Upgrade of the CERN Proton Synchrotron Booster bending magnets for 2 GeV Operation

A. Newborough, M. Buzio, R. Chritin

Abstract— **Since its first operation in 1972 at an energy of 800 MeV the CERN Proton Synchrotron Booster, which consists of 4 super imposed synchrotrons, has seen two upgrades: once to 1.0 GeV in 1988 and then to 1.4 GeV in 1999. During this time the main magnets of the machine have remained largely unchanged with small differences (<1%) between the inner and outer gaps of the main bending magnet fields being compensated by trim power supplies. The future upgrade of the machine will demand to extract protons at an energy of 2.0 GeV and require almost double the original dipole field. At this field, due to saturation effects, the inner and outer gaps of the main dipole magnets will differ by up to 4%. This paper presents the design and implementation of a modification of the magnetic circuit strongly reducing these effects. We also discuss the results of experimental tests concerning the effects on field quality and eddy current transients, including the implications for the real-time magnetic field measurement system to control RF and power supplies.**

***Index Terms*—Accelerator normal conducting magnets.**

I. Introduction

THE Proton-Synchrotron Booster (PSB), in operation since 1972, is the first of several pre-injectors in the way to the Large Hadron Collider (LHC) located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland.

The PSB was installed as part of the CERN Proton-Synchrotron (PS) upgrade in order to achieve higher intensity where it first accelerated protons up to an energy of 800 MeV. By 1988 the PSB was capable of providing 1.0 GeV protons to the PS and also to a dedicated experimental area, the On-Line Isotope Mass Separator (ISOLDE). Later in 1999 the PSB was upgraded in preparation for LHC operations to 1.4 GeV. During the two consecutive upgrades the main magnets in the ring remained largely unchanged with small differences in the fields (~1%) between the inner and outer apertures of the main bending magnets due to saturation and the asymmetric design being compensated by a trim power convertor which injects the missing current onto the outer rings [1]. In 2010 following the outcome of the LHC performance workshop [2] a working group was put together to study the feasibility of increasing the beam energy to 2.0 GeV in order to ease the injection of high intensity and high brilliance beams into the PS [3], and thus help removing bottlenecks in the LHC injector chain. The study concluded that the energy increase was feasible with upgrades or replacements to several systems including the powering, RF and magnet systems. For the magnets of the PSB ring and transfer lines, operation at 2.0 GeV will be possible with a variety of modifications to existing units, replacing units or changing the method of operation to allow existing units to operate at higher currents. For the main dipoles of the machine as shown in Fig. 1, modifications are needed to the cooling circuits, the method of operation (faster cycling) and to the magnetic circuit due to the higher levels of saturation and the increased difference in the field (~ 4%) between the inner and outer gaps.

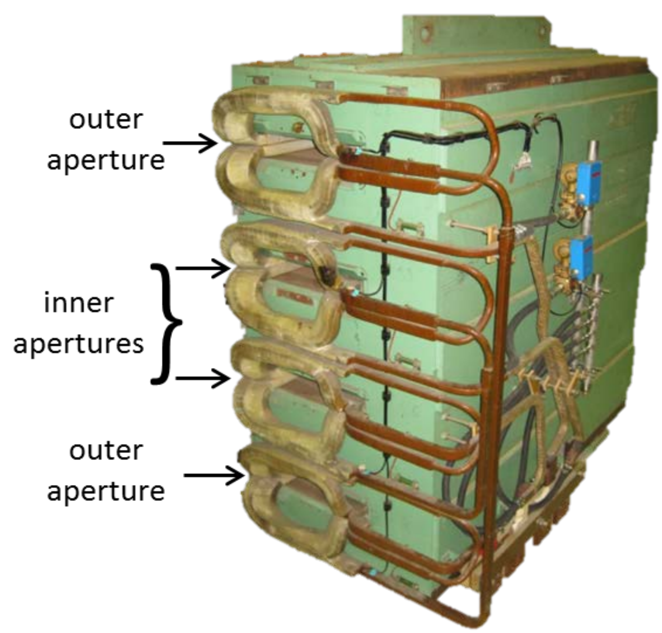

Fig.1. The PSB four aperture main dipole magnet

This paper reports on the technical choices made to allow the main dipole magnets to be operated at 2.0 GeV, including magnetic simulations and the design, production and implementation of a modification to the magnetic circuit to strongly reduce the levels of saturation. We also discuss the results of experimental tests concerning the effects on field quality and eddy current transients, including the implications for the real-time magnetic field measurement system to control RF and power supplies.

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II. The PSB Dipole Magnet

The PSB main dipole magnet features four apertures one on top of the next. The top and bottom halves are symmetric within the limits of measurement accuracy, and this symmetry is also exploited in the simulations. There are thirty two of these magnets connected in series to make up the main dipole field of the PSB, plus one used as a reference for controlling the RF and power supplies. The magnets are of an 'asymmetrical window frame' design and are constructed of 1-mm-thick laminations pressed and welded between solid endplates. The water cooled coils are entered into the aperture of the magnet and are held in place with solid steel side plates and epoxy resin shims. The characteristics of the dipole magnets at 1.4 GeV are shown in Table I.

TABLE I

Main Dipole Magnet Characteristics

Parameter	Units	Main dipole magnet
Overall height	(mm)	1700
Overall width	(mm)	980
Overall length	(mm)	1750
Iron length	(mm)	1550
Aperture height	(mm)	70
Aperture width	(mm)	200
Peak current (at 1.4 GeV)	(A)	4032
R.M.S. current	(A)	2267
Dissipated power (per aperture)	(kW)	12.6
Coils resistance @ 20°C (per aperture)	(mΩ)	2.5
Cooling circuit pressure drop	(bar)	11
Water flow (magnet)	(l/min)	26
Water temperature rise	(°C)	29
Magnetic inductance (per aperture)	(mH)	1.5
Peak flux density (per aperture)	(T)	0.86
Nominal integrated flux density @ 1.4 GeV	(Tm)	1.376
Nominal integrated flux density @ 2.0 GeV	(Tm)	1.824

Simulations of the dipole magnet performed with Cobham Opera-3D [4] software was used to identify the influence of increasing the magnetic field for 2.0 GeV operation, the results are compared in Table II.

TABLE II

Simulated Integral Field Before Modifications

Parameter	Units	1.4 GeV	2.0 GeV
Flat-top current	(A)	4032	5200
Inner apertures	(Tm)	1.416	1.815
Outer apertures	(Tm)	1.401	1.729
Difference	(%)	1.07	4.97

The increase in the differences in current between inner and outer apertures to achieve the same fields in the inner and outer apertures would imply the use of a much larger trim power converter than at 1.4 GeV. Furthermore, as the main quadrupoles are connected in series with the dipoles the trim supply required also increases in size. This additional current would also imply that the dissipated power increases in the outer apertures further increasing the temperature rise for the same cooling flow. For these reasons a study has been completed to evaluate if it is possible to reduce the saturation effects. By replacing the solid steel coil retaining plates with a laminated version, thus allowing some of the magnetic flux to be routed around the new plate and reducing the field in the normal return yoke, the level of saturation is reduced, minimizing the differences between the inner and outer apertures: this principle is shown in Fig. 2 with a 2D Poisson Superfish [5] and Opera-3D simulation. Table III shows the simulated improvement with the new side plate.

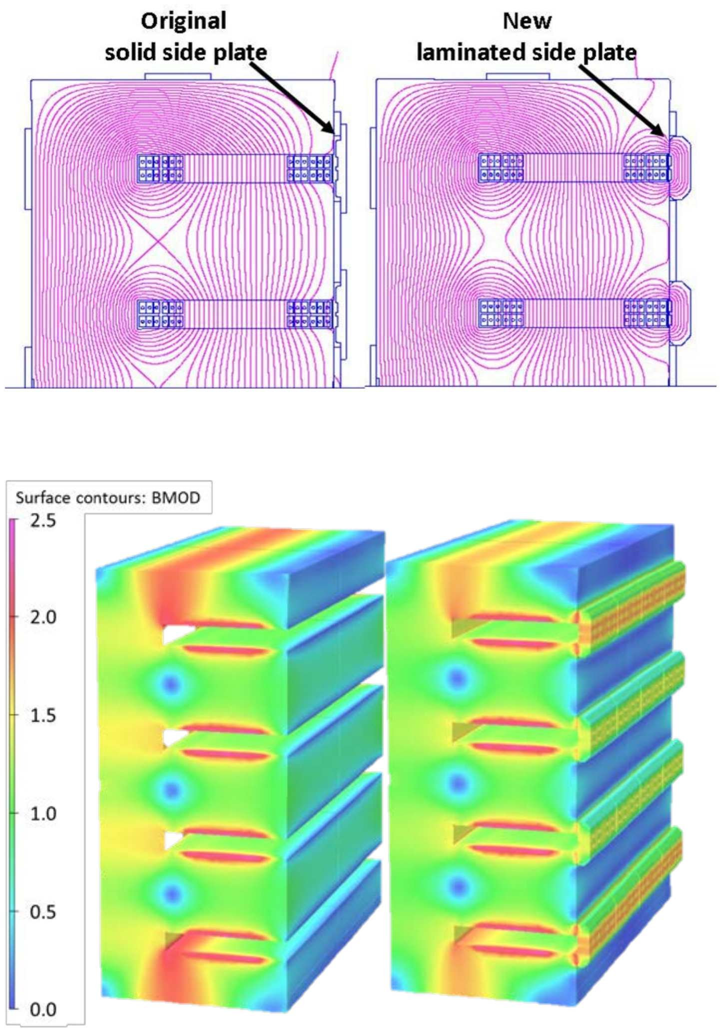

Fig.2. Poisson Superfish 2D (above) and Opera-3D (below) simulations showing the effect of introducing the laminated side plate

TABLE III

Simulated Integral Field Strength After Modification

Parameter	Units	1.4 GeV	2.0 GeV
Flat-top current	(A)	4032	5200
Inner apertures	(Tm)	1.418	1.823
Outer apertures	(Tm)	1.416	1.800
Difference	(%)	0.14	1.3

III. Design & fabrication

The laminations for the new side plates have been stamped from a similar electrical steel (M1200-100A) to the one used in the original dipole yoke. The steel is pre-coated with epoxy resin allowing the laminations to be bonded together to produce the side plate. The laminations are assembled by stacking them into a precise stacking tool utilizing spring washers to guarantee the correct geometry of the plate during bonding at 190 °C in an oven. To guarantee the contact between the side plate and the magnet, the side plates have been produced with a flatness of < 0.05 mm over a length of 378 mm, this has been achieved by designing the stacking tooling to minimize any deformation: Fig. 3 shows the ANSYS mechanical [6] deformation simulation and photo of the stacking tool.

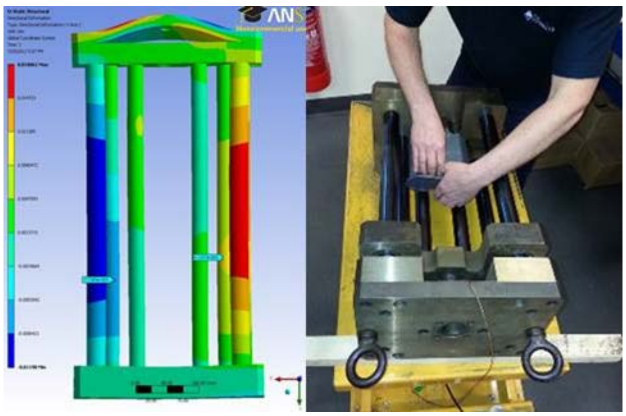

Fig. 3. ANSYS simulation and stacking tool for the laminated side plates

There are four plates per aperture with a total of 16 plates per magnet. As the side plates will be installed into the machine by hand the geometry of the plate has been optimized to have a mass of less than 25 Kg, the side plates are then held into position via a solid steel retaining cover. The side plates must still maintain the coils in the aperture, for this purpose slots are positioned in the plates where woven glass fibre epoxy resin shims will be positioned, and then pushed into contact with the coils via screws which pass through machined holes. This method of shimming guarantees an even distribution of the force exerted by the coils to avoid damage to the coil insulation: the relevant assembly is shown in Fig. 4, if implemented onto the magnets of the PSB additional plates will be included clamping the assembly longitudinally to avoid delamination.

Fig. 4. The assembled laminated side plate on the dipole

IV. Magnetic measurements

The performance of the magnet at 2.0 GeV field levels was evaluated measuring the differences in field strength and field quality between the inner and outer apertures before and after the introduction of the new side plates. The field integral was measured with a calibrated 2.5-m-long, 10-mm-wide straight search coil placed along the mechanical axis of each aperture. The flux change measured as the current is ramped from 0 to the desired flat-top level is proportional to the integrated dipole field. The flux change is measured at the end of the flat-top, so that the result is not affected by eddy current effects. This method does not take into account the contribution of the residual field, which is however less than 10^{-3} of the peak field. The results shown in Table IV include measurements at two current levels achieving the correct field integral in all apertures in both configurations. We remark that a perfectly matched field requires the use of separate power supplies for inner and outer apertures, which was not possible at the time of testing. With the side plates, the difference between the inner and outer apertures at 2.0 GeV field levels is 1.1%, well within the range that can be corrected with the upgraded power supplies, which confirms their effectiveness.

TABLE IV

Measured Integrated Field Strength

Parameter	Units	1.4 GeV	2.0 GeV
BEFORE MODIFICATION			
Flat-top current	(A)	4065	5515
Inner apertures	(Tm)	1.408	1.913
Outer apertures	(Tm)	1.392	1.834
Difference	(%)	1.10	4.13
AFTER MODIFICATION			
Flat-top current	(A)	4032	5200
Inner apertures	(Tm)	1.397	1.798
Outer apertures	(Tm)	1.394	1.778
Difference	(%)	0.18	1.10

We remark that the measured results of table IV and simulated results of table III are in agreement; minor differences between the two are likely to be a combination of differences between the actual and modeled steel properties, and the influence of the magnetic solid steel retaining cover which is not included in the simulation.

The field quality was measured by adding a second coil, which was used as a fixed reference in the bottom inner aperture, while the first one was translated stepwise across the mid-plane of the aperture being measured. This differential technique allows more precise comparison between subsequent measurements, which may be affected by poor reproducibility or ripple of the excitation current. The results of the field quality measurement before and after the modification are shown in Fig. 5. The peak-to-peak field uniformity in the ±60 mm horizontal range, which is about $\pm 2.2\times10^{-4}$ in the current configuration, becomes $\pm 1.4\times10^{-4}$ thanks to the new end plates.

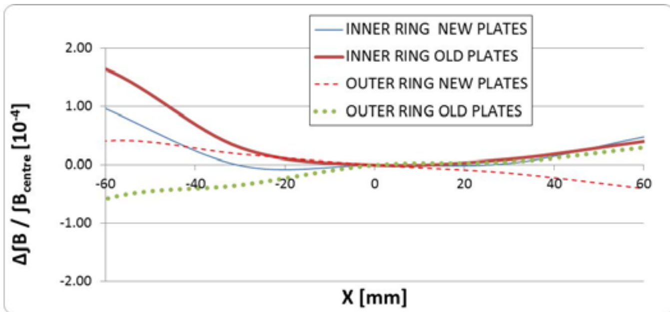

Fig. 5. Field quality comparison with and without modifications

The operation of the booster at 2.0 GeV will dictate a faster cycle so that the limiting r.m.s current seen by the magnets is not exceeded [7]. Today, operation at 1.4 GeV corresponds to a maximum rate of change of approximately 3.6 T/s (10.5 kA/s). In the most demanding 2.0 GeV scenario, corresponding to 900 ms cycles, this is expected to increase to about 9 T/s (26 kA/s).

Transient field measurements have been carried out at 20 kA/s to measure the settling time of the field due to eddy current decay. The curves plotted in Fig. 6 represent the normalized current difference i.e. the relative difference between the central integrated field, scaled so as to coincide with the excitation current at the end of the flat-top, and the excitation current [8]. Since the excitation current is well stable on the flat-top, this difference is proportional to the instantaneous value of the eddy current, which is assumed to flow mainly in the magnet poles and solid magnetic end plates.

In Fig. 6, we observe that at the reference 5200 A flat-top level the time constant of the decay is approximately 230 ms in both apertures, but the amplitude of the effect at the end of ramp-up, i.e. 3×10^{-3}, is about 3 times as large in the outer aperture.

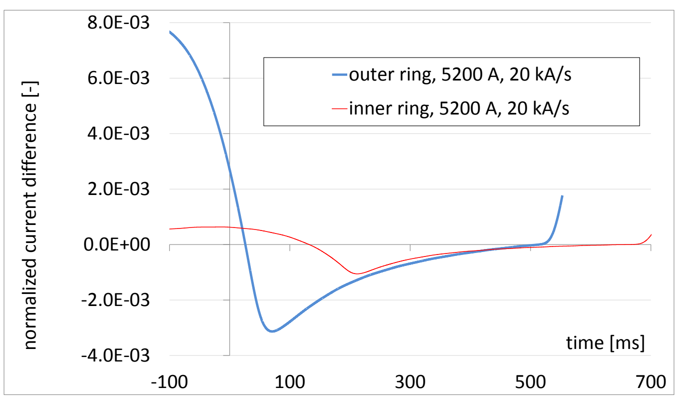

Fig. 6. Field decay transient in the inner and outer apertures with the side plates installed. The origin of the time axis is arbitrarily taken,

V. Real Time Magnetic Measurement System

The real-time magnetic measurement system ("B-train") currently in operation, which shares the electronics with the other systems in CERN PS complex, will become inadequate in the energy upgrade scenario. The main limitation is due to the electronics of the flux loop voltage integrator, which has practically been proven unable to reach the required resolution of 10 μT already at 6 T/s. High measured field accuracy will be crucial due to eddy current and saturation effects. A new B-train system made of two independent channels measuring the field in one inner and one outer aperture is currently being developed to feed back both parallel power converters. The new system will share the acquisition electronics with a broader project, aimed at the consolidation of all systems of this type at CERN [9].

VI. Conclusion

The addition of the laminated side plates on the four aperture PSB dipole magnet allow the increase of extraction energy from 1.4 to 2.0 GeV energy without further increasing the difference between the inner and outer apertures. The modification also allows for the required improvements in coil shimming due to increased fields and forces. Further study is required before implementing the change in the machine, one difficulty is at the injection and extraction where the vacuum chamber passes through the magnet aperture and bespoke side plates will be required.

The introduction of the side plates also improves field quality, in accordance with simulations. The measured long time constant observed through magnetic measurements confirms the need of real-time field control.

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