Status and Progress of a Fault Current Limiting HTS Cable To Be Installed In The Consolidated Edison Grid

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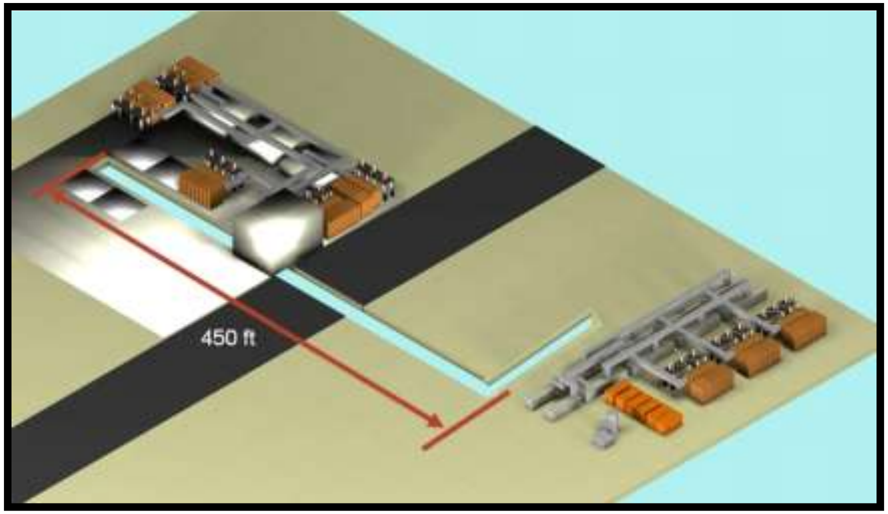
Outline

- Hydra Project Overview
  - Specification
  - Team roles and responsibility
  - Main goals and objectives
- Fault Current Limiting Cable Operation Principle
- FCL Cable System Components
- 3m & 25m Prototype Cable Test Results
- Refrigeration System
- Conclusions

HYDRA Project Overview

- **Consolidated Edison's Substations**
- **Electrical Characteristics**
  - **Design Voltage/Current – 13.8kV, 4,000 amp ~96MVA**
  - **Design Fault Current – 40kA @ 67ms**
- **Physical Characteristics**
  - **Length ~ 170m**
  - **HTS Conductor Length ~50km**
  - **Cold Dielectric, Triax Design**
- **Hardware Deliverables**
  - **One ~170m Long, 3 Phase HTS Cable**
  - **Two 13.8kV Outdoor Terminations**
  - **One Refrigeration System**
- **Commissioning – Summer 2014**



World's First FCL Distribution Cable to be Installed in Operating Grid

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Team Roles and Responsibilities

- **DHS Science & Technology Directorate**
  - **AMSC Prime Contractor**
    - **AMSC**
      - System Design
      - Wire Development
      - Project Management
      - Wire Manufacturing
      - Technical Oversight
      - System Hardware Development
    - **Altran Solutions**
      - Site Design
    - **Consolidated Edison**
      - Utility Requirements
      - Construction Management
        - Permitting
        - Civil Work
      - System Planning
    - **DH Industries**
      - Cooling System
      - Installation Support
      - O&M Contract
    - **Ultera**
      - Cable & Accessory Design
      - Cable Manufacturing
      - Cable & Accessory Installation
  - **ORNL Test Agency**
    - 25m Prototype Cable Test Site
    - Technical Support

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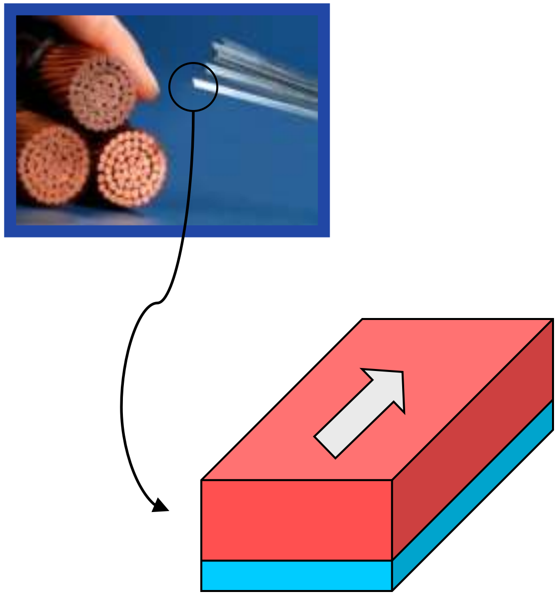
HYDRA Project Main Objectives

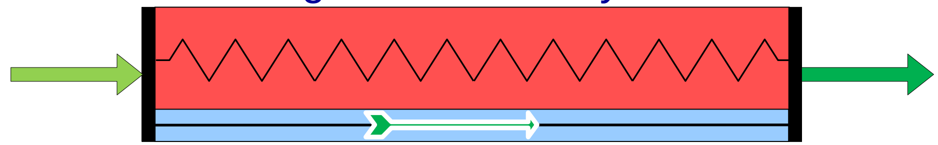
- Demonstrate High Temperature Superconductor Fault Current Limiting Link Between Substations
- Demonstrate Feasibility of an Installation of a Fault Current Limiting HTS System in Population-Condensed Urban Area
- Demonstrate an Installation and Operation of a Reliable Cryogenic System

Fault Current Limiting Cable Operation Principal



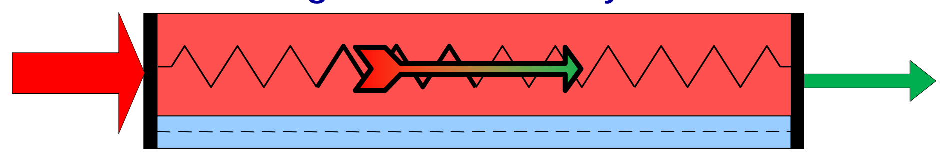
Simplified View of Superconductor wire

Load Current



- Superconductor wire has zero resistance up to the "critical" current

Fault Current



- AMSC supplies a superconductor wire that instantly introduces high resistance above the critical current
- Immediate limitation of fault current magnitudes
- Insertion of resistance decreases X/R and fault asymmetry

Allows the construction of fault current limiting cables

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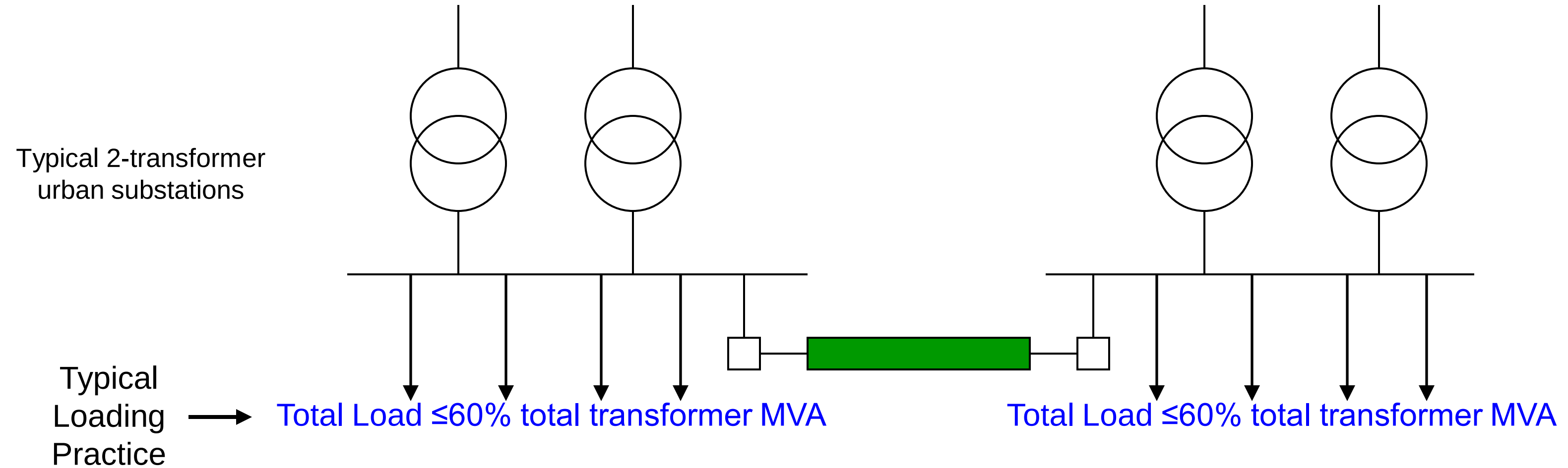
Paralleling Urban Buses: The Appeal

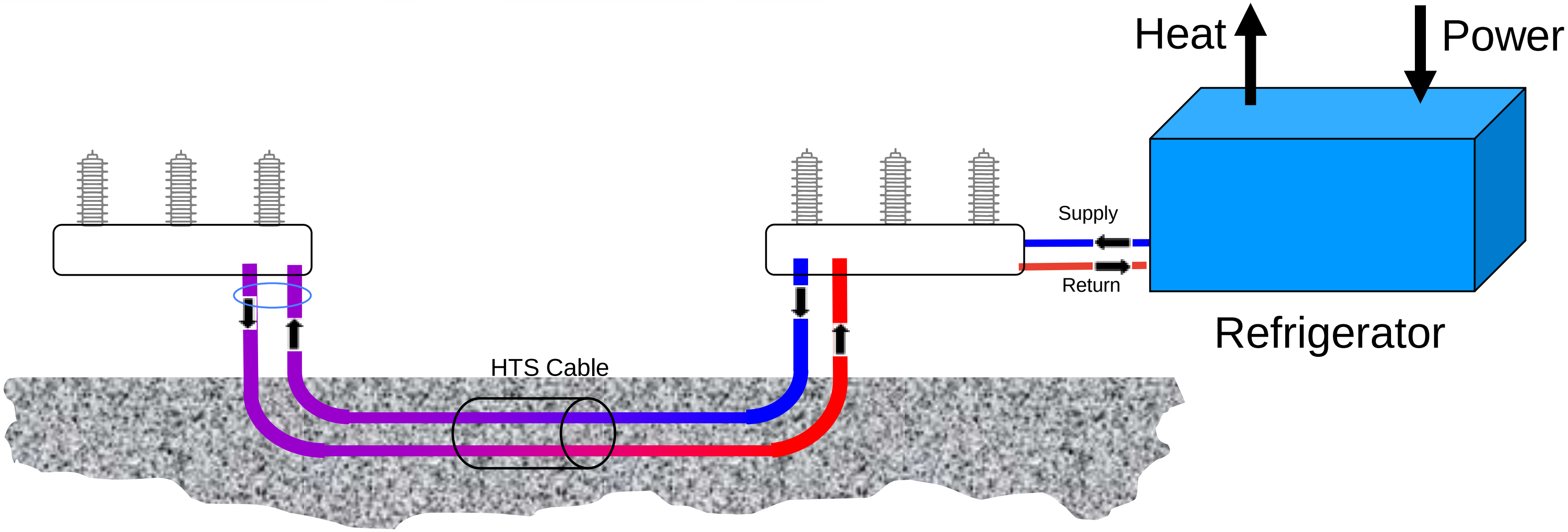


Advantages of Paralleled Substations – Simple Case

- **Connect additional load without additional transformers or new substations**
- **Increases transformer asset utilization**
- **Reduces cost of N-1 contingency planning; only 1 transformer required versus 2**
- **Increased interconnectivity protects vulnerable, critical loads in the event of a catastrophic failure**

Paralleling Dense Urban Load Centers Leads to Operational Efficiencies

HYDRA HTS Cable System

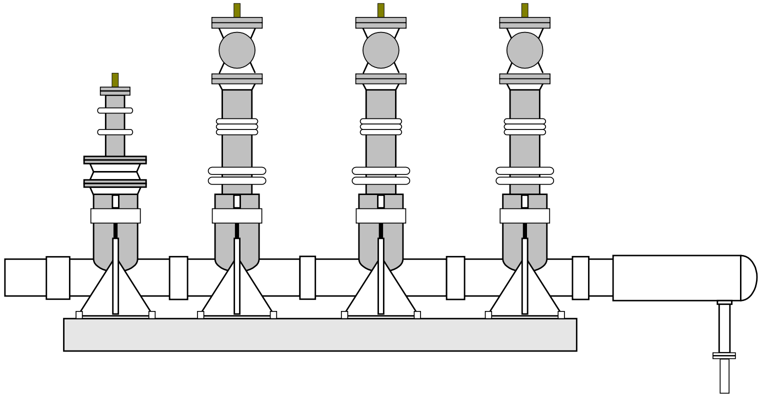


Main Components of HTS Cable Systems

- HTS Cable
- Cryostat
- Terminations
- Cryogenic Cooling System

Components of the HTS Cable System

- Superconducting Cable System
  - Cable Core
    - Transport the current
    - Limit the fault current
    - Withstand the voltage
  - Cryostat
    - Insulate thermally – keep the cable cold
    - Transport the liquid nitrogen
  - Termination
    - Connect the system to the grid
    - Manage the transition between cold temperature and room temperature
    - Provide connection to the cooling system



Cable Design- Triax® by Southwire

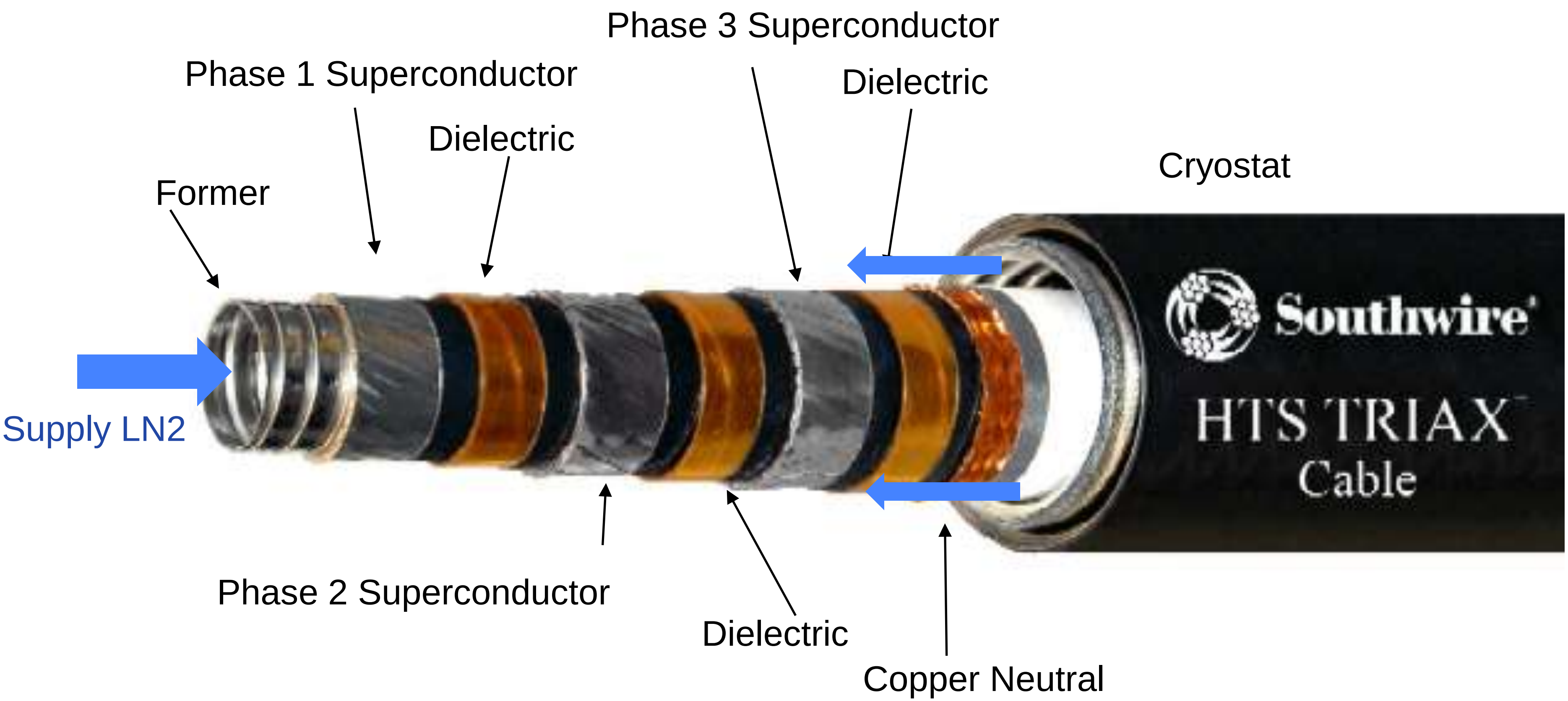


Photo courtesy of Ultera
Triax is a trademark of Southwire

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HYDRA Project Status and Progress

System Specs

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Wire Development →
- Wire Bulk Properties
- Temperature Rise Verification
- Over-current Behavior Verification

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3m Prototype Cable →
- Operating Current 4kA Verification
- Manufacturability Verification
- Cryogenic Requirements Verified

↓

25m Prototype Cable →
- Fault Current Limiting Verified
- Thermal Stability Verified
- Manufacturability Verified
- System Operating Parameters Verified
- Operating Capacity Verified
- Dielectric Performance Verified

↓

Final Installation Cable

solutions

3m Cable FCL Test Setup

- Open Bath Test

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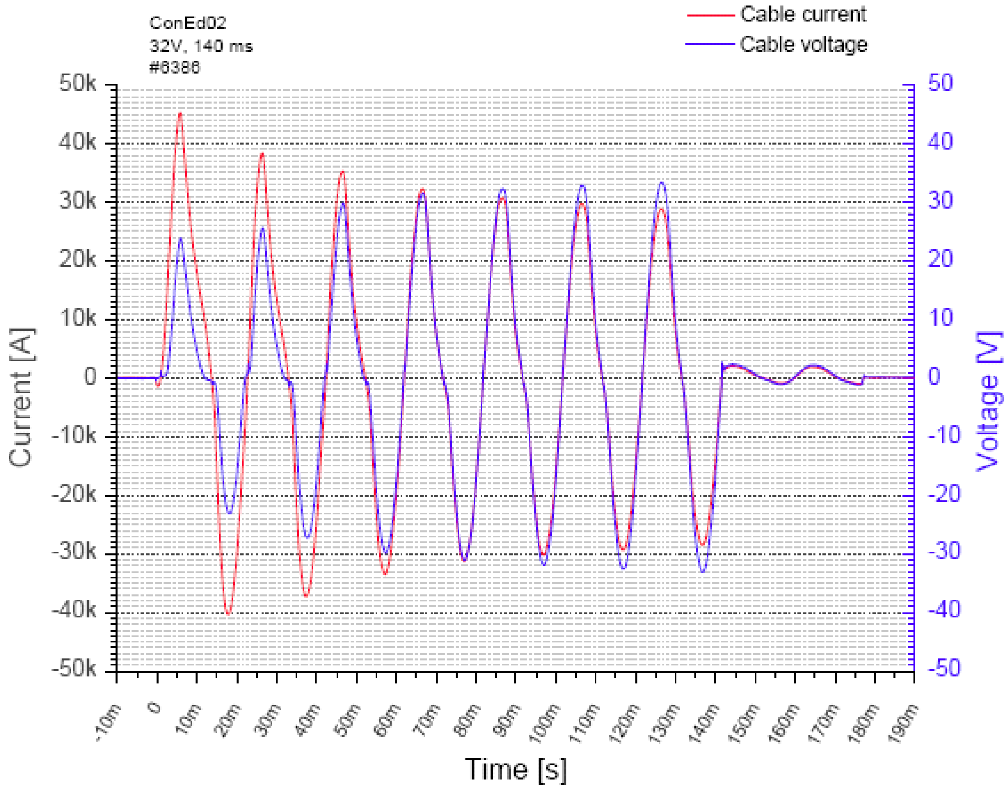
3m cable FCL Tests

Voltage and Current, 32 V_{EMF} 140 ms



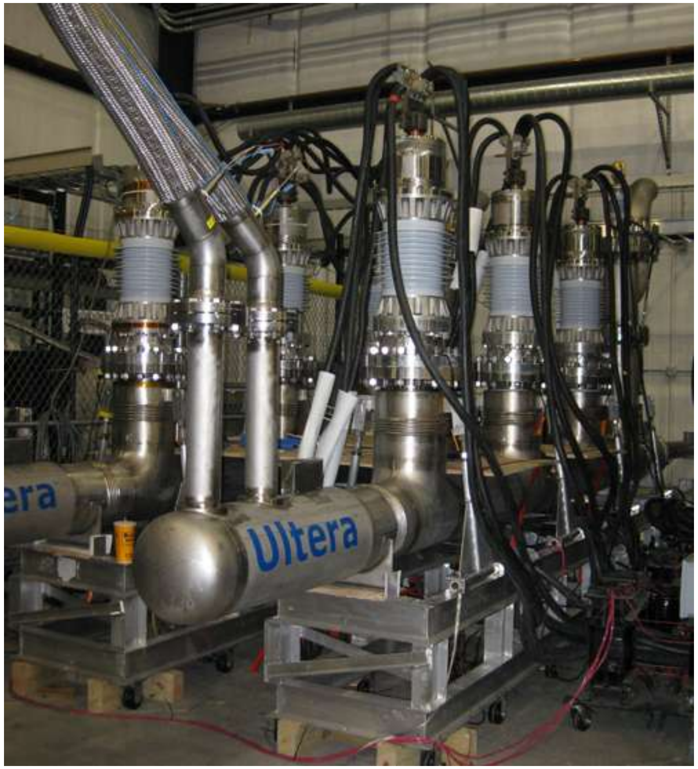
3m Cable Let-Through Tests

- Three 9.1kA 270ms shots
  - ~20min apart
  - Three faults within one hour
- Results
  - Cable is superconducting throughout the current surge
  - No evident heating observed

3m Cable FCL Test Conclusions

- The cable is superconducting after the tests
- No change in temperature seen in 9.1kArms 270ms thru fault tests
- Less than 1K in temperature rise in 7.2kArms 2000ms thru fault tests.
- Current limiting capability is evident
  - Prospective current of 60kArms limited to 30kArms
  - Cable voltage is $8V_{peak}$ / m at first cycle and $11V_{peak}$/ m at last cycle

25m Prototype Cable Test Setup



Termination

Refrigeration system

25m HTS Triax® Cable

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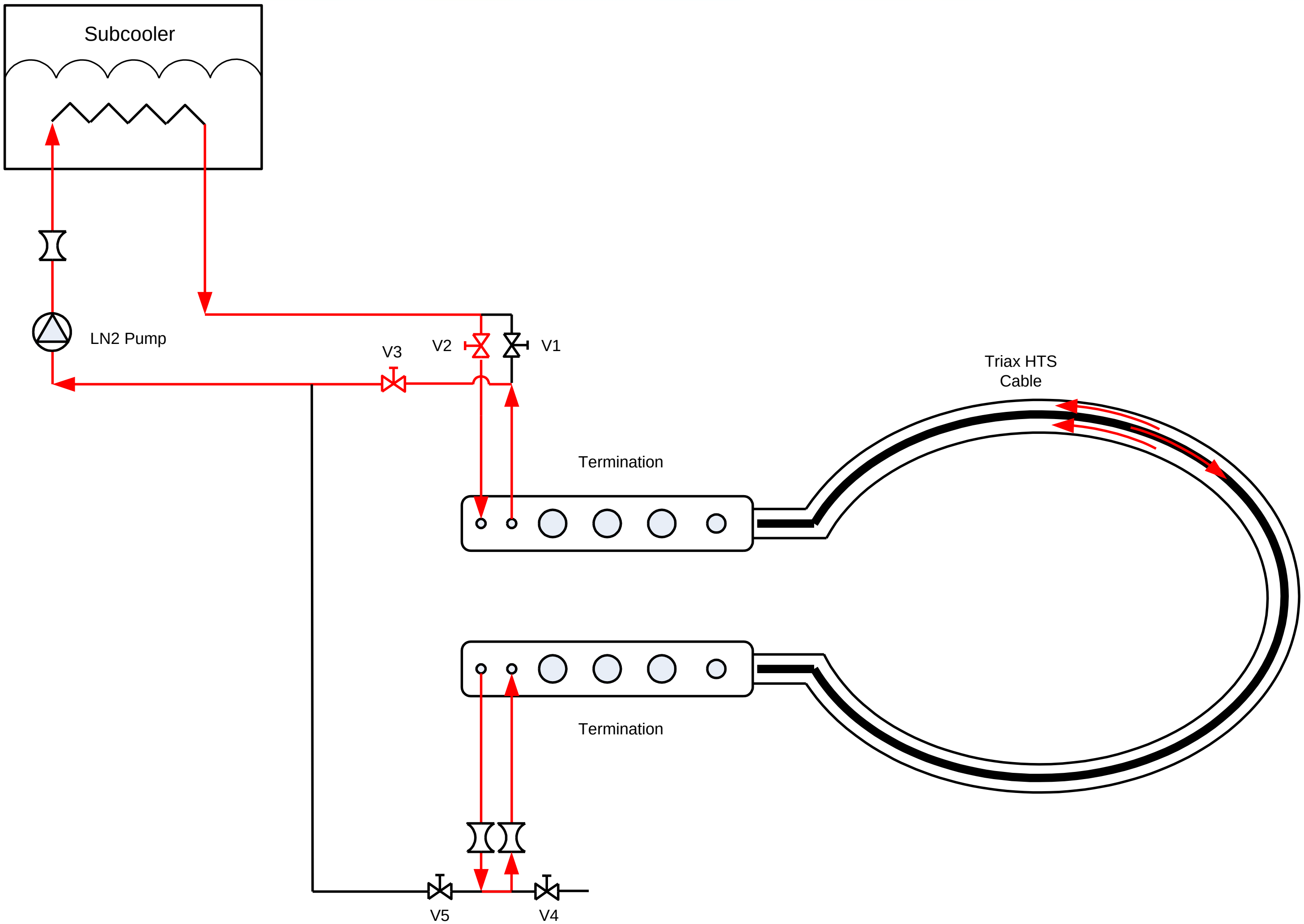
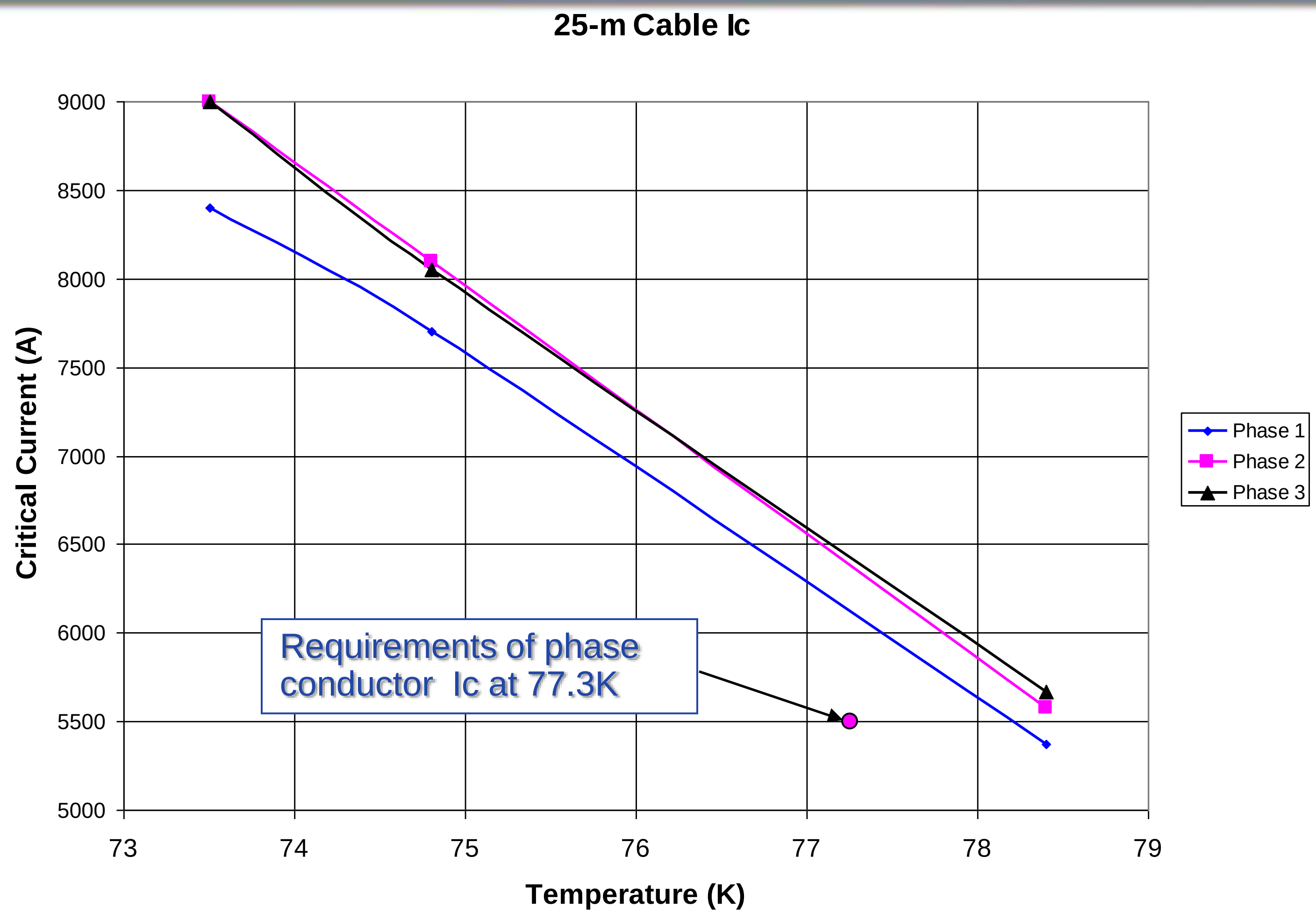
25m Cable Test LN2 Flow Diagram



25m Cable Test Plan

- 25m Prototype Cable Tests
  - Performance Characteristics
    - Cable Resistance
    - DC Critical Current
    - AC Loss
    - FCL Low Voltage
    - FCL High Voltage
  - Thermal Tests
    - Thermal Stability
    - Thermal Cycle
  - Dielectric Tests
    - Voltage Soak
    - Partial Discharge
    - AC Withstand
    - Lightning Impulse
  - Other Tests
    - Leak Check
    - Post-BIL
      - Partial Discharge
      - AC Withstand
    - Post BIL& FCL DC Ic
    - Post Thermal Cycle DC Ic

25-m HTS Cable I_c Tests



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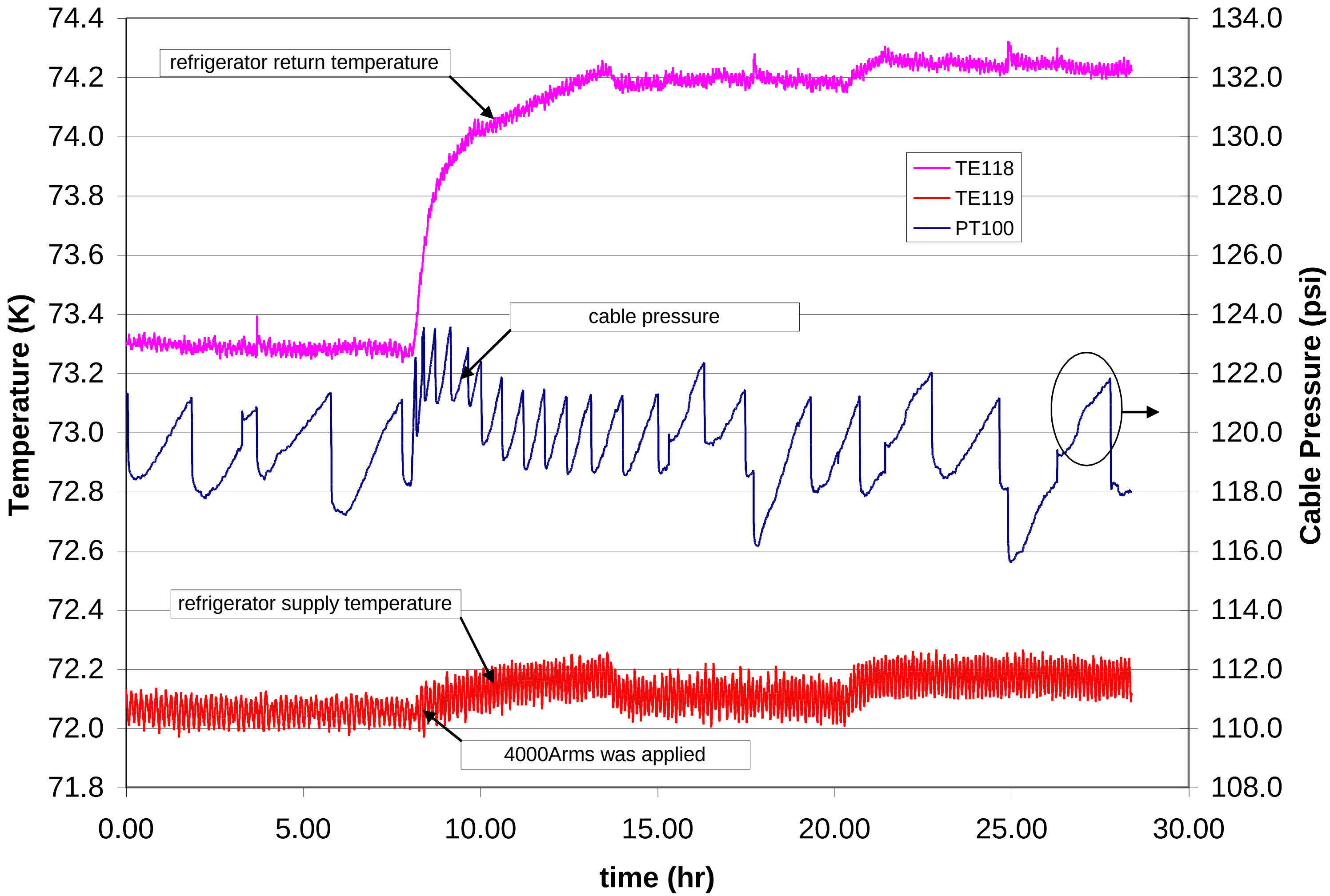
Stability Test



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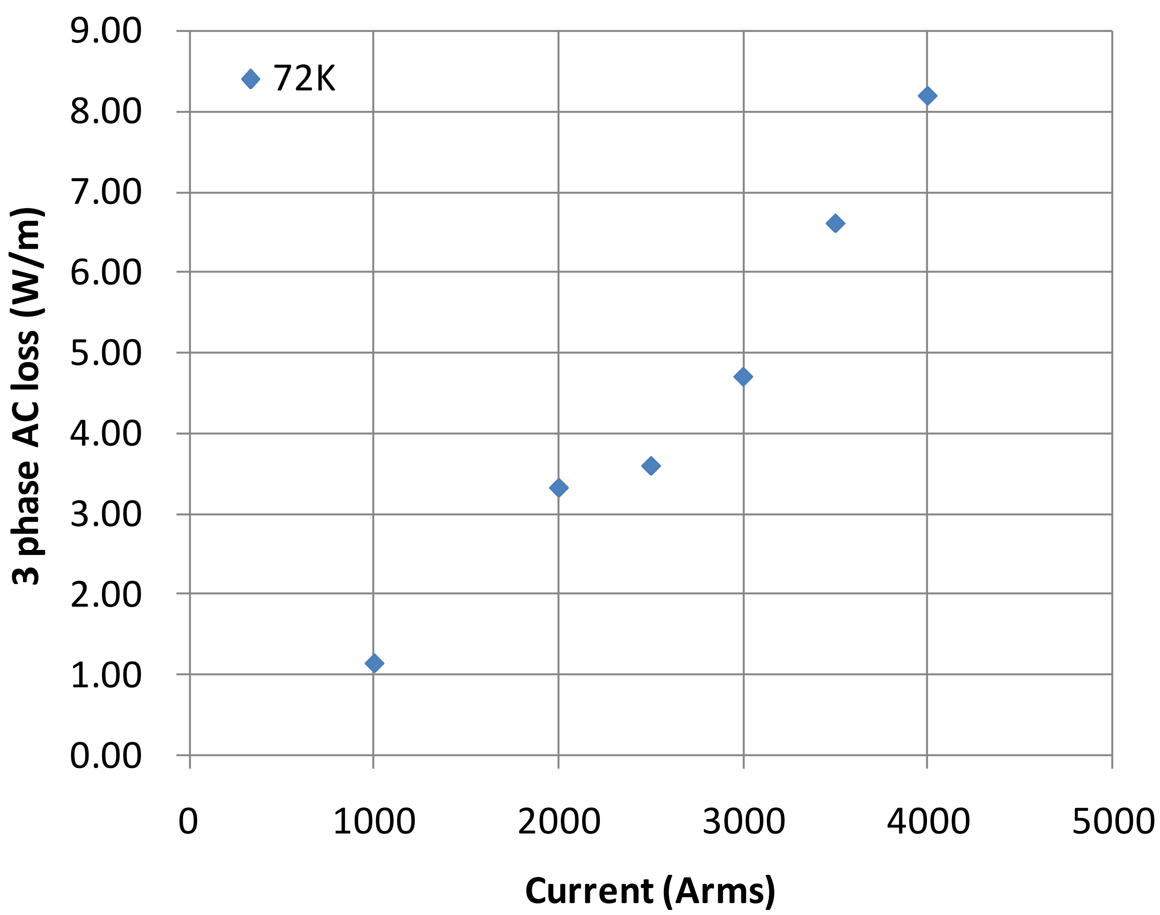
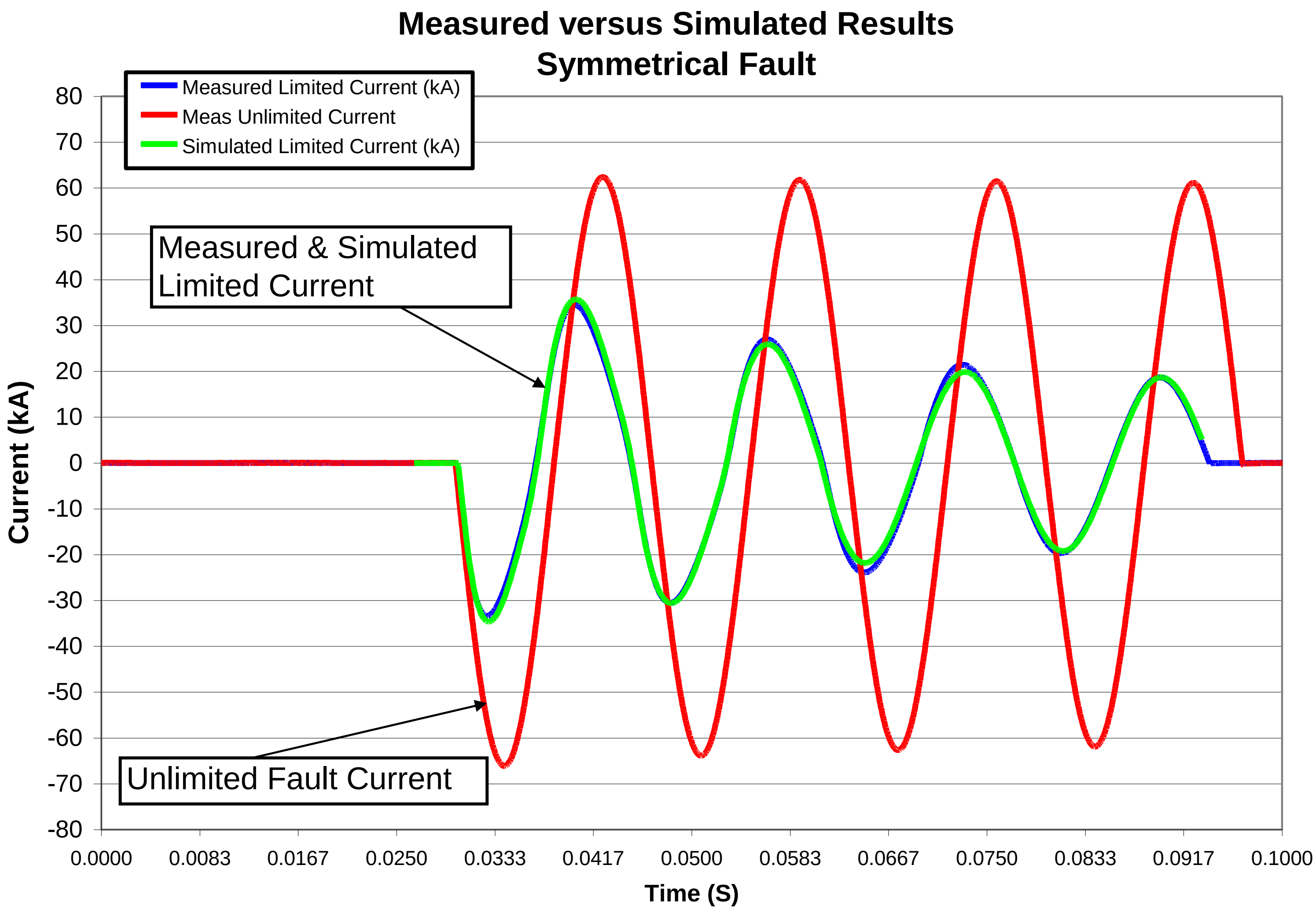
AC Loss



72K
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
3 phase AC loss (W/m)
0
1000
2000
3000
4000
5000
Current (Arms)

FCL Test



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Cable and Termination Dielectric Test

- 25m Cable type tests have been completed to a test requirement that was discussed and agreed to by the Team
  - Three phase voltage soak test 15.2kV, 60 minutes
  - Partial discharge measurement in accordance with Southwire's HTS cable standard
  - AC withstand test – 37 kV, 5 minutes
  - Lightning impulse voltage test – 110 kV ±10 shots
  - Post BIL partial discharge test
  - Post BIL AC withstand 37.5kV, 5 minutes

Cable has passed all type tests listed above

Cryogenic System Requirements

- Cryogenic specification
  - 6.2 kW @ 72 K
  - ~1kW @ 72 K (Additional load for LN_2 pumps and thermal leaks from cooling system)
  - 90L/min LN2 Flow Rate
  - Pressure drop less than 3 bar
- Multiple technological solutions have been investigated
  - Gifford-McMahon Cryocooler
  - Stirling Cryo-generator
  - Reverse Brayton

Refrigerator Requirements

- Refrigeration Cycle chosen is Stirling Cryo-generator
  - Modulated design (3 x 4kW @ 77K)
  - Best return on specific efficiency (We/Wc) vs. capital cost

- Flexibility Requirement:
  - 80% of time at 50% heat load on HTS cable
- Reliability
  - Redundancy accomplished at component level, pumps
  - No 1st order single point of failure allowed
- Capacity Margin
  - Current design has 20% safety margin to the expected losses

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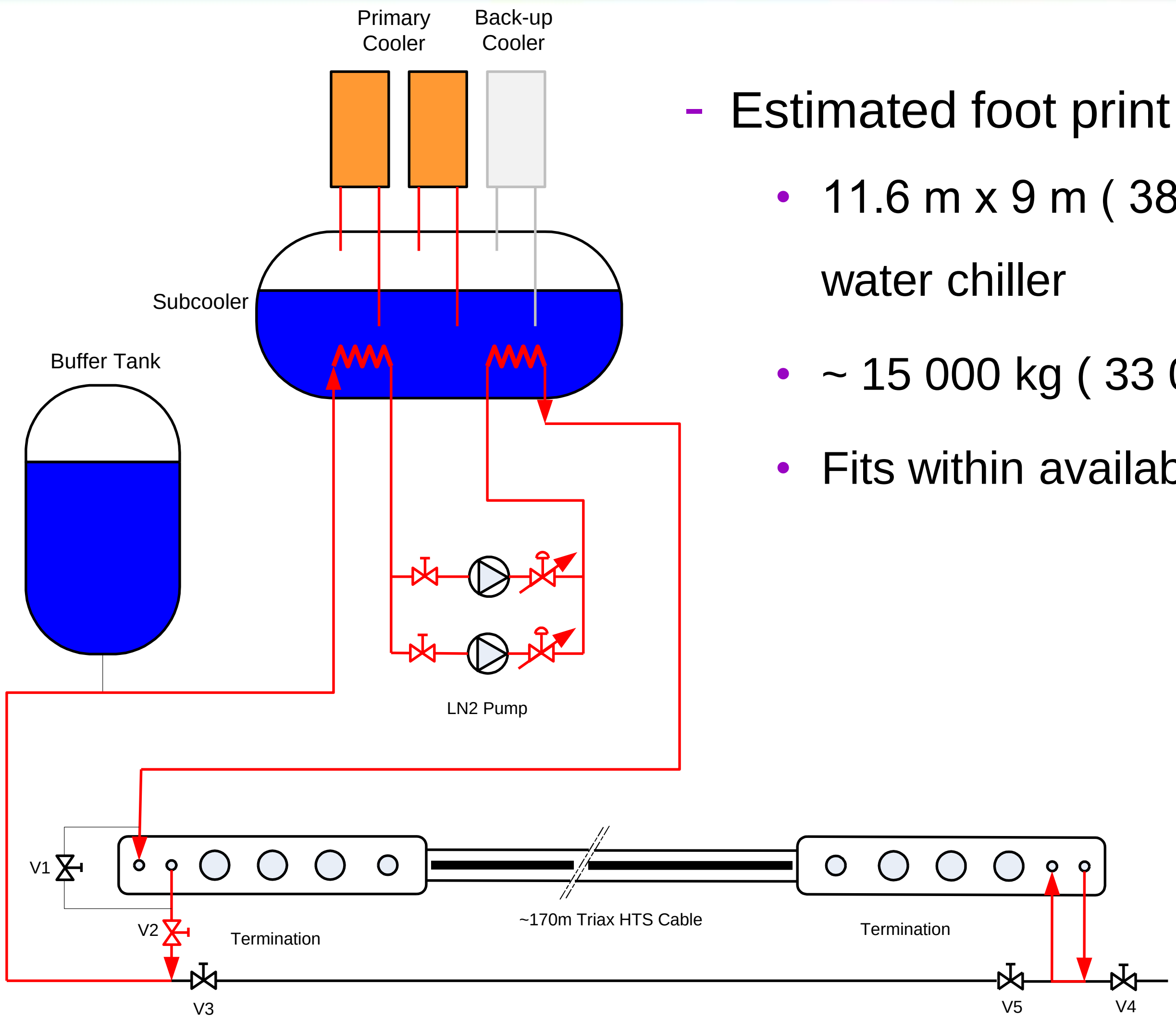
Refrigeration System Diagram



- Estimated foot print size & weight
  - 11.6 m x 9 m (38' x 30') + outdoor water chiller
  - ~ 15 000 kg (33 000 lbs) empty
  - Fits within available space

Accomplishments to Date

The key invention has been demonstrated

- Demonstration of the Fault Current Limiting aspects of 2G wire and the cable design
- Exceptionally good agreement between Fault Current Limiting model predictions and measured performance in 25 meter cable demonstration
- The HTS FCL Cable successfully passed all the qualification tests for installation in the power grid

Conclusions

- American Superconductor and the project team are demonstrating significant progress toward the development of a long length fault current limiting superconducting cable for integration into the Consolidated Edison grid.
- Short cable tests demonstrated the current limiting capability
- 25m cable and termination type tests have been successfully completed.
- Cable manufacturing process has been approved
- A 170m long HTS cable with fault current limiting functionality is planned to connect two of Con Edison’s substations in late 2014.

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