Magnetic Reconnection and Ion Flows During Point Source Helicity Injection on the Pegasus Toroidal Experiment

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PEGASUS
Toroidal Experiment

Abstract

A passive ion temperature polychromator has been deployed on Pegasus to study power balance and non-thermal ion distributions that arise during point source helicity injection. Spectra are recorded from a 1 m F/8.6 Czerny-Turner polychromator whose output is recorded by an intensified high-speed camera. During helicity injection, stochastic magnetic fields keep T_e low and thus low ionization impurities penetrate to the core. Under these conditions, high core ion temperatures are measured ($T_i \approx 1.2$ keV, $T_e \approx 0.1$ keV) using spectral lines from CIII, NIII, and BIV. This rapid ion heating is seen to coincide with internal MHD activity. The ion temperature closely follows the injection bias voltage, indicating that power from the guns is strongly coupled to the ions through this MHD activity. Bi-directional toroidal ion flows of ~60 km/s have been observed on the BIV line during helicity injection when looking near the front of the injectors. The flow is on the order of the Alfvén velocity, as predicted by Sweet-Parker reconnection, and is indicative of magnetic reconnection occurring near the injectors. When looking away from the helicity injectors, the bi-directional flow appears to be replaced by strong toroidal rotation, suggesting that ion acceleration during helicity injection is asymmetric and 3D in nature.

Summary

- High speed passive ion doppler spectrometer deployed on the Pegasus Toroidal Experiment to study ion dynamics during local helicity injection (HI) and Ohmic current drive
- Strong ion heating during HI, indicative of magnetic reconnection
- Ion temperature anisotropy observed with $T_{\perp} > T_{\parallel}$, similar to results on MST
- Large n=1 oscillations correlate with T_i rise
- Anomalous spectral line splitting observed during HI
- Toroidal flow reversal during L $\rightarrow$ H transition
- Helicity injector arc channel density measured to be on the order of 10^{21} m^{-3} using pressure broadening of Balmer series

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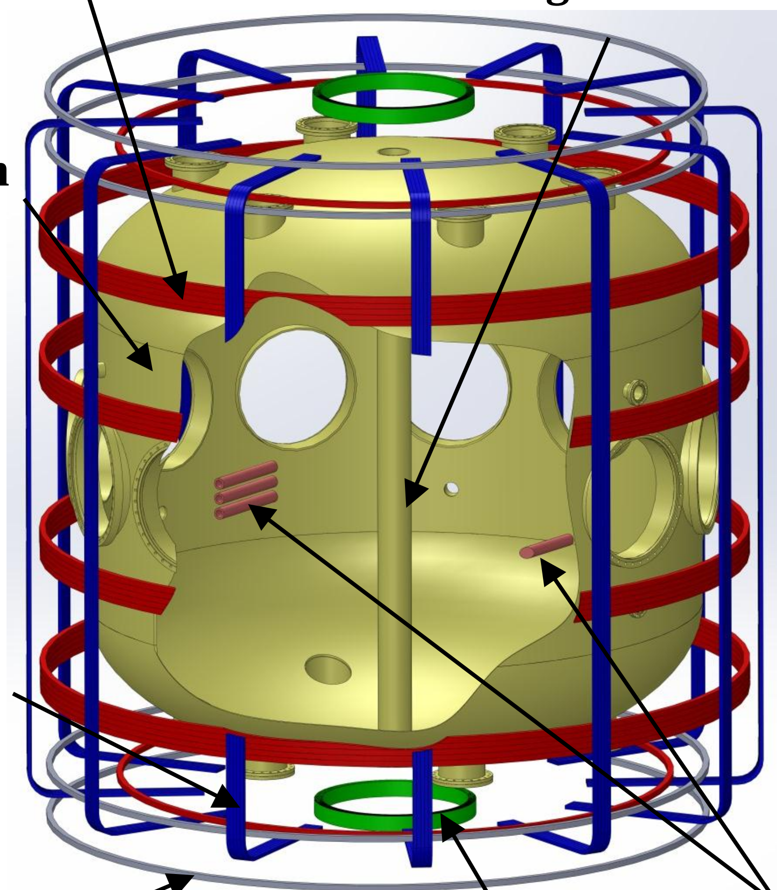
Pegasus is a Compact, Ultralow-A ST



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

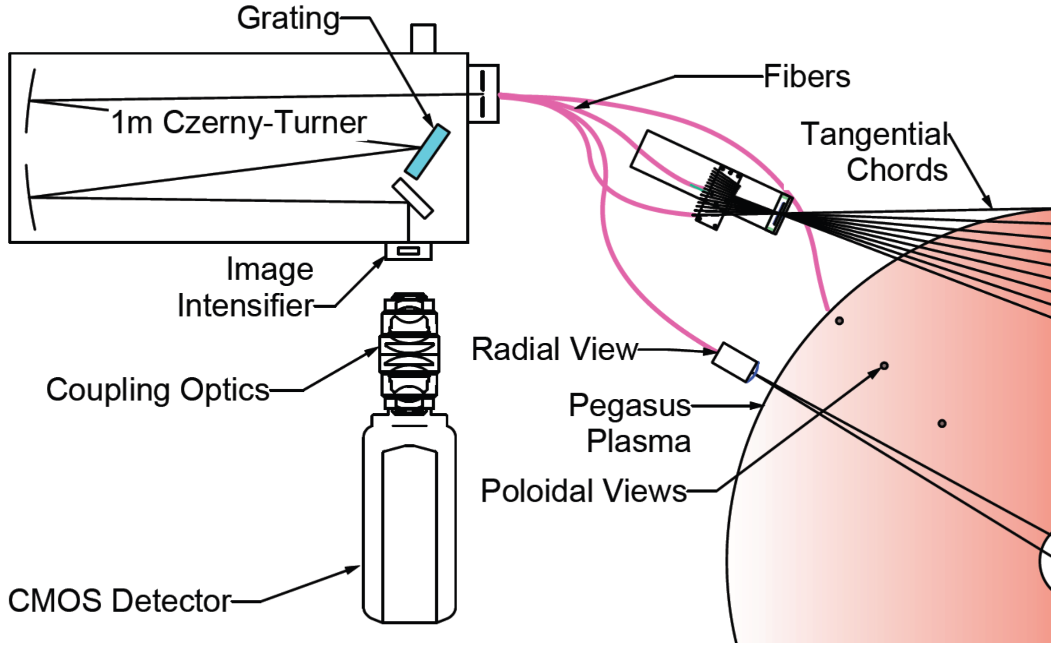
Major research thrusts include:

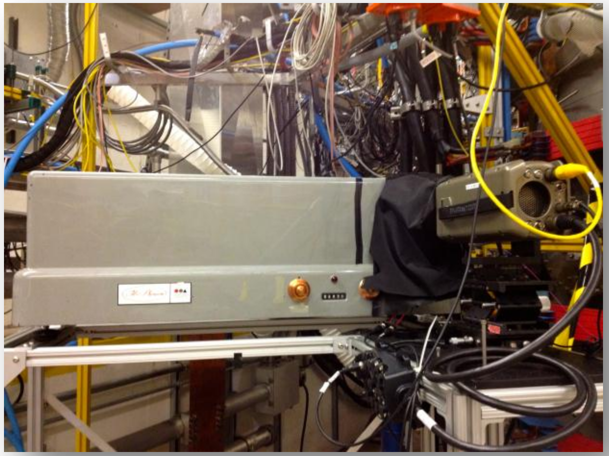
- *Non-inductive startup and growth*
- *Tokamak physics in small aspect ratio*
  - *High-I_N, high-β operating regimes*
  - *ELM-relevant edge MHD activity*

Magnetic Reconnection in the Pegasus Toroidal Experiment

- A hallmark signature of magnetic reconnection is anomalous ion heating
- Strong ion heating readily observed through spectroscopy on dedicated reconnection experiments (MRX, TS-3) and tokamaks during sawtooth crashes (MST)
- High, anomalous ion heating has been observed in measurements during local helicity injection
- Observation points to magnetic reconnection playing an important role in dc helicity injection on Pegasus

Diagnostic Setup on Pegasus



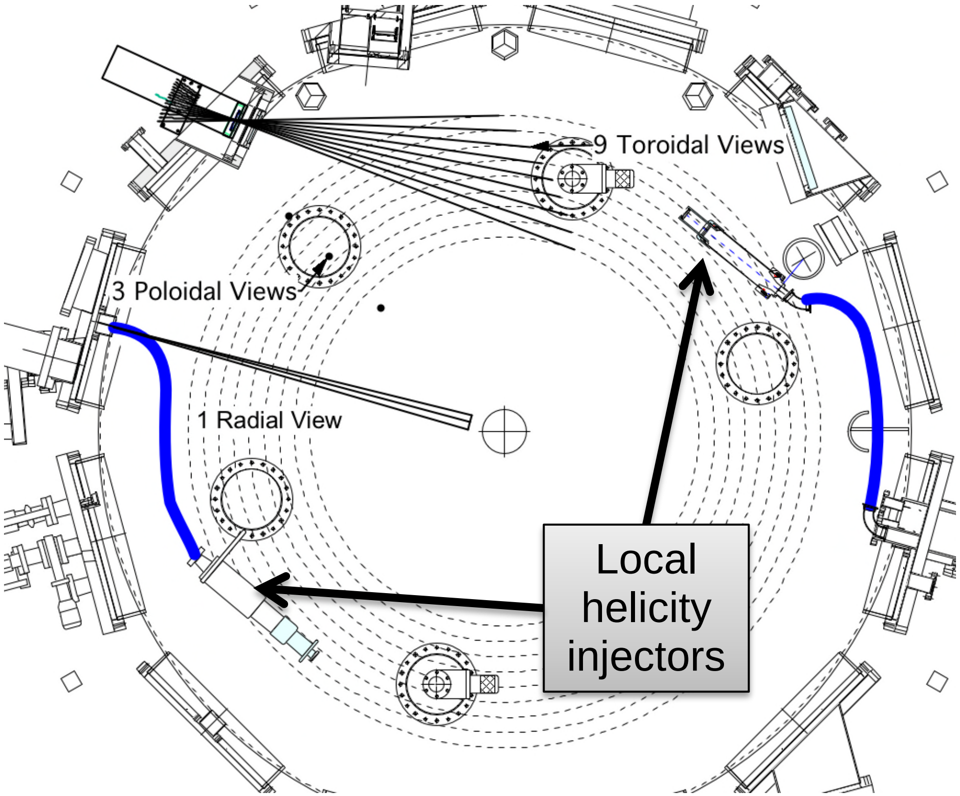


Diagnostic Characteristics:*

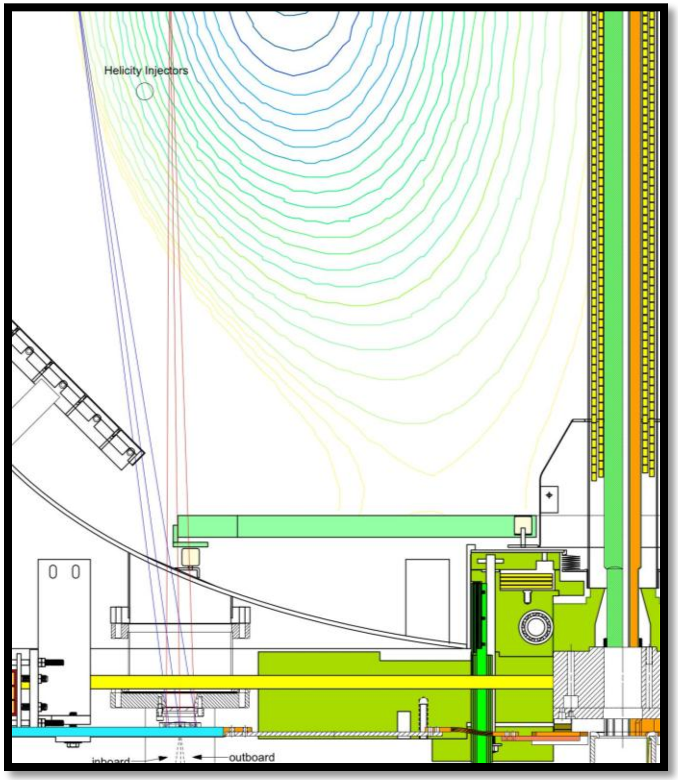
- Spectrometer: UV 1m f/8.6 Czerny-Turner
- Spectral Range: 200 – 600 nm
- Spectral Resolution: 0.15 Å
- Total etendue: 1.8×10^{-4} cm^2-str
- Time resolution: 5 kHz
- 3D velocity distribution measurements with chords in the toroidal, poloidal, and radial directions
- High spectral resolution
  - 3^{rd} order instrument effective temp: 40 eV
  - 5^{th} order instrument effective temp: 6 eV

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

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



Poloidal Views



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

Ion Heating and Flows During Local Helicity Injection

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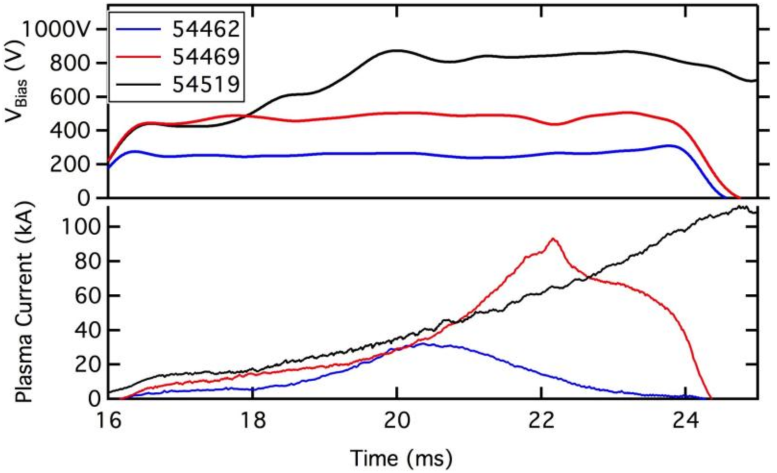
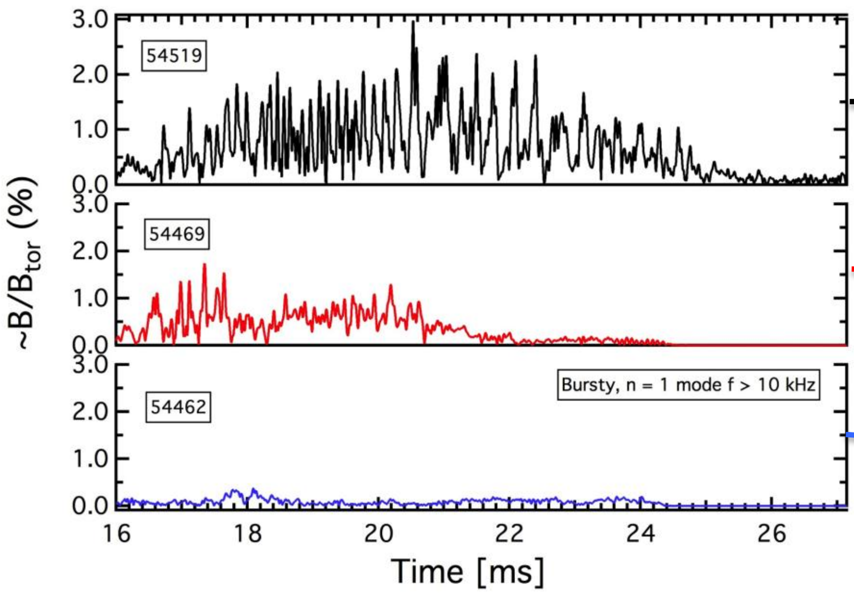
Strong Ion Heating Observed on Radial Line Integrated Chord; Correlates With MHD Amplitude and Power Input

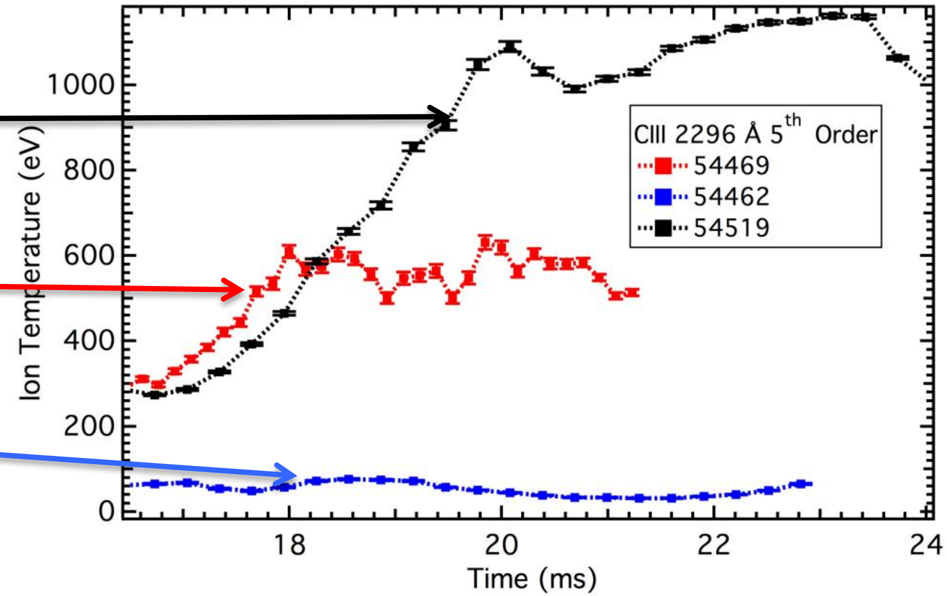
- Ion heating observed on multiple line species (CIII, NIII, OIII) during helicity injection

- Heating correlated with n = 1 burst activity
  - Larger amplitudes → more reconnection heating

- See NP8.00061 for Pegasus MHD







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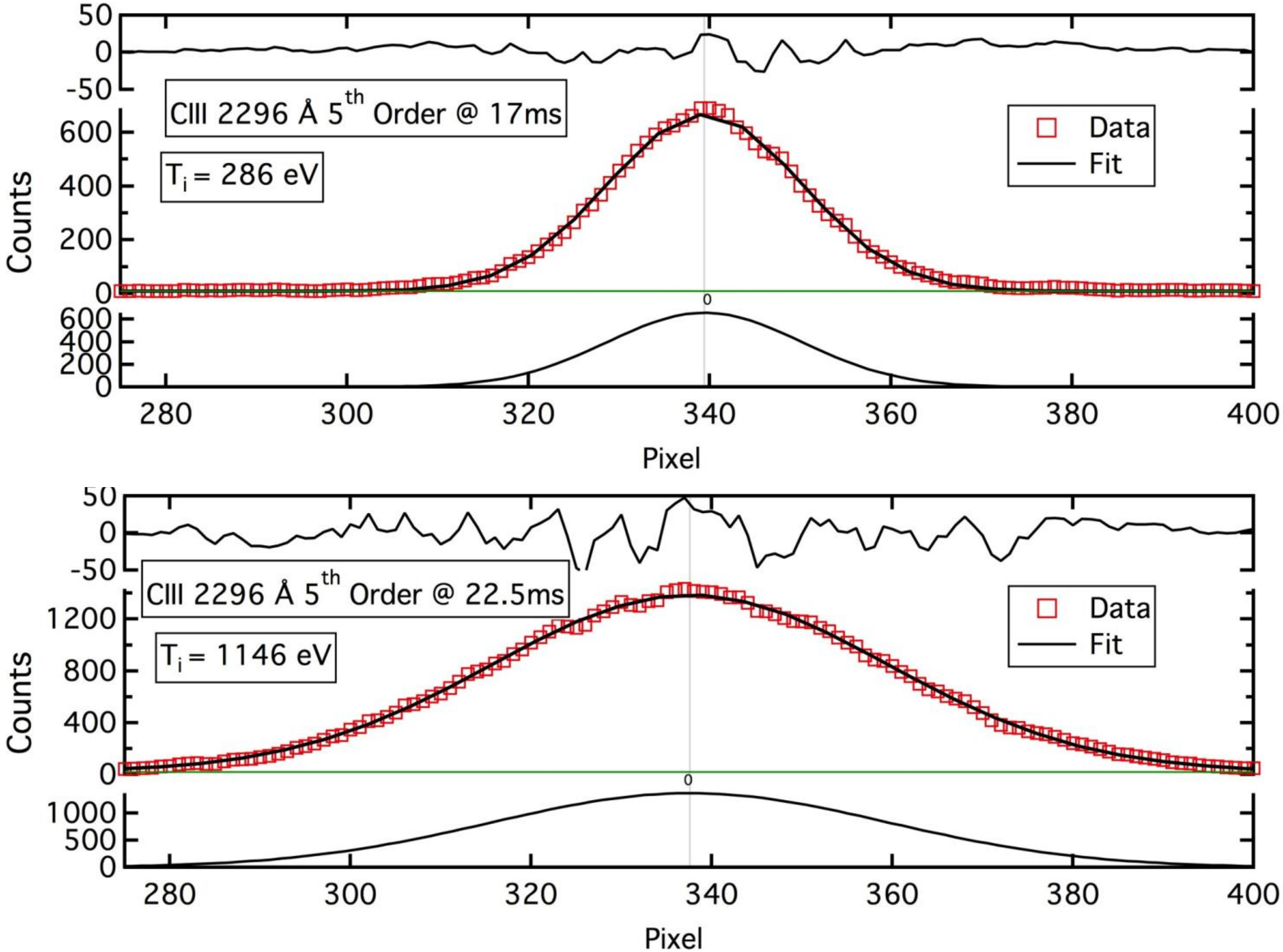
Radial Line Integrated Profiles Show Thermal Ion Distribution

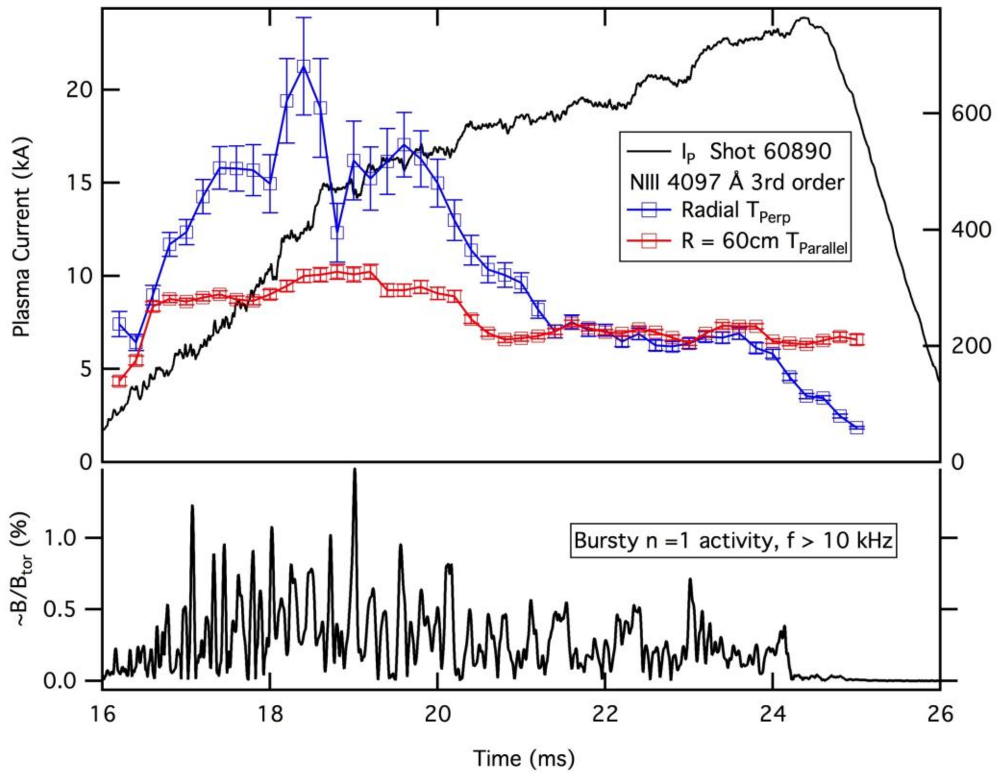
Shot 54519



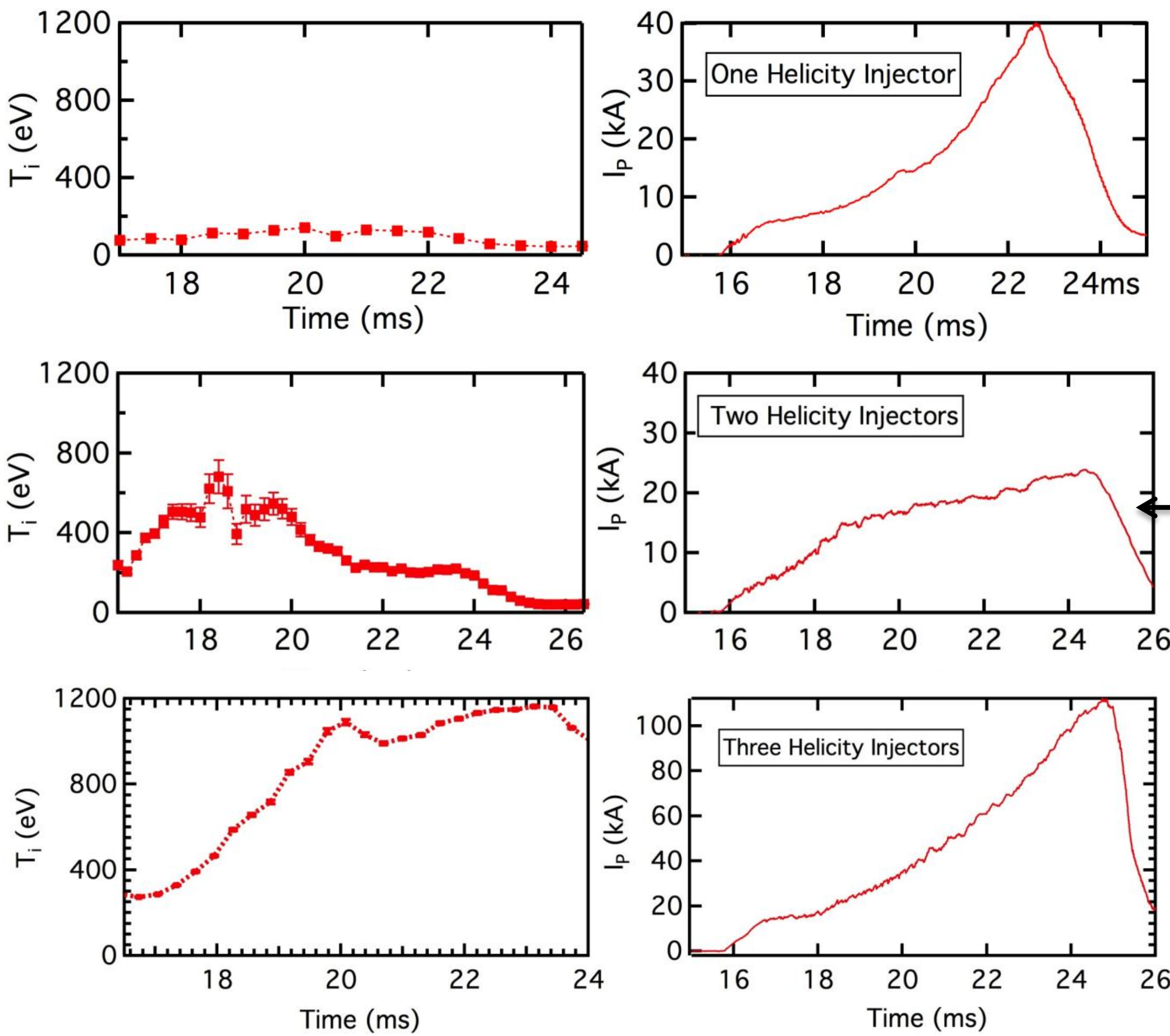
Temperature Anisotropy Observed During Local HI with $T_\perp > T_\parallel$

- A temperature anisotropy between $T_\perp$ and $T_\parallel$ has been observed during local HI current drive
- This indicates that the reconnection heating mechanism favors the direction perpendicular to the global magnetic field

- Similar phenomenon observed on MST during sawtooth events
  - Magee R.M., *et al*. Phys. Rev. Let. 2011 **107** 065005



Additional Helicity Injection Sources Leads to Higher Achieved Ion Temperatures



No Poloidal Field induction

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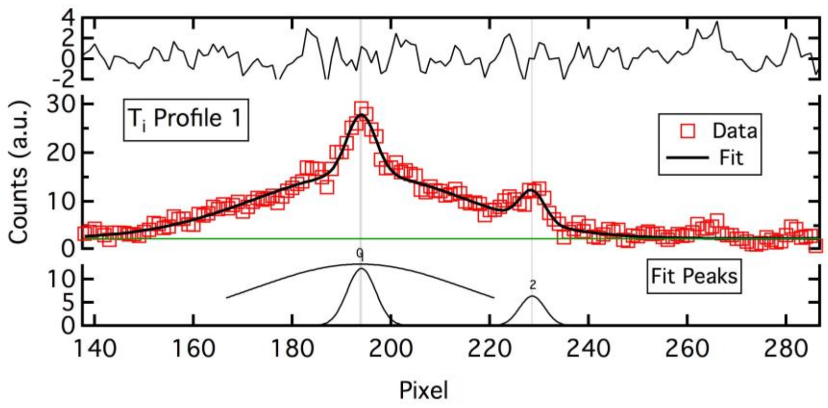
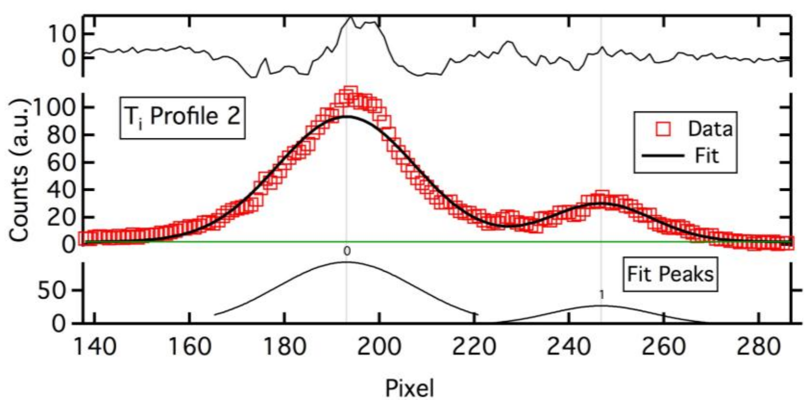
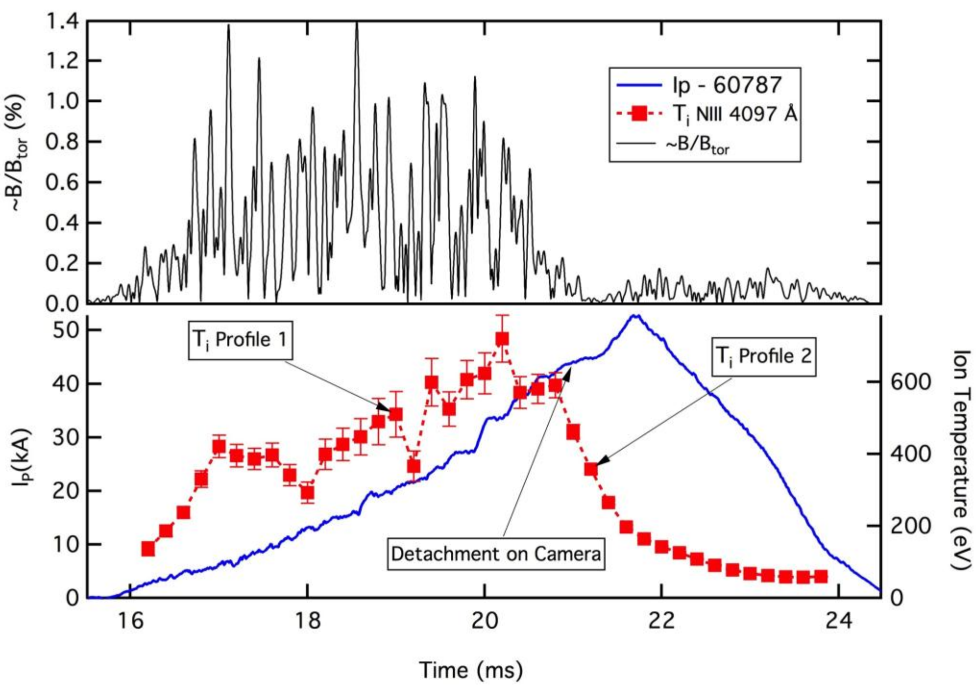
Ion Heating and n = 1 Fluctuations Stop When the Plasma Detaches

- T_i and n = 1 amplitude remain high during helicity injection and then drop as the plasma detaches from the injectors

- Hot ion temperature profile polluted by cold component of unknown origin







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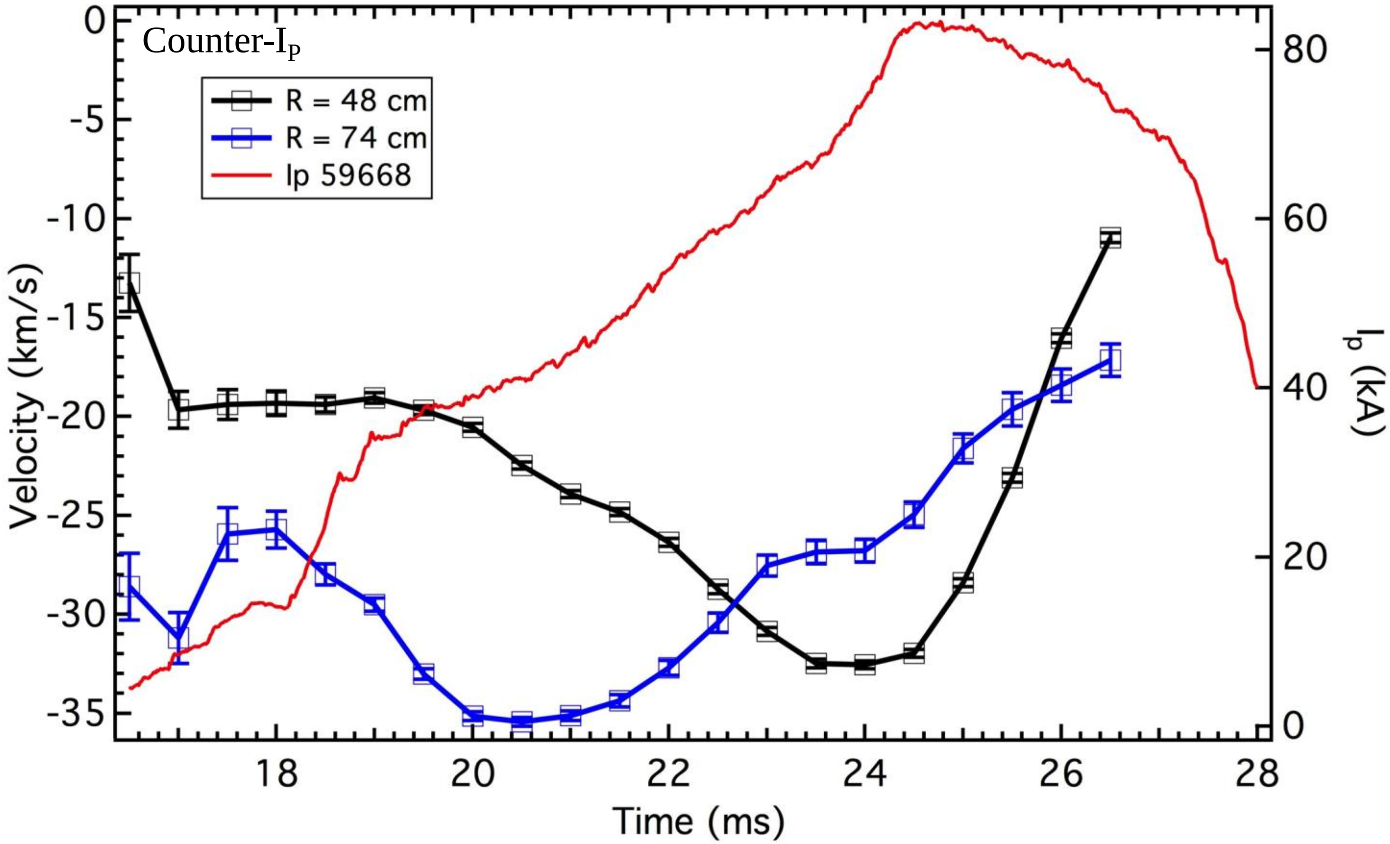
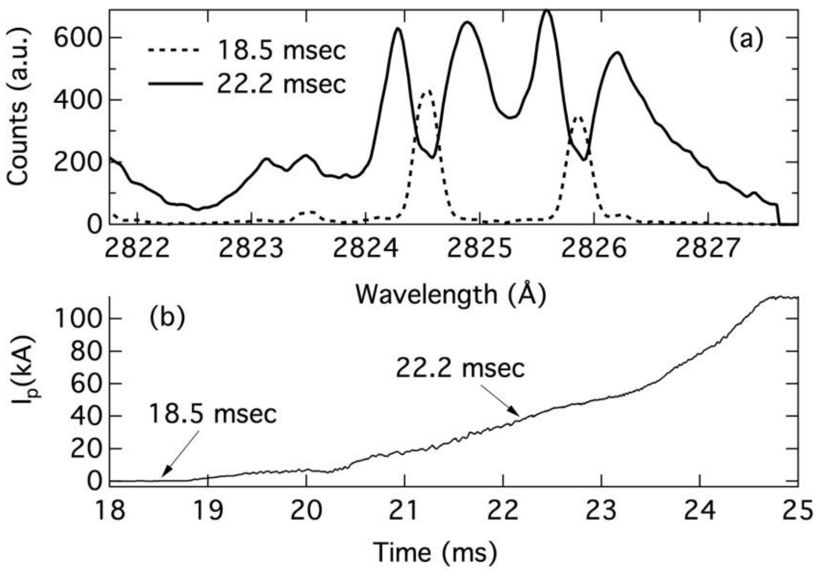
Toroidal Spin Up in co-I_P Direction is Observed with Application of -V_{Bias}

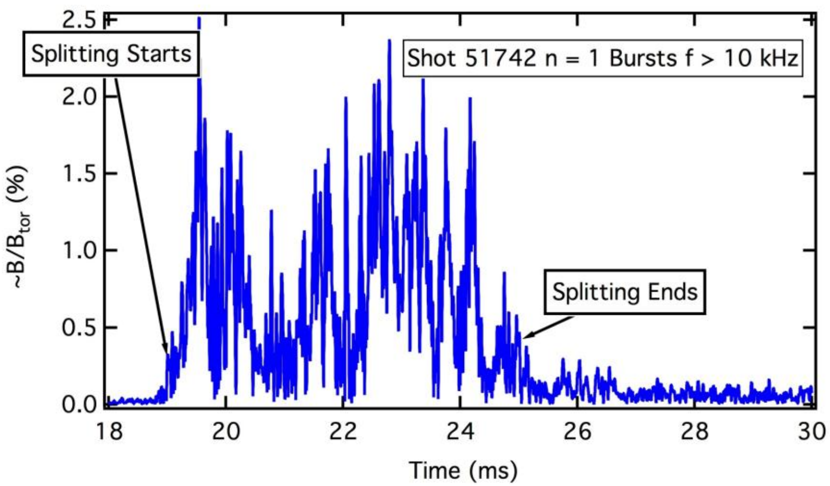
- Follows $E_r x B_z$ directionality for a negatively biased electrode in the edge of a tokamak plasma
- Rotation is in co-I_P direction
  - Intrinsic toroidal rotation during ohmic drive is in the opposite direction



Strong Line Splitting Seen on Multiple Lines During Local HI

- Splitting of BIV and NIII lines in bulk plasma observed in past high HI discharges
- Splitting velocity ~ 60 km/s is on the order of the Alfven velocity at the edge of the plasma
- Magnitude of of splitting may depend on viewing geometry
- Strong splitting has not been observed in the present low HI discharges from this year
- Reinstallation of old helicity injector geometry underway to explore this phenomenon further





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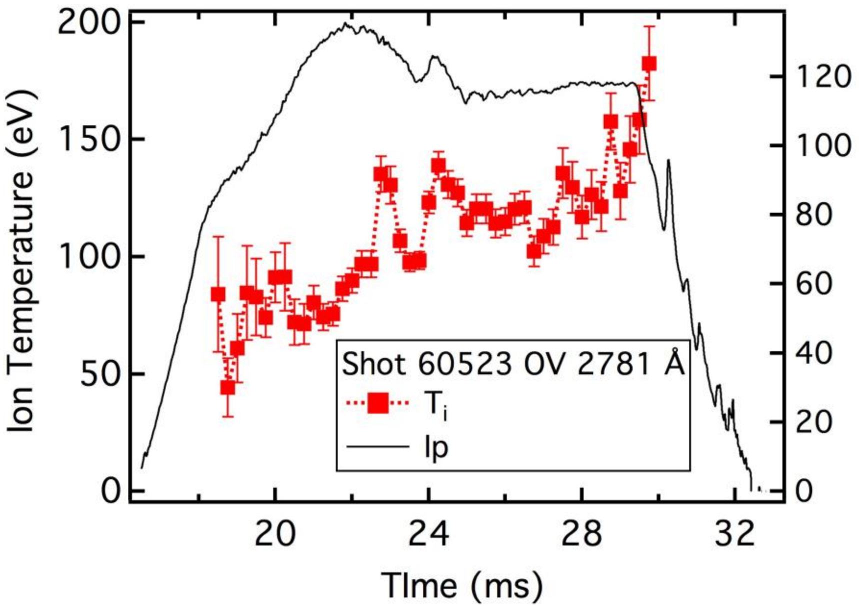
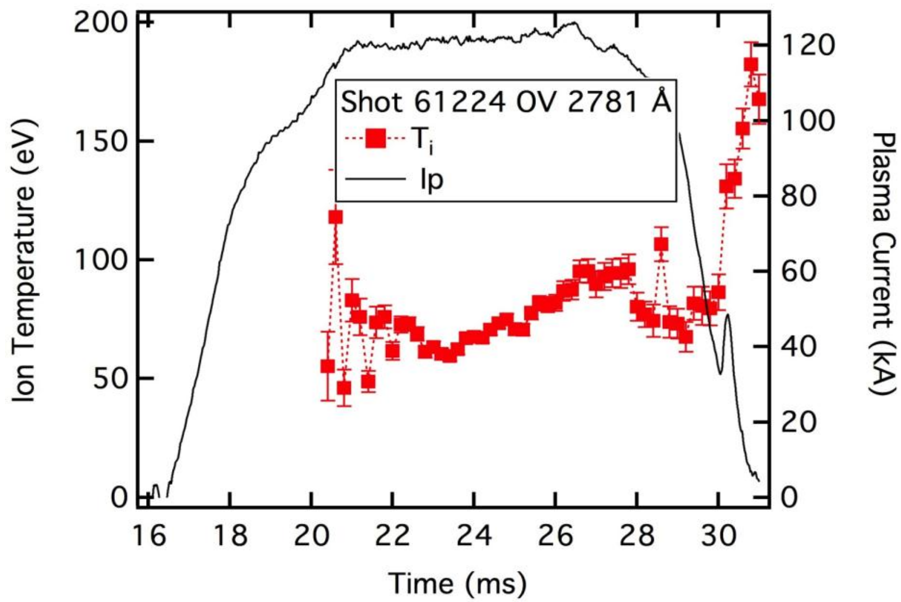
Ion Temperature and Flows During L and H Mode Ohmic Plasmas

Higher Ion Heating Rate Indicative of Better Confinement

H-Mode



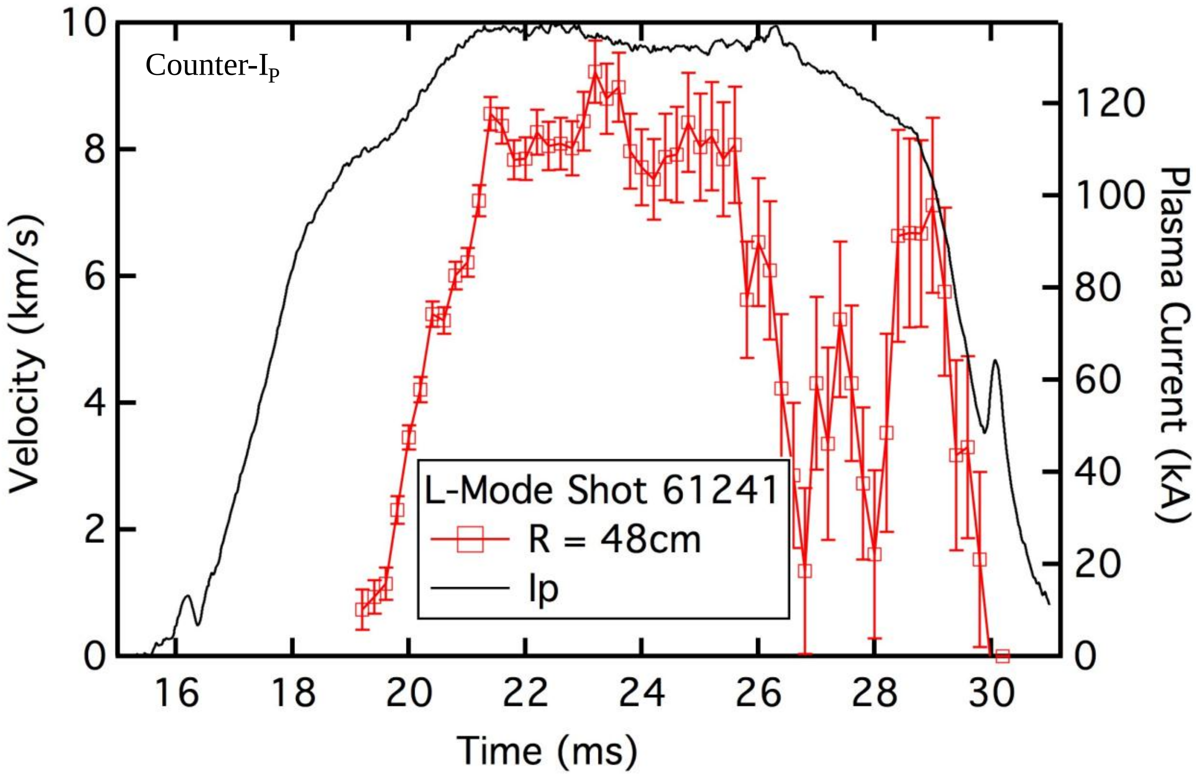
L-Mode



- More rapid ion heating observed during H-mode confinement
- T_i heating rate of 8 keV/s during H-mode
- T_i heating rate of 2.8 keV/s during L-mode
- Strong ion heating during IRE’s

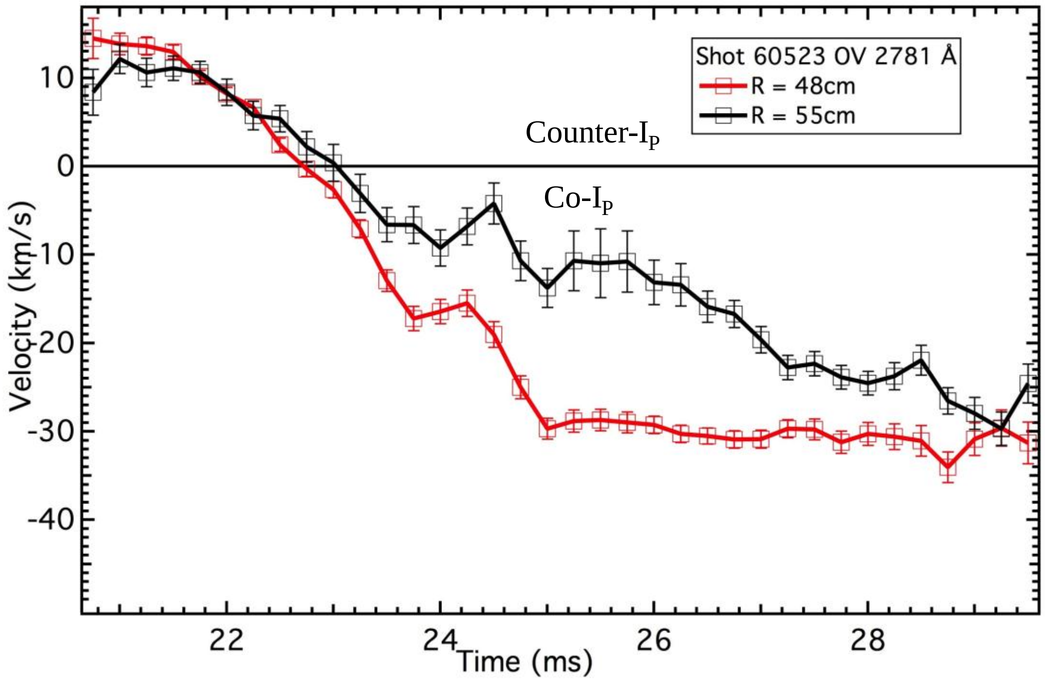
L-mode Discharges Develop Intrinsic Counter Current Rotation

- L-Mode intrinsic rotation observed in the counter current direction, as seen on other tokamaks
  - Rice J.E., *et al*. Nucl. Fus. 2007 **47** 1618

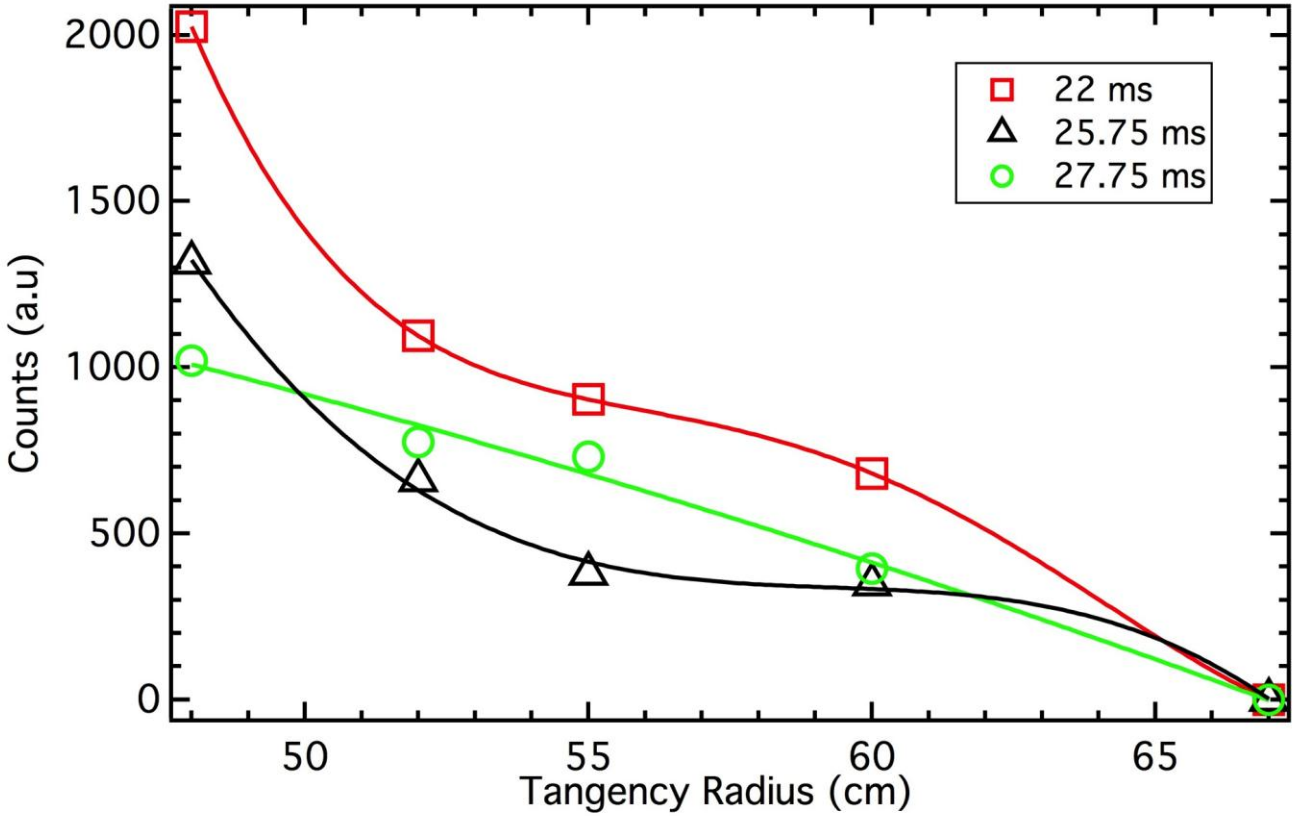


Toroidal Flow Reversal Observed at L → H Transition

- Observed co-I_P spin up of plasma during H-mode
- Toroidal rotation reverses direction during H-mode onset, as seen by MAST and NSTX during HFS fueling
  - *Meyer H. *et al* 2008 J. Phys. Conf. Ser. **123** 012005



Flattening of OV Intensity Profile Suggests Broadening T_e Profile

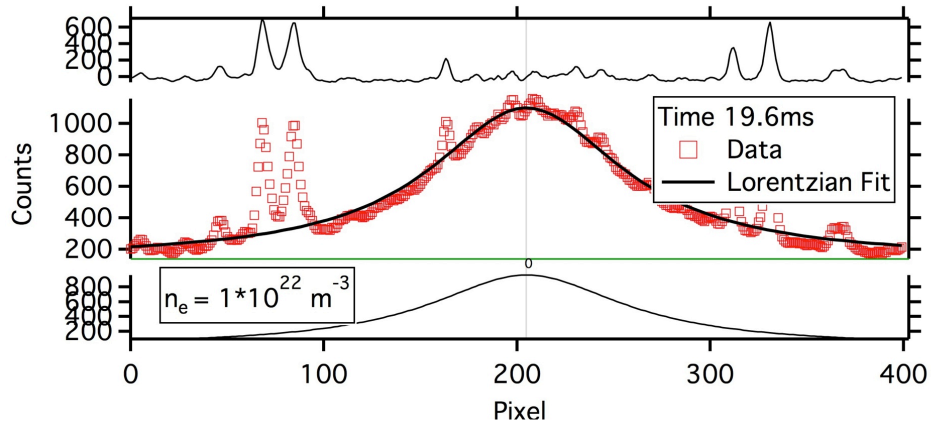


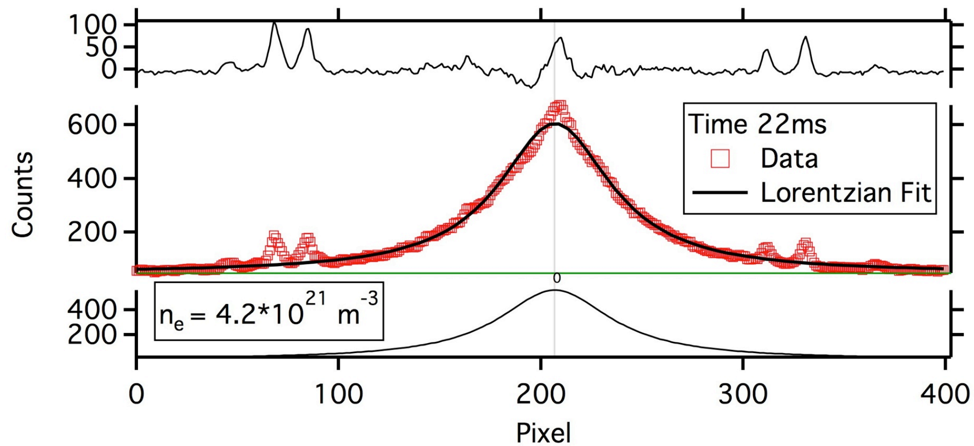
- Observation of high energy charge states such as CV on radial line integrated chord is suggestive of high T_e in core
- See NP8.00064 for more on Pegasus Ohmic discharges

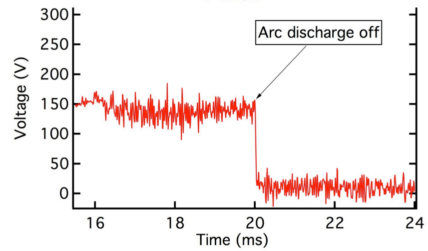
Helicity Injector Arc Discharge Electron Density Measured to be ~10^{21} m^{-3}

$$\Delta\lambda_{H_\delta}^{FWHM} = 0.92\left(n_e^{20}\right)^{2/3} [\text{A}]$$

- Pressure broadening of Balmer series lines used to measure electron density
- n_e of order 10^{21} m^{-3} plasma resides in arc chamber
- See NP8.00062 for more details

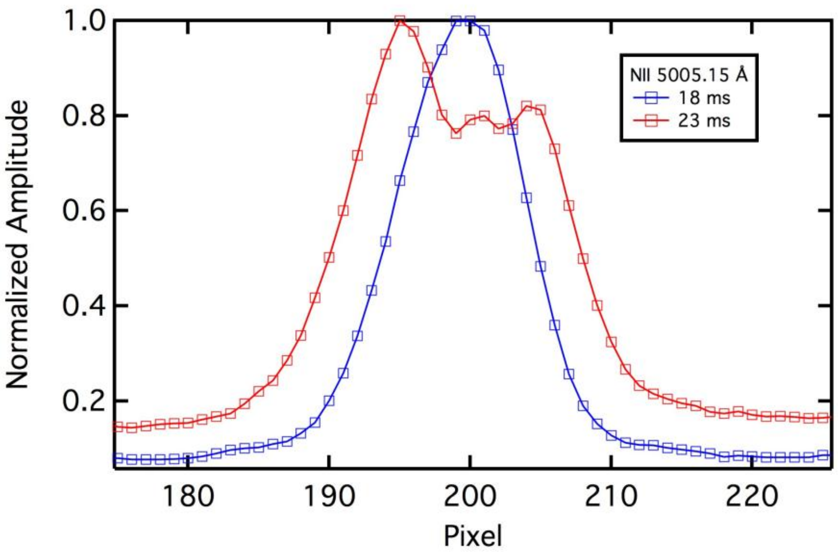


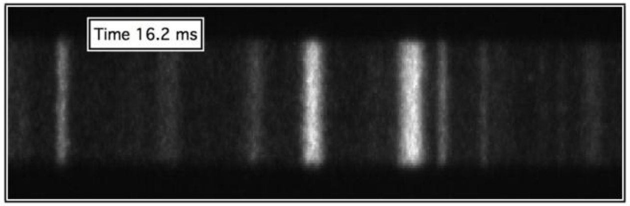


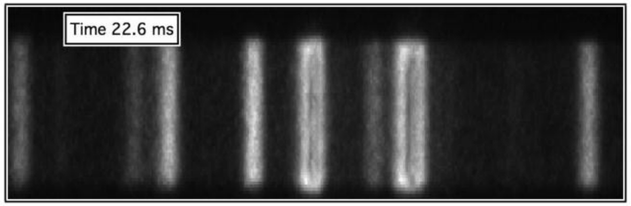


Modest Splitting Also Observed in Helicity Injector Arc Channel on NII Line

- Splitting occurs both in biased and unbiased arc discharges
- Biased discharges show bulk line shift at ~20 km/s into the helicity injectors
- Merits further investigation







Summary

- Strong anomalous ion heating has been observed on Pegasus during local helicity injection
- Heating correlates with n = 1 amplitude in $\tilde{B}/B_{tor}$
- Ion temperature anisotropy observed with $T_{\perp} > T_{\parallel}$
- Strong anomalous line splitting observed in the past and needs more exploration
- Toroidal flow reversal during L → H transition
- Spatial resolution of reconnection heating and flows needed to resolve issues encountered here
  - A DNB would be very beneficial!!

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