The New PEGASUS-III Experiment and Plans for RF Heating and Current Drive

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University of Wisconsin-Madison

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PEGASUS-III Experiment

Elimination of Solenoid Greatly Simplifies ST Design But Requires Non-inductive Startup Pathway

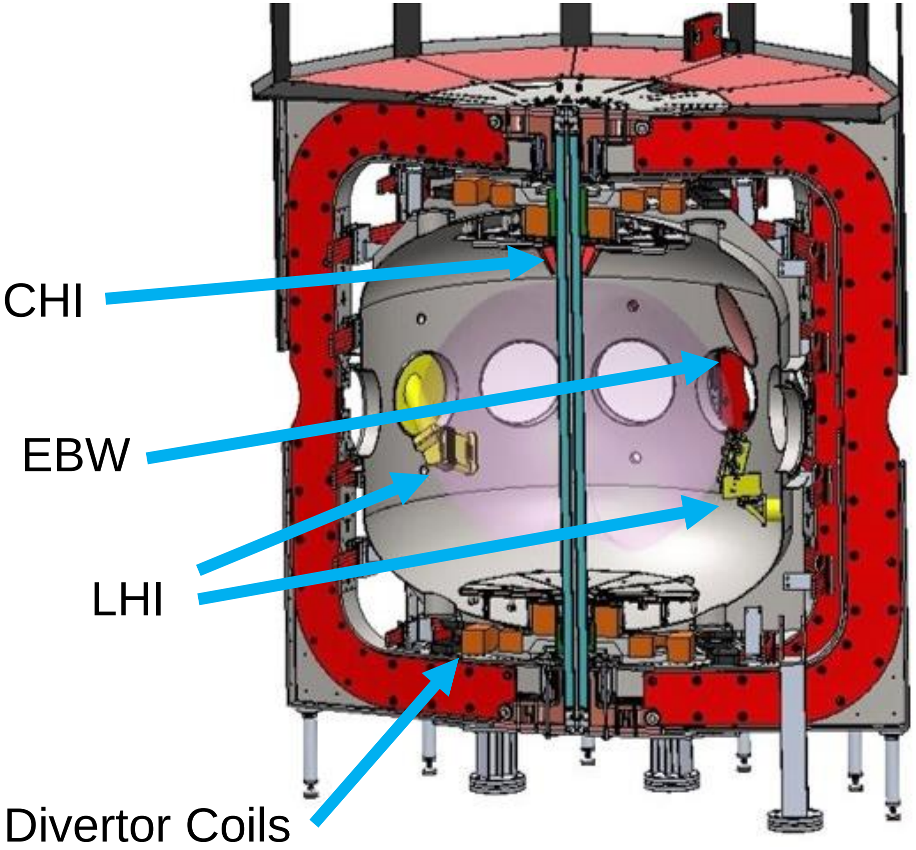
- Future ST designs call for solenoid-free operation
  - Nuclear ST: no OH due to shielding/cost

- PEGASUS-III Mission: Solving solenoid-free startup for STs (and ATs)
  - Advanced Local Helicity Injection
  - Floating Coaxial Helicity Injection
  - RF assist, sustainment and startup
  - Compatibility with NBI heating and current drive

- Research program will provide a predictive understanding of these solenoid-free techniques
  - Extrapolatable techniques to next-step devices

PEGASUS-III features:

- No solenoid
- 4x toroidal field
- Advanced control
- Expanded diagnostics



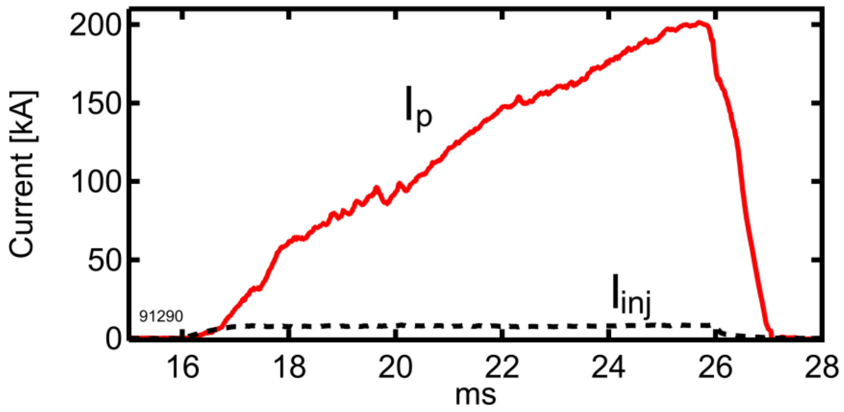
Projecting LHI to High Performance Facilities Requires Tests at Increasing B_T

- Critical physics issues:
  - Confinement tests: linear (OH) , saturated (L-mode), open field line
  - Turbulence-driven dynamo current drive mechanisms

Taylor Limit

$$I_p \leq I_{TL} = I_{inj}\Psi/\psi_{inj}$$

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

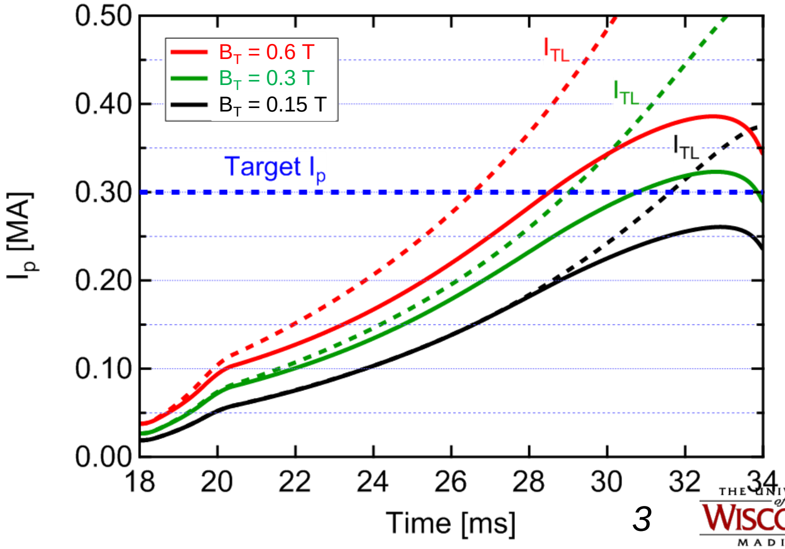


- Utilize two injector configurations
  - Two arrays of 2x4 cm^2 circular injectors
  - Advanced non-circular "Kama" injector – monolithic port mounted injector

Monolithic LHI Injector

- Goal: routine experiments at ~ 0.3 MA

Power balance projections for PEGASUS-III ops



Diem, APS-DPP, 11/2020

Comparative Studies of Helicity Injection Techniques Will be Explored at Increased B_T PEGASUS-III

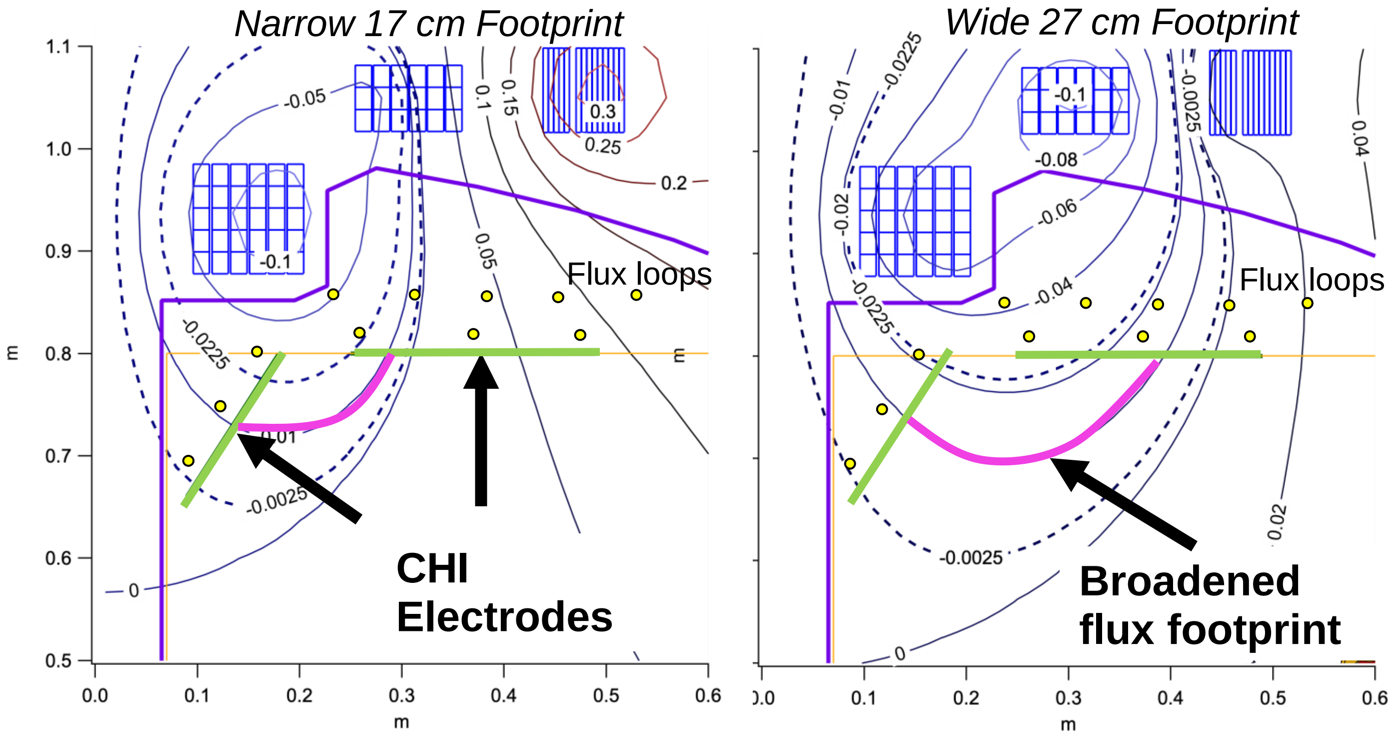
- Novel, flexible CHI system in dedicated experiment
- Address critical physics
  - Flux conversion efficiency
  - Role of footprint in efficiency
  - Comparison and synergies with other methods
  - Role or advantages of non-axisymmetric current flows & structures

"Bubble burst" criterion

$$I_{inj} \geq \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}; C \sim O(1)$$

- Validate projection to ≥1 MA system
  - Test bubble burst and Taylor limit up to 0.3 MA
  - Vary flux distribution across electrodes
- CHI requires auxiliary heating to raise $T_e(0)$

Floating electrodes, flexibility high field divertor coil system



Diem, APS-DPP, 11/2020

RF Heating/CD to be Explored as Component of Non-solenoidal ST Startup Program

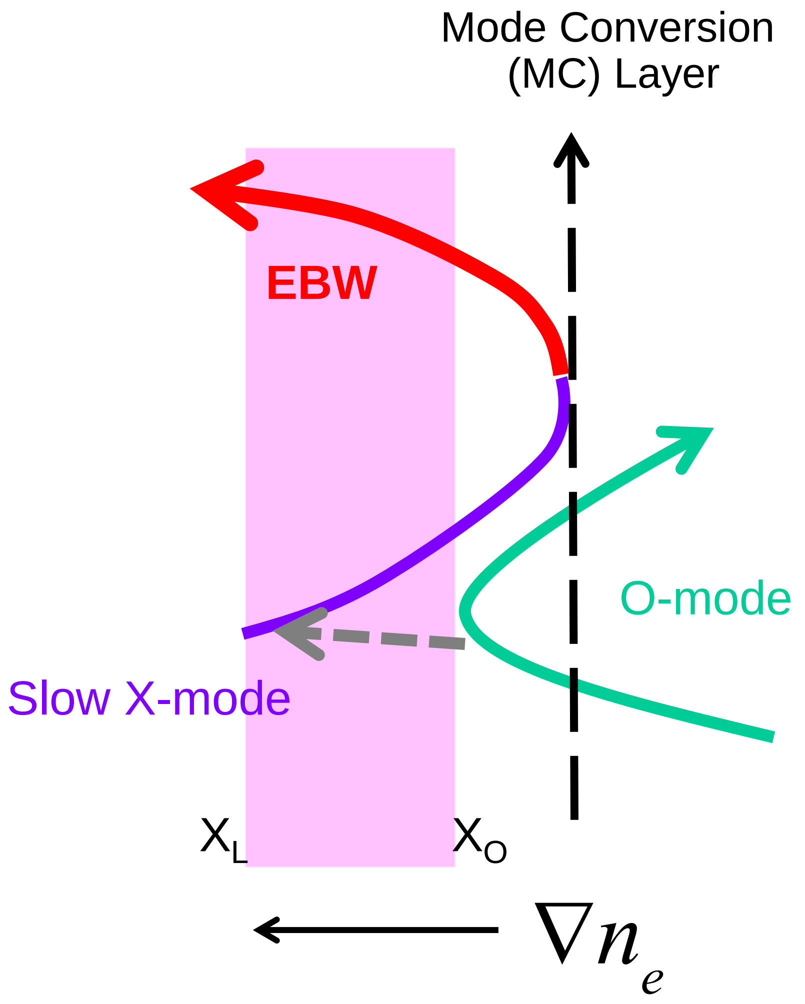
- RF auxiliary heating and CD system will enable long-term scientific campaigns
  - Synergistic effects for improving helicity injection and RF current drive efficiency
  - Comparative tests of most major non-solenoidal startup techniques
  - Current profile tailoring
  - Handoff from non-solenoidal startup to non-inductive sustainment utilizing reactor-relevant tools

- Initial experimental campaigns focus on RF coupling to overdense plasmas
  - EBW heating capability may synergistically enhance LHI induced I_p current by lowering resistivity

- Long term develop RF-only startup

Initial EBW Program Seeks to Explore Synergies

- Relative low B_T, high n_e of STs necessitates use of EBWs for fundamental absorption
- EBW heating: synergistically enhance LHI induced I_p current by lowering resistivity
  - 500 kW EBW RF, 8 GHz
- T_e increases compatibility with non-inductive sustainment (i.e. NBCD)
- T_e control as test of confinement models



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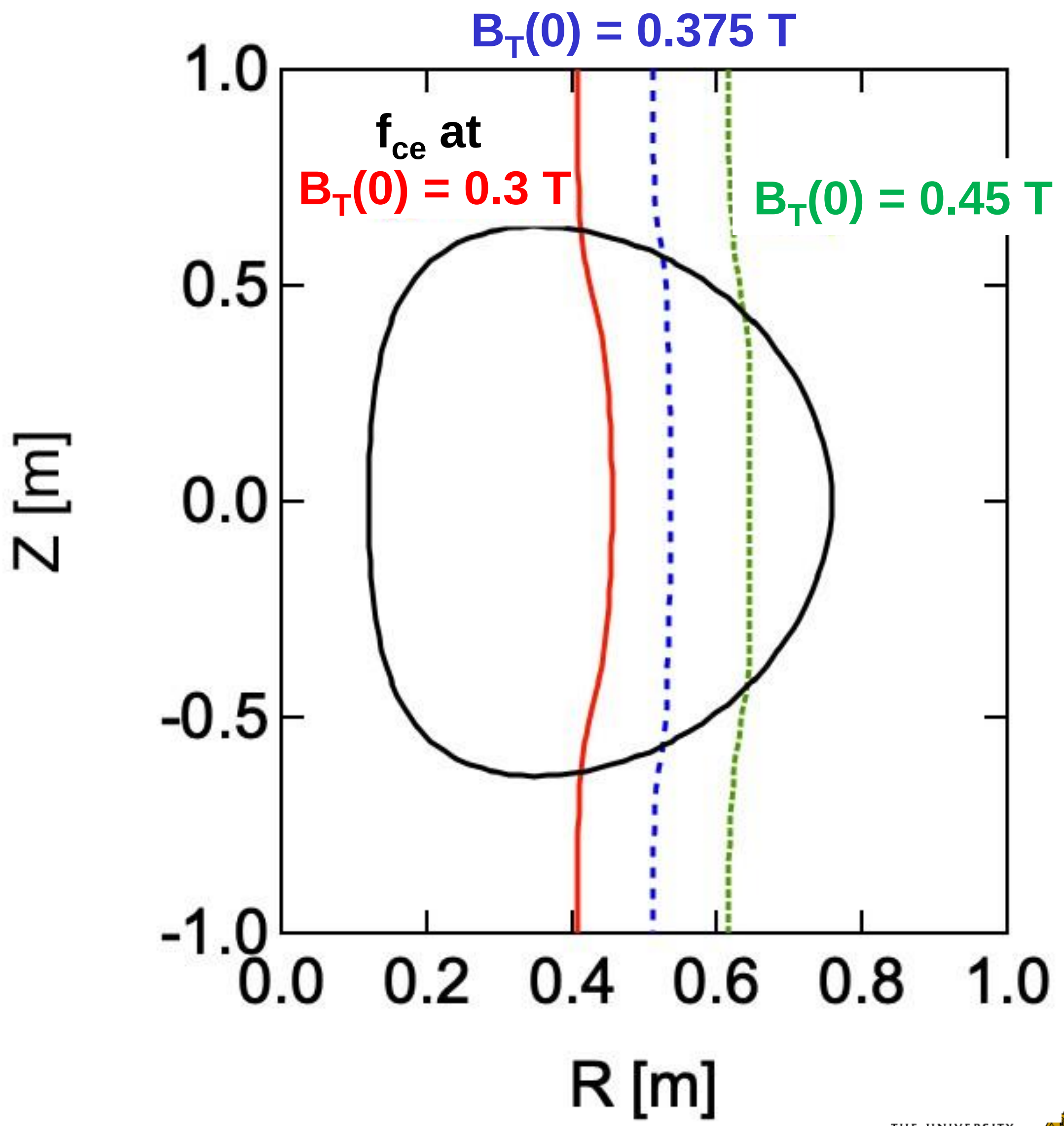
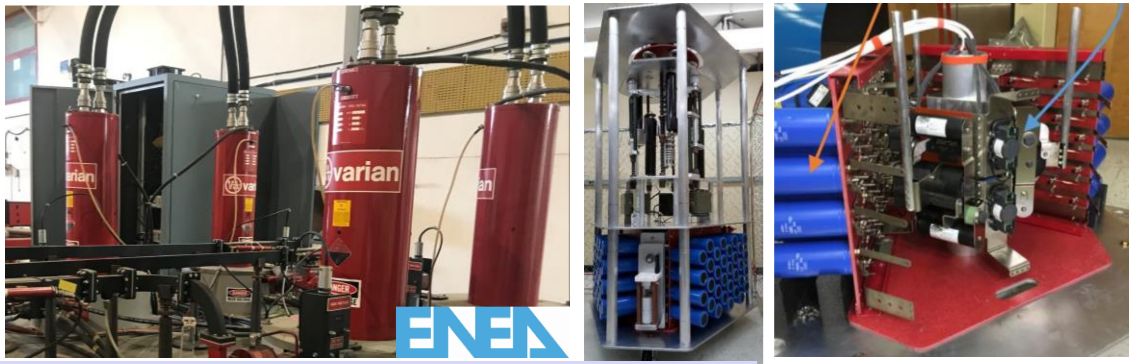




Klystrons powered by new DC-DC resonant supplies

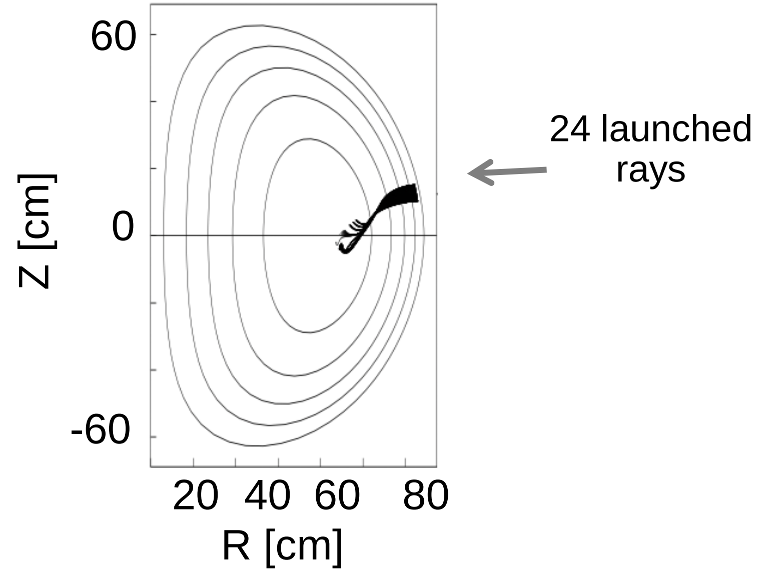
Collaboration between ORNL, ENEA and UW-Madison

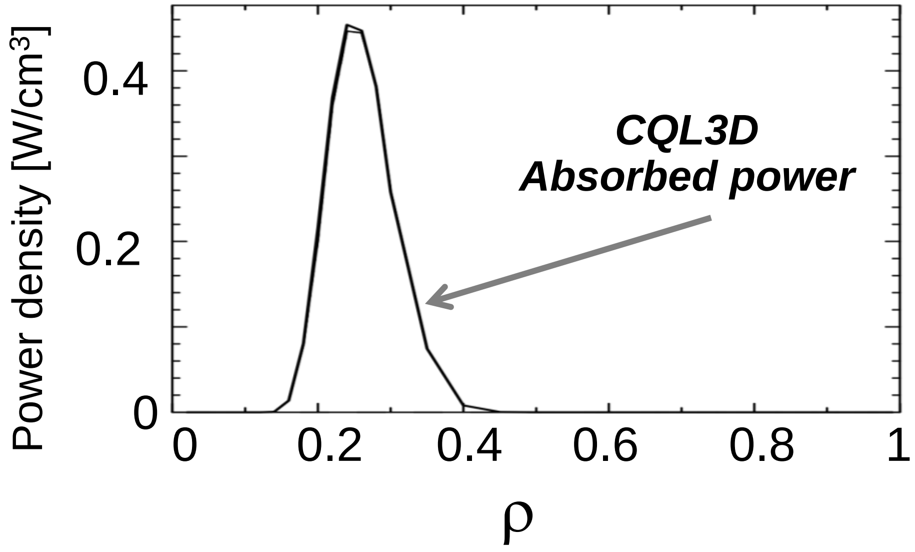
Demonstration of EBW CD for Future Sustainment Studies

- 8 GHz absorption at fundamental EC
  - ~400 kW injected into decaying HI-produced plasma (B_T = 0.339 T)
  - Poloidal launch angle of 30 above midplane
    - $n_{||}$ = -0.55 to -0.45
  - Increasing T_e can increase current drive efficiency

- Modeling shows current drive peaked off-axis
  - I_{EBW} ~ 30 kA comparable to j(0) from LHI
  - Perform current profile tailoring
  - Varying B_T can be used to change absorption location

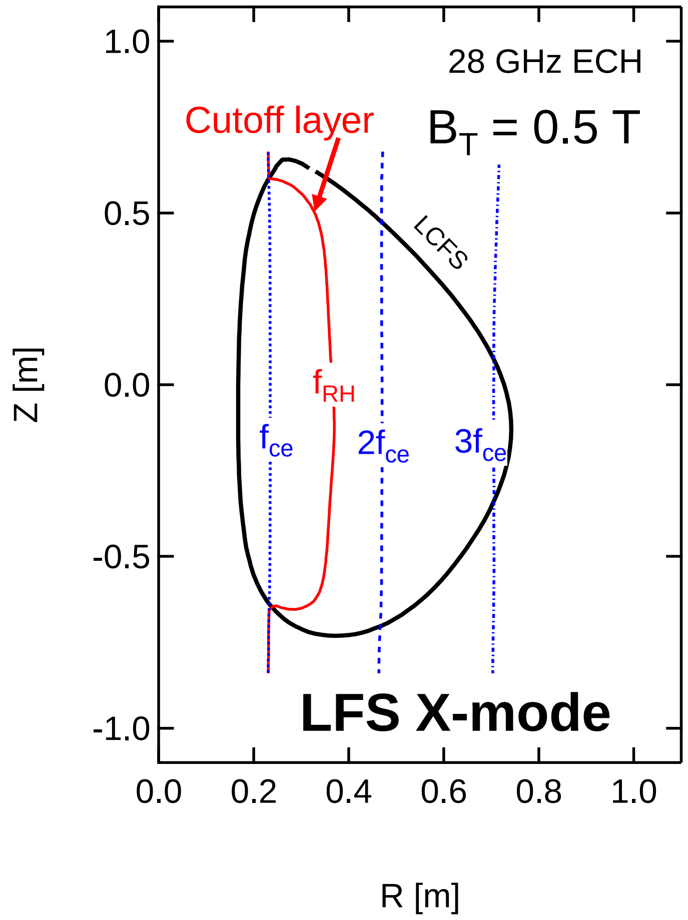
GENRAY EBW Ray-tracing





2^{nd} Phase RF: add ECH/ECCD for HI Synergies and Direct RF Startup

- Heating during post-CHI decay phase
  - 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 2^{nd} harmonic EC resonance
  - Significant EC absorption can occur at 2^{nd} harmonic
  - Density cutoff < 5×10^{18} m^{-3}, accessible during startup

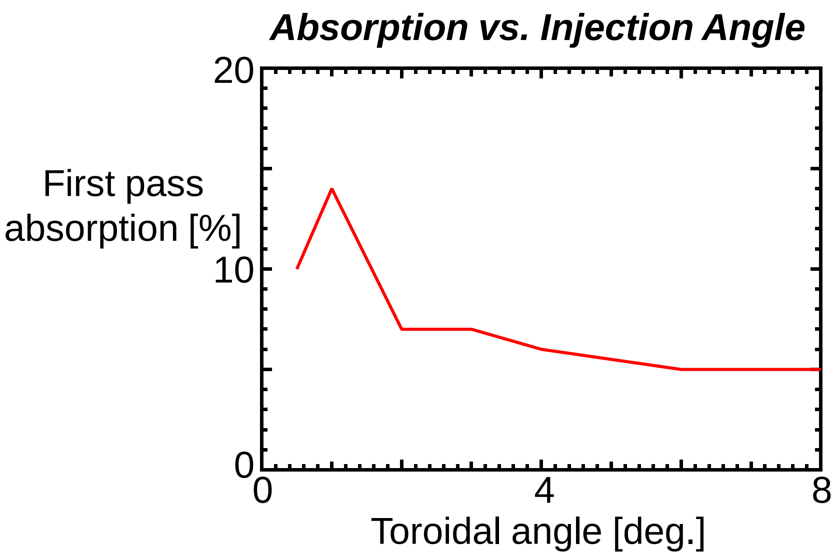


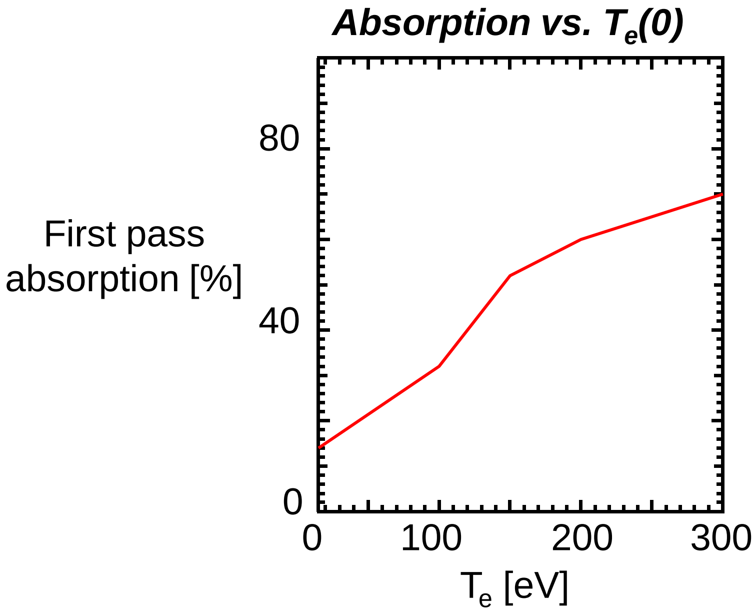
Mode	O1	X1	X2	O2	X3
Frequency	Ω_{ce}	Ω_{ce}	$2\Omega_{ce}$	$2\Omega_{ce}$	$3\Omega_{ce}$
Density	n_{01}	$2n_{01}$	$2n_{01}$	$4n_{01}$	$6n_{01}$

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

ECH Modeling Shows Paths to High Absorption During LHI

- LHI-produced targets are accessible to ECH
  - Wide range of $<n_e>$ available
- Peak 15% first pass absorption possible for $T_e(0)$ = 15 eV
  - Single ray launch injection angle scan via GENRAY
  - Launcher at z = 5.5 cm, poloidal angle = -15°, toroidal angle 1°
  - Applicable to CHI targets
- First pass absorption reaches 70% for $T_e(0)$ = 300 eV
  - Efficacy of ECH dependent on confinement scaling of $T_e(0)$ with B_T, n_e, etc.
- Initial ECH modeling shows promising capabilities



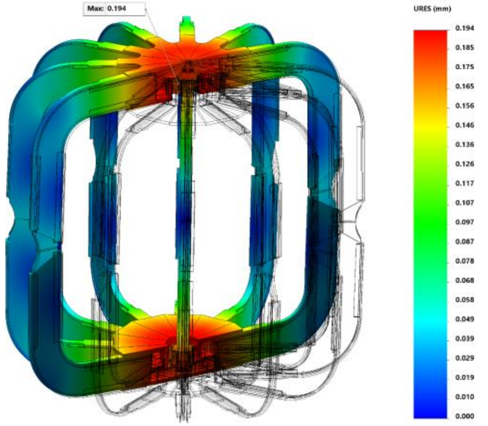


Long-term Plans for RF Seek to Enhance Non-solenoidal Tools on the PEGASUS-III ST

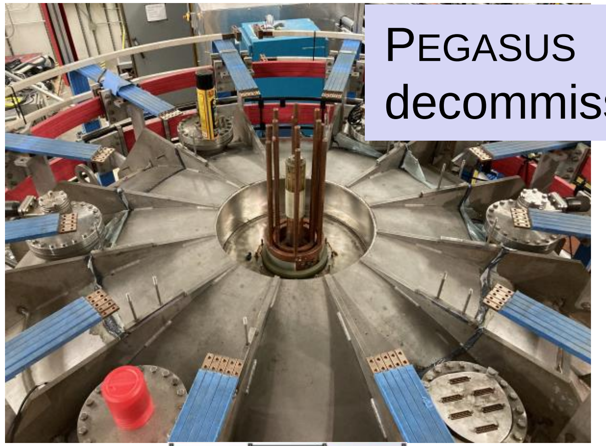
- Bold tests of non-solenoidal ST startup using reactor relevant techniques
  - Local Helicity Injection
  - Coaxial Helicity Injection (transient, sustained)
  - EBW assist and sustainment
  - Future: EC heating and current drive
- RF auxiliary heating and CD system will enable long-term scientific campaigns
  - Synergistic effects for improving helicity injection and RF current drive efficiency
  - Comparative tests of most major non-solenoidal startup techniques
  - Current profile tailoring
  - Handoff from non-solenoidal startup to non-inductive sustainment utilizing reactor-relevant tools
- Also allows unique studies of near unity β_T, low-A physics

PEGASUAS-III is Under Construction

- **ZP06.00001**, “Integrated Studies of Solenoid-Free Tokamak Startup with Pegasus-III”, M.D. Nornberg, et al.
- **ZP06.00002**, “CHI Research on Pegasus-III”, R. Raman, et. al,
- **ZP06.00003**, “Magnetic Activity During LHI Startup and Sustainment”, N.J. Richner, et. al.
- **ZP06.00004**, “Ohmic Sustainment of Local Helicity Injection Initiated Plasmas on the Pegasus ST”, C. Pierren, et. al.



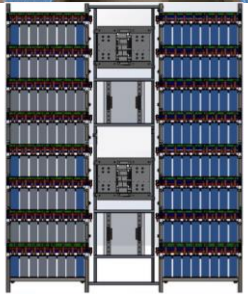
Complete electromechanical design & analysis of TF system



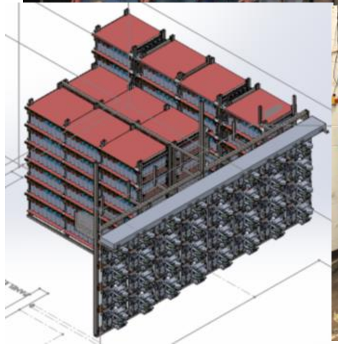
PEGASUS decommissioned

TF center rod, conductors, & return structures delivered

DNB supporting new diagnostics (PPPL loan)



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



Assembly of 240 MVA power systems underway

Backup

Projecting LHI to high-performance facilities requires tests at increasing B_T

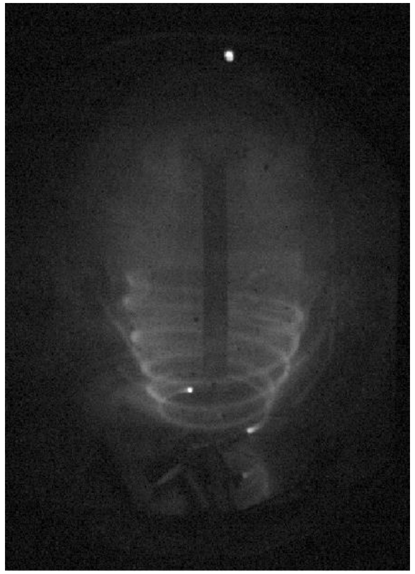
- Critical physics issues:
  - Experiments to develop test of linear vs. saturated vs. open field line confinement
  - Role of turbulence driven dynamo current drive mechanisms

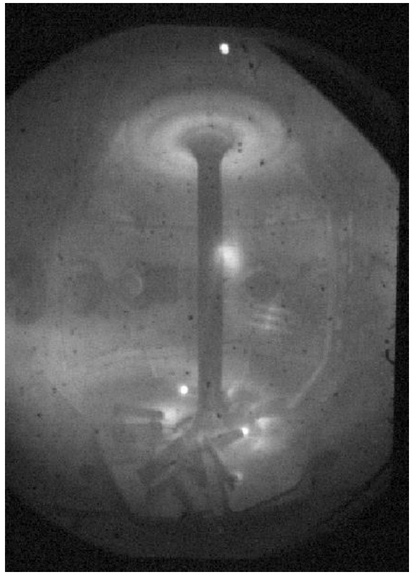
- Utilize two injector configurations
  - Two arrays of 2x4 cm^2 circular injectors
  - Advanced non-circular "Kama" injector – monolithic port mounted injector

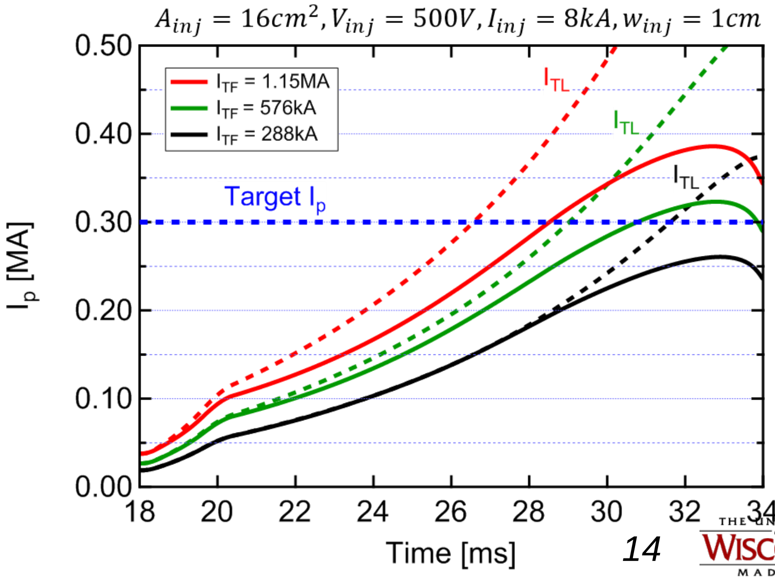
- Goal: routine access to 0.3 MA plasmas

Taylor Limit

$$I_p \leq I_{TL} = I_{inj}\Psi/\psi_{inj}$$







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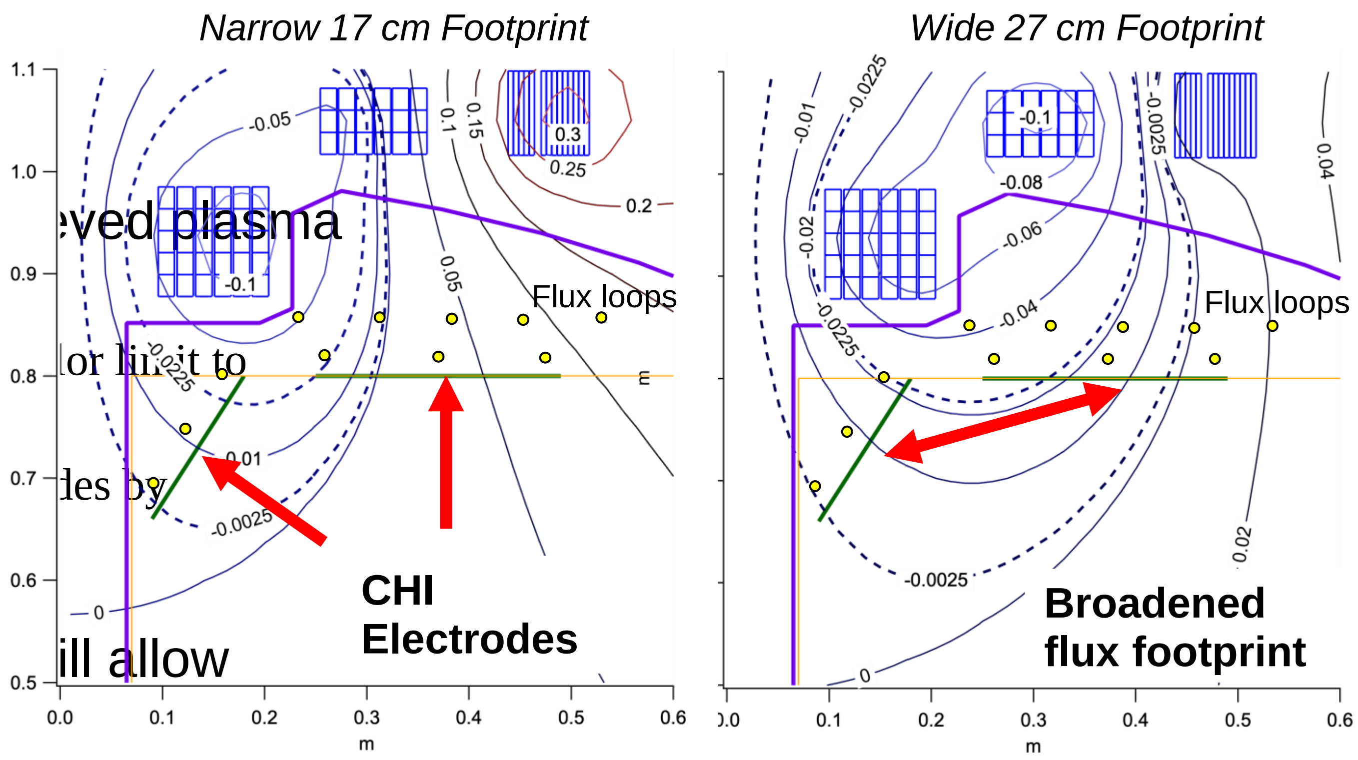
Comparative studies of helicity injection techniques will be explored at Increased B_T PEGASUS-III

- Novel, flexible CHI system in dedicated experiment
  - Studies of CHI with dedicated flexible experimental system
  - Expand investigation of helicity space
  - Validation of MHD simulations
  - Flux conservation efficiency
  - Comparison and synergies with other methods

"Bubble burst" criterion

$$I_{inj} \geq \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}; C \sim O(1)$$

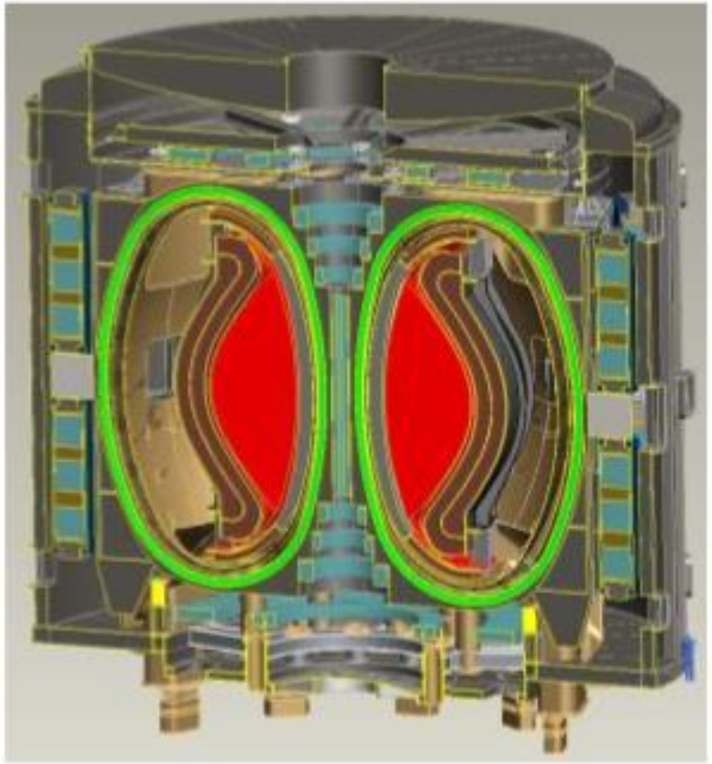
- Validate the design criteria used to project a … eved plasma current to 1 MA system
  - Designed to satisfy the bubble burst criterion and the … lor limit to produce 100-300 kA plasma
  - Explore importance of flux distribution across the el… des by broadening the flux across the outer electrode
- Direct comparison to LHI at similar conditior … ill allow evaluation of scaling possibilities of each tec…



Non-solenoidal startup remains a critical challenge for spherical tokamaks

- Future ST designs call for solenoid-free operation
  - Nuclear ST designs generally prohibit OH due to shielding/cost
  - Small solenoid considered as a fallback; insufficient for I_p ramp-up
- OH solenoid removal simplifies tokamak design
  - Potential cost reduction
  - More space for inboard shielding/blanket
  - Lower electromechanical stress
- Requires physics understanding of optimal non-solenoidal tokamak startup

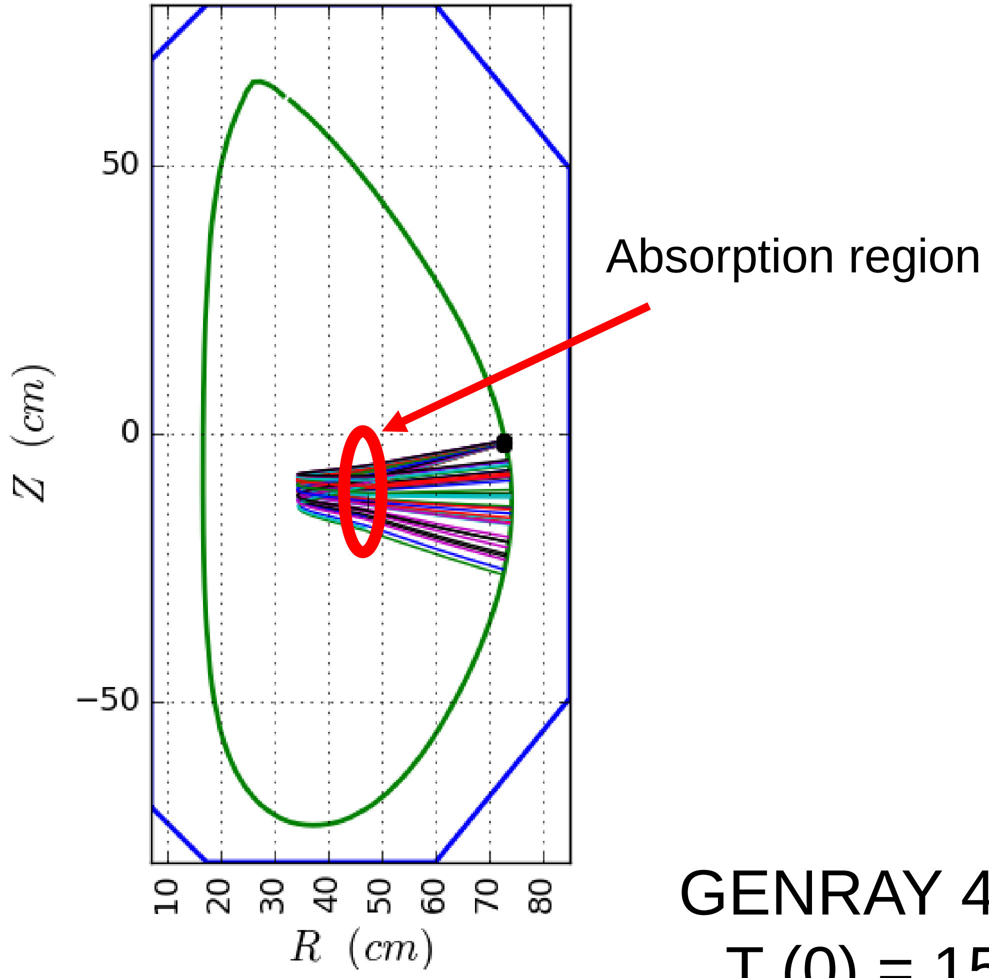
No/small OH HTS ST-FNSF/Pilot Plant
Shielding needs severely constrain OH viability



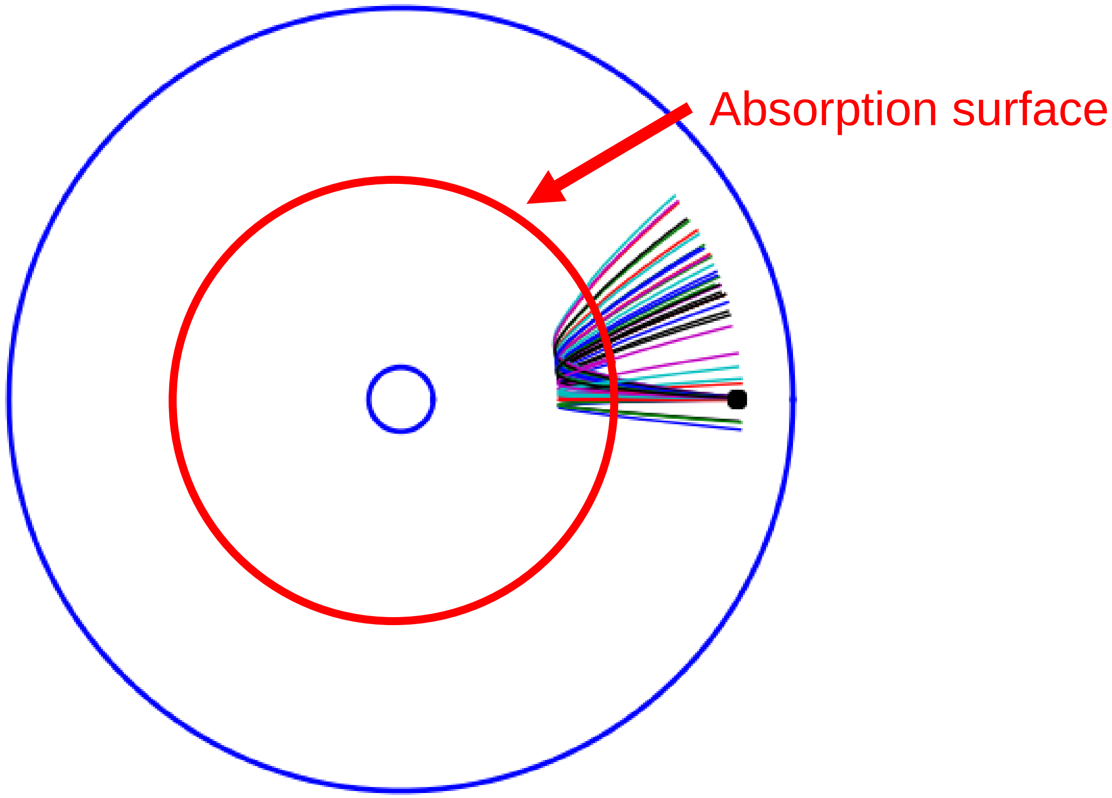
J.E. Menard, Phil. Trans. R. Soc. A 377, 20170440 (2019)

28 GHz X2 ECH feasible at full B_T in Pegasus-III

Poloidal Cross Section



Toroidal Cross Section



GENRAY 48-ray bundle trajectory shown for $T_e(0)$ = 150 eV, 42% first pass absorption

Comparative studies of helicity injection techniques will be explored at Increased B_T Pegasus-III

- Explore CHI physics at B_T = 0.6 T
  - Expand investigation of helicity space
  - Validation of MHD simulations
  - Flux conservation efficiency
  - Comparison and synergies with other methods
- Direct comparison to LHI at similar conditions will allow evaluation of scaling possibilities of each technique

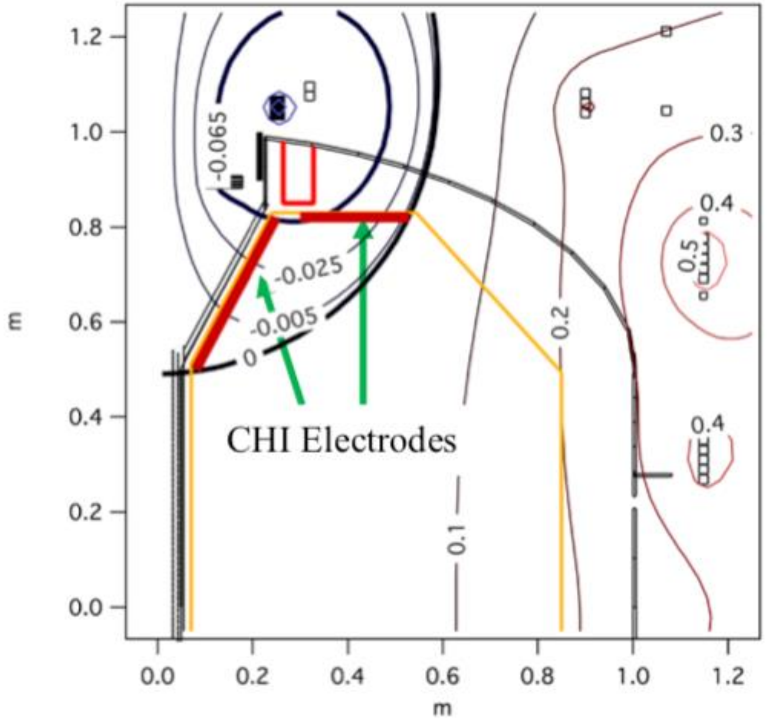
Taylor Limit

$$I_p \leq I_{TL} = I_{inj}\Psi/\psi_{inj}$$

"Bubble burst" criterion

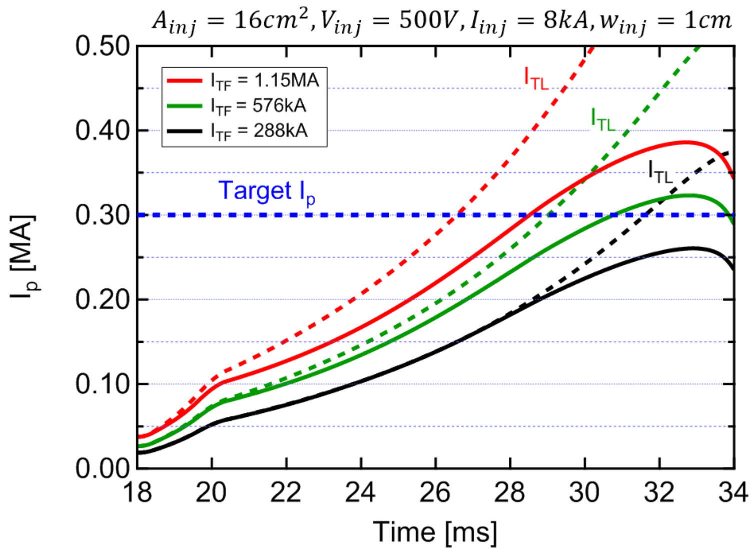
$$I_{inj} \geq \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}; C \sim O(1)$$

65 mWb Connecting CHI Electrodes



Projecting LHI to high-performance facilities requires tests at increasing B_T

- Critical physics issues:
  - I_p gains with increased Taylor limit
  - Initial tokamak formation
  - Scaling of core confinement
  - Current drive mechanisms
  - Current stream stability
- Advanced geometery – i.e. non-circular “Kama” - injector designs may lead to higher performance
  - Increase $A_{inj} \rightarrow$ lower V_{inj} for reduced PMI
  - Narrow current channel (w)
  - Increase I_{inj}
  - Single LFS port assembly
  - Programmable $V_{inj}(t)$ capability
- 0-D model projects I_p > 300 kA at 50% of Pegasus-III max toroidal field



2^{nd} Phase RF: add ECH/ECCD for HI Synergies and Direct RF Startup

- Low n_e startup plasma accessible to harmonic ECH, ECCD
  - During helicity injection, densities favorable to ECH, ECCD for harmonic absorption
  - EC waves propagate in vacuum, readily couple to plasma and are absorbed near EC resonance locations

- Pegasus-III maximum B_T = 0.5 T at R_0 = 0.46 m provides access to 2^{nd} harmonic EC resonance
  - Density cutoff < 5×10^{18} m^{-3}, accessible during startup
  - Significant EC absorption can occur at 2^{nd} harmonic

Mode	O1	X1	X2	O2	X3
Frequency	Ω_{ce}	Ω_{ce}	$2\Omega_{ce}$	$2\Omega_{ce}$	$3\Omega_{ce}$
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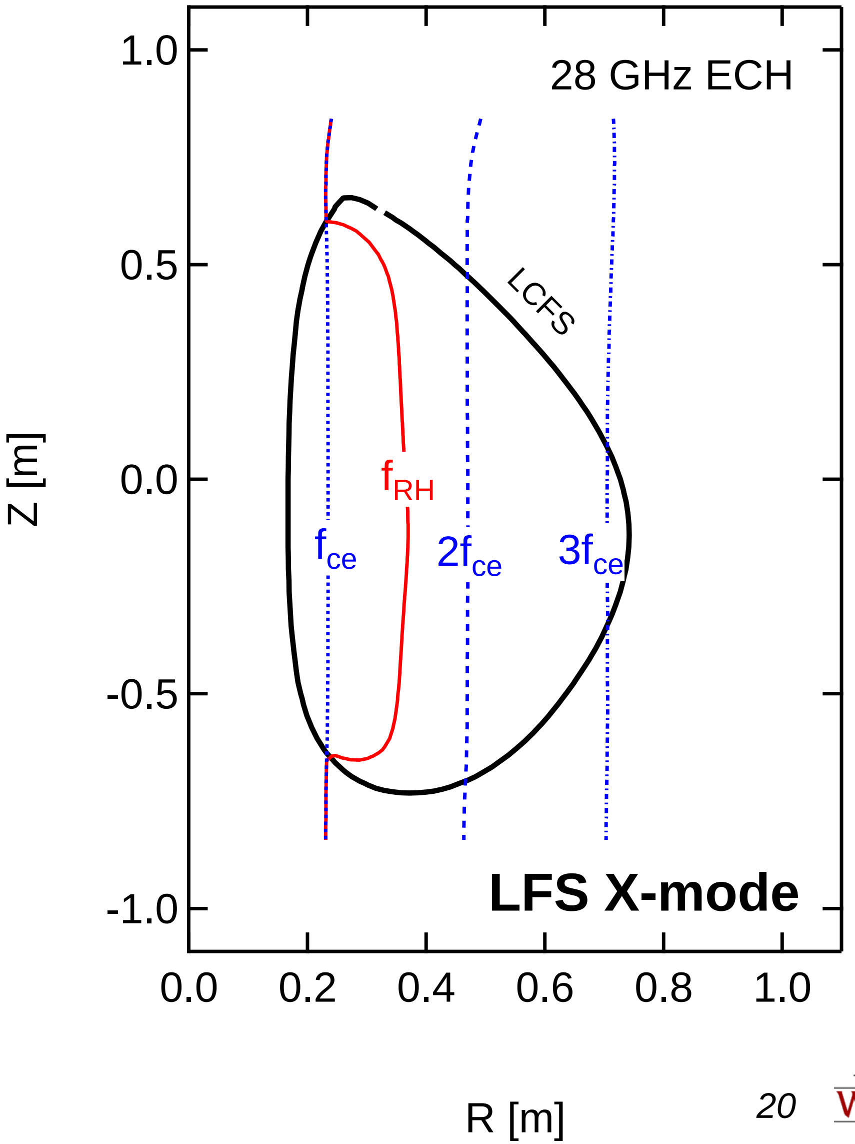

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