Continuous, Localized Ion Heating due to Magnetic Reconnection in a Low Aspect Ratio Tokamak

M. G. Burke,

J.L. Barr, M.W. Bongard, R.J. Fonck, E.T. Hinson, J.M. Perry, J.A. Reusch, D.J. Schlossberg



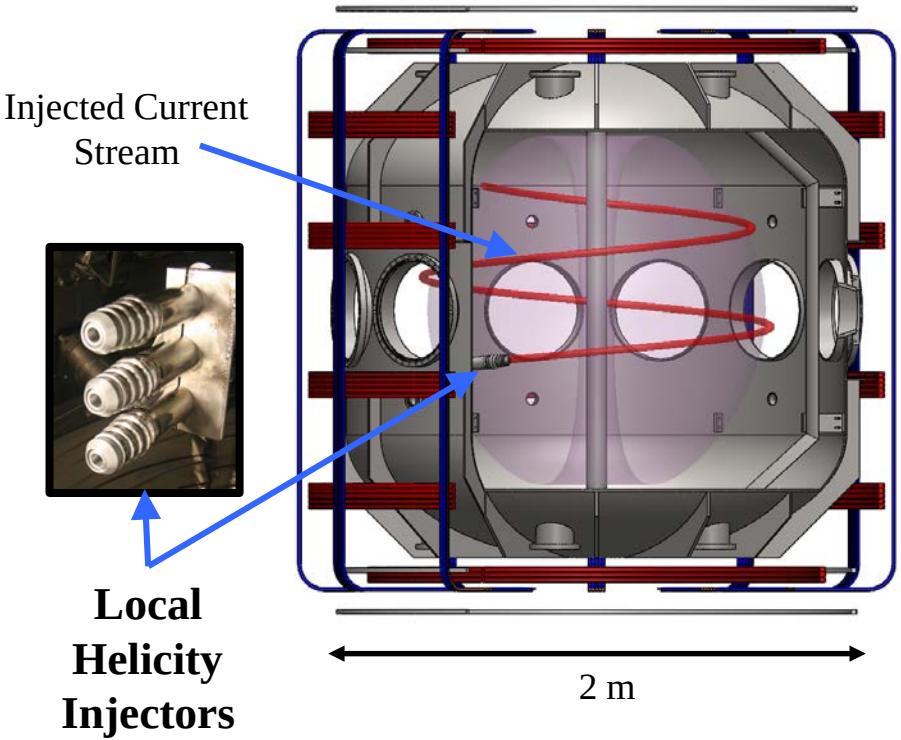
EPR Workshop

February 23th, 2016

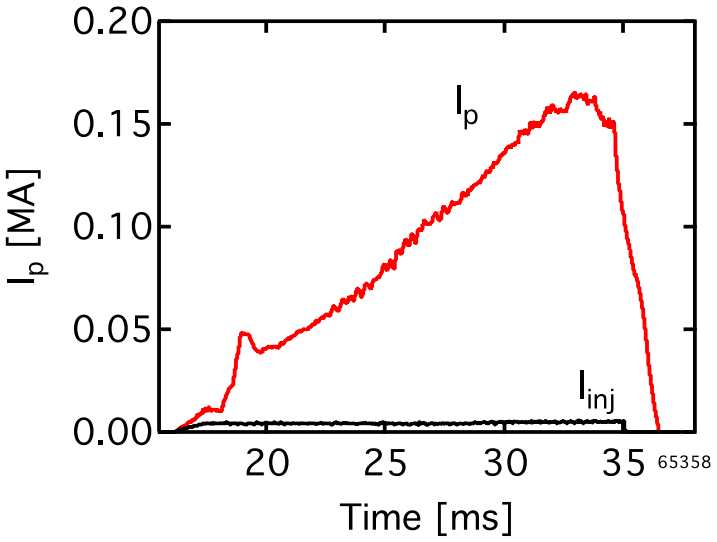
Auburn, AL



Pegasus Spherical Tokamak Uses Local Helicity Injection Initiates and Sustains Plasmas

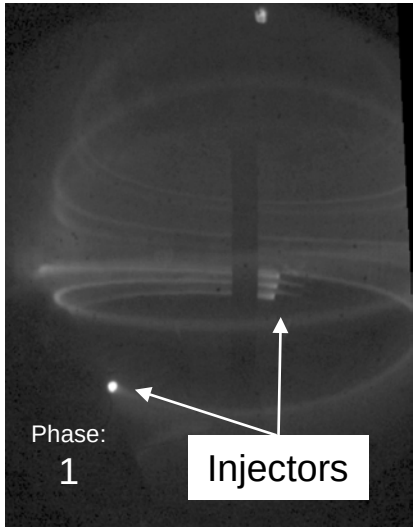


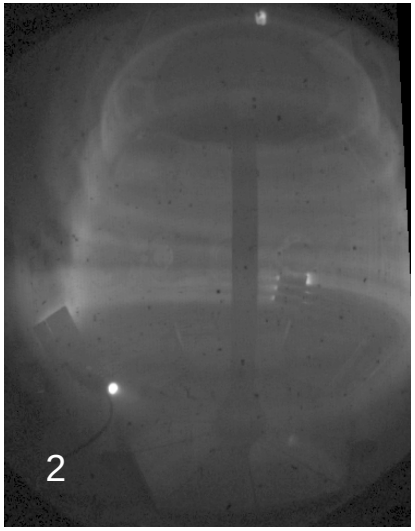
$I_p \leq 0.18$ MA via LHI (I_{inj} = 5 kA)

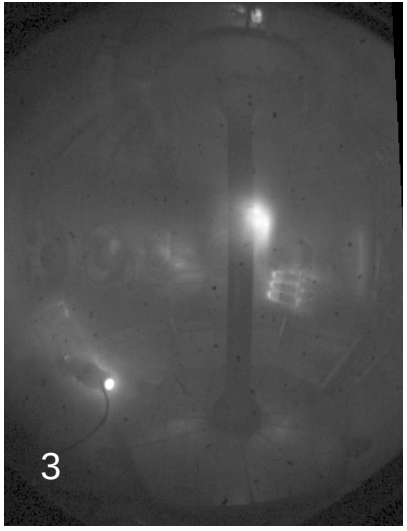


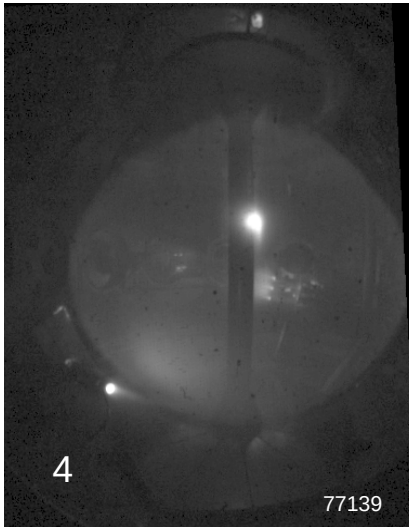
- Reconnection: fundamental mechanism for LHI
- See Jayson Barr talk 2 PM Wed

Local Plasma Sources Inject Current Streams that Reconnect, Form Tokamak-like Plasma









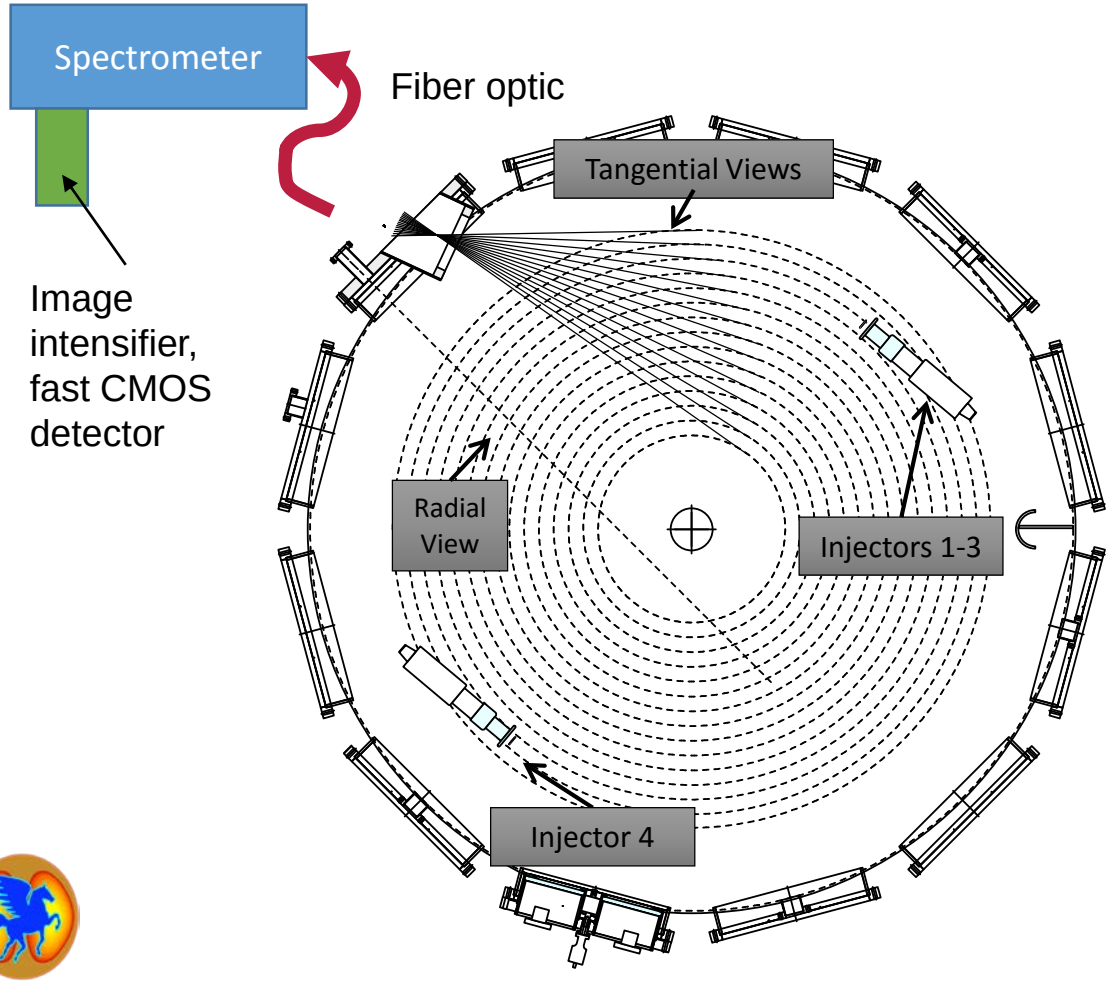
- Local source: Helical plasma streams
- $I_{inj} = 0$

- Instability: Current driven along streams
- $I_{inj} \neq 0$

- Reconnection: relaxation to tokamak-like state, current growth
- $I_{inj} \neq 0$

- Result at bias shutdown: Tokamak
- $I_{inj} = 0$

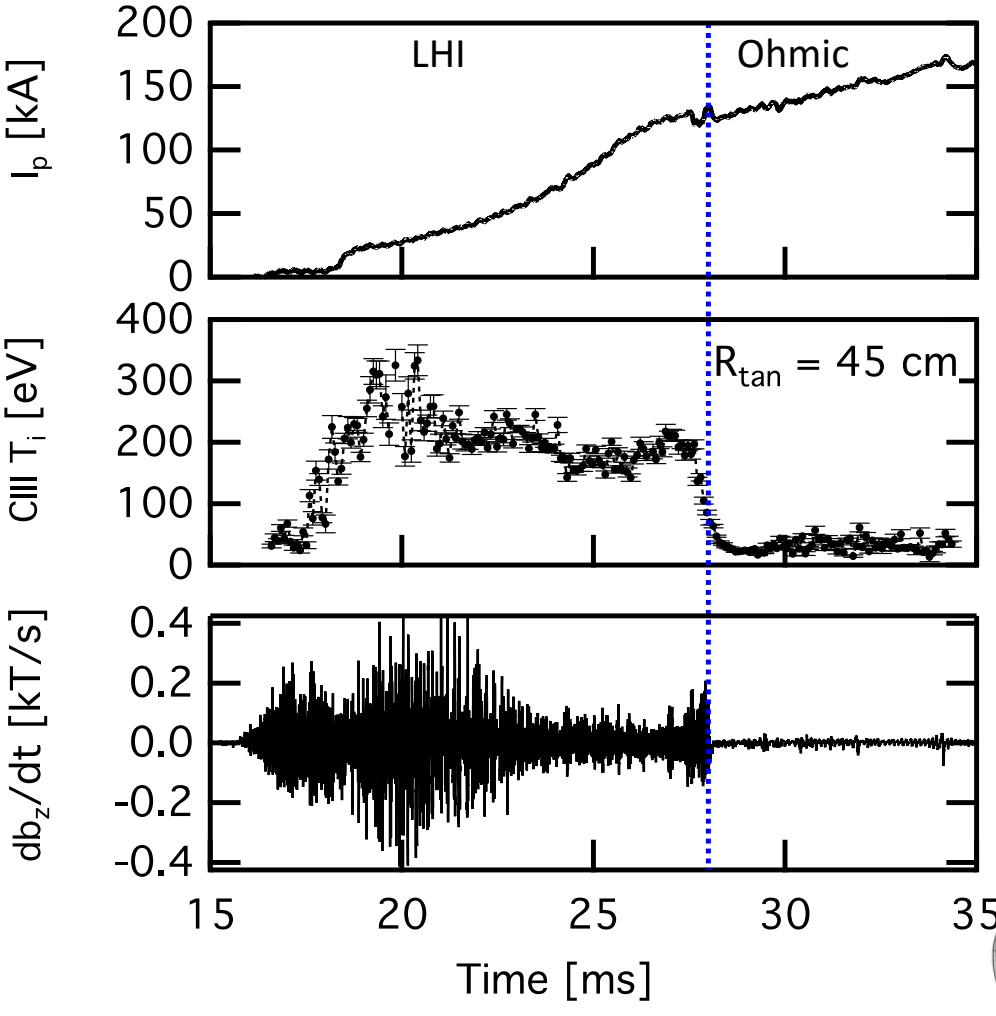
LHI Ion Dynamics Studied Using Passive Ion Spectroscopy



- Diagnostic Parameters:
  - 1m f/8.6 spectrometer
  - 15 tangential sightlines
  - UV image intensifier
  - Fast CMOS detector

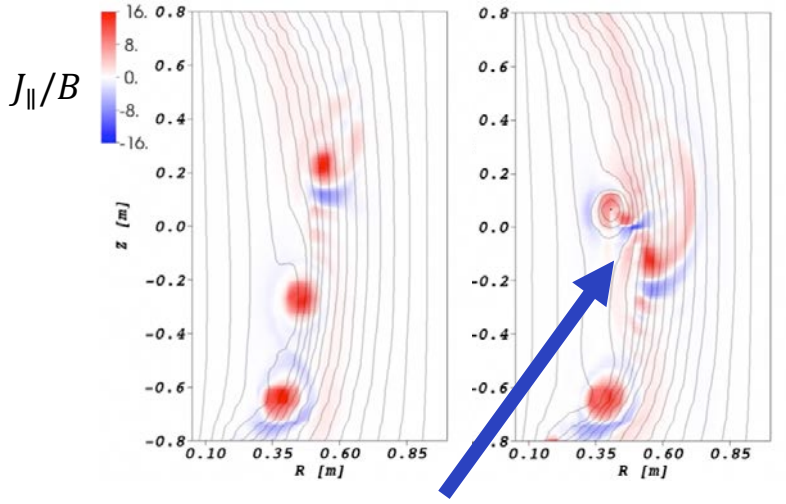
During LHI Current Drive $T_i > T_e$

- $T_i \geq T_e \sim 100$ eV
- $T_{i,LHI} > 10x\ T_{i,OH}$
- $T_{i,LHI}$ as large as 700 eV
- Large amplitude MHD associated with magnetic reconnection
- T_i increase agrees with reconnection theory

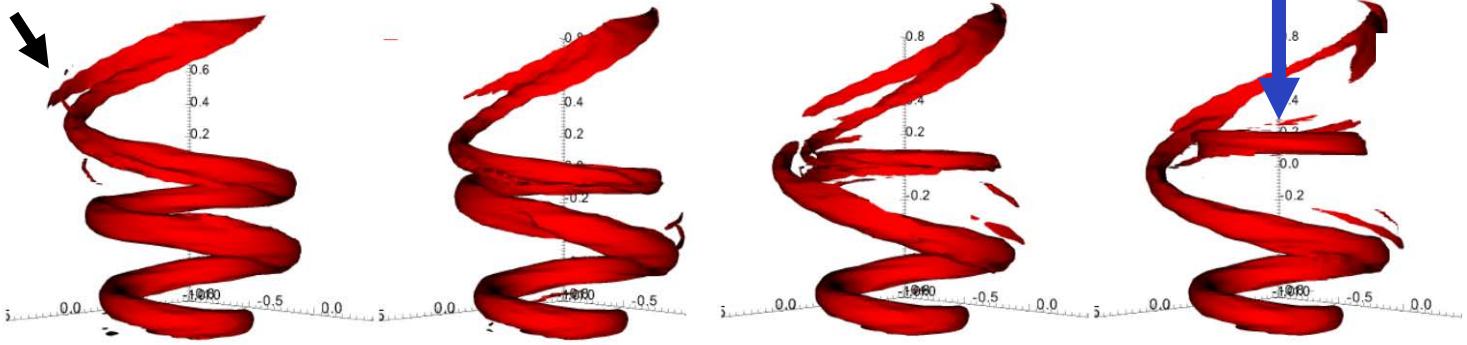


Reconnection Between Helical Windings is the Mechanism of LHI Current Drive

- NIMROD current drive mechanism:
  - Helical windings attract, reconnect
  - Axisymmetric current ring released
- Manifests as n = 1 burst at Alfvénic frequency (10 - 40 kHz)



Helical current stream

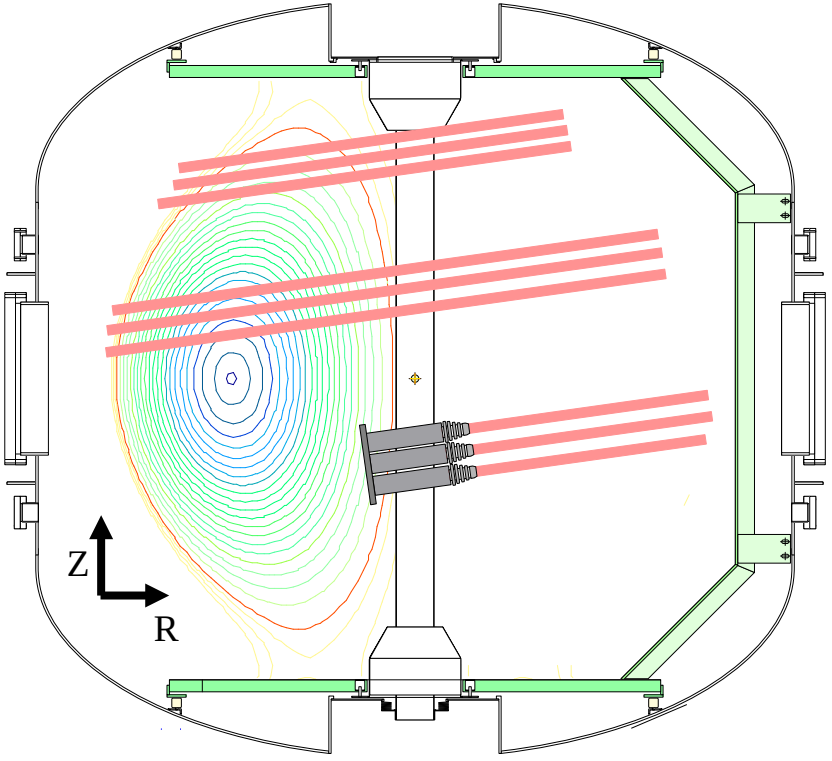


Time

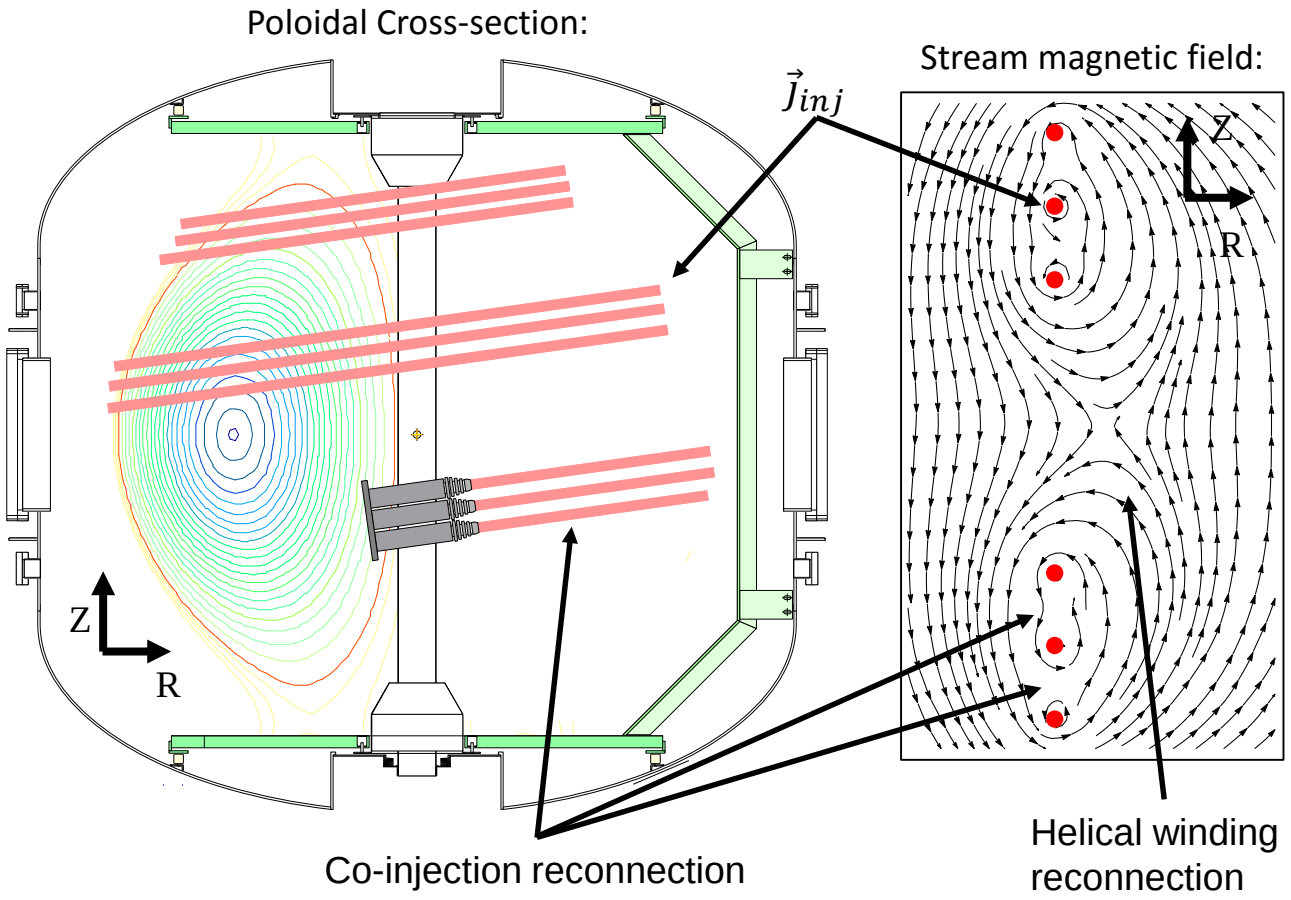
J. B. O'Bryan *et. al.*, PPCF, **56**, 2014.

In Addition, Continuous Magnetic Reconnection Occurs Between Co-Injected Current Streams

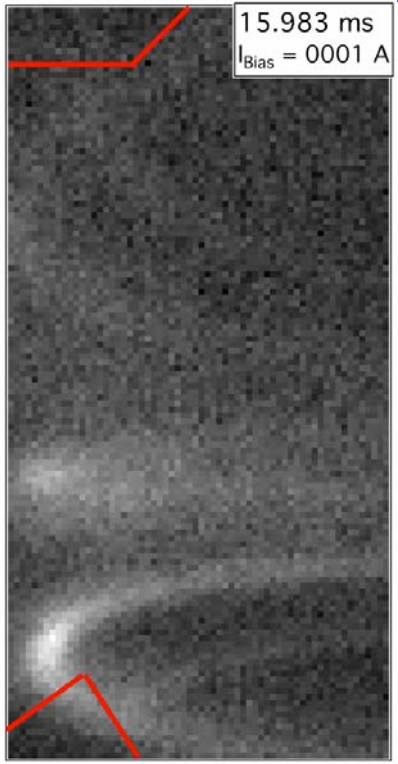
Poloidal Cross-section:



In Addition, Continuous Magnetic Reconnection Occurs Between Co-Injected Current Streams

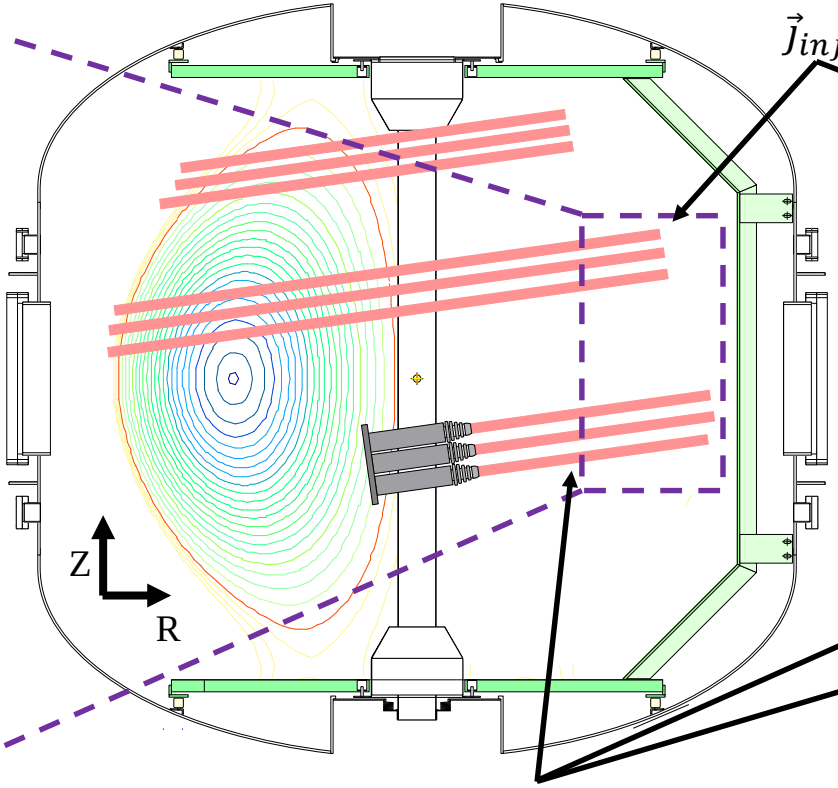


In Addition, Continuous Magnetic Reconnection Occurs Between Co-Injected Current Streams



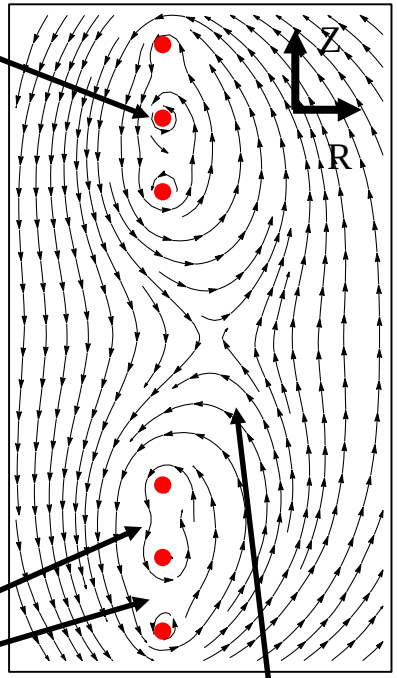
$\Delta t_{frame} = 3\ \mu s$

Poloidal Cross-section:



Co-injection reconnection

Stream magnetic field:



Helical winding reconnection (NIMROD)

Anomalous Ion Heating is Commonly Observed in Reconnecting Plasmas

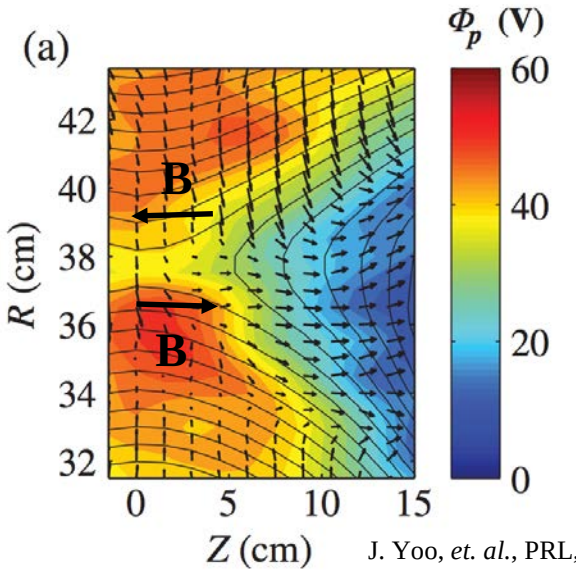
- Reconnection converts magnetic energy to particle kinetic energy
- **Hypothesis:** Reconnection is the source of ion heating during LHI

Ions accelerated by in-plane potential drop:

$$\Delta\Phi_p = -\int dR\, E_R \approx \int dR \frac{1}{en_e}\left(J_Y B_Z - \frac{\partial p_e}{\partial R}\right)$$

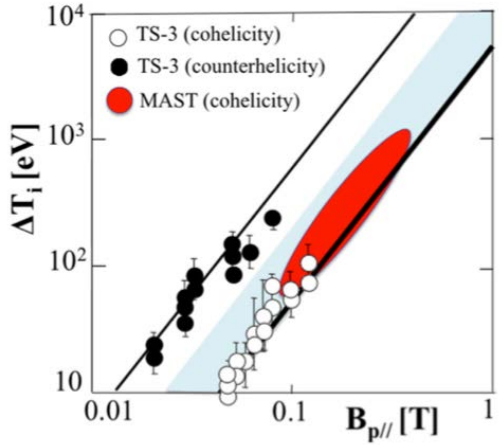
$$\approx \frac{B_{sh}^2}{2\mu_0 e\langle n_e\rangle} + \Delta T_e \propto \Delta T_i$$

Physics of reconnection ion acceleration (MRX, TS-3):



J. Yoo, *et. al.*, PRL, **110**, 2013.

Reconnection heating with guide field (TS-3, MAST):



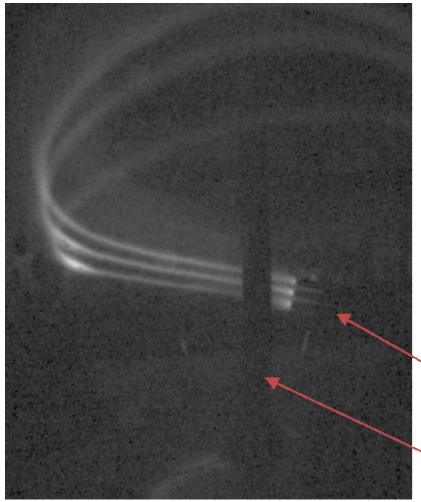
Y. Ono *et al.*, PPCF, **54**, 2012.

Experiment Designed to Test if Ion Heating due to Magnetic Reconnection

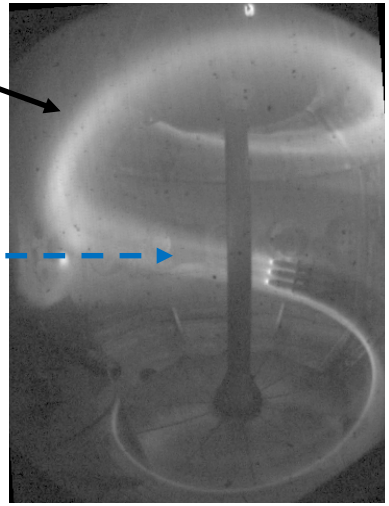
- No reconnection between helical windings→ <u>No tokamak plasma present</u>
- Accelerating potential $\Delta\phi$ estimated assuming coherent current streams

$$n_b \propto \frac{I_{inj}}{\sqrt{V_{inj}}} \qquad \Delta\phi \approx \frac{B^2}{2e\mu_0 n_b} \propto I_{inj}\sqrt{V_{inj}}$$

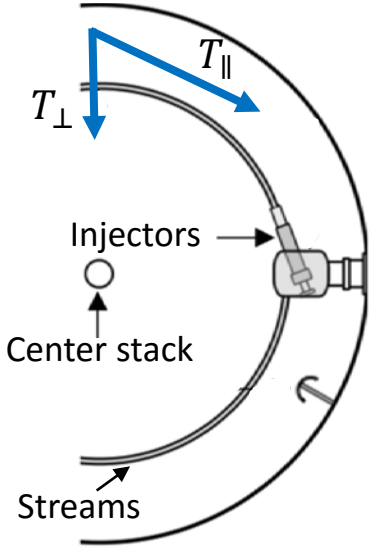
Plasma stream, I_{inj} = 0



I_{inj} = 2 kA



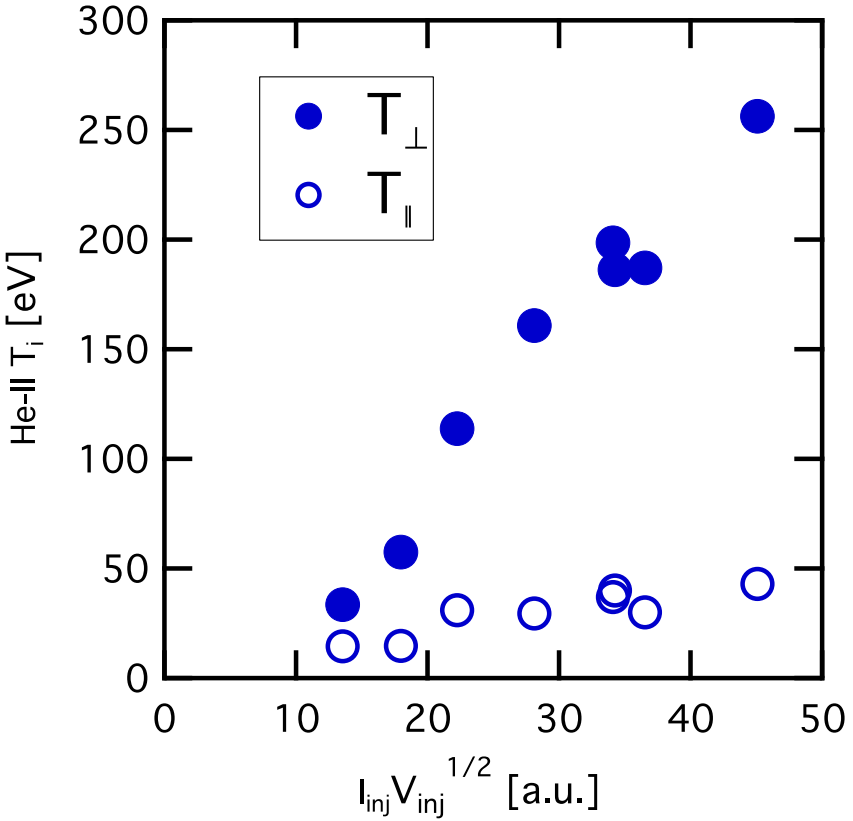
Sightlines (top down)



Ed Hinson, PhD Thesis, 2015

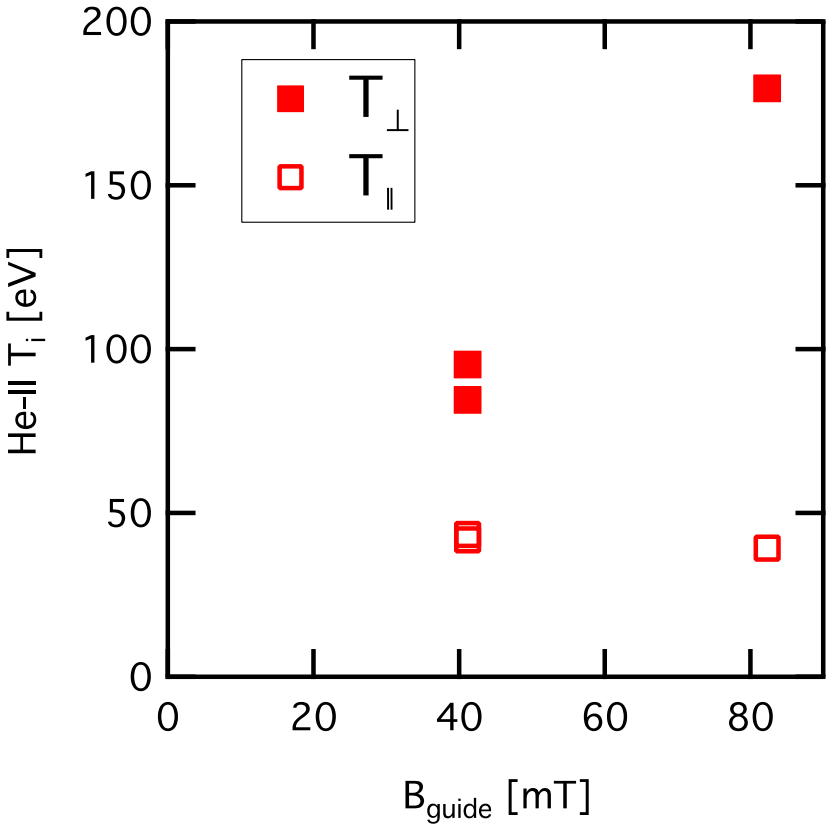
Helium-II T_i Scales as Predicted by Magnetic Reconnection Theory

- Co-injected stream reconnection only
- $T_{HeII,\perp} \propto I_{inj}\sqrt{V_{inj}} \propto \Delta\phi$
- $T_\perp \gg T_\parallel$
- T_i increases with changes in I_{inj} and V_{inj}



He-II T_i Also Increases with Guide Field Strength at Injectors

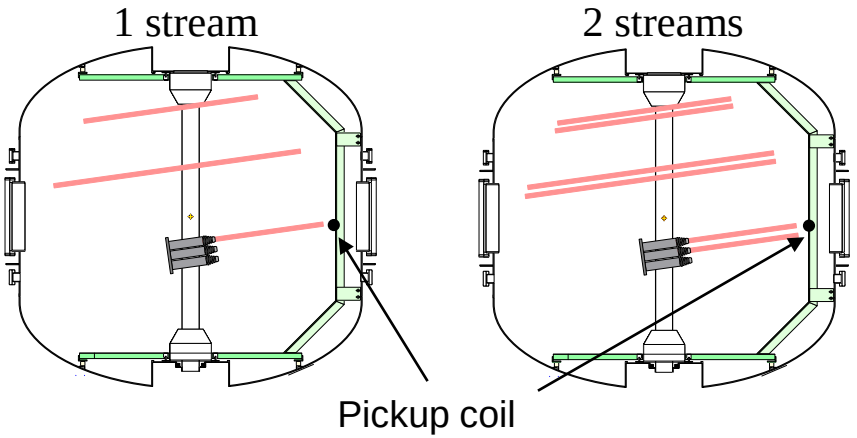
- B_{guide} varied by 2
  - Constant $I_{inj}V_{inj}^{1/2}$
- PIC and MHD Simulation: preferential ⊥ heating
  - $T_\perp$ increases with B_{guide}
- MST: $T_\perp$ increases during reconnection

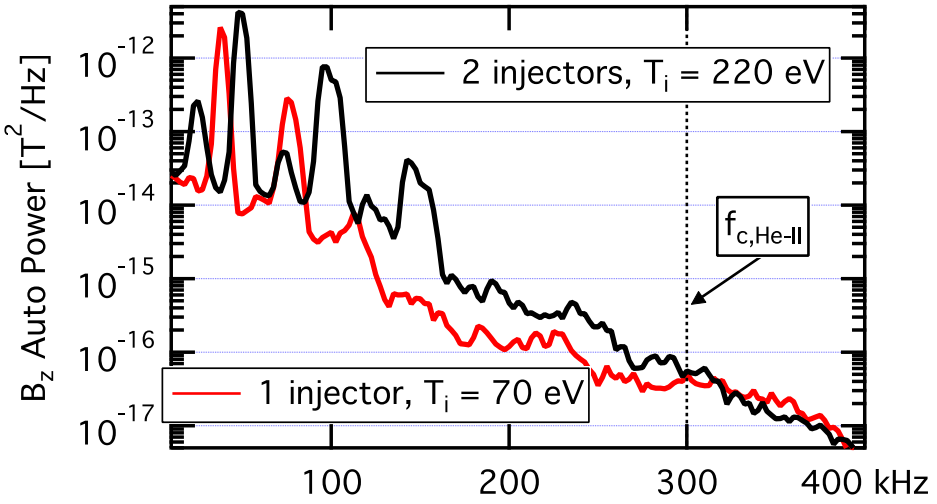


J. F. Drake *et. al.*, PoP, **21**, 2014
J. Birn *et. al.*, PoP, **17,** 2010
R. Magee, *et. al.*, PRL, **107**, 2011

Power at High Frequency Indicates Reconnection Activity

- MHD compared in 1 vs 2 streams
- Total I_{inj} kept constant
- Magnetic auto-power:
  - 2 streams: 2-10x more power between 100-300 kHz
- MRX: High frequency turbulence linked to reconnection rate

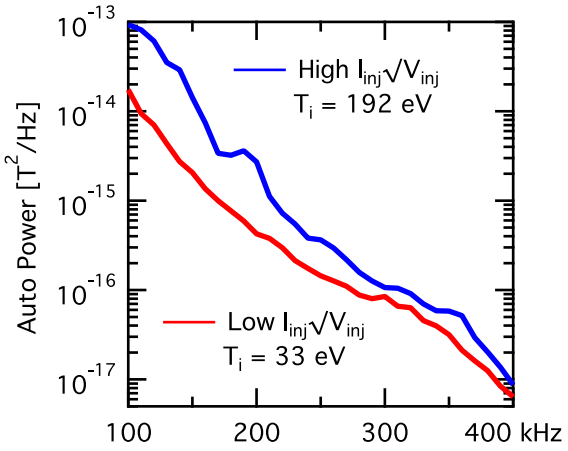


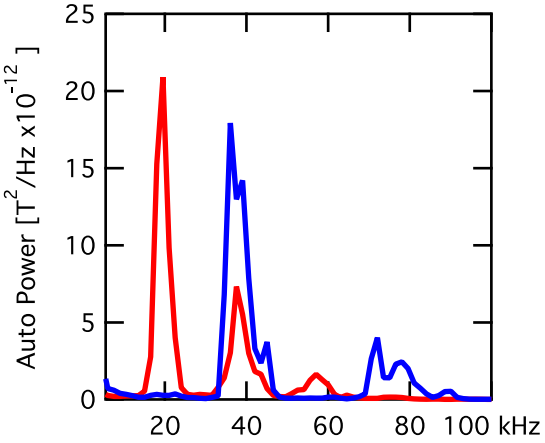


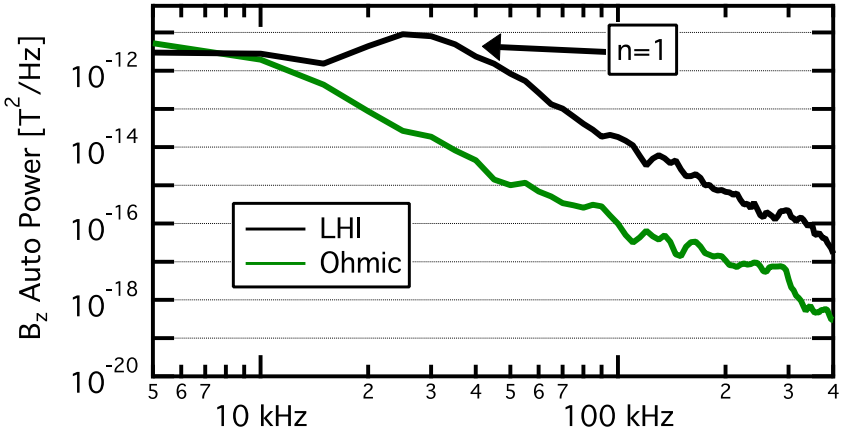
H. Ji, *et. al.*, PRL, **92**, 2004

T_i Correlated with the Power Spectral Density at High Frequencies

- High frequency power increases with $I_{inj}V_{inj}^{1/2}$
  - Correlated with T_i increase
- n = 1 Power ~ constant
  - $\Delta f_{n=1}$: changes in local Alfvén speed
- Magnetic auto power:
  - $P_{LHI} >> P_{Ohmic}$

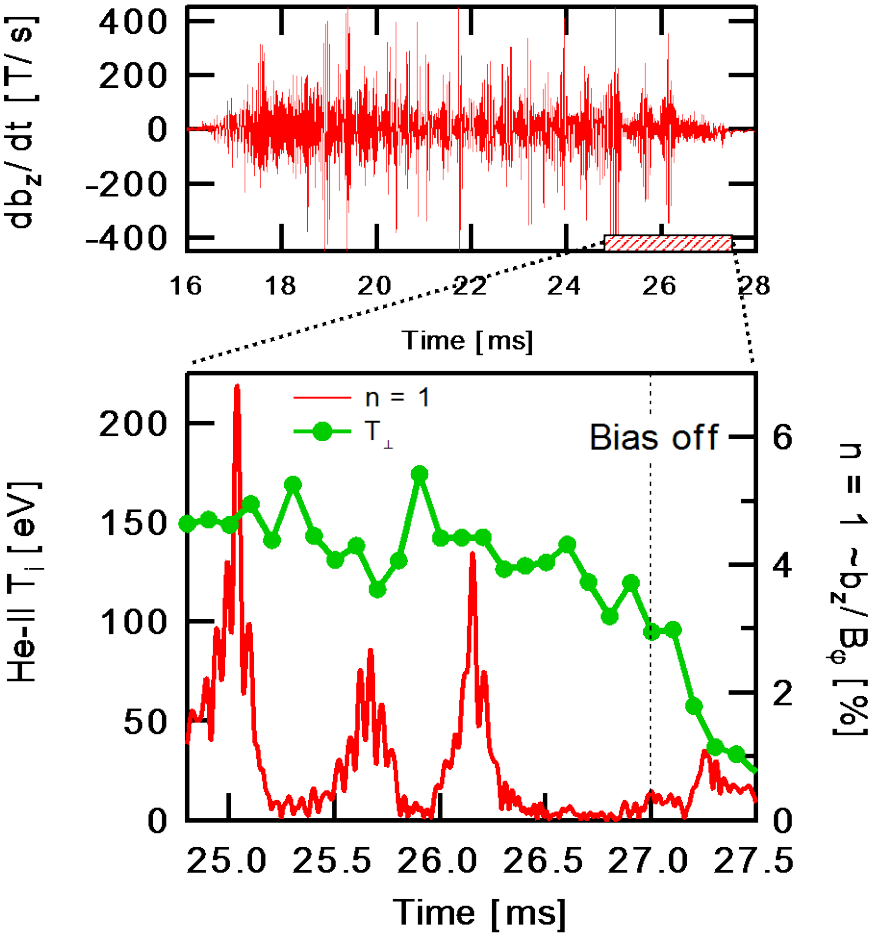






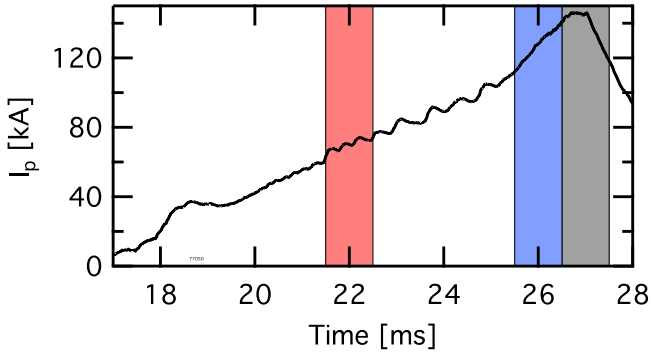
With Tokamak Present, T_i Uncorrelated with Helical Winding Reconnection

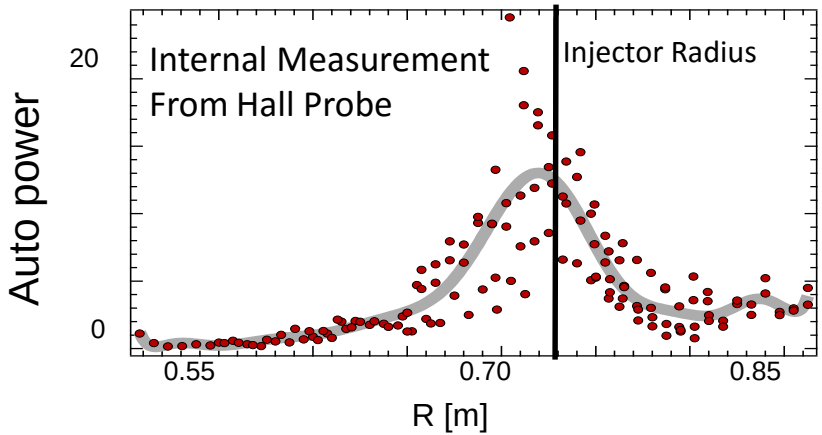
- NIMROD: n = 1 burst indicates reconnection
- $T_i(t)$ uncorrelated with n = 1
- T_i falls <u>after</u> bias shut off at 27 ms
  - After co-injection reconnection off
- Ion heating reconnection and current drive reconnection are <u>separate</u> phenomena

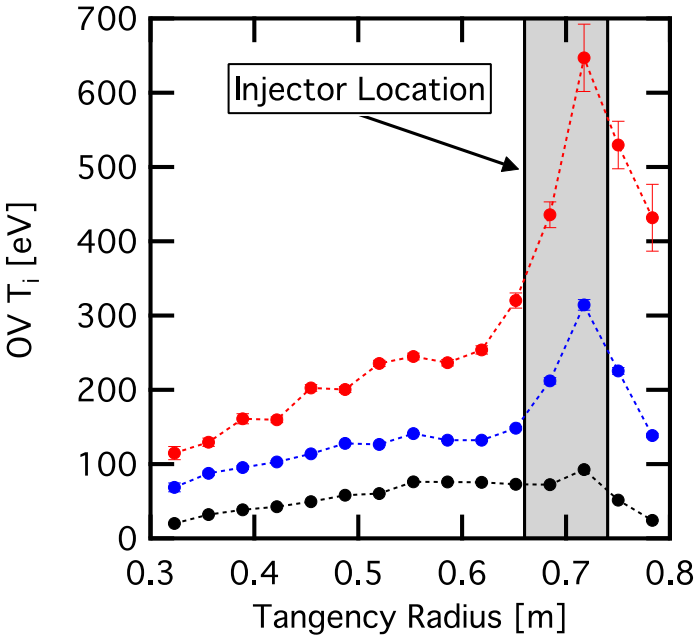


$T_i(R_{tan})$ Indicates Edge Localized Heating, Consistent with Stream Location

- OV T_i peaks near injector location
  - Reconnection localized to plasma edge
  - Consistent with NIMROD stream localization







Summary

- Ion heating observed during local helicity injection due to reconnection between co-injected current streams
- The ion temperature scales with parameters predicted by magnetic reconnection physics
- The ion temperature and reconnection appears correlated with the power of high frequency MHD
- Spatial OV T_i indicates edge localized heating, consistent with n = 1 mode location and NIMROD