The Coupling of Local Helicity Injection to Ohmic Current Drive on the PEGASUS ST

C. Pierren,

M.W. Bongard, G.M. Bodner, R.J. Fonck, N.J. Richner,
C. Rodriguez Sanchez, C.E. Schaefer

University of Wisconsin-Madison

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PEGASUS
Toroidal Experiment

The Coupling of Local Helicity Injection to Ohmic Current Drive on the PEGASUS ST

Ohmic (OH) operations on PEGASUS have been restored to provide comparison of MHD activity in OH and local helicity injection (LHI) driven discharges and to provide tests of handoff from LHI to OH current drive. Temperatures of 250 eV and densities of $2 * 10^{19} \mathrm{m}^{-3}$ were measured with Thomson scattering in OH H-mode plasmas. LHI discharges at similar density show $T_e \sim 150$ eV and are comparable to OH L-mode plasmas. An insertable radial array of magnetic pick-up loops observed typical $n = 1$ internal tearing mode MHD activity and a large reduction in broadband MHD fluctuations relative to LHI plasmas. The magnetic and kinetic boundaries coincide in OH plasmas, in contrast to LHI plasmas, where the kinetic boundary appears to occur several cm inside the magnetic edge. This supports the suggestion of a dual-zone confinement behavior at the edge of LHI plasmas. Spectroscopic measurements show a reduction in OH impurity content compared to LHI. Both low-field-side and high-field-side LHI initiated plasmas have been successfully coupled to purely OH sustainment at $I_p \sim 100$ kA. Remaining OH studies are concentrating on optimizing LHI-OH handoff through variations in $j(R)$, T_e, B_T, n_e, etc.

Work supported by U.S. DOE Grant DE-FG02-96ER54375

Layout Slide (Include for Posters)

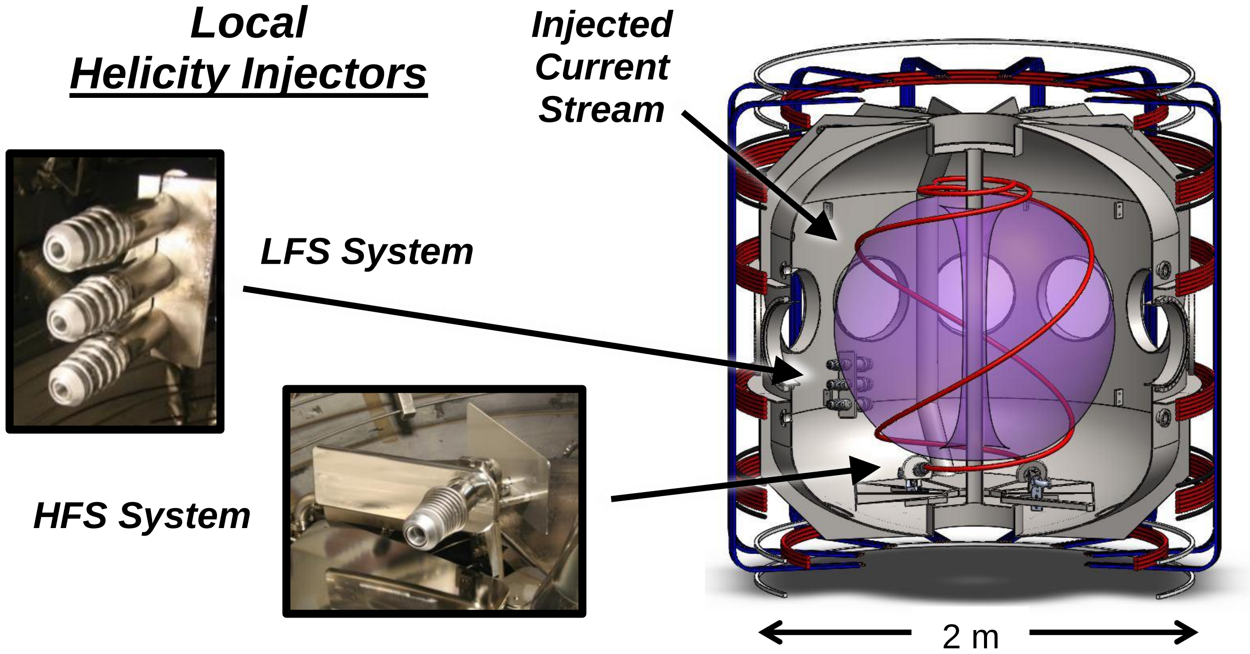
12:1 scale Panel size: 8' x 4'

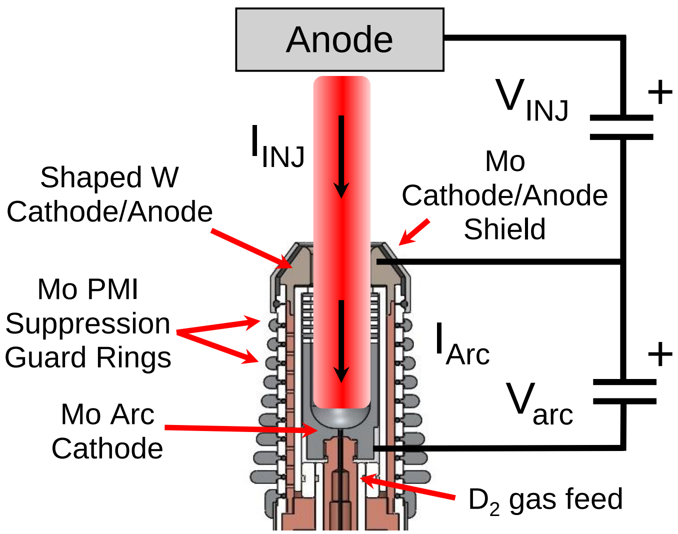
US Legal 8.5 x 14"
US Letter 8.5 x 11"

The Coupling of Local Helicity Injection to Ohmic Current Drive on the PEGASUS ST

OH Operations Restored for Diagnosing LHI Plasmas	Documentation of OH-only Plasmas for Comparison to LHI	LHI Robustly Couples to OH CD	Features of the LHI-OH Handoff	Summary	Column 6
Local Helicity Injection (LHI) Creates Solenoid-Free I_p	Documentation of OH Only Discharges for Diagnostic Baselines	LFS & HFS LHI Successfully Couple to OH Current Drive	LHI-Produced Handoff Targets Have Favorable MHD Properties	Takeaways of LHI-OH Handoff Experiments & Future Work	Slide 1
Control System Upgrade Restored Ohmic (OH) Operations	Representative Thomson Profiles From OH H-mode Plasmas Show Peaking $p_e(R,t)$	LHI-OH Handoffs Robust to Temporal Variations in OH V_{loop}	Evolution of T_e Across Handoff Sensitive to V_{loop} Timing	Slide 2	Slide 2
OH Used for Diagnostic Baselines and as an LHI Diagnostic	OH / LHI Comparisons Show Markedly Different Edge Magnetic Activity and Structure	LHI Plasmas Provide OH Flux Savings For Sustainment	Unexpected Success of HFS-OH Handoffs at High $\dot{I}_p$	Slide 3	Slide 3
OH Provides Current Drive to Test LHI Sustainment	Impurity Baseline Measurements of OH H-mode Plasmas	OH Flux Savings Motivates Analysis of LHI Flux Consumption Efficiency	OH Impurity Charge State Balance in Handoff Similar to OH Baseline	Slide 4	Slide 4

Local Helicity Injection (LHI) Creates Solenoid-Free I_p

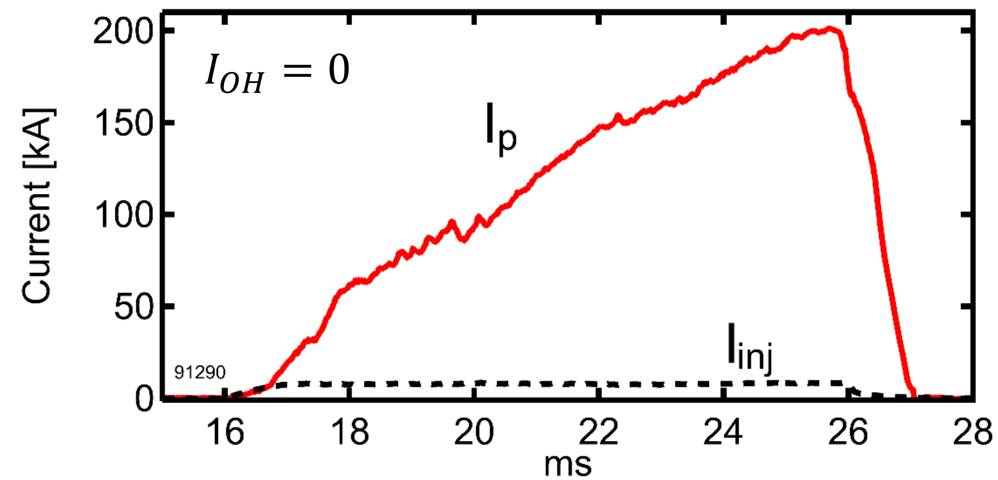




PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.25 MA	ΣI_{inj}	≤ 14 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	= 2-4 cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

M.W. Bongard et al., Nucl. Fusion ***59****, 076003 (2019)*

Non-Solenoidal $I_p = 0.2$ MA via LHI startup ($I_{inj} \leq 8$ kA)

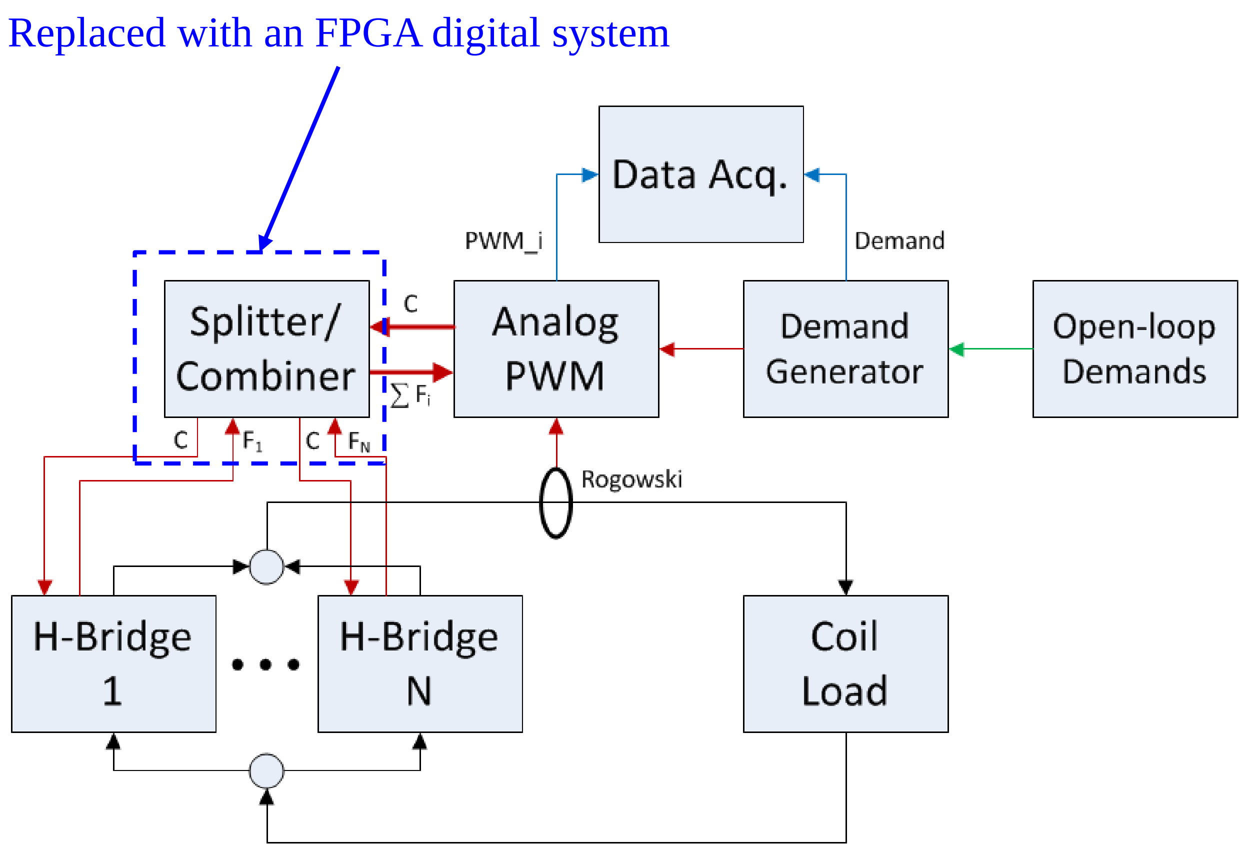


- LHI is promising method for solenoid-free startup
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - Global current limits from Taylor relaxation, helicity balance
  - Hardware retractable prior to nuclear phase in reactor
- Routinely used for startup on PEGASUS

Control System Upgrade Restored Ohmic (OH) Operations

- Ohmic specific protection system, "Splitter/Combiner," required replacement
- Upgraded with a Field Programmable Gate Array (FPGA) digital system
- FPGA Splitter/Combiner Improvements:
  - Additional device-level protections
  - Increased number of controllable H-bridges
  - Continuous fault monitoring
  - Reduced fault response time 25–200 ns
- OH solenoid will be removed during upgrade to PEGASUS-III device (FY2020)
  - *J.D. Weberski BO8.00012*
  - *A.T. Rhodes GP10.00125*

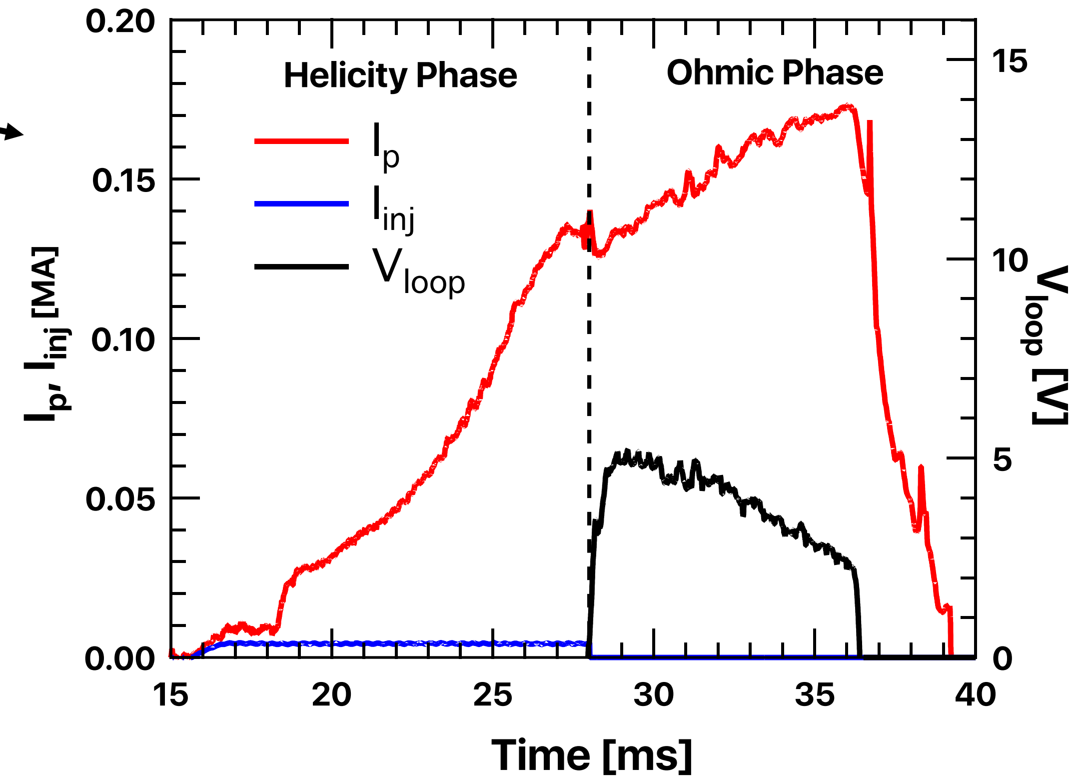
Block Diagram of PEGASUS Combined
Analog/Digital Control System



OH Used for Diagnostic Baselines and as an LHI Diagnostic

- OH as an LHI diagnostic tool:
  - LHI coupling to non-LHI current drive (CD)
  - Taylor limit studies
- OH only plasmas for diagnostic baselines:
  - Thomson Scattering
    - *G.M. Bodner GP10.00125*
  - Magnetics (MHD)
    - *N.J. Richner BO8.00011*
    - *C.E. Schaefer GP10.00124*
  - Impurity diagnostics
    - *C. Rodriguez Sanchez GP10.00125*

Example of Previous LFS LHI-to-OH Handoff



K. E. Thome, H-Mode Access and Characteristics at Near-Unity Aspect Ratio on the Pegasus Toroidal Experiment, PhD Thesis 2015

OH Provides Current Drive to Test LHI Sustainment

- Condition for viable solenoid-free startup is ability to couple to solenoid-free CD, e.g. NBI, rf, etc…

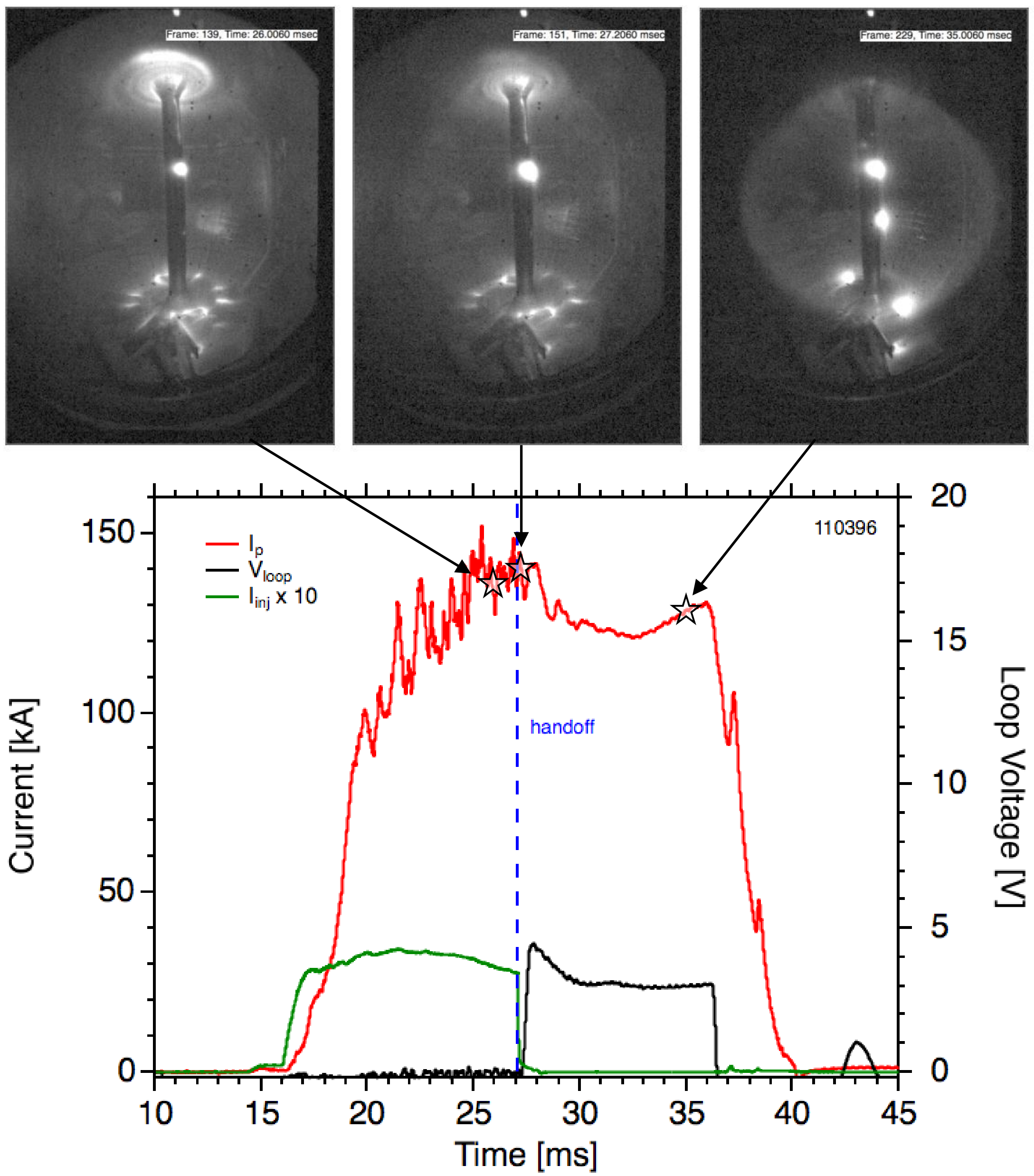
- OH serves as sustainment method on PEGASUS

- Goals of LHI-to-OH Handoff Experiments:

  1. Demonstrate coupling of LHI plasmas to subsequent (OH) current drive with different sources
     - HFS LHI to OH
     - LFS LHI to OH

  2. Identify LHI plasma parameters important for current drive coupling, e.g. $J(R), \ell_i, \dot{I}_p$, etc.
     - Can these parameters provide basis to predict coupling of future PEGASUS-III LHI plasmas?

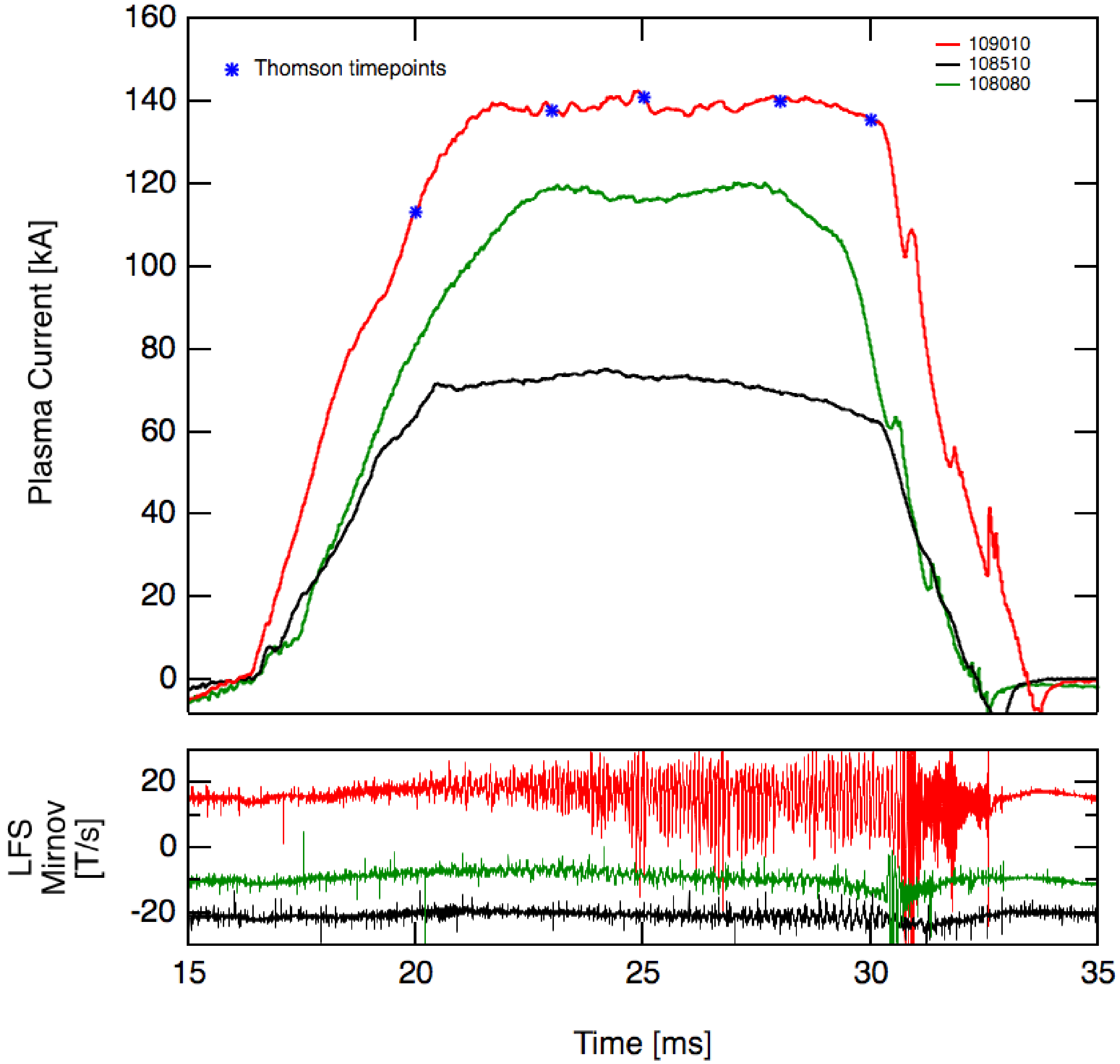
Example HFS LHI to OH Handoff



Documentation of OH Only Discharges for Diagnostic Baselines

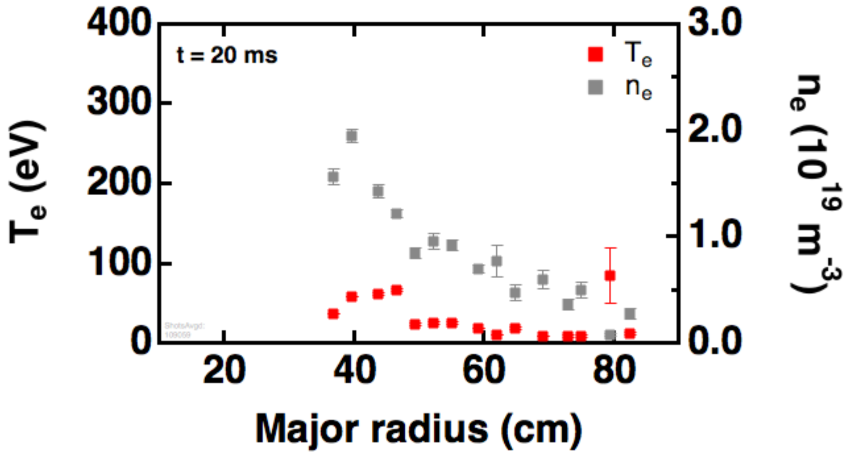
- OH baselines provide for comparison to LHI
- Variety of OH discharges diagnosed:
  - 140 kA H-mode, 109010
  - 120 kA L-mode, 108080
  - 70 kA, low MHD L-mode, 108510
- First Thomson profile measurements
- MHD and magnetic topology with new insertable $\boldsymbol{B}(R,t)$ and $\dot{\boldsymbol{B}}(R,t)$ probes
- Baseline impurities with improved diagnostics

OH Diagnostic Baseline Discharges

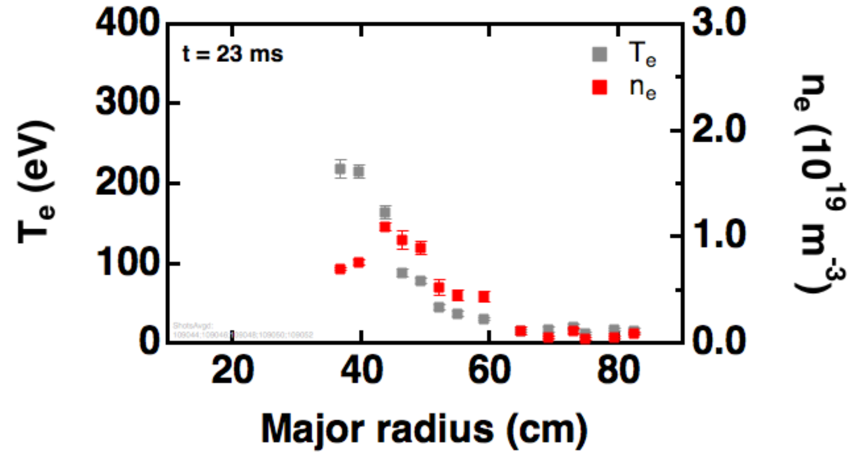


Representative Thomson Profiles From OH H-mode Plasmas Show Peaking $p_e(R,t)$

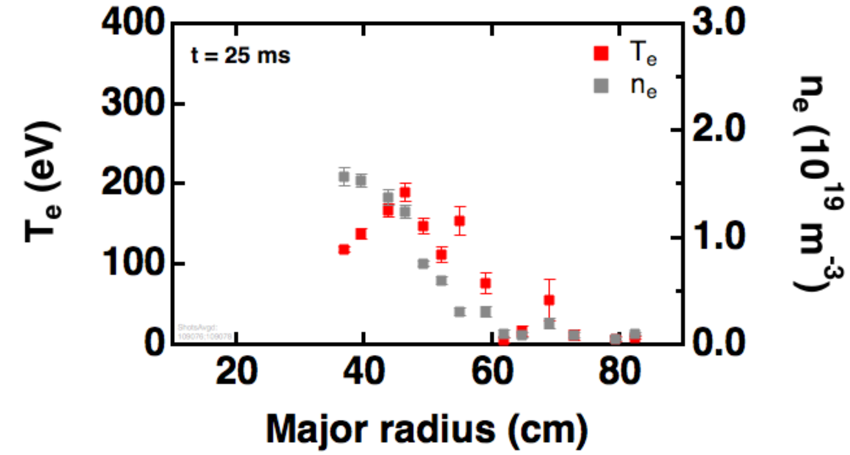
$n_e, T_e(R), t = 20$ ms



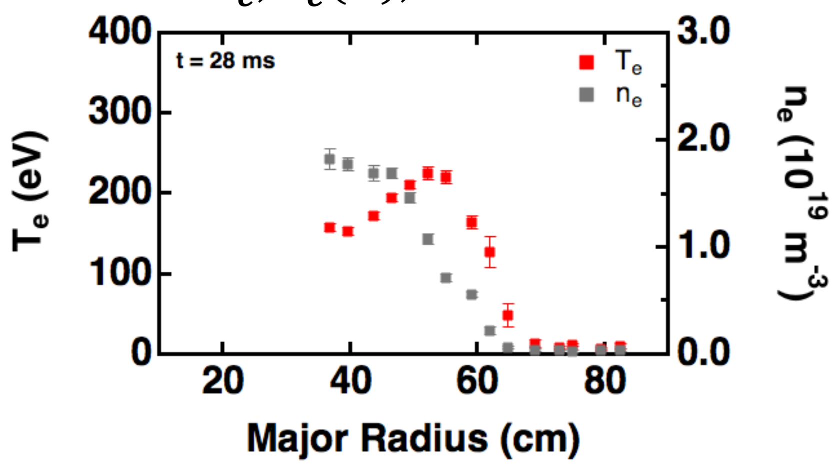
$n_e, T_e(R), t = 23$ ms



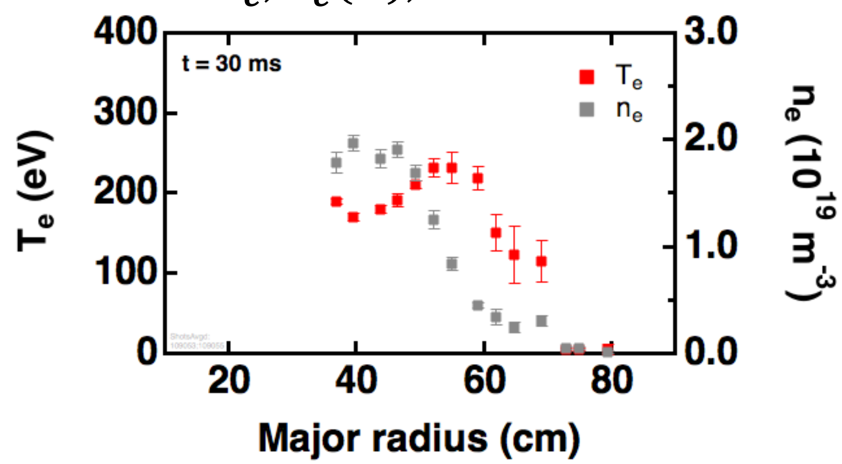
$n_e, T_e(R), t = 25$ ms



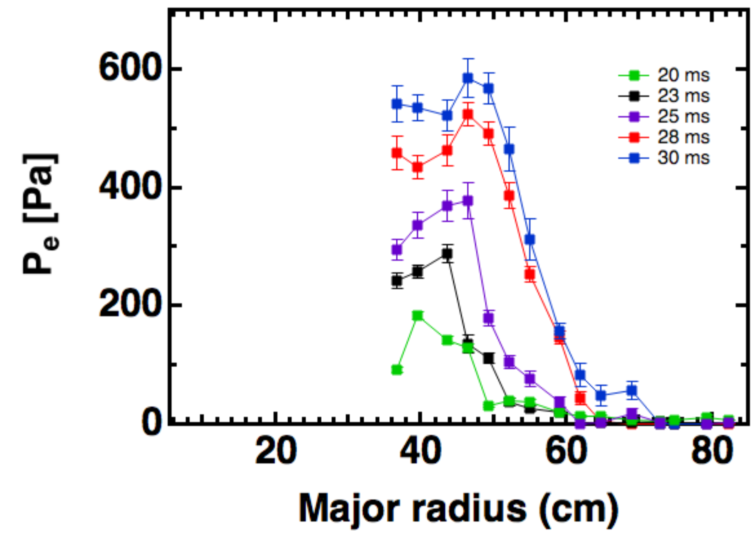
$n_e, T_e(R), t = 28$ ms



$n_e, T_e(R), t = 30$ ms



$p_e(R,t)$



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G.M. Bodner GP10.00125

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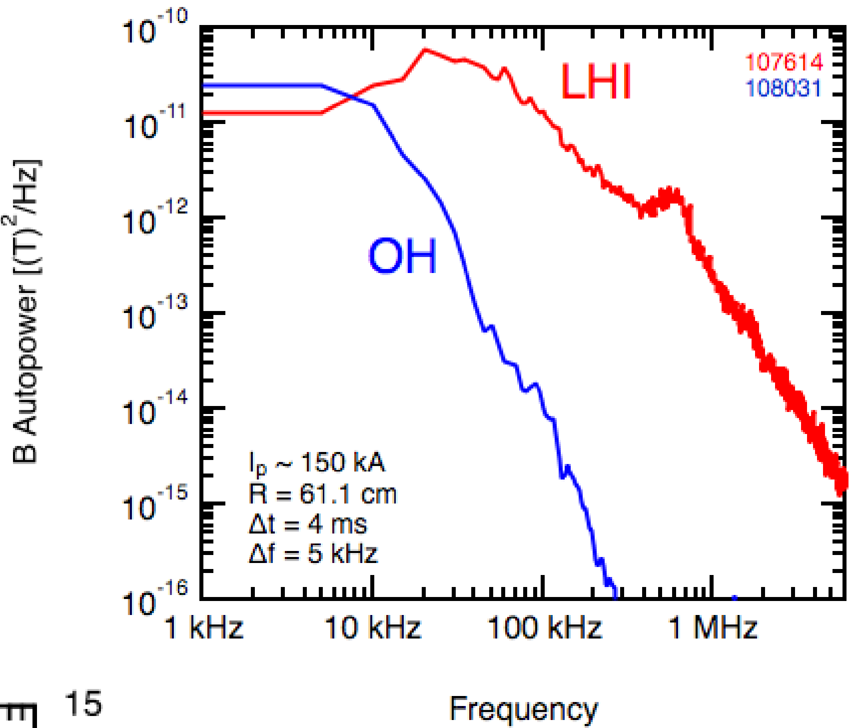
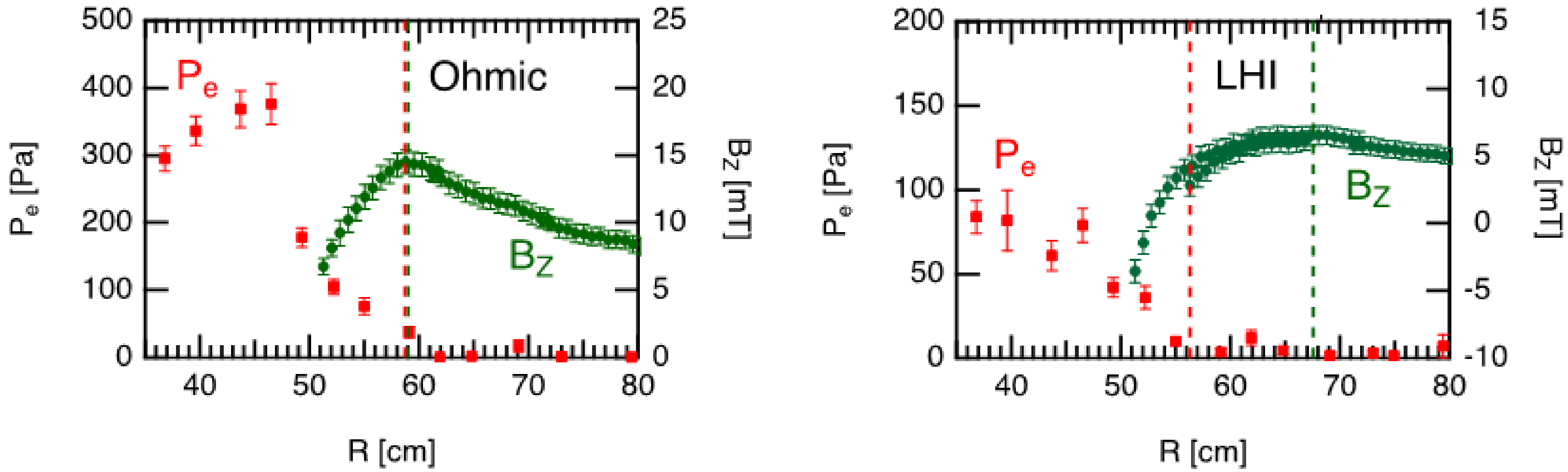
OH / LHI Comparisons Show Markedly Different Edge Magnetic Activity and Structure

- MHD compared between OH and LHI discharges with similar I_p and plasma size
- Low f activity comparable, LHI high f >> OH
- Observed magnetic and kinetic boundaries coincide in OH, but diverge in LHI
  - Suggests dual-zone confinement





C. E. Schaefer GP10.00124

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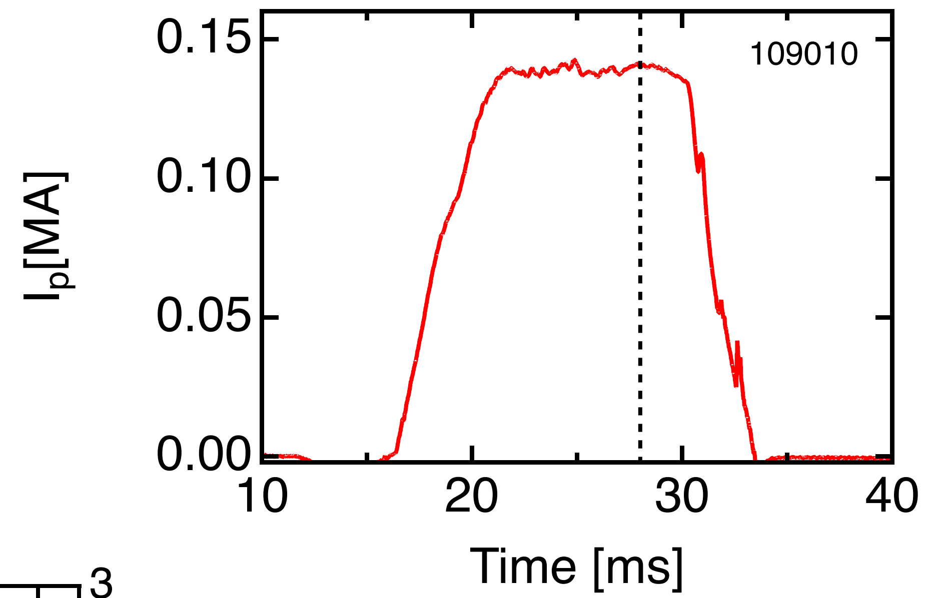
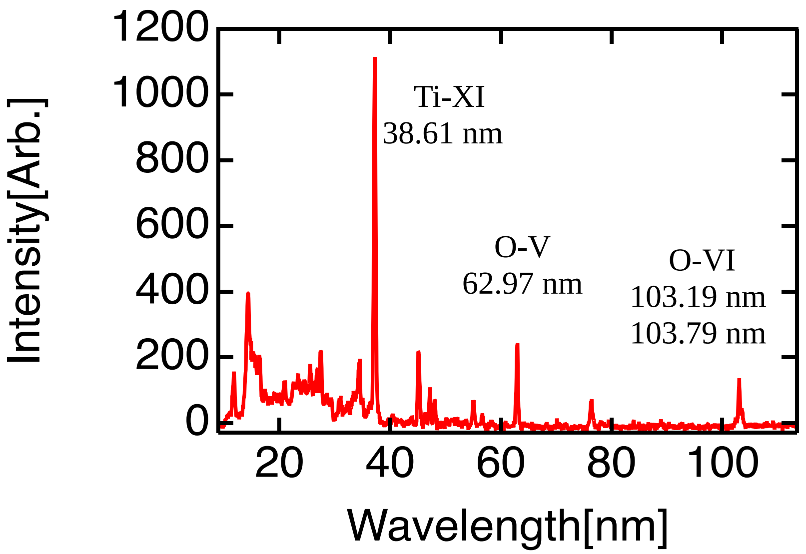
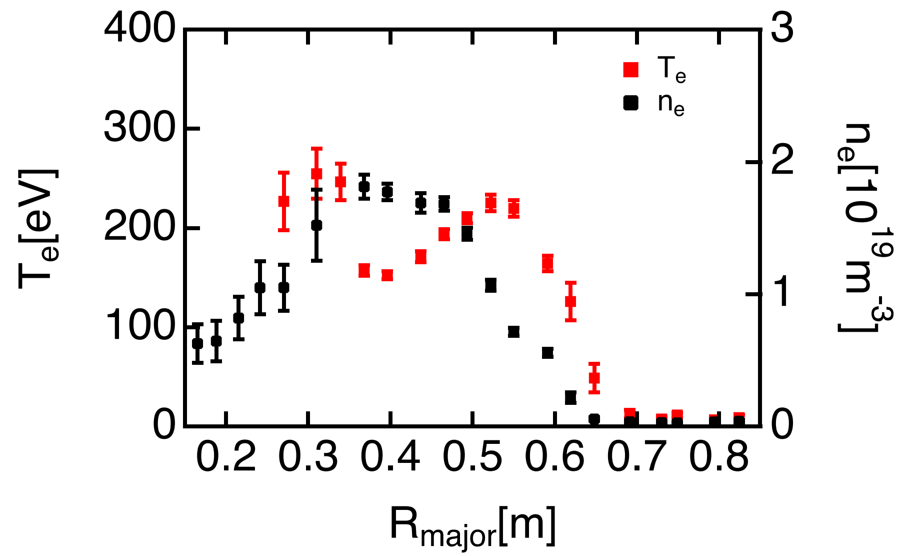
Impurity Baseline Measurements of OH H-mode Plasmas

- I_p flattop ~140 kA, H-mode
- Hollow T_e ~200 eV
  - Not in transport eq. (τ_e long relative to flattop) *
- P_{XUV} emission ~ 0.5 kW/m^3
- Bright Ti-XI line observed







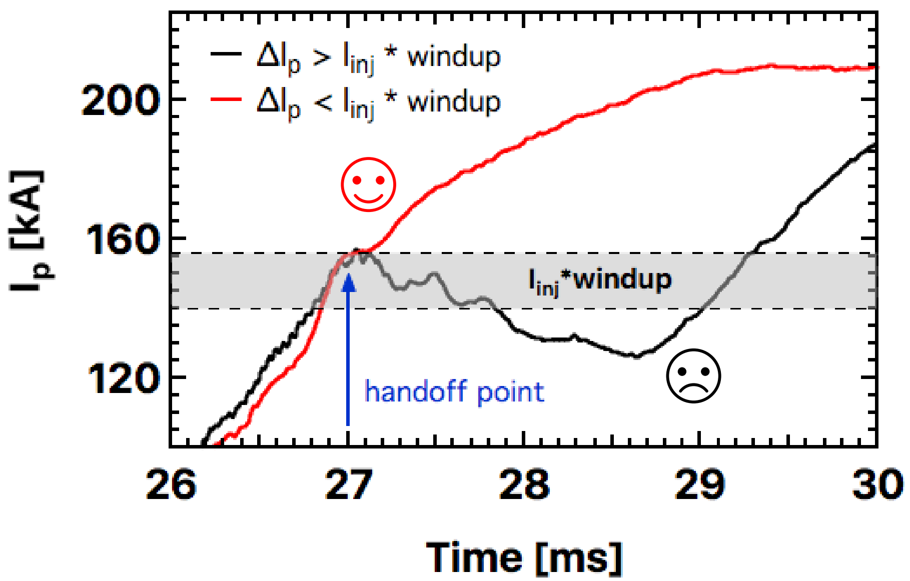
C. Rodriguez Sanchez GP10.00125

* *K.E. Thome et al., Nucl. Fusion* **57**, *022018 (2016)*

LFS & HFS LHI Successfully Couple to OH Current Drive

Definition of Handoff Success

- Minimum requirement: smooth $I_p(t)$
  - W_M conserved → $\Delta I_p \leq I_{inj} * windup$



- Desirable requirements
  - W_K conserved
  - Handoff plasma profiles compatible with sustainment-phase actuator

Recent Handoff Experiments Successful

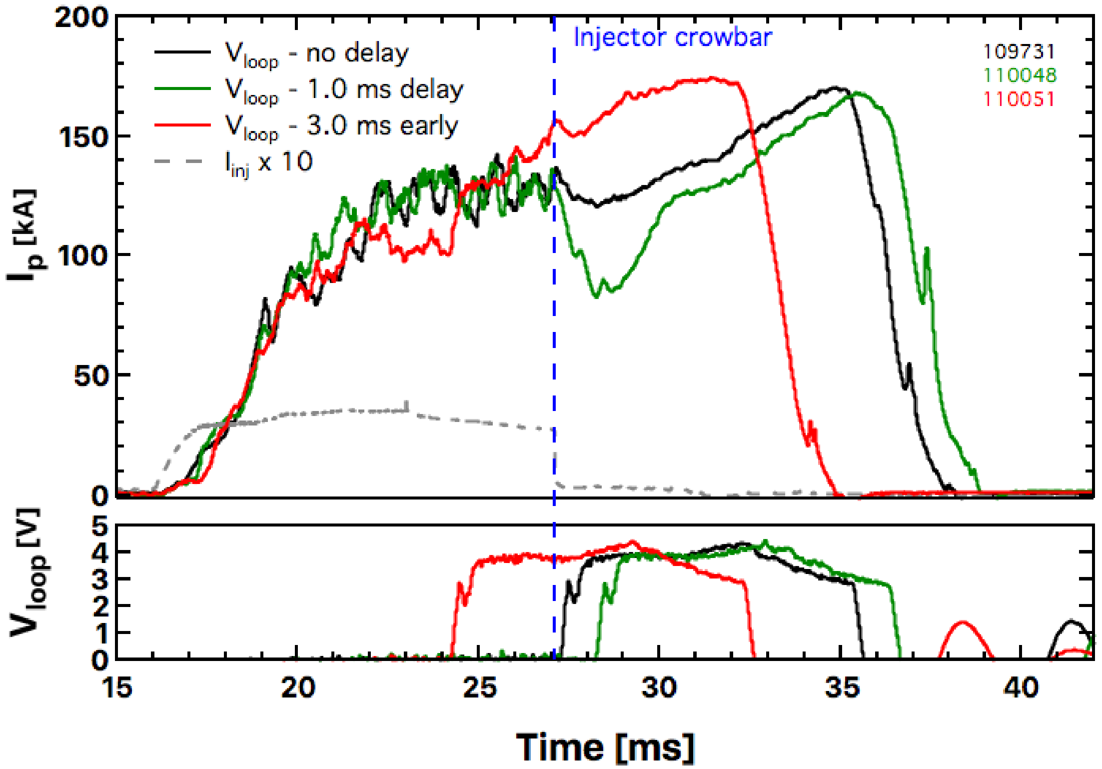
- Relatively insensitive to variations in V_{loop} timing
- LHI provides OH Flux savings
- Successful HFS-OH Handoff at high $\dot{I}_p$
- OH tearing modes stabilized by LHI $J(R)$ profile

Open questions from previous work addressed:

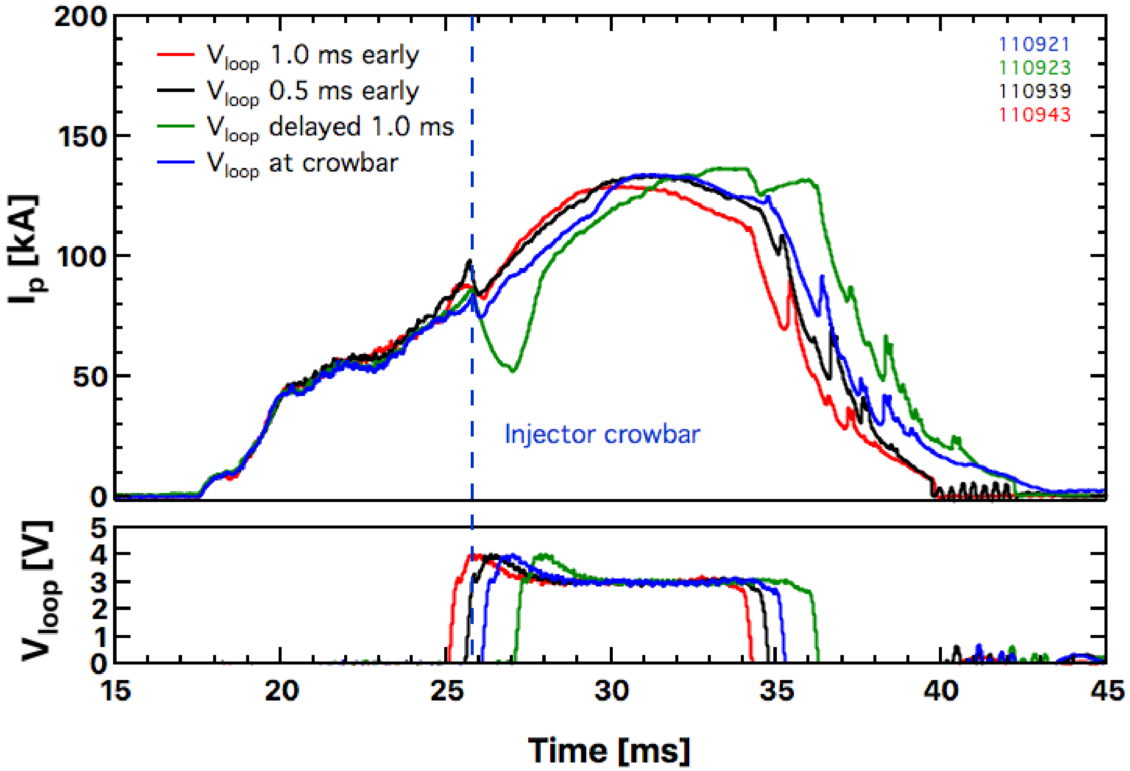
- Can HFS LHI plasmas couple to OH?
- Is there an $\dot{I}_p$ limit to successful coupling?
- Impurity content of LHI and resultant plasmas?

LHI-OH Handoffs Robust to Temporal Variations in OH V_{loop}

Examples of HFS-OH V_{loop} Timing Shifts



Examples of LFS-OH V_{loop} Timing Shifts

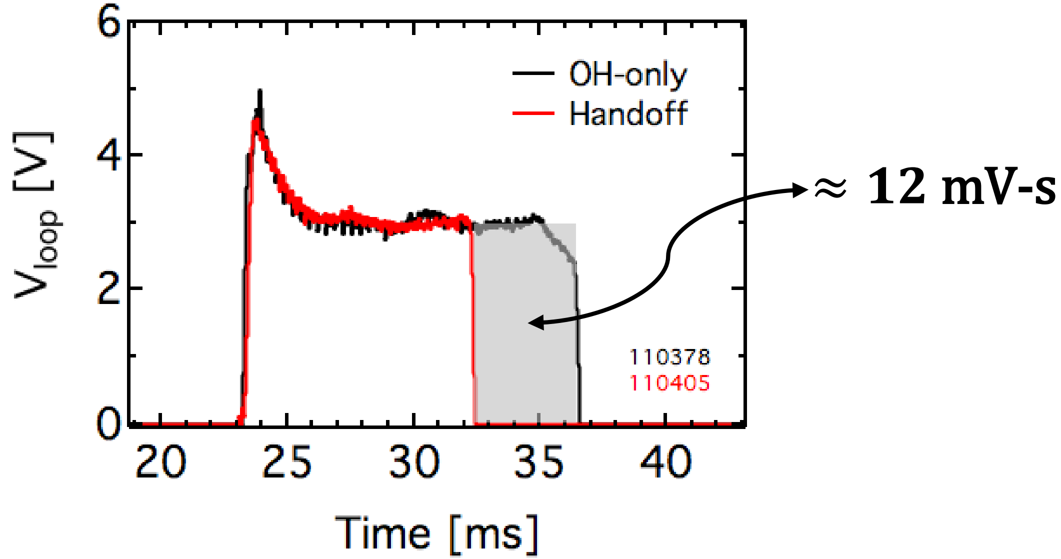


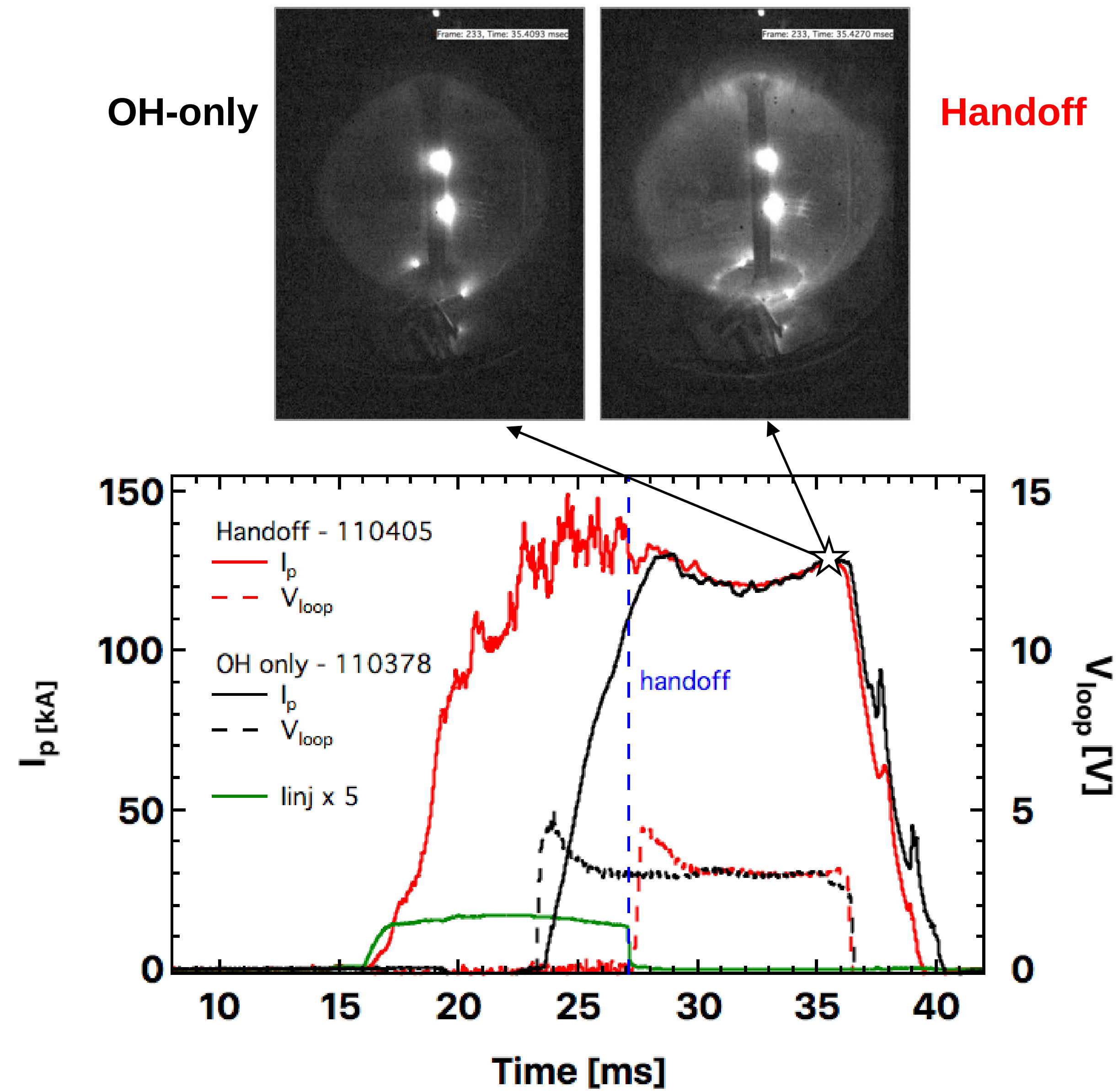
- Overlapping V_{loop} with LHI increased OH I_p
  - Demonstrates non-LHI CD can compliment LHI CD
- Realized same OH I_p when V_{loop} applied in the LHI decay phase, $I_{inj} = 0$

LHI Plasmas Provide OH Flux Savings For Sustainment

- Compare OH flux of LHI-OH handoff and OH-only
  - Matched $V_{loop}, I_p, \dot{I}_p$, size, shape & fueling
- LHI flux savings quantified by V-s difference required to drive equivalent OH-phase flattops
  - LHI: ≈ 29 mV-s
  - OH-only: ≈ 41 mV-s
  - Flux savings: ≈ 12 mV-s (30% of OH-only)

V_{loop} Comparison, Handoff Shifted 4 ms to Highlight Vs Difference





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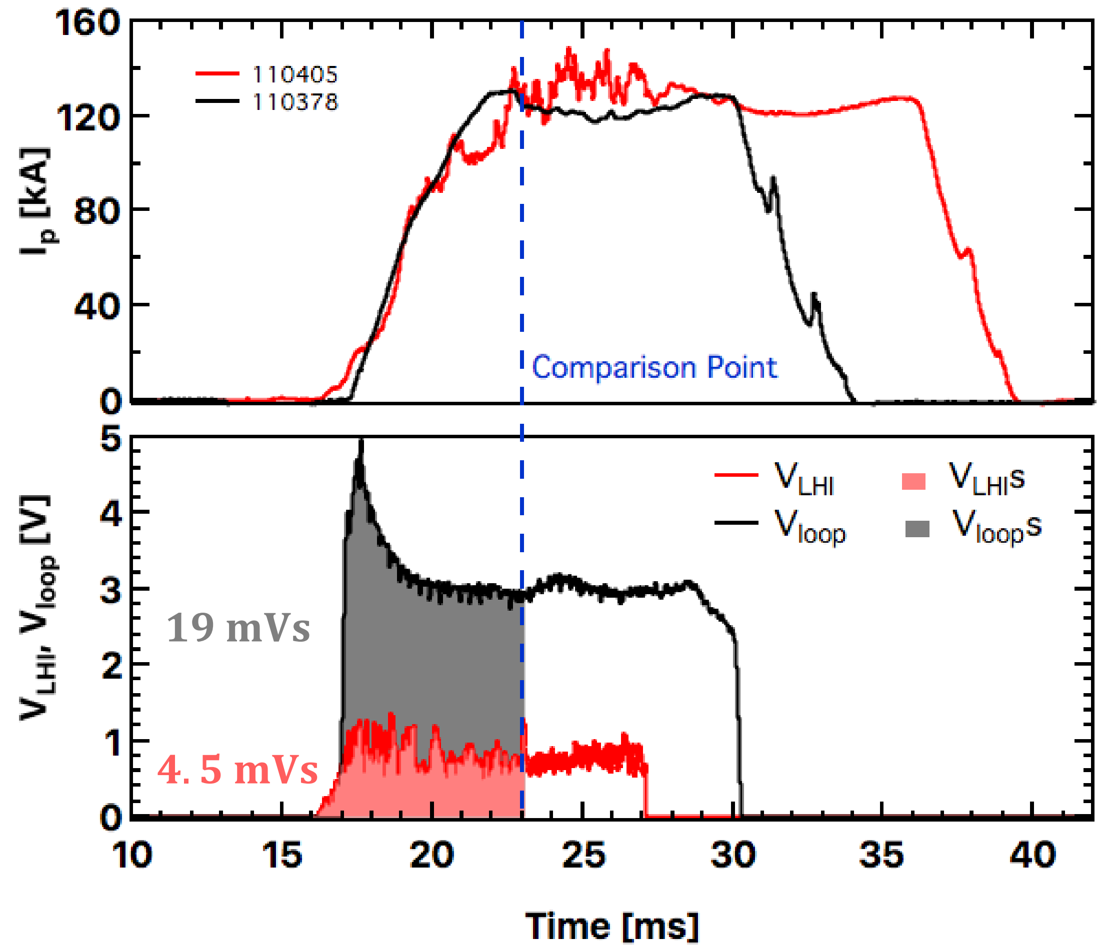
OH Flux Savings Motivates Analysis of LHI Flux Consumption Efficiency

- Alternate flux savings metric: how many V-s were saved by initiating the plasma with LHI startup?
  - OH required ~ 20 mV-s to reach flattop
- Data allows comparison to helicity balance model and calculation of equivalent LHI-driven V-s
  - Effective LHI loop voltage approximated with:*†

$$V_{LHI} \approx \frac{A_{inj} N_{inj} B_{t,inj}}{\Psi_t} V_{inj}, \quad \text{where} \quad \begin{aligned} A_{inj} &= \text{injector area} \\ N_{inj} &= \text{number of injectors} \\ B_{t,inj} &= \text{toroidal field at injector} \\ \Psi_t &= \text{toroidal flux} \\ V_{inj} &= \text{injector voltage} \end{aligned}$$

- LHI creates a comparable I_p flattop target with ~5 effective mV-s
  - **Improved flux consumption efficiency?**

Example Flux Comparison with OH-only* (110378) *Time Shifted

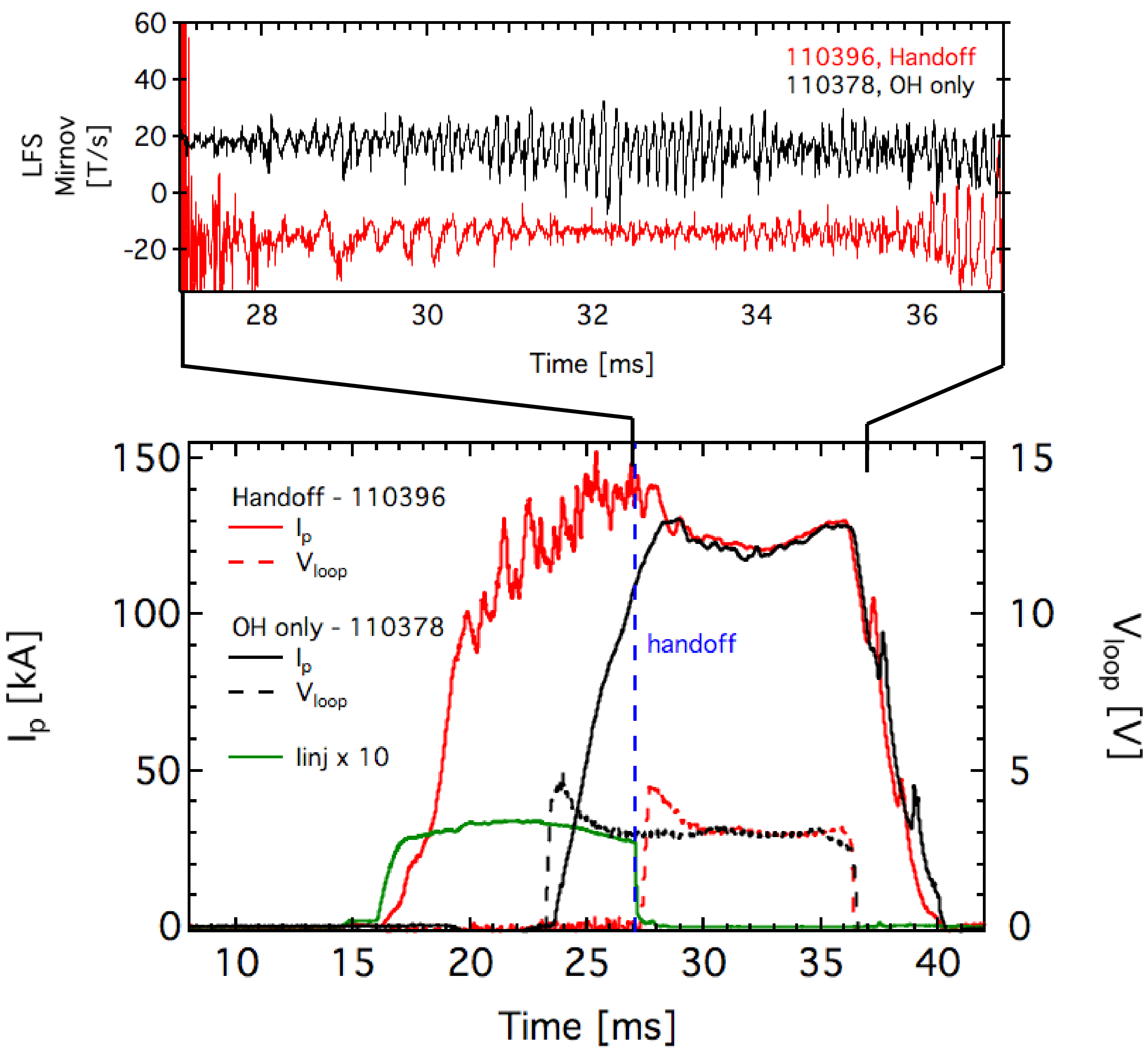


*Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)
†Battaglia *et al.*, Phys. Rev. Lett. **102**, 225003 (2009)

LHI-Produced Handoff Targets Have Favorable MHD Properties

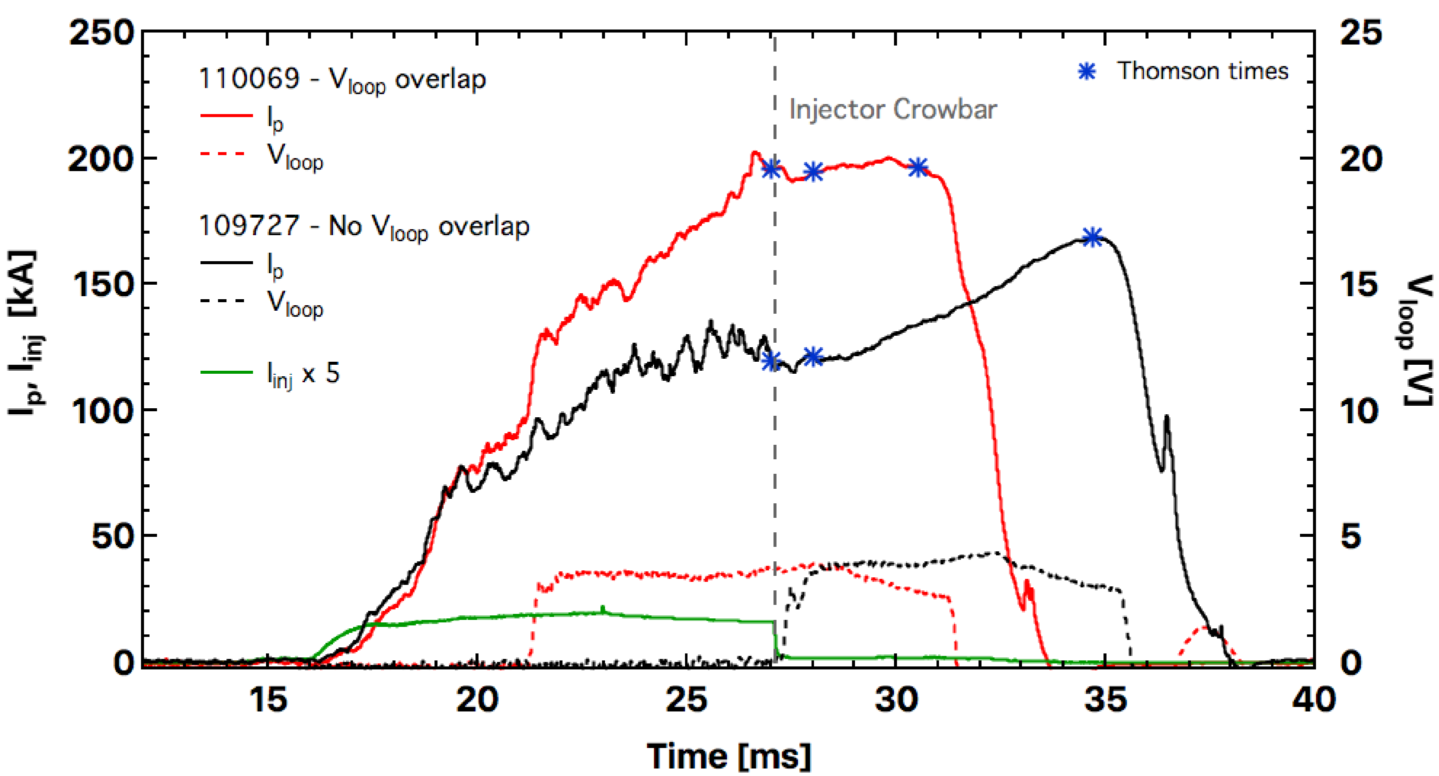
- Many OH discharges in PEGASUS limited by strong low-m, $n = 1$ tearing modes as $J(R)$ evolves
  - Corresponds to flat q profile with low magnetic shear
- Edge current drive of LHI establishes low ℓ_i targets
  - Hollow $J(R)$ can improve MHD stability
- OH vs LHI-OH scenarios show both effects
  - Pure OH: Saturated $n = 1$ activity
  - LHI-OH: Decaying $n = 1$ followed by quiescent period
- LHI-OH quiescent period terminated by n=1 mode
  - Interpretation: $J(R)$ growing more peaked due to OH drive
  - In principle, LHI-produced $J(R)$ could be frozen via P_{aux}

OH: Saturated n=1 mode
LHI-OH: Stable n=1 mode and quiescent period

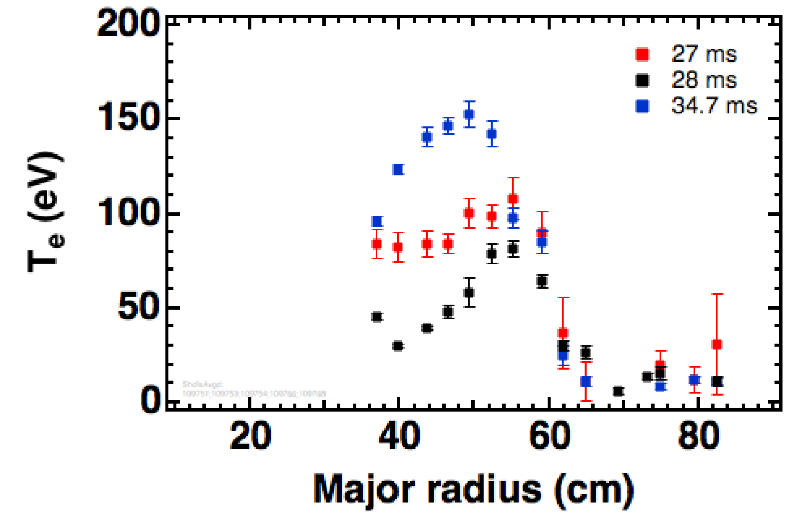


Evolution of T_e Across Handoff Sensitive to V_{loop} Timing

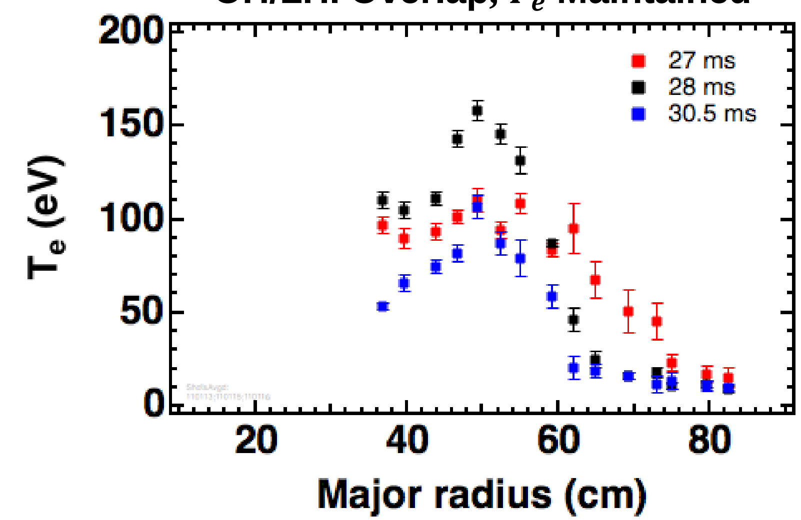
- Applying V_{loop} at termination of LHI → central T_e decreases
  - No loss of I_p, n_e; T_e drops ~ 50% in 1 ms
- Applying V_{loop} before LHI end → $T_e(R)$ maintained after handoff
- T_e evolves on typical OH timescales after LHI handoff to OH



No OH/LHI Overlap, T_e Decreases



OH/LHI Overlap, T_e Maintained



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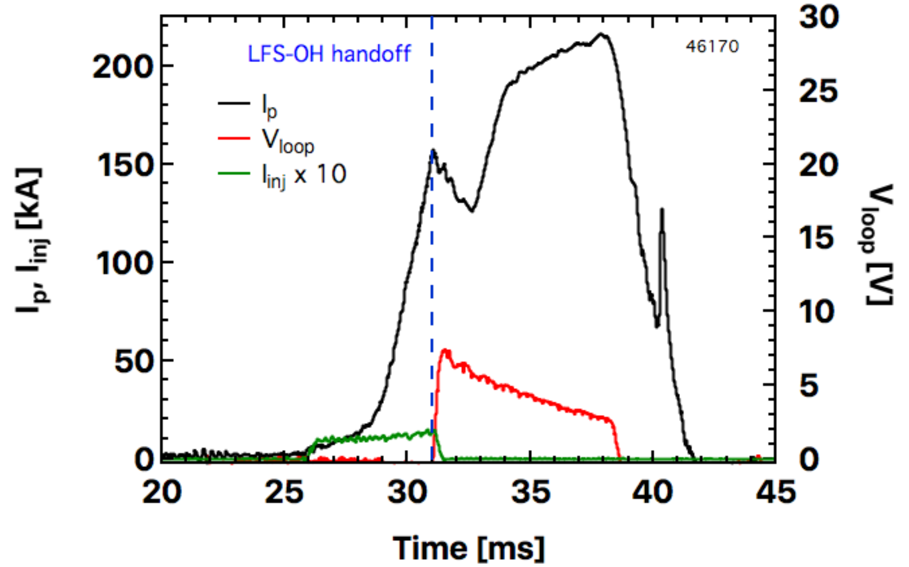
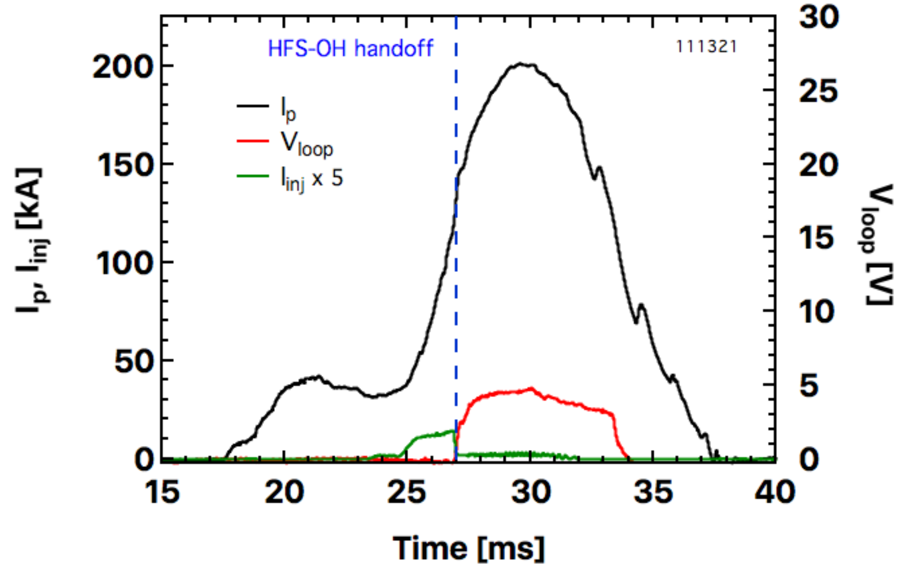
Unexpected Success of HFS-OH Handoffs at High $\dot{I}_p$

- Previous work identified $\dot{I}_p$ as a proxy for ℓ_i, $J(R)$, and as a potential predictor of LHI-OH coupling success
  - High $\dot{I}_p$ → lower ℓ_i, more hollow $J(R)$ → poor OH coupling
  - Low $\dot{I}_p$ → higher ℓ_i, less hollow $J(R)$ → good OH coupling
- Recent HFS-OH handoffs successful at high $\dot{I}_p > 100\,\frac{\text{MA}}{\text{s}}$
  - Eliminates $\dot{I}_p$ as a simple predictor of handoff success
- Higher $\dot{I}_p$ may provide desireable $J(R)$ in LHI target plasmas
  - Profiles could be “frozen-in” with sustainment CD technique
- Equilibrium reconstructions are underway to verify expected lower ℓ_i and hollow $J(R)$ at higher $\dot{I}_p$

Poor coupling at $\dot{I}_p \approx 80\ \mathbf{MA/s}$



Good coupling at $\dot{I}_p \approx 150\ \mathbf{MA/s}$



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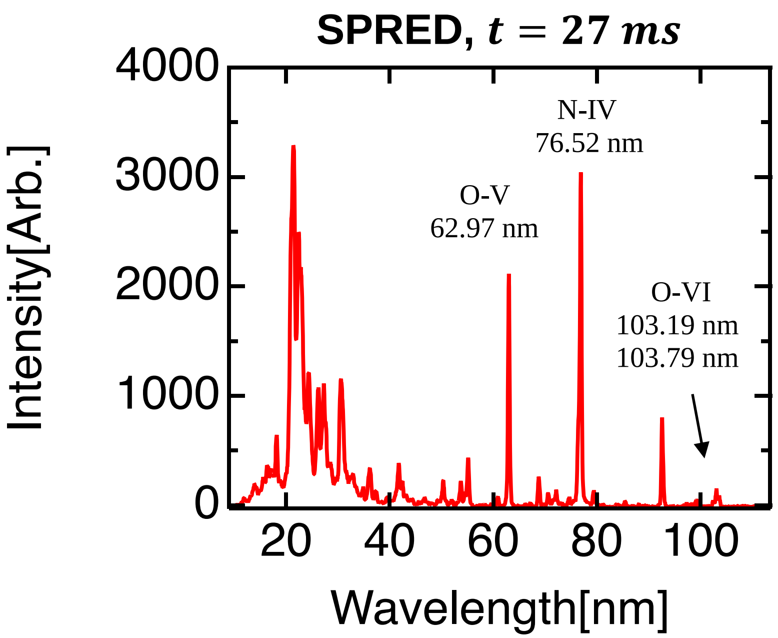
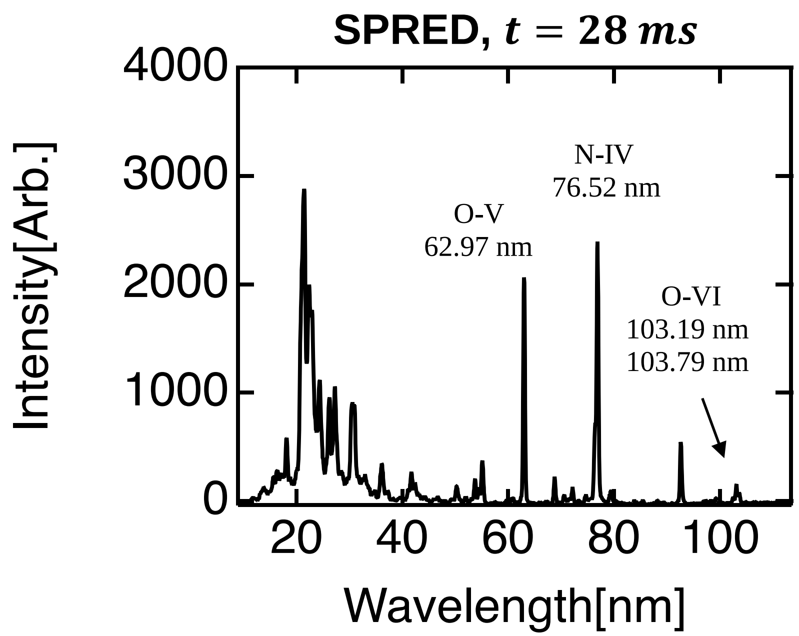
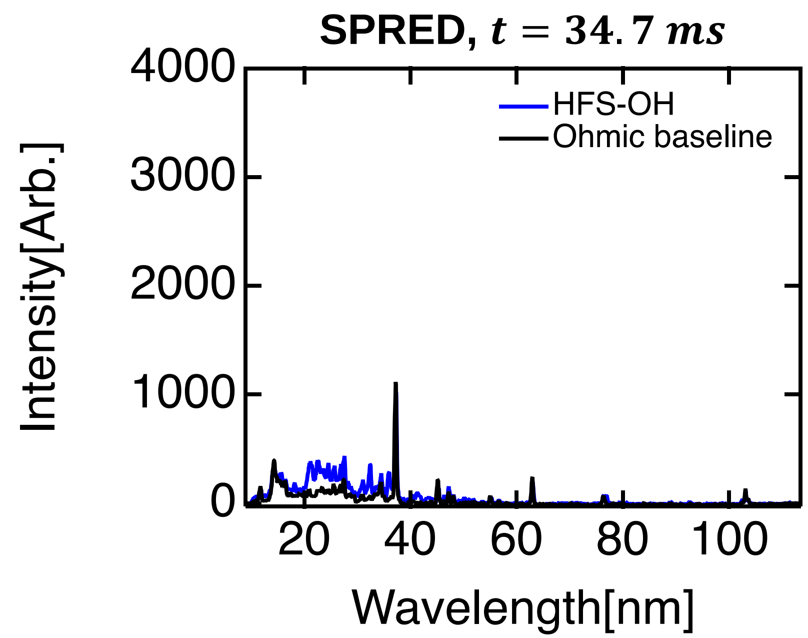
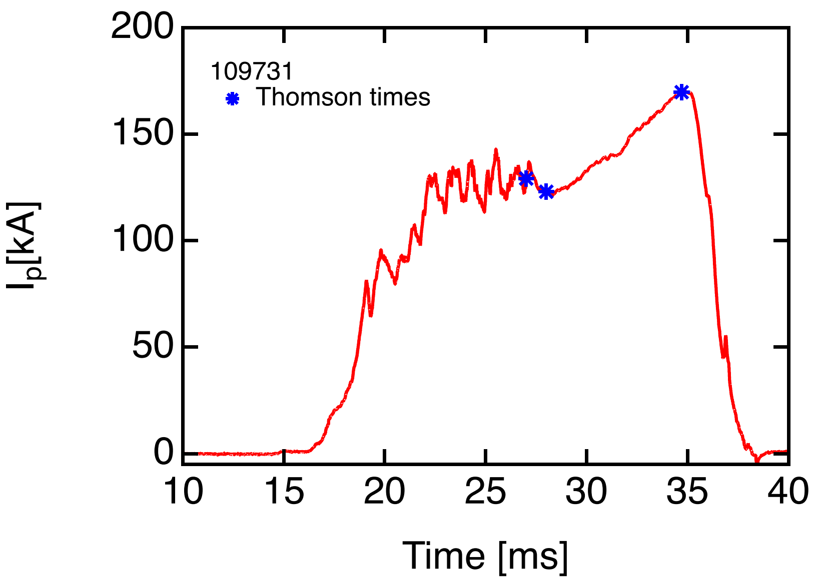
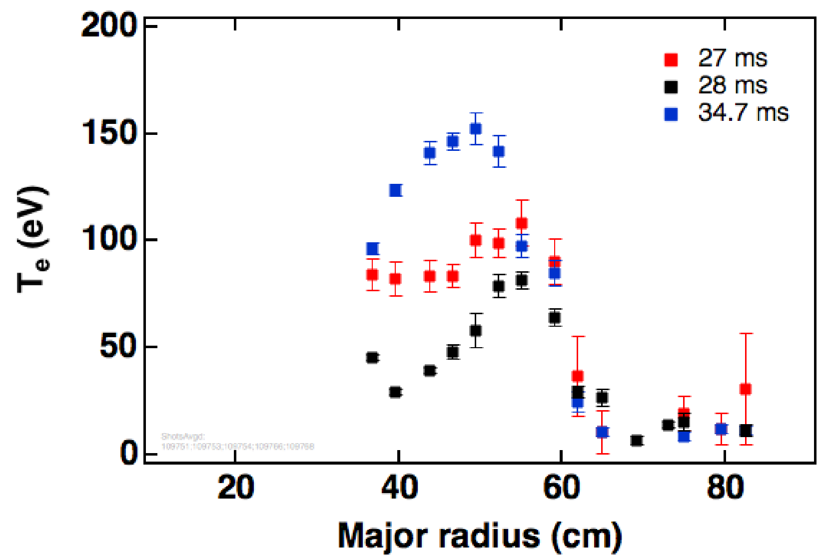
OH Impurity Charge State Balance in Handoff Similar to OH Baseline











C. Rodriguez Sanchez, 61st APS-DPP 2019

C. Rodriguez Sanchez GP10.00125

Takeaways from LHI-OH Startup and Future Work

Takeaways

- LHI successfully couples to OH CD
  - Robust to variations in handoff timing
  - HFS-OH handoff successful at high $\dot{I}_p$
  - Handoff OH impurities similar to OH baseline
- Demonstrated OH flux savings
- Favorable initial sustainment-phase $J(R)$ inferred from improved tearing stability of LHI-OH targets

Future Work

- Interpretive equilibrium analysis
  - Compare OH, LHI-OH profile structures
  - Test low ℓ_i hypothesis for LHI-OH scenarios with stabilized $n = 1$ activity
- Assess effective flux consumption of LHI plasmas with respect to OH startup

OH Operations Restored for Diagnosing LHI Plasmas

Documentation of OH-only Plasmas for Comparison to LHI

LHI Robustly Couples to OH CD

Features of the LHI-OH Handoff

Reprints

Reprints of this and other PEGASUS presentations are available online at

http://pegasus.ep.wisc.edu/Technical_Reports