H-mode and Non-Solenoidal Startup in the Pegasus Ultralow-A Tokamak

R. J. Fonck for the Pegasus Group

University of Wisconsin-Madison

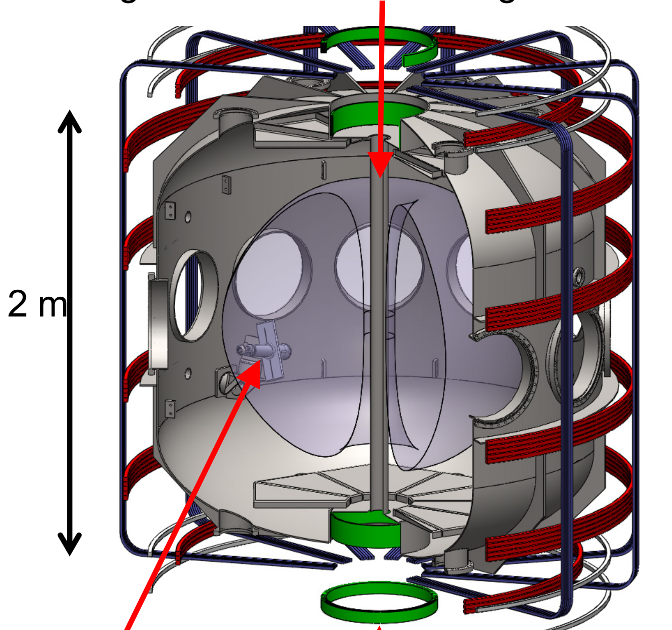
26th IAEA Fusion Energy Conference

17-22 October 2016

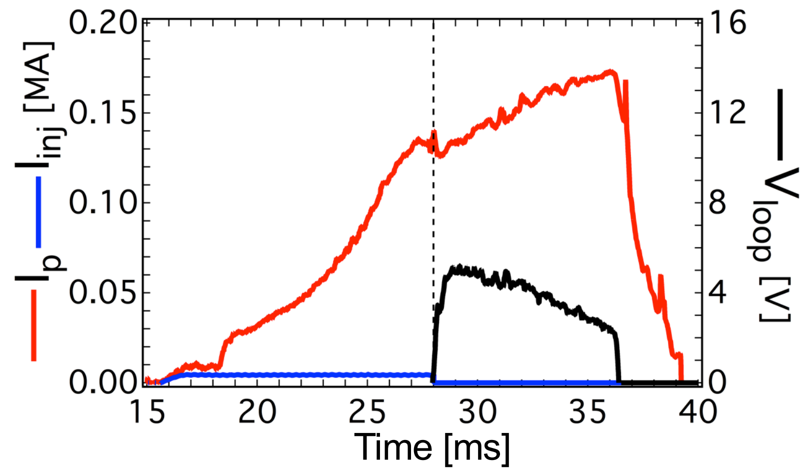
Kyoto International Conference Center
Kyoto, Japan

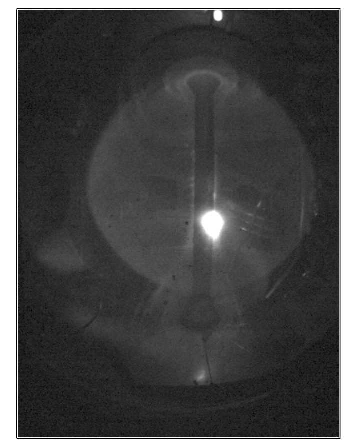
PEGASUS
Toroidal Experiment

Pegasus ST at A~1 Facilitates AT Science Studies at Small Scale



A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	$\leq$ 0.25
B_T (T)	< 0.2
$\Delta\tau_{shot}$ (s)	$\leq$ 0.025





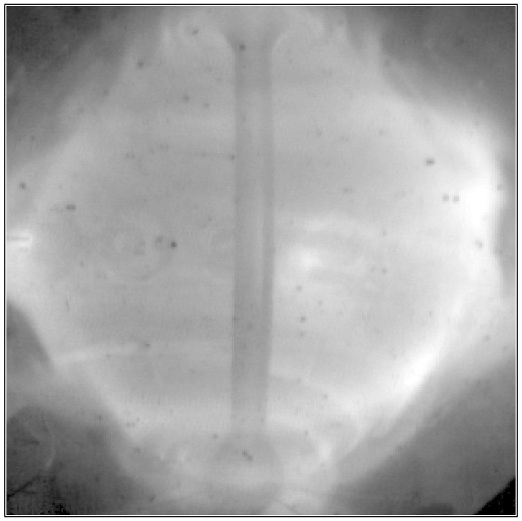
- Local Helicity Injection (LHI) for ST Startup
  - Inject current streams in plasma edge
- H-mode Physics at Ultralow-*A*
  - H-mode and ELM characteristics
- Access to high I_N > 10
  - Tokamak stability limits at A ~ 1

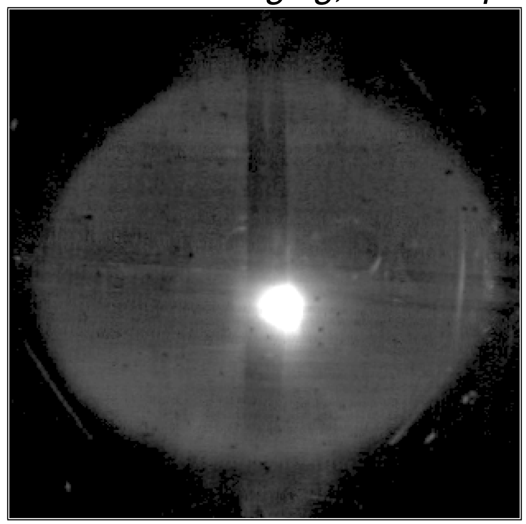
THE UNIVERSITY of WISCONSIN MADISON

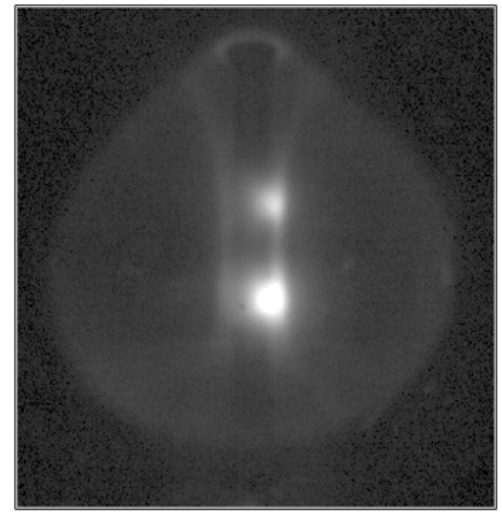
H-mode Readily Accessed at A ~ 1

Limited L | **Limited H** | **Diverted H**

Fast visible imaging, Δt ~ 30 μs





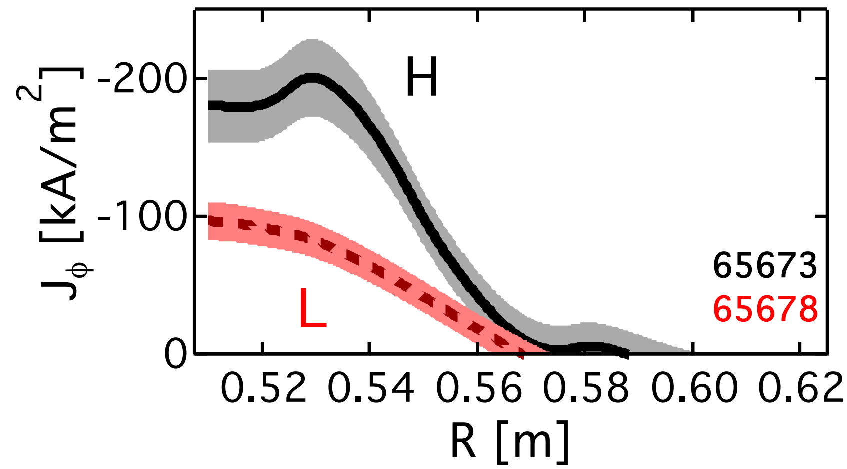


- Low B_T at A ~ 1 -> low H-mode P_{LH}
  - $P_{OH} >> P_{ITPA08} \sim B_T^{0.80} n_e^{0.72} S^{0.94}$
  - Limited or Diverted topology
- Standard H-mode features
  - Quiescent edge
  - Reduced H_α
  - Improved τ_E
  - Some differences compared to high-A

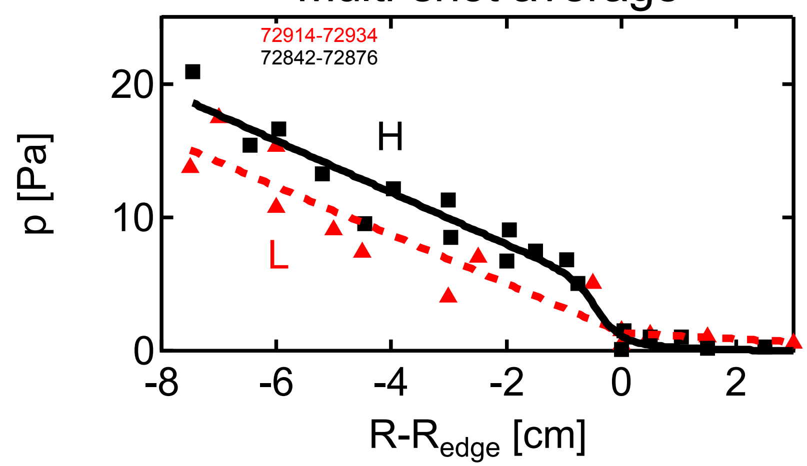
Edge Pedestals, Increased Confinement

- Short pulse, low $T_{e,edge}$
- Simple probe access through the pedestal in H-phase
  - $J_\phi(R,t)$: multichannel Hall probe[1,2]
  - p(R): triple Langmuir probe
- Confinement increases 2x
  - Requires time-evolving reconstructions
  - L: $H_{98} \sim 0.5\pm0.2$
  - H: $H_{98} \sim 1.0\pm0.2$

Single-shot, Δt = 6 μs

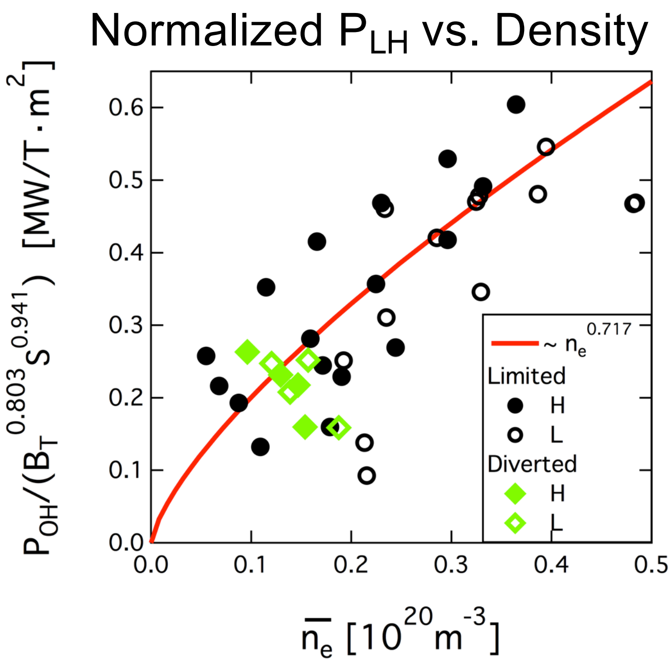


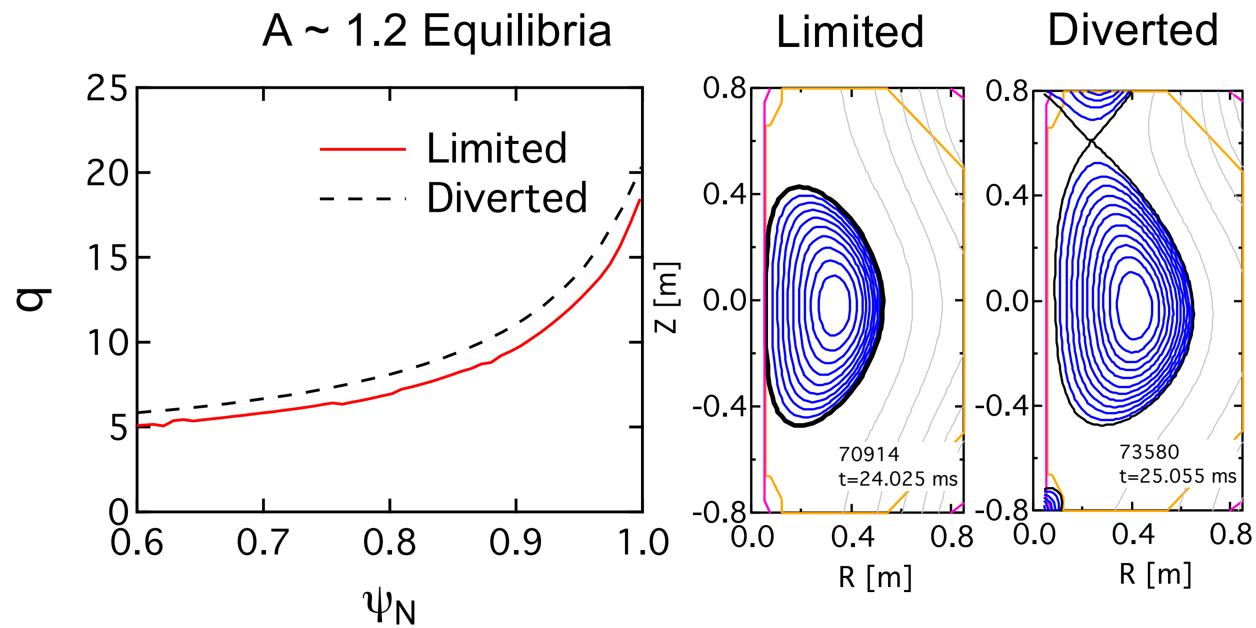
Multi-shot average



Bongard et al., Rev. Sci. Instrum. ***81****, 10E105 (2010)*
Bongard et al., Phys. Rev. Lett. ***107****, 035003 (2011)*

P_{LH} Consistent with Global Scalings, but Low-A Differences





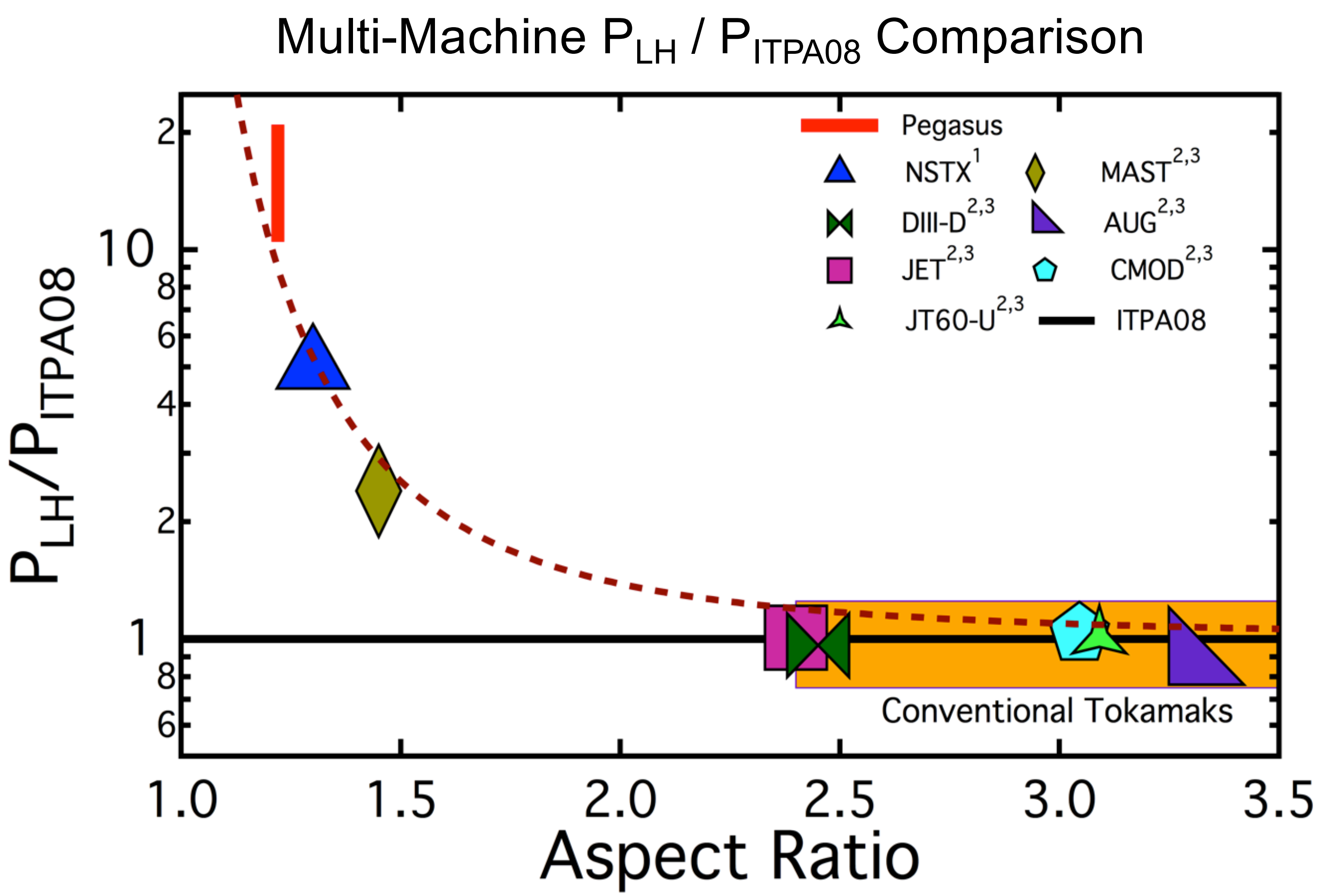
- Follows ITPA n_e scaling
  - FM^3: min $n_e \sim 1\times10^{18}$ m^{-3}

- Magnetic topology independence
  - Diverted, limited edge $q(\psi)$ similar
  - FM^3 model:

$$(P_{LH}^{LIM}/P_{LH}^{DIV}) \sim (q_\psi^{LIM}/q_\psi^{DIV})^{-7/9} \sim 1$$

Fundamenski et al., Nucl. Fusion ***52****, 062003 (2012)*

At Low A, $P_{LH} \gg P_{ITPA08}$

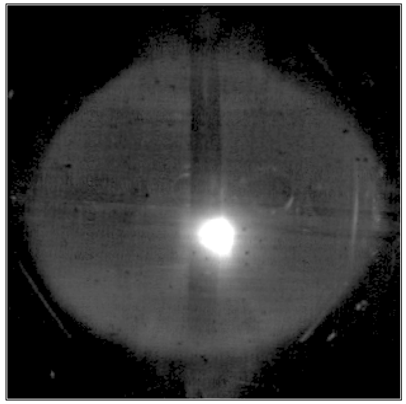


[1]*Maingi et al., Nucl. Fusion* ***50****, 064010 (2010)*
[2]*Martin et al., J. Phys.: Conf. Ser.* ***123****, 012033 (2008)*
[3]*Wesson, Tokamaks, 4th ed. (2011), p. 630*

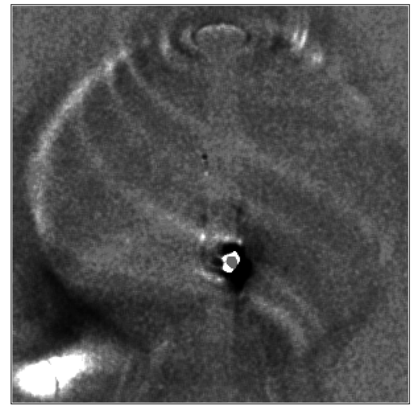
A ~ 1: ELMs n-numbers tend lower

- Small (“Type III”):
  - Ubiquitous, less perturbing
  - At $P_{OH} \sim P_{LH}$
  - Low-n: *A*-dependent structure
    - Peg., NSTX: n ≤ 4
    - *A* ~ 3: n > 8
- Large (“Type I”)
  - Infrequent, violent
  - At $P_{OH} >> P_{LH}$
  - Intermediate-n: lower range at low-*A*

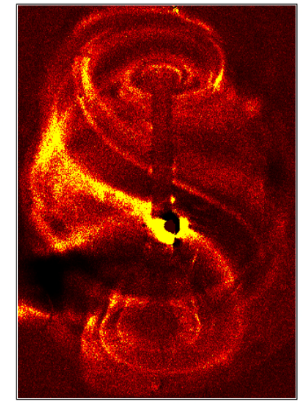
Quiescent



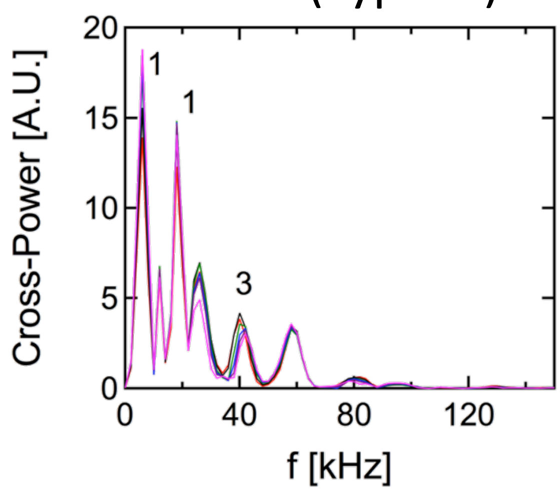
Small (Type III) ELM



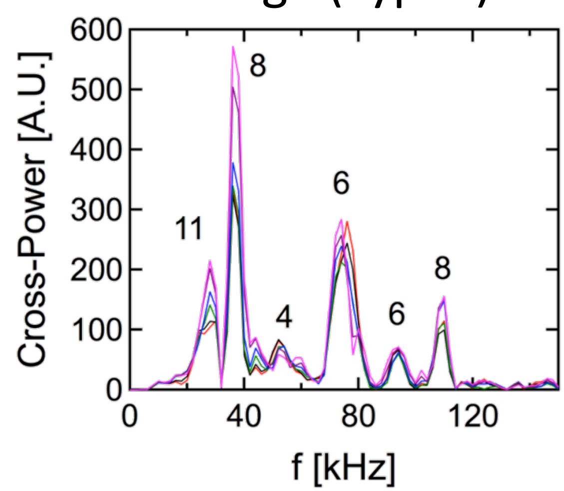
Large (Type I) ELM



Small (Type III)



Large (Type I)



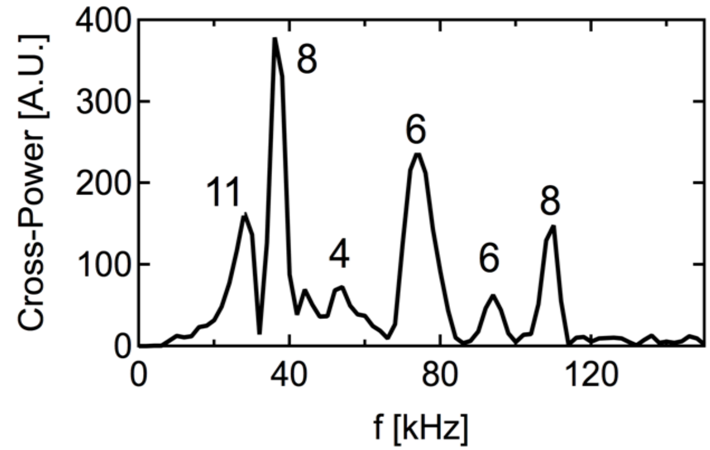
Maingi, Nucl. Fusion ***45****, 1066 (2005)*
Perez, Nucl. Fusion ***44****, 609 (2004)*
Kass, Nucl. Fusion ***38****, 111 (1998)*

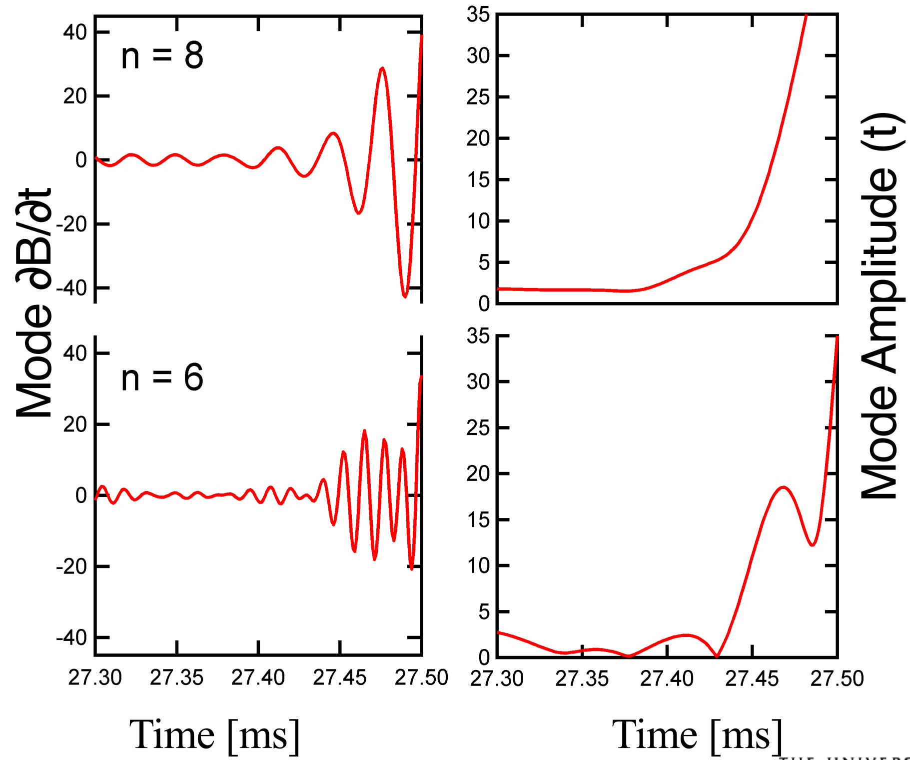
THE UNIVERSITY of WISCONSIN MADISON

Nonlinear ELM Precursors Observed

- Magnetic signature of ELMs have multiple n components
  - Simultaneously unstable modes

- Modes show different time evolutions
  - n = 8 grows continuously
  - n = 6 fluctuates prior to crash

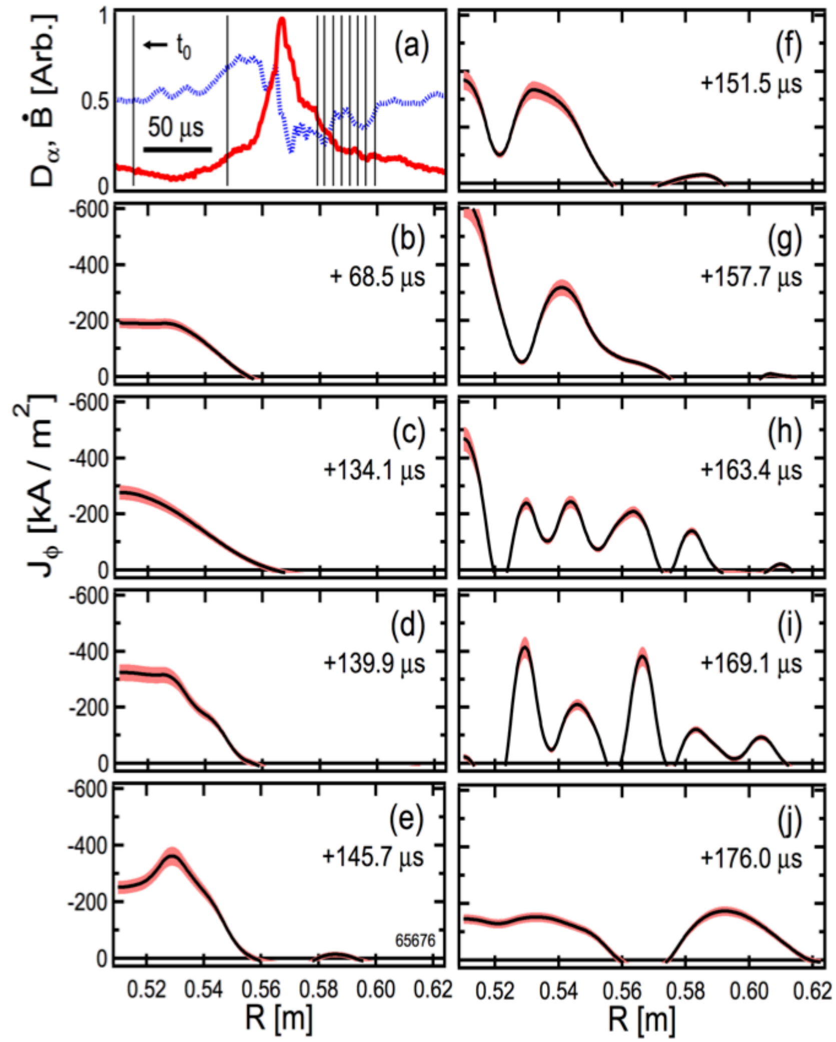




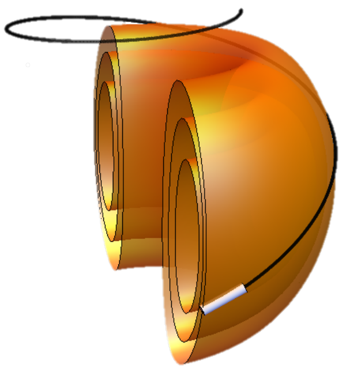
Complex Evolution of $J_{edge}(R,t)$ Measured During ELMs

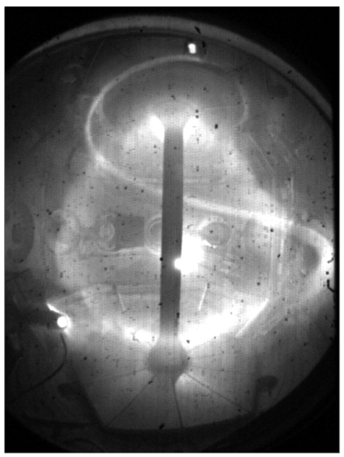
- **Challenge:** nonlinear ELM dynamics at Alfvénic timescales
- Ubiquitous current hole formation observed:
  - Type III: smaller, slower, no filament evident
  - Type I: larger, faster, evident filament
  - Qualitatively similar to JOREK
  - Probe access: simulation validation opportunities
- Complex, multi-modal collapse of edge and filament formation

Large, Type I ELM nonlinear $J_{edge}(R,t)$ evolution

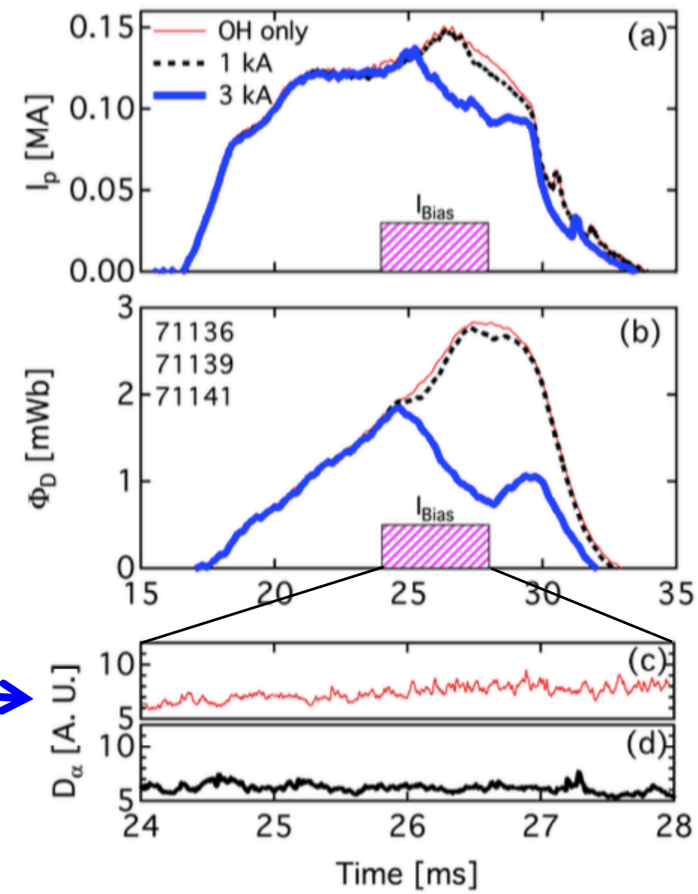


3D Edge Current Injection May Influence ELM Stability





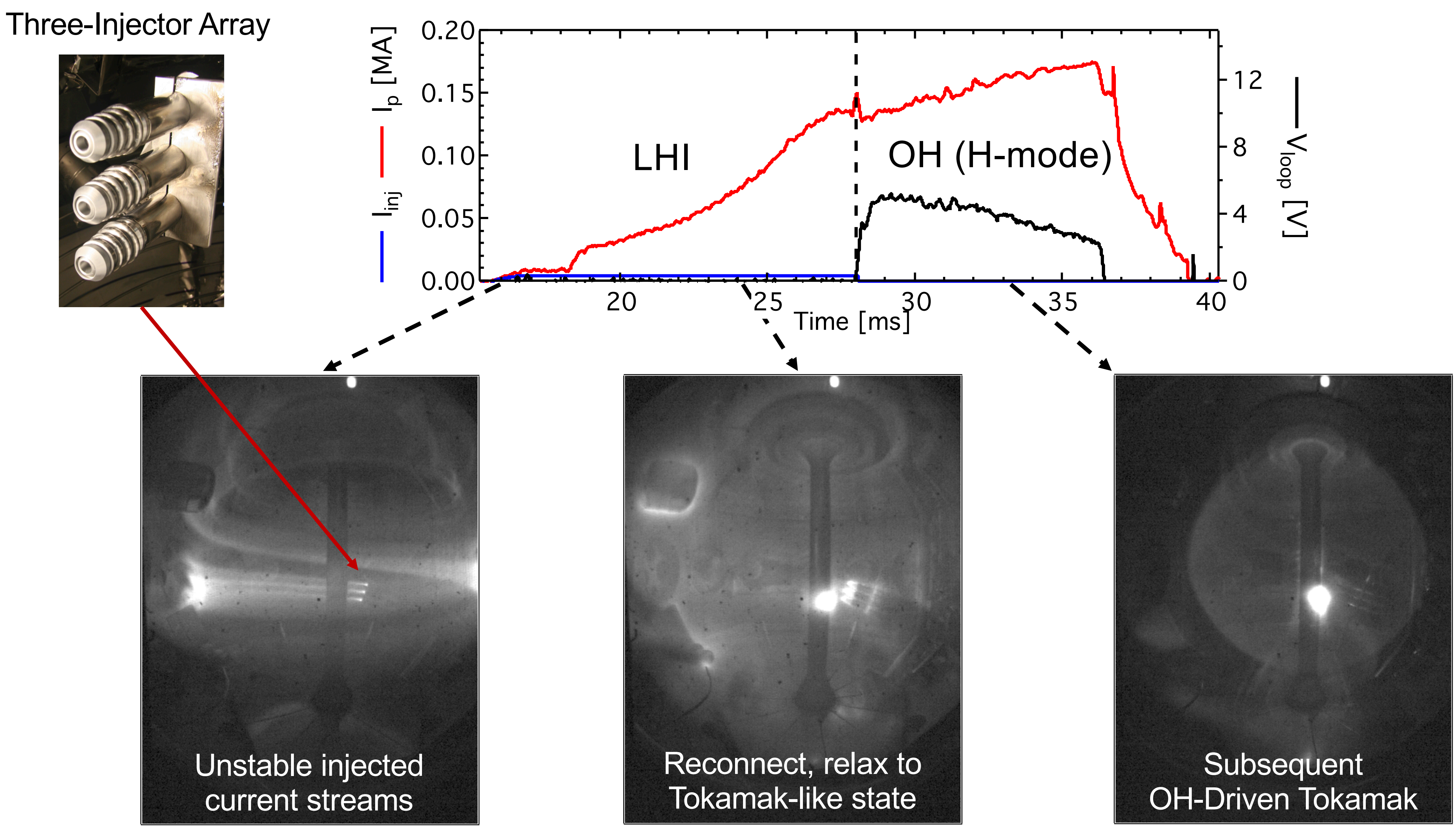
- LHI system affects edge plasma
  - Strong 3D edge current perturbation
  - Edge biasing to modify rotation
  - Similar to LHCD on EAST[1]
- J_{edge} injection in H-mode suggests ELM suppression
  - Low I_{inj} = ELM suppression
  - High I_{inj} = edge and discharge degradation



1: Liang et al., Phys. Rev. Lett. **110**, 235002 (2013)

THE UNIVERSITY of WISCONSIN MADISON

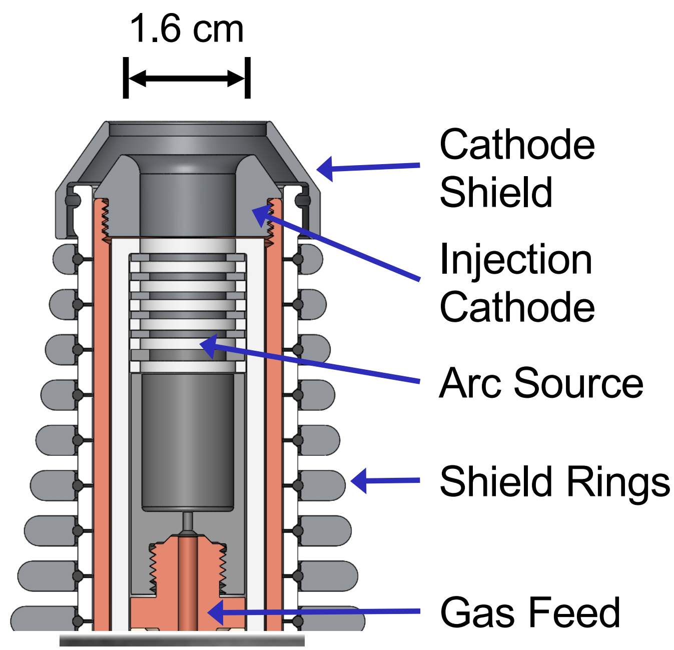
Local Helicity Injection (LHI) Provides Robust ST Startup without OH Solenoid



THE UNIVERSITY of WISCONSIN MADISON

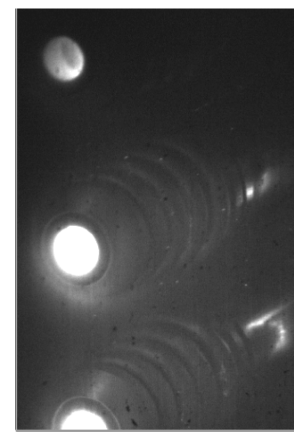
Multi-Year Technology Development has Produced Robust, High Performance Current Injectors

- Washer-stack arc source:
  - J_{inj}~1kA/cm²
- High-voltage in SOL: V_{inj} > 1kV
  - Frustum cathode
  - Floating cathode shield
- PMI control: 1-2 cm from LCFS
  - Cascaded shield rings
  - Local limiter
  - Mo PFCs



Three-Injector Array

Clean, High-V_{inj} Operation



THE UNIVERSITY of WISCONSIN MADISON

Physics Models Provide a Predictive Understanding for LHI Startup

1. Taylor relaxation, helicity conservation
   – Steady-state maximum I_p limits

Taylor Relaxation

$$I_p \leq I_{TL} \sim \sqrt{\frac{I_{TF} I_{inj}}{w}}$$

Helicity Conservation

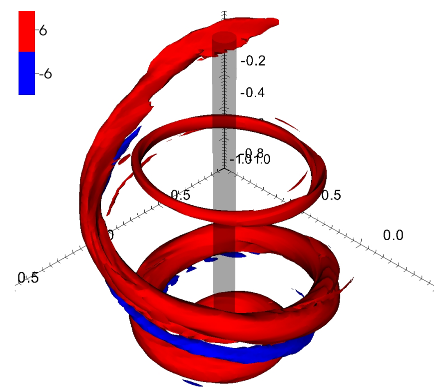
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   – V_{LHI} for effective LHI current drive

$$I_p \left[V_{LHI} + V_{IR} + V_{IND} \right] = 0 \; ; \; I_p \leq I_{TL}$$

3. 3D Resistive MHD (NIMROD)
   – Physics of LHI current drive mechanism

Reconnecting LHI Current Stream



D.J. Battaglia, et al. Nucl. Fusion **51** (2011) 073029.
N.W. Eidietis, Ph.D. Thesis, UW-Madison, 2007.
J. O'Bryan, Ph.D. Thesis, UW-Madison, 2014.
J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)

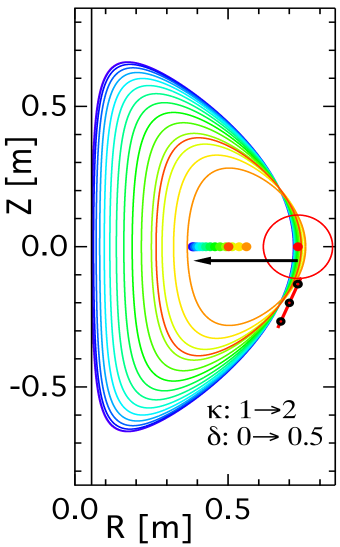
THE UNIVERSITY of WISCONSIN MADISON

Power Balance Model Provides Predictive Tool for $I_p(t)$

$$I_p\left[V_{LHI}+V_{IR}+V_{IND}\right]=0$$

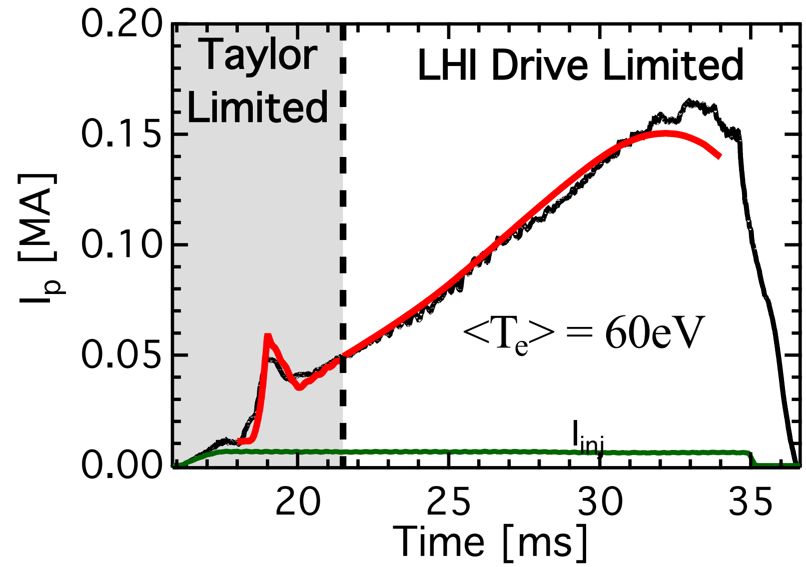
- V_{LHI}: effective drive
- V_{IR}: resistive dissipation
- V_{IND}: analytic, from shape(t)
- Taylor relaxation limit: $I_p \leq I_{TL}$

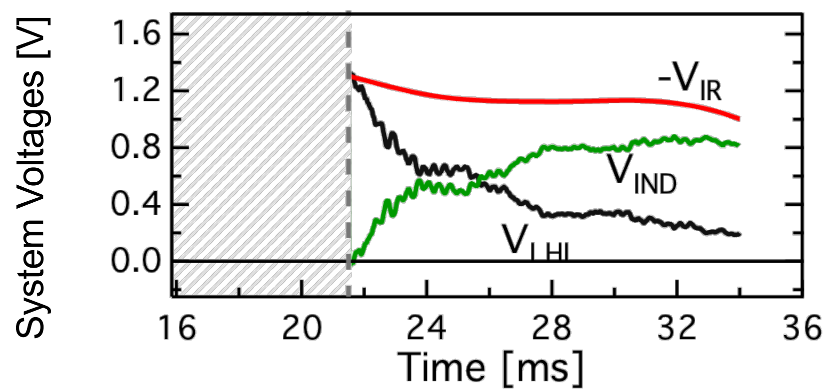
Shape Evolution



- V_{IND} dominates current drive

- Model reasonably recreates $I_p(t)$





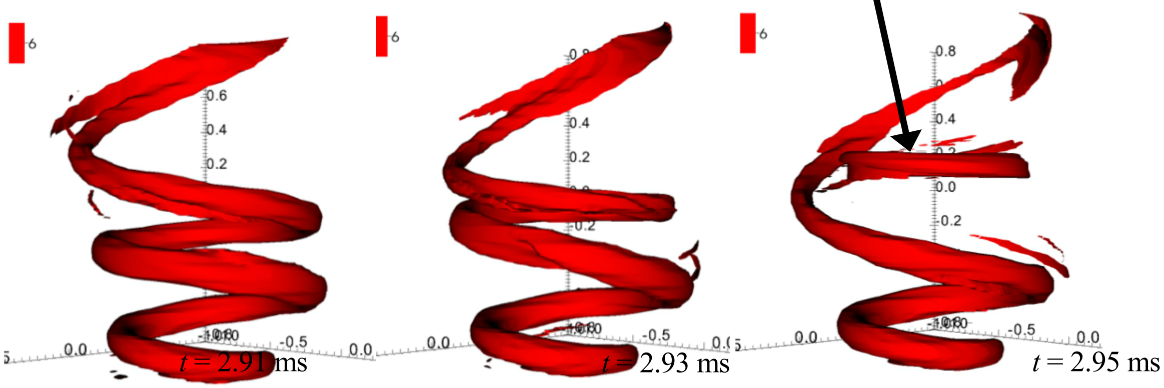
*Eidietis et al., J. Fusion Energ. **26**, 43 (2007)*
*S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids **29** 790*
O. Mitarai and Y. Takase 2003 Fusion Sci. Technol.
*Battaglia et al., Nucl. Fusion **51**, 073029 (2011)*

NIMROD Describes Current Helical Current Stream Reconnection as Drive Mechanism

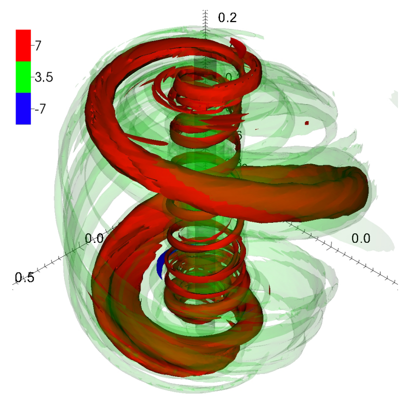
- Divertor injection = no inductive drive

Divertor LHI Startup Shows suggestive commonality between experiment and NIMROD modeling

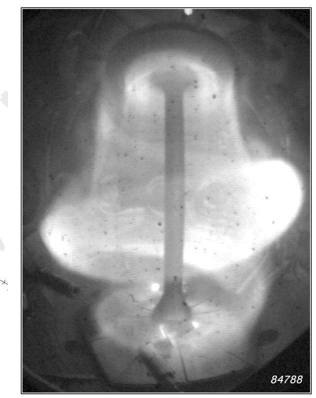
Current Ring



1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection pinches off current rings



NIMROD Simulation [O'Bryan PhD 2014]

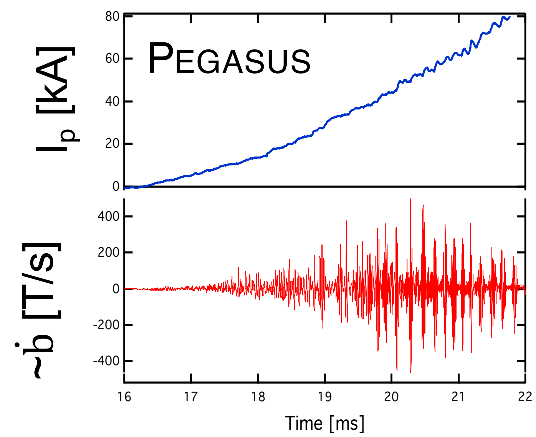


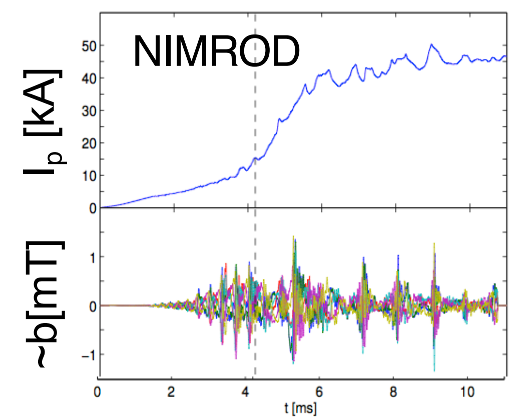
May 2016 PEGASUS High-speed Imaging

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

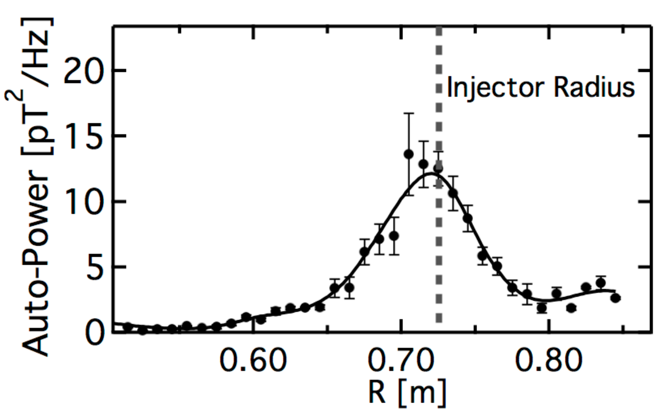
Current Stream Interaction Manifests as Edge-Localized MHD Burst

- Magnetics localize coherent streams in edge
  - Infers NIMROD streams in edge
- Reconnection-drive edge ion heating
- Any stochastic reconnection region may be localized to edge

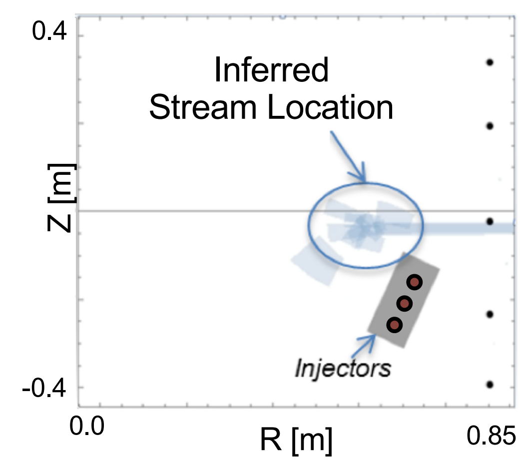




Internal B_z Measurements



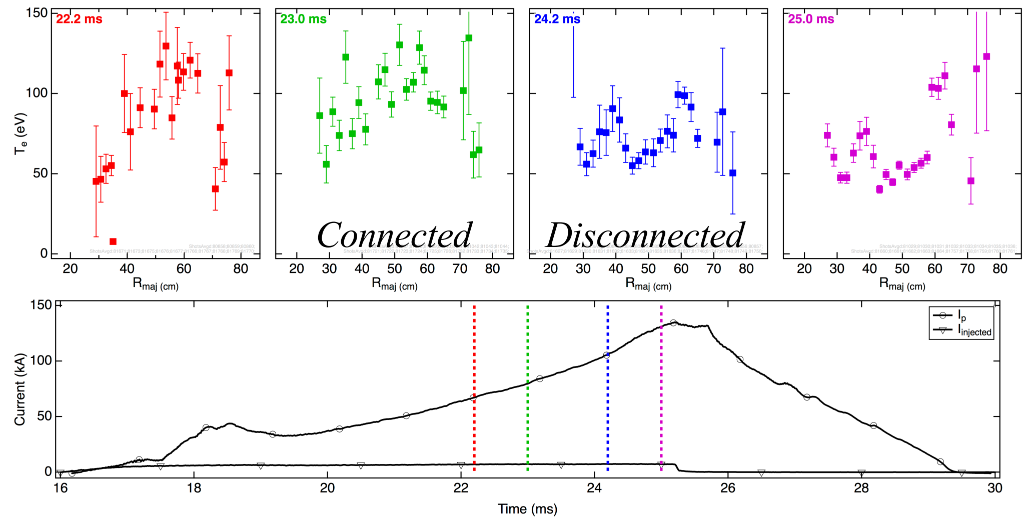
External B_z Phase Correlation



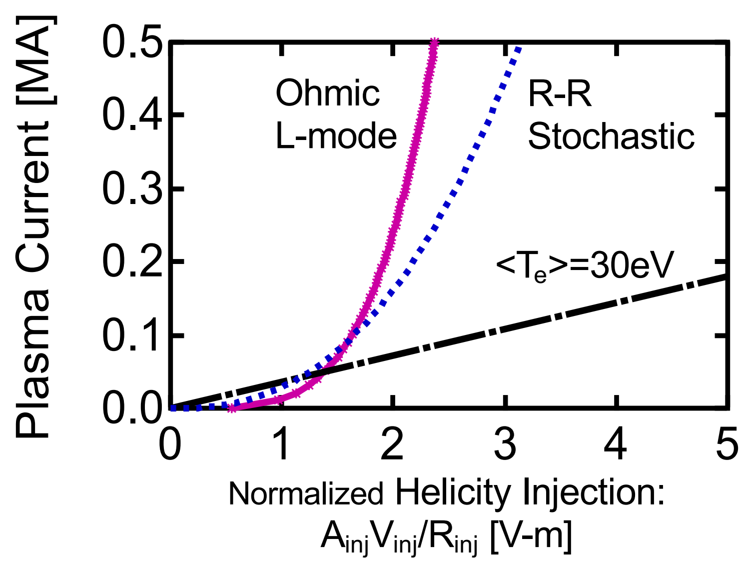
$T_e(0)$ > 100 eV Suggests Favorable Confinement Scaling?

- $T_e(0) \gtrsim 100$ eV comparable to Ohmic L-mode
  - With $n_e \gtrsim 10^{19}$ m^{-3}, provides good target plasmas for subsequent sustainment
- Possible two zone confinement
  - *Not* strongly stochastic across profile
  - Drive: V_{IND} (across plasma), V_{LHI} (edge)
- Confinement estimates suggest favorable scaling to NSTX-U
  - OH, stochastic models

Peaked $T_e(R)$ while Connected to Injectors



Confinement Scaling Estimates



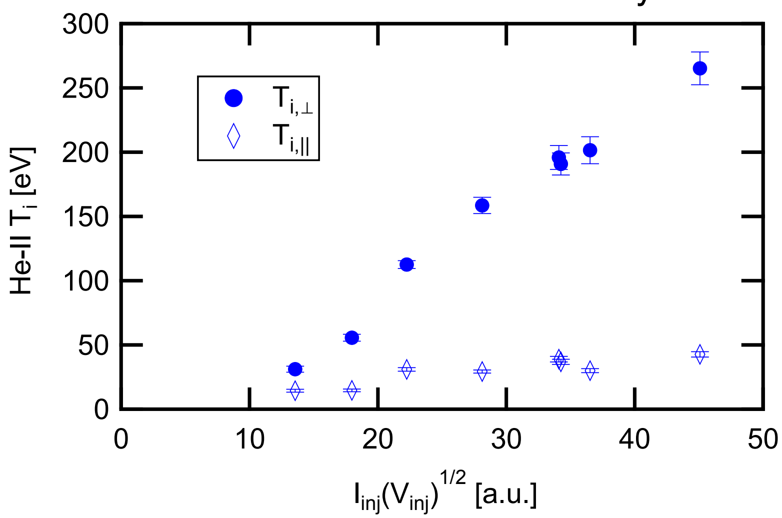
A.B. Rechester and M.N. Rosenbluth, PRL ***40*** *(1) 1978*
C.R. Sovinec and S.C. Prager, Phys. Plasmas ***3*** *(3) 1996*
Stoneking, et al., Phys. Plasmas ***5*** *(4) 1998*

THE UNIVERSITY of WISCONSIN MADISON

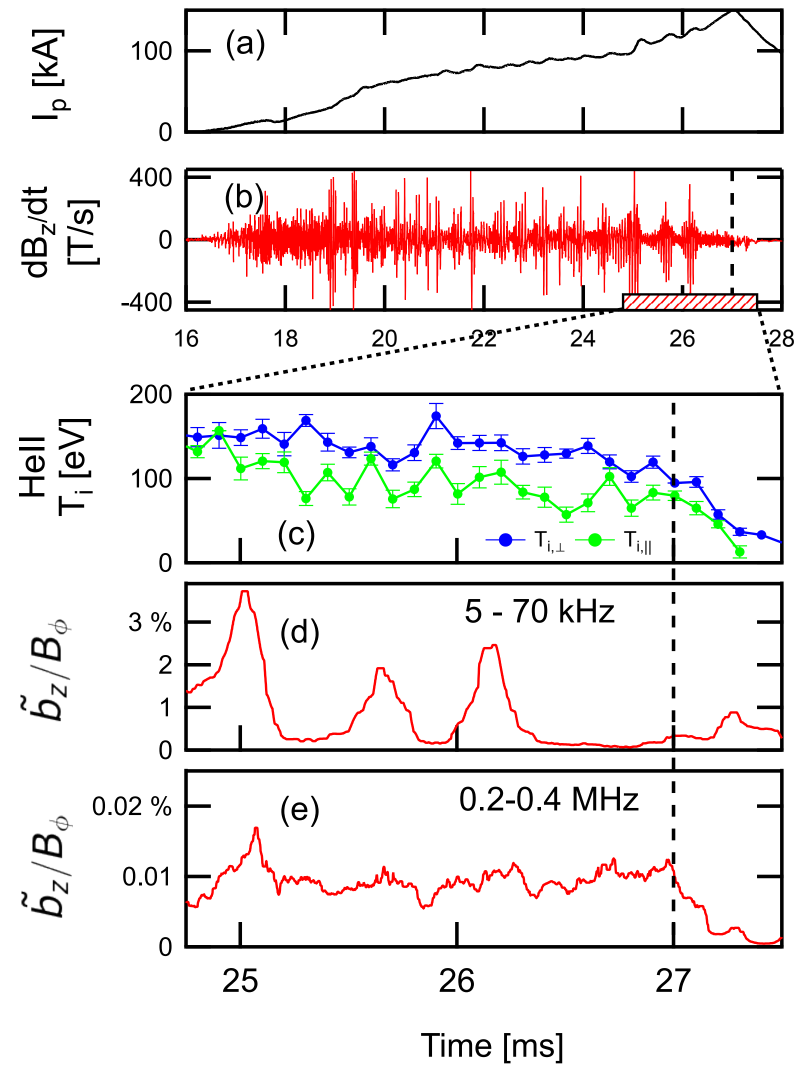
Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

- Impurity $T_i(0) \sim 100 – 500$ eV > T_e routinely observed during LHI
- Continuous ion heating from reconnection between collinear current streams
  - No effect on current drive efficiency
  - Significant ion heating (~ few 0.1 MW)

Ion heating consistent with 2-fluid reconnection theory



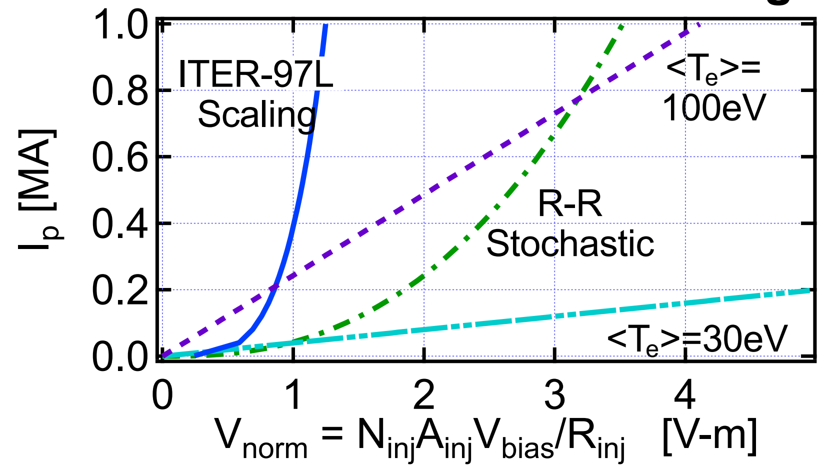
Ion heating correlated with high frequency MHD fluctuations, not with discrete reconnection between helical streams



Understanding Confinement Scaling in LHI is Critical for Predicting to NSTX-U and Beyond

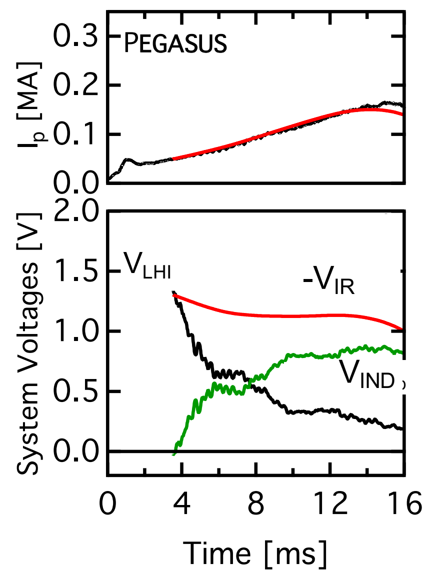
- Rapid improvement with V_{LHI} under favorable scalings
  - Possible reduction in injector requirements

NSTX-U: Confinement Scalings

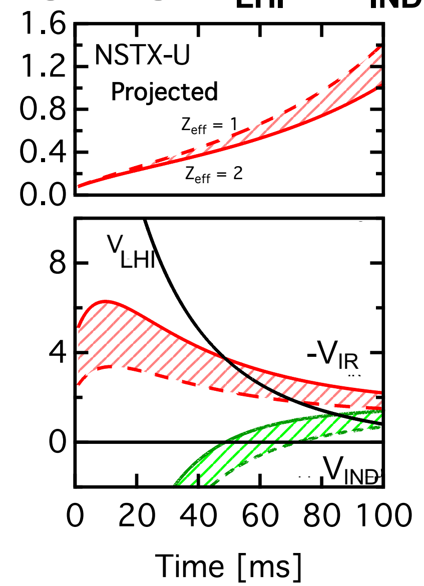


- Current projections: I_p~1 MA on NSTX-U accessible

PEGASUS: V_{LHI} < V_{IND}



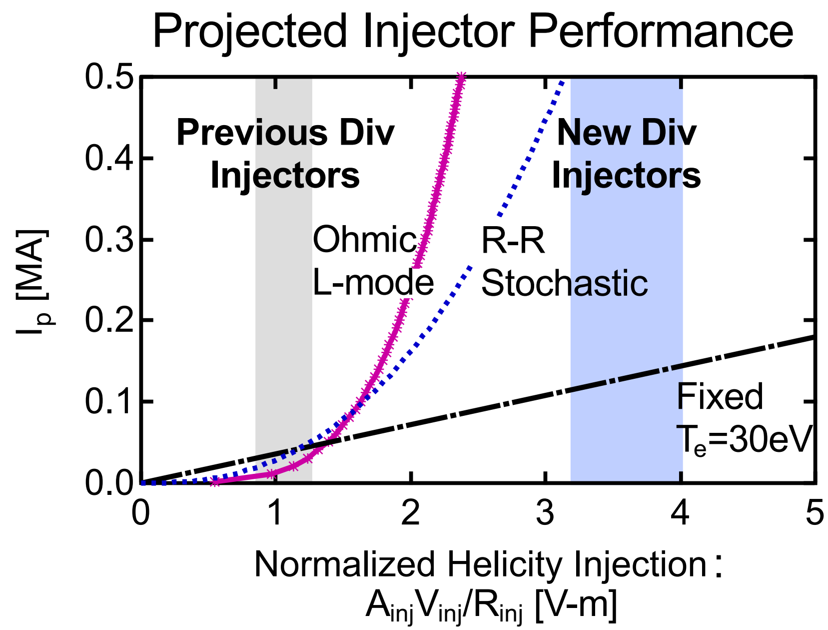
NSTX-U: V_{LHI} ~ V_{IND}

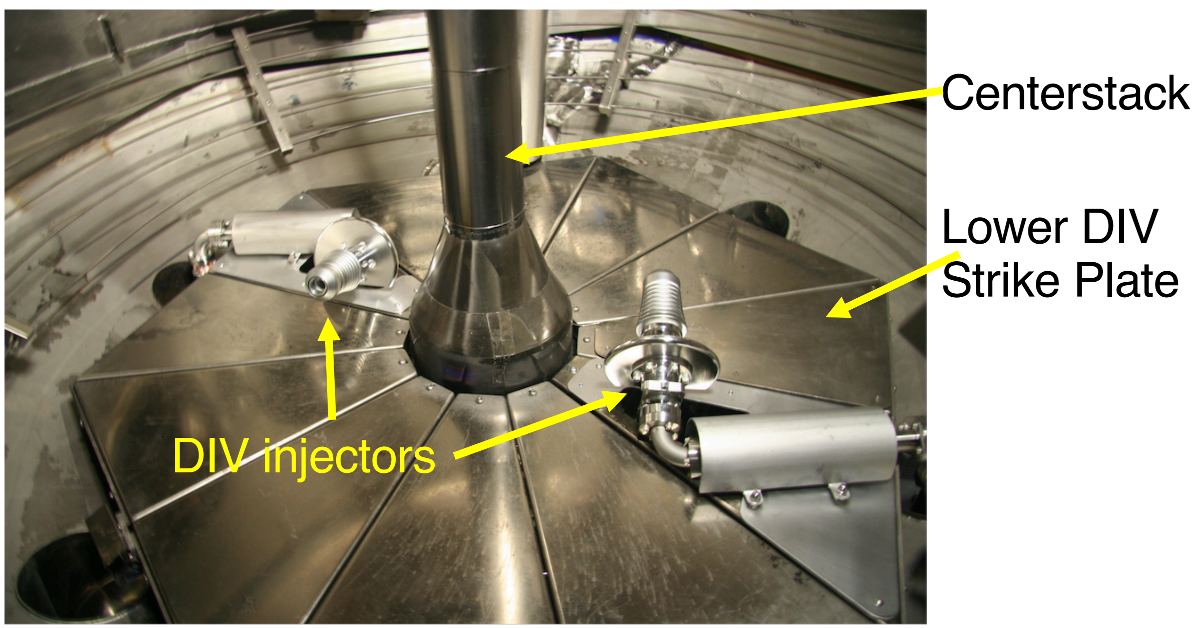


- Will need V_{LHI} ~ V_{IND}
  - Confinement studies needed when sustained by V_{LHI}

Divertor Injection Experiments Provide Confinement Test & Higher I_p

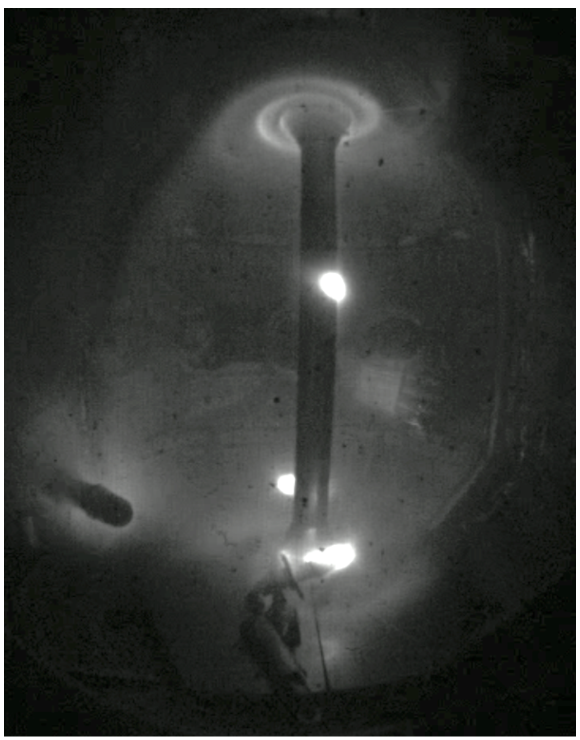
- Initial DIV injector campaign in progress
  - Development to minimize PMI as B_{TF} increases
- Minimal V_{IND}
- 3-4x increase in HI drive: $V_{eff} \sim A_{inj}V_{inj}/R_{inj}$
- Reconnection mechanisms to higher I_p, B_{TF}
- Injectors at longer pulse, high-B_{TF}

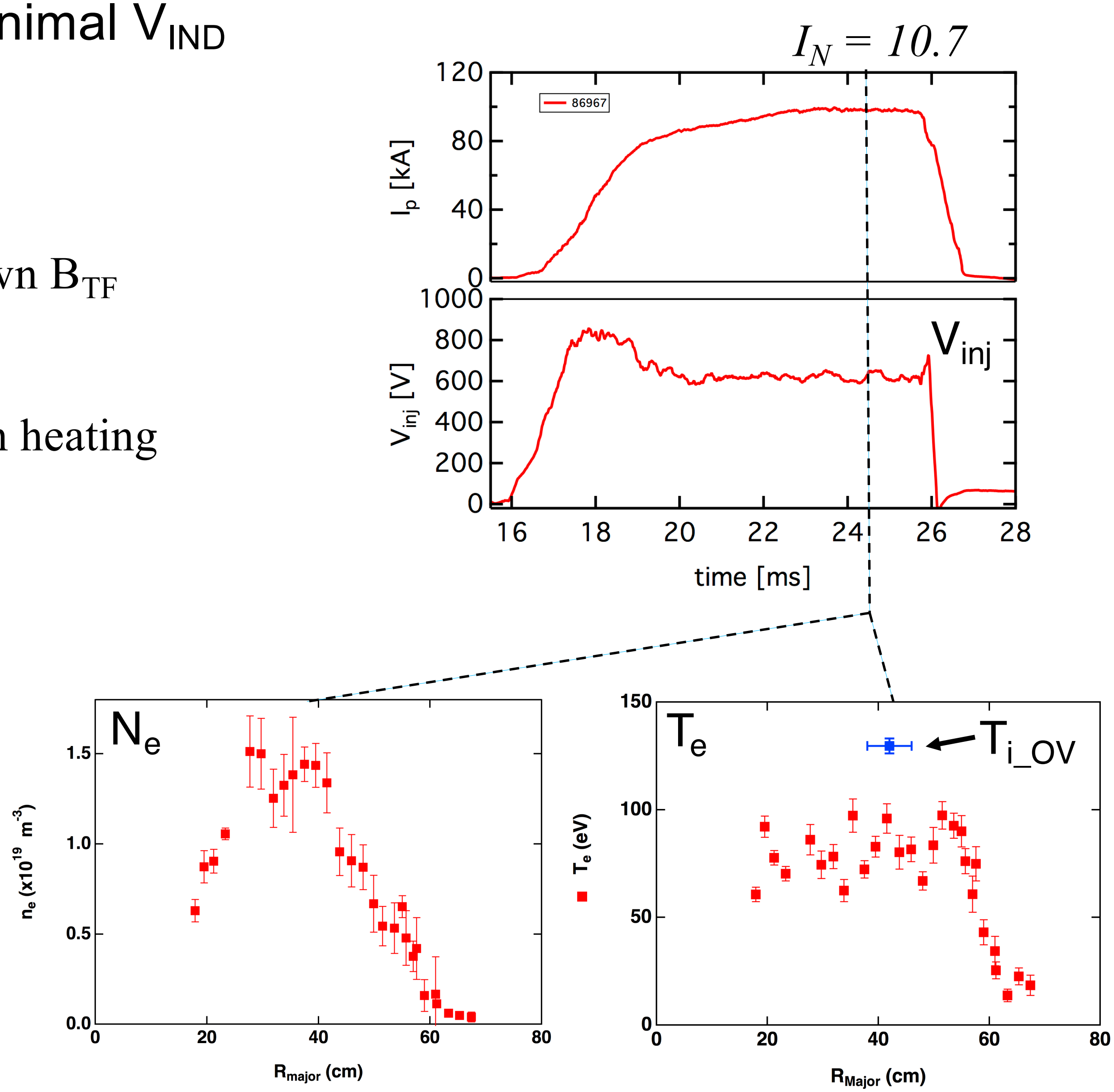




Divertor Injection Provides Non-solenoidal Sustainment at High I_N

- Constant geometry: minimal V_{IND}
- Low $I_{TF} \sim 0.6\ I_p$
- $I_N > 10$ accessible
  - Constant or ramped-down B_{TF}
- Potential for high β_T
  - Aided by anomalous ion heating



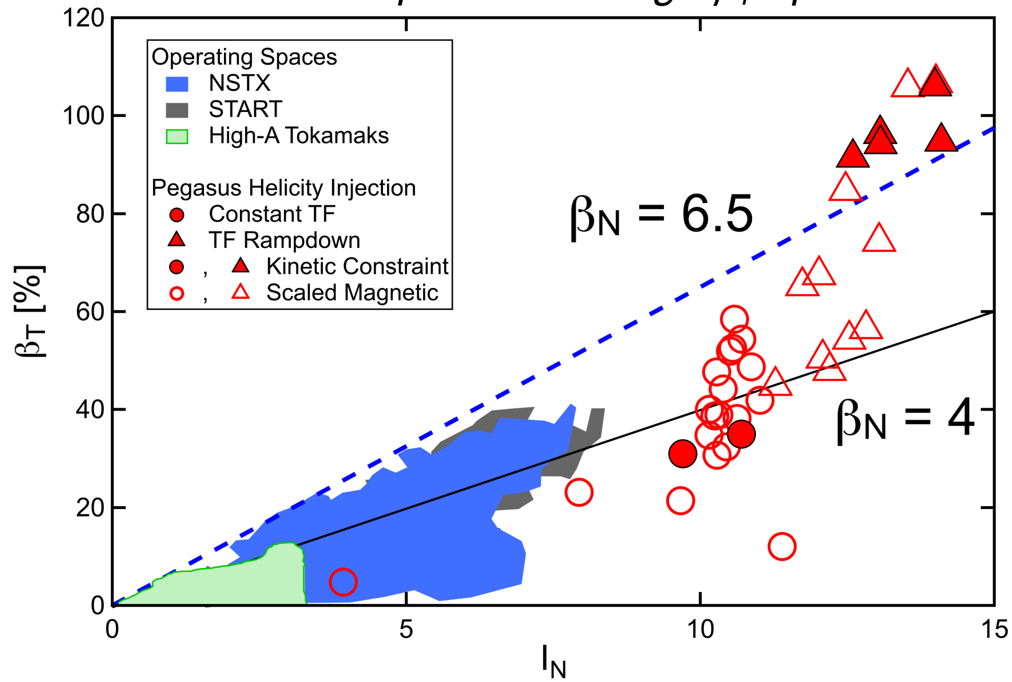


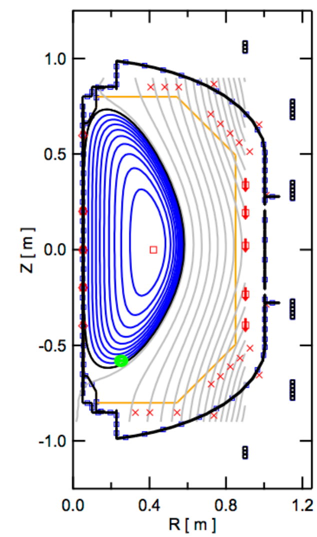
THE UNIVERSITY of WISCONSIN MADISON

LHI Provides Access to High-β_T at A ~ 1 with Non-Solenoidal Sustainment and Anomalous Ion Heating

- Equilibrium reconstructions estimate β_T (~<P>/B_{T0}^2)
  - Matches external magnetics, $P_{tot}(0)$, and edge in $T_e(R)$
  - Includes anomalous $T_i(0)$
  - Some caveats for these initial results
    - Assumes closed flux surfaces inboard of injectors
    - Role of SOL edge current
    - Magnetics-only reconstructions scaled via comparison to those with kinetic constraints
    - Need full kinetic profiles in future
- High β_T plasmas often terminated by disruption
  - n = 1, low-m precursors
- Expands accessible high I_N, β_T space for tokamak stability studies at extreme toroidicity
  - Campaign underway to document, extend to higher I_p
  - Improved LHI injector hardware to increase I_p, B_{TF} access

Initial Exploration of High-β_T Space





Equilibrium Parameters
Shot 87332, 24.50 ms, Undo 72

I_p	102 kA	R_0	0.317 m
β_t	0.95	a	0.263 m
ℓ_i	0.22	A	1.21
β_p	0.45	κ	2.6
W	545 J	δ	0.54
B_{T0}	0.0249 T	q_{95}	7.24

Studies at *A* ~ 1 Support Development of the Tokamak Concept

- H-mode plasmas with pedestal diagnostic access
  - Standard characteristics: pedestal; low D_α; increased τ_e; H_{98}
  - Strong P_{LH} scaling with *A*
  - Insensitivity to magnetic topology
  - Transient current hole formation during ELMs
  - ELM mode structure reflects strong peeling drive

- Local Helicity Injection provides non-solenoidal startup and sustainment
  - I_P up to ~ 0.18 MA with I_{inj} ~ 5-6 kA
  - Taylor Relaxation, Helicity conservation, and resistive MHD modeling
  - Appears scalable to large scale, but questions on confinement and reconnection dynamics
  - Flexible geometry options for helicity and inductive drive tradeoffs, and engineering constraints

- Non-solenoidal $I_p(t)$ via LHI enables access to stability tests at extreme toroidicity
  - Sustained operation at high I_N, high β_T

THE UNIVERSITY of WISCONSIN MADISON