Advancing US Non-Solenoidal Tokamak Startup Studies with a Proposed Upgraded PEGASUS Experiment

M.W. Bongard

G.M. Bodner, R.J. Fonck, C. Pierren, J.A. Reusch, A.T. Rhodes,
N.J. Richner, C. Rodriguez Sanchez, C.E. Schaefer, J.D. Weberski

University of Wisconsin-Madison

60th Annual Meeting of the APS
Division of Plasma Physics
Portland, OR

8 November 2018
Presentation TP11.00107

PEGASUS Toroidal Experiment

Layout

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Advancing US Non-Solenoidal Tokamak Startup Studies with a Proposed Upgraded PEGASUS Experiment

The Urania Experiment: Unified Study of Non-Solenoidal Startup Techniques	Engineering / Power Systems	Local Helicity Injection	Coaxial Helicity Injection	EBW Heating and Current Drive	Diagnostic Systems
Non-Solenoidal Startup Remains a Critical Need for the Spherical Tokamak, and May Benefit Advanced Tokamaks	Heart of the Facility is A New TF Assembly	A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Devices	CHI Produces High-Ip Plasmas with Axisymmetric Electrodes	Electron Bernstein Waves Provide Path to Electron Heating / Current Drive in Overdense Plasmas	Improved Diagnostic Suite of Urania Facilitates Physics Understanding for Extrapolation to Larger Scale
Research on the A~1 PEGASUS ST Has Advanced the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup	Divertor / PF System Design Status	Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs	T-CHI Experiments Pursued on Several Devices Worldwide	Overdense Plasmas Require Alternative Heating Methods	Diagnostic Neutral Beam Development
Several Solenoid-Free Startup Techniques Pursued Globally, But Challenges Remain to Provide Reliable, High-Performance Operation	Power Supply and Control Enhancements for URANIA	New Scenarios Developed to Transfer Between LFS -> HFS Injector Systems and Combine Strengths of Each Geometry	Next-Generation CHI Electrode Geometry Planned for URANIA	High BT of URANIA Facilitates RF / EBW	
URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Startup Development Station	FPGA Digital Control Systems Developed for URANIA	Advanced LFS Injectors Projected to Attain Ip = 0.3 MA in URANIA		Flexible Port Access in URANIA Favorable to Explore Different Antenna Designs	Broadening Studies of Non-Solenoidal Startup on PEGASUS with Transition to URANIA

THE UNIVERSITY of WISCONSIN MADISON



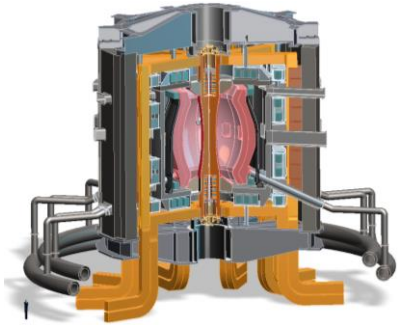
The URANIA Experiment

Unified Study of Non-Solenoidal Startup Techniques

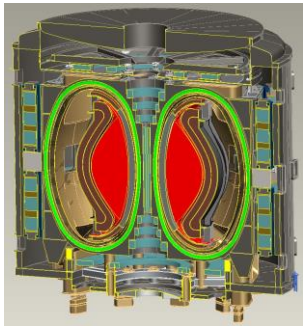
Non-Solenoidal Startup Remains a Critical Need for the Spherical Tokamak, and May Benefit Advanced Tokamaks

- Reactor-class nuclear tokamaks minimize the need for inductive sustainment from an Ohmic solenoid
  - Pulse lengths: O(month → year); startup: O(minute)
  - OH remains useful in principle for plasma initiation and ramp-up
- Instead, such devices must be sustained non-inductively
  - Self-generated bootstrap current
  - Auxiliary NBI, RF non-inductive current drive
- Spherical tokamaks (A < 2) place strong constraints on available solenoid flux due to device geometry
  - Nuclear ST designs generally 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



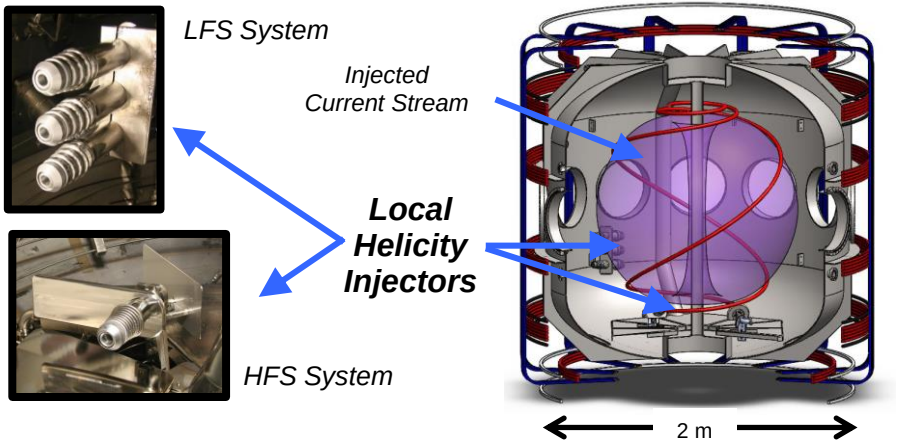
Solenoid-free
Cu ST-FNSF

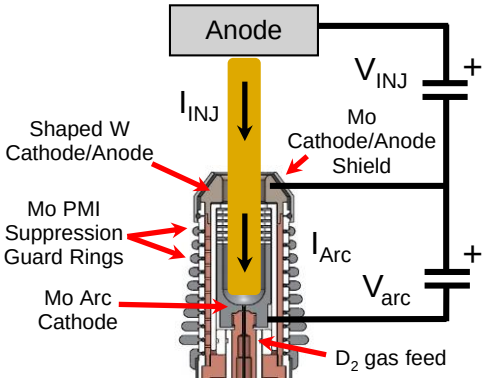


No / small OH
HTS
ST-FNSF / Pilot Plant

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

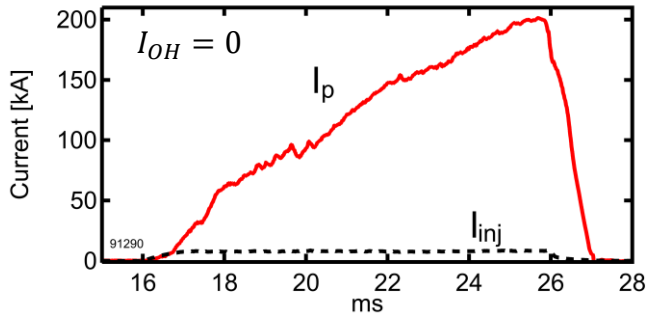
Research on the A ~ 1 PEGASUS ST Has Advanced the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup





PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 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 cm²
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

M.W. Bongard, APS-DPP 2018

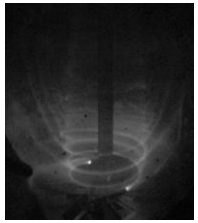
THE UNIVERSITY of WISCONSIN MADISON

Several Solenoid-Free Startup Techniques Pursued Globally, But Challenges Remain to Provide Reliable, High-Performance Operation

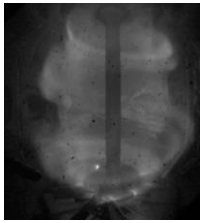
- Several techniques show promise
  - Local helicity injection (LHI)
  - Coaxial helicity injection (CHI)
  - Radiofrequency plasma initiation, heating, and current drive
  - Poloidal field induction
  - Neutral beam current drive

- A focused research program can timely address challenges
  - Technique, technology development requires extended operational time
  - Hardware and physics development
  - Avoids impact on other research programs at facility
    - Run time, interfering hardware during development
    - Machine conditioning, impurity status, etc.

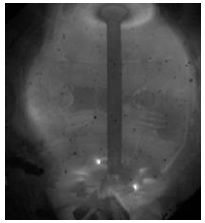
PEGASUS HFS LHI



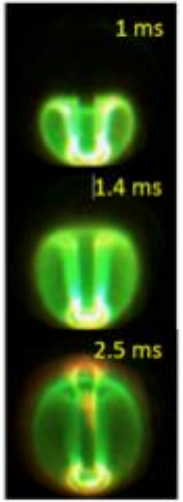
$I_p \sim N_{turns}\, I_{inj}$



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



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



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

THE UNIVERSITY of WISCONSIN MADISON

URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Startup Development Station

- Mission: compare / contrast / combine reactor-relevant startup techniques
  - Goal: guidance for ~1 MA startup on NSTX-U, beyond

- Major upgrades from PEGASUS to URANIA:
  - New solenoid-free centerstack and divertor assembly
  - Next-generation LHI injectors
  - Transient, Sustained CHI (w/ Univ. Washington, PPPL)
  - EBW RF heating & CD (w/ ORNL, PPPL)
  - Improved diagnostics, including diagnostic neutral beam



URANIA Experiment

Collaborative Enterprise:

WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

UNIVERSITY of WASHINGTON

OAK RIDGE National Laboratory

PPPL

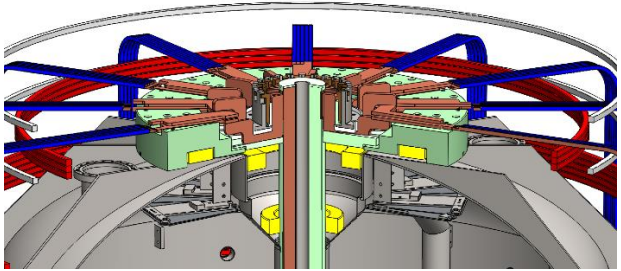
THE UNIVERSITY of WISCONSIN MADISON

Engineering / Power Systems

Heart of the Facility Enhancement Is A New TF Assembly

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	12
TF Conductor Area [cm^2]	13.2	151
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.60
B_T Flattop [ms]	25	100
ΔT_{bundle}	< 10℃	< 40℃
R_0 [cm]	45	48
A	1.15–1.3	1.33–1.4

URANIA Concept Drawing



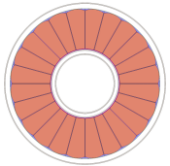
PEGASUS



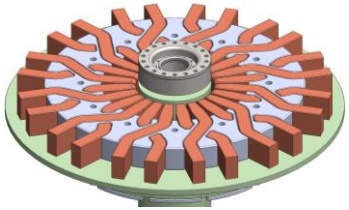
High-Stress OH Solenoid
12-turn TF Bundle



URANIA



Solenoid-free
24-turn TF Bundle

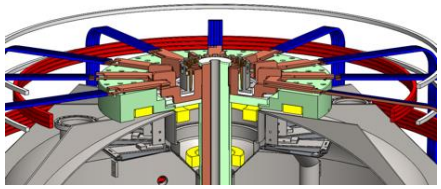


M.W. Bongard, APS-DPP 2018

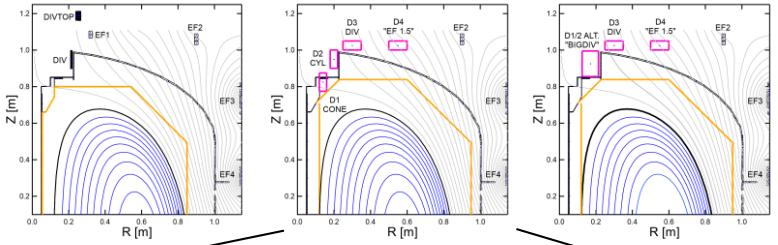
THE UNIVERSITY of WISCONSIN MADISON

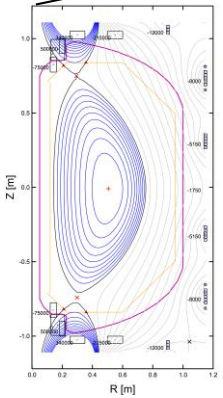
Divertor / PF System Design Status

- Proposal concept: triplet of PF / DIV coils in cone region
- Predictive equilibrium modeling used for conceptual design
  - kA-t, position requirements / tradeoffs
  - Baseline target: 0.3 MA, moderate pressure
- Status / findings:
  - At least two upper coils needed for reliable diverted configurations
    - Needed improved field stability index with respect to PEGASUS coils
  - High A-t needed to keep X-point in vacuum vessel
  - Suggests a triplet akin to configuration 'B' may be favorable
- Next evaluations / steps in design process:
  - Engineering / manufacturing feasibility (heating, inductance, etc.)
  - Optimize (minimize) required power systems to drive coil sets
  - Assess compatibility with CHI
    - X-point position, strike point control, flux magnitude/footprint



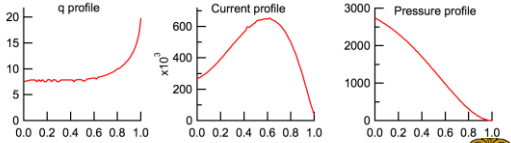
Proposal Concept For Triplet DIV Coils





Coil	kA-t
Ip	300
D1	-75
D2	500
D3	340
D4	-215

I_p	291 kA	R_0	0.448 m
β_t	0.014	a	0.305 m
ℓ_i	0.42	A	1.47
β_p	0.29	κ	2.4
W	7314 J	δ	0.47
B_{T0}	0.542 T	q_{95}	14.2



M.W. Bongard, APS-DPP 2018

THE UNIVERSITY of WISCONSIN MADISON

Power Supply and Control Enhancements for URANIA

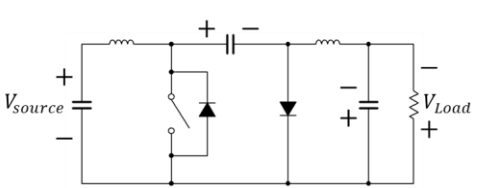
Near-Term

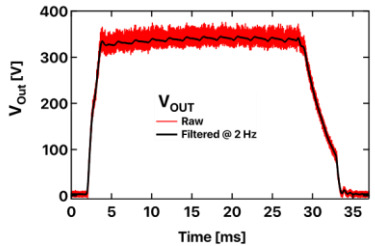
- Complete FPGA “splitter-combiner” deployment
  - Improves device protections for IGBT, IGCT power switches
  - Enables OH experiments prior to final removal of solenoid
- FPGA digital feedback controllers
  - Programmable coil / LHI control with modern hardware
  - Support advanced control algorithms
- DNB power supply, control system
- Ćuk converter for LHI / CHI power supplies
  - Low ripple, programmable voltage control of helicity injection

Longer-Term

- Active control for helicity injection
  - Injector gas control → $Z_{inj}(t)$
  - Cathode spot detection / mitigation
- OH → B_T power supply conversion
- RF / EBW power supply and control

Prototype Ćuk Converter Tests

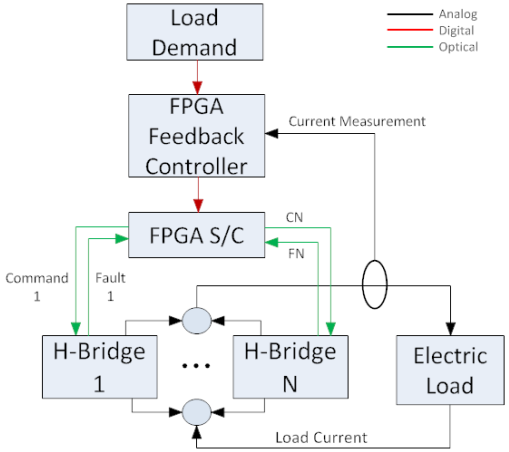




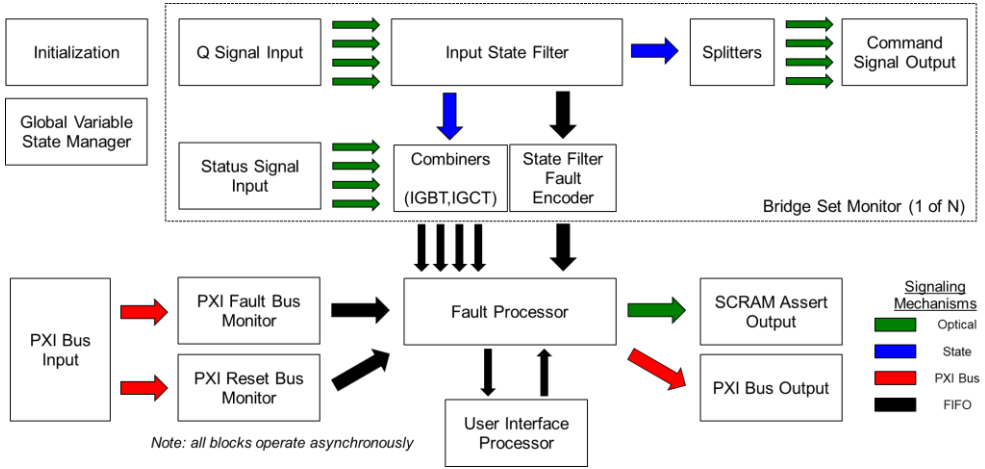
Pierren, TP11.00108

FPGA Digital Control Systems Developed For URANIA

FPGA Control System Components



PEGASUS Splitter/Combiner Power Semiconductor Interface and Protection System Block Diagram



- Field-programmable gate array technology modernizes P/S safety, control
  - Power semiconductor interface, fault monitoring, response
  - Digital feedback control for coil sets, helicity injection, and DNB/RF power systems
  - Commercial, off-the-shelf hardware

Local Helicity Injection

A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Machines

LHI Physics Models

- Global I_p limits:
  - Taylor relaxation

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

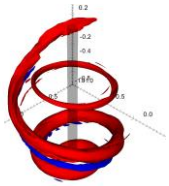
  - Helicity conservation

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

- Predictive power balance: $I_p(t)$

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

- 3D resistive MHD / NIMROD
  - Initial relaxation
  - Role of reconnection

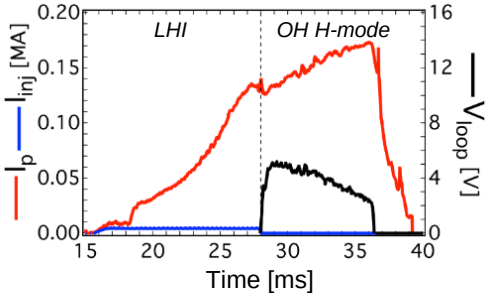


Reconnecting LHI Current Stream

M.W. Bongard, APS-DPP 2018

Coupled Physics/Engineering Needs

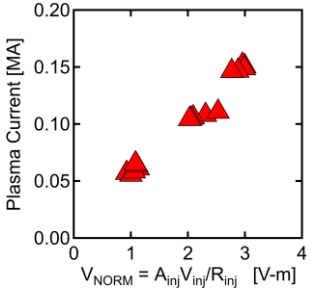
- Helicity injector source design
  - I_{inj}, w: set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$: attain / sustain I_p
  - Armoring, limiters to minimize PMI
- Injector system geometry
  - Provide initial relaxation via near-PF null
  - Site conformal to desired plasma shape
  - Facility port access compatibility
- Injector impedance and power systems
  - $Z_{inj} = Z_{inj}(n_{arc}, n_{edge}, \ldots)$



Outstanding Issues

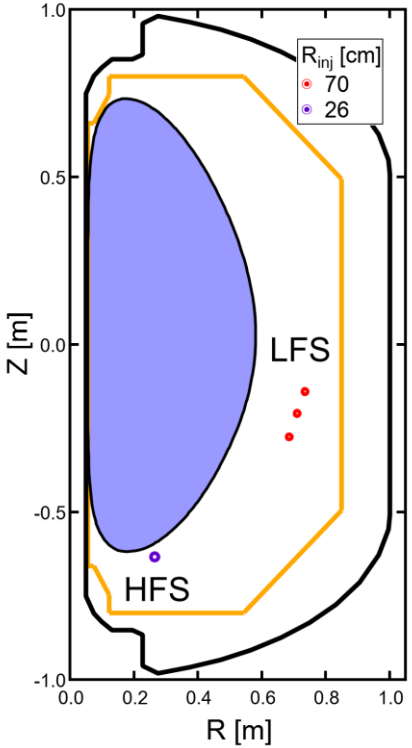
- Scaling to high I_p
  - Larger size
  - High B_T
  - Longer pulse
- Handoff to non-inductive CD
  - LHI → OH H-mode demonstrated
- Confinement, impurities, and dissipation during LHI
- LHI current drive mechanism

Low-B_T $I_p(V_{LHI})$ Scaling



Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs

Location of LHI Systems, Static HFS Plasma Geometry



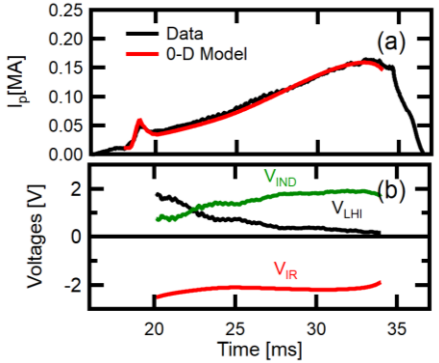
Injector System Comparisons

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}	$\leq$ 0.08 T	$\leq$ 0.22 T
V_{inj}	$\leq$ 1.5 kV	$\leq$ 1.5 kV
I_{inj}	6 kA	8 kA
P_{inj}	9 MW	12 MW
$\frac{V_{LHI}}{V_{LHI,LFS}}$	1	3.7

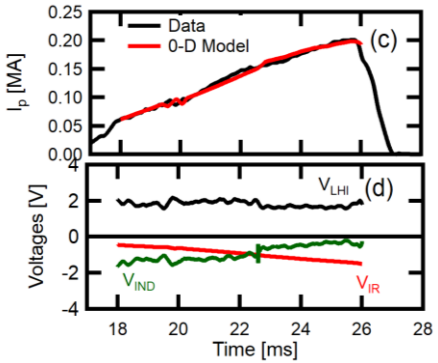




LFS: Non-solenoidal Induction



HFS: Helicity Injection



- Extrema of feasible LHI geometries deployed in Pegasus

- Low-field-side (LFS) injection
  - Injectors on outboard midplane
  - High R_{inj} → low V_{LHI}
  - Dynamic shape → strong V_{IND}
- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Low R_{inj} → strong V_{LHI}
  - Static shape → minimal V_{IND}

- I_p ~ 0.2 MA attained in both geometries
  - Power supply and PMI limited

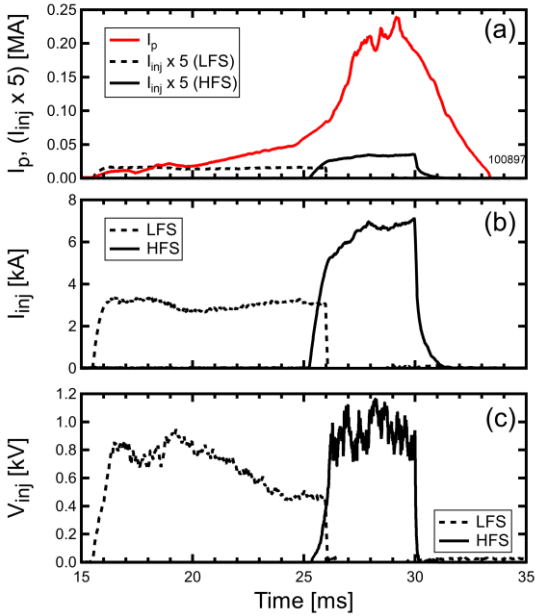
M.W. Bongard, APS-DPP 2018

THE UNIVERSITY of WISCONSIN MADISON

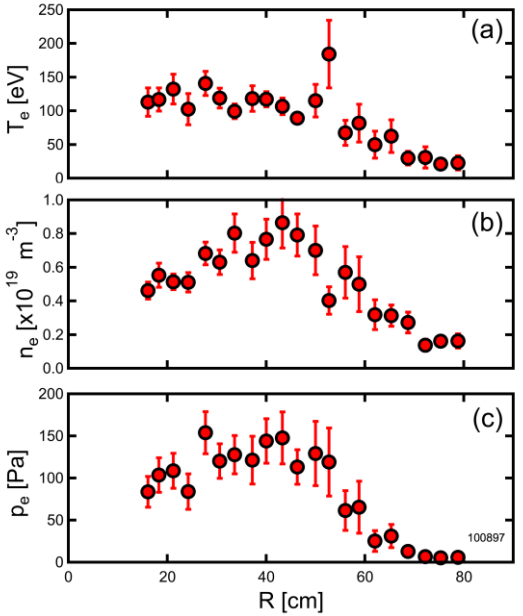
New Scenarios Developed to Transfer Between LFS → HFS Injector Systems and Combine Strengths of Each Geometry

- LFS → HFS handoff provides ready access to full-B_T operations with HFS injectors
  - LFS: Simpler relaxation access, lower PMI
  - HFS: Higher V_{LHI}
  - Seamless transfer between separate LHI systems
- Informs HFS high-B_T LHI system design
  - Relaxation, sustainment requirements may demand separate hardware features in higher-field machines
- Record LHI I_p = 0.225 MA attained
  - Peaked temperature, density pressure profiles
  - T_e > 100 eV, n_e ~ 1×10^{19} m^{-3}

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



Thomson Scattering Profiles
R_{inj} = 26 cm, t = 28.5 ms



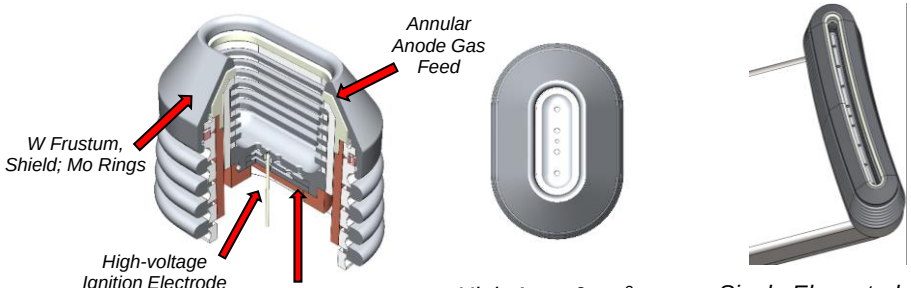
M.W. Bongard et al., IAEA FEC 2018, EX/P6-34
Rhodes, TP11.00106

THE UNIVERSITY of WISCONSIN MADISON

Advanced LFS Injectors Projected to Attain I_p = 0.3 MA in URANIA

- LFS LHI presently is favored geometry for next-step devices
  - Port-mount design concept, avoids high heat flux divertor region
  - Strong non-solenoidal inductive drive
- 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
- URANIA strategy: Increase I_{TL} via injector improvements, high B_T
  - Non-circular active sources: Optimize Taylor, helicity balance limits
    - High I_{inj}, narrow width: High I_{TL}
    - Large-area, modest V_{inj}: High helicity input, reduced PMI
    - Analog control of arc fueling rate: Dynamic injector impedance control
  - Improved LHI power supply capacity
- Initial experiments on PEGASUS support this approach

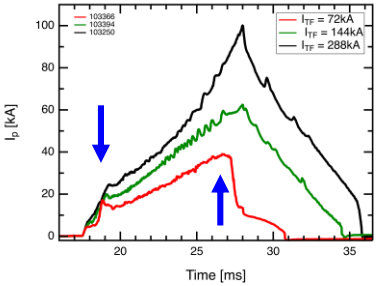
Two Non-Circular, High-A_{inj} Helicity Injector Concepts



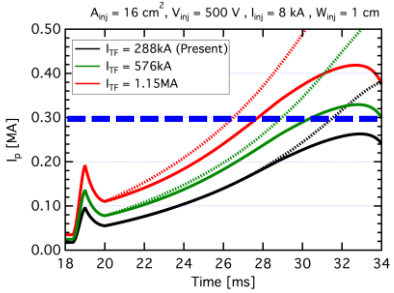
High A_{inj} = 6 cm², Low w_{inj} = 1.6 cm Aperture

Single Elongated Helicity Injector A_{inj} = 16 cm² w_{inj} = 1 cm

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



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



M.W. Bongard, APS-DPP 2018

Weberski, TP11.00112

THE UNIVERSITY of WISCONSIN MADISON

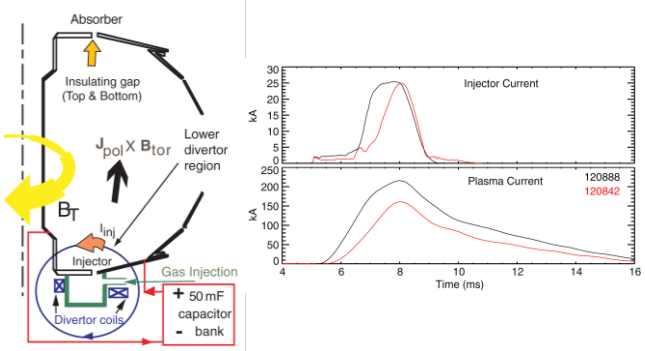


Coaxial Helicity Injection

CHI Produces High-I_p Plasmas with Axisymmetric Electrodes

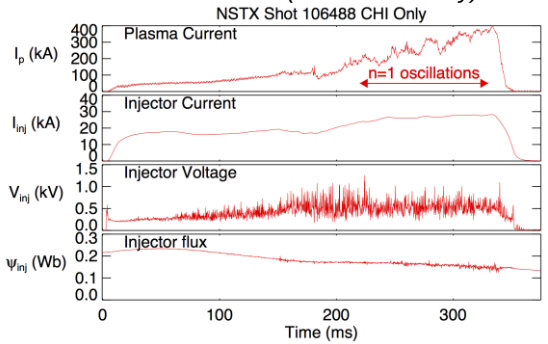
- CHI uses large-area, axisymmetric, passive electrodes to supply helicity
  - Current driven along vacuum poloidal flux surface intercepting electrodes
- If "bubble burst" criterion satisfied, $J_{inj} \times B_T$ force expands ψ_{inj} in vessel
  - $I_{inj} \geq \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}$; $C \sim O(1)$; d is separation of flux footprints
- Maximum I_p constrained by Taylor limit, as in LHI
  - $I_p \leq I_{TL} = I_{inj}\,\Psi/\psi_{inj}$
- Transient CHI (T-CHI) rapidly terminates $I_{inj}(t)$, leading to forced reconnection of injected flux
  - $\psi_p \leq \psi_{inj}$
  - Physics issues: axisymmetric vs. 3D reconnection; flux conversion efficiency
- Sustained CHI (S-CHI) sources helicity continuously
  - 0.4 MA demonstrated in NSTX experiments

Transient CHI (NSTX Geometry)



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

Sustained CHI (NSTX Geometry)

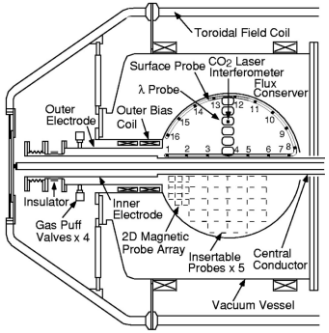


T. Jarboe et al., IAEA FEC 2002, IC/P-10

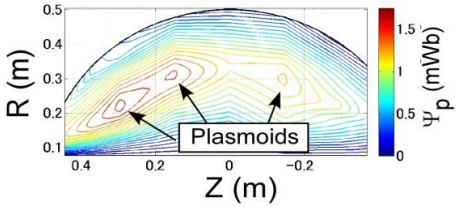
THE UNIVERSITY of WISCONSIN MADISON

T-CHI Experiments Pursued on Several Devices Worldwide

HIST

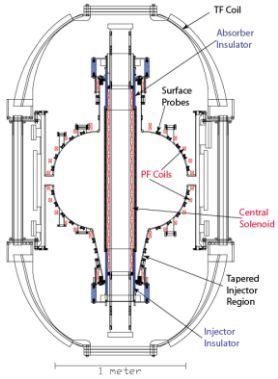


Detailed internal measurements observe plasmoid instability

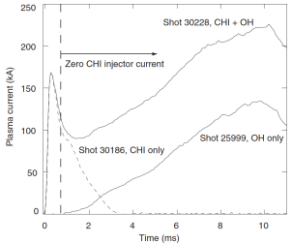


M. Nagata et al., IAEA FEC 2018, EX/P-3

HIT-II

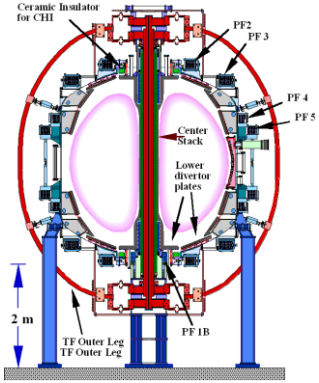


Flux Savings via T-CHI → OH Handoff

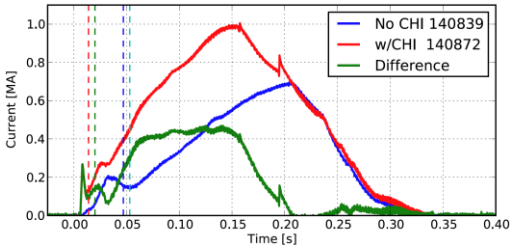


*R. Raman et al., Nucl. Fusion **45,** L15 (2005)*

NSTX

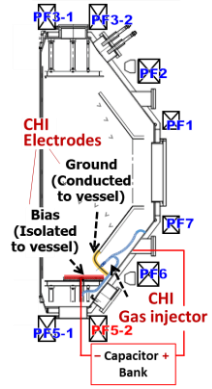


0.2 MA T-CHI Raised to 1 MA with OH

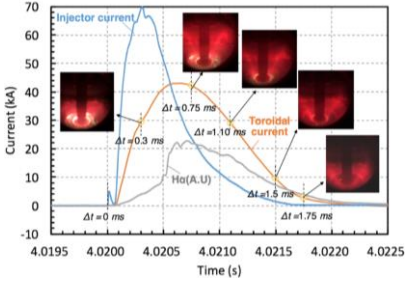


*B.A. Nelson et al., Nucl. Fusion **51**, 063008 (2011)*

QUEST



First Tests with Isolated Electrode



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

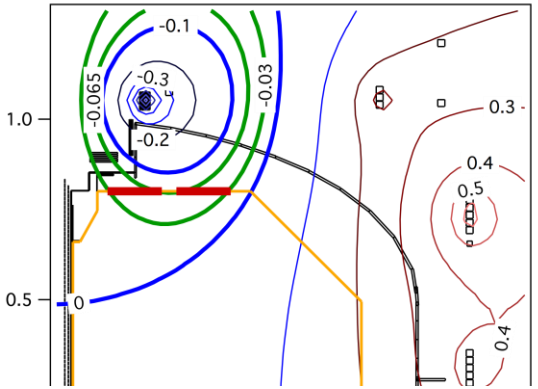
M.W. Bongard, APS-DPP 2018

THE UNIVERSITY of WISCONSIN MADISON

Next-Generation CHI Electrode Geometry Planned for URANIA

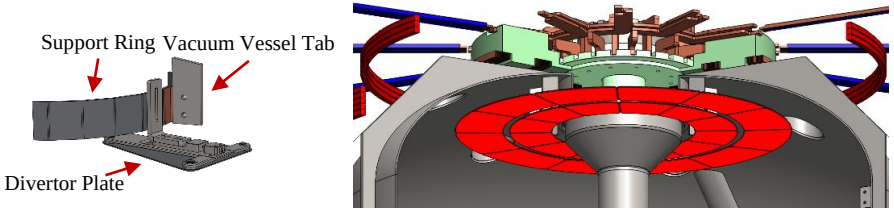
- CHI system targets I_p = 0.3 MA
  - No vacuum vessel break
  - Flexible, segmented floating electrodes
    - Refractory metal conductor: impurity control
    - Consider active (LHI-like) electrode as needed
  - $\psi_{inj} \sim 35$ mWb for 0.3 MA Taylor limit

Vacuum Field for 0.3 MA T-CHI on URANIA



- Support transient, sustained CHI studies
  - Sustained CHI scaling
  - Synergies with RF/EBW heating
  - 3D vs. 2D reconnection activity
  - Collaboration w/ U. Washington, PPPL

Pre-Conceptual Segmented CHI Electrode Concept on URANIA

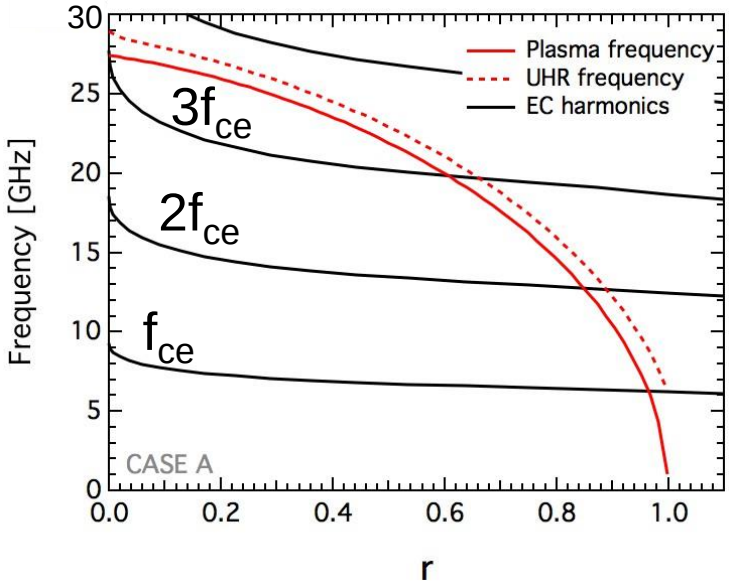


EBW Heating and Current Drive

Electron Bernstein Waves Provide Path to Electron Heating / Current Drive in Overdense Plasmas

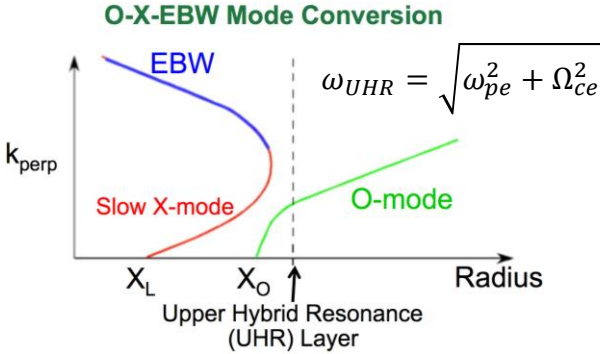
- Additional heating / current needed for non−solenoidal startup and sustainment
  - B_T, n_e of URANIA plasmas prohibit use of traditional ECH for many scenarios
  - Electron Bernstein Waves (EBWs) can couple to, propagate in overdense plasmas ($\omega_p > \Omega_{ce}$)
- EBWs used successfully in STs, stellarators, and RFP for heating and current drive

Characteristic Frequencies in URANIA
B_{T0} = 0.35 T, $n_e(0) = 10^{19}$ m^{-3}

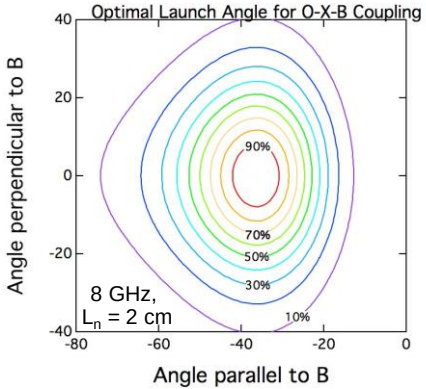


Overdense Plasmas Require Alternative Heating Methods

- EBWs are perpendicularly propagating, electrostatic, hot plasma waves
  - No density cutoff in the plasma
  - Cannot propagate in vacuum → must launch O- or X-modes to mode couple to EBW

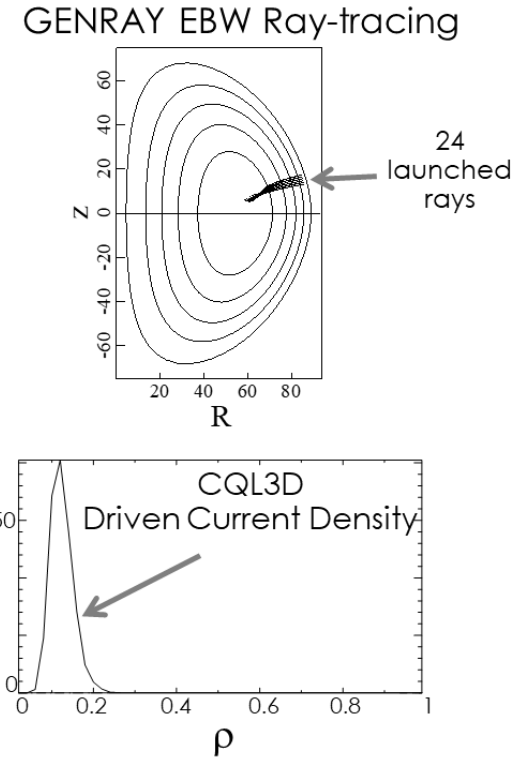


- EBWs absorbed near Doppler-broadened resonance
  - Increase in $n_\parallel$ results in shift of resonance location: $\omega - k_\parallel v_\parallel - n\Omega = 0$
  - Observed for off-midplane launch in STs



High-B_T of URANIA 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, 8 GHz (TBD)
  - Collaboration w/ ORNL, PPPL



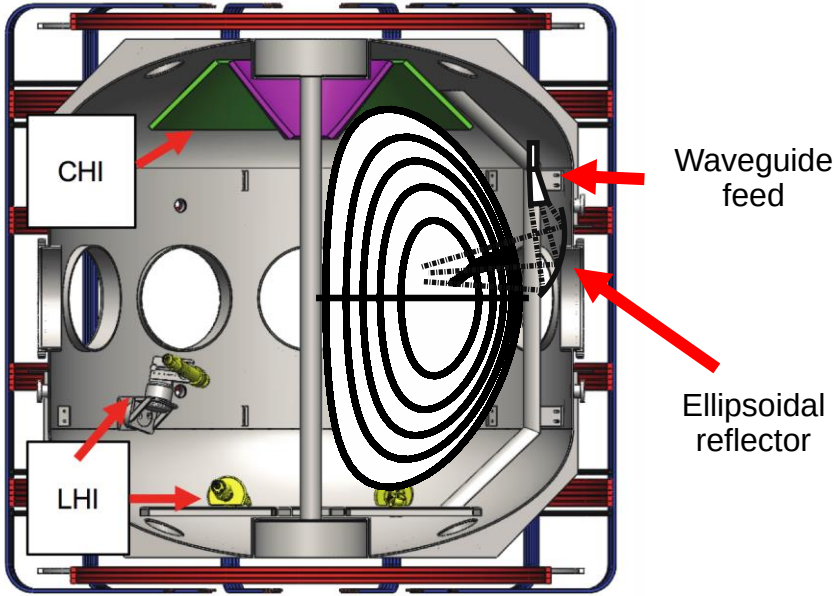
S.J. Diem et al., 2018 US-EU-JP RF Technology Workshop

M.W. Bongard, APS-DPP 2018

Flexible Port Access in *URANIA* Favorable to Explore Different Antenna Designs

- Several port options provide flexibility in antenna design

- Preliminary concept incorporates:
  - Upper port for waveguide access
  - Midplane port for ellipsoidal reflector



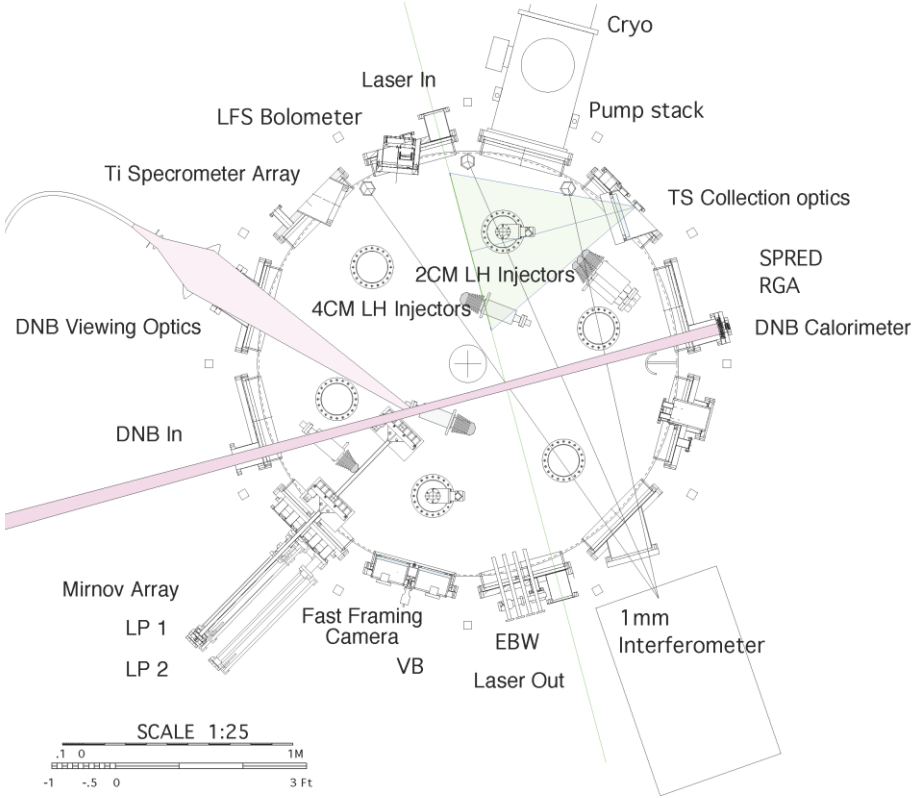


Diagnostic Systems

Improved Diagnostic Suite of URANIA Facilitates Physics Understanding for Extrapolation to Larger Scale

- DNB spectroscopy
  - $\tilde{B}(R,t), J(R,t), T_i(R,t), n_e(R,t), n_Z(R,t), \mathrm{v}(R,t)$
- Impurity diagnostics
  - SPRED
  - Bolometry
- Insertable probe arrays
  - 3D magnetics (Hall, $\dot{B}$)
  - Langmuir, Mach, Rogowski

Diagnostic Layout for URANIA

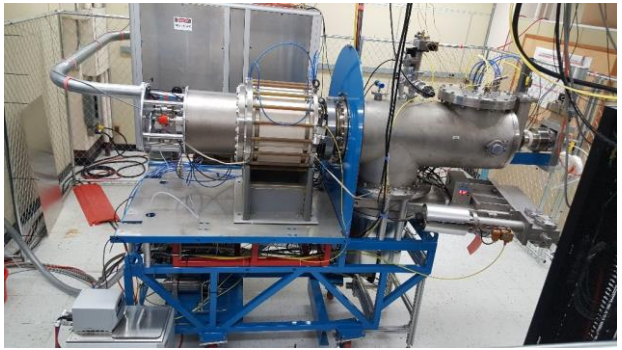


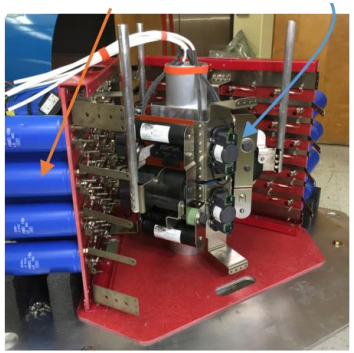
M.W. Bongard, APS-DPP 2018

Diagnostic Neutral Beam Development

- Using H^0 DNB on loan from PPPL
  - Extracted ion current: 2–3 A
  - Full-energy J at focus: 3–6 mA/cm^2
  - Diameter ~ 9 cm
  - Pulse length ~ 100 ms
- Favorable features
  - Low divergence: $\leq 0.5^\circ$
  - High E_b ~ 60–80 keV maximizes MSE broadening
- New plasma arc source
  - Optimize signal at full energy component
- 80 kV / 400 kW IGBT resonant converter implemented

Refurbished PBX-M DNB





Three-phase Resonant Bridge and Stored Energy



Assembled HV Power Supply

M.W. Bongard, APS-DPP 2018

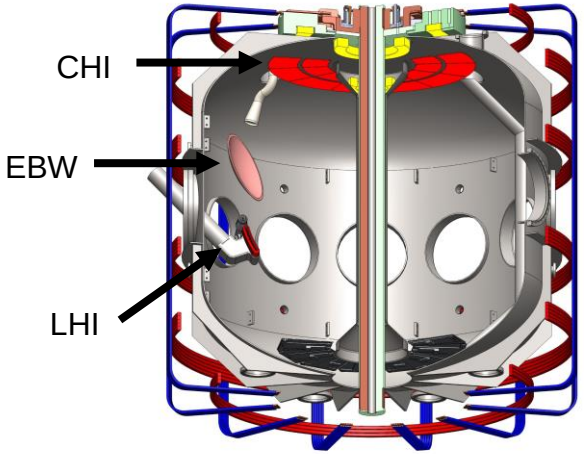
J.R. Coupland et al., Rev. Sci. Instrum. ***61****, 472 (1990)*
I.L.S. Gray et al., SOFE 1989; DOI: 10.1109/FUSION.1989.102193

THE UNIVERSITY of WISCONSIN MADISON

Broadening Studies of Non-Solenoidal Startup on PEGASUS with Transition to URANIA

- **Evaluate leading concepts for non-solenoidal startup in single dedicated facility**
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - EBW startup and assist
  - Poloidal field induction
  - Future: NBI heating and current drive
- **Develop common understanding & validation of all approaches**
- **Goal: develop validated concept, equipment for ~1 MA startup on NSTX-U and beyond**

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



Collaborative Enterprise:

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

M.W. Bongard, APS-DPP 2018