Digital Control and Power Systems for the PEGASUS-III Experiment

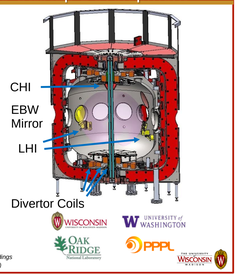
M.W. Bongard, M.T. Borchardt, S.J. Diem, R.J. Fonck, J.A. Goetz, A.K. Keyhani, B.A. Kujak-Ford, B.T. Lewicki, M.D. Nornberg, J.K. Peery, C. Pierren, J.A. Reusch, N.J. Richner, C.E. Schaefer, A.C. Sontag, J.D. Weberski

University of Wisconsin - Madison

*Work Supported by US DOE grants DE-SC0019008 and DE-SC0020402

PEGASUS-III Spherical Tokamak Is a Dedicated US Platform for Solenoid-Free Startup Development

- Major upgrade to the PEGASUS ST facility in progress*
  - 4× B_T, new divertor coils, increased pulse length
- Compare / contrast / combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - RF assist and sustainment (EBW presently, ECH, ECCD in future)
  - Assess compatibility with NBI heating and current drive
- Goal: develop validated physics and technology basis for MA-class startup on NSTX-U and beyond

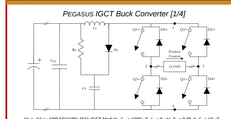


*Sontag et al., presentation 535, these proceedings
Garstka et al., Nucl. Fusion **46** S603 (2006)

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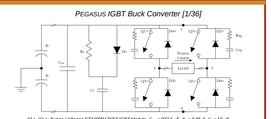
Modular IGBT and IGCT Buck Converters Drive Magnets and LHI

PEGASUS IGCT Buck Converter [1/4]



Q1 ± ,Q3 ±: ABB 5SHY35L4511 IGCT Module. C_r = 1000 μF, L_r = 5 μH, R_s = 0.65 Ω, C_s = 10 μF,
D_1, D2 ±, D4 ±: ABB 5SDF16L4503.

PEGASUS IGBT Buck Converter [1/36]



Q1±,Q3 ±: Eupec / Infineon FZ2400R17KE3 IGBT Module. C_{dc} = 937.5 μF, R_s = 0.65 Ω, C_s = 10 μF,
D_1, D2 ±, D4 ±: Dynex DSP21545SV. R_{sn} = 0.5 Ω, C_{sn} = 1.5 μF.

Q1±,Q3 ±: ABB 5SNA2600E170300 IGBT Module. C_{dc} = 1875 μF, R_s = 0.65 Ω, C_s = 10 μF,
D_1, D2 ±, D4 ±: Dynex DSP21545SV. R_{sn} = 0.5 Ω, C_{sn} = 1.5 μF.

- PEGASUS operated multiple 4 MVA IGBT, 12 MVA IGCT buck converter modules from 2004–2019
  - 1, 2, 4 quadrant topology
  - BT: Retained for PEGASUS-III PF
  - CT: Repurposed for LHI bias system
- New IGBT bridges built for PEGASUS-III
  - Longer pulse, newer Si
  - TF, MLBC arc supplies
- Semiconductors actuated optically via control system

PEGASUS IGCT Bridge



PEGASUS 2400A IGBT Bridge



PEGASUS-III 3600A IGBT Bridge

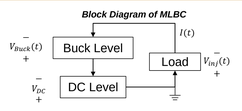


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Voltage Controlled Helicity Injection Enabled by New Multi-level Buck Converter (MLBC)

- $V_{inj}(t)$ during helicity injection → $I_p(t)$ control
  - Effective loop voltage $V_{eff} \propto V_{inj} A_{inj} B_T$
  - Sub-ms time response, low ripple desirable
  - Most efficient utilization increases $V_{inj}(t)$ and avoids overdrive of Taylor limit
- MLBC system to drive LHI, S-CHI startup methods
  - $V(t)$ regulating buck converter floats on DC level
  - 0–1800 V from IGCT level, ±900 $V(t)$ from IGBT level @ 4 kA
  - Driven by ~2 MJ capacitively stored energy
  - Initial pulse length 25 ms; future 50 ms
  - Four independently controlled converters, sub-ms timescale
- System in commissioning phase
  - Functionally verified at low voltage ~200 V
  - Day 1 stored energy fully built and commissioned
  - Charge/dump system verified

Block Diagram of MLBC



Constructed Power Supplies



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Zero Voltage Switching (ZVS) Resonant Converter to Power Diagnostic Beam and RF Sources

- DNB and RF source requirements
  - 5-10 A @ 60-90 kV
  - Low ripple (RF < 0.5%)
  - Load fault energy transfer < 5J
- Resonant converter meets requirements
  - Fast ramp times < 500 μs
  - Low voltage ripple
  - Up to 30× voltage gain
  - Low energy in HV stage
- Features
  - Low-voltage 3-phase IGBT-driven primary
  - ZVS switching increases working frequency
    - High frequency reduces HV stored energy
    - Improves passive fault safety
  - Oil-immersed HV resonant stage with rectifier and passive output filter
  - Ferrite core snubber load protection

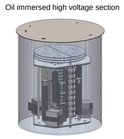
DNB requires a 60–80kV 5A-DC power supply



200 kW gyrotron requires an 80 kV, 8 A DC, <0.5% ripple



Oil immersed high voltage section



Low voltage section



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PEGASUS-III Will Initially Pursue Three Techniques







Local Helicity Injection

- Drives current on SOL open field lines
  - Small discrete injectors at boundary
  - Relaxation to tokamak via helicity-conserving instabilities
- I_p growth: sustained $V_{inj}(t)$, $I_{inj}(t)$

Coaxial Helicity Injection

- Drives current on SOL open field lines
  - Large axisymmetric electrodes
  - Drive 'flux bubble', reconnection
  - Sustained, transient approaches
- S-CHI I_p growth: sustained $V_{inj}(t)$, $I_{inj}(t)$

Radiofrequency

- Heating, current drive, and pure startup
  - Low n_e: Electron cyclotron
  - Higher n_e: Electron Bernstein wave
  - Potential synergies with HI startup

V ~ 1-2 kV, I ~ 10 kA, t_{pulse} ~ 25-100 ms | V ~ 0.5-1 kV, I ~ 20 kA, t_{pulse} ~ 25-100 ms | V ~ 60-90 kV, I ~ 5-10 A, $t_{pulse} \leq$ 100 ms

Bongard et al., Nucl. Fusion **59**, 076003 (2019) Raman and Shevchenko, Plasma Phys. Control. Fusion **56**, 103001 (2014)
Bongard et al., APS-DPP-CPP Initiative (2019)

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Bridge Sets Monitored and Controlled by Distributed Real-Time and FPGA Systems

- Buck converter systems connected in parallel to drive magnets and helicity injection systems
  - Output transmission lines balanced to mm length
- Feedback and protection logic implemented with real-time LabVIEW computers and FPGA modules
  - Feedback control RT host
    - PID feedback on load current or voltage
    - Over-current fault detection
  - Splitter-combiner RT host
    - Multiplex / demultiplex bridge signals
    - Fast fault response and shutdown
  - Power supply diagnostic system
    - Individual bridge waveforms recorded during pulse
- Digital host processes aggregate information and report to plant control system / data archival services
  - Configuration control, fault history, bridge-level waveforms

Logical and Physical Control Systems

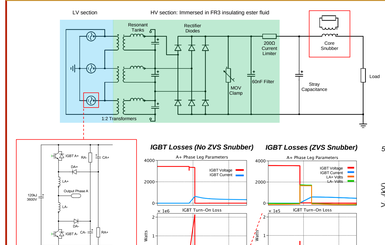
Operator "Virtual Switch Wall" Fault Reporting Interface

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New Multi-level Buck Converter (MLBC) Topology Used for LHI Bias

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ZVS Switching and Scalable Low-Ripple Operation Demonstrated at Low Voltage in Air

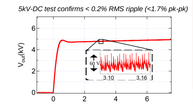


Test Power Supply Assembly (40nF Filter)



IGBT Losses (No ZVS Snubber) ***IGBT Losses (ZVS Snubber)***

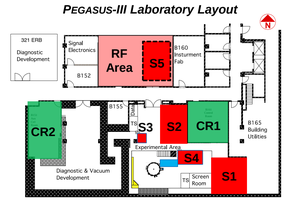
5kV-DC test confirms < 0.2% RMS ripple (<1.7% pk-pk)



Note: Increased filter C will further reduce ripple

Five Power Systems Support PEGASUS-III Operations and Diagnostics

PEGASUS-III Laboratory Layout



- Major reconfiguration for PEGASUS-III capabilities and COVID safety
  - One → five switchyard zones (red)
  - Expanded control room space (green)
  - New diagnostic neutral beam (blue)
  - New RF system space (pink)
- Switchyard zones integrate capacitor bank stored energy and power supplies

Yard	Drives	Topology
S1	Electromagnets	Buck Converter
S2	LHI, S-CHI	Multi-level Buck Converter
S3	T-CHI	Low Inductance Capacitor Bank*
S4	DNB	ZVS Resonant Converter
S5	RF Sources	ZVS Resonant Converter

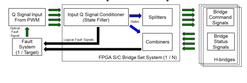
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*Reusch et al., presentation 497, these proceedings

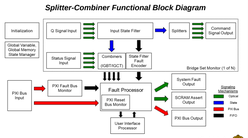
FPGA-Based Splitter-Combiner System Protects Switching Power Amplifiers

- Protection system implements a state-aware, bridge set controller
  - Accepts bridge state commands from feedback controller
  - Validates and multiplexes input to bridge command lines
  - Monitors and aggregates fault metrics from power Si
- Implements device-protecting fast shutdown sequences
  - Enforces minimum dwell times in given bridge state
  - Dwell suppresses any/all transients prior to fault entry
  - Worst-case response time: ≤10 μs (~ t_{RR} for Si)
- Prototype successfully tested on PEGASUS
  - FPGA-level independent three-target architecture
  - Filtered legacy analog feedback controller inputs
  - Reduced diode loss rate
- PEGASUS-III implementation expands functionality
  - New Real-time host ↔ FPGA architecture
    - 3 → 4 FPGA targets; 11 → 16 independent bridge sets
  - Fault sequence capture, logging, and reporting
  - "Virtual switchwall" user interface for operator fault reporting

Splitter-Combiner High-Level FPGA Architecture [1/16 Controllers]



Splitter-Combiner Functional Block Diagram

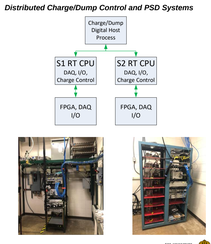


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Distributed Stored Energy Control System Implemented

- Standardized control for switchyard stored energy
  - New Lumina charging actuators with custom optical control
  - TF/PF S1: Re-use PEGASUS charge isolation, dump systems
  - LHI S2: Floating power supply with isolated charge, dump system
  - Expandable to T-CHI, DNB
- Real-time LabVIEW and FPGA modules with optical I/O
  - Plant safety interlock system interface
  - Optical control of charge actuators
  - Control of dump actuators
- Voltage monitoring and system state stored to SQL database
  - All capacitor bank voltage levels recorded at 1 Hz timescale
  - Derived metrics (bank stored energy) also logged

Distributed Charge/Dump Control and PSD Systems

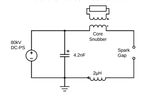


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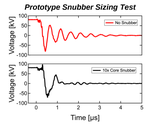
Core Snubber Protects Sensitive Loads Under Arc Fault Conditions

- Goal: rapidly dissipate stored energy in transmission line and HV stage parasitic capacitance
  - Current limiting R + snubber
  - Limit dissipation in load to ≤ 5 J
- Magnetic core stack inductively couples, damps high-frequency fault currents*
  - Number, material properties of cores balance dissipation capacity and working frequency
- Initial tests confirm choice of dual core materials and number of cores needed
  - Parasitics estimated in test circuit
  - Finemet, Deltamax cores

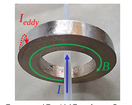
Core Snubber Test Circuit



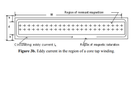
Prototype Snubber Sizing Test



Core Snubber [1 / N]



Tape-wound Toroidal Transformer Core
Fault current, Flux swing, Eddy current



*Fei et al., Plasma Sci. Technol. **15**, 459 (2013)
*Jiang et al., Rev. Sci. Instrum. **87**, 123302 (2016)

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PEGASUS-III Buck Converters Supply ~175 MVA of Programmable Power

	Load	Max Voltage [V]	Max Current [kA]	# H-bridges	Topology (Quadrants)	# of Si Devices	# of Control Channels	Capacitor Bank Stored Energy [kJ]*	Controllable Power [MVA]
Magnets (8 control sets)	EF123	900	16	4	2Q	8	16	336	14.4
	EF45	900	8	2	4Q	8	16	168	7.2
	EF678	900	16	4	2Q	8	16	336	14.4
	Divertor 1	900	16	4	2Q	8	16	336	14.4
	Divertor 2	900	16	4	2Q	8	16	336	14.4
	Radial	900	4	1	4Q	4	8	84	3.6
	Toroidal Field	900	48	12	2Q	24	48	2,784	43.2
	Stray Field Mitigation	900	4	1	4Q	4	8	84	3.6
Helicity Injection (8 control sets)	LHI Arc (×4)	900	4	1/set	2Q	2/set	4/set	84/set [336]	3.6/set [14.4]
	LHI, S-CHI Bias (×4)	2,700 (1800 ± 900)	4	2 + SCR crowbar/set	2Q IGBT, 2Q IGCT	6/set	10/set	422/set [1,688]	10.8/set [43.2]
Totals						104	200	6,488 (min) ~7,000 (avg)	172.8

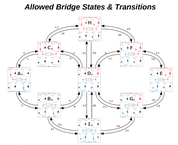
*Capacitor energy quoted as minimum; $W = W_{min} - 0/+30\%$; $W_{avg} = 1.08\, W_{min}$

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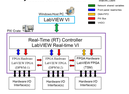
Fully Digital FPGA-Based Facility Timing and Control Systems Implemented for PEGASUS-III Operations

- Digital Feedback Controllers
  - 16 coil set controllers, 25 kHz PID loop rate
  - 1Q, 2Q, 4Q, MLBC bridge set topologies
  - IGBT, IGCT power silicon communications
  - Over-current fault protection
  - Archival of feedback control state
  - Expandable to more sophisticated feedback algorithms
  - Output coupled to splitter-combiner system
- Timing, Clocks, and Triggering
  - FPGA-generated timing, optical trigger distribution
  - GPS-synchronized absolute time triggering
  - Provides IEEE 1588 grandmaster for lab systems

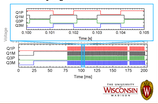
Allowed Bridge States & Transitions



Digital Feedback and Timing System Architecture



Q-Signal Generation

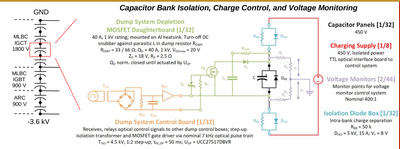


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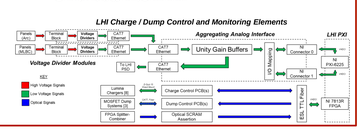
Isolated Capacitors in MLBC System Led to Modular Charge Control Strategy

- LHI, S-CHI bias requires floating energy storage
  - Four 8-stage capacitor banks in MLBC systems
  - 900 V arc
  - 900 V IGBT
  - 1800 V IGCT
- Isolated parallel bank charging
  - Custom optical control circuits driven by FPGA encoder
- Distributed bank-level dumping
  - Per-bank dump resistors and control circuits
  - Depletion MOSFET dump system allows trim of bank voltage
- Logical bank operator control
  - Arc, IGBT, IGCT charge / dump

Capacitor Bank Isolation, Charge Control, and Voltage Monitoring



LHI Charge / Dump Control and Monitoring Elements



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Multiple Power Systems Support PEGASUS-III Physics Mission

- 175 MVA of switching power amplifiers deployed for PEGASUS-III electromagnets and HI systems
  - Reallocating legacy PEGASUS systems
  - New TF bridge configuration
- Multi-level buck converter for advanced LHI $V_{inj}(t)$
- Zero voltage switching resonant converters for diagnostic beam and RF sources
  - Successful tests at low power; scaling to high voltage and reduced ripple
- Distributed energy storage and control systems developed
  - 7 MJ stored energy commissioned
- Digital control and protection systems implemented
  - Real-time computing and FPGA programmable hardware
  - 16 digital feedback controllers



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