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A NOVEL FABRICATION TECHNIQUE FOR THIN METALLIC VACUUM CHAMBERS WITH LOW EDDY CURRENT LOSSES

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Abstract

Eddy current problems in synchrotrons have been avoided until now by using costly and thick ceramic vacuum chambers which reduce the free magnet aperture. These disadvantages are eliminated by a novel fabrication technique developed for the chambers of the new 9 GeV electron synchrotron DESY II operating with 12.5 Hz repetion rate. The elliptical chambers 80x40 mm are made from .3 mm thick stainless steel tubes reinforced by thin ribs. The ribs are brazed on the tubes by a high temperature Ni-base brazing alloy. The linear eddy current losses are 60 W/m and increase the chamber temperature to only 50°C. The available beam aperture is now 93% of the magnet gap. A still higher repetion rate up to 100 Hz can be achieved by reducing the wall thickness to .1 mm and using tubes made from a Ti-alloy having higher resistivity than stainless steel.

Introduction

A new 9 GeV electron synchrotron DESY II has recently been built at DESY to replace the old 7 GeV synchrotron DESY I as an injector for the storage rings DORIS II, PETRA and HERA [1]. DESY I will be then modified into a proton accelerator as a part of the injection chain for HERA. A significant reduction of the down-time and repair costs as compared to DESY I is expected. This will mainly be due to lowering the repetition frequency from 50 to 12.5 Hz and to using thin metallic instead of ceramic vacuum chambers. In DESY I, the 50 Hz operation causes strong vibrations which often led to large vacuum leaks in the joints of the ceramic vacuum chamber elements. This modification will also provide better injection conditions into PETRA at 9 GeV.

Normally, the magnet vacuum chambers in synchrotrons are made of ceramic elements to avoid eddy currents induced by the alternating magnetic field. These currents can perturb the applied magnetic field and heat up the vacuum chamber [2]. Both effects can be decreased to an acceptable level by reducing the repetition frequency and the thickness of the metallic chamber, and by using a high resistivity material. However, it is then a problem to make such a chamber sufficiently rigid against the atmospheric pressure, since its thickness should be of the order of a few tenth of a millimeter only. One way of solving this problem is to use a thin corrugated bellow-type stainless steel vacuum chamber[3]. But the effective thickness of the corrugations reduces significantly the magnet space available for the beam, increasing therefore the magnet fabrication and operation costs. The corrugations also increase the chamber impendance, causing beam instabilities and limitations in the max. accelerated current. Also, the fabrication costs for a corrugated chamber are high.

Therefore, we developed for DESY II a new thin metallic vacuum chamber without corrugations, which is smooth inside and allows max. beam space in the magnets. In this paper we will first give a brief discussion of the eddy current problem, followed by considerations of the choice of material regarding its specific resistivity and mechanical strength. Finally the developed fabrication techniques and the vacuum chamber design will be described, and the limits of these techniques will be discussed.

The eddy current problem

The alternating field of the synchrotron magnets induces eddy currents in metallic vacuum chambers placed in the gap. These currents cause field distortions as well as heating of the vacuum chamber due to power losses. The linear heat losses (N) of the eddy currents along the chamber are inversely proportional to the resistivity (k) of the chamber material and proportional to the square of the time derivative of the magnetic field (dB/dt), to the chamber thickness (d) and to the third power of the chamber dimension (a) perpendicular to magnetic field [4]:

$$N \sim (dB/dt)^2 \cdot d \cdot a^3 / k \qquad (1)$$

When keeping these thermal losses to an acceptable level, the main bending field distortion is of the order of 1%, but additionally induced sextupole components can considerably change the chromaticity of the machine [4]. This change of chromaticity could be compensated by installing additional sextupole magnets steered in amplitude and phase such as to compensate the induced sextupole ac-component. But there still remains the problem of dimensioning the vacuum chamber for acceptable thermal losses.

An elliptical 80x40 mm beam aperture is needed for the standard vacuum chambers of DESY II. The aperture is increased to 110x40 mm in the regions where beam injection or ejection takes place. At least 2 mm wall thickness is needed for a normal vacuum chamber of these dimensions to make it sufficiently strong against atmospheric pressure. But even in case of a chamber made from stainless steel, which has a relatively high resistivity of $70\,\mu\Omega\cdot$cm, this wall thickness is not acceptable with regard to eddy current losses. Numerical calculations[4] have shown that these losses can be reduced to the acceptable linear thermal load of 60 W/m by reducing the wall thickness to .3 mm. Although such a chamber satisfies the requirements of vacuum tightness and handling stability, an additional reinforcement is needed in order to achieve rigidity against atmospheric pressure. This is done as described in the following chapter, by brazing 1 mm thick stainless steel ribs onto the outer surface of the elliptical chamber.

Fabrication Technique

The vacuum chambers for DESY II are made completely out of stainless steel, although other alloys seem to be more suitable concerning eddy current losses. In view of delivery problems for these other alloys, and because of the large experience in our laboratory in welding and brazing stainless steel, we have decided for this material. Even here, delivery problems made us to use the Ti-stabilized stainless steel AISI 321 instead of the preferred 316L which has a lower magnetic susceptibility and is more suitable for welding and brazing. The benefits and problems of using other alloys for this purpose will be discussed in the last chapter of this paper.

Fig. 1 shows the main types of ribs used for the two different vacuum chambers in the gaps of the bending magnets in DESY II. The free apertures of the ribs are 80x40 and 110x40 mm for the standard and for the injection/ejection chambers, respectively. The increase of the effective chamber height, due to the ribs, is only 1 mm for each chamber side, allowing therefore a large free beam aperture. This is about 93% of the magnet gap, including also mechanical tolerances and the space used for the chamber electrical insulation against the magnet poles. The appropriate stiffness of the ribs is achieved by increasing their height to 10 mm in the horizontal direction of the magnet gap, where only a smaller fraction of the magnet aperture is required for the beam.

Outside the bending magnets, the ribs are made with a constant width of 10 mm around the circumference of the elliptical chamber in order to eliminate welding problems when joining the chambers to each other, to flanges, monitors, etc.. These joints are made by TIG-welding of two ribs around their outer circumference. The same enlarged ribs are used for the chambers inside the quadrupole and sextupole magnets. These magnets have a larger aperture than needed for the beam, owing to additional space requirement in the horizontal plane for beam injection and ejection. Depending on the required quantity, the ribs are produced from 1 mm thick stainless steel sheet either by stamping or by cutting with a laser beam.

The thin elliptical vacuum chamber was made from a round seam-welded stainless steel tube .3 mm thick. The round tube was then flattened approximately to the needed elliptical shape by using simple wooden tools. The initial outer circumference of this tube was approx. 2 mm smaller than the circumference of the rib aperture so that the ribs could easily slip over the tube. The reinforcement of the tube is made by placing a rib every 20 mm. This is a compromise between rigidity, costs and modular design of the chamber. The ribs are positioned in a wooden holding fixture, and then the elliptical tube is pushed through their aperture. The tight fit between ribs and chamber wall - needed for brazing and rigidity - is achieved by expanding the elliptical tube against the ribs with an elliptical plug with slide rings made of 3 mm bronze wire(Fig. 2). This plug is pulled through the preformed tube.

The ribs and the tube are brazed in a vacuum furnace at 1100 °C with the high temperature braze BNi-2 deposited in paste form. The paste is made by dispersing 3 weight parts braze powder in one part of colloidal mass consisting of 25 gr methylcellulose dissolved in 600 gr distilled water and diluted by 400 gr ethyl alcohol. The braze paste is carefully deposited in small amounts near the joints by using an injection applicator. This is necessary in order to avoid additional eddy current losses resulting from excessive braze, and to assure a low magnetic permeability for the chamber.

The 4 m long chamber part lying in the bending magnets is produced as a single unit. After brazing and leak testing, it is bent horizontally to fit the beam curvature. This is made by pressing small bumps into one side of the chamber. The bumps are produced with an hydraulic tool shown in Fig. 3. The 1 m long straight chamber parts in the quadrupole magnets are produced separately and joined subsequently to the bends by TIG-welding of the last ribs. The resulting 5 m long vacuum chamber(Fig. 4) is provided with flanges, position monitors(Fig. 5), bellows etc., by using the same rib welding technique. Additionally, a thin ceramic ring is incorporated at the end of each chamber to avoid induced currents circulating around the machine. About 50 vacuum chambers were produced and installed in DESY II. They show excellent mechanical and vacuum properties also after prolonged bake-out at 200 °C under vacuum. During magnet operation, their temperature increases only to a maximum of 50 °C.

Discussion

Schedule and state of the art were the two main factors that made us decide to fabricate the chambers from .3 mm thick stainless steel tubes. Although these chambers satisfy the DESY II requirements, additional work has been done in our laboratory towards lowering the eddy current losses further. The same fabrication technique was applied to produce chamber prototypes with .2 mm and .1 mm wall thickness. These chambers have been successfully tested.

A further reduction of eddy current losses can be achieved by using Ti-Al alloys as commonly used in aerospace technology. Typically, the alloys Ti-Al6-V4 and Ti-Al8-Mo1-V1 have resistivities of 170 and 200 $\mu\Omega\cdot$cm, which are almost a factor of 3 higher than for stainless steel. Additional advantages of using these alloys are their high strength, the low modulus of elasticity and the low thermal expansion coefficient. Two disadvandages in welding these alloys compared to stainless steel, are more precise mechanical tolerances for the joints and higher purity for the inert shielding gas. In brazing these alloys, the desired joining operation should be accomplished below the beta transus(935 °C) to eliminate solution heat treating after brazing. Therefore only silver-base alloys and the Ni-base alloy BNi-6 are recommended as brazing filler.

According to equation (1), it seems possible to increase the repetion frequency of future accelerators up to 100 Hz by reducing the horizontal dimension of the chamber and making it out of .1 mm thick Ti-Al-alloy tube reinforced with ribs.

References

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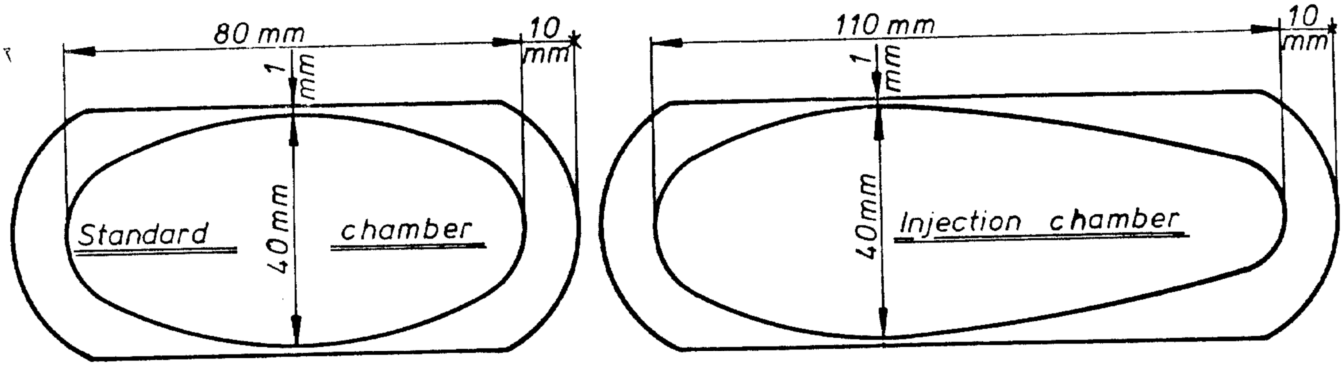

Fig. 1: Reinforcement rips for the DESY II vacuum chambers

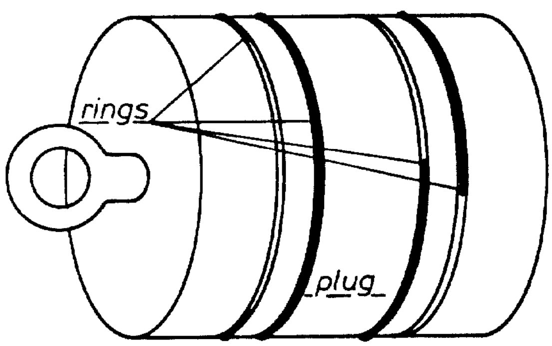

Fig. 2: Expansion plug with slide rings

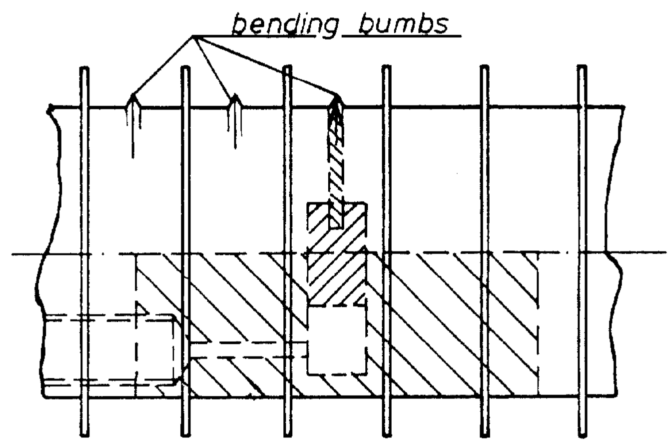

Fig. 3 Vacuum chamber bending tool

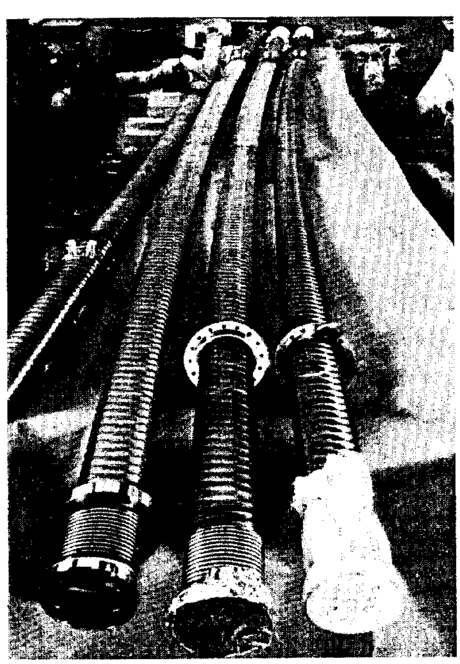

Fig. 4: DESY II vacuum chambers

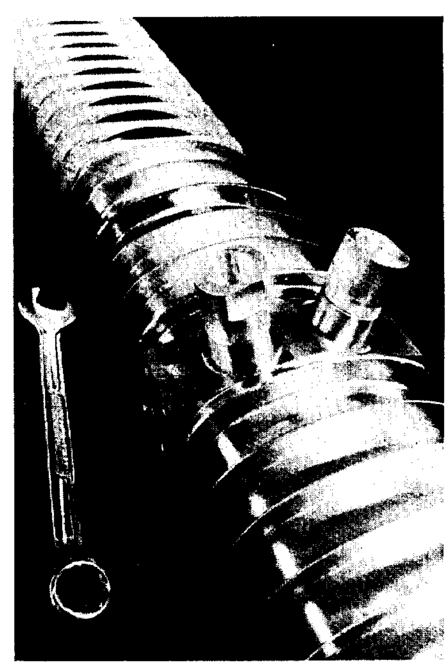

Fig. 5: Position monitor