Initiatives in Non-Solenoidal Startup and H-mode Physics at Near-Unity *A*

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University of Wisconsin-Madison

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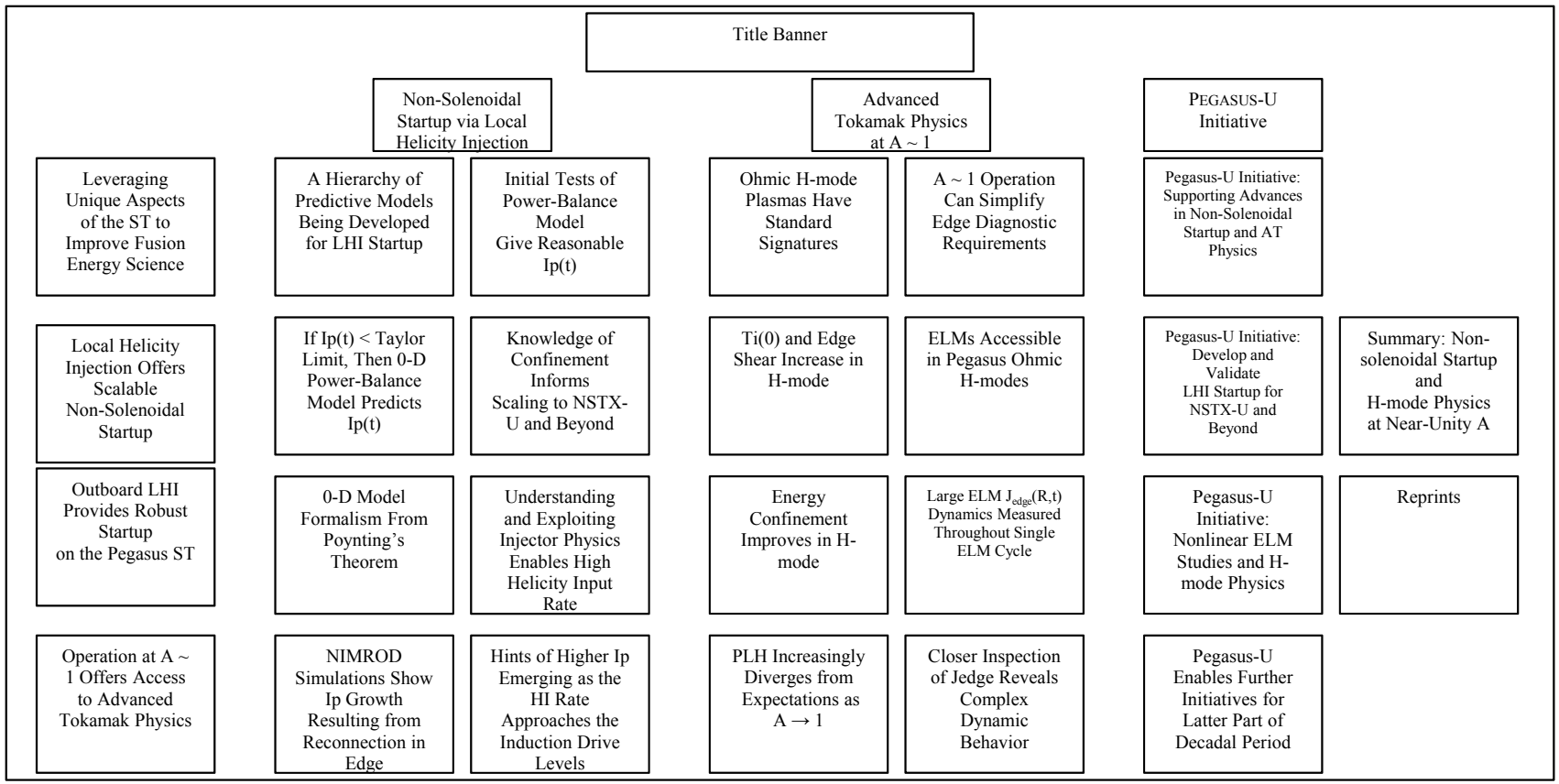


PEGASUS Toroidal Experiment

Layout

8.5” x 11”

8’ W x 4’ H



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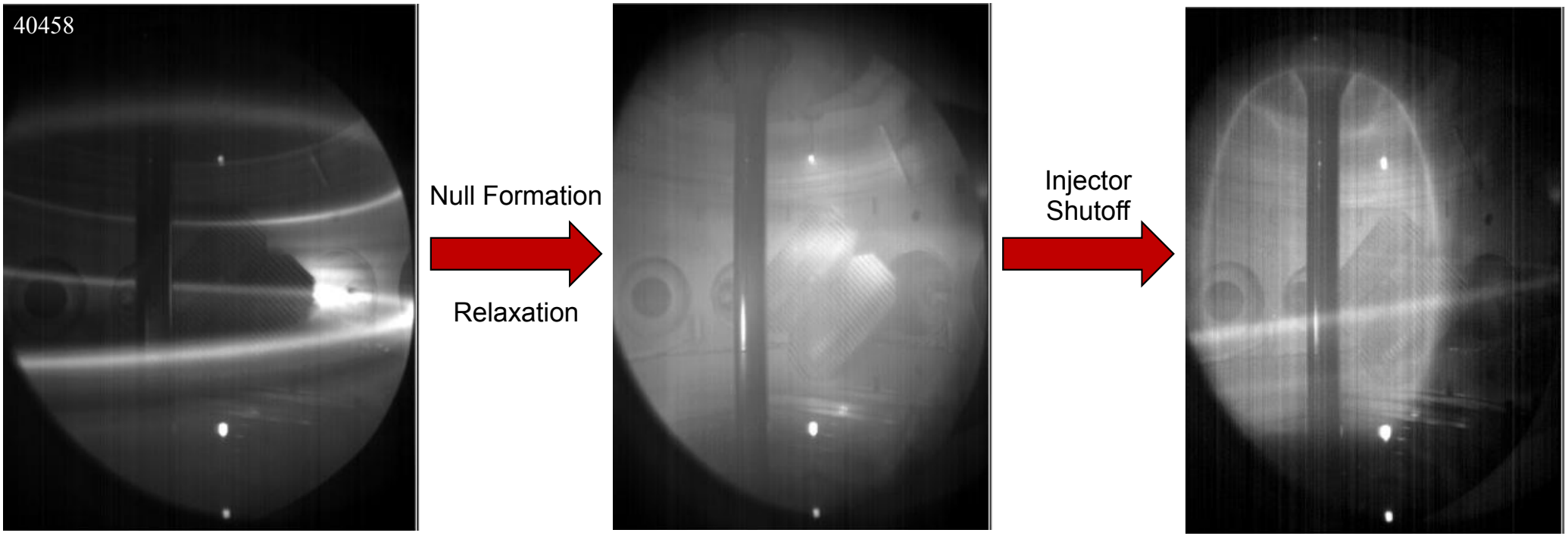
Leveraging Unique Aspects of the ST to Improve Fusion Energy Science

- Advancing the physics, technology basis for non-solenoidal startup
  - Local Helicity Injection produces tokamak plasmas using edge current drive
    - Predictive understanding arising from 0-D power-balance + Taylor relaxation model
  - Critical issue for NSTX-U and FNSF
    - However, applicable to any tokamak; not just ST

- Exploiting A ~ 1 to study reactor-relevant H-mode and edge physics
  - Low $B_T \rightarrow$ Low P_{LH}; ready H-mode access
    - P_{LH} markedly higher than present scalings as $A \rightarrow 1$
  - Detailed measurements of pedestal, ELM dynamics
    - Simplified diagnostic access $\rightarrow$ unique $J_{edge}(t)$ measurements

- Pegasus-U initiative proposed to further LHI, H-mode studies
  - Tests of LHI at NSTX-U BT, startup pulse length
  - H-mode studies in transport equilibrium

Local Helicity Injection Offers Scalable Non-Solenoidal Startup



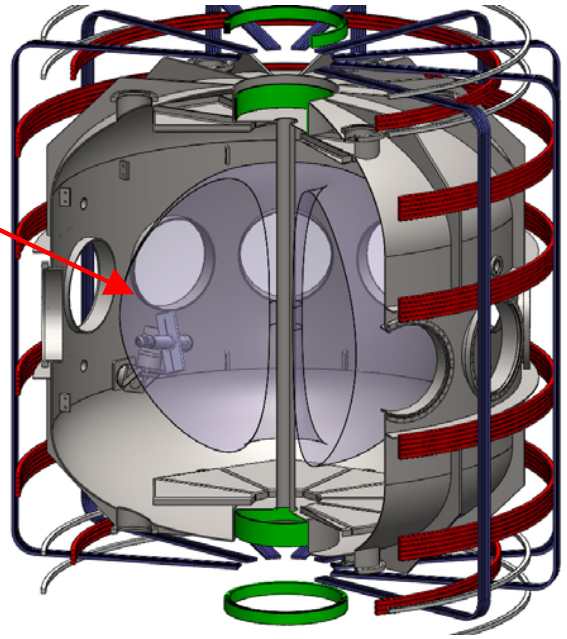
- Current injected along helical vacuum field
  - Local, active current sources
- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits
- Tokamak plasma produced
  - Couples to alternative current drive sources

D.J. Battaglia *et al.*, *Nucl. Fusion* **51**, 073029 (2011)

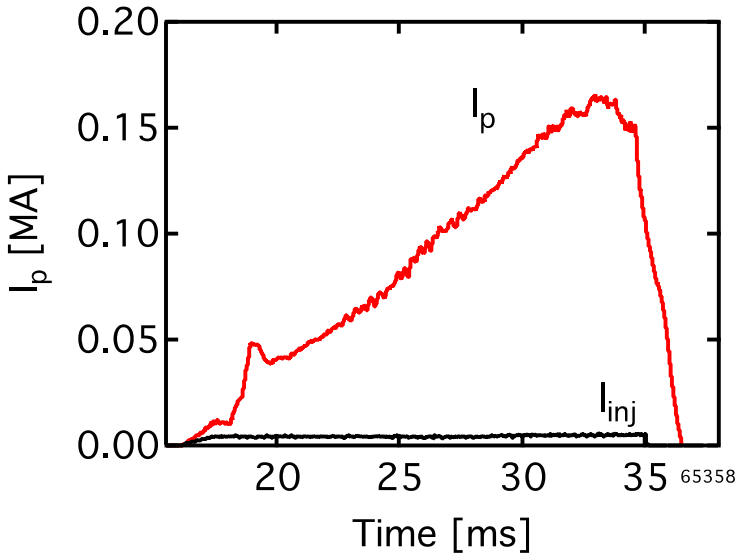
Outboard LHI Provides Robust Startup on the PEGASUS ST

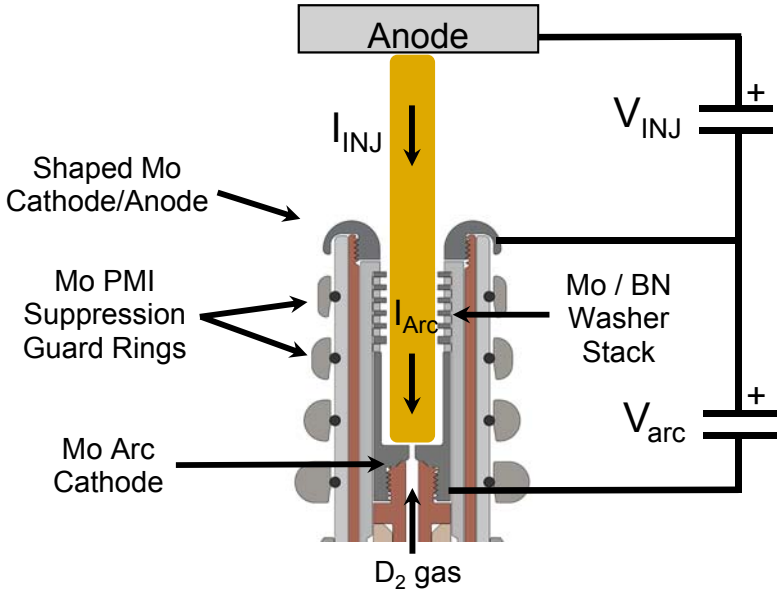
Helicity Injectors





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





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

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Operation at A ~ 1 Offers Access to Advanced Tokamak Physics

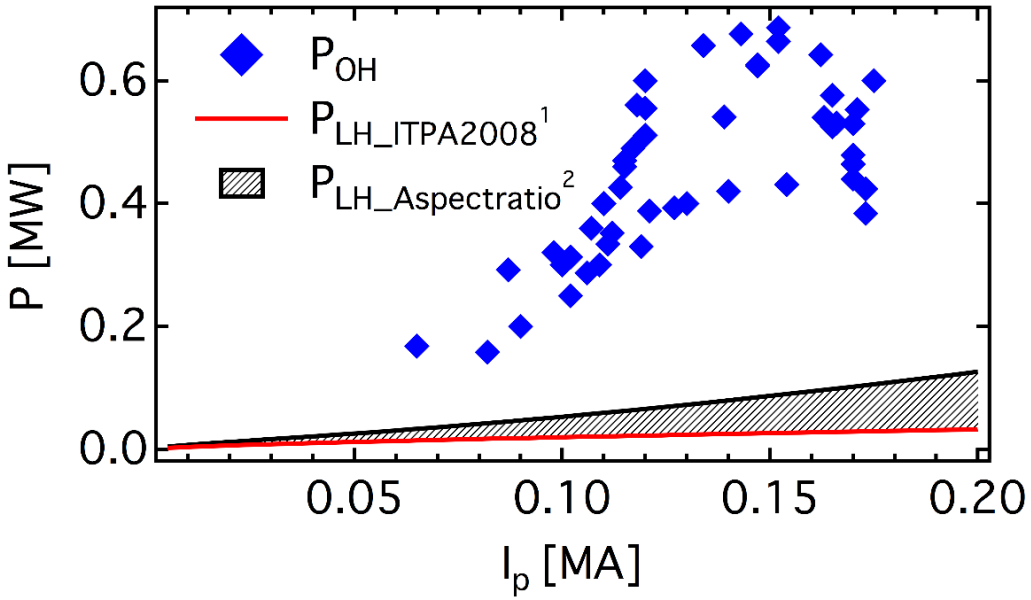
- Low B_T at modest I_p → very low H-mode power threshold P_{LH}

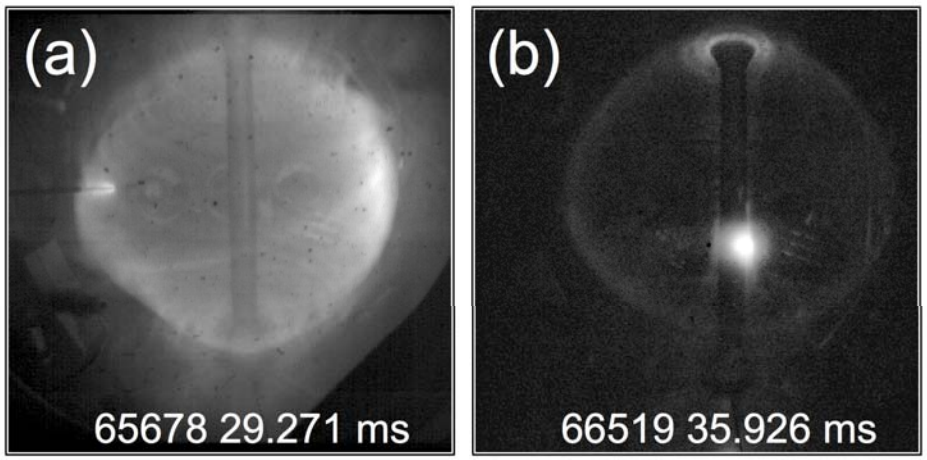
$$P_{LH} \sim n_e^{0.7} B_T^{0.7} S$$

  - High edge shear → separatrix not necessarily needed

- Ohmic H-mode routinely attained
  - $H_{98} \sim 1$
  - Type I, III ELMs accessible

- With short pulse and low $\langle T_e \rangle$, easy diagnostic accessibility
  - *e.g.*, probes in pedestal region





10 μs visible images of limited L-mode (a) and H-mode (b) plasmas.

[1] E.J. Doyle *et al., Nucl. Fusion* **47,** S82 (2007)
[2] T. Takizuka *et al., Plasma Phys. Control. Fusion* **46**, A227 (2004)



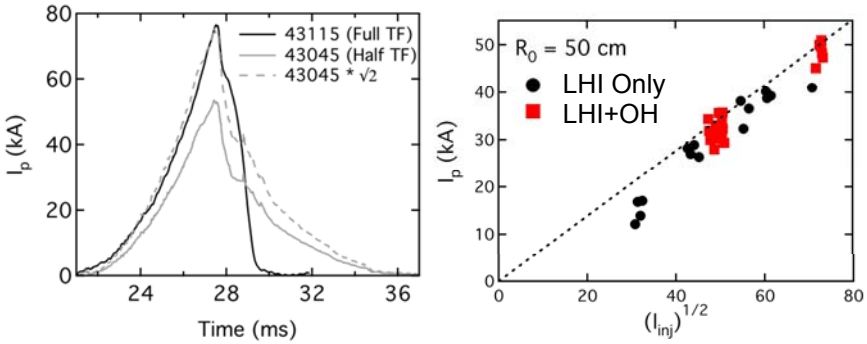
Non-Solenoidal Startup via Local Helicity Injection

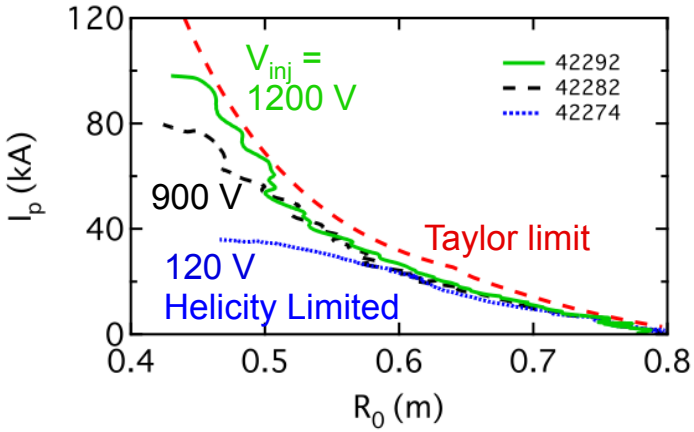
A Hierarchy of Predictive Models Being Developed for LHI Startup

1. Maximum I_p limits[1]

   – Taylor Relaxation: $$I_p \le I_{TL} \sim \sqrt{\frac{I_{TF} I_{INJ}}{w}}$$

   – Helicity Conservation: $$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

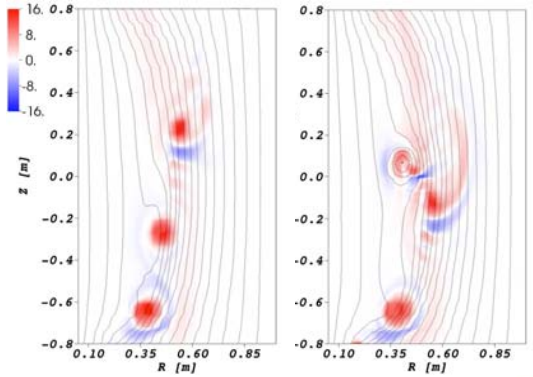




2. 0-D power-balance $I_p(t)$

3. 3D Resistive MHD (NIMROD)[2]

   – First principles model



[1] D.J. Battaglia *et al., Nucl. Fusion* **51**, 073029 (2011)
[2] J.B. O'Bryan *et al., Phys. Plasmas* **19**, 080701 (2012)

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If $I_p(t) < $ Taylor Limit, Then 0-D Power-Balance Model Predicts $I_p(t)$

- Lumped parameter model + helicity conservation:

$$\begin{cases} I_p\left[V_{eff} + V_R + V_{IND}\right] = 0 & I_p < I_{TL}; \\ I_p = I_{TL} & otherwise \end{cases}$$

  - V_{eff}: From helicity conservation
  - V_R: Resistive dissipation
  - $V_{IND} = V_{PF} + V_{Lp}$: Inductive voltages arising from poloidal induction and plasma self-inductance

- Inputs: $R_0(t)$, $a(t)$, $Ip(t_0)$, $\langle\eta_0\rangle$, $\kappa(t)$, $\ell_i\,(t)$
  - Analytic low-A descriptions of L_p, B_z, plasma shape

- Differential equation in $I_p(t)$ solved when $I_p(t) < I_{TL}(t)$

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0-D Model Formalism From Poynting's Theorem

$$I_p V_s = \iiint \frac{\partial}{\partial t}\left(\frac{B_\theta^2}{2\mu_0}\right) dV + I_p^2 R_p - I_p V_{NICD}$$

Plasma surface voltage

- Force-balance explicitly enforced
- Inductive current-drive from OH, PF-ramping
- Plasma external inductance

$$V_s = -\frac{\partial}{\partial t}\left(\psi_{OH} + \sum_i \psi_{PF,i} + L_e I_p\right)$$

Internal magnetic energy

- Plasma internal inductance
- Estimated with constant boundary for now, later application of Reynold's Transport Theorem

$$\frac{1}{I_p}\frac{\partial}{\partial t}\left(W_{B,p}\right) = \frac{1}{I_p}\frac{\partial}{\partial t}\left(\frac{1}{2} L_i I_p^2\right)$$

Resistive Dissipation

- Spitzer resistivity assumed

$$V_R = I_p R_p = I_p\left(\frac{\langle \eta_p \rangle 2\pi R_0}{A_p}\right)$$

Non-inductive current drive

- From Local Helicity Injection

$$V_{NICD} = V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi_T} V_{inj}$$

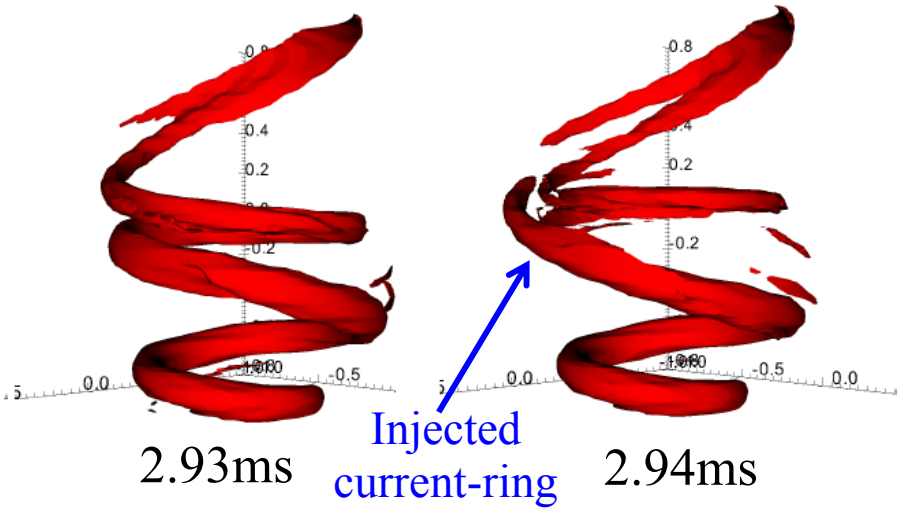
J.A. Romero *et al., Nucl. Fusion* **50,** 115002 (2010)
S.P. Hirshman *et al., Phys. Fluids* **29,** 790 (1986)
S. Ejima *et al , Nucl. Fusion* **22,** 1313 (1982)

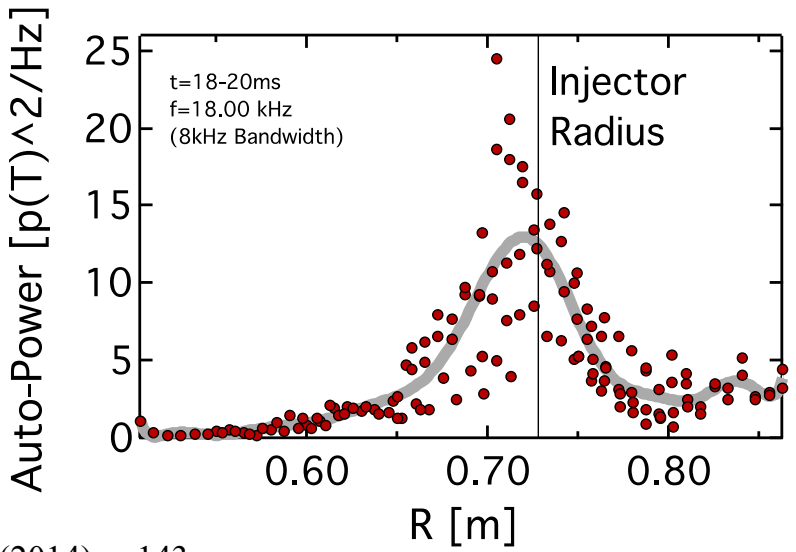
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NIMROD Simulations Show I_p Growth Resulting from Reconnection in Edge

- Resistive MHD modeling (NIMROD)
- Divertor injection
  - Coherent current streams reconnect
  - Inject current rings
- Overlap in model, experiment:
  - Injector localized MHD
  - Intermittent MHD bursts
  - $\Delta I_p \sim I_{inj}$ jumps
  - Reconnection driven anomalous ion heating observed[3]

Calculated current rings in NIMROD[1,2]



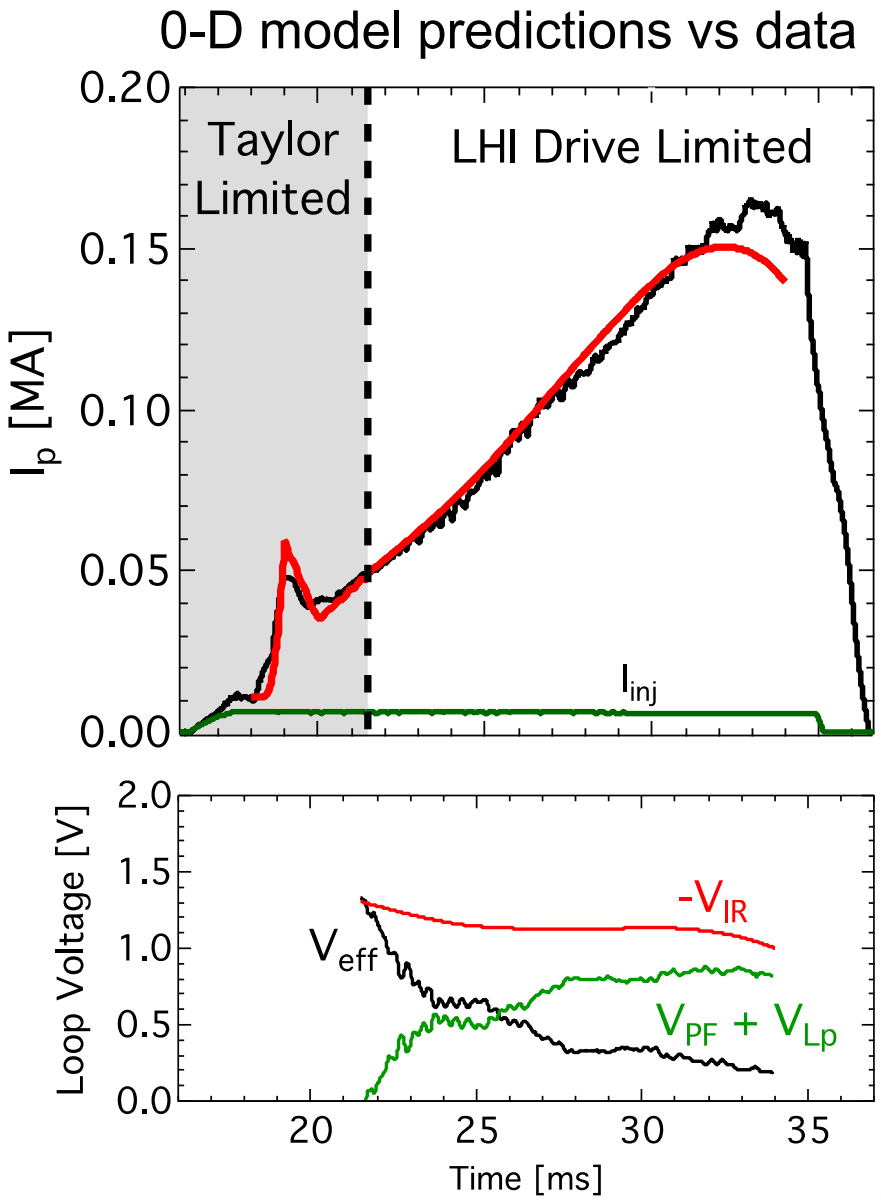


[1] J.B. O'Bryan, UW-Madison PhD Thesis (2014) p. 143
[2] J.B. O'Bryan and C.R. Sovinec, *Plasma Phys. Control. Fusion* **56**, 064005 (2014)
[3] M.G. Burke *et al.*, PP8.00095 (this session)

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Initial Tests of Power-Balance Model Give Reasonable $I_p(t)$

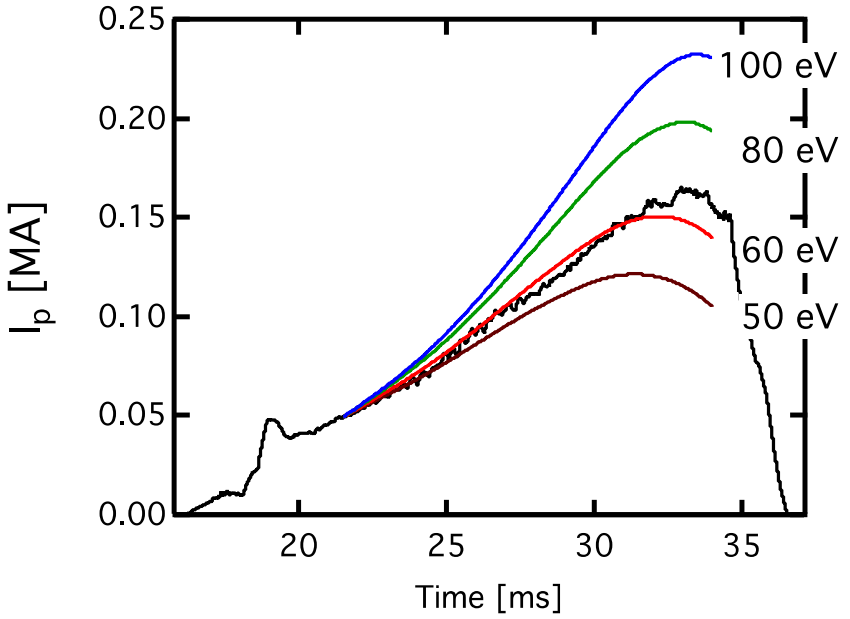
- 0-D Model elements:
  - Low-A inductance, force-balance
  - Confinement
  - Taylor limit
  - Helicity balance
- Reasonable agreement between calculated $I_p(t)$ and measurement
  - Early time: Taylor limit
  - Later: helicity limited
- High-I_p: current drive dominated by inductive contributions



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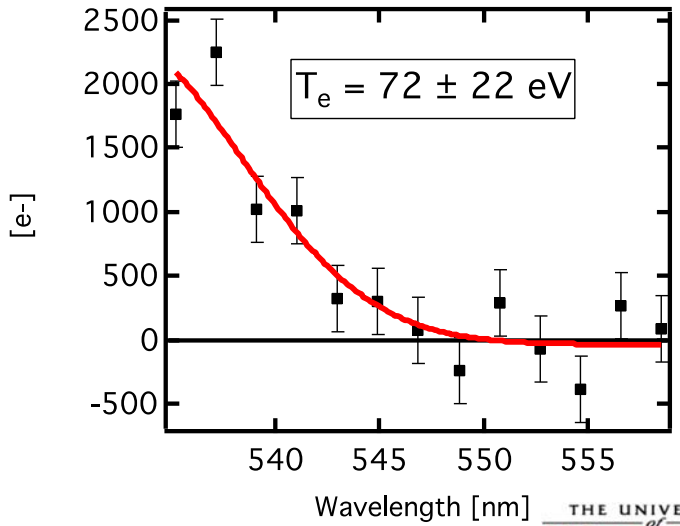
Knowledge of Confinement Informs Scaling to NSTX-U and Beyond

- $I_p(t)$ model depends critically on η
  - $\langle T_e \rangle \sim 60–70$ eV fits present data
  - Initial Thomson scattering[1]: $T_e(0) \sim 70$ eV



- Dual confinement regimes?

Warm Core	Cool Edge
OH-like	Stochastic
Inductive drive	Reconnection
Low $\tilde{B}/B$	Large $\tilde{B}/B$



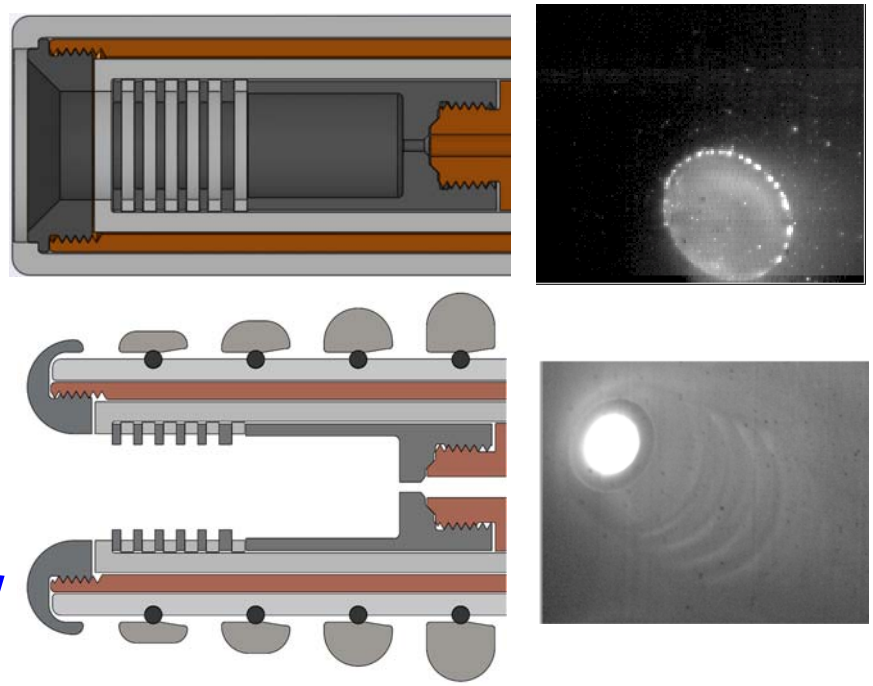
[1] D.J. Schlossberg *et al.*, PP8.00096 (this session)

Understanding and Exploiting Injector Physics Enables High Helicity Input Rate

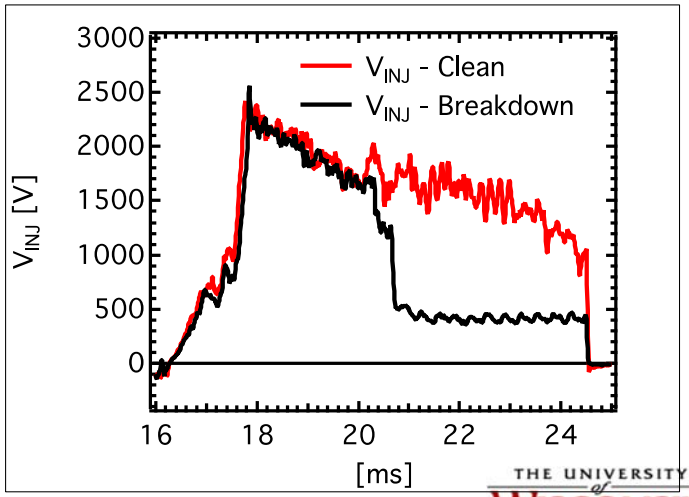
- Injector requirements include
  - Large A_{inj}, J_{inj}
  - $V_{inj} > 1$ kV
  - $\Delta t_{pulse} \sim 10–100$ ms
  - Minimize PMI

  …all adjacent to tokamak LCFS

- Advanced injector designs enable high V_{inj} operation
  - Cathode shaping to mitigate cathode spots
  - Shielding of cathode, insulators to prevent injector breakdown
  - 3× improvement in V_{inj}, Δt_{pulse}



Voltage of quiescently operating injectors (red) and voltage after breakdown of overdriven injectors (black)



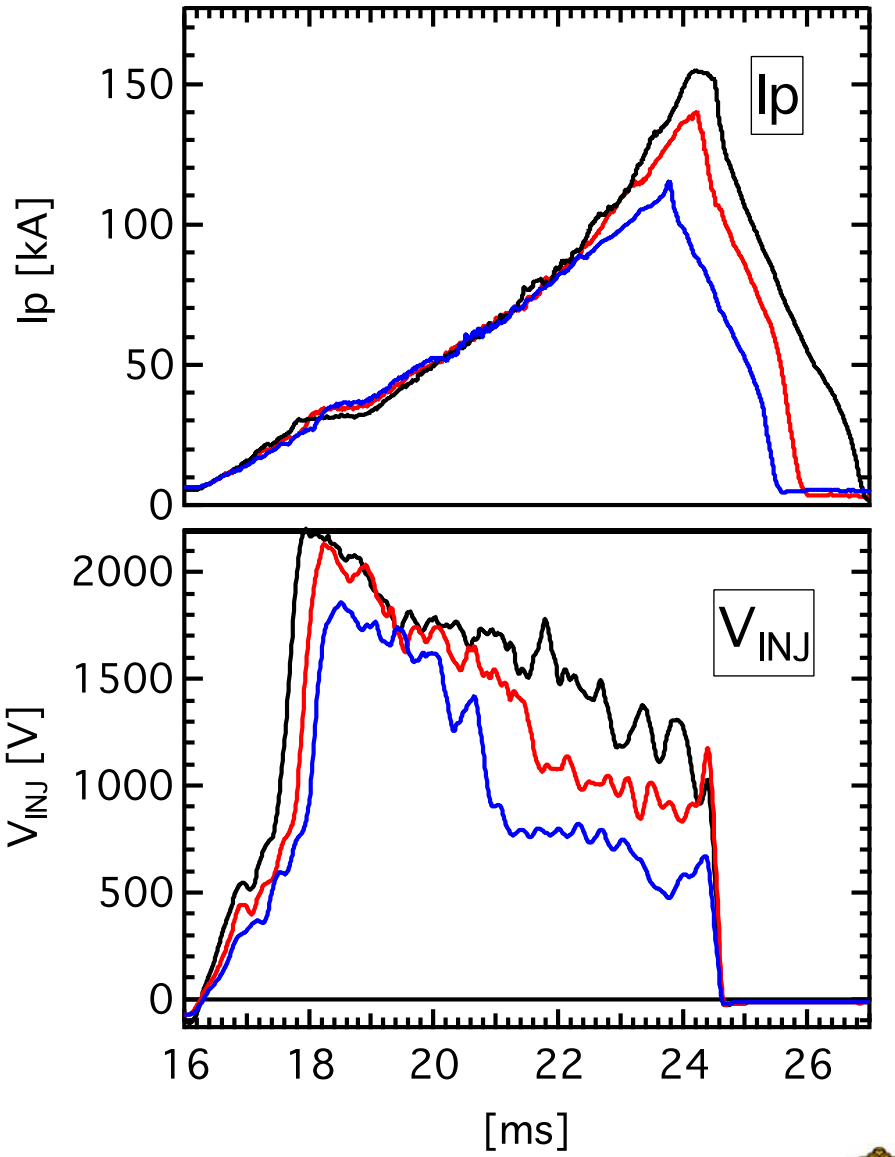
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Hints of Higher I_p Emerging as the HI Rate Approaches the Induction Drive Levels

- Increased $V_{inj} \rightarrow$ increased I_p
  - Enabled by new injector technology
  - However, V_{inj} cannot be arbitrarily raised
- V_{inj} limits related to edge plasma density
  - Hard limit: avoid cathode spot onset
    - Mechanism: thermo-field arc ignition
    - Constraint: minimize local E ~ V_{inj}/λ_D
  - "Soft" limit: injector impedance[1]
    - J_{inj} space-charge neutralization limit

$$J_{INJ} = n_{edge} e \sqrt{\frac{2e}{m_e}} \sqrt{V_{INJ}}$$

Injector voltages and associated I_p



[1] E.T. Hinson *et al.*, PP8.00094 (this session)

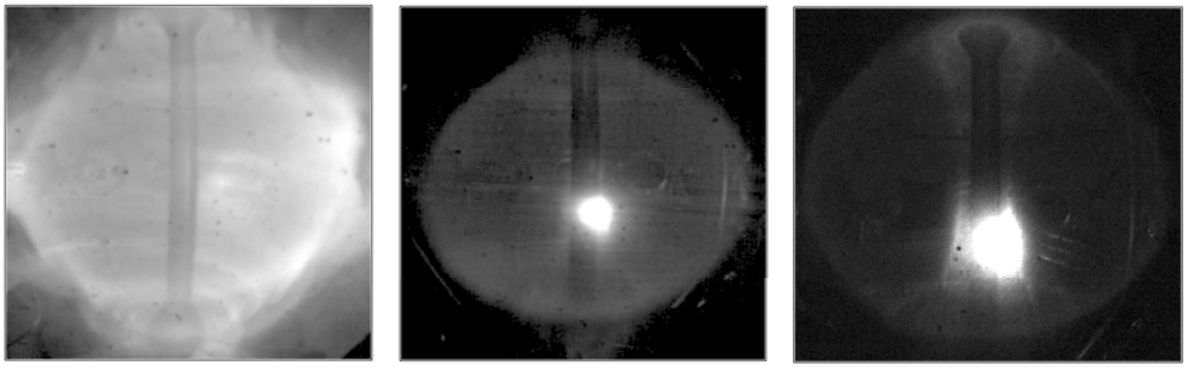
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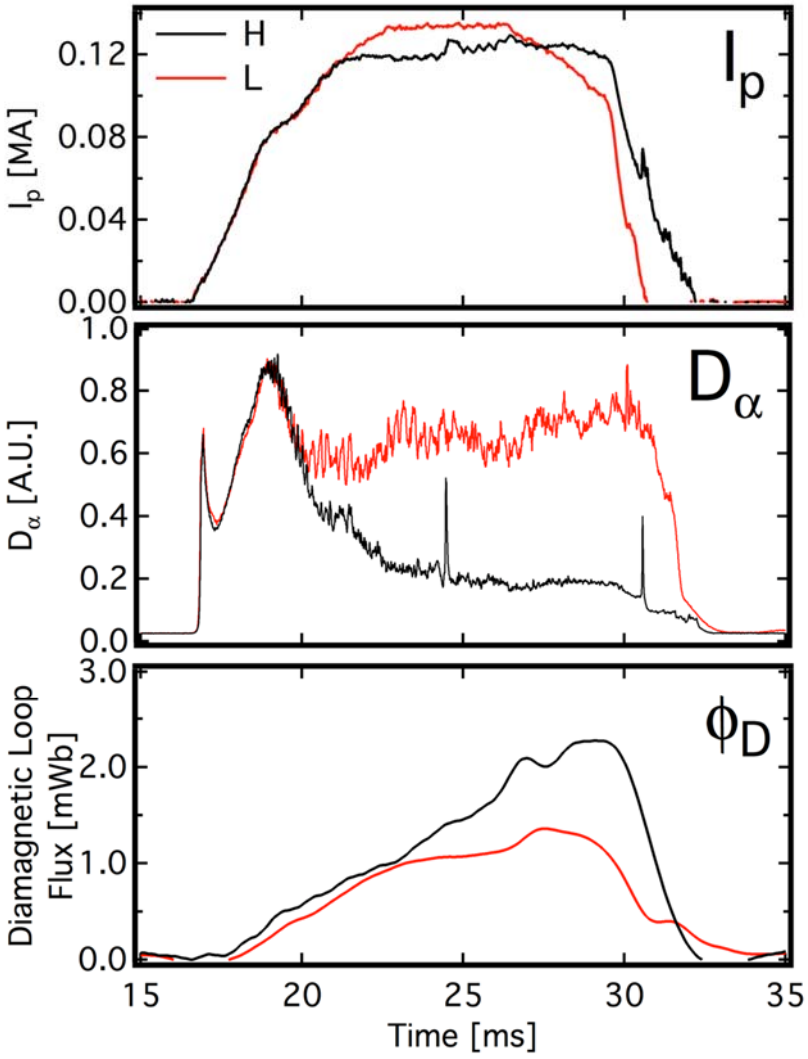
Advanced Tokamak Physics at A ~ 1

Ohmic H-mode Plasmas Have Standard Signatures

Limited L **Limited H** **Near-diverted H**



- H-mode achieved using HFS fueling
- Quiescent edge
- Reduced D_α, Increased ∇D_α
- Large and small ELMs
- Bifurcation in ϕ_D
  - Transport equilibrium not attained

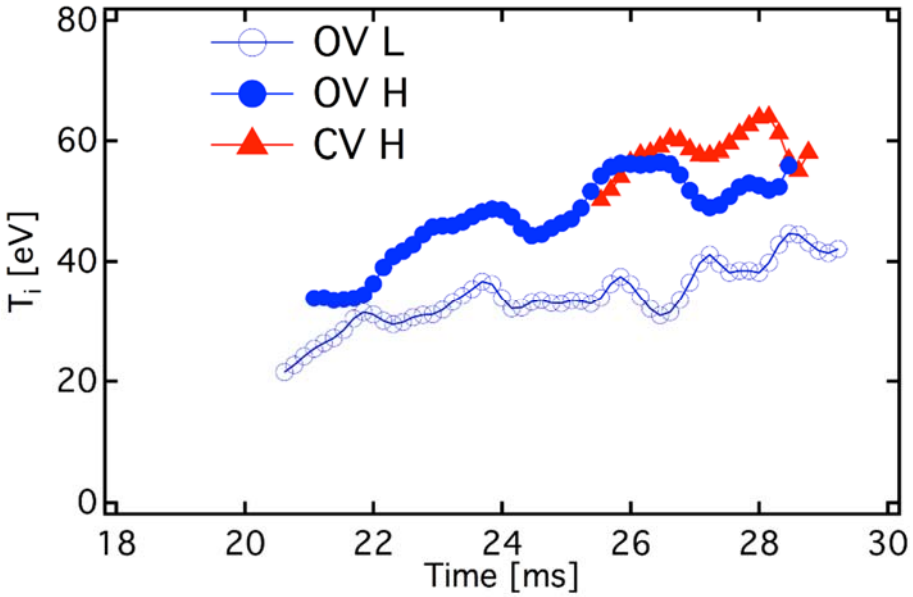


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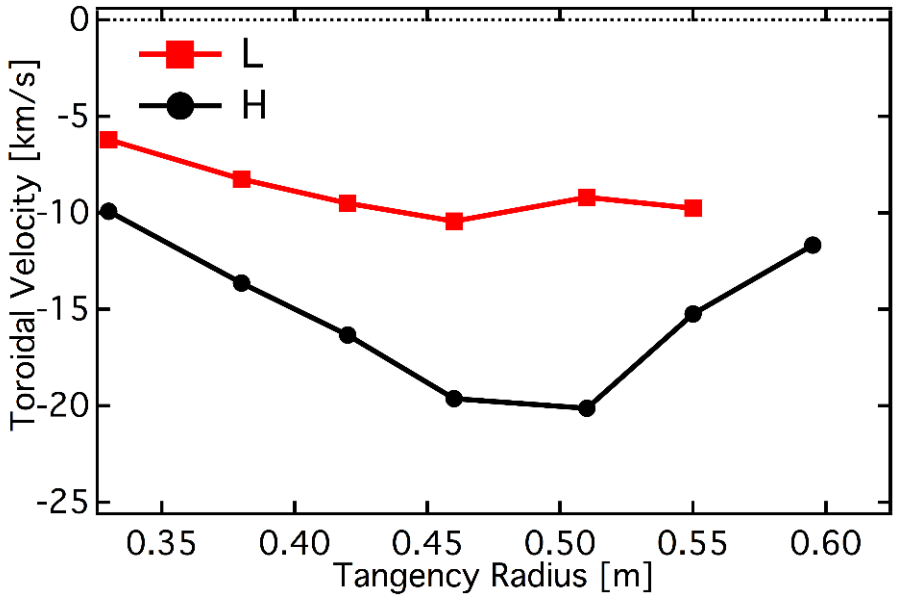
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$T_i(0)$ and Edge Shear Increase in H-mode

- Impurity $T_i(0)$ doubles
  - CV only seen in core H-mode plasmas
  - Transport equilibrium not attained

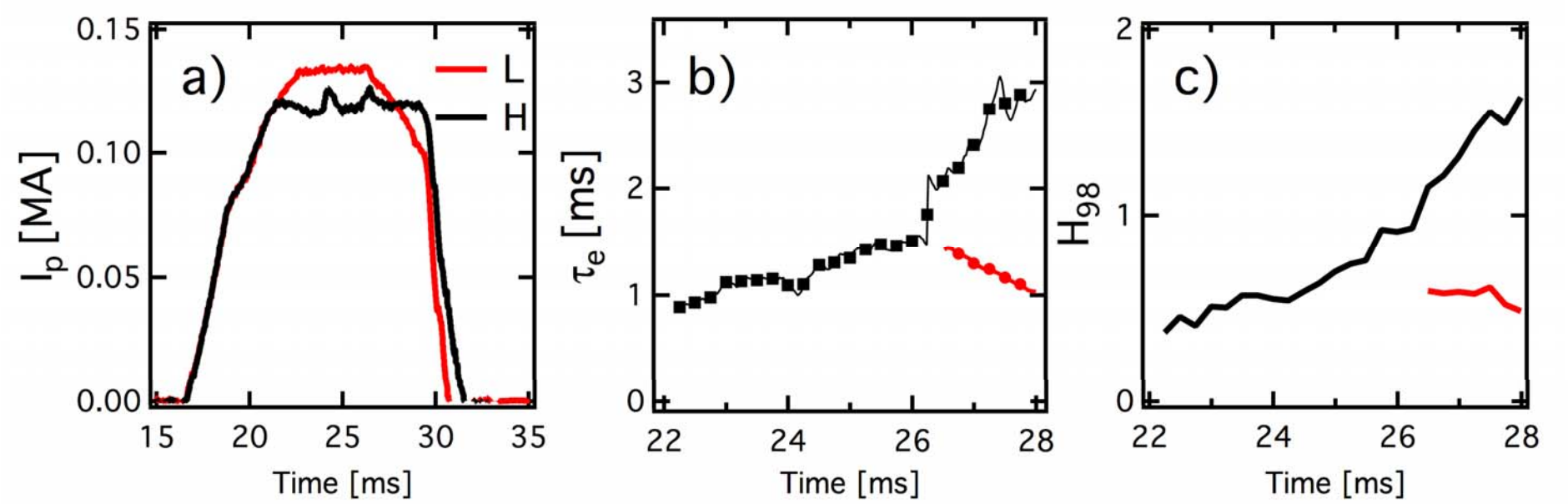


- Chordally-integrated velocity profiles show increased shear in the outer region in H-mode
  - Indirect evidence of E_r well



Energy Confinement Improves in H-mode

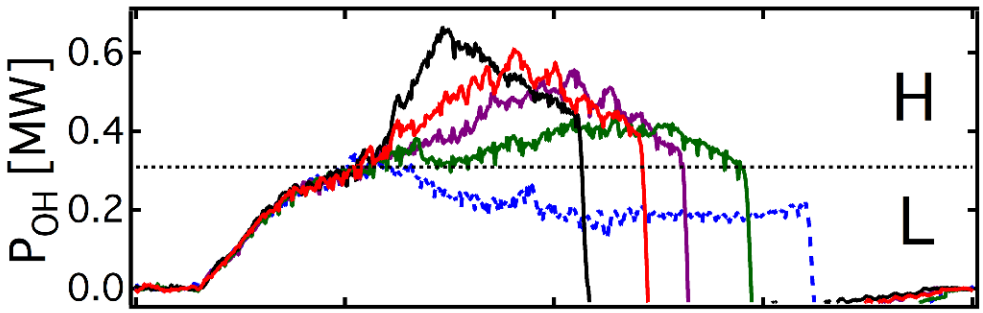
- τ_e from time-evolving magnetic equilibrium reconstructions
- L-mode: $\tau_e \sim 1.5$ ms, $H_{98} \sim 0.5$
- H-mode: $\tau_e \sim 3$ ms, $H_{98} > 1$
  - Due to short pulse; not in transport equilibrium

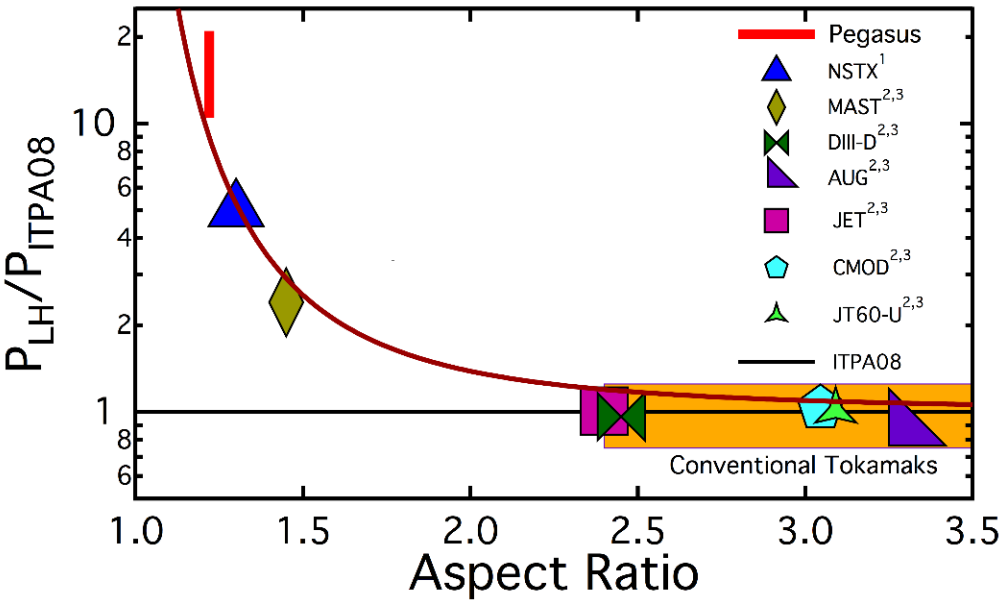


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P_{LH} Increasingly Diverges from Expectations as $A \rightarrow 1$

- P_{LH} studied by varying P_{OH}, n_e
  - n_e dependence observed
  - Near-diverted P_{LH} similar to limited
- PEGASUS $P_{LH}/P_{ITPA08} \approx 10$
- P_{LH}/P_{ITPA08} continues to increase as A→1
  - Similar to dependence with q_{edge}, β_T



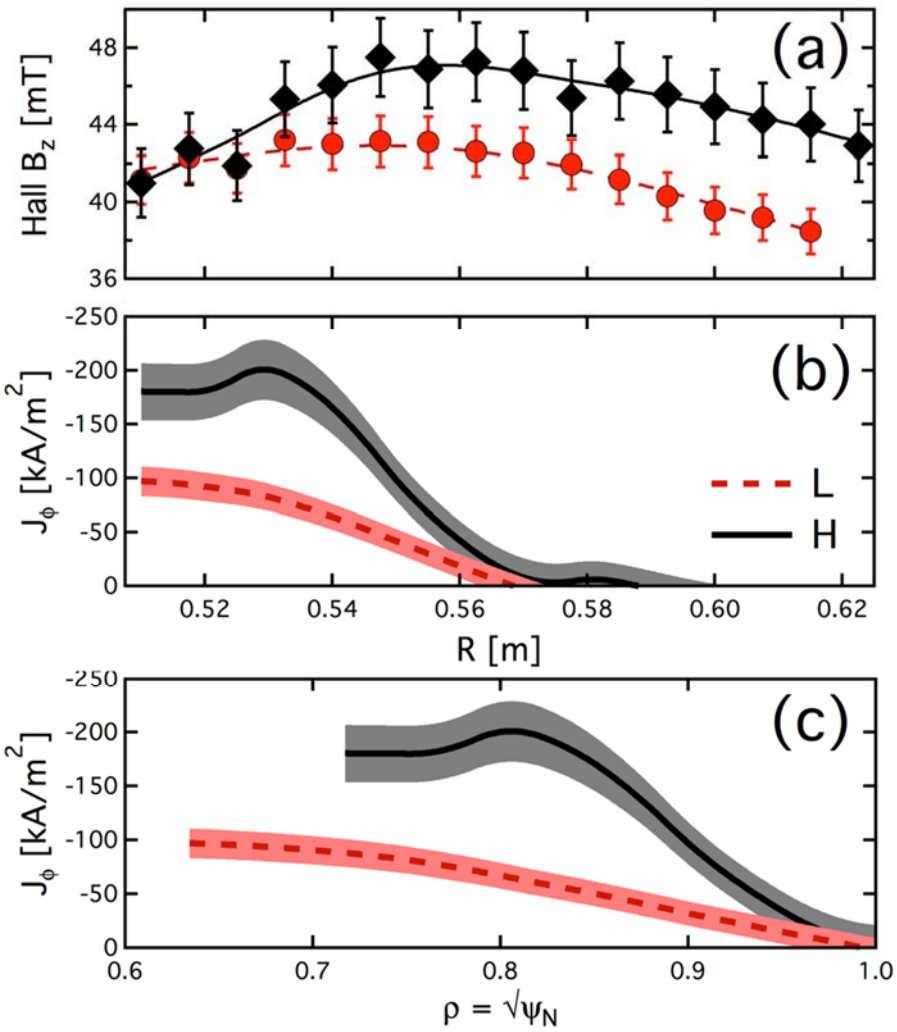


[1] R. Maingi *et al., Nucl. Fusion* **50**, 064010 (2010)
[2] Y.R. Martin *et al., J. Phys.: Conf. Ser.* **123**, 012033 (2008)
[3] J. Wesson, Tokamaks (4th ed.), Oxford Univ. Press (2011), p. 630

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A ~ 1 Operation Can Simplify Edge Diagnostic Requirements

- Short pulse, low T_e permit detailed edge measurements[1-3]
  - $J_\phi(R,t)$ from multichannel Hall probe
    - High spatial, temporal resolution
  - p(R) via triple Langmuir probe
    - Present: shot-to-shot averages
- Current pedestal forms in H-mode
  - Scale lengths: ~4 cm (L), ~2 cm (H)
- Goal: Simultaneous measurement for model validation
  - *e.g.* EPED

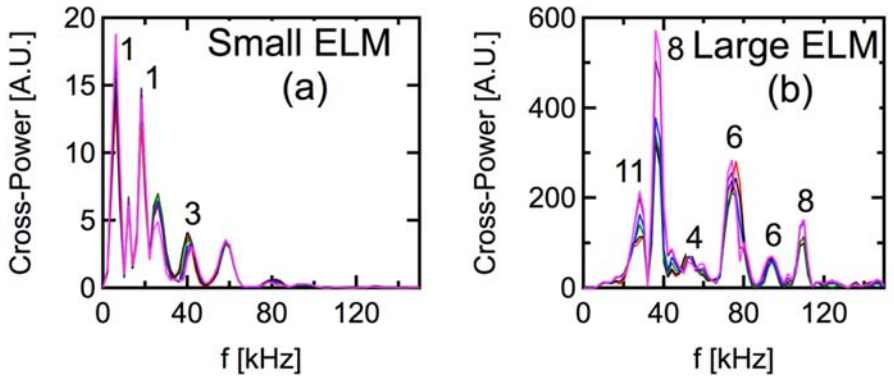


[1] M.W. Bongard *et al., Rev. Sci. Instrum.* **81**, 10E105 (2010)
[2] M.W. Bongard *et al., Phys. Rev. Lett.* **107**, 035003 (2011)
[3] G.M. Bodner *et al.,* PP8.00097 (this session)

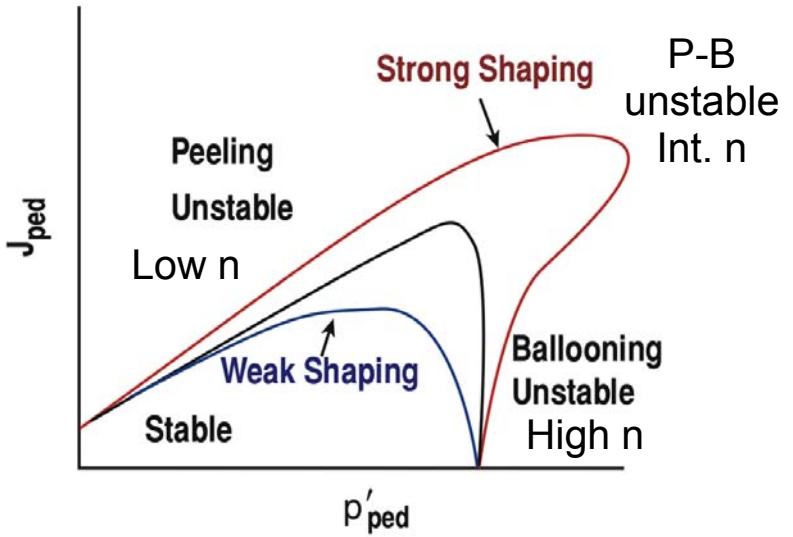
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ELMs Accessible in PEGASUS Ohmic H-modes

- Two ELM types observed to date
  - Filamentary structures during event
    - Temporally coincident with D_α bursts
  - Distinct toroidal mode numbers n
    - Large ("Type I"): intermediate 5 < n < 15
    - Small ("Type III"): low n ≤ 3
    - Similar n ranges reported for NSTX[1]



- Differences in machines' ELM toroidal mode spectra attributable to A effects?
  - STs naturally provide strong peeling drive
    - Toroidal field utilization $I_p/I_{TF} \sim J_\parallel/B$
    - Stronger peeling drive lowers n
  - AT shows opposite relative n relationship between Type I, III ELMs[2]

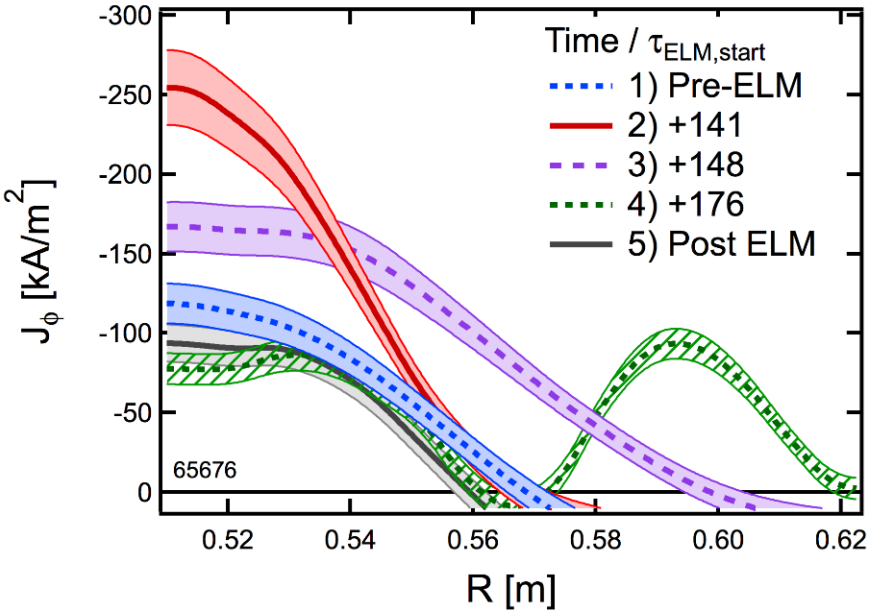


[1] Maingi *et al.*, *Nucl. Fusion* **45**, 1066 (2005)
[2] Example: Perez *et al.*, *Nucl. Fusion* **44**, 609 (2004)

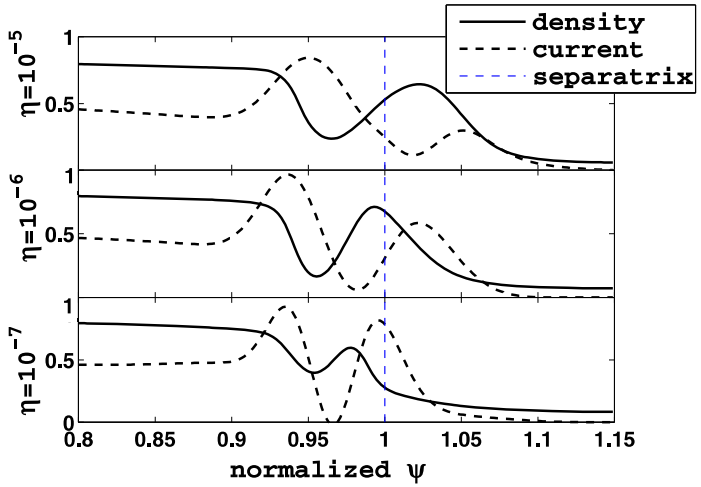
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Large ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Cycle

- Complex $J_{edge}(R,t)$ evolution
  1) Modest but steep pedestal
  2) Rapid buildup until crash
  3) Collapse with wider pedestal gradient
  4) Current-hole filament ejection
  5) Recovery: lower than pre-ELM pedestal



- $J_{edge}(R,t)$ evolution similar to that seen in JOREK MHD[1] simulations
  - Potential for unique simultaneous measurements of $J_{edge}(R,t)$ and $p_{edge}(R,t)$

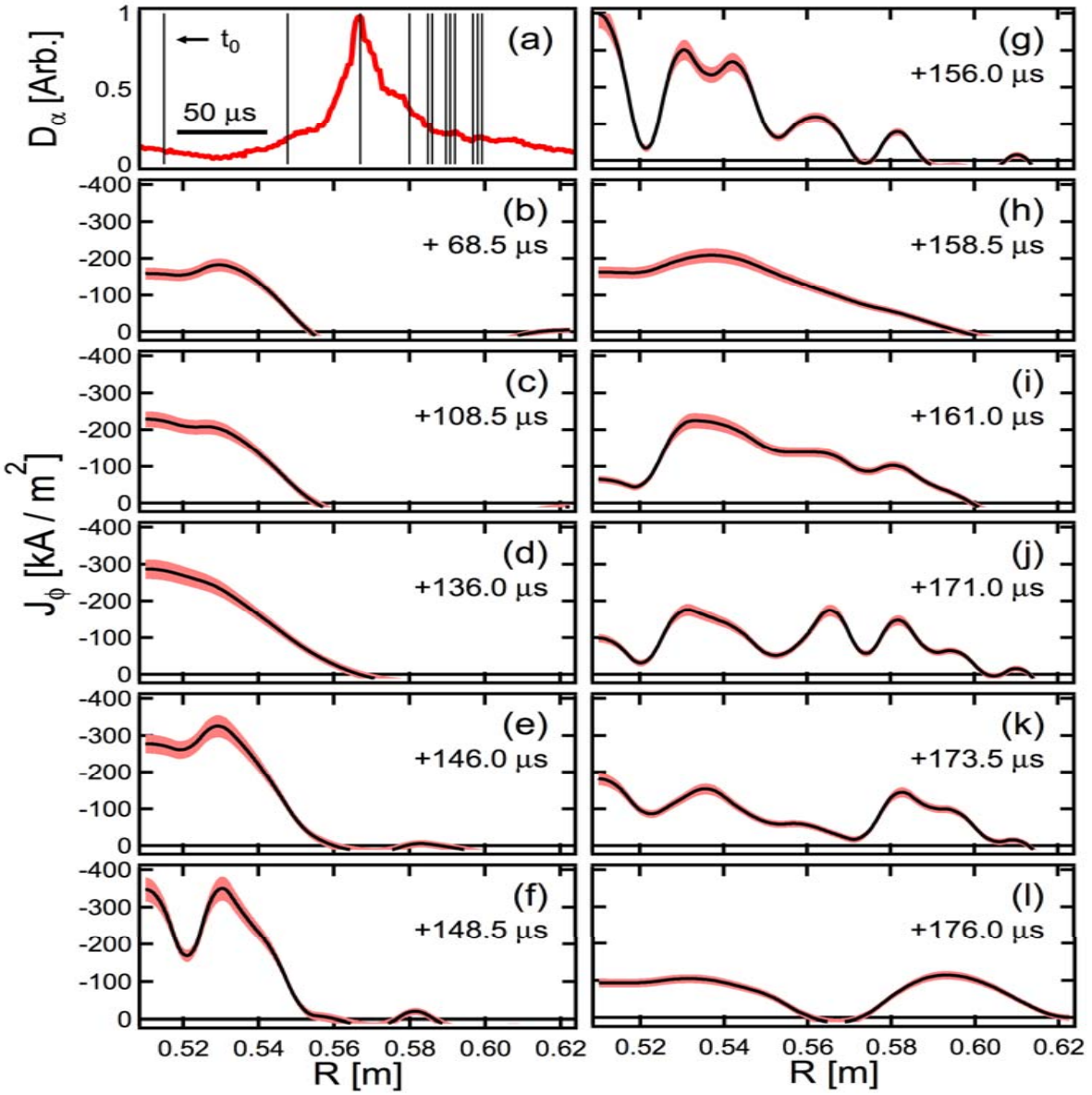


[1] S.J.P. Pamela *et al.*, *Plasma Phys. Control. Fusion* **53**, 054014 (2011)

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Closer Inspection of J_{edge} Reveals Complex Dynamic Behavior

- Current profile evolution through ELM cycle shows complex multimodal behavior
- Opportunities for detailed comparisons to nonlinear MHD simulations
  - *e.g.* NIMROD, JOREK, BOUT



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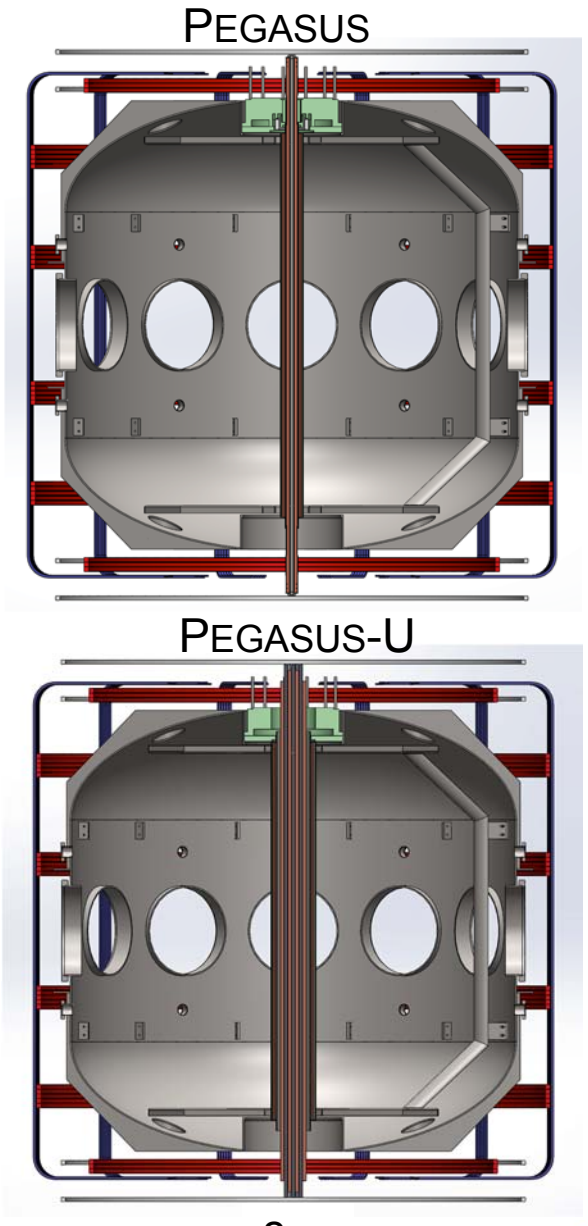


PEGASUS-U Initiative

PEGASUS-U Initiative: Supporting Advances in Non-Solenoidal Startup and AT Physics

- Mission
  - Physics and technology of LHI
    - For NSTX-U and beyond (FNSF)
  - Nonlinear ELM dynamics, H-mode physics
  - Tokamak stability limits: A ~ 1 high β_T regime

- Facility enhancements[1]
  - New centerstack assembly
    - B_{TF} increases 5×
    - Δt_{pulse} increases to 0.1 s
    - V-s increases 6× (*solenoid from PPPL*)
    - Improved separatrix operation
  - NSTX-U relevant LHI injector arrays
    - Helicity input rate increases 2×
  - Diagnostics: multipoint TS; CHERS via DNB



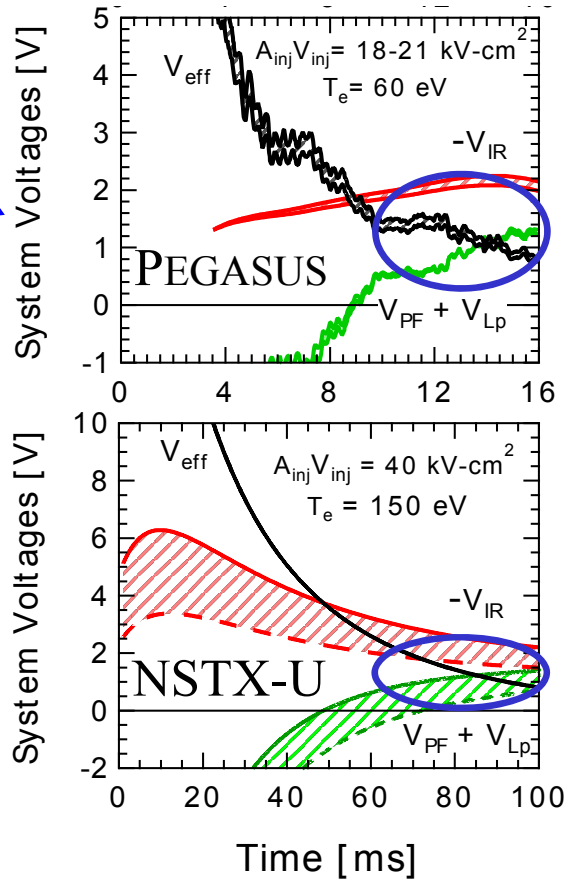
[1] R.C. Preston *et al.*, PP8.00092 (this session)

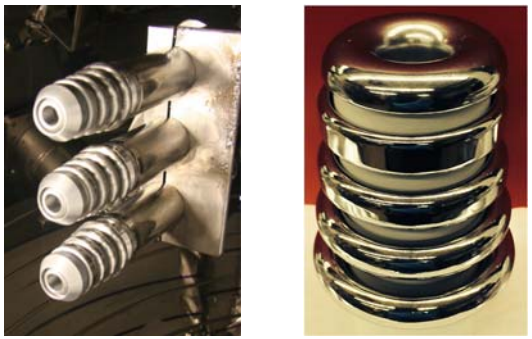
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PEGASUS-U Initiative: Develop and Validate LHI Startup for NSTX-U and Beyond

- Critical physics issues
  - Confinement behavior and helicity dissipation
  - Edge λ=J/B, J penetration processes
  - Injector geometry optimization
- Technology development
  - Long-pulse, large-area injectors in high B_{TF}
- Models & predictive understanding
  - 0-D Power Balance $I_p(t)$ model
  - NIMROD
  - TSC

PEGASUS @ 0.3 MA = same regime as NSTX-U @ 1MA:





Advanced helicity injectors sustain $V_{inj} \leq 1.5$ kV, $I_{inj} \sim 2$ kA with no PMI effects within 1-2 cm of LCFS

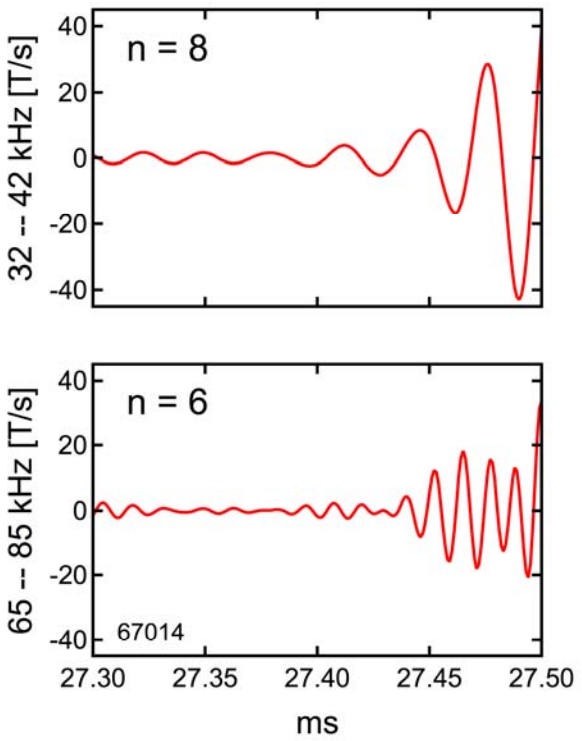
Thermal shock-resistant Mo shield ring set minimizes deleterious cathode spot onset and arc-back

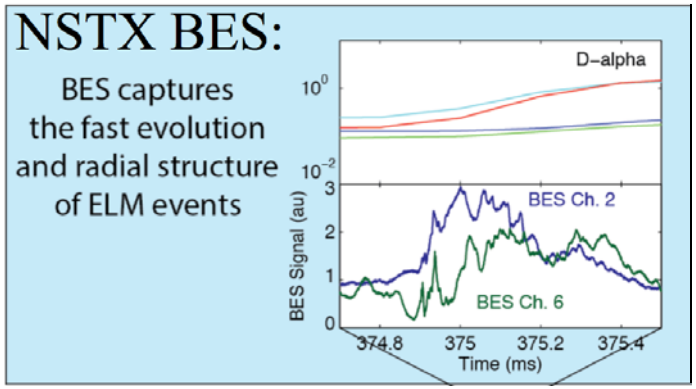
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PEGASUS-U Initiative: Nonlinear ELM Studies and H-mode Physics

- P(r,t), J(r,t), v_ϕ(r,t) through ELM cycles
  - Nonlinear evolution of magnetic structures
- ELM, H-mode modification and mitigation
  - Vary J_{edge}(r), modify edge v_ϕ and shear via LHI
- Synergistic studies with BES on NSTX-U, DIII-D
- Models to test
  - NIMROD
  - BOUT++
  - EPED

Nonlinear Evolution of ELM Magnetic Toroidal Modes in PEGASUS:





Comparison of J(R,t), n_e(R,t), T_e(R,t) on Pegasus to detailed n_e(R,t) on NSTX-U will aid interpretation of BES ELM studies on NSTX-U & DIII-D

M.W. Bongard, APS-DPP 2014

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PEGASUS-U Enables Further Initiatives for Latter Part of Decadal Period

- Non-solenoidal startup
  - PEGASUS-U, NSTX-U LHI program for ~ 1 MA startup demonstration
  - New non-solenoidal startup studies: Stellarator windings; Iron core, EBW…
- Current sustainment with LHI via MHD control
  - Passive or active injector feedback system
- ELM modification and mitigation
  - C-pellet injection for tests of models for ELM-pacing (w/ORNL)
- Neoclassical physics tests
  - J_{BS} model tests: Test Sauter model if sufficient edge pressure achieved
- High β_t plasma studies at $I_p/I_{TF} \geq 3$

Summary: Non-solenoidal Startup and H-mode Physics at Near-Unity A

- Advancing non-solenoidal Local Helicity Injection startup
  - Hierarchy of models providing predictive capabilities, understanding
    - Global limits: Helicity conservation, Taylor relaxation
    - $I_p(t)$: 0-D power balance (future: TSC)
    - Detailed dynamics: resistive MHD (NIMROD)
  - Advanced injector technology increases V_{inj}, helicity injection rate

- AT physics tests at near-unity A
  - H-mode plasmas with simplified diagnostic access
    - Detailed pedestal measurements complement experiments on larger facilities
  - Unique low-A features emerging
    - P_{LH} scaling with A
    - ELM mode number spectra

- PEGASUS-U to address critical physics, technology issues
  - Economical tests of LHI at NSTX-U relevant field, startup pulse length
  - Supports 5-year NSTX-U research plan

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