

# PEGASUS-III: A Spherical Tokamak for Developing Non-Solenoidal Plasma Startup Techniques

**J.D. Weberski**

M.W. Bongard, S.J. Diem (ORNL), R.J. Fonck, J.A. Goetz, B.A. Kujak-Ford, A.K. Keyhani, B.T. Lewicki, M.D. Nornberg, A.C. Palmer, R. Raman (U. Wash.), J.A. Reusch, A.T. Rhodes, and G.R. Winz



University of  
Wisconsin-Madison

61<sup>st</sup> Annual Meeting of the APS  
Division of Plasma Physics  
Fort Lauderdale, FL

21 October 2019



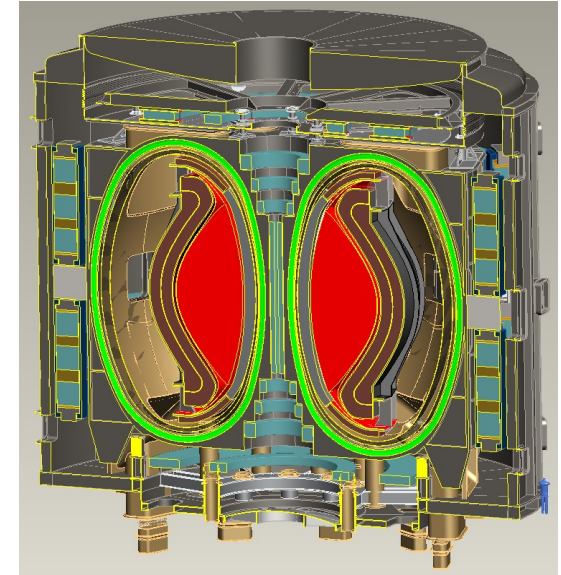
PEGASUS-III  
Toroidal Experiment



# Solenoid-Free Operation is a Critical Need for ST, and May Benefit Future Tokamak Designs

- Minimizing solenoid simplifies tokamak design
  - Potential cost reduction
  - More space for inboard shielding/blanket
  - Reduce PF system requirements
  - Lower stresses
- Solenoid-free techniques may offer  $J(R)$  control

***ST-FNSF, FNSF / Pilot Plant Concept***



*J.E. Menard, Phil. Trans. R. Soc. A 377, 20170440 (2019)*

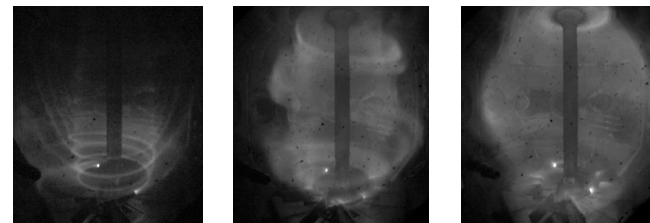


# Several Methods Tested Worldwide, but Independently

- Need for dedicated facility
  - Predictive understanding
  - Sufficient runtime
  - Comparative studies
  - Exploit possible synergies
- Goal: Establish routine startup tool

*Bongard et al., APS-DPP-CPP Initiative (2019)*

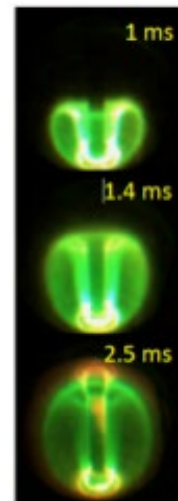
## PEGASUS HFS LHI



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

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

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



## 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

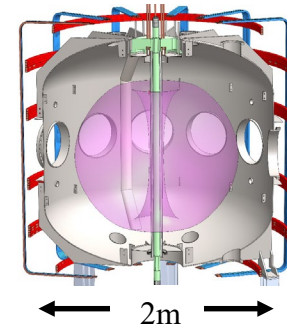
## NSTX Transient CHI



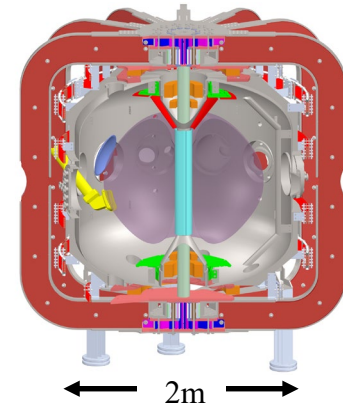
# PEGASUS-III: A Facility Dedicated to Comparative Study of Solenoid-Free Startup and Possible Sustainment

- **Mission:** compare / contrast / combine reactor relevant startup techniques at  $I_p \sim 0.3$  MA
  - **Goal:** guidance for 1 MA startup on NSTX-U, beyond
- **Features of PEGASUS-III:**
  - New center rod assembly:  $B_T = 0.6$  T
  - New power systems
  - Next generation LHI injectors
  - Transient & Sustained CHI (with Univ. Washington, PPPL)
  - EBW RF heating & CD (with ORNL, PPPL)
  - Improved diagnostics

**PEGASUS-II (Present)**



**PEGASUS-III**

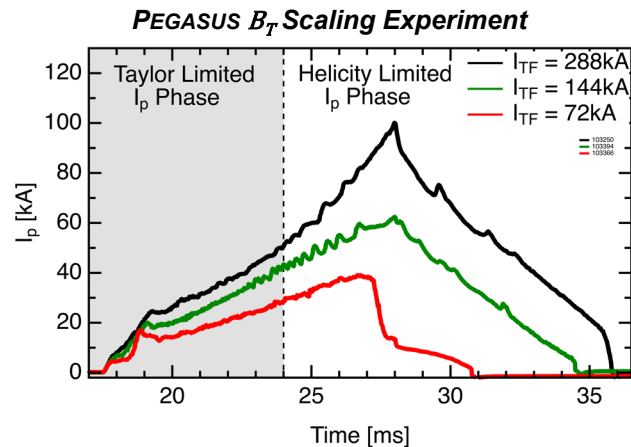




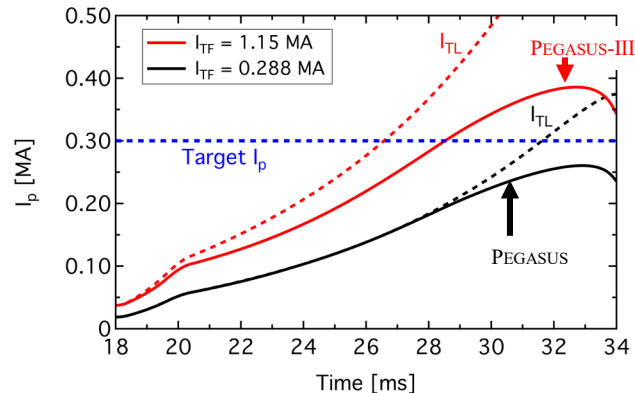
# Projecting LHI to Larger Facilities Requires Tests at Increasing $B_T$

- Critical physics issues:

- $I_p$  gains with increased Taylor limit  $\sim \sqrt{I_{TF}}$
- Initial tokamak formation
- Scaling of core confinement
- Current drive mechanisms
- Stochastic edge transport properties
- Current stream stability



## 0-D Power-Balance Projections for LHI on PEGASUS-III





# Advancing LHI Technology with Non-Circular Injector Design in PEGASUS-III

- To date, circular helicity injector development
- Future: non-circular injector concept
  - Increase  $A_{inj} \rightarrow$  lower  $V_{inj}$  for reduced PMI
  - Narrow current channel ( $w$ )
  - Increase  $I_{inj}$
  - Single LFS port assembly
  - Programmable  $V_{inj}(t)$  capability

Taylor limit

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

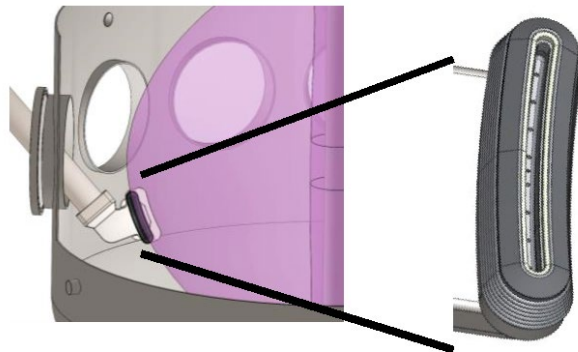
Helicity limit

$$I_p \leq V_{LHI} / R_p \sim A_{inj} V_{inj}$$

*Array of 3 circular injectors installed in PEGASUS*



*Advanced “Kama” Injector in PEGASUS-III*





# Increased $B_T$ Enables Comparative Studies of CHI on PEGASUS-III

- CHI system targets  $I_p = 0.3$  MA
  - No vacuum vessel break
  - Segmented, floating refractory metal electrodes
- Explore CHI physics at  $B_T = 0.6$  T
  - Comparison and synergies w/other methods
  - Scenario optimization
  - Flux conversion efficiency
  - Validation of MHD simulations

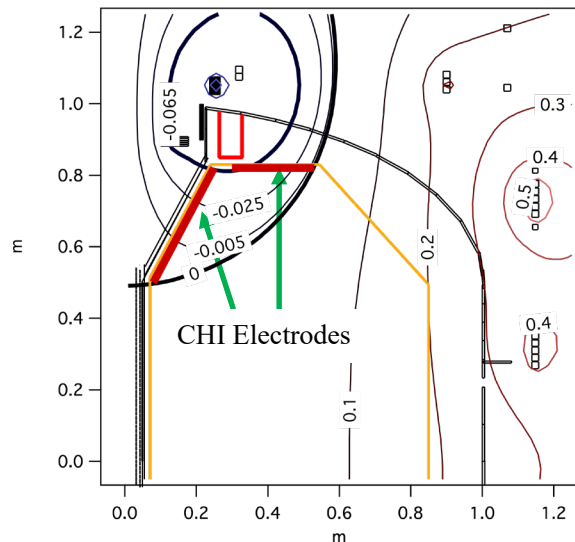
Taylor Limit

$$I_p \leq I_{TL} = I_{inj} \Psi / \psi_{inj}$$

“Bubble burst” criterion

$$I_{inj} \geq \frac{C \psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}; C \sim O(1)$$

**65 mWb Connecting CHI Electrodes**



\*see R. Raman poster [Tuesday AM: GP10.00128]

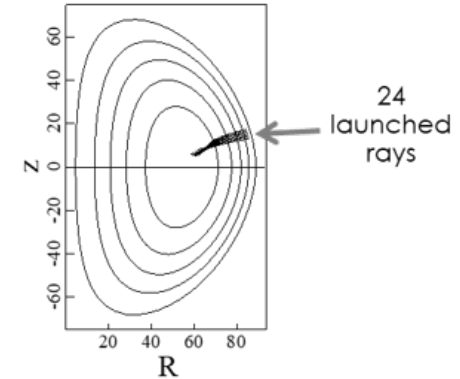
R Raman and V F Shevchenko, PPCF **56**, 103001 (2014)



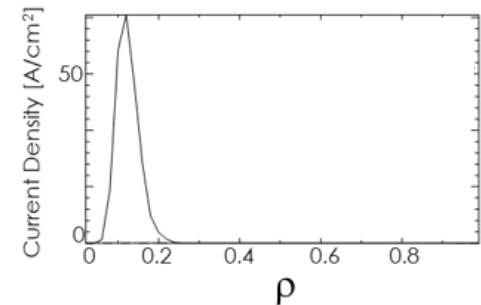
# PEGASUS-III Will Explore EBW Synergies with Helicity Injection, with Potential for Expanded RF Capabilities

- EBW for heating and current drive\*
  - Improve HI startup via electron heating
  - Post-HI sustainment
- EBW implementation
  - Steerable O-mode mirror on LFS
  - 8 GHz, 500 kW FTU system
- Possible expansion: ECH and ECCD
  - Direct RF startup
  - Explore proposed NSTX-U startup scenario\*\*

**GENRAY EBW Ray-tracing**



**CQL3D Driven Current Density**



\*S.J. Diem et al., 2019 US-JP RF Heating Workshop

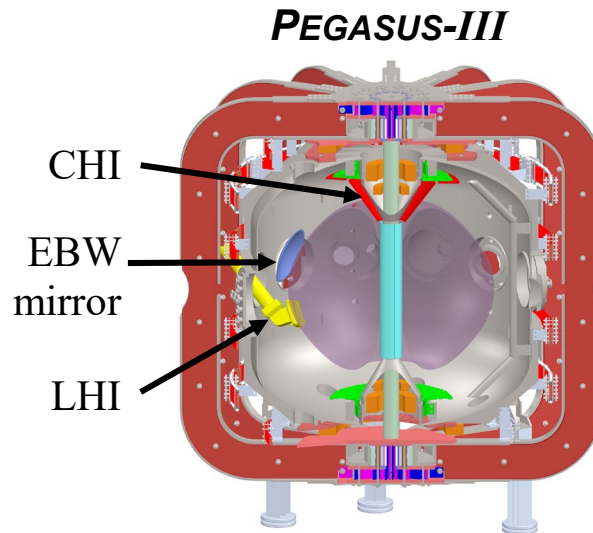
\*\*F.M. Poli et al., Nucl. Fusion **55**, 123011 (2015)





# PEGASUS-III: Design and Fabrication in Progress

- Magnetic field upgrades
  - 24-turn TF bundle
  - TF return legs accommodate axial stresses
  - PEGASUS-like wedge compression TF joint
  - New divertor coils
- Power supply upgrades
  - 300 MVA of digitally controlled power
- In-vessel modifications
  - LHI and CHI support assemblies
  - Upgraded magnetic diagnostics



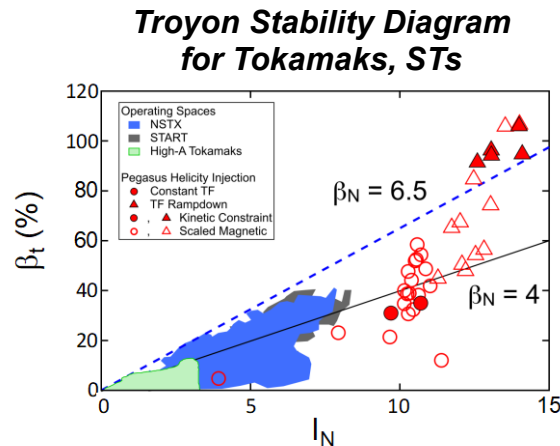
Parameter	PEGASUS	PEGASUS-III
$\psi_{sol}$ [mWb]	40	0
$B_{T,max}(R_0)$ [T]	0.15	0.58
$B_T$ Flattop [ms]	25	50-100
$A$	1.15	1.18

*\*see A.C. Palmer poster [Tuesday AM: GP10.00126]*

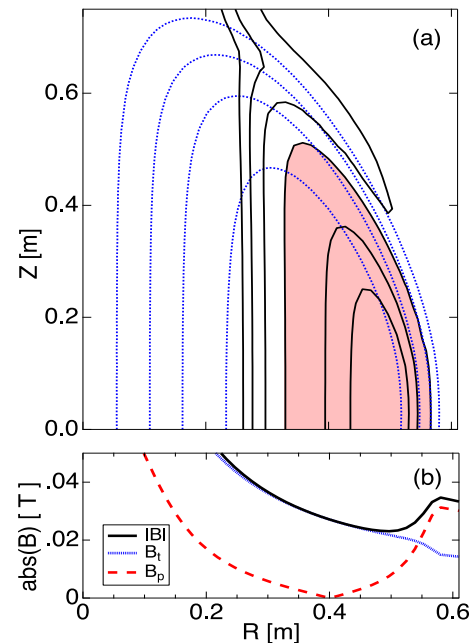


# Small Central Rod Assembly Supports Access to Unique Low $A \sim 1$ Tokamak Physics

- Diagnose with insertable probes
- Unique operating regimes
  - High  $\beta_t^*$
  - Min  $|B|$  well configuration\*
  - H-mode studies\*\*



**Min  $|B|$  Well in  $\beta_t \sim 100\%$  Plasma**



\*Schlossberg et al., *Phys. Rev. Letters* **119** 035001(2017)

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

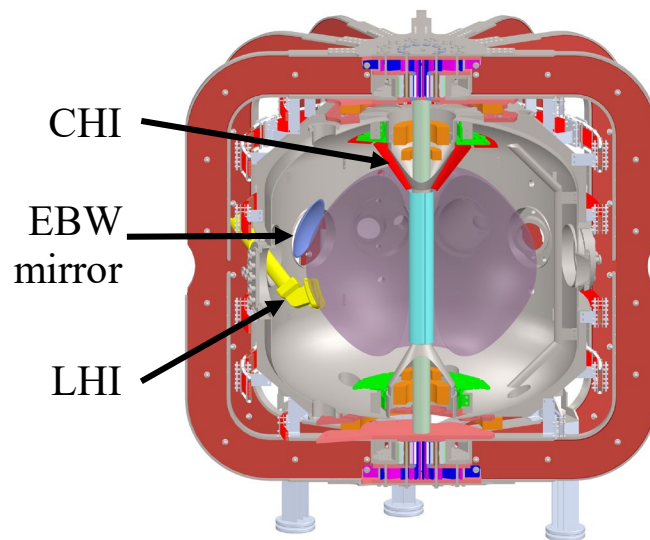
\*\*Thome et al., *Nucl. Fusion* **57** 022018 (2017)



# Evaluation of Leading Techniques for Reactor Relevant Solenoid-Free Startup on PEGASUS-III

- Compare/contrast/combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - EBW assist and sustainment
  - Future: EC heating and current drive
- Goal: develop validated concept, equipment for 1 MA startup on NSTX-U and beyond
- Construction underway, operational in 2020

## *PEGASUS-III: US Startup Development Station*



### **Collaborative Enterprise**





## PEGASUS-III Posters at Tuesday AM Session

- A.T. Rhodes [GP10.00125]: Pegasus-III overview
- A.C. Palmer [GP10.00126]: Status of new central rod assembly
- A.K. Keyhani [GP10.00127]: Status of new diagnostic neutral beam
- R. Raman poster [GP10.00128]: Pegasus-III CHI system overview