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TRANSIENT THERMAL ANALYSIS OF INTENSE PROTON BEAM LOSS ON A KICKER MAGNET CONDUCTOR PLATE

P. Knaus, J. Uythoven

Abstract

The Super Proton Synchrotron SPS will be used as injector for the Large Hadron Collider LHC and needs adaption to meet LHC requirements. The SPS injection kicker magnets MKP will undergo important modifications to comply with the requirements on magnetic field rise-time and ripple. The injection kicker presently installed has a return conductor of beryllium to minimise the risk of metal evaporation from its surface due to heating caused by beam impact. In the context of refurbishing the MKP to satisfy LHC requirements these conductors need replacement, preferably with a less delicate material.

This article presents the transient thermal analysis of energy deposition caused by beam loss on the conductor plate. The expected time structure of the beam is taken into account. Simulations comparing different conductor materials have been performed, leading to the result that a significantly cheaper and fully inoffensive titanium alloy can satisfy the needs.

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1 INTRODUCTION

A study is presented of the damage expected to be caused by beam loss in the MKP hadron kicker magnet during injection into the SPS. The energy deposition on the return current conductor plate actually made of beryllium (Be) is compared to a less delicate titanium alloy, Ti6Al4V. Relevant material properties are listed in Table 1. The possible failure modes, resulting in different beam impact angles, were determined and the most critical scenario analysed in detail. The Monte-Carlo code FLUKA [1] was used for the simulation of the instantaneous energy deposition by the beam and its secondary particles. The transient thermal analysis is then performed by numerical integration of the diffusion equation.

2 SPS INJECTION KICKER SYSTEM

The SPS injection kicker magnets MKP [2] are of the travelling wave type with the ferrite yoke, matching capacitive plates, HV and return conductor as a part of the vacuum system (Figure 1). For the injection of the LHC type lead ion beam in the SPS a field rise-time of less than 115 ns is required. To obtain this short rise-time the magnets presently installed will be increased in characteristic impedance from 12.50 to 16.67 Ω and the number of cells will be decreased from 22 to 17. This reduction requires a shortening of the actual Be return conductor. As Be dust is highly toxic, an alternative conductor material has been investigated. The modified injection kicker system will consist of 16 travelling wave magnets, located in four different vacuum tanks (Figure 2). The return conductor limits the horizontal physical aperture towards the inside of the SPS (negative horizontal position in Figure 2). Due to bad steering in the transfer line it can not be excluded that injected beam hits the return conductor. Optics calculations were made to determine the angles under which the beam can impinge on the conductor. The possible angles range from less than 1 mrad to a few mrad. As the path length of the beam through the conductor determines the amount of energy deposited, the worst case, a 0° angle between incident beam and conductor plate, is taken for the thermal analysis calculations.

Table 1: Material properties of Be and Ti6Al4V at 20°C. In the simulation the temperature dependence of these parameters is taken into account.

Parameter	**Be**	**Ti6Al4V**
Density ρ [g/cm^3]	1.85	4.43
Specific heat c_p [J/(kg K)]	1840	561
Therm. conductivity λ [W/(m K)]	147	6.6
Diffusivity a [cm^2/s]	0.42	0.029

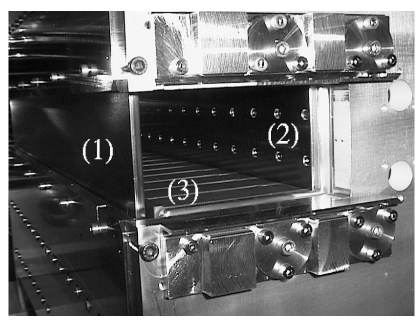

Figure 1: MKP magnet gap limited by return current conductor (1), high voltage conductor (2) and ferrites (3).

3 SPS BEAM TYPES

During the LHC era three beam types will be injected in the SPS: a 26 GeV p beam for LHC, a 14 GeV p beam for CNGS (CERN Neutrino beam to Gran Sasso) or fixed target physics, as well as a 5.11 GeV/u Pb^{82+} beam for LHC or fixed targed physics. From the point of view of expected damage in case of beam loss the p beam for LHC represents the most critical case, because of its high intensity and brightness. The present study focuses on this beam.

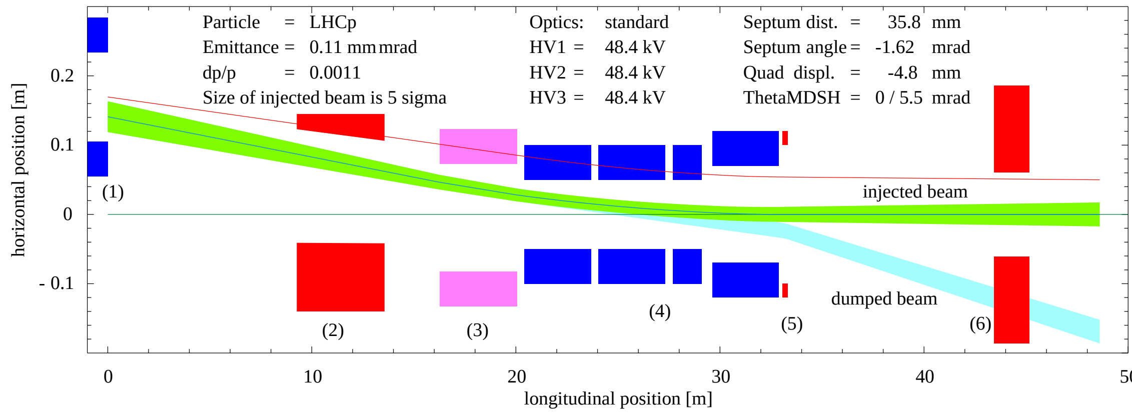

Figure 2: Layout of the SPS injection region with the MKP kicker magnets. The numbers in the drawing correspond to the following elements: (1) injection septum magnet, (2) high–energy beam dump, (3) quadrupole magnet, (4) kicker magnet vacuum tanks, (5) dump magnet for injected beam, (6) beam dump for the injected beam.

3.1 SPS Proton Cycle For LHC

The LHC proton cycle in the SPS [3] will consist of either three or four PS injections at 3.6 s intervals: the injection plateau will last up to 10.8 s. To bring the beam from 26 GeV/c to 450 GeV/c a 8.3 s acceleration phase is required. A 1 s flat top is presently assumed to prepare the extraction equipment and about 1.5 s are reserved to reset the RF system and prepare the next injection. This results in a total SPS proton cycle of 18.0 s or 21.6 s, for three or four PS batches respectively.

Each PS batch contains 72 bunches, spaced by 25 ns. For the ultimate LHC beam the single bunch intensity will be $1.70\,10^{11}$p. A three-batch SPS cycle will thus accelerate $3.67\,10^{13}$p while the four-batch intensity will rise to $4.90\,10^{13}$p. The described SPS cycle is repeated 12 times for each LHC ring. The three– and four–batch cycles will be interleaved in the form 334 334 334 333 in order to fill each ring with a total of 2808 bunches.

4 ENERGY DEPOSITION CALCULATIONS

4.1 Energy to Temperature Conversion

A small amount of energy dE deposited in a volume dV of a material with density ρ causes a temperature rise ΔT determined by $dE = c_p\,\rho\,dV\,\Delta T$. The proportionality constant c_p is the specific heat of the considered material. The larger the value of c_p, the smaller the temperature rise caused by an energy deposit dE. For important energy depositions the specific heat can no longer be considered as constant, but its temperature dependence must be taken into account. The specific heat $c_p(T)$ for the two materials of interest, beryllium and Ti6Al4V, is shown in Figure 3. Now ΔT must be extracted from

$$\frac{dE}{dV} = \rho \int_{T_0}^{T_0+\Delta T} c_p(T)\,dT \qquad (1)$$

by solving numerically for the upper limit of the integral. The conductor temperature before the beam impact is T_0.

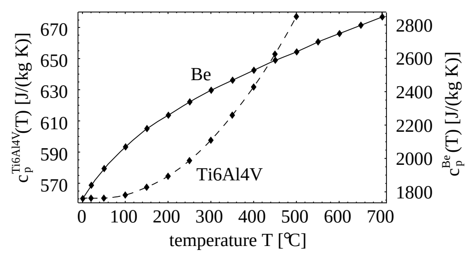

Figure 3: Specific heat $c_p(T)$ of Be and Ti6Al4V [4].

4.2 Instantaneous Energy Deposition

Beam impact on the MKP kicker produces a hadronic and electromagnetic cascade resulting in energy deposition all along the conductor plate. For the longest possible particle trajectory in matter, i.e. for a zero angle beam impact on the conductor, the longitudinal total energy deposition profile was simulated by FLUKA. The equivalent temperature increase ΔT in a slab of 52 bins of size $1.0 \cdot 1.0 \cdot 10.0$ mm each, all along a conductor that was hit centrally by a PS batch is displayed in Figure 4. The curves shown correspond to a 1.0 and a 2.5 mm thick conductor plate of either Be or Ti6Al4V. As long as the beam size is larger than the conductor, any further increase in conductor thickness will result in a higher temperature along the bins on the beam axis. The reason is that secondary particles produced outside the central bins are scattered such that they end up in the central bin slab and contribute to the energy deposited there. For this to happen the impact of the primary proton must be less than a Molière radius away from the central bin.

Similar temperature profiles are obtained for both materials. Due to the lower density of beryllium the Bethe-Bloch formula predicts a lower dE/dx and the high values of $c_p(T)$ cause the corresponding temperature increase to be modest: the temperature profiles reach maxima of 5.6°C for a 1 mm and 6.4°C for a 2.5 mm Be conductor as compared to the 22 and 26°C for Ti6Al4V.

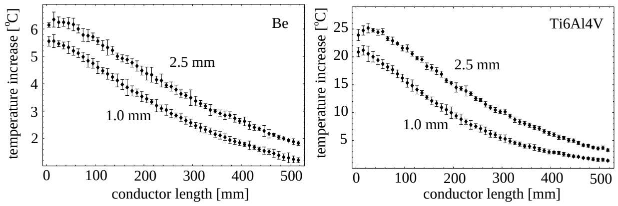

Figure 4: Instantaneous longitudinal temperature increase caused by a single PS proton batch impinging on a 1.0 and 2.5 mm thick Be and Ti6Al4V conductor.

4.3 *Transient Thermal Analysis*

In case of repeated beam loss the temperature builds up with time and leads to a hot spot on the conductor: material could sublimate from its surface and be deposited on sensible parts of the kicker which could provoque sparking or even a short circuit.

To determine the peak temperature that may occur the beam time structure must be taken into account: every injected batch measures 1.80 μs only (72 bunches, 25 ns spacing) and thus its energy deposition is considered instantaneous. Then 3.6 resp. 10.8 s are left to the induced temperature distribution to diffuse (Figure 5). The temperature distribution $T(x,t)$ before injection of the subsequent batch is determined by numerical solution of the diffusion equation

$$\partial_t T(x,t) = a \cdot \partial_x^2 T(x,t) \qquad (2)$$

with the initial condition $T(x,0) = T_0(x)$ and boundary conditions $T_x(\pm b,t) = \mp h \cdot T(\pm b,t)$ quantifying the heat flux through the top and bottom boundary of the conductor (cf. (1) in Figure 1). Diffusivity a and Biot's number h are temperature dependent.

Biot's number is defined as the ratio of convection k and thermal conductivity $\lambda(T)$. It is also weighted with the ratio between the contact surfaces of the conductor and the stainless steel support which is 2.5:1. A particular problem resides in finding a significant numerical value for h because the convection coefficient k depends strongly on characteristics of the contact surfaces like surface roughness, contact pressure, presence of an oxide layer or eventually presence of a contact liquid in the interspace between the two materials. An approximate numerical value of $3000\,W/m^2K$ for a stainless steel to stainless steel contact [5] was assumed. The influence of under– and overestimating this value by a factor 100 was examined and is found to cause only a minor change of ± 10 % in the equilibrium temperature reached after about 100 injections (Figure 6).

The temperature increase ΔT with every new injection adds to the remainings of the previous injection. Though, ΔT will decrease with increasing temperature because of the temperature dependence of the specific heat $c_p(T)$. At some point an equilibrium between additional temperature rise by new injections and diffusion is reached: this equilibrium temperature is 30°C for Be and 190°C for the titanium alloy (Figure 6). Cooling by thermal radiation is negligible at these temperatures.

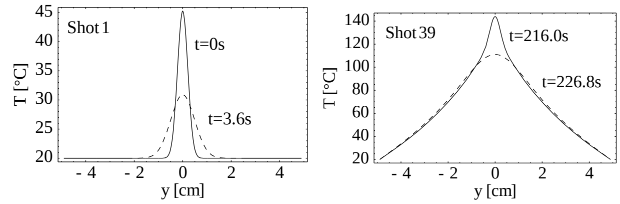

Figure 5: Instantaneous transverse temperature profile (continuous line) in a 2.5 mm thick Ti6Al4V conductor and 3.6 resp. 10.8 s later (dashed line).

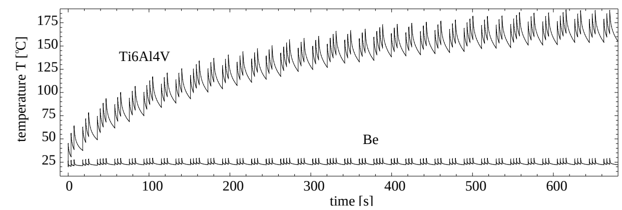

Figure 6: Temperature built-up of the hottest spot on the Ti6Al4V conductor due to continued beam loss. A non-critical equilibrium temperature is found.

5 CONCLUSIONS

The maximum temperature attained by repeated LHC type proton beam impact in a Ti6Al4V conductor is 190°C and is about six times higher than the maximum of 30°C reached in pure beryllium. Nevertheless this value is fully acceptable: no material sublimation is expected.

Due to the toxicity of beryllium dust special care must be taken when machining the material. By avoiding this machining considerable financial savings were realized.

6 REFERENCES

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