Characteristics of dust-induced beam losses in the cryogenic arc sectors of the LHC

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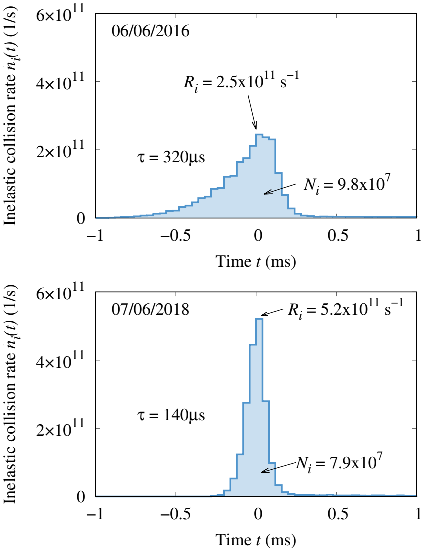
Introduction



UFO-induced nuclear collisions:

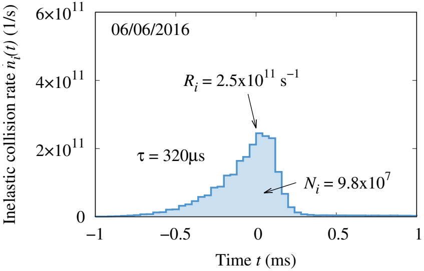
- Primary observables (through BLM signals)
- Can reveal more about the nature of dust particles
- Are directly related to the risk of quenches

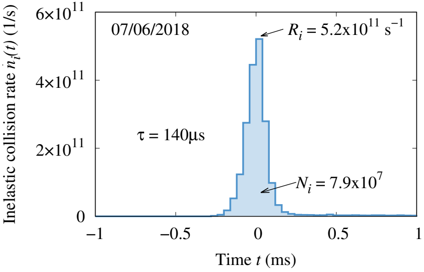
This study:

- Reconstruct distribution of events as a function of different observables (6.5 TeV, Run 2)
- Probe the ability of UFO dynamics model[†] to reproduce experimental data (learn more about UFO properties)
- Understand dependence of UFO characteristics on beam parameters

[†] *Based on latest model version described in* ▸ Link

Observables





UFO events can be characterized by the **inelastic nuclear collision rate $\dot{n}_i(t)$**.

The collision rate profile is not available for all events
$\rightarrow$ can still reconstruct different quantities:

- **Integral number of collisions per event:**

$$N_i = \int \dot{n}_i(t)\mathrm{d}t, \tag{1}$$

- **Maximum collision rate:**

$$R_i = \max[\dot{n}_i(t)], \tag{2}$$

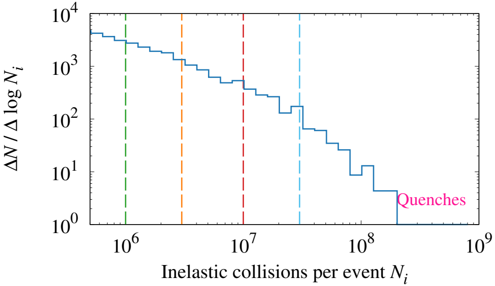
- **Loss duration (FWHM):**

$$\tau = t_2 - t_1 \ \ \textit{where} \ \ \dot{n}_i(t_1) = \dot{n}_i(t_2) = \frac{R_i}{2} \tag{3}$$

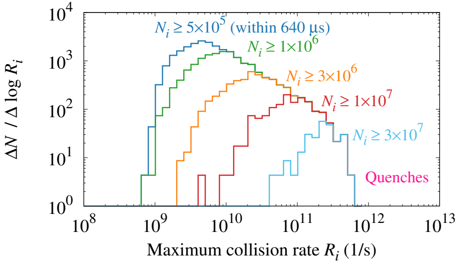
Reconstruction of R_i and τ entails some approximations (see backup)

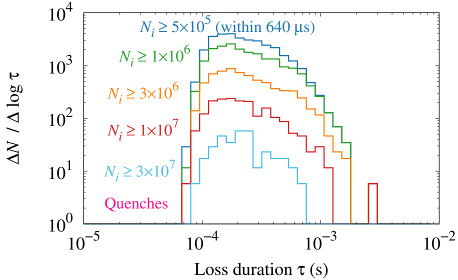
Reconstructed experimental distribution of N_i, R_i and τ (6.5 TeV, Run 2)

Events with $N_i < 5 \times 10^5$ collisions within 640 μs (RS04) not uniformly detected in arcs → events below this detection threshold are discarded



- Max. number of collisions*: $N_i \approx 2 \times 10^8$
- Highest collision rate: $R_i \approx 6 \times 10^{11}\ \mathrm{s}^{-1}$

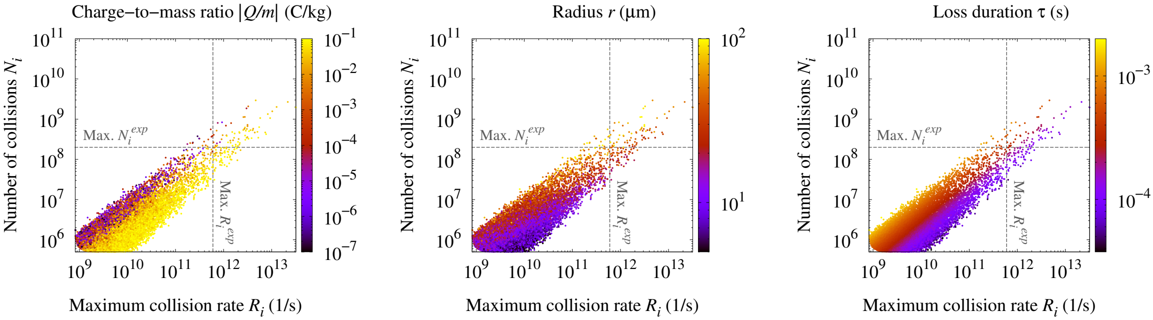




** 2-3 events could have lead to higher losses but were cut short by BLM trigger*

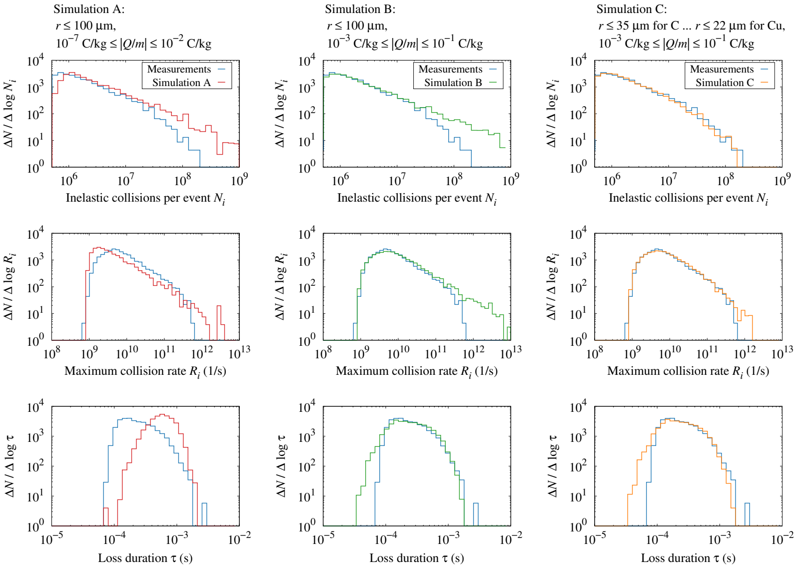
Predicting UFO-induced nuclear collisions with UFO dynamics simulations

- Dust volumes distributed as $1/V^2$, with radius r ranging from 5 μm to 100 μm
- Composition: C, Al, Si, Cu
- Charge-to-mass ratio Q/m: -10^{-1} C/kg to -10^{-7} C/kg
  Evidence of negative pre-charge found in rise time of loss profiles, PRAB paper ▸ *Link*



Simulation yields events exceeding max. exp. N_i, R_i → **need to constrain further the dust properties**

Comparison of measured and simulated N_i, R_i and τ distributions



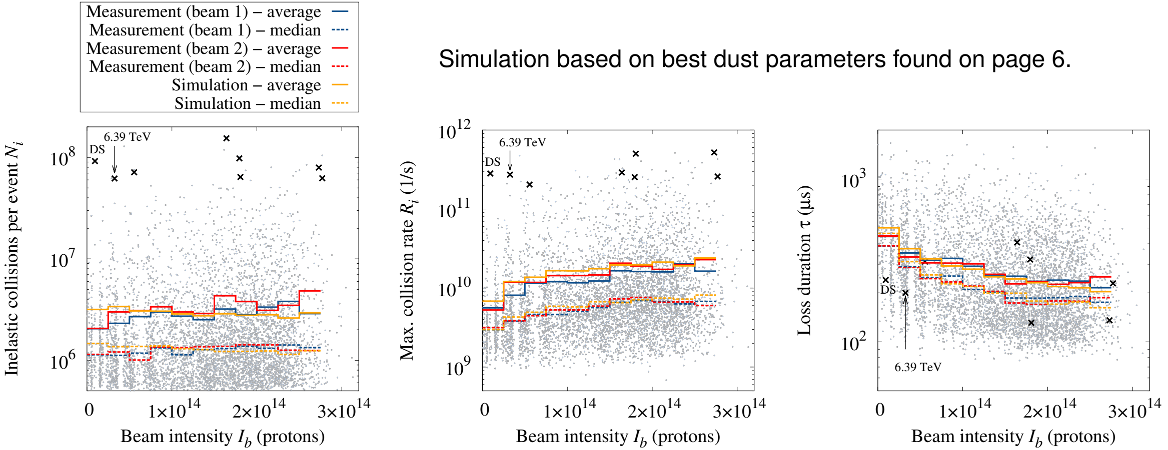
Can reproduce measurements if:

- UFOs are negatively charged (-10^{-1} C/kg to -10^{-3} C/kg)
- the UFO radius is $<$O(30 μm) or larger UFOs acquire a smaller $|Q/m|$

Note: the remaining discrepancies for the R_i and τ distributions can be attributed to measurement artefacts

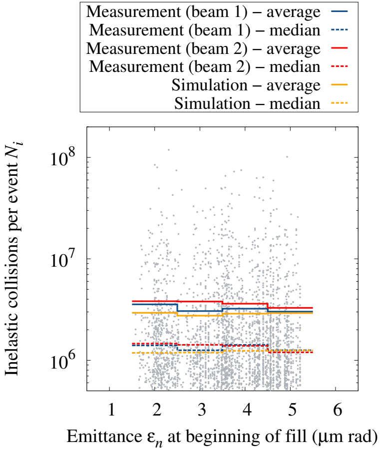
Dependence of the mean and median N_i, R_i and τ values on beam intensity

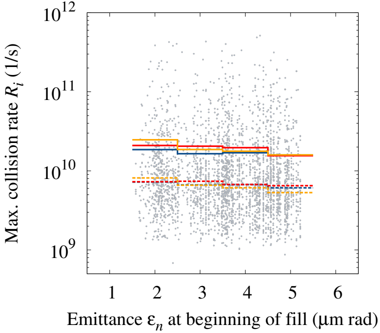
Simulation based on best dust parameters found on page 6.

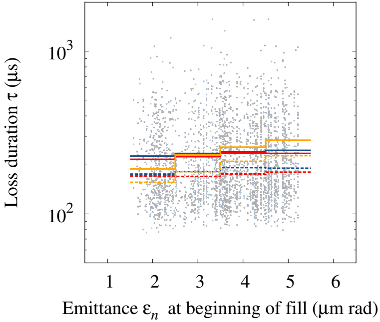


Dependence of the mean and median N_i, R_i and τ values on emittance

Simulation based on best dust parameters found on page 6.

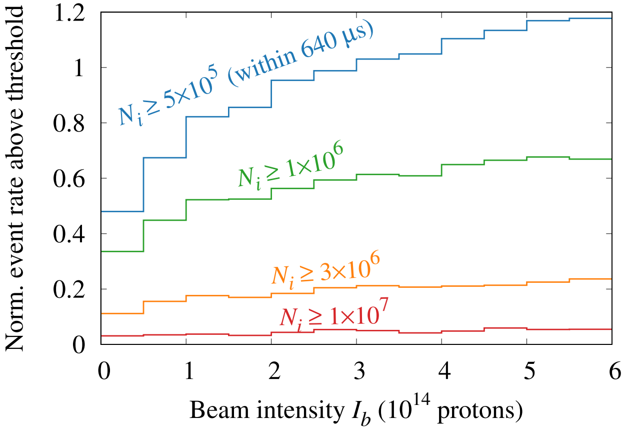






Intensity dependence of the number of events above a given loss threshold

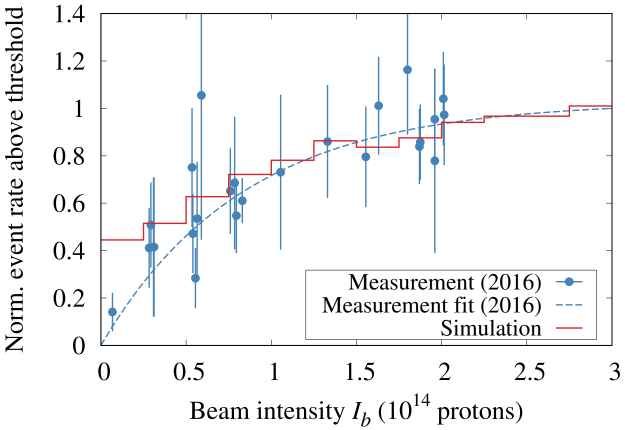
Simulation predictions:



- Let's assume we only look at events which produce a minimum number of collisions N_i → *is of practical importance for estimating the risk of quenches*
- With the found dust properties, the simulation predicts that **number of events** exceeding this threshold **increases with beam intensity**
- In other words, even if the UFO rate is constant the number of potentially dangerous UFOs increases with increasing intensity

Figure is arbitrarily normalized.

Intensity dependence of the UFO rate

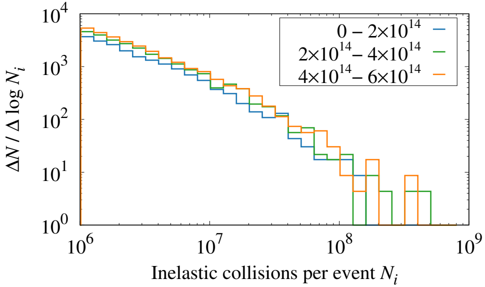


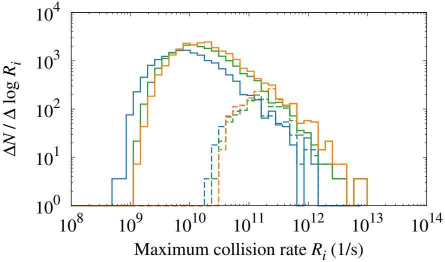
- In years with fast intensity ramp-up, an intensity dependence of the UFO rate was observed (not biased by conditioning)
- This intensity dependence can be mainly explained by the fact that more UFOs exceed the detection threshold
- This means that **the total UFO rate seems (almost) independent of the intensity**

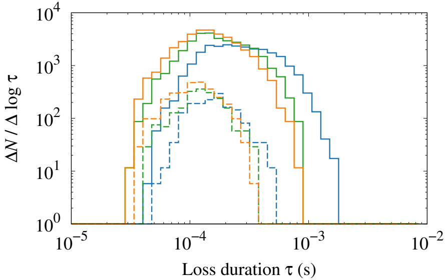
Figure is arbitrarily normalized to rate at 3×10^{14}.

Simulated distribution of N_i, R_i and τ for different beam intensities

Events with $N_i \geq 1 \times 10^6$ (solid lines) and $N_i \geq 1 \times 10^7$ (dashed lines) are considered







- Assumption: constant UFO rate

Conclusions

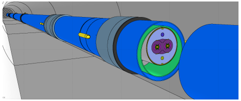
- The distribution of UFO events as a function of different observables (integral collisions, peak collision rate, loss duration) can be consistently reproduced if
  - UFOs are negatively charged (-10^{-1} C/kg to -10^{-3} C/kg)
    Is in line with findings in recent studies for the loss rise time (PRAB paper ▸ *Link)*
  - the maximum UFO radius is limited [$<$O(30 μm)] *or*
    the absolute charge, which larger UFOs can acquire, is limited

  The latter finding possibly indicates that larger dust grains, although expected to be present in the vacuum chamber, cannot be attracted by the beam anymore
- The obtained UFO properties also explain the dependence of observables on beam parameters, in particular the increase of the peak collision rate with beam intensity
  No evidence was found that the charge-to-mass ratio acquired by dust particles depends on the beam intensity
- Assuming a certain UFO rate, the studies show that more UFOs can be expected above a given loss threshold N_i if the beam intensity increases
  On the other hand, no evidence is found that the total UFO rate depends on the beam intensity (except maybe for small intensities)

Contents

Appendix

Reconstructing the number of UFO-induced inelastic nuclear collisions



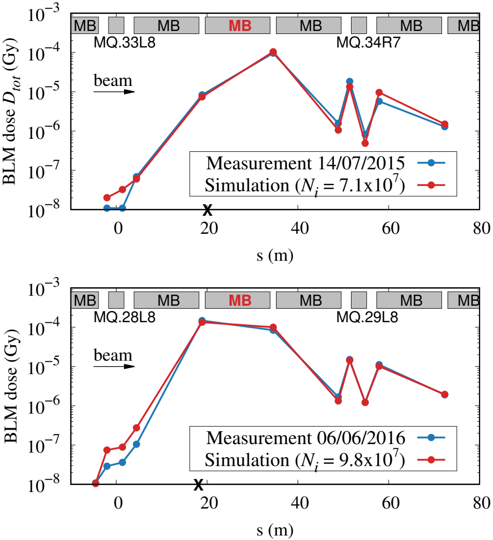
Following expression is minimized

$$Q(N_i, s_j) = \sum_k \frac{[D_{tot,k} - N_i d_k(s_j)]^2}{N_i d_k(s_j)}, \qquad (4)$$

where $D_{tot,k}$ is the time integral of the dose rate $\dot{D}_k(t)$ recorded in BLM k during the loss event,

$$D_{tot,k} = \int \dot{D}_k(t')dt' \qquad (5)$$

and $d_k(s_j)$ is the corresponding simulated dose per proton-nucleus collision assuming that the collisions occur at s_j.



Reconstructing the peak collision rate R_i

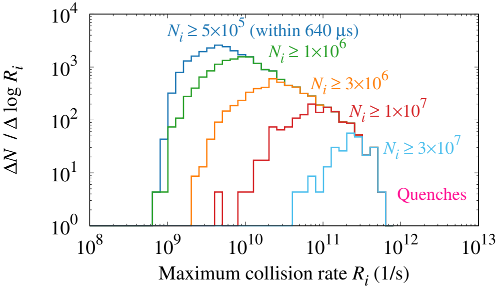
The peak collision rate was derived from the following expression,

$$R_i = \frac{N_i}{D_{tot}} \frac{D_{max}^{40\ \mu\mathrm{s}}}{\Delta t}, \tag{6}$$

where N_i is the integral number of collisions, $D_{max}^{40\ \mu\mathrm{s}}$ is the highest dose recorded in the shortest sliding time window of BLMs ($\Delta t = 40\mu$s),

$$D_{40\ \mu\mathrm{s}}^{max} = \max\left[\int_{t_n}^{t_{n+1}} \dot{D}(t')dt' \ : t_n = n \times 40\ \mu\mathrm{s}\right], \tag{7}$$

and D_{tot} is the time-integrated dose in the same BLM where $D_{max}^{40\ \mu\mathrm{s}}$ was measured.



Note: delayed charged collection (ions in gas) and read-out leads to a distorted profile → underestimate some of the values (theoretically upt to a factor of 2.5). In addition, intrinsic limit due to 40 μs time resolution.

Reconstructing the peak collision rate R_i

The loss duration τ was reconstructed by assuming that the $\dot{n}_i(t)$ profiles are of Gaussian shape, neglecting any possible asymmetry.

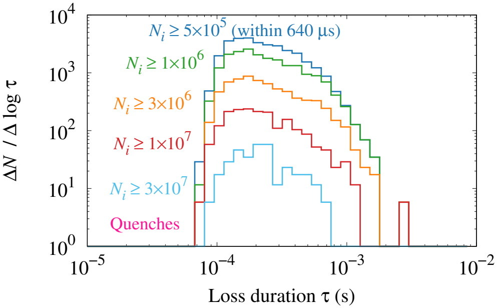
The width of the Gaussian profiles was determined by calculating the number of standard deviations contained in a 80 μs time window centered around the mean.

The number of collisions contained in this time interval was estimated from following expression,

$$N_i^{80\mu s} = N_i \frac{D^{max}_{80\mu s}}{D_{tot}}, \tag{8}$$

where $D^{max}_{80\,\mu s}$ is the maximum dose recorded in the 80 μs sliding time window of BLMs, which is updated every 40 μs,

$$D^{max}_{80\,\mu s} = \max\left[\int_{t_n}^{t_{n+2}} \dot{D}(t')dt' \ : \ t_n = n \times 40\ \mu s\right]. \tag{9}$$



Note: results become unreliable for faster events ($<10^{-4}$s)