URANIA: A Dedicated Spherical Tokamak Experiment for Developing Non-Solenoidal Plasma Startup Techniques

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URANIA Experiment

Layout

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

URANIA: A Dedicated Spherical Tokamak Experiment for Developing Non-Solenoidal Plasma Startup Techniques

The URANIA Experiment	Local Helicity Injection	Magnet Engineering	Injector / Power Engineering	CHI and EBW Systems	Diagnostic Systems
URANIA is a Modification of the PEGASUS Experiment	LHI is a Promising Method for Solenoid-Free Startup	Heart of the Facility Enhancement Is A New TF Assembly	LHI Source Development Confirms Active Arc Injector Preferred	CHI Produces High-Ip Plasmas with Axisymmetric Electrodes	Significant In-Vacuum Machine Modifications Planned for *URANIA*
URANIA: Comparative Study of Solenoid-Free Startup Techniques	Physics Models Contribute to the Understanding of LHI	TF Magnet is Being Upgraded for 4x Field and Pulse Length	URANIA LHI System Will Use Next-Generation Current Injectors	Two-Electrode CHI System to be Implemented on URANIA	Diagnostic Neutral Beam Commissioning is Underway
Non-Solenoidal Startup Critical Need for the Spherical Tokamak	Higher Toroidal Field Increases Taylor Limit, Achievable I_p	Initial Stress Analysis Acceptable for 4x B_T Operation	Existing Power Systems Will Be Updated for URANIA Operation	RF Heating and Current Drive Studies Will Focus on the EBW	Conceptual Design for Expanded URANIA Diagnostic Suite
Several Solenoid-Free Startup Techniques Pursued Globally	LHI Provides Access to Unique ST Operating Space	TF Assembly Structure Accommodates New Divertor Coil Set	Significant Facility Changes Planned for Expanded Capabilities	Port Access is Favorable for Exploring Launcher Designs	Upgrades to Control and Data Acquisition Systems Underway

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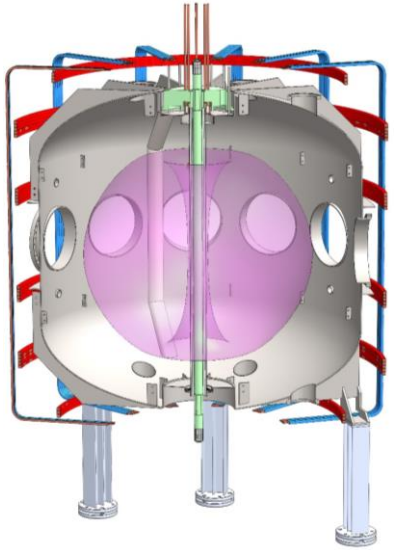
The URANIA Experiment

Dedicated ST for Developing Non-Solenoidal Startup Techniques

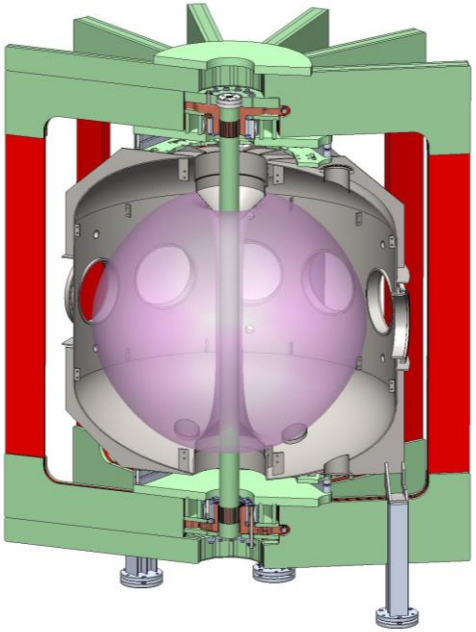
URANIA is a Modification of the PEGASUS Experiment

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

PEGASUS



URANIA



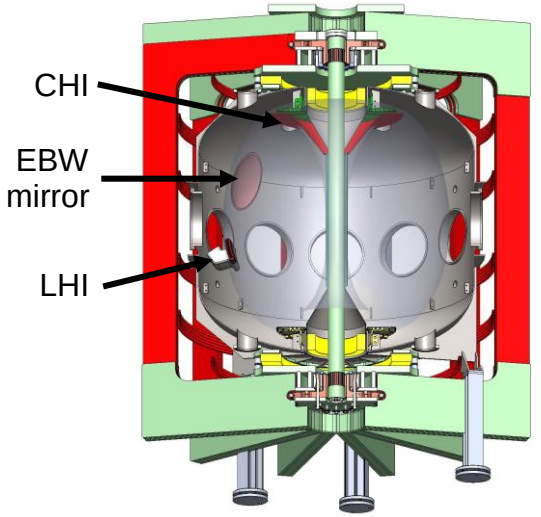
Parameter	PEGASUS	URANIA
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50-100
ΔT_{bundle}	< 10°C	< 20°C
R_0 [cm]	45	45
A	1.15–1.3	1.18–1.35

URANIA: Comparative Study of Solenoid-Free Startup Techniques

- Goal: guidance for ~1 MA startup on NSTX-U and beyond

- Evaluate concepts for non-solenoidal startup in single dedicated facility
  - Local helicity injection
  - Transient & Sustained coaxial helicity injection (with University of Washington, PPPL)
  - EBW rf heating & CD (with ORNL, PPPL)
  - Poloidal induction
  - NBCD, *etc.* in the future

$B_T \leq 0.6$ T; Multi-coil Divertor
No OH Solenoid



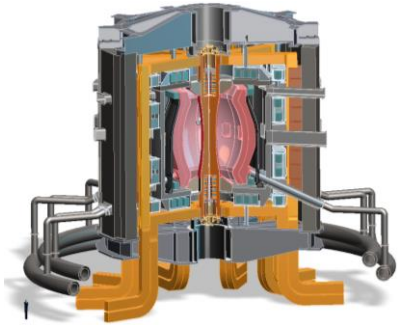
Collaborative Enterprise

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
UNIVERSITY of WASHINGTON
OAK RIDGE National Laboratory
PPPL

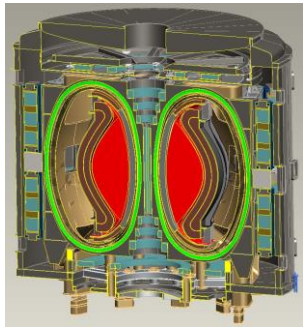
Non-Solenoidal Startup Critical Need for the Spherical Tokamak

- Reactor-class tokamaks minimize the need for inductive sustainment from an Ohmic solenoid
  - Pulse lengths: O(month → year); startup: O(minute)
  - OH for plasma initiation and ramp-up
- Instead, such devices must be sustained non-inductively
  - Self-generated bootstrap current
  - Auxiliary NBI, rf current drive
- Spherical tokamaks (A < 2) place strong constraints on available solenoid flux due to device geometry
  - Nuclear ST designs preclude OH solenoid due to shielding & cost
  - Small solenoid considered as fallback; insufficient for I_p ramp-up
- Solenoid-free startup and ramp-up techniques needed

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



Solenoid-free
Cu ST-FNSF



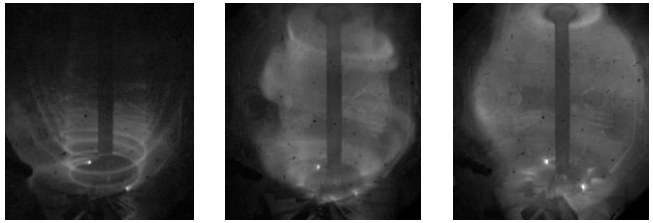
No / small OH
HTS
ST-FNSF / Pilot Plant

J.E. Menard et al., Nucl. Fusion ***56,*** *106023 (2016)*

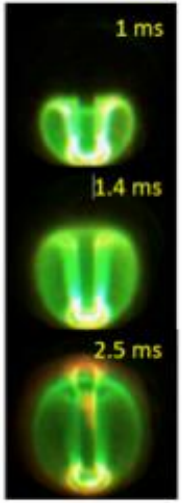
Several Solenoid-Free Startup Techniques Pursued Globally

- Multiple methods have shown promise
  - Local helicity injection (LHI)
  - Coaxial helicity injection (CHI)
  - Radiofrequency plasma initiation, heating, and current drive
  - Poloidal field induction
  - Neutral beam current drive
- A dedicated research program can address challenges in a timely manner
  - Technique & technology development requires operational time
  - Hardware and physics development
  - Avoids impact on other research programs at facility
    - Run time, interfering hardware during development, *etc.*
    - Machine conditioning, impurity status, *etc.*

PEGASUS HFS LHI



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



NSTX Transient CHI

RF Startup Experiments

RF Method	Device	I_p [kA]
ECH + PF induction	DIII-D	166
	JT60-U	100
ECH	QUEST	70
	DIII-D	33
	KSTAR	15
ECH + LHCD	T-7	20
EBW	MAST	73
	LATE	15
LH	PLT	100
	TST-2	25
	GLOBUS-M	21

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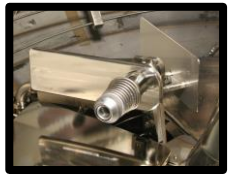
Local Helicity Injection

LHI is a Promising Method for Solenoid-Free Startup



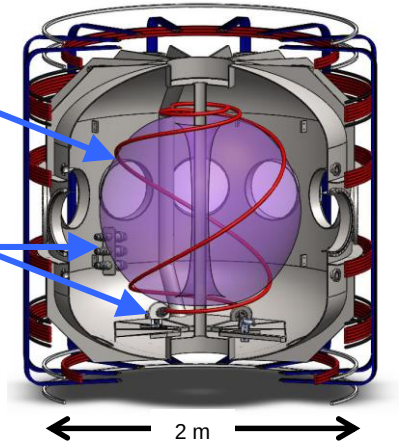
LFS System

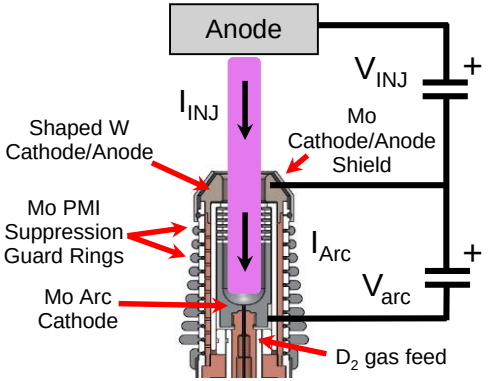
Injected Current Stream



HFS System

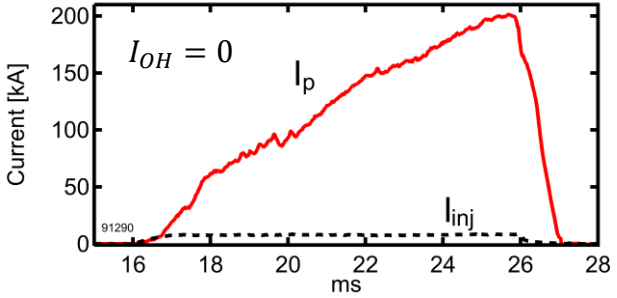
Local Helicity Injectors





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

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



- Routinely used for startup on the A ~ 1 PEGASUS ST
  - Current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities

- Global current limits from:

Taylor relaxation

$$I_p \leq I_{TL} \sim \sqrt{I_{TF} I_{inj} / w}$$

Helicity conservation

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

*M.W. Bongard, et al., Nuclear Fusion **59**, 076003 (2019)*

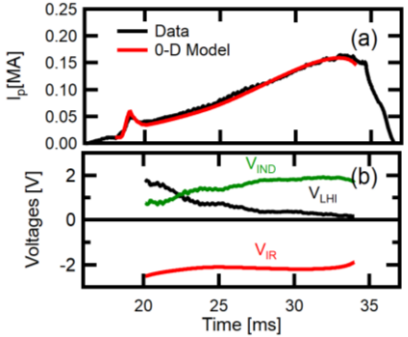
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Physics Models Contribute to the Understanding of LHI

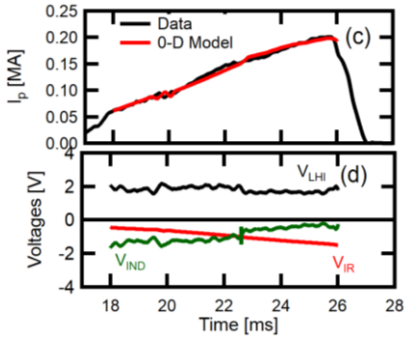
- 0-D power balance model predicts I_p(t) and quantifies contributions to current drive

$$I_p[V_{LHI} + V_{IR} + V_{IND}] = 0 \; ; I_p \leq I_{TL}$$

LFS: Non-solenoidal Induction



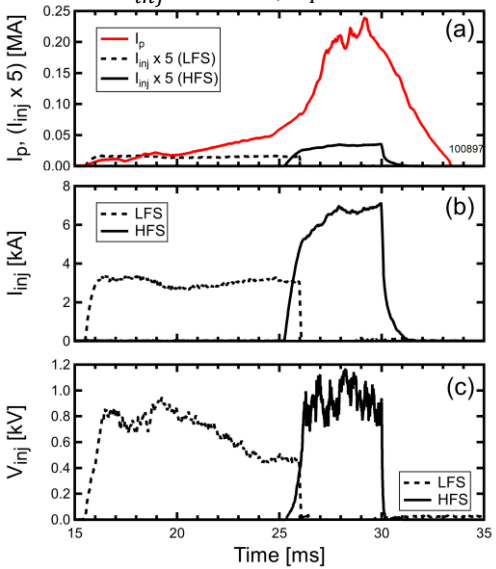
HFS: Helicity Injection



- Low-field-side (LFS) injection
  - Injectors on outboard midplane
  - High R_{inj} → weak V_{LHI}
  - Dynamic shape → strong V_{IND}
- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Low R_{inj} → strong V_{LHI}
  - Static shape → weak V_{IND}
- I_p ~ 0.2 MA attained in both geometries
  - Power supply and PMI limited

- Strengths of each geometry can be combined
  - LFS has simpler relaxation, lower PMI
  - HFS has higher V_{LHI}
  - Seamless transition between separate systems

I_p = 0.225 MA LFS → HFS LHI Startup
R_{inj} = 26 cm, B_T = 0.15 T



*J.A. Reusch, et al., Phys. Plasmas **25** 056101 (2018)*

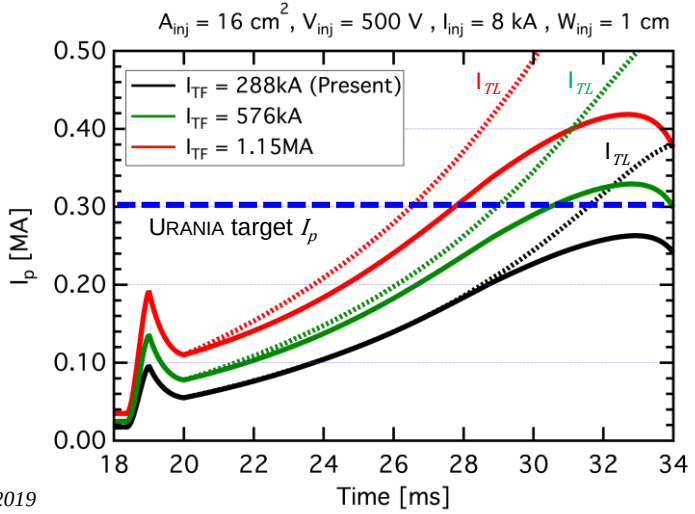
*M.W. Bongard, et al., Nuclear Fusion **59**, 076003 (2019)*

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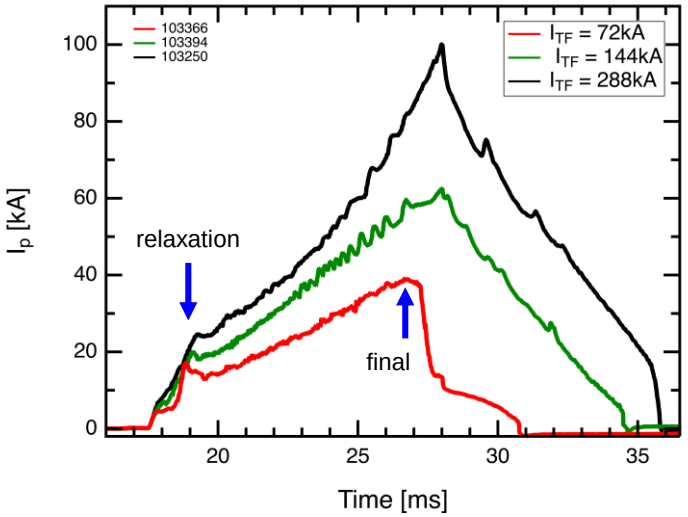
Higher Toroidal Field Increases Taylor Limit, Achievable I_p

- Power-balance modeling: LFS LHI scenarios have 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
  - (20 – 30) kA at relaxation results in (30 - 100) kA

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

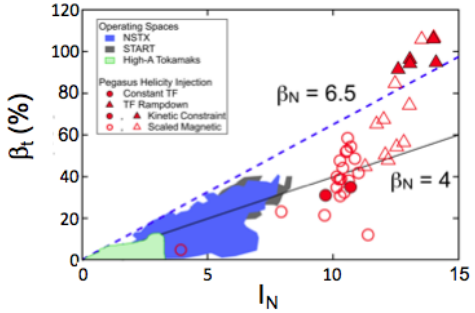


PEGASUS Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



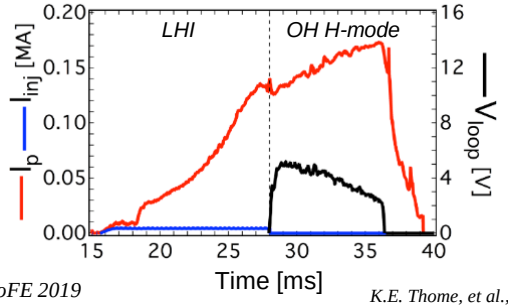
LHI Provides Access to Unique ST Operating Space

- LHI allows access to novel physics
  - β_t ~ 1 readily achieved
  - Minimum |B| well observed



*D.J. Schlossberg, et al., PRL **119**, 035001 (2017)*

- Volt-sec savings from LHI startup can be used for high performance plasmas

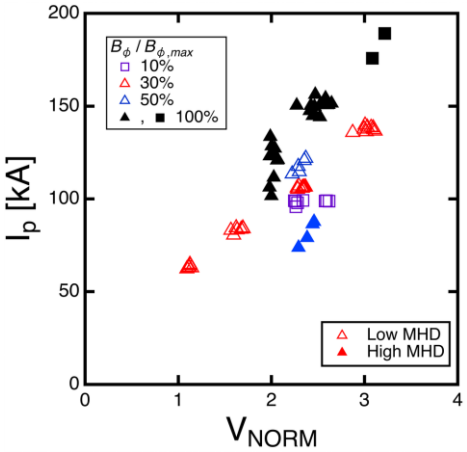


J.A. Goetz, SoFE 2019

*K.E. Thome, et al., NF **57** (2017)*

Outstanding issues for LHI still exist

- Scaling to high I_p
  - Larger size, high B_T, longer pulse
- Handoff to other non-inductive CD
  - LHI → OH H-mode demonstrated
- Confinement, impurities, & dissipation during LHI
- LHI current drive mechanism



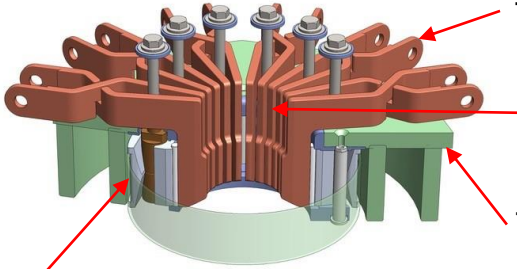
Low-B_T $I_p(V_{LHI})$ scaling indicates positive field dependence exists

Magnet Engineering

Heart of the Facility Enhancement Is A New TF Assembly

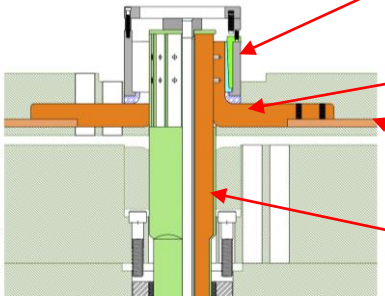
- TF based on successful PEGASUS design
  - TF bundle (centerstack)
  - Finger joints and wedge compression assembly
  - Torque frame
  - Outer return leg assembly
  - Space for divertor coils

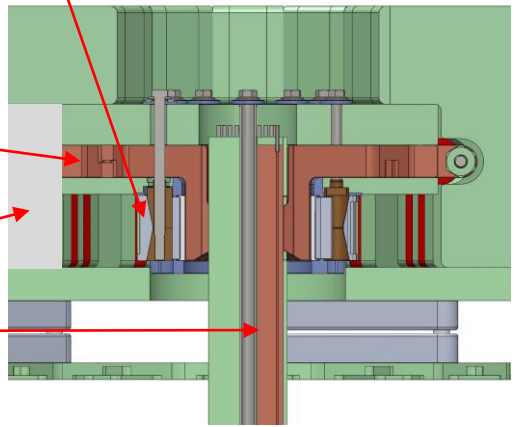
Fingers and compression assembly



Compression provided by band & wedges

PEGASUS



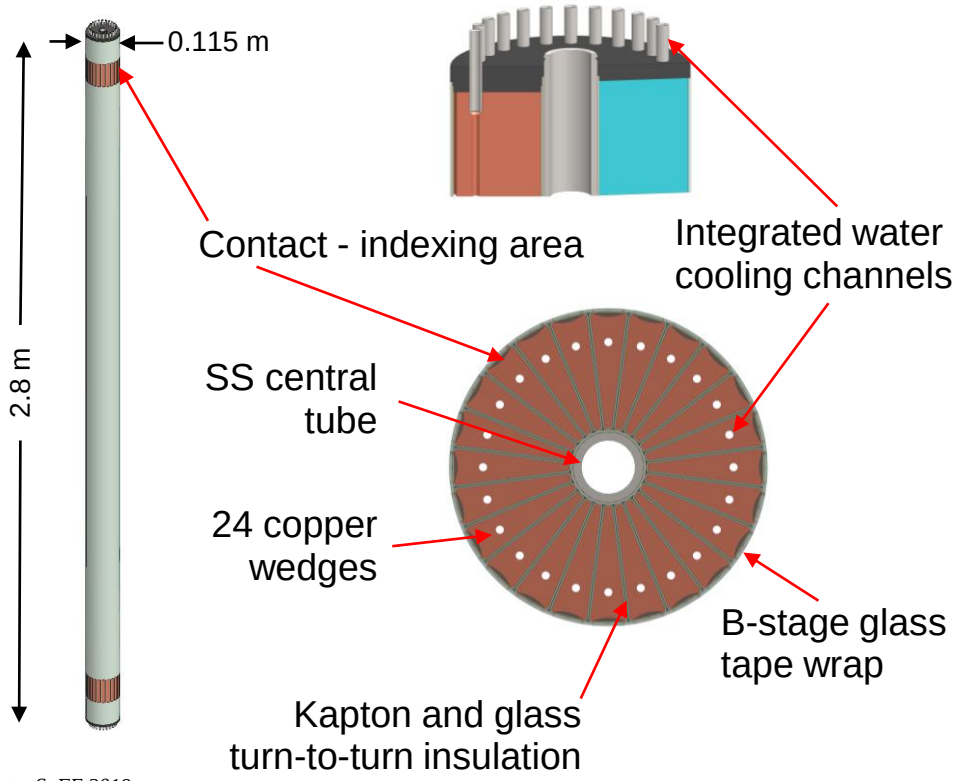


URANIA

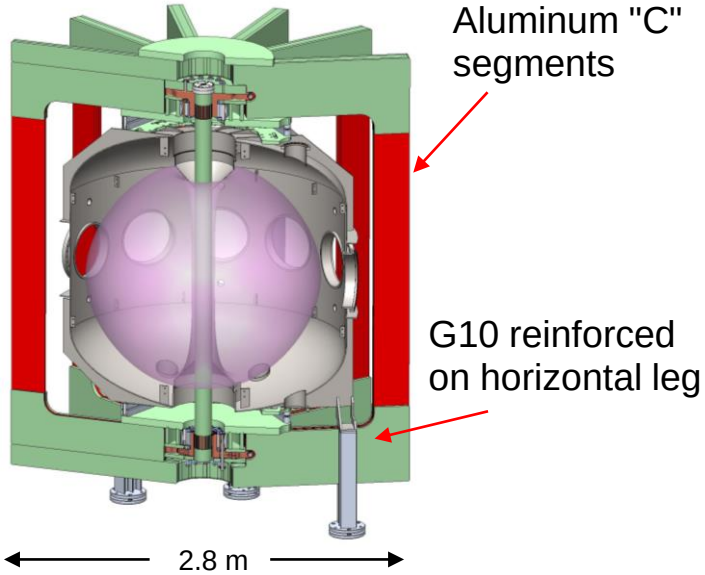
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TF Magnet is Being Upgraded for 4x Field and Pulse Length

TF centerstack



TF outer return legs



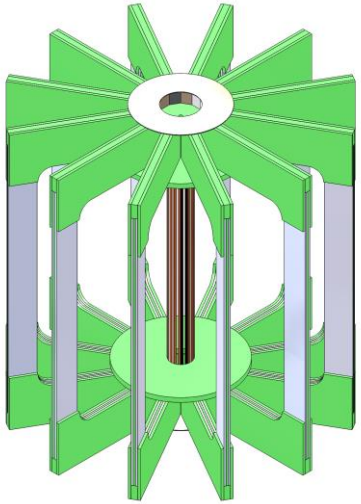
- TF centerstack fabrication in progress

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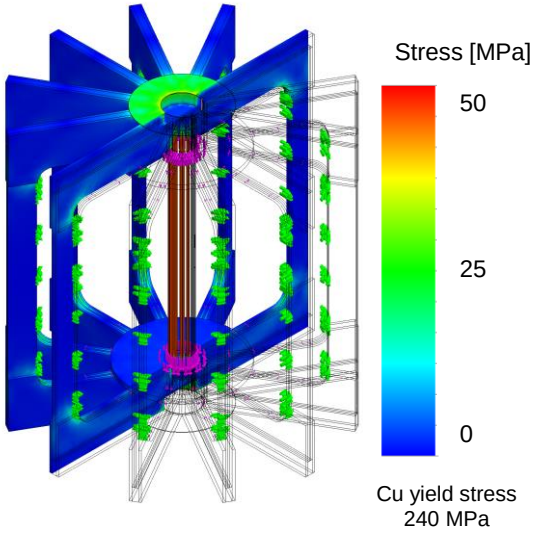
Initial Stress Analysis Acceptable for 4x B_T Operation

- 4x B_T operation results in 16x 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

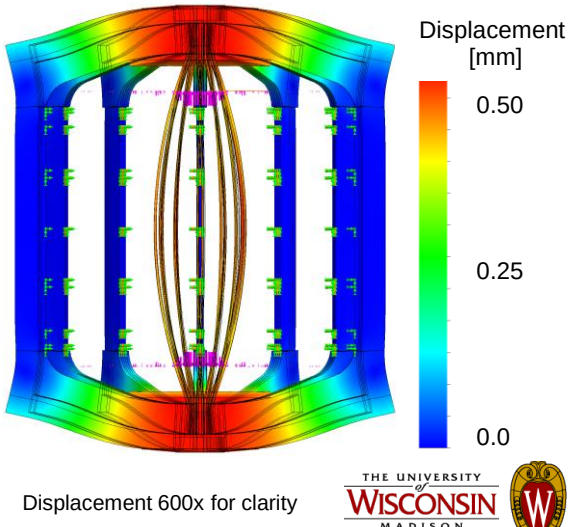
Simplified URANIA model



Magnetic stress distribution



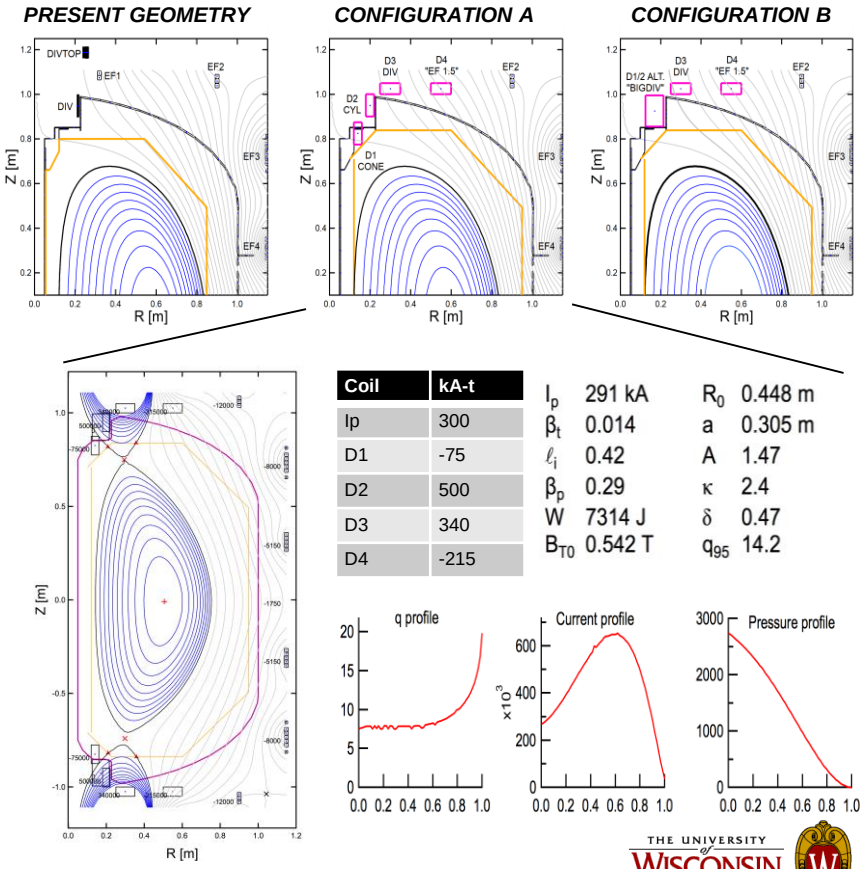
Expansion stress deformation



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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



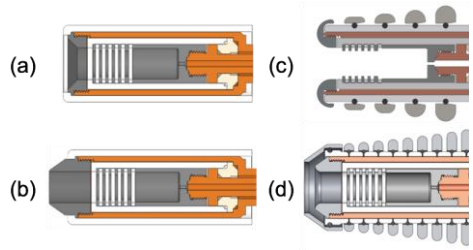
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Injector / Power Engineering

LHI Source Development Confirms Active Arc Injector Preferred

- Helicity injector source design criteria
  - I_{inj} and w set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$ to attain/sustain I_p
  - Armoring, limiters to minimize PMI
- Injector system geometry constraints
  - Provide initial relaxation via near-PF null
  - Conformal to desired plasma shape
  - Port access
- Cathode, shield ring features evolved to limit PMI
  - Concave → convex cathode: cathode spot control (PMI)
  - Shield rings, frustum shield: reduce PMI frequency



- Shaped electrode sources evaluated

Passive



High I_{inj}

$A_{inj} << A_{elec}$

high PMI

Active gas-fed



High I_{inj}

$A_{inj} \leq 10\% A_{elec}$

high PMI

- Active arc sources maximize V_{inj}, minimize PMI



V_{inj} ~ 400 V

high PMI



V_{inj} ~ 1000 V

medium PMI



V_{inj} ~ 2000 V

low PMI

J.A. Goetz, SoFE 2019

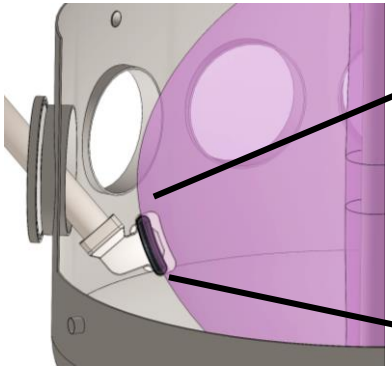
M.W. Bongard, et al., Nuclear Fusion ***59****, 076003 (2019)*

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URANIA LHI System Will Use Next-Generation Current Injectors

- PEGASUS has shown LFS LHI is favored geometry
  - Port-mount design avoids high heat flux of divertor region
  - Strong non-solenoidal inductive drive
- Increase I_{TL} via injector improvements, higher B_T
- New large-area, active, shaped injector (Kama) in development to optimize Taylor, helicity balance limits
  - High I_{inj}, narrow width → high I_{TL}
  - Large area, modest V_{inj} → high helicity input and reduced PMI
- Kama injector fabrication underway
  - Validation needed in PEGASUS
- Dynamic injector impedance control (future)
  - Voltage programmable power supply
  - Analog control of arc fueling rate

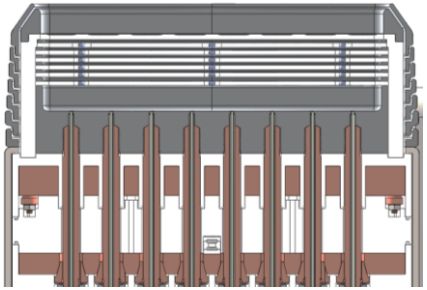
Mockup of Kama assembly



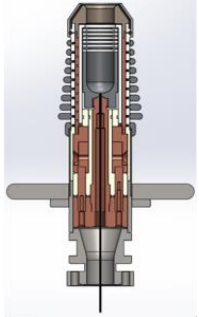
Advanced 16 cm² Kama Injector



Kama internal cutaway

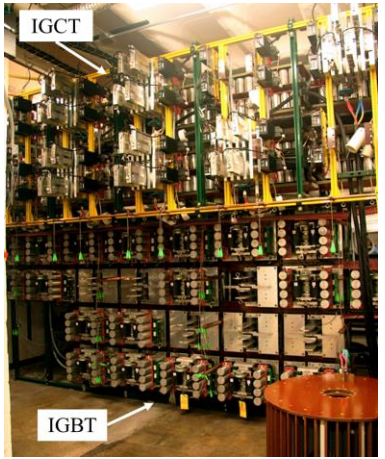


Present injector (4 cm²) installed in divertor region

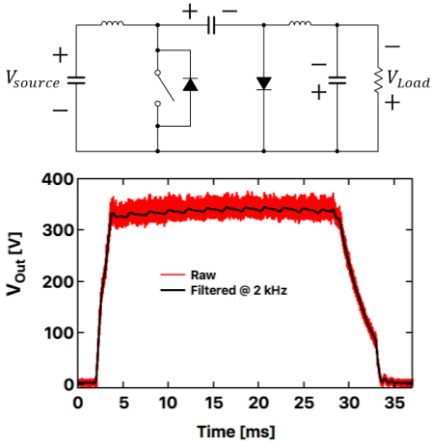


Existing Power Systems Will Be Updated for URANIA Operation

- Expand and reconfigure available stored energy
  - Construct new 6 MJ energy farm
  - Expand charge / dump systems
- Reconfigure switching power amplifiers
  - Convert 2700V OH IGCT to TF Pre-charge
  - Reconfigure IGBT for URANIA PF & TF systems
- Develop voltage programmable 32 MVA power supply for LHI arc/bias
  - Prototype tests with Eagle Harbor Technologies
  - Internal development required following industry bids
- Field-programmable gate array technology used to modernize PS safety & control



PEGASUS Power Systems [215 MVA]



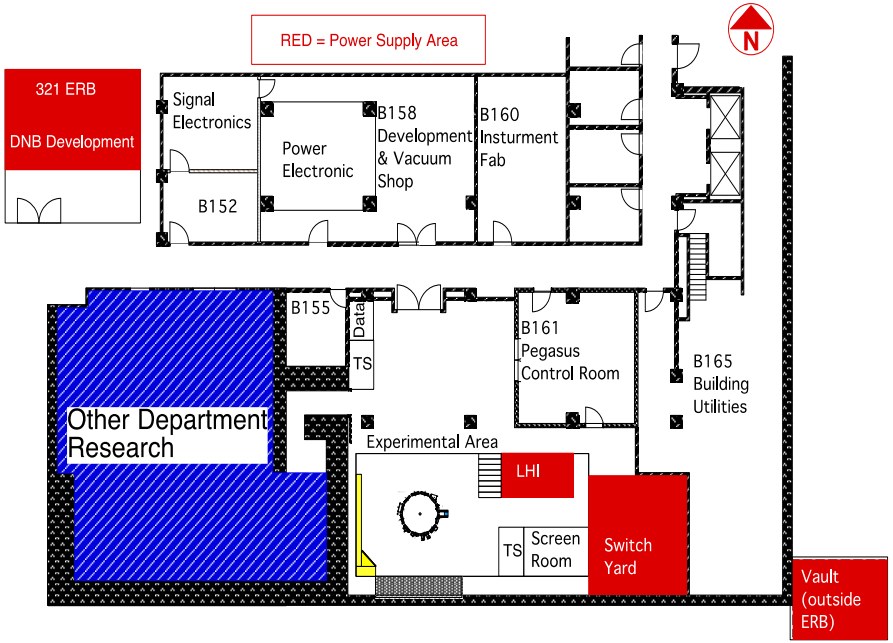
EHT Prototype Ćuk Power Module Test

See Pierren, P3-51, Wednesday afternoon

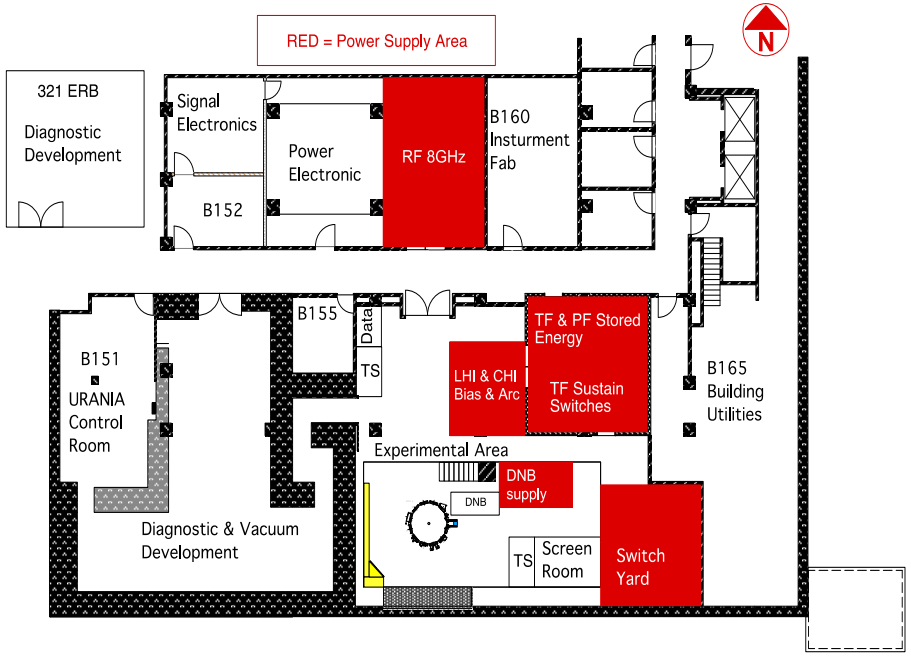
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Significant Facility Changes Planned for Expanded Capabilities

PEGASUS



URANIA



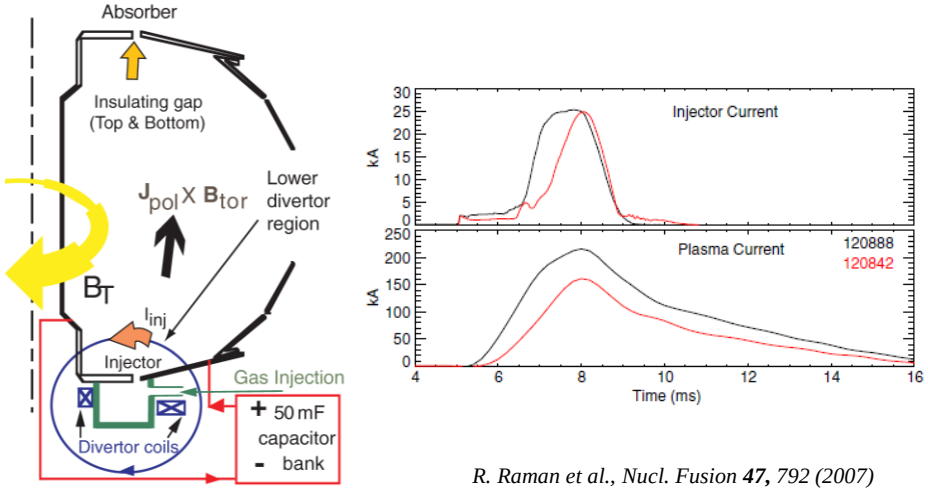
- Relocate and expand energy storage and power supplies
- New control room
- Helicity injection and rf systems, neutral beam

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CHI and EBW Systems

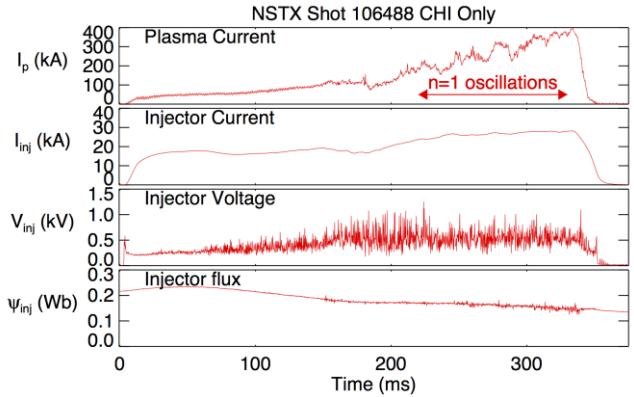
CHI Produces High-I_p Plasmas with Axisymmetric Electrodes

Transient CHI (NSTX Geometry)



R. Raman et al., Nucl. Fusion ***47,*** *792 (2007)*

Sustained CHI (NSTX Geometry)



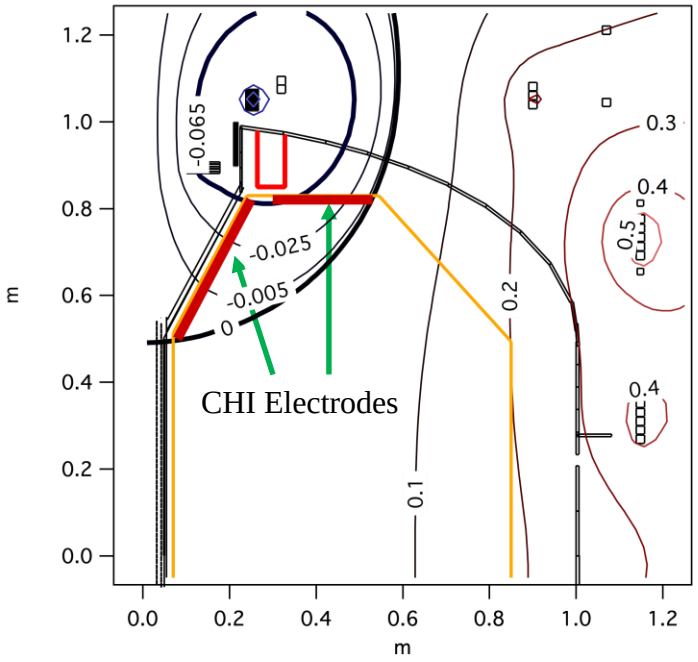
T. Jarboe et al., IAEA FEC 2002, IC/P-10

- CHI uses large-area, axisymmetric, passive electrodes to initiate I_p
- Relaxes to a tokamak-like state forming closed-flux current
- Maximum I_p constrained by Taylor limit, similar to LHI
- Hardware typically intrinsic to machine; retractable electrodes may be possible

Two-Electrode CHI System to be Implemented on URANIA

- CHI system targets I_p = 0.3 MA
  - No vacuum vessel break
  - Flexible, segmented floating electrodes
  - Ψ_{inj} ~ 35 mWb to reach 0.3 MA Taylor limit
- Support transient (T-) and sustained (S-) CHI studies
  - Scaling experiments and synergy with rf heating
  - Electrolytic T-CHI power supply being built
  - 32 MVA LHI supply to be used for S-CHI
- Design work needed to specify I_{inj}, divertor coil current, and diagnostics needed for CHI
- UW collaboration team (Raman (PI), Nelson, Rogers)

65 mWb Connecting Simple CHI Electrodes

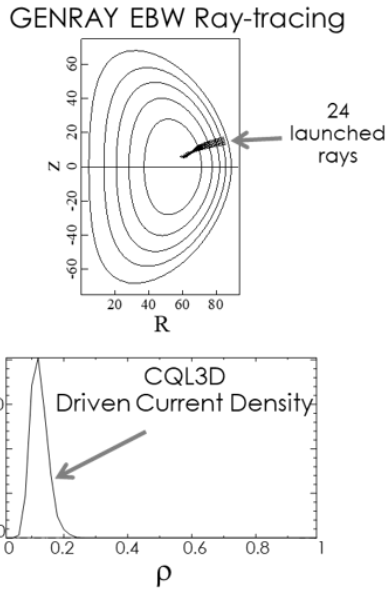


RF Heating and Current Drive Studies Will Focus on the EBW

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

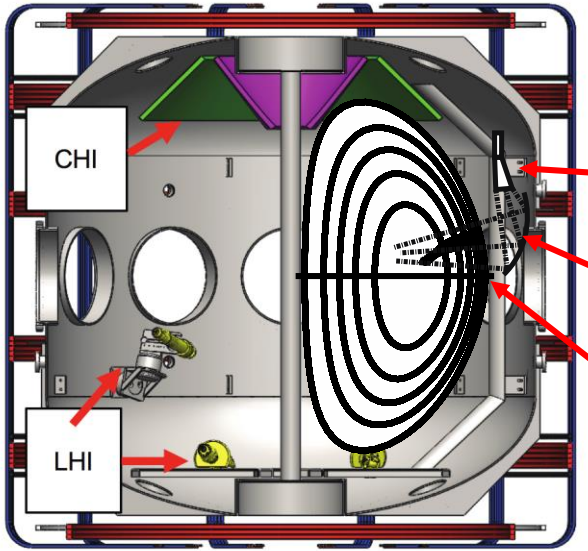
- EBW heating and current drive synergies with helicity injection:
  - Heating for increased LHI efficiency
  - T_e increase for compatibility with non-inductive sustainment (*e.g.* NBCD)
  - Potential for direct rf startup
  - Efficiency and localization
  - EBW CD as potential handoff tool

- 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



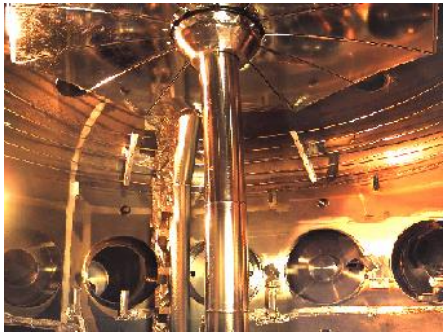


Diagnostic Systems

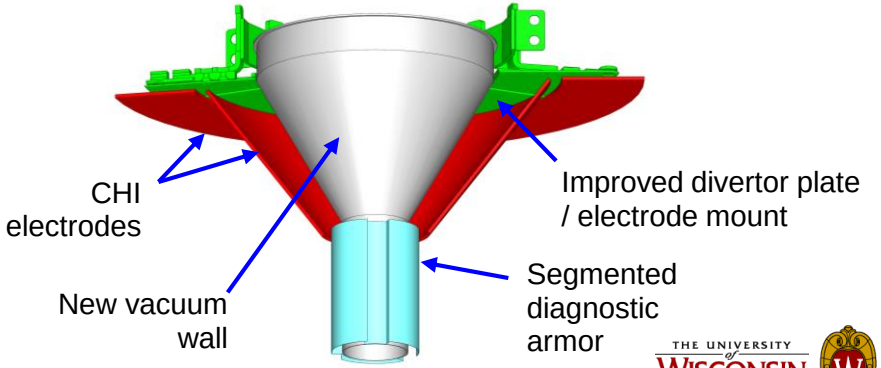
Significant In-Vacuum Machine Modifications Planned for URANIA

- 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

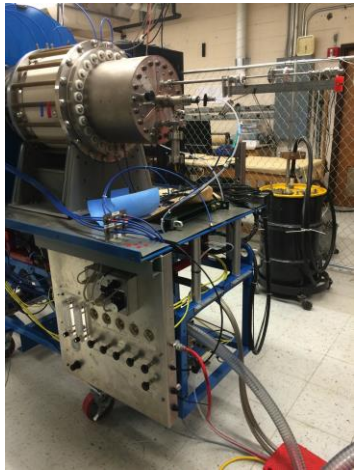


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Diagnostic Neutral Beam Commissioning is Underway

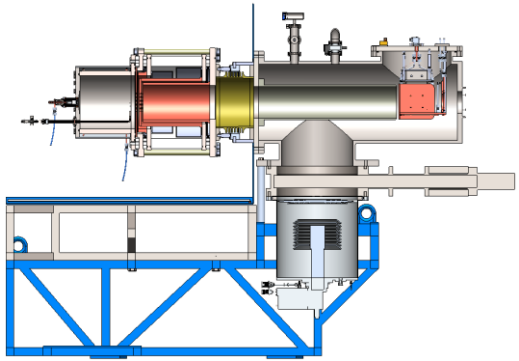
- Deploy H^0 neutral beam (PPPL loan)
  - Charge Exchange Recombination Spectroscopy
  - Motional Stark Effect
  - Beam attenuation (density diagnostic)
- Beam has favorable features
  - Low divergence, $\leq 0.5°$
  - High $E_b \sim 60 – 80$ keV maximizes MSE broadening
- New plasma arc source
  - Optimize signal at full energy component
  - Form and characterize beam
- 80 kV / 400 kW IGBT resonant converter low-ripple PS
  - Tuning and testing underway

Refurbished PBX-M DNB



Assembled HVPS



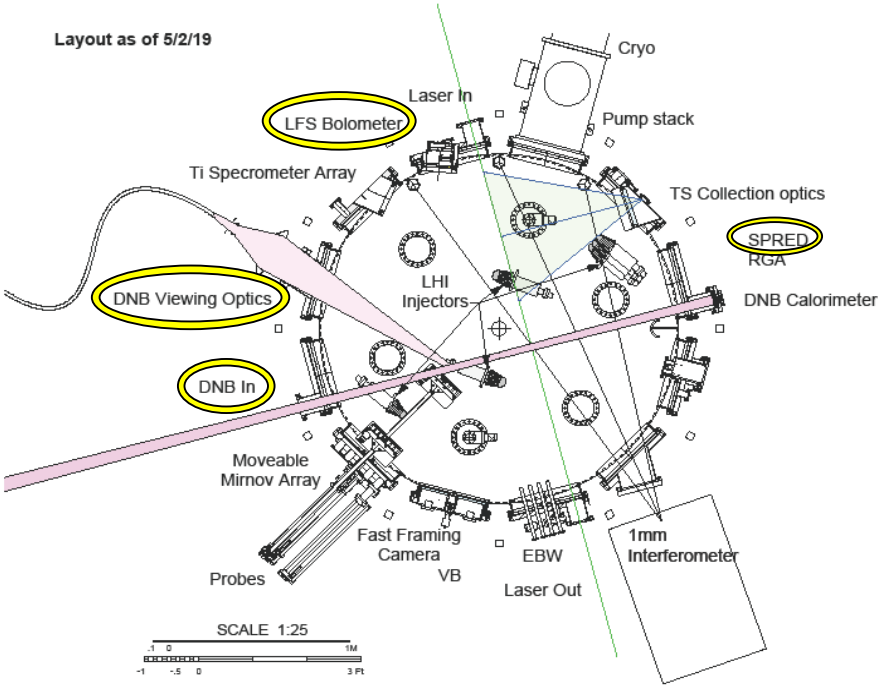


J.R. Coupland et al., Rev. Sci. Instrum. ***61****, 472 (1990)*

Conceptual Design for Expanded URANIA Diagnostic Suite

- Diagnostics based on mission-critical requirements
  - Current drive mechanisms
  - Kinetic equilibrium reconstruction
  - Helicity dissipation scaling
  - MHD activity
  - Injector PMI
- New systems under design
  - DNB based $[\tilde{B}(R,t), J(R,t), T_i(R,t), n_e(R,t), n_Z(R,t), \mathrm{v}(R,t)]$
  - Impurities [Bolometry, higher-resolution VUV spectroscopy (SPRED)]
  - Electron distribution function [x-ray]
- Insertable probe arrays
  - 3D magnetics [Hall, $\dot{B}$]
  - Langmuir, Mach, Rogowski
- Identify additional diagnostic needs for CHI & EBW

Diagnostic Layout for URANIA



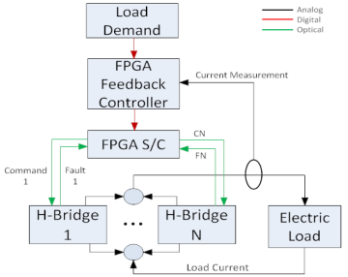
Upgrades to Control and Data Acquisition Systems Underway

- New URANIA data archival / backup systems
- LabVIEW control code infrastructure to integrate new URANIA power systems, DNB
- FPGA-based digital safety and control systems
  - IGBT, IGCT Splitter-Combiner system
  - Digital feedback controllers
- Reduce/eliminate aging CAMAC technology
  - Implement modern multichannel digitizers and trigger/clock systems

New 32 TB Data Storage Server Deployed



Digital FPGA Control, Safety Systems



Modern D-TACQ Digitizers

