CONCEPTUAL DESIGN OF THE LINAC4 MAIN DUMP

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Abstract

Linac4 is the new CERN linear accelerator intended to replace the ageing Linac2 as the injector to the Proton Synchrotron Booster (PSB) for increasing the luminosity of the Large Hadron Collider (LHC). By delivering a 160MeV H^- beam, Linac4 will provide the necessary conditions to double the brightness and intensity of the beam extracted from the PSB. This paper describes the conceptual design of the Linac4 Main Dump, where two different concepts relying respectively on water and air cooling were compared and evaluated. Based on the application of analytical models for the energy deposited by the beam, heat conduction and cooling concepts, a parametric study was performed. This approach allowed the identification of the "optimal" configuration for these two conceptual geometries and their relative comparison. Besides giving the theoretical guidelines for the design of the new dump, this work also contributes to the development of analytical tools to allow a better understanding of the influence of the several design parameters in this type of low-energy beam intercepting devices.

INTRODUCTION

The design of a beam dump can have a big impact on the operability of an accelerator complex. The aim of the design is to ensure a safe absorption and dissipation of the beam energy under all possible loading cases, for a lifetime of at least 20 years with minor maintenance. This requires an interdisciplinary approach and specific analyses, like particle interaction with matter, to determine the distribution of energy deposition by the beam, heat transfer analysis (transient and steady state) to calculate the temperature distribution as function of time and to determine the efficiency of the cooling system. Based on these analyses, stress (quasi-static and dynamic) as well as fatigue life are evaluated for mechanical engineering considerations, while other particles cascade simulations are performed to assess and solve any possible ionizing radiation issue [1]. The design of the Linac4 main dump was separated in two phases, the conceptual design and detailed design as presented in Figure 1. Usually, the conceptual design is fully accomplished with numerical tools but this process is computational and time demanding, since several design options and variables have to be considered in order to converge to the optimum solution. In this study, an analytical approach was preferred for the first phase, and a set of tools was developed. For the second phase, the validation and optimization of the conceptual design using more advanced numerical techniques was performed. This paper focuses on the conceptual design phase of the LINAC4 main dump.

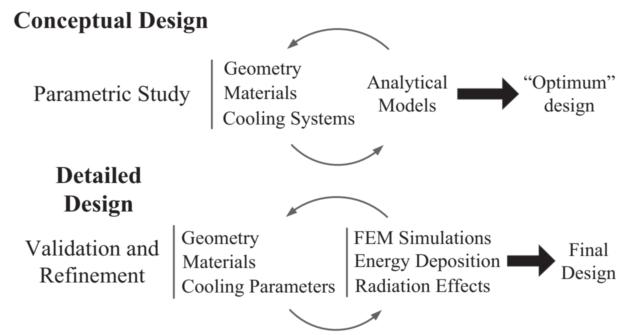

Figure 1: Diagram of the design phases for the Linac4 Main Dump.

GEOMETRY & COOLING

Two geometry concepts were considered, one composed by a Cylindrical Core (CC), typical design found in beam dumps developed at CERN and the other composed by Circular Plates (CP) as presented in Figure 2 a) and b), respectively.

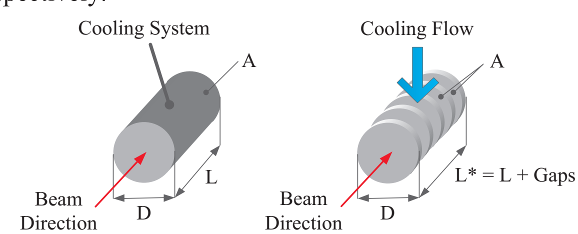

Figure 2: Geometries studied: a) Cylindrical Core (CC) and b) Circular Plates (CP).

From a qualitative analysis it is possible to conclude that the CP geometry could be significantly better in terms of heat dissipation throughout the core. Assuming the same main dimensions, diameter D and effective length L and working conditions, this geometry has a greater area A to transfer heat to the cooling system and therefore it will reach a lower temperature in comparison with the CC Geometry. However, in the CP geometry the beam crosses the plates and this would increase the complexity of the finally engineered solution in case of cooling by water. Consequently, the cooling should be accomplished with air or an inert gas and the typical convection coefficient would be two orders of magnitude lower. This makes the CP geometry less efficient when considering its practical ability to transfer the deposited power to the cooling circuit. For the CC geometry, the water cooling system is placed around the core. Typical convection coefficients of 5000W/m²·°C (water cooling) and 30 W/m²·°C (air cooling) were used in the two models. The length of each plate in the CP geometry was assumed to be 5 mm.

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BEAM CHARACTERISTICS

The beam characteristics for the Linac4 Main Dump are presented in Table 1. At this early stage it is possible to define the diameter of the dump core as 4 RMS of the maximum beam dimension (99.99% of the particles being contained within the core). An uncertainty of 20% in both beam dimension and position was also considered. On top of these, a safety factor of 2 was added, resulting in a diameter of 200 mm.

Table 1: Beam Parameters

Parameter	Units	Value
Energy	MeV	160
Average current	mA	40
Pulse length	μs	400
Pulse rate	Hz	1.1
Minimum beam size (RMS)	mm x mm	3 x 6
Maximum beam size (RMS)	mm x mm	6 x 8

MATERIALS

The conceptual design phase includes the identification of the type of material which is most suitable for each geometry. Table 2 presents the materials considered, where each material aims to represent a class of materials. Also, since this design phase does not foresee structural analysis it was necessary to define a critical limit of application of every material, which is represented by the maximum service temperature (above which the strength of the material decreases rapidly) [2]. The length of the core for the CC geometry is defined on the base of the projected range of the particles, which represents the minimum length to stop all incoming particles. On the other hand, since the CP geometry is made of plates and the cooling fluid flows between the plates, only the plate where the peak of energy deposition occurs will be considered.

ENERGY DEPOSITION MODEL

Figure 3 presents the results of the estimated energy deposition for different materials along the axial direction.

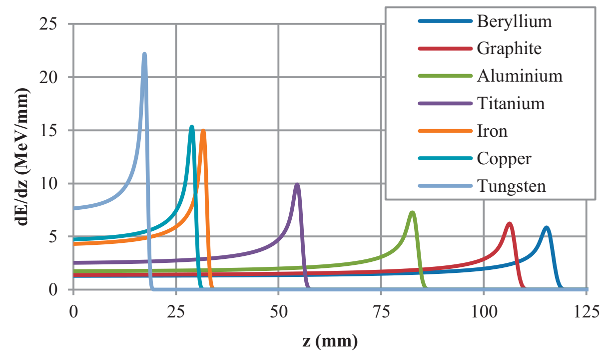

Figure 3: Energy deposition for the different materials along the axial direction.

To obtain a quick estimate of the deposed energy, an analytical model was developed based on the results of a pencil beam model [3]. This model gives a good approximation for proton energies between about 10 and 200 MeV [3]. The model is based on a polynomial relationship between the range and the initial energy of the beam and also accounts for the linear fluence reduction due to nonelastic nuclear interactions. It was also assumed a local deposition of a fraction of the released energy and a Gaussian approximation of the range strangling distribution [3].

HEAT TRANSFER MODEL

The heat transfer model is based on the analytical solution of the heat conduction equation [4], as presented in equation 1.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T(r,z,t)}{\partial r}\right)+\frac{\partial^2 T(r,z,t)}{\partial z^2}=\frac{1}{\alpha}\frac{\partial T(r,z,t)}{\partial t} \quad (1)$$

Table 2: Materials Considered for the Conceptual Design (Room Temperature Properties)

Parameter	Units	Beryllium	Graphite	Aluminium	Titanium	Iron	Copper	Tungsten
Atomic Number	--	4	6	13	22	26	29	74
Specific Heat (C_p)	J/Kg· °C	1793.9	699.5	893.5	521.1	445.7	383.0	132.2
Thermal Conductivity (k)	W/m·°C	315.1	118.1	236.1	21.3	80.5	401.0	174.5
Density (ρ)	Kg/m³	1850	1830	2700	4500	7870	8940	19300
Maximum Service Temperature	°C	620	2350	150	450	650	200	660
Projected Range	mm	116.8	107.7	83.9	55.6	32.4	29.6	18.0

where T is the temperature, α is the thermal diffusivity, t is the time and r and z are the radial and axial coordinates, respectively. In the case of the CC geometry the boundary conditions used in equation (1) represent water cooling in the outside surface and no heat transfer in the front and rear walls. For the CP geometry, the boundary conditions represent air cooling in all the surfaces. The initial temperature for the beginning of each pulse is given by equation 2.

$$T_i = \Delta T_{en}(r,z) + T_{Last\ pulse} + T_0 \qquad (2)$$

where T_0 is the temperature of the medium at t=0, $T_{Last\ pulse}$ is the temperature distribution at the end of last pulse and $\Delta T_{en}(r,z)$ is the distribution of adiabatic temperature increase due to energy deposition and is given by equation 3.

$$d(r,z) = \int_0^{\Delta T_{en}(r,z)} \rho\, C_p(T) dT \qquad (3)$$

The profile of the beam was assumed Gaussian and given by $f(r) = exp(-br^2)$ where b is a constant that defines the width of the Gaussian distribution. Figure 4 presents the peak temperature in the material along the axial direction after one pulse.

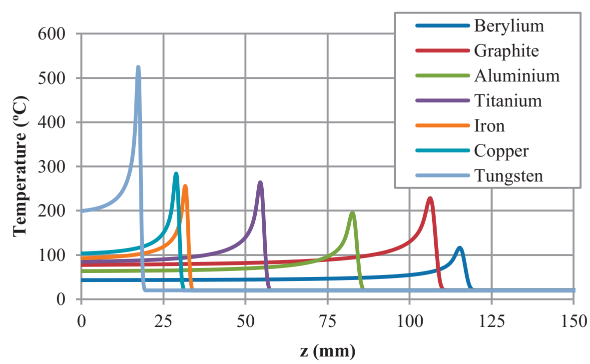

Figure 4: Peak temperature along the axial direction for each material after the first pulse.

RESULTS

Table 3 summarizes the results of peak temperature in steady state for the CC and CP geometry. It is possible to see that with respect to the CC geometry the best material choice for the core is graphite or beryllium, but due to the toxicity of beryllium and to the increased safety factor of graphite in relation to beryllium core (2x), graphite is preferred. With respect to the CP geometry, the best choice is also graphite or beryllium, but since graphite burns in air at moderately high temperature (~450°C), this design choice would require an inert gas cooling system in closed loop, which would heavily affect the complexity of the final design. Hence, the material choice for the CP design is beryllium. Finally, when comparing the two geometries, the choice is oriented to the CC geometry because the core material is not toxic and due to the lower peak temperature reached. Figure 5 presents the evolution in time of the peak temperature for a CC design made of graphite and CP design made of beryllium.

Table 3: Peak temperatures in steady state and safety factors

	Geometry CC		Geometry CP	
Material	Peak Steady Temperature	Safety Factor	Peak Steady Temperature	Safety Factor
Beryllium	215	2.9	295	2.1
Graphite	360	6.5	408	5.8
Aluminium	303	0.5	415	0.4
Titanium	1921	0.2	1674	0.3
Iron	937	0.7	1023	0.6
Copper	400	0.5	697	0.3
Tungsten	999	0.7	1292	0.5

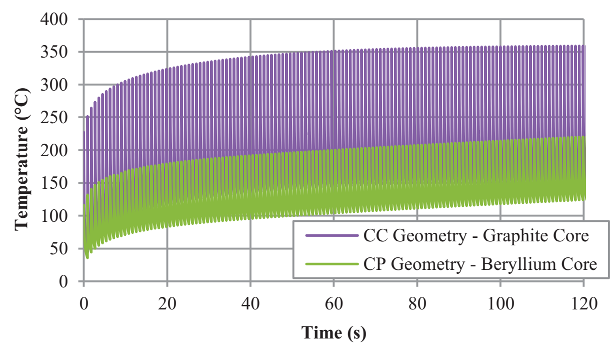

Figure 5: Peak temperature evolution in the CC geometry with graphite core and in the CP geometry with beryllium core.

CONCLUSIONS

In this paper the most suitable type of geometry, cooling configuration and material for the Linac4 main dump have been identified. Results show that the Cylindrical Core (CC) geometry with water cooling and a core made of graphite represent the best solution of the ones that have been analysed.

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