



High Voltage Design for a 138 kV Superconducting Fault Current Limiter

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HTS Solutions for a New Dimension in Power
IEEE – CEIDP 2005 Workshop on Cryogenic Dielectrics



High Voltage Design for a 138 kV Superconducting Fault Current Limiter

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HTS Solutions for a New Dimension in Power

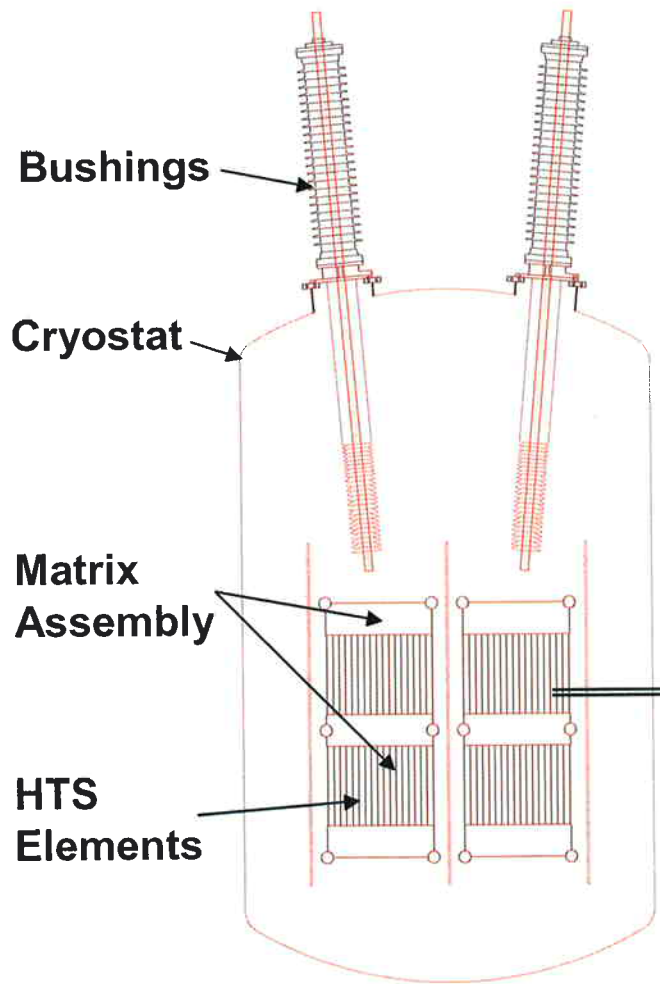
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High Voltage Development - Objectives

Objectives

1. **Build confidence in designing a 138 kV, 650 kV BIL transmission line Fault Current Limiter per AEP requirements**
 - Improve understanding of the dielectric performance of Insulation materials in a cryogenics environment
 - Published information is scarce at transmission line voltage levels
 - Develop experimental test setups and test to voltages higher than device ratings
 - Develop Finite Element Analysis Simulation tools to computed Electric Field Distribution
 - Develop Transfer Function between FEA and test results
 - Develop design tools based on the experimentally verified transfer functions
2. **Identify and Study the Main Insulation Areas**
 - Bushings/Leads
 - Matrix Assembly – Internal Insulation and Impulse Voltage Distribution
 - Bushings/Leads and Matrix Assembly to Cryostat – External Insulation
3. **Design a 138 kV, 650 kV BIL transmission line Fault Current Limiter**

MFCL Design - Main Components



Single Phase of Alpha

High Voltage Insulation System

1. Bushings
2. Cryostat insulation system
3. Matrix internal insulation

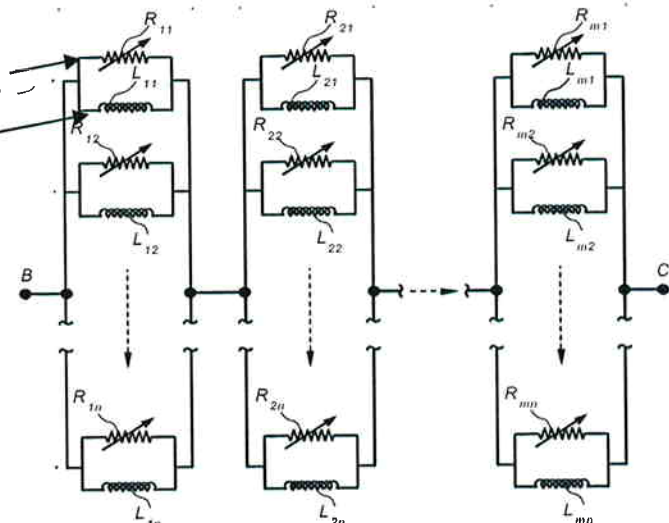
Matrix Assembly

1. HTS Elements
2. Connections of HTS elements and current limiting coils

Cryostat System

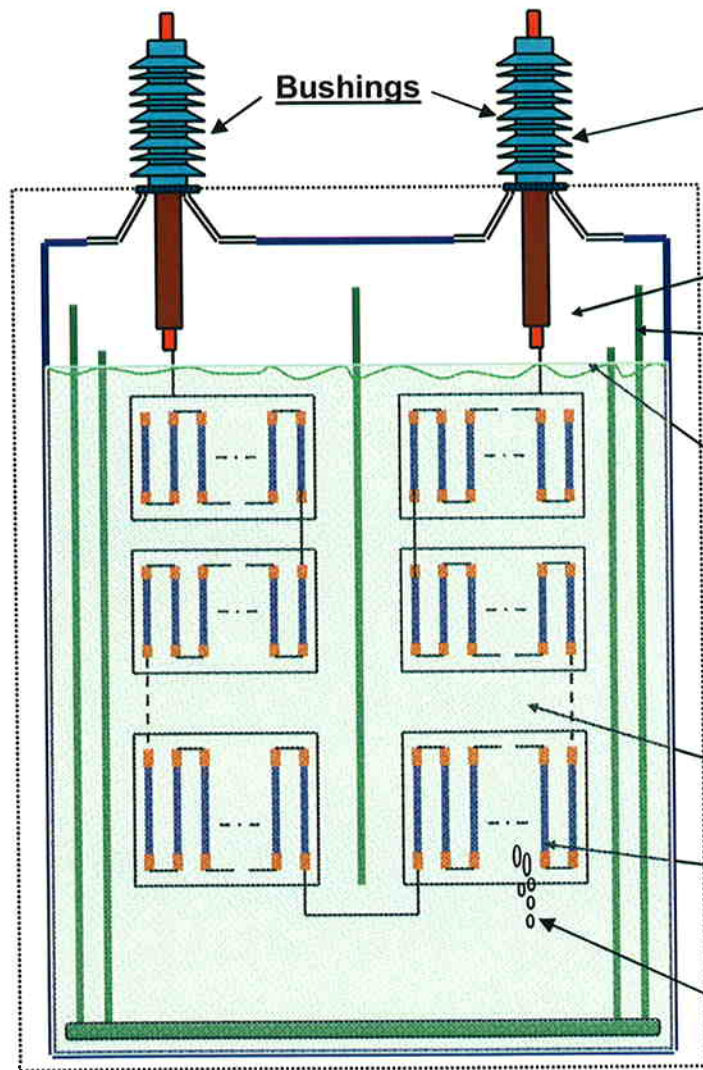
1. Vessels to provide stable pressurized sub-cooled environment
2. Cryogenics and cryo-coolers

HTS Element
Shunt Impedance



Simplified Matrix Assembly Schematic

High Voltage Development – Main Dielectrics



Main Dielectrics

1. Bushings

- Custom bushing using modified conventional bushings
- Special bushing based on HTS Cable terminations

2. Gas Nitrogen (GN2)

- Gas breakdown mechanisms

3. Gas/Solid Composite

- Partial breakdown of gas dielectric
- Puncture strength of solid insulation and
- Surface Flashover

4. Gas/Solid/Liquid (GN2/Solid/LN2) Composite

- Partial breakdown of GN2 and LN2
- Field enhancement and Partitioning
- Puncture strength of solid insulation and
- Surface Flashover

5. Liquid Nitrogen (LN2)

- LN2 breakdown strength

6. Liquid/Solid Composite

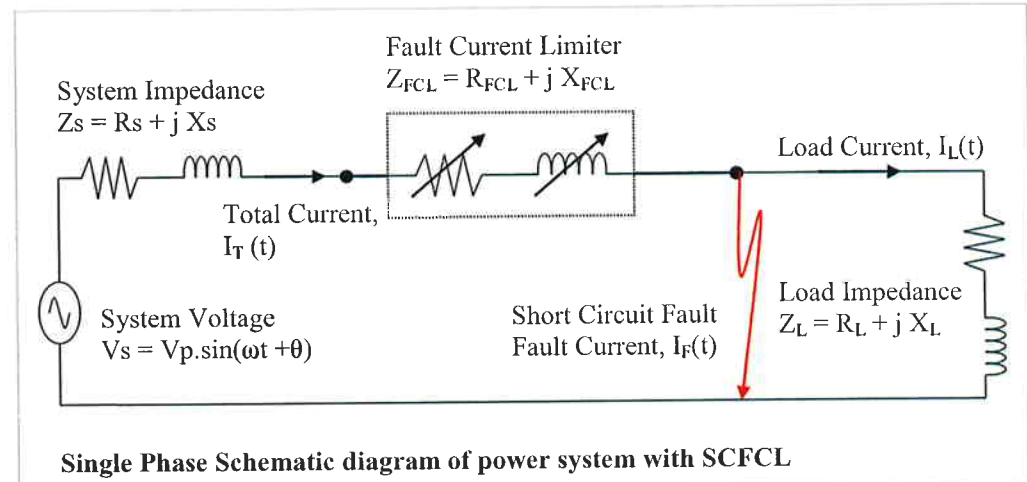
- LN2 partial breakdown and Partial Discharge (PD)
- Solid insulation puncture and Surface flashover

7. Bubble effects

Matrix Fault Current Limiter (MFCL) – An Alternative

New concept with no conventional counterpart:

- Passive - no active controls needed
- No Burden on system during normal operation
- Modular and Scalable
- Environmental benefit

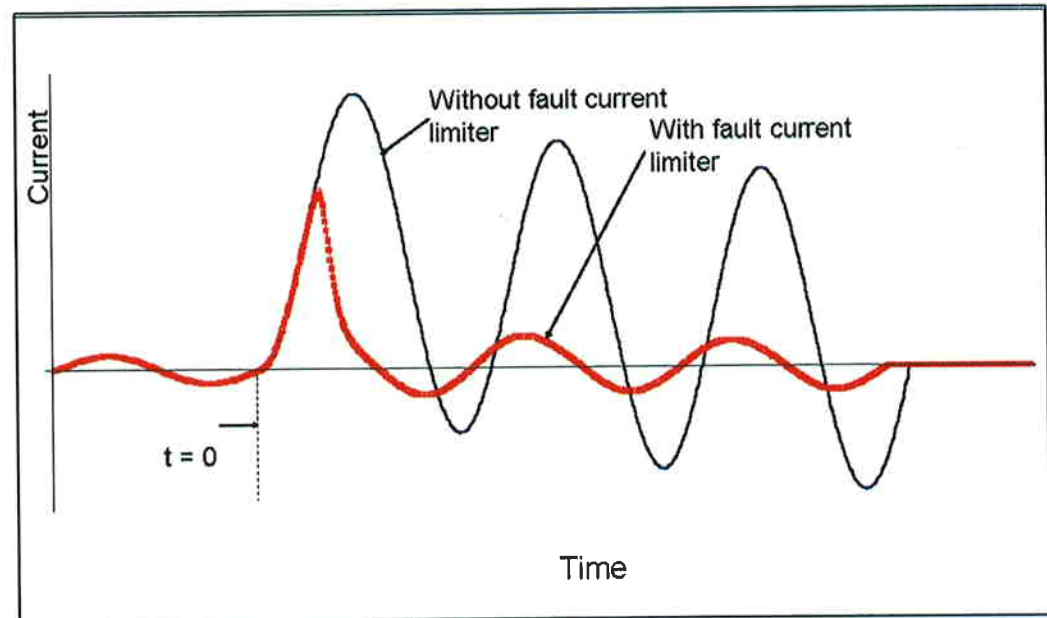


Operating conditions – HV design considerations

- Under normal operating condition
- Under short circuit fault conditions

HV Test Conditions

- AC withstand tests
- PD measurement
- Impulse Tests



Matrix Fault Current Limiter (MFCL) – Operating Conditions

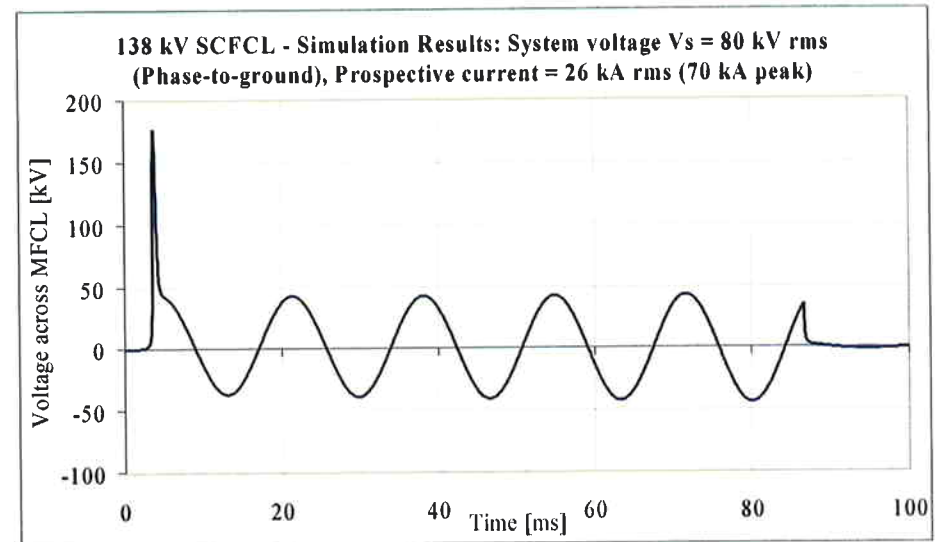
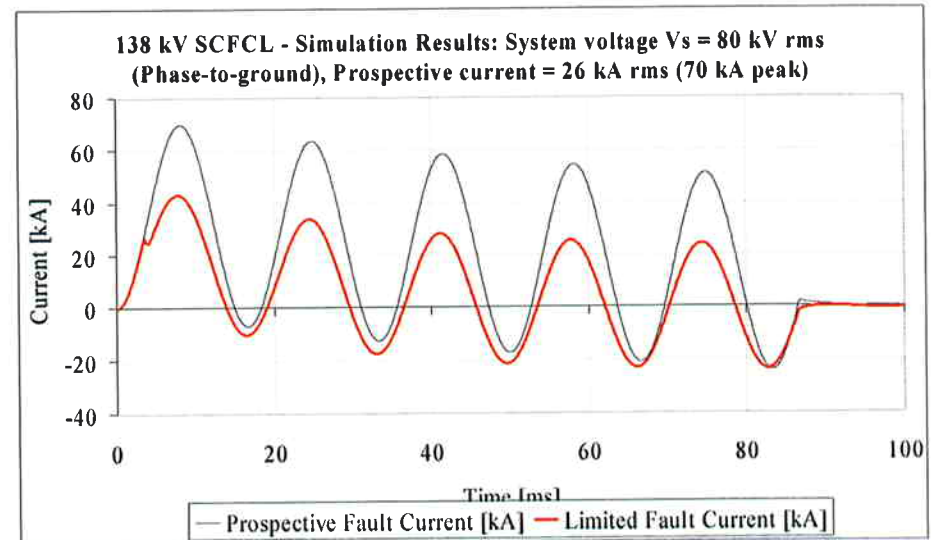
Operating conditions – HV design considerations

Under normal operating condition

- MFCL is invisible to the system
- It has very low impedance
- Negligible voltage drop and minimal steady state losses
- HV design – Bushings and assembly to cryostat insulation

Under short circuit fault conditions

- Critical current exceeded and the superconductor transitions to a resistive state
- Introduces current limiting impedance
- Generates voltage drop (steady state and transient overvoltages) across MFCL
- HV Design Issues
 - Bushings
 - Assembly to cryostat and
 - Internal MFCL assembly insulation

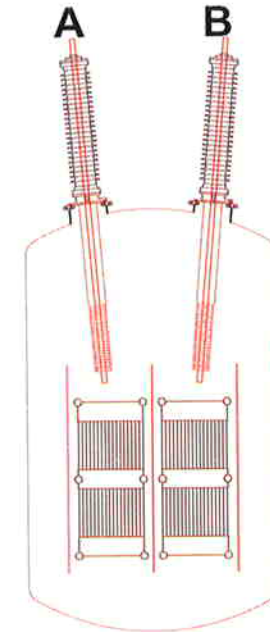


High Voltage Test Requirements

Tests based on typical 138kV requirements for Breakers, Transformers and Current Limiting Reactors

Based on input from AEP and NEETRAC Members

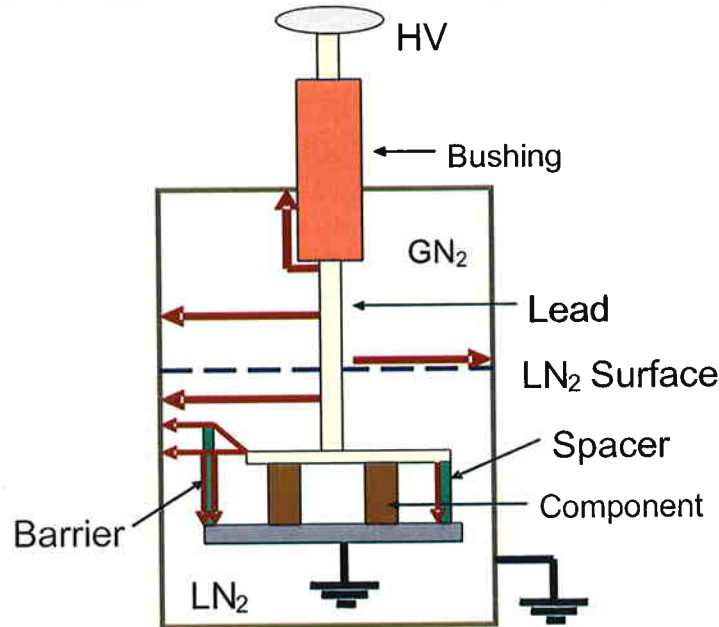
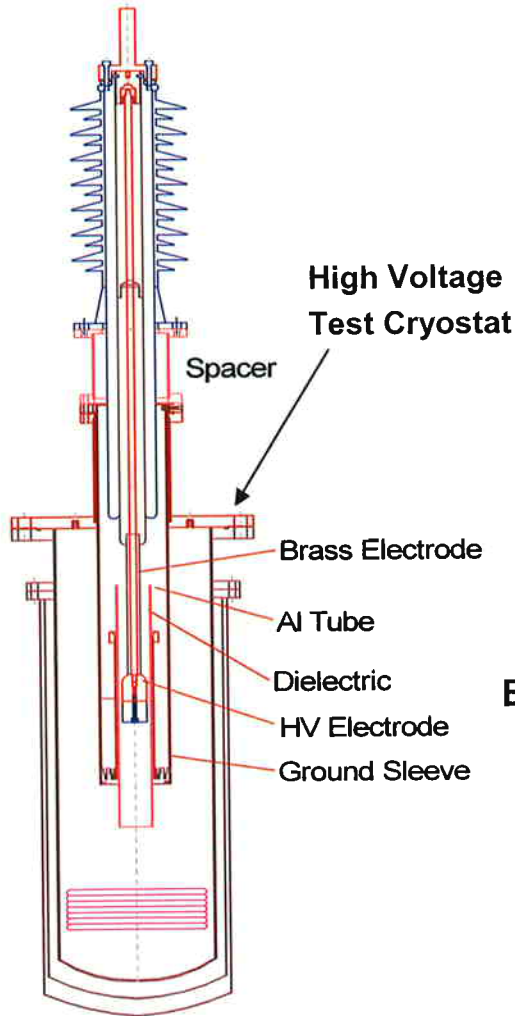
Tests to be Conducted	Proposed MFCL Requirement
60Hz Withstand	Based on ANSI Breaker C37.06 Table 4
Partial Discharge	Based on ANSI Transformer C57.12.00 Table 6
BIL Lightning Impulse	Based on ANSI Reactor C57.16 Table 5
Chopped Wave	Based on ANSI Transformer C57.12.00 Table 6
Switching Impulse	Based on ANSI Transformer C57.12.00 Table 6



Configurations for impulse testing:

- Impulse terminal A wrt to ground, with B open
- Impulse terminal B wrt to ground with A open
- Tie A & B together and impulse wrt to ground

High Voltage Development – Test Configurations



HV Test rig to test the dielectric strength of GN₂, LN₂, Flashover and solid insulation (G10) puncture under various electrode configurations, bubble activities, pressure & temperature

Bushing designs

- Conventional bushings tested for cryogenic applications
- Focus on insulation integrity - must not crack when exposed to cold gas or immersed in LN₂
- Two bushings a 38 kV AC (200 kV BIL) and 52 kV AC (250 kV BIL) from two different manufacturers were tested
- PD tests done before and after cooling and immersing – Meets IEEE standards on PD
- Similar type bushings considered for scaling up to 138 kV class

High Voltage Development – Predictive Design Tools

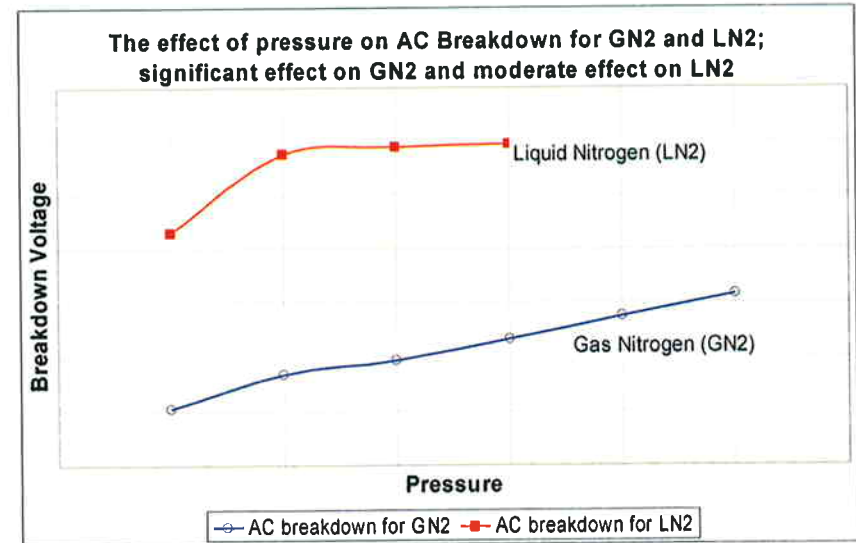
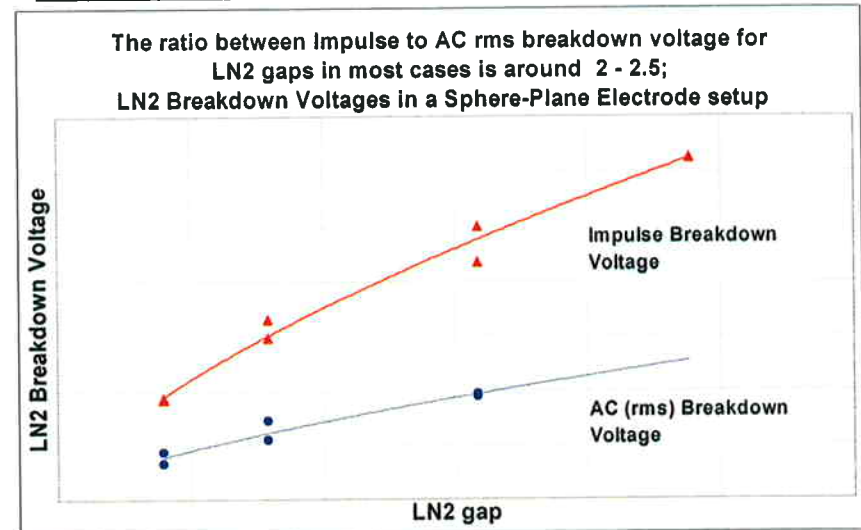
Transfer Function – Predictive Design Tool

- ◆ Based on Experimental and Computed (FEA) results
- ◆ Experimental test rigs were tested up to 200 kV AC rms and 900 kV Impulse
- ◆ Defined the mean Breakdown Voltage (V_{BD}) or Mean Breakdown Field (E_{BD})
- ◆ Main Parameters considered for the transfer function are;
 - g = Dielectric gap
 - η = Utilization factor = E_{av}/E_{max}
 - v = Volume of LN2 under stress
 - P = Pressure, T = Temperature and Bubble effects
- ◆ V_{BD} or $E_{BD} = f(g, \eta, v, P, T, \text{Bubble effects})$
- ◆ Well defined experimentally verified design tools are emerging

Why do we need to do basic research?

- ◆ Information is scarce at higher voltages and larger gaps
- ◆ Usually limited to distribution voltage levels
- ◆ Extending the range to transmission voltage levels
- ◆ Voltages higher than 200 kV AC rms and 650 kV BIL

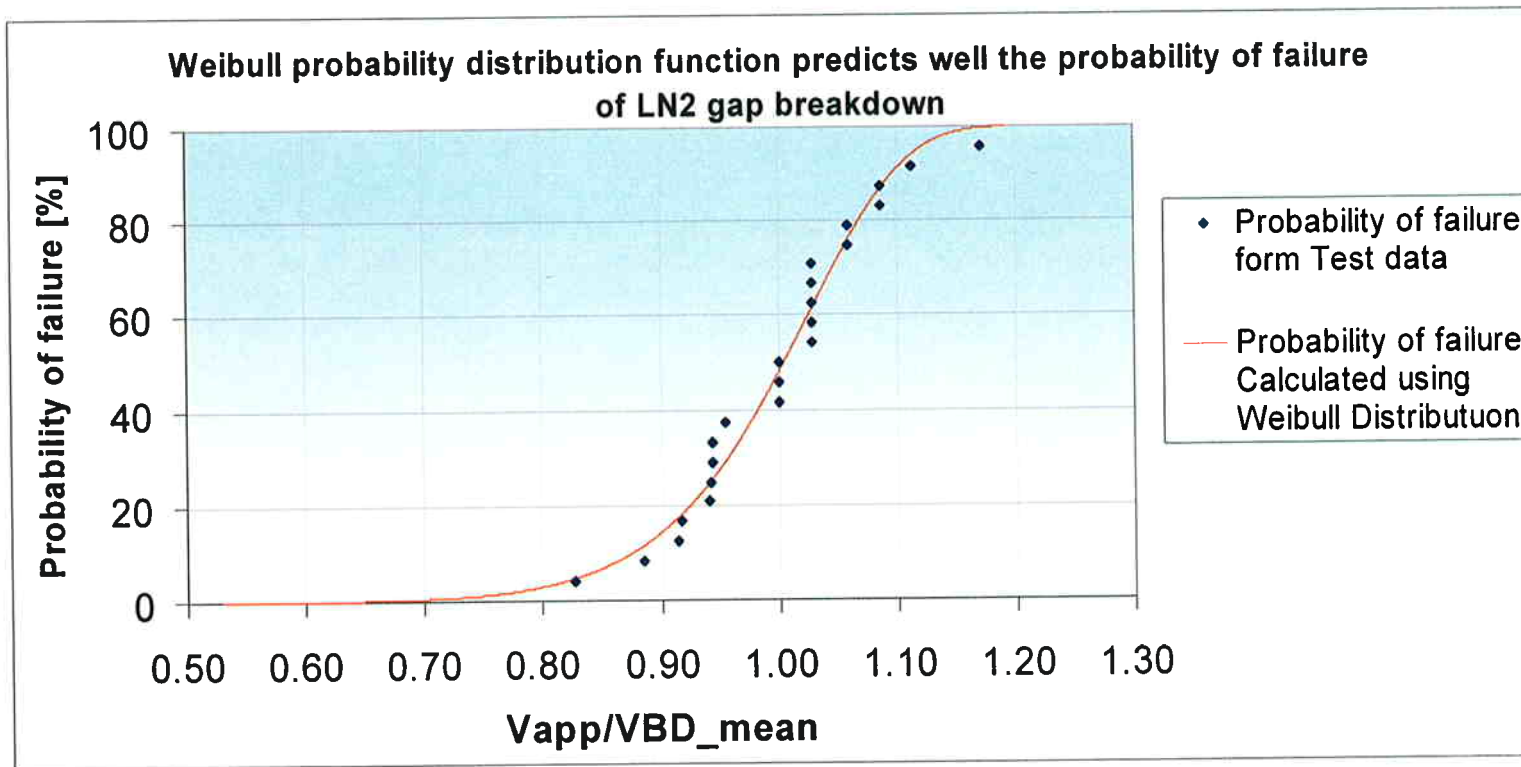
Plots of HV test results used to develop design tools



High Voltage Development – Predictive Design Tools

Probability of Failure – Predictive Tool

- ◆ Experimental data and Weibull probability distribution with two parameters, α and β , used
- ◆ Predicts the probability of the dielectric failure at a given applied voltage or Field



$$P(f) = 1 - e^{-(V / \beta)^\alpha}$$

α and β are the two Weibull parameters

High Voltage Development – Bushing Design

Bushing designs

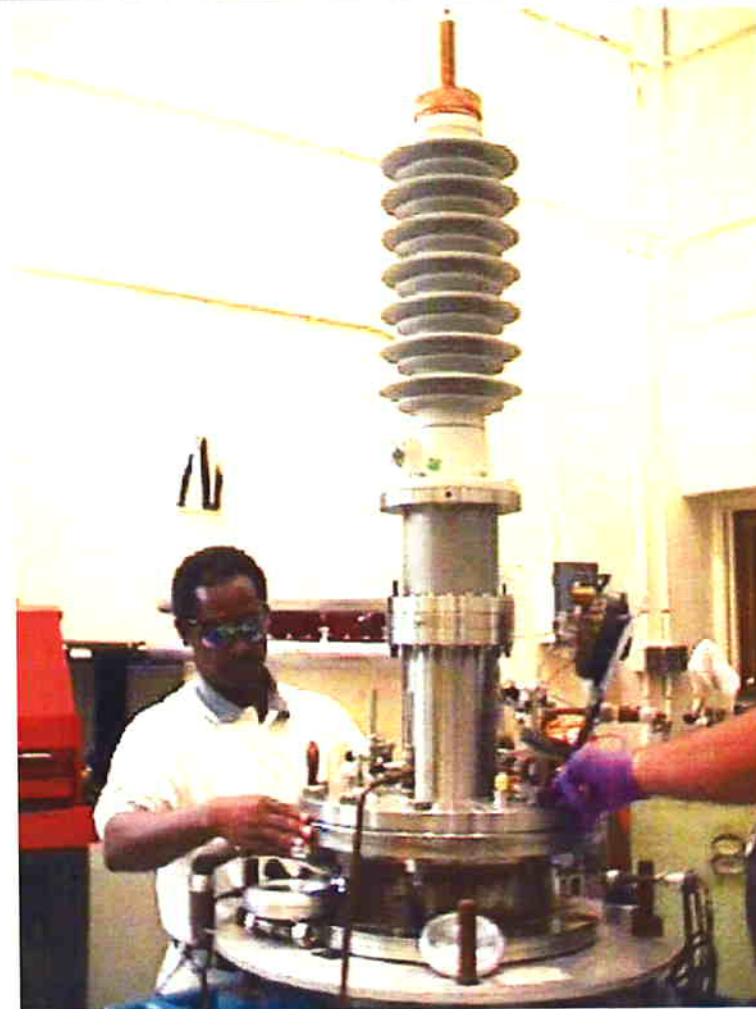
- Conventional bushings tested for cryogenic applications
- Insulation must not crack when cold
- Will be exposed to cold N₂ gas or immersed in LN₂

Two commercial bushings tested

- 38 kV AC (200 kV BIL) and 52 kV AC (250 kV BIL)
- Two different manufacturers
- PD tests done before and after cooling and immersing
- Good results on PD
- Similar type bushings considered for scaling up to 138 kV class

Future Approach – two alternatives

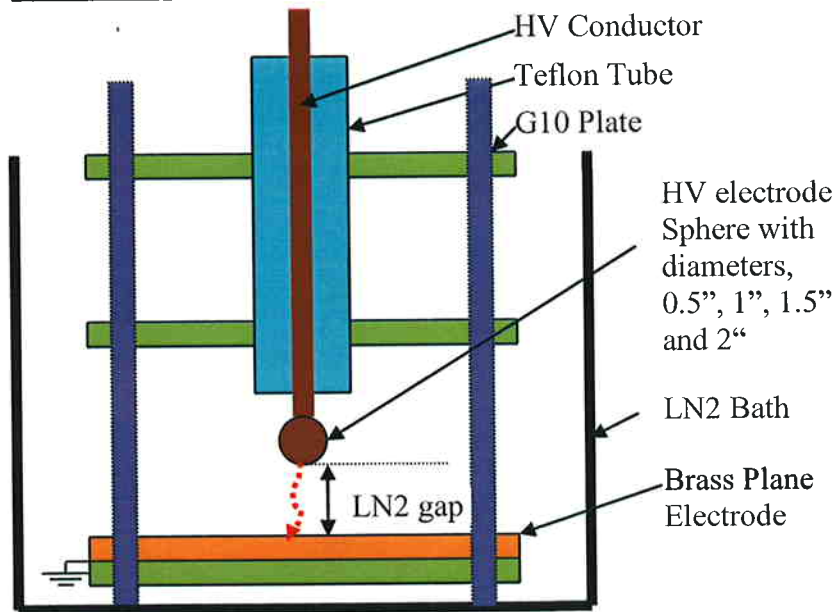
1. Custom bushing using modified conventional bushings
2. Special bushing based on HTS Cable terminations



Kasegn Tekletsadik of SuperPower and Alvin Ellis of ORNL install bushing for test

High Voltage Development – Test results for LN2 gap dielectric strength

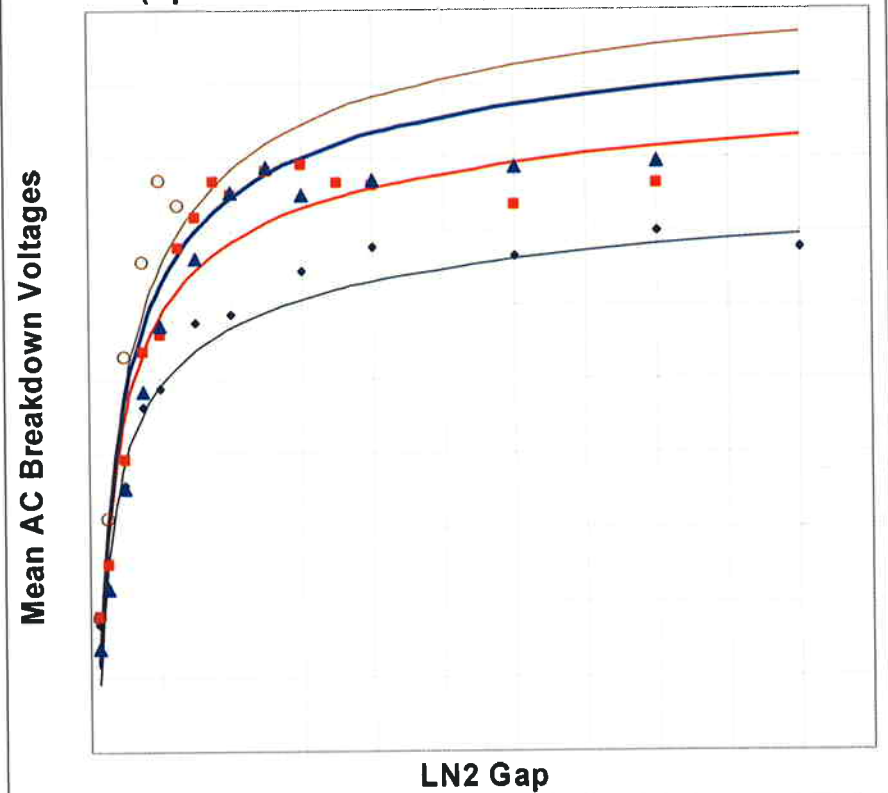
Sphere - Plane Electrode HV Test Setup



LN2 gap breakdown Characteristics

- Dielectric strength of large LN2 gaps becomes flat as the gap length increases
- Rely on reducing/minimizing the electric field
- Field Inhomogeneity effect is critical to the dielectric strength of LN2
- *Calculated $V_{BD} = f(g, \eta, v, P, T, \text{Bubble effects})$ fits well with the experimental test data*

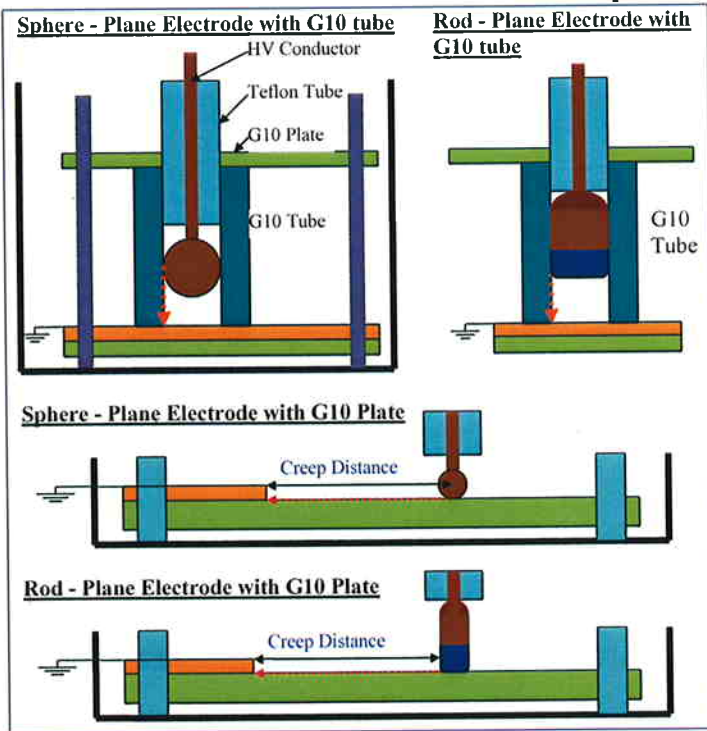
A single transfer function fits all electrode geometric and LN2 gap variations - Experimentally verified design tool emerging. LN2 gap with Sphere-Plane electrodes (Sphere diameters 0.5", 1", 1.5" and 2.0")



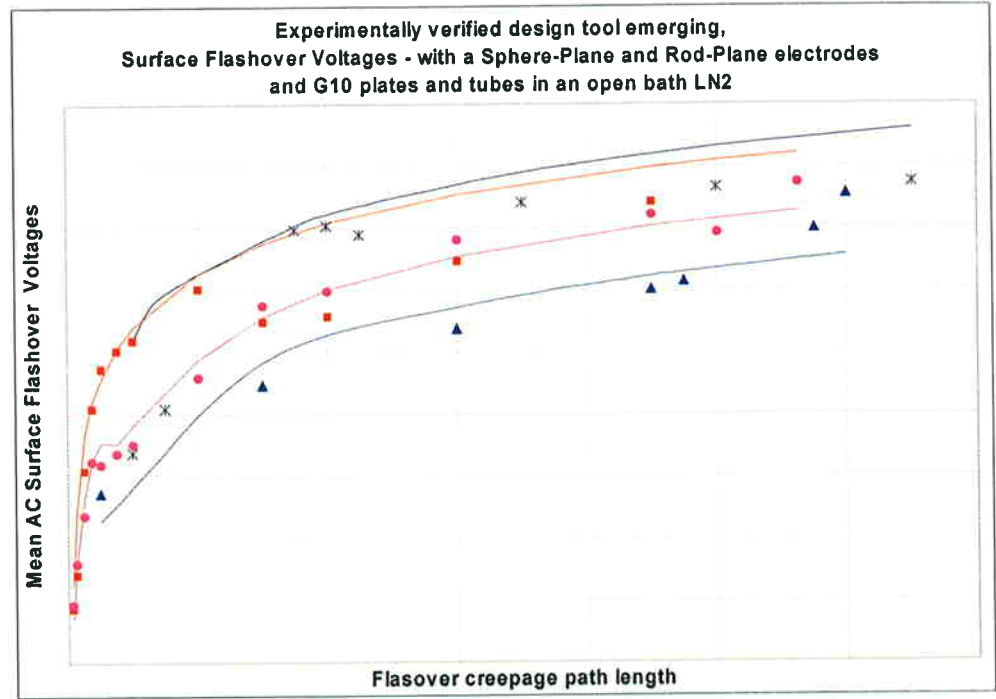
General Conclusion: Increasing gap may not buy you much in breakdown voltage!
Rely on reducing/minimizing electric field

Trends Emerging – Reduce E Field Rather Than Increasing Gap

Surface Flashover Test Setup



Typical Surface Flashover marks

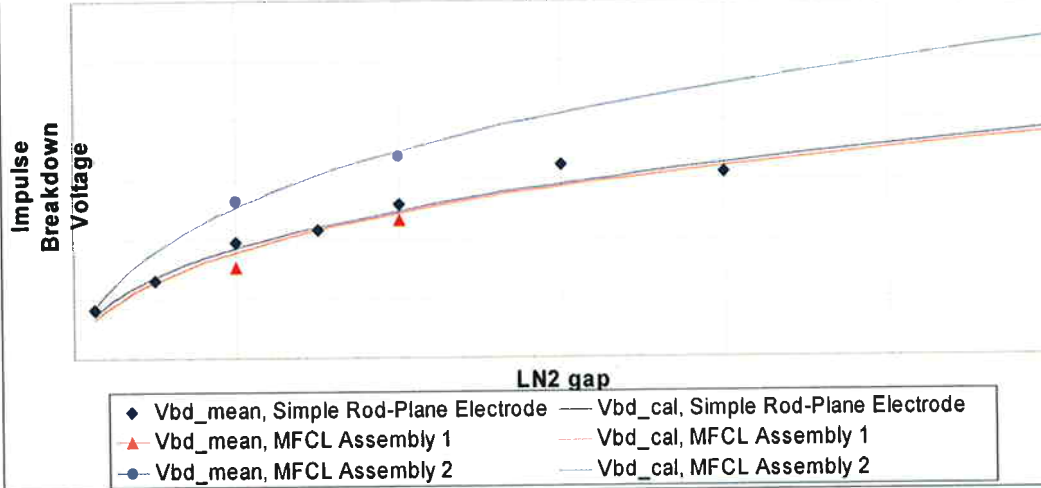


Flashover in LN2/G10 gaps

- Studied the effects of electrode/insulator interface on surface flashover
- Developed transfer functions between flashover voltages and electric field and electrode/insulator geometries
- *Surface Flashover Voltages, $V_{FO} = f(g, \eta, v, P, T, \text{Bubble effects})$* fit well with derived transfer functions
- Increasing gap may not buy you much in breakdown voltage! Rely on reducing/minimizing electric field

HV development – Design Tools development and Verification

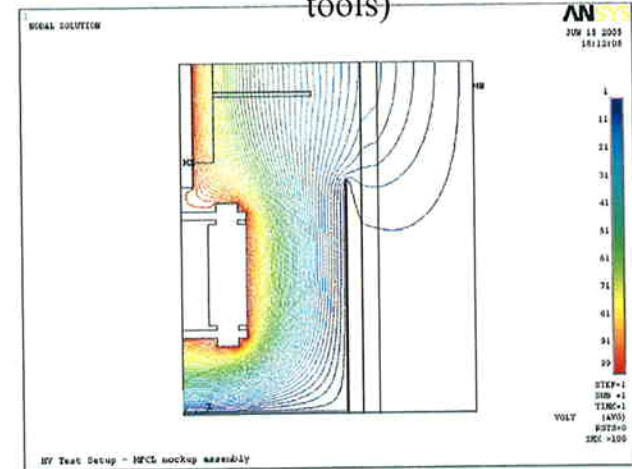
Simplified electrode test setups, such as Rod-Plane electrodes, give very useful test data to predict the performance of larger MFCL assemblies; LN2 gap Impulse Breakdown Voltages



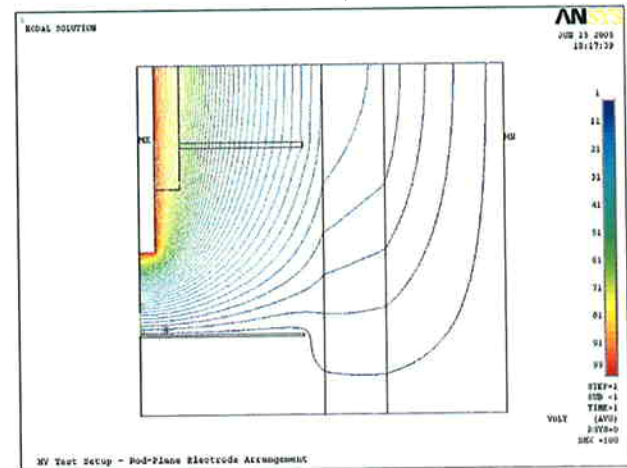
Impulse Test Results – Verification of Design Tools

- Tested 3 electrode configurations with Negative and Positive Impulse – Polarity effect was significant at larger gaps and higher pressure
- MFCL assembly 1 is using a simple Rod-Plane electrode geometry, simplified geometries give useful test data to generate transfer functions
- MFCL assembly 2 is a MFCL mockup assembly
- MFCL assembly 3 uses an optimized MFCL assembly design
- Developed predictive design tools based on transfer functions between test and FEA results, $VBD = f(g, \eta, v, P, T, \text{Bubble effects})$
- Finalized design tools follow after verification tests

MFCL mockup – FEA is critical for generating transfer function (HV design tools)



Rod-Plane Electrode – FEA for generating transfer function (HV design tool)



HV Development – Impacts of Findings on MFCL design Concept

HV Design

- ◆ HV design targets to reduce/minimize the electric field, and less reliance on increasing gaps
 - Minimize the impacts of bubbles
 - Minimize local high field enhancement regions and interfaces
 - Minimize the effect of field induced corona discharges and bubble formation
- ◆ HV design includes partition of LN2 gap by solid insulation
- ◆ Currently consider a 0.01 % (1 in 10,000) probability of failure, design to around 50% of mean breakdown voltage
- ◆ Design optimization to reduce gaps and insulation clearances is a follow up consideration
- ◆ Predictive design tools developed so far and the HV development method used show encouraging results

HV Development – Next steps

Next Steps - Development Plan

- ◆ Finalize the Bushing design;- Custom bushing using modified conventional bushings or Special bushing based on HTS Cable terminations Technology
- ◆ Further tests at higher voltages on basic geometries and MFCL mockups to fill up a matrix of various parameters and develop design tools
- ◆ Verify design tools with a practical and larger MFCL module assemblies to at least 200 kV AC and 900 kV Impulse (Negative, Positive, Chopped wave and Switching Impulses)
- ◆ Investigate the Partial Discharge activities and characterize the relationship between PD initiation and breakdown voltages – use PD values as dielectric condition monitoring tool
- ◆ Impulse Voltage Distribution - Quantify the impulse voltage distribution for MFCL assembly, using transient simulation testing and calculation of circuit parameters (Resistance, Inductance and Capacitance) for the MFCL assembly
- ◆ Finalize MFCL HV design – specify clearances within the MFCL assembly, assembly to cryostat, bushings to cryostat and specify the solid insulation structure
- ◆ HV Test Standards – Refine and develop HV test standard for superconducting fault current limiters