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The Septum Magnet System of the New Fast Extraction Channel of the SPS at CERN

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Abstract

In the Long Straight Section LSS4 of the Super Proton Synchrotron (SPS) at CERN, a new fast extraction system has been installed in order to extract the beam to ring 2 of the Large Hadron Collider (LHC) and the CERN Neutrino to Gran Sasso facility (CNGS). The system consists of horizontal closed orbit bumper magnets, extraction kicker magnets, enlarged aperture quadrupoles and six conventional DC electromagnetic septum magnets (MSE). A protection element (TPSG) has been placed immediately upstream of the first septum coil. The septum magnets and TPSG are mounted on a single mobile retractable support girder. The MSE septa are connected by a so-called plug-in system to a rigid water-cooled bus-bar, powered by water-cooled cables. The whole system is kept at the required vacuum pressure by ion pumps attached to separate pumping modules. In this note we present the design features and parameters of the MSE septum magnets, describe the function of the related main equipment elements, briefly report on the control and interlock requirements, and finally discuss the magnet cooling system.

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***Abstract*—In the Long Straight Section LSS4 of the Super Proton Synchrotron (SPS) at CERN, a new fast extraction system has been installed in order to extract the beam to ring 2 of the Large Hadron Collider (LHC) and the CERN Neutrino to Gran Sasso facility (CNGS). The system consists of horizontal closed orbit bumper magnets, extraction kicker magnets, enlarged aperture quadrupoles and six conventional DC electromagnetic septum magnets (MSE). A protection element (TPSG) has been placed immediately upstream of the first septum coil. The septum magnets and TPSG are mounted on a single mobile retractable support girder. The MSE septa are connected by a so-called plug-in system to a rigid water-cooled bus-bar, powered by water-cooled cables. The whole system is kept at the required vacuum pressure by ion pumps attached to separate pumping modules. In this note we present the design features and parameters of the MSE septum magnets, describe the function of the related main equipment elements, briefly report on the control and interlock requirements, and finally discuss the magnet cooling system.**

***Index Terms*—Electromagnetic, Extraction channel, Septa, Septum magnet, Water-cooled copper coils.**

I. INTRODUCTION

For the extraction of the beam from the SPS to the CNGS facility and ring 2 of the LHC a single turn fast extraction system will be used [1]. In this configuration, a horizontal closed orbit bump is introduced to bring the beam close to the extraction septum, as illustrated in Fig. 1. An extraction kicker magnet [2], [3] then moves horizontally the entire beam across the active septum element into the high field region of six MSE septum magnets which then deflect the beam 12.5 mrad horizontally out of the SPS vacuum chamber and into transfer line TT40 [4], [5]. In case of a mis-steered beam, the MSE septum coils are protected by a TPSG diluter element placed immediately upstream of the first septum coil.

The MSE magnets are installed on a 23 m long support girder, which is motorised for the purpose of aperture optimisation, and are connected by a 'plug-in' system to a fixed water-cooled bus-bar system powered by water-cooled cables. A cross-section of the system is shown in Fig. 2.

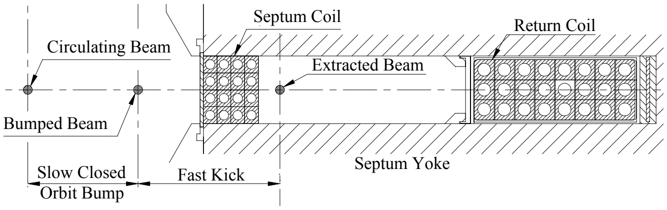

Fig. 1. Fast extraction process.

II. MSE ELECTROSTATIC SEPTA

At extraction the $\int Bdl$ required for the 12.5 mrad horizontally deflection is 18.9 Tm. To achieve this, the extraction channel LSS4 has been equipped with 6 conventional electromagnetic septum magnets (MSE), which for reasons of standardisation are identical to those used in extraction channels LSS2 and LSS6 of the SPS. The main parameters of the MSE magnets are given in Table I [6].

TABLE I
MSE SEPTUM MAGNET PARAMETERS

Septum Thickness	mm	17.25
Gap Height	mm	20
Maximum Field	T	1.508
Kick at 450 GeV/c	mrad	2.249
Magnetic Length	m	2.237
$\int$B.dl max	Tm	3.373
Peak Current	A	24,000
$\int$B.dl / I	Tm/A	$1.41\ 10^{-4}$
Total Resistance	mΩ	3.48
Total Inductance	μH	84
Peak Voltage	V	80
Minimum rise/fall Time	ms	200
Magnet Spacing (centre)	mm	3,234

A. Septum Coils

Each magnet consists of a 2460 mm long copper coil, formed by the septum- and return-coils, powered in series. The coils, of which the main parameters are given in Table II, are manufactured from cold drawn OFHC (Oxygen Free – High Conductivity) copper tubes [7]. The copper tubes are cleaned and locally annealed at 800°C followed by bending and machining to the required shape and dimension. Assembled in special purpose moulds the coils are vacuum brazed in several stages using braze with increasing melting points. After assembly, the coils are fitted tightly inside the 20 mm gap of two 1100 mm laminated yokes, the return coil being insulated by 4x250 μm layers of polymerised Polyimide insulation Pyralin®.

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TABLE II
MSE SEPTUM COIL PARAMETERS

		Septum Coil	Return Coil
Height	mm	17.24	17.8
Thickness	mm	19.9	48
Length	mm	1105	
Number of Conductors		16	24
Size of Conductor	mm	4.95 x 4	6 x 6
Hole in Conductor	mm	ø2.8	ø3.8
Copper Septum Plate	mm	22 x 0.94	
Mean Copper Area	mm^2	240	592
Min. Coil Copper Area	mm^2	213	196
Insulation Thickness	mm		1
Peak Current Density	A.mm^{-2}	112.8	122.2

B. Laminated Yoke

The yoke, of which the main parameters are given in Table III, consists of laminations blanked from 1.5 mm thick "steam-blued" Magnetil® BC mild steel, oxidized in an air-circulation furnace at 340°C for 4 hours in order to ensure a good primary insulation [8]. During assembly, each pack of 25 laminations is separated by a Kapton® layer for additional insulation and the yoke is assembled by means of 4 tie rods and insulation washers with a torque of 50 Nm. The total longitudinal electric resistance is then higher than 10 MΩ.

C. Support Structure

Both yokes are supported inside the vacuum tank by use of stainless steel support structures, which comprise a 2456 mm large semi-circular cross-member on which left and right-hand base-plates are fitted on 6 hardened steel balls ∅16 mm. By using special flanges and ceramic rods, the yoke is locked in position allowing an alignment to within ±0.15 mm [9].

TABLE III
MAIN CHARACTERISTICS OF MSE LAMINATED YOKE

Mass of yoke	kg	520 (approx.)
Nominal length	mm	1,100 ± 0.5
Straightness, surface planeness	mm	0.3
Compression between laminations	daN/cm	5
Minimum Stacking factor		0.97
Area of a lamination	m^2	0.05975
Maximum burr	mm	0.03
Resistance of 10 laminations	Ω/cm^2	> 0.033
Resistance of 1 yoke	MΩ	> 10
Vacuum Bake-out temperature	ºC	200
Residual gas pressure	Pa	10^{-7}

D. Vacuum Tank

Finally the whole assembly is mounted inside the special purpose vacuum tanks. These tanks form an integral part of the SPS vacuum system, inside which the residual pressure has to be around 10^{-7} Pa (10^{-9}mbar) [10]. The power and water feedthrough of the coil is ensured by special purpose Ultra High Vacuum (UHV) flanges, equipped with a bellows insulator, consisting of ceramic (Al_2O_3) insulators to which

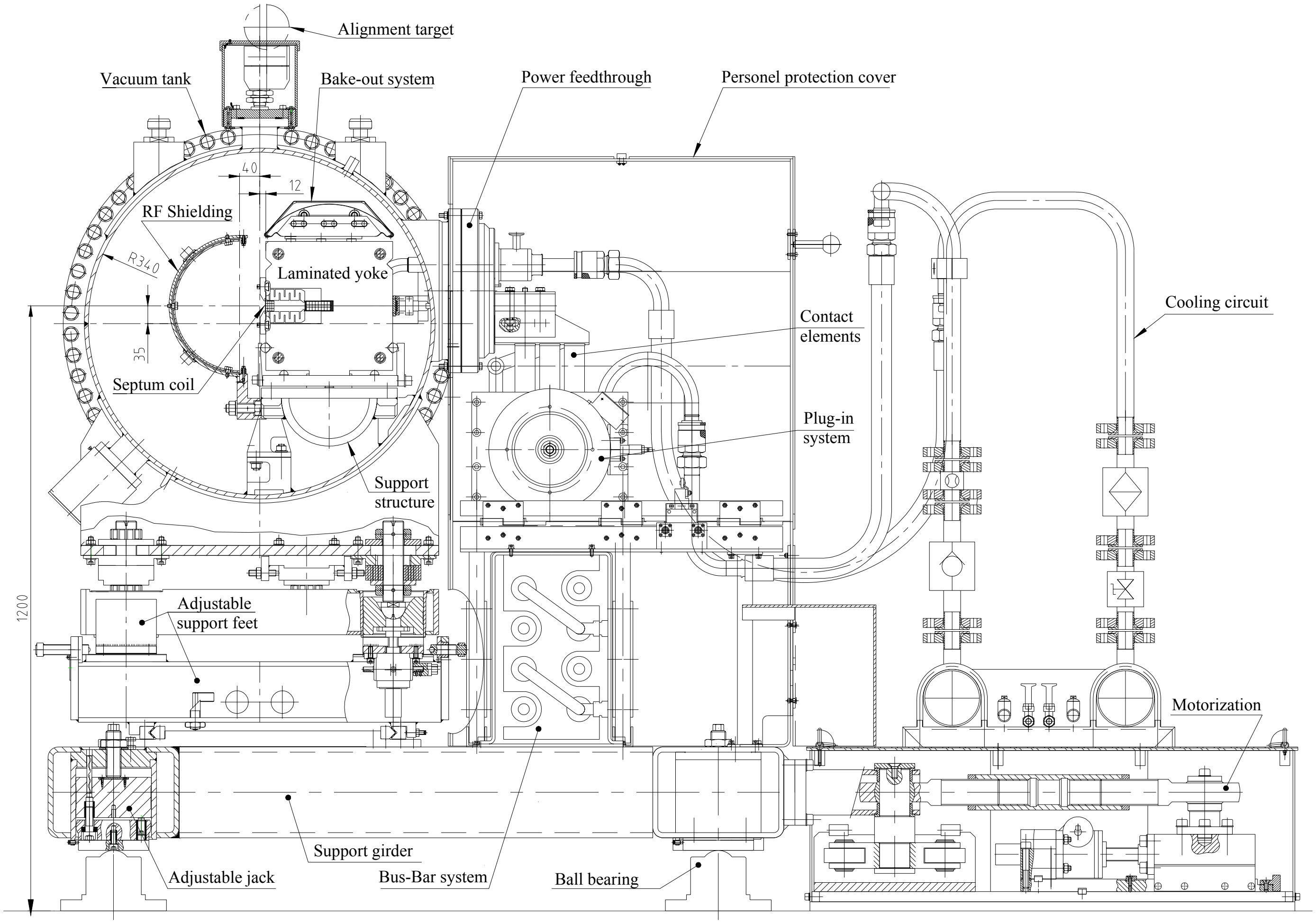

Fig. 2. Typical cross-section of the electromagnetic extraction septa installation (beam coming towards the reader).

ends small NiFeCo collars are brazed. Two bellows with their end-pieces are welded onto each side of these insulators forming a vacuum barrier and allowing for movement due to thermal expansion of the coils.

III. PLUG-IN SYSTEM

At the outside of the magnet tank, high current contact elements are connected to the coils by aid of flat braided strands (tresses). These contact elements consist of 40 mm thick copper plates equipped with multi-contact strips and are pressed with an 870 daN force against the contact plates of the bus-bar system. This is done by a so-called plug-in system, as shown in Figure 2, which allows rapid exchange of magnets in the generally radioactive environment [11]. The force on the contact plates is exercised by a stack of 40 spring-washers (∅50/∅25.4x2.5 mm, h=1.4 mm, l_0=3.9 mm) and can be released by use of bellows assemblies with a working pressure of 4.5 bars [12]. The choice and design of all components has been made such that a reliable operation in the radioactive environment can be guaranteed.

IV. VACUUM PUMPING MODULES

Between each MSE septum, there is a vacuum pumping module (MP) equipped with two 400 Torr $l.s^{-1}$ ionic vacuum pumps. The MP's are equipped with 'pirani-penning' gauges and the first and last MP's of the extraction equipment are also used to house the beam instrumentation systems. Without beam the system vacuum pressure will be about $2x10^{-9}$ mbar, changing to about $8x10^{-9}$ mbar due to outgassing once the power supply is switched on and the magnets are pulsing.

V. BUS-BAR SYSTEM

A 25 kA, water-cooled, copper bus-bar system is used to power all the magnets in series. The bus-bar consists of four in-series connected tubes with crossing return bars to minimise stray magnetic field during pulsing of the magnets.

The material used for the bus-bar system, Table IV, consists of straight high purity oxygen free (Cu-OF) copper tubes annealed after cold work with a minimum electrical conductivity of 100% IACS [13]. The copper was certified to be free of cracks, porosity and voids and very good characteristics for brazing were required. In order to ensure optimum electrical contact and avoid oxidation, all parts of the bus-bar have been brazed in a vacuum oven.

The bus-bar system is connected to the power supply by use of 10 water-cooled cables giving sufficient margin for the I_{RMS} requirements of all possible SPS cycles, mentioned in Table V. The cooling requirements of the bus-bar system are given in chapter VIII, Table VII.

TABLE IV
MAIN PARAMETERS OF CU-OF TUBES USED FOR THE MSE BUS-BAR SYSTEM

External diameter & tolerances	mm	$49.5^{0/-0.2}$
Internal diameter & tolerances	mm	$22^{\pm0.2}$
Nominal cross section	mm^2	1544
Mass resistivity at 20°C	$\Omega g/m^2$	<0.15344
Volume resistivity at 20°C	μΩm	<0.01724
Electrical conductivity	%	100 IACS
Cu content	%	99.95
Oxygen content	ppm	<10

TABLE V
REQUIREMENTS FOR MSE POWER SUPPLY

CNGS Cycle Length	s	6
LHC$_{proton}$ Cycle Length	s	21.6
LHC$_{lead}$ Cycle Length	s	49.2
Peak Current (I_{max})	A	24,000
I_{RMS} CNGS 400GeV	A	7,950
I_{RMS} CNGS 450GeV	A	8,944
I_{RMS} CNGS 350GeV	A	6,957
I_{RMS} LHC$_{proton}$ 450GeV	A	4,714
I_{RMS} LHC$_{lead}$ 450GeV	A	3,123
Max. RMS Current (I_{RMS})	A	10,000
∑ RMS Power dissipation	kW	348
Total Peak Power	kW	2,099

VI. MOTORIZED SUPPORT GIRDER

The magnets, MPs and TPSG are mounted on a 23 m long support girder using adjustable support feet, allowing horizontal and vertical alignment. The girder is assembled from seven elements, typically 3.3 m long and consisting of a welded structure made of 260x180x10 MSH profiles [14], connected together by intermediate joining plates. To allow vertical alignment, each element is equipped with 4 adjustable jacks, which themselves stand on ball bearings.

The girder has been motorised in order to optimise the local SPS aperture during setting up. The girder movement is achieved with a precision and reproducibility of ±0.1 mm using two independent motors. The magnets on the girder are pre-aligned to follow the trajectory of the extracted beam to maximise the aperture [15], [16]. The longitudinal position of the two motors was confirmed by ANSYS® calculations to exercise minimum flexion of the girder, which occurs due to friction of the ball bearings, mechanical resistance of the water-cooled cables and tension of the vacuum bellows at both ends. Table VI shows the boundary values and calculation results. Position measurement devices are installed near the extremities of the girder for reasons of accessibility and to increase the measurement precision.

VII. BEAM INSTRUMENTATION

Each MSE magnet is equipped with a Beam Loss Monitor (BLM) and the measurements of the beam losses can be used for correcting the beam trajectories in order to keep the irradiation level of the accelerator components at the lowest possible level. Furthermore, to control the extracted beam, Beam Position Monitors (BPM) are placed directly upstream of the extraction equipment, in front of the TPSG diluter and downstream after the last MSE magnet.

VIII. COOLING

In order to evacuate the dissipated power during pulsing of the magnets (~350 kW) and to maintain the septa at ~20°C, a special purpose cooling system has been installed. This cooling system constitutes of a primary circuit of chilled water

TABLE VI

BOUNDARY VALUES AND RESULT OF CALCULATIONS ON HORIZONTAL DEFLECTION DUE TO GIRDER MOVEMENT

Girder Length	mm	23,012
Position Upstream Motor	mm	6,020
Position Downstream Motor	mm	18,956
Weight / Girder Section	kg	5,000
Rolling Coefficient Ball Bearings	%	1
Friction Force / Bearing	N	250
Assumed Bellows Force	N	1,000
Resistance Water-cooled Cables	N	1,000
Required Force Upstream Motor	N	5,025
Required Force Downstream Motor	N	5,875
Maximum Deflection Upstream End	mm	0.05
Maximum Deflection Downstream End	mm	0.04
Maximum Deflection Centre	mm	0.01

(~13°C) passing through a heat exchanger cooling the secondary circuit which is powered by a 50 $m^3.h^{-1}$ pump. The de-mineralised water of the secondary circuit is filtered by a 10 µm filter and isolated from the MSE septa cooling circuit by special purpose valves.

The MSE cooling circuit has been equipped with a by-pass valve in order to fill the entire circuit and circulate water without passing through the septa coils, this in order to ensure that all trapped air and contaminations, which could damage the coils, are filtered out. Each MSE magnet is independently connected to this circuit and is equipped with a valve to isolate the magnet from the circuit, a 20µm filter in order to avoid residual particles to enter into the septum, a water temperature gauge, a flow meter and a non-return valve.

Table VII shows the main parameters of the MSE cooling system which are controlled and regulated by the MSE control system as described in chapter IX.

TABLE VII

MAIN PARAMETERS OF MSE COOLING REQUIREMENTS

Inlet Water Temperature	°C	18
Outlet Water Temperature	°C	27.8
Pressure Drop Magnet	Bars	10.23
Pressure Drop Bus-Bars+Cables	Bars	1.88
Min. Flow Rate Magnet	$l.s^{-1}$	1.0
Flow Rate Bus-Bars+Cables	$l.s^{-1}$	2.1
Total Flow Rate	$l.s^{-1}$	8.2
ΔT water magnet at (I_{RMS})	°C	8
ΔT water Bus-Bars (I_{RMS})	°C	1.1
ΔT water cables (I_{RMS})	°C	15
Nom. Water Speed in Septum	$m.s^{-1}$	6.3
Water Speed in Bus-Bars	$m.s^{-1}$	0.68
Water Speed in Cables	$m.s^{-1}$	1.33
ΔT Septum Coil (copper)	°C	10.4
ΔT Return Coil (copper)	°C	16.0

IX. CONTROLS

In order to protect the system, a multitude of measurements, such as water-flow, pressure, temperature, vacuum limits, water resistance, plug-in closure, personnel security, etc. are checked against a defined set of parameters by a PLC operated control system. This system regulates the required values and manages an interlock with the power supply in case of failure of the equipment or functioning above the predefined set of limits. This system also controls the girder position and motorisation settings and regulates the power supply for compensation.

The PLC controller can be accessed remotely for data acquisition, changing of parameter settings or modification of the interlock status and an alarm system is incorporated which directly informs the control room of any abnormal situation.

X. CONCLUSION

A 23 meter long rigid and retractable support girder equipped with six MSE septum magnets, six pumping modules and a TPSG diluter with associated instrumentation, control, powering and cooling equipment has successfully been installed, commissioned and tested in the long straight section LSS4 of the SPS.

On 8 and 9 September 2003 the new beam extraction system and the subsequent downstream transfer line TT40 were commissioned and tested for the first time with beam when single "LHC pilot bunches" were extracted from the SPS.

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