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A HOLISTIC APPROACH TO SIMULATING BEAM LOSSES IN THE LARGE HADRON COLLIDER USING BDSIM

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Abstract

To fully understand the beam losses, subsequent radiation, energy deposition, backgrounds and activation in particle accelerators, a holistic approach combining a 3-D model, physics processes and accelerator tracking is required. Beam Delivery Simulation (BDSIM) is a program developed to simulate the passage of particles, both primary and secondary, in particle accelerators and calculate the energy deposited by these particles via material interactions using the Geant4 physics library. A Geant4 accelerator model is built from an optical description of a lattice by procedurally placing a set of predefined accelerator components. These generic components can be refined to an arbitrary degree of detail with the use of user-defined geometries, detectors, field maps, and more. A detailed model of the Large Hadron Collider has been created in BDSIM, validated with existing tracking codes and applied to study beam loss patterns.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is at the forefront of the accelerator energy frontier, with a design energy of 7 TeV and with a stored energy of 386 MJ per beam [1]. This extremely large stored energy presents a challenge to protect the experiments, and machine elements both from irradiation and prevent any superconducting magnets from quenching, where as little as 1 mJ cm^{-3} is sufficient to cause a quench [2]. Beam losses are inevitable in any machine and it is due to the aforementioned factors that a dedicated collimation system has been designed and built. It is primarily located in two insertion regions (IRs)—IR3 for momentum cleaning, and IR7, for betatron cleaning. Common to both is the concept of a collimation hierarchy, which consists of a sequence of collimators with increasing apertures, such that large amplitude particles will first hit the primary (smallest aperture) collimator, followed by the secondary collimators (wider aperture), and finally the absorbers (larger still). Added to this are tertiary collimators (TCTs) on either side of the experimental IRs, which protect the final focus magnets and reduce beam-induced backgrounds. This design has proven exceedingly successful in protecting the machine.

Detecting beam losses reliably in critical regions requires the presence of 3600 beam loss monitors (BLMs) placed around the ring [2]. These are used to detect abnormal beam conditions, and if one detects losses above a given threshold, a beam dump is triggered. In order to characterise the pattern of losses around the ring and study the effectiveness of the collimation system, special runs are performed where a low-intensity beam is blown up to produce losses and the signal from the BLMs is recorded. This is referred to as a loss map of the machine.

To ensure the collimation system works effectively both in normal-functioning as well as in adverse scenarios, such as an asynchronous beam dump, effective simulation tools are necessary. The tool of choice used at CERN for collimation studies is SixTrack, and is used to generate loss maps [3]. SixTrack is a fully symplectic 6-D thin lens tracking code which was originally used for dynamic aperture studies, but was extended for use in aiding the design and implementation of LHC collimation system [4]. SixTrack is often paired with another standard CERN code, FLUKA [5], for irradiation and beam background studies to study specific areas of interest. Together these have demonstrated themselves to be extremely effective in aiding the design and optimisation of the LHC collimation system.

SixTrack's approach to primary impacts on collimators is to call Monte Carlo scattering procedures, whereby the primary is either lost in an inelastic collision, or undergoes an elastic process and is reintroduced to the tracker. Elsewhere, if a primary particle exceeds the aperture at a given point, it is treated as lost immediately at that location. Secondary particles that would generally stem from these impacts are not treated.

Beam Delivery Simulation (BDSIM) is a novel code which seeks to track the passage of the primary particle as well as any resulting secondary particles [6]. As a result it is it will be more capable of capturing the details in LHC loss maps which are otherwise missing in existing tools, and present a more holistic method for simulating beam losses in particle accelerators.

In this paper, preliminary results comparing LHC loss maps from BDSIM, SixTrack, and BLM data from a recent run are presented.

BDSIM

BDSIM is a C++ particle tracking code based on a collection of high energy physics libraries, including Geant4 [7], CLHEP [8], and ROOT [9]. It automatically builds a Geant4 3-D accelerator model from a set of generic components which enables the seamless tracking of both primary and secondary particles throughout an accelerator or detector. In using Geant4 it has access to all of the standard particle physics processes, but is supplemented with accelerator tracking routines. Standard Geant4 numerical integrators are replaced with transfer matrices for elements such as drifts,

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dipoles (including fringe fields) and quadrupoles. This approach only is possible because of the use of a curvilinear transform, provided by BDSIM, from the Geant4 Cartesian coordinate system, to the curvilinear system. Higher thick order multipoles are handled with the use of symplectic Euler integrators.

BDSIM models are described with the use of a MAD-X-style ASCII input and typically converted from an existing optical description, such as MAD-X TFS [10] using the Python package *pybdsim*, allowing one to build a Geant4 model of a given accelerator within minutes. Whilst models are built from a set of generic components, the user may choose to provide more detailed geometries, field maps, and more to further improve their simulation's accuracy. BDSIM supports all MAD-X apertures, which are shown in Figure 1, including the LHC aperture shown on the top left, that includes the copper beam screen and cooling tubes.

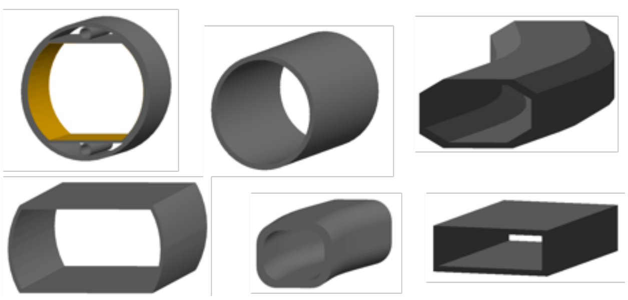

Figure 1: A selection of MAD-X apertures as rendered in BDSIM. Note that the top left LHC aperture has been supplemented with additional detail.

Geant4 mandates that there must be no overlaps between solids, otherwise the particle tracking is prone to becoming stuck in a loop, and fail. Therefore it is absolutely necessary that overlaps are not present in any BDSIM model. BDSIM guarantees that the default-provided generic geometries respect this requirement. Not only do overlaps result in problematic behaviour, but also coplanar faces do as well. This means that not only must there be no overlaps, but also there must be a gap between solids. In BDSIM this manifests itself most noticeably as the introduction of a small 1 nm gap between all accelerator components. The introduction of this small gap has minimal impact for linear accelerators, but ultimately manifests itself as an emittance growth over many turns in a circular collider model. This is not a physical process, but instead simply a limitation of Geant4 as applied to accelerators.

In order to mitigate the detrimental effects of geometry safety separations, multi-turn tracking is synchronised with a 14$^{\text{th}}$ order one turn map (OTM) from PTC. For any one turn the tracking is first done in the OTM and the results are cached. The same full-turn tracking is then done in BDSIM, which includes a comprehensive set of physics interactions, accurate aperture intersection calculation and tracking in external magnetic fields outside the beampipe. At the end of the turn, if and only if a beam particle is primary and has not undergone an interaction in this turn, its coordinates are set to the coordinates from the OTM. All secondary particles and primary particles that have interacted keep the coordinates from BDSIM and the tracking continues. This approach ensures stable tracking of particles that survive inside the aperture for many turns, while leveraging all the benefits of the 3D model for the particles that survive. Figure 2 shows a reference particle tracked in BDSIM with and without the use of the one turn map. The tracking accuracy is clearly drastically improved when using the one turn map.

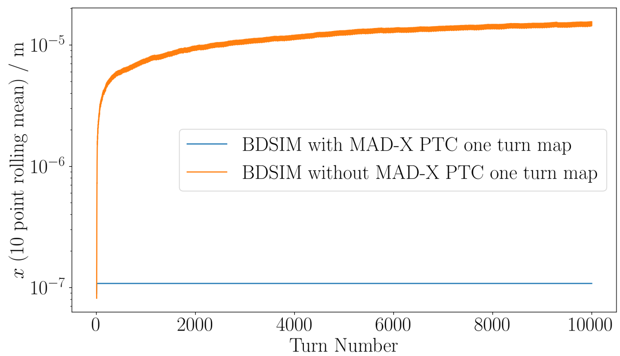

Figure 2: BDSIM long term tracking comparison for a reference particle. The transverse position x is recorded at the end of each turn for 10,000 turns with and without the use of a one turn map to correct the particle's trajectory.

MODELLING

BDSIM and SixTrack models were both prepared from the same MAD-X TFS optical description of a recent LHC configuration. The model parameters are the 2018, 6.5 TeV, $\beta^* = 30$ cm, "end-of-squeeze" optics and a summary of the collimator openings is shown in Table 1. The only difference is that SixTrack, a thin lens tracker, uses a thin description, whereas BDSIM was prepared from the thick version to ensure the desired geometry is built.

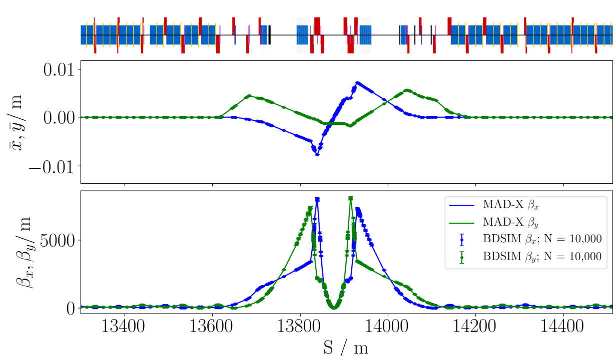

Figure 3: A comparison of the beam centroids (top) and the horizontal and vertical Twiss β-functions (bottom) between MAD-X and BDSIM.

BDSIM's tracking with respect to this model is validated by tracking 10^4 protons over a single turn, where the optical

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Table 1: The Collimator Openings, Corresponding to the 2018 6.5 TeV, $\beta^* = 30$ cm, "End-of-Squeeze" Optics Used in the Comparisons Described in this Paper

Collimator	**Opening / σ**
TCP IR7	5.0
TCSG IR7	6.5
TCLA IR7	10.0
TCP IR3	15.0
TCSG IR3	18.0
TCLA IR3	20.0
TCSP IR6	7.4
TCDQ IR6	7.4
TCT IR2	37.0
TCT IR8	15.0
TCT IR1/5	8.5

functions are extracted directly from the beam distribution using moments of the beam sigma matrix of up to 4th order and comparing with MAD-X. Excellent agreement between BDSIM and MAD-X is shown in Figure 3. However, to correct BDSIM's longer term tracking, as described in more detail in the previous section, a 14th order Taylor map from MAD-X PTC is used to reset primaries onto their correct trajectory at the end of each turn.

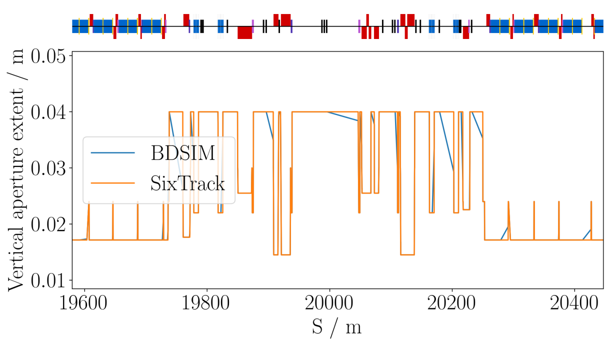

Figure 4: A comparison of the vertical aperture extents between BDSIM and SixTrack. The difference between the two shown is an artefact of the way apertures are described in BDSIM. A BDSIM does not have an aperture, but instead an *opening*, whereas the aperture is defined throughout for SixTrack, even where apertures are located.

An accurate aperture model is mandatory for a faithful simulation of losses in the LHC. SixTrack uses an interpolated aperture description with a resolution of 10 cm by default. To further enhance the geometrical description, this same aperture description was loaded from SixTrack into BDSIM. A comparison of the aperture model in IR5 is shown in Figure 4, where excellent agreement is shown. The geometric description was supplemented with further details to improve the model accuracy: the *lhcdetailed* aperture type, shown in Figure 1, was used throughout; the detailed LHC magnet geometries; and the correct handedness for the magnet geometries featuring two beampipes.

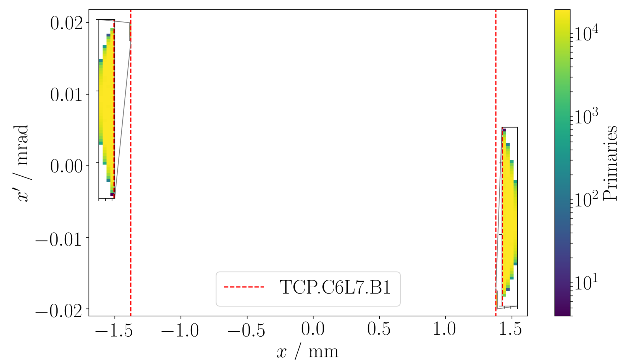

Figure 5: Primary distribution with collimator jaws marked. The primary distribution is shown zoomed inset as the region in phase space is extremely small.

In this paper only results from the simulation of hits on the the horizontal primary collimator (TCP.C6L7.B1) in IR7 have been simulated. To reduce the simulation time, only primaries with an initial position overlapping with the collimator jaws are generated. Again, these same primaries are loaded into BDSIM from SixTrack. The initial primary distribution is shown in Figure 5, with the jaws of the collimator marked in red. This primary distribution results in an impact parameter distribution shown in Figure 6. The impact parameter is simply the shortest transverse distance from the impact on the collimator jaw to its edge. The $\leq$10 µm impact parameter is relevant here as this is typical of beam halo particles impacting on the collimator jaws.

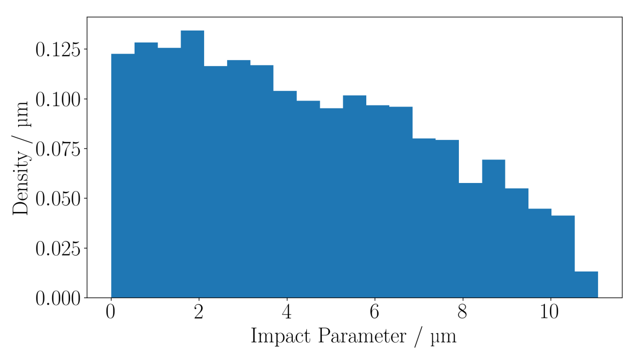

Figure 6: Probability density for the impact parameters on the horizontal collimator in IR7.

RESULTS

6.4×10^6 protons in SixTrack, and 3×10^6 protons in BDSIM were simulated. When comparing measured losses to predicted losses it is important to make the distinction of what the results compared are. In the case of standard SixTrack, the total energy of the particle is considered to have been deposited at the aperture impact location. In contrast, the BLMs record losses that escape the magnet and have

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thus propagated from the aperture impact location through the beampipe, coils, yoke and cryostat fixtures. In BDSIM the whole shower development is captured and energy deposition is recorded along the full path of any nominal or secondary particles in the corresponding materials. As a result, a direct one-to-one comparison is inappropriate. Instead BDSIM energy deposition, and SixTrack losses, both normalised with respect to their corresponding peaks in IR7 are shown, as well as the BLM dose, again normalised with respect to the peak in IR7.

Figure 7 shows a comparison between the three different loss maps for the whole machine. The maps are colour coded to highlight in particular losses in cold regions, as these are the regions in which it is most necessary to avoid losses. The two largest peaks in the collimation insertions, the larger in IR7 and the smaller in IR3, are correctly reproduced in BDSIM and good agreement is shown between all three loss maps. Low-level noise is present throughout the BLM loss map, and as this is completely missing in the SixTrack loss map, one might imagine it is a result of secondary particles depositing energy in these regions. However, whilst BDSIM does record some energy deposition in these regions, it mostly missing in BDSIM as well. This suggests that this energy deposition does not stem from primary losses in IR7. Instead it could be originating in losses from the beam, which neither SixTrack nor BDSIM account for. Finally a longer tail in the region following IR7 in the BDSIM loss map compared to the SixTrack loss map is clearly visible. This is likely explained as secondary particles which originate from primary losses in IR7 travelling further downstream and depositing energy.

In Figure 8, one can see a zoomed section of IR7 and the dispersion suppressor immediately following it. Inspecting this region is useful for a number of regions, firstly to ensure the collimator hierarchy is obeyed, where the number of losses in the collimators decreases further downstream. Secondly, the cold section immediately following IR7 is the dispersion suppressor, which is generally the cold region in the LHC exposed to the greatest number of losses, and therefore the section closest to quenching.

A number of features are notable in Figure 8. The collimation hierarchy is recreated as expected, however in BDSIM the peak energy deposition actually occurs in the warm quadrupole immediately following the primary collimator. The BLM data in this region shows that the dose in this quadrupole is indeed very large, but still marginally smaller than detected in the collimator BLMs. This could simply due to the fact that BDSIM integrates all energy deposition within a given S bin, whereas the actual BLM volume is much smaller than this. It may also be necessary to further improve the geometry in this location to resolve these features more accurately: it was mentioned above that the quadrupole geometry used was the geometry of superconducting quadrupoles. However one can plainly see that in this case, the quadrupoles are warm, and therefore normal conducting, not superconducting.

The BLMs placed between the collimators show that there are sizeable losses in these regions. These features, which are almost entirely missing in SixTrack, appear to be faithfully recreated in BDSIM, with similar losses relative to the maximum.

In the dispersion suppressor more detail is present in the loss map generated with BDSIM. The losses are much more smeared out, which is most likely explained by the fact that SixTrack will immediately kill all particles lost in this region, as they are aperture losses, whereas BDSIM will model any primary elastic or inelastic scattering and track any resulting secondary particles. However the presence of two populations in this region, clear in SixTrack, is still discernible in BDSIM. Finally, the relative sizes of the losses in this region appear to be more comparable to the BLM data in BDSIM than SixTrack, where in this region the BLM losses are on the order of 10^{-4}, in BDSIM also 10^{-4}, and in SixTrack between 10^{-5} and 10^{-6}.

CONCLUSION

A Geant4 accelerator model for the LHC has been built using BDSIM and used to generate loss maps. These BDSIM loss maps have been contrasted and compared with ones from the standard CERN LHC collimation code SixTrack, as well as BLM data from a recent qualification run.

Whilst the results presented here are preliminary in advance of further, more detailed studies, it is nevertheless apparent that many of the features present in the BLM data which are missing in SixTrack seem to be recreated with BDSIM. This includes the warm losses present between the collimators, explained simply as energy deposited by secondaries, as well as the more smeared out losses in the dispersion suppressor. Some features remain unexplained, such as the low-level noise-like present in the BLM data.

Further refinement of the model geometry can be explored to improve the accuracy of the model. For example, the differences in the geometries between warm and cold magnets is not accounted for in this model, instead only cold magnet geometries are used. Moreover BLM elements can be placed along the ring model in a one-to-one correspondence with those in the actual LHC. This will enable a direct comparison between detector dosages calculated with BDSIM and real LHC BLM dosages.

On the BDSIM side, developments to further improve its use for LHC collimation studies are planned. Firstly, additional data pertaining to losses in collimators will be stored. Secondly, BDSIM can be engineered to treat collimator impacts and aperture losses in the same way as SixTrack—enabling a direct one-to-one comparison between the two codes. Finally, development of a dedicated tracker is in progress. This will allow for a dramatic decrease in simulation time, allowing for greater statistics, as well as tracking which is both more accurate and symplectic.

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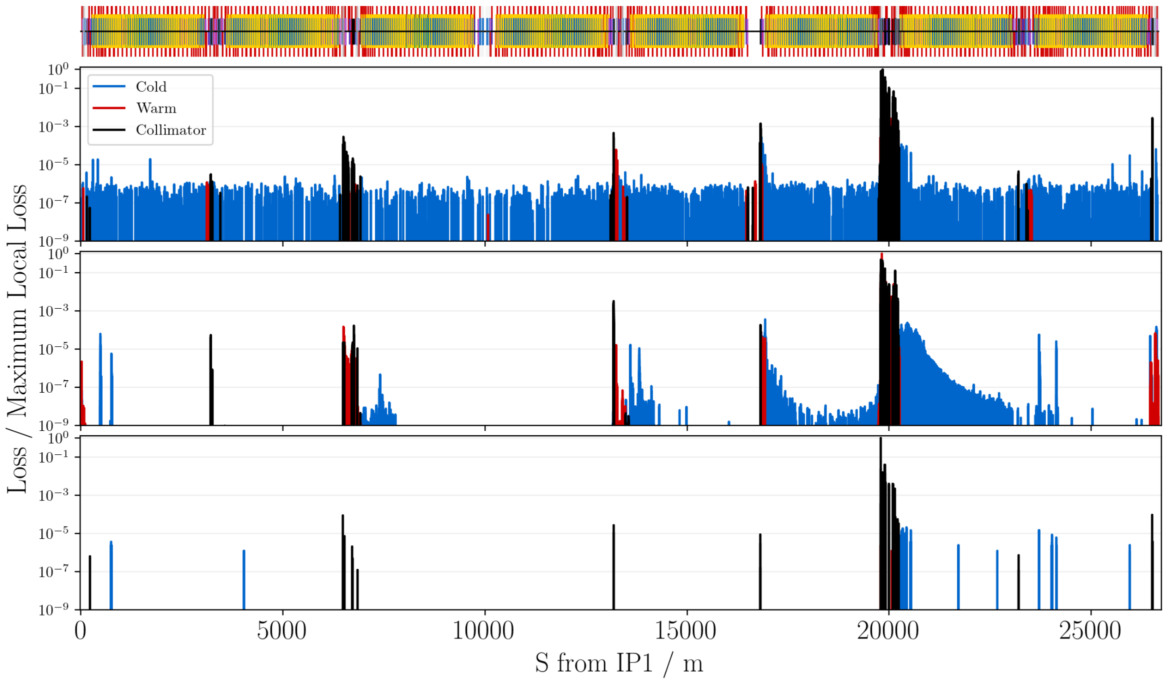

Figure 7: Loss map comparison for the whole LHC between beam loss monitor signal (top), BDSIM energy deposition (middle), and SixTrack losses (bottom). Each is normalised to the corresponding peak in IR7. Cold, warm, and collimator losses are encoded to highlight the various features, and a diagram of the machine is displayed along the top.

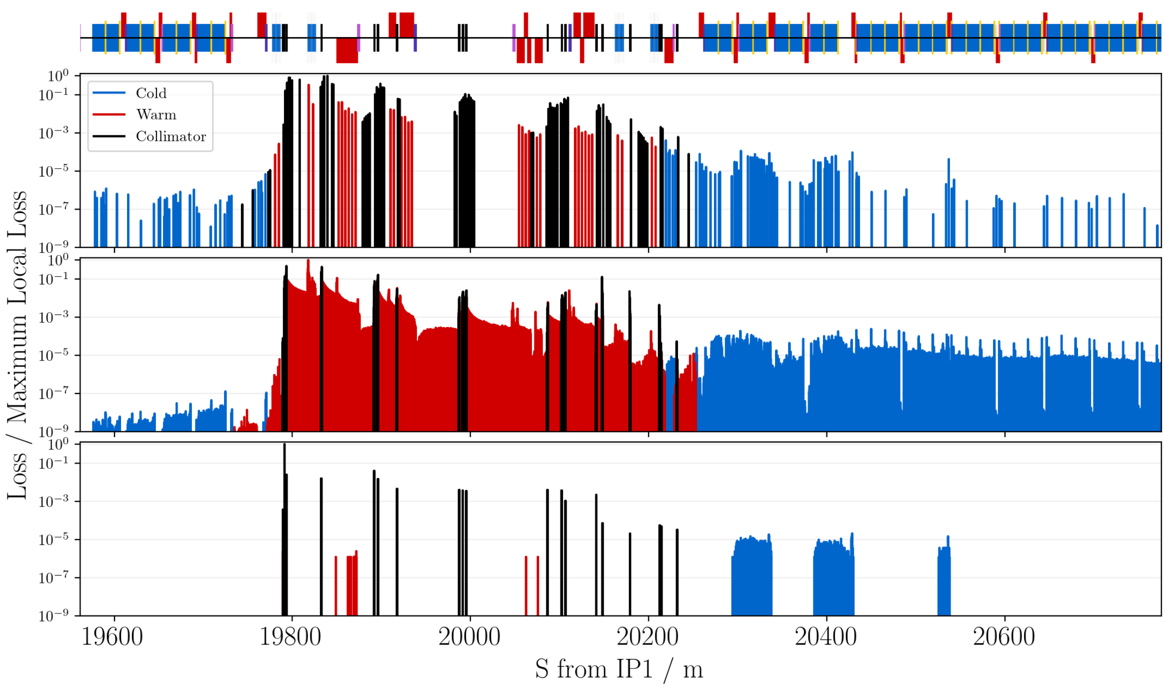

Figure 8: Loss map comparison, zoomed to IR7 where the betatron collimation is located, between beam loss monitor signal (top), BDSIM energy deposition (middle), and SixTrack losses (bottom). Each is normalised to the corresponding peak in IR7. Cold, warm, and collimator losses are encoded to highlight the various features, and a diagram of the machine is displayed along the top.

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