



## **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*

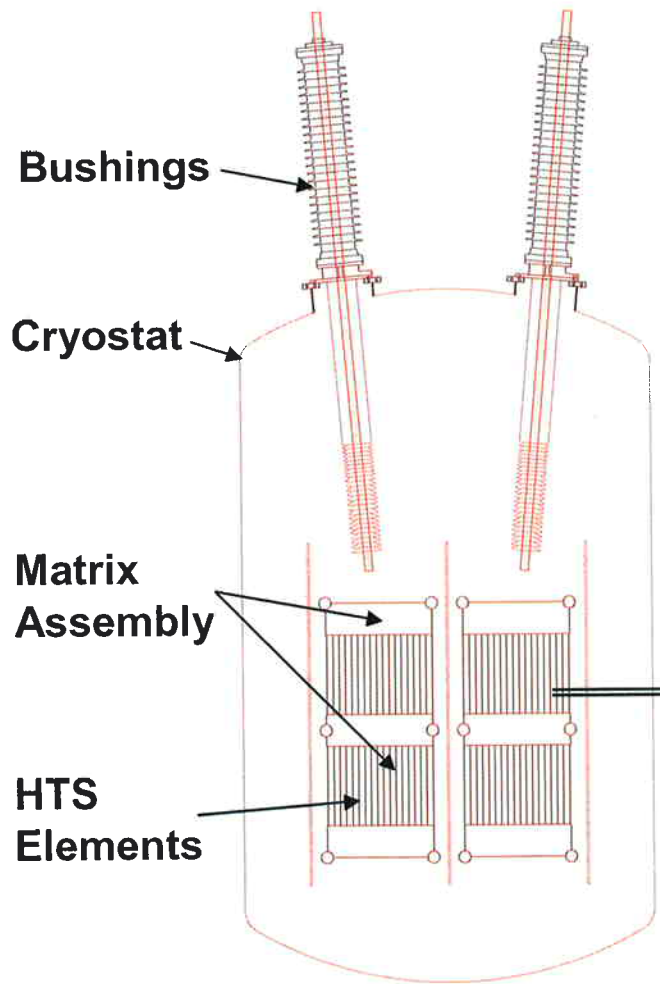
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## High Voltage Development - Objectives

### 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

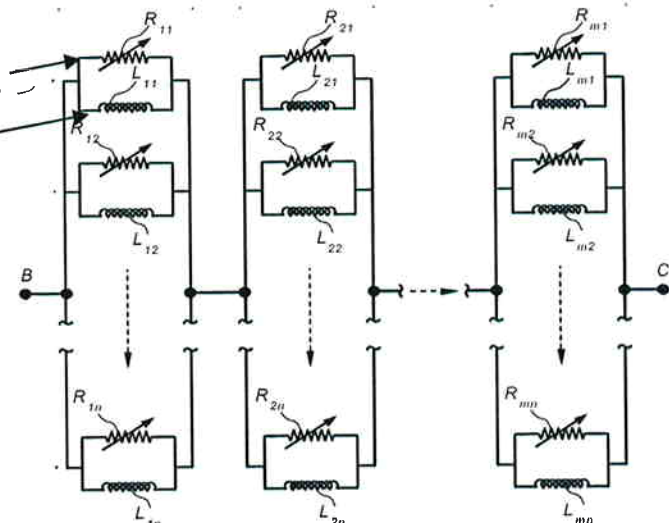
## Matrix Assembly

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

## Cryostat System

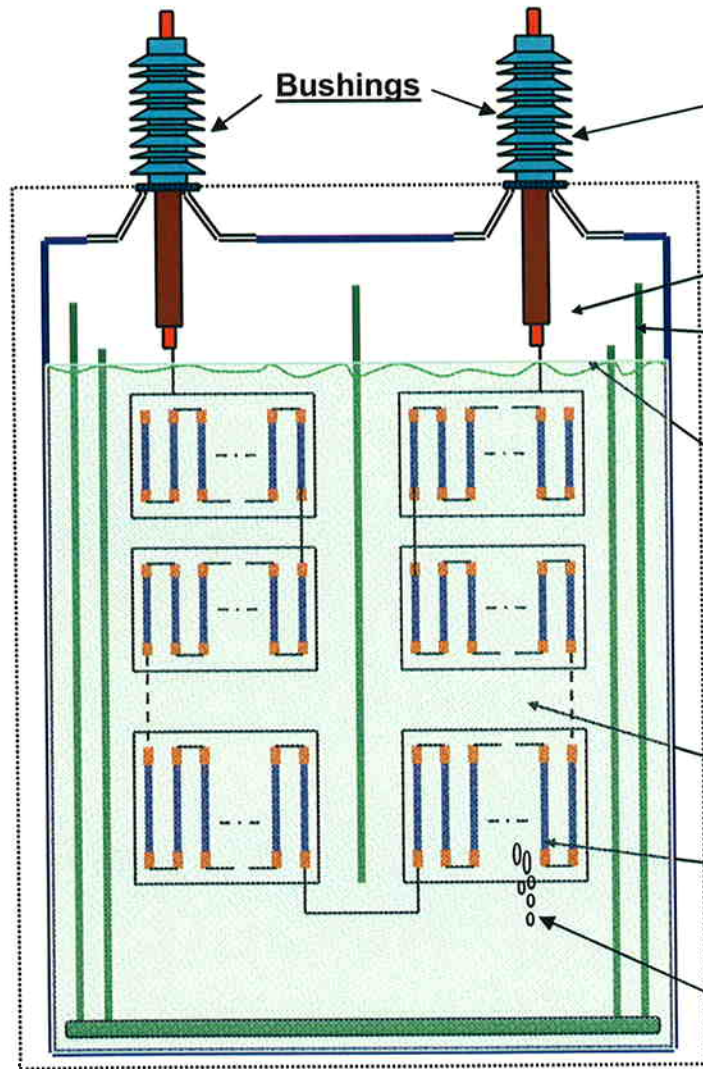
1. Vessels to provide stable pressurized sub-cooled environment
2. Cryogenics and cryo-coolers

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

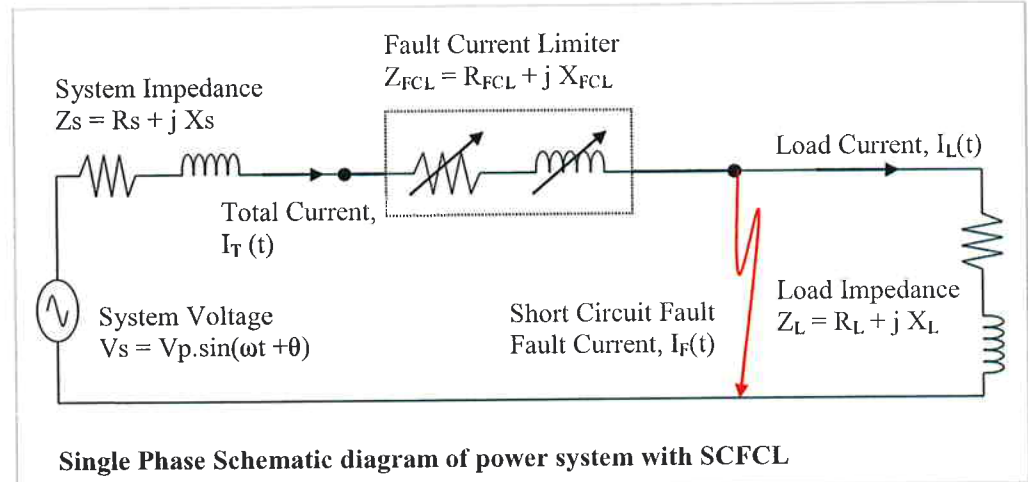
### 7. Bubble effects



# 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

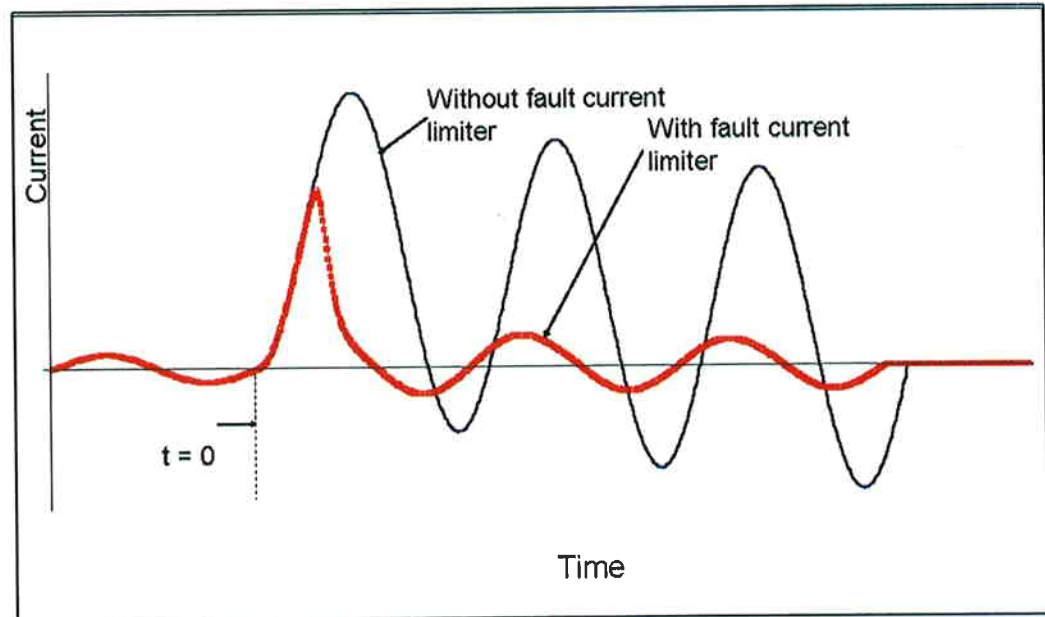


## Operating conditions – HV design considerations

- 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

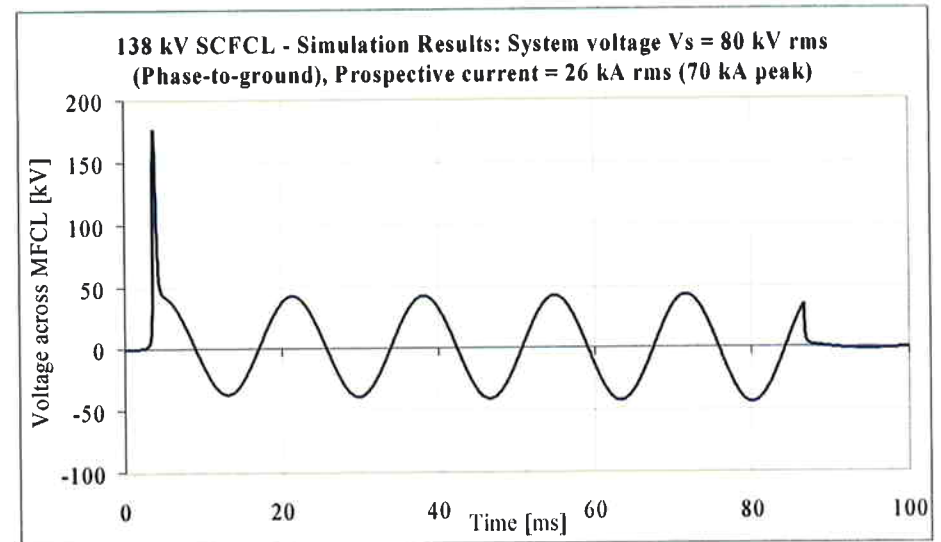
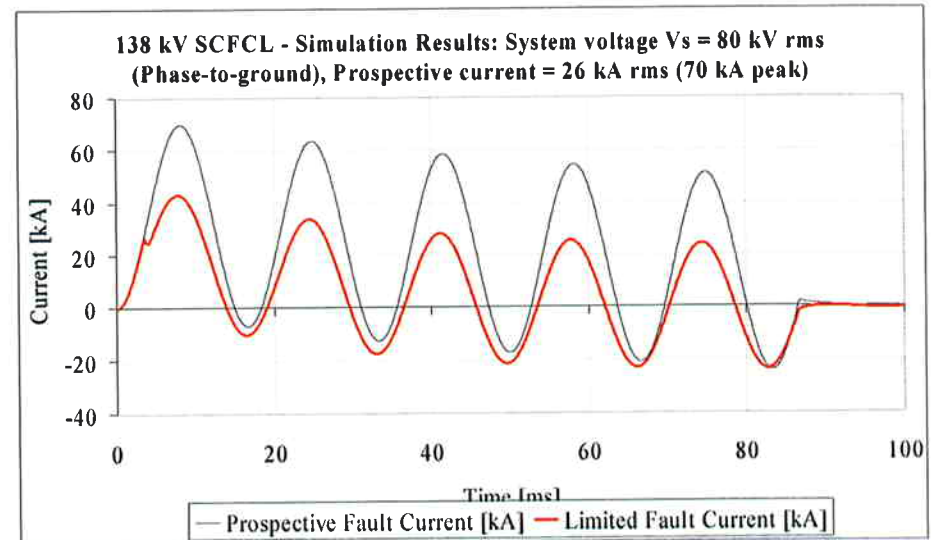
### Operating conditions – HV design considerations

#### 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

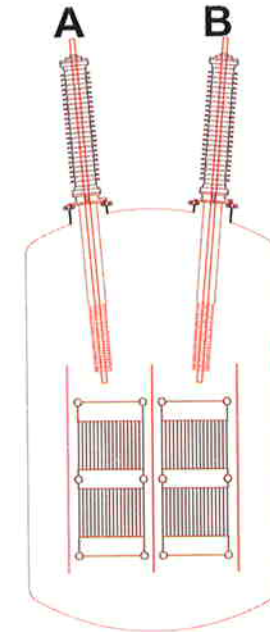


## High Voltage Test Requirements

**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

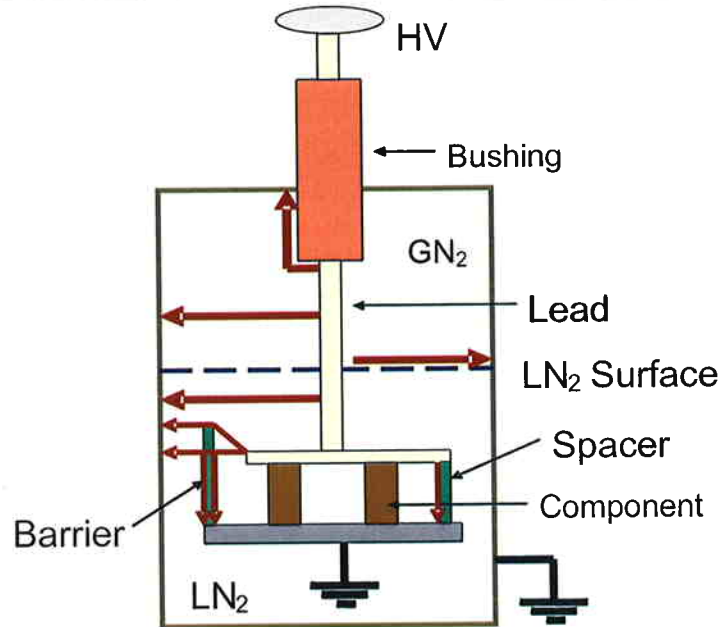
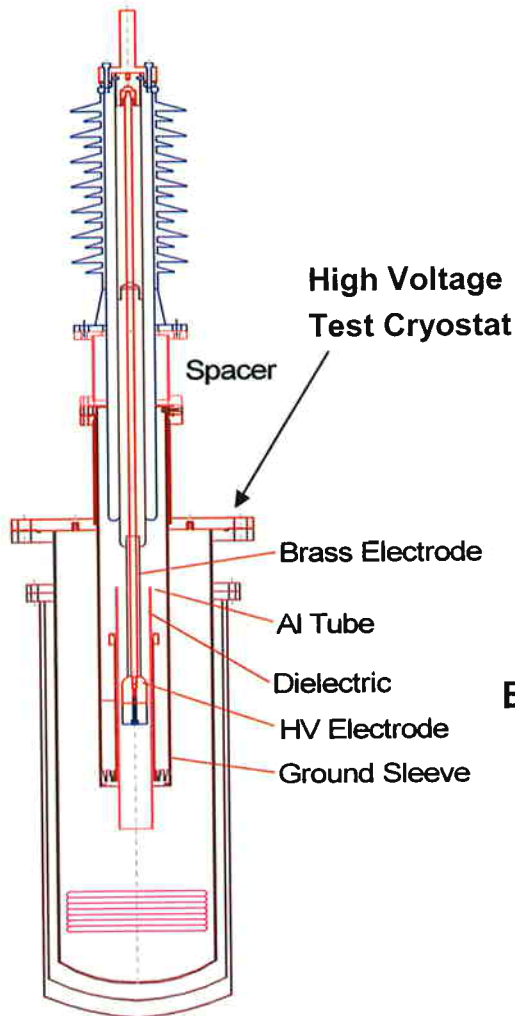


**Configurations for impulse testing:**

- 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 GN<sub>2</sub>, LN<sub>2</sub>, 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 LN<sub>2</sub>
- 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

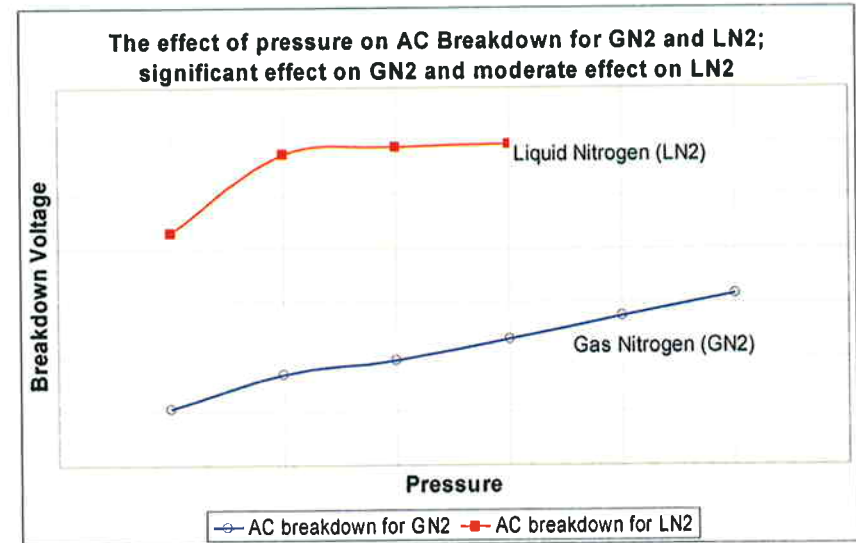
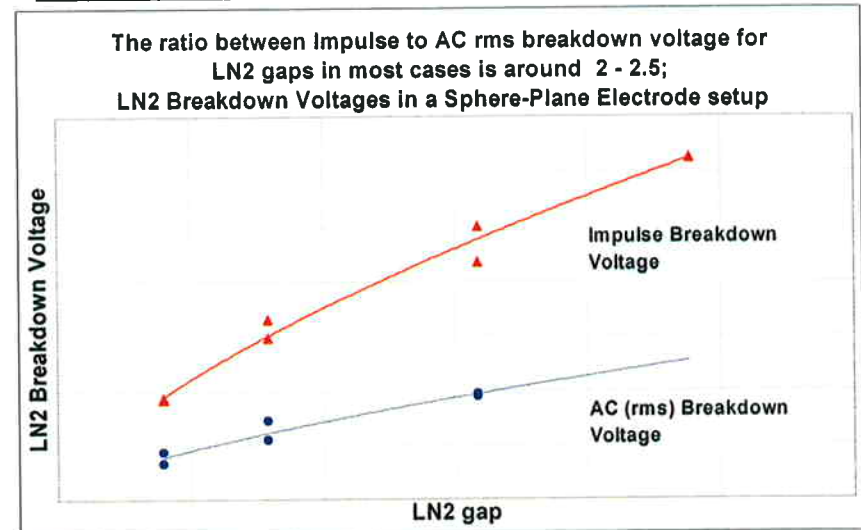
## Transfer Function – Predictive Design Tool

- ◆ 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
  - $\eta$  = 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

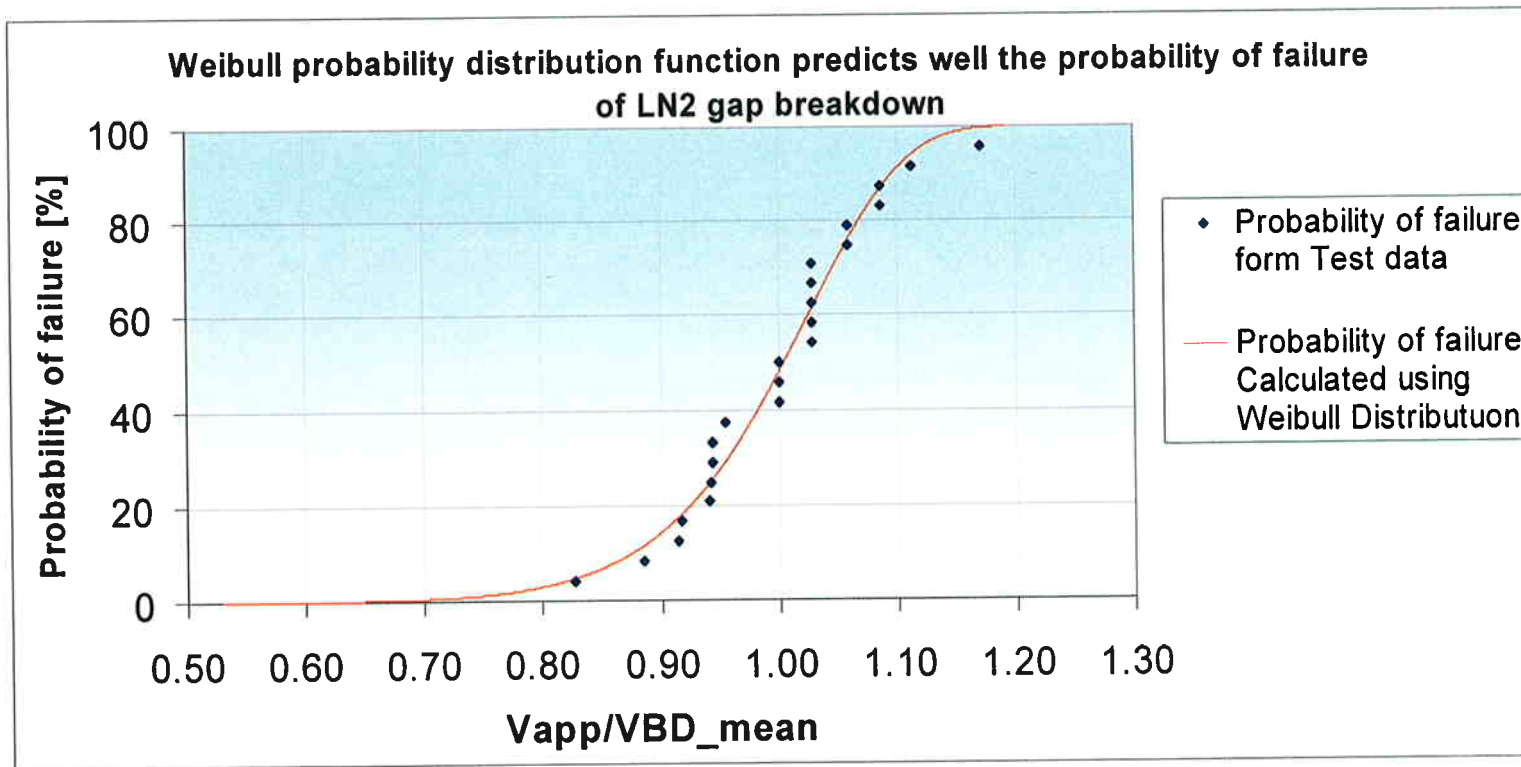
## Plots of HV test results used to develop design tools



# High Voltage Development – Predictive Design Tools

## Probability of Failure – Predictive Tool

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



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

$\alpha$  and  $\beta$  are the two Weibull parameters