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Ultrathin Polyimide-Stainless Steel Heater for Vacuum System Bake-out

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ULTRATHIN POLYIMIDE-STAINLESS STEEL HEATER FOR VACUUM SYSTEM BAKE-OUT

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Space constraints in several normal conducting magnets of the LHC required the development of a dedicated permanent heater for vacuum chamber bake-out. The new heater consists of stainless steel bands inside layers of polyimide. The overall heater thickness is about 0.3 mm. The low magnetic permeability is suitable for applications in magnetic fields. The material combination allows for temperatures high enough to activate a NEG coating. Fabrication is performed in consecutive steps of tape wrapping. Automation makes high volume production at low costs possible. About 800 m of warm vacuum system of the long straight sections of the LHC will be equipped with the new heater. This paper covers experience gained at CERN from studies up to industrialization.

INTRODUCTION

Beam stay clear requirements combined with limited space inside magnet yokes initiated the development of the heater. Additional reasons are the small separation between the two LHC beams and transparency for experiments. Table 1 lists all normal conducting LHC magnets which will be equipped with the new heater. The heater is also foreseen for the following areas with space constraints: recombination chambers, experimental chambers and chambers adjacent to collimators. Special requirement arise also from the fact that all chambers are NEG (TiZrV) coated which requires homogeneous activation temperatures beyond 200°C.

Table 1: LHC magnets with new heater (all dimensions in mm, chamber lengths vary between 1275 and 4150 mm; Dimensions: two external ellipse diameters and thickness; Gap: radial)

Magnet	Qty.	Dimensions	Material	Gap
MBW, MCBW(H/V)	20, 18+18	63x48x2	Cu	2
MBXW	24	134x59x3	Cu	2
MBXW(H/S/T)	1+2+2	56x56x2	Cu	2
MSI, MSD	10, 30	60x60x1.4	µ-metal	2
MQW	48	56x34x2	Cu	1.1

POLYIMIDE-STAINLESS STEEL HEATER

The polyimide-stainless steel (PI-SS) heater has been applied to aluminium, copper and stainless steel chambers of different cross-sections. Figure 1 shows a finished MBXW chamber. A typical heater consists of:

I. First electrical insulation layer: 2 layers of 60 µm thermoplastic PI tape (Kaneka Pixeo, AST 252); currently wrapped with one single 20 mm tape and 50% overlap. The PI tape is coated on both sides with 5 µm thermosetting PI resin to keep all layers together after a heat treatment (polymerisation).

II. SS heater bands of 50 µm thickness, 5 mm wide, wrapped in spaced helixes; the number of helixes and the spacing is used to adjust the heater resistivity. See Figure 2.

III. Second electrical insulation layer (as layer I).

IV. Optional reflective screen to reduce heat losses by radiation: One layer without overlap of 50 µm PI tape coated on one side with aluminium (customized supply, Tricon, Germany). See Figure 1.

(V.) Temporary layer of shrinkable polyester tape for polymerisation (117803-M11S, Fratec AG, Switzerland). The tape creates an external pressure on the chamber when heated up in order to improve the polymerisation process and to avoid delamination of the layers.

The thickness of the final heater varies depending on the number of layers between 0.29 and 0.4 mm.

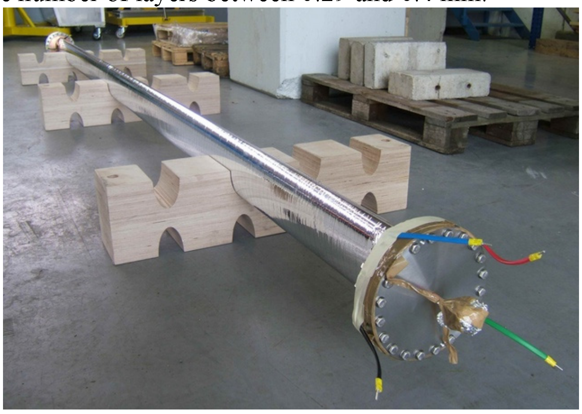

Figure 1: Finished MBXW chamber.

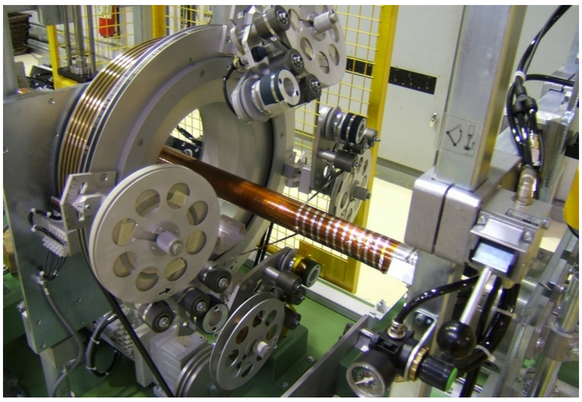

Figure 2: Simultaneous wrapping of two heater bands.

To avoid damage of layer III by overheating, temperature sensors have to be placed above the SS band in order to measure the maximum temperature of the PI.

The electrical connection of the heater bands to standard cables is critical at high currents. It was necessary to develop a special connection technique (see Figure 3) to avoid not insulated connections, hot spots due to bad thermal contact, insulation damage due to rigid and/or piercing connections, and band rupture due to handling errors. A flexible SS braid is slid around the ends of the heater band in order to increase the electrical and mechanical cross-section. The braid (with or without the band inside) can be easily connected by standard mechanical means (e.g. clips, crimping or screws) to normal cables. A final insulation sleeve (e.g. PI or silicon) can be added to the SS braid for electrical insulation. Between layer I and III folding is possible in order to change the routing direction. The SS braid is glued rigidly to the PI layers after the polymerisation process which results in a very reliable mechanical connection. An insulation sleeve should therefore leave at least 3 cm of SS sleeve uncovered between layers I and III. Figure 3 gives a typical example.

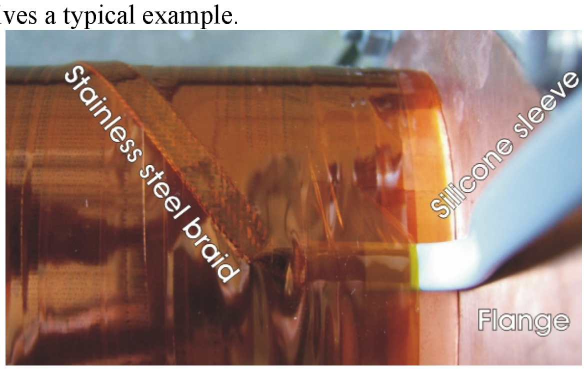

Figure 3: Electrical connection of heater bands.

PERFORMANCE

In order to use standard CERN bake-out control racks (230 V, max. 10 A) all heaters produced so far were designed with a resistance of at least 23 Ω. This corresponds to 8 m heater length (5 mm wide band of 50 μm thickness) and 5.5 W/cm^2 (roughly half the power of a hotplate). Using four heater bands per chamber the maximum bake-out power is about 9 kW. The heater can therefore be considered as an alternative to coax-heaters.

Figure 4 shows a test performed on chambers inside an MQW magnet. For this case heat losses split up in three parts: radiation, conduction and convection. While convection and conduction effects are approximately linear with temperature, radiation varies with the fourth power of the absolute temperature. The contribution from radiation in Figure 4 corresponds to the difference between the lower and the upper line. Figure 5 shows a simulation for the case with reflective screen (i.e. negligible losses due to radiation). The star in Figure 4 indicates the maximum temperature in Figure 5. According to the calculations, at 200°C, conduction accounts for 150 W/m and convection for 380 W/m.

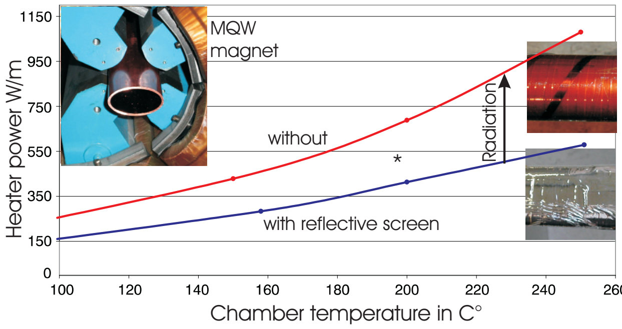

Figure 4: Bake-out test of MQW chamber.

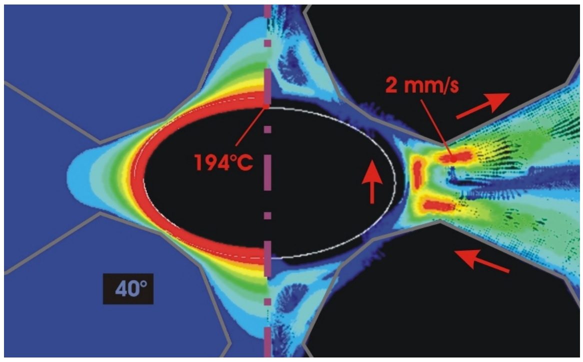

Figure 5: Temperature distribution (left) and velocity field of convection (right) at 523 W/m heater power.

13 chambers without reflective screen underwent cycling tests to 250°C in order to investigate long term performance. Apart from one welded connection which pierced the insulation of layer I, all chambers were functional after 10 cycles (which corresponds to the expected cycles during LHC life time). Damage of layer III occurred on stainless steel chambers where thermocouples were not positioned on top of the heater band. The low thermal conductivity between the heater band and the temperature sensor caused temperature gradients above 50°C (i.e. higher than 300°C for the PI). This effect is much less pronounced on copper and aluminium chambers. Figure 6 shows a thermography image of an aluminium chamber (ESRF prototype). The heater bands are visible but the gradient is less than 10°.

As a rule of thumb it can be concluded that temperatures above 300°C should be avoided. Even if PI withstands higher temperatures, the material deteriorates faster in time as the temperature rises. Above 350°C deterioration becomes unacceptably fast for most applications.

Damage occurs also if the thermal contact between the SS band and the chamber is poor. This can happen locally if chamber profiles are used that have groves or other concave features. In another test chamber having cavities of different width, chamber temperatures above 200°C could not be attained without burning layer III. The heater was still functioning but no longer electrically insulated to the outside. Cavities wider than 5 mm should be avoided between the chamber and the heater.

PI gets darker after several cycles. However, mechanically the material stays in its hard glass like state which it gets after the polymerisation. Removal of the heater from the chamber after polymerisation is very difficult. Since PI is chemically quite resistant, sandblasting is at the moment the only method that works without damaging the chamber too much.

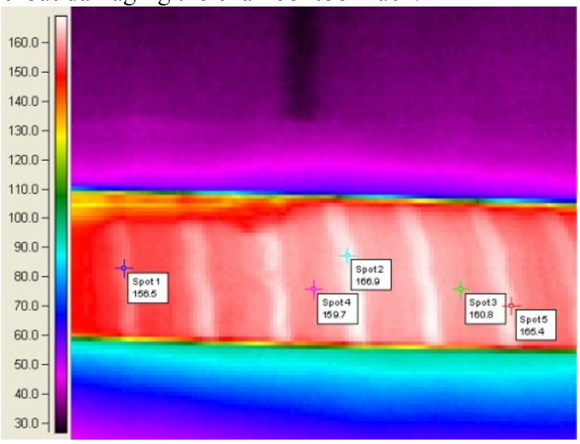

Figure 6: Thermography of heater (no reflective screen)

PRODUCTION FOR THE LHC

In addition to the 287 chambers listed in Table 1, prototype chambers, spare chambers and special chambers have to be fabricated for the LHC, leading to a grand total of 400 chambers to be produced. To industrialise the production and to ensure a good quality, a special wrapping machine was designed in collaboration with industry. This machine shown in Figure 7 is the first of its kind since automatically wrapping of chambers with flanges had not been done before. Special requirements came also from different diameters, flange sizes and chamber cross-sections. The machine has a central wrapping unit with a rotating ring carrying up to four wrapping heads (see also Figure 2). The wrapping angle of the heads is adjustable. The chamber (not rotating) is advanced by a traction unit which attaches to one flange. The rotational speed of the wrapping unit is synchronized to the advancement speed of the chamber. Technical data of the machine: max. chamber length 7m, max. chamber/flange diameter 306 mm, 0.3 mm turn to turn accuracy for a single head, 2 mm accuracy between layers wrapped with different heads.

A typical production work flow is as follows:

- Reception of cleaned and leak tested chambers from mechanical production; changing of machine settings for new chamber type; 1-2 h
- Insertion of one chamber into the machine and wrapping of layers I and II; 1-1.5 h
- Preparation of electrical connections; 2-3h
- Wrapping of layer III; 0.5 h
- Installation of two thermocouples; 0.25 h
- Wrapping of layer IV and V; 1 h
- Removal of chamber and installation of equipment for polymerisation; 0.5 h
- Polymerisation at 190° for at least 1 hour; 4-6 h
- Transport preparation to NEG coating facility; 0.25 h

A typical production rate for one operator is one chamber per day, provided he has temporary help for handling if objects are long or heavy.

Figure 7: Wrapping machine; insertion table left, wrapping unit middle, traction unit right

OUTLOOK

The cost for material and manpower to equip a chamber with the new heater is in the order of 1000 CHF. The same chamber equipped with coax-heaters is at least 5 times more expensive. From the financial point of view, already small series can justify the installation of a wrapping machine. This makes the heater interesting even for applications smaller than at the LHC. A prototype chamber has been produced to evaluate the new heater for a machine upgrade of the synchrotron light source at the ESRF, which will be installed this summer. First operational experience in the synchrotron light source will also give feed back for the preparation of the LHC.

The heater described here is used without thermal insulation. If required, thermal insulation (e.g. Microterm®) in order to reduce heat losses has to be added by hand. To automate and improve the quality, wrappable insulation in the form of bands would be desirable. A heat resistive “super insulation” (as used in cryogenic applications) type outer layer would significantly reduce heat losses.

Connection techniques should be improved with respect to preparation time. The use of 48 V power supplies could simplify the connection and improve electrical safety.

CONCLUSION

The heater presented has several advantages compared to standard techniques, in particular if the space for the bake-out system is very limited, i.e. smaller than 4 mm. Heaters can be customized depending on the application. Homogeneous heating of non-insulated chambers can be achieved which is particularly important for NEG activation. Materials are low cost. The potential financial gain has to be partly reinvested in a manufacturing process with high quality standards. However in machine aperture limited applications, like the LHC, this investment can find the last millimeters of aperture.

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