ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF082

DESIGN AND CONSTRUCTION OF THE CERN PS BOOSTER CHARGE EXCHANGE INJECTION CHICANE BUMPERS

B. Balhan, C. Baud, J. Borburgh, M. Hourican, CERN, Geneva, Switzerland

Abstract

In the framework of the LIU project and the connection from LINAC4 to PS Booster, the 160 MeV H- beam will be injected horizontally into the PSB by means of one charge-exchange injection system for each PSB ring. A set of four outside vacuum pulsed dipole magnets (BSW) creating the required injection bump has been designed and built. The dynamic requirements for the bump ramp down determine, to a large extent, the field homogeneity due to the eddy currents induced in the corrugated Inconel vacuum chamber. Magnetic simulations were performed to determine the field harmonics during bump ramp down, and the results subsequently used for the dynamic tracking of the beam during injection. The mechanical design and construction of the magnets will be briefly outlined, and the article will conclude with the magnetic measurements of the magnets. The magnetic performance of the as built magnets will be compared with the simulations and the influence of the vacuum chambers on the magnetic field will be quantified.

INTRODUCTION

A major upgrade of the CERN PS Booster (PSB) within the LHC Injector Upgrade (LIU) Project foresees the increase of the injection energy from 50 MeV to 160 MeV, to mitigate space-charge effects and to allow doubling the beam brightness and fulfill the needs of the High Luminosity LHC [1]. At the same time, the conventional multi-turn injection of protons from Linac2 will be replaced with an H^- charge-exchange injection of ions from Linac4, which is presently under construction on the CERN site.

The main challenge for implementing the new H- injection scheme in the PSB is the tight space available in the injection region [2, 3] with a straight section of only 2.6 m (see Fig. 1). The LINAC4 beam will subsequently be injected horizontally into the PSB [4], by means of an H- charge-exchange injection system using for each PSB ring, a set of 4 pulsed dipole magnets (BSW) creating the required injection bump and a stripping foil to convert the H^- beam to p^+. Four internal H^0/H^- beam dumps [5], one per ring, are installed downstream of the stripping foil to intercept the unstripped H^0/H^- and any H^- which is missing the foil.

CONCEPT

Considering a symmetric injection bump, the strength of the BSW magnets is determined by the 66 mrad injection angle from the transfer line from the Linac 4. An integral field of 126 mT.m will be required to achieve this deflection. The chicane consists of a septum magnet (BSW1) followed by 3 bumper magnets (BSW2-4) for each PSB ring. Corrugated Inconel vacuum chambers are located inside the gap of the chicane magnets.

Figure 1: The injection chicane magnets for all 4 booster rings, installed in a mock-up prior to the installation.

To fit all elements in the injection straight section, the BSW magnets do not exceed 0.38 m in length, and have a magnetic length of 0.316 m. The vertical space available for each magnet and its support is limited by the PSB ring separation of 360 mm. The main parameters of the BSW magnets are given in Table 1. The magnet apertures are adapted to the vacuum chamber dimensions.

To inject the H^- beam into the PSB, the chicane is powered and the beam is injected at the flat top. After injection the chicane is ramped down linearly in 5 ms.

Table 1: Main BSW Magnet Parameters

Parameters	BSW1	BSW2-4
Field in the centre [T]	0.399	0.399
$\int B_y dl$ at magnet centre [m.Tm]	126	126
Electric peak current [kA]	6.7	3.4
RMS current [A]	463	231
R (mΩ)	3.5	7
L (μH)	13	77
Number of turns	4	8
End Plate thickness [mm]	13.6	12
Physical length [mm]	373	380
Aperture HxV [mm]	162x85	242x85
Good field region 1% [mm]	140x85	220x85

MAGNETIC DESIGN & SIMULATIONS

When the chicane is ramped-down, eddy currents are generated in the metallic chambers which deform the field seen by the beam. The consequences of these eddy currents are two-fold. Firstly, that they introduce a delay in the magnetic field of the order of 50 μs [6, 7], which can be compensated by individual power supplies for the BSWs. Secondly, they provoke field inhomogeneities, whose impact on the beam was evaluated.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF082

The first BSW magnet (BSW1) must act as a septum, dividing the high-field region of the circulating beam from the field-free region through which the injected H- beam shall pass. The BSW2 and BSW3 magnets are identical to obtain a symmetric bump. The BSW4 magnets contain the partial or unstripped particle dumps for integration reasons. The field in the BSW4 is influenced by the presence of dump and unstripped particle observation system.

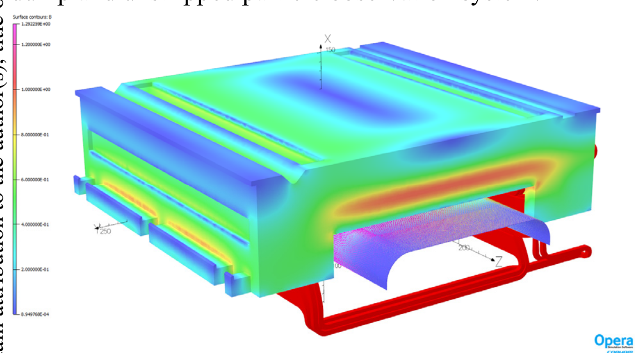

Figure 2: Magnetic model of the BSW2-4.

Magnet design and field simulations were performed using Cobham Opera software to optimise the conductor shape and size to obtain the required field quality and strength inside the vacuum chamber. Subsequently a simplified vacuum chamber was added to the magnet models (see Fig. 2). The simplification consists of a thin walled race track shaped vacuum chamber and application of anisotropic characteristics to the chamber. The conductivity has been divided by a factor to represent the reduced conductivity in the beam axis.

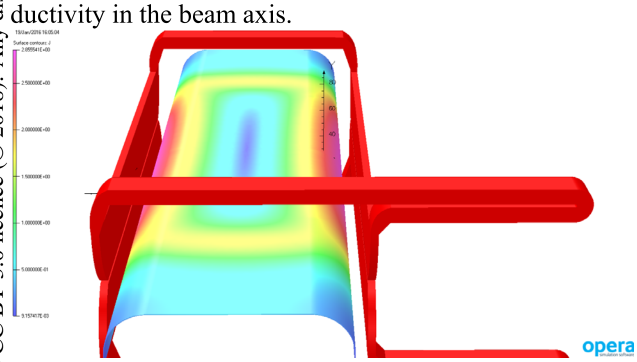

Figure 3: Current density on the surface of the Inconel BSW1 chamber.

In order to reliably calculate the eddy currents, it was necessary to mesh very finely the vacuum chamber and the air gap region where we want to determine the field. The finals models consist of about 20 million elements. Dynamic field calculations have been done starting at the end of the flat top and during the ramp using steps of 0.5 10^{-3} ms, with an adaptive time step.

The eddy currents in the vacuum chamber have been calculated during the ramp down (see Fig. 3). The maximum currents observed are 2.95 A for BSW1, 2.05 A for BSW2-3 and 4.85 A for BSW4.

To determine the effect of the eddy currents in the vacuum chamber on the field, two simulations were done. The first one with the Inconel® chamber and the second one where the material properties of the Inconel® chamber were set to 'air' characteristics. The advantage of this method is to conserve the meshes of the two simulations identical, therefore avoiding effects of interpolation between nodes.

The effect of the Inconel chamber on the vertical field (B_y) component is the difference between the results of the two models (see Fig 4). The eddy currents induce a sextupolar field component proportional to the ramp rate of the magnets.

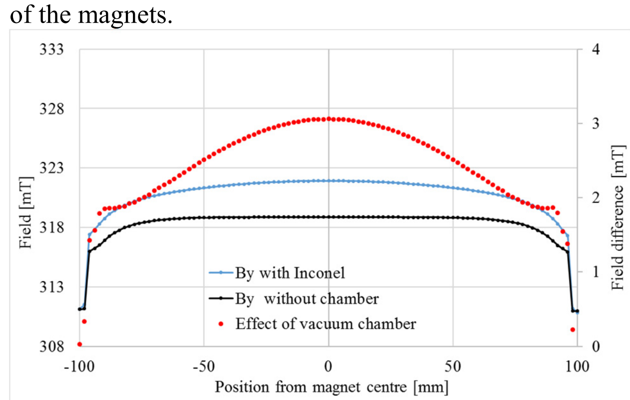

Figure 4: Punctual field of By at the midplane of the BSW2 magnet with and without Inconel chamber, during ramp, 1ms after flat top.

MECHANICAL DESIGN AND CONSTRUCTION

The magnetic design completed, the cross section of both the bumper as well as septum magnets was determined. Laminations were punched from 0.5 mm thick electrical steel Voestalpine ISOVAC M270-50A HP, with a thin layer of epoxy type glue (Backlack). The laminations were subsequently stacked and precisely aligned on a stacking tool, and cured to obtain a solid yoke. In the final stage of manufacturing of the yokes, stainless steel tie rods were welded to the yokes and the final reference surfaces and fixation holes were machined in industry. This also included machining the conductor passage in the yoke and adding chamfers to the pole ends to avoid non-linearities when ramping the magnets. The field clamps were manufactured following the same procedure using the standard laminations.

The magnet coils were produced starting with a hollow 5 mm square tube and an inner Ø 3 mm cooling water hole. To achieve the required field uniformity, vertical stiffeners were flame brazed onto the straight parts of the conductor inside the gap. Once the copper coil was formed, the conductor windings were insulated from each other using Vetronite spacers before half lapped glass fibre tape was used to wrap the outside of the coils. The coils were subsequently impregnated in a high precision mould with CTD 101 epoxy resin, chosen for its compatibility with high radiation. The final coil connection insulation was moulded separately using a small dedicated mould and a flexible polyurethane resin (RE11820 Polyol+RE1020 Isocyanate).

The final assembly consisted of the installation of the coils into the yokes. To improve the life time of the magnets, Vetronite shims were laterally inserted between the

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF082

septum part of the conductor of the BSW1 magnet and the magnetic screen, to minimise the play.

The magnets are installed on tailor made supports. To avoid time consuming re-alignment when a magnet needs to be exchanged, all magnets are individually calibrated to a common reference on their dedicated support. Each support/magnet unit is individually aligned in the common support structure. This will minimise the dose taken by personnel during preventive exchange and repair interventions in the future.

Each BSW magnet is water cooled and both half coils (top and bottom) are hydraulically as well as electrically connected in series. This reduces the number of flow meters, and subsequently the complexity of the interlock electronics.

Each magnet is connected individually to its bus-bar by means of a flexible multi-layer copper connection. The layout configuration has been designed to minimise the inductance in addition to reducing the stray field generated.

MAGNETIC MEASUREMENTS

A series of measures have been performed using a test power converter. Instead of the trapezoidal current shape that will be used in the PSB, to the test converter could only provide a 5 ms half sine pulse shape. Using this power converter, the field homogeneity has been measured for BSW1 and BSW2-4 magnets. Integrated field measurements were made on the mid-plane of the magnets, both with and without vacuum chamber.

Influence of Vacuum Chamber on the Field

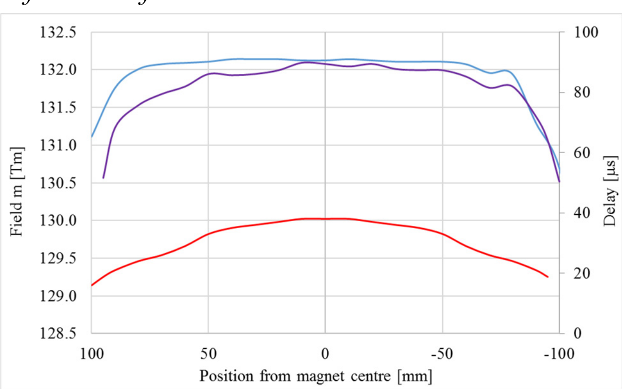

Figure 5: Measurement of integrated field of B_y at the mid-plane of the magnet without (blue line) and with (purple line) Inconel chamber, during ramp, 1 ms after flat top, for BSW2.

The field delay between the current and field is shown in red for the case with vacuum chamber. The effect of the vacuum chamber can be clearly observed (see Fig. 5). An asymmetry is observed of the field inside the vacuum chamber, where the field is slightly lower on the side where the current feedthroughs are located. Also shown in Fig. 5 the so-called delay between the current peak and the maximum field By due to the eddy currents induced in the vacuum chamber. It can be observed that this delay is not equal over the cross section of the magnet.

Leak Field of the Septum

An accurate measurement of the leak field of the BSW1, showed a relative high leak field up to 50 mT using a 0.5 mm thick mu-metal screen. Subsequently a new soft steel clamp has been designed making most use of the space available between the septum and the vacuum chamber to optimise the mechanical support of the septum conductor, and at the same time attenuating the leak field. The efficiency was considerably improved and the peak leak field is 3 mT and the integrated leak field on the beam axis is better than 0.14 % of the nominal integrated field. This steel clamp prevents the septum part of the coil from bending under load, and is expected to significantly increase the life time of the magnet.

CONCLUSIONS

After the initial simulations were completed for the BSW magnets and the mechanical design was finished, the magnets were constructed partly in industry for the yokes, and in house for the coils. Particular attention was paid to increase the life time of the magnets by minimising the clearance between the coils and the magnet yokes. A new field clamp was developed to improve the support of the septum conductor of the BSW1 septum in addition to reducing the leak field to acceptable levels.

Magnetic measurements were made on all magnets to validate their performance prior to installation using a half sine shape current pulse. On the first magnet of the series, detailed measurements were made to verify the field homogeneity and the effect of the vacuum chamber on the field. The field homogeneity is within specification, even with the vacuum chamber inserted in the magnet gap.

The assembly of the 12 BSW2-4 magnets and 4 BSW1 septa has finished, and all magnets are presently installed in a mock-up to validate the integration of all services in the injection region. They are ready to be installed in the PS Booster during Long Shutdown 2 (2019-2020).

The effect of the H^0/H^- dump and its monitor, both installed inside the BSW4 vacuum chamber, still needs to be quantified, but is expected to be minimal since they are located in the end field of the magnet only.

REFERENCES

[1] G. Rumolo, “HL-LHC beam parameters”, CERN EDMS 1296306, `https:// edms.cern.ch/document/1296306/1`
[2] M. Aiba, et al., in *Proc. PAC’09*, Vancouver, CA, May 2009, p. 3781.
[3] W. Weterings, *et al.*, in *Proc. IPAC’12*, New Orleans, USA, May 2012, p. 2041.
[4] W. Weterings, “Baseline Parameters For PSB Injection Region”, CERN EDMS 1166277.
[5] C. Maglione *et al.*, “The H0/H- dumps for the PSB injection region”, EDMS, 1293512
[6] B. Balhan *et al.*, CERN, EDMS 1157402, 2014.
[7] C. Carli, Presentation at PSB Beam Dynamics with Linac4 WG Meetings, 19 Nov. 2009.