# GLOBAL VISION OF MPS AFTER LS1 AND BEYOND

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*Abstract*

The most critical failures in machine protection systems will be revisited, in particular failures discussed in [1]. This paper takes into account recent work on hydrodynamic tunneling by high intensity beam and studies of the consequences of an asynchronous beam dump for the magnet system. An outlook to failure scenarios during the next (few) years will be given and the consequences on machine protection systems will be discussed.

## INTRODUCTION

The LHC Machine Protection Systems are designed for very high reliability. Possible causes and consequences of serious failures of the LHC Machine Protection Systems were addressed in [1] [2], some of the failure scenarios are discussed below:

1. The beam dumping system deflects the beam with non-nominal strength, e.g. due to a wrong evaluation of the energy e.g. 450 GeV instead of 6.5 or 7 TeV.
2. Spontaneous firing of one (or more) kicker magnets and a failure of the retriggering system.
3. After a failure when the beams should be dumped, the beam dumping kickers are not triggered due to a failure in the protection systems.

An asynchronous beam dump is not considered a serious failure since the machine protection systems were designed to cope with such events without risking equipment damage.

The failure of a quenching superconducting dipole magnet and the energy extraction not activated is also considered as a serious failure due to the large energy stored in the RB circuit of one GJ per sector. Other magnet powering circuits are also critical, in particular for the triplet magnets MQXA/B (large stored energy, critical situation of spare magnets, difficult to replace). Protection related to the magnet powering systems is addressed in session 5 of this workshop.

## CASE I

Several failures could lead to the beam deflected with non-nominal angle, e.g. if one (out of 15) kicker magnets fires and the retriggering does not work, or the LHC operates at 7 TeV and the kicker extract the beams with an angle corresponding to 450 GeV. In both cases, the beam will be deflected with an amplitude of about 15 $\sigma$ into the TCDQ / TCSG absorber assembly (about 10 m of graphite). Qualitatively, the first bunches will be absorbed by the absorbers and heat the graphite. Part of the protons will be re-scattered into the LHC ring. Several 10 bunches are sufficient to melt and then vaporize the graphite. Bunches arriving later will therefore not be absorbed, travel through the absorbers further into the ring and are likely to hit the next aperture limitation, either collimators in IR7 or collimators in another insertion. Two studies help to understand what could happen:

- The energy deposition of protons and their showers scattered from the TCDQ / TCSG absorber into the magnets downstream in case of an asynchronous beam dump was calculated [3]. This allows understanding if magnets could be damaged by the energy deposition from the full beam hitting the TCDQ / TCSG.
- Calculations were performed during the last 10 years on the impact of a full 7 TeV beam on graphite and copper targets [4], and recently an experiment was performed at HiRadMat to validate the simulation method [5]. These studies allow to predict the number of bunches impacting on a long absorber before hydrodynamic tunneling will have created a channel for the beam to pass through the absorber.

For the studies of beam impact on TCDQ / TCSG in case of an asynchronous beam dump, a 7 TeV beam with 50 ns bunch spacing was assumed. About 42 bunches with $4.8\times10^{12}$ protons are hitting the TCDQ. The maximum coil temperature of the MQ4 and MQ5 in such an event, will be of the order of 220 K, assuming a peak energy deposition of 200 J/cm$^3$ (for a failure scenario that is more likely the energy deposition will be a factor of 5-10 less). The energy deposition into the superconducting magnets in the adjacent arc 6-7 is shown in Fig 1.

The energy deposition into the adjacent magnets in the arc is considered if the TCDQ and TCSG absorber remain intact during the full beam pulse. The energy deposition would be a factor of 50-80 higher compared to the results presented in [3]. MQ4 and MQ5 are likely to be damaged for such event. The maximum energy deposition for the arc magnets is less than 50 J/cm$^3$, therefore no damage is expected.

Hydrodynamic tunneling of beam through the target becomes important after the impact of some 10 bunches. The first bunches arrive, deposit their energy, and lead to a reduction of the target material density. Bunches arriving later travel further into the target since the material density is reduced. This effect has been already predicted for SSC [6]. The calculation of hydrodynamic tunneling is complex and performed in several steps. Firstly, the 3D energy deposition in the target for a few bunches is calculated with FLUKA. The hydrodynamic code BIG2 [4] uses the energy deposition to calculate temperature, pressure and material density in the target. The density changes and the energy deposition by the following bunches needs to be recalculated with the modified density distribution by FLUKA. The programs are run iteratively in several steps. Typical parameters for the simulation are: 2808 bunches with $1.1\times10^{11}$ protons,

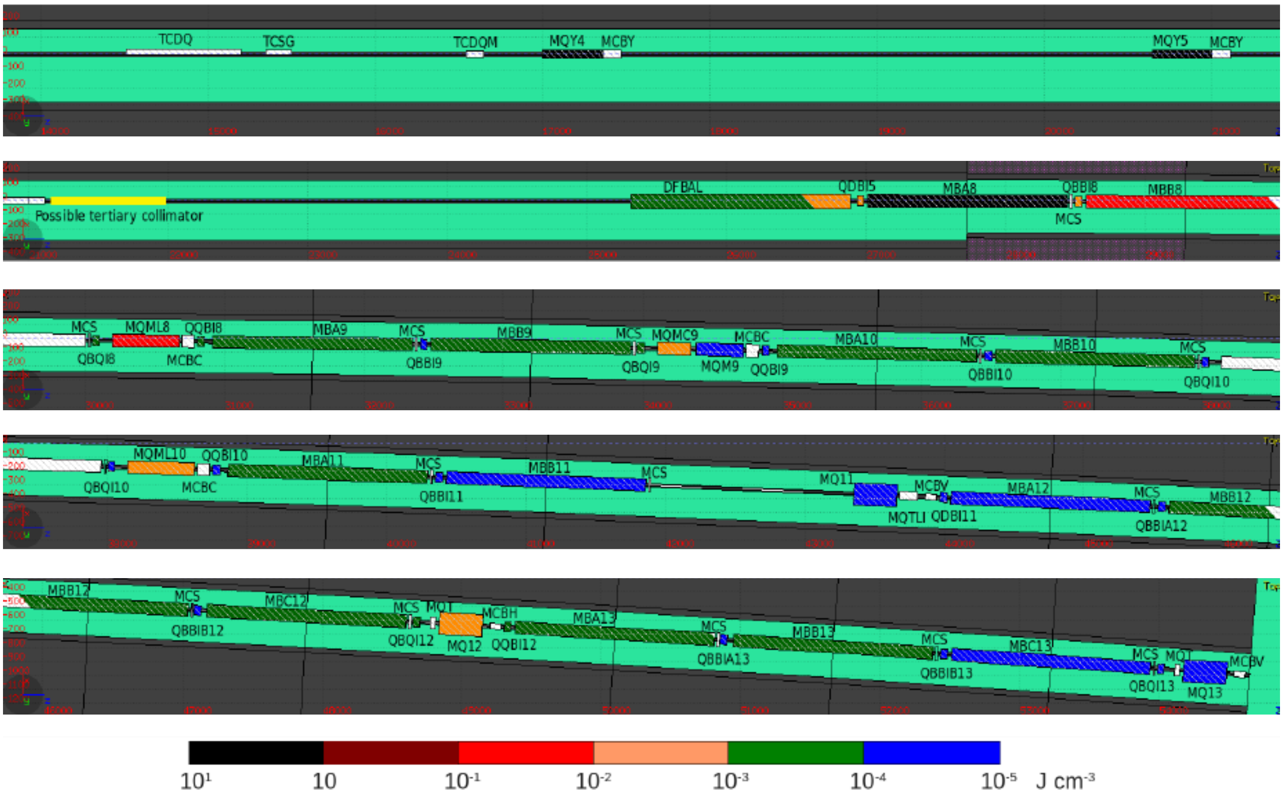


Figure 1: Energy deposition of an asynchronous beam dump for a 7 TeV beam with 50 ns bunch distance with beam impact on the TCDQ / TCSG assembly.

$\sigma$ = 0.5 mm and 25 ns bunch distance. The solid cylindrical target has a length of 6 m, a radius of 5 cm, and a density of 2.3 g/cm3 in case of graphite.

In Fig. 2 the target density for three different time steps is shown in 2D. Fig. 3 shows the change of density along the axis of a graphite block by more than a factor of 10. The new TCDQ/TCSG assembly of 10 m length will not absorb bunches arriving after about 25-30 μs, but these bunches will travel further from IR6 to IR7 or IR5. A number of other collimators will be damaged but a precise estimation of the damage is not yet possible. A long additional absorber in IR6 could reduce the damage for this failure mode.

For a validation of the code an experiment was performed at the SPS HiRadMat facility by irradiating three copper targets with the following SPS 440 GeV beams (see the target assembly in Fig. 4 [7]):

- Target 1: 144 bunches about $1.9\times10^{11}$, 50ns, $\sigma$=2.0 mm – no tunneling expected
- Target 2: 108 bunches about $1.9\times10^{11}$, 50ns, $\sigma$=0.2 mm – tunneling expected
- Target 3: 144 bunches about $1.9\times10^{11}$, 50ns, $\sigma$=0.2 mm – tunneling expected.

Each target consists of copper blocks with a length of 10 cm and a slit between the blocks. When the copper melts or vaporizes, material escapes through the slits and is projected against the cover of the targets. This allowed us to estimate the depth of the damaged zone and therefore provide and idea of hydrodynamic tunneling. The traces on the cover are shown in Fig. 5. The range of the beam in target 3 is larger than in target 1 and 2. Although a detailed analysis is not yet completed, this gives already a clear indication for tunneling. After radiological cool down of the setup, it is considered to examine the blocks to establish a more precise measure of the depth.

## CASE II

The second failure case considered is the beam dumping system not working. If this happens following a request from an operator to dump the beams, then there is still the option of forcing a beam dump trigger, and if this does not work of reducing the intensity by slowly scraping the protons away (see [8]).

If the beams are not extracted after a failure affecting the particle trajectories (e.g. after a quench of a magnet, a failure of a power converter, an object moving into the beam) there is no time for scraping. The orbit will move and possibly the beam emittance will blow up. Initially, particle losses are captured by collimators. It is likely that superconducting magnets will quench after a short time. Depending on the time constant of the failure, collimators will be damaged first, or superconducting magnets will quench. In case of a collimator being damaged the cleaning efficiency is reduced, which also leads to a superconducting magnet quench shortly later.

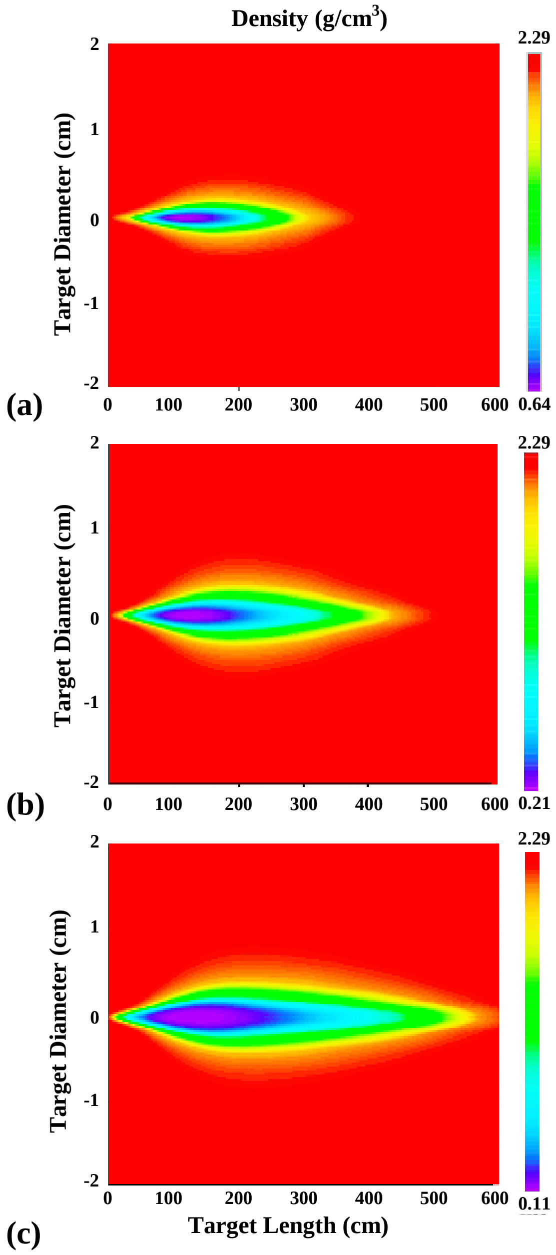


Figure 2: Density distribution calculated in BIG2 in the carbon cylinder, r = 5 cm, L = 6 m, irradiated by a 7 TeV LHC beam, at the left face; (a) at t = 5 μs; (b) at t = 10 μs; (c) at t = 15 μs.

If we assume a quench in a dipole magnet, the orbit will change even further. After about 10-20 ms the beam will hit one of the collimators. The collimator will be destroyed within a few ms, the beam will continue to move further out and more collimators will be destroyed. It is not clear if the beam will reach the vacuum chamber aperture, but the computational tools to study hydro-dynamic tunneling and the results from HiRadMat should allow a better quantification of the damage to be expected.

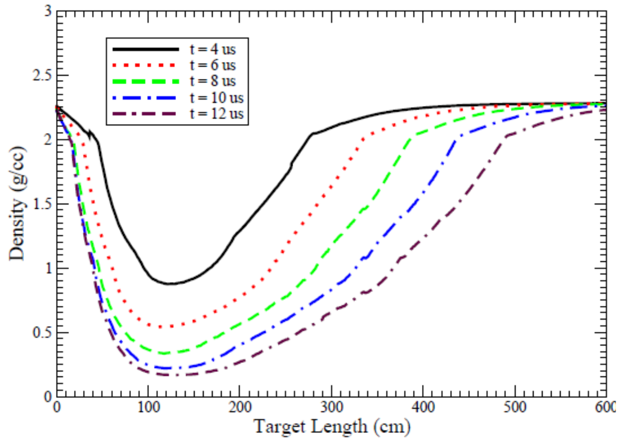


Figure 3: Target density reduction as a function of time.

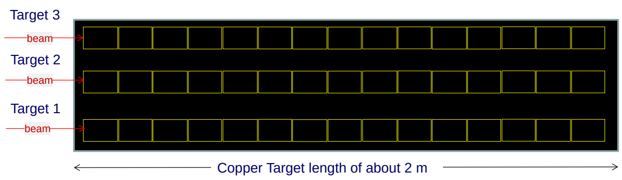


Figure 4: Layout of the copper targets.

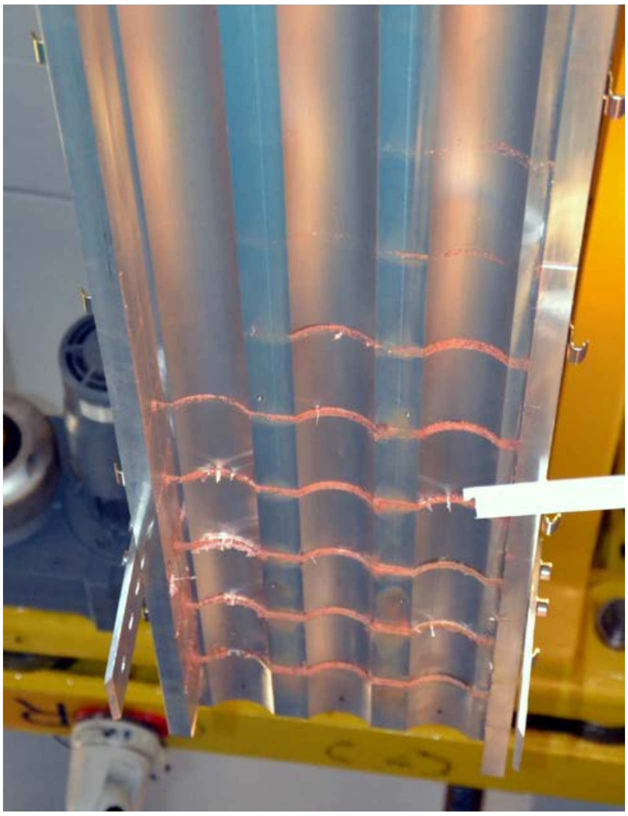

Figure 5: Target cover with the projected copper.

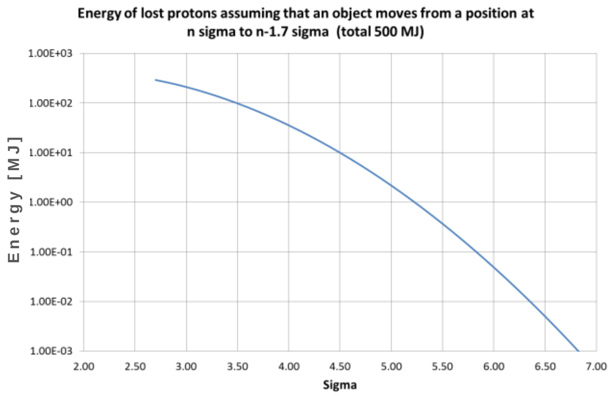


Figure 6: Energy loss assuming that an object cuts into the beam tail by 1.7 σ.

## POSSIBLE MITIGATION

To mitigate against failure of the LBDS kicker magnets not firing, one option would be the installation of one (or two) kicker magnets that deflect the beam by an angle of about 30 μrad into internal absorbers. These absorbers should have a length of at least about 20 m and will be destroyed if such event occurs. The kicker magnets should never fire before triggering the kicker magnets of the LBDS and would therefore be delayed by about 1 ms. Considering recent experience, a delay of 1 ms is acceptable for all failures that have been observed. There should be no charged elements in the kicker power supply to prevent any spontaneous pre-firing. This mitigation does not help if an LBDS kicker pre-fires and the retriggering fails. For this case, massive absorbers at an aperture further out than the secondary collimators, but closer than the tertiary collimators, could reduce the damage. If such absorbers would be installed in IR6 they would capture most of the beam energy. It might be possible to install such devices behind the TCDQ / TCSG assembly.

Are such absorbers beneficial for all scenarios where the beam is not extracted after a failure? To some extent yes, massive absorbers close to the beam are likely to capture part of the beam energy, but it is not yet possible to quantify this effect.

## KNOWN FAILURE SCENARIOS REVISITED

During the design of the LHC machine protection systems, no failure leading to massive beam losses faster than about one ms was identified. A change of the closed orbit after a powering failure of the normal conducting D1 magnet is still considered to be the most critical failure for operation with circulating beams. During the three years of experience, this assumption proved to be correct (except UFOs that lead to beam losses in less than one ms but are not threatening to damage equipment).

The transverse beam intensity distribution has tails. It had always been assumed that the distribution is Gaussian, but several measurements show overpopulated tails with respect to a Gaussian distribution. If the beam tails touch the collimators when the beam moves, say, by one sigma in one ms, the BLMs detect the losses and there is enough time to dump the beam before any damage occurs.

For the future, new failure scenarios need to be considered:

- Crab cavities that are discussed for HL-LHC might lead to a deflection of the beam within a very short time in the order of μs by 1.7 σ in case of a single crab cavity failure.
- Long range beam-beam interactions change the orbit of both beams. When one beam is dumped, the orbit of the other beam changes in a very short time.
- Fast vacuum valves: for the protection of critical equipment (such as the SC-RF cavities in IR4) in case of a major vacuum leak it had been proposed to install vacuum valves that close much faster than the valves installed today.

In the following paragraphs, only issues related to the installation of crab cavities are discussed.

For the transverse planes, a Gaussian distribution for the intensity is assumed and a collimator at a position corresponding to 4 σ. In case of a crab cavity trip and a fast displacement of the beam by 1.7 σ, all particles above an amplitude of 2.3 σ would be scraped away. If the energy stored in the beam corresponds to about 500 MJ, the energy loss would correspond to 35 MJ. For a collimator at 5 σ the energy loss is 2.2 MJ and for a collimator at 6 σ the energy loss is less than 0.1 MJ. The energy loss as a function of collimator setting in case of such failure is shown in Fig. 6.

It is not yet clear if crab cavities can generate such beam movements. Mitigation methods are being discussed, such as a passive increase of the time constant τ for critical failures through LLRF and cavity design (available power, Qext, ...). If this is not possible and such failures need to be anticipated, a particle free aperture between collimators and beam of, say, two sigma might be required (or at least a strongly reduced particle population that still allows the early detection of beam displacement with beam loss monitors). Such gap could be produced by hollow electron lenses or other halo cleaning techniques. A dependable measurement and interlocks on the particle population in the transverse tail and possibly on the longitudinal head-tail oscillations would be needed.

Ideas for upgrade of protection systems:

- Dependable and fast detection of failures at/close to cavities (in about one μs).
- Direct links between the crab cavities and the beam dumping system to reduce the delay for a beam dump, between IR1/5 and IR6. In addition, asynchronous beam dumps might have to be accepted for limited failure cases to further reduce the delay time.
- Additional abort gaps.

- Position of collimators further outside (between 5.5 σ and 6.0 σ).

Future work: understand details of loss scenario, extract beam as fast as possible, possibly accept some limited damage to collimators if the probability for such event is low and if collateral damage can be minimized to an acceptable level.

## QUESTIONS

Instead of a conclusion, it is suggested to address several questions:

- Do we have the tools for a credible estimation of consequences of "catastrophic" failures? How far should such consequences be further investigated?
- How to evaluate mitigation methods such as absorber blocks, or redundant kicker plus absorber blocks?
- Are crab cavities introducing a new type of very fast failures and can we protect the LHC efficiently if such failures occur?
- Should we continue using only robust collimators, or reconsider the materials if possible damage is understood and limited, if we gain in overall integrated luminosity?
- Do we have to reconsider our protection strategy in case of missing beam halo?
- What other changes are expected that can have an impact on machine protection?

## ACKNOWLEDGMENT

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## REFERENCES

[1] R. Filippini, B. Goddard, M. Gyr, V. Kain, R. Schmidt, J. Uythoven, and J. Wenninger, "Possible Causes and Consequences of Serious Failures of the LHC Machine Protection Systems", in 9th European Particle Accelerator Conference, Lucerne, Switzerland, 5 - 9 Jul 2004, pp.620, 2004.

[2] B. Goddard, "What are the weak points of LHC operation?", in Evian 2010 Workshop on LHC Commissioning, Evian-les-Bains, France, 19 - 20 Jan 2010, 2010.

[3] R. Versaci, V. Boccone, B. Goddard, A. Mereghetti, R. Schmidt, and V. Vlachoudis, "Fluka Studies of the Asynchronous Beam Dump Effects on LHC Point 6 for a 7 TeV beam", Tech. Rep. CERN-ATS-Note-2012-030 TECH, CERN, Geneva, Jan 2012.

[4] N. A. Tahir, J. B. Sancho, A. Shutov, R. Schmidt, and A. R. Piriz, "Impact of high energy high intensity proton beams on targets: Case studies for super proton synchrotron and large hadron collider", Phys. Rev. ST Accel. Beams, vol. 15, p. 051003, May 2012.

[5] J. Blanco et al., "An experiment on hydrodynamic tunnelling of the SPS high intensity proton beam at the HIRdmat facility", in Proceedings of HB2012, Beijing, China, 2012.

[6] D. C. Wilson et al., "Hydrodynamic Calculations of 20-TeV Beam Interactions with the SSC Beam Dump," in Proceedings of PAC 1993, San Sebastian, Spain, 1993.

[7] J. Blanco et al, "Results of an experiment on hydrodynamic tunnelling at the SPS HiRadMat high intensity proton facility", in Proceedings of IPAC2013, Shanghai, China, 2013.

[8] M. Zerlauth, V. Kain, and J. Wenninger, "Procedure in case of non-working dump trigger", Tech. Rep. EDMS Id: 1166480 v.1, CERN, Geneva, Aug 2011.