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Dielectric, thermal and mechanical properties of insulation systems for quench heaters for the protection of superconducting magnets

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Abstract. High dielectric strength, low thermal resistance and mechanical robustness are conflicting requirements on the insulation system between the superconductors in magnet coils and the quench heaters placed on the coil for active protection in case of a quench. To investigate possibilities to further improve the performance of quench heaters for future superconducting magnets, we have characterised polyimide, PEEK and fibre reinforced PEEK films that can be used to produce large flexibly quench heater circuits. The dielectric strength (at RT and at 77K), low temperature thermal conductivity, tensile strength (at RT and at 77K) and the force needed to puncture the different materials are compared.

Keywords: Superconducting magnet, quench protection, quench heater, dielectric strength, thermal conductivity, PEEK, polyimide, puncture resistance

1. Introduction

Quench heaters for the active protection of superconducting magnets [1],[2] are large flexible circuits that are produced in a photolithographic process [3]. The quench heater base material is a lamination of a thin steel foil, from which the circuits are produced by chemical etching, and an insulating film, which provides electrical insulation between the quench heater circuit and the magnet coil.

The insulating film should have highest possible breakdown voltage under operating conditions to prevent short circuits between coil and heater. On the other hand, the thermal conductivity of the film should be as high as possible to limit the coil hot spot temperature in case of a magnet quench. Another requirement of the quench heater insulation system is that it needs to withstand the mechanical stresses exerted during assembly, thermal cycles and operation of the magnet.

To investigate possibilities to further improve the performance of quench heaters for future superconducting magnets, in the present study we have characterised the dielectric properties, the thermal conductivity, and the mechanical properties of different insulating films made of polyimide, charged polyimide, PEEK and fibre reinforced PEEK.

2. Experimental

2.1 The samples

Polyimide APICAL AV
The 50 µm-thick polyimide film Apical 200AV from Kaneka is the baseline material for the quench heaters used for the HL-LHC interaction region magnets [4],[3]. Samples have been produced by chemically etching the 25 µm thick steel foil from the GTS laminate L960461. After the etching process the 15 µm thick epoxy adhesive GTS AS1084 remains on the polyimide film, and the entire film thickness tested is 65 µm.
Polyimide Apical NP from Kaneka [5].
Polyimide Kapton HN from Du Pont. The ambient temperature thermal conductivity stated by the supplier is 0.20 W/ m K [6].
Polyimide PIT 050 from Mortech Corporation is a 75 µm thick charged polyimide film with enhanced thermal conductivity properties. The ambient temperature thermal conductivity stated by the supplier is 0.46 W/ m K [7].
PEEK XRL2020 from Compolam BV, is a 200 µm-thick, non-reinforced PEEK film. The ambient temperature thermal conductivity stated by the supplier is 0.3 W/ m K.
PEEK XRL2110 from Compolam BV is a 50 µm-thick PEEK film with bidirectional woven glass reinforcement. Mechanical tests have been performed in [0°/90°] and [±45°] direction.

Before dielectric and tensile tests the samples were conditioned according to procedure B of ASTM D618 [8], consisting in placing samples in an air circulating oven at 50 °C for 48 hours, and subsequently placing them in a desiccator for at least 5 hours during cooldown. Samples were then stored in the desiccator until the tests started.

2.2 Puncture resistance tests

Puncture resistance tests have been performed with a dedicated punching tool, using Ø4×100 DIN 9861 D hardened flat type and 45° type steel penetration probes in a matrix with Ø4.05 H8 holes (Figure 1 (a)). The penetration force as a function of displacement is measured with a universal test machine Figure 1 (b).

Figure 1. (a) Technical drawing of punching tool, (b) penetration probes 4×100 DIN 9861 D, flat type, 90° type and 45° type and (c) punching tool installed in the universal test machine.

2.3 Tensile tests

Tensile tests of samples with nominal width of 10 mm and length of 150 mm were performed based on ISO 527-3:2018 [9], with a stroke rate of 50 mm/min, an initial distance between the grips of 100 mm, a displacement resolution of 0.0001 mm and a force resolution of 0.2 N.

2.4 Thermal conductivity test

Thermal conductivity is measured in a cryocooler based test stand. The sample is attached to the cooling platform at the 2nd stage of the cryocooler. The applied heat load at the other sample end generates a temperature difference of less than 500 mK across the length of the sample, which is measured by two clamped Cernox temperature sensors. Each measurement value is derived from a step heating, waiting for equilibrium conditions before changing to the next platform temperature. The sample environment is surrounded by two thermal screens at 35 K. Each step for thermal conductivity requires around 10 h of stabilization including the in-situ calibration of the two temperature sensors for zero applied heat load at the sample. The measurement uncertainty for thermal conductivity is estimated to be $\Delta\lambda=\pm 7.5$ %. A detailed description of the measurement setup can be found in [10].

2.5 Dielectric breakdown tests

Measurements of dielectric strength in dielectric oil or liquid nitrogen can suppress flashover across the electrodes, enabling tests with comparatively small 40 mm × 40 mm samples. Dielectric breakdown voltage tests in dielectric oil with a voltage ramp rate of 500 V/s are based on ASTM D3755-20 [11], using an in-house dielectric strength measurement apparatus [12] consisting of a 0.5 mA, 150 kV FUG HCP 140-150000 DC power supply and 21 mm-diameter brass electrodes. Dielectric tests in liquid nitrogen were conducted using an identical method, but with a 5 mA, 65 kV FUG HCP 350-65000 DC power supply.

2.6 Electrical resistivity test

Electrical resistivity tests in ambient air were conducted based on ASTM D257 [13] with a guarded brass electrode configuration, using a 360 W, Keithley 2260B-800-1 DC power supply and a Keithley 6485 Picoammeter. Measurements at an electrification voltage of 500 V were recorded each 500 milliseconds up to an electrification time of 60 seconds.

3. Results

3.1 Tensile properties

Uniaxial tensile stress-strain curves of the different polyimide and PEEK films acquired at RT and at 77K are compared in Figure 2.

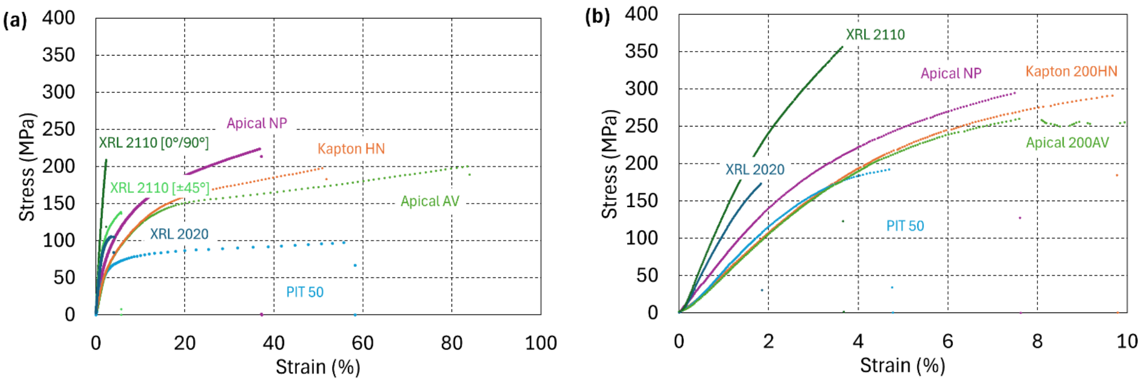

Figure 2. Tensile stress-strain of pure polyimides Apical AV, Apical NP, Kapton HN, of charged polyimide PIT50, of PEEK XRL2020, and of fibre reinforced PEEK XRL2110 measured et (a) RT and (b) 77K.

Average tensile properties of the different materials are shown in Table 1. The PEEK foils exhibit a comparatively high Young's modulus (typical PEEK RT Young's modulus values are between 3.7 and 4.0 GPa [14]).

Table 1. Young's modulus (E), ultimate stress (σ_m) and strain at ultimate stress (ε_{max}). *Including 15 µm epoxy adhesive GTS AS1084.

Material	*Thickness (µm)*	*Temperature*	E (GPa)	σ_m (MPa)	ε_{max} (%)
Polyimide Apical AV-AS1084	65*	RT	2.8±0.1	163±9	92±12
Polyimide Apical 200AV	50	RT	3.2±0.2	195±9	79±5
		77K	5.8	287	16
Polyimide Apical 200NP	50	RT	4.7±0.3	216±22	36±10
		77K	7.8	128	8
Polyimide Kapton 500HN	125	RT	3.4±0.3	200±13	55±7
		77K	5.8	291	10
Polyimide PIT 050	75	RT	3.6±0.1	90±2	51±4
		77K	6.7	192	4.8
PEEK XRL2110 [0°/90°]	50	RT	14±0.6	240±17	2.7±0.3
		77K	14.8	356	3.7
PEEK XRL2110 [±45°]	50	RT	10±0.3	159±5	9±2
PEEK XRL2020	185	RT	8.8±0.3	109±4	3.8±0.5
		77K	12.1	173	1.8

3.2 Puncture resistance

In Figure 3 the force needed to puncture the different films with the penetration probes flat type and 45° type is plotted as a function of probe displacement. In Table 2 the force needed to puncture the different films with the 45° type and flat type probes is summarised, as well as the average force per film thickness. The pure polyimide films exhibit comparatively higher punch through resistance than the charged polyimide, pure PEEK and fibre reinforced PEEK films.

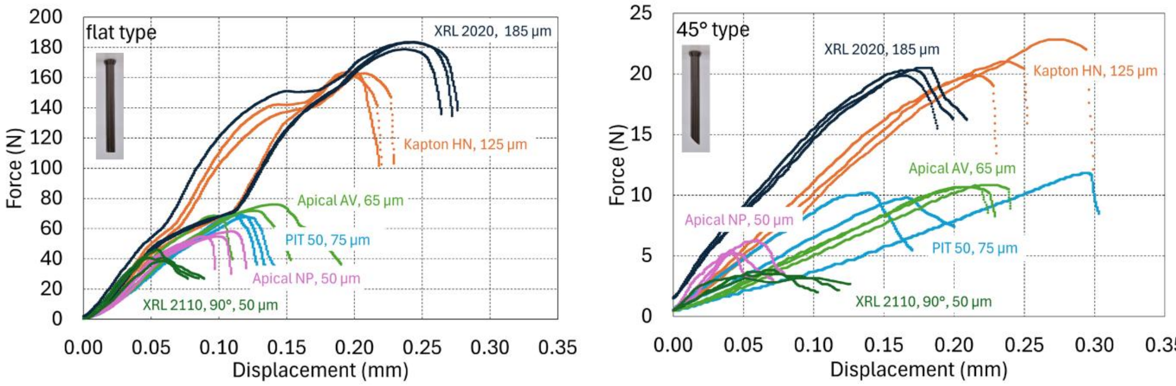

Figure 3. Force vs displacement of Ø4×100 DIN 9861 D hardened steel penetration probes flat type and 45° type through different polyimide and PEEK films.

Table 2. Maximum puncturing force for penetration probes 45° type ($F_{45°}$) and flat type (F_{flat}), and puncturing force per unit film thickness.

Material	*Thickness (µm)*	$F_{45°}$ (N)	$F_{45°}/t$ (N/µm)	F_{flat} (N)	F_{flat}/t (N/µm)
Polyimide Apical 200AV	50	9.7±2.2	0.19	62±4	1.24
Polyimide Apical 300AV	75	11±2.5	0.15	99±11	1.32
Polyimide Apical 200NP	50	5.7±0.5	0.11	56±2	1.12
Polyimide Kapton 200HN	50	9.5±1.4	0.19	58±4	1.16
Polyimide Kapton 500HN	125	21±1.3	0.17	160±1	1.28
Polyimide PIT 050	55	8.6±1	0.16	59±2	1.07
PEEK-S2 glass XRL2110	50	3.5±0.3	0.07	42±4	0.84
PEEK XRL2020	50	5.3±0.2	0.11	40±1	0.80
PEEK XRL2020	185	20±0.3	0.11	180±2	0.97

3.3 Thermal conductivity

Steady-state thermal conductivity data of the charged polyimide film PIT050 between 8 K and 42 K is shown in Figure 4. For comparison thermal conductivity reference data from the NIST Cryogenic Material Properties Database [15] of Kapton and of glass fibre-epoxy composite in the warp direction are shown as well. As expected, the thermal conductivity of the charged polyimide PIT050 film is higher than the reference data of Kapton (pure polyimide). Below 10 K the glass fibre-epoxy composite thermal conductivity exceeds that of the charged polyimide PIT050.

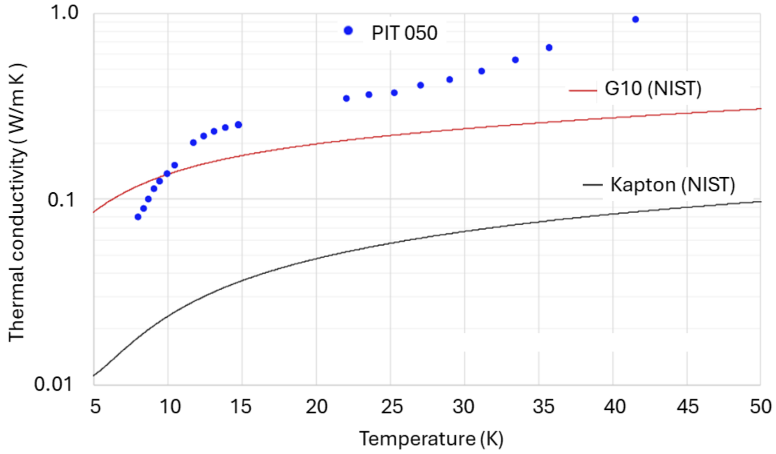

Figure 4. Thermal conductivity of PIT050 charged polyimide film in plane direction, and of Kapton and epoxy composite (G10 in warp direction) reference data from NIST.

3.4 Dielectric breakdown voltage and electrical resistivity

In Table 3 the dielectric breakdown voltage and dielectric strength of the different polyimide and PEEK films is summarised. In dielectric oil at ambient temperature the pure polyimide films Apical AV, Apical NP, and Kapton HN, and PEEK XRL2020 exhibit very high dielectic strength of about 400 kV/mm. The charged polyimide PIT050 and fibre reinforced PEEK XRL2110 have a RT dielectic strength of about 250 kV/mm. At 77K the dielectric strength of the pure polyimide and PEEK films is reduced, while the dielectric strength of charged polyimide and glass fibre reinforced PEEK is increased.

Table 3. DC breakdown voltage and dielectric strength in oil and in liquid nitrogen (LN2). *Including 15 μm epoxy adhesive.

Material	Thickness (μm)	Test medium	Breakdown voltage (kV)	Dielectric strength (kV/mm)
Apical AV	65*	Oil	24.7±0.6	380
		LN2	19.7±1.2	310
Apical NP	50	Oil	20.9±0.2	410
		LN2	16.2±1.4	310
Kapton HN	125	Oil	48.6±2.0	390
		LN2	27.6±2.5	220
PIT 050	75	Oil	18.2±1.4	240
		LN2	19.1±1.9	260
XRL2110	49	Oil	12.0±1.4	250
		LN2	15.4±0.7	290
XRL2020	185	Oil	76.3±5.5	410
		LN2	33.2±1.3	180

Electrical resistivity results are compared in Table 4. The PEEK and fibre reinforced PEEK films exhibit higher RT resistivity than the polyimide films. The charged polyimide has the lowest RT resistivity of the films tested.

Table 4. Resistivity after 60 s at 500 V in air (25 °C, 58% RH). *Including 15 μm epoxy adhesive.

Material	Thickness (μm)	Resistivity (Ω·m)
Apical AV	65*	$8.26×10^{13}±4.58×10^{13}$
PIT 050	75	$1.33×10^{13}±3.27×10^{12}$
XRL2110	49	$3.18×10^{14}±1.16×10^{13}$
XRL2020	185	$7.24×10^{14}±4.37×10^{14}$

4. Discussion and conclusion

High dielectric strength, low thermal resistance and mechanical robustness are conflicting requirements on the insulation system between the superconductors in magnet coils and the quench heaters placed on the coil. Charged polyimide (PIT050) has improved thermal conductivity on the expense of dielectric breakdown strength and punch through resistance. Fibre reinforcement of PEEK (XRL2110) increases the tensile strength but reduces the mechanical punch through resistance. Glass fibre reinforced composites can have 10-fold thermal conductivity at 4.2K as compared to polyimide and may therefore be used as an additional insulation layer to improve the robustness of the quench heater insulation system, with a moderate increase of its thermal resistance.

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