CHAPTER 18

EXTRACTION TOWARDS THE LHC

18.1 INTRODUCTION

Two fast extraction systems are required in the SPS to deflect the 450 GeV proton and ion beams into the transfer lines and then to the LHC. This chapter describes the requirements, the equipment used, the modifications to the existing systems and the performance aspects of the extraction channels.

The proton and lead ion beams for the anti-clockwise ring (beam 2) of the LHC will be extracted using a new system built in LSS4 and transferred to LHC Point 8 via the transfer line TT40-TI8. The same extraction channel will be used to transfer protons to a neutrino target for the proposed long baseline Neutrino to Gran Sasso (CNGS) project.

For the clockwise LHC ring (beam 1), the existing extraction channel in LSS6 will be modified, for beam transfer to the LHC point 2 via the transfer line TT60-TI 2. The existing resonant extraction system will be upgraded for fast extraction only.

18.2 REQUIREMENTS

Conventional fast extraction will be used in both LSS4 and LSS6 with horizontal closed orbit bump, fast kicker and magnetic septum. Vertical closed orbit bumpers will also be used for precise vertical beam positioning at high energy. For LSS4, additional requirements are imposed by CNGS, including the need for a sequence of two fast extractions. The general requirements that must be satisfied are:

- A large enough aperture for injected, bumped and circulating beam
- Loss-free fast extraction of the entire 8μs long LHC type beam
- Compatible with FT beams for CNGS and resonant extraction in LSS2

18.2.1 LSS4

In the long straight section LSS4 of the SPS a new conventional fast extraction [1,2,3] has been installed using horizontal closed orbit bumpers, extraction kickers and conventional DC electromagnetic septum magnets (MSE) located just after the quadrupole QFA418. The beam is moved close to the MSE 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. The extraction septum then deflects the beam out of the SPS vacuum chamber and into the transfer line TT40, with the required position and angle. The extraction channel in LSS4 requires the installation of five kickers MKE, eight bumper magnets, three enlarged quadrupoles (QDA417, QFA418 and QDA419), an absorber TPSG (dummy septum) and six extraction septum magnets, for which the existing design of the 17 mm thick MSE septum is used. The extraction has been designed for two different proton beams, LHC and CNGS. The Pb^{82+} beam for LHC is considered as having the same transverse dimensions as the proton beam and as such is not considered explicitly.

18.2.2 LSS6

The extraction channel in LSS6 has been in use for many years for the resonant extraction of beams towards experiments in the west area. After the closure of this area at the end of 2004, the extraction system will be upgraded for LHC [4] with removal of the electrostatic ZS septa, modification of the girder for the existing DC septa, addition of extraction kickers and other modifications concerning the replacement of a machine quadrupole, a new scheme for the extraction bumpers, new instrumentation and interlocks. The extraction uses the existing MST and MSE septum magnets, located before and after the quadrupole QFA618. The beam is moved close to the MST 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. The extraction septum then deflects the beam out of the SPS vacuum chamber and into the transfer line TT60, with the required position and angle. The upgrade of the extraction channel in LSS6 requires the installation of four kickers MKE, bumpers, the removal of one enlarged quadrupole (QFA416), an absorber TPSG (dummy septum) and the modification of the bumper magnet system. The new fast extraction channel in LSS6 will be used only for small emittance LHC beams.

18.3 EXTRACTION EQUIPMENT SYSTEMS

The modification or construction of several equipment systems is necessary for the extraction channels. These are listed in the following sections.

18.3.1 Horizontal Bumper Systems

For each extraction, four horizontal bumper magnets will be used at locations near QFx14, x16, x20 and x22, to allow an adequate closed orbit bump at the entrance of the septum. The largest horizontal bump that could be envisaged in operation is about 60 mm at the entrance to the MSE septum (determined by the 90 mm good field limit in QFA418, the septum thickness and the required clearances). With this size bump there is about 25% strength remaining for horizontal orbit correction up to about ±20 mm at QFAx18. All power supplies are 400 A, 700 V as specified in [5]. The rather unfavourable position of HB2 with β_x of around 50 m is a consequence of the location of the extraction kickers in this half-cell which, because of their limited strength, have to be located as close as possible to QFx16.

18.3.2 Vertical Bumper System

Vertical bumper magnets installed at locations near QDx13, x15, x21 and x23 will allow a vertical orbit correction of ±15 mm at QD419. A vertical correction of ±8 mm is possible at the septum in half-cell 418. All power supplies are 80 A, 200 V [5]. The obvious location at x17 is not possible, since an enlarged bumper magnet aperture would here be necessary, requiring a new design.

18.3.3 Kickers

For LHC and CNGS the existing MKE kickers are upgraded and/or renewed [6,7] to meet the specifications, as shown in Tab. 18.1. For LSS4, the extraction towards CNGS needs two extractions per SPS-cycle, requiring a rise time / fall time of less than 1.1 μs and a flat-top of 10 μs. For LHC there is only have one extraction per SPS-cycle, requiring a flat top length of 8 μs. In LSS6 the rise-time can be much longer since this extraction channel is only for LHC extraction. The MKE kicker system is a characteristically terminated travelling wave system, powered by a resonant charging circuit consisting of two parallel 2 kV 50Hz AC. power supplies. These charge two capacitor banks, which feed a 60 kV step-up transformer via (safety) thyristors. The resonant charging circuit is connected to the pulse forming networks (PFNs) via a capacitor, diode and resistor auxiliary circuit permitting switch-off and over-voltage limitation. Extraction is triggered by a pre-pulse to the resonant charging supply, charging the PFNs to the required voltage. After this the “main” thyratron switches are triggered, discharging the PFNs into the magnets and terminating magnet resistors (TMR). For LSS4, the fall time requirements mean that five “clipper” switches are used to cut the magnetic field and dump the remaining PFN energy into the diode-stack and Terminating Dump Resistor (TDR). For CNGS the second extraction starts with recharging the PFN with the second capacitor bank.

The usual thyratron (gas discharge) “dump” switches are replaced by semiconductor power diodes to reduce long term costs and improve lifetime and reliability. In LSS4, if a switch “missing” (switch doesn’t close when triggered) or “erratic” (switch closes without being triggered) occurs, all clipper switches are triggered to protect the septa [2].

To meet the rise/fall time specification, several changes to the existing MKE design have been made, including modification/adjustment of the PFN front cells, sorting of PFN capacitor/coil section values and magnet and TMR wave impedance matching. In addition, two capacitive pick-ups are installed per magnet enabling measurement of the “kick” when installed in the SPS machine [8]. These diagnostics give a detailed picture of the “kick” field rise, fall and pulse length (flattop) times including the magnet filling time and the overshoot. The extraction kicker system will be equipped with PT100 temperature probes to provide an interlock for the loss of ferrite permeability above the Curie temperature.

For the proposed LHC and CNGS beam-operating conditions, the SPS extraction kickers will be exposed to a large beam induced thermal power. The ferrites will be heated due to the high frequency polarisation (power losses) of the magnetic dipole moments. Above the Curie-temperature the spontaneous magnetisation disappears and the material becomes paramagnetic. To cope with the ferrite heat dissipation cooling measures are implemented and the magnets are equipped with water-cooled AlN cooling plates on the top and bottom of the ferrites [8]. More details are given in Chap. 17. Fig. 18.1 shows a cross section of the MKE magnet with the cooling plates.

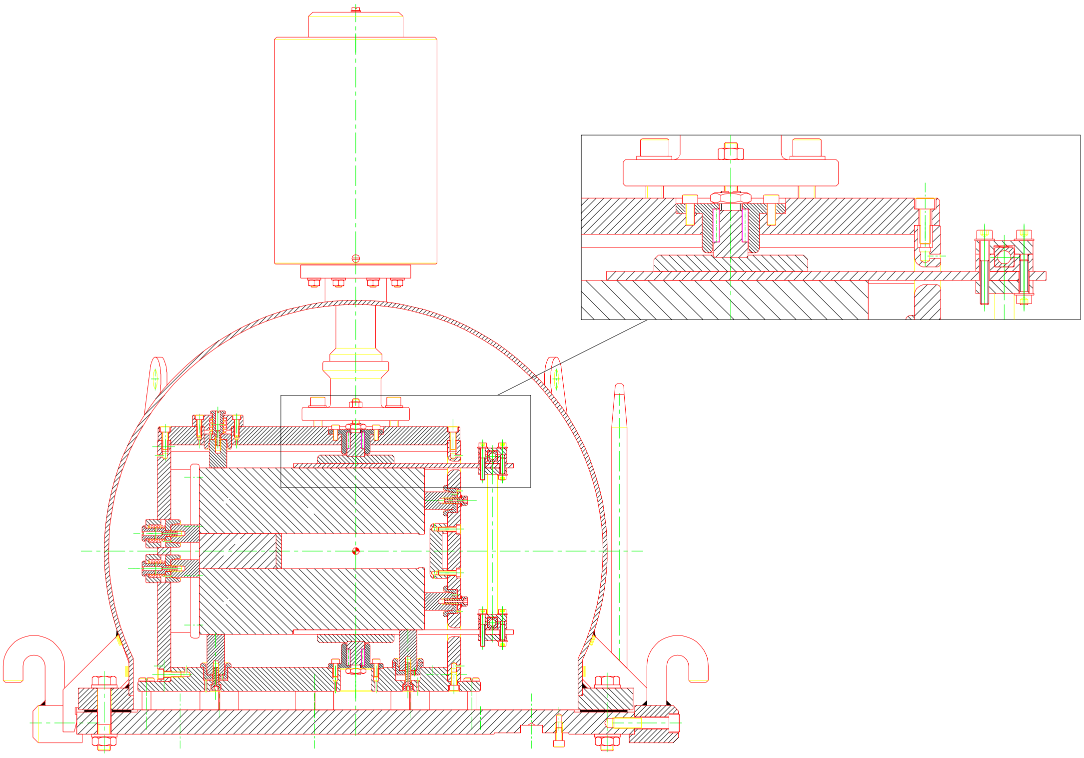

Figure 18.1: Cross-section of the MKE kicker magnet, with the cooling system detail enlarged.

18.3.4 Absorber or Dummy Septum

To protect the first extraction element from the impact of a mis-steered beam, an absorber TPSG (dummy septum) will be installed just upstream of the first MST or MSE. This element will serve to dilute the beam to a safe level in the event of an accidental mis-steering. Direct impact of a small fraction (approximately $2x10^{12}$ protons or 5%) of the extracted beam intensity could damage or destroy one or more septum magnet coils. A comprehensive interlock system is required to survey the beam positions, beam 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, the TPSG, 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 in the copper does not exceed 100°C. In addition, the instantaneous temperature rise in the cooling water should not exceed 10°C.

For LSS4 the 2.9 m TPSG4 absorber [9] 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 250 mm x 300 mm cross-section similar to the MSE laminated yoke. 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 19.25 mm x 30 mm and 1 unit of 800 mm 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 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 and a new design will be needed, based on the absorber for LSS6. It should also be noted that beam losses on the absorber and MSE septa will generate high radiation levels for which sufficient shielding must be provided [10].

For LSS6, the TPSG6 will use graphite to dilute, followed by titanium and Inconel to absorb the energy [4]. To keep the absorber relatively easy to handle, it will be constructed as a set of 2 consecutive absorbing blades, each within its own vacuum envelope. The total longitudinal length between flanges of this assembly will be limited to 4 m. The absorbing elements will be edge cooled with a copper tube connected to the demineralised water circuit available on the MST girder. This cooling circuit will limit the temperature rise caused by beam losses during normal operation, as well as remove the energy deposited in the absorbing elements after a beam sweep or impact.

Table 18.1: MKE kicker parameters.

Parameter	**Unit**	**MKE-L**	**MKE-S**
Number of magnets (LSS4)		3	2
Number of magnets (LSS6)		2	2
Vertical gap	Mm	35	32
Horizontal gap	Mm	148	135
Nominal voltage	kV	52	52
Nominal field	T	0.0702	0.0772
Magnetic length	Mm	2174	2174
∫B.dl max	Tm	0.1525	0.1678
Kick at 450 GeV/c	Mrad	0.1017	0.1118
Kick / kV at 450 GeV/v	µrad / kV	1.956	2.151
2-98% rise time (LSS4)	µs	1.1	1.1
2-98% rise time (LSS6)	µs	5.0	5.0
98%-2% fall time (LSS4)	µs	1.1	1.1
98-2% fall time (LSS6)	µs	5.0	5.0
Flat-top duration (LHC)	µs	7.9	7.9
Flat-top duration (CNGS)	µs	10.5	10.5
Flat-top ripple (LHC)	%	±0.5	±0.5
Flat-top ripple (CNGS)	%	±1.0	±1.0

18.3.5 Septum Magnets

The magnetic septum must deflect the beam by about 12 mrad and must also give the required 265 mm offset and 10 mrad exit angle at the extraction point. The extraction uses six of the DC septa, MSE [11,12] already installed in the extraction channels in LSS2 and LSS6. This approach has the advantage of using proven equipment and also keeping the number of sub-systems to be maintained to a minimum. The performance of the equipment is well known and the construction straightforward. The main parameters of the MSE magnets are given below in Tab. 18.2. The six MSE magnets are mounted on a single rigid girder, pre-aligned to follow the trajectory of the extracted beam and optimise the aperture available [13]. A cross-section of the system configuration in extraction channel LSS4 is shown in Fig. 18.2.

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 standard girder element is 3.3 m long and consists of a welded structure made of 260×180×10 mm MSH profiles. To allow vertical alignment, each element is equipped with 4 adjustable jacks, which stand on low-friction ball bearings. The complete girder is motorised in order to retract the septum and optimise the local SPS aperture during machine setting up. This retracted position is achieved by a girder movement of 35 mm upstream and -10 mm downstream, with a precision and reproducibility of ±0.1mm using two independent motors.

The magnets positions on the girder are pre-aligned to the trajectory of the extracted beam in order to give it a maximum aperture. The longitudinal position of the two motors has been carefully chosen and confirmed by ANSYS calculations to minimise the 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 18.2: MST and MSE Septum magnet parameters

Parameter	**Unit**	**MST**	**MSE**
Septum thickness	mm	4.2	17.25
Gap height	mm	20	20
Maximum field	T	0.471	1.508
Kick at 450 GeV/c	mrad	0.702	2.249
Magnetic length	m	2.247	2.237
∫B.dl max	Tm	1.0583	3.373
Peak current	A	7,500	24,000
∫B.dl / I	Tm/A	1.41 10^{-4}	1.41 10^{-4}
Magnet spacing (centre)	mm	3,234	3,234

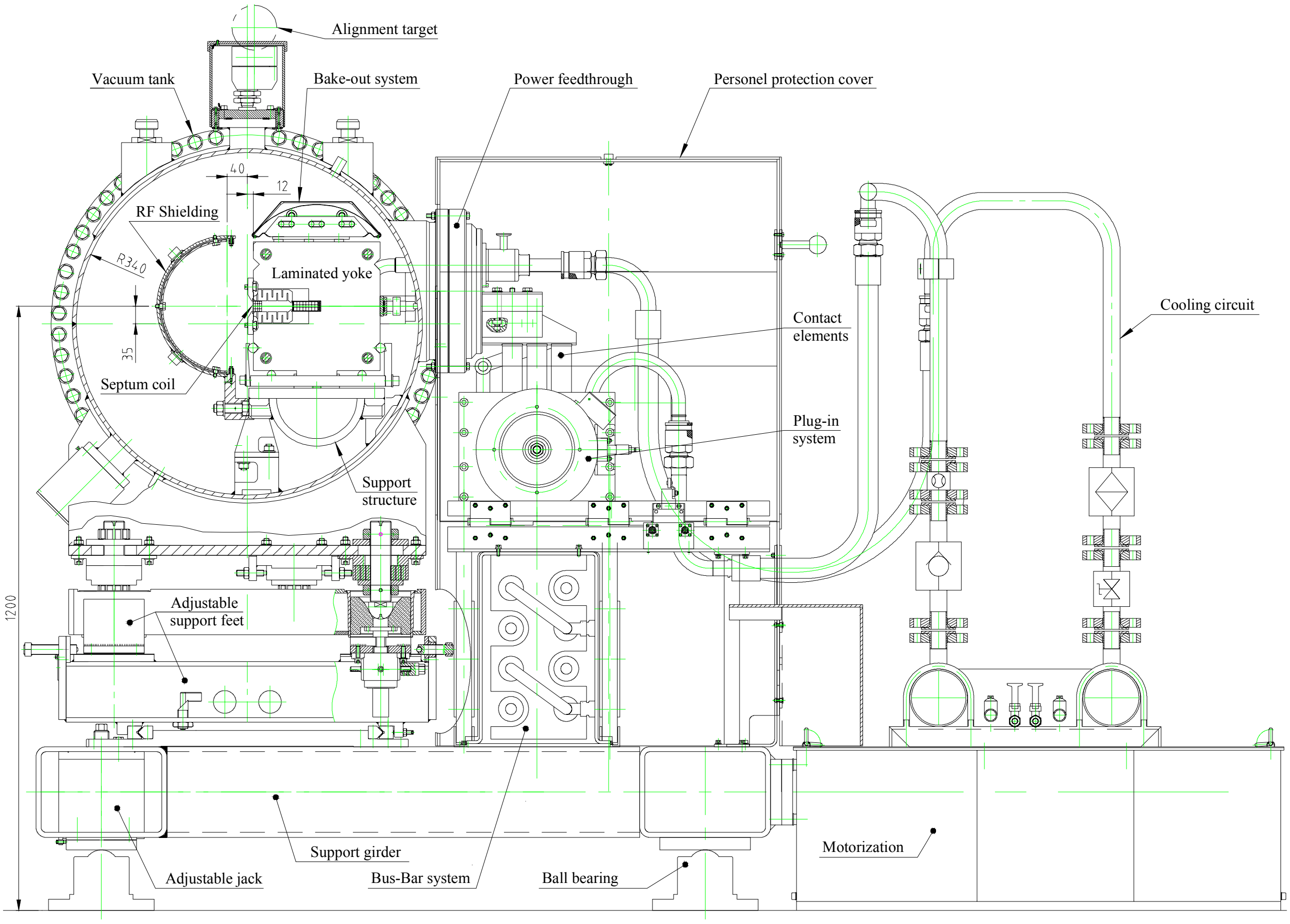

Figure 18.2: Cross section of MSE extraction septum showing vacuum tank, alignment girder, hydraulic and electrical connections.

18.3.6 Beam Instrumentation

The extraction channels are equipped with screens on the septum girder at the beginning of the first and end of the last septum magnets. Beam loss monitors are installed along the extraction channel, at the extraction element locations. For the circulating beam, large aperture BPCE couplers are installed on the quadrupoles in the extraction region, to accurately measure the bumped beam position [14]. The linearity and stability of the system should allow interlocking of the bumped beam position to within 0.5 mm. More details of the instrumentation are given in Chap. 19.

18.3.7 Main Ring Magnets

In LSS4 the main machine quadrupoles QD417, QF418 and QD419 with good field regions extending to 70 mm have been replaced by enlarged quadrupoles. QFA418 must have an enlarged aperture (90 mm good field region) to accommodate large beam excursions and QDA419 will be an enlarged quadrupole with a coil window through which the extracted beam passes. The field in this window is quadrupolar (F-quad), with a gradient of -0.16 of the main gap and an axis displaced by 0.3009 m [15]. In LSS6 the enlarged quadrupoles exist already in these locations; the QFA616 must be replaced by a normal QF in order to optimise the downstream kicker position.

18.3.8 Radiation Protection

In LSS4 some modifications are necessary to improve the radiation shielding between ECX4 and ECA4. The existing access chicane has been modified to increase the safety factor in the case of beam loss in the extraction and precautions in ECX4 taken concerning access during operation [16]. Beam loss monitors should help minimise losses during extraction and activation monitors are also planned.

18.4 TRAJECTORIES

The trajectories were calculated using MAD and the optimum extraction angle and position obtained. The constraints imposed were a flat orbit outside the extraction bump, a horizontal extraction bump of the required amplitude at the septum and that the maximum beam excursion in QFA418 should not exceed 89 mm (good field region of the quadrupole). The required element strengths are shown in Tab 18.3. The extraction uses a ‘slow’ (of the order of a hundred ms rise time) closed orbit bump to move the circulating beam near to the septum at extraction energy. During this time the field of the septum is also ramped up. At the correct timing the extraction kicker MKE is powered and the beam deflected into the gap of the septum.

The layouts of the extraction channels have been optimised with the present equipment parameters, to maximise the aperture available for the injected, circulating and extracted beams. Fig. 18.3 and Fig. 18.4 show the horizontal trajectories through the LSS4 and LSS6 extraction for the LHC beam at injection, at maximum bump amplitude and during extraction. A $\pm 3\sigma$ beam envelope is plotted.

Table 18.3: Nominal strengths of extraction elements (mrad).

Element	LSS4 LHC	LSS4 CNGS	LSS6 LHC
HB1	-0.002	-0.001	0.000
HB2	0.565	0.5004	0.438
HB3	0.383	0.339	0.320
HB4	0.162	0.144	0.090
MKE-S	0.100	0.110	0.102
MKE-L	0.110	0.121	0.112
MST	-	-	0.535
MSE	2.078	2.083	1.827

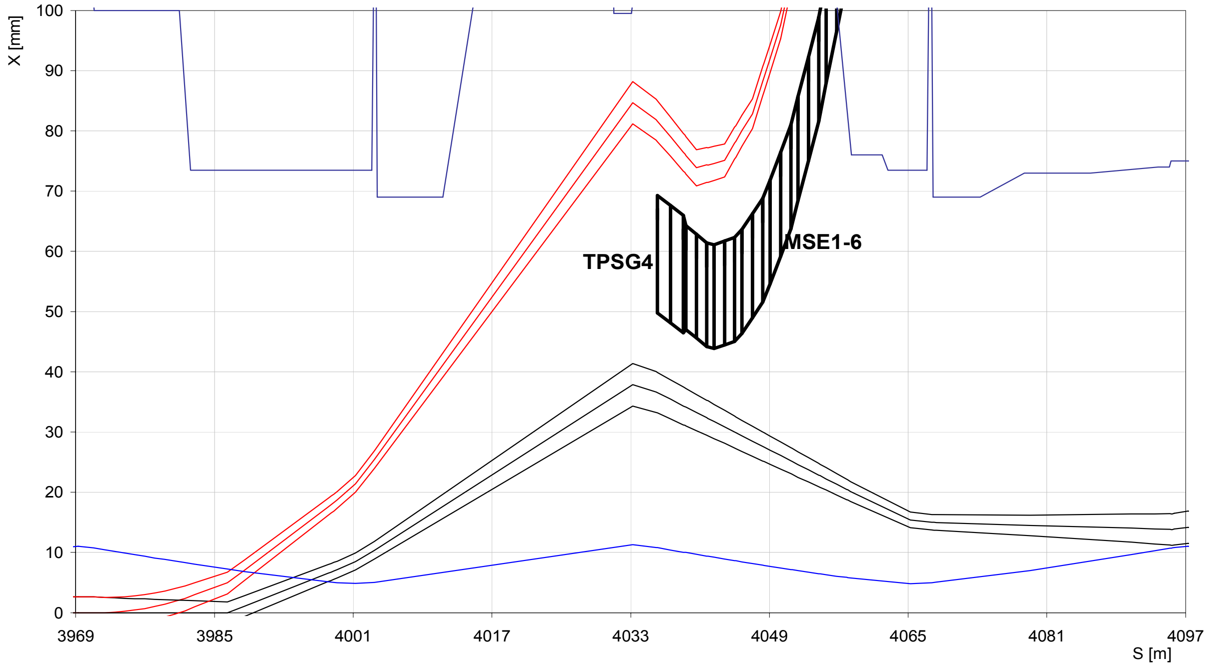

Figure 18.3: Beam envelopes in the extraction channel in LSS4.

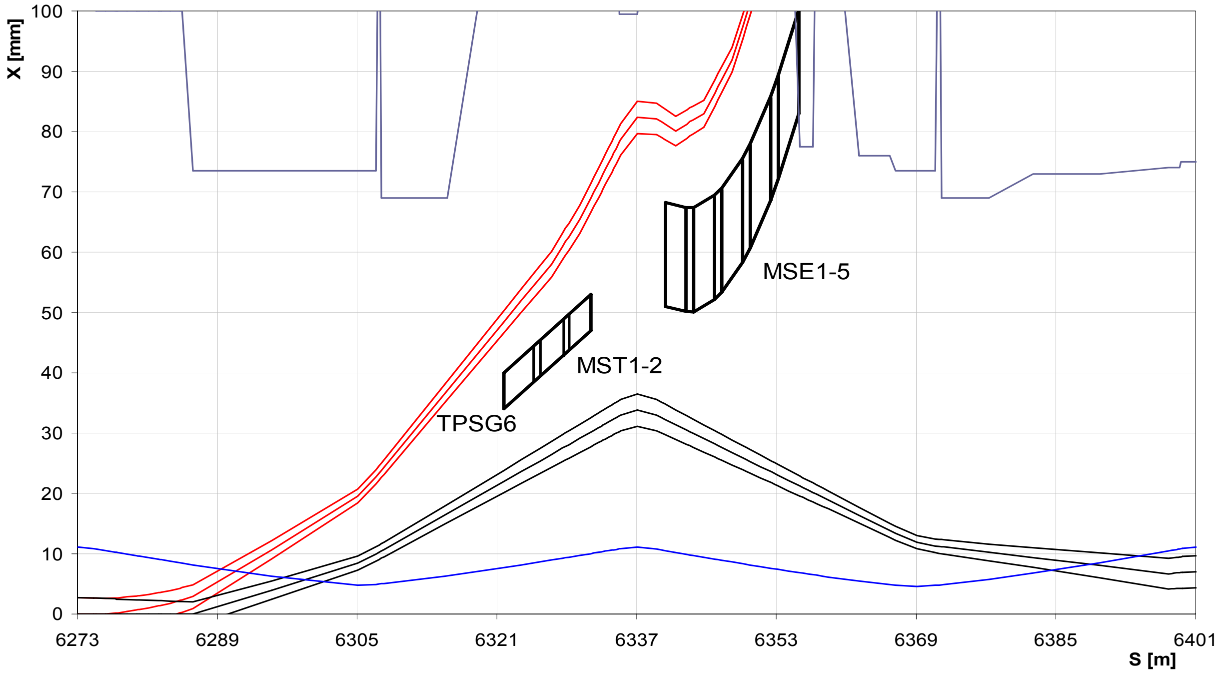

Figure 18.4: Beam envelopes in the extraction channel in LSS6.

18.5 APERTURE

18.5.1 Assumptions and Errors

In the following, the apertures for the LHC beam are discussed and where relevant, the fixed target (FT) beam at injection. The assumptions made in the analysis are:

- ε_N = 3.5 mm.mrad (12 mrad for CNGS beam)
- at injection: p = 14 GeV/c for the CNGS beam.
- $\Delta p/p = \pm 0.1\%$

In the vertical plane the contributions to the error in the beam position through the septum magnet come from the alignment of the machine quadrupoles and the quality of the closed orbit. At present in the SPS in fixed-target operation the total rms of the closed orbit in the vertical plane is of the order of 2.5 mm. Since the vertical bumper system will be used to adjust the orbit to compensate for long-term drifts, the somewhat pessimistic assumption is made that the maximum vertical orbit error at the septum is $O_y = \pm 2$ mm.

In the horizontal plane the septum position can be adjusted, to reduce the orbit error contribution. The assumption is made that at injection $O_x = \pm 4$ mm and at high energy $O_x = \pm 1$ mm. Taking the contributions from the pulsed horizontal bending elements, the bumpers and kickers, these two systems together add another ±0.4 mm error. The maximum horizontal orbit error is then $O_x = \pm 1.4$ mm at extraction.

There are several sources of mechanical imprecision or instability which contribute to the overall mechanical tolerance to be assumed for the calculation of the beam aperture. For the MSE system these are estimated as follows:

- Single MSE magnet septum mechanical precision (±0.5 mm)
- Tolerance between MSP assembly in vacuum tank and external alignment socket (±0.1 mm)
- Initial alignment of magnets on girder (±0.1 mm)
- Short- and long-term stability of the SPS tunnel floor in LSS4 (±0.3 mm)

Adding these figure gives a maximum possible mechanical error in both horizontal and vertical planes of $M_y = M_x = \pm 1.0$ mm.

18.5.2 Vertical Aperture at Extraction

The extracted beam must pass within the gap of the septum magnet, which is kept as small as possible to minimise the current required to produce a given field. Assuming zero local vertical dispersion and a vertical aperture of A_y, the aperture N available in numbers of beam sigma is given by:

$$N_y = (A_y/2 - O_y - M_y) / (K_\beta (\beta \varepsilon_y)^{1/2})$$

The aperture available in the vertical plane at extraction is shown in Fig. 18.5 and Fig 18.6, for LSS4 and LSS6 respectively.

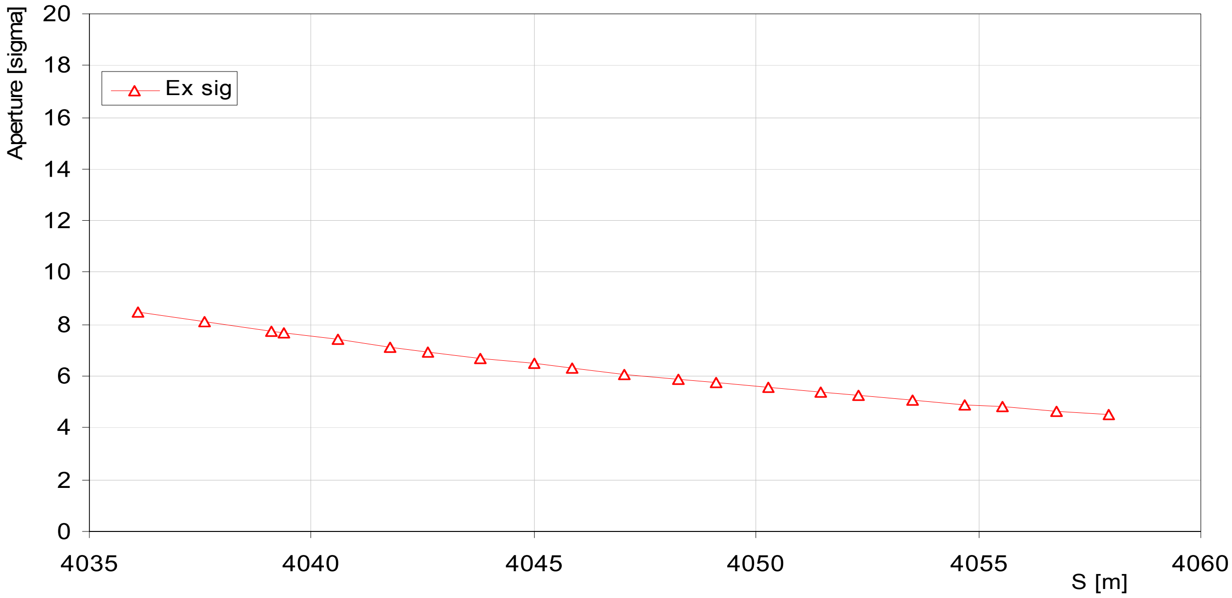

Figure 18.5: Vertical aperture for extracted beam (CNGS emittance) in the extraction elements in LSS4.

18.5.3 Horizontal Aperture for Bumped Beam

The bumped beam must pass close to the first septum (and the absorber element). With non-zero local dispersion D_x and a momentum spread δp/p and a physical spacing A_{xb} between beam axis and outer (circulating beam side) septum edge, the available aperture in sigma is given by:

$$N_{xb} = (A_{xb} - O_y - M_y)/(K_\beta(\beta\varepsilon_x + |D_x\,\delta p/p|^2)^{1/2})$$

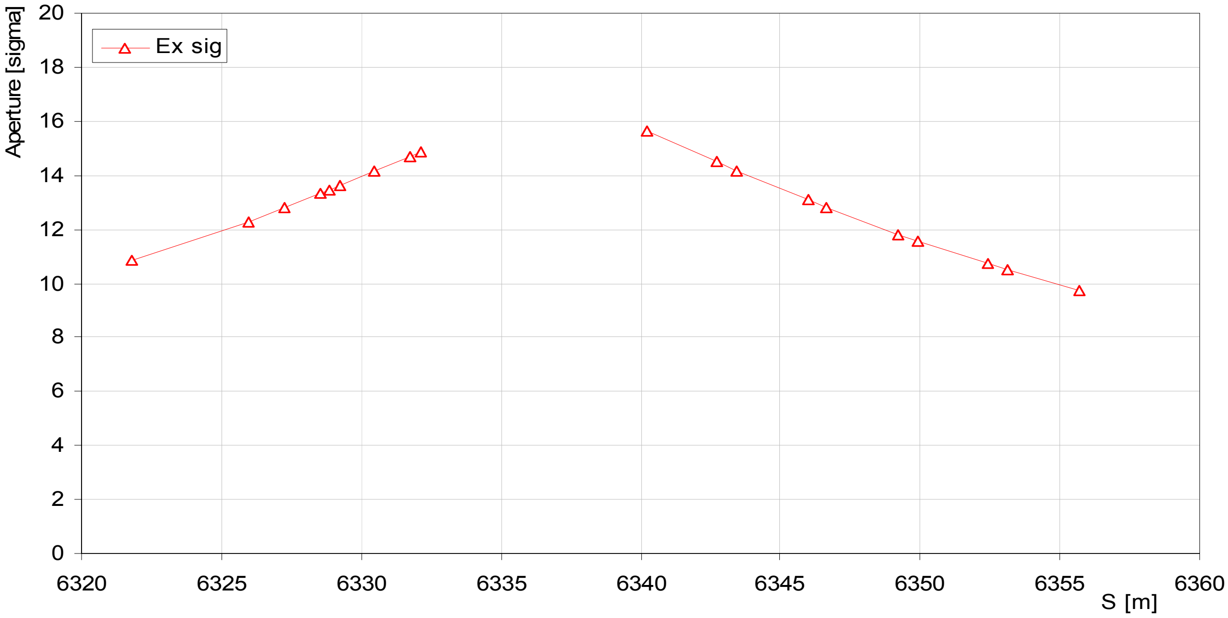

Figure 18.6: Vertical aperture for extracted beam (LHC emittance) in the extraction elements in LSS6.

18.5.4 Horizontal Aperture at Extraction

The extracted beam must also pass as close to the first septum (and the absorber element) as possible, to maximise the aperture available for the circulating beam. With a physical spacing A_{xe} between beam axis and outer (extracted beam side) septum edge, the available aperture in sigma is given by:

$$N_{xe} = (A_{xe} - O_y - M_y)/(K_\beta(\beta\varepsilon_x + |D_x\,\delta p/p|^2)^{1/2})$$

18.5.5 Horizontal Aperture at Injection

While the strength of the extraction kicker and the beam size at the septum define aperture at extraction (above), the transverse septum position and the beam size at the septum define the aperture at injection. The septum is positioned as far outside as possible; this is however limited by the maximum particle excursion allowed in the enlarged quadrupole QFA418. Taking a limit of 89 mm for this excursion and placing the centre of the beam about 5σ inside this limit, the limiting position of the septum is at A_{xi}. The available injection aperture is given by

$$N_{xi} = (A_{xi} - O_y - M_y)/(K_\beta(\beta\varepsilon_x + |D_x\,\delta p/p|^2)^{1/2})$$

here, ε_x is the emittance at injection energy. The FT beam is here the limiting case. Note that these figures could be improved, if necessary, by the application of a negative injection bump at the septum, for example a bump of -10 mm would give about an extra 1.4 sigma for the aperture at injection.

The aperture available in the horizontal plane at injection, bump and extracted is shown in Fig. 18.7 and Fig. 18.8, for LSS4 and LSS6 respectively. Note that the injected beam shown is the FT one, where the emittance is much larger.

18.6 EFFECTS OF MST AND MSE STRAY FIELD

The stray field from the MST and MSE septum magnets has been measured [17] and simulations made, with measurements performed in the SPS to determine the extent of the effect on the beam. The stray field is not expected to degrade the circulating beam emittance.

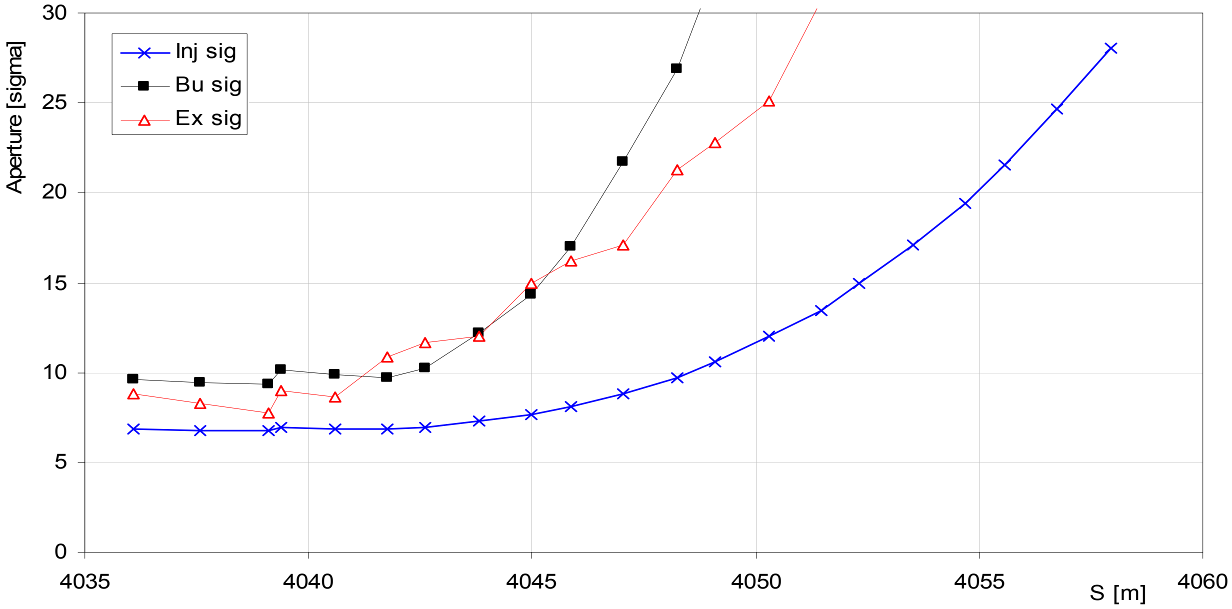

Figure 18.7: Aperture available at extraction elements in LSS4

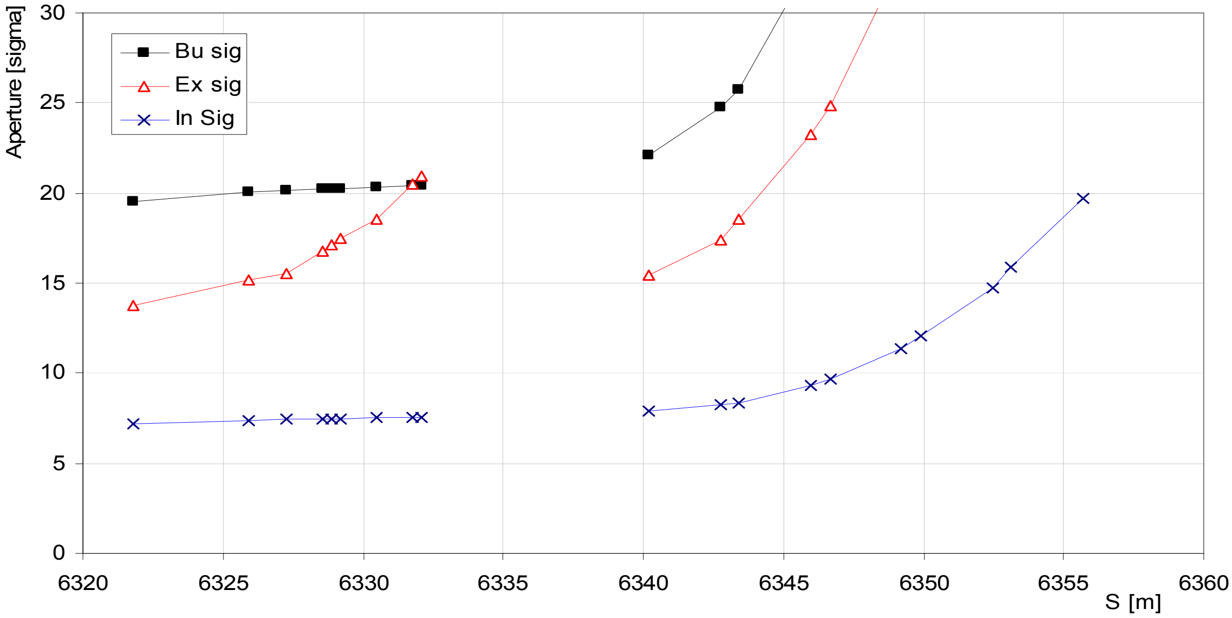

Figure 18.8: Aperture available at extraction elements in LSS6

18.7 STABILITY AND FIELD ERRORS

The stability of the extraction has been treated in detail in [18]. With the specified tolerances, the random contribution (rms variation) from the SPS orbit and the extraction system is expected to be ±0.16 σ_x and ±0.11 σ_y, with a further ±0.22 σ_x systematic variation due to the kicker waveform. These are included in the total delivery imprecision figures discussed in Chap. 22.

18.8 INTERLOCKING AND MACHINE PROTECTION

Active surveillance and interlocks are required to minimise the risk of equipment damage following a failure. The protection of the extraction equipment and the downstream transfer lines will depend heavily on a fail-safe interlock (or veto) system, which surveys critical equipment and beam parameters. Just prior to extraction (ideally around 1 ms before the kicker is triggered) the system should verify the bumper currents, the septum current, the charging of the kicker supply, the girder position, the horizontal orbit and the beam emittance. If any of these are not within the predefined tolerances then the extraction must be inhibited and the beam should be dumped. Full details can be found in [19].

Some failures cannot be covered by a surveillance system, notably extraction kicker faults such as erratics or missing triggers. In this case the TPSG element must safely intercept the beam and prevent damage to the extraction equipment, in particular the MSE septum. The correct set-up of the extraction channel in this respect, together with the surveillance and interlocking of the bumped beam position and the MSE girder position is essential.

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