CONCERNS WITH LOW EMITTANCE BEAM OPERATION

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Abstract

New techniques for the production of 25 ns bunch trains in the LHC injector chain have been successfully tested in the last year of the LHC run 1. These new techniques can produce bunches with unprecedented brightness for bunch intensities similar to the nominal scheme, but with significantly reduced emittances. The material damage potential depends however roughly on the ratio of intensity to emittance. The effect of the new beams in case of impact on protection devices and their attenuation therefore has to be carefully evaluated. This talk will summarize the result of material survival simulations for various possible beams after LS1 and LS2 for protection devices and dumps. Possible implications on operation with these beams and limitations of emittance measurement devices will be discussed as well. The talk will also highlight the necessity of beam based material tests in HiRadMat to fully understand material properties under the severe conditions of shock impact from high intensity beams.

INTRODUCTION

The LHC injectors will have to provide beams with unprecedented brightness to meet the performance goals of the High-Luminosity LHC (HL LHC) [1]. New techniques for the production of the 25 ns trains in the injectors have been developed in the recent years involving significantly reducing the transverse emittance. An example is the BCMS beam from the CERN PS [1]. The HL beam parameters from the injectors for the standard production scheme and the BCMS parameters after the LHC Injector Upgrade (LIU) are summarized in Table 1.

Table 1: Number of protons per bunch, normalized transverse emittance and number of bunches per SPS batch for the HL LHC 25 ns standard beam and the low emittance BCMS LIU beam.

	$p^+/bunch$	ε	$N_{bunches}$
HL 25 ns standard	2.3×10^{11}	$2.1\mu m$	288
BCMS LIU	2×10^{11}	$1.3\ \mu m$	288

Low emittance beams like BCMS have many advantages. The LHC peak luminosity is higher for BCMS than for the standard scheme for the same β^* and intensity. At the same time lower β^* is possible due to more available aperture in sigma and the requirement of smaller crossing angles. Other advantages include reduced injection losses on the transfer line collimators for the same collimator settings in mm and more margin for emittance growth through the LHC cycle.

On the other hand very low emittance beams also bring a number of disadvantages. The Intra-beam Scattering growth rate will be larger and hence the luminosity life time worse. Preliminary estimates for the growth rates during the LHC injection flat bottom for LHC run 2 indicate 50 % more growth than for the 25 ns standard scheme [2]. Emittance measurements with the LHC profile monitors will be close to the limit at 7 TeV and even more so with the significantly smaller beam sizes with BCMS emittances [2]. Due to the production technique of the BCMS beams in the injectors more holes will be in the filling scheme resulting in 5 % fewer bunches (if 288 bunches can be extracted from the SPS). The stabilizing effect of the Landau octupoles with the smaller beams might also be reduced. The main topic of this paper is however the increased energy density from high brightness, small emittance beams in case of beam impact and the arising attenuation and robustness issues for passive protection devices.

Attenuation Requirements for Protection Devices

The peak energy deposition in material and hence the damage potential of a beam does not only depend on the intensity but also on the spot size of the beam $\sigma_x \times \sigma_y$ at the impact location. The peak energy deposition ΔE is proportional to

$$\Delta E \propto \frac{I_{beam}}{\sigma_x \cdot \sigma_y} \quad (1)$$

where I_{beam} is the beam intensity. If the effect of different beams is compared at locations with the same optics, then the energy deposition scales with the brightness of the beam:

$$\Delta E \propto \frac{I_{beam}}{\varepsilon} \quad (2)$$

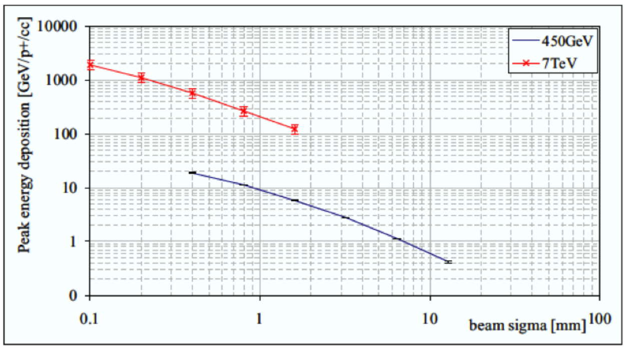

Figure 1: Peak energy deposition in Cu for 450 GeV and 7 TeV as a function of the spot size. Round beams were assumed in the FLUKA simulations.

Passive protection devices are designed to attenuate the beam energy density to a safe level for downstream equipment. Protection devices have to attenuate by a factor A:

$$\frac{I_{after}}{\varepsilon_{after}} = \frac{1}{A} \cdot \frac{I_{beam}}{\varepsilon_{beam}} \quad (3)$$

The acceptable energy density $I_{after}/\varepsilon_{after}$ for equipment comes from either experiment or simulation. In the case of the passive absorbers for the LHC injection protection system the damage limit was obtained from the TT40 material damage test [3]. Most of the LHC passive protection devices have been designed for ultimate LHC intensity (1.7×10^{11} protons per bunch in $3.5 \mu m$ normalized emittance) with material and length of absorber to match the required attenuation from the TT40 experiment. Table 2 compares the brightness of the different types of LHC beams with the brightness of the ultimate beam $N_b/\varepsilon : N_u/\varepsilon_u$ and hence the attenuation requirement.

Table 2: The brightness of the different LHC beams compared to the ultimate brightness. The maximum number of injected bunches for all schemes is 288 bunches with 25 ns bunch spacing.

	$p^{+}/bunch$ $[10^{11}]$	ε $[\mu m]$	$\frac{N_b/\varepsilon}{N_u/\varepsilon_u}$
nominal	1.15	3.5	0.68
ultimate	1.7	3.5	1
standard run 2	1.2	2.6	0.95
BCMS run 2	1.3	1.3	2.1
HL standard	2.3	2.1	2.3
BCMS LIU	2	1.3	3.1

As can be seen from Table 2 the protection devices for LIU beams (beams for run 3) and BCMS after LS1 will have to attenuate a factor 2 to 3 more than currently required. For example for BCMS after LS1 the protection devices will have to attenuate 100 % more than the current design. If the design does not provide sufficient margin - as is the case for the transfer line collimation system - the protection devices will have to become either longer or their jaws have to be made of higher Z materials to deal with the future beams.

Attenuation is only one of the issues for protection devices for very bright beams. The other problem is insufficient robustness in case of beam impact. This topic will be discussed in detail in the following section with the example of the LHC transfer line collimation system for LIU.

LIU TRANSFER LINE COLLIMATORS

To cope with LIU BCMS beams, the transfer line graphite collimators will have to become significantly longer. For graphite this attenuation requirement at 450 GeV implies a collimator length of ~ 1.9 m instead of 1.2 m.

Thermo-mechanical simulations including shock waves revealed another problem with the increased brightness of the LIU beams. Beam impact close to the surface of the graphite collimator, e.g. $1\ \sigma$ impact parameter, causes stresses above the material strength. The generated stresses depend strongly on the beam size of the impacting beam. It was hence decided to not only look for locations with sufficient space to install 1.9 m long jaws, but also to modify the optics of the lines such that the beta functions at the entrance of the collimators fulfill the criterion $\beta_x \times \beta_y > 3500\, m^2$. A full redesign of the LHC transfer line collimation system was inevitable to deal with LIU beams. Optics changes in the lines in this range were still deemed feasible.

With the spot size criterion the maximum temperature reached with BCMS stays below 1500° C. As is however discussed in [4], the beam size increase is still not sufficient to safely conclude that the transfer line collimators would survive beam impact under all conditions. Different materials were studied. Graphite R4550 - as is currently used for the transfer line collimators - is still the best compromise compared to other materials such as hBN5000 or 2D - CfC.

The most severe conditions are reached with LIU BCMS beams, nevertheless also for impact with the HL 25 ns standard beam the material strength limit is reached, see Table 3.

Table 3: Comparison of the maximum stresses in graphite R4550 for BCMS LIU and HL 25 ns standard for 1 sigma impact. The Mohr-Coulomb Safety (M.-C. S.F.) factor indicates the ratio of maximum stress versus strength of the material and has to be > 1 for the material to survive [5]. Column three shows the tensile strength versus the maximum tensile stress and column four the compressive strength versus the maximum compressive stress.

	M.-C. S.F.	$\frac{\sigma_{1limit}}{\sigma_1}$	$\frac{\sigma_{3limit}}{\sigma_3}$
BCMS LIU	0.8	30/37	118/87
HL standard	0.98	30/29	118/69

OTHER SPS AND LHC PROTECTION DEVICES

Robustness limitations with BCMS beams have not yet been evaluated for all passive protection devices. The extraction septum protection in the SPS - the TPSG, the LHC collimators and the LHC moveable dump protection absorber TCDQ have not been studied in detail concerning this aspect. Many studies have however been carried out for the high energy beam dump in the SPS, the TIDVG. Due to the sweep, emittance is of less importance in this case and the HL 25 ns standard beam with the higher total intensity causes more severe conditions. The TIDVG will have to be upgraded for LIU beams.

The other passive protection device that was studied in great detail, is the TDI LHC injection stopper - the protection against injection kicker errors. At the TDI, the beam size with BCMS LIU will be similar to the smallest spot sizes at the transfer line collimators with the LIU optics change. The first part of the jaws is made of hBN5000 and will not be robust enough for small impact parameters with LIU beams. There is however enough margin in terms of attenuation.

BCMS BEAMS AFTER LS1

Energy deposition and thermo-structural simulations were carried out for the transfer line collimators and the TDI injection stopper with the 25 ns beam parameters after LS1. Different number of bunches were simulated to be able to compare. The results are summarized in Table 4. In case of BCMS beams after LS1, the TDI injection stopper will be robust enough only for 192 bunches maximum per batch from the SPS. In terms of robustness the TCDI transfer line collimators could take up to 240 BCMS bunches at 450 GeV, but they only provide sufficient attenuation for maximum 144 BCMS bunches. For the 25 ns standard scheme no limitations have been found for run 2. The possible 80 bunch schemes from the PS have not been studied.

MATERIAL TESTS

The error on the so far obtained results for robustness is not known. This is due to the fact that material properties for the highly dynamic regime with shock waves and high temperatures are rarely available. Room temperature properties are therefore very often used. To gain more confidence on the results and understand the properties of typical collimator materials better, two tests are proposed for the HiRadMat test facility [6].

One test will address probing the material properties with high intensity LHC beam. The test setup will be similar to the HiRadMat experiment HRMT14-LCMAT. The different material samples will have simple geometries - discs and half-moon discs - to easily measure and cross-check different properties, see Fig. 2. The material samples will be heavily instrumented to obtain as much information as possible.

The other proposed test will address the robustness of a TCDI transfer line collimator assembly under the impact with LIU energy density. As the LIU intensities are not available yet in the SPS, an optics will be used that results in a smaller beam size at the test location than what is proposed for the collimators in the LIU transfer lines. The beam size was matched to provide the same energy density and stress during beam impact as for the LIU case. The current TCDI design will be used with some modifications for additional instrumentation. The two TCDI jaws will allow for precise alignment and hence for small impact parameters to create the maximum stress in the jaw material.

PRELIMINARY LATEST NEWS

The baseline material choice for the new transfer line collimators and new TDI injection stopper for LHC run 3 is Graphite R4550 despite of its insufficient robustness for 1 σ impact parameters and LIU beams. It was still the best out of all studied materials and the HiRadMat tests will show whether the so far applied criteria for robustness were too conservative. However, the recently investigated 3D Carbon-Carbon by SAFRAN-Herakles would withstand the stress

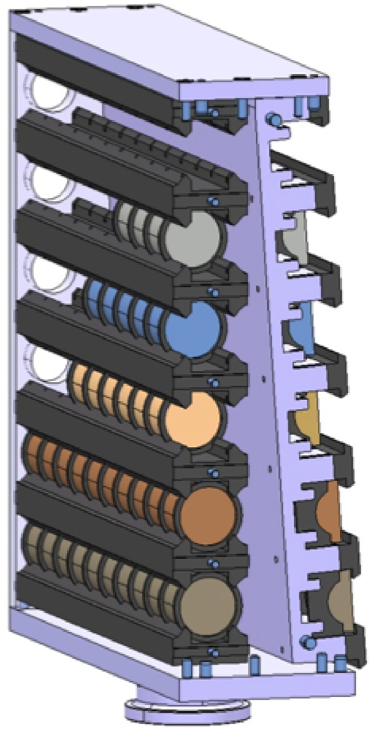

Figure 2: Material HiRadMat test sample holder for test HRMT14-LCMAT. Courtesy A. Bertarelli

from LIU BCMS beam impact in all directions according to FLUKA and ANSYS simulations. This material will also be possibly tested in HiRadMat if samples can be purchased in time.

SUMMARY & CONCLUSION

High brightness beams with very small transverse emittances like the proposed BCMS beam have many operational advantages. Considerable disadvantages are however the increased energy density and the resulting stresses in case of beam impact on protection devices. The stresses are beyond material strength. Also the High Luminosity 25 ns standard beam parameters are challenging in this respect.

Research is still ongoing to find new absorber materials. HiRadMat tests have been proposed to test new materials or confirm the design material choice.

For LHC run 2 the passive protection devices will still have the current limitations and operation with BCMS beam will be significantly limited. For more than 144 BCMS bunches the TCDI transfer line collimators cannot guarantee sufficient protection and an impact of more than 192 BCMS bunches could damage the TDI.

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Table 4: Comparison of the maximum stresses in the absorbers TDI and TCDIs for run 2 BCMS and 25 ns standard beam for 1 sigma impact. The Mohr-Coulomb Safety (M.-C. S.F.) factor indicates the ratio of maximum stress versus strength of the material and has to be > 1 for the material to survive. Tensile strength versus the maximum tensile stress and compressive strength versus the maximum compressive stress are shown for different numbers of bunches. The status column indicates whether the absorber material is robust enough for impact under these conditions.

Absorber	beam	ε	p^+/bunch	# bunches	$\frac{\sigma_{1_{limit}}}{\sigma_1}$	$\frac{\sigma_{3_{limit}}}{\sigma_3}$	M.-C. S.F.	Status
TDI (h-BN5000)	BCMS run 2	1.39	1.3	288	7/12	59/37	0.53	NOT OK
				240	22/13	59/32	1.1	(OK)
				192	27/12	59/26	1.28	OK
	standard run 2	2.6	1.2	288	39/12	74/25	1.88	OK
TCDI (graphite)	BCMS run 2	1.39	1.3	288	30/32	118/81	0.9	NOT OK
				240	30/24	118/75	1.44	OK
				192	30/18	118/58	1.75	OK
	standard run 2	2.6	1.2	288	30/15	118/42.5	2	OK