Ion Heating During Local Helicity Injection Plasma Startup in the Pegasus ST

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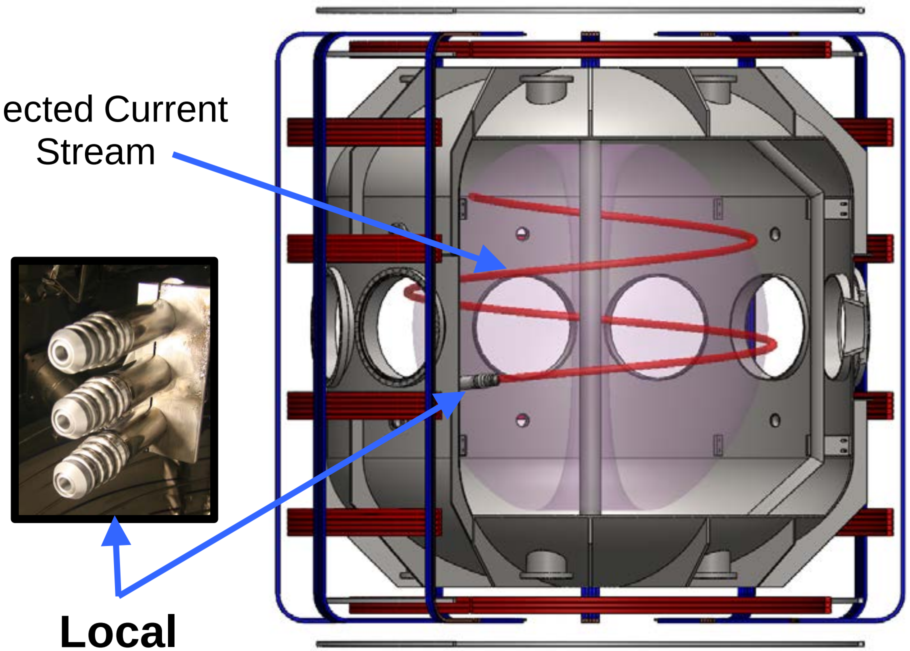
57th Annual Meeting
of the APS-DPP

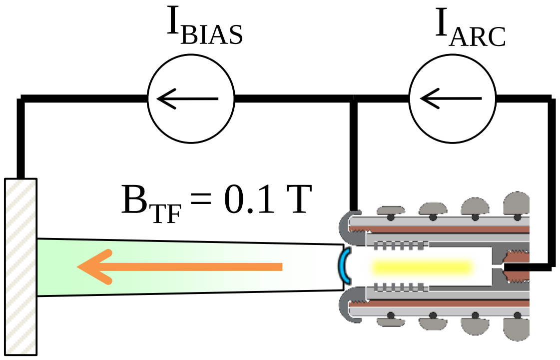
Savannah, GA
November 17, 2015

University of
Wisconsin-Madison

PEGASUS
Toroidal Experiment

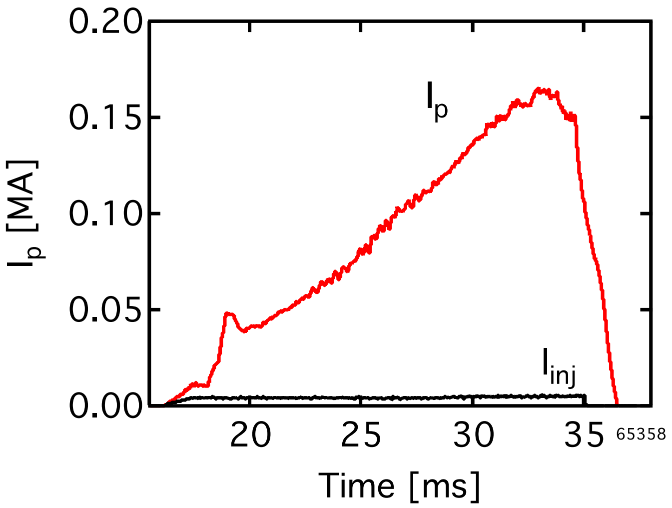
Outboard LHI Provides Robust Startup on the PEGASUS ST





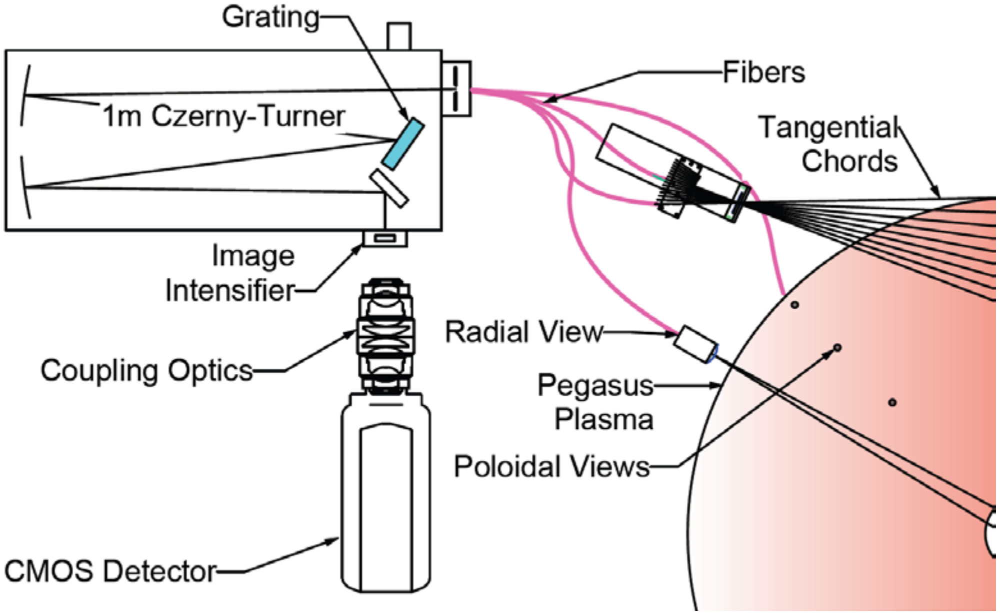
Vessel GND

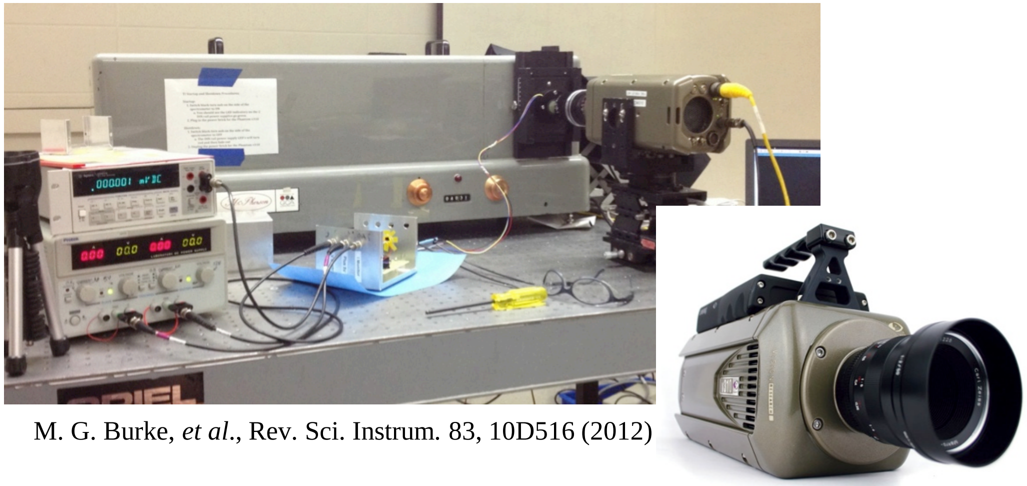
$I_p \leq 0.18$ MA via LHI ($I_{inj} = 5$ kA)



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

Ion Spectroscopy Diagnostic Deployed to Study Local Helicity Injection on Pegasus





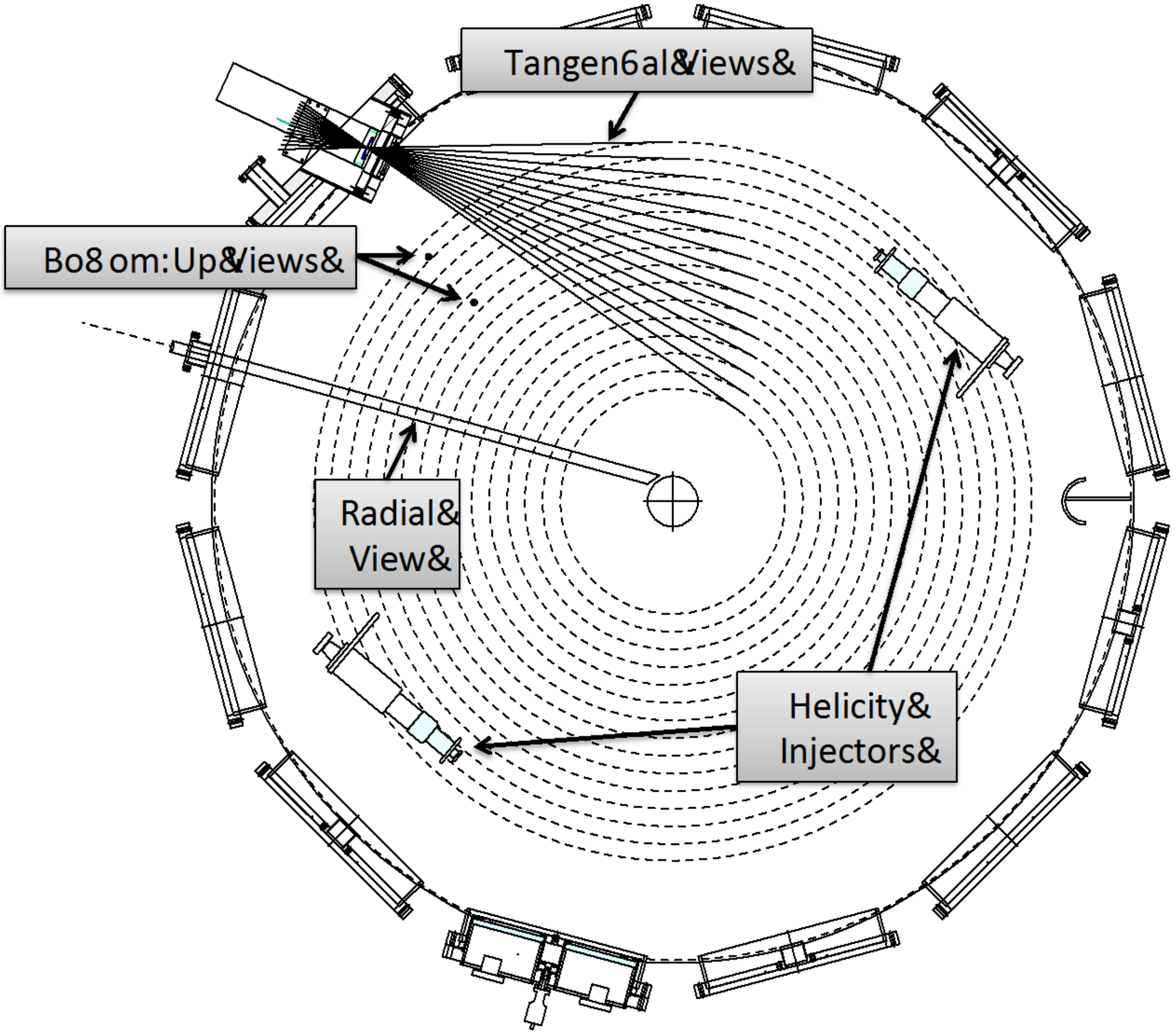
M. G. Burke, *et al.*, Rev. Sci. Instrum. 83, 10D516 (2012)

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

LHI Plasmas Studied Using Multiple Viewing Chords

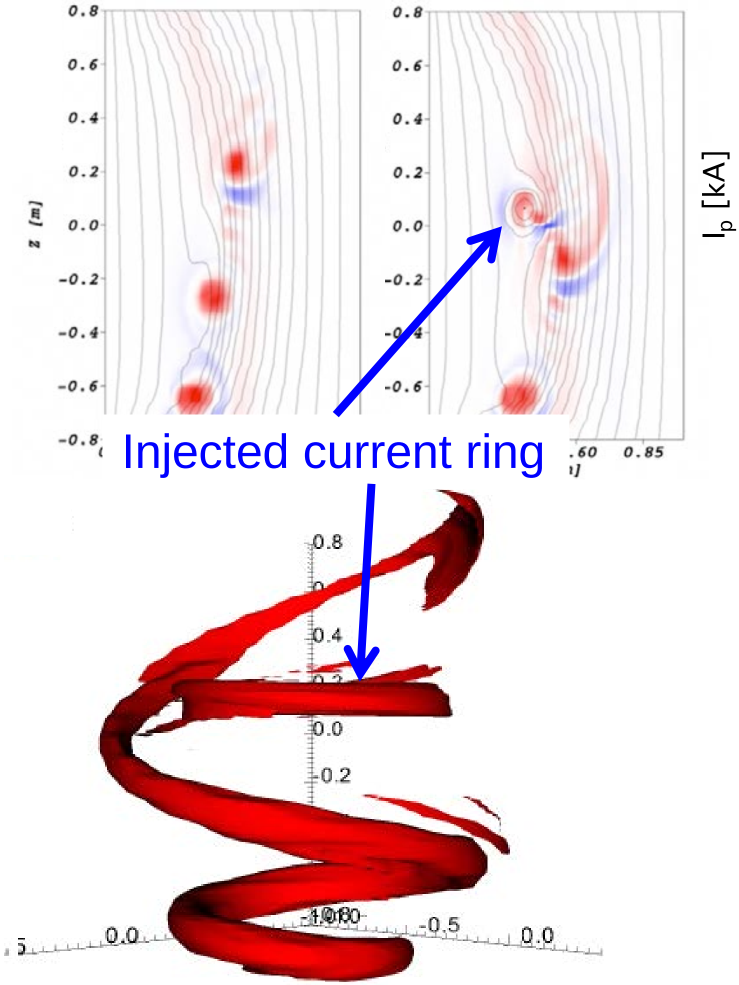
- 19x 1mm Quartz fibers used for collection
- Tangential viewing chords cover R = 25 to 80 cm with 4 cm resolution
- Poloidal views at R = 80 and 65 cm
- Single radial chord
- All chords recorded simultaneously with the possibility of adding additional fibers to increase SNR



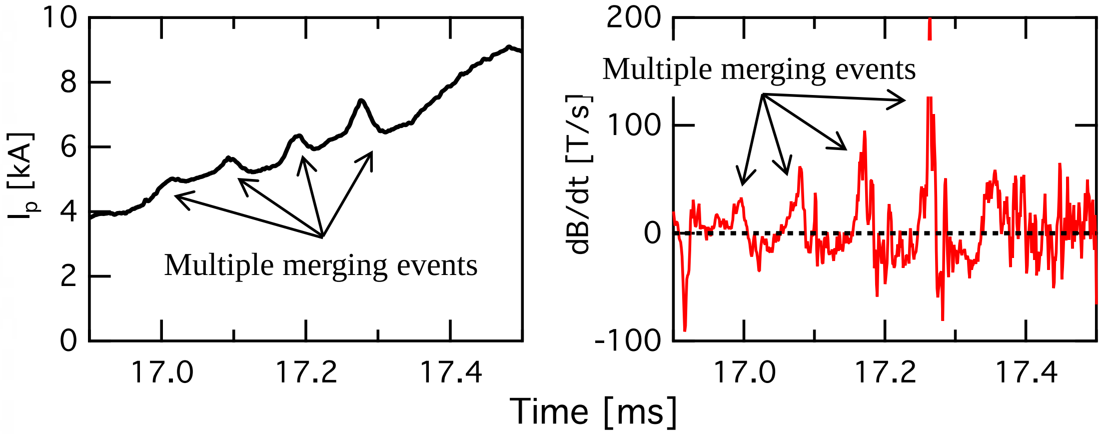
Top Down Cutaway

Magnetic Reconnection Activity Observed in NIMROD Simulation and Experiment During LHI

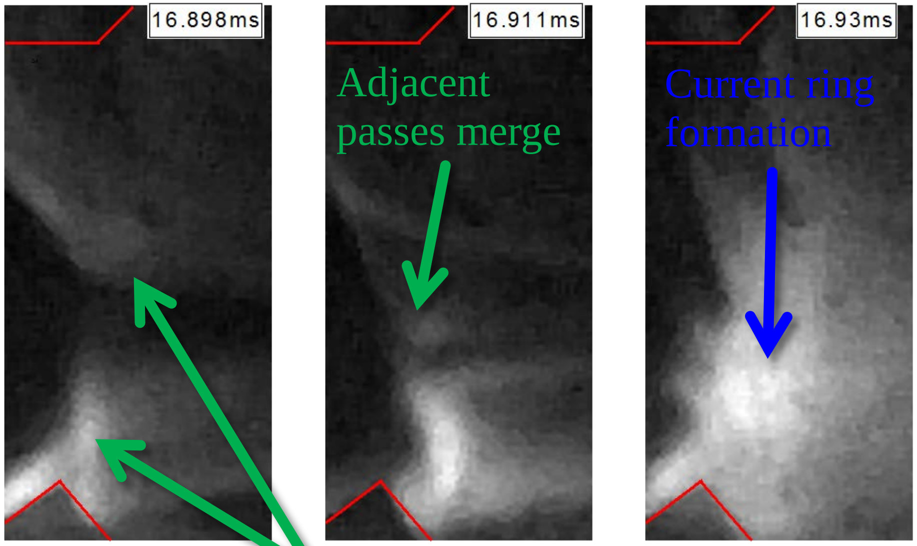
Current rings in NIMROD*



Observed current rings in PEGASUS (pre-tokamak plasma)



Single merging event:



Adjacent injector stream passes

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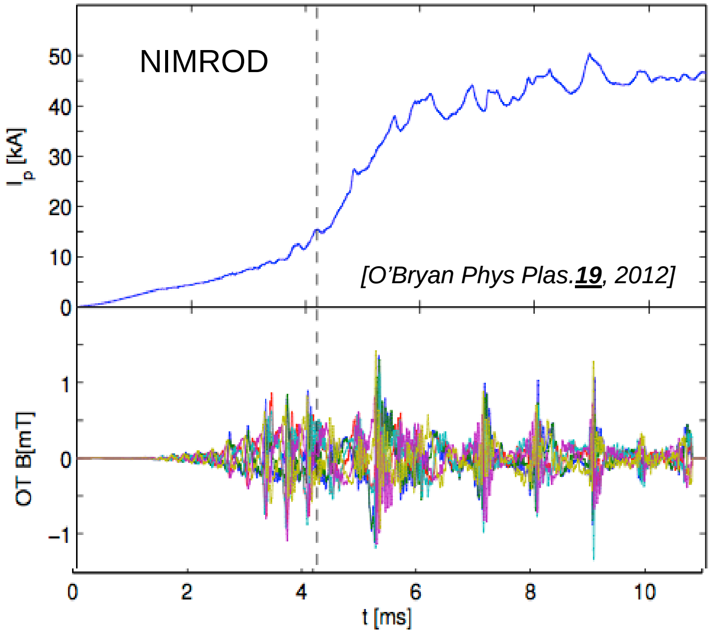
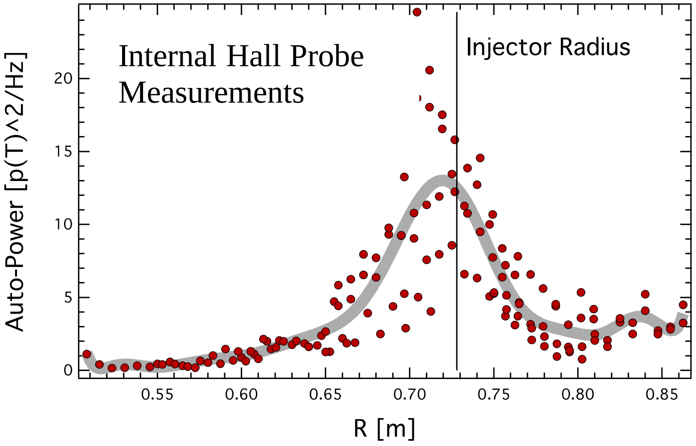
* *J. O'Bryan, et al., Physics of Plasmas,* ***19****, 080701 (2012)*
J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion ***56*** *064005 (2014)*

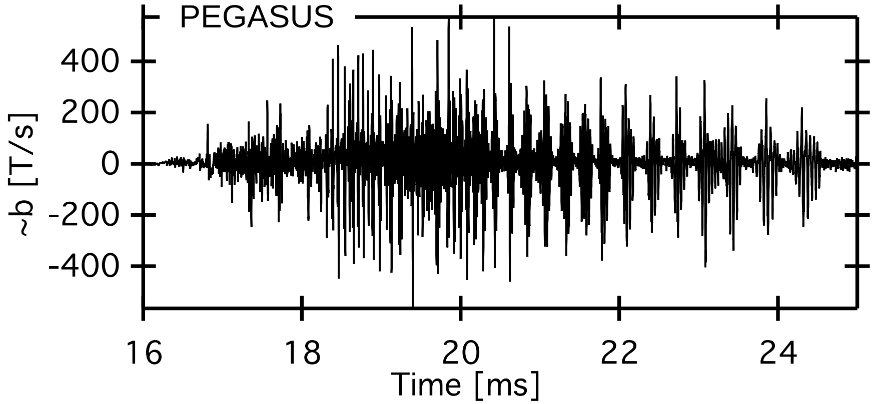
NIMROD Simulations of LHI on Pegasus Show Magnetic Reconnection Activity and Bursty MHD

- MHD bursts accompany I_p growth
  - Localized in edge*
  - n=1 line-tied kink structure
- Coherent streams persist in edge, matching NIMROD predictions
- NIMROD and experiment see wave excited at Alfven frequencies for device scale wavelengths
- Suggests edge localized reconnection



[O'Bryan Phys Plas.**19**, 2012]



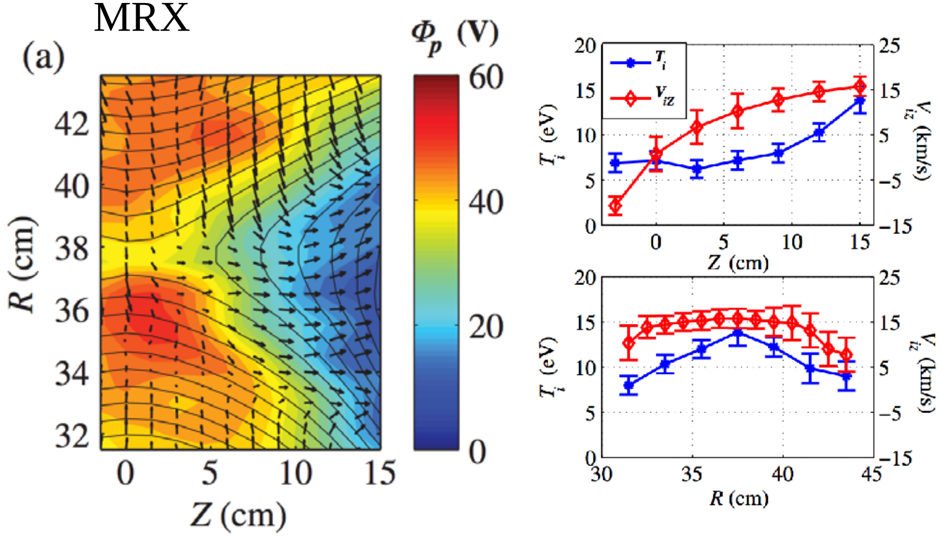


* E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.

Magnetic Reconnection Leads to Ion Heating in a Variety of Plasmas

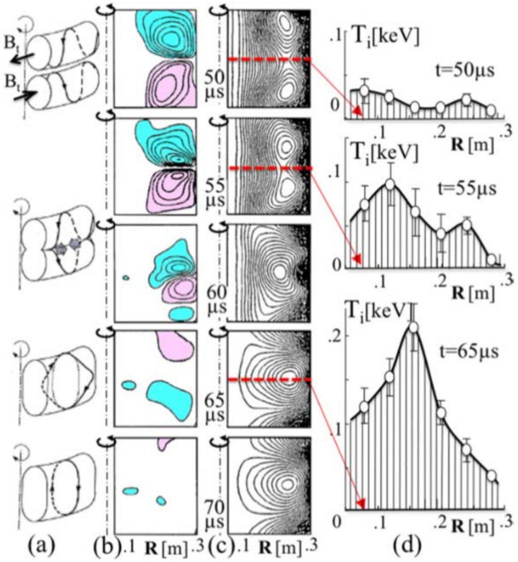
- Anomalous ion heating observed during magnetic reconnection in numerous devices such as MRX, TS-3, MST, HIT-II, MAST, SSX, etc., and in astrophysical plasmas

MRX



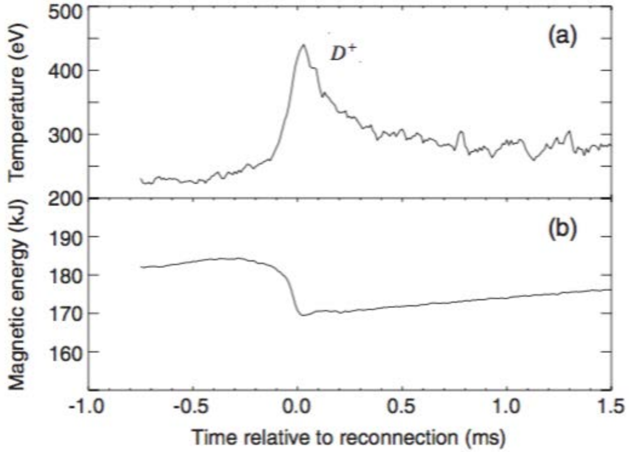
J. Yoo, M. Yamada, H. Ji, and C. E. Myers,
Phys. Rev. Lett., vol. 110, no. 21, p. 215007, 2013.

TS-3, MAST



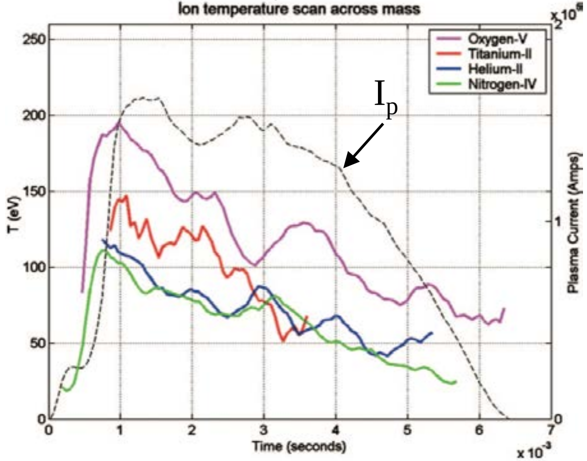
Y. Ono *et al.*, Plasma Phys. Control. Fusion, vol. 54, no. 12, p. 124039, 2012.

MST



G. Fiksel, *et* al., Phys. Rev. Lett., vol. 103, no. 14, p. 145002, Sep. 2009.

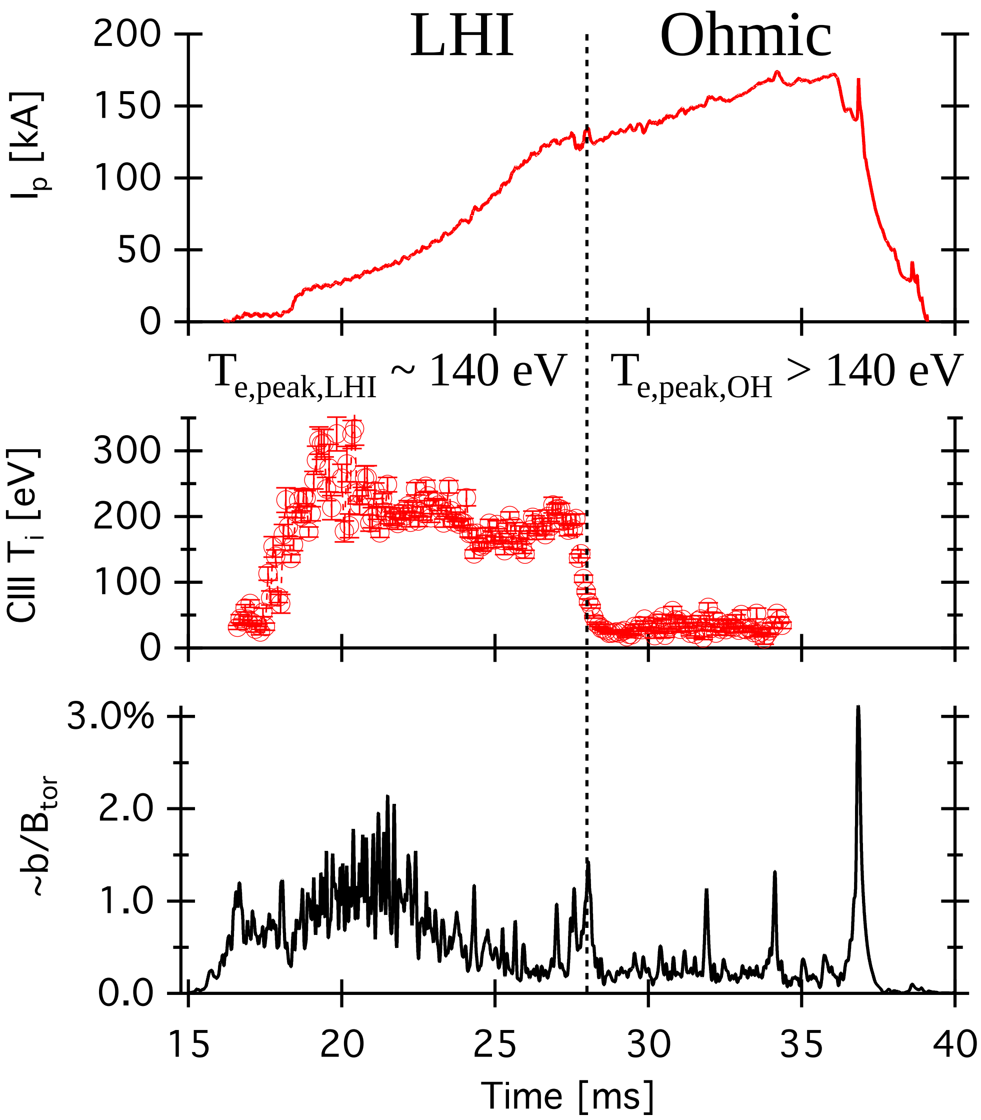
HIT-II, Helicity Injection



R. G. O'Neill *et al.*, Phys. Plasmas, vol. 12, no. 12, p. 122506, 2005

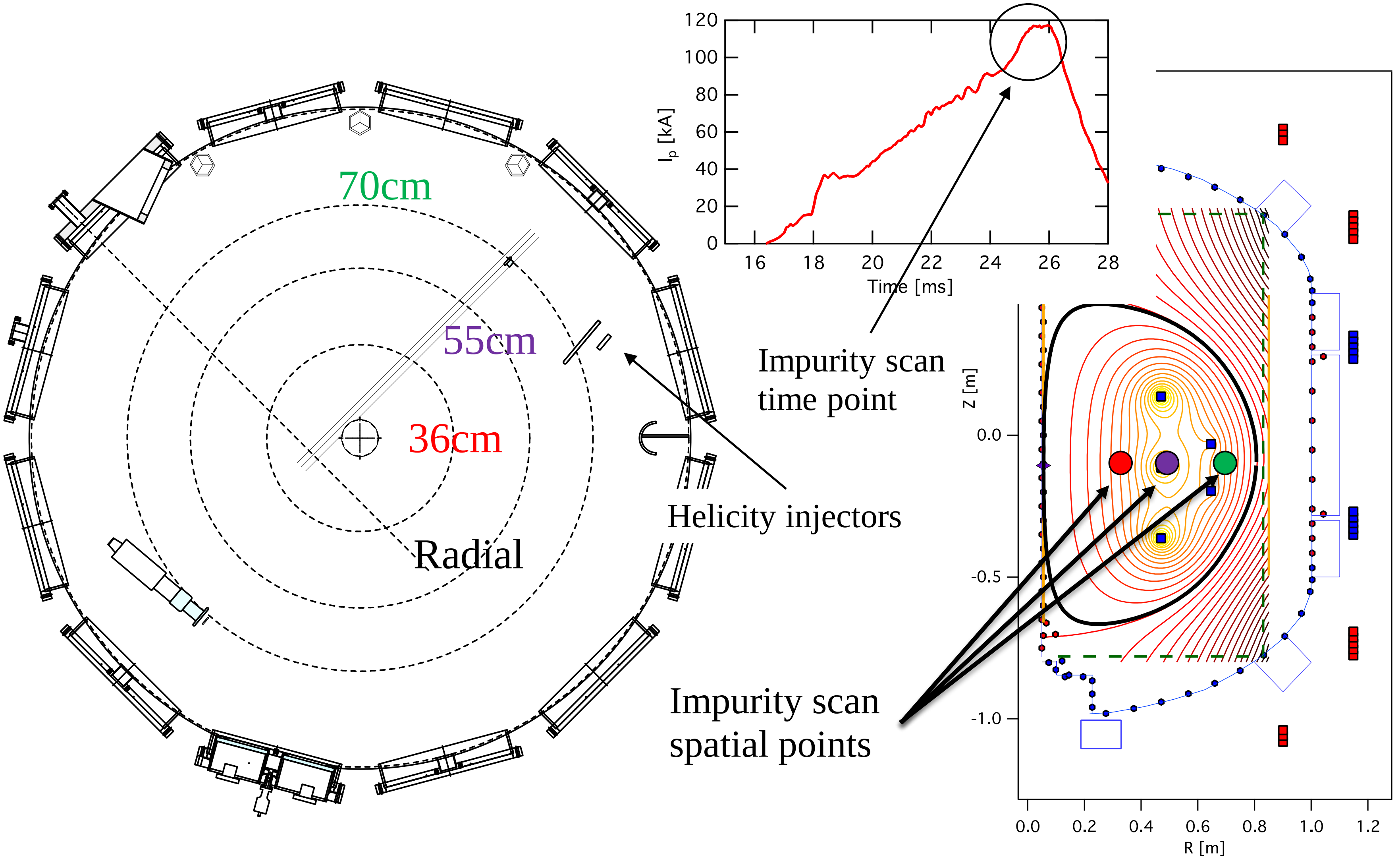
LHI Current Drive in PEGASUS Leads to Continuous Impurity Ion Heating

- Large impurity temperatures temporally correlated with large magnetic oscillations near the plasma edge
- $T_i > T_e$ during LHI current drive phase
- Immediately following handoff to Ohmic current drive, $T_i < 1/4 T_e$
- Large T_i attributed to ion heating due to magnetic reconnection



Impurity Spectral Profiles During LHI Reveal Edge Localized Heating and Apparent Non-thermal Distributions

- Studies of different impurity lines present in LHI plasmas performed in order to understand ion heating characteristics and dynamics



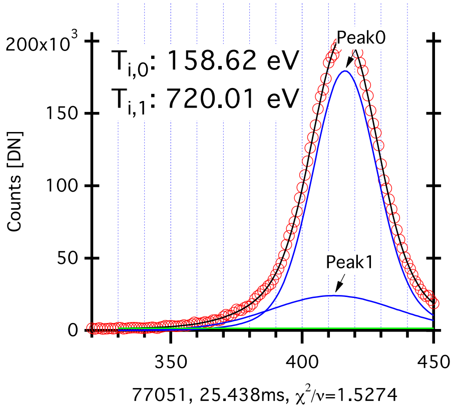
Impurity scan time point

Helicity injectors

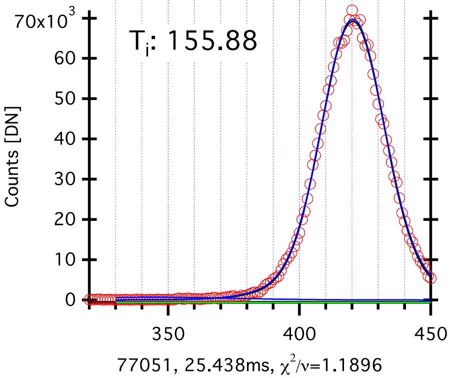
Impurity scan spatial points

Oxygen-V Spectral Profiles Indicate Edge Ion Heating, Diffusion of Energy to Plasma Core

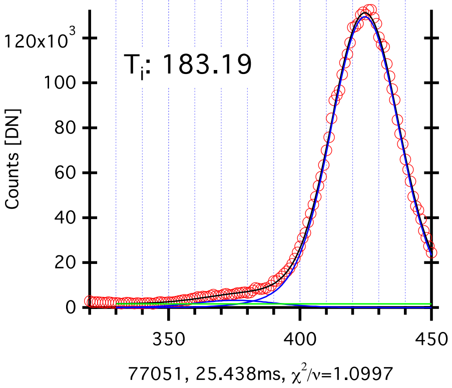
Radial



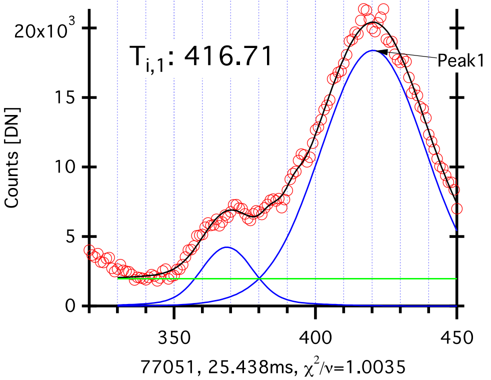
36cm



55cm



70cm



- Edge OV temperature much larger than core temperature during LHI
- In a comparable Ohmic plasma with similar applied loop voltage $T_{i,OV}$ ~ 50 eV
- Initial Thomson profiles indicate T_e~140 eV, peaked in plasma core (See David Schlossberg APS Poster) → OV, OVI terminal charge state

OV Emissivity Profile Peaked in Core, $T_{i,core}$ Uncontaminated by Hot Edge Emission

- Onion peeling method used to calculate emissivity, Abel integral used to forward model $T_{i,}$(R)

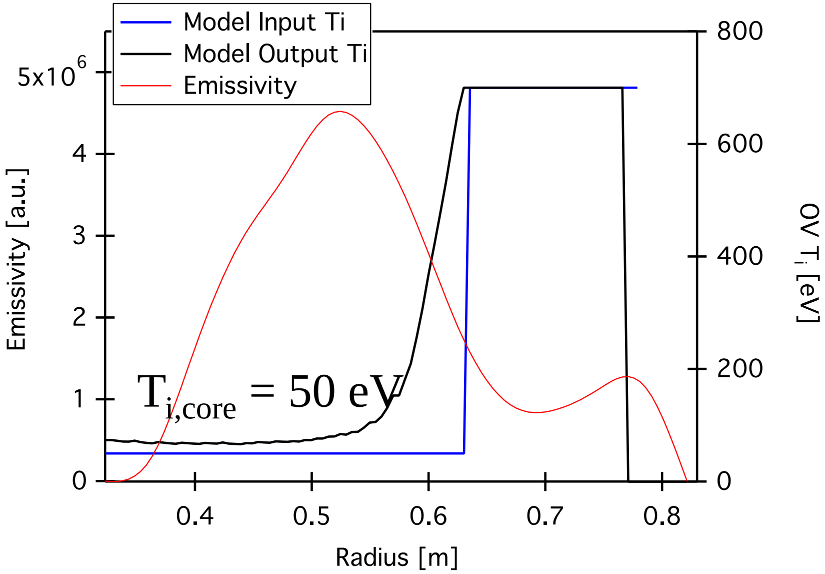
Abel Integral: $$I(y) = 2\int_y^1 \frac{g(r)r}{\sqrt{r^2 - y^2}}\,dr$$

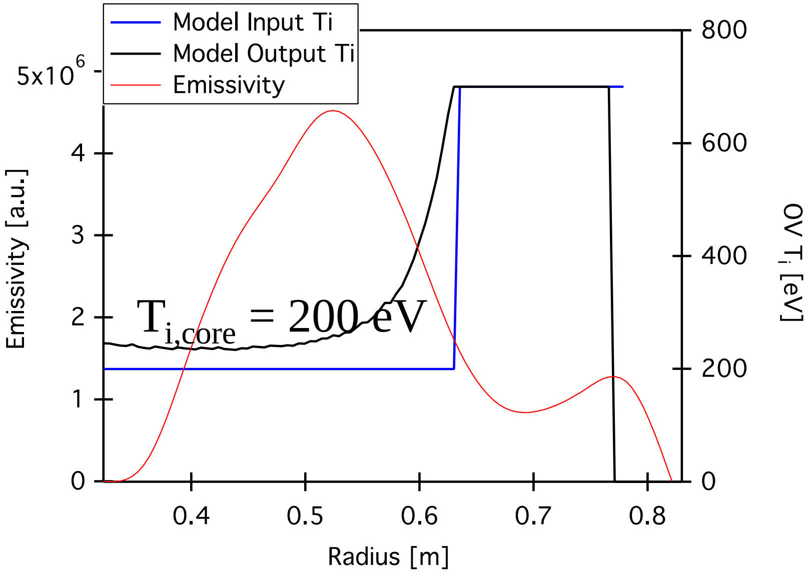
Onion:

$$\mathbf{g} = \mathbf{D}^{-1} * \mathbf{I}$$

$$D_{ij} = \begin{cases} 0 & j < i, \\ 2\sqrt{\left(r_j + \frac{\Delta r}{2}\right)^2 - r_i^2} & j = i, \\ 2\left(\sqrt{\left(r_j + \frac{\Delta r}{2}\right)^2 - r_i^2} - \sqrt{\left(r_j - \frac{\Delta r}{2}\right)^2 - r_i^2}\right) & j > i, \end{cases}$$

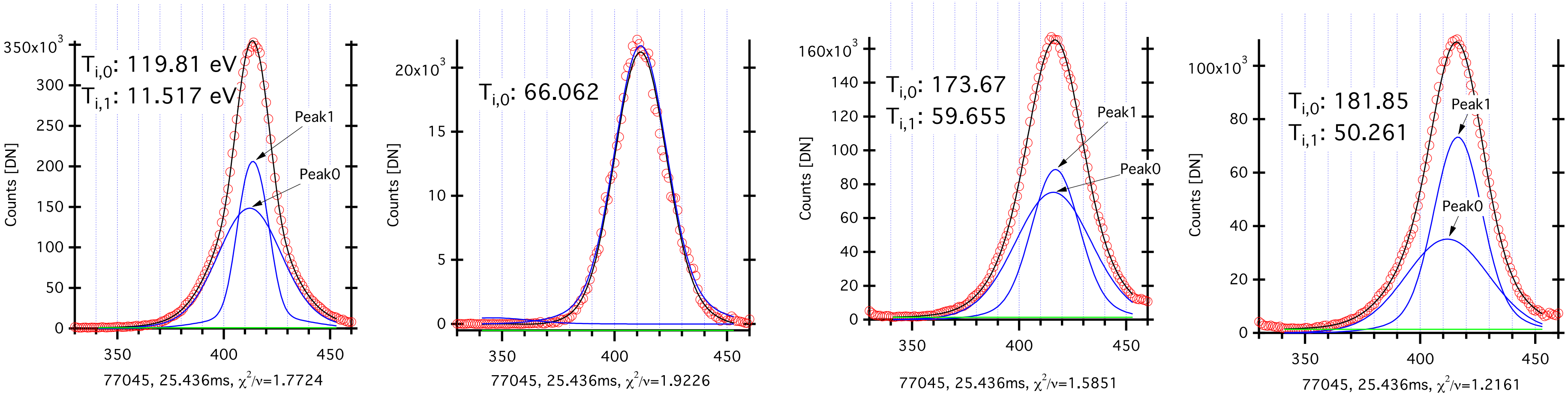
- Forward modeling of a prescribed temperature profile shows that the hot edge component does not pollute core temperature





Helium-II Impurity Spectral Distributions Appear Non-thermal during LHI

Radial 36cm 55cm 70cm



- Plasma edge chord shows clear bi-Gaussian (non-thermal) spectral profile
- High signal-to-noise needed to resolve bi-Gaussian
- Profiles fit using analytic form of multi-Gaussian convolution with 3-gaussian instrument profile

Heidi and OV Thermalization Times help Explain Differences in Observed Spectral Profiles

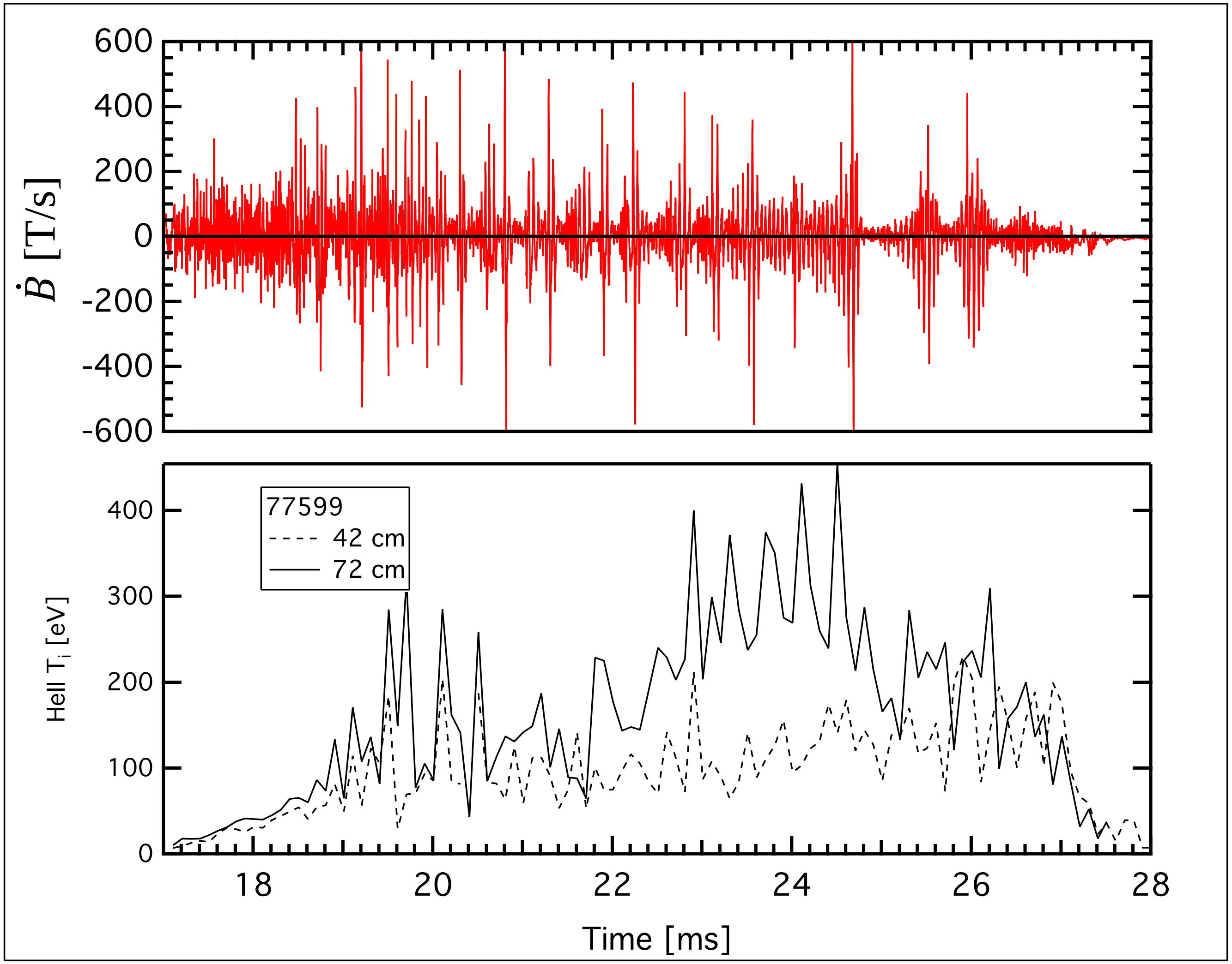
$$\frac{\upsilon_E^{HeII,HeII}}{\upsilon_E^{OV,OV}} = \frac{1}{128}\frac{\left(T_{i,OV} + T_{i,OV,hot}\right)^{3/2}}{\left(T_{i,HeII} + T_{i,HeII,hot}\right)^{3/2}}$$

$$\frac{\Delta x_{radial}}{\Delta t} \approx 1 - 5\ cm/s \qquad \upsilon_E^{OV,OV} \approx 526\ s^{-1}$$

$$\Delta x_{OV,therm} \approx 5.4\ cm \qquad \Delta x_{HeII,therm} \approx 750\ cm$$

- Thermalization length ~100 times larger for HeII than for OV explaining the persistence of the double Gaussian HeII spectral profile across the plasma major radius

High Speed HeII T_i Measurements Indicate Edge Localized Heating and Temporal Correlation with Bursty MHD



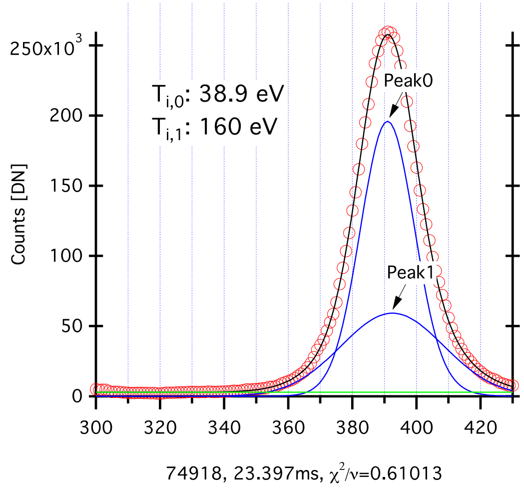
- Using single temperature fits, HeII heating temporally correlates with bursty MHD linked to reconnection activity (NIMROD)

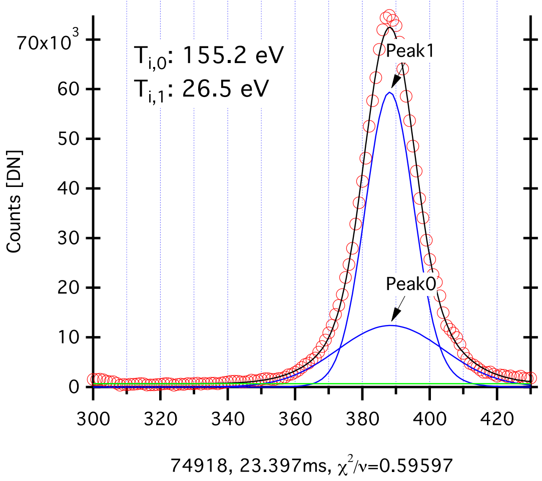
Ion Heating is Toroidally Symmetric and Not due to Sightline Intersection with Local Injector Emission

55cm

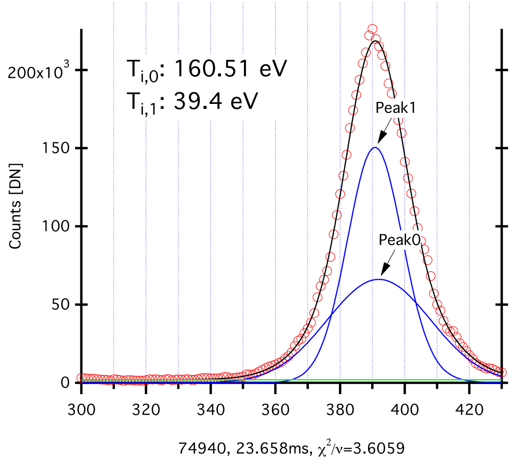
70cm

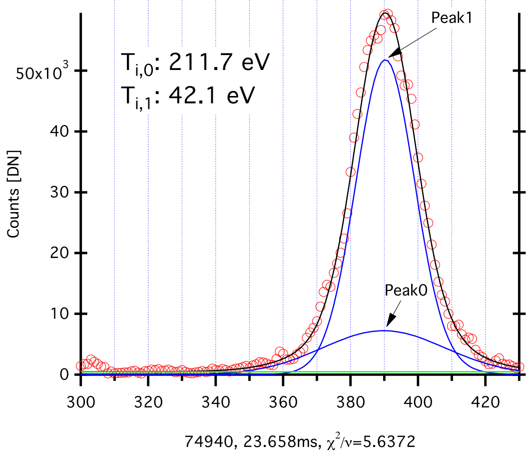
Injector 4 Only



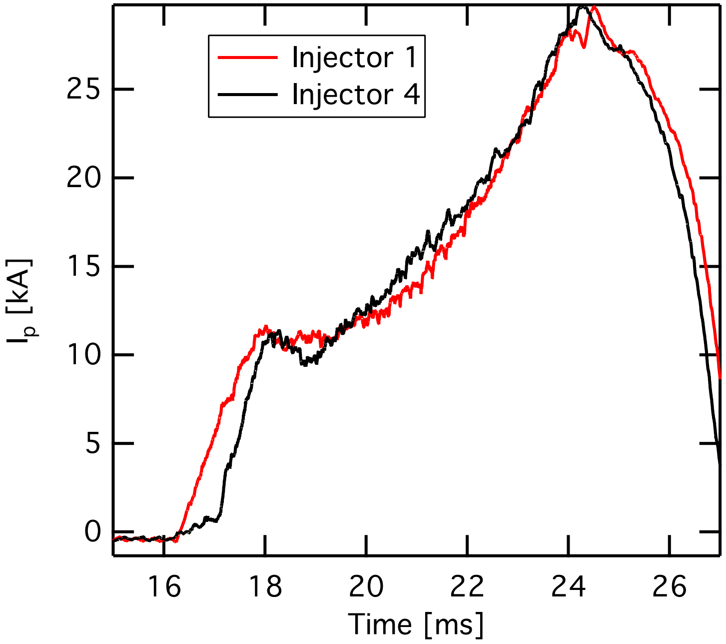


Injector 1 Only

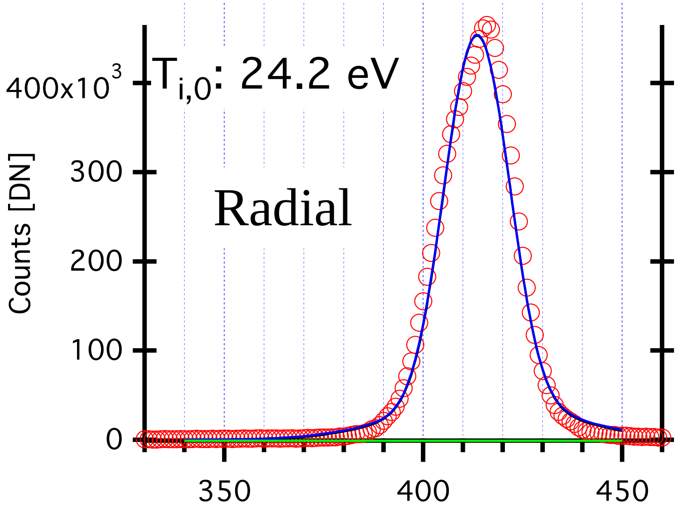




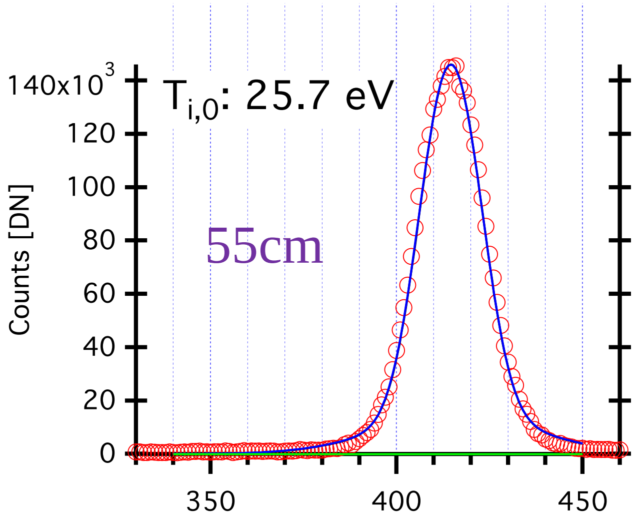
Single injector driven discharges:



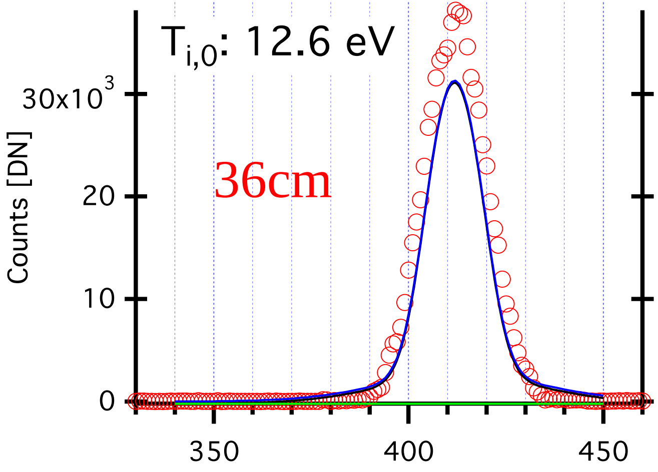
Upon Fast Interruption of I_{inj}, Apparent Non-thermal He-II Spectral Profiles Quickly Become Thermal



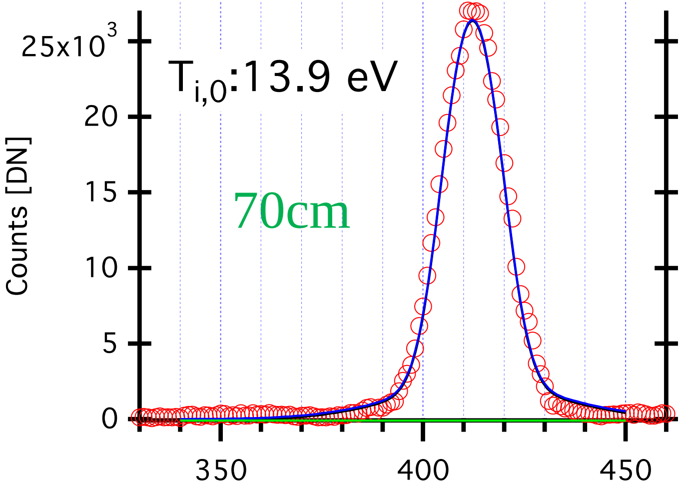
77045, 28.437ms, χ^2/ν=128.55



77045, 28.437ms, χ^2/ν=20.432



77045, 28.437ms, χ^2/ν=53.049



77045, 28.437ms, χ^2/ν=7.907

Reconnection Theory Allows for Testing of Scaling on PEGASUS

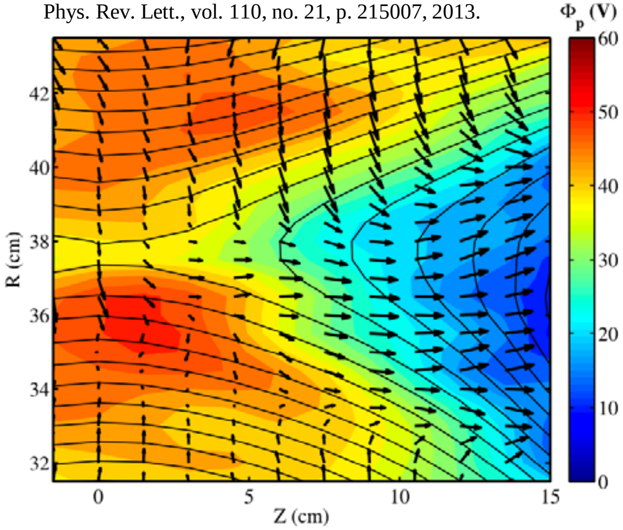
- Two-fluid effects inside the ion diffusion region lead to the development of an in-plane electrostatic potential

- Consideration of electron momentum equations allows the estimation of the in-plane electric field:

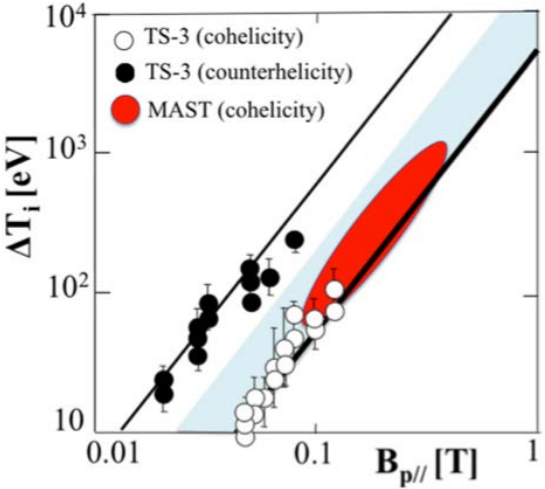
$$\cancel{n_e m_e \frac{d\mathbf{v}_e}{dt}} = -en_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla \cdot \bar{\mathbf{p}} + \cancel{en_e\bar{\eta} \cdot \mathbf{J}} \longrightarrow E_R \approx -V_{eY}B_Z - \frac{1}{en_e}\frac{\partial p_e}{dR}$$

$$\Delta\phi = -\int dRE_R \approx \int dR\,\frac{1}{en_e}\left(J_Y B_Z - \frac{\partial p_e}{\partial R}\right) \longrightarrow \Delta\phi \approx \frac{B_{rec}^2}{2\mu_0 e\langle n_e\rangle} + \Delta T_e$$

J. Yoo, M. Yamada, H. Ji, and C. E. Myers,
Phys. Rev. Lett., vol. 110, no. 21, p. 215007, 2013.



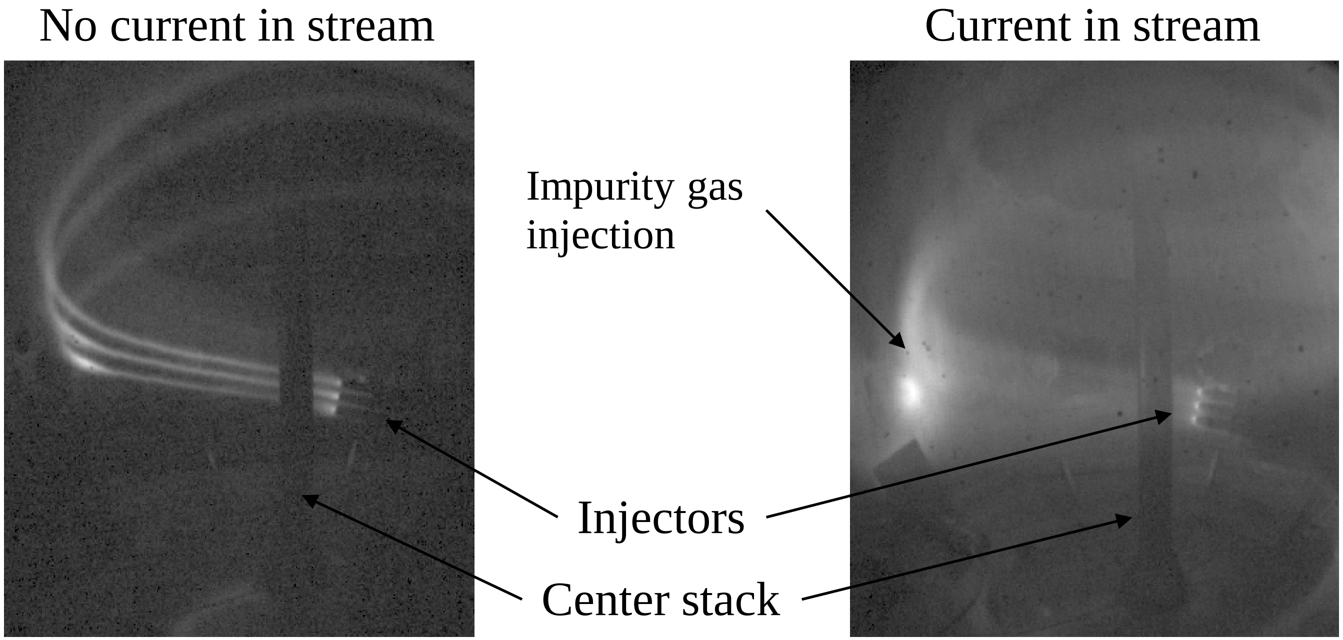
Detailed studies at MRX show ions being accelerated by in-plane electric field



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

TS-3 and MAST merging tokamak experiments found temperature increment scaled with $\Delta T_i \sim v_A^2 \sim B_{rec}^2/n$

Experiment Preformed to Isolate Heating due to Reconnection Between Adjacent Current Streams



No current in stream

Current in stream

- Stream density set by double layer density at injector which in turn is set by injector parameters*
  - $I_{DL} \sim \beta n_{stream} \sqrt{V_{DL}}$, I_{DL} and V_{DL} are injector parameters I_{inj} and V_{inj}
- From reconnection theory, ion kinetic energy gain expressed in terms of measurable parameters:

$$\Delta\phi \approx \frac{B_{rec}^2}{2\mu_0 e\langle n_e\rangle} + \Delta T_e \longrightarrow \Delta\phi \propto \frac{I_{inj}^2}{I_{inj}/\sqrt{V_{inj}}} \longrightarrow KE_{ion} \propto \frac{q}{m} I_{bias}\sqrt{V_{bias}}$$

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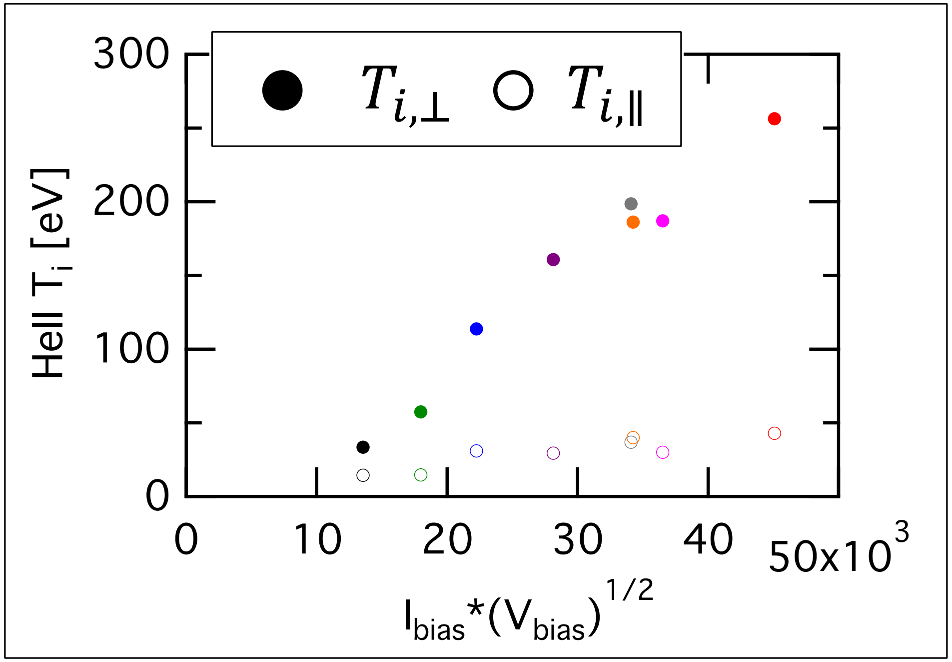
* *E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.*

Heating Observed in Biased Current Streams Scales with Parameters Predicted by Two-fluid Reconnection Theory

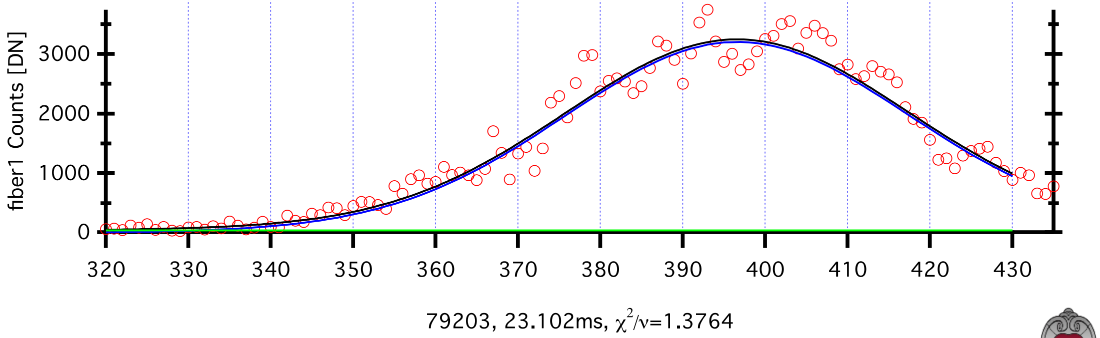
- Sightline perpendicular to current streams indicates large amounts of heating on the HeII spectral line

- Sightline parallel to the streams see little to no heating, consistent with radial flows out of a X-point

- Spectral profiles fit well with single temperature distribution

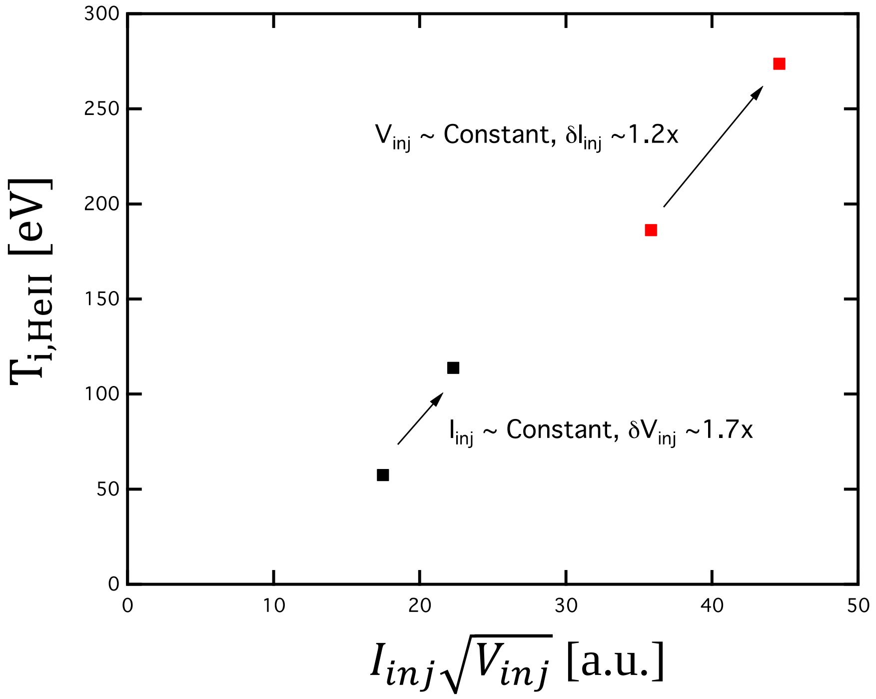


Sample spectral profile from scan:

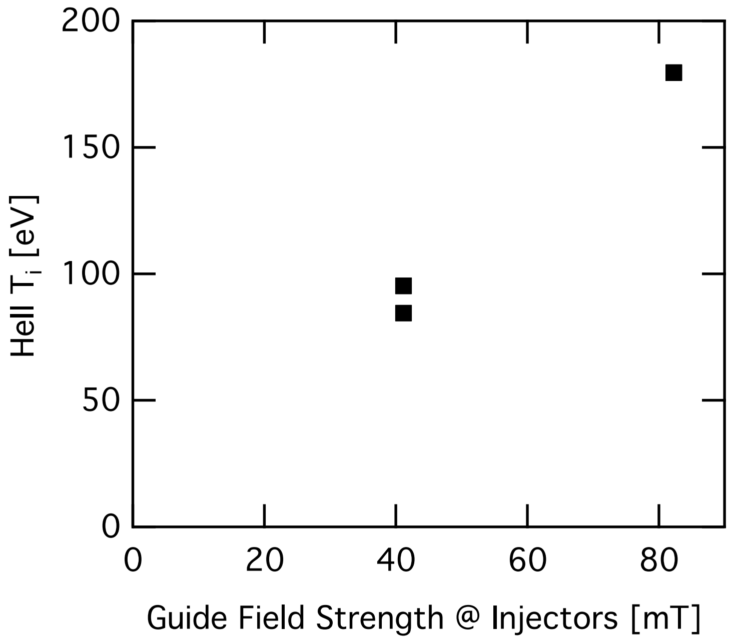


$T_{i,HeII}$ Changes with both I_{inj} and V_{inj} and Scales Linearly with Toroidal Field Strength (Guide Field)

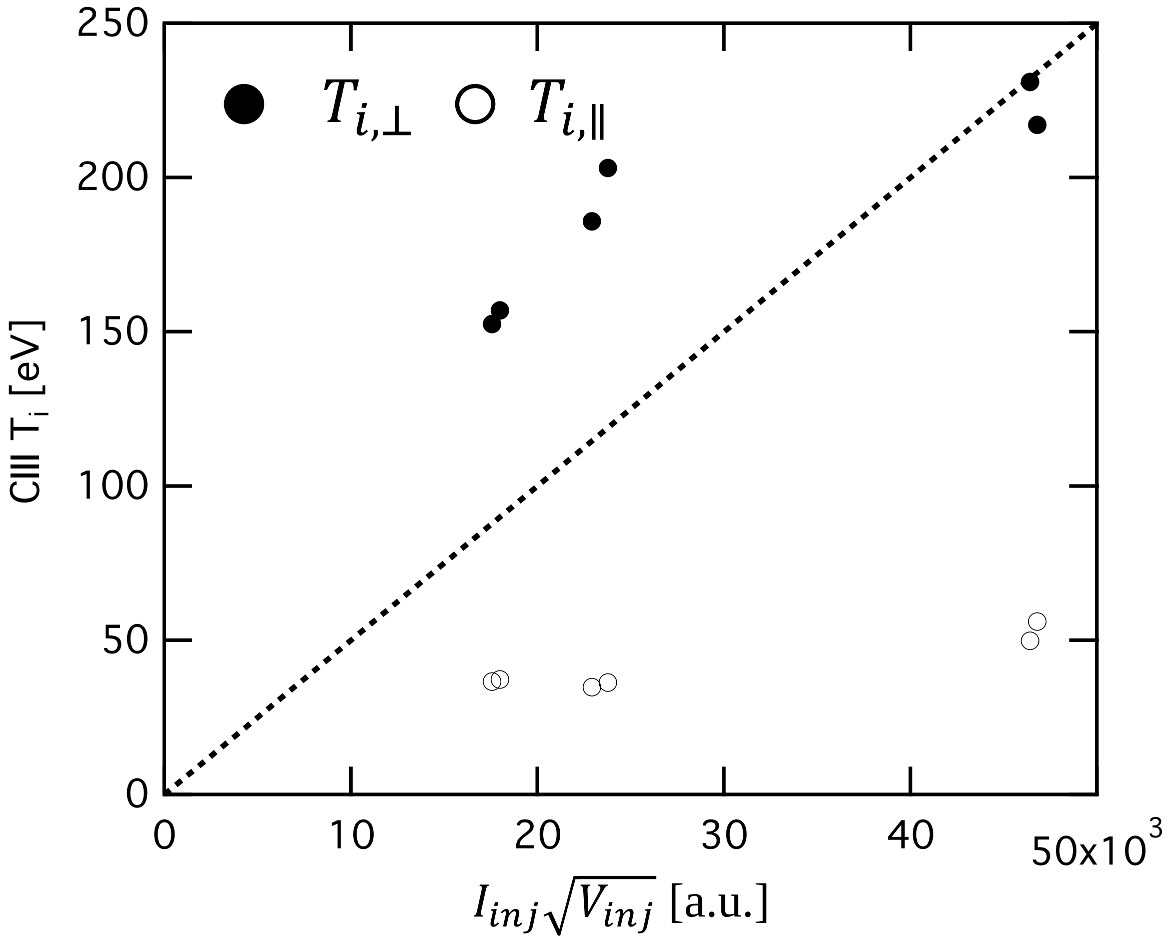
Heating changes with both I_{inj} and V_{inj}:



Heating increases linearly with B_{tor}:

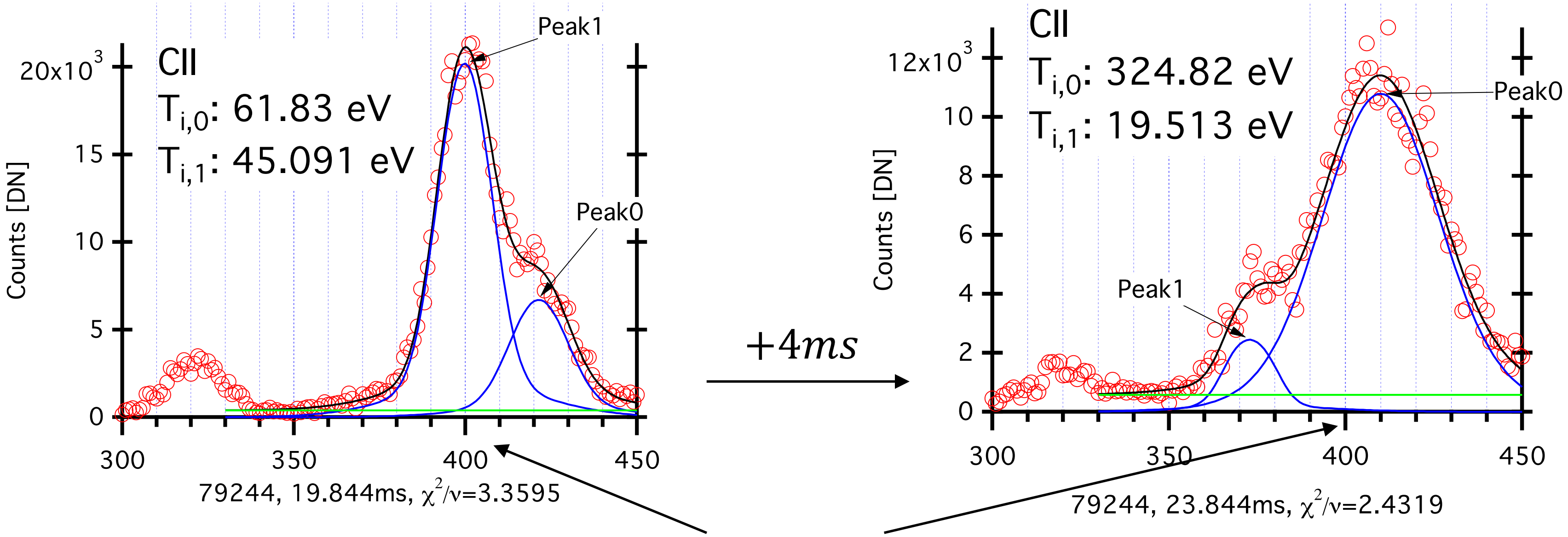


$I_{inj}\sqrt{V_{inj}}$ Scanned While Looking at CIII T_i



- CIII $T_{i,\perp} >> T_{i,\parallel}$, similar to HeII
- CIII $T_{i,\perp}$ appears to saturate at high values of $I_{inj}\sqrt{V_{inj}}$

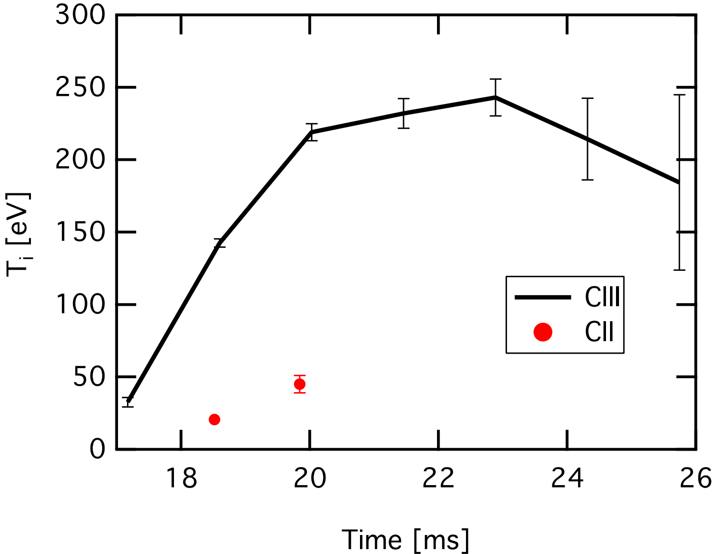
Potential q/m Scaling of Heating Explored By Comparing C-II and C-III T_i



Peak at 400 (CII) either moved or confused by broadening of Peak 0

- Kinetic energy of ions being accelerated by in-plane electric field should scale $\sim \frac{q_{ion}}{m_{ion}}$

- CII T_i initially appears much lower than CIII however spectrum is complex



Summary

- Continuous edge ion heating observed during steady helicity injection current drive

- Ion heating penetrates to plasma core as indicated by high core $T_{i,OV}$ and forward modeling on spatial emissivity profiles

- Impurity $T_i > T_e$ during LHI driven discharges and is temporally correlated with large MHD activity
  - Additionally, $T_{i,LHI} >> T_{i,Ohmic}$

- HeII T_i found to scale with parameters predicted by magnetic reconnection theory