Integrated Studies of Solenoid-Free Tokamak Startup with PEGASUS-III

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University of Wisconsin-Madison

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Presentation ZP06.00001

PEGASUS-III Experiment

PEGASUS Phase III

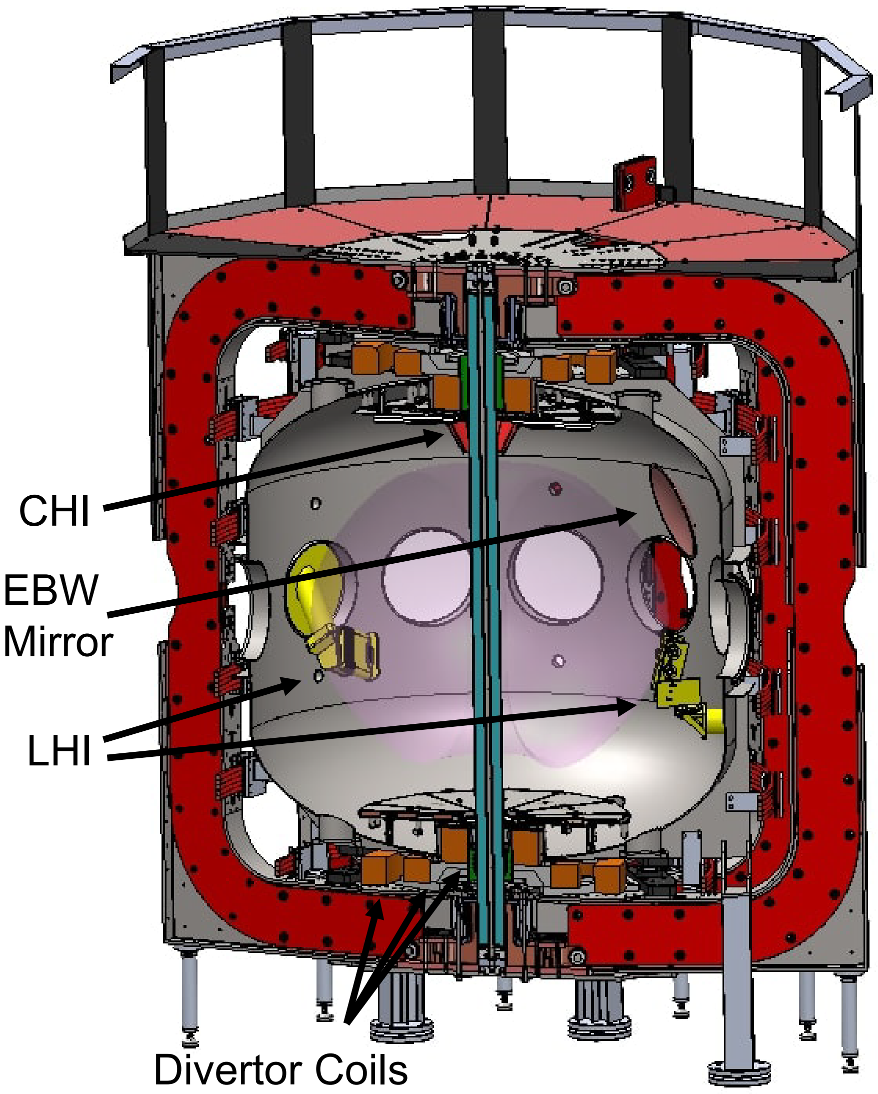
- PEGASUS-III: Motivations for developing non-solenoidal startup techniques
- Overview of approaches to plasma startup using Local Helicity Injection (LHI), Coaxial Helicity Injection (CHI) and Electron Bernstein Wave (EBW) heating & current drive
- Summarize recent work developing LHI on PEGASUS
- Outline the upcoming experimental program following upgrade activities
- Updates on the facility upgrades

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

- Major upgrade to present Phase II PEGASUS facility*

- Compare / contrast / combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - RF assist and sustainment (EBW studies presently, ECH, ECCD in future)
  - Compatibility with NBI heating and current drive

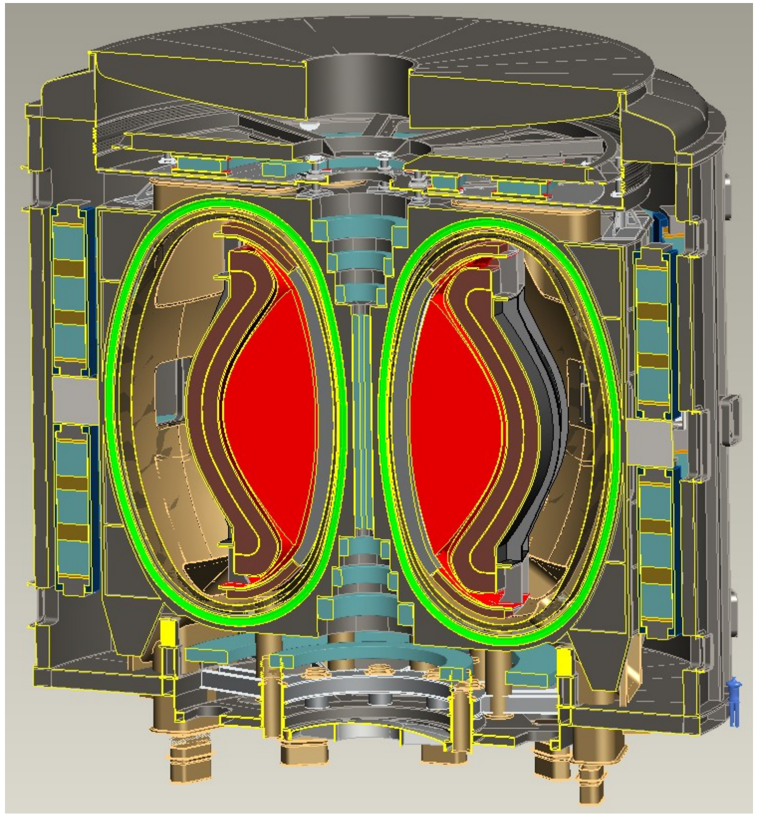
- Goal: develop validated concept, equipment for 1 MA startup on NSTX-U and beyond



*Garstka et al., Nucl. Fusion **46** S603 (2006)

Non-Solenoidal Startup is Critical for the Spherical Tokamak

- Future ST designs call for solenoid-free operation
  - Nuclear STs 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 $J(R)$

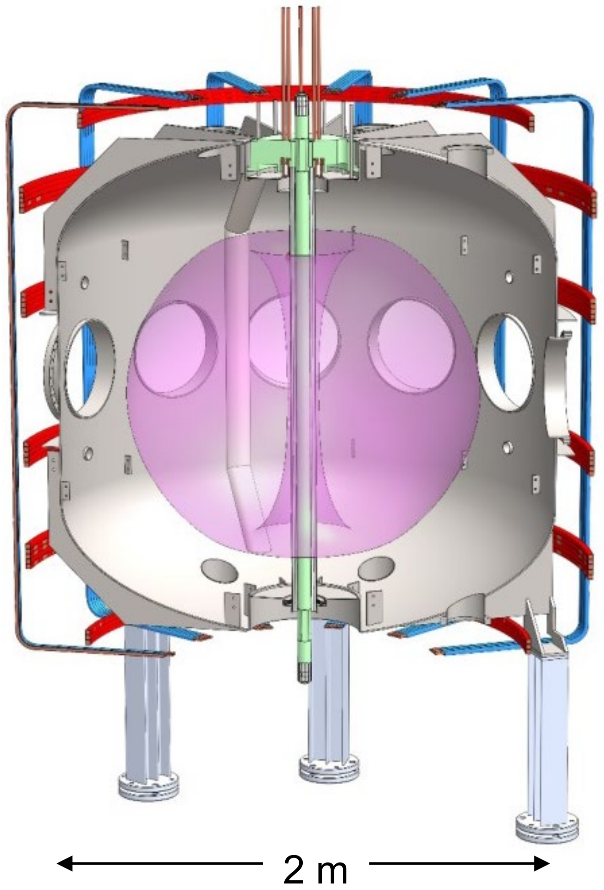


No / small OH HTS ST-FNSF / Pilot Plant

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

PEGASUS-III Upgrades Enable Comparative Study of Multiple Startup Methods

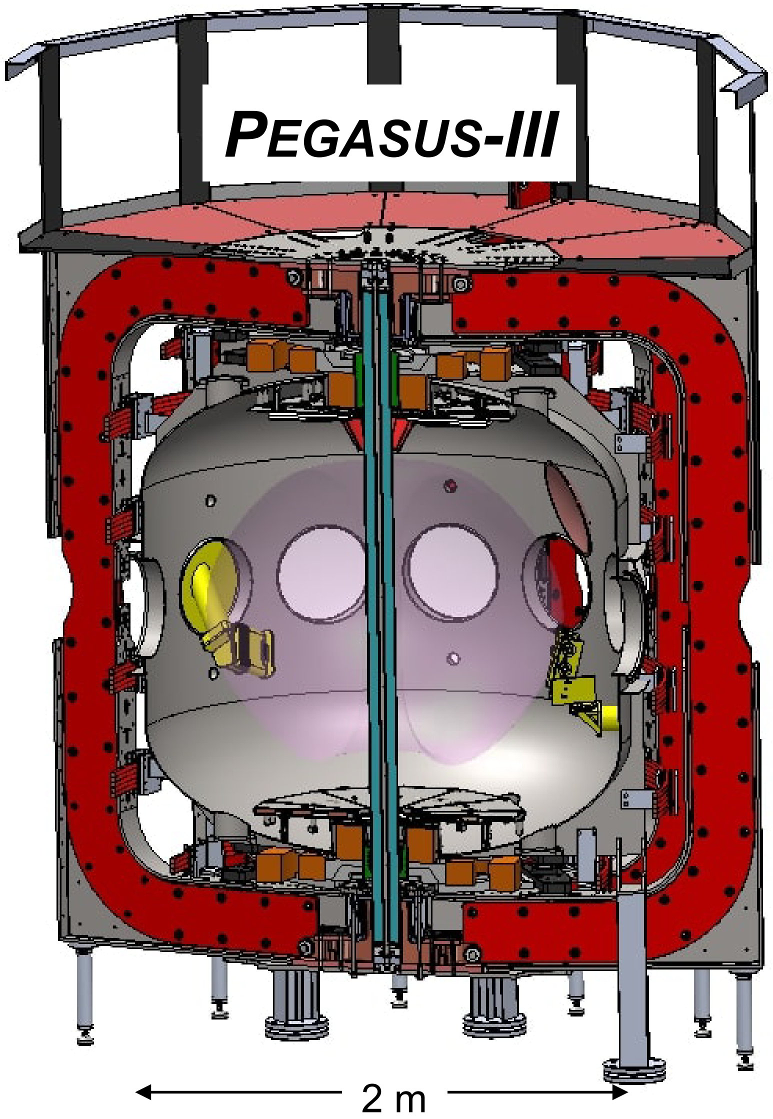
PEGASUS



- 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 $R_0 \sim 0.4$ m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

PEGASUS-III



Helicity Injection and RF startup

- PEGASUS-III: Motivations for developing non-solenoidal startup techniques
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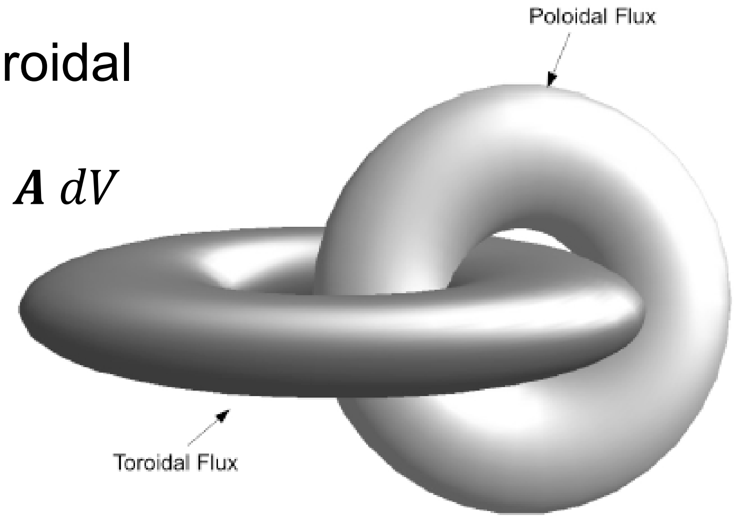
Helicity Injection Techniques Can Initiate and Drive Tokamak Plasmas

- Current drive increases the amount of poloidal flux ψ_p linked with the toroidal flux created by external coils (magnetic helicity)

$$K = \int_V \boldsymbol{B} \cdot \boldsymbol{A}\, dV$$



$$\frac{dK}{dt} = -2\frac{\partial \psi}{\partial t}\Psi - 2\int_S \Phi B \cdot dS - 2\int_V \eta \boldsymbol{J} \cdot \boldsymbol{B} dV$$

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

- DC helicity injection can be represented by an effective loop voltage:

$$V_{LHI} = \frac{\oint_S \Phi\, \vec{B} \cdot d\hat{s}}{\Psi} = \frac{V_{inj} A_{inj} B_{inj}}{\Psi}$$

- Plasma current scales with injector **voltage**, **area**, and **location**

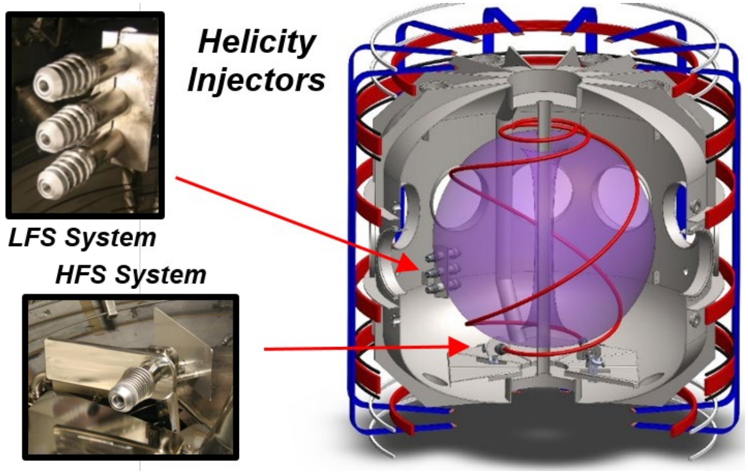
$$I_p = \frac{A_p V_{LHI}}{2\pi R_0 \langle \eta \rangle} \approx \frac{V_{inj} A_{inj}}{2\pi R_0 \langle \eta \rangle}\left(\frac{B_{inj}}{B_0}\right)$$

- Taylor relaxation limits I_p to lowest energy state that conserves K

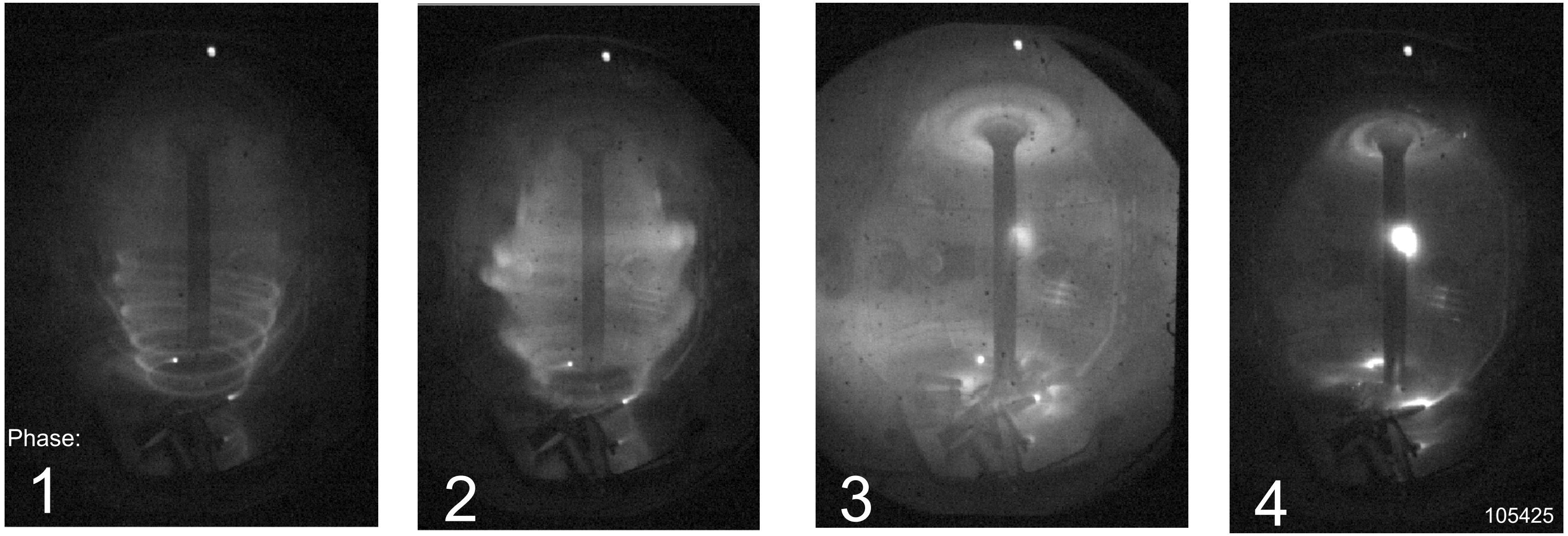
$$\lambda \equiv \frac{\vec{J} \cdot \vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \quad \rightarrow \quad \boxed{I_p \le I_{inj} \frac{\phi_p}{\psi_{inj}}}$$

Two extremes:
- LHI: Local, small-aperture sources
- CHI: Large, coaxial electrodes

Local Helicity Injection: Edge-localized Sources Inject Current Streams That Reconnect, Form Tokamak-like Plasma

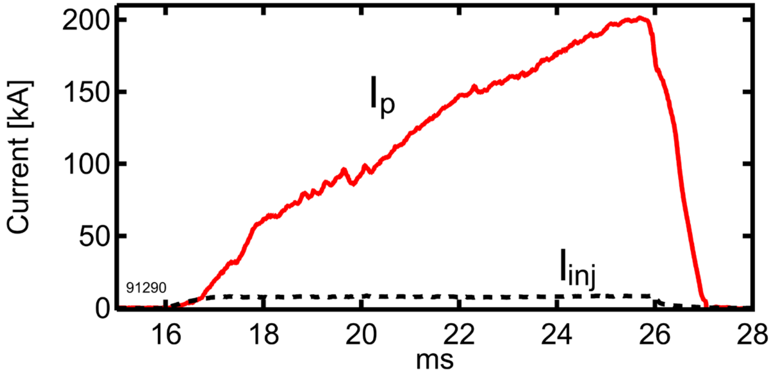


LHI Startup Scenario Temporal Evolution



1. Local plasma sources create helical plasma streams along field lines
2. Current driven along streams leads to helicity-conserving instabilities
3. Current streams reconnect and relax to a tokamak-like state, current grows
4. Decaying tokamak plasma after injectors terminate

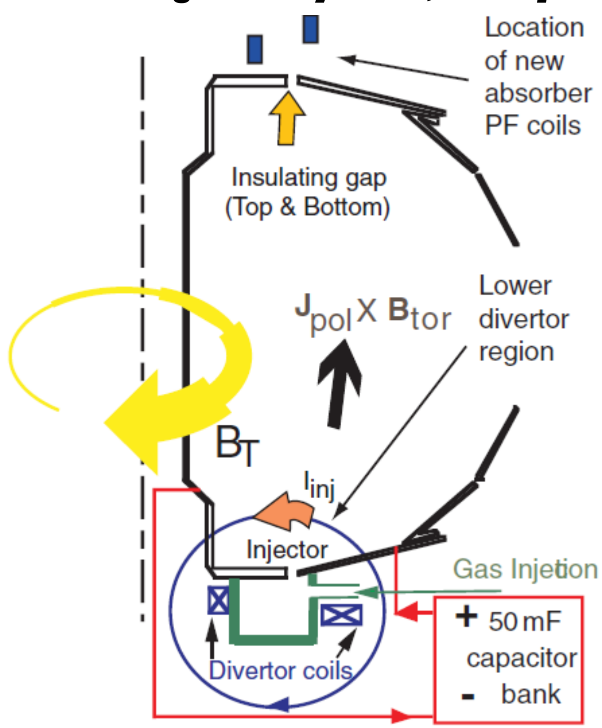
LHI Produces High-I_p = 0.2 MA Tokamak Plasma (I_{inj} ≤ 8 kA)



*Battaglia et al., Nucl. Fusion **51** 073029 (2011)*
*Perry et al., Nucl. Fusion **58**, 096002 (2018)*
*Bongard et al., Nucl. Fusion **59**, 076003 (2019)*

Coaxial Helicity Injection: Axisymmetric Electrodes Drive Poloidal Current Into A "Magnetic Bubble"

CHI via Biased Vacuum Vessel Segments [NSTX, HIT-II]



Drive sufficient current along open field lines to overcome field line tension and allow the injected poloidal flux to expand into the vessel

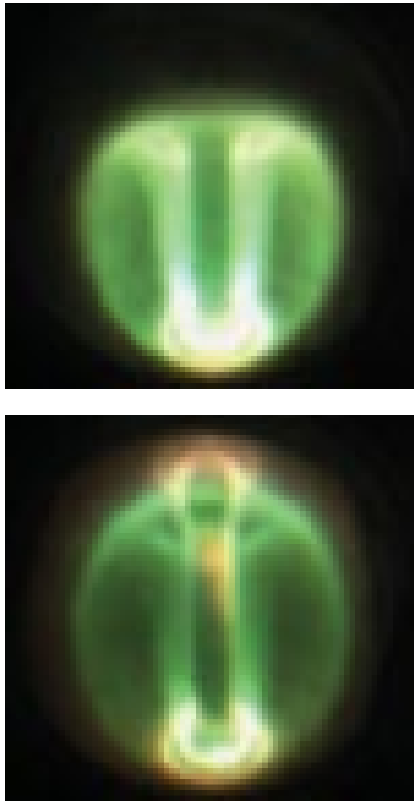
Two techniques:

- Transient (T-CHI): stretch connected flux and quickly force reconnection to create closed flux by terminating injection
- Sustained (S-CHI): build up connected flux by continued current drive

"Bubble burst" condition requires threshold $J \times B$ stress across the current layer to overcome field line tension

$$I_{inj} = \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}$$

T-CHI in NSTX

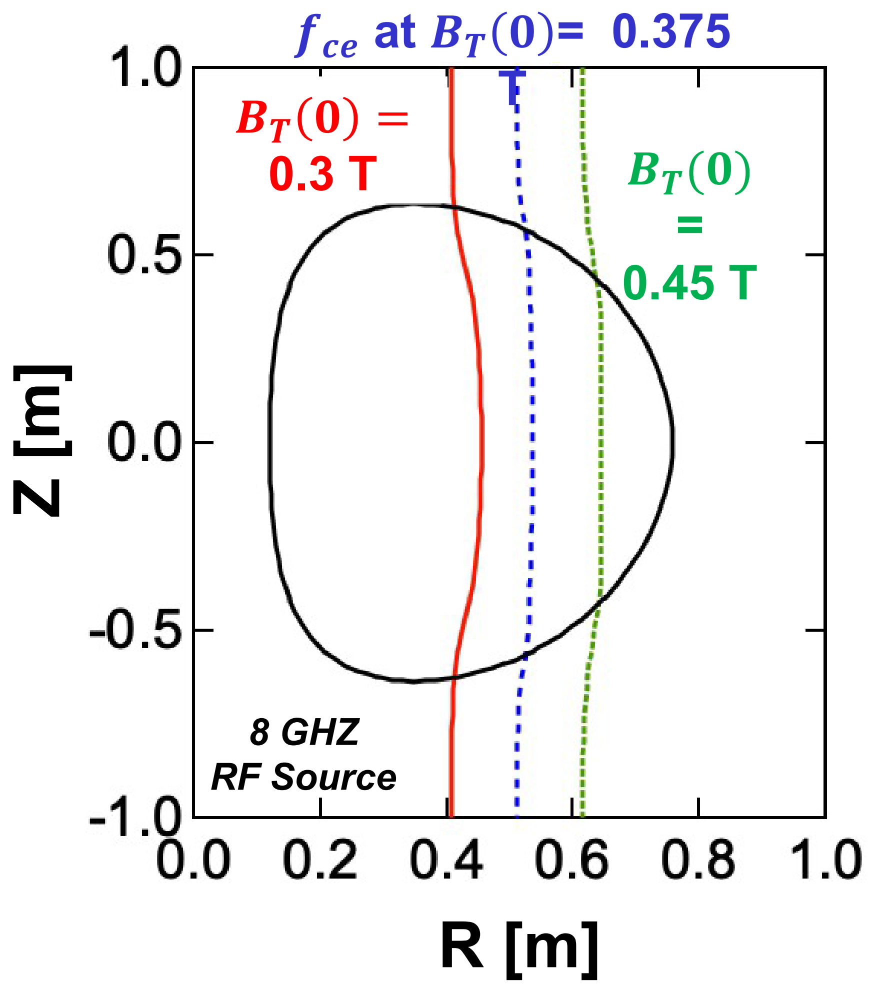


R. Raman et al., *Nucl. Fusion* **53** (2013)
R. Raman et al., *Fusion Sci. Tech.* **68** (2015)

RF Heating and Current Drive Can Enhance Helicity Injection

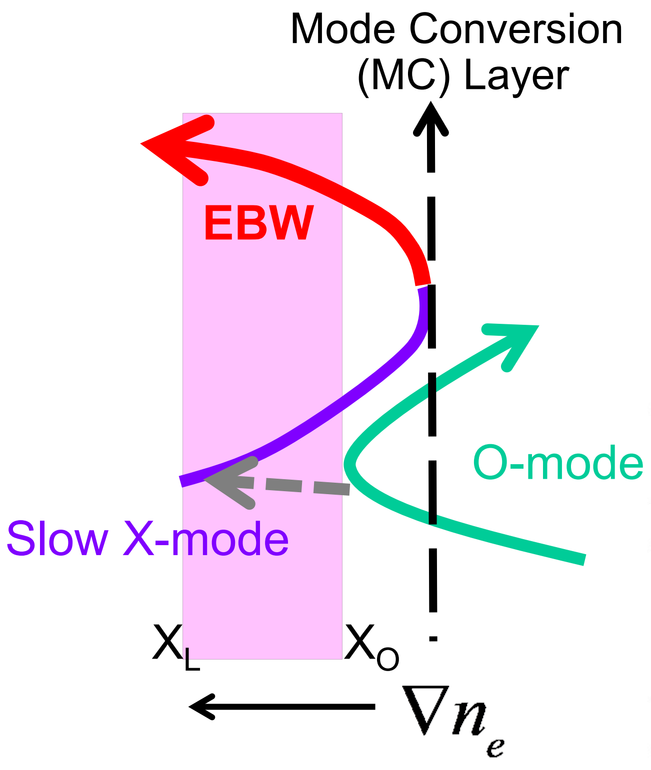
- RF heating can work synergistically with LHI/CHI by:
  - Lowering resistivity to reduce helicity dissipation
  - Freezing the low-inductance helicity-driven current profile
  - Providing $J(R)$ tailoring for improved MHD stability
  - Lengthening the slowing down time of fast ions for NBCD
- PEGASUS-III will explore these effects with a 0.5 MW 8 GHz electron Bernstein wave (EBW) RF system
  - Suitable for overdense ST plasmas for heating & CD
  - Significant heating capability (0.4 MW)
  - Modest current drive capability for RF sustainment tests
- Future: expand RF capability to include 28 GHz ECH/ECCD
  - RF heating and current drive at higher B_T
  - Enhance EBW CD efficiency
  - Direct RF startup studies

Range of EBW Absorption Locations Available in PEGASUS-III

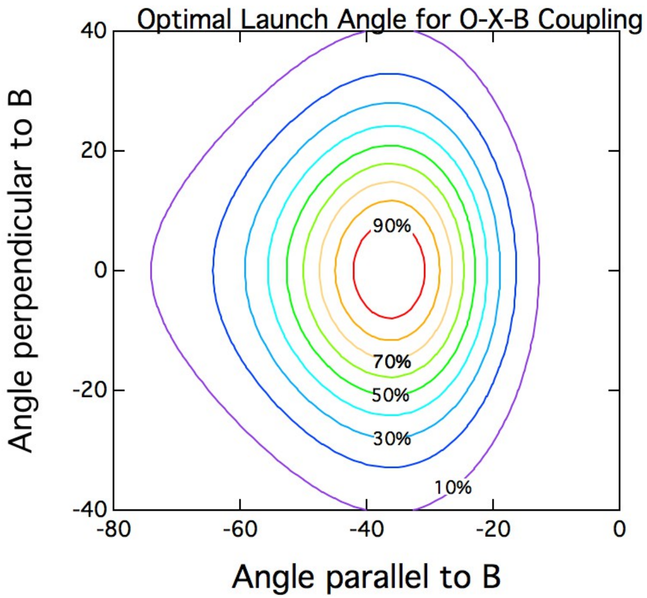


Electron Bernstein Waves Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, $k_{\|}=0$
  - No density cutoff
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum, requires coupling
- Coupling efficiency depends :
  - Density gradient
  - Magnetic field pitch
- Provide a means of localized heating and current drive in helicity injected plasmas



O-mode launch from outboard midplane provides convenient access



Direct X-mode launch possible from inboard side

Summary of Recent Work on PEGASUS

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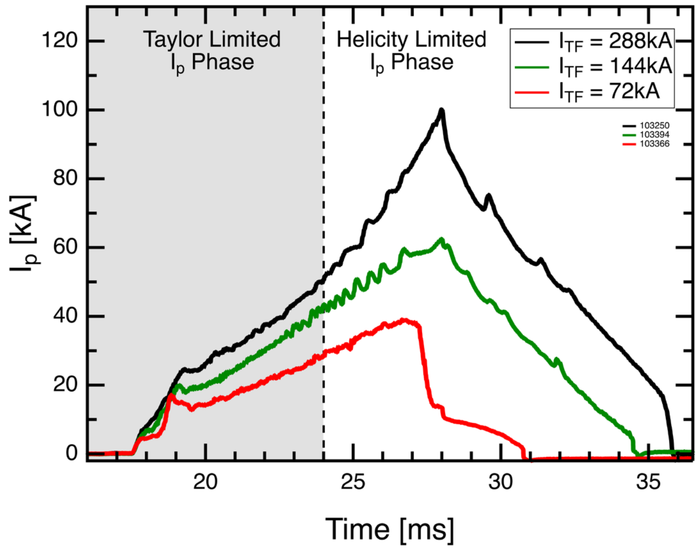
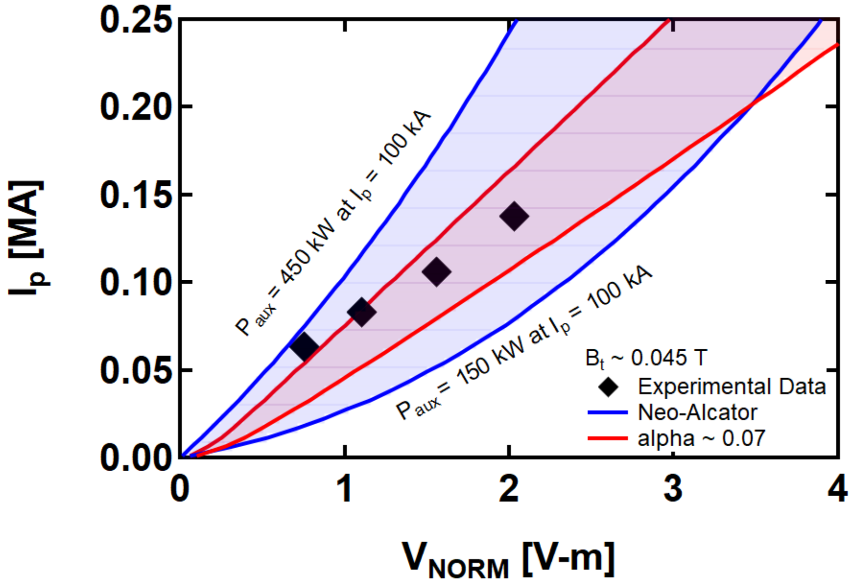
Recent Work on PEGASUS Has Refined the Understanding of LHI-Driven Startup Plasmas

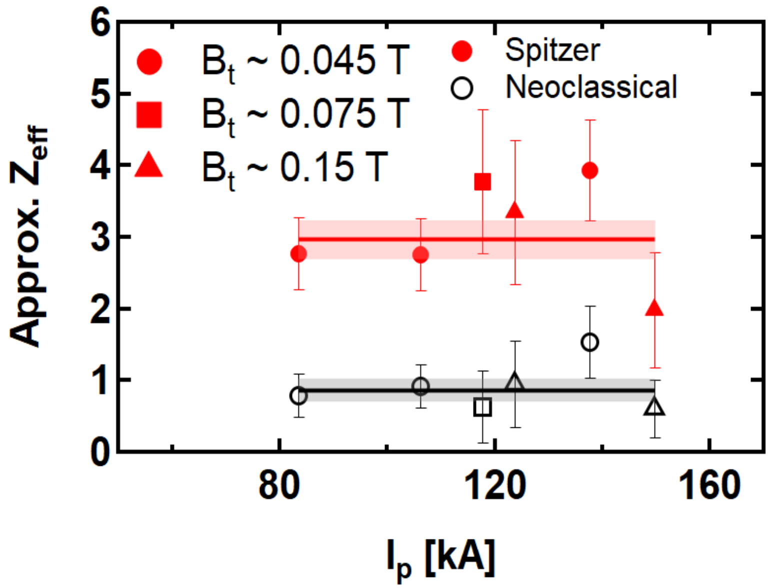
PEGASUS B_T Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



I_p Scaling Assuming Linear Ohmic or Stochastic Confinement Regimes



Z_{eff} Scaling with I_p Determined From Volume-Averaged Resistivity



Helicity Injection limits:

I_p increased with B_T by raising Taylor-limit early in current ramp

Confinement:

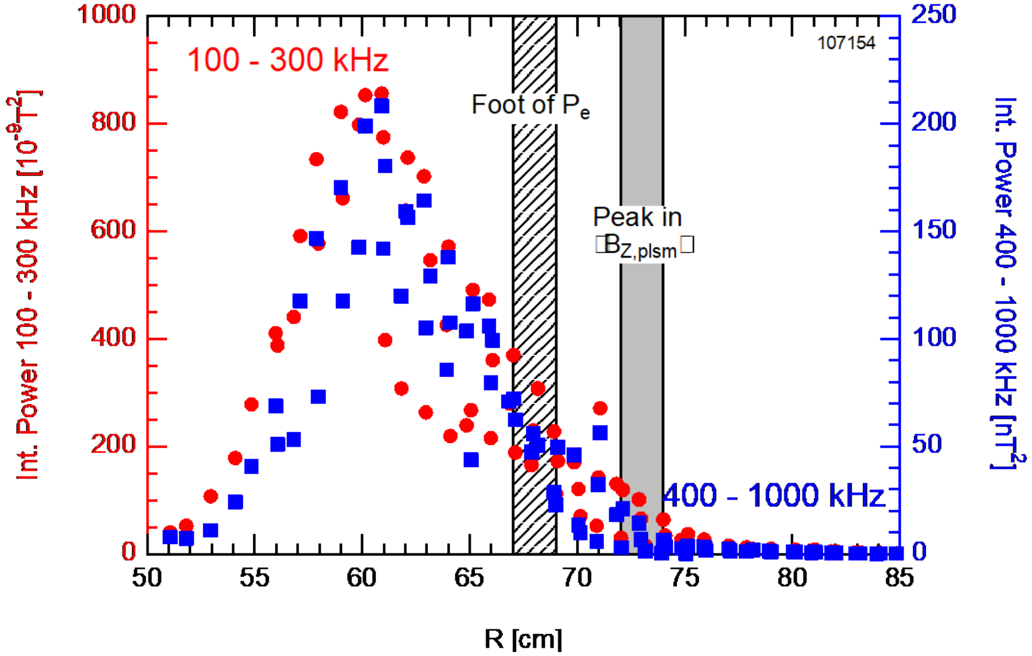
Predictive model requires $\eta(T_e)$ evolution; at low B_T typical turbulent scale length much larger than $\tilde{B}$ scale length; suggests cross-field transport may be important

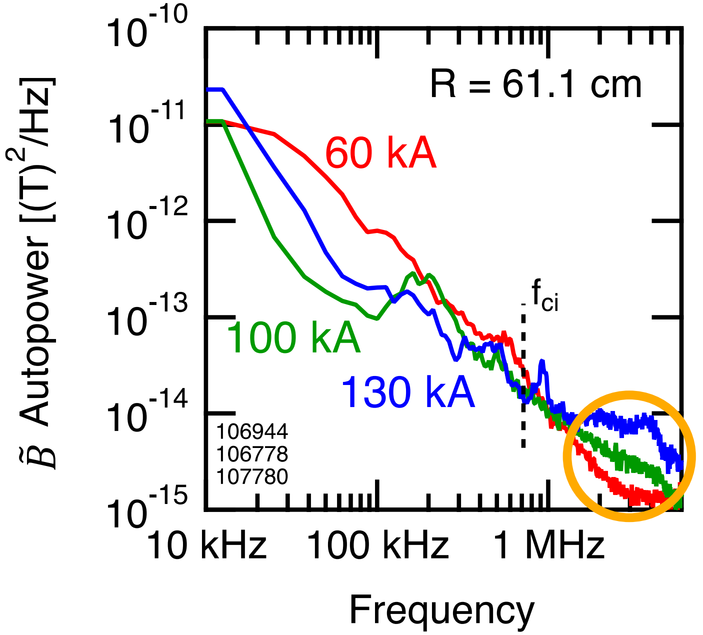
Plasma Material Interaction:

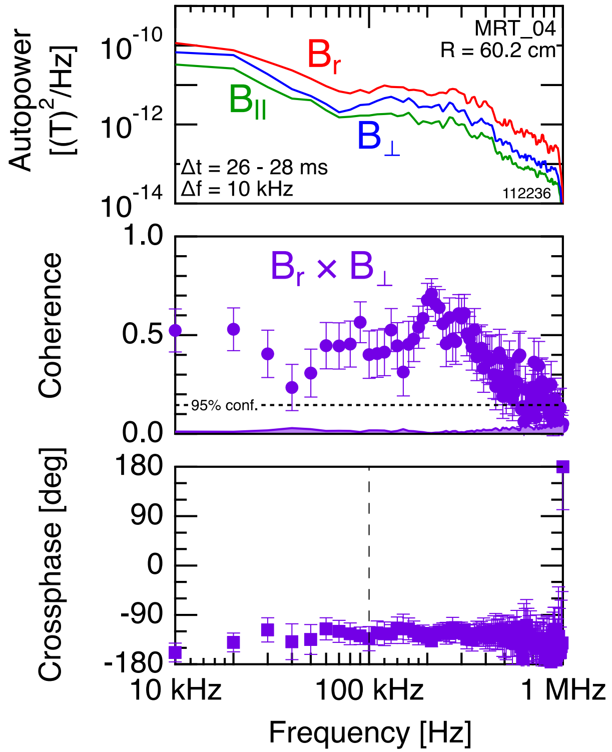
$\langle Z_{eff} \rangle$ ~ 1 derived from plasma neoclassical conductivity

G.M. Bodner NO07.00001 Wed. 9:30AM

Edge-localized $\tilde{B}$ Scales with I_p and Has Co-current Magnetic Helicity From MHD to Kinetic Scales







Broadband $\tilde{B}$ radial extent is ~ ρ_s with radial correlation lengths only 1-3 cm and evidence of shorter correlation lengths for higher frequencies

Only the highest-frequency (smallest scale) fluctuations scale with achieved I_p

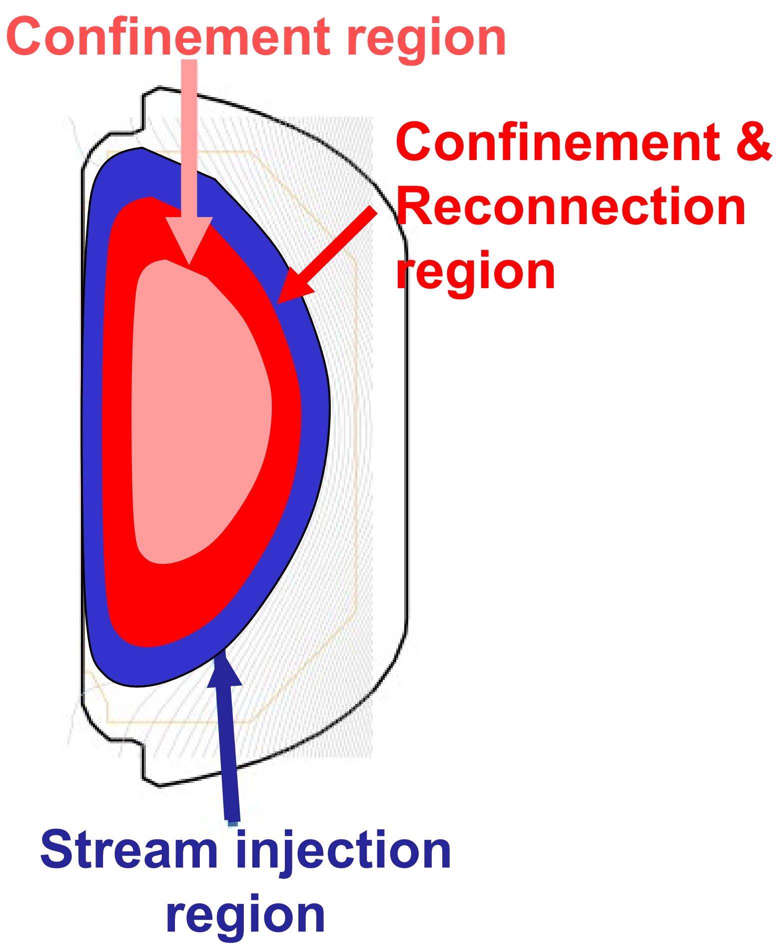
Both broadband and kinetic-scale fluctuations have $-90°$ cross-phase indicating co-current helicity consistent with Taylor's hypothesis

N.J. Richner ZP06.00003 Fri. 9:30AM

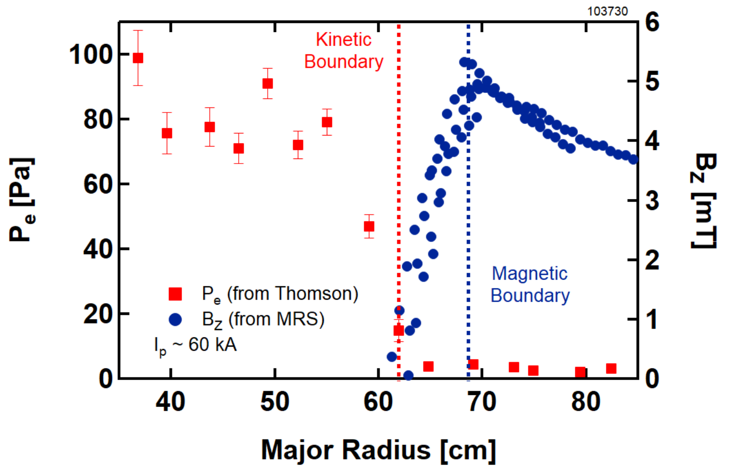
Observations Suggest Sustained Injection Has Region of Magnetic Reconnection in Edge with Quiescent Core

- Stream injection region
  - Force-free current streams in dynamic helical equilibrium
- Reconnection Region
  - Localization of high-frequency $\tilde{B}$ and anomalous ion heating*
  - Good confinement indicated by co-location with pressure gradient
- Confinement Region
  - Tokamak-like toroidally-averaged closed flux surfaces

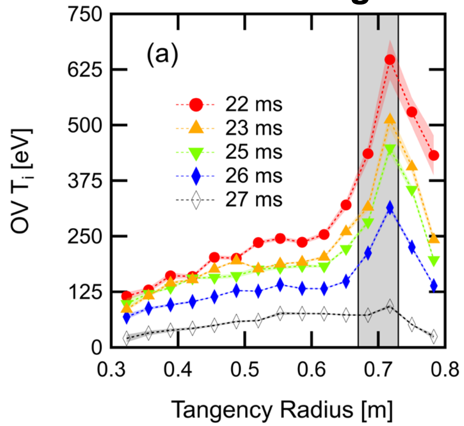
Multi-Zone LHI Confinement Hypothesis



Overlapping Regions of Confined, MHD Turbulent, and Force-Free Plasmas in LHI



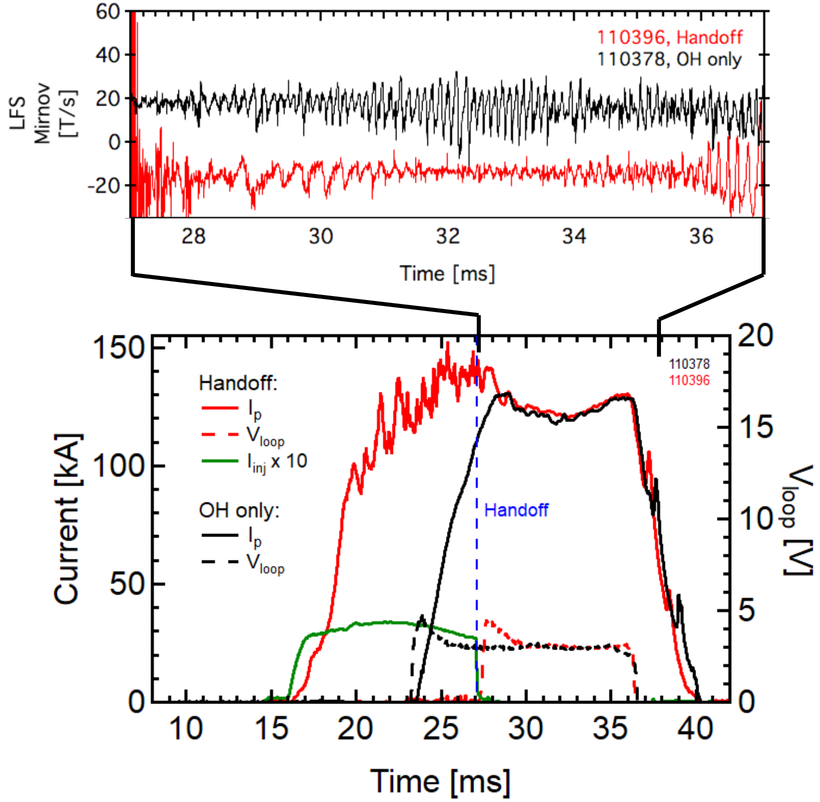
Edge-Localized Reconnection-Driven Ti during LHI*



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

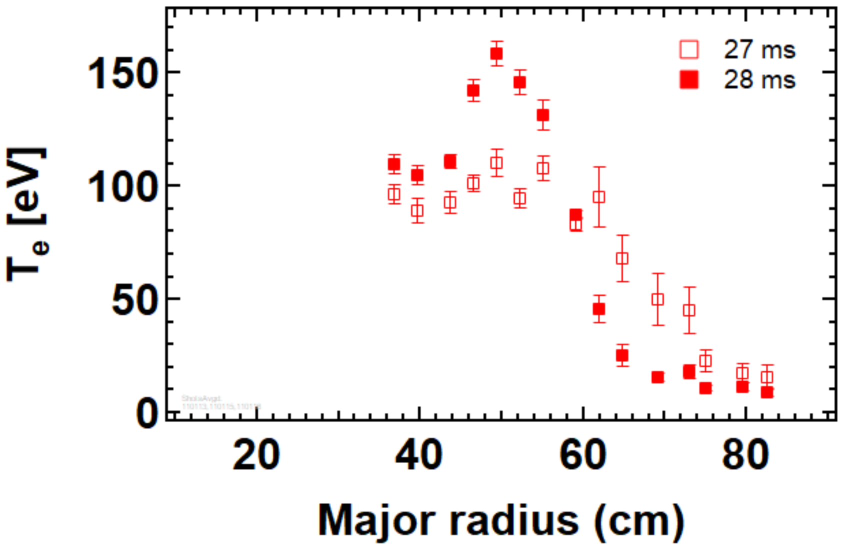
LHI Handoff to Ohmic Drive Shows Benefits From MHD Stability and Core Auxiliary Heating

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



Edge LHI establishes low ℓ_i targets that maintain good MHD stability through transition to ohmic induction

LHI/OH overlap, T_e maintained



Ohmic induction during helicity injection provides additional core heating

Suggests synergies with core auxiliary heating

C. Pierren ZP06.00004 Fri. 9:30AM

PEGASUS III Experimental Program

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Projecting LHI to Larger Facilities Requires Tests at Increasing B_T

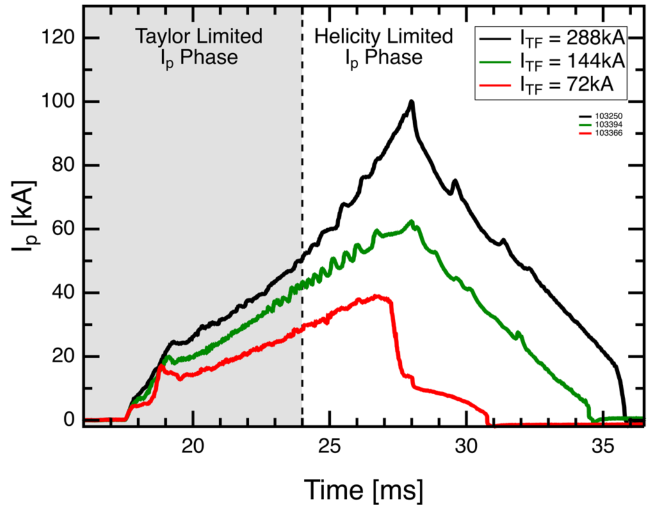
Physics

- Realize the increased I_p expected with higher B_T
- Test projection of core confinement models
- Further explore role of short-wavelength fluctuations in current drive and relaxation mechanisms
- Determine role of current stream instabilities in helicity transport
- Provide access to RF resonances for auxiliary heating and CD

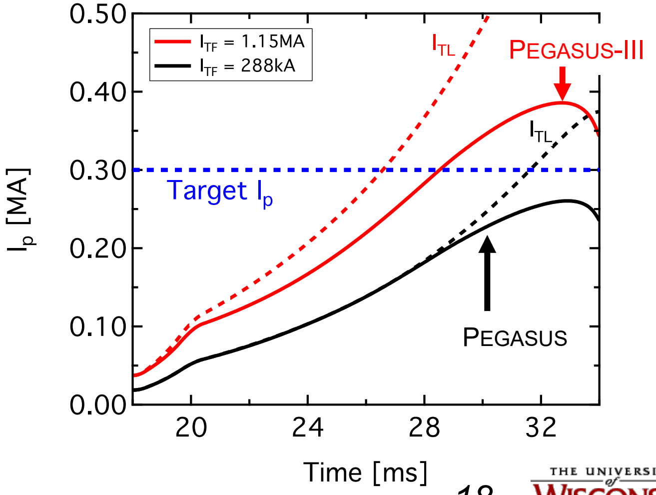
Technology

- Optimized geometry for reduced V_{inj} and improved reliability
- Exploit fueling and V_{inj} control for effective loop voltage control
- Minimize need for, duration of injector conditioning
- Optimize injector control & material selection to minimize PMI
- Develop long-pulse capabilities

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

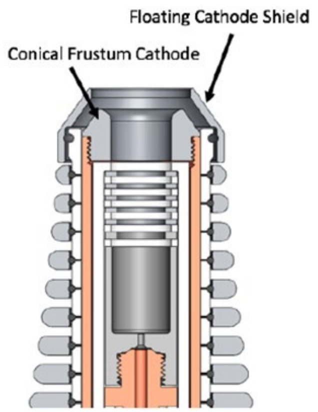


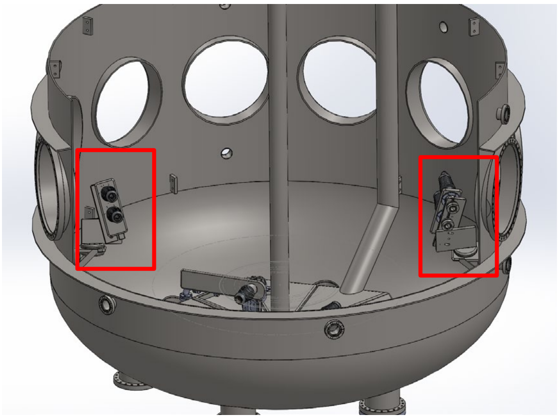
0-D Power-Balance Projections for LHI on PEGASUS-III



First LHI Experimental Campaigns Will Employ Complimentary LHI Systems

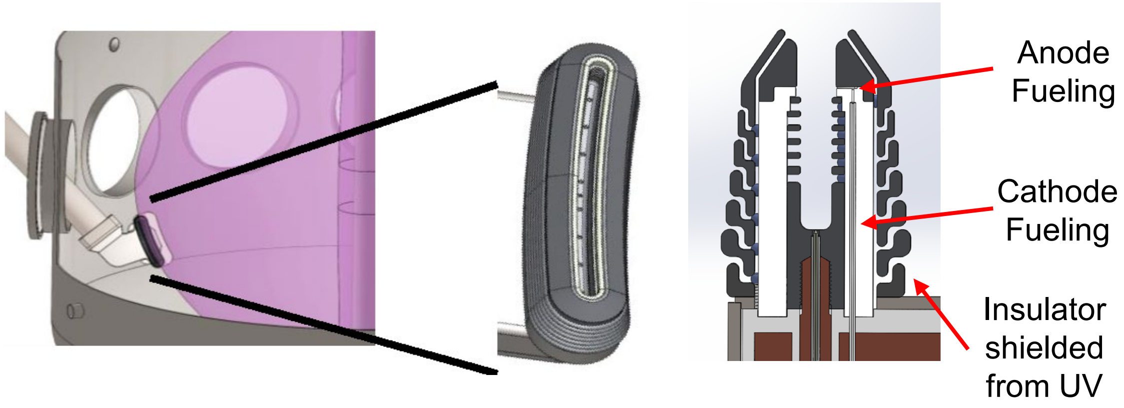
Two Arrays of 2×4 cm² Circular Injectors





- Proven injector design, high confidence in demonstrating 300 kA current at 0.3 T
  - Total $A_{inj} = 16\ \mathrm{cm}^2$; $I_{inj} \leq 16\ \mathrm{kA}$, $4\ \mathrm{kA/injector}$
- Develop MHD-stable startup scenarios to handoff to non-inductive sustainment
- Study helicity drive via dynamo & kinetic mechanisms due to flux rope merging and beam instabilities
- Test proposed transport models to determine $\langle T_e \rangle$ evolution
- Quantify impurity sourcing with increasing injected power

Advanced Non-circular Injector in PEGASUS-III



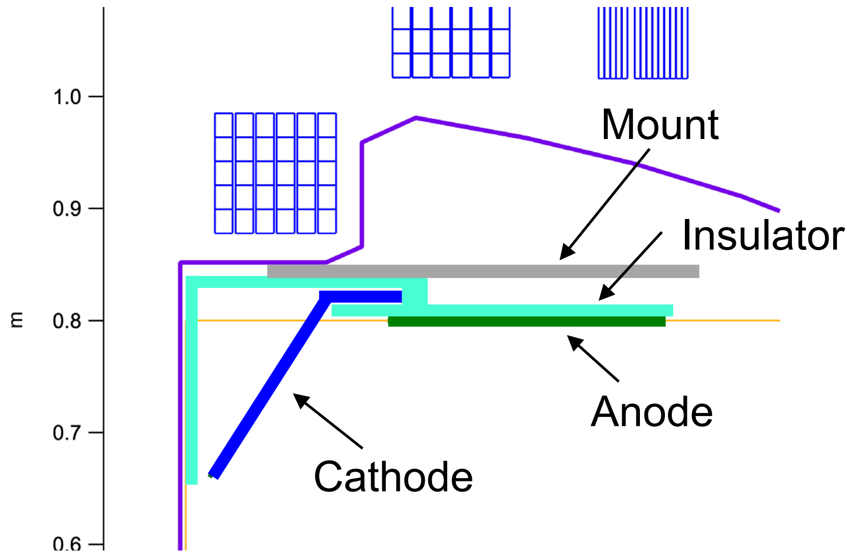
- Port mounted monolithic injector appropriate for fielding on NSTX-U and beyond
  - $A_{inj} = 16\ \mathrm{cm}^2$, $I_{inj} \leq 8\ \mathrm{kA}$, $w_{inj} = 1\ \mathrm{cm}$
- Smaller radial width optimizes helicity drive and Taylor-limit

$$I_{p,TL} = I_{inj}\frac{\phi_p}{\psi_{inj}} \propto \sqrt{\frac{I_{inj}I_{TF}}{w_{inj}}}$$

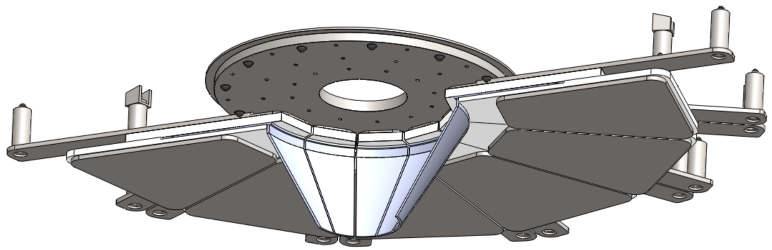
- Anode fueling may allow changing I_{inj} stability characteristics
- Study changes to helicity drive due to current sheet geometry

- Quantify and validate design criteria for high-I_p CHI
  - Dual insulated electrodes: no vessel break required
  - Support CHI-driven plasmas to machine PF limits ($I_p \sim 0.3$ MA)
  - Segmented design to test axisymmetry of current extraction
  - Explore the importance of the flux distribution across the electrodes by broadening the flux across the outer electrode
- Evaluate role of impurities in T-CHI, S-CHI
  - Demountable electrode segments: test refractory material
  - Confinement impact in S-CHI scenarios
- Explore the continuum of injector area
  - CHI maximizes injector area in comparison with LHI
  - By constraining the active segments of the electrode assembly we can test effects of non-axisymmetry on relaxation physics.

2D Sketch of Electrode Plate Concept



3D Sketch of Electrode Plate Concept



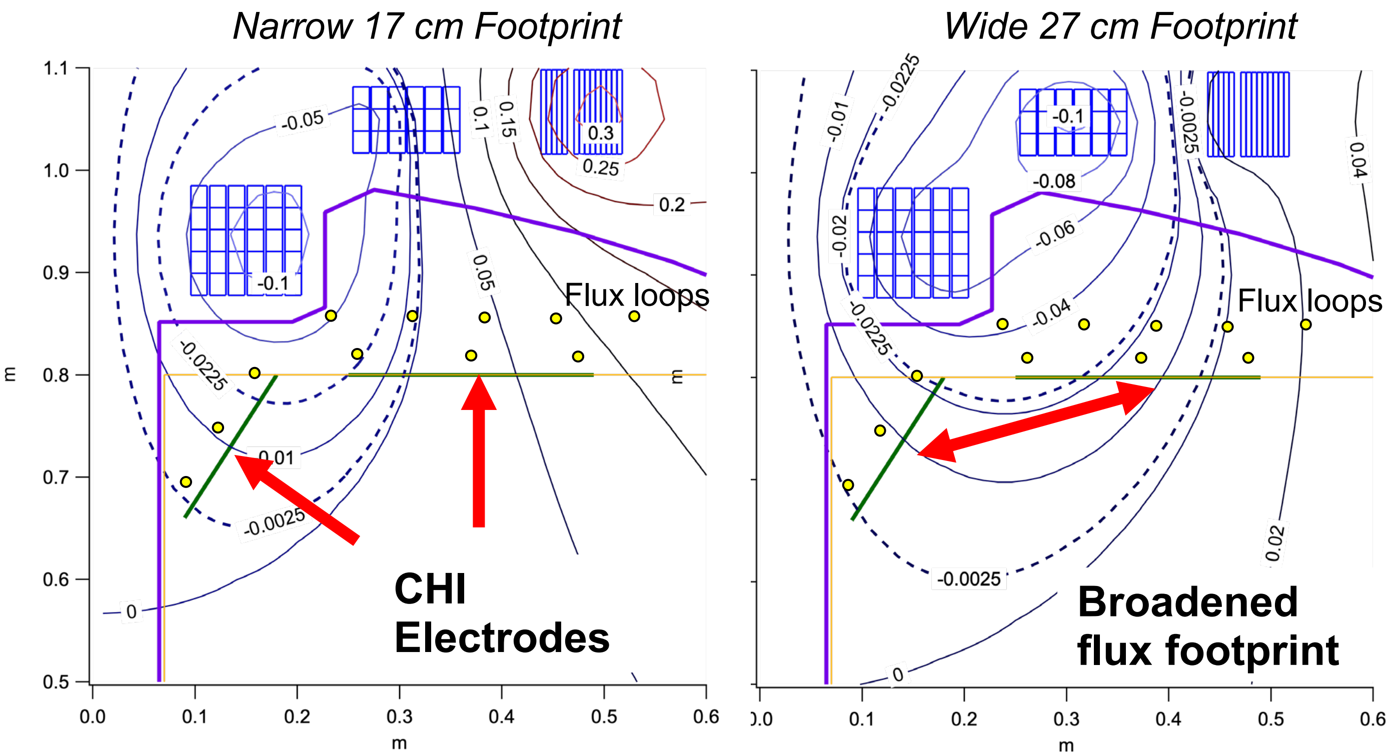
New Flexible Divertor Fields Enable Tests of T-CHI & S-CHI Performance with Footprint Separation

- Ability to modify flux distribution across the outer electrode allows tests of bubble burst scaling and Taylor limit

$$I_{inj} = \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}} \qquad I_p < I_{inj}\left(\frac{\phi_p}{\psi_{inj}}\right)$$

- Predictions of the extracted injector current from the bubble burst scale strongly with d, ψ_{inj}

- Flux conversion efficiency in T-CHI and flux amplification in S-CHI both scale with d



T-CHI power supply provided by U. Wash

S-CHI will use LHI cascaded multi-level invertor

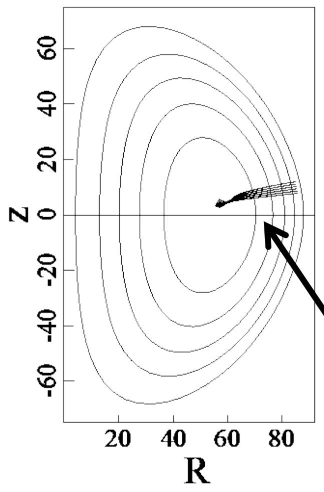
Initial EBW Heating Experiments Seek to Enhance LHI & CHI Current Drive

- Experimental target of injecting 400 kW
  - Source frequency of 8 GHz launched into decaying LHI-produced plasma ($B_T = 0.339$ T)
  - Poloidal launch angle of 30 above midplane
    $n_{\|} = -0.55$ to -0.45
  - Current drive comparable to on-axis current density from LHI
  - Varying B_T can be used to change absorption location

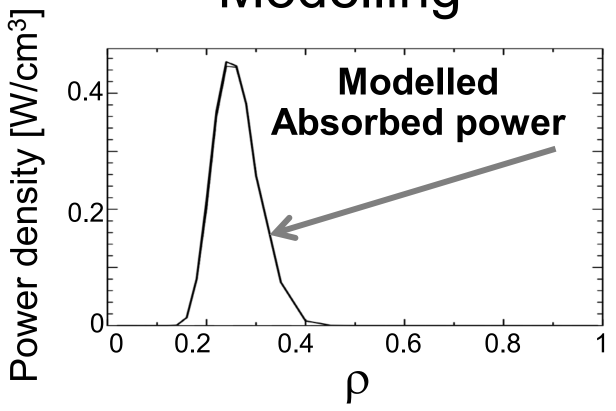
- Test EBW drive concurrent with LHI
  - Increasing T_e can increase current drive efficiency
  - Explore tailoring the current profile

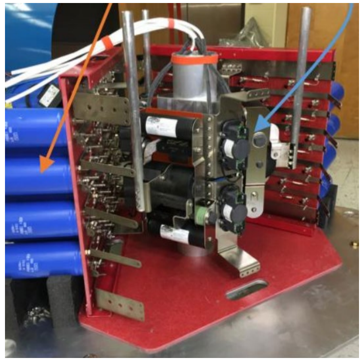
S.J. Diem NO07.00002 Wed. 9:30AM

GENRAY Ray-tracing



CQL3D Modelling





Klystrons supplied by DC-DC resonant supplies developed for DNB

PEGASUS-III Upgrades

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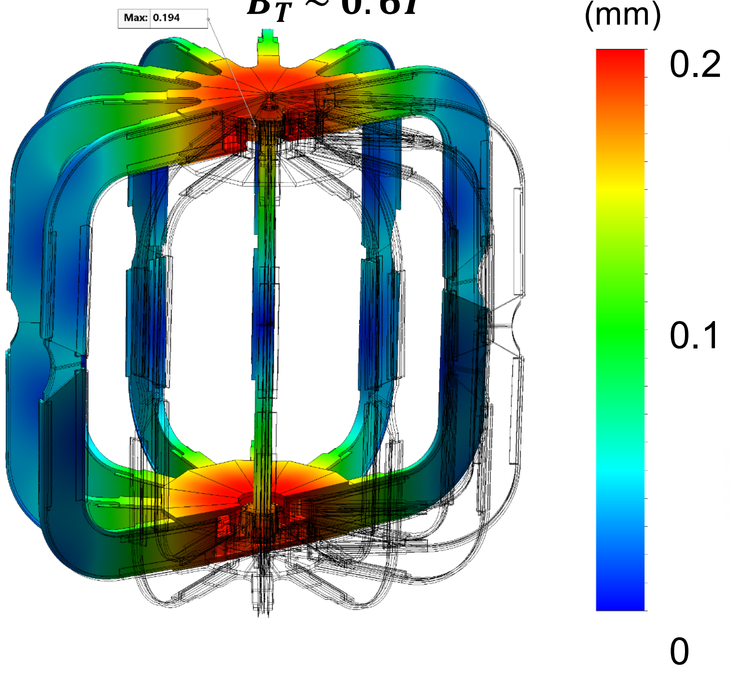
Central to PEGASUS-III mission is an Increased Toroidal Field, Requiring a New Center Column, Support Assembly, and TF Return Conductors

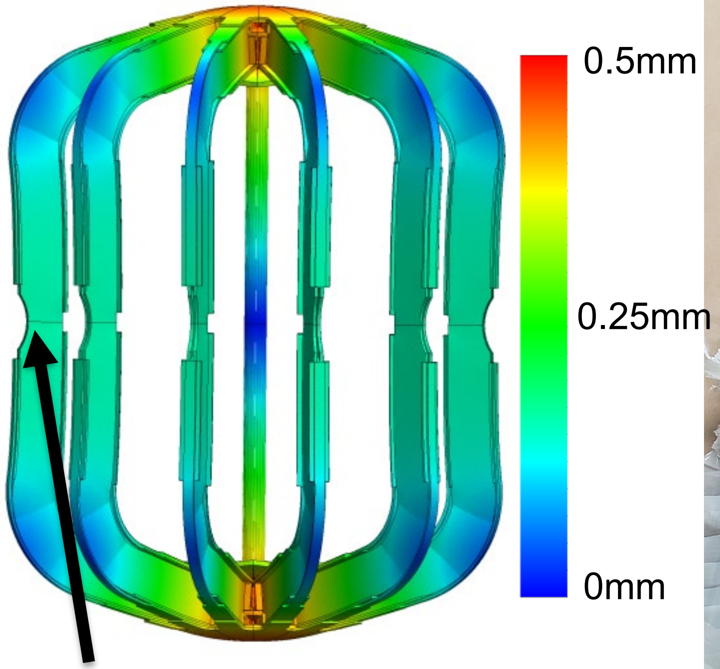
- New, 24 turn toroidal field bundle and center column *without* central Ohmic solenoid is designed for up to 0.6 T

Displacement at 20°C

$B_T \sim 0.6T$



Displacement at 40°C



Complete electromechanical design & analysis of TF system

Flex joint relieves thermal stresses while opposing magnetic stresses

TF center rod, conductors, & return structures delivered

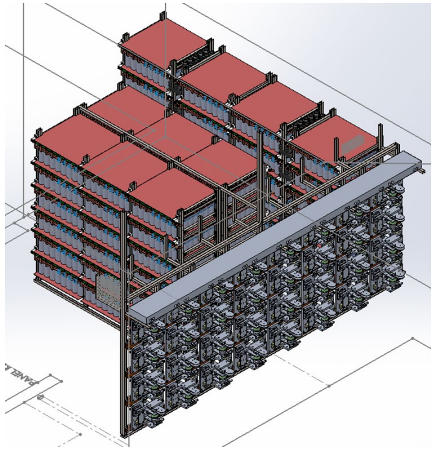
Expanded Set of Programmable Switching Power Amplifiers to Supply 240 MVA for Electromagnets

- Reconfigured Switching Power Amplifiers
  - 32 independent 4 kA 900V IGBT for coils
  - Expansion to 40 units planned

- Replaced and expanded stored energy
  - 3.0 MJ for Toroidal Field Power Supply
  - 1.7 MJ for Poloidal Field & Divertor Power Supplies
  - 1.7 MJ for LHI Arc & Bias Power Supplies

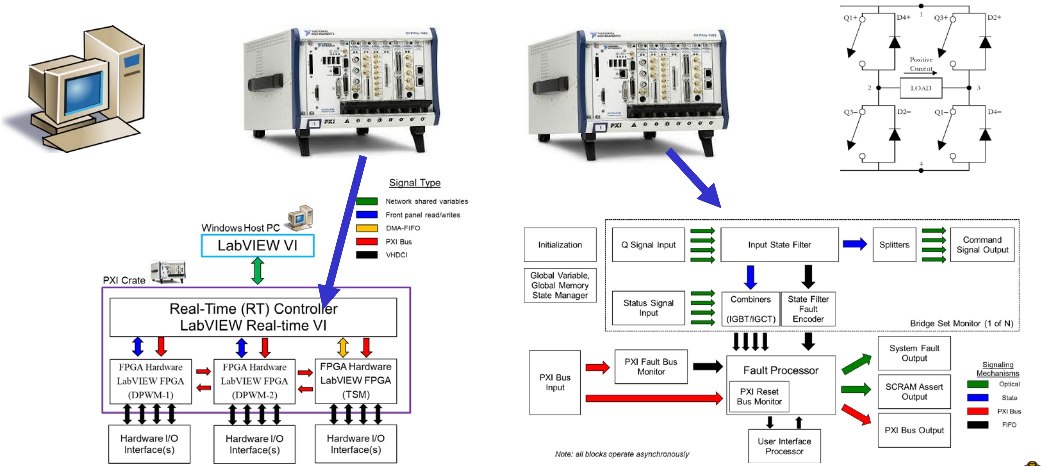
- Fully digital facility timing, control, and protection
  - 16 coil set feedback controllers, 15 kHz PID loop rate
  - FPGA-generated timing and triggering distribution
  - Continuous hardware fault protection on < 10 μs timescales

New TF/PF Energy Storage and Switchyard Built



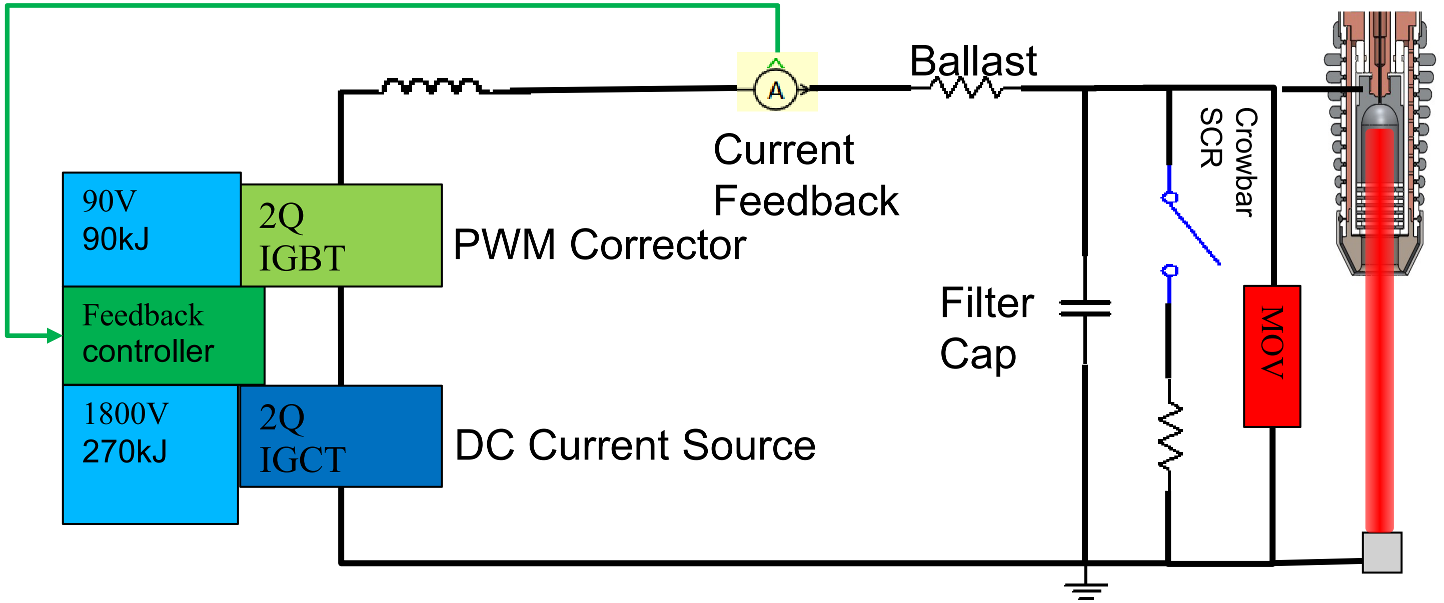
New PEGASUS-III Control Systems

Operations | RT Host + FPGA Feedback/Timing | FPGA Bridge Interface, Hardware Protection | SPA H-Bridge

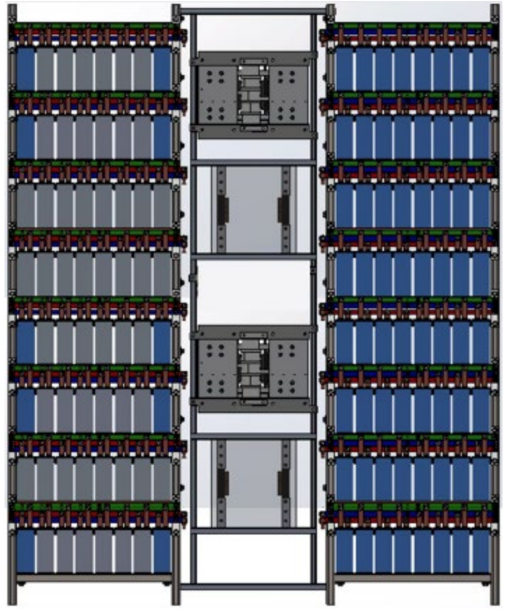


New Cascaded Multilevel Inverter Designed for Active Control of the Effective Helicity-Driven Loop Voltage

CMLI Concept – One Inverter per LHI Source



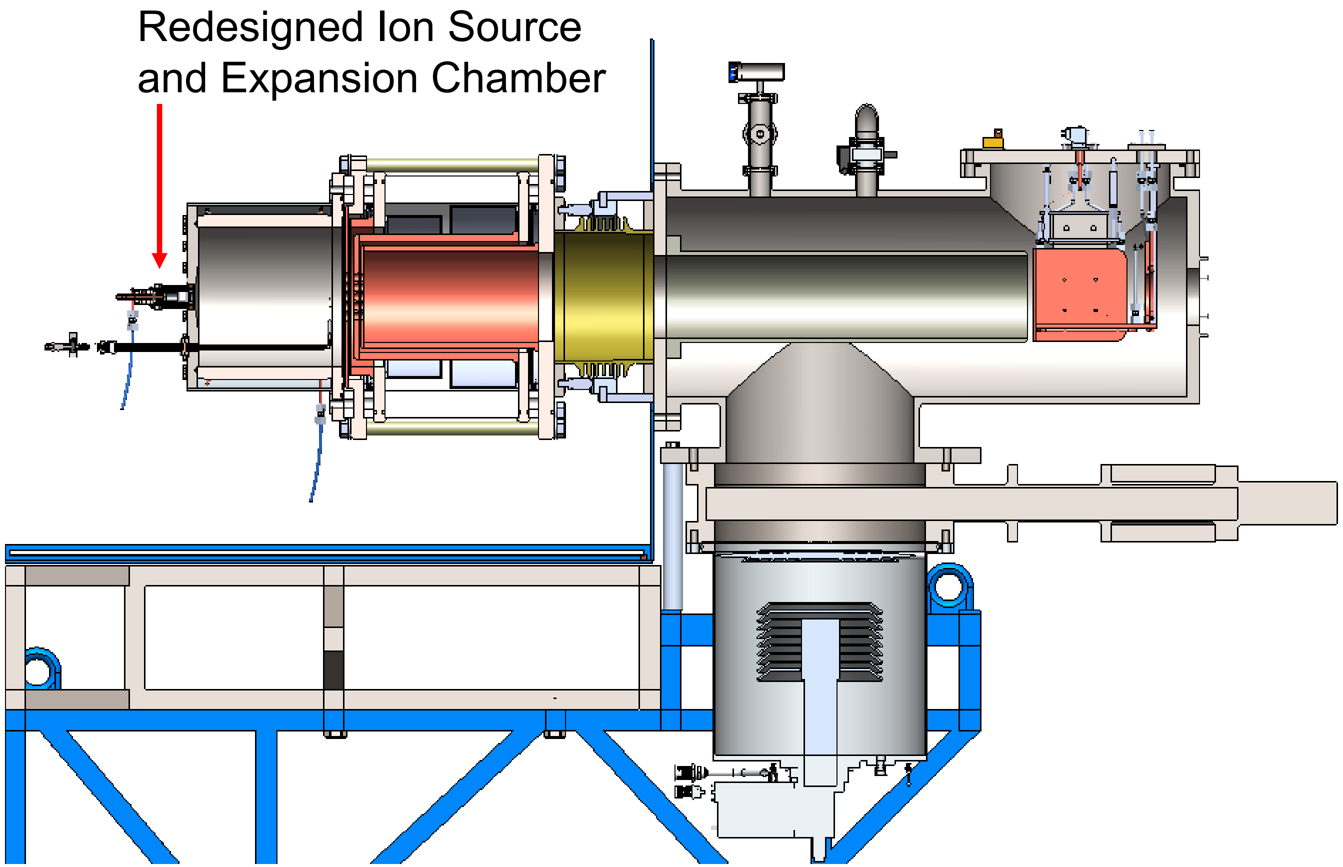
Integrated Stored Energy, IGBT, and IGCT Bridges



- CMLI inverter to drive 4 kA at 1 kV with sub-ms V_{out} control
  - 1800 V from IGCT system +/- 900 V(t) on fast timescales from corrector
- 16 MVA planned for initial experiments

80 kV Diagnostic Neutral Beam Provides New Diagnostic Capabilities

- DNB from PBX received from PPPL
- Ion source redesigned and achieved target n_e, T_e to draw 3 A at 80 kV
- Enables several advanced diagnostics:
  - Core $|B|$ measurements
  - Impurity ion dynamics (T_i, v_i, n_z)
  - Density profile information through beam attenuation



Diagnostic Set Focuses on Characterizing the Nature of Helicity Injection and the Tokamak Plasmas Produced

Diagnostics based on mission-critical requirements

- Kinetic equilibrium reconstruction
- Helicity dissipation
- MHD & kinetic activity associated with current drive & magnetic relaxation
- Plasma material interaction with injector surfaces

New systems under design

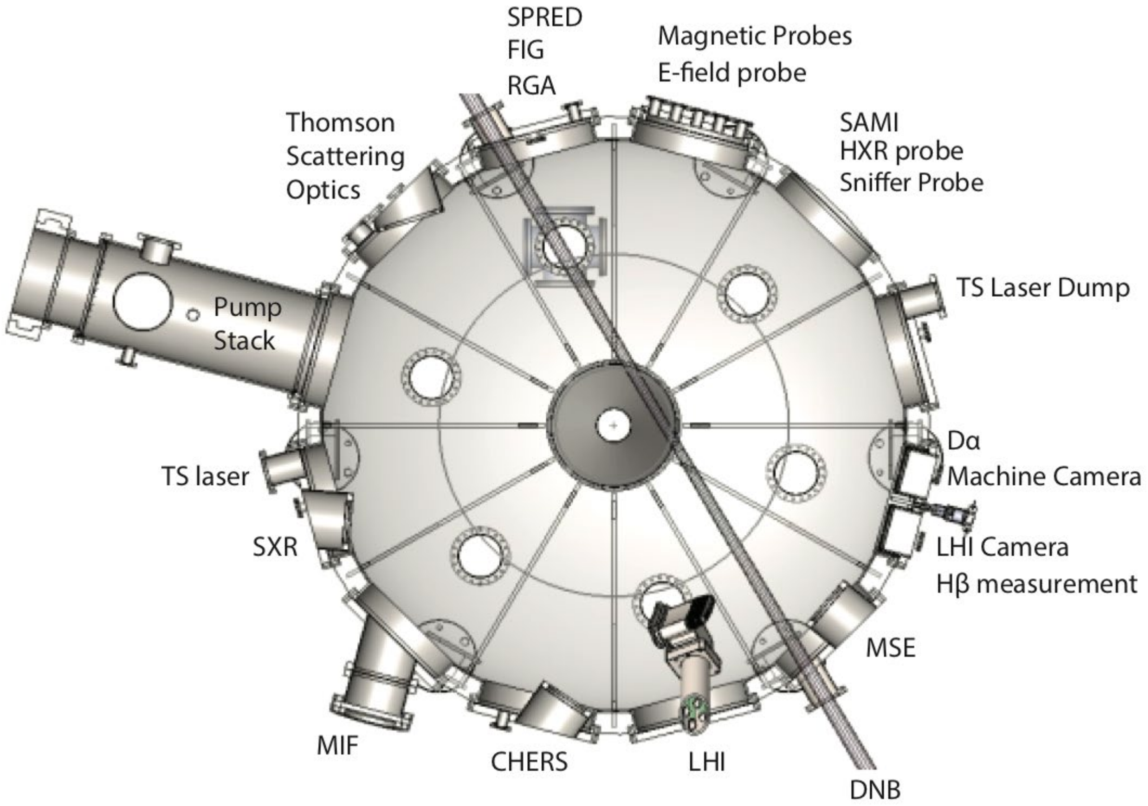
- Neutral Beam emission diagnostics for magnetic field, ion dynamics
- Impurities [Bolometry, higher-resolution VUV spectroscopy (SPRED), VB]
- Spectroscopic measurements of arc plasmas (Stark Broadening)
- IR imaging

Insertable probe arrays

- 3D magnetics [Hall, $\dot{B}$]
- Langmuir, Mach

Flux footprint measurements and imaging for CHI

RF Probe and diagnostics to measure absorption & heating

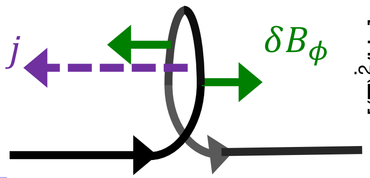


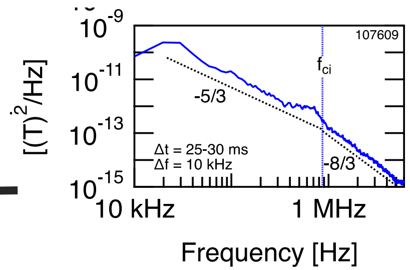
SUMMARY

- PEGASUS-III: Motivations for developing non-solenoidal startup techniques
- Overview of approaches to plasma startup using Local Helicity Injection (LHI), Coaxial Helicity Injection (CHI) and Electron Bernstein Wave (EBW) heating & current drive
- Summarize recent work developing LHI on PEGASUS
- Outline the upcoming experimental program following upgrade activities
- Updates on the facility upgrades

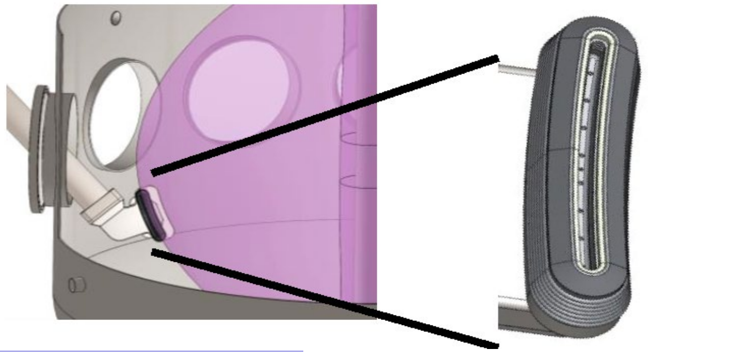
Exciting Physics Anticipated From Upcoming Experiments

Realize predicted gains in I_p and develop attractive scenarios for non-inductive sustainment



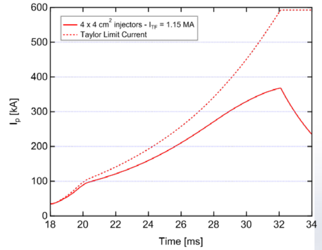


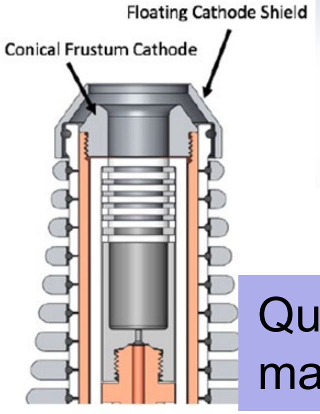
Field a flux-conforming monolithic injector as envisioned for large facility

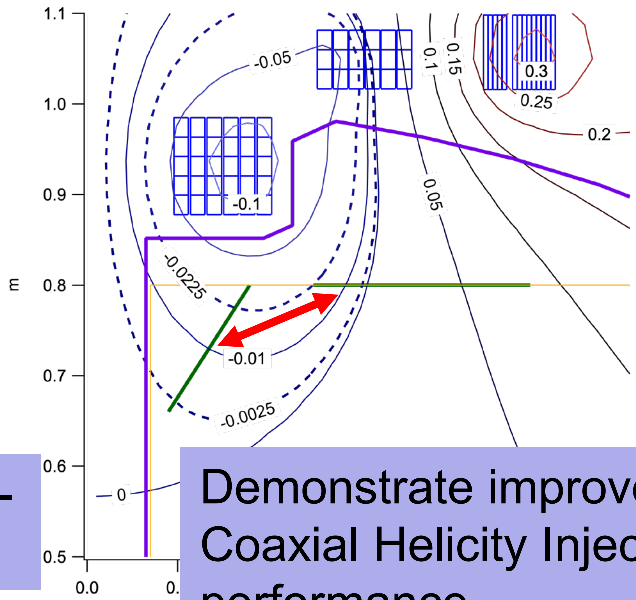


Determine how helicity drive & transport due to MHD & kinetic scale turbulence change with B_T

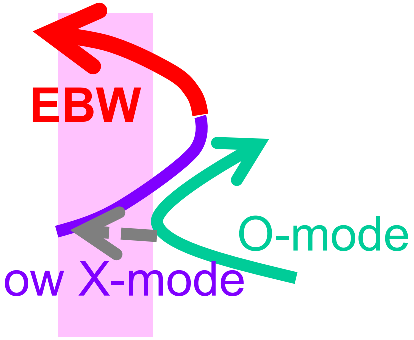
Develop a transport scaling model for predictive modelling of helicity injection







Explore differences in reconnection & relaxation between flux ropes & current sheet

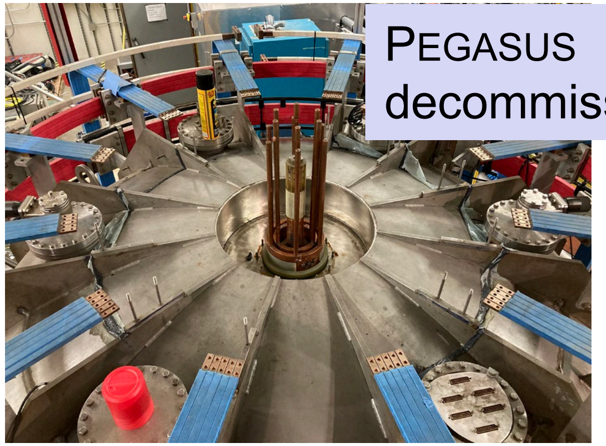
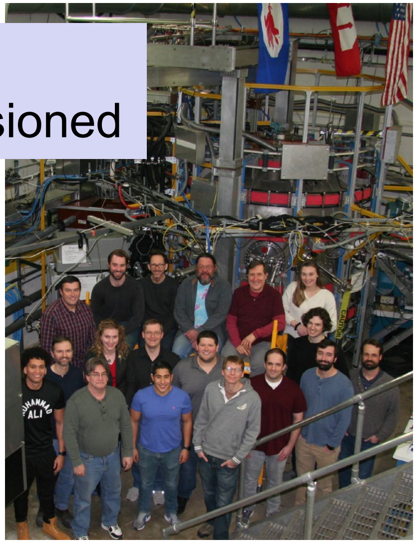


Quantify and mitigate plasma-material interactions

Demonstrate improved Coaxial Helicity Injection performance by narrowing flux footprint

Use EBW to heat helicity-driven plasmas to reduce dissipation & tailor the current profile

PEGASUS-III is Now Under Construction

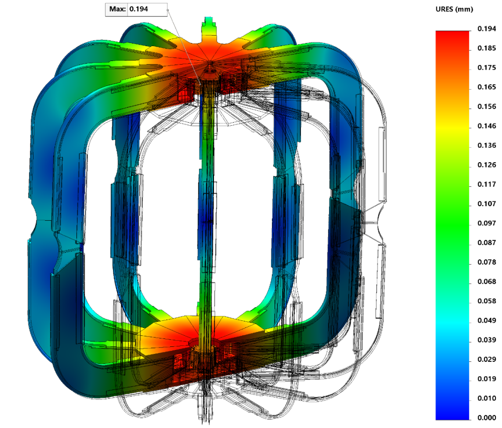



PEGASUS decommissioned

Advanced non-circular injector design fabricated & assembled


T-CHI power supply built (Univ. Washington collaboration)

8 GHz Klystrons (ENEA collaboration)



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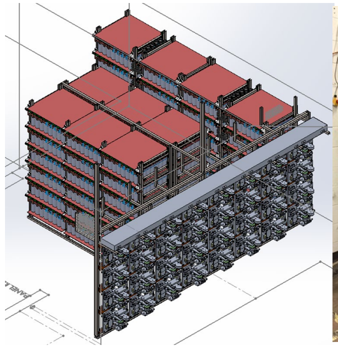
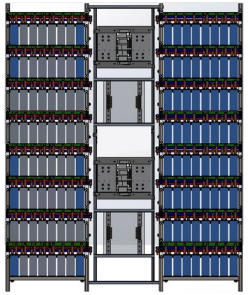



Assembly of 240 MVA power systems underway



New cascaded inverter in fabrication to drive LHI, S-CHI systems

DNB supporting new diagnostics (PPPL loan)