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DESIGN OF THE DIPOLE VACUUM CHAMBER FOR THE CNAO SYNCHROTRON (Based on the PIMM Study)

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Abstract

The thin walled vacuum chamber of the CNAO synchrotron dipole has been studied in the framework of the Proton Ion Medical Machine Study (PIMMS). Sixteen curved chambers, one for each dipole, about 1.9 m long and with inner aperture 130 mm × 64 mm are needed. The rapidly changing magnetic field in the dipole (maximum field rate of 3 T/s) imposes a stainless steel wall of thickness not bigger than 0.4 mm. Different construction schemes of the chamber have been investigated and two prototypes have been simulated, realised and measured.

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1. INTRODUCTION

The thin walled vacuum chamber of the CNAO synchrotron dipole has been studied in the framework of the Proton Ion Medical Machine Study (PIMMS) aiming at an optimised design of a synchrotron for radiation therapy. The mean required pressure in the synchrotron ring is about 10^{-9} Torr. At this pressure level, in situ bakeout is not absolutely necessary and it is ruled out by the complications of bakable diagnostics and of other components, by the cost increase of the magnets (larger gap size) and by the increased complexity of the control system and operating procedures [1].

The synchrotron ring is composed of 16 dipoles shown in Fig. 1 [2]. Sixteen curved chambers, one for each dipole, are needed. A chamber is composed of two major parts: a thin part inside the dipole yoke (length of the core equal to 1553 mm) and a thicker part that makes the transition between the thin part and the flange which is positioned outside the coil return path. In this latter part, comprised between the end of the yoke and the end of the coil along the beam trajectory, will be placed, the welded manifold of a pumping station. The second paragraph of this paper presents the design characteristics of the thin vacuum chamber inside the iron yoke of the dipole.

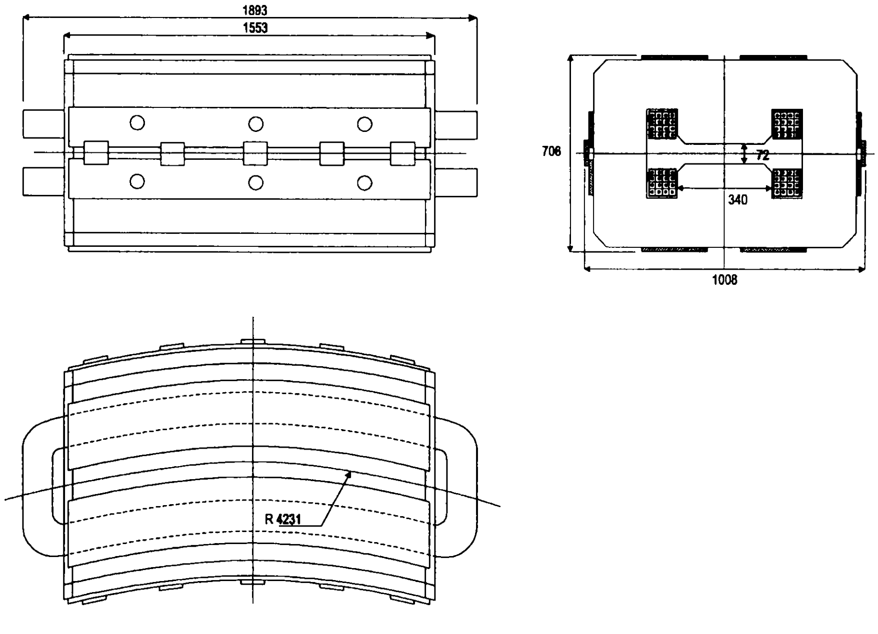


Fig. 1 Geometry of the CNAO dipole (all dimensions in mm) [2].

The dipole vacuum chamber is designed trying to satisfy the following requirements:

- to produce a minimum influence and distortion of constant magnetic field, i.e. by using a chamber material with very low magnetic permeability;
- to reduce the effects of the eddy currents on the beam due to pulsed magnetic field, i.e. small thickness of the vacuum chamber wall. In the case of CNAO, the rapidly changing magnetic field in the dipole (maximum field rate of 3 T/s) imposes a stainless steel wall of thickness not bigger than 0.4 mm;
- to have the smallest possible external chamber dimensions for a required beam aperture, to reduce the impact on the magnet aperture;
- to be low in cost and easy to handle, therefore excluding large scale use of expensive materials (e.g. ceramic chambers).

Different construction schemes of the chamber, presented in the third paragraph, have been investigated and two prototypes have been simulated, realised and measured.

2. DESIGN CHARACTERISTICS

In the CNAO synchrotron the horizontal aperture and good field region are determined by the length of the separatrices at extraction, while the vertical aperture and good field region are fixed by the vertical dimensions of the carbon beam at injection. To fix the aperture of the vacuum chamber the following assumptions have been made [3]:

1. a beam model with uniform distribution in 3D and beam envelope at $\pm \sqrt{5}\ \sigma$ (σ being the rms value of the distribution);
2. a maximum margin for the horizontal closed orbit distorsion of ± 10 mm, scaling with the horizontal betatron Twiss function;
3. a maximum margin for the vertical closed orbit distorsion of ± 7.5 mm, scaling with the vertical betatron Twiss function;
4. a security margin for collimation equal to half the maximum closed orbit margin, i.e. ± 5 mm both horizontally and vertically, scaling with the related betatron Twiss functions.

In Table 1 the aperture of the vacuum chamber and the good field region, inside the dipoles, are summarised together with the available space in the dipole aperture. In Fig. 2 the various contributions to the vertical aperture of the dipoles are presented: beside the chamber aperture and thickness, twice 2.6 mm are foreseen for the supports to give mechanical strength to the thin chamber and twice one extra millimetre for alignment.

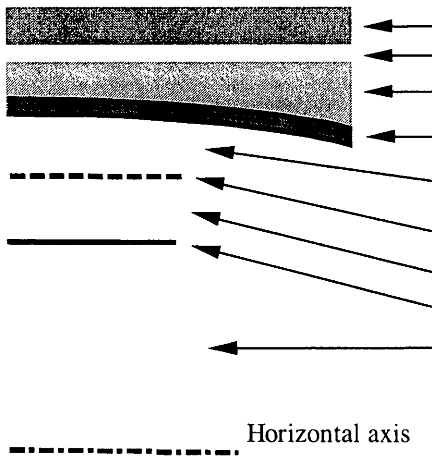
***Table 1** Apertures and good field region.*

Aperture of the dipole H × V [mm]	280 × 72
Chamber aperture in the dipole H × V [mm]	130 × 64
Good field region H × V [mm]	114 × 56

As shown in the Figure 2, from the edge of the beam to the pipe there are 11 mm at the centre, position where the buckling deformation is maximum. It seems reasonable to accept a maximum buckling under vacuum within few percent of this margin (e.g. 0.5 mm of total deformation correspond to 2% of this margin).

During extraction the separatrices have a constant length and extend across the horizontal aperture of the vacuum chamber. Moreover the circulating beam is displaced inside the vacuum chamber at extraction to build the required spiral step and during injection to avoid losses on the extraction septa. Therefore, in a medical synchrotron with resonant slow extraction, the form of the vacuum chamber have to guarantee a sufficient vertical clearance at the extremes of the horizontal aperture.

In PIMMS a super-ellipse cross section of the dipole vacuum chamber (equation of the chamber contour $(x/a)^3 + (y/b)^3 = 1$) has been proposed [3]. For the prototypes described in the next paragraph the racetrack design has been chosen; as shown in Fig. 3, it gives a larger clearance and fully accommodate the good field region.



	Space [mm]	*Height [mm]*
Pole face		36
Alignment	1	36
Ribs	2.6	35
Pipe thickness	0.4	32.4
Margin for collimation, pickup plates etc.	3.8	32
Dump shadow		28.2
Closed orbit	7.2	
Edge $\sqrt{5}\,\sigma$		21
Beam	21	

***Fig.** 2 Vertical half aperture of synchrotron dipoles.*

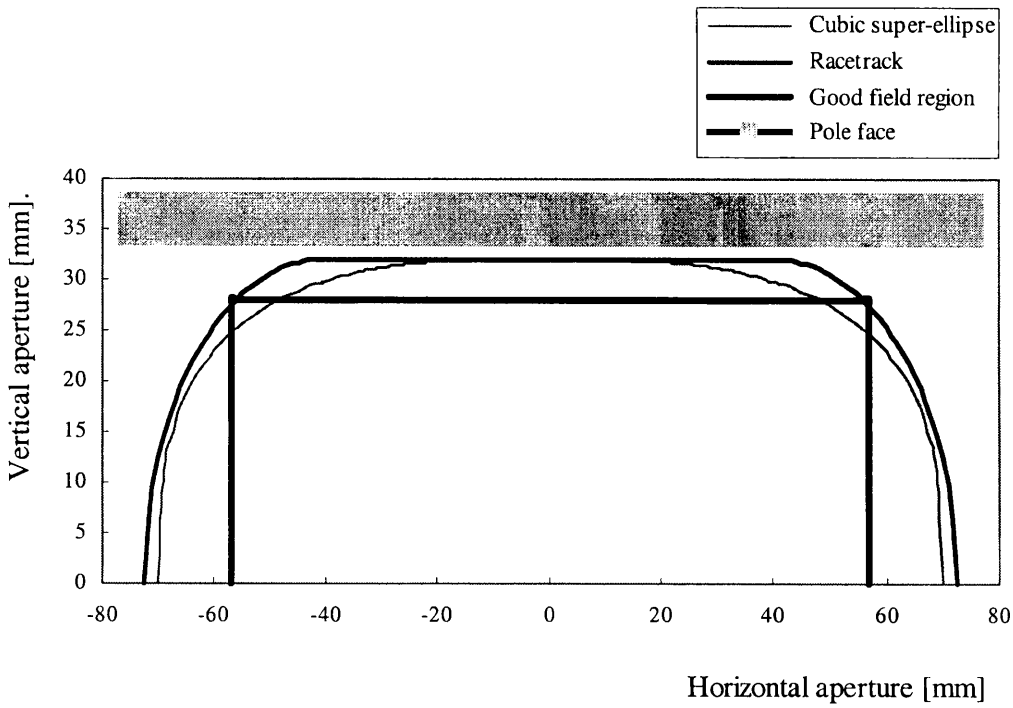


***Fig.** 3 Cross sections comparison.*

The cycle of the dipoles gives a maximum field rate of 3 T/s. This rather fast variation of the magnetic field gives rise to induced current in the yoke laminations and in the vacuum chamber, that tend to reduce and distort the magnetic field in the good field region. The time constant of these effects and the consequent field distortions have been estimated [4 and 5].

The effect of the eddy currents in the vacuum chamber is reduced increasing the resistance to their flow in the material: this is obtained reducing the wall thickness and also choosing a material with high resistivity. The purpose is to reduce the effects of eddy currents in the vacuum chamber below the level of the lamination effects. These effects are here estimated in terms of response time constant and consequent field distortion. For a stainless steel chamber (resistivity equal to 72 μΩ cm), 0.4 mm thick, the principal time constant is approximately of the order of 40 μs. The corresponding field distortion is expected to be of the order of 14×10^{-4} for proton injection at 7 MeV. This value is obtained considering a constant ramp rate of the field of 3 T/s and is given by the ramp rate times the time constant. It is lower that the field distortion produced by the eddy currents in the dipole laminations (thickness of the carbon steel lamination of 1.5 mm), estimated to be 24×10^{-4} [5].

3. CONSTRUCTION TECHNIQUES AND PROTOYPES

Due to the reduced thickness, a way of strengthening the chamber against buckling is necessary. Two different designs have been analysed: corrugation and the reinforcement using ribs. Other less conventional methods, like for example a thin layer deposit of stainless steel on a glass or carbon support, have been discarded, since reliability and easy maintenance are of major concern for a radiation therapy facility.

Both techniques have been already developed and applied in rapid cycling magnetic fields: the corrugated chamber in the PS Booster synchrotron of CERN [6], the reinforced chamber in the switching magnets of Daphne in Frascati and in the Booster of the ESRF in Grenoble [7].

In the case of the PS Booster of CERN the chamber has a thickness of 0.4 mm, outer dimensions of 69 mm and 138 mm for the vertical and the horizontal plane, respectively. The corrugation height is 3 mm and the material is the high nickel alloy Inconel X – 750. The material has been chosen for its high resistivity (121 μΩ cm) compared to stainless steel AISI 316 LN (72 μΩ cm) and for its mechanical characteristics, high module of elasticity (21'100 kg/mm^2, 19'100 kg/mm^2 for AISI 316 LN), and good machinability. In the PSB were installed 128 corrugated chambers, each 1822 mm long. The high number of chambers (realised by Calorstat, France) justified the high cost of the tooling that was needed for the chamber realisation. The tooling cost represents the major drawback of this solution, because of the limited number of chambers of the CNAO synchrotron.

Reinforced thin chambers were realised by Ansaldo, Italy for the switching magnet in Frascati, see Table 2, and by Calorstat for the Booster of Grenoble. In both cases reinforcement ribs have been brazed to the thin vacuum tube. In the case of Frascati, the chamber thickness is 0.3 mm. It is inserted in a fast switching magnet and it is designed to stand ramping fields of several tens of Tesla per second.

Table 2 *Characteristics of the chamber for Frascati switching magnet.*

Internal dimensions H × V [mm]	54 × 18
External dimensions H × V [mm]	74 × 24.3
Chamber length [mm]	1397
Geometry	Ellipse
Ribs pitch [mm]	20
Rib thickness [mm]	1
Pipe thickness [mm]	0.3

The chambers in Grenoble are in stainless steel with a nominal wall thickness of 0.3 mm (0.275 mm minimum, 0.325 mm maximum). Internal form and dimensions are varying, to give an idea of the dimensions, one portion is elliptical 59.7×36.1 mm^2. The ribs have a thickness of 1 mm and a typical pitch of 20 mm. The shape, dimension and frequency of ribs is different for Frascati and Grenoble and it is adapted to minimise the chamber deformation under vacuum. With this construction technique the brazing material constitute the most expensive part of the chamber realisation.

A first prototype, 4 cm long, of the CNAO vacuum chamber has been realised at Frascati. The thickness of the chamber is 0.28 mm and the transversal dimensions are 145×64 mm^2; the profile is racetrack and the material is stainless steel. The ribs, with thickness of 2 mm, pitch of 18 mm and realised with a milling machine, have been brazed with a silver - copper - titanium alloy. The measured total buckling under vacuum has been of 0.4 mm. Even if this measure cannot be taken into account because of the particular geometry of the prototype, it was very helpful in order to demonstrate that a brazed solution can be feasible.

A second prototype has been realised still in Frascati (Figures 4 to 6 and Table 3) adopting a different construction technique. It has been obtained from a solid block of stainless steel (AISI 316 L forged) which has been first machined to get the external profile of the chamber and the reinforcement ribs; the inner hole has been obtained by electron discharge machining. In the case of this prototype, electron discharge machining has been applied twice with decreasing granularity to get a smooth inner surface. The smoothness of the surface could be further improved by electrochemical polishing.

For this prototype, pipe and ribs thickness were fixed at 0.4 mm and 2 mm, respectively. The rib pitch has been evaluated by means of the ANSYS code (finite element analysis -- fea), on a basis of 0.5 mm pipe maximum deflection.

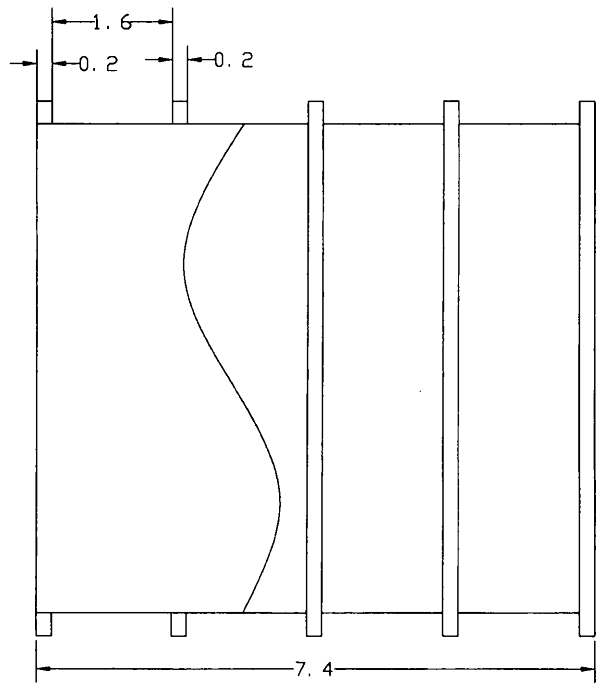


***Fig. 4** The second thin chamber prototype: ribs thickness and pitch (dimensions in cm).*

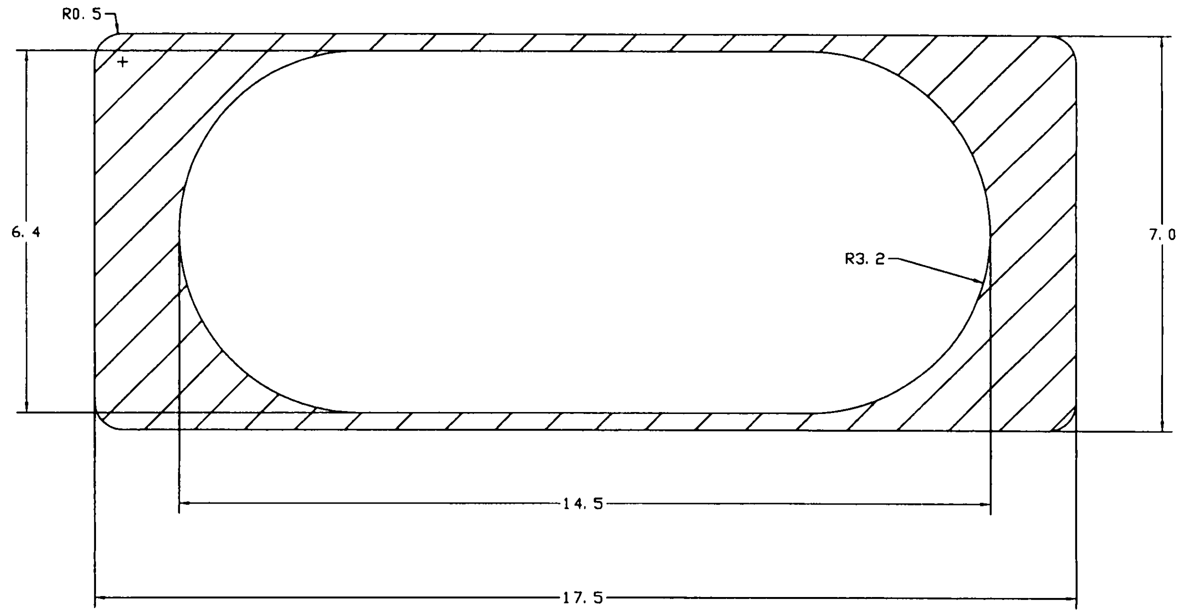


Fig. 5 *Cross section of the second thin chamber prototype (dimensions in cm).*

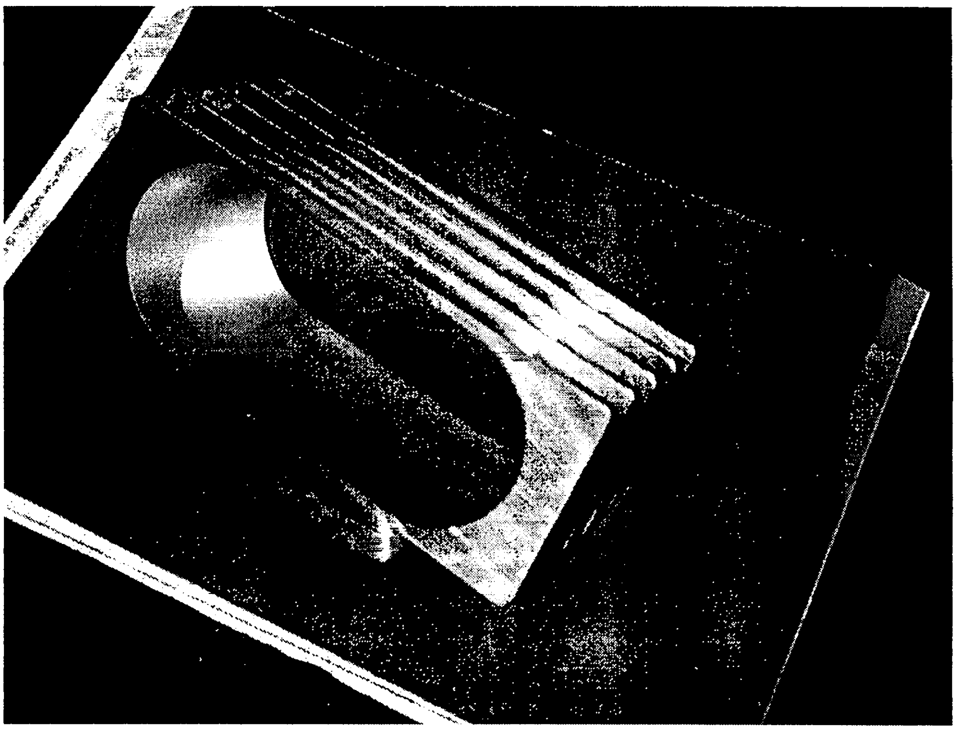


Fig. 6 *The second thin chamber prototype realised in Frascati.*

Table 3 *Characteristics of the second prototype.*

Internal dimensions H × V [mm]	145 × 64
External dimensions H × V [mm]	175 × 70
Prototype length [mm]	74.5
Geometry	Racetrack
Ribs pitch [mm]	18
Rib thickness [mm]	2
Pipe thickness [mm]	0.3 – 0.4

The machining process limits the maximum length of each piece to about 150 mm. The ribs at the two extremities could be of half thickness and tilted, so that it is possible to weld consecutive pieces along the rib profile and also give the necessary curvature to the dipole chamber.

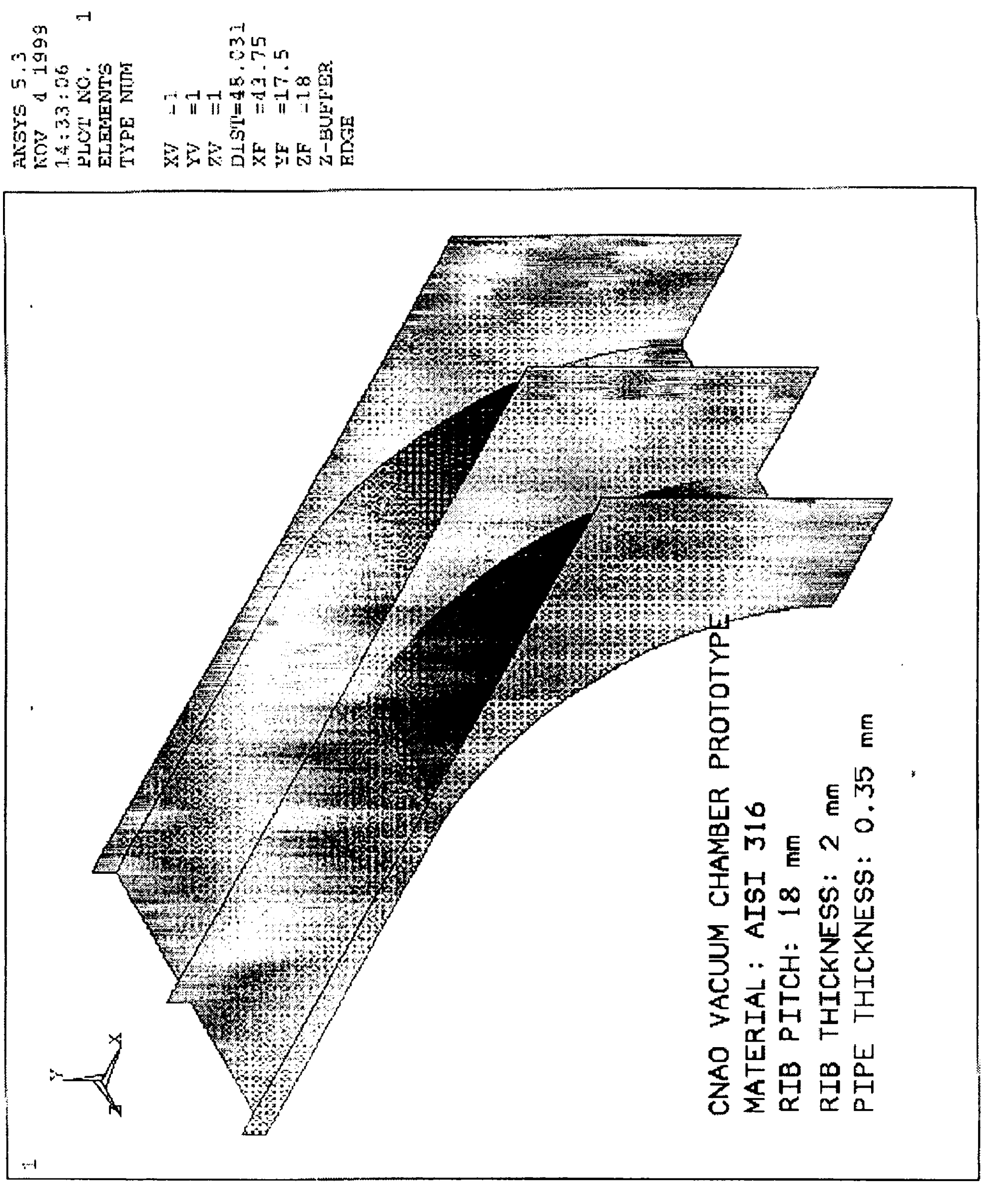


***Fig.** 7 Vacuum chamber geometry for ANSYS fea.*

This second construction technique has the advantage of being completely automated and thus with very precise reproducibility. No brazing, no heating in furnace and no special tooling are necessary. The second prototype have been tested under vacuum too and the results are summarised in Table 4.

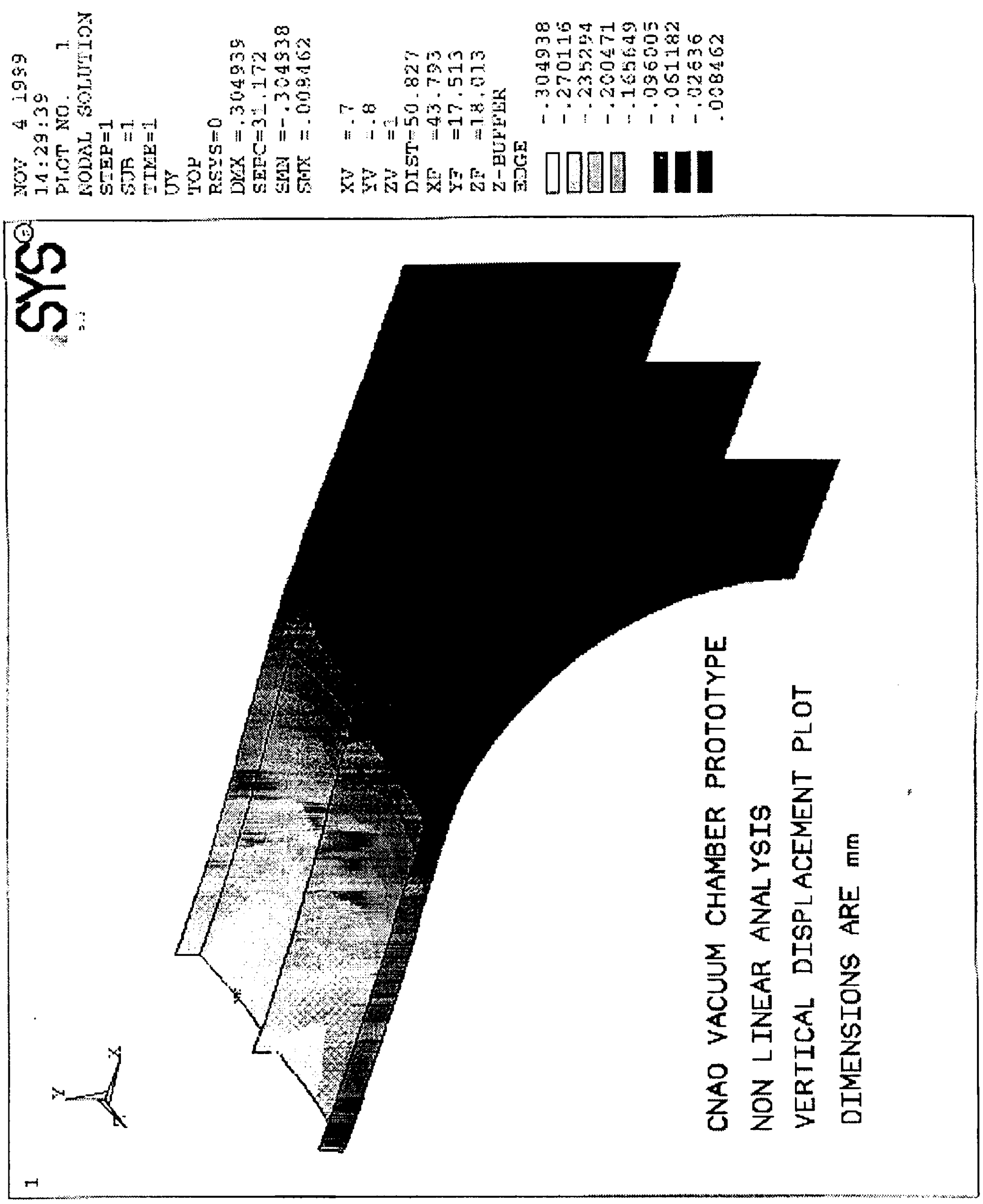


Fig. 8 Vacuum chamber buckling, ANSYS fea results.

Table 4 Buckling tests under vacuum.

Test pressure [mbar]	$5\ 10^{-2}$
Maximum total buckling [mm]	0.5
Upper face buckling [mm]	0.25
Lower face buckling [mm]	0.25

The total buckling measured on the prototype has been equal to 0.5 mm and it is within the design limits set in the previous paragraph. The deformation is elastic and agrees quite well with the simulations.

The fea of the prototype has been made considering the 3 planes of symmetry of the structure. The tolerance of the pipe thickness between 0.3 mm and 0.4 mm obtained with the technique mentioned above, has not be considered, so that a mean value of 0.35 mm was adopted (see Figure 7). Moreover being the structure not affected by buckling behaviour, the modelling of geometric imperfection is not effective on the results.

The analysis performed is a non linear type. The result shows a reduction in height of the pipe cross section of 0.61 mm (Fig. 8).

4. CONCLUSIONS

The characteristics of the thin walled vacuum chamber of the CNAO synchrotron have been presented. The necessity to reduce the effects of the eddy currents imposes a stainless steel wall of thickness not bigger than 0.4 mm.

Various construction techniques have been compared and simulations and prototypes have been realised. The thin walled chamber reinforced with ribs represents the most attractive solution. In particular the technique adopted for the second prototype has the advantage of being completely automated and thus with very precise reproducibility. No brazing, no heating in furnace and no special tooling are necessary and also the costs seem to be competitive.

The simulations and tests under vacuum have shown that the chamber prototype presents a total buckling within the design limits.

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