ESRF - The Storage Ring Magnets

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ABSTRACT

The European Synchrotron Radiation Facility (ESRF) is now entering the Storage Ring Commissioning phase. This ring of 844m circumference which is designed to store a 6 GeV, low emittance, electron beam includes 64 dipoles, 320 quadrupoles and 224 sextupoles. All these conventional magnets were designed, built and measured between 1988 and 1991. This paper presents some of the more significant aspects or events of this realisation.

1. INTRODUCTION

All the ESRF Storage Ring magnets are conventional, room temperature, DC magnets. Their magnetic design was done at the ESRF mainly in 1987, the construction contracts were awarded in late 1988 and all of them were delivered in the course of 1991.

Despite the conventional design of these magnets, the program presented some outstanding features which it could be interesting to highlight on this presentation.

The first challenging point was the high level of field quality required. The quality of the field, in term of differences between magnets and harmonic content required of the mechanical tolerances to be fixed at the limit - typically 10 or 15 µm for the gaps - of what can be expected for such realisation.

The second important point is that these performances had to be maintained even after dismounting and remounting the magnets because it was - unfortunately - mandatory to open the quadrupoles and the sextupoles to install the vacuum chambers and their pumping ports.

The third important aspect is the fact that most of the tasks had to be subcontracted for two reasons : one being the very limited number of people in charge with magnets at the ESRF - One full time engineer and two machine physicists part time. And the second reason being that, starting from scratch, there was no space or laboratory available at the ESRF. As a consequence, it was foreseen since the very beginning that the magnetic measurements would be carried out at the manufacturers premises, with the participation of the manufacturers but under the control and the responsibility of the ESRF. That policy was fruitful and all magnets were manufactured and measured according to this scheme with the exception of the quadrupoles which, for planning reasons, were finally measured at the ESRF.

2. DIPOLES

The main characteristics of the dipoles are given in Table 1. These C-shaped, laminated magnets, are rather classical except for the so-called 'soft-end'. This 'soft-end' zone is a constant field region, at least 200mm long in which the field must be decreased to 0.4 T in order to emit softer X-rays ($\lambda c = 1.3$ Å).

For symmetry this soft-end must be alternatively at the left or at the right end of the magnets thus creating two separate families.

The tolerances on field integral and harmonics are shown in table 2 as well as the results of the magnetic measurements. Note that the systematic multipole contributions were measured on the two prototypes only whilst the variations of the field integral were measured on all the magnets.

Magnetic calculations were carried out mainly using the 2D program POISSON which allowed to determine the pole profile in the central region (Fig. 1).

Nominal field	0.8566 T
Trajectory length	2.45m
Soft-end field	0.4 T
Nominal Radius of curvature	23.366m
Good field region • Horizontal • Vertical	 +/- 35mm +/- 16mm
Minimum gap	48mm
Pole width	130mm

Table 1 - SR Dipoles main characteristics

	TOLERANCE		MEASURED
Integrated field $\Delta Bl/Bl$ (1 std dev.)		5.0 E-04	3.3 E-04
Harmonic contents $\Delta Bl/Bl$ at 25mm (Systematic)	3	5.0 E-03	-2.6 E-04
	4	7.0 E-04	Negligible
	5	2.0 E-03	-1.1 E-04

Table 2 - SR Dipoles, Field Tolerances

Some attempts were made to use 3D programs (TOSCA, FLUX3D) mainly to design the soft-end region, but the results were judged not precise enough to be really useful, compared to the requirements.

Soft-end

Several possibilities were explored to create this low field region at one end of the magnet whilst keeping the same field quality in term of harmonic components as elsewhere. The solution which was finally adopted was to add two air gaps, 27.7mm each between poles and yoke in order to increase the reluctance.

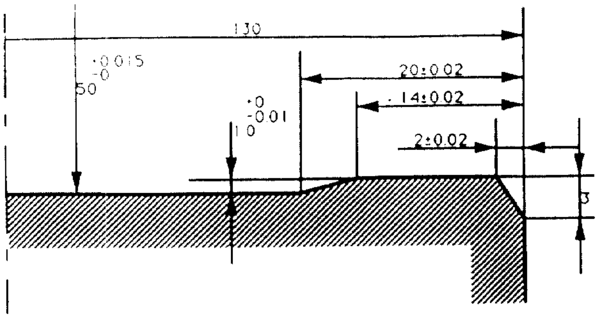

Fig. 1 - SR dipole - Central region pole profile

This idea gave rise to the so-called 'floating pole' concept (Fig.2). The radial profile of the floating poles is nearly the same as the central profile. It was optimized to produce the best field quality at this low field level.

It was found useful also to add an 'Auxiliary floating pole' between the central region and the floating pole. The role of this auxiliary pole is to produce a transition between high and low field regions and to minimize the volume of steel saturated as much as possible. This is very important in order to keep the field quality produced by the pole profile, which is only efficient if there is no saturation.

Manufacture

The manufacture was very classical. The yokes were obtained by stacking 1.5mm thick laminations punched in magnetil BC steel sheets from Cockerill. Laminations were shuffled in such a way that the same number was present on every magnet.

After stacking, the laminations were maintained in place by welding 10mm thick steel plates around the yoke. Some difficulties were encountered to keep the required straighteness of the assembly after welding, they were solved by a careful setting of the automatic machine which performed 4 weldings simultaneously.

Each coil, made up of two curved pancakes, 12 turns each, of hollow copper conductor is very classical. Insulation is ensured by fiber glass and epoxy resin.

Controls and magnetic measurements

All mechanical measurements were carried out by Tesla and controlled by Risley Technical Services on behalf of the ESRF.

The two prototypes were sent to the LNS (CEA Saclay) where they were measured by points with an array of Hall probes at several excitation levels. The results of these measurements were satisfactory so it was not necessary to make any modifications for the series.

At the end of the manufacture, each magnet was magnetically controlled at Tesla, using an automatic bench specially manufactured by the LNS (CEA Saclay). The principle of this bench is to compare the field integral produced by the controlled magnets at 5 different radial positions with those produced by a reference magnet at the same positions.

The two magnets are powered in series and the comparison is made by integrating the voltage at the ends of a set of moving coils. A test magnet was periodically checked in order to detect any shift of the measuring bench.

No differences larger than the tolerances were found between magnets which were all accepted. Nevertheless, a sorting procedure was applied to place the dipoles around the storage ring.

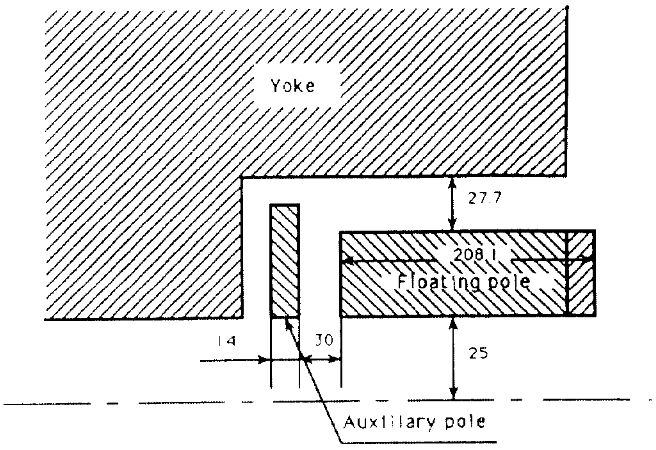

Fig. 2 - SR dipole - Longitudinal section of the floating pole

3. QUADRUPOLES

The storage ring includes 320 quadrupoles which are divided into 8 families powered by one power supply per family. 3 types of quadrupoles differing mainly by their yoke length (0.4, 0.5 and 0.9m) constitute the 8 families. All the quadrupoles have 36mm bore radius and 56.57 pole width. The maximum gradient is respectively 15.3, 17.0 and 18.1T/m.

The yokes of the shorter quadrupoles (type A and BS) are made of 1.5mm thick glued laminations while the longer ones are welded with steel corners for every quadrant. As it is necessary to leave space for the X-Ray beam lines, the yokes are split into two symmetric parts - upper and lower - with no magnetic connections in between. (Fig. 3). The mechanical cohesion of the assembly is ensured by two strong aluminium spacers. These spacers are straight if there is no beam line or U shaped otherwise. The spacer inside of the storage ring is also used to support the board, which is at one or the other end according to the quadrupole position.

The spacers are also used to leave space for the ionic or NEG pump as the pumping of the machine is distributed around the ring.

The lamination shape is identical for all families. The central region was studied in 2D using POISSON. Regarding the high level of requirements for the harmonic content, the pole shape was carefully studied. The final design is a 56.57mm wide pole with hyperbolic profile on the central region (40.3mm) followed by two straight lines and two 1.4mm chamfers parallel to the horizontal and the vertical axis. 3D calculations were made to determine the end effects but the accuracy was not found to be sufficient compared to the tolerances.

Finally 4 prototypes were assembled (2 type A, 1 BS and 1 BL) with various end chamfers and, after magnetic measurements, the chamfer which produced the integrated harmonic field within tolerances was determined. It was found that the same chamfer : 7mm depth at 45° was in fact convenient for the three types of magnets.

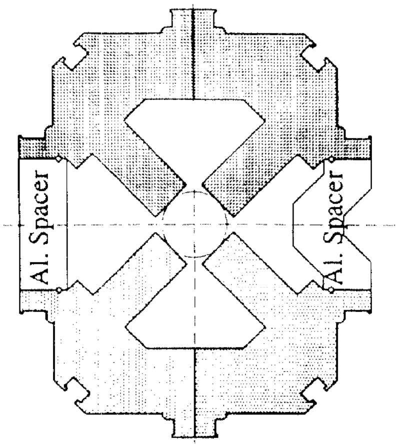

Fig. 3 - SR quadrupole - Yoke cross section

The magnetic tolerances being very tight, it was calculated that the mechanical tolerances on the bore diameter and the interpole distances have to be maintained to respectively ±0.07 and ±0.08mm.

The preliminary tests with the prototypes proved that it was very difficult to obtain such an accuracy and to maintain it after dismounting and remounting the magnet. Despite the thickness of the spacers and the quality of the blocks, the yoke assembly, composed of 6 different parts revealed itself to be relatively soft and flexible. It was necessary to develop a special tool and procedure to overcome these difficulties during the final assembly.

Controls and magnetic measurements

All mechanical controls were made by Ansaldo under the supervision of the ESRF representative. The magnetic measurements of all the magnets, including the prototypes were made with a rotating coil bench manufactured by Danfysik with the help of the CERN - LEP division.

In order to be sure of the reliability of the measuring bench, a reference magnet was measured every week.

The table 3 summarizes the results of these measurements (expressed as rms values of ΔGl/Gl at 32mm from the axis)

	Systematic		Random		Bench
	Specified	Measured	Specified	Measured	Accuracy
n = 2			$1\ 10^{-3}$	$1.3\ 10^{-3}$	$3.8\ 10^{-4}$
n = 3			$1.2\ 10^{-3}$	$0.7\ 10^{-3}$	
n = 4	$5.0\ 10^{-3}$	$1.8\ 10^{-3}$	$1.5\ 10^{-3}$	$1.2\ 10^{-3}$	
n = 5			$1.8\ 10^{-3}$	$0.3\ 10^{-3}$	
n = 6	$5.0\ 10^{-3}$	$1.8\ 10^{-3}$	$2.3\ 10^{-3}$	$0.5\ 10^{-3}$	

Table 3 - SR Quadrupoles, systematic and random harmonic contents

One can see that, due to the difficulties during manufacturing, the rms value of the distribution (1.3 10^{-3}) is slightly larger than the tolerance. This difficulty was overcome by an adequate sorting of the magnets around the storage ring.

4. SEXTUPOLES

There are 224 sextupoles in the storage ring divided into 7 families. On each cell, 3 sextupoles are on the achromat - to correct the natural chromaticity - and 4 are on the straight sections for correction of the other non linearities.

All these sextupoles are identical - but for the position of the connecting board - with a bore diameter of 82mm, a yoke length of 400mm and a nominal gradient (defined as 1/2 d2B/dr2) ranging from 54 to 155 T/m2. The six pole field is obtained by circulating a DC current of 146.3A (maximum) in the 19 turns of the water cooled pole coils.

Six additional air cooled 'backleg coils' of 380 turns each are used to generate a horizontal (B=0.03T) or vertical (B=0.045T) dipole field for steering. The field homogeneity is acceptable. For the horizontal field dB/B = -5.10-3 for z = ±12mm and, for the vertical field dB/B = ±1.10-2 for x = ±20mm.

The yoke made very classically of welded 1.5mm thick laminations is divided into three parts

As for the quadrupoles, it was unfortunately necessary to open the sextupoles by dismantling 1/3 yoke during their installation in order to place the vacuum chambers. Many tests were made including magnetic measurements before and after dismantling in order to control the reproducibility. It was shown that two successive opening and closing operations were necessary in order to eliminate any systematic effect of this exercise. The first one was easy to understand as the first assembly was made by the manufacturers with the axis vertical. The second opening operation is not so easy to understand. It could be explained by some 'memory' effect of the yoke due to the fact that we did not leave the magnet open for long.

Controls and magnetic measurements

All mechanical controls were made by Alsthom. The magnetic measurements were made using a second rotating coil bench identical to the one used for the quadrupoles, but installed at Belfort on the Alsthom premises.

These magnetic measurements were made by APAVE under the ESRF responsibility.

As for the quadrupoles, the stability of the bench was controlled by measuring one test sextupole every week. The bench was found to be somewhat less stable than the quadrupole one due to the fact that it was installed in a workshop without air temperature regulation. The results of these measurements are summarized in Table 4.

	Systematic	Random		Bench
	Measured	Specified	Measured	Accuracy
n = 3		$5.0\ 10^{-3}$	$1.8\ 10^{-3}$	$8.8\ 10^{-4}$
n = 4			$3.7\ 10^{-4}$	
n = 5			$1.6\ 10^{-4}$	
n = 6	$4.3\ 10^{-4}$		$7.0\ 10^{-4}$	
n = 9	$-1.4\ 10^{-4}$		$2.4\ 10^{-4}$	
n = 15	$- 3.3\ 10^{-4}$		$2.0\ 10^{-4}$	

Table 4 - SR Sextupoles, harmonic contents (expressed as ΔB/B at 30mm from the axis)

CONCLUSION

All these magnets are now installed in their final position in the Storage Ring. The first tests with beam of the Storage Ring have been successful, the first turn being obtained without correctors. This first success demonstrates that in spite of the difficulties encountered, the program was succesfully completed.