Review of the LHC Collimation System – Report of the Review Committee

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1. General Impressions

The LHC collimation system is complex in view of the engineering design of the components and individual mechanical units as well as the interaction with other aspects of the accelerator as beam dynamics, machine protection or machine controls. The committee is impressed by the quality and quantity of the work that has been achieved so far. Particularly the analysis of the IR3 momentum collimation system has been performed very thoroughly and in great detail. Also the mechanical and heating tests of the prototype collimator units are promising.

The committee has not seen a single issue that could be considered as show-stopper. However, many issues are still being investigated and major problems may still arise. The committee feels that several aspects are critical and there is not yet enough information available to assess them in depth. The approach of building the system in several phases is considered to be prudent given the tight schedule. However, the committee is concerned by the lack of a detailed plan for the transition between phases.

The LHC collimation project organization is clearly well coordinated, realizes where it needs to go and is moving as rapidly as resources allow to get there.

2. Response to the Charge

Are the baseline assumptions for the collimation design reasonable?

The assumption of a minimally tolerable beam lifetime of 0.2 hours over a short period seems reasonable based on experiences made at the TEVATRON, HERA and RHIC. However, a wide spectrum of combinations between enhanced loss rates and their durations exists and fast loss mechanisms were insufficiently considered. Details on halo production models and the resulting impact parameter distributions were not presented in depth.

While the studies on collimation of momentum induced losses were presented in a complete and clear way, the corresponding work on losses caused by large betatron amplitudes is still in progress.

An explicit assessment of safety factors and tolerances throughout the design and parameters was not presented.

Have the LHC collimation requirements been specified thoroughly and completely?

A simple model for quench protection was used to provide guidance for system design. Detailed studies, such as that used in IR3, are preferable. Full tracking of lost particles and specification of tertiary collimators and absorbers in IR7 is needed.

Concern remains that detector related requirements were not fully considered. A presentation of quantitative estimates for allowed and expected beam losses in the experimental areas would have been desirable.

Another concern remains that source terms to the energy deposition studies were not fully explored.

The requirements for the Machine Protection System (MPS) and their connection to the collimation system need further definition.

Does the phased approach of the LHC collimation system address the requirements?

The committee supports the phased approach as it allows additional time to solve difficult engineering issues. However, radiological issues may complicate the implementation of Phase II. A detailed plan for Phase II installation will be required.

Are the basic hardware choices correct?

The committee fully agrees that C-based materials are appropriate for the secondary collimators. It may be beneficial to revisit high Z materials for the primary collimators.

The committee has concerns about the risk of coating the carbon collimators with Cu and does not see significant gains from the coating. The diagnostics required to operate the system were not presented in detail corresponding to their importance.

What problems (with the basic system) should be expected?

Radiation damage assessments are required for the collimator material considered, especially the C-C, but also concerning the NEG coating and the metallic springs which have an important function for the efficient cooling of the jaws. The motors and possibly other components are critical in this context as well.

The committee recommends to develop a backup plan for the case that unexpected difficulties arise during operation of the collimation system. Other laboratories, e.g. BNL and FNAL, can be consulted to benefit from their experiences concerning material damage.

Is the detailed engineering solution adequate or can any problems be identified?

The mechanical design of the collimator units looks well considered. To achieve the goal of 25μm flatness of the jaws under heat-load may be difficult. On the other hand, it is not clear if this is a real design requirement.

A detailed plan for the control system was not presented, especially in view of the high reliability which is required to fulfil the function of a MPS.

Concerns remain with respect to maintenance and serviceability of the system given their significant impact on up-time due to long cool-down periods.

Are the preliminary thoughts on collimation set-up and operation reasonable?

The basic thoughts presented in this critical area are certainly correct.

The committee is concerned that the plan presented relied on low current setup. It is advisable to develop a plan for high current operation. Furthermore a detailed plan for a collimation setup that considers machine protection is required.

An adequate diagnostics to achieve a correct setup of the jaw positions and to allow for tuning is required. A feasible system for jaw damage detection has to be developed.

3. Performance Limiting Concerns and Required Studies

3.1. Insufficient Halo Cleaning Efficiency

A collimation system shaves the beam halo and localizes beam losses in the dedicated warm regions, thus providing the tolerable radiation levels in superconducting magnets and collider detectors. The main purposes of the collimation system are to reduce beam losses in superconducting magnets below the quench limit and minimize machine-related backgrounds in the detectors at normal operation, and to protect these critical components against damage at accidental beam losses. While the beam loss minimization in the superconducting arcs and machine protection are considered by the LHC collimation team in great details, the effect on the collider detectors is hardly ever addressed. But as the Tevatron and HERA experience says, the backgrounds in the detectors and protection of expensive detector components is the most demanding issue to the collimation system performance and efficiency. This is, of course, with a well tuned machine, probably after two or three years after commissioning. The detailed well documented MARS studies at Fermilab over last 8 years have shown that the main concern is that large instantaneous ionization over the sensitive detector elements could cause irreversible damage by creating breakdown in these components. Background rates at normal operation and integrated dose at beam accidents is of much lesser worry, of course, with all the proposed collimation system components in IR1, IR3, IR5, IR6 and IR6 at their optimized conditions. The Committee recommends to consider these issues and to add detector backgrounds and protection to the collimation system specs, certainly for the Phase II.

The TEVATRON and also HERA suffer from bursts of losses over a short time. These losses may lead to trips of the drift chambers in the experiments and other detector components, but with more stored energy it is also imaginable that quenches are triggered. In principle there exists a whole spectrum of enhanced loss rates and durations of these losses. In the presentations two points within this spectrum were considered – the average equilibrium loss rate corresponding to a beam lifetime of 20 hours, and the enhanced loss rate of 0.2 hours lifetime that can be accepted for a few minutes. This spectrum should be extended towards shorter timescale of the order of milliseconds. For example a short burst of losses with a duration of 50 ms might not damage the collimators but might lead to a quench because of the limited efficiency of the collimation system. Ideally these studies result in a curve that separates safe and unsafe operating conditions

in a plane spanned by loss rates and loss duration. Next one should consider the expected loss mechanisms in more detail to find out whether the machine will remain most of the time within the stable area. If this is not the case it could be possible that frequent beam dumps triggered by the loss monitor system interrupt the desired continuous luminosity operation.
A possible way to decrease the sensitivity of the loss rate on transverse beam motions is the installation of a thin pre-target at the front edge of the primary collimator with a thickness of a fraction of a radiation length. Details are found in an addendum to this report.

Another concern is a decrease of the collimation efficiency due to damage of the jaw surface. The high collimation efficiency seems to rely on the flatness of the collimator surface. On the other hand the deterioration of the collimator surface may be hard to detect. Possibly this danger can be minimized by performing specialized tests of the collimator material in the SPPS.

3.2. Reliability of the System

The LHC has a number of subsystems with complexity, and presumably reliability requirements similar to the collimation system. The review committee did not see specific requirements for collimation system reliability / uptime, but the committee suggests that it should be designed to cause no more than a hundred hours of unscheduled downtime per year. There are several possible downtime effects from collimation system failures.

- Beam abort: Incorrect positioning of the collimator jaws can produce excessive beam loss and trigger a beam abort. This will cause a loss on the order of an hour of beam time per occurrence.
- Downtime until repair: The committee did not see an analysis of which, if any, specific collimators could fail (in the open position) without preventing beam operation. It is likely that (a less probable) failure of any of the collimators in the closed position would prevent beam operation. Any failure resulting in air to vacuum, or water to vacuum leaks, or leading to obstruction of the beam aperture would prevent beam operation. Radiation cool down time is expected to cause approximately 2 weeks or more of downtime before repairs could begin.
- Failure of MPS: The collimation system is expected to protect downstream components including bend magnets from various machine failures, including abort kicker errors (inadvertent single cell firing, or missed abort gap). If the collimator jaws are incorrectly positioned and such a fault occurs, substantial downtime could result.

<u>Category 1 failures</u>: The required position for the collimator jaws is a function of the beam energy and optics. Collimator control hardware (for example a run-away stepper motor controller), or software can drive the collimator jaws into the beam and produce a dump. Incorrect collimator position could also result from a jaw position read-back error (hardware or software). There are 4 control motors and read-backs per collimator, for a total of about 600 devices. Individual device reliability (against incorrect positioning), must be >>10,000 hours. The committee was not provided with estimates of the expected reliability of the system. This MTBF is reasonable for automated mechanical systems.

Note that it may also take considerable beam time to develop the correct collimator position control algorithms, and that these may under some conditions result in improper positioning and beam dumps, even without hardware or software failures. The committee recommends that to the extend possible, the collimator tuning algorithms be studied as soon as practical. In addition any setup or tuning algorithm depends on input from other beam diagnostics equipment such as loss monitors and beam position monitors and possibly profile monitors. The reliability requirements for these components need to be defined and included in reliability estimates for the collimation system. Failure or offsets in the loss monitor or beam position monitor system will contribute to any category of collimation failure.

<u>Category 2 failures</u>: Electronic failures may have short repair times if they occur in equipment outside of the tunnel, but hardware failures most likely require a full two week cool down to allow time for either component, or entire collimator replacement. This long down time (~200 hours), suggests that less than 1 failure / year can be tolerated. The committee does not know which collimators are critical for beam operation, but even 10 such collimators, containing 40 motors, would require motor MTBFs on the order of 200,000 hours. The mechanical systems are operating in a high radiation environment. The dose on the motors has not been calculated yet. The dose at the jaws was reported to be 30X the limit for the present motors.

While many failures of the motors will allow for automatic jaw retraction, there will be a class of failures where the collimator jaws seize in the inserted position. This could for example be due to radiation damage to the lubrication, or to ozone cause corrosion of moving parts.

The cooling of the collimator jaws requires good contact with the water cooled backing plate. Failure of the springs or warping of the carbon jaws can result in a run-away condition where increasing thermal warping decreases the cooling efficiency. This scenario is likely to require replacement of the entire collimator system.

Jaw cooling also requires high water flow rates. The design water speed of 3m/s is near the limit for erosion damage in the copper cooling lines. The erosion locations are in the bends in the cooling lines near the jaws, and would lead to water to vacuum leaks. The committee believes that either the maximum design power should be reduced (with reduced water flow), or more erosion resistant piping materials be considered (eg. Glidcop).

Non-uniform energy deposition in the vacuum flanges could result in warping and vacuum leaks. The radiation hardness of the NEG vacuum coatings used in this system is also unknown. These issues and other unknowns about the performance of the vacuum system under high radiation need to be assessed.

<u>Category 3 failures</u>: The collimation system is required to protect downstream components from failures including partial beam dumps, and in this sense it must be considered part of the Machine Protection System. The committee believes it is important that the effects of mis-positioning (too wide) of the collimator jaws be considered in the event of abort system failure. If the downstream systems including the main bend magnets are at risk if the collimator jaws are mis-positioned, there are strong requirements on the reliability of the mechanical systems, software, and control algorithms.

Another potential source of down time or performance reduction arises from routine operation/positioning. It is not recommended to move collimators 'blindly' to preset positions (i.e. values in databases or files). Since configuration setup is required to happen with low beam currents possible differences between low and high beam current operation such as beam instabilities, beam emittances and store to store differences have to be considered and taken into account. Positions found at low currents or in another store cannot simply be used for high current operation. Save and reliable positioning mechanisms for high current operation need to be investigated and their processing time needs to be optimized. No such possible mechanism was presented.

3.3. Impedance

The status of the impedance and beam stability calculations was presented by Elias Metral. The present estimates of the collimator impedance indicate that the collimators will be a very large contribution to the total machine impedance and will limit the beam current to roughly half of the design value – this implies a significant limitation on the LHC luminosity.

The impedance of the Carbon LHC collimators is difficult to calculate. The normal resistive wall theory does not work in the LHC collimator regime where the skin depth is large compared to the collimator gap. Modifications to the theory have been developed by Vos and by Burov and Lebedev. These modified theories predict significantly lower impedance from the Carbon collimators than does the normal resistive wall theory. The modified theories were not discussed in detail. Published papers can be found in the literature although this is still a topic of active research.

Additional support for the LHC collimator impedance estimates comes from HFSS calculations. The HFSS code should be able to perform the full calculation correctly although it also should be noted that complex computer codes like HFSS can be prone to error due to set up difficulties; the details of the computer calculations were not presented to the committee.

The stability of the LHC ring was calculated based on the estimated impedance. Distributed octupoles have been included to control transverse beam stability in the LHC. However, the design strength of the octupoles is not be enough to accommodate for the impedance of the graphite collimators 2 mm from the beam and it was found that the ring would only be stable with 45% of the nominal bunch charge. It was also stated that the transverse feedback system could easily suppress the resistive wall instability and it would be expected that the beam-beam collision would also suppress the instability. Thus, the primary concern about the resistive wall impedance arises because the present LHC operating procedures called for suppressing the transverse feedback system before establishing collisions to prevent emittance growth during the store.

One possible solution to reduce the collimator impedance was presented where a few micron coating of Copper would be added to the collimator surface. It was suggested that this would allow operation at a higher bunch charge although the full improvement was not clear.

The other element of the collimator impedance comes from trapped modes in the vacuum tank and the tapers at either end of the collimator section. The trapped modes have been calculated using GDFIDL for two different geometries. These calculations were not discussed in detail but seem less developed than the resistive wall calculations. However it is not expected that a fundamental limitation will be encountered due to trapped modes and beam tests that will resolve some of these issues are planned in the SPS this fall.

Recommendations:

1) The committee would urge investigating alternate methods of improving the beam stability including (but not limited to): increased chromaticity, increased detuning due to increased octupole strengths, verifying that the beam-beam collision will stabilize the beams, or different operational procedures such as establishing collisions before turning off the transverse feedback (assuming that the beam-beam forces do suppress the instability).
2) The committee would urge extensive beam and wire impedance measurements of the prototype (uncoated) collimators as planned.
3) The committee would also suggest revisiting the Carbon thickness in the collimator. Since the skin depth of Carbon was stated to be 2cm, reducing the Carbon thickness to 1cm may reduce the impedance however such a choice should be based on impedance measurements and knowledge of the possible failures due to showers in the Copper cooling plates.
4) The committee had concerns about the possible failure modes of a Copper coating on the collimators and thus would recommend to avoid using a coating on the collimators unless it is clear from additional stability calculations and additional impedance measurements that nominal Phase I operation is not possible with the uncoated collimators.

4. Major Concerns

4.1 Disfunction of the Collimation System as Machine Protection System

A general concern is connected with the anticipated role of the collimation system as machine protection system and the necessity to use relatively complicated algorithms for the proper positioning of the jaws. The jaw positions depend for example on the beam energy and the machine optics. The optimum jaw angles generally depend on the jaw positions. If the jaws are not continuously driven to their required positions the safety of the magnets and other components may not be guaranteed. The involved software may fail, but a hard wired solution seems to be excluded because of the complexity of the algorithms. Obviously there is no simple solution to this problem. One should try to design the control system as reliable as possible and to include hard wired interlocks wherever possible. A detailed plan for the jaw adjustments in the individual machine conditions has to be developed. Tolerances for the jaw positions within which machine protection is ensured have to be determined.

The radiation hardness of the collimator material at the required doses raises concerns. It is well known that carbon suffers from radiation damage effects. A summary of radiation damage effects in graphite can be found in chapter 7 of Ref. [i]. Most of the properties of interest to the designer, change as a result of irradiation: induced changes in dimensions, thermal expansion coefficient, thermal conductivity and Young’s modulus. In this case the use of the material is essentially a design problem, i.e., to utilize the properties to advantage and to accommodate the volume conserving dimensional changes for as long as possible. Issues would be: (1) damage by atomic displacements, and (2) products from nuclear transmutations (e.g., gas which may induce swelling). A lot is known about radiation damage in graphite (mainly by neutrons) because of its use as a moderator in fission reactors. This is now also true for some type of C/C composites, which are of interest in fusion. More details on possible damage mechanisms and references on this subject are given in an addendum to this report by G.Federici. An ad-hoc evaluation of the damage must be seriously carried out, and compared with theory. Only when this information is available, it will be possible to estimate the longevity of the collimator jaws.

The committee recommends to perform a material properties characterisation program to measure material properties (physical, thermal, mechanical) to check data provided by the manufacturer before procurement. This should be done for samples coming from different material batches. The critical properties to be considered include thermal conductivity properties, thermal expansion, Young's modulus, mechanical strength, coefficient of thermal expansion, etc.

Some attention must be given in further tests of jaw performance in the SPS accelerator to check whether macroscopic effects of sputtering and chemical erosion of the jaws are observed and they lead to the formation of visible debris.

The committee feels that the C-C composite would be a good choice for the jaw material. There exist experimental results at BNL that support this choice. However, given the uncertainty concerning the stability of the material the committee recommends to consider a backup plan for the case that the C-C composite fails. Possibly one could consider an alternative material with lower allowed beam current. At BNL studies are under way to characterize other potential collimator materials. Some comments on this subject are given in another addendum by N.Simos.

4.2. Failure to Detect Jaw Damage

The carbon collimator jaws are designed to not be damaged under both normal operation and expected fault conditions. It is possible however, that damage can occur either from unexpected fault events, or from long term radiation damage. Damage could consist of "grooves" eroded into the jaw surface, or large scale cracking of the jaws. Accelerators at SLAC, HERA, and other locations have unknowingly operated for extended periods of time with damaged collimator jaws.

Damaged collimator jaws could produce tuning difficulties, and result in a decreased efficiency. A more dangerous possibility is that damaged jaws may fail to protect downstream components against damage from abort kicker pre-fires. The Committee believes that it is important that a method for detecting jaw damage be developed.

The collimator group recognizes that direct imaging of the collimator jaws is likely to be impractical due to radiation darkening of windows, or the necessity of using long UHV periscope systems to relay the image to a shielded environment.

One suggested method was to use sensors to detect the acoustic signals produced when the collimator jaws are damaged. This technique is in principal simple and non-invasive, however preliminary testing of a similar system at SLAC (using copper rather than carbon) jaws failed to discriminate between damage and normal beam impacts.

An alternate proposal is to slightly move the collimator jaws transverse to the beam and measure the scattering by a downstream instrumentation. Under stable low current beam conditions, this method is likely to reliably detect damage. The invasiveness of this method to beam running should be considered by the collimation team, especially at high beam currents.

5. Other Concerns and Comments

The committee feels that the production of the collimator units needed to go on-line is very ambitious regarding the schedule. One key concern is the availability of the CC-composite material in the form that is considered in the collimator design and at quantities that can support the fabrication of all the units. The possibility that, in order to meet the tight production schedule, there will be more than one vendor working on the production should be explored. That of course, will complicate matters regarding availability of raw, custom-made material. It is recommended that the vendor for the production of the composite is in the loop early on and is aware of both the quantities and the schedule.

Given that the LHC collimator design has no provisions for integrated shielding, the motors supporting the function of the collimator will experience high levels of activation. In the SNS collimator design, which included heavy, multi-layered shielding around the collimating elements, special care was taken for the motors to be protected from radiation. This was due to the fact that there are questions regarding the claim of radiation-hardened motors or other components as defined by the industry that produces them. In the case of the LHC, the motors are both unprotected and inaccessible for replacement. The committee recommends that the selected motor design be tested (possibly after irradiation exposure) to verify the claim of it being irradiation-hardened prior to committing an all-out purchase. The committee also feels that a layout option be explored that will allow for the back-side motors to be accessible from the isle-side. A design modification, already discussed with the LHC design team during the review proceedings, may easily accomplish that and thus allowing a much quicker turn-around in the event of a motor failure.

Estimated activation levels in the collimator section of a few mSv/h even after cool-down times raise serious concerns about the serviceability of the collimator components. Given the presented activation levels and allowable yearly doses of 2 mSv/y for personnel it seems unrealistic to do maintenance or repair within the limit of 1-2 hours per person per year. In addition there is only a limited number of knowledgeable and trained personnel available for about 90 collimators and absorbers. For the transition to phase II it is necessary to install the yet to-be-designed phase II collimators within or very close to the area of highest activation, exposing the same personnel to high radiation levels. A "plug-in" design for the phase I (and supposedly phase II) collimators was mentioned but not detailed.

The issue of tritium production in the cooling water has not been addressed.

Parasitic bunches in the abort gap are potentially harmful. Limits for the population of such parasitic bunches were not presented. The option of abort gap cleaning was not discussed.

A formula for an allowable intensity – used throughout many presentations at the Review – contains two not well-defined terms: (1) a beam loss rate of 7.5e6 p/m/s that depends on a magnet type, geometry and parameters of beam interaction with the aperture – rather than a well-known quench limit; (2) some dilution length of 50 m – rather than a calculated peak loss rate.

Beam loss distributions which are uniform as a function of the azimuthal angle, as presented, are rather unlikely to occur in practice.

Results on the energy deposition in collimators jaws were shown for a fixed impact parameter with a pencil beam rather than for a calculated transverse beam density distribution.

6. General Recommandations

1. Add minimization of machine-related backgrounds and protection of the collider detector components to the collimation system specifications.
2. The Committee agrees with the choice of carbon based material for the secondary collimators and recommends to go ahead with the production of the Phase I system. One should reconsider the use of a thin high-Z spoiler for the primary collimator without changing the basic mechanical design.
3. It is important to make the choice between C-C and graphite as collimator material relatively quickly and to start the production.
4. The possibility to avoid major damage to critical machine and detector components in a catastrophic beam loss scenario by "sacrificial collimators" should be evaluated.
5. Safety margins and tolerances on engineering and beam physics throughout the system should be carefully collected and tabulated.
6. Consider use of local shielding for the hottest spots in IR3 and IR7 as implemented already in the IP1 and IP5 interaction regions
7. It might be helpful to organize another external review before industrial contracts are finalized.
8. Use experience on high-energy beam radiation damage to graphite at BNL and Fermilab with establishing a possible collaboration in addition to contacts with Kurchatov institute on low-energy data.

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[i] B.T. Kelly, Physics of Graphite, Applied Science Publishers, London and New Jersey, 1981.

Contribution to the Report being prepared as outcome of the External Review of LHC Collimation Project

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Material choice for the jaws (secondary collimators):

The collimator design consists of monolithic carbon-carbon composite or more precisely carbon fibre reinforced carbon composites (C/C) or graphite jaws (1200 mm long for secondary collimators) cooled by OFE Cu bars with embedded pipes clamped against the jaws. The heat sink is brazed to a stiff support bar made of Glidcop and clamping springs are mounted on the back to maintain low thermal contact resistance, while allowing for differential thermal expansion and minimise deformations. Cooling is provided by water (inlet temp. up to 27ºC) flowing at a speed <3 m/s. Accurate positioning of the jaws, in each collimator, is achieved by means of two motors.

The choice of the collimator material is not driven by the continuous losses during nominal operation but by the energy deposition in the collimator jaws during failure scenarios where a large fraction of the beam hits a small fraction of the collimator jaws. Heat deposition simulations for proton losses were performed with the FLUKA code for different scenarios and only C-based materials were found to satisfy the demanding LHC design criteria on robustness in case of failure scenarios. Beryllium is deemed to be very marginal from the mechanical stress point of view. Also, alternative design concepts, which rely on a thin film of Cu (few µm thick) deposited on C-based jaws, to minimize resistive impedance, are considered to be speculative at this stage, mainly because of the uncertainties of the lifetime of the thin film.

C-based materials have been extensively used in magnetic fusion research[1] and a large database exist (for a review see for example Ref. [1] and reference herein). Specific plasma-material interactions and technological issues associated with the development of robust C-based plasma-facing components for ITER and future fusion power reactors are dealt with elsewhere [2-6].

The C-based material currently considered for the jaws of LHC collimator are: 2D C/C composites (e.g., SGL C1001, Tatsuno AC150), isotropic graphite (e.g., SGL R4550). Because of intrinsic limitation in fabrication capability, the current length of jaws of the secondary collimators prevents the use of 3D C/C composites (e.g., SNECMA NB31). Based on considerations of strength and availability, and on calculated deformations under assumed design loads, only AC150 and R4550 are currently retained and are going to be further tested.

[1] Carbon has been the most favoured limiter/divertor material in magnetic fusion research since the early 80's. Carbon has allowed optimization of plasma performance - in combination with oxygen gettering techniques and enabled access to a large machine operational space. In addition C does not melt if overheated - it simply sublimes. During last years, many fusion devices have used more heat resistant C/C composites[1]. However, it is now recognized that C-based materials have substantial drawbacks for next-step burning plasma experiments, i.e., ITER and future reactors. On one hand, chemical erosion (Y ~ 0.1 C/D+), and ability to trap tritium in co-deposited layers provide operation and erosion lifetime concerns. On the other hand, the poor thermal and mechanical properties in a neutron environment (which had been known for many years from operating experience in fission reactor) prevent use of carbon in power producing fusion reactors. This has led to the consideration of alternatives, e.g., Be, and W which are used in ITER with the exception of the area near the strike-points where C is still retained.

Engineering and testing

The engineering concept is sound and robust and the accompanying testing program, part of which is in progress and part is planned, is well thought. The mechanical design allows for differential thermal expansion and minimise deformations. Results of thermo-mechanical analysis were presented on the basis of FLUKA input and assuming known properties data. It should be mentioned that the deformations and stresses of the jaws calculated by the Finite Element Method (FEM) code ANSYS strongly depend on assumed material properties, some of which are poorly characterised. Effect of radiations on material properties adds significant uncertainties on behaviour during normal and off-normal operation (see below). One should try to do some sensitivity thermo-mechanical analyses to better quantify the effects of variations resulting from changes of the thermal and mechanical properties of interest, within the range of uncertainties, and to determine the safety margins. In addition (see recommended work below) material properties have to be measured *in-house* and values provided by the manufacturer must be verified and confirmed prior to fabrication of the components.

The results reported on the heat test carried to investigate the heat transfer of the contact interface between graphite jaw and substrate were in good agreement with numerical predictions. The test must now continue and ensuing deformations should also be measured in addition to temperatures.

Based on available experience from fusion and pending upon results of functional and performance tests in SPS accelerator, it is recommended to manufacture collimator jaws out with C/C composites. Although, it is true that in general the scatter of the C/C composite physical and mechanical properties is larger than that of graphites and the quality of the C/C composites depends strongly on the grade of the materials, C/C are generally stronger and tougher than graphites, yet retain the excellent machinability exhibited by graphites. The presence of the fibres provides a better deformation stability and structural integrity. In general C/C composites have strength properties exceeding those of pyrolytic graphite by factors of 2-3. In addition, graphites (e.g., pyrolytic graphite) exhibit a worse resistance to thermal shocks and a tendency to delaminate under heat flux and large deformations/swelling is observed during irradiation. T

Possible surface degradation and production of erosion debris (e.g., dust) arising from erosion effects induced by energetic particle impact was not discussed. However, some attention must be given in further tests in the SPS accelerator to check whether these effects are observed. Abundant literature on the subjects of sputtering and chemical erosion of C-based materials is available in fusion (see for example [2]).

Effects of radiation:

It is well known that carbon suffer from radiation damage effects. A summary of radiation damage effects in graphite can be found in chapter 7 of Ref. [7]. Most of the properties of interest to the designer, change as a result of irradiation: induced changes in dimensions, thermal expansion coefficient, thermal conductivity and Young's modulus. In this case the use of the material is essentially a design problem, i.e., to utilize the properties to advantage and to accommodate the volume conserving dimensional changes for as long as possible. Issues would be: (1) damage by atomic displacements, and (2) products from nuclear transmutations (e.g., gas which may induce swelling). A lot is known about radiation damage in graphite (mainly by neutrons) because of its use as a moderator in fission reactors. This is now also true for some type of C/C composites, which are of interest in fusion [8-15]. For graphite, collisions produce interstitial carbon atoms, which migrate and agglomerate to form prismatic dislocation loops, or extra basal planes of graphite inserted between the original basal planes. This causes expansion of the lattice along the c-axis and contraction of the lattice perpendicular to the c-axis. In polycrystalline graphite this damage reduces mechanical strength and thermal conductivity. All of these effects have been well characterized and can be related to the amount of damage often characterized by the number of displacements per atom (dpa), although effects depend on the type of graphite and microstructure. The major difficulty here is the accuracy with which the displacement damage A and dA/dt can be calculated for the conditions of interest. An *ad-hoc* evaluation of the damage must be seriously carried out, and compared with theory. Only when this information is available, it will be possible to estimate the longevity of the collimator jaws.

Recommendations for further work

The following recommendations are made:

- A proper material properties characterisation program must be put in place to measure material properties (physical, thermal, mechanical) to check data provided by the manufacturer before procurement. This should be done for samples coming from different material batches. The critical properties to be considered include thermal conductivity properties, thermal expansion, Young's modulus, mechanical strength, coefficient of thermal expansion, etc.

- Pin down effects of radiation damage in graphite. Evaluate (by theory and possibly by experiments) damage i.e., dpa as a function of operation time and irradiation temperature, and products from nuclear transmutations (e.g., gas, which may induce swelling). This is issue is now recognised and a collaboration with experts from the Kurchatov Institute of Moscow has been initiated. Nevertheless it is recommend that a backup plan be developed and that also BLN and FNAL be consulted.

- It is also recommended to conduct further thermo-mechanical calculations of the collimator by reducing the length of the carbon part of a jaw of a factor of 2. Evaluate dimensional stability during normal operation and fault operation.

- Some attention must be given in further tests of jaws performance in the SPS accelerator to check whether macroscopic effects of sputtering and chemical erosion of the jaws are observed and they lead to the formation of visible debris.

- Cooling issues: the velocity of water in cooling circuits should be in the range of 1÷2m/s. If higher nominal velocities are required, particular attention should be paid to the risk of erosion-corrosion. Use of Glidcop instead of OFE copper would mitigate the problem.

- Evaluate shielding requirements to protect most sensitive components (e.g., cabling. motors).

- Develop detailed maintenance procedure for servicing and exchanging collimators.

- Quantify radiation effects on metal springs and motors and implication on operation and maintenance.

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Radiation Damage Assessment & Back-up Option, N.Simos

Carbon-based materials (either graphite of different grades or carbon-carbon composites) have been used in a variety of applications especially reactors and accelerators. Neutron-induced irradiation effects on these materials have been accumulated and provide a basis of expectation for the applicability of these materials to different environments, such as accelerator targets and collimating materials. The need, however, for materials that can withstand high intensity proton bunches has led the accelerator community to look closer into the special properties of the carbon-carbon composites. Recent experimental studies at BNL have confirmed that carbon-carbon composites are superior to graphite in the way they respond to shock induced by energetic proton bunches. Figure 1 demonstrates the ability of CC-composite to minimize the mechanical shock as compared to graphite. The experimental data of Figure 1 resulted from a 24 GeV proton pulse of intensity 4×10^{12} protons impinging on 1-cm diameter graphite and CC-composite rod targets. Therefore, and as initial assessment, the choice of material for the LHC collimators is on the right track given that the LHC collimators are expected to experience the effect of misguided pulses that will, in turn, induce shock stresses. The chances for the CC-composite surviving a misguided beam are much higher than those of graphite due to the fact that CC-composite exhibits higher strength combined with much lower thermal expansion coefficient. This is true, provided that the material does not experience extensive degradation of its key properties due to irradiation from intercepted protons.

This is an open question for the LHC collimators regarding the longevity of the baseline material and its ability to maintain the properties for which it was chosen. Irradiation studies at BNL on materials such as INVAR, which exhibits thermal expansion properties similarly attractive as those of the CC-composites, showed that there is significant degradation of that key property with small levels of irradiation. Figure 2 shows the dramatic effect that irradiation may have on such material. The primary reason why this is pointed out is that special alloys or composites may be more susceptible to irradiation that pure counterparts. This basically stems from the way these alloys or composites are made.

These uncertainties associated with the material choice (CC-composite and/or graphite) are in the process of being addressed through an extensive irradiation study that is under way at BNL. Specifically, an array of “smart” composites and other materials have been irradiated at the BNL accelerator facility in March of 2004. These include carbon-carbon composite (3-dimensional weaved structure that is slightly different than the LHC 2-D choice), graphite (IG-43 grade from Japan), AlBeMet (a special Beryllium/Aluminium alloy that combines properties of both materials, see Table 1), and titanium alloy known as “gum metal” that combines high strength with low thermal expansion.

The above materials, amongst others, will be post-irradiation tested in the Fall of 2004 for mechanical and physical property changes due to proton irradiation. The tests will assess changes in the material strength, thermal expansion coefficient and conductivity. The irradiation-induced changes in the CC-composite and the graphite will be of special interest both to BNL and subsequently to the LHC in that it will provide a direct comparison of the two materials. While more is known about irradiation of graphite [APT Materials Handbook, TPO-P00-MDD-X-

00001, LANL, 20001], different grades may exhibit different response. Thus, information relevant to the LHC regarding graphite as a back-up option will become available as a result of the BNL study. The other two materials (AlBeMet and "gum metal") may have some applicability to the LHC collimators either as baseline material for collimators (AlBeMet) in the event that both CC-composite and graphite are eliminated (highly unlikely) or as back-bone collimator structure ("gum metal") to eliminate potential structural distortions induced by the thermal loads and help maintain the high tolerances of the jaws.

Therefore, as a way forward that allows for a back-up option to be considered can be envisioned as follows:

- Maintain the CC-composite as the material of choice for the LHC collimators until upcoming experimental results (BNL studies) indicate that there might be issues associated with such choice

- Consider Graphite as the best possible alternative and perform system studies for collimation efficiency, accident scenarios, activation, etc., using graphite as the baseline (the whole exercise may have already been done!)

- Maintain contact with BNL regarding the upcoming post-irradiation assessment of these two key candidates

- Re-examine the ability to maintain collimator tolerances in the event the experimental studies indicate significant effects on the thermal expansion and look into alternative materials to support the collimator jaws.

- Re-examine the ability of the compression springs to withstand radiation and hold onto the design compression load. Loss of compression due to spring hardening will have a profound effect on the overall heat removal process and may change the system performance dramatically

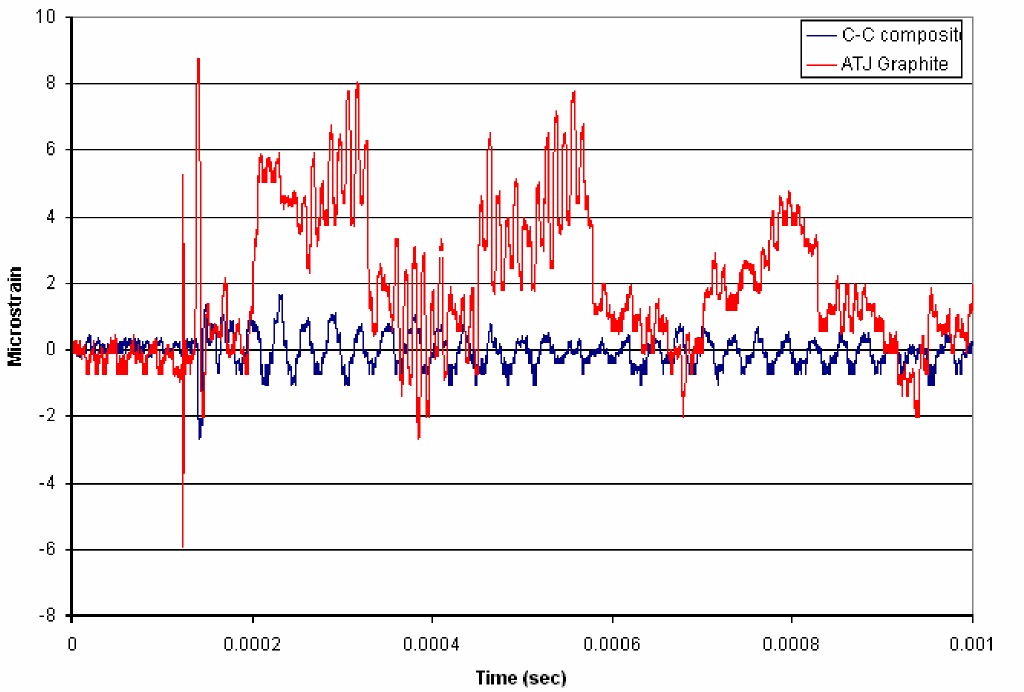

Figure 1: Graphite (ATJ) and Carbon-Carbon Composite Response to 24 GeV Protons (BNL Experiment E951)

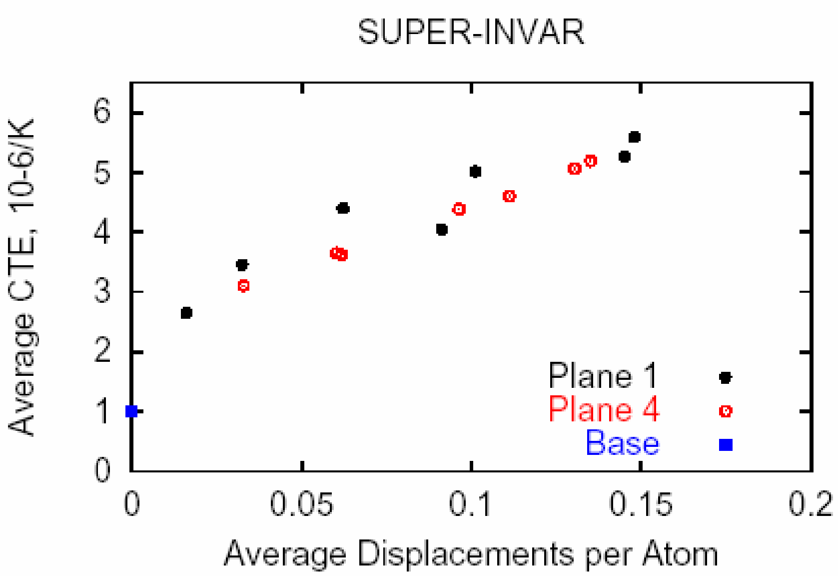

Figure 2: Irradiation effects on Thermal Expansion Coefficient (CTE) of Super-Invar (BNL Experiment E951-Irradiation Phase I)

Table 1: Comparative Properties of the AlBeMet composite/alloy cuurently under study for irradiation effects

AlBeMet® Property Comparison

Property	Beryllium S200F/AMS7906	AlBeMet AM16H/AMS7911	E-Material E-60	Magnesium AZ80A T6	Aluminum 6061 T6	Stainless Steel 304	Copper H04	Titanium Grade 4
Density lbs/cuin (g/cc)	0.067 (1.85)	0.076 (2.10)	0.091 (2.51)	0.066 (1.80)	0.098 (2.70)	0.29 (8.0)	0.32 (8.9)	0.163 (4.5)
Modulus MSI (Gpa)	44 (303)	28 (193)	48 (331)	6.5 (45)	10 (69)	30 (205)	16.7 (115)	15.2 (105)
UTS KSI (Gpa)	47 (324)	38 (262)	39.3 (273)	49 (340)	45 (310)	75 (515)	45 (310)	95.7 (660)
YS KSI (Gpa)	35 (241)	28 (193)	N/A	36 (250)	40 (275)	30 (205)	40 (275)	85.6 (590)
Elongation %	2	2	< .05	6	12	40	20	20
Fatigue Strength KSI (Gpa)	37.9 (261)	14 (97)	N/A	14.5 (100)	14 (95)	N/A	N/A	N/A
Thermal Conductivity btu/hr/ft/F (W/m-K)	125 (216)	121 (210)	121 (210)	44 (76)	104 (180)	9.4 (16)	226 (391)	9.75 (16.9)
Heat Capacity btu/lb-F (J/g-C)	.46 (1.95)	.373 (1.56)	.310 (1.26)	.251 (1.05)	.214 (.896)	.12 (.5)	.092 (.385)	.129 (.54)
CTE ppm/F (ppm/C)	6.3 (11.3)	7.7 (13.9)	3.4 (6.1)	14.4 (26)	13 (24)	9.6 (17.3)	9.4 (17)	4.8 (8.6)
Electrical Resistivity ohm-cm	4.2 E-06	3.5 E-06	N/A	14.5 E-06	4 E-06	72 E-06	1.71 E-06	60 E-06

Thin Target on Primary Collimator, M.Seidel

At HERA variations of the loss rate at the primary collimators are observed that increase during the course of a luminosity run, presumably due to the development of beam tails. To illustrate these observations we include a graph of a typical loss rate recording at the HERA collimators that shows variations of the loss rate by up to a factor 10 already for a relatively large 1 second integration time of the counting rate. It is possible that these variations are considerably larger on a millisecond time scale.

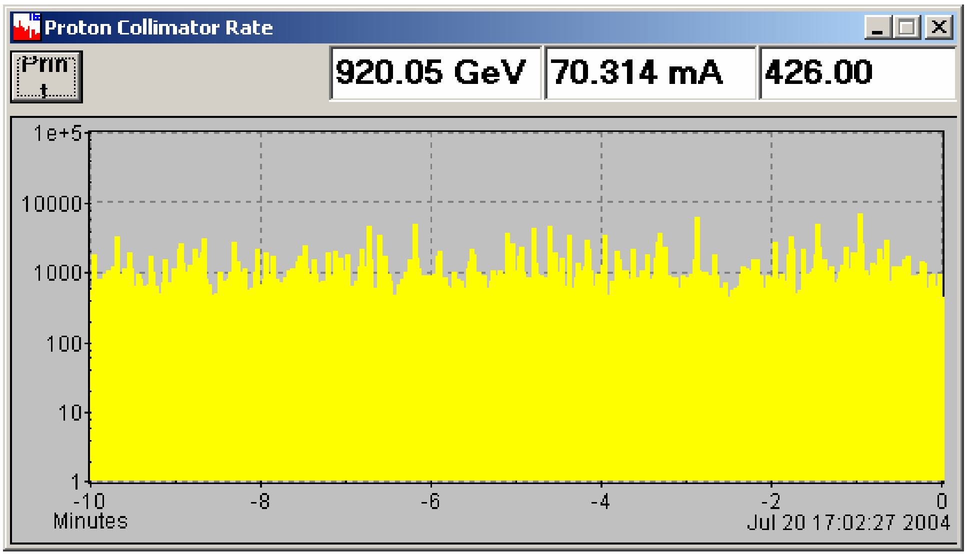

Fig.: Collimator loss rate recording at HERA-p.

Stochastic and harmonic motion of the beam at the primary collimator leads to modulation of the loss rate. A small modulation depth is obviously desirable for smooth operation. If we assume that the particle motion in the beam halo can be characterized by a diffusion process in the particle action *I*, the loss rate is proportional to the diffusion rate *D* and the slope of the distribution function *f*(*I*):

$\dot{N} \propto -D(I) \cdot \left. \frac{\partial f(I)}{\partial I} \right|_{I=I_c}$. I_c is the amplitude corresponding to the collimator position.

After some time of operation under collisions the beam will be blown up and the distribution at the edge will become rather steep. This enhances the average loss rate but also the sensitivity of the rate against small beam motion. With a steep edge the collimator cuts into dense halo regions already for small displacements. A thin pre-target would act like “bad vacuum” beyond a certain particle amplitude. In this region *D* would be much larger, while the average loss rate will roughly stay the same as without the target. This implies that the slope of the distribution should be smaller beyond the target amplitude which decreases the sensitivity against beam motions. The transverse thickness of the target has to be somewhat larger than the expected beam motions, i.e. 100µm?, and its longitudinal thickness a small fraction of a radiation length. The principle is demonstrate in the second figure.

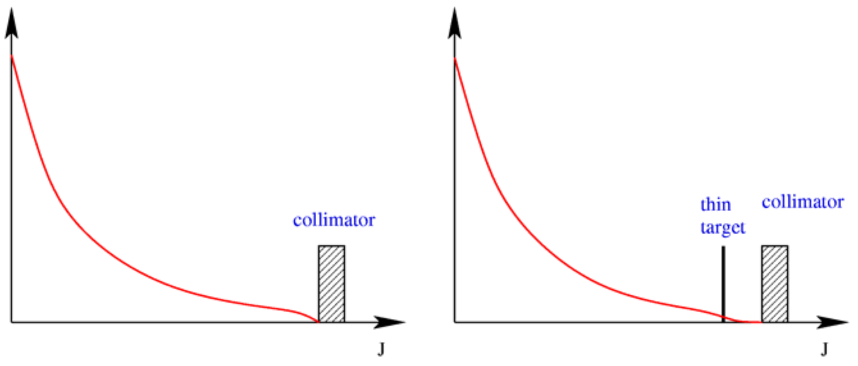

Fig.: Qualitative particle density distribution with and without thin target.

The function of this concept is not really proven in practice, although at HERA we had the experience that background spikes were suppressed when the HERA-B experiment operated wire targets at smaller amplitudes than the primary collimators. I would recommend to study this numerically as a possible option. A little step machined out of the graphite at the leading edge of the jaw would be sufficient.

A thin target was also proposed in the SSC design, although not for the purpose of smearing out losses in time, but for increasing the average impact parameter.

It would certainly be helpful to study the typical time distribution of the losses at existing accelerators. One possibility is HERA and we would be happy to collaborate with CERN colleagues on this subject.