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FOR LHC AND CNGS OPERATION**

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The extraction kickers of the Super Proton Synchrotron (SPS) need to be upgraded to meet the Large Hadron Collider (LHC) and CERN Neutrino to Grand Sasso (CNGS) requirements. Commissioning of the extraction towards one of the LHC rings and the CNGS facility under construction is foreseen for 2003. The ferrites of the kicker magnets will be heated significantly by the circulating beam and need to be cooled to stay below the Curie temperature. A cost-effective solution to this problem is presented consisting of AlN water cooled plates on the top and bottom of the ferrites. Model predictions are compared with preliminary laboratory measurements and machine data from the SPS. Commissioning of the extraction towards the other LHC ring is planned for 2006. Beyond the heat load issues, this latter extraction needs a larger horizontal “kick” and thus a higher magnetic field and larger horizontal beam aperture. The rise and fall time requirements of these kickers are less strict, therefore a new system with lower impedance permitting a larger magnetic field can be used.

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# UPGRADE OF THE SPS EXTRACTION KICKERS FOR LHC AND CNGS OPERATION

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## Abstract

The extraction kickers of the Super Proton Synchrotron (SPS) need to be upgraded to meet the Large Hadron Collider (LHC) and CERN Neutrino to Grand Sasso (CNGS) requirements. Commissioning of the extraction towards one of the LHC rings and the CNGS facility under construction is foreseen for 2003. The ferrites of the kicker magnets will be heated significantly by the circulating beam and need to be cooled to stay below the Curie temperature. A cost-effective solution to this problem is presented consisting of *AlN* water cooled plates on the top and bottom of the ferrites. Model predictions are compared with preliminary laboratory measurements and machine data from the SPS. Commissioning of the extraction towards the other LHC ring is planned for 2006. Beyond the heat load issues, this latter extraction needs a larger horizontal “kick” and thus a higher magnetic field and larger horizontal beam aperture. The rise and fall time requirements of these kickers are less strict, therefore a new system with lower impedance permitting a larger magnetic field can be used.

## 1 INTRODUCTION

The extraction from the SPS (as used since late 70’s until 2000) is being upgraded to comply with the LHC and CNGS requirements [1]. The extraction in LSS4 is common between the LHC and CNGS. For LHC and particularly CNGS the existing MKE kickers are upgraded and/or renewed to meet these specifications, see **Table 1**. For extraction towards CNGS two extractions per SPS-cycle are foreseen, requiring the field to increase from 0 to  $B_{max}$  or vice versa in a rise time / fall time  $< 1.1 \mu s$ . This is the space between two ( $10.5 \mu s$  long) bunch trains. For LHC there is only have one extraction per

SPS-cycle, requiring a field rise time / fall time  $< 10 \mu s$  and a flat top length of  $7.9 \mu s$ . For the planned 2003 SPS LSS4 kicker extraction the implemented cooling solutions for the expected significant magnet’s ferrite heating are being reported.

## 2 SYSTEM OVERVIEW

### 2.1 General Layout

The kicker system is a characteristically terminated travelling wave system, powered by a resonant charging circuit consisting of two parallel  $2 kV 50Hz$  a.c. power supplies that charge two capacitor banks, which feed via (safety) thyristors a  $60 kV$  step-up transformer. The resonant charging circuit is connected to five Pulse Forming Networks (PFN’s) 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 PFN’s to the required voltage, after which the five “main” thyatron switches are triggered discharging the PFN’s into the magnets and Terminating Magnet Resistors (TMR). Subsequently triggering of the five “clipper” switches quenches the magnetic field and dumps the remaining PFN energy into the diode-stack and Terminating Dump Resistor (TDR). The second extraction starts with recharging the PFN with the second capacitor bank. **Figure 1** shows the LSS4/ECA-4 kicker installation’s schematic.

Beyond the kickers, septa deflect the extracted beam into the transfer line. 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].

### 2.2 Semiconductor power diodes

A system (configuration) has been developed in which the thyatron (gas discharge) “dump” switches are replaced by semiconductor power diodes to reduce long term costs and improve lifetime and reliability. The  $72 kV$  diode-stack, with  $36 1 M\Omega$  series’ resistors in parallel for a uniform voltage distribution, consists of  $6 \times 6 2 kV$  series diode-units. If one diode-stack unit short-circuits the dump still functions properly.

### 2.3 Kicker diagnostics

The magnetic field is measured within the required tolerance in the laboratory with an inductive probe. A measured pulse is shown in **Fig.2**. Here the 2-98% rise

Table 1 SPS LSS4 MKE kicker parameters

	LHC*	CNGS
Energy [GeV]	450	400
Total system deflection angle $\theta$ [mrad]	0.4788	0.4788
# MKE-L magnets	3	3
# MKE-S magnets	2	2
Magnet length [m]	2.174	2.174
2-98% Rise time [ $\mu s$ ]	$< 10$	$< 1.1$
Operating voltage [kV]	47.0	47.0
Induction field MKE-L [T]	0.0828	0.0828
Induction field MKE-S [T]	0.0905	0.0905
Flat top length duration [ $\mu s$ ]	7.9	10.5
Overshoot (flat top ripple)	$< 1\%$	$< 2\%$
98-2% Fall time [ $\mu s$ ]	$< 10$	$< 1.1$

\*: for protons

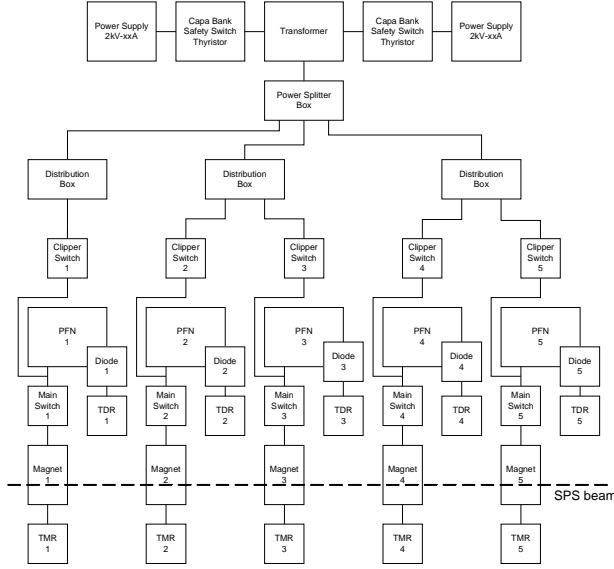


Fig. 1 MKE LSS4 installations schematic layout.

and 90-10% fall times are  $1.0 \mu\text{s}$  respectively  $0.93 \mu\text{s}$  and the overshoot was 5% at a  $10 \mu\text{s}$  pulse length for the non-modified PFN frontcells, capacitors and coils. The fall time and overshoot are not yet meeting the specifications. These are expected to come within the specifications after further modification/adjustment of PFN front cells, sorting of PFN capacitor/coil section values and magnet and TMR wave impedance matching.

In addition, two capacitive pick-ups per magnet are installed enabling measurement of the “kick” also when installed in the SPS machine [3]. These diagnostics give a detailed picture of the field “kick” rise, fall and (flattop) pulse length times including the magnet filling time, as well as the overshoot.

The extraction kicker system will be equipped with *PT100* temperature probes to provide an interlock for the

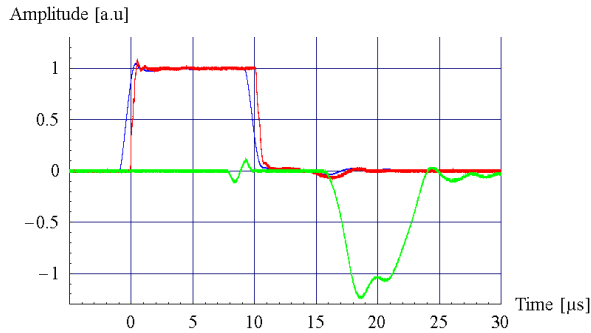


Fig. 2 Measured MKE normalized magnetic field pulse. (Positive thick line): magnetic field measured with inductive probe; (positive thin line, lagging behind): TMR signal; (negative line): TDR (diode-stack PFN dump signal).

Table 2 MKE kicker beam induced ferrite dissipation for typical operating conditions (bunch length:  $l\sigma$ ) [5].

Bunch length	LHC	CNGS	CNGS
	Ferrite 8C11	Ferrite 8C11	Ferrite 4E2
0.35 ns	$1.02 \text{ kW}\cdot\text{m}^{-1}$	$0.79 \text{ kW}\cdot\text{m}^{-1}$	$0.72 \text{ kW}\cdot\text{m}^{-1}$
0.49 ns	$0.43 \text{ kW}\cdot\text{m}^{-1}$	$0.33 \text{ kW}\cdot\text{m}^{-1}$	$0.30 \text{ kW}\cdot\text{m}^{-1}$

loss of ferrite permeability above the Curie temperature, i.e. loss of (magnetic field) extraction kick-ability.

## 2.4 Second phase: LSS6

For the 2006 LSS6 extraction it is planned to make a new kicker design. The PFN('s) and magnets will need to meet the earlier described required specs for “kick” and “timing”. There is only space for two ( $l=2.2\text{m}$ ) MKE kickers requiring a larger (horizontal) “kick”/larger  $B$  field together with a larger horizontal beam aperture. The voltage rating of the system is limited by the maximum operating voltage for the thyatron switches, so as to obtain a larger current  $I$  (at the same voltage  $U_0$ ), a reduced impedance ( $Z=\sqrt{L/C}=6.25\Omega$ ) for the PFN's and the magnets is needed. A similar cooling solution as for the LSS4 MKE-L and MKE-S magnets is foreseen for the LSS6 MKE magnets to assure proper extraction for future LHC and CNGS experiments [4].

## 3 COOLING

In the SPS a beam induced temperature rise of  $24 \text{ K}$  was measured in the MKE kickers for  $2.9\cdot 10^{13}$  protons in a so-called “fixed target proton machine cycle” at a calculated ferrite power dissipation of  $43 \text{ W}\cdot\text{m}^{-1}$ . For the proposed LHC and CNGS beam-operating conditions the SPS extraction kickers will be exposed to a much larger beam induced thermal power. **Table 2** shows the operating conditions for the upgraded MKE kicker magnets. The ferrites will be heated due to the high frequency polarization (power losses) of the magnetic (ion) dipole moments. For kicker applications in particle accelerators the used magnetic materials are ferrites (ferromagnetic, typically:  $\text{NiZn}$ ), which have spontaneous magnetisation at room temperature, and show hysteresis and saturation effects. Above the Curie-temperature (see **Fig.3**) the spontaneous magnetisation disappears and the material becomes paramagnetic [7, 8, 9].

To cope with the ferrite heat dissipation ratings quoted in Table 2 cooling measures are implemented in the MKE kicker magnet. Temperature probe measurements were taken under lab conditions and compared to those measured in the SPS machine.

The results from the various cooling tests combined with the modelling results are shown in Fig.3 together with 0-dimensional equivalent electrical-circuit model and 3-dimensional STAR-CD<sup>®</sup> steady-state calculations. It also shows the results of cooling options under study: a copper block connecting frame and base plate, and a

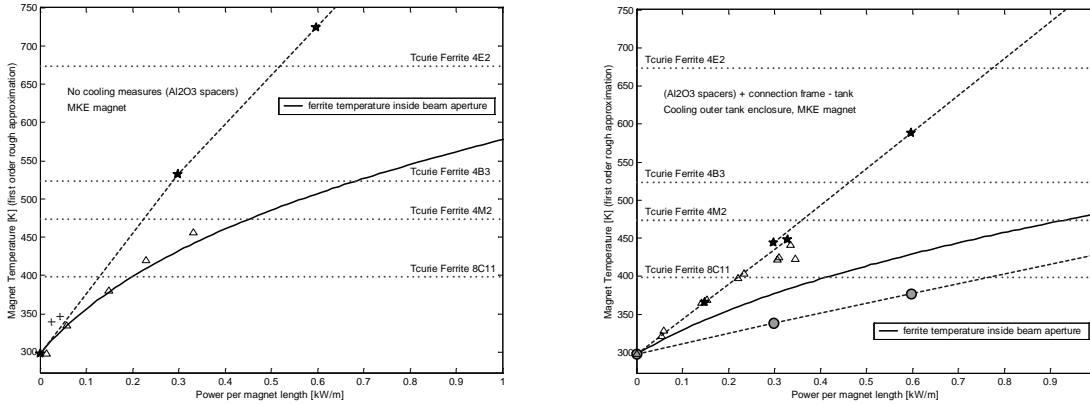


Fig. 3 MKE extraction kicker temperatures: (left) no cooling measures, (right) copper block and water-cooled base plate. Solid lines: 0-D model; Stars + dashed lines: 3-D model; Triangles: measured values (laboratory set-up); Circles + dashed line: Calculated maximum temperatures (3-D model) for the final chosen cooling solution (*AlN* cooling plates on the top and bottom of the ferrites combined with water cooling at the *AlN* plates' extremities).

water-cooled base plate. The 0-D modelling corresponds well with the measured values describing the various temperatures before implementation of additional cooling measures, since radiative cooling previously was the then dominant mechanism (not included in our 3-D model). The tests after the cooling (heat conduction) modification are more accurately described with the 3-D model.

From Fig.3 it can be seen that the effect of the magnet's frame-base plate connection and water-cooled baseplate is marginal. For the series it has been decided to equip the magnets with *AlN* (aluminium nitride, thermal conductivity  $\sigma = 180 \text{ W}\cdot\text{m}^{-1}\text{K}^{-1}$ ) cooling plates on the top and bottom of the ferrites combined with water-cooling at the *AlN* plates' extremities. For this solution we found  $343 \text{ K}$  as the maximum temperature for  $0.33 \text{ kW}\cdot\text{m}^{-1}$  (according to the 3-D model) corresponding to  $8\cdot 10^{13}$  protons (CNGS type beam) with a  $0.49 \text{ ns}$  bunch length, which is well below the ferrite *8C11*'s Curie temperature  $T_c = 398 \text{ K}$  (at which also out-gassing will become relevant). The observed kicker heating has a typical time constant of several days.

To reduce the ferrite heat dissipation it is also foreseen to increase the bunch length as indicated in Table 2.

A further option is the use of an alternative ferrite (e.g. make: Ferroxcube, grading *4E2* instead of grading *8C11* [10]) with a higher Curie temperature (see Fig.3). Out-gassing tests will be performed on this ferrite type.

#### 4 CONCLUSIONS

A cooling solution is being implemented on the MKE-S and on the newly built MKE-L magnets for the extraction kicker system in point LSS4 of the SPS, which will be installed in the SPS machine shutdown 2002/2003. A similar solution is foreseen for the MKE magnets in point LSS6 of the SPS.

Kicker ferrite temperature diagnostics are added. Capacitive pick-ups are added as a field "kick" quality diagnostic.

A new PFN energy dump clipper switch / diode-stack system has successfully been tested at full voltage.

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