Ohmic Sustainment of Local Helicity Injection Initiated Plasmas on the PEGASUS ST

C. Pierren,

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

University of Wisconsin-Madison

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PEGASUS
Toroidal Experiment

Ohmic Sustainment of Local Helicity Injection Initiated Plasmas on the PEGASUS ST

Local helicity injection (LHI) is being developed on the PEGASUS ST for non-solenoidal tokamak startup. The startup viability of LHI-initiated plasmas will depend upon how readily they efficiently handoff to subsequent heating and current drive (CD) sustainment phases. Final experiments on the Pegasus ST tested handoff to sustainment using the Ohmic solenoid (OH). LHI-initiated plasmas were found to robustly couple to OH CD, even at high I_p ramp rates >100 MA s^{-1}. The relative impurity content during LHI appeared higher than comparable OH-only discharges; however, these impurities appeared to quickly decay to OH-only like levels during the OH phase of handoff scenarios. Magnetic energy was readily conserved across the LHI-OH handoff as evidenced by minimal drops in I_p. The LHI target's $j(R)$ profile appears to be MHD favorable as the onset of internal low $m, n = 1$ tearing modes typical of PEGASUS OH discharges was mitigated with LHI startup. Unique high $\beta_T \sim 1$ plasmas at extremely low B_T could not be Ohmically sustained because they suffered from an edge kink instability that was presumably stabilized by the LHI edge current streams. Reconstructions and stability analyses are underway to further explore the MHD stability properties of LHI plasmas.

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Layout Slide (Include for Posters)

12:1 scale Panel size: 8’ x 4’

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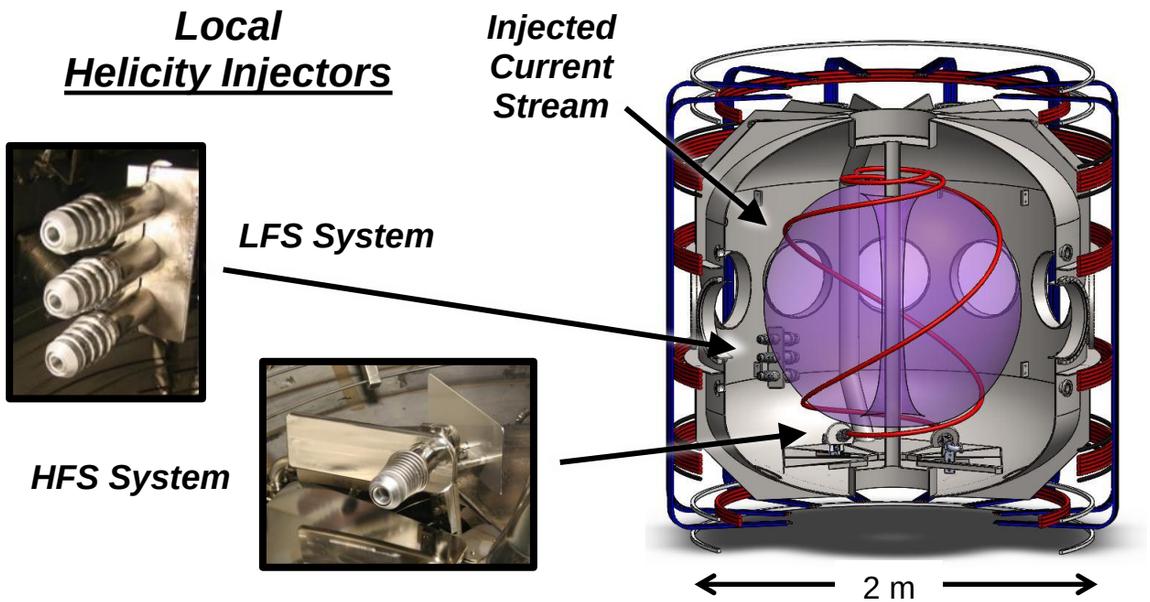
Ohmic Sustainment of Local Helicity Injection Initiated Plasmas on the PEGASUS ST

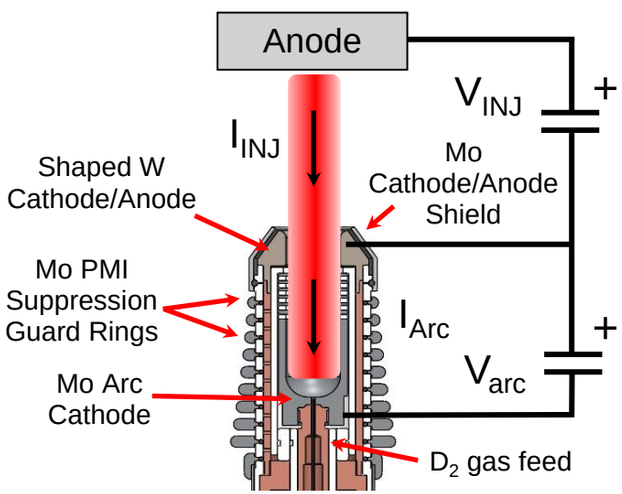
LHI Promising for ST Non-inductive Startup	LHI Robustly Couples to OH CD	Features of the LHI-OH Handoff	Summary	Column 5	Column 6
Local Helicity Injection (LHI) is a Promising Solenoid-free Startup Technique	LFS & HFS LHI Targets Successfully Couple to OH Current Drive	LHI-Produced Handoff Targets Have Favorable MHD Properties	Takeaways of LHI-OH Handoff Experiments & Future Work	Slide 1	Slide 1
ST path motivates the development of solenoid-free startup	LHI-OH Handoffs Robust to Temporal Variations in OH V_{loop}	High Frequency LHI MHD Activity Decays to OH Levels After $I_{inj} \rightarrow 0$	Slide 2	Slide 2	Slide 2
Viable Solenoid-free Targets Meet Requirements for Sustainment with Tokamak CD Systems	LHI Plasmas Provide OH Flux Savings	T_e Evolution Improved with Simultaneous LHI and OH CD	Slide 3	Slide 3	Slide 3
NSTX-U: Direct Coupling of LHI Target to NBI-CD?	Simultaneous LHI and OH CD Achieved Record PEGASUS I_p	Handoff OH-phase Impurity Emissions Similar to OH-only Spectra	Slide 4	Slide 4	Slide 4

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LHI is a Promising Non-inductive Startup Technique

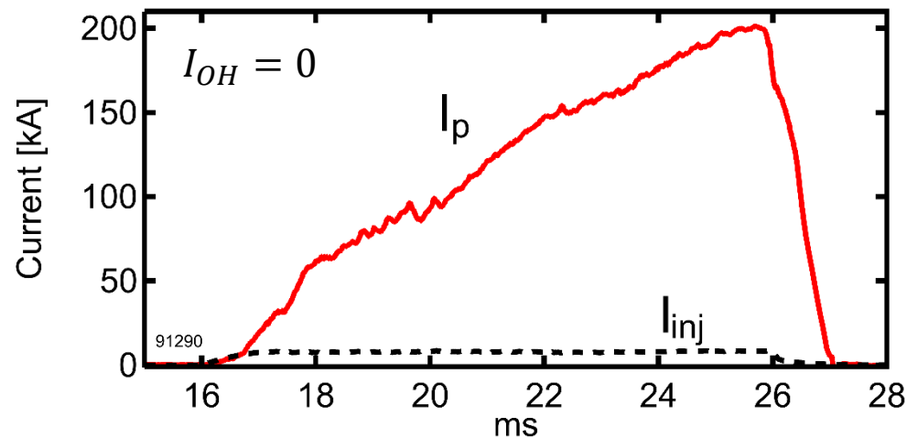
Local Helicity Injection (LHI) is a Promising Solenoid-free Startup Technique





PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.25 MA	$\sum I_{inj}$	≤ 8 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 1.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R_0	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

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



- Current injected at plasma boundary
- Relaxation via helicity-conserving instabilities
- I_p limited by Taylor relaxation & helicity balance
- Hardware retractable after startup

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

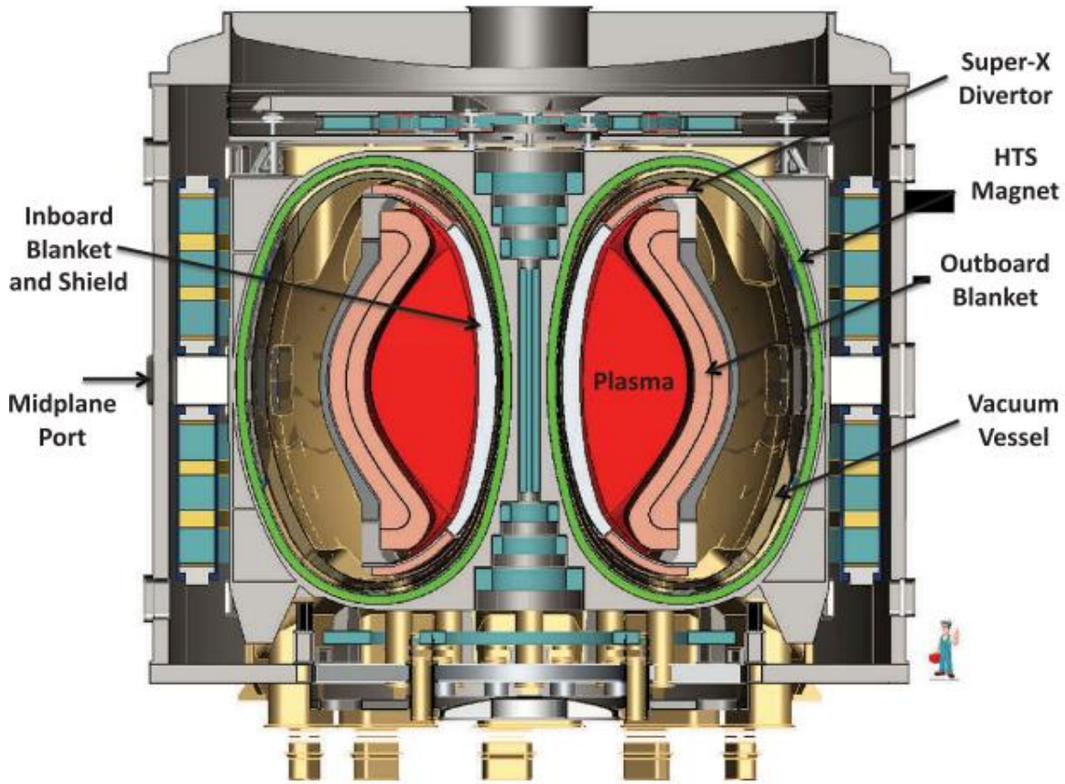
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ST Path Motivates the Development of Solenoid-free Startup

- Reduced aspect ratio limits core size
- Elimination of ohmic solenoid (OH) frees core space critically needed for*:
  - Neutron shielding of TF conductors
  - Tritium breeding blanket
- Removing OH also simplifies engineering design and reduces facility cost
- Solenoid-free startup provides target plasma for sustainment CD, e.g. RF, NBI, bootstrap

Proposed ST HTS-FNSF Design*



*L. El-Guebaly, et al., 2017, Fusion Science and Technology, 72:3, 354-361, DOI: 10.1080/15361055.2017.1333864

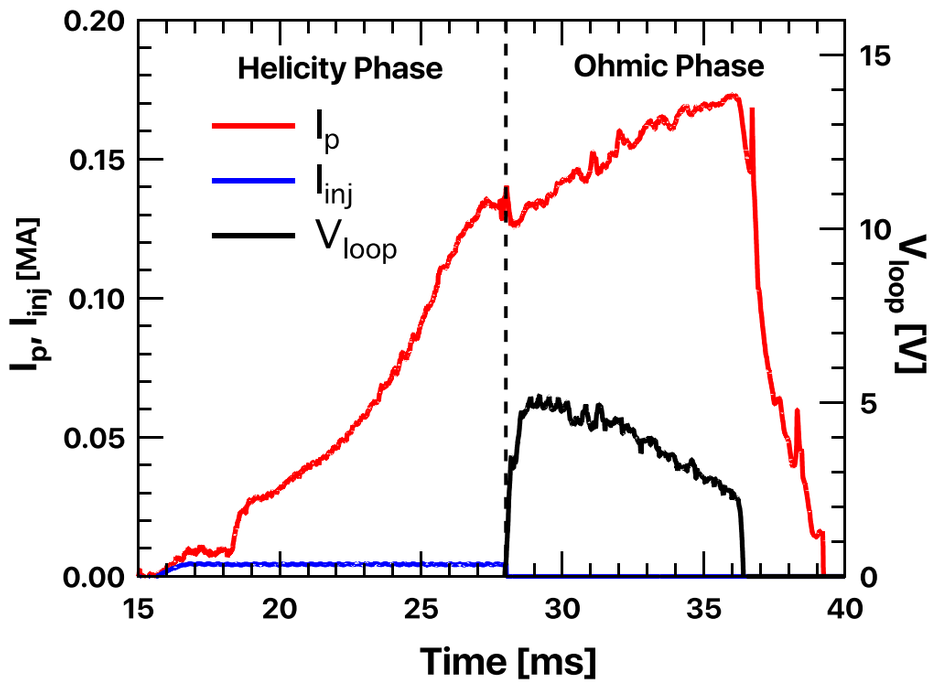
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Viable Solenoid-free Targets Meet Requirements for Sustainment with Tokamak CD Systems

Desirable Target Properties

- Conservable poloidal flux and I_p across handoff
  - Reduces requirements on startup system
- Target profiles compatible with sustainment CD
  - e.g. bootstrap, RF, NBI, or combination
- MHD stable
  - Stability can be maintained with sustainment CD

Sustainment with OH-CD to Evaluate LHI Targets



*K.E. Thome et al., 2017 Nucl. Fusion **57** 022018*

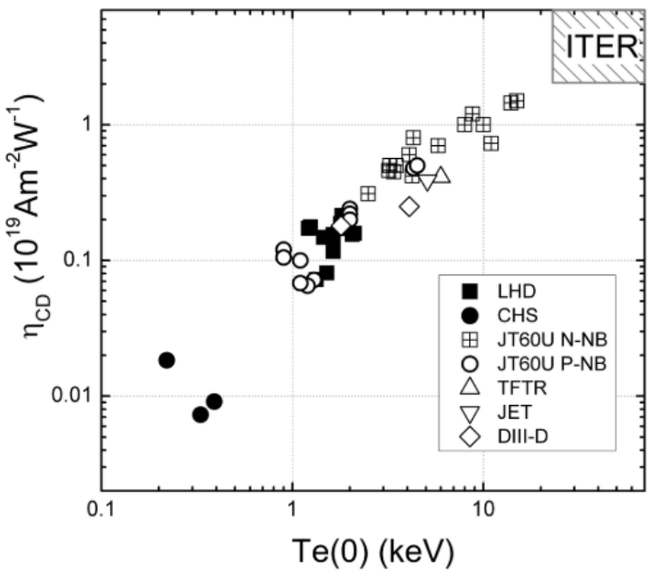
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NSTX-U & Beyond: Direct Coupling of LHI Targets to NBI-CD?

Requirements for NBI-CD Compatibility

- Sufficient I_p to confine fast ions
- Minimum n_e to prevent shine-thru
- Minimum T_e for efficient CD

NBI-CD Efficiency Improves as T_e Increased



Potential LHI to NBI-CD Coupling Scenarios

1. LHI directly provides NBI-CD target:
   - *$I_p \sim 0.4 - 1$ MA, $n_e \sim 2 * 10^{19}\mathrm{m}^{-3}$, $T_e \sim 1$ keV
   - Terminate LHI and sustain/ramp I_p with NBI-CD
2. LHI T_e too low: simultaneous LHI + NBI
   - No intrinsic n_e limit in LHI: $n_e > n_{shine-thru}$
   - LHI maintains I_p while NBI heats core electrons
   - End LHI when T_e sufficient to sustain/ramp I_p with NBI-CD

- Scenarios to be explored with M3D-C^1 simulations
- PEGASUS-III: test LHI at higher B_T and test synergy with RF heating & CD
  - See M.D. Nornberg ZP06.1

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F.M. Poli et al., 2015 Nucl. Fusion **55 123011*

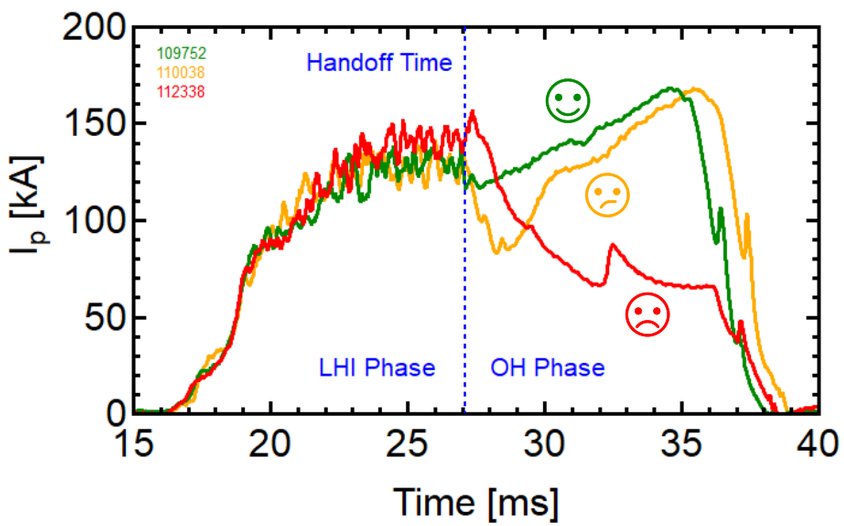
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LHI Robustly Couples to OH CD

LFS & HFS LHI Targets Successfully Couple to OH Current Drive

Definition of Handoff Success

- LHI I_p sustained and/or ramped w/ OH-CD
  - Minimal ΔI_p desirable



- Other desirable features:
  - MHD stable
  - W_K conserved
  - Profiles compatible with sustainment CD
  - Low impurity content

Features of Successful PEGASUS Handoffs

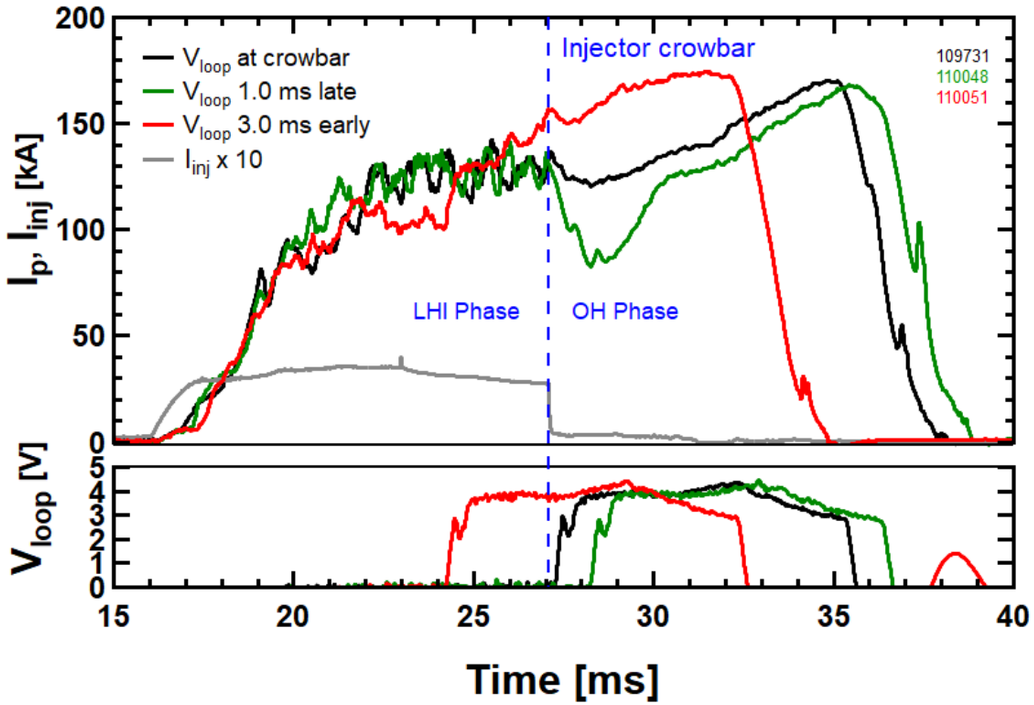
- OH tearing modes stabilized by LHI $J(R)$ profile
- LHI compatible with simultaneous OH-CD
  - Achieved higher I_p and improved T_e evolution
- High frequency LHI MHD decays to OH-levels
- LHI poloidal flux readily conserved → low ΔI_p
- LHI impurity content compatible with OH-CD
- Relatively insensitive to variations in V_{loop} timing

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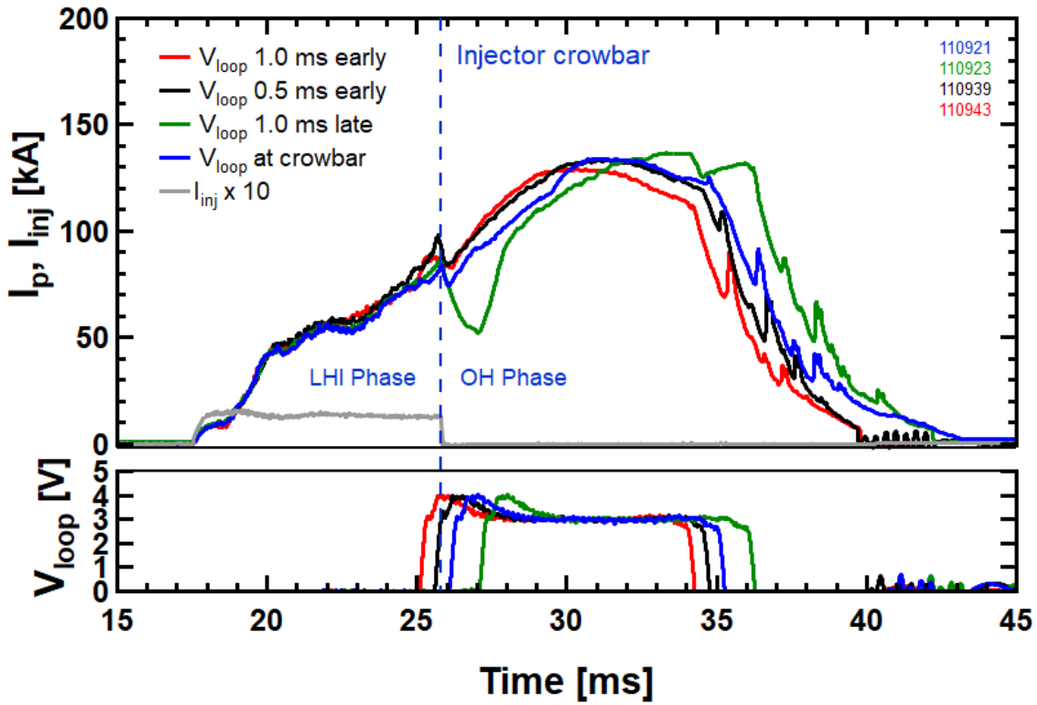
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LHI-OH Handoffs Robust to Temporal Variations in OH V_{loop}

Examples of HFS-OH V_{loop} Timing Shifts



Examples of LFS-OH V_{loop} Timing Shifts



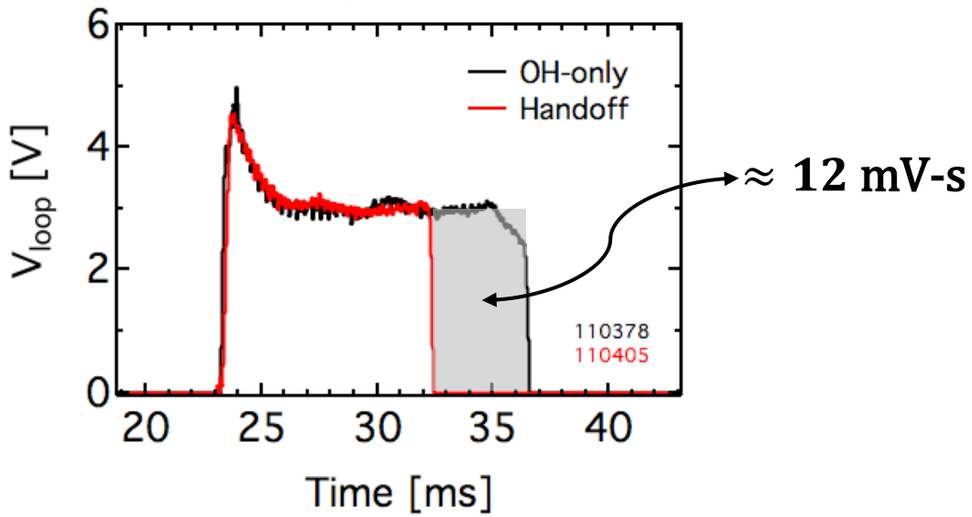
- Overlapping V_{loop} with LHI increased OH I_p
  - Demonstrates non-LHI CD can compliment LHI CD
- Realized same OH I_p when V_{loop} applied in the LHI decay phase, $I_{inj} = 0$

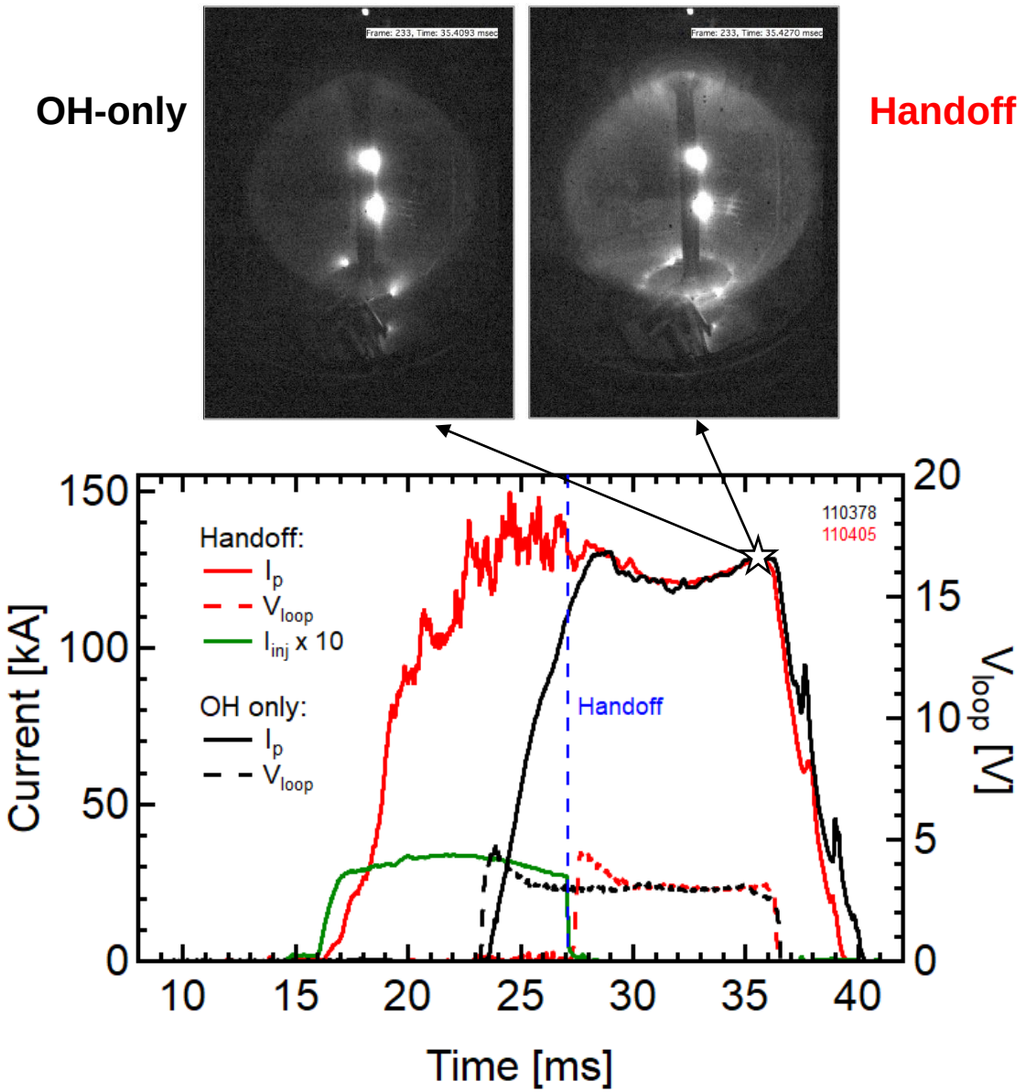
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LHI Plasmas Provide OH Flux Savings

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

V_{loop} comparison with handoff shifted 4 ms to highlight flux difference





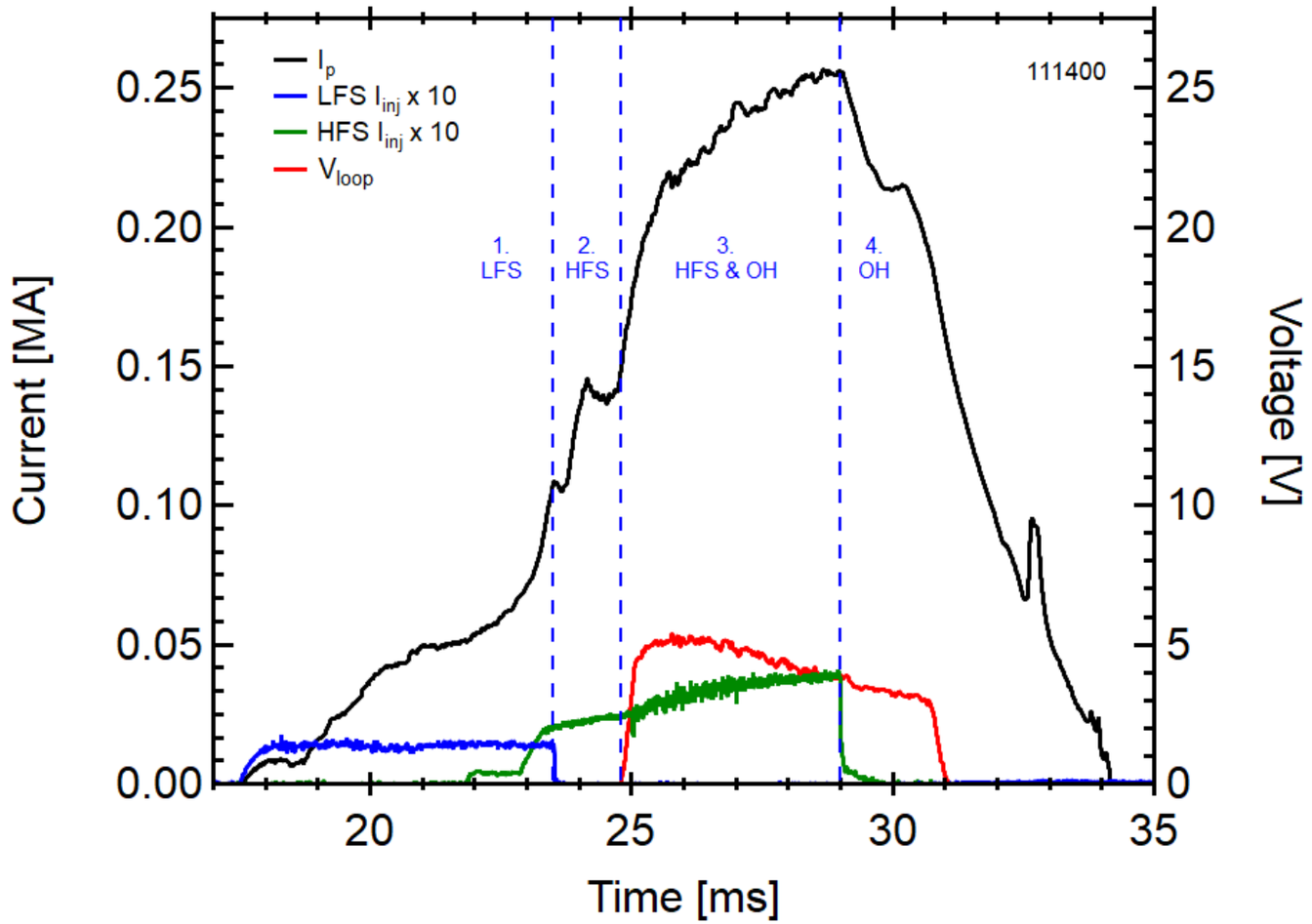
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Simultaneous LHI and OH CD Drove Record PEGASUS I_p

- Leveraged compatibility of LHI with simultaneous OH-CD
- Multi-stage discharge combined all CD systems available on PEGASUS:

1. Discharge initiated with LFS-LHI
2. LFS-LHI target coupled to and grown with HFS-LHI
3. HFS-LHI and OH simultaneously drive to an $I_p = 0.25$ MA.
4. Minimal OH flux available for continued sustainment

Record I_p achieved with HFS-LHI and OH co-drive with different CD regions identified



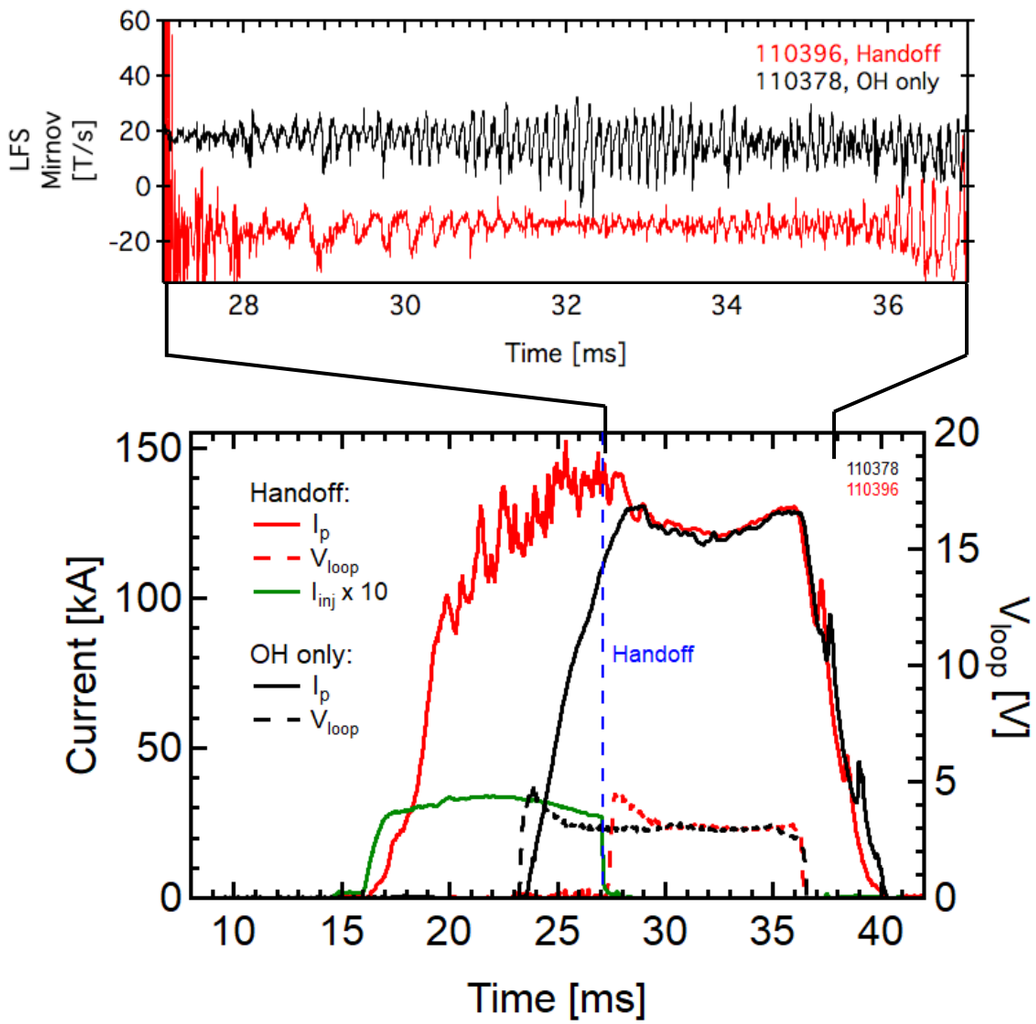
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Features of the LHI-OH Handoff

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}
- Estimated resistive diffusion time: $\tau_R = \frac{\mu_0 a^2}{\eta} < 12$ ms

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



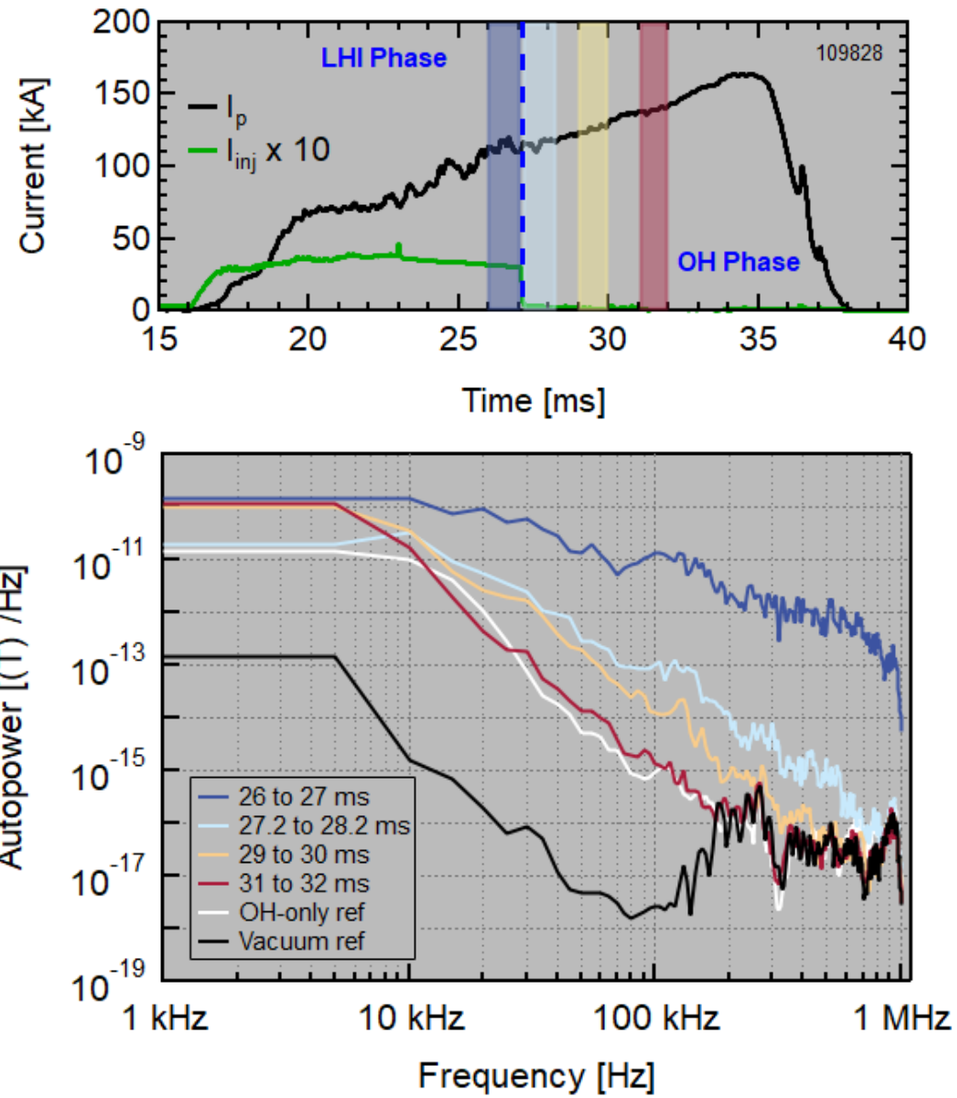
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High Frequency LHI MHD Activity Decays to OH-only Levels After $I_{inj} \rightarrow 0$

- $\tilde{B}$ measured with insertable 3D $\dot{B}$ probe at plasma midplane
- Measurement taken ~ 5 cm inside kinetic edge
- $\tilde{B}_r$ autopower across LHI-OH handoff decays to typical OH levels after $I_{inj} \rightarrow 0$
- Decay to typical OH $\tilde{B}$ levels suggests flux surfaces becoming OH-like after $I_{inj} \rightarrow 0$
- Flux surface healing at LHI termination predicted by NIMROD simulations*

J.B. O'Bryan & C.R. Sovinec, Plasma Phys. Control. Fusion **56 064005 (2018)*

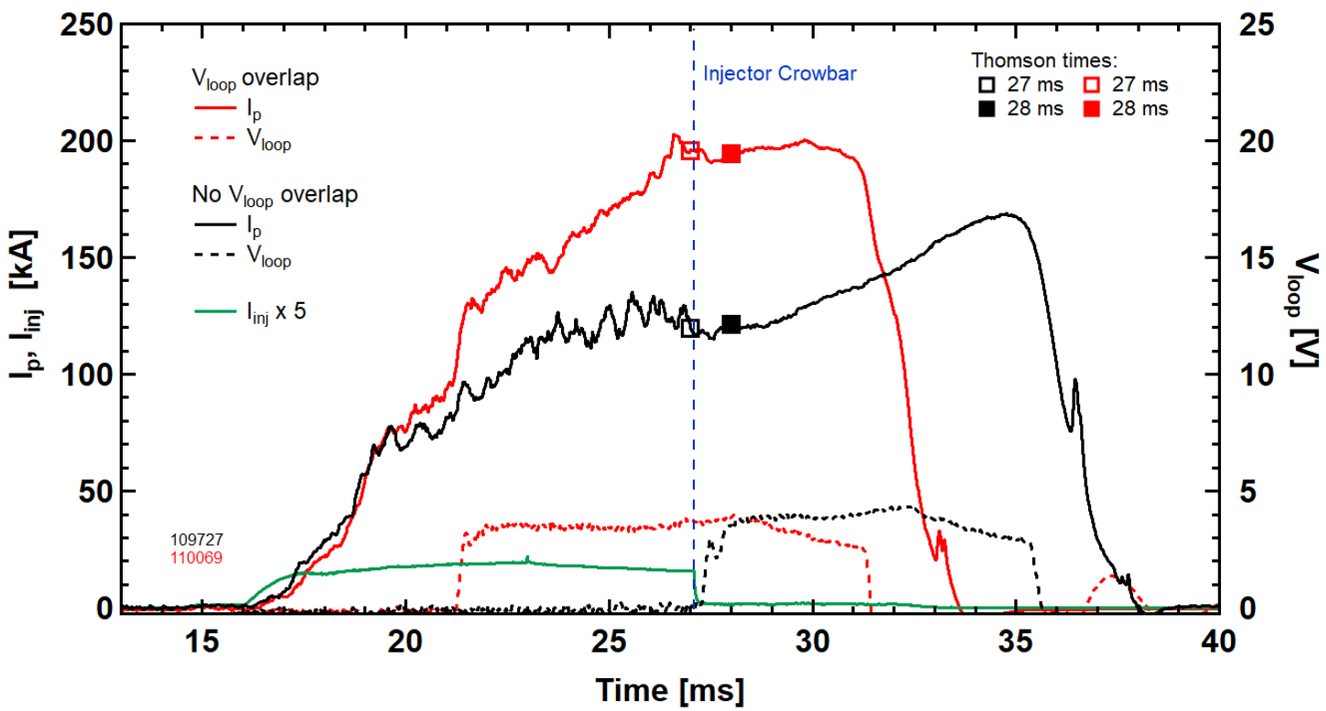
I_p trace with autopower windows highlighted and $\tilde{B}_r$ autopower spectra showing decay to OH-levels



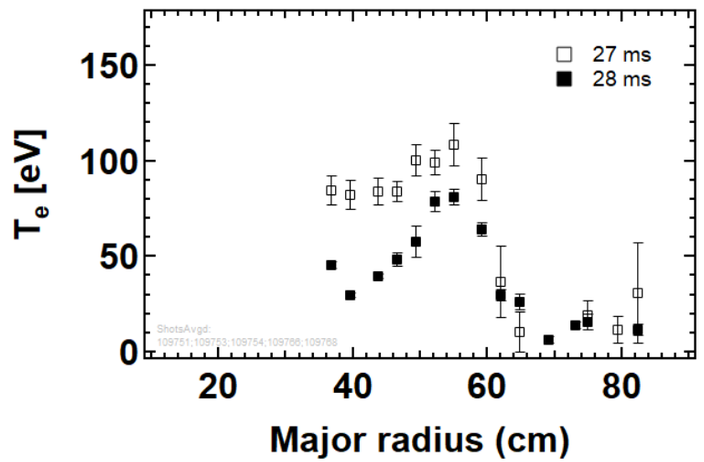
See N.J. Richner ZP06.3

T_e Evolution Improved with Simultaneous LHI and OH CD

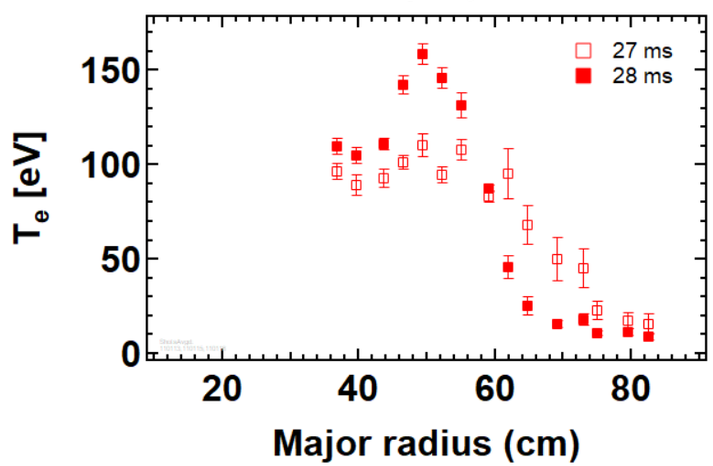
- Applying V_{loop} at termination of LHI → central T_e decreases
  - No loss of I_p, n_e; T_e drops ~ 50% in 1 ms
- Applying V_{loop} before LHI end → $T_e(R)$ maintained after handoff
- Results suggest LHI potentially compatible with auxilary heating



No LHI/OH overlap, T_e decreases

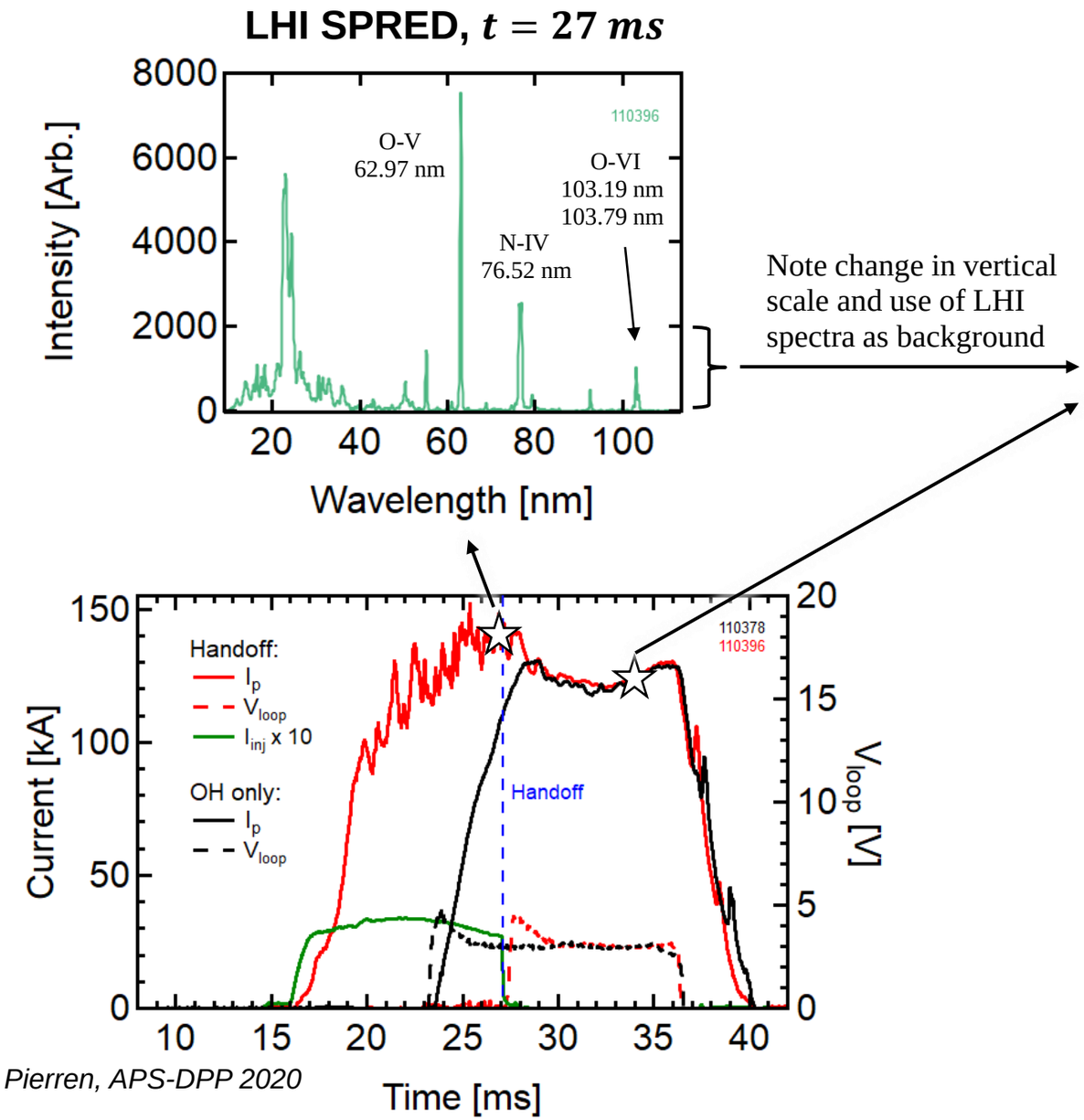


LHI/OH overlap, T_e maintained

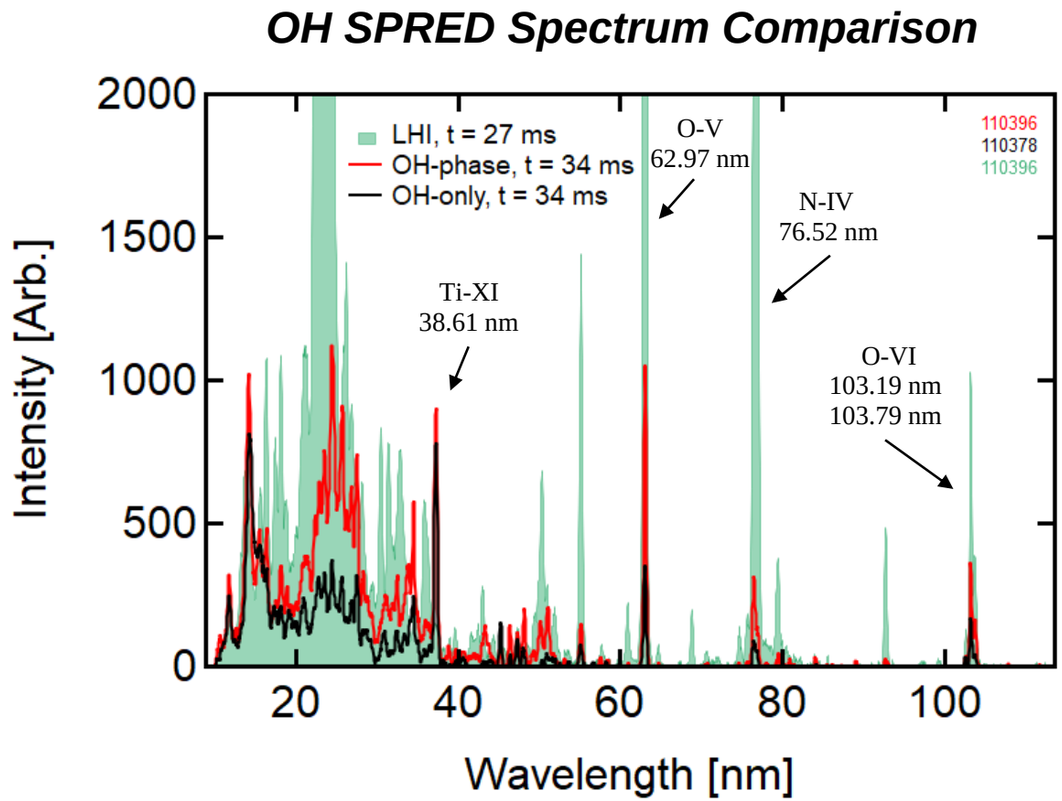


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Handoff OH-phase Impurity Emissions Similar to OH-only Spectra



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- LHI emission profiles relax to typical OH levels after $I_{inj} \rightarrow 0$
- LHI impurity content sufficiently low for OH-CD sustainment/ramping of LHI targets

Summary

Takeaways from LHI-to-OH Handoffs and Future Work

Takeaways

- LHI successfully couples to OH CD
  - Poloidal flux readily conserved
  - Robust to variations in handoff timing
  - LHI compatible with OH co-drive
- Demonstrated OH flux savings
- High frequency MHD activity associated with LHI decays to typical OH levels after $I_{inj} \rightarrow 0$
- Favorable initial sustainment-phase $J(R)$ inferred from improved tearing stability of LHI-OH targets
- LHI impurity content not problematic for OH-CD

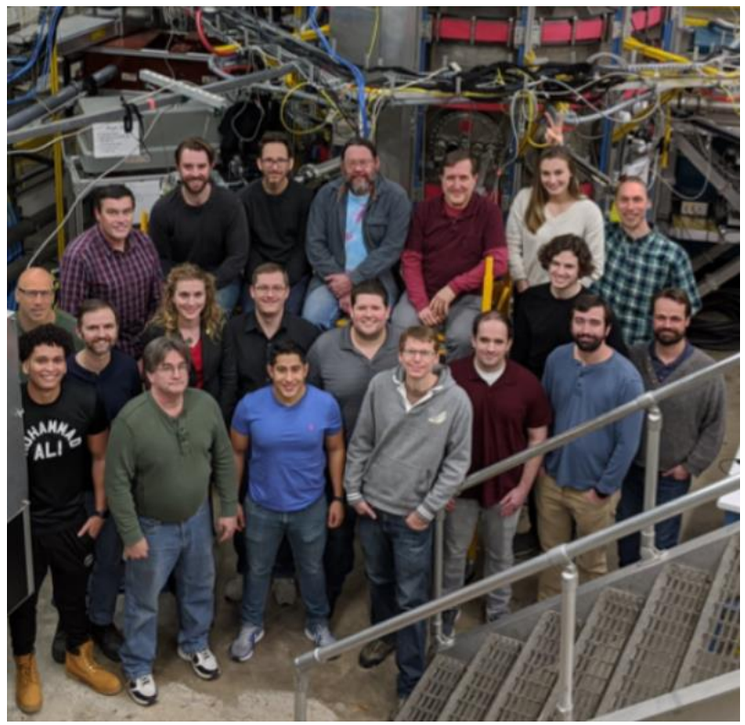
Future Work

- Continued characterization of $\tilde{B}(t)$ and equilibrium $B(t)$ evolution across handoff
- Interpretive equilibrium analysis:
  - Compare OH-only and handoff profile structures
  - Test low ℓ_i hypothesis for LHI-OH handoff scenarios with stabilized $n = 1$ activity
- Simulation work with M3D-C^1:
  - Potential coupling of LHI targets to NBI-CD
  - Stability analysis of PEGASUS LHI-OH handoffs

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More PEGASUS Info

- Talks:
  - S.J. Diem, *The New Pegasus-III Experiment and Plans for RF Heating and Current Drive*, **NO07.01**
  - G.M. Bodner, *Characterization of T_e and n_e Profiles of Discharges Driven Purely by Helicity Injection in the PEGASUS Toroidal Experiment*, **NO07.02**
- Posters:
  - M.D. Nornberg, *Integrated Studies of Solenoid-Free Tokamak Startup with Pegasus-III*, **ZP06.1**
  - R. Raman, *CHI Research on Pegasus-III*, **ZP06.2**
  - N.J. Richner, *Magnetic Activity During LHI Startup and Sustainment*, **ZP06.3**
- Website:
  - **https://pegasus.ep.wisc.edu/**



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