Commissioning of Pegasus-III CODAC and Power Systems

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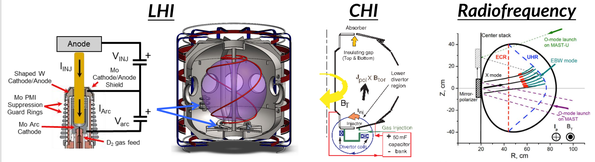
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Pegasus-III Experiment

Pegasus-III: A Platform for Solenoid-Free Startup

- Solenoid-free startup can reduce cost, complexity of fusion devices
  - Critical to the spherical tokamak, beneficial to tokamaks in general
- New Pegasus-III facility [1] enables comparative startup studies
  - Compare / contrast / synergistically combine startup concepts

LHI ***CHI*** ***Radiofrequency***



Helicity Injection

- Drives current on SOL open field lines
- Local Helicity Injection (LHI) [2,3]
- Coaxial Helicity Injection (CHI) [4–7]

Radiofrequency

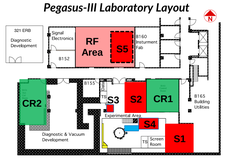
- Ionize gas; ramp to desired plasma configuration
- EC, LH, EBW [5]
- Potential synergies with HI startup

- Goal: Develop validated physics, technology basis for MA-class startup
- New control, data access, and communication (CODAC) and power systems [8] developed, commissioned to support first physics operation
  - Implementation comprises: >90 logical, >65 networked, >80 physical subsystems

Power Systems Upgraded and Expanded

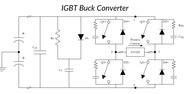
- Pegasus-III facility contains five new power supply switchyards [8]
  - Buck, multi-level buck, zero voltage switching active converters
  - Low-inductance capacitor bank
  - 155 MVA controllable power online
- New stored energy control systems
  - Voltage monitoring, charge/dump control
  - Switchyard-level control customizations
  - Total stored energy raised to ~8.5 MJ
  - Replaced Lumina charging actuators with Keysight, GW Instek supplies for reliability
- Digital/FPGA control systems online

Pegasus-III Laboratory Layout

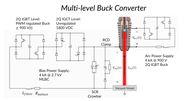


Yard	Drives	Topology	Status
S1	Electromagnets	Buck Converter	Operational
S2	LHI, S-CHI	Multi-level Buck Converter	Operational
S3	T-CHI	Low Inductance Capacitor Bank [RR]	Ready for Deployment
S4	DNB	ZVS Resonant Converter	In Development
S5	RF Sources	ZVS Resonant Converter	Planned

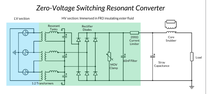
IGBT Buck Converter



Multi-level Buck Converter



Zero-Voltage Switching Resonant Converter



S1 Electromagnet Supplies



S2 Helicity Injection Supplies



S3 T-CHI Capacitor Banks



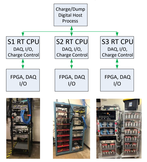
S4, S5 ZVS Prototype



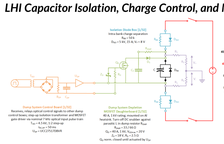
Facility Control Systems

- Multiple, distributed control systems implemented
  Stored energy management for capacitor banks
  - Operator interfaces: discharge configuration, execution
  - Digital / FPGA real-time feedback control, timing systems
  - Intra-shot fault detection and hardware protection
  - Laboratory CCTV, personnel access lockout system
- Distributed stored energy control systems
  - Switchyard-level real-time host with FPGA I/O
  - Logging of charge, operator state to SQL database

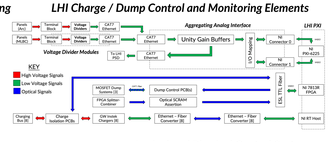
Distributed Charge Control, PSD Systems



LHI Capacitor Isolation, Charge Control, and Monitoring

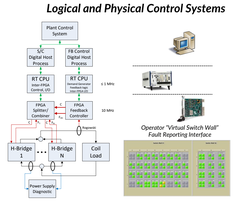


LHI Charge / Dump Control and Monitoring Elements



- Bridge sets monitored and controlled by distributed real-time and FPGA systems
  - Power converters may be parallelized for magnet, helicity injection loads
- Feedback and protection in LabVIEW
  - Feedback control: PID on load I/V
  - Splitter-combiner: Bridge interface, fault detection and protection logic
  - Power supply diagnostic system
- FPGA pulse-width modulation control
  - 16 coil set controllers, 25 kHz PID rate
  - 1Q, 2Q, 4Q, MLBC bridge set topologies
  - IGBT, IGCT power silicon communications
  - Over-current fault protection
  - Archival of feedback control state
- Timing, clocks, and triggering
  - FPGA timing, optical trigger distribution
  - GPS-synchronized absolute time triggering
  - IEEE 1588 timing grandmaster
- FPGA-based splitter-combiner system protects switching power amplifiers
  - Accepts bridge state commands from feedback controllers
  - Validates, multiplexes input to power Si
  - Monitors, aggregate reported fault metrics
- Fast shutdown sequences protect bridges under fault conditions
  - Aborts shot, dumps facility stored energy
- LHI injector cathode spot protection
  - Aborts shot (suppression of activity)
  - Planned: cathode spot mitigation

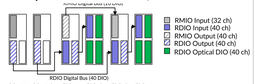
Logical and Physical Control Systems



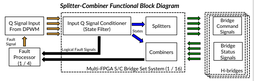
Feedback Controller Allowed Bridge States & Transitions



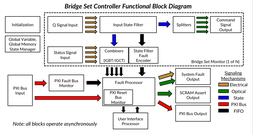
Splitter-Combiner FPGA, I/O Allocation



Splitter-Combiner Functional Block Diagram



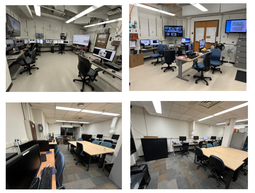
Bridge Set Controller Functional Block Diagram



Data Access and Communication

- Two control room areas built for facility operations, analysis
  - Stations for internal, external collaborators
  - Videoconferencing links between control rooms and/or off-site personnel
  - Layout partly driven by UW-Madison COVID-19 personnel density requirements

Main, Auxiliary Pegasus-III Control Rooms



- New physical data storage, backup, and access infrastructure implemented
  - Enterprise-grade Linux server
    - Version control, MDSplus, relational databases, file sharing, firewall, time synchronization, DNS, DHCP, backup
  - High-reliability RAID6 storage
    - 32 TB redundant, protected storage
    - 180 TB raw storage (3 locations)
    - Triplicate replication: on-, off-site
  - 10 Gb/s Ethernet laboratory data transport

Data Storage Systems



Laboratory Intranet Zones



- Data archival system updated for modern data digitization devices
  - All legacy CAMAC systems retired
  - 2G, 4G D-TACQ waveform digitizers
    - 480 channels, MHz-level, 16-bit
    - Six physical sites
  - PicoScopes for high-bandwidth signals

DAS User Interface



4G D-TACQ



2G D-TACQ



PicoScopes

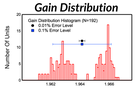


- Antialiasing and signal conditioning
  - 192 channels, 200 kHz 8-pole AAF
  - NIM form factor
  - CAT7 shielded Ethernet I/O
  - /1, /5, /20 voltage division
  - Differential line driver
  - Gains measured to ~ 0.04% on average

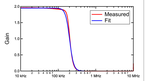
Signal Conditioning System



Signal Conditioner Gain Distribution



Antialiasing Performance

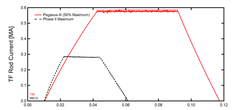


- Diagnostic control system integration API developed
  - LabVIEW network shared variables communicate shot status
    - Optional shot cycle hold if diagnostic encounters error
  - Multiple diagnostic interfaces developed for first run campaign
    - Thomson scattering, strain/temperature/vacuum/GDC, SPRED, VB, high-speed imaging, SAMI

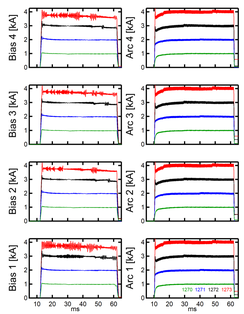
Pegasus-III Commissioning Complete

- CODAC integral to commissioning [9]
- Pre-integration component testing
  - Stored energy commissioning
  - Switchyard 1 individual power systems
    - Legacy IGBT bridges
    - New TF IGBT bridges
  - Switchyard 2 individual power systems
    - LHI arc IGBT bridges
    - LHI MLBC systems
  - Switchyard 3 individual power systems
    - T-CHI charge/dump
    - T-CHI firing waveforms
  - Divertor / EF coil assemblies
    - Operate to rated current, pulse length, mechanical stresses
    - Verify FEM stress modeling of clamp assemblies
- Post-assembly commissioning
  - Toroidal field verified to I_{TF} = 0.576 MA
    - 50% of Pegasus-III B_T for first physics ops
  - Electromagnet coil sets
    - EF23, EF45, EF67, Radial
  - Cross-field testing, strain verification
  - "Cu plasma" for magnetics calibration [10]
    - 0.3 MA-t driven; assists Rogowski, wall modeling

Pegasus vs. Pegasus-III TF Waveforms



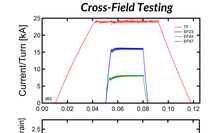
LHI MLBC Integrated Test Waveforms



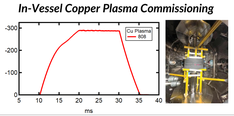
Ex-Situ DIV Assembly Testing



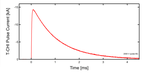
Cross-Field Testing



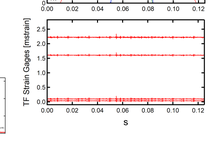
In-Vessel Copper Plasma Commissioning



T-CHI Test Fire



TF Strain Gages [mstrain]



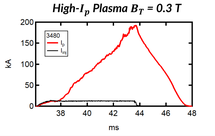
Control and Power Systems Support Pegasus-III Physics Mission

- New control and power systems fielded and verified for Pegasus-III Experiment
  - Multi-level buck converter, TF bridge technology brought to operation
- Digital control and protection systems online
  - Real-time, FPGA technology
- Robust data archival and access
  - High-reliability, high-availability storage
  - Fast on-, off-site access to authorized users
- Integrated commissioning complete and physics operations commenced [6,9]

Pegasus-III



High-I_p Plasma B_T = 0.3 T



References: [1] A.C. Sontag *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3184626; [2] M.W. Bongard *et al.*, Nucl. Fusion **59**, 076003 (2019); [3] Sontag *et al.*, YP11.00032; [4] Reusch *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3171510; [5] Raman and Shevchenko, Plasma Phys. Control. Fusion **56**, 103001 (2014); [6] Reusch *et al.*, YP11.00029; [7] Ingram *et al.*, YP11.00041; [8] M.W. Bongard *et al.*, IEEE Trans. Plasma. Sci. (2022), doi: 10.1109/TPS.2022.3165694; [9] Goetz *et al.*, YP11.00030; [10] Aslin *et al.*, YP11.00037

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