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KICKER MAGNET UPGRADING FOR THE SPS OPERATING AS LHC INJECTOR

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Important modifications and improvements are needed on the existing SPS fast pulsed magnet systems for injection and extraction, to make them compatible with the use of the SPS as the injector for the LHC. The ripple on the flat top of the magnetic field pulses will be lowered by at least 50% to conserve the small emittance of the beam. For ion operation the rise time of part of the injection kickers will be reduced by increasing the characteristic impedance from 12.5 to 16.7 Ω. Furthermore, two new kicker magnets will be installed to compensate the resulting loss of deflection strength. In addition, a fast kicker system must be built for the new east extraction channel and the west extraction kicker system must be upgraded. This paper describes the new requirements and discusses the solutions envisaged to meet these goals.

Keywords: Kicker magnets; Pulsed power; High voltage; Modulators

1 INTRODUCTION

The SPS fast pulsed magnet systems have been designed more than 20 years ago for the needs of the fixed target accelerator. The new role of the SPS as the injector for the LHC requires two important modifications of these systems. The ripple on the flat top of the magnetic field pulses of about ±1% must be reduced by a substantial amount and for heavy ion injection the rise time of part of the injection kicker system must be lowered by more than 25%. Also the west

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extraction kickers must be upgraded and a new kicker system must be installed for the east extraction.

2 MODIFICATIONS TO THE INJECTION KICKER SYSTEM

2.1 The Present Layout

The SPS injection kicker magnet system, the largest fast pulsed magnet system at CERN, is composed of 12 travelling wave magnets, each of 0.7 m length and 12.5 Ω impedance. The magnets occupy a total length of more than 12 m in Long Straight Section 1 of the SPS. They are connected in pairs via a 200 m long transmission line to six pulse generators with an impedance of 6.25 Ω.[1,2]

The nominal deflection strength of the inflector is 0.34 T m, corresponding to an injection angle at 26 GeV/*c* of 3.9 mrad. Because of the considerable total length of the system the aperture of the magnets follows the beam profile, with consequences for the kick rise time. The eight upstream magnets (numbers 1–8) have a horizontal and vertical aperture of 101 and 61 mm and a kick rise time of 150 ns (type 'S'). They are housed in groups of four in two vacuum tanks of about 3.5 m length each. The four remaining downstream magnets (numbers 9–12) have an aperture of 141 and 54 mm with a kick rise time of 220 ns (type 'L'). They are housed in a third vacuum tank of the same dimensions. Figure 1 shows a schematic layout of the overall system.

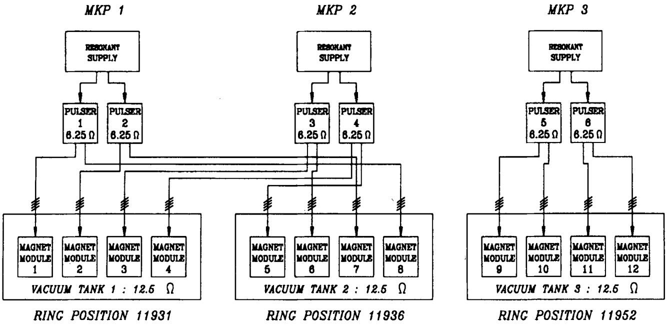

FIGURE 1 Schematic layout of the actual SPS injection kicker system.

The inductance of the magnets is divided into 22 elementary ferrite sections which are matched to the characteristic impedance of the system by parallel plate capacitors inside the vacuum tank (delay line type construction), in order to achieve a good pulse response with low reflections of the wave front. The resulting flat top ripple of the magnetic field is about ±1%.

The matched transmission line between each magnet in the accelerator tunnel and its pulse generators at surface level is composed of four coaxial cables in parallel, each with a characteristic impedance of 50 Ω (type RG 220/U).

The pulse generators are lumped element pulse forming networks (PFN's) equipped with three high power electronic gas switches per generator (thyratrons of type EEV CX1171B), in order to produce pulses of adjustable duration and short fall time. The maximum operation voltage is 60 kV and the maximum continuously adjustable pulse duration 12 μs.

Figure 2 gives the equivalent electrical circuit of a pulse generator connected to its pair of magnets.

Table I summarises the main system parameters.

2.2 The New Requirements

For the operation of the SPS as LHC injector the following new requirements arise.

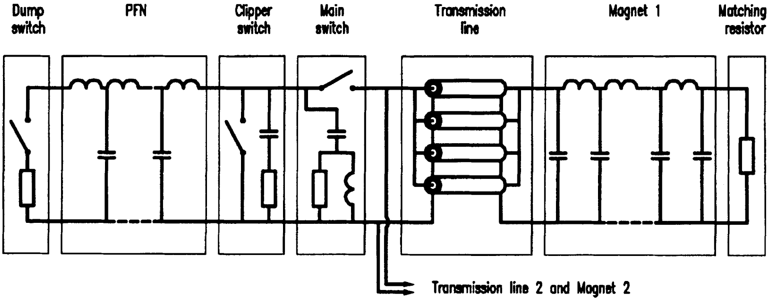

FIGURE 2 Schematic electrical circuit of one of the injection kicker magnet systems.

TABLE I Main parameters of the actual SPS injection kicker system

Maximum injection momentum [GeV/c]	26
Deflection angle at 26 GeV/c [mrad]	3.9
Kick strength at 26 GeV/c [T m]	0.34
Kick flat top duration [μs]	1–12
Kick rise time of 'S' magnet [ns]	150
Kick rise time of 'L' magnet [ns]	220
Aperture (horizontal, vertical) of 'S' magnet [mm]	101, 61
Aperture (horizontal, vertical) of 'L' magnet [mm]	141, 54
Magnet length [m]	0.7
Maximum pulse generator voltage [kV]	60
Characteristic impedance of pulse generators [Ω]	6.25
Characteristic impedance of magnets [Ω]	12.5
Number of magnets of type 'S'	8
Number of magnets of type 'L'	4

(a) The flat top ripple of the magnetic field pulse should be smaller than at least ±0.5%.

(b) For ion injection at an equivalent proton momentum of 12.97 GeV/c, corresponding to a required kick strength of 0.19 T m, the rise time of the magnetic field pulse must be reduced by nearly 25% to about 115 ns.

(c) The maximum required pulse duration is only 500 ns for ions and 2.1 μs for protons. The full 12 μs pulse duration must however remain available for fixed target operation of the SPS.

2.3 Flat Top Ripple Reduction

2.3.1 Causes of Ripple

Assuming that the number of cells of PFN and kicker magnet have been chosen sufficiently large to avoid, for the given rise time, oscillations due to bandwidth limitations, the ripple on the flat top of the magnetic field pulse has two main causes.

- Wave reflections are generated by mismatch between the impedance of the PFN and that of the transmission line, the magnets and the termination resistors. They are avoided by a careful matching, up to sufficiently high frequencies.
- Slight electromagnetic differences between the individual cells of the PFN cause non-negligible ripple due to reflections of the discharge wave which travels forwards and backwards through the PFN.

The lowest ripple is obtained when the cells are aligned in one row rather than in the usual serpentine arrangement. The latter is more convenient for the mechanical construction of the PFN tank, but has the tendency to increase the ripple, originated by the change in the mutual inductance between the cells at the position of the serpentine bends. During the design of the actual system in 1976, a compromise has been made between these conflicting requirements. The cells are aligned in only two and a half rows of which the first eight cells are arranged in a straight line for not to perturb the begin of the pulse, particularly sensitive to mismatch. The ripple is then minimised by adjusting individually the inductance of the cells. The result is given in Figure 3 and shows that with this procedure a minimum ripple of about ±1% can be obtained.

2.3.2 A Novel Strategy for Ripple Reduction

For a further ripple reduction of at least 50% it is now intended to apply methods developed recently during the design of the prototype of the LHC injection kicker system.[3,5] Instead of a separate coil for each cell of the PFN a continuous coil will be used for the first straight part of the PFN. This section is large enough to produce the 2.1 μs long pulse needed when the SPS is operated in LHC injector mode. The continuous coil is wound onto a precision-machined insulating support tube to assure high geometrical accuracy, needed for inductance stability and accurate simulation of the equivalent circuit.

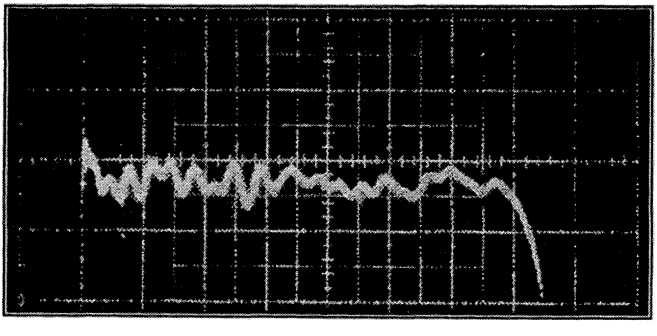

FIGURE 3 Actual flat top ripple of the injection kicker system. Horizontal scale: 2 μs/div.; vertical scale: 2%/div.

In addition to the use of a continuous coil the design developed in Ref. 3 takes into account for the PFN design all known stray elements as well as their frequency dependence. The ripple is then minimised by an optimiser code. As an example of the new method Figure 4 shows the equivalent circuit for each central cell of the PFN of the LHC injection kicker prototype:[3] Lcell represents the series inductance of the cell, Ccell the shunt capacitors, and Lparasitic the associated parasitic inductance. The nominal value of the shunt capacitor is defined as $\mathrm{Ccell} = \mathrm{Lcell} \cdot (1 + 2k)/Z^2$, where k is the coupling coefficient between adjacent cells and Z the characteristic impedance of the system. A 100 Ω damping resistor which is effective at helping to reduce the ripple is connected in parallel with each PFN cell. In order to obtain a realistic prediction it is necessary to simulate the skin effect. This has been achieved for frequencies from almost DC up to 10 MHz by using a series resistance and four inductor–resistor networks. {Rdc} represents the DC resistance of the PFN cell, assuming a copper tube of Ø 8 mm, and wall thickness of 1 mm, for the coil. Each of the four inductor–resistor networks predominantly affects a different part of the frequency range of interest. Analytical equations were utilised to determine initial guesses for the resistor–inductor networks. The values of these elements were then refined using the PSpice Optimizer.[6] The optimised values resulted in an excellent fit to the calculated skin-effect resistance.

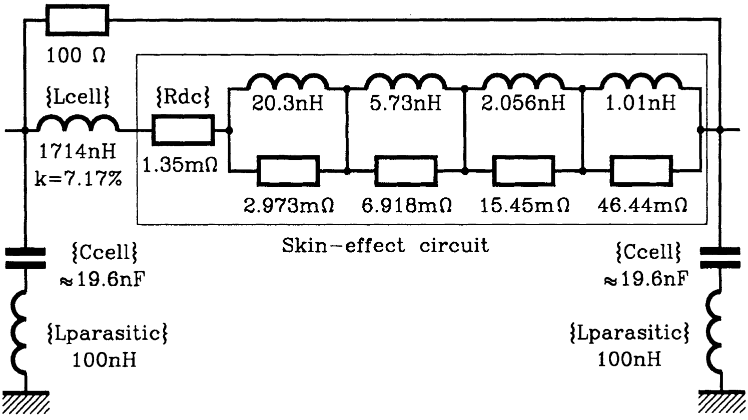

FIGURE 4 Equivalent circuit of a central PFN cell of the LHC inflector.

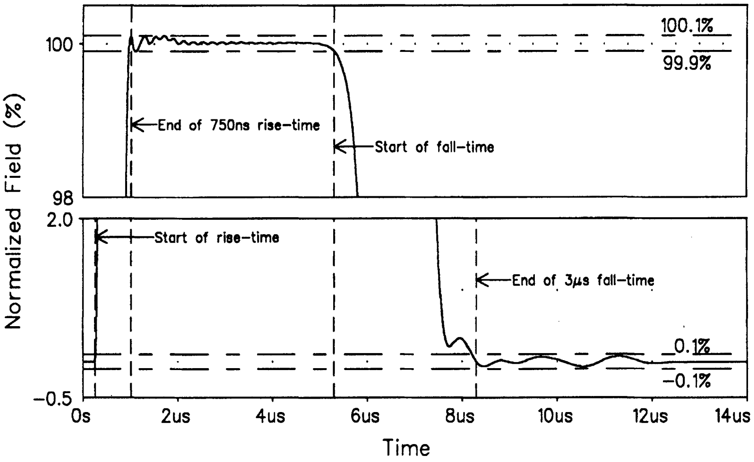

FIGURE 5 Predicted magnetic field pulse of the LHC inflector.[3]

Conduction losses along the coil result in a droop of the top of the magnetic field pulse in the kicker magnet. These losses can be compensated for by grading the values of the capacitors such that they increase in value starting with the 'main-switch' side of the PFN. Linear grading is suitable and the natural production spread of the capacitors can be used.

The results of this study are given in Figure 5 and show that it is theoretically possible to achieve the required magnetic field pulse with a flat top ripple and reflections of less than ±0.1%.

2.4 Rise Time Reduction

For ion injection the kick rise time of the 'S' magnets needs to be lowered by nearly 25% to about 115 ns. The 'L' magnets of 220 ns kick rise time are far too slow for this application. They will not be used and only the rise time of the 'S' magnets will be improved. The following scenario will be applied.

The rise time reduction will be achieved by increasing the characteristic impedance of the magnets and their pulse generators. This can only be done in steps and is conditioned by the impedance of the 200 m long transmission line, which is matched to pulse generators and magnets. The line is actually composed of four coaxial high voltage cables per magnet, each of 50 Ω impedance, resulting in a magnet impedance of 12.5 Ω. It is now intended to connect only three cables per magnet which gives a system impedance of 16.67 Ω. The generator impedance needs then to be increased from 6.25 to 8.33 Ω.

The resulting lower deflection strength is just sufficient for the injection of heavy ions at an equivalent proton momentum of 12.97 GeV/*c*, taking into account that due to the small emittance the incoming ion beam can be steered nearer to the septum magnets. However, for 26 GeV/*c* proton injection momentum the loss in deflection strength must be compensated by the addition of further magnets.

The proposed solution of an impedance increase is preferred to a length reduction of the magnets and the addition of a fifth magnet per tank to preserve the deflection strength. A length reduction would only decrease the filling time of the magnet whereas the rise time of the generator and the cut-off frequency of the system would remain constant. This would result in a largely over proportional length reduction compared to the gain in kick rise time. It would be more costly and also result in an inferior pulse response.

The impedance increase of the magnets will be obtained in the following way. The 22 matching capacitors of each magnet are composed of three large parallel plates, two ground plates on each side of the high voltage plate. By suppressing one of the ground plates and slightly adjusting the size of the remaining ground plate the correct capacitance can be achieved.

The loss of deflection strength due to the impedance increase cannot be tolerated for the injection of 26 GeV/*c* protons. To compensate the loss a combination of two measures will be taken.

- The low emittance bunches for LHC will be injected closer to the injection septum allowing a reduction of the deflection angle of about 10%.
- Two additional 'L' magnets (numbers 13 and 14) of increased aperture and installed in a short vacuum tank will be added immediately down streams of the existing system.

Figure 6 shows a schematic layout of the upgraded system.

The additional magnets 13 and 14 are available, as well as the short vacuum tank for these magnets. However, their aperture must

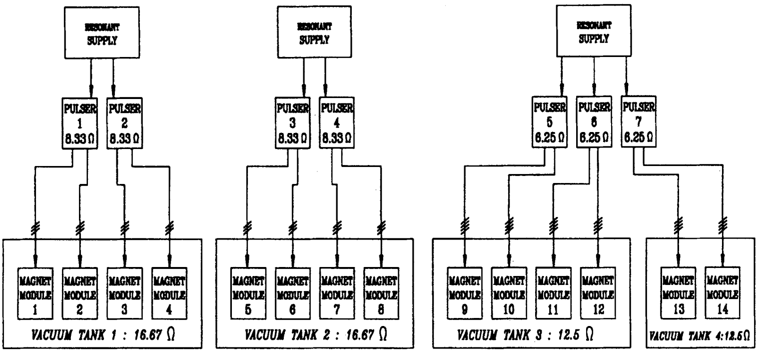

FIGURE 6 Schematic layout of the upgraded injection kicker system.

be increased. The impedance increase of four pulse generators requires new PFN inductors. The existing spare PFN will be employed for the seventh pulse generator but the three switch assemblies for the generator must be constructed. Space for this assembly is available in building BA1 at a distance of about 50 m from the present installation.

The synchronisation of four large pulse generators with an accuracy of < 10 ns is not an easy task and will require a substantial continuous surveillance effort. The following accompanying studies, aiming at reducing the kick strength and charging voltage or the number of required kicker systems, should therefore be undertaken.

- Addition of a slow bumper system to deflect the circulating beam nearer to the septum.
- Addition of a thin pulsed septum magnet to reduce the actual effective 'septum' thickness of 47.5 mm.

This scheme is not compatible with positron injection and can therefore only be implemented after the closure of LEP.

3 THE EXTRACTION KICKER SYSTEMS

3.1 Layout

For the west and east extraction to the LHC two fast kicker systems are needed to extract the proton and ion batches within one turn.

In the west a fast kicker system is available which has only rarely been used in the beginning of the SPS in 1976. It needs a substantial upgrading. For the east extraction a new kicker system is needed. Its high power components can be assembled from available spares which need also a substantial improvement.

Both kicker systems will be composed each of three travelling wave magnets and pulse generators with a characteristic impedance of 10 Ω. (If DC septum magnets should be used for the east extraction, instead of the fast pulsed eddy current systems now under development, four kicker units would be needed.) The continuously adjustable kick duration is up to 23 μs, the rise and fall times are 1.1 μs and the flat top ripple about ±1%. The magnets have a length of 1.7 m each and a horizontal and vertical aperture of 135 and 32 mm.[4] The deflection angle at 450 GeV/*c* is about 0.12 mrad per magnet.

Both kicker systems will be installed in the short straight section down streams of QF14. The high voltage equipment like pulse generators and resonant charging systems including most of the command and interlock electronics will be located in the ECA4 cavern for the east extraction and in surface building BA6 for the west extraction.

3.2 Upgrading

For LHC operation the following upgrading and streamlining is planned for both systems.

- The flat top ripple will be decreased to at least ±0.5%. The pulse forming networks of the power generators will therefore be modified in a manner similar to the one used for the injection kickers. The task is here less demanding because for LHC operation only 3/11 of the SPS circumference are filled with beam. One can then profit from the partial filling and start the extraction well after the beginning of the pulse when the ripple reduction is simpler.
- The pulse generators are actually equipped with three power switches. In addition to the main switch a second switch is used for change of pulse duration and a third for fall time reduction. For LHC operation these facilities are not needed and will not be installed. They will, however, be kept as option for a possible future neutrino extraction.

- To reduce the cost for power switches, the pulse duration will be shortened to about 10 μs by disconnecting part of the PFN. The disconnected section will be kept in place for possible future needs.
- The main switch consists actually of a thyratron bypassed by three ignitrons in series. The thyratron provides the fast and precise turn on while the ignitrons conduct the bulk of the current. The thyratron was previously not capable to conduct alone the high current during the long duration pulse. This is, however, no longer true for the reduced pulse length. The ignitron chain will therefore be disconnected.
- The command and interlock electronics and the software of both extraction systems are out of date and must be replaced.
- The 160 m long 30 kV transmission line for the east extraction system between pulse generators in ECA4 and magnets in LSS4 must be purchased. The line is composed of 18 coaxial high voltage cables of 50 Ω impedance each, equipped with coaxial connectors.

4 OUTLOOK

The upgrading of the SPS injection and extraction kicker magnet systems is a demanding task and requires, especially for the verification of the simulated pulse response of the very fast inflector, a full scale test system including the power switches and the complete length of the transmission line. This test system must be operated at full voltage. Spare equipment to be modified is available except the transmission line which is on order and will later be used for the new east extraction. It is intended to start in 1997 with the impedance increase of a spare pulse generator and a spare magnet and to test a complete upgraded injection system in 1998/1999. The upgrading of the installed system must await the closure of LEP and is planned for the long shutdown in 2000/2001.

Acknowledgements

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