Status and Plans for the New Solenoid-Free PEGASUS-III Spherical Tokamak

J.A. Reusch,

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Poster BP11.00002

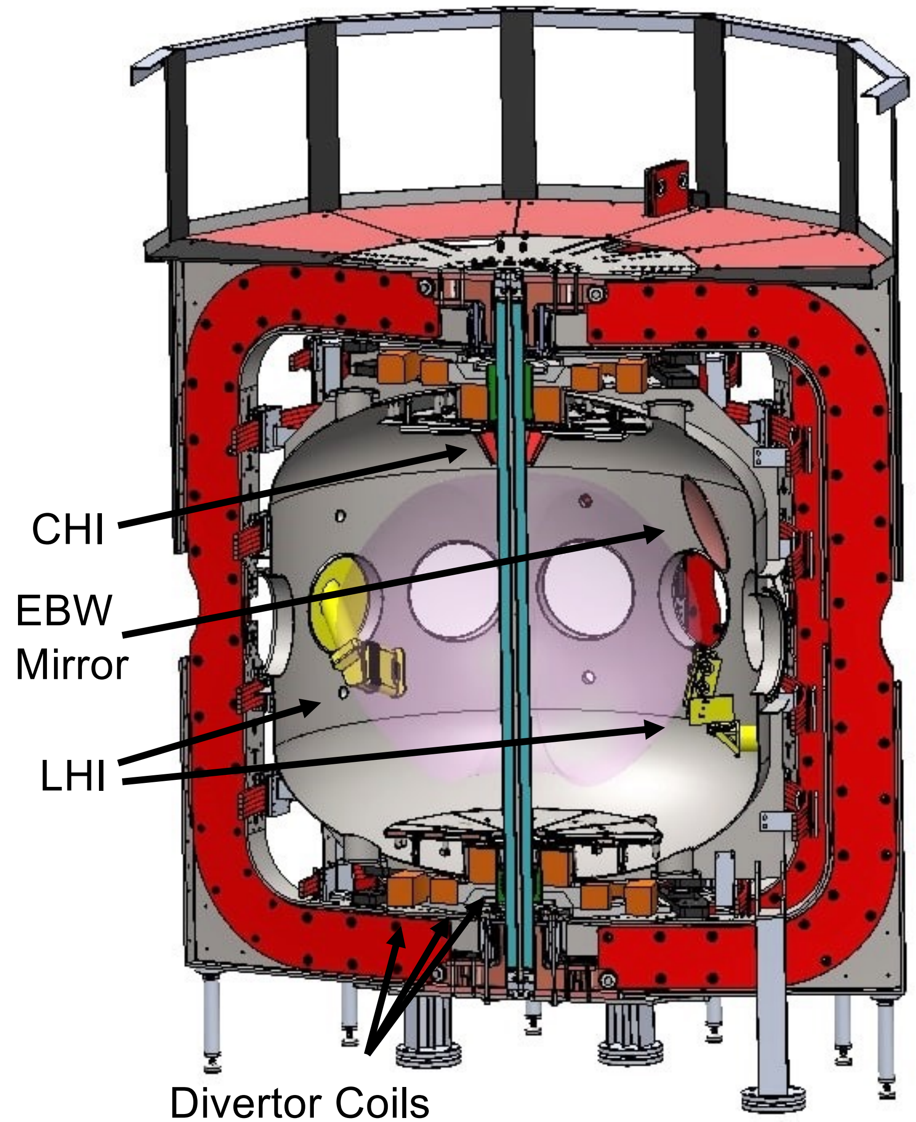
PEGASUS-III Experiment

Pegasus III

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

- Major facility upgrade to PEGASUS*
- 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, ECH, ECCD)
  - Assess compatibility with RF/NBI heating and current drive
- Goal: develop validated physics and technology basis for MA-class startup on NSTX-U and beyond

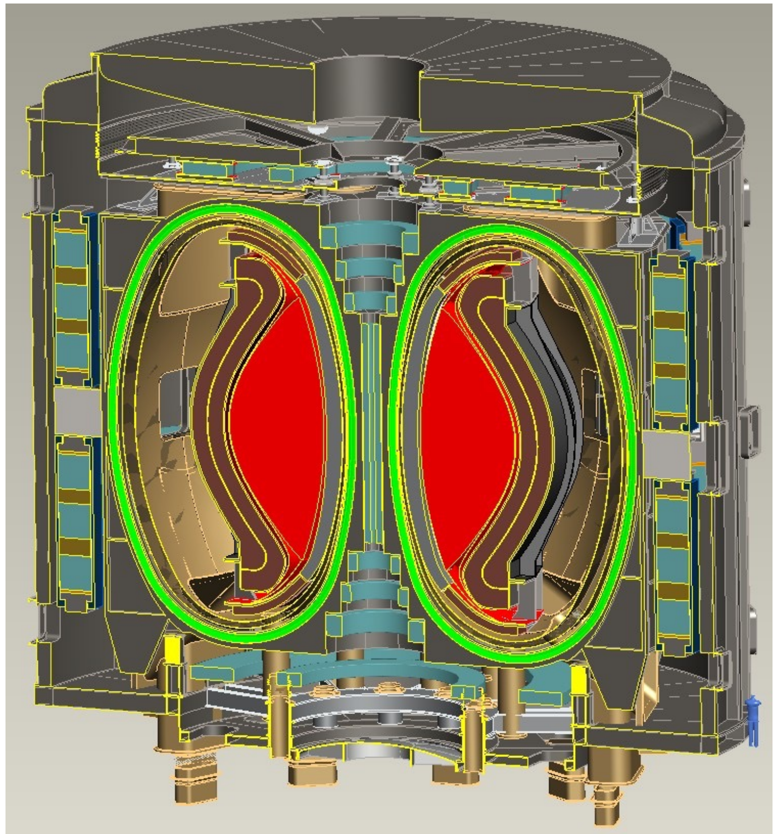
See also: S.J. Diem UO08.00001, Tue. 2:00PM



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

Non-Solenoidal Startup is Critical for the Spherical Tokamak and May Benefit Advanced Tokamaks

- 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 $J(R)$

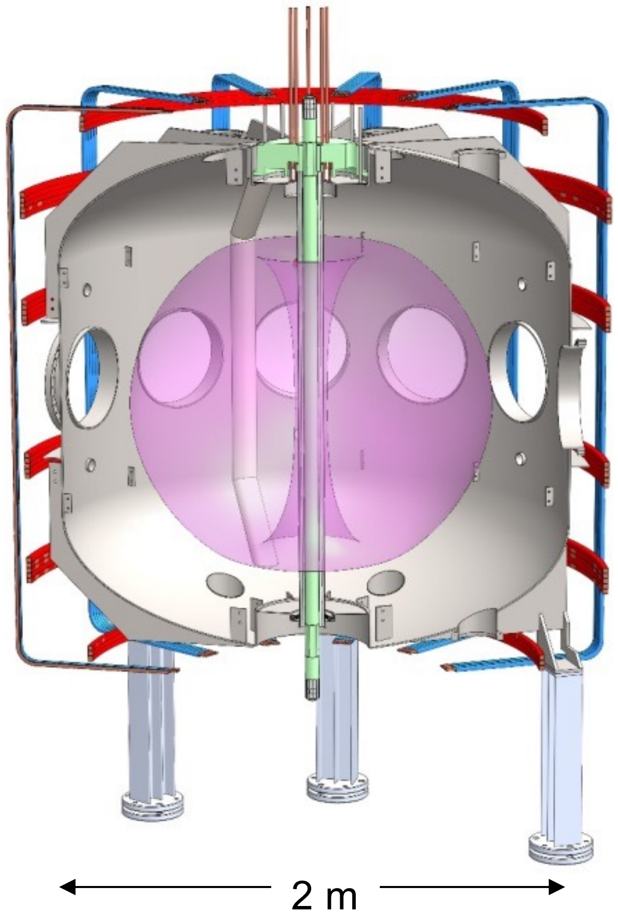


No / small OH HTS ST-FNSF / Pilot Plant

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

PEGASUS-III Upgrades Enable Comparative Study of Multiple Startup Methods

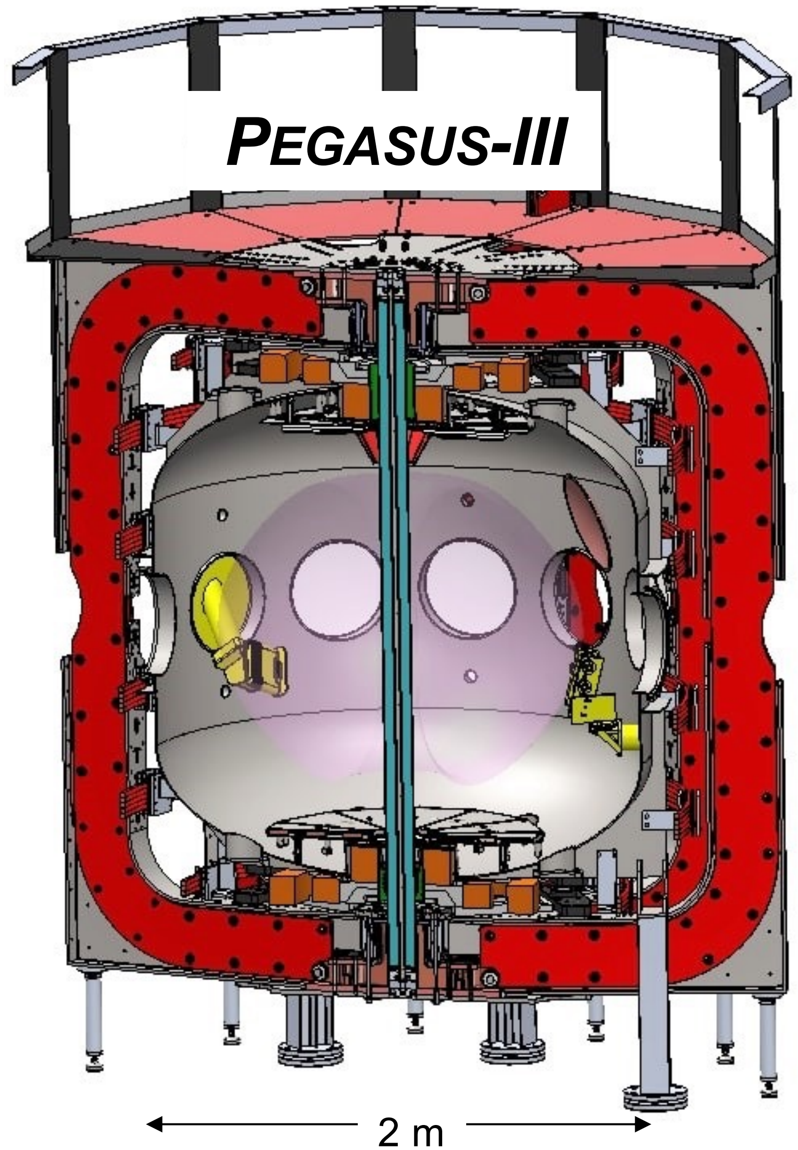
PEGASUS



- **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



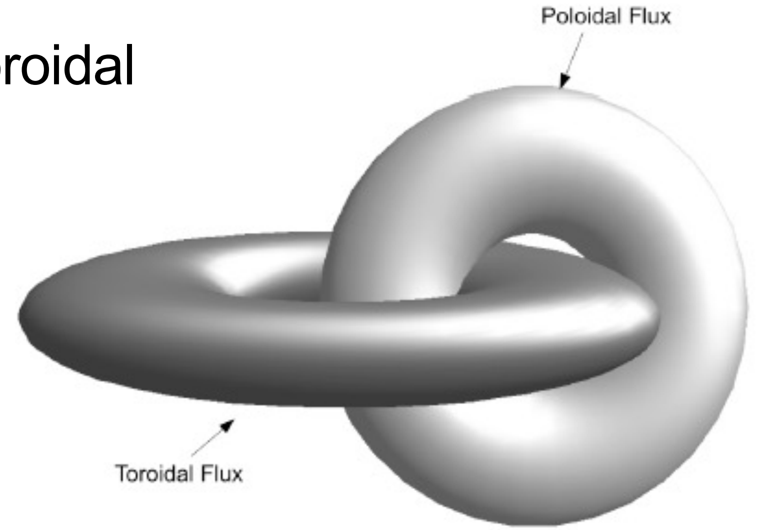
Helicity Injection and RF startup

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)

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

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**

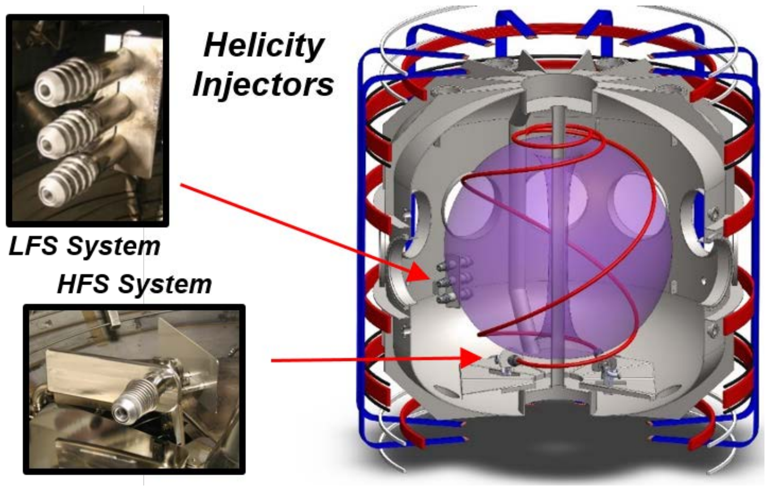
$$I_p = \frac{A_p V_{LHI}}{2\pi R_0 \langle \eta \rangle} \approx \frac{V_{inj} A_{inj}}{2\pi R_0 \langle \eta \rangle}\left(\frac{B_{inj}}{B_0}\right)$$

Limits of DC HI geometry:
- LHI: Local, small-area sources
- CHI:* Large, coaxial electrodes

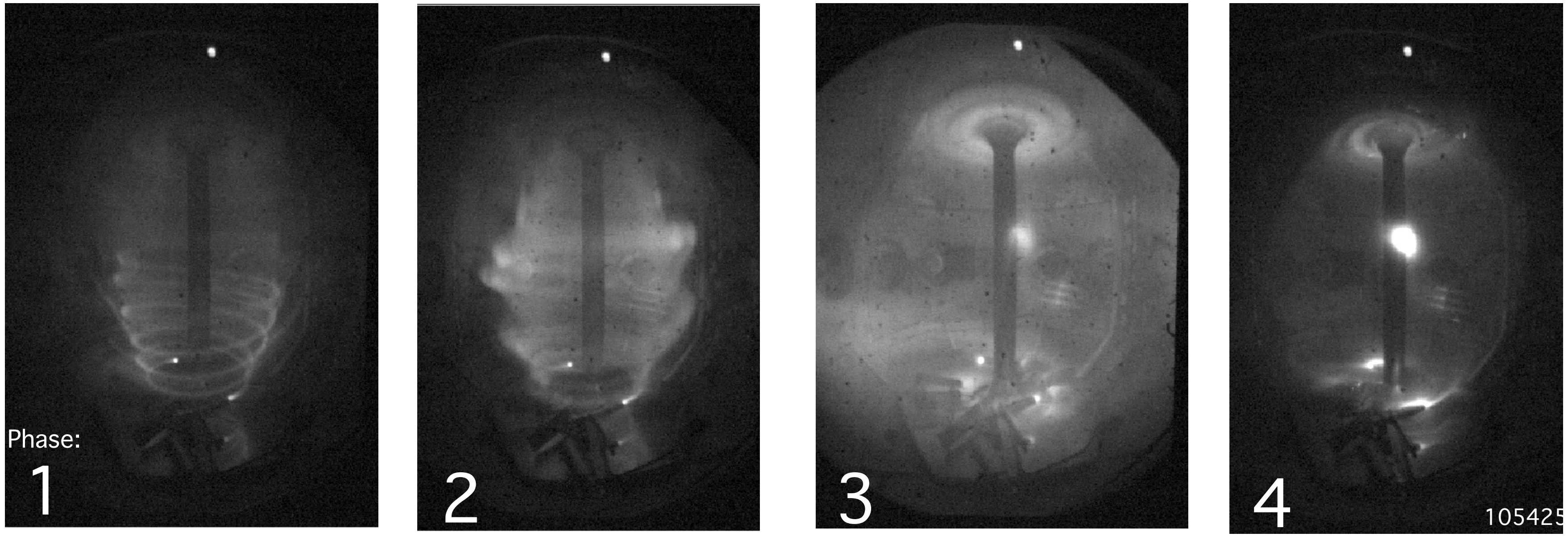
- Taylor relaxation limits I_p to lowest energy state that conserves K

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

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

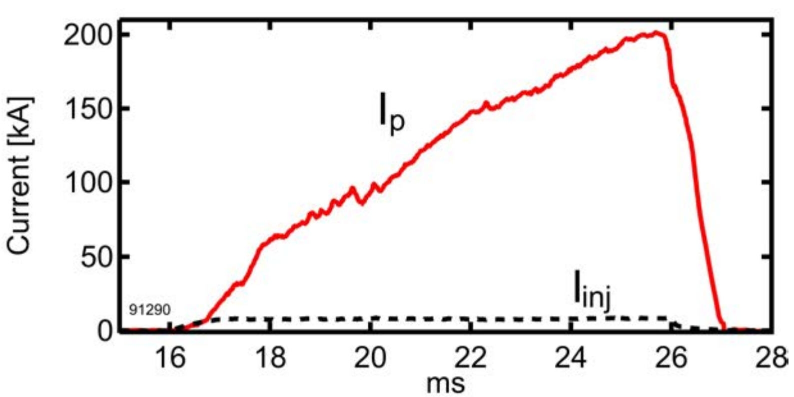


LHI Startup Scenario Temporal Evolution



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

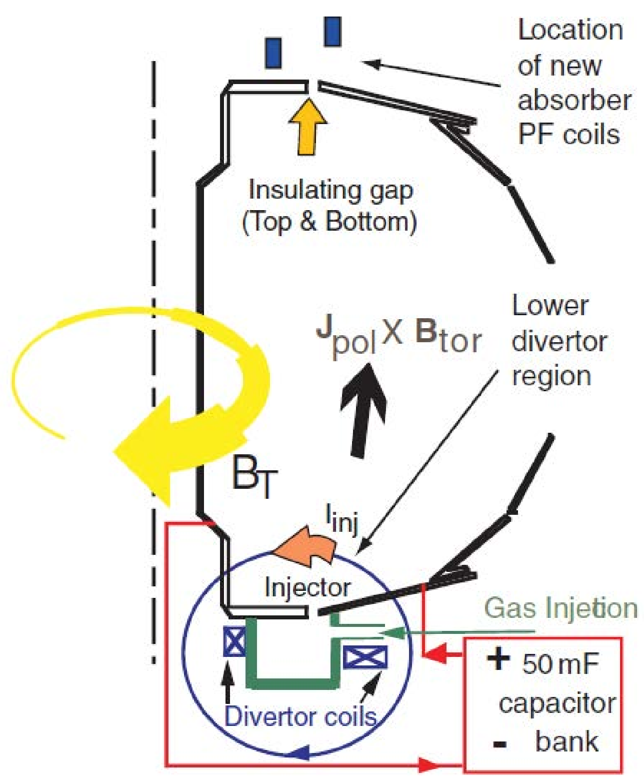
LHI Produces High-I_p = 0.2 MA Tokamak Plasma ($I_{inj} \leq$ 8 kA)



*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 That Reconnects, Forms Tokamak-like Plasma

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



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

Two techniques:

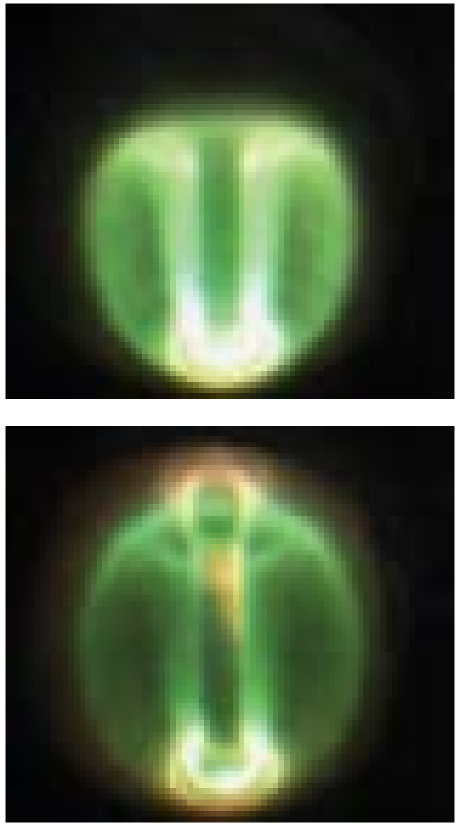
- Transient (T-CHI): stretch connected flux and quickly force reconnection to create closed flux
- Sustained (S-CHI): build up connected flux by continued current drive

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

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

Maximum I_p set by Taylor Limit

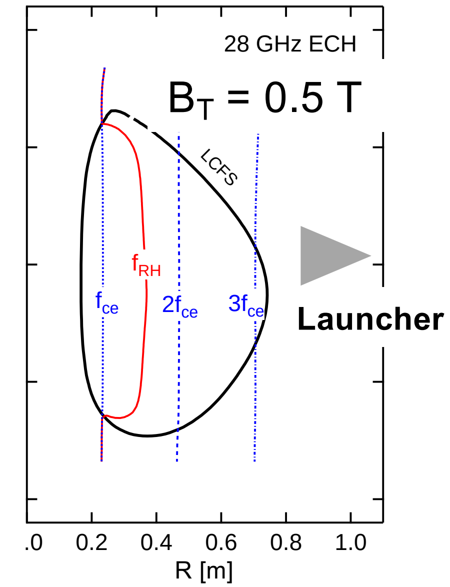
T-CHI in NSTX



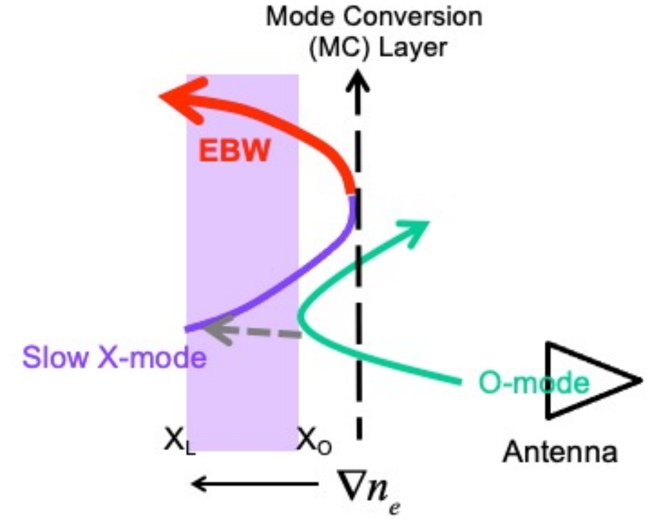
RF Heating and Current Drive Can Enhance Helicity Injection, Provide Standalone Startup

- RF heating synergistic with LHI/CHI through:
  - Lowering resistivity to reduce helicity dissipation
  - Freezing low-inductance helicity-driven current profile
  - Providing $J(R)$ tailoring for improved MHD stability
- PEGASUS-III will explore these effects with a 0.2 MW, 28 GHz RF system
  - ECH/ECCD for lower n_e scenarios
  - Electron Bernstein wave (EBW) via O-X-B mode conversion for overdense ST plasmas for heating
- Future: Increase RF power at 28 GHz for heating and current drive
  - Handoff to RF sustainment
  - Tests of enhanced EBW CD efficiency at higher power/currents
  - Direct RF startup studies

LFS X-mode Launch



O-X-B coupling



PEGASUS III Experimental Program

Projecting LHI to Larger Facilities Requires Tests at Increasing B_T

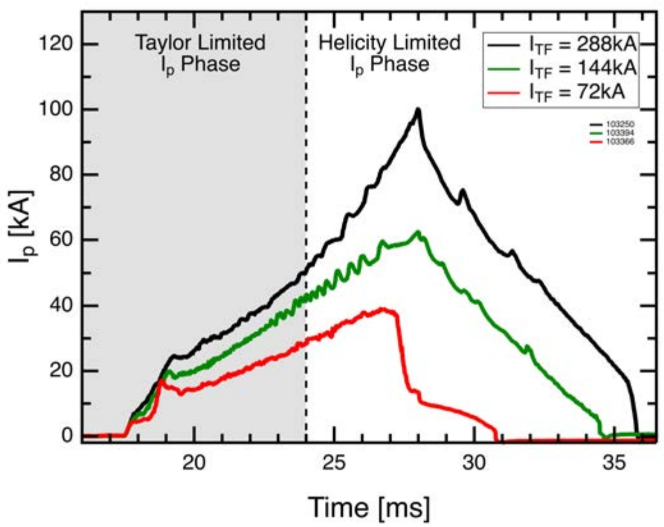
Physics

- Realize the increased I_p expected with higher B_T
- Test projection of core confinement models
- Develop and test model for current drive via beam-instability driven Alfvénic turbulence
- Determine role of current stream instabilities in helicity transport
- Provide access to RF resonances for auxiliary heating and CD

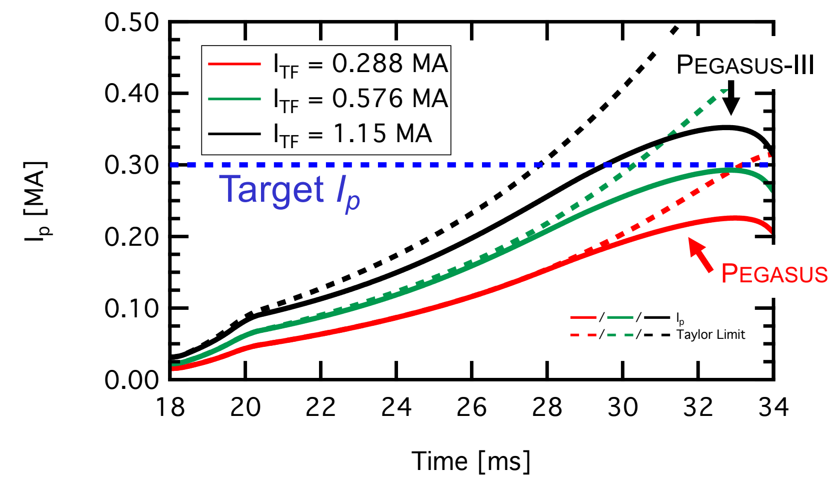
Technology

- Optimize 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

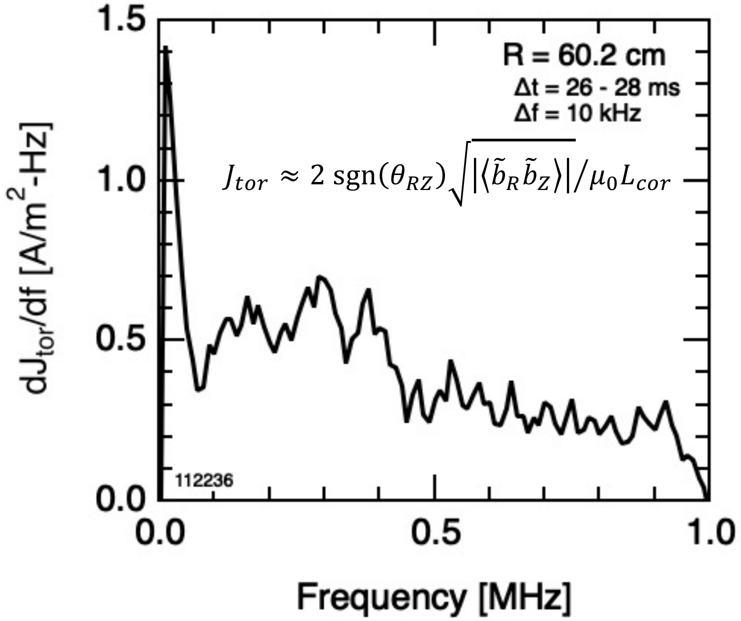


0-D Power-Balance Projections for LHI on PEGASUS-III

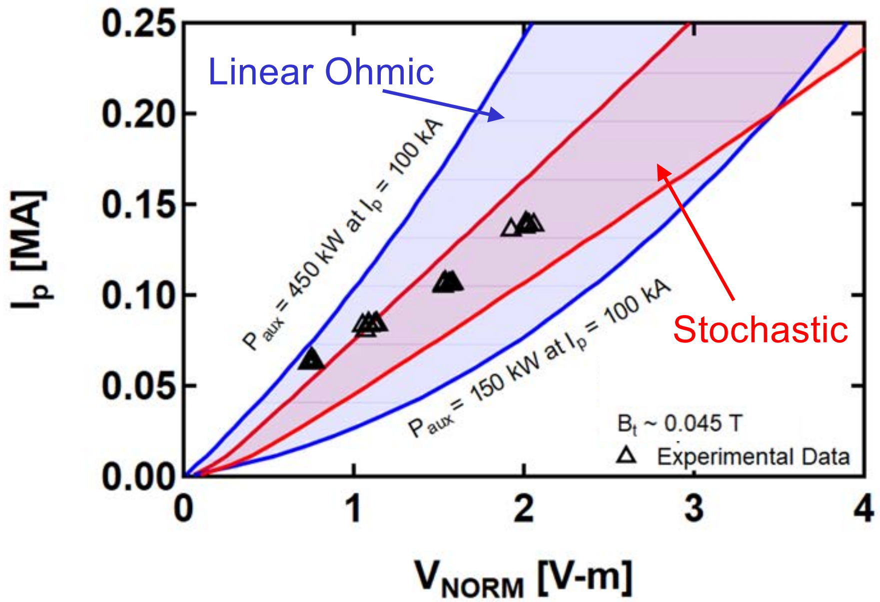


Recent Results from PEGASUS Have Refined Understanding of LHI-Driven Startup Plasmas

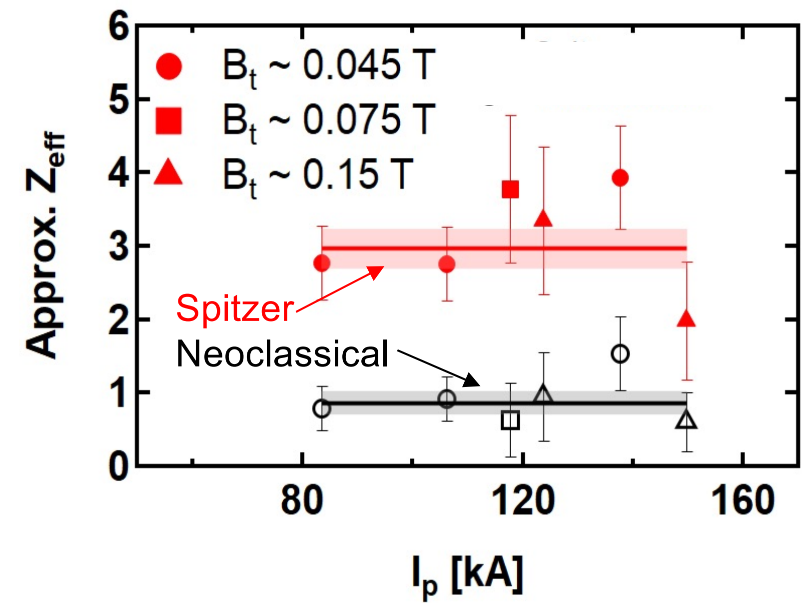
PEGASUS $\tilde{B}$ measurements indicate net J_{tor} from broadband fluctuations



*I_p Scaling Assuming Linear Ohmic or Stochastic Confinement Regimes**



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



Current Drive:
Correlated fluctuations drive net J_{tor} at nearly every frequency; integrated $J_{tor} \approx 400 kA/m^2$, comparable to equilibrium current density

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 dominant

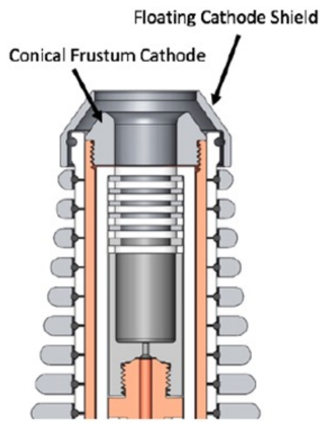
Plasma Impurity Content:
$\langle Z_{eff} \rangle$ ~ 1 derived from plasma neoclassical conductivity

M.W. Bongard BP11.00003, Mon. 9:30AM
N.J. Richner JI01.00004, Tues. 3:30PM

*G.M. Bodner PoP **28**, 102504 (2021)

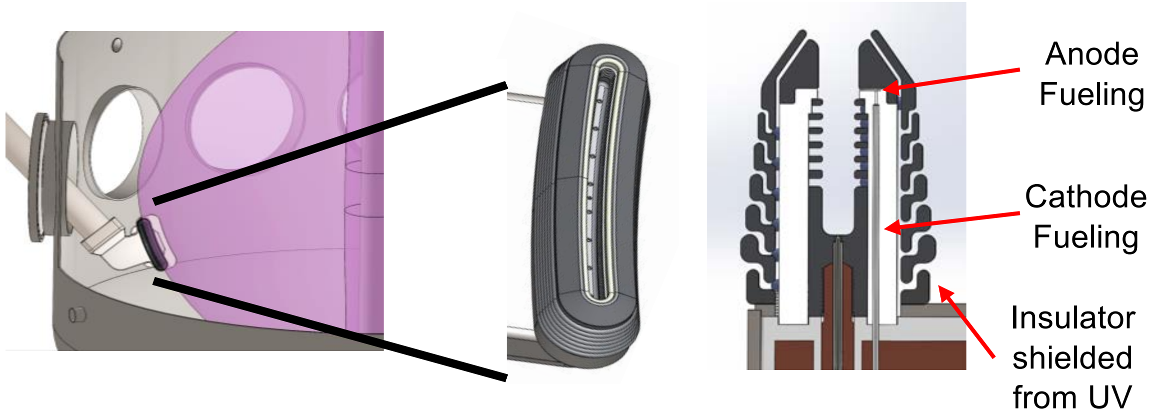
PEGASUS-III Employs Complimentary LHI Systems with Expanded Capabilities to Explore New Insights from PEGASUS

Two Arrays of $2\times$ ***4 cm²*** ***Circular Injectors***



- Proven injector design, high confidence in demonstrating 300 kA current at 0.3 T
  - Total $A_{inj} = 16\,\text{cm}^2;\ I_{inj} \leq 16\,\text{kA},\ 4\,\text{kA/injector}$
- 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
- Quantify impurity sourcing with increasing injected power
- Test proposed transport models to determine $\langle T_e \rangle$ evolution

Advanced Non-circular Injector in PEGASUS-III



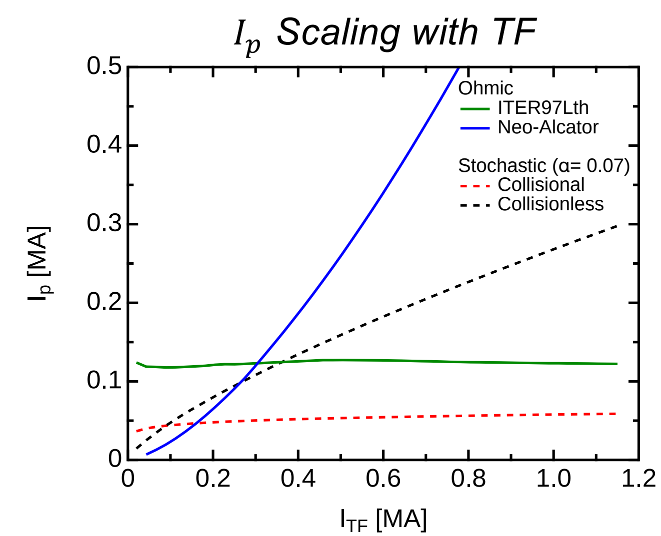
- Port mounted monolithic injector appropriate for fielding on NSTX-U and beyond
  - $A_{inj} = 16\,\text{cm}^2, I_{inj} \leq 8\,\text{kA}, w_{inj} = 1\,\text{cm}$
- Smaller radial width optimizes helicity drive and Taylor-limit

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

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

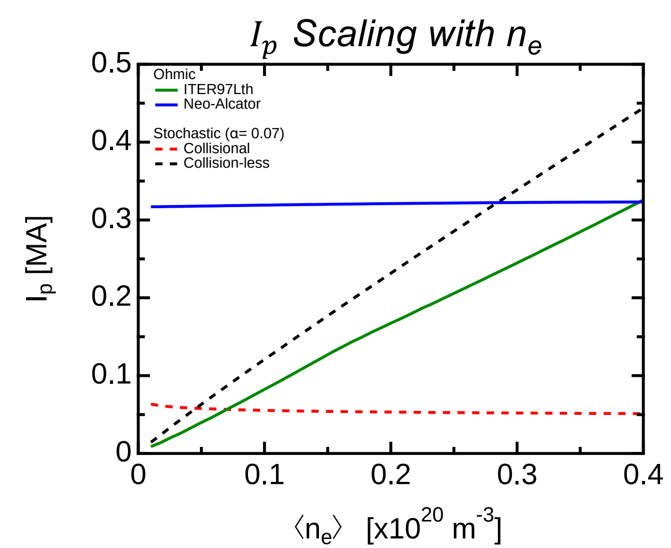
Early Experiments on PEGASUS-III will Explore Proposed Confinement and Transport Models

- Ohmic and stochastic electron confinement models consistent with observations
  - Injector/machine capabilities of PEGASUS could not distinguish
  - Low field/n_e may have been pathological
- Higher B_T, V_{LHI} range allows confinement tests over broader parameter space
- Early experiments will establish qualitative trends, should identify type of scaling



Summary of Qualitative I_p Trends for Different Assumed Confinement Scalings

	I_p Trend w/		
Confinement Scaling Estimates	**Increasing V_{NORM}**	**Increasing B_ϕ**	**Increasing n_e**
Linear Ohmic (neo-Alcator)*	↑	↑	—
Saturated Ohmic (Iter97L)**	↓	—	↑
Collisional stochastic***	↑	—	—
Collisionless stochastic	↓	↑	↑

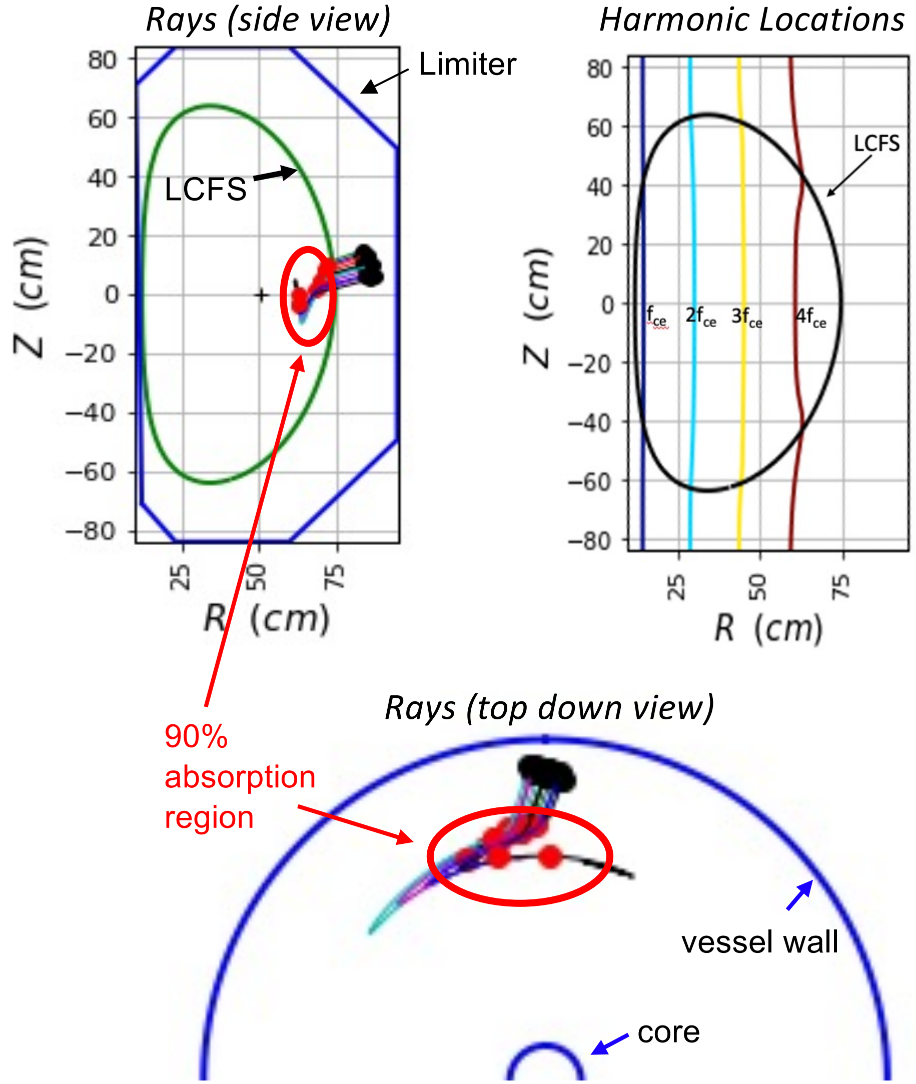


* J.E. Rice et al., Nucl. Fusion 60, (2020).
** ITER physics basis, *Chapter 2* (1999)
***G.M. Bodner PoP **28**, 102504 (2021)

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

- Initial experiments: heat LHI/CHI afterglow
  - Heating post CD shutoff extends decay, tailors profiles
- Test EBW drive concurrent with LHI
  - Increasing T_e can increase current drive efficiency
  - Explore tailoring the current profile
- Experimental target of injecting 100+ kW
  - Source frequency of 28 GHz launched into decaying LHI-produced plasma ($B_T = 0.33$ T)
  - Near midplane launch
    $n_{\parallel} = -0.55 \text{ to } -0.45$
  - Varying B_T can be used to change absorption location

O-X-B mode conversion case at B_T = 0.33 T

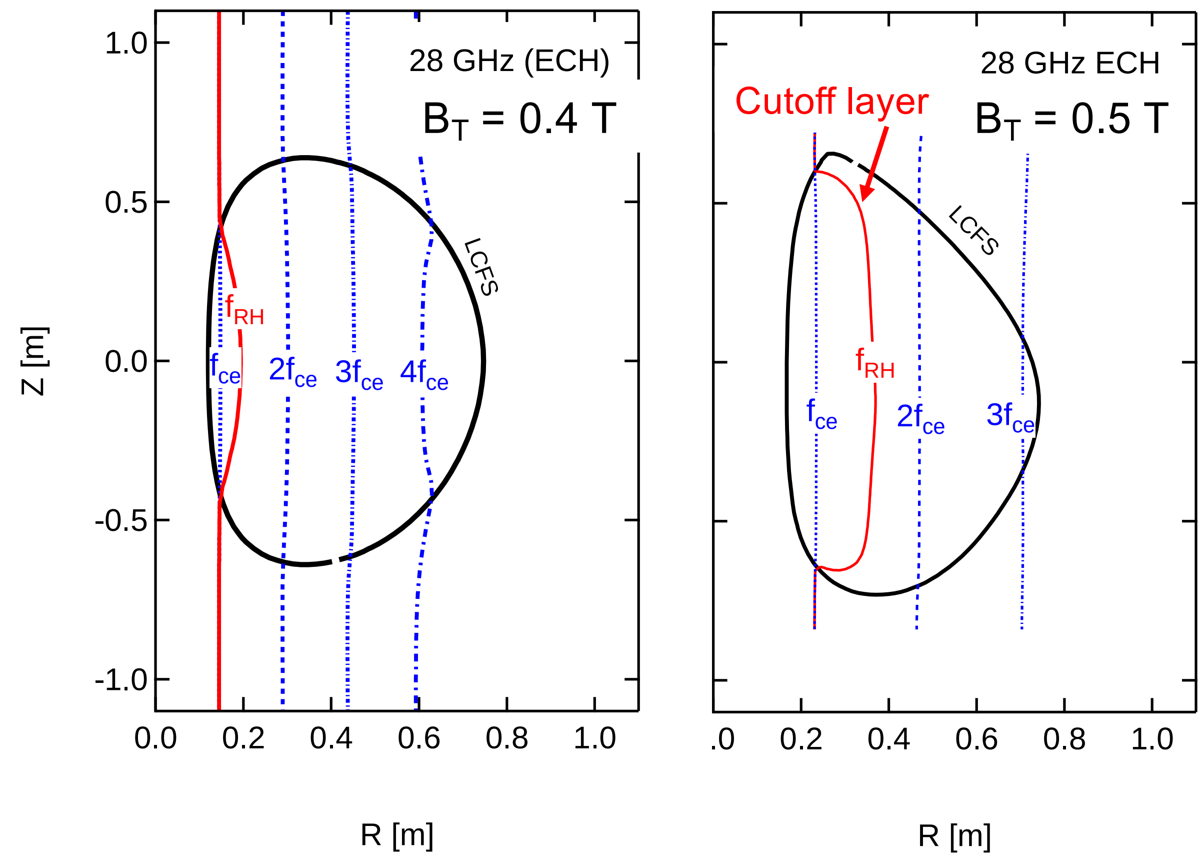


J. Peery BP11.00004, Mon. 9:30AM

LHI Produced Plasmas are Accessible with ECH

- Electron Cyclotron Heating (ECH) in post-CHI decay
  - Significantly increase T_e^*
- LHI coupling:
  - T_e heating during LHI for increased CD efficiency
  - Post-LHI heating for subsequent heating and CD
- Pure-RF startup scenarios
  - ECH/ECCD initiation and current channel formation
  - Subsequent EBW heating and CD for full I_p, n_e growth
- Exploit 2nd harmonic EC resonance
  - Significant EC absorption can occur at 2nd harmonic
  - Density cutoff < 5×10^{18} m^{-3}, accessible during startup

LFS x-mode 2nd harmonic accessible for PEGASUS-III B_T range



Mode	O1	X1	X2	O2	X3
Frequency	Ω_{ce}	Ω_{ce}	$2\Omega_{ce}$	$2\Omega_{ce}$	$3\Omega_{ce}$
Density	n_{01}	$2n_{01}$	$2n_{01}$	$4n_{01}$	$6n_{01}$

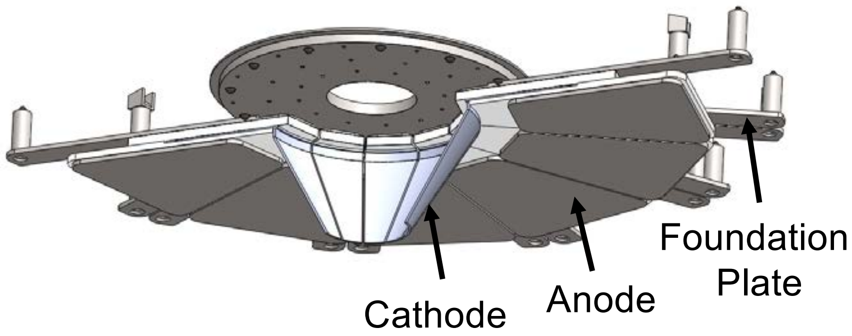
J. Peery BP11.00004, Mon. 9:30AM

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

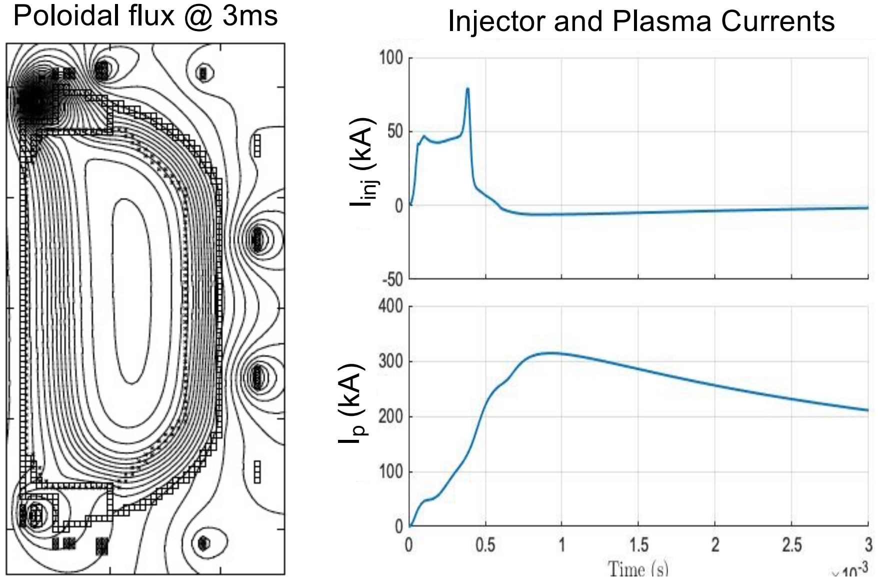
PEGASUS-III CHI Studies Enabled by A Novel Dual-Electrode System

- Quantify and validate design criteria for high-I_p CHI
  - Dual insulated electrodes: no vessel break required
  - Support CHI-driven plasmas to PF limits ($I_p \sim 0.3$ MA)
  - Segmented design to test axisymmetry of current extraction
  - Explore importance of flux distribution across electrodes
- 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
  - Use sets of segments to test impact of non-axisymmetry

3D Sketch of Electrode Plate Concept



TSC simulations indicate 300kA achievable with this electrode set



R. Raman BP11.00005, Mon. 9:30AM

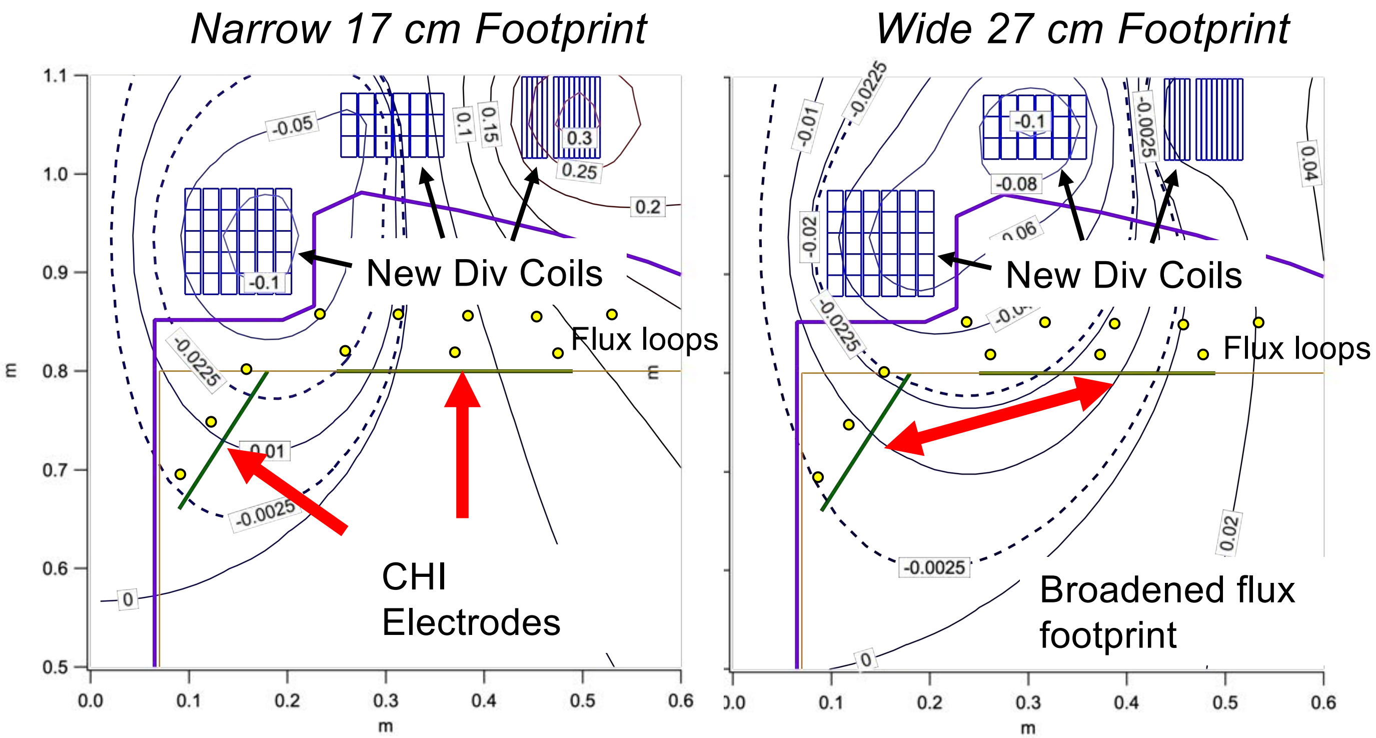
New Flexible Divertor Fields Enable Tests of T-CHI & S-CHI Performance with Footprint Separation

- 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 injector current at bubble burst scale strongly with d, ψ_{inj}

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

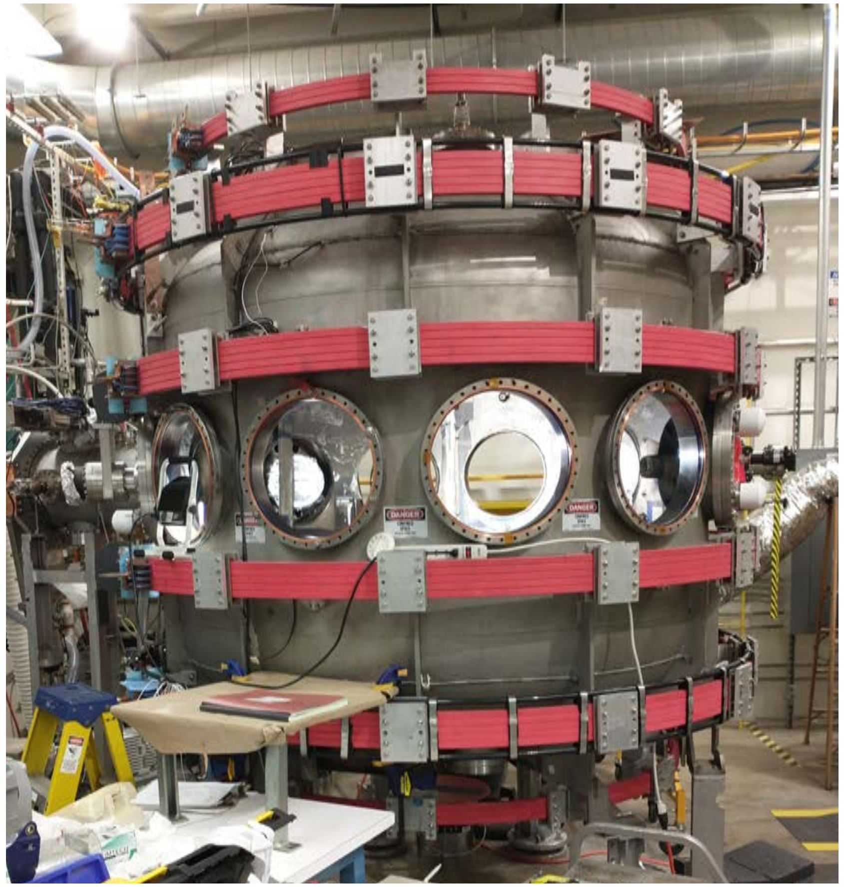


Pegasus-III Upgrades

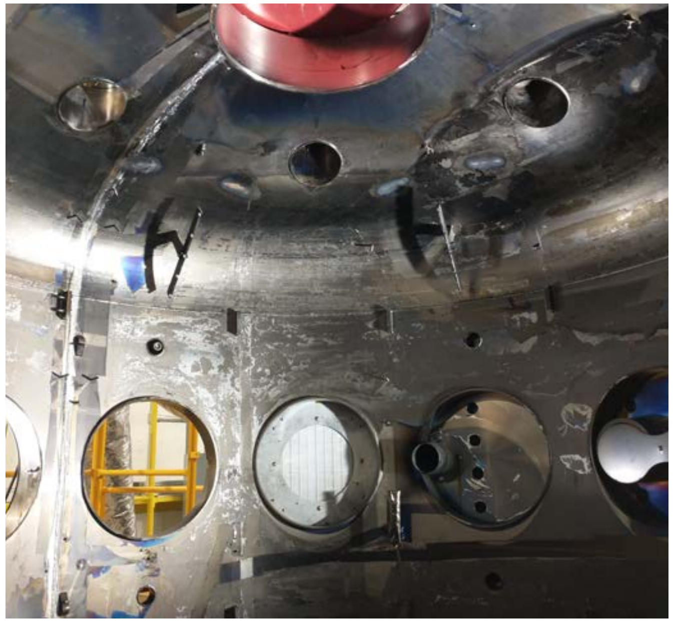
PEGASUS Experiment & Facility Fully Decommissioned

- Mechanical components of facility being upgraded:
  - New solenoid free center stack
  - New outer TF assembly
  - Structural enhancement to tank
  - New divertor assembly
  - Refurbished magnetic diagnostics
  - Gas system
- Only parts that remain
  - Primary vacuum vessel
  - Equilibrium field (red) coils
  - Vacuum system

All External diagnostics, TF returns, and bus work removed



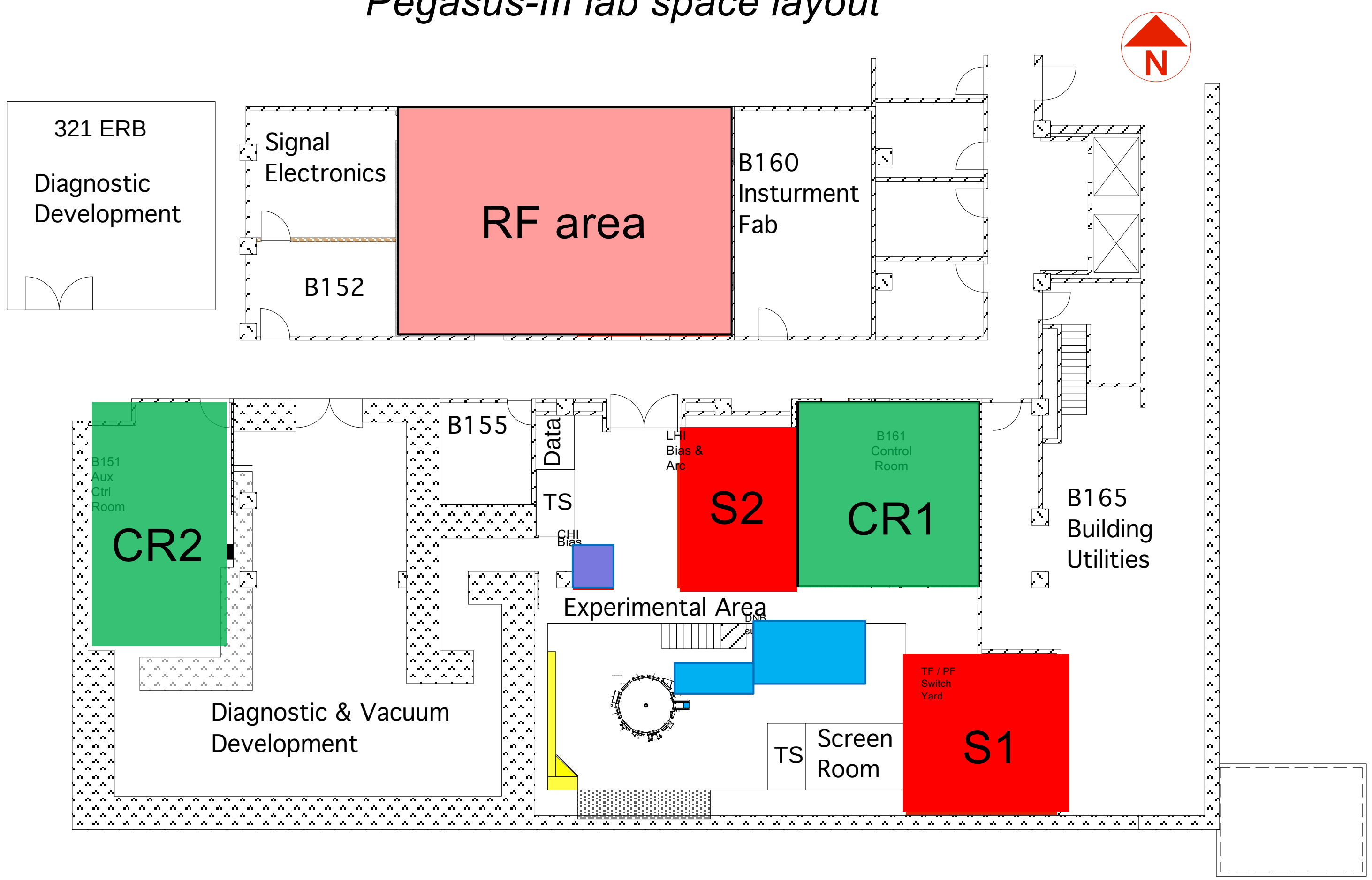
Old centerstack cut out and majority of internal diagostics removed



Reentrant cylinder prepped for new core

Lab Space Nearly Completely Reconfigured for New PEGASUS-III Systems

Pegasus-III lab space layout

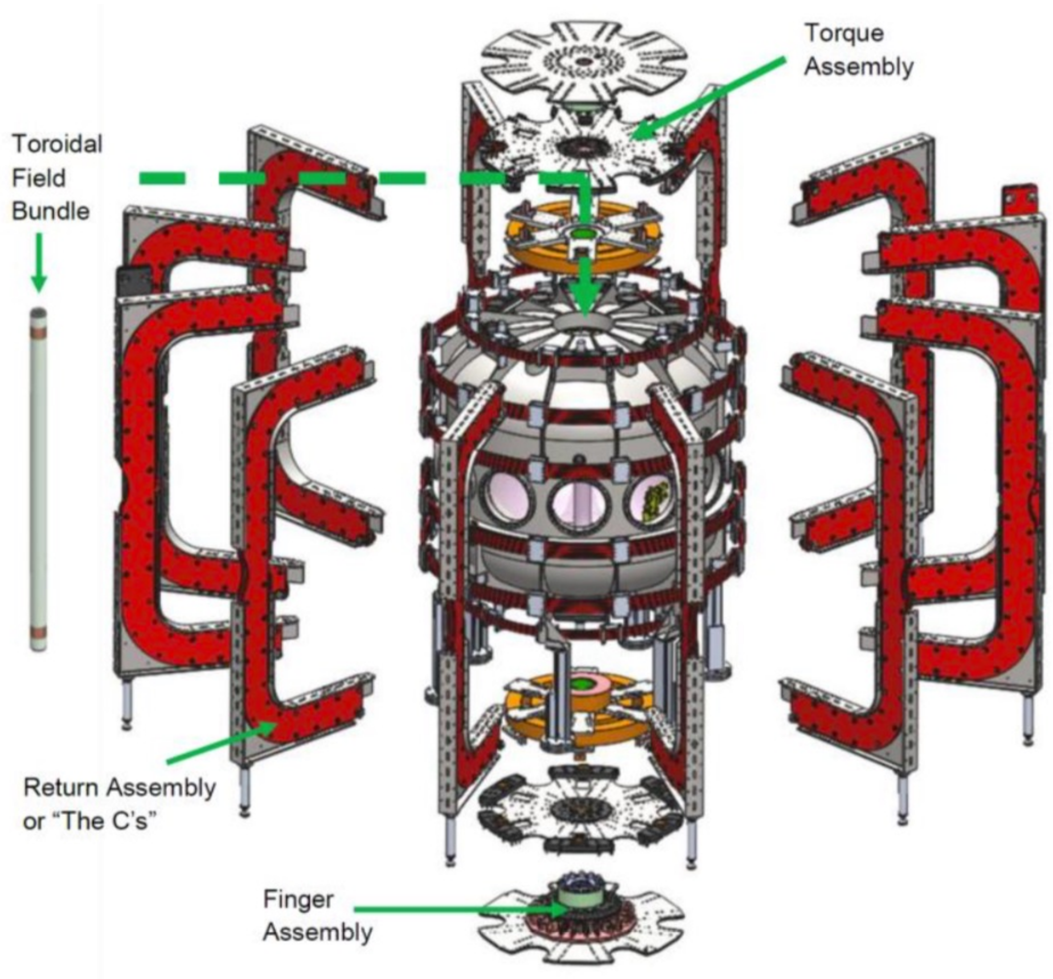


- Two new switchyards and 7 MJ stored energy built (red)
- Control room space (green) expanded, split for Covid safety
- RF system space (pink)
- DNB and power supply (blue)
- T-CHI power supply (purple)

THE UNIVERSITY of WISCONSIN MADISON

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

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

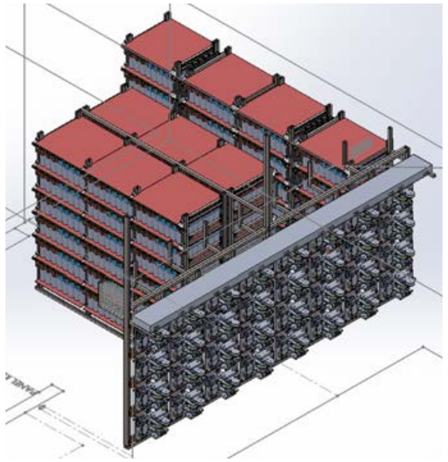


- All major components of TF in house, assembly in progress

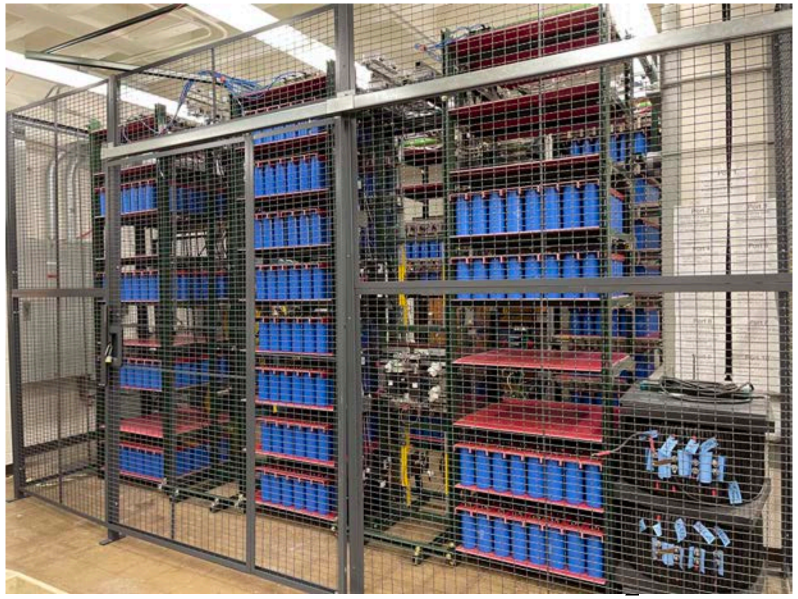
Expanded Set of Programmable Switching Power Amplifiers to Supply 175 MVA for Electromagnets, HI systems

- Reconfigured Switching Power Amplifiers
  - 32 independent 4 kA 900V IGBT for coils
  - Expansion to 40 units planned
- Replaced and expanded stored energy
  - 3 MJ for Toroidal Field Power Supply
  - 2 MJ for Poloidal Field & Divertor Power Supplies
  - 2 MJ for LHI Arc & Bias Power Supplies
- New LHI supply: Multi-level Buck Converter topology
  - 16 kA at 2.7 kV with sub-ms V_{out} control
  - 1800 V from slow IGCT system
  - +/- 900 V(t) on fast timescales from corrector
- 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

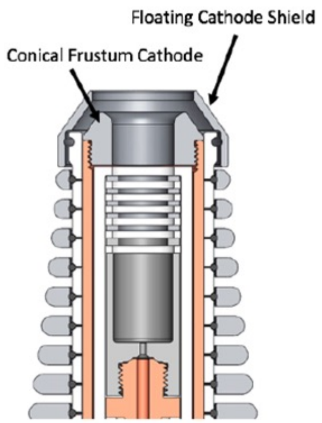


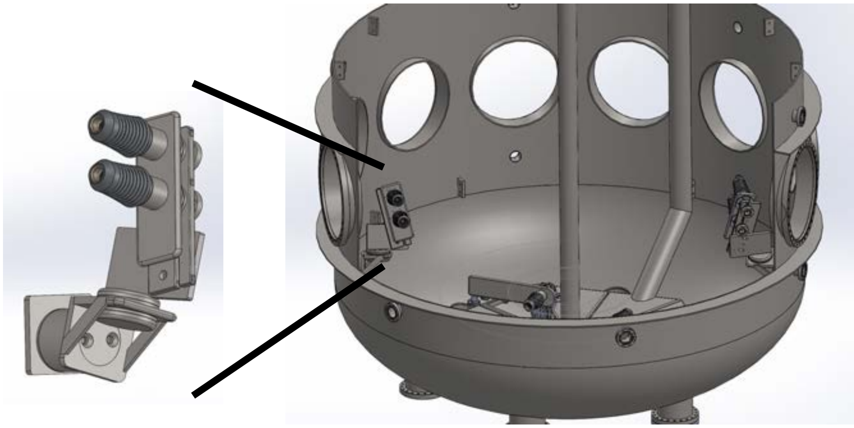
New LHI Arc and Bias Energy Storage and Switchyard Built



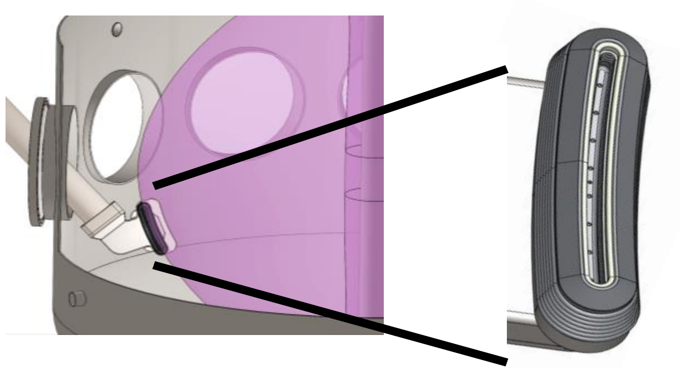
Most Powerful LHI Systems to Date Ready for Install

Two Arrays of 2× 4 cm^2 Circular Injectors (Twice Area on PEGASUS)





Advanced Non-circular Injector in PEGASUS-III



LHI injector assembly

LHI injector socket

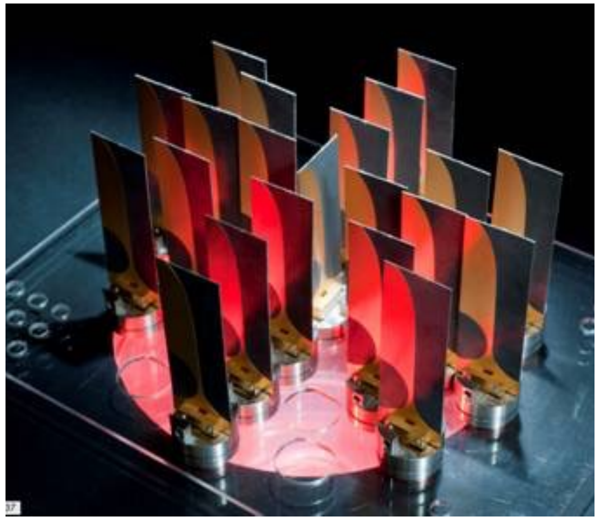
Port mounted injector assembly completed

28GHz RF System for EBW/ECH Planned

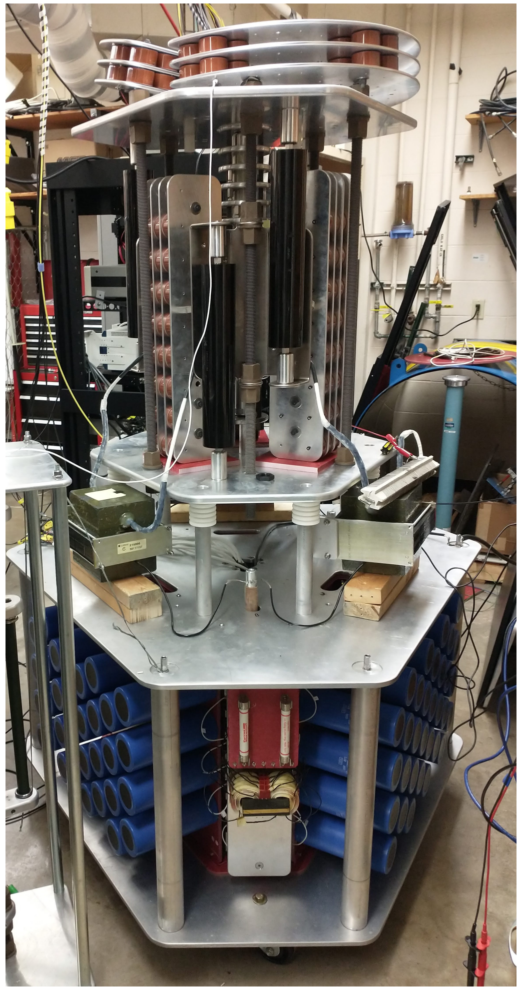
- Initial RF studies will utilize 28GHz sources
  - 200kW Varian Gyrotron
  - 80kV, 8A power supply
- EBW emission studied with Synthetic Aperture Microwave Imager (SAMI) diagnostic on loan from University of York

Varian Gyrotron

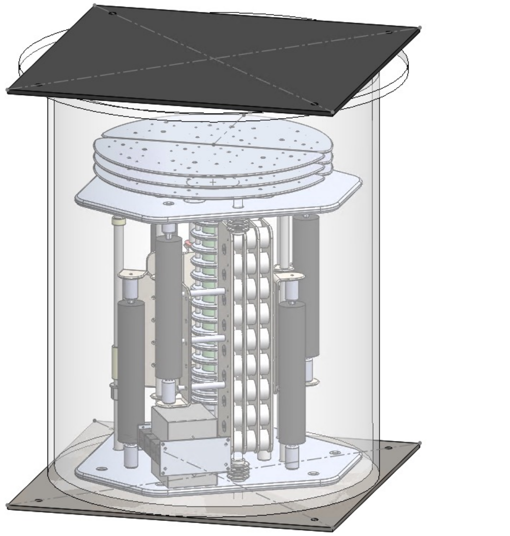
Vivaldi antennas for SAMI



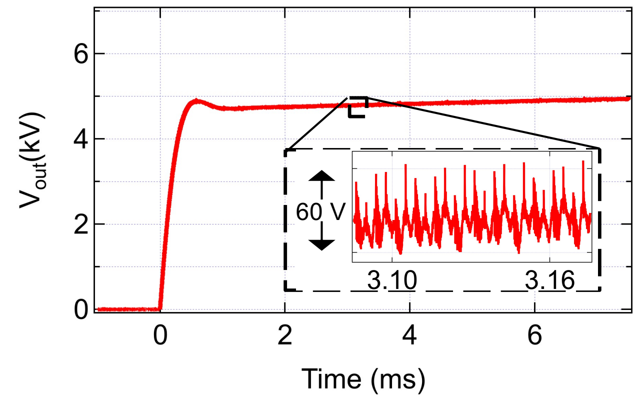
PS based on low ripple 5A, 80kV DNB power supply



HV section of new power supply to be housed in oil bath



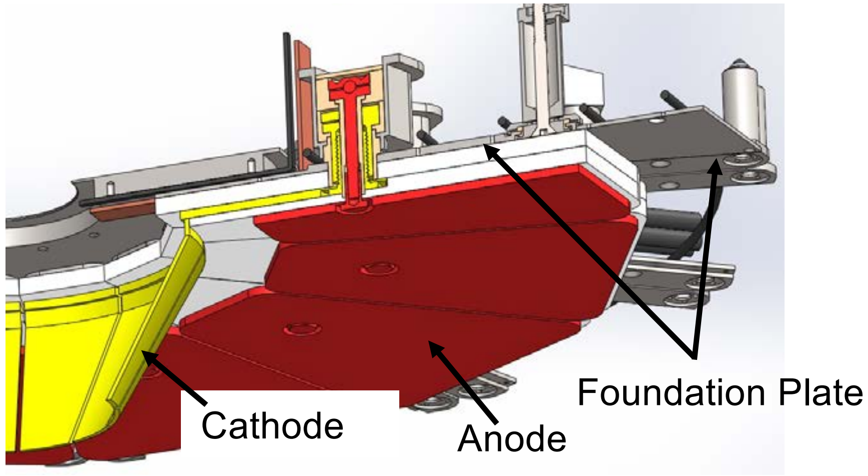
5kV test confirms power supply produces <1.7% ripple pk-pk



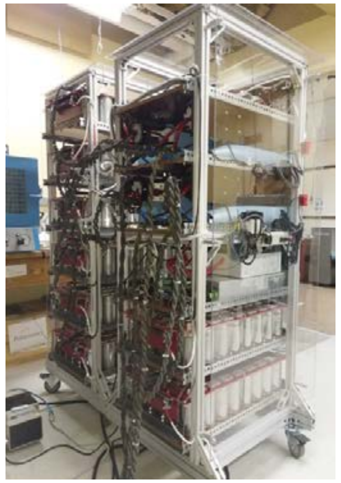
Novel Dual Floating Electrode CHI System in Design

- CHI system to be deployed in upper divertor
- Modular divertor support structure fabricated
  – CHI system mounts off divertor foundation plates
- Power systems complete
  – T-CHI bank provided by U. Wash.
  – S-CHI to use LHI bias power supply (MLBC)

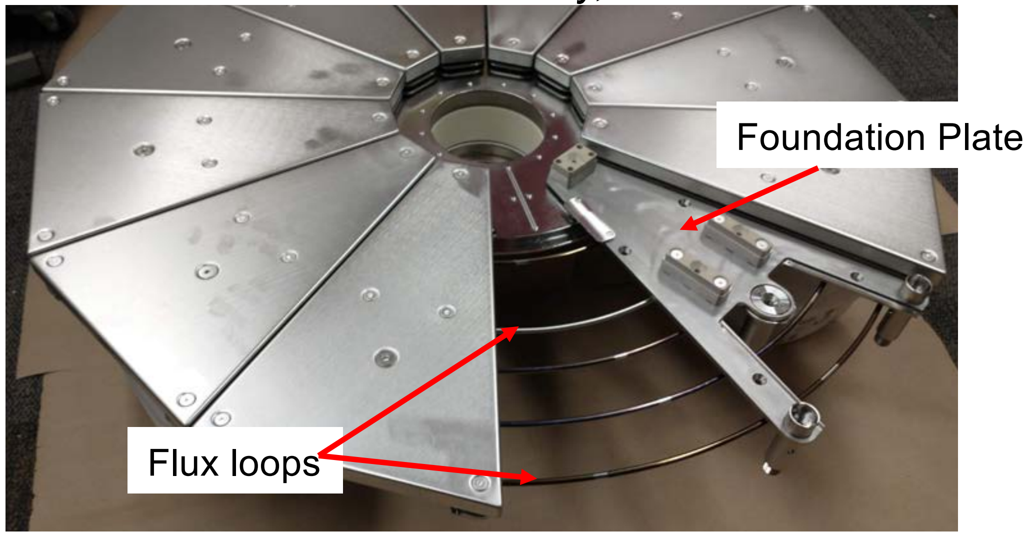
3D CAD of PEGASUS-III CHI electrode concept



T-CHI power supply



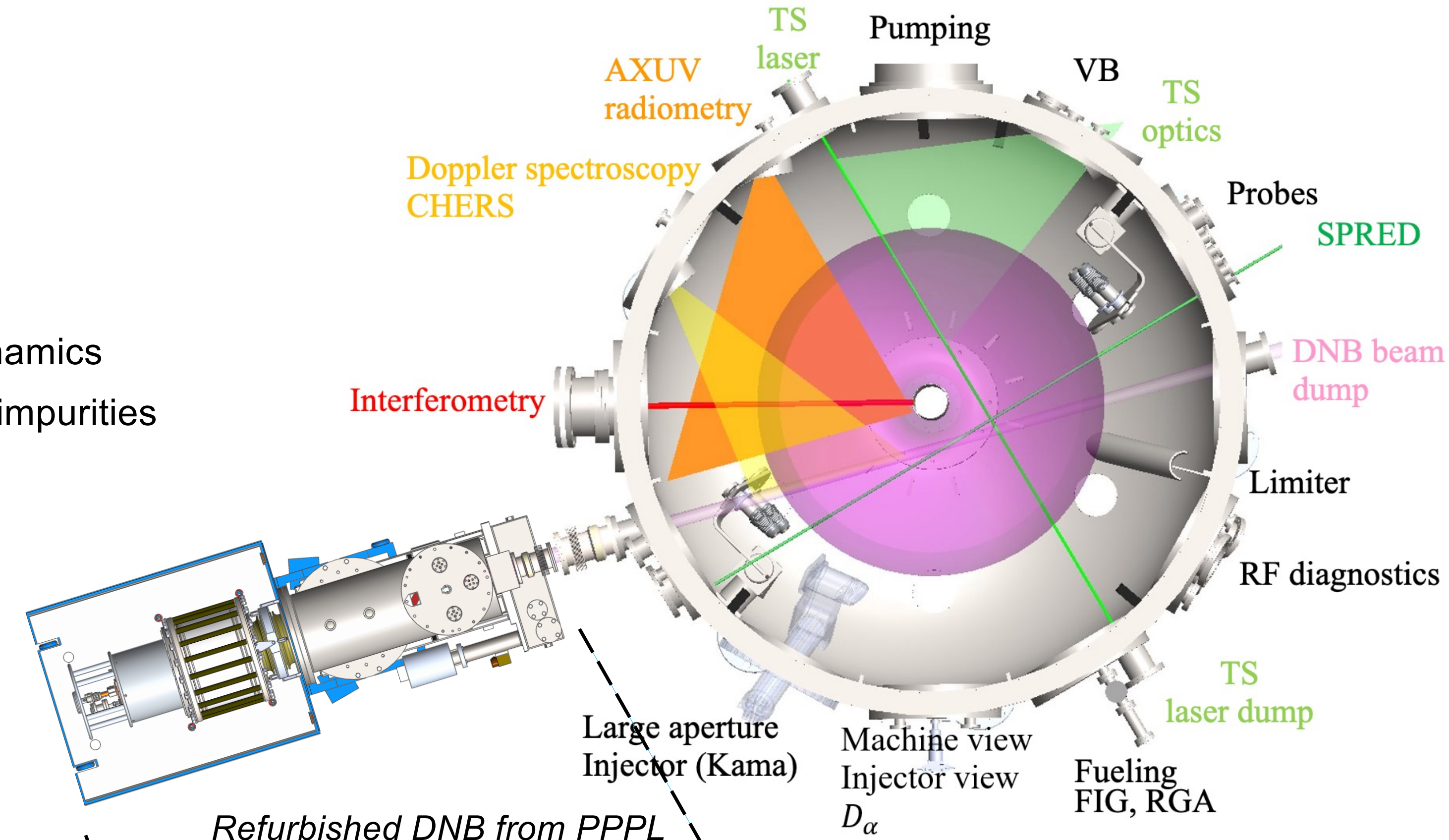
Test fit of divertor assembly, CHI foundation



Enhanced Diagnostic Set for Improved Characterization of Non-solenoidally Produced Plasmas

- Diagnostics based on mission-critical requirements
  - Kinetic equilibrium reconstruction
  - Helicity dissipation
  - MHD & kinetic activity associated with current drive
  - Plasma material interaction with injector surfaces
- New systems under design
  - Neutral Beam emission diagnostics for *B* field, ion dynamics
  - Bolometry, high resolution VUV spectroscopy, VB for impurities
  - n_e measurements of arc plasmas
  - IR imaging
- Insertable probe arrays
  - 3D magnetics
  - Langmuir, Mach
- Flux footprint measurements and imaging for CHI
- RF diagnostics to measure absorption & heating

Layout of PEGASUS-III external diagnostic set



Refurbished DNB from PPPL