# BEAM INDUCED HEATING OF THE SPS FAST PULSED MAGNETS

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*Abstract*

Fast pulsed magnets with ferrite yokes are used in CERN's SPS accelerator for beam injection, extraction and excitation for tune measurements. The impedance of the ferrite structures can provoke significant beam induced heating, especially for beams with high peak currents as for LHC operation, even beyond the Curie temperature. The expected heating in the different kicker systems for various operational modes is compared with beam measurements. Estimates of the beam induced power have been derived from measured beam spectra. A fast extraction kicker system has recently been equipped with a cooling system. The measured cooling performance is compared with data from laboratory set-ups and numerical simulations.

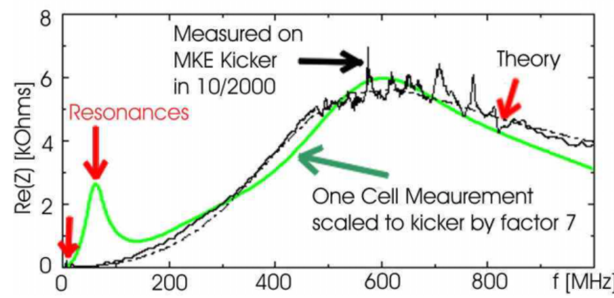


Figure 1: Single kicker cell impedance measurements compared to the measurement of a complete 7 cell magnet and calculations [8].

## INTRODUCTION

CERN's SPS accelerator will serve as injector for the LHC [1] and will also provide intense proton beams for the CNGS experiment [2]. The foreseen intensities are much larger than those used so far and the impedance of the SPS becomes an important issue. Large impedances can lead to beam instabilities [3] but also to equipment problems due to power deposition by the beam. In the SPS the different types of kicker magnets, used for injection, extraction and tune measurements, have ferrite yokes and present a relatively high impedance. Ideally the ferrites are screened from the beam [4], but sufficient aperture is not always available. In the case of the recently rebuilt SPS extraction kicker magnets (MKE) the ferrites are water-cooled to limit the temperature rise of the magnets [5]. The ferrites have to stay below the Curie temperature - for the type of ferrite used this is around 125 °C - to maintain their magnetic properties.

## MAGNET IMPEDANCE AND POWER DEPOSITION

The longitudinal coupling impedance of the ferrites of the different SPS kicker magnets can be calculated as a function of the frequency with the model as presented in [6], taking into account the metal conductors in the horizontal plane. The ferrites used are of the low conductivity NiZn family (type 8C11). In the model initial relative permeabilities $\mu_i = 460$, $\varepsilon_{r,i} = 12$ and a maximum frequency for ferri-magnetic losses of 9.8 GHz are used.

The calculated impedance for the MKE magnet has been compared with wire measurements using the log formula for impedance evaluation [7], see Figure 1. It shows a good agreement, although the characteristic impedance of the wire (about 200 Ω) is much lower than the distributed impedance of the magnet to be measured (up to 4 kΩ). The magnets are equipped with transition cones, shielding the cavity between vacuum tank and the actual magnet. It was found that these transition pieces are very important to reduce the impedance as seen by the beam, although they do not effect the power deposition by the beam in the ferrites. The impedance measurements without transition pieces can be misleading, as the electromagnetic waves can bypass the ferrite, and do not reflect the behaviour of the beam.

To calculate the power deposition in the magnet the impedance needs to be multiplied with the bunch spectrum. With the assumption of a Gaussian bunch spectrum the deposited power can easily be calculated. The result is very sensitive to the assumed bunch length. Some resulting powers are given in Table 1 for the different SPS extraction kicker magnets (MKE) and injection kicker magnets (MKP), using a CNGS type beam. For a nominal LHC beam being accelerated in the SPS the power deposition is even more important due to the higher bunch intensities. Assuming a bunch length (1 σ) of 0.5 ns, 4 batches of 72 nominal LHC bunches of

Table 1: Deposited power in the SPS kicker magnets, assuming CNGS nominal parameters: total number of protons = $4.8 \cdot 10^{13}$, in 4200 bunches and duty factor of 0.6.

| | *Full H-Apert. [mm]* | *Full V-Apert. [mm]* | *σ [ns]* | *P [W/m]* |
|---|---|---|---|---|
| MKE-S | 32 | 135 | 0.5 | 126 |
| | | | 0.35 | 314 |
| MKE-L | 35 | 148 | 0.5 | 132 |
| | | | 0.35 | 316 |
| MKP-S | 61 | 100 | 0.5 | 15 |
| | | | 0.35 | 45 |
| MKP-L | 54 | 140 | 0.5 | 53 |
| | | | 0.35 | 145 |

$1.1{\cdot}10^{11}$ protons each and a duty factor of 0.5 results in a calculated power deposition of about 700 W/m in the MKE magnets. The duty factor is an important parameter, as generally the bunch length will shorten during acceleration, while the calculation is made for a constant bunch length. The uncertainty on the bunch length is the most important and very often unknown variable.

### *Machine Measurements: Spectra*

The power spectra at the harmonics of the bunch spacing frequency of 40 MHz up to 1 GHz have been measured during SPS operation with an LHC beam. These spectra can then be multiplied with the impedance of the magnets as given in Figure 1. The resulting power as a function of time in the SPS cycle is shown in Figure 2. The spikes are caused by the four injections into the SPS. After the fourth injection the power increases due to the shortening of the bunch length during acceleration. The calculated average power deposited during the 21.6 s cycle is 467 W/m for the MKE magnets (measured for 4 x 72 bunches, $1.2{\cdot}10^{11}$ protons per bunch).

Figure 3 shows the measured amplitudes for the different frequencies together with a Gaussian distribution before acceleration. It clearly shows that a Gaussian distribution is not a realistic representation. The measured amplitudes for frequencies above 400 MHz correspond more to a cosine-squared distribution. The 0.5 ns bunch length used in the calculations for the LHC beam presented above, leads to higher estimated powers than deduced from the measured bunch spectra, although the impedance is high between 400 MHz and 1 GHz.

## TEMPERATURE INCREASE FOR THE WATER-COOLED MKE SYSTEM

Calculations show that the powers mentioned for the MKE system in Table 1 would make it impossible to operate with a nominal CNGS beam over longer periods, as the ferrites would soon reach the Curie temperature of about 125 °C. For this reason the newly installed MKE kicker magnets are equipped with water-cooled aluminium nitride plates which are in good thermal contact with the ferrites. Temperature probes are positioned on the outside of the ferrites. A finite element model of the magnet including its cooling system has been made with the programs Design Space® and Ansys® which has been used to optimise the design and estimate its performance [9].

The results of the model were compared with the temperature measurement in a laboratory set-up and with temperature and kick measurements made in the SPS.

### *Laboratory Test Bench*

The Laboratory set-up consisted of one cell of an MKE magnet ($1/7^{th}$ of a complete magnet) equipped with the cooling system and kept under vacuum. Two titanium bars were placed inside the magnet gap in contact with the ferrites to resistively heat them at positions similar to the beam heating. The results from the test set-up were difficult to interpret because of important contact resistances, resulting in uncertainties of the deposited power, and the problem of obtaining good thermal contacts with temperature probes under vacuum. Figure 4 shows a comparison between the finite element model and the laboratory set-up. There is good agreement between the highest temperatures measured and the calculated ones (close to the heating bars, labelled as T side). For some other temperature probes, including the probes as they are installed in the machine (location labelled with T front) a significant difference was found. These differences might also be caused by inappropriate assumptions made in the finite element model.

### *Machine Measurements*

After heating the MKE magnets with beam in the SPS the kick strength of a magnet was evaluated by measuring the amplitude of the beam position oscillation induced by a single kick at different kicker temperatures. The results are shown in Figure 5. The horizontal axis is the temperature measured on the MKE magnet, which is not the highest temperature inside the ferrite. For the MKE magnet it can be seen that from a measured temperature of about 80 °C onwards the kick strength is reduced, indicating that the core of the ferrite has reached the Curie temperature.

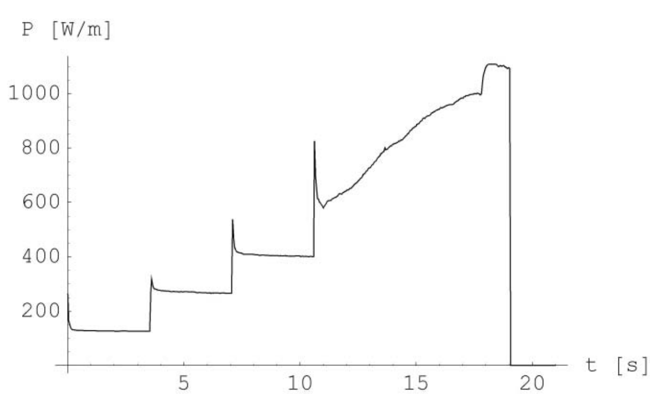


Figure 2: Deposited power in an MKE magnet, calculated from measured spectral amplitudes, during one SPS cycle.

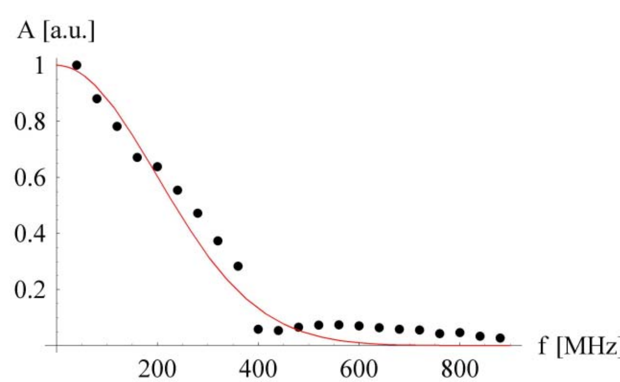


Figure 3: Comparison of spectral amplitudes of measured data (dots) at t = 4 s into the cycle and a Gaussian bunch (line) with σ = 0.8 ns.

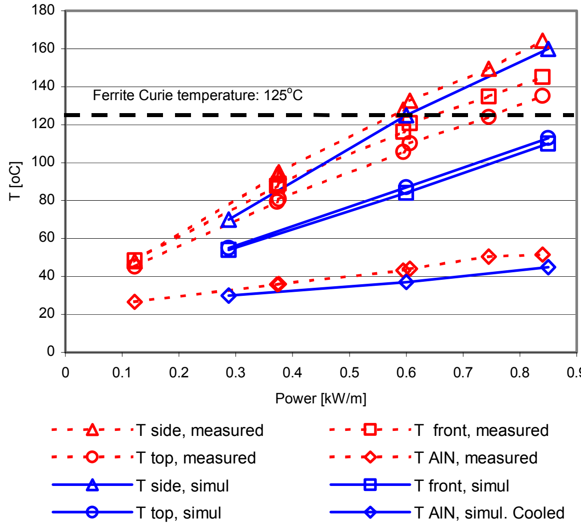


Figure 4: Relation between deposited power and temperatures of the ferrites of a water-cooled MKE magnet. Results are shown for the laboratory set-up, dashed lines, and for Design Space® simulations, solid lines.

Figure 5 shows also measurements for the MKQH magnet, the horizontal Q kicker in the SPS. It is basically identical to the MKE magnet but not equipped with water-cooling. The kick strength of this magnet is reduced for temperatures above about 45 °C measured at the MKE temperature probe. This suggests that the cooling system allows more than twice the power to be deposited in the magnet before the Curie temperature is reached.

From Figure 5 it can also be derived that for a measured temperature of about 80 °C the core of the ferrite reaches a temperature of about 125 °C. This agrees very well with the Design Space® model shown in Figure 4 for a deposited power of about 600 W/m.

## CONCLUSIONS

The measurement of the SPS longitudinal coupling impedance agrees very well with the theoretical impedance. Calculations of the deposited power can be made using Gaussian bunches, but spectral measurements show that in reality the bunches are not Gaussian and significant deviations from the results obtained with calculations assuming Gaussian bunch lengths are expected.

The water-cooling system on the newly installed MKE extraction kicker magnets allows the power deposition by the beam to be doubled, with respect to a non-cooled system. The calculated powers for a CNGS type beam (Table 1) show that it should be possible to operate the SPS with a nominal CNGS beam without reaching the Curie temperature. For continuous operation with an LHC type of beam, the power estimates predict temperatures above the Curie temperature. As it is not foreseen to continuously accelerate a nominal LHC beam in the SPS, injection periods into the LHC are assumed to be of the order of 15 minutes, interleaving LHC and CNGS beams

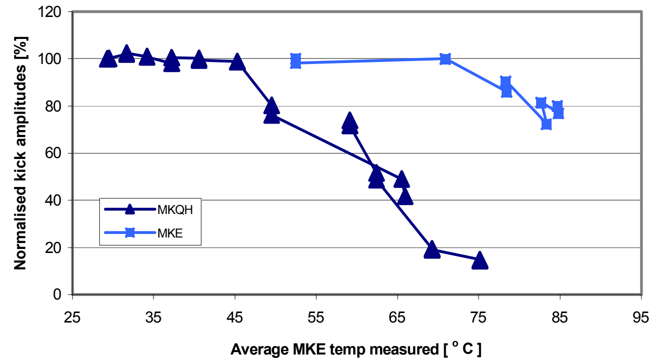


Figure 5: Different MKE and MKQH kick strengths at different measured MKE temperatures.

in the SPS is expected to result in temperatures which are always below the Curie temperature. If nevertheless temperatures higher than the Curie temperature are reached, improvement can be expected by lengthening the bunches, which is an acceptable solution for the CNGS beams.

During extended machine runs with high intensity LHC beams, like electron cloud studies or vacuum conditioning, the MKE heating could still lead to operational constraints.

## ACKNOWLEDGEMENTS

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