An Integrated Program to Develop Scalable Solenoid-Free Startup Scenarios for Spherical and Advanced Tokamaks

M.W. Bongard

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PPPL
NSTX-U

Initiative Proposal

Joint Community Planning Workshop for Magnetic Fusion Energy and Fusion Materials & Technology

Madison, WI
23 July 2019

URANIA
Experiment

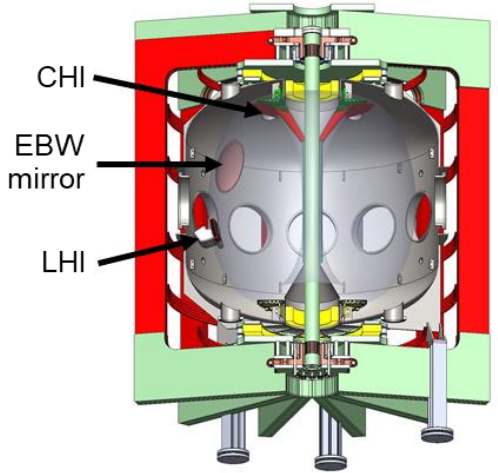
Addressing the Challenge of Non-Solenoidal Tokamak Startup

Objective: Develop solenoid-free startup and possibly sustainment techniques applicable to next-step nuclear devices

- **DOE-Funded Mission:** Solving 1 MA solenoid-free startup in NSTX-U

- **Approach**: Develop understanding and comparative concept assessments
  - Helicity injection, RF, poloidal induction, NB…
  - Domestic: Pursue/expand development on new URANIA facility
  - International: Collaborative efforts [Ono, Raman]

URANIA ST: US Startup Development Station
Domestic Collaborative Activity
No OH Solenoid!



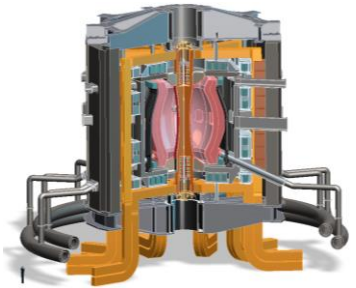
Non-Solenoidal Startup Remains a Critical Need for the Spherical Tokamak, and May Benefit Advanced Tokamaks

- Critical need for ST
  - Need confirmed in repeated FESAC/community studies
  - Nuclear ST designs generally preclude OH due to shielding / cost
  - Small solenoid considered as fallback; insufficient for I_p ramp-up

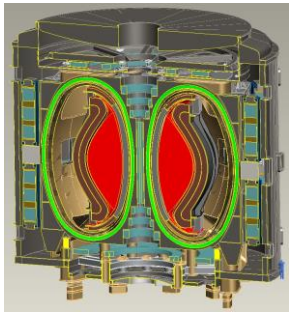
- May benefit the tokamak in general
  - Possible reduction in cost/complexity of STs, ATs
  - More space for inboard shielding / blanket / RF
  - Lowers electromechanical stresses
  - Reduce/eliminate need for breakdown B_p null from PF system
  - May be required to fully support A optimization of next-step devices

- Solenoid-free startup and ramp-up techniques desired

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



Solenoid-free
Cu
ST-FNSF



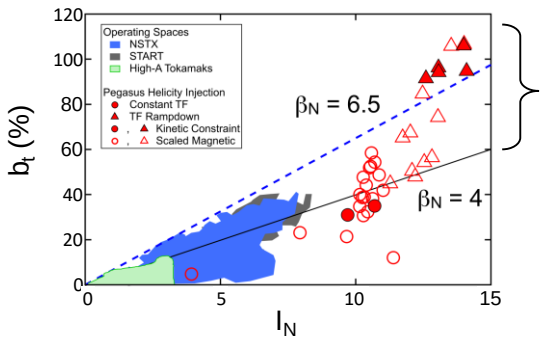
No / small OH
HTS
ST-FNSF / Pilot Plant

*J.E. Menard et al., Nucl. Fusion **56,** 106023 (2016)*
*J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019)*

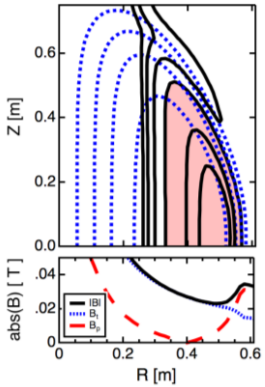
New Techniques Can Also Provide Access to Novel Physics

- Access to extreme ST space
  - $\beta_t \sim 100\%$ at $A \sim 1$
  - Low ℓ_i, high κ, high I_N, high β_N
- Access to large min-|B| region
  - ~50% of plasma volume
  - High degree of flux surface omnigeneity
  - Potential reduction of transport?
- Reconnection physics
  - 3D reconnection of injector streams
  - Anisotropic $T_{i\perp}$ scaling verified

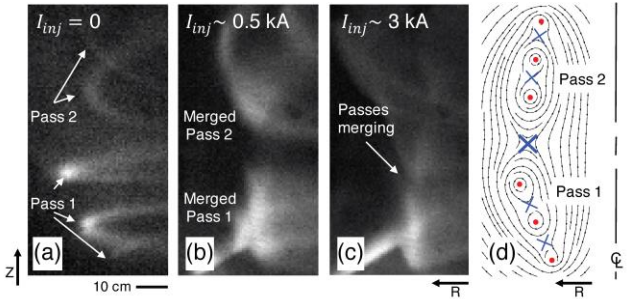
Min |B| Well at $\beta_t \sim 100\%$



PEGASUS LHI
$\ell_i < 0.3$
$2 < \kappa < 2.7$
$\beta_N/\ell_i \sim 20$



Anisotropic Reconnection-Driven Ion Heating ($T_{i\perp} \propto B_{rec}^2$)

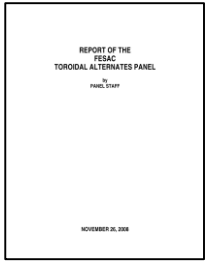


J.A. Reusch et al., Phys. Plasmas **25**, 056101 (2018) M.G. Burke et al., Nucl. Fusion **57**, 076010 (2017)
D.J. Schlossberg et al., Phys. Rev. Lett. **119**, 035001 (2017)

Need for Solenoid-Free Startup Consistently Articulated in Community Planning Exercises

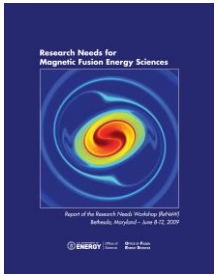
FESAC TAP [2008]

- Solenoid-free startup and rampup identified as top priority issue for ST and relevance to burning plasma applications [Tier 1 Critical Issue]
- Gap: Low I_p shown experimentally
- Recommendation: MA-class solenoid-free startup demonstration



ReNeW [2009]

- Solenoid-free startup is critical issue for ST (Thrust 16 Key Issue)
- Reinforces / expands TAP:
  - MA-class solenoid-free startup with handoff to NI sustainment
  - Validated, predictive, physics models
  - Develop EBW RF startup
  - Perform comparative studies of multiple startup methods in single experimental facility



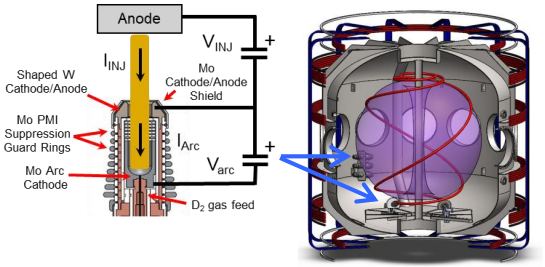
NAS Report [2018]

"NSTX-U will be the leader in assessing whether high-performance STs can be sustained without a transformer, a critical research component since the compact nature of an ST-based Pilot Plant, for instance, will preclude a substantial OH transformer."

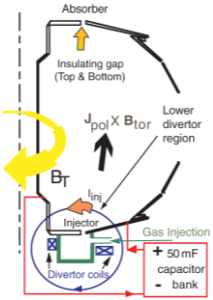


Several Approaches Developed to Solve the Problem…

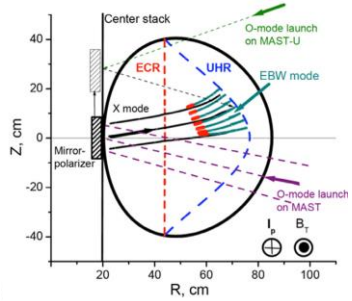
LHI



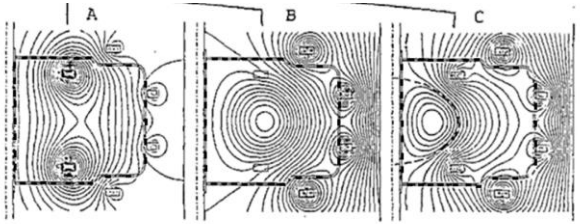
CHI



EBW RF



Merging / Compression



Helicity Injection

- Drives current on SOL open field lines
- Local Helicity Injection (LHI)
- Coaxial Helicity Injection (CHI)

Radiofrequency

- Ionize gas and ramp to desired plasma configuration
- EC, LH, EBW
- Potential synergies with HI startup

Reconnection

- Seed plasmas made by PF coils rapidly merged into center of VV
- Reconnects to make target plasma

Bongard et al., Nucl. Fusion ***59****, 076003 (2019)* *Raman and Shevchenko, Plasma Phys. Control. Fusion* ***56****, 103001 (2014)*
Gryaznevich and Sykes, Nucl. Fusion ***57****, 072003 (2017)*

… and Tested Independently Worldwide

Method	Facility	I_p [MA]	t_{pulse} [ms]	n_e [10^{19} m^{-3}]	T_e [eV]	Sustainment Phase(s)
LHI	PEGASUS	0.225	10–30	~1	~125	Ohmic
	VEST	0.004	4	—	—	N/A
	CDX	≤ 0.001	60	$\bar{n}_{e0}$ ~ 2	~25	N/A
	CCT	0.006	20	$\bar{n}_{e0}$ ~ 0.5	30–50	N/A
S-CHI	NSTX	0.400	350	—	—	N/A
	HIST	0.150	5	$\bar{n}_e$ ~ 2–7	20–30	N/A
	HIT-II	0.350	5	$\bar{n}_e$ ~ 5	~40	N/A
T-CHI	HIT-II	0.100	1	~2	~15	Ohmic
	NSTX	0.200	5–20	~1	10–30	Ohmic, Ohmic + NBI heating
	HIST	0.100	0.3	~10	10–15	N/A
	QUEST	0.045	15	—	—	N/A
ECH+PF induction	DIII-D	0.170	50	~2	1000	RF, RF + NBI
	JT60-U	0.100	250	—	—	RF
ECH	QUEST	0.070	1,500	0.01	< 100	RF
	DIII-D	0.033	50	0.5–1	~100	RF
	KSTAR	0.015	1,800	~0.05	~250	RF
ECH + LHCD	T-7	0.020	175	$\bar{n}_{e0}$ ~ 0.1	75	RF
EBW	MAST	0.073	450	0.1	100–200	RF
	LATE	0.015	80	$\bar{n}_e$ ~ 0.05	30	RF
LH	PLT	0.100	2,500	$\bar{n}_e$ ~ 0.1	350	RF
	TST-2	0.025	70	$\bar{n}_e$ ~ 0.05	10	RF
	GLOBUS-M	0.021	140	$\bar{n}_e$ ~ 0.2	15–20	RF
DNM	UTST	0.080	1	1–3	~5	N/A

References (and more context) for all entries available in M.W. Bongard et al., white paper, these proceedings

An Integrated Research Program Can Accelerate Progress

- Independent studies to date provide breadth, but not depth
  - Widely varying facility capabilities, runtime availability
  - Difficult to evaluate potential synergistic effects

- Integrated, comparative studies needed
  - Develop sufficient physics/technology basis for scaling up
  - Inform, develop choice of approach for specific facilities

- Overarching identified gaps to address
  - Comparative assessment of non-solenoidal startup
    - *e.g.* efficiency, accessibility, impurity production, engineering compatibility…
  - Solenoid-free startup to full device I_p
  - Handoff to long-pulse sustainment

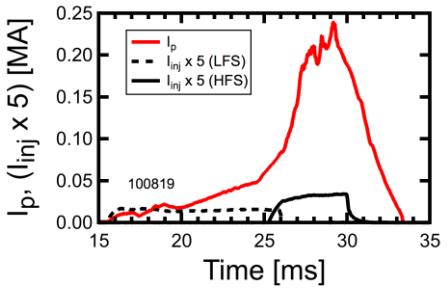
The US Strongly Contributes to Worldwide Solenoid-Free Startup Efforts

- The US is presently a leader on helicity injection startup (LHI, CHI)
  - $I_p \geq 0.2$ MA, low ℓ_i targets
  - Handoff of HI-plasmas to OH phase with H-mode
  - Modeling of HI startup and physics mechanisms

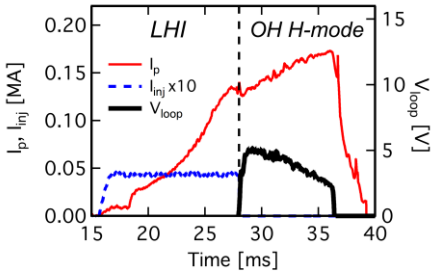
- International activities currently support studies of RF startup and RF-HI synergies

US LHI Research on PEGASUS Featured as July 19 NF Cover Article

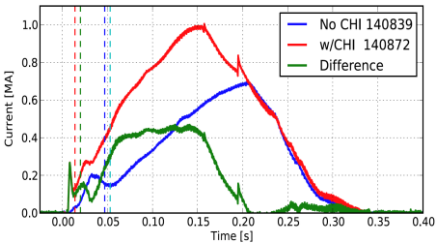




PEGASUS: LHI–OH Handoff



NSTX: T-CHI–OH Handoff



*M.W. Bongard et al., Nucl. Fusion **59**, 076003 (2019)*
*K.E. Thome et al., Nucl. Fusion **57**, 022018 (2017)*
*B.A. Nelson et al., Nucl. Fusion **51**, 063008 (2011)*

This Initiative Addresses Gaps Through Focused Domestic Research and International Collaboration

- Proposal incorporates/builds upon presently-funded activities

PEGASUS → URANIA



Planned shutdown 2019



- Domestic comparative startup studies on new URANIA ST
  - Compare/contrast/combine reactor-relevant techniques at $I_p \sim 0.3$ MA
  - LHI, CHI, RF/EBW, PF induction
  - *Expansion:* high-power EBW CD, ECH/ECCD, NBI CD

- International RF / T-CHI research [Ono, Raman Initiatives]
  - QUEST: T-CHI and EC RF synergies; tests of T-CHI electrode
  - *Expansion:* T-CHI design studies for ST-40, MAST-U





- Identify, build, and test 1 MA startup system for NSTX-U

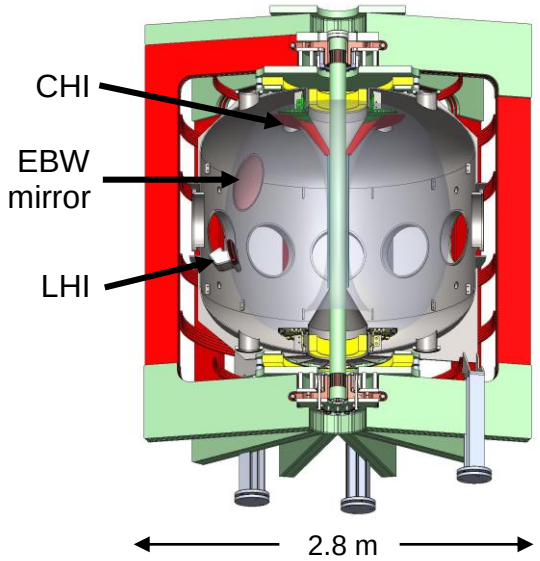


URANIA Experiment: A Dedicated US Facility for Comparative Study of Solenoid-Free Startup and Sustainment

- URANIA is a DOE-approved upgrade to PEGASUS
  - Funding through FY21 for facility, diagnostic upgrades
- Presently-supported upgrades include:
  - New centerstack assembly: ***No solenoid magnet***
  - Increase B_T 4×: 0.15 → 0.6 T
  - Longer pulse: 25 → 100 ms
  - Improved shape control with new PF, divertor coils
  - Diagnostic neutral beam: kinetic and impurity diagnostics
  - Next-generation LHI systems
  - EBW RF Heating & CD (w/ ORNL)
  - Transient, Sustained CHI (w/ Univ. Washington, PPPL)
- Engineering design/procurement in progress

URANIA ST

No OH Solenoid!



Initiative Timeline and Costs

Initiative Component	Near-Term [1–2 years]	Medium Term [2–5 years]	Long Term [5+ years]
Domestic Total: O($3M/yr) Includes URANIA team, collaborators	• URANIA construction and commissioning [FY20] • Initial high-I_p, high-B_T LHI • CHI install / commissioning	• Full-power CHI • Initial EBW studies • HI-RF synergy studies • Long-pulse (0.1 s) LHI	• Design / test NSTX-U 1 MA startup system • NI handoff optimization • Sustainment scenarios
Domestic + Enhancements +O($2M/yr); Total: O($5M/yr)		• High-power EBW • Deploy ECH, ECCD RF • Deploy NBI • Evaluate effects of passive plates [as needed] • Pure RF startup studies • High-I_p HI-NI handoff	
International	*See Ono, Raman Initiatives, these proceedings*		

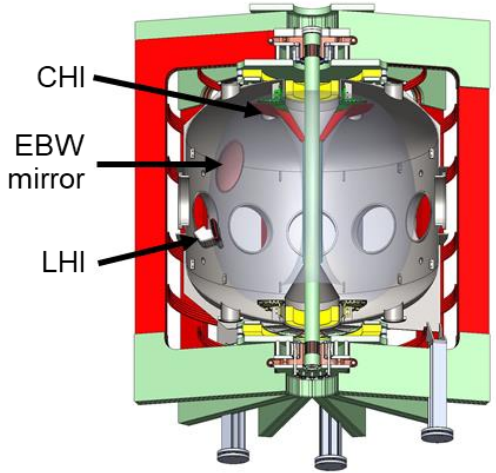
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URANIA ST: US Startup Development Station
Domestic Collaborative Activity
No OH Solenoid!

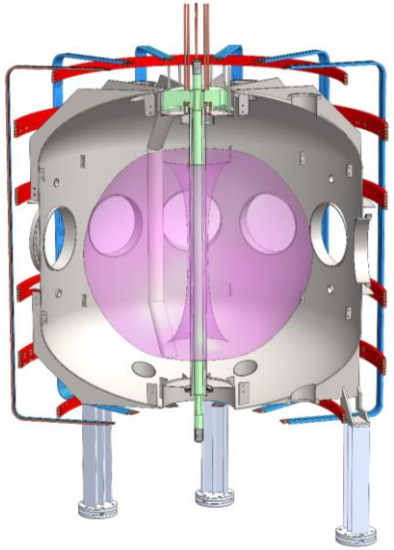


Back-up Content

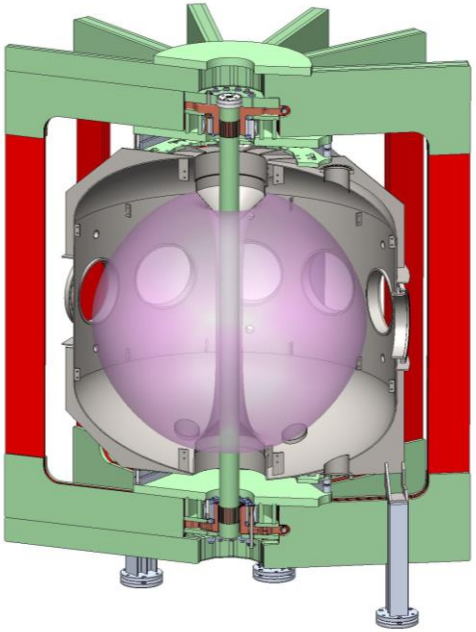
URANIA is a Modification of the PEGASUS Experiment

- Solenoid-free centerstack assembly
- Stronger, less resistive TF return legs
- Torque frame with integrated divertor coils
- Modified power systems
- Select added diagnostics

PEGASUS



URANIA

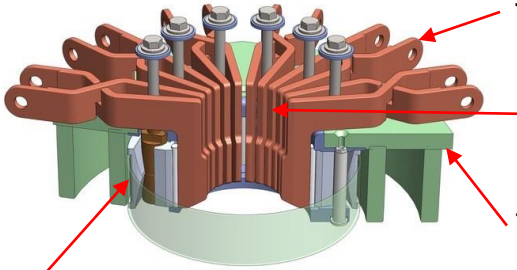


Parameter	PEGASUS	URANIA
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
ΔT_{bundle}	< 10°C	< 20°C
R_0 [cm]	45	45
A	1.15–1.3	1.18–1.35

Heart of the Facility Enhancement Is A New TF Assembly

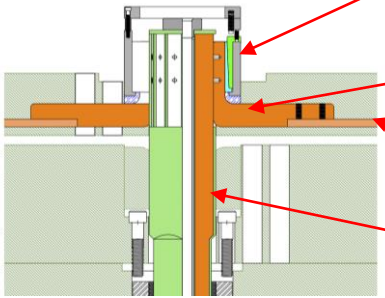
- TF based on successful PEGASUS design
  - TF bundle (centerstack)
  - Finger joints and wedge compression assembly
  - Torque frame
  - Outer return leg assembly
  - Space for divertor coils

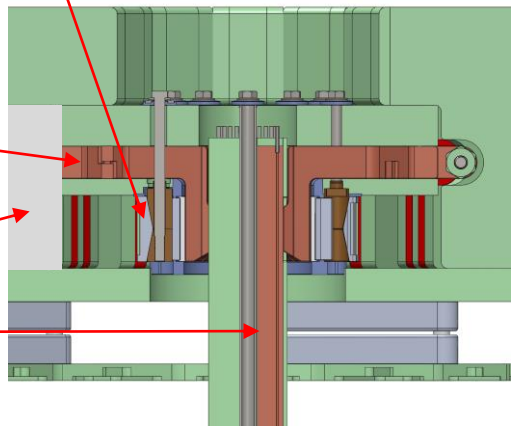
Fingers and compression assembly



Compression provided by band & wedges

PEGASUS

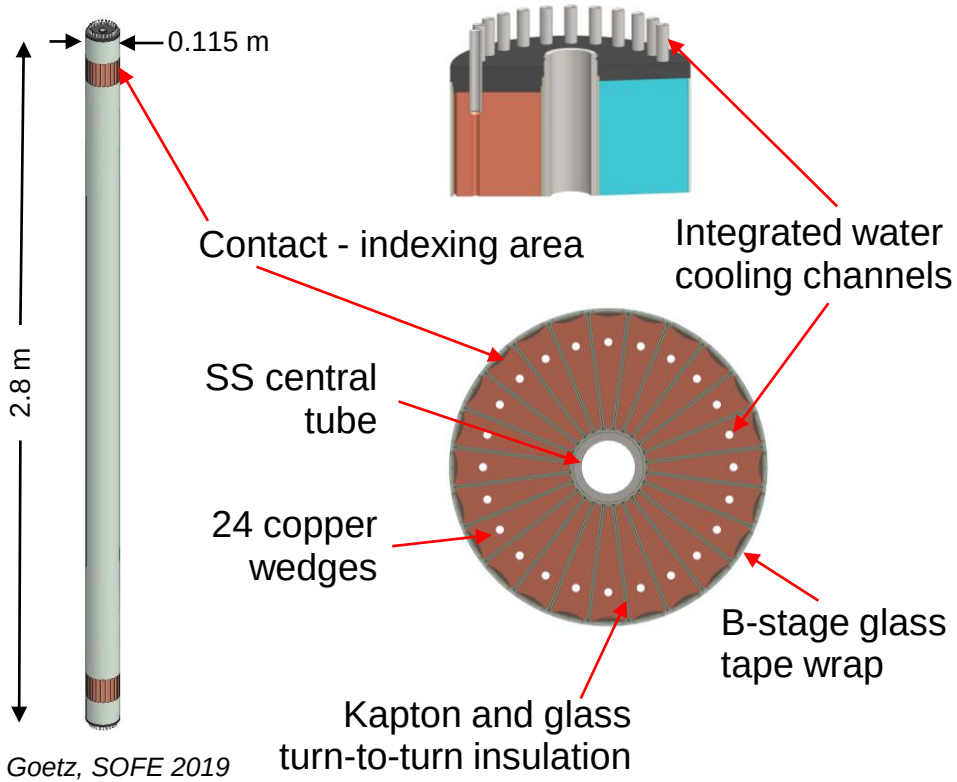




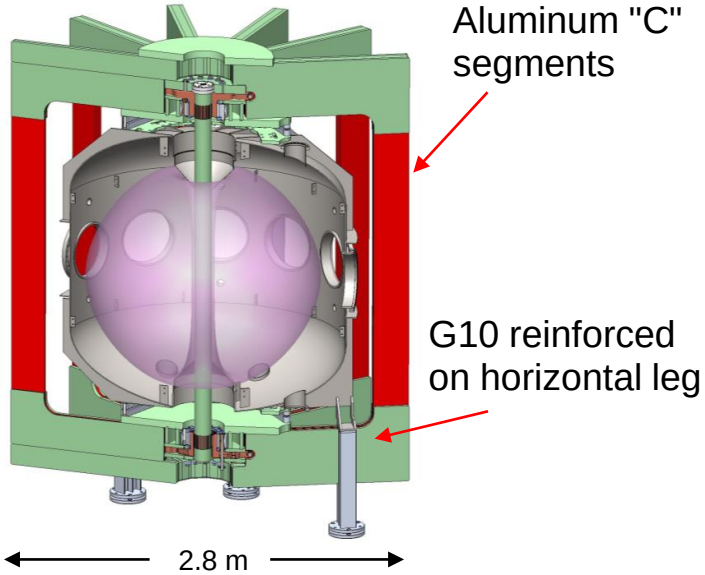
URANIA

TF Magnet is Being Upgraded for 4× Field and Pulse Length

TF centerstack



TF outer return legs

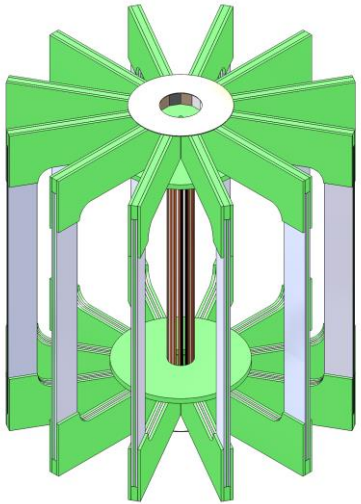


- TF centerstack fabrication in progress

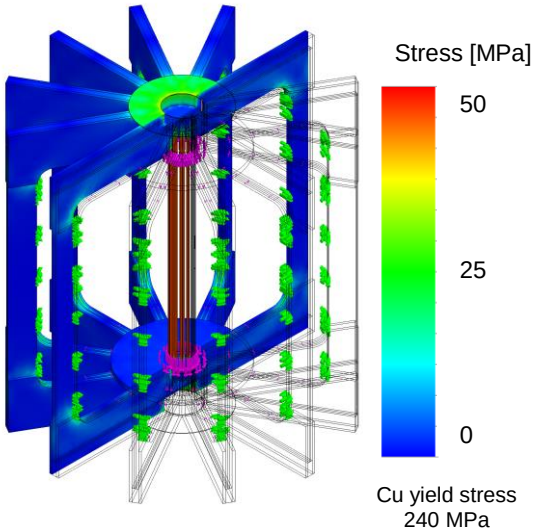
Initial Stress Analysis Acceptable for 4× B_T Operation

- 4× B_T operation results in 16× magnetic stress
  - Expansion stress analyzed; torsional, thermal stress analyses in progress
- Final design to be evaluated with full ANSYS model of TF assembly
  - Determine fixed or sliding joint approach

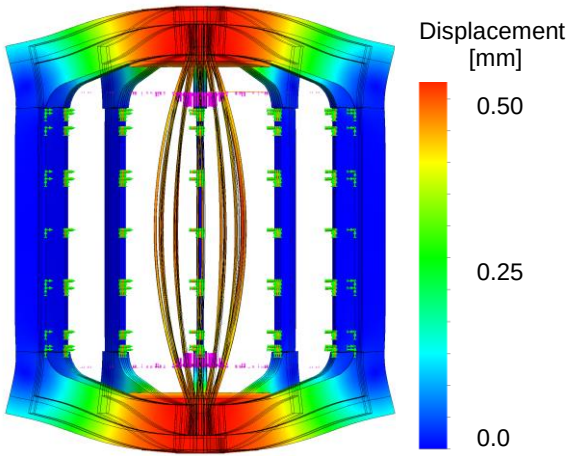
Simplified URANIA model



Magnetic stress distribution



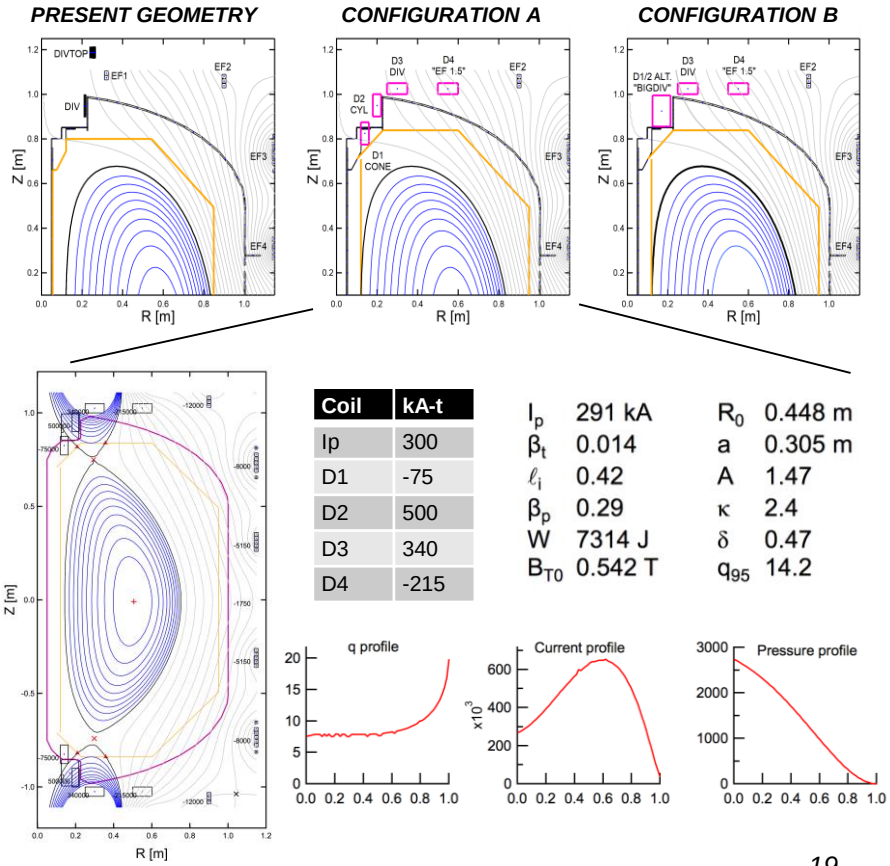
Expansion stress deformation



Displacement 600x for clarity

TF Assembly Structure Accommodates New Divertor Coil Set

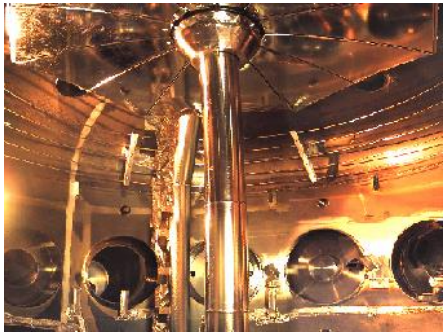
- Conceptual design via equilibrium modeling
  - Identify kA-t, position requirements / tradeoffs
  - Baseline plasma: 0.3 MA, moderate pressure
- Status / findings:
  - At least two upper coils needed
  - High A-t needed to keep X-point in vacuum vessel
  - Triplet akin to configuration ‘B’ preferred
- Next steps:
  - Engineering / manufacturing feasibility
  - Optimize (minimize) required power systems
  - Verify compatibility with CHI



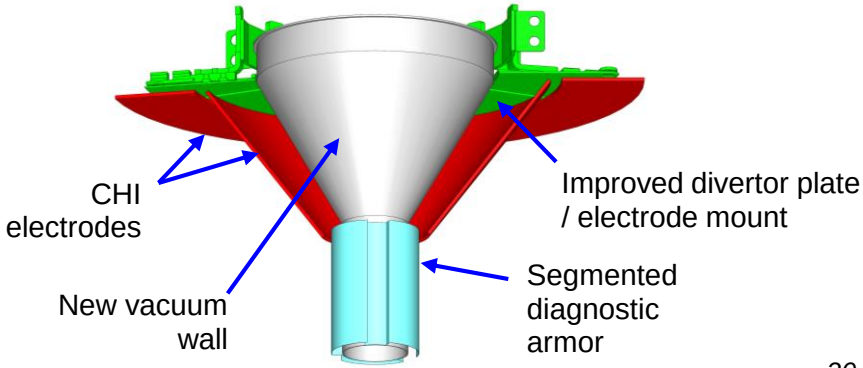
Significant In-Vacuum Machine Modifications Planned for URANIA

- New center-stack vacuum wall
  - Core and internal diagnostics to be added to wall
    - Operational diagnostics
    - Equilibrium reconstructions
    - MHD activity
    - Improve coverage in x-point and CHI regions
- New divertor / CHI electrode plate structure
- New core diagnostic armor
  - Segmented design easily accommodates changes
- Design to be finalized after diagnostic and divertor coil designs are complete

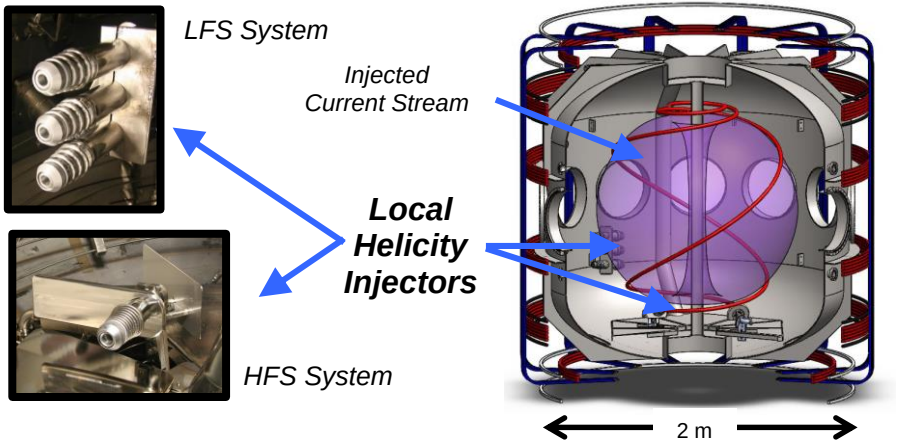
PEGASUS Vacuum Vessel Interior

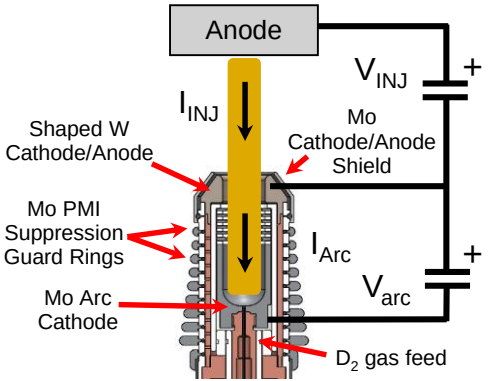


Planned Modifications for URANIA



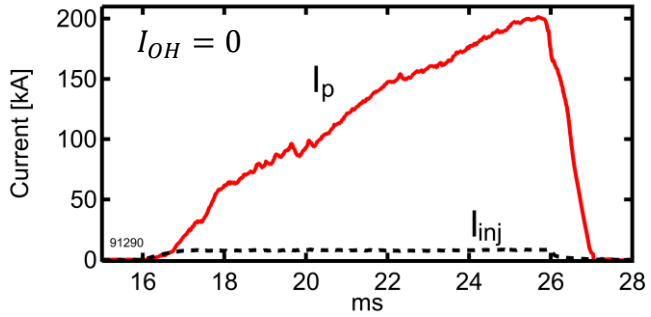
Research on the A ~ 1 PEGASUS ST Has Advanced the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup





PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.23 MA	ΣI_{inj}	≤ 14 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	= 2-4 cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

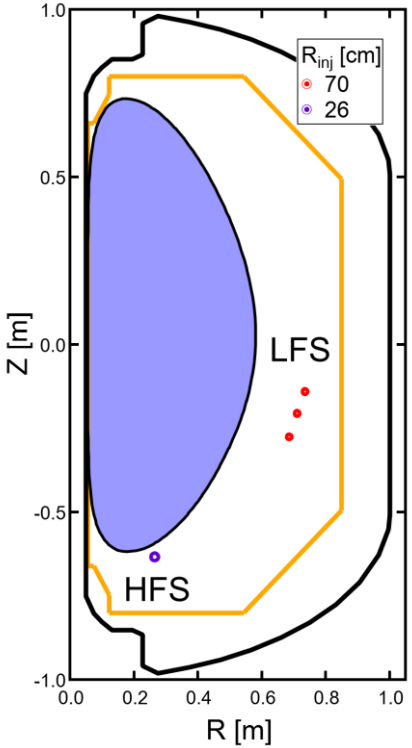
Non-Solenoidal I_p = 0.2 MA Plasma via LHI (I_{inj} ≤ 8 kA)



- LHI is promising method for solenoid-free startup
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - Global current limits from Taylor relaxation, helicity balance
  - Hardware retractable prior to nuclear phase in reactor
- Routinely used for startup on PEGASUS

Assessing Physics and Engineering Tradeoffs of Injector System Location

Location of LHI Systems, Static HFS Plasma Geometrv



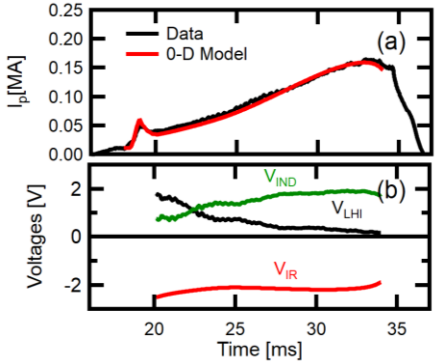
Injector System Comparisons

Quantity	LFS	HFS
N_{inj}	≤ 3	≤ 2
A_{inj}	2 cm^2	4 cm^2
R_{inj}	0.70 m	0.26 m
B_{inj}	≤ 0.08 T	≤ 0.22 T
V_{inj}	≤ 1.5 kV	≤ 1.5 kV
I_{inj}	6 kA	8 kA
P_{inj}	9 MW	12 MW
$\frac{V_{LHI}}{V_{LHI,LFS}}$	1	3.7

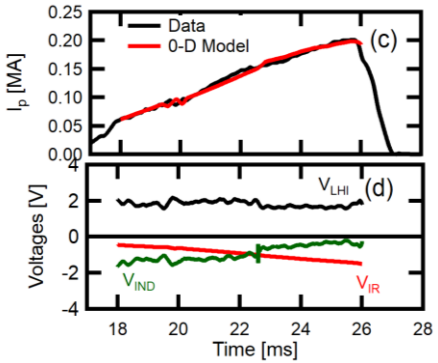




LFS: Non-solenoidal Induction



HFS: Helicity Injection



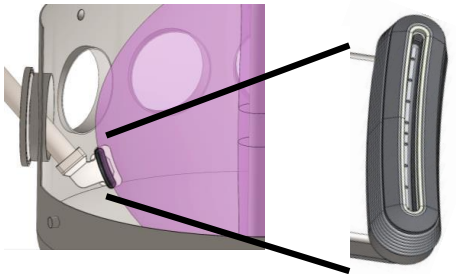
- Extrema of feasible LHI geometries deployed in Pegasus
- Low-field-side (LFS) injection
  - Injectors near outboard midplane
  - Relaxation readily achieved
  - High R_{inj} → low V_{LHI}
  - Dynamic shape → strong V_{IND}
- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Relaxation challenging
  - Low R_{inj} → strong V_{LHI}
  - Static shape → minimal V_{IND}
- I_p ~ 0.2 MA, similar T_e and n_e attained in both geometries
- Conclusion: Choice of injector location driven by practical rather than physics considerations

J.A. Reusch, EPS-DPP 2019

Next Step LHI: Physics/Engineering Requirements Make LFS Injection More Attractive, Reactor Relevant Solution

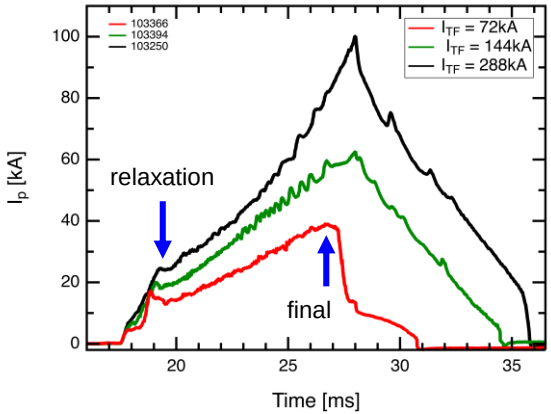
- Outboard midplane access allows fully retractable system
- Power-balance modeling: LFS LHI has extended Taylor-limited I_p phase
  - Suggests strong I_p gains possible by increasing I_{TL} early in time
- B_T scan experiments on PEGASUS support this
  - Increase of < 20 kA at relaxation results in > 60 kA final
- URANIA will have 4x increase in B_T to raise I_{TL}

Next Step LFS LHI System

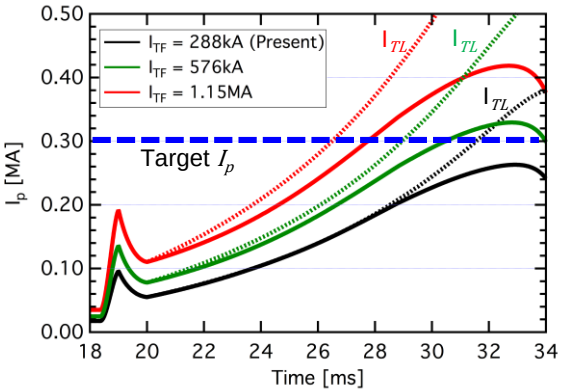


High $A_{inj} = 16\text{cm}^2$
High $I_{inj} = 16\text{kA}$
Low $w = 1\text{cm}$
Low $V_{inj} < 1\text{kV}$

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

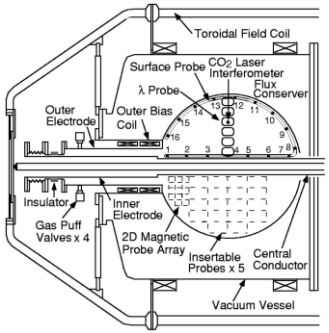


0-D $I_p(t)$ Power-Balance Projections with New Injector System

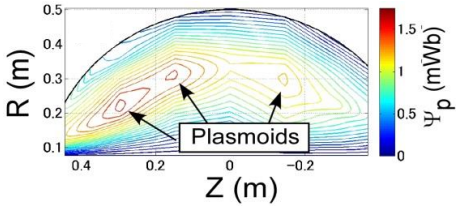


T-CHI Experiments Pursued on Several Devices Worldwide

HIST

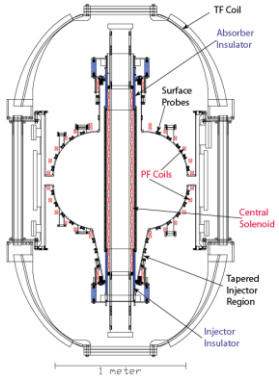


Detailed internal measurements observe plasmoid instability

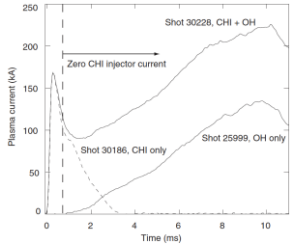


M. Nagata et al., IAEA FEC 2018, EX/P-3

HIT-II

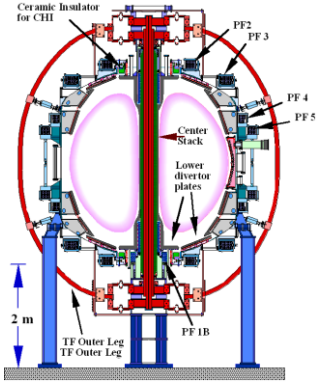


Flux Savings via T-CHI → OH Handoff

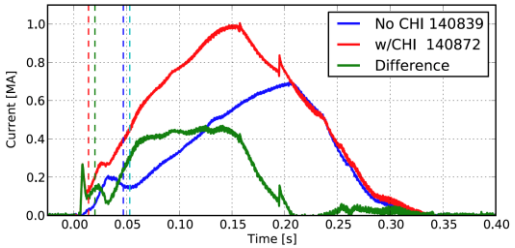


*R. Raman et al., Nucl. Fusion **45,** L15 (2005)*

NSTX

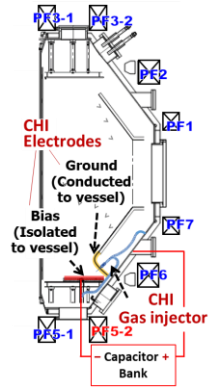


0.2 MA T-CHI Raised to 1 MA with OH

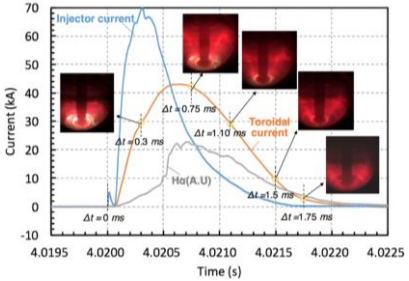


*B.A. Nelson et al., Nucl. Fusion **51**, 063008 (2011)*

QUEST



First Tests with Isolated Electrode



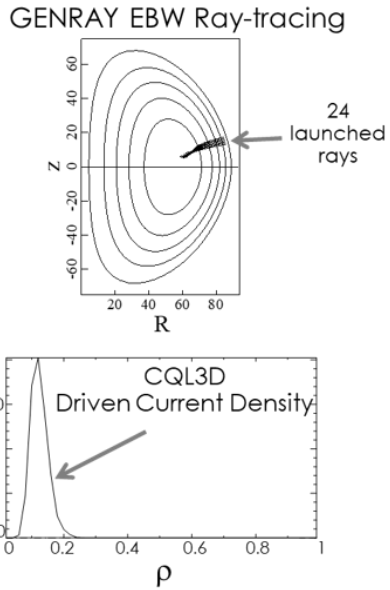
*K. Kuroda et al., PPCF **60,** 115001 (2018)*

RF Heating and Current Drive Studies Will Focus on the EBW

- Electron Bernstein waves (EBW) used successfully in STs, stellarators, and the RFP for heating and current drive

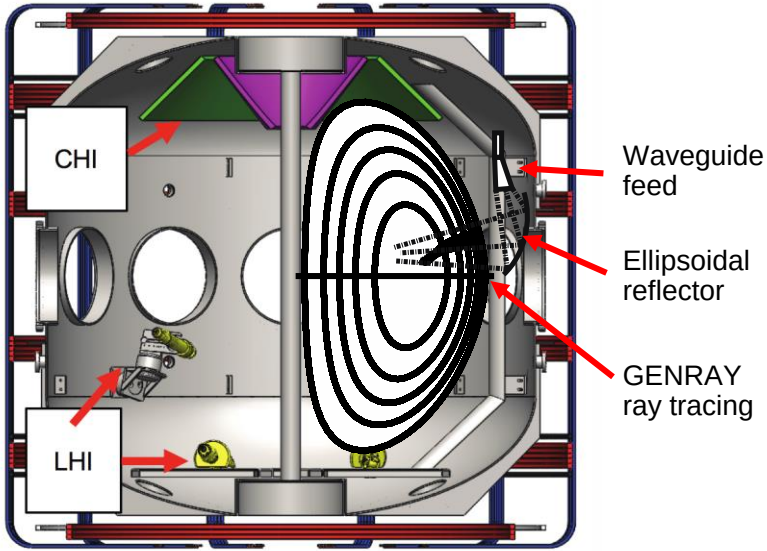
- EBW heating and current drive synergies with helicity injection:
  - Heating for increased LHI efficiency
  - T_e increase for compatibility with non-inductive sustainment (*e.g.* NBCD)
  - Potential for direct rf startup
  - Efficiency and localization
  - EBW CD as potential handoff tool

- ORNL collaboration team (Diem (PI), Bigelow, Lau)
  - Loan agreement for the 8 GHz, 500 kW FTU system from Frascati in progress



Port Access is Favorable for Exploring Launcher Designs

- Flexibility in launcher design and access
  - Compatibility with HI systems
  - Off-midplane launch allows current profile control
- Preliminary concept incorporates:
  - Upper port for waveguide access
  - Midplane port for ellipsoidal reflector
- ORNL will provide modeling, hardware expertise, and operations support
  - Determine optimal launch location considering heating and current drive needs



END