A Magnetic Diagnostic Suite for the Pegasus-III Experiment

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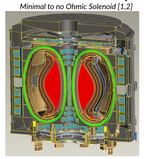
Pegasus-III Experiment

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UNIVERSITY OF WISCONSIN–MADISON

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

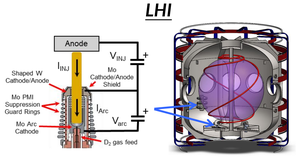
- Solenoid-free startup can reduce cost, complexity of tokamak pilot plants
  - Critical to spherical tokamak concepts
    - Nuclear STs preclude OH due to shielding / cost
    - Solenoid, if available, insufficient for full I_p ramp-up
  - Benefits tokamaks generally
    - Space for inboard shielding / 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

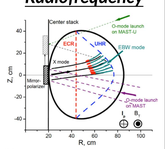
LHI



CHI



Radiofrequency



Helicity Injection

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

Radiofrequency

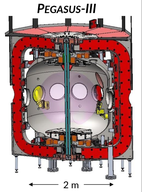
- Ionize gas; ramp to desired plasma configuration
- EC, LH, EBW [4]
- Potential synergies with helicity injection startup

Primary Upgrades Complete, Initial Operations Underway

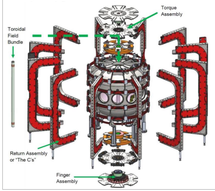
- PEGASUS-III upgrade retains A ~ 1 with solenoid-free central column [5-7]
  - B_T capable of 0.6 T
  - 6 new divertor coils
  - 8.5 MJ stored energy
  - 175 MVA controlled power
  - Fully digital control systems
  - New magnetic diagnostics
    - Switching noise immune
    - Arc/Bias noise immune

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



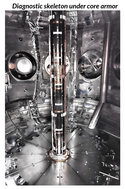
Major Upgrade Component Assemblies



New Power Switchyards



Vessel Interior
Diagnostic skeleton under core armor



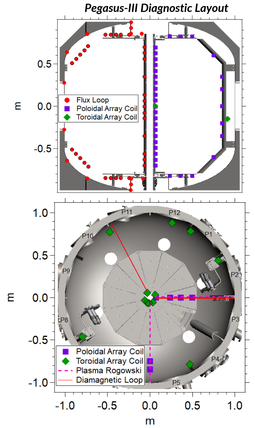
Vessel Exterior



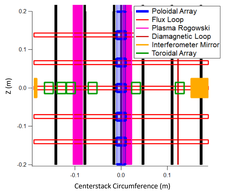
Expanded Magnetic Diagnostic Suite

- New central column installed
  - All magnetic diagnostics replaced or refurbished and shielded
- Magnetics suite designed to diagnose magnetic equilibrium and low frequency (< 200 kHz) MHD
- Installed magnetics:
  - 33 in-vessel flux loops
  - 16 ex-vessel flux loops
  - 34 poloidal array B-dot coils
  - 6 coil HFS and LFS toroidal arrays
  - 3 diamagnetic loops
  - 2 plasma Rogowskis
- Diagnostic locations measured in-vessel to ± 0.5mm, typically < 0.5%
- Combine location / calibration error ~1%

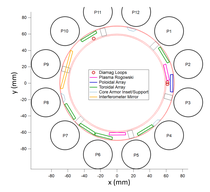
Pegasus-III Diagnostic Layout



Side view of Centerstack, midplane



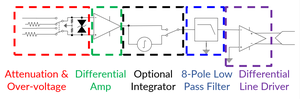
Centerstack Diagnostic Layout



Differential Signal Processing

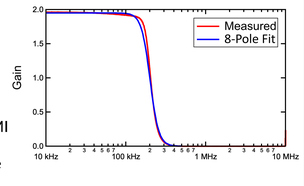
- Power supply switching noise requires fully differential signal chain
  - LHI arcs and unstable current streams generate additional EMI
  - Expect order unity noise up to several MHz

Signal Processing Chain



- Antialiasing and signal conditioning
  - 192 channels 16-bit sampling at 1MHz
  - 200 kHz 8-pole anti-aliasing filter
    - Cutoff chosen to keep fold back below 1-bit
  - NIM form factor
  - CAT7 double-shielded twisted-pair I/O
  - /1, /5, /20 voltage division
  - 100 Ohm signal termination impedance
  - Volt-level common-mode rejection for EMI
  - Gains measured to ~ 0.04% on average
  - Compact: system fits in 15U of rack space

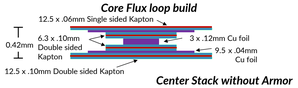
Realized Antialiasing Performance



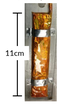
Full EMI Shielding for Noise Rejection

- Pegasus-II magnetic diagnostics were contaminated with V_{cm} driven EMI
  - Hard switching of buck convertor power supplies produced broadband noise
  - Back EMF from reconnecting injected current streams also generates EMI
  - Capacitively coupled $\frac{dV_{cm}}{dt} \sim 1kV/\mu s$
- Pegasus-III has more power systems + increased arc and bias currents
  - Magnets: 8 independent power supplies
  - LHI: 4 independent arc, 4 bias supplies

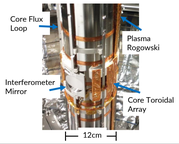
Core Flux loop build



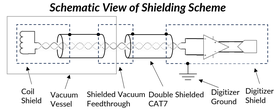
Outboard Toroidal Array Coil



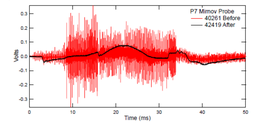
Center Stack without Armor



Schematic View of Shielding Scheme



Pegasus-II Data Showing Impact of Proper Shielding [8]

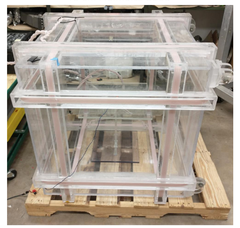


- Solution: Full end-to-end EMI shielding of magnetic suite
  - Signal runs made with 24awg shielded twisted pair
  - Low profile single turn core flux loop build via Kapton, Cu foil stack
  - 0.0254mm Cu foil wrap completes shield over coils (f_{cutoff}~834kHz)
  - 0.05mm Kapton foil wrap of coils for electrical isolation

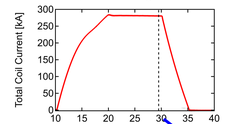
B-dot Coil and Plasma Rogowski Calibration

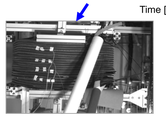
- Helmholtz cube for NA_{eff} calibration
  - Cube 0.43m on a side
  - Produces region of < 0.1% B field variation over volume of coils calibrated
  - RMS current in Helmholtz coil measured via shunt resistor with Agilent 34401A DMM
  - AC calibration: Textronix AFG 3011 into Peavey CS-800 audio amplifier as driver
  - NA_{eff} determined to 0.5%
- RMS voltage of coil under test measured with Agilent 34401A DMM

43 cm Helmoltz Cube



In-Vessel Coil for Plasma Rogowski Calibration





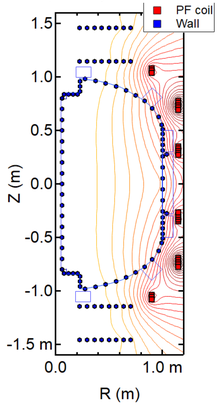


- Plasma Rogowski's calibrated in place
  - Temporarily installed a frame in-vessel
  - Wound a 20 turn coil on frame
  - Calibration made and verified up to 280kA
  - Linearity checked up to 54MA/s
  - 0.1% accuracy via transfer from calibrated Rogowski (PEM LFR 30/300)

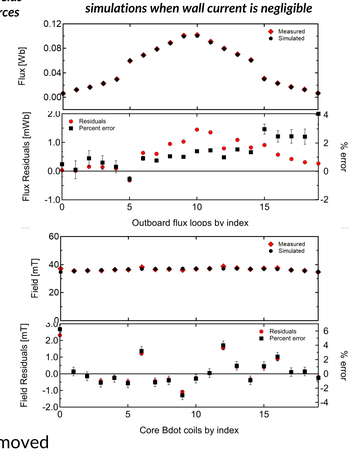
Measurements and Modelling Agree Well

- Pegasus-III has a toroidally continuous SS vessel
  - requires wall model for AC analysis
  - Quasi-DC analysis provides diagnostic position / calibration cross check
  - Modelled and measured values agree to better than 1.5% on average

Wall Code Provides Static and Dynamic Fields In-vessel from Axisymmetric Current Sources

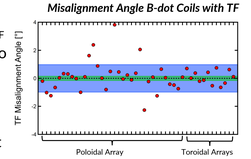


Measurements from diagnostics correspond with simulations when wall current is negligible



- TF pickup characterized/removed
  - TF pickup removed with empirically calibrated transfer function from measured I_{TF}
  - Shift/tilt errors and capacitive coupling lead to TF pickup in flux loops
  - B-dot coil misalignment → TF pickup
    - Typical coil misalignment < 1°
    - NA corrected to account for misalignment angle (worst case < 0.35% effect)

Misalignment Angle B-dot Coils with TF



Magnetic Diagnostic Suite Fully Commissioned

- Pegasus-III magnetic diagnostic set has been deployed and commissioned
  - 100 coils and flux loops deployed in vessel
  - Total measurement uncertainty < 1% for all signals
- Differential signal processing and end-to-end EMI shielding provide switching noise free measurements
- Measurement and modelling agree to better than 1.5% for majority of diagnostic signals
  - A scheme for TF pickup removal and NA correction has been implemented and can now automatically be applied
- Magnetic measurements now being used for fast boundary and Grad-Shafranov equilibrium reconstructions and MHD analysis

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] Bongard, M.W., *Edge magnetohydrodynamic instability studies in the Pegasus Toroidal Experiment* [Doctoral dissertation, University of Wisconsin-Madison]. ProQuest Dissertations and Theses Global.

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