# Progress and Plans for Solenoid-Free Startup in the Pegasus-III Experiment

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Pegasus-III Experiment

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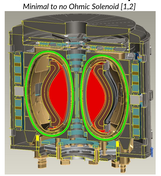
*65th Annual Meeting of the APS Division of Plasma Physics, Denver, CO, Presentation YP11.00029, 3 November 2023*

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## Pegasus-III: US Platform for Solenoid-Free Startup Studies

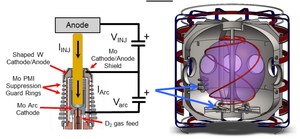
- Solenoid-free startup can reduce cost, complexity of tokamak pilot plants
  - Critical to spherical tokamak concepts
    - Nuclear STs preclude OH due to shielding / cost
    - Solenoid, if available, insufficient for full $I_p$ ramp-up
  - Benefits tokamaks generally
    - Space for inboard shielding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

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



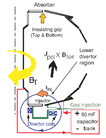
- New PEGASUS-III facility enables comparative startup studies
  - Compare / contrast / synergistically combine solenoid-free startup concepts

***LHI***

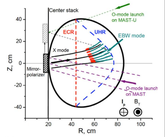





***CHI***




***Radiofrequency***




***Helicity Injection***

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

***Radiofrequency***

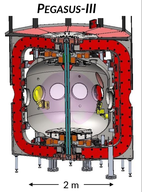
- Ionize gas; ramp to desired plasma configuration
- EC, LH, EBW [4]
- Potential synergies with HI startup

## Upgrade / Initial Commissioning Complete

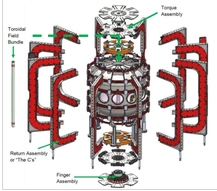
- PEGASUS-III upgrade retains A ~ 1 with solenoid-free central column [5-7]
  - $B_T$ capable of 0.6 T
  - 6 new divertor coils
  - Diagnostic neutral beam
  - Expanded diagnostics
  - 175 MVA controlled power
  - 8.5 MJ stored energy
  - Fully digital control systems
  - LHI, CHI, and RF systems
  - See [YP11.30, YP11.31]

| Parameter | PEGASUS | PEGASUS-III |
|---|---|---|
| $I_{TF}$ [MA] | 0.288 | 1.15 |
| $N_{TF}$ | 12 | 24 |
| $\psi_{sol}$ (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***



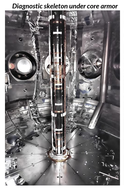

***Major Upgrade Component Assemblies***




***New Power Switchyards***



***Vessel Interior***
*Diagnostic skeleton under core armor*



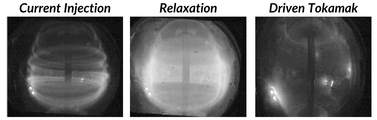
***Vessel Exterior***



## Local Helicity Injection Operating

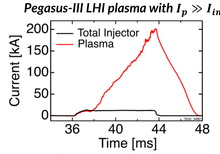
- New system reliably produces solenoid free high $I_p$ plasmas [YP11.32-34]

***Current Injection*** | ***Relaxation*** | ***Driven Tokamak***



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

***Pegasus-III LHI plasma with $I_p \gg I_{inj}$***

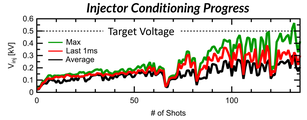



- New high power LHI system deployed and fully commissioned
  - Four-injector array for initial operation
    - Two arrays of two 4 cm² injectors
    - New $I_{inj}$ bias power supplies [6]
    - Achieved highest $I_p$ to date from LFS LHI
    - Injectors conditioned in < %5 of lifetime

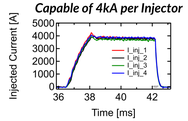
***Next-Generation LHI Injectors***



***Injector Conditioning Progress***




***Capable of 4kA per Injector***




- 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: $I_p(t)$

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

- 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
  - $Z_{inj} = Z_{inj}(n_{arc}, n_{edge}, \ldots)$

***Outstanding Issues***

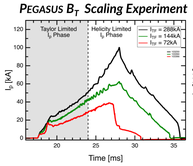
- Scaling to high $I_p$, $B_T$
- Confinement, impurities, and helicity dissipation
- Current drive mechanism
- Handoff to non-inductive sustaining current drive

- Tests at higher $B_T$ are key
  - Favorable $I_p(B_T)$ scaling: Increased $I_{TL}$
  - Confinement, heating, dissipation [8]
  - Extend models of LHI current drive [9]
  - Assess, mitigate impurity production
  - Facilitate RF heating and current drive
  - Overlap $B_T$ with NSTX-U, MAST-U

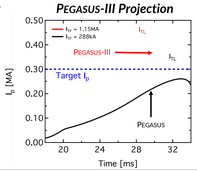
***Projections of Core Confinement Models***

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

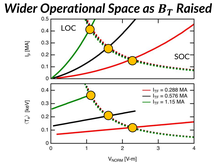
***PEGASUS $B_T$ Scaling Experiment***




***PEGASUS-III Projection***




***Wider Operational Space as $B_T$ Raised***



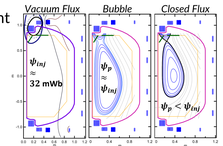

## Coaxial Helicity Injection in Development

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

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

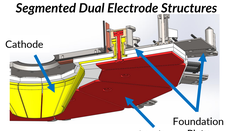
  - Scalings with footprint $d$ critical test

***Modeled T-CHI Plasma***



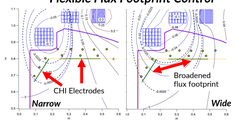

- PEGASUS-III to test novel CHI system with segmented dual electrodes [7]
  - No vessel breaks required
  - Support $I_p$ to ~0.3 MA
  - Segmented design tests axisymmetry of current extraction, electrode materials

***Segmented Dual Electrode Structures***




- 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

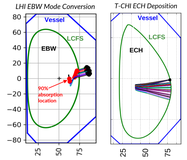
***Flexible Flux Footprint Control***



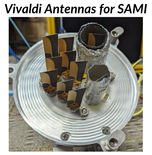

## RF Heating and Current Drive Planned

- PEGASUS-III well-suited to 28 GHz RF heating, current drive
  - 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 [YP11.39]
  - Synthetic Aperture Microwave Imaging diagnostic on loan (U. York)
  - Results will inform launcher design
- 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

***GENRAY Modeling***




***Vivaldi Antennas for SAMI***



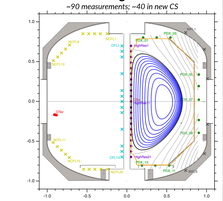
***Varian Gyrotron***



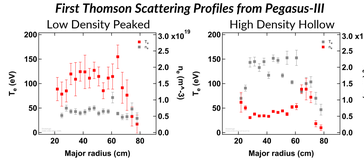
## Major Diagnostic Systems Deployed

- Diagnostic deployed for first operations [YP11.35]:
  - Internal magnetics [YP11.37]
    - ~40 flux loops, ~45 Mirnov coils
    - 2 Rogowski coils, 3 diamagnetic loops
  - Thomson scattering [YP11.40]
  - Microwave interferometer
  - AXUV radiometry
  - SPRED VUV spectroscopy
  - VB spectrometer
  - High-speed visible imaging
  - Insertable probes [YP11.38]
  - SAMI (EBE) [YP11.39]

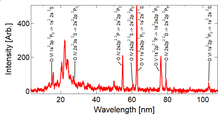
***Internal Magnetics Suite***
*~90 measurements; ~40 in new CS*



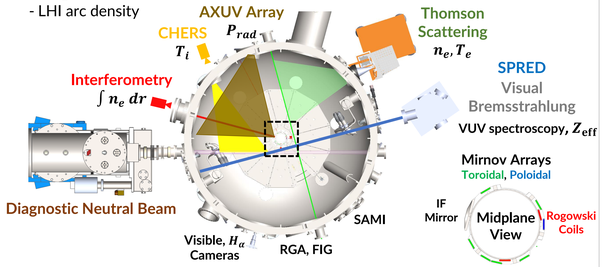
***First Thomson Scattering Profiles from Pegasus-III***




***First Pegasus-III VUV Spectra are Li-like & Be-like Oxygen Dominated***




- New systems being developed and commissioned
  - Diagnostic neutral beam and CHERS
  - LHI arc density




## Summary and Plans

- New PEGASUS-III Experiment addressing solenoid-free startup challenge
  - **Solenoid-free** A ~ 1 spherical tokamak
  - Increased $B_T$ capability to 0.6 T; new divertor coils
  - LHI, CHI, & RF systems
  - Expanded diagnostic suite
- LHI operations underway
  - High-$I_p$ solenoid-free plasmas achieved; starting science operations
- Increase $B_T$ to full 0.6T rating planned for the near term
- Advanced LHI and CHI installs planned for calendar year 2024
- New diagnostics neutral beam and diagnostics also planned for 2024

*Reprints available at https://pegasus.ep.wisc.edu/technical-reports.*

**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] Reusch *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3171510; [8] G.M. Bodner *et al.*, Phys. Plasmas **28**, 102504 (2021); [9] Richner et al., Phys. Rev. Lett. **128**, 105001 (2022);