EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN - AT DIVISION

AT-VAC/GS

Vacuum Technical Note 03-02
EDMS No: 371994
February 2003

THIN HEATERS AND THERMAL INSULATION FOR TEMPERATURES UP TO 300°C IN A RADIOACTIVE ENVIRONMENT

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Table of Contents

1. Introduction

The vacuum chambers for the LHC experiments (ALICE, ATLAS, CMS and LHCB) need to have distributed heating to activate the internal Non-Evaporable-Getter (NEG) pump. In certain locations, the heating system, consisting of an electric heater and thermal insulation, stays in place during machine operation. The request from the experiments is that the permanently installed heaters are transparent to particles, reliably heat to NEG-activation temperature, are as thin as possible and low cost. The thermal insulation must have additionally low thermal conductivity.

A study was made in order to find in-situ bakeout equipment that fulfils this request. This note compiles materials, manufacturing techniques and experiments made with spray deposited heaters, polyimide foil heaters, multilayer insulation, ceramic powder and polyimide foam insulation.

Aerogel thermal insulation and classical bakeout heaters [1] such as heater strips in glass cloth or co-axial heaters are not discussed here. The heaters were not qualified to meet with standard norms for electrical equipment.

2. Design parameters

The following parameters were defined for the specification and test of all materials:

- Minimum temperature resistance 300 °C
- Minimum 5 MGray irradiation resistance
- As thin as possible
- As transparent for particles as possible
- Safe and reliable operation
- Low cost

3. Overview of development and tests performed

All tests performed were made in order to simulate the environment close to the IP of the experiments, both during machine operation and NEG-activation.

Polyimide tape, resin, foam and foil heaters, were submitted to irradiation up to 5 MGray from a Cobalt 60 source.

Chapter 4 describes the design, attachment and test of heaters. The spray deposited heaters and the polyimide foil heaters needed development for this application. New processes for the attachment of the polyimide foil heater to tubes were developed, using a special polyimide resin or polyimide band impregnated with polyimide resin on one side. The manufacture of the spray deposited heaters are described in detail in an existing note [2].

Chapter 5 describes attachment and performance of different thermal insulation materials on the heaters. Thermal cycles and/or heating for longer durations were made for all heaters.

Chapter 6 gives an overview of the irradiation treatments performed up to 5 MGray on the polyimide foil heaters with both attachment methods and the two types of polyimide foam insulations.

4. Heaters

4.1 Spray deposited heater

A first feasibility study by EMPA (Eidgenössische Materialprüfungs- und Forschungsanstalt) and CERN[2] was made to develop beam tubes with a thermally sprayed heating system. This heating system as seen in Figure 1 is made in the following manufacturing steps:

- Thermally spray electrical insulation (ceramic)
- Mask all parts except for resistor
- Thermally spray Resistor (Stainless steel or Titanium)
- Remove mask
- Attach electrical connection
- Electrical and thermal insulation as top layer (thermally sprayed ceramic or chemically deposited polyimide)

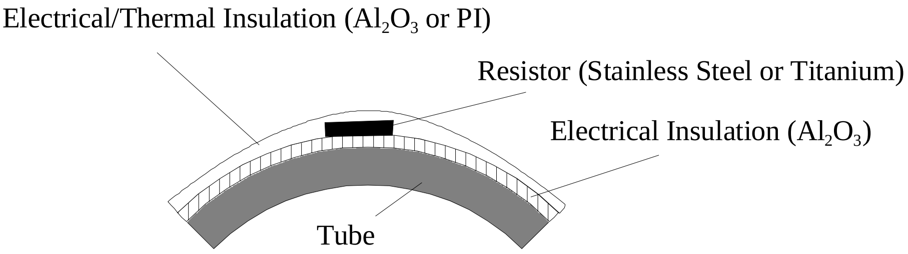


Figure 1: Layers of spray deposited heater

After this study, a collaboration contract (CERN collaboration agreement No. K522/LHC) between CERN and EMPA was made with the aim of optimising this heating system and studying various dimensions and materials. Within the framework of this contract, EMPA delivered 7 tubes with a thin deposited heating system to CERN. All tubes have an overall diameter (OD) of 60 mm and a wall thickness of 0.8 mm. Examples are shown in Picture 1.

The tubes have either the connection on only one side (U-Type) or on both sides (Linear Type), as seen in Figure 2.

The electrical connections were made by thermally spraying aluminium on top of the resistor and fixing the lead in the sprayed material (see Picture 2 and Picture 3).

Properties of the coating materials are given in Table 1.

The various tube and material combinations tested are shown in Table 2.

Picture 1: Tubes delivered by EMPA before (top) and after (bottom) top ceramic coating

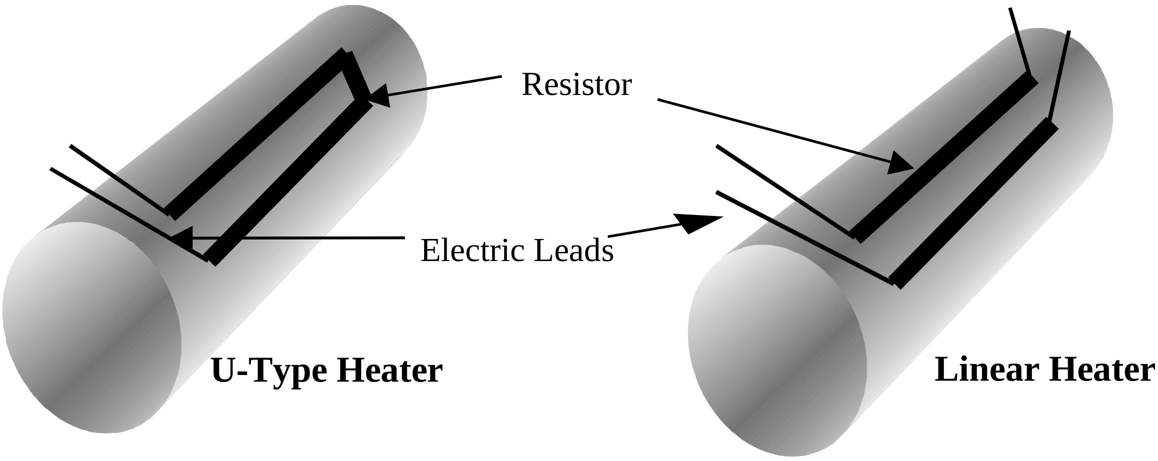
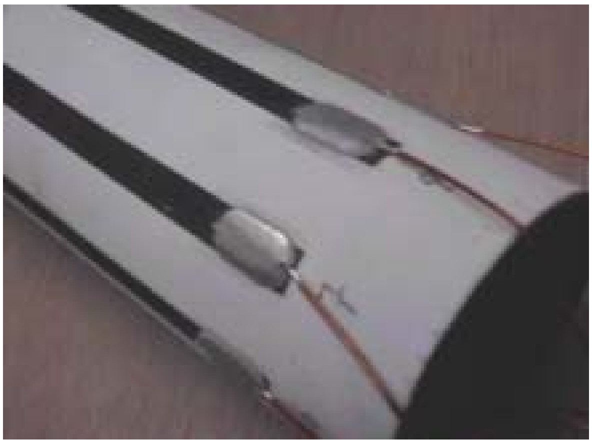


Figure 2: U-type and linear heater



Picture 2: Electrical connection without top layer

Picture 3: Electrical connection with top layer

Table 1: Spray coatings and their relevant properties

Application	Coating material	Description of property	Thickness
Electrical insulation between pipe and heating lines	Alumina (Al_2O_3)	Electrical insulation Specific Resistance R = 1 to 10 MΩ/mm	0.15 mm +/- 0.05 mm
Resistor	Stainless Steel 316 L or Titanium	Resistivity R = 50 to 100 Ω/m	0.08 mm +/- 0.02 mm
Electrical and thermal insulation of the resistor	Alumina (Al_2O_3) or Polyimide	Electrical insulation Resistivity R = 1 to 10 MΩ/mm	0.15 mm +/-0.05 mm (for Al_2O_3)
Total thickness of the heater:			0.38 mm +/- 0.12 mm
Electrical contact between resistor and power supply wires	Aluminium	Mechanical Connection Rupture force: 30 to 100 N per cable [3]	1.25 mm +/- 0.25 mm

Table 2: Coated tubes delivered by EMPA

	Tube Material	Resistor Material	Resistor Shape (Number) See Figure 2	Top Layer	Length
Tube 1	Stainless steel	Stainless steel	U (4)	Al_2O_3	1 m
Tube 2	Stainless steel	Stainless steel	U (4)	Polyimide	1 m
Tube 3	Stainless steel	Titanium	Linear (8)	Al_2O_3	1 m
Tube 4	Stainless steel	Stainless steel	Linear (8)	Al_2O_3	2 m
Tube 5	Stainless steel	Stainless steel	U (4)	Al_2O_3	2 m
Tube 6	Aluminium	Stainless steel	U (4)	Al_2O_3	1 m
Tube 7	Aluminium	Titanium	Linear (8)	Al_2O_3	1 m

4.1.1 Experiments performed

All tubes were heated in insulation vacuum with a pressure in the order of 10^{-2} Pa using their own resistor as heater.

All stainless steel tubes were heated to 300 °C, all aluminium tubes were heated to 250 °C. Tube No. 7 was cycled 50 times between room temperature and 200 °C, and 50 times between 200 °C and 250 °C.

4.1.2 Discussion of tubes and the thermal cycling

All tubes delivered by EMPA to CERN could be heated up to 300 °C, with the exception of the aluminium tube, which can only be heated to 250 °C maximum due to the aluminium material properties.

The polyimide top-layer of tube 2 showed to be inefficient since the electrical insulation was very poor. Holes in the polyimide were detected using an electrical short circuit tester. We suppose the reason is the very thin polyimide layer compared with the rough surface of the stainless steel resistor. With additional effort, this problem might be overcome.

Cyclic testing shows that results are repetitive and a power can be fixed to heat at a given temperature without regulation system [2].

Thin walled tubes ($ø_{ext}$ 60x0.8 mm) of stainless steel and aluminium can be used as base material. An Al_2O_3 ceramic seems to be a robust electrical insulator. Titanium and stainless steel can be used as a resistor. Top coatings of Al_2O_3 seem to be robust.

The electrical connections developed by EMPA work well, they resist to a transverse "pull-out" load [3] up to 100 N and to a cyclic test of heating.

4.2 Polyimide foil heater

Polyimide foil heaters are made out of a thin resistive foil circuit laminated between two polyimide foils, see Figure 3. Various types of polyimide foil heaters can be found on the market. Those described here consist only of a stainless steel resistor and polyimide. Due to the material used and the manufacturing process, the use of epoxy resin could be avoided, so that the temperature and irradiation resistance was improved.

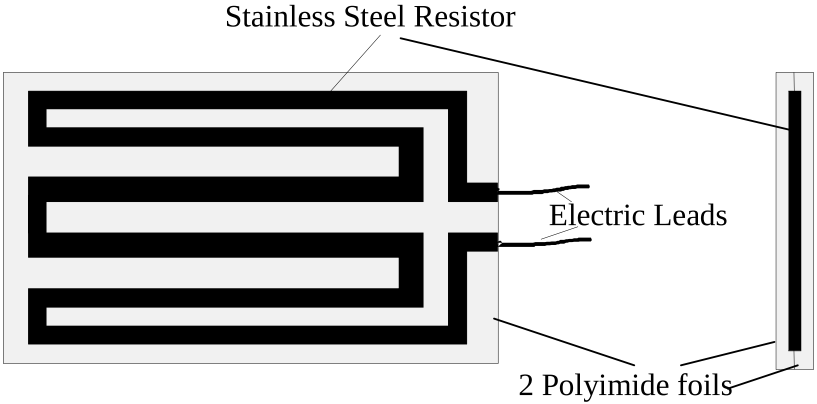


Figure 3: Polyimide foil heater

Some heaters were tested without the second polyimide foil, so the electric circuit was not insulated in the "as received" state. Two heaters of this type mounted to a 1.1 m long tube of diameter 60 mm can be seen in Picture 4. This heater was electrically insulated on the outside using a polyimide tape.

Picture 4: Polyimide foil heater without top layer mounted to a tube diameter 60 mm.

The materials used for the polyimide foil heater can be seen in Table 3.

Table 3: Composition of a polyimide foil heater

Foil	Application	Description of property [4]	Thickness
Polyimide	Electrical insulation	Radiation length 28.6 cm Density 1420 kg/m^3	55.9 µm
Inconel 600 Stainless Steel	Resistive heater	Radiation length for iron 1.73 cm 7870 kg/m^3	12.7 µm
Polyimide	Optional electrical and thermal insulation	Radiation length 28.6 cm Density 1420 kg/m^3	55.9 µm
Total thickness of the heater:			124.5 µm

Table 4: Polyimide foil heaters delivered by Rica [#]. The base material is always a polyimide foil and the resistor is Inconel 600.

	Top Layer	Length	Width	Mounting Method	Total Thickness (heater + mounting)
Type 1	Polyimide Foil	500 mm	148 mm	Polyimide Resin	About 200 µm (estimated)
Type 2	No top layer	550 mm	180 mm	Polyimide Tape	About 180 µm
Type 3	Polyimide Foil	3410 mm	180 mm	Polyimide Tape	About 230 µm

4.2.1 Manufacture of the polyimide foil heater

Dupont and Kaneka were the only two suppliers of polyimide foil found. The trade names are “Kapton HKJ” [5] for the Dupont product, and “Pixeo” for the Kaneka product. The polyimide foil used is special since it has a polyimide resin on one side of the foil, to which the stainless steel foil can be bonded under pressure and temperature in the order of 200 °C to the polyimide. Minko[##] and Rica are the only companies found that produce these polyimide foil heaters out of the base materials (polyimide, stainless steel foil and connecting leads). All heaters delivered to CERN were produced by Rica, since the useful surface of the bonding press is 600 mm x 600 mm. At the time of buying the heaters the useful surface of the bonding of Minco was only 400 mm x 400 mm, which would have resulted in smaller patches.

The production steps are the following:

- bond one layer of polyimide with the stainless steel foil
- etch the resistive circuit out of the stainless steel foil
- bond a polyimide top layer on the resistive circuit, with the exception of the electrical connection (not used in heater Type 2)
- make electrical connection by spot resistive welding
- close top layer polyimide around the electrical connection (not used in heater Type 2)

The maximum patch length was 550 mm, with an electrical connection of 20 mm on one side for the single patch (Type 2) and end patch (Type 3), and 20 mm connection on either side for the intermediate patches, see Figure 4. The Type 3 was used as the

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[#] RICA, Zoppas Industries, Vittorio Veneto, Italy

[##] MINCO, Sinrach, Switzerland

prototype polyimide foil heater for the ATLAS Inner Detector and made out of 6 elements to achieve the total length of 3410 mm. Two of these heaters were mounted on a 7.2 m long beam pipe of diameter 60 mm.

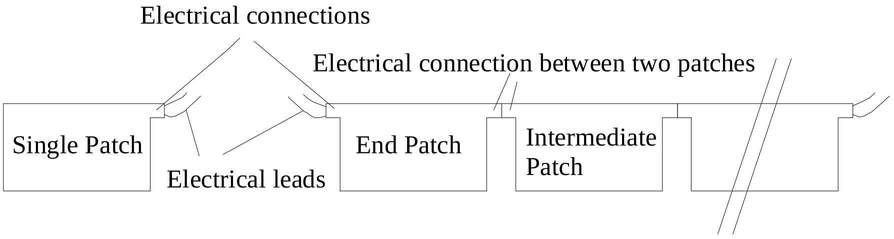

Figure 4: Electrical connection of patches

4.2.2 Polyimide foil heater bonded to a tube with polyimide resin

4.2.2.1 Mounting the polyimide foil heater with polyimide resin

A polyimide resin was found to glue the foil heater to the tube: “Resine polyimide isolante P100” by Epotecny/France.

Mounting steps

- Both the tube surface and the polyimide foil heater surface were covered with the polyimide resin.
- A polyimide foil heater was wrapped around the tube.
- A wire mesh was wrapped around the polyimide foil heater.
- Three foils consisting of a polyimide foil, aluminium foil and polyimide foil were wrapped around the wire mesh to better re-distribute the load from a clamp (used to compress the assembly) and to reduce the heat loss during curing.
- A clamp consisting of a tube in two half shells was mounted in order to press the layers to the tube.
- Evaporation of the solvents at 150 °C under vacuum for 1 hour.
- Final curing at 275 °C under vacuum for 1 hour.
- Demount everything apart the polyimide foil heater.

4.2.2.2 Thermal conduction test made on aluminium tube with bonded polyimide foil heater

A test was performed with the tube in an insulation vacuum tube as seen in Figure 3 to verify three things at the same time:

- Whether bonding the polyimide foil heater to a tube is practical
- Whether conduction heating over part of the central beam pipe for ATLAS could be an option
- Whether gold coating would be an effective reflector under insulation vacuum

One Type 1 polyimide foil heater (Table 4) was bonded to a 1.8 m long aluminium tube of OD 53 mm with 1.5 mm wall thickness, as seen in Figure 5.

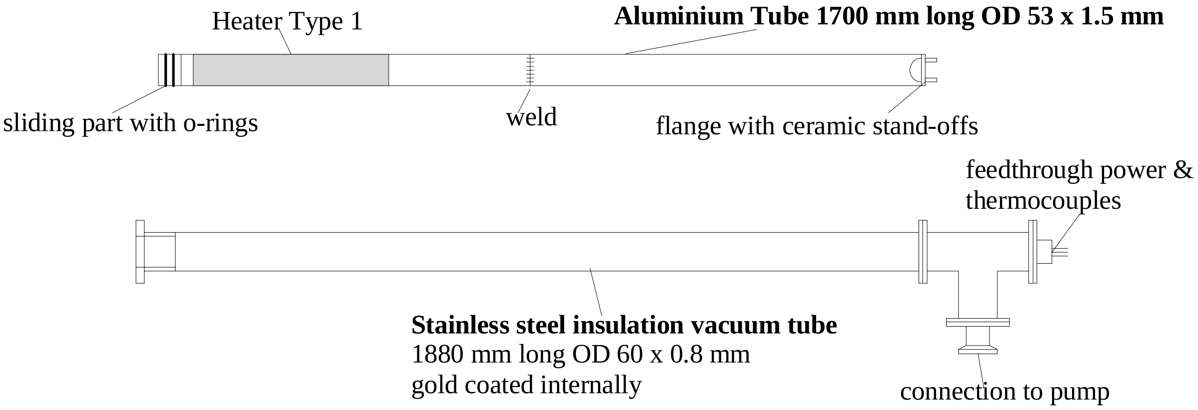

Figure 5: Polyimide foil heater bonded to aluminium tube and insulation vacuum chamber

The assembly was put in a tube of overall diameter 60 mm with 0.8 mm wall thickness, which served as insulation vacuum tube. To reduce the heat loss, the insulation vacuum tube was gold coated internally. No additional reflector material was added between the two tubes. This test should verify whether conduction heating over part of the central beam pipe for ATLAS could be an option. A double wall chamber would be used, one for the beam vacuum and one for the insulation vacuum.
The part of the tube which had the polyimide foil heater was heated up to about 250 °C.
The pressure in the tubes was in the order of 10^{-2} Pa.
After the tests performed, the tube was cut to 0.7 m length for the irradiation tests with intermediate bakeout cycles, as listed chapter 6.

4.2.2.3 Result of the thermal conduction and bonding test

The tube was heated to 250 °C. The temperature profile at various times beginning at the start of the bakeout can be seen in Figure 6.

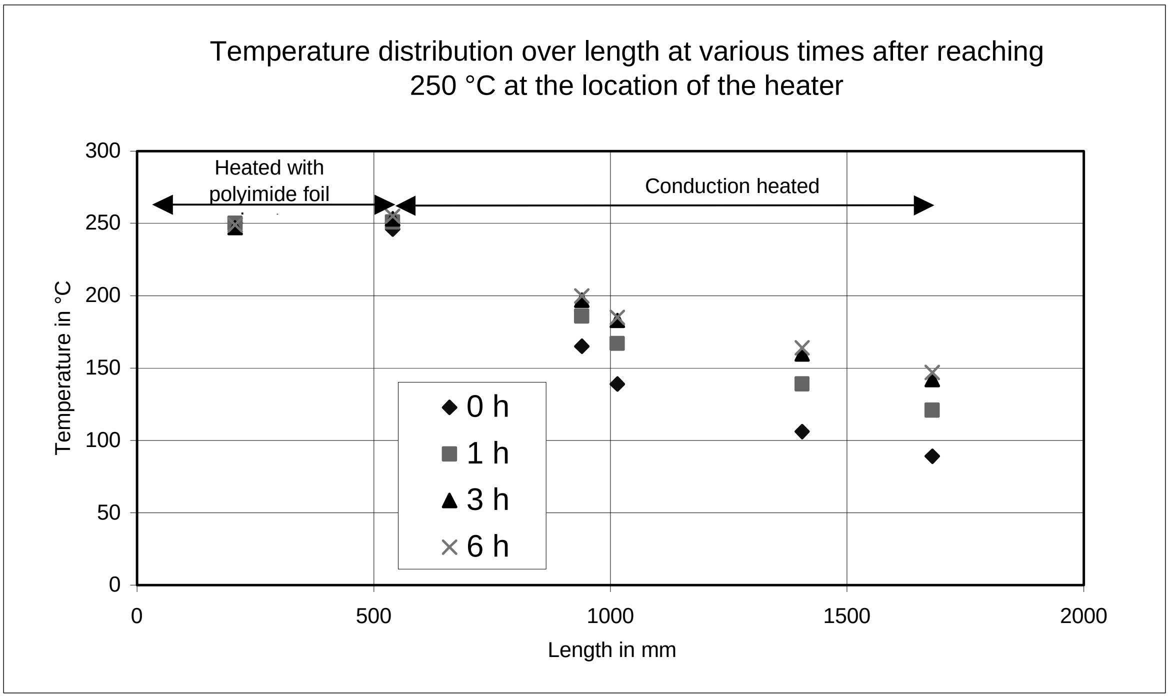

Figure 6: Temperature distribution of alumiumium tube in gold coated insulation vacuum tube

In total, the tube was heated 4 times between room temperature and 250 °C before irradiation. All irradiation tests are listed in chapter 6. In-between and after the irradiation tests, the tube was heated up additionally 4 times. No damage could be observed on the polyimide resin or on the polyimide foil heater.

4.2.2.4 Maximum temperature test

Two type 1 heaters were glued to a 1 m long stainless steel tube of diameter 48 mm. This tube was than thermally cycled 7 times under vacuum between room temperature and 350 °C. The time the tube stayed at 350 °C was 8 hours for each thermal cycle.
The heater and the glue withstood the temperature cycles. The colour of the heater changed from the “normal” polyimide foil brighter brown to a dark brown.

4.2.3 Polyimide foil heater mounted with polyimide tape

4.2.3.1 Mounting of the heaters

The process was inspired by the insulation procedure used for the cold bores of the LHC cryomagnets. Polyimide tape with a polyimide resin on one side similar to the foils used for the heaters and a thermo-retractable tape are used for this mounting process. This mounting process was used for the heaters Type 2 and Type 3. The pictures below were taken during the mounting of Type 3. The mounting process is described in more detail in a note [6].

Mounting procedure:

- Mount the polyimide foil heater around the tube, as seen in Picture 5	 **Picture 5**
- Roll polyimide tape around the heater, with an overlap of 50 %, as seen in Picture 6	 **Picture 6**
- Wrap thermo-retractable tape around the polyimide tape, as seen in Picture 7 (Polyester Tape, Type 117803, from Fratec AG/ Switzerland)	 **Picture 7**
- Heat the assembly to 200 °C for 1 h under vacuum, using the polyimide foil heater as heater	
- Remove the thermo-retractable tape	

4.2.3.2 Experiments made

Tubes equipped with heaters of Type 2 and Type 3 were heated under insulation vacuum in the order of 10^{-2} Pa.

Type 2 was heated continuously for 2 weeks at 250 °C. After cooldown to room temperature another thermal cycle was performed at 300 °C for 2 weeks. After this, the tube was irradiated to 5 MGray, followed by a bakeout cycle to 300 °C.

Type 3 underwent 7 bakeout cycles: One to 150 °C, one to 200 °C, three to 250 °C and two to 300 °C.

All irradiation tests are listed in chapter 6.

4.2.3.3 Results of the thermal cycling including irradiation tests

No change in heating performance could be observed during the bakeout and irradiation tests for Types 1, 2 and 3 (no irradiation applied to Type 3). The polyimide darkened slightly after the continuous bakeout at 300 °C for 2 weeks. The irradiation up to 5 MGray did not have any clear visual impact.

5. Thermal insulation

5.1 Ceramic powder insulation

5.1.1 Material properties

The company Microtherm[#] produces flexible sheets with extremely good thermal insulation properties, a sheet with ceramic filling contained in glass fibre cloth blanket. The material used for the thermal properties test [1] was a 5 mm thick “semi-matelasse en qualité Super G”. Microtherm produces the flexible sheet in thickness between 3 mm and 30 mm. The properties are shown in Table 5.

Table 5: Properties of Microtherm insulation [7]

Thermal conductivity in air	0.022 $W \cdot m^{-1} \cdot K^{-1}$	with 300 °C hot face temperature
Thermal conductivity under vacuum	0.007 $W \cdot m^{-1} \cdot K^{-1}$	with 300 °C hot face temperature
Density	240 kg/m^3	
Chemical composition by weight of ceramic filling	SiO_2 65% TiO_2 32% Al_2O_3 2%	
Chemical composition of glass cloth	SiO_2 54% Al_2O_3 15% CaO_2 17% B_2O_3 8% MgO 5%	Thickness about 0.2 mm
Radiation Length [8]	87 cm	
Weight of 1 m long, 5 mm thick sample for diameter 48.3 mm tube	0.32 kg	measured at CERN

[#] Microtherm, Sint-Niklaas, Belgium

5.1.2 Test and measured heat losses

A number of tests were made at atmospheric pressure to evaluate the thermal properties of the material (described in detail in [1]).
A 1 m long tube of overall diameter 48.3 mm was used and heated up to 300 °C. A 5 mm thick Microtherm sheet was used as insulation. The cold side of the insulation was cooled with an airflow of 20 °C inlet temperature, and an airflow of 3 to 24 m^3/h.
The heat loss was between 151 W and 200 W.

5.2 Multilayer insulation

5.2.1 Types of multilayer insulation used

Two different types of MultiLayer Insulation (MLI) were tested [1].
The first one was an about 9 µm thick aluminium foil with a glass fibre tissue spacer type LYDALL Cryotherm ® 243. An additional 30 µm thick aluminium foil was wrapped around to avoid damage to the extremely fragile MLI. The width of the glass fibre tissue was 63 mm with a density of 186 kg/m^3. The width of the aluminium foil was 76 mm, the width of the glass fiber spacer was 88 mm. The strips of Cryotherm 243 were mounted using adhesive tape, as shown in Figure 7.
The second type of MLI tested was a double sided aluminised polyimide of 25 µm thickness supplied by Tricon/Germany. No spacer material was used between the reflectors.

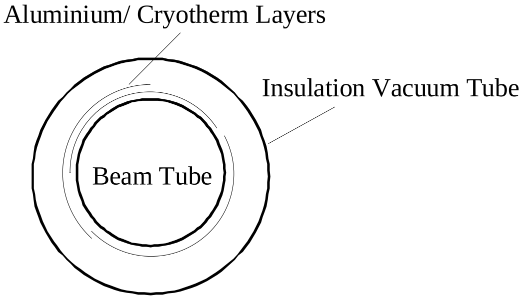

Figure 7: Mounting of Aluminium/Cryotherm 243 multilayer insulation

5.2.2 Tests made

All tests were made using a 1m long stainless steel tube of diameter 48.3 mm [1]. The pressure of the insulation vacuum was in the order of 10^{-2} Pa, the tube temperature was 200 °C and 300 °C, respectively.
The gap between the heated tube and the insulation vacuum tube was varied between 2.5 mm and 6 mm, the number of reflecting layers was varied between 1 and 10.
One test was made at atmospheric pressure without insulation vacuum tube.
The tubes heated were either spray coated tubes delivered by EMPA or a polyimide foil heater was used. For these tests, the polyimide foil heater was fixed to the tube with

polyimide adhesive tape, the bonding or taping methods mentioned in 4.2 were not applied. More details are given in reference 1.

5.2.3 Results

Table 6: Power required to maintain the tube at temperature as a function of design and number of reflective layers under vacuum and 6 mm gap between beam tube and insulation vacuum tube

Tube temperature 300 °C	1 Layer	5 Layers	10 Layers
“EMPA” heating with Cryotherm spacers/reflectors	29 W	22 W	15 W
Polyimide foil heater with Cryotherm spacer/reflector	-	-	24 W
Polyimide foil heater with polyimide foil reflector	34 W	26 W	25 W
Tube temperature 200 °C			
Polyimide foil heater with polyimide foil reflector	14 W	13 W	9 W

Table 7: Power dependence of gap width between beam tube at 300 °C and insulation vacuum tube using 10 layers of insulation

	2.5 mm	4 mm	6 mm
“EMPA” heater with Cryotherm spacer/reflector	25 W	22 W	15 W
Polyimide foil heater with polyimide foil reflector	53 W	-	25 W

5.3 Polyimide foam

5.3.1 Material supplied to CERN

Inspec Foams (USA) delivered to CERN two different types of polyimide foams (trade name “Solimide” via their French outlet Laport/Jehier). Two 1 m long half-shells of internal diameter 61 mm and thickness 15 mm were supplied, each in two densities (20 kg/m^3 and 50 kg/m^3). These 4 half shells were cut out from a thick sheet of foam. The foam was densified.

According to the product information, the material has the properties as described in Table 8.

Table 8: Production information by supplier concerning HT-340 Polyimide Foam [9]

Density	6.4 kg to 50 kg/m^3
Tensile Strength	48 kPa
Thermal conductivity	0.046 W/m^{-1}K^{-1}
Maximum temperature for continuous use	300 °C
Acoustical absorption coefficient for 25 mm thickness	
125 Hz	0.08 metric sabins/ m^2
500 Hz	0.56 metric sabins/ m^2

5.3.2 Tests

Both types of half shells were mounted around a 1 m long EMPA tube diameter 60 mm as thermal insulation with additionally one layer of aluminised polyimide foil on the outside of the assembly. The half shells underwent each a thermal cycle to 250 °C and 300 °C before irradiation. Further cycles were performed after total exposure to 1Mgray, 3 Mgray and 5 Mgray. The samples were kept always 4 hours at both 250 °C and 300 °C.

5.3.3 Results

A slight discoloration could be observed after heating to 300 °C. The irradiation up to 5 Mgray, however, did not seem to have any influence on the aspect and on the thermal insulation characteristic, see Table 9.

6. Overview of irradiation and vibration tests

The irradiation tests were made by Gammamaster/Germany using a Cobalt 60 source.
The materials and assemblies irradiated are seen in Table 10.

Table 9: Power needed to heat a 1 m long tube OD 60 mm to 250 °C with 15 mm thick polyimide foam insulation

Foam density	Before irradiation	After 1 MGray	After 3 MGray	After 5 MGray
20 kg/m^3	153 W	156 W	157 W	150 W
50 kg/m^3	136 W	132 W	132 W	132 W

Table 10: Materials irradiated with Cobalt 60 source and thermal cycles

	No radiation		1 MGray		3 MGray		5 MGray	
	Cycles	Temp.	Cycles	Temp.	Cycles	Temp.	Cycles	Temp.
Polyimide foil heater Type 1 (with polyimide resin)	4 4	250 °C 300 °C	1 1	250 °C 300 °C	1 1	250 °C 300 °C	1 1	250 °C 300 °C
Polyimide foil heater Type 2 (with polyimide tape)	1 1	250 °C 300 °C	-	-	-	-	1	300 °C
Polyimide foam 20 kg/m^3	1	250 °C 300 °C	1	250 °C 300 °C	1	250 °C 300 °C	1	250 °C 300 °C
Polyimide foam 50 kg/m^3	1	250 °C 300 °C	1	250 °C 300 °C	1	250 °C 300 °C	1	250 °C 300 °C

The functionality and the aspect of the heaters and thermal insulation did not change due to the irradiation.

Table 11: Vibration properties of the dense polyimide foam before irradiation [10]

Material	Young's modulus	Loss factor
Polyimide foam density 50 kg/m^3	E = 5.7*10^5 (N/m^2) at 50 Hz	η=0.13 at 50 Hz

7. Summary

Two types of heaters (spray deposited heater and polyimide foil heater) and three types of insulators (multilayer thermal insulation, ceramic powder and polyimide foam insulation) were studied. A polyimide resin and a polyimide tape with polyimide resin were used to mount the polyimide foil heaters to the vacuum tubes.
All materials were tested at maximum temperature of 300 °C, with the exception of one polyimide foil heater and the polyimide resin, which were heated up to 350 °C.
All polyimide materials, the heaters, resin, foam and tape were tested up to 5 MGray.
No deterioration of the material was observed during the heating and irradiation tests.
A summary of the tests made can be found in Table 12.

The thinnest and most transparent heater is the polyimide foil heater without second or top layer, mounted with polyimide tape.

The polyimide foam can also be used as a vibration damping material, depending on the requirements.

Table 12: Main properties of material tested

Item	Max. Test Temperature	Irradiation Test	Minimum Thickness	Heat loss at 300 °C normalised to a 1 m long tube ∅ 60 mm
Spray deposited heater	300 °C	-	0.4 mm	-
Polyimide foil heater	300 °C	5 MGray	70 µm	-
	350 °C	-		
Polyimide resin	250 °C	5 MGray	Not measured, 70 µm estimated	-
	350 °C	-		
Polyimide tape with resin	300 °C	5 MGray	56 µm	-
Polyimide Foam	300 °C			15 mm thick
$20\ \text{kg/m}^3$		5 MGray	-	155 W
$50\ \text{kg/m}^3$		5 MGray	-	135 W
Ceramic powder insulation	300 °C	Not tested	3 mm	5 mm thick 186 W to 250 W
Alumium/Cryotherm 243 multilayer	300 °C	Not tested	Not measured	10 Layers, under vacuum 10^{-2} Pa 18 W to 31 W
Aluminised Polyimide foil reflector	300 °C	Not tested	Typically 24 µm per layer	10 Layers, under vacuum 10^{-2} Pa 31 W

References

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[1] H. Kos, G. Schneider, R. Veness, In-situ Bakeout for LHC Experimental Chambers Report on 1 m Test Model, Vacuum Technical Note 00-03, February 2000

[2] H. Kos, G. Schneider, J. Vaissière, R. Veness, Tests on Deposited Bake-out Heaters Manufactured by EMPA, Vacuum Technical Note 00-08, July 2000

[3] EMPA communication by letter, O. BRANDT. Date:16.09.1999

[4] The European Physics Journal C, Volume 15, Number 1-4, 2000, Springer Verlag, p. 80

[5] Information from RICA/Italy

[6] H. Kos, Assembly Procedure “Polyimide Heaters on ATLAS beam pipe”, July 2002, EDMS document 351247

[7] From Mircotherm product information

[8] M. Huhtinen, privat communication, 30.10.2002

[9] Solimide, Inspec Foams, Plano, Texas, 75074 USA, product information

[10] P. Cupial, M. A. Gonzalez, J. R. Knaster, R. Veness, “Assessment of the resistance of damping polymers against radiation“, Note to be published