Digital Control and Power Systems for the URANIA Experiment

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University of Wisconsin-Madison

28th IEEE Symposium on Fusion Engineering

2 - 6 June 2019
Ponte Vedra Beach, FL
Presentation P3-51



URANIA Experiment

Layout Slide (Include for Posters)

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
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Digital Control and Power Systems for the URANIA Experiment

URANIA: Non-Solenoidal Startup	Overview of Primary Power Supplies	Planned Digital Control Systems		Ćuk Topology: LHI/CHI Power Supply	DNB & EBW Power Supplies
URANIA: US Non-Solenoidal Startup Development	URANIA Power Systems to Supply ~280 MVA of Programmable Power	FPGA Power Supply Control System in Development	FPGA Controllers to Use Pulse Width Modulation (PWM) for Voltage Control	LHI Requires Low Ripple, Programmable $V_{inj}(t)$	DNB and RF to Provide Diagnostic, Plasma Heating & Current Drive
Local Helicity Injection (LHI) = Solenoid-Free Startup	Increased TF and Expanded PF Coil Sets Are Required	FPGA S/C Implementation Leverages LabVIEW & FPGA Parallelism	FPGA Controllers Will Use a Multitiered Architecture: Windows Host, RT Host, Target	Ćuk Power Supplies: Low Ripple, Variable Voltage Control	DNB and EBW: Zero Voltage Switching (ZVS) Resonant Converter
CHI Produces High-I_p with Axixymmetric Electrodes	TF & PF Coil Sets Require ~225 MVA of H-bridge Controllable Power	FPGA S/C Deployment Has Improved Device Protections	Bench Testing Will Leverage Coupled Simulation Capability	Ćuk Modularity Enables Parallel & Series Topologies	Resonant Converter Topology Well Suited for HV, Low Current Applications
EBW RF Heating & Current Drive		Improved Device Protection Example: Freewheeling Diode	Optically Transmitted Voltage Measurement in Development	Ćuk Flexibility Verified with Prototype Testing Into Resistive Load	Development and Deployment Plan for Power Supply & Control Systems

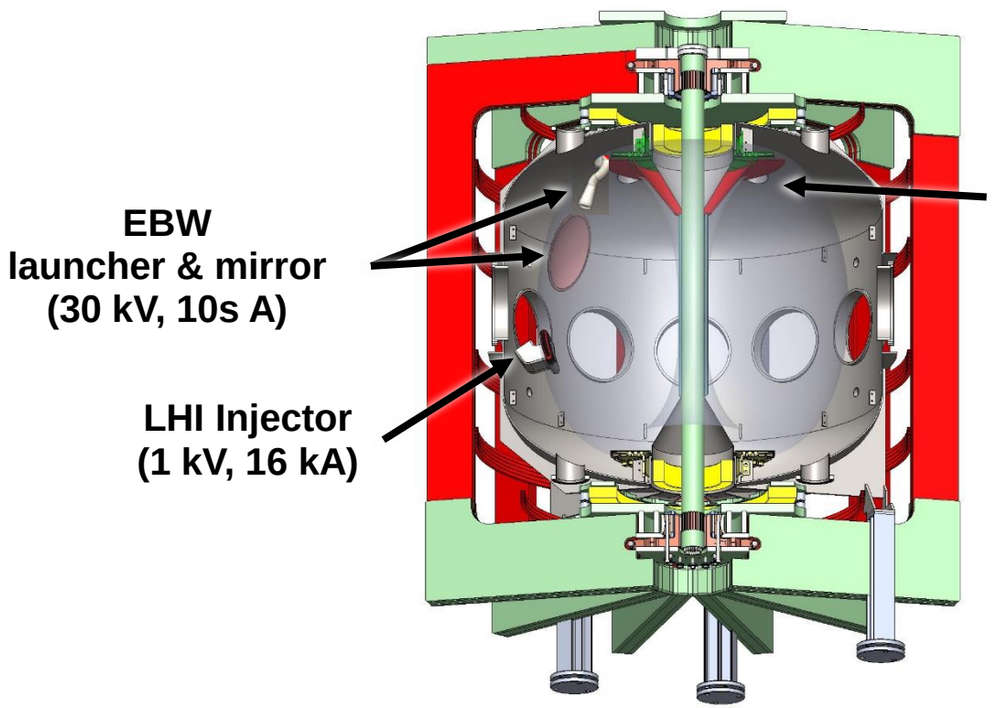


URANIA: Non-Solenoidal Startup

URANIA : US Non-Solenoidal Startup Development

- Converted PEGASUS facility *(J. A. Goetz, P2-65)*
  - $4 \times B_T$, increased pulse length $(50 - 100\ \text{ms})$
- Evaluate leading concepts for non-solenoidal startup in single dedicated facility
  - Local Helicity Injection (LHI)
  - Coaxial Helicity Injection (CHI)
  - Electron Bernstein Wave (EBW) startup and assist
  - Poloidal Field Induction
  - Future: NBI heating and current drive
- Develop common predictive understanding & experimental model validation of all approaches
- **Goal: develop validated concept, equipment for ~ 1 MA startup on NSTX-U and beyond**

$B_T \leq 0.6$T; Multi-coil Divertor
No OH solenoid



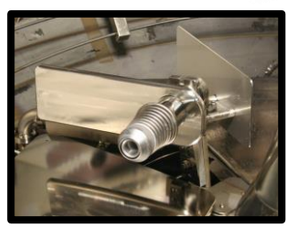
Collaborative Enterprise:

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
UNIVERSITY of WASHINGTON
OAK RIDGE National Laboratory
PPPL

Local Helicity Injection (LHI) = Solenoid-Free Startup



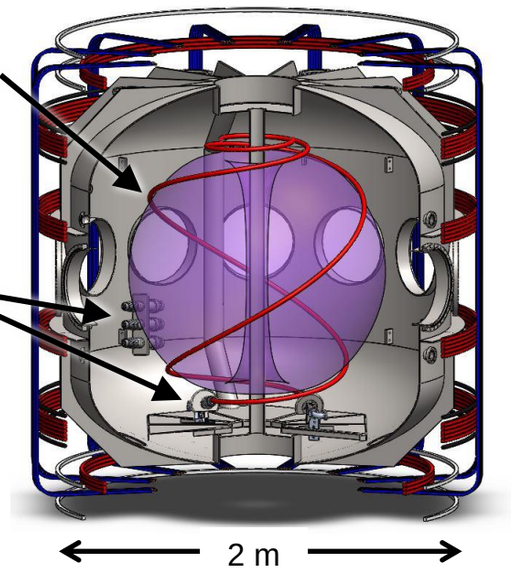
LFS System

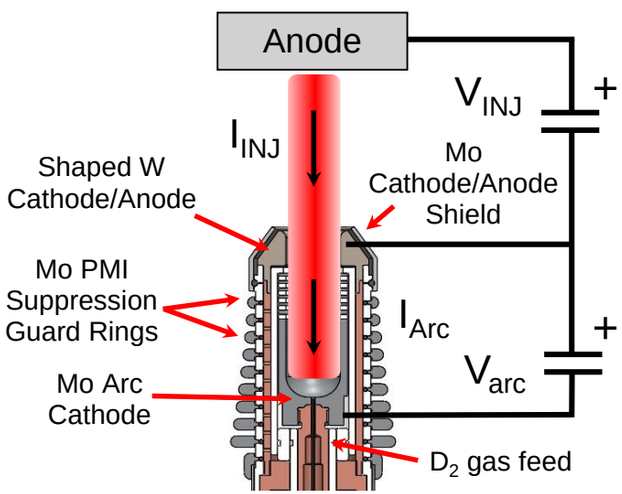


HFS System

Local Helicity Injectors

Injected Current Stream

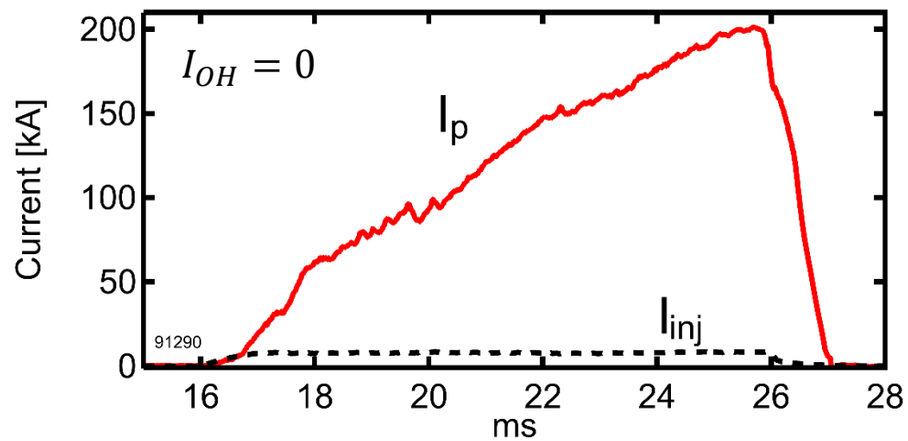




PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 14 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	= 2-4 cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

M.W. Bongard et al., Nucl. Fusion (2019)

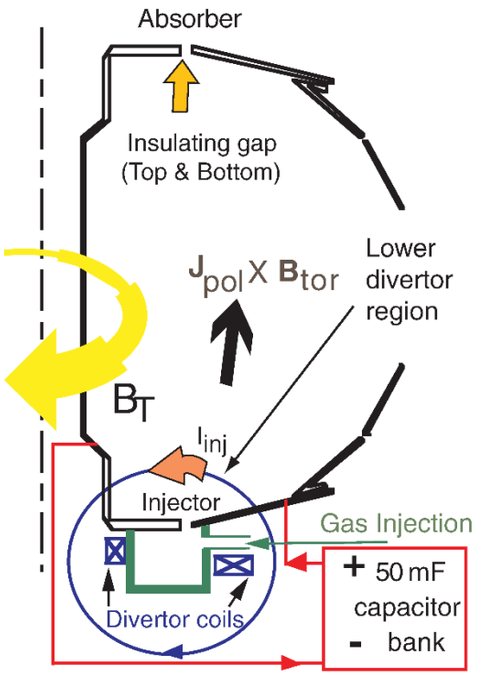
Non-Solenoidal I_p = 0.2 MA via LHI startup (I_{inj} ≤ 8 kA)

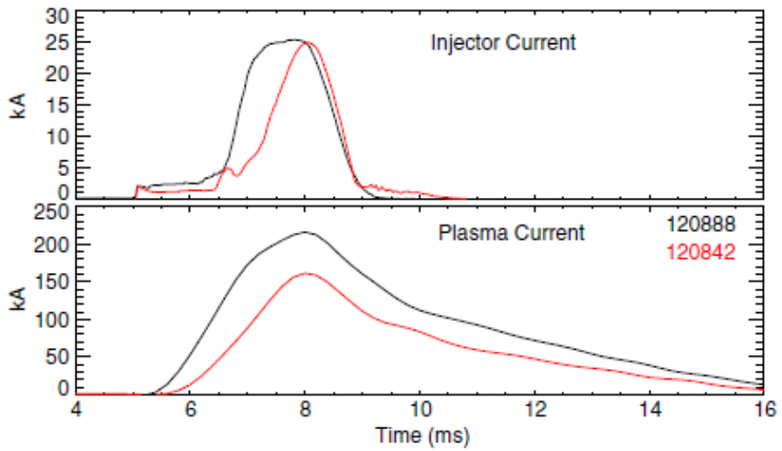


- LHI is promising method for solenoid-free startup
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - Global current limits from Taylor relaxation, helicity balance
  - Hardware retractable prior to nuclear phase in reactor
- Routinely used for startup on PEGASUS

CHI Produces High-I_p with Axisymmetric Electrodes

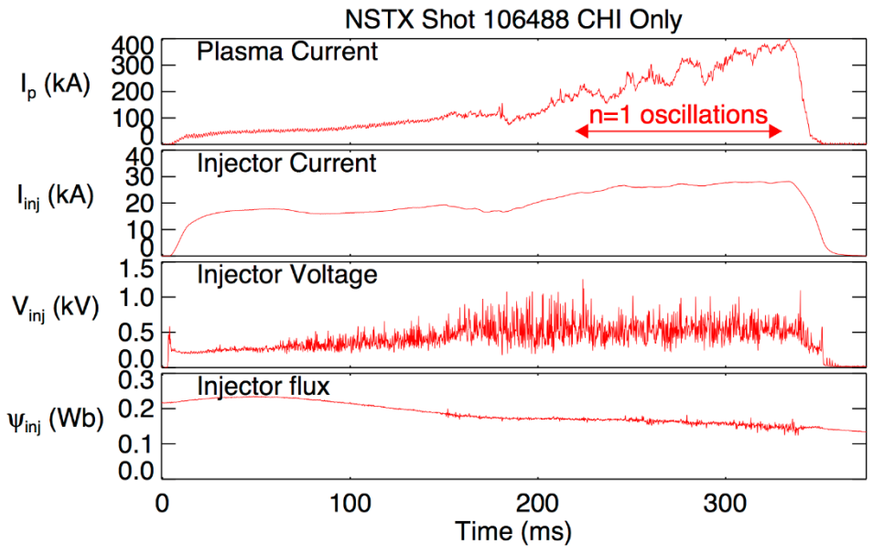
Transient CHI (NSTX Geometry)





*R. Raman et al., Nucl. Fusion **47,** 792 (2007)*

Sustained CHI (NSTX Geometry)

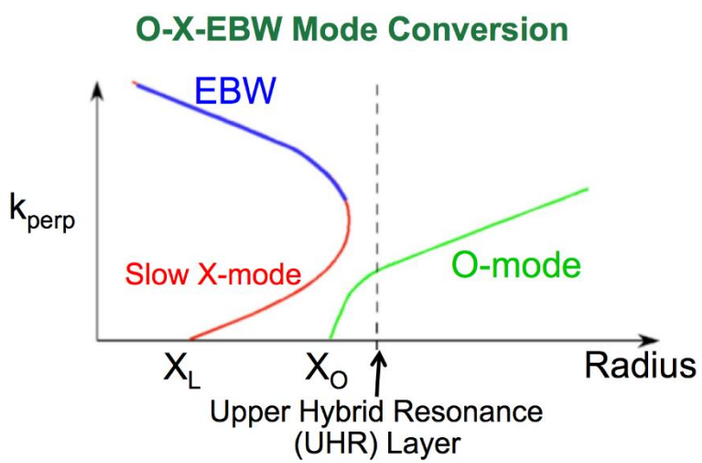


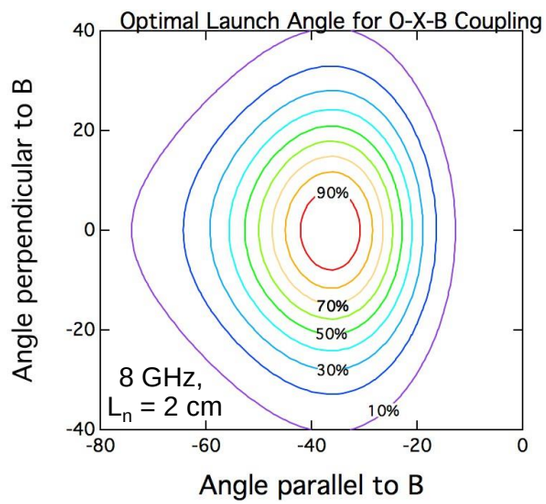
T. Jarboe et al., IAEA FEC 2002, IC/P-10

- CHI uses large-area, axisymmetric, passive electrodes to initiate I_p
- Relaxes to a tokamak like state forming closed-flux current
- Maximum I_p constrained by Taylor limit
- Hardware typically intrinsic to machine; retractable electrodes may be possible

EBW RF Heating & Current Drive

- EBW heating projected to assist LHI/CHI startup
- EBWs are perpendicularly propagating, electrostatic, hot plasma waves
  - Couple to and propagate in overdense plasmas $(\omega_{pe} > \Omega_{ce})$
  - Launched at plasma boundary as O- or X-modes and mode couple in plasma to EBW
  - Absorbed at Doppler-broadened resonance

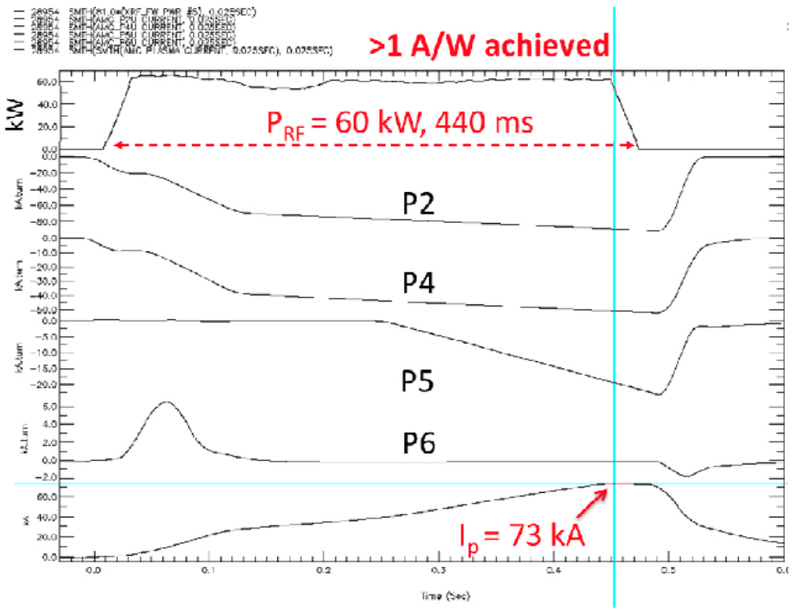




Courtesy of S.J. Diem, ORNL

- Pure EBW is startup method itself
  - Demonstrated on MAST

MAST EBW Startup



V.F. Shevchenko et al., EPJ Web of Conferences ***87****, 02007 (2015)*



Overview of Primary Power Supplies

URANIA Power Systems to Supply ~280 MVA of Programmable Power

	Summary of Planned URANIA Power Supply Systems								
	Load	**Max Voltage [V]**	**Max Current [kA]**	**# H-bridges / Ćuk Modules**	**H-bridge / Module Type**	**# of Si Devices**	**# of Control Channels**	**Capacitor Bank Stored Energy [MJ]**	**Controllable Power [MVA]**
PF Coil Sets	EF123	900	16	4	2 quadrant	8	8	0.337	14.4
	EF45	900	16	4	4 quadrant	16	16	0.337	14.4
	EF678	900	16	4	2 quadrant	8	8	0.337	14.4
	Divertor	900	16	4	2 quadrant	8	8	0.337	14.4
	Radial	900	4	1	4 quadrant	4	4	0.084	3.6
TF Coil Set	TF Charge	2,500	48	16	1 quadrant	16	16	1.685	120
	TF Sustain	900	48	12	2 quadrant	24	24	1.348	43.2
Helicity Injection*	LHI Arc (x2)	400	16	4/set	Ćuk	12/set	12/set	0.337	12.8/set
	LHI Bias (x2)	1,000	16	12/set	Ćuk	36/set	36/set	1.6	16/set
	Totals					**168**	**168**	**6.4**	**282**

LHI Ćuk power supplies will also be used to drive the sustained CHI system.

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Increased TF and Expanded PF Coil Sets Are Required

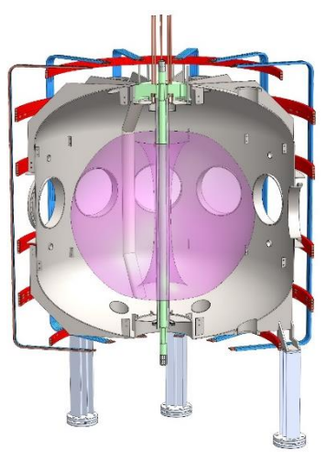
Increased Toroidal Field

- B_T increasing from 0.15 to 0.6 T
- Enables investigations of startup scaling:
  - Reconnection & relaxation requirements
  - Injector performance & PMI susceptibility
  - MHD dependence on B_T
  - Energy confinement
  - Confirm Taylor limit scaling with TF
- Will employ two-stage power supply
  - LC resonant drive for I_{TF} buildup
  - Switched H-bridge for I_{TF} sustainment

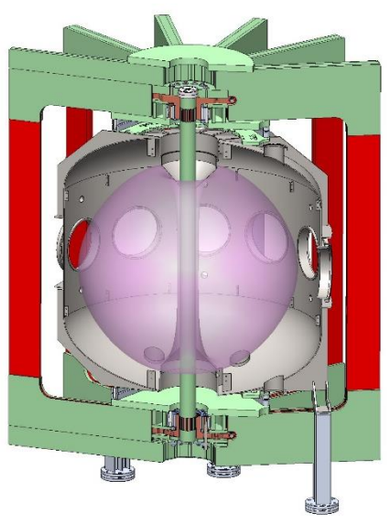
Poloidal Field Enhancement

- Upgrades to improve shape and position control
  - New Divertor coil set
  - Additional PF coils
  - New vertical position coil set
  - Mitigation of stray field at experimental site boundary

Comparison Of TF Coil Sets



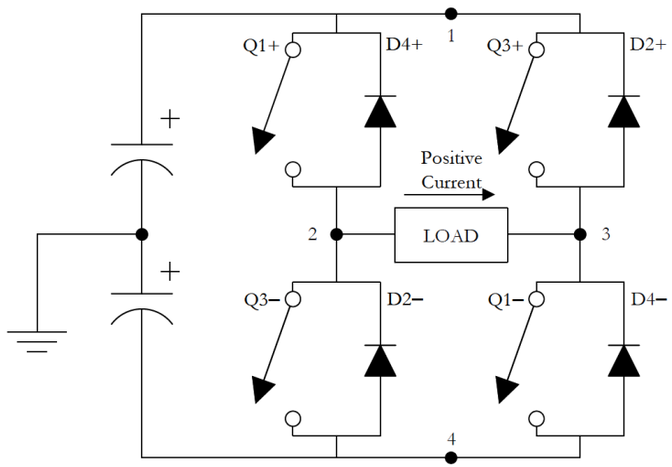
PEGASUS



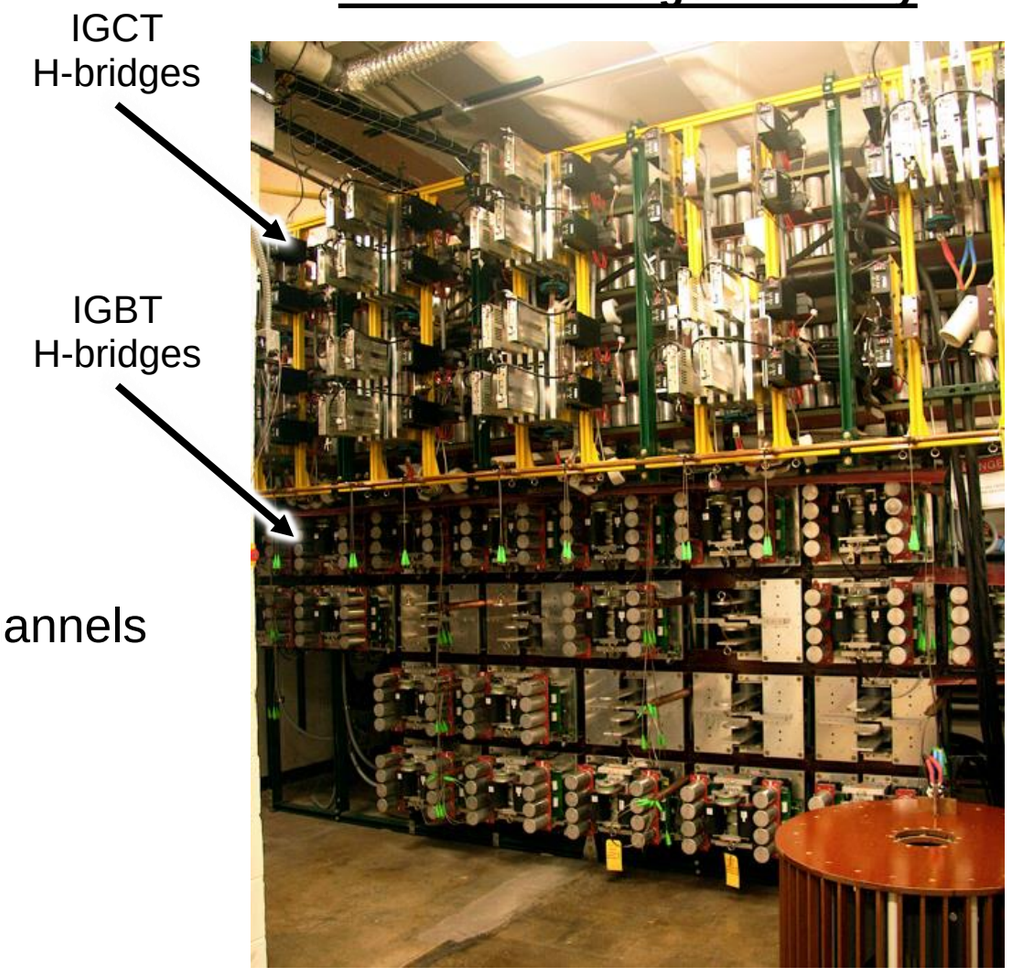
URANIA

TF & PF Coil Sets Require ~225 MVA of H-bridge Controllable Power

H-bridge Topology



PEGASUS H-bridge Inventory



- 45 optically isolated H-bridges (12 new, 33 reused)
- PF expansion requires 6 additional H-bridges
- TF increase requires doubling its H-bridges and control channels
  - 12 H-bridges, 24 control channels, 24 status channels
  - I_{TF} buildup system: 16 repurposed PEGASUS IGCTs
  - I_{TF} sustain system: 2-quadrant H-bridges built with new IGBTs
- All coil sets to employ digital feedback control
  - FPGA-based system in development

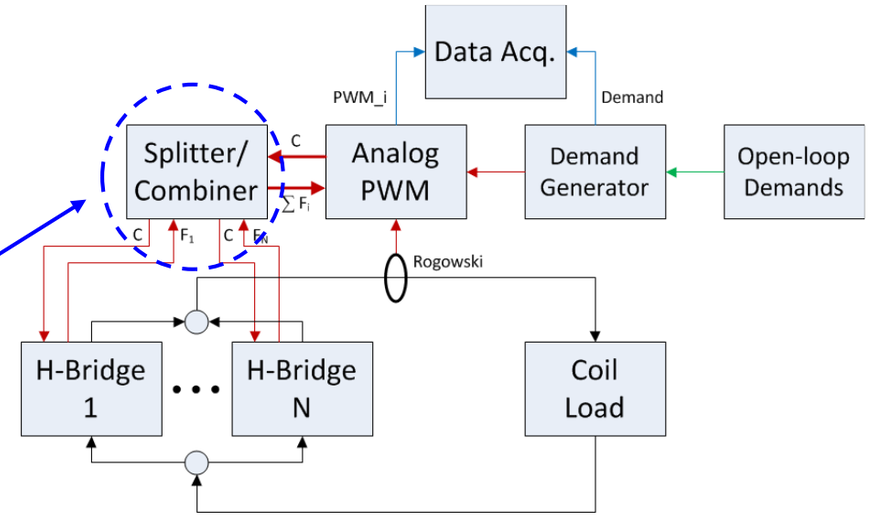
Planned Digital Control Systems

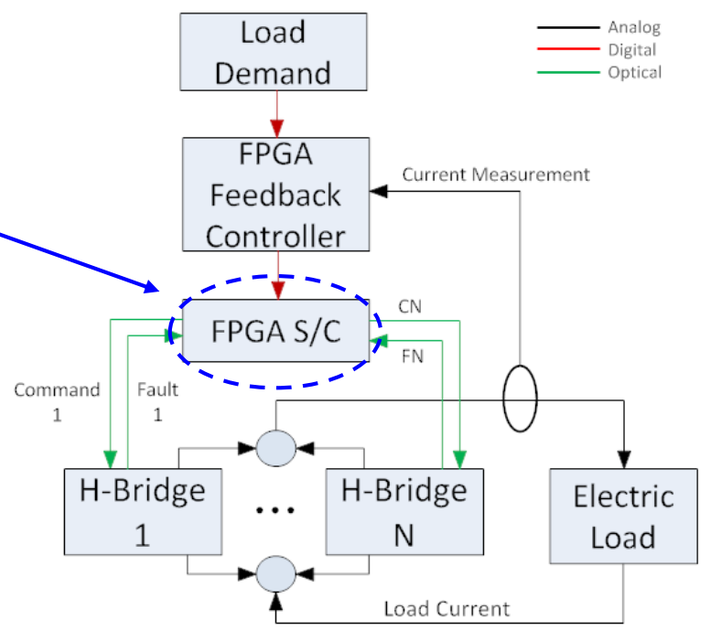
FPGA Power Supply Control System in Development

- Benefits of Field Programmable Gate Array Technology (FPGA):
  - Programmable control algorithms
  - Programmable in LabVIEW
  - Expandable with off-the-shelf hardware
  - Improved EMI resilience
  - Increased stability (e.g. no comparator drift)

- Builds upon PEGASUS FPGA based 'Splitter/Combiner' system
- First digital feedback controllers will employ PID control algorithm

PEGASUS Analog Control System



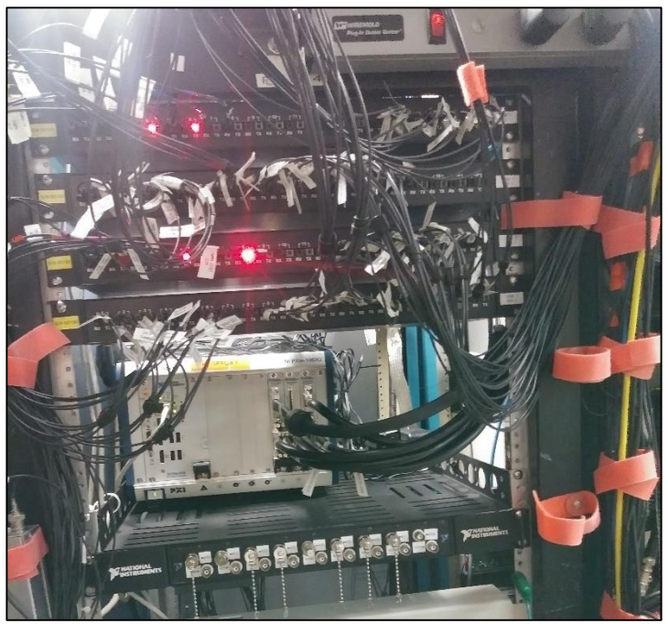


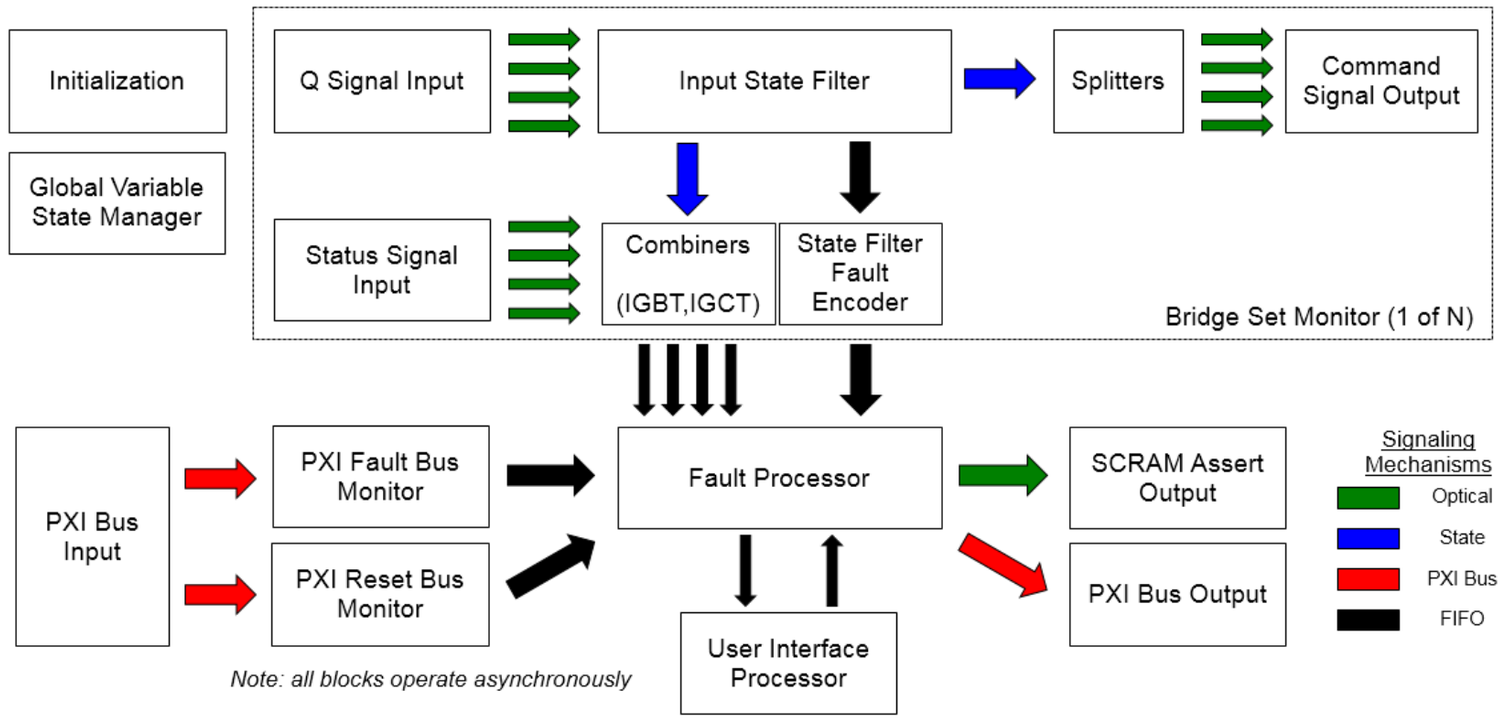
URANIA Digital Control System

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FPGA S/C Implementation Leverages LabVIEW & FPGA Parallelism

FPGA S/C System



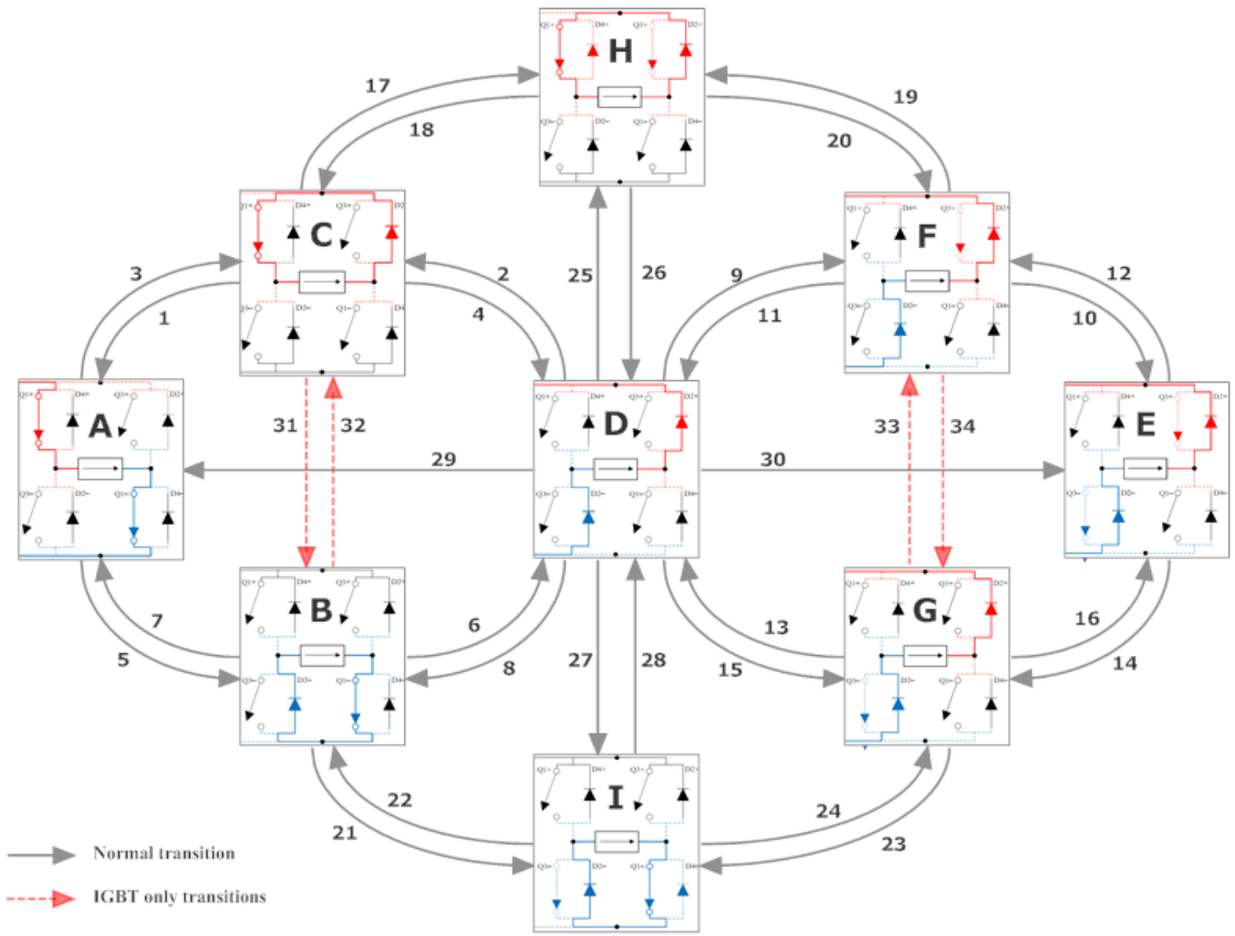


- FPGAs mounted in NI PXIe-1062Q chassis
- Intra-FPGA communication via PXI bus
- System utilizes 3 FPGAs running in parallel
- FPGAs implement logic depicted in block diagram

FPGA S/C Deployment Has Improved Device Protections

- Splitter functionality:
  - Synchronously multiplexes command signals
- Combiner Functionality Retained:
  - Device-level interpretation of IGBT/IGCT status signals
  - Aggregation of bridge status signals to single assertion of "coil set OK"
  - Fault assertion for SCRAM shutdown system
  - Identification of faulted device(s)
- FPGA Enabled Improvements:
  - Continuous monitoring of device status
  - State filtering for invalid PWM commands
  - Improved fault detection time ≤ 200 ns
  - Improved fault response time ≤ 7 µs

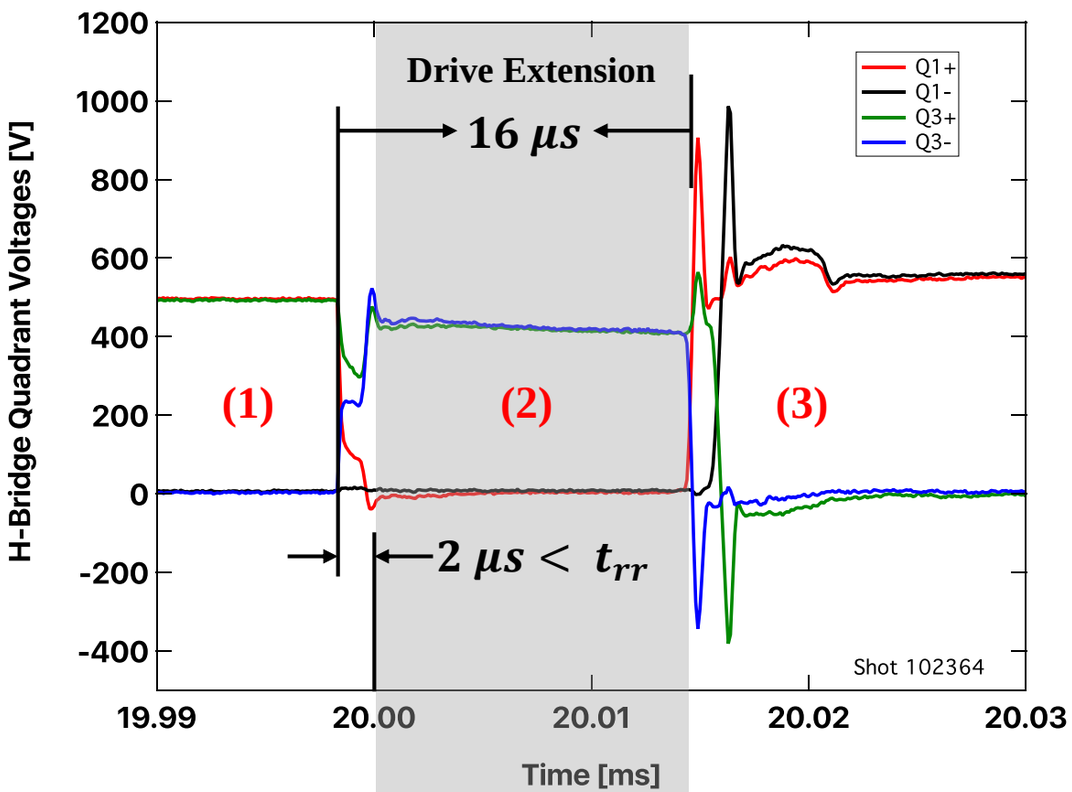
State-Diagram of Allowed H-bridge States & Transitions



Improved Device Protection Example: Freewheeling Diode

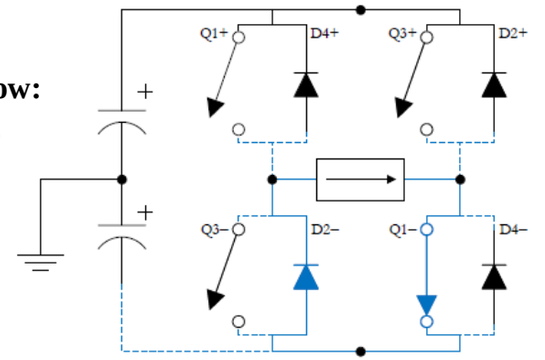
- FPGA command filtering ensures diode reverse recovery time respected ($t_{rr} \approx 7\ \mu s$)
  - Example H-bridge drive state duration extension to satisfy t_{rr}

Drive Duration Extended to Provide Recovery Time

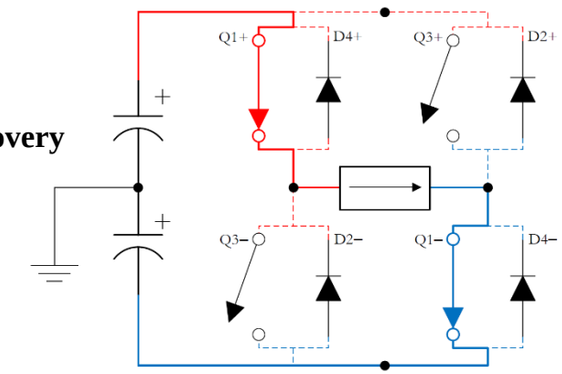


FPGA Command Input	(1)	2 (3)	→ Diode Failure
FPGA Filtered Output	(1)	(2) (3)	→ Diode Protected

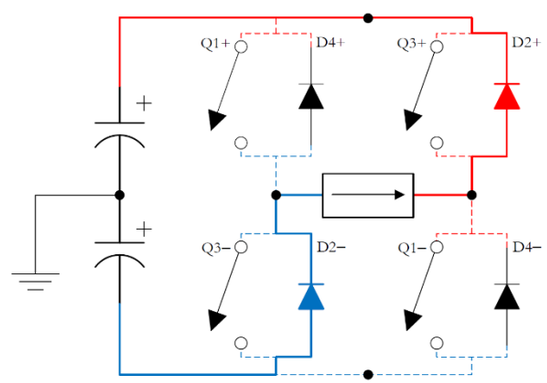
(1)
4Q Positive Freewheel Low:
Diode D2- conducting



(2)
4Q Positive Drive:
Diode D2- in reverse recovery



(3)
4Q Positive Regen:
Diode D2- conducting



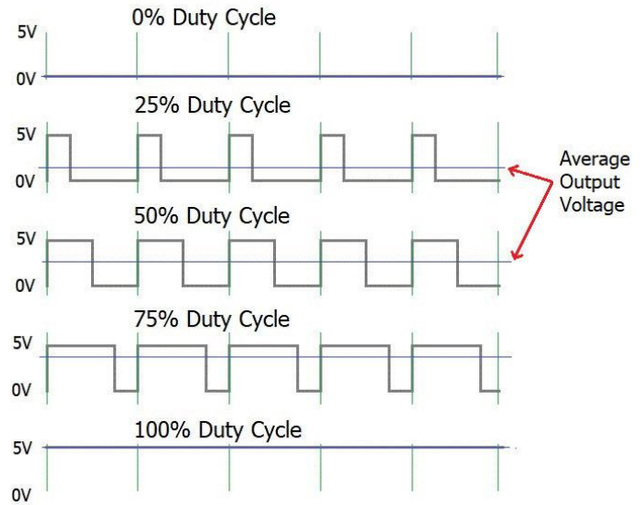
FPGA Controllers to Use Pulse Width Modulation (PWM) for Voltage Control

- Actuator: Device (switch) on-time duty cycle, D, in feedback period T
- Output voltage related to input voltage through the duty cycle (D):

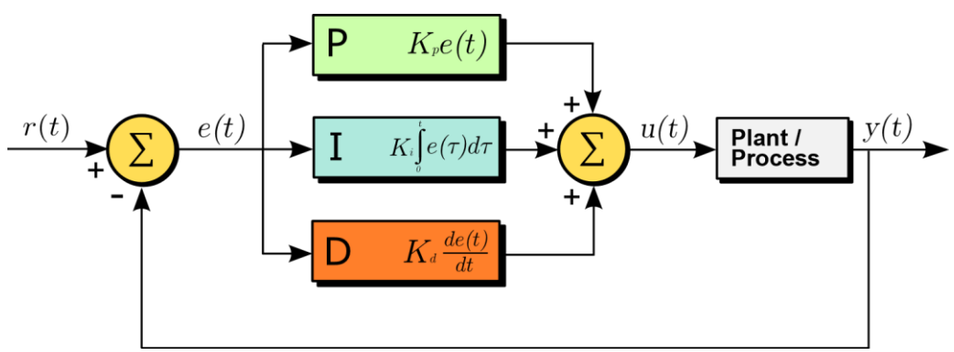
H-bridge	Ćuk
$V_{out} = D * V_{in}$	$V_{out} = -\frac{D}{1-D} * V_{in}$

- FPGA PID controller will assert $D(t)$

Example of 5 V H-bridge PWM



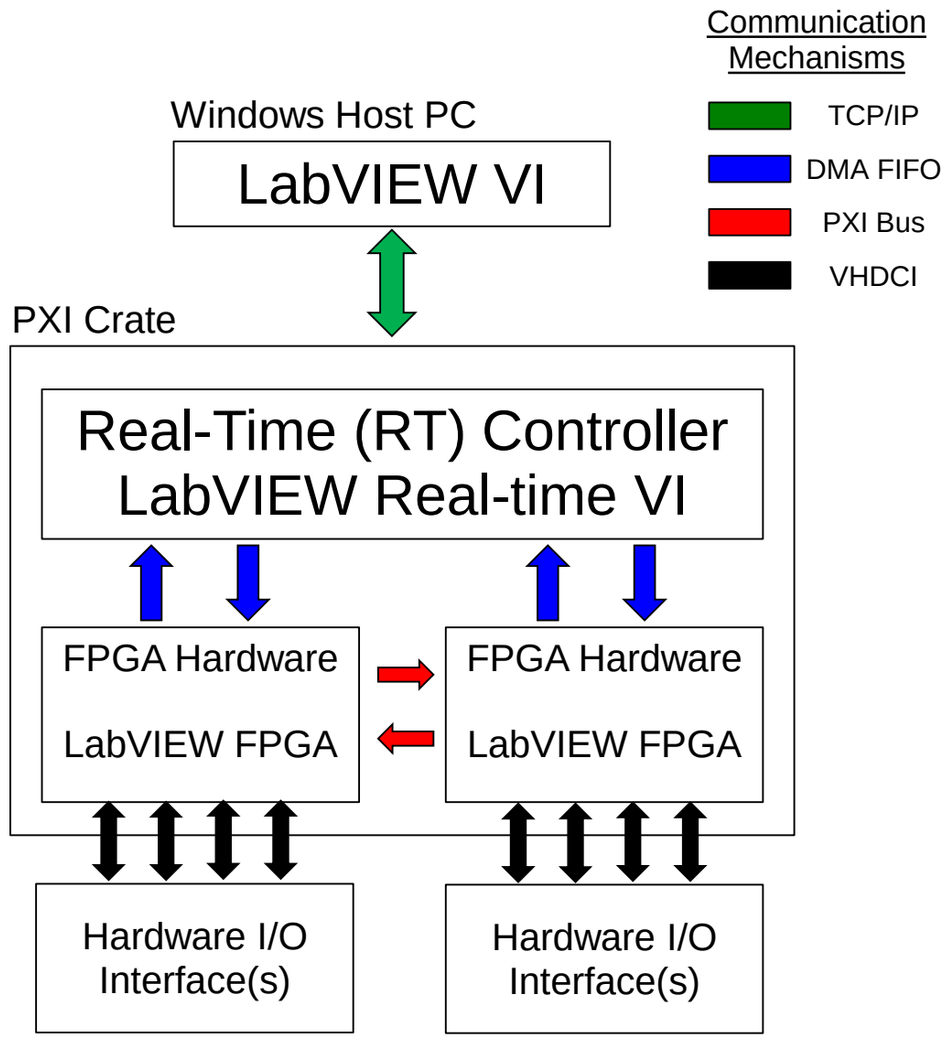
Aswinth Raj, https://circuitdigest.com/tutorial/what-is-pwm-pulse-width-modulation



A. Urquizo, http://commons.wikimedia.org/wiki/File:PID.svg

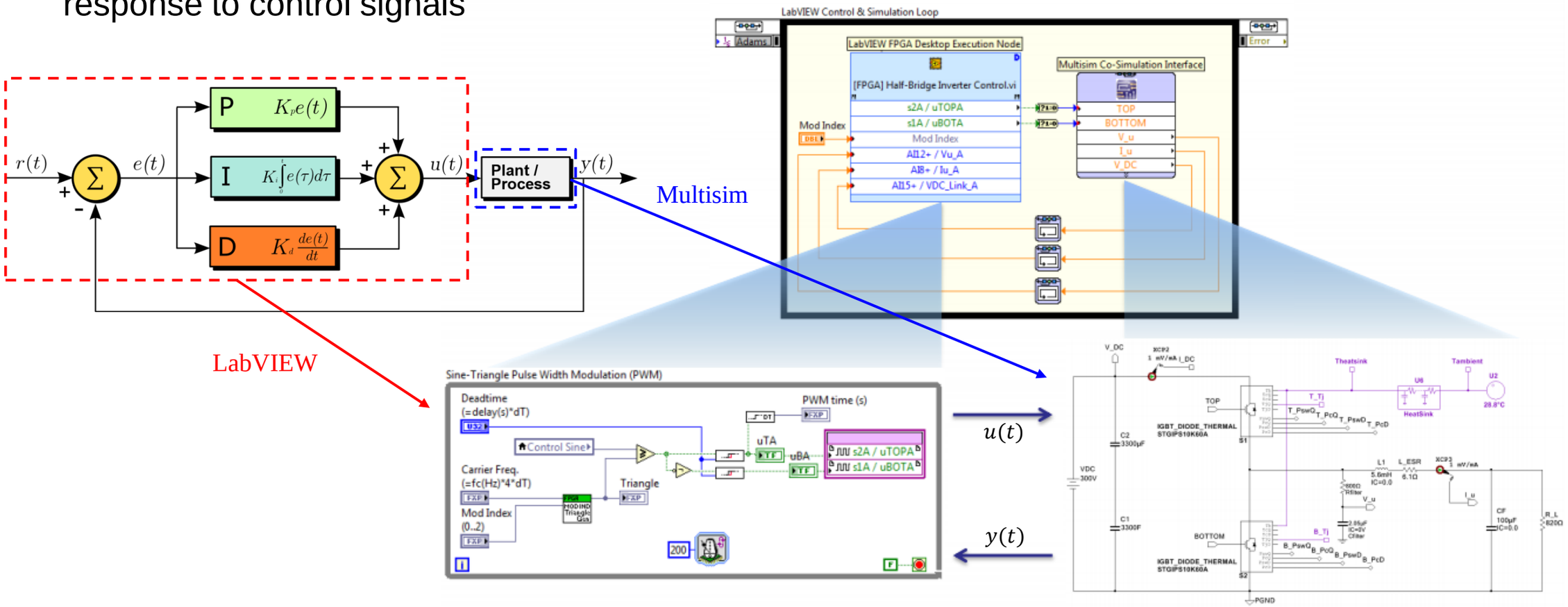
FPGA Controllers Will Use a Multitiered Architecture: Windows Host ↔ RT Host ↔ Target

- Windows Host:
  - User interface (PWM settings, system status, etc.)
  - Main Control Code interface
- RT Host:
  - Between shots:
    - Update PWM settings from Windows Host
    - Write shot data to main data server
  - During shot:
    - Receive feedback signal, $y(t)$, and generate demand signal $r(t)$
    - Calculate error signal $e(t) = r(t) - y(t)$
    - Calculate plant signal, $u(t)$, from $e(t)$
    - Transmit plant signal to Target
- FPGA Target:
  - Measure feedback signal, $y(t)$ & transmit to RT
  - Receive plant signal, $u(t)$, from RT (signed duty cycle)
  - Use plant signal to decide on next action
    - State & duration of next PWM cycle



Bench Testing Will Leverage Coupled Simulation Capability

- LabVIEW simulation of PWM control (plant) signal generation
- Multisim simulation of circuit (plant) response to control signals
- Data passed between simulation environments each time step



B. MacCleery, https://www.energy.gov/sites/prod/files/2016/11/f34/Panel%202_NI_MacCleery.pdf

Optically Transmitted Voltage Measurement in Development

- Current measured with series shunt resistor: $I = \frac{V}{R}$
- Shunt voltage locally converted to a 1-bit stream with Sigma-Delta ADC
  - Voltage encoded in the duty cycle of the bit stream
- Bit stream transmitted optically to FPGA
- FPGA digitally filters bitstream to recover analog signal
- Benefits include:
  - Linear response
  - Can measure DC currents
  - Improved signal to noise ratio
  - No integration

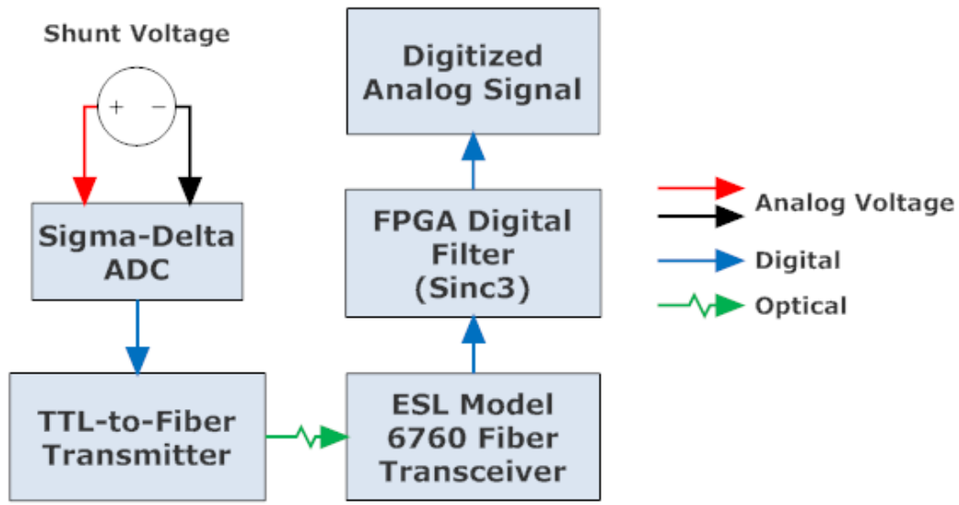


Table 11. Sinc3 Filter Characteristics for 10 MHz

Decimation Ratio (DR)	Throughput Rate (kHz)	Output Data Size (Bits)	Filter Response (kHz)
32	312.5	15	81.8
64	156.2	18	40.9
128	78.1	21	20.4
256	39.1	24	10.2
512	19.55	27	5.1

Analog Devices, AD7402 datasheet, accessed online:
https://www.analog.com/media/en/technical-documentation/data-sheets/AD7402.pdf

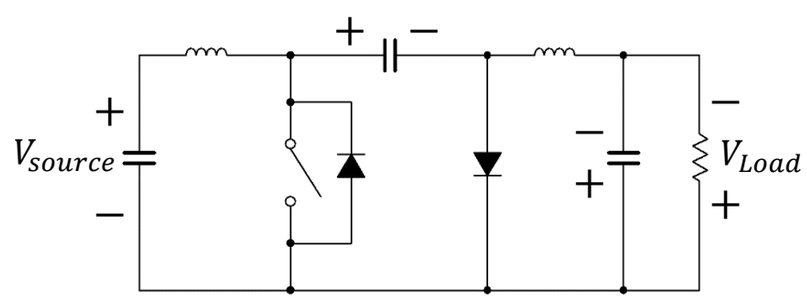
Ćuk Topology: LHI/CHI Power Supply

LHI Requires Low Ripple, Programmable $V_{inj}(t)$

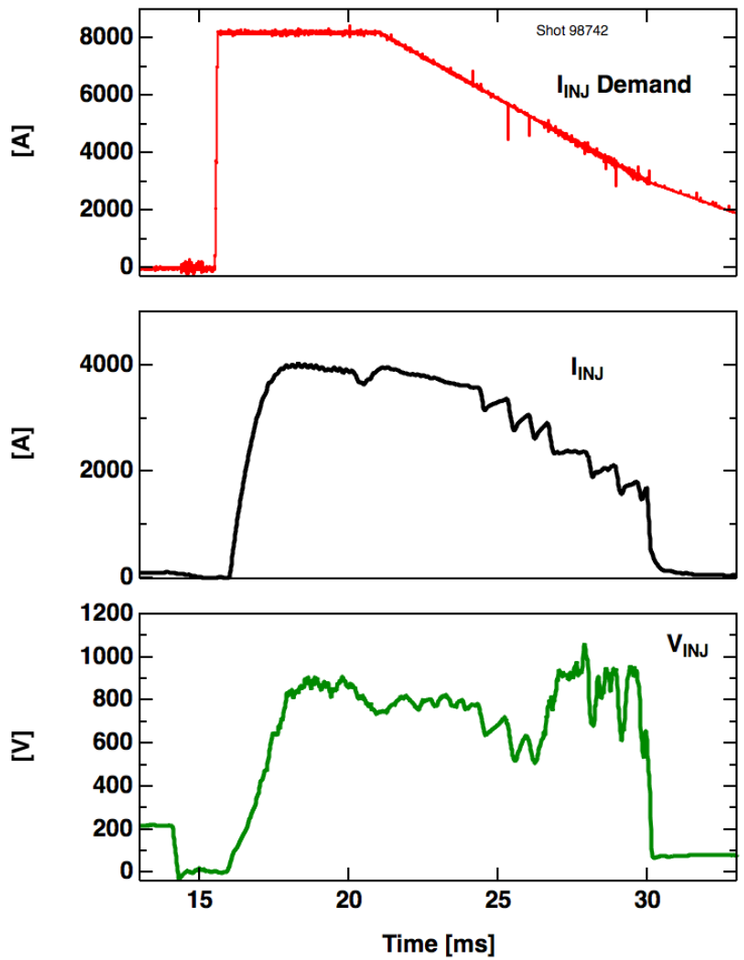
- H-bridge regulation of injector voltage creates large voltage swings that can hamper operations
  - Increases deleterious injector cathode spot frequency
  - Typically operate with no active regulation
  - V_{inj} controlled with capacitor bank charge voltage
  - V_{inj} voltage droops during shot

- Ćuk converter topology free from H-bridge type voltage oscillations with voltage gain capability
  - Low ripple will enable $V_{inj}(t)$ control, i.e. $V_{loop}(t)$
  - Voltage gain expands $V_{inj}(t)$ controllability

Ćuk Converter Topology ⇨



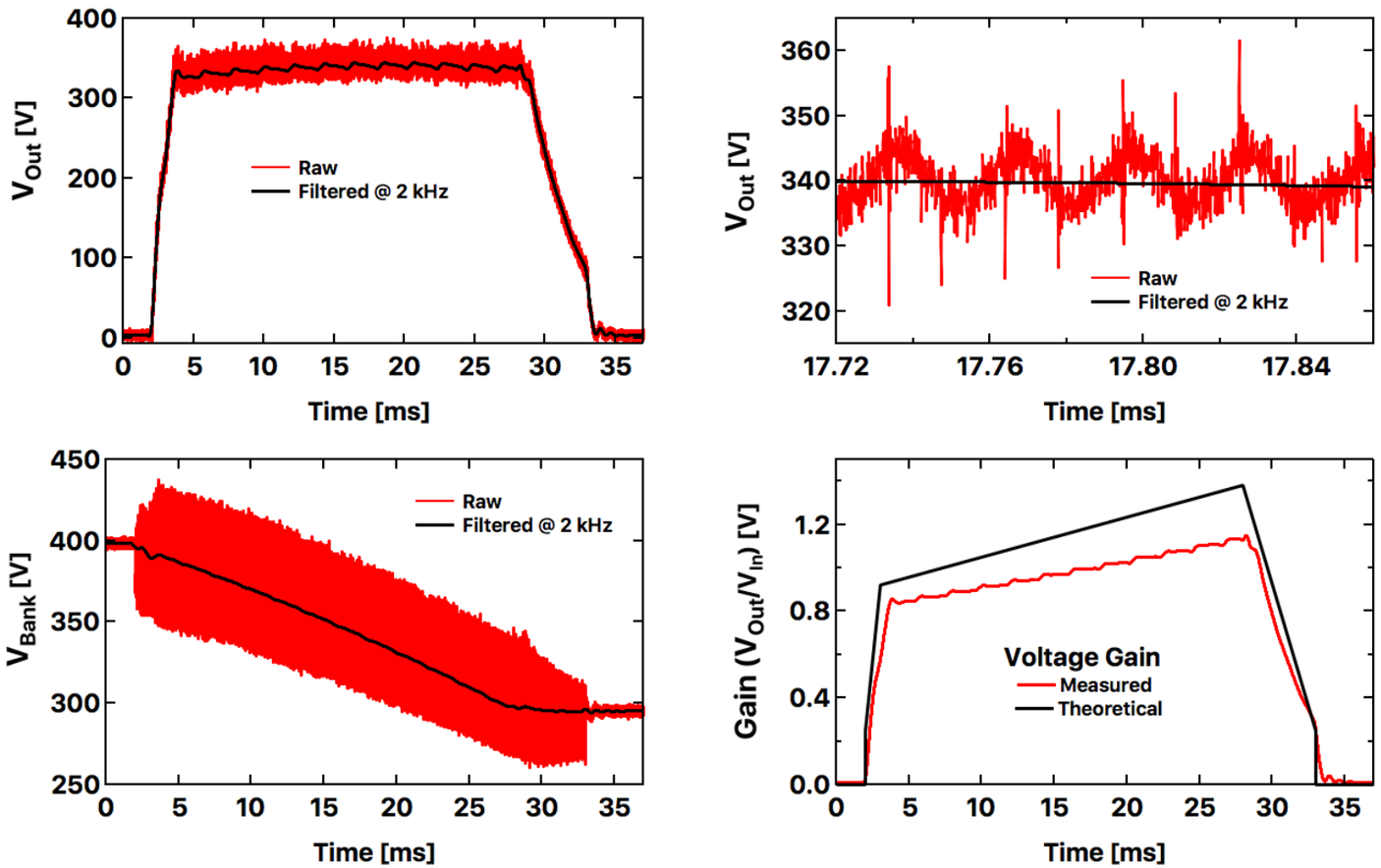
Example of Regulation Induced Oscillations



Ćuk Power Supplies: Low Ripple, Variable Voltage Control

- Goal: demonstrate low ripple, voltage control
- Low ripple voltage control
  - Active V_{inj} regulation
- Programmable voltage gain
  - Voltage droop compensation
  - Improved stored energy utilization
- Eagle Harbor Technologies (EHT) Ćuk module test results:
  - 340 V, 3.4 kA into 100 mΩ load
  - 60% stored energy utilized
  - No droop in V_{out} with 100 V droop in V_{bank}
  - 3% peak-to-peak ripple

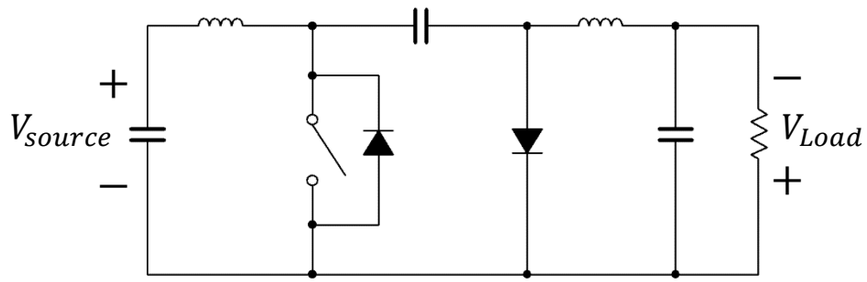
Single Ćuk Module Prototype Testing*



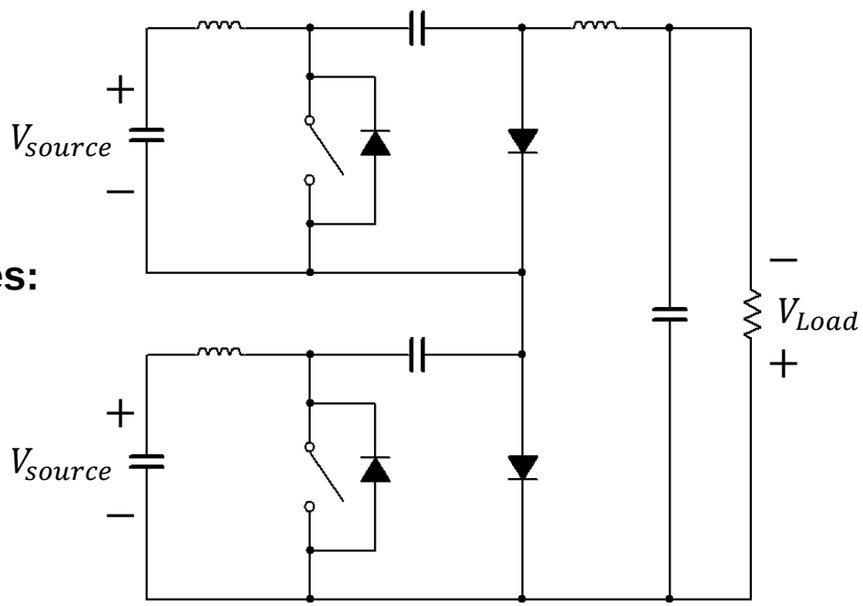
**Testing in collaboration with Eagle Harbor Technologies*

Ćuk Modularity Enables Parallel & Series Topologies

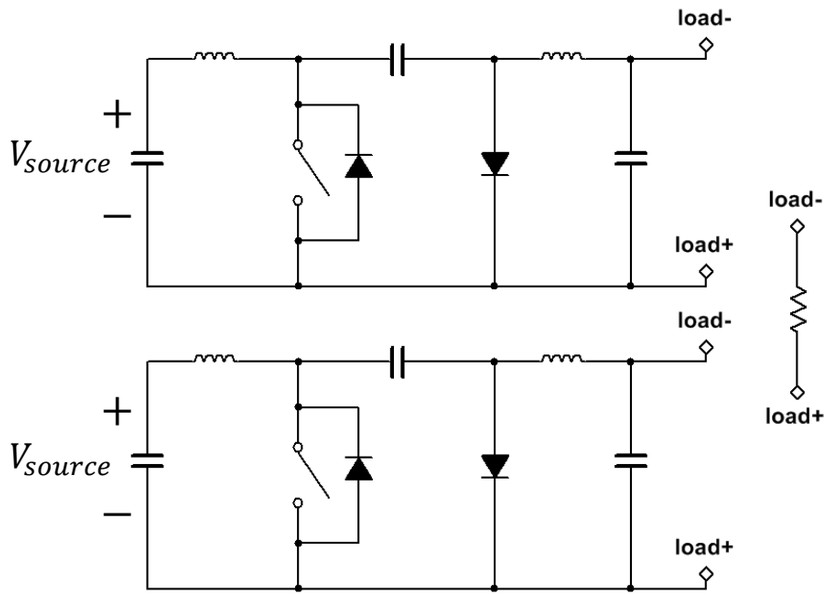
Single Module:
400 V & 4 kA



Two Series Modules:
800 V & 4 kA



Two Parallel Modules:
400 V & 8 kA

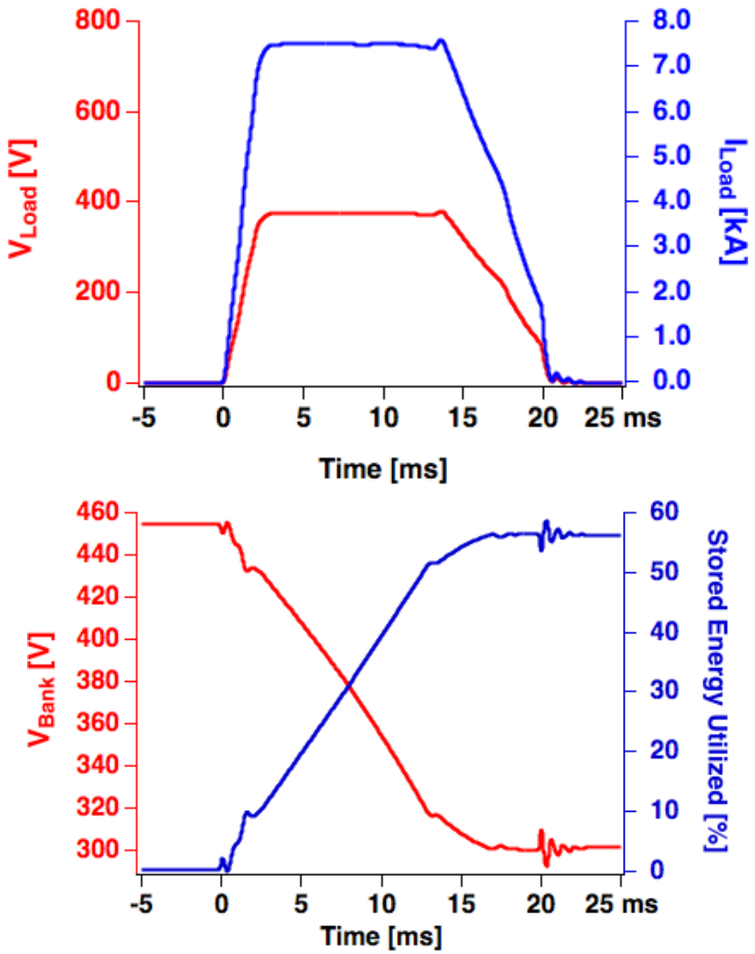


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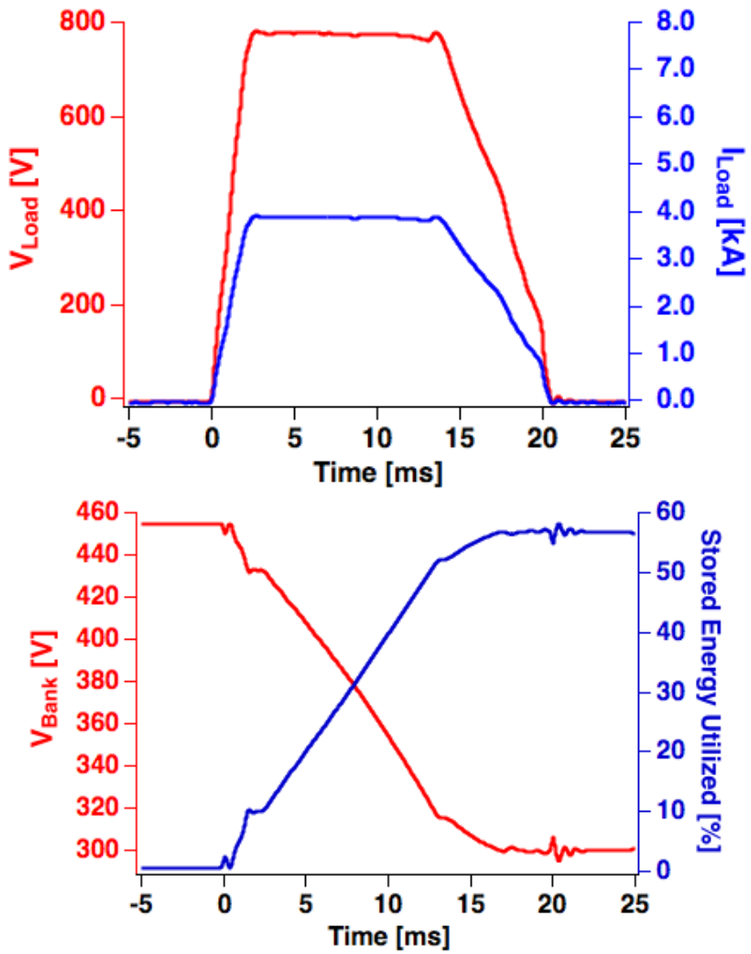
Ćuk Flexibility Verified with Prototype Testing Into Resistive Load

- Testing goals:
  - Verify topology operation
  - Investigate fault response
  - Measure transient voltages across solid state devices
- 450 V capacitor bank energy source sized to droop
  - Demonstrate voltage gain utility
- Parallel EHT modules:
  - Ideal: 400 V, 8 kA
  - Realized: 375 V, 7.5 kA
- Series EHT modules:
  - Ideal: 800 V, 4 kA
  - Realized: 775 V, 3.6 kA

Parallel Modules*



Series Modules*



**Data filtered at 2 kHz;*
In collaboration with Eagle Harbor Technologies

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DNB & EBW Power Supplies

DNB and RF to Provide Diagnostic, Plasma Heating & Current Drive

Diagnostic Neutral Beam (DNB)

- Charge Exchange Recombination Spectroscopy (CHERS) will provide:
  - Impurity ion temperature profiles, $T_i\ (R,t)$
  - Impurity ion density profiles, $n_z\ (R,t)$
- Beam attenuation to provide electron density profiles $n_e\ (R,t)$
- Motional Stark Spectroscopy for internal magnetic field and current density profiles, $B(R,t)$ and $J(R,t)$

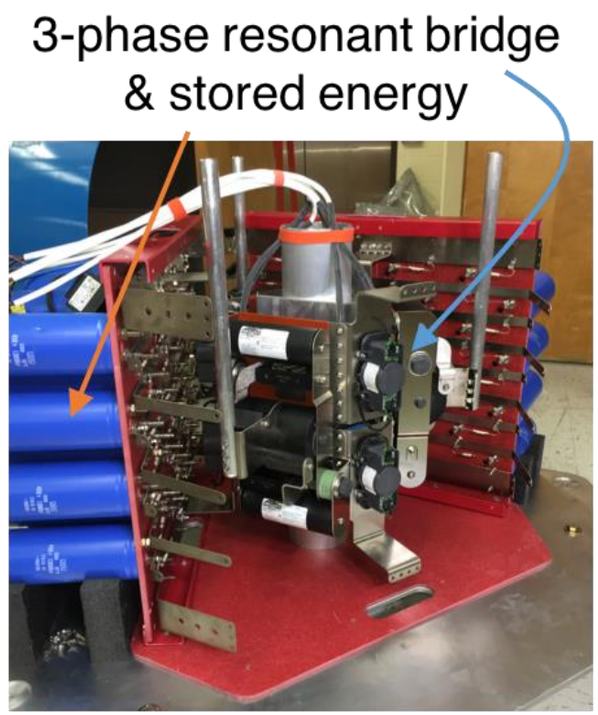
EBW Heating & Current Drive

- Heating expected to improve helicity injection startup by augmenting T_e
  - Reduce resistive losses
  - Increase current diffusion timescale, helping maintain favorable low-ℓ_i
  - Raise $T_e(0)$ for better coupling of LHI plasmas to neutral beam or RF current drive
- RF as possible startup technique
- RF as possible sustainment current drive

DNB and EBW: Zero Voltage Switching (ZVS) Resonant Converter

- Resonant converter features:
  - 35 kHz base switching frequency enabled by zero voltage switching
  - Very low simulated voltage ripple < 1%
  - Up to factor 20 voltage gain on output
  - Fast ramp times, < 200 μs
  - No crowbar required
  - Fully digital FPGA control
- DNB powered by a 400 kW (80 kV, 5 A) resonant converter
- EBW powered by four, 30 kV, 4 A resonant converters
  - Each converter will drive an 8 GHz klystron sourcing a 125 kW, 5 ms pulse

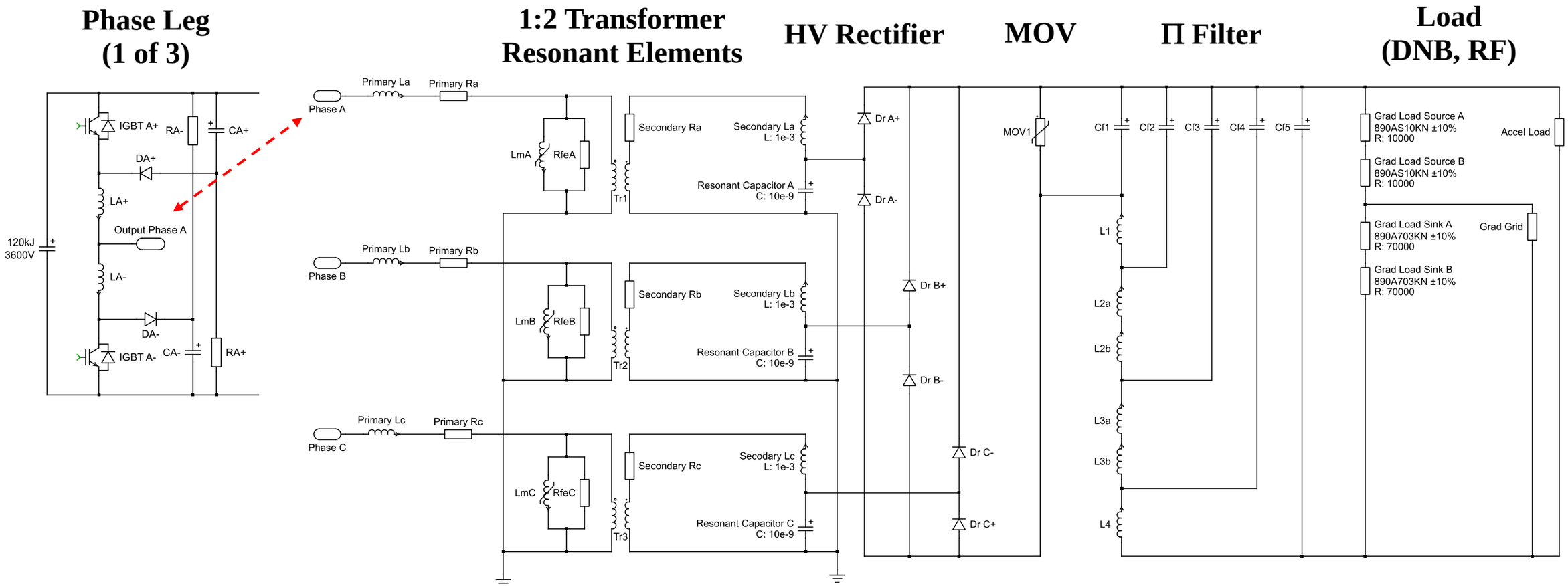
Pictures of DNB Resonant Converter



Assembled HV Power Supply



Resonant Converter Topology Well Suited for HV, Low Current Application



- Passive filtering reduces primary switching losses and output voltage ripple
- Low secondary stored energy significantly reduces crowbar requirements

Development and Deployment Plan for Power Supply & Control Systems

Near-Term

- TF and PF systems power supplies
- FPGA digital controllers
  - Programmable coil & LHI control
  - Advanced control algorithms
    - Combined feedforward & PID control
- DNB power supply & control
- Ćuk converter for injector Arc and Bias power supplies
  - Low ripple, programmable voltage control of helicity injection

Longer-Term

- Active control of helicity injection
- Active injector gas control for injector impedance control
- FPGA replacement of CAMAC timing modules
- EBW power supply & control