PERFORMANCE WITH LEAD IONS OF THE LHC BEAM DUMP SYSTEM

R. Bruce, B. Goddard, L. Jensen, T. Lefevre, W. Weterings, CERN, Geneva, Switzerland

Abstract

The LHC beam dump system must function safely with $^{208}\mathrm{Pb}^{82+}$ions. The differences with respect to the LHC proton beams are briefly recalled, and the possible areas for performance concerns discussed, in particular the various beam intercepting devices and the beam instrumentation. Energy deposition simulation results for the most critical elements are presented, and the conclusions drawn for the lead ion operation. The expected performance of the beam instrumentation systems are reviewed in the context of the damage potential of the ion beam and the required functionality of the various safety and post-operational analysis requirements.

INTRODUCTION

The LHC beam dump system is built to extract the beams without losses from the two rings and steer them onto absorber blocks (TDE) at the end of dedicated extraction lines. The system for each of the two beams consists of extraction kicker magnets (MKD) that deflect the beam to the septum magnets (MSD) in IR6. The MSDs guide the beam in the vertical plane out of the main ring into the extraction line, where it is finally dumped on the TDE, which is located in a cavern some 650 m away. A set of horizontal and vertical dilution kickers (MKBH and MKBV) in the extraction line sweep the beam in a Lissajous figure approximately 100 cm long on the TDE. The system also contains beam intercepting devices: diluters designed to protect other LHC elements against badly extracted beams, specifically the TCDS in front of the MSD septum and the TCDQ in front of the superconducting magnet Q4; a large 60 cm diameter carbon-composite window (VDWB) used to separate the vacuum of the extraction lines from the TDE block; a 60 cm diameter fixed beam profile screen (BTVDD) used to measure the impact position of the dumped beam.

The beam dump system has been primarily designed for protons but will be used also during operation with $^{208}\mathrm{Pb}^{82+}$ions. Tab. 1 summarizes the beam parameters. Although the stored beam energy per beam is only 3.81 MJ compared to 362 MJ for protons [1], ions require additional considerations since the interactions between heavy ions and matter are very different from the proton case, as discussed in [2]. The cross-section for ionization in a material (described by the Bethe-Bloch formula [3]) is proportional to Z^2, Z being the charge of the impinging particle. This means that the ionization energy loss of a proton is exceeded by a factor 82^2 by a $^{208}\mathrm{Pb}^{82+}$ion of the same energy. The electrons set free during this process are mostly soft (they deposit their energy close to the trail of the incoming particle) and give rise to a very localized energy deposition. This in turn makes the peak temperature much higher in the case of ions. The peak energy deposition for ions is usually found very close to the impact point, since the ions fragment as they propagate through the material. When they are fully fragmented the shower resembles a shower of independent nucleons.

The different physics means that it is necessary to determine the energy deposition from the ion beam in critical elements where one might fear heat induced damage very close to the impact locations. In the beam dump line these elements are the VDWB, TCDS, TCDQ, TDE and the BTVDD screen. Another performance issue is the response of the various beam instrumentation (BI) devices during ion operation.

Table 1: LHC beam parameters for $^{208}\mathrm{Pb}^{82+}$and p^+ operation (nominal collision).

	$^{208}\mathrm{Pb}^{82+}$ions	Protons
Energy per nucleon	2.76 TeV	7 TeV
Number of bunches	592	2808
Ions per bunch	7×10^7	1.15×10^{11}
Bunch spacing	100 ns	25 ns
Peak luminosity	10^{27} cm^{-2} s^{-1}	10^{34} cm^{-2} s^{-1}

BEAM INTERCEPTING DEVICES

Beam Dump Window VDWB

Before hitting the TDE dump block, the beam has to pass through the VDWB. This window is made of 15 mm thick carbon-composite (CC) backed by a 200 μm stainless steel foil on the high pressure side and has a diameter of 60 cm.

The geometry of the window was implemented in the FLUKA 2006.3 [4, 5] Monte Carlo code and the energy deposition from one $^{208}\mathrm{Pb}^{82+}$bunch hitting the window was simulated. The resulting energy deposition from the full bunch train was obtained through a superposition of all the bunch positions in the sweep. This profile was converted into temperature rise using the temperature dependent specific heat $C_p(T)$ of the CC plate and the steel foil. The heating process was approximated as instantaneous without heat flow. The resulting temperatures for the nominal sweep are shown in Tab. 2 and Fig. 1 for the CC plate, where it can be seen that the maximum temperature rise, assuming a starting temperature of 300 K, is only 4.7 K.

It was also considered that the dilution kickers might fail—either horizontal or vertical or all—meaning that the bunches would be swept over a much shorter length. The

1-4244-0917-9/07/$25.00

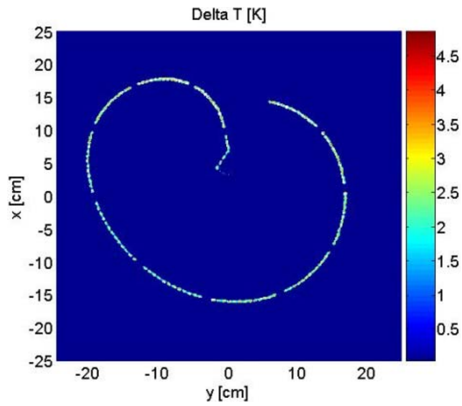

Figure 1: ΔT in the CC plate during the nominal ion sweep.

maximum temperature increases in all these scenarios are summarized in Tab. 2. In the case of a total failure of all dilution kickers, the temperature rise is 209 K in the CC plate and 301 K in the foil. These numbers should be compared to the melting points: approximately 4270 K and 1670 K in the plate and foil respectively. As a comparison, during proton operation in the event of a total dilution failure, the temperature rise in the plate is 891 K and 3580 K in the foil [6]. The result is plausible, as every ion is expected to give much less than a factor $82^2 = 6700$ higher temperature, but the number of particles is a factor 7800 higher in the proton beam with a much larger overlap between the bunches due to the smaller bunch spacing.

Table 2: ΔT in the CC plate and steel foil for different $^{208}\mathrm{Pb}^{82+}$ ion load cases

Load case	ΔT CC (K)	ΔT foil (K)
Single bunch	1.5	1.6
Nominal 592 bunch sweep	4.7	5.2
592 bunches no MKBH	35.2	39.1
592 bunches no MKBV	39.6	43.9
592 bunches no MKB	209	301

Septum Protection Diluter TCDS

The TCDS [7] will protect the elements in the extraction from particles in the abort gap and unsynchronized beam aborts. The TCDS should dilute around 1.8% of the nominal LHC energy by intercepting 40 proton bunches or 10 ion bunches, to prevent damage of the downstream septum elements. It consists of two 3 m long and 24 mm thick blocks with a graded composition of different materials. The first 0.5 m is made of graphite, followed by high density CC and titanium.

Since the large difference in peak energy deposition is found very close to the impact point, only the first part of the diluter block was simulated for the comparison. An ion bunch hitting the graphite block was simulated in FLUKA and the total energy deposition from the 10 bunches calculated through post-processing routines. Again, the temperature rise was calculated pessimistically using $C_p(T)$ assuming no heat flow. The resulting superposition can be seen in Fig. 2. Since there is negligible overlap between the bunches for the ions, it was found that the maximum temperature rise is only 23 K, which is almost exactly the same as for one bunch. Thus there is no risk of instantaneous material damage in the TCDS due to the $^{208}\mathrm{Pb}^{82+}$ ion beam.

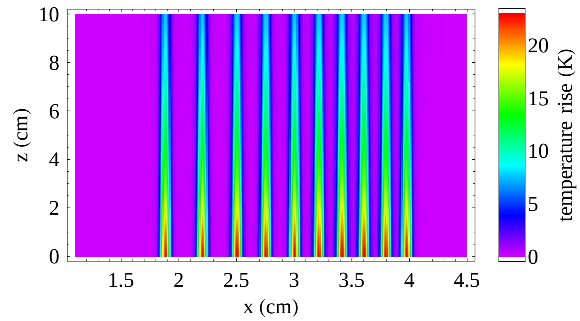

Figure 2: ΔT in the first 10 cm in the carbon part of the TCDS during nominal ion operation.

Mobile Diluter TCDQ

The TCDQ is made of graphite and is installed in front of the Q4 magnets. In case of an asynchronous firing of the MKD, the load case here will be less severe than for the TCDS, due to the larger beam size, However, the TCDQ might intercept a significant part of the beam halo during normal operation, causing shower particles to hit the Q4. During $^{208}\mathrm{Pb}^{82+}$ operation however, ICOSIM simulations show that no significant losses are expected at the TCDQ [8]. Detailed simulations of the shower in the TCDQ with ions were therefore not performed.

Beam Dump Block TDE

The TDE itself is of course also subject to impacting beam particles. However, no detailed study of it was needed. The peak temperature might differ significantly from the proton case only in the CC close to the impact point. Simulations in the previous sections show that even during a complete failure of the dilution kickers, the peak temperature in this material for the ions will be a factor of about 4 less than that for protons, due to the much smaller number of particles. Since the temperature rise in the TDE during proton operation is about 1100 K with the ultimate intensity, the conclusion is that ion operation poses no problems for the TDE block.

Beam Imaging Screen BTVDD

The Beam TV system (BTV) systems [9] are used to monitor the transverse shape of the beam, intercepting it on a single passage. There are BTVs in the extraction line after the ejection septum, after the dilution kicker and at the end of the dump line. The first two are based on a retractable mechanical system, equipped with two screens: a

12 μm thick titanium foil (50% reflectivity) producing Optical Transition Radiation (OTR) [10] and a 1mm thick luminescent screen in chromium doped Al_2O_3. The last (and most critical) one, BTVDD, is a fixed 3mm thick screen made of chromium doped Al_2O_3. The impact of a single ion bunch on the BTVDD was again simulated in FLUKA and the energy deposition superimposed on the sweep pattern and transformed into temperature rise for the different failure cases. This is summarized in Tab. 3. Even in the total dilution failure case the screen may survive, which is not the case for protons.

Table 3: Maximum ΔT in the Al_2O_3 BTVDD screen for different load cases

Load case	ΔT (K)
Single bunch	1.6
Nominal 592 bunch sweep	4.1
592 bunches no MKBH	27.6
592 bunches no MKBV	32.0
592 bunches no MKB	223

BEAM INSTRUMENTATION PERFORMANCE

The dedicated BI for the dump lines has to be considered. This has been done elsewhere for the main LHC ring [1, 2] and apart from the BTV screens the instrumentation in the beam dump extraction line consists of the same type of hardware.

The sensitivity of the BTV screens (OTR and luminescent) to ions was evaluated. For luminescence, the number of photons is directly proportional to the deposited energy in the material [11]. Simulated with Fluka, we found that a 2.76 TeV/nucleon $^{208}\mathrm{Pb}^{82+}$ion produces 3320 more photons than a 7 TeV proton. The OTR intensity scales linearly with the particle charge and is therefore 82 times higher for a $^{208}\mathrm{Pb}^{82+}$ion than for a proton. The expected number of photons for each type of screen was calculated as in [9, 11] and is shown in Tab. 4. Using radiation hard-cameras, the detection is limited to intensities higher than 10^9 photons (assuming a beam size of 8 pixels per sigma), which would be sufficient to observe a single bunch with the alumina and higher beam charges with the OTR screen.

Table 4: The expected photon intensities from the BTV screens for one bunch.

	p+ nominal 1.15×10^{11}	p+ pilot 5×10^9	$^{208}\mathrm{Pb}^{82+}$ 7×10^7
OTR	2.2×10^9	9×10^7	9×10^7
luminescent	4×10^{10}	1.9×10^{10}	8×10^{10}

The Beam Position Monitors (BPMs) and Fast Beam Current Transformers (FBCTs) are insensitive to particle type, since they function via induced currents. However, the dynamic range for the BPMs may be inadequate. The resolution limit of the BPMs is 2×10^7 $^{208}\mathrm{Pb}^{82+}$ions per bunch [1] while the nominal ion scheme is only a little more than a factor three over this limit (see Tab. 1), so problems might arise during commissioning. This is however an already well-known issue for the main ring. The FBCTs have a resolution limit of 5% of the proton pilot bunch, equivalent to a bunch current of 0.45 μA, so the $^{208}\mathrm{Pb}^{82+}$ion bunch current of 10 μA should be clearly visible.

The response of the Beam Loss Monitors (BLMs) to $^{208}\mathrm{Pb}^{82+}$ions has been simulated in [2]. There it was concluded that when considering magnet quenching, the ratio of energy deposition from a generic beam loss in a main dipole magnet, averaged over the minimum propagating zone of 1 cm^3, to the energy deposition in the N_2 gas in the BLM outside the cryostat, is the same for $^{208}\mathrm{Pb}^{82+}$ions and protons. Because the hadronic shower, similar for the two species, is the dominant factor for energy deposition on this volume scale, the BLMs protecting against quenches can be used without any modifications in $^{208}\mathrm{Pb}^{82+}$operation. However, if we are interested in the ionization dominated peak temperature in the material, the ratio might change.

CONCLUSION

The energy deposition from $^{208}\mathrm{Pb}^{82+}$ions in sensitive elements in the beam dump extraction line was simulated with FLUKA, both for nominal operation and failure scenarios, and the resulting temperature rise was calculated. It was concluded that although the energy deposition from a single ion is much higher than from a proton, the total number of protons in the beam is much larger and the ion bunches more spread out, meaning that the resulting temperature rise for ions is lower. Therefore these elements should work just as safely with $^{208}\mathrm{Pb}^{82+}$ions as with protons. Also the beam instrumentation was considered, and the only issue found was the resolution of the BPMs, which, due to the lower ion bunch population, could be wished to be higher. This is however an already known problem that exists also for the main ring.

We wish to thank G. Bellodi for the ion loss map in IR6.

REFERENCES

[1] O.S. Brüning et al (editors), “LHC design report v.1 : the LHC main ring”, CERN-2004-003-V1, (2004)

[2] R. Bruce et al, MOPLS007, Proc. of EPAC06, (2006)

[3] S. Eidelman et al, Phys. Lett. B 592, 1 (2004)

[4] A. Fasso et al, CERN-2005-10, 2005

[5] A. Fasso et al, Proc. of the Computing in High Energy and Nuclear Physics 2003 Conf., La Jolla, (2003)

[6] A. Presland et al, LHC Project Report 823, CERN (2005)

[7] B. Goddard et al, MOPLT038, Proc. of EPAC04, (2004)

[8] G. Bellodi, private communication, CERN 2007

[9] T. Lefevre et al., TUPB28, Proc. of DIPAC07, Venice 2007.

[10] L. Wartski et al, J. Appl. Phys. 46, 3644, (1975)

[11] A. Variola, L. Bruno, LHC Project Note 241 (2000)