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Heating and Current Drive of Overdense Plasmas in Spherical Tokamaks Utilizing Electron Bernstein Waves

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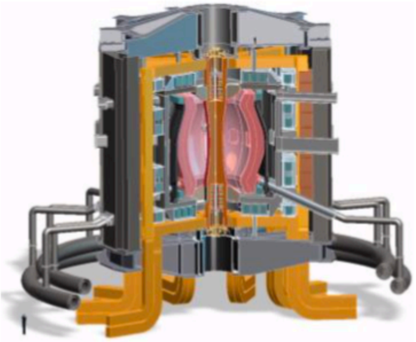
in collaboration with colleagues from UW-Madison and ENEA

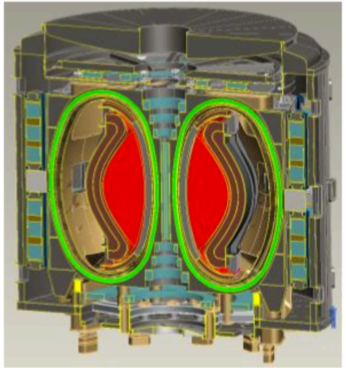
2019 ISTW – Frascati, Italy

U.S. DEPARTMENT OF ENERGY

ORNL collaborating world-wide to help close science and technology gaps for low-A tokamaks

- U.S. community-driven, long term planning is considering a mid-sized, high power density tokamak that would enable development of a compact, fusion pilot-plant
- Can sustained, low-A H-mode scenarios move beyond carbon PFCs? Are alternative divertors required?
  - Assisting in NSTX-U PFC engineering for Recovery, exploring advanced radiative divertors in MAST-U and studying SOL heat flux width scaling to high field in ST40
  - Examining the effect of Li PFCs on core T_i, rotation in LTX-β
- Can the reliance on steady-state NBI be reduced?
  - Starting collaboration with ST40 on scoping use of ECH/EBW
  - Expect to resume HHFW participation on NSTX-U post-Recovery
- Can STs reduce the need for inductive startup?





J.E. Menard et al., NF (2016)
J.E. Menard, Phil. Trans. R. Soc. A (2019)

Initiating current without induction from central solenoid remains critical challenge facing STs

- Follow up experiment to *Pegasus* at University of Wisconsin-Madison focused on non-inductive startup techniques
- Electron Bernstein waves (EBW) can be used to address non-solenoidal plasma startup, ramp-up and sustainment in overdense plasmas
- Update on *Pegasus-III* EBW activities

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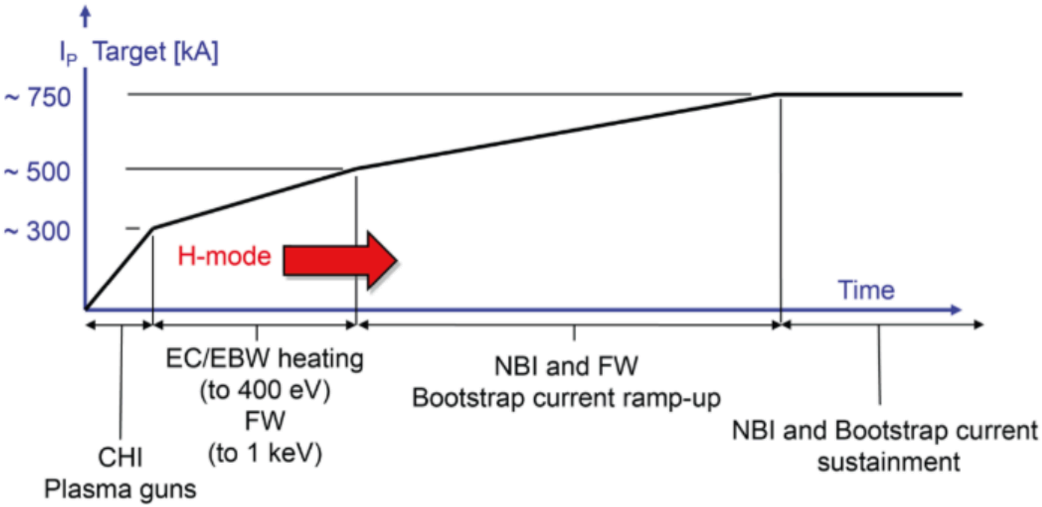
Elimination of solenoid greatly simplifies ST design but requires non inductive startup pathway

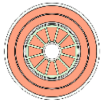
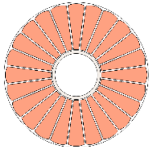
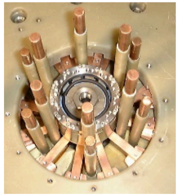
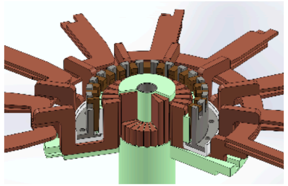
- **DOE-Funded Mission:** Solving 1 MA solenoid-free startup in NSTX-U
- Non-solenoidal startup and rampup techniques being studied both in US and internationally
- Collaboration will focus on EBW and ECH techniques



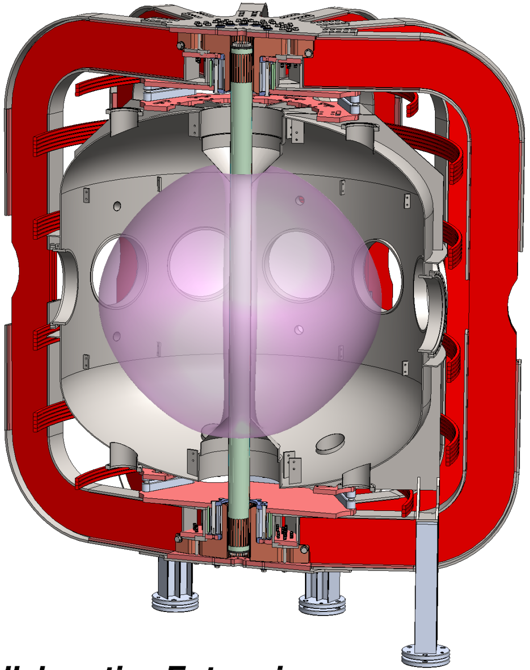
G. Taylor, et al, RF Power in Plasmas (2015)

PEGASUS-III provides the US with a non-solenoidal startup development station

PEGASUS-III: US Startup Development Station

PEGASUS	PEGASUS UPGRADE
	
High-Stress OH Solenoid	*Solenoid-free*
12-turn TF Bundle	*24-turn TF Bundle*
	

Parameter	PEGASUS	PEGASUS - UPGRADE
R_{sol} [cm]	4.9	N/A
I_{sol} [kA]	24	0
ψ_{sol} (mWb)	40	0
N_{TF}	12	24
N_{TFT} X I_{TF}	0.288 MA	1.15 MA
$B_{T,max}$ [T] at R_0 ~0.4 m	0.15	0.60
A	1.15	1.22
B_T Flattop [ms]	50	100
TF Conductor Area [cm^2]	13.2	151
I_p Target [MA]	0.2	0.3



Collaborative Enterprise:

Initiating current without induction from central solenoid remains critical challenge facing STs

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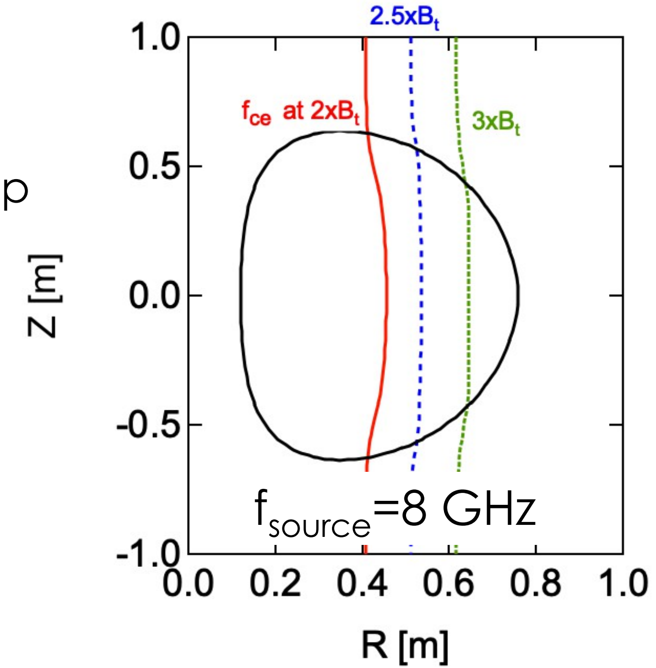
EBW heating/CD to be explored as component of fully non-inductive ST startup and sustainment

- EBW heating capability may synergistically enhance LHI induced I_p current by lowering resistivity
  - T_e increases compatibility with non-inductive sustainment (i.e. NBCD)
  - Potential for direct RF startup
  - Initial concept: *~500 kW EBW RF, 8 GHz*



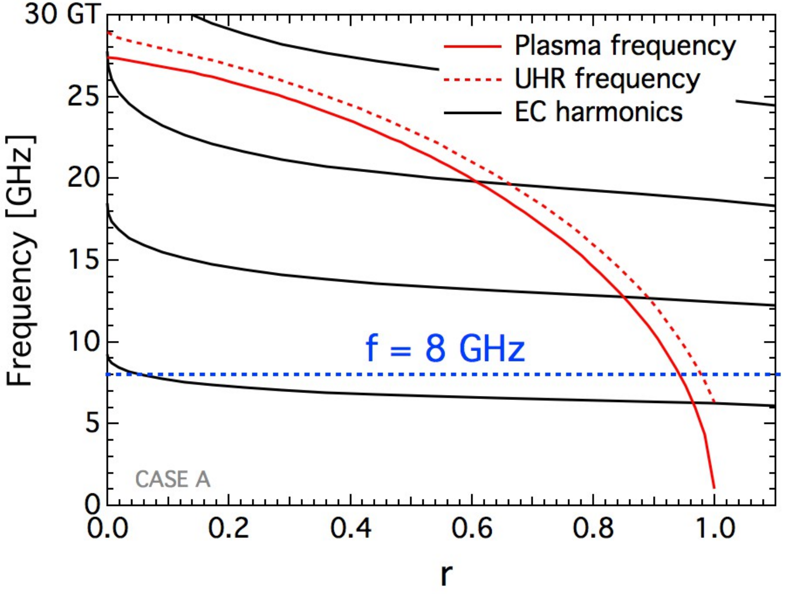
- Collaboration between ORNL, ENEA, UW-Madison
  - Providing modeling, hardware expertise and experimental operations support

EBWs provide path to electron heating/current drive in overdense plasmas

- Low magnetic fields, high n_e of *Pegasus-III* plasmas prohibit use of traditional ECH for many scenarios
  - Additional heating/current needed for non-solenoidal startup
  - EBW can couple to and propagate in overdense plasmas ($\omega_{pe} > \Omega_{ce}$)

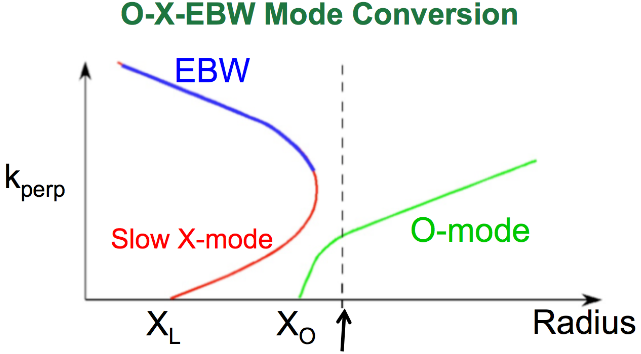
- EBWs have been used successfully in STs and stellarators for heating & CD

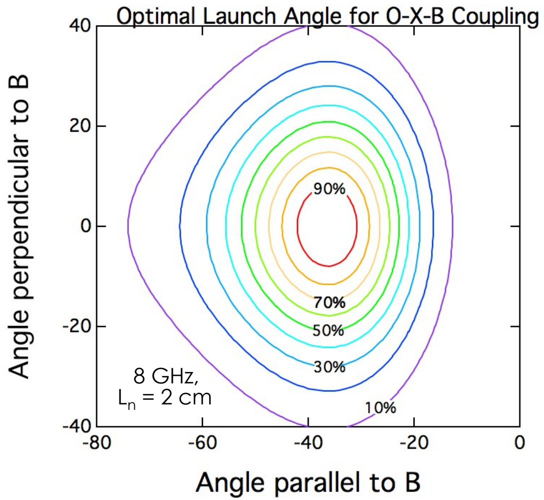
Example of characteristic frequencies in *Pegasus Upgrade* with B_{T0}=0.346 T, $n_e(0) = 10^{19}$ m^{-3}



Overdense plasmas require alternative to EC heating methods

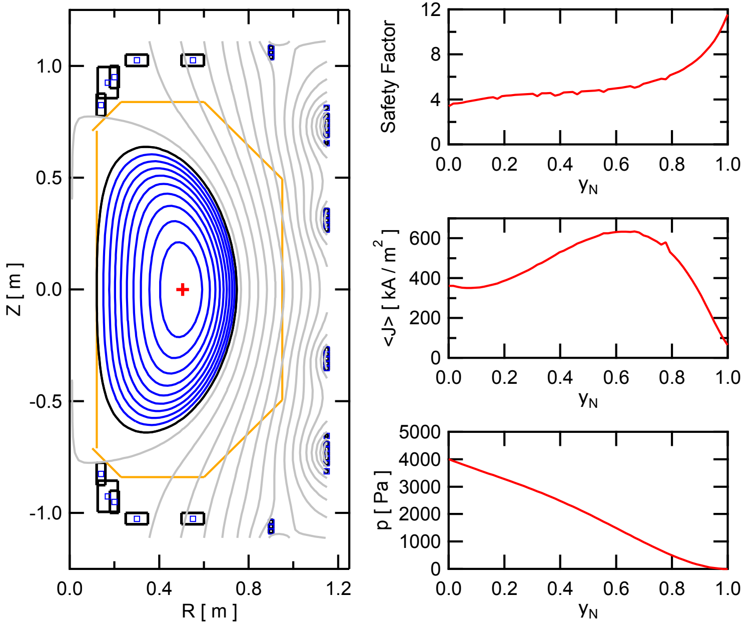
- EBWs are perpendicularly propagating, electrostatic, hot plasma waves
  - EBWs do not experience a density cutoff in the plasma
  - EBWs cannot propagate in vacuum ➔ must launch O- or X-modes to mode couple to EBW
- EBWs absorbed near Doppler broadened resonance
  - Increase in $n_{\|}$ results in shift of resonance location: $\omega - k_{\|} v_{\|} - n\Omega = 0$
  - Observed for off-midplane launch in STs





Preliminary modeling to assess EBW feasibility with increase in *Pegasus* toroidal field

- Projections suggest increase in toroidal field may result in higher T_e for LHI target plasmas for EBW modeling
  - Currently, $T_e(0)$ = 200 eV in LHI discharges



Equilibrium Parameters
Shot 12366, 0.000 ms, Undo 234

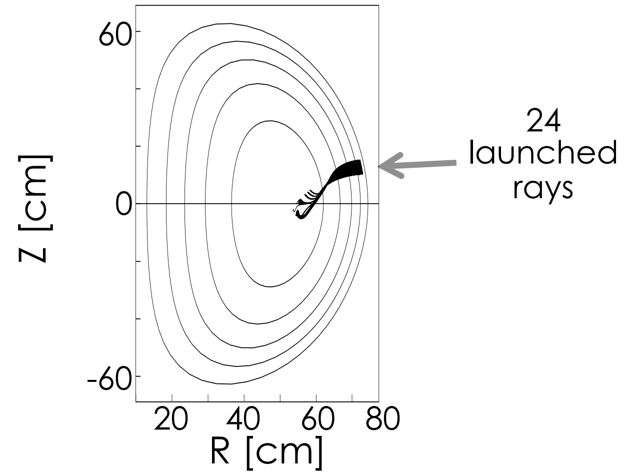
I_p	297 kA	R_0	0.434 m
β_t	0.045	a	0.313 m
ℓ_i	0.41	A	1.38
β_p	0.37	κ	2.0
W	9089 J	δ	0.27
B_{T0}	0.339 T	q_{95}	9.19

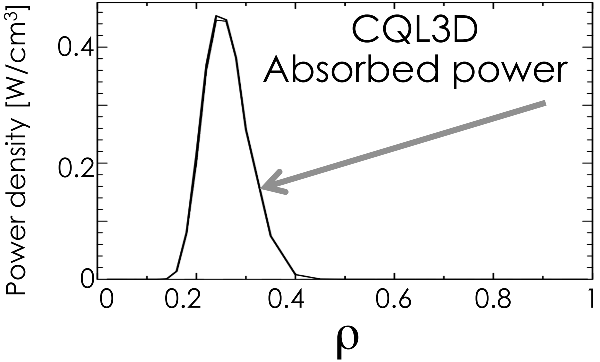
$n_e(0)=1\times10^{19}$ m^{-3}, $T_e(0)$ = 400 eV

GENRAY/CQL3D modeling shows absorption, current drive near $\rho = 0.2$

- Source frequency of 8 GHz was used for preliminary modeling
  - Experimental target of ~400 kW injected into the plasma
  - B_{T0}=0.339 T, 2.5x current TF in Pegasus
  - Poloidal launch angle of 30° above midplane, $n_{||}$=-0.55 to -0.45
- Absorption localized near fundamental EC resonance
  - ~30-40 kA of driven current with 400 kW of injected power

GENRAY EBW Ray-tracing





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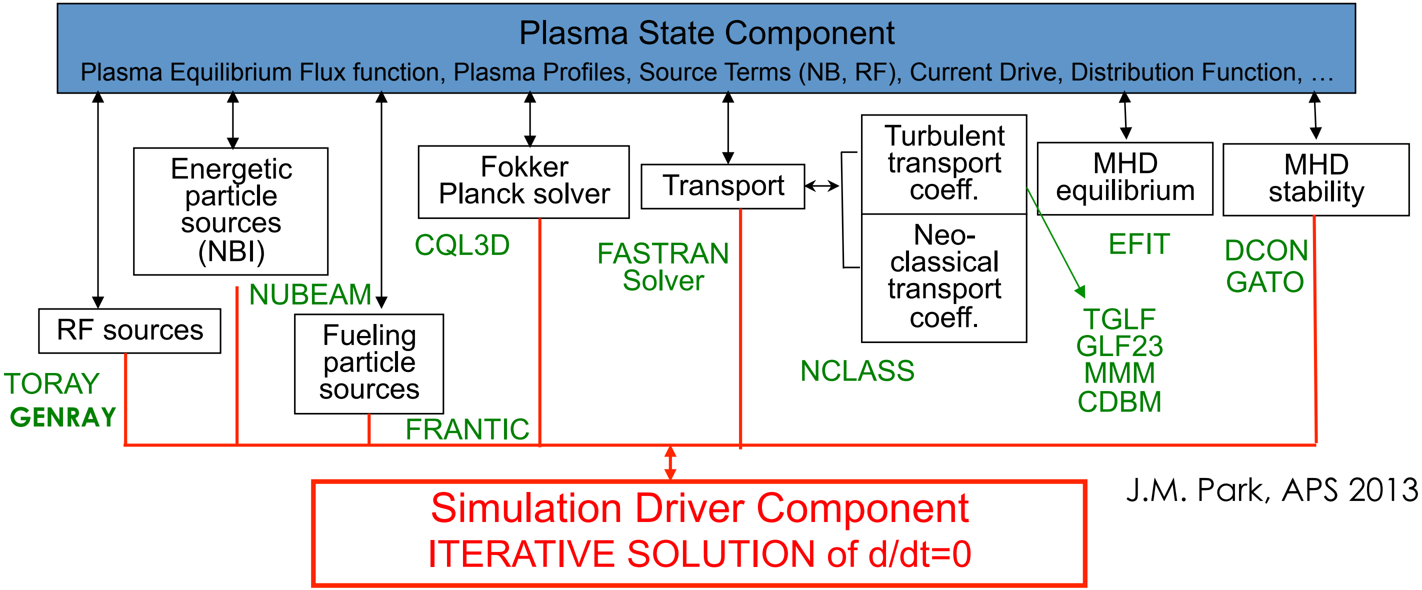
Modeling to provide optimization of EBW system

- GENRAY/CQL3D will calculate EBW propagation, absorption and driven current
  - OXB model in GENRAY includes analytic formula, providing a rough estimate of conversion efficiency, includes collisional damping calculations
  - CQL3D can simulate SXR signals
- IPS-FASTRAN framework to provide integrative modeling approach
- Finite-element COMSOL Multiphysics code will be used to model antenna and O-X coupling
  - Full-wave modeling with a cold plasma slab
  - Allows for direct comparison to measured electric field

IPS-FASTRAN provides integrative modeling approach



J.M. Park, APS 2013

- Allows modeling of self-consistent plasma evolution
- Accelerates repeated cycle of modeling, experimental validation and scenario design/development

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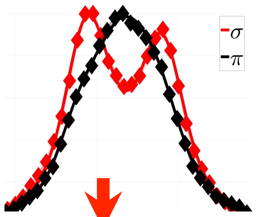
Experimental measurement of RF wave fields for full-wave model validation

- Optical emission spectroscopy (OES) used to measure of RF waves by taking advantage of the **dynamic Stark effect**
  - Spectral line profile is affected by RF electric field vector
  - Schrodinger equation is fit to the spectral line profile to extract the RF electric field vector



D_β spectral line profile obtained experimentally using OES

FIT

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[H + H^{B} + H^{E_{RF}}(t)\right]\Psi$$

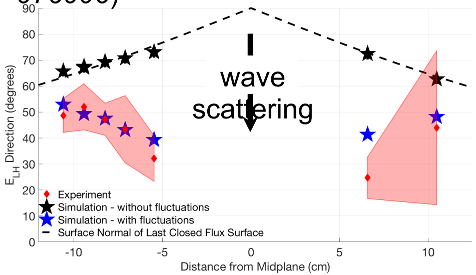
Schrodinger equation

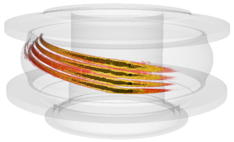
E_{RF}

Measurement of RF wave field

TECHNIQUE SUCCESSFULLY IMPLEMENTED IN TORE SUPRA, C-MOD, AND WEST TO MEASURE LH WAVE FOR MODEL VALIDATION AND PHYSICS IDENTIFICATION

Direct experimental measurement of LH wave scattering by turbulence in C-Mod (*NF 59 (2019) 076006*)





FULL-WAVE LH SIMULATION

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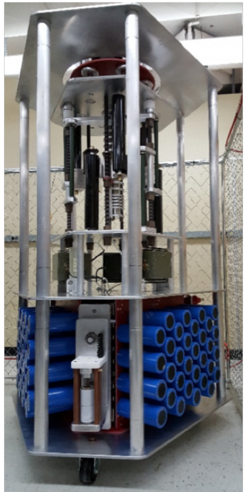
Initial RF system focuses on fundamental absorption with 8 GHz source frequency

- Four 8 GHz klystrons (Varian VKX-7879A)provide total of 500 kW of power for experiments on Pegasus
  - Previously used for LHCD on Frascati Torus
  - Pulse length of 0.5 s
- UW-Madison developing high voltage power supplies
  - Solid-state resonant amplifying power supplies provide low voltage ripple needed for klystrons

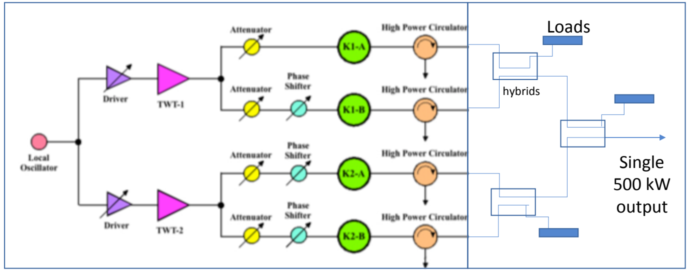
ENEA



High voltage power supply designed/ built at UW-Madison

Design and testing of RF system components underway

- Power combiner network can couple all 4 klystrons
  - Existing system has the phase and amplitude controlled drive hardware
  - Low power testing has begun at ORNL
- Tallguide reduces power loss
- Small feed horn gives best focus at mode conversion layer
  - Ellipsoidal reflector provides ~17 cm beam waist

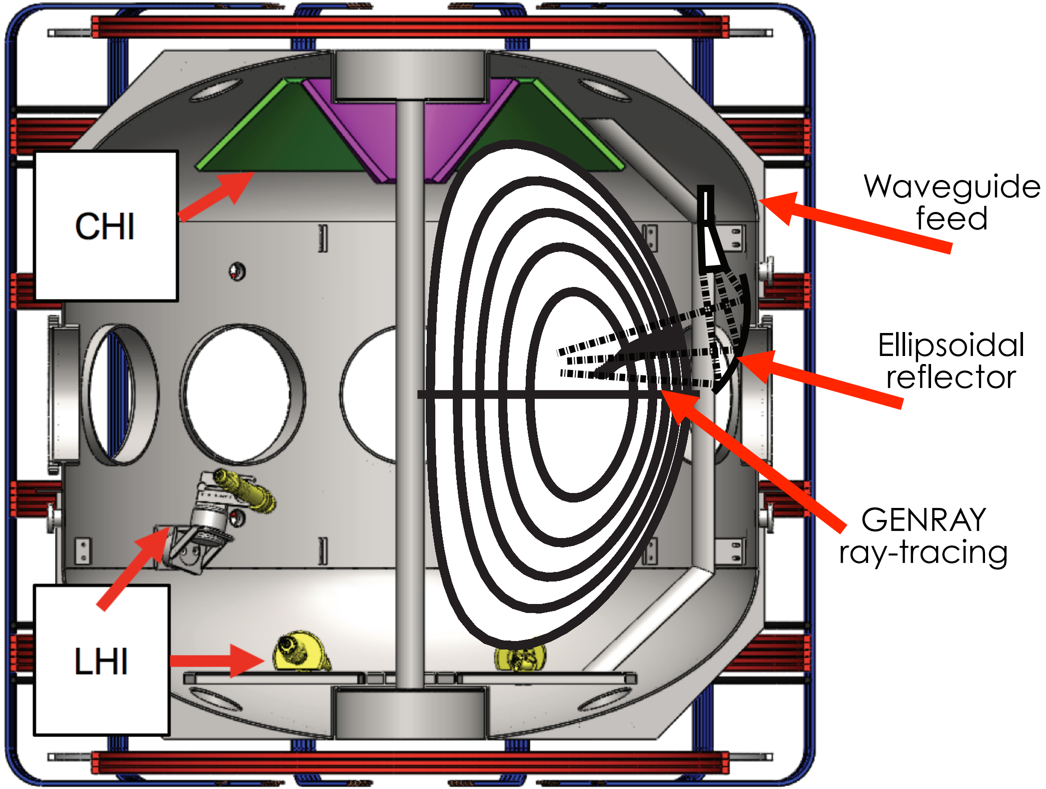


8 GHz klystrons, 500 kW WR137 combiners

Scaled model w/WR62

Flexible port access favorable to explore different antenna designs

- Flexibility in launcher design and access
  - Compatible with HI systems
  - Off-midplane launch allows current profile control
- Preliminary concept incorporates:
  - Upper port for waveguide access
  - Midplane port for ellipsoidal reflector



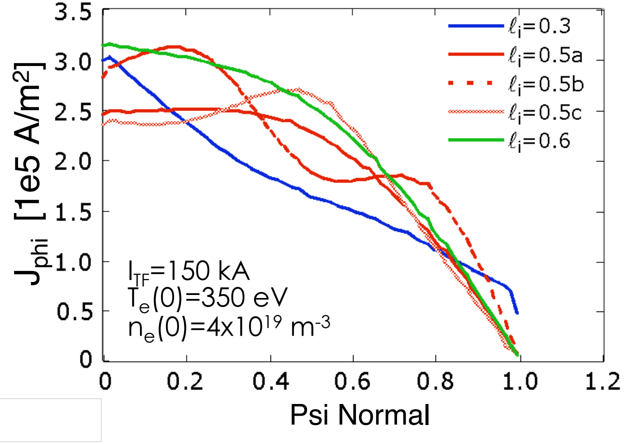
Pegasus-III operational space provides test bed for EBW heating/CD studies

- *Pegasus-III* provides a unique opportunity to compare efficiency of a variety of ST startup techniques
  - Collaboration with university project provides large amount of dedicated machine time to devote to target plasma development and focused EBW startup, heating/CD experiments
  - Will investigate: helicity injection, ECH/EBW, CHI, etc.
- High-power EBW experiments led by ORNL in collaboration with UW-Madison and ENEA to be performed and compared with theoretical predictions
  - Modeling shows EBW absorption at fundamental resonance possible for injection at 8 GHz with 500 kW of power, providing heating and CD
- Developing a means to initiate and sustain ST plasmas without central induction will allow *Pegasus-III* to perform the explorations of high-pressure, low-A plasmas which are inaccessible with Ohmic heating alone
  - Future work includes exploration of ECH

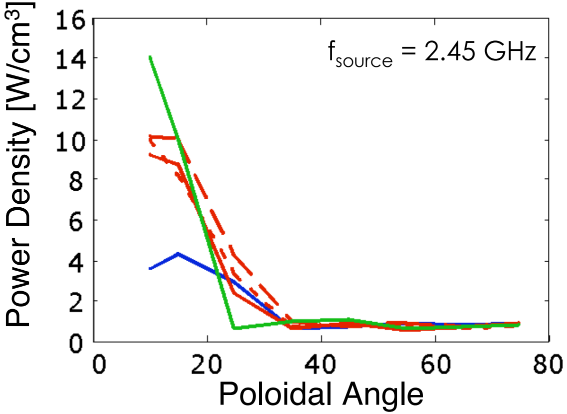
Backup slides

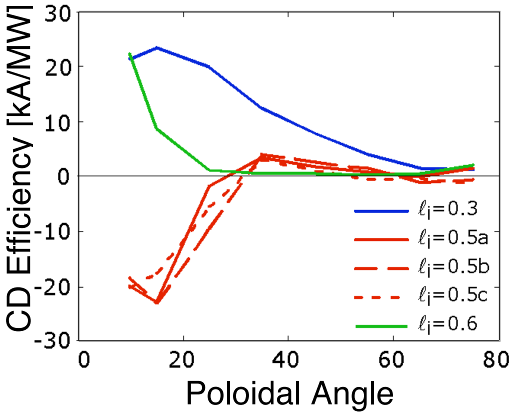
Previous modeling shows EBW effective for a variety of plasma current profiles in *PEGASUS*

- Heating, CD peaked for near midplane launch at all ℓ_i values
  - LHI yields typical ℓ_i of 0.2-0.45
  - More extensive scan at appropriate TF, source frequency will be performed



- ℓ_i scan reveals sign of current is sensitive to profiles



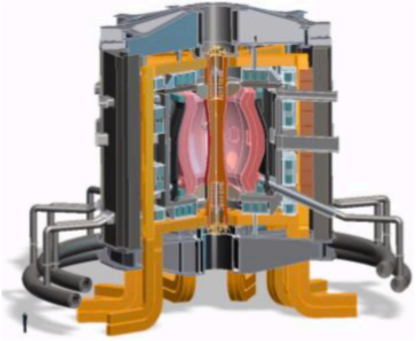


T_e, n_e, I_p, κ, β all constant

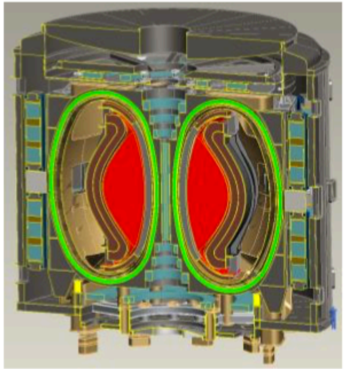
Initiating current without induction from central solenoid remains critical challenge facing STs

- Non-solenoidal startup remains a critical need for spherical tokamaks (ST), may benefit advanced tokamaks
  - Nuclear ST designs generally prohibit OH due to shielding/cost
  - Small solenoid considered as a fallback; insufficient for I_p ramp-up
- Requires physics understanding of optimal non-solenoidal tokamak startup
  - Can be applied to future large-scale ST
- *Pegasus* Toroidal Experiment at University of Wisconsin-Madison focused on non-solenoidal plasma startup, ramp-up and sustainment

ST-FNSF, FNSF / Pilot Plant Concepts
Shielding needs severely constrain OH viability



Solenoid-free
Copper
ST-FNSF



No / small OH
HTS
ST-FNSF / Pilot Plant

J.E. Menard et al., NF (2016)
J.E. Menard, Phil. Trans. R. Soc. A (2019)

Off-midplane launch allows for current profile control

- Increase in poloidal launch angle increases Doppler shift, radius of damping location
  - Poloidal launch angle of 45° yields ~10 kA of driven current with 400 kW of injected power at $\rho = 0.5$
  - Absorption region spreads at higher values of ρ

- Flexibility of launcher may provide tool to study current profile control
  - Varying plasma vertical height in *PEGASUS UPGRADE* may allow for small changes in poloidal launch angle