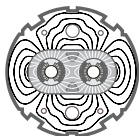EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1164

Summary of the CERN Workshop on Materials for Collimators and Beam Absorbers

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Abstract

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The event was driven by the LHC challenge, with more than 360 MJoule stored in each proton beam. The entire beam or its fraction will interact with LHC collimators and beam absorbers, and with the LHC beam dump blocks.

Collimators and beam absorbers are also of the interest for other labs and accelerators:

- CERN: for the CNGS target, for SPS beam absorbers (extraction protection) and collimators for protecting the transfer line between SPS and LHC
- GSI: SIS18 and SIS 100/200, Super-FRS target, HED experiments, Antiproton target, etc.
- Fermilab: Tevatron and Main Injector collimation systems; neutrino production targets (MINOS, SNuMI, NOVA); antiproton production targets; pion production targets and beam absorbers for neutrino factories and muon colliders
- ILC: positron production targets, beam absorbers and collimators for a beam delivery system.

Department AB

CERN Workshop on Material for Collimators and Beam Absorbers, 3 to 5 September 2007

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SESSION OVERVIEW

The workshop included the following sessions:
1. Introduction – collimators and beam absorbers for different accelerators.
2. New ideas / new materials.
3. Experimental results and future tests.
4. Codes and simulations results.
5. Discussion of plans and opportunities for studies and tests at CERN, and summary.

ISSUES FOR THE WORKSHOP

During the preparations for the workshop a series of questions was compiled that should be addressed by the speakers and in the discussions:

- What problems were encountered for systems used in different accelerators and what solutions were adopted?
- What materials are being used? What led to the choice of these materials? What are the limits of the present solutions? Why will more robust devices be needed in the future? What is the perspective in the framework of new or upgraded machines? What are the relevant parameters for beam impact on the material, such as deposited beam energy, beam power and time structure of the beam impact?
- What material parameters are relevant, such as specific heat capacity, enthalpy, Young's modulus, yield stress, coefficient of thermal expansion, thermal conductivity? What are the relevant figures of merit? Are the bulk or microscopic parameters the relevant ones, particularly for composite and anisotropic materials?
- What materials are most suitable, e.g. robust and with low electrical resistance? Other parameters such as anisotropy of materials and secondary electron yield? Are there new materials on the horizon?
- What happens in case of shock impact (time constant ~µs or ~ns) and continuous impact (time constant ~s)? What are the relevant physics effects to be considered?
- What are the limits of the domain of application of the classical thermo elastic / plastic theory with respect to the hydrodynamic theory of shock waves?
- What happens to the material beyond melting / vaporisation temperature? (Example: beam tunnelling through materials).
- What is the design limit based on, e.g., maximum temperature? When do we require renewable / disposable / sacrificial devices?
- What is the status of the codes for energy deposition calculations (FLUKA, MARS etc.)? When do calculations for shock impact with mechanical engineering codes (e.g., ANSYS, AUTODYN, LS-DYNA) break down? What are the domains of validity for simulation?
- How to compare the results from different codes, possibly for some (simple) test cases to be defined?
- What experimental evidence and experience with benchmarking do exist?
- How to formulate an equation of state (EOS) for materials in advanced codes?
- What are the short- and long-term effects of radiation? What is the effect of the total dose on material properties, and on equation of state? Is there an effect of the dose rate?
- DPA (displacements per atom) is a measure of the material change. Is this a universal measure for different radiation fields? Is there temperature

dependence during radiation? What about annealing? Can this be used to 'repair' devices?

- What tests of materials are possible? What to test? Where to test? How to analyse test results? Test bench at SPS?
- Material requirements for special concepts or locations, e.g. collimators and absorbers at cold or at intermediate temperature, collimators with superimposed magnetic fields, etc.
- What R&D is being done or is in the pipeline for investigating devices with special locations and concepts?

SESSION 1: INTRODUCTION – COLLIMATORS AND BEAM ABSORBERS FOR DIFFERENT ACCELERATORS

Requirements from LHC Collimation, R.Assmann (CERN)

LHC foresees a staged implementation of collimation. The first stage is presently being constructed and installed. A second stage should allow an even higher performance reach and should address several possible limitations in the initial installation. Collimators are the closest elements to the high-intensity LHC beam and must be designed to directly intercept beam particles. The question of materials close to the beam in the presence of high power load and high activation is a crucial ingredient in the studies towards an upgraded collimation system.

The Phase 1 system should already deliver outstanding performance and allow reaching a 200 MJ regime (100 times above Tevatron/HERA).

However, limitations are expected on the way towards the requirements for the LHC nominal, ultimate and upgrade intensities. R&D for the Phase 2 system is starting now. Critical for this work:

- Theme 1: Understanding material limitations and operational procedures (experiments and theory) for Phase 1.
- Theme 2: Selection of materials R&D for Phase 2.
- Theme 3: Define test needs for materials of Phase 2.

The installation of new Phase 2 collimators will be done when the LHC has already been operated. Since a certain level of activation in the LHC tunnel is expected, the necessary supporting systems have already been installed.

Work for the Phase 2 collimation is ongoing at LARP (collaboration with US), at CERN and in the framework of the FP7 programs. This workshop is expected to provide input to the ongoing activities.

Discussion: The collimators have been designed to allow for fast exchange, and the necessary equipment for future collimators has been installed. Fully remote handling of collimators is not possible.

Beam Absorbers for Machine Protection at LHC and SPS, B.Goddard (CERN)

A variety of machine protection collimators and beam absorbers are foreseen for the SPS and LHC to protect against failures ("Zoo of absorbers").

The high-intensity high-energy beam accelerated in the SPS is already far above the damage threshold. Absorbers for the SPS extraction are installed, as well as in the transfer lines from the SPS to LHC. The challenge is to develop robust absorbers in the presence of many constraints.

For the LHC injection, protection is done with Boron Nitride absorbers, Al and Cu absorbers and masks upstream.

The LHC beam dumping system requires a set of beam absorbers: the beam dump block, absorbers for protection of the extraction septum magnet and quadrupole magnets in the insertion and LHC ring.

There are specific problems for each device and different solutions were adopted such as:

- Local protection with sandwich structures of materials with different Z to absorb all energy.
- Diluters to increase the emittance, absorbing only a small part of the energy, followed by a drift space and a mask.

Material robustness is a general issue and any improvement of materials might find an application. Graphite is already a very good material for beam absorbers, but other materials are on the horizon, that could be of interest in particular for the LHC intensity upgrade.

Discussion: For some devices, the increase of the water temperature must be limited to 9 ^{0}C. This range is considered to be too small. With an increased temperature margin, the design of the absorber would become much simpler.

What is the effect of radiation damage on the beam dump blocks? In the Tevatron graphite absorber blocks are already installed since 1980 and did not show any sign of radiation aging.

Tevatron Collider Collimators and Absorbers, N.Mokhov (Fermilab)

Beam collimation is mandatory at any superconducting collider to protect components against excessive irradiation during normal operation and accidental situations:

- Minimize backgrounds in the experiments.
- Maintain operational reliability over the life of the machine.
- Reduce the impact of radiation on environment.
- Minimise radiation dose for hand-on maintenance.
- Minimise radiation damage of equipment.

The Tevatron collider uses external and internal beam absorbers. A highly-efficient two-stage collimation system at the Tevatron reliably serves these purposes. The system

evolved over 25 years. MARS-STRUCT Monte Carlo simulation results – which match the experimental observations - give the current Tevatron cleaning system efficiency 99.9 %.

Recent developments include marble shells and crystal collimation. Tests on crystal collimation gave first good results, with the background in experiments reduced. The full crystal collimation project was recently approved. Crystal channelling is an interesting option for the LHC upgrade.

A particular risk is equipment damage at an un-synchronised beam abort. One accident with the full beam lost in the Tevatron damaged collimators in 2003.

The external beam dump – with the core comprised of graphite plates encapsulated in an aluminium shell with cooling channels - has worked for 17 years without any damage. The internal beam dump, used in the Tevatron Collider, is also based on graphite followed by aluminium and steel, and is in a successful operation for almost 20 years. The designs of the both dumps were based on MARS calculations.

Discussion: Based on the Tevatron experience, a maximum temperature rise of ~1000 ^{0}C in graphite at a pulsed irradiation is not a problem if the material does not get into contact with air. With air, the limit is about 300 ^{0}C. Titanium windows are used since a long time, with a beam spot of the order of 1 mm, and no problems are reported. The temperature rise of the internal dump block after a beam dump is of the order of tens degrees C.

Phase II Collimators for LHC Upgrade at SLAC Material Issues, E.Doyle (SLAC)

A rotating collimator as developed at SLAC for NLC is proposed for the LHC Phase 2 upgrade to provide a low impedance metal collimator, able to recover from several damaging hits by the beam. A particular challenge is to absorb 10 kW with less than 25 µm deflection. The collimator has 20 facets and needs to be cooled. FLUKA/ANSYS simulations have guided the design decisions and the materials considered for the jaws. Although Cu is the best material for cleaning efficiency, thermal distortion and manufacturability, Glidcop has been selected for the jaws for mechanical stability.

In case of an accident, permanent deformation of 54 µm is expected. Some 20 cm long pieces were fabricated, but there are still many material issues.

Testing is required, in particular for the case of a beam accident. A question to be addressed: one bunch will damage the collimator, but will the damage be limited to the surface (this would be acceptable).

Discussion: Would it be possible to build a jaw using several slices longitudinally? Probably not, since this would increase the impedance. It was stressed that it is very important to test these devices, and compare the results with simulations.

Lattice Optimization for Low Charge State Heavy-ion Operation - Collimation Concepts for Beam Ions after a Charge Change, J.Stadlmann (GSI)

A new lattice design concept for heavy ion synchrotrons has been developed that is optimized for the control of beam loss by projectile ionization. The lattice of the FAIR SIS100 synchrotron has been designed as charge separators. Thereby ionized projectiles are well separated from the reference beam. The generated peaked loss distribution enables the operation of a highly efficient scraper system.

The main purpose of the scraper system is to suppress and control the production of desorption gases and thereby stabilize the residual gas pressure dynamics. Ions get lost because of several effects: vacuum instability etc. Every cell is optimized to catch U29+ ions. After optimising the lattice using DF doublet structure, the efficiency close to 100% of capturing is achieved. The efficiency has been optimized for single ionization since the probability for double ionisation is very low. The scrapers are outside of the acceptance region. The simulations were done with the code STRAHLSIM developed at GSI.

Such a lattice could be also of interest for beta beams at CERN, and for PS ion operation.

Discussion: What about ions coming out at the back side of the jaw, could they lead to desorption? For future machines like a new CERN PS, is an accelerator with superconducting or normal conducting more appropriate with respect to ion induced desorption? No conclusion was given.

Beam Dynamic Vacuum - Collimator Technology for Suppression and Control of Desorption Gases, C.Omet (GSI)

During operation with low-charge state heavy ions (e.g. U28+) in the GSI synchrotron SIS18, fast beam losses have been observed. At the same time, a dynamic behaviour of the residual gas pressure was observed that compromises operation. To overcome these problems, a collimator system has been developed and is now in the final preparation for installation into two of the twelve sectors of the SIS18 in the next shutdown. An optimum collimator positioning for the SIS18 is not possible.

This upgrade is required for the SIS18 to operate as a FAIR injector in order to get to a requested performance. It incorporates the use of the CERN developed NEG coating as well as low-desorption rate materials found out by systematic studies using the ERDA (Elastic Recoil Detection Analysis) technology at GSI. The collimator system will both reduce the desorption rate as well as control of unavoidably produced desorption gases. Only little beam power will heat the collimators. Simulation studies include static and dynamic vacuum calculations.

The cross section for ion-induced desorption decreases with the beam energy, the most important effects is at low energy. For the SIS18, a series of improvements such as a higher ramp rate, better pumping, etc. resulted in much more ions being extracted. A very low desorption rate of 25 mol/ion (Au normal 1200 mol/ion) is achieved.

Discussion: Experiments demonstrate that there are no problems with Ni used as diffusion barrier in the collimators.

Design and Testing of ILC Beam Delivery System collimators, J.L. Fernandez Hernando, (STFC/ASTeC)

At the ILC with up to 500 GeV per electron and positron beams, the removal of halo particles having large amplitudes relative to the ideal orbit is mandatory to both minimise damage to beam line elements and particle detectors and to achieve tolerable background levels in the latter. In the high-energy, high-intensity environment of the linear collider, the low background levels will largely be ensured by placing a set of mechanical spoilers/absorbers very close to the beam. This presents two problems:

- Short-range transverse wake-fields excited by these collimators may perturb beam motion and lead to both emittance dilution and amplification of position jitter at the IP.
- Impact of even a small number of bunches at the expected energy densities can damage the spoilers due to the small beam size.

Simulations were done for different spoiler designs to determine the energy deposition of an ILC bunch using FLUKA, Geant4 and EGS4. Solid Cu becomes too hot; the temperature of C and Ti should be acceptable. The shower simulations were used as input to thermal and mechanical studies using ANSYS.

Measurements of the transverse wake-fields induced by collimators of differing geometries were performed at the "End Station A" of SLAC. The jaws have long shallow tapers to limit the impedance. The trajectory of the beam upstream and downstream of the collimator test apparatus was calculated from the outputs of ten BPMs (four upstream and six downstream), thus allowing a measurement of the angular kick imparted to the beam by the collimator under test. The transverse wake-field was inferred from the measured kick. The wakefield has been measured for many different collimator shapes and materials.

A preliminary analysis of the collected data and comparison to theoretical and analytic predictions indicate that the kick from experiments is smaller than the kick from models, but the results are preliminary.

A proposal for tests is under preparation to optimise the material choice and mechanical design of the ILC spoiler jaws using ATF, and benchmark the energy deposition simulations and the ANSYS studies. Material damage tests are planned at the ATF KEK. It is recalled that some damage tests have been done at SLAC FFTB during 2000, similar to CERN experiments.

General discussion: Zoo of collimators and beam absorbers

There are many different types of collimators and beam absorbers that are required for the LHC and its pre-accelerators as well as for other machines:

- in general these objects are long (typical 1 m, up to 8 m);
- some of them are very close to the stored circulating beam (~1 mm);
- some of them are designed for high heat load;
- some of them are designed for occasional or regular shock impact (1 MJ …. 360 MJ);
- some of them require a very flat surface (~10 μm);
- some of them require very good surface conductivity (although the impedance issues are still not fully understood);
- most of them require to operate in UHV.

For most types several requirements come together.

SESSION 2: NEW IDEAS / NEW MATERIALS

LHC Collimators (Phase II): What is an ideal material? A. Bertarelli (CERN)

The collimation system which is being installed in the LHC has been designed to ensure high robustness during the start-up and initial luminosity runs (Phase 1). However, since the collimators are the closest elements to the beam, RF studies predict that the Phase 1 collimator impedance will prevent the machine from attaining its nominal luminosity. Hence, from the early phases of design, it has been envisaged to complement this system with a series of secondary collimators (Phase 2), allowing to overcome the impedance issue and increase the collimation efficiency. The Phase 2 collimators will have a new design / new concept.

One essential parameter to meet such an ambitious goal will certainly be the type of material chosen for the new collimator jaws. Given the Phase 2 collimation requirements, this "ideal" material shall have a low electrical resistivity and a relatively high mass density. On top of this, a close-to-zero coefficient of thermal expansion (CTE), high yield strength, high thermal conductivity and good shock resilience are desirable. It must be possible to well process the material since the jaws have a length of more than 1 m. Several new materials could be considered, such as Diamond based Cu and Al.

Discussion: The cost of the material is left for future considerations. Materials with carbon fibres are more expensive than Diamond.

The maximum temperature at beam impact can be derived from material parameters.

Coating has been discarded earlier for Phase 1 collimators. However, it might still be an option, for example, coating that does not cover the part where the beam is expected to hit the jaw.

Diamond-based Metal Composites, L.Weber (EPFL)

High-end applications as the beam collimators for the LHC, first wall materials in fusion reactors and applications for electronics heat sinks require both, innovative engineering of the assembly and the structural parts as well as unique property combinations of the materials they are made of, e.g., good electrical conductivity, high thermal conductivity, low absorption of elementary particles, low coefficient of thermal expansion, high stiffness, high strength etc.

Some of these requirements may even be mutually exclusive in monolithic materials. A common strategy to cope with such unprecedented property combinations is to use a composite approach, which is essentially a structural solution on the micron scale. Materials combining diamond particles and metallic matrices combine low CTE, high thermal and electrical conductivity, and high stiffness.

There are some few fundamental issues concerning the potential and the limitations of these materials as well as possibilities for manufacturing and current challenges in the development.

Production is by a liquid metal infiltration process. Pieces can be produced in the required shape. Good results have been obtained with Ag-Si or Cu-B alloy, 60% volume diamonds. The content of Si and B should still be optimised. Ni is added to improve the performance of the material as it binds access of Si. Low content of nitrogen is for good thermal conductivity. The thermal properties of Al Diamond depend on the production.

The price for industrial diamonds is not particularly high.

Discussion: The porosity of the material depends on the production process and can be very small. Concerning short temperature shocks, not much detoriation was observed when emerging the material in liquid Nitrogen.

The radiation resistance of Diamond based composites is not known and tests should be made.

Copper Based Composites Reinforced with Carbon Nanofibres, R.Nagel (ARC)

The Powder Technology Centre of the Austrian Research Centre (ARC) GmbH is working since several years ago on the development of materials with advanced thermal properties. Different Cu and Al based fibre or particle reinforced composites have been studied.

As reinforcement materials carbon fibres, carbon nanofibres (nanotubes), SiC or diamond particles have been used to prepare materials with high thermal conductivity and reduced coefficient of thermal expansion. Such materials are of interest for heat sinks or heat spreaders in electronics cooling. One material with a high potential - but big challenges - is copper reinforced by carbon nanofibres. The high thermal conductivity of carbon nanofibres (up to 2000 W/mK) is expected to improve the thermal properties of the composite material. One main problem is the lack of any interfacial reaction between copper and carbon based materials, which requires either a pre-treatment of the nanofibres and/or modification of the matrix (e.g. via alloying). In addition, microstructure analyses are carried out in order to assess the nanofibre distribution and the quality of the interface.

The fabrication process is still being refined. There are various ways to produce the material such as powder metallurgical processing, liquid processing etc.

Further increase of the thermal conductivity of up to 100% can be expected when the fabrication process is further improved.

Coefficient of thermal expansion and delamination at higher temperatures is a worry.

Discussion: Customised directions of fibres are not desirable. The measurement of the mechanical properties is planned.

By increasing the fibre content one might improve the thermal expansion coefficient.

For the time being the dimensions of sample are limited to the order of 100 mm.

Development and Manufacturing Status of Diamond-based Composites, S.Knippscheer, (PLANSEE SE)

Advanced metal diamond composites with silver, aluminium and copper matrices exhibit high thermal conductivity in the range of 400-700 W/mK and low CTE of about 7–9 ppm/K. Diamond and C composites have the highest thermal conductivity.

A gas pressure assisted infiltration process has been developed for cost-efficient industrial production of diamond composite substrates and heat sinks. The composite microstructure and interface morphology determine the thermal properties and reliability during thermal cycling and represent the key to advanced composite formation. An industrial scale pilot production has been installed and the product has reached a degree of maturity allowing the application for current and future high end thermal management applications. The market for such products is essentially the electronics industry.

The material has anisotropic properties. Thermal cycles are no problem. An Ag and Cu layer allows for machining, such layer can be put on several sides. This allows joining the material with Cu. The largest parts that are currently fabricated are of the order of 200 mm, but fabrication with a length of up to 1.2 m should be possible.

Discussion: Coatings for the material can be applied with a thickness of 100 μm to 1 mm. The surface roughness is 2-3 μm. Different pieces can be joined together by brazing. The cost per kg is about 3-8 times compared to Cu and depends on the shape.

Carbon-metal Composites for Thermal Management, J.Narciso (Alicante University)

Carbon-metal matrix composites are very attractive materials for thermal applications, given their very high thermal conductivity in at least two planes. The motivation for the development of such materials is for heat spreaders in the electronics industry. The thermal conductivity must be good and the thermal expansion should be close to that of Si.

Therefore, in an attempt to obtain a good thermal conducting material as well as a low coefficient of thermal expansion, a mixture of reinforcements (graphite and carbon fibre) was infiltrated with liquid alloys. The role of two reinforcing materials is twofold: while graphite reinforcement increases thermal conductivity in the plane direction, the carbon fibre helps to reduce the CTE of the alloy in the same direction. In the present work, graphite-carbon fibre pre-forms were infiltrated with Al/Si and Ag/Si alloys by means of gas pressure to produce an anisotropic composite. The influence of the volume fraction in the thermal conductivity and CTE was evaluated. The experiments determined that the manufactured composites have adequate thermal behaviour to be used as low cost materials in heat spreaders. Thermal conductivity of up to 2000 W/mK was achieved.

Carbon materials come as graphite, diamond, fibres, and carbon nanotubes. There is also graphite foam that could be isotropic. There are all kinds of different types of Carbon fibres. Relevant parameters are compactness, thermal conductivity coefficient and threshold pressure.

These composites have typically 80% C and about 10% volume fraction of metal. The thermal expansion depends on direction.

Discussion: The length of the pieces is of order of 40 to 80 mm. A low CTE and low conductivity are correlated.

General discussion

What is the most interesting material for beam absorbers and collimators? There is no general answer, since the zoo of collimators and beam absorbers results in different requirements for different devices.

- Radiation resistance is an important issue. The different materials considered for collimators and beam absorbers should be tested. Plansee could provide such materials within short time.
- The question of the surface resistance was discussed. In case of coating, how thick does the conducting part have to be? The question of the inductive bypass appears not be fully understood, at least to the participants.
- For most applications the compatibility with ultra-high vacuum needs to be considered. New materials should be tested for vacuum compatibility, including bake-out.
- Surface flatness is important when the jaw is close to the beam.

- Resilience to shock impact is required for some of the devices, but not for all.
- Alloy development might increase mechanical properties, but compromise other properties.
- Does coating reduce shock parameter? Could one do tests? What about coated Diamond Metal composite?
- Machining of Diamond based material is difficult.
- Graphite can have 10 times more conductivity than normal C-C composites.
- A table of materials and their mechanical properties for the materials is required. This also should include ideas where to test the materials.
- Tests of several materials should be done.

It is too early to finally decide on the best material and concept for the design of the device. There might be unexpected problems seen when starting the LHC operation. Complementary concepts are required.

SESSION 3: EXPERIMENTAL RESULTS AND FUTURE TESTS

Measurement of Shock Waves and Vibrations, H.Richter (CERN)

A Laser Doppler Vibrometer (LDV) was used to measure the vibrations of the collimator block when hit by the beam. Analysis of the data allows to measure displacement and velocity. The LDV measurements are reproducible.

The displacement of the block („first response") scales with beam intensity. Frequency spectra have also been obtained by LDV in parallel.

The results demonstrated that this is a very interesting technique to measure in real-time the effect of a high intensity beam on a collimator.

Accelerometer and Microphone Measurements of the LHC Collimator, S.Redaelli (CERN)

Sound and vibration measurements of the LHC collimator were performed with various accelerometers and a microphone during collimator robustness tests in 2004 and 2006. The collimator jaws were hit by a 450 GeV proton beam of up to $3.5 \cdot 10^{13}$, equivalent to a total energy of about 2.4 MJ (0.65% of the nominal LHC beam at 7 TeV). It was demonstrated that these measurements can be used to detect beam impacts of LHC beams on the collimators and hence possibly damaged collimators.

The analysis of the impact uses:
- comparison of opposite accelerometers;
- wavelet subtraction of low-frequency, exponential offsets.

With these tools, a local measurement of the beam hitting a jaw was achieved, and hence detecting an event that might cause damage. For the LHC, this might allow

to detect accidental beam impact on one jaw within the multi-collimator system. Quantitative estimates of the impact are challenging due to the high radiation and high electromagnetic noise environment.

Experimental Methods for Material Measurements at High Strain-rate, M.Avalle (POLITECNICO DI TORINO)

The detailed mechanical characterization of a material is the very first step in the design of structural components. Depending on the type of application (dynamic, impact, thermal loading, fatigue etc.) different types of tests, experimental methods, and testing equipments are required. Several related test methods are available at the Reliability and Safety Laboratory of Politecnico di Torino for static and dynamic characterization of materials. This allows qualification of metals, polymers, and various types of composites and joints.

Irradiation Damage in LHC Beam Collimating Materials, N.Simos (BNL)

Demands for high-performance materials intercepting the LHC proton beam have prompted an extensive experimental study focusing on material degradation due to long radiation exposure.

For the collimating structures, intercepting the halo of an intense beam under normal operation or the entire beam during off-normal conditions, performance issues are essential and directly tied to materials and their ability to maintain key properties and absorb a beam-induced shock. The limitations of most materials in playing such pivotal roles have led to an extensive search and experimentation with new alloys and composites that appear to possess the right combination of properties.

Post-irradiation analysis results following exposure to the 200 MeV protons at the end of the BNL Linac were performed. Preliminary results of estimated neutron-induced damage on LHC materials have been obtained as a result of experimentation with a "unique" neutron source at BNL.

While carbon composites (including the 2-D carbon used in LHC collimation Phase 1) exhibit stability in their thermal expansion coefficient in the temperature range they are expected to operate normally, they experience a dramatic change in their CTE with increased radiation. However, they are able to fully reverse the "damage" with thermal annealing.

Carbon composites experience serious structural degradation with increased proton fluence ($>0.2 \cdot 10^{21}$ p/cm^2). This finding was confirmed for the family of such composites and not only for the 2-D composite used in the LHC. It was also experimentally shown that under similar conditions graphite suffers structurally the same way as the carbon composites. Thermal conductivity of graphite decreases with radiation. The electrical conductivity decreases with

radiation, for graphite by a factor of 6. Bonding graphite with Ti was damaged by irradiation.

Proton radiation was shown to not affect the thermal expansion of copper and Glidcop that are considered for Phase 2. Encouraging results were obtained for super-Invar, Ti-6Al-4V alloy and AlBeMet.

Not only the dose is important, but also dose rate. Extrapolation from reactors can be misleading: if graphite material survives installation in reactors it might still not be the optimum material for LHC.

Discussion: The question was asked on how to quantify radiation damage and how the damage it related to DPA (displacement per atom). The general opinion is that theoretical models do not yet allow the reliable prediction of radiation damage, and irradiation tests are always required to qualify a material.

Studies of Radiation Effects on Graphite Collimator Materials, A.Ryazanov (KURCHATOV INSTITUTE)

The effect of the 7 TeV proton beam irradiation on degradation of physical mechanical properties of graphite collimator materials for the LHC is very important for the understanding of stability of the collimators during the machine operation.

At such high energies, the carbon atoms in graphite collimator materials can get also very high energy with primary knock-on carbon atoms (PKA) reaching an energy of up to hundred GeV due to elastic collisions with secondary particles formed in nuclear reactions. Carbon PKA atoms with such high energy will produce radiation damage. The radiation resistance of graphite collimator materials will be determined by the microstructure change under irradiation and defect cluster formation in atomic collision cascades.

The main aim of these investigations is to measure the effect of fast particle irradiation (carbon ions) on physical-mechanical property changes of different graphite materials: thermal conductivity, thermal expansion coefficient, mechanical properties (including the measurements of compression ultimate tensile stress, dynamic elastic module, and static elastic module), electrical resistivity, lattice constant and microstructure change.

Samples of various types of graphite collimator materials prepared by different firms for CERN were investigated: C-C composite graphite REC, C-C composite graphite material AC and high-density graphite material R4SSO. The initial physical-mechanical properties of these materials were measured as well as the effects of irradiation by carbon ions with energy of 5 MeV, such as radiation swelling and radiation erosion.

The microstructure investigations of irradiated samples have been performed as a function of the irradiation dose of fast carbon ions up to a total flux of 10^{18} cm^{-2}. The best radiation resistance properties including dose dependence of radiation swelling at room temperature has the

composite material R4SS0. Other C-C composite materials such as REC and AC have lower radiation resistance as confirmed by the dose dependence of radiation swelling.

SESSION 4: CODES AND SIMULATIONS RESULTS

Issues Raised by the Design of the LHC Beam Dump Entrance Window, R.Veness (CERN)

The LHC beam dump entrance window consists of a carbon-carbon composite structural sheet backed by a thin stainless steel foil for leak tightness. The window is made out of C-C composites 15-mm thickness plus 0.6-mm Stainless Steel. In case of a total failure of the dilution kicker the beam goes into one spot, the temperature will reach up to 900 ^{0}C and a high-temperature gradient is expected.

The design of this window has highlighted the issues that merit further investigation. The use of the bulk coefficient of thermal expansion coefficient for the composite should be questioned where there is a significant temperature gradient between individual fibres. Differential thermal expansion between fibre and matrix could lead to thermally induced fatigue. The validity of the analytical dynamic stress model used should be confirmed by finite element calculations and experiments.

For a semi-empirical solution, a small dynamic stress is expected but no full analysis was done. An analysis relies on several assumptions, and it is questionable if for new composites in this field the bulk material properties are valid. The fibre matrix could be damaged that might not be shown for bulk materials.

Several questions were raised: is such analysis justified? What a simulation tool should be taken? Could tests be performed to validate the simulation results? What diagnostic methods are available?

Discussion: On one hand, windows are different from collimators and beam absorber since they are not stopping beams. On the other hand, some of the issues are similar (low Z, low CTE, etc.). Finite element analysis of the window in presence of beam loading could be done with ANSYS. 3-d modelling is required here. There are other (expensive) codes that include microscopic considerations that might be applicable. What happens if the beam is not in the centre? For modelling, the parameters of C-C composite used should be known. The material could be qualified at a reasonable cost.

Overview of FLUKA Energy Deposition and Design Studies for the LHC, M.Brugger (CERN)

In order to assess the energy deposition in sensitive LHC components, extensive simulations were performed with the Monte Carlo cascade code FLUKA. In many cases specialized solutions needed to be found, challenging in several aspects, i.e., from the calculation as well as from the design point-of-view. Depending on the problem, detailed geometrical implementations, an accurate consideration of magnetic fields, tracking of particles over hundreds of meters, grazing angles and special biasing need to be considered.

The uncertainties of the results depend on input parameters, assumptions in the simulation and have both statistical and systematic nature. It is also recalled that 7 TeV beams do not yet exist, and there is some uncertainty on the physics, although from experiments at the SPPbarS Collider and at the ISR the relevant cross-sections are known.

FLUKA addresses several issues and detailed models of large sections of the LHC accelerator are available. A FLUKA model of a SLAC collimator designed for phase 2 has also been developed.

It is stressed that the FLUKA results such as energy deposition and activation do not include any safety margins. Small details, for example of the geometry, can change the results in a significant way. As an example, the design of equipment SNS assumes a safety factor of 5.

Generic Studies of Radioactivity Induced by High-Energy Beams in Different Absorber Materials, M.Brugger, S.Roesler (CERN)

Accurate estimates of isotope production and residual dose rates are important during all phases of an accelerator, i.e., design, operation and decommissioning.

Induced radioactivity must already be considered when designing collimators and beam absorbers in order to avoid maintenance problems after irradiation.

A rigorous campaign of benchmark measurements for materials typically used at accelerators has shown the high accuracy of FLUKA calculations. Isotopes are calculated to some 10%, the residual dose to 10-20%.

A detailed implementation of geometries and accurate consideration of loss assumptions allows optimizing the layout of components and performing detailed intervention planning starting already efficiently during the design phase. Recent design modifications have shown the need to derive practical scaling coefficients in order to quickly asses how estimated results can be roughly scaled for different assumptions affecting the calculated quantities, e.g.: chosen materials, beam energies and particles, loss conditions, cooling times and beam impact parameters. Scaling laws allow predicting the residual dose within 50%.

The major contributing isotopes were derived and obtained results are compared to those of dedicated simulations (TDI, IR7 collimators, etc.). Benchmarking measurements were done at CERN. Most activity is induced in devices made of stainless steel.

Discussion: Scaling factors work well. However, it is necessary to be careful when objects with different lengths are considered. Further development of the code is very important.

Simulating Radiation Damage Effects in LHC Collimators (code development status), G.Smirnov (CERN)

A code is being developed for simulating the structural damage of the graphite jaws of the LHC collimators produced by 7 TeV protons. The technique, which is being developed in the framework of the Monte Carlo code FLUKA, combined with the results of experimental tests of carbon-carbon composite materials in radiation hard environment will be capable of evaluating lifetime of the collimation system.

It is planned to implement calculation of radiation damage in FLUKA, such as dimension, properties and structure changes. However, the relation between DPA and macroscopic damage is not obvious.

Part of the energy that is deposited in the material causes ionisation, and part of it leads to displacement. Displacements can disappear after a very short time (10 ps).

An algorithm is being implemented in FLUKA to calculate DPA. Another code (NJOY) calculates the DPA for neutrons at low energies.

Discussion: What about other particles and other energies above 150 MeV?

Beam Impact on Collimator Materials: Studies for LHC and SPS using BIG, N.Tahir (GSI)

As already been published, the interaction of the full LHC beam with a solid Cu target was addressed and penetration into the target of up to 35 m is considered as worst case by tunnelling of bunches deeper and deeper. More realistic simulations are likely to reduce the penetration depth. Penetration into a Carbon target is less but the target would also be destroyed.

Assuming that the SPS beam is directed onto a high-Z target, the same effect of tunnelling as predicted for the LHC is expected. In a further refinement, a table of energy loss as function of density could be used.

Discussion: The question was addressed what code should be used for what application, since the physics is complex. Shock waves in solid states require special theoretical models. Is it necessary to consider the energy transfer from the beam to electronic and ionic subsystem? The energy loss in plasma is different from solid state. What mechanisms lead to damage, e.g. for a collimator? Best is to perform experiments to validate simulations. It was also suggested to compare predictions for the LHC with prediction for the SSC done 14 years ago. Codes could be applied to the Beam Dumping System and the results could be compared with results documented in publications. In the case that an EOS is not available, such EOS could possibly be obtained.

ANSYS is limited to calculations without change of state as it does not include EOS. However, it was pointed out that there is a new code in the ANSYS family available for such calculations that includes also EOS.

FE Simulation of 450 GeV Injection Error Test, A. Dallocchio (CERN)

Dynamic phenomena provoked by the rapid interaction of energetic particle beams with slender structures lead to thermally induced vibrations. This has been addressed for the accident case triggered by a beam injection error at 450 GeV, recently tested at CERN on LHC collimator prototypes. A simplified analytical method, which was previously developed, has proved useful to obtain a preliminary estimation of the vibrations induced on a collimator jaw. Already with this model, deformations of the order of 200 μm are expected. A 3D Finite Element ANSYS model for thermo-structural fast-transient elastic-plastic analysis has been fully studied. The numerical method took particular attention to initial conditions, boundary conditions and integration scheme. Down to timescales of less than one ns, the Fourier law can be used. The numerical results are in a good agreement with experimental measurements performed via the Laser Doppler Vibrometer.

Both, experiment and simulation show a bending of the structure ("banana" effect). An improved mechanical structure was suggested with a much reduced "banana effect" of 16 μm. The support was modified and a reduced bending as expected from the simulations was observed in a further test.

In the simulation the oscillation frequencies are correctly described, the amplitude might be overestimated. No shock waves are included (speed is below the speed of sound).

Beam Impact on Collimator Materials: Studies for LHC, A.Ryazanov (KURCHATOV INSTITUTE)

Theoretical models and numerical calculations were developed to understand an influence of the impact of a 7 TeV proton beam on the physical-mechanical properties of collimator materials (C, Cu).

In particular, theoretical models for shock wave propagation and for calculations of primary radiation damage formation including calculations of a generation rate of point defects and atomic cascades in collimator materials under 7 TeV proton beam irradiation were developed.

In the calculations, it was assumed that each of a 7 TeV proton bunch has $1.1 \cdot 10^{11}$ protons with a bunch length of 0.5 ns and a bunch spacing of 25 ns. The high energy stored in each bunch can produce a shock wave and radiation damage near the impacting proton beam in these materials.

The model takes into account ionization, electronic excitation, and energy transfer from excited electronic subsystem of material to the ionic subsystem. The changes of some physical properties of the collimator materials during shock wave propagation are considered. The deposited energy is calculated with FLUKA.

The numerical results of the microstructure changes in collimator materials produced by shock wave propagation near a 7 TeV proton beam were evaluated for different numbers of bunches. This allows investigating changes of density and internal pressure, the distributions of atomic and sound velocities, and the temperature profiles in electronic and ionic subsystems of materials near the front of shock wave.

The new theoretical models and computer tools are developed for investigations of radiation damage formation: point defects, cascades and sub-cascades near a 7-TeV proton beam in collimator materials (Cu and Graphite), taking into account electronic excitation, energy loss, elastic and inelastic collisions in materials.

The estimation of generation rates of point defects are based on the numerical calculations of displacement cross sections for point defect production taking into account primary knocked atom (PKA) energy spectra for nuclear products and neutron spectrum in collimator obtained using FLUKA program.

Discussion: What is the role of the electronic subsystem? The accumulated electrons in the material, could they lead to an effect such as a Coulomb explosion?

Finite Element Methods for the Thermo-mechanical analysis of the Phase I Collimators, A.Bertarelli (CERN)

The functional requirements of the LHC Collimators impose a collimation system with a very high dimensional stability in nominal operating conditions, under considerable thermal loads, for the start-up of the machine and the initial luminosity runs (Phase 1). At the same time the system requires maximum robustness in case of accidental beam impacts.

In order to meet these requirements and to optimize the complex mechanical design, the extensive use of in-depth numerical analyses was essential. Given the number and the details of the elements which had to be taken into account in the collimator model, the recourse to a general-use, comprehensive, multiphysics finite-element code was necessary: ANSYS Multiphysics proved very effective in dealing with the coupled thermal/structural problems which were typically encountered and the disparate nature of used materials.

Methods were developed to correctly apply the thermal loads and to study coupled-field problems in the steady-state and transient domains, using both fully elastic and elastic-plastic material properties.

The collimator needs to be modelled in detail. The first step is to calculate the energy deposition in the material with FLUKA. With ANSYS, different types of analysis are possible, such as continuous beam loading, transient loading for 10 µs, with defined load, 20 s for continuous load, goes to 100 µm when short beam lifetime

Fast transient accident cases can be calculated with ANSYS Multiphysics, in the elastic domain, but also can permanent deformations can be predicted.

ANSYS can be used if there is no change of phase and if the stress level is well below materials Young modulus.

Discussion: A temporal scenario in the simulations needs further clarification.

Experience with Implicit and Explicit Codes in Analysing Beam-induced Thermo-mechanical Shock, N.Simos (BNL)

In an effort to extrapolate the interaction of intense proton pulses with materials to power levels beyond those achieved to-date in accelerators, computational schemes based on finite element formulation are being widely employed.

Long-term interactions between particles and materials result in a reduced ability of a material to absorb the induced shock. A concern addressed in other studies is the rapid heating and shock generation in a material that results from short exposure to intense pulses. For the power levels under consideration this is accompanied with serious uncertainties.

Experimental studies at power levels generated by currently operating accelerators have been used to benchmark the computational processes which will be used to extrapolate the material response to desired, but yet to be achieved power levels. Different computational schemes that may serve different stages of the interaction problem may be utilized. The choice of such scheme is inherently bound between accuracy and computational cost.

There are similarities as well as differences between implicit and explicit numerical formulations applicable to the thermo-mechanical shock problem where realistic description of the problem itself requires high-fidelity modelling or discretisation and high computational cost regardless of the scheme selected. Implicit formulations (ANSYS) are more appropriate for steady state load, explicit formulation more for transients.

The results for some experiments and simulations with ANSYS were compared and the results were in a good agreement.

Projectile impact studies were performed with LS-DYNA, the test results agree with results from simulations. As an example, for mercury jet tests with beam the material splash could be calculated.

Experience shows that LS-DYNA could be used in our domain, but should be benchmarked. Routines that describe phase changes have to be provided by the user.

Numerical Tools for the Design of Beam Intercepting Devices, L.Bruno (CERN)

Beam intercepting devices (collimators, targets, absorbers) capable of sustaining high-intensity beams are the key elements to meet the future physics needs. The highly non-linear phenomena involved in their design study (cavitations, transient magnetic-hydrodynamic effects on liquid metal jets, phase change, fluid-structure interactions) require advanced simulation tools at the

forefront of today's numerical technology. This goes beyond the software usually available which uses numerical techniques not capable of modelling effectively or even unable to study such complex phenomena.

In order to address this issue, a technical survey has been performed to investigate the state-of-the-art in numerical simulations. The capabilities of existing advanced numerical tools have been assessed and a code has been identified which combines comprehensive equations of state, strength and failure material libraries, phase transition models and simulation techniques (mesh less finite element methods) indispensable to satisfy the design needs. The code AUTODYN, a member of the ANSYS family, has been selected and benchmarked with experimental results on liquid metal targets performed at CERN. The results have been rather impressive, e.g. showing splashes of mercury moving out under beam irradiation, at least qualitatively as predicted.

It is very desirable to develop an interface to FLUKA. MHD is being developed.

Discussion: Phase changes of a material are covered by the code, as it has been shown for simulations for the LHC beam dump. Models that are defined in ANSYS can be transferred to AUTODYN.

Dynamic Structural Analysis of Absorbers with Spectral-element Code ELSE, L.Massida (CRS4)

The dynamic structural behaviour of beam diluter elements TCDS (LHC) and TPSG (SPS), protecting the extraction septum magnets in the event of an asynchronous firing of the extraction kickers, has been studied. The deposited energy densities, estimated by FLUKA, were converted to internal heat generation rates according to the time dependence of the extracted beam. The transient response to this thermal load was obtained by solving the power deposition and subsequent structural deformation by using the spectral-element code ELSE.

SEM methods with numerical approximation, extension of FEM, accuracy increase by higher frequency at run time, explicit code (but also implicit version).

Limitations of such simulations should be considered: What about stress in C-C on the very short time scale for beam impact? There are uncertainties of material properties, in particular for C-C composites. Limits to apply classical continuum formulation when applying to materials based on fibres need to be considered. Fault tolerant design should be considered if possible.

Discussion: It was pointed out that the results might well depend on the type of the C-C composite. Properties of C-C have been used; the question was raised if this is justified beyond continuum and if the microstructure has to be considered? In general, experimental validation is required. In particular for small deformations, the results should be reasonably accurate. It is also required to determine the type of damage that might be acceptable for some applications.

SESSION 5: DISCUSSION OF PLANS AND OPPORTUNITIES FOR STUDIES AND TESTS AT CERN AND SUMMARY

The objective is to install into the operating LHC accelerator only collimator assemblies and materials that are tested and fully qualified. One result from this workshop is that many questions require experiments to obtain an answer.

In the session the plans and opportunities for studies and tests at CERN and elsewhere have been discussed. There are several objectives:

- Make sure facilities and tools for required tests exist.
- Profit from synergy and available expertise.
- Avoid duplication of work.

Tests can be split into two categories:
1. Qualification of candidate materials.
2. Tests of complete assemblies or parts of them.

What materials?
- Blocks of CFC, C, Glidcop, diamond-based metal composites, copper composites, AU coated copper, Boron Nitrite, nanotechnology materials, materials with nano-deposition, SiC, etc.
- Coated materials: Cu (1-100 micron) on C
- Cu or CuNi water pipes, SC cables, windows, crystals for extraction, etc.

An exploratory experimental study is required to eliminate non-suitable materials before detailed studies of most promising materials can start.

What collimator assemblies?
- Proton collimators: 3 secondary collimators for phase 2 (1 from SLAC, 2 from CERN).
- 1 primary scraper/collimator possibly with a crystal that could also be used for ions.
- Ion collimators: "catcher" collimators in cold regions, 1 magnetic collimator.
- Absorber assembly: TPSG (3m+2m).
- Sacrificial absorber?

Measurements to be performed on materials
- Mechanical properties (according to well defined norms) for different radiation doses and different strain rates.
- Electrical and thermal properties (according to well defined norms) for different radiation doses.
- Damage thresholds.
- Damage extent.
- Pressure increase in water pipes.
- Desorption.
- Vacuum properties versus temperature.
- Radiation resistance.

Measurements for collimators & absorber assemblies
- Robustness against beam shock impact.

- Cooling efficiency.
- Geometrical stability (flatness, deformations, …).
- Vacuum in operation.
- Impedance.
- RF trapped modes.
- Vibrations

Where to perform tests for material characterisation?
- Turin: high-strain rate measurements, multi-axial material characterization.
- EPFL: electrical, thermal, mechanical properties.
- Plansee: electrical, thermal, mechanical properties, simulations, production feasibility.
- GSI: vacuum properties, desorption, coating, surface treatment.
- SLAC: thermo-mechanical tests.
- ARC: electrical, thermal, mechanical properties.
- Alicante University: electrical, thermal, mechanical properties.
- CERN: vacuum, micro-structural characterization.

Radiation damage and change of properties in irradiated materials (mechanical and electrical).

The conditions for the tests must be well defined. There are a number of institutes for testing:
- BNL: 100-200 MeV p and n and PIT, after January 2008.
- Kurchatov: 35 MeV protons, 17 MeV neutrons, and 80 MeV C ions (same material to be used, that will allow comparison).
- Fermilab: 1 TeV protons p on crystal, 120 GeV p on target (2009 or 2010).
- CERN: under discussion (possibly ISOLDE, nToF).

Tests with ion beams:
- GSI (different facilities): HLI (3.5 MeV/nucleon, high intensity) for desorption, HHT (1-2 GeV/nucleon, 3e9 U in 120ns, 1mm spot size) for plasma physics, collimator test in synchrotron.

Tests with proton and ion beams:
- Stage 1: CERN beam test stand (450 GeV p, 2.4 MJ, 6.25 µs, variable around 1 mm^2, 25 ns time structure, define minimum spot size useful).
- Stage 2: CERN LHC (7 TeV p, 360 MJ, ~70 µs, 0.04 mm^2, 25 ns bunch structure).

ACKNOWLEDGEMENT

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