Stefano Redaelli, 01-06-2004

38$^{\text{th}}$ Meeting of the LHC Collimation Working Group, May 28, 2004

Present: Ralph Assmann (chairman), Hans Braun, Enrico Chiaveri, Markus Brugger, Helmut Burkhardt, Gianluca Guaglio, Barbara Eva Holzer, Miguel Jimenez, Stefano Redaelli (scientific secretary), Alexander Ryazanov, Guillaume Robert-Demolaize, Rudiger Schmidt, Vasilis Vlachoudis.

1 Plan for future work on the (A. Ryazanov)

Ralph Assmann (RA) introduced to everybody Prof. Alexander Ryazanov, from Kurchatov Institute. Prof. Alexander Ryazanov (AR) has recently started a collaboration with CERN on material studies for the LHC collimators. The collaboration has been organized as a shared program between the LHC Collimation Project (RA) and the Protection Project (Rudiger Schmidt). The goal is to understand better what will happen to collimator and protection devices when interacting with the LHC beams. AR is an expert of material science, in particular of material damage from exposition to radiation and neutrons. It is hoped that the knowledge of AR and his team will be helpful also for our collimator studies. For example, a question of great interest for us is how long the LHC collimator material (C) will resit, knowing the expected number of protons that will hit the graphite jaws.

AR has been at CERN for approximately one month to get contacts with the people involved in this collaboration. On May 12th, a more restricted meeting took place between AR and various members of the collimator team to discuss in more technical details the effects relevant for future collimator material studies. The minutes of this meeting are appended below for whom is interested. In the Collimation Working Group, AR has briefly summarized his views on how he could help us. People involved in this studies, can be contacted at the following e-mail addresses:

ryazanoff@comail.ru
ryazanov@cityline.ru

AR is convinced that interesting new phenomena will be found by studying the extreme conditions of a 7 TeV proton beam interacting with the LHC collimators. AR believes that, in order to estimate the collimator life time, future studies should focus on the topics listed below. These issues are also important to study the degradation of thermal and electrical properties of the collimators due to radiation.

1) **Temperature rise due to the impact with the beam.**
The temperature rise of the graphite collimator jaws due to the impact with the LHC beam has to be estimated by taking into the interaction of the beam particles with the C atoms. Unlike for metals, where the thermal conductivity is dominated by the free electrons, for the carbon also the phonons must be considered. According to AR, the FLUKA results should provide a good starting point for the temperature rise simulations because they allow estimating the energy deposited by the impacting beam.

2) **Damage due to atomic displacements.**
The energy deposited by the beam does not only induce a temperature variation but can also cause atomic displacements. When hit by the protons, the carbon atoms recoil and, for sufficiently large deposited energies, can produce showers of atomic cascades and sub-cascades. The size of the cascades and their location strongly influence the material properties. Typically, atomic displacements can create "bubbles" of atomic vacancies that make the material brittle and increase the material porosity.

3) **Shock waves.**
Shock waves are typically generated by temperature spikes inducing local thermal

expansions. However, another possible source of shock waves is the so-called *Coulomb explosion*: the passage of protons through the collimator can produce electrons that in turn generate a strong electrical field. This field can be sufficiently high to move coherently the atoms of the crystal and generate waves. At the front of the shock waves, there can be a local increase of temperature large enough to induce fractures of the material.

4) **Accumulation of gasses (H, He).**
Light gasses such as H or He are produced due to the interaction between the beam protons and the graphite. Rather small proton energies of approximately 100 keV are sufficient to induce this phenomenon. About 8×10^{20} atoms could be produced per year with the expected number of protons impacting on the collimators (to be verified). The accumulated atoms cannot easily be expelled because they can combine and generate larger molecules which cannot leave the material through the porosities (answer to a question by Miguel Jimenez).

Enrico Chiaveri (EC) welcomed the presentation of all these interesting effects for future studies. He asked about a specific plan for the future work. RA stressed again that our important goal is to obtain real estimated of the collimator life time in order to see how often the collimators should be replaced.

Helmut Burkhardt (HB) asked why the choice of the shower codes was limited to FLUKA. Other codes, such as GEANT, could also have been considered. AR Answered that from several interactions with Alfredo Ferrari and the CERN FLUKA team, he got the impression that all informations required as inputs for his simulations can be already extracted from what is provided by FLUKA. It is then pointless to waist time on repeating the already available results with other codes.

2 Impressions on the RHIC collimation system (R. Assmann)

See slides at http://www.cern.ch/lhc-collimation/files/RAssmann_2004-05-28.pdf

RA reported on its trip to RHIC of last week. Angela Drees showed to him in detail the RHIC collimation system, several pictures of which are available in RA's presentation. RA highlighted some aspect that was particular interesting. He noted that at RHIC the collimators have bellows much longer than what we foresee for the LHC.

RA pointed out the strong connection between the RHIC collimation and Beam Loss Monitor (BLM) systems. Dedicated BLMs are attached to each collimator and their position is manually optimized to obtain the best signal. After getting the required experience, the collimator set-up time was reduced from 30 minutes to 5 minutes (a beam-based optimization is repeated before each run). RS suggested that it would be interesting to cross-check the optimization of the RHIC BLM system with simulations, in order to assess our simulation tools.

EC asked if there are radiation issues for the RHIC collimators. There should be none, according to RA (at least, this is what he hopes because he visited them from very close).

3 Discussion on collimation review (R. Assmann)

RA shown a tentative program for the Review of the LHC collimation system, that will take place in early July. The preliminary program, with the full list of invited reviewers, is available on the web. A link to the external review web page can be found on the collimation project page: `http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/` RA welcomed suggestions about possible changes of the program.

Stefano Redaelli, 01-06-2004

4 AOB

- RA announced that the Engineering Change Request with the final layout of IR3 and IR7 was finally released and presented to the TCC. No objections were raised.
- RA also announced that the collimator prototyping proceeds well. Flatness measurements have been performed (some preliminary data analysis show that we are only a factor 2 larger than our flatness requirements) and the electrical circuits will be installed next week.
- Helmut Burkhardt announced the half day general meeting on "Clean injection into the LHC", which will be held on Friday, 11 June 2004 (9:00 - 12:30). The aim is to combine people and subjects spread over several groups and meetings like Protection WG, Collimation WG, SLI, LHC optics team, LHCOP and InjWG, to try to give answers/status on questions related to the collimation in the transfer lines.
- Miguel Jimenez mentioned that there is a problem with the 3D integration of various components in the insertion lines. HB will follow this issue up.

The next meeting will be held on June 4th at 14h30, J.B. Adams room.

Stefano Redaelli, 01-06-2004

Informal meeting with Prof. A. Ryazanov, Kurchatov Institute
May 12, 2004

Present: Oliver Aberle, Ralph Assmann, Alessandro Bertarelli, Alfredo Ferrari, Alexander Ryazanov, Stefano Redaelli, Rudiger Schmidt, Vasilis Vlachoudis.

1 Introduction

This informal meeting was organized by Ralph Assmann and Rudiger Schmidt to introduce to the people of the collimation team Prof. Alexander Ryazanov, who has recently started a collaboration with us on material studies for the LHC collimators. Professor Ryazanov is an expert of material science, in particular of material damage from exposition to radiation and neutrons. Nowadays a lot of effort is worldwide devoted to the study of damages of some components the nuclear power stations due to the exposition to neutrons. A better understanding of the degradation of some material properties, such as lifetime and density, is envisaged to estimate the lifetime of the power stations and to optimize the interventions on some critical components. For instance, the behavior of the graphite bars, used as reflector material for neutrons, still needs clarifying. It is hoped that knowledge of AR and his team will be helpful also for our collimator studies, which will also operate in a high radiation environment. For example, an interesting question for us is how long the LHC collimators will survive, knowing the expected number of protons that will hit the graphite jaws.
During the meeting, the interest was mainly focus on three possible topics for future studies in collaboration with AR:

- Effect of deposited energy on the graphite properties.
- Effect of neutrons on the graphite properties, including cascade and sub-cascade of formation due to elastic collisions of atoms.
- Shock waves induced by protons impacting on the collimator.

As summarized below, AR explained at the board his thoughts and views about the aforementioned items. It is noted that for items (1) and (2), some work with well-defined goals has been discussed. Next week a more restricted meeting will take place (AR, A. Ferrari, R. Schimdt) to define how the FLUKA simulations can be extended to properly take into account the effect of neutrons. On the other hand, the discussion item (3) was focused on a new phenomenon (shock waves induced by "Coulomb explosion") and no actions were defined.

2 Effect of neutrons on the graphite properties

Three are the main phenomena relevant for the interaction between neutrons and graphite:

- Temperature rise;
- Atomic displacement and cascade and sub-cascade formation;
- Production of gas (H, He, ...).

The temperature rise, which is the effect typically taken into account by codes like FLUKA, is not sufficient to explain all the experimental observations. Namely, when the graphite is irradiated with neutron, it first shows a shrinkage of approximately 0.5 % to 5 %. Then, for increasing neutron fluxes, the material expands up to approximately 20 % to 30 % of its original volume. The smallest dimension is attained at fluxes of the order of 10^{19} neutron per cm^2. The flux at which the maximum elongation takes place is not well defined (it strongly depends on the manufacturing procedure), even though it is of major concern for the life-time of some crucial components of the nuclear power station reactors. When a neutron hits a carbon atom, the atom recoils and can possibly generate a cascade of atomic displacements. If the cascade has a typical length larger than the average atomic displacement, it can irreversibly generate in the graphite clusters of atomic vacancies and clusters of point defects, which eventually changes the properties of the graphite. In particular, the material becomes brittle.

The atomic vacancies can close again and disappear if they are sufficiently small, or can stay forever in the material. In addition, they be filled by the gas molecules produced by the interaction between graphite and particle shower. Mainly atoms of H and He are produced and can progressively accumulate in those "bubbles", making them more stable and reducing the probability for the vacancies to disappear. The accumulation of many bubbles is dangerous because they deteriorate the mechanical properties of the graphite, such as density and porosity, and can become centres of creeps.

The effect of neutron fluxes related to the atomic displacements is generally expressed in *dpa* units (displacement per atom). One dpa corresponds to 10^{20} neutrons per cm^2. It was generally agreed that for the collimation studies it would be very useful to estimate how many dpa are induced into the collimator jaw per impacting proton. Together with the information of the expected gas production from the particle shower, this would allow estimating in detail the combined effect of atomic displacements and gas production. One could think of generating a sort of "phase diagram" of the parameters for which those two combined effects become critical for the collimator survival. Also the "standard" thermal effects have obviously to be taken into account.

For the time being, FLUKA simulations do not include in detail all the relevant effects. However, according to A. Ferrari, it seems that most of the inputs required AR for more detailed studies of atomic displacement effects can indeed be calculated with FLUKA. For example, the deposited energy which is transmitted to the carbon atoms can be calculated but for the time being it is only translated into equivalent temperature rise, instead of being used to quantify the dpa experienced by the graphite block. It was noted that the produced gas can instead be provided directly with FLUKA. This should be enough as a starting point for the simulations of AR. More detailed discussions and plans for future studies will take place between AR and AF.

3 Shock waves

It is generally believed that shock waves in materials can only be generated by quick temperature variations induced by the deposited energy from the beam. However, AR explained another possible effect that can be important, the so-called "Coulomb explosion". It is fair to note that so far, such an effect has not been experimentally observed. When a proton travels through a material along a straight line, it produces a large number of electrons, travelling perpendicularly to the proton direction of motion. This generates a local variation of the charge around the proton trajectory and consequently a cylindrically symmetric electrical field. This field transmits a momentum to the atom nuclei and can induce a strong shock wave. Since all electrons are emitted with a cylindrical symmetry around the proton path, all the forces on the atoms sum and result in a strong radial stress, which can generate a shock wave.

In a metal, the electric field generated by the Coulomb explosion is quickly compensated by the available free electrons, which re-arrange their positions to reduce the induced fields. The typical dimension of the cylindrical region around the proton trajectory is of the order of 5 to 10 Armstrong and typical field life-times are of the order of 10^{-15} s. The effect of

Stefano Redaelli, 01-06-2004

Coulomb explosion is potentially more important for the graphite because no free electrons are available. The field life-time is expected to becomes larger and hence large shocks can have time to add-up (the effects of several protons passing through the graphite have more time to accumulate). It remains to be verified whether this can be a problem for the LHC collimators.
AF noted that FLUKA can calculate the distribution of electrons with energy larger than 1 KeV produced by the protons travelling through the graphite. This should be a good starting point for AR to estimate the effect of Coulomb explosion on the LHC collimators.