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THE NEW SPS EXTRACTION CHANNEL FOR LHC AND CNGS

B. Goddard, P. Knaus, G. Schröder, W. Weterings, J. Uythoven

Abstract

The Large Hadron Collider (LHC) and CERN Neutrino to Gran Sasso (CNGS) projects require the construction of a new fast-extraction system in the long straight section LSS4 of the Super Proton Synchrotron (SPS) at CERN. A conventional DC septum magnet will be used, in conjunction with the installation of horizontal and vertical extraction bumpers, main quadrupoles with enlarged apertures, extraction kicker magnets and additional hardware protection, instrumentation, controls and electronics. The extraction channel must be able to accept the bright LHC proton beam at 450 GeV/c, and also the high intensity, large emittance fixed target CNGS proton beam at the nominal 400 GeV/c extraction momentum. This paper describes the extraction channel to be installed in 2003, and shows how the requirements for both the LHC and CNGS projects can be met.

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The Large Hadron Collider (LHC) and CERN Neutrino to Gran Sasso (CNGS) projects require the construction of a new fast-extraction system in the long straight section LSS4 of the Super Proton Synchrotron (SPS) at CERN. A conventional DC septum magnet will be used, in conjunction with the installation of horizontal and vertical extraction bumpers, main quadrupoles with enlarged apertures, extraction kicker magnets and additional hardware protection, instrumentation, controls and electronics. The extraction channel must be able to accept the bright LHC proton beam at 450 GeV/c, and also the high intensity, large emittance fixed target CNGS proton beam at the nominal 400 GeV/c extraction momentum. This paper describes the extraction channel to be installed in 2003, and shows how the requirements for both the LHC and CNGS projects can be met.

1 FAST EXTRACTION REQUIREMENTS

The extraction channel to be installed in SPS LSS4 [1] has to accept the high brightness beam for the LHC collider, and also the high intensity, large emittance CNGS beam for the neutrino production target. The relevant nominal beam parameters are summarised in Table 1. Note that round beams are assumed for both LHC and CNGS, and that the numbers in parenthesis for LHC refer to the ultimate beam parameters.

Table 1: Main parameters of CNGS and LHC beams

	LHC	CNGS
Number of spills	1	2
Inter-spill gap (ms)	-	50
Protons per spill (10^{13})	3.2 (4.9)	2.25
Spill length (μs)	<7.8	10.5
Emittance (1σ norm.)	3.5	12
p inject (GeV/c)	26	14
p extract (GeV/c)	450	400

The design has to satisfy the following conditions.

- The channel should provide a large enough vertical and horizontal aperture for injected, bumped circulating and extracted beam.
- The rise times and flat-top duration should be compatible with the above figures.
- The influence of the various field errors and supply ripples should be low enough for acceptance by the LHC injection system and CNGS target.
- The extraction magnet stray field should not give a significant emittance blow up of the stored beam.
- The extraction system should be adequately protected against mis-steered beams.

2 CONCEPTS

The extraction region optics is shown in Figure 1.

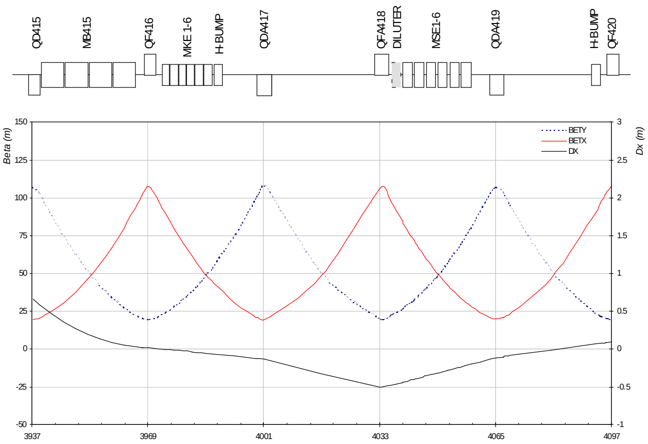

Figure 1. Optics functions in the extraction region.

A conventional fast extraction will be used in LSS4 with horizontal closed orbit bumpers, extraction kicker and conventional DC magnetic septum located just after the focusing quadrupole 418.

The beam will be moved close to the extraction septum using the horizontal closed orbit bump, and is then kicked horizontally across the septum 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.

A vertical closed orbit bumper system (in fact a set of strong orbit correctors) will also be used for precise vertical beam steering at high energy.

3 SYSTEMS AND PERFORMANCE

3.1 Extraction bumpers

Four horizontal bumper magnets, located at quadrupoles 414, 416, 420 and 422, allow the circulating beam to be bumped by the required 40 mm at the extraction septum next to quadrupole 418, with ample margin for additional orbit correction at 450 GeV/c.

Four vertical 'bumper' (strong corrector) magnets are located at defocusing quadrupoles. The obvious location at position 417 would require the construction of a special magnet with an enlarged aperture - for standardisation purposes the correction will be done using magnets at the positions 413, 415, 421 and 423. This configuration allows a ±10 mm vertical orbit correction at the extraction septum.

3.2 Extraction Kicker System MKE

The bumped stored beam will be deflected by six fast pulsed kicker magnets by a total angle of 0.5mrad. The kicker magnets are of travelling wave type with external matching capacitors. There will be six or seven cells per magnet. The CNGS beam will be extracted in two batches requiring a rise and fall time of the kicker pulse smaller than 1.1 μs. An additional clipper and dump switch on the Pulse Forming Network are used to obtain the rapid fall time. Studies are ongoing to replace the thyratron of the dump switch by fast diodes. The layout of the kicker system, most likely two families of magnets with different apertures to combine maximum magnetic field and sufficient vertical aperture, is presently under study. Measurements on a prototype magnet installed in the SPS showed a temperature rises of more than 20 K due to heating of the ferrites by the beam. Extrapolation to final CNGS and LHC beam currents indicates the necessity of water-cooling of the magnet. This needs to be designed with great care as the whole system is part of the machine vacuum.

3.3 Extraction Septum Magnet MSE

For the extraction septum magnet an alternative to the conventional DC septum (MSE) was evaluated [2]. The fast-pulsed septum (MSP) takes advantage of the short (maximum 10.5 μs) flat top required for the fast extraction. The magnet is powered by a 250 μs long sinusoidal pulse with a superimposed 3rd harmonic to give the required flat-top precision of about ±0.02 %. The MSP septum uses a yoke of tape wound silicon steel of 50 μm thickness. The septum element is a passive electro-magnetic eddy current screen of 5 mm thickness, not connected to the excitation current loop. The development of this magnet has made significant progress, and is now at a stage where a full sized magnet can be built. However, for reasons of planning, resources and compatibility, and also because of the cost savings which can be made by reusing existing equipment, the LSS4 extraction channel will be equipped with the conventional MSE magnet.

The main parameters of the MSE magnet are shown in Table 2 [3]. Six magnets will be required to provide the 12 mrad deflection necessary, and these will be mounted on a rigid retractable girder for alignment purposes and to ease the setting up of the SPS.

Table 2. 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	mΩ	2.9
Total inductance	μH	84
Peak voltage	V	80
Minimum rise/fall time	ms	200
Magnet spacing (centre)	mm	3,234

3.4 Septum Protection

Direct impact of the extracted beam would destroy the 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. A physical protection element (diluter) will therefore be required. This will be placed immediately upstream of the first septum coil, and will reduce the particle flux on the coil to a safe level, such that the temperature does not exceed 100° C. The diluter will be a composite shield made up of graphite, graphite/copper composite and aluminium. Monte Carlo simulations with the FLUKA code have determined that a length of 3 m should be adequate for this element. Figure 2 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. The coil temperature is kept to about 100° C.

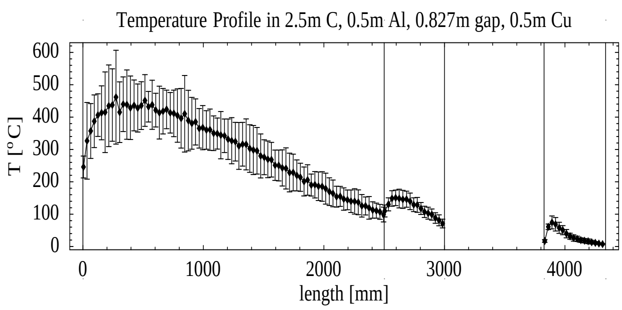

Figure 2. Simulated temperature profile in diluter and MSE coil ($4.1\ 10^{13}$ protons, 450 GeV/c, 3.5 μm ε_{nh}).

3.5 Aperture

The layout of the LSS4 extraction channel has been optimised with the present equipment parameters, to maximise the aperture available for the injected, circulating and extracted beams.

Figure 3 shows the horizontal trajectories through the LSS4 extraction for the CNGS beam at injection, bumped and during extraction. A ±3σ beam envelope is plotted.

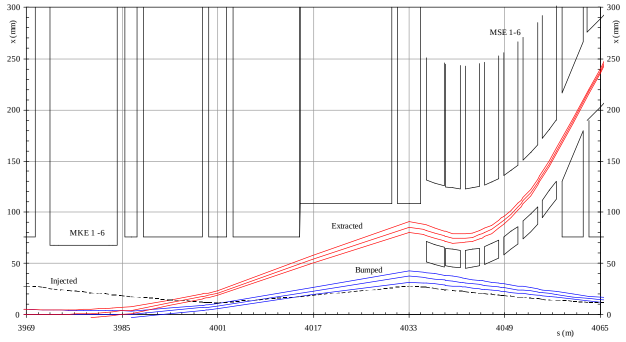

Figure 3. Trajectories of CNGS beam (±3σ) in the LSS4 extraction channel.

The minimum vertical and horizontal half-apertures and half-openings, in both mm and numbers of beam sigma, are given in Table 3 for both CNGS and LHC beams. Note that only the extracted beam has any vertical limit imposed by the extraction channel, due to the 20 mm gap height of the MSE.

Table 3. Minimum half-apertures (numbers of sigma) and half-openings for CNGS and LHC beams.

	σ h	**σ v**	**mm h**	**mm v**
CNGS inject	5.6	-	45.4	-
CNGS bump	8.0	-	12.9	-
CNGS extract	6.5	6.7	10.5	10
LHC inject	14.1	-	45.4	-
LHC bump	12.4	-	11.2	-
LHC extract	8.2	13.3	8.0	10

3.6 Effect of Stray Field

The stray field of the MSE magnet was measured in the region traversed by the circulating bumped beam. A multipole expansion with just dipole and decapole coefficients gave a good fit, Figure 4.

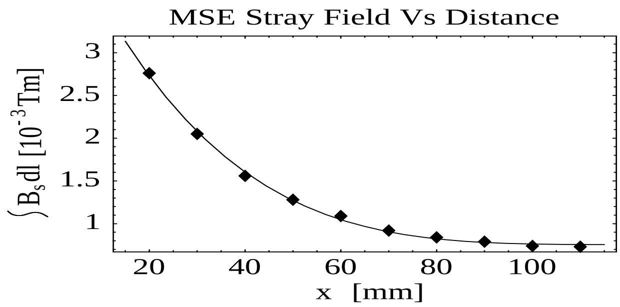

Figure 4. Measured MSE stray field (points) and fit (solid line) using dipole and decapole coefficients.

These values were used in MAD to make tracking over 10^4 turns, corresponding to about 200 ms. For the largest beam (CNGS), the emittance increase in this case was below 1%, with a small effect seen on the closed orbit. This effect was measured in the SPS with low energy beams bumped close to the existing MSE septa. The effect observed on the orbit agreed with the simulations.

3.7 Stability and field errors

It is assumed that the static field errors (e.g. caused by alignment tolerances, different gap heights, etc.) are reproducible and will be corrected for. These are not considered in this analysis. For LHC injection [4], the important parameter is

$$\Delta x / \sigma = \Delta k \sqrt{(\beta_1 \beta\gamma / \varepsilon_n)} = 1.17\ 10^4\ \Delta k \sqrt{(\beta_1)}$$

where Δx is the relative error produced by Δk the kick error, at the location with horizontal beta of β_1. As expressed above, the total contribution of all pulsed extraction elements must be less than 0.5.

The systems contributing to this error are the bumper magnets, the kicker magnets and the extraction septum. The kicks, betas, power supply ripples and resulting injection error contributions are given in Table 4.

Table 4. Contributions to LHC injection errors.

System	**β (av.) (m)**	**k (mrad)**	**$\Delta I/I_{max}$**	**Δx/σ**
Bumpers	77.3	1.04	0.00055	0.059
MKE	75.3	0.5	0.005	0.254
MSE	54.2	12.0	0.00025	0.259

Assuming that the contributions from the different systems add quadratically, the total contribution is

$$\Delta x / \sigma = \sqrt{(0.059^2 + 0.254^2 + 0.259^2)} = 0.37$$

3 CONSTRUCTION TIMESCALE

The installation of the extraction channel begins in the 2000/2001 SPS shutdown, and is expected to be completed at the end of the 2002/2003 shutdown. The modification of the existing MKE kicker system is expected to be the critical element in the planning.

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