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DEVELOPMENT OF AN EDDY CURRENT SEPTUM FOR LINAC4

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Abstract

A linear accelerator (linac) is the first stage of the CERN accelerator complex. The linac defines the beam quality for subsequent stages of acceleration and the reliability has to be high as a fault of the linac shuts down all other machines. The existing linacs at CERN were designed 30 or more years ago: recent upgrades allowed the linacs to reach LHC requirements but also showed that they are at the limit of their brightness and intensity capabilities. A replacement Superconducting Proton Linac (SPL) has been proposed; the initial part of the SPL is termed LINAC4. The LINAC4 injection bump would be made up of a set of four pulsed dipole magnets; the first of these magnets (BS1) must act as a septum with a thin element dividing the high-field region of the circulating beam from the field-free region through which injected H^- beam must pass. The initial specifications for BS1 required; a deflection of 66 mrad at 160 MeV, achieved with a peak field of 628 mT and a length of 250 mm: the field fall time was 40 μs with a flattop of at least 100 μs. The ripple of the flattop should be below ±1%. This paper discusses the design of an eddy current septum for BS1.

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A linear accelerator (linac) is the first stage of the CERN accelerator complex. The linac defines the beam quality for subsequent stages of acceleration and the reliability has to be high as a fault of the linac shuts down all other machines. The existing linacs at CERN were designed 30 or more years ago: recent upgrades allowed the linacs to reach LHC requirements but also showed that they are at the limit of their brightness and intensity capabilities. A replacement Superconducting Proton Linac (SPL) has been proposed; the initial part of the SPL is termed LINAC4. The LINAC4 injection bump would be made up of a set of four pulsed dipole magnets; the first of these magnets (BS1) must act as a septum with a thin element dividing the high-field region of the circulating beam from the field-free region through which injected H^- beam must pass. The initial specifications for BS1 required; a deflection of 66 mrad at 160 MeV, achieved with a peak field of 628 mT and a length of 250 mm: the field fall time was 40 µs with a flattop of at least 100 µs. The ripple of the flattop should be below ±1%. This paper discusses the design of an eddy current septum for BS1.

INTRODUCTION

The proposed LINAC4 is an H^- linear accelerator, intended to replace LINAC2 as the injector to the PS Booster (PSB) [1]. The PSB consists of 4 superimposed synchrotron rings. The 160 MeV beam from the LINAC4 transfer line will be distributed to the four rings by a vertical bending magnet, a system of five kicker magnets, another vertical bend and 3 septum magnets [2]. The beam will be subsequently injected horizontally into the PSB by means of an H^- charge exchange injection system: the 160 MeV beam from LINAC4 is injected into the ring through a graphite stripping foil to convert ~98% of the beam to protons [2].

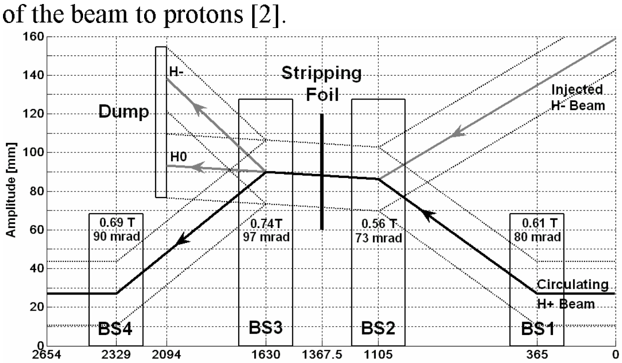

Figure 1: PSB injection region, showing injected and circulating (first turn) beam envelopes [2].

Two independent closed orbit bump systems are foreseen [2]: the first bump, called the injection bump, is made by a set of four pulsed dipole magnets (BS1−BS4), located in the injection straight section (Fig. 1), which displace the beam by a constant 60 mm during the injection process. The second bump, called the painting bump, is made by a set of four pulsed kickers.

The first BS magnet (BS1) must act as a septum, with a thin element dividing the high-field region of the circulating beam from the field-free region through which the injected H^- beam must pass. Table 1 shows the main parameters for magnet BS1 together with values for a prototype BS1 magnet. Recent beam dynamics investigations indicate that the BS magnet fall time may not be critical for the injection process: in this case the specification might be relaxed to several hundred µs or even a few ms - this could have significant implications on the magnet design, since a direct drive septum becomes technically the more attractive choice. The design presented in this paper is based on the 2006 parameter set [1].

Table 1. Main Parameters for BS1 magnet [1, 2]

Parameter	BS1[1] 2006	BS1[2] 2008	BS1 prototype	
Deflection angle	66	80	n.a.	mrad
Integrated field	126	152	119	mT·m
Gap field	628	609	411	mT
Gap height	46	68	48	mm
Gap width	110	140	110	mm
Magnetic length	200	250	290	mm
Physical length	250	300	300	mm
Number of turns	10	10	1	
Peak current	2.3	3.3	16	kA
Inductance	57	67	0.9	µH
Repetition rate	2	1.1	n.a.	Hz
Fall time	40	400	n.a.	µs
Flattop	>100	>100	n.a.	µs

CONCEPTUAL DESIGN

Magnet BS1 could be designed as either a direct drive septum [3] or an eddy current septum. The latter type has the advantage of being relatively simple mechanically: hence, in this paper, an eddy current septum design is presented. The coil sits around the back leg of a C-shaped core. The field in the gap is proportional to the current in the coil. To avoid significant leakage field the magnet opening is screened off with a copper plate, the so called septum. When the magnet is pulsed, the magnetic field induces eddy currents in the septum, counteracting the leakage field which would otherwise be created. The specification for the leakage field is presently assumed to be ≤1% of the gap field.

As a result of the limited available space, the magnetic length of the BS1 magnet is only 250 mm, which is relatively short in comparison to the gap height and width. Transient electromagnetic simulations have been carried out, using finite element codes, to assess end fields and leakage fields. The initial electromagnetic simulations, which are reported in this paper, were carried out for the 2006 BS1 design parameters [1]. 23 kA·Turns are required for BS1, with a fall time of not more than 40 μs [1]. The time duration for the flattop field is >100 μs; during this time the field must be flat with a ripple ≤±1%.

2D Simulations

2D electromagnetic simulations of the BS1 magnet have been carried out using codes from both Ansys and Vector Fields; there is excellent agreement between the predictions from these codes. The main purpose of the 2D simulations was to determine the required thickness of the septum: thicknesses in the range of 5 mm to 20 mm have been simulated. The highest frequency component of the pulse's rising and falling edges is approximately 9 kHz; this corresponds to a skin-depth of ~0.7 mm in copper. In general 3 or 4 finite elements have been modelled per skin-depth, for both the 2D and 3D simulations.

Fig. 2 shows the predicted leakage field as a function of time, close to the outside edge of the septum blade, for septum thicknesses of 5 mm and 20 mm aluminium and 20 mm copper. The eddy currents induced in the septum blade diffuse from the inside edge to the outer edge. The diffusion process is dependent upon both the conductivity and thickness of the septum blade. Fig. 2 shows a peak leakage field of 0.8% for 5 mm thick aluminium and 0.13% for 20 mm thick copper. A 5 mm thick septum is adequate for achieving a leakage field of <1% close to the septum; however a greater thickness results in reduced leakage.

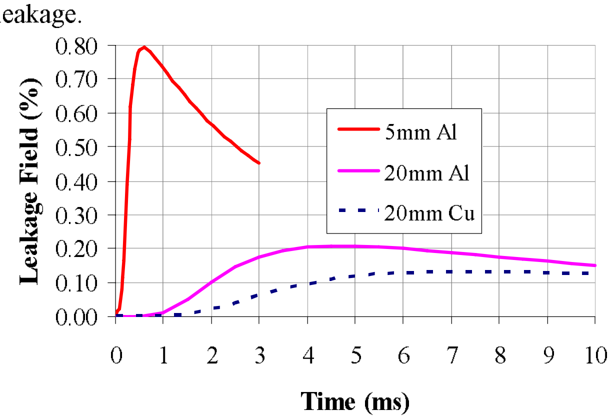

Figure 2: Predicted leakage field, 25 mm from the inside edge of the septum blade, as a function of time.

3D Simulations

Opera 3D transient analysis code Elektra was used to simulate the septum magnet. A 200 mm long, isotropic, core with a constant relative permeability and infinite resistivity were modelled; the infinite resistivity prevents the flow of eddy currents in the model of the core. In reality the core would likely be constructed from laminated silicon steel (resistivity in the range 150 to 750 nΩ·m, depending on the silicon content). The BS1 magnet was modelled as being housed in a 25 mm thick copper box; the only exception was a septum thickness of 20 mm. The predicted effective length of the BS1 magnet is 220 mm, i.e. 10% greater than the length of the core.

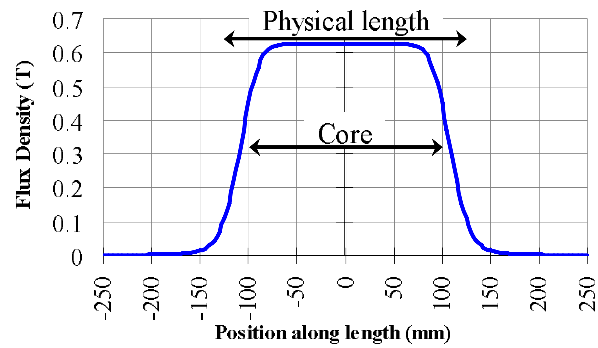

Figure 3: Predicted flux-density, along centre-line of aperture, as a function of position along length.

Fig. 4 shows the predicted leakage field, normalized to the central gap field, along the closest envelope of the injected beam to the septum (Fig. 1); the maximum value is 0.4%. The peaks in Fig. 4 are due to end fields.

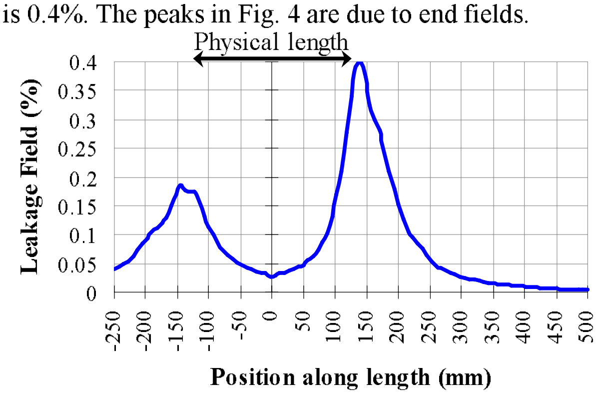

Figure 4: Predicted leakage field, normalized to gap field, along closest envelope of injected beam to septum.

BS1 PROTOTYPE

To provide a benchmark for the simulations, a simplified prototype was built, reusing part of a core initially manufactured for the CERN LEIR extraction septum, but which was rejected since its straightness was found to be out of tolerance.

Mechanical Construction

The core of the prototype BS1 magnet (Fig. 5) is constructed from 0.35 mm thick laminated silicon steel of constant cross-section. A single turn copper conductor, measuring 2 × 46 mm, is wound around the back-leg of the magnet and insulated with a shrink sleeve. On the front face there is a 10 mm copper septum blade. Two end-plates connect the septum blade to a return conductor plate placed behind the core. If required a top and bottom plate can be fitted to box-in the core completely, to reduce the leakage field.

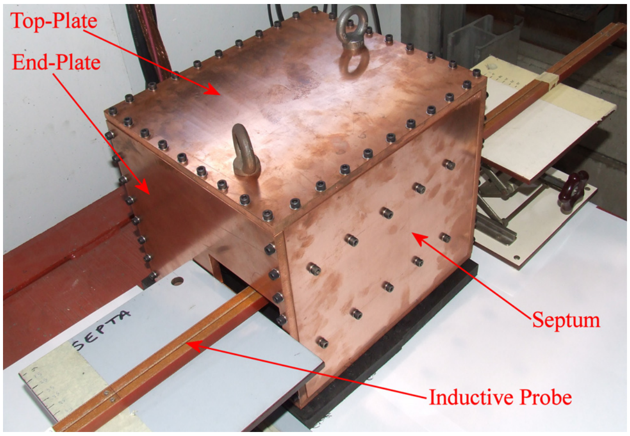

Figure 5: BS1 prototype test setup.

Magnetic Tests

To limit the voltage on the coil (limited by its insulation) and to minimise the effect of eddy currents in the core, the magnet was powered with a relatively slow capacitor discharge power supply. The maximum voltage for the capacitor bank is 2 kV; the bank is connected to the coil through a transformer with a primary to secondary turns ratio of 1 to 12. The capacitor bank was selected to have a value of 400 µF; the half sine base of the current pulse is 1.35 ms (Fig. 6). At this frequency the skin depth in the steel core is greater than the lamination thickness, hence the core laminations are adequately thin. The current of the test setup is limited to approximately 16 kA by the maximum voltage on the capacitor bank.

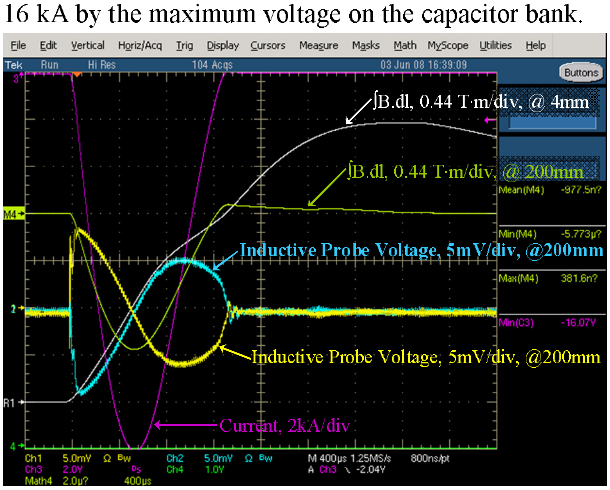

Figure 6: Leakage field measured on BS1 prototype magnet (no top and bottom plates fitted). [400 µs/div].

The magnetic length of the prototype BS1 magnet and the integral of the leakage field (∫B·dl), at a position parallel to the septum blade, outside of the septum, have been measured using an inductive probe. The measured magnetic length is 290 mm, which is 15% greater than the core length.

Fig. 6 shows two leakage field integrals, ∫B·dl, at distances of 4 mm and 200 mm from the outside edge of the septum blade: these measurements are made without top and bottom plates on the magnet. Close to the septum the ∫B·dl increases to a positive maximum at an elapsed time of 2.8 ms into the pulse. At a distance of 200 mm from the septum the ∫B·dl first increases to a negative maximum, at 0.5 ms, and then a positive maximum at 1.3 ms. The value of the negative maximum of ∫B·dl (which occurs at 0.5 ms) and the positive maximum of ∫B·dl are plotted in Fig. 7, as a function of the distance from the outer edge of the septum blade to the centre of the inductive probe. The positive maximum ∫B·dl dominates for distances from the septum of less than ~50 mm, whereas the negative maximum ∫B·dl dominates for distances from the septum of greater than ~50 mm: the reasons for this are not yet understood. In reality the closest approach of the injected beam is ~40 mm (Fig. 1); thus the negative maximum curve, of Fig. 7, would dominate (−1.1% worst-case for ∫B·dl).

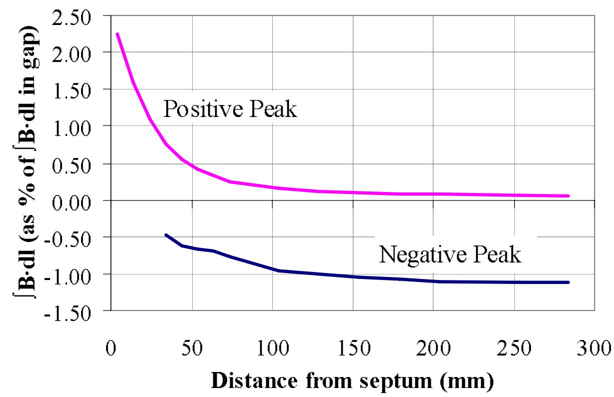

Figure 7: Measured ∫B·dl for BS1 prototype magnet with 10 mm septum blade (no top and bottom plates fitted).

The ∫B·dl measurements, for the leakage field, were repeated with the top and bottom copper plates installed, and the reduction of the leakage field was only ~4%.

CONCLUSIONS

Electromagnetic simulations have been carried out for an eddy current septum for the 2006 parameters for BS1: with a 20 mm thick copper septum blade the peak leakage field is 0.13% close to the septum: simulations will be carried out to assess the leakage field further from the septum. The measured integrated leakage field, ∫B·dl, with a 10 mm septum blade, is −1.1% worst-case: further measurements are planned with a 20 mm thick copper septum. The predicted and measured effective lengths of the magnet are 10% and 15%, respectively, greater than the core length.

REFERENCES

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[2] W. Weterings et al., "160 MeV H- Injection into the CERN PSB", PAC07, Albuquerque, USA, pp16285-1630.

[3] J. Borburgh et al., "Septa and Distributor Developments for H^- Injection into the Booster from LINAC4", proceedings of this conference.