DESIGN OF A BEAM DUMP FOR 3 TO 100 MeV FOR THE NEW H- BEAM IN THE CERN LINAC4

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Abstract

In this paper the design of a beam dump for the energy range from 3 to 100 MeV is reported.

The dump is developed as temporary dump for the commissioning phase of the Linac4 Project, under construction at CERN, and will be installed in different periods to withstand a beam of different intensities and energies, following the chronological assembly of the linac. The dump design and its functionalities, as well as material choice, criticalities and cooling system are described. Finally, the results from the numerical and analytical thermo-mechanical analyses are reported, while the use of the dump also at 160 MeV is investigated.

INTRODUCTION

The new 160 MeV H- normal conducting Linac4 will be installed and commissioned at CERN during the 2013/14 Long Shutdown, to substitute the 50 MeV Linac2 as injector to the Proton Synchrotron Booster (PSB) [1].

In this paper the design procedure for a beam dump which will operate for the first four commissioning stages is described and the conceptual design is proposed. The dump will temporarily end the linac optics withstanding a wide range of beam parameters, between 3 and 100MeV, for a limited period of time (Table 1),

Figures of merit (FOM_x) are individuated for the choice of materials and design constraints like overall size limitation, integration within the beam line, mechanical stability, vacuum tightness and quality, energy density and power evacuation, cooling system requirements, and radioprotection are taken into account.

Finally, the Linac4 main dump is planned to be used for the last commissioning stage at 160MeV, but the partial use of the commissioning dump is not excluded and is hence investigated.

DESIGN CONSIDERATIONS

Transient Conditions and Energy Density

At first approximation, at very low energy E_0 particles interacting with matter lose energy mainly by ionization, and the mean energy loss per unit length, the stopping power $-dE/dz$, follows the Bragg curve. This loss increases with decreasing residual particle energy E, and is described by the Bethe-Bloch formula for moderately relativistic charged particles [2]:

$$-\frac{dE}{dz} \propto \frac{Z\rho}{EA} \tag{1}$$

where Z and A are respectively the atomic number and the atomic mass of the intercepting material of density ρ.

Observing that $-dE/dz$ is higher at lower energies, the particle range $R(E_0)$ is consequently shorter, so that the beam energy is deposited over a smaller volume for lower energy beams:

$$R(E_0) = \int_0^{E_0} \left(-\frac{dE}{dz}\right)^{-1} dE \propto \frac{AE_0^2}{Z\rho} \tag{2}$$

This fact makes the 3MeV loading case one of the most severe in terms of energy deposition per unit volume ($q = dE/dV$), as it can be seen in Table 1, where its maximum value q^* in the Bragg Peak spot and also $R(E_0)$ are reported for the case of 1.7g/cm^3-dense graphite core [3].

Table 1: Commissioning Parameters

Parameter	Units	Load case			
Energy E_0	MeV	3	12	50	100
Use (months-h/day)		1-12	1-12	2-12	1-12
Beam size $2\pi\sigma_X\sigma_Y$	πmm^2	40.5	40.5	6.26	7.22
Average. current $\bar{I}$	mA	6.5		16	
Avg beam power $\overline{W}$	W	19.5	78	800	1600
Pulse length τ	µs	100		400	
Pulse rate $1/T$	Hz	1			
Peak current	mA	65		40	
Orthogonal peak energy density $q^*_\perp$	J/ cm^3/ pulse	4510	750	8875	3250
5.5°-tilt peak energy density $q^*_{5.5}$	J/ cm^3/ pulse	677.2	108.7	2780	1188
H- Range $R(E_0)$	mm	0.1	1.12	14.6	50.8
Integrated number of H-	E+20	0.53	0.53	1.29	2.59

Considering a simplified adiabatic non-diffusive model of the dump core, which is a good and conservative approximation during the short duration of a beam pulse, the maximum temperature rise $\Delta T^*_{A\,ND} = T^* - T_i$ due to this peak energy density is given by the energy balance

$$q^* = \Delta u = \int_{T_i}^{T^*} \rho(T)c(T)dT \tag{3}$$

where Δu represents the increase of specific internal energy in the peak spot, T_i its initial temperature, T^* the maximum temperature reached in that spot during the pulse and $c(T)$ is the specific heat capacity. It is then

$$\Delta T^*_{A\,ND} \propto \frac{Z}{A E \bar{c}} \tag{4}$$

where the average specific heat capacity has been introduced. For a given set of beam parameters, $\Delta T^*_{A\,ND}$ depends only on the core material, for which T^* has to be lower than its critical working temperature T_C:

$$FOM_1 = \frac{T^*}{T_C} \leq 1 \quad (5)$$

Moreover, since the maximum quasi-static compressive thermal stress is proportional to $E_C \alpha \Delta T^*_{A\,ND}$, where E_C, α and R_C are respectively the compressive Young modulus, the coefficient of thermal expansion and the ultimate compressive strength, the figure of merit for the choice of the core material to be minimized is given by:

$$FOM_2 = \frac{Z}{A} \cdot \frac{E_C \alpha}{\bar{c} R_C} \quad (6)$$

Equation (6) has been used to compare different materials: low-density, low-Z and high-specific heat capacity materials are necessary to reduce the peak working temperature of the dump core, while low-thermal expansion, and relatively highly elastic, high-strength materials are favoured to help reducing any risk of thermo-mechanical and long-term fatigue damage.

Finally, for all the promising materials individuated with (6), equations (3) and (5) have been used to exclude some of them. From these equations it can also be understood that there is no material able to withstand the peak value of the orthogonal energy density $q^*_\perp$ at 3MeV.

As a matter of fact, even for low-density, low-Z intercepting materials, the particle range at 3MeV is so short that the power deposition during one pulse can be described as a superficial heat flux H

$$\dot{q} = \frac{q}{\tau} = \frac{1}{\tau}\frac{dE}{dV} = \frac{1}{\tau}\frac{dE}{dS} \cdot \frac{1}{dz} = H\frac{1}{dz} \quad (7)$$

where dE is the energy deposited over the volume dV, dz is the depth extension of the Bragg Peak and S is the normalized area of the beam imprint over the dump entrance surface, equal to $2\pi\sigma_X\sigma_Y$ for a Gaussian beam of transversal sizes σ_X and σ_Y. Hence H, and consequently q, is reduced at low energies by increasing S, for example by tilting the dump entrance surface with an angle γ such that

$$S' = 2\pi\sigma_X\sigma'_Y = 2\pi\sigma_X \frac{\sigma_Y}{\sin(\gamma)} \quad (8)$$

Furthermore, in the case where this superficial effect hold, the adiabatic but diffusive temperature increase due to this heat flux has a simple and closed form [4]:

$$\Delta T^*_{AD} = 2H^*\sqrt{\frac{\tau}{\pi k \bar{c} \rho}} \quad (9)$$

where k is the thermal conductivity. From (9) it can be verified that diffusivity plays a big role in case of low energy beams, leading to much lower temperatures than those given by the non-diffusive model.

This preliminary analysis, combined to considerations about material availability as well as to the need of reducing the core activation and the dose to the personnel, led to Graphite as the only possible choice for the dump core material. The choice of a tilt angle $\gamma = 5.5°$ requires then a minimum graphite thickness of 10mm, to guarantee together the total adsorption of the primary beam and the core mechanical stability.

On the other hand, graphite usually shows a drastic variation of its mechanical and physical properties under high proton fluxes [5], which may be the case if the maximum beam parameters are assumed for the whole commissioning. This leads to ~5E+20 integrated number of H- ions and imposes the need of at least one spare core.

Vacuum degradation, due to carbon degassing starting from the bake-out temperature, is avoided by using a vacuum pump at the entrance of the dump, while fire risk is excluded thanks to the low superficial temperatures of the core in all loading cases.

Steady State Conditions and Cooling System

For a beam-intercepting device working in continuous mode (Table 1), the average deposited power

$$\overline{W} = \frac{1}{T}\int_V q \quad (10)$$

also represents an important design parameter, since it is the basis for the dimensioning of the dump cooling. On top of this, the coolant is constrained on its temperature increase, pressure drop, volumetric flow and speed, and finally potential radiation issues to it have to be assessed.

As a matter of fact, all the actively-cooled components installed in the Linac4 are made of copper alloy and will share the same water-cooling system, dump included. To avoid corrosion of the most sensible ones, the choice of the material for the commissioning dump cooling system is then restricted to copper alloy.

It is then critical to guarantee a good contact between the graphite core and the copper base, where the cooling pipes are integrated. This is usually done by shrinking the core into a Cu or Al jacket [6], but the tilted entrance surface of the core, together with overall size limitations does not allow us such a simple approach.

Other solutions like mechanical joints, copper-graphite brazing [7] or the use of thermal glues [8] have been analyzed and compared, but none of them guarantees the fulfilment of all the requirements, mainly due to the maximum temperature, stress, and strain levels reached.

The chosen solution is schematically shown in Fig.1: it foresees a soft aluminium ring that exerts a longitudinal pressure on the graphite core, thanks to the clamping of the connection flanges (a). When an oblique cylinder-like base-core interface is chosen, this longitudinal pressure is translated into a radial one, thanks to the presence of the stainless steel vacuum chamber externally to the base-core assembly. A longitudinal pressure of ~5MPa (white arrow) produces a mean interface pressure ~0.75MPa over a sufficiently extended area, which guarantees the necessary thermal contact.

Finally, four identical 9mm diameter cooling pipes are drilled from the back flange of the copper base, parallel to and at constant distance from the base-core interface. These ducts are then coupled in pairs by drilling two transversal holes, and made leak-tight by brazing a copper tap. This water circuit operates at 22°C and 11.5.l/min extracting an average power of 1.6kW.

Use of the Dump at 160MeV

Using the commissioning dump also for the last stage at 160MeV would require a core thickness of at least 20mm, to avoid depositing energy on the copper base, while the total power deposited, of the order of ~3kW requires the same cooling system to be used with almost the double of the mass flow and water speed (3m/s). This increases the pressure drop, the risk of leaks and of damage of the base, but it is not a priori preclusive for few weeks of operation.

ANALYSIS RESULTS

The thermal behaviour of the beam dump has been numerically modelled and analyzed, allowing the validation of the preliminary design choices.

The dump model has been firstly implemented in the Monte Carlo code FLUKA [9] from which the 3D energy deposition maps for all loading cases are obtained. Secondly, the thermo-structural behaviour is studied by converting these maps into internal heat generation or heat flux, and applying it respectively in transient and steady thermo-structural FE models developed in ANSYS [10]. In these models the diffusivity is intrinsically taken into account, while the interface thermal contact, water cooling and thermal radiation have been implemented, as well as temperature-dependant material properties.

Table 2 summarizes some results. Peak temperatures during one single pulse are calculated, as from (3) but also from diffusive analytical and numerical models. The consequent maximum quasi-static compressive stresses σ^*_C in the core are then evaluated, based on the equivalent Stassi-d'Alia criteria [11]. From these values, the core fatigue lifetime can be finally estimated.

The steady state maximum temperatures in the two components are also numerically calculated, which are indicative of the steady behaviour, and the equivalent stresses under steady conditions are estimated.

Table 2: Results summary

	Parameter	Units	Load case			
	Energy E_0	MeV	3	12	50	100
1 pulse (τ)	$\Delta T^*_{A\,ND}$ (analytical)	K	331	52.4	953	507
	$\Delta T^*_{A\,D}$ (analytical)	K	201	33.3	945	500
	ΔT^* (FE model)	K	183	-	834	501
	Max eq. Stassi σ^*_C	MPa	17.2	-	54.5	26.4
Steady (T)	Max T Graphite	°C	63.3	-	201	147
	Max T Copper	°C	47.2	-	40.5	85.5
	Max eq. Stassi σ^*_C	MPa	~5	-	~13	9.4

CONCLUSIONS

In this paper the design of the beam dump for the intermediate commissioning of the new CERN Linac4 has been presented and the design procedure detailed. The dump is made of a copper-graphite assembly within a vacuum tank, and is designed to operate with H- or p+ beams between 3 and 100MeV, with energy density up to 2790 J/cm^3/pulse and average power up to 1.6kW.

The proposed solution addresses several constraints and meets specified requirements and functionalities. Finally, the results from numerical and analytical thermo-mechanical analyses have been reported, while the use of the dump also at 160 MeV has been investigated.

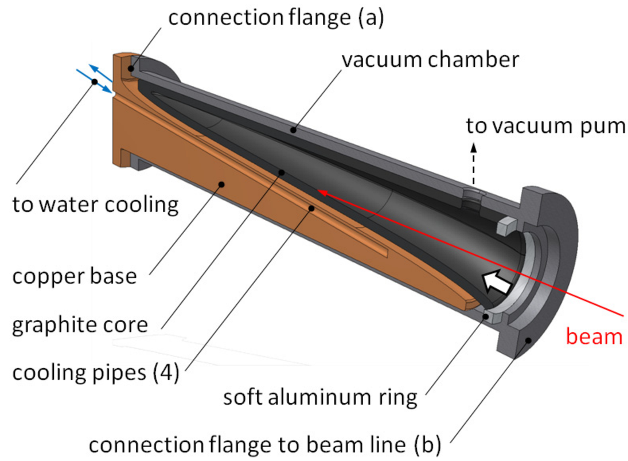

Figure 1: Cut view of the dump assembly

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