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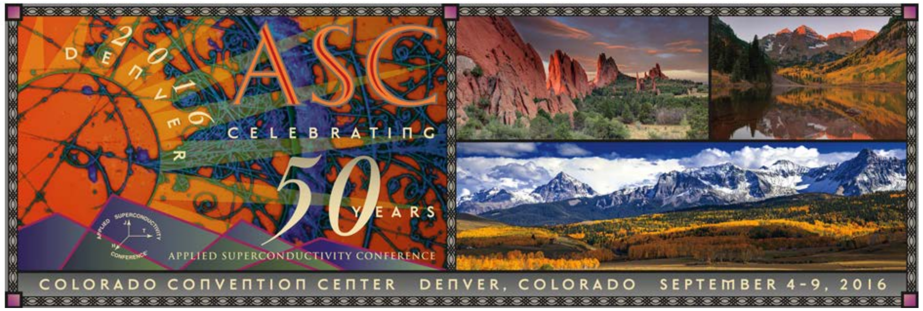
Invited presentation 1MOr3C-01 was given at ASC 2016, Denver, Colorado, USA.



Heat Shrunk Polyethylene Terephthalate as Dielectric Material for HTS Power Cables

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Helium Gas Cooled Superconducting Devices

Benefits

- Wide operating temperature (10 K–80 K)
- Enhanced superconducting properties at lower temperatures
- Lower temperatures allow higher power densities when necessary (Tunability)
- Larger temperature gradients can be maintained without a phase change
- Easier to integrate multiple devices to operate with a single helium loop
- Increased flexibility in power system design optimization with multiple devices

Challenges

- Low heat capacity of helium gas – requires high pressures and flow rates
- Helium gas has low dielectric strength – dielectric designs need solid dielectric – developments are needed to overcome this deficiency

Helium gas cooled HTS power device technology is attractive for some applications

GHe Cooled HTS Devices

Currently US Navy is the driver of helium gas cooled superconducting applications and helium gas cryogenics technology development

- HTS degaussing systems
- HTS ship propulsion motors
- HTS power cable systems

Other studies on GHe cooled HTS devices

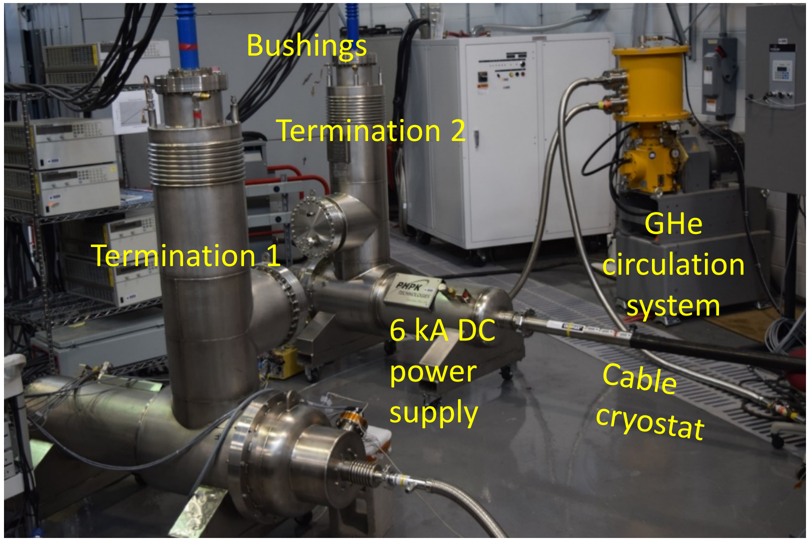
- EPRI DC cable feasibility study: S. Eckroad, "A Superconducting DC Cable," Electric Power Research Institute, Palo Alto, CA, 2009
- MIT study on GHe cooling for MgB2 DC cable: M. J. Cheadle et. al., IEEE Trans. on Appl. Supercond., vol. 23, no. 3, p. 6200805, 2013
- The MgB_2 20-meter long, 20 kA transmission line tested at 24 K at CERN in the framework of the High-Luminosity LHC project
- 3 GW class MgB_2 HVDC links - part of BEST-PATHS program

HTS Power Cables cooled by helium gas, A Chapter in Superconductors in the Power Grid, editor Christopher Rey, Woodhead Publishing

Successful Demonstration of GHe Cooled HTS Power Cables

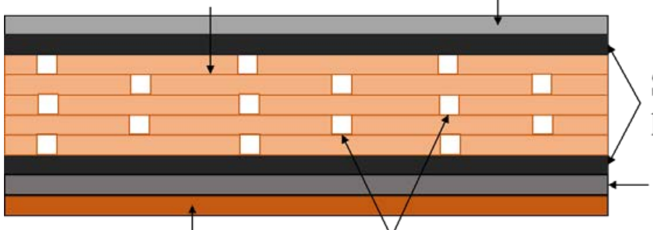
- Two GHe cooled HTS cables have been successfully demonstrated at FSU
  - 30 m DC Cable
    - Up to 5.5 kA at 65 K; 3.5 kV
  - 30 m 3- Phase AC cable
    - Up to 3.2 kA per phase at 60 K
- Successful demonstrations motivated us to develop MVDC HTS cables for US Navy All-Electric Ship applications (12 kV, DC)

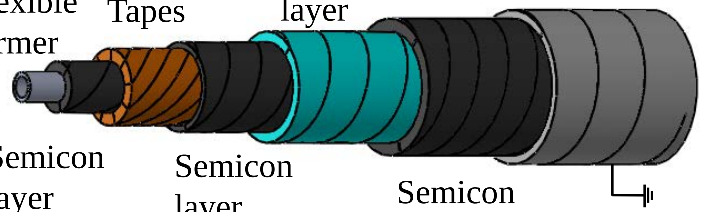
CAPS Facility for GHe Cooled HTS Power Cables



- P. Cheetham, W. Kim, C. H. Kim, S. V. Pamidi, L. Graber, H. Rodrigo, " Use of Partial Discharge Inception Voltage Measurements to Design a Gaseous Helium Cooled High Temperature Superconducting Power Cable," IEEE Transactions on Dielectrics and Electrical Insulation, 2017 *(in press)*.
- L. Graber, C. H. Kim, H. Rodrigo, D. Knoll and S. V. Pamidi, "Dielectric Design Validation of a Helium Gas Cooled Superconducting DC Power Cable," IEEE Electrical Insulation Conference, Philadelphia, Pennsylvania, 157, 2014.

Gas Cooled HTS Power Cables





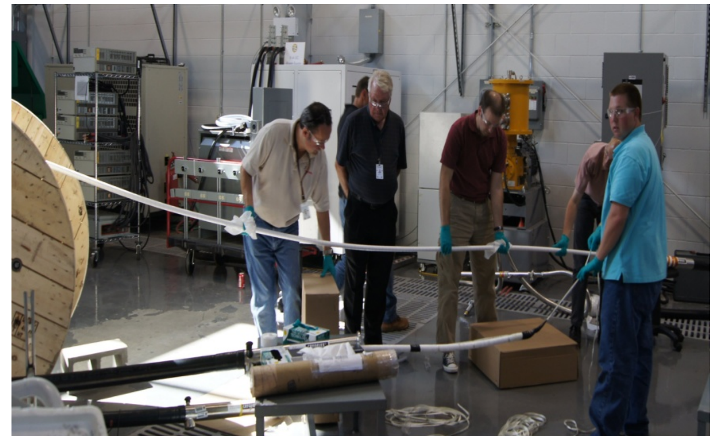
Butt gaps in HTS lapped tape insulated cable

Typical layout of HTS lapped tape insulated cable

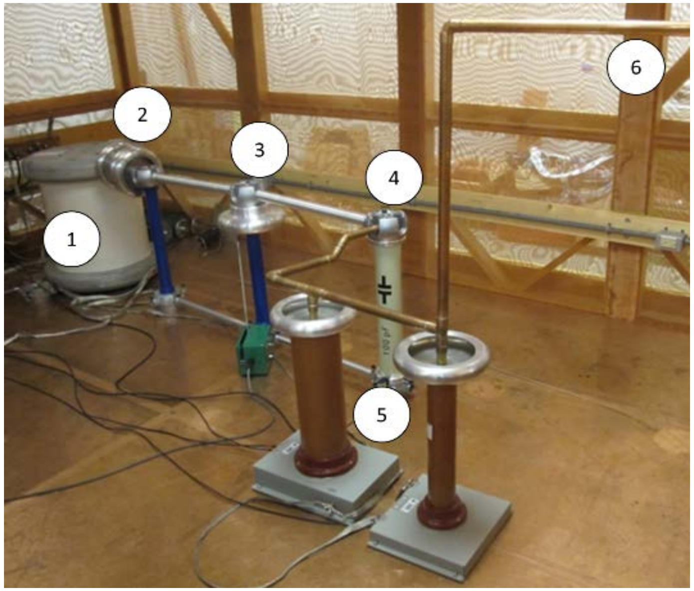
- Partial Discharge Inception Voltage currently is the limiting factor for the voltage rating of lapped tape insulated cables
- We are investigating alternative cryogenic dielectric materials and designs for superconducting devices

Areas of Our Research to Increase the Voltage Ratings of GHe Cooled HTS Cables

- Cryogenic dielectric studies on increasing dielectric strength of GHe:
  - 4 mol% Neon balanced with GHe
  - 4 mol% Hydrogen balanced with GHe
  - Collaborative theoretical understanding of dielectric properties of gas mixtures
- Studies to increase Partial Discharge Inception Voltage (PDIV) of GHe cooled HTS Power Cables:
  - Use of 4 mol% H2 as cryogen
  - Development of Superconducting Gas Insulated Line (S-GIL)
  - Heat Shrink Insulated HTS Tapes



Our Cryogenic Dielectric Experimental Capabilities



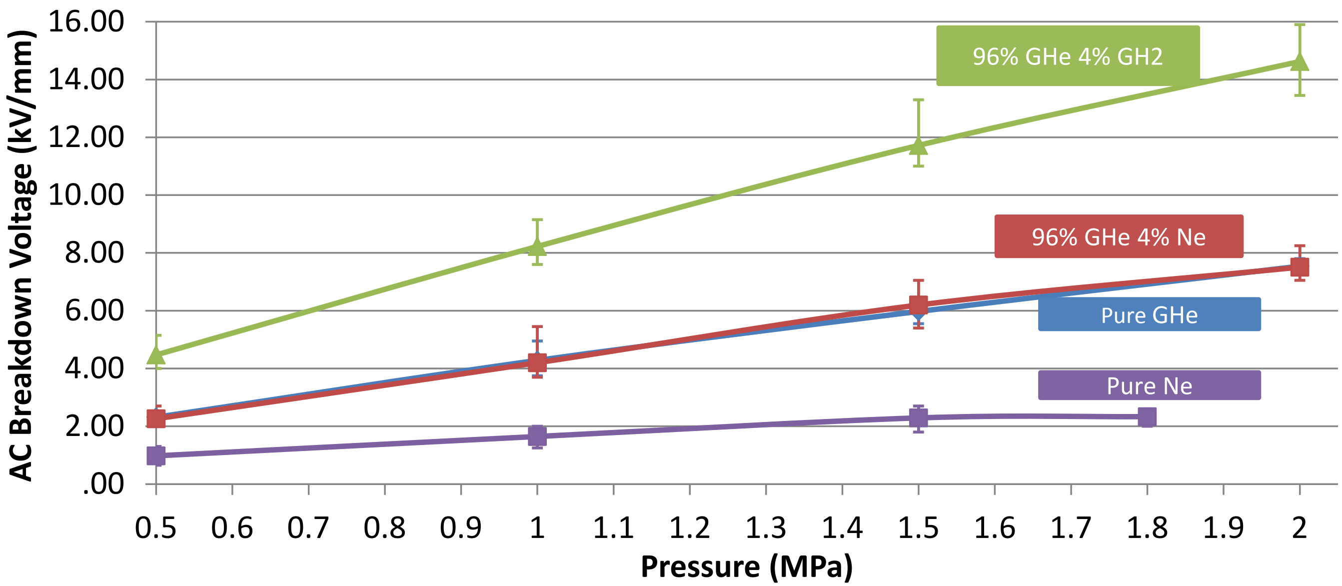
Experimental setup for AC measurements

Transformer (1), Filter (2), Grounding Switch (3), Voltage Divider (4), PD capacitors (5), and conductor to the pressure vessel (6)

- Cryogenic dielectric studies can be performed in either GHe or LN2
- Types of dielectric measurements at cryogenic temperatures
  - AC Breakdown (100 kV, rms)
  - DC Breakdown (140 kV)
  - Partial Discharge (100 kV, rms)

Our Research on Cryogenic Gas Mixtures

AC Breakdown Strength at 77 K

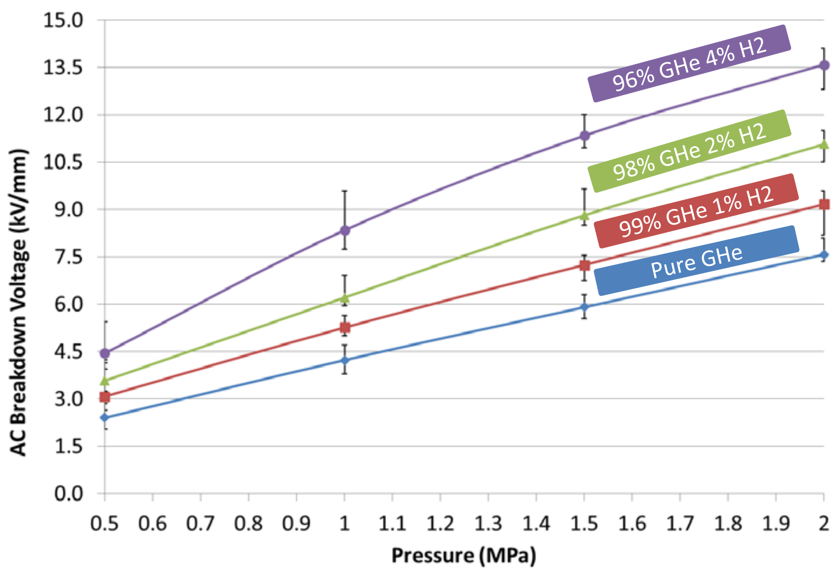


- The dielectric strength of helium gas with small mol% of neon is identical to that of pure GHe
- Addition of 4 mol% of GH_2 to GHe increases the dielectric strength by 80%

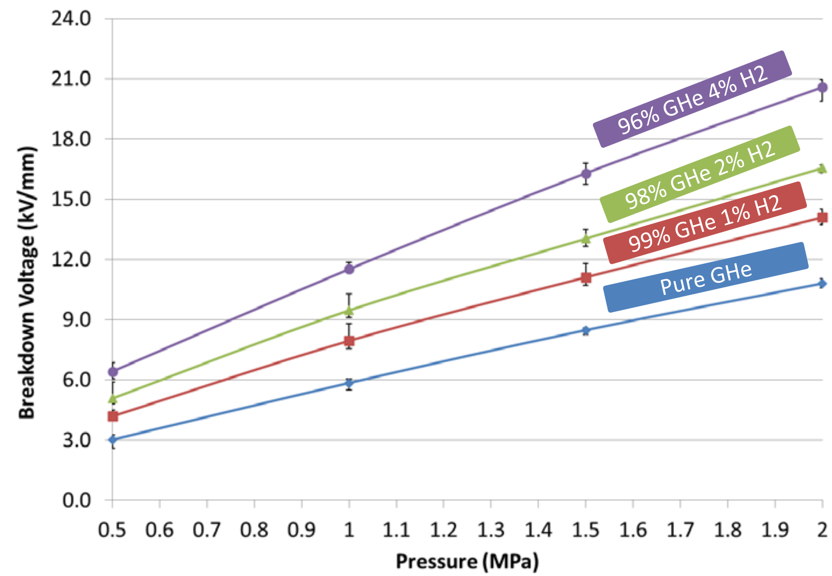
L. Graber, W. J. Kim, P. Cheetham, C. H. Kim, H. Rodrigo, and S. V. Pamidi, "Dielectric Properties of Cryogenic Gas Mixtures Containing Helium, Neon, and Hydrogen," *IOP Conference Series: Materials Science and Engineering*, vol. 102, p. 012018, 2015.

Experimentally Determined Breakdown Voltage Levels as a Function of Pressure

AC (rms) @ 77 K



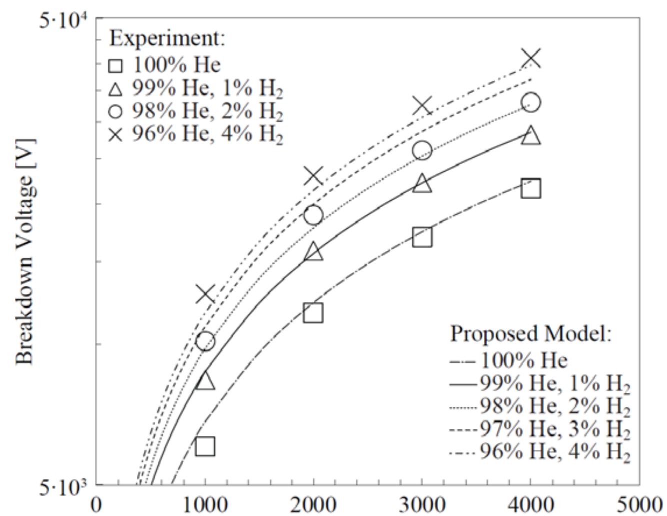
DC @ 77 K



- Linear relationship exists between H_2 mol% and breakdown strength
- DC breakdown strengths are higher by ~ 1.4 times
- Potential higher breakdown strengths for mixtures with > 4 mol% H_2
- Safety concerns associated with flammability limited our experiments to 4 mol% H_2

Theoretical Understanding of Dielectric Properties of Gas Mixture

- Collaborative work with Georgia Tech
- Boltzmann analysis has been undertaken to understand the dielectric properties of GH2-GHe mixtures
- Analysis indicates the breakdown strength increases with mol% of GH2
- Allows for higher H2 mol% to be studied without flammability safety concerns.
  - Important in determining the dielectric saturation point of H2-GHe mixtures



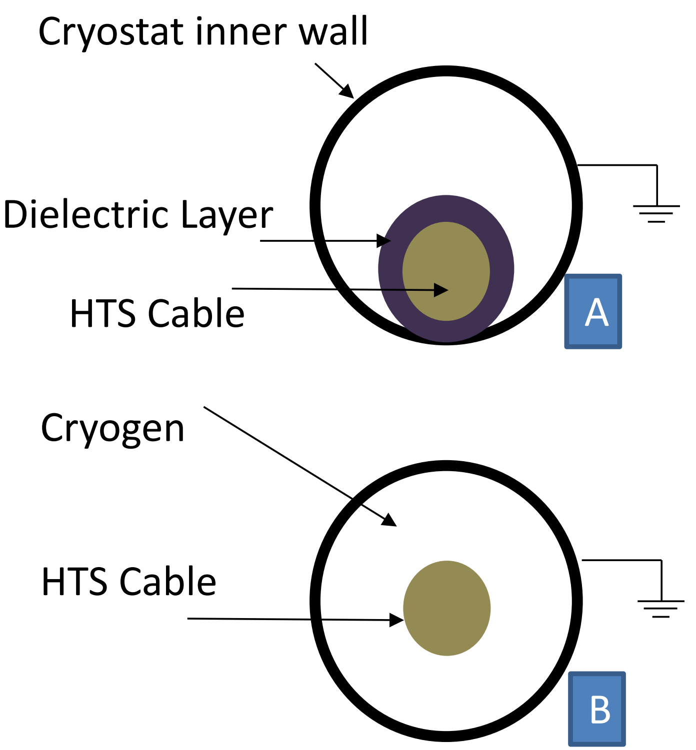
Breakdown voltage comparison of experimental measurements vs. calculated values of the versatile breakdown voltage model

Our experimental and theoretical analysis is shedding light on the dielectric behavior of cryogenic gas mixtures which is currently non-existent

New Cable Design Idea - Superconducting Gas Insulated Transmission Line

- A gas insulated HTS cable will utilize the cryogen as both the coolant and the dielectric for the cable
- Dielectric characteristics dependent on:
  - Electric field within the cryostat
  - Cryogen used
- Advantages of this cable design:
  - Continuous flow of gas should reduce space charge accumulation – important in DC cables
  - PD due to the trapped gas will not be a limiting factor for the voltage rating
  - Superior heat transfer characteristics
  - Utilize the improved dielectric properties of GH2-GHe mixtures

S-GIL



Conventional HTS Cable Design (A) versus Gas Insulated Cable Design (B)

Heat Shrink Insulated HTS Tapes

- Electrically no difference in insulating individual tapes or entire cable
- Individual insulated HTS tapes allow for simplification of large scale manufacturing process
- Heat shrink insulated HTS tapes have been used as turn-to-turn insulation for magnetic coils
- Determine suitability as a dielectric design for HTS power cables

U. P. Trociewitz, M. Dalban-Canassy, M. Hannion, D. K. Hilton, J. Jaroszynski, P. Noyes, *et al.*, "35.4 T field generated using a layer-wound superconducting coil made of (RE)Ba2Cu3O7−x (RE = rare earth) coated conductor," *Applied Physics Letters,* vol. 99, p. 202506, 2011.

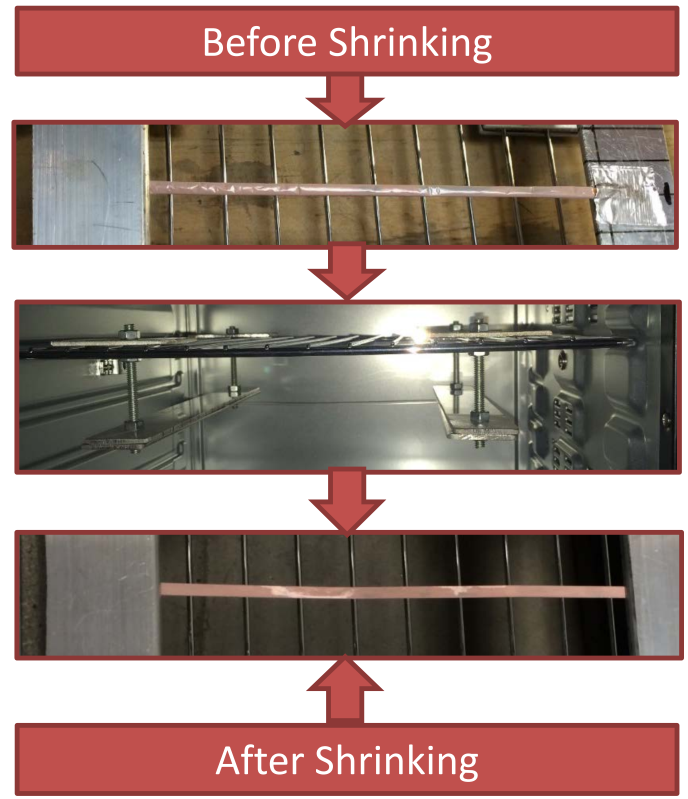
Important Properties for Selected Heat Shrink Materials

Material	Shrink Temp (°C)	Dielectric strength (kV/mm)	Relative permittivity	CTE (μm/m-K)	Thermal conductivity (W/m-K)
PTFE	346-354	7.44-24.02	2.1	126-180	0.167-0.3
FEP	204-216	19.69-78.74	2-2.1	100-135	0.19-0.25
PEEK	330-360	19.96	2.2-2.8	47	0.25
PET	85-190	17	3.3	59.4	0.15
Ideal Heat Shrink	< 175	As high as possible	1	10-20	As high as possible

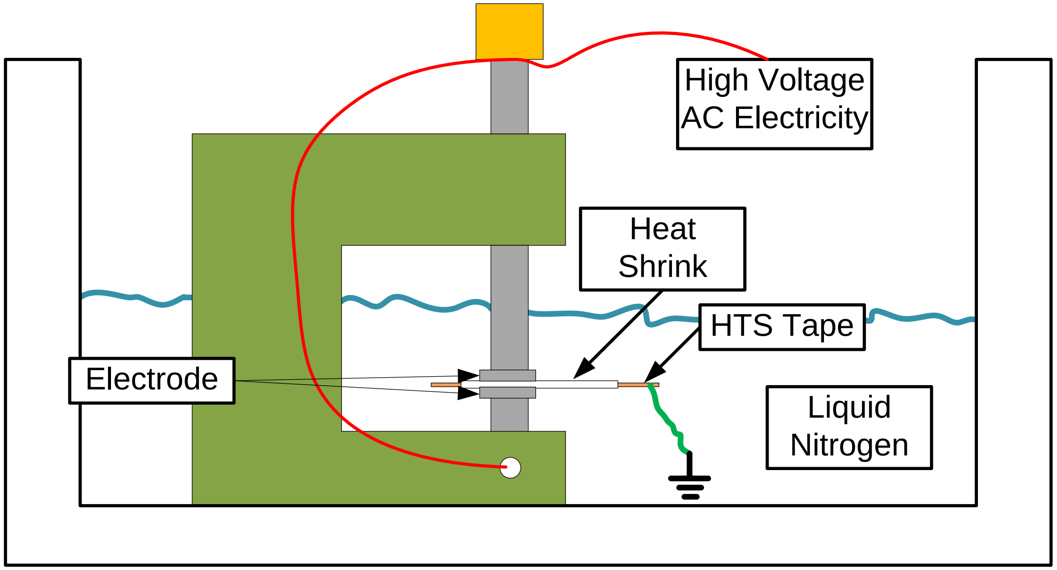
- PTFE, FEP and PEEK all have a minimum shrink temperature >175°C
- At > 175°C HTS tapes delaminate
- PET was the only material suitable for further studies

Preparation of Heat Shrink Insulated HTS Tapes

- Characterization of dielectric properties of PET Heat Shrinks with various wall thickness
  - Determine if multiple layers of a thinner heat shrink are equivalent to a single thicker heat shrink
- Wall thickness of 12.7 µm (1X), 25.4 µm (2X), 50.8 µm (4X) and 76.2 µm (6X) selected for measurements
- Shrink ratio < 15 %
- Heated at 100 °C for 10 minutes
- Fixing the heat shrink in place at both ends prevented wrinklings
- Many samples were prepared
- 3 breakdown measurements conducted on each sample

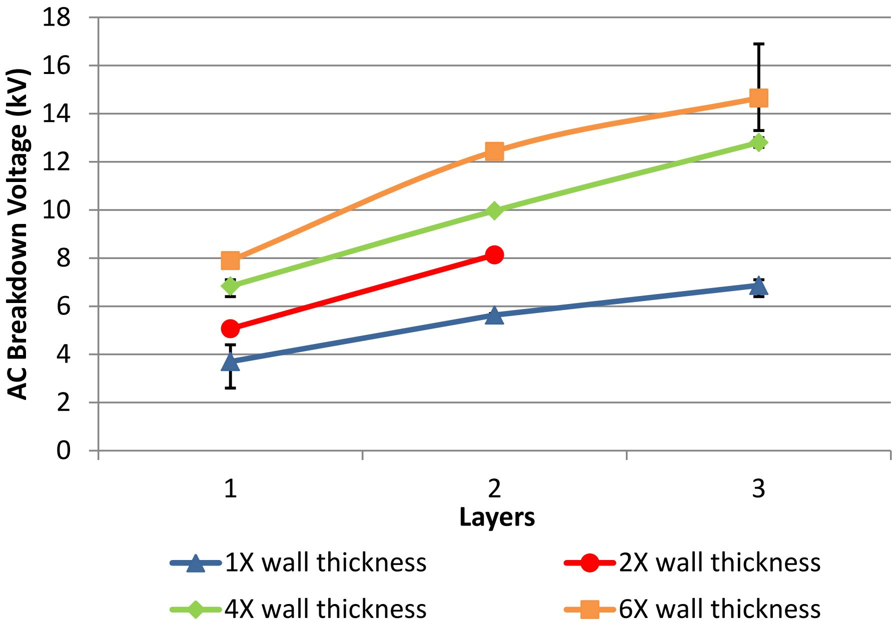


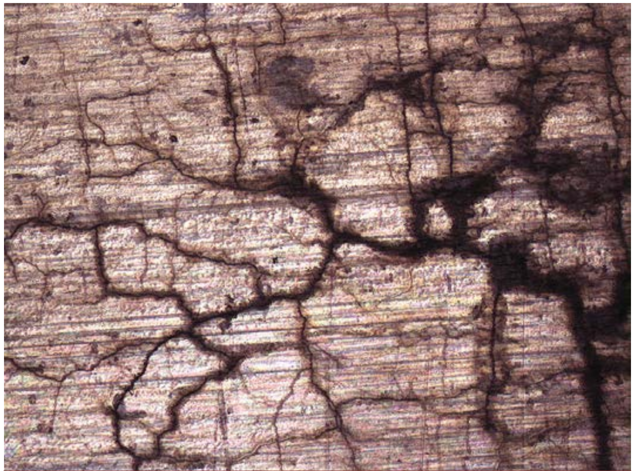
AC Breakdown Measurement on Individually Insulated HTS Tapes in LN2



- AC Breakdown measurements performed at 77 K in a LN2 bath
- Measuring in LN2 allows for the collection of statistically relevant data to be collected in a short period
- Both electrodes were connected to the HV source to ensure a uniform electric field
- Ground wire soldered onto bare section of HTS tape
- Voltage increased at a ramp rate of 300-500 V/s
- Once breakdown occurred sample was repositioned to allow for next measurement

Results of AC Breakdown Measurements on Heat Shrink Insulated Tapes





Optical micrograph of a multiple layered sample after AC breakdown

- Breakdown voltage is a function of insulation thickness
- Doubling the thickness did not result in double the breakdown voltage
- Multiple layers of a thinner material had similar breakdown voltages to fewer layers of a thicker heat shrink
- Multiple layer samples showed signs of partial discharge occurring before breakdown
- Therefore a signal layer of heat shrink with 6X (76.2 µm) wall thickness was selected for development of HTS model power cables

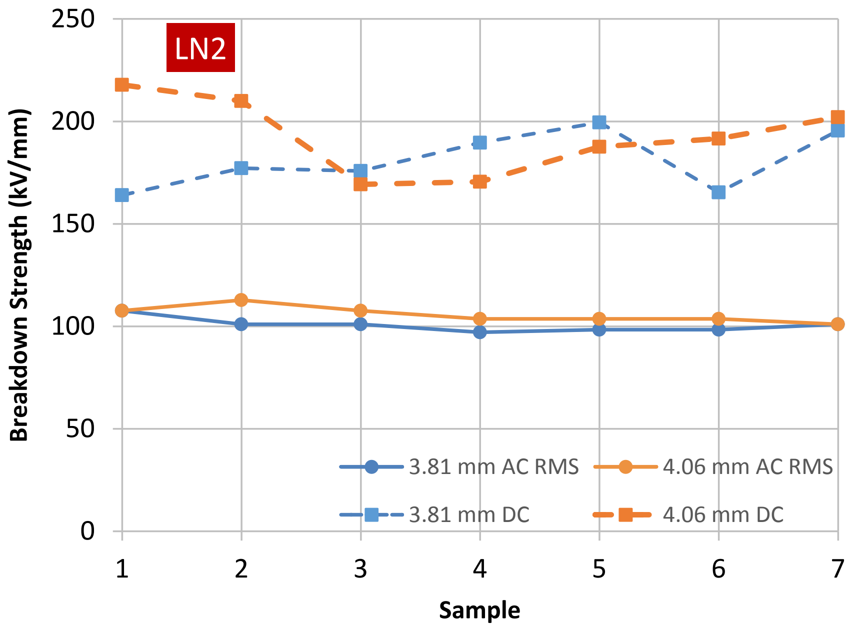
Heat Shrink Model Cable

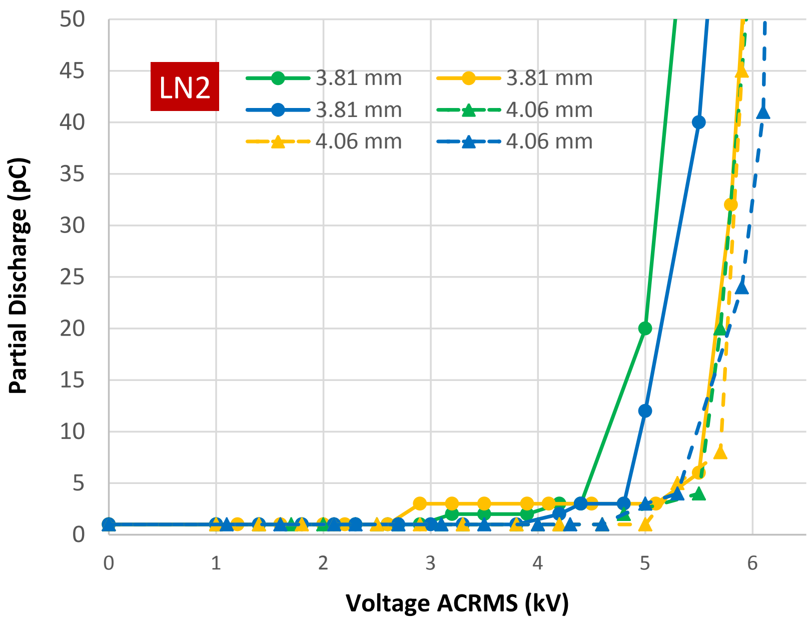
DIMENSIONS OF HTS TAPES USED IN 1 M MODEL CABLE FABRICATION

HTS Tape	Width	Thickness	Circumference
Tape 1	4.4 mm	0.4 mm	9.6 mm
Tape 2	4 mm	0.2 mm	8.4 mm

- Two types of HTS tape were chosen to build model cables
- Excessive mechanical stress while preparing samples meant larger sized heat shrink required
- Shrink ratio of 25% selected for both HTS tapes
- AC breakdown, DC breakdown and partial discharge measurements were performed in LN2 to verify dielectric properties of larger sized heat shrink

AC Breakdown Measurements on Individually Insulated HTS Tapes in LN2





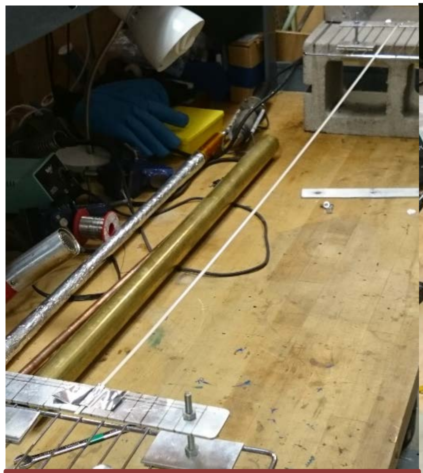
AC RMS and DC breakdown voltages of 1 layer of 76.2 µm PET heat shrink in LN2

Partial discharge measurements of 1 layer of 76.2 µm PET heat shrink in LN2

The results show that the dielectric properties scale with wall thickness and not the inner diameter. Therefore a larger sized heat shrink can be used which is easier to apply on long lengths of HTS tape.

Fabrication of Model Cable with Individually Insulated HTS Tapes

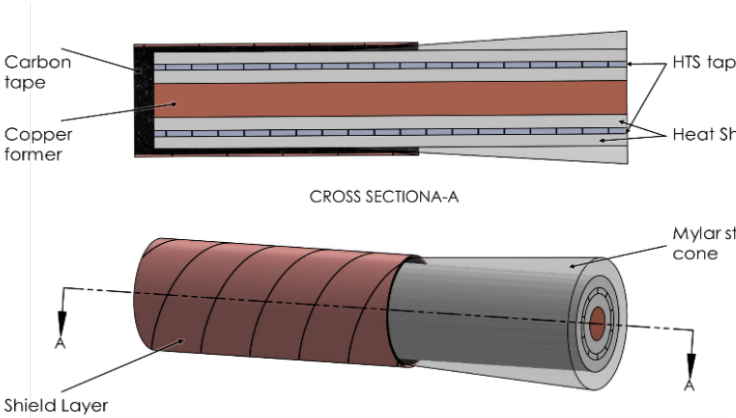
- Four cables were fabricated; two for each type of the HTS tape
- Hot air (heat gun) was used to shrink heat shrink onto HTS tapes
- Tapes were helically wrapped onto a cable former (15.9mm diameter)
- Pitch angle of 25°
  - 10 insulated tapes of 4.4 mm HTS tape
  - 11 insulated tapes of 4 mm HTS tape



Heat Shrink being applied to HTS Tape

Heat Shrink Insulated HTS tape being wrapped onto former

Model Cable Layout



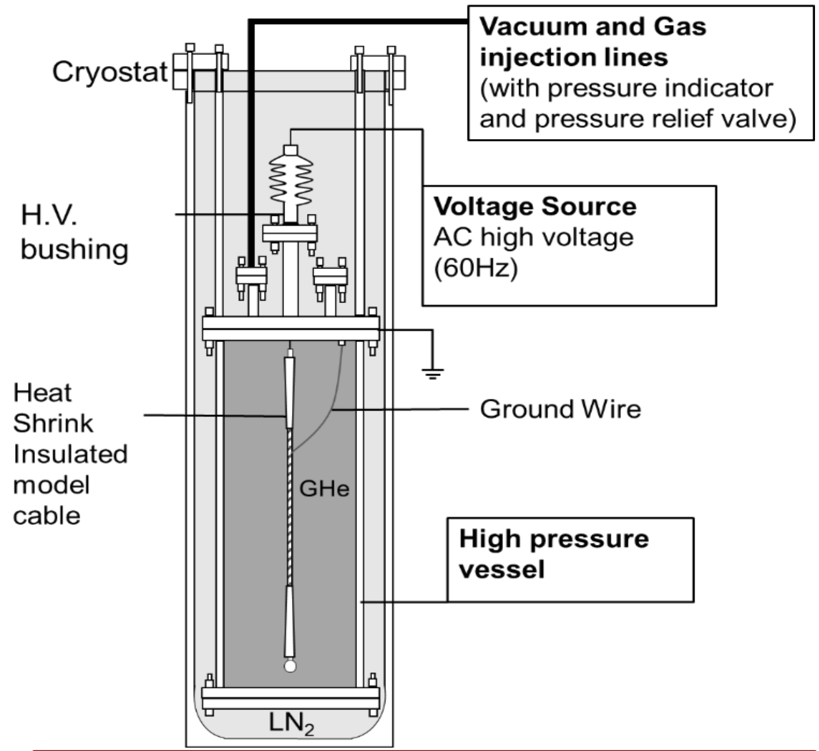
Model Cable Layout

Cable after wrapping HTS tapes onto former

- Small sections of heat shrink removed from ends of HTS tape to allow for HTS tape to be soldered onto former
- Stress cones were fabricated using a PET sheet with similar thickness as the heat shrink
- Semiconductive layer and shield layer built onto cable

Heat Shrink Model Cable GHe Experiment Setup

- Model cable installed within GHe pressure vessel
- High purity GHe environment achieved through pumping and flushing cycles
- Partial discharge measurement and AC breakdown measurements conducted in 2.0 MPa of GHe at 77 K



A schematic of the model cable installed in the pressure vessel for measurements

Heat Shrink Cable Experimental Result

- All cables broke down suddenly without any indication of partial discharge
- Breakdown occurred away from stress cones
- AC breakdown voltages significantly reduced from individual HTS tape measurements
  - Different electric fields
  - Cryogen used
  - Fabrication procedure
  - Sample size
  - Thickness of heat shrink

AC BREAKDOWN MEASUREMENTS OF HEAT SHRINK MODEL CABLES

HTS tape	Cable 1 (kV)	Cable 2 (kV)
4.4 mm	1.8	1.8
4 mm	1.0	1.4

A picture of a multiple layered sample after AC breakdown

Conclusion

- Dielectric design for HTS cables involving individually insulated HTS tapes was explored
- This method of applying insulation has benefits in large scale applications because this technique lends itself to continuous manufacturing process
- The dielectric characteristics of insulated HTS tapes as well as model cables were measured at 77 K in liquid nitrogen and gaseous helium environments
- Breakdown strength scales with insulation thickness independent of the number of layers
- A single layer of thicker insulation is better for preventing trapped gas between the layers that causes partial discharge at lower voltages