**Minutes of EuCARD2 WP11 2nd annual meeting**

(GSI, Dec 4-5 2014)

Partecipants: A. Bertarelli (AB), M. Beghi (MB), S. Bizzaro (SB), F. Carra (FC), M. Kitzmantel (MK), A. Lechner (AL), N. Mokhov (NM), L. Peroni (LP), E. Quaranta (EQ), S. Redaelli (SR), A. Rossi (AR), A. Ryazanov (ARy), O. Sacristan de Frutos (OS), N. Simos (NS), M. Tomut (MT), C. Trautmann (CT)

**Summary**

Aim of the meeting was reporting on past activities, setting future work, and discussing how to characterise materials in terms of radiation resistance for LHC operations. This summary refers to the latter; the minutes of the whole meeting follow.

1. **Parameters to account for damage are:**
   * 1. **DPA**
     2. **He/H transmutation** (especially for high energetic particles);
     3. **Electronic stopping** (presently taken into account only as temperature increase, could produce damage – DPA – in non-metallic materials);
   * **H/He transmutation** can be calculated and should be measured.
   * **MT proposed to bombard samples charged with He.**
2. Extrapolating from ion irradiation damage to protons and high energetic protons is very challenging. Damage correlation between different types of irradiations (projectile and energy) should take into account:
   * 1. Primary recoil energy spectra;
     2. Displacement dose rate, DPA/s;
     3. Transmutation production rates, He/DPA and H/DPA;
     4. Kinetics of irradiation-induced defect production and accumulation behaviour due to pulsed irradiation.
     5. Production of single point defects and defect clusters.
   * **MT proposed to bombard new samples with light ions below track formation threshold.** Drawback is that damage accumulation would be too slow.
3. **Damage threshold for graphitic material under proton irradiation ~ 0.2 DPA**.
   * 1. 30-40% degradation in **electrical conductivity** could be nevertheless relevant to LHC.
     2. Is this threshold valid also for energetic protons, where He/H transmutation is relevant?
     3. It should be noted that according to FLUKA, for **ultimate HL-LHC (at 4000 fb-1), horizontal primary collimators would reach 0.3 DPA**.
     4. MoGr seems less radiation resistant than CuCD. It could still be ok if DPA estimations are confirmed.
   * **Graphite** is a metal-like in the graphitic plane and an insulator in the perpendicular one. **The electronic contribution to DPA is should be taken into account.**
4. A campaign shall be launched to benchmark DPA calculations against experimental data (Latest from GSI? Other data?).
5. Should DPA calculation include electronic stopping for non metallic materials?
6. Is it possible to measure DPA (to be linked to measured properties degradation) on GSI data?
7. Do we all agree on the proposed Figure of Merit (see minutes for legend)?:

**List of action from the meeting**

* Action: review impact parameters of thermo-mechanical codes for HiLumi scenario. Find worst case in terms of impacting beam sizes, after on going tests with old reference case (F. Carra).
* Action: finalize proposal for microphone measurements in HRMT tests, with clear responsibilities for different experiments (CERN + University of Graz).
* Action: provide CuCD samples for characterization by end of 2014 (M. Kitzmantel) and measure them (O. Sacristan).
* Action: irradiate samples treated at 1800˚C (M. Tomut).
* Action: provide energy loss profile in the irradiated samples (M. Tomut).
* Action: compile a list of available data, continue and finalise characterisation of samples irradiated in 2014 (M. Tomut + bachelor student at GSI).
* Action: specify axis label (A. Ryazanov).
* Action: compile a list of available data, continue and finalise characterisation of samples irradiated in 2014 (N. Simos).
* Action: confirm DPA calculated for primary collimators represents the worst-case scenario (A. Lechner).
* Action: renormalize plot (slide 44) in DPA/y for comparison with results showed by AL (A. Ryazanov).
* Action: online measurement of the degradation of the electrical conductivity in the material during light ions irradiation (M. Tomut).

**Presentations and discussions Day 1**

* **F. Carra**: Presentation of the design of the new low impedance collimators (TCSPM) and the future tests foreseen in HiRadMat. Results of the preliminary simulations presented: HL-LHC scenario, CuCD experiences major failure, CFC and MoGr show minor damage.
  + SR: MoGr and CuCD mandatory to achieve -50% impedance for HL-LHC scenario (for HL-LHC, no scenarios available other than including low-impedance collimators)
  + AR asked if MoGr and CFC share the same graphite composition; MT replied that, although the two materials are mostly made by graphite, their structure is different: MoGr has a graphite matrix with inclusions of Molybdenum carbides, while CFC has a graphite matrix reinforced with carbon fibres. In the initial composition, also MoGr has fibres (even if much shorter than CFC ones), but during the sintering process they merge with the graphite particles.
  + Action: review impact parameters of thermo-mechanical codes for HiLumi scenario. Find worst case in terms of impacting beam sizes, after on going tests with old reference case (F. Carra).
  + Action: finalize proposal for microphone measurements in HRMT tests, with clear responsibilities for different experiments (CERN + University of Graz).
* **O. Sacristan**: latest results of thermo-mechanical characterization of MoGr and CFC presented, together with the measuring methods. A full characterization of CuCD will be done in the future, when samples from RHP are available.
  + Important outcome: different resistance in the 2 planar directions of CFC (previously considered as transversally isotropic material).
  + ARy: proposal to perform TEM on MoGr to analyse starting points for cracks (number of cracks would only be enhanced by irradiation).
  + FC pointed out that the measurements done on MG6530Aa are particularly important, because they show that the new thermal cycle is able to almost completely relax the internal stresses generated during the sintering process, which are considered as the main responsible for the large deformations experienced by the material under irradiation. In fact, new samples are annealed at high temperature just after production.
  + Action: provide CuCD samples for characterization by end of 2014 (M. Kitzmantel) and measure them (O. Sacristan).
* **L. Peroni**: dynamic characterisation of collimator materials at high temperature.
  + The tests have a limit of 1000˚C in temperature, because of the steel holders adopted.
  + CuCD can be tested in the facility devised for brittle materials, although its high Young Modulus could give problems in the measurements, due to the high speed of the propagating waves.
  + A strong tension/compression asymmetry was found in Inermet180.
  + Next step: improvement of the setup to test brittle materials (ex: MoGr, CuCD, CFC, ...).
* **E. Quaranta**: failure scenarios for TCTs and SixTrack simulations with advanced collimators.
  + The impact distribution coordinates in TCT for different scenarios are available for FLUKA and AUTODYN simulations.
  + Next step: benchmark models used for MoGr and CuCD in SixTrack with FLUKA, MARS and other codes. Provide inputs to other simulation teams in UK, not participated to the meeting.
* **M. Tomut**: results of irradiation tests at GSI on LHC collimator material samples.
  + Irradiated carbon fibers showed strong radial contraction; more studies are necessary to evaluate the effects of irradiation on the fibres.
  + Beneficial effect of heat treatment on MoGr radiation-induced deformation: temperature anneals internal vacancies in the graphitic planes.
  + Different types of samples were irradiated (note that penetration depth is expected to be about 50 μm):
    - Thin samples (100-150 μm) were used for thermal characterization with LFA;
    - 1-2 mm thick samples (only a thin layer + non-irradiated bulk for comparison) were used for RAMAN spectroscopy, SEM analysis, nano-indentation test, and electrical resistivity measurements.
  + Very preliminary thermal diffusivity analysis on samples irradiated at low fluence (1E11) shows a larger degradation for samples treated at 1300°C than for those treated at 1150°C. This is no longer true at higher fluences. For more statistics, FC suggested performing the same type of analysis on samples treated at 1800°C, but MT replied that unfortunately those samples had been irradiated with a different ion species and maybe a direct comparison is not possible.
  + Action: irradiate samples treated at 1800˚C (M. Tomut).
  + Action: provide energy loss profile in the irradiated samples (M. Tomut).
  + Thermal diffusivity relative degradation in MoGr faster at low fluencies with respect to CuCD; the slope is decreasing with the fluence for MoGr (more linear for CuCD). Same level of degradation of CuCD reached by MoGr, but at half of the fluence. However, MoGr shows a better behaviour than pure graphite (which degrades by one order of magnitude).
  + AR and AB proposed an intermediate material meeting in February to discuss latest results more in details before the milestone due in May 2015.
  + Action: compile a list of available data, continue and finalise characterisation of samples irradiated in 2014 (M. Tomut + bachelor student at GSI). Who/how other teams can help?.
  + Next step: plan and prepare tests to perform during short run in summer 2015 (3 months, Xe as heaviest available ion): new samples from final grades for final feedback on prototype.
  + Main experimental results with U-beam:
    - No macroscopic damage in CuCD.
    - Behavior shown by MoGr:
      * Following deformation, transversal sample detached from the holder at fluencies above 5e12, loss of thermal contact, increase of temperature -> internal stresses released?
      * Thin transversal samples for LFA broke at fluences between 1e13 and 5e13 -> how the graphitic planes are disposed? Along the diameters of the samples -> contraction.
    - SEM: cracks after irradiation.
    - EDX: slight increase in MoC concentration, maybe some phase change due to irradiation.
    - XRD: increase in η-hexagonal phase in sample heat treated at 1150C (blue curve, 3rd peak from the left).
    - RAMAN foreseen for the future.
    - SEM on 1150˚C: very small increase in MoC concentration after 1e12 i/cm2.
    - Thermal diffusivity degradation with LFA (post-irradiation):
      * 2 layers composite model, L+T MoGr (not HT) irradiated with U vs CuCD -> catalytic effect of MoC in re-graphitization -> lower thermal diffusivity degradation than CuCD.
      * Thermal diffusivity degradation with thermal camera (online): frame rate not sufficiently high in the first irradiation campaign in Feb-Mar ’14.
  + Main experimental results with Bi-beam:
    - Hardness test with nanoindentation on MoGr: hardening of sample with fluence, corresponding maybe to hardening of the carbides, but less with respect to CFC.
    - MoGr with low load: less plastic deformation with fluence, material seems weak -> improve reinforcement?
  + AR: higher temperature in MoGr and different energy deposition: may those factors be a reason for the higher deformation?

MT replied that the absolute temperature is anyway not high enough to induce deformation in the material (~150°C, the material is a refractory so it should not be affected by it). Moreover, MT assessed that the defect propagation in graphite is faster than the temperature increase shown by MoGr.

* + ARy: was the DPA calculated for these cases?

MT: with SRIM we calculate some vacancy formation, but not enough.

* + MK: what about CuCD?

MT confirmed that similar measurements as on MoGr were performed on CuCD sample too. Only thermal characterization is still pending: MT wants first to perform microstructure analysis before spraying the samples with graphite to uniform the emissivity for LFA test.

* **A. Ryazanov**: results on MoCuCD and CuCD
  + Cooling time of few months before handle and measure irradiated samples
  + CT: change of density depends on the geometry?

ARy: depends on point vacancies, interstitials migrates which blows up the lattice, tendency exists but changes are very low (less than 1%), maybe negligible

* + Open question: Young’s modulus measured on MoCuCD seems very low! Much lower than CuCD, to be investigated. Also, in slide 31, ARy describes an increase of the CTE with the irradiation (as expected), but the data show on the contrary a decreasing in 2 samples over 3.
  + Action: specify axis label (A. Ryazanov).
* **N. Simos**: post irradiation evaluation of LHC collimator material samples at BNL.
  + Have to wait for the most radioactive samples to cool down before handling for measurement.
  + CuCD irradiated with fast neutron spallation spectrum at BLIP: overall fluence much lower than proton irradiation, possible to open the capsule and extract the samples for the first analysis. After XRD, sample apparently intact after irradiation (slide 18).
  + First results from Mo samples (200 MeV protons at BLIP): shinier surface of some sample in the capsules after irradiation -> some transformation occurred?
  + Important outcomes:
    - Damage threshold for graphitic material under proton irradiation at 0.2 DPA (lower than expected from reactor data).
    - DPA counted by Si-detector.
  + SR: What would be the impact of different grades of MoGr? Note that the irradiated samples are older than 2 years.
  + FC: MoGr grade tested at BNL (MoGr 10/7-8-9) was not annealed and had different composition with respect to the latest produced grade. For the latest and heat-treated MoGr grades, lower deformation and damage are expected
  + SR: status of samples irradiated with neutrons?  
    NS: CuCD (slide 18) intact, overall fluence much lower than proton irradiation, possible to open the capsule and extract the samples
  + Open question: Strategy for analysis to be defined in order to optimize the exploitation of beam tests. How do we analyse the X-ray data?
  + Action: compile a list of available data, continue and finalise characterisation of samples irradiated in 2014 (N. Simos).   
    A student from CERN will be sent in February to help with measurements. Who/how other teams could help?
  + Open question: ARy questioned in slide 29 why intensity decreases after irradiation, while Bragg peak should increase.   
    NS suggested looking at the different teta angles in the X-ray spectra.

**Presentations and discussions Day 2**

* **N. Mokhov**
  + What they can do at Fermilab: short pulses with energy deposition density (EDD) in the range from 200 J/g (W), 600 J/g (Cu), ~1 kJ/g (Ni, Inconel) to ~15 kJ/g to induce damage in the material: thermal shocks resulting in fast ablation and slower structural changes (mechanical damage) in W, or melting (thermal limit) in the others.
  + AL pointed out that it would be useful to have energy deposition limits also for stainless steel.
  + ORGANIC materials -> damage is proportional to the dose.
  + INORGANIC materials -> DPA to describe damage -> study process up to 3h after the impact (using kinetic Monte Carlo method).
  + **CT pointed out that graphite is like a metal in the graphitic plane and an insulator in the perpendicular one. This is neglected when calculating DPA.**
  + MARS15 uses microscopic model for DPA calculation: all products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV contribute to DPA in this model.
    - With appropriate corrections, they cover different type of projectiles (He, p, e-, π, μ, …). FRONTIER is used for thermo-mechanical simulations, coupled with MARS.
    - Strong temperature impact on displacement cross section (σd).
  + In order to compare damage induced by different projectiles, one shall consider production of single point defects and defect clusters.
  + FLUKA+MARS: good agreement to model DPA induced by hadrons and heavy ions beam at high energies.
  + Important outcomes:
    - Need of a correlation between different parameters (flux, fluence, temperature …) to have information on material damage.
    - Schedule new experiments (GSI, BNL, neutrons at Kyoto, NRC-KI …) to correlate results at different E, projectiles.
    - Possibility to count DPA using in Si-detectors.
    - Follow up the kinetic MC model development (up to 1e4 s).
  + Linking DPA, dose, and fluence to thermo-physical properties changes is still a dream!
  + Hydrogen/Helium production add to damage: material to be characterized also in terms of gas production in addition to DPA estimation.
    - H/He production rate grows with energy up to ~10 GeV, is proportional to hadron fluence and can be estimated.
    - SR asked how to measure H and He production. NM and MB replied that it could be performed irradiating a very thin layer of material where the reaction pp is induced.
  + AR: irradiation-> damage -> rearrangement; does the rearrangement depend on the initial damage?

ARy: damage depends on flux and many other factors. He production is important but also depends on irradiation temperature. In LHC, gas production must be taken into account!!

* + **Proposal of a new figure of merit including a damage limit factor!! (see “Final discussion”).**
  + No standard way to calculate DPA in compounds.
  + AB: degradation of thermal diffusivity is much lower in MoGr than in isotropic graphite.  
    MT: Mo can catalyse graphitisation in the tracks after irradiation, even at room temperature when Gr is not liquid. One should be able to calculate it.
  + NM, ARy, CT agreed on the fact that DPA is not enough to estimate radiation-induced damage: CT: damage depends on the material. Electromagnetic regime damage (electronic stopping) has also to be taken into account: energy dissipation in metals strongly enhanced by a lot of free e-, it is ignored by DPA.
* Summary by NM:
  + Radiation damage by high-energy protons includes displacement cascades and transmutation production of helium and hydrogen and other impurities.
  + DPA is the parameter commonly used to correlate displacement damage. However, the extent of radiation damage cannot be fully characterized by a single parameter.
  + Damage correlation between different types of irradiations should consider:
    - Primary recoil energy spectra
    - Displacement dose rate, DPA/s
    - Transmutation production rates, He/DPA and H/DPA
    - Kinetics of irradiation-induced defect production and accumulation behavior due to pulsed irradiation
  + Further quantification is needed on annealed vs non-annealed defects.
  + Develop an approach to accurate calculation of DPA induced by low-energy neutrons in compounds.
  + Radiation damage by high-energy beams is more intense (for the same fluence) due to Coulomb elastic scattering ~Zp2; codes which include this process, nuclear interactions, and same DPA model parameters agree quite well; radiation damage at high energies is amplified by intense helium gas production.
  + Move from occasional comparisons of calculated radiation-damage related quantities to a comprehensive code with “standardized” DPA models and benchmarking at well defined irradiation conditions including temperature, dose rate, H2/He gas production, etc. The correlation factors - DPA/D, DPA/Fn, NHe/DPA – need to be generated, compared and related to reactor data.
* **A. Lechner**
  + FLUKA is based on microscopic model to DPA calculation. It takes into account the contribution of different particle types. Particles are transported up to a certain threshold of damage depending on the material.
  + Coupling SixTrack-FLUKA used to performed simulations.
  + Important outcomes from simulations:
    - Peak DPA estimated for horizontal primary collimator (contribution only from recoil particles, no primary protons; NM: primary contribute should be negligible):
      * Nominal 7 TeV: 3e-3 DPA (at 40 fb-1)
      * Ultimate HL-LHC: 0.3 DPA (at 4000 fb-1)
    - Peak DPA estimates for inner triplets in IR1/5:
      * HL-LHC: 1.8e-4 DPA (at 3000 fb-1, dominant contribution due to neutrons <20 MeV).
  + AR: Is it possible to calculate DPA for compounds in FLUKA?

NM: averaging DPA in composite material is a problem especially if it is not homogenous. **We have to review present model used in the codes (FLUKA, MARS, …).**

* + AB: do we expect other collimators (e.g. secondaries) to be less exposed to damage respect to primary?

AL: preliminary calculations have been shown on primary collimators, but we expect secondaries to be less loaded.

* + Action: confirm DPA calculated for primary collimators represents the worst-case scenario (A. Lechner).
* **M. Tomut**
  + Results of irradiation studies on Higly Oriented Pyrolytic Graphite (HOPG, similar to mono-crystalline graphite) and Polycrystalline Isotropic Graphite (PIG) were presented.
  + After Swift Heavy Ions (SHI) irradiation, nuclear stopping produces several defects in HOPG, while the electronic effects become more relevant on the surface. PIG under SHI irradiation showed a hard disordered sp2 phase in the electronic stopping regime.
  + AR: What can be done to further improve the behaviour of MoGr against radiation?

MT: problems mostly concerning the mechanical strength, focus on how to reinforce the material without changing the composition

* + AB: damage threshold for graphite: 0.2 DPA (NS), 1.8e13 i/cm2 (MT). Does a correlation between the two values exist?

MT: limit for graphite irradiated at GSI refers to phase changes and not displacement, it is not possible to calculate the DPA for that specific fluence.

* **A. Ryazanov**
  + Modeling of point defect formation under different types of irradiation.
  + Displacement cross section (σd) depends on cascade function (ν(T)). ν(T) can be estimated using Kinchin-Pease formula and NRT model for monoatomic material, or numerical calculation for polyatomic material.
  + Models were developed to calculate the generation rates of point defects and cascade and sub-cascade formation in LHC collimator materials. Composite materials are considered as “multi-layer sandwich”. The methods take also into account electronic excitation, energy loss, elastic and inelastic collisions of fast particles with atoms of these materials.
  + Main results:
    - Graphite:
      * Pions and secondary electrons do not produce cascades, only point defects.
    - SiC:
      * Radiation penetration depth in the material is important for mechanical test after irradiation -> penetration depth increases with energy.
      * Proposed formula to calculate ν(T) in composite materials.
      * Boltzmann transport equation to calculate displacement, equation is for 1D, but promising also for multi-layer.
  + **NCR-KI could help BNL calculating defects at 200MeV, theoretical models for tracks for GSI.**
  + AL: swelling on SiC at CERN. Possible issues in operation?

ARy: point defect in dielectric materials might lead to charge effects, which can be related to swelling. Degradation of resistivity.

* + SR: SiC not useful for collimators, it was ruled out due to its high impedance.
  + SR: need to compare different simulation codes (FLUKA, MARS…) in simplified case. Use same normalisation in order to compare results: AL uses DPA/y, while ARy DPA/s/bunch.
  + Action: renormalize plot (slide 44) in DPA/y for comparison with results showed by AL (A. Ryazanov).
  + CT assessed that SiC has an interesting behaviour, because it may anneal defects by electronic contribution (experimental observation in Dubna). Could it be simulate?

ARy proposed a collaboration for this scope.

* + Two important phenomena to be distinguished:
    - Electronic interactions: become relevant at high energy.
    - Elastic interactions: damage the material also at low energies (contribution to DPA).
* **M. Beghi**
  + Review of basic concepts of radiation-induced damage mechanisms in materials.
  + Usually irradiation temperature plays a role, it is not so relevant for collimators where operation temperature is relatively low.
  + Slow (w.r.t. impact event) evolution of defects is strongly temperature dependent.
  + DPA is induced by elastic nuclear collisions. Electronic interaction translates only into heat for metals, while for insulators there is a contribution in heat and damage too.
  + DPA for composite materials: different mass and bound between the components make the calculation of DPA more difficult than in pure metals or than in alloys where components have similar mass.
  + The DPA rate has an effects on parameters’ degradation, so the effect of ion bombardment is difficult to extrapolate to protons.
* **C. Trautmann**
  + For most ions, if the penetration depth is about ~50 µm, ~49 µm interacting with electrons (so called “tracks”) and ~1 µm with atoms/nuclei.
  + Electronic stopping is relevant for high-energy ions interaction with matter. It is a two-steps process, where at the end defects are produced. This phenomenon is not relevant for metals, where the high conductivity dissipates away the electronic heating before the [ion track](http://en.wikipedia.org/wiki/Ion_track) has time to form.
  + As it accounts only for nuclear effects, DPA can be considered sufficient for metal but not for insulators, where the electronic stopping is not negligible.
  + Track production by electronic stopping shows a threshold behaviour, which is low for insulators, medium for semiconductors and high for metals, with some exception that may depends on the material structure: diamond produces point defects and stress, but no tracks were found so far, probably due to very high thermal conductivity. Pure materials (ex: Ti, Ni) are not sensitive to electronic stopping but the compound NiTi can be.
  + Localised melting occurs when a particle passes through a low-conductive material, generating tracks. The defects mobility and annealing are both induced by temperature increase, even if melting point is not reached.
  + SR asked if this phenomenon is interesting for collimator at LHC energy.

MT replied that considering protons at LHC energies, we are still below threshold of tracks formation for metals, to be checked for light particles or semi-conductors.

**Final discussion**

* ARy pointed out that in addition to DPA calculation, we should look at microscopic level, focusing at the interface between different compounds to better understand behaviour of composite materials under irradiation.
* AB confirmed that DPA is a good indicator of damage induced by protons, not helpful for heavy ions. Moreover, he asked which theoretical work could be done to understand the behaviour of composite material with 7 TeV protons in the LHC and which experimental program to launch in the next months.
* MT proposed a future irradiation test at GSI using light ions, below the threshold of track formation.
* MT and ARy agreed on the need to study gas (H, He) formation in collimator materials. MT asked if it makes sense to plan irradiation of He implanted samples.
* NM stresses that below track formation threshold, electronic stopping should not matter: FLUKA and MARS consider electronic stopping contribution as deposited energy: the effect is accounted in dose and T increase, but it is not part of DPA calculation. It can induce annealing but it is not taken into account in DPA calculation.
* NM underlined the need of an extended campaign of benchmarking and model verification: use a simplified geometry, perform simulations with different codes using the same conditions, compare simulation results with available data: if results are in agreement, simulate also 7 TeV case for the LHC.
* ARy pointed out that sub-cascades must also be taken into account to have a complete picture of the radiation-induced damage.
* AB asked if the track formation is a relevant process in our graphite-based collimator materials. CT replied that track formation in semiconductors is still not deeply investigated so far. HOPG is affected by tracks in the direction perpendicular to the graphitic plane.
* AL confirmed that it is true that proton irradiation does not produce tracks at 7 TeV, but one should also look at the recoil spectrum and at the type of secondary particles that come out when the primary beam impacts the collimator jaw. This is not yet included into calculation.
* MB warned that ion beam tests induce only localized damage and recoils formation, while recoils from protons during LHC operation can affect the whole collimator jaw.
* MT reminded that it is not possible to calculate DPA from low-level irradiation reached at GSI with heavy ions.
* ARy: DPA + gas production + track formation give information on radiation-induced damage
* NM proposed a new figure of merit:

Legend:

* + - *FoMAB* is any thermo-mechanical figure of merit given by AB.
    - *DPAmax* is the DPA threshold which usually indicates the integrated radiation load level (as measured in DPA) at which the certain property starts to show a significant change. Usually it uses a 30 to 50% change in the property of interest to define that threshold.
    - *σH,He* is the gas production cross section.
    - *σ0* is a normalization factor.
    - *KMT* is a factor accounting that it is not always possible to reach *DPAmax*, especially for ion irradiation.
* AL said that it is also important to consider the irradiated volume (ex: TCSG sees a broader beam than TCP)
* MB pointed out that setting a limit for efficiency of damage production implicitly assumes damage accumulates with fluence.
* AL said that 0.3 DPA expected in the ultimate HL-LHC simulated by FLUKA is close to 0.2 DPA presented by NS.   
  AB pointed out that this would imply that CFC could have problems only in 15 years from now!
* MT assessed that Raman spectroscopy is important to study defects formation in irradiated material.
* AB asked if it would be meaningful to have an irradiation test using light ions, since they are closer to protons?   
  MT replied yes, but longer time is required to reach high fluence. The beam will not be available at GSI in the next months and decision about collimator material must be take before one year.
* AB stated that for secondary collimators, the electrical properties degradation is the most relevant parameter to look at rather than thermal conductivity, swelling, etc.
* Action: online measurement of the degradation of the electrical conductivity in the material during light ions irradiation (M. Tomut).
* AB said that we should think also about a system to anneal defects and damage, to be integrated in the present collimator layout.

**Annexe by N. Mokhov for non-experts**:

* + **DPA thresholds** usually indicate the integrated radiation load level (as measured in DPA) at which a property of interest starts to show a significant change. People usually use a 30 to 50% change in the property to define that threshold.  At BLIP we observed even more substantial changes quoted in slide 19 of my presentation. These days, NM would use a single number as a DPA threshold for a graphite-based material at high energies ~ 0.1.
  + **Energy Loss, Energy Transfer and Energy Deposited:**

Let’s consider a charge particle (projectile) with initial kinetic energy E1 traversing a layer of material. Then

* + - **Energy loss** ∆E = E1 – E2, where E2 is its kinetic energy at the exit from the layer.
    - **Energy transfer** (ET) is a fraction of ∆E transferred to the layer’s material in the electronic (ionizing) and non-ionizing forms.
    - The first part results in **energy deposition** (ED or dose) and heating. The second part (non-ionizing energy loss) is due to elastic collisions of the projectile and nuclei; it is directly related to DPA; normally NIEL is less than the first part.
    - At very high energies and for light particles emission of bremsstrahlung photons adds to ED. In thick layers, ED+NIEL is almost equal (slightly less) than ∆E. In thin layers, ED+NIEL is always less than ∆E, because some energy is leaked out from a thin layer in the form of energetic knock-on or delta-electrons.