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

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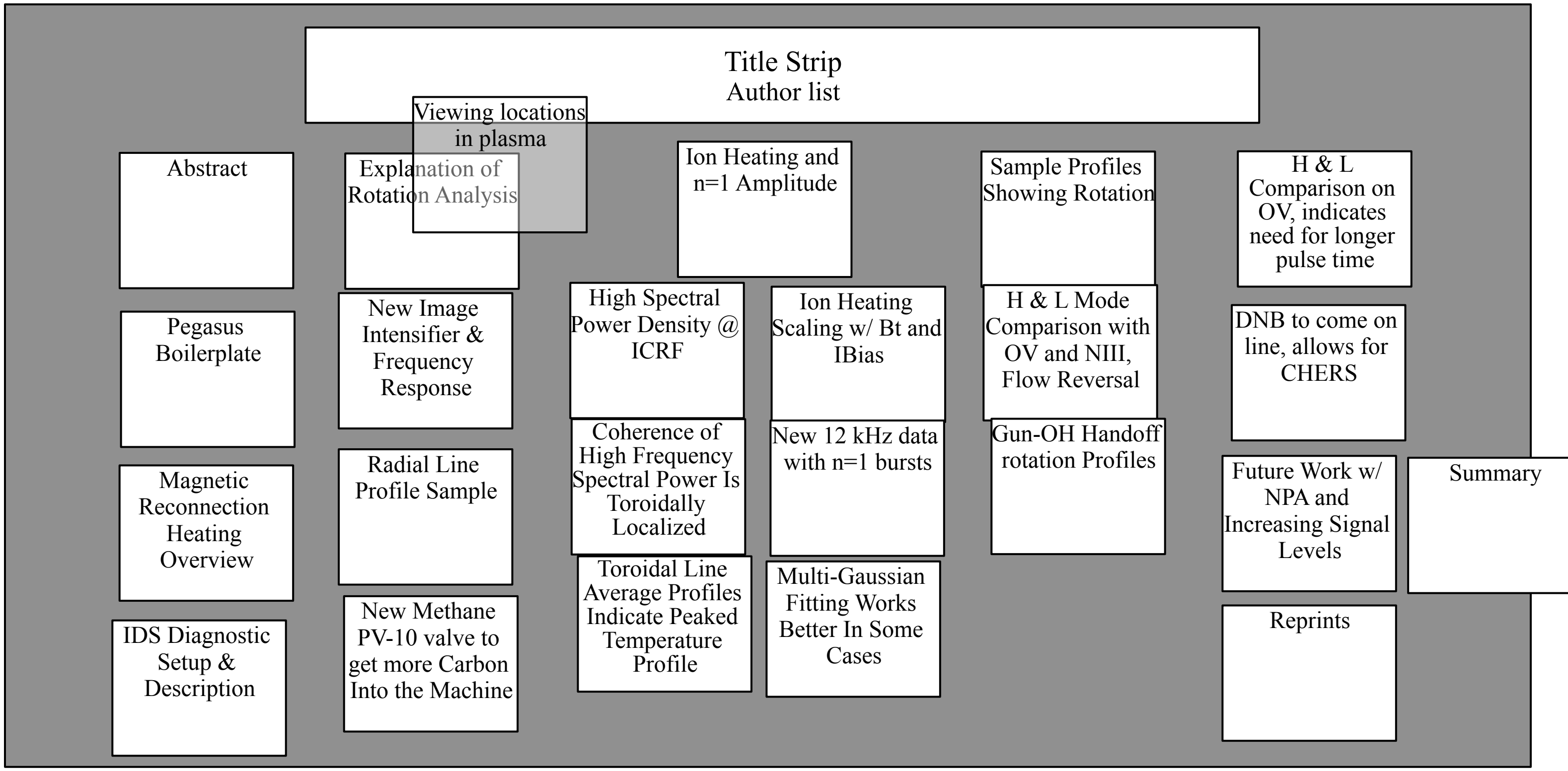
55th Annual APS-DPP

Poster
Denver, CO
Date

University of Wisconsin-Madison

PEGASUS Toroidal Experiment

Layout



Title Strip
Author list
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Sample Profiles Showing Rotation
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Abstract

Anomalous energetic thermal and non-thermal minority ion distributions are observed during local helicity injection current startup. Energetic ions in significant numbers can transfer a large amount of power to plasma electrons during helicity injection, which can alter the helicity balance and consequent plasma startup via reduced resistive dissipation. Multi-spatial point spectra from a 1 m F/8.6 Czerny-Turner polychromator are recorded by an intensified high-speed camera with a time resolution of 500 μs. T_e remains low during helicity injection, wherein the plasma experiences large magnetic fluctuations and strong reconnection activity near the injection region. Partially ionized low-Z impurities (CIII, NIII, and OIII) exist in the core plasma region, which allows core T_i measurements. Strong impurity ion heating ($T_i \approx 500$ eV, $T_e \approx 50$ eV) correlates with n=1 MHD activity. High frequency magnetic fluctuations are indicated at frequencies close to the impurity ion cyclotron frequencies and may act as the source of energy for the ions. These observations motivate the deployment of a neutral particle analyzer to measure the working gas ion distributions in these plasmas. In addition, a high-throughput polychromator with 2 μs resolution is being installed to more directly correlate the observed impurity ion heating and flows with MHD and reconnection activity.

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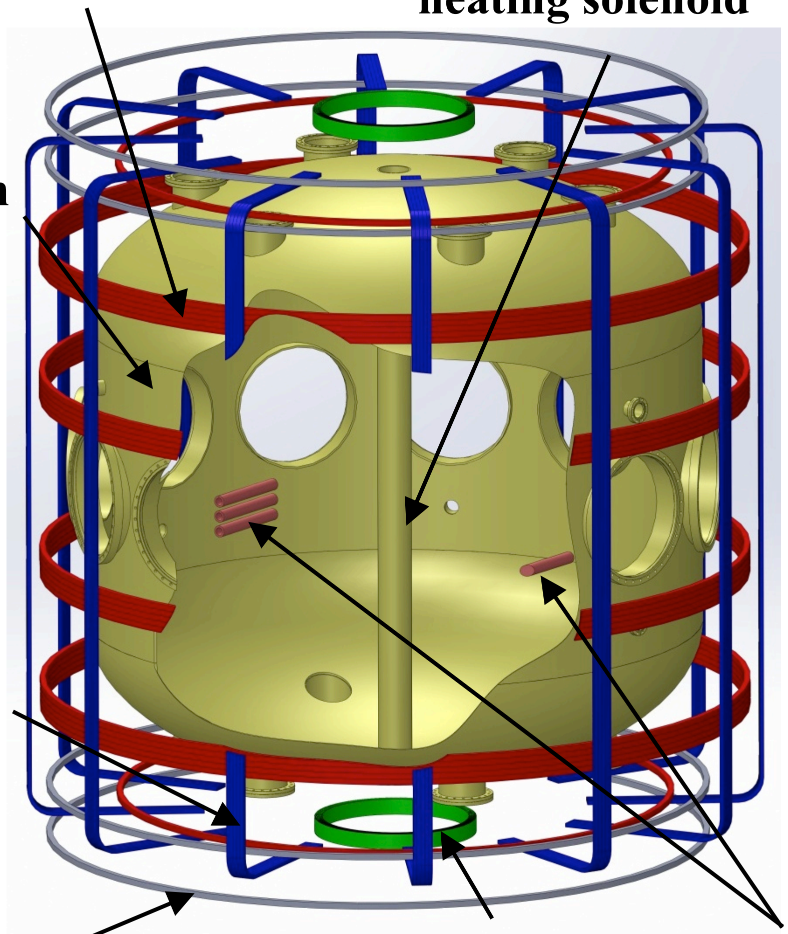
Pegasus is a Compact, Ultralow-A ST



Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	$\leq$ .21	$\leq$ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	$\leq$ 0.06	$\leq$ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025	$\leq$ 0.05
β_t (%)	$\leq$ 25	> 40

Major research thrusts include:

- **Non-inductive startup and growth**
  - *Local Helicity Injection (LHI)*
- **Tokamak physics in small aspect ratio**
  - *High-I_N, high-β operating regimes*
  - *ELM-relevant edge MHD activity*

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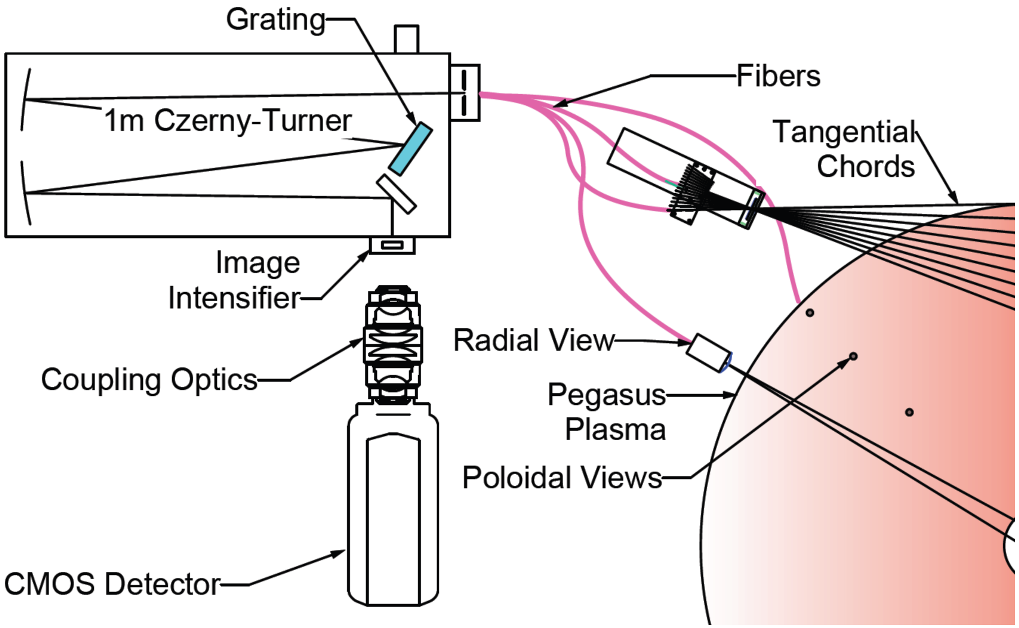
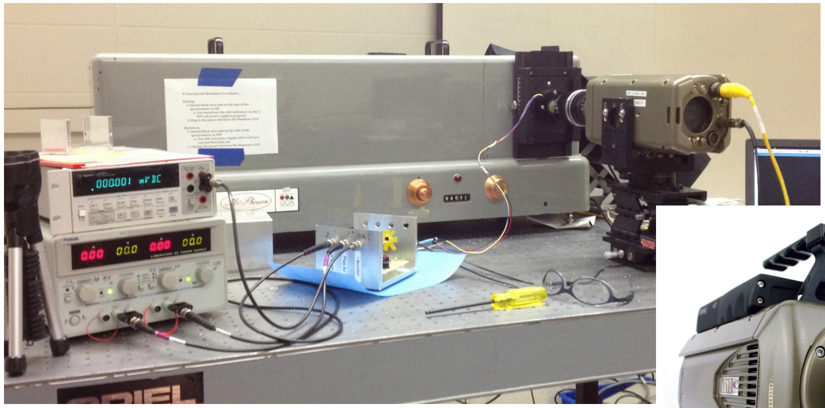
Magnetic Reconnection and Anomalous Ion Heating in Pegasus During LHI

- A widely observed consequence of magnetic reconnection is anomalous ion heating
- Anomalous ion heating observed via spectroscopy on dedicated reconnection experiments (MRX*, TS-3**), in spheromaks (SSX***), during coaxial helicity injection (HIT-II****), and RFPs during sawtooth crashes (MST*****)
- High, anomalous impurity ion heating has been observed during local helicity injection on Pegasus using passive spectroscopy

*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.

Pegasus IDS Diagnostic Setup





Diagnostic Characteristics:*

- **Spectrometer:** UV 1m f/8.6 Czerny-Turner, 1200 g/mm blazed @ 1 um
- **Spectral Range:** 200 – 600 nm
- **Spectral Resolution:** 0.13 Å
- **Total etendue:** 8×10^{-4} cm^2-str @ 0.1 mm slit
- **Detector:** UV Intensified Phantomv310
  - Flexible frame rate: 1-500 kHz
  - Max Time resolution: 1 MHz

↓

- Fast 3D $T_i(t)$ and v(t) distribution measurements with chords in the toroidal, poloidal, and radial directions

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

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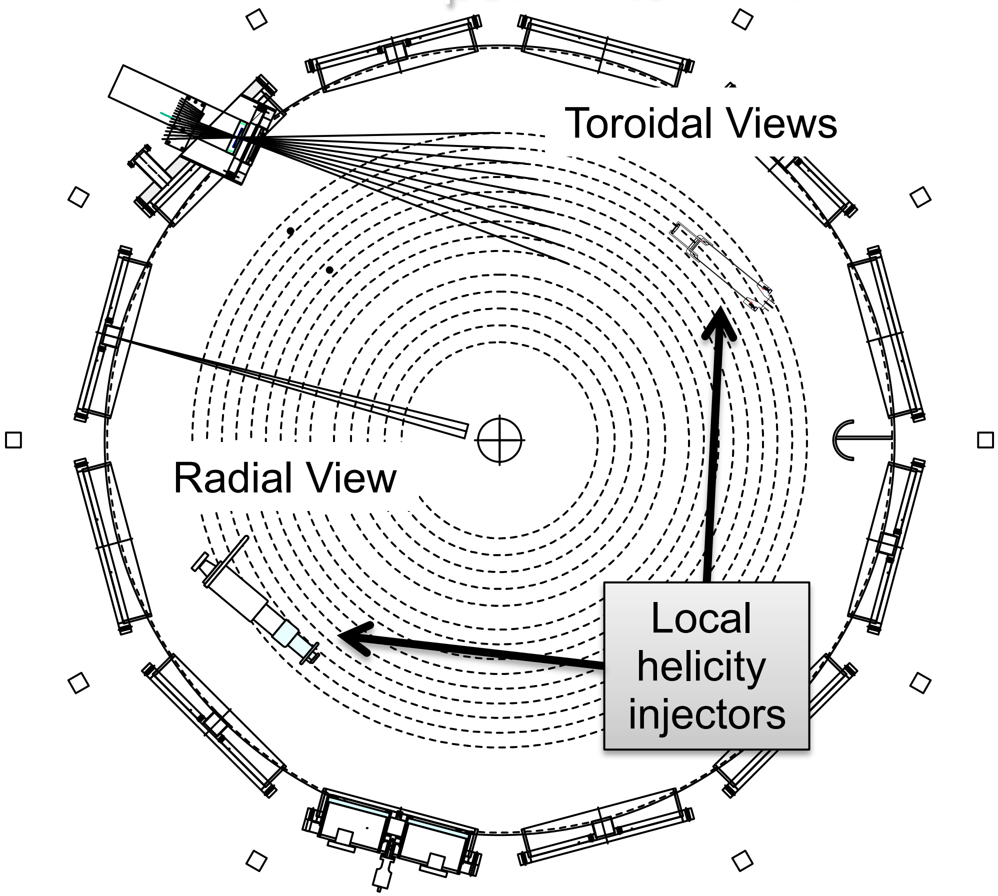
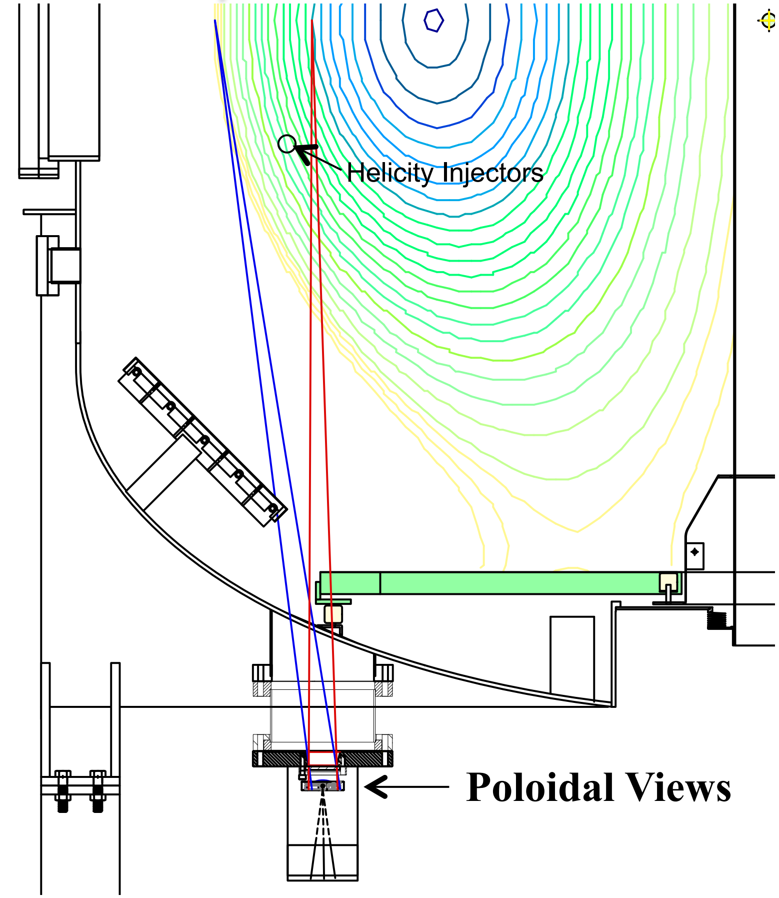
Multiple Views Allow for Measurement of V_{pol}, V_{tor}, $T_i(R)$, and $\langle T_{i,radial} \rangle$



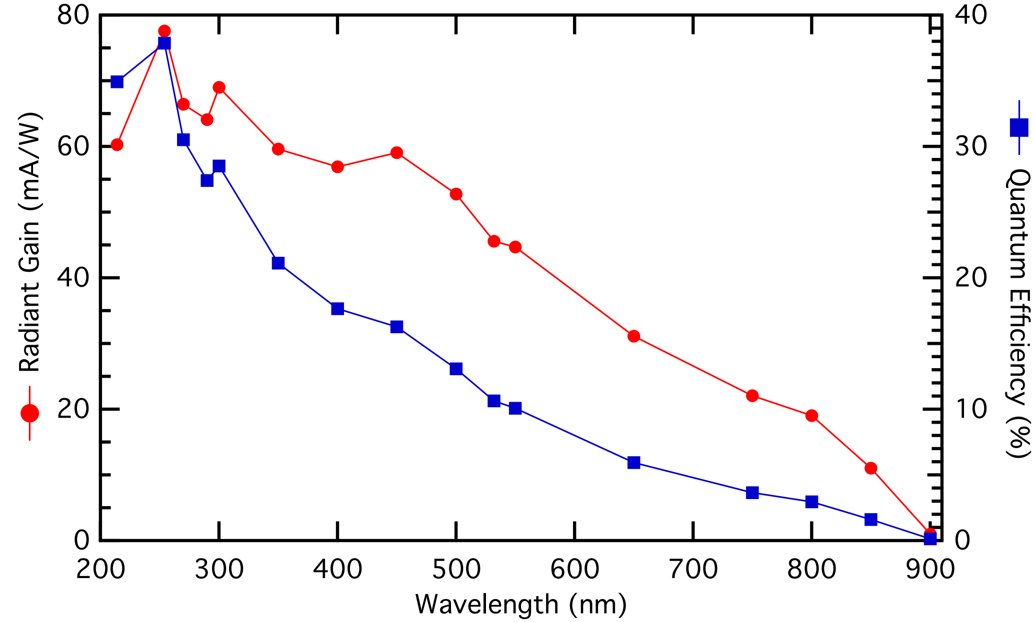


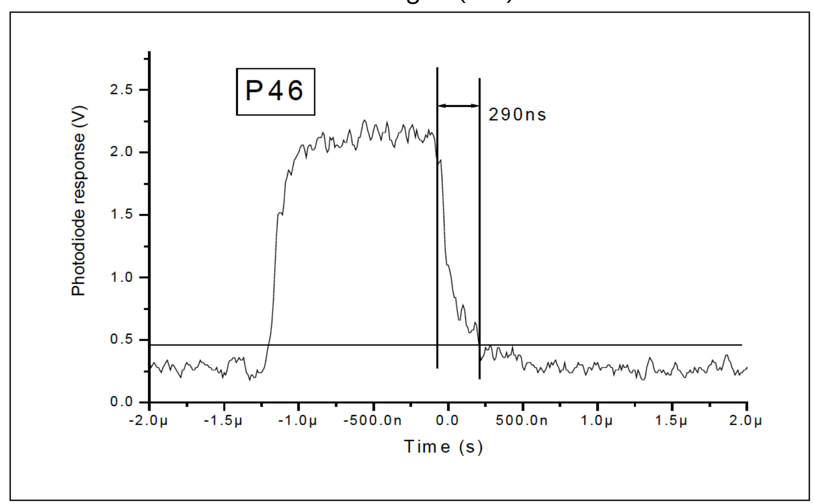
R_{tan} (cm)	R_{pol} (cm)
48, 52, 56, 60, 63.3, 67, 71, 74.5, 78.3	66.4, 80.5

New Image Intensifier Installed to Increase Max Frequency Response to 1 MHz

- Photek MCP125 tube
- UV enhanced photocathode
- 90%-10% decay time ~300 ns vs old 1.3 ms
- New image intensifier matches max Phantom v310 speed:
    - New: 225 kHz @ 128X64 Single spatial channel

      Or
    - New: 30 kHz @1024X100 Full 3D spatial profiles



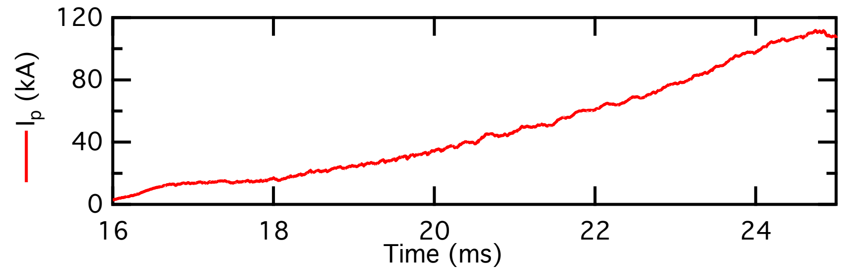


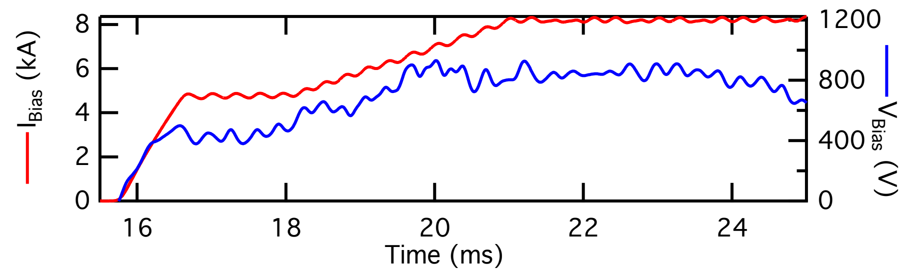
*Plots from manufacturer

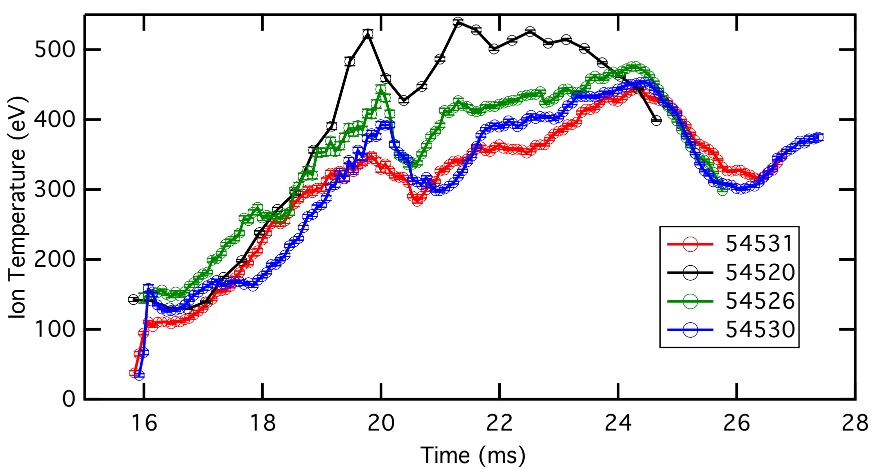
Thermal Ion Distribution of ~500 eV Observed During LHI on Radial Line Integrated Chord

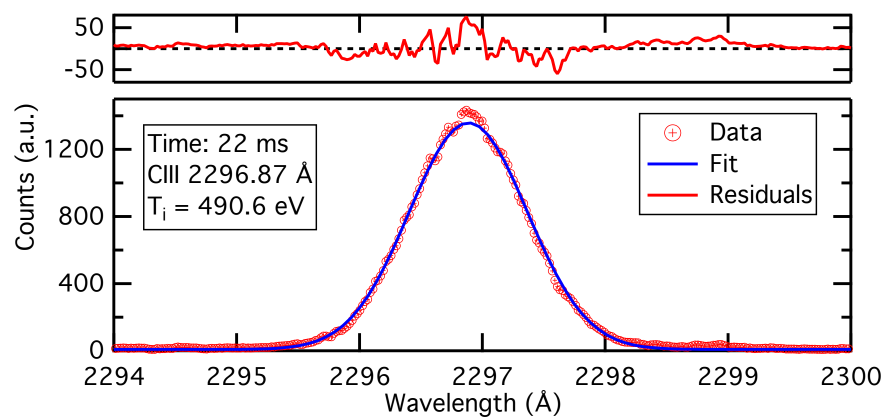
- Stochastic fields and virulent MHD keep T_e low and allow CIII to penetrate to the plasma core

- Instrumental width ~5 eV



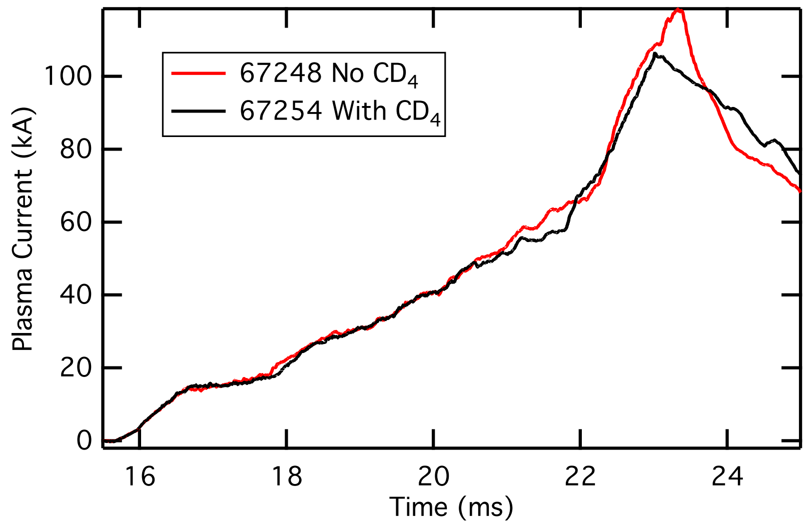


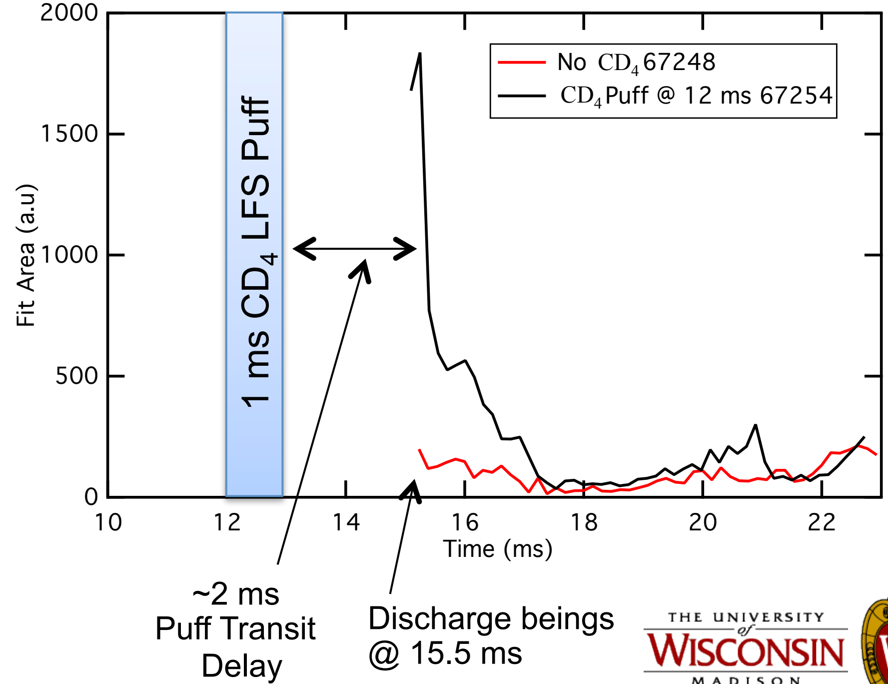




CD_4 Puffing Increases Carbon Signal In Plasma Allowing Faster Data Sampling

- Installed low field side PV-10 valve to puff high purity Deuterated Methane into plasma edge
- 10X increase in signal
- Work underway to puff from high field side to allow for more efficient use of impurity gas
- Initial results do not indicate hindrance to plasma performance from prefill or continuous puffing





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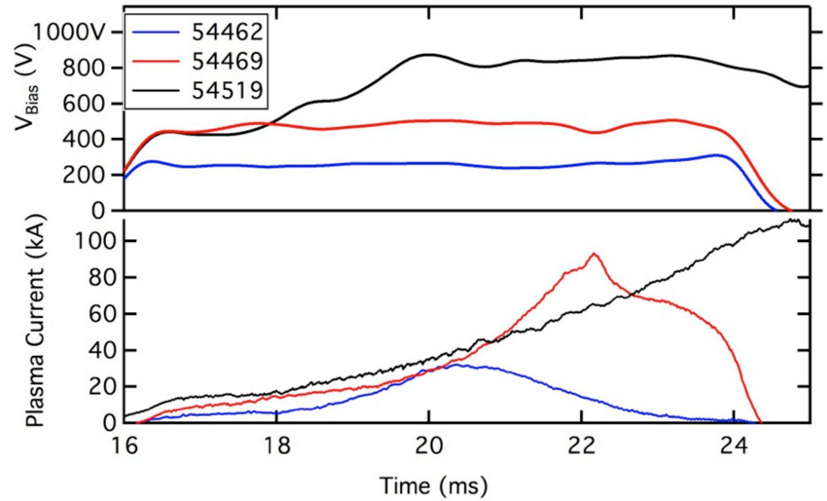
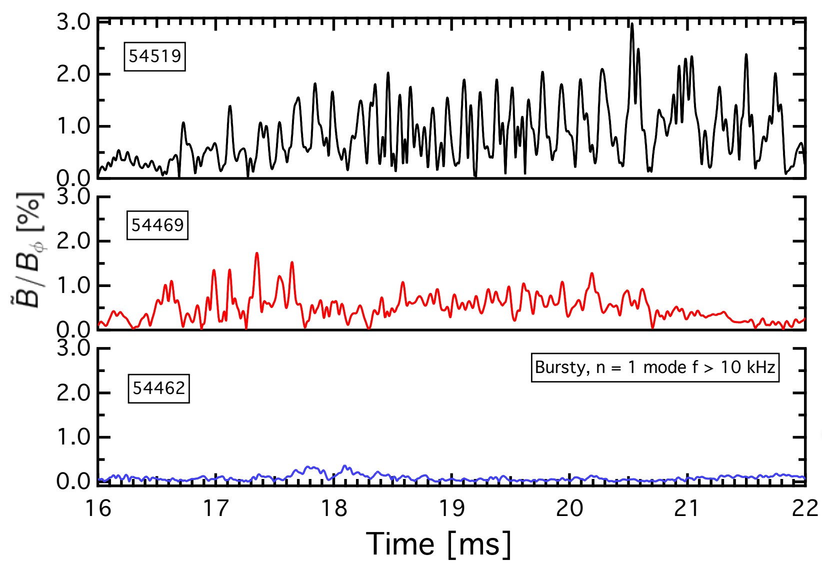
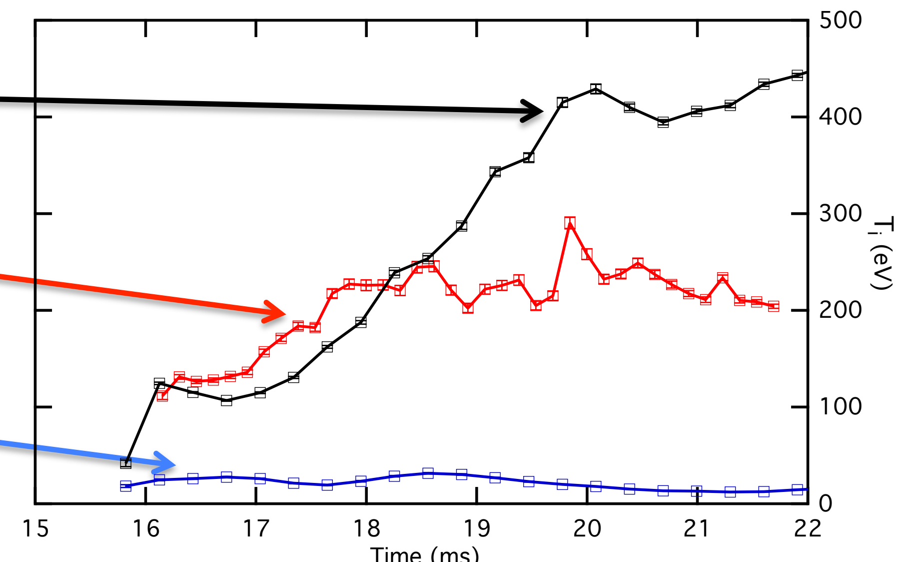
Strong Ion Heating Observed on Radial Line Integrated Chord; Correlates With MHD Amplitude and Power Input

- Ion heating observed on multiple line species (CIII, NIII, OIII, OV) during helicity injection
- Heating correlated with n = 1 burst activity
  - Old Hypothesis: Larger amplitudes → more reconnection heating







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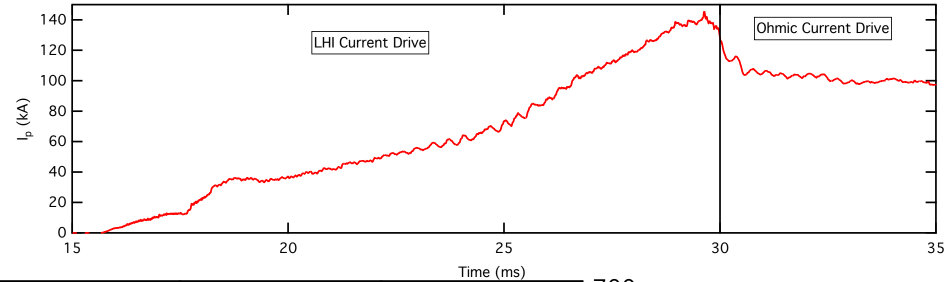
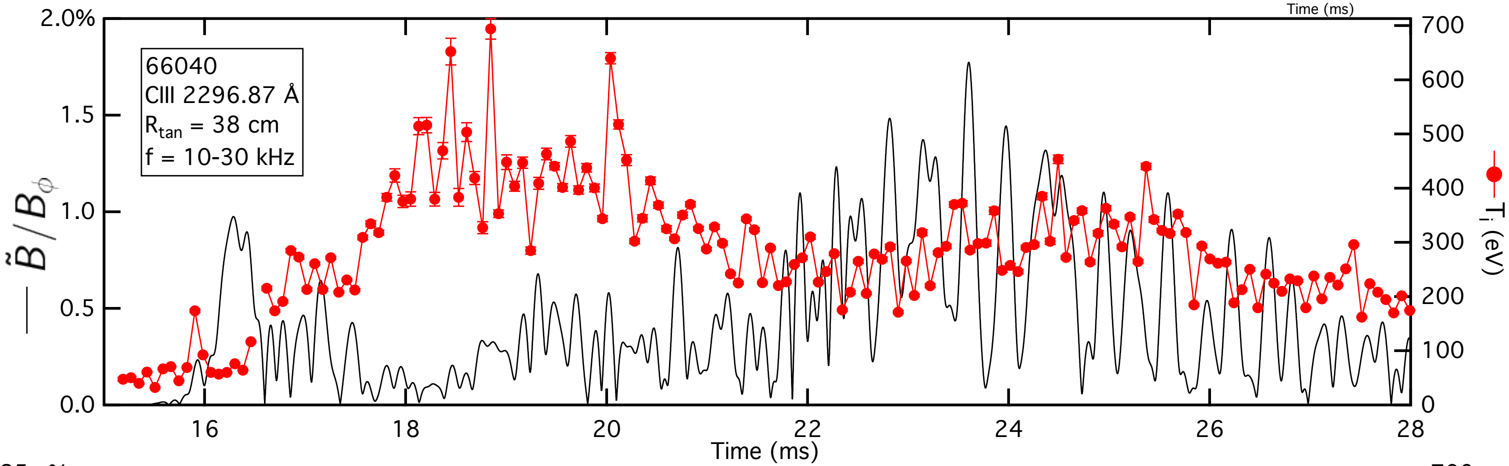
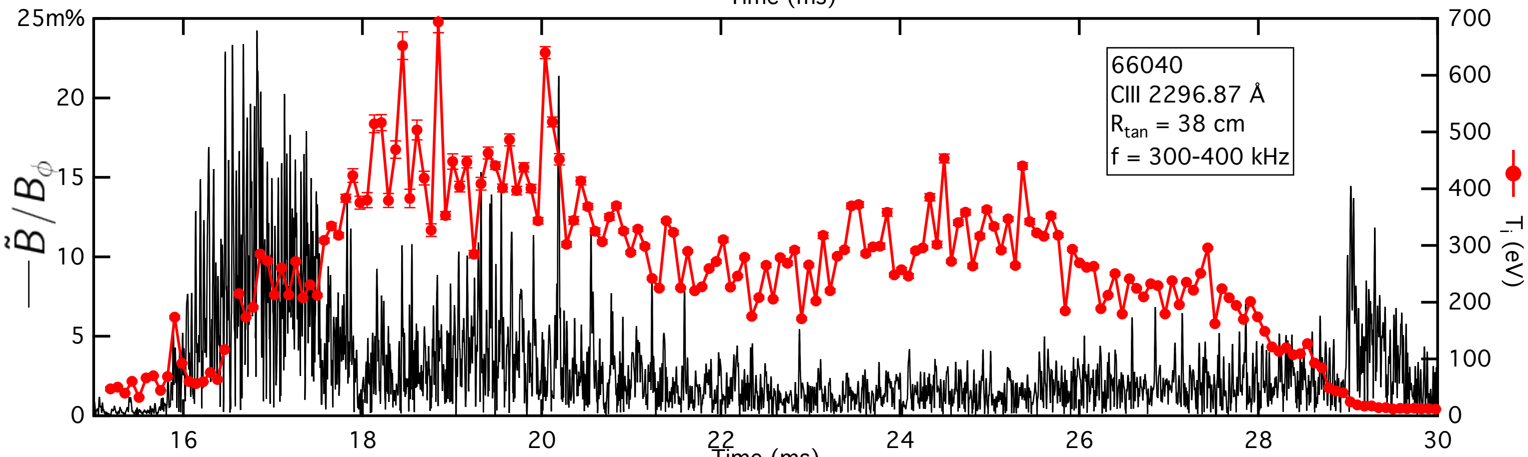
New Image Intensifier Allows Improved Correlation of n =1 MHD activity with T_i

- New data illustrates T_i not linearly correlated with $\tilde{B}/B$ amplitude of n=1 mode





Amplitude of bursty n=1 mode between 10-30 kHz



Fluctuation amplitude around f_{ci} between 300-400 kHz

Significant Spectral Power Density @ f_{ci}; Corresponding Correlation with Ion Heating

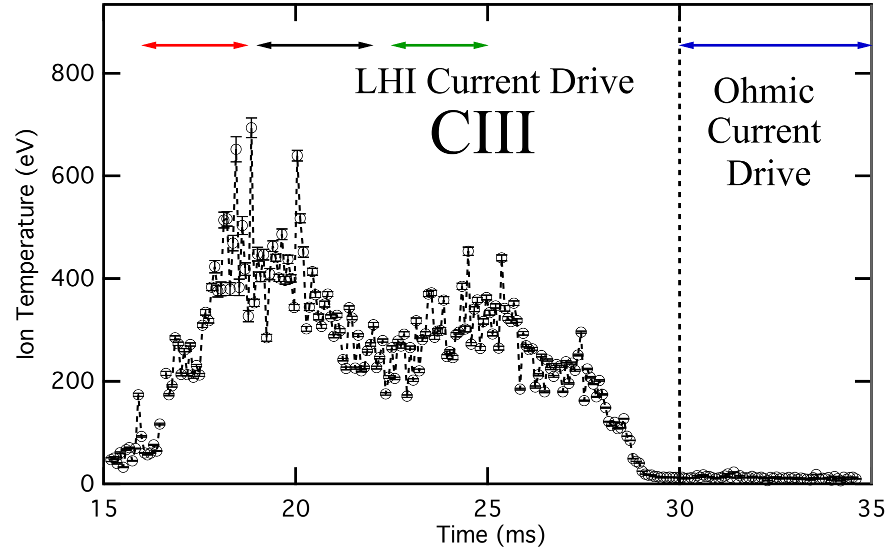
- MST observed high spectral power density at f_{ci} during sawtooth crash*

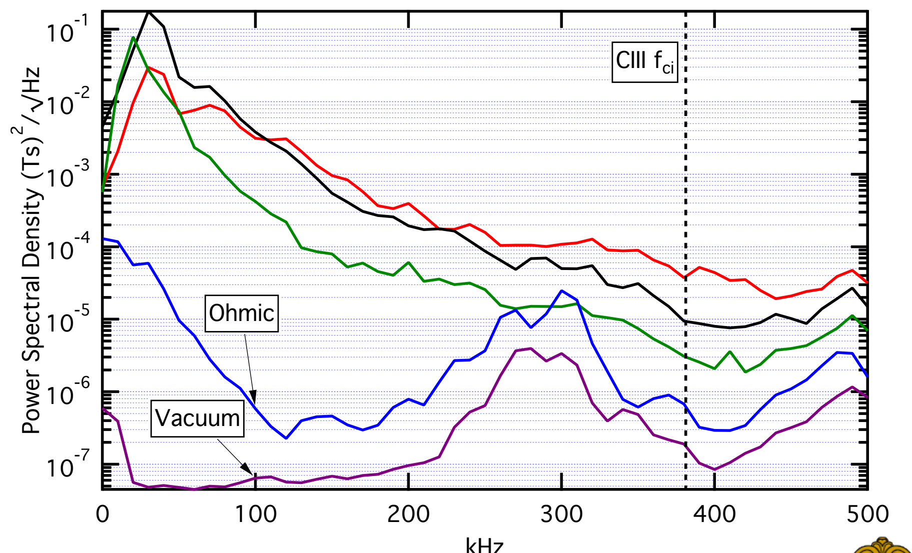
- Heating rate from ion cyclotron damping in cold plasma:

$$\frac{3}{2} n_i \frac{dT_i}{dt} = \frac{1}{16} \omega_p^2 \tilde{B}^2(\omega_{ci})$$

- Heating rate scales with spectral power density @ f_{ci}, $\tilde{B}^2(\omega_{ci})$

- Calculated heating rate in the correct order of magnitude as observed heating rate:
  - Observed: 0.1-1 MeV/s
  - Calculated: ~10 MeV/s

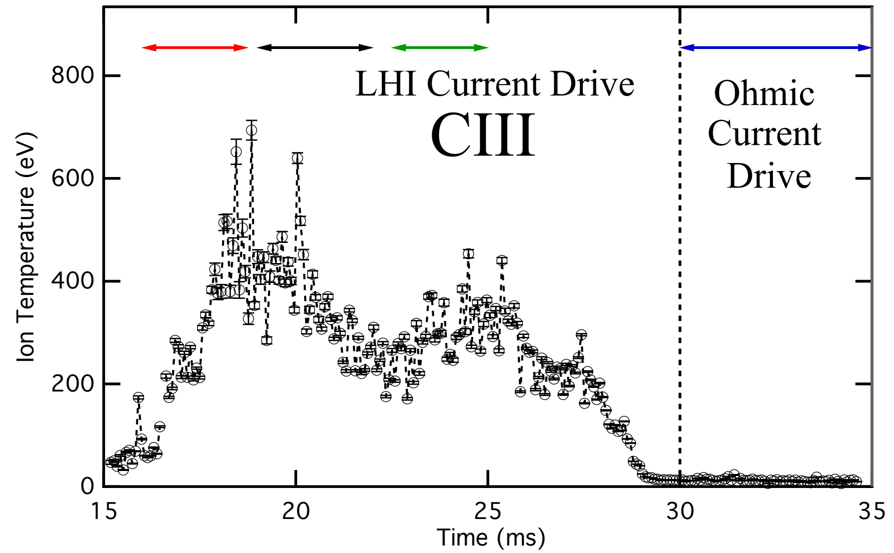




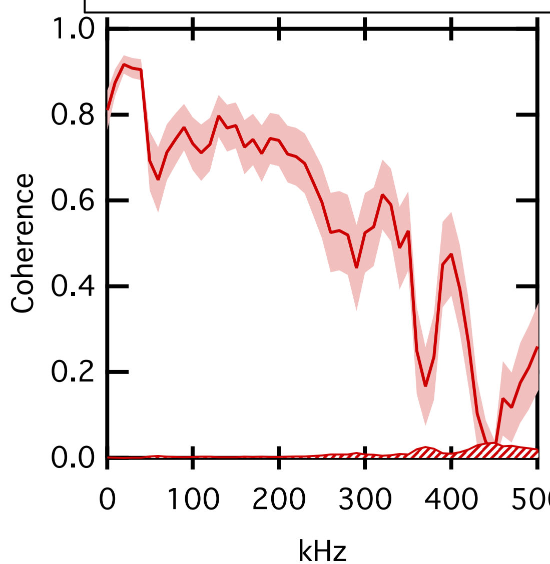
*V. Tangri *et al.*, Phys. Plasmas, vol. 15, no. 11, p. 112501, 2008.

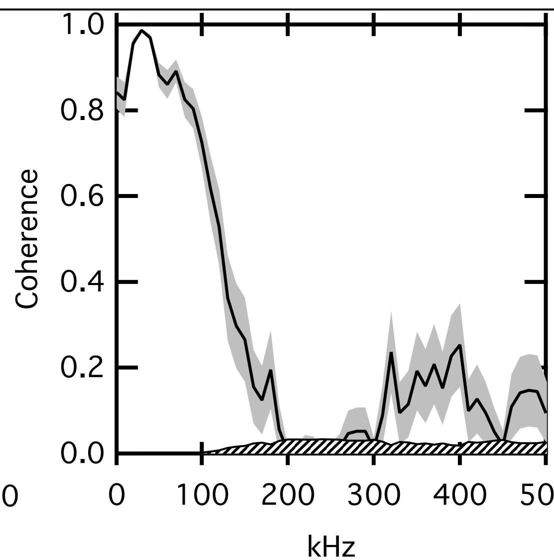
High Frequency Spectral Power is Toroidally Localized As Indicated by Coherence of Adjacent Magnetic Pickup Coils

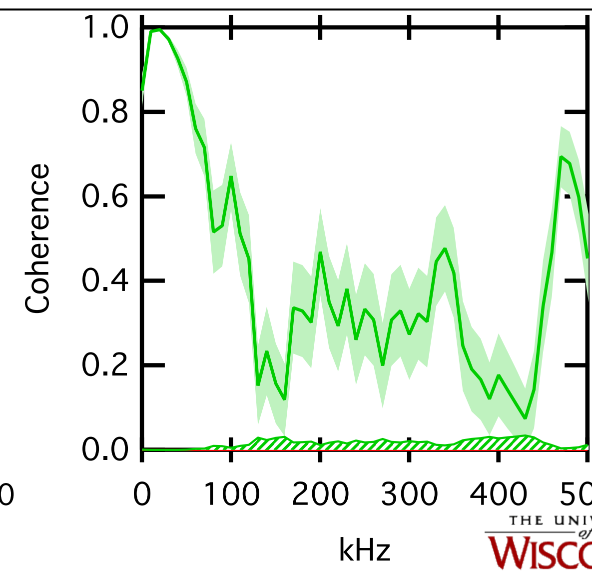
- High frequency power is toroidally localized ~180 degrees from local helicity injectors
- Indicates need to look for toroidal asymmetries in T_i during LHI



Cross coherence between two adjacent pickup coils @ ϕ ~180 degrees from injectors

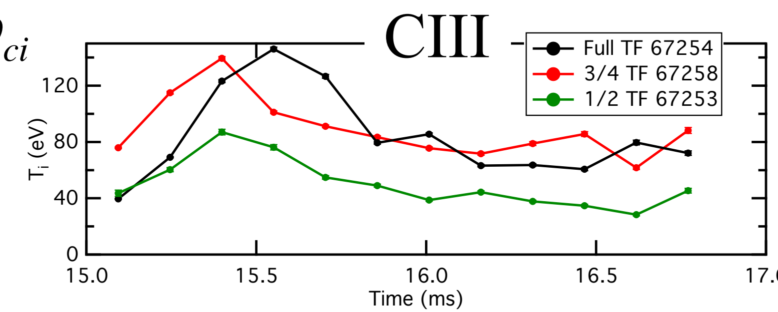


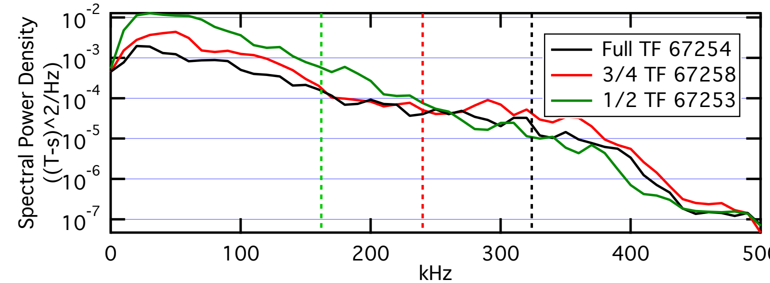


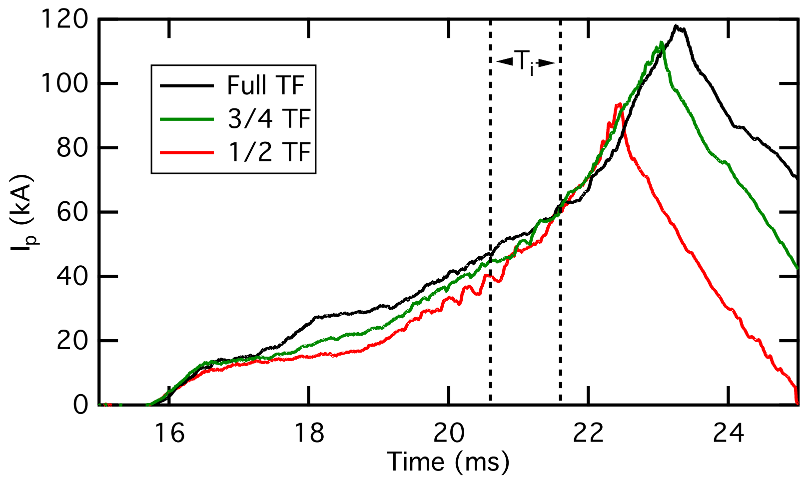


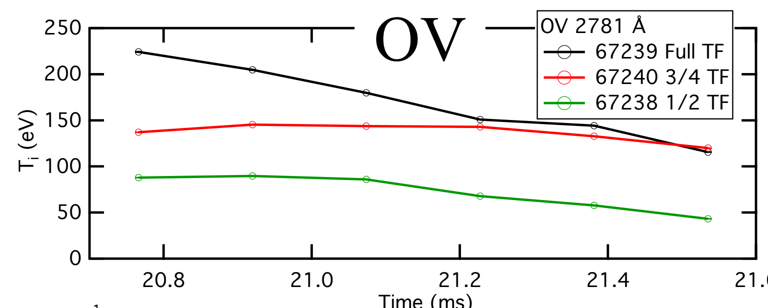
Ion Heating Scales with Toroidal Field Strength

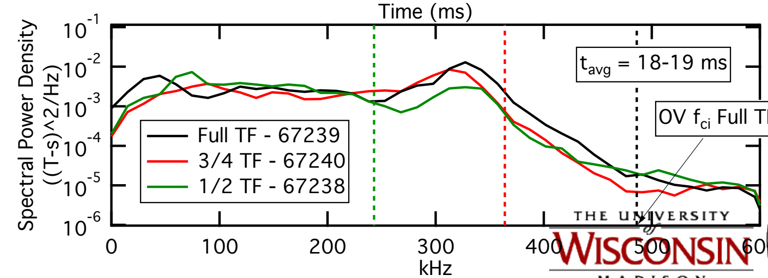
- Changing TF strength changes ω_{ci} but also $\tilde{B}^2(\omega_{ci})$ and thus could alter T_i
- X100 in $\tilde{B}^2(\omega_{ci})$ does not result in X100 in ion heating
- More detailed physics understanding of confinement changes with TF strength needed











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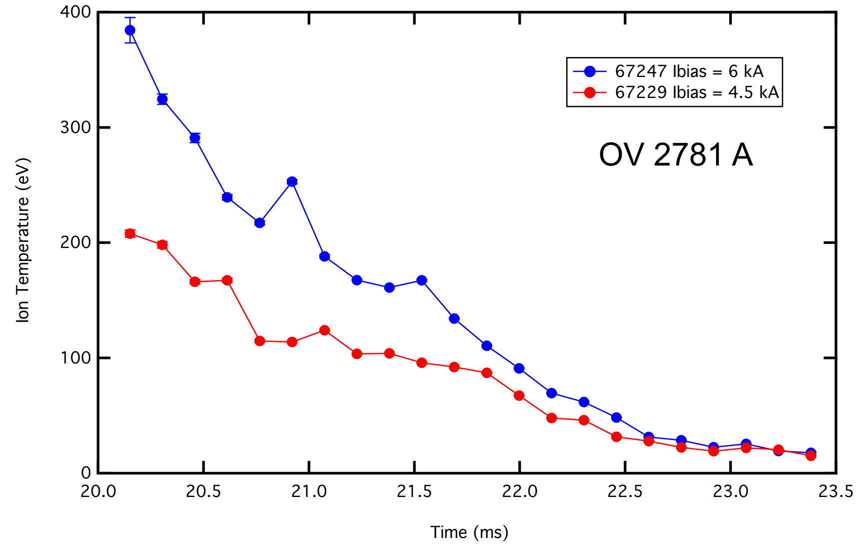
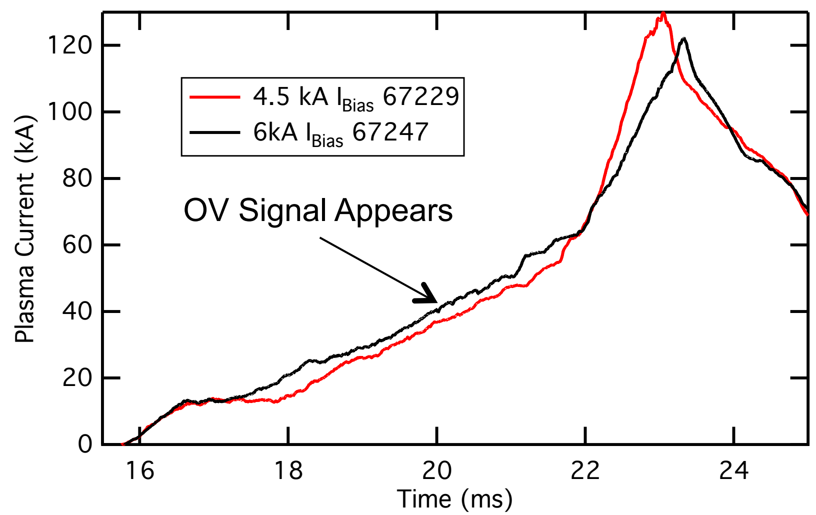
Ion Heating Also Scales with I_{bias} As Observed by Dedicated Reconnection Experiments

- Current stream reconnection indicated by NIMROD
  - O'Bryan JO4.03
- Increasing I_{bias} increases the stream self field and increases the reconnecting field strength
- TS-3 has shown that ion heating scales with reconnecting field strength squared*

$$\Delta T_i \approx \alpha\beta B_{\parallel}^2 / \mu_0 n_i k$$

- Increasing field by ~1.33 should increase ΔT_i by ~1.8
  - Transient T_i increase of ~1.8
  - However time evolution needs more investigation





*Y. Ono *et al.,* Plasma Phys. Control. Fusion, vol. 54, no. 12, p. 124039, 2012.

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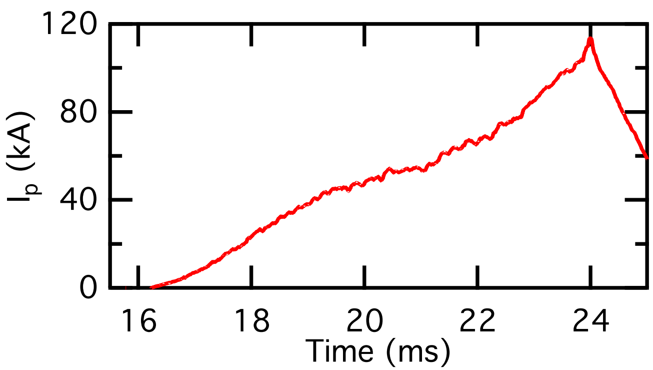
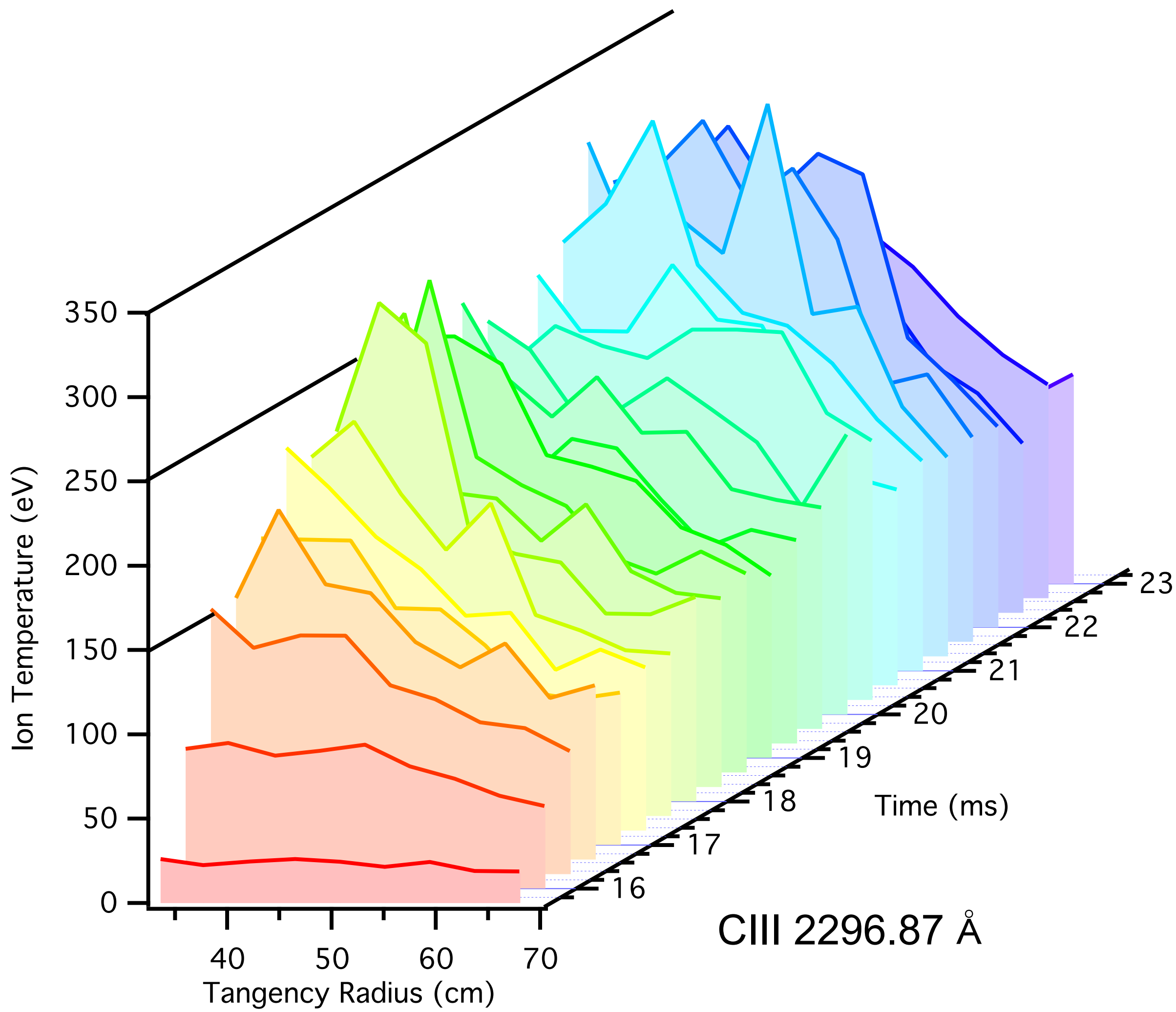
Toroidal Profiles Indicate Ion Heating Penetrates to Core Region During LHI

- First $T_i(R,t)$ profiles show gradual peaking in core of T_i during LHI current drive

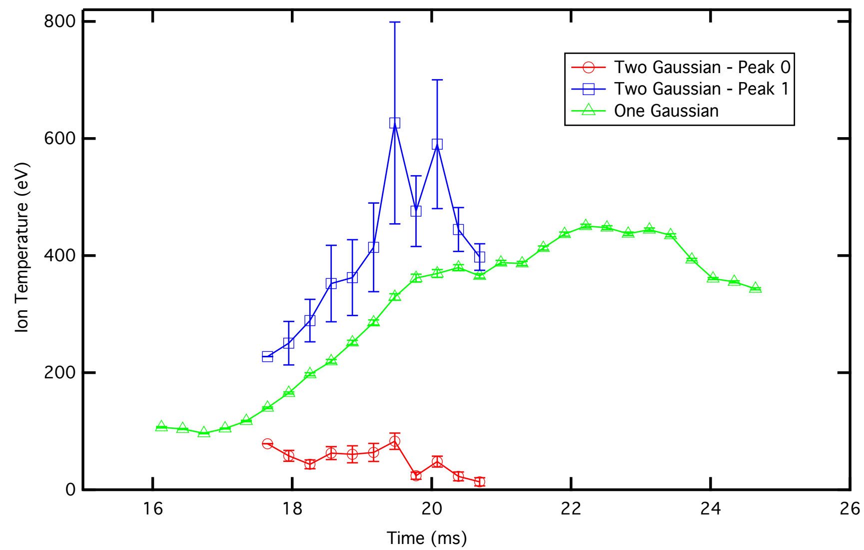


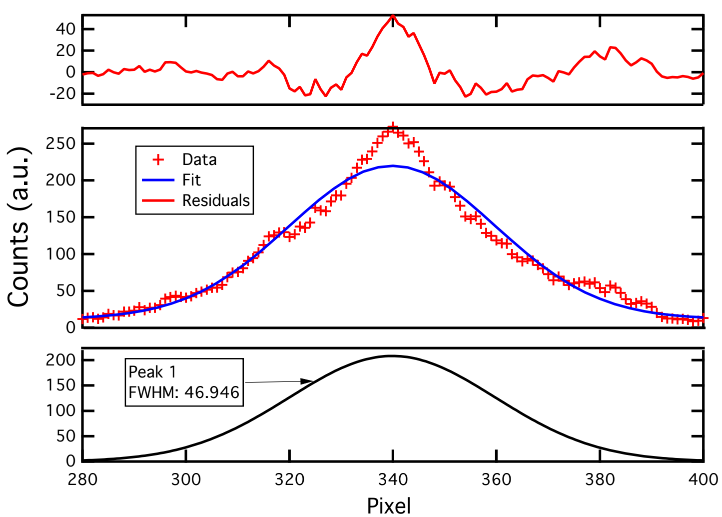


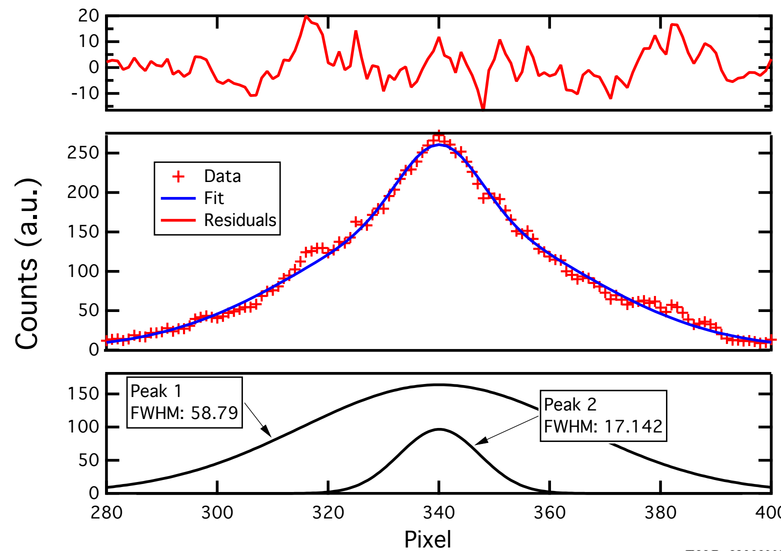
CIII 2296.87 Å

Non-Gaussian Profiles Indicate Possible Integration Through 2 Thermal Distributions

- May indicate two thermal distributions at different locations
- Unclear where the hotter of the two distributions is in radius
    - Data obtained before tangential chords available







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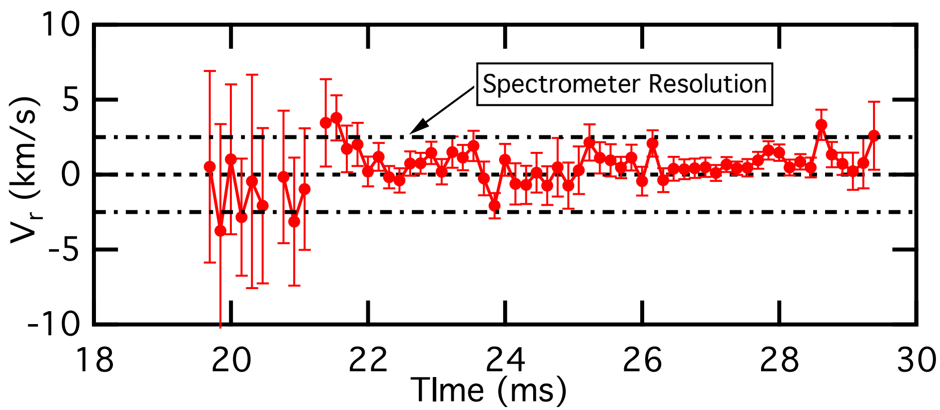
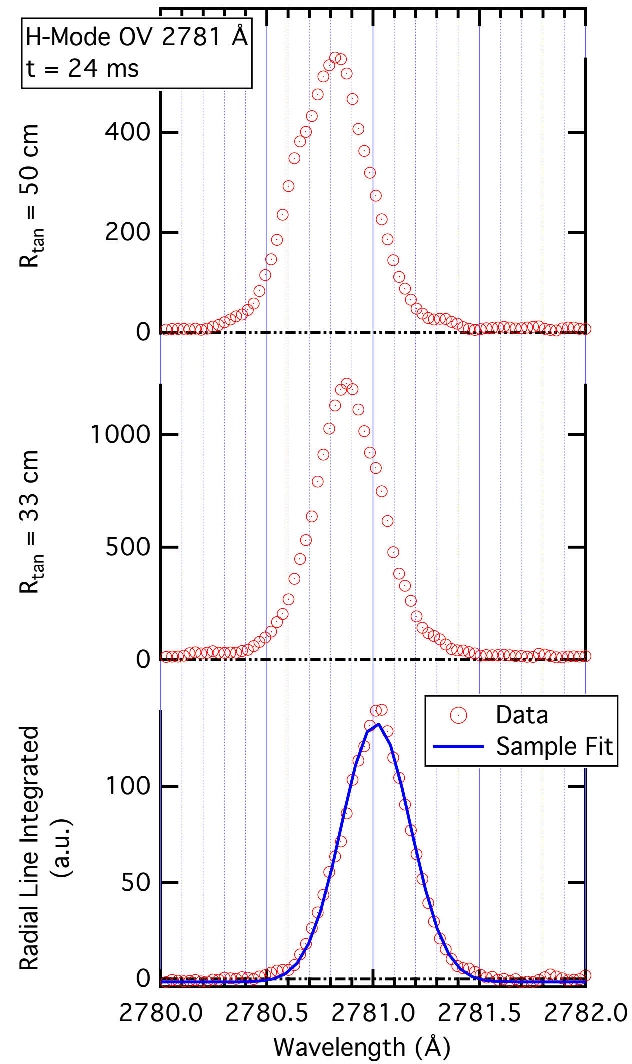
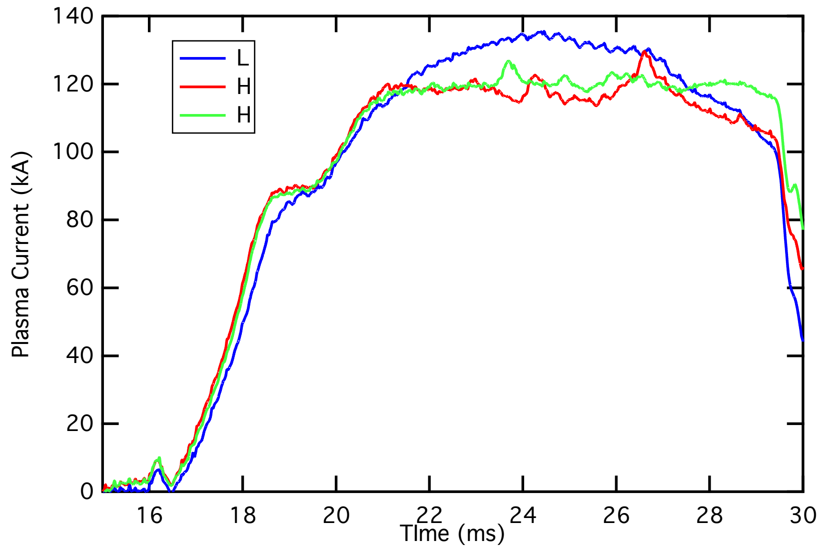
Toroidal Flows Indicated During H-Mode and LHI

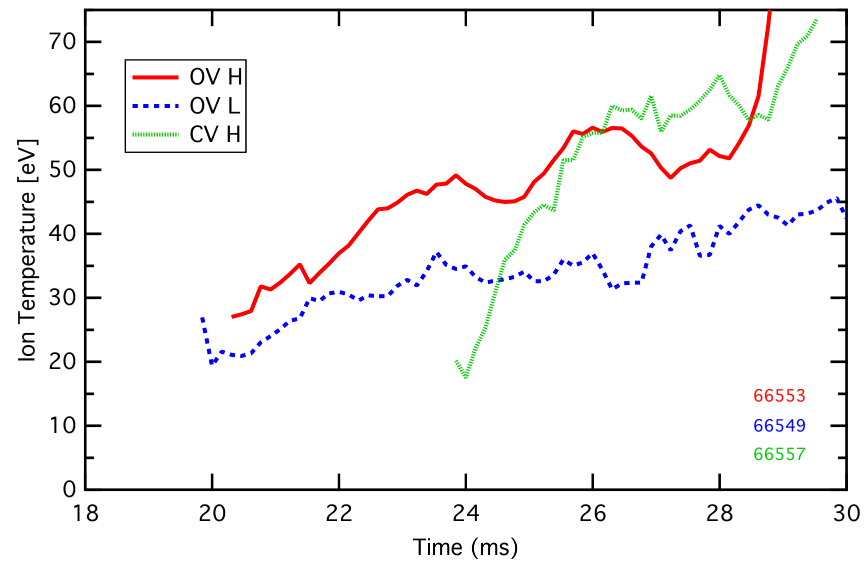
- Rotation measured using Doppler shift
- λ_0 found using radial line position @ t=0 in discharge OR on tangential lines @ t=0
- Spectrometer resolution:
  - OV: 5 km/s
  - CIII: 3 km/s
- Off-axis parabolic mirrors mean very little slit curvature, <1 pixel across chip

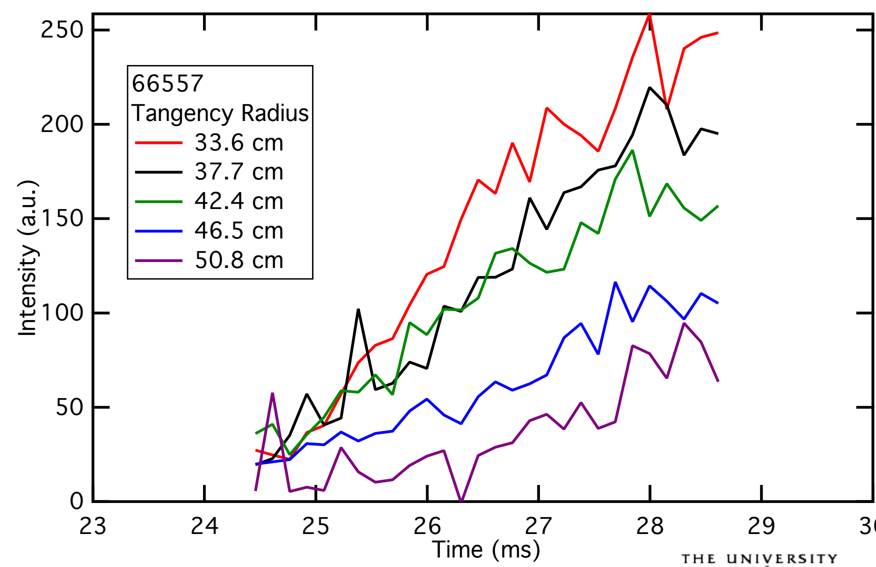




T_i and T_e increase Indicated During H-mode



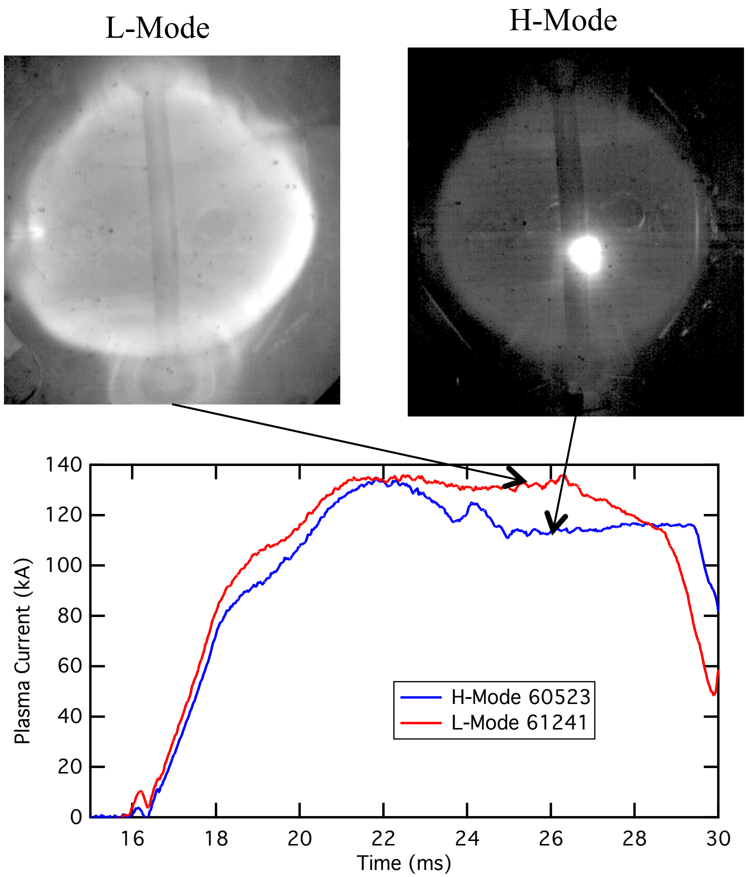




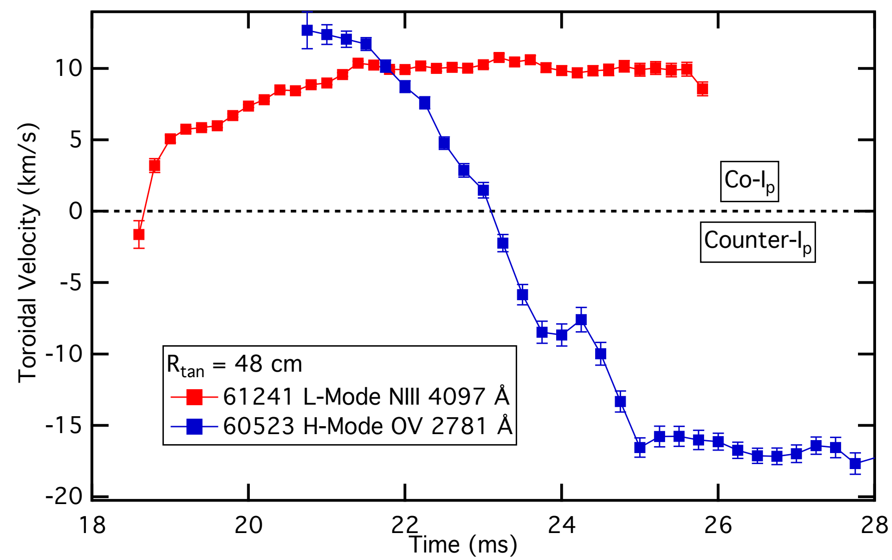
- CV emission not present in L-mode discharges
- CV emission profile grows outward in H-mode as core grows
- T_i heating rate consistent with impurity thermal equilibration if $T_e \sim 300$ eV

Difference in Toroidal Rotation Velocity Observed in L and H Mode

- Observed counter-I_P spin up of plasma during H-mode*
  - *Meyer H. *et al* 2008 J. Phys. Conf. Ser. **123** 012005
- L-Mode intrinsic rotation observed on NIII in co-I_p direction

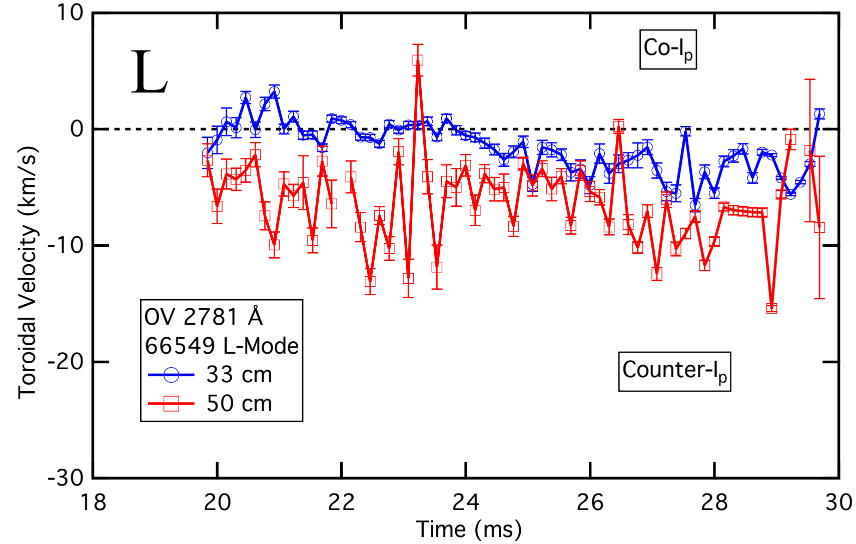


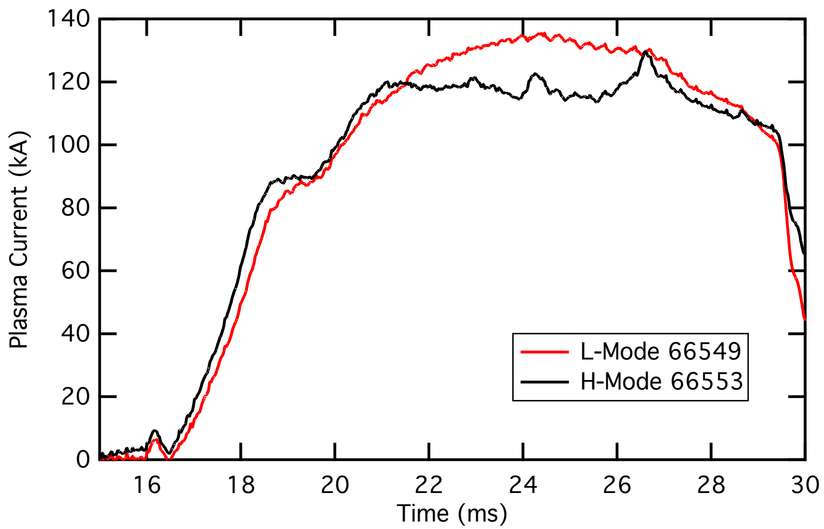
- H-Mode induced via HFS gas valve

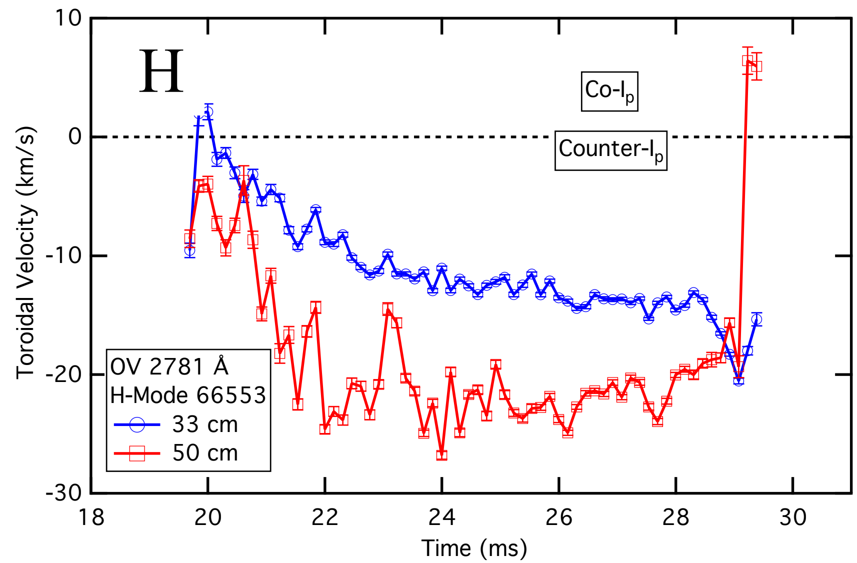


H & L Comparison Indicates Need For Longer Pulse Length at Pegasus

- Velocity shear indicated during H-mode discharges in contrast to L-mode where little shear is observed
- Equilibrium not reached in T_i or v_ϕ data indicating need for longer pulse on Pegasus



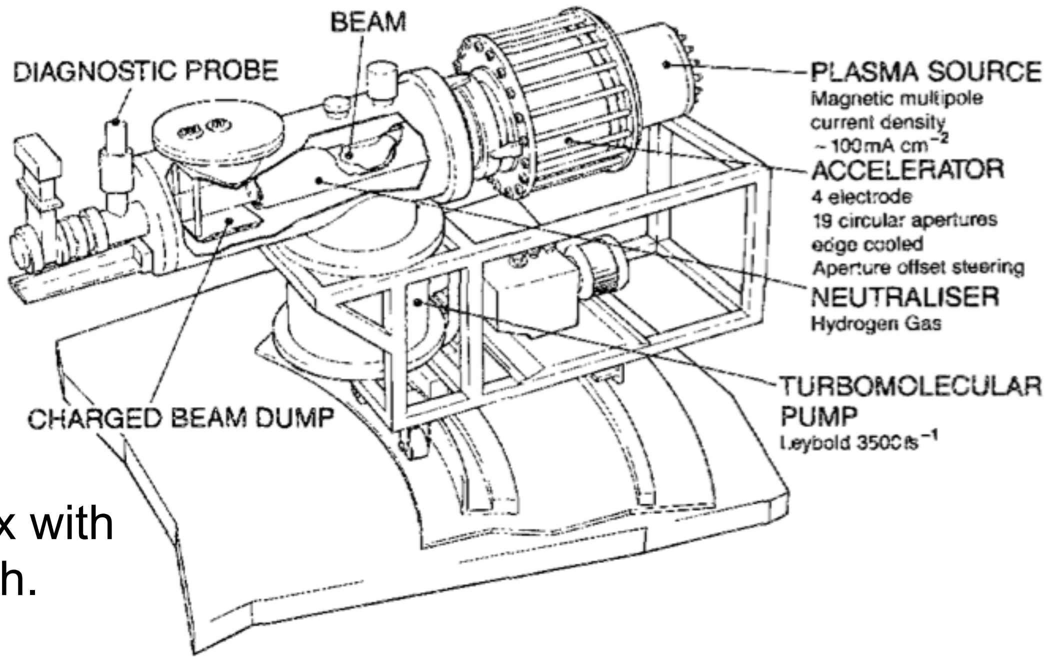




-See Fonck TF8.021 for more H-mode information

Diagnostic Neutral Beam to be Deployed On Pegasus

- Beam Energy: 60-80 kV
- Extracted Ion Current: 2-3 A
- Focal Length: 400 cm
- Full Energy Current Density @ 400 cm: 3-6 mA/cm^2
- Beam Divergence: 0.5°
- Species Ratio: (H:H/2:H/3)
  - Measured 22:35:43 @ 67 kV
  - Looking to increase species mix with our own arc plasma injector tech.
- 1/e diameter: 3.3 cm @ 400 cm
- Extraction plane diameter: 8.8 cm
- Extensive effort underway to design power supplies and new ion source



*See TP8.024 for more DNB details

*J. R. Coupland *et al.*, Rev. Sci. Instrum., vol. 61, no. 1, pp. 472–474, 1990.

Summary & Future Work

- Anomalous impurity ion heating observed during LHI with T_i~500 eV while T_e~50 eV
- While heating phenomenology is complex, a correlation with MHD readily apparent
- Toroidal rotation shear observed in Pegasus H-mode discharges, longer pulse length desired

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- Use Helium working gas in LHI discharges to get first majority ion temperature
  - Use HeII 4685 Å, 54 eV Ionization Energy
  - Low T_e during LHI makes line useable throughout plasma
  - Use of Argon as working gas has already been demonstrated
- Develop Neutral Particle Analyzer to look for energetic majority ion
- Diagnostic Neutral Beam development underway

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