Exploring Transformative Startup Solutions for Magnetically Confined Fusion Plasmas

S.J. Diem, G.M. Bodner, M.W. Bongard, R.J. Fonck, J.A. Goetz, A.K. Keyhani, B.A. Kujak-Ford, B.T. Lewicki, M.D. Nornberg, A.C. Palmer, J. Peery, C. Pierren, J.A. Reusch, A.T. Rhodes, N.J. Richner, C. Rodriguez Sanchez, C.E. Schaefer, A.C. Sontag, T. Tierney, J.D. Weberski, G.R. Winz

University of Wisconsin-Madison

Presented at the Michigan Institute for Plasma Science and Engineering

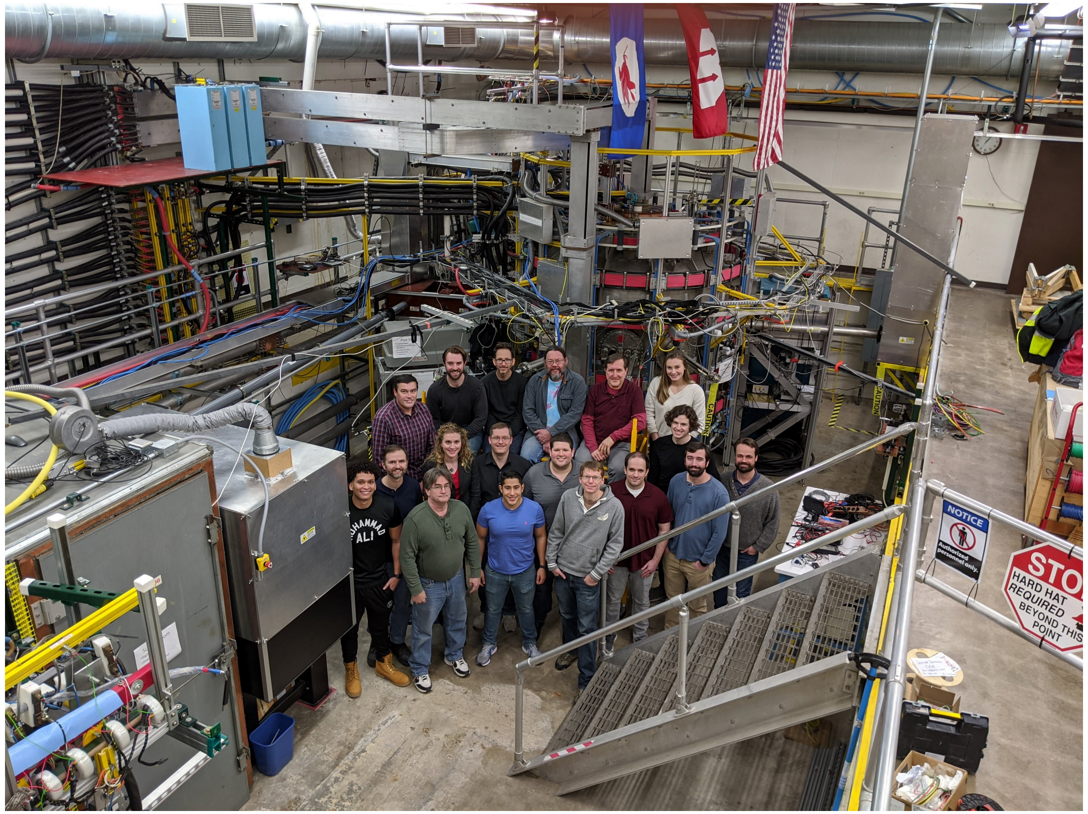
02 December 2020

Work supported by DOE

PEGASUS-III Experiment

Why Investigate Startup for Tokamaks?

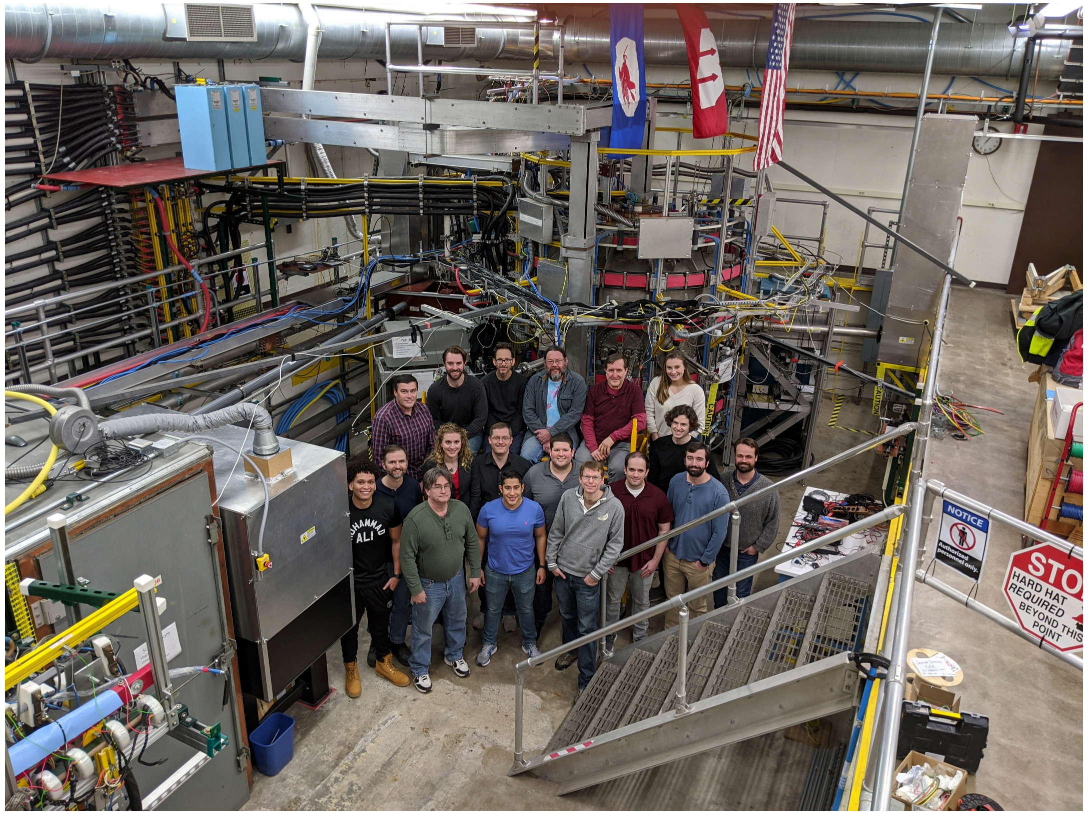
- More efficient use of main magnetic field by compact toroidal geometry
  - Reduces central induction (main startup technique) capacity
  - Spherical Tokamaks (STs) study this operation space, low-A
- Lighting a match for fusion: new PEGASUS-III Experiment to study innovations in plasma startup techniques
  - Focused on techniques to help reduce cost and complexity of future fusion reactors
- Radiofrequency waves can be used to heat, drive current in STs, synergistically enhance non-solenoidal techniques



PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

Why Investigate Startup for Tokamaks?

- More efficient use of main magnetic field by compact toroidal geometry
  - Reduces central induction (main startup technique) capacity
  - Spherical Tokamaks (STs) study this operation space, low-A
- Lighting a match for fusion: new PEGASUS-III Experiment to study innovations in plasma startup techniques
  - Focused on techniques to help reduce cost and complexity of future fusion reactors
- Radiofrequency waves can be used to heat, drive current in STs, synergistically enhance non-solenoidal techniques



PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

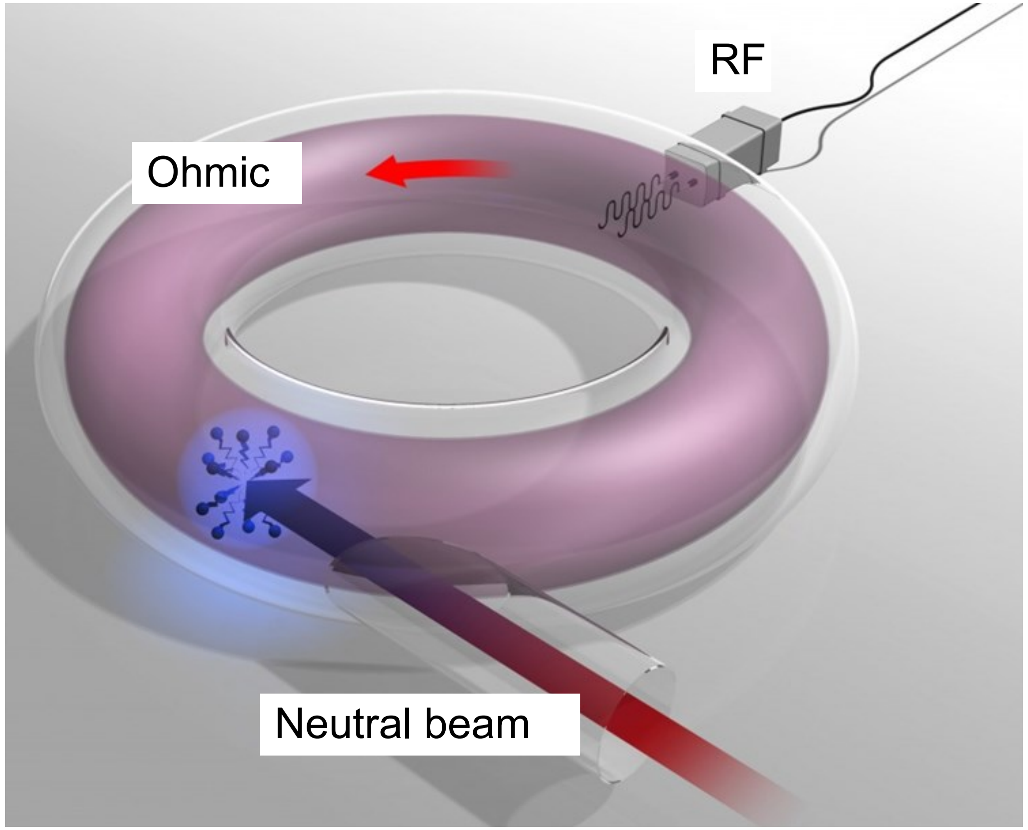
Tokamak Plasmas Require Current Drive and Heating to Achieve Fusion

- Fusion power proportional to:

$$n \bullet T \bullet \tau_E$$

  - External heating required to reach temperature for ignition
  - After ignition, self-heating sustains plasma

- Several methods of external heating & current drive available
  - Electron cyclotron (EC) resonance is in microwave range of frequencies
  - At high densities, injected microwave can be reflected – requires alternative methods of coupling microwave power

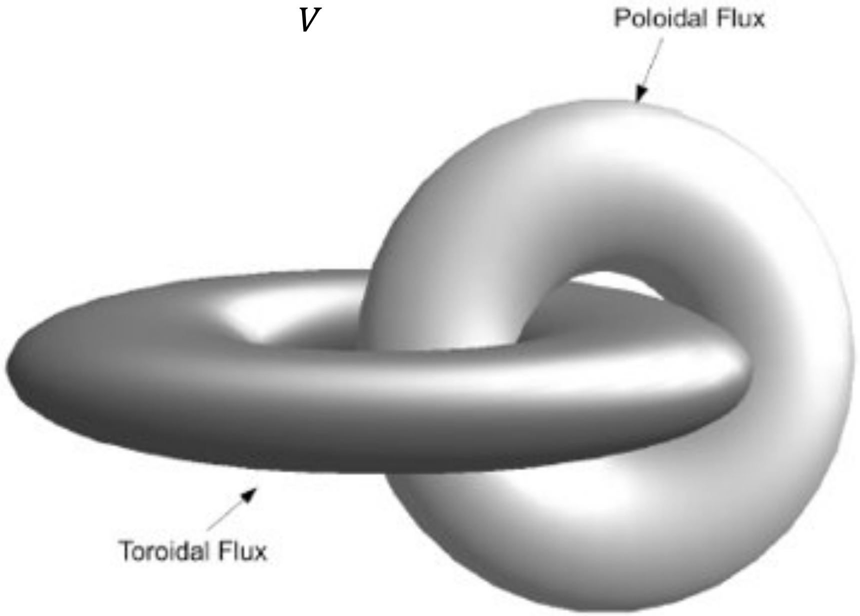


Helicity Injection Techniques Can Initiate and Drive Tokamak Plasmas

- Magnetic helicity, K ≡ “linkedness” of magnetic flux in a volume

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

- In a tokamak, K_{plasma} results from linking Ψ_T and ψ_p
- Increasing K_{plasma} → increase in toroidal plasma current
- Two methods of adding helicity:
  - AC helicity injection – increasing flux via magnetic induction within target volume
  - DC helicity injection – potential applied along open field lines that penetrate magnetic boundary



Schematic illustrating flux linkage in a toroidal (tokamak) geometry

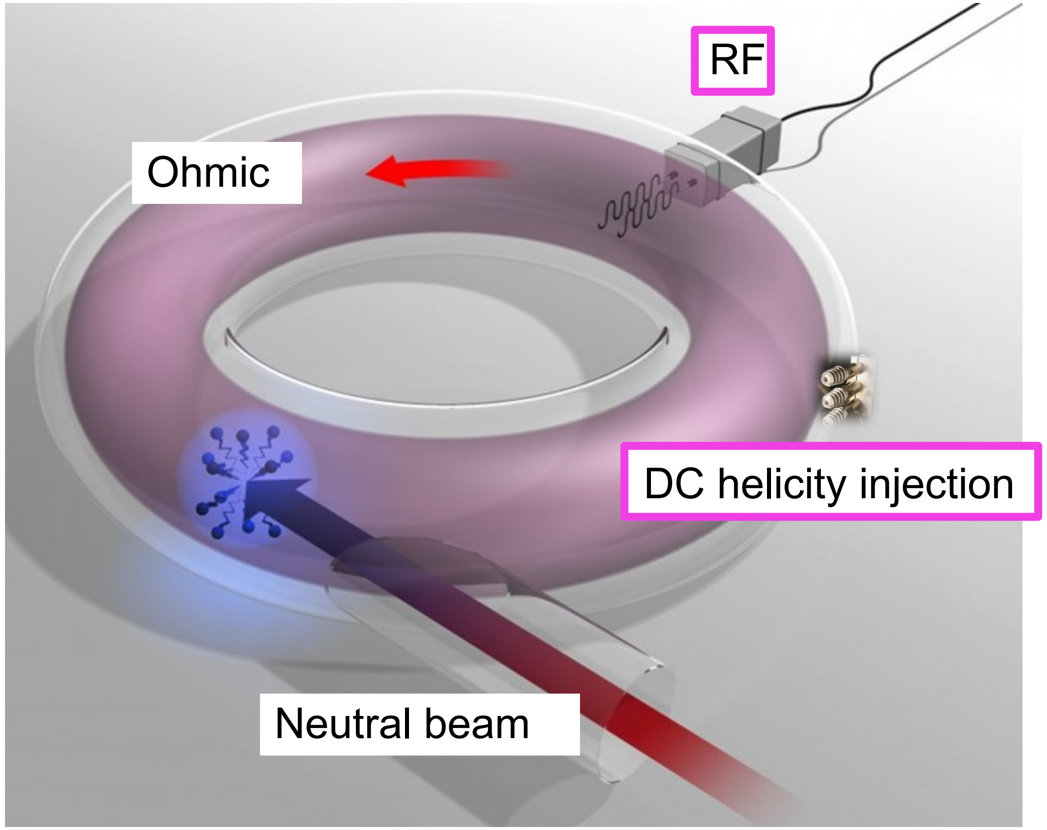
Tokamak Plasmas Require Current Drive and Heating to Achieve Fusion

- Fusion power proportional to:

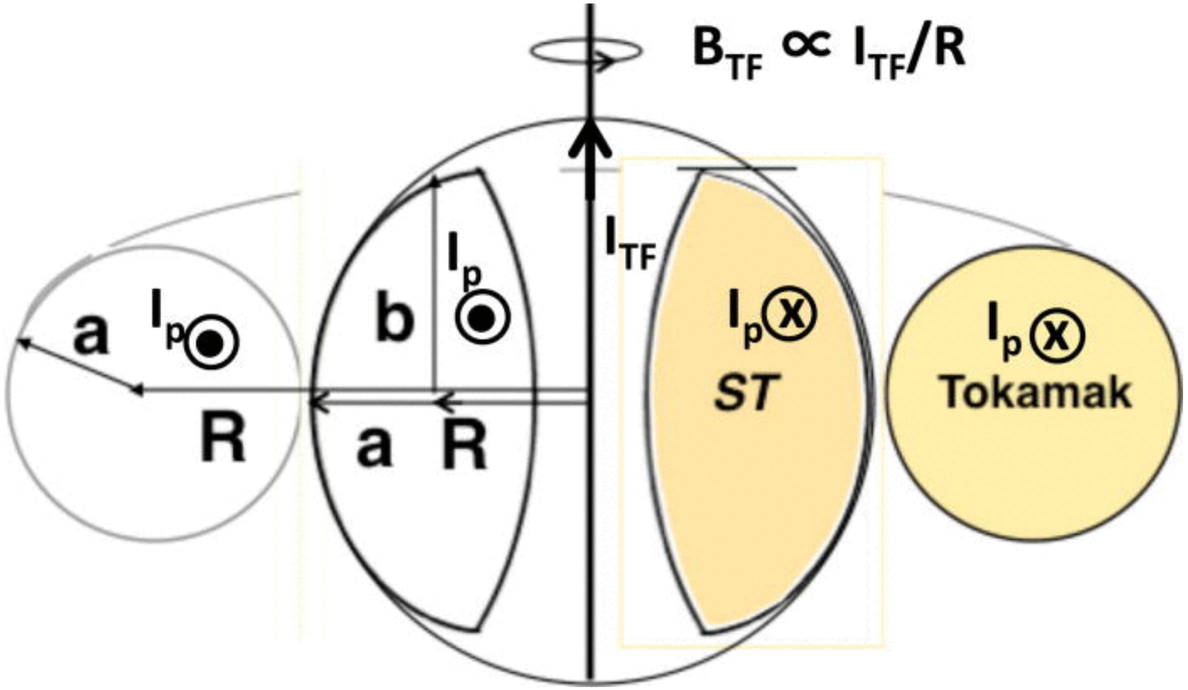
$$n \bullet T \bullet \tau_E$$

  - External heating required to reach temperature for ignition
  - After ignition, self-heating sustains plasma

- Several methods of external heating & current drive available
  - Electron cyclotron (EC) resonance is in microwave range of frequencies
  - At high densities, injected microwave can be reflected – requires alternative methods of coupling microwave power



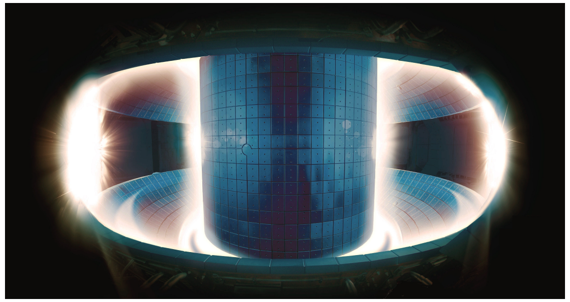
The Spherical Tokamak (ST) is a Low Aspect Ratio Tokamak



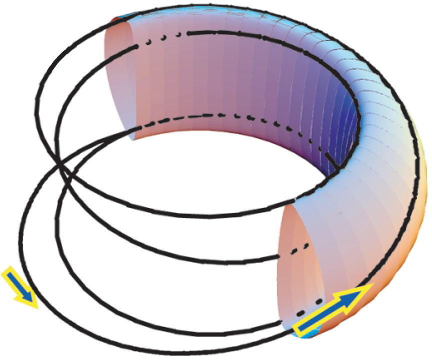
- Low aspect ratio: $A = R/a < 2$
- Natural elongation: $k = b/a$ without active shaping coils
- Strong toroidicity: $B_T(R)$ varies significantly across plasma

Y.-K.M. Peng, Nucl. Fusion **26**, 769 (1986)
M. Ono, Phys. Plasmas **22**, 040501 (2015)

ST Configuration Efficiently Utilizes B



KSTAR Tokamak



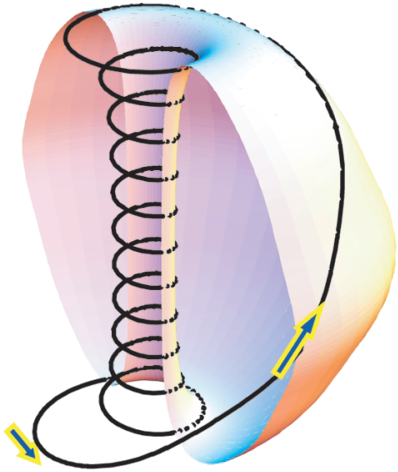
Tokamak

$A \sim 4$

$q_a \sim 4$

$\beta_T < 10\%$

$I_p/I_{TF} << 1$



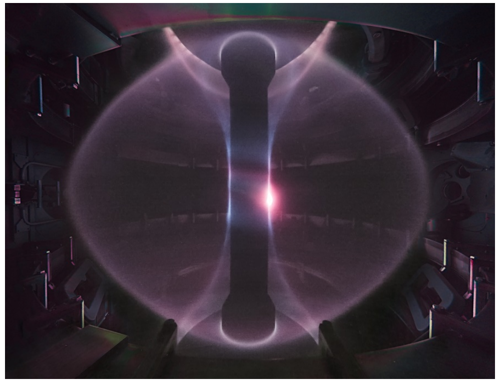
Spherical Tokamak

$A \sim 1.25$

$q_a \sim 12$

$\beta_T < 100\%$

$I_p/I_{TF} \sim 1$



MAST Spherical Tokamak

- Average field line curvature optimizes MHD stability for given toroidal field
  - Also, device cost ($B_T \sim \$\$$)

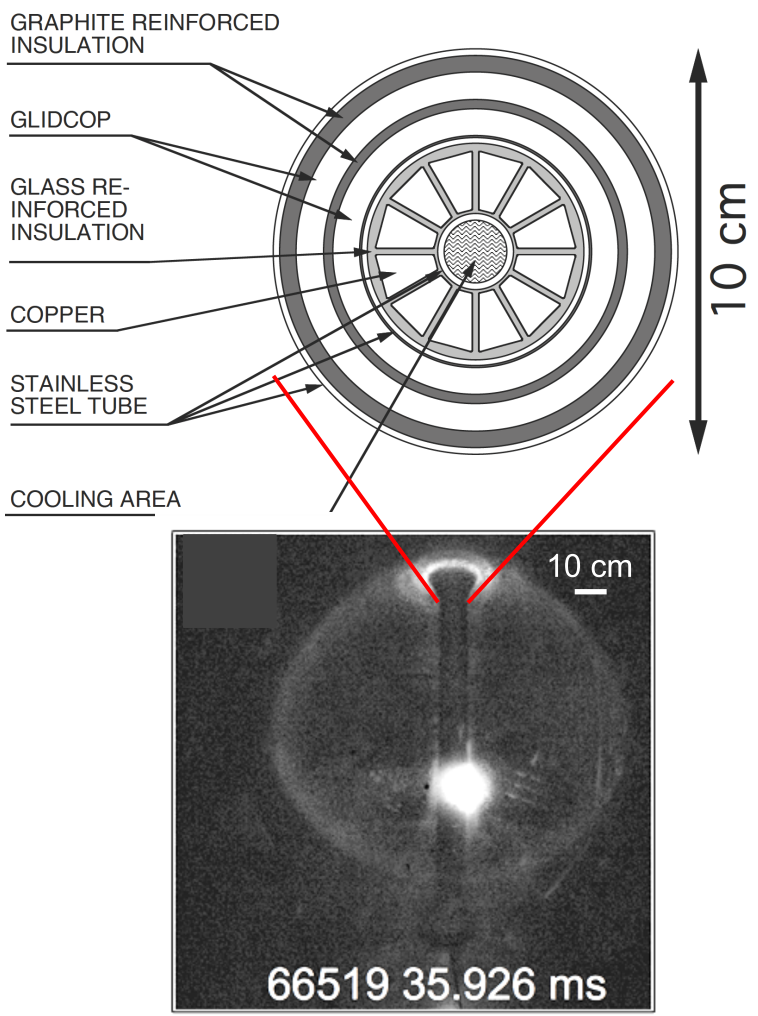
- Efficiency leads to high $\beta_T = \langle p \rangle/(B_T / 2\mu_0)$

Y.-K.M. Peng, Phys. Plasmas **7**, 1681 (2000)
D.J. Schlossberg, Phys. Rev. Lett. **119**, 035001 (2017)
J.A. Reusch, Phys. Plasmas **25**, 056101 (2018)

Engineering Tradeoffs Arise at Low A

- Low-A → small central column
  - Little/no space for needed tokamak coils, diagnostics, cooling
- Limited Ohmic volt-seconds
  - Small solenoid area
  - PEGASUS: $B_{sol} < 15$ T; $R_{sol} \sim 3$ cm
- Feasibility of reactor central column neutron shielding
  - $I_p \sim I_{TF}$: Copper TF rod possible
    - Nonetheless, high recirculating power
  - Non-solenoidal startup preferred

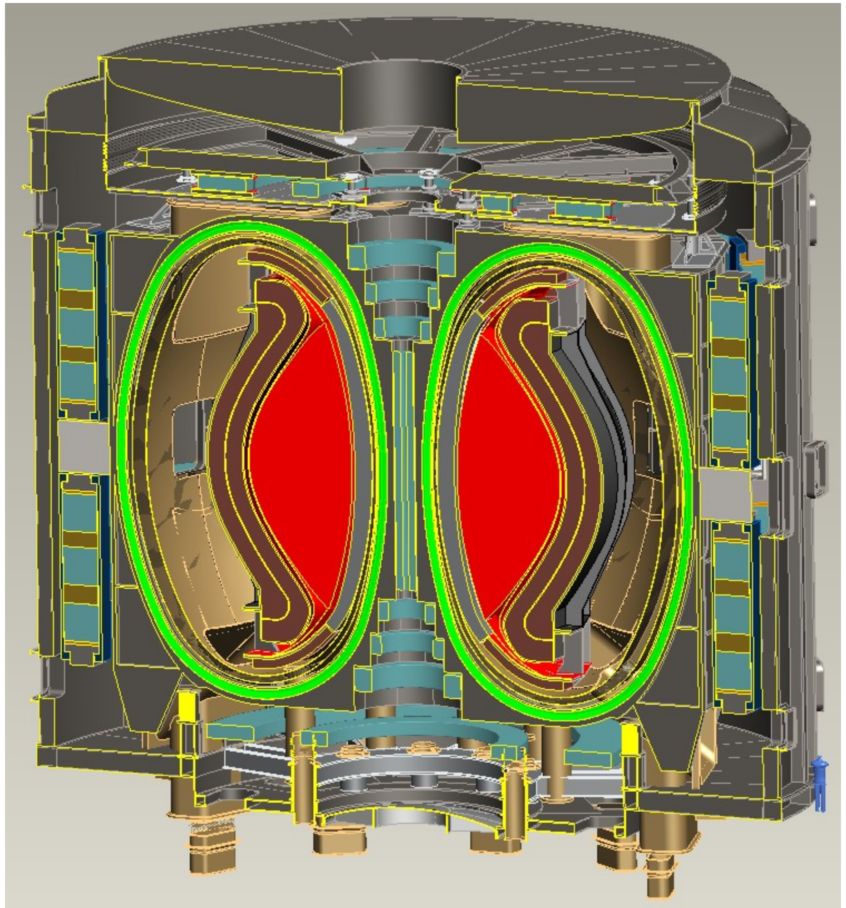
Radial build of PEGASUS central column and its proportion to typical A ~ 1.2 H-mode plasma



J. Menard *et al.*, Nucl. Fusion **56**, 106023 (2016)   Bongard, IAEA FEC 2016 EX/P4-51

Non-Solenoidal Startup is Critical for the ST

- 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
  - Reduce PF system requirements
  - Lower electromechanical stresses
- Solenoid-free startup techniques may offer tools for modifying J(R)

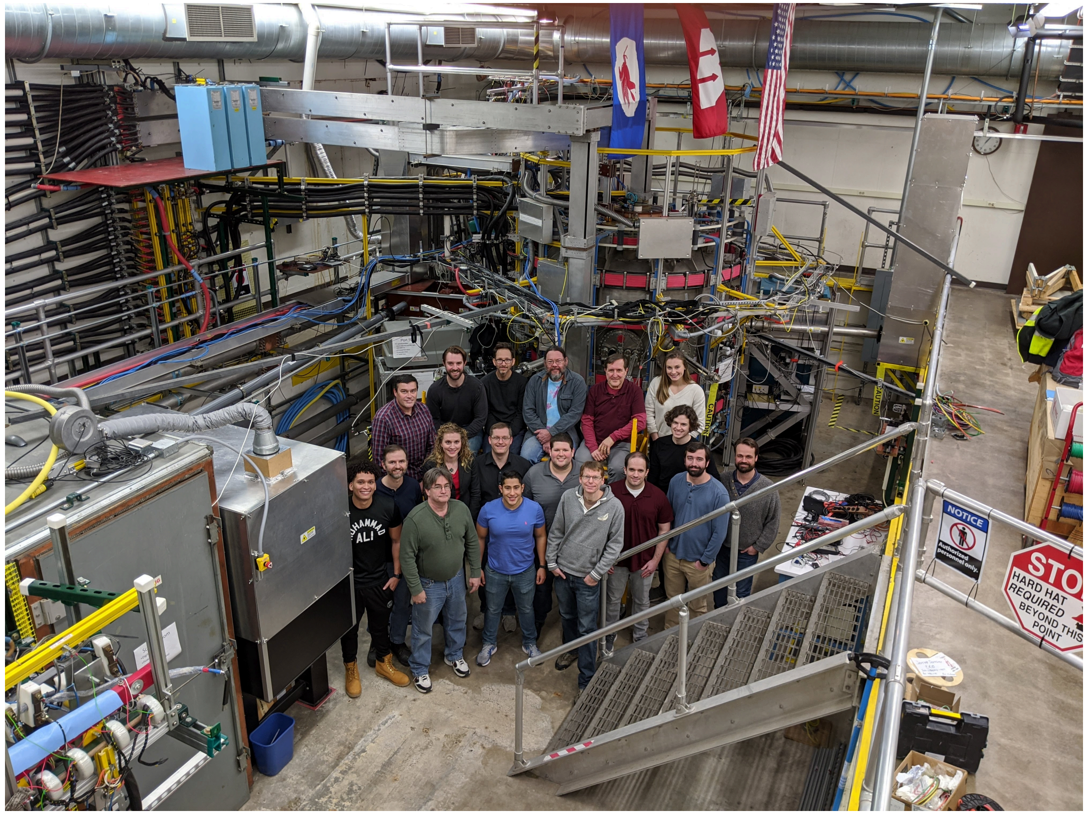


No / small OH HTS ST-FNSF / Pilot Plant

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

Why Investigate Startup for Tokamaks?

- More efficient use of main magnetic field by compact toroidal geometry
  - Reduces central induction (main startup technique) capacity
  - Spherical Tokamaks (STs) study this operation space, low-A
- Lighting a match for fusion: new PEGASUS-III Experiment to study innovations in plasma startup techniques
  - Focused on techniques to help reduce cost and complexity of future fusion reactors
- Radiofrequency waves can be used to heat, drive current in STs, synergistically enhance non-solenoidal techniques



PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

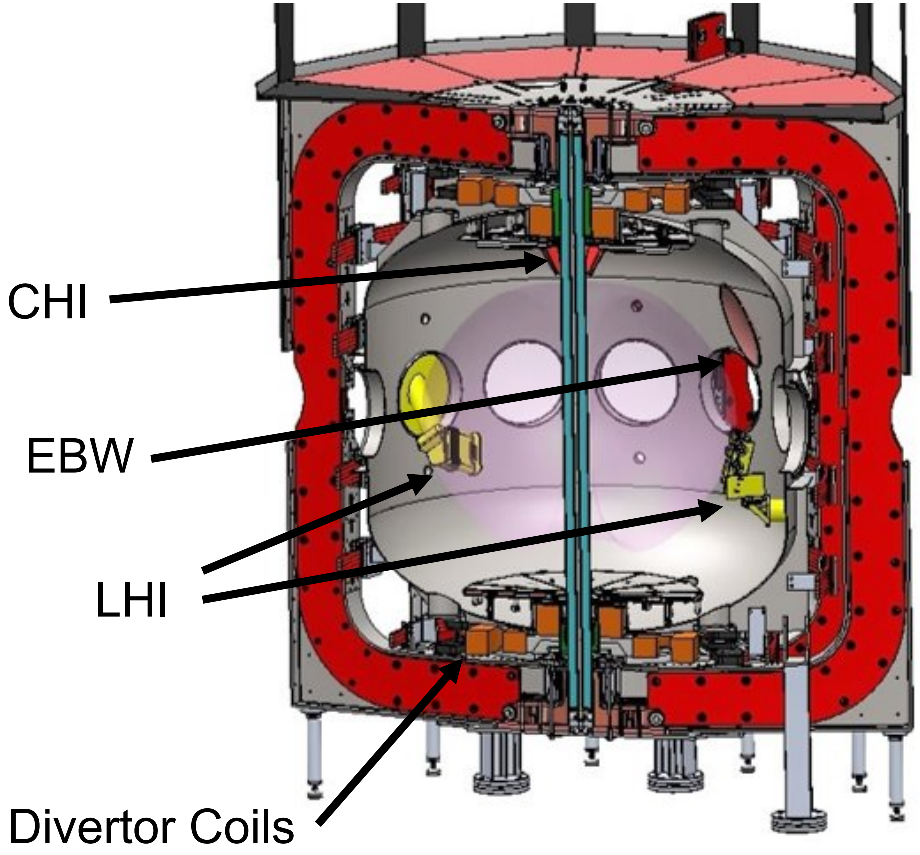
Elimination of Solenoid Greatly Simplifies ST Design and Requires Non-Inductive Startup Pathway

- 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

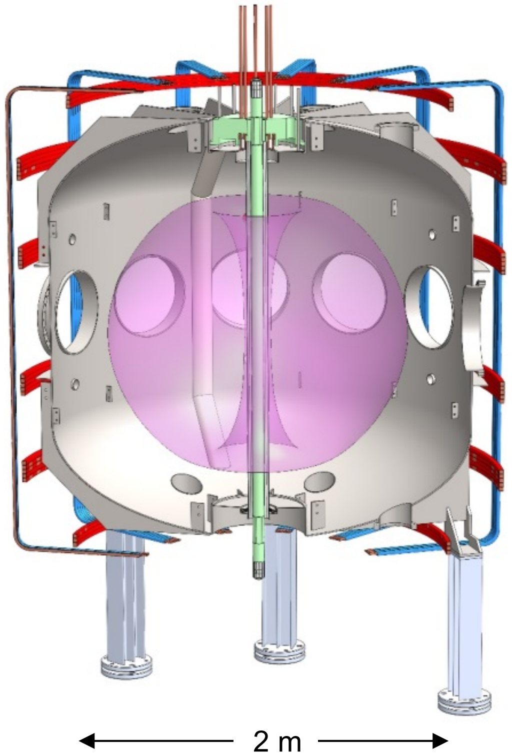
- Research program will provide a predictive understanding of these solenoid-free techniques
  - Extrapolatable techniques to next-step devices

PEGASUS-III



PEGASUS-III is a Major Upgrade of the PEGASUS Experiment

PEGASUS

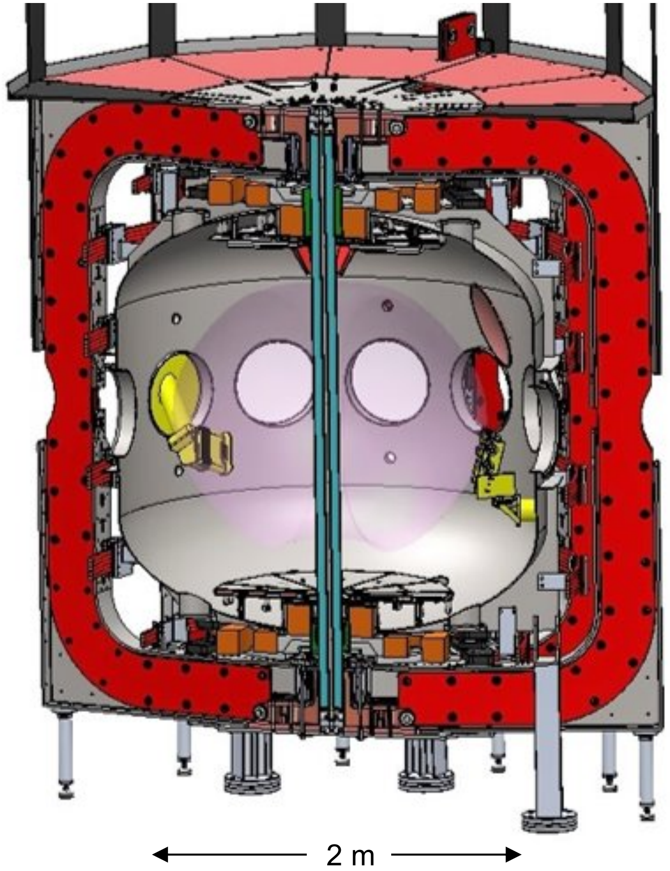


PEGASUS-III features:

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

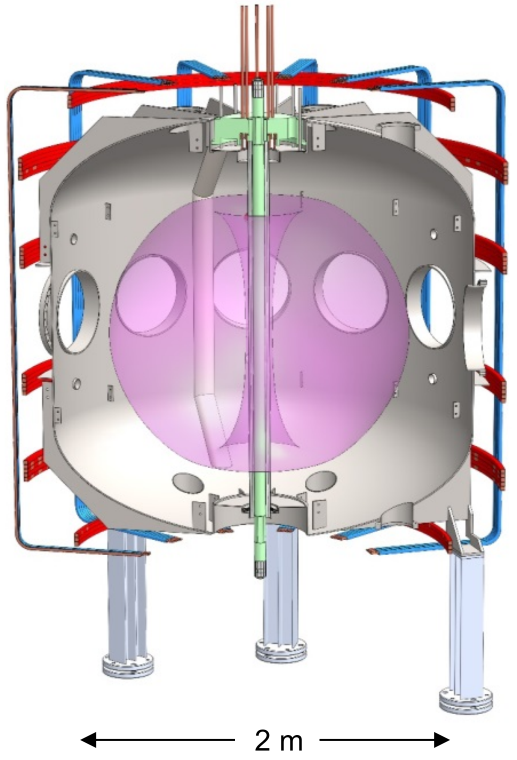
Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at $R_0 \sim 0.4$ m	0.15	0.58
B_T Flattop [ms]	25	50-100
A	1.15	1.18

PEGASUS-III

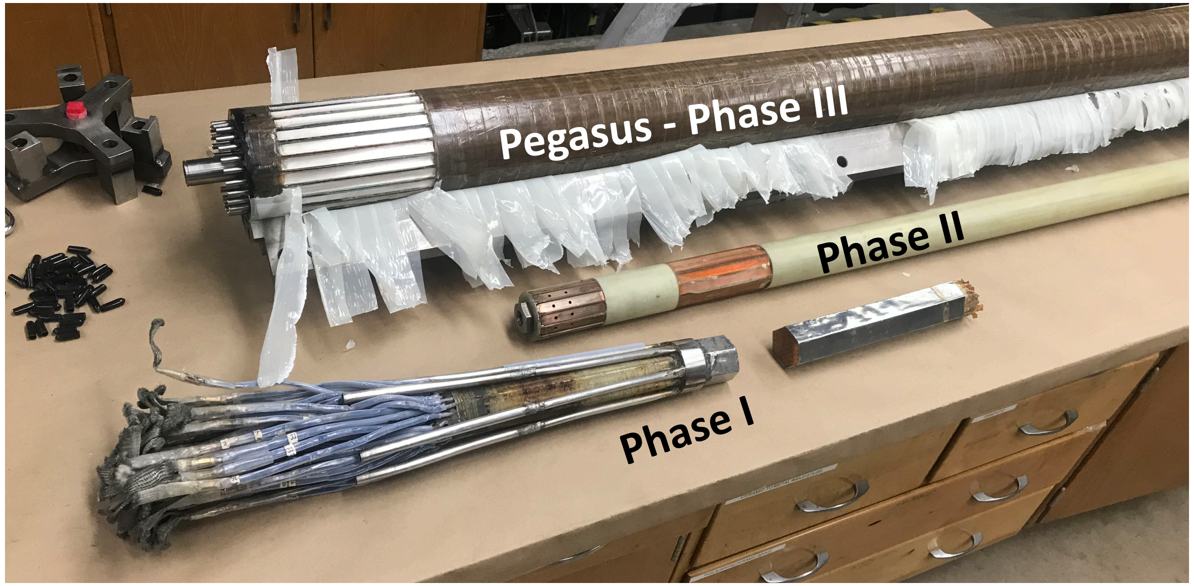


PEGASUS-III is a Major Upgrade of the PEGASUS Experiment

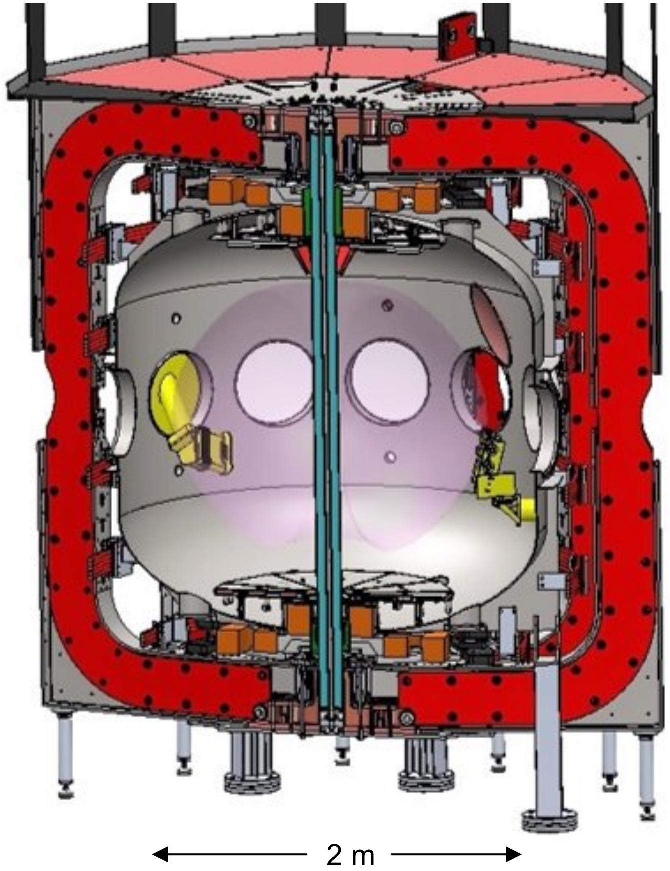
PEGASUS



Phases of PEGASUS Toroidal Field Coil

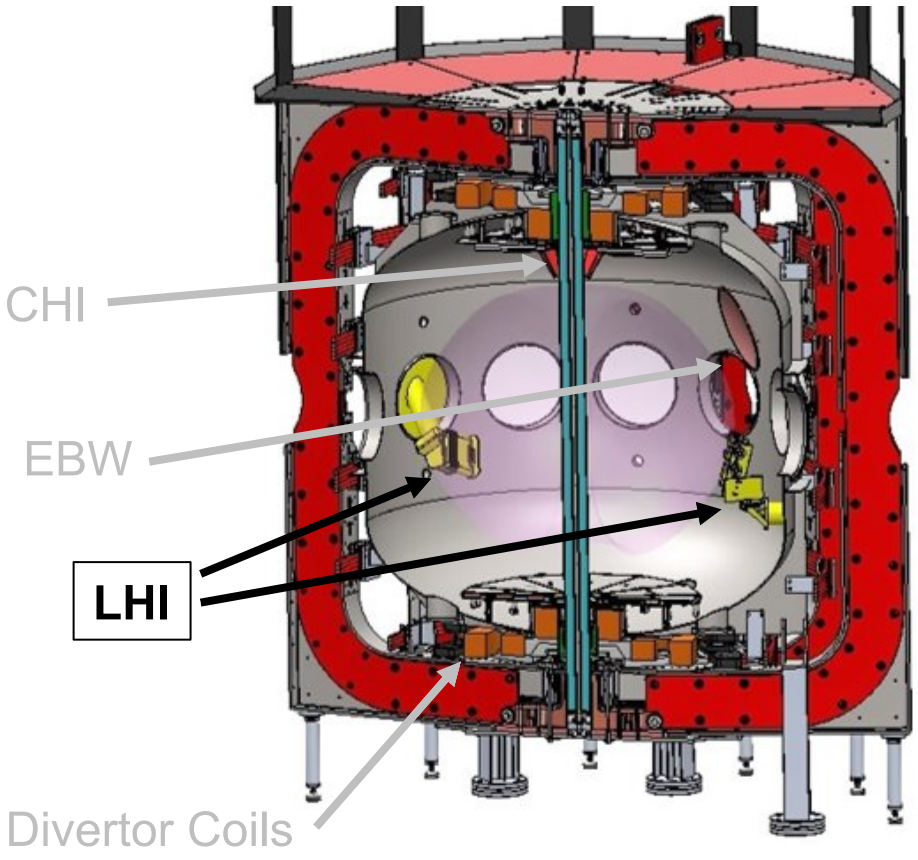


PEGASUS-III



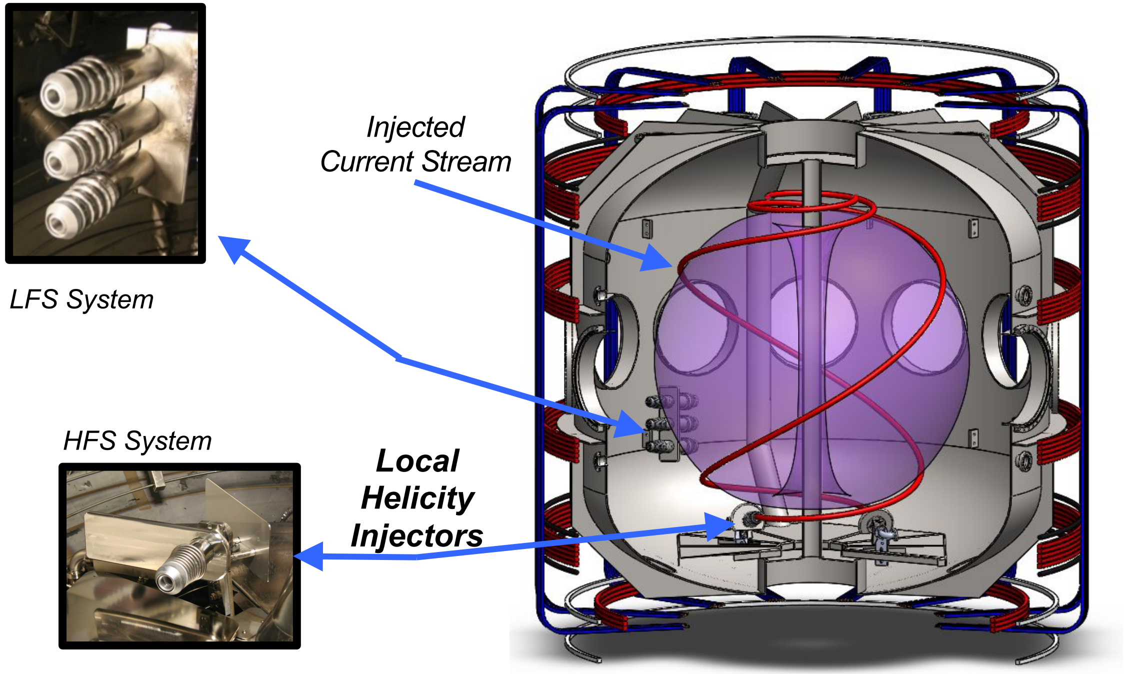
Local Helicity Injection

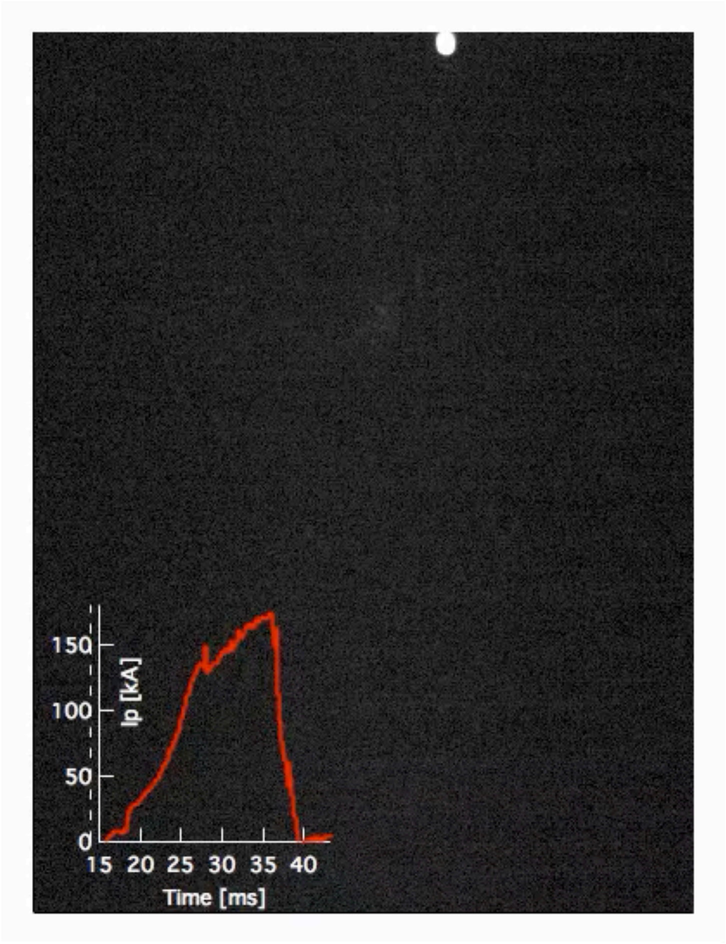
PEGASUS-III



Local Helicity Injection is a Promising Non-Solenoidal Startup Technique

- Edge current extracted from injectors
  - Relaxes to tokamak-like state
- Used routinely for startup on PEGASUS





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

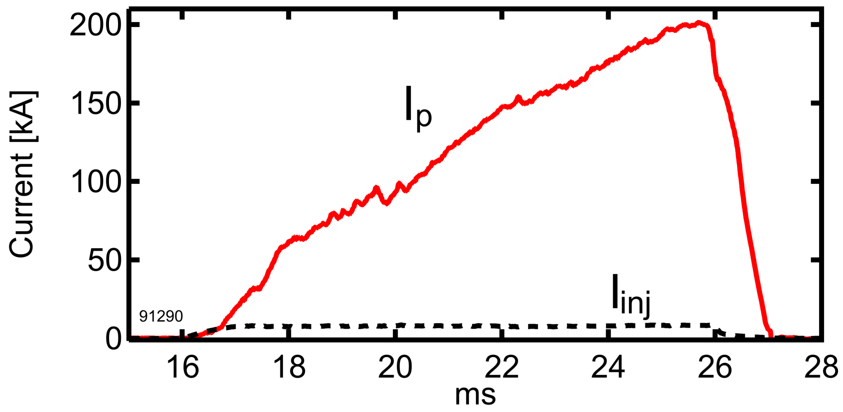
Projecting LHI to High-Performance Facilities Requires Tests at Increasing B_T

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

Taylor Limit

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

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

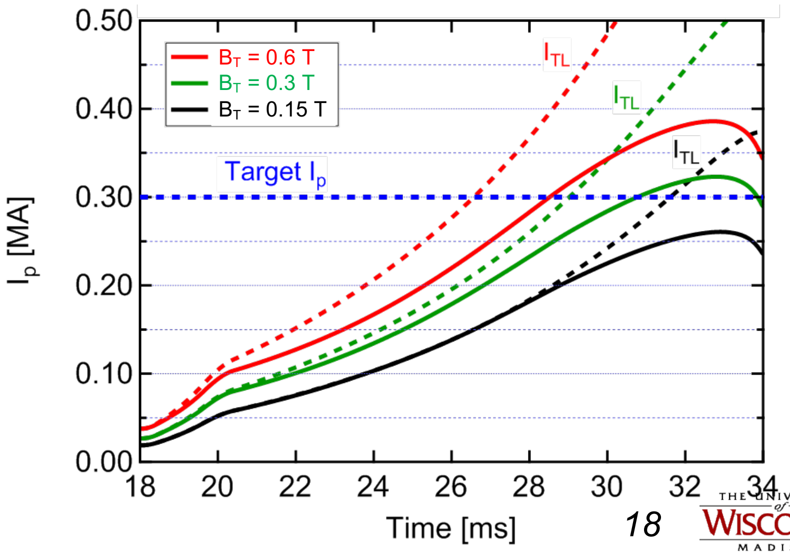


Monolithic LHI Injector

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

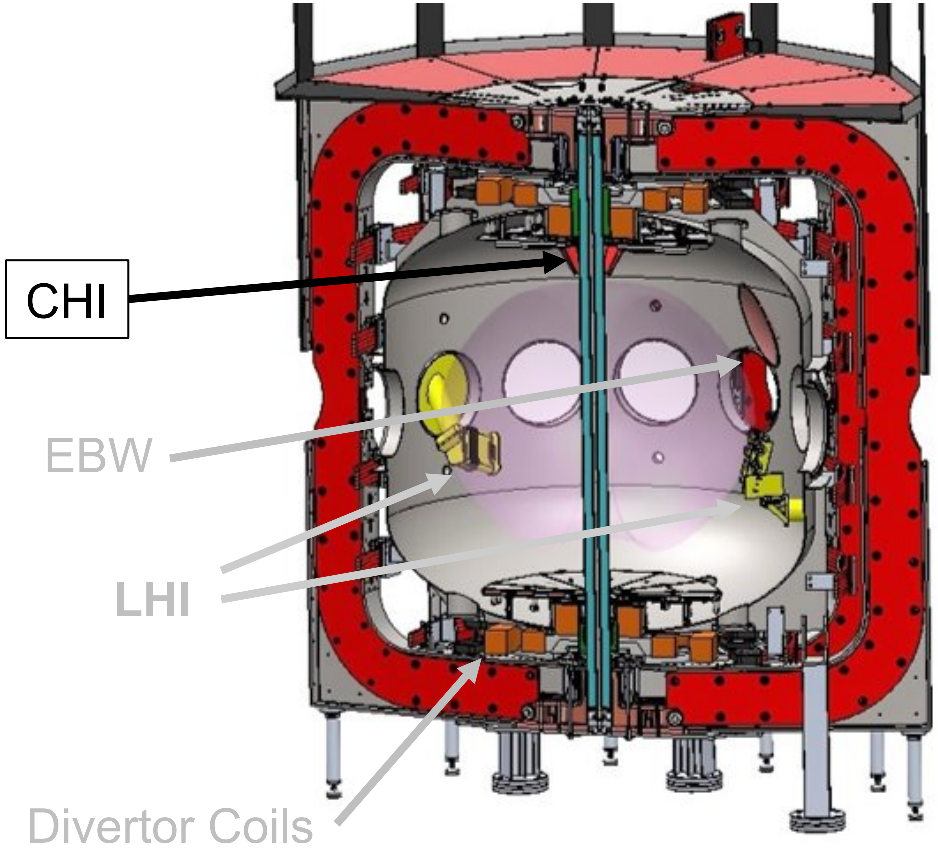
- Goal: routine experiments at ~ 0.3 MA

Power balance projections for Pegasus-III ops



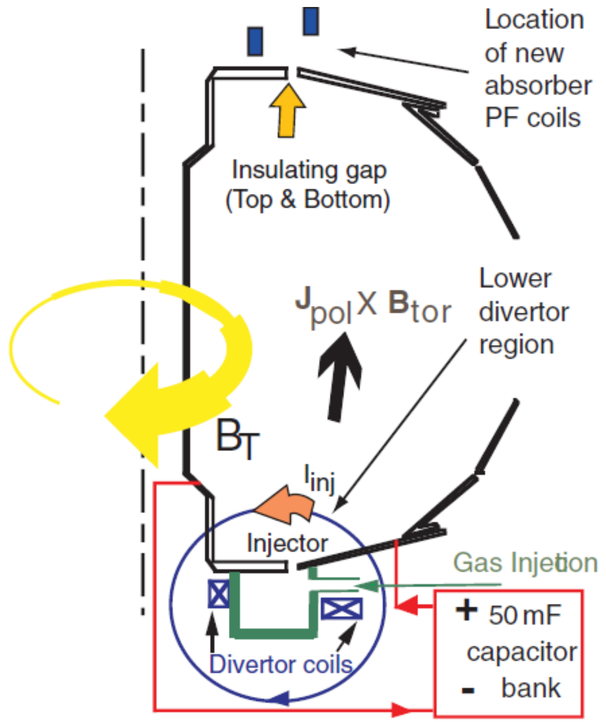
Coaxial Helicity Injection

PEGASUS-III



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

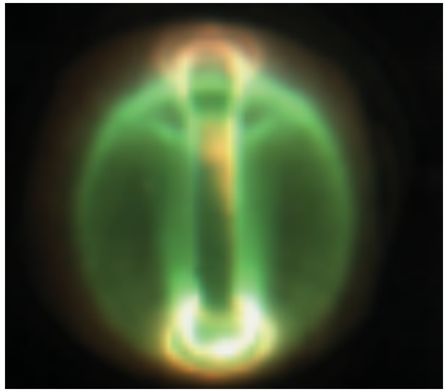
Two techniques:

- 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

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

T-CHI in NSTX



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

Comparative Studies of Helicity Injection Techniques will be Explored at Increased B_T Pegasus-III

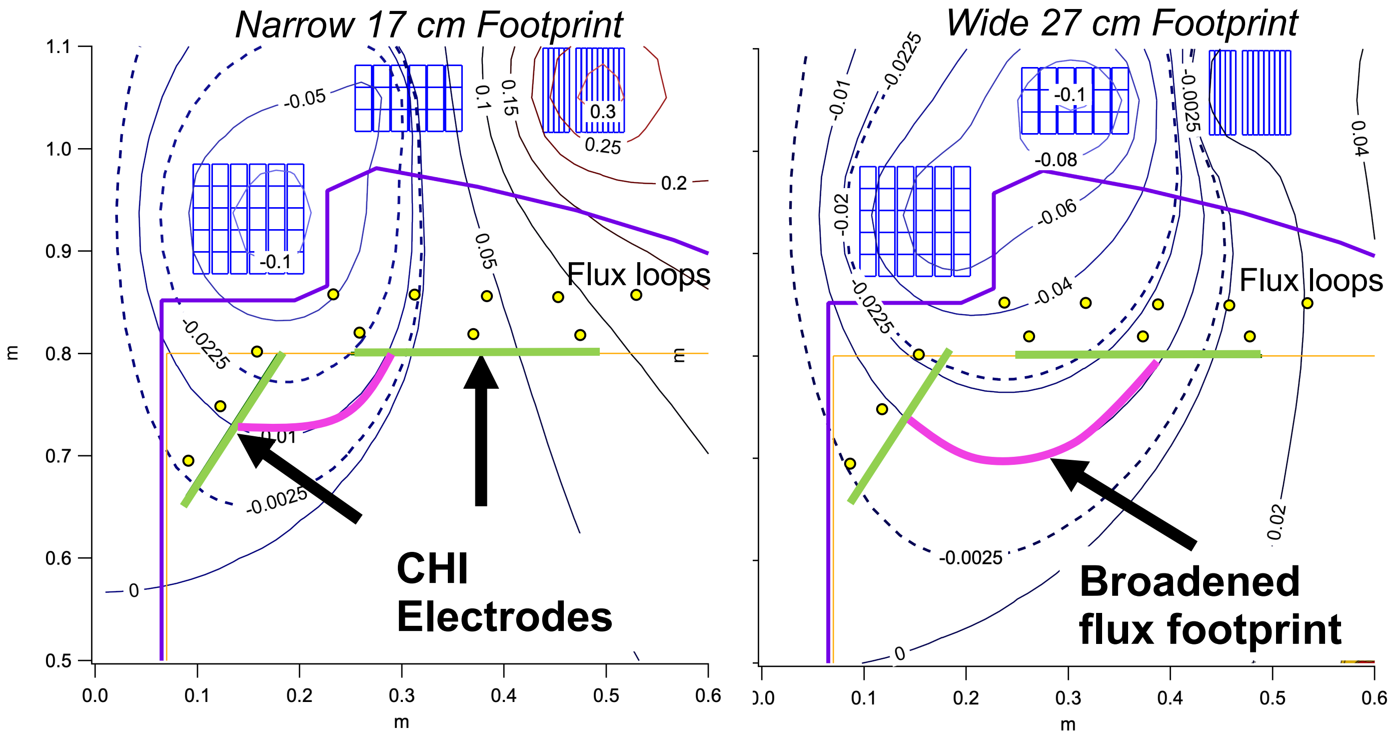
- Novel, flexible CHI system in dedicated experiment
- Address critical physics
  - Flux conversion efficiency
  - Role of footprint in efficiency
  - Comparison and synergies with other methods
  - Role or advantages of non-axisymmetric current flows & structures

"Bubble burst" criterion

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

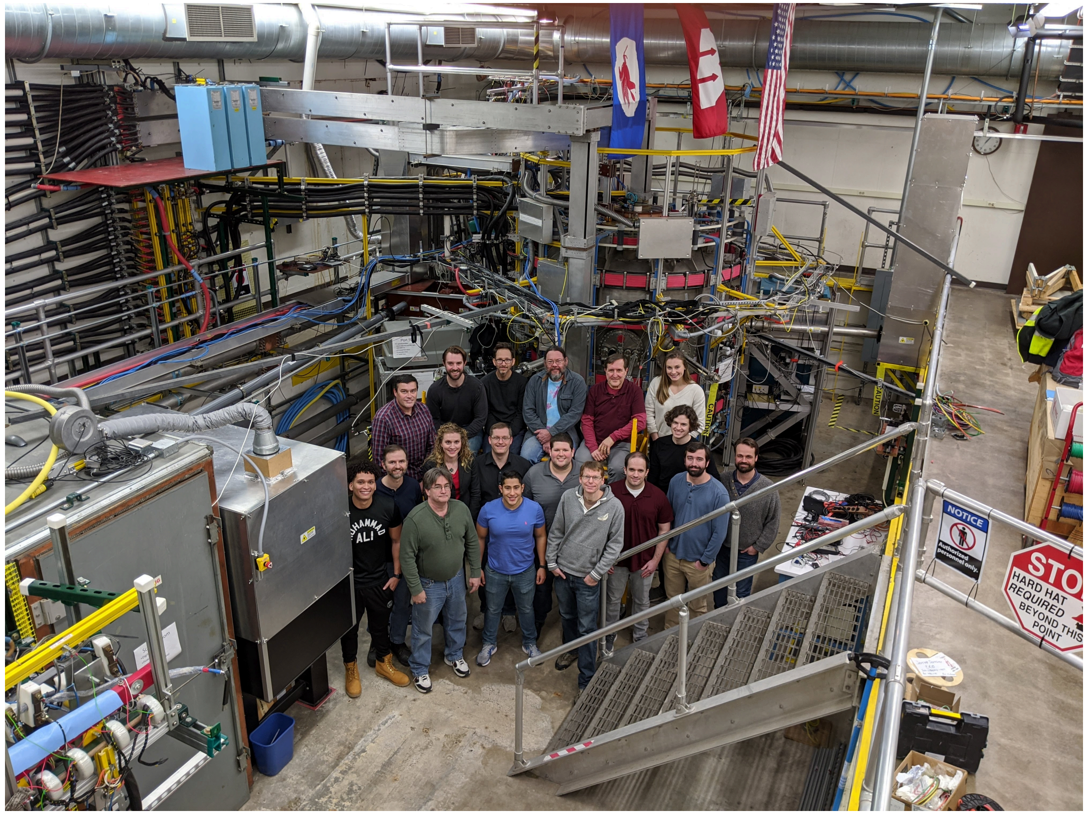
- Validate projection to ≥1 MA system
  - Test bubble burst and Taylor limit up to 0.3 MA
  - Vary flux distribution across electrodes
- CHI requires auxiliary heating to raise $T_e(0)$

Floating electrodes, flexibility high field divertor coil system



Why Investigate Startup for Tokamaks?

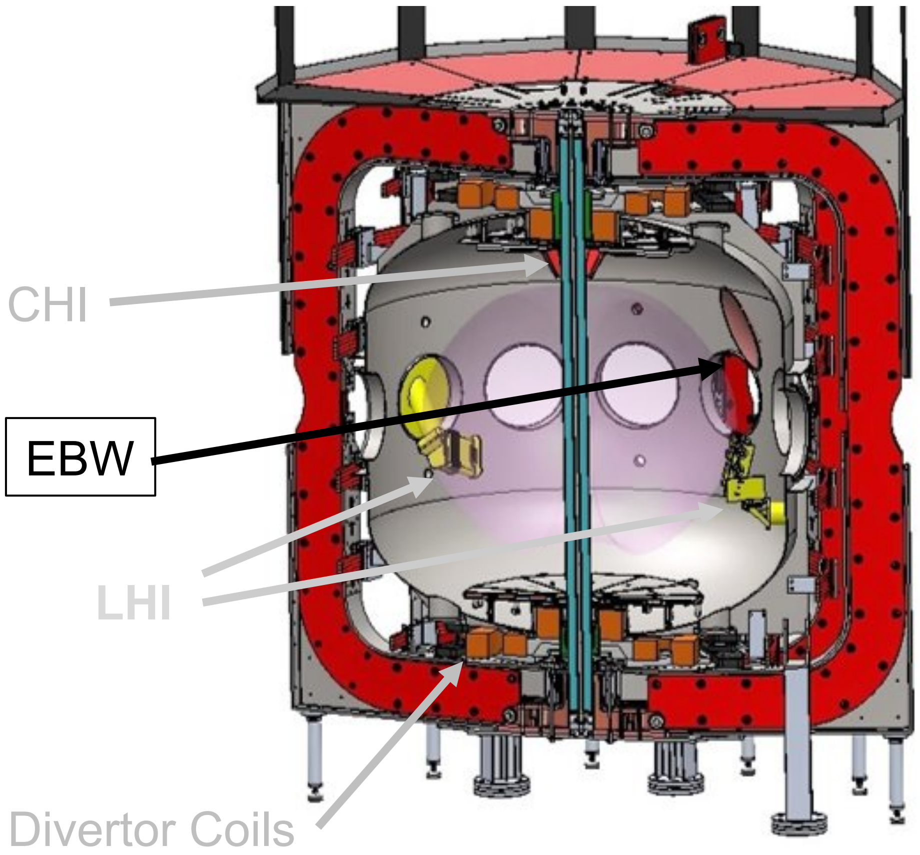
- More efficient use of main magnetic field by compact toroidal geometry
  - Reduces central induction (main startup technique) capacity
  - Spherical Tokamaks (STs) study this operation space, low-A
- Lighting a match for fusion: new PEGASUS-III Experiment to study innovations in plasma startup techniques
  - Focused on techniques to help reduce cost and complexity of future fusion reactors
- Radiofrequency waves can be used to heat, drive current in STs, synergistically enhance non-solenoidal techniques



PEGASUS-III – Research in fusion energy and plasma science, UW-Madison Engineering Physics Department

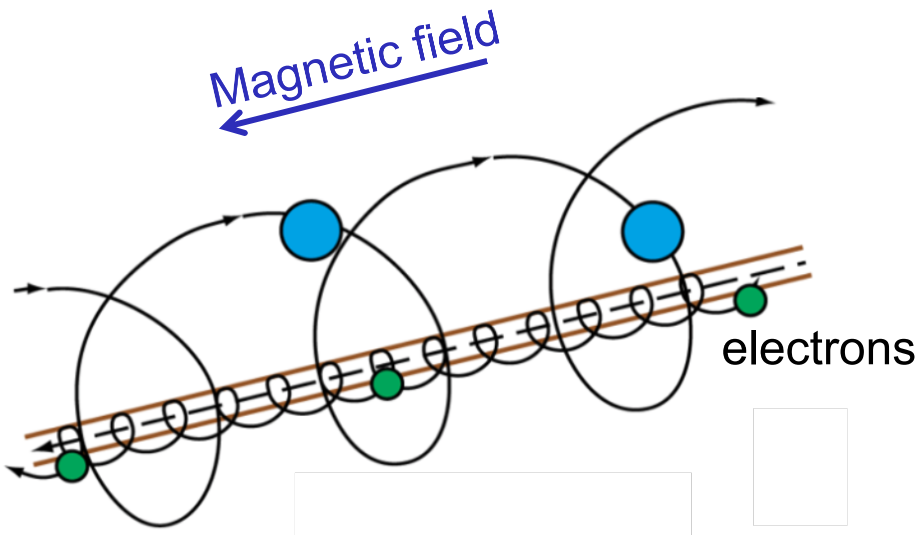
Radiofrequency Wave Injection

PEGASUS-III



RF Waves Resonate with Natural Frequencies in the Plasma Can Provide Heating/CD

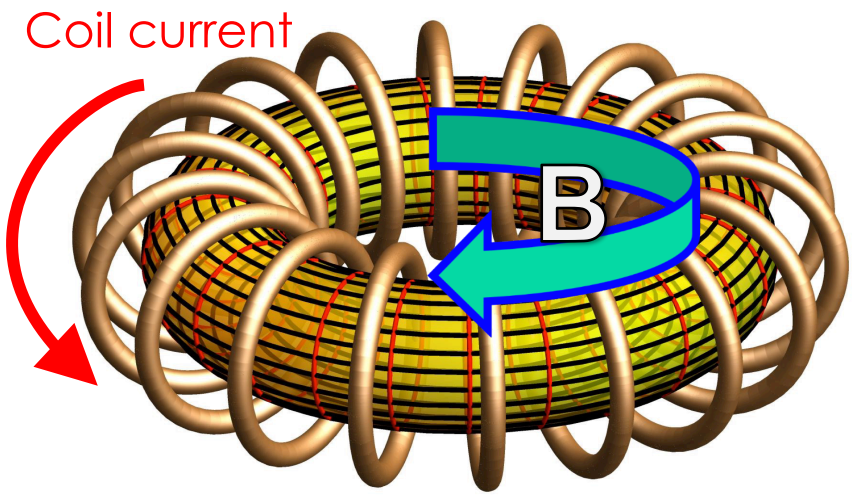
Magnetically confined plasma



$$F = q(\cancel{E} + \boxed{v \times B})$$

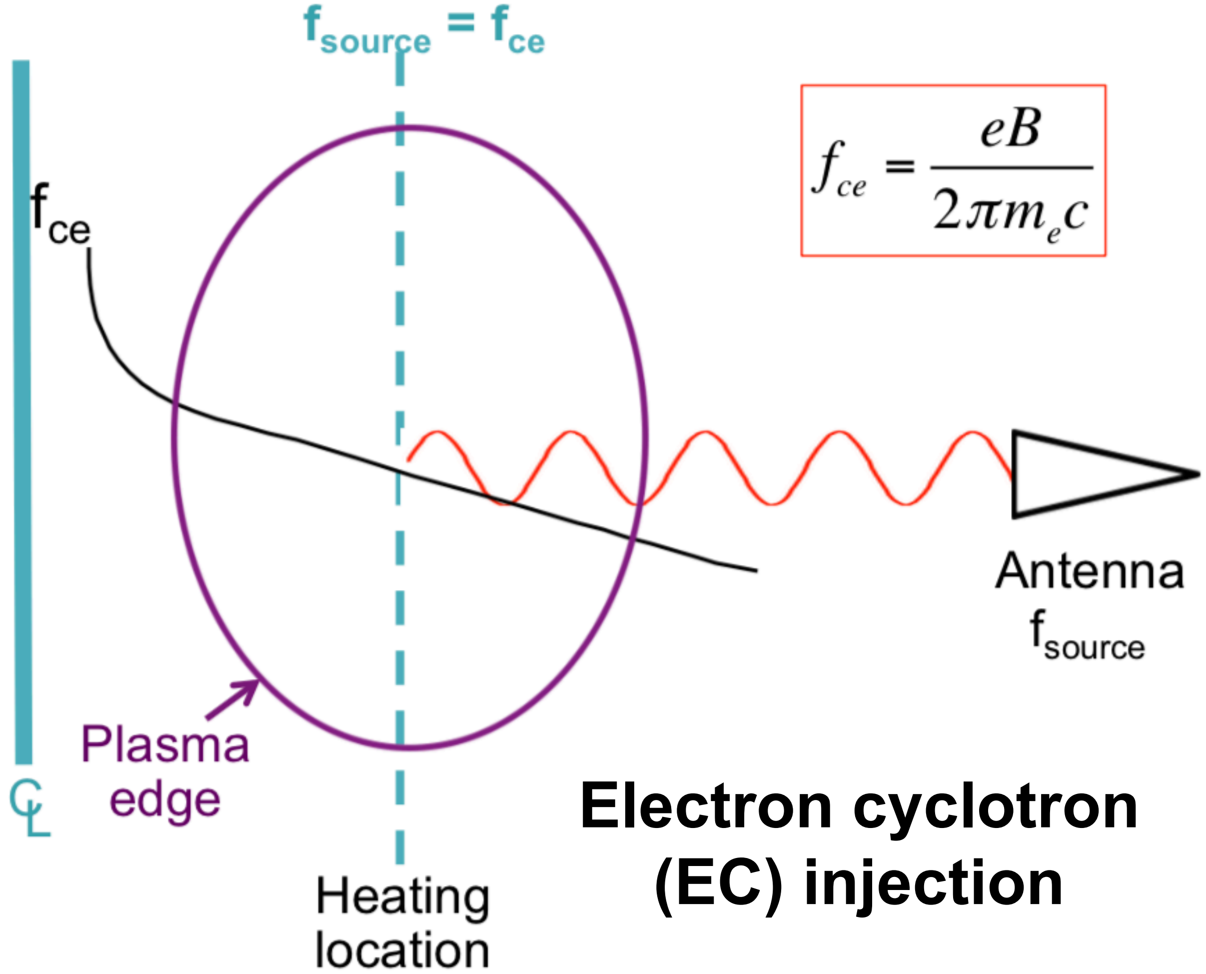
Cyclotron motion

Toroidal magnetic field



Launched Microwaves Absorbed Near Cyclotron Resonances

- Tuned to either electron or ion cyclotron motion
- RF source frequency can be chosen to be absorbed at precise location
  - Can provide heating or drive current
- For tokamas, STs, $B_t \propto 1/R$
- Inject either:
  - Ordinary mode (O-mode), E || B
  - Extra-ordinary mode (X-mode), E ⊥ B



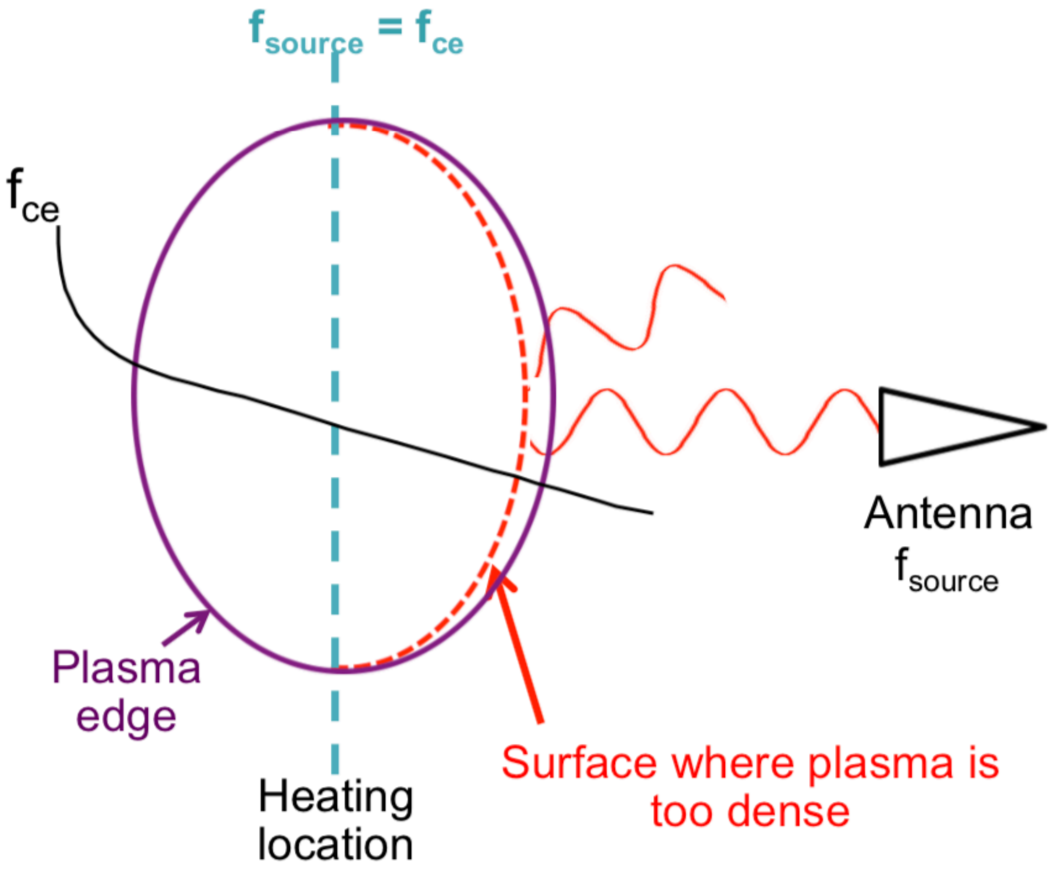
Electron cyclotron (EC) injection

EC Wave Injection Provides Plasma Heating and Current Drive – in Certain Conditions

- For plasmas with relatively low B_T, high density, O-mode & X-mode reflected near plasma edge
  - Happens in ST, RFP, stellarators
  - Refer to these plasmas as being "overdense"

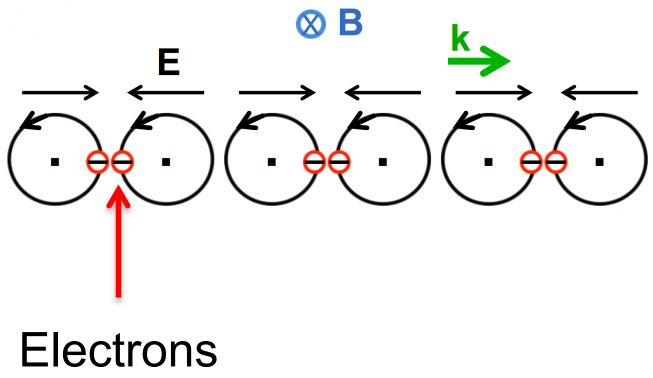
$f_{pe} > f_{ce}$, where $$f_{pe} = \sqrt{\frac{n_e e^2}{\pi m_e}}$$

- Alternative heating method required



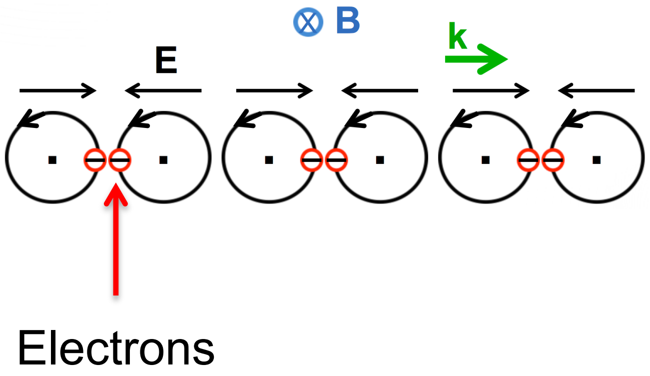
Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves



Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics



EBW dispersion relation

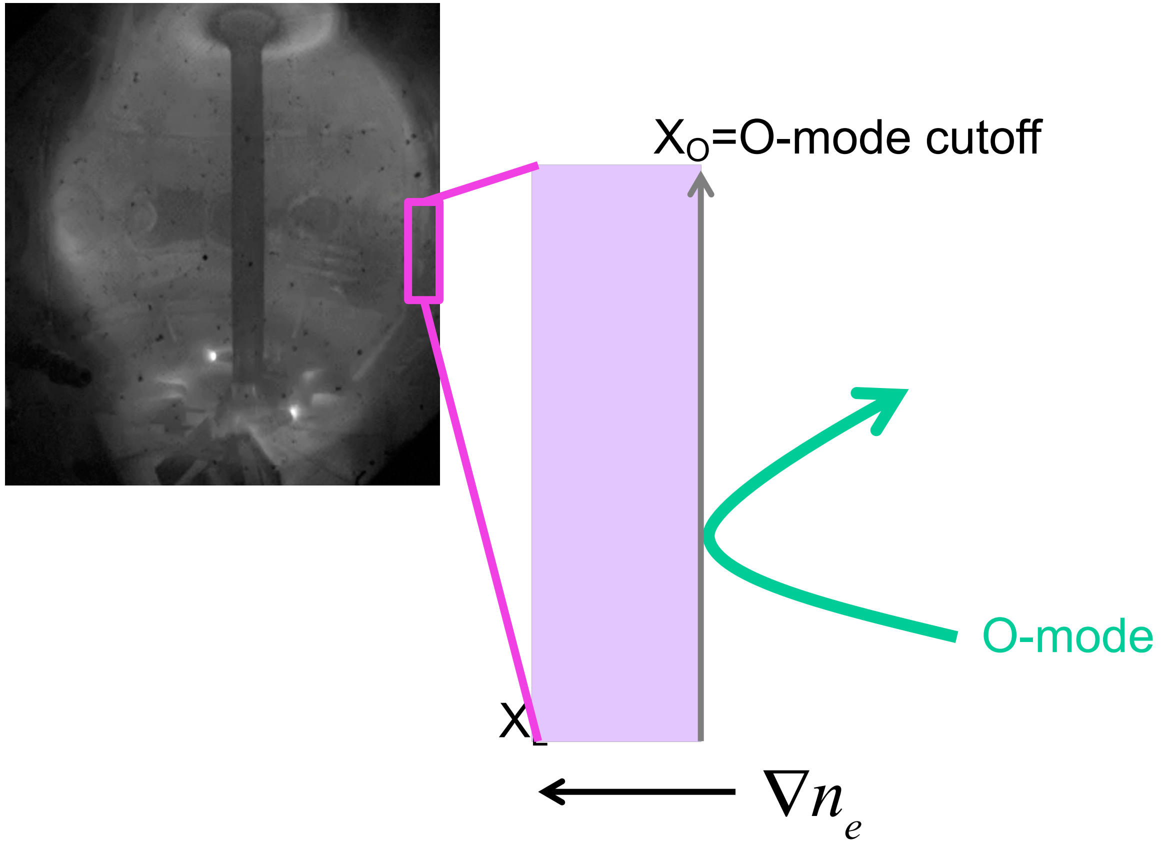
$$1-2\sum_{s}\frac{4\pi n_s m_s c^2}{\lambda B_0^2}\left[\sum_{s} e^{-\lambda} I_n(\lambda)\frac{n^2}{\left(\omega/\Omega\right)^2-n^2}\right]=0$$

As wave frequency approached EC harmonic, $\omega = n\Omega$, wave is strongly absorbed

Where: $\lambda = \dfrac{k_{\perp}^2 \kappa T_{\perp}}{m\Omega^2}$

Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics

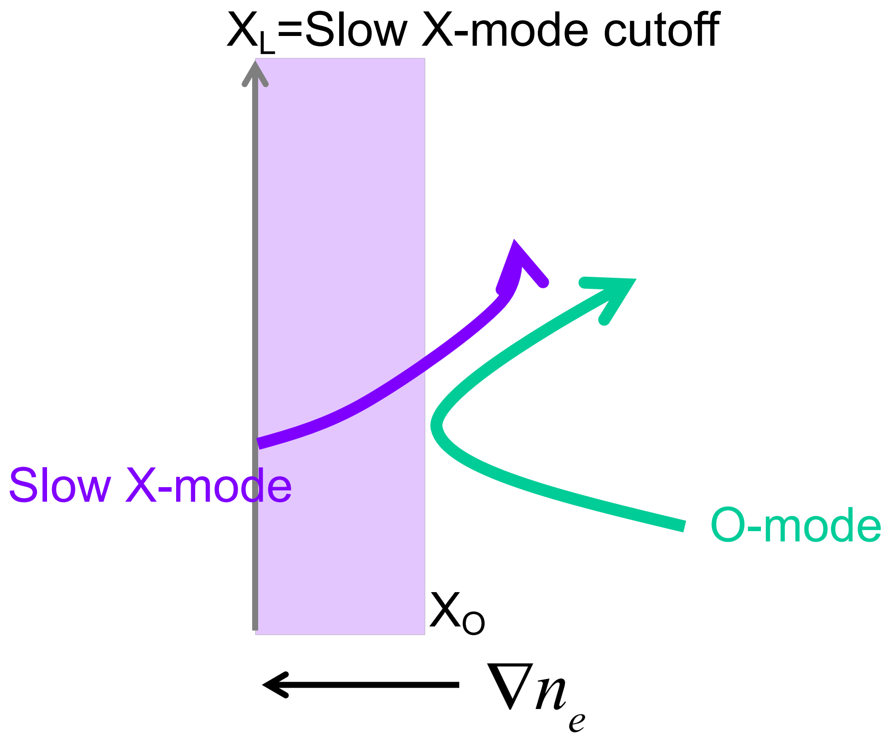


- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch

Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics

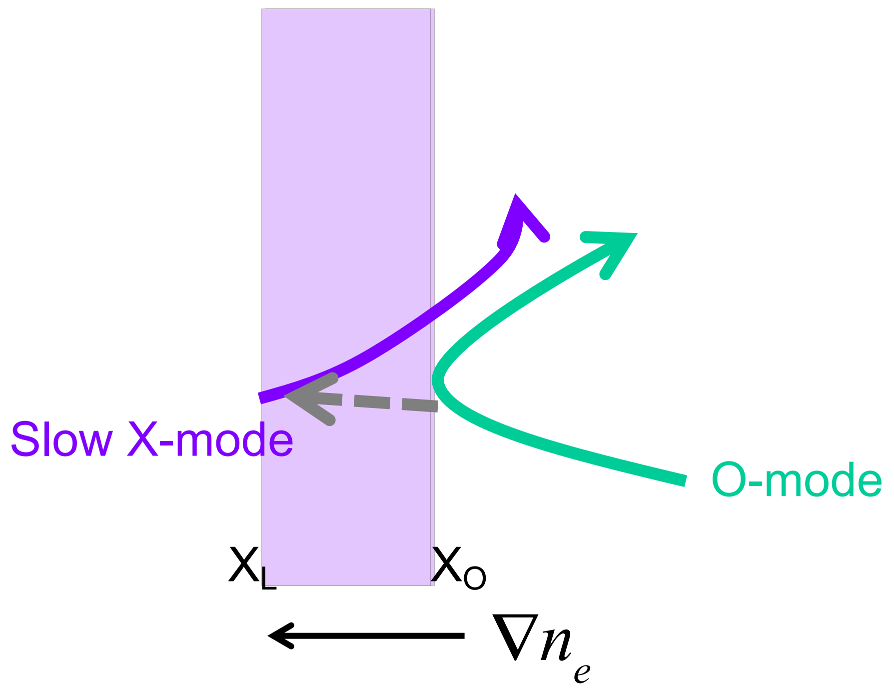
- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch



Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics

- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch

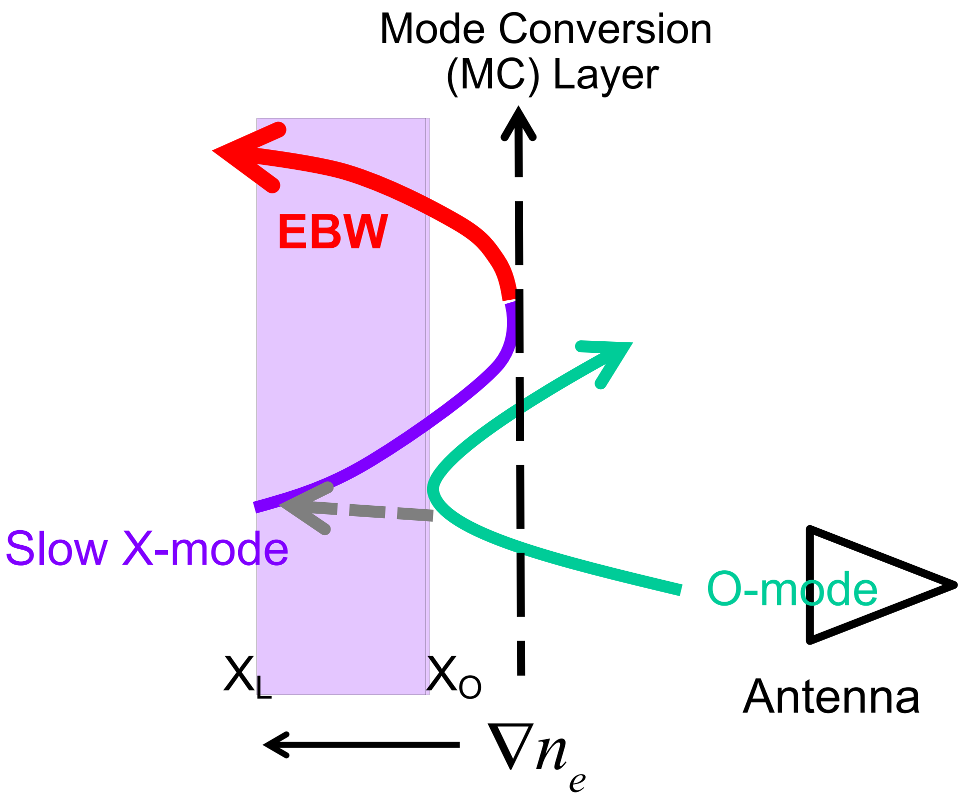


Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, k|| = 0
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics

- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch

O-X-B Coupling

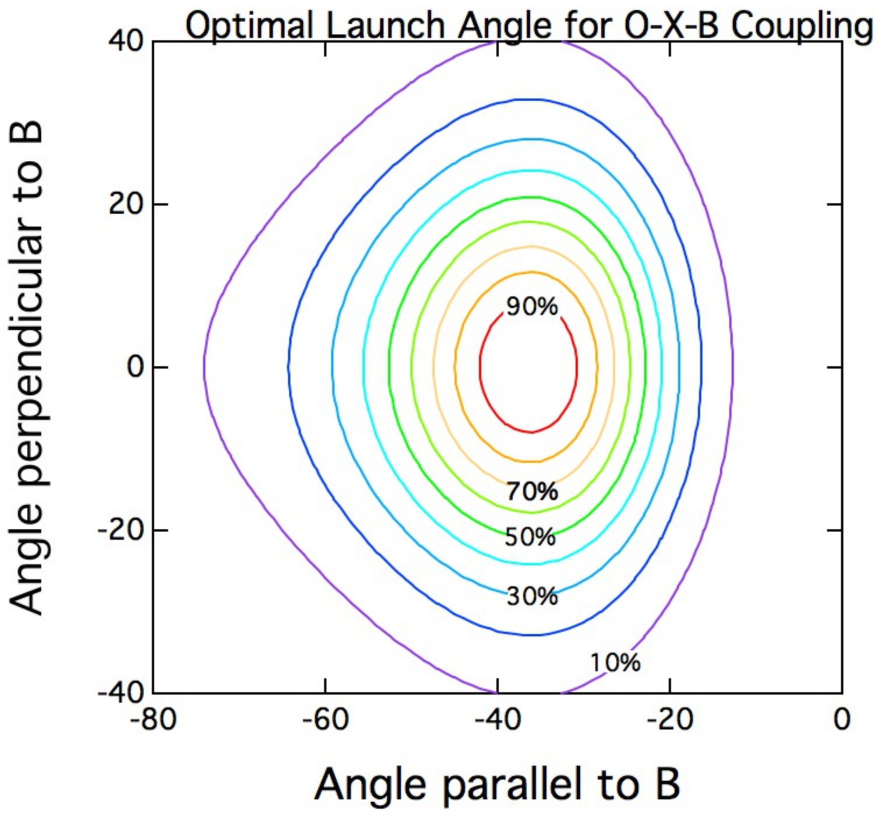


Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, $k_{||} = 0$
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics

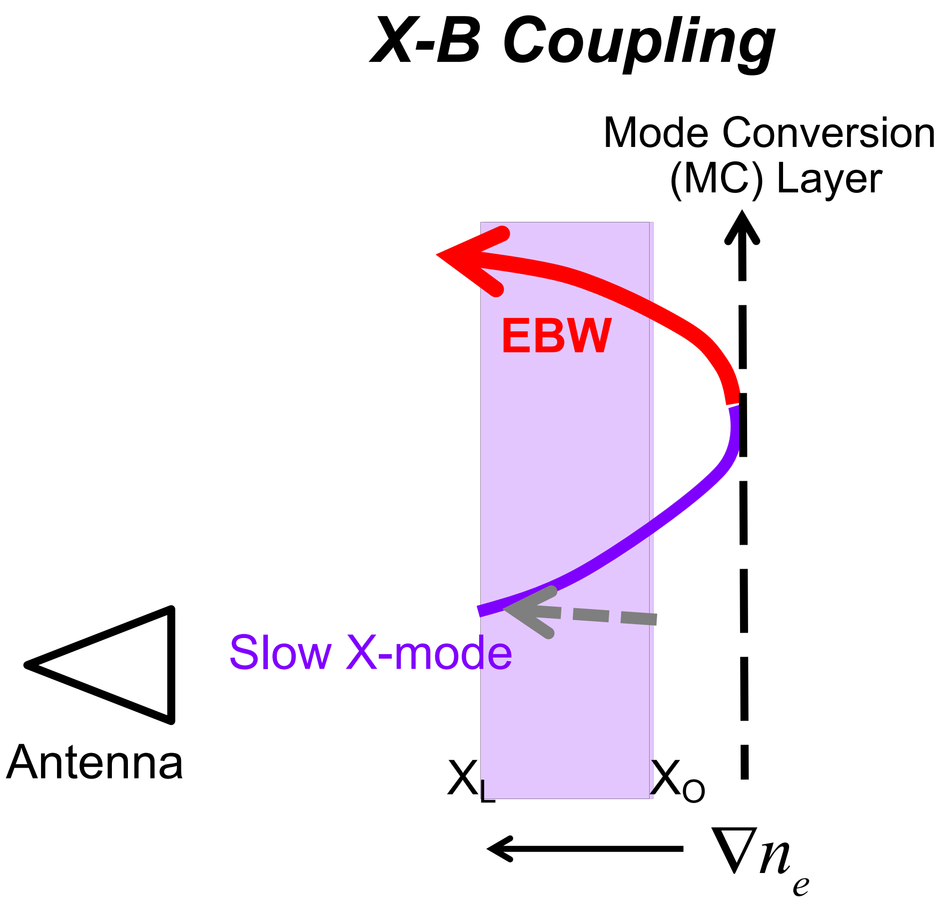
- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch

O-X-B Coupling



Electron Bernstein Waves Can Propagate in Overdense Plasmas

- Electron Bernstein waves (EBW) are hot plasma waves:
  - Perpendicularly propagating, $k_{||} = 0$
  - Do not experience a density cutoff in the plasma
  - Longitudinal, electrostatic waves
  - Cannot propagate in vacuum
  - Absorbed near cyclotron harmonics



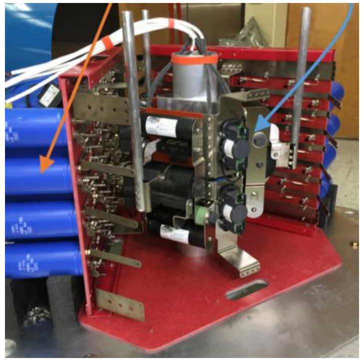
- EBW coupling efficiency depends on plasma parameters near plasma edge
  - Density gradient
  - Magnetic field pitch

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

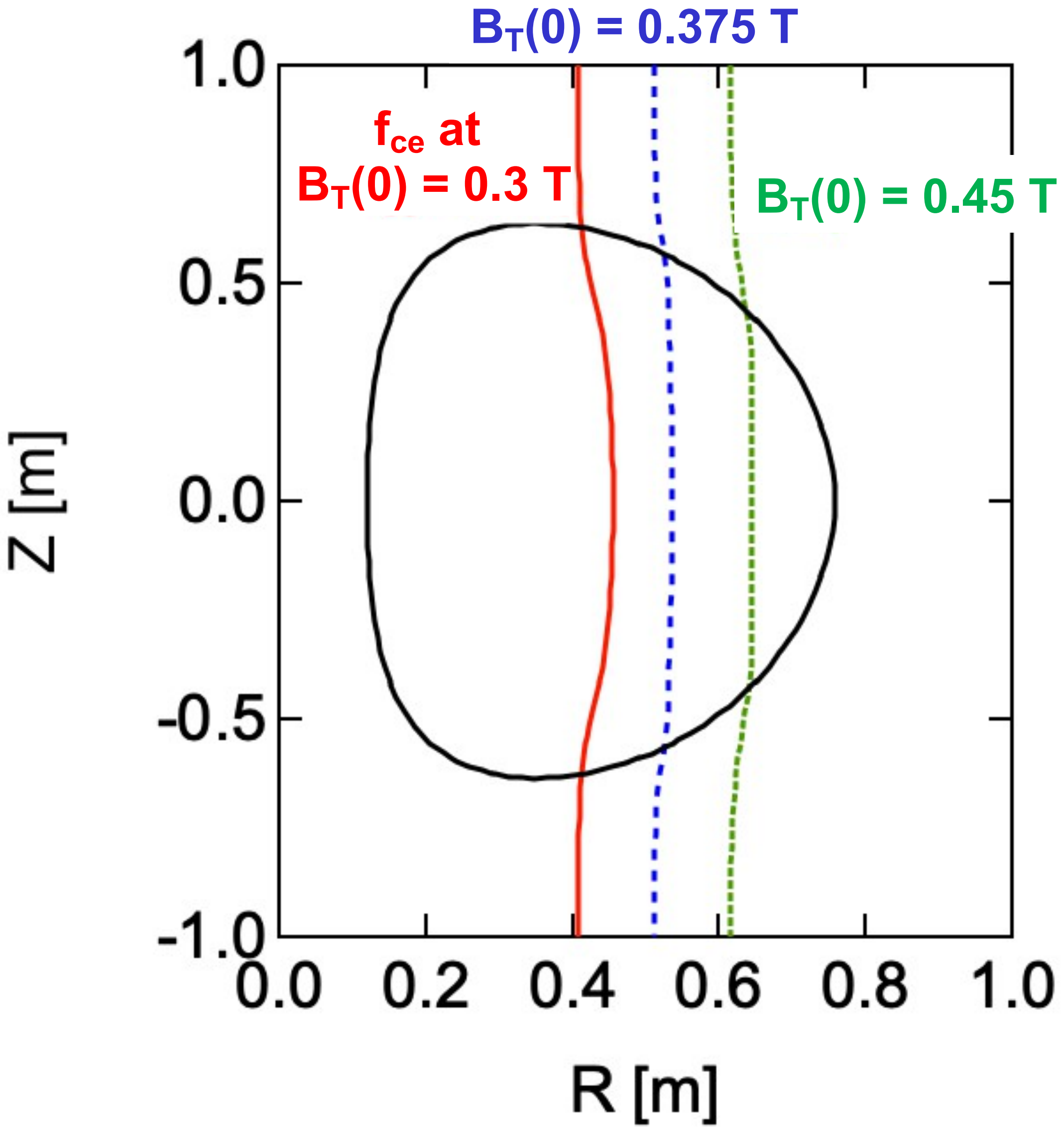
- RF auxiliary heating and CD system will enable long-term scientific campaigns
  - Synergistic effects for improving helicity injection and RF current drive efficiency
  - Comparative tests of most major non-solenoidal startup techniques
  - Current profile tailoring
  - Handoff from non-solenoidal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



Klystrons powered by new DC-DC resonant supplies

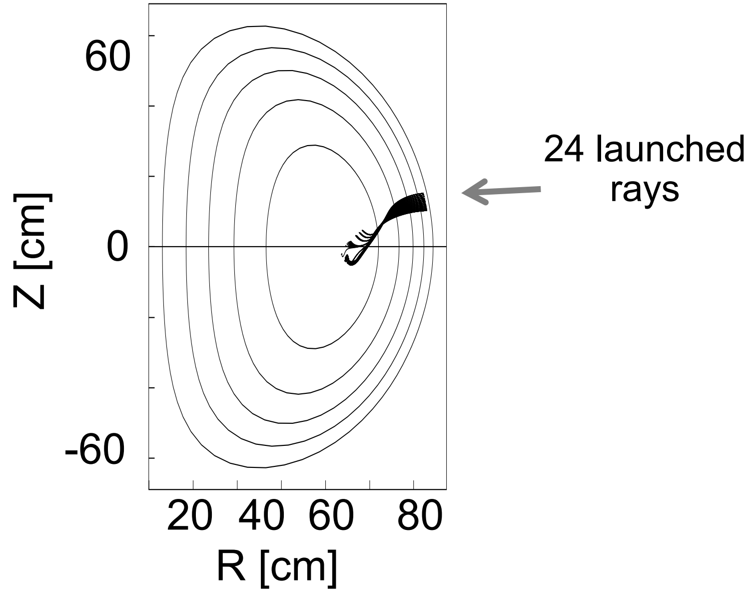


Collaboration between ORNL, ENEA and UW-Madison

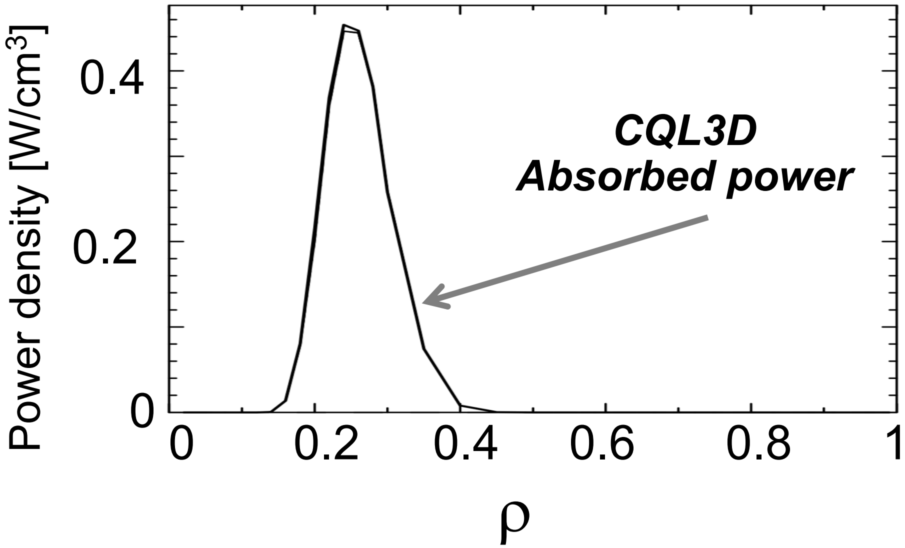
Demonstration of EBW CD for Future Sustainment Studies

- 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

GENRAY EBW Ray-tracing

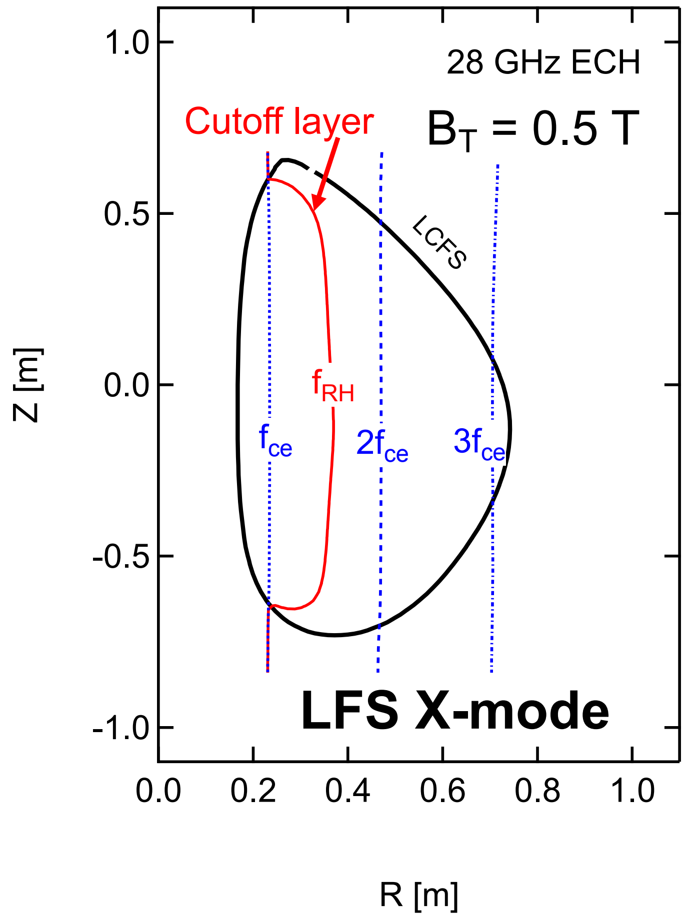


- Modeling shows current drive peaked off-axis
  - I_{EBW} ~ 30 kA comparable to j(0) from LHI
  - Perform current profile tailoring
  - Varying B_T can be used to change absorption location



2^{nd} Phase RF: Add ECH/ECCD for Helicity Injection 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

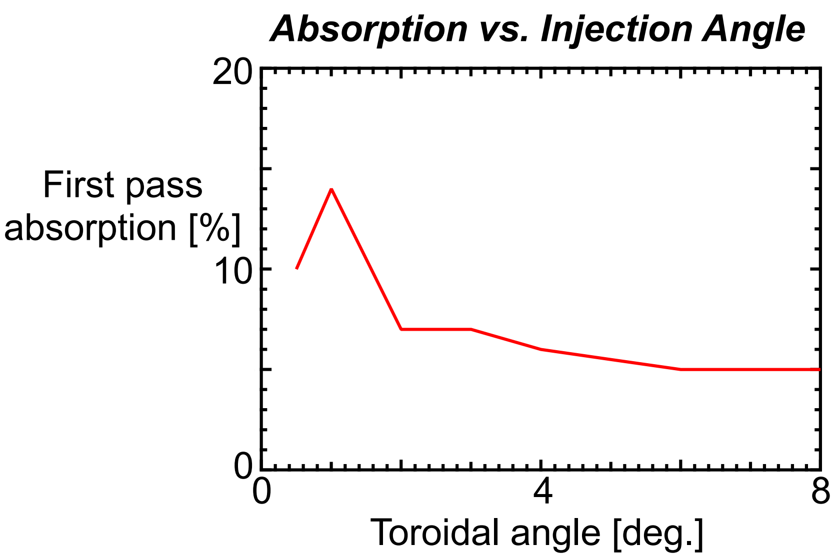


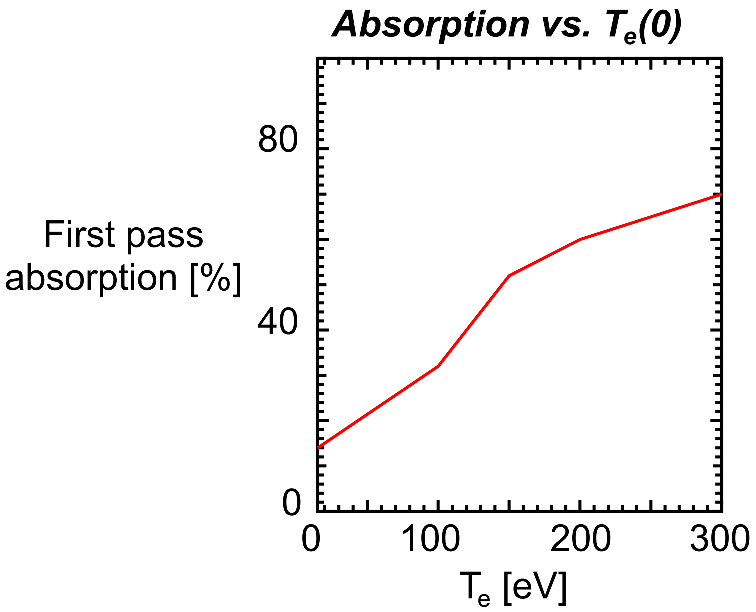
Mode	O1	X1	X2	O2	X3
Frequency	Ω_{ce}	Ω_{ce}	$2\Omega_{ce}$	$2\Omega_{ce}$	$3\Omega_{ce}$
Density	n_{01}	$2n_{01}$	$2n_{01}$	$4n_{01}$	$6n_{01}$

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

ECH Modeling Shows Paths to High Absorption During LHI

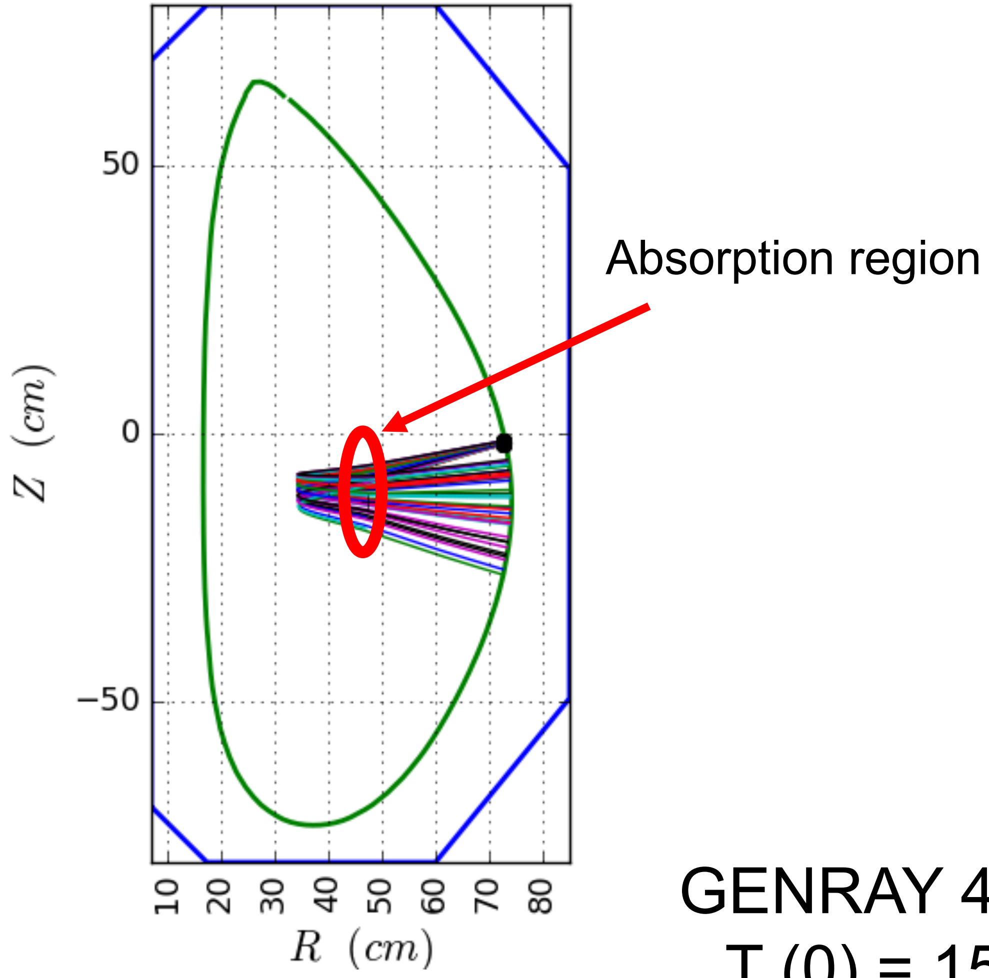
- LHI-produced targets are accessible to ECH
  - Wide range of $<n_e>$ available
- Peak 15% first pass absorption possible for $T_e(0)$ = 15 eV
  - Single ray launch injection angle scan via GENRAY
  - Launcher at z = 5.5 cm, poloidal angle = -15˚, toroidal angle 1˚
  - Applicable to CHI targets
- First 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



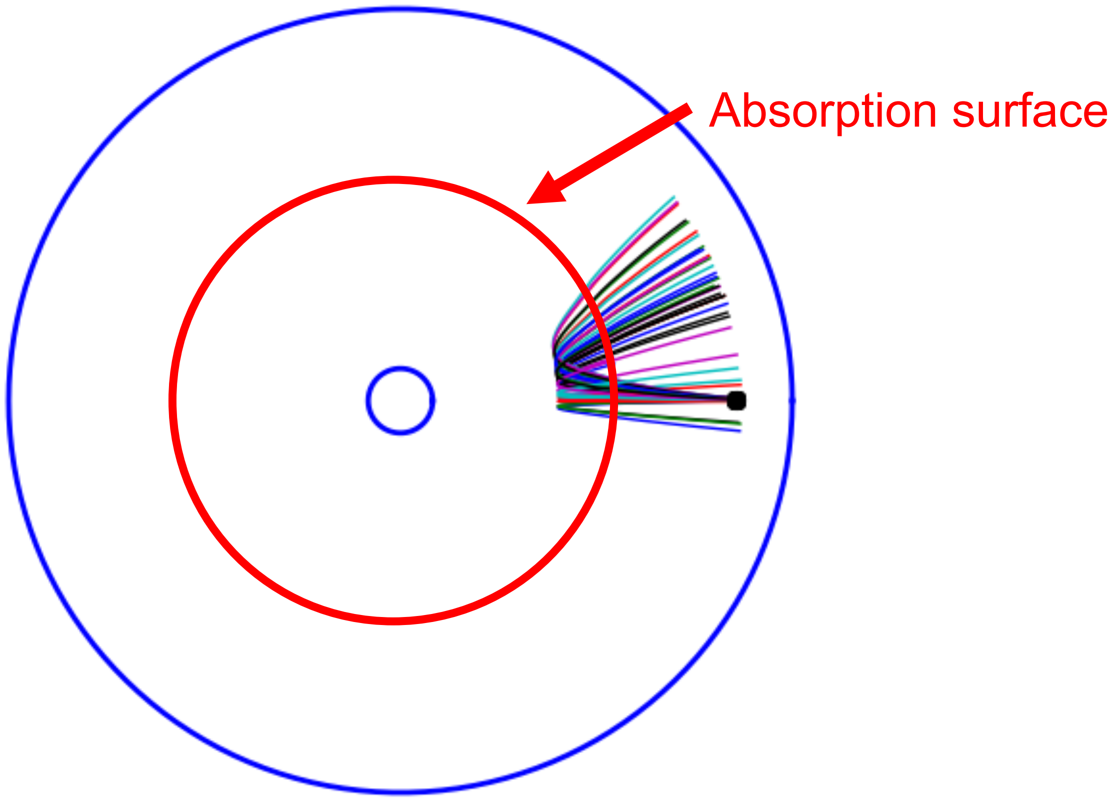


28 GHz ECH Feasible at Full B_T in PEGASUS-III

Poloidal Cross Section



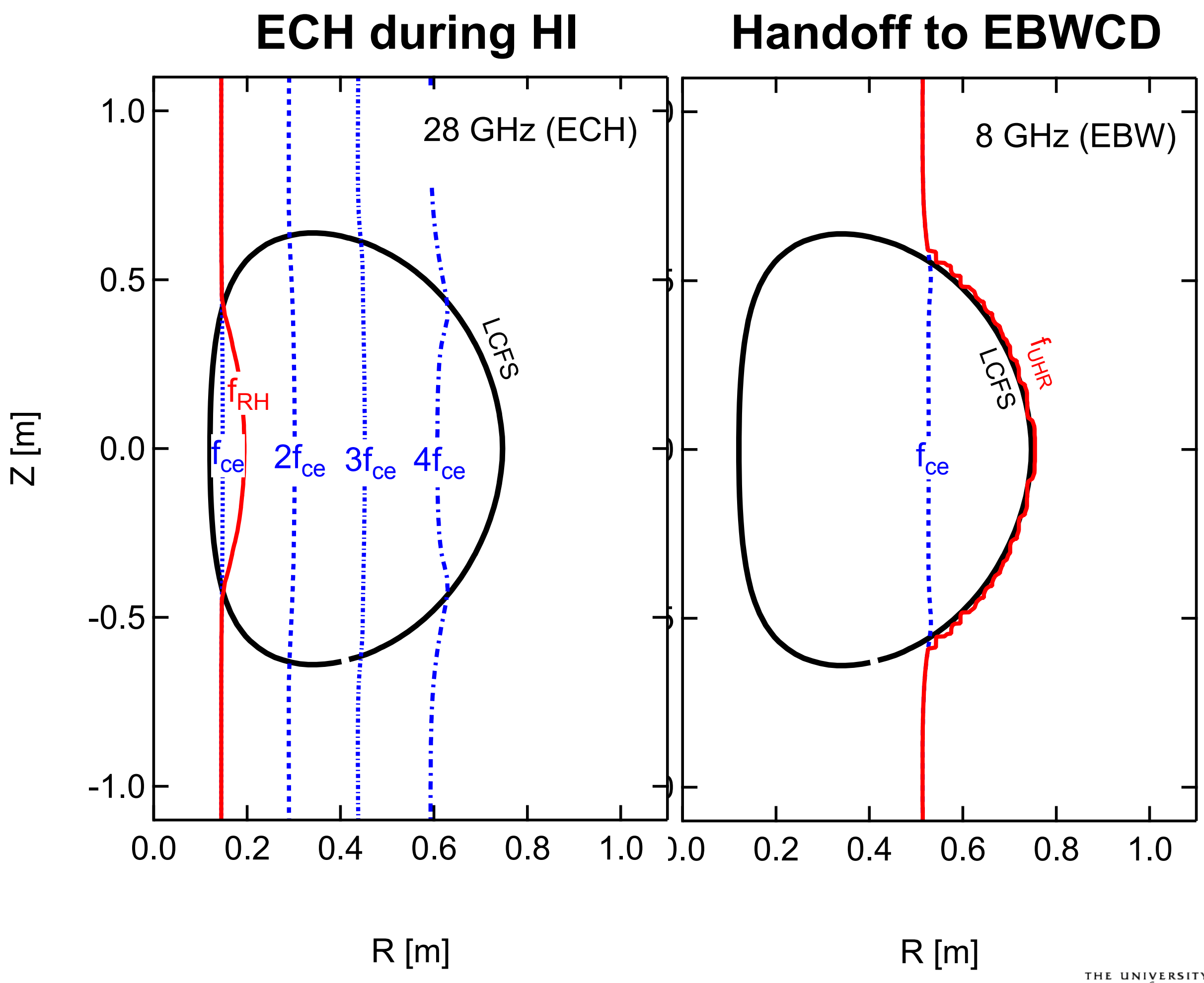
Toroidal Cross Section



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

Long term: 28 GHz, 8 GHz RF Systems Can Be Used Simultaneously for Scenario Development

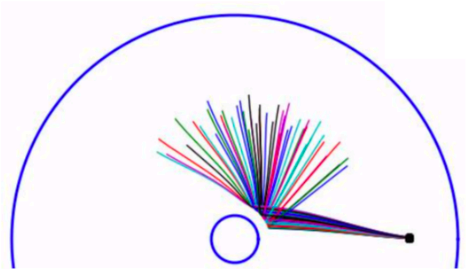
- ECH can be used during active helicity drive to significantly increase $T_e(0)$, improving EBW CD efficiency
  - EC resonant locations with significant absorption obtained for both systems with B_T = 0.4 T
- First pass absorption 0% for 3rd, 4th EC harmonic
  - 28 GHz, X2 absorbed near R = 0.3 m
- Assuming ECH during HI provides significant increase in T_e, 1 keV, EBW current drive increases by ~ 2x



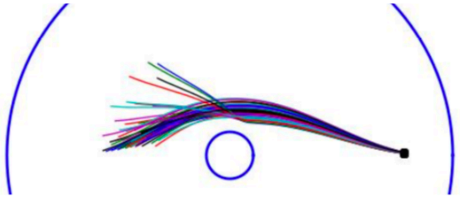
RF Systems Can be Used Simultaneously to Study Synergistic Effects, Study Scenario Optimization

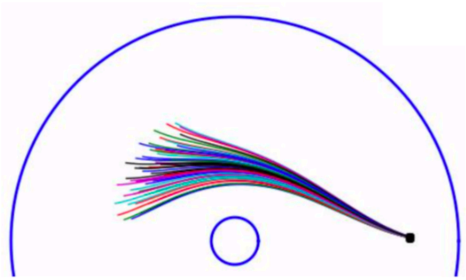
- ECH can be used during active helicity drive to significantly increase $T_e(0)$, improving EBW CD efficiency
  - EC resonant locations with significant absorption obtained for both systems with B_T = 0.4 T
- First pass absorption 0% for 3rd, 4th EC harmonic
  - 28 GHz, X2 absorbed near R = 0.3 m
- Assuming ECH during HI provides significant increase in T_e, 1 keV, EBW current drive increases by ~ 2x

ECH during HI

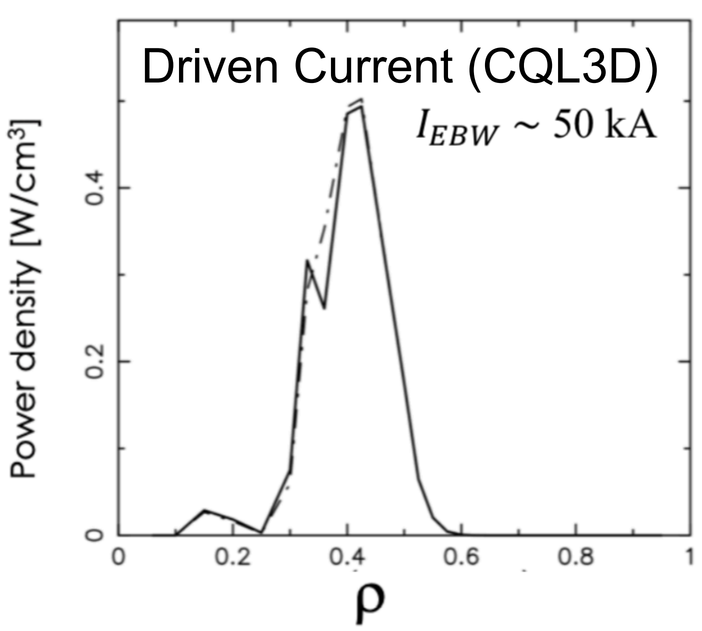


GENRAY ray-tracing
Tilting injection angle can drive current

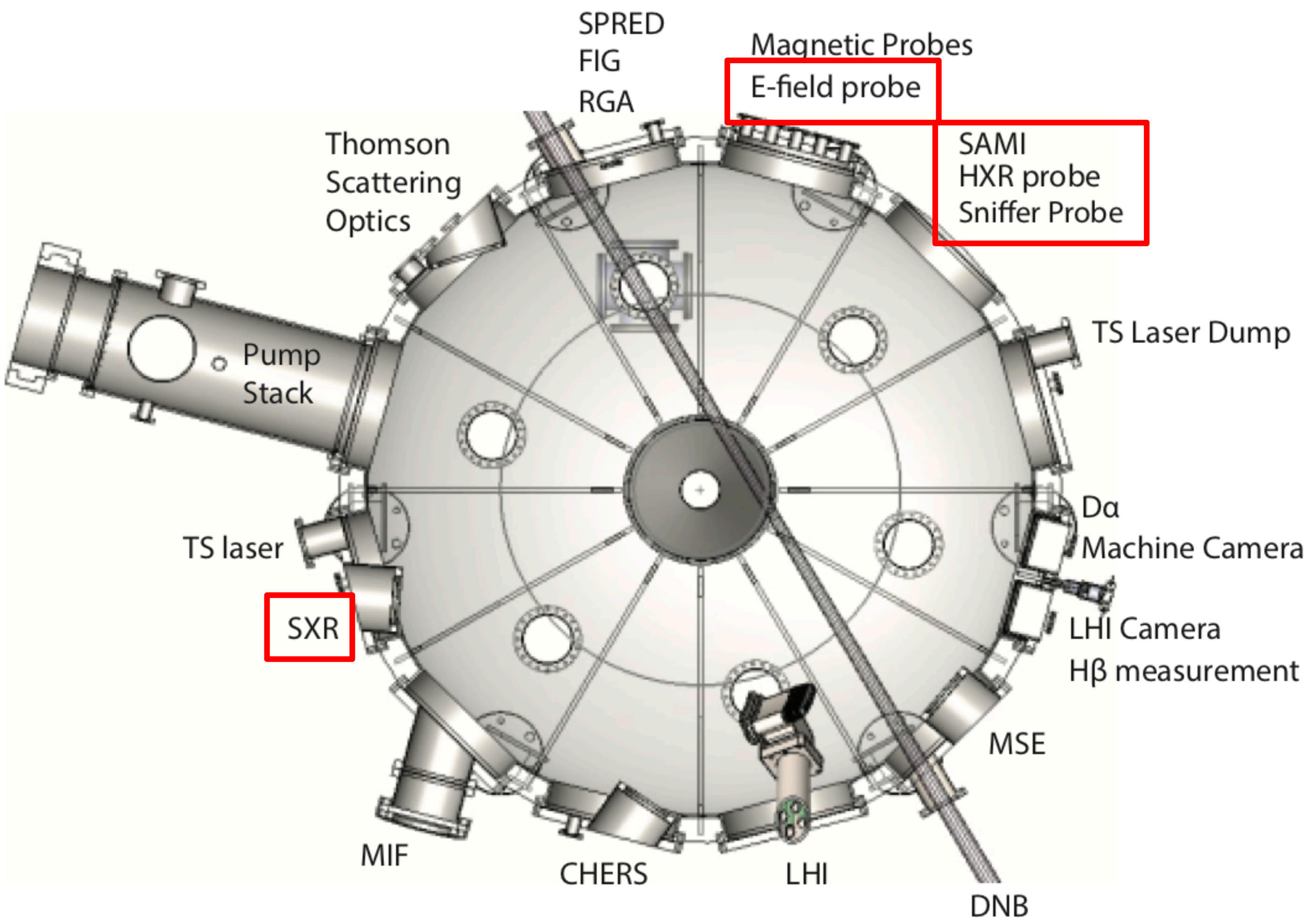




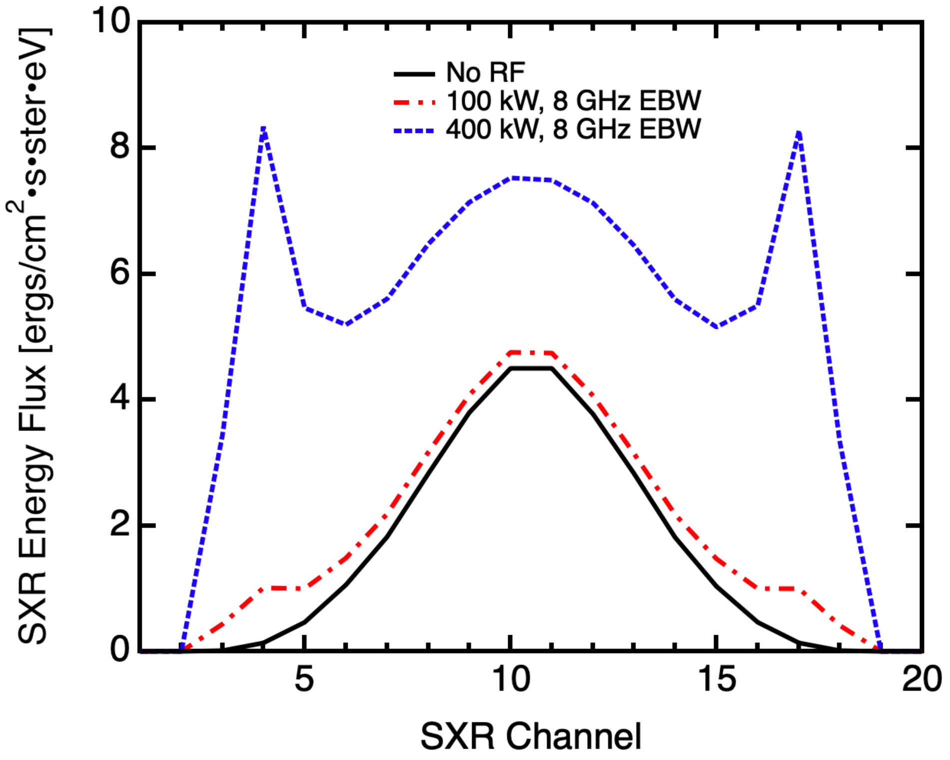
Handoff to EBWCD



Diagnostics Required to Verify RF Heating, Current Drive



CQL3D modeling of SXR



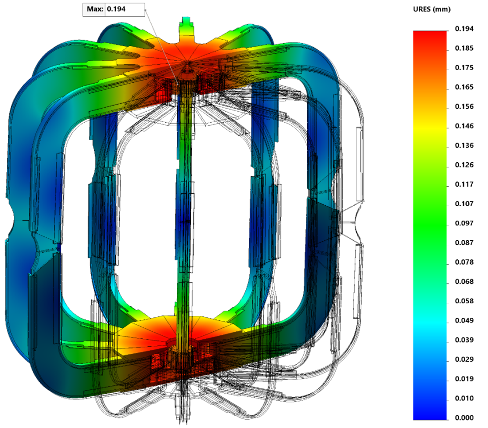
Long Term Plans for RF Seek to Enhance Non-Solenoidal Tools on PEGASUS-III Experiment

- 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 non-inductive sustainment tools

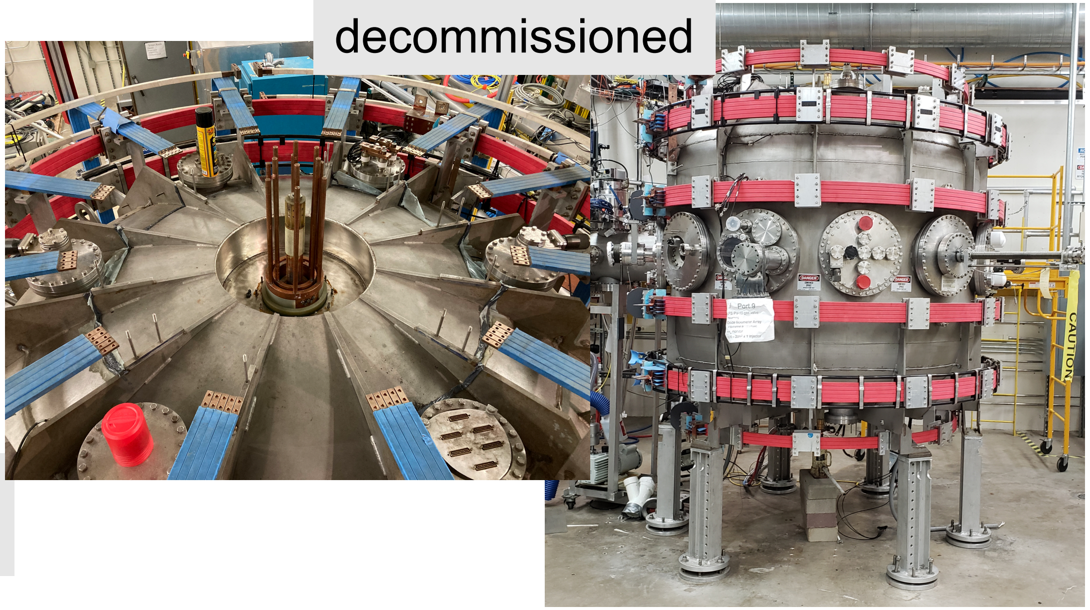
- Also allows unique studies of near unity β_T, low-A physics

PEGASUAS-III is Under Construction

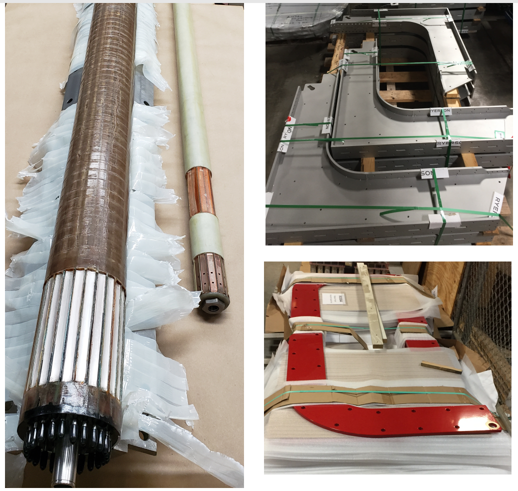


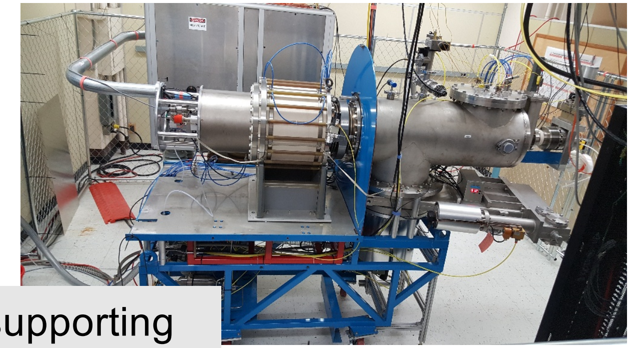
Complete electromechanical design & analysis of TF system

PEGASUS decommissioned

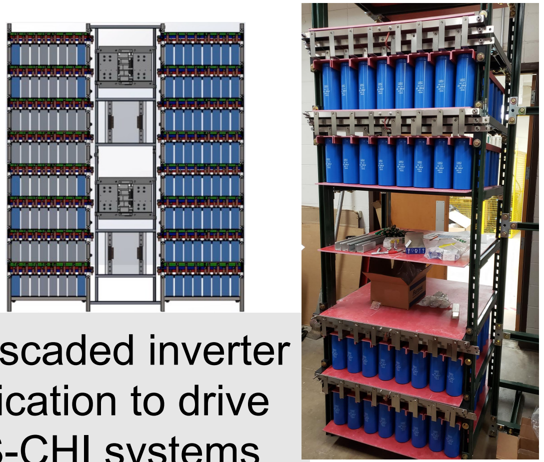


TF center rod, conductors, & return structures delivered

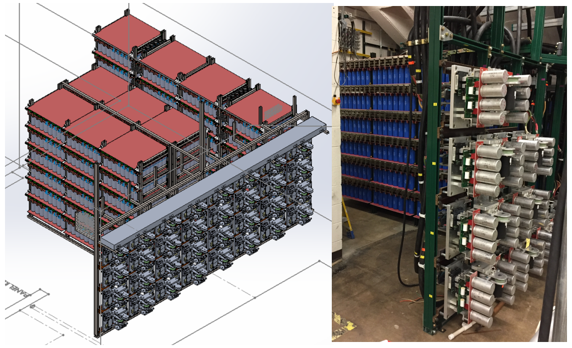




DNB supporting new diagnostics (PPPL loan)



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



Assembly of 240 MVA power systems underway

https://pegasus.ep.wisc.edu

THE UNIVERSITY of WISCONSIN MADISON