

# MERLIN CLEANING STUDIES WITH ADVANCED COLLIMATOR MATERIALS FOR HL-LHC

A. Valloni<sup>\*1 2</sup>, H. Rafique<sup>2 3</sup>, A. Mereghetti<sup>1</sup>, J. G. Molson<sup>4</sup>, R. Appleby<sup>2</sup>, R. Bruce<sup>1</sup>,  
E. Quaranta<sup>1</sup>, S. Redaelli<sup>1</sup>

<sup>1</sup> CERN, Geneva, Switzerland

<sup>2</sup> Manchester Cockcroft Accelerator Group, University of Manchester, Manchester, UK

<sup>3</sup> University of Huddersfield, Huddersfield, UK

<sup>4</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

## Abstract

The challenges of the High-Luminosity upgrade of the Large Hadron Collider require improving the beam collimation system. An intense R&D program has started at CERN to explore novel materials for new collimator jaws to improve robustness and reduce impedance. Particle tracking simulations of collimation efficiency are performed using the code MERLIN which has been extended to include new materials based on composites. After presenting two different implementations of composite materials tested in MERLIN, we present simulation studies with the aim of studying the effect of the advanced collimators on the LHC beam cleaning.

## INTRODUCTION

In order to meet the collimation requirements for the HL-LHC an upgrade of the collimation system is required [1]. As well as novel collimation schemes [2], new jaw materials are under investigation [3]. Due to the small collimator gaps required to achieve the design performance, collimators provide the largest contribution to the machine impedance. In order to reduce the instability caused by the collimator impedance, a number of possible upgrade materials have been narrowed down to the most promising pair, copper-carbon-diamond (CuCD), and molybdenum-carbide-graphite (MoGr). Rigorous experimental testing is performed to obtain the material properties and limitations [4], and numerical simulations use the observed properties to investigate the effect on the cleaning performance of the LHC collimation system. In simulation codes such as MERLIN [5] and SixTrack [6] a palette of new composite materials has been introduced. Both codes construct composite materials in similar ways, but differ in the approach to performing point-like scattering in these composites.

In this paper we compare the two different approaches and we present particle tracking simulations to assess the collimation efficiency performed with MERLIN. The same analysis using SixTrack has been previously published in [3].

## IMPLEMENTATION OF NEW MATERIALS IN MERLIN

The properties of materials relevant for the collimator upgrade are compared with the existing jaw materials in Table 1.

In order to construct a composite from constituent materials, we must know the mass fraction  $m_i$  of constituent  $i$  in the composite, which is given by:

$$m_i = \frac{n_i A_i}{\sum_i n_i A_i}, \quad (1)$$

where  $A_i$  is the constituent atomic mass and  $n_i$  is the number fraction of the constituent in the composite. These fractions may be used to define some composite material properties as a weighted average of the constituent properties. For example the mean atomic mass of the homogeneous composite  $\bar{A}$  is

$$\bar{A} = \sum_i n_i \cdot A_i. \quad (2)$$

and the radiation length of a compound material is

$$\frac{1}{\chi^0} = \sum_i \frac{m_i}{\chi_i} \quad (3)$$

where  $\chi_i$  is the radiation length of the  $i$ th element. In order to define the path length for a proton scattering in the composite in MERLIN, *i.e.* the distance traversed before interacting with a nucleus, the sum of the calculated cross sections  $\sigma_{pN\ tot}$  is used to find the mean free path

$$\lambda_{tot} = \frac{\bar{A}}{\sigma_{pN\ tot} \cdot \rho N_a}, \quad (4)$$

where  $N_a$  is Avogadro's constant and  $\rho$  the density. Cross sections for composite nuclear interactions are generated in MERLIN for the composite (as a homogeneous mixture) in order to calculate the mean free path, but are not used for point-like scattering. Working from the constituent cross sections, equation 5 is used to find the reference nuclear cross sections (total, inelastic, elastic, or Rutherford).

$$\sigma_{pN} = \sum_i n_i \sigma_{pN\ i}. \quad (5)$$

These properties are used in the application of bulk scattering in MERLIN, *i.e.* multiple Coulomb scattering (MCS) and

**01 Circular and Linear Colliders**

**T19 Collimation**

Table 1: Collimator Material Parameters [3]

| Material | Density<br>[ $\frac{g}{cm^3}$ ] | Electrical Conductivity<br>[ $\frac{MS}{m}$ ] | Atomic Content<br>[%]         | Mean Free Path<br>[cm] |
|----------|---------------------------------|---|-------------------------------|------------------------|
| CFC      | 1.67                            | 0.14  | 100 C                         | 35.45                  |
| Inermet  | 18                              | 8.6   | 86.1 W, 9.9 Ni, 4 Cu          | 6.03                   |
| MoGr     | 2.5                             | 1   | 2.7 Mo <sub>2</sub> C, 97.3 C | 24.84                  |
| CuCD     | 5.4                             | 12.6  | 25.7 Cu, 73.3 CD, 1 B         | 13.56                  |

energy loss via ionisation for a composite material. When point-like scattering occurs, a weighted random constituent element nucleus is selected and the proton scatters from the constituent nucleus with corresponding cross sections and all other properties (in the present paper we refer to this approach as the "MERLIN-method"). This is where MERLIN differs from SixTrack, which performs point-like scattering from the imaginary composite nucleus (the imaginary nucleus is the weighted average of the constituent nuclei). In MERLIN the user may enable point-like scattering from the composite nucleus instead of the constituent nuclei, in this case a weighting approach similar to SixTrack is implemented (we refer to this approach as the "MERLIN-6T method"). The latter approach is clearly non-physical but was implemented in an attempt to adapt the Sixtrack scattering routine to the treatment of composite materials. These two approaches will be compared in MERLIN to quantify the errors.

## COMPARISON OF DIFFERENT METHODS

In order to compare the different approaches used in the two codes a test case is defined. We studied the effect of a pencil beam of  $6.4 \cdot 10^6$  protons impacting upon a 1 cm long block of composite material. Simulations have been performed in MERLIN and SixTrack and the results are shown in Figs. 1, 2, 3. In each plot the red curve represents simulations performed in MERLIN using the MERLIN-method, the blue curve the MERLIN-6T-method and the green curve the results obtained from SixTrack. The changes in polar angle  $\theta$  and momentum offset  $dp$  are recorded for particles that survive the length of material without point-like scattering, and those that undergo single diffractive (SD) scattering. All particles are subject to MCS and energy loss via ionisation.

In the case of single diffractive interactions, the MERLIN-method results in a smaller cross section than SixTrack. It is also the case that the momentum transfer is smaller in SixTrack, these two differences are shown in Fig. 1 for CuCD, and Fig. 2 for MoGr, where in MERLIN the polar angle distribution and spread in energy loss is larger. Differences between the MERLIN-method and MERLIN-6T-method are not evident in these plots.

The angular and momentum spread for particles that do not undergo point like scattering events are compared in Fig. 3. It is evident that MERLIN and SixTrack provide very similar results, which is expected as for MCS and ionisation

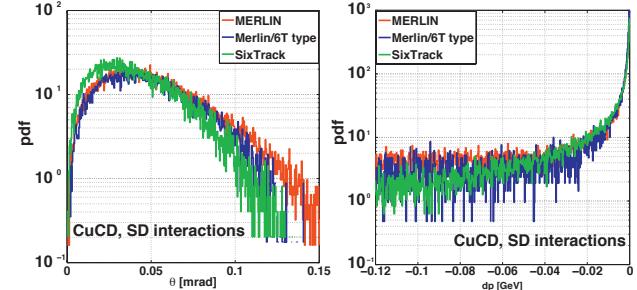


Figure 1: Polar angle (left) and energy loss (right) distribution after single diffractive scattering in 1cm of CuCD, comparing MERLIN and SixTrack.

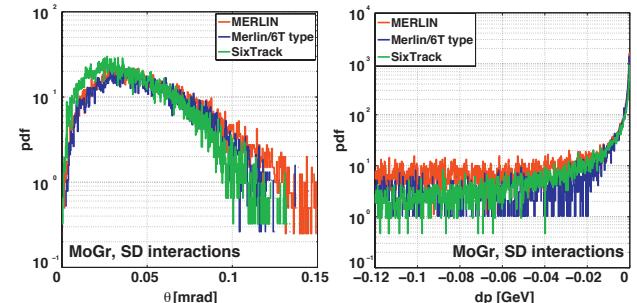


Figure 2: Polar angle (left) and energy loss (right) distribution after single diffractive scattering in 1 cm of MoGr, comparing MERLIN and SixTrack.

the method used for composites is the same in both codes. As shown in Fig. 1 and Fig. 2, SD interactions resulting in a small energy loss are less frequent in MERLIN.

## COLLIMATION CLEANING SIMULATIONS

In order to study the effect of the new collimator materials on the collimation cleaning efficiency, MERLIN simulations were performed with the full LHC collimation system in place. The horizontal halo case was studied for the nominal 7 TeV machine, with optics squeezed to 55 cm. The same collimator settings as in [3] are used to enable a direct comparison to SixTrack results. Three different cases were simulated where all the secondary collimator (TCSG) jaws in IR 7 were either made of MoGR, CuCD or CFC. Simulations indicate that cold losses in the dispersion suppressors around IR 7 [7] are essentially unaffected by the change of

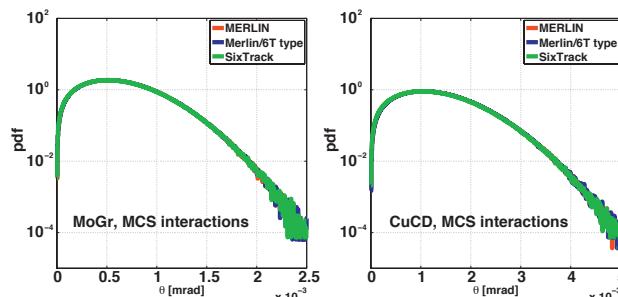


Figure 3: Polar angle distribution after 1cm of CuCD (left) and in 1 cm of MoGr (right) without point-like scattering, comparing MERLIN and SixTrack.

TCSG material. We therefore focus this analysis on the loss distribution on the TCSG collimators.

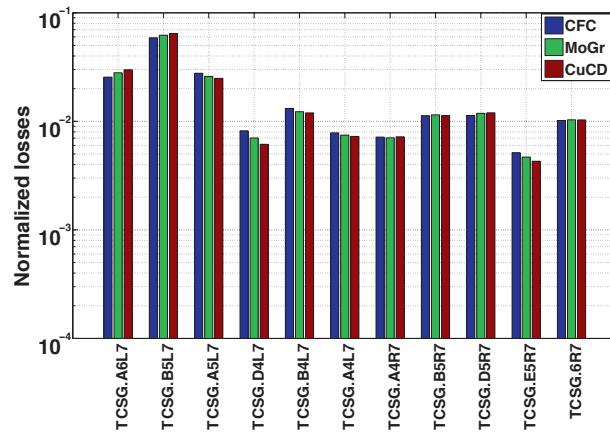


Figure 4: Normalized losses on secondary collimators in IR 7 for different jaw materials, CFC, MoGr, CuCD.

In the first two secondary collimators downstream of the primary collimators, losses are higher in the composite materials with higher effective Z, MoGr and CuCD. These are the secondary collimators that intercept the products of the scattering with the primary collimators and larger Z values have a direct impact on the absorption of particles.

The loss ratio calculated collimator by collimator for the two new composite materials over the standard CFC (Fig. 5) shows an increase by 18% in the worst case. Accounting for an additional factor 2 for HL-LHC beam intensity, the load on collimators due to beam impact appears still compatible with the present estimates of dynamic deformation limits during beam losses [8]. Detailed energy deposition simulations are needed to assess the corresponding energy deposited in each collimator [9].

Figure 6 shows the distribution of the particles absorbed along the length of both jaws in the most loaded secondary collimator (TCSG.B5L7.B1). The exponential decrease due to inelastic scattering events is, as expected, steeper for materials with higher density and atomic number.

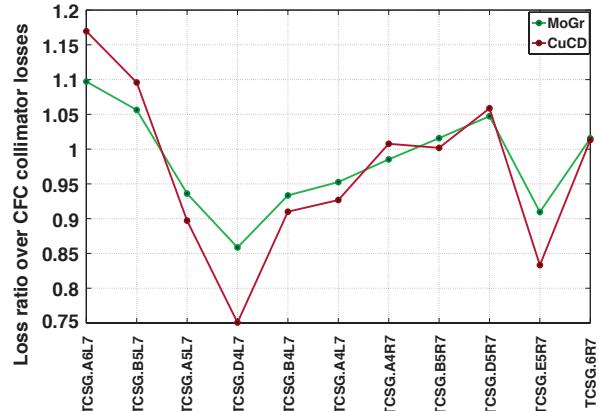


Figure 5: Ratio between simulated losses on secondary collimators in IR7 for different jaw materials over the CFC ones.

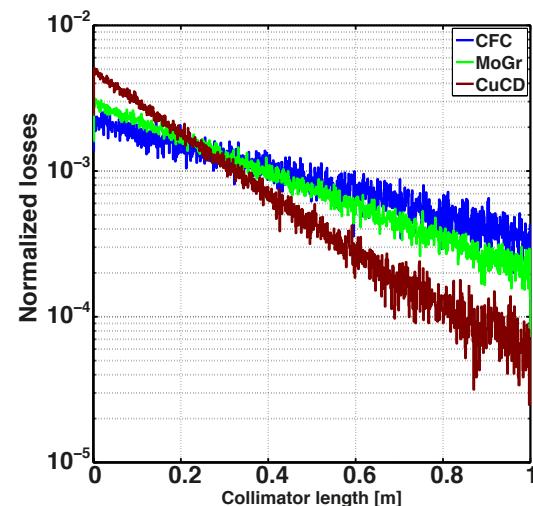


Figure 6: Distribution of particles lost along the length of the most loaded TCSG in IR 7.

## CONCLUSIONS

Composite materials have been successfully implemented in MERLIN and are available for simulations of collimation cleaning at the LHC. From a first comparison between MERLIN and SixTrack we have observed no relevant differences between the different approaches of the two codes in treating composite materials. This is an important validation of previous results. It is planned to extend this comparison by including tools like FLUKA [10] and GEANT [11]. We also presented simulation results of halo cleaning in the LHC ring using novel materials for the secondary collimators instead of CFC. Results of complete layouts are consistent with those previously published and this enforces further the validity of the methods developed for the treatment of composite materials.

## REFERENCES

- [1] G. Apollinari, *et al.*, “High-Luminosity Large Hadron Collider (HL-LHC) : Preliminary Design Report”, CERN-2015-005 (2015)
- [2] D. Mirarchi *et al.*, “Cleaning performance of the collimation system of the High Luminosity Large Hadron Collider”, presented at IPAC’16, Busan, Korea, May 2016, paper WEPMW030, this conference.
- [3] E. Quaranta *et al.*, “Collimation Cleaning at the LHC with Advanced Secondary Collimator Materials”, in *Proc. of IPAC’15*, Richmond, VA, USA, paper TUPTY029, p. 2068.
- [4] N. Mariani, “Development of Novel, Advanced Molybdenum-based Composites for High Energy Physics Applications”, PhD Thesis, Politecnico di Milano (2014).
- [5] <https://github.com/MERLIN-Collaboration/MERLIN>
- [6] <http://SixTrack.web.cern.ch/SixTrack/>
- [7] A. Valloni *et al.*, “MERLIN simulations of the LHC collimation system with 6.5 TeV beams” presented at IPAC’16, Busan, Korea, May 2016, paper WEPMW037, this conference.
- [8] A. Bertarelli *et al.*, “Updated robustness limits for collimator material”, LHC Machine Protection Workshop, Annecy, France, 2013.
- [9] E. Skordis, “FLUKA estimation of DPA for ion irradiation and update on IR7 DPA calculations for LHC operations”, presented at the EuCARD-2 WP11 Topical Meeting, (2016).
- [10] <http://www.fluka.org/fluka.php>
- [11] <https://geant4.web.cern.ch/geant4>