Non-Inductively Driven Tokamak Plasmas at Near-Unity β_t in the Pegasus Toroidal Experiment

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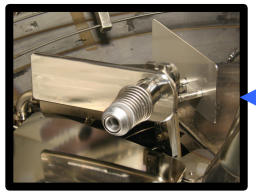
PEGASUS
Toroidal Experiment

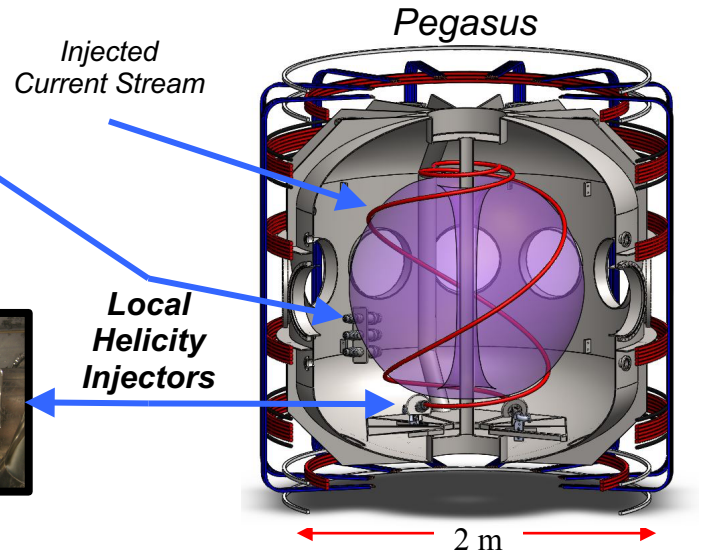
Local Helicity Injection Provides Non-Inductive Startup at Low *A*



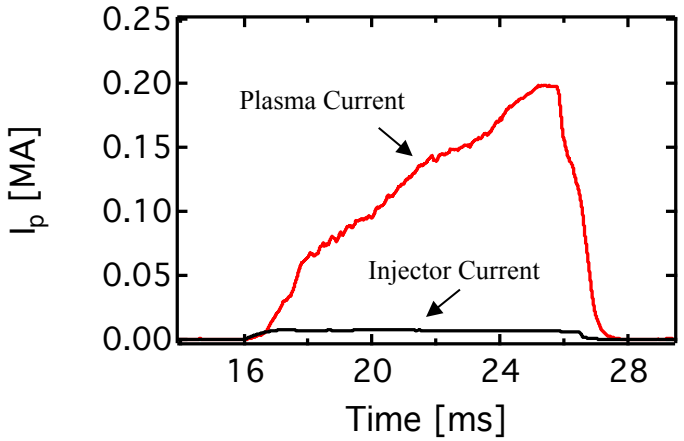
LFS System

HFS System





Non-Solenoidal, High $I_p \leq 0.2$ MA ($I_{inj} \leq 8$ kA)



Pegasus Parameters

A	$1.15 - 1.3$
R [m]	$0.2 - 0.45$
I_p [MA]	≤ 0.25
B_T [T]	< 0.15
Δt_{shot} [s]	≤ 0.025

- Edge current extracted from small, modular injectors
- Relax to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

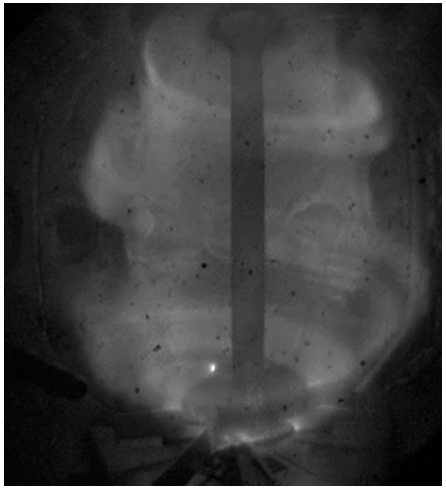
Startup with LHI Accomplished through Relaxation of Injected Current Streams

Injected current weakens vacuum B_Z



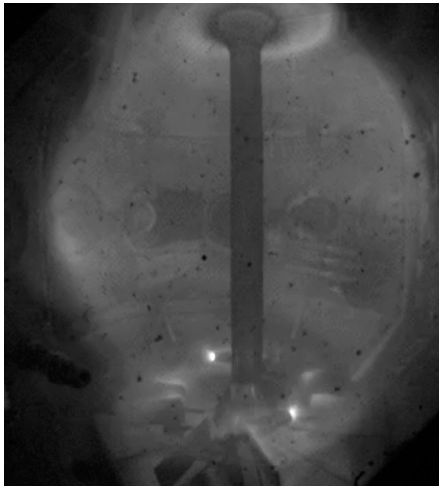
$I_p \sim N_{turns}\, I_{inj}$

Unstable current streams attract, reconnect



$I_p \gtrsim N_{turns}\, I_{inj}$

Tokamak-like plasma; rapid I_p growth



$I_p \gg N_{turns}\, I_{inj}$

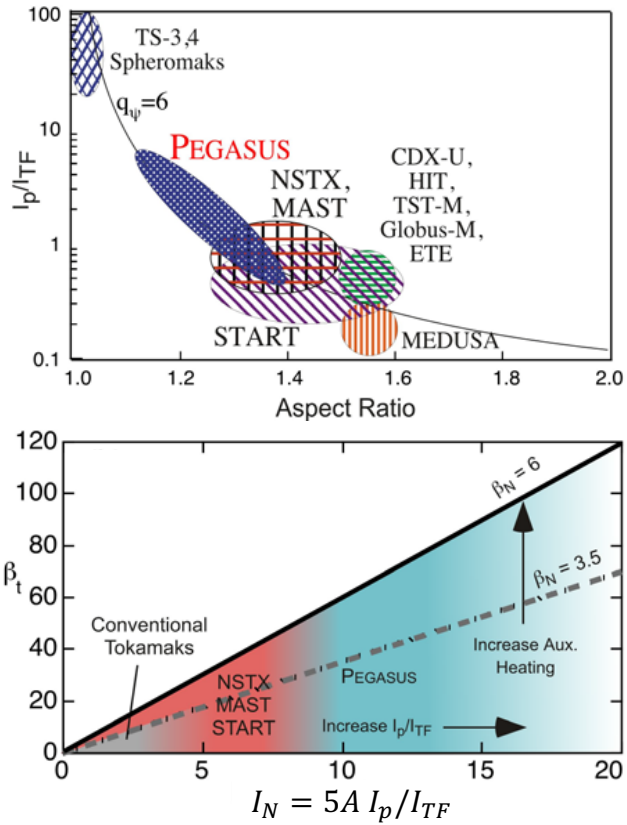
Plasma Operation at Low *A* with LHI Enables Access to High I_N, High β_t

- Pegasus extends MHD stability studies to *A~1*
- Kink stability: I_p/I_{TF} scales strongly with *A*
- High I_N is equivalent to high field utilization

$$\beta_{t,Max} \leq \beta_{N,Max} I_N = \beta_{N,Max} \frac{I_p}{aB_{T0}} = \beta_{N,Max} 5A \frac{I_p}{I_{TF}}$$

$$\left(\beta_t \equiv \frac{2\mu_0 \langle p \rangle}{B_{T0}^2}\right)$$

- High β_t accessible at high I_N with auxiliary heating
- *LHI enables access to this unique operating space*



Y-K.M. Peng and D.J. Strickler, Nuclear Fusion, 26(6), 769 (1986).
Garstka, G. D., et al. Physics of Plasmas, *10*(5), 1705 (2003).

Hierarchy of Physics Models Contribute to the Understanding of 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

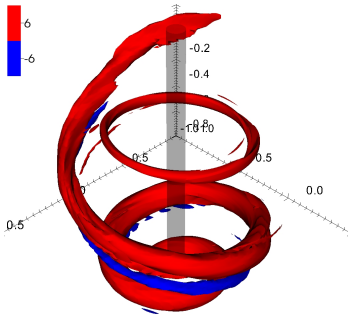
$$I_p R_p \leq V_{LHI} \approx \frac{A_{inj} B_{t,inj}}{\Psi_t} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   - V_{LHI} is effective LHI current drive
   - V_{IND} is net drive from PF, shape, I_p and L changes

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

3. 3D Resistive MHD (NIMROD)
   - Physics of LHI current drive mechanisms

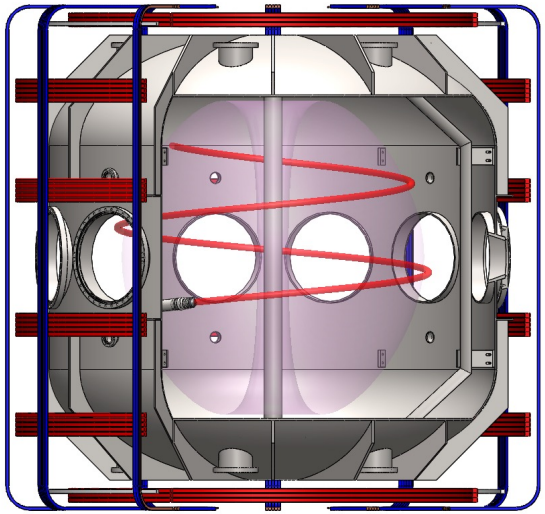
Reconnecting LHI Current Stream

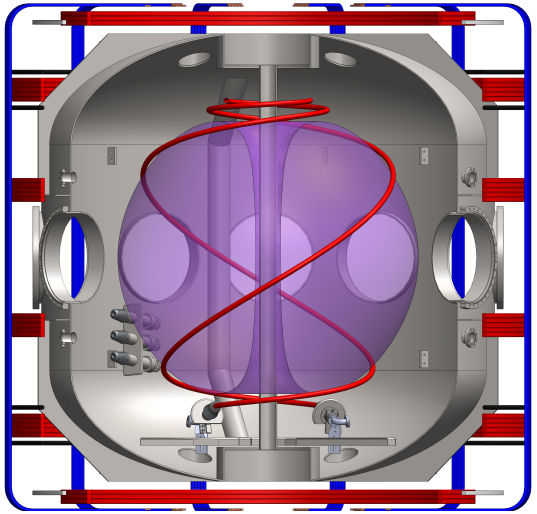


J.D. Weberski Poster UP11.00098

J.L. Barr (to be submitted to Nucl. Fusion 2017)
*D.J. Battaglia, et al. Nucl. Fusion **51** 073029 (2011)*
N.W. Eidietis, Ph.D. Thesis, UW-Madison (2007)
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

Different Injector Geometries Emphasize Different Current Drive Mechanisms





Low-Field-Side (LFS) Injection:

- Injectors near outboard midplane
- Shape evolution → V_{IND} dominates

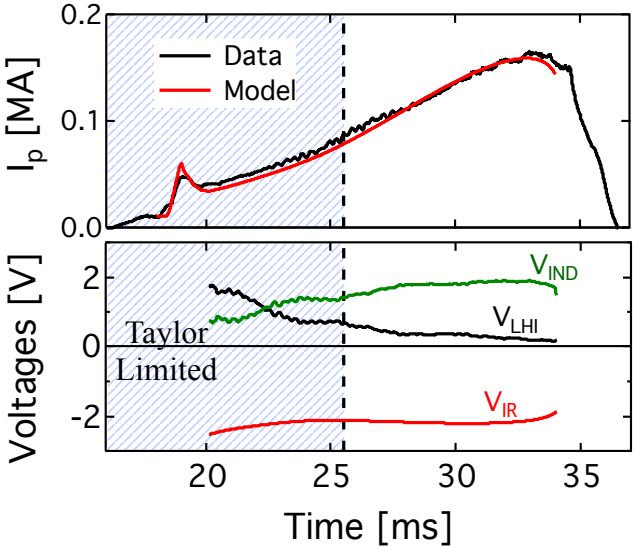
High-Field-Side (HFS) Injection:

- Injectors in lower divertor
- Static geometry → V_{LHI} dominates

Power Balance Analysis Quantifies Contributions to Current Drive

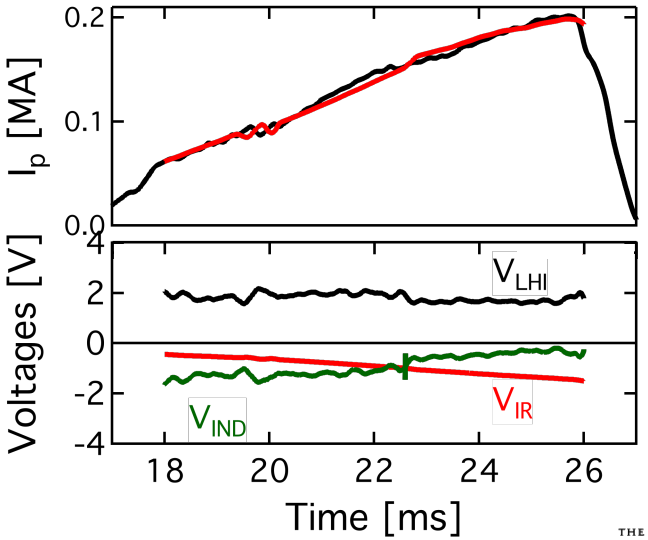
Low-Field-Side Injection:

- Higher R_{inj} → decreased V_{LHI}
- Initially outboard limited
- Dynamic shape evolution → Large V_{IND}



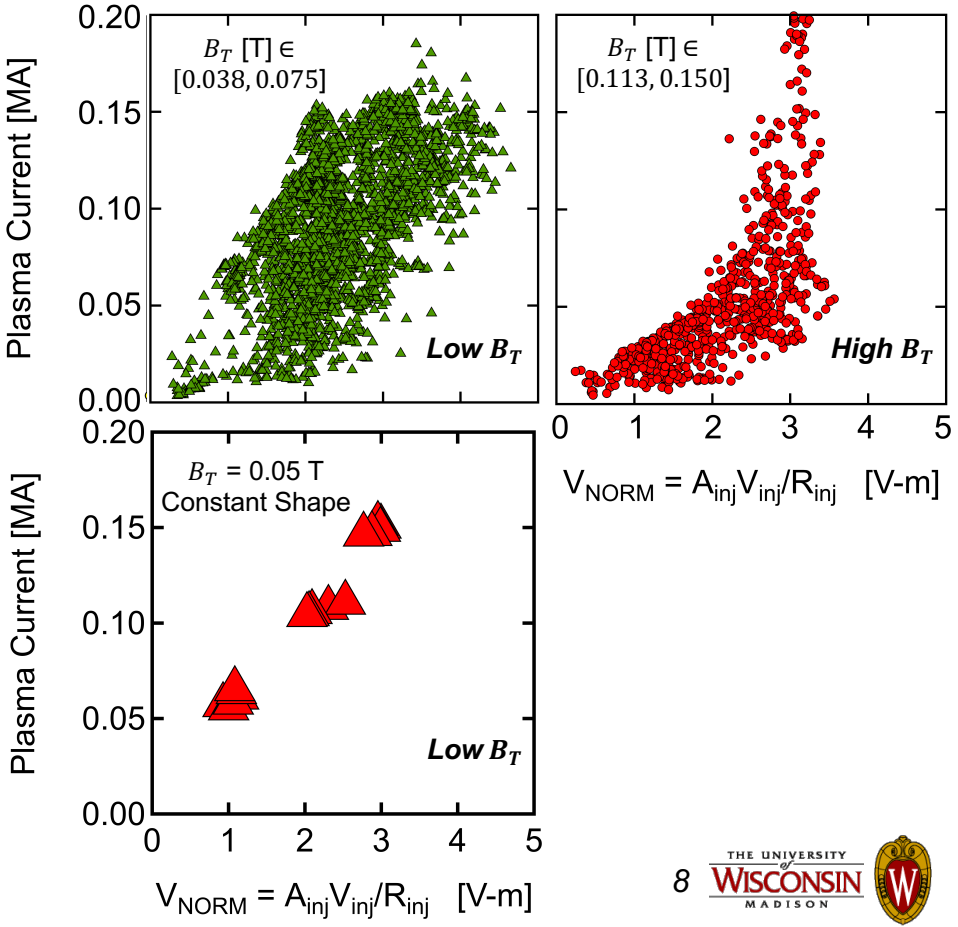
High-Field-Side Injection:

- Lower R_{inj} → Increased V_{LHI}
- Center stack limited, high κ
- Static geometry → Minimal V_{IND}



HFS Injection: I_p Increases with V_{LHI}

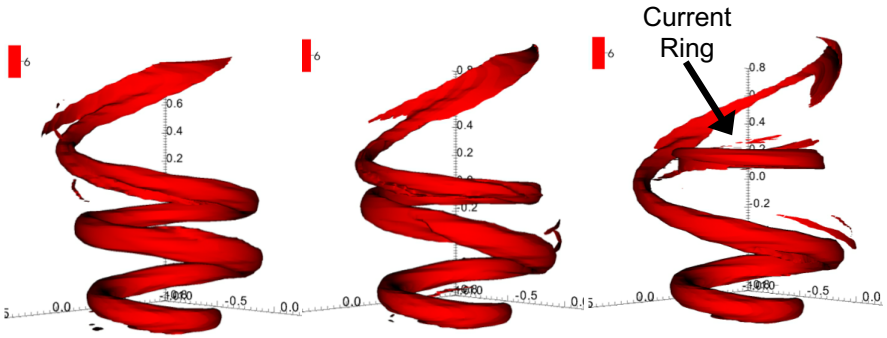
- Relatively high I_p at very low B_T readily achievable (i.e. high I_N)
- Maximum I_p may vary with B_T
- Fixed geometry V_{LHI} scans suggest linear scaling
- Predictive understanding requires more detailed knowledge
  - *e.g.* effects of Z_{eff}, n_e, B_T, shape, …



J.A. Reusch, APS-DPP 2017

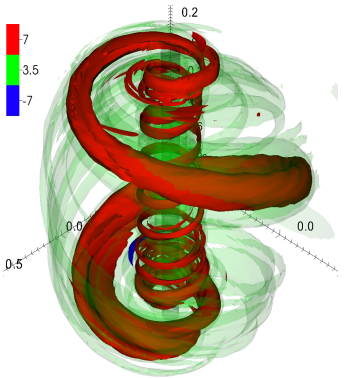
NIMROD Simulations Indicate a Reconnection Based Mechanism for Plasma Formation and Current Drive

NIMROD: Early Relaxation Phase in Divertor LHI Geometry



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

Sustainment Phase



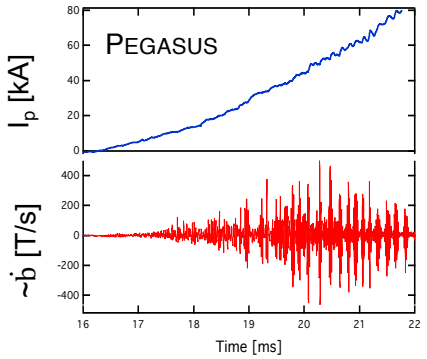
NIMROD Simulation
[O'Bryan PhD 2014]

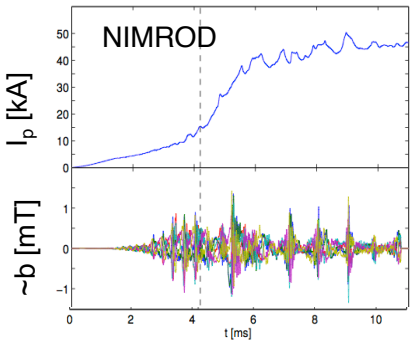
- Reconnection of coherent current streams occurs throughout the discharge

*O'Bryan et al., Phys. Plasmas **19** 080701 (2012)*
*O'Bryan and Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

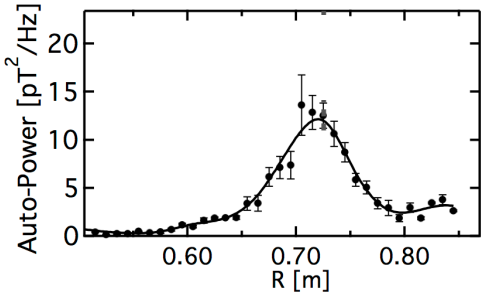
LFS injection: Current Stream Interaction Manifests as Edge-Localized MHD Burst

- MHD bursts and ion heating support presence of outboard stream reconnection
  - Low frequency: 20–80 kHz, $n = 1$
- Internal magnetic measurements localize coherent streams
- Suggests any stochastic reconnection region may be localized to edge
- However, continuous ion heating and new observations with HFS injection imply additional CD mechanisms

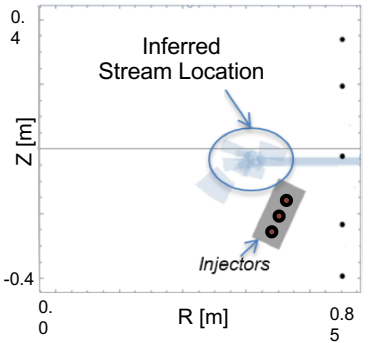




Internal B_z Measurements



External B_z Phase Correlation

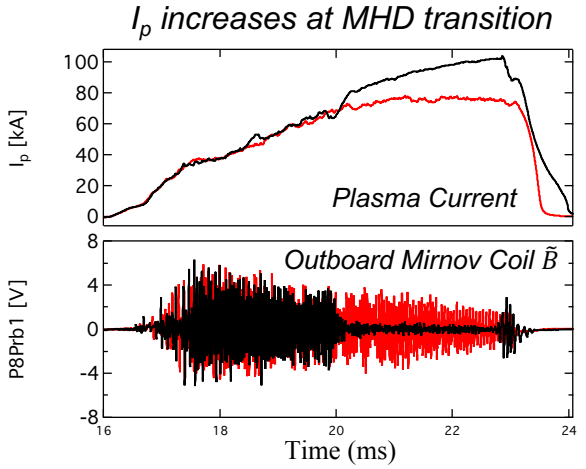


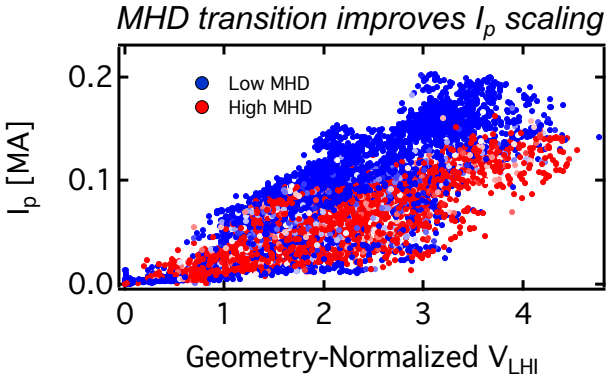
J.L. Barr, UW-Madison PhD Thesis (2016)
J.B. O'Bryan, UW-Madison PhD Thesis (2014)
E.T. Hinson, UW-Madison PhD Thesis (2015)

J.A. Reusch, APS-DPP 2017

HFS Injection: Spontaneous Reduction in Large-Scale MHD and Increased I_p Observed

- Abrupt MHD transition can occur:
  - Low-f $n = 1$ activity reduces 10×
  - n_e rises, edge sharpens visibly
  - Indicates strong CD mechanism independent of n=1 activity
  - Extremely sensitive to B_T, B_Z, I_p, fueling
- I_p scaling with V_{LHI} improves at transition
- All high β_t discharges to date exhibit this feature





N.J. Richner UP11.00088
J. L. Pachicano UP11.00092

Magnetic Reconnection Provides Auxiliary Ion Heating During LHI

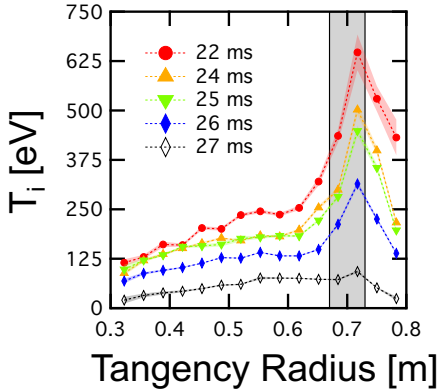
With tokamak present:

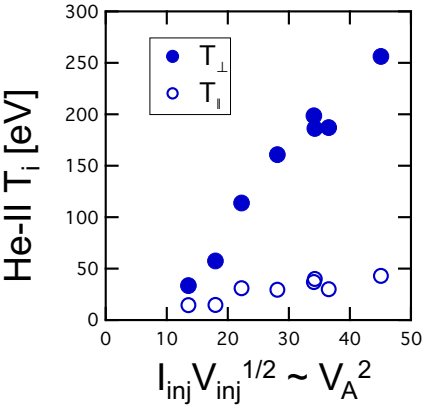
- $T_i > T_e$ typically observed
- Hollow $T_i(R)$ indicates edge heating

Without tokamak present:

- Anisoptropic ion heating in injector streams consistent with two-fluid reconnection
  - $T_{i,\perp} \sim V_A^2$ of injected current streams

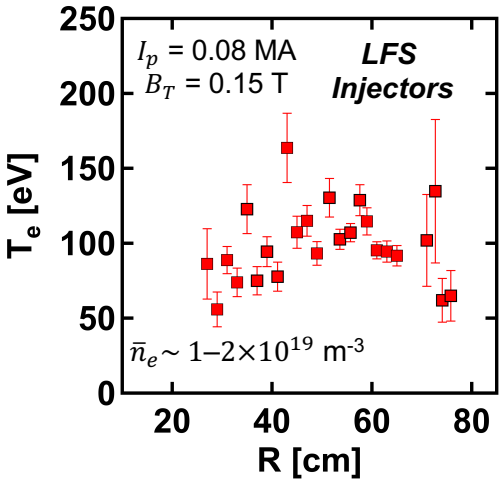
Edge reconnection ion heating generates relatively large p_i, increased β_t

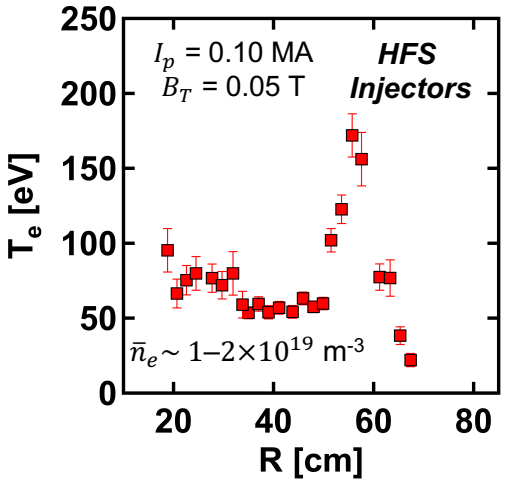


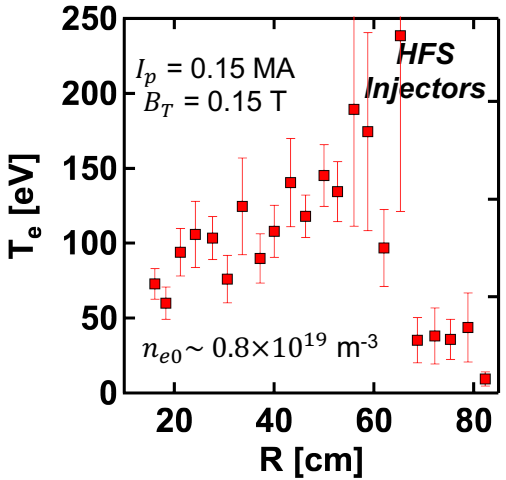


Thomson Scattering Indicates Range of $T_e(R)$ Realized During LHI

- T_e profiles vary with discharge evolution, n_e, shape, and B_T







- Issues under study:
  - Core vs. edge transport
  - Z_{eff}, P_{rad}
  - Pulse length
  - B_T, n_e effects

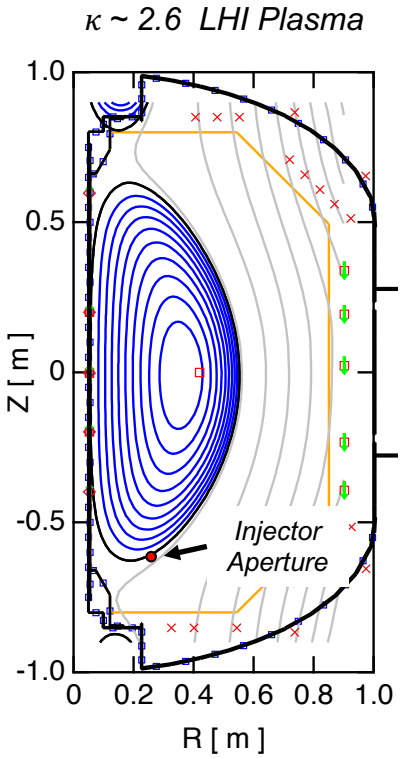
G.M. Bodner, UP11.00087

D.J. Schlossberg, Rev. Sci. Instrum. **87**, 11E403 (2016); UW-Madison PhD Thesis (2016)

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Putting This All Together, LHI Provides Access to Unique ST Operating Space

- ST research goal: Non-solenoidally sustained high κ, high I_N, low ℓ_i, high β_t plasmas*
- Low A + LHI: access to highly shaped plasmas
  - Naturally high κ
  - Kink stability at very low B_t: High I_N
- LHI drives hollow $J(\psi)$ profile
  - Low ℓ_i (~ 0.2-0.4)
  - Internal tearing mode stability
- LHI gives anomalous ion heating → high β_t



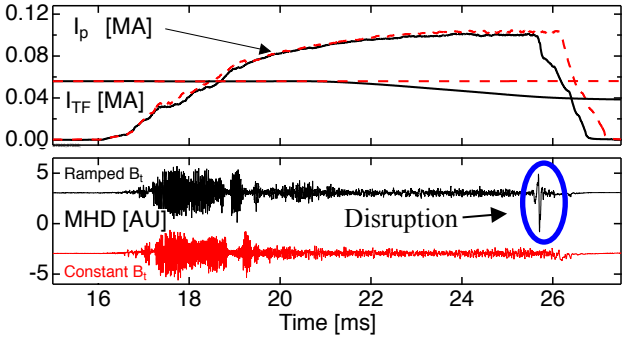
*J.E. Menard et al., Nucl. Fusion **56** 106023 (2016)

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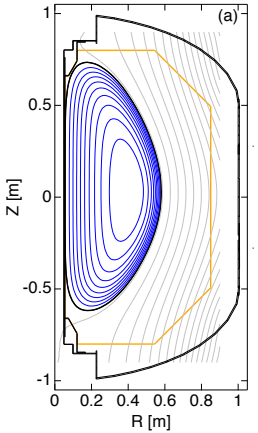
LHI Enables Operation at Extremely Low B_T, $I_N > 14$, and $\beta_t > 95\%$

- Access to high I_N plasmas
  - $I_N = 5A\frac{I_p}{I_{TF}} > 10$ accessible
  - With I_{TF} rampdown: $I_N > 14$
- Ramped B_T discharges terminate disruptively at ideal no-wall stability limit
- Analyzed through partial kinetic equilibrium reconstructions
  - Core pressure, plasma edge location constraints
- β_t~1 achieved with I_{TF} rampdown

High β Discharge Evolution



Reconstructed LHI Plasma with β_t=95%



$A = 1.21$
$\kappa = 2.6$
$I_N = 14.1$
$\ell_i = 0.22$
$\beta_t = 0.95$
$\beta_N = 6.7$
$\beta_p = 0.45$

J.A. Reusch, APS-DPP 2017

*D.J. Schlossberg et al., PRL **119** 035001 (2017)*

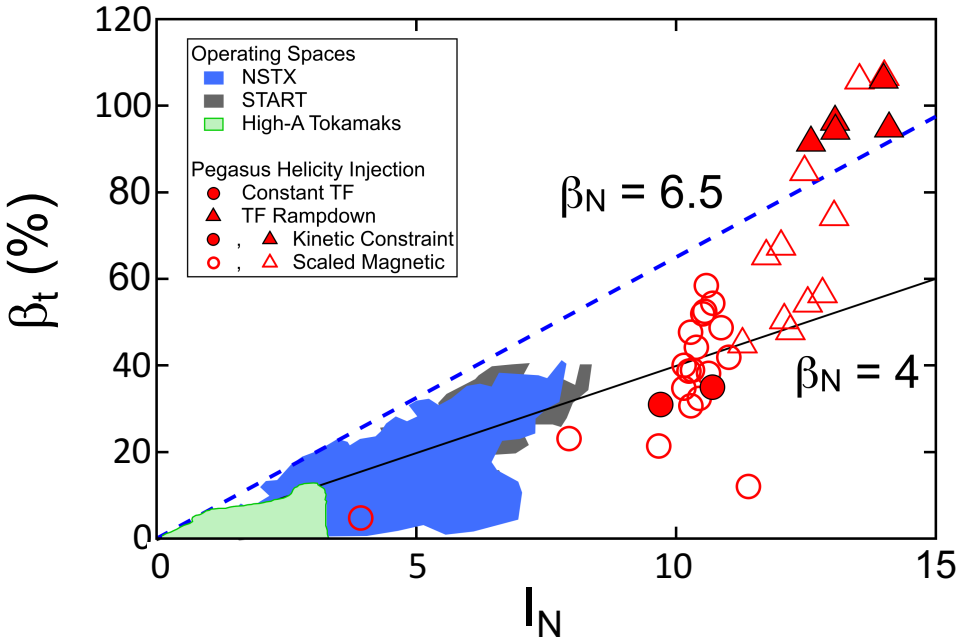
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LHI at $A \sim 1$ Expands the Operating Space for the ST to $\beta_t \sim 1$

- Access to $\beta_t \sim 1$ readily achieved
  - Facilitated by $A \sim 1$ and LHI
- $A \sim 1$:
  - Naturally high κ
  - High I_N stability limit
- LHI:
  - Strong ion auxiliary heating
  - Edge current drive → low ℓ_I
  - Enables very low B_t operation
- Low ℓ_i at low-A: high $\beta_{N,max}$

J.A. Reusch, APS-DPP 2017

Troyon Stability Diagram for Tokamaks, STs

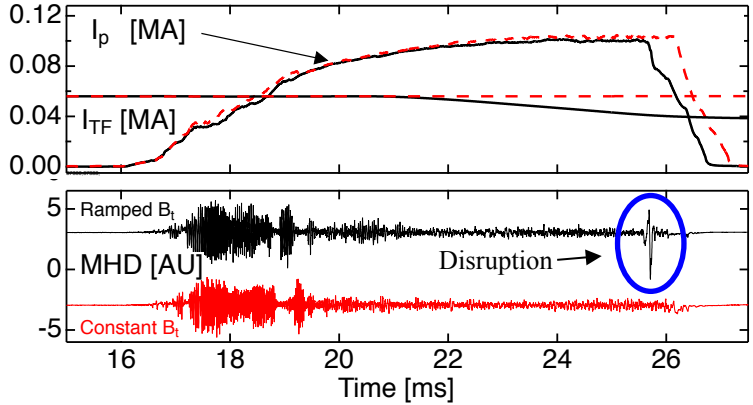


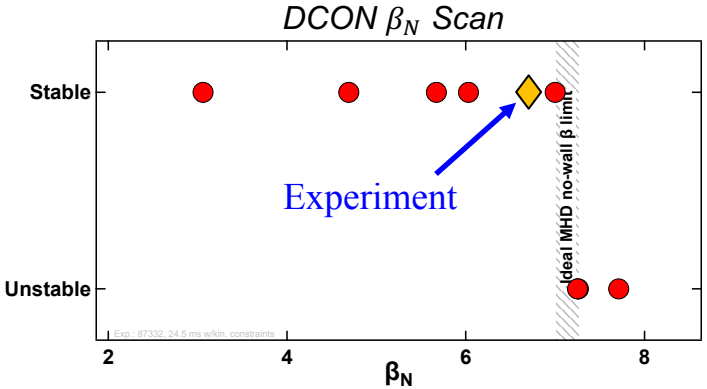
R.J. Fonck, IAEA FEC 2016 OV/5-4
D.J. Schlossberg et al., Phys. Rev. Lett. ***119*** *035001 (2017)*
J.E. Menard et al., Phys. Plasmas ***11****, 639 (2004)*

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Discharge Terminates From Intermediate-m, n=1 MHD Disruption As B_t is Decreased

- Terminating MHD timing varies with B_t ramp rate
- Mode identified through cross phase analysis of poloidal array of magnetic sensors
  - Best fit: m ~ 9, n = 1 at $\psi_N \approx 0.85$
- DCON: disruption at ideal no wall limit
  - Terminating mode: intermediate m, n=1 at $\psi_N = 0.84$





LHI in Pegasus Accesses Desirable ST Operating Space, Albeit at Modest Parameters

- Non-solenoidally sustained high-β_t, low ℓ_i, high κ, high I_N operation a ST research goal
  - Target operating space of NSTX-U at high performance
  - PEGASUS employs different mechanisms to access this space

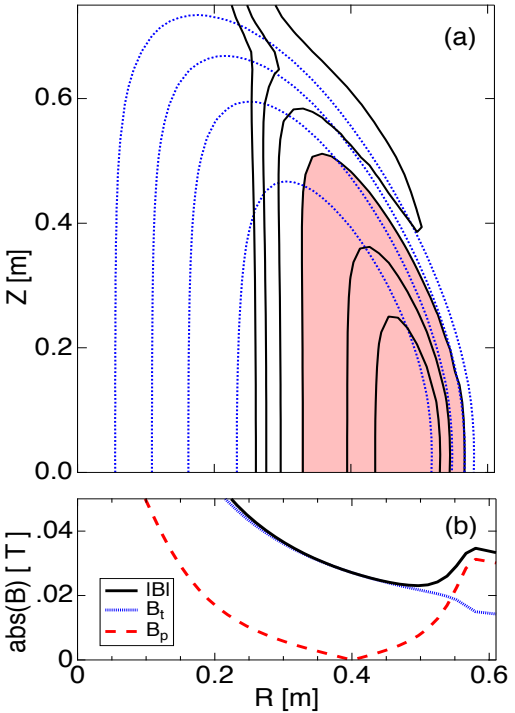
ST Target	NSTX, NSTX-U	PEGASUS
High κ	Low A	$A = 1.15 \rightarrow \kappa \approx 2.5$
Low ℓ_i	Bootstrap, Off-axis NBI, RF	LHI edge CD $\rightarrow \ell_i \approx 0.2$
High I_N	High I_p, low A, wall stabilization	Low B_T, $A \sim 1$, no-wall limit
High β_t, β_N	NBI, RF Heating	Reconnection Ion Heating
Non-solenoidal sustainment	Bootstrap, NBI, RF	LHI
Collisionality	Very low	Modest

- LHI facilitates access and stability studies

Sustained Large Volume Minimum $|B|$ Region Observed in High β_t LHI Plasmas

- High β_t equilibrium contains large minimum $|B|$ region
  - Up to 47% of plasma volume
  - Well deepens and broadens as β_t increases
  - Persists for several energy confinement times
- Minimum $|B|$ regime arises from 3 major influences
  - $B_p \sim B_T$ at $A \sim 1$
  - Hollow $J(R)$
  - Pressure-driven effects (although $\beta_p < 1$)
- Potentially favorable for transport
  - Under investigation…

High-β_t equilibrium flux surfaces (blue), $|B|$ (black), and min-$|B|$ region (red)



Local Helicity Injection and $A \sim 1$ Enable Stable High I_N, High β_t Operation

- Non-solenoidal startup and sustainment with LHI
  - I_p up to 0.2 MA with $I_{inj} \leq 8$ kA
  - Varying injector location emphasizes different current drive mechanisms
  - New reduced MHD regime discovered
  - Edge reconnection based current drive provides low ℓ_i, ion heating

- LHI and $A \sim 1$ enable access to high-β_t regime
  - $I_N > 14$, $\beta_t \sim 1$ achieved
  - Stability tests at extreme toroidicity
  - Access to novel min |B| region

More Information Can Be Found at the Pegasus Posters this Afternoon

Poster session: UP, Thursday PM:

- M.W. Bongard UP11.00085 Non-Solenoidal Startup via Helicity Injection in the Pegasus ST
- C.M.B. Pierren UP11.00086 Enhanced Control for Local Helicity Injection on the Pegasus ST
- G.M. Bodner UP11.00087 Veff Scaling of Te and ne Measurements During Local Helicity Injection on the Pegasus Toroidal Experiment
- N.J. Richner UP11.00088 Investigating High Frequency Magnetic Activity During Local Helicity Injection on the Pegasus Toroidal Experiment
- C. Rodriguez Sanchez UP11.00089 Studies of Impurities in the Pegasus Spherical Tokamak
- D.R. Smith UP11.00090 Microstability Properties of the Local Minimum |B| Regime in Pegasus
- A.T. Rhodes UP11.00091 Initial Measurements of Electrostatic Turbulence in Local Helicity Injection Plasmas
- J.L. Pachicano UP11.00092 High Field Side MHD Activity During Local Helicity Injection
- M.G. Burke UP11.00093 Progress Towards a New Technique for Measuring Local Electric and Magnetic Field Fluctuations in High Temperature Plasmas
- J.D. Weberski UP11.00098 Power Balance Modeling of Local Helicity Injection for Non-Solenoidal ST Startup