Converter Topologies

Pulsed Power Engineering
Michigan State University
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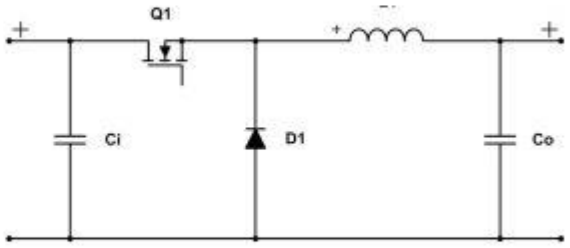
Converter Topologies in Pulsed Power Systems

- Useful in longer pulse applications where $\tau >> 1/f_s$ (τ >100 μs to DC)
- Enabled by high voltage (≤10 kV) high current (multi-kA) semiconductor power modules
- Pulsed power applications often require use of transformers to achieve required voltage levels (or series-stacked modules)
- Typical converter topologies utilized shown – there are several other options and various switching schemes

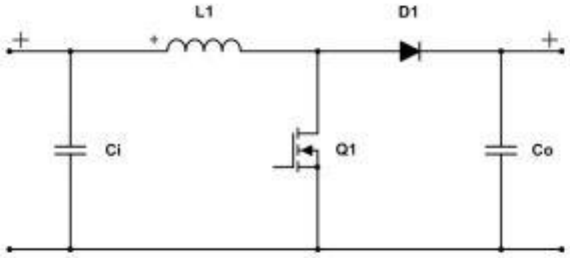


Buck converter

$V_{out} = D\ V_{in}$

(continuous conduction)

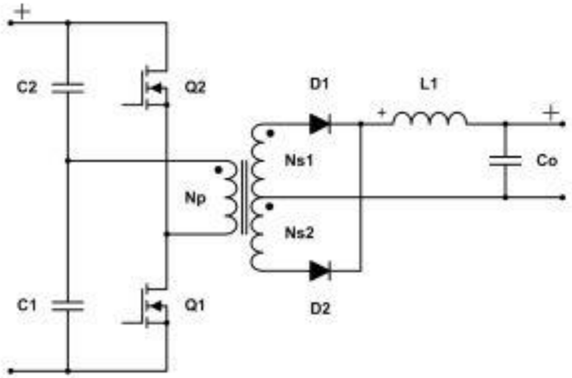
$D=t_{on}/T_s$



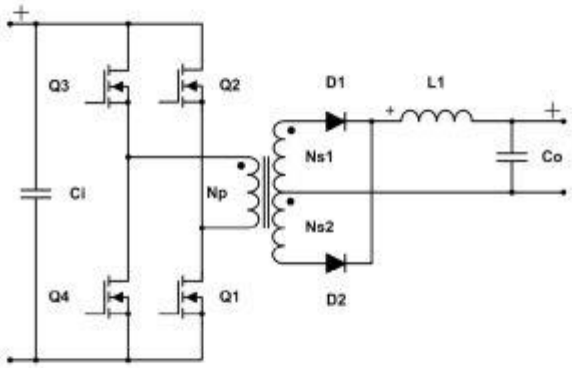
Boost converter

$V_{out} = 1/(1\text{-}D)\ V_{in}$

(continuous conduction)



Half bridge converter (1/2 Vin)



Full bridge converter (Vin)

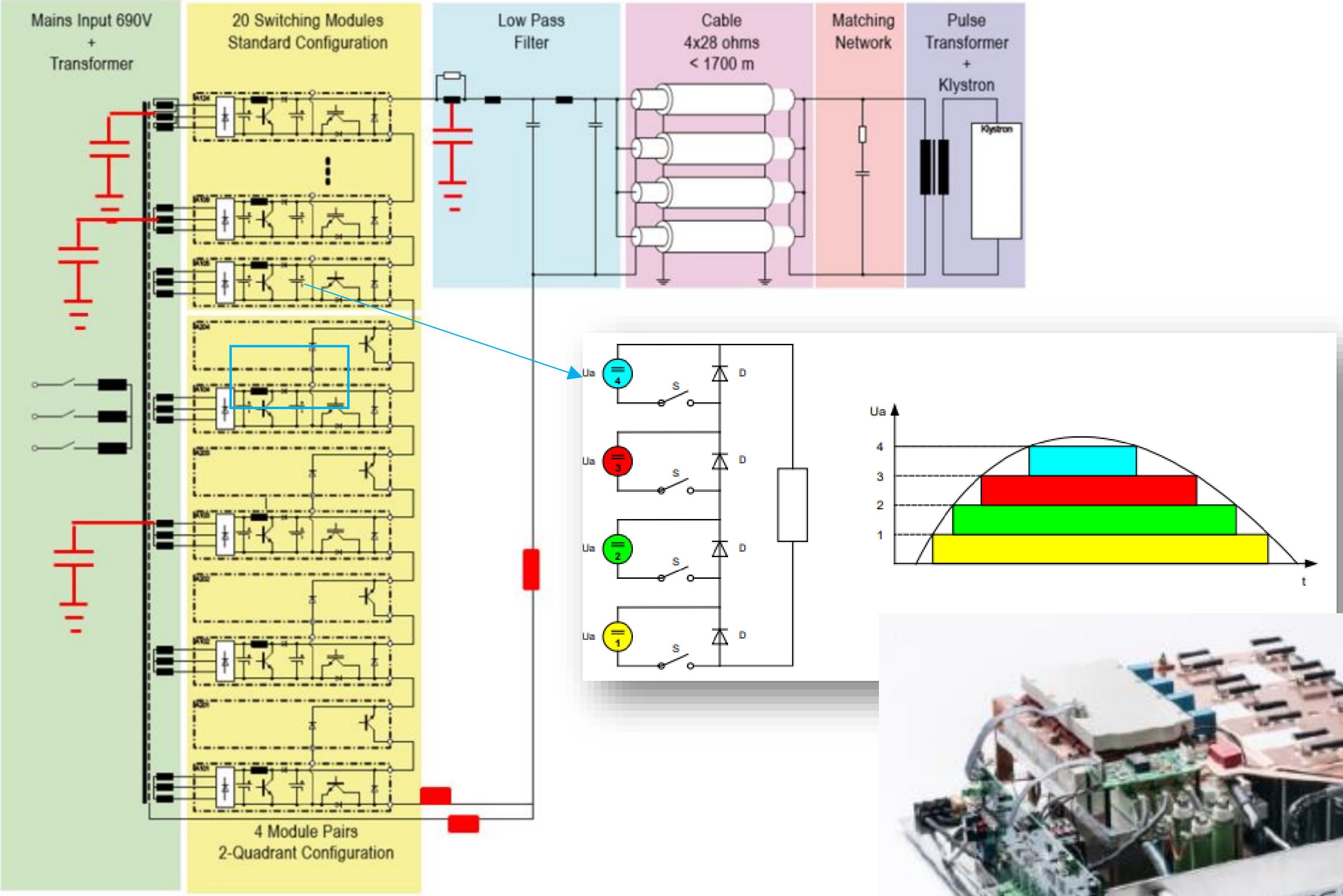
Converter Topologies Benefits

- Evolution of solid-state switching modules to relevant power and voltage levels enabled this technology in 1990s
- Draws heavily on Power Electronics field of Electrical Engineering

Advantages	Disadvantages
High efficiency (>90%) achievable due to soft switching	Often use many solid-state switching devices and diodes
Reduces stored energy requirements compared to hard tube modulator	Large number of components may lead to less reliable design
Can eliminate need for crowbar circuit	Complex controls with multiple feedback loops and precise device timing
Modular architectures	Not feasible for short pulse applications
Can incorporate redundancy in some topologies	
Can mitigate PF and harmonics on utility grid	
Overall system volume can be reduced compared to traditional topologies	

Ampegon Pulse Step Modulator

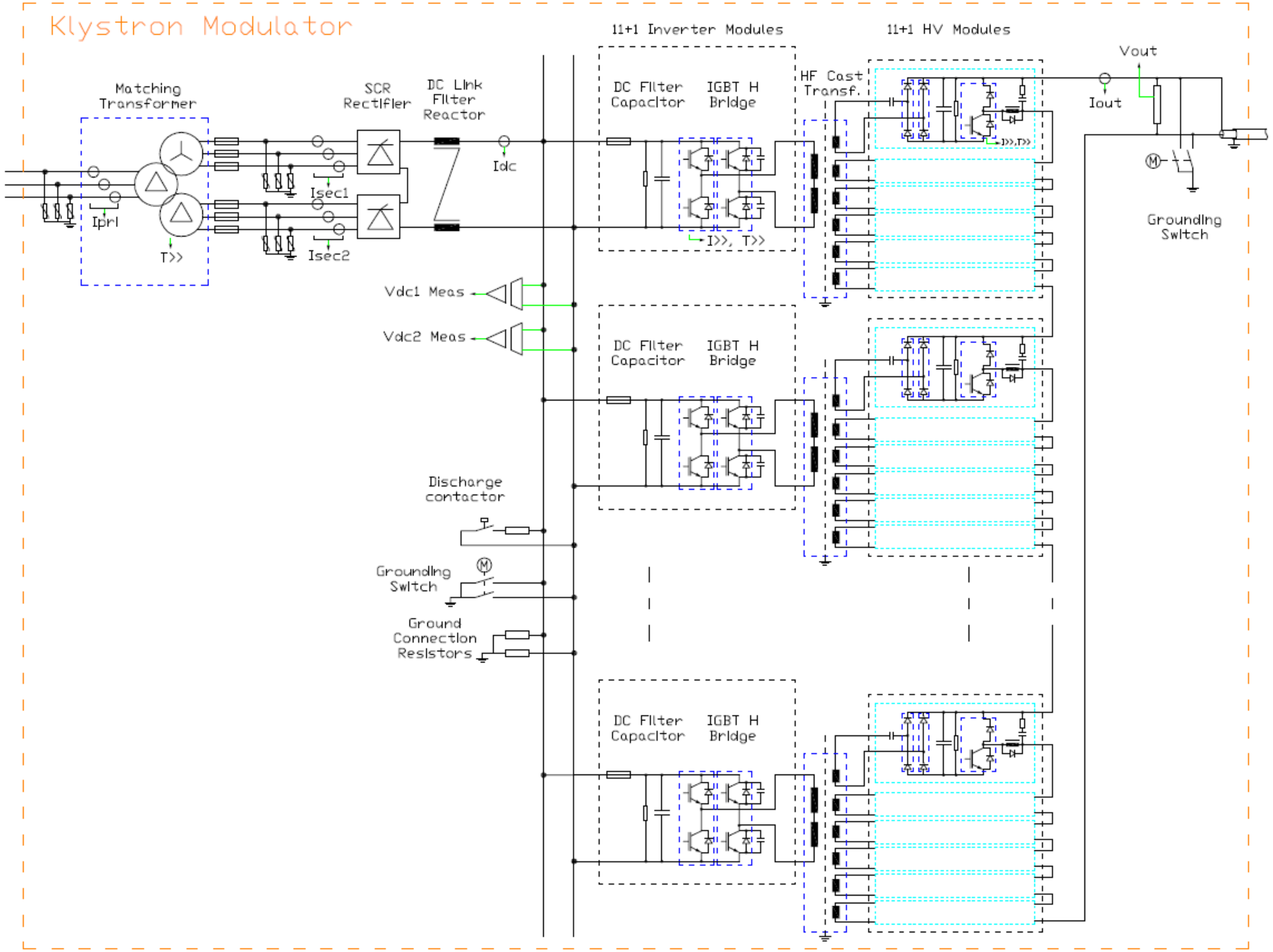
- •Line frequency diode rectifiers with isolation transformers to create unregulated DC power
- •Series-stacked boost converters to create HV in individual modules
- •Add redundancy with additional modules, diode/switch to bypass inactive modules
- •Modulator configuration with reduced MTTR



H-J. Eckoldt, “Long Pulse Modulators”, CAS-CERN Accelerator School: Power Converters, Switzerland, 2014.

JEMA Modulator

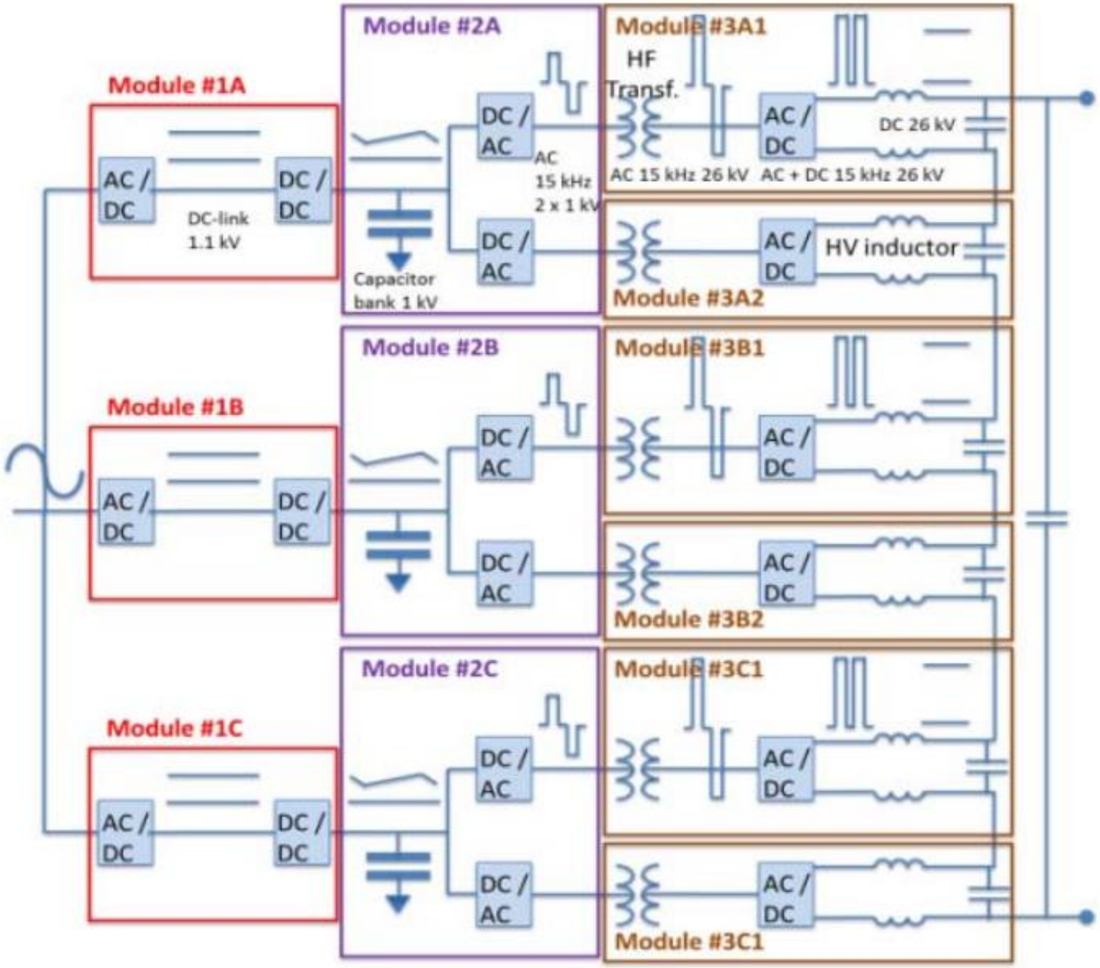
- Developed for the European Spallation Source
- Inverters charge series-stacked capacitors through transformer
- Add redundancy with additional modules, diode/switch to bypass inactive modules
- Modulator configuration with reduced MTTR



O.D. Cortazar, et al., “A 100 kV, 60 A solid state 4 kHz switching modulator for high power klystron driving”, Rev. Sci. Instrum. 2013;84(5):054706.

ESS-Lund Modulator

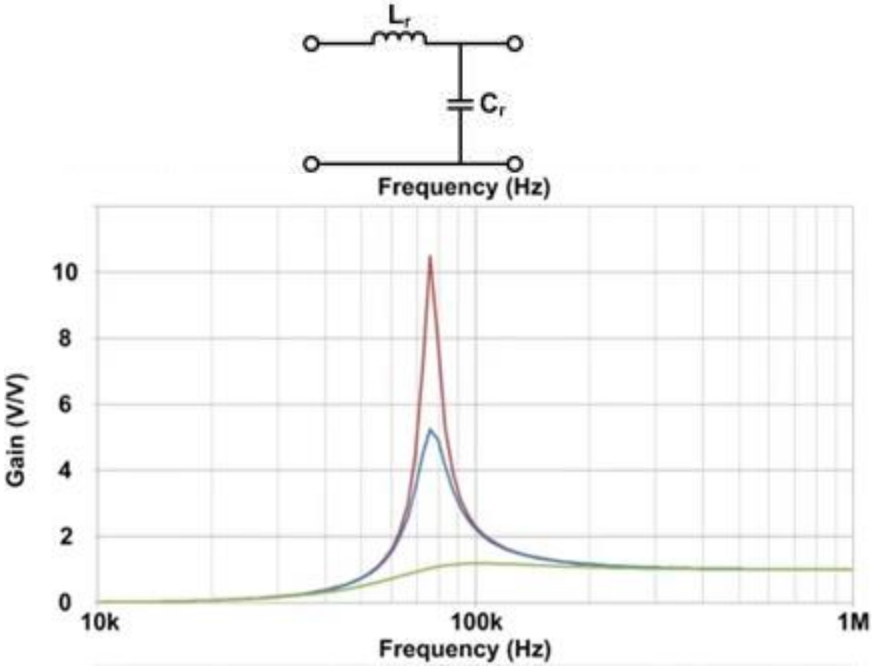
- Developed for the European Spallation Source
- Active front end and constant power charging maintains stringent Swedish PF, harmonics and flicker requirements
- Inverters drive step-up transformers to charge series-connected capacitors

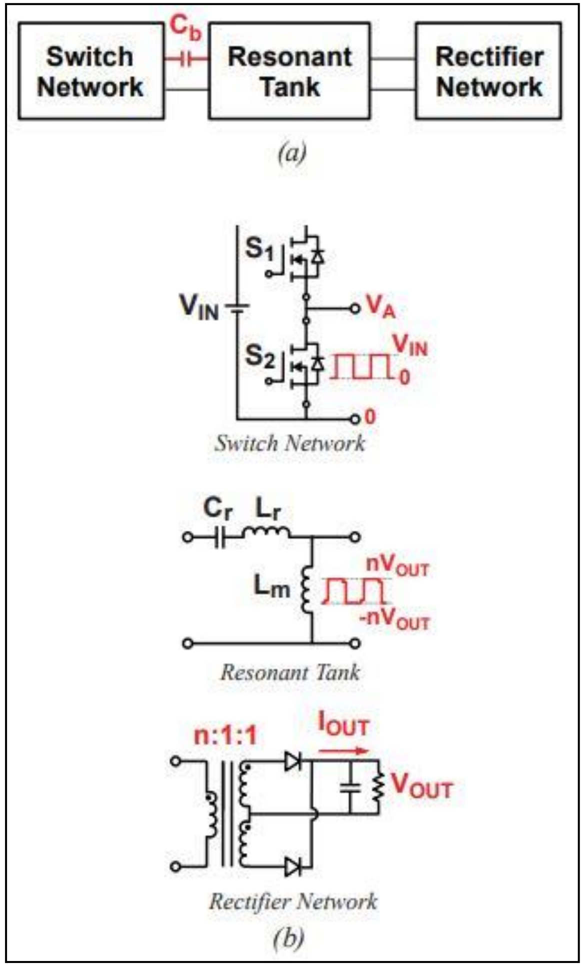


M. Collins, et al., “Stacked multi-level long pulse modulator topology for ESS”, Proc. IEEE Intl. Power Modulator Conf., San Francisco, 2016, p. 552.

Parallel Resonant Converter - Modulator

- Parallel resonant converter
  - Chopping at solid-state switch voltage
  - AC transformer steps up to high voltage
  - Soft (zero-voltage switching) ZVS achievable
- Poly-phase for high power operation within safe operating area of switches
- Resonant circuit
  - Transformer leakage inductance
  - Tuning capacitor
- Rectification
- Filtering
  - LC circuit



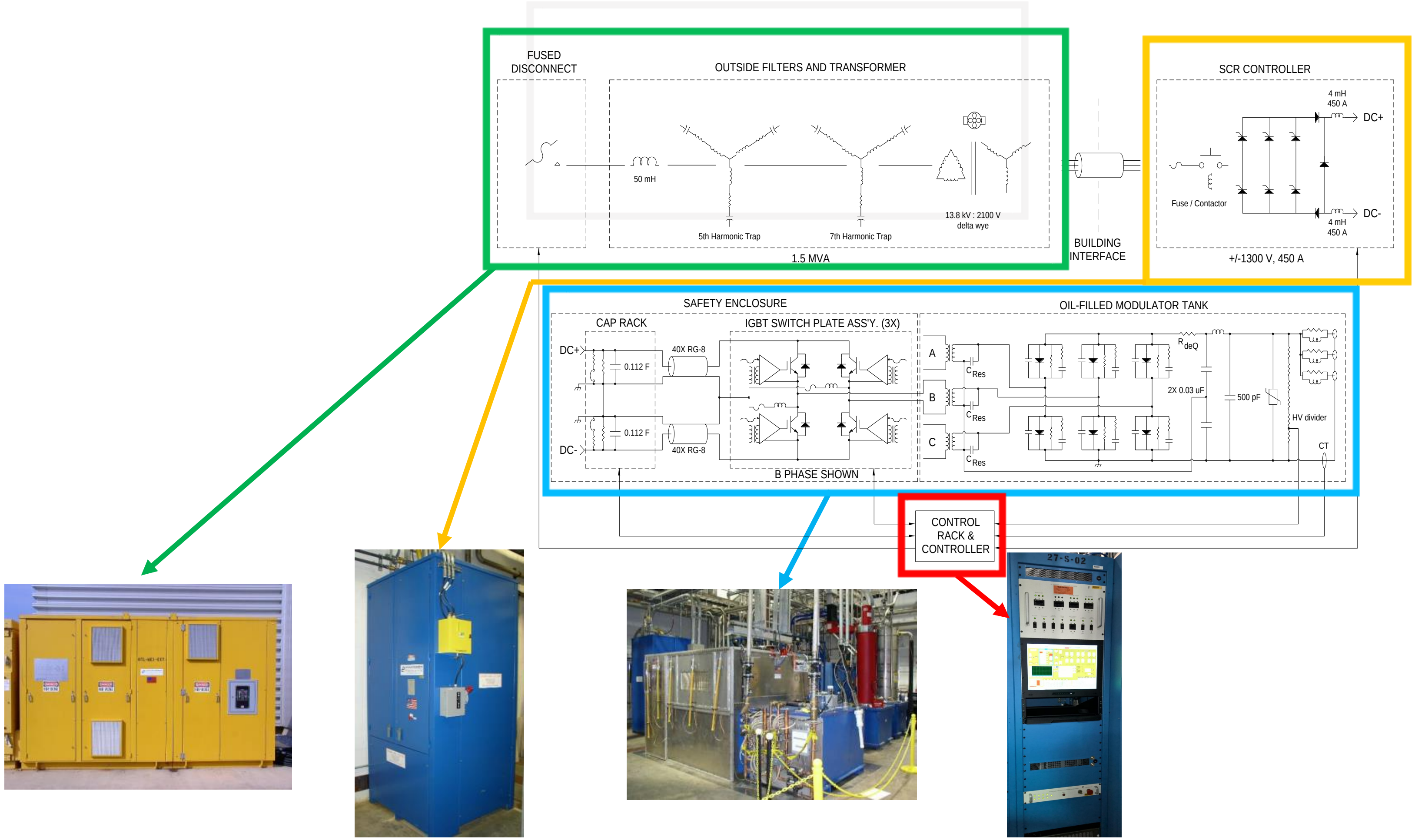


Resonant Circuit Example

Yu, S., Chen, R. and Viswanathan, A., “Survey of Resonant Converter Topologies”, TI SLUP376, 2018.

High Voltage Converter Modulator System Overview

- Provides up to 135 kV, 1.35 ms pulses at 60 Hz to amplify RF up to 5 MW
- Variable pulse widths 0.3-1.4 ms
- IGBTs chop at 20 kHz nominal
- Powers multiple klystrons up to 11 MW peak power, 1 MW average
- 18 operational modulators, 3 test stand modulators
- Approximately 1.5×10^6 combined hours



Spallation Neutron Source High Voltage Converter Modulator

AC Input
- 13.8 kV Switchgear
- Harmonic Traps
- 1.5 MVA Transformer

Rectifier Stage
- 2.1 kV AC Input
- SCR Assembly
- Control Circuits

Safety Enclosure
- Energy Storage Capacitor Bank
- DC Bus Connection
- IGBT Switchplates

High Voltage Tank
- Resonant Circuit
- Step-Up Transformers
- Rectifiers
- Filter Components
- Klystron Output

AC 60 Hz
13.8 kV Primary Δ
2.1 kV Secondary Y

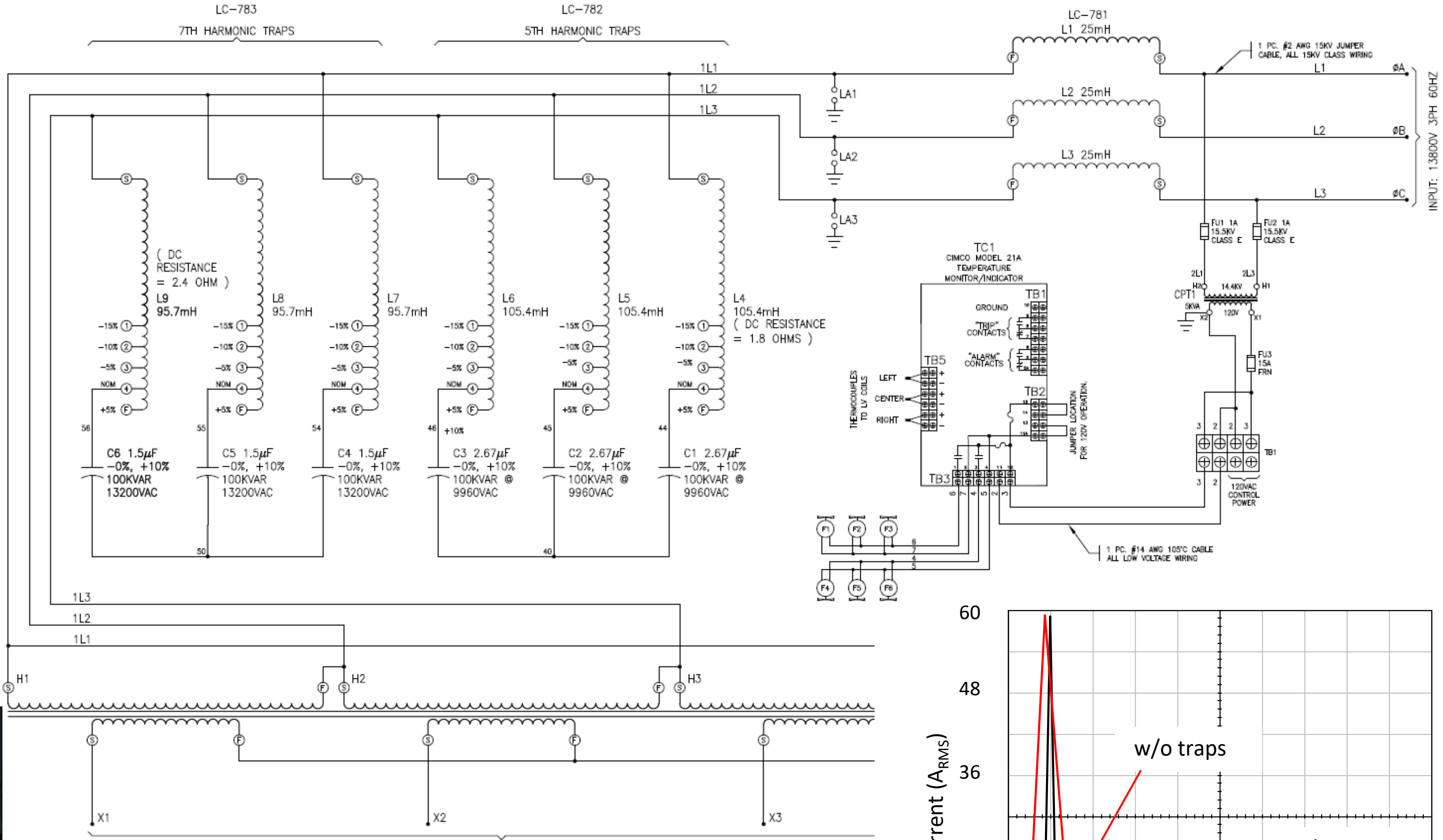
AC 60 Hz 3 Phase Input
DC Output: $\pm$ 1.3 kV

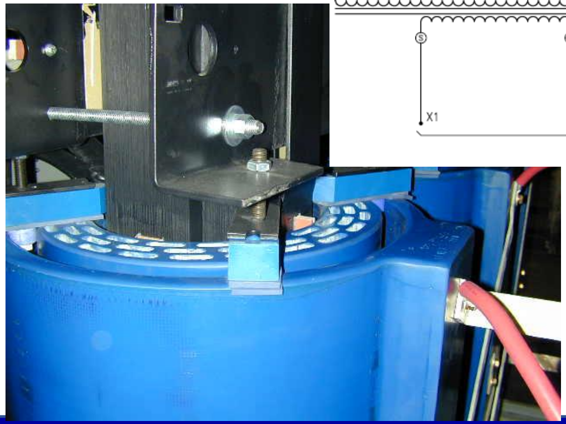
DC Input: $\pm$ 1.3 kV
~20 kHz Interleaved 3 Phase Resonant Converter

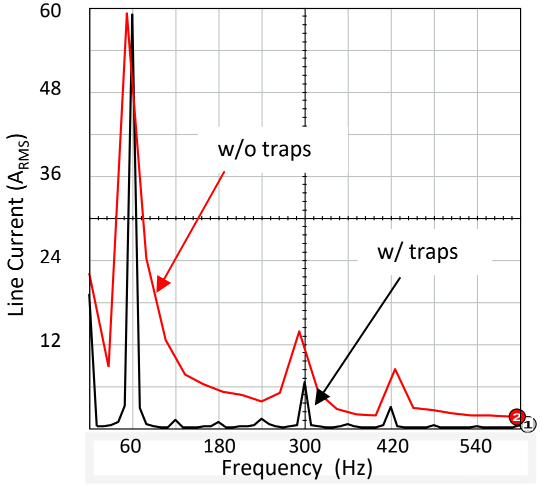
Pulsed Output
70-140 kV
~1.3 ms
60 Hz Repetition

HVCM Substation Power Transformer

- Operates at 13.8 kV distribution voltage
- Meets IEE-519 harmonics standard
  - h=5, 7.8% measured
  - h=7, 5.2% measured
- Cast coil construction
- Over 225 years combined operation, no major failures

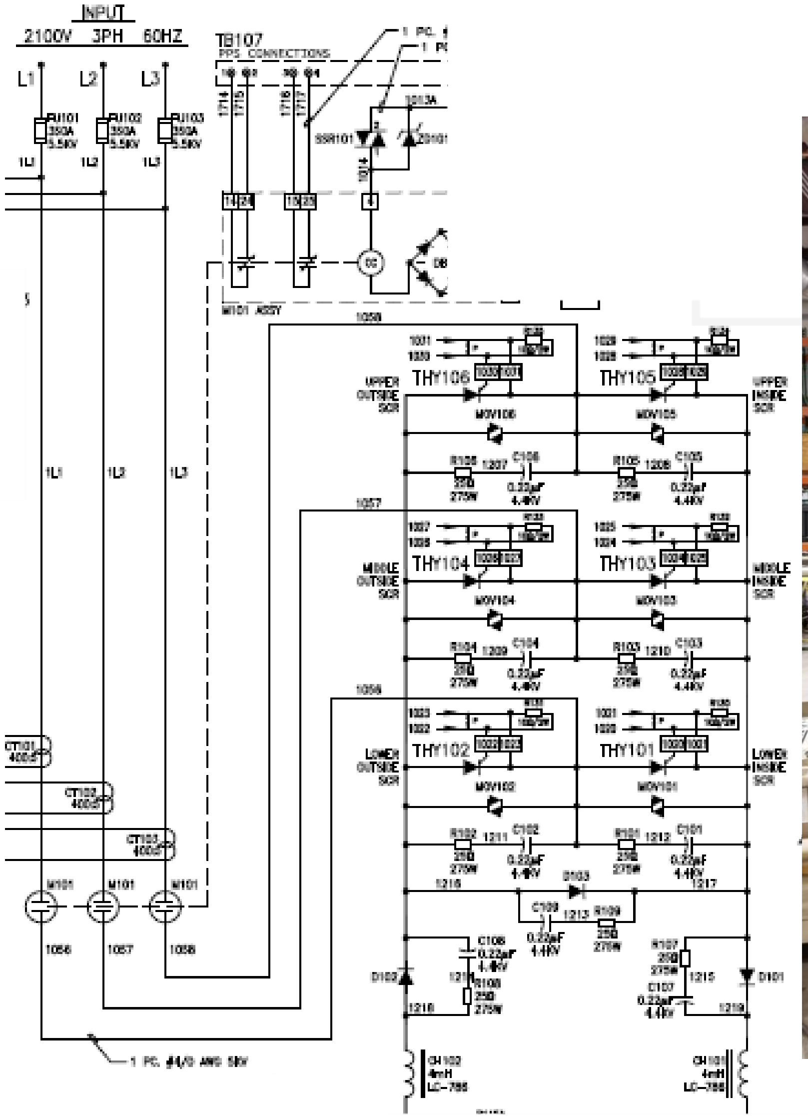


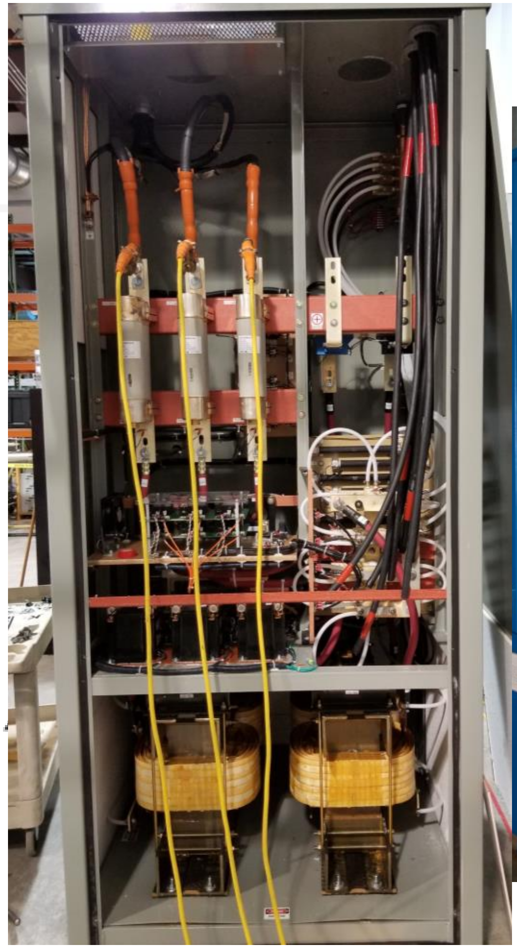




HVCM SCR Controller

- Converts 2100 V_{RMS} to ±1300 V, 450 A DC
- Voltage stability ≤0.1% at constant load
- Regulation ≤2% from 25-100% full load
- Simple 6-pulse system with thyristor control
- System self-contained with rudimentary remote interface capability



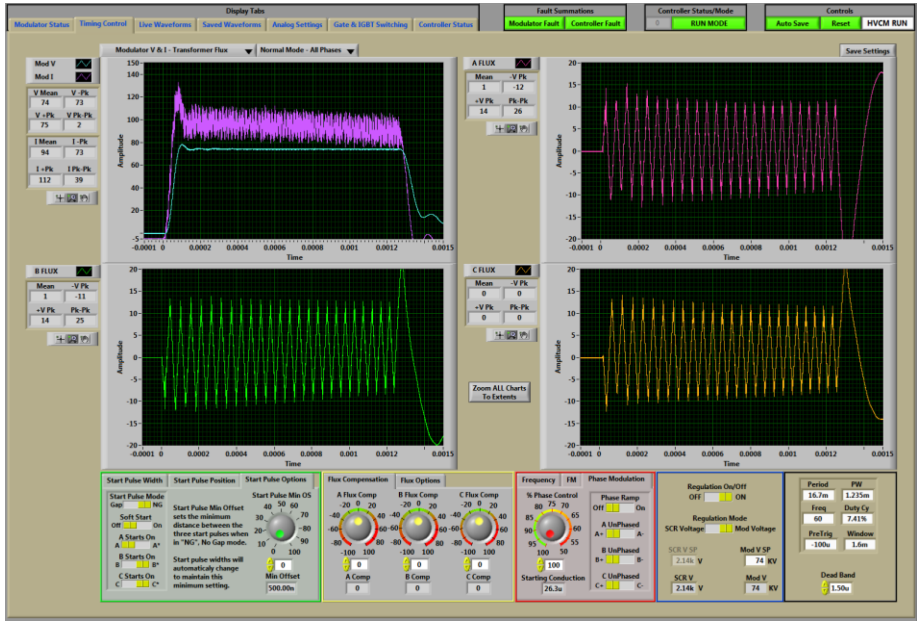


HVCM Modulator System

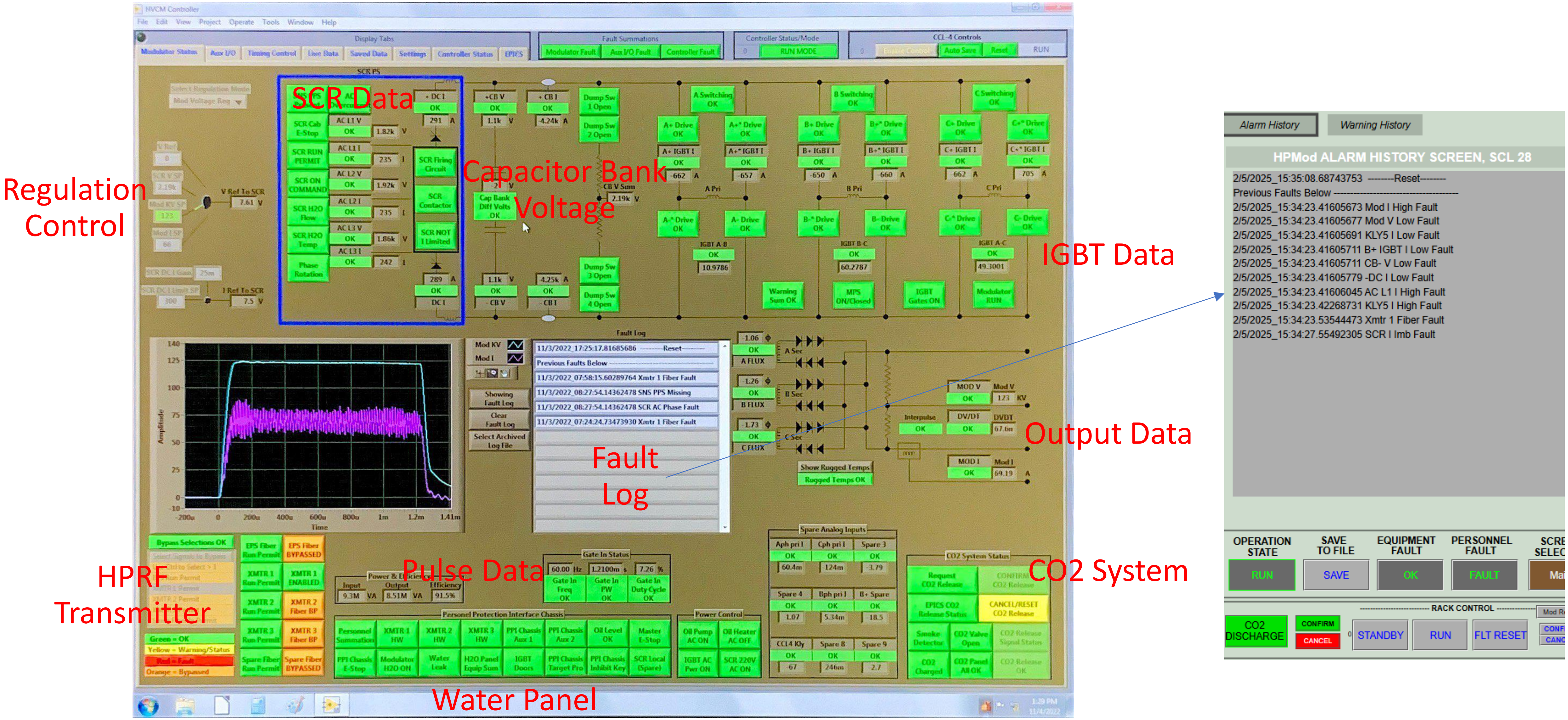
- Energy storage capacitors and IGBT H-bridge switch plates located inside Safety Enclosure
- HV boost transformers, rectifiers and filter components inside oil-insulated tank
- Ancillary systems for cooling water distribution, oil circulation, CO_2 fire suppression system and diagnostics/controls

HVCM Control System

- New controller developed at ORNL using National Instruments FlexRIO FPGAs and analog/digital I/O
- Enhanced capabilities over previous controller
  - First Fault detection to 25 ns resolution
  - Pulse Flattening
  - Full waveform capture
  - Set warning/trip levels
  - Additional operational modes
  - Enhanced IGBT functionality integrated
  - Intellectual property ownership
  - Expandable



HVCM Control System

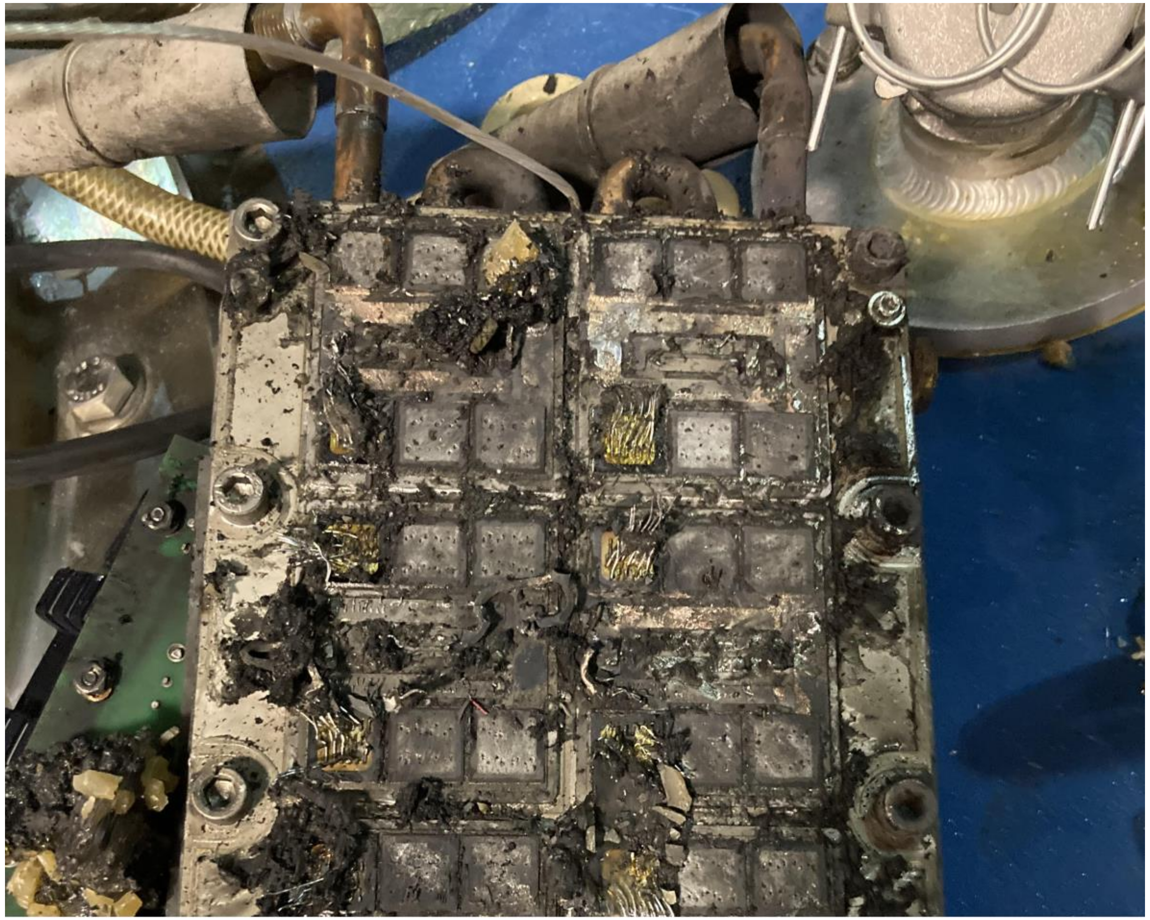


SNS HVCM Advantages

- 20 kHz inverter frequency
  - Small transformers
  - Small output filter
    - Fast risetime (<100 µs)
    - Low stored energy: minimize arc fault energy
- Low inverter voltage (~2 kV)
  - H-bridge is air insulated
  - Only low maintenance HV components are in oil
- The resonant peaking capacitors allow fault “ride-through” capabilities.
  - Load impedance changes (such as klystron discharges) de-tune the resonant circuit.
- Modulator utilizes frequency modulation (FM) operation to obtain a well-regulated output pulse
- Excellent fault detection, equipment protection and troubleshooting tools

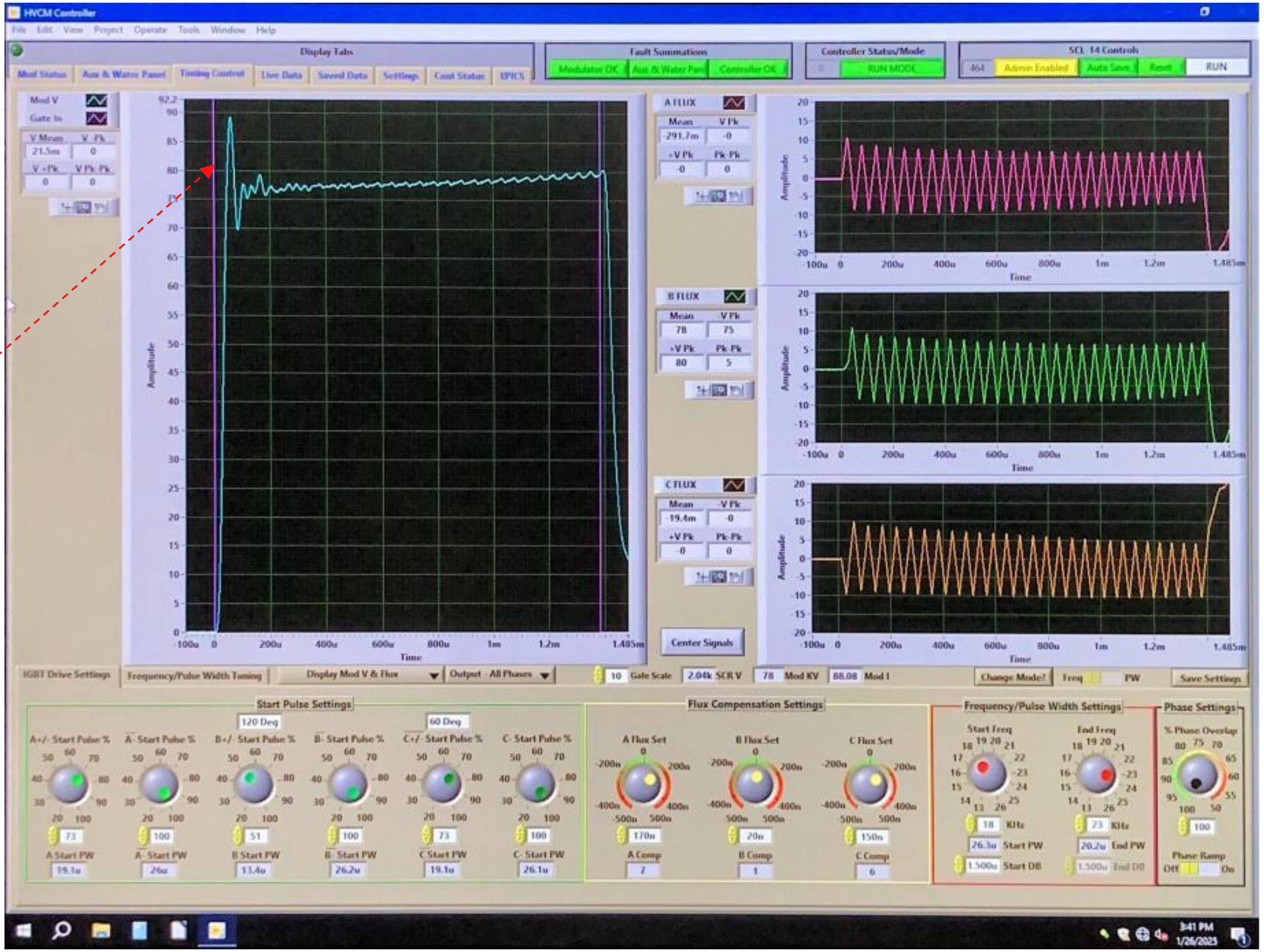
SNS HVCM Disadvantages

- IGBTs operation exceeds intended application(s) and with reduced engineering safety margins
  - 20 kHz operation requires careful attention to IGBT gate drivers
  - Nominal operation at ~70% of device rating requires fast snubbers and low parasitic inductance in H-bridge
- Load-sensitive topology requires variations for variety of klystron load configurations at accelerator facility
- Resonant capacitor sees full voltage reversal – difficult to design high reliability capacitor
- 6-pulse controller rectifier converter generates harmonics and variable PF on utility grid



SNS HVCM Disadvantages

Voltage Overshoot
(90 kV Trip Limit)



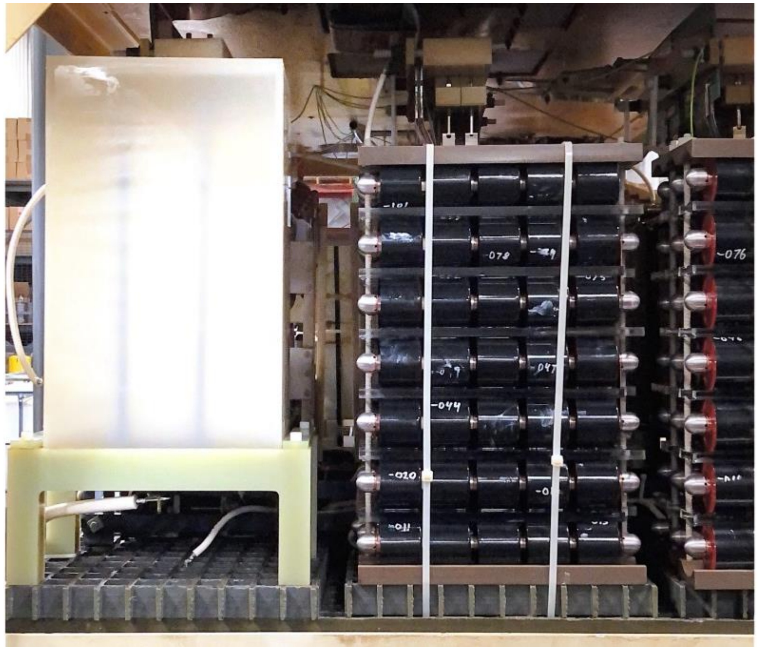
Nominal Conditions:
78 kV, 114 Amps

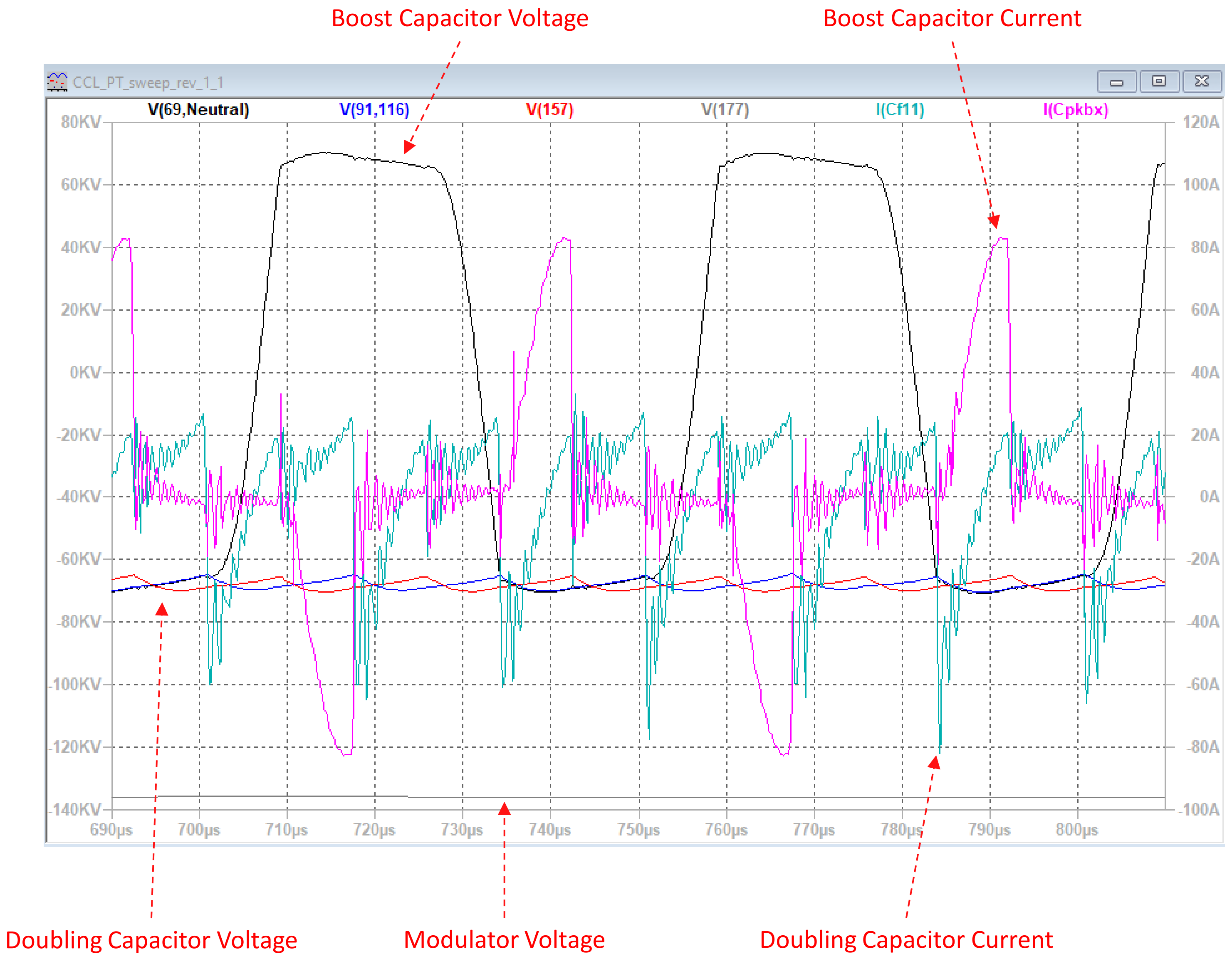
Waveform:
78 kV, 88 Amps
10 kV Overshoot

Scenario:
HPRF Klystron
Emission Curve Testing

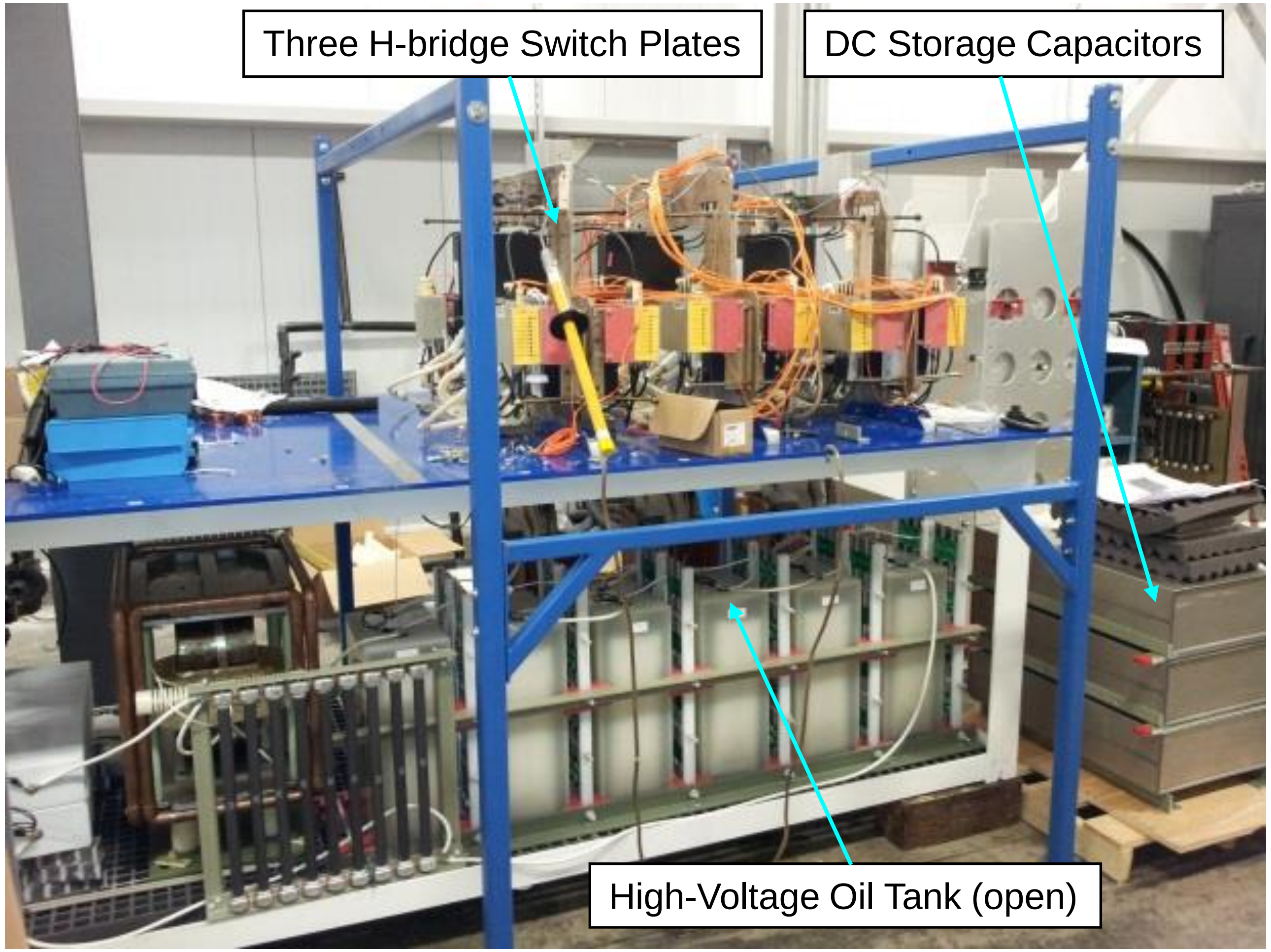
Capacitor Requirements

- Capacitance 3100 pF
- Rated Voltage 150 kV DC
- Test Voltage 220 kV DC
- Operating Voltage 80 kV AC
- Operating Frequency 20 kHz
- Operating Duty Cycle ≤10%
- Peak Fault Current 25 kA
- Peak Operating Current 90 A
- RMS Current 10 A





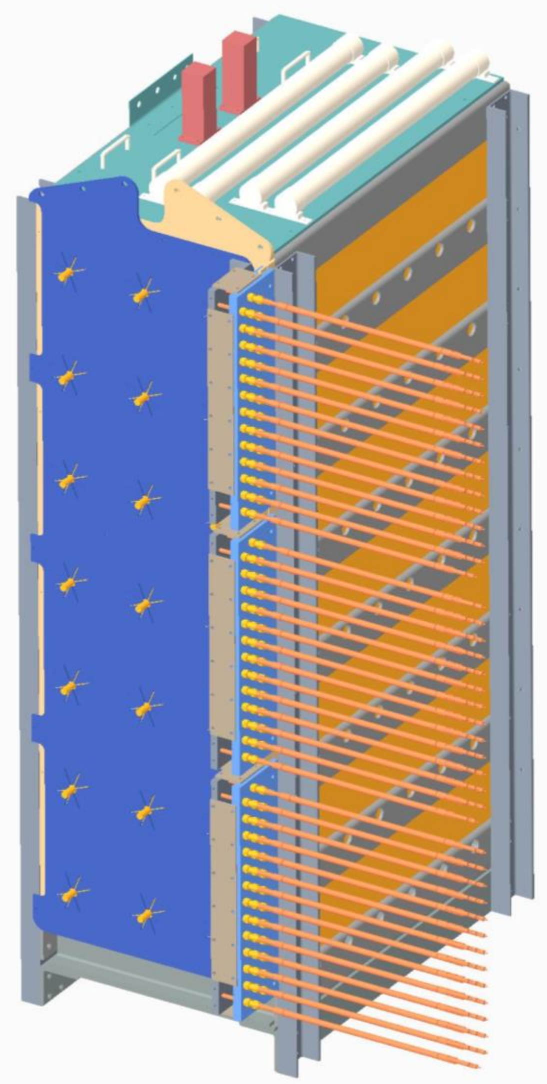
SNS HVCM Assemblies

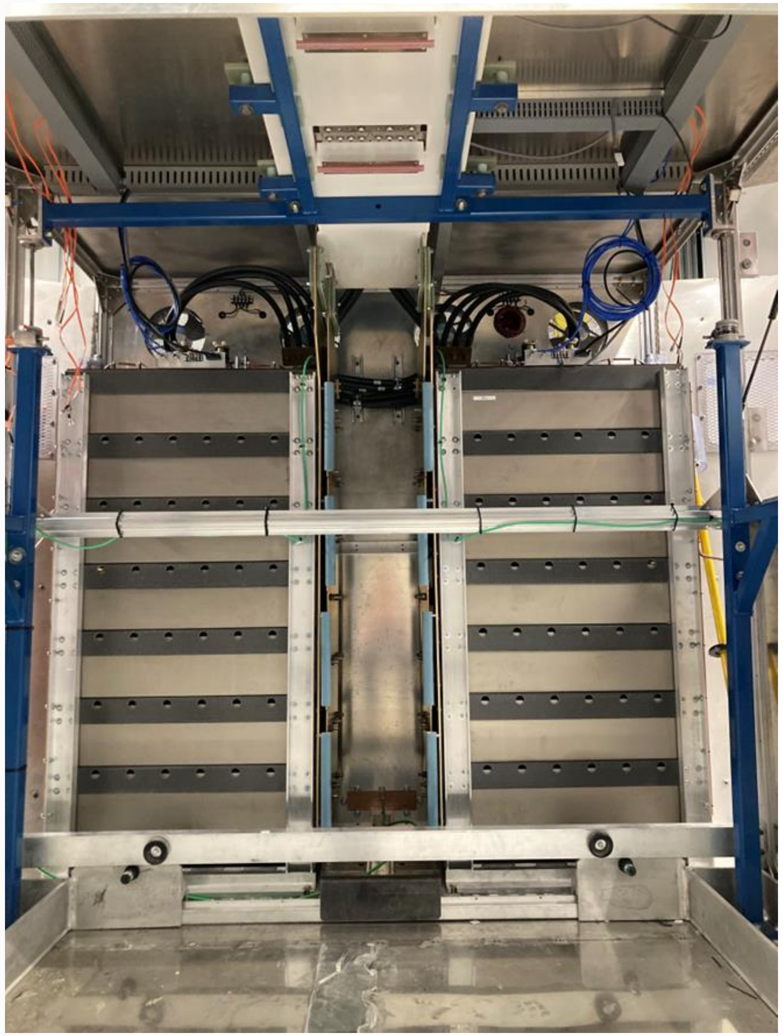


HVCM under test with Safety Enclosure removed and partial storage capacitor array

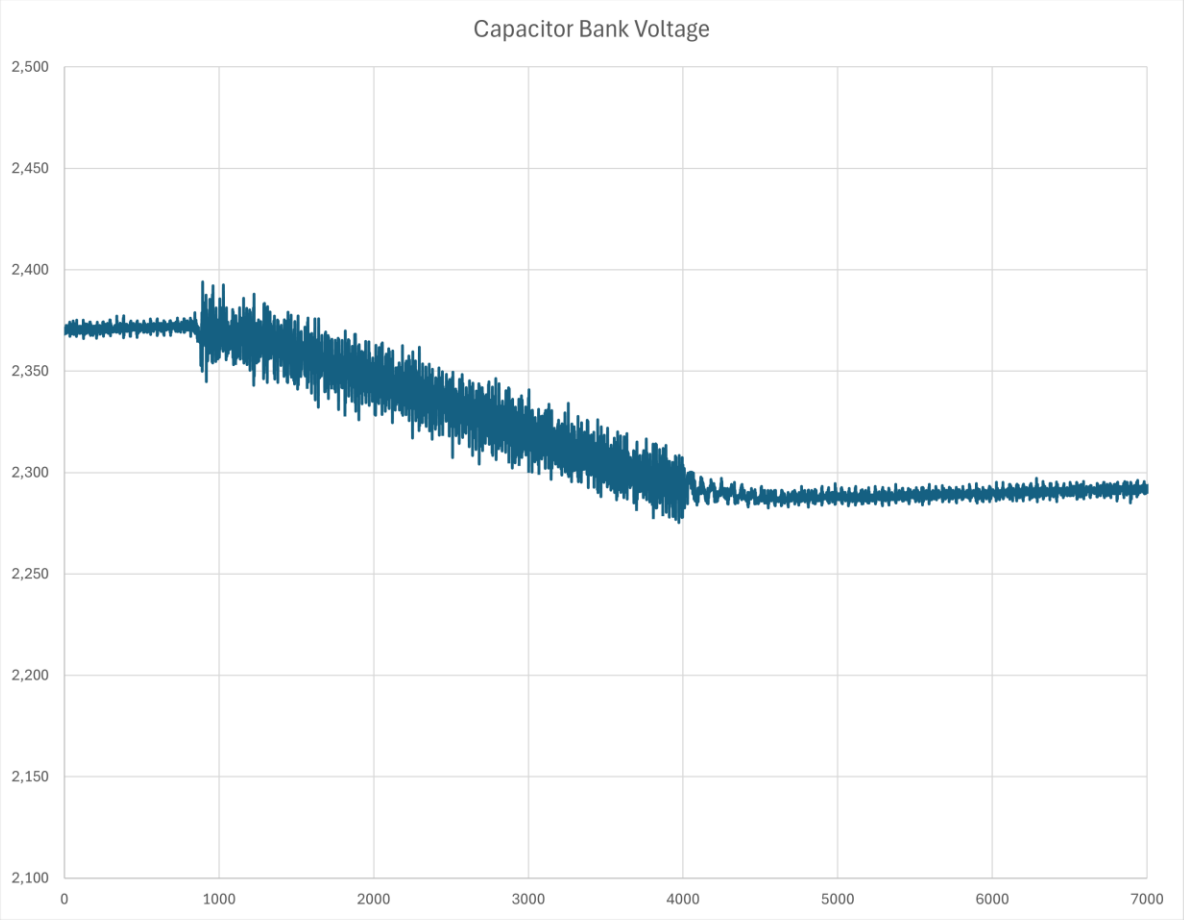
Energy Storage Capacitors

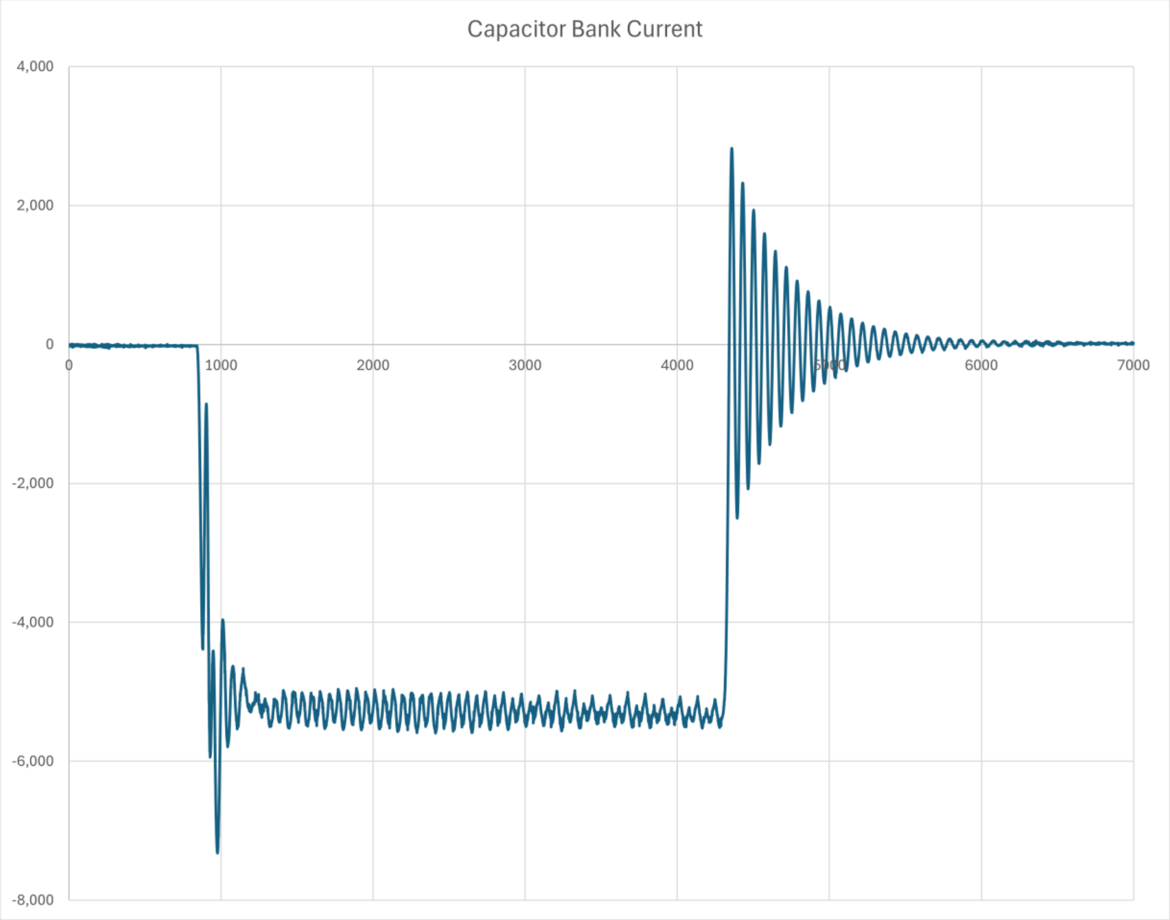
- 112 mF (16 mF × 7) at up to ±1300 V
- 75 kJ nominally each, rated for up to 95 kJ each
- Large metallized film units provide self-clearing capabilities in the event of an internal fault
- Bus work to H-bridge switch plates consists of 40 parallel fire-retardant RG-8 coaxial cables
- Safety circuitry, bleeder resistor, DC voltage diagnostics mounted on top





HVCM Energy Storage Capacitor Waveforms

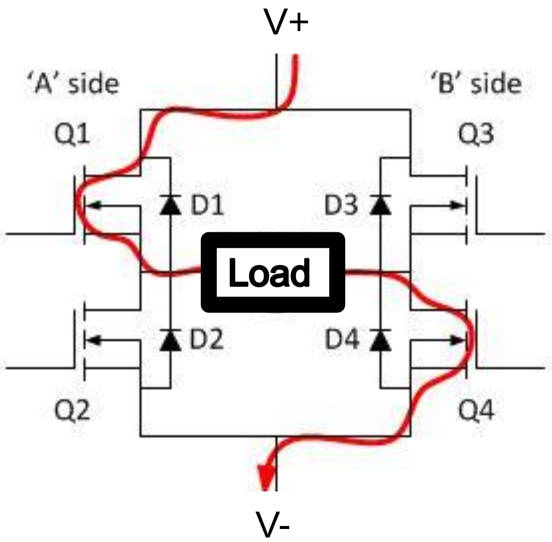


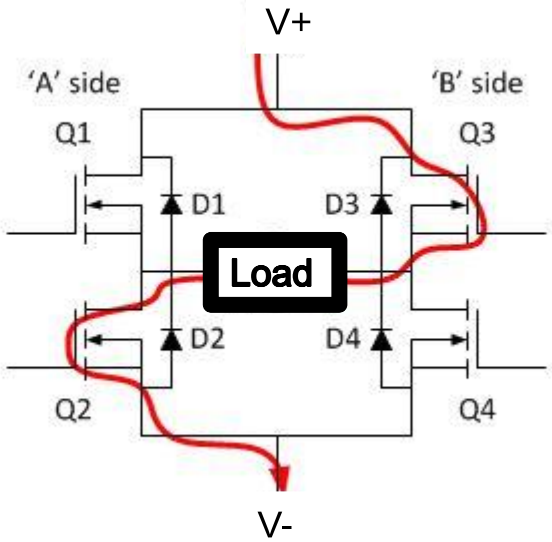


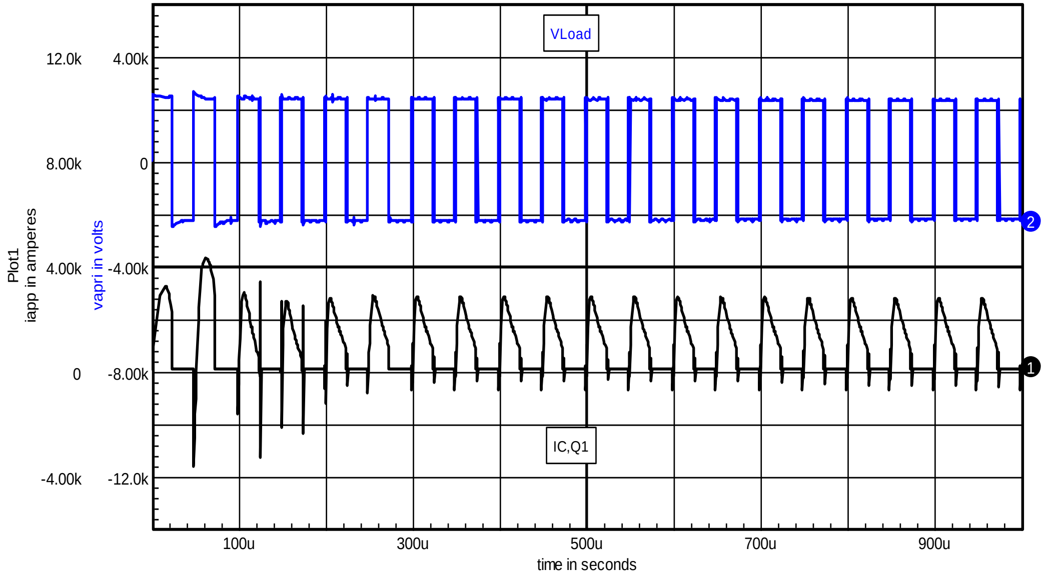
SNS HVCM – Safety Enclosure

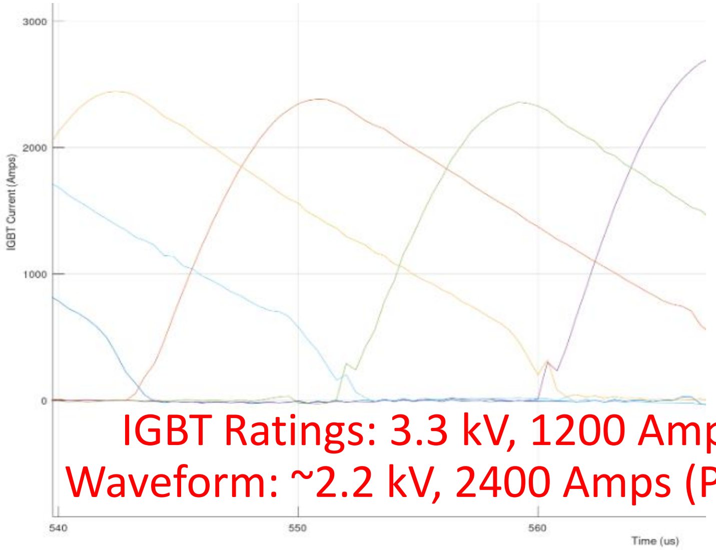
H-bridge Operation Fundamentals

- Four solid-state switches create bipolar square voltage pulses across the load
- Dead-time necessary to allow switches to recover
- If switches don't recover, shoot-thru event can occur and destroy switches on left- or right-hand of bridge

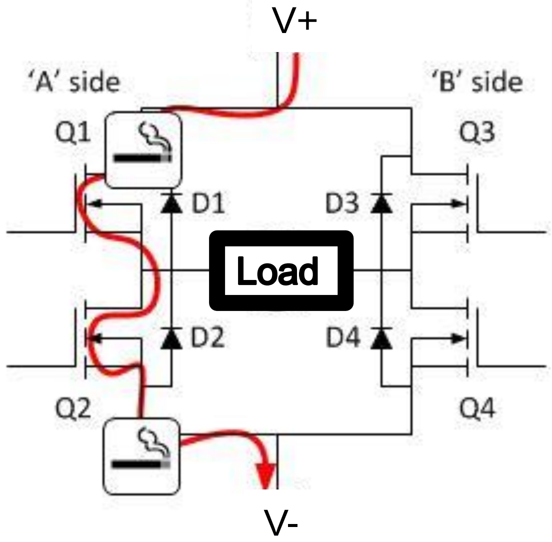




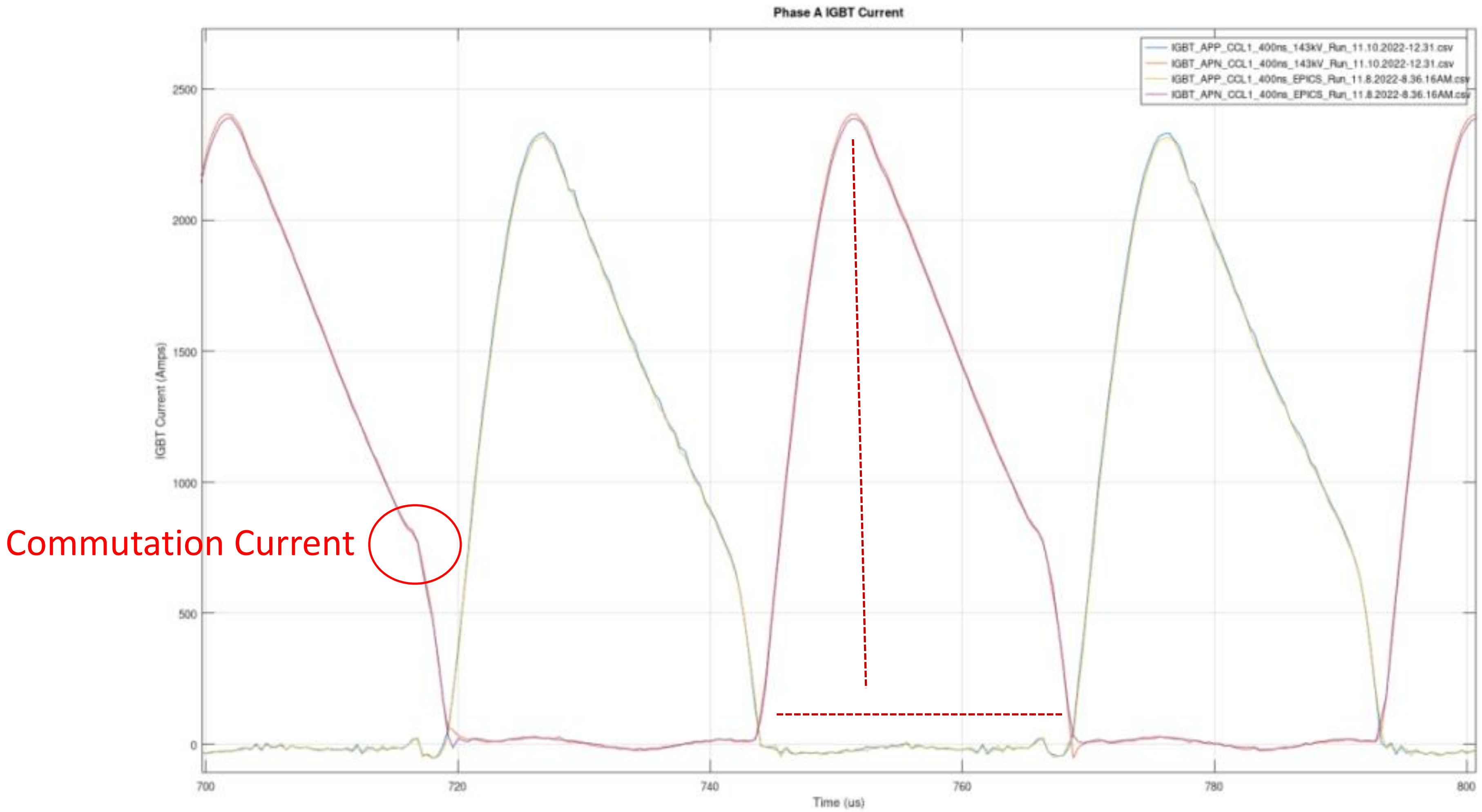




IGBT Ratings: 3.3 kV, 1200 Amps
Waveform: ~2.2 kV, 2400 Amps (Peak)



HVCM IGBT Waveforms



HVCM IGBT H-bridge switch plate

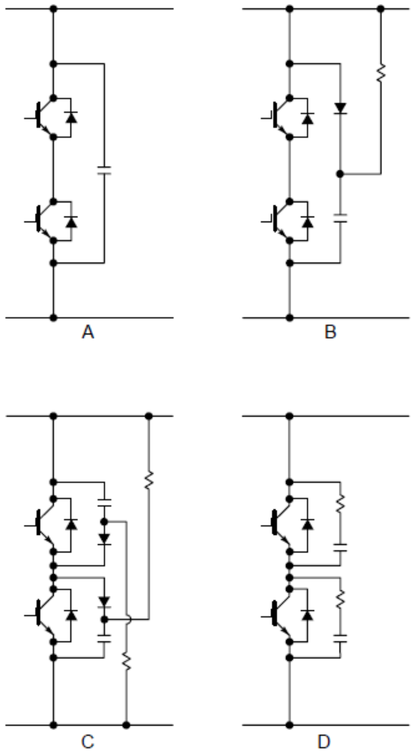
- Four H-bridge 3300 V, 1200 A Infineon IGBTs switching nominal 20 kHz mounted on discrete cold plates with bus work towards center.

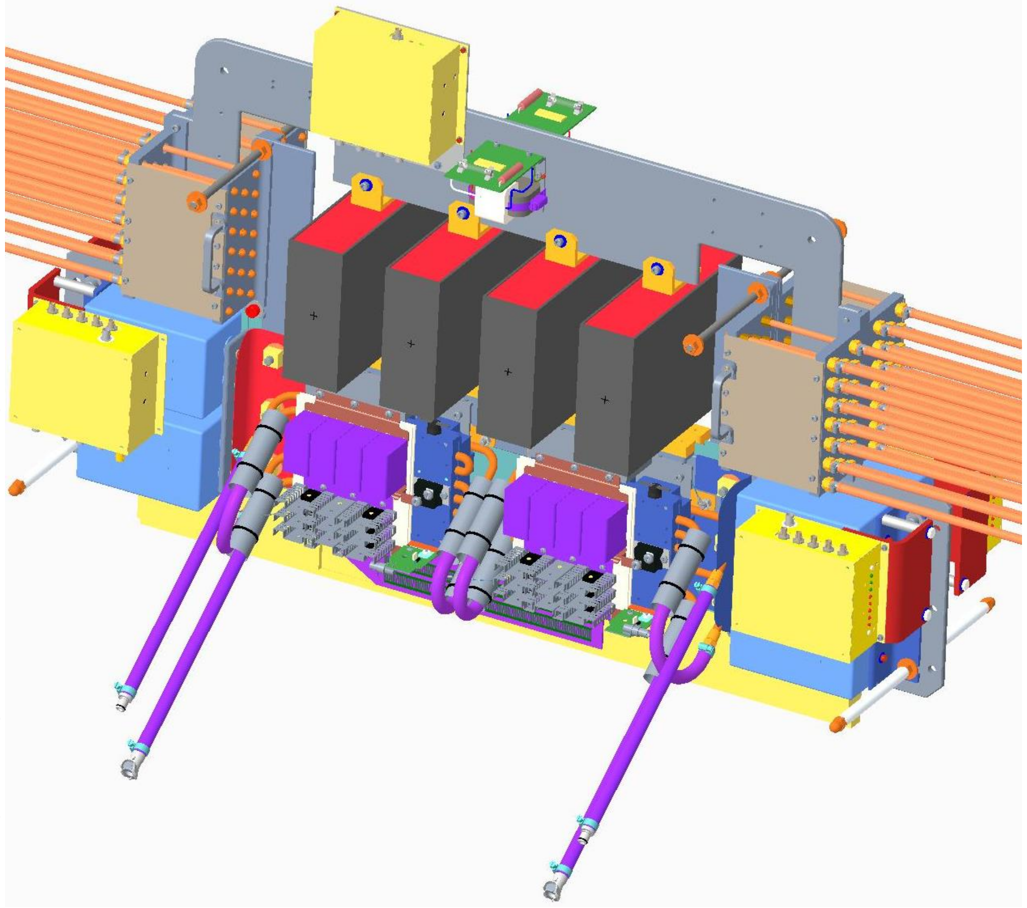
- Unipolar and bipolar capacitors provide high frequency bypass

- Gate drivers located remotely with low impedance cabling to IGBT terminals

- Gate driver power supply distributes 24 V DC

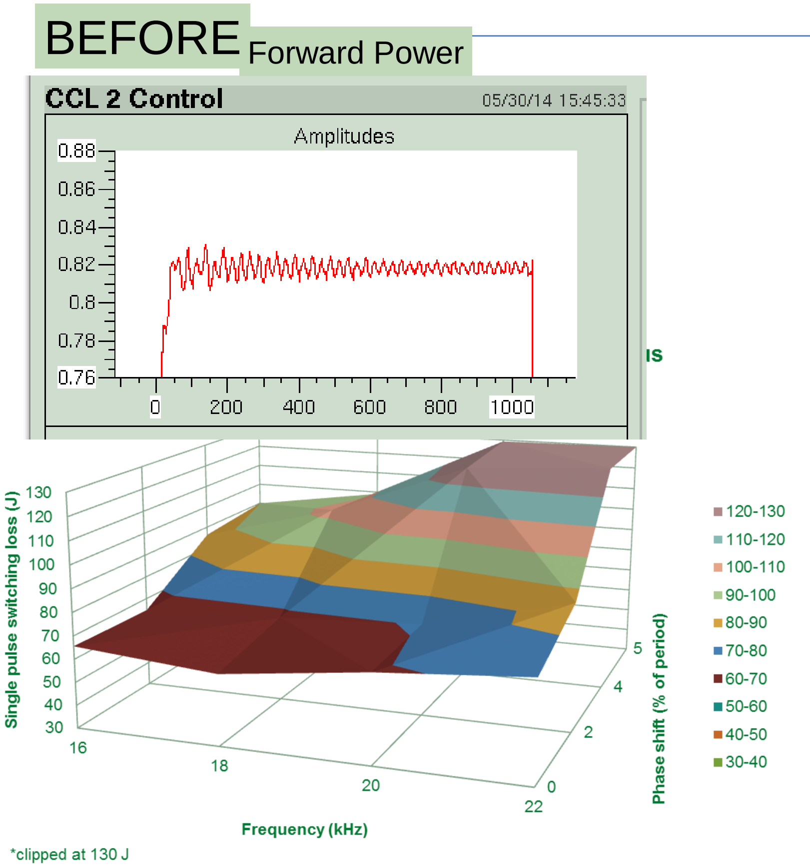
- RCD snubbers incorporated to eliminate IGBT overvoltage

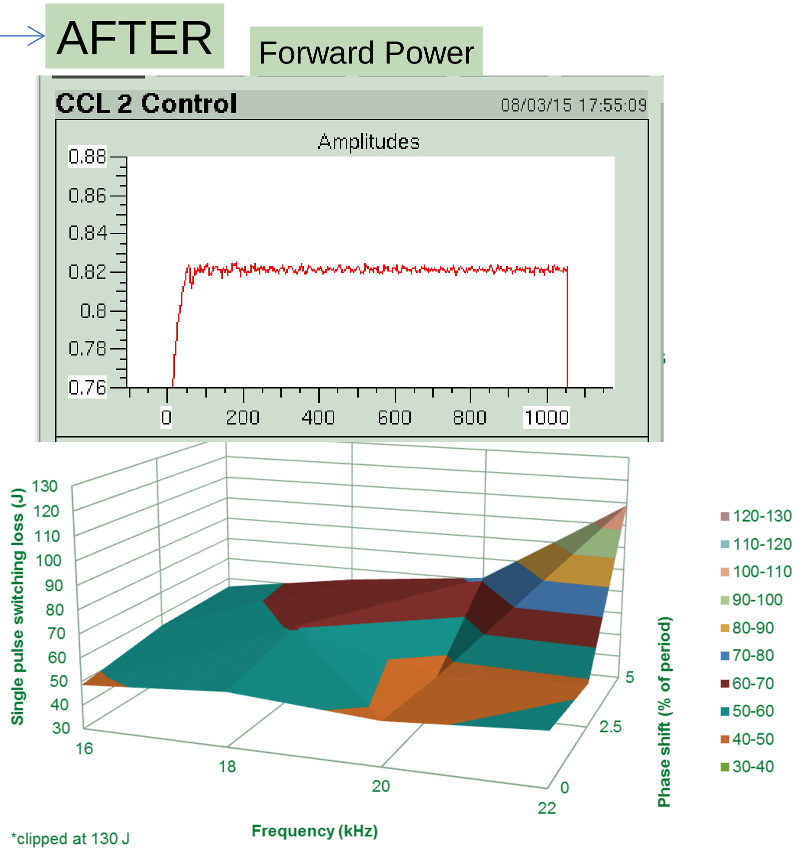


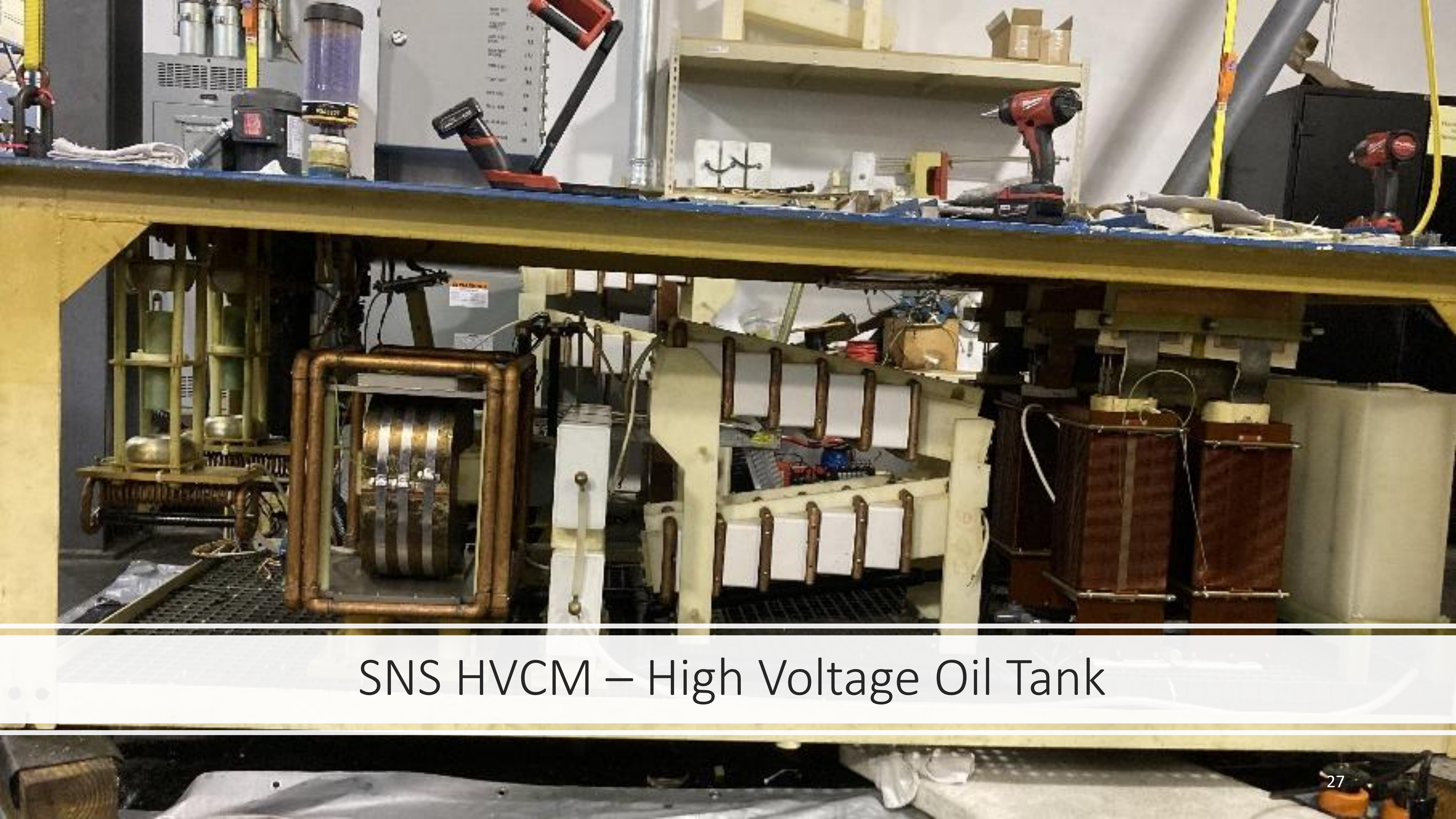


New IGBT gate drivers also lower losses & reduce ripple

- Uses commercial Power Integrations 30 A driver
- Demonstrated IGBT switching loss reduction of 30%
- ~5X reduction in RF forward power ripple due to reduced dead band

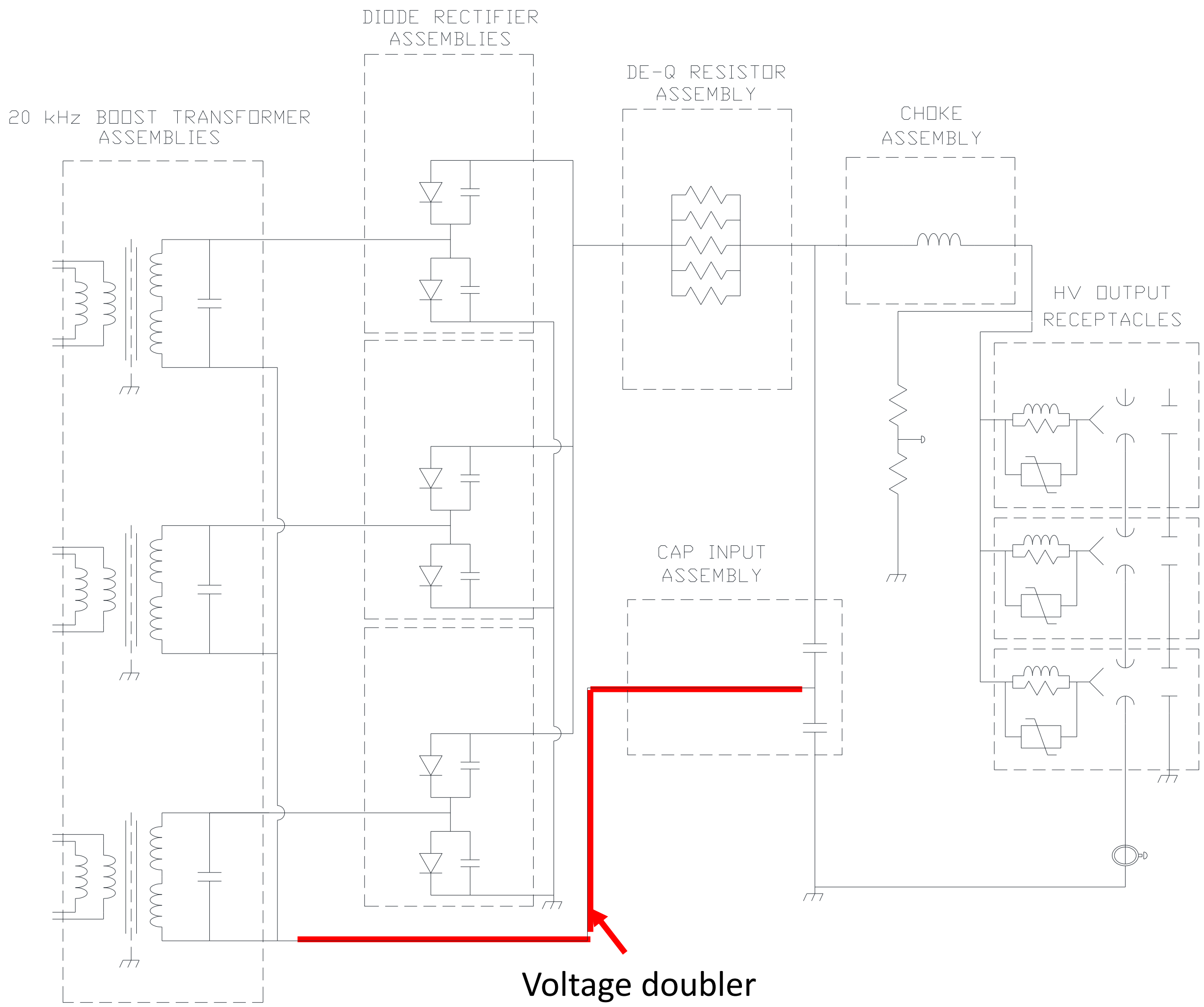


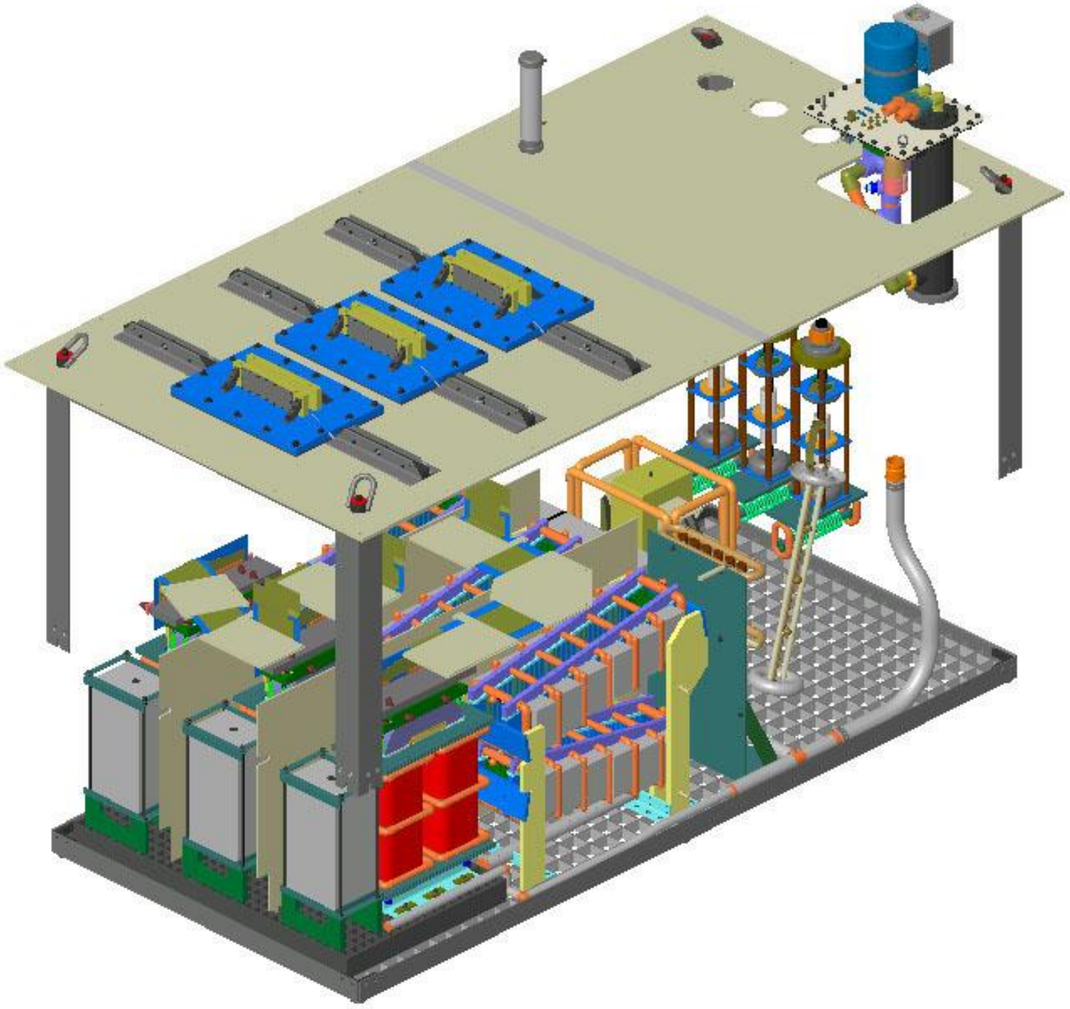




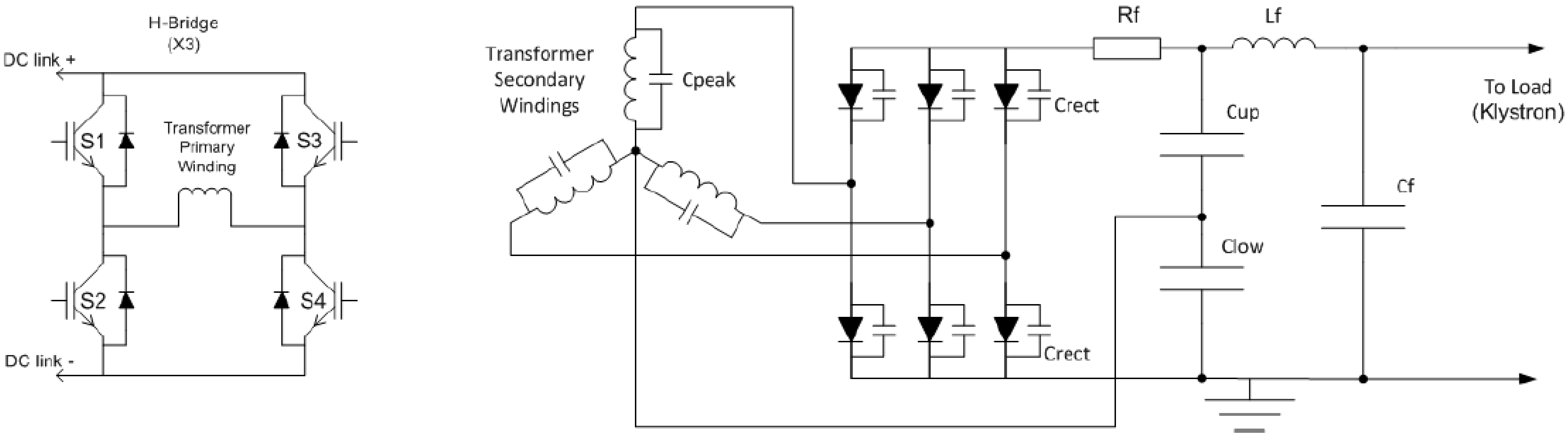
SNS HVCM – High Voltage Oil Tank

High voltage components inside oil-filled tank



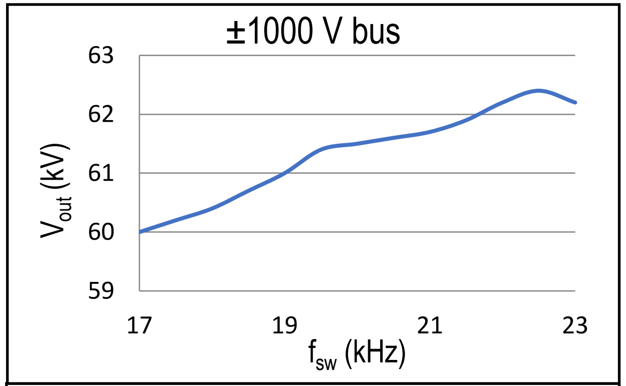


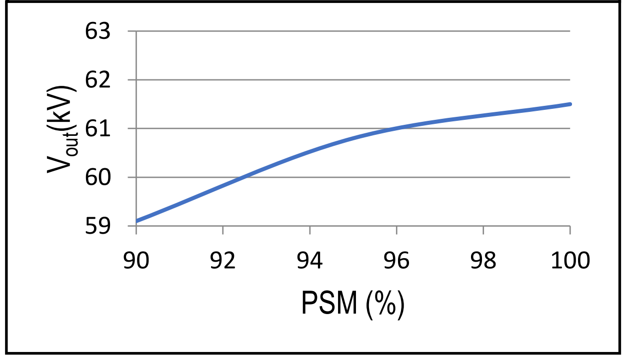
HVCM Schematic

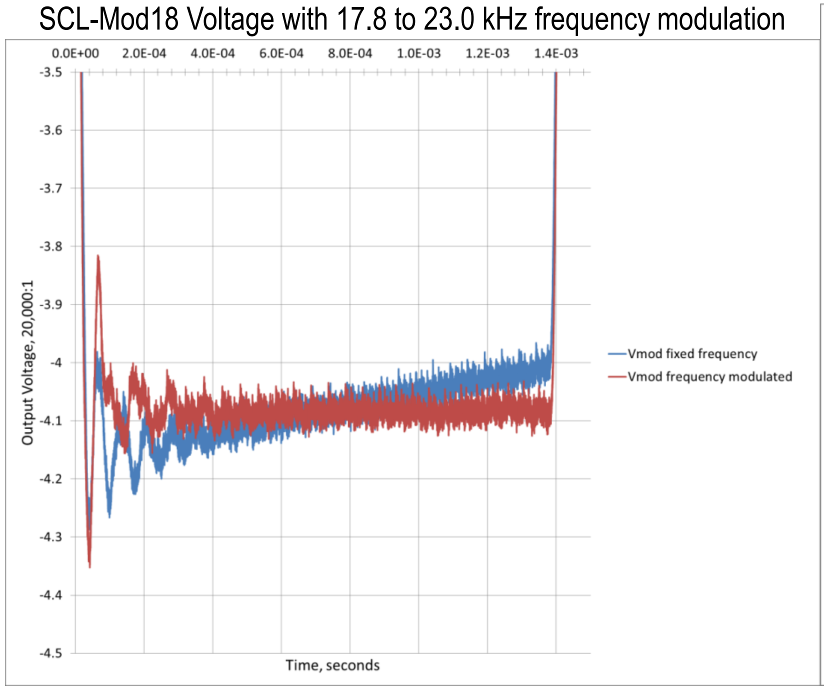


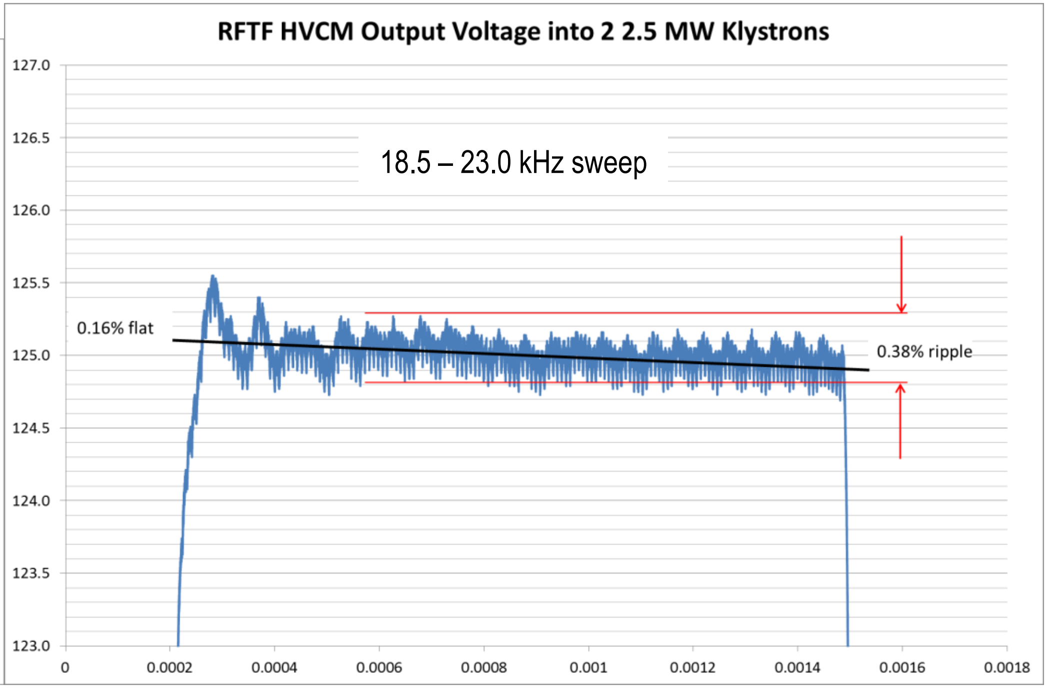
Pulse flattening to compensate for capacitor droop

- Reduces voltage stress on klystrons & modulator components
  - Utilizing frequency modulation only
  - Phase shift pulse width modulation effective but increases switching losses in right-hand side of H-bridge
- IGBT commutation currents increase by 40% but still acceptable – hard switching in some cases
- Reduces LLRF bandwidth requirements

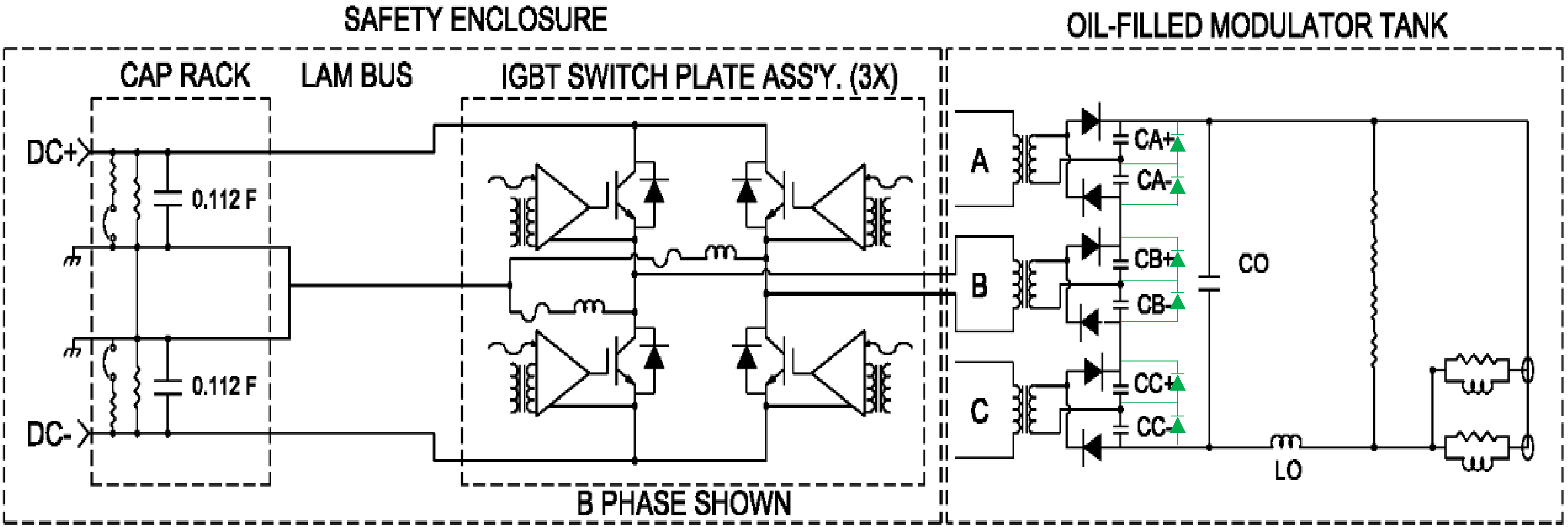








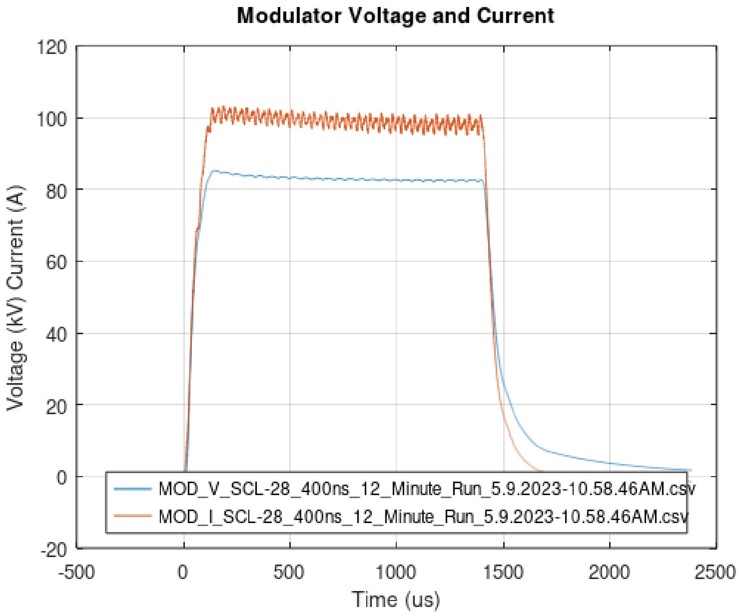
Alternate Topology (AT)-HVCM Developed to Reduce Component Stress and Achieve Soft Switching

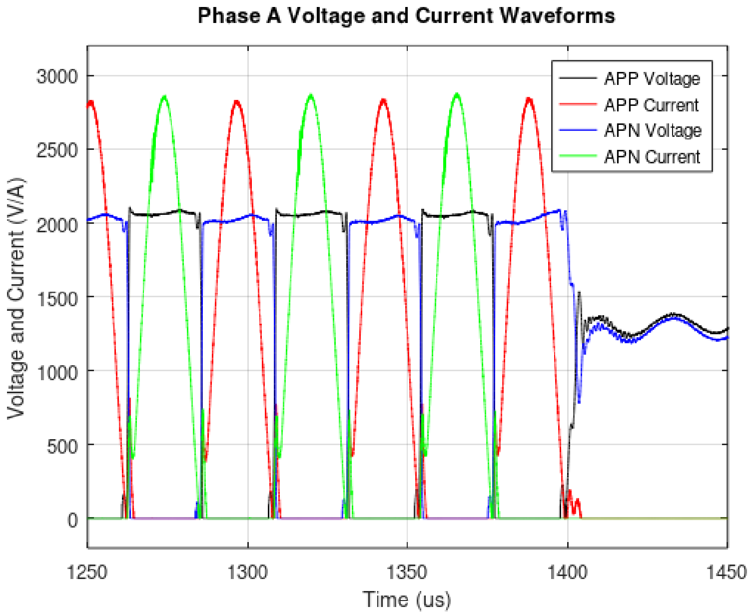


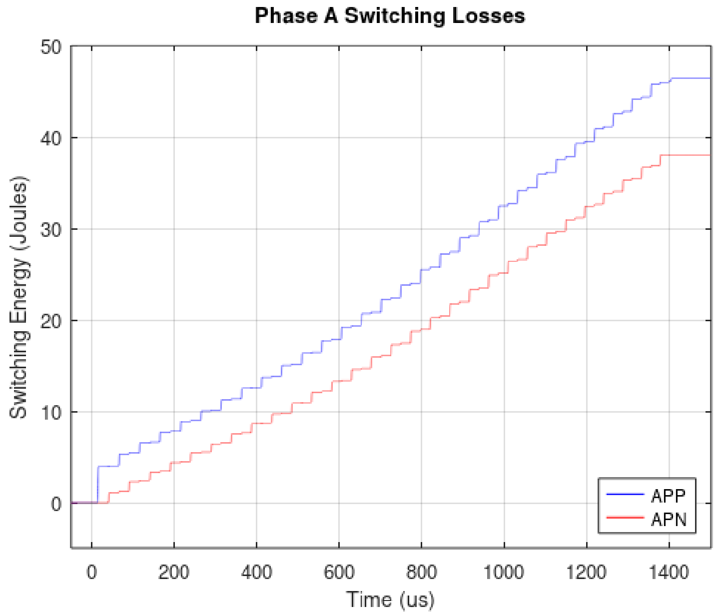
Cold Linac Alternate Topology (AT)-HVCM

Warm Linac Alternate Topology (AT)-HVCM

Alternate Topology (AT)-HVCM Developed to Reduce Component Stress and Achieve Soft Switching





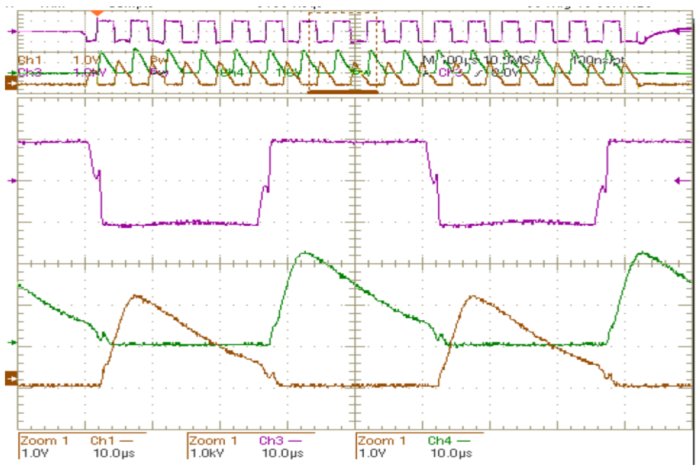


Necessary Conditions to Achieve zero voltage switching (ZVS)

Conditions for ZVS in resonant converter

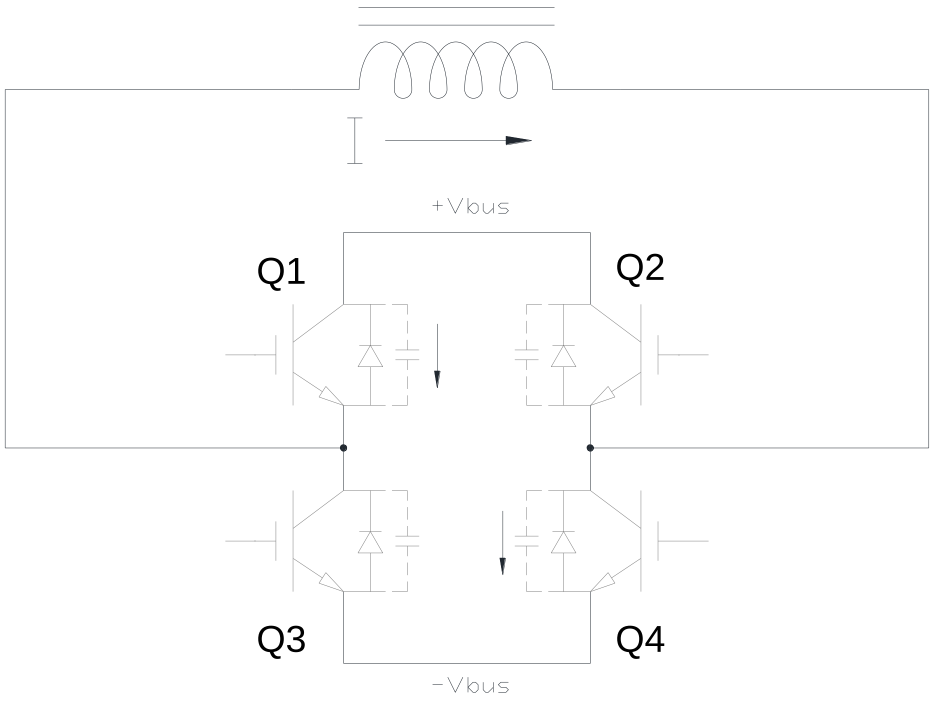
1. Inductive load impedance for bridge
   Insures current is circulating at turn-on
2. Sufficient energy stored in resonant tank inductor
   $\frac{1}{2} LI^2 > C_{OES} V_{CE}^2$
3. Sufficient dead-time

In the AT-HVCM topology, the transformer magnetizing inductance provides the stored energy



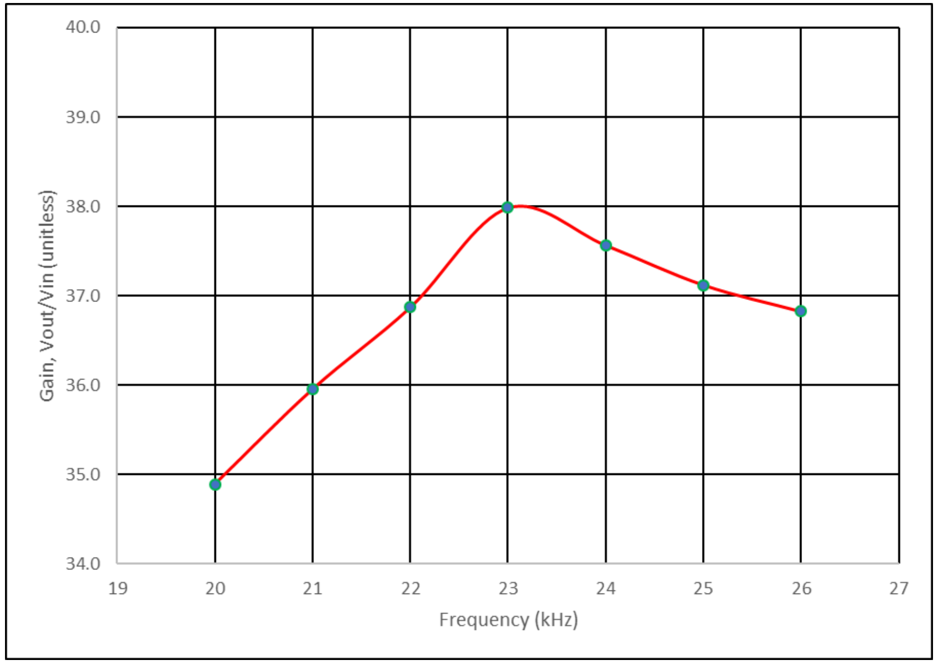
HVCM IGBT Q1 V_{CE} (magenta), Q1 I_C (gold) and Q2 I_C (green)

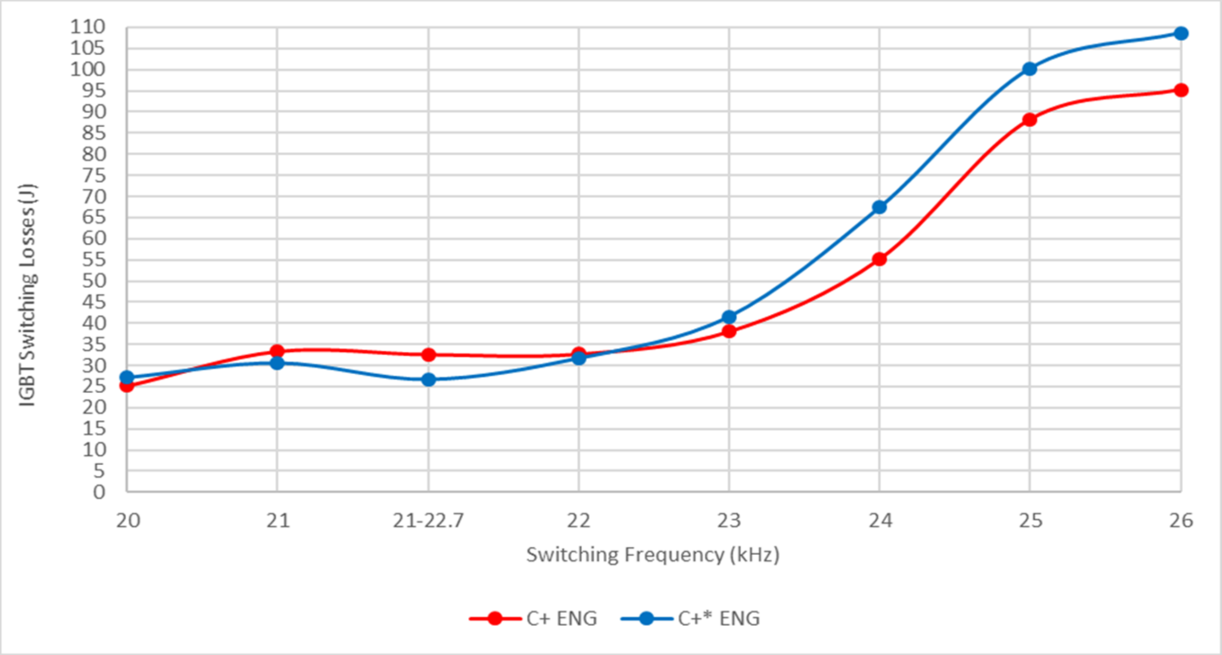
AT-HVCM IGBT Q1 V_{CE} (gold) and I_C (cyan) ZVS @ turn-on from magnetizing current



Q1 and Q4 have just been gated off. I_L stored energy charges C_{OES} of Q1 and Q4. Current then transfers to the freewheeling diode of Q2 and Q3 allowing zero voltage at turn on of those transistors.

AT-HVCM Frequency Modulation Performance





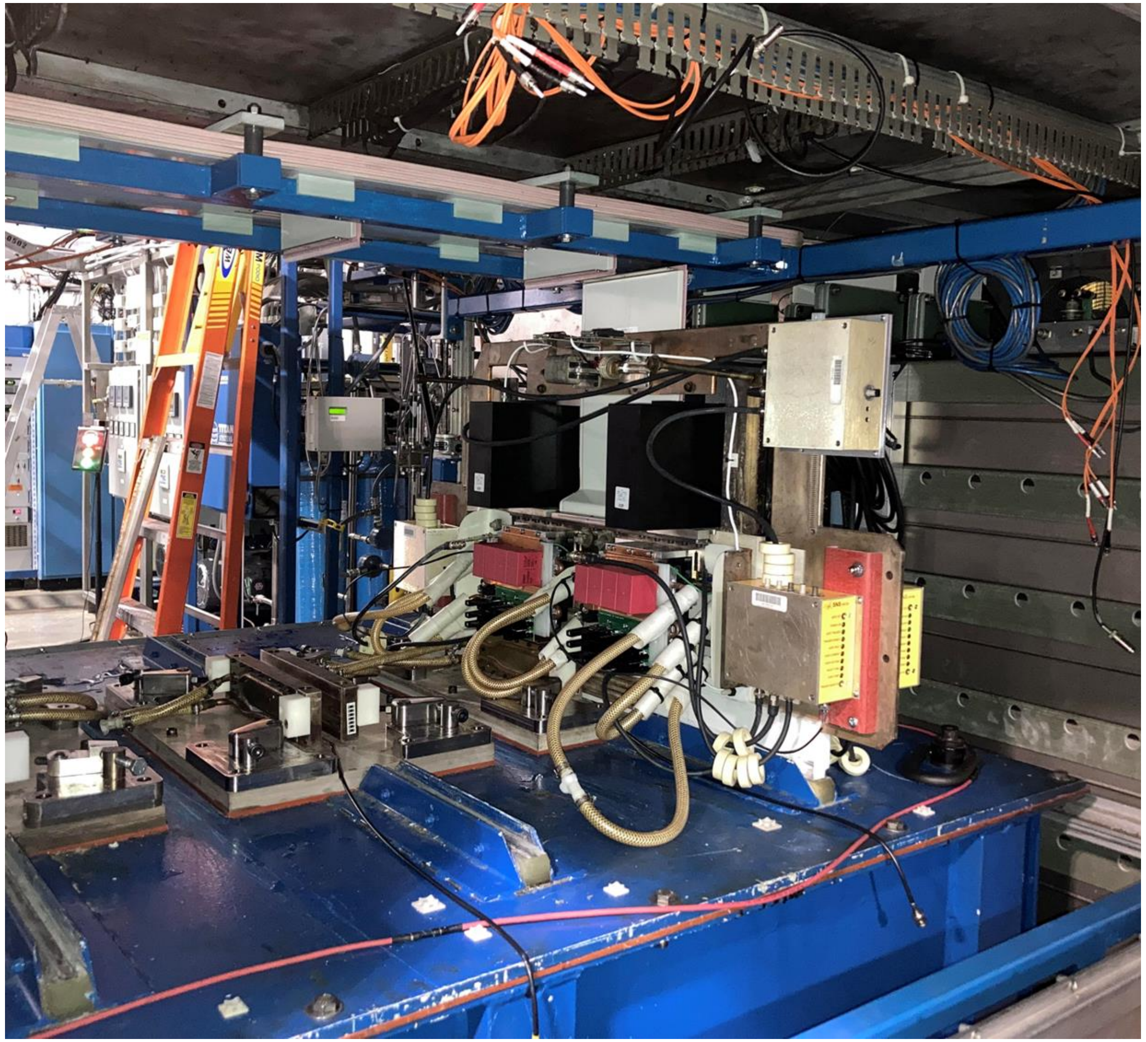
- Transfer function peaks at 23kHz and falls off below and above resonance.
- Gradient is 2x greater when operating below resonance.
- A 5% droop in capacitor bank voltage (equivalent to 2/37 gain change) compensated by 2kHz frequency sweep.

- Operating below resonance provides minimum IGBT switching loss and minimum frequency sweep for pulse flattening.
- Typical AT-HVCM IGBT losses are 30 J/macropulse (1.8kW) compared with 50 J/macropulse (3.0kW) for the present HVCM, further improving system efficiency.

Laminate bus assembly provides a low impedance DC bus connection to IGBT switchplates from capacitor bank

240 Electrical Connections → 6 Electrical Connections

New Laminate Bus Installation



Present SNS Status