BEAM SCRAPING TO DETECT AND REMOVE HALO IN LHC INJECTION

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Abstract

Fast scrapers are installed in the SPS to detect and remove beam halo before extraction of beams to the LHC, to minimize the probability for quenching of superconducting magnets in the LHC. We shortly describe the current system and then focus on our recent work, which aims at providing a system which can be used as operational tool for standard LHC injection. A new control application was written and tested with the beam. We describe the current status and results and compare these with detailed simulations.

INTRODUCTION

Transverse beam scrapers are useful for both measuring beam properties and for removing beam halo. Beam halo can lead to magnet quenches in the LHC. To avoid quenches during injection, before the LHC collimation system can clean the beam, it is foreseen to scrape the proton beam in the SPS. The need for scrapers in the SPS is explained in detail in [1, 2].

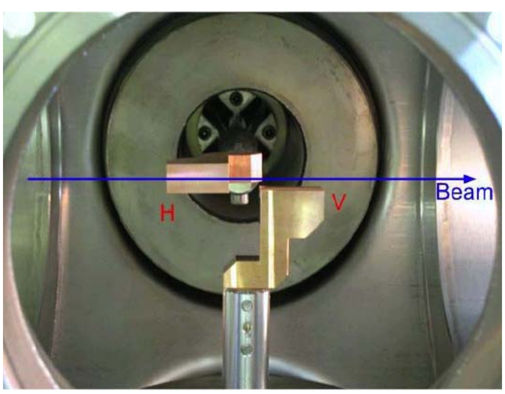

Figure 1: The two scraper jaws, horizontal and vertical.

The scrapers consist of two one-sided copper jaws, one for each of the transversal planes. Scraping is always conducted by sweeping one or both jaws quickly through the beam. A schematic drawing of the horizontal scraper jaw's movement cycle is shown in Figure 2. The jaws each have an active length of $30\ \mathrm{mm}$ and a transverse width of $12\ \mathrm{mm}$.

Primary and secondary collimators are installed downstream from the scrapers. The design idea is that the main scraping mechanism should be scattering of protons to higher betatron amplitudes, causing them to be absorbed in the collimators. This approach has proved problematic due to aperture requirements of the collimators at injection.

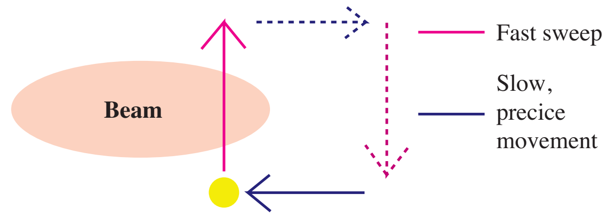

Figure 2: Schematic view of the scraper jaw's movement relative to the beam. Note that the scrapers always sweep through the beam quickly, with velocity $v = 20\ \mathrm{cm/s}$. Only the horizontal scraper is shown here.

HIGH LEVEL APPLICATION

A high level application has been written and used in machine studies. The application controls the scrapers while hiding expert level settings from the user. As most other accelerator control applications at CERN, the application is written in Java. The development of this application is an important step towards making the scrapers operational. Acting as a graphical interface, the application mainly communicates settings and status messages to and from the hardware control server.

LOSS MAPS

To find the distribution of scraping induced beam losses around the SPS ring, both simulations and machine studies have been performed. Results from a scraping simulation using the SixTrack code [3] are shown in Figure 3.

The loss maps give an understanding of how the scraper works. Downstream betatron collimators were installed to absorb scattered protons from the beam. This mechanism is inefficient when collimators are moved out to fulfill aperture requirements at injection. Figure 3 shows a simulation of this scenario: losses are concentrated in the scraper jaw. During pulsed mode operations, as will be used in LHC injection, the collimators may not be moved during the energy ramp. If collimators are adjusted to be more efficient, they no longer fulfill the aperture requirement at injection.

Momentum loss in the scrapers could cause beam losses in the momentum collimator; however, this is also a very small effect. This can be seen in simulations, see Figure 3, and in measurements [1].

The conclusion is that the main beam loss mechanism is nuclear interactions between beam protons and copper nuclei. These reactions lead to particle showers from the scraper, and potentially significant heating of the scraper jaws.

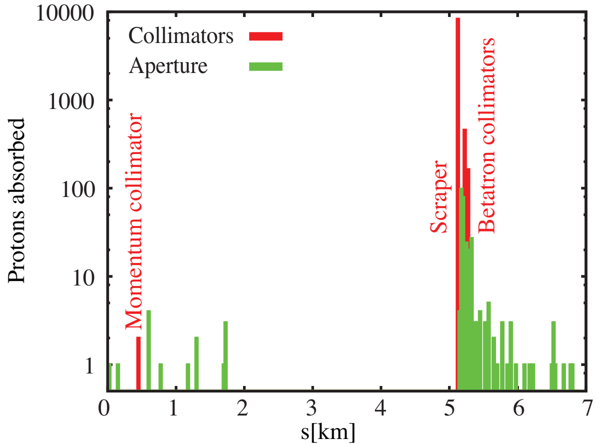

Figure 3: Simulated proton losses around the SPS ring. Note that the scrapers absorb over 80% of the protons, while collimators and aperture absorb roughly 10% each. A beam halo of 10^4 protons at 4 σ was simulated.

Previous machine studies show qualitatively the same pattern as these simulations [1].

TAIL REPOPULATION

Previous machine studies have revealed tail repopulation in both transverse planes [1]. The tail repopulation was found to be significantly faster in the horizontal than in the vertical plane. To find the source of tail repopulation, new machine studies have been performed. One suspected source was the transverse feedback; this was tested for and has now been ruled out. Remaining possible sources include power supply ripple, mechanical vibrations of dipoles, and intrabeam scattering.

TIME DEPENDENCE OF SCRAPING

The time dependence of beam losses caused by scraping can be measured, simulated and modeled analytically. A summary plot of the three is given in Figure 4.

The disagreement between the curves is only in one parameter: the scraper speed in beam sigma, v/σ. Measurements were done at lower energy than simulations, giving a larger beam size. This makes us confident that the time dependence of scraping is well understood. The blue and red curves in Figure 4 can be fitted very well to each other by rescaling the time axis. Using this technique, the scrapers can be used to estimate the beam size.

The analytical model assumes a "black", i.e. totally absorbing, and slow scraper. We can see that this approximation is good except towards the end of the scraping. All calculations and measurements are done with a tune far from integer, semi-integer and quarter-integer resonances. If the tune is close to any of these resonances, the time dependence of scraping becomes heavily tune dependent, and scraping less efficient.

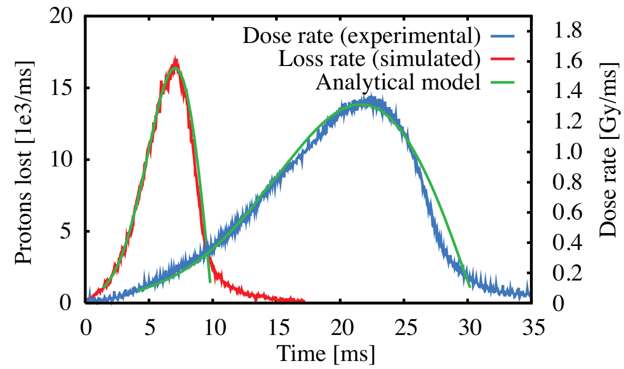

Figure 4: Simulation, analytical model and experimental measurement of the time dependence of scraping. The only parameter difference between simulation and experiment is the scraper speed in units of RMS beam size.

During machine studies, oscillations have been observed on the time dependent beam losses. These oscillations have frequency components compatible with power supply ripple ($150\ \mathrm{Hz}$) and betatron tune. This type of measurements has been able to reveal interesting details about the beam.

ROBUSTNESS OF SCRAPERS

The nominal LHC intensity beam carries a kinetic energy sufficient to melt more than $3\ \mathrm{kg}$ of copper. To estimate at which intensities the scrapers can be used without suffering damage, several accident scenarios have been simulated using the Geant4 toolkit [4]. No analysis has been made of heat transfer during scraping, meaning all estimates on safe intensities assume instantaneous energy deposit with no heat transfer.

Figure 5 shows the simulated energy deposit after scraping the whole beam. The energy deposit has a sharp peak in the upper edge of the scraper. For the nominal LHC beam intensity, the maximal energy density is about $0.19\ \mathrm{MJ/cm^3}$. For comparison, the energy density required to melt copper is $5.5\ \mathrm{kJ/cm^3}$. Even if the affected volume is only a small part of the scraper jaw, melting it is undesirable. It is clear from these results that the scrapers are not suited to be used for beam shaping of high intensity beams.

If the melting point is set as the maximum allowed temperature of the scraper jaw, we can infer a safe beam intensity of 6.2×10^{11} protons with nominal LHC beam parameters. This is only 1.9% of the nominal beam intensity of 3.3×10^{13}, and does not include a safety factor. It should be stressed that this is the number for accidentally scraping the whole beam. For regular halo scraping at 3.5 σ, only 0.22% of the beam intensity is scraped if the beam distribution is Gaussian.

Similar simulations have been performed to examine potential heating of downstream aperture elements. In this simulation, no problematic heating has been discovered; the affected areas are heated about three orders of magni-

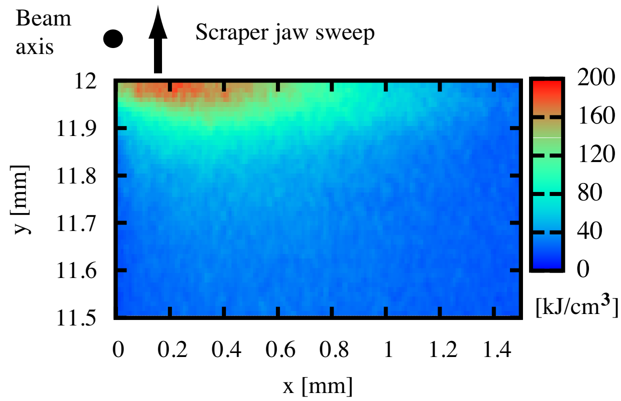

Figure 5: Simulated energy deposit in the current scraper jaw's end face for scraping of the whole SPS beam.

tude less than the scraper jaws.

It has been suggested that the current scraper jaws could be replaced with similar jaws of graphite. Graphite has a higher melting point and a longer nuclear interaction length, which are desirable properties. However, a longer interaction length means that the protons make a larger number of passes through the scraper. Simulations show that the energy deposit spreads across a larger volume, but is not dramatically reduced. Graphite also sublimates when heated, which could be a problem for vacuum pollution. As a preliminary conclusion, graphite is not necessarily a good material for fast beam scrapers.

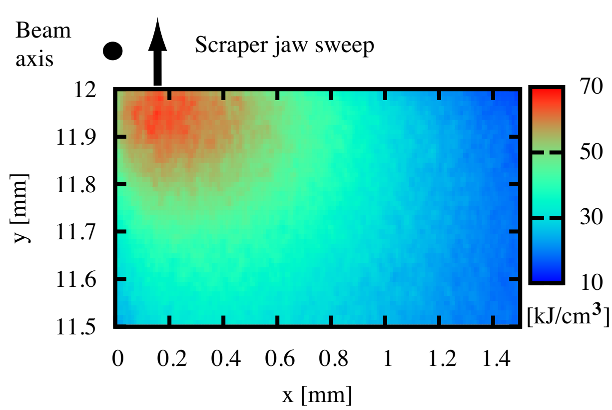

Figure 6: Energy deposit density for a faster and thinner copper scraper jaw. Note that the heat load spreads out more than in Figure 5.

A possible way of making the scrapers more robust against damage is to make thinner and faster scraper jaws. Simulations have been made for a system with a $10\ \mathrm{mm}$ active length and a sweep speed of $2\ \mathrm{m/s}$. Comparing Figure 5 and Figure 6, we find that a factor of 3 in energy deposit density can be gained by this approach. Simulations also suggest that even thinner scraper jaws will be efficient at removing beam halo, while reducing the heat load.

We see that for high intensity operation, the scrapers are susceptible to damage under the current conditions. Non-Gaussian beam halo could potentially lead to melting of parts of the jaws. The current beam interlock system monitors the beam with a $20\ \mathrm{ms}$ time resolution, more than the time scale of scraping of the nominal beam (see Figure 4). It has been foreseen that a fast beam interlock should be installed for efficient protection of the scrapers. A fast beam interlock system could also be used as a last minute quality assurance to prevent injection of dirty beams into the LHC. A thinner, faster scraper jaw would be more robust against hardware damage.

SUMMARY AND FUTURE PLANS

With the development of a high level control application, the scrapers are one step closer to being operational. The interaction between the scraper jaw and the beam is also better understood, and an estimate of safe beam intensities has been done. The current scrapers are not suited for beam shaping. It has been demonstrated that the time dependence of scraping induced beam losses can be used to estimate the beam size. Spatial loss maps have shown that nuclear interactions inside the jaws is the main mechanism performing the scraping. Downstream collimators are essentially inefficient at absorbing scraped protons when compatible with LHC injection. Scrapers have proven efficient at revealing beam tails.

Installation of diagonal scrapers has been staged, but not completed. Diagonal scrapers will help gain aperture at injection in the LHC, as discussed in [5]. The scrapers should be complemented with a fast beam interlock before they are declared operational.

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