Integrated Studies of Solenoid-Free Tokamak Startup (on the Pegasus-III Experiment)

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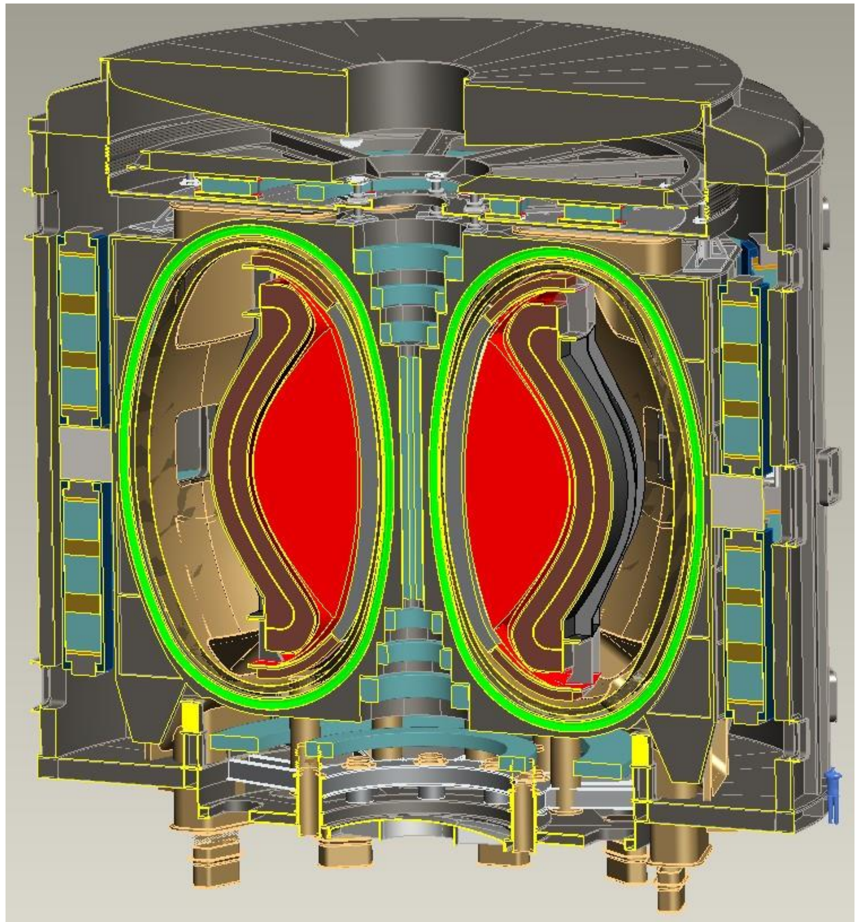
Pegasus-III Toroidal Experiment

Non-Solenoidal Startup is Critical for the Spherical Tokamak

- Future ST designs call for solenoid-free operation
  - Nuclear ST designs generally minimize OH due to shielding/cost
- OH solenoid removal simplifies tokamak design
  - Potential cost reduction
  - More space for inboard shielding/blanket → Critical for ST
  - Reduce PF system requirements
  - Lower electromechanical stresses
- Solenoid-free startup techniques may offer tools for modifying $J(R)$



No / small OH HTS ST-FNSF / Pilot Plant

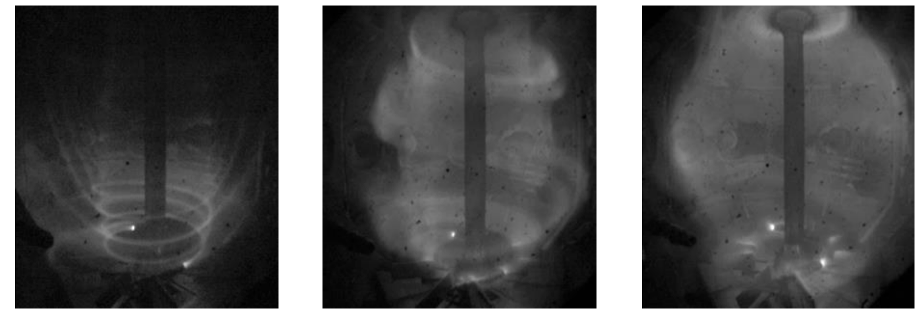
J.E. Menard, Phil. Trans. R. Soc. A ***377****, 20170440 (2019)*

Several Solenoid-Free Startup Techniques Pursued Globally

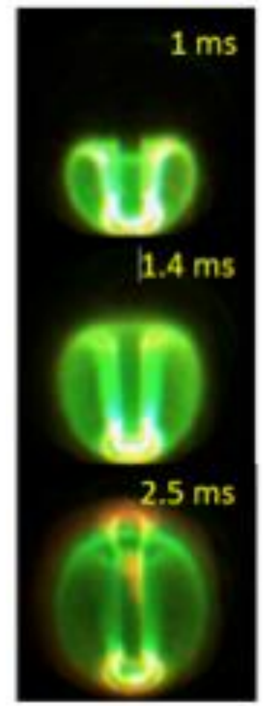
- Multiple methods have shown promise
  - Local helicity injection (LHI)
  - Coaxial helicity injection (CHI)
  - Radiofrequency plasma initiation, heating, and current drive
  - Poloidal field induction
  - Neutral beam current drive

- Need a dedicated facility to develop understanding and scalability
  - Develop, validate predictive understanding
  - Provide sufficient runtime, experience
  - Comparative studies and exploit synergies
  - Establish routine startup tools

Pegasus HFS LHI



$I_p \sim N_{turns} I_{inj}$ $I_p \gtrsim N_{turns} I_{inj}$ $I_p \gg N_{turns} I_{inj}$



NSTX Transient CHI

RF Startup Experiments

RF Method	Device	I_p [kA]
ECH + PF induction	DIII-D	166
	JT60-U	100
ECH	QUEST	70
	DIII-D	33
	KSTAR	15
ECH + LHCD	T-7	20
EBW	MAST	73
	LATE	15
LH	PLT	100
	TST-2	25
	GLOBUS-M	21

Bongard et al., APS-DPP-CPP Initiative (2019)

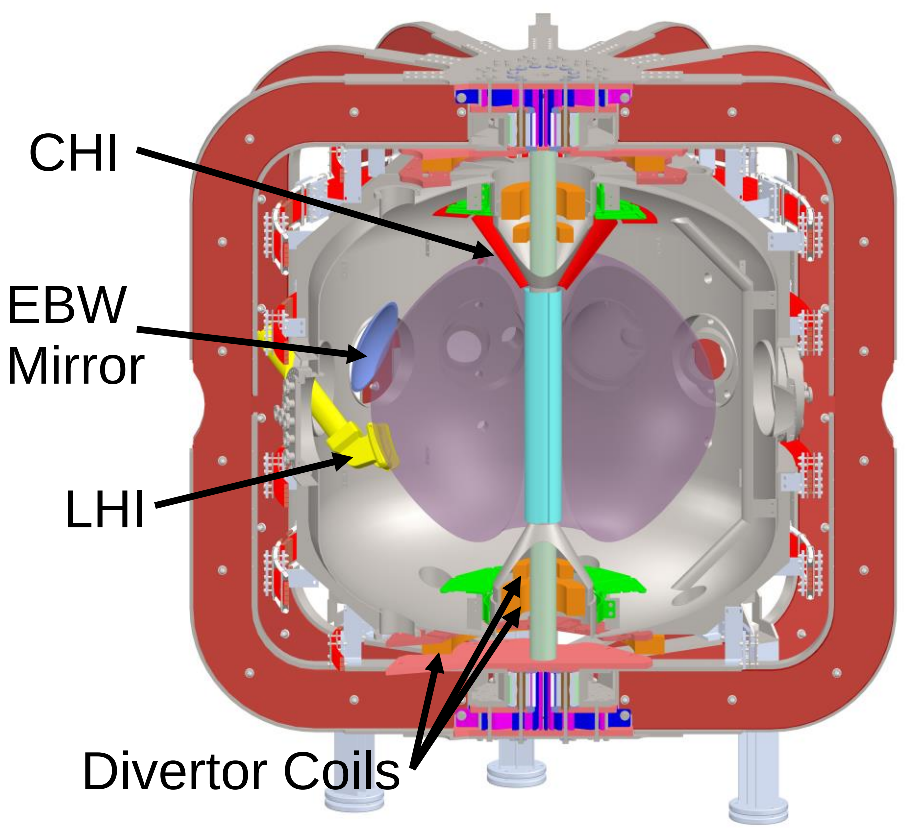
PEGASUS-III Will Provide a Dedicated US Platform for Solenoid-Free Startup Development

- Compare/contrast/combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
    - *Discussed herein*
  - Coaxial Helicity Injection (Transient, Sustained)
    - *See R. Raman, this meeting*
  - EBW assist and sustainment (ECH, ECCD in future)
    - *See S. Diem, this meeting*
  - Future: NBI heating and current drive?

- Goal: develop validated concept, equipment for 1 MA startup on NSTX-U and beyond

- Construction underway, operational in 2020

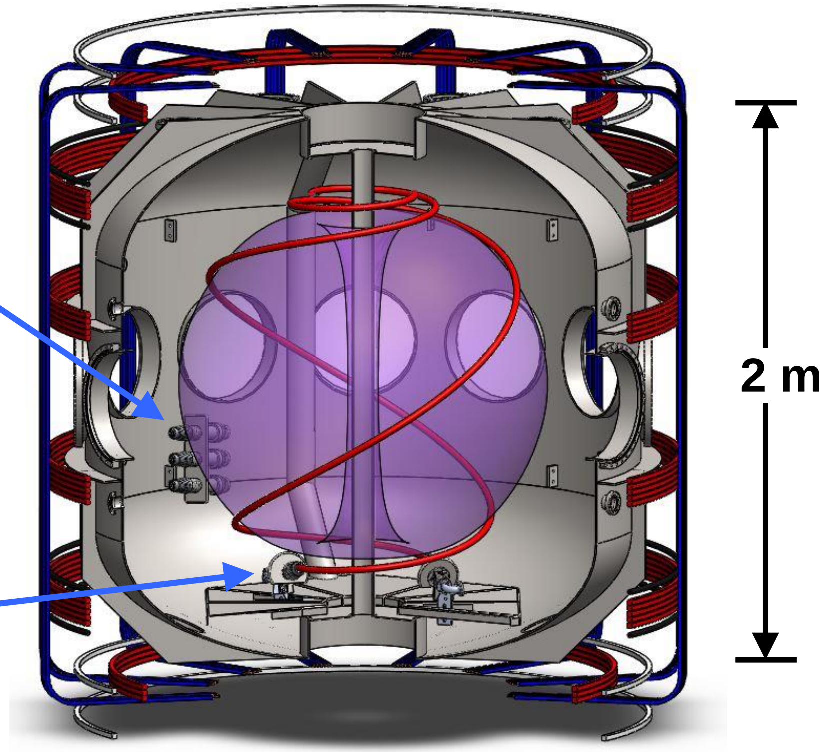
PEGASUS-III

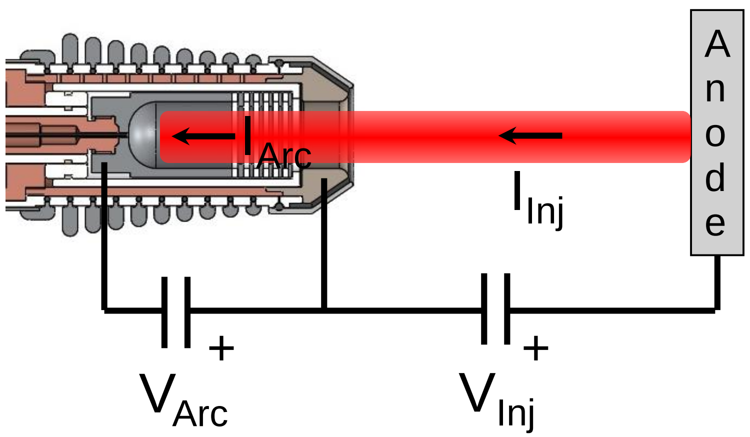


Local Helicity Injection (LHI) Routinely Used for Non-Solenoidal Startup on PEGASUS ST

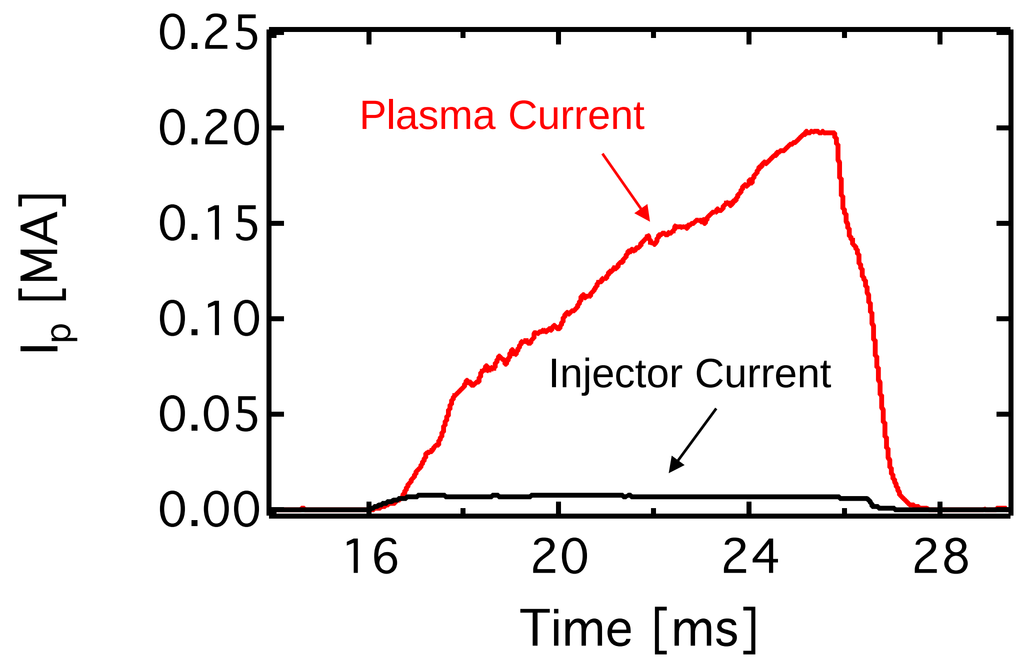
LFS Injectors

HFS Injectors





Non-Solenoidal, I_p ≤ 0.2 MA (I_{inj} ≤ 8 kA)



- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities

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

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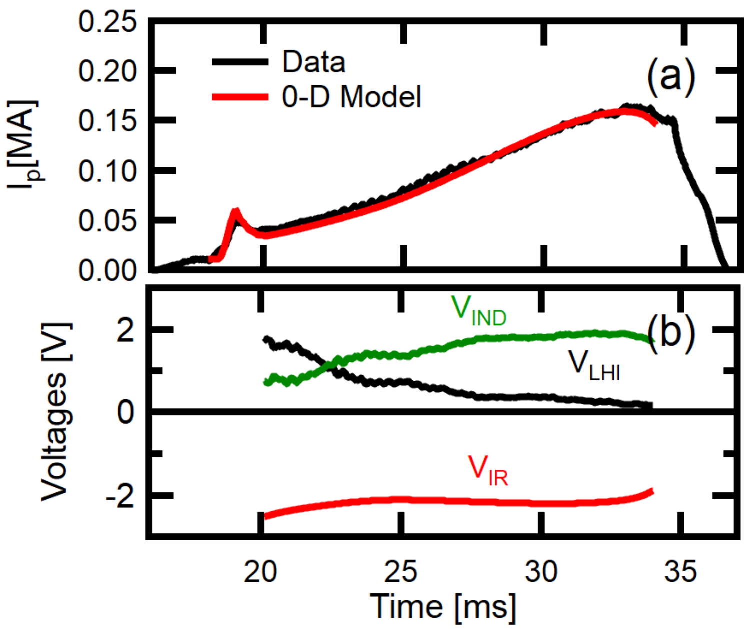
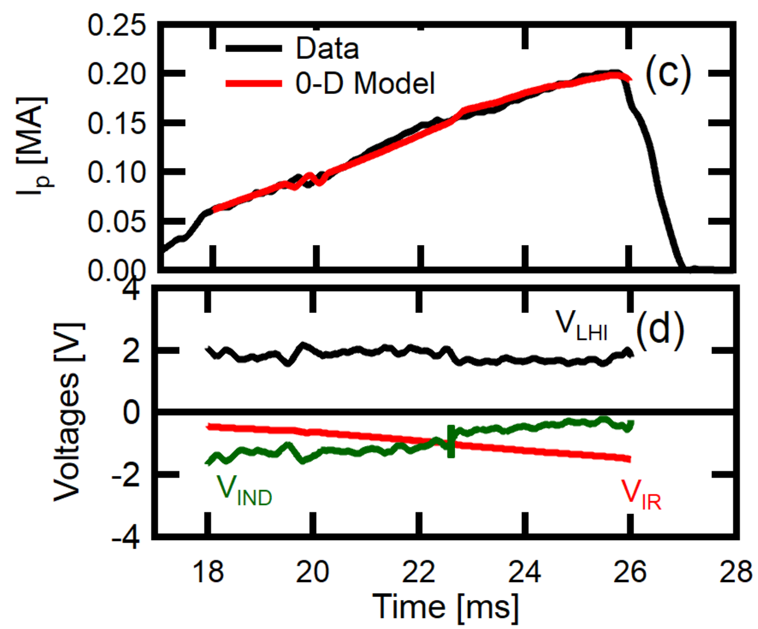
Flexibility in LHI Current Injectors Location Validated

- Comparable I_p via two methods

LFS: Dominant Non-solenoidal Induction

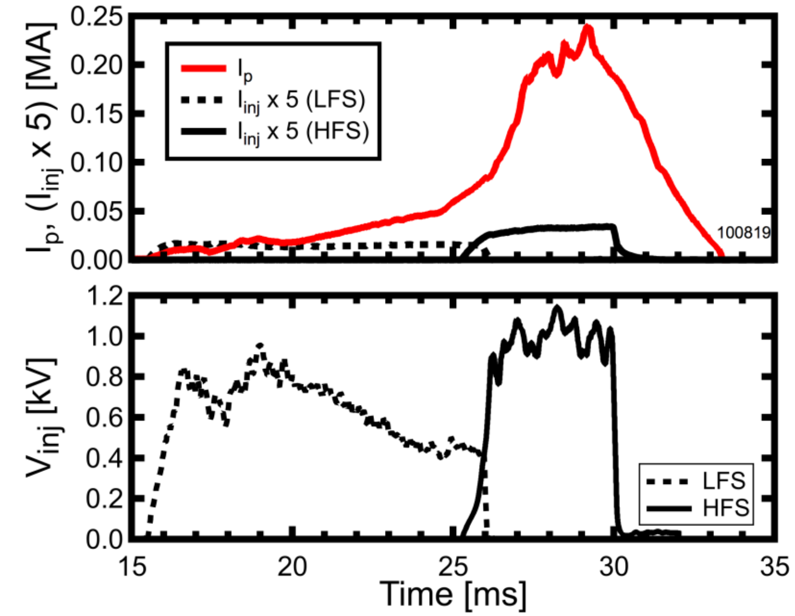


HFS: Dominant Helicity Injection



- LFS: Outer midplane injection
  - High R_{inj} → weak V_{LHI}
  - Dynamic shape → strong V_{IND}
- HFS: Lower divertor injection
  - Low R_{inj} → strong V_{LHI}
  - Static shape → weak V_{IND}

- Helicity input adds from all sources



- Efficient LFS → HFS transfer
  - Aid high B_T relaxation

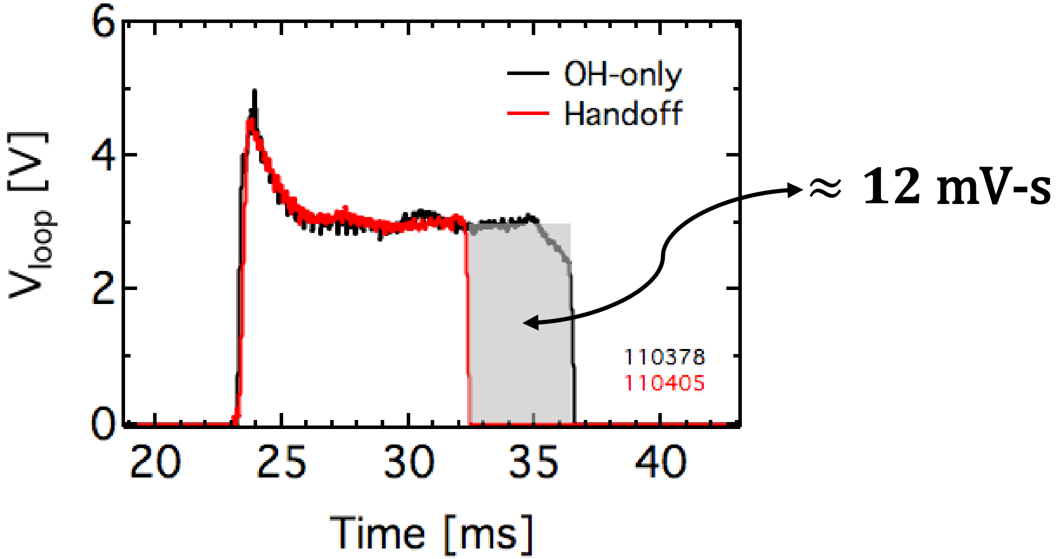
- LFS geometry preferred for Pegasus-III and NSTX-U
  - Port mounted injector; avoid crowded divertor region
  - SC coils in future may influence this

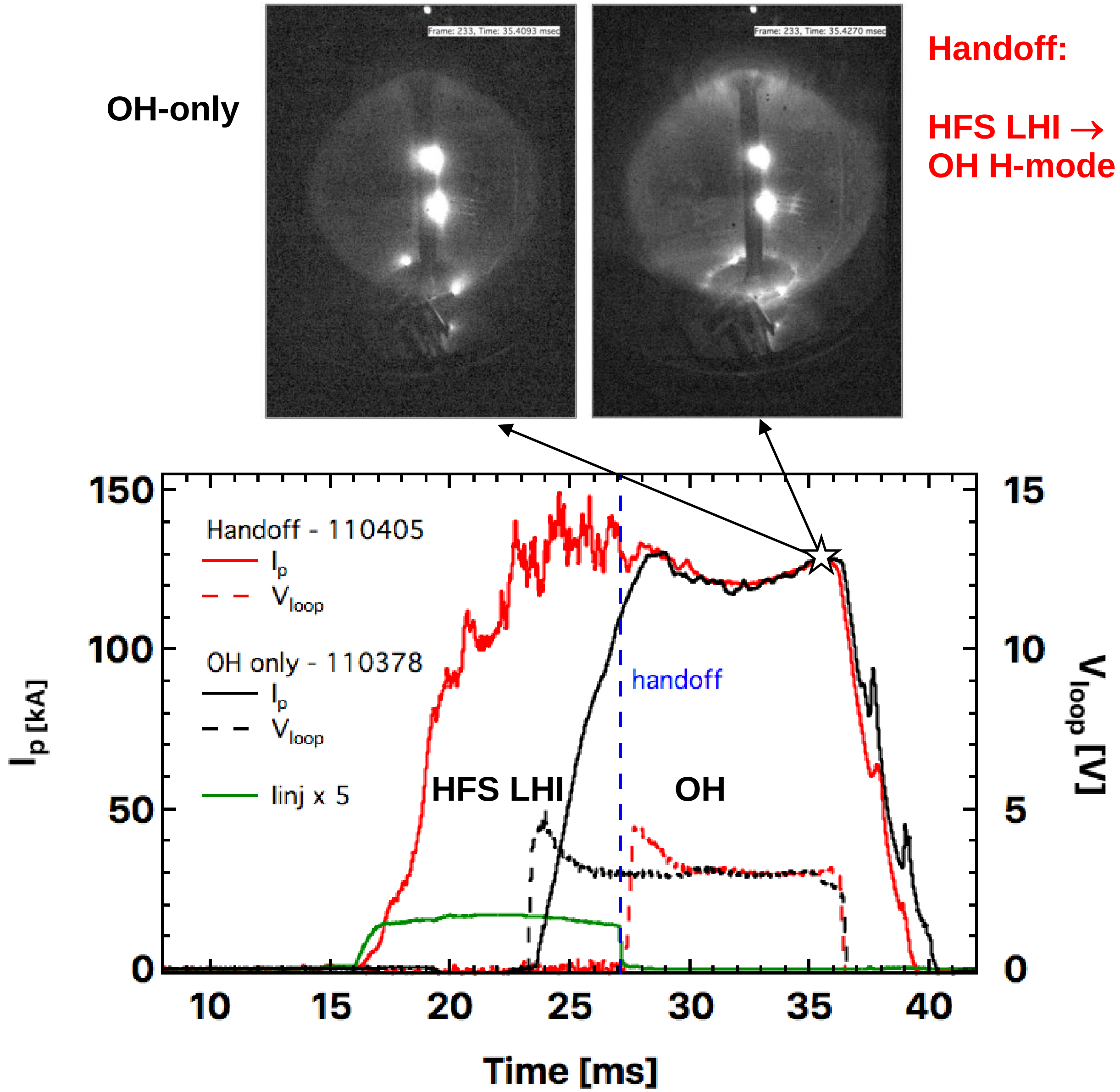
J.A. Reusch et al., Phys. Plasmas ***25*** *056101 (2018)*
M.W. Bongard et al., Nucl. Fusion ***59*** *076003 (2019)*

LHI Startup Transitions Smoothly to OH and Adds Effective V-sec

- Robust transfer of I_p to subsequent OH drive
- LHI current and poloidal flux add to equivalent OH-phase V-s
  - LHI: ≈ 29 mV-s
  - OH-only: ≈ 41 mV-s
  - Equivalent OH Flux savings: ≈ 12 mV-s

V_{loop} Comparison, Handoff Shifted 4 ms to Highlight V-s Difference



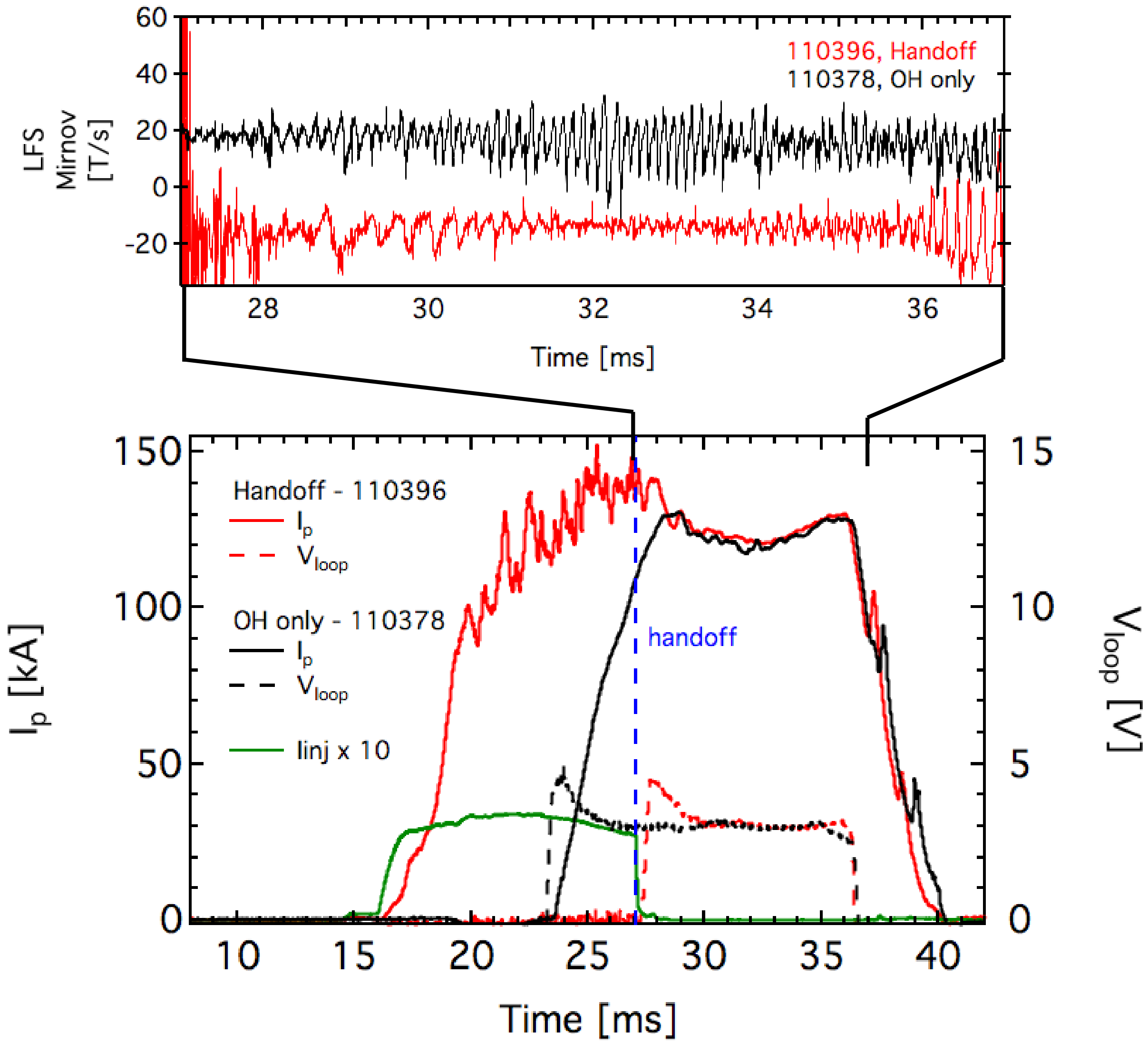


LHI-Produced Handoff Targets Have Favorable MHD Properties

- OH usually limited by strong low m/n tearing modes
  - Due to flat q profile with low magnetic shear
  - Pure OH: Saturated low-order activity

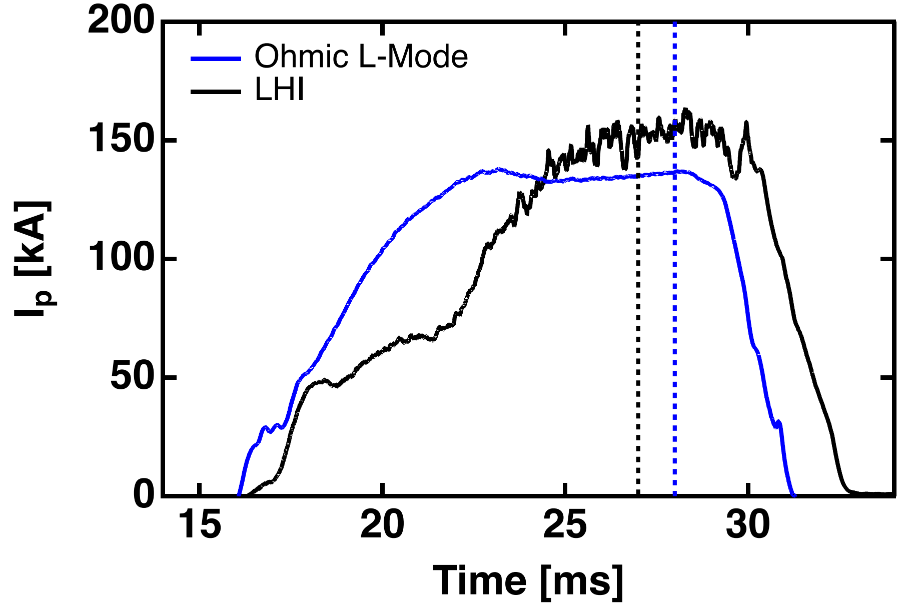
- Internal modes suppressed via LHI startup
  - Hollow $J(R)$ improves stability
  - LHI-OH: Decaying $n = 1$ followed by quiescent period
  - In principle, LHI-produced $J(R)$ could be frozen via subsequent P_{aux}

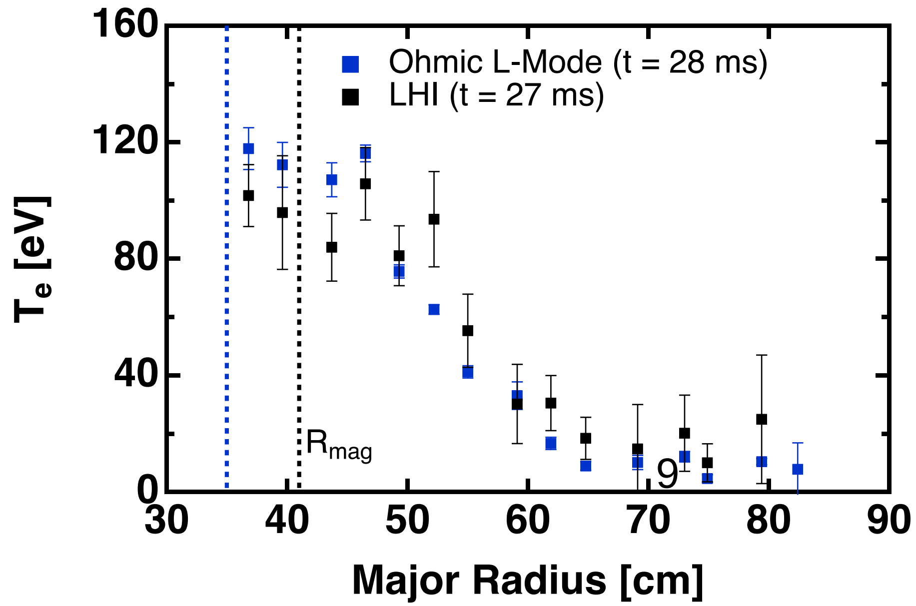
OH: Saturated n = 1 mode
LHI-OH: Stable n = 1 mode and quiescent period



At B_t ~ 0.15 T, LHI T_e Profiles Comparable to L-Mode Profiles

- First Thomson measurements made in ohmic discharges on Pegasus
- Similarity of T_e (R) suggests high B_t LHI may resemble L-mode like confinement
- Ability to test V_{LHI} scaling at B_t ~ 0.15 T limited
  - Geometric constraints of LHI system
  - Operation limits of V_{LHI}





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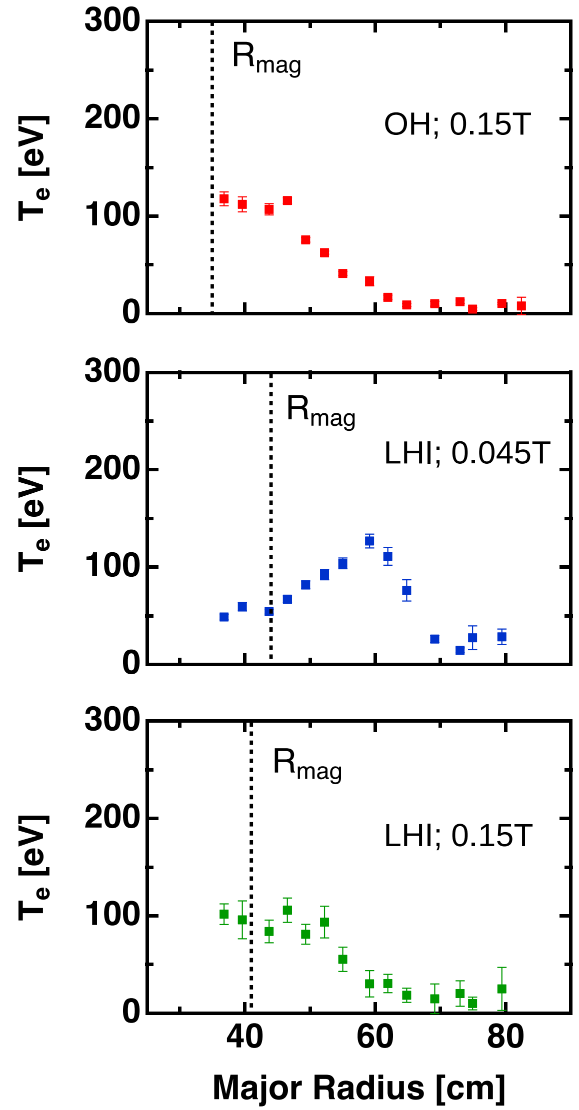
Low Central Heating Power Density in LHI Discharges May Explain Sustained Hollow T_e Profiles

- Very low ℓ_i of LHI → low $\eta^* j^2$ in core

- Minimum P_{rad} estimated from AXUV bolometers ($P_{AXUV} \leq P_{RAD}$)
  - Ohmic, LHI ($B_t \sim 0.15$ T):
    - core $\eta^* j^2 \geq P_{AXUV}$
  - LHI ($B_t \sim 0.045$ T):
    - core $\eta^* j^2 \leq P_{AXUV}$

- Higher I_p and/or adding P_{aux} should yield peaked T_e profile
  - A heating power problem, not impurity problem



ℓ_i [H]	$\eta^* j^2_{(0)}$ [kW/m³]	P_{AXUV} [kW/m³]
0.44	45	1
0.28	7.4	25
0.22	2	2

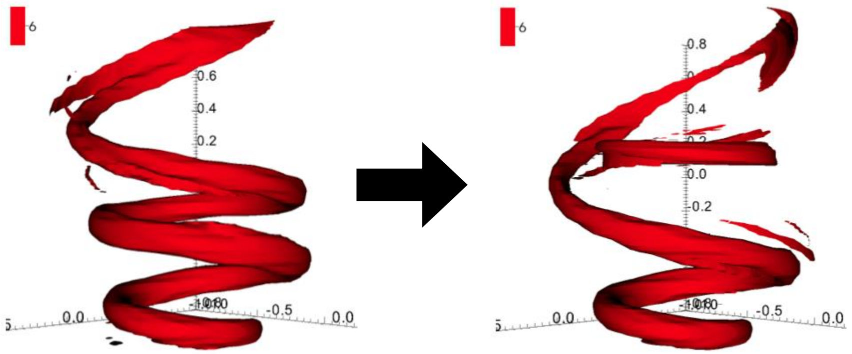
$N_e(0) \sim 1\text{-}2 \times 10^{19}$ m^{-3}

Need Physics Understanding of LHI Current Drive

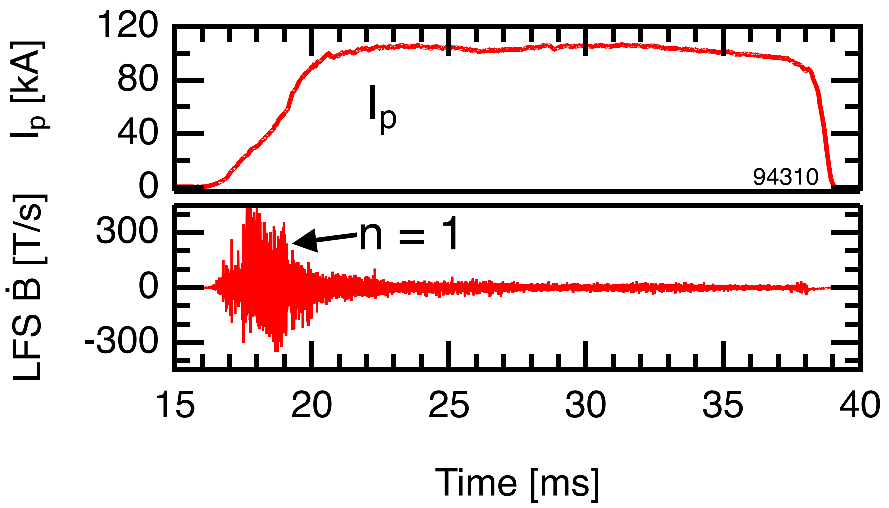
- LHI V_{eff} from helicity balance: $$V_{LHI} \lesssim \frac{A_{inj} B_{\phi,inj}}{\Psi_{tor}} V_{inj}$$
- Reconnection of I_{inj} = potential CD (NIMROD*)
  - Associated with bursts of low-f $n = 1$ activity
- Additional physics/CD mechanism(s) active
  - Sustained I_p *and* suppressed $n = 1$
  - Anomalous T_i correlated with high freq. activity**

→ Insertable probes used to investigate

*Reconnecting I_{inj} in NIMROD**



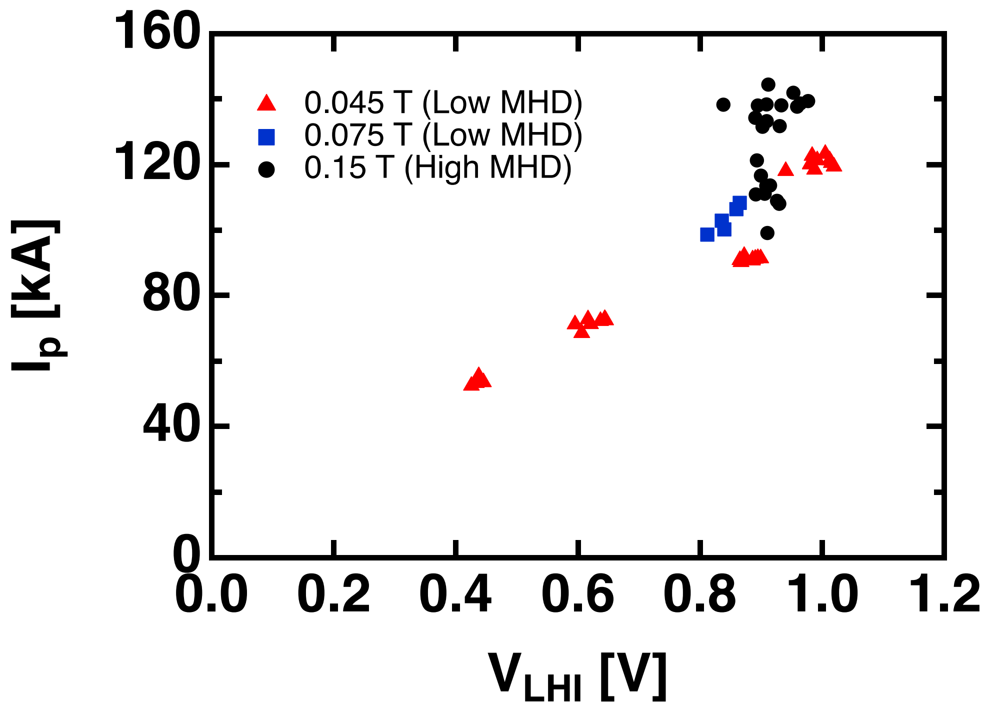
Sustained I_p with $n = 1$ activity suppressed

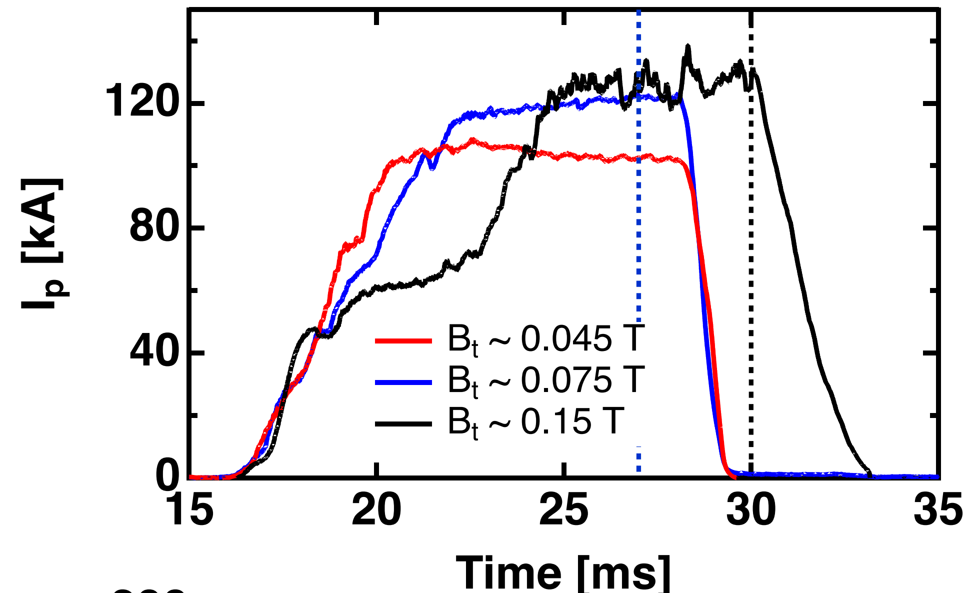


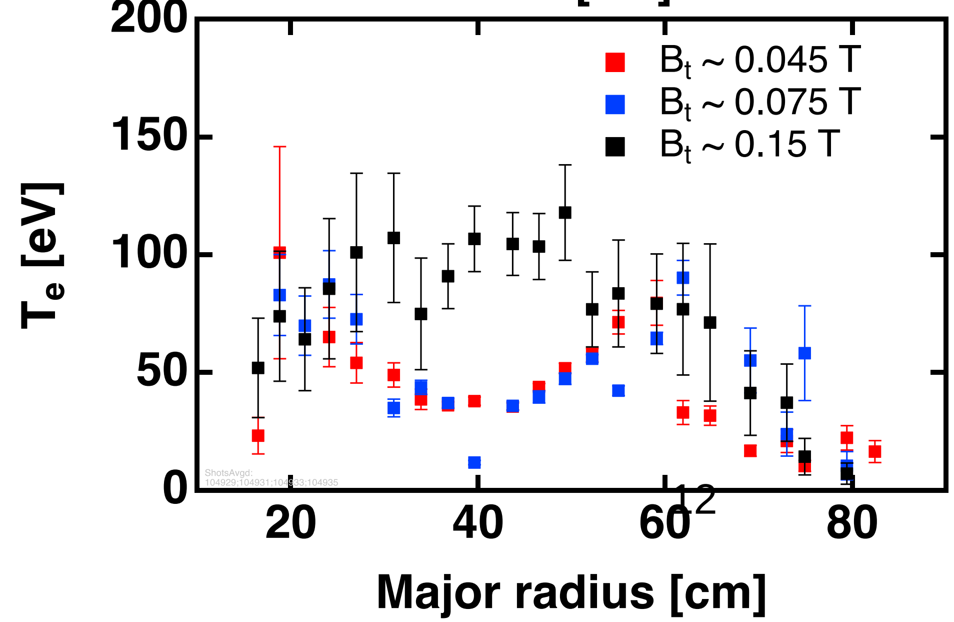
*O'Bryan et al., Phys. Plasmas **19** 080701 (2012)
O'Bryan and Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)

Burke et al., Nucl. Fusion **57 076010 (2017)

Current Drive Scaling Shows Linear Dependence on V_{LHI}



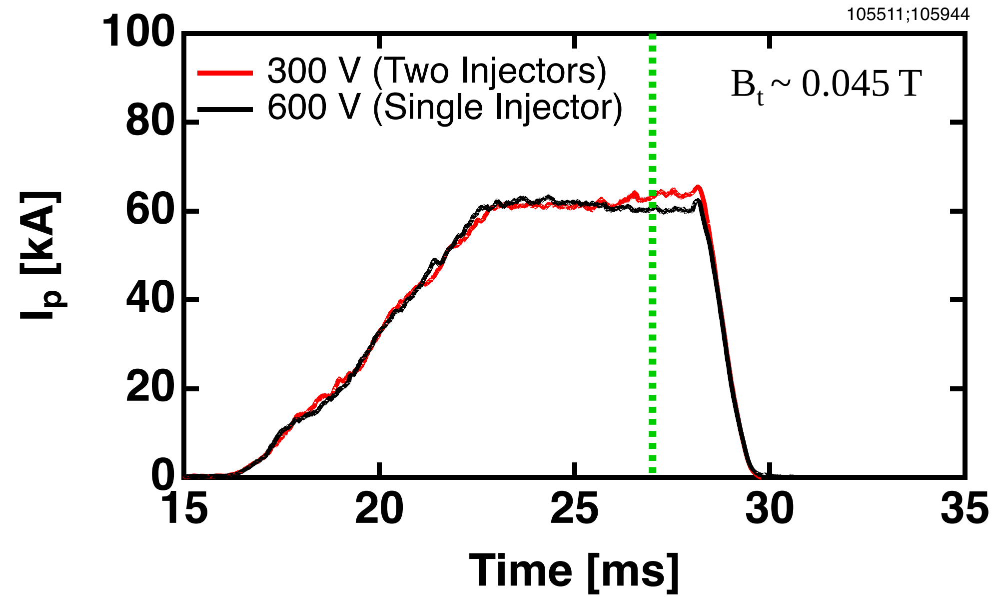


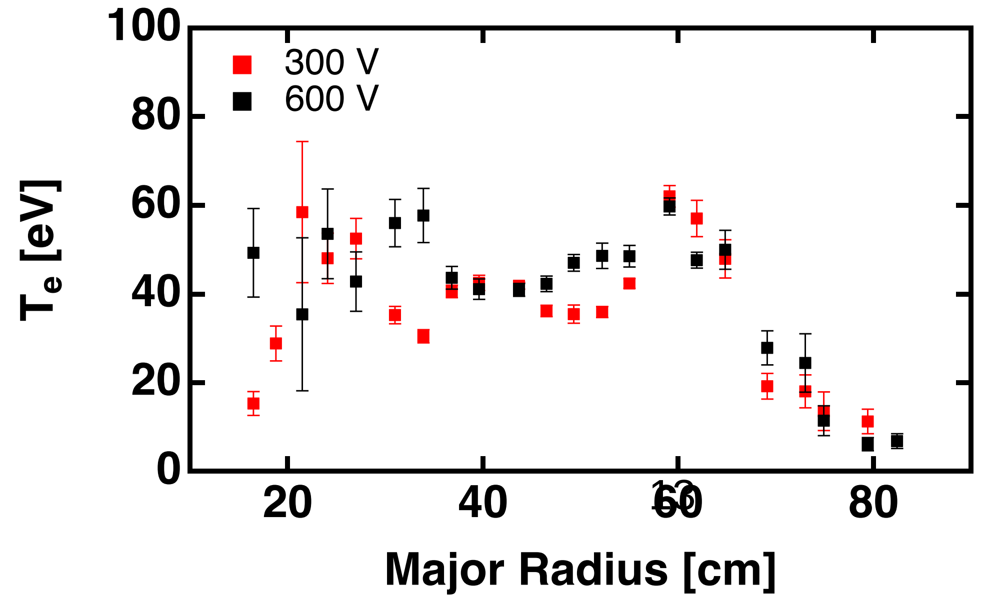


- T_e profile structure fills in at $B_t \sim 0.15$ T
- Operating space narrows as B_t is increased
  - MHD transition not observed at 0.15 T
  - Relaxation issues with low V_{inj}

LHI I_p Depends Upon Helicity Input Rate, Not V_{inj}

- Same total input helicity rate, V_{LHI}, but different levels of V_{inj}
- Same V_{LHI} results in similar levels of I_p and T_e
- Open field line theory* suggests $T_{e,max} \sim \frac{V_{inj}}{4}$
  - Data doesn't challenge T_e limit
  - Observed T_e not proportional to V_{inj}





*Moses et al. Phys. Plasmas **8** 4839 (2001)

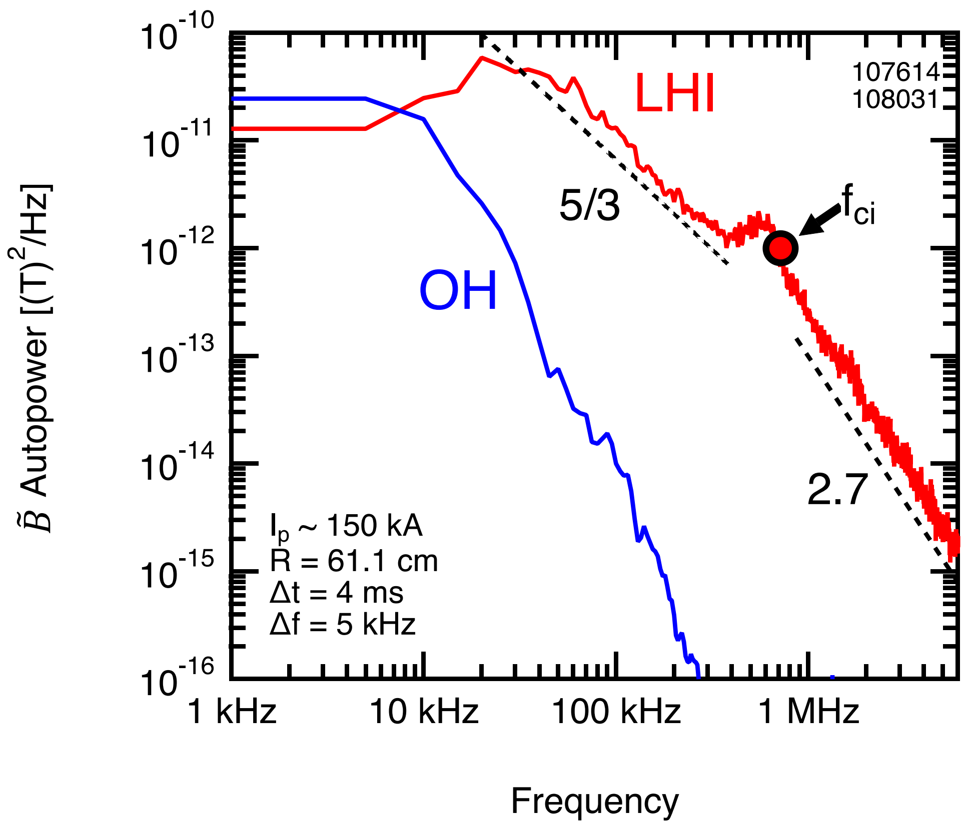
Magnetic Activity During LHI Resembles Alfvénic Turbulence

- Edge-localized high-f $\tilde{B}_{LHI} \gg \tilde{B}_{OH}$

- LHI spectral decay similar to Alfvénic turbulence:*
  - ~5/3 for $f < f_{ci}$ → MHD turbulence
  - ~2.7 for $f > f_{ci}$ → KAW and/or whistler turb.

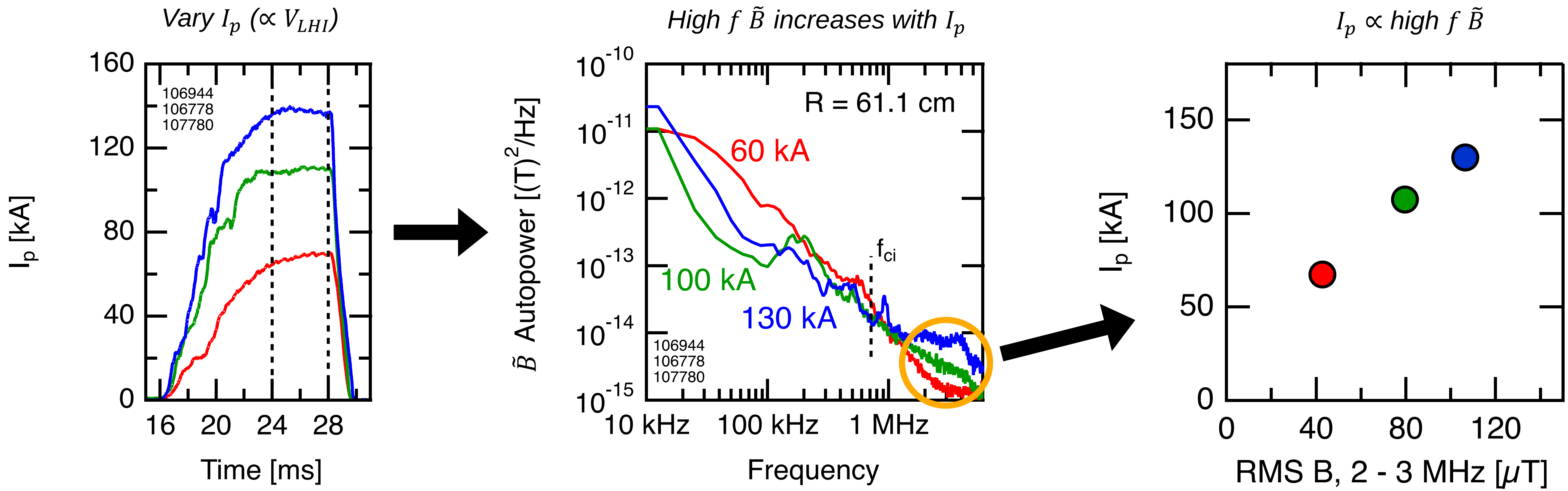
- Such turbulence often associated w/ reconnection:
  - Localized turbulence → localized reconnection ?

Edge-localized $\tilde{B}$ Autopower Spectra



*C.C. Chaston et al., PRL **100**, 175003 (2008)
J.P. Eastwood et al., PRL **102**, 035001 (2009)*

High $f \gg f_{ci}$ Activity Correlated with LHI Drive

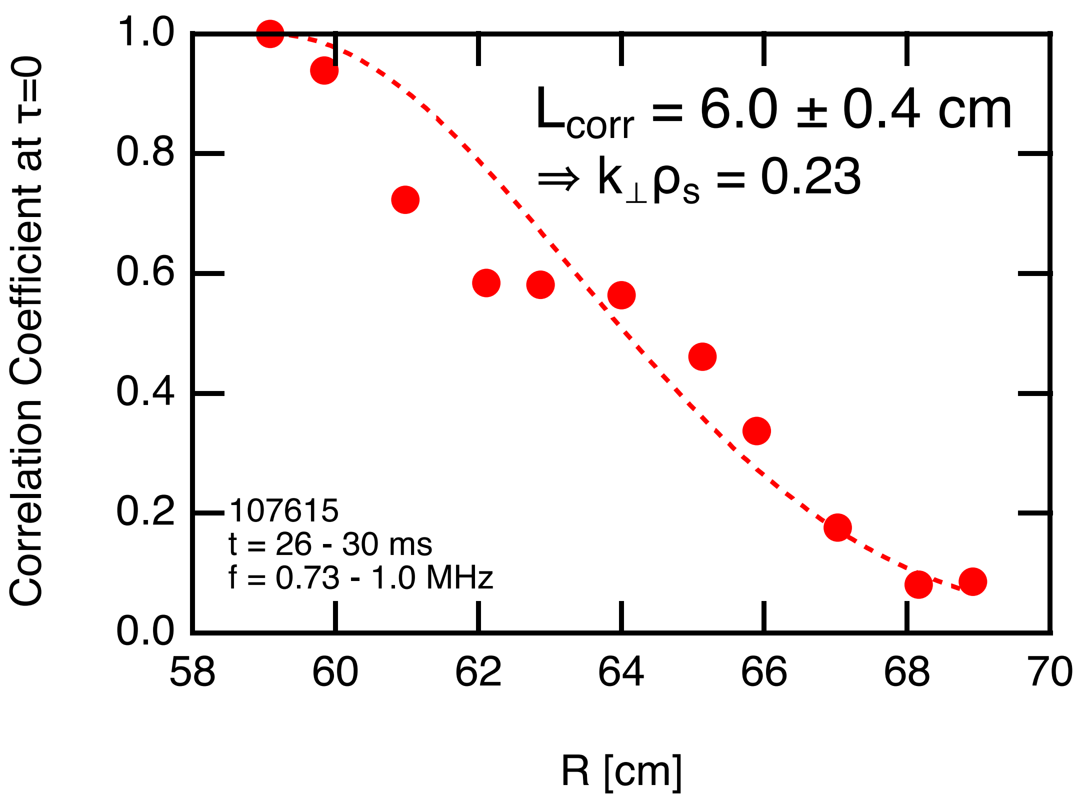


- Study helicity-sustained discharges w/ varying V_{LHI} → focus on LHI current drive

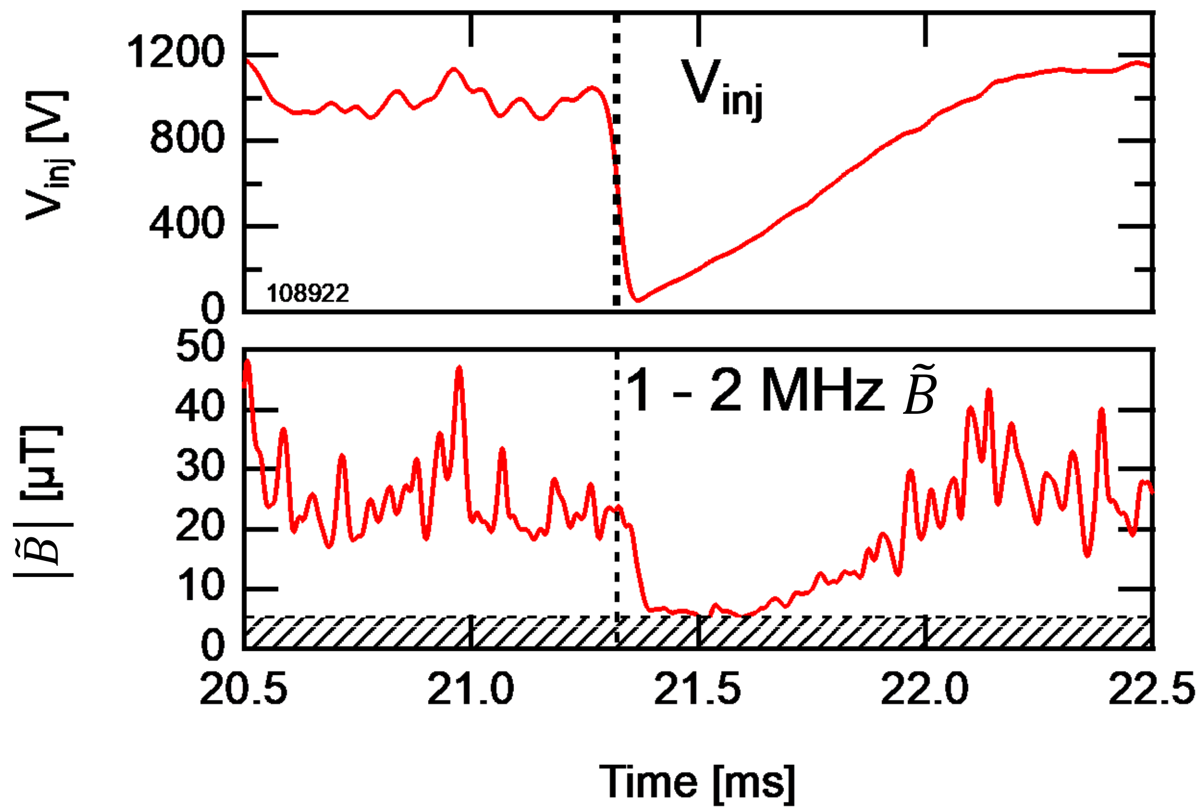
- Activity above ~ 1 MHz ($\gg f_{ci}$) increases linearly with I_p, V_{LHI}

Other Observed High-f Characteristics Suggest Kinetic Nature

- KAWs have $k_\perp \rho_s \sim 1$
  - Meas. $L_{corr,R} \sim 2-10$ cm → $k_\perp \rho_s \sim 0.1-0.7$
  - k_R^{-1} comparable to inj. diameter



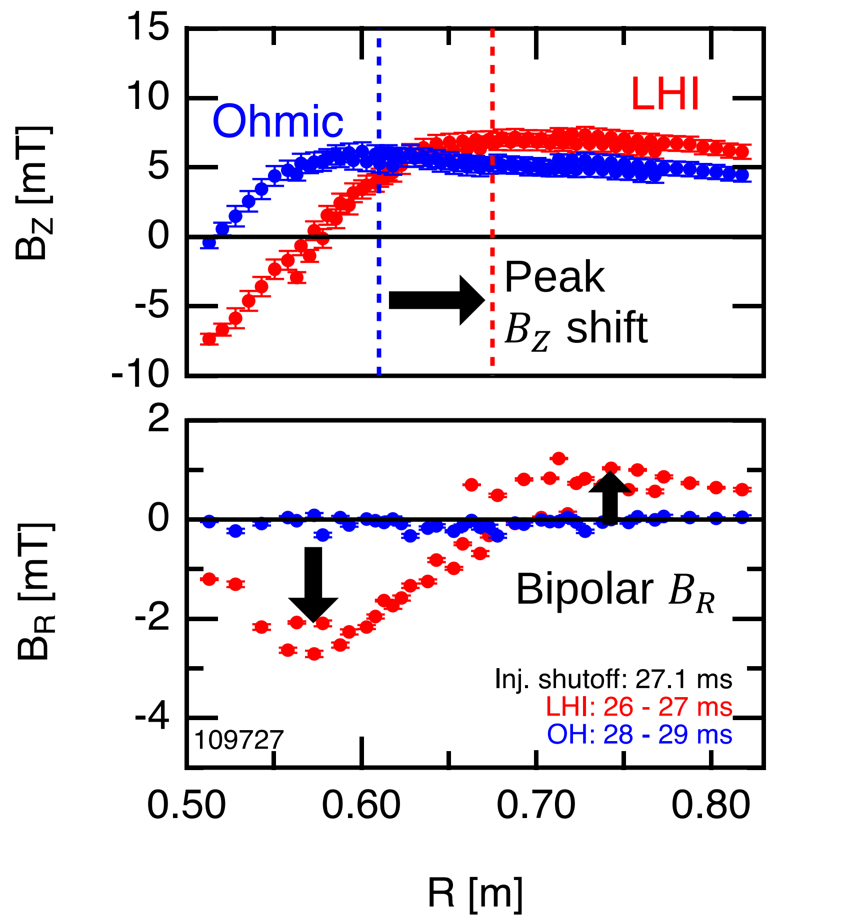
- $\tilde{B}$ strong function of V_{inj}
  - LHI e⁻ beam: $v_{beam} \propto V_{inj}^{1/2}$
- e⁻ beam-driven KAWs: $\gamma = \gamma(v_{beam})$



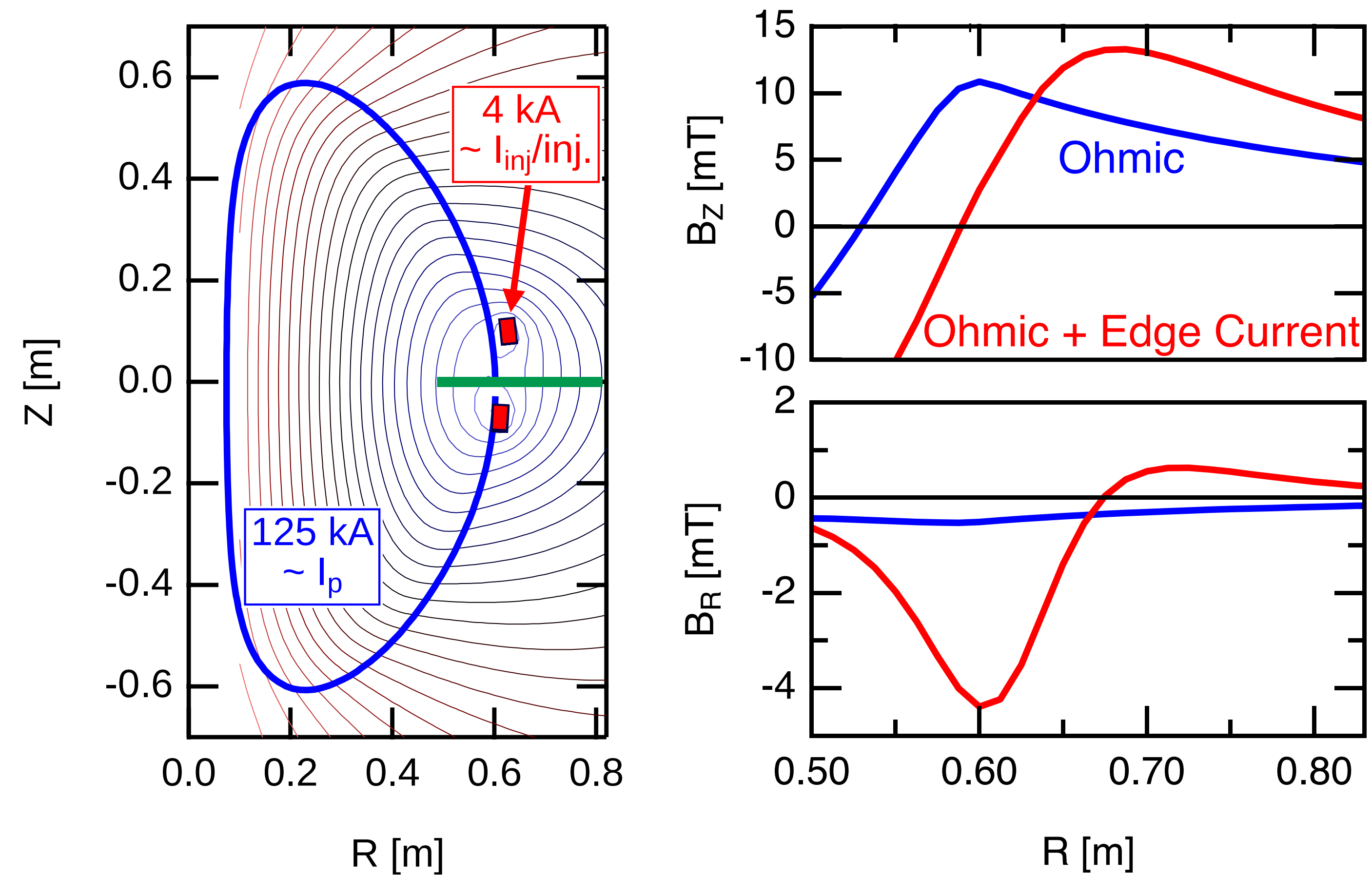
*Chen et al., Astrophys. J. **793** 13 (2014)

Average B Structure Consistent with Outer Localized I_{inj} Streams

Different Field Structure during LHI and OH



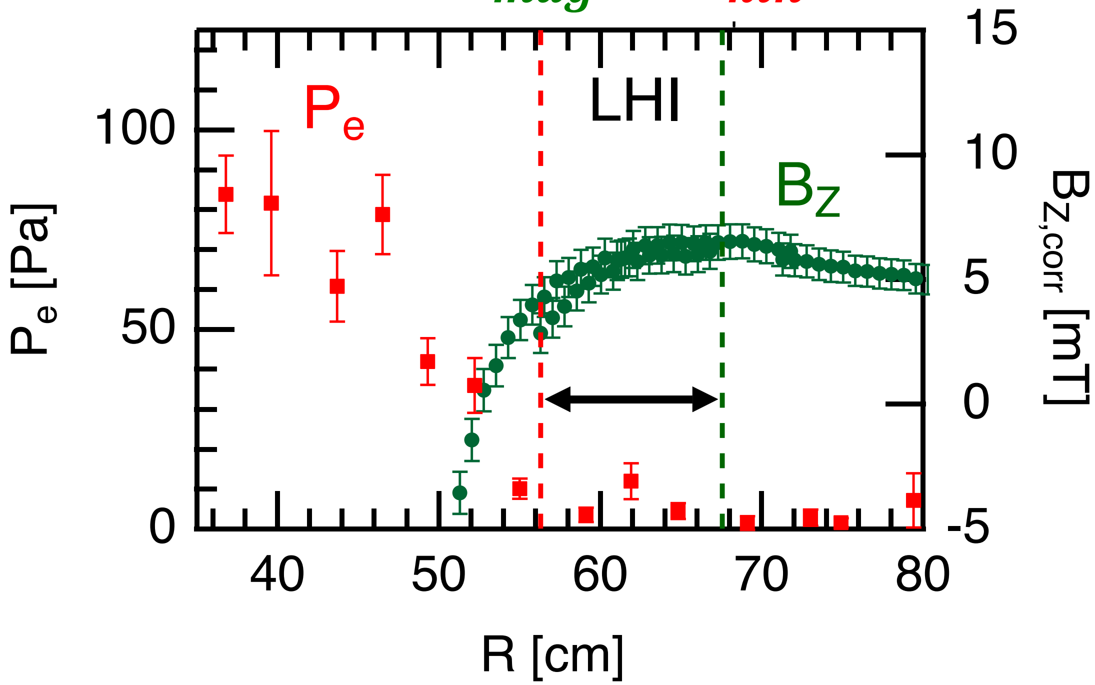
2D axisym. model qual. replicates observed structure



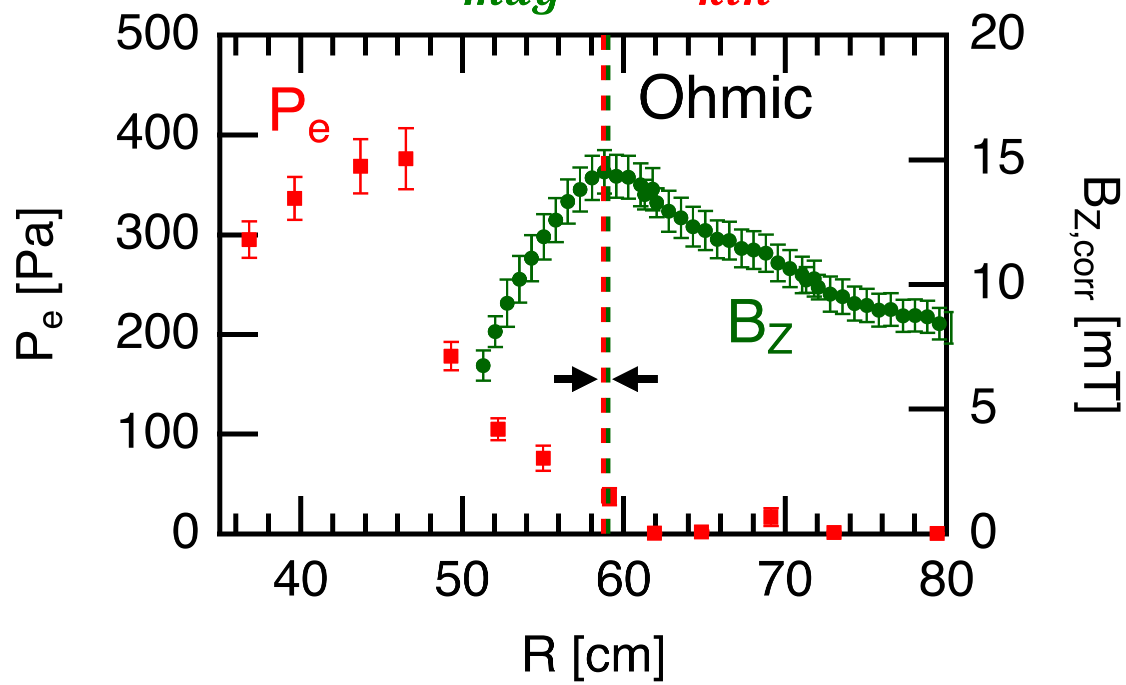
- Edge I_{inj} streams & high-freq MHD persist during LHI in outer P_e ~ 0 region
- Low-MHD, reduced n = 1 phase shows stationary I_{inj} structures

Edge Field Structure and Fluctuations Suggest Two-Zone Hypothesis

- LHI: $R_{mag} > R_{kin}$



OH: $R_{mag} \approx R_{kin}$



- Implies (simplistic) two-zone structure during LHI:
  - 1) Inner tokamak-like plasma 2) Outer region with turbulent injected current streams
- High-f (≥ 900 kHz) magnetic turbulence localized in region between boundaries
  - Reconnection and/or turbulence give rise to edge current source?

Developing Non-Circular Injector for Future LHI Applications

- Non-circular *Kama* injector
  - Increased I_{inj} with low w_{inj} => increase Taylor limit
  - Conform to flux surfaces => optimize coupling
  - Re-entrant port-mount => larger facilities, such as NSTX-U

Taylor limit

$$I_p \leq I_{TL} \sim \sqrt{I_{TF} I_{inj} / w}$$

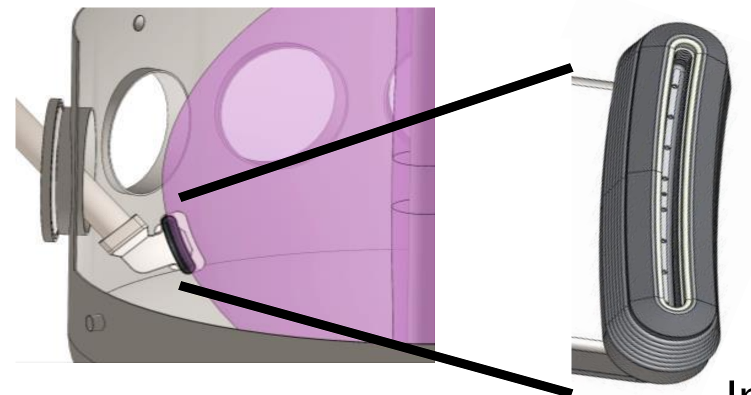
Helicity limit

$$I_p \leq V_{LHI}/R_p \sim A_{inj} V_{inj}$$

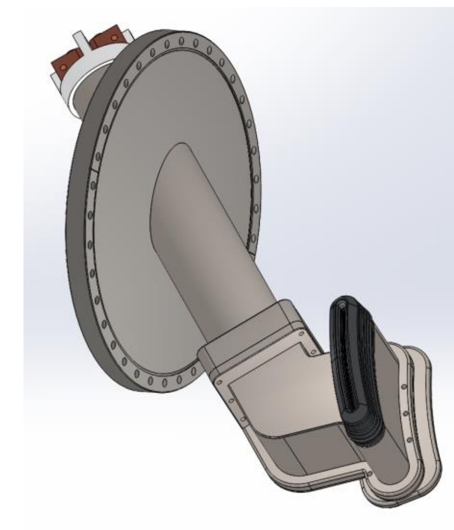
  - Large A_{inj} => high V_{LHI} at low V_{inj}

- Prototype *Kama* fabricated for Pegasus
  - Arc channel: 1 cm x 16.2 cm
  - $A_{inj} = 16\ cm^2$
  - Arc channel to LCFS: 1.8 cm
  - Non-refractory to simplify fabrication
  - Tests this Fall

Advanced "Kama" Injector in Pegasus-III



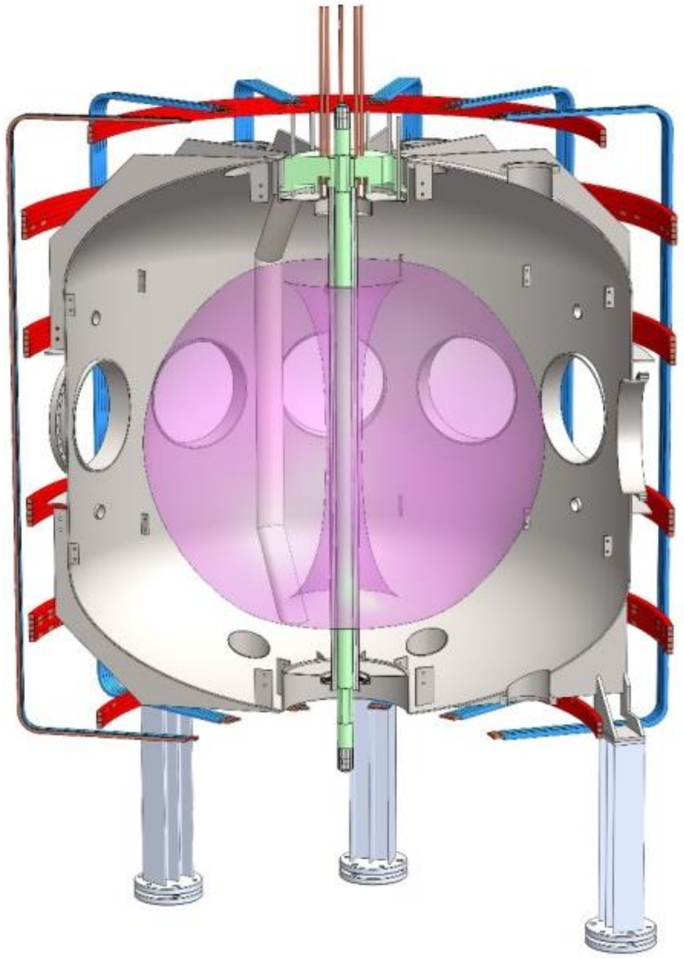
Integrated Kama Assembly



Stainless steel Kama prototype components

PEGASUS-III is a Modification of the PEGASUS Experiment

PEGASUS



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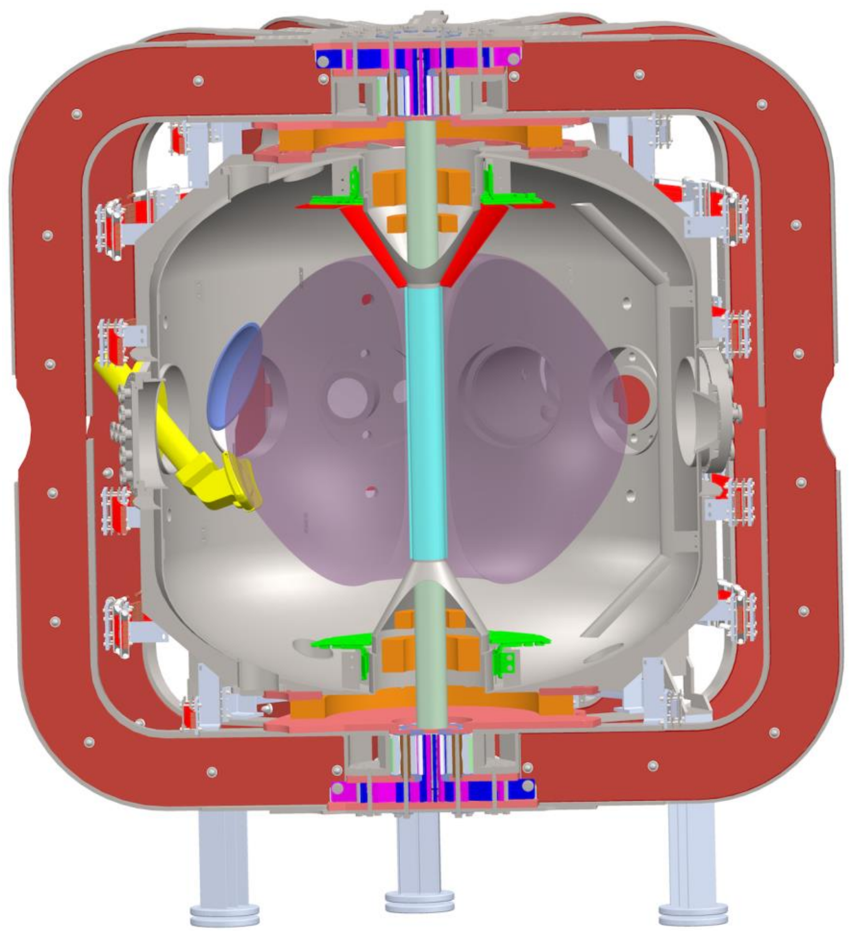
- Solenoid-free central column
- Stronger, high-B_T assembly
- Active divertor coils
- CHI, RF, and next-gen LHI
- Expanded diagnostics

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

PEGASUS-III



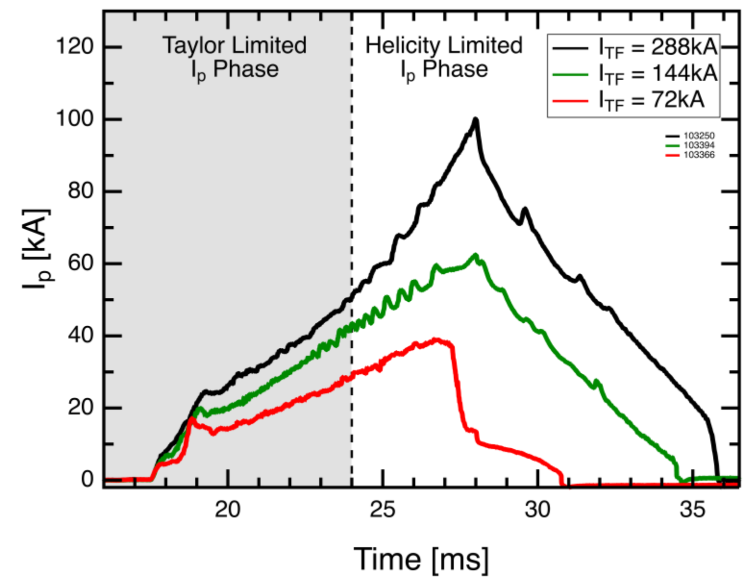
← 2 m →

Projecting LHI to Larger Facilities Requires Tests at Increasing B_T

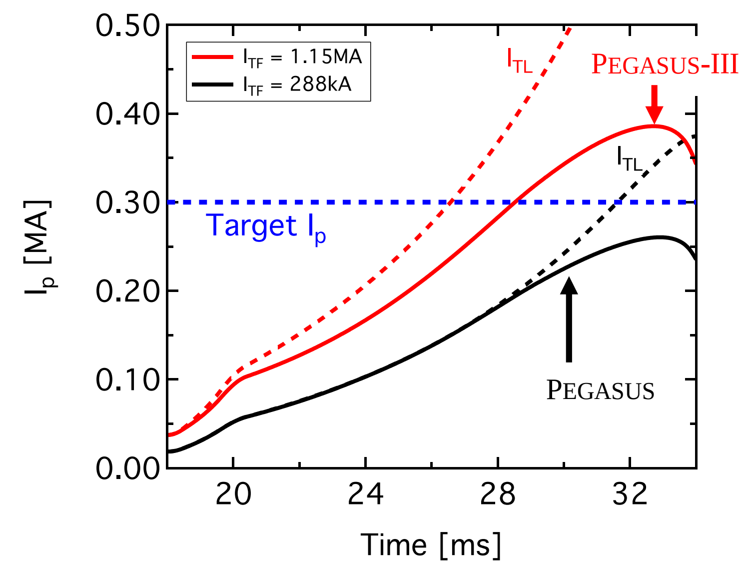
- Physics issues with B_T
  - Core confinement
  - I_p gains via increased Taylor limit $\sim\sqrt{I_{TF}}$
  - Reconnection and current drive
  - Stochastic edge transport
  - Current stream stability and CD
  - B_p null formation, tokamak relaxation
  - Demonstration of increased I_p

- Technology
  - Optimized geometry for reduced V_{inj}
  - Current channel uniformity
  - PMI mitigation
  - Long-pulse capabilities

PEGASUS B_T Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



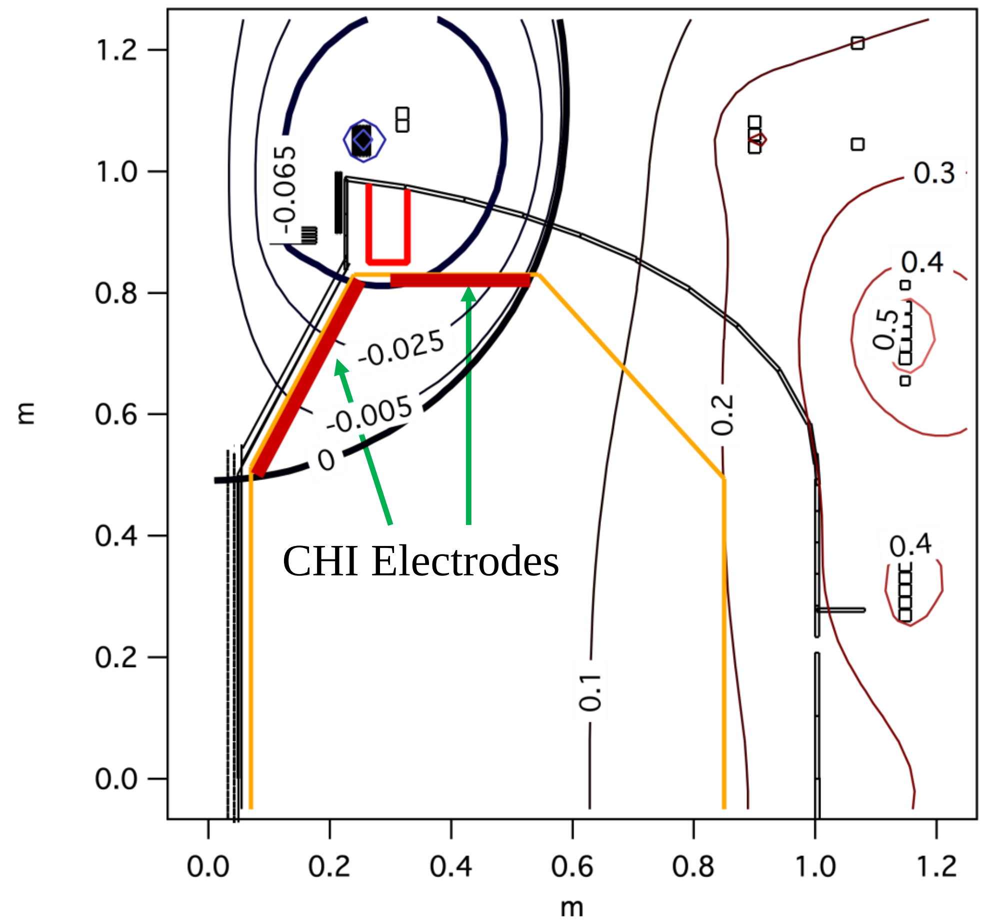
0-D Power-Balance Projections for LHI on PEGASUS-III



Two-Electrode CHI System to be Implemented on PEGASUS-III

- CHI system targets I_p = 0.3 MA
  - Segmented floating electrodes
  - B_T ~ 0.6 T for increased Taylor limit and decrease I_{inj}
  - Ψ_{inj} ~ 35 mWb to reach 0.3 MA Taylor limit
- Explore CHI physics at B_T = 0.6 T
  - Optimization of T-CHI and/or S-CHI scenarios
  - 2D axisymmetry vs 3D effects
  - Flux conversion efficiency
  - Validation of MHD simulations
  - Comparison and synergies w/other methods (LHI, RF, etc.)
- UW collaboration team (Raman, Nelson, Rogers)

65 mWb Connecting Simple CHI Electrodes



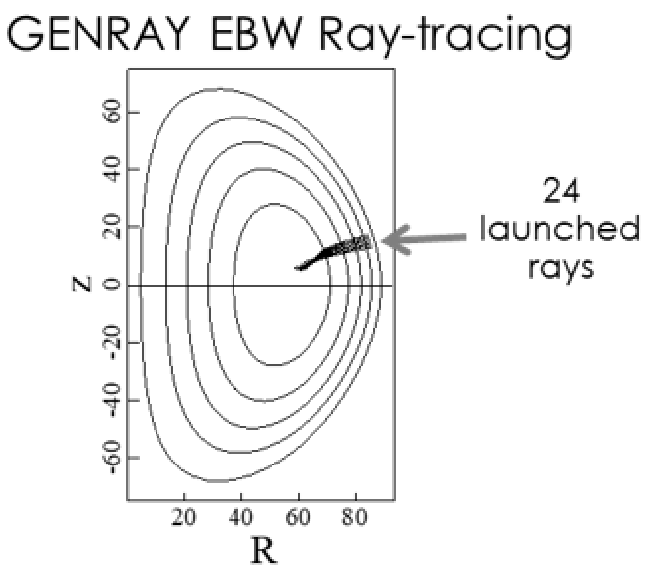
R Raman and V F Shevchenko, Plasma Phys. Control. Fusion ***56,*** *103001 (2014)*
R. Raman - GP10.00.00128

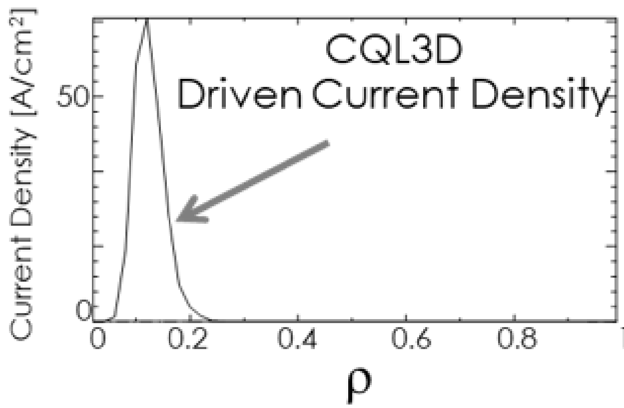
RF Heating and Current Drive: Synergies with LHI; Handoff/Startup

- Initial focus on EBW heating and current drive:
  - Heating for increased LHI/CHI efficiency
    - Classical helicity dissipation scaling: $\dot{K} \sim I_p R_p \sim T_e^{-3/2}$
  - Efficiency and localization
  - EBW CD as potential current sustainment

- ORNL collaboration team (Diem, Bigelow, Lau)
  - Loan agreement for the 8 GHz, 500 kW FTU system from Frascati in progress
  - Modeling of scenarios (GENRAY, CQL3D) ongoing
  - Implementation: Steerable O-mode mirror on LFS

- Planned expansion: add ECH and ECCD
  - Direct RF startup: Trapped electron precession → ECCD (see M. Ono (2019))
  - Explore proposed NSTX-U startup scenario (Poli et al.): HI + electron heating

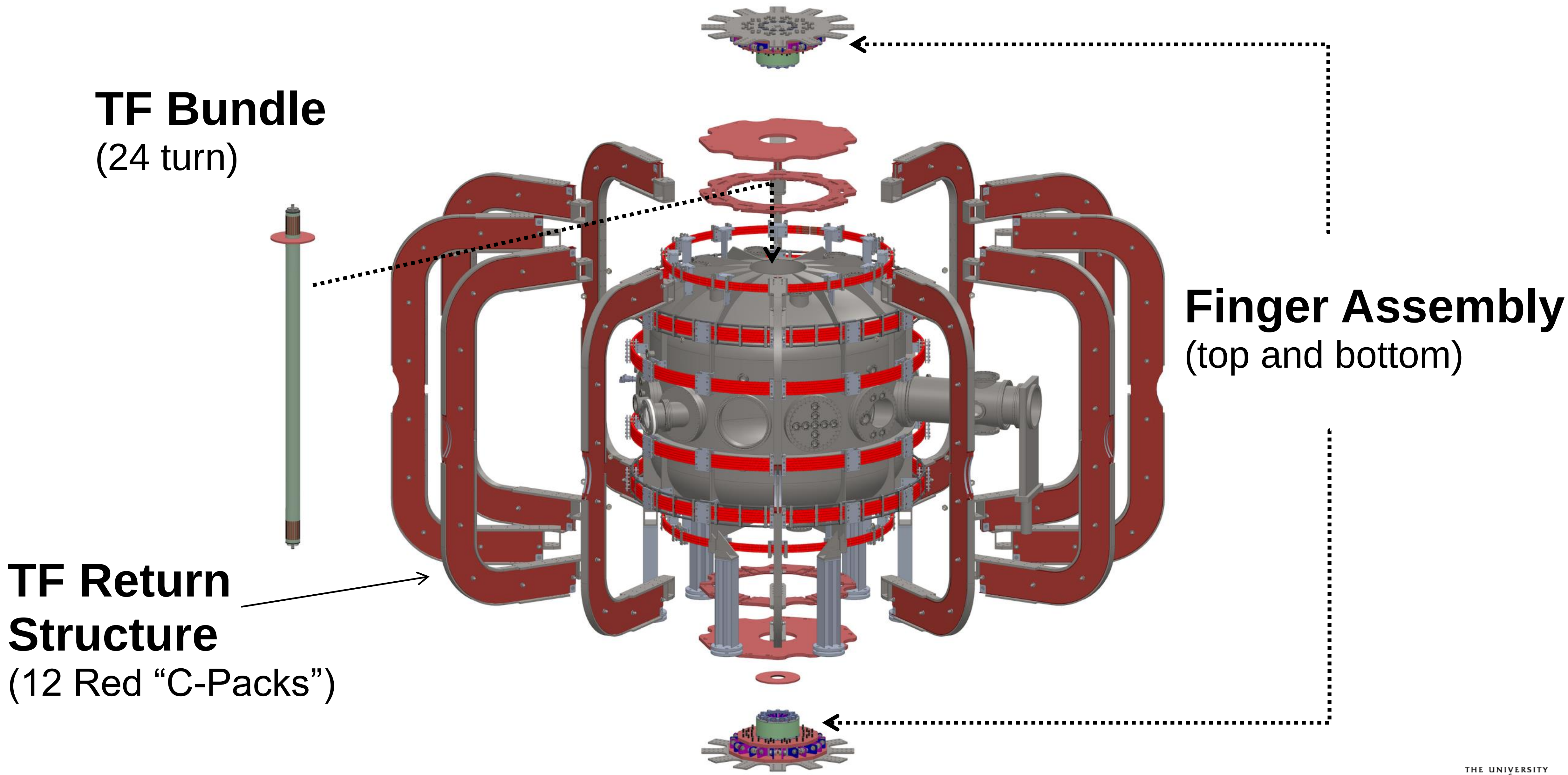




S.J. Diem et al., 2018 US-EU-JP RF Technology Workshop
F.M. Poli et al., Nucl. Fusion ***55****, 123011 (2015)*

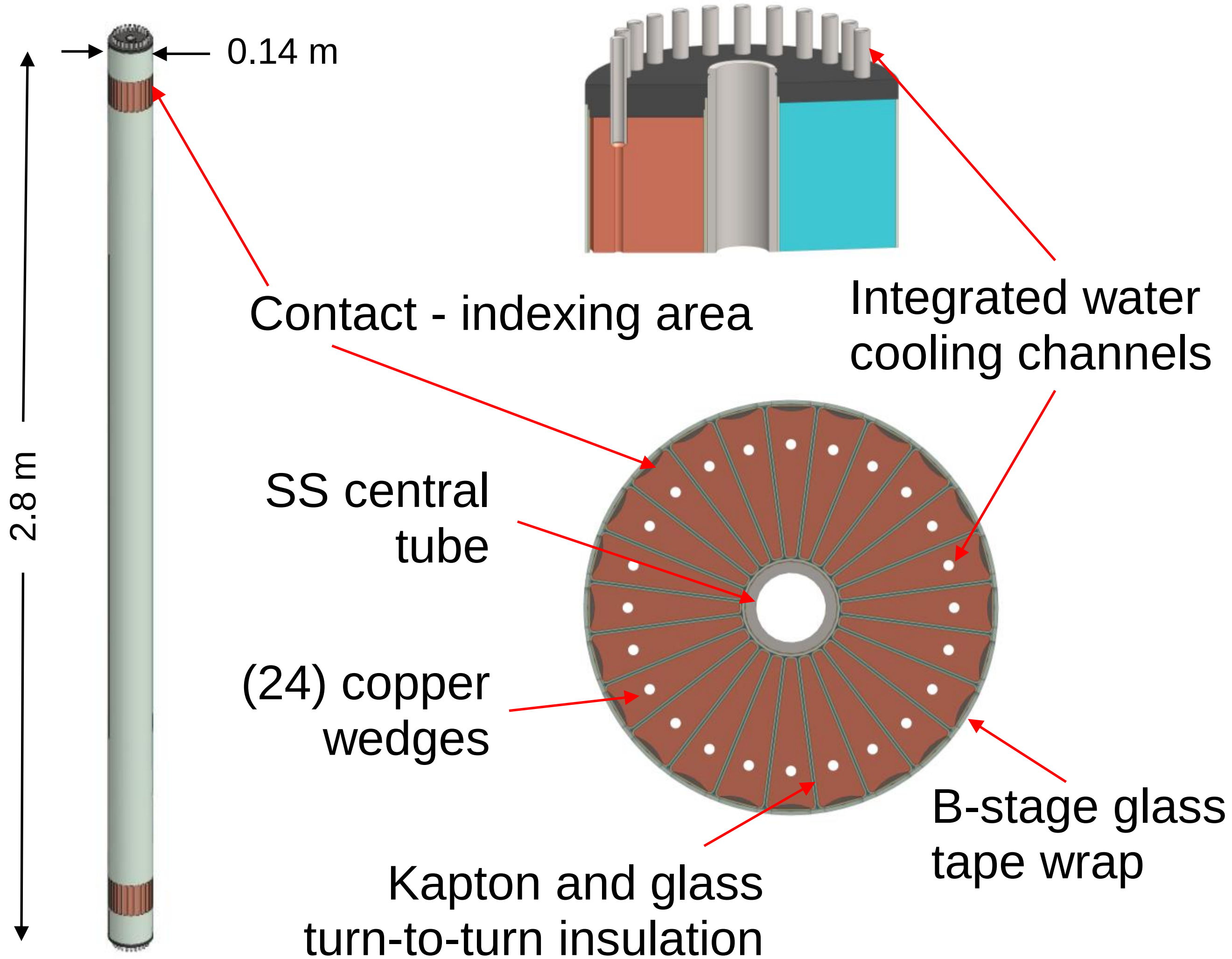
Oak Ridge National Laboratory
PPPL
The University of Wisconsin Madison

PEGASUS-III TF Magnets Consist of 3 Major Subassemblies

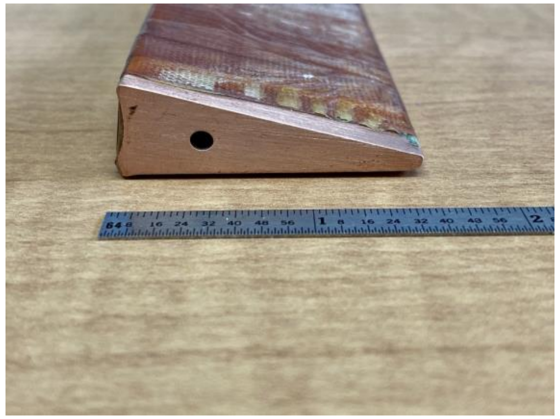


PEGASUS-III Features New 24-Turn TF Bundle Capable of Creating 4x B_T of PEGASUS

TF Bundle

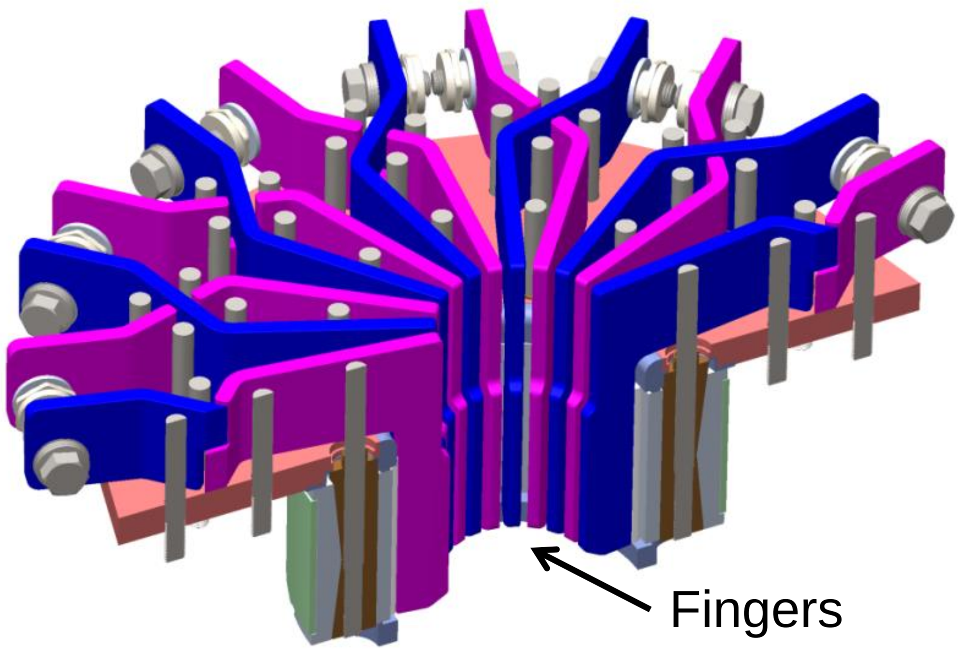


- Maintains access to low-A physics
- 12 → 24 turns
- Expands capability to B_T = 0.6T



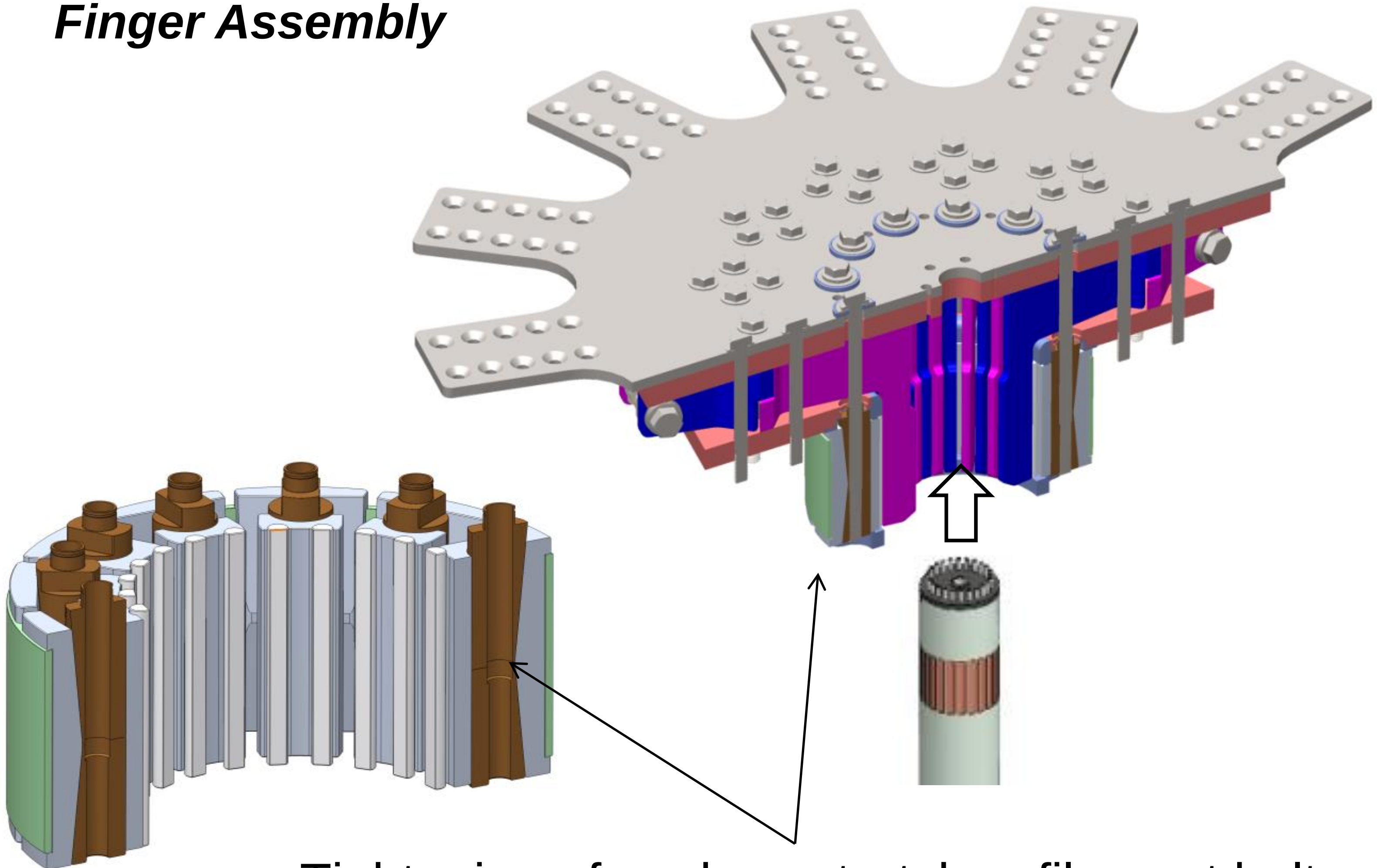
Wedge conductor sample draw for integrity checks

Finger Assembly Satisfies Electro-Mechanical Constraints with Compact Design



- 30N/mm^2 compression provided by Finger Assembly
- Minimizes electrical resistance and prevents slippage

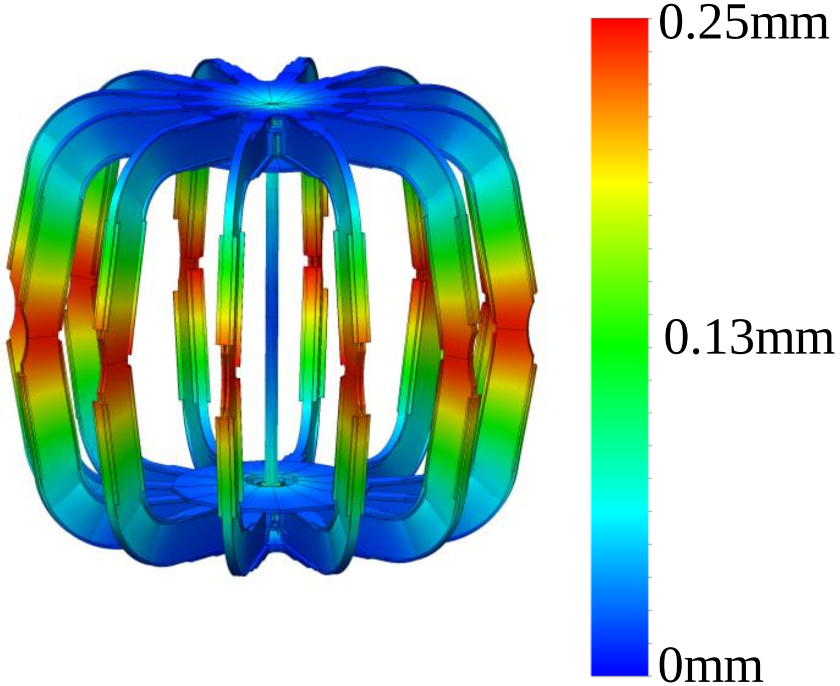
Finger Assembly



- Tightening of wedges stretches filament belt and produces radial compression

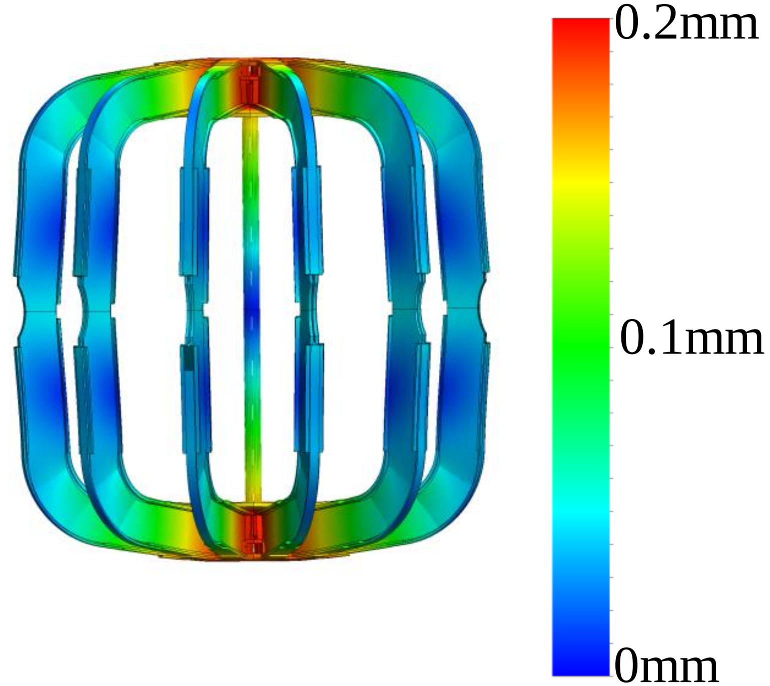
FEM Simulation Captures Range of Structural Behavior

Displacement of Overall Structure:



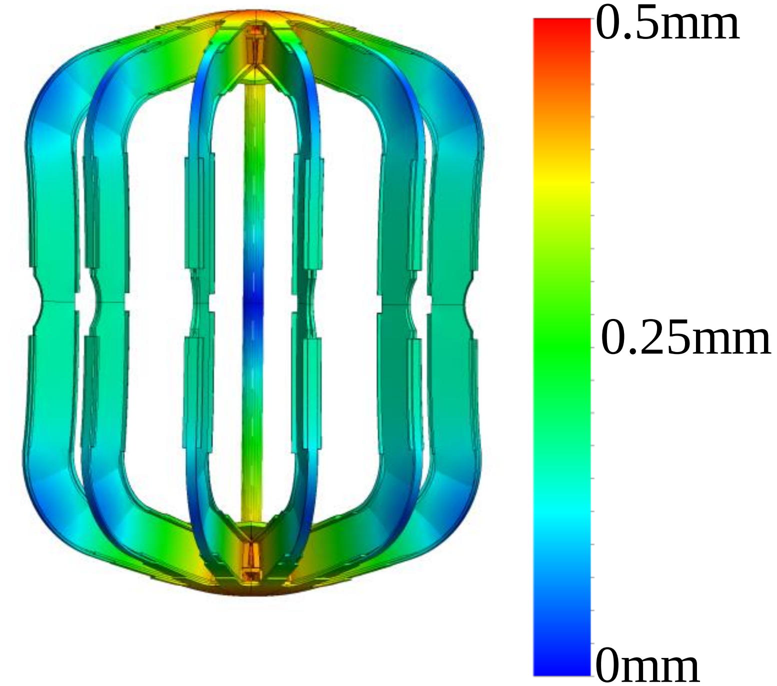
Cold Bundle

$B_T = 0.6T$
$T = 10C$



Initial Temperature

$B_T = 0.6T$
$T = 25C$



Hot Bundle

$B_T = 0.6T$
$T = 40C$

Movement to PEGASUS-III is Underway

- Compare/contrast/combine multiple non-inductive startup techniques in a single facility
  - Local Helicity Injection (LHI)
  - Transient and Sustained Coaxial Helicity Injection (CHI)
  - EBW/EC radiofrequency heating and current drive

- Understanding of LHI processes increasing
  - Handoff to OH with MHD mitigation
  - $T_e(R,t)$ profiles indicate increase with B_T
  - Alfvenic-like fluctuations correlate with I_p
  - Two-zone magnetic geometry suggested

- Operational in 2020
  - New centerstack and TF assembly
  - Expanded power supplies
  - Next-generation LHI current injectors
  - Expanded diagnostics