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DESIGN AND INSTALLATION OF THE MSE SEPTUM SYSTEM IN THE NEW LSS4 EXTRACTION CHANNEL OF THE SPS

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For the extraction of the beam from the Super Proton Synchrotron (SPS) to ring 2 of the Large Hadron Collider (LHC) and the CERN Neutrino to Gran Sasso (CNGS) facility, a new fast-extraction system has been installed in the long straight section LSS4 of the SPS. Besides extraction bumpers, enlarged aperture quadrupoles and extraction kicker magnets (MKE), six conventional DC septum magnets (MSE) are used. These magnets are mounted on a single mobile retractable support girder, which is motorised in order to optimise the local SPS aperture during setting up. The MSE septa are connected by a so-called plug-in system to a rigid water-cooled bus-bar, which itself is powered by water-cooled cables. In order to avoid destruction of the septum magnet coils by direct impact of the extracted beam, a dilution element (TPSG) has been placed immediately upstream of the first septum coil. The whole system is kept at the required vacuum pressure by ion pumps attached to separate modules (MP). In this note we present the design features of the main equipment elements, describe the control and comprehensive interlock system requirements, and finally report on the details of the magnet cooling system.

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1 INTRODUCTION

In the long straight section LSS4 of the SPS a new conventional fast extraction has been installed using horizontal closed orbit bumpers, extraction kickers and conventional DC electromagnetic septum magnets (MSE), the latter located just after the quadrupole QFA4180 [1].

The beam will be moved close to the extraction septum using a horizontal closed orbit bump, and is then kicked horizontally across the septum, with the kicker field rising during a gap in the circulating beam [2, 3]. The extraction septum then deflects the beam out of the SPS vacuum chamber and into the transfer line TT40 [4], with the required position and angle [5].

Six MSE magnets will be required to provide the 12.5 mrad deflection necessary. These MSE septa are connected by a so-called plug-in system to a rigid water-cooled bus-bar system, which is powered by water-cooled cables. The whole system is mounted on a single mobile retractable support girder. This girder is motorised for the purpose of alignment optimisation and to optimise the local SPS aperture during setting up, in order to avoid the risk of circulating beam impact on the septum coils. In case of a mis-steered beam, the MSE septum coils are protected by a TPSG absorber element placed immediately upstream of the first septum coil. A typical cross-section of the system configuration in extraction channel LSS4 is shown in Figure 1.

2 MSE ELECTROMAGNETIC SEPTA

In order to horizontally deflect the beam, the extraction channel LSS4 has been equipped with a total of 6 conventional DC electromagnetic septum magnets (MSE), which for reasons of standardisation are identical to those being used in extraction channels LSS2 and LSS6 of the SPS. The main parameters the MSE magnets are shown in Table 1 [6].

Table 1: 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*
∫B.dl max	*Tm*	*3.373*
Peak current	*A*	*24,000*
∫B.dl / I	*Tm/A*	$1.41\ 10^{-4}$
Total resistance	$m\Omega$	*3.48*
Total inductance	μH	*84*
Peak voltage	*V*	*80*
Minimum rise/fall time	*ms*	*200*
Magnet spacing (centre)	*mm*	*3,234*

Each magnet consists of a 2460 mm long copper septum coil, formed by two half-coils, powered in series. The coils are manufactured from OFHC (Oxygen Free – High Conductivity) copper [7] and the main parameters of the coil are given in Table 2.

Table 2: MSE septum coil parameters.

		Return Coil	***Septum Coil***
Thickness	*mm*	*47.6*	*17.25*
Height	*mm*	*17.5*	*63.5*
Length	*mm*		*1105*
Number of Conductors		*24*	*16*
Size of Conductor	*mm*	*6 x 6*	*4.95 x 4*
Hole in Conductor	*mm*	*ø3.8*	*ø2.8*
Copper Plate	*mm*		*22 x 0.94*
Mean Septum Cu Area	mm^2	*592*	*240*
Min. Coil Cu Area	mm^2		*196*
Insulation Thickness	*mm*	*1*	
Peak Current Density	$A.mm^{-2}$	*122.2*	*112.8*

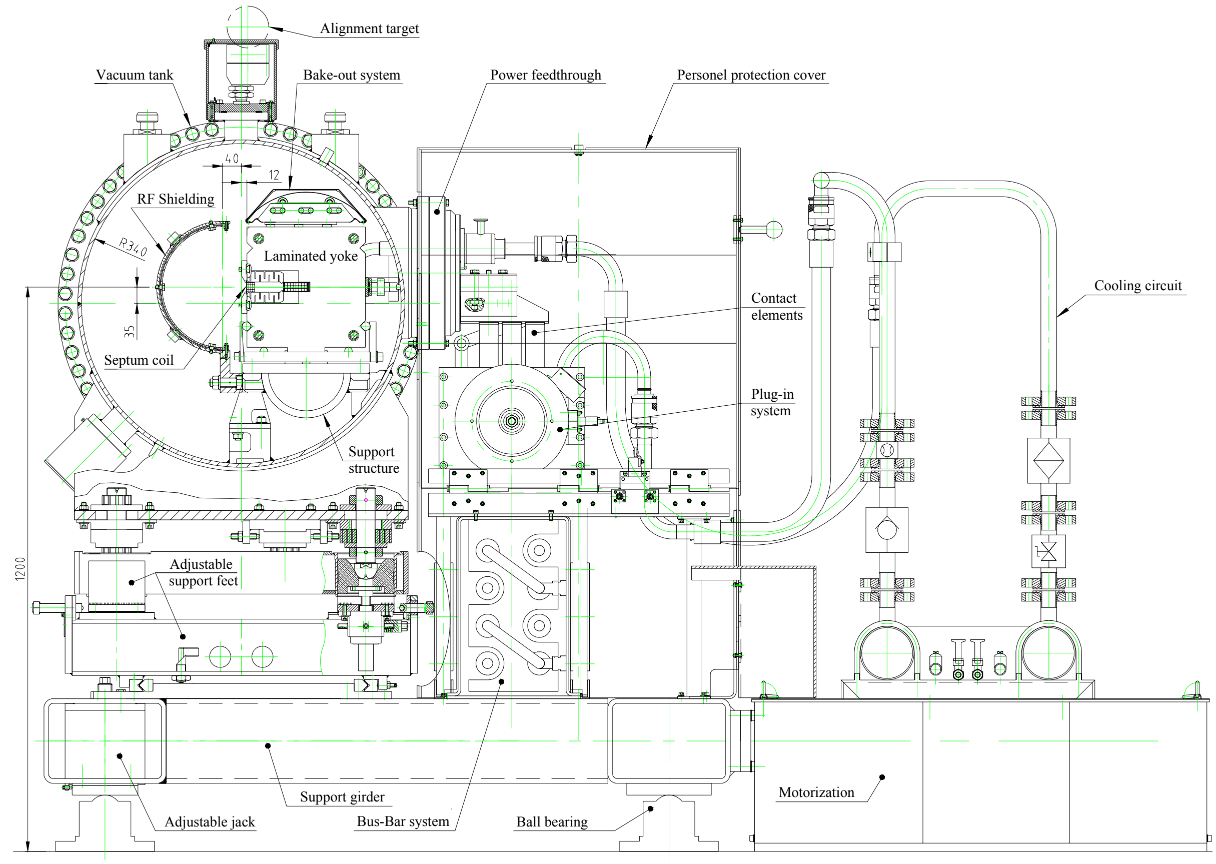

Figure 1: Typical cross-section of electromagnetic extraction septum MSE.

The coils fit tightly inside the 20 mm gap of two 1100 mm long laminated yokes, the septum coil being insulated by 4x250 µm layers of polymerised Polyimide insulation Pyralin[1)]. The yokes, of which the main parameters are given in Table 3, are assembled of laminations blanked from 1.5 mm thick "steam-blued" Magnetil BC[2)] mild steel and 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[3)] layer for additional insulation and the total length of yoke is adjusted, by means of 4 tie rods and insulation washers, with a torque of 50 Nm.

Table 3: Main characteristics of MSE laminated yoke.

Mass of yoke	*kg*	*520 (approx.)*
Nominal length	*mm*	*1100 ± 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	$M\Omega$	*> 10*
Vacuum Bake-out temperature	*C°*	*200*
Residual gas pressure	*Pa*	10^{-7}

[1] Registered trade mark of Dupont de Nemours
[2] Cockerill, Belgium
[3] Registered trade mark of Dupont de Nemours

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

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 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.

3 MOTORIZED SUPPORT GIRDER

The magnets, pumping modules (MP) and TPSG diluter are mounted on a 23 m long rigid support girder using adjustable support feet, allowing horizontal and vertical alignment. The support girder is assembled from seven elements connected together by intermediate joining plates. Each girder element is typically 3.3 m long and consists of a welded structure made of 260x180x10 MSH profiles [11]. To allow vertical alignment, each element is equipped with 4 adjustable jacks, which themselves stand on ball bearings allowing a low friction movement.

The complete girder has been motorised in order to optimise the local SPS aperture during setting up, so as to avoid the risk of circulating beam impact on the septum coils. This, so-called retracted position, is achieved by a girder movement of 35mm upstream and -10mm downstream with a precision and reproducibility of ±0.1mm using two independent motors. Furthermore, the position of the equipment on the girder has been optimised and the magnets are pre-aligned so as to follow the trajectory of the extracted beam in order to give it a maximum aperture, yet keeping sufficient clearance for the circulating beam [12, 13]. The longitudinal position of the two motors has been carefully chosen and confirmed by ANSYS[4)] calculations in order to exercise a minimum flexion of the girder, which will occur due to the friction of the ball bearings, mechanical resistance of the water-cooled cables and tension of the vacuum bellows at the quadrupoles. Table 4 shows the boundary values and results of these calculations. Furthermore, to allow the operators to identify the precise position of the girder, measurement devices are installed, near the extremities of the girder for reasons of accessibility and in order to increase the precision of the measurement due to the lever of the girder.

Table 4: Boundary values and results of calculations on horizontal girder deflection due to movement.

Girder length	*mm*	*23012*
Position Upstream motor	*mm*	*6020*
Position Downstream motor	*mm*	*18956*
Weight / Girder Section	*kg*	*5000*
Rolling coeff. Ball Bearings	*%*	*1*
Friction Force / Bearing	*N*	*250*
Assumed Bellows Force	*N*	*1000*
Resistance Water-cooled Cables	*N*	*1000*
Required force Upstream Motor	*N*	*5025*
Required Force Downstream Motor	*N*	*5875*
Maximum deflection Upstream End	*mm*	*0.05*
Maximum deflection Downstream End	*mm*	*0.04*
Maximum deflection Centre	*mm*	*0.01*

4 BUS-BAR SYSTEM

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

The material used for the bus-bar system, of which the main parameters are given in Table 5, consists of straight high purity oxygen free (Cu-OF) copper tubes annealed after cold work with a minimum electrical conductivity of 100% IACS [14]. 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 system have been brazed in a vacuum oven.

Table 5: Main parameters of Cu-OF tubes used for the MSE magnet bus-bar system

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

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 different possible SPS cycles as mentioned in Table 6. The cooling requirements of the bus-bar system are given in chapter 9, Table 7.

Table 6: 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*	*24000*
I_{RMS} *CNGS 400GeV*	*A*	*7950*
I_{RMS} *CNGS 450GeV*	*A*	*8944*
I_{RMS} *CNGS 350GeV*	*A*	*6957*
I_{RMS} LHC_{proton} *450GeV*	*A*	*4714*
I_{RMS} LHC_{lead} *450GeV*	*A*	*3123*
Max. RMS Current (I_{RMS})	*A*	*10000*
$\sum$ *RMS Power dissipation*	*kW*	*348*
Total Peak Power	*kW*	*2099*

5 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 the so-called plug-in system, as shown on Figure 1, which allows rapid exchange of magnets in the generally radioactive environment [15]. The force on the contact plates is exercised by a stack of 40 spring-washers (∅50/∅25.4x2.5, h=1.4, l_0=3.9) and can be released by use of bellows assemblies with a working pressure of 4.5 bars [16]. The choice and design of all components has been made such that reliable operation in radioactive environment can be guaranteed.

6 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

[4] Registered trade mark of ANSYS Inc. Corporate

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 once the power supply is switched on and the magnets are pulsing. This phenomenon is well illustrated in Figure 2, showing normal pulsing of the magnets with occasional stops and three 24 hours periods without extraction.

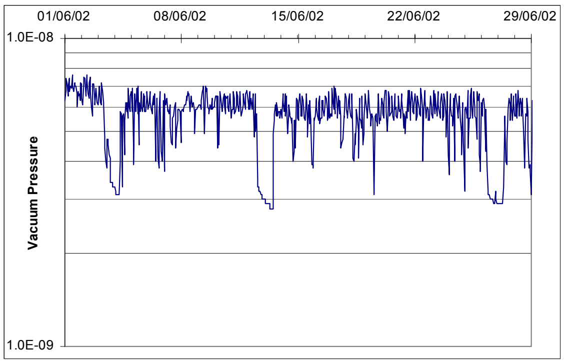

Figure 2: A typical month of SPS exploitation with three periods of 24h without beam extraction.

7 TPSG DILUTER ELEMENT

Direct impact of a small fraction (approximately $5x10^{11}$ protons or 1%) of the extracted beam intensity could damage or destroy one or more septum magnet coils. A comprehensive interlock system will be required to survey the beam positions, losses, bumper and septum currents, kicker charging voltages, etc. However, operator error can never be excluded, and several other modes of failure are also possible. Therefore, a physical protection element, so-called TPSG absorber, has been placed immediately upstream of the first septum coil to reduce the particle flux on the coil to a safe level, such that the temperature does not exceed 100°C.

This 2.9 meter long absorber is a composite shield made up from 2.1 meter of graphite and 0.8 meter of aluminium alloy installed in a 2.9 meter long solid stainless steel core of 250mm x 300mm cross-section similar to the MSE laminated yoke. The whole assembly is installed in a LEP (Large Electron Positron Collider) recuperated and modified ZX type UHV tank. In detail the absorber element consists of 10 units of 210mm long isostatic pressed graphite bars (density 1.77 g/cm^3) with a cross-section of 19.25mm x 30mm and 1 unit of 800mm long DIN AlMgSi0.5 type aluminium alloy bar (density 2.7g/cm^3) having the identical cross-section as the graphite parts.

Simulations of the conditions to which the absorber will be subjected have shown that no cooling of the yoke will be needed and the maximum temperatures remain safely below the melting point. However, the maximum equivalent stresses may slightly exceed the elastic limit in the aluminium section of the diluter. Also, the predicted maximum temperature rise in the MSE septum coil exceeds the design value such that the simulated solid copper coil is locally heated to about 165° C. However, the high pressure and flow rate (see paragraph 8), together with the high heat capacity and enthalpy of the cooling water in the coils, mean that a local temperature rise in the copper to 165° C, although undesirable, should not pose a problem for the septum [17]. Figure 3 shows a simulated temperature profile for an LHC-type beam impact along a 3 m graphite/ aluminium diluter and in the first part of the MSE coil, indicating that the coil temperature is kept to about 100°C. Nevertheless, beam losses on the absorber and MSE septa will generate high radiation levels for which sufficient shielding should be provided [18, 19].

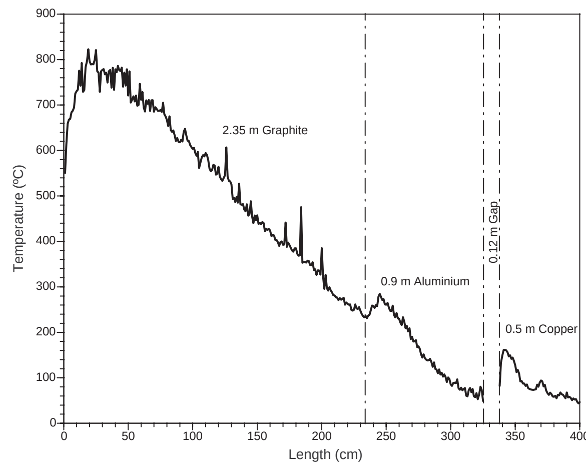

Figure 3: Calculated temperature profile in diluter and MSE coil (*$4.9x10^{13}$* protons, *450 GeV/c*)

8 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.

9 COOLING

In order to evacuate the dissipated power during pulsing of the magnets (~350kW) 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 (~13°C) passing through a heat exchanger cooling the secondary circuit which is powered by a 50m^3/h pump. The de-mineralised water of the secondary circuit is filtered by a 10μm 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 7 shows the main parameters of the MSE cooling system which are controlled and regulated by the MSE control system as described in chapter 10.

Table 7: 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*

10 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 an abnormal situation.

11 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 in the long straight section LSS4 of the SPS.

12 ACKNOWLEDGEMENT

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