THE 5 T SUPERCONDUCTING UNDULATOR FOR THE LHC SYNCHROTRON RADIATION PROFILE MONITOR

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Abstract

A synchrotron radiation profile monitor will be used in the LHC to measure the beam profiles from the injection energy of 450 GeV to the nominal energy of 7 TeV. The radiation will be provided by a sequence of two separate magnets: a two-periods superconducting undulator and the beam separation dipole D3. After a short description of the profile monitor layout, the paper reviews the electromagnetic and mechanical design of the undulator, providing 5 T at 4.5 K in a 60 mm gap with a period of 280 mm and reports on the fabrication and cold test results of a first half period prototype.

THE LHC SR PROFILE MONITOR

The budget for emittance blow-up over a full LHC cycle is only 7%. It is hence important to measure with precision the proton beam profile evolution from injection at 450 GeV to physics production at 7 TeV. These measurements have to be performed continuously over the whole beam cycle in order to isolate the events leading to beam blow-up. While wire scanners are the most precise instruments for beam profile measurements, they cannot make single turn measurements, are limited to beam intensities well below nominal beams and produce beam blow-up, which limits the number of measurements [1]. On the other hand, synchrotron light monitors are the only non-intercepting monitors able to produce 2-dimensional beam images down to single turn measurements, giving not only the beam size along any axis but also any beam tilt or coupling. The difficulty with proton beams in the LHC is to provide enough photons in the sensitivity region of commercially available imaging detectors over the whole beam energy range and to extract the light out of the magnet chain. While there is no problem to produce light with the fringe and bulk fields of normal bending magnets above 2 TeV, a dedicated undulator had to be introduced to cover energies from 450 GeV to 2 TeV, which is a large energy extent for conventional undulators. To cover the full energy range, the emission spectrum has to be kept wide, which implies a small number of periods, two in our case. To provide then enough photons, the magnetic field has to be as high as possible. For performing single turn measurements down to a single bunch, a design field of 5 T has been taken, which imposes a superconducting magnet. Finally to intercept the central core of the produced synchrotron radiation (SR), the deflection of the D3 bending in IP4 is used. The principle of implementation of the resulting monitor [2] is given in Figure 1. The proton beam leaving Interaction Point 4 at the right top of the figure, enters the undulator before being deflected by 1.6 mrad by the D3 magnet. The distance between D3 and the undulator has to be kept small because the light source will move from the undulator to the edge of D3 and later to the inside of D3 when the beam energy will increase during the acceleration cycle. A distance of 80 cm from yoke to yoke was found as an optimum. The undulator and D3 are hence located in the same cryostat, which is economical from a cryogenics point of view.

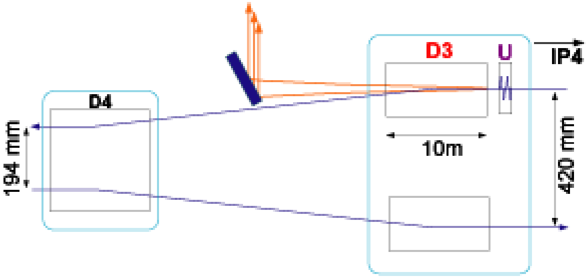

Figure 1: Layout of the SR monitor for beam 2 in LHC IP4

UNDULATOR DESIGN

The electromagnetic design is reported in [3], and the preliminary conceptual design done in 2002 in [4].

Table 1 gives a summary of the main parameters retained as specification for the magnet design.

Table 1: Main design parameters

Period length	280 mm
Number of periods	2
Pole gap	60 mm
Max gap field	5 T
Max field error over ±10mm	0.25 %
Gap field/peak field ratio	0.83
Operating current	450 A.
Magnet inductance	1.5 H
Total stored energy (450 A).	150 kJ
Operating temperature	4.5 K
Strand size (bare)	1.53x0.67 mm
Strand size (insulated)	1.65x0.97 mm
Cu/SC ratio	1.63
Cu RRR (Resid. Resistance Ratio)	>80
Margin to quench on the load line	27 %
Coil cross section	36.5x42.5 mm^2
Overall coil size (racetrack)	140x223x36.5 mm^3
Number of turns per coil	884
Number of coils	8

As the half period length is only about twice the poles gap, the magnetic field intensity on the beam axis is much lower than the peak field at the pole-tip: to provide 5 T to the beam 7.1 T have to be produced at the pole-tip. The magnet has been designed with highly saturated ferromagnetic poles, which limit the peak field on the coil to about 6 T.

The magnet assembly (Figure 2) consists of two superposed iron yokes housing on their pole expansions 4 racetrack coils each. The two yokes are spaced by a 60 mm gap. A 3-D magnetic field analysis with Opera-3D has been performed for this magnet and is shown in Figure 2.

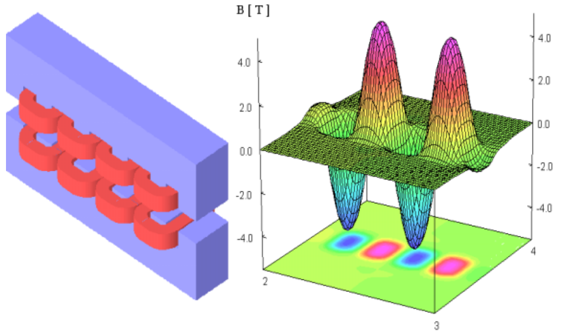

Figure 2: The undulator layout and a 3D view of the gap field distribution on the mid plane.

The undulator will be installed as an independent cold mass housed in a cryostat closing the non-lead end of the D3 dipole. This allows keeping the distance between the magnetic edges D3/undulator as small as 865 mm. The integration design has been already defined (Figure 3).

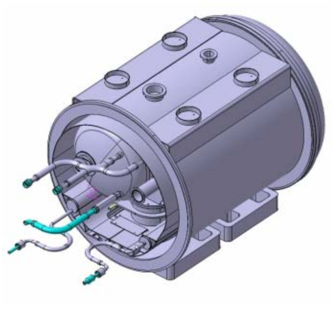

Figure 3: Final Cryostat integration

HALF PERIOD PROTOTYPE

A half period prototype has been built and successfully tested in the nominal operating conditions. The magnet was assembled with two coils and with reduced length iron yokes. The gap was instrumented with an array of calibrated Hall probes to measure the longitudinal field distribution and the corresponding pole field during the cold tests.

Description

The coils are impregnated with epoxy resin during the winding process and after a first curing cycle they are vacuum surfaced with charged epoxy. Thereafter they are mounted in a stainless steel clamping structure to counteract the Lorentz forces. The pre-stress exerted on the coils by the clamping structure is provided by copper-beryllium tie bolts which during cool down, retract more than the stainless steel structure (Figure 4).

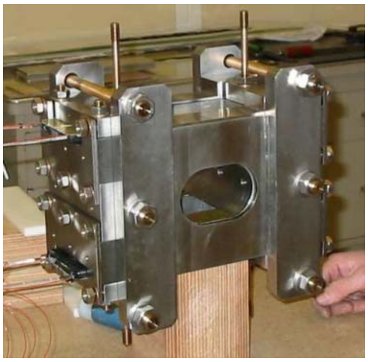

Figure 4: The clamping structure of the coils

The coil package is clamped between the iron yokes and a stainless steel strip is connected in parallel to each coil to act as a 150 milliohms energy extraction resistor. Finally some voltage taps are soldered to the interconnection points for diagnostics and quench protection purposes. Figure 5 gives an overview of the full half period prototype.

Test campaign and results

The first half period prototype was tested in February 2004 in a vertical cryostat at 4.2 K. During the first cold run (Figure 6) the magnet reached 440 A, corresponding to 4.86 T at the beam axis level. After a warm up procedure the pre-stress on the coils was readjusted first releasing it, and then setting it to a higher value (from former 30 MPa to 150 MPa in the longitudinal direction). Fig. 6 shows that this action did not affect the performance of the magnet, which continued (2nd run and 3rd run) to train slowly on the same curve and finally reached 468 A, corresponding to 5.16 T gap field. As almost all the quenches were located in only one of the two coils, the latter was excluded from the circuit to allow the second coil to be further trained. On the next cold run the second coil reached 572 A (Figure 7), which is close to the cable critical current at the coil peak field corresponding to this specific configuration.

The central magnetic field was measured as a function of the excitation current by means of a calibrated Hall probe located in the centre of the gap. The current-field curve shows saturation at about 1.5 T, and the high field part of it is linear with a slope of 8.6 mT/A. The longitudinal field distribution as measured at 470 A by the array of Hall probes is shown in Fig. 8, together with the results of a POISSON simulation.

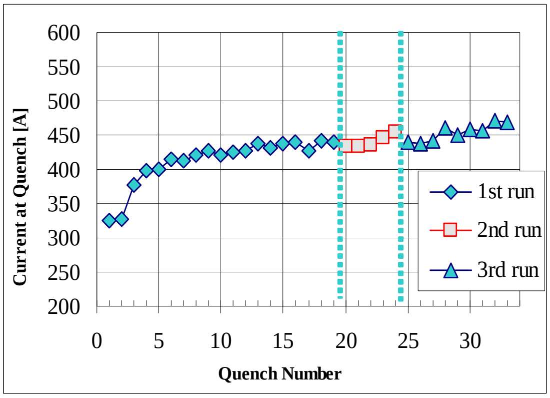

Figure 6: Training curves of the first half period prototype

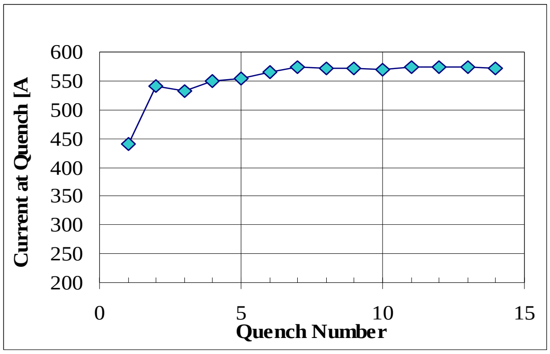

Figure 7: Training of the new coil

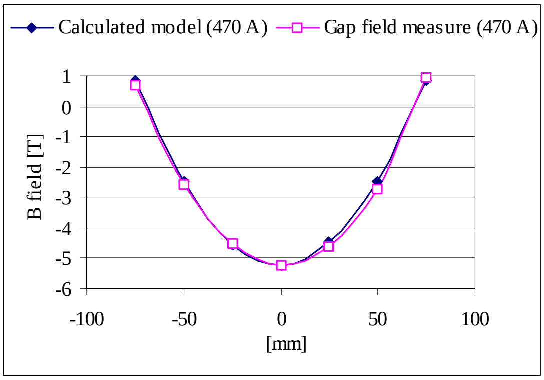

Figure 8: Longitudinal field distribution in the mid plane gap as measured and as simulated with POISSON

CONCLUSION

A half period superconducting undulator prototype for the LHC synchrotron radiation monitors has been designed, built and tested. Its performance fully meets the requirements: in particular the magnetic field produced on the beam axis exceeded the nominal operating field of 5 T. After some training, the magnet reached its cable short sample limit corresponding to about 5.8 T.

The training was relatively long, as expected from such kind of impregnated coils with many hundreds of turns, however the observed training memory after a thermal cycle was extremely good. One of the two coils was of inferior quality with respect to the best performing one giving space for further improvements.

Remaining issues are consolidating coil manufacture, keeping the highest standard of quality and homogeneity, simplifying the clamping structure, and finally building a prototype full-scale two periods undulator, which may become the spare magnet for the beam monitor system.

The chosen undulator will be able to acquire the profile of individual proton bunches in turn by turn mode. For the heavy ion program, it will be possible to acquire profiles of full beams in TV mode, i.e. over a 20ms integration time. Initial studies have been made of a more powerful undulator with a 12T peak field and a different period if turn by turn information will be requested for Lead ion beams.

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