

Progress report : UFO Dynamics studies

(From the collaboration on UFO studies between TRIUMF and CERN HL-LHC)

Context

Unidentified Falling Objects (UFOs) present in the LHC beam pipe have been under continuous study since the start of LHC operation. While there are still a lot of unknowns related to UFOs, they are believed to be micrometer-sized dust particulates falling into the LHC beam and causing proton losses, which can lead to protective beam dumps and magnet quenches.

Initial Task Description

The agreement between the two parties stipulates that "TRIUMF shall contribute to the investigation of the origin, the generation mechanism and dynamics of UFOs and their criticality for the operation of LHC at 7 TeV as well as with increased beam intensities in the HL-LHC era". The project is divided into three main objectives :

1. Analysis of UFO loss data recorded during standard beam operation and dedicated beam experiments
2. Modelling of the UFO movement dynamics
3. Simulation of beam particle interactions and their impact on accelerator equipment like superconducting magnets

At this stage of the project, the first three milestones out of the following were planned to be attained:

- 6 months** : Analysis of all available UFO-MD data and results and comparison of the UFO movement dynamics with the existing models and first proposal for an adaptation of the model.
- 12 months** : Updated UFO dynamics model and its simulations to compare to the UFO MD data. A full analysis of the UFO loss data recorded during standard beam operation with a summary of the findings.
- 18 months** : Tracking simulations with UFO Monte-Carlo considering the updated UFO dynamics model for the LHC run II and comparison to the measured UFOs during beam operation in Run II.
- 24 months** : Tracking simulations with optimized UFO Monte-Carlo for predictions of LHC Run III and HL-LHC UFO activities with the increased particle momentum (7 TeV - LHC Run III) and increased bunch intensities (HL-LHC).

Project status

The first progress report (July 31, 2019) presented an update of the simulation tool and a global analysis of ICBLM UFO loss data recorded during standard beam operation. Following this work, an in-depth analysis of UFO loss events was carried out on a case-by-case basis. This work confirmed the validity of simulated bunch-by-bunch losses coming from macroparticulate interactions with the proton beam. However, it also showed that the asymmetric time evolution of measured UFO losses cannot be explained by the current model. The following sections discuss these findings in greater detail. Tracking simulations, planned in the initial project milestones, were not performed yet.

Skew Normal Distribution

In order to gather meaningful information from the ICBLM loss measurements, a Skew Normal Distribution fit was proposed to represent UFO losses. This allows to compare loss profiles using only four fit parameters : A, σ, μ, α (respectively the amplitude, scale, location and shape parameters), following:

$$\Phi(t) = Ae^{-\frac{(t-\mu)^2}{2\sigma^2}} \left[1 + \operatorname{erf} \left(\frac{\alpha(t-\mu)}{\sqrt{2\sigma^2}} \right) \right] \quad (1)$$

The shape parameter α is linked to the skewness of the distribution (third standardized moment), γ_1 :

$$\gamma_1 = \frac{4-\pi}{2} \left(\frac{\delta}{\sqrt{\pi/2-\delta^2}} \right)^3 \quad \text{with} \quad \delta = \frac{\alpha}{\sqrt{1+\alpha^2}} \quad (2)$$

Fitting eq.(1) to the inelastic collision rate yields excellent fits, both in simulations and measured UFO time profiles.

UFO Candidate : bunch-by-bunch loss simulations

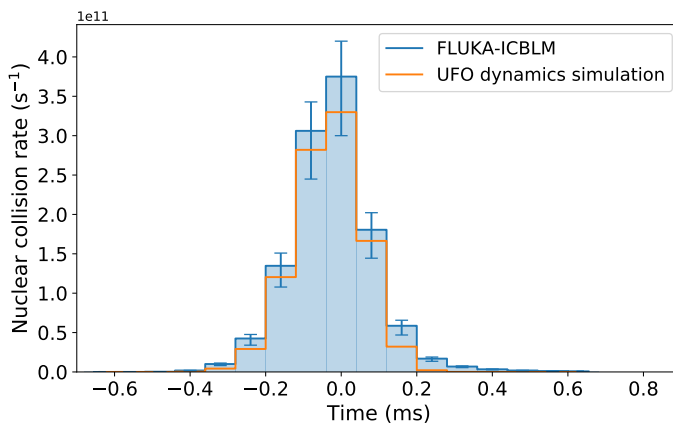


Table 1: Best Candidate Parameters

Parameter	
Material	Cu
Radius	33 μm
Initial Charge	$-2 \times 10^7 e$
Initial x position	1.1 mm off-center
Position in arc-cell	57.9 m

Figure 1: Comparison of best simulated UFO candidate with ICBLM measurement for the 2018-09-30 22:47:52 UFO event. The number of nuclear collision rate for the measurement was computed with FLUKA. The error is shown by the blue error bars.

On 2018-09-30 22:47:52, a UFO event was recorded at 6.5 TeV during a LHC fill in which the two bunches had an increased emittance, one horizontally and one vertically. An analysis of this event was carried out to exploit the additional information coming from the blown-up bunches.

The ICBLM loss measurement was compared to simulated losses coming from Monte-Carlo simulations with varying UFO parameters in order to identify the best UFO candidate. Therefore, the fitting parameters discussed above were determined for the measured loss profile as well as the simulated loss profile, and the sum of their squared residuals was minimized. The comparison is shown in Fig.1.

The bunch-by-bunch losses coming from the interaction of the best UFO candidate with the beam was also simulated using the beam parameters present in the LHC at the time of the event. The result is compared in Fig.2 with the bunch-by-bunch loss measurement recorded by diamond BLMs located at the TCP.

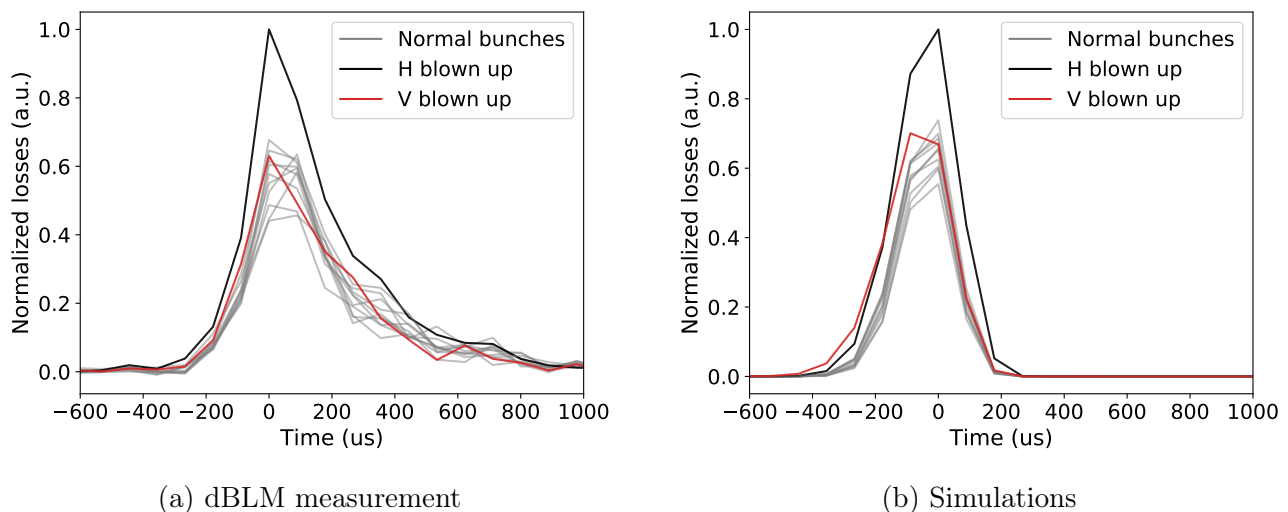


Figure 2: Comparison of the turn-by-turn bunch losses for the best simulated UFO candidate with dBLM measurement with blown-up bunches in the LHC for the 2018-09-30 22:47:52 UFO event. The first 12 bunches are shown.

This analysis shows that the model can be used to identify a UFO candidate which reproduces well the two independent measurements (ICBLM and dBLM) of the same beam-UFO interaction. The results shown in Fig.1 is dependant on the inelastic collision rate and on the energy deposited in ICBLMs. As for the result shown in Fig.2, it is dependant on the elastic collision rate (detection at the TCP) and is coming from the fine time structure (single bunch interaction) of the UFO event recorded by a dBLM. In both cases, simulations are in very good agreement with measurements.

Assymmetric time signal : positive skewness

During the global analysis of ICBLM UFO loss data, it was found that about half the Run II UFO events showed an asymmetric tail on the left side (negatively skewed) and half showed an asymmetric tail on the right side (positively skewed). Examples for both, positively skewed and negatively skewed UFO events are shown in Fig.3.

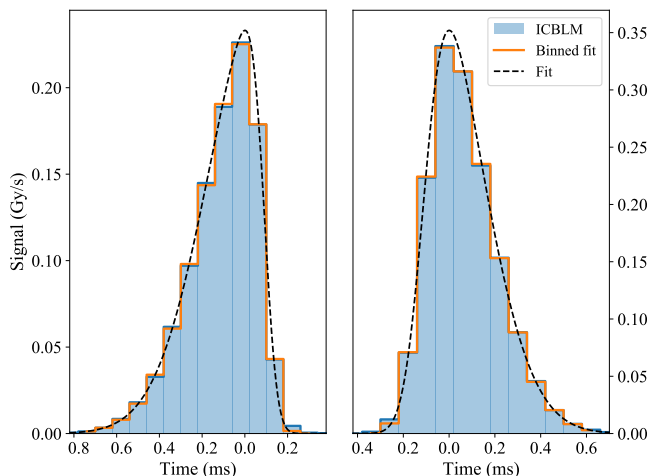


Figure 3: Example of UFO events with negative skewness (left) and positive skewness (right). The fit for the underlying inelastic collision rate is shown, as well as the resulting binned signal.

This observation is important as it cannot be reproduced by the current UFO simulation tool, which can only account for negatively skewed time profiles. This asymmetry was already observed in Run I and briefly discussed [2, Figure 5.9, p.68]. However, no explanation of this observation was provided. The relevant figure is reported in Fig.4a, and the equivalent for Run II events is presented in Fig.4b. Note that Fig.4a shows an estimate of $-\gamma_1$ on the vertical axis whereas Fig.4b shows the statistical third standardized moment γ_1 from the $80 \mu\text{s}$ binned ICBLM signals. In both cases, there is a slight decrease of the skewness as a function of the peak loss rate. The distribution observed during Run II is similar to the one observed during Run I.

Different hypothesis are currently being investigated to explain the positive skewness, with no success so far. These include:

1. Shielding effects from ionisation electrons might affect the repelling forces.
2. Different release mechanisms (i.e. not leaving from the beam screen, initial velocity, etc.) could affect the beam entry and exit speed of the UFO.
3. Thermal expansion of the UFO as it interacts with the proton beam could impact its cross section as a function of time.

Within these investigations, the charging mechanism used in the model was reviewed and benchmarked against FLUKA. The results of this is discussed in the section below.

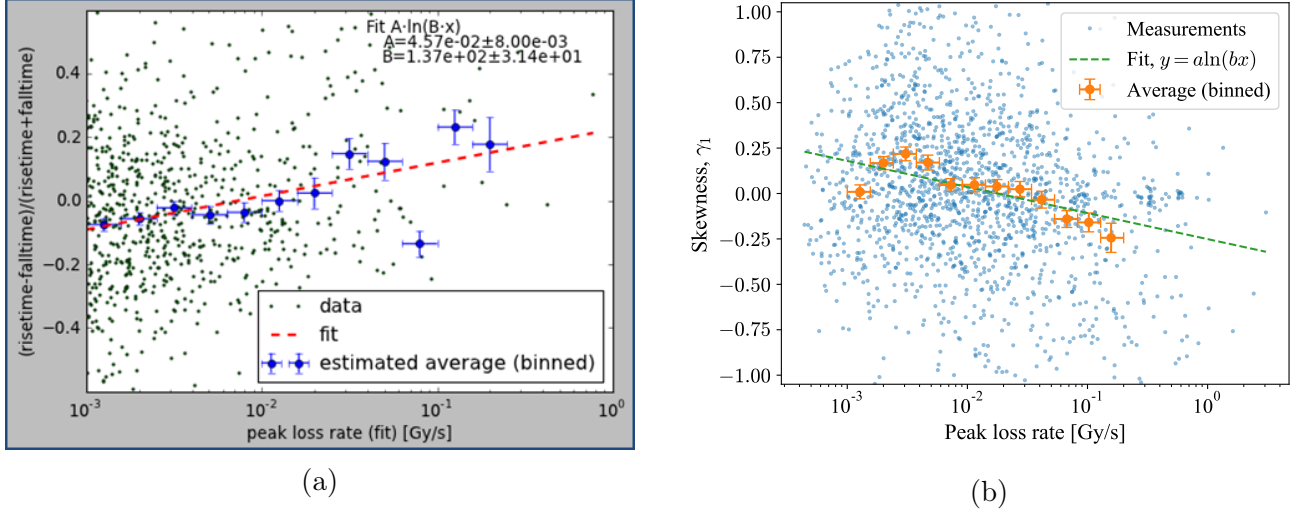


Figure 4: Measured skewness and peak loss rate of UFO events observed during (a) Run I, from [2]. (b) Run II. The fit parameters are $a = -0.062 \pm 0.007$ and $b = 56 \pm 11 \text{ (Gy/s)}^{-1}$. Only events with sufficient signal which occurred in stable beam are shown. The orange dots indicate the average skewness and average peak signal of the data within the bins defined by the horizontal bars and standard error of the mean shown with vertical bars.

Model Validation : Charging Mechanism

Correctly describing the charging rate of UFOs interacting with the beam is key to correctly simulating their dynamics. The calculation of the average number of escaping electrons per passing protons in the macroparticulate was reviewed and compared to FLUKA, a validated tool widely used at CERN. In the model, we assume that UFOs get charged from escaping knock-on electrons created by the passage of high energy protons in the macroparticulate. The energy and angular distribution for energetic knock-on electrons is given in [3]. To compute the UFO charging rate, the distribution of secondary electrons with sufficient energy to escape the macroparticulate is integrated. The minimal energy required is :

$$T_{min} = \frac{Qe}{3\pi\epsilon_0 R} + W \quad (3)$$

where Q is the UFO charge and W is the work function of the macroparticulate. The first term of eq.(3) is the averaged coulomb potential in a uniformly charged sphere. To find the work function of high energy electrons, the calculation from previous authors [4] is used with small adjustments. Following the empirical relation described in [5] for 0.3 keV - 20 MeV electrons, the practical range $L(T)$ of electrons in matter is given by:

$$L(T) = \frac{AT}{\rho} \left(1 - \frac{B}{1+CT} \right) \quad (4)$$

where $A = 12.303 \times 10^{-6} \text{ kg m}^{-2} \text{ eV}^{-1}$, $B = 0.9815$, $C = 3.123 \times 10^{-6} \text{ eV}^{-1}$ and ρ is the density of the material. The first empirical constant, A , was adjusted for the current model, based on

FLUKA simulations. From there, the work function of the macroparticulate is found by equating the practical range to the average path length an electron created anywhere inside of the UFO has to travel to reach the surface when travelling transversely to the direction of the proton beam. For a spherical UFO, [4] gives $L(W) = 0.7358 \times R$ so that $W = L^{-1}(0.7358 \times R)$, where R is the radius of the spherical macroparticulate.

Following these changes to the model, the average number of escaping electrons per passing protons for a neutral UFO agrees very well with FLUKA, as shown in Fig.6a. The spectrum of the electrons' kinetic energy as they exit the macro particle agrees also very well with FLUKA, as shown in Fig.6b. However, the impact of the UFO charge on these results cannot be validated using FLUKA and another tool should be used to eventually benchmark this part of the model. It is also noteworthy that (3) assumes isotropic escape probabilities and does not take into account the effect of the magnetic field. Further studies are needed to validate these assumptions. To assess the improvement from the previous model, the number of escaping electrons per passing proton and the energy spectrum computed from the previous model are shown in appendix, Fig.6.

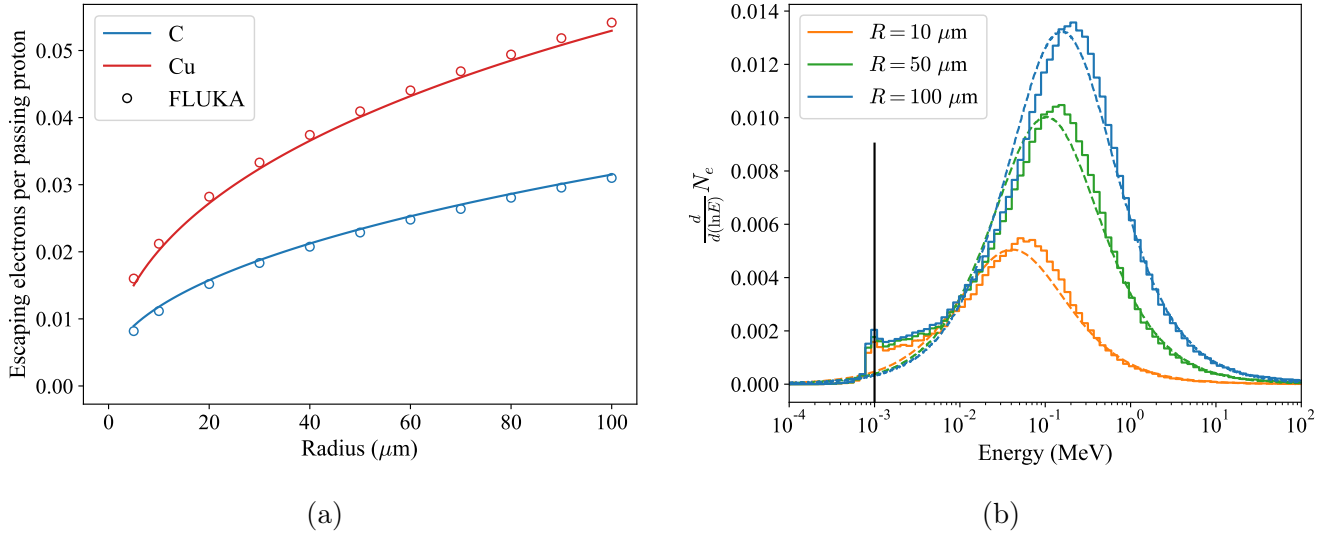


Figure 5: Comparison of the current model with FLUKA. (a) Average number of escaping electrons per passing protons for a neutral UFO. The previous model (solid lines) is compared to FLUKA (circles). (b) Energy spectrum of knock-on electrons as they escape the UFO. The previous model (dashed lines) is compared to FLUKA (solid lines) for three UFO radii. The energy cut for electron transport in FLUKA is shown by the black line, at 1 keV.

References

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Appendix – Comparison with previous model

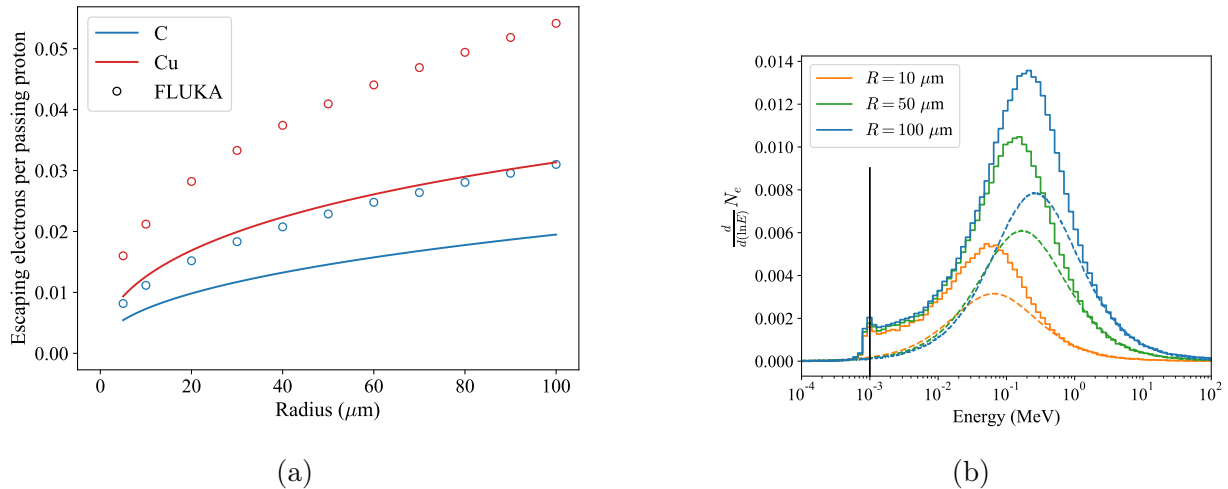


Figure 6: Comparison of the previous model with FLUKA. (a) Average number of escaping electrons per passing protons for a neutral UFO. The current model (solid lines) is compared to FLUKA (circles). (b) Energy spectrum of knock-on electrons as they escape the UFO. The current model (dashed lines) is compared to FLUKA (solid lines) for three UFO radii. The energy cut for electron transport in FLUKA is shown by the black line, at 1 keV.