Impurity Ion Temperature and Flow Dynamics During Local Helicity Injection on the Pegasus Toroidal Experiment

M.G. Burke, E.T. Hinson, J.L. Barr, J.M. Perry, R.J. Fonck



University of Wisconsin-Madison

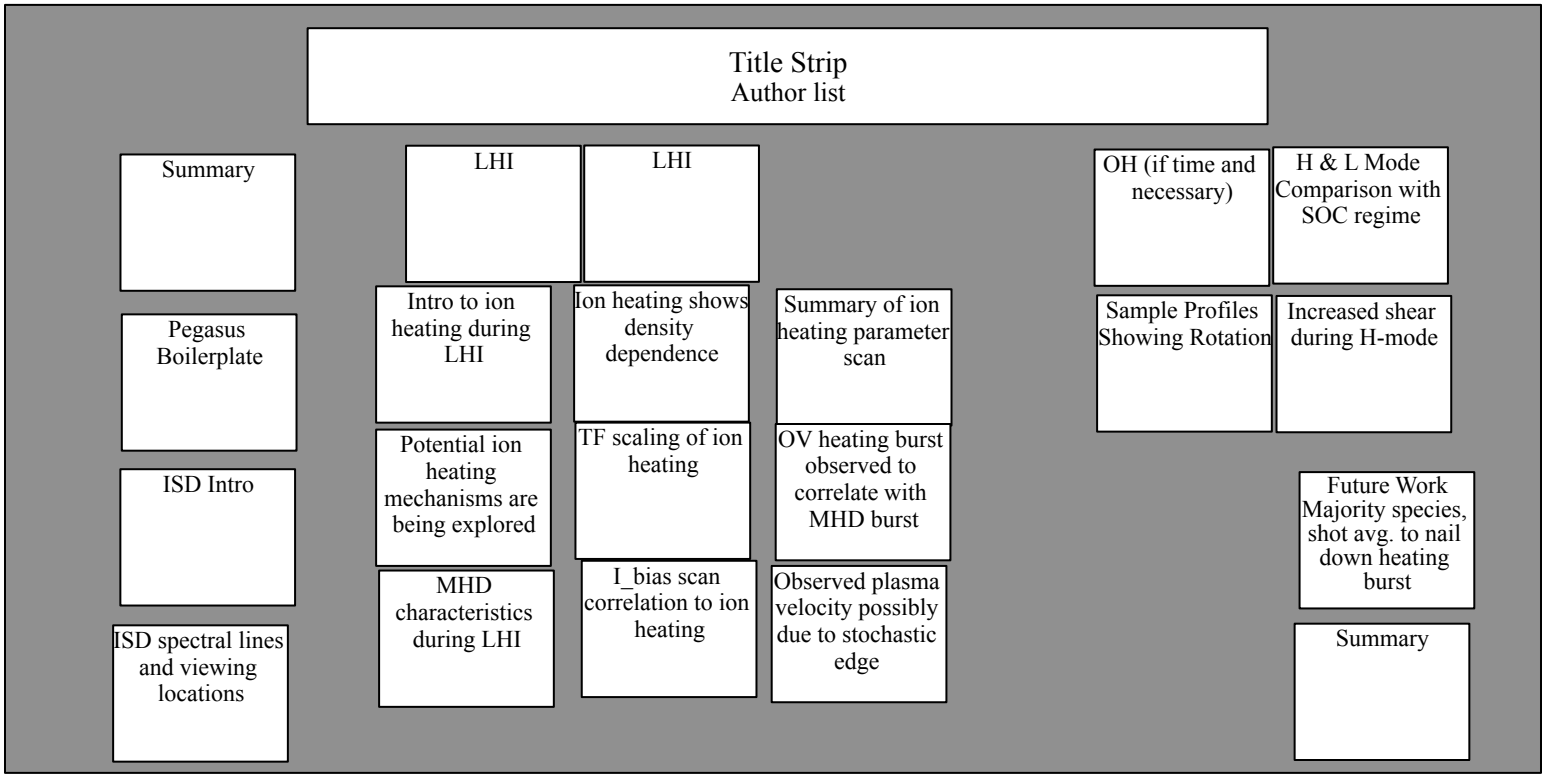
56th Annual APS-DPP

Poster
New Orleans, LA
Date



PEGASUS Toroidal Experiment

Layout

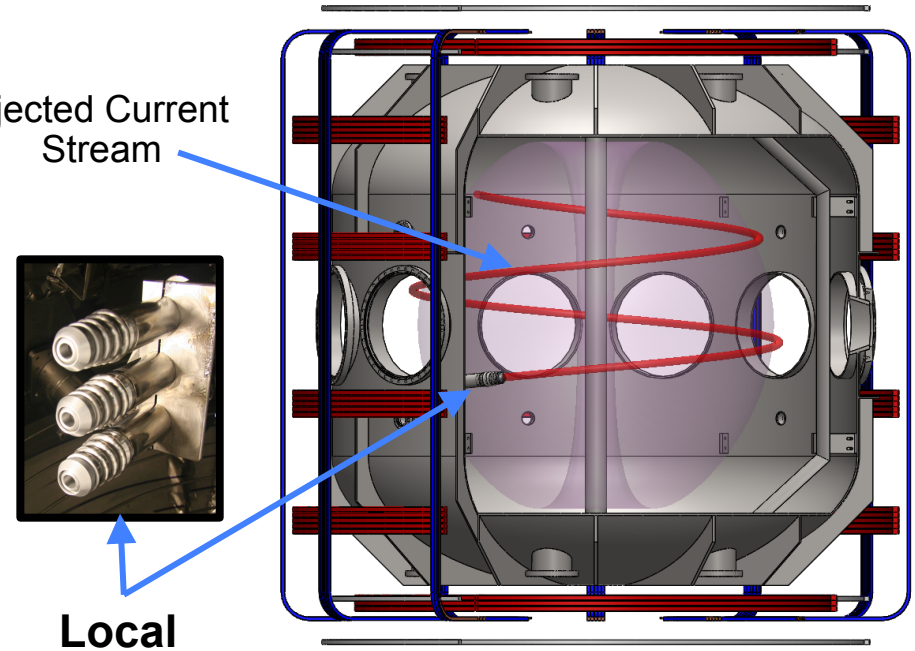

Title Strip
Author list
Summary
Pegasus Boilerplate
ISD Intro
ISD spectral lines and viewing locations
LHI
LHI
Intro to ion heating during LHI
Ion heating shows density dependence
Summary of ion heating parameter scan
Potential ion heating mechanisms are being explored
TF scaling of ion heating
OV heating burst observed to correlate with MHD burst
MHD characteristics during LHI
I_bias scan correlation to ion heating
Observed plasma velocity possibly due to stochastic edge
OH (if time and necessary)
H & L Mode Comparison with SOC regime
Sample Profiles Showing Rotation
Increased shear during H-mode
Future Work Majority species, shot avg. to nail down heating burst
Summary

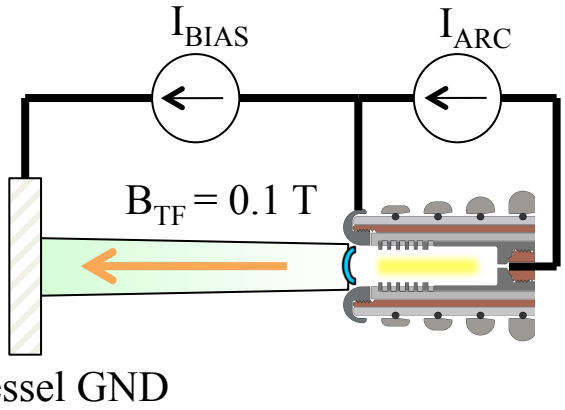
Summary

- Anomalous ion heating is observed during local helicity injection (LHI) current drive at the Pegasus ST
- This heating has been correlated with large bursts of MHD activity thought to be signatures of magnetic reconnection
- Plasma parameters were broadly varied to investigate various anomalous ion heating mechanisms
- During LHI current drive, plasma were found to rotate in the counter-I_p
- A stochasticization of the inner plasma edge is invoked to explain the direction of the plasma rotation

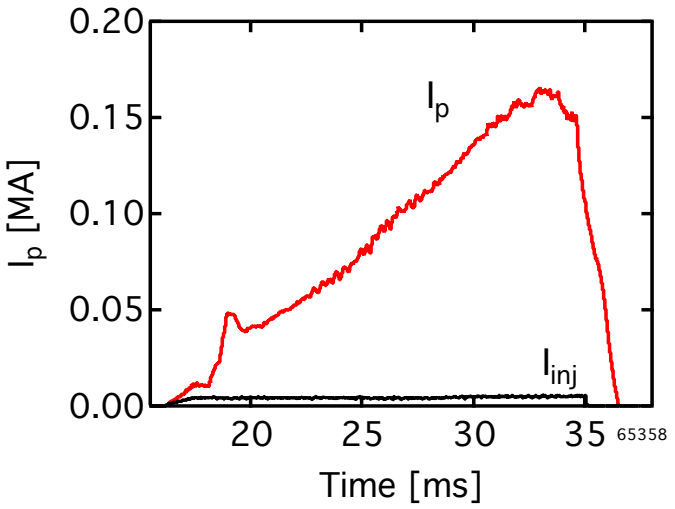
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Outboard LHI Provides Robust Startup on the PEGASUS ST





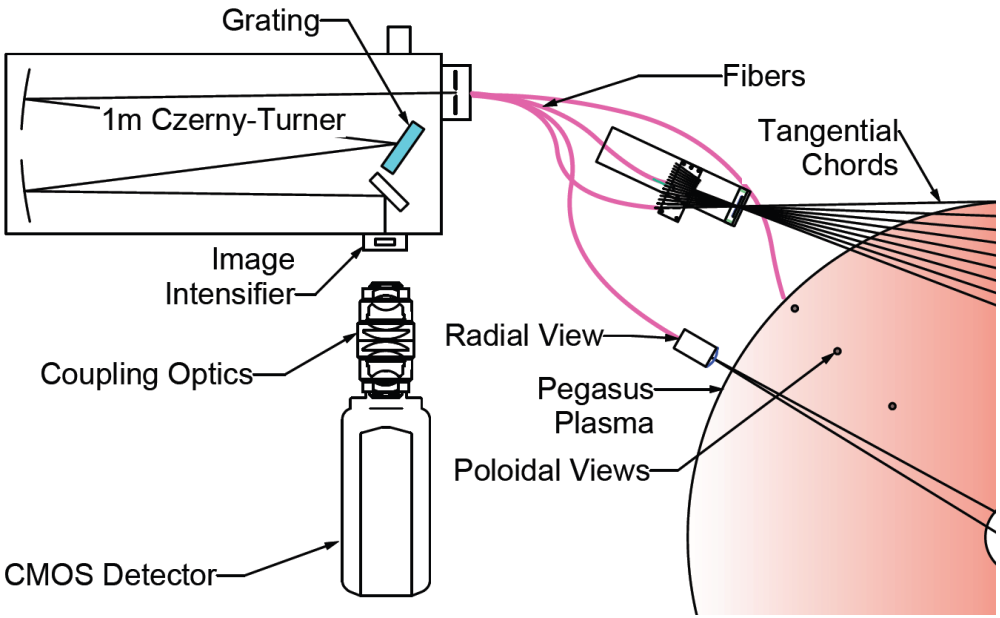
$I_p \leq 0.18$ MA via LHI ($I_{inj} = 5$ kA)

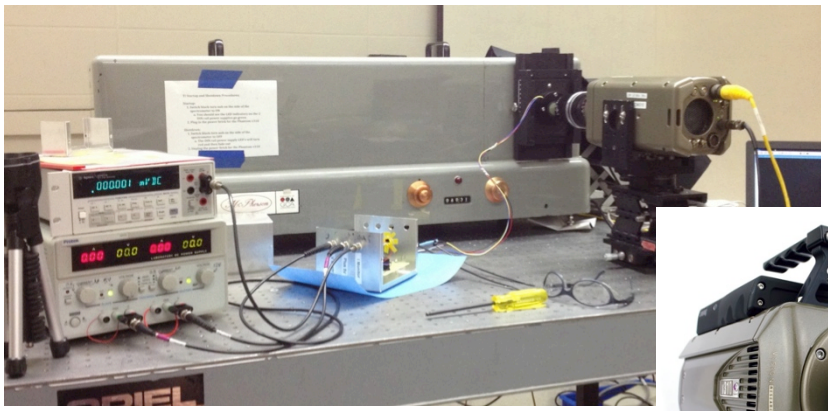


Plasma Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 14 kA
τ_{shot}	≤ 0.025 s	I_{inj}	≤ 2 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	$= 2$ cm^2
a	≤ 0.4 m	I_{arc}	≤ 2 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

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Ion Spectroscopy Diagnostic Deployed to Study Local Helicity Injection on Pegasus







M. G. Burke, *et al.*, Rev. Sci. Instrum. 83, 10D516 (2012)

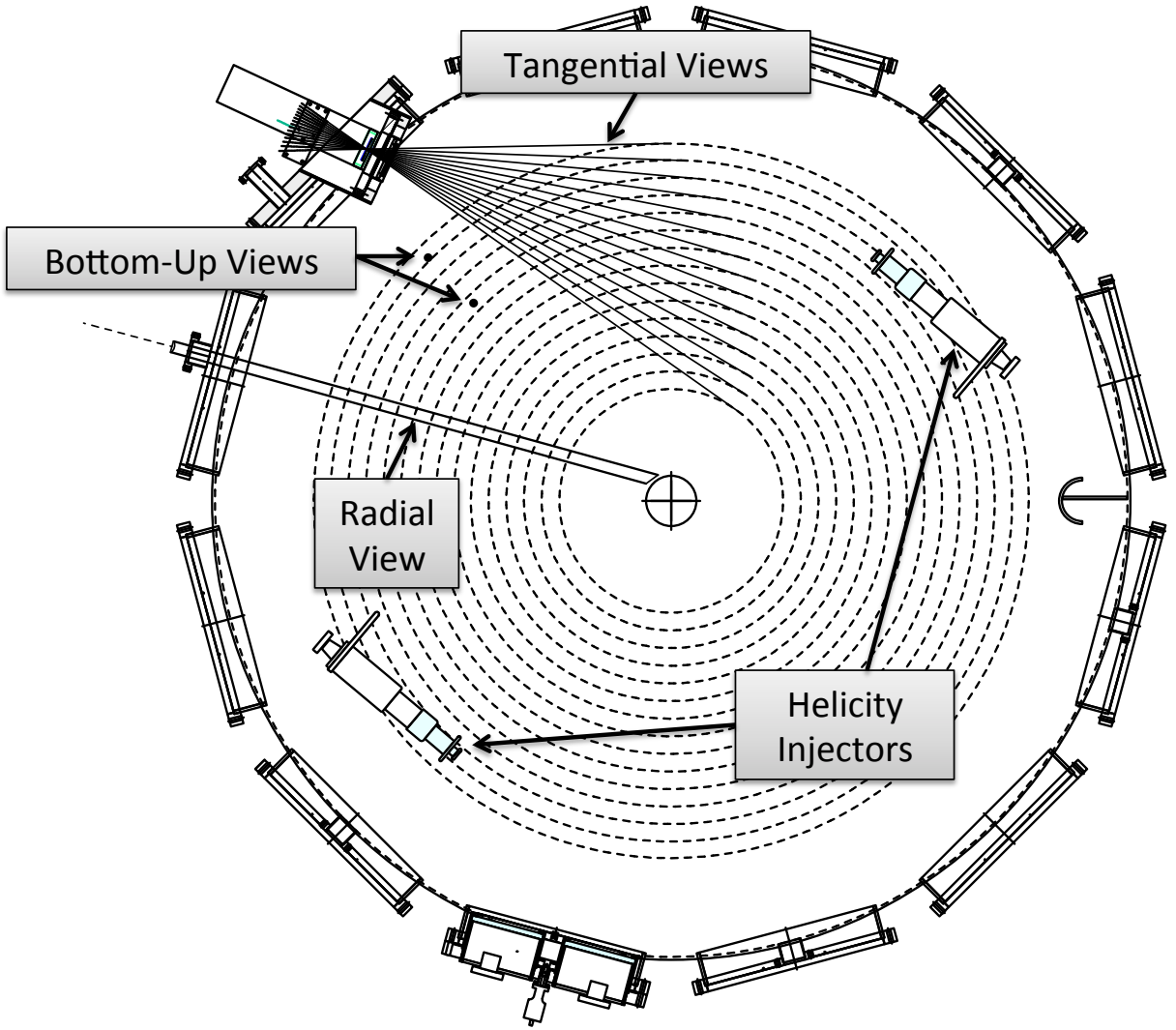
Diagnostic Characteristics:

- **Spectrometer:** UV 1m f/8.6 Czerny-Turner, 1200 g/mm blazed @ 1 um
- **Spectral Range:** 200 – 800 nm
- **Spectral Resolution:** 0.13 Å
- **Total etendue:** 8×10^{-4} cm^2-str @ 0.1 mm slit
- **Detector:** UV Intensified Fast CMOS (Phantom v310)
  - Flexible frame rate: 1-500 kHz
  - Max Time resolution: 1 MHz

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LHI Plasmas Studied Using Multiple Viewing Chords

- 19x 1mm Quartz fibers used for collection
- Tangential viewing chords cover R = 25 to 80 cm with 4 cm resolution
- Poloidal views at R = 80 and 65 cm
- Single radial chord
- All chords recorded simultaneously with the possibility of adding additional fibers to increase SNR



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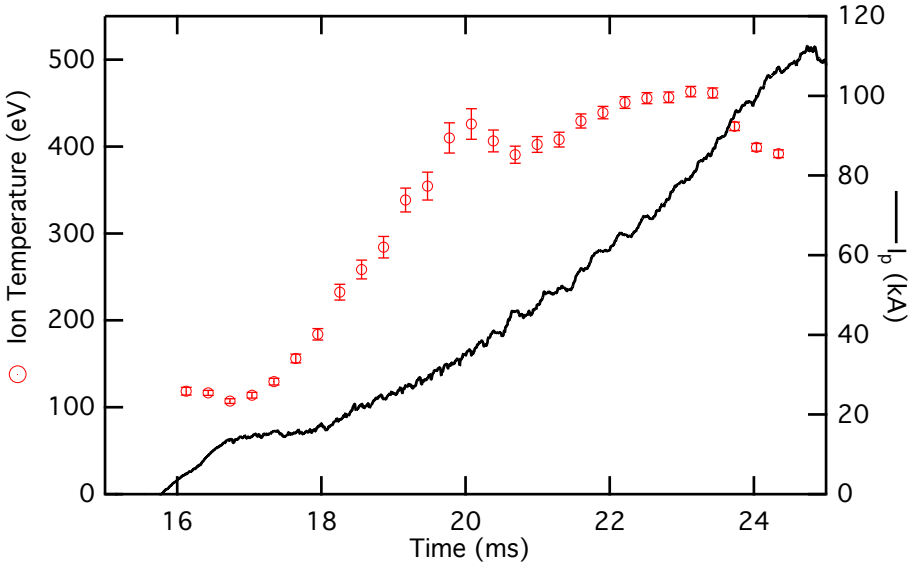
Ion Heating During Local Helicity Injection

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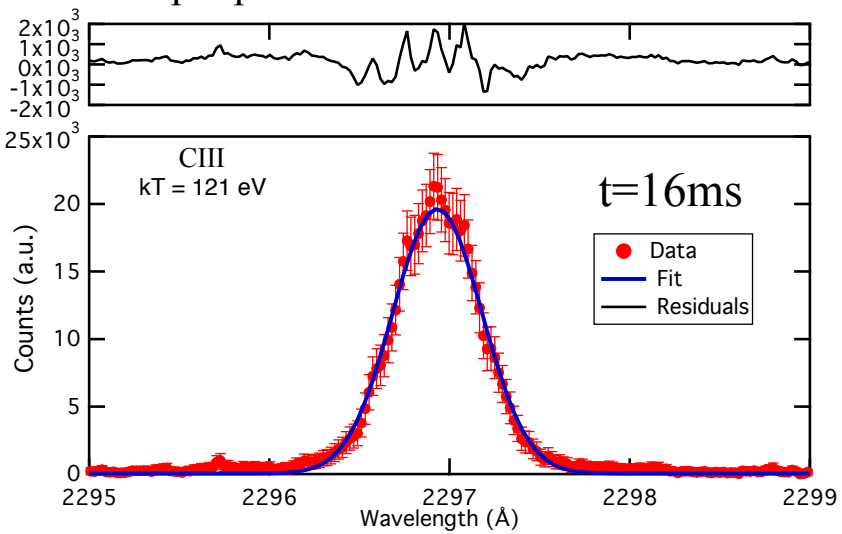


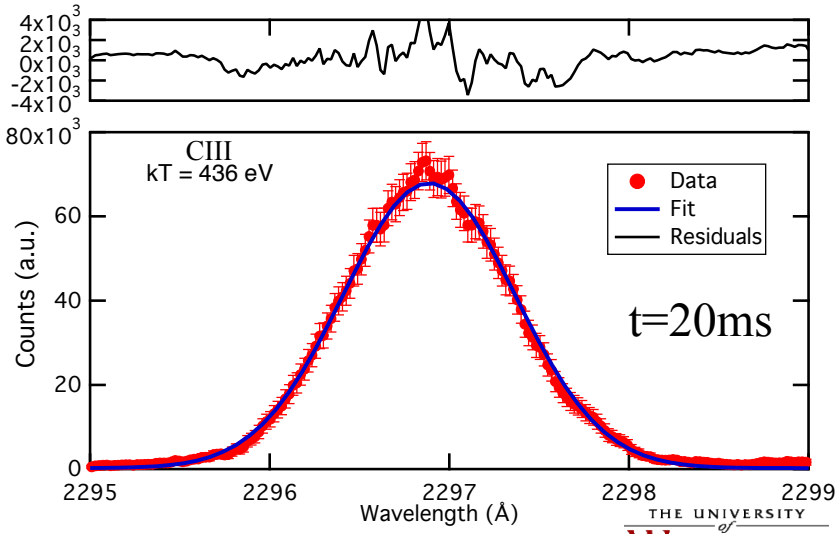
Overview: Sustained T_i ~500 eV while T_e~70 eV during Local Helicity Injection

- Strong broadening of CIII 2296 Å line observed on radial chord during LHI discharges
- Broadening also observed on OV, HeII, and NIII lines
- Ion Heating is considered anomalous in that $T_i >> T_e$ during LHI



Sample profiles:

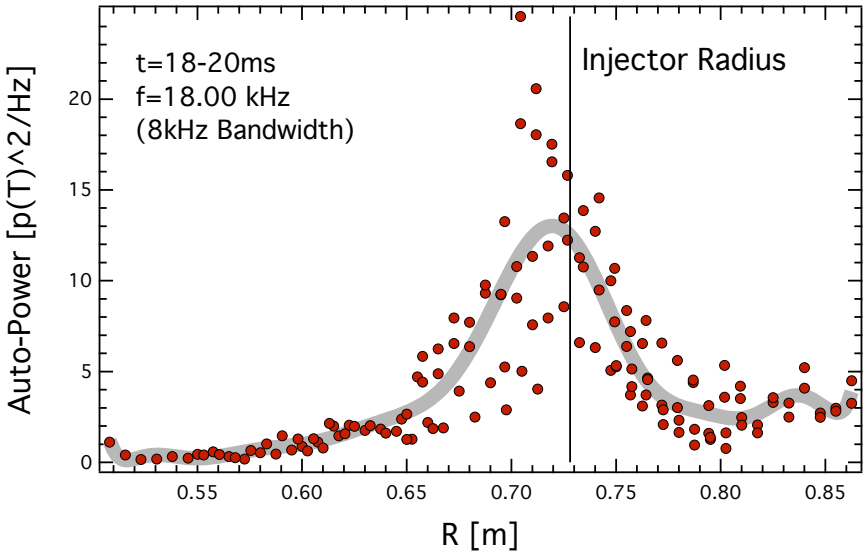


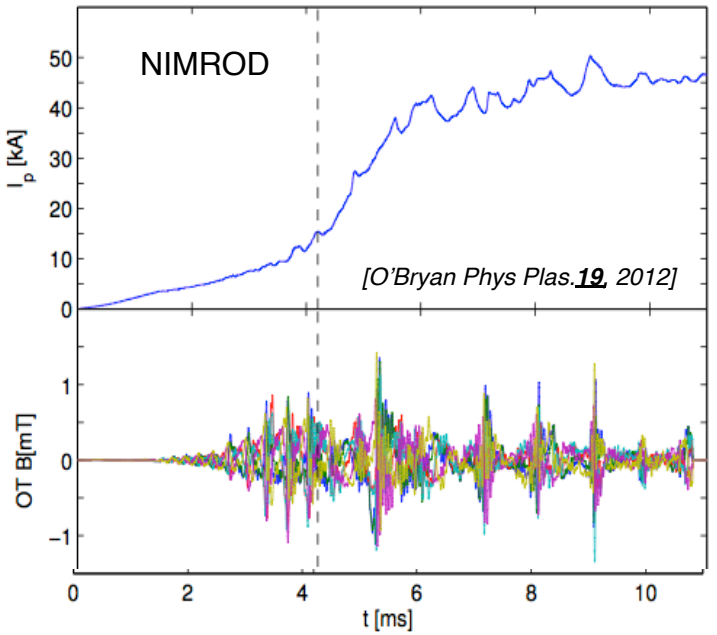


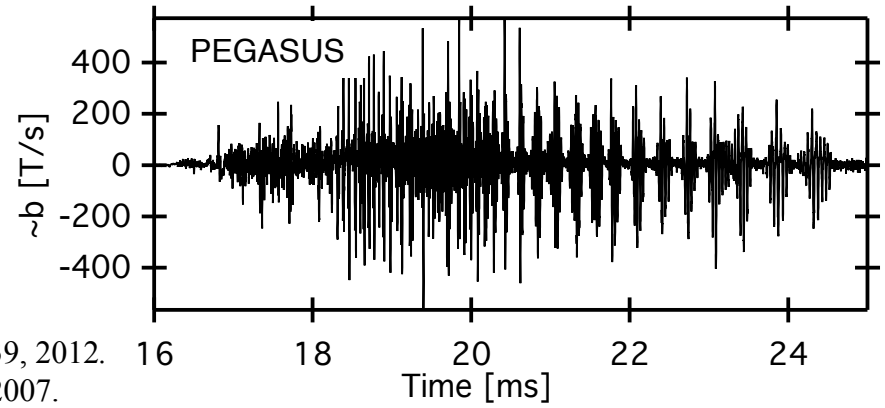
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Overview: NIMROD Simulations of LHI on Pegasus Show Magnetic Reconnection Activity and Bursty MHD

- Anomalous ion heating observed during magnetic reconnection in numerous devices (MRX*, TS-3**, SSX***, HIT-II****, MST*****)
- MHD localized near injectors







*S. C. Hsu *et al.*, Phys. Plasmas, vol. 8, no. 5, pp. 1916–1928, 2001.
**Y. Ono *et al.*, Plasma Phys. Control. Fusion, vol. 54, no. 12, p. 124039, 2012.
***M. R. Brown, *et al.*, J Fusion Energ, vol. 27, no. 1, pp. 16–19, Jul. 2007.
****R. G. O'Neill *et al.*, Phys. Plasmas, vol. 12, no. 12, p. 122506, 2005.
*****R. Magee *et al.*, Phys. Rev. Lett., vol. 107, no. 6, p. 065005, 2011.

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Overview: Several Theoretical Ion Heating Mechanisms are Being Explored

- Ion cyclotron resonance damping of magnetic fluctuations

  Important predictions: $\frac{dT_i}{dt} \propto \frac{Z^2}{\mu}\tilde{B}^2(\omega_{ci})$ $T_{i,\perp} \neq T_{i,\parallel}$ [Tangri, PoP, 2008]

- Stochastic diffusion of ions through strong E_r

  Important predictions: $\frac{dT}{dt} \propto \frac{E_r^2 D_\perp}{\delta_r^2 B_0^2 v_{Ti}^2}$ $D_\perp \propto m_i^{-1/2}$ $T_{i,\perp} \neq T_{i,\parallel}$ [Fiksel, PRL, 2009]

- Viscous damping of reconnection outflows

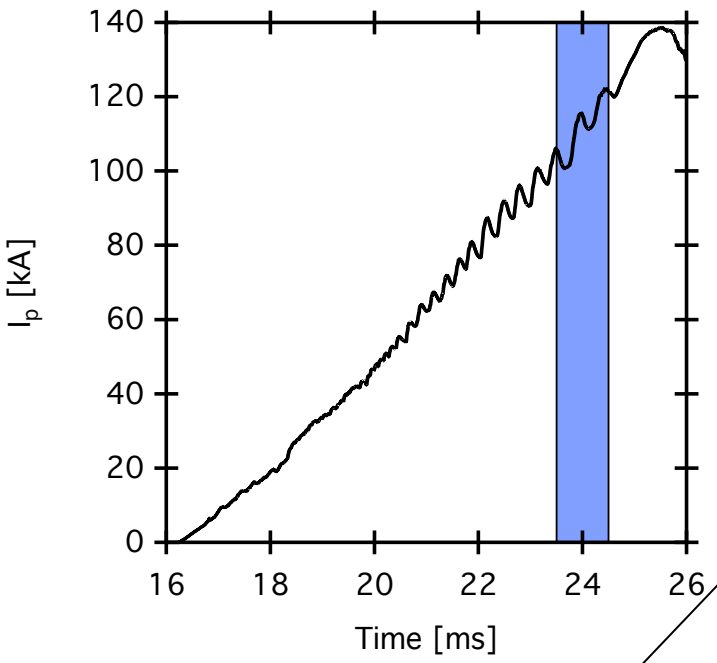
  Important predictions: $Q_{vis} = \eta_\perp \left(\frac{\partial v_y}{\partial x}\right)^2$ $\eta_\perp = \frac{3}{10}\frac{n_i T_i}{\omega_{ci}^2 \tau_{ii}}$ $\tau_{ii} \propto \left(\frac{m_i^2}{n_i Z^4 \ln\Lambda}\right)\left(1.3 v_{Thi}^3 + v_i^3\right)$ [Svidzinski, PoP, 2008]

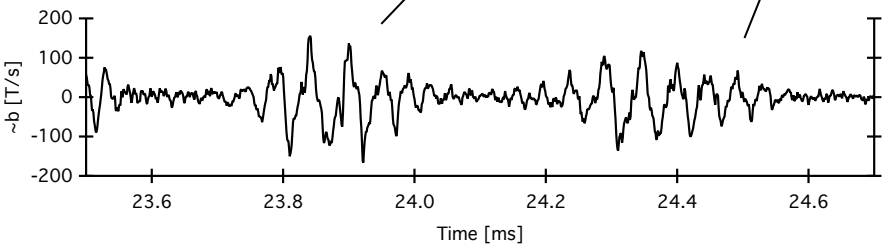
- Acceleration of ions through reconnection region

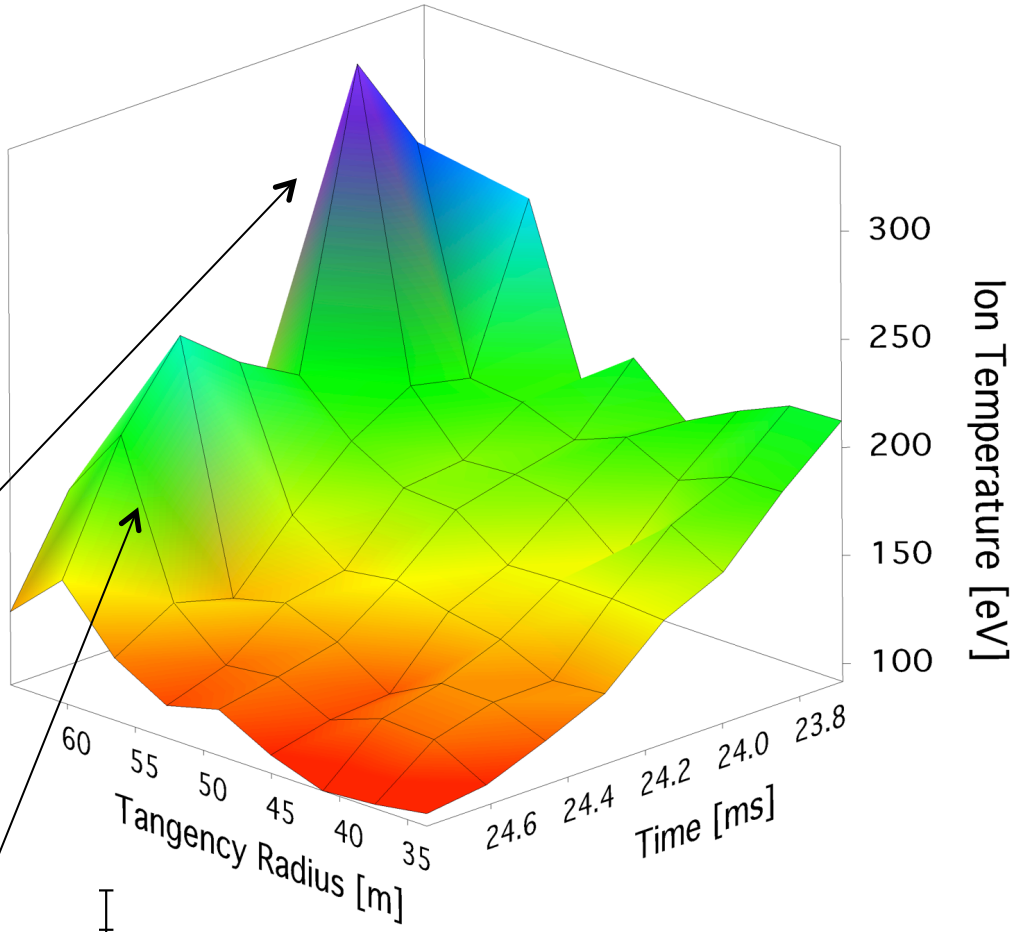
  Important predictions: $\Delta T_i \propto m_i v_A^2 \propto \frac{B_{rec}^2}{n_i}$ [Ono, Phys. Pla. Cont. Fus., 2012]

- Parameter scans needed to explore theoretical heating mechanisms

T_i Localization: Bursty MHD Observed to Correlate with Bursts in Edge OV T_i

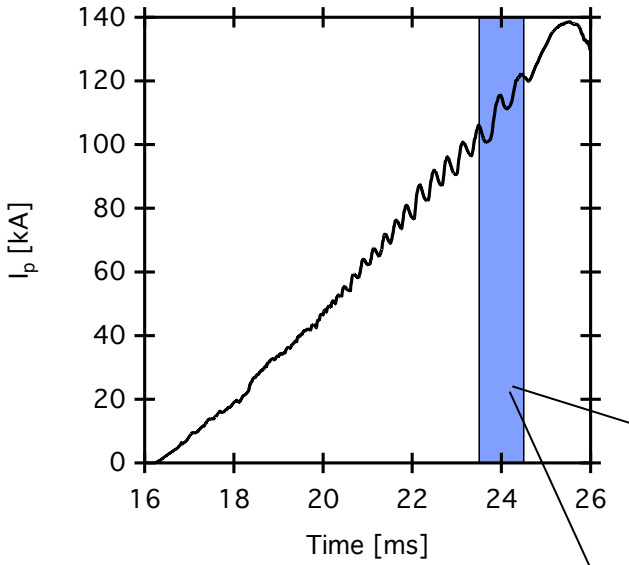


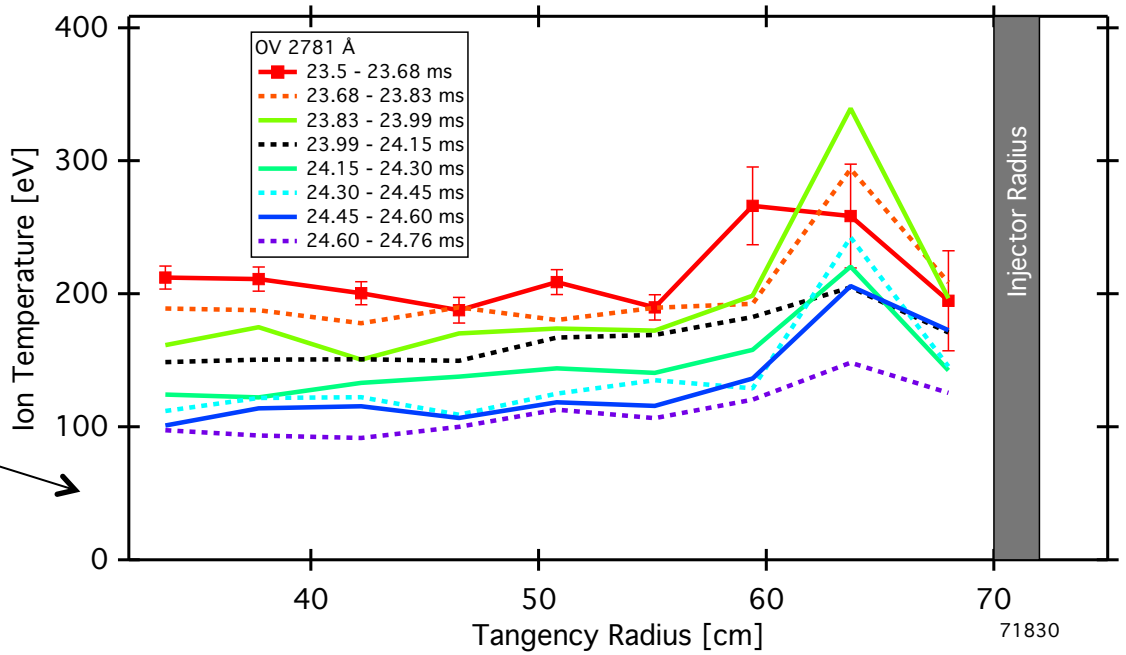


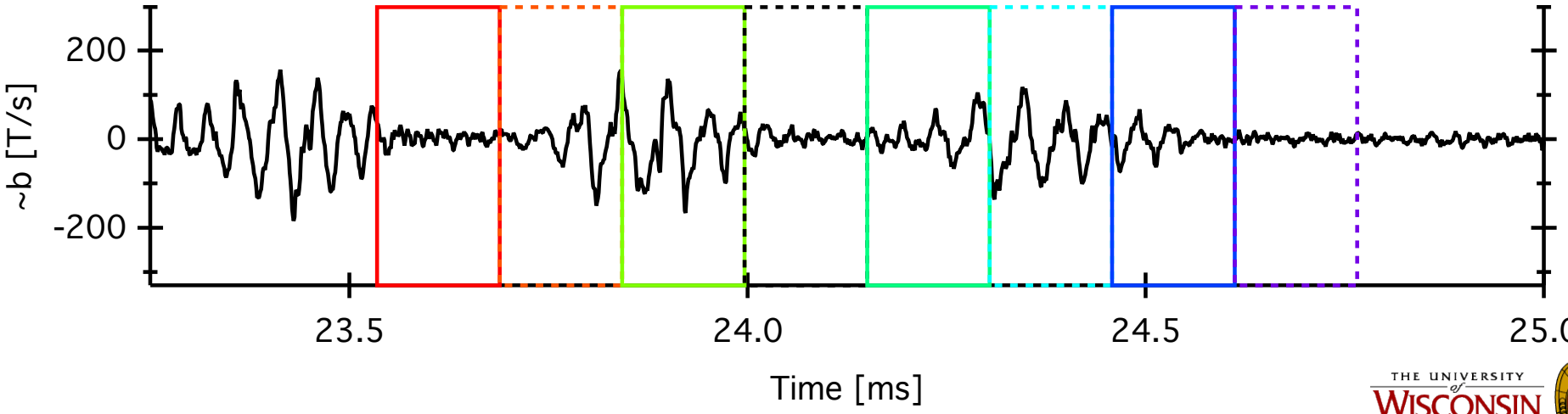


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T_i Localization: Bursty MHD Observed to Correlate with Bursts in Edge OV T_i

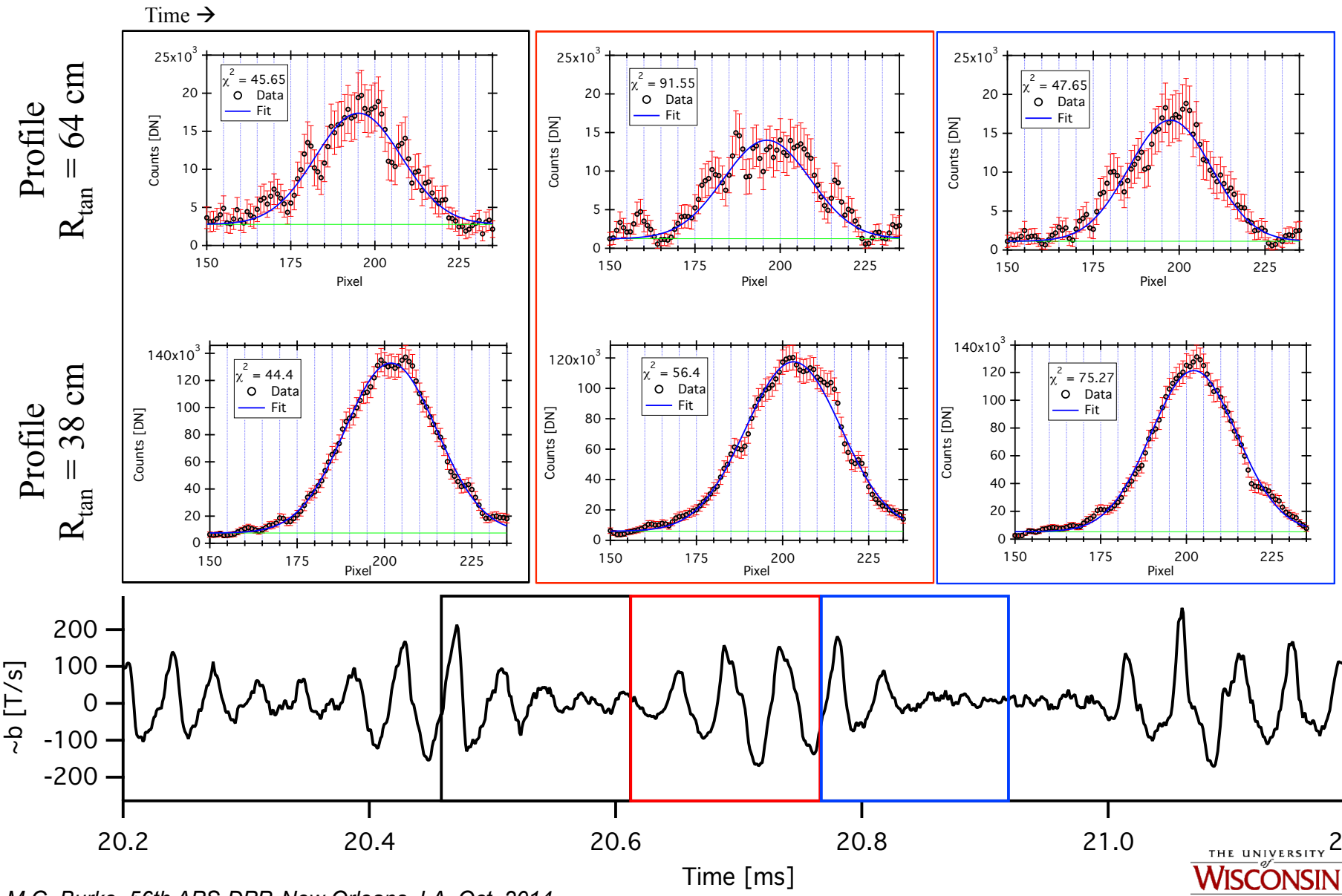






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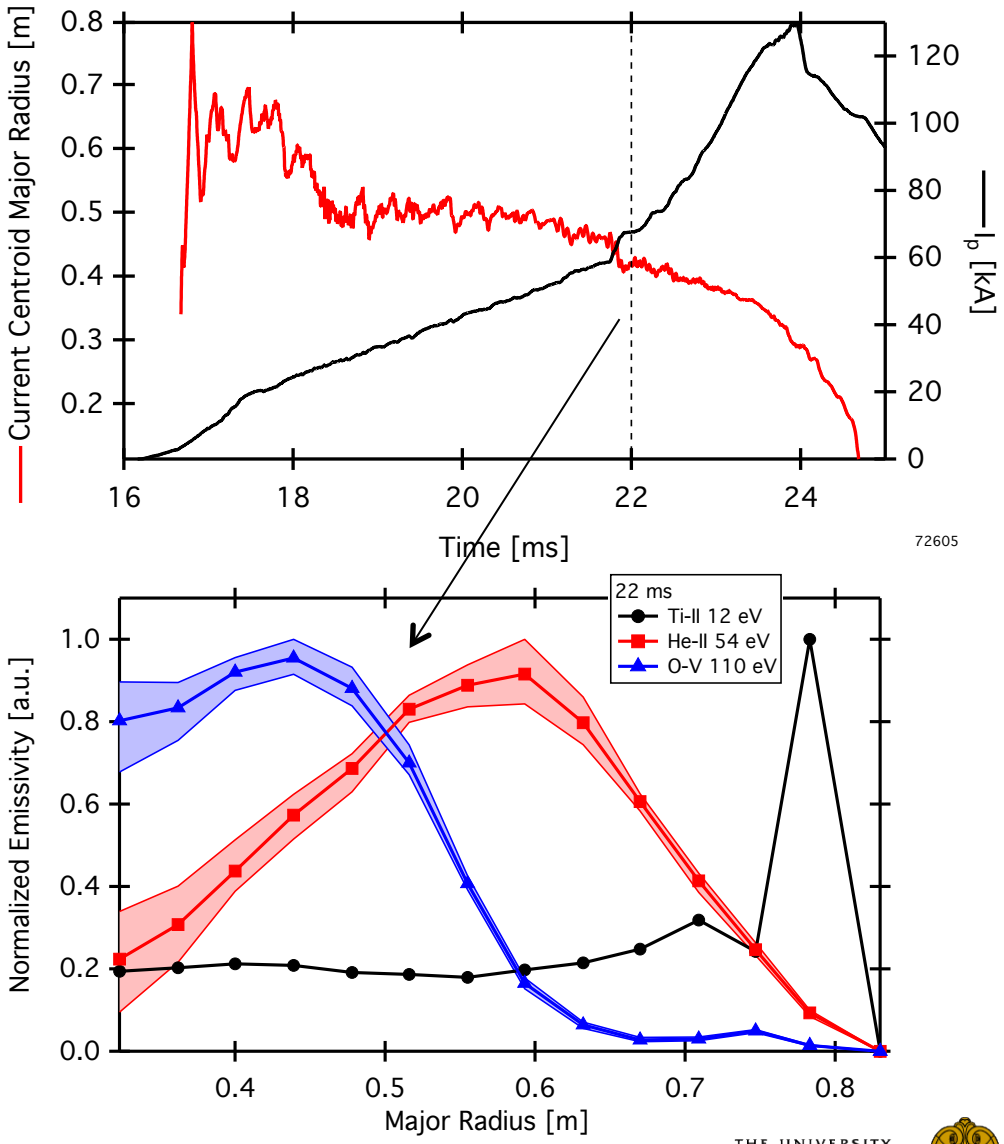
T_i Localization: During MHD Bursts, Ion Distribution Becomes Distorted from Gaussian, More so in Plasma Edge



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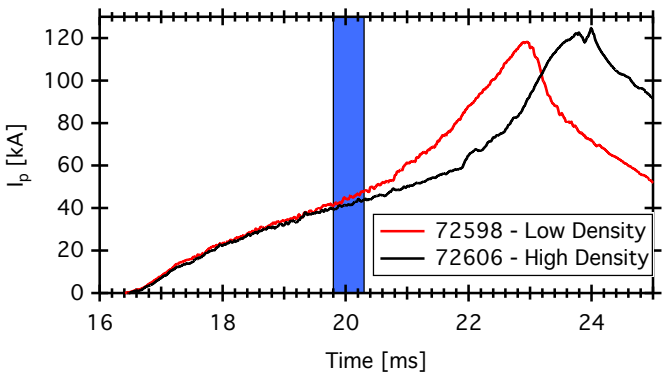
T_i Localization: Helium Injected into LHI Plasma Edge to Increase SNR

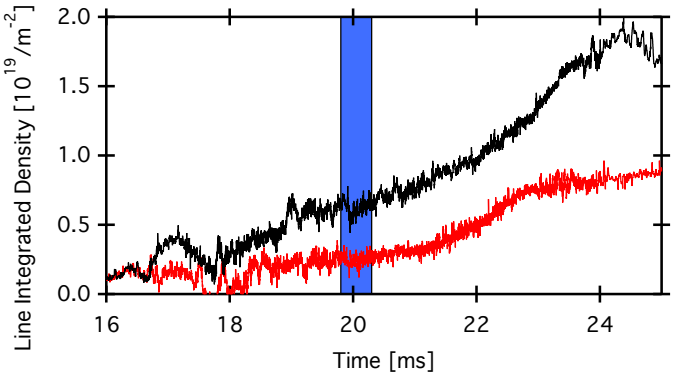
- Helium-II has 54 eV ionization potential, will be localized to plasma edge where MHD and injectors are located
- Emissivity reconstructions during LHI drive show a burn out of He-II charge state, similar to standard tokamak impurity charge state profiles
- Passive spectroscopy strategy: Use He injection to look for T_i bursts in plasma edge during plasma parameter scan

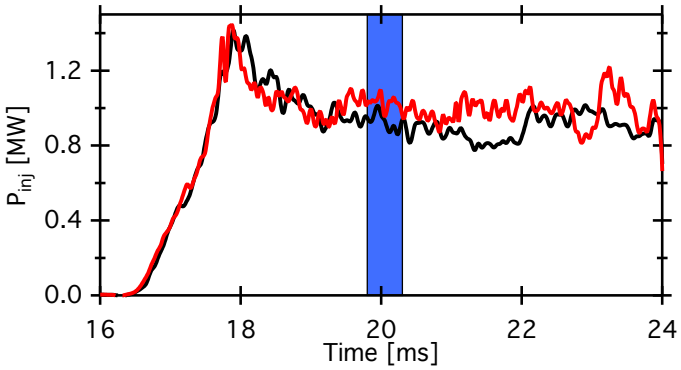


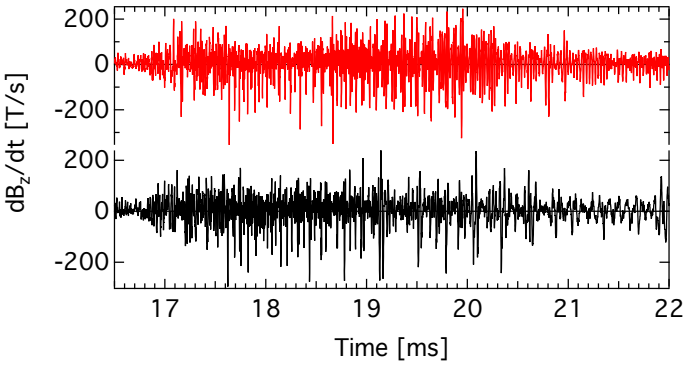
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n_e Scan: Several Plasma Parameters Varied Independently in Order to Evaluate Heating Theories







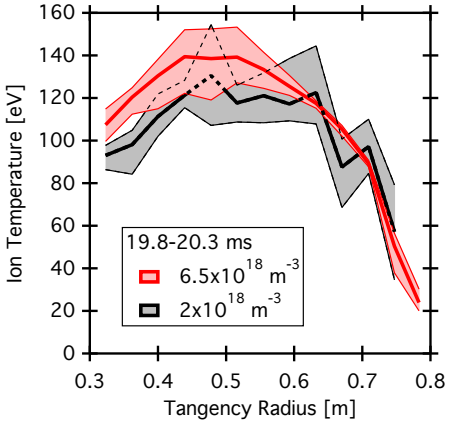


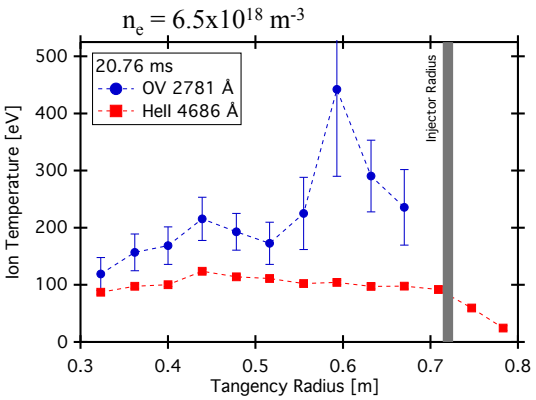
- Shaded areas indicate regions where He-II and O-V profiles were examined
- Plasma density increased by ~x3
- Ion heating due to viscous damping of reconnection outflows contains ion density dependence → flow profiles to be analyzed

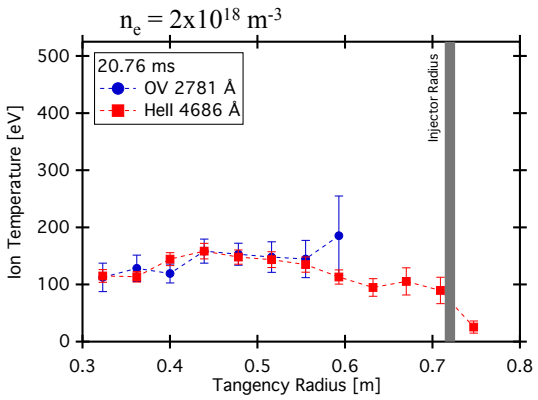
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n_e Scan: At high plasma density, heavier impurities receive more thermal energy

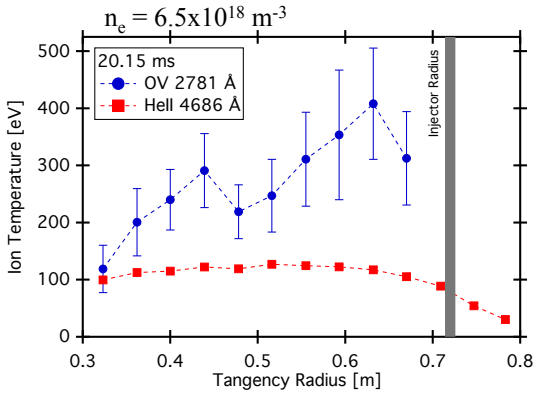
- T_{HeII} independent of n_e, T_{OV} is peaked in the edge, at high density T_{OV} ~2-4xT_{HeII}

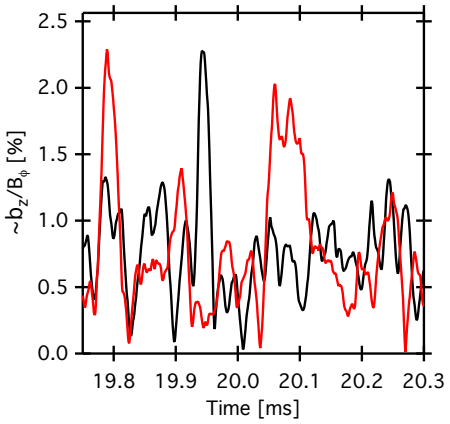






- ICRH implications: OV Z^2/μ~1, HeII Z^2/μ~0.25, f_{ci}~570 kHz @ 0.15 T for both species. This implicates ICRH as a possible mechanism for ion heating during LHI with the added wrinkle of a unforeseen plasma density dependence



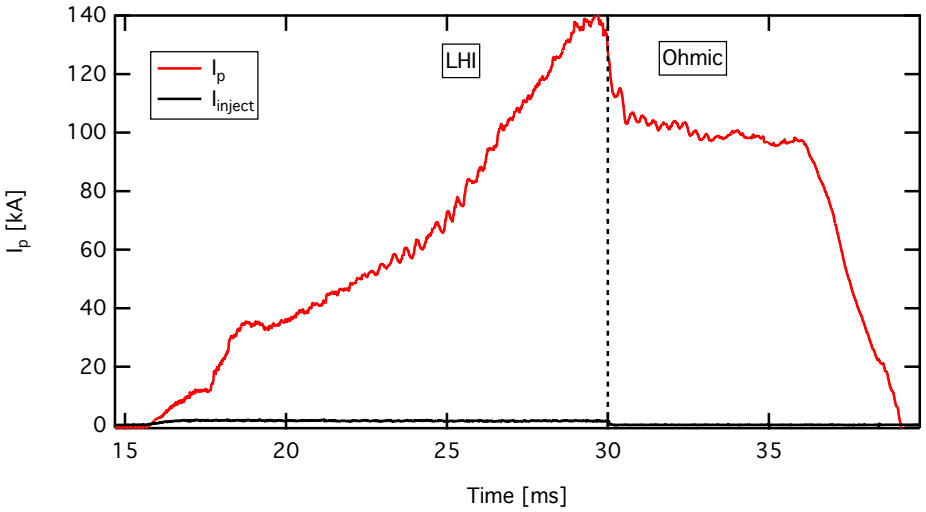


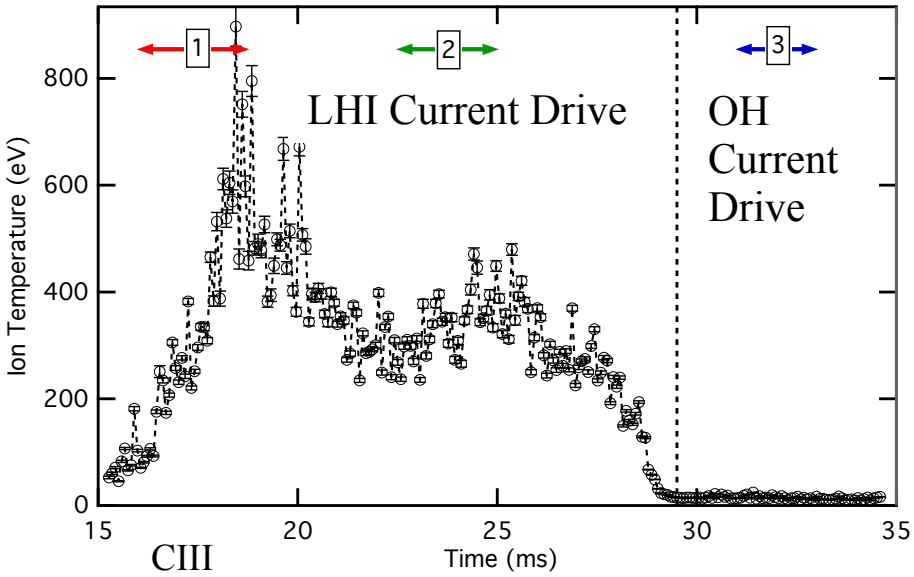
*Similar MHD activity in both discharges

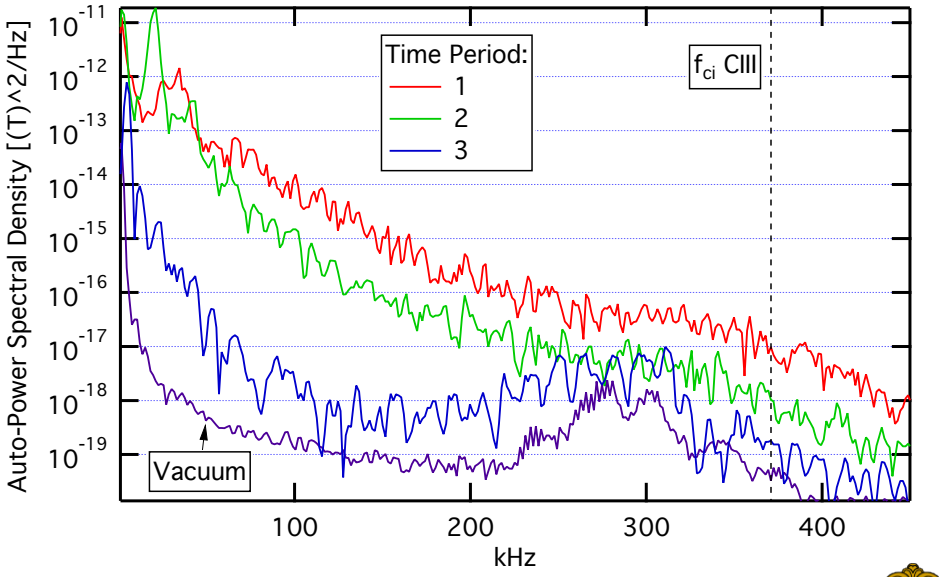
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ICRH: LHI Discharges Contain High Spectral Power Density at $f_{c,CIII}$ Temporally Correlated with High T_{CIII}

- During periods of rapid ion heating the spectral power density at the ion cyclotron frequency is highest
- Ohmic and vacuum fluctuations are many orders of magnitude lower

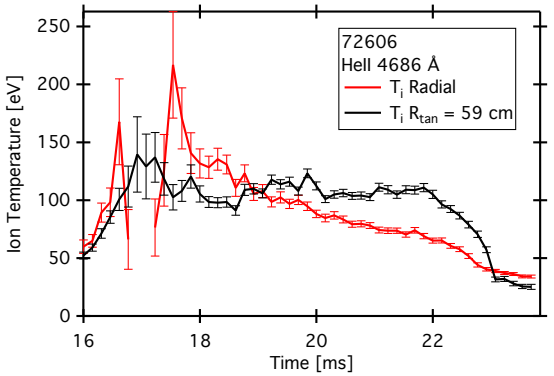


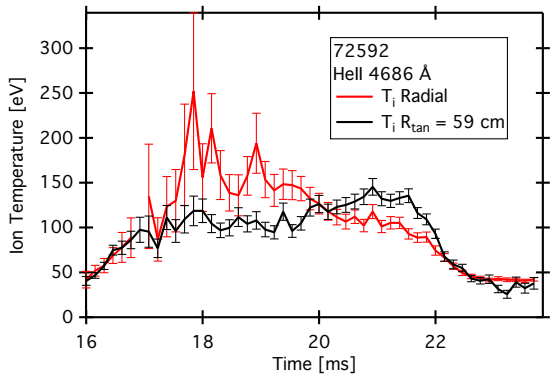


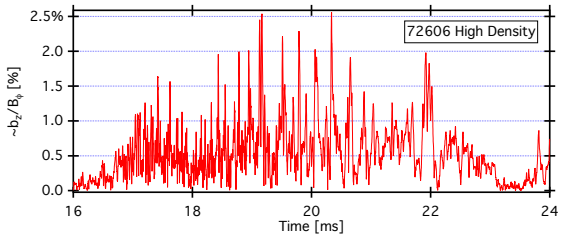


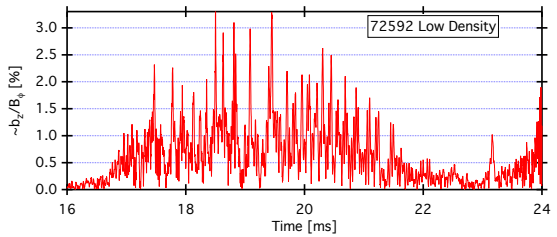
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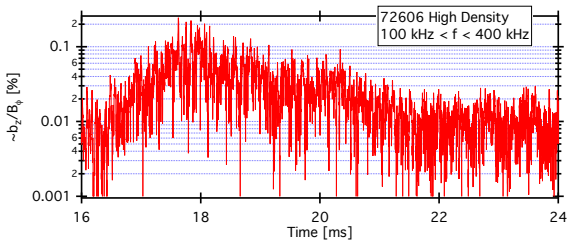
ICRH: $T_\perp > T_{||}$ When High Frequency Magnetic Fluctuations are Largest

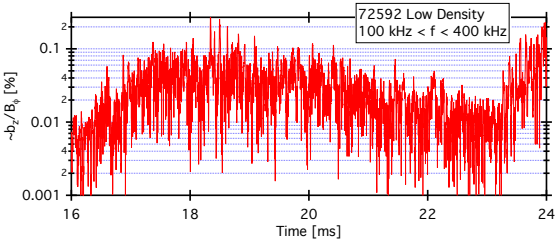










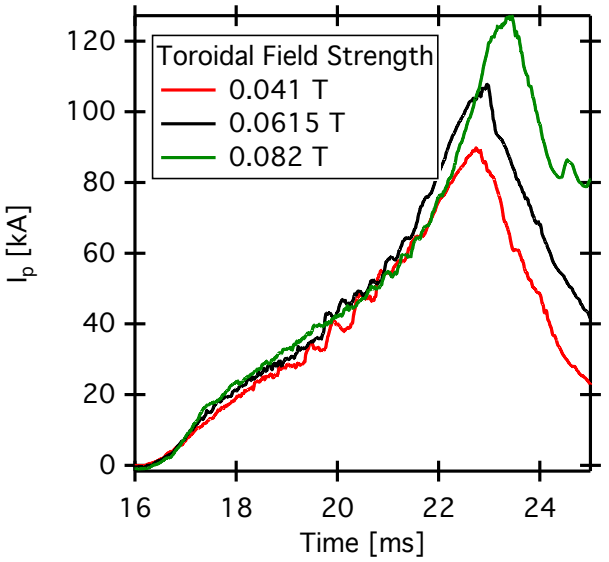


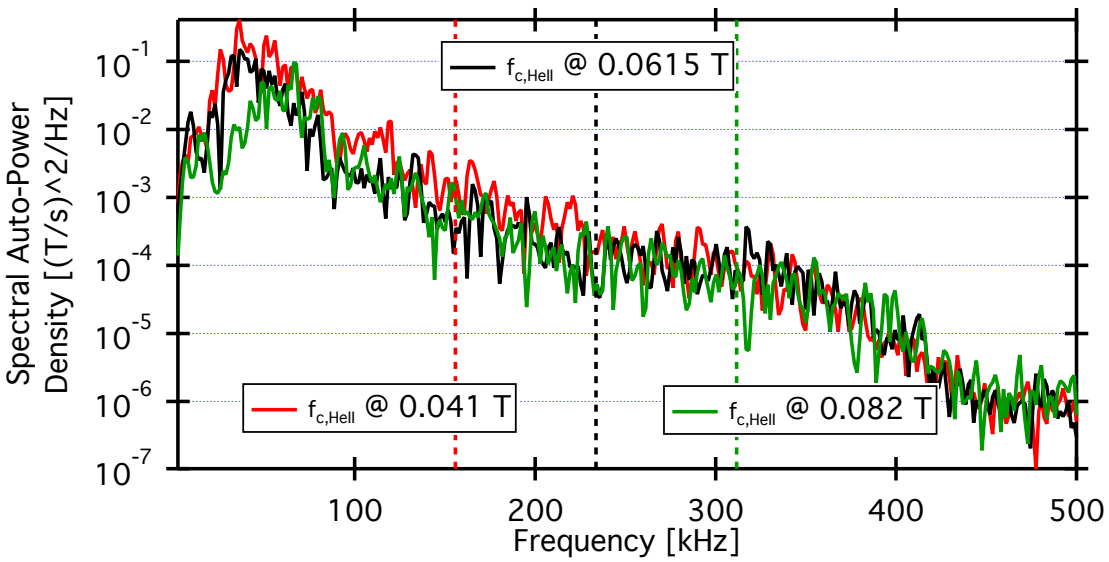
- Suggests heating is anisotropic, a prediction of many of the theoretical ion heating models currently under investigation

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TF Scan: Toroidal Field Varied to Change the Spectral Power Density at f_{ci}

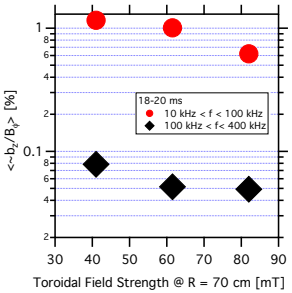
- Toroidal field strength changed by a factor of 2





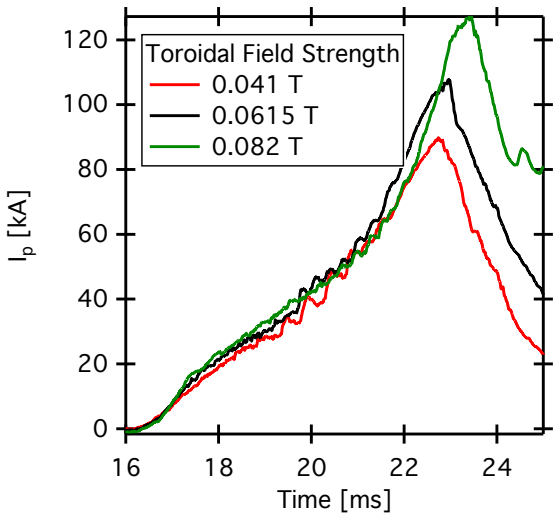
- ICRH heating theory strongly depends on fluctuation amplitude at f_{ci}, therefor large changes in the TF should lead to large changes in $\tilde{B}^2(\omega_{ci})$

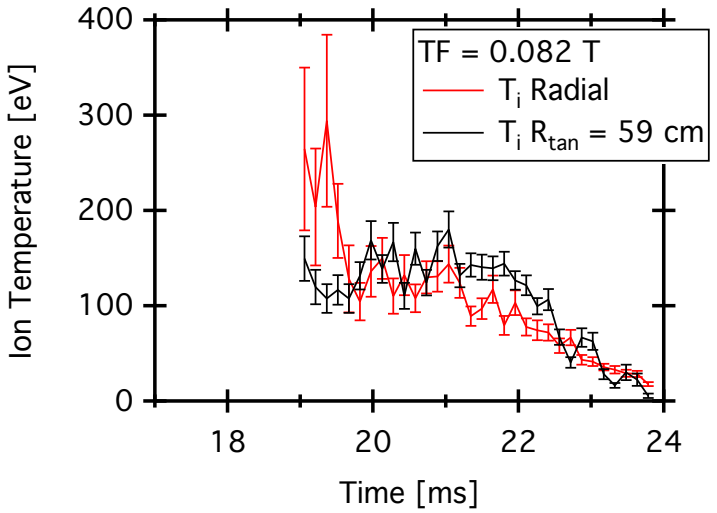
- $<\sim b_z/B_\phi>$ decreases with TF →

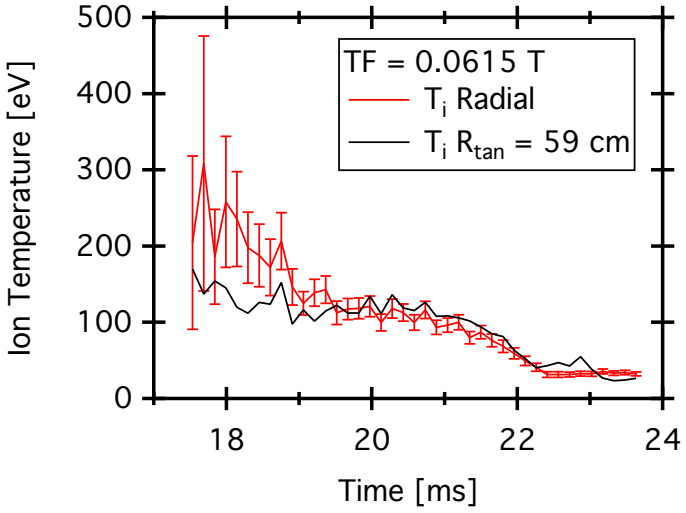


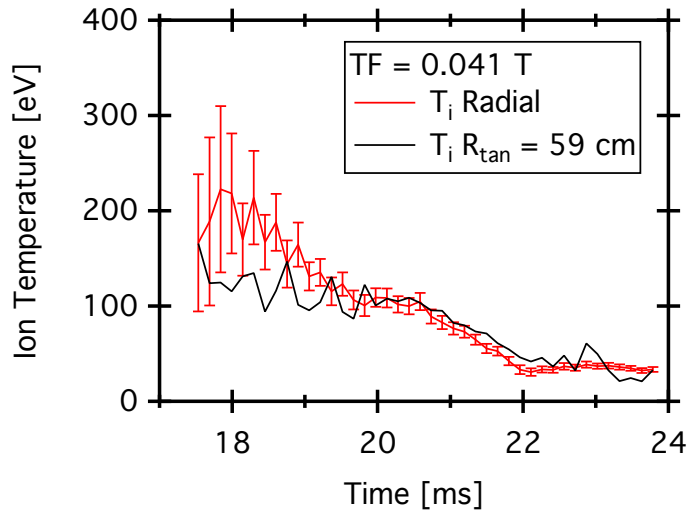
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TF Scan: He-II Temperature not Affected by Large Changes in Toroidal Field Strength, $T_\perp > T_{||}$ observed





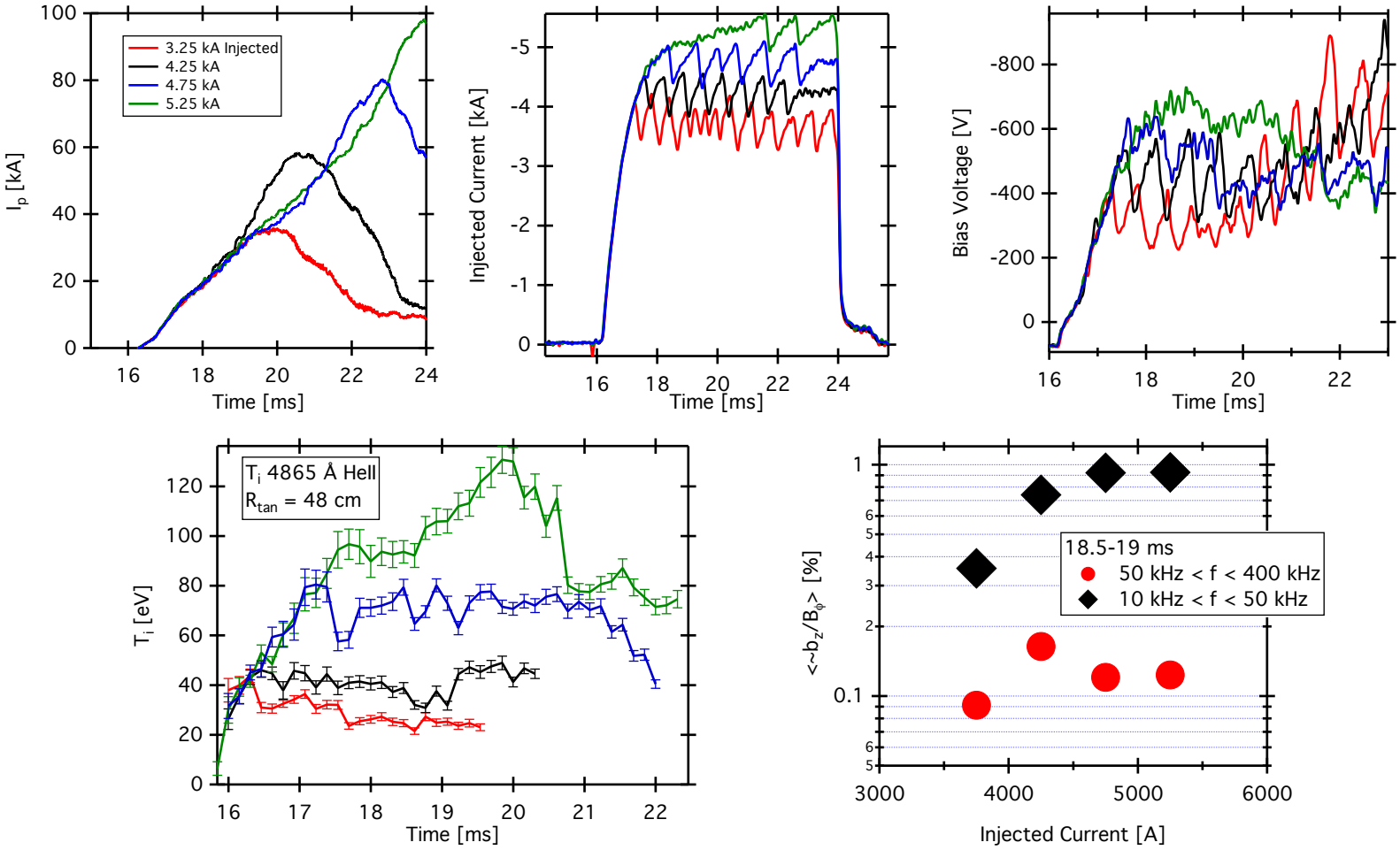




While some experimental results generally agree with ICRH predictions (Z^2/μ dependence and $T_\perp > T_{||}$), contradictory observations need investigation

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I_{inj} Scan: ~b Saturates, Heating Increases with Increasing I_{inj}



- Work on dedicated reconnection experiments suggests $\Delta T_i \sim B^2_{rec}$ and initial T_i data is strongly correlated with increasing I_{inj}

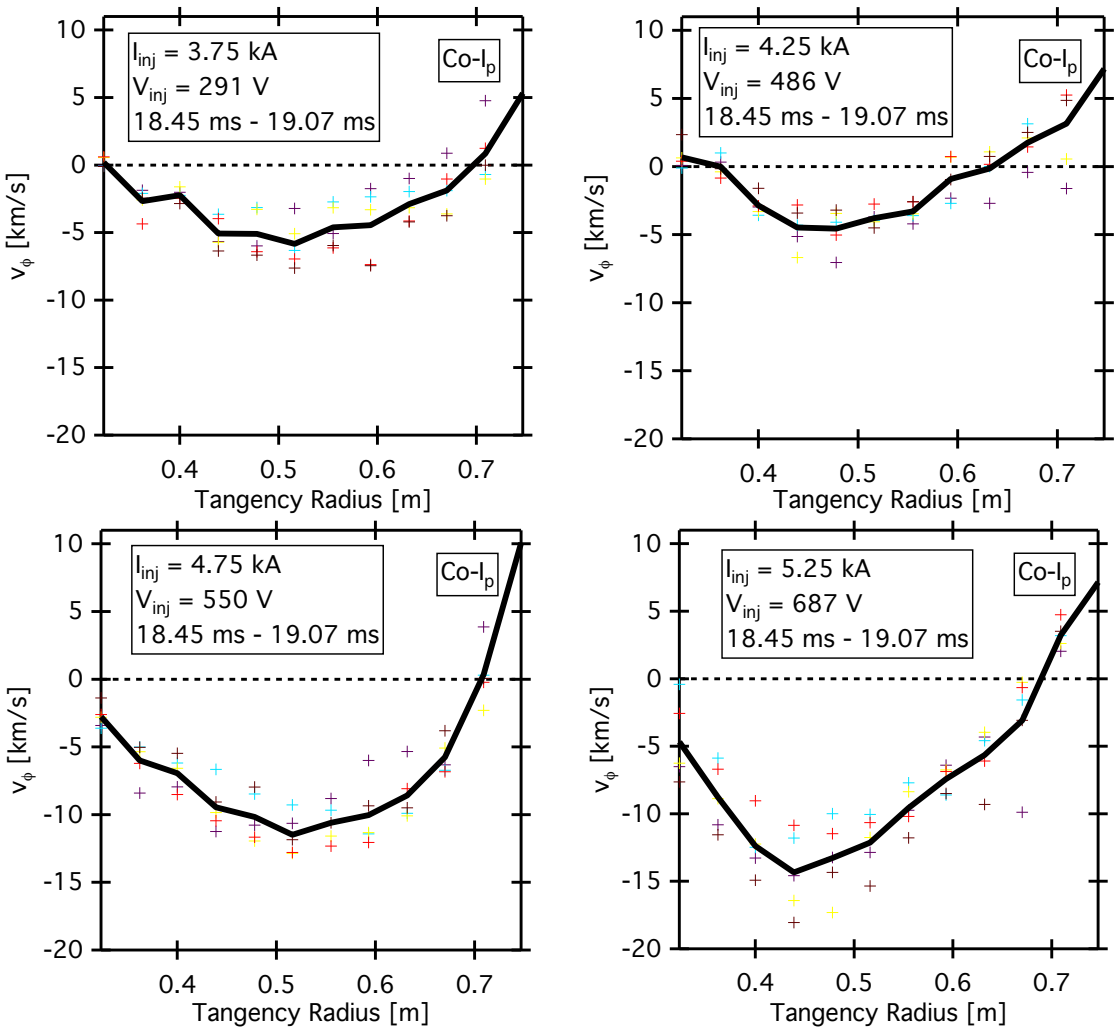
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Summary of Observations of Anomalous Ion Heating During Local Helicity Injection

- Large MHD bursts are correlated with large bursts of anomalous ion heating in the edge of LHI discharges
- Heating increases with increasing injector current
- $T_{\perp,i}$ and $T_{||,i}$ are not equal during periods of rapid heating
- Impurity ion temperatures (He-II and O-V) display a dependence on their charge to mass ratio at high plasma density
- Large changes in the toroidal field strength did not affect the amount of heating Helium impurities received
- At the moment these observations do no distinguish between heating theories
- Following this broad survey we now require detailed scans of n_e, ~b, and I_{inj}

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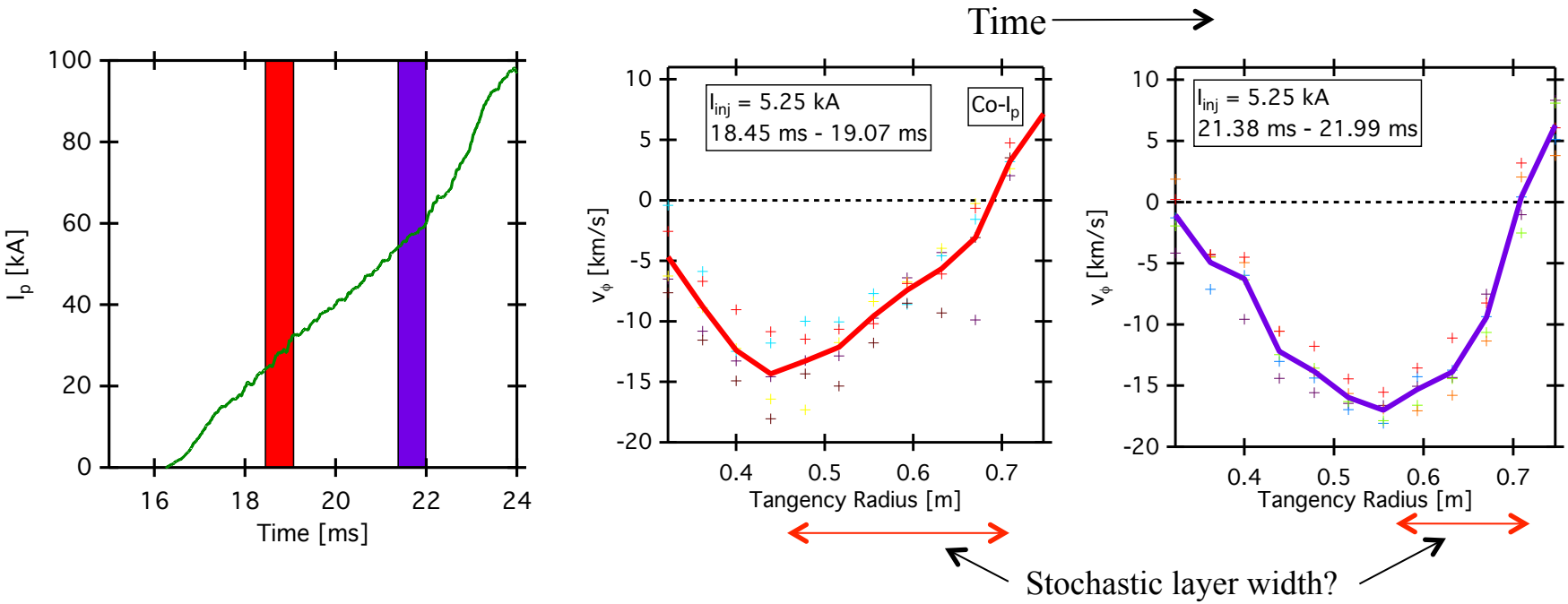
Plasma Rotation: Helium Toroidal Velocity Shows Strong Dependence on I_{inj}



- Increasing bias current and voltage spins the plasma in the counter-I_p direction
- ExB velocity direction at 70 cm inward is consistent with rotation induced by a loss of electrons and net positive E_r resulting from a stochasticization of the edge region due to the injected current streams
- This mechanism was invoked during DED operation on TEXTOR [Coenen, Nuc. Fus., **51**, 2011]

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Plasma Rotation: Toroidal Velocity Shear Observed to Increase as I_p Increases

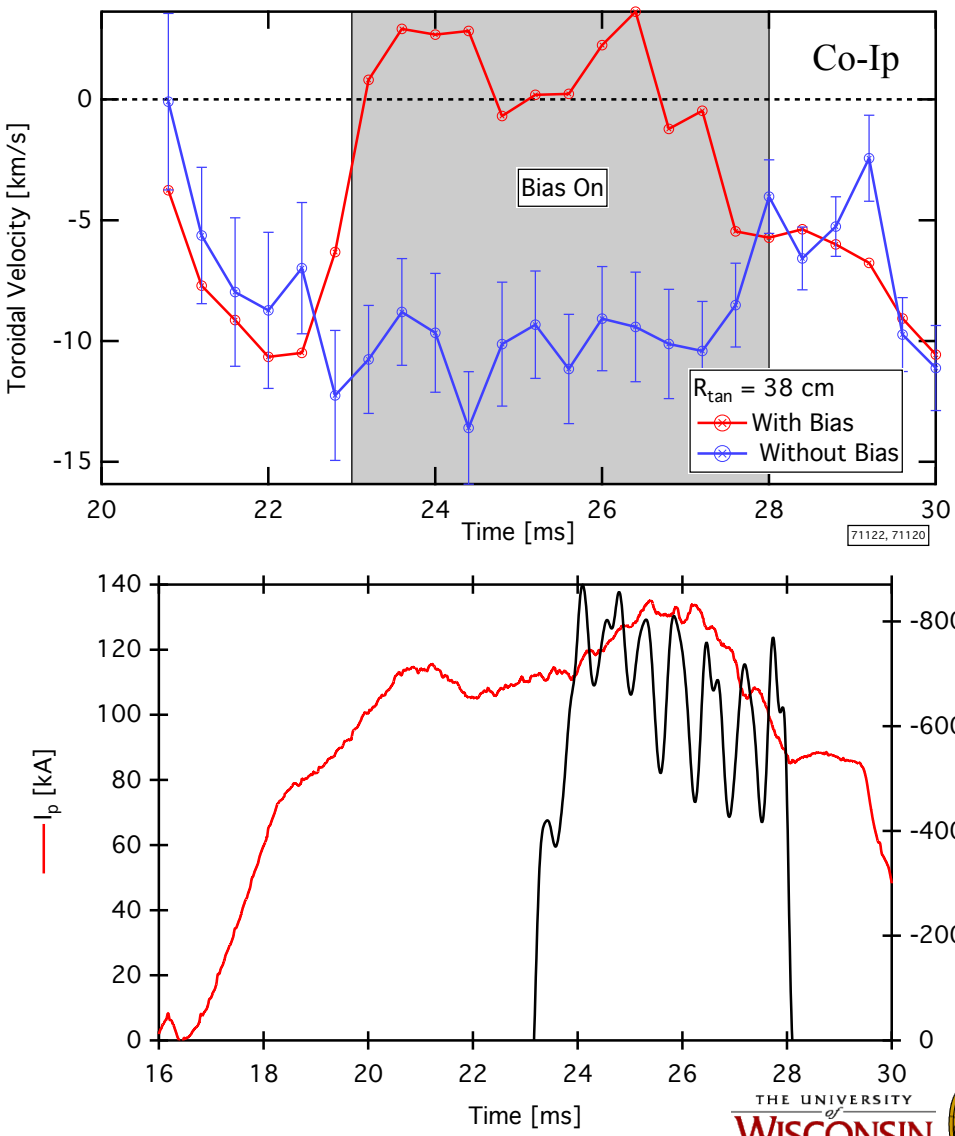


- Hypothesis: The amount of stochasticity in the plasma edge should be on the order of a few island widths. As the plasma current increases, the island width shrinks and thus the stochastic layer width shrinks.
- Could the large amount of velocity shear result in better than stochastic confinement in the core of LHI plasmas?

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Plasma Rotation: Intrinsic Rotating in Ohmic Plasmas can be Modified Using Injectors

- Plasmas are observed to rotate without any external momentum input during ohmic current drive
- Rotation direction is consistent with OH plasmas in the saturated ohmic confinement regime [Podpaly, Phys. of Plas., **19**, 2012]
- Application of negative voltage to plasma edge causes torque opposite to intrinsic torque, can knock plasma out of H-mode



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Conclusions & Future Work

- MHD bursts linked to magnetic reconnection have been correlated to edge localized bursts in T_{OV}
- A broad plasma parameter scan shows intriguing ion heating dependencies such as a dependence on the injected current, $T_{\perp} > T_{||}$, and a charge to mass ratio dependence at high plasma density

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- Detailed scans are needed to distinguish between different anomalous ion heating theories
- Floating potential measurements in plasma edge are needed to corroborate plasma velocity hypothesis and distinguish between ion heating theories

Reprints:

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