Next Generation Polyphase Resonant Converter-Modulators Suitable for European Spallation Source Use

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Outline

- HVCM System Technology Overview
- Existing Installations
- KAERI Design Approach
- HVCM Fabrication
- Recent and Ongoing Developments
- Conclusion

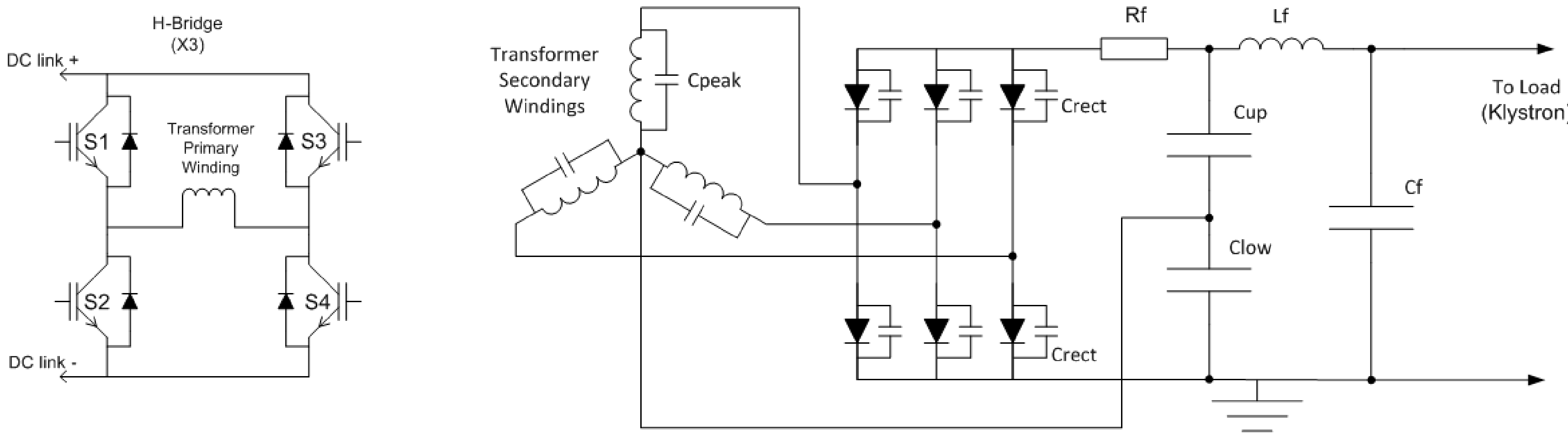
LANL HVCM Team

William Reass	Team Leader & Lead Design Engineer for SNS, KAERI, and SLAC HVCMs
Michael Bland	Power Circuit Design & Modulation Techniques, Project Lead - Next Generation HVCM
Alex Scheinker	Optimization and Control
David Baca	Mechanical Design

Polyphase Resonant Power Conditioning - Review

- A highly efficient method to generate high voltages at high power
  - First generation designs > 93% efficient
  - Newer designs > 96% efficient
- A polyphase and resonant DC-DC Converter
  - At least 1/10 size, weight, and volume of any previous method
  - Next generation designs can achieve soft switching and droop compensation using Combined Phase and Frequency Modulation (CFPM) developed at the University of Nottinham, UK
- Uses proven modern technologies
  - Multi-megawatt capable Insulated Gate Bipolar Transistors (IGBTs) used in the traction industry
  - DSP control techniques
- Transformer cores of amorphous nanocrystalline alloy
  - 1,000 times more efficient than steel
  - 1/300 core <u>volume and weight</u> for same power as 60Hz steel
  - Considerable developments
- Design is fault tolerant and inherently self-protective
  - Protect systems not necessary
  - Can drive long output coaxial cable lengths to 1 km

HVCM Overview Schematic



HVCM Development – Major Milestones

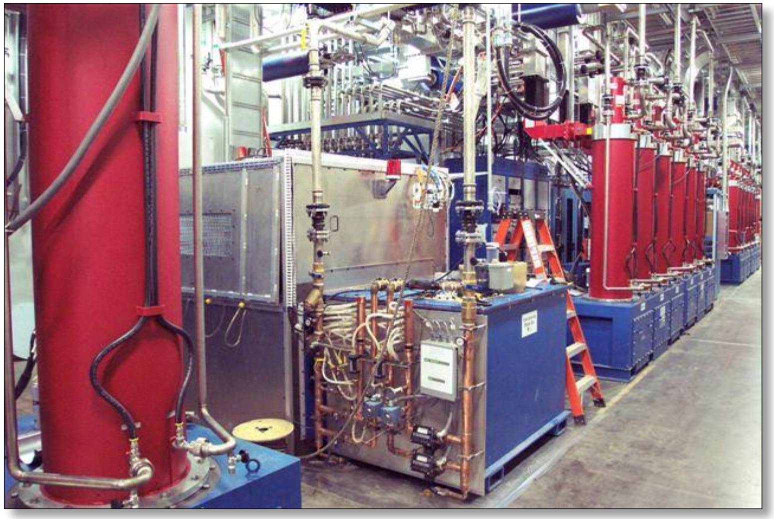
2000-2001	First prototype development started at LANL for SNS Component development contracts for capacitors, nanocrystalline cores Evaluation of semiconductor characteristics
2002-present	Reliability improvements at SNS
2005-2007	Combined Phase & Frequency Modulation (CPFM) for soft switching and droop compensation technique developed at the University of Nottingham, UK
2009	KAERI systems delivered
2011-2012	• Soft switching and droop compensation implemented on prototype HVCM at LANL • New analysis, design, and optimization techniques co-developed at LANL & the University of Nottingham allow further improvements in efficiency and cost.
2012-2014	2nd Generation HVCM development

KAERI Test Installation

HVCM Units Installed And Operational

(Oak Ridge SNS)

CCL-ME1
with Klystron

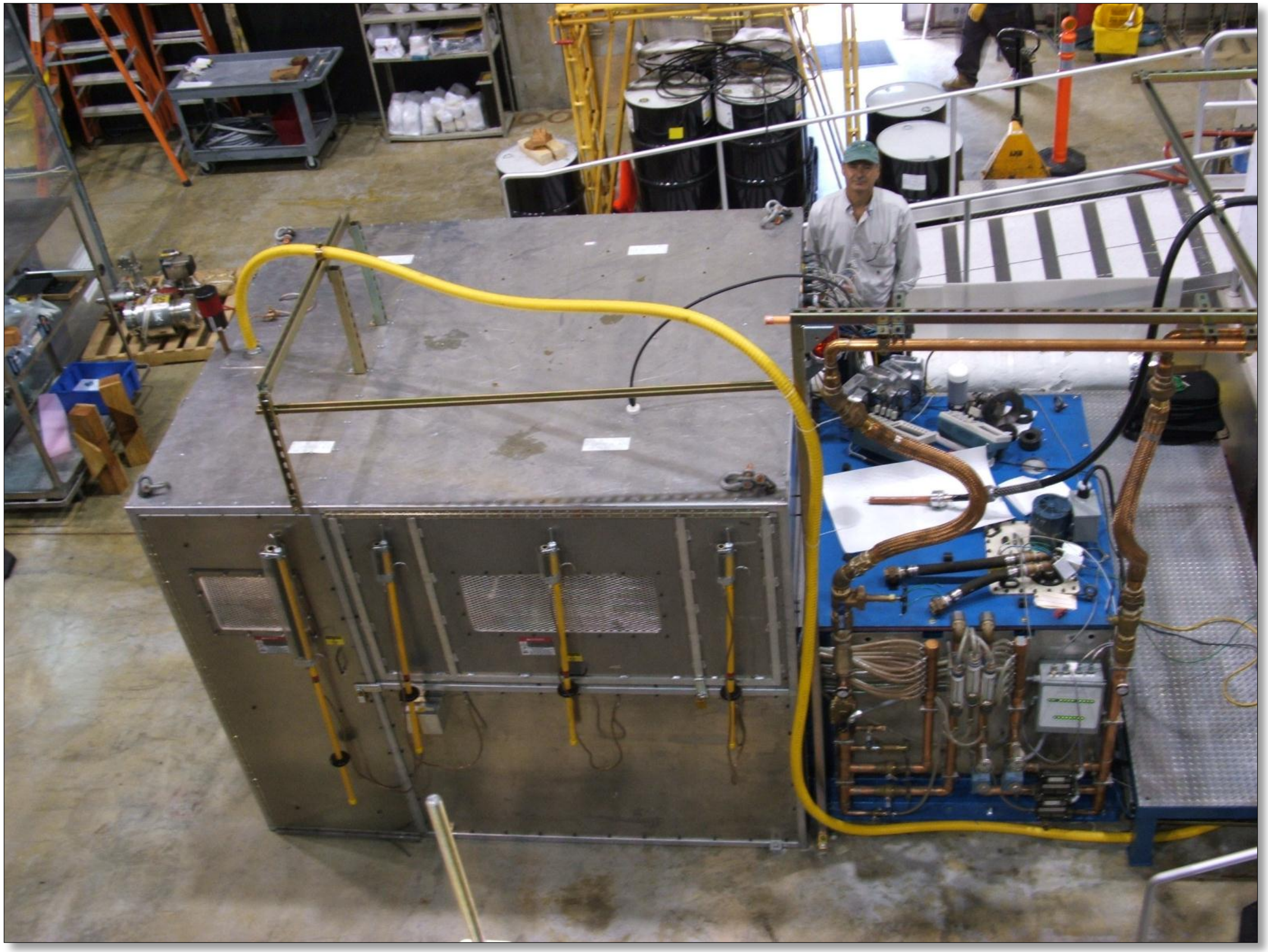


SCL-ME1 with 12 pack

DTL-ME3
with Klystrons

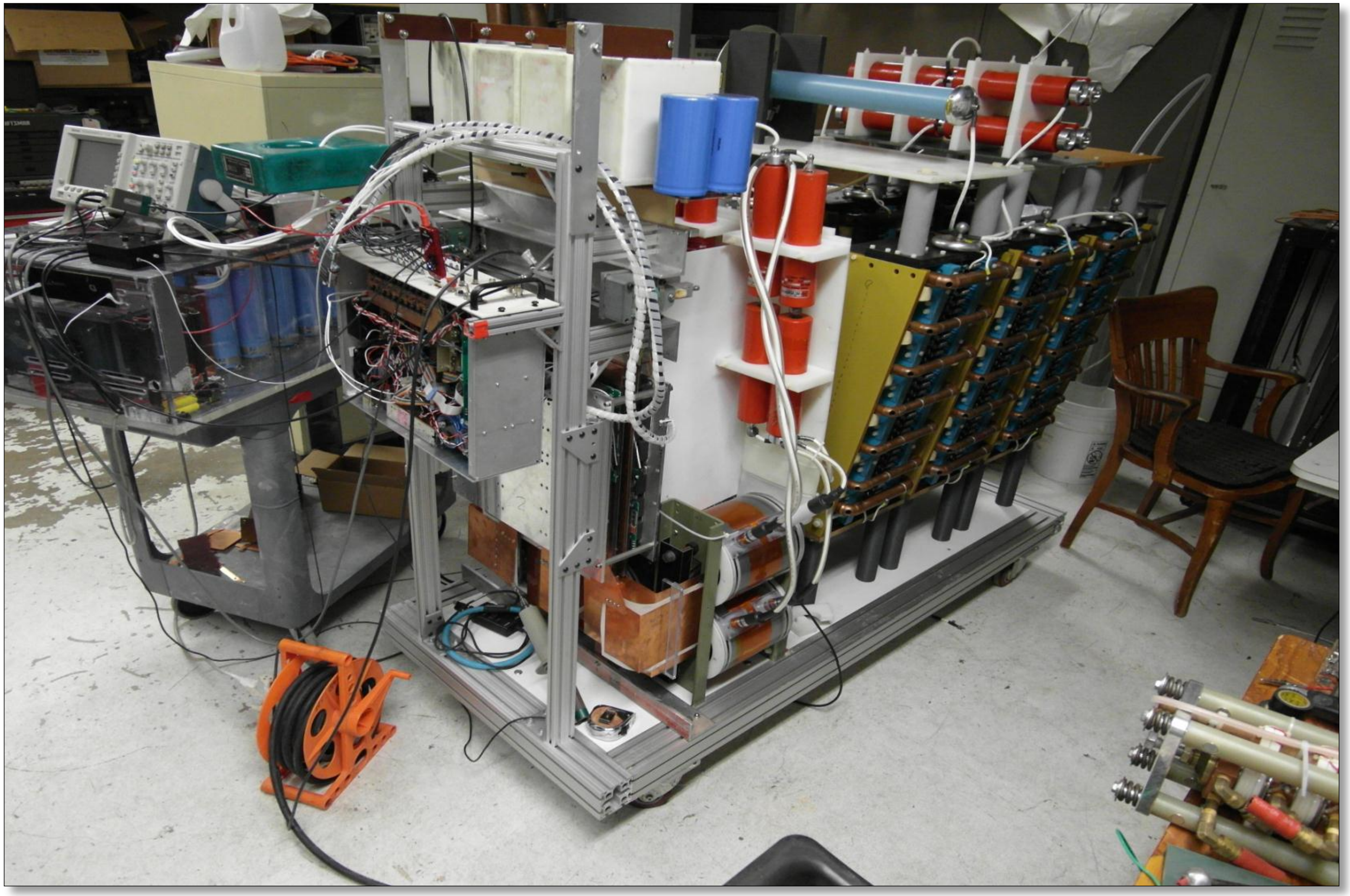
SNS HVCM Installation Crew

ILC L-Band Test Stand (SLAC)



80 kV Air Insulated HVCM

University of Wisconsin



University of Nottingham Prototype Modulator

Pulse Power = 300kW (@25kV) for 1ms

H-Bridges and DC-link capacitors

High Voltage Transformer

IGBT Reliability Studies

Electro-Thermal characterisation

High speed thermal imaging test **(1072 frames per sec., 45 sec)**

The University of Nottingham

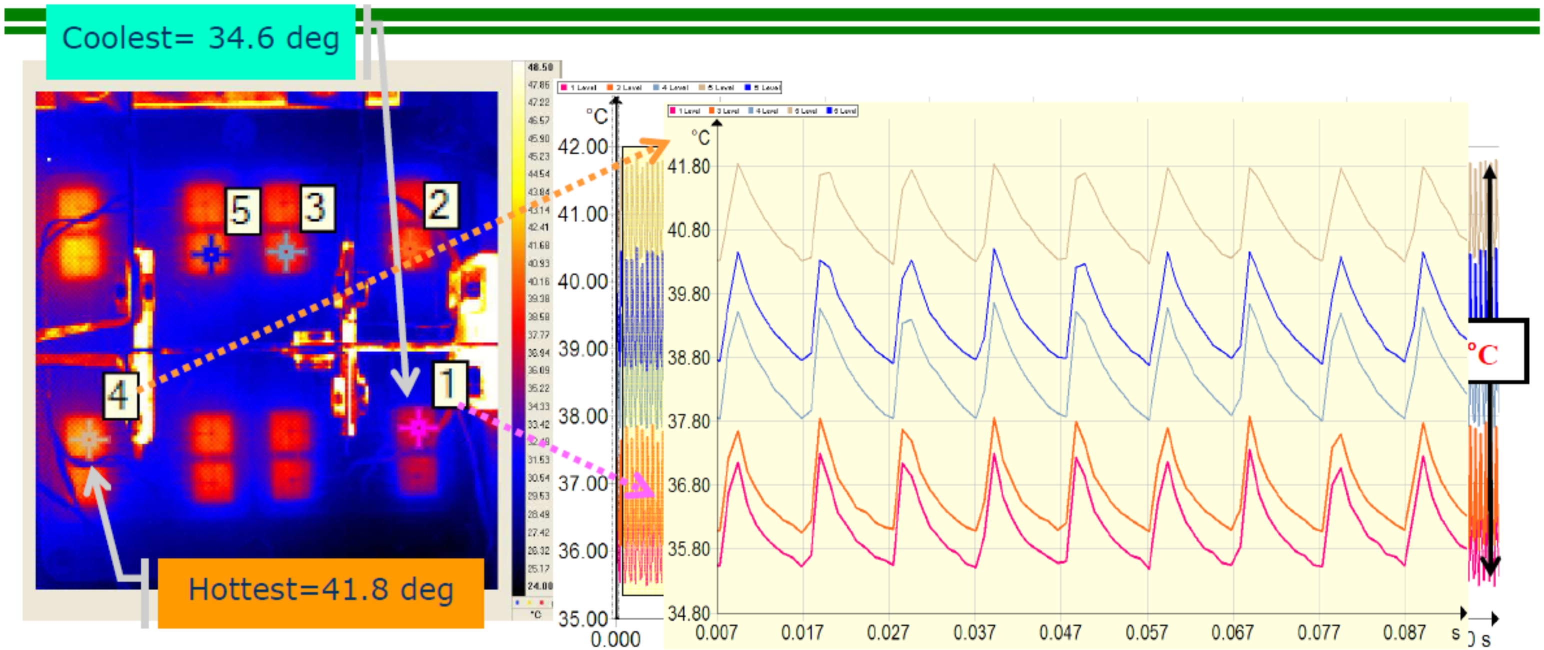
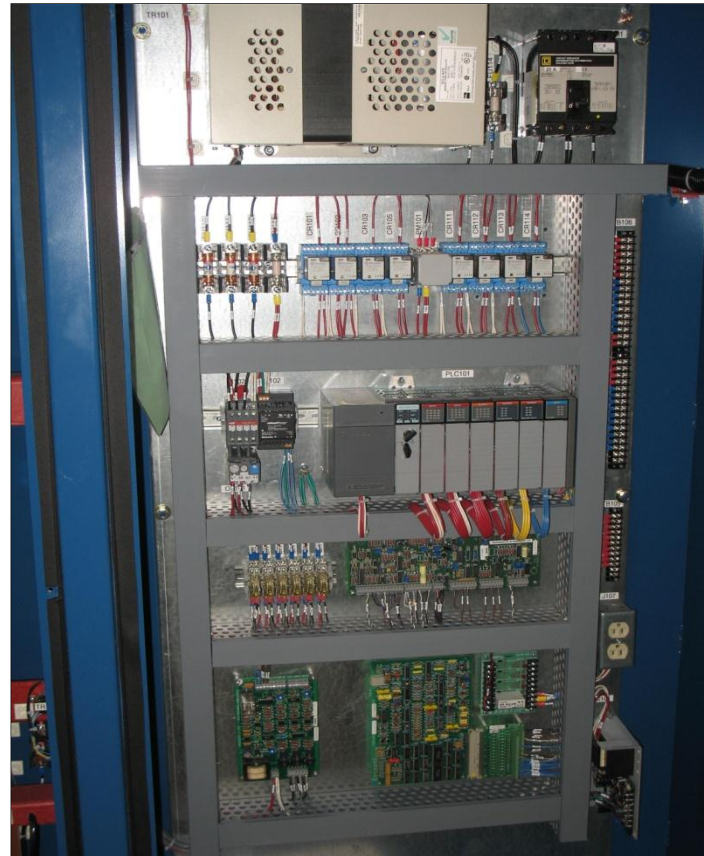


Figure 1: IGBT infrared thermal imaging, **Figure 2:** Sampled thermal transient during the test.

- Maximum junction temperature of **41.8°C** obtained from the experimental results, during steady state cold plate temperature conditions.
- During the 1ms pulse (i.e., the low-frequency waveform), the maximum temperature rise below **1.4°C** is observed..

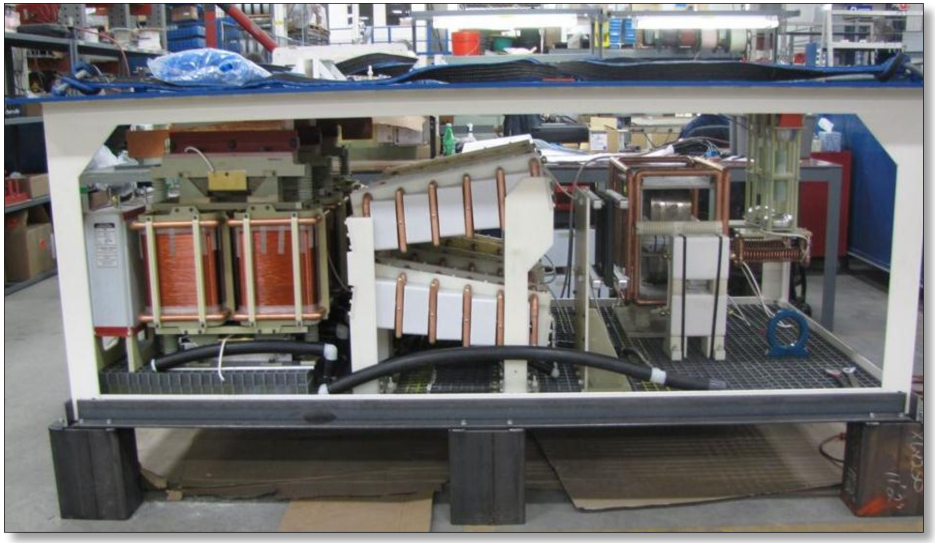
SCR Controller / Substation Assemblies

- Substation Vacuum Cast Coil Transformer
- Mitered and cruciform core
- Pancake Windings



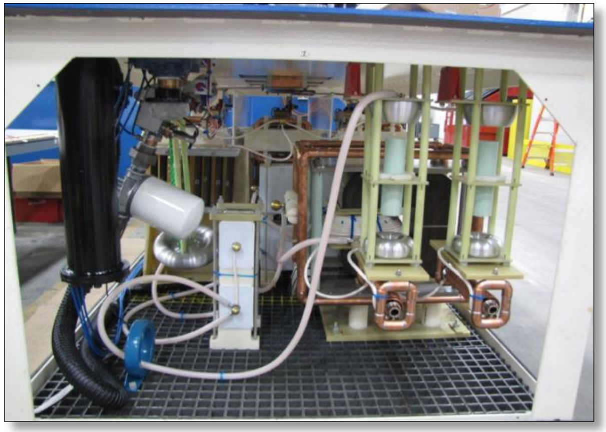
- Electronics Control Cabinet
- A/B SLC 500 PLC
- Open door operation

KAERI Converter-Modulator Assemblies

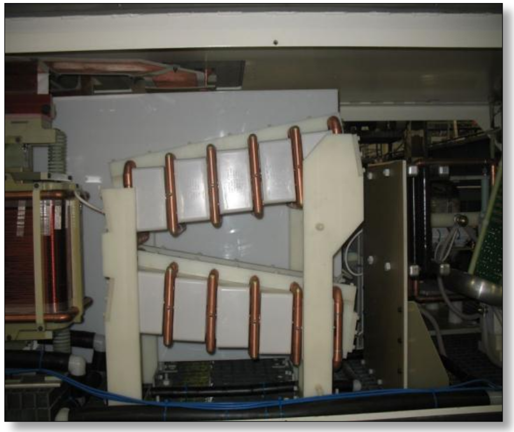


Tank Basket

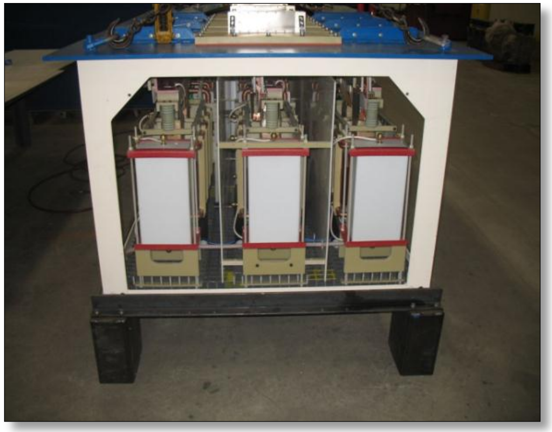
Nanocrystalline Transformers



Output



Resonant Rectification



Transformer Resonating Capacitors

KAERI & ESS – Requirement Comparison

	KAERI	ESS
Output Voltage	105 kV	105 kV, 80kV
Output Current	75A, 50A	75A, 60A
Pulse Length	1.5ms	3.5ms
Duty	9%	5%
PRF	60Hz	14Hz
Mean Power	750kW	400kW

KAERI & ESS Requirement Similarities

- 105 kV Output at 50 Amps or 75 Amps
- 3 HVCMs operate 2 parallel 1.6 MW output 352 MHz klystrons each
- 1 HVCM operates 3 parallel klystrons
- All systems delivered

- 9% Duty
- 1.5 ms pulses at 60 Hz

- Up to 750 kW Average Power

- <1% Flat Top Regulation (with FM control)

- Existing KAERI (#4) system can operate 3 klystrons with ESS 3.5ms pulse

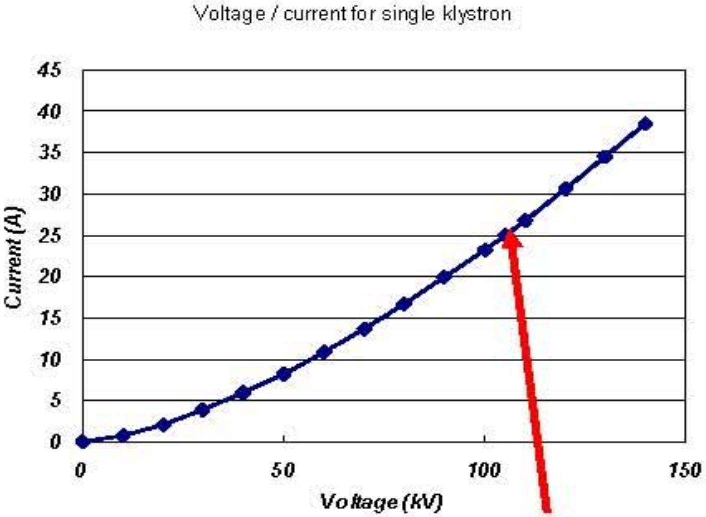
KAERI Klystron

Klystron for 20~100MeV

PEFP Proton Engineering Frontier Project

- Manufacturer : THALES Electron Devices (Modified Version of TH2089F)
- 9% duty (1.5ms, 60Hz) : 1.6MW peak rf power with 105kV, 25A e-gun

TH2089F Klystron



Design operation point : 105kV, 25A

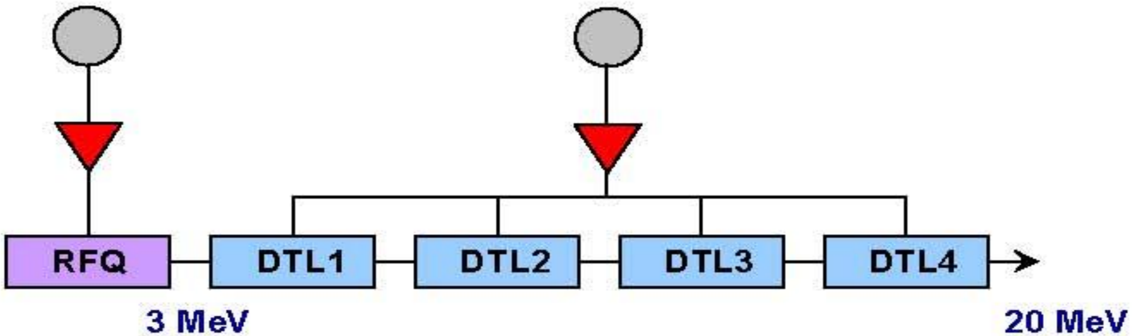
A HVCM to drive two klystrons or three.

5

KAERI LINAC RF Drive Line

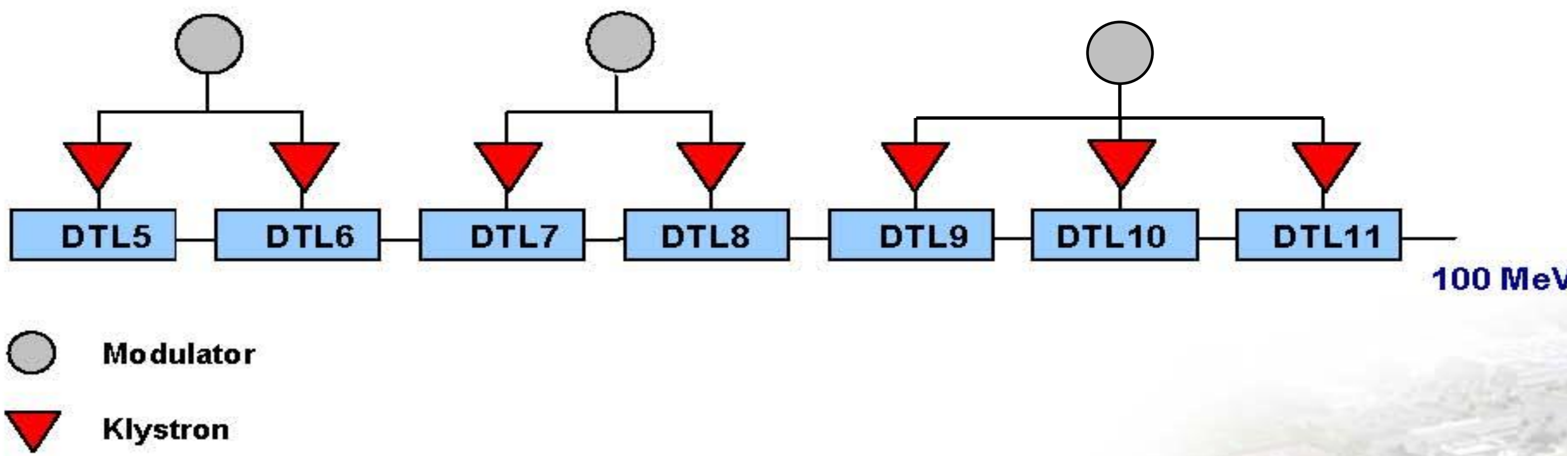
Conceptual Diagram for PEFP RF system

PEFP Proton Engineering Frontier Project



20 MeV Linac
- Klystron peak RF power : > 1.1 MW
- RF Duty : 24 %
- status : under operation

20 MeV-100MeV Linac
- Klystron peak RF power : > 1.6 MW
- RF Duty : 9 %
- status : under design



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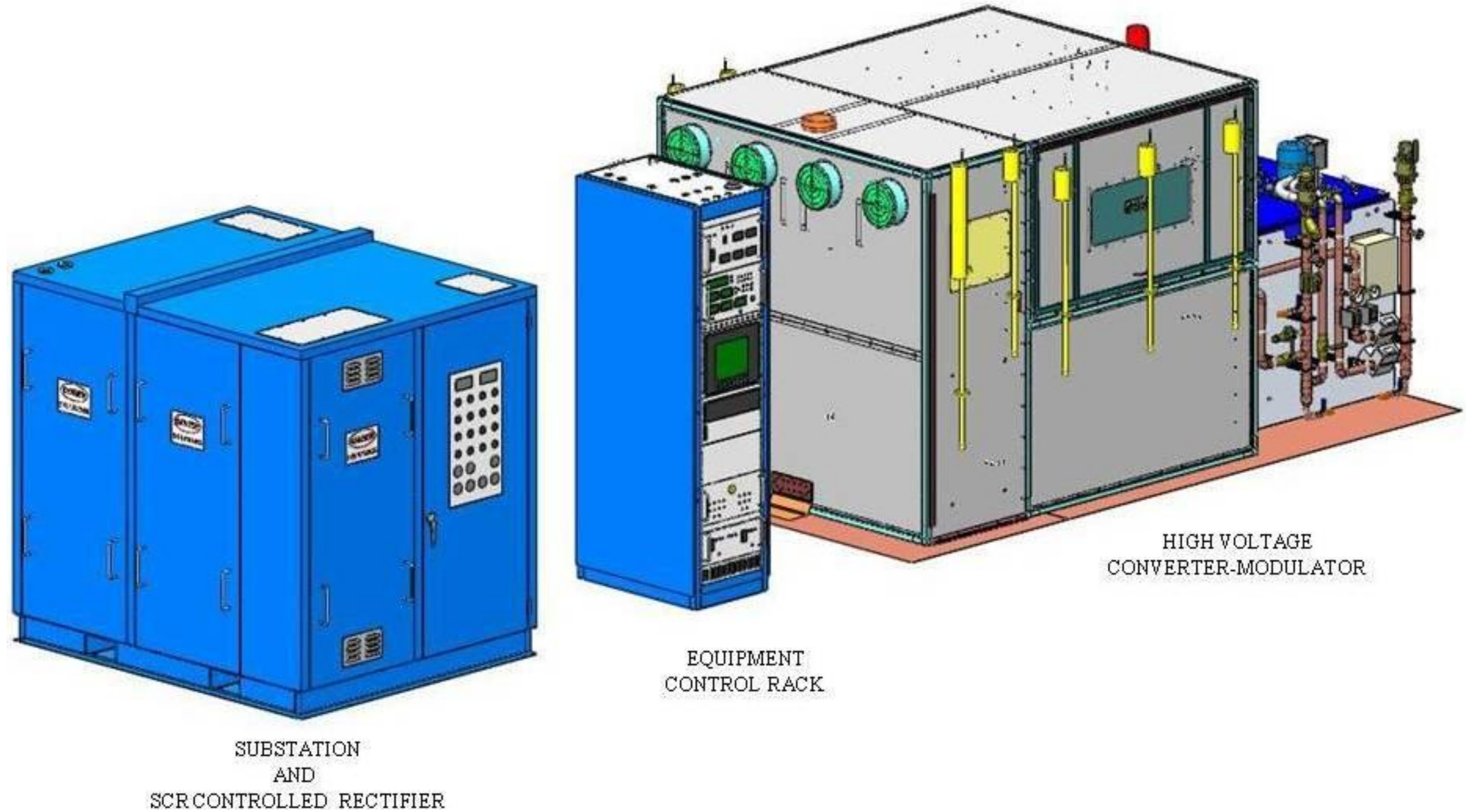
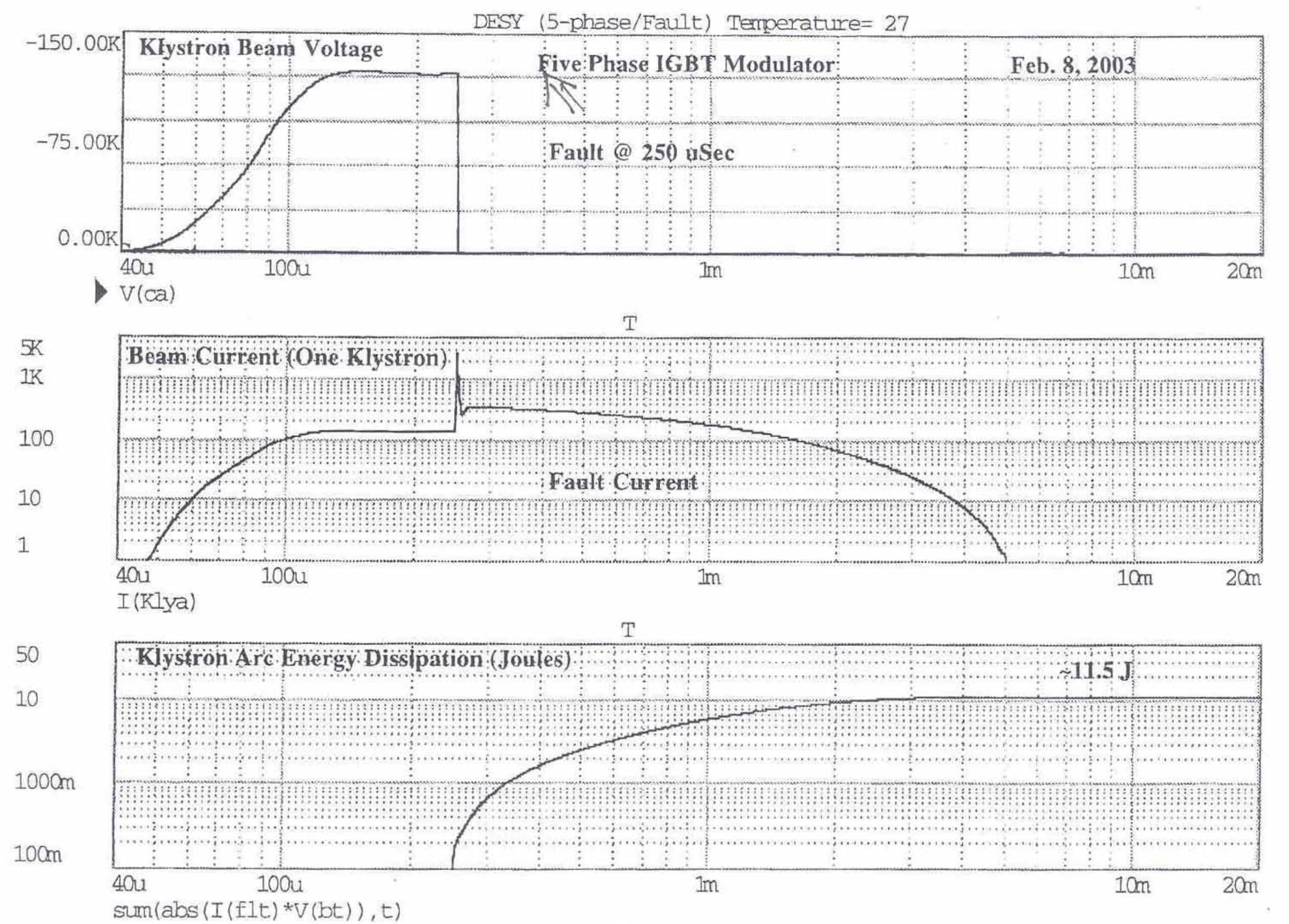
KAERI Converter - Modulator System



Klystron Fault Energy

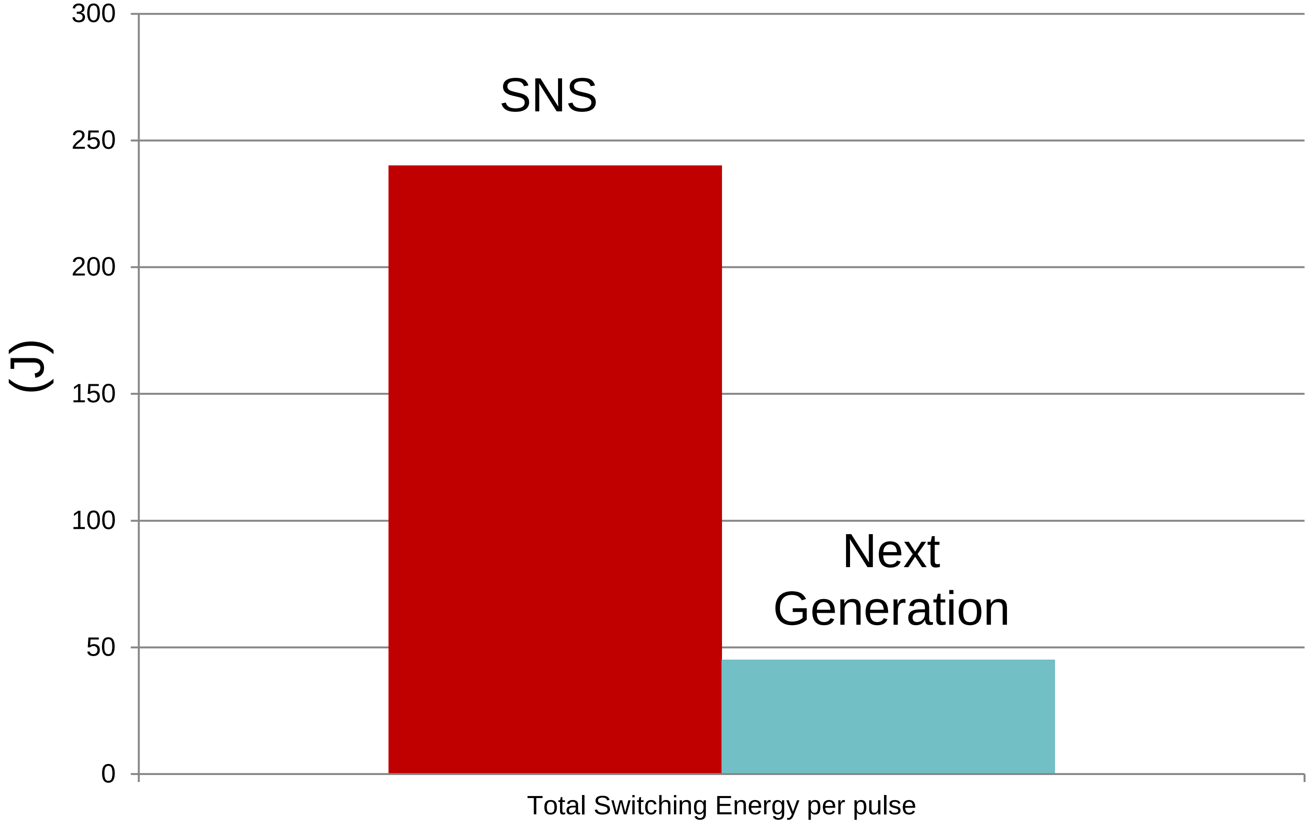
1KM Of Cable (HVCM system)



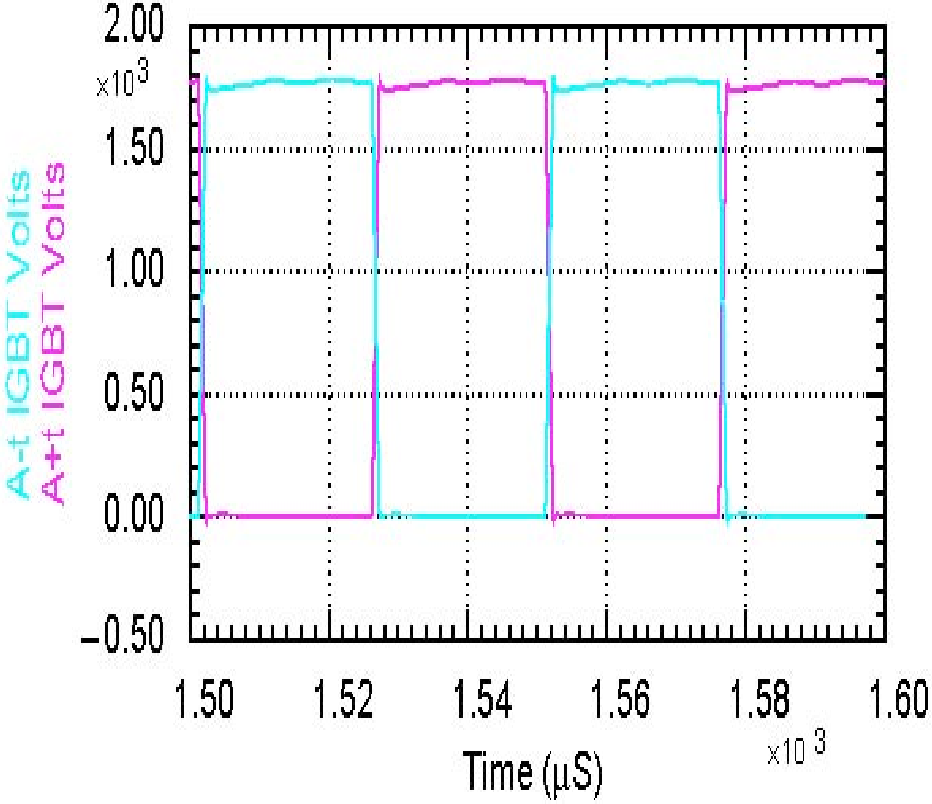
KAERI “Switch Plate” Assemblies

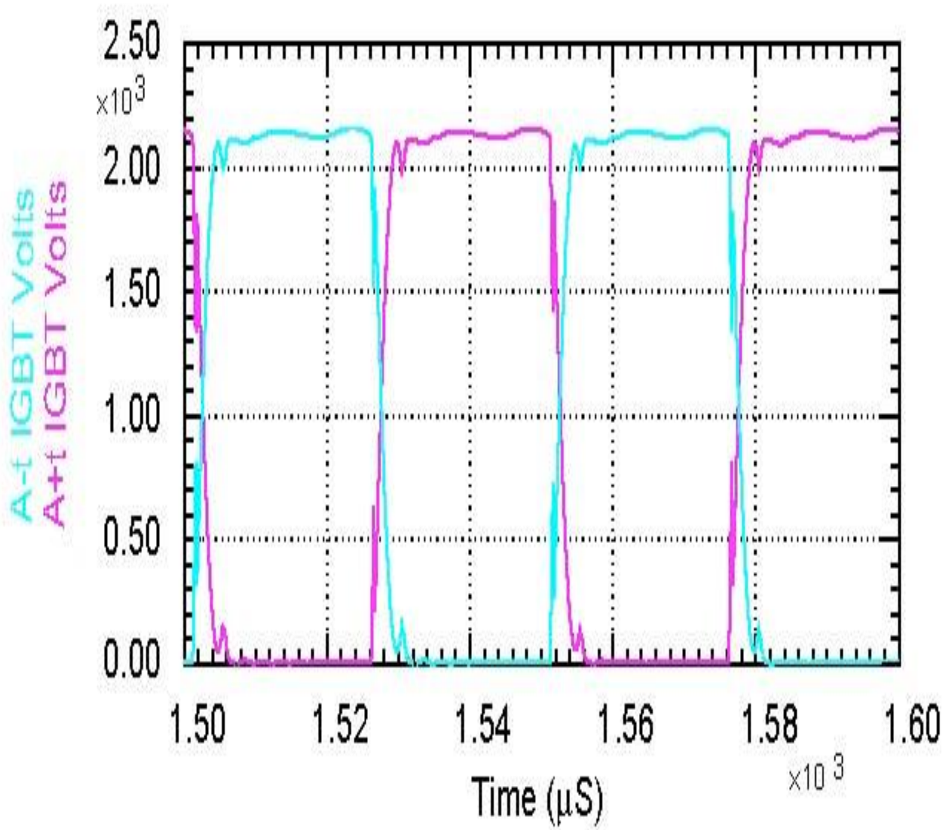
- 3300V IGBT Assembly
- Low Inductance Bus and Capacitors
- Low inductance coaxial connection to primary DC capacitors
- Dynamic shoot-thru protection
- Link bypass capacitors re-designed – to solve high circulating currents (related to network tuning at SNS)
- Complete testing with all failure modes

80% Reduction in IGBT Switching Losses
(Predicted)



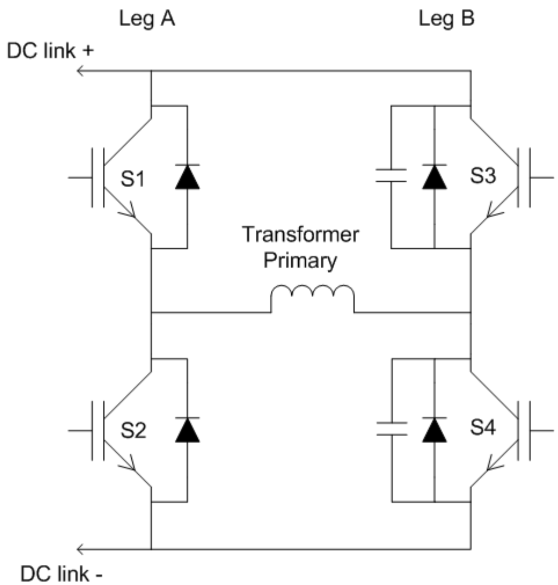
Reduction in Switching dV/dT with ZVS

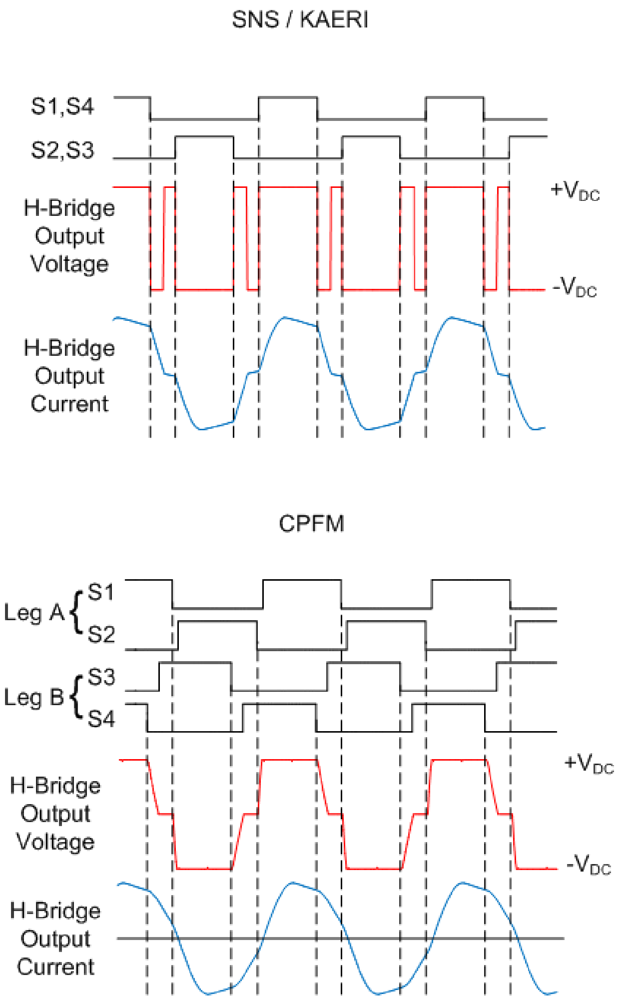




- Reduced dV/dT also reduces Electro-Magnetic Interference (EMI)

Modulation Schemes for Droop Compensation



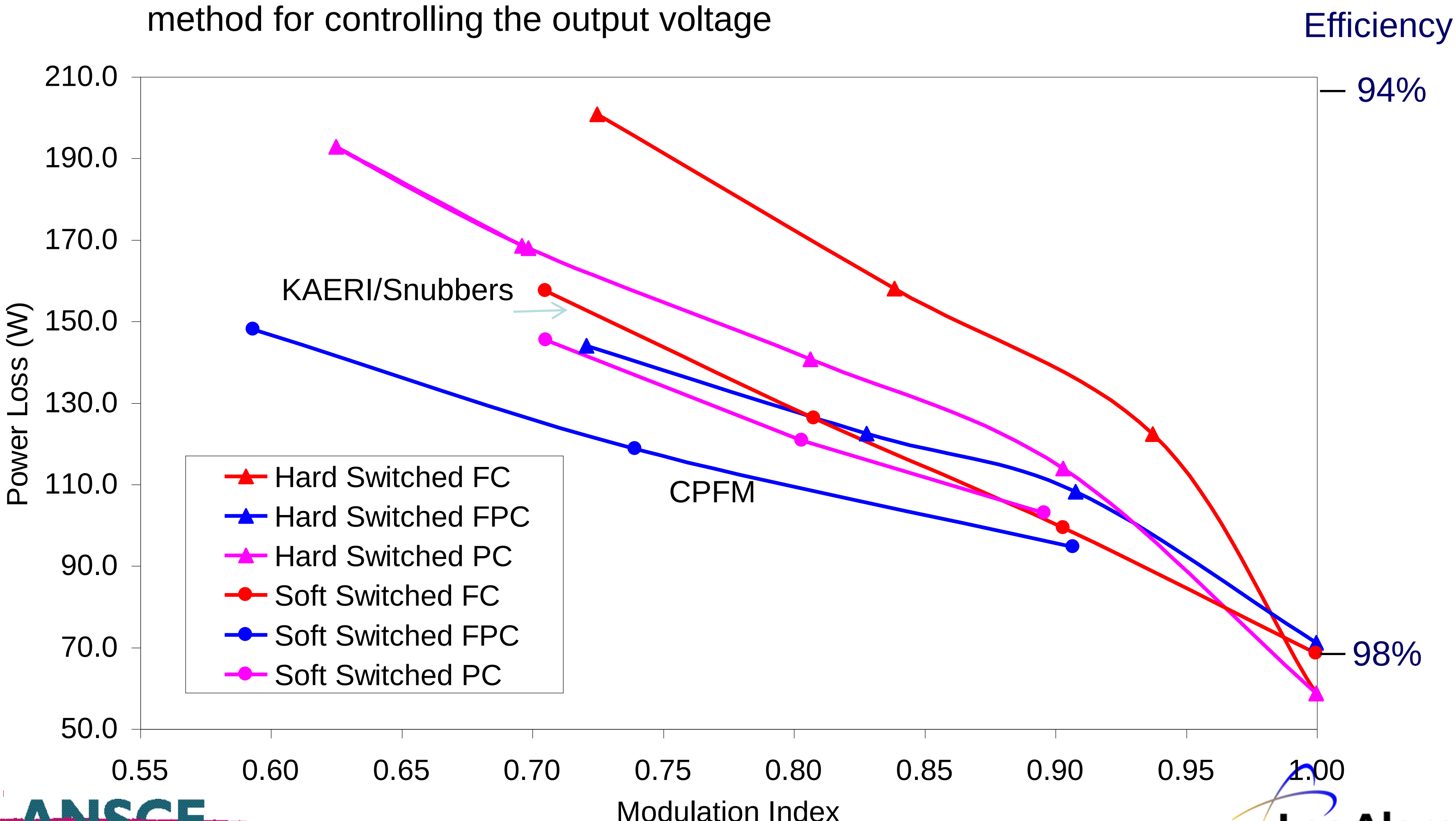


"Dead-time" (PWM) modulation leads to VERY high switching losses, circulating currents, and failure of the IGBTs (without snubbers)

With CPFM, soft switching is achieved throughout the pulse even with significant capacitor droop (can be >25%).

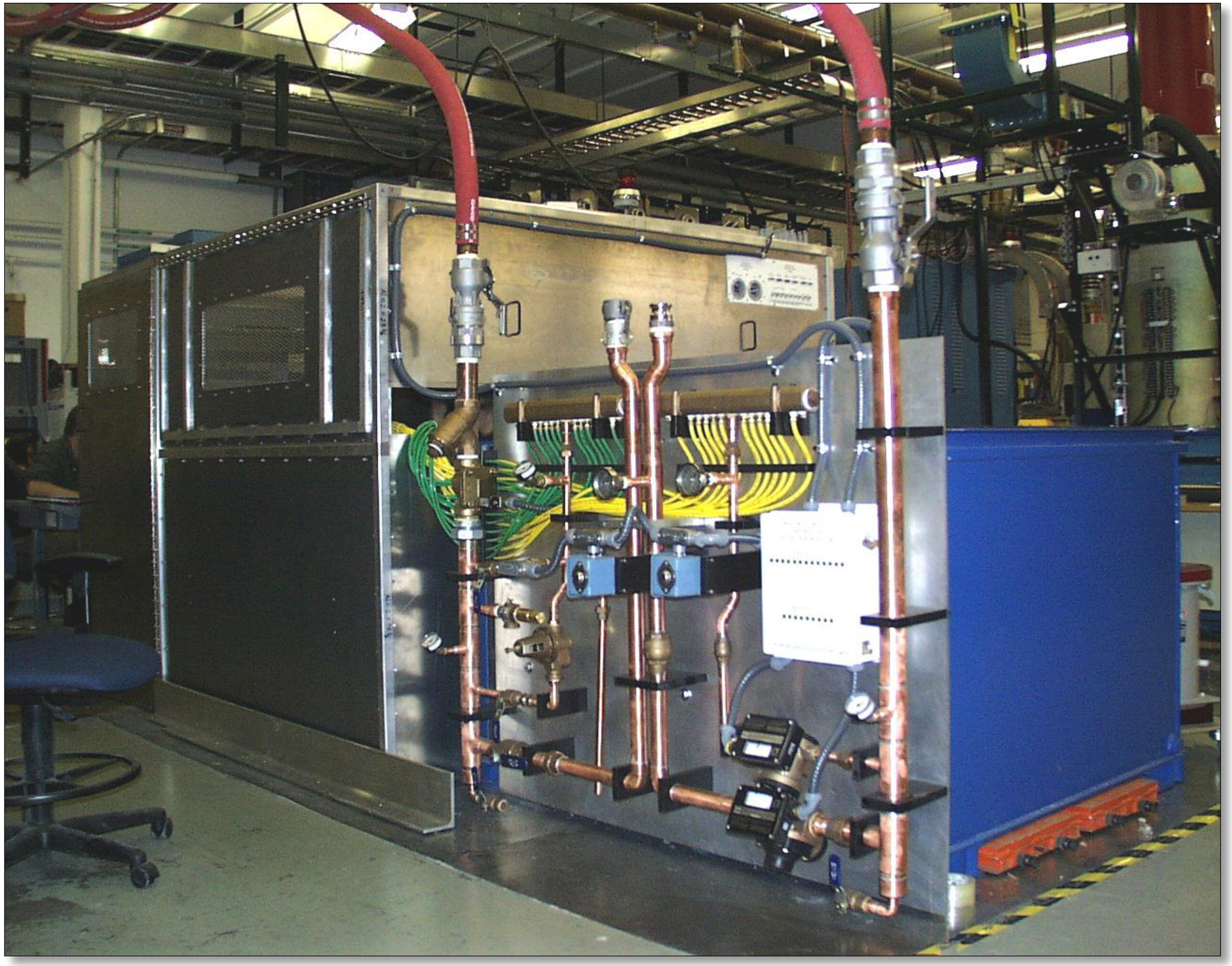
H-Bridge Power Loss vs Modulation Index

- A simple calorimeter was used to measure the semiconductor losses
- Soft Switching with Frequency and Phase Control is the most efficient method for controlling the output voltage



LANL 140 kV Prototype HVCM

Developed for SNS, now used for the MUON interrogation experiment.



Recent Developments at LANL

Prototype HVCM has been modified to enable CPFM soft switching droop compensation

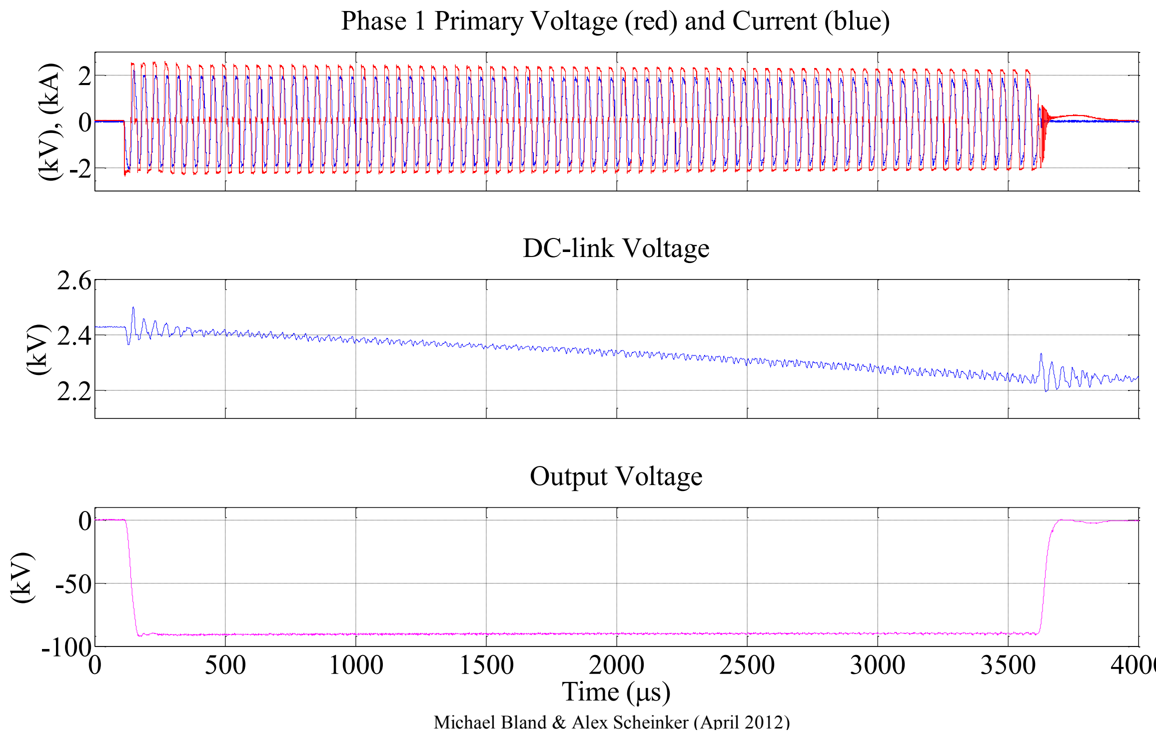
- Soft switching capacitors added
- New DSP controller
- Extremum Seeking-Based Optimization has been used to optimise rise time.

Note: Time and budget restrictions did not allow changes to the HV transformers or “resonant” capacitors so the prototype is not optimized for the ESS requirements. With better optimized circuit parameters the ESS specifications will easily be met.

Long Pulse HVCM Test Results – LANL Prototype

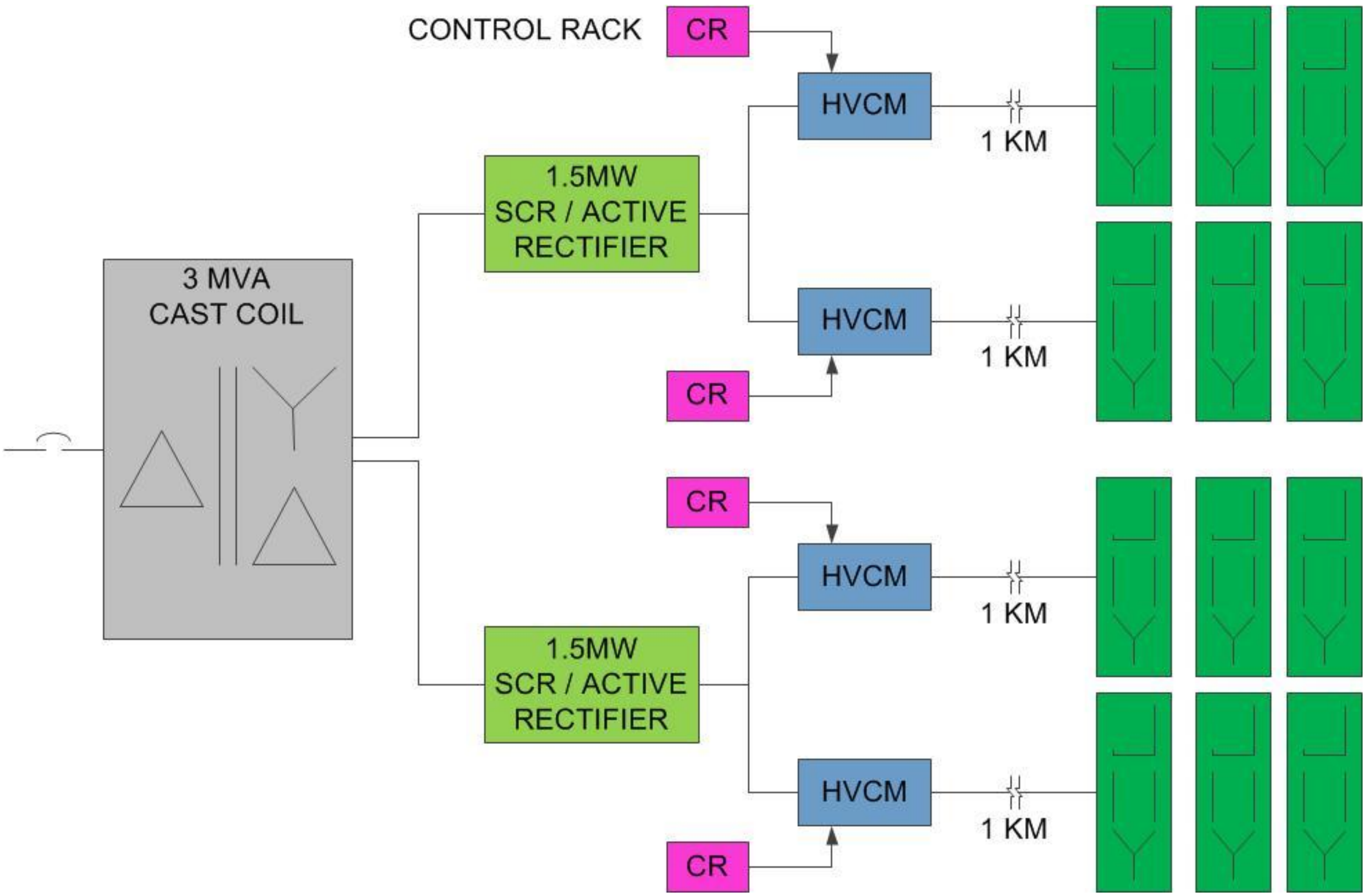
ESS Parameters

Pulse Voltage	90kV
Pulse Length	3.5ms
Load Impedance	1236 Ω
DC-link Capacitor Droop	8%
Flat top regulation	<1%
Rise time, Fall time	40us



3 klystron equivalent load impedance

Possible ESS Klystron Configuration for 3.5mS Pulses at 14Hz with Demonstrated HVCM Technology



1.5 MW Sinusoidal (Active) Rectifier

- IEEE 519 Compliant Draw – all load conditions
  - variable rep-rates and pulse widths
  - Near unity power factor
  - Minimal line harmonic content
- Multi Parallel Modules
- 1% voltage regulation
- Local and remote control options
- Onboard diagnostics

Next Generation HVCMs - key points

- Optimized design procedure for maximum efficiency and low cost
- Droop compensation minimizes energy storage for improved safety and cost
- Multi-Stage transformer design minimizes AC voltage stress and allows better cooling for air insulated designs
- Active rectifier utility interface for near unity power factor and negligible harmonic distortion
- Laminated bus bar DC-link
- New DC-link capacitors with improved power density
- Modular design approach will allow common parts to be used for high and lower power modulators

Review of key points

- HVCM is very efficient ~96%
- Can drive km cable lengths
- Can use more “phases” for higher power or for even lower link voltages
  - KAERI (IGBT’s) operates at 100 FIT
  - penta-phase converters
- HVCM is fault tolerant – cannot harm klystrons
  - fault currents are limited
- Soft switching and droop compensation permits very long pulses (>10 ms) and improves system efficiency
  - Reduced Electro-Magnetic Interference (EMI)
  - Attractive for spallation sources

Conclusion

- KAERI Design Significantly Different From LANL, SNS, and SLAC Installations
  - Optimized from "lessons learned"
  - Very similar to ESS requirements – available on short time scale
    - No design changes needed for power circuitry
    - Gives time to optimize control / feedback design
    - Evaluate RF system components

- HVCM Has Very High Efficiency ~96%
  - Overall system has excellent efficiency ~94% from utility to load (probably highest)
  - Excellent utility power factor

- Los Alamos, University of Nottingham, and Dynapower Furthering Technology for Next Generation Needs

- All Parties Glad to Collaborate as Needed