Solenoid-Free Startup in the PEGASUS-III Experiment

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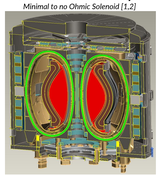
Work supported by US DOE Grants DE-SC0019008 and DE-SC0020402

PEGASUS-III Experiment

PEGASUS-III: A US Platform for Solenoid-Free Startup Studies

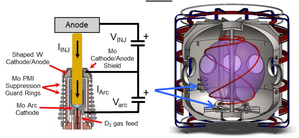
- Solenoid-free startup can reduce cost, complexity of tokamak pilot plants
  - Critical to spherical tokamak concepts
    - Nuclear STs preclude OH due to shielding / cost
    - Solenoid, if available, insufficient for full I_p ramp-up
  - Benefits tokamaks generally
    - Space for inboard shielding / blanket / RF
    - Lower electromechanical stresses
    - Reduce/eliminate need for breakdown B_p null

ST Pilot Plant Concept
Minimal to no Ohmic Solenoid [1,2]

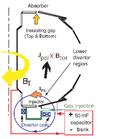


- New PEGASUS-III facility enables comparative startup studies
  - Compare / contrast / synergistically combine solenoid-free startup concepts

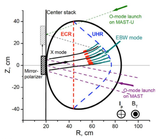
LHI



CHI



Radiofrequency



Helicity Injection

- Drives current on SOL open field lines
- Local Helicity Injection (LHI) [3]
- Coaxial Helicity Injection (CHI) [4]

Radiofrequency

- Ionize gas; ramp to desired plasma configuration
- EC, LH, EBW [4]
- Potential synergies with HI startup

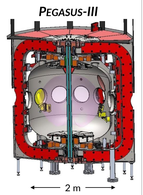
- **Goal:** Develop validated physics, technology basis for MA-class startup

Upgrade Nearly Complete and Commissioning Underway

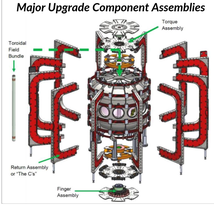
- PEGASUS-III upgrade retains A ~ 1 with solenoid-free central column [5–7]
  - B_T increased 4× to 0.6 T
  - 6 new divertor coils
  - Diagnostic neutral beam
  - Expanded diagnostics
  - 175 MVA controlled power
  - 8.5 MJ stored energy
  - Fully digital control systems
  - LHI, CHI, and RF systems

Parameter	PEGASUS	PEGASUS-III
I_{TF} [MA]	0.288	1.15
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm²]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50–100
A	1.15	1.18

PEGASUS-III



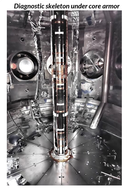
Major Upgrade Component Assemblies



New Power Switchyards



Vessel Interior
Diagnostic skeleton under core armor



Vessel Exterior



Advancing Local Helicity Injection

- LHI produces high I_p tokamak plasmas without solenoidal induction [3,8]

Current Injection



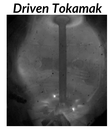
$I_p \sim N_{turns}\, I_{inj}$

Relaxation



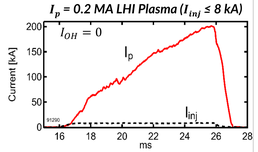
$I_p \gtrsim N_{turns}\, I_{inj}$

Driven Tokamak



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

I_p = 0.2 MA LHI Plasma ($I_{inj} \leq$ 8 kA)



- Growing understanding informs application of LHI 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

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

- Power balance: $I_p(t)$

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

- 3D resistive MHD/NIMROD

Coupled Physics/Engineering Needs

- Helicity injector source design
  - High I_{inj}, low w for high Taylor limit
  - High $A_{inj} V_{inj}$ for helicity drive
  - Armoring: V_{inj} standoff in SOL
- HI system geometry, port access
- Source impedance, power systems
  - $Z_{inj} = Z_{inj}(n_{arc}, n_{edge}, \ldots)$
  - Active cathode spot mitigation

Outstanding Issues

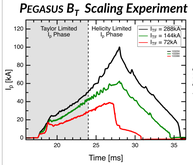
- Scaling to high I_p, B_T
- Confinement, impurities, and helicity dissipation
- Current drive mechanism
- Handoff to non-inductive sustaining current drive

- Tests at higher B_T are key
  - Favorable $I_p(B_T)$ scaling: Increased I_{TL}
  - Confinement, heating, dissipation [9,10]
  - Extend models of LHI current drive [11–13]
  - Assess, mitigate impurity production [14]
  - Facilitate RF heating and current drive [15]
  - Overlap B_T with NSTX-U, MAST-U

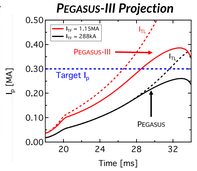
Projections of Core Confinement Models

Confinement Scaling	I_p Trend with V_{LHI}	B_T	n_e
Linear Ohmic (Neo-Alcator)	↑	↑	–
Saturated Ohmic (ITER97L)	↓	–	↑
Collisional Stochastic*	↑	–	–
Collisionless Stochastic	↓	↑	↑

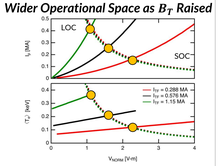
PEGASUS B_T Scaling Experiment



PEGASUS-III Projection



Wider Operational Space as B_T Raised

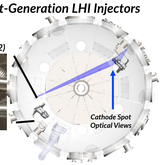


- New LHI systems for first campaigns [8]
  - Four-injector array for initial operation
    - Two arrays of two 4 cm² injectors
    - Most powerful HI system fielded
  - Non-circular injector as next advance
    - Port mounted active arc source
    - Optimize Taylor limit, HI rate
  - New I_{inj} bias power supplies [6]
  - Improved cathode spot mitigation

Next-Generation LHI Injectors

New Circular Injectors (1/2)





Prototype Non-Circular Injector



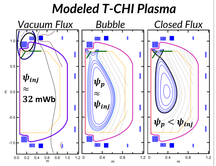
Coaxial Helicity Injection

- CHI starts plasmas by driving I_{inj}, reconnecting ψ_{inj} with electrodes
  - Two techniques: Transient, Sustained [4]
    - T-CHI: Rapid ψ injection; single reconnection event
    - S-CHI: Continuous helicity injection
  - Must satisfy Taylor limit and "bubble burst" condition

$$I_{inj} = I_{bb} = \frac{C\psi_{inj}^2}{\mu_0 d^2 I_{TF}}$$

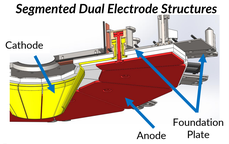
  - Scalings with footprint d critical test

Modeled T-CHI Plasma

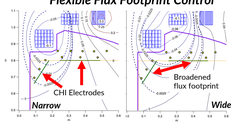


- PEGASUS-III to test novel CHI system with segmented dual electrodes [16–18]
  - No vessel breaks required
  - Support I_p to ~0.3 MA
  - Segmented design tests axisymmetry of current extraction, electrode materials
- PEGASUS-III B_T, divertor coils enable CHI studies
  - High $\psi_{inj} \rightarrow$ high I_p; flexible flux footprint
- First experiments planned target T-CHI
  - Flux conversion efficiency as function of d
  - Impurity production and control

Segmented Dual Electrode Structures



Flexible Flux Footprint Control



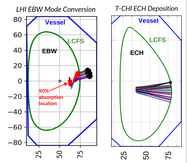
RF Heating and Current Drive

- PEGASUS-III B_T well-suited to 28 GHz RF heating and current drive [15]
  - System under design to provide > 0.1 MW to plasma
    - Low density: X2 electron cyclotron
    - High density: O-X-B electron Bernstein wave
  - 0.2 MW Varian gyrotron
  - 80 kV, 8 A power supply
  - Low field side launcher
- RF system supports HI experiments and can provide standalone startup
  - Synergistic effects with HI may include
    - Lowering resistivity/reduce helicity dissipation
    - Freezing low-inductance, helicity-driven current profile
    - Tailoring $J(R)$ to improve MHD stability
- RF modeling supports both EC, EBW scenarios
  - Post-heating of HI-produced targets
  - Favorable accessibility, propagation and absorption
- Near-term work will diagnose EBW emissions in LHI, CHI scenarios
  - Synthetic Aperture Microwave Imaging diagnostic on loan (U. York)
  - Results will inform launcher design

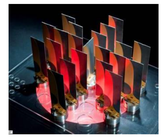
Varian Gyrotron



GENRAY Modeling



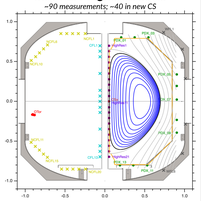
Vivaldi Antennas for SAMI



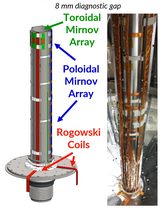
Diagnostic Systems

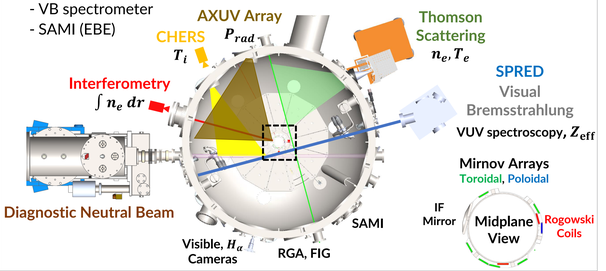
- New, improved diagnostic suite being fielded to support solenoid-free startup studies [19]
  - Kinetic equilibrium reconstruction
  - MHD activity associated with relaxation
  - Impurity content
  - Characterizing HI sources
- Refurbished / enhanced systems include
  - Internal magnetics
    - ~40 flux loops, ~45 Mirnov coils
    - 2 Rogowski coils, 3 diamagnetic loops
  - Thomson scattering [20]
  - Microwave interferometer
  - AXUV radiometry
  - SPRED VUV spectroscopy
  - High-speed visible imaging
  - Insertable probes
- New systems being deployed
  - Diagnostic neutral beam and CHERS [21]
  - LHI arc density
  - VB spectrometer
  - SAMI (EBE)

Internal Magnetics Suite
~90 measurements; ~40 in new CS



Centerstack Detail
8 mm diagnostic gap





Summary and Status

- New PEGASUS-III Experiment addressing solenoid-free startup challenge
  - **Solenoid-free** A ~ 1 spherical tokamak
  - Increased 0.6 T B_T; new divertor coils
  - LHI, CHI, & RF systems
  - Expanded diagnostic suite
- Entering commissioning phase
  - First plasma expected 4Q 2022
- First operations planned 1Q 2023
  - Initial campaign: LHI at increased B_T

PEGASUS-III Team



References: [1] J.E. Menard *et al.*, Nucl. Fusion **56**, 106023 (2016); [2] J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019); [3] M.W. Bongard *et al.*, Nucl. Fusion **59**, 076003 (2019); [4] Raman and Shevchenko, Plasma Phys. Control. Fusion **56**, 103001 (2014); [5] A.C. Sontag *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3184626; [6] M.W. Bongard *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3165694; [7] Goetz *et al.*, CP11.00041; [8] Sontag *et al.*, CP11.00045; [9] G.M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021); [10] Weberski *et al.*, CP11.00049; [11] Richner *et al.*, Phys. Rev. Lett. **128**, 105001 (2022); [12] Sassella *et al.*, CP11.00048; [13] Schaefer *et al.*, CP11.00047; [14] Rodriguez Sanchez *et al.*, CP11.00050; [15] Peery *et al.*, CP11.00042; [16] Reusch *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3171510; [17] Reusch *et al.*, CP11.00044; [18] Raman *et al.*, CP11.00053; [19] Nornberg *et al.*, CP11.00046; [20] Tierney *et al.*, CP11.00051; [21] Keyhani *et al.*, CP11.00052

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