Local Helicity Injection Startup and H-mode Studies at Ultralow-*A* on Pegasus

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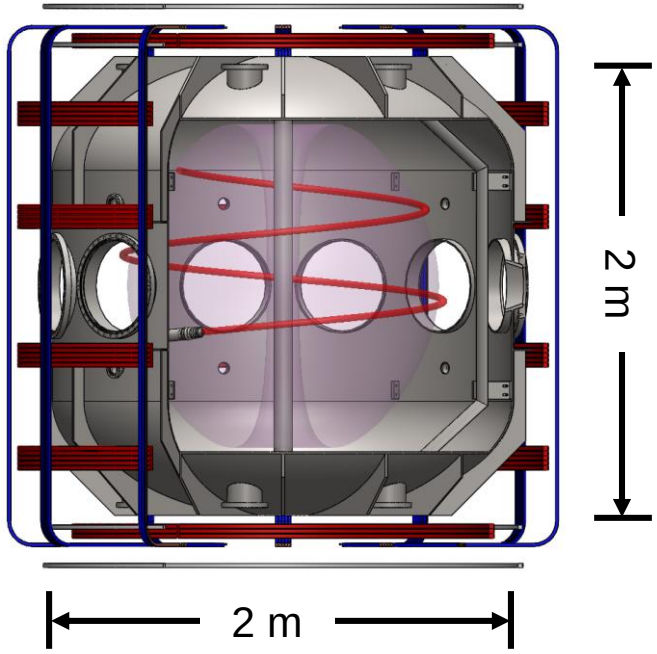
EPR 2016

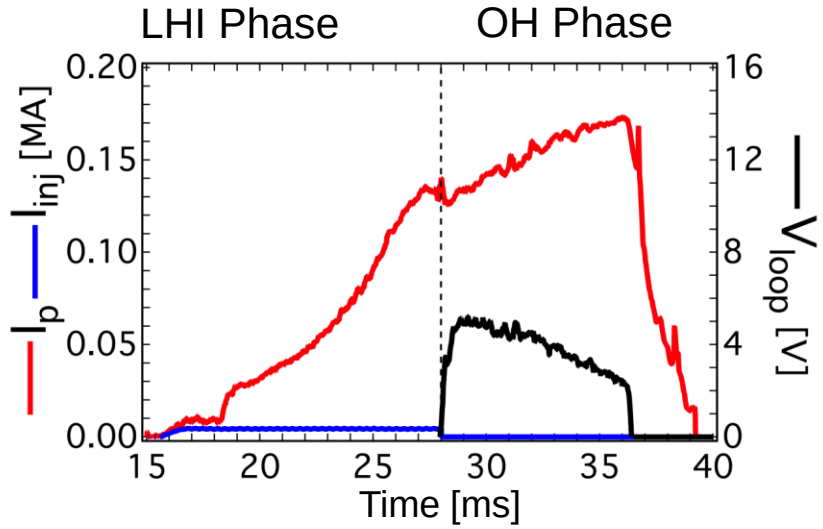
February 24th, 2016
Auburn, AL

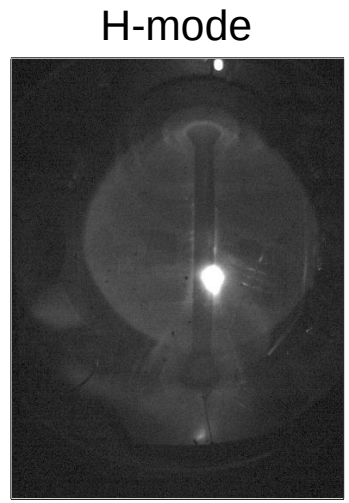


PEGASUS Toroidal Experiment

Pegasus is an Ultralow-A ST with a Targeted Physics Mission





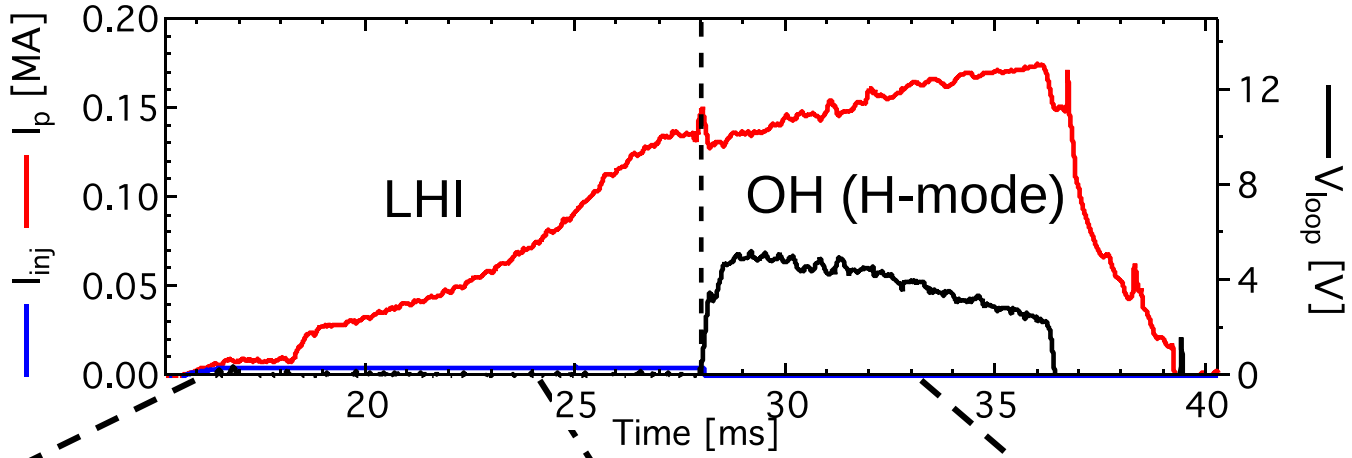


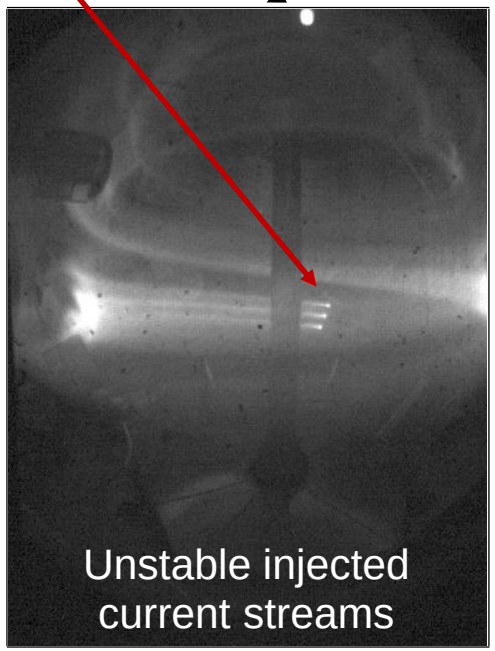
- Local Helicity Injection (LHI) for ST Startup
  - Startup technique injects current streams in plasma edge
- H-mode Physics at Ultralow-*A*
  - Edge and H-mode physics at low-*A*

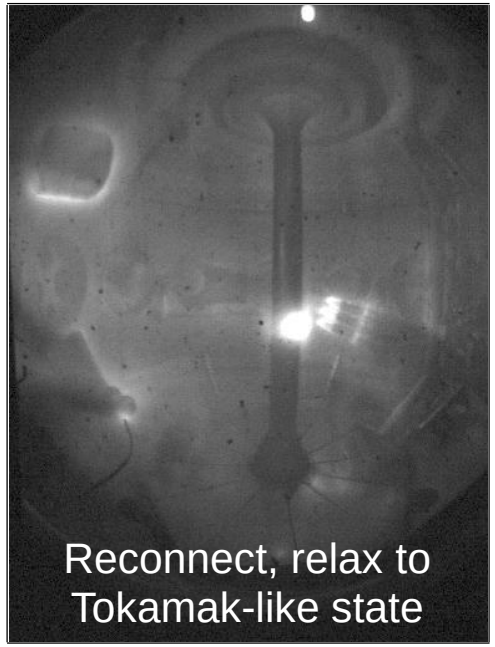
Local Helicity Injection (LHI) Provides Robust ST Startup

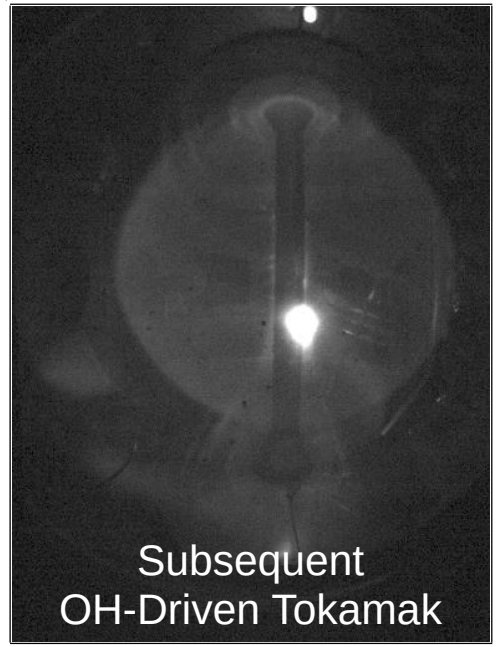
Three-Injector Array











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

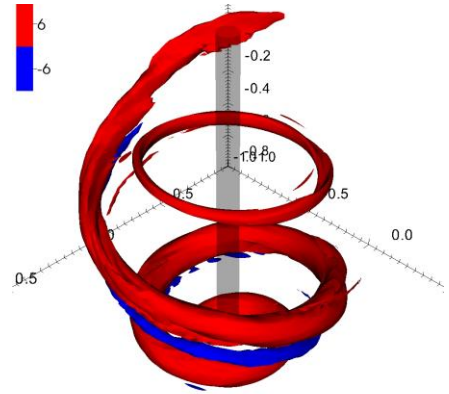
$$V_{LHI} \approx \frac{A_{inj} B_{j,inj}}{\Upsilon} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   - Incorporates 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)
   - Detailed physics of LHI current drive mechanism

Reconnecting LHI Current Stream



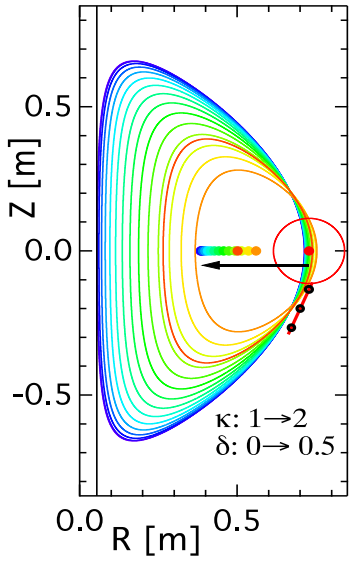
*D.J. Battaglia, et al. Nucl. Fusion **51** (2011) 073029.*
N.W. Eidietis, Ph.D. Thesis, UW-Madison, 2007.
J. O'Bryan, Ph.D. Thesis, UW-Madison, 2014.
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

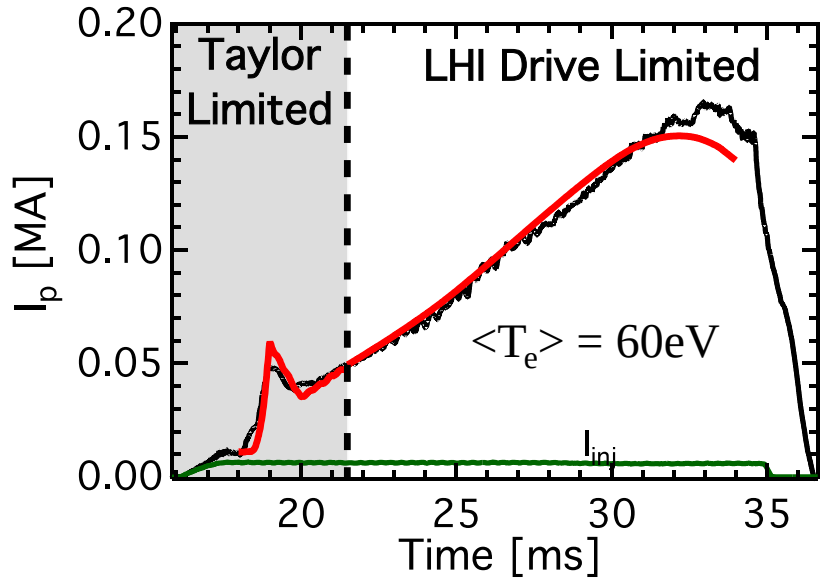
Power Balance Model Reproduces $I_p(t)$

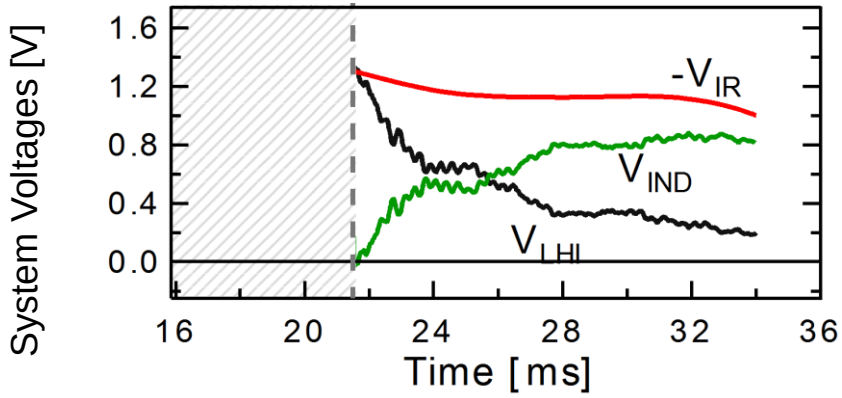
$$I_p\left[V_{LHI}+V_{IR}+V_{IND}\right]=0$$

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

Shape Evolution





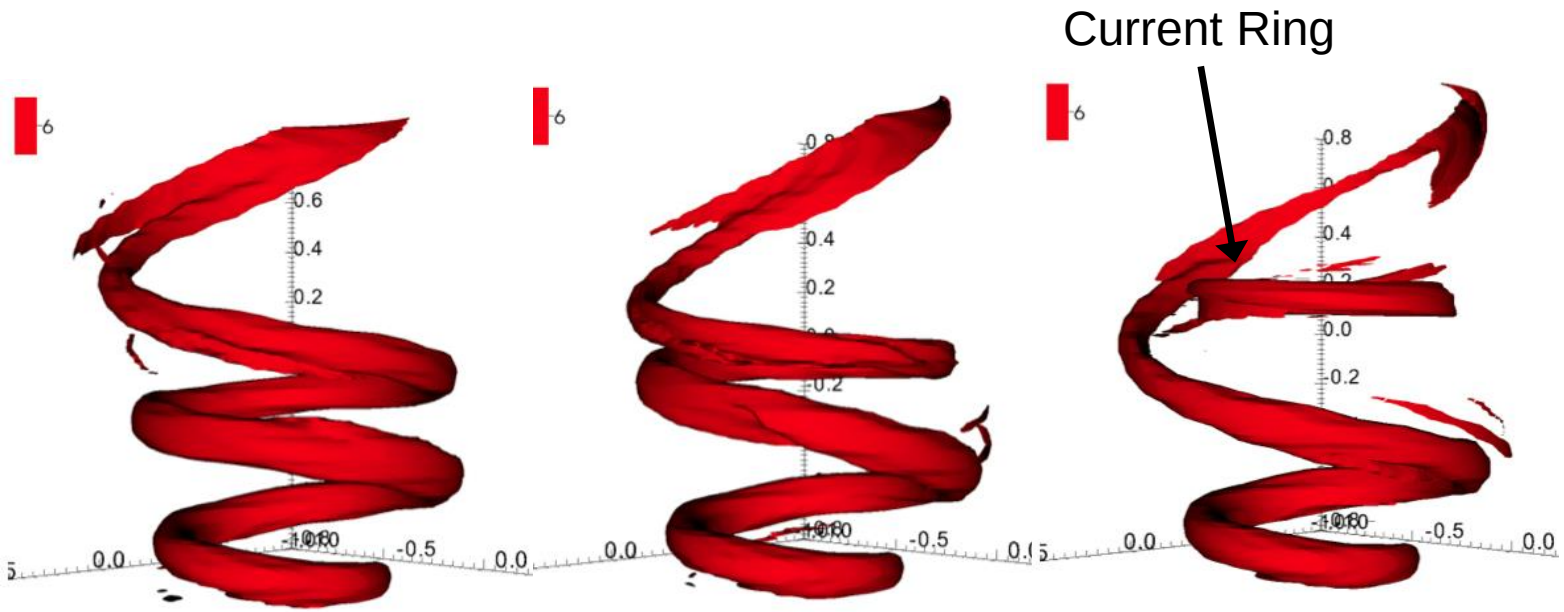


- Model reasonably recreates $I_p(t)$
- V_{IND} dominates current drive

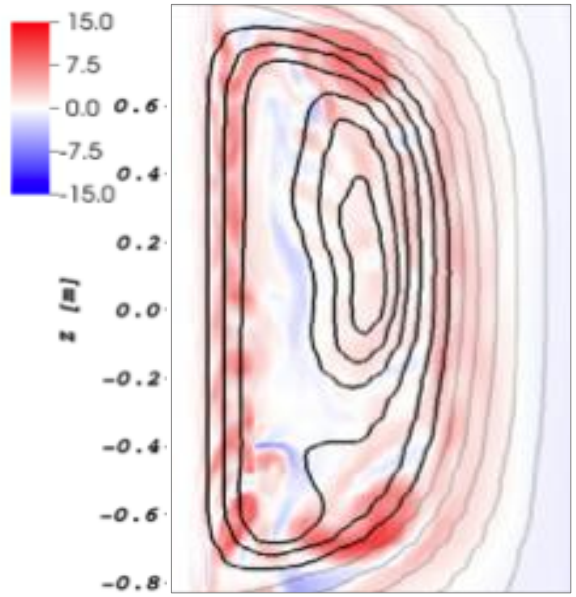
Eidietis et al., J. Fusion Energ. ***26****, 43 (2007)*
S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids ***29*** *790*
O. Mitarai and Y. Takase 2003 Fusion Sci. Technol.
Battaglia et al., Nucl. Fusion ***51****, 073029 (2011)*

NIMROD Describes Current Stream Reconnection as Drive Mechanism

- Divertor injection: no inductive drive



t = 2.91 ms | t = 2.93 ms | t = 2.95 ms

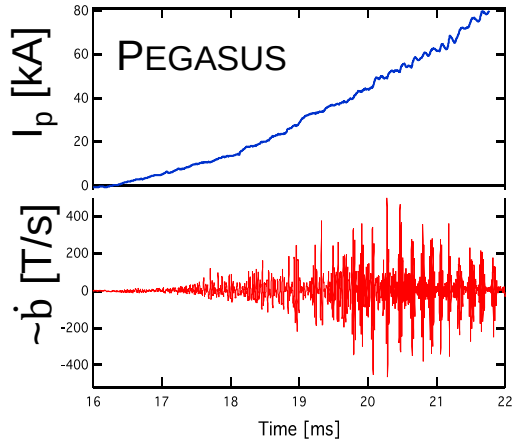


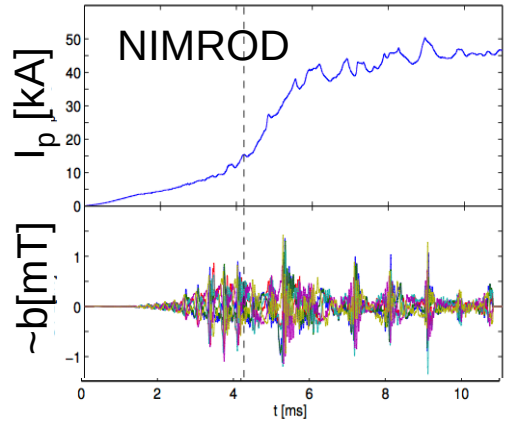
1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection pinches off current rings
4. Accumulation of I_p, poloidal flux; current filaments persist

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

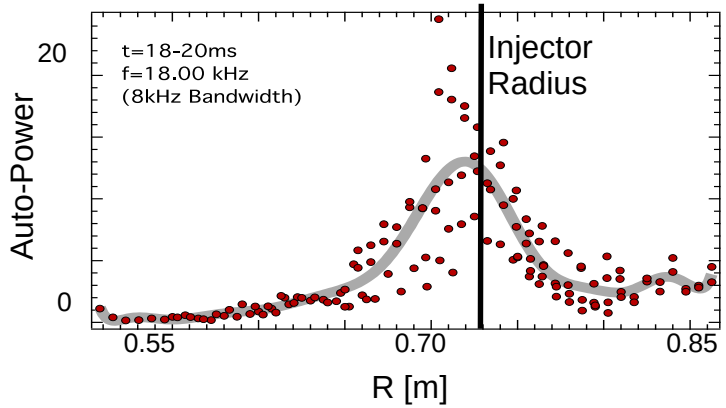
Current Stream Interaction Manifests as Edge Localized MHD Burst

- Magnetics measurements localize coherent streams in edge
  - Confirms NIMROD prediction of streams in edge
- Reconnection-drive edge ion heating
  - M.G. Burke: poster today
- Stochastic reconnection region may be localized to edge

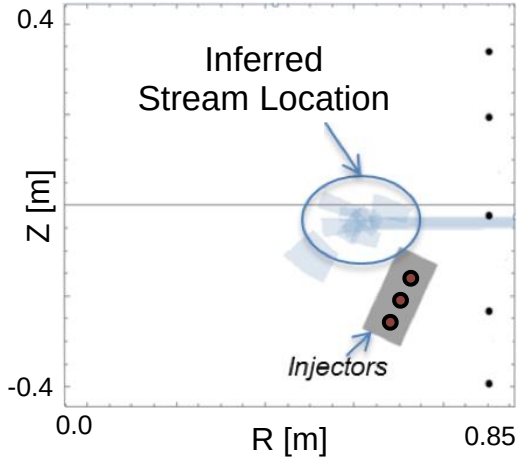




Internal B_z Measurements



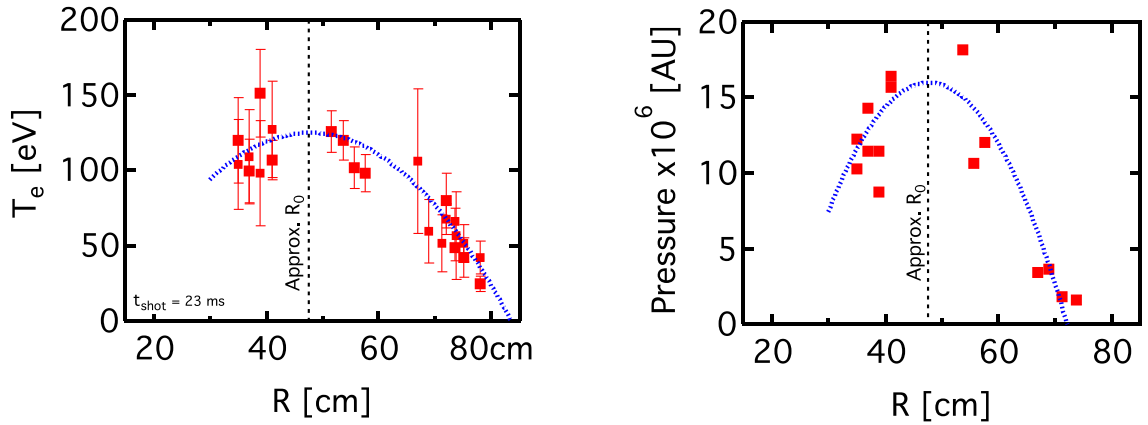
External B_z Phase Correlation



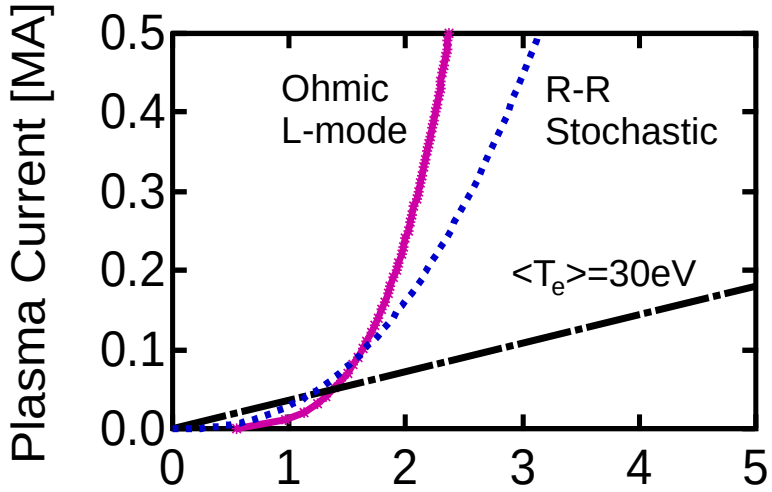
$T_e(0)$ > 100 eV Suggests Favorable Confinement Scaling

- $T_e(0) \gtrsim 100$ 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
  - Drive: V_{IND} (across plasma), V_{LHI} (edge)
- Confinement estimates suggest favorable scaling to NSTX-U
  - OH, stochastic models

First Thomson Scattering Results



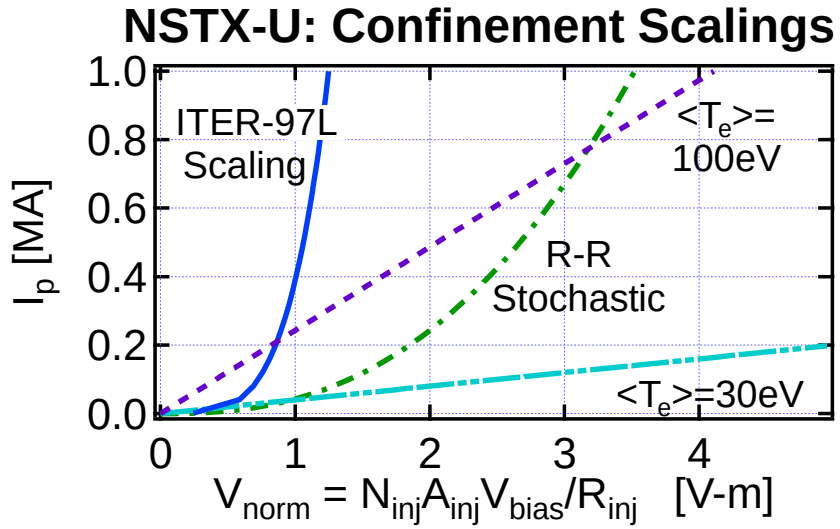
Confinement Scaling Estimates

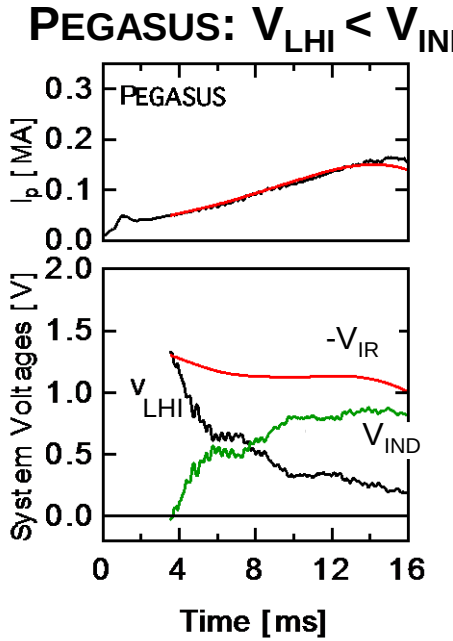


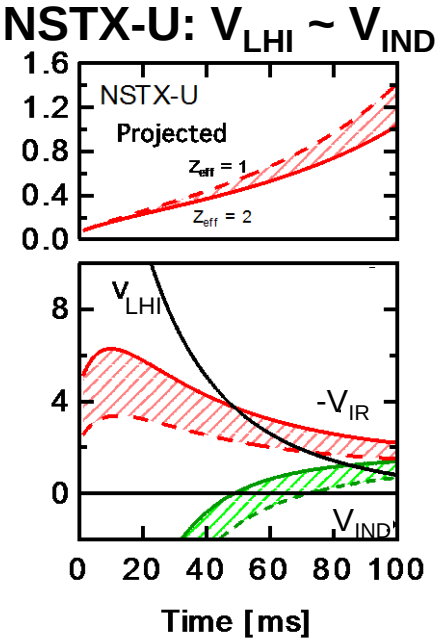
*A.B. Rechester and M.N. Rosenbluth, PRL **40** (1) 1978*
*C.R. Sovinec and S.C. Prager, Phys. Plasmas **3** (3) 1996*
*Stoneking, et al., Phys. Plasmas **5** (4) 1998*

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

- Rapid improvement with V_{LHI} under favorable scalings
  - Possible major reduction in injector requirements
- Current projections: I_p~1 MA on NSTX-U
- Will need V_{LHI} ~ V_{IND}
  - Confinement studies needed when sustained by V_{LHI}

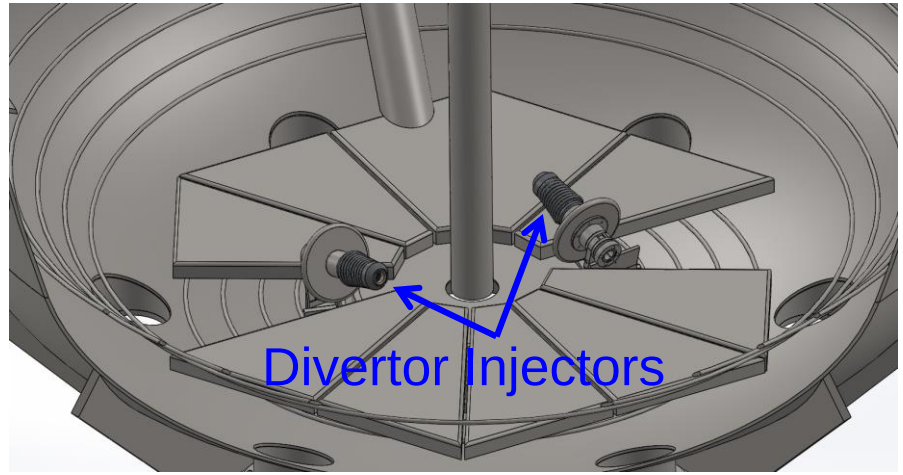


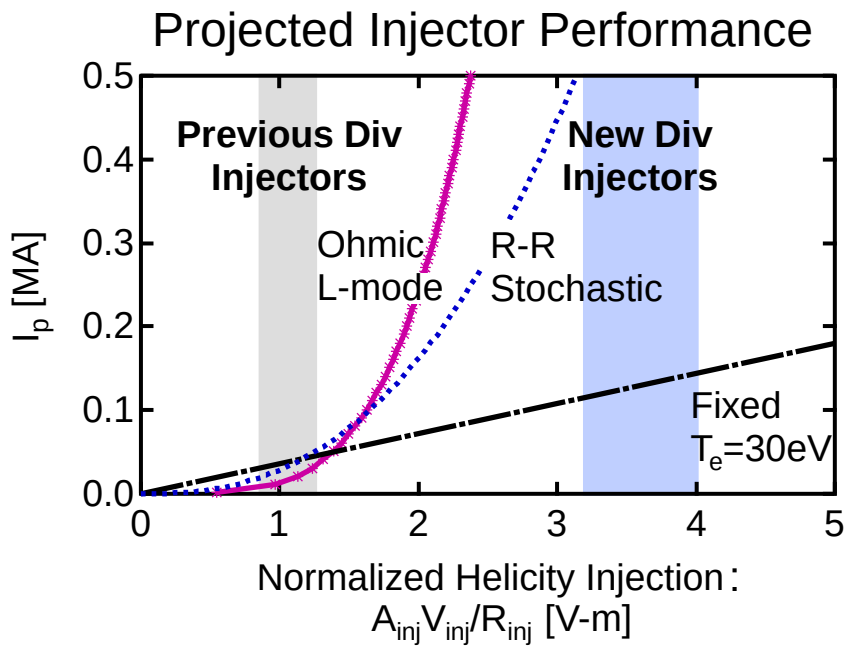




Divertor Injection Experiments Provide Critical Confinement Test

- Confinement scaling experiments:
  - Minimal V_{IND}
  - 4x increase in HI drive for definitive test
- Other NSTX-U relevant physics:
  - Scaling reconnection mechanism to high-B
  - Higher I_p
  - Increased B_{TF}
- Injector operation at long-pulse, high-B
- New injectors fabricated, ready for install



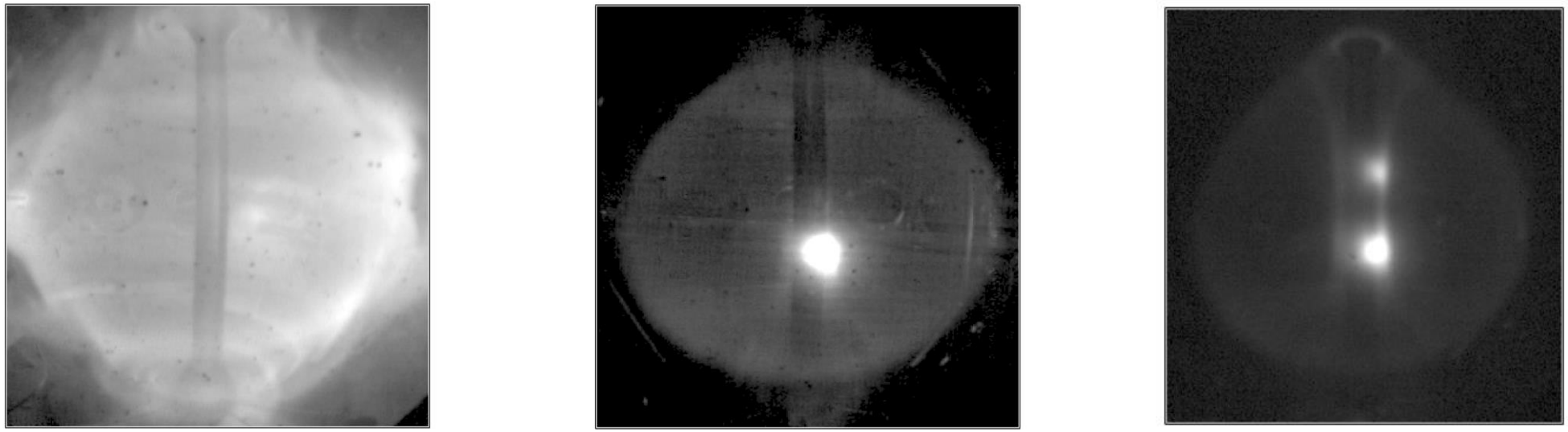


Building the Technology and Physics Basis for Scalable LHI

- Developing predictive understanding of LHI startup
  - 0-D power balance model provides prediction of $I_p(t)$:
    - *Reconnection localized to edge, strong inductive drive*
  - Evidence supports NIMROD current drive mechanism
  - Thomson Scattering: $T_e(0)$ comparable to OH
    - *Favorable scaling to high current startup?*
- Next steps: confinement and scalability studies
  - Divertor injectors
  - NSTX-U relevant physics regime ($V_{LHI} \sim V_{IND}$)

H-mode Readily Accessed in A ~ 1 PEGASUS ST

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

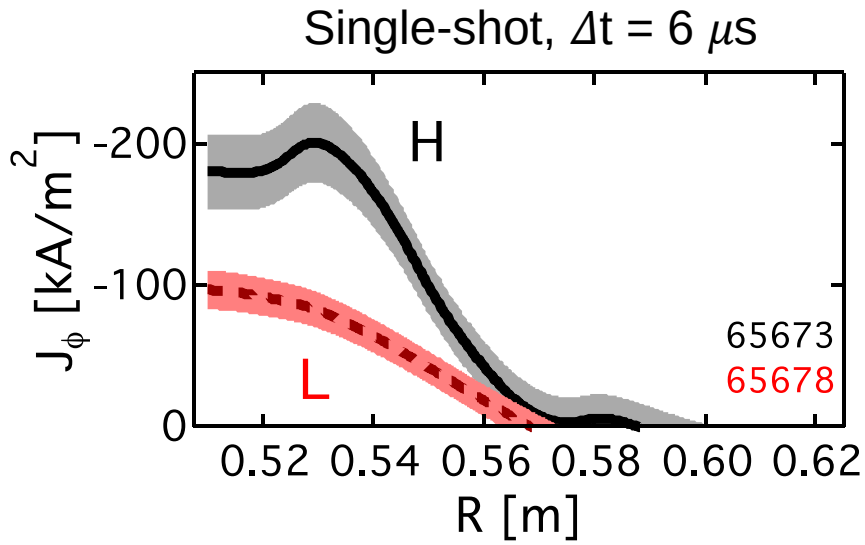


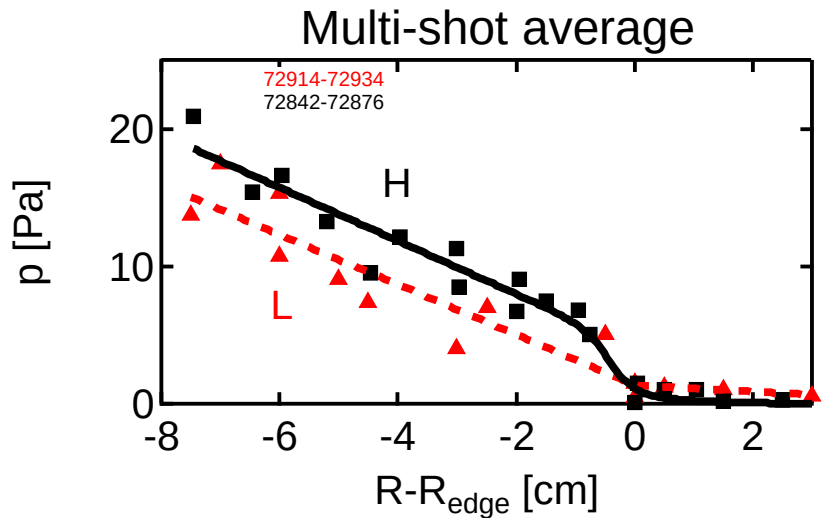
Fast visible imaging, Δt ~ 30 μs

- 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 observed
  - Quiescent edge, improved τ_E, ELMs
  - Differences compared to high-A observed

H-mode: Pedestal Formation, Increased Confinement

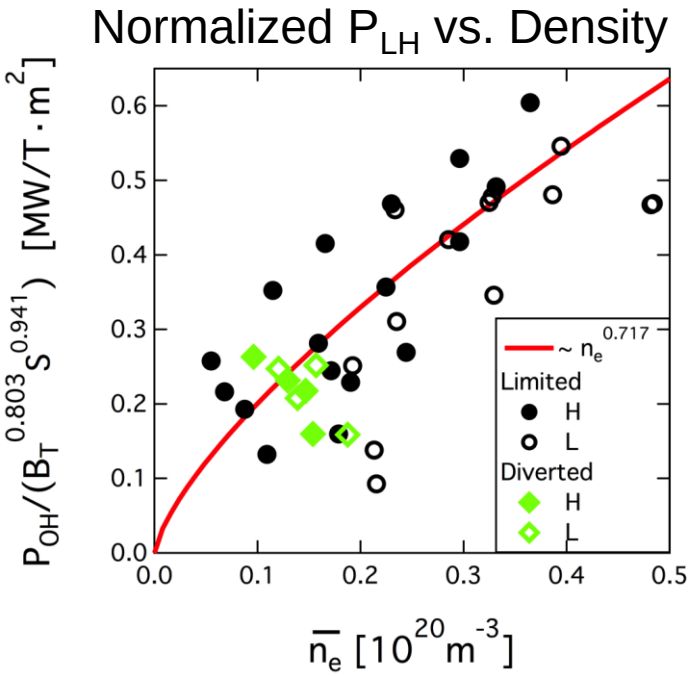
- Short pulse, low $T_{e,edge}$
- **Simple probe access through the pedestal**
- J_ϕ, P pedestals in H-phase
  - $J_\phi(R,t)$: multichannel Hall probe[1,2]
  - p(R): triple Langmuir probe
- Confinement increases 2x
  - Requires time-evolving reconstructions
  - L: $H_{98} \sim 0.5 \pm 0.2$
  - H: $H_{98} \sim 1.0 \pm 0.2$

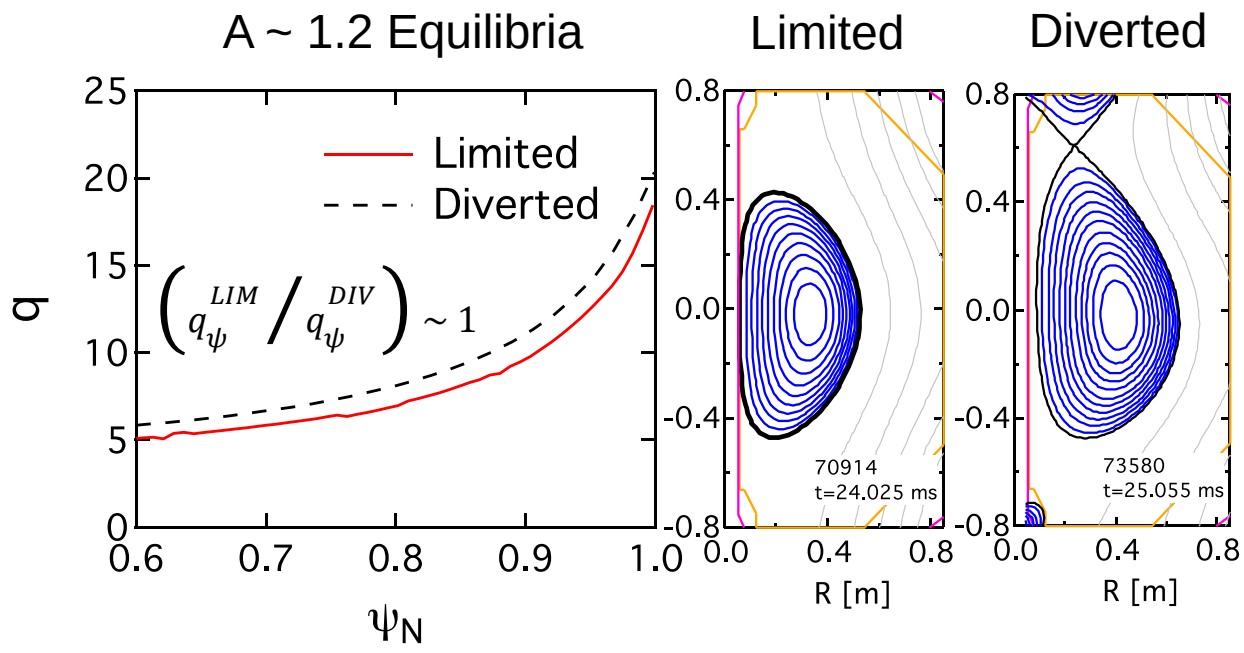




Bongard et al., Rev. Sci. Instrum. ***81****, 10E105 (2010)*
Bongard et al., Phys. Rev. Lett. ***107****, 035003 (2011)*

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

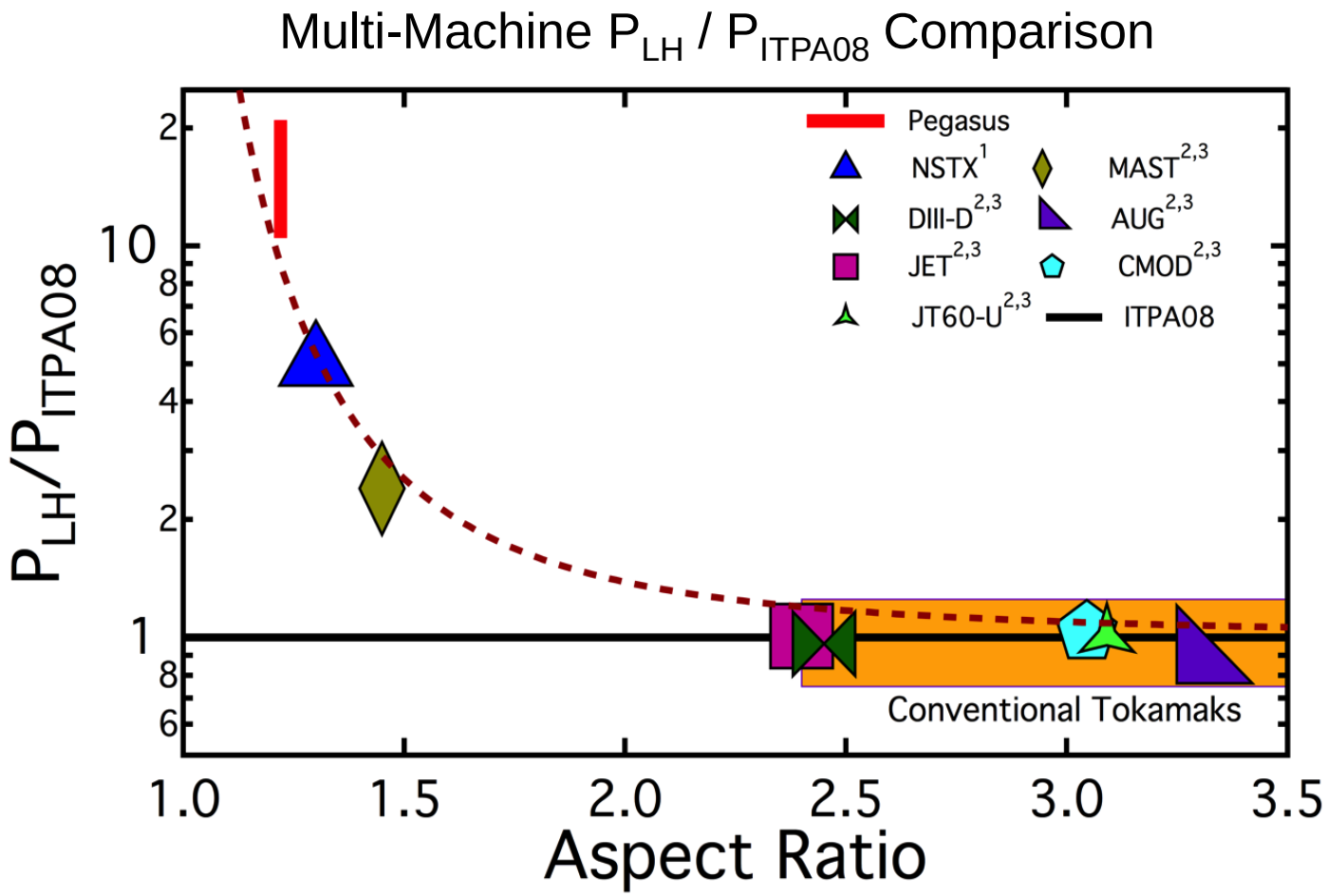




- Follows ITPA n_e scaling
  - FM^3: min $n_e \sim 1\times10^{18}$ m^{-3}
- Magnetic topology independence
  - Diverted, limited edge topology similar
  - FM^3: $P_{LH}^{LIM} / P_{LH}^{DIV} \sim \left(q_\psi^{LIM} / q_\psi^{DIV}\right)^{-7/9}$

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

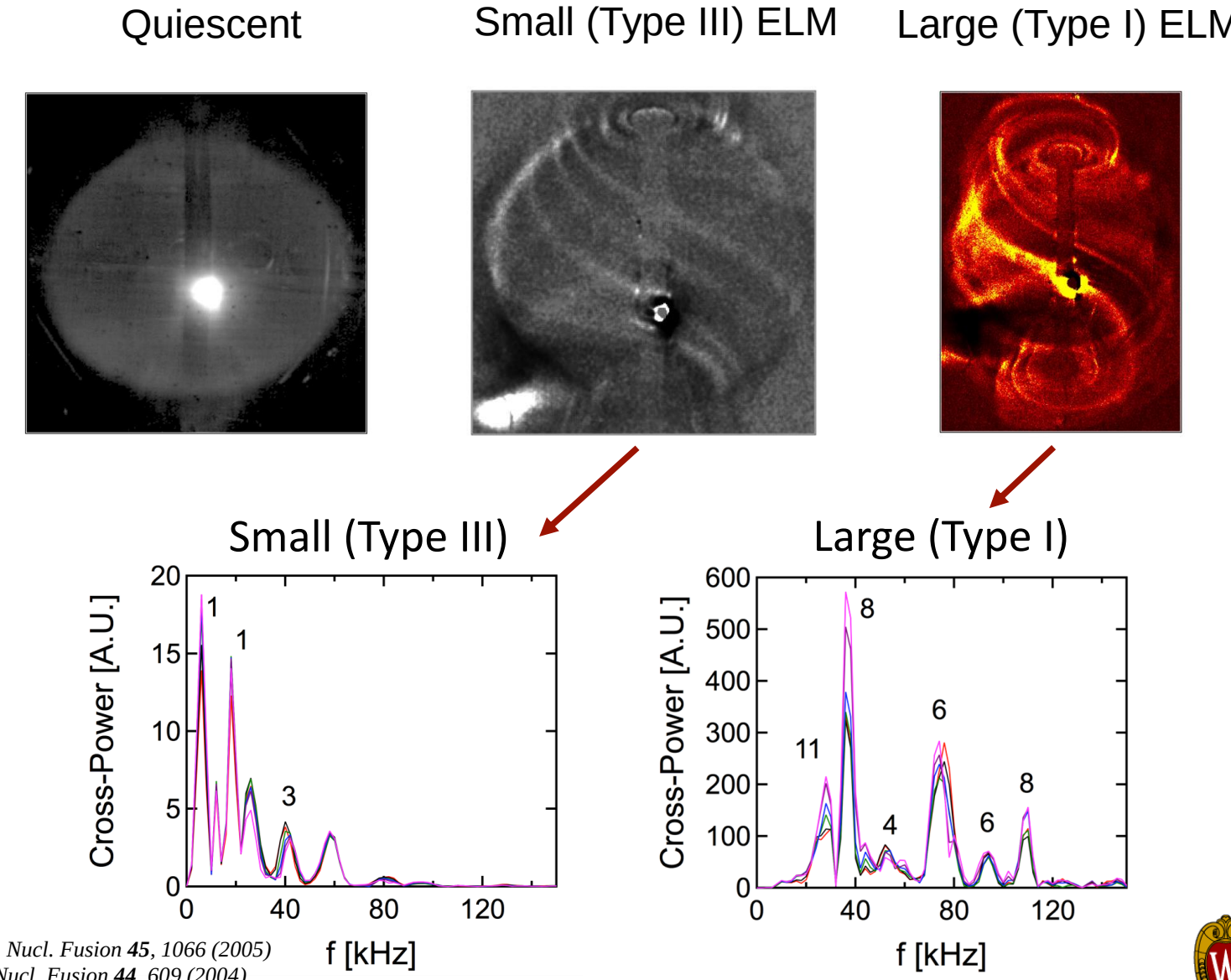
At Low A, $P_{LH} \gg P_{ITPA08}$



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

A ~ 1 Regime Well-Suited for Studies of ELMs and their Nonlinear Dynamics

- Small ("Type III"):
  - Ubiquitous, less perturbing
  - Observed at $P_{OH} \sim P_{LH}$
  - Low-n: *A*-dependent structure
    - Pegasus, NSTX: $n \leq 4$
    - $A \sim 3$: $n > 8$
- Large ("Type I")
  - Infrequent, violent
  - Observed at $P_{OH} >> P_{LH}$
  - Intermediate-n: lower range at low-*A*



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

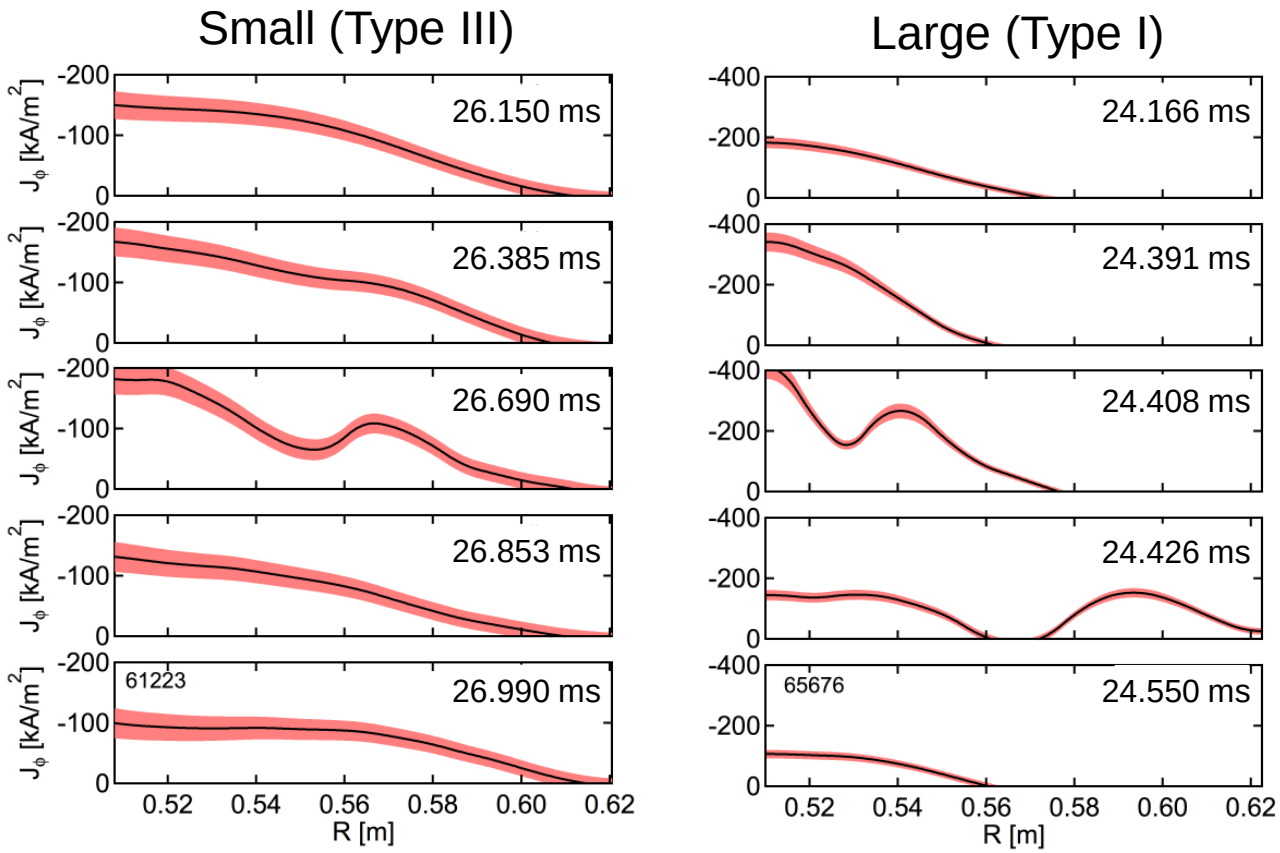
Complex Evolution of $J_{edge}(R,t)$ Measured During ELMs

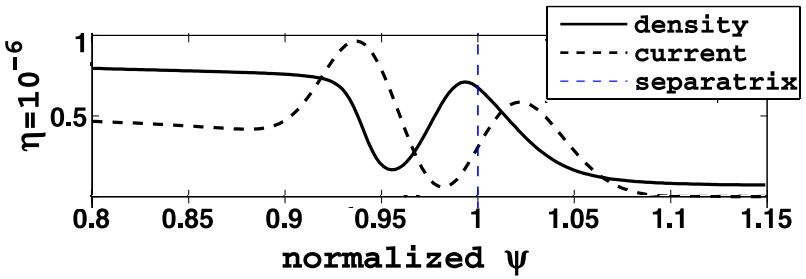
- **Challenge:** non-linear ELM dynamics at Alfvénic timescales

- Ubiquitous current hole formation observed:
  - Type III: smaller, slower, no filament evident
  - Type I: larger, faster, evident filament

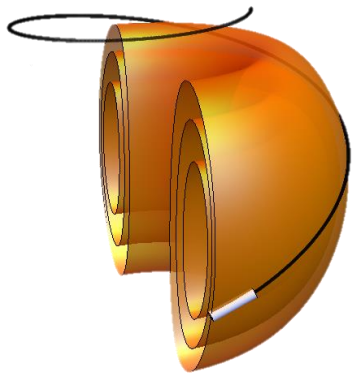
- Qualitatively similar to JOREK
  - Unique probe access: simulation validation opportunities

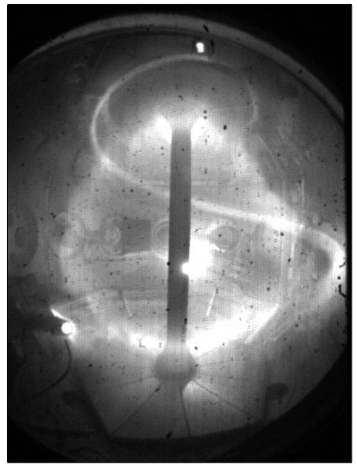
*Pamela et al., Plasma Phys. Control. Fusion **53**, 054014 (2011).*





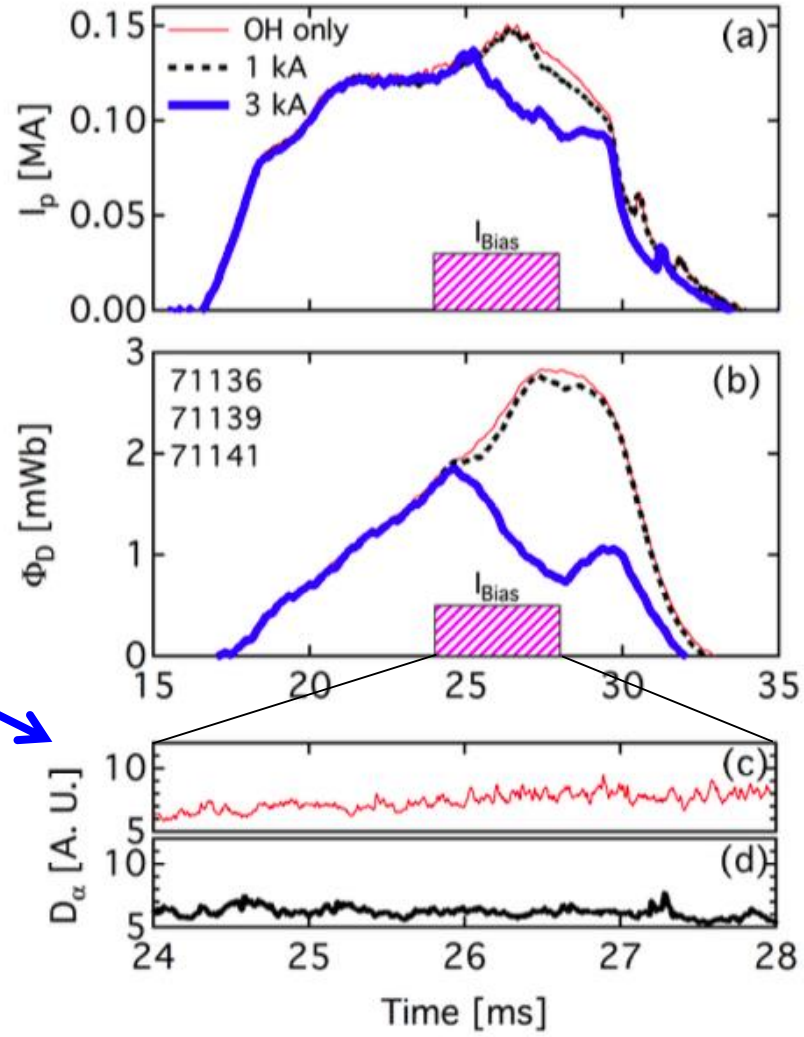
3D Edge Current Injectors Extend ELM Studies





- LHI system affects edge plasma
  - Strong 3D edge current perturbation
  - Edge biasing to modify rotation
  - Similar to LHCD on EAST[1]

- J_{edge} injection into 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)*

Unique Studies of H-mode Physics at $A \sim 1$

- H-mode plasmas with pedestal diagnostic access
  - Standard characteristics: pedestal; low D_α; increased τ_e; $H_{98} \sim 1$
- Features unique to low-A emerging
  - Strong P_{LH} scaling with A
  - Insensitivity to magnetic topology
- Fast ELM dynamic measurements
  - Transient current hole formation
  - Magnetic mode structure reflects strong peeling drive

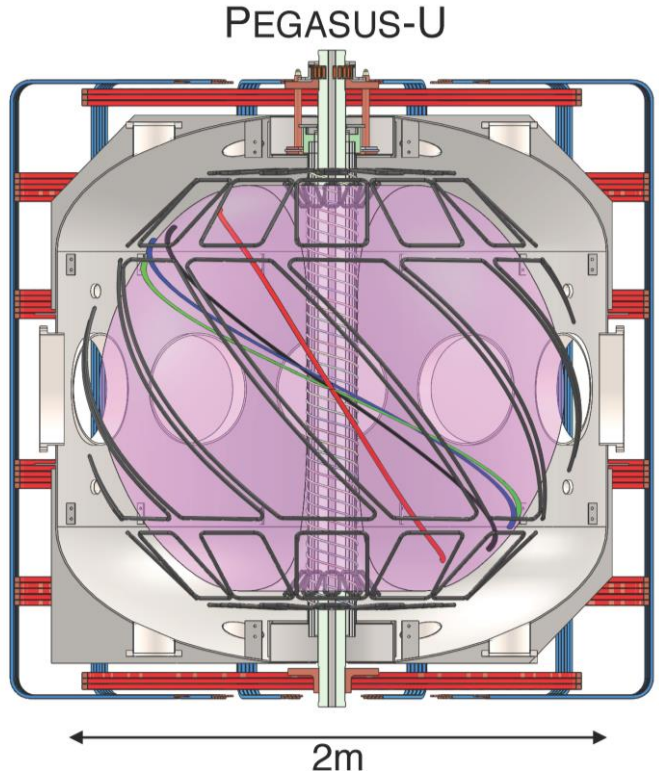
The Pegasus ST: Non-solenoidal LHI Startup and H-mode Studies at Ultralow-*A*

Non-solenoidal Startup with Local Helicity Injection

- Increased technical capability
- Developing predictive understanding of LHI startup
- Next steps: confinement and scalability studies

H-mode Physics with Pedestal Diagnostic Access

- H-mode plasmas with pedestal diagnostic access
- Features unique to low-*A* emerging
- Fast ELM dynamic measurements



Proposed Upgrades:

- Pedestal physics, nonlinear ELM physics and mitigation
- Local Helicity Injection in NSTX-U relevant conditions