INTERNAL H^0/H^- DUMP FOR THE PROTON SYNCHROTRON BOOSTER INJECTION AT CERN

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Abstract

In the frame of the LHC Injectors Upgrade Project at CERN (LIU), the new 160MeV H^- Linac4 will inject into the four existing PS Booster rings after the conversion of H^- into H^+ in a stripping foil. Given a limited stripping efficiency and possible foil failures, a certain percentage of the beam is foreseen to remain partially (H^0) or completely (H^-) unstripped. An internal dump installed into the chicane magnet to stop these unstripped beams is therefore required.

This paper presents the conceptual design of the internal dump, reviewing loading assumptions, design constraints, limitations and integration studies. Power evacuation through the thermal contact between the core and the external active cooling is addressed and, finally, results from the numerical thermo-mechanical analyses are reported.

INTRODUCTION

The 160 MeV H^- pulsed beam from Linac4 will be distributed to the 4 superimposed synchrotron rings of the PS Booster (PSB) after being converted into H^+ beam thanks to a stripping foil.

Four internal dumps, one per ring, will be installed downstream of the stripping foil to intercept the unstripped H^0/H^- and any H^- which is missing the foil [1].

In normal working condition, the stripping efficiency is assumed to be 98% (Case1), while if the foil is degraded a stripping efficiency of 90% can be tolerated for a limited period of 8 hours (Case2). Finally, the accident scenario of sudden failure of the foil is considered, for which 100% of the H^- beam would impact the dump until the interlock system intervenes (within 0.5s [2]) so that only one full pulse can hit the dump (Case3).

Table 1 reports the beam parameters for each loading case.

Table 1: Beam Parameters

Parameter	Units	Case1	Case2	Case3
Stripping efficiency	%	98	90	0
Energy	MeV		160	
Power $\bar{P}$	W	14	71	710
Pulse Current I	mA	0.8	4	40
Pulse length	μs		100	
Pulse Frequency	Hz		1.11	
Pulse intensity	-	$5\cdot10^{11}$	$2.5\cdot10^{12}$	$2.5\cdot10^{13}$

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Due to limited space, these internal dumps need to be integrated inside the ceramic vacuum chambers of the BSW4 magnets. Furthermore, they must be equipped with instrumentation to monitor the injection efficiency and so, diagnose foil degradation and eventual failure.

Finally, the circulating H^+ beam must not be disturbed by the dump itself [1].

DESIGN

All the requirements specified above have to be considered and weighted carefully from the earliest possible stage of the study, since they induce constraints for all design choices.

Space Constraints

The presence of the dump and the circulating H^+ beam within the same vacuum chamber leaves very limited space to intercept and stop the unstripped particles, complicating the support and possible cooling of the dump core itself. Indeed, the dump can be supported only on its rear face from the flange of the vacuum chamber (Fig. 1), where also an eventual cooling system has to be integrated.

Here, no space is available for a clamping system so that the brazing technique is the only possible choice for the attachment of the dump. As consequence, the material of the dump core must allow this joining technique.

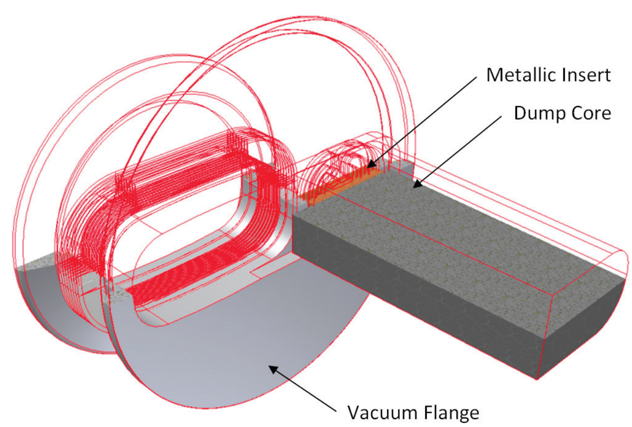

Figure 1: Assembly of the dump and its support.

Since the core cannot be directly brazed to the flange, due to thermal restrictions on the latter, a metallic insert has to be brazed to the dump core firstly and subsequently welded to the flange.

Cooling Consideration

If an active cooling is needed, it has to be located into the metallic insert previously specified, complicating the design of the support.

To avoid this complexity in this preliminary phase, the dump has been studied considering only passive cooling due to thermal radiation.

In this case, taking into account the total power deposited by the beam *P*, the uniform temperature T_{dump} on the external surface of the core can be estimated with [3]:

$$P(W) = \varepsilon \cdot \sigma \cdot S \cdot (T_{dump}{}^4 - T_{env}{}^4) \quad (1)$$

with σ being the Stefan-Boltzmann constant, ε the emissivity of the material, *S* the total emitting surface of the core and T_{env} the temperature of the environment of the dump, supposed as a large surrounding. This simplified approach is useful for the choice of the material. In a second instance, the exact surface-to-surface heat exchange with the surrounding chamber is considered (see Results at the end of this paper).

To this steady and uniform temperature, the peak temperature rise due to the instantaneous impact of the beam has to be added.

Thermal Consideration

At the considered energy (E =160 MeV) the stopping power $-dE/dx$, as described by the Bethe-Bloch equation, provides a preliminary yet useful estimate of the mean energy loss per unit length of particles interacting with matter [4]:

$$-\frac{dE}{dx} \propto \frac{Z\rho}{A} \quad (2)$$

with Z, A and ρ respectively the atomic number, atomic mass and material density of the intercepting material.

Simplifying and considering conservatively an adiabatic non-diffusive approach, it is possible to evaluate the maximum instantaneous increase of temperature $\Delta T^* = T^* - T_i$ due to the energy deposited by the beam for each pulse [5]:

$$\Delta T^* \propto \frac{Z}{Ac_p} \quad (3)$$

where c_p is the specific heat capacity of the intercepting material and T^* the final peak temperature reached in the core during one pulse. Here, $T_i = T_{dump}$ since the dump is considered initially in its steady state temperature as from (1).

This peak temperature T^* must be lower than the critical working temperature of the material T_c, which leads to the first figure of merit to be minimized for the material selection:

$$FOM_1 = \frac{T^*}{T_c} \leq 1 \quad (4)$$

Structural Consideration

The quasi-static thermal stresses due to the instantaneous increase of temperature ΔT^* are proportional to $\alpha E \Delta T^*$ with α the coefficient of thermal expansion and E the Young Modulus of the material. Using (2), a figure of merit for the structural behaviour of the dump can hence be defined through material properties only:

$$FOM_2 = \frac{Z.\alpha.E}{A.C_p.R_c} \leq 1 \quad (5)$$

where R_C is the Ultimate Compressive Strength of the material. By minimizing (5), the materials with the best mechanical behaviour are identified.

It appears from (5) that low Z or, equivalently, low density materials are preferred to reduce the stress level. On the other hand, particle range in matter is inversely proportional to the material density which cannot hence be too low, due to space considerations.

Vacuum Constraints

Vacuum constraints on the nearby stripping foil require the material of the dump to have a low outgassing rate.

The porosity of the materials has been chosen as preliminary indicator for possible vacuum degradation in operating conditions, and thus has to be minimized (FOM_3). Outgassing tests shall be carried out for the candidate materials.

Electromagnetic Constraints

Due to its location inside the ceramic chamber of the BSW4 magnet, the dump core has to be amagnetic to avoid disturbing the BSW4 dipole field.

Furthermore, very little eddy currents should be induced in the core and thus highly resistive materials are preferred.

However, if the electrical resistivity is too high, the core would accumulate charge from the intercepted particles, with consequent risk of breakdown or, again, electromagnetic disturbance.

Hence, the electrical behaviour of the core becomes a concern for highly resistive, highly capacitive materials, like ceramics.

An approximated approach is here proposed which models the dump core as a parallel RC circuit during the time where the beam hits (charge of the capacitor C) and as a series RC circuit when the beam is not present (discharge).

With this approach, it can be demonstrated that the higher are electrical resistivity and capacity, the higher is the charge of the core and the higher is the time needed to discharge it. It has hence been decided to define the parameter RC as another figure of merit to be minimised (FOM_4).

Induced Activation

At this preliminary stage, the induced activation is considered as approximately proportional to the atomic number of the material Z, to be minimised too (FOM_5). For compounds, the higher atomic number has been considered.

ISBN 978-3-95450-115-1

MATERIAL CHOICE

Seven different ceramics (Oxides, Carbides and Nitrides) have been individuated by minimising the combination of all previously mentioned figures, each of them being appropriately weighted due to their relative importance.

Graphite was also preliminarily studied but finally rejected due to vacuum degradation. Alumina, as well as Aluminum Nitride, does not fulfil the electrical requirements. Boron Carbide appears difficult to be brazed to the insert, while Boron and Silicon Nitrides cannot be brazed at all.

Finally Silicon Carbide (SiC) appears to be the most suitable candidate, and one of the few that can be brazed to a metal-based insert.

ANALYSIS RESULTS

More accurate numerical analyses were then performed to validate the preliminary choices of material and non-active cooling.

The distribution of specific energy deposited by the beam was firstly evaluated thanks to the Monte Carlo code Fluka [6]. This map was then used as input for the thermo-structural analysis performed with the FE code ANSYS®.

Firstly, the numerical analyses were performed for one pulse only, considering a transient thermal model associated to a transient structural one, where the support was approximated by a fixed constraint.

Secondly, the steady state thermal behaviour of the non–actively cooled core was analysed, considering only thermal radiation with the environment first (S/a), and with the surrounding vacuum chamber then (S/S).

The Stassi-d'Alia criterion [7] was used to evaluate the equivalent stresses in tension $\sigma_T{}^*$ and compression $\sigma_C{}^*$ in the core, to be compared respectively to the tensile and compressive strength of the material. Table 2 summarizes the results for a core made of SiC.

Table 2: Results Summary for SiC Core

	Parameter	Units	Case1	Case2	Case3
1 pulse	ΔT^*(A.)	°C	3.6	18.2	177
	ΔT^*(FE)	°C	3.5	17.7	171
	$\sigma_C{}^*$ (FE)	MPa	16.1	80.4	766
	$\sigma_T{}^*$ (FE)	MPa	0.9	4.5	49
Steady	$T_{max\ S/a}$ (A.)	°C	87.1	205.7	-
	$T_{max\ S/a}$ (FE)	°C	86.1	206.6	-
	$T_{max\ S/S}$ (FE)	°C	160	346	-

Silicon Carbide maximum service temperature is reported to be close to 1900 °C, while its tensile and compressive strengths are estimated respectively at 390 MPa and 3900 MPa [8].

For one pulse, temperatures and stresses induced are not an issue, even when considering a full pulse (Case3). The estimated steady state temperature plus the temperature rise due to the pulse for the load cases 1 and 2 largely satisfy equation (3) even when considering the more realistic model of radiation exchange between surfaces (S/S).

However, the temperatures induced on the metallic insert, on the ceramic chamber and on the flange have to be carefully evaluated and could limit the choice of non-active cooling.

Furthermore, the stresses on the insert/core interface and on the insert/flange welding must be considered as well.

Finally, the horizontal thermal expansion have to be evaluated for the steady state working conditions to ensure not disturbing the circulating H^+ beam.

CONCLUSIONS

Due to the several and specific constraints, the use of a ceramic material seems to be the only choice for the internal H0/H- dump, and Silicon Carbide has been identified as the most suitable candidate with respect to all of them.

First results from the numerical simulations with this material are encouraging, even though considering a passive cooling due to thermal radiation only. However, several aspects have still to be considered carefully.

The technology to braze the SiC core to the metal insert has to be evaluated and proved. Several tests have to be performed to validate this technique and to ensure it can withstand the working condition.

Tests have also to be performed to clearly assess material thermal and mechanical properties in function of temperature and radiation exposure, and to detail its degassing behaviour under vacuum.

Furthermore, the analyses reveal that the choice of a passive or active cooling mainly depends on the functional requirements and on the material of the vacuum chamber and of its flange, to which the dump core is connected.

Finally, instrumentations to measure the stripping foil efficiency will probably be installed on the dump entrance face, and its integration must be also taken into account.

ACKNOLEDGEMENTS

The author would like to thanks J. Borburgh and J. Tan for their advices in the material choice.

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