Solenoid-Free Startup at Increasing B_T in the Pegasus-III Experiment

M.W. Bongard, M.W. Aslin, M.T. Borchardt, S.J. Diem, J.A. Goetz, B.A. Kujak-Ford, B.T. Lewicki, M.D. Nornberg, J.K. Peery, S. Redd, J.A. Reusch, C. Rodriguez Sanchez, C.E. Schaefer, A.C. Sontag, T.N. Tierney, and J.D. Weberski

Pegasus-III Experiment

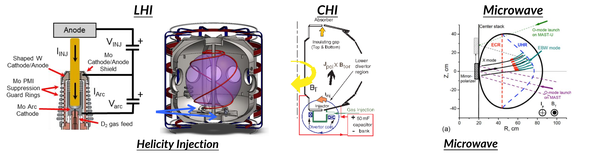
Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

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Non-Solenoidal Startup Benefits Spherical, Advanced Tokamaks

- Eliminating need for central solenoid reduces cost, complexity of tokamak pilot plants
  - Critical to nuclear ST concepts where center column space is limited [1,2]
- Pegasus-III objective: develop physics and technology basis of solenoid-free startup
  - Demonstrate, compare and/or combine techniques in single dedicated facility



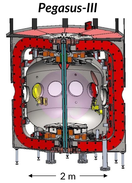
- Drives current on SOL open field lines
- Local Helicity Injection (LHI) [3]
- Coaxial Helicity Injection (CHI) [4]
- Ionize gas; ramp to desired plasma configuration
- EC, LH, EBW [4]
- Potential synergies with HI startup

Pegasus-III Enables High-B_T Comparative Startup Studies

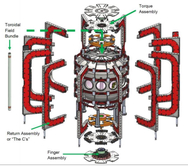
- Upgrade retains A ~ 1 with ***solenoid-free*** centerstack [5-7]
  - B_T capable of 0.6 T
  - 6 new divertor coils
  - Expanded diagnostics
  - 175 MVA controlled power
  - 8.5 MJ stored energy
  - Fully digital control systems
  - LHI, CHI, and microwave systems
  - Diagnostic neutral beam
  - See [JP12.70, JP12.73]

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 [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
A	1.15	1.18

Pegasus-III



Major Upgrade Component Assemblies



New Power Switchyards



Vessel Interior
Diagnostic skeleton under core armor



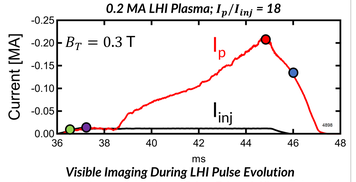
Vessel Exterior



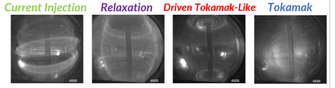
Extending LHI Physics to B_T > 0.15 T

- High-I_p scenarios established
  - 0.23 MA at 0.3 T
  - 0.13 MA at 0.6 T to date
- New 4 cm^2 injector systems reliably operate at B_{inj} = 0.33 T
  - Consistent with low-I_p Pegasus HFS injectors at R_{inj} = 0.17 m
- Relaxation more challenging
  - Expected with increased B_T from pitch angle considerations [JP12.66]
  - Revised LFS injector geometry considered

0.2 MA LHI Plasma; I_p/I_{inj} = 18

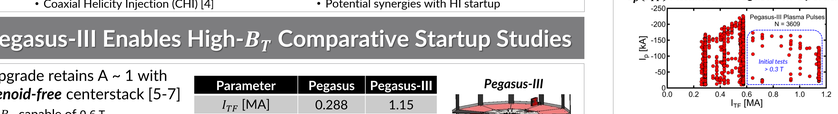


Visible Imaging During LHI Pulse Evolution



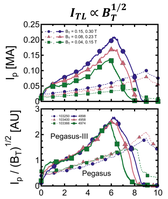
$I_p \sim N_{turns}\, I_{inj}$ | $I_p \gtrsim N_{turns}\, I_{inj}$ | $I_p \gg N_{turns}\, I_{inj}$ | $I_{inj}, V_{inj} = 0$

$I_p(I_{TF})$ Attained in Pegasus-III Operations

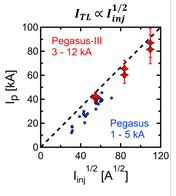


- Experimental tests of Taylor limit extended with new capabilities
  - $\sqrt{B_T}$ scaling expanded via experiments on Pegasus, Pegasus-III
  - $\sqrt{I_{inj}}$ expanded via power systems
  - $\sqrt{1/w_{inj}}$ varied via injector ΔR_{inj}

$I_{TL} \propto B_T^{1/2}$

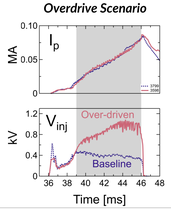


$I_{TL} \propto I_{inj}^{1/2}$

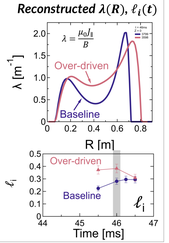


- High helicity input allows study of Taylor-limited plasma phenomena
  - V_{inj} scan with fixed shape, B_T, I_{inj}, $l_p(t)$
  - Low-frequency $n = 1$ $\tilde{b}$ burst amplitude correlated with excess applied drive
    - T_{burst} correlated with surplus drive
    - Little change in intermediate-high f $\tilde{b}$
  - Overdriven scenarios have higher ℓ_i
    - Core $\lambda = \mu_0 I_t / B$ flattening

Overdrive Scenario



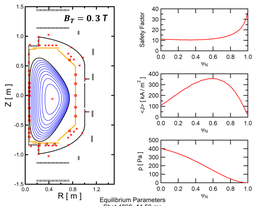
Reconstructed $\lambda(R)$, $\ell_i(t)$



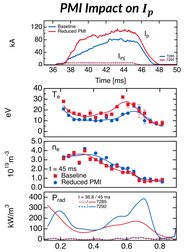
Enhanced and Upgraded Diagnostics Fielded

- Commissioned magnetics for equilibrium reconstruction and low-frequency (< 200 kHz) MHD measurements [8]
  - Flux loops: 33 in-vessel, 16 ex-vessel
  - B_p coils: 34 in poloidal array; 6 coil HFS and LFS toroidal arrays
  - 3 diamagnetic loops; 2 plasma Rogowski coils
  - Combined location / calibration error ~1%
- Thomson scattering system brought into routine operation
  - LHI densities > 3 × 10^{19} m^{-3} observed as B_T increases [JP12.70]
- Impurity diagnostic suite fielded to constrain impurity transport modeling [9]
  - 32 channel AXUV diode array
  - SPRED VUV spectrometer
  - Visible spectrometer
  - Fast NIR / D_α photodiode system
  - Initial measurements identifying Ti from injector-limiter PMI as source [JP12.68]
- Systems under development for microwave, ion dynamics studies
  - SAMI EBE diagnostic to assess, optimize antenna positioning for EBW injection [JP12.72]
  - Neutral particle analyzer to provide line-of-site main ion T_i for reconnection heating [JP12.69]
  - Diagnostic neutral beam [CHERS]

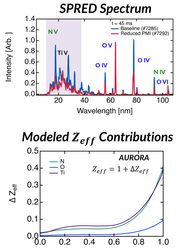
Reconstructed 0.2 MA LHI Plasma



PMI Impact on I_p

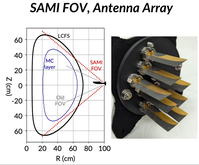


SPRED Spectrum



Modeled Z_{eff} Contributions

SAMI FOV, Antenna Array



CNPA On Test Stand



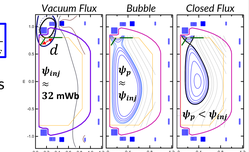
Upcoming CHI and Microwave Capabilities

- CHI starts plasmas by driving I_{inj}, reconnecting ψ_{inj} via electrodes [4]
  - Satisfies Taylor limit, "bubble burst":
  - Scalings with footprint d critical test

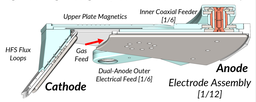
$$I_{inj} = I_{bb} = \frac{C\psi_{inj}^2}{\mu_0^2 d^2 I_{TF}}$$

- Novel CHI system with dual segmented electrodes capable of 0.3 MA I_p in fabrication [7]
  - No vessel breaks required
  - Tests axisymmetry of I_{inj} extraction, electrode materials
- Pegasus-III B_T, divertor coils enable CHI studies
  - High $\psi_{inj} \rightarrow$ high I_p; flexible flux footprint
  - Embedded magnetics to diagnose d
- First experiments planned target T-CHI
  - Flux conversion efficiency as function of d
  - Impurity production and control

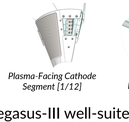
Modeled T-CHI Plasma



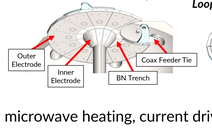
Engineering Design of CHI Electrode Assembly



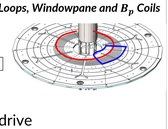
Cathode Assembly with Embedded Magnetics



Dual-Electrode CHI System

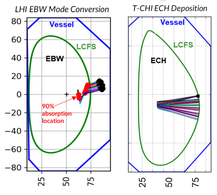


Buried UHMW Plate Embeds Flux Loops, Windowpane and B_p Coils



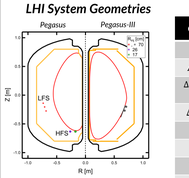
- Pegasus-III well-suited to 28 GHz microwave heating, current drive
  - Modeling supports both EC, EBW scenarios [JP12.72, JP12.73]
  - Post-heating of HI-produced targets
  - Favorable accessibility, propagation and absorption
- System in design to deliver > 0.1 MW [JP12.73]
  - Low n_e: X2 electron cyclotron; High density: O-X-B EBW
  - 0.2 MW gyrotron, 80 kV, 8 A power supply, LFS launcher
- Microwave system supports HI experiments, provide standalone startup
  - Lowering resistivity/reduce helicity dissipation
  - Freezing low-inductance, helicity-driven current profile
  - Tailoring $J(R)$ to improve MHD stability

GENRAY Modeling



High-Power LHI System Operated at 0.6 T B_T

LHI System Geometries



LHI System Design Metrics

Quantity	Pegasus LFS	Pegasus HFS	Pegasus-III LFS	Pegasus-III LFS-NC
N_{inj}	≤ 3	≤ 2	≤ 4	1
A_{inj} [cm^2]	2	4	4	16
$\Delta R_{inj} \propto w_{inj}$ [cm]	1.60	2.26	2.26	1
ΔZ_{inj} [cm]	1.60	2.26	2.26	16
R_{inj} [m]	0.70	0.26	0.70	0.70
B_{inj} [T]	≤ 0.08	≤ 0.22	≤ 0.33	≤ 0.33
V_{inj} [kV]	≤ 1.5	≤ 1.5	≤ 1.5	≤ 0.5
ΣI_{inj} [kA]	6	8	16	8
ΣP_{inj} [MW]	9	12	24	4
$\Sigma I_{inj}/\Delta R_{inj}$ [kA/cm]	3.8	3.5	7.1	16

LHI Injector Technology Evolution



Taylor Relaxation: Maximum I_p

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

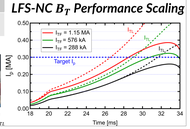
Helicity Conservation: Effective V_{loop}

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

Coupled Power Balance: $I_p(t)$

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

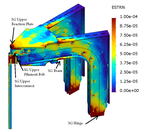
LFS-NC B_T Performance Scaling



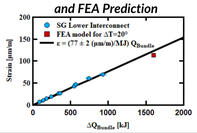
Facility TF Improvements, 1.15 MA I_{TF} Commissioning, and Ongoing Magnet Upgrades

- Fielded instrumentation, cooling system to support 0.6 T operations
  - 10 kW chilled water cooling system
  - Strain gages, thermocouples on key structures/locations to validate FEA models from design
- Power system/TF electrothermal model verifies long-pulse operation capability
  - Predicts H-bridge, bundle element thermal losses over I_{TF} pulse (≤ 225 ms)
  - Active cooling required for B_T > 0.3 T to avoid thermal ratcheting
- Thermal stress modeling validated
  - Thermal resistance, capacitance calibrated from experiment and agree with time-dynamic simulations

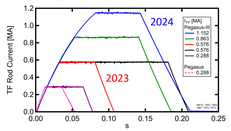
Sensor Locations Maximize Sensitivity



Strain Measurements and FEA Prediction



TF Current, Power Commissioned for 0.6 T



- TF commissioned to 0.6 T
  - Observed strain, ΔT within FEA predictions
  - Power system performance agrees with model
- Torsion-based failure encountered at bundle-finger joint
  - ~200 pulses above 0.3 T prior to event
  - Silver meshes at bundle-finger interface shorn, migrated → turn-turn short via air arc
  - Unexpected torsion of bundle by ≤ 5/8° observed

Finger-Bundle Interface

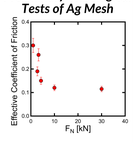


New Torque Arrestor and Revised Finger Assembly



- Refactored TF joint assembly in fabrication
  - Torque arrestor to prevent rotation and improve alignment of bundle-finger interface
  - New finger interconnect assembly
    - Fabricate from Cu (vs prior Al) to improve thermal, electrical response given improved supply chain
    - Tighter mechanical tolerances on nose cone radius
  - New finger-bundle interface approach
    - Glidcop foil vs silver mesh (working) preferred
    - Material TBD pending ongoing tribology tests [10]

Preliminary Tribological Tests of Ag Mesh



First Pegasus-III Run Campaign Extended LHI To High B_T

- Pegasus-III Experiment addressing solenoid-free startup challenge for tokamaks
  - **Solenoid-free** A ~ 1 spherical tokamak
  - Increased B_T capability to 0.6 T; new divertor coils
  - LHI in operation, CHI in fabrication, 28 GHz microwave design maturing
- 2023-24 research campaign extended LHI from 0.15 → 0.6 T
  - Validated Taylor limit scalings for B_T, I_{inj} in expanded operating space (B_T < 0.3 T)
  - I_p to date consistent with injector capabilities; projects to 0.3 MA
  - Scenarios developed for EBE / microwave design optimization studies
- Expanded diagnostic suite supports detailed physics studies
  - Magnetics, Thomson scattering, impurity quantification/dynamics, EBE systems fielded
  - Ion-channel diagnostics in development (NPA, DNB/CHERS)
- Refactored TF joint assembly, non-circular LHI and CHI installs underway

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. **50**, 4009 (2022), doi: 10.1109/TPS.2022.3184626; [6] M.W. Bongard *et al.*, IEEE Trans. Plasma. Sci. **50**, 4021 (2022), doi: 10.1109/TPS.2022.3165694; [7] Reusch *et al.*, IEEE Trans. Plasma. Sci. **50**, 4015 (2022), doi: 10.1109/TPS.2022.3171510; [8] Reusch *et al.*, Rev. Sci. Instrum. **95**, 093518 (2024), doi:10.1063/5.0219341; [9] Rodriguez Sanchez *et al.*, Rev. Sci. Instrum. **95**, 083525 (2024), doi: 10.1063/5.0219339; [10] Kind acknowledgments to Profs. M. Eriten and C. Bronkhorst.

Reprints: