RADIATION HARDNESS OF INSULATING COMPONENTS FOR THE NEW HEAVY-ION ACCELERATOR FACILITY

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Abstract

The planned International Facility for Antiproton and Ion Research (FAIR) will consist of a superconducting double-ring synchrotron offering ion beams of intensity increased by a factor of 100-1000 compared to the existing GSI accelerators. Materials close to the beam tube will be exposed to secondary radiation of neutrons, protons, and heavier particles, limiting the lifetime and reliable function of various device components. The present study investigates the radiation hardness of insulating components with focus on polyimide as electrical insulation and thermal barrier. Dedicated irradiation experiments were performed with different projectiles. Degradation tests of irradiated materials include breakdown voltage and low temperature thermal conductivity measurements. Special attention is given to effects induced by heavy ions (e.g., Ta, Au), because they are known to create extensive damage at rather low doses.

INTRODUCTION

During long-term operation of the new FAIR facility, some parts of the superconducting magnets (sc magnets) will be exposed to high radiation levels, cryogenic temperatures, and dynamic mechanical loads (Lorentzian forces during pulsed operation). Depending on the position, different components will be hit by secondary radiation, showing a complex spectrum of gammas, neutrons, protons and heavier particles [1]. Although the number of heavy particles is small compared to the amount of neutrons or light fragments (*e.g.* alpha particles), their large energy deposition can induce extensive damage at rather low fluencies. Dose calculations show that depending on the angle of beam loss and position of the magnet component, the contribution of heavy ions to the total accumulated dose can reach up to 80%. In contrast to slow projectiles (keV–MeV), producing primarily elastic collisions with target atoms, the energy deposition of relativistic ions is dominated by electronic excitation and ionization processes. In the MeV to GeV energy regime, beam-induced radiation damage strongly depends on the material properties. Most metals are rather insensitive [2], whereas the irradiation of polymeric insulators results in material degradation [3-7]. The degree of damage depends on the specific sensitivity of the material and scales with the electronic stopping power.

Most of the superconducting magnets of the FAIR project will use polyimide to electrically and thermally insulate their conductors or cables. Significant decreases of the dielectric strength of polymeric insulators are observed after irradiation with gamma, neutron and proton of high doses [8-11]. Further, the thermal conductivity of ion irradiated polymers was found to decrease with irradiation dose [12]. To the best of our knowledge not many results are shown in literature with regard to the radiation hardness of polymeric insulators under heavy ion irradiation.

In the present work, we present our results on swift heavy ion and proton induced changes in the dielectric strength of polyimide as well as heavy ion induced changes of the thermal conductivity at low temperature.

EXPERIMENTAL

Material

The polyimide (Kapton HN from Du Pont de Nemours, Apical AV from Kaneka Texas) having a thickness of 50 & 125 (+/- 2) μm were cut into 5x5 cm^2 samples from commercial rolls.

Irradiations

Polyimide samples were irradiated with various ion beams at different facilities. Table 1 lists all irradiation experiments and parameters performed. For clarification only the maximum dose applied is given. It has to be noted that in each experiment different doses were accumulated as seen in Fig. 1 to explore the trend of each irradiation.

In one explicit experiment the temperature rise of a polyimide sample was measured during irradiation with 11 MeV/u Xe beam having a flux of 10^8 ions/cm^2. The increase was found to be less than 2°C during 30 min of continuous ion bombardment. Effects due to a heating through the ion beam is therefore neglected under the given conditions.

Breakdown Voltage Measurements

Dielectric strength tests were performed in ambient atmosphere. Humidity and temperature was controlled during all the measurements (22-24°C and 35-45% humidity). Cylindrical stainless steel electrodes 12 mm in diameter with an edge of 1 mm were used. The voltage across each foil was ramped at 1.2 kV/s until breakdown or up to the limit of the supply (18.5 kV). The voltage was measured by means of a high voltage probe. Current measurement was performed by a voltage divider and a oscilloscope having a minimum current limitation of about 1uA.

After the measurements, the positions of holes induced by the breakdown were measured. The majority of holes was located inside the flat area of the electrodes. This confirms that increased electrical fields, which arise due to the geometry of the electrodes, did not disturb the measurements.

Table 1: Irradiation Experiments

Type of Ion	Max. Dose (MGy)	$-dE/dx_{el}$ (keV/nm)	Kinetic Energy (MeV)	Facility
Protons (H)	82	0.003	21	ITEP
Protons (H)	3	0.0003	800	ITEP
Carbon (C)	4.4	0.21	132	GSI
Nickel (Ni)	50	4	638	GSI
Gold (Au)	10.1	15	2200	GSI
Uranium (U)	4	17	2840	GSI

In our measurements (DC Voltage, ramping rate: 1.2 kV/s) a dielectric strength of about 365 kV/mm is found for a polyimide foil having 50 µm. For measurements under standardized conditions (ASTM D149-91, 60 Hz, AC) [14], the manufacturer specify 240 kV/mm. The higher dielectric strength measured for DC tests are in agreement with the literature [10].

Thermal Conductivity Measurements

The apparatus used to measure the thermal conductivity (λ) of polyimide foils is based on the method of unidirectional heat flow according to reference [15]. One of the two copper blocks fixing the specimen is connected to the cooling finger of a Gifford-McMahon refrigerator (B in Fig. 1).

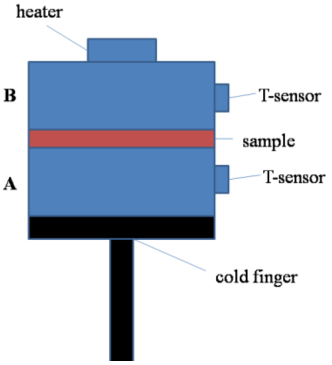

Figure 1: Schematic view of the apparatus used for measuring the thermal conductivity of polyimide foils. Note that for better clearance no cabling or thermal shielding is shown in the figure.

The upper copper block (A in Fig. 1) can be heated via a resistor and the temperature of both blocks is measured using silicon diodes (Fig. 1). Steady state measurements on 125 µm polyimide specimen were performed inside of the cryochamber at a pressure of 2e-6 mbar and mean temperatures from 6-100 K. The thermal gradient applied to measure the thermal conductivity was in the range of 2-3 K. A reproducibility test was performed by cutting 3 different samples out of one pristine polyimide foil. The reproducibility in all 3 measurements was better than 10%. Thermal conductivity was measured in "through thickness direction". The thermal properties of the holder itself are known from reference measurements without sample.

RESULTS AND DISCUSSION

Breakdown Voltage of Ion Irradiated Polyimide

Breakdown voltage measurements of ion irradiated polyimide samples show an overall decrease of the breakdown voltage with increasing dose (Fig. 1). For light projectiles, such as protons and C ions of rather small electronic energy loss (dE/dx between 0.0003 and 0.21 keV/nm), the decrease of the breakdown voltage becomes significant at doses above 1 MGy. In the case of heavy ions (dE/dx > 15 keV/nm), the breakdown voltage changes at a much lower dose (note the semi-log presentation of Fig. 2). The expected maximum voltage in the superconducting coils of the FAIR magnets is about 3 kV. In the tested dose regime up to ~80 MGy, the degradation due to light ions is insignificant for the operation voltage. The situation is much more crucial for heavy ions, where already a dose of a few kGy results in a severe decrease of the breakdown voltage. At around 0.1 MGy, the values are close to the intended voltage requirement for the FAIR magnets. At 1-10 MGy, the material has nearly lost all its insulating properties having a breakdown voltage slightly exceeding the response of 50 µm of air (~700 V).

These results give a first indication that individual damaged tracks completely passing through the polyimide insulation may represent a serious security risk for the insulation of the FAIR magnet coils. Whereas is can be noted that in parts of the accelerator were only light particles or gamma radiation is expected, the insulation is within the specifications.

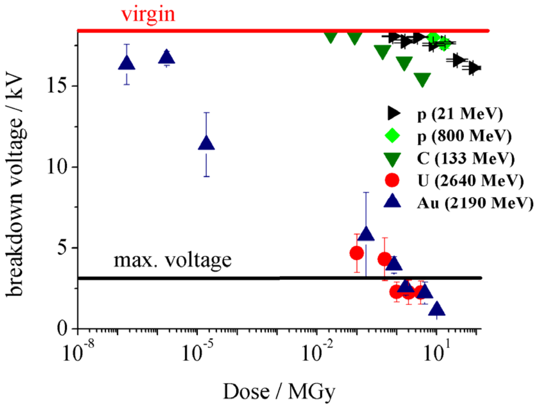

Figure 2: Breakdown voltage of 50-µm thick Kapton foils as a function of dose for various irradiations.

Thermal Conductivity of Irradiated Polyimide

Several groups reported on the thermal conductivity of Kapton-type polyimide over a wide temperature range [16-21]. In all of these works the conductivity is found to be proportional to T in the investigated temperature range. In Fig. 3, a fit of our data (blue line) is compared to plotted fit functions of values given in literature. Due to the different measuring techniques used for determination of this material property, direct comparison of the reported values of λ is difficult. However, it can be seen that the obtained values scatter by a factor of approximately 5 and our measurements on a single 125 µm foil are of the same order of magnitude.

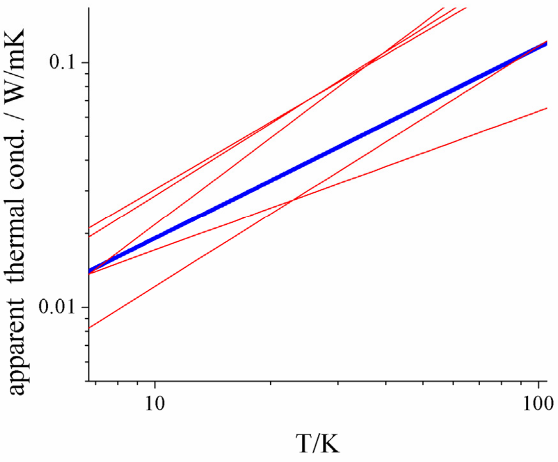

Figure 3: Comparison of the thermal conductivity of polyimide measured in this work (blue line) with curves simulated from the data in Refs. [16-20].

For heavy ion irradiation, the thermal conductivity of polyimide is decreasing with increasing irradiation dose (Fig. 4.). At the maximum dose of 25 MGy of Ni-ion irradiation the thermal conductivity has decreased by 50%, which can be explained by the formation of defects and amorphization. This result is not unexpected since Ref. [22] reported a decrease of the thermal conductivity of polyethyleneterephtalate (PET) irradiated with high energy protons, but also not obvious since it is known that the electrical conductivity of ion irradiated polyimide is strongly enhanced. Since electrons contribute to thermal transport an opposite trend would have also been reasonable. Even though this effect is not as drastic as the change in breakdown voltage it should be considered for future sc magnets that thermal conductivity of polyimide insulations could decrease over operation time. In the case of the quench heater design for the future SIS300 magnets, polyimide is considered for the electrical insulation. As the heater is necessary to warm up the superconducting coils, the dose dependent reduction of the thermal conductivity leads to the conclusion that higher heater powers need to be taken in consideration for long beam time operation.

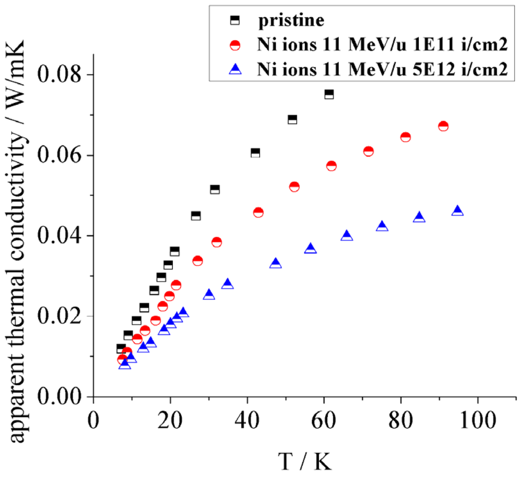

Figure 4: Thermal conductivity of pristine polyimide (black squares) and samples irradiated with 11 MeV/u Ni-ions. The red point and blue point curve correspond to irradiation doses of about 1 and 25 MGy respectively.

SUMMARY

The breakdown voltage of various irradiated 50 µm polyimide foils was investigated. Furthermore, the thermal conductivity of Ni-irradiated 125 µm polyimide samples was measured at low temperatures. The results are summarized as follows.

1. Breakdown voltage of polyimide was found to decrease for all irradiations performed. Light ions make less damage than heavy ions which is explained by individual damaged tracks completely passing through the polyimide insulation created by the heavy ions. For light ions the degree of damage is still within the specifications of the insulation of the later machine. For heavy ions the security limit of the later machine may be reached but more work on precise failure probability calculations are needed.
2. Thermal conductivity at low temperature was found to decrease within the investigated dose regime. For the maximum dose applied (25 MGy of Ni-ions having a kinetic energy of 11 MeV/u) the decrease of thermal conductivity reaches about 50% and should be considered in the quench heater design in future superconducting magnets working in radiation environments.

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