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Transient beam losses on a time scale of a few ms have been observed in the LHC injection kickers, occurring mainly shortly after beam injection with a strong correlation in time to the kicker pulsing. The beam losses, which have at times affected LHC availability, are attributed to micron scale ceramic dust particles detached from the alumina beam pipe and accelerated into the beam. The beam related observations are described, together with laboratory measurements of beam pipe contamination and kicker vibration, simulations of electric field in the beam pipe and the basic dynamic model. Energy deposition simulations modelling the beam losses are presented and compared to measurement. Extrapolations to future LHC operation at higher intensities and energies are made, and prospects for mitigation are discussed.

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TRANSIENT BEAM LOSSES IN THE LHC INJECTION KICKERS FROM MICRON SCALE DUST PARTICLES

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INTRODUCTION

The first years of high intensity LHC operation revealed an important performance limitation: so called UFOs (Unidentified Falling Objects) [1]. These fast beam losses were first observed in July 2010 and led to a total of 35 protection beam dumps in 2010 and 2011. The origin is presumed to be micrometer sized dust particles interacting with the beam. The duration of the beam losses is of the order of 1 ms, or 10 LHC turns. A significant concentration of UFO events occurs at the injection kicker magnets (MKIs) [2], which contain ceramic (Al_2O_3) tubes, Fig. 1. Studies have been performed with beam, operational equipment has been measured and simulations performed to try to understand the processes and origin.

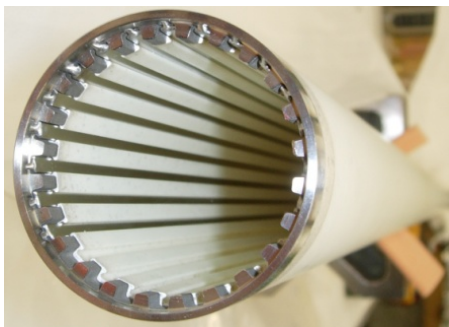


Figure 1: MKI ceramic tube, with screen conductors to carry the beam image current.

OBSERVATIONS

Extensive diagnostic improvements have been made, in order to capture fast loss data and better understand the phenomena in the MKI and around the LHC [3]. The main results relevant to the MKIs are described below.

UFO Concentration at MKIs

Of ~7800 UFO events analysed [4] the vast majority had peak beam loss below the dump threshold: around 500 (6%) were located around the MKI kickers, which represent only 0.06% of the LHC length. The ceramic vacuum tube and pulsed high voltage are unique to the MKI – tests with the MKQ tune kickers did not produce UFOs [5], but these have metalised ceramic tubes.

Correlation with MKI Pulse Timing

It was observed from operational data that the MKI UFOs occurred during or shortly after injection, with a rather rapid decay of the rate after about 30 minutes. Dedicated studies [5] revealed a clear correlation with the pulsing of the MKI kickers, Fig. 2. Many events occur within the first 100 ms after the kicker pulsing, with the fastest UFO only 3 ms after the pulse. Approximately 60 ms would be expected were the particles falling under gravity alone and the shorter times imply particles accelerated at $>3000 \text{ ms}^{-2}$ from the ceramic wall.

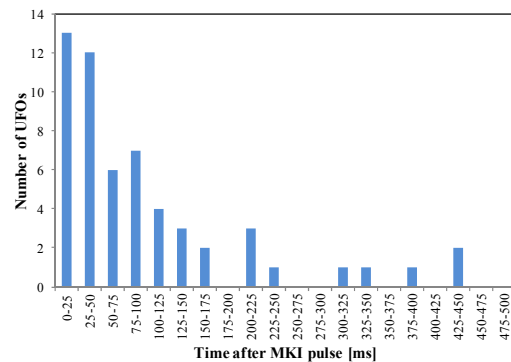


Figure 2: Temporal distribution of UFOs after MKI pulse.

Dependence on Vacuum and Electron Cloud

A positive correlation has been observed between the MKI UFO rate and the local vacuum pressure [6]. The source of the vacuum pressure rise was probably electron cloud in the magnet and its interconnects, which suggests that the flux of electrons may play a role in the MKI UFO process, possibly by charging of insulated particles.

Amplitude of Loss Peaks

FLUKA simulations were used to estimate the particle sizes, by calibrating the signals in a beam loss monitor (BLM) adjacent to the MKI to around 4×10^7 interactions per Gy at 3.5 TeV. An observed peak loss of 8.5 Gys^{-1} then corresponds to 3.4×10^{12} inelastic nuclear interactions per second [1]. For particle sizes much less than the beam sigma ($\sigma_x=325\mu\text{m}$, $\sigma_y=325\mu\text{m}$), the particle is calculated to have a minimum radius of about $40 \mu\text{m}$.

Loss patterns at the MKIs

Additional BLMs were added in the LHC at the MKIs to improve the spatial resolution of the losses. In parallel, the entire region was modelled [7] in detail in FLUKA, including quadrupole and dipole field maps, vacuum modules and accurate BLM positions. Losses were generated by adding test aluminium particles at various longitudinal locations. Examples of the results are shown in Fig. 3, with measured values. Overall the simulations clearly point to a loss source within, or very close to the MKIs, rather than in upstream elements such as the superconducting Q5 magnet or the BTV monitor.

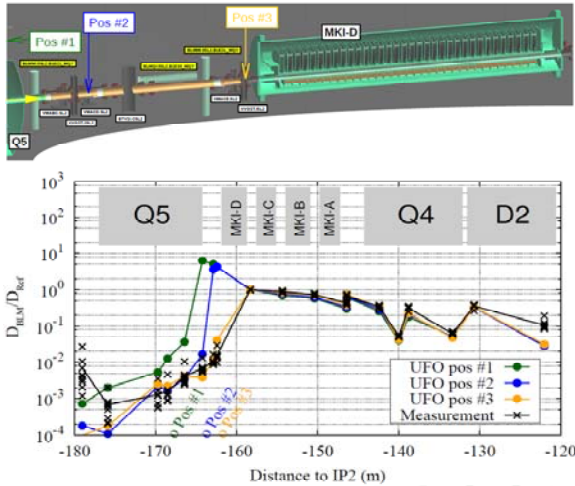


Figure 3: Comparison between simulated and measured loss patterns in the injection kicker region.

Laboratory Vibration Measurements

Measurements were carried out using accelerometers and laser interferometers on a spare MKI magnet, pulsing under vacuum [8]. The measurements were complicated by electrical noise and spurious vibration, but indicated vibrations of the tank with small amplitudes (10 nm) in the 60-300 Hz range when the kickers pulse, Fig. 4.

Analysis of Ceramic Tube Contamination

An MKI tank removed from the LHC at the end of 2010 was flushed with N_2 through a filter. Inspection by scanning electron microscope showed an estimated 5×10^6 particles on the filter [9]. Most particles were of μm size, but particles up to about $100 \mu\text{m}$ were found, Fig. 5. Energy-dispersive X-ray spectroscopy revealed that most

macro particles consist of Al and O, and most likely originate from the Al_2O_3 tube. For reference, the clean room air gave about 100 particles on a filter, with 10^4 particles for a new tube before conductor insertion.

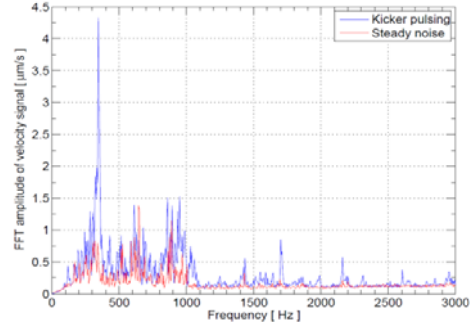


Figure 4: Laser interferometer measurement (preliminary) of vibration when pulsing an MKI kicker magnet.

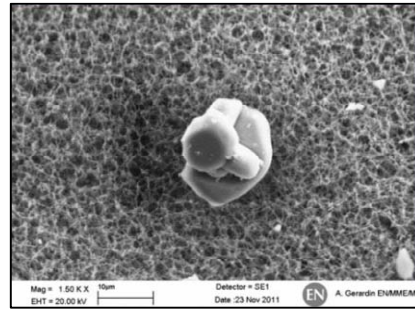


Figure 5: Al_2O_3 macro particle from MKI ceramic tube.

Electric Field in the Ceramic Tube

The electric field during the $10 \mu\text{s}$ flat-top of the kicker pulse was modelled [10]. In Fig. 6 the potentials on the impedance stripes are shown through the kicker pulse. The voltages jump to positive voltage of up to 20 kV during field rise, then drop to 0 V during the flat top of the field pulse, then jump to negative voltage during the field fall. During the flat top, with 15 screen conductors the field exceeds 1 MV/m in some locations at the bottom of the tube (HV busbar side). This electric field is reduced by a factor of 7 if all 24 conductors are installed.

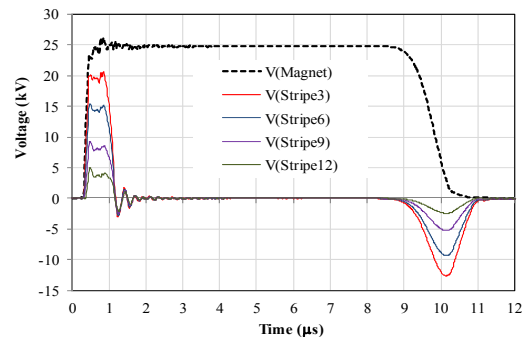


Figure 6: Voltage on screen conductors during kicker pulse. Screen 3 is at the bottom of the tube, 12 at the top.

DYNAMIC MODEL

From the observations, simulations and measurements detailed above, the losses are assumed to originate from micron sized dust particles in the kickers, which come from the manufacturing and assembly of the Al_2O_3 tubes. The particles could be detached and accelerated towards the beam by the electric field when the kicker is pulsed, and then accelerated towards the beam by the beam potential. Interaction with the beam would both remove electrons from the particle and produce beam losses. A numerical model has been constructed to simulate the different dynamic processes [11]. The electric field from the kicker pulse has also been included, as this is actually much stronger than the field from the proton beam. The results show that particles cannot be picked up from the bottom of the tube and reach the beam – instead it appears that particles must be detached from the top of the tube, and also have a high initial charge state so as to be sufficiently accelerated by the kicker pulse during its $10\ \mu\text{s}$ duration. To reach a few ms drift time, a $1\ \mu\text{m}$ radius particle with $A = 10^{13}$ would need a negative charge of the order of $10^5 e$, Fig. 7. Since the acceleration depends on Q/A , a $40\ \mu\text{m}$ radius particle as implied by the FLUKA results would require a charge state of about $10^{10} e$.

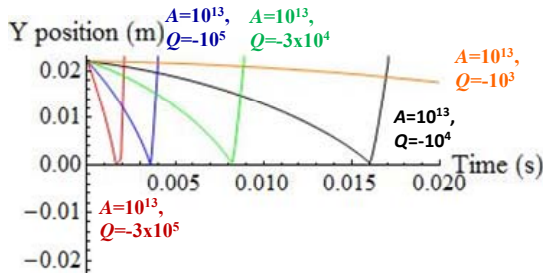


Figure 7: Simulated trajectories for particles of different charges, taking account of the MKI field, beam field and particle charging. A/Q must be around 10^{-8} to reach the observed times of a few ms.

EXTRAPOLATION TO HIGHER ENERGY AND INTENSITY

The effects of operating with 25 ns bunch spacing are expected initially to be worse, through the increased electron cloud. However this should condition away with beam scrubbing. Extrapolations to higher beam energy and intensities have been made [3], based on the statistics, FLUKA simulations and wire scanner data. There is not expected to be a significant change for even higher total beam intensities. However, 7 TeV energy will result in UFOs which have $\times 4$ higher amplitude, and in addition the superconducting magnet quench thresholds will reduce by a factor of 5, with lower BLM thresholds. Even with a constant UFO rate at 7 TeV, the effects will be worse for the LHC, with ≈ 25 dumps expected per year due to MKI UFOs. For the overall machine, a much sharper rise is expected in the arc UFO rate [3].

MITIGATION POSSIBILITIES

The most promising means of reducing the MKI UFO rate is by greatly reducing the number of Al_2O_3 macro particles. Various mitigation measures have been considered. Metalised ceramic tubes have been simulated but will result in an unacceptably long kicker field rise times of $4.5\ \mu\text{s}$ [2], compared to $1\ \mu\text{s}$ at present. Burying the screen conductors beneath the surface of the ceramic would reduce particle contamination but is very difficult to manufacture and may affect beam impedance [12]; adding screen conductors [2], to reduce the electric field, is being implemented. An improved cleaning procedure for the MKI tubes was tested and succeeded in reducing the measured particle density by a factor of 5-7 to below 10^6 particles; further improvements are planned in this direction. The extra screen conductors will also reduce the electric field. In addition, improvement of the vacuum and electron cloud in the MKI region is also being pursued, with options such as NEG coatings in the copper beam pipe, for the circulating beam. Finally, BLM thresholds in the nearby magnets could also be increased, until quenches occur.

CONCLUSIONS

UFOs at the injection kickers seem to be due to the combination of high concentrations of Al_2O_3 macro-particles from the tube manufacture or assembly, charging of these particles and then detachment and/or acceleration by the kicker electric field into the beam. Extrapolation to 7 TeV indicates that ≈ 25 fills per year could be dumped by this phenomenon, to be compared to ≈ 100 expected from arc UFOs. Realistic mitigation for the MKIs will focus on reducing the particle density as much as possible by improved cleaning and production techniques, with a factor of 10 certainly feasible, while continuing to reduce electron cloud in the region and incorporating more screen conductors to reduce the electric field.

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