CERN/DG-2008-196-O 15th July 2008

MEMORANDUM

Interaction of the CERN Large Hadron Collider (LHC) Beam with the Beam Dump Block

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Introduction

The LHC will start to operate at CERN during 2008. All safety analysis have been reviewed many times during the long period of design and construction; their conclusions are clear: there is no matter of concern in safety against nuclear hazards.

Nevertheless, an “independent researcher” (as he calls himself), holding a PhD in nuclear reactor physics and engineering, has questioned publicly the “possibility of a chain reaction from nuclear fusion” in the graphite dump of the LHC beams, in particular when the “diluter” action fails to distribute the beams in a large volume of the dump as expected.

The proposed concept probably refers to the assumed similarities with the physical conditions prevailing in “inertial fusion” experiments where a small sphere of D+T is compressed to very high densities by a set of high power beams (laser radiation, or particles) with almost spherical symmetry to reach conditions of ignition in the center: an achievement not yet realised with hydrogen isotopes, in spite of quite many years of research and development, not to mention carbon when it would be many orders of magnitude more difficult to achieve.

The following provides evidence, in simple terms, that the LHC beam dumping conditions are far away from the relevance of the proposed hypothetical concept.

Beam size in the beam dump block

The LHC will collide protons with a momentum of 7 TeV/c and achieve a luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This requires two beams, each with 2808 bunches and $1.15\cdot10^{11}$ protons per bunch. Two neighbouring bunches are in general separated by 25 ns and the total length of the bunch train is about 85 μs. The total energy stored in each beam is about 360 MJ. At the end of a physics fill, in case of equipment failure or beam instability, the beam is extracted into the graphite block of the beam dump system. There is one extraction system for each beam.

For extraction, the beam is deflected by kicker magnets within 89 μs and travels through a 700 m long transfer line towards the graphite block located about 940 m downstream from the kicker magnets. When entering the graphite block, the bunch size is about $\sigma = 1.5$ mm both in the horizontal and vertical plane (Gaussian particle distribution).

The bunch size of σ = 1.5 mm at the graphite block is determined by the beam emittance and the beam optics and cannot be much smaller. There is no focusing magnet installed in the 940 m long beam dump line which could modify the spot size on the graphite block.

In order to limit the energy density that the beam deposits in the graphite block and to avoid damage, dilution kicker magnets deflect the beam. Therefore, each bunch hits another location of the graphite block, limiting the maximum temperature inside the graphite to about 700 ^{0}C.

In case the dilution kicker magnets do not work, the transverse dimensions of the beam at the entrance of the graphite block is determined by the bunch size and the deflection angle of the extraction kicker magnets. The deflection angle changes during the time of extraction, it is therefore not possible that all bunches hit the same spot on the graphite block. The spread of the beam in the horizontal plane will still reduce the maximum energy density deposited in the graphite block by a factor of about 2.5.

If it would be possible to deflect the full beam into a spot with the size of less than a mm, this energy deposit over 85 µs is long enough to change the density of the target material. The density decreases at the inner part of the beam heated region because of the outgoing shock waves in the transverse direction. As an example, after the impact of 200 bunches with a size of σ = 0.2 mm, a maximum temperature of 7000 ^{0}C and a density decrease by a factor of 4 is expected. Bunches that will be delivered in the later part of the pulse will penetrate further into the target. The beam tunnels through the target and deposits the energy with a penetration depth of 10 m to 15 m in case of a long target. This tunnelling effect has previously been observed for intense heavy ion beams with pulse durations of the order of 1 µs irradiating solid targets.

Interaction of a 7 TeV/c proton with matter

The energy deposition of a proton with a momentum of 7 TeV/c in carbon is mostly due to the hadron shower after the proton enters the material. The shower proceeds through successive nuclear non-elastic interactions that generate secondary particles, mostly pions, until the energy is degraded enough that no further particle production takes place. The mean free path for nuclear non-elastic interactions at 7 TeV is roughly 80 g cm^{-2} for carbon, as a consequence the energy deposition as a function of depth shows a broad build-up and peaks at about 140 cm. Hadron showers have an intrinsic lateral spread due to the transverse momentum of the secondary particles produced in nuclear interactions. The energy distribution at the shower maximum is therefore not point-like, but has minimum dimensions in the order of 0.5 mm even for a 7 TeV/c pencil beam with zero transverse dimensions.

During the development of a hadron shower, at each nuclear interaction roughly one third of the incident energy is transferred to neutral pions, which in turn decay into photons and generate electromagnetic showers. A large fraction of the remaining energy is spent by fast charged particle ionization and excitation energy losses with atomic electrons. Out of the roughly 5000 nuclear non-elastic interactions occurring in each 7 TeV shower, most of them are endo-energetic. The overall balance between endo-energetic and exo-energetic reactions, mostly neutron captures, is negative.

It is important to stress that, contrary to naive expectations, the basic features of hadron-nucleon interactions of 7 TeV protons with particles in a fixed target are well known. The corresponding centre-of-mass energy, 115 GeV, is in between the maximum energy, 63 GeV, of the Intercepting

Storage Ring CERN collider (ISR), and the energy range, 200-360 GeV, explored by the CERN SPS collider.

The development of a hadron shower is common knowledge within the High Energy Physics community. Monte Carlo codes are used for calculating the energy deposition profiles of hadron showers, as well as the kind and the amount of nuclear reactions taking place in the target material. These codes are based on physics models carefully benchmarked against experimental data and cross-checked among themselves over a wide energy range. In particular, the most critical ingredients, longitudinal and transverse momentum distributions and particle multiplicities, are strongly constrained by the available experimental data. The accuracy of these codes when estimating the maximum energy deposition density in bulk matter is very conservatively assumed to be within a factor 2-3, and it is likely much better. For experiments with the CERN SPS beam deflected into a target the temperature increase was predicted with an error of less than some 10%.

It might be noted that a spinoff of the studies for SPS beams impacting into material demonstrated the interest of using these accelerators to create through the original nuclear reactions high-energy density (HED) “exotic” states in matter. These include expanded as well as compressed hot liquid states, two phase liquid-gas region, critical point region, etc. Study of fundamental properties of these exotic states of matter, especially the equation of state (EOS) properties, is of considerable interest to many branches of physics, astrophysics for example. Experiments in this field are being planned at the FAIR facility at GSI, Darmstadt.

Parameters for inertial fusion and LHC

In all inertial fusion concepts with hydrogen isotopes D+T the fuel must be compressed to up to 500 times the solid density and a small hot spot be generated (“ignited”) at the centre of the compressed material by selective shock heating. If conditions suitable for “ignition” are achieved (T> 5.10^7 K and pressure in multi megabars) and the dimensions of this central hot zone are large and dense enough, the α particles generated in the D+T fusion reactions are captured in the surrounding burning zone helping the burn to propagate outwards. This requires that the $\rho\cdot R$ (product of density and radius) of the burning zone is $\rho\cdot R = 0.4$ g/cm^2, which is the range of the alpha particles. For a density of 100 g/cm^3, the radius should be 40 µm. For solid density a radius of the order of 2 cm should be required, but in these conditions no means exist to deliver the power density necessary to first ignite the center.

D+T fusion reaction is most easy to achieve requiring a temperature of “only” $5\cdot10^7$ K to ignite the fuel. The ignition temperature for C+C reactions is much higher, requiring a much higher power density, and accessible only in the interior of a star when it collapses at the end of its life.

In case of the LHC, the material is not compressed, but strongly diluted in the beam heated region. As an example, after 40 µs the density decreases to less that 1% solid density.

In summary, even if some fusion reactions are occurring in carbon in the beam heated region (extremely low probability compared to other nuclear reactions), ignition will be very far to be reached. The whole process will be endo-energetic.

A chain reaction from nuclear fusion due to an impact of the LHC beam on the graphite dump is completely excluded.

Material for further reading

1. N.A. Tahir et al., Impact of 7 TeV/c CERN Large Hadron Collider Proton Beam on a Copper Target, J. Appl. Phys. 97 (2005) 083532.

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3. N. A. Tahir et al., Interaction of the CERN Large Hadron Collider (LHC) Beam with Carbon Collimators and Absorbers, Proceedings of European Particle Accelerator Conf. EPAC 2006, Edinburgh, Scotland

4. V.E. Fortov, B.Goel, C.D.Munz, A.L.Ni, A.Shutov, O.Yu.Vorobiev, Nucl. Sci. Eng. 123, 169 (1996).

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