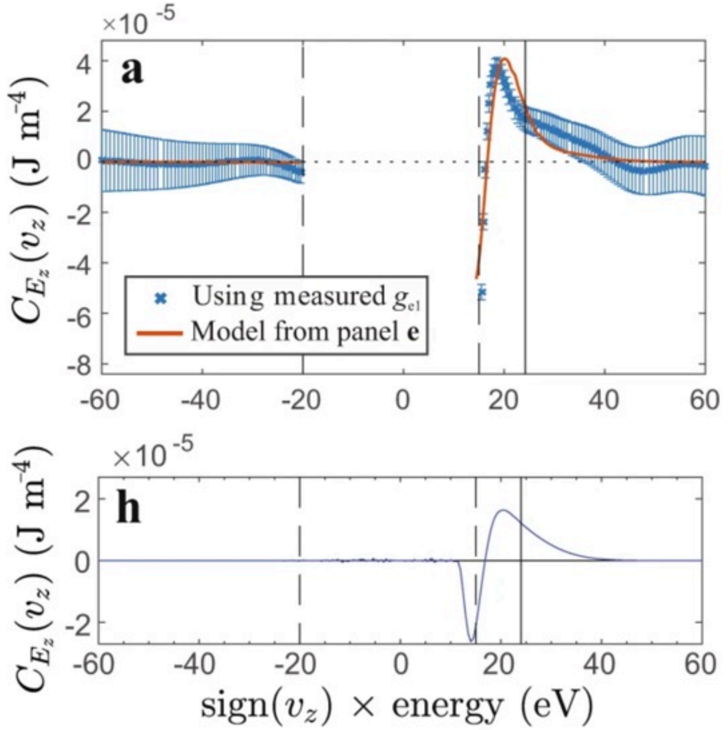
https://plasma.physics.ucla.edu/

Electron acceleration by inertial Alfvén waves









- **Kletzing**/Skiff/Howes/Schroeder (Iowa): interest in understanding electron acceleration by Alfvén waves; relevance to generation of Aurora
- Used novel electron distribution diagnostic (whistler wave absorption (Skiff)) to demonstrate acceleration of electrons by inertial Alfvén waves

Schroeder, et al., Nature Comm.12, 3103 (2021)

User Research: Electron acceleration by inertial Alfvén waves

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SPACE'S NEXT CHAPTER

The mysterious origin of the northern lights has been proven

By Jennifer Gray, CNN meteorologist
Updated 2:32 PM ET, Tue June 8, 2021

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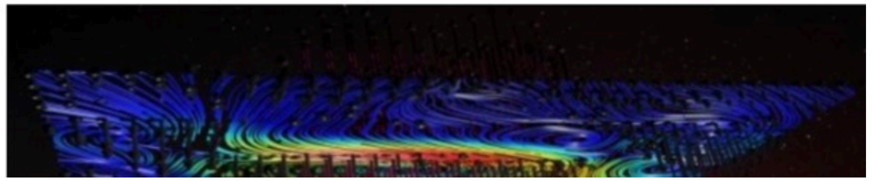
PLASMA PHYSICS | RESEARCH UPDATE

Electrons 'surf' on Alfvén waves in plasma-chamber experiments

22 Jun 2021



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The Secret to Brilliant Auroras? 'Surfing' Electrons

New research sheds light on the complex physics behind the Northern lights.

By Brianna Barbu | Aug 6, 2021 8:00 AM

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Auroras form when electrons from space ride waves in Earth's magnetic field

The same physics could give rise to auroras on Jupiter and Saturn

We finally know what sparks the Northern Lights

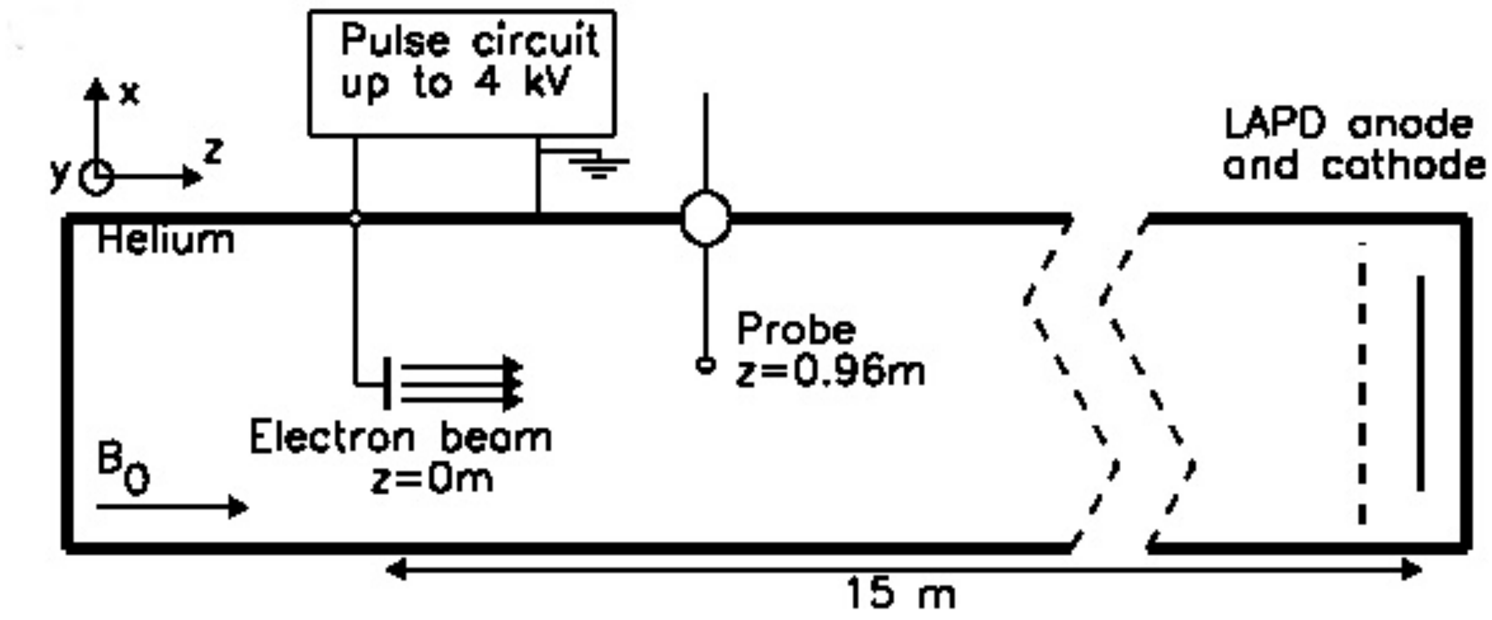
It took researchers more than 20 years to figure out this light show mystery.

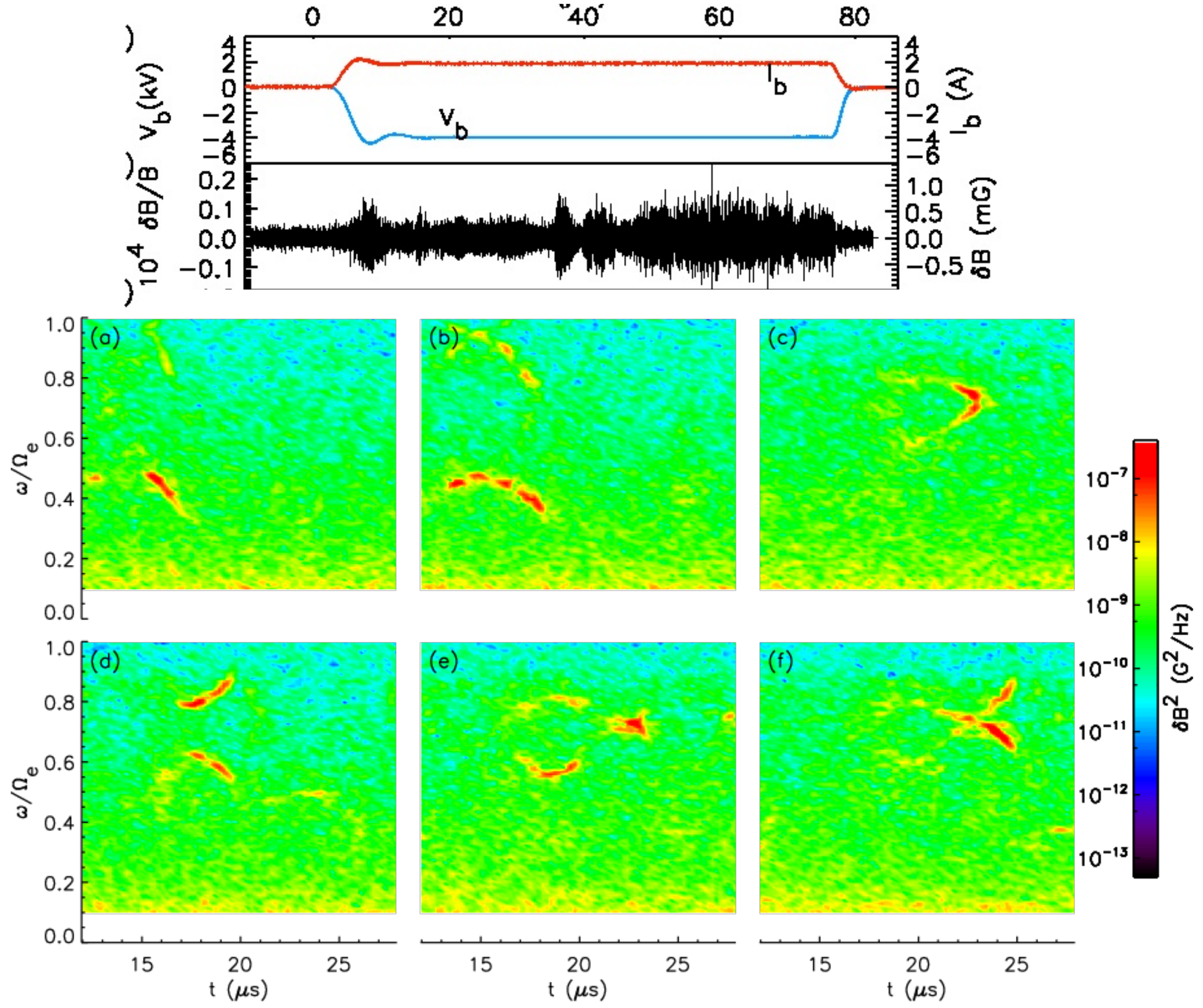
BY RAHUL RAO | PUBLISHED JUN 21, 2021 7:00 PM

Schroeder, et al., Nature Comm.12, 3103 (2021)

Production of whistler-chorus-like emission by energetic electrons

- Xin An, J. Bortnik (UCLA): interactions between energetic electrons and whistler waves, chirping/chorus-like events, relevance to Earth's radiation belts





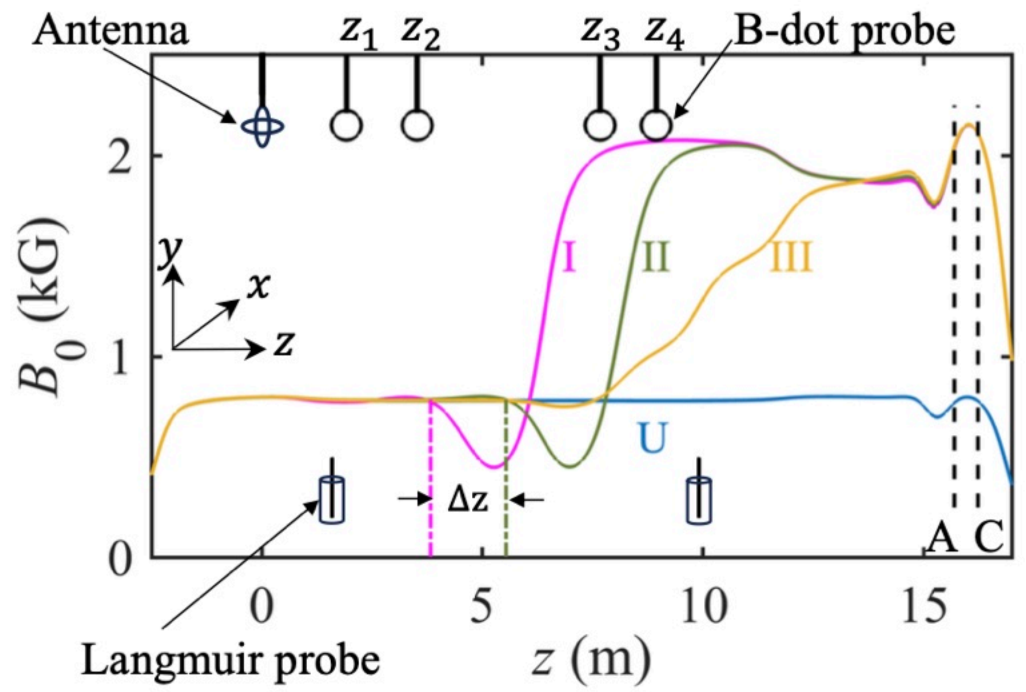
- Inject ~4 keV electron beam into LAPD; observe frequency chirped wave emission

Van Compernolle, et al., Phys. Rev. Lett. 114, 245002 (2015)

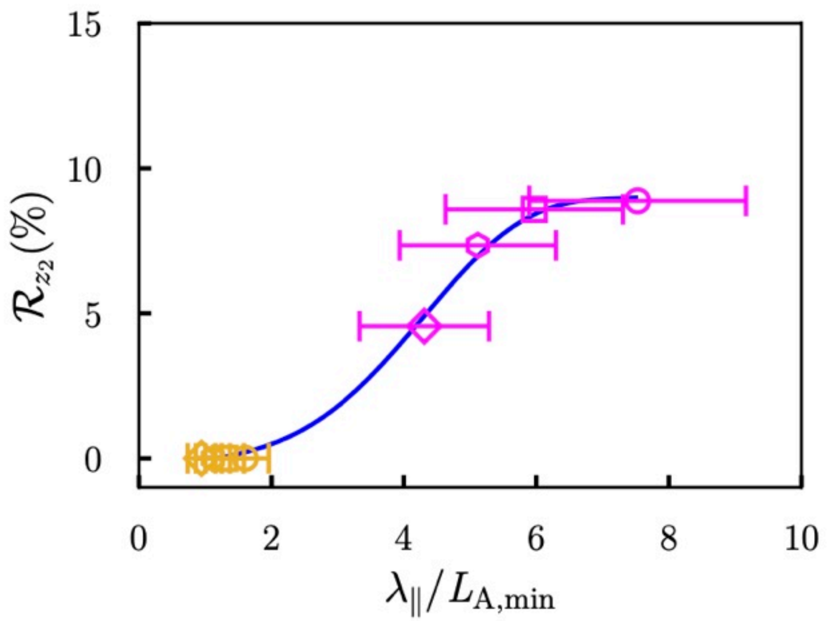
An, et al. Geophys. Res. Lett., 43, 2413–2421 (2016)

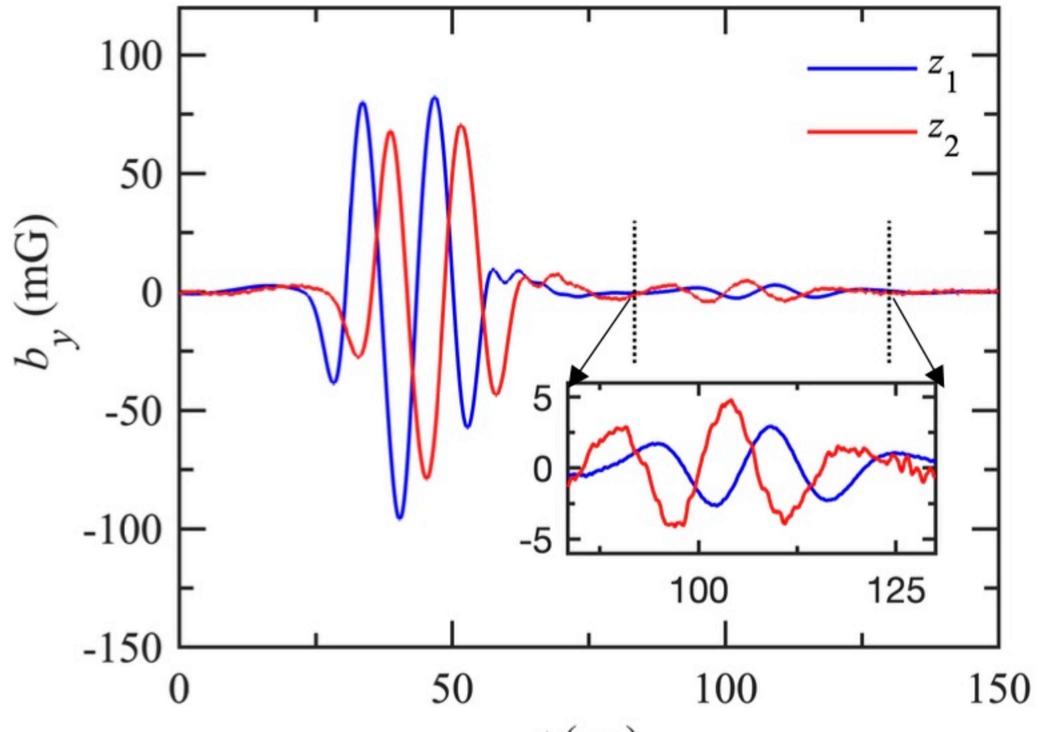
Understanding turbulence in the solar corona: reflection of Alfvén waves in parallel Alfvén speed gradients

- Columbia/PPPL collaboration (D. Wolf Savin, M. Hahn, S. Bose, G. Joshi): measured reflection/absorption of AWs propagating into speed gradient
  - Need counter propagating spectrum of waves to generate MHD turbulence/cause heating
  - See reflection off of magnetic field gradient, documented reflection coefficient vs gradient scale length

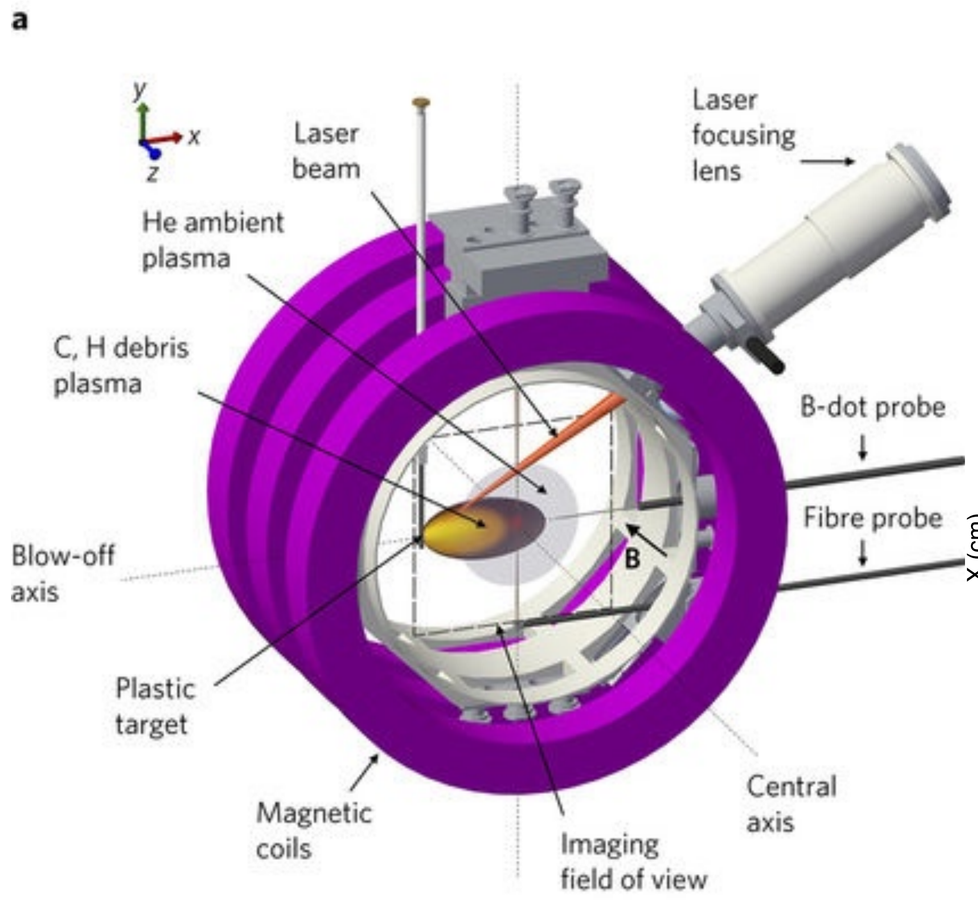


Bose, et al., ApJ 882 183 (2019)
Bose, et al. ApJ (2024), in press
Joshi, et al. ApJ, submitted

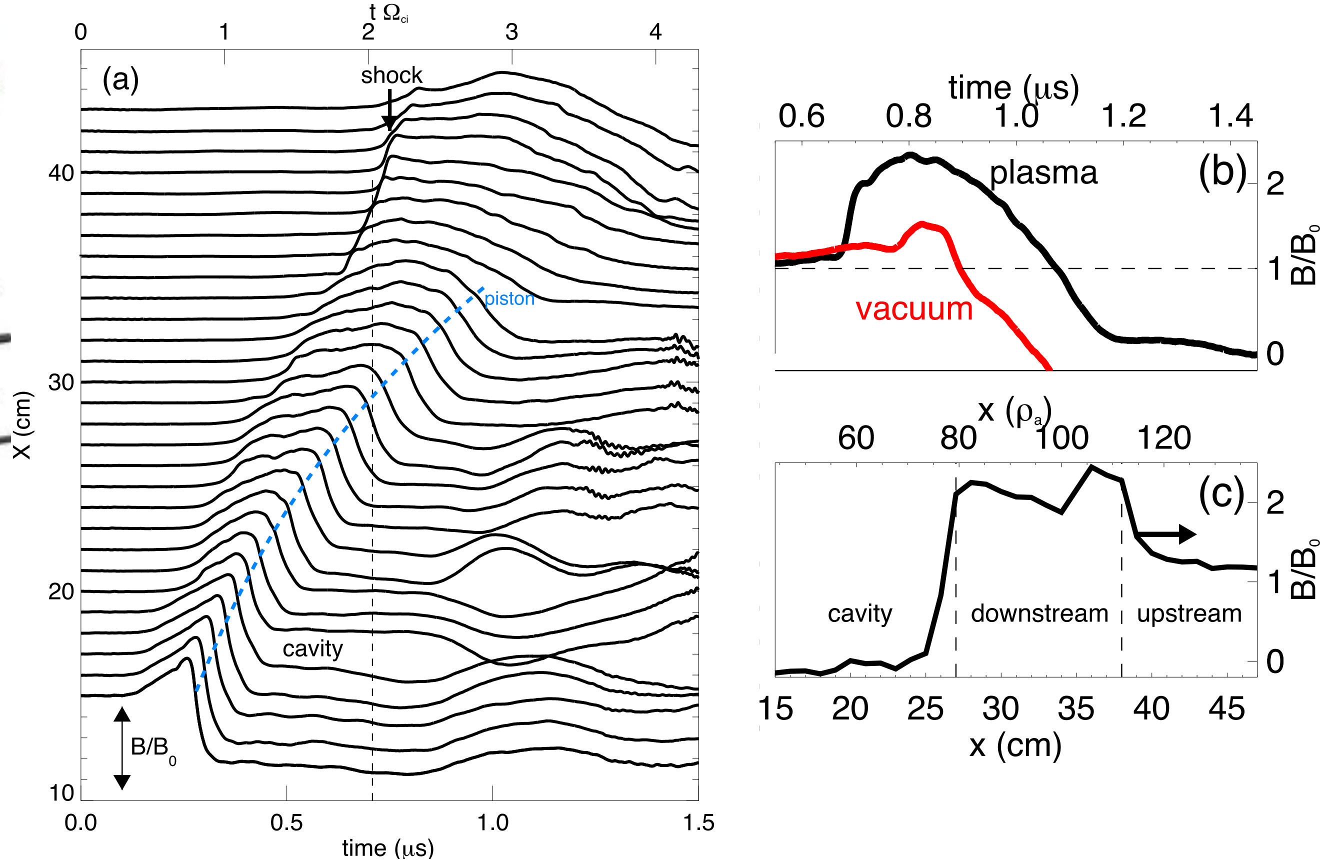




Creating collisionless shocks in the laboratory



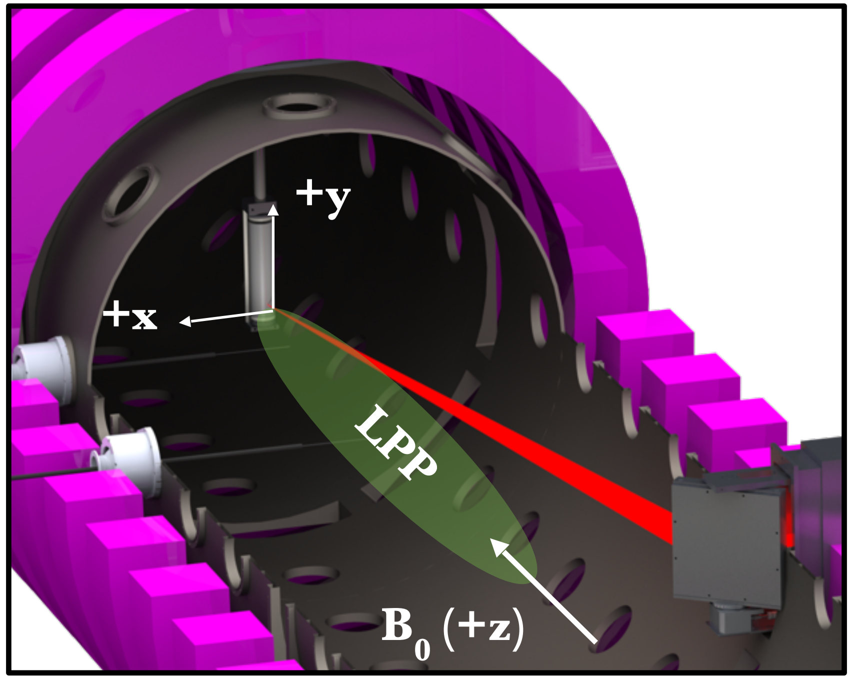
Magnetic pulse at bubble edge separates from piston and steepens into M_A~2 shock

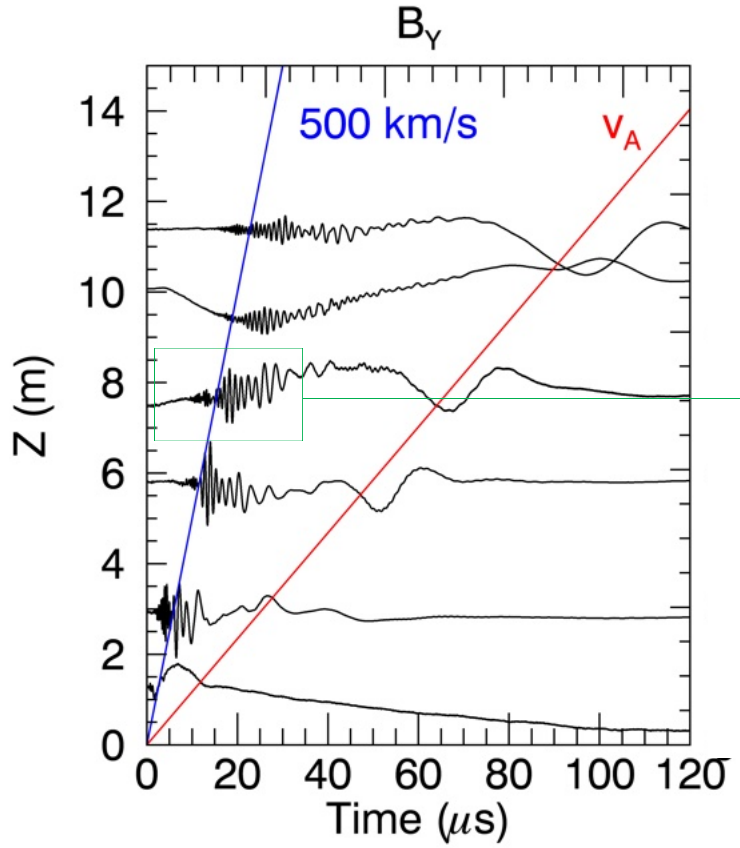


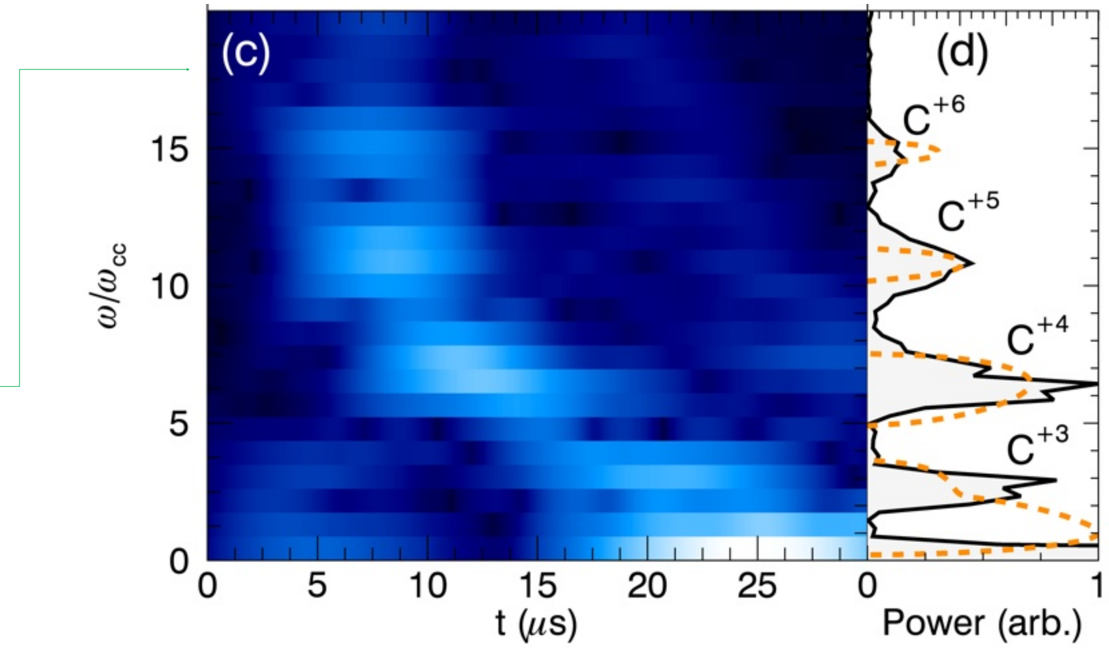
- Quasi-perpendicular collisionless, magnetized shocks created using 200J laser (Niemann, UCLA); consistent with "Larmor Coupling" mechanism

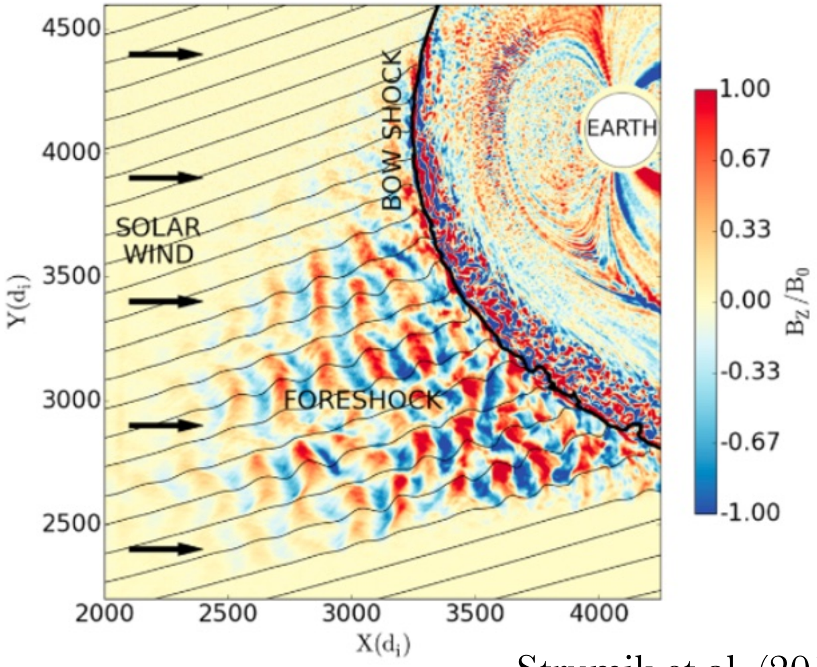
Bondarenko, et al., *Nature Physics* **13**, 573–577 (2017)

Creating collisionless shocks in the laboratory: Right-hand resonant instability observed with parallel "piston"







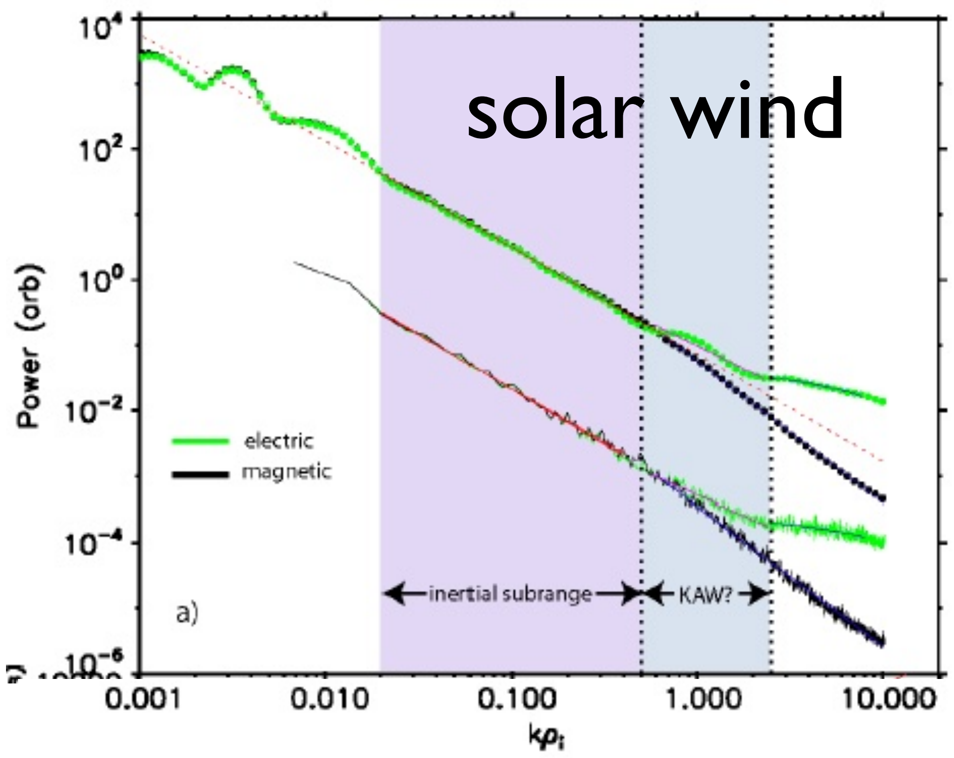


Strumik et al. (2015) GRL

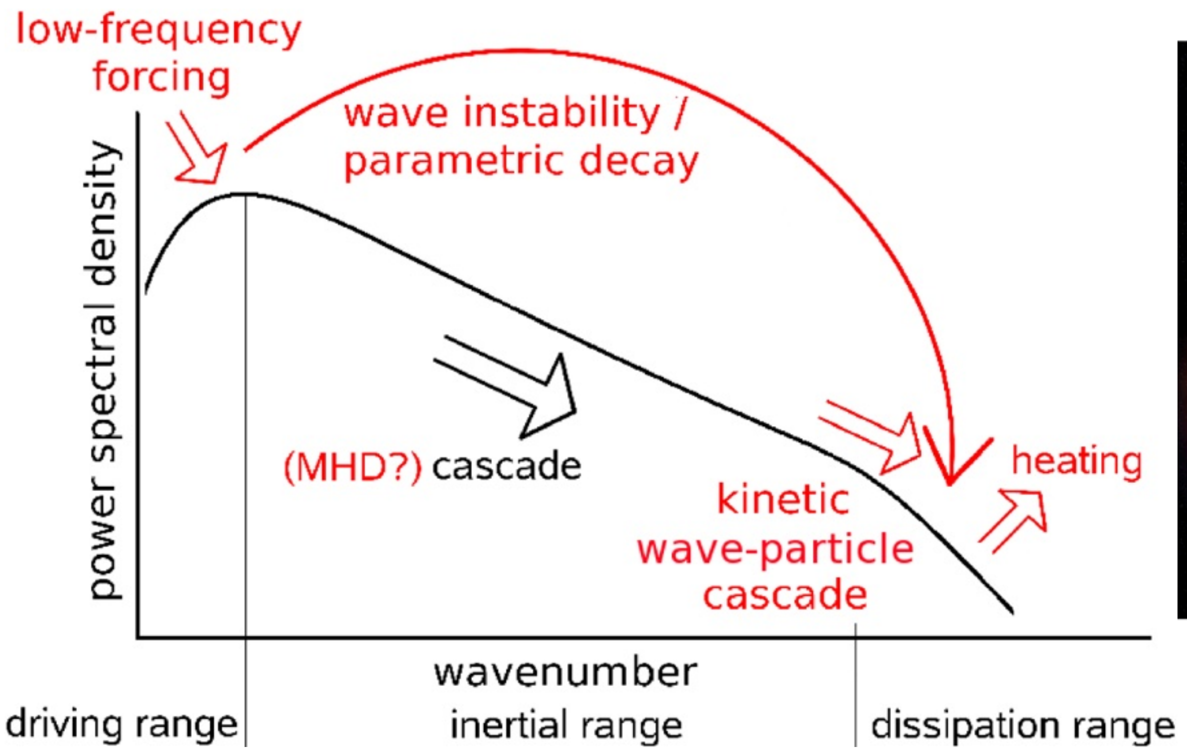
- With parallel drive, see development of instability that is thought to mediate quasi-parallel collisionless shocks: right-hand resonant instability (RHI). Relevant to Earth's bow shock

P. Heuer et al., ApJL 891, L11 (2020)

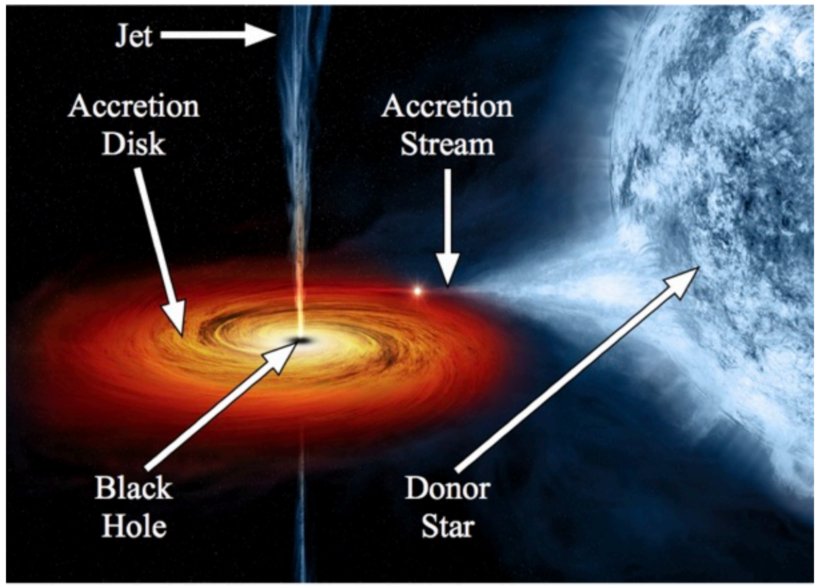
Importance of nonlinear processes associated with Alfvén waves



(Bale et al. 2005)



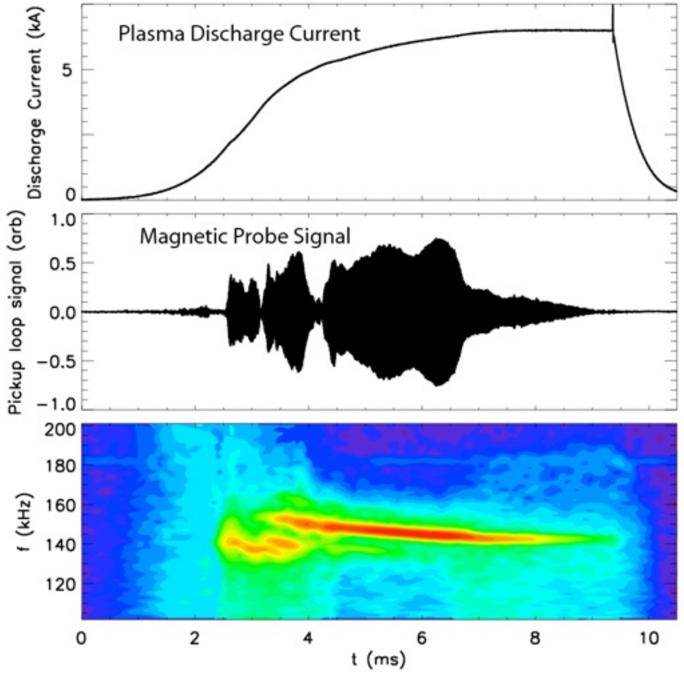
D.Verscharen

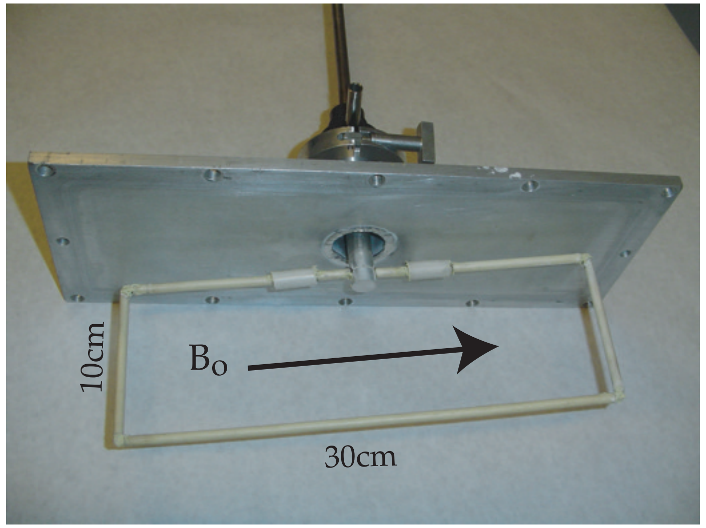


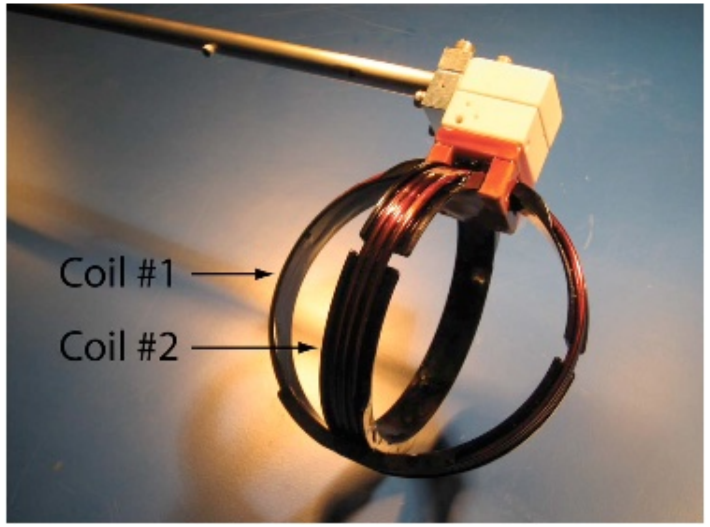
accretion disk

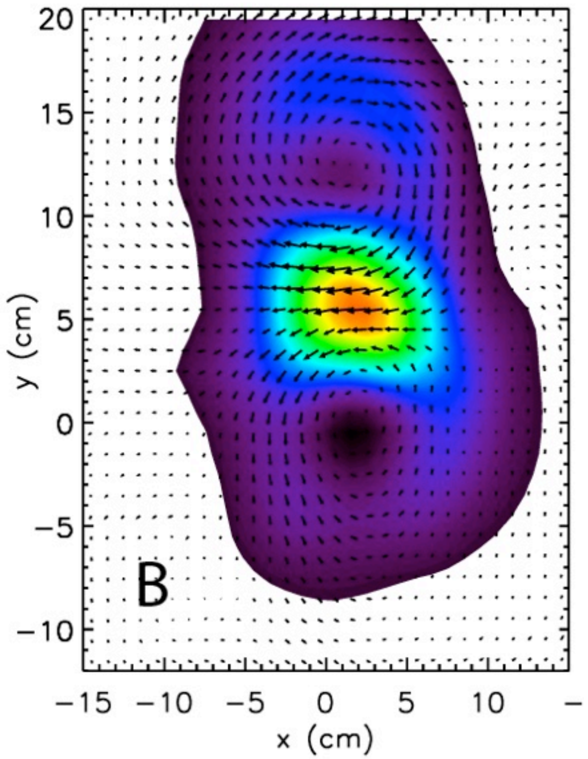
- Alfvénic turbulence: inertial range mediated by Alfvén three-wave interactions; dissipation scale (e.g. heating in solar wind and accretion disks) potentially explained by damping of Alfvén waves
- Decay instabilities: parametric decay (AW → AW + Sound Wave), e.g. might help generate counter-propagating spectrum of AWs in solar corona/solar wind or possibly bypass cascade

Making large amplitude Alfvén waves in the lab



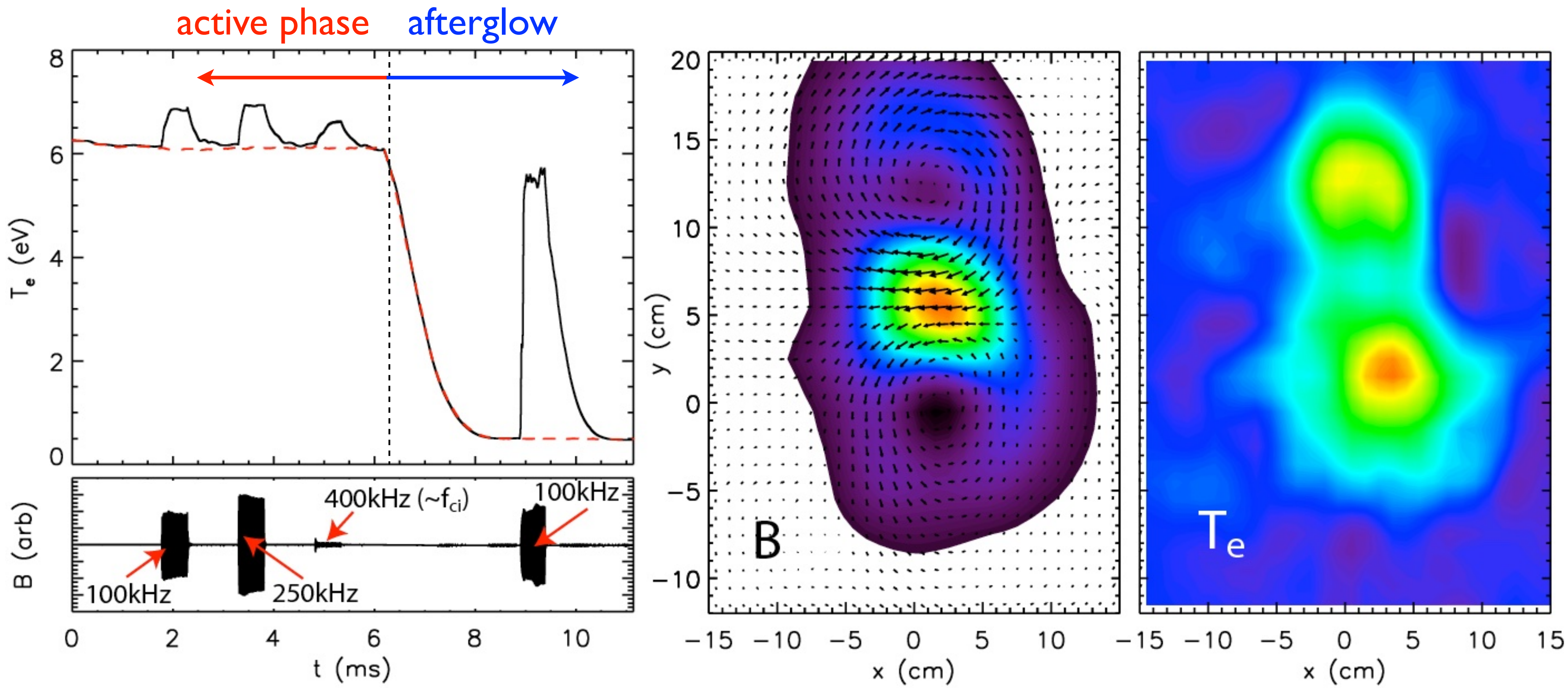






- Resonant cavity (MASER, narrowband), loop antenna (wideband)
- Both can generate AWs with δB/B ~ 1% (~10G or 1mT); large amplitude from several points of view:
  - From GS theory: stronger nonlinearity for anisotropic waves; here $k_{\|}/k_{\perp}$ ~ δB/B
  - Wave beta is of order unity $\beta_w = \frac{2\mu_o p}{\langle \delta B^2 \rangle} \approx 1$
  - Wave Poynting flux ~ 200 kW/m², same as discharge heating power density

Strong electron heating by large amplitude Alfvén waves in LAPD

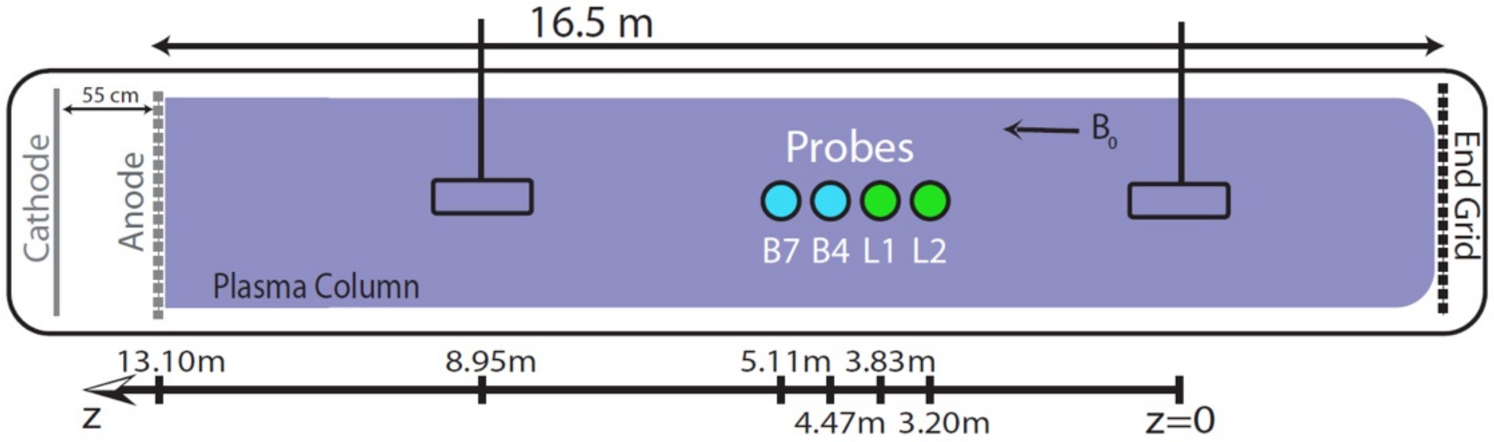


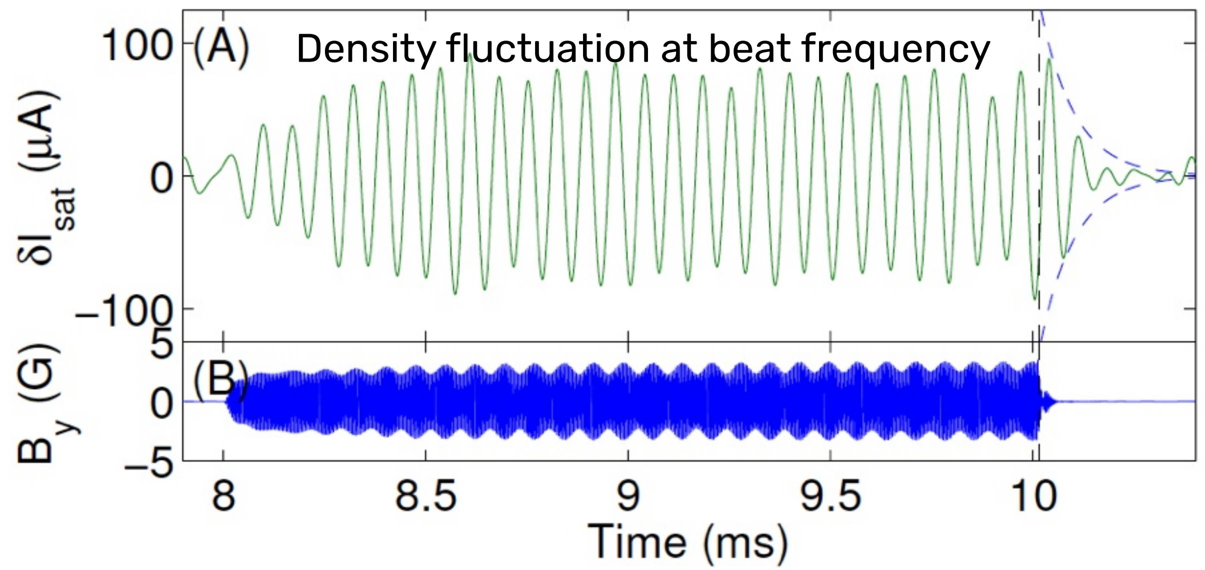
- Localized heating observed, on wave current channel (collisional and Landau damping: Note damping length is comparable to machine length!)
- Results in structuring of plasma (additionally see parallel outflows, density, potential modification, cross-field flows)

Studies of three-wave interactions among and decay of Alfvén waves

- 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)]**
- And more from others (Chris Chen, Mal Abler, Alfred Mallet, ...)

Stimulated parametric decay: interaction of counter-propagating AWs to drive a sound wave

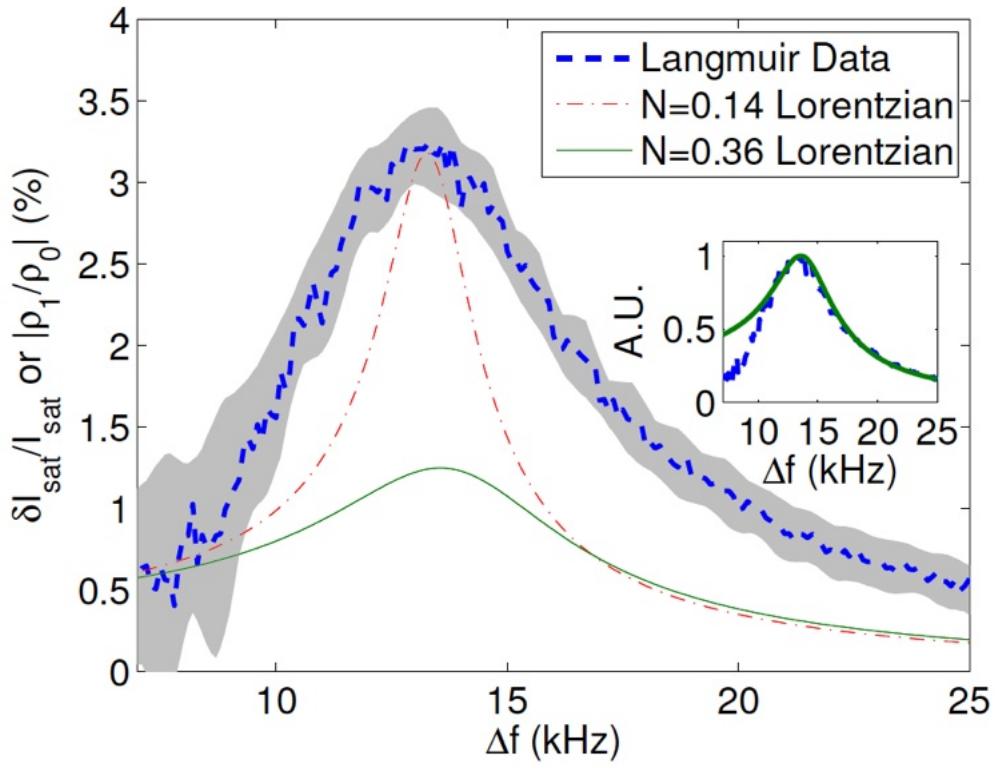


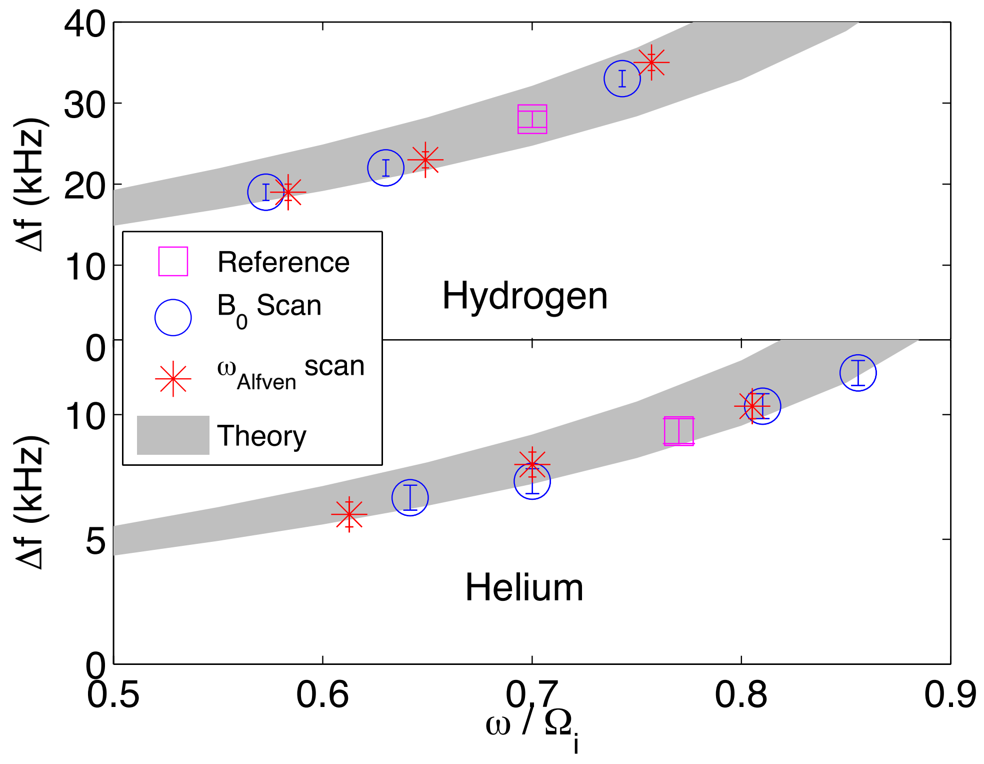


- Launch two counter-propagating AWs at slightly different frequencies
- Drive beat wave at difference frequency, see nonlinear response
- When beat frequency (and wavenumber) match IAW dispersion, see strong (resonant response) (and wave persists after drive is turned off)

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

Stimulated parametric decay: interaction of counter-propagating AWs to drive a sound wave



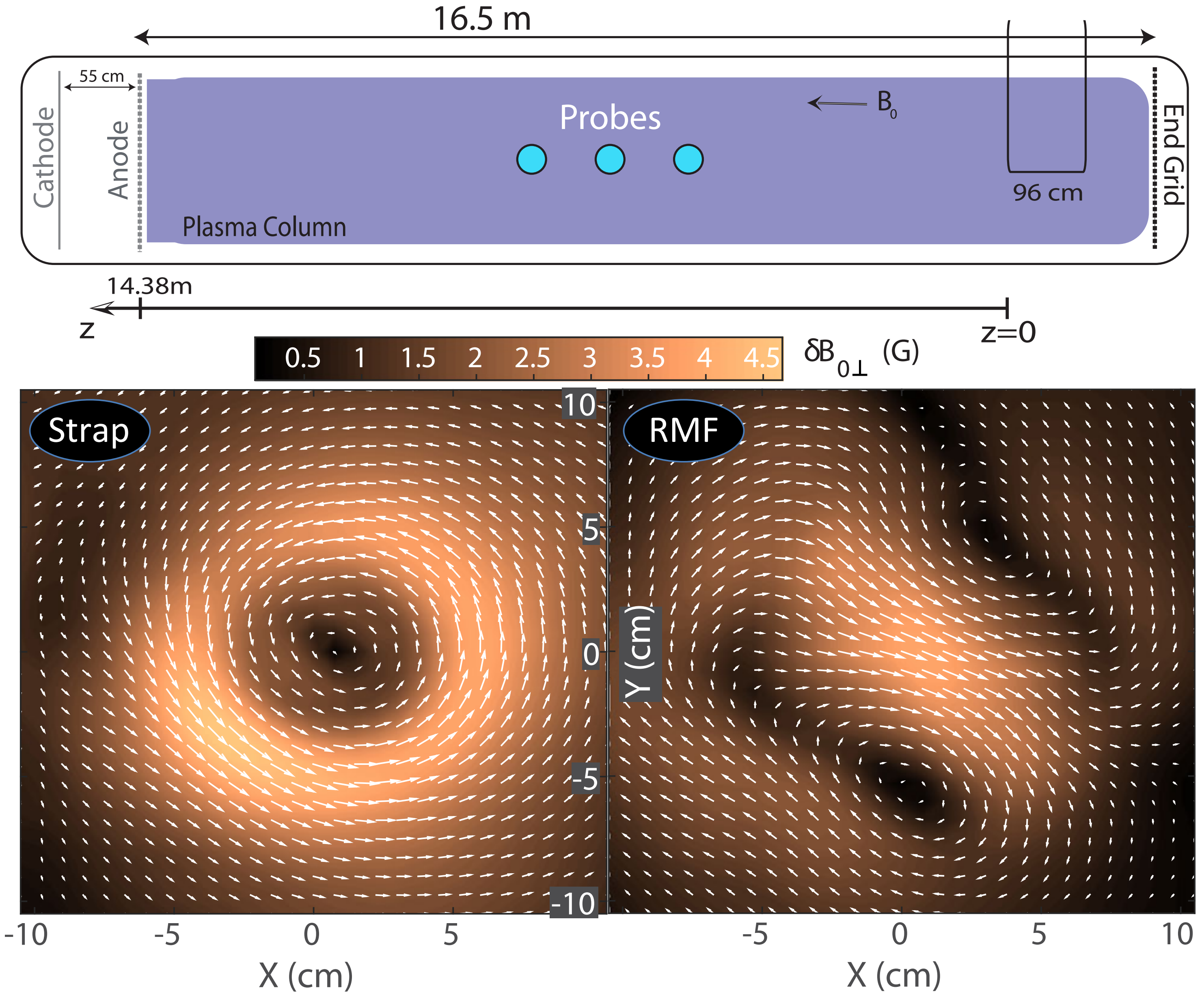


- Peak of response consistent with frequency and wave number matching, consistent with simple fluid theory (AW + AW -> IAW)

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

Observation of a parametric instability of kinetic Alfvén waves in LAPD

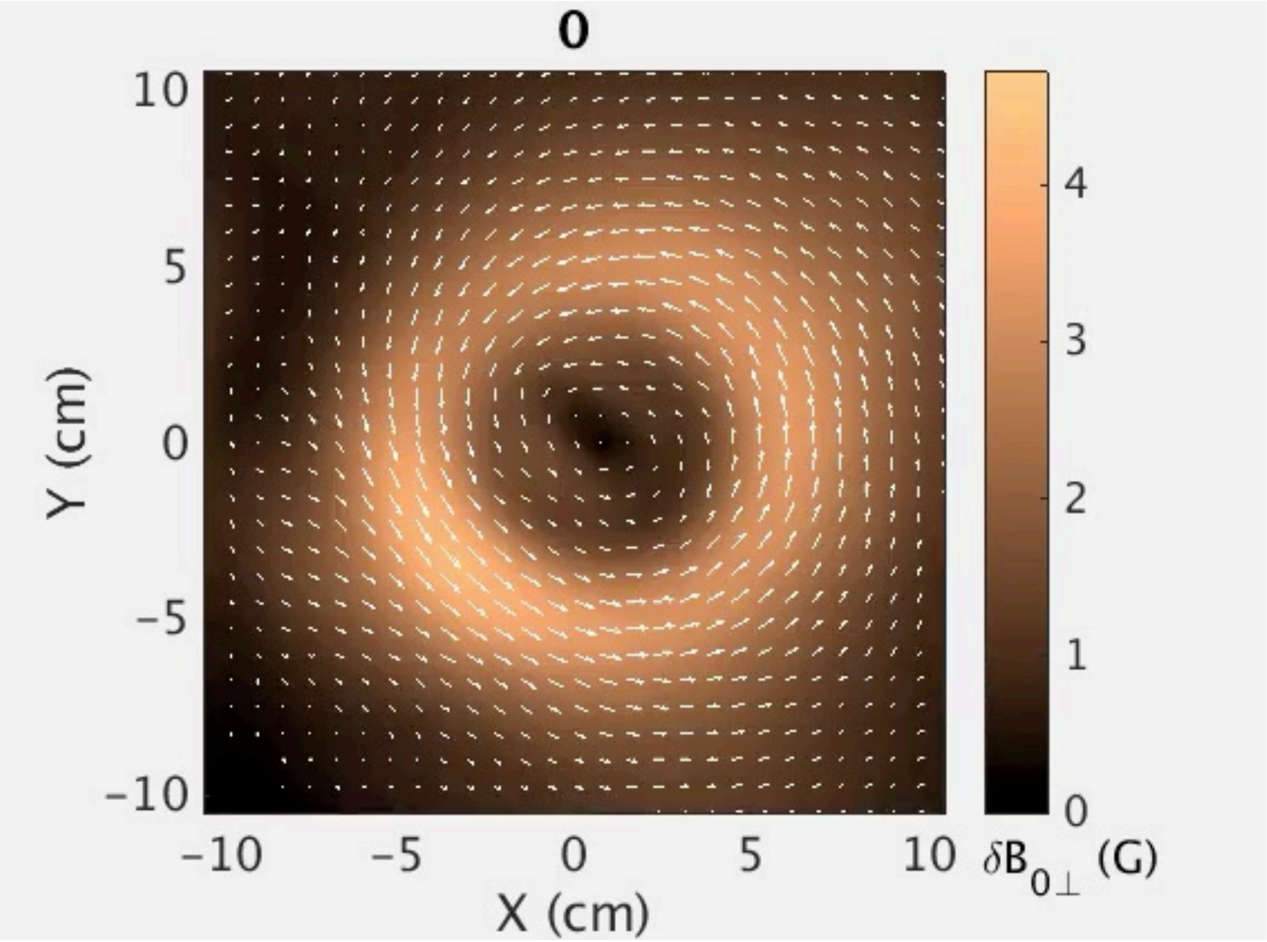
Pump wave spatial patterns (two different kinds of antennas)

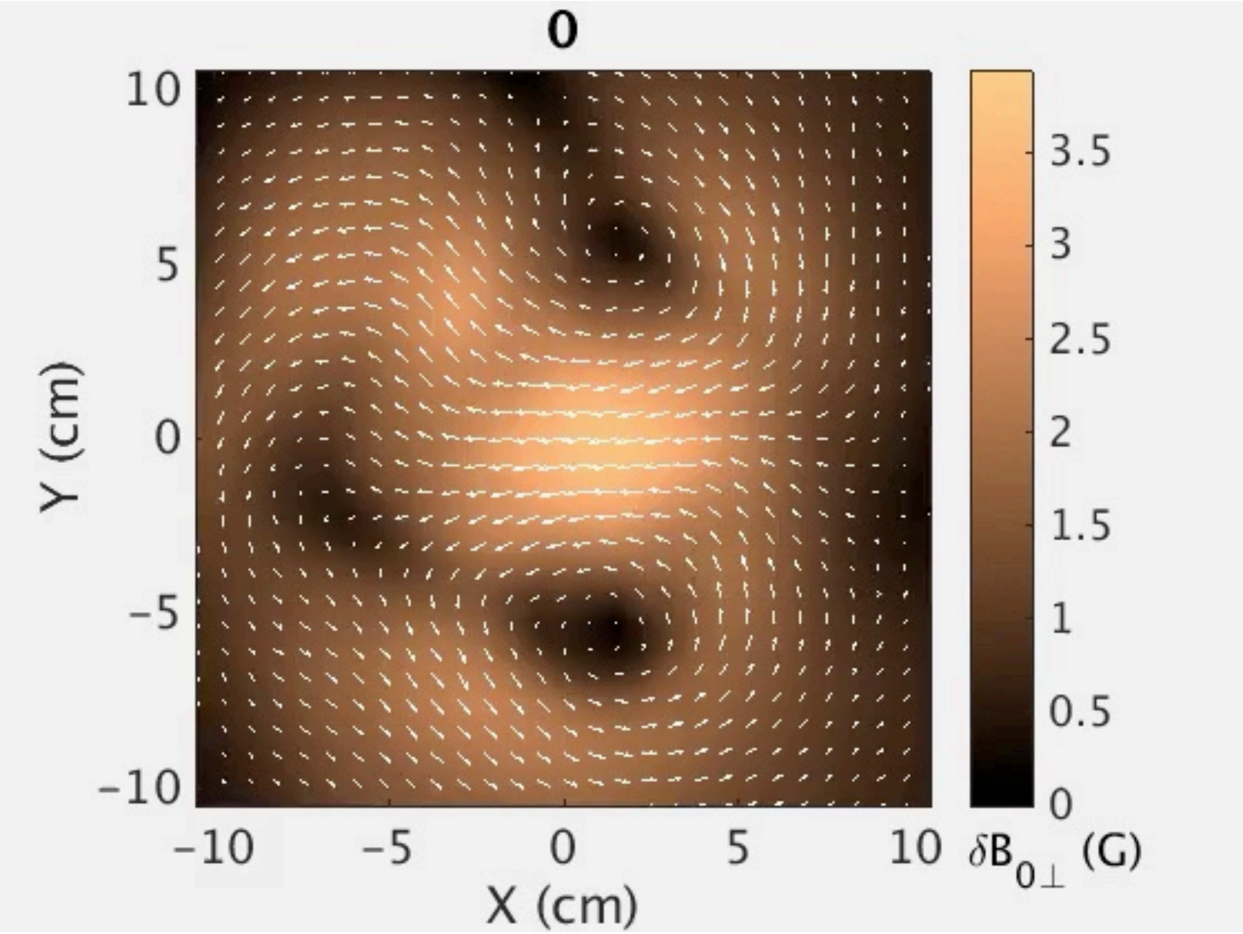


- Single, large amplitude KAW launched. Above an amplitude threshold and frequency, observe production of daughter modes.

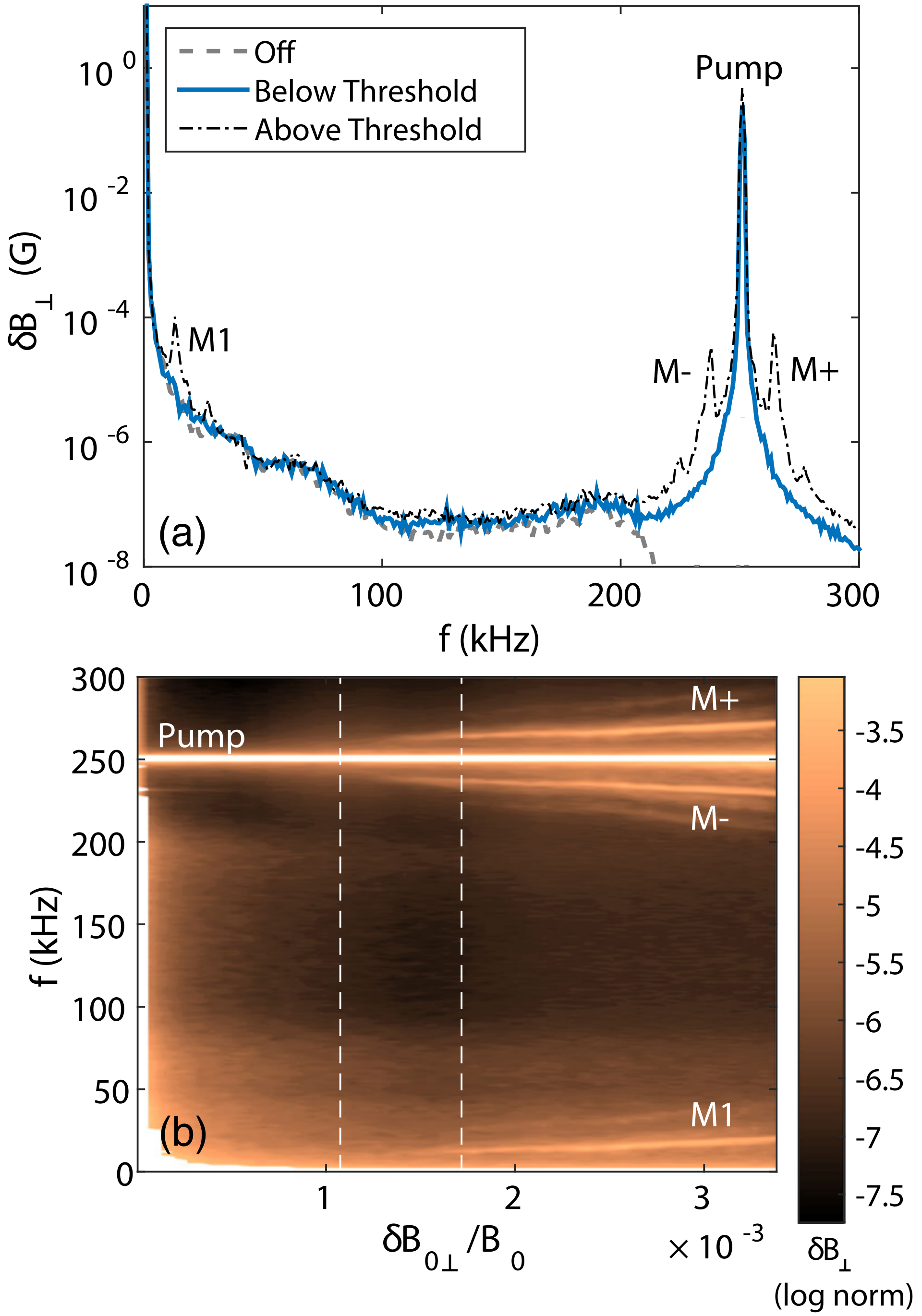
[Dorfman & Carter, PRL, 116, 195002 (2016)]

Pump waves: linearly and circularly polarized



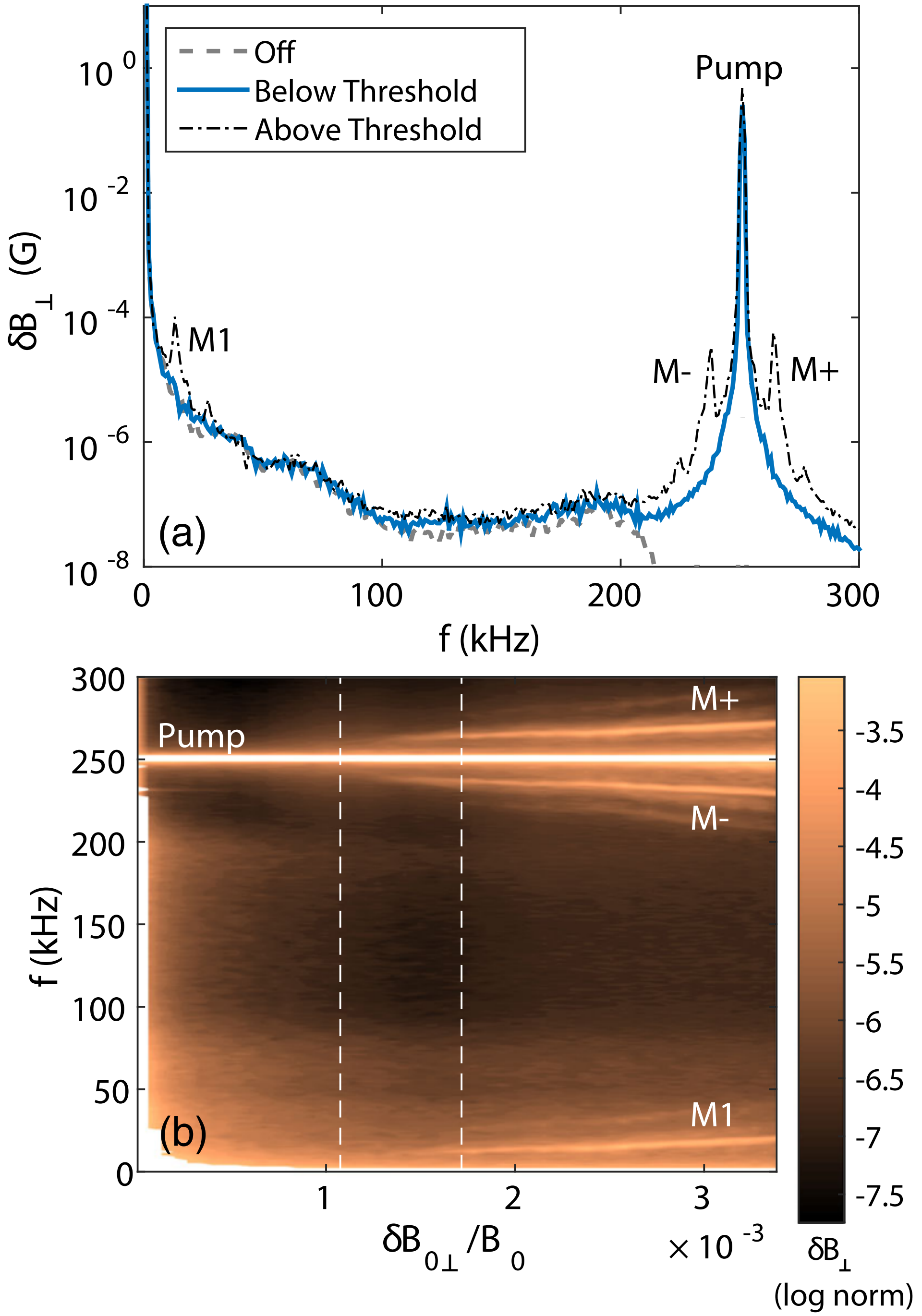


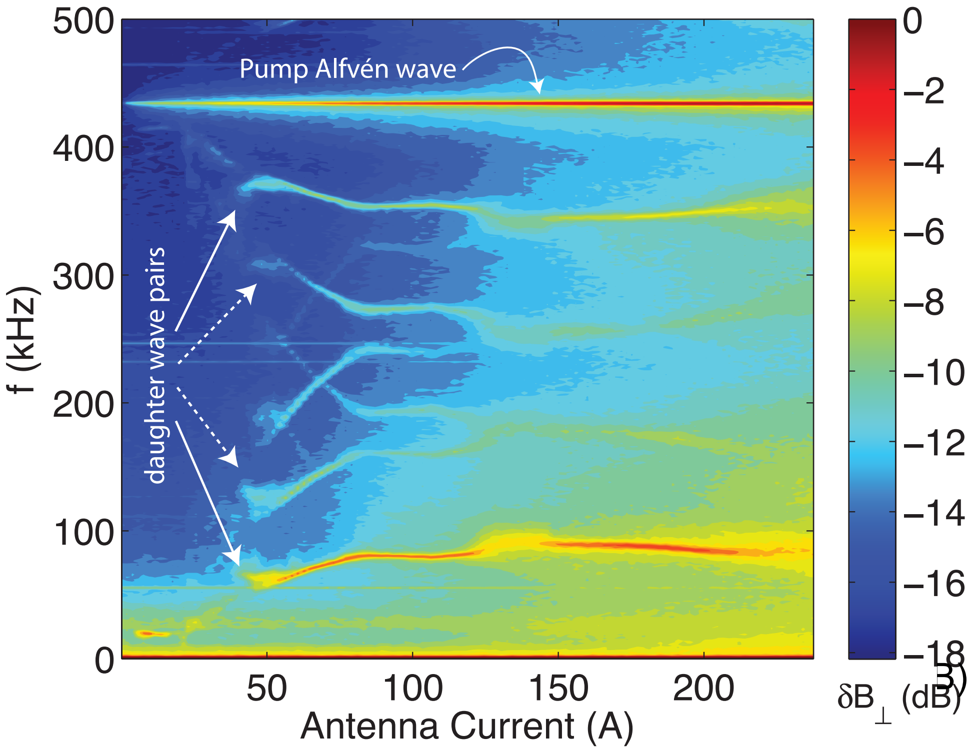
Above a threshold in pump amplitude, see production of sidebands and low frequency mode



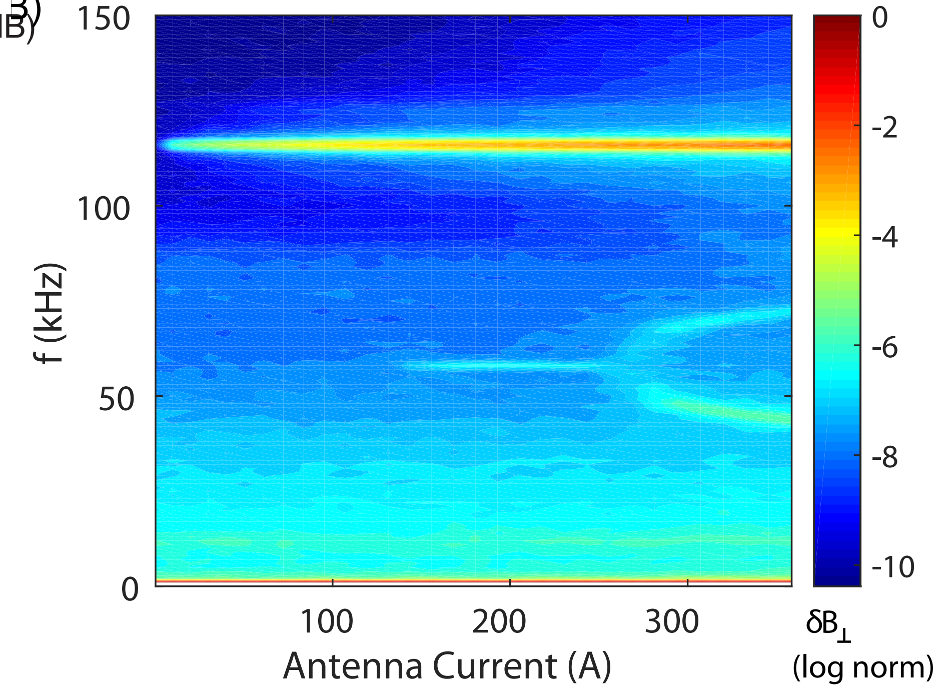
- Threshold in amplitude and in pump frequency (only observed for $f \gtrsim 0.5\ f_{ci}$)
- All three daughter waves co-propagating with pump. Need dispersive AWs
- Modes satisfy three-wave matching rules

Above a threshold in pump amplitude, see production of sidebands and low frequency mode

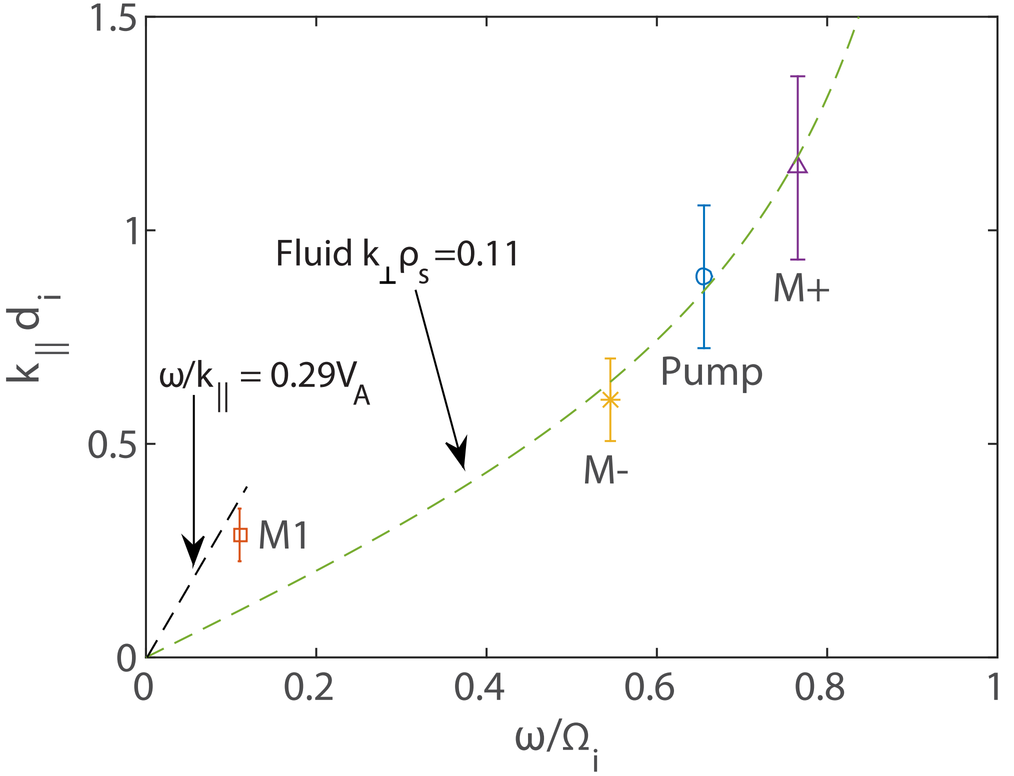


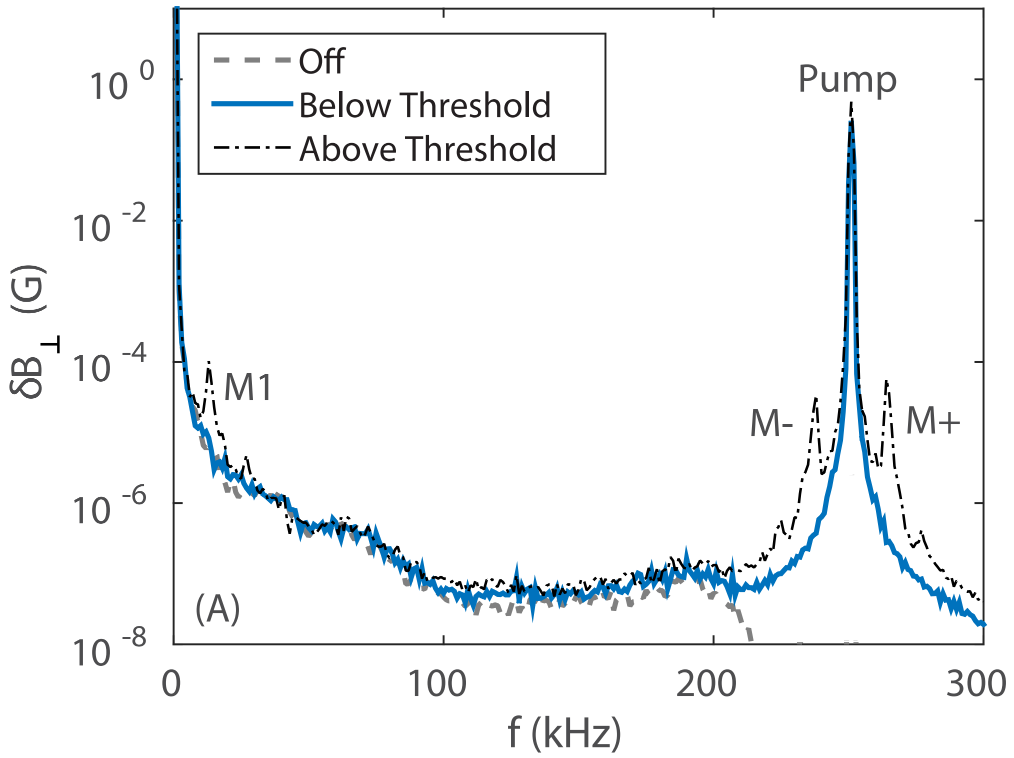


Variety of behaviors observed as plasma parameters are changed



Sidebands are KAWs, low frequency mode is quasimode

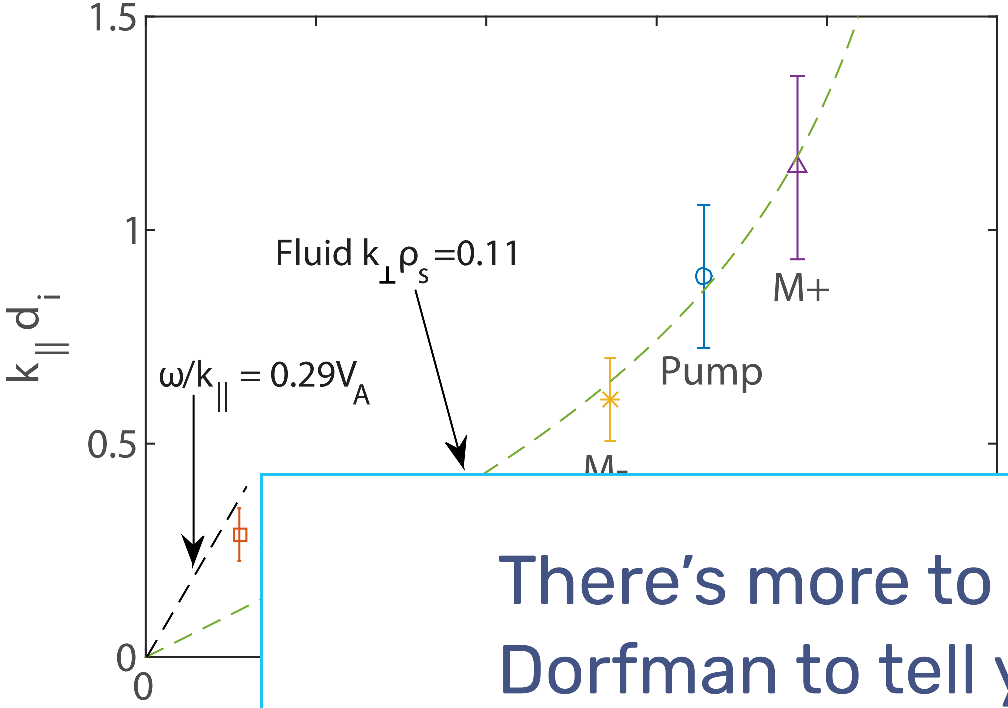


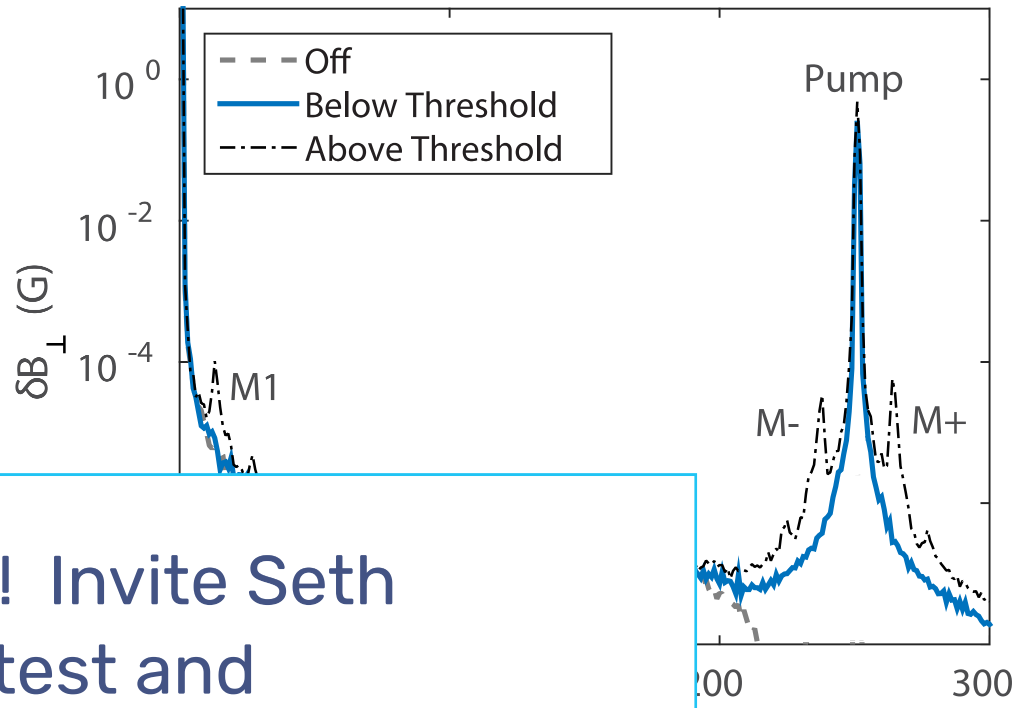


- Sideband waves are consistent with KAW dispersion relation
- Low frequency mode is a non-resonant mode/quasimode: phase speed inconsistent with sound wave or KAW
- **Participant modes consistent with modulational decay instability (but why don't we see parametric decay?)**

[Dorfman & Carter, PRL, 116, 195002 (2016)]

Sidebands are KAWs, low frequency mode is quasimode



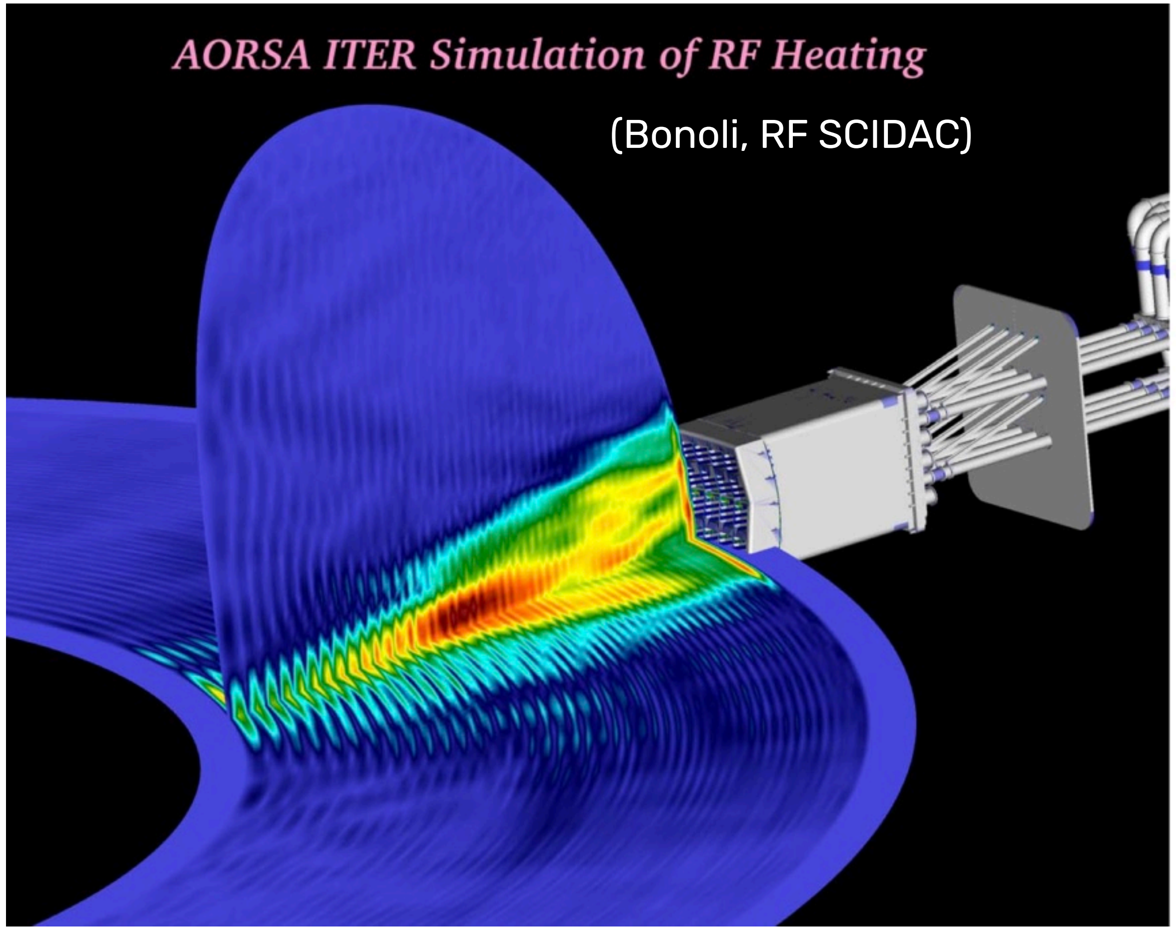


There's more to this story! Invite Seth Dorfman to tell you the latest and greatest

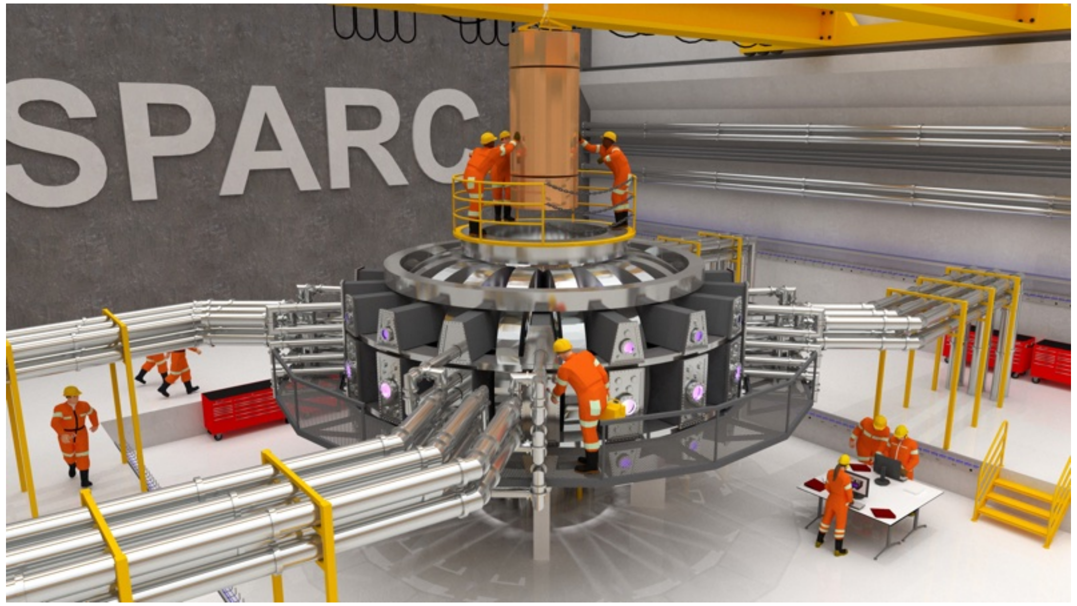
- Sideband v
- Low frequency mode is a non-resonant mode/quasimode: phase speed inconsistent with sound wave or KAW
- **Participant modes consistent with modulational decay instability (but why don't we see parametric decay?)**

[Dorfman & Carter, PRL, 116, 195002 (2016)]

ICRF heating in fusion devices

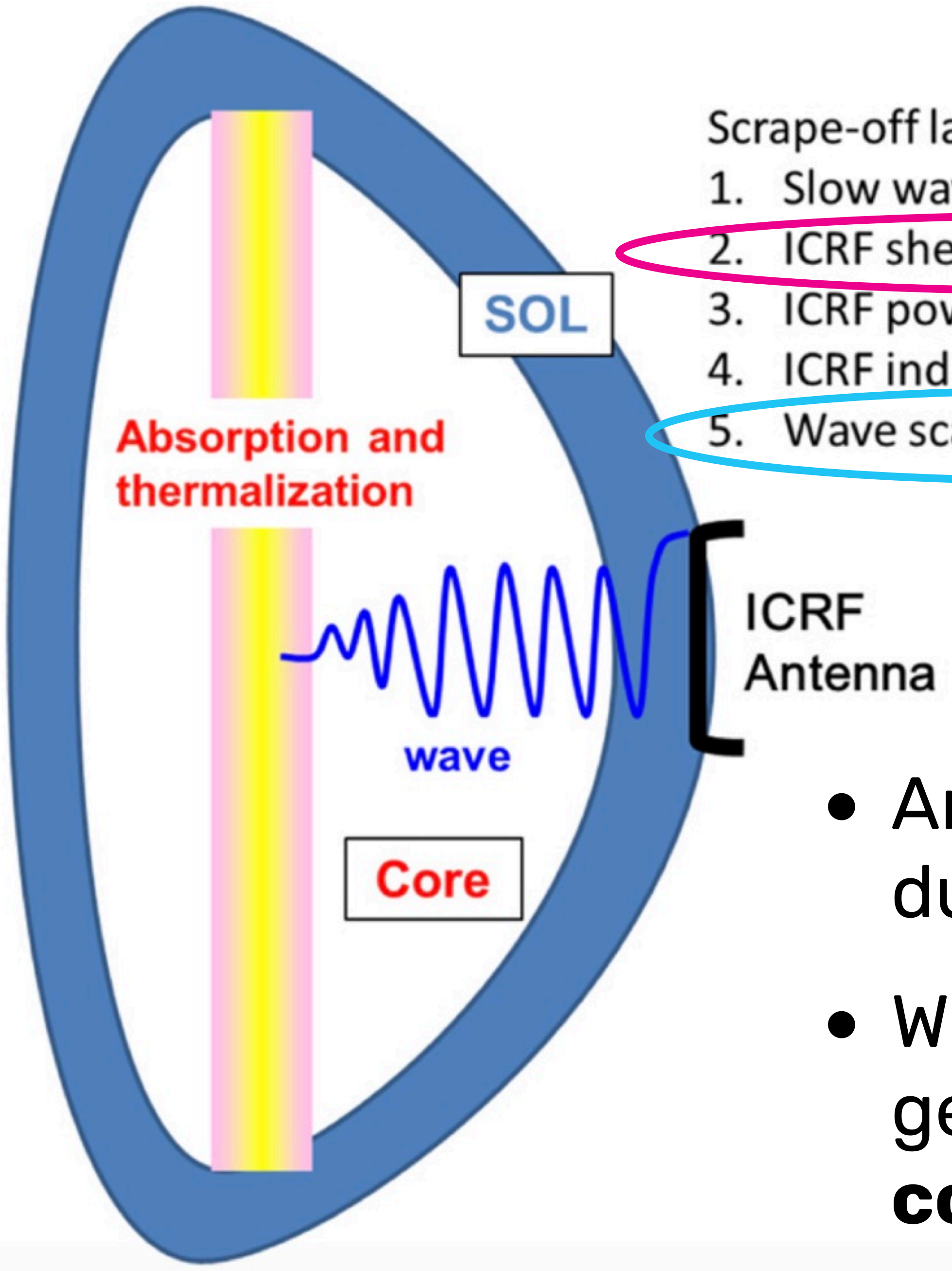


"Ion cyclotron range of frequencies"



- Launch high power EM waves into plasma, get absorption/heating via, e.g. ion cyclotron resonance
- Key heating system for ITER, CFS' SPARC tokamak

Challenges in RF heating

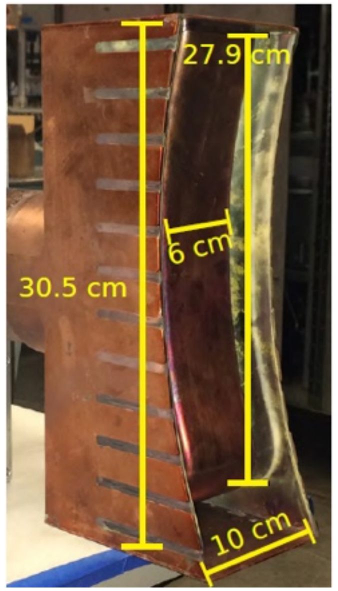


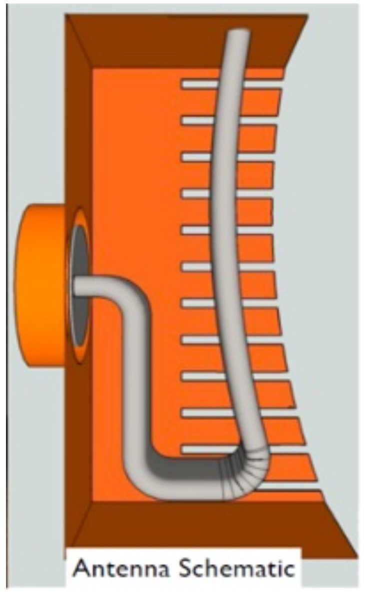
Scrape-off layer (SOL):

1. Slow wave propagation and LH resonance
2. ICRF sheath and impurity sputtering
3. ICRF power coupling and edge power loss
4. ICRF induced drifts and convection
5. Wave scattering by turbulence

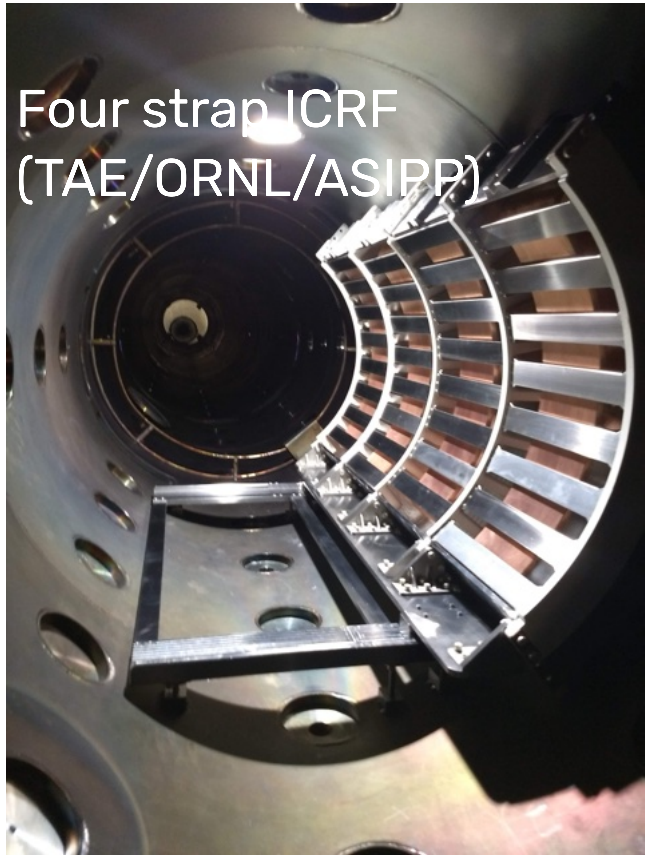
- Antenna sits outside of plasma, many “parasitic effects” due to interaction with edge plasma/scrape-off layer
- We’ve focused on: “RF Sheaths” and impurity generation & **wave scattering/stimulated mode conversion due to turbulence/turbulent structures**

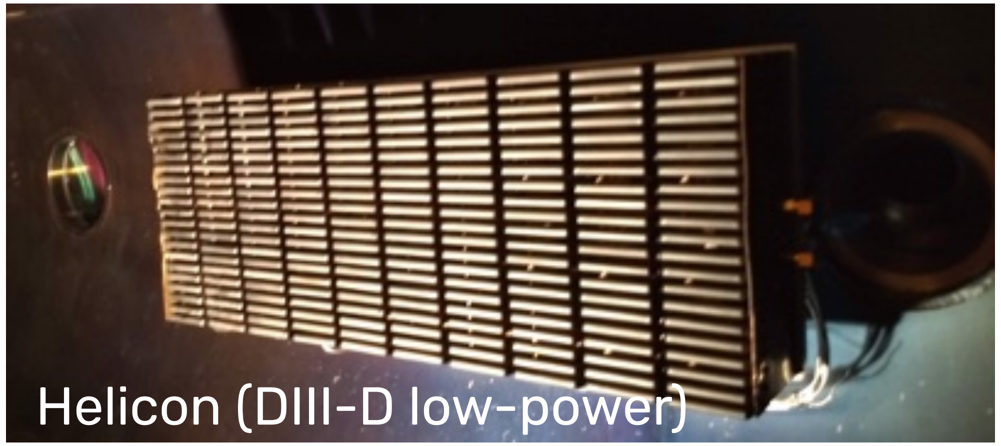
Infrastructure for exciting waves on LAPD

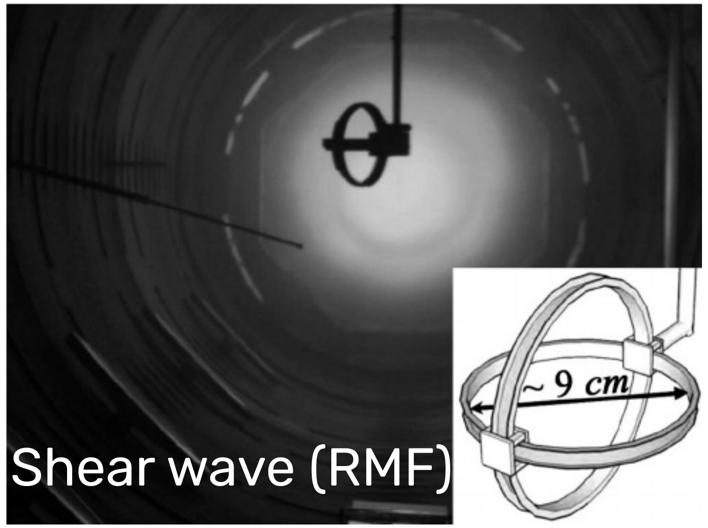




Single-strap ICRF
insertable, rotatable

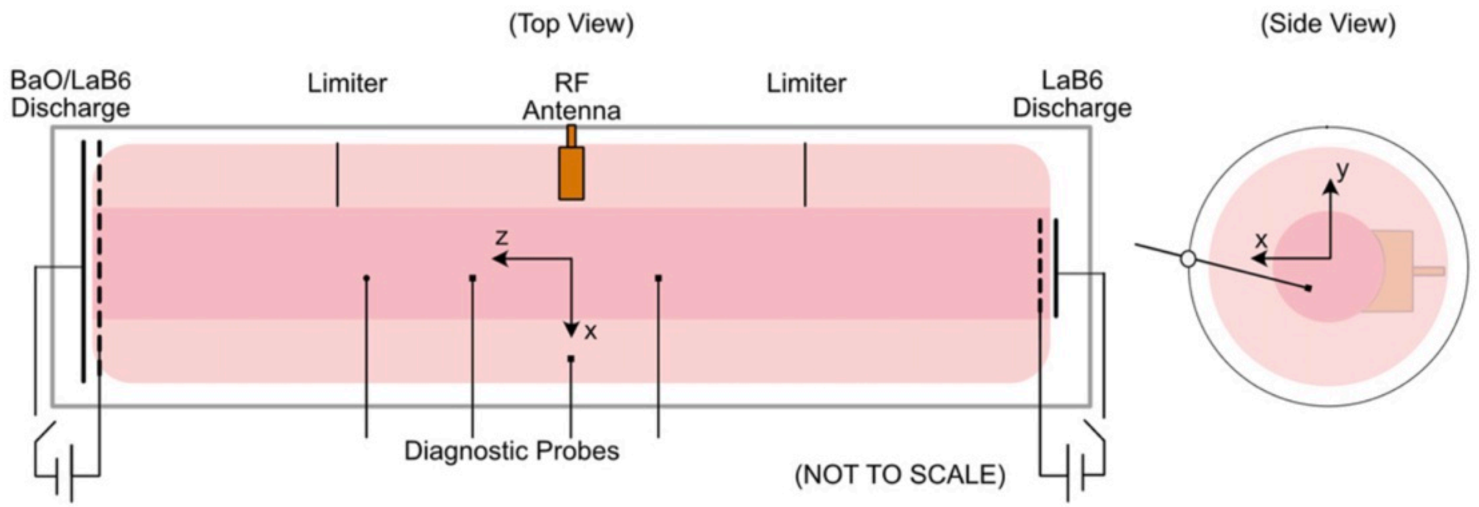






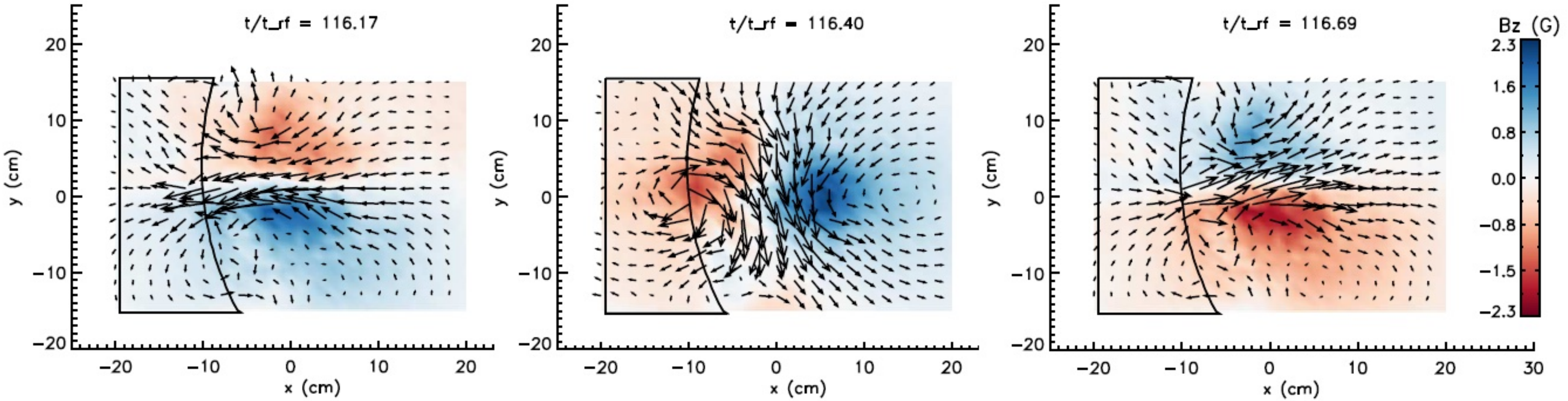
- Multiple high and low-power antennas available
- High power triode source: ~2.5MHz, f=1-10 fci, ~200 kW
- High power solid state sources: up to 1MHz, ~100kW+
- Low power (~400W) sources up to 600MHz+

Large amplitude fast waves excited using single-strap antenna

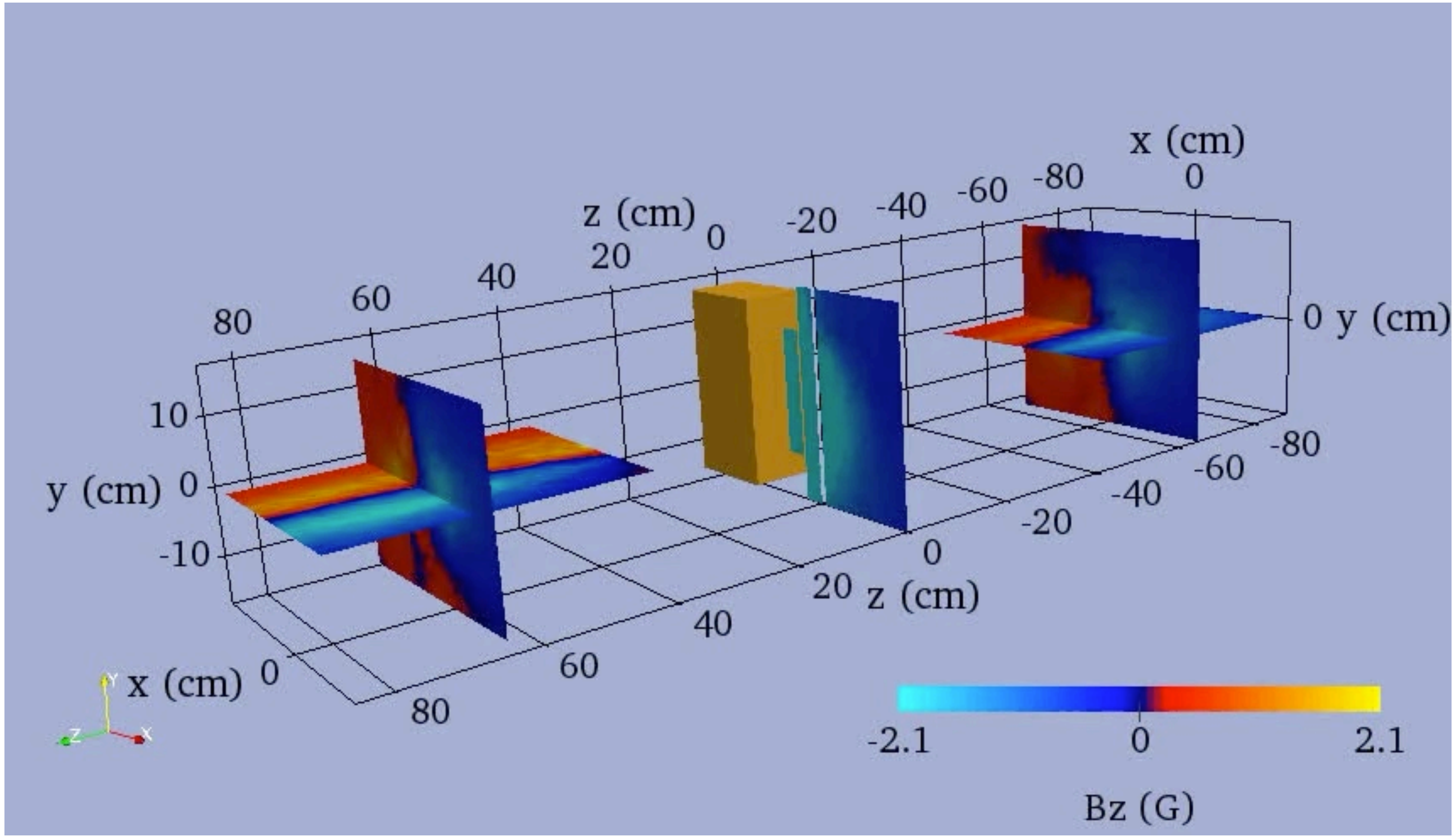


- High power (triode) source: f=1-10 fci, ~200 kW
- Coupled fast wave: m=1 mode structure observed

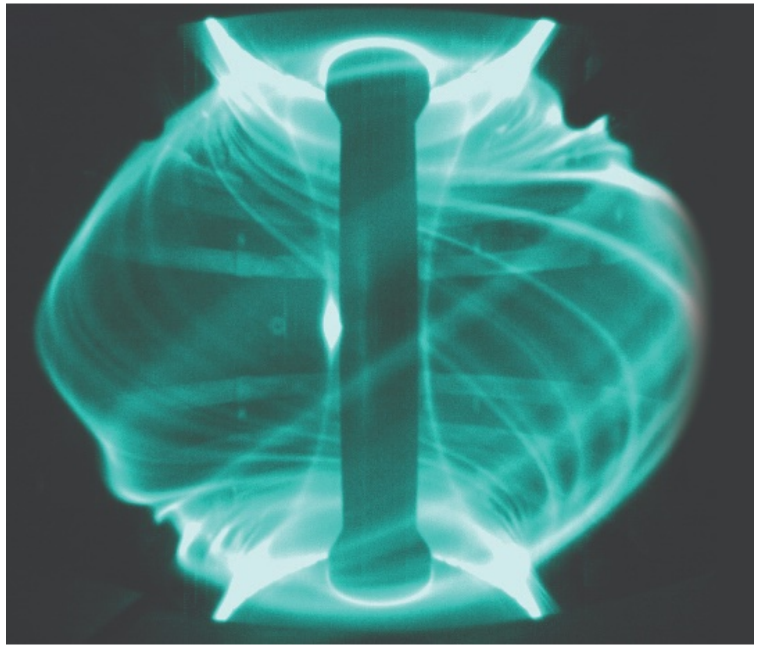
magnetic fluctuations



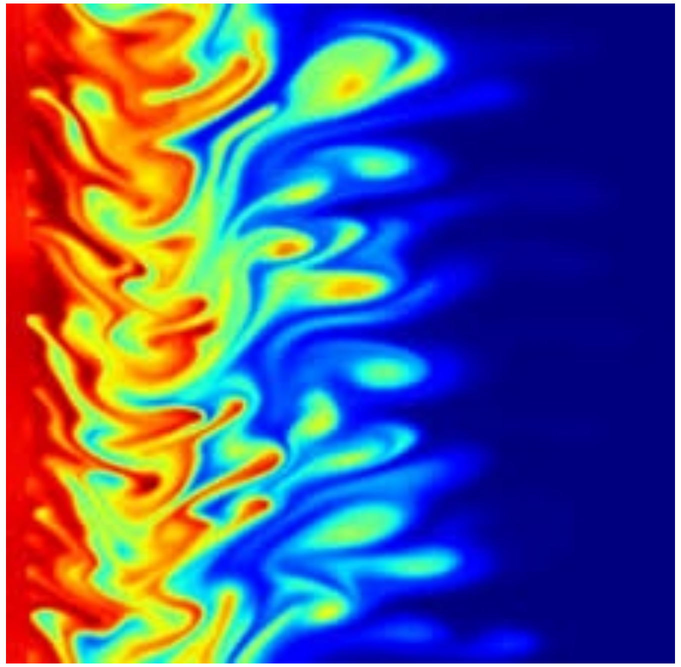
3D wave measurements: m=1 fast wave eigenmode excited by single-strap antenna



∇p driven turbulence generates filamentary structures in the edge of fusion devices

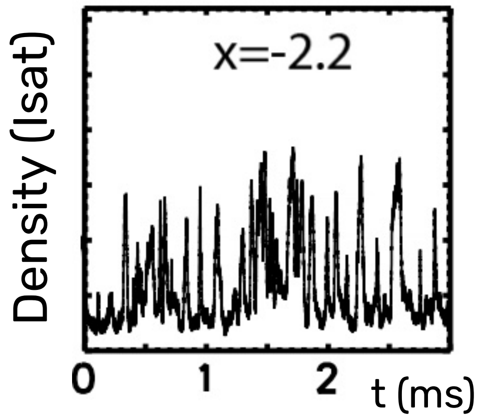


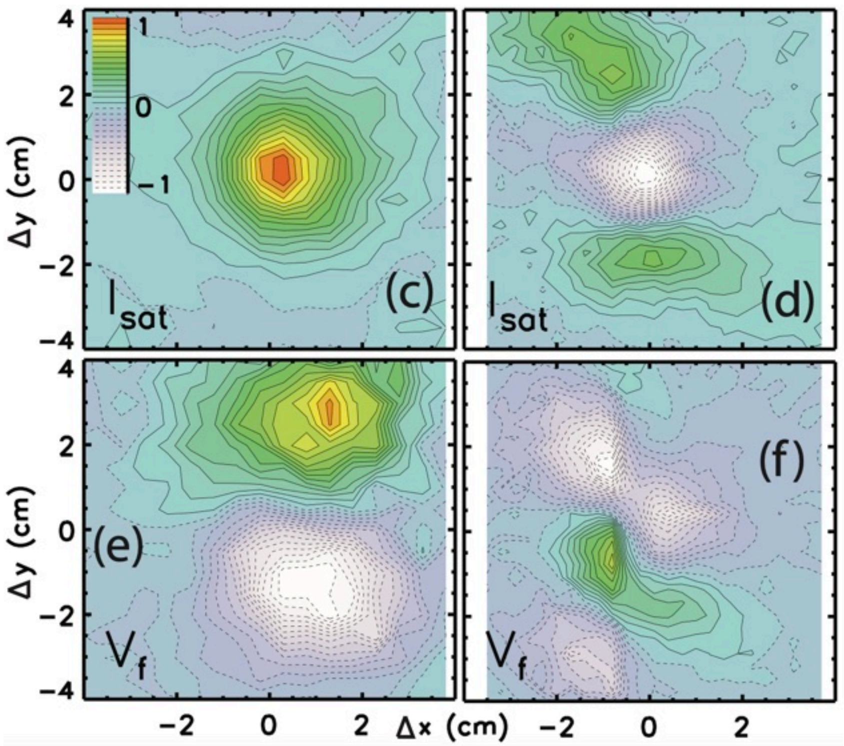
MAST-U (actually an ELM)



B. Dudson, BOUT++

T.A. Carter, PoP 13, 010701 (2006)

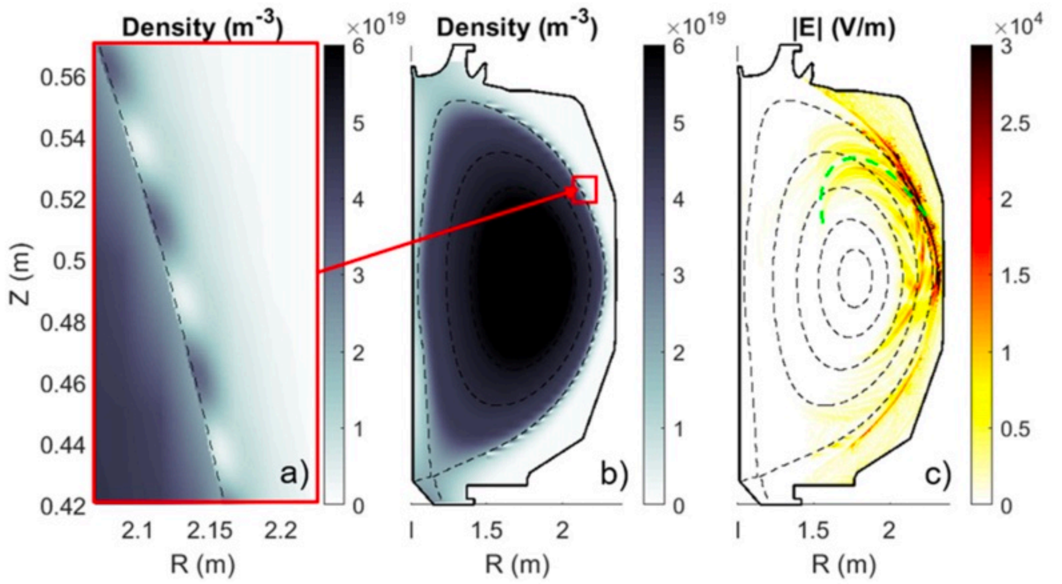




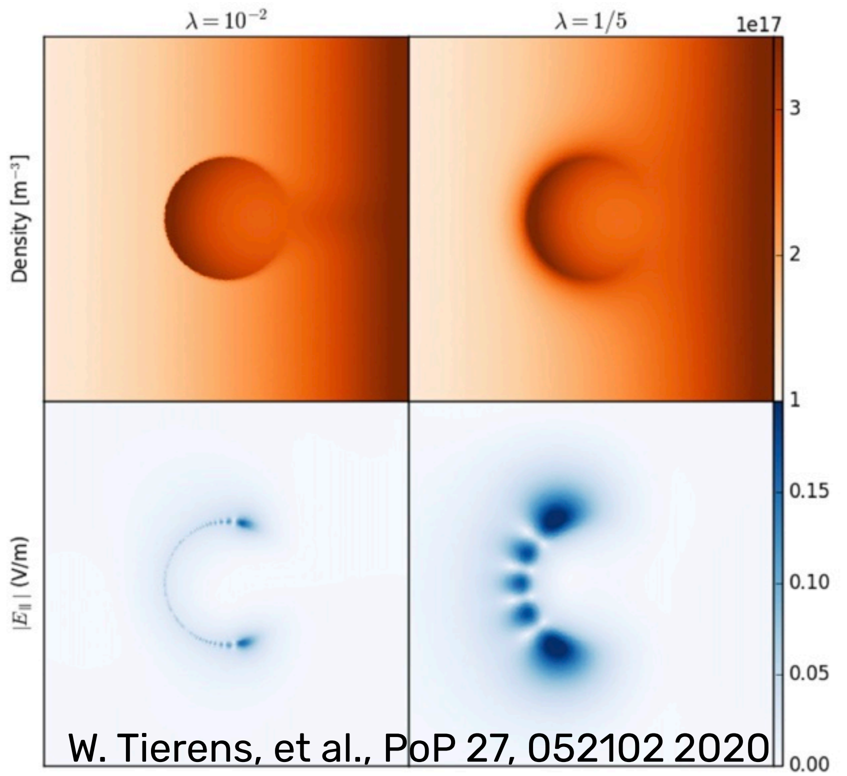
- Coherent structures or "blobs" are generated in turbulent edge of devices like tokamaks
- Filamentary structures that propagate outward radially (need interchange drive/polarization), cause most particle transport in the edge of these devices

Wave interaction with filaments: scattering, mode conversion

- Scattering & mode conversion of fast waves by edge turbulence a focus of ICRF research
  - Wave interaction with filament: can cause "stimulated mode conversion" from FW to slow mode
  - Slow mode propagates parallel to field, wave energy is trapped in and dissipates in edge (not where you want heat to go)
  - Project on LAPD to study this scattering/mode conversion process (Josh Larson)

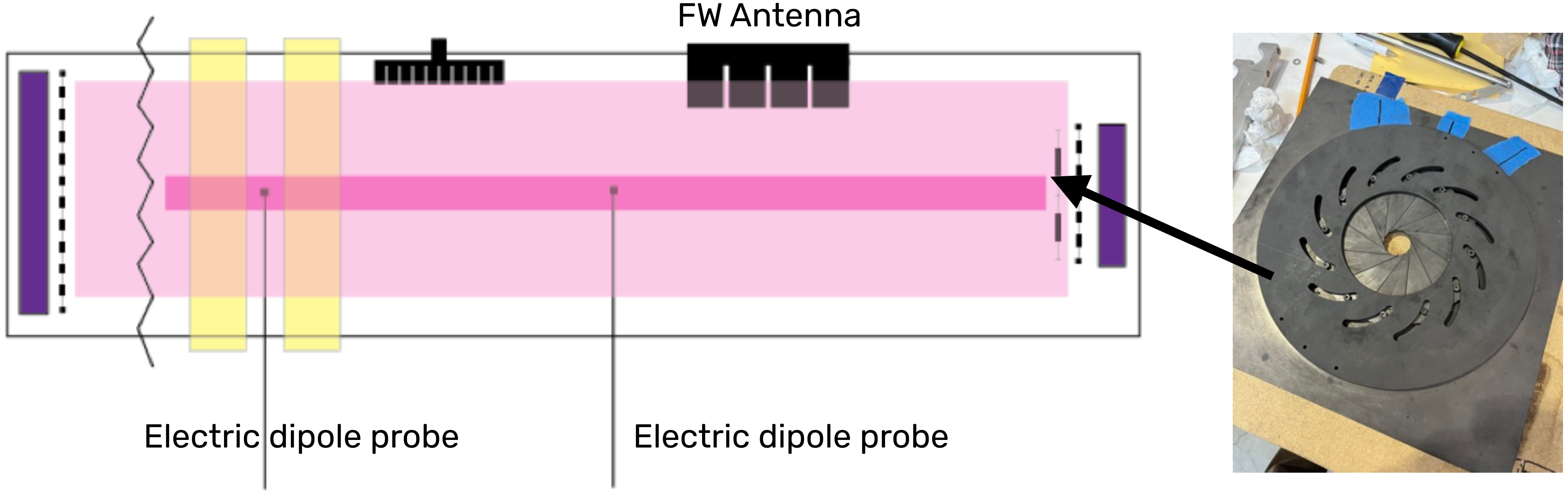


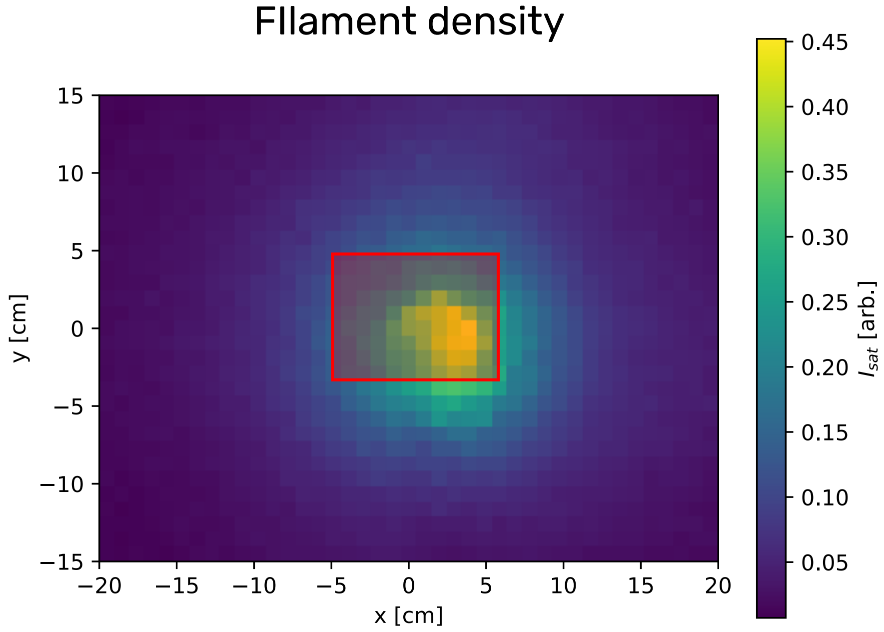
C. Lau *et al.* 2021 *Nucl. Fusion* **61** 126072



W. Tierens, et al., PoP 27, 052102 2020

Interaction of fast waves with stationary filament produced by secondary cathode

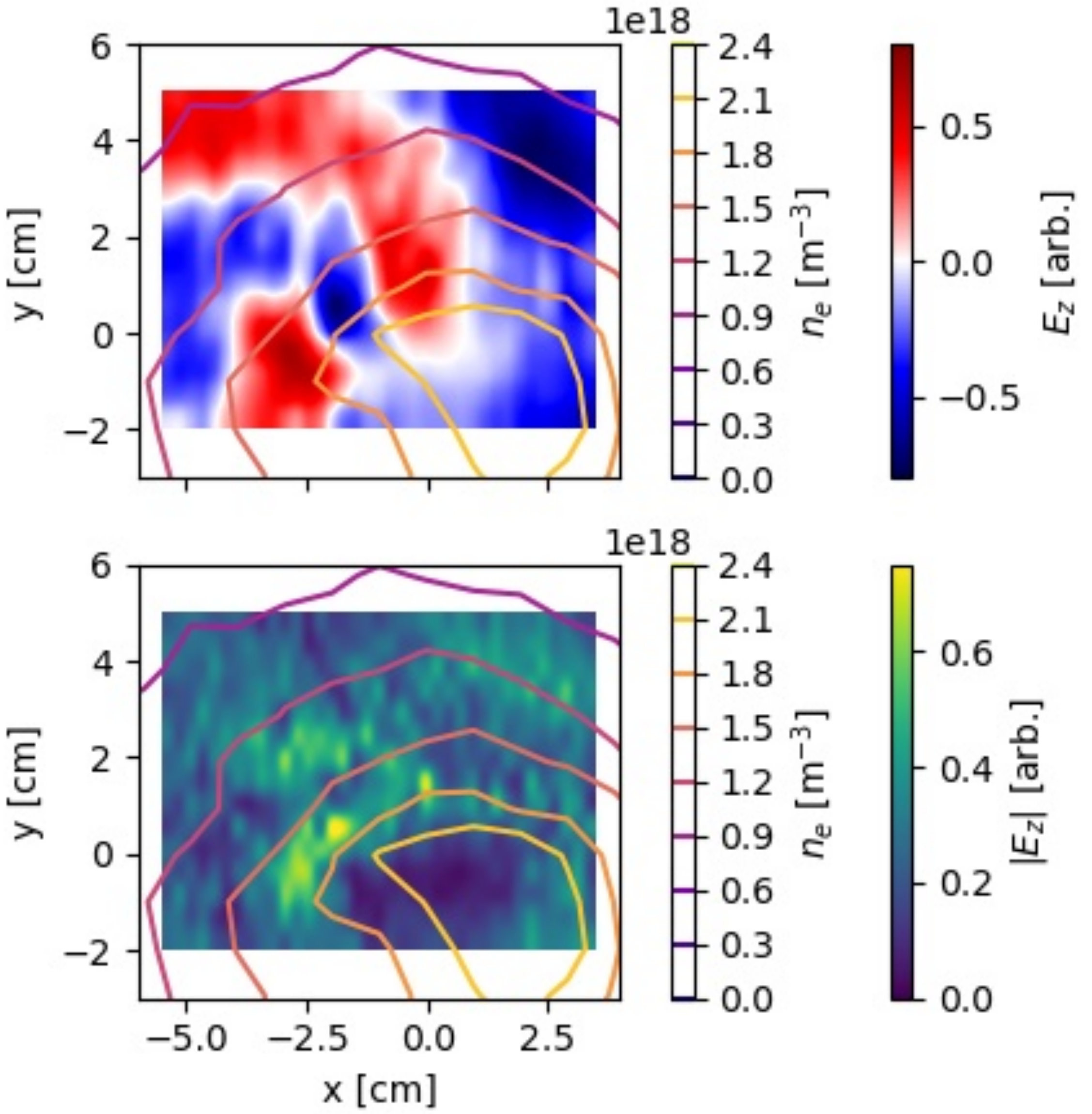




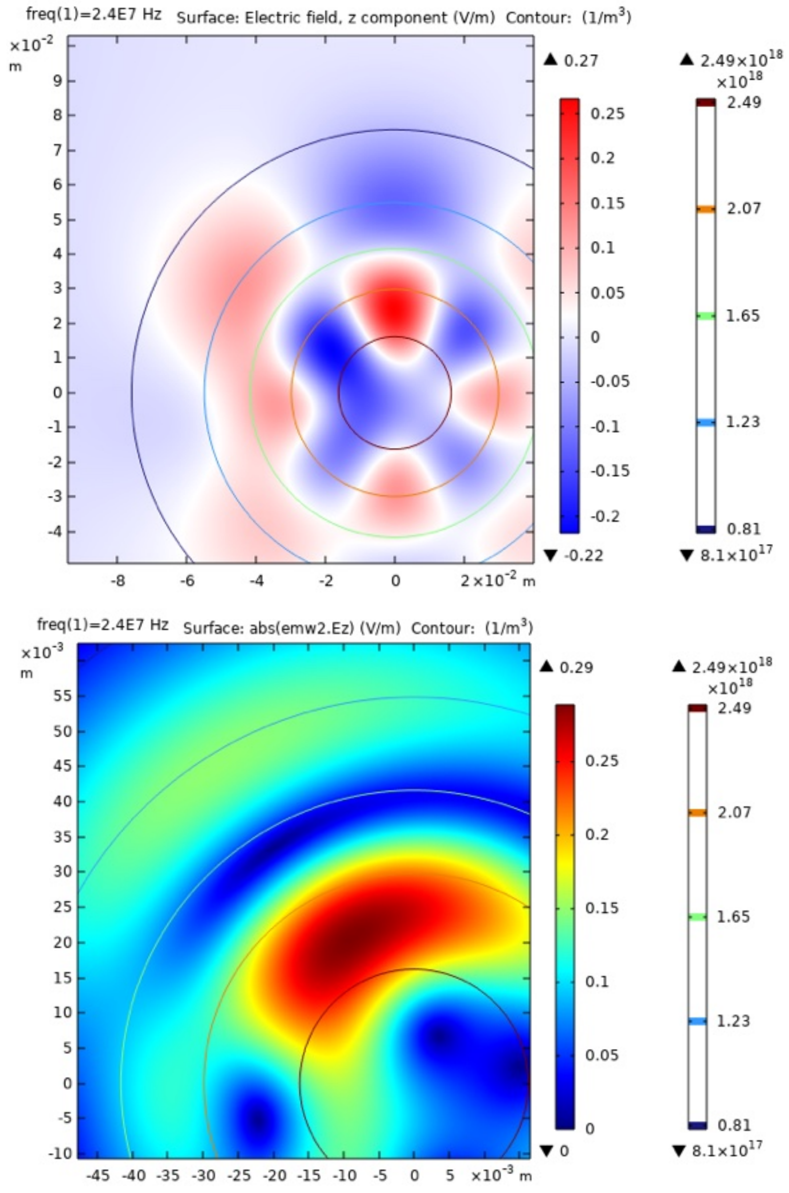
- Use second cathode + carbon iris to make variable-size filament
- Launch fast wave from edge, look for conversion to slow mode on filament: primary tool for this is wave polarization. FW has very little $E_{||}$, slow wave has large $E_{||}$

Evidence of mode-conversion/SW surface wave on filament, qualitative agreement with modeling

Experiment



Model (COMSOL)

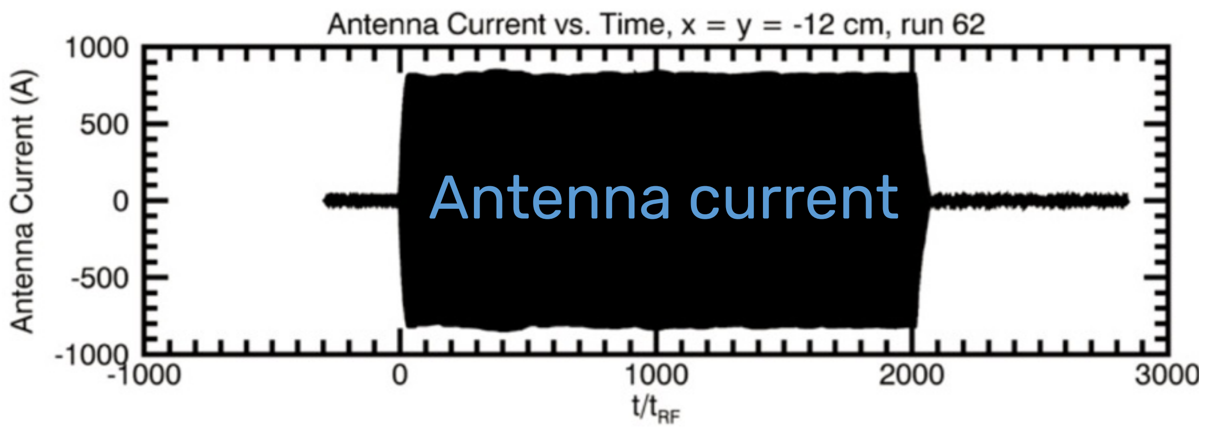


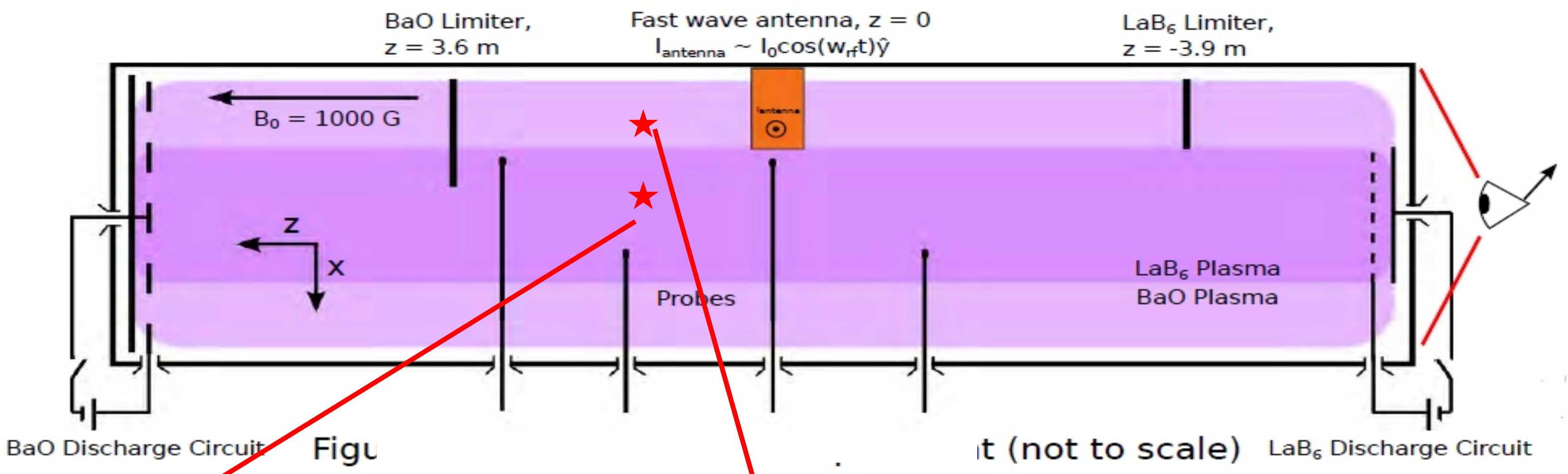
Larson, et al., in prep

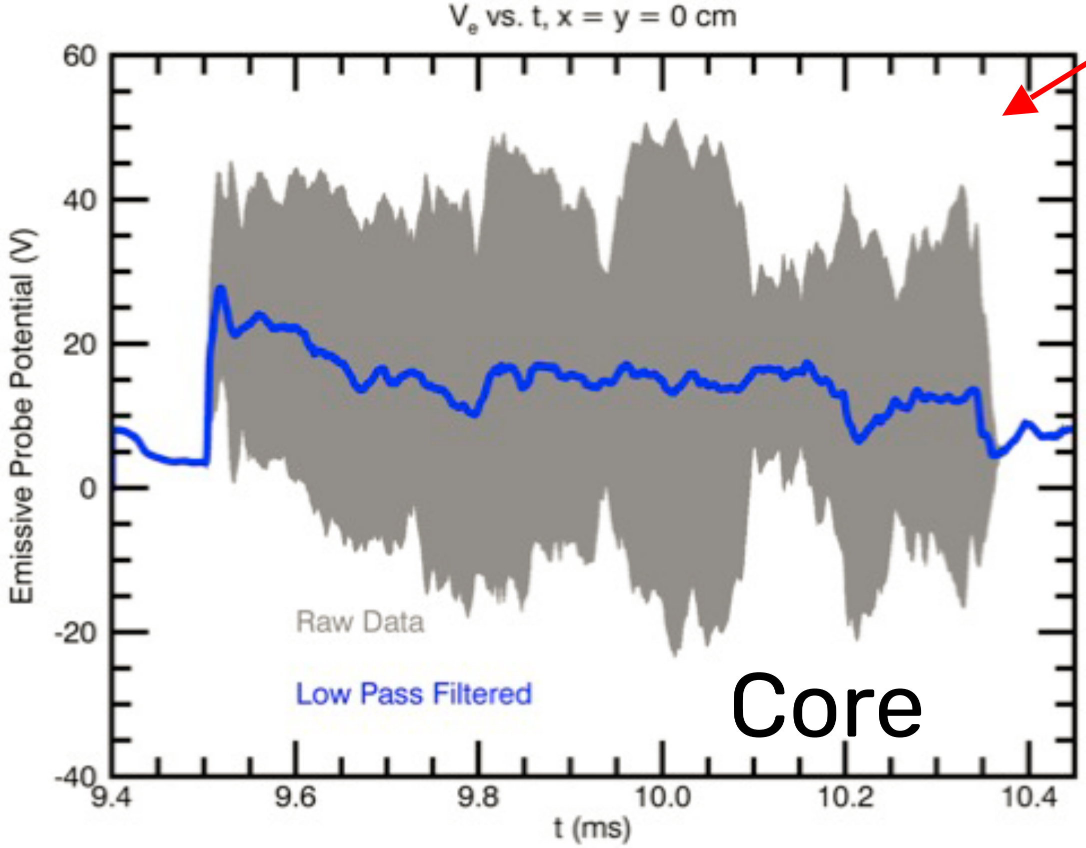
Summary

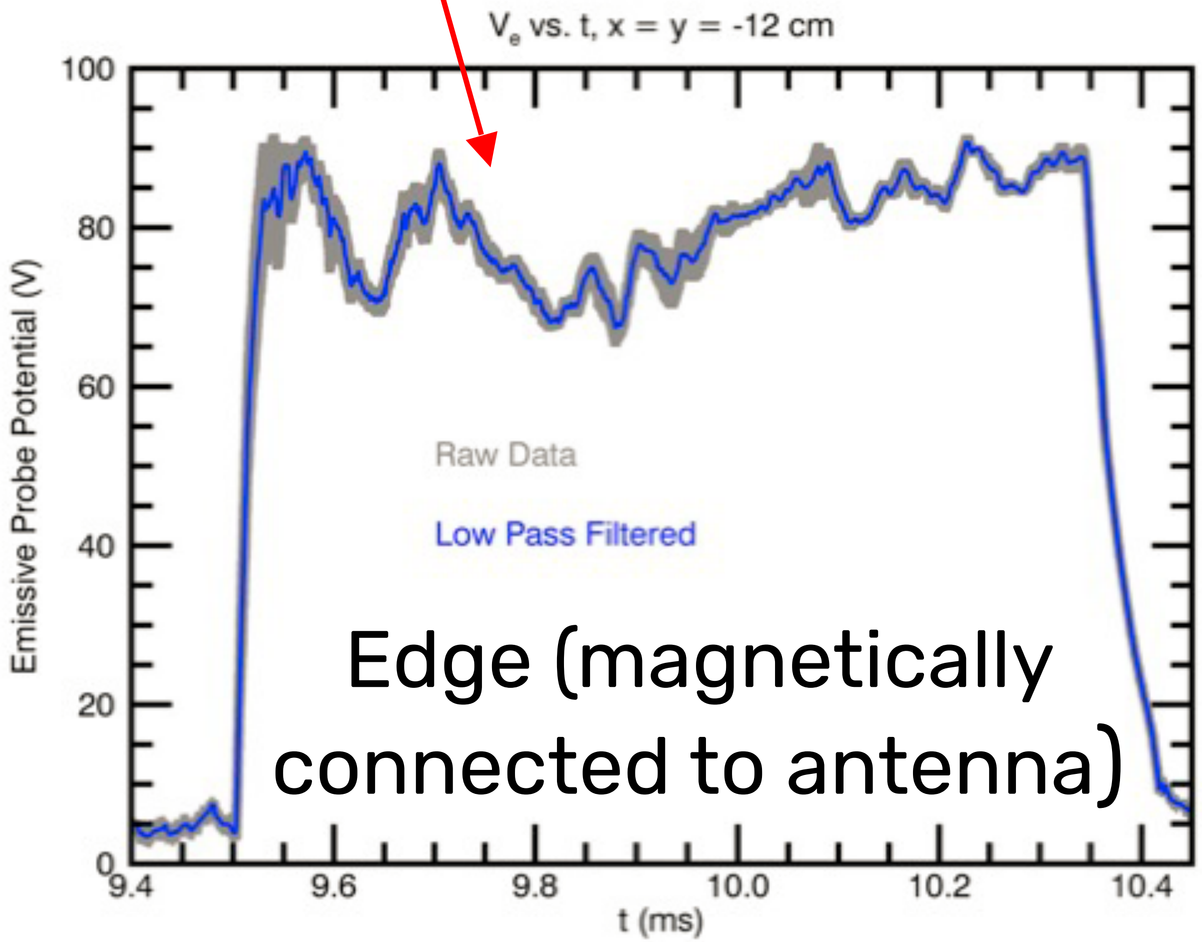
- Basic Plasma Science Facility: US DOE and NSF sponsored collaborative research facility for study of fundamental processes in magnetized plasmas. Primary device is Large Plasma Device (LAPD).
- Wide range of studies performed: waves, instabilities, turbulence & transport, shocks, reconnection. Will cover recent work on the linear and nonlinear physics of plasma waves:
  - **Parametric instabilities of Shear Alfvén waves:** Above an amplitude threshold, observe production of daughter waves consistent with Modulational decay instability [Dorfman & Carter, PRL 2016]
  - **Fast Waves/ICRF**: Scattering/Mode conversion of FW on density filaments, Mitigation of RF sheaths using insulating antenna enclosure [Bal et al., NF (2022)]

Plasma potential measurements show evidence of RF rectification

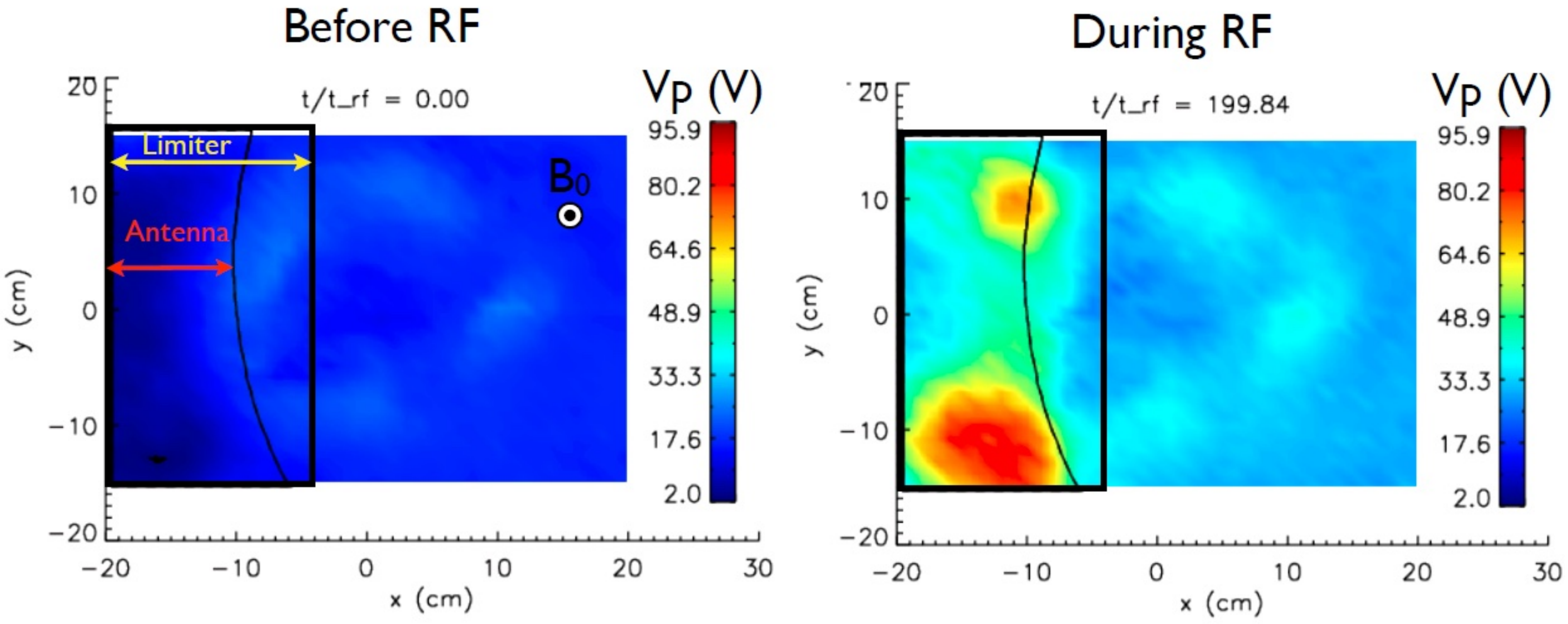






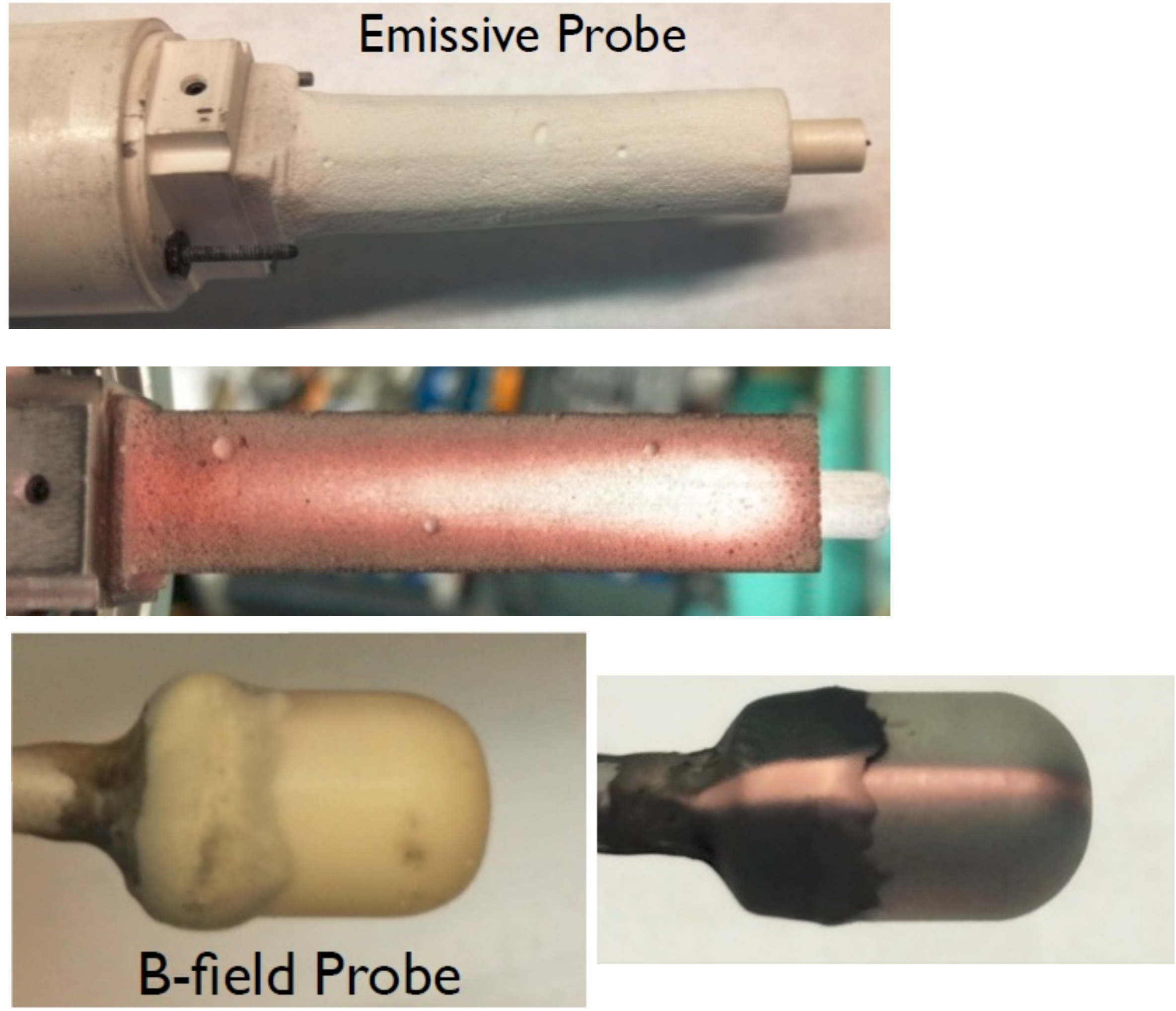


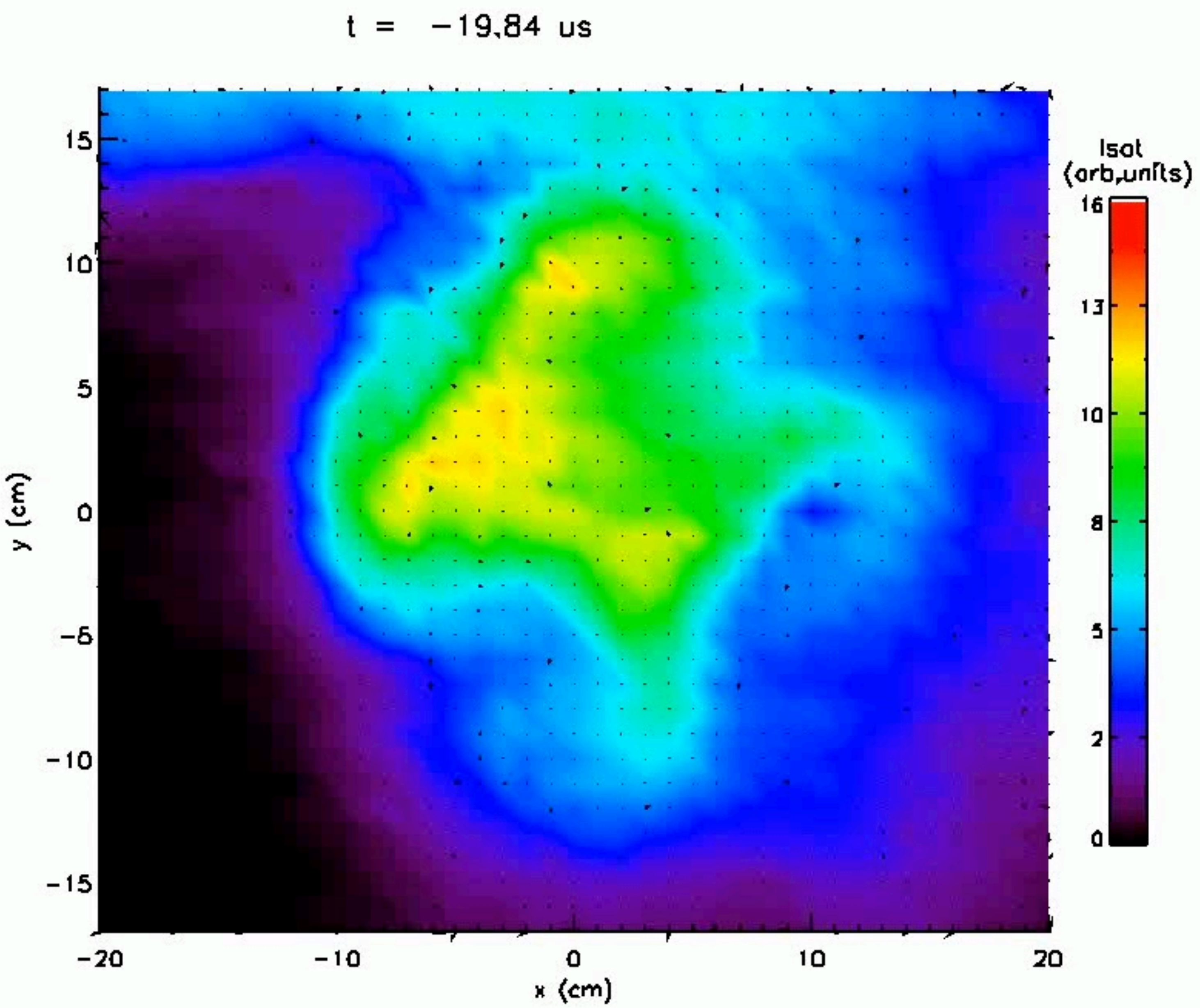
2D Potential measurements: Near-field RF sheaths localized on antenna structure



Martin, et al. PRL 119, 205002 (2017)

Impacts of RF Sheaths: sputtering and density modification

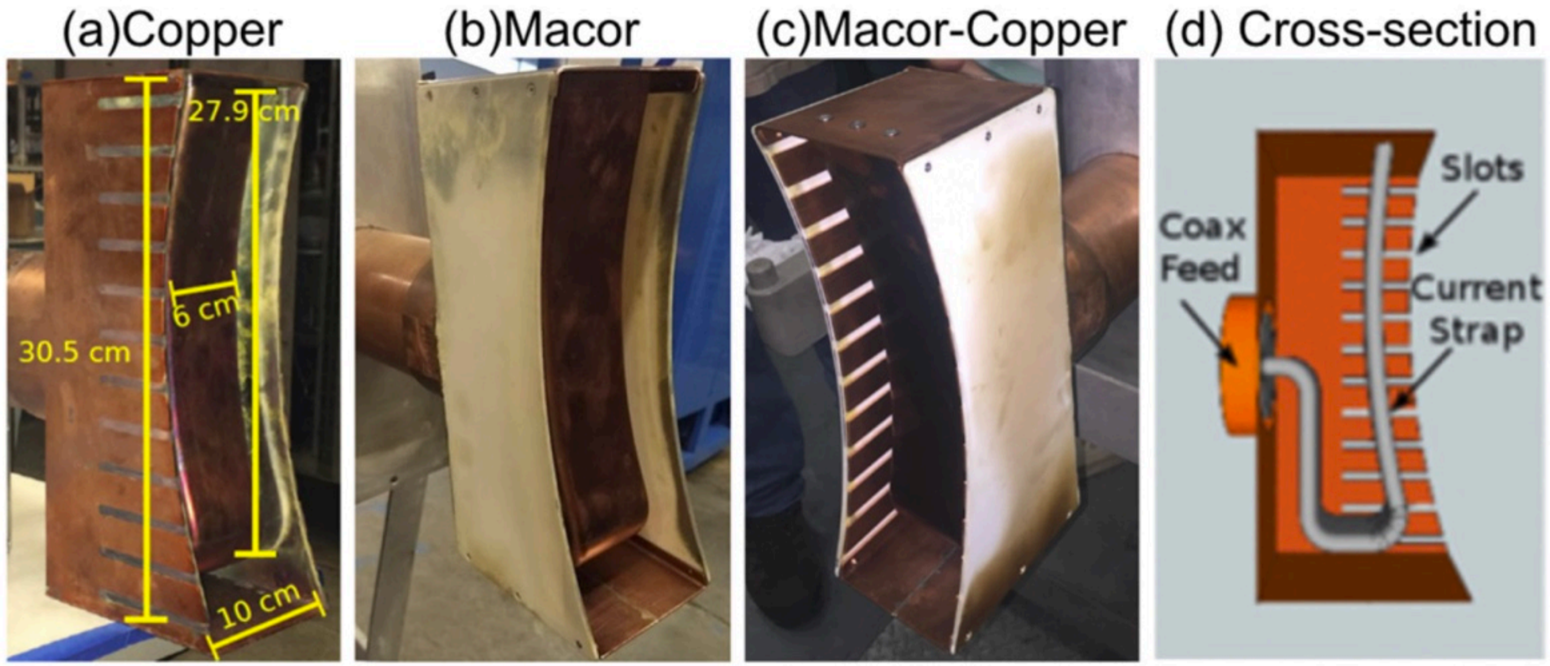


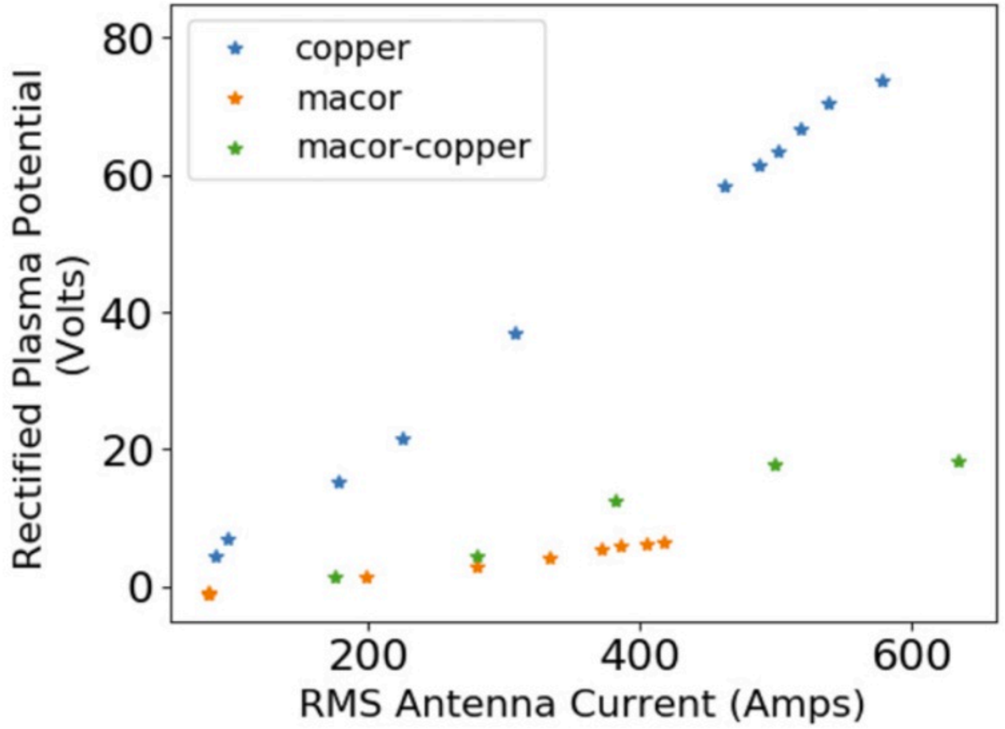


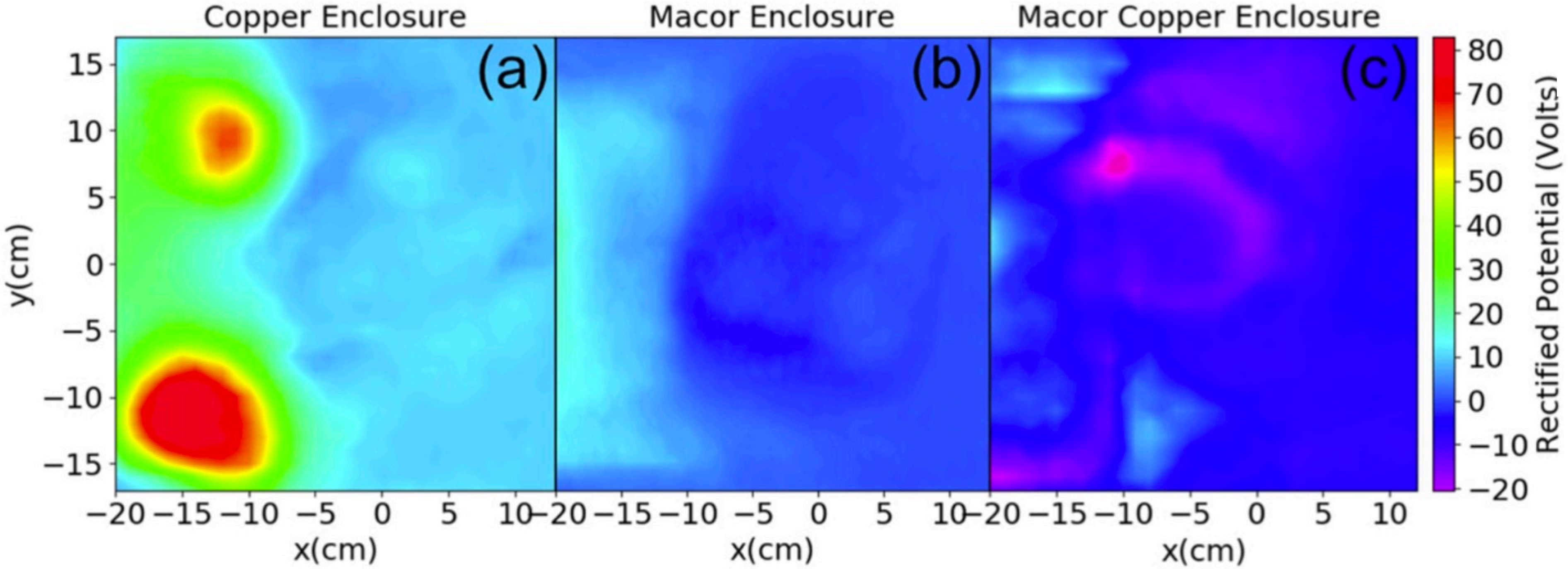
- Copper coatings on probes following high-power RF run: sputtering from copper antenna enclosure

Colors: Ion saturation current ~ density
Vectors: ExB flow, deduced from V_p

Insulating antenna sidewalls mitigate RF sheath



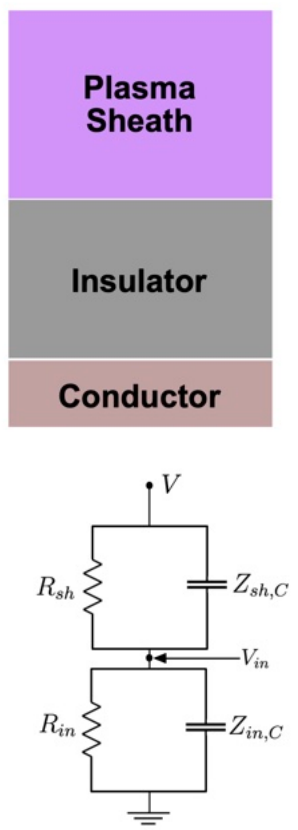


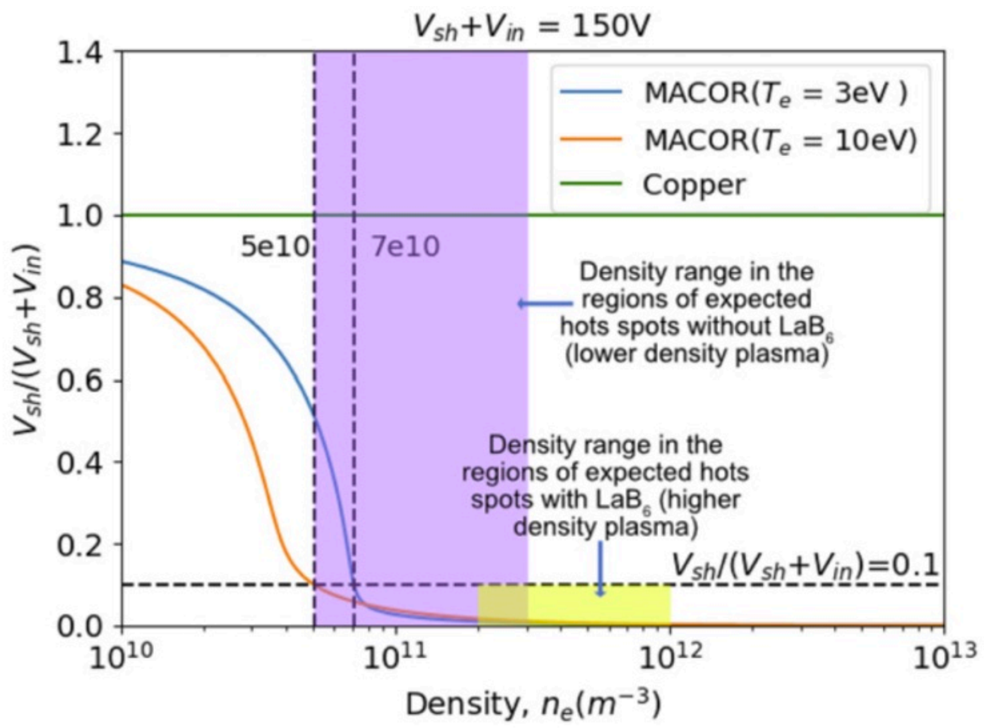


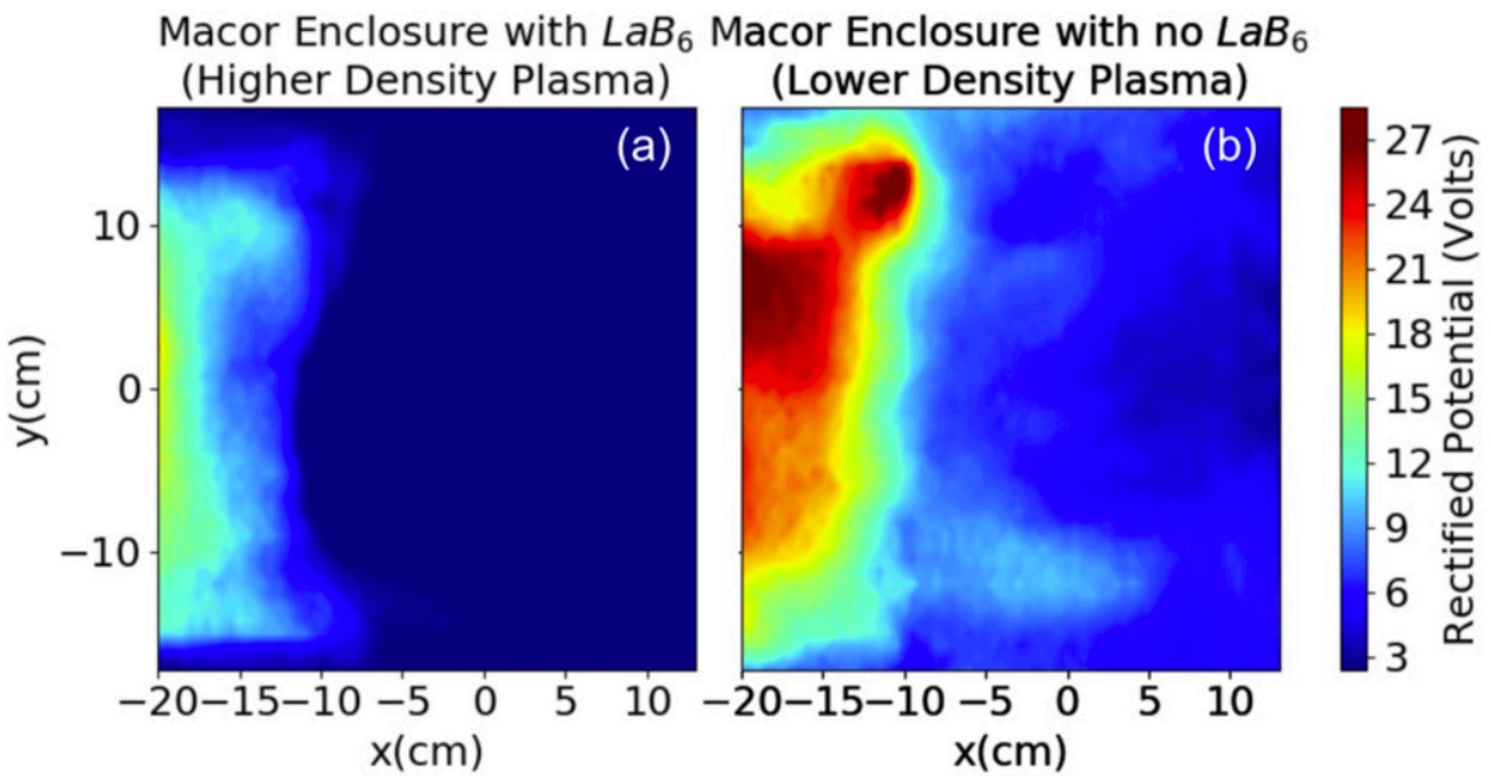
G. Bal, NF 62 086043 (2022)

Consistent with Phaedrus-T results (Majeski)

Mitigation consistent with model predictions







- Myra/D'Ippolito model: Insulator effectively forms voltage divider with plasma sheath. RF Sheath mitigation when insulator impedance is much larger than plasma sheath impedance

- Increased RF rectification seen in lower-density plasmas, consistent with model