SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation

Superconductivity for Electric Systems
DOE 2006 Wire Development Workshop

St. Petersburg, FL
Jan. 31- Feb. 1, 2006

HTS Solutions for a New Dimension in Power

SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation

2G HTS Conductors for Fault Current Limiter Applications

Yi-Yuan Xie

K. Tekletsadik
V. Selvamanickam

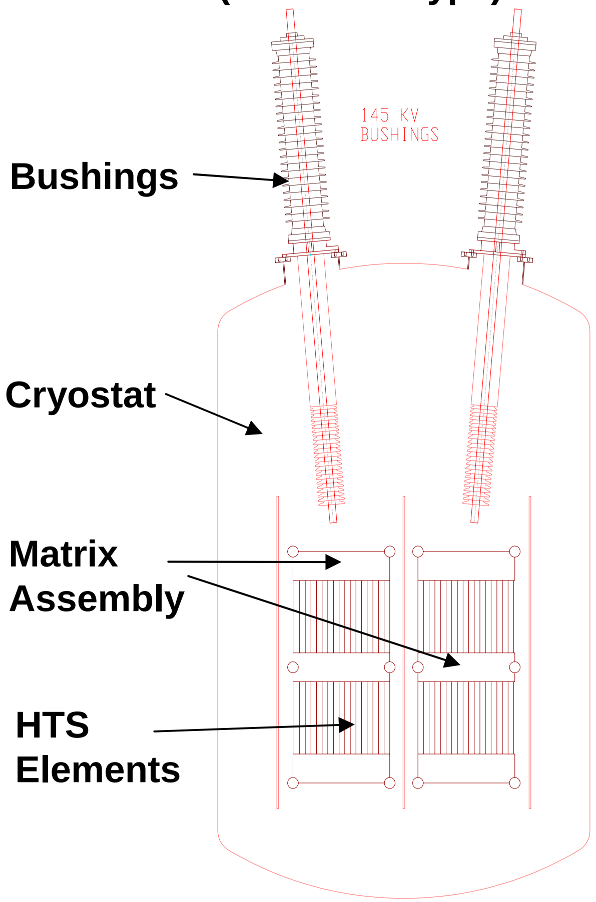
Pre-prototype Superconducting Fault Current Limiter (SFCL) Demonstrated by SuperPower in July 2004

High Voltage Insulation System
- Bushings
- Cryostat insulation system
- Matrix internal insulation

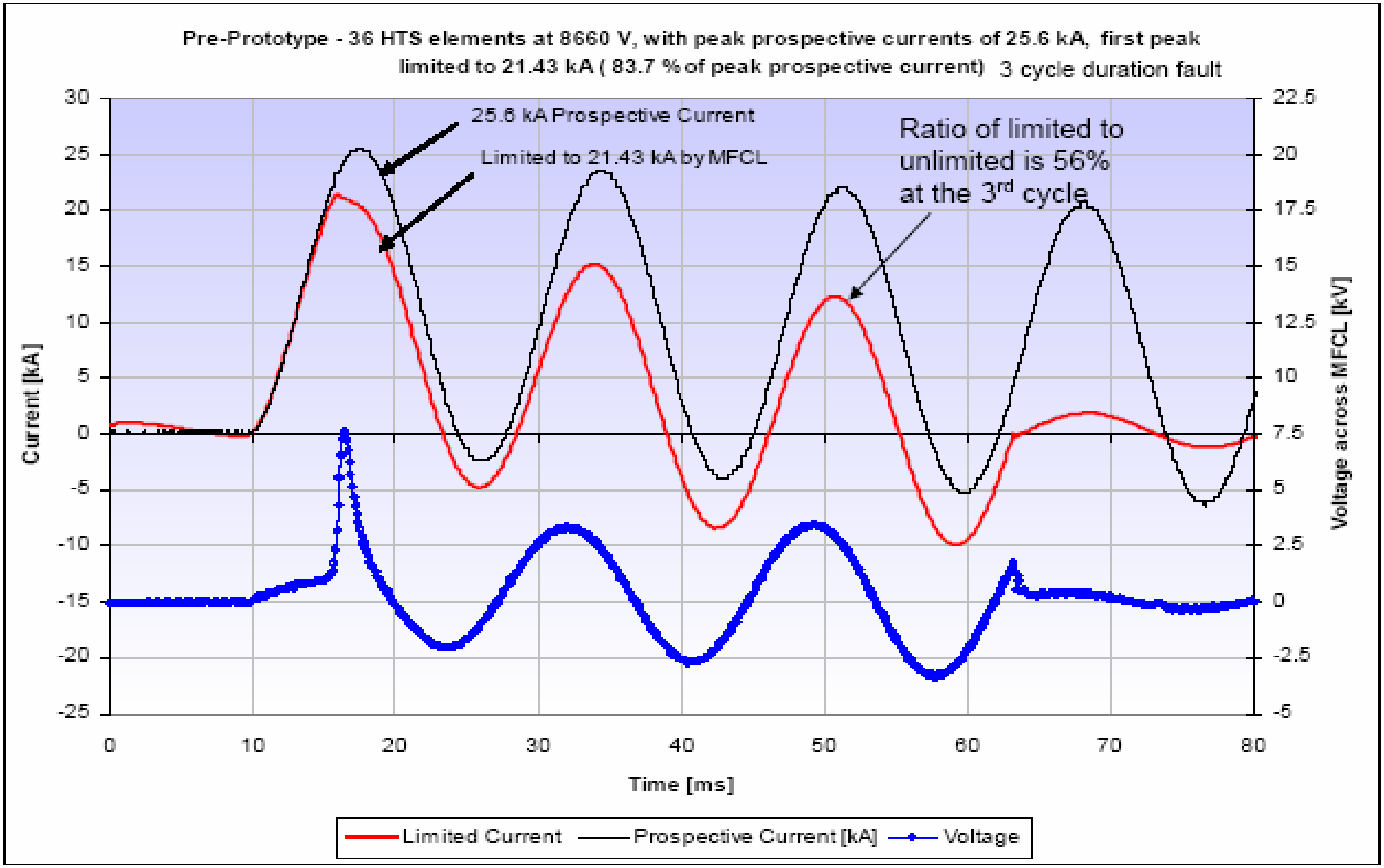
Matrix Assembly
- HTS elements
- Connections of HTS elements and current limiting coils

Cryogenic System
- Vessels to provide stable pressurized sub-cooled environment
- Cryogens and cryo-coolers

Single Phase SFCL (Resistive Type)



Pre-prototype Superconducting Fault Current Limiter (SFCL) Demonstrated by SuperPower in July 2004

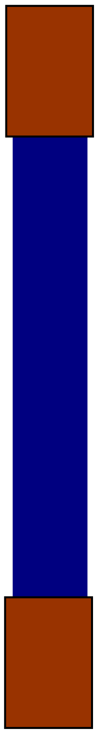


Current Limiting Performance Test Results in Cryostat @ 8660VAC, 74 K, 1 atm

HTS Elements

A High Risk Challenge Using BSSCO Bulk in Alpha Prototype (138 KV, 1ϕ)

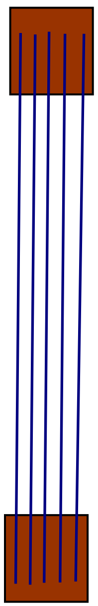
SuperPower Inc.



- Low n-value (8-12) – the quench current is much higher than the critical current, it requires higher current to quench, in the order of $>10*I_c$. This increases the total material volume needed in SFCL
- Number of elements determines device size (along with high voltage), steady state losses (connections) and rating of device cryogenic system – Keep number per phase to a manageable level, i.e., < 500 Max. Must develop longer elements with high individual energy level to minimize total number of parts
- Very high reliability required. Loss of elements has negative impact on heat load and introduces debris that could compromise high voltage
- Return to superconducting state while carrying load current - Recovery Under Load (RUL). Bulk material with limited cooling surface area

Advantages of Using 2G HTS Conductor for SFCL

SuperPower Inc.



- High n-value (20-40) – the 2G conductor quenches at around 2 – 3 times Ic, it limits fault current faster and to low level;
- 2G conductors in 100 + m length and good uniformity are already available
- Superior electro-mechanical properties have been shown in SuperPower's 2G conductor – reduce the chance for mechanical failure and increase the flexibility of element configuration/design;
- Elements with larger cooling surface area – Faster recovery
- Several structural features of 2G conductors can be tuned to optimize SFCL element performance

2G SFCL
Preliminary Test Experiment at SuperPower

Objectives

- **Test 2G conductors for current limiting performance - including**
  - Quench speed - related to quench time and quench current
  - Current transfer speed to external shunt
  - Failure mechanism and life expectancy of the 2G conductors
  - Dynamic resistance development
- **Evaluate the advantages and disadvantages of 2G conductors for SFCL applications**

Test Setup

- **Voltage supply**
  - Isolating transformer, primary 208 V, Secondary 5V, 10V, 20V and 40V
  - Short circuit current could vary up to 7000 A peak
  - Line frequency – 60 Hz
- **Shunt impedance**
  - Variable pure resistive or resistive/inductive impedances

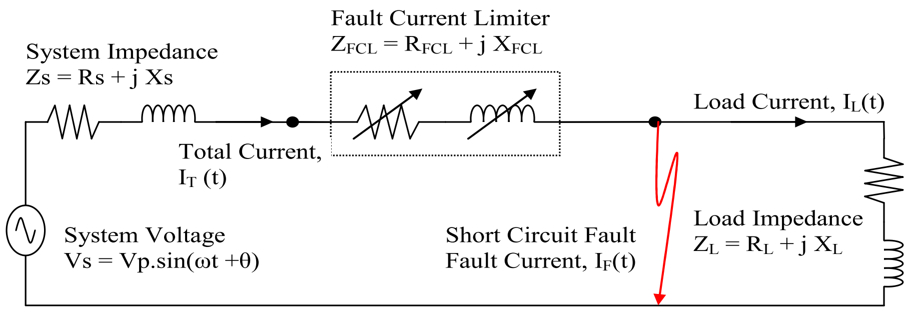


Figure 2 (a) Schematic Diagram of a single phase power system representation

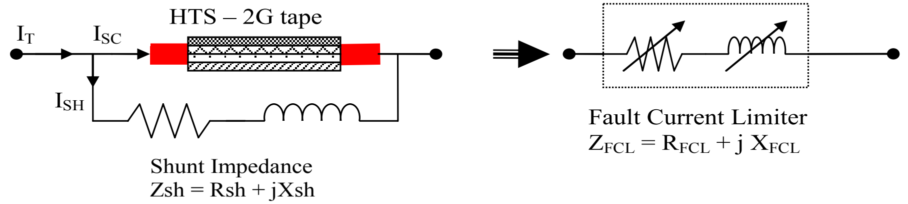
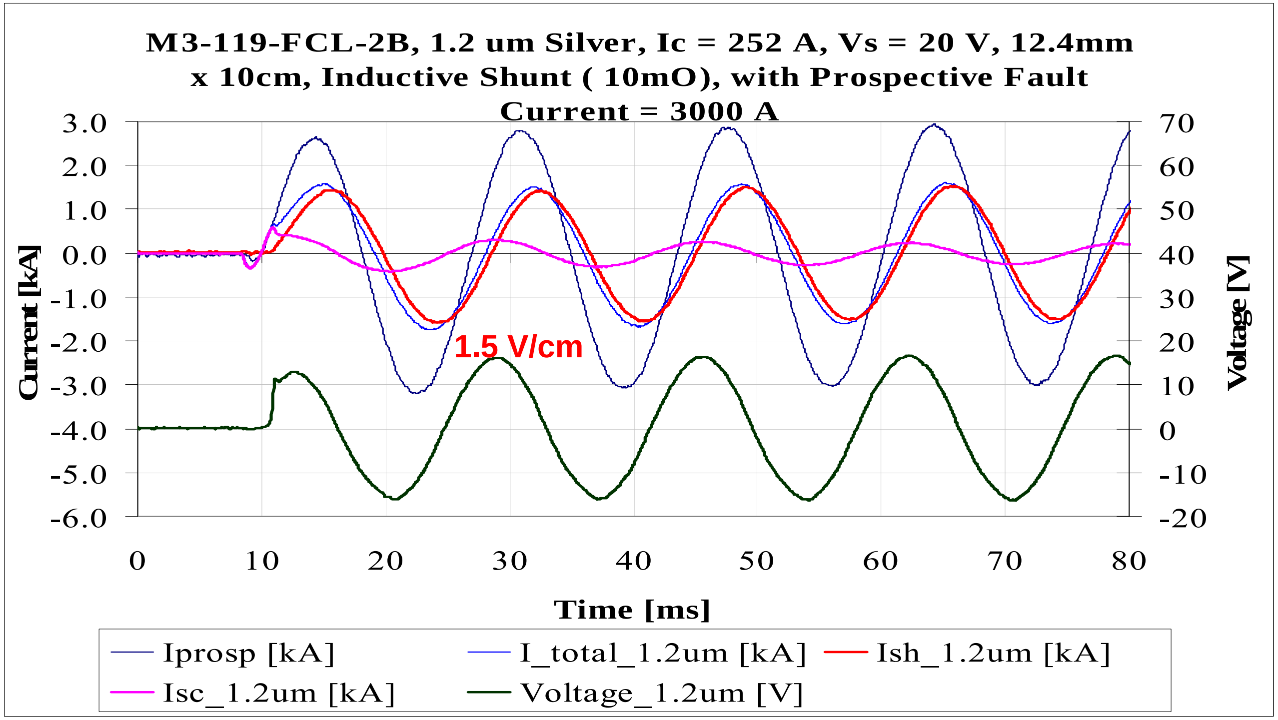


Figure 2 (b) Equivalent circuit of FCL

Performance of Single 2G Conductors

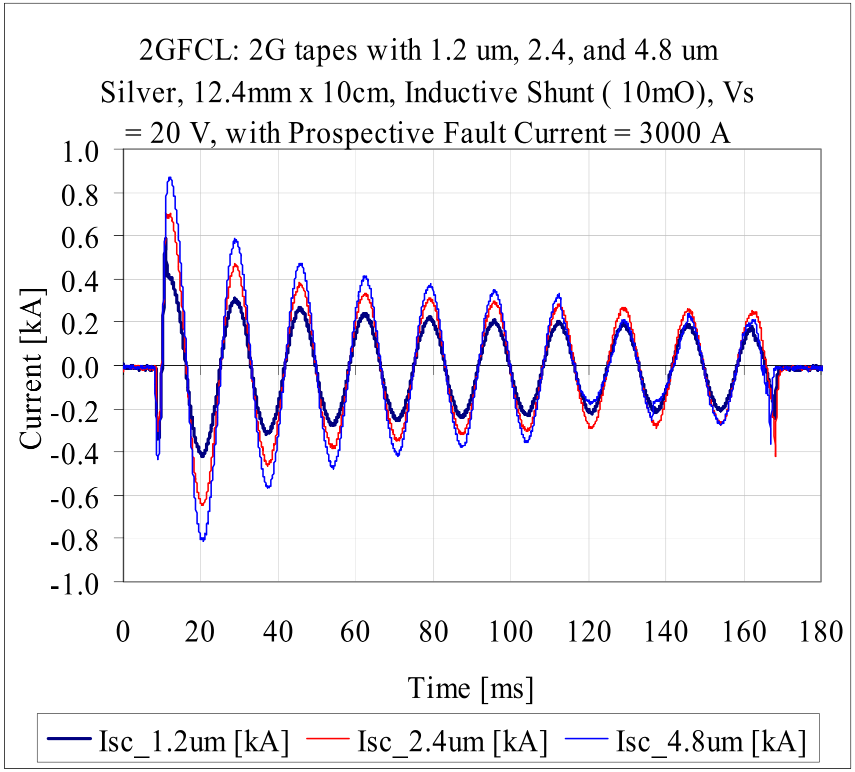
A typical 2G conductor:

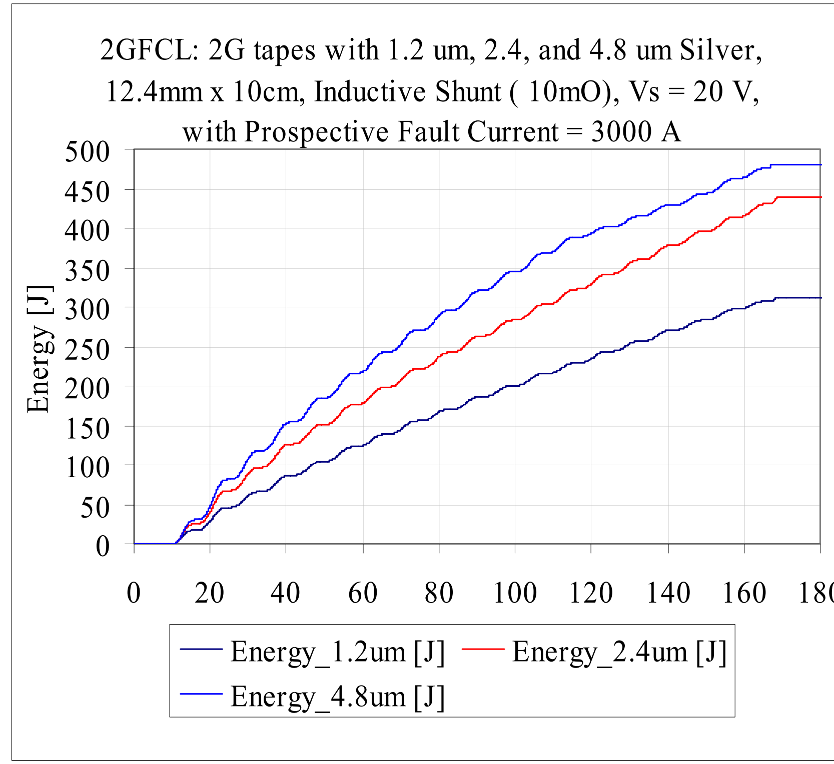
- Width: 12.4 mm
- Length: 10 cm
- Ic = 252 A
- 1.2 μm metal overlayer
- Subject to a 8 cycle fault current
- V = 20 Volt on the circuit



- Multiple samples tested and all demonstrated good current limiting performance, including 1st peak limitation
- Quench current under AC (60 Hz) fault current was in the range of 1.8 to 3 times critical current
- Response time is within 1 ms
- With 10 mΩ shunt, the total current can be limited to half of the prospective current

SFCL Element Performance Optimized by Tuning 2G Conductor Structural Parameters



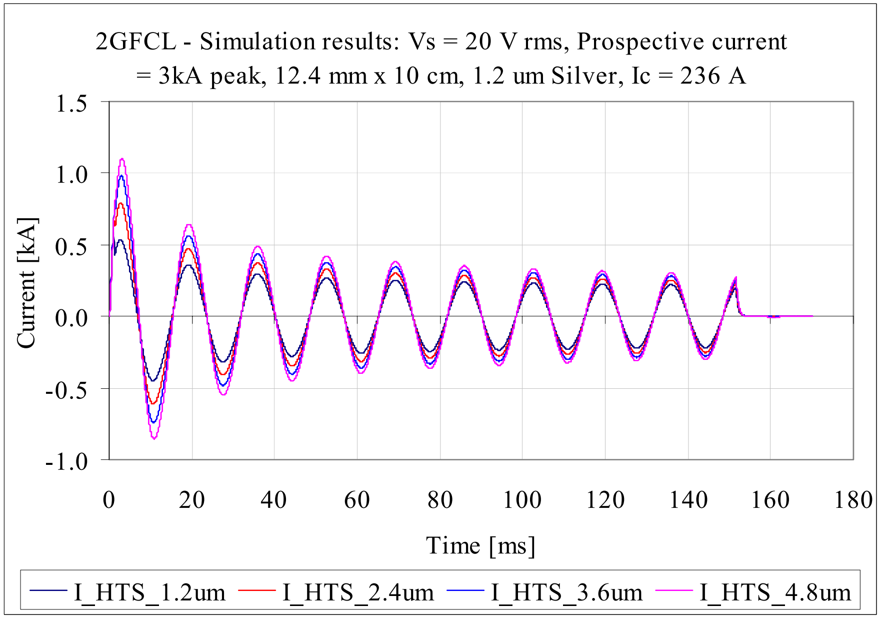


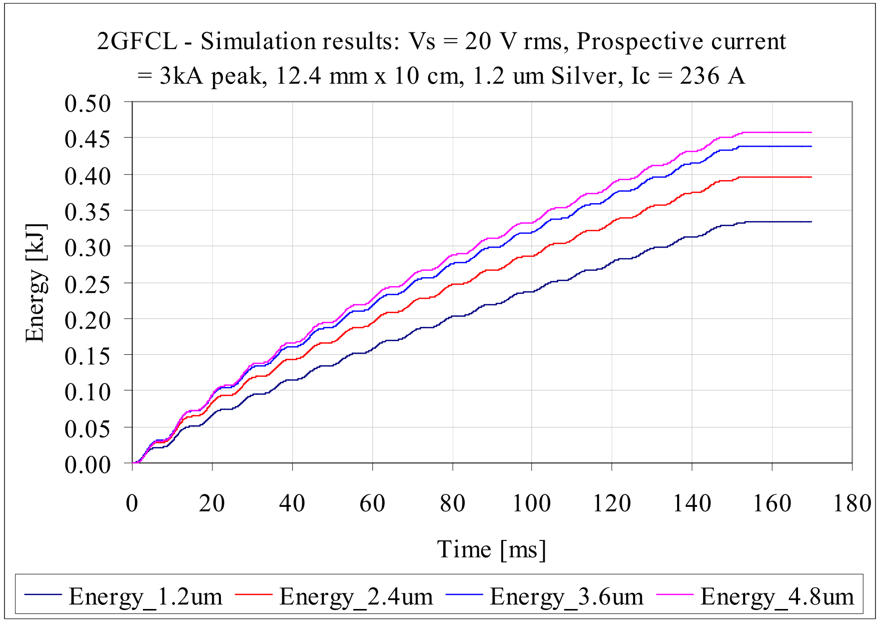
When metal overlayer thickness was increased from 1.2 μm to 4.8 μm

- Current at first peak increased from ~ 2 x Ic to 3.4 x Ic
- Accumulative energy increases from 32 J/cm to 48 J/cm with increased metal overlayer thickness. Substrate thickness also plays a critical role in thermal management of the 2G SFCL conductor

== > SFCL based on 2G conductor optimization shows satisfactory current limiting performance

Software Developed to Simulate Performance





- Thermal and electrical properties of 2G conductors and electrical circuit including the test transformer, current limiting impedance and connector conductor impedances (measured/ approximated) as input parameters
- 2G conductors with variable metal overlayer thickness simulated; 1.2 um, 2.4um , 3.6 um and 4.8 um. Current limiting performance simulation is in good correlation with test results
- Fine tuning the model will be required, especially during the 1st peak quench progress, e.g., thermal model needs to be refined to improve heat transfer parameters and cooling effects, this will become a useful tool to guide 2G conductor optimization and predict performance of 2G conductor element assemblies.

Testing 2G Conductors in Parallel Connection

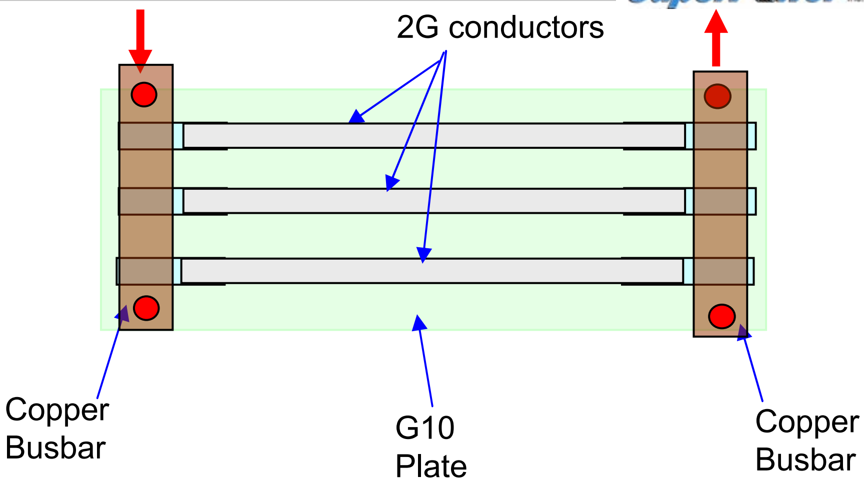
Current Limiting Performance

Three 2G conductors tested in parallel

- Each 20 cm long x 12.4 mm wide with 2.4 μm metal layer. Ic = 277 A or 831 A (total)

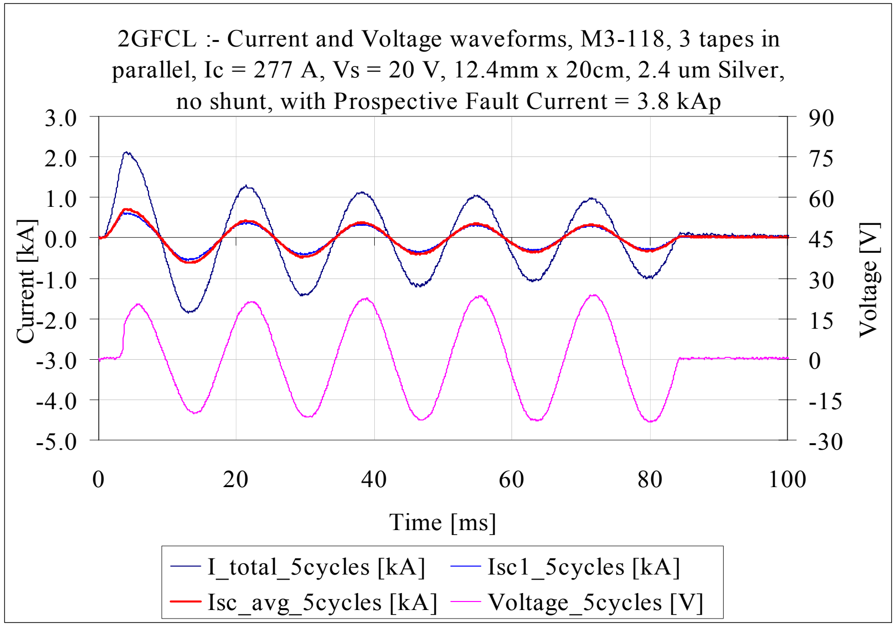
Test procedure

- Apply fault currents with prospective current of 442 A, 705A, 1140A, 1360A, 1650A, 2320A, and 3800A at 20 V. No shunt.
- Fault duration from 5 cycles up to 12 cycles until 2-G conductors failed.



Test results

- At 3.8 KA prospective fault current, first peak current was 600 - 700 A for each wire
- Two samples failed at the same time during 11 cycles test at 35 J/cm/tape energy level; 3rd sample failed during the next 12 cycles test
- Failure of conductors in parallel connection close to each other means small variation and predictable life expectancy

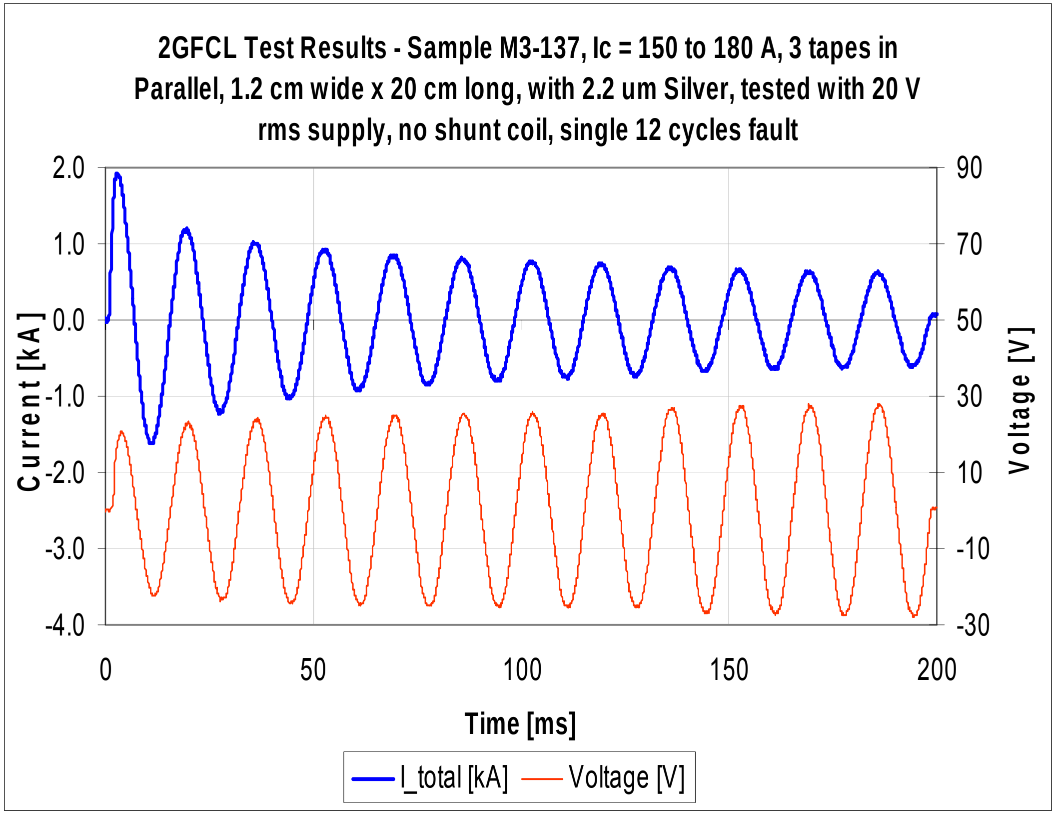


Testing 2G Conductors in Parallel Connection

Recovery Performance

A different set of three 2G conductors tested in parallel:

- Each is 20 cm long x 1.24cm wide with 2.2 μm metal layer.
  Ic ~ 180 A
- Survived single 12 cycle faults at 35 J/cm/tape (2G conductor with 2.2 - 2.4 μm metal layer fail around 35 J/cm/tape)
- Current decreases and voltage increases with time during fault, implying accumulative heating to the tapes and temperature rise

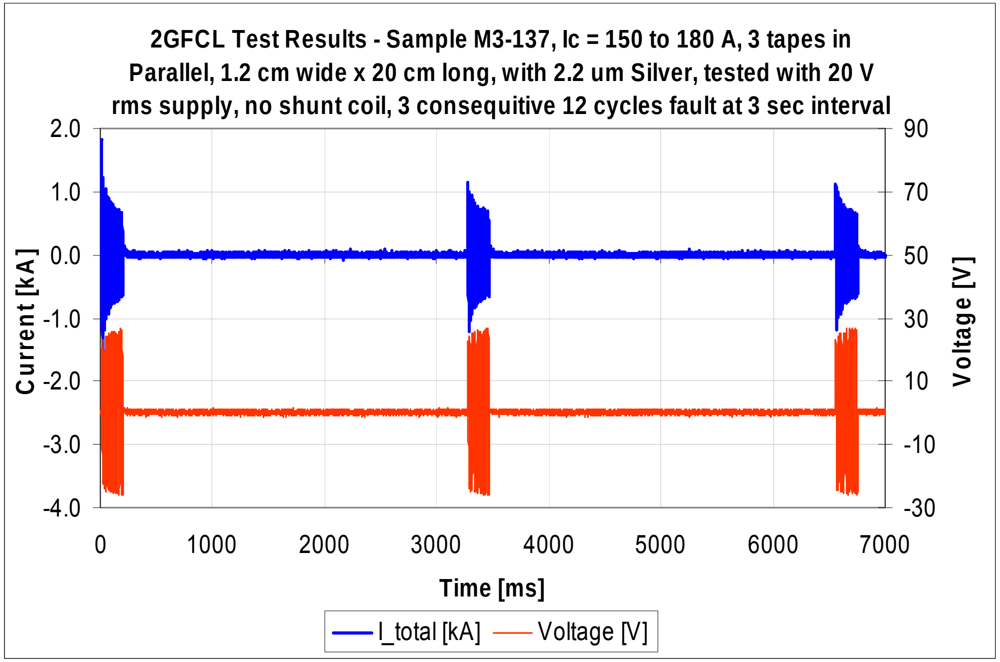


Testing 2G Conductors in Parallel Connection

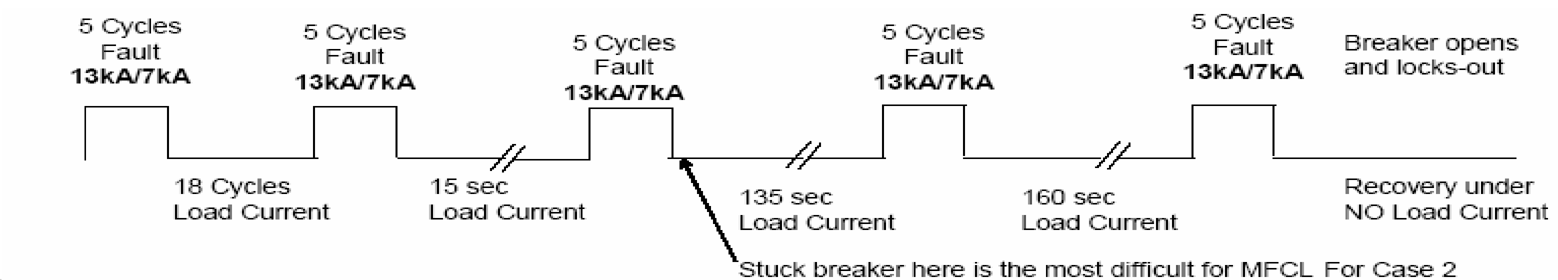
Recovery Performance

Repetitive fault performance - Recovery under no load test

- Simple estimation of recovery time based on LN_2 bubble activities showed that conductors recover within 4 to 6 seconds. 3 repetitive faults of 12 cycles shown in chart – accumulated energy ≈ 100 J/cm/Tape ≈ 3 times the single fault energy
- Up to 6 repetitive faults of 12 cycles at an approximately 3 sec. interval were applied. One of the 3 tapes failed after 5 recovery tests.



- Large cooling surface area is beneficial to recovery. RUL performance needs to be tested under different breaker switching sequence scenarios. For example, the worst case:



2G SFCL – Summary

- 2G conductors demonstrated current limiting performance, including 1^{st} peak limitation
- Quench current was in the range of 1.8 to 3 times critical current – responds fast within 1 ms
- Optimized performance can be achieved by tuning structural parameters of 2G conductors. Further optimization is in progress
- Preliminary parallel connection test showed good performance and uniform current sharing with very close life expectancy at energy levels of 35 J/cm/tape
- Recovery under no load conditions was tested with up to 6 repetitive faults of 12 cycles. Conductors completely cooled down in 4-6 sec after each fault with energy up to 35 J/cm/tape, and survived energy level higher than 100 J/cm/tape under repetitive faults at 3 sec. interval
- Computer program developed to simulate the performance of 2G conductors and assemblies