IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE NEW INTERNAL BEAM DUMP AT THE SPS. TEMPERATURE AND STRESS CALCULATIONS AND ITS DESIGN.

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Summary

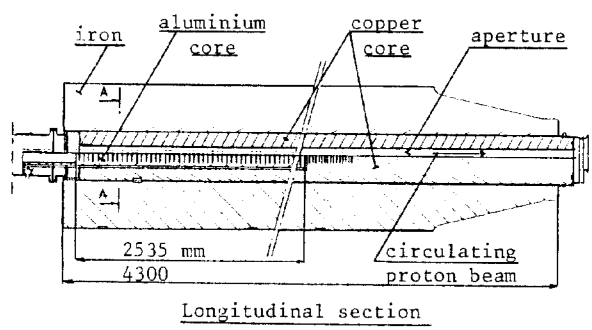
A method of calculation of the temperature distribution and the thermal stress distribution in an internal beam dump is described. The calculation results and the stress limits are discussed for the new SPS beam dump designed for high proton intensities.

1. Introduction

In the CERN-SPS accelerator the circulating proton beam is dumped over one revolution of 23 μs on an internal beam dump whenever it is not extracted or in case of operational emergencies. Recently, the beam intensities have increased up to 2.7 10^{13} protons per pulse (ppp) and a future intensity of 5 10^{13}ppp may be attained whereas the momentum will rise from 400 to 450 GeV/c. Therefore a detailed study of the expected temperatures and thermal stresses in the newly built dump core has been undertaken.

2. Description of the Beam Dump

The dump is composed of a core mounted in a cylindrical iron shielding (Fig. 1)



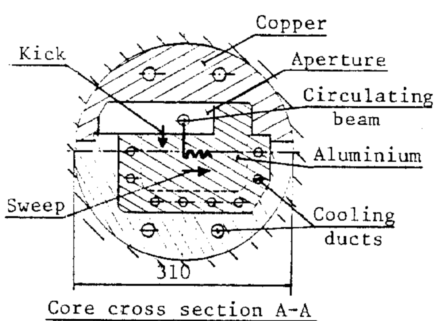


Fig. 1 The internal beam dump

The upstream part of the core is made of aluminium and the downstream part of copper. The circulating beam passes through an aperture in the core. In case of dumping the beam is kicked downwards into the material of the core during one beam revolution.

A vertical oscillation on top of the kick, together with a horizontal deflection produced by a sweeper system[1] are designed to spread the beam over a rectangular area of 15 x 42 mm^2 at 450 GeV/c, increasing the effective beam cross-section to 630 mm^2 (Fig. 2) in order to reduce the local energy deposition density and thus the peak temperatures and stresses.

The aluminium part of the dump core is made of the alloy A-2219, which has the highest mechanical strength of all aluminium alloys at 250-300^{o}C[2] and is weldable. To reduce the longitudinal stresses in the block (section 6) it has been subdivided over its length by machining every 24 mm slots of 1.5 mm width through electro erosion.

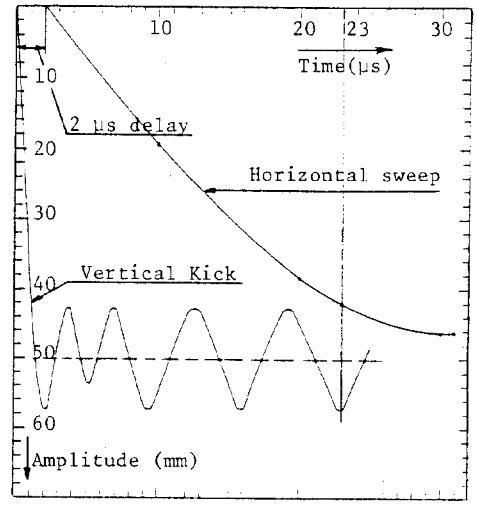


Fig. 2 The kick and the sweep

The copper part is made of Cu Cr Zr alloy chosen for its high temperature strength, weldability and good heat conductivity. It forms the vacuum chamber around the aluminium part, and stops the particles which escape from the rear of the latter. The highest temperatures in the copper are reached just behind the aluminium and therefore slots of 2 mm width have been machined every 20 mm over a length of 300 mm to relieve the longitudinal stresses.

The aluminium and the copper core are water cooled through deep-drilled holes close to their peripheries.

3. The energy deposition produced by the absorption of one SPS pulse

At 450 GeV/c and 5 10^{13} protons the beam contains a kinetic energy of 3605 kJ. The distribution of the energy deposition density inside the absorber material is computed with the "Monte-Carlo" program ZYLKAZ[3]. The energy deposition density is a function of the momentum and the cross-section of the proton beam, of the atomic number and the density of the absorber material. In our case, for aluminium, the radial energy deposition density p(r) in the cross-section where the temperature reaches a maximum, "the hottest cross-section", can be described empirically[4] for the momentum range between 400 and 450 GeV/c and an expected beam area of 8.2 mm^2 (r = 0.16 cm) as :

$$p = 265 - 1190\, r \quad \frac{\text{cal}}{\text{cm}^3\ 10^{13}\ \text{protons}} \quad \text{for } r < 0.16 \text{ cm}$$

$$p = \frac{1860}{r(r+15)^2} \quad \frac{\text{cal}}{\text{cm}^3\ 10^{13}\ \text{protons}} \quad \text{for } r \geq 0.16 \text{ cm}$$

One pulse with an intensity of 5 10^{13}ppp, dumped without blow-up by kick and sweep, would cause an adiabatic temperature increase in the centre of 2324^{o}C (melting heat neglected), well above the melting point of aluminium. The kick oscillation and sweep deflection are therefore indispensable.

To calculate the temperatures due to this deposition pattern a computer program has been written, called DEPO, which subdivides the sinusoidal kick and sweep path of the beam into a hundred impact points each of which is irradiated by 1/100 of the total beam intensity. The temperature distribution due to each of these sources is calculated with the formulas given above. The final temperature field is readily obtained by summation of each of the local depositions.

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4. The Steady State Temperature

Repetitive beam dumping, as used during accelerator tests, causes a build up of the temperature until an equilibrium is reached between the heat input and the cooling. The temperatures steadily oscillate between the maximum values just after the dumping of one pulse and the lower values just before the dumping of the next one. The steady state temperature distribution can, for convenience, be defined as the temperature field, existing just before a new pulse is dumped. The maximum temperatures are found by summation of this temperature field with that due to the absorption of one SPS pulse described in the previous section.

A computer program, called HEAT, has been written for the calculation of the temperatures as a function of time. The program uses a method which is based on the fact that the time dependent heat transport can be described as a diffusion process[5] : The heat input is subdivided into heat particles which are allowed to walk randomly during each time increment, with an r.m.s. step length of :

$$\sigma = \sqrt{\frac{2\lambda t}{\rho c_p}}$$

where λ = heat conductivity, t = time increment, ρ = density and c_p = specific heat.

At insulated boundaries the heat particles are reflected like light and if the boundary is cooled the particles change sign upon reflection.

For each proton pulse which is dumped, heat particles are introduced at the moment of the dumping with a spatial distribution resulting from the program DEPO and all are tracked up to the time at which the temperature field must be known. Compared to a finite element program, this method is much more flexible but it has the disadvantage of taking more computer time.

5. The Thermal Stresses

Like the temperature, the thermal stresses can be subdivided in static stresses caused by the steady state temperature field and those caused by the nearly adiabatic temperature rise due to the absorption of one proton pulse. The dynamic part of the latter (thermal shock) is expected to be relatively small[5] and the precise calculation of these being rather cumbersome, their effect has been taken into account in the final calculations by imposing a multiplication factor on the intantaneous stresses.

The hot spot in the cross-section of the dump core is situated relatively close to the lower flat boundary of the aperture and relatively far from the circumference. It is therefore convenient for the calculations to replace the cross-section of the dump core by a half-space (semi-infinite body). There exist analytical formulas for the stresses in a half-space caused by the thermal expansion of a hot cylindrical inclusion which is perfectly bonded to the half-space and of the same material[7].

A computer program (LOADS) has been written which makes use of these formulas. The program fills that part of the half-space which corresponds to the cross-section of the dump core with a large quantity of cylindrical inclusions of 1 mm in diameter, perfectly bonded to the half-plane, and attributes to each a constant temperature corresponding to the local temperature. The stress in any point of the half-space can then be calculated by adding the contributions of each of the hot inclusions. The periphery of the core however should be stress free. To simulate this, an offset is given to the temperature field such that the average temperature of the cross-section of the core becomes zero. As a result, somewhat outside this cross-section the stresses in the half-space become pratically zero, as desired. The advantage of this method compared to finite element programs is again the flexibility of programming and the high spatial resolution ; a disadvantage is the long computing time.

As mentioned before, it appeared necessary to subdivide the core into thin plates in order to eliminate the longitudinal stresses and to approach the plane stress condition. The program PLATE has been written for the calculation of the thermal stresses in a plate of finite thickness and is used to calculate at which plate thickness the longitudinal stresses will be eliminated. If a plate perpendicular to the beam axis is cut out of the block, then the stresses in the plate can be found by superimposing on the original plane strain stresses the effect of a surface load which cancels the longitudinal stresses on the surface of the plate.

There exist approximate formulas for the stresses in a thick circular plate loaded by a distributed surface load on a small circle in the centre[8]. These formulas are used in the computer program PLATE in such a way that the two plate surfaces are covered with small circles to which is attributed the local longitudinal stress taken from the plane strain solution but with opposite sign. The stress inside the plate in an arbitrary point is then found by summation of the contributions of each of these local surface loads and adding this to the already known plane strain stresses. An example showing the influence of the plate thickness on the maximum stress is given in Fig. 3 below. The plotted values have been taken from the calculation of the aluminium core (Fig. 4).

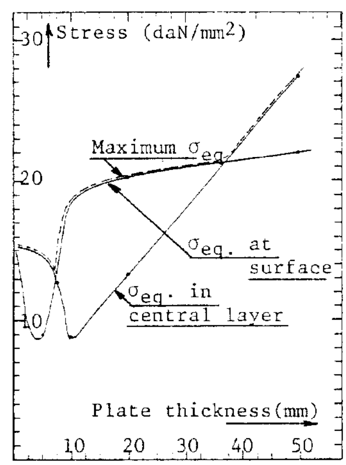

Fig. 3

The maximum equivalent stress as a function of the plate thickness (values taken from Fig. 4)

It appears that at certain, relatively small thicknesses the maximum equivalent stresses can be even less than those of the plane stress solution. The reason is that in the central plane of the plate, the equivalent stress shows a minimum at that plate thickness where the longitudinal stress approaches the value of the lateral stresses. In a similar way, in the surface layer of the plate, the equivalent stress has a minimum at the plate thickness where the lateral stresses, negative in the plane stress condition, pass through zero to become positive for still thicker plates.

6. Calculation results for the aluminium core

The material constants and the beam properties used in the calculation are given below.

Material constants :

$E = 7000\ daN/mm^2$
$\nu = 0.34$
$\rho = 2.7\ g/cm^3$
$\alpha = 23\ 10^{-6}/^oC$
$c_p = 0.22\ \frac{cal}{g^oC}$
$\lambda = 0.36\ \frac{cal}{cm\ sec^oC}$

Beam :

Cross-section = 8.2 mm^2
Intensity = 5 10^{13} ppp
Energy = 450 GeV
Machine cycle = 10 seconds

The number of kick oscillations is not sufficient to spread the energy homogeneously and the highest temperature is found at the location where the amplitude of the last kick oscillation reaches its minimum. The calculated stresses in this hottest point have been plotted in Fig. 4 together with the material strength as a function of the proton intensity respectively the temperature.

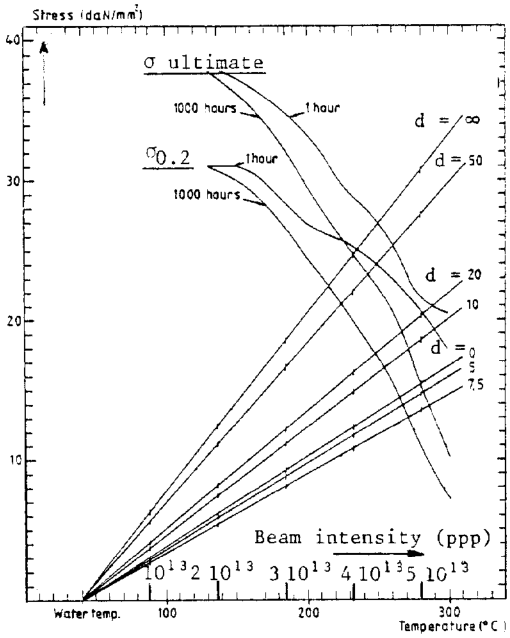

Fig. 4

The calculated stresses (for various plate thicknesses d) and the strength (for various soaking times) for the upstream aluminium alloy A2219 as a function of the beam intensity and the corresponding maximum temperature.

In these calculations, the thermal shock was estimated to be 25% of the instantaneous stresses. It results from the figure that a full block ($d = \infty$) would be stressed far beyond the yield limit for intensities of 5 10^{13}ppp.

A plate thickness of 7.5 mm would be the most favourable. For the finally selected plate thickness of 22.5 mm however, the initial yield stress limit will be reached at beam intensities of 5 10^{13}ppp but after a longer period of dumping, the corresponding intensity, will drop to 4.2 10^{13}ppp due to the decrease of material strength.

7. The calculation results for the copper core

The radial distribution of the energy deposition in the hottest cross-section of the downstream copper block close to its front face can be described by the empirical relations :

$$p = 127.8 \times e^{-0.626r}\ \frac{cal}{cm^3.pulse} \quad \text{for } r < 4\ cm$$

$$p = 375.5 \times e^{-1.79\sqrt{r}}\ \frac{cal}{cm^3.pulse} \quad \text{for } r \geq 4\ cm$$

The material constants used in the calculations are $E = 12'750\ daN/mm^2$, $\nu = 0.32$, $\rho = 8.94\ g/cm^3$, $c_p = 0.093\ \frac{cal}{g^oC}$, $\lambda = 0.76\ \frac{cal}{cm\ sec^oC}$, $\alpha = 16.5\ 10^{-6}/^oC$.

The highest temperatures and stresses are found in the centre of the dumping area. The stresses have been plotted in Fig. 5. The dynamic shock stresses were estimated to be 33% of the instantaneous stresses.

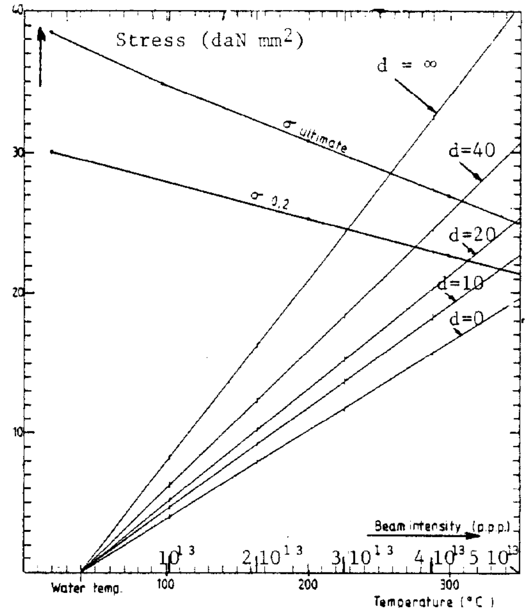

Fig. 5

The calculated stresses (for various plate thicknesses d) and the strength of the downstream copper part (CuCrZr) as a function of the beam intensity and the corresponding maximum temperature.

The plain strain stresses are about 76% higher than the yield limit and therefore also the copper had to be cut into plates over a length of at least 300 mm. With the selected plate thickness of 18 mm the yield limit will be reached at about 4.5 10^{13}ppp. At 5 10^{13}ppp the material will be over-stressed by about 15% and approach the ultimate stress.

8. Conclusion

The calculations show that the aluminium will stand repetitive beam dumping at 5 10^{13}ppp during a limited time whereas the copper will be overstressed beyond the dumping of 4.5 10^{13}ppp. However it is expected that the plastic deformations due to overstressing will, after some pulses, create a field of opposite internal self-stresses, such that these self-stresses will counteract the overload. This "shake down" effect[4] will probably allow for some additional safety when beams of 5 10^{13}ppp would have to be dumped.

9. Acknowledgements

The authors would like to thank W.C. Middelkoop for his continuous interest and support of this work.

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