Superconductivity for Electric Systems
2004 Annual DOE Peer Review

HTS Matrix Fault Current Limiter Program

- L. Kovalsky, X. Yuan, SuperPower, Inc.
- J. Bock, Nexans SuperConductors
- S. Schwenterly, ORNL

Market Pull for FCLs

New generation facilities, distributed generation, IPP hookups, and power import have resulted in requirements to upgrade existing transmission grid protection

Conventional solutions to fault current over-duty problems are costly and/or have negative impact on system reliability and integrity

- Construction of new substations
- Breaker upgrades
- Bus splitting
- Current limiting reactors and high impedance transformers
- Control schemes (sequential breaker tripping)

SuperPower has developed new "Matrix" Fault Current Limiter (MFCL) technology using High Temperature Superconducting (HTS) technology

MFCL base concept covered in US Patent #6,664,875 B2

MFCL Operating Principle

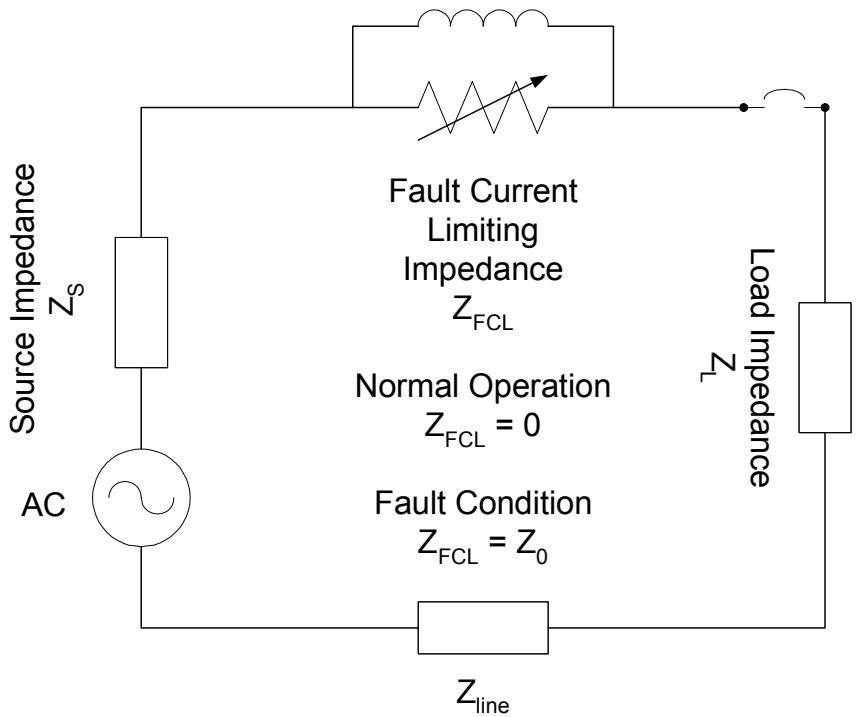
Under the normal operating condition, the AC current is below the critical current level of the superconductors

The MFCL device operates in a "superconducting" state

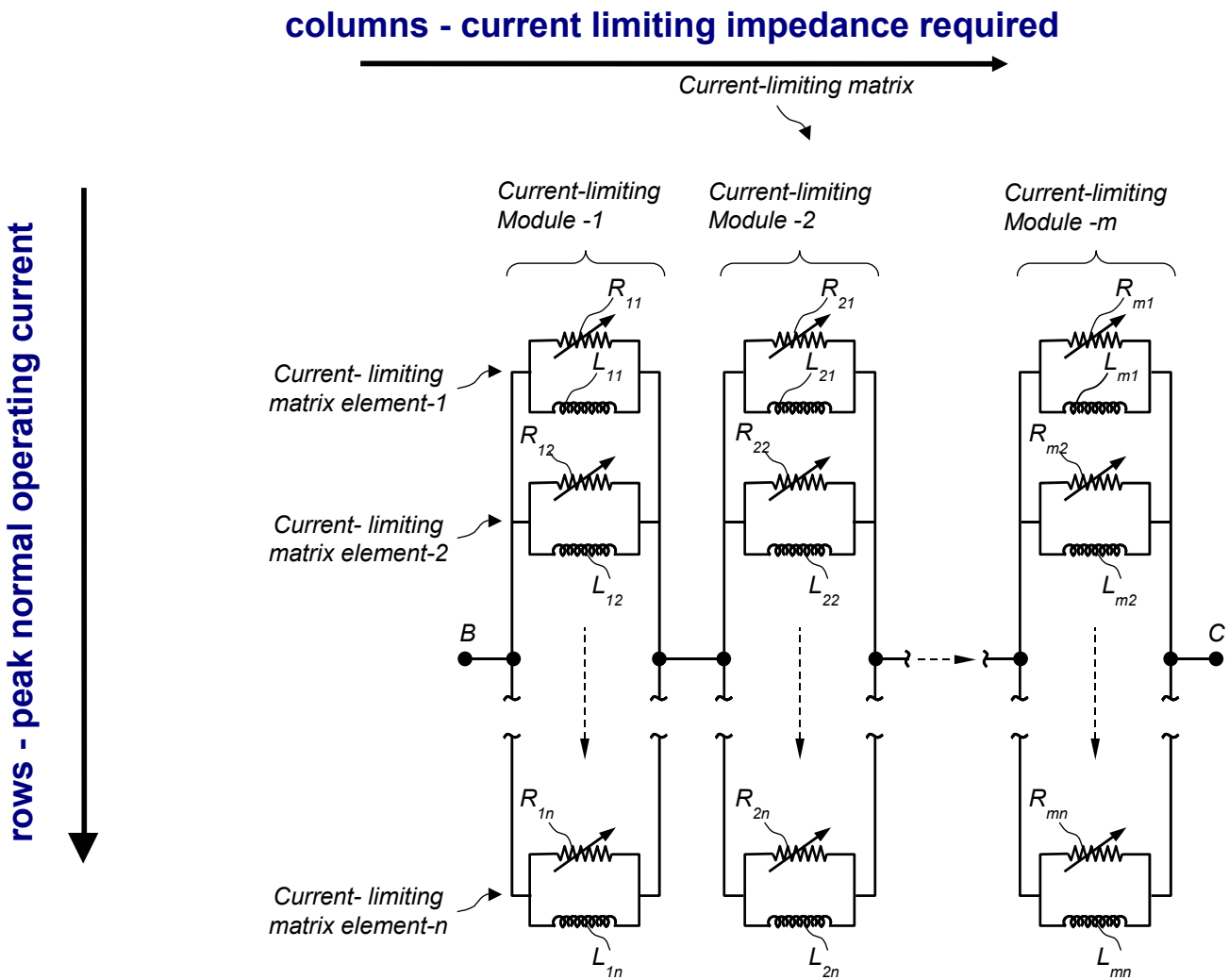
No major I^2R losses or voltage drop will be developed across the device - the MFCL is basically "invisible" to the grid

Under fault conditions critical current is exceeded

The superconductor transitions to a resistive state, introducing current limiting impedance into the grid with a parallel inductor



Scalable MFCL Design



MFCL Benefits

Passivity - Detection of fault and insertion of current limiting impedance without active monitoring and control mechanism

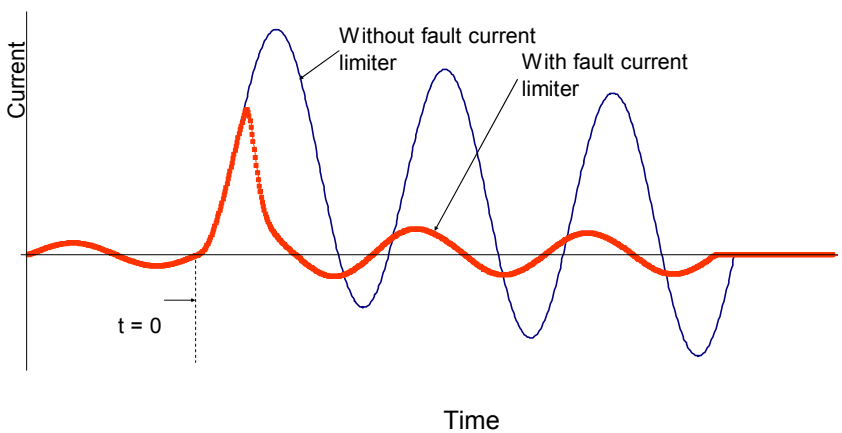
Burdenless - No substantial I^2R losses and voltage drops

Modularity and scalability - By way of the matrix configuration

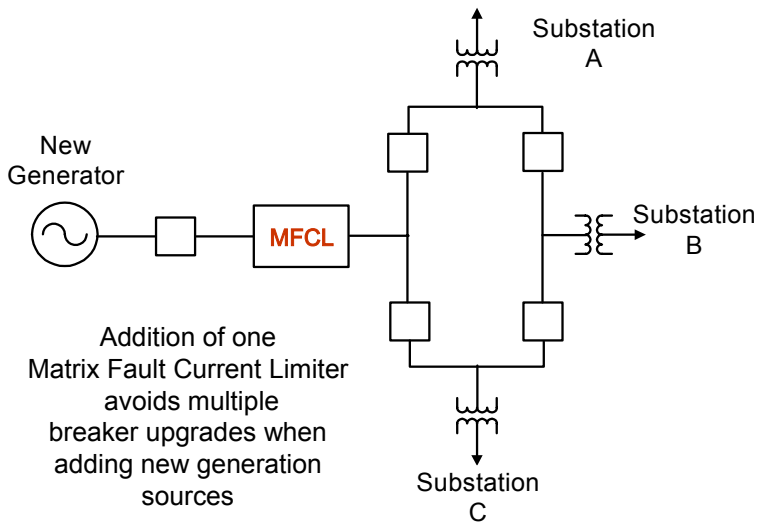
Reliability - Redundancy can be easily built in

Cost benefit – No conventional counterpart, more economical than most other solutions

Environmental benefit - No flammable or environmentally hazardous oil. No SF6



Reduce mechanical and electrical stress with first peak current limiting



Addition of one Matrix Fault Current Limiter avoids multiple breaker upgrades when adding new generation sources

Project Description & Research Integration

Project Team

- SuperPower, Inc.: Program Lead, basic IP for technical approach
- Nexans SuperConductors GmbH: BSCCO-2212 Materials
- DOE National Labs – CRADA with ORNL on High Voltage Development, CRADAs with LANL and ANL dependent on funding

$12.2M total cost, with $6.1M DOE and $600K EPRI support - DOE Contract Project Period 5/02 to 2/07

Technical Advisory Board:

- Meets 3 – 4 times a year to review program, assess progress, provide technical input
- Utility members: American Electric Power, New York Power Authority, Southern California Edison, Con Edison, Tennessee Valley Authority
- Academia: Rensselaer Polytechnic Institute (RPI)
- Funding sponsors: DOE and EPRI
- National Labs: ORNL, LANL, ANL
- National Electrical Energy Testing, Research And Applications Center (NEETRAC)

Milestone Driven Program

Major Milestone	Objectives	Completion Date
Concept Feasibility & Application Studies	• Complete Conceptual Design • Use Technical Advisory Board (TAB) to understand application requirements and perform power system studies	Completed June 2003
Proof-of-Concept Demonstration	• Focus: Scaled hardware non-grid demonstration of matrix concept • Rating: 8kV, 800Arms steady state current, single phase, limit faults up to 25kA asymetrical	Completed July 2004
Alpha Prototype	• Focus: Scale up for non-grid demonstration at high voltage • Rating: 138kV, application specific current, single phase	Design by June 2005, Prototype by Dec 2005
Beta Prototype	• Focus: In-grid demonstration for specific utility application • Rating: 138kV, application specific current, three phase	December 2006

Program Year 2 Progress Summary

Pre-Prototype Conceptual Design review with the TAB in June 2003

Completed tests of small scaled matrix in open LN2 bath and test cryostat at Center for Advanced Power Systems (CAPS) in December 2003 with LANL

Finalized design and procured long lead items in January 2004

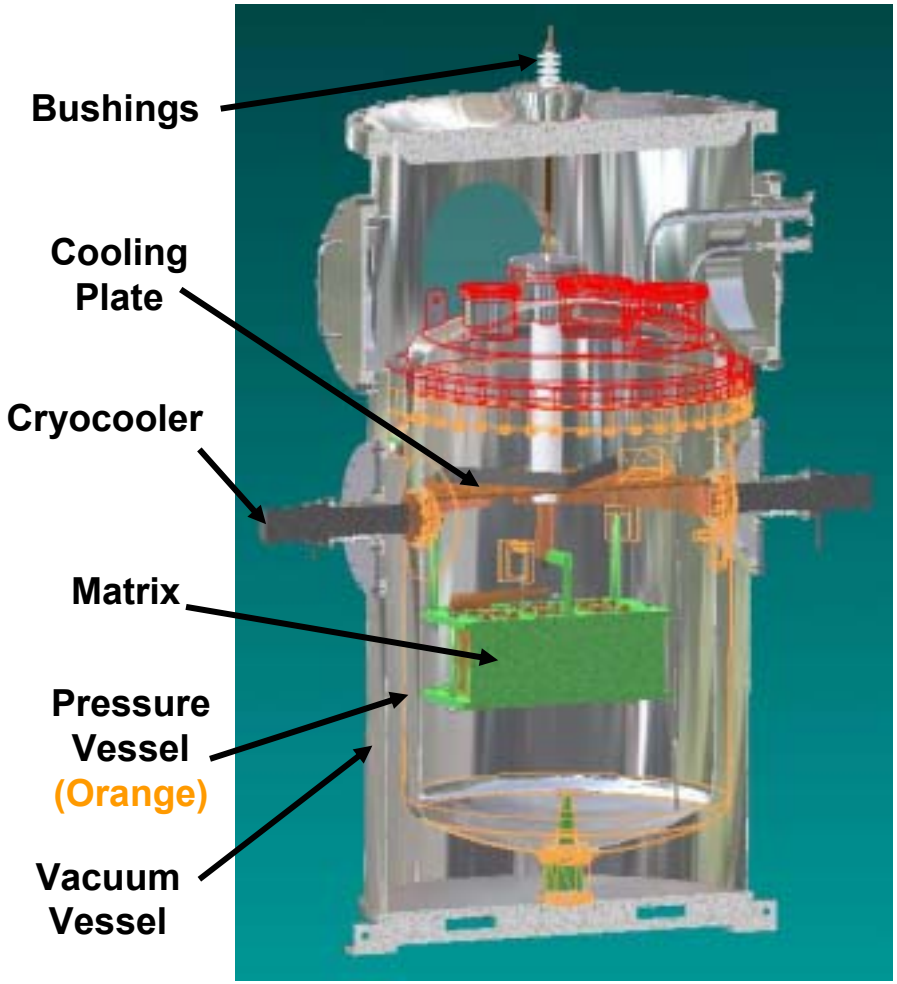
Fabricate components and subassemblies from Feb. to April 2004

Completed subassembly tests in May 2004 – Open LN2 bath tests of matrix (results shown later)

Completed component integration, final assembly and proof-of-concept test in June and July 2004

Test cryostat for study of current sharing, current limiting and quench of HTS elements In a small scaled matrix

Proof-of-Concept Prototype Design



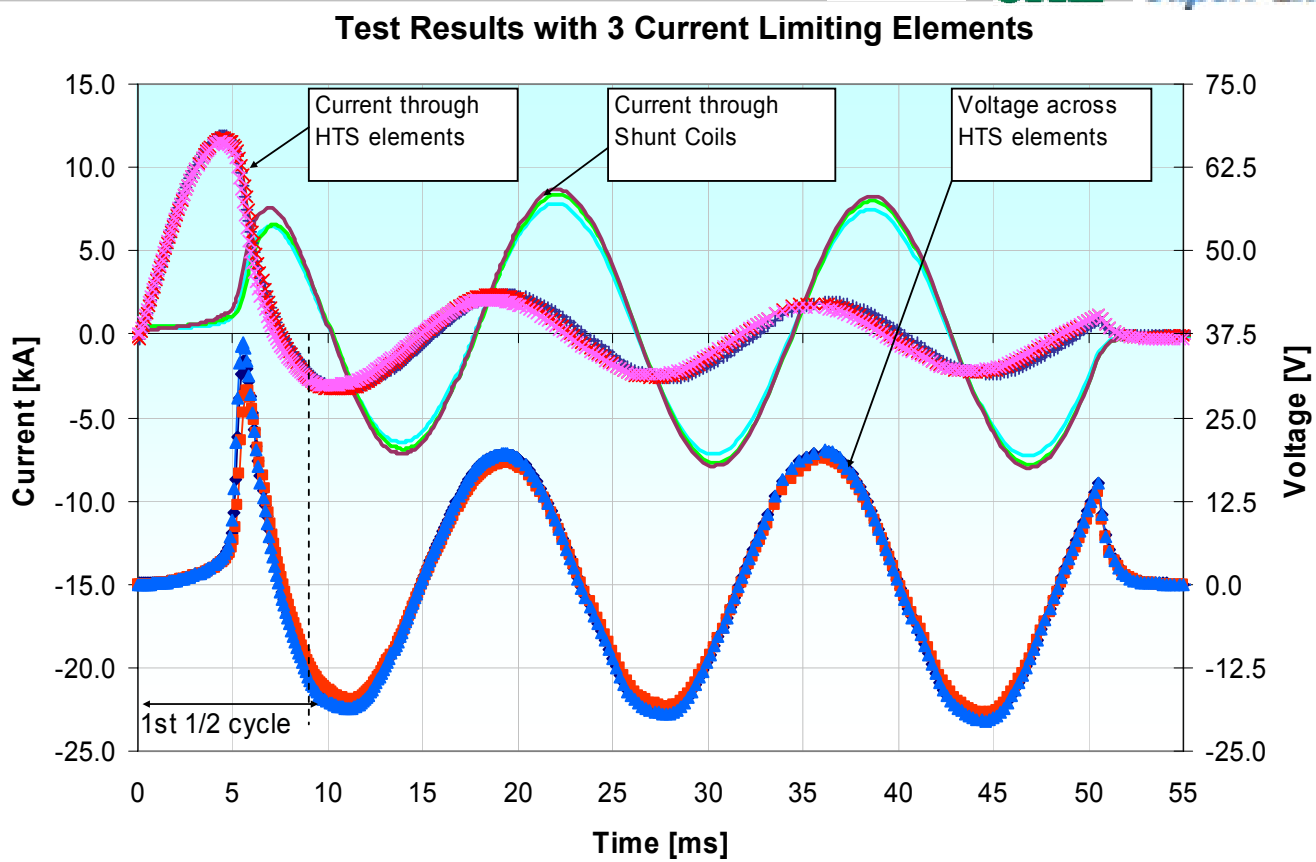
Low Voltage Pre-prototype for proof-of-concept in June 2004
8.6kV single phase to ground, 800Arms nominal current

Test Results on Small Matrix at CAPS

Desired results achieved:

1. Good sharing among current limiting elements

2. No excessive stress on any element



3. Fast dynamic resistance development and 1st peak limitation

4. Fast current transfer from HTS elements to shunt coils – Reduces stress on HTS elements during fault

Proof-of-Concept Prototype Design Specifications

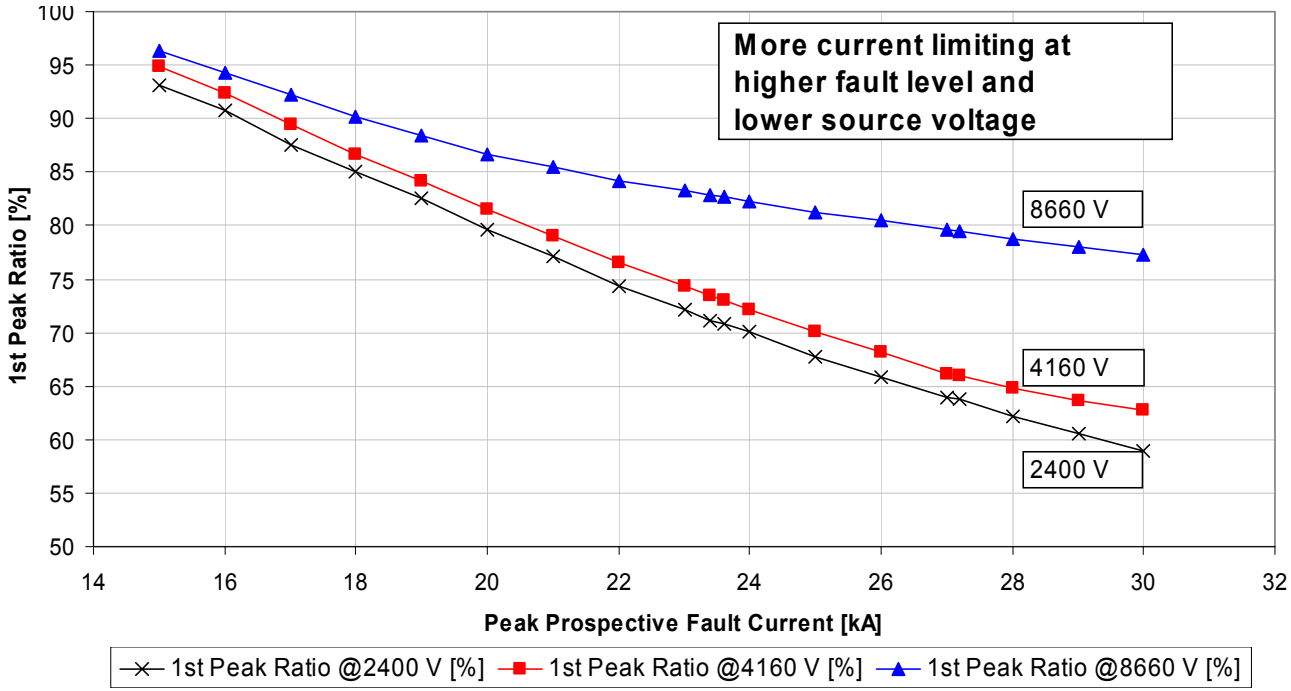
Max normal operating current: 800Arms - Corresponds to Ic requirement of 1360A for HTS elements

Nominal operating voltage – 4.16kV and 8.66kV, single phase (to ground)

MFCL operating temperature range – 74K to 77K, Pressure range – 1 to 3 atm

Prospective fault current, asymmetrical – 25kA, with first peak current limiting within ¼ 60Hz cycle, Fault duration – Three 60Hz cycles (50ms)

Calculated First Peak Limiting Based on MFCL Analytical Model and System Parameters



Development of Components for HTS Cable Systems at Nexans

Nexans Deutschland Industries Hanover

Development and manufacturing of cryo sleeves and power cables

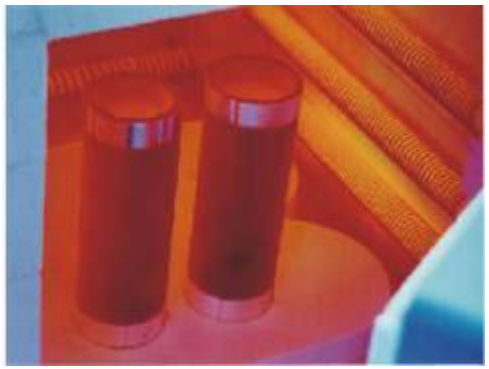
Nexans SuperConductors Knapsack

Development and manufacturing of FCL components

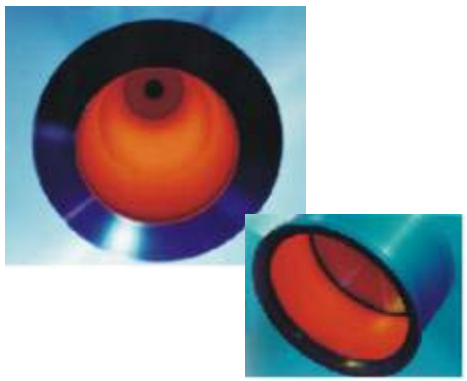
Development of HTS Bulk Parts for Electrical Power Applications

Nexans ornl SuperPower

Annealing at 750 - 840°C



Melt in rotating mould



Nexans Bulk Parts are:

- Inorganic ceramics (Bi-Sr-Ca-Cu-O
- Available in a large variety of shapes and sizes
- Ready for assembling in electrical devices, system components or magnets

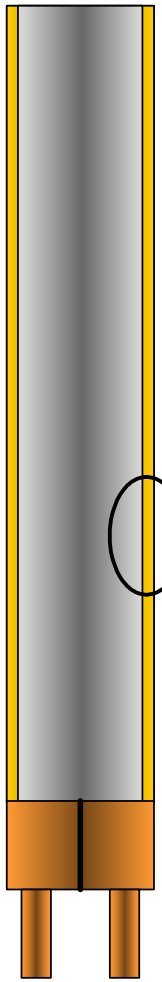
Characteristics:

- rigid el. conductors
- easy machining
- high current carrying capacities (100A - 12kA)
- low thermal conductivity

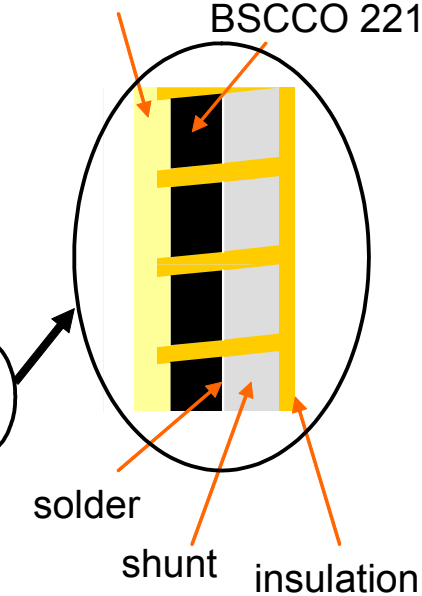
Bi-2212 for commercial use in current leads since 1995

General Atomics
(Current Controller)

MCP BSCCO 2212 Bifilar Component



mechanical design:



main data of the bifilar component:

outer diameter:	58 mm
superconductor - length:	5.4 m
superconductor - tube:	300 mm
superconductor - cross section:	0.24 cm²
crit. current (65K):	850 A
protected power (65K):	>130 kVA

Most powerful HTS element for resistive SCFCL!

90 Bifilar Components, 30 / Phase

Conducted successful 10 MVA field test RWE Netphen, Germany on 10 kV grid

MFCL Tubes – Bifilar Coils Comparison of the Components

Much higher performance and simpler element design due to MFCL concept!

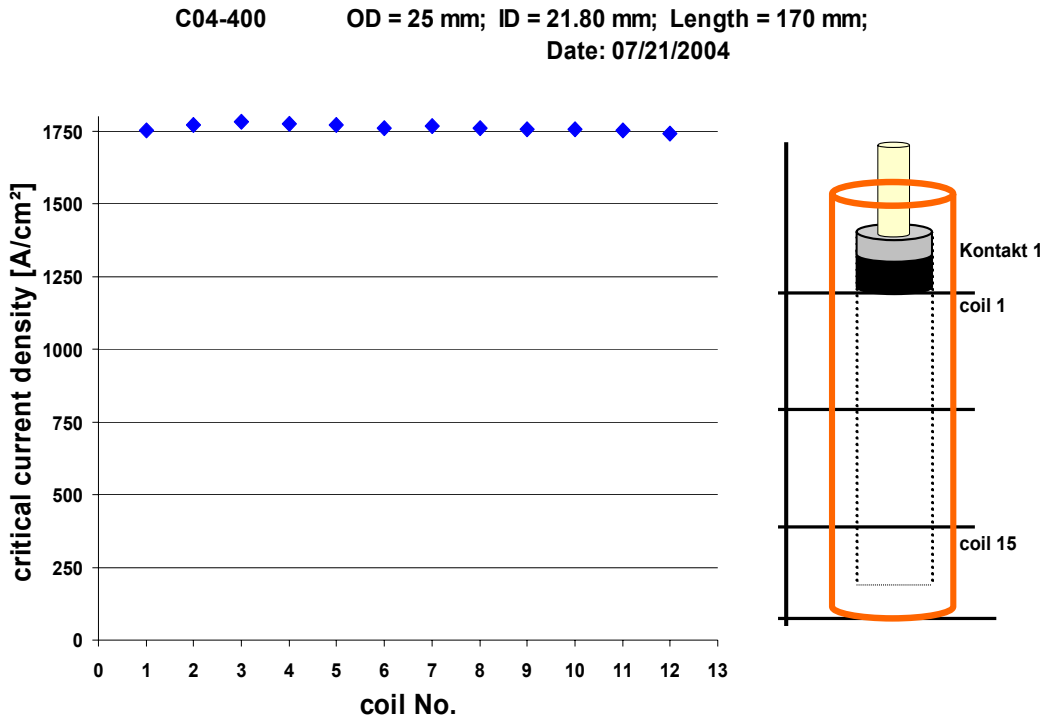
	bifilar coil	MFCL tubes
E – field:	0.6 Vpeak/cm	6 Vpeak/cm
current @66K	600 A	2500 A
300 mm tube	212 Vrms	180 Vrms
re-cooling	> 30 sec	< 10 sec
AC losses	100 %	< 10 %
volume / element	1000 cm³	200 cm³
power / element	130 kVA	450 kVA

Manufacturing Steps of an Element

1. Mixing of the raw materials
2. Melt casting of the tube
3. Annealing
4. Inductive measurement of the raw tube
5. Machining process
6. Inductive measurement of the machined tubes
7. Mounting of copper contacts
8. Eight short circuit tests (3 x partial load, 5 x full load)
9. Measurement of the critical current in axial direction
10. Inductive measurement of the finished element, final quality control

- 100 elements were manufactured
- Uniformity of critical current 10 %

Machining Process for the BSCCO Tubes and Inductive Measurement



MCP BSCCO 2212 tubes are machined at the inner and outer surface to tailor the wall thickness and the current carrying capability.

Optimizing of melt casting and machining procedure results in higher critical current density and further improved uniformity.

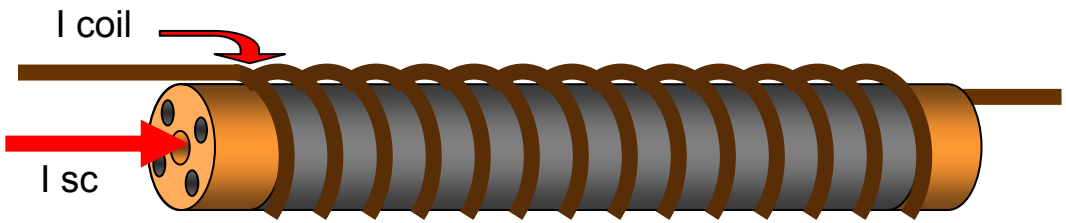
Elements for the Proof-of-Concept Prototype

Technical data:

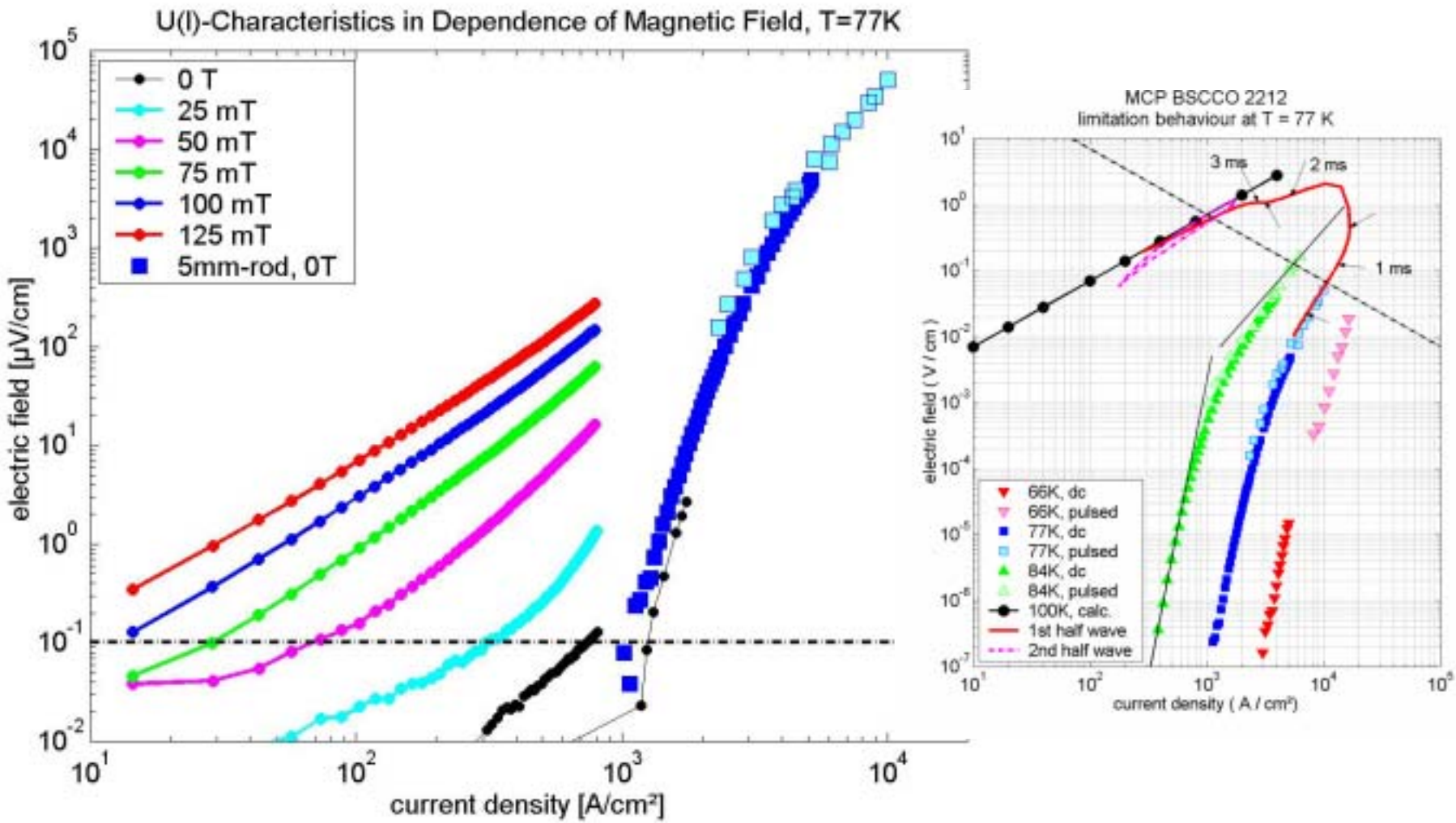
Ic =	1590 A	@ 77K
Jc =	1360 A/cm²	@77K
Jc =	4000 A/cm²	@66K
A =	1.17 cm²	
s =	1.6 mm	
L =	210 / 170 mm	

Rated current (AC):

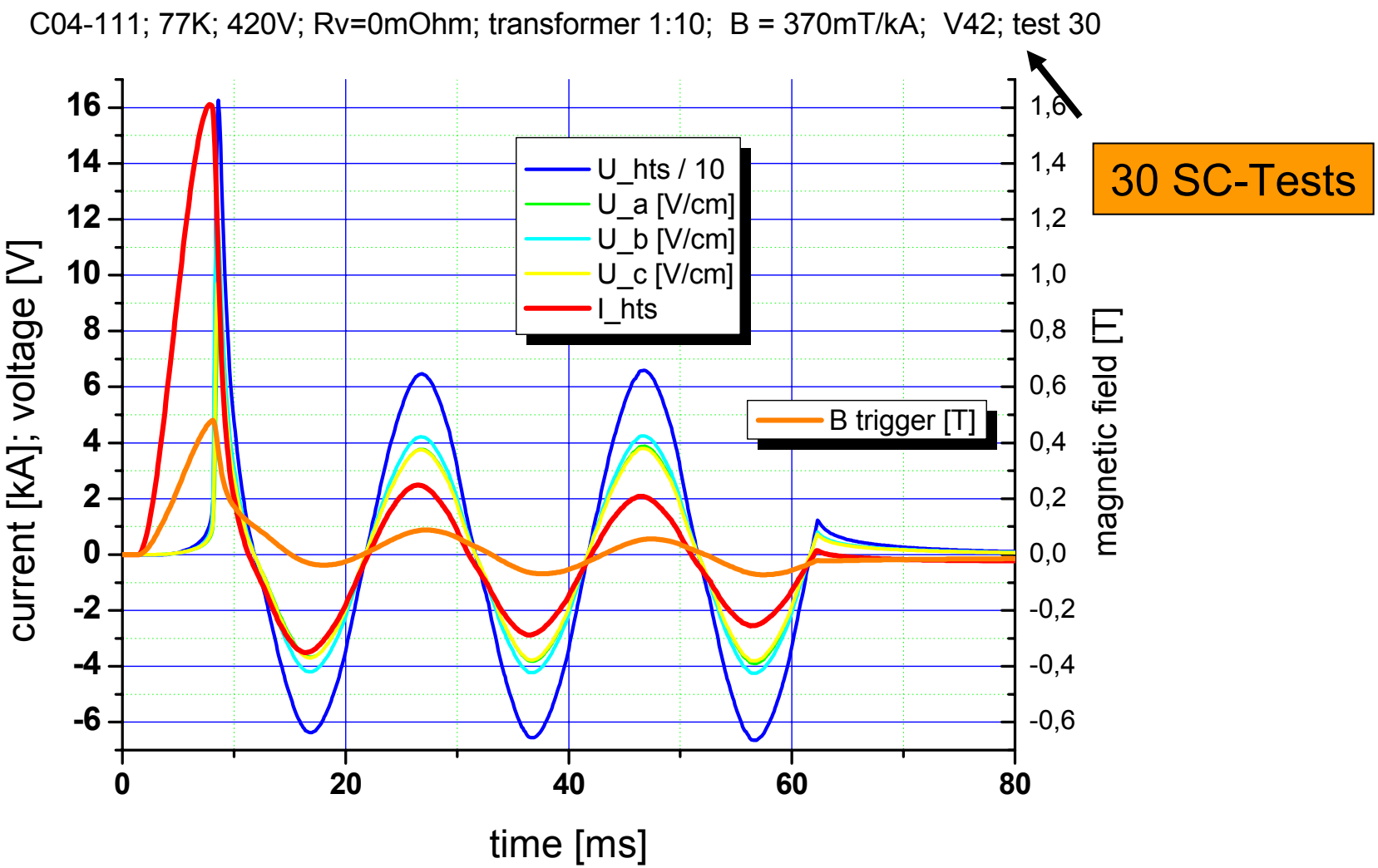
I r =	800 A	@ 77K
I r =	2400 A	@ 66K



Magnetic Field Impact on the MCP BSCCO 2212 Material



High Power Tests at Nexans Lab up to 20kA / 65V => 4 Vpeak/cm



ORNL Program Role

Serve on Technical Advisory Board and general technical program support – design reviews and reports

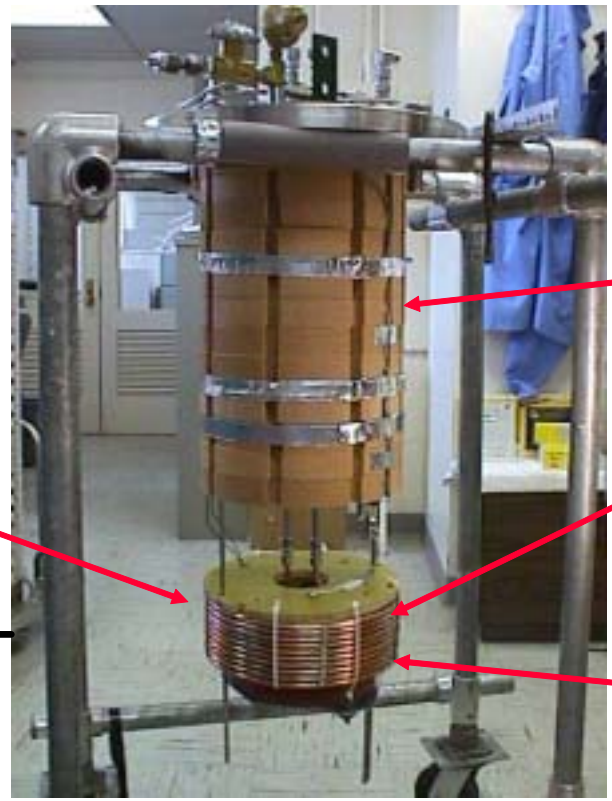
Cryogenic subsystem R&D and design support

Component design, assembly process, qualification & materials tests.

High-voltage subsystem R&D and design support

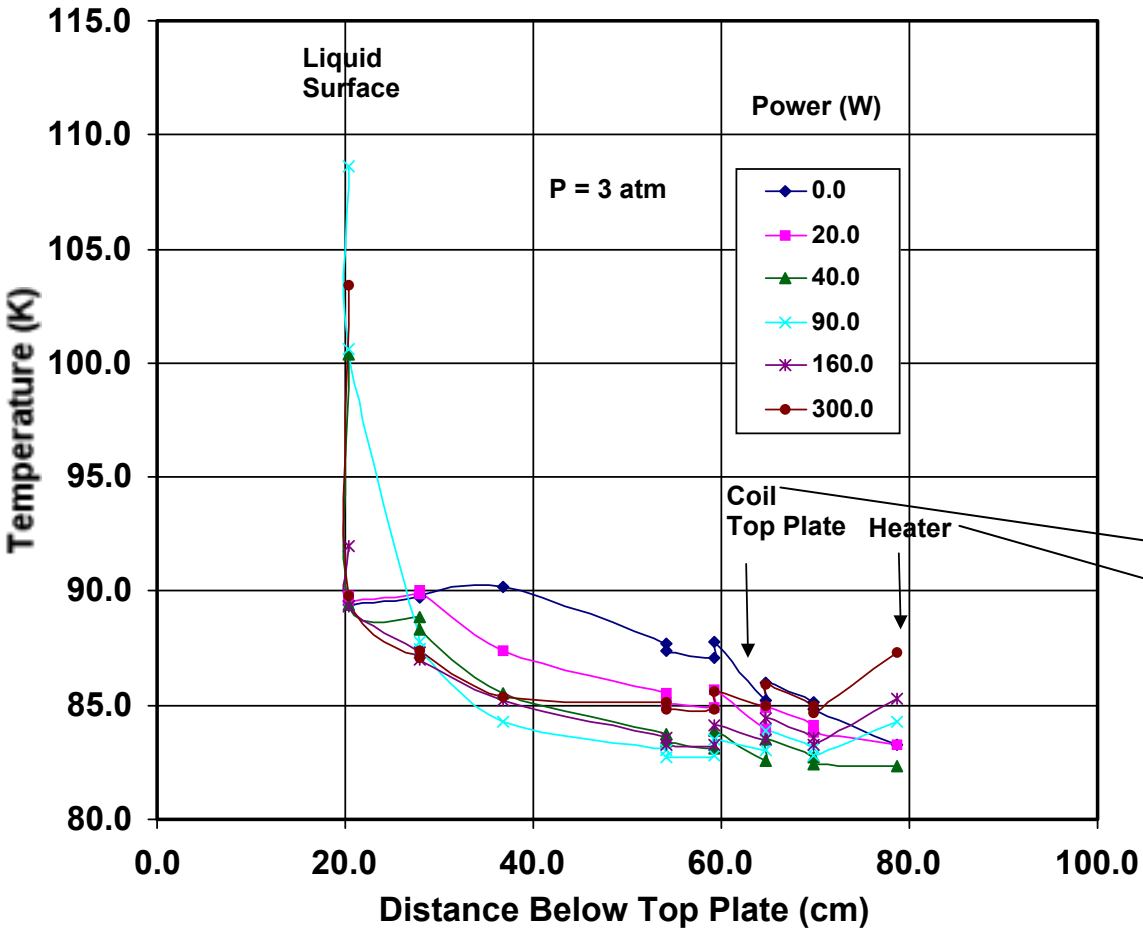
Component design, HV tests in LN2 using test cryostats developed at ORNL

Program Year 2 - Conducted tests simulating aspects of MFCL cooling system



An existing cryostat was provided with a cooling coil to simulate the MFCL cooling ring.

Program Year 2 - ORNL Thermal Testing Results



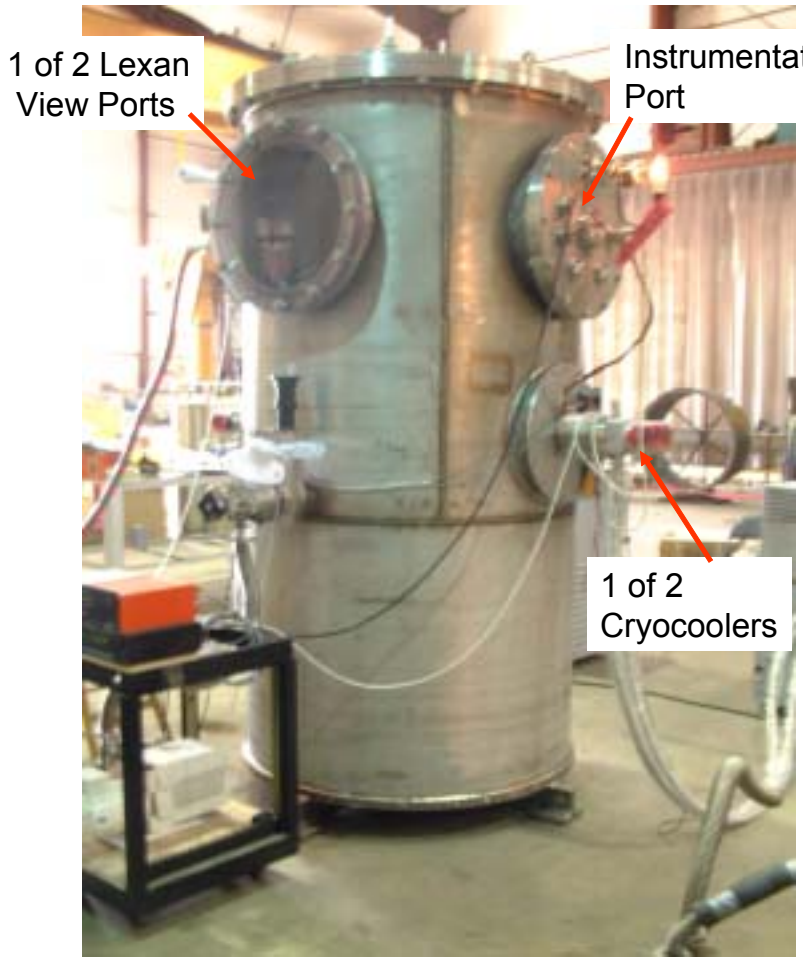
Temperature profiles did not vary much with power

Proof-of-Concept Test Objectives

Test Objective	Achieved	Comment/Status
Verify current limiting performance	Yes	Very good current limiting achieved in all tests
Verify current sharing between HTS elements and trigger and shunt coils	Yes	Measurements taken on select elements in low voltage open bath tests
Dynamic voltage and current limiting resistance development, R = f(B, T,J)	Yes	Measurements taken on select elements in low voltage open bath tests
Speed of superconducting-to-normal transition under fault current condition	Yes	Measurements taken on select elements in low voltage open bath tests
Effects of trigger magnetic field	Partial	Ongoing, additional testing forthcoming
Electromagnetic interference between coils	Partial	Ongoing, additional testing forthcoming
HTS material properties characterization	Partial	Additional R&D needed to understand some of the element failures during the tests
Obtain test data to improve simulation accuracy and capability	Yes	Able to improve analytical model so calculated result matches actual result
Verify operation at sub-cooled conditions	Yes	Very good cryostat performance

Construction & Sub-Assembly Qualification Tests

ASME code test on pressure vessel at Cryogenics, Vacuum, Instrumentation & Piping (CVIP)



Integrated cryo system under Test at CVIP
Leak checks, pressure tests

Proof-of-Concept Tests Conducted at KEMA-Powertest

KEMA has two short circuit generators G1 and G2 rated 1000 MVA and 2250 MVA respectively

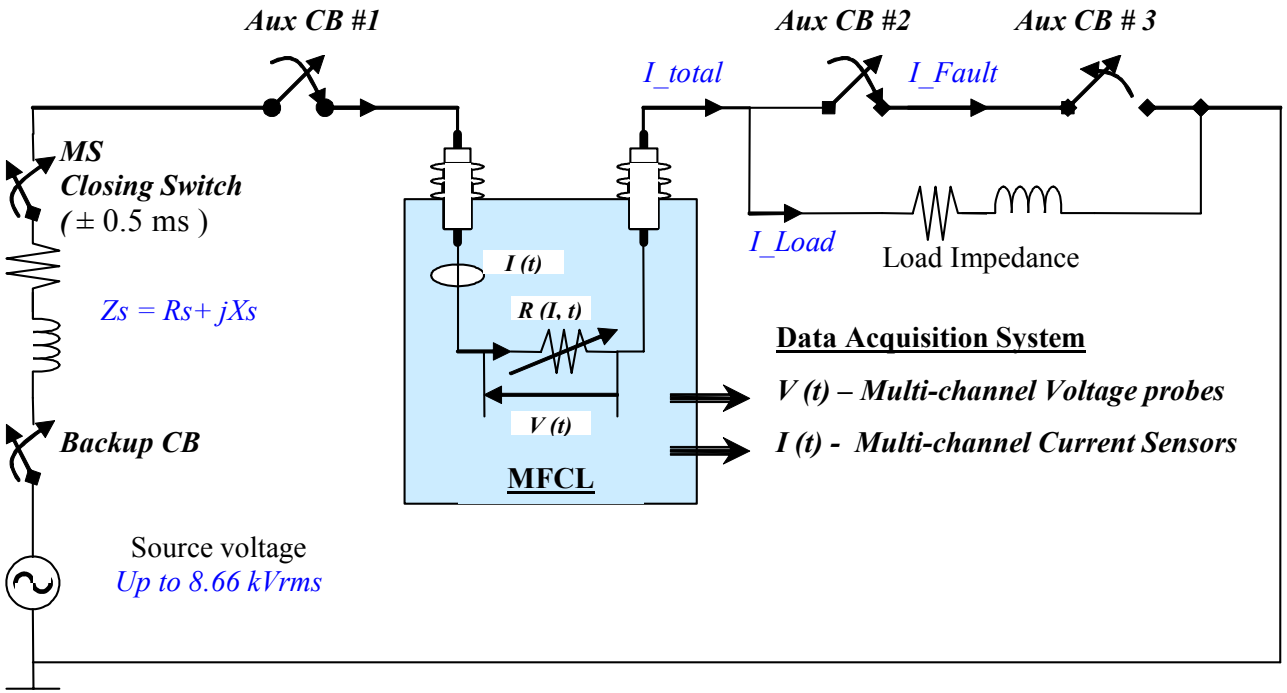
Largest high power electrical testing laboratory in the United States. Located in Chalfont, PA near Philadelphia

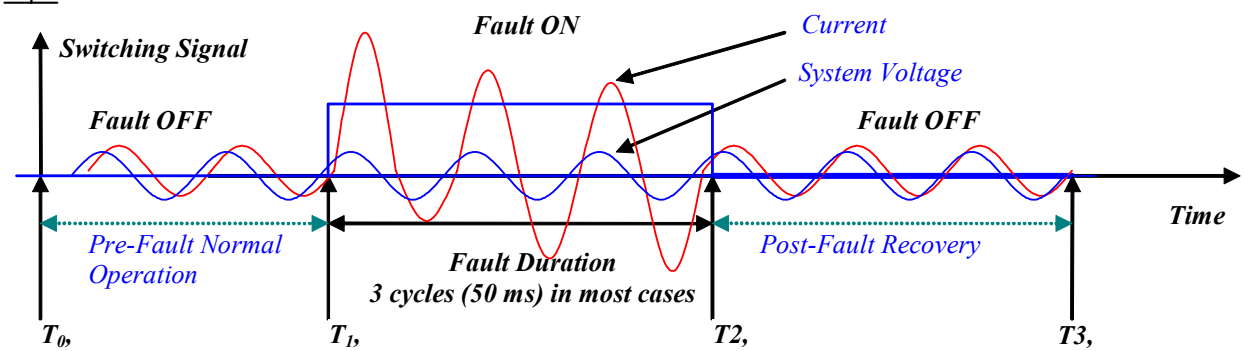
Facility was originally designed for short circuit testing and breaker development up to 138kV

KEMA has capability for Alpha and Beta testing – Current up to 63kA

KEMA provides full set of Performance Reports

Proof-of-Concept Test Circuit at KEMA





Testing in Open Bath at KEMA

Qualified matrix assembly in open bath test with instrumentation to verify current sharing, dynamic resistance development

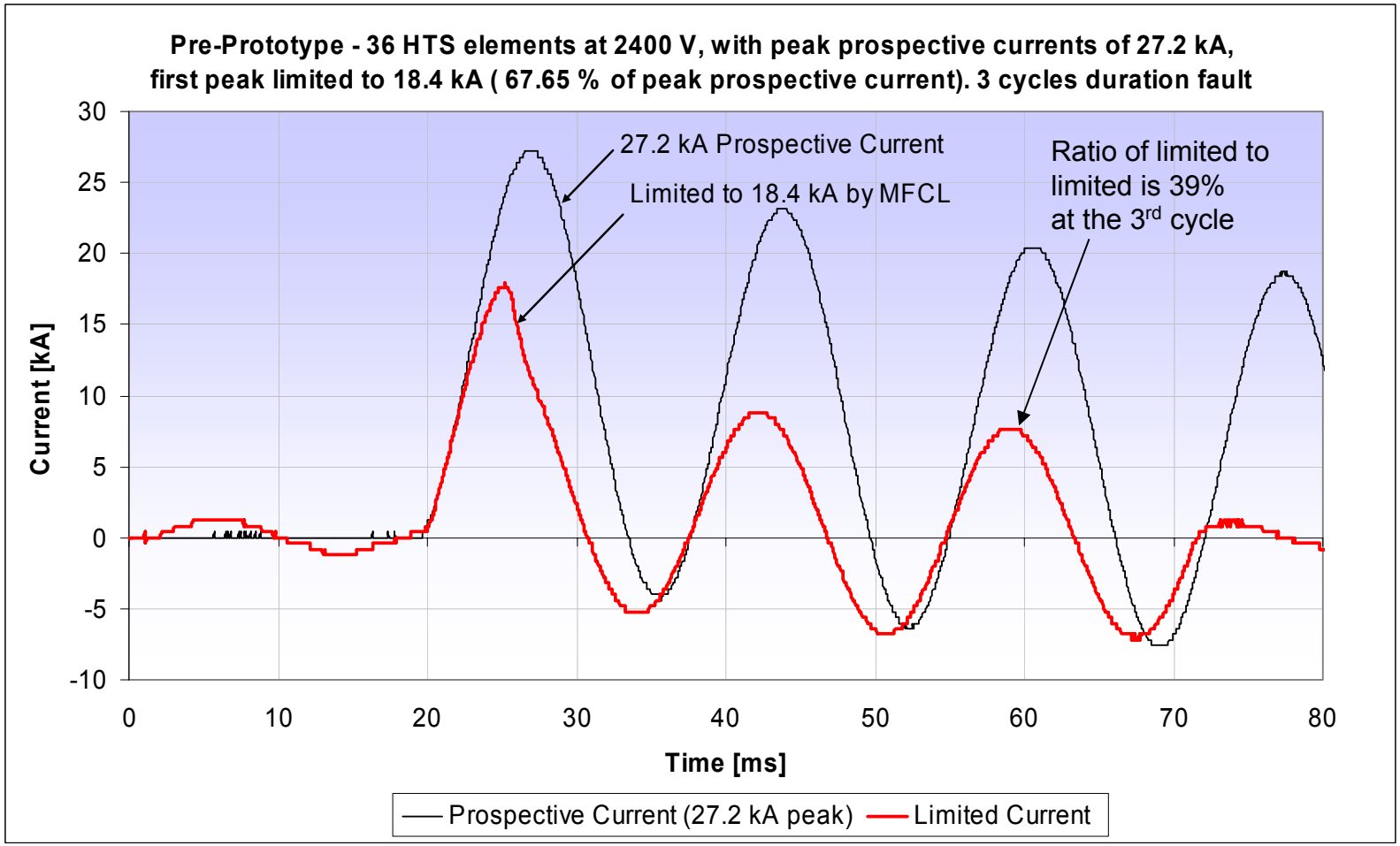
480VAC Tests:

- Matrix populated with 6 elements
- Faults applied at various combinations of .5, 1, 1.5,2, 2, 2.5, 3 cycles at fault levels ranging from 20kA to 27kA prospective first peak
- Total of 22 faults applied

2400VAC Tests:

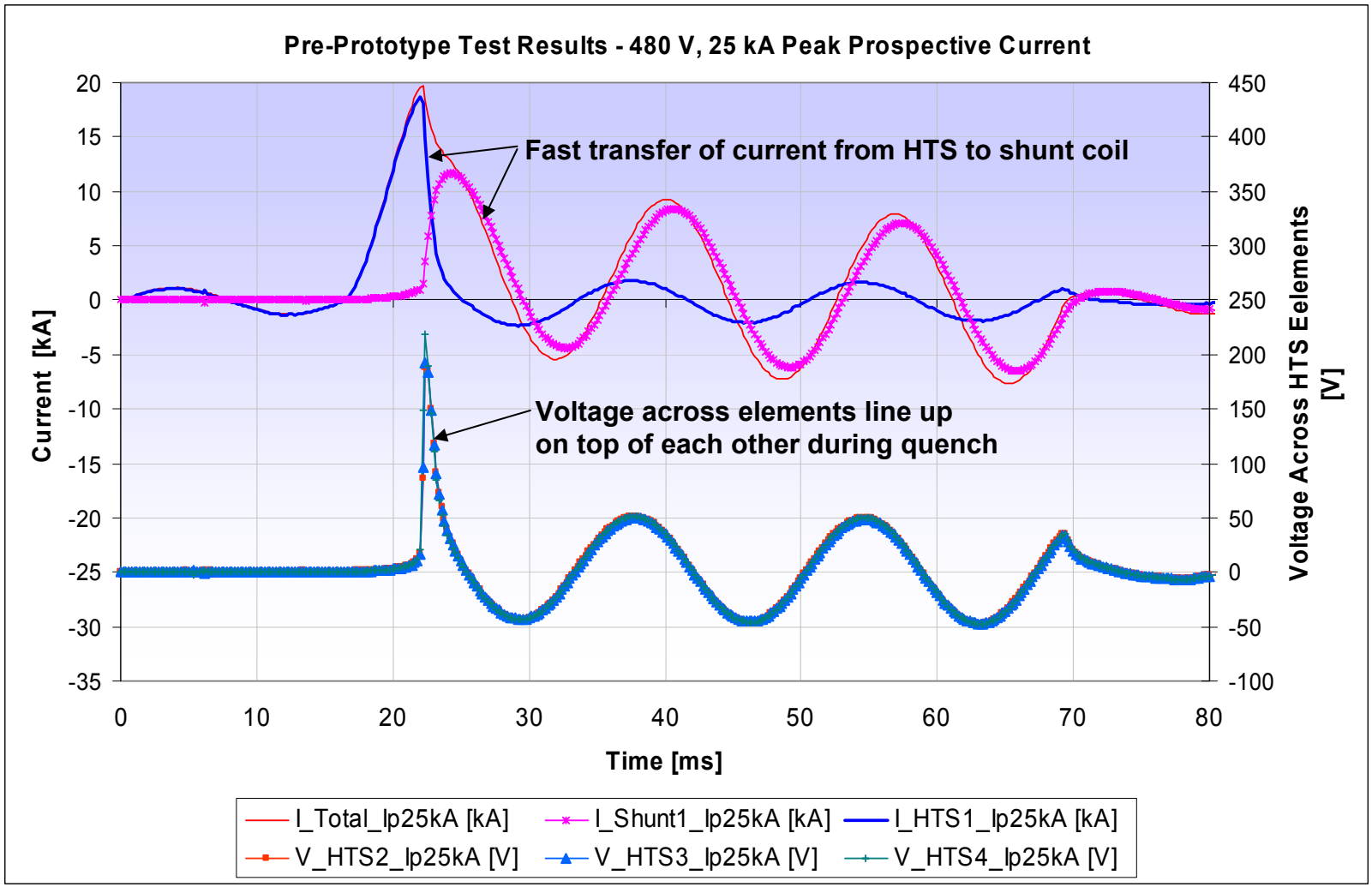
- Matrix populated with full 36 elements
- Faults applied for .5, 1.5, and 3 cycles each at 17.2kA, 23.6kA and 27.2kA prospective first peak
- Total of 9 faults applied

Current Limiting Performance Test Results in Open Bath @ 2400VAC



Reduction of 1st peak fault reduces stresses on bus work, transformers and other utility equipment
Reduction at the 3rd cycle reduces current to a level where breakers can safely open

Current Transfer and Current Sharing



Testing at KEMA in Cryostat

Successful Hi-pot test at 20kV for 5 minutes

First round of tests at bath temperature of 77K and 1 atm pressure

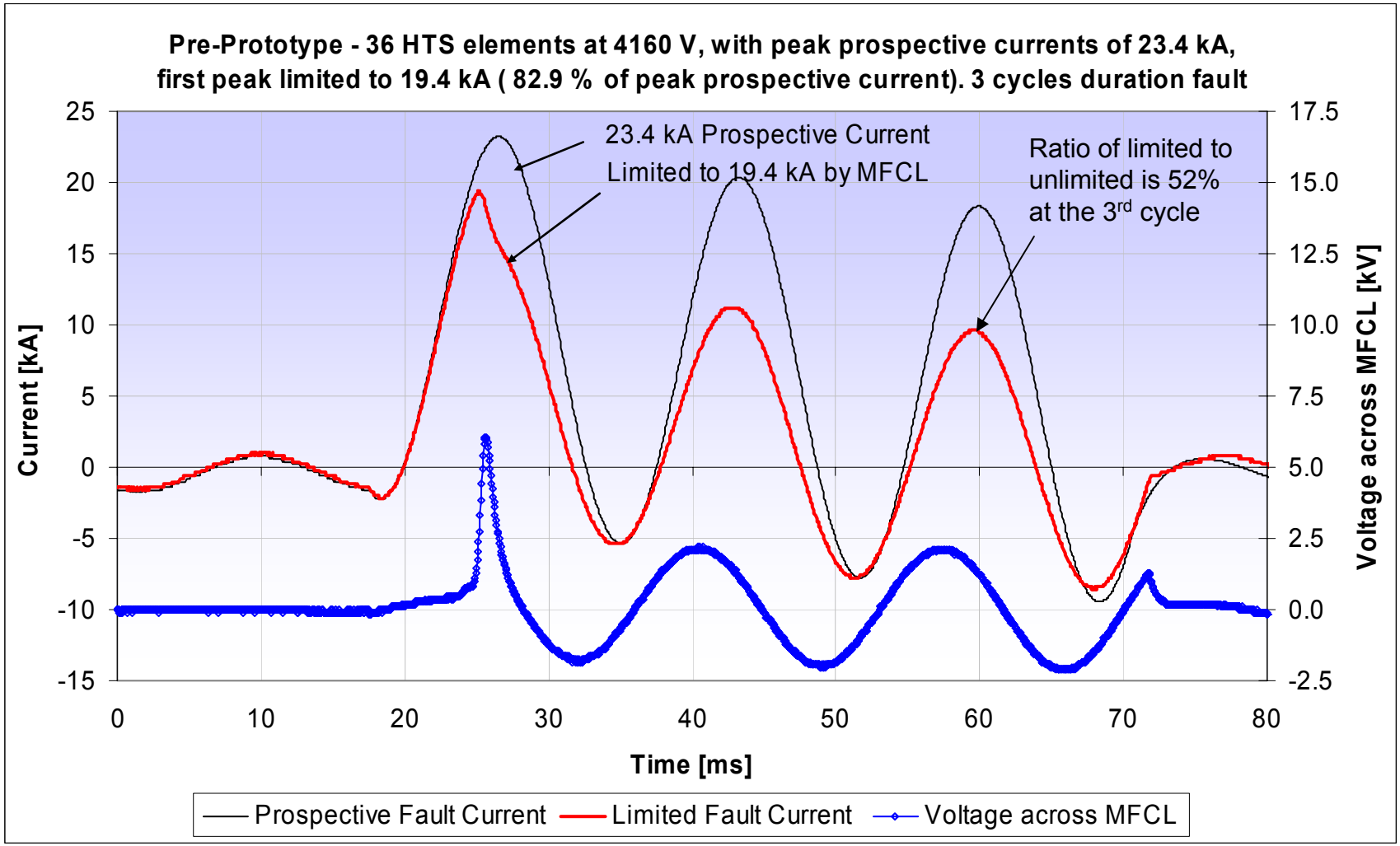
- 4160 Tests - Faults applied for .5, 1.5, and 3 cycles each at 19.4kA and 23.4kA prospective first peak – 6 faults total
- 8660 Tests - Faults applied for .5, 1.5, and 3 cycles each at 18.6kA and 23.4kA prospective first peak – 5 faults total

Noted some element failures and took measurements on performance of elements that withstood multiple faults

Second round of tests at bath temperature of ~74K and 1 atm pressure. All faults applied for 3 cycles

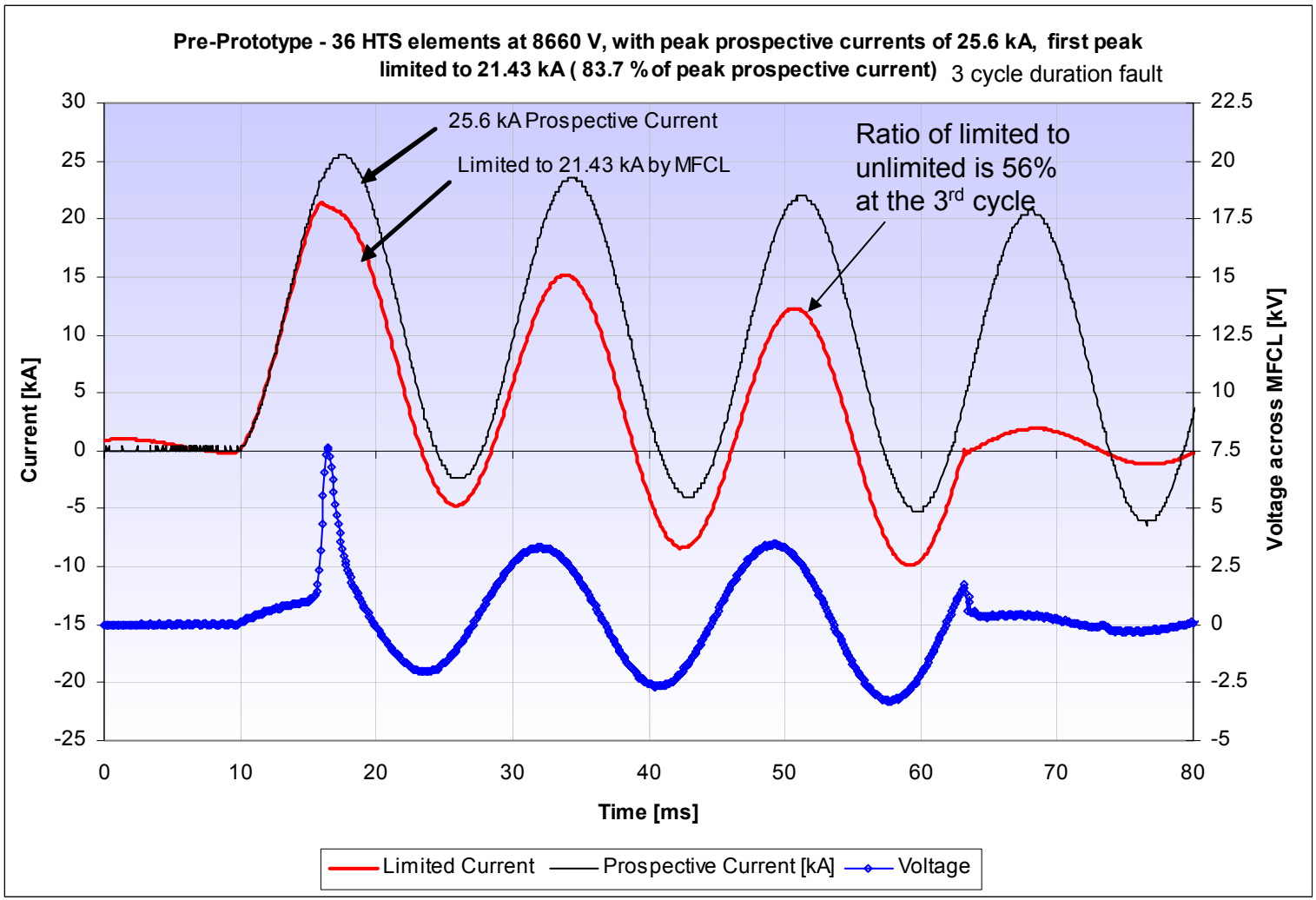
- 4160 Tests – Faults applied at 17.2kA, 20.2kA and 25.6kA prospective first peak
- 8660 Tests – Faults applied at same levels
- 6 faults total at sub-cooled conditions

Current Limiting Performance
Test Results in Cryostat @ 4160VAC



Test at 77K and 1 atm pressure

Current Limiting Performance Test Results in Cryostat @ 8660VAC



Test at 74K and 1 atm pressure

Element Performance During First Round of Tests

Total of 100 elements manufactured for tests – 77 delivered to populate the matrix in various combinations during the tests

As noted, based on electrical measurements and visual inspections, there were some element failures during the tests

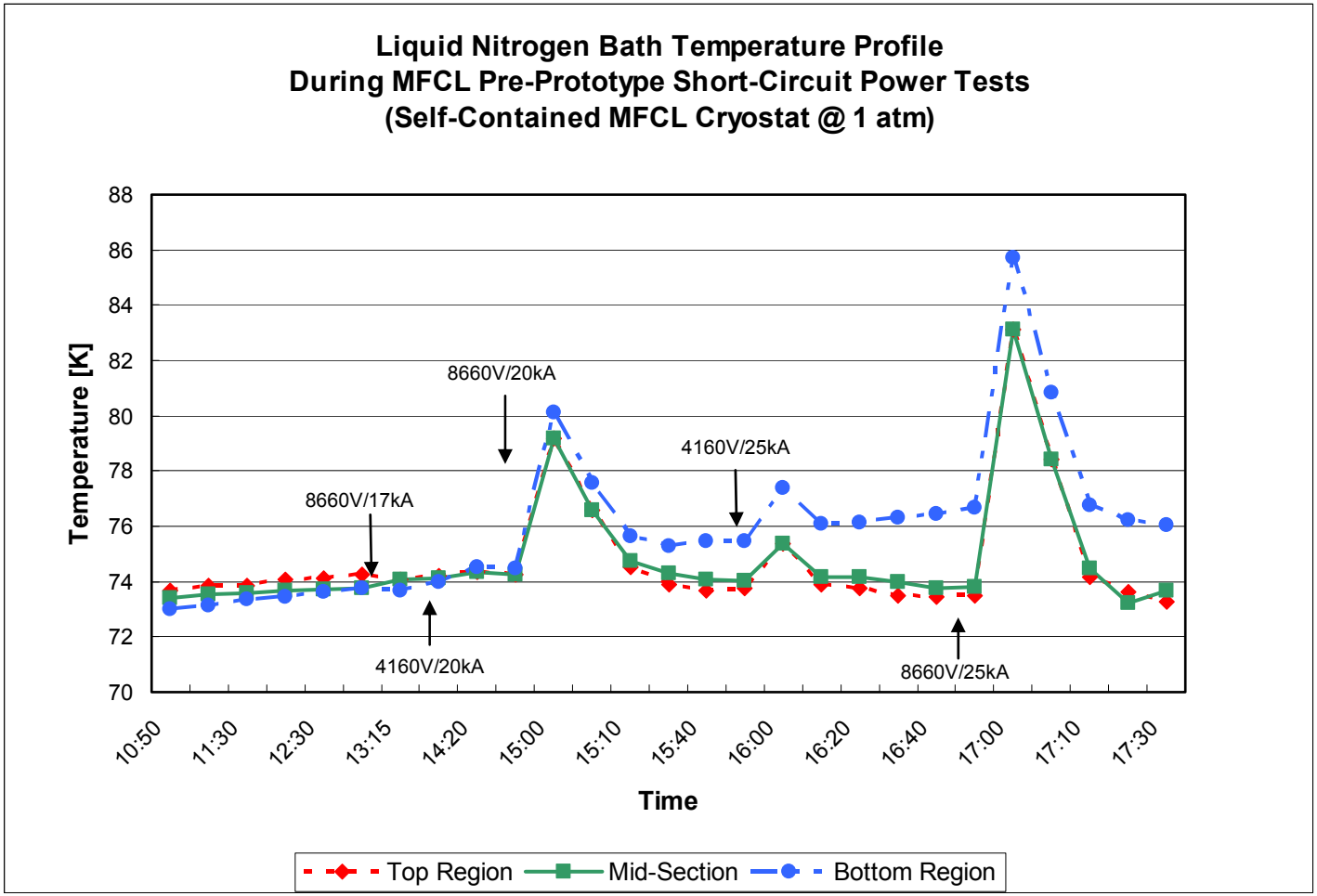
Quality checks were conducted mid-course in the test program for any signs of degradation (change in Ic, micro cracks). Several elements that had been exposed to many faults were sent back to Nexans to repeat the standard quality checks:

- For elements that had been exposed to 33 faults, 80% showed no change over the initial performance. The remainder showed small cracks.
- For elements that had been exposed to 19 faults 85% showed no change over the initial performance. The remainder showed slight changes that were indicative of possible micro cracks.

Additional R&D will be conducted to improve element design robustness

Since the majority of the elements are surviving without any sign of degradation, this is not considered a fundamental issue

Cryostat Performance



Achieved steady state sub-cooled cryogenic operating environment - Sub-cooling is critical for handling high normal load current in a power grid

Achieved fast recovery to normal cryogenic operating environment after fault

Program Year 2 Result Summary

Proof-of-Concept achieved

- Rapid element quench - First peak current limiting to reduce stress on utility equipment
- Significant limiting at time breaker opens at 3rd cycle – Reduces fault current to safe levels so existing protection equipment can isolate faults
- Current sharing
- Improved analytical models to match actual results
- Rapid recovery of temperature in cryostat after application of fault

Voltage VAC	First Peak Current (kA)	Avg. First Peak Limiting	Limiting at 3rd cycle
2400	23.6	73.4%	44.4%
2400	27.2	68.6%	39.2%
4160	23.4	82.6%	52.3%
8660	25.6	83.7%	55.9%

Program Year 3 Plans

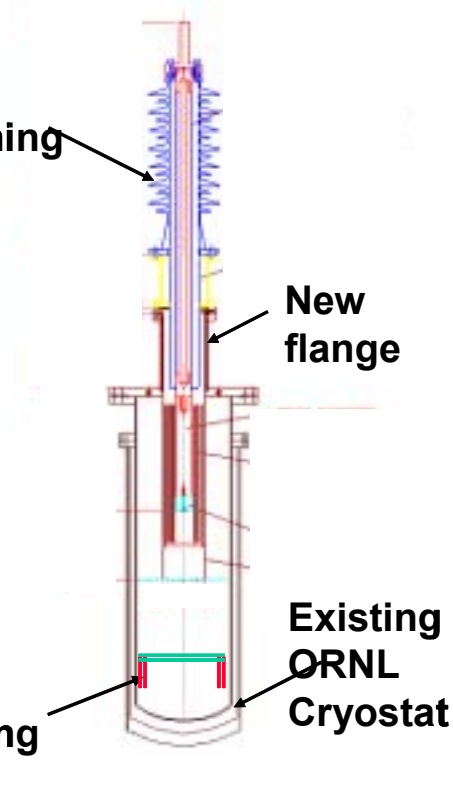
SuperPower & ORNL: High Voltage Scale-Up under Cryogenic conditions

- Develop High Voltage design tools
- Experimental and mock-up tests – develop empirical formulas to predict breakdown voltages
- Evaluate materials
- Utilize test cryostats at ORNL
- Establish HV test standards

Nexans - Continued R&D in BSCCO element design to support scale up to high voltage application

SuperPower – Scale up matrix and conduct additional short circuit tests

Milestones: 138kV Alpha prototype design by June 2005, Alpha Prototype test by December 2005



Modified high-voltage cryostat at ORNL