Helium Gas Cooled Superconducting DC Cable Project

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Benefits of Helium Gas Cooled Superconducting Power Devices

- Flexibility in operating temperatures (30 K–80 K)
- Enhanced superconducting properties at lower temperatures
- Lower temperatures allow higher power densities when necessary
- Larger temperature gradients can be maintained without accompanying a phase change
- Easier to integrate with other superconducting devices operating under helium gas cooling
- Increased flexibility in power system design optimization

Helium Gas Based Systems - Challenges

- Low heat capacity of helium gas – requires high pressures and flow rates for efficient heat removal
- Helium gas has low dielectric strength
- Little experience on helium gas cooled superconducting power devices
- Commercial cryocoolers are inefficient – technological developments necessary

Superconducting DC Cable Nominal Specifications

Current Phase – Validate cryogenic and thermal issues

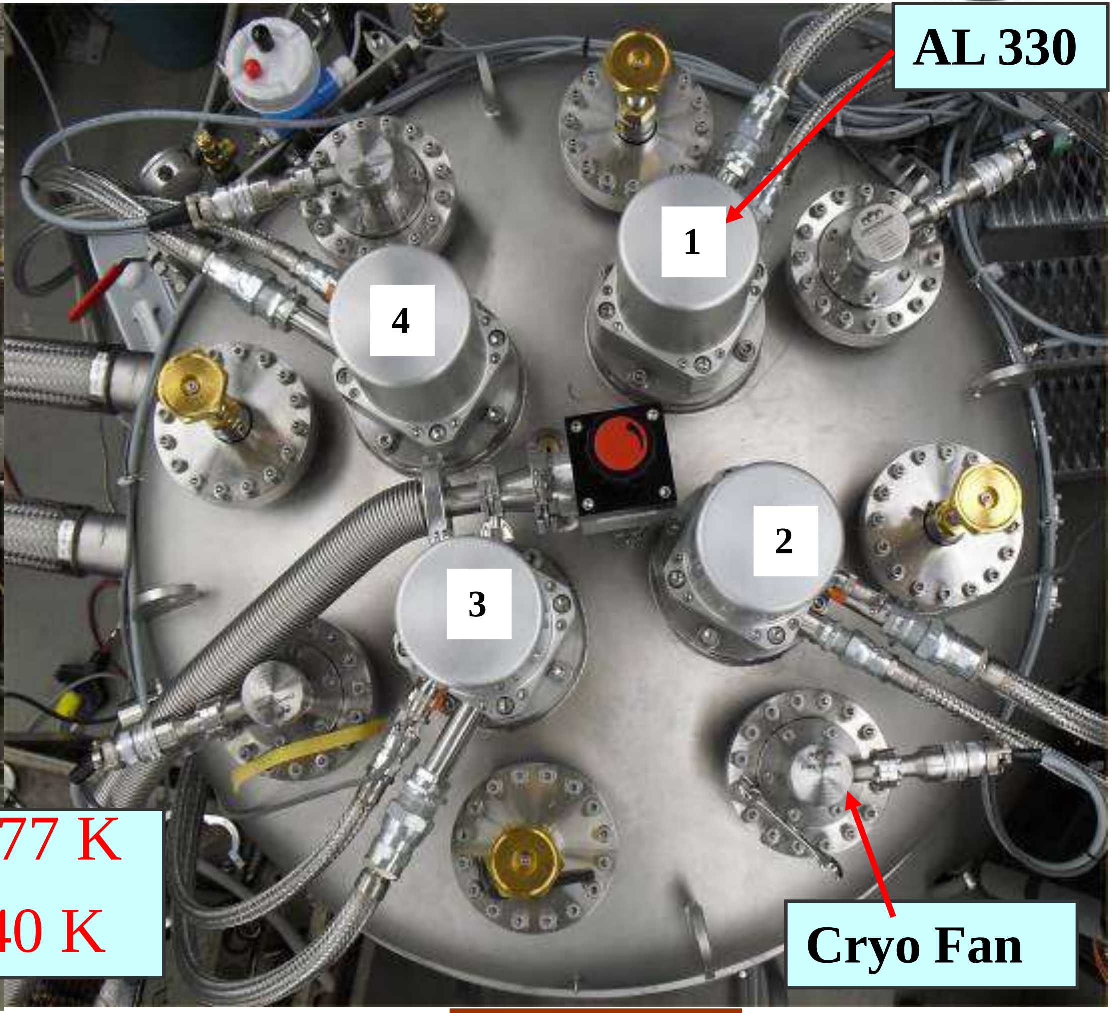
- Monopole
- Current rating: 3 kA and @ 77 K (up to 10 kA @ 40 K)
- Voltage rating: 1 kV

Next Phase

- Coaxial dipole
- Current rating: 3 kA and @ 77 K (up to 10 kA @ 40 K)
- Voltage rating: ± 5 kV

Cryogenic Helium Circulation System

Side View



Top View

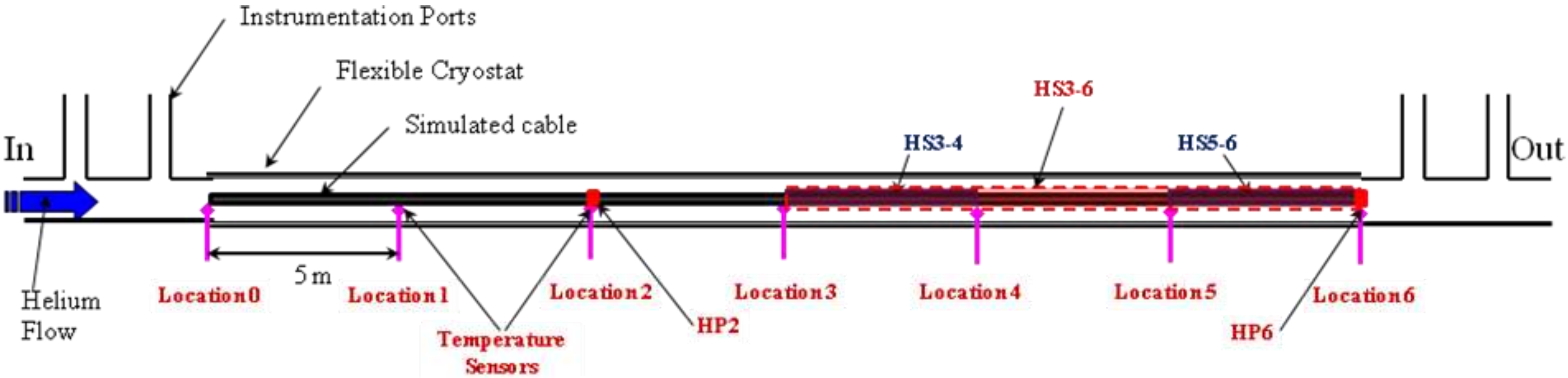
Operating Pressure: up to 250 psi, Expected flow rate: up to 20 g/s

Cryostat and Helium Circulation System for Superconducting DC Cable

Tin = 35-40 K, Tout = 42 – 45 K; Operating Pressure: Up to 250 psi

Length: 30 m, Extensive instrumentation and heater arrangements for comprehensive thermal studies

Instrumentation in Cable Cryostat for Thermal Studies

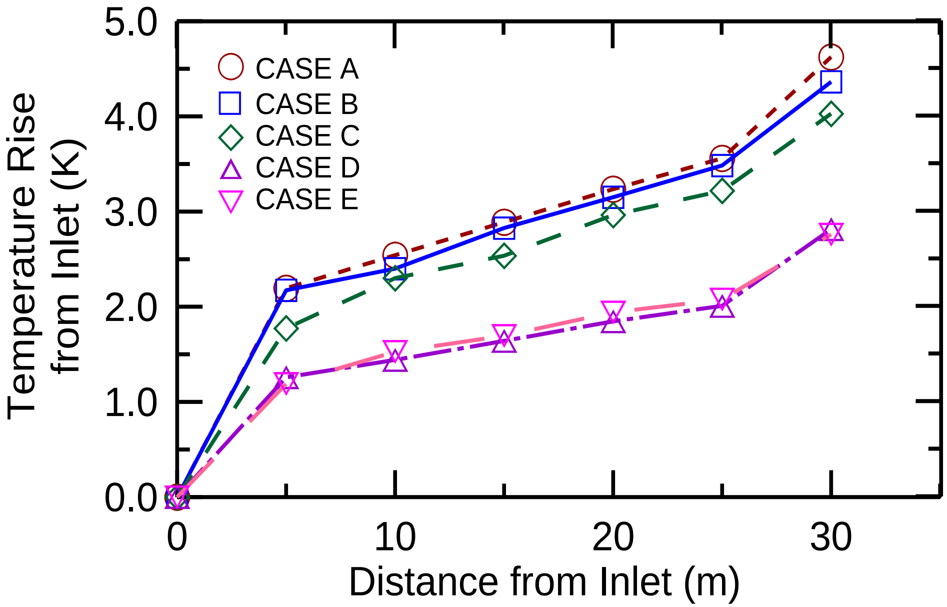


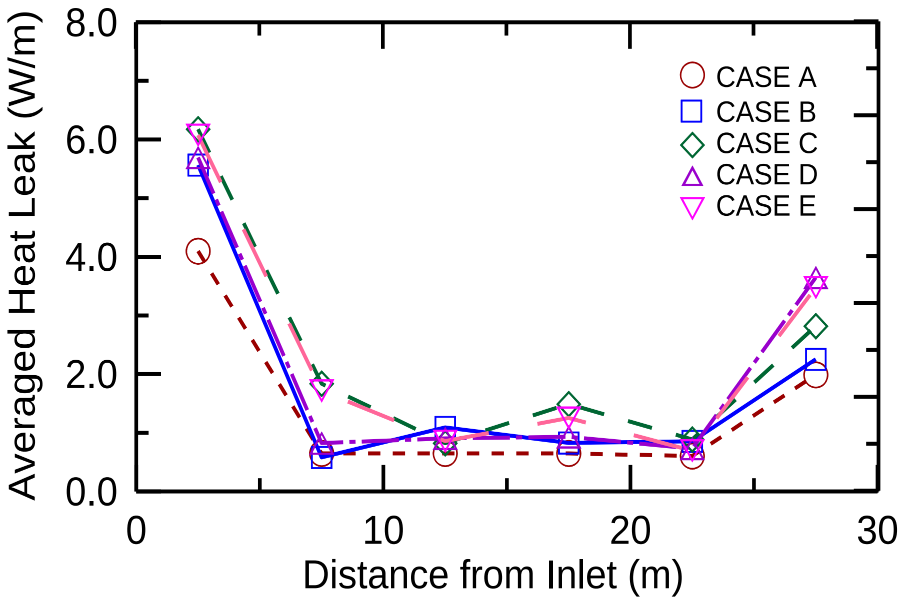
HP: Point Heater; HS: Sectional Heater;

- Cernox temperature sensors are installed at every 5 m
- Thermocouples are installed at every 2 m
- Multiple spot heaters for generating local hotspots (R=18 Ω)
- Multiple 5-meter long sectional heaters (R =110 Ω)
- Two 15 m long heaters cover the entire length of cryostat (R =330 Ω)

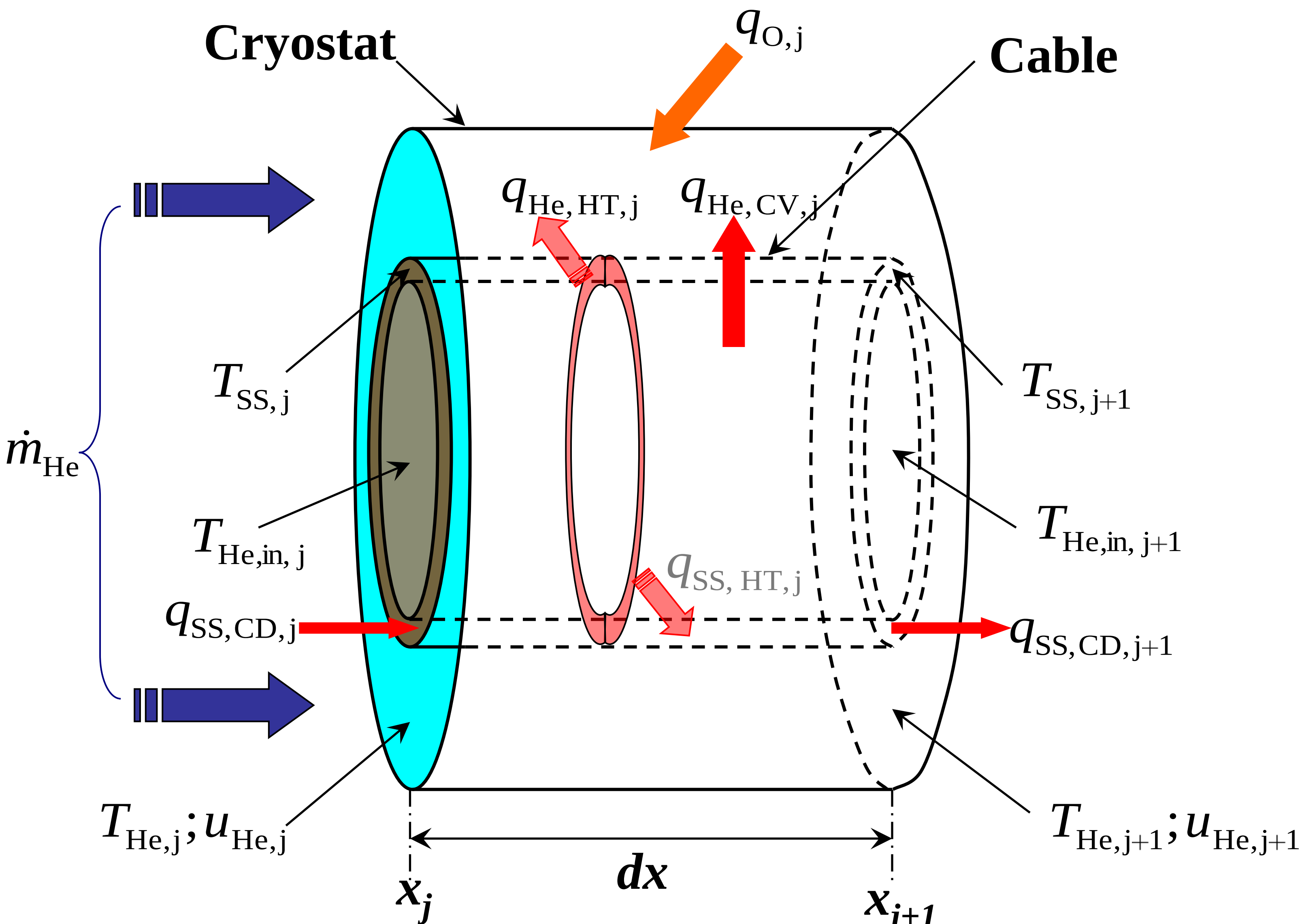
Helium Circulation Experimental Parameters

	unit	Case A	Case B	Case C	Case D	Case E
Pressure, p	psi	154	187	177	155	177
Density, ρ	kg/m³	10.8	12.5	11.8	10.4	11.8
Flow velocity, u	m/sec	0.17	0.21	0.33	0.50	0.50
Mass Flow rate, m	**g/s**	**1.8**	**2.5**	**3.3**	**4.3**	**4.9**





Thermal Model for Helium Gas Cooled HTS DC Power Cable



Thermal Model for Helium Gas Cooled HTS DC Power Cable

$T_{SS,j}$ **: Temperature of cable represented by stainless steel tube at j-th**

$T_{He,j}$ **location**

$T_{He,in,j}$**: Temperature of Helium gas at j-th location**

$\dot{m}_{He}$ **: Temperature of Helium inside cable at j-th location**

$u_{He,j}$**: Mass flow rate of Helium gas**

$q_{O,j}$ **: Heat leak from outside of cryostat**

$q_{He,HT,j}$**: Heat generated by heater within *dx* and transferred to helium flow**

$q_{SS,HT,j}$**: Heat generated by heater within *dx* and transferred to stainless steel**

$q_{He,CV,j}$**cable**

$q_{SS,CD,j}$**: Convective heat transferred “to” helium flow “from” cable**

A_{SS} **: Cross-sectional area of stainless steel cable**

$D_{SS,in}$ **: Inside diameter of stainless steel cable**

ρ, C_p **: Density, Specific heat capacity**

Thermal Model for Helium Gas Cooled HTS DC Power Cable

Governing Equation

1. For Helium flow

$$q_{\mathrm{O,j}} + q_{\mathrm{He,HT}} + q_{\mathrm{He,CV}} = \dot{m}_{\mathrm{He}} C_{\mathrm{p,He,j}} (T_{\mathrm{He,j+1}} - T_{\mathrm{He,j}})$$

Heat exchanged in helium flow = Enthalpy change in Helium flow

2. For Stainless Steel Cable

$$q_{\mathrm{SS,HT}} - q_{\mathrm{He,CV}} + q_{\mathrm{SS,CD,j}} - q_{\mathrm{SS,CD,j+1}}$$ ← **Heat exchanged on SS cable within dx**

$$= \rho_{\mathrm{SS}} A_{\mathrm{SS}} u_{\mathrm{He,j}} C_{\mathrm{p,SS,j}} (T_{\mathrm{SS,j+1}} - T_{\mathrm{SS,j}})$$ ← **Enthalpy change of SS cable**

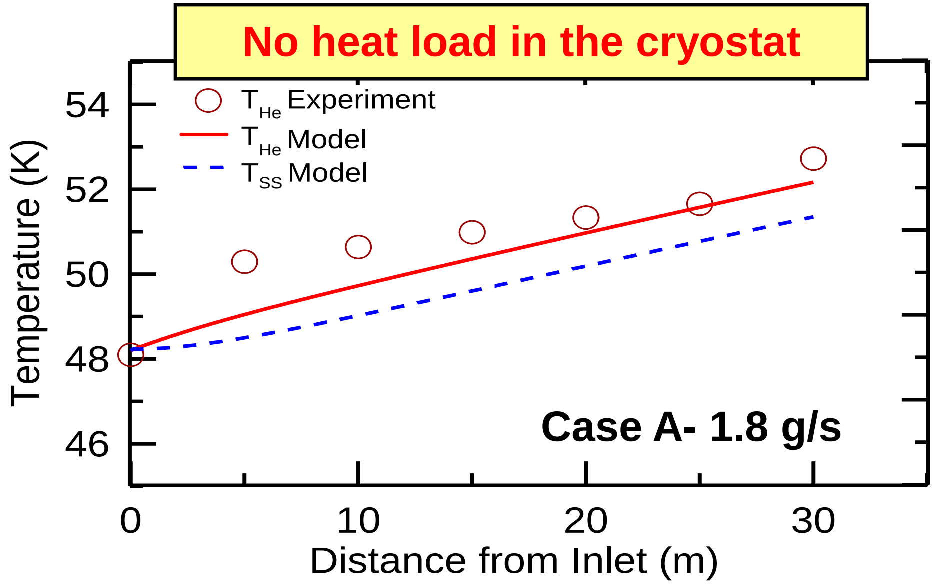
$$+ \rho_{\mathrm{He,in,j}} \pi D^2_{\mathrm{SS,in}} u_{\mathrm{He,j}} C_{\mathrm{p,He,in,j}} (T_{\mathrm{He,in,j+1}} - T_{\mathrm{He,in,j}})$$ ← **Enthalpy change of Helium Inside cable**

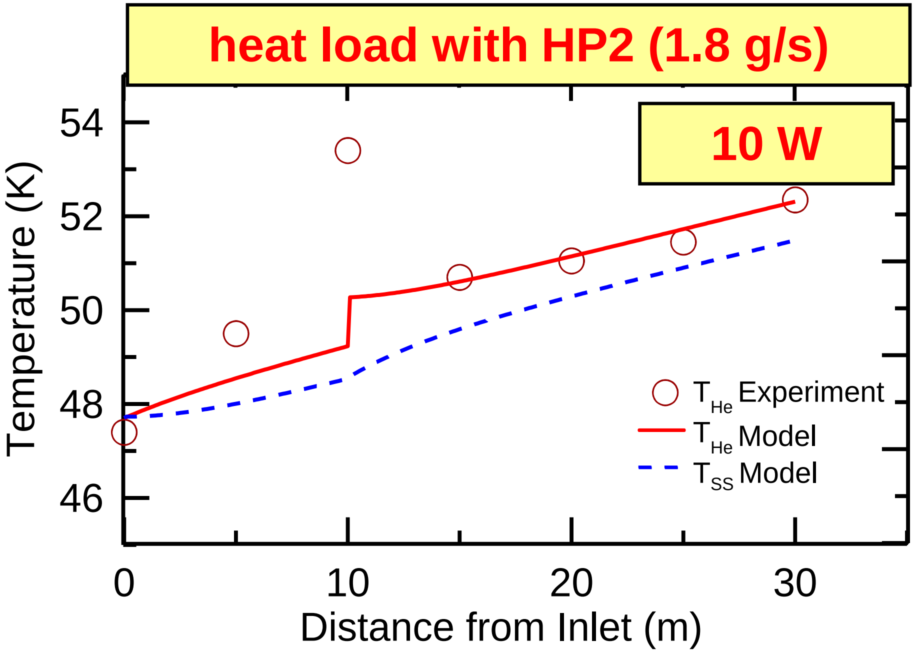
- **Conductive heat through cable is based on temperature gradient.**

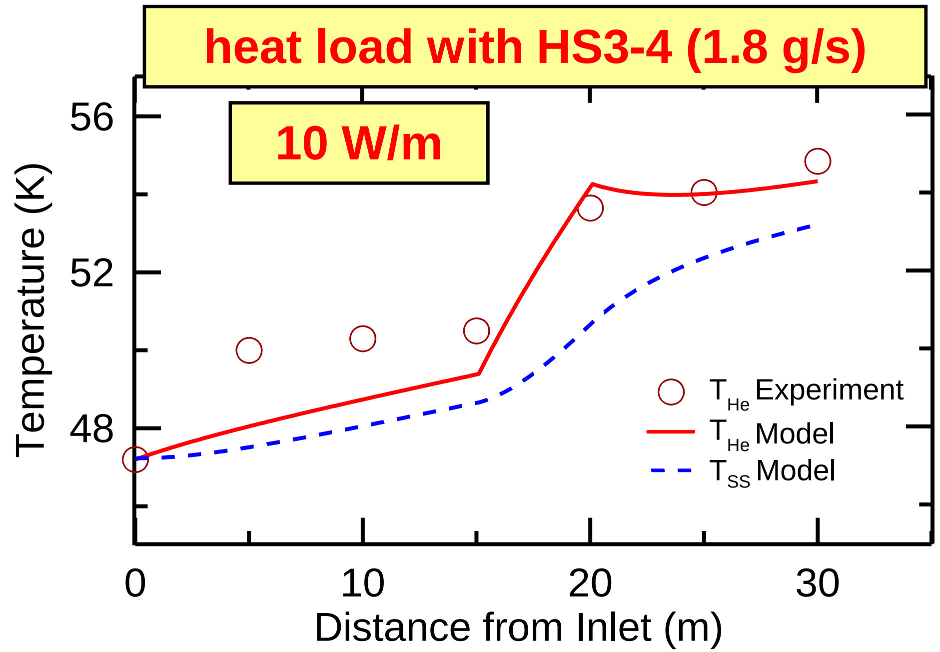
$$q_{\mathrm{SS,CD,j}} = -k_{\mathrm{SS}} A_{\mathrm{SS}} (T_{\mathrm{SS,j+1}} - T_{\mathrm{SS,j}}) / dx$$

- **Properties are evaluated at j-th location and assumed same within dx**
- **All terms are known except temperatures of helium and stainless steel cable at j+1. (Solvable)**

Steady State Temperature Profiles at Various Heat Loads and Flow Rates

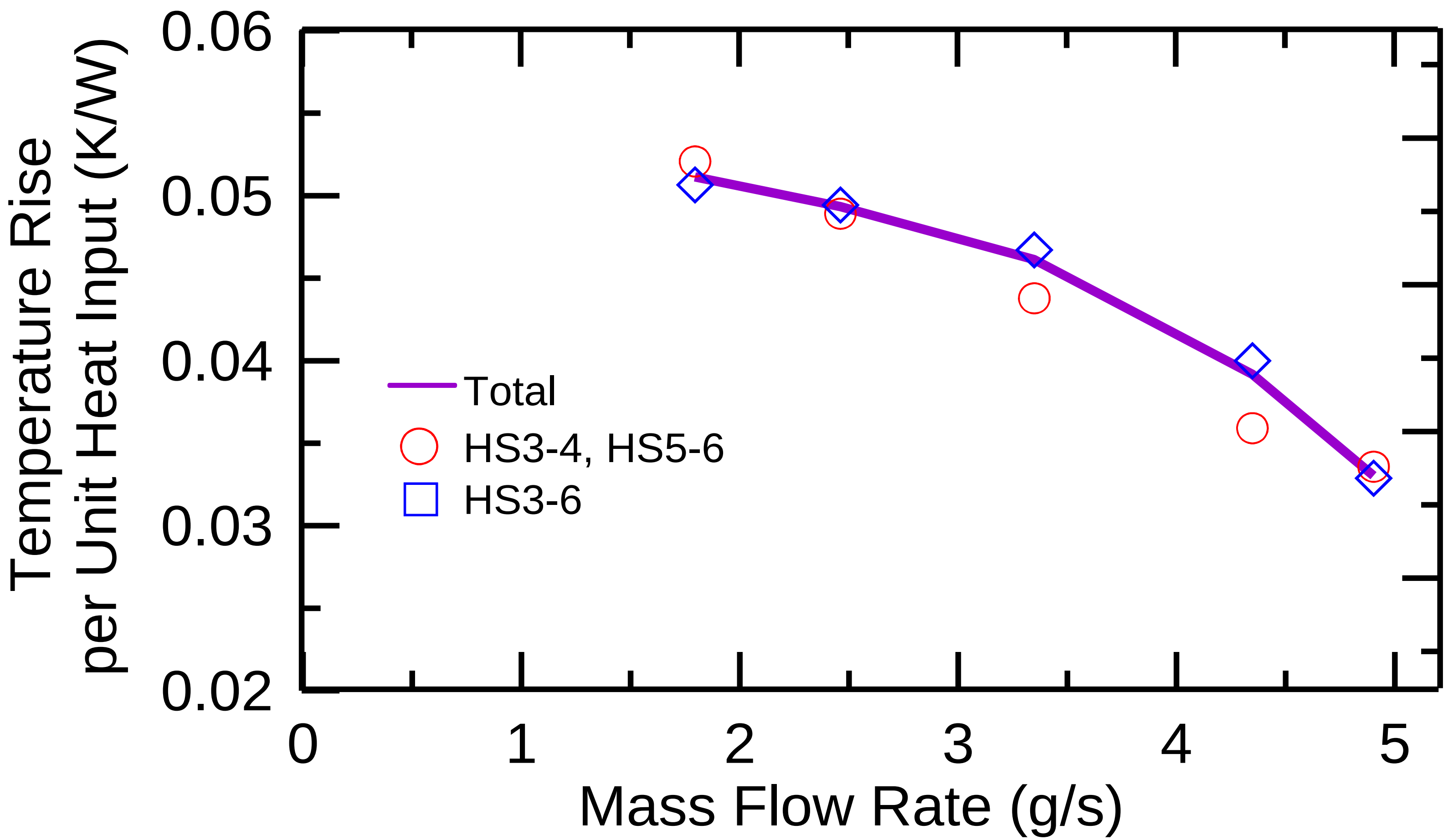






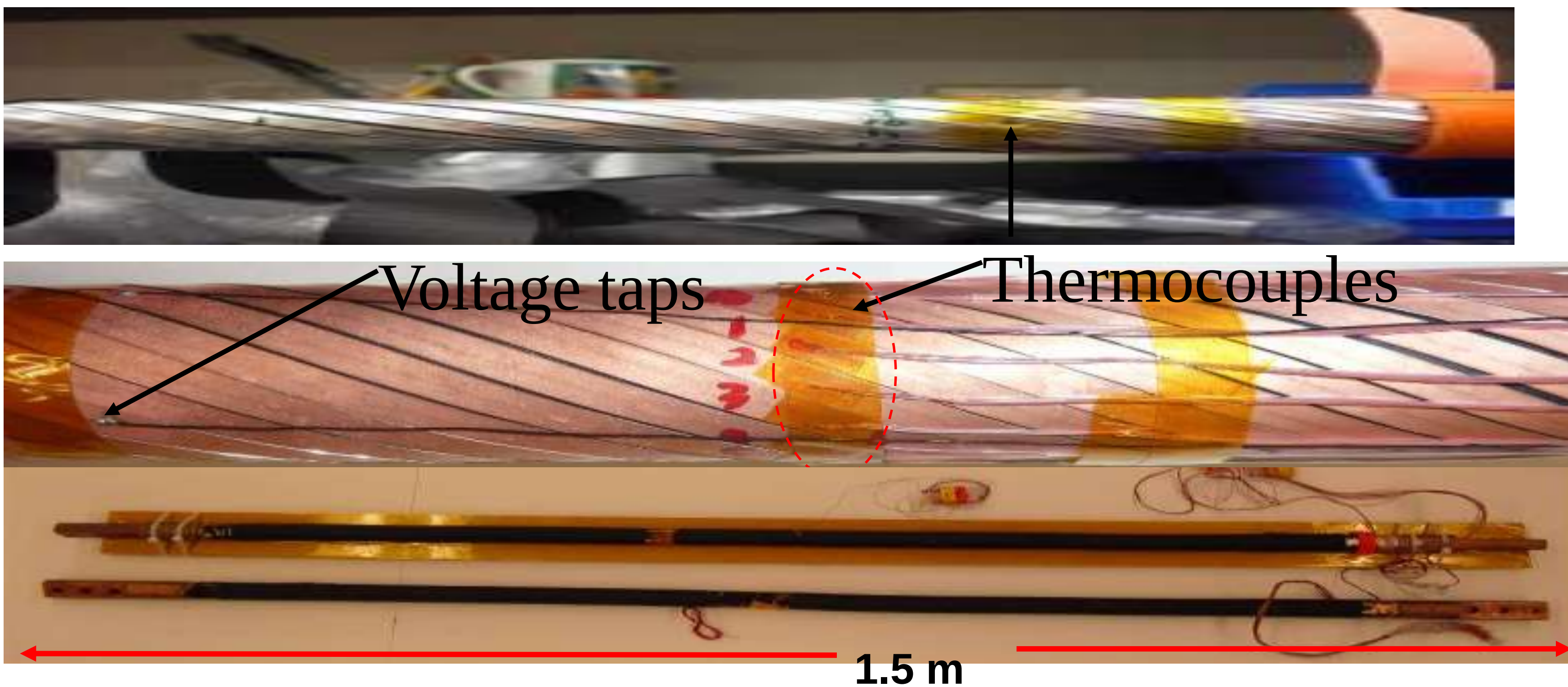
Average Temperature Rise With Heat Load

- Average ΔT is about 0.03 K per 1 W of heat load in the cryostat
- ΔT is independent of the source of heat



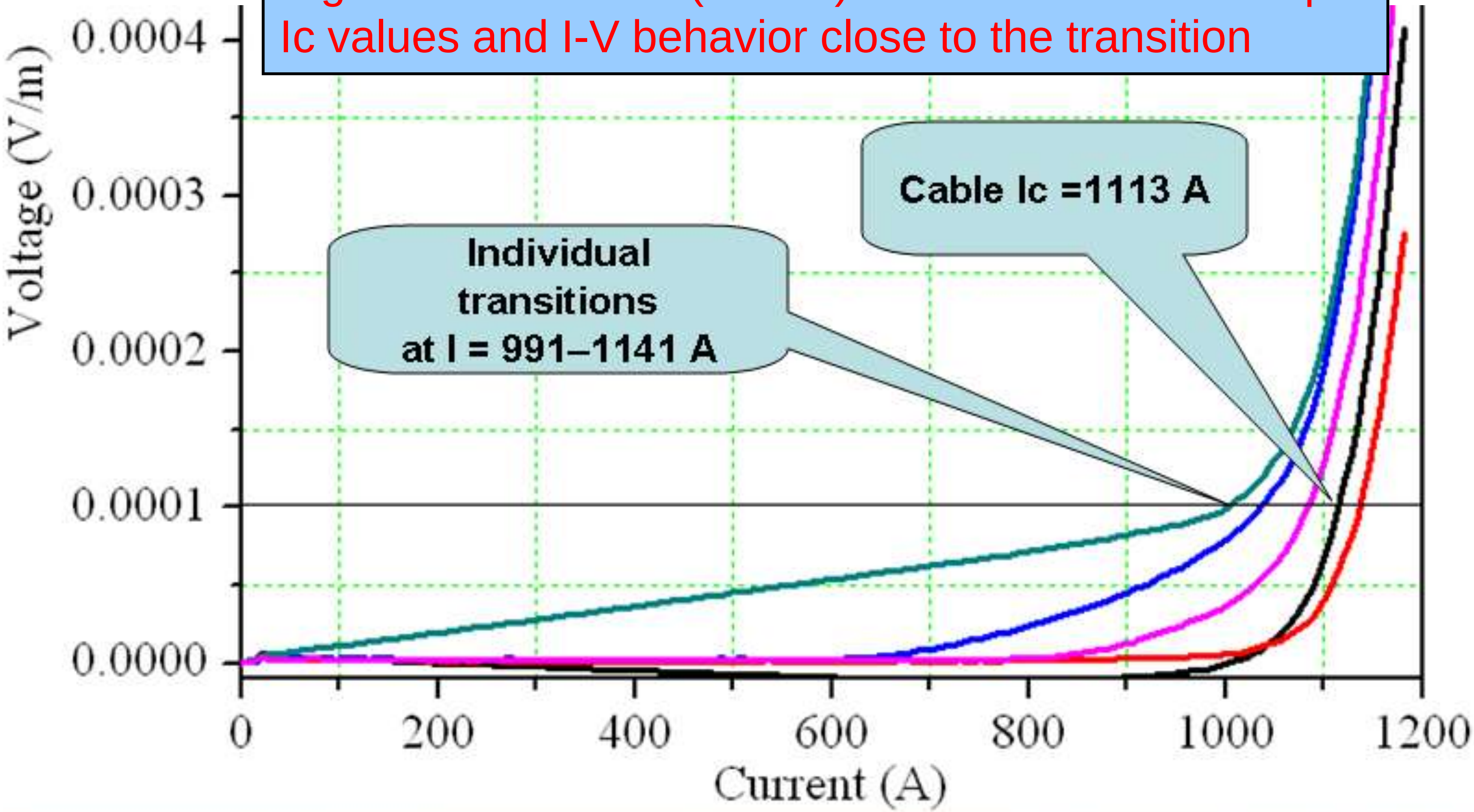
Tests on Cable Sections

- Six 1-meter long sections with thermocouples and voltage taps on each tape
- Cables were made from both RABITS and IBAD tapes
- Tested extensively in LN2 and GHe at 65-77 K
- Some cables had thermocouples and voltage taps on each tape
- Thermal & electrical performance followed under over-current (up to 1.5 I_c)



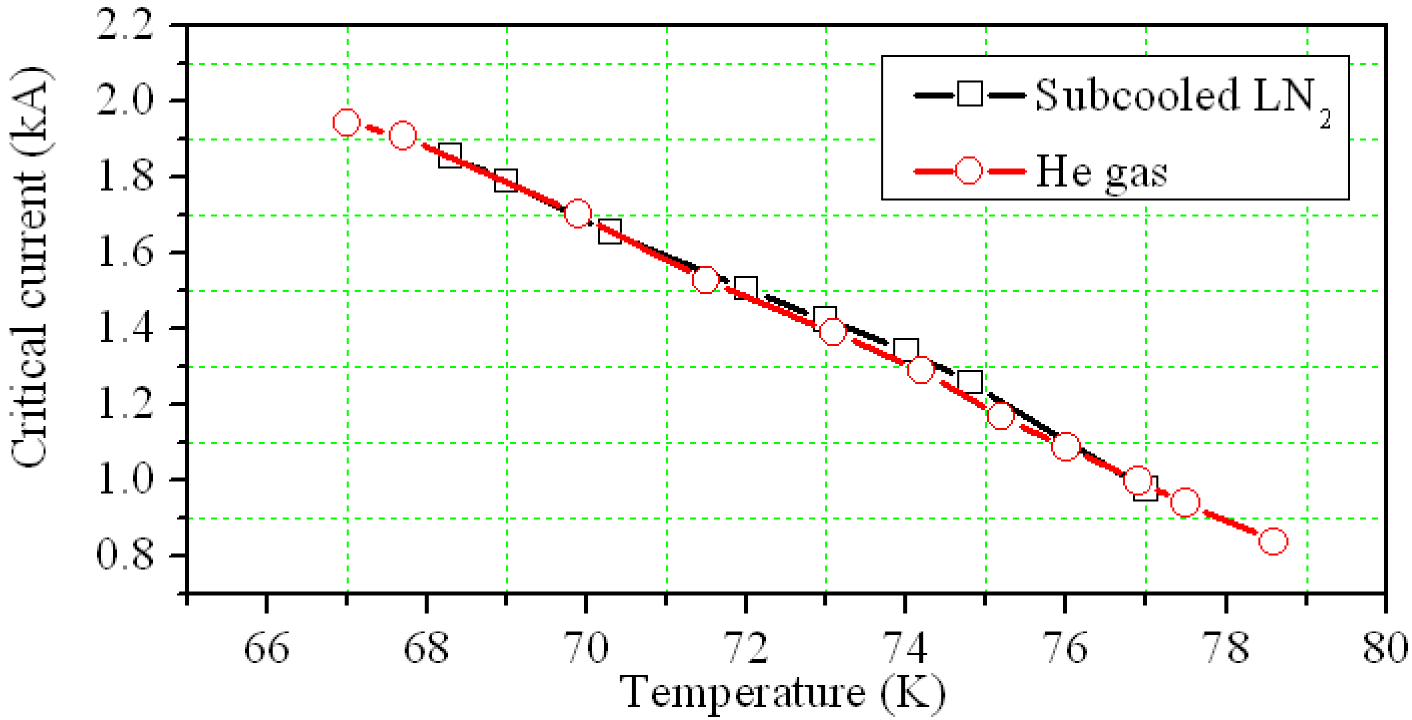
Variation of critical current of tapes

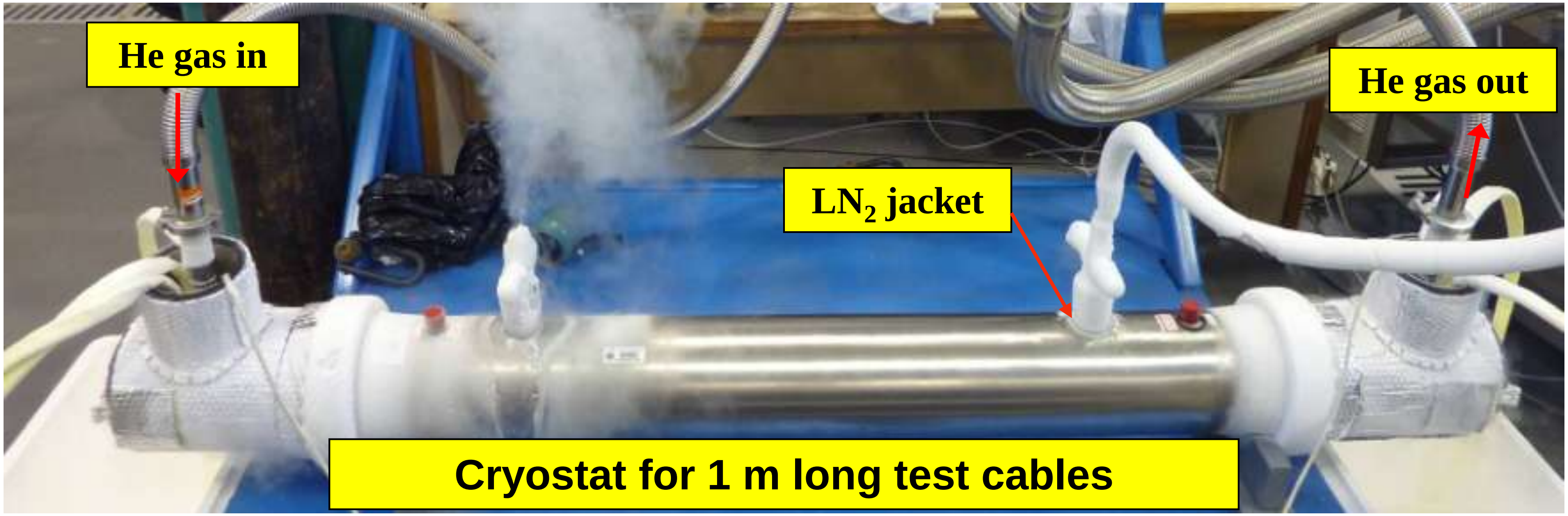
Significant variation (~ 10%) observed individual tape Ic values and I-V behavior close to the transition



The variation is not an artifact due to the differences in contact resistance – Voltage taps are away from the soldered contacts

Critical Current Measurements at 67-78 K

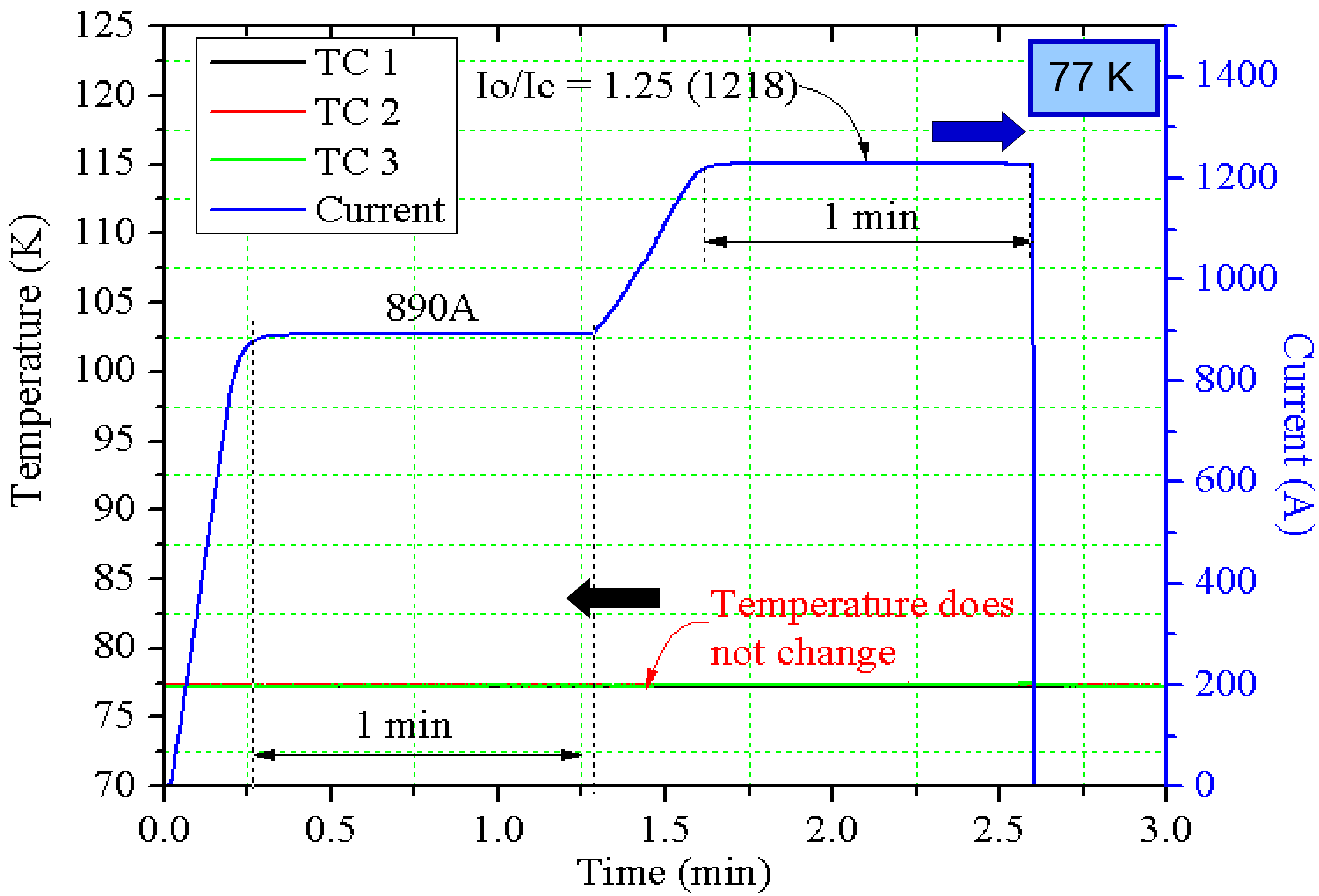




Over-Current Tests in LN_2

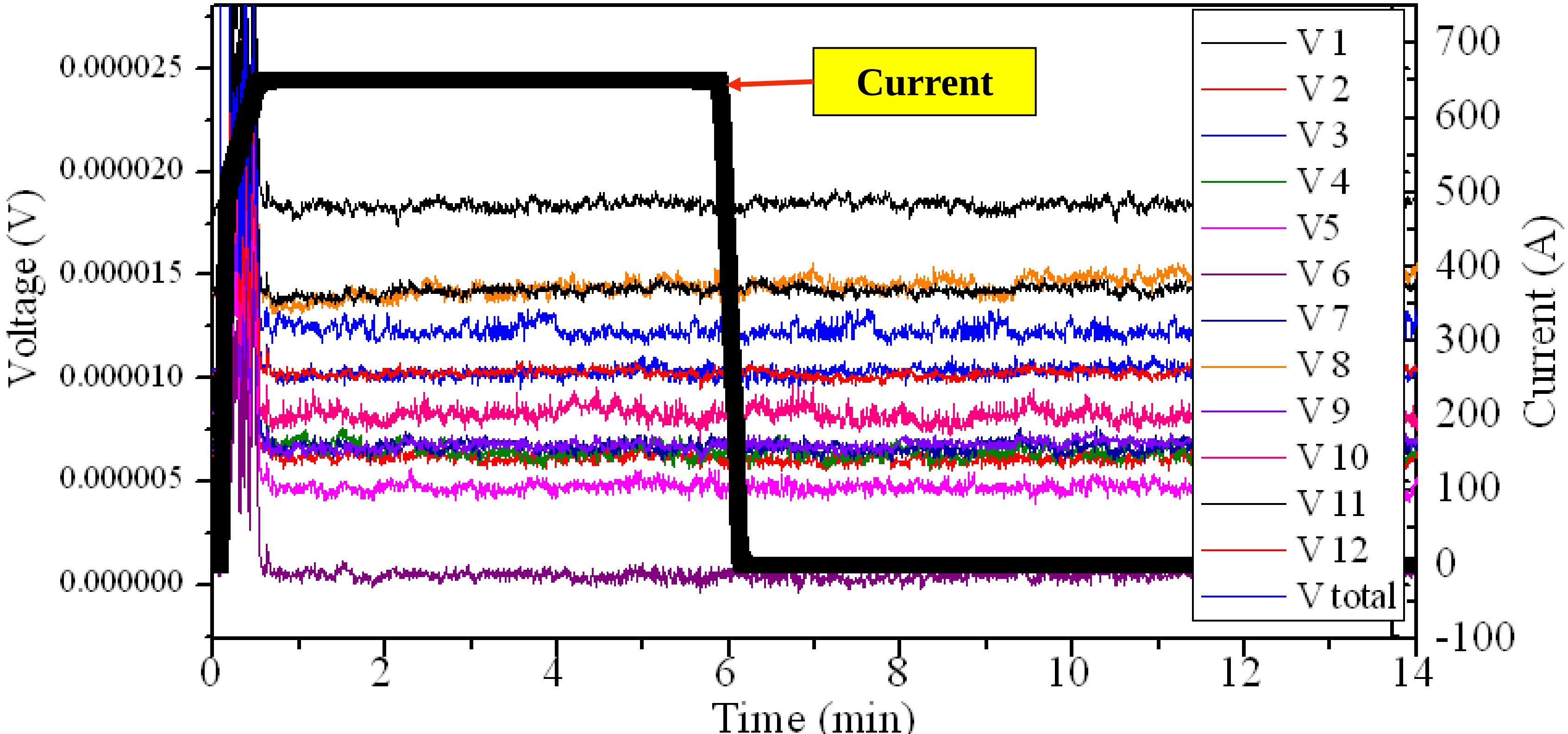
1 min @ 890 A → 1218 A (1.25 Ic) → Dwell 1 min

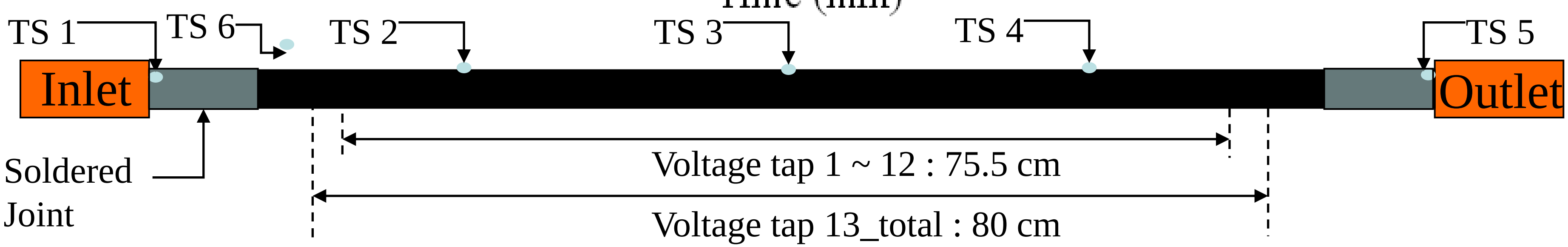
- No temperature increase noticed



Stability Test of the Cable in GHe Under 650 A (55% of Ic) at 75 K

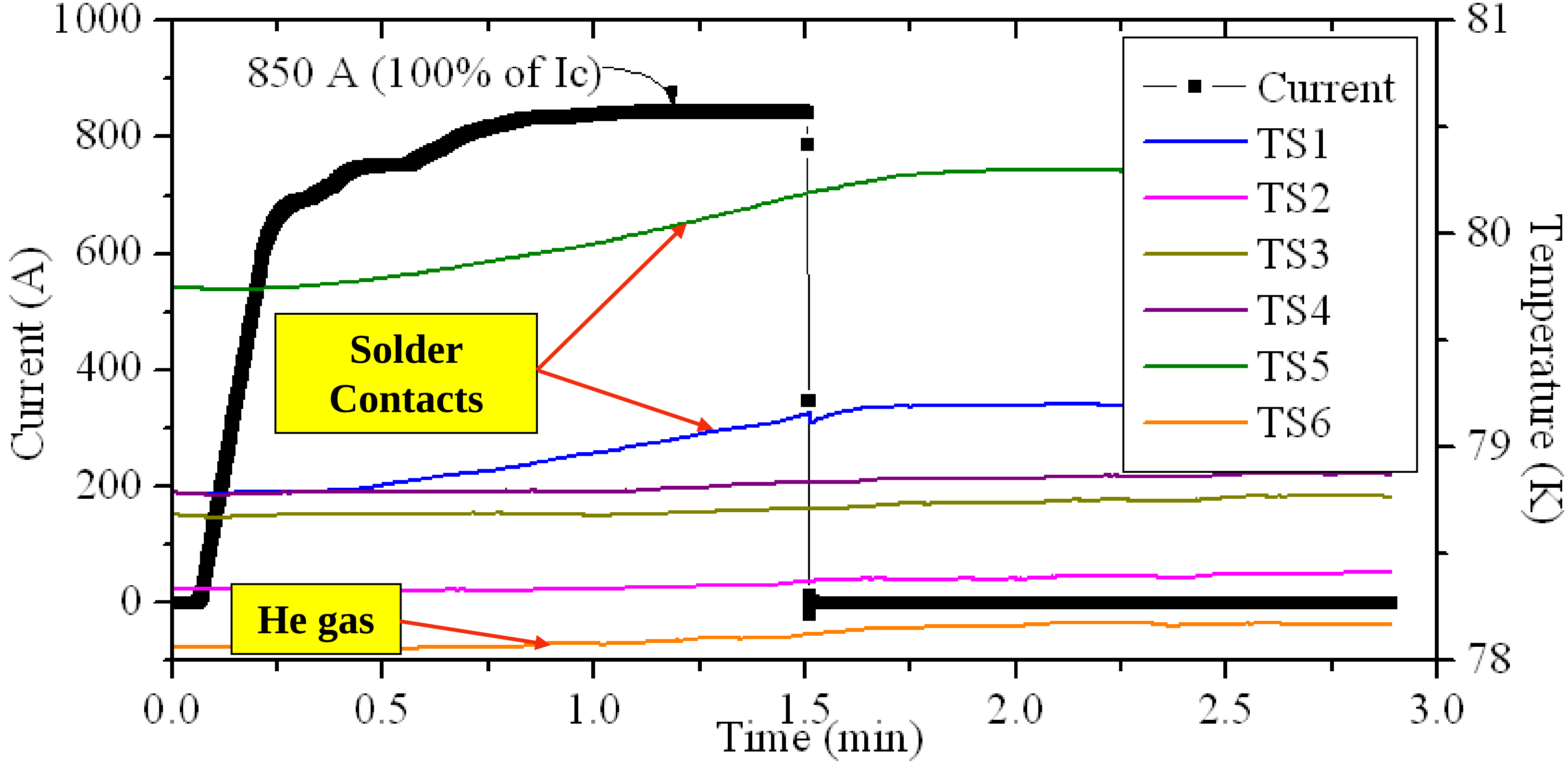
- At 650 A, no voltage creep observed – cable is stable at that current and the heat load from terminals does not affect the cable

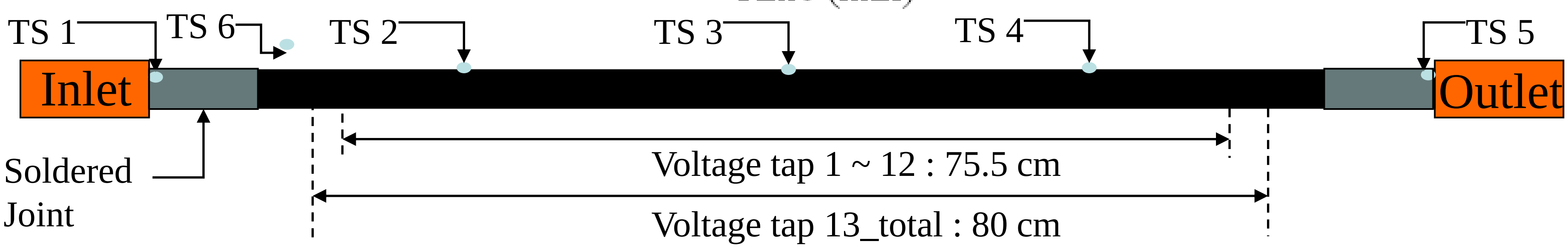




Stability of the Cable in GHe Under 850 A (100% of Ic) at 78 K

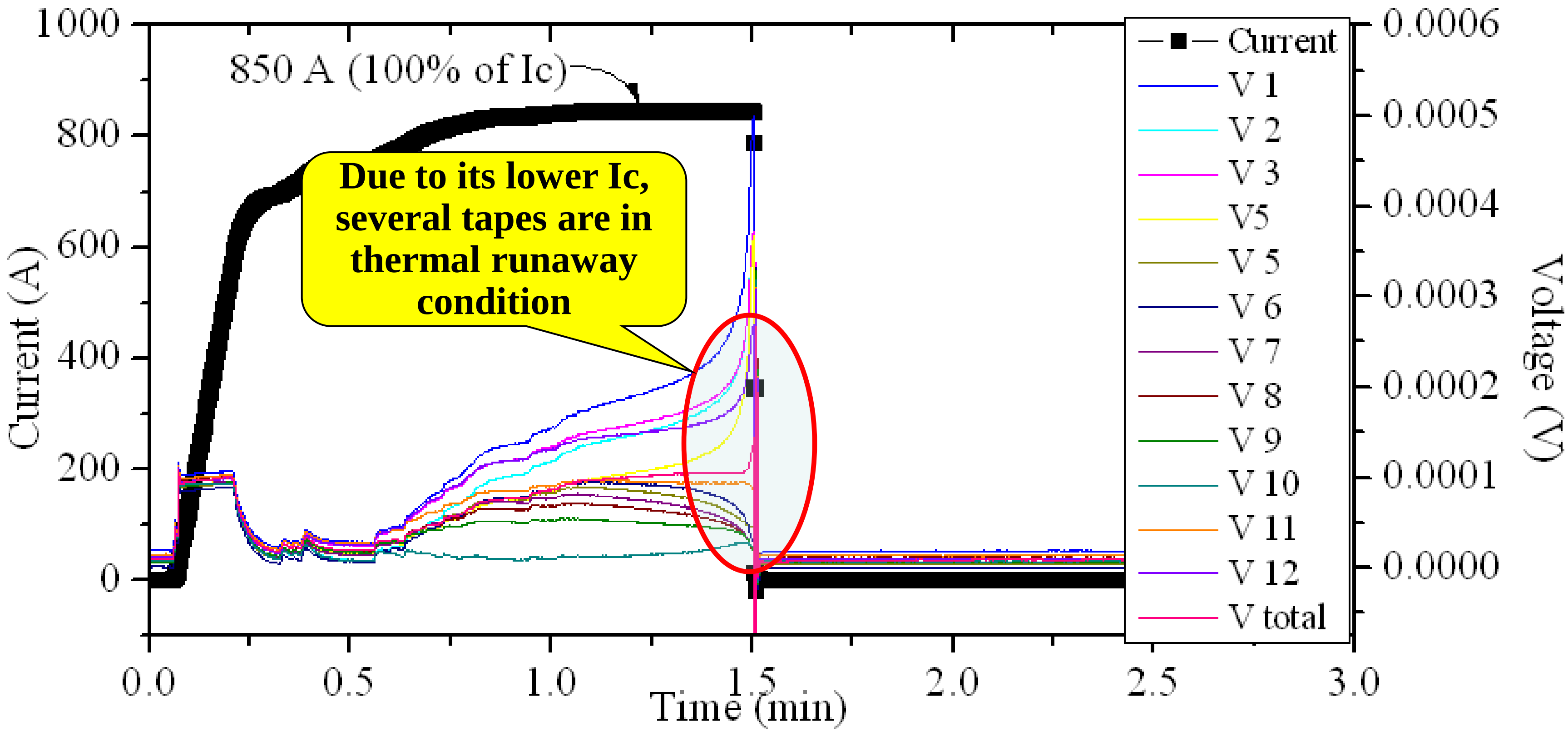
At 850 A, temperature at the terminals and the helium gas stream increases gradually

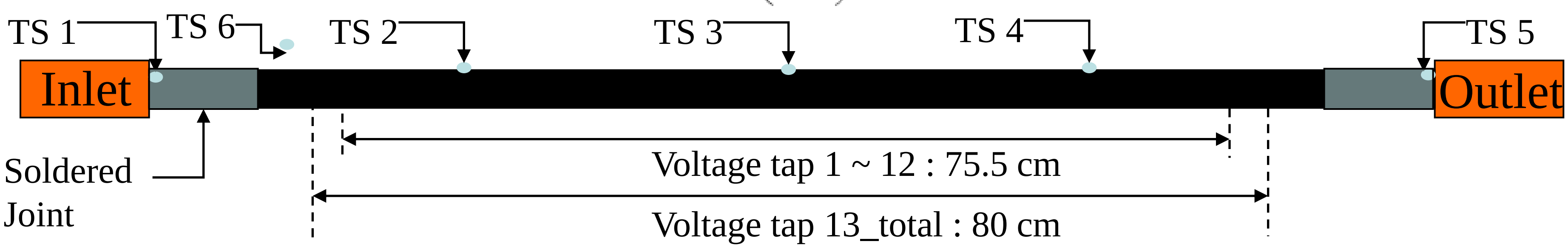




Stability of the Cable in GHe under 850 A Applied (100% of Ic) at 78 K

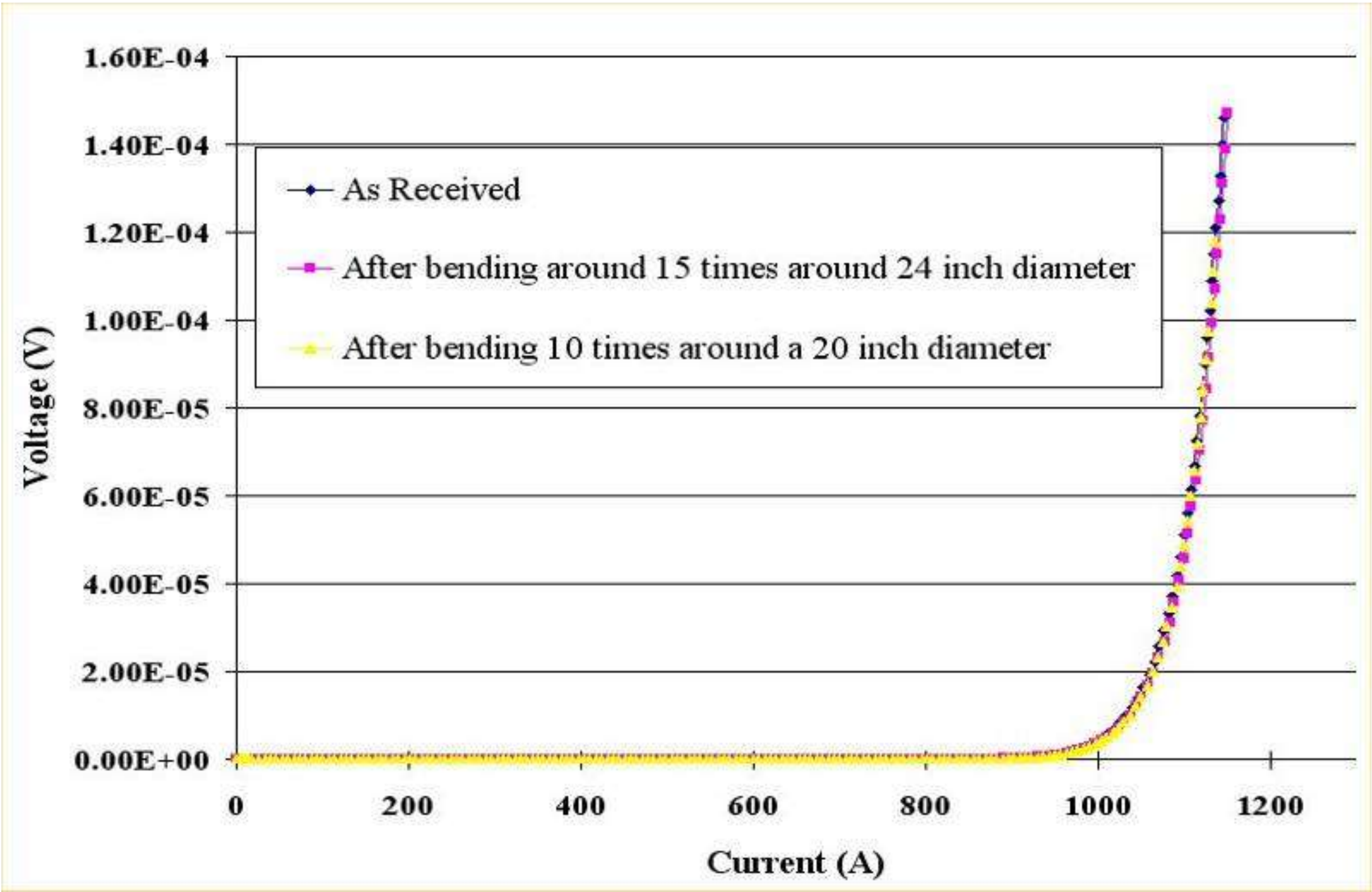
- Voltages increase/decrease rapidly after 1.5 min suggesting thermal runaway
- Complex current redistribution occurs in the transient state





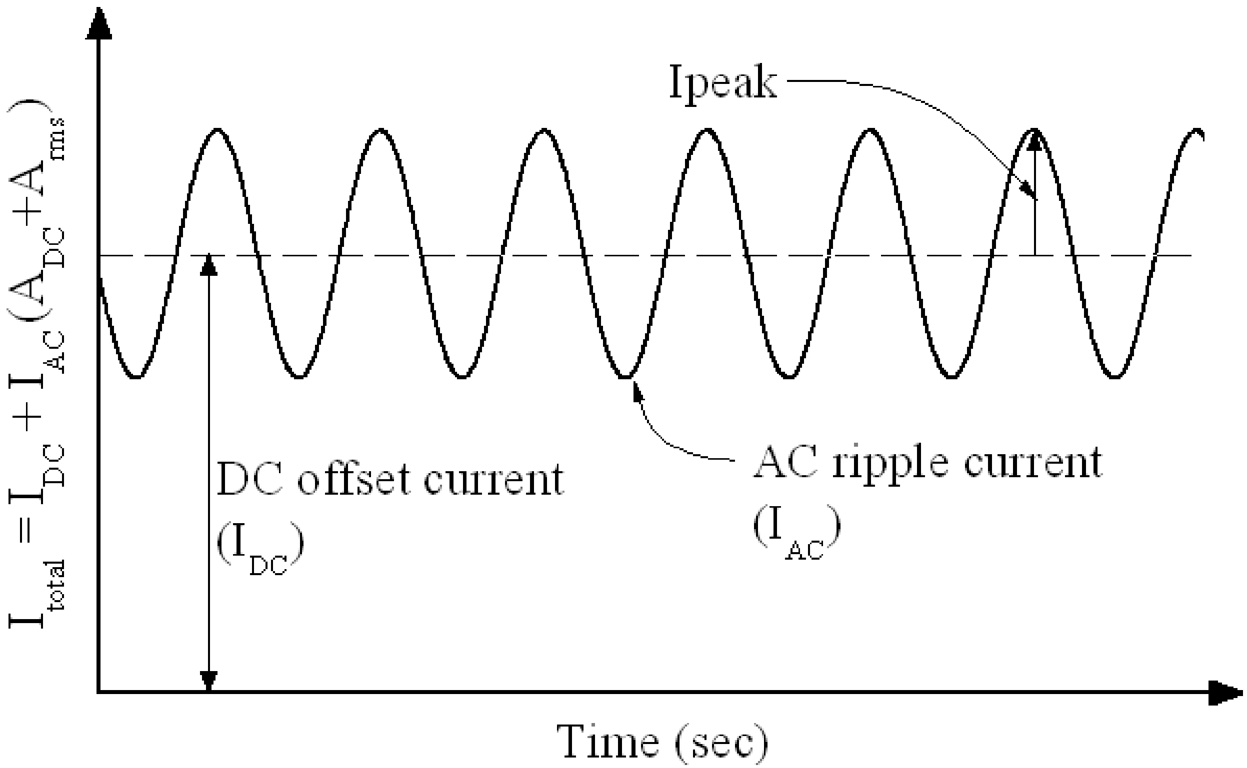
Bend-tolerance tests

Test cables have tolerated multiple bend tests on 24 and 20 inch diameters



Tests and AC Ripple

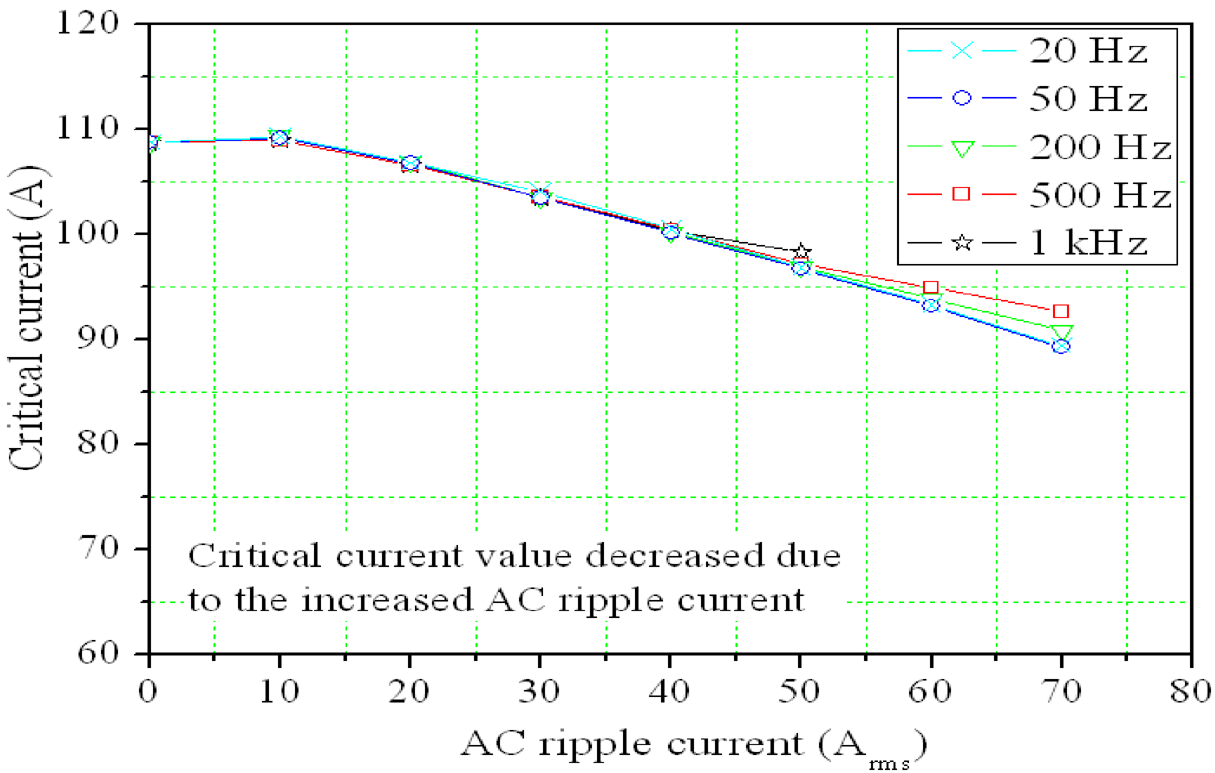
High frequency harmonics and ripple currents due to switching devices of power converters cause losses



- Electrical characteristics and AC losses were studied for several combinations of $\mathbf{I_{DC} + I_{AC}}$ at many frequencies

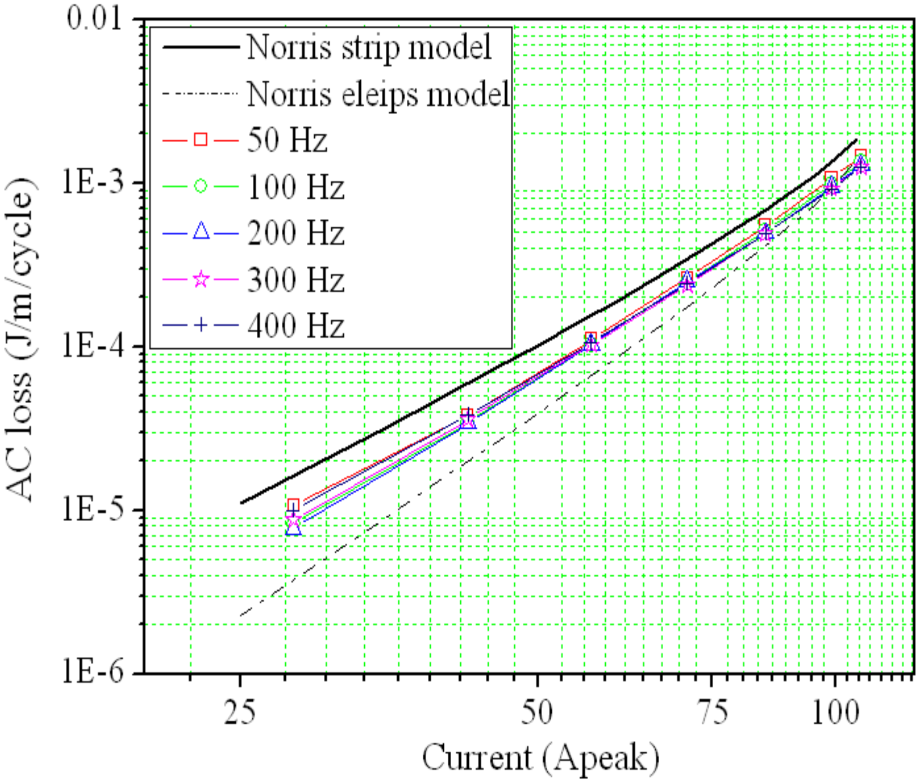
Critical Currents Under AC Ripple

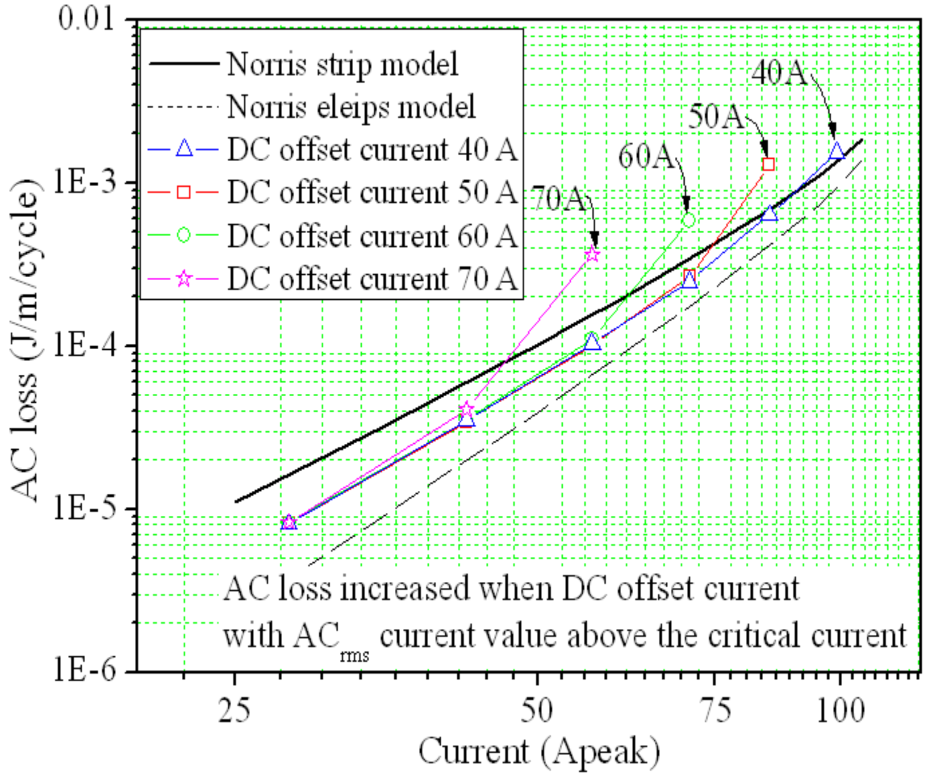
- A preset AC ripple current was applied to the test sample ⟹ the DC current is ramped up until a superconducting to normal transition is observed in the current-voltage trace
- Critical current is recorded as total $I_{DC} + I_{AC}$ when the 1μV/cm criterion is reached.



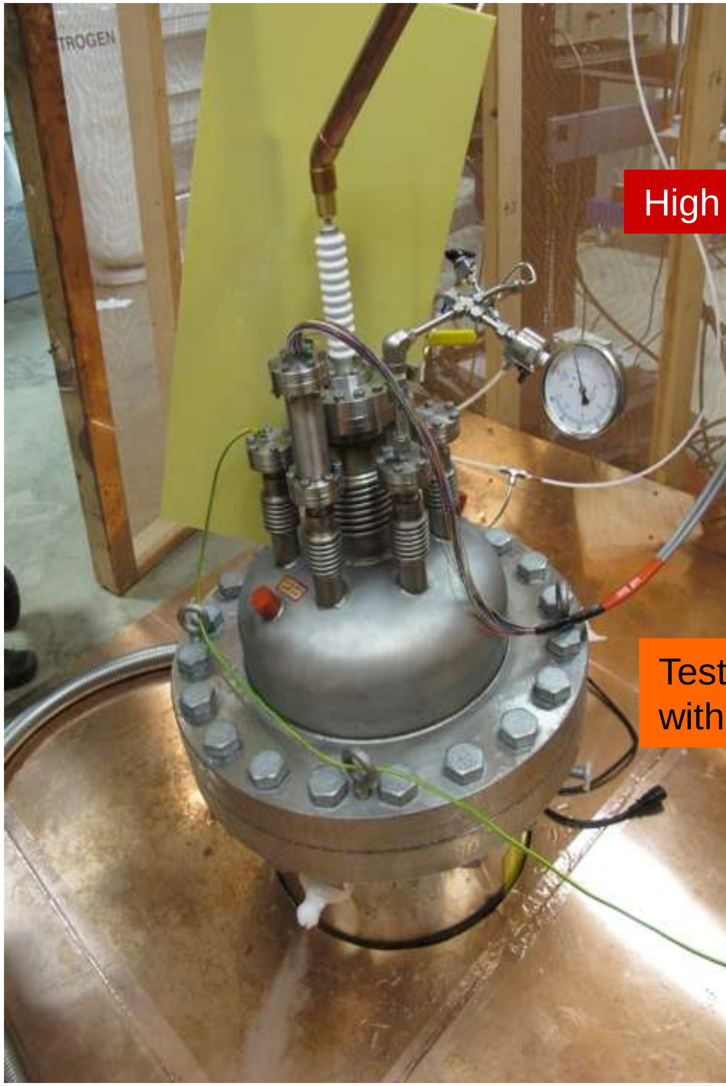
AC Losses Under AC Ripple

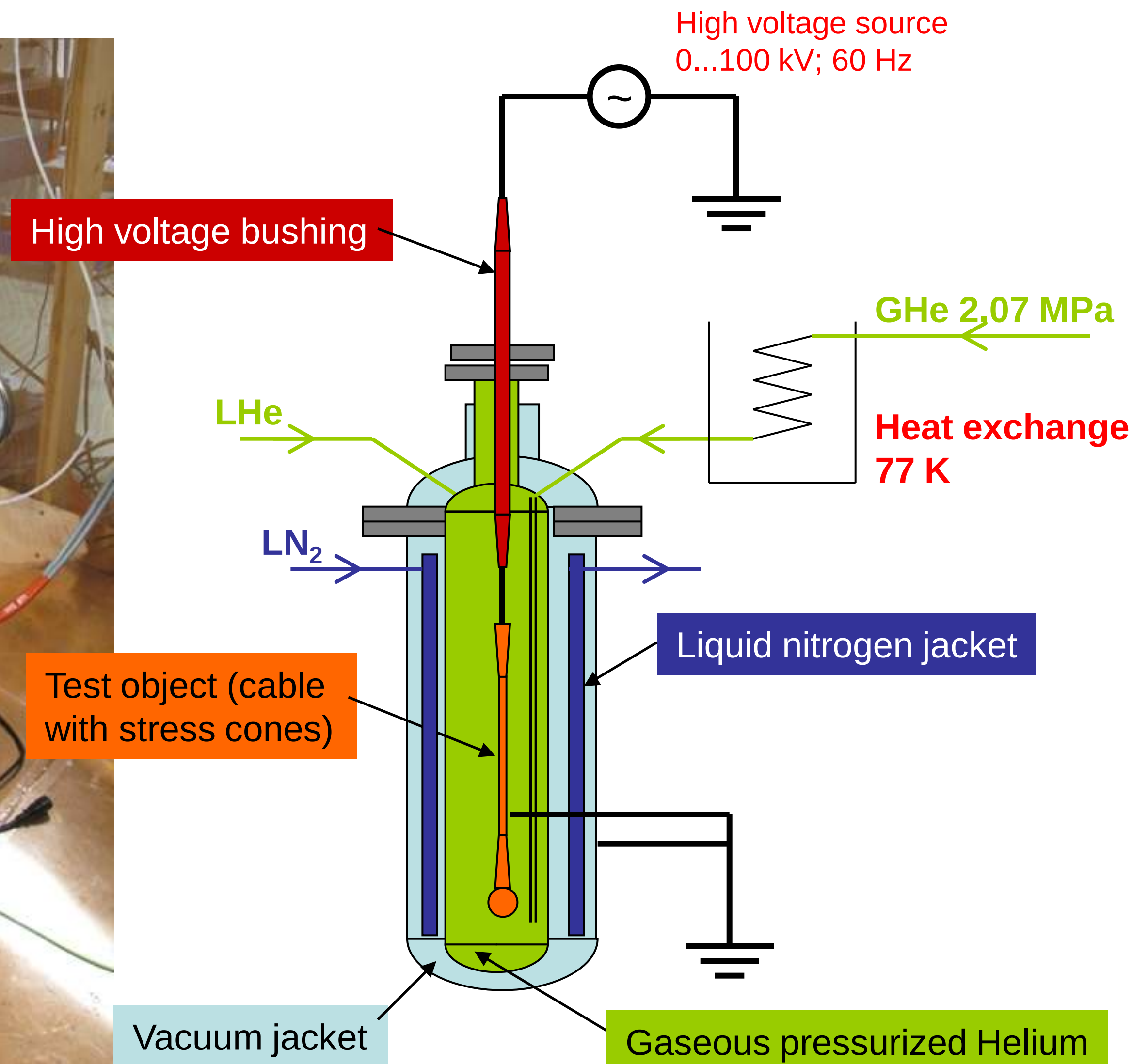
- AC losses are the same for a given IAC with and without DC offset when I_{total} (DC offset + AC rms) is below the critical current
- AC loss increase sharply when I_{total} is above the critical current
- Care should be taken during the operation of superconducting DC cable systems to prevent the AC ripple conditions that cause the total current exceeds critical current of the cable





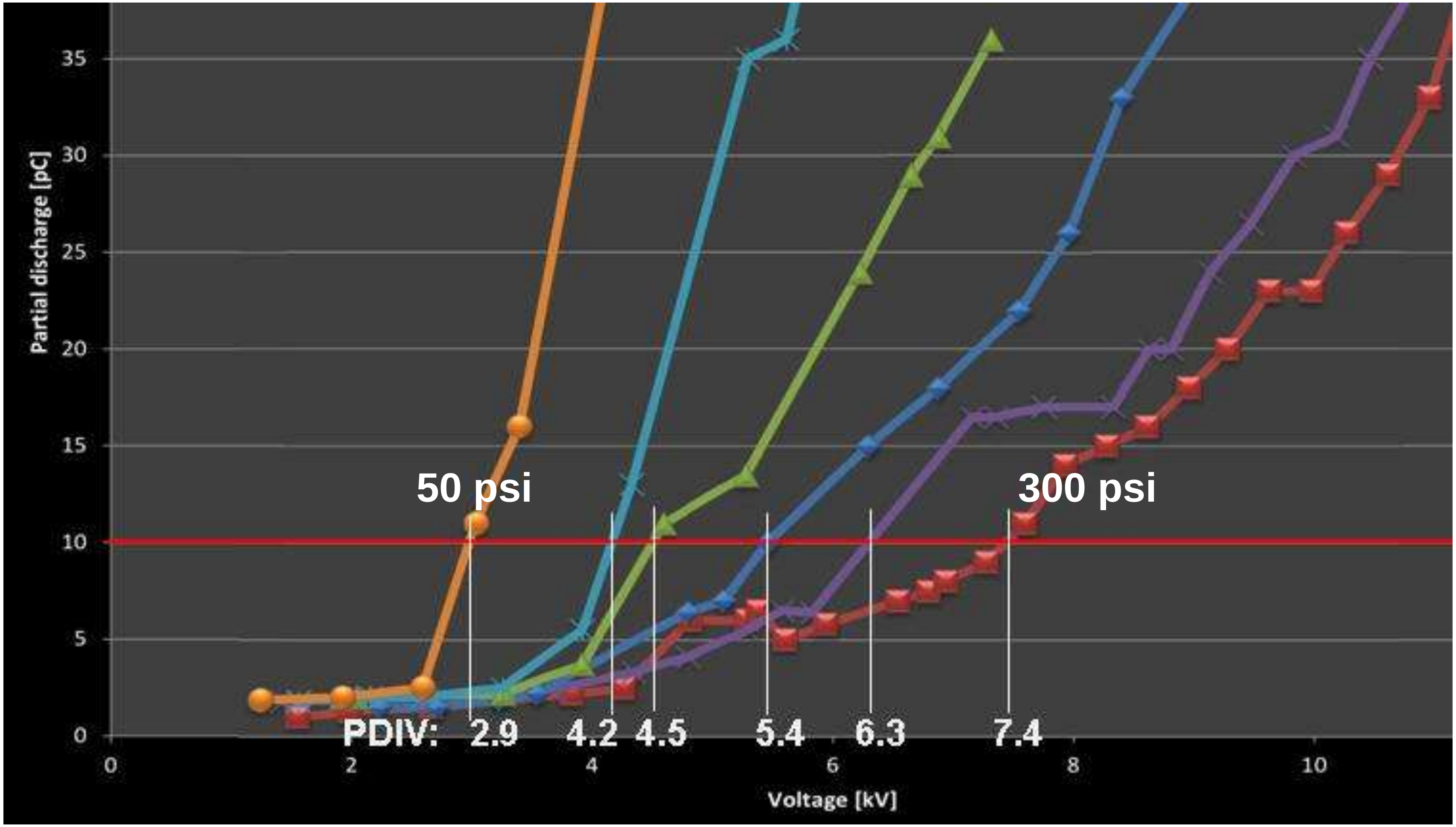
Dielectric Characterization of Cable Sections in GHe Environment





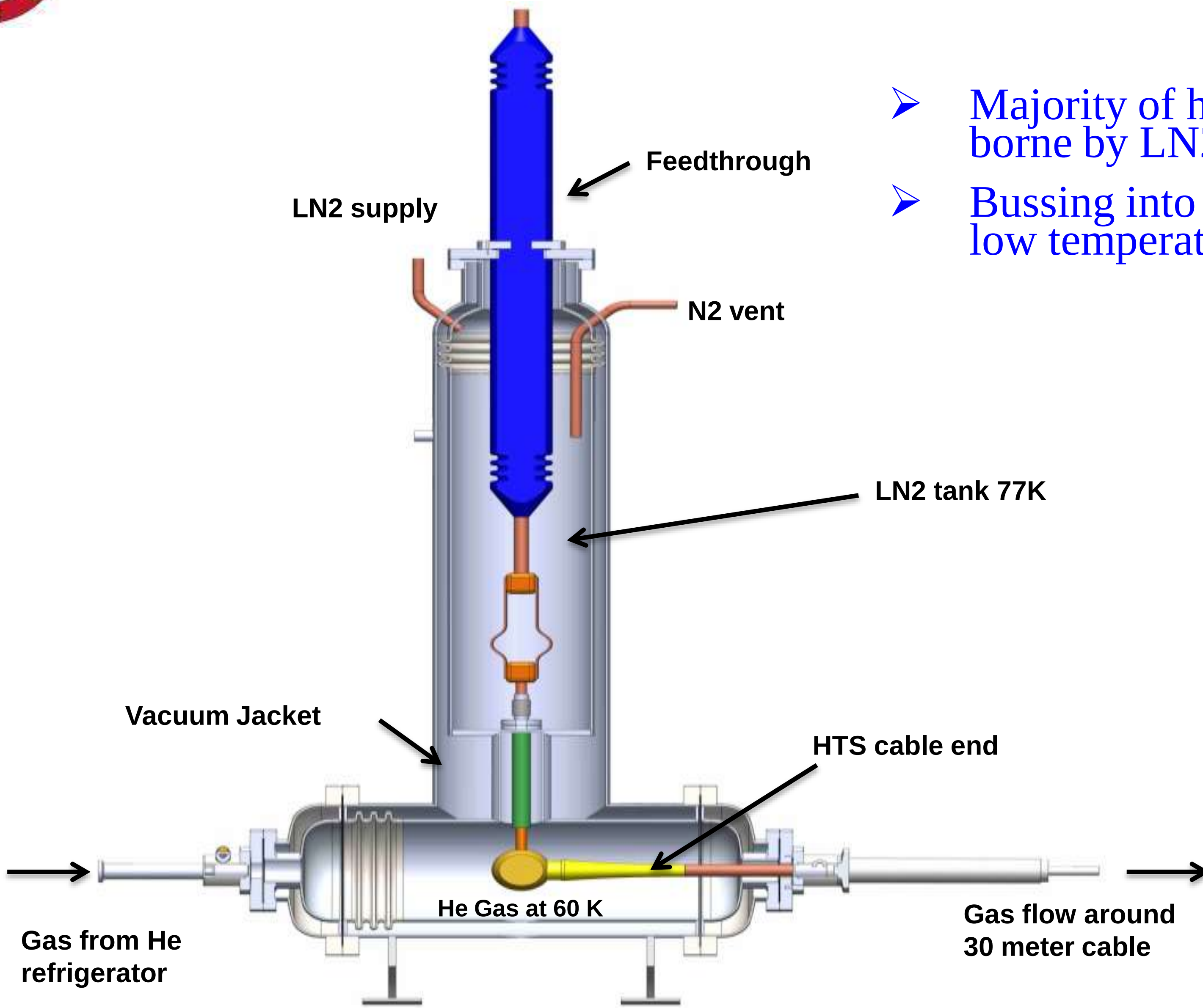
Variation Partial Discharge Inception Voltage with GHe Pressure

- As expected, PDIV increases with GHe pressure
- At 300 psi, PDIV is 7.4 kV peak for the current dielectric design



Conceptual Design of Termination

- Majority of heat leak is borne by LN2
- Bussing into GHe faces low temperature gradient



Summary

- Cryogenic helium circulation system maintains a $\Delta T<4$ K from inlet to outlet of the 30 m cryostat
- Thermal load tests using simulated cable did not create large temperature gradients
- Experimental data on temperature gradients matched with that of the thermal model
- Identical Ic(T) behavior of test cables in LN2 and GHe
- Test cable sections performed well GHe for I < Ic
- Cables are stable up to 120% Ic in LN2, but only at I < Ic in GHe
- Measurements in GHe validated dielectric design for 1 kV monopole – more tests are in progress