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Simulations of collimation losses at RHIC

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Abstract
State-of-the-art tracking tools were developed at CERN to determine the cleaning efficiency of the Large Hadron Collider (LHC) collimation system. In order to properly assess the accuracy of such simulations, benchmarking studies were required using actual beam loss measurements from a machine featuring a similar multi-stage collimation system. The following reviews the results obtained from the analysis of specific data collected from operations at the Relativistic Heavy Ion Collider (RHIC) and compares them to the simulation of these beam conditions in the new SixTrack collimation module after its first official release.

Keywords
CERN report; collimation; tracking.

1 Introduction

RHIC is a circular accelerator made of two individual beam lines (Blue and Yellow) with six common interaction regions (IR's), two of which are currently dedicated to the STAR (IR6) and PHENIX (IR8) experiments. Physics programs include 100 GeV heavy ions collisions, either symmetric (A-A) or anti-symmetric (A_1-A_2), and 100 GeV and 255 GeV polarized protons collisions. While it is used solely for machine protection during the ramp, the primary purpose of the RHIC collimation system at store is to control the background for the detectors: the layout is therefore not designed as a machine protection system, a major difference from the LHC case. In total, there are four collimators per beamline: one primary, dual-plane jaw ($H0$, $V0$) and three secondary one-sided scrapers (two horizontal $H1$, $H2$ and one vertical $V1$). Figure 1 gives a schematic view of how this equipment is installed around IR8, as well as a front view (from the beam perspective) of the primary collimator jaws.

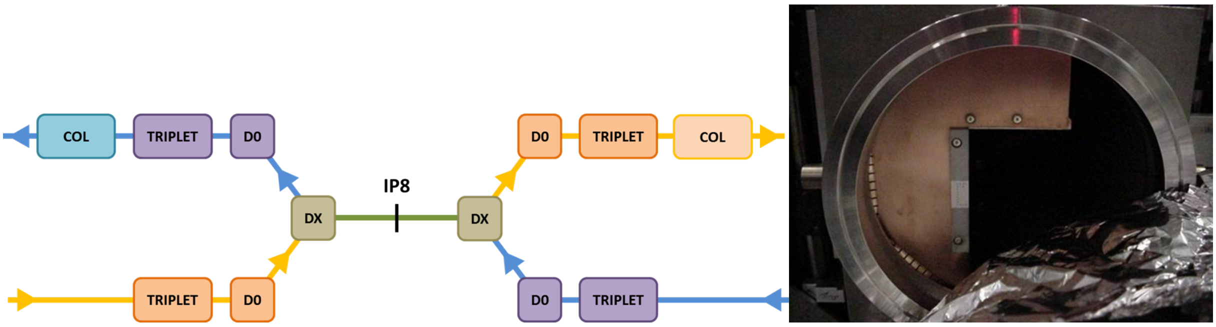

Fig. 1: Left: Schematic layout of the RHIC Collimation System layout in IR8 for both Blue and Yellow beamlines. - Right: Front view of a RHIC primary collimator jaw.

Pin diodes are installed downstream of each collimator to get a direct loss signal when setting its position. This allows controlling experimental background signals while maintaining low levels of local beam losses. The RHIC collimation system setup is overall similar enough to that of the LHC (despite different intended purposes) to allow using data collected during routine physics operation for SixTrack benchmarking purposes. The data considered in the following was taken during the 2005 polarized proton Run (Run5), whose parameters are listed in Table 1.

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Table 1: Parameters for 100 GeV p^+-p^+ Run5 operations.

Number of bunches	111
Protons per bunch	2.0×10^{11}
E_{store} [GeV]	100
Working point Q_x, Q_y	0.690/0.685
ϵ_N [π mm.mrad]	20.0
L_{peak} [10^{30} cm^2.s^{-1}]	7.0
β^* STAR // PHENIX [m]	0.94 // 0.92
β^* IR10, IR4 [m]	10.0
β^* IR12 [m]	5.0
β^* IR2 [m]	3.0

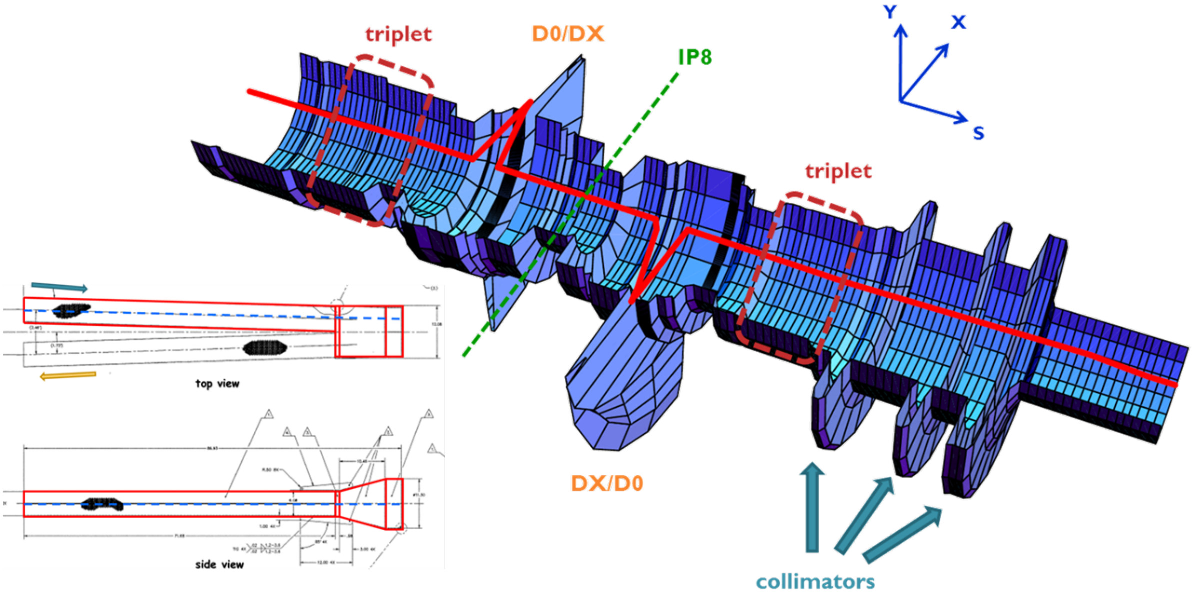

Fig. 2: 3D model of the mechanical aperture in the IR8 insertion. The solid red line represents the closed orbit. The two regions with a larger transverse opening and a large orbit offset correspond to the DX separation magnets. The three "discs"on the right hand side are the location of the RHIC collimators.

Benchmarking studies are aimed at reproducing realistic beam conditions from RHIC operations: this is done by generating a lattice with MAD-X (using the offline model) and convert it to SixTrack for tracking through the collimation system. The transverse coordinates of tracked particles are then processed through a model of the mechanical aperture, and the resulting loss maps are then compared with measurements from beam loss monitors (BLMâĂŹs). Figure 2 presents an example of the 3D modeling of the RHIC mechanical aperture. Similar to what was created for LHC studies, the RHIC aperture model is split into 10 cm bins to be as close as possible to the real shape of all elements. On the beam operations side, dedicated data sets were taken by moving the RHIC collimators close to the beam, with all relevant informations (jaw positions, closed orbit, BLM's signal) being logged during the entire experiment.

2 Results from tracking simulations

The datasets used for benchmarking were collected over the Fill #06981 for the Blue beam during Run5. Figure 3 shows the positions of the collimator jaws and the signal from local BLM's. One can clearly establish when a given jaw is scraping the beam, which corresponds to a spike in the loss signal. For the benchmarking studies, collimator positions are reproduced from their value at 12:27:50 (dashed blue line on Figure 3), when the secondary jaw $V1$ is the closest to the beam. The resulting simulated beam loss map is then compared to the longitudinal loss locations given by the BLM's.

Results from simulations are shown in Figure 4. The impact parameter on the $V1$ collimator jaw was taken as 5 μm. The BLM data is shown for comparison and corresponds to the difference in the intensity of beam losses between the collimator positions "all out" and "all in". The predicted loss locations are given by the solid red lines and match with most of the BLM peaks, meaning that the tracking tools developed for LHC collimation studies have reached a satisfying level of accuracy. One should note that while the simulation tools allow locating proton losses with a 10 cm resolution, the live signal from the BLM's is only given at predetermined positions around the machine.

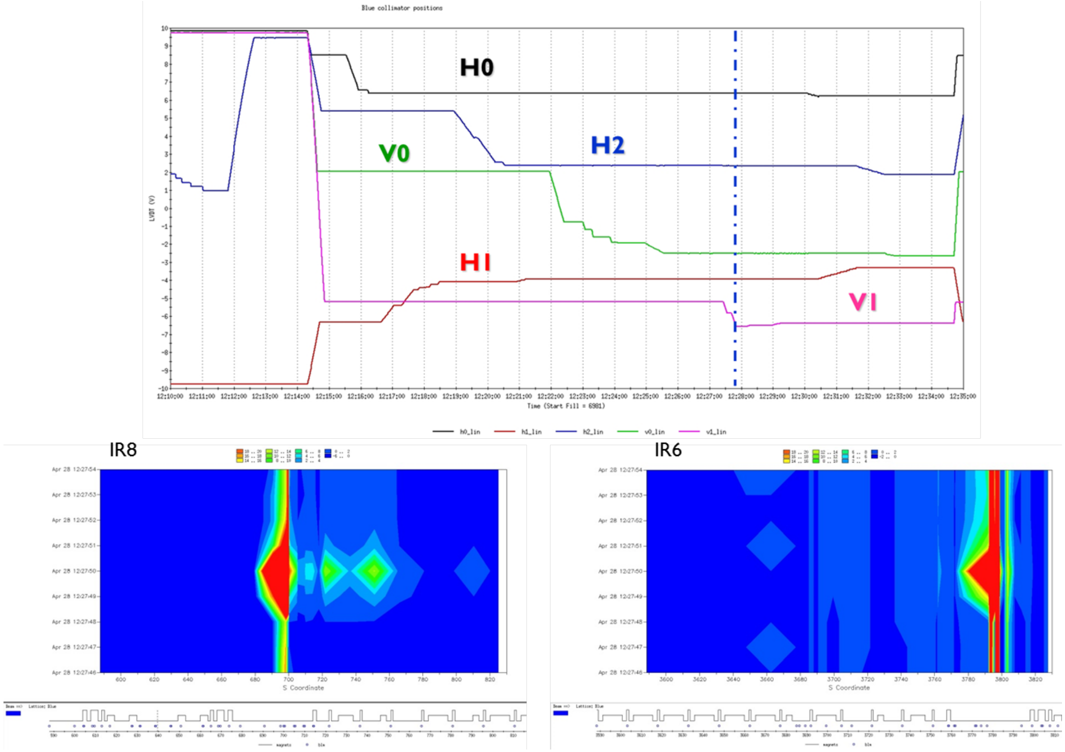

Fig. 3: Top: positions of the Blue collimator jaws in LVDT units versus time during Fill #06981 of the RHIC 2005 p^{+}-p^{+} Run. - Bottom: BLM signal in the PHENIX and collimation insertion (left) and the STAR insertion (right). There is a clear increase in the loss signal at the time when the $V1$ jaw scrapes the beam.

Figure 5 shows details of the simulations around the collimation region (IR8) and the STAR experiment (IR6). Losses seen at the triplet magnet upstream of the collimation system (s = 600 m) and around IP6 (s = 0 m) are due to some of the halo protons that were scattered by the collimators and managed to escape further downstream. These protons face an aperture bottleneck at these quadrupoles since β^{*} in both experimental insertions is squeezed down to 0.9 m for higher luminosity. The high level of losses seen by the BLM's in IR8 around s = 700 m is due to showers coming from inelastic interactions in the collimator jaws. This is shown by the green dashed lines in the simulated loss maps, giving the statistics of inelastic interactions in each jaw.

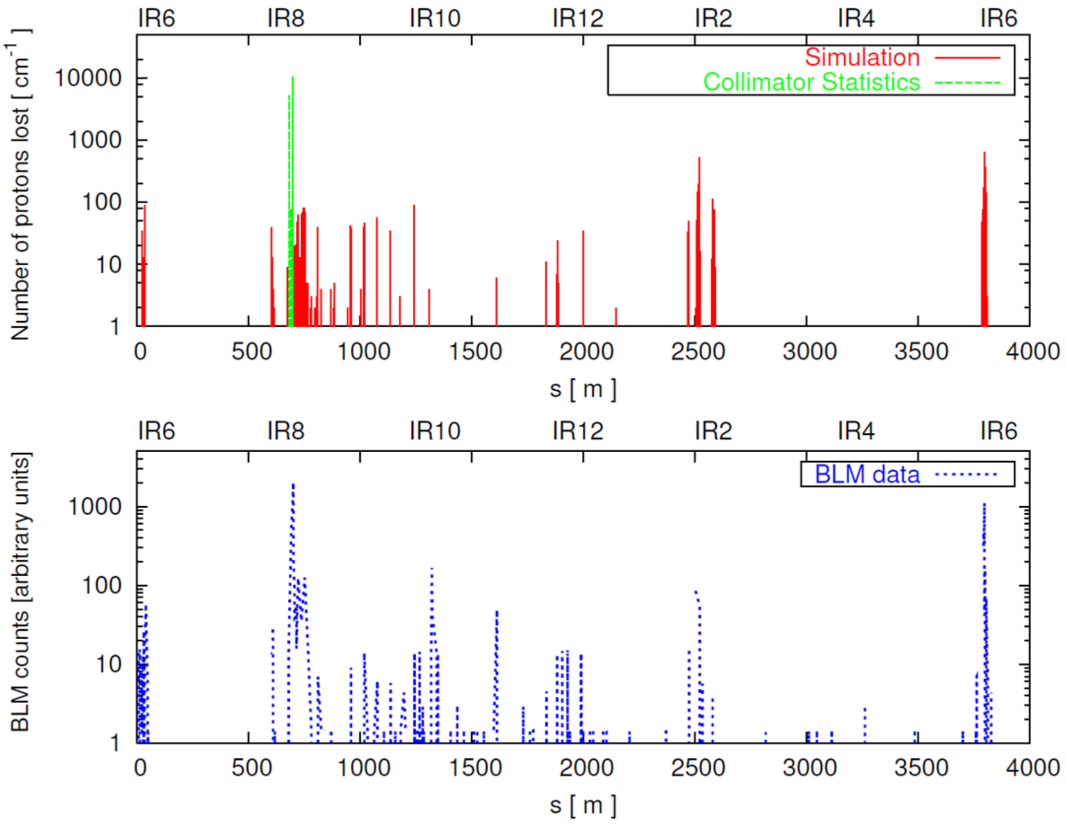

Fig. 4: Comparison between simulated loss maps (top) and BLM measurements (bottom) due to beam impacts on the V1 collimator jaw for the Blue beam circulating from left to right.

The relative height of the peaks in the simulations can be compared with the live measurements too. When studying the statistics of the predicted losses, one can consider that each BLM can only “see” beam losses up to a certain distance upstream of it, taken as d = 5 m here. Table 2 presents a quantitative comparison between simulations and measurements for the region close to the collimators (between s = 700 m and s = 750 m as seen in Figure 5). It shows that the overall variation of loss amplitudes at the various BLM locations is to the first order reproduced by the simulations.

Table 2: Comparison between simulations and live measurements for the statistics shown in Figure 5 of beam losses induced by the RHIC collimation system.

BLM location (from IP6)	**BLM signal** [rad.h^{-1}]	**N$_{losses}$ upstream** over $d = 5$ m
(1) s = 705.5 m	38.021	89 ± 9
(2) s = 710 m	50.979	132 ± 11
(3) s = 714.2 m	55.743	127 ± 11
(4) s = 721.7 m	124.600	496 ± 22
(5) s = 736.5 m	35.136	97 ± 10
(6) s = 751.2 m	125.331	495 ± 22

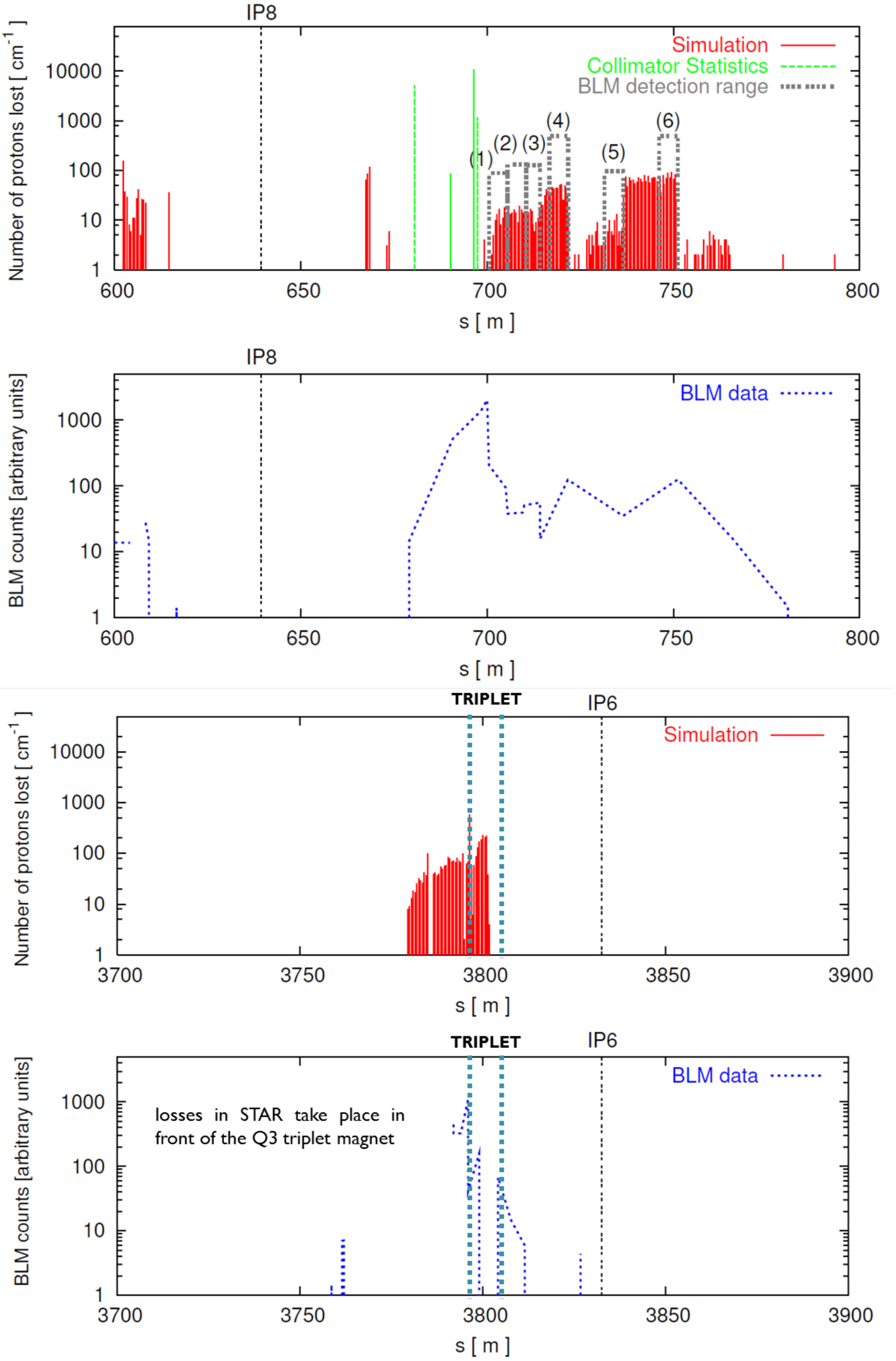

Fig. 5: Zoom of the simulated loss maps and BLM signal around the collimation region (top) and the STAR experiment (bottom) following the Blue beam. Beam losses can be spotted at the triplet magnet upstream of the collimators.

Deriving a scaling law from the loss location statistics is complicated, since the tracking tools were at the time designed to show only the locations where the protons scattered by the collimation system are lost, while particle showers induced by the proton-matter inelastic interactions in each collimator are the source of signal seen by the BLM's. Recent upgrades to SixTrack now include in-tracking checks on the mechanical aperture limitation, as well as a better interfacing to FLUKA for energy deposition studies. Repeating the simulations described in this section with up-to-date tracking tools would therefore allow for refining the statistics in Table 2.

3 Machine Protection Studies

With the stored beam intensity reaching record highs every Run, protecting RHIC's detectors as well as RHIC's superconducting magnets from excessive losses became more and more important. The most prominent reason for massive instantaneous beam losses are, notably, RHIC abort kicker prefires as described in [2]. A prefire is an event in which one of the five RHIC abort kickers self-triggers asynchronously. Given the location of the abort system (IR10) with reference to the location of the two low β^* experimental insertions (IR6 and IR8) it is obvious that the location of the collimators on the outgoing sides of IP8 are in no position to protect experiments from one-turn type losses such as occuring during a prefire event. While prefires of the blue abort system pose the highest risk to the STAR detector at IP6, prefires of the yellow abort system are most dangerous to the PHENIX detector at IP8, one arc downstream of the abort kicker location. Therefore, two additional titanium masks were installed in RHIC, each one arc downstream of the respective abort system, i.e. just upstream of the triplets on the incoming side in IR8 (yellow) and IR12 (blue). Figure 3 shows a design drawing of one the installed masks.

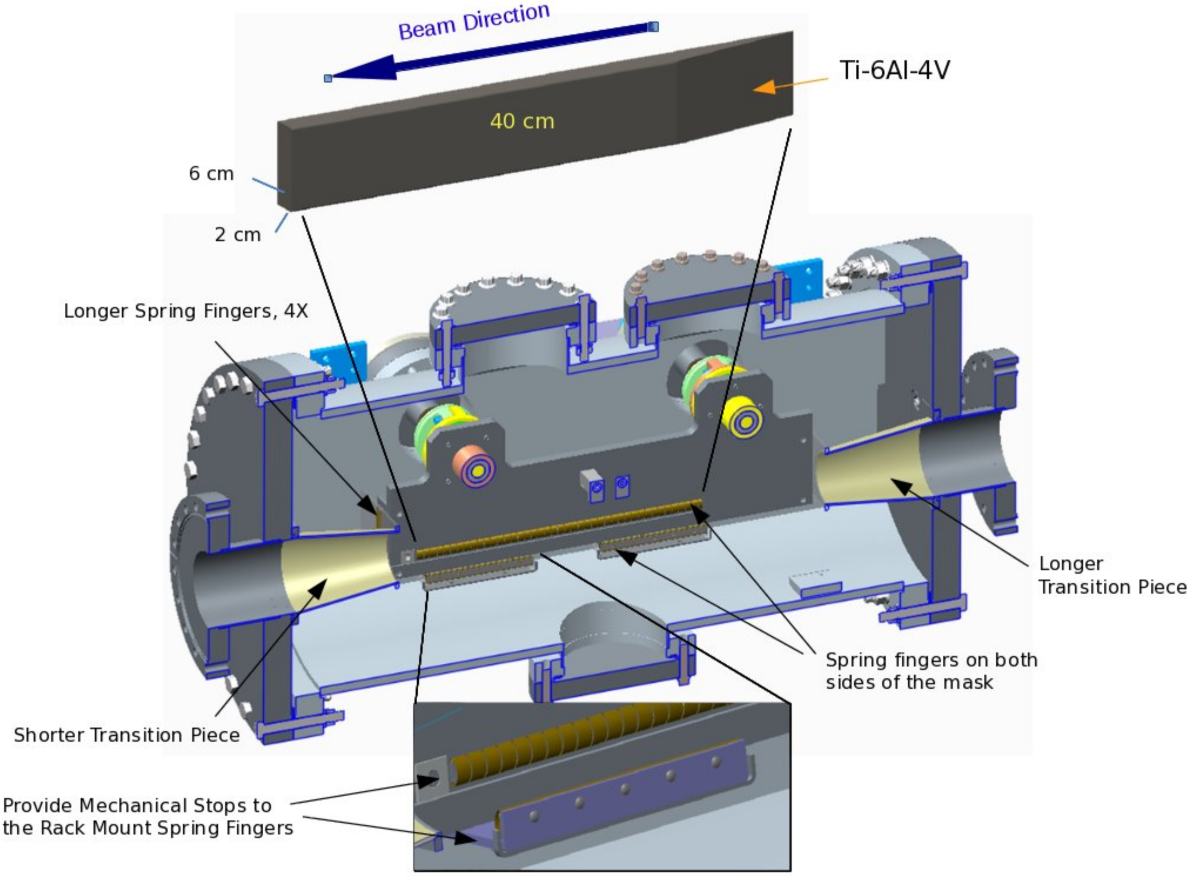

Fig. 6: Design drawing of titanium mask

Operational experience with these masks during the 2015 RHIC operations (Run15) showed them to be insufficient to protect in particular the PHENIX detector from damage in a prefire. One subdetector's preamplifiers got almost entirely destroyed in two prefire events during the p-Au mode of Run15. Two aspects turned out to eliminate the effectiveness of the masks: the tight restrictions to the phase advance between the abort system and the mask location and, in the yellow ring, the unfortunate location of the mask within the same straight section and thus immediately upstream of the experiment itself. Therefore, a protection scheme with large orbit protection bumps as shown in Figure 3 got reinstated. Currently studies are underway to prevent prefire events entirely with a focus on the abort kicker trigger circuits.

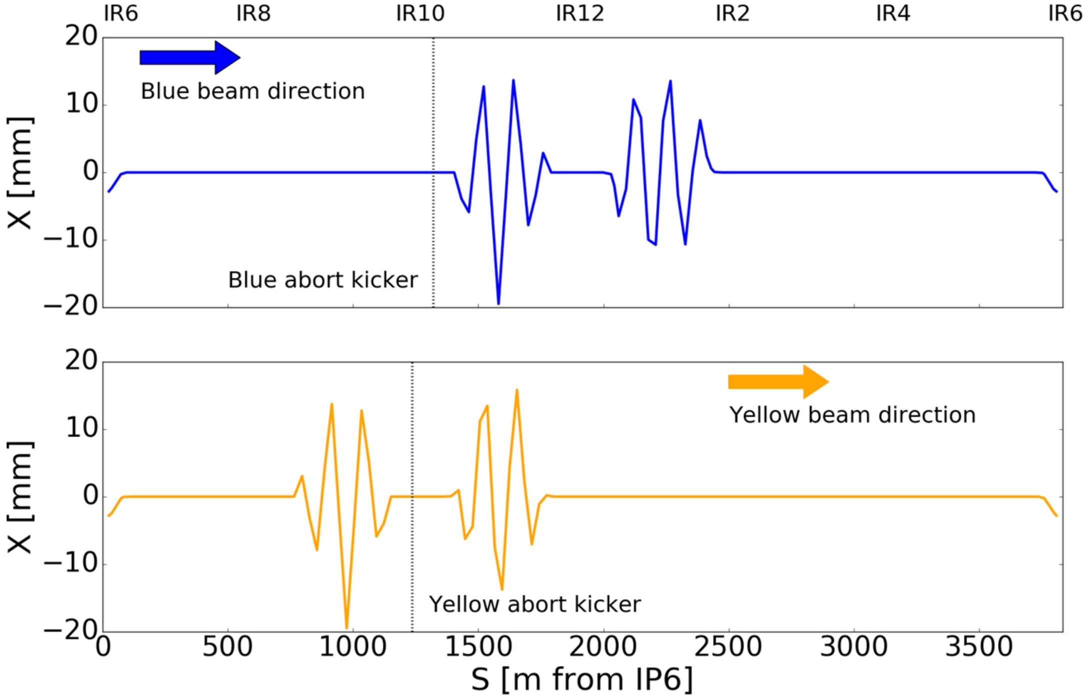

Fig. 7: Closed orbit bump for the Blue (top) and Yellow (bottom) beam in RHIC for abort kicker prefire protection

References

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[2] A. Drees et al., *RHIC Prefire protection masks*, C-A/AP/533, January 2015.