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**A NOVEL EDDY CURRENT SEPTUM MAGNET  
FOR SPS EXTRACTION TOWARDS LHC AND CNGS**

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**Abstract**

A new East Fast-Extraction System is under construction in the SPS, to supply particles with a maximum batch length of 7.8  $\mu\text{s}$  and 10.5  $\mu\text{s}$  to the LHC and to CNGS (CERN Neutrino to Gran Sasso), respectively. The extraction septum magnets actually used at the SPS have been designed for slow extraction over several seconds and have large cooling and electrical power demands. A fast system of only 250  $\mu\text{s}$  pulse duration has therefore been developed, using a half-sine excitation pulse with a superimposed third harmonic. The short pulse duration requires very thin magnetic yoke laminations, which can not easily be stamped and stacked. Profiting from a development for the LHC beam dump kicker magnets, the yoke is therefore built-up from tape-wound cylindrical cores, employing 50  $\mu\text{m}$  thick Si-steel tape. Thirty two cores are stacked longitudinally to produce a yoke of 3.2 meter length. The aperture is cut in radial direction into each cylinder. The cores are radial compressed by spring-loaded pistons inserted in strong stainless-steel frames to provide mechanical stability. The 5+1 mm-thick copper/iron septum is separated from the excitation current loop and acts as a passive eddy current screen. This allows separating the vacuum of the magnet from that of the circulating-beam channel, avoiding the need of using UHV material. This paper presents the magnet and generator prototype design as well as simulation and measurement results.

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## Abstract

A new East Fast-Extraction System is under construction in the SPS, to supply particles with a maximum batch length of  $7.8 \mu\text{s}$  and  $10.5 \mu\text{s}$  to the LHC and to CNGS (CERN Neutrino to Gran Sasso), respectively. The extraction septum magnets actually used at the SPS have been designed for slow extraction over several seconds and have large cooling and electrical power demands. A fast system of only  $250 \mu\text{s}$  pulse duration has therefore been developed, using a half-sine excitation pulse with a superimposed third harmonic. The short pulse duration requires very thin magnetic yoke laminations, which can not easily be stamped and stacked. Profiting from a development for the LHC beam dump kicker magnets, the yoke is therefore built-up from tape-wound cylindrical cores, employing  $50 \mu\text{m}$  thick Si-steel tape. Thirty two cores are stacked longitudinally to produce a yoke of 3.2 meter length. The aperture is cut in radial direction into each cylinder. The cores are radial compressed by spring-loaded pistons inserted in strong stainless-steel frames to provide mechanical stability. The 5+1 mm-thick copper/iron septum is separated from the excitation current loop and acts as a passive eddy current screen. This allows separating the vacuum of the magnet from that of the circulating-beam channel, avoiding the need of using UHV material. This paper presents the magnet and generator prototype design as well as simulation and measurement results.

## 1 INTRODUCTION

Proton and ion beams for the anti-clockwise LHC ring will be extracted from SPS at LSS4 and transferred via transfer line TT40-TI8 to LHC point 8. The same extraction channel will also be used to transfer protons to the target for the CERN Neutrino to Gran Sasso long-baseline experiment. A new fast extraction facility is therefore needed [1]. Alternatively to the actually used slow septum magnet system (MSE), a prototype of a novel fast pulsed eddy current septum magnet (MSP) with only  $250 \mu\text{s}$  pulse duration is under construction. The MSP magnet offers several technical advantages. The septum thickness can be reduced from 17 mm to only 6 mm, and large cooling and electrical power supplies become unnecessary. SPS batches of  $7.8 \mu\text{s}$  and  $10.5 \mu\text{s}$  duration will be extracted towards LHC and CNGS at an energy of up to 450 GeV, corresponding to a kick strength of 20.7 Tm. To preserve the beam emittance, the field inhomogeneity should not exceed

$10^{-3}/\text{cm}$ . The stray field affecting the circulating beam should be less than  $5 \cdot 10^{-4}$ .

## 2 MAGNET DESIGN

The proposed extraction septum system will consist of six 3.2 m long magnets, operating at a field of about 1.1 T at 450 GeV. A cross section of the magnet is shown in Fig.1.

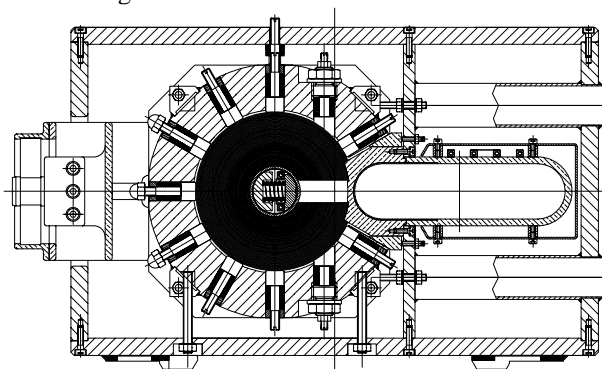


Figure 1: Cross-section of MSP prototype magnet

The main parameters of the magnet are given in Tab. 1.

Table 1: Main MSP magnet parameters

Parameter	Unit	Value
Peak field at 450 (400) GeV/c	T	1.078 (0.958)
Magnetic length	m	6 x 3.2
$\int Bdl$ at 450 (400) GeV/c	Tm	20.7 (18.4)
Kick at 450 (400) GeV/c	mrad	13.8
Pulse duration	$\mu\text{s}$	250
Min. field flat top ( $\leq 1 \cdot 10^{-4}$ ) duration	$\mu\text{s}$	7.8 (LHC) 10.5 (CNGS)
Aperture height	mm	20
Aperture width	mm	40
Septum thickness	mm	5 (Cu) + 1 (Fe)
Peak current at 450 (400) GeV/c	kA	17.16 (15.25)
Peak voltage at 450 (400) GeV/c	kV	3.40 (3.02)

The distinctive feature of this novel septum magnet is a yoke built from thin tape-wound steel. Conventional septum magnets use stamped sheets, which are thicker and longitudinally stacked. The origin of this design stems from our experience with tape-wound steel kicker magnets, developed for the LHC beam dump system. Thin magnetic laminations have several advantages. A fast excitation pulse can be chosen, which in turn permits a thin passive copper screen as septum. These eddy-current-type septum magnets have already been employed for the LEP injection system [2] and distinguish themselves by their simplicity and

reliability. An important advantage of the eddy current type is the possibility of separating the vacuum of the magnet from that of the circulating-beam channel by differential pumping, allowing the use of non-UHV material for the magnet construction. Last but not least, the cooling requirements are very low. A half-sine pulse of only  $250 \mu\text{s}$  duration with a superimposed third harmonic has been chosen, providing the required flat top ripple of  $<10^{-4}$  over more than  $11 \mu\text{s}$ . The  $3.2 \text{ m}$  long yoke is built-up from 32 longitudinally stacked cylindrical cells of  $50 \mu\text{m}$  thick steel laminations. Each cell has  $100 \text{ mm}$  length and  $138 \text{ mm}$  diameter. Standard Si-steel (3% Si) of high permeability ( $\mu_{\text{initial}} = 6000$ ) and high saturation flux density ( $>1.6 \text{ T}$ ) has been chosen, providing a homogeneous radial field distribution and low leakage field at the yoke surface. The aperture of  $20 \text{ mm}$  height and  $40 \text{ mm}$  width is cut into the pre-impregnated and de-stressed yoke by means of electrical wire cutting. To provide stable magnetic pulse conditions over many years of operation ( $>3 \cdot 10^7$  pulses) particular attention has been paid to the geometrical stability of the mechanically relatively weak yoke. The latter is therefore compressed between a strong outer C-shaped frame and a pressure resistant inner support tube, both made of stainless steel (Fig. 2).

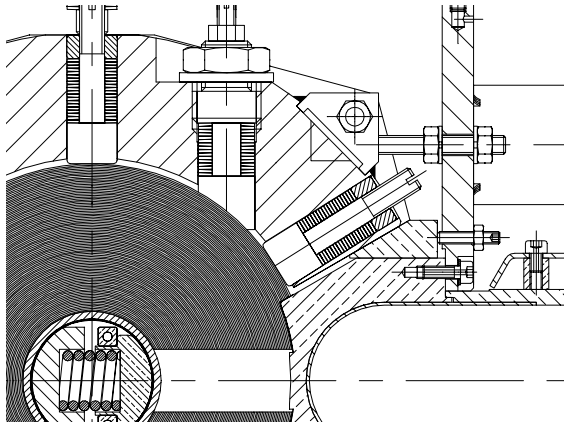


Figure 2: Cross-section of MSP prototype magnet

Spring-loaded pistons, inserted in the outer C-frame, compress the yoke with a total force of up to  $15 \text{ kN}$  per core. The mechanical stability is furthermore improved by the short pulse duration, which prevents appreciable movements due to the mass of the yoke. Fig. 2 also shows the half-cylindrical copper conductor, spring-compressed with the double magnetic force of  $26 \text{ kN}$  against the inner support tube. A chicane-structured Kapton insulation between conductor and support tube guarantees sufficient high voltage strength. The  $5+1 \text{ mm}$ -thick copper/iron septum, separated from the excitation loop, acts as passive eddy current screen. An external  $1.5 \text{ mm}$  thick iron sheet around the  $5 \text{ mm}$  thick copper beam pipe serves, together with the iron layer of the septum, as additional magnetostatic screen, shielding low frequency pulse components. The magnet will operate at a pressure of about  $10^{-4} \text{ Pa}$ , whereas the circulating-beam channel, which traverses the vacuum tank, has an independent UHV system with a pressure  $<10^{-7} \text{ Pa}$ . At both magnet ends a  $12 \text{ cm}$  long tube

surrounds the extracted beam providing a connection of low gas conductivity between the different pressure domains of the two enclosures.

### 3 PULSE GENERATOR DESIGN

The electrical circuit of the pulse generator is shown in Fig. 3 and the pulse shape in Fig. 5.

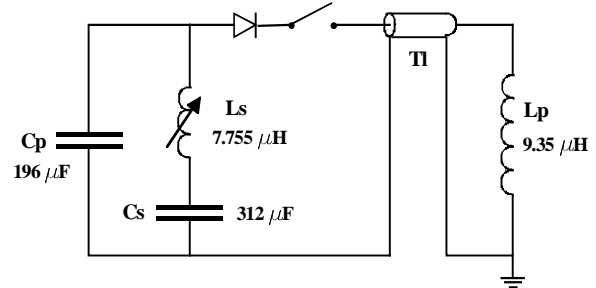


Figure 3: Basic electrical circuit diagram

The circuit has several interesting properties and has previously, to our knowledge, not been used for similar applications. Under ideal conditions (no losses, without diode and cable), the circuit can be regarded after switch closure as connection of a series and a parallel oscillation circuit of the same resonance frequency and inverse values of the characteristic impedance. Remarkable symmetries are present:  $L_s/L_p = C_p/C_s = 3/4$ , the pulse duration is  $T_p = \pi \cdot \text{Sqrt}(3L_s C_s) = \pi \cdot \text{Sqrt}(3L_p C_p)$ . The symmetry is however lost when losses or the transmission cable are introduced. Contrary to alternative third-harmonic circuits, the full stored electrical energy is available as magnetic energy at the time of beam deflection.

### 4 MAGNETIC FIELD SIMULATIONS

The characteristics of the magnet have been analysed and optimised mainly by means of the finite element package OPERA-2D<sup>®</sup>, transient fields option. The cylindrical yoke has, due to the insulation between the laminations, different magnetic properties in azimuthal and radial direction, an effect, which can not be simulated in a straightforward way. The yoke has therefore been replaced by a massive core with zero conductivity and different magnetic hysteresis curves in both directions. Field leakage into the septum and probably also eddy current losses in the laminations cause a slight field droop in radial direction towards the septum. The droop can efficiently be compensated by means of two measures: Insertion of the septum into the aperture by  $1.1 \text{ mm}$ , with a reduced height of  $18$  instead of  $20 \text{ mm}$ , and a recess of  $5 \text{ mm}$  on the yoke's outer circumference adjacent to both sides of the aperture. Simulation studies of the leakage field resulted in a significantly improved screen structure. Electromagnetic (eddy current) screening in the  $5 \text{ mm}$  copper septum reduces the field only to about  $2 \%$ . A further strong reduction is then obtained by a magnetostatic screen, an iron layer of  $1 \text{ mm}$  thickness. Due to strong field enhancement, the layer must be relatively thick and of high saturation induction rather than of high

permeability (Fig. 4). With a 1 mm layer the peak leakage field is  $<1 \cdot 10^{-4}$ .

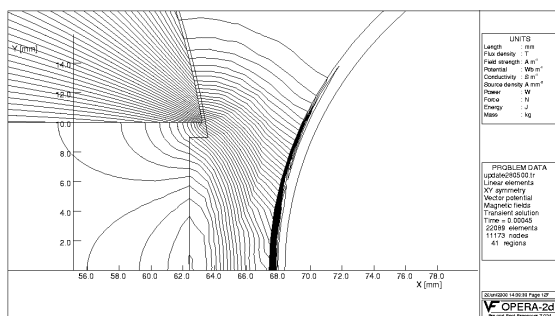


Figure 4: Magnetic flux line distribution in the septum region at the leakage field peak after 450  $\mu$ s

## 5 MEASUREMENT RESULTS

The main and leakage magnetic fields are measured with a long single turn pick-up coil of 2 mm width, mounted on a motor driven scanning machine. The output voltage of the coil is analogue-integrated and displayed on an oscilloscope with a precision of  $2 \cdot 10^{-5}$ , making use of a low noise offset amplifier (see Fig. 5).

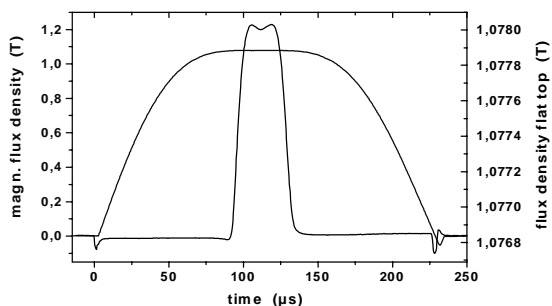


Figure 5: Flux density pulse and offset amplified flat top

The magnetic field in the aperture is scanned in a cross section raster spaced by 1 mm and graphically combined in a contour plot. Fig. 6 shows the field distribution over the aperture with the geometry described above.

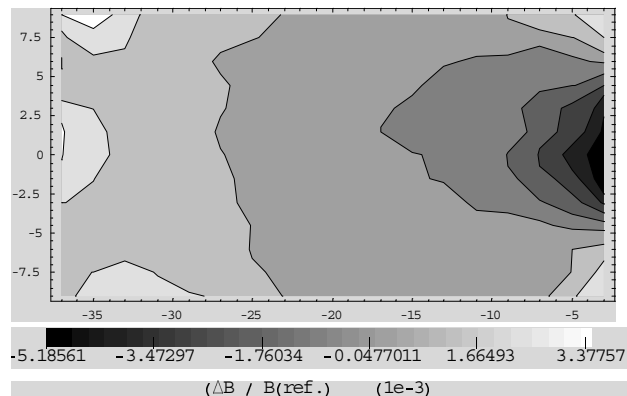


Figure 6: Distribution of flux density deviation  $\Delta B/1.08T$  in per mil over aperture (abscissa: distance to septum, ordinate: height to mid-gap). Contour line step  $1 \cdot 10^{-3}$ .

The good field region of  $1.08 T \pm 1 \cdot 10^{-3}$  extends over an area of 26 x 18 mm. The droop close to the septum is due to a 0.3 mm deep recess in the front face of the septum, an over-correction of a previous field enhancement in this region. It will be compensated by a slight shape modification of the final septum face. The temporal leakage field is shown in Fig. 7 together with the field pulse in the aperture. The low frequency components will be strongly reduced by the iron screen around the beam pipe, which is described above and missing in this set-up.

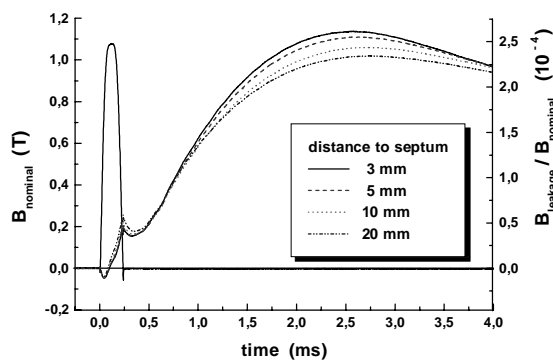


Figure 7: Temporal leakage field at different distances to the septum

## 6 CONCLUSION AND OUTLOOK

During the last years the main aspects of the system have been tested on prototypes of 50 cm and 1 m length, indicating that with high probability all requirements will be met. A full size 3.2 m magnet has been ordered and a full size power supply delivers already pulses of the required characteristics. Whether the MSP septum magnet system will be used for the LSS4 extraction will depend on an overall evaluation, taking into account the available stock of MSE-compatible equipment.

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