Non-Solenoidal Startup Research Directions on the Pegasus Toroidal Experiment

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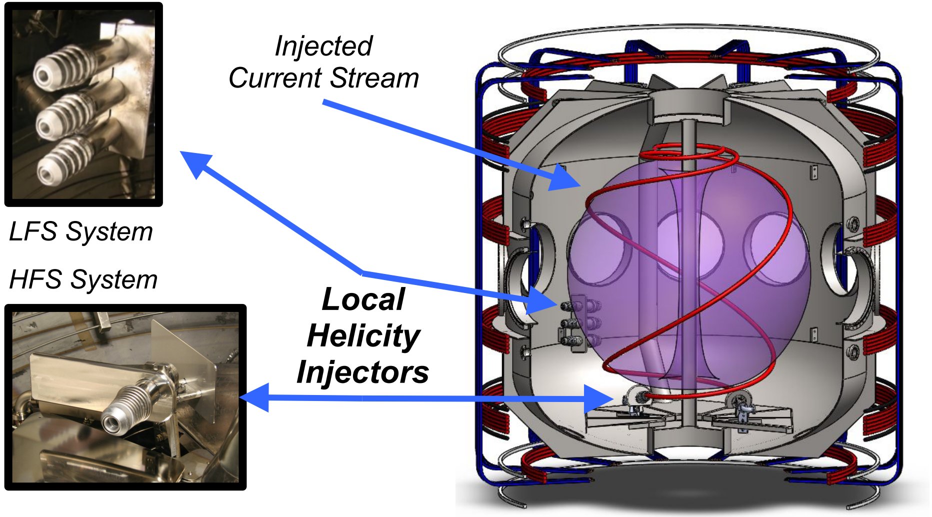
University of Wisconsin-Madison

59th Annual Meeting of the APS Division of Plasma Physics
Milwaukee, WI

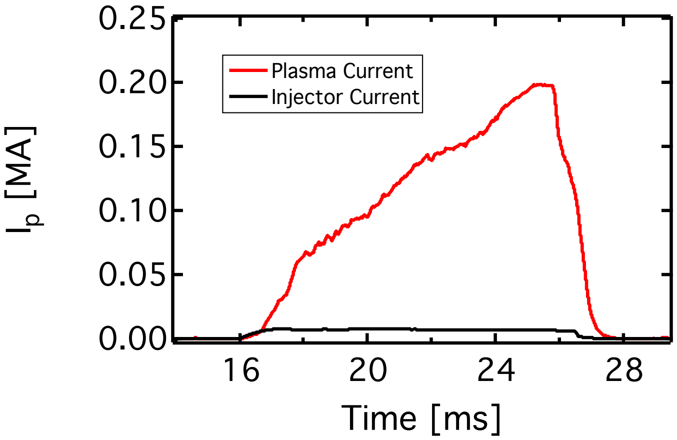
26 October 2017

PEGASUS Toroidal Experiment

Local Helicity Injection is a Promising Non-Solenoidal Startup Technique



Non-Solenoidal, High $I_p \leq 0.2$ MA ($I_{inj} \leq 8$ kA)



- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

- Current drive quantified by

$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}$$

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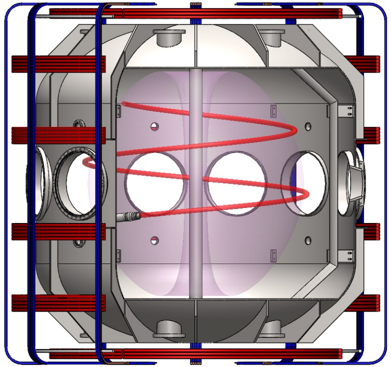
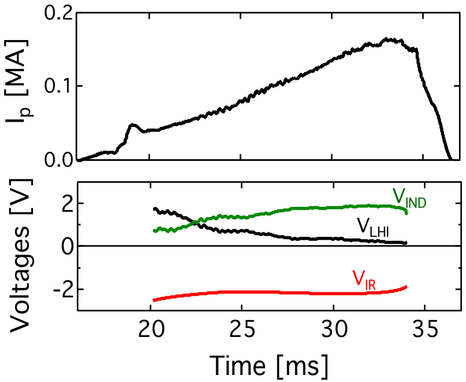
Injector Geometries Emphasize Different Current Drives

Low-Field-Side Injection:

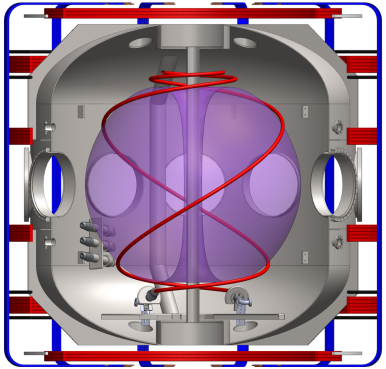
- Dynamic shape → strong V_{IND}

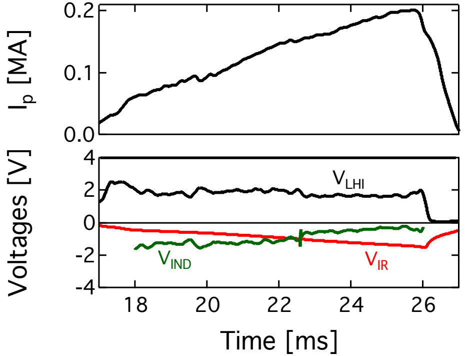




High-Field-Side Injection:

- Static shape → minimal V_{IND}





- Geometry choice impacts potential for scaling to fusion scale
  - Type and localization of heating; transport differences
  - Different facility and technical requirements
- "Taylor Limit" for ultimate I_p applicable to both $I_{TL} \sim \sqrt{\frac{I_{TF} I_{INJ}}{w_{INJ}}}$

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Path to High I_p Depends on Choice of LHI Injector Geometry

LFS (~ midplane)

- Increase Taylor limit in first half of discharge
  - Increase $I_{TF}, \frac{I_{INJ}}{W_{INJ}}$
- Increase A_{INJ}, lower V_{INJ}
  - Location allows for larger Injector Area
  - Mitigate PMI
- Plasma position and shape control challenges
  - Maintain coupling to guns
  - Geometry evolution sets inductive drive

HFS (divertor)

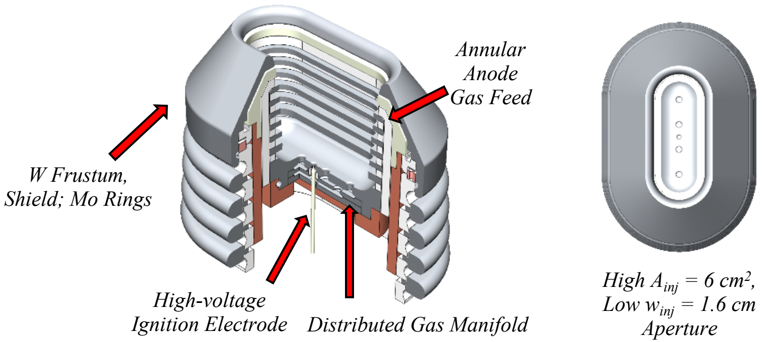
- Decrease R_{INJ}
  - $V_{LHI} \sim \frac{1}{R_{INJ}}$
- Increase A_{INJ}, V_{INJ}
  - More engineering challenges
  - Increased V_{INJ} increases PMI
- Improved performance at increased TF?
- $V_{LHI}(t)$ control for $I_p(t)$ path optimization

APPROACH: Demonstrate scaling to higher I_p through injector and facility enhancements

Access to Higher I_p: Taylor Limit Increase Early in LFS Discharges

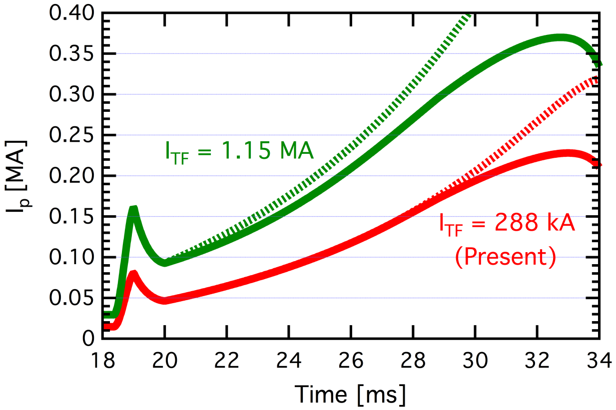
- LFS discharges experience an extended Taylor-limited I_p phase
  - Increase $I_p(t)$ through increase in TL during first half of discharge
- Increase Taylor limit through injector design and/or facility modifications
  - $I_{TL} \sim \sqrt{\frac{I_{TF} I_{INJ}}{w_{INJ}}}$
- Access to high I_p with reduced V_{inj}
  - Mitigates PMI
- **Increase A_{inj}, I_{TF}**; decrease w_{inj}, V_{inj}

Non-Circular, High-A_{inj} Helicity Injector Renderings



0-D Power-Balance Projections of $I_p(t)$:

A_{inj}= 8cm^2, V_{inj} = 1 kV, I_{inj} = 16 kA , W_{inj} = 2.83 cm

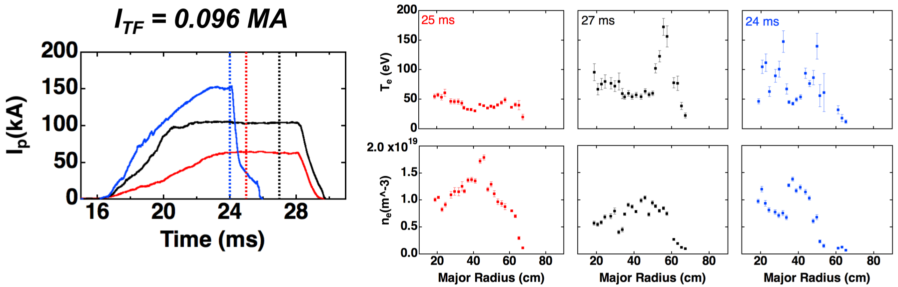


Several Issues Need Addressing to Scale LHI Startup to Larger Fusion Experiments or Facilities

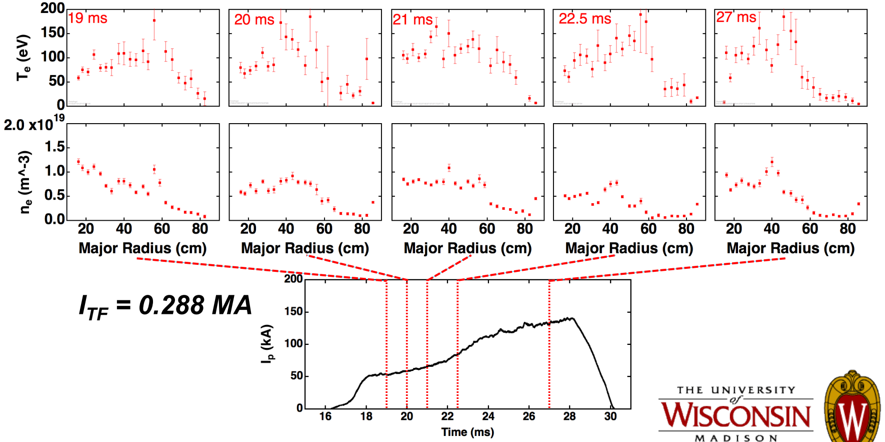
- **Establishing LHI Physics Basis**
  - PMI & impurities
  - **Heating, confinement scaling**
  - MHD & CD mechanism
  - Predictive $I_p(t)$ model
  - Discharge evolution, optimization
  - **B_T effects on PMI & MHD**
  - Compatibility with heating and sustainment techniques

- **Technology Issues also arise**
  - Compatibility with PF, divertor systems
  - Large-area, conformable injector systems
  - Injector development for low V, high B_T operation
  - Power system requirements

HFS LHI at low B_{TF} typically show low $T_e(0)$ and Hollow $T_e(R)$



HFS LHI at max B_{TF} indicates increasing $T_e(0)$ and Peaked $T_e(R)$



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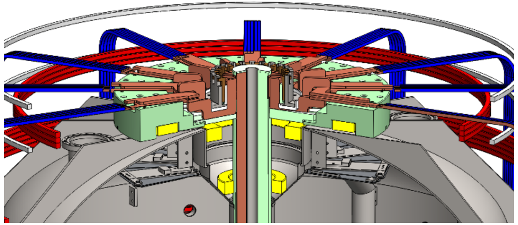
LHI Research on PEGASUS-E CanTest Critical Scalings

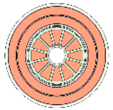
- **Physics Issues**
  - Increased I_p access demo
  - Efficiency / confinement scaling
  - Relaxation accessibility
  - MHD behavior & CD mechanisms
  - PMI and impurities
  - Advanced injector technology
    - Increased drive & Taylor limit

- **Facility Enhancements**
  - 24-turn TF rod; power system
  - Programmable $V_{LHI}(t)$ control
  - PF coils and power systems
    - X-point, shape control
  - DNB spectroscopy
    - $\tilde{B}(R,t)$, $J(R,t)$, $T_i(R,t)$, $n_e(R,t)$, $n_Z(R,t)$
  - Impurity diagnostics
    - SPRED, VB, bolometry

Parameter	PEGASUS	PEGASUS-E
R_{sol} [cm]	4.9	N/A
I_{sol} [kA]	$\pm$ 24	0
ψ_{sol} (mWb)	40	0
N_{TF}	12	24
$N_{TF} \times I_{TF}$	0.288 MA	1.15 MA
$B_{T,max}$ [T] at $R_0 \sim 0.4$ 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

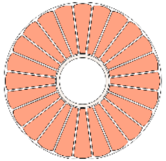


PEGASUS

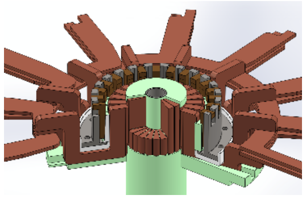


High-Stress OH Solenoid
12-turn TF Bundle

PEGASUS-E



Solenoid-free
24-turn TF Bundle



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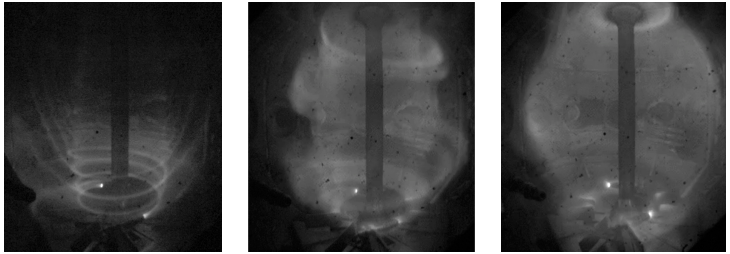
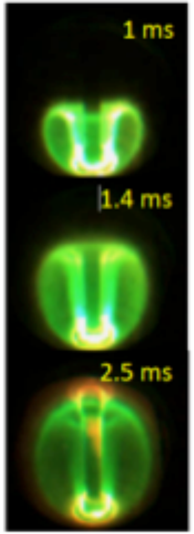
Non-Solenoidal Startup Remains a Critical Need for Spherical Tokamak, and May Benefit AT

- PEGASUS research program has focused on LHI
  - Local DC helicity injection + poloidal field induction
  - Questions remain for projection to larger fusion scale
  - Need enhancements to test scalability of LHI to larger scale
- Need for dedicated NS startup studies
  - Technique, technology development requires extended operational time
  - Hardware and physics development
  - Impact on other research programs at facility
    - Run time, interfering hardware during development
    - Machine conditioning, impurity status, etc.
- Enhancements to Pegasus can provide a dedicated development station for non solenoidal startup

Pegasus HFS LHI



$I_p \sim N_{turns} I_{inj}$ $\quad$ $I_p \gtrsim N_{turns} I_{inj}$ $\quad$ $I_p \gg N_{turns} I_{inj}$



NSTX Transient CHI

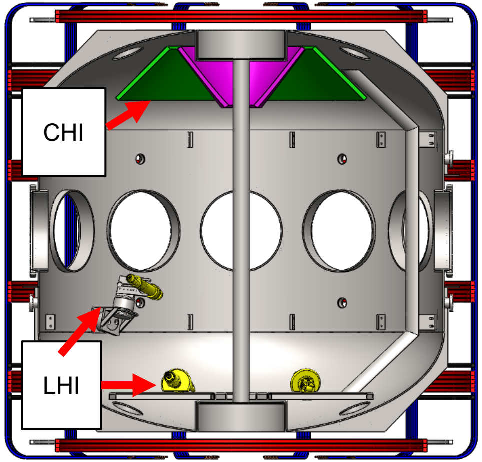
RF Startup Experiments

RF Method	Device	I_p [kA]	Δt_{pulse} [ms]	Reference
ECH + PF induction	DIII-D	166	50	[15]
	JT60-U	100	500	[22]
ECH	QUEST	70	1,500	[17]
	DIII-D	33	50	[23]
	KSTAR	15	1,800	[24]
ECH + LHCD	T-7	20	175	[25]
EBW	MAST	73	450	[16]
	LATE	15	80	[17,26]
LH	PLT	100	2,500	[27]
	TST-2	25	70	[17,28]
	GLOBUS-M	21	140	[29]

PEGASUS-E Proposed as US Non-Solenoidal Development Station

- **Evaluate leading concepts for non-solenoidal startup in single dedicated facility**
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - RF (ECH, EBW, ECCD) startup and assist
  - Poloidal Feld Induction
  - Neutral Beam CD (future)
- **Develop common understanding & validation of all approaches**
  - Compare T_e, n_e, Z_{eff}, $J(r)$, usable I_p, impurities
  - CD mechanisms and scalability
  - Power & engineering requirements
- **Goal: develop validated concept, equipment for ~ 1 MA startup on NSTX-U and beyond**
  - Integrate features of all concepts, as appropriate
  - "Plug and Play" installation for minimal impact and costs

$B_T \leq 0.9T$; Multi-coil Divertor
No OH solenoid



Collaborative Enterprise:

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UNIVERSITY of WASHINGTON
OAK RIDGE National Laboratory
PPPL
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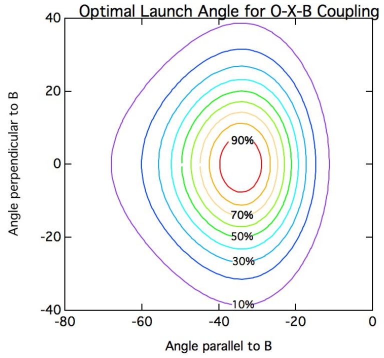
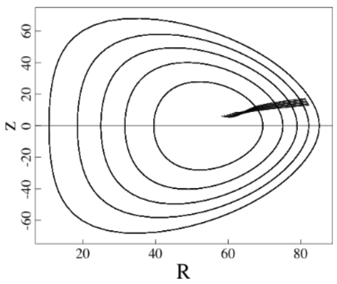
High-B_T of PEGASUS-E Facilitates RF/EBW

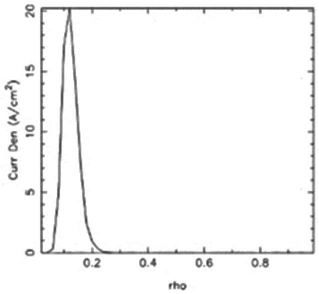
- EBW heating and CD; synergy with HI
  - Heating for increased LHI efficiency
  - T_e increase for compatibility with non-inductive sustainment (e.g. NBCD)
  - Potential for direct RF startup
  - Launcher design and access
  - Efficiency & Localization
  - EBW CD as potential handoff tool
  - Initial concept: ~ 400 kW EBW RF, 9 GHz (TBD)
  - Collaboration w/ ORNL

Favorable wide range of injection angles for O-X-B



GENRAY, CQL3D Modeling Indicates Core Absorption for EBW Heating, CD

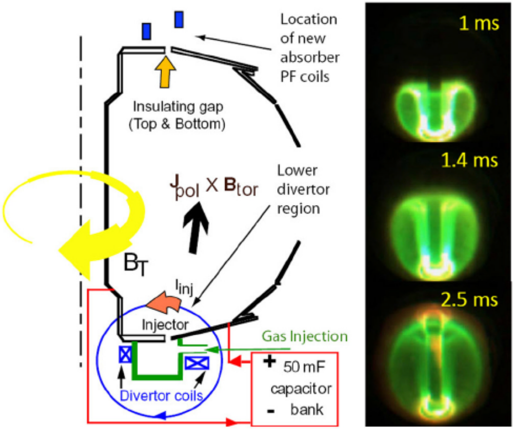




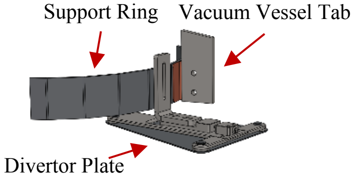
High-B_T of PEGASUS-E Facilitates CHI Studies

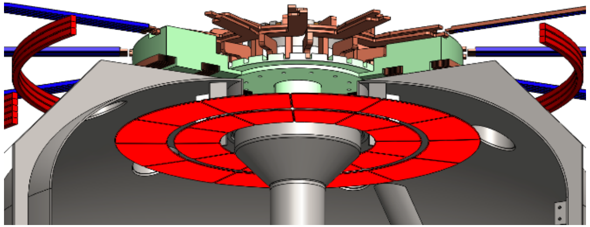
- Deploy "simple" CHI systems
  - Flexible, segmented floating electrodes
  - Transient CHI scaling (large seed flux)
  - Sustained CHI scaling
  - Demonstrate access to predictable high I_p
  - Impurity mitigation
  - Add RF/EBW heating to raise $T_e(R,t)$
  - Consider active (LHI-like) electrodes
  - Collaboration w/U. Washington, PPPL

Transient CHI on NSTX:



Pre-Conceptual Segmented CHI Electrode Concept on Pegasus-E





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Broadening Studies of Non-Solenoidal Startup on PEGASUS and PEGASUS-E

- Local Helicity Injection provides non-solenoidal startup and sustainment
  - Injection geometry balances V_{LHI} and V_{IND} drive, engineering constraints
  - Appears scalable to large scale; questions on confinement, reconnection dynamics and B_T scaling

- Present understanding suggests advantages to LFS, near-midplane injection
  - Added PF induction and Lower relaxation constraints
  - Nonlinear advantage from increased Taylor limit at early time
  - Path to decreased V_{inj}, increased A_{inj} in injector design
  - Continue HFS examination

- PEGASUS-E: Proposed US integrated non-solenoidal R&D facility
  - LHI, RF, CHI, Induction startup at $B_T > 0.5$ T
  - Projection to NSTX-U and beyond

Details on Local Helicity Injection Studies in Poster Session

Poster session: UP, Thursday PM:

- M.W. Bongard UP11.00085 — Non-Solenoidal Startup via Helicity Injection in the Pegasus ST
- C.M.B. Pierren UP11.00086 — Enhanced Control for Local Helicity Injection on the Pegasus ST
- G.M. Bodner UP11.00087 — V_{eff} Scaling of T_e and n_e Measurements During Local Helicity Injection on the Pegasus Toroidal Experiment
- N.J. Richner UP11.00088 — Investigating High Frequency Magnetic Activity During Local Helicity Injection on the Pegasus Toroidal Experiment
- C. Rodriguez Sanchez UP11.00089 — Studies of Impurities in the Pegasus Spherical Tokamak
- D.R. Smith UP11.00090 — Microstability Properties of the Local Minimum |B| Regime in Pegasus
- A.T. Rhodes UP11.00091 — Initial Measurements of Electrostatic Turbulence in Local Helicity Injection Plasmas
- J.L. Pachicano UP11.00092 — High-Field-Side MHD Activity During Local Helicity Injection
- M.G. Burke UP11.00093 — Progress Towards a New Technique for Measuring Local Electric and Magnetic Field Fluctuations in High Temperature Plasmas
- J.D. Weberski UP11.00098 — Power Balance Modeling of Local Helicity Injection for Non-Solenoidal ST Startup