DESIGN OF THE NEW PROTON SYNCHROTRON BOOSTER ABSORBER SCRAPER (PSBAS) IN THE FRAMEWORK OF THE LARGE HADRON COLLIDER INJECTION UPGRADE (LIU) PROJECT

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Abstract

The Large Hadron Collider (LHC) Injector Upgrade (LIU) Project at CERN calls for increasing beam intensity for the LHC accelerator chain. Some machine components will not survive the new beam characteristics and need to be rebuilt for the new challenging scenario. This is particularly true for beam intercepting devices (BIDs) such as dumps, collimators, and absorber/scrapers, which are directly exposed to beam impacts. In this context, this work summarizes conceptual design studies on the new Proton Synchrotron Booster (PSB) Absorber/Scraper (PSBAS), a device aimed at cleaning the beam halo at the very early stage of the PSB acceleration. This paper outlines the steps performed to fulfill the component design requirements. It discusses thermo-mechanical effects as a consequence of the beam-matter collisions, simulated with the FLUKA Monte Carlo code and ANSYS® finite element software; and the impedance minimization study performed to prevent beam instabilities and to reduce RF-heating on the device.

INTRODUCTION

The beam cleaning system (collimation and scraping) is essential for the entire CERN accelerator chain. This system absorbs unstable external beam particles, i.e. beam halos, in controlled areas preventing them from irradiating against sensitive equipment, minimizing the risk of damage [1]. In the framework of the CERN HL-LHC [2] and the LIU [3] projects, the beam intensity will be increased and the current cleaning system needs to be upgraded accordingly. In this context, Cieslak-Kowalska et al. [4] have demonstrated that the present scraping device in the PSB, the windows beam scope, will not be able to scrape the high intensity HL-LHC beams. This paper presents the conceptual design of its upgrade: the PSBAS.

The PSBAS will represent the major aperture restriction of the PSB. It will scrape up to 6% of the total number of protons ($2.95\ 10^{12}$ [5]) for a HL-LHC beam during the very early stages of acceleration (kinetic energy per nucleon up to 200 MeV). It must be able to survive a direct accidental beam impact and its impedance (the electromagnetic resistivity at the beam transit) has to be minimized. Further, in order to correctly scrape halos the PSBAS geometry has to follow the beam transverse envelope shape (i.e. the square root of the beta function) and its longitudinal evolution inside the device itself, [6]. To fulfill the outlined requirements the design shown in Fig. 1 was conceived. The two graphite masks, cylinders with a truncated squared based pyramid holes to follow the beam β function, are the actual beam scraper. They can be positioned in two working configurations (Fig. 1) according to the operational requirements: movable mask out provides a wide aperture for the initial beam commissioning while movable mask in limits the aperture for an optimal beam cleaning during nominal operation.

IMPEDANCE

With the increase in beam intensity foreseen by the HL-LHC [2] device impedance has become a key design parameter. It needs to be minimized for the beam frequency spectrum range in order to avoid beam instabilities or excessive RF-Heating of the component [7, 8]. To achieve this goal we implemented an iterative loop from the initial PSBAS design simulating the device impedance, identifying the problematic geometries and modifying the mechanical drawing accordingly [9]. The final design (Fig. 1) is extremely robust and reliable with regard to impedance. In configuration mask out, the replacement vacuum chamber works as RF-Shielding, preventing the tank, a potential low frequency parasitic cavity, from trapping electromagnetic resonating High Order Modes (HOM). The electrical connections between the fixed mask housing and the out pipe (Fig. 1 Detail 2) shields the empty volume between the bellow and the housing-itself avoiding trapped resonating electromagnetic HOM inside. This connection is made of a ring of stainless steel material with two copper spirals mounted on it, which will be installed inside a circular groove, machined in the fixed mask housing. This will allow an easy assembling of the components guaranteeing the electrical contact at all times. The movable components, the replacement vacuum chamber and the movable mask with its housing, are separated from the fixed components, in pipe and fixed mask housing, by a gap of 2 mm, however, they are electrically connected by means of sliding connections. As shown in Fig. 1, Detail 1 and 3, there are copper wire spirals inserted on grooves realized on the replacement vacuum chamber and on the movable mask housing. They provide a path for the image currents (an electron current that moves in the device wall with the beam) and limit the detrimental effects of the trapped electromagnetic resonant modes in the gaps.

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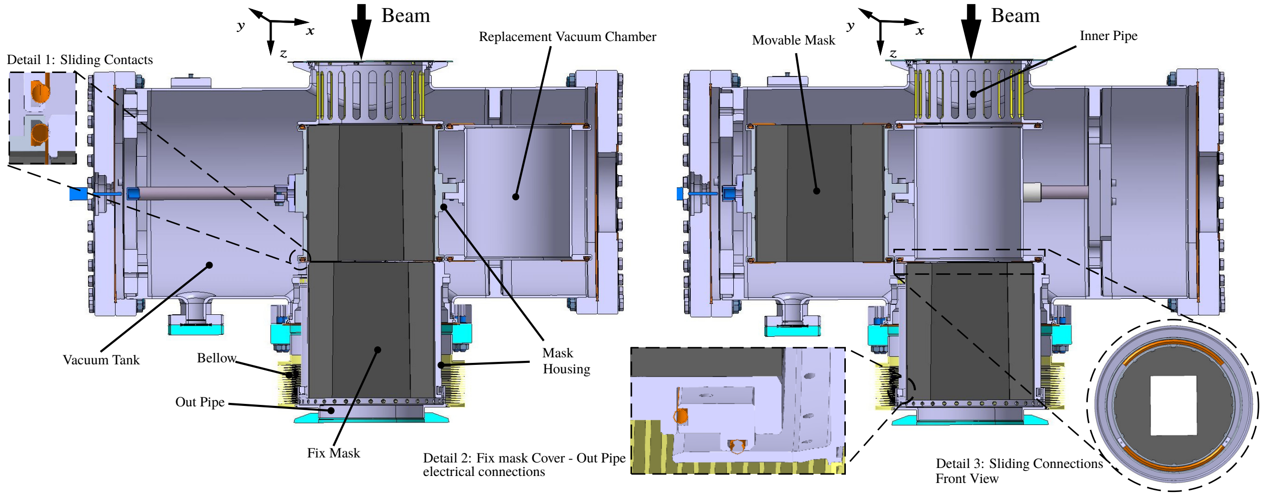

Figure 1: Design of The PSBAS with nomenclature and detail of the electrical connections. The two working configurations are also shown: movable mask in (left) and movable mask out (right).

The real parts of the longitudinal and transverse impedance of the device (critical for heating and beam instabilities [8]) are shown in Fig. 2.

The transverse impedance of the scraper is three order of magnitude smaller than the global transverse impedance of the PSB [10], thus, the device has negligible impact on beam instabilities. Indeed, there is not a relevant effect on the rise time of the head-tale instabilities [8] in the z-x plane, where the PSBAS impedance contribution is maximum. This is shown in Fig. 3, where the rise time of the first two unstable beam modes is plotted for a cromaticity value of -0.8.

Impedance RF-Heating

In order to enhance the reliability of the thermomechanical simulations the RF-heating, a heating flux deposited in the material by the circulating beam through electromagnetic interactions, was taken into account. The 3D map of the dissipated power was obtained following the work of Teofili, Garcia and Migliorati [12] and has been plotted in Fig. 4 for the scenario 1 movable mask in (refer to the next section). The total estimated RF-heating for the device is 0.43 W, only 1.69% of the power deposition due to nuclei matter interaction (refer to the next section).

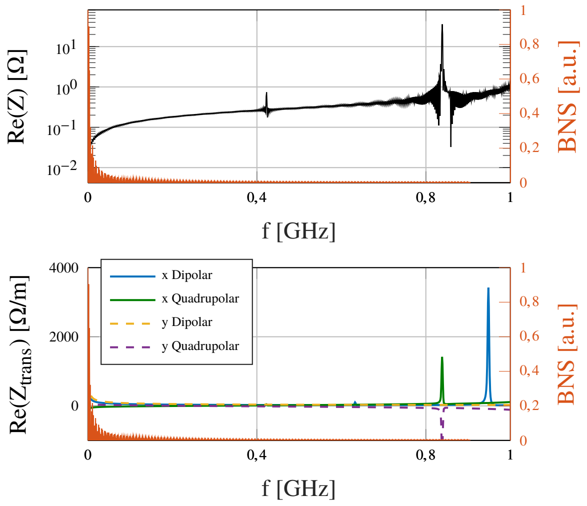

Figure 2: Real parts of the longitudinal (log scale) and the transverse (linear scale) impedance and the PSB beam normlized spectrum (BNS) in linear scale.

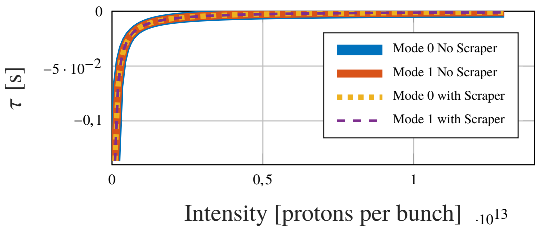

Figure 3: Comparison of the PSB rise time of the first two modes of the head-tales instabilities in the horizontal plane with and without the PSBAS (values are calculated for a horizontal chromaticity of -0.8).

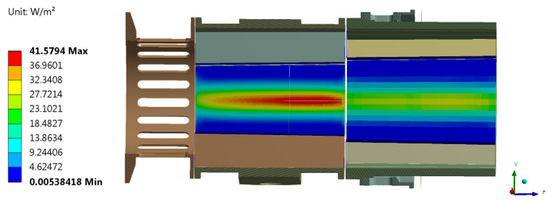

Figure 4: RF-Heat Flux imported in ANSYS$^{®}$ [11].

THERMOMECHANICAL STUDIES

The incidence of the proton beam on the scraper material results in an energy deposition on the scraper as a consequence of beam particles-material interaction. The time duration of the beam impact is very short and very local-

Table 1: Beam Scenarios for the PSBAS design [6]

Scenario		**1**	**2**	**3**
Kinetic energy [MeV]		160	181	2000
Intensity [p/pulse]		$2 \cdot 10^{13}$	$2.8 \cdot 10^{12}$	$2 \cdot 10^{13}$
Pulse time [s]		1.2	1.2	$2.4 \cdot 10^{-7}$
Size [mm]	σ_x	9.08	3.92	4.84
	σ_y	11.15	4.40	4.96

ized. Under these conditions, materials suffer non-uniform and sudden temperature increases that can generate high stress levels. These thermo-mechanical phenomena must be considered in the design of the PSBAS.

According to the LIU project, the beam injection and extraction kinetic energies in the PSB complex are set to 160 MeV and 2 GeV, respectively, [5]. Among the possible beam scenarios in the PSB, three representative cases were identified for the design of the PSBAS (see Table 1). The first two scenarios were assumed to happen routinely, scraping the halo of the beam at low energies. The last scenario is an accidental direct impact at high energy.

Beam-matter interaction was simulated using the FLUKA Monte Carlo code [13, 14]. The two absorber masks, as well as the surrounding components, susceptible to receive primary or secondary particles after the beam-masks interaction, were modelled. Low-density materials were selected for masks and housings (i.e. graphite and Ti_6Al_4V alloy, respectively). This provides a good compromise between thermo-mechanical and residual radiation requirements. Stainless steel 316L was chosen for the rest of the components. Figure 5 shows the energy deposition due to scraping in scenario 1. FLUKA simulations revealed that the incident primary particles are completely stopped in one graphite mask under nominal conditions (scenarios 1 and 2) with scenario 1 being the most energetic (average power deposition per pulse time equal to 25.42 W). In the impact scenario, the beam particles traverse the masks losing around 5.5% of its initial energy. The 3D energy density map obtained from FLUKA and the impedance RF-heating heat flux (Fig. 4) were imported to the software ANSYS®, to analyze the thermo-mechanical behavior of the device. Preliminary simulations under nominal conditions showed temperatures over $80°C$ in the graphite. This could produce out-gassing compromising the vacuum in the PSB. In the vacuum tank a dynamic vacuum pressure of 10^{-8} mbar or below has to be maintained [6], so, the outgassing must be minimized reducing the graphite temperature. Due to this, copper braided connectors between tank and housings were simulated, this reduced the graphite temperature below $63°C$ (see Fig. 6). Moreover, a press-fitting technique is plan to be used between the masks and the housings. This technique ensures a good thermal contact and confers a beneficial pre-compression state to the graphite masks. Further simulations demonstrated the mechanical safety of the design under nominal conditions (see Fig. 7).

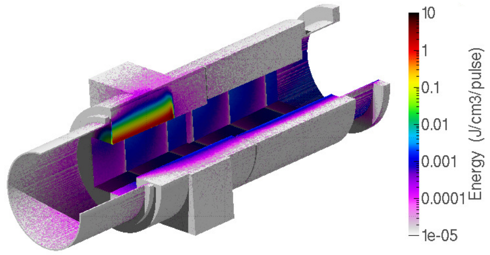

Figure 5: 3D view of the energy deposited for vertical scraping in Scenario 1 obtained from FLUKA simulations.

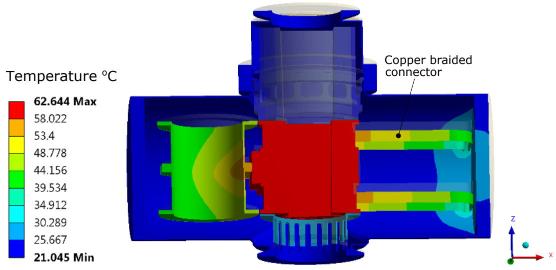

Figure 6: Temperature distribution at the steady state for scenario 1 and config. 1 considering the beam-matter interaction and impedance effect.

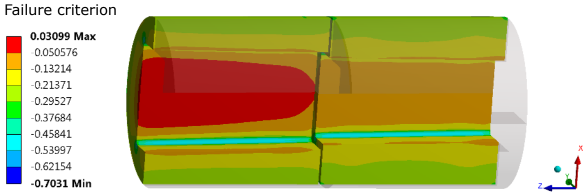

Figure 7: Christensen failure criterion [15] for scenario 1 and config. 1 at the steady state (A value superior or equal to unity implies material failure).

CONCLUSION

In this study, we summarized the main features of the PSBAS conceptual design and we assessed its quality in the HL-LHC framework. By electromagnetic simulations we showed that it has low impedance and negligible effects on beam dynamics. The thermo-mechanical studies demonstrated that the PSBAS is able to withstand the worst case accidental or operational scenario. In the last case, the design was optimized to minimize the graphite temperature and so the induced outgassing, as demanded by the vacuum constraints, [6]. Further, the mechanical stresses induced by the temperature distributions are well below the ultimate strength and the yield limit of the materials, making the design extremely robust and reliable.

Further studies will benchmark the obtained results against real measurements taken on a prototype under construction at CERN.

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