TESTING MATERIAL PROPERTIES WITH HIGH ENERGY BEAMS IN HIRADMAT AT CERN

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Abstract

HiRadMat is a new facility under construction at CERN that will provide the users with the possibility to investigate the behavior of materials when irradiated with pulsed high energy and high intensity beams extracted from the CERN SPS. The need for such a facility was raised by the LHC collimation project to expand our present knowledge about the resistance of materials under impact with high energy protons. This paper will discuss the material parameters for which a deeper knowledge would be needed for extensive use in high-energy accelerators, and the kind of test that can be conducted in HiRadMat to improve this knowledge. In particular we will discuss destructive testing, meaning test of materials beyond the limit of rupture or at phase change, and damage testing that should reveal changes in materials properties due to long term irradiation below the rupture limit. The facility could be used as well for calibration of radiation detectors like BLMs. The main difficulty connected with the test is how to observe material changes. Some preliminary ideas on on-line and post-irradiation tests will be outlined.

INTRODUCTION

The construction of the LHC at CERN has raised interesting questions about the resistance of materials to accidental beam impact. The energy stored in the beams, already at a very early stage of operation, is such that even a single nominal bunch (~10^{11} protons) can cause significant damage to the materials used for the most common equipment. For this reason the LHC has been equipped with a complex protection system where the level of protection of the machine depends on several factors, the main being beam energy and intensity. In order to understand how to fix the limits among the different levels of protection, several studies and tests have been performed [1].

The first question in the line was to decide how to classify damage to materials. Several laboratories classify radiation damage according to the DPA (Displacement Per Atom) calculated through simulation codes like MARS [2] or PHITs [3]. CERN groups pragmatically decided to consider that, at least for metallic materials, “a clear sign of melting” [4] could be more convenient. It is in fact not possible to measure the DPA, and the estimate through different codes may bring results that differ by orders of magnitude [5], and would oblige to include in the limits large safety factors that may become overwhelming for practical use. In addition, for accidental beam impact, melting or structural damage are much more of concern than DPA, which is an effect depending rather on integrated dose.

The pragmatic approach has the advantage to be verifiable by testing materials in a beam with known characteristics. An experiment conducted in 2004 by the LHC Machine Protection team (see [4]) assessed this limit on different materials (Copper, different grades of stainless steels, Zinc) at 450 GeV finding that already $10^{12}p^+$ can create serious damages to metallic structures. By simulations, this result was extrapolated to 7 TeV finding that at the nominal emittance damage would start occurring at an even lower intensity ($10^{10}p^+$). This result, while important for the design of the machine protection system, was not exhaustive of all the possible damage cases in the LHC, therefore a thorough discussion about how to measure material damage following the impact of a beam started. R. Assmann, leader of the LHC collimation project [6], proposed and pushed for the creation of a facility where candidate materials as well as full collimator assemblies could be tested in controlled conditions, as important validation test before their installation in LHC.

The facility, called HiRadMat [7], was approved by the CERN management and is presently under construction, expected to become operational by Autumn 2011. It would allow testing of materials at 440 GeV for protons, and 173.5 GeV/u for lead ions extracted from the CERN SPS.

At the same time, HiRadMat has been proposed as a trasnational access facility within the European Project EUCARD [8], to make it easily accessible to European teams wishing to perform experiments there. As all other beam facilities at CERN, HiRadMat will be open to all CERN users. Experiment proposals will be evaluated by a dedicated committee and scheduled in the available slots in the yearly planning of the CERN accelerators. Details on the application procedure and conditions can be found in [7] .

THE HIRADMAT FACILITY

The HiRadMat Facility will be located in the TNC tunnel in the SPS BA7 area, used in the past by the West Area Neutrino Facility (WANF). CERN is presently dismantling the WANF components before installation of the new irradiation area, the new beam dump, and the new primary line, specially designed to shape the beam according to the user requirements and equipped with all the instrumentation necessary to measure the beam conditions.

HiRadMat will provide proton and ion beams through a fast extraction channel from the SPS already used to inject into the LHC the clockwise rotating beam 1. The momentum of the beams will therefore be close to that used for injection in the LHC, namely 440 GeV/c for protons and 173.5 GeV/c per nucleon for heavy ions. Table 1 shows the key parameters for the beam [7]:

Table 1: Beam Parameters for Proton Tests in HiRadMat.

Beam Energy	440 GeV
Pulse Energy	up to 3.4 MJ
Bunch intensity	$3.0 \cdot 10^9$ to $1.7 \cdot 10^{11}$ p+
Number of bunches	1 to 288
Bunch length	11.24 cm
Bunch spacing	25, 50, 75, or 150 ns
Pulse length	7.2 µs
Beam size at target	variable around 1 mm^2

The 1σ radius of the beam at the target point can be varied from 0.1 mm up to 2 mm, to provide the possibility to test within the same experiment the effect on a material of different energy densities.

Two experimental configurations have been designed, allowing for the installation of either a single 9 m long device, or two 2,2 m long devices that can be tested at the same time, however other configurations can be envisaged. It will be possible to tune the beam waist position along the experimental area and to tweak the beam size according to the requests of the user as shown in Table 1.

A survey has been launched with potential users by the HiRadMat Project Leader to understand the possible uses of the facility. The main proposals are coming from groups working in Machine Protection, near beam devices, high-power targetry, and radiation test of materials.

Radioprotection aspects have been considered from the very beginning. Starting from the maximum number of protons available per year, (10^{16}), it has been decided to provide 10 slots per year for experiments with a maximum of 10^{15} protons each. In average, it will be necessary to wait two weeks before accessing again (in a controlled way) the zone after an experiment. Remote handling facilities will be provided for mounting/dismantling operations including an overhead crane.

The experimental conditions shall have to comply with strict safety requirements, the main being the confinement of the material or device under test. Any spray of melted (or sublimated, or evaporated) material in the area shall have to be prevented. The experiment shall have to foresee a containment vessel for any material or device under test, and provide a detailed risk analysis with the experiment proposal.

The key issue to be faced for the execution of any experiment is the definition of the parameter to be measured, and the method to measure it. A few examples of experiments that may be conducted in HiRadMat, or components that require testing in HiRadMat will be presented in the following. In most of the examples, CERN groups may be able to perform some of the on-line measurements needed, but not the post-irradiation analysis, due to lack of hot-cells and workshops for radioactive materials and of experience in this kind of analysis. Establishing close collaborations with external institutions is therefore essential for the success of the facility.

RADIATION DAMAGE IN MATERIALS

Radiation damage in materials has been extensively studied since decades for nuclear power generation, particle accelerators, aerospace etc. A huge amount of data is available in different compilations, books, and journals. However most of the data concern long term exposure to (even relatively low) radiation fields, inducing damage essentially by the modification of the material structure, that changes in turn also its physical and chemical properties. The visible effect of the modification of the material structure (e.g., displacement of atoms in crystalline materials), are increased brittleness, creep, volume growth, increase of hardness etc.

In particle accelerators, in addition to that, it is important to understand the resistance of materials to an accidental impact of the beam on an accelerator component (typically the vacuum pipe, but also beam intercepting devices like wire scanners, slits, collimators, targets, dumps and beam windows). In this case the modification of the material structure is not necessarily the cause of the damage, but rather its consequence, while the cause has to be looked for in the high energy deposition rate in the material. Energy deposited in very short timescale causes on one side a temperature increase that is difficult to evacuate for a standard cooling system, and on the other side shock waves that can create critical stress conditions in localised parts of the material.

For the LHC in particular, given the high energy stored in the beams and the heavy consequences that damage to one of its components might induce on the rest of the machine, it is important to understand the risk of failure as the intensity increases. We may divide the problem in two classes, presented in the next two paragraphs.

IMPACT OF BEAM INDUCING INSTANTANEOUS STRESSES BELOW THE ELASTIC (OR RUPTURE) LIMIT OF THE MATERIAL.

This case does not necessarily damage the material at the moment of the impact, but can be as dangerous as a destructive event on long term, since repeated impact of beam on a material may modify its characteristics due to fatigue, and modify its intimate structure by DPA and therefore provoke a dramatic breakage after some years of smooth operation. That is, for instance, the case of vacuum windows that interface the machine vacuum with downstream components (e.g. experiments, or beam dumps).

Experiments with neutrons, for example, require very tiny windows to reduce the probability of capture of the neutrons in a thick window material. The thin window often constitutes a high risk since a dramatic failure due to fatigue may cause severe damage to the installations but also create danger to humans if happening during beam off mode. Calculation of rupture due to fatigue is usually performed taking into account estimated DPA and classic fatigue, but no systematic experimental data is available for practical use. The possibility to perform such tests in HiRadMat is under discussion. The main difficulty is that a much larger number of pulses than available in a standard two-week experiment is needed to provoke any observable change in material properties. One of the possible approaches is to age the material with some other kind of irradiation campaign and then to measure the modifications in material properties after a given number of pulses in HiRadMat. The question of course is how to determine the level of material damage before the irradiation in HiRadMat (DPA?). The possibility to have in HiRadMat a test station for long term irradiation tests of small samples is not in its baseline but could be envisaged at the request of an experiment.

IMPACT INDUCING STRESSES ABOVE THE ELASTIC (OR RUPTURE) LIMIT.

This is the case for which HiRadMat may give the most profitable results. Two main types of different test cases can be imagined:

- Test of material samples in well defined conditions.
- Test of mechanical assemblies.

The first case will be driven by studies for machine protection, and for the choice of materials in the design of systems that have to sustain beam impact (targets, collimators dumps etc...). The most important point is to crosscheck our capability to simulate the behaviour of materials under those extreme conditions. The added value of HiRadMat will be to provide the experimenter with very well defined and adjustable conditions like beam size, current and a number of detectors to measure the effect of the impact. HiRadMat will be particularly useful to understand and crosscheck dynamic models, in which the stress level will be locally enhanced by constructive interference of multiple shock waves. As an example we present in the following the case of the TCDQ [9], a single sided collimator installed in the LHC to protect the machine elements downstream the extraction channel from asynchronous beam dumps.

The TCDQ is a 6 m collimator made of 12 graphite blocks, designed to intercept up to 36 nominal LHC bunches (1.67 $10^{11}p^{+}$ each) during an asynchronous dump. Under those circumstances, the stresses calculated by simple energy deposition considerations, in a steady state analysis performed with ANSYS® [10], provide the distribution of temperature indicated in Fig. 1, and the maximum stress starts after about six or seven blocks, where the bragg peak determines the maximum of energy deposition. The block tends to expand and stresses are therefore mainly compressive.

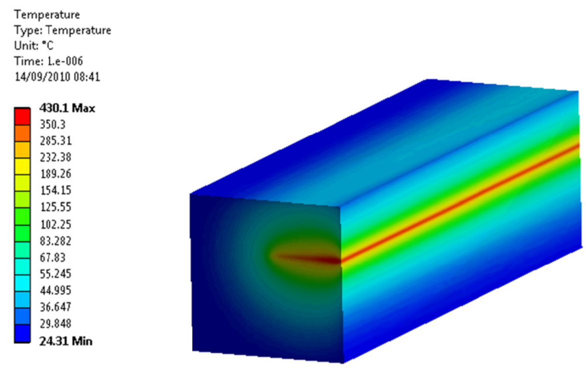

Figure 1: temperature distribution in one of the blocks of the TCDQ after impact of 28 bunches.

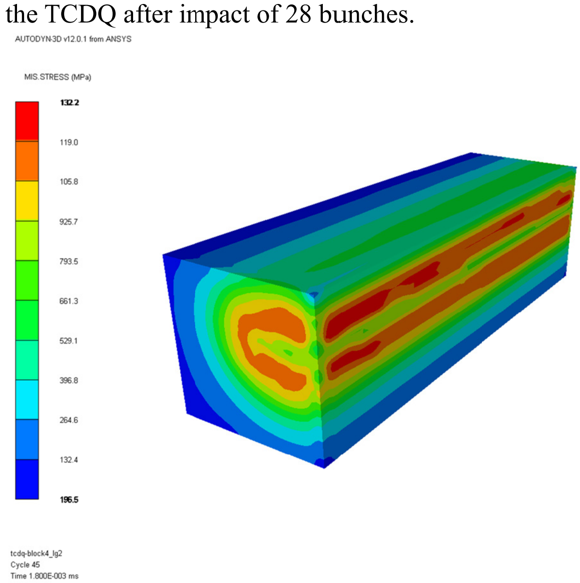

Figure 2: distribution of dynamic stresses calculated with AUTODYN®.

Dynamic simulations (made in this case with AUTODYN® [11]) provide a better interpretation of the energy deposition process. The power deposited has been computed with FLUKA [12] using a longitudinally uniform beam with the energy distributed in about a microsecond period (i.e., the bunch structure inside the train of 36 bunches is, for the moment, not taken into account to simplify the simulation). The beam energy is deposited instantaneously, in a time period that does not allow heat to be transferred adiabatically: the energy deposition period is much shorter than the time constant of heat transfer. The area of material hit by the beam, where the energy is deposited will increase in temperature and expand quickly. The material around, due to the fact that heat has not had the time to be transferred, is still cold and does not expand, creating a resistance to the expansion of the inner material. The stresses are therefore mainly compressive, and a shock wave starts (see Fig. 2). AUTODYN® simulations provide the time evolution and the maximum stress due to the shock wave. Similar results may be obtained with other codes dedicated to dynamic stress analysis.

It is clear that the shock wave evolution will not only depend on the material properties, but also on the geometry of the block and of the mechanical assembly. Anticipating the evolution of such a shock wave is therefore a very complex problem, and validating the simulation process with one (or more) real-life experiments is fundamental to allow robust design of beam intercepting devices.

In addition it is necessary to correctly understand the real impact of local material damage on the functionality of a system. Very localised damages in a thick target may not necessarily compromise the function of the target, meaning that particle production yield may not be affected in a measurable way. Measurements of production yields after this kind of damage, as well as analysis of structural resistance, may improve the understanding of such cases.

Test of complete assemblies also provides information that may be difficult to simulate due to the complexity of an assembly. As an example we may quote the experiment done in 2004 on an LHC collimator prototype in the TT40 tunnel, along the injection line to the LHC [13]. The collimator was made of a 1.2 m graphite block, brazed on a copper substrate used to evacuate heat towards a cooling channel welded on it. The collimator was hit with a number of bunches representing typical accident scenarios in the LHC, for which the collimator was designed to survive. After the experiment, the collimator was dismantled and the graphite block found indeed without visible damage. However, a measurement of the planarity of the side exposed to the circulating beams revealed a permanent deformation of the block in the form of a banana. Detailed analytical and numerical (ANSYS) simulations were performed to understand the reasons of this deformation, and the conclusion was that the heat deposited on the copper substrate had created compressive stresses that drove copper beyond the elastic limit, inducing the permanent deformation. Such an effect may be easy to simulate a posteriori, but more difficult to anticipate in a complex mechanical system. A test in HiRadMat may therefore validate complex numerical simulations or reveal unexpected weak points of mechanical design due to a complex interaction of the different mechanical subsystems, which cannot be classified as direct material damage.

TEST OF LIQUIDS, POWDERS, JETS

HiRadMat will be able to host experiments of special targets like liquid metal targets, powder targets, gas jets etc... Here the aim of the test may be to evaluate the yield production from such a target, to measure heat evacuation in the circuit, and to observe the disruption of the flow in the impact area, or explosion of the powders (or mini-spheres) following the impact. CERN has already a relevant experience with liquid target experiments in ISOLDE, and following the MERIT experiment conducted in the TT2 line of the Proton-Synchrotron, now used for the nTOF facility. Information about MERIT can be found in [14].

HiRadMat may also be useful for the study of material damage in thick targets for the production of radioactive ion beams as in ISOLDE, where lifetimes of the targets get close to the available number of protons in HiRadMat. The interest in this case is again both in the direct observation of thermomechanical phenomena, and in the measurement of lifetime under well defined beam conditions.

ON-LINE AND OFF-LINE OBSERVABLES

In order to extract the maximum information from an experiment, it is important to precisely define in advance which are the observables to monitor during the experiments and the post-irradiation analysis. In fact, the intellectual effort to prepare an experiment where access to the experimental area will not be easy during the two weeks of execution should not be underestimated. As part of the facility, CERN will provide all the information about the beam characteristics, plus radiation detectors and remote handling equipment. Some basic instrumentation, detectors and measurement equipment for the experiment may be provided but they strongly depend on the specifics of each experiment.

For on-line analysis, equipment that has proven its effectiveness in such kind of experiments, and that may be made available from CERN in the future are:

- Any kind of radiation detectors, either counters and triggered on the event.
- Laser vibrometer, to precisely measure instantaneous deformations of materials.
- Laser scanner, to measure remotely permanent deformations of materials without exposing humans to radiations.
- Fast cameras, to visualise instantaneous deformations of materials, liquids, powders etc... Fast cameras can provide images at a rate of few kHz.
- Accelerometers, to measure the propagation of shock waves.
- Local and remote thermometers and infrared cameras to measure the propagation of the heat wave, and the steady state temperature distribution.
- Pressure measurements and flow meters on circuits for liquids (especially water cooling, to verify that the heat transferred to the water circuits does not create a dangerous pressure wave in the hydraulic circuit).

Presently CERN has very limited capabilities of post-irradiation analysis, and has no specific plans for the near future to provide hotcells, while work in radioactive workshops for slightly radioactive materials may be authorised on case by case. Collaborations shall therefore have to be established with laboratories that have those kinds of facilities. A hot cell will be available in the ISOLDE area in 2013, but will be dedicated to the dismantling of spent ISOLDE targets and be made available only in exceptional cases.

CONCLUSIONS

HiRadMat will be a very powerful tool for material and system studies, and will provide more insight into the damage process of materials exposed to beam impact.

It is in general expected that every experiment will involve considerable resources in terms of manpower, but may easily attract universities due to the potential of scientific research on materials. In particular one can easily expect that each experiment (or family of experiments) may constitute the subject of one or even several PhD thesis. Institutes and Universities are therefore strongly encouraged to submit proposals, or to contact CERN in order to join collaborations for the execution of specific experiments.

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