RECENT DEVELOPMENT AND RESULTS WITH THE MERLIN TRACKING CODE*

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Abstract

MERLIN is a high performance accelerator simulation code which is used for modelling the collimation system at the LHC. It is written in extensible object-oriented C++ so new physics processes can be easily added. In this article we present recent developments needed for the Hi-Lumi LHC and future high energy colliders including FCC, such as hollow electron lenses and composite materials. We also give an overview of recent simulation work, validation against LHC data from run 1 and 2, and loss maps for Hi-Lumi LHC.

INTRODUCTION

MERLIN [1] is an accelerator physics library written in C++, originally for studying the International Linear Collider [2], and then extended to be suitable for synchrotrons such as high energy proton colliders. The modular design of MERLIN made it a good candidate to add functionality needed for Large Hadron Collider (LHC) collimation studies [3].

The LHC has a stored energy 362 MJ per beam and so loss of even a small fraction of the beam can cause a quench of the superconducting magnets or damage to hardware. At the high energies many protons will survive their initial interaction with the collimator jaw and be deflected back in to the beam pipe. Therefore a multistage collimation system is needed to clean the tails of the beam. The primary collimators (TCP) are made from carbon and sit closed in to intercept the beam halo. The secondary collimators (TCS), also made of carbon, absorb the deflected protons and secondaries, and the tungsten tertiary collimators (TCT) provide extra protection for the experiments [4].

The High Luminosity upgrade (HL-LHC) [5] will increase the stored energy to 675 MJ per beam, making the collimation system even more critical. It calls for upgrades to the collimation system including new collimators within split 11 T dipoles in the dispersion suppressor regions, new collimator materials and Hollow Electron Lenses (HELs) for enhanced beam cleaning.

For collimation studies MERLIN reads a lattice description from a TFS file generated with MADX. Details of the machines physical aperture and collimator setup are then read to give a complete model. A bunch of protons is tracked by symplectic integration around the ring. At each element physics processes can be attached, for example a scattering routine to the collimator elements. Online aperture checking is used to create a loss map without the need for post processing. MERLIN simulates the scattering of protons in matter, including new models for elastic and single diffraction as described in [6]. For performance reasons only the leading proton from the scatter is simulated, rather than the full shower.

In the past few years MERLIN has been upgraded in order to study collimation for HL-LHC, and future machines such as FCC [7,8] and SPPC [9], with new materials including composites [10] and models for advanced collimation methods such as the HEL.

RECENT DEVELOPMENTS

Recently efforts have been made to improve the code quality, usability and reliability of MERLIN. An automated test suite, using CDash [11], has been added which is run nightly with results submitted to a test server from computers running on a range of operating systems, compilers and CPU architectures. The tests check the behaviour of the code, but also build warnings and for runtime memory issues. This allows new issues to be quickly identified.

Use of new features of the C++11 standard have made parts of the code simpler and more robust. We have also begun work on refactoring to improve the class hierarchy and take greater advantage of object oriented design. We have improved documentation and error messages. We have moved to a strict workflow where new features and fixes are developed on branches before merging into the master version, using the revision control system Git.

The aperture configuration system has been updated in order to support the Future Circular Collider (FCC) accelerator lattice including its octagonal beam screen.

SQUEEZE LOSSES

Losses recorded around the LHC ring during run I and II give a good opportunity to validate MERLIN simulations. MERLIN records the location that each proton is lost in the ring. This is used to calculate the local cleaning inefficiency, i.e. what fraction of loss escapes the primary collimators and arrives at a given point. In the real machine the losses are recorded by the Beam Loss Monitors (BLMs) which measure the radiation dose at points outside the accelerator components as a function of time.

During the squeeze the beam intensity at the interaction points (IPs) is increased by squeezing the beta function therefore reducing the beam size. This causes the beta function in the inner triplets to grow large. The TCT jaw gaps in

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the interaction regions are therefore reduced to give greater protection to the triplet magnets. As the squeeze transitions through a range of optics configurations, it is useful for comparing MERLIN simulations to BLM data. By normalising to the final squeeze point the changes in cleaning inefficiency can be compared independently to the BLM response.

For Run I there were no loss maps made during Machine Development (MD) sessions for the intermediate squeeze settings. Instead, we have used BLM data from 4 TeV physics fills during 2012. Here the comparison is difficult because the data at any point contains an unknown mixture of losses in horizontal and vertical and from both beams. The signal on the TCTs is also small compared to the noise floor.

For Run II loss maps were made during MDs at steps within the squeeze, by exciting the beams individually in one plane at a time. This gives a stronger signal and allows simpler comparison with simulations. Figure 1 shows the good agreement between MERLIN and the BLM signals for the 2015 squeeze configurations.

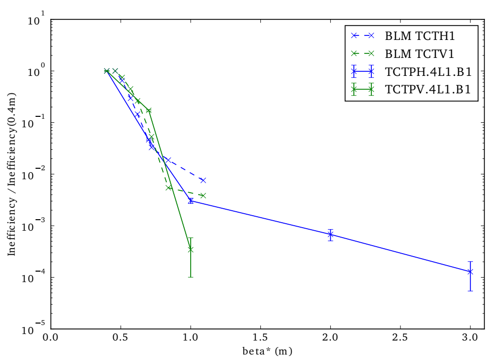

Figure 1: TCT in IR1 loss as a function of β^*. BLM data is shown in dashed and MERLIN simulations in solid lines.

HIGH LUMINOSITY LHC

The HL-LHC upgrade brings a number of changes in order to increase the luminosity for the experiments. The Achromatic Telescopic Squeezing (ATS) optics, as shown in fig. 2, and stronger inner triplet quadrupoles allows for reducing β^* to 15 cm at IP1 and IP5. Upgrades to the injector chain allow increasing the beam current. These require upgrades to the collimation system in order to protect the machine and keep experimental backgrounds low.

The dispersion suppression regions at the end of the long straight sections are found to need additional protection from particles that have received significant changes in rigidity. It is proposed to replace some of the present 8 T dipoles in these regions with two shorter 11 T leaving space in between for a collimator.

Figure 3 shows the loss map for the whole ring and zoomed in on the betatron collimation region in IR7. The losses in the collimation regions and the TCTs at the experimental regions are visible.

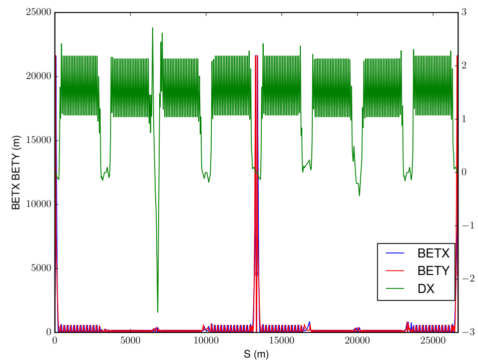

Figure 2: β-functions and dispersion for HL-LHC ring, 15 cm round optics, calculated by MERLIN.

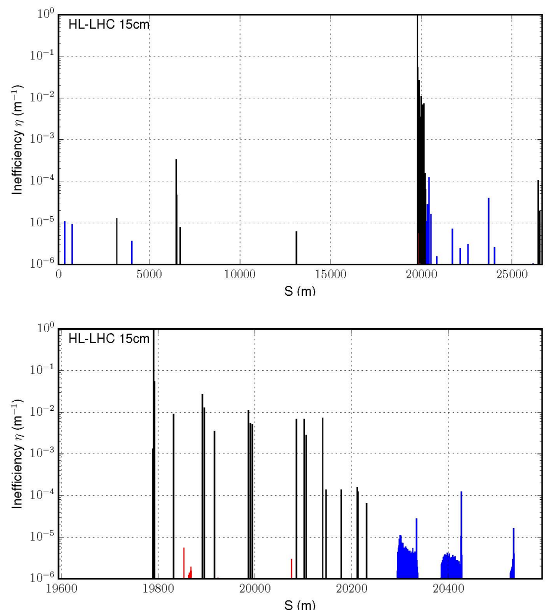

Figure 3: Loss maps for HL-LHC 15cm squeezed optics, whole ring above and IR7 below. Collimator, warm and cold losses are shown in black, red and blue respectively.

HOLLOW ELECTRON LENS

The HEL is a hollow beam of electrons that is co-propagated with the beam in order to enhance diffusion of the halo. It can be operated with a smaller gap than a physical collimator as it does not contribute significantly to the impedance budget and is not damaged by proton impacts.

The crab cavities in the HL-LHC upgrade introduce the possibility of fast beam losses in catastrophic failure scenarios. By depleting the number of protons in the halo, the HEL reduces the damage that could be caused in these cases.

A HEL process has been added to MERLIN which implements DC, AC, diffusive and turn-skip modes. Two radial profiles are offered, ‘perfect’ which gives an ideal uniform electron charge density and ‘radial’ which is a parametrisation based on the prototype LHC HEL cathode, as shown in fig. 4. Figure 5 shows the survival fraction of halo particles

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for the HL-LHC lens parameters placed at the round beam position 30 m upstream of IP4.

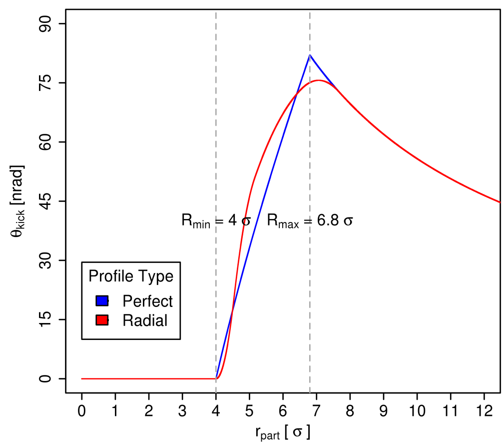

Figure 4: Kick strength for perfect and radial electron density profiles.

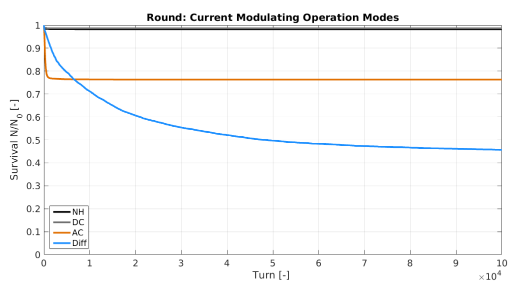

Figure 5: Halo survival fraction as a function of turn for different beam modes in HL-LHC at the round beam position.

Detailed studies of the HEL implementation for HL-LHC are given in [12, 13].

CONCLUSION

MERLIN is an actively developed accelerator simulation code, which is used for collimation studies on current and future hadron colliders. New features are being added to allow simulations of the next generation of accelerators while the current code base is being improved.

MERLIN is designed to make it simple to add new physics processes, this as been demonstrated by the addition of a HEL element which is need for HL-LHC studies.

REFERENCES

[1] MERLIN, `github.com/MERLIN-Collaboration/MERLIN`

[2] F. Poirier, D. Krücker and N. Walker, “An ILC Main Linac Simulation Package Based on MERLIN”, in *Proc. 10th Euro. Particle Accelerator Conf. (EPAC’06)*, Edinburgh, UK, 2006, paper MOPLS065, pp 694-696.

[3] H. Rafique, R. B. Appleby, R. J. Barlow, J. G. Molson, S. Tygier, A. Valloni, “Status of MERLIN” in *Proc. of Collimation Workshop 2015*, CERN, 2017.

[4] R.W. Assmann et. al., “The Final Collimation System for the LHC” in *Proc. 10th Euro. Particle Accelerator Conf. (EPAC’06)*, Edinburgh, UK, 2006, paper TUODFI01, pp 986-988.

[5] O. Brüning and L. Rossi, “The High Luminosity Large Hadron Collider”, World Scientific Publishing, 2015.

[6] R.B. Appleby, R.J. Barlow, J.G. Molson, M. Serluca and A. Toader, “The practical Pomeron for high energy proton collimation”, *Eur. Phys. J. C* 76:520, 2016.

[7] H. Rafique et. al., “Proton Cross-Talk and Losses in the Dispersion Suppressor Regions at the FCC-hh”, presented at IPAC’ 17, Copenhagen, Denmark, May 2017, paper TUPIK037, this conference.

[8] J. Molson, P. Bambade, S. Chancé and A. Faus-Golfe, “Simulation of the FCC-HH Collimation System”, in *Proc. 7th Intl. Particle Accelerator Conf. (IPAC’16)*, Busan, Korea, 2016, paper TUPMR054, pp 1381-1383.

[9] Y. Zou, J. Yang, J. Tang, “A Novel Collimation Method for Large Hadron Colliders”, arXiv:1611.05492, 2016.

[10] A. Valloni et. al., “MERLIN Cleaning Studies with Advanced Collimator Materials for HL-LHC”, in *Proc. 7th Intl. Particle Accelerator Conf. (IPAC’16)*, Busan, Korea, 2016, paper WEPMW036, pp 2514-2516.

[11] CDash, `http://www.cdash.org/`

[12] H. Rafique, R. B. Appleby, R. J. Barlow, J. G. Molson, S. Tygier, A. Valloni, “HL-LHC Hollow Electron Lens Integration using MERLIN” in *Proc. of Collimation Workshop 2015*, CERN, 2017.

[13] H. Rafique, MERLIN for High Luminosity Large Hadron Collider Collimation, Ph.D thesis, University of Huddersfield, Huddersfield, UK, 2017.