A REVIEW OF THE BEAM DELIVERY SIMULATION (BDSIM) USER COMMUNITY

W. Shields*, John Adams Institute at Royal Holloway, University of London, Egham, UK
L. J. Nevay, CERN 1211 Meyrin, Switzerland
S. T. Boogert, Cockcroft Institute, Daresbury, UK

Abstract

Beam Delivery Simulation (BDSIM) is a Monte Carlo particle tracking simulation tool for modelling energy deposition in 3D models of particle accelerators. Initially conceived in 2001 to model the collimation system in the International Linear Collider (ILC), in recent years BDSIM has undergone a significant transformation across virtually it's entire code base. As a result of its newer features, functionality, and performance, BDSIM is becoming increasingly adopted throughout the particle accelerator community for a wide variety of applications. Here, we review recent BDSIM studies by members of the BDSIM user community, including but not limited to linear and circular colliders, fixed target experiments, light sources, and medical accelerators.

INTRODUCTION

BDSIM is an open source C++ code based that can model beam dynamics, beam losses, and energy deposition in particle accelerator models with full 3D geometry and electromagnetic fields [1, 2]. Based on the Geant4 toolkit [3], BDSIM programmatically constructs accelerator models from simple optical descriptions of beam lines, offering a high degree of model control and customisation. With access to Geant4's extensive physics libraries, particle-matter interactions for primary and secondary particles can be accurately simulated throughout BDSIM accelerator model.

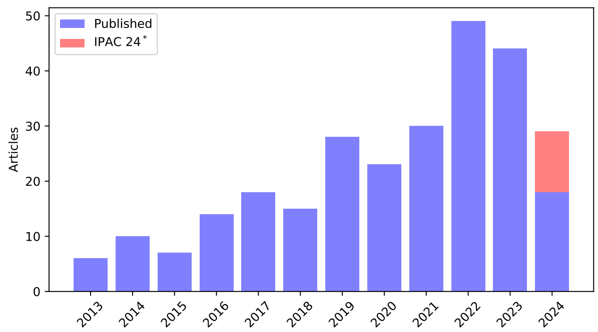

Figure 1: Articles in which BDSIM is used or highlighted by year as listed by Google Scholar. IPAC24 articles are taken from the pre-conference list of abstracts.

We present here a light review of BDSIM's user community. The literature discussed here is based on results collated from Google Scholar. Results were filtered to remove duplicate entries and unrelated articles. Figure 1 shows a clear growth in articles recognising BDSIM as a beneficial tool. Results start in 2013 when modernised versions of BDSIM were released [4] through to today where new BDSIM features continue to be regularly developed [5]. Instances of BDSIM mentions in IPAC'24 abstracts are also included, these were filtered to prevent double counting of student contributions.

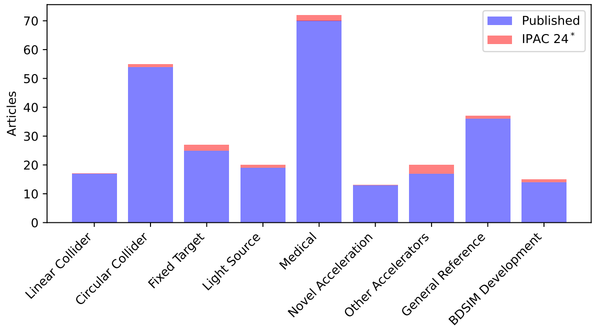

Figure 2: Particle accelerator themes of articles in which BDSIM is used or highlighted including IPAC24 abstracts.

The collated results were broken down into topics by accelerator theme, general references where BDSIM was highlighted in discussion only, and BDSIM development papers. Fig. 2 shows a broad range of accelerator themes to which BDSIM has been applied. The popularity of medical accelerators particularly highlights how BDSIM has expanded well beyond it's original purpose, especially considering that the first known medical articles were published in 2018 [6]. Figure 2 also include contributions at IPAC24. The following sections briefly highlight just a small selection of articles in which BDSIM has been used to model accelerators.

LINEAR COLLIDERS

BDSIM studies of linear colliders are predominantly on CLIC, with its muon background rate studied and contributions shown to originate from electron beams hitting a spoiler in the beam delivery system [7]. Magnetised shielding was shown to reduce the muon rate including variation in sweeper length & field strength [8]. In studies of the post-collision line where beams are transported to a dump, magnet variations were modelled with energy deposition results indicating no major resulting issues [9].

BDSIM modelling of ATF2 with a vertical beam halo collimation prototype installed was compared to experimental

---

[*] william.shields@rhul.ac.uk

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR70

data. Results showed the collimators cleaned background photons that could limit the performance of final focus diagnostic devices [10].

CIRCULAR COLLIDERS & EXPERIMENTS

Modelling of circular colliders in BDSIM is primarily CERN-centric, including the LHC for collimation studies and backgrounds for detector experiments, as well as future collider designs. Other circular colliders include the Circular Electron Positron Collider (CEPC) in China, and the KLOE-2 detector at the DAΦNE collider at INFN, Italy.

First LHC collimation studies with bdsim showed a SixTrack-BDSIM comparison of losses and energy deposition for a 3.5 TeV beam [11]. Proton collimation simulations later were compared to beam loss monitor data, with many of the features of the loss map matching well [12].

The proposal of the FASERν neutrino detector located in line of sight from the ATLAS IP highlighted BDSIM as critical for determining detector backgrounds [13]. Events from p-p collisions at the IP were propagated in BDSIM up to the FASER's Machine Detector Interface plane, aiming to estimate the flux and energy of particles.

The large stored energy of the FCC-ee beam requires that collimation systems be given significant consideration. Model particle interaction in a vast accelerator model necessitated the coupling of BDSIM & Xsuite, exploiting the strengths of both codes [14]. The coupled code was developed and benchmarked against a SixTrack-FLUKA coupling, showing good agreement in early loss maps studies.

Simulations of beam halo and synchroton radiation (SR) collimators were performed for a collimation configuration of FCC-ee [15]. Examining beam losses, the halo collimation system demonstrated good loss cleaning, with negligable power reaching the IRs. SR studies investigated a lattice to simulate edge scattering from the horizontal halo collimator [16]. Results show losses occur over the whole accelerator due to particles out-scattering from the collimator. The primary IP background sources of SR were identified in BDSIM with collimators subsequently implemented [17].

FCC-hh collimation has also been modelled in a novel high-beta optics configuration, with it's performance assessed with the BDSIM-Xsuite coupling [18]. First simulations demonstrated significant loss suppression, however loss clusters were found to exceed the estimated quench limit.

Beam induced backgrounds at the CEPC were expected to have a significant SR contribution; BDSIM studies found that the SR rate was much higher than detector tolerances [19, 20]. Similar to FCC-ee, it was shown that SR rates can be significantly suppressed by collimators around the IR.

BDSIM contributed to detector choice for the KLOE-2 detector at the DAΦNE electron-positron collider in investigations of correlations between energy and loss coordinates [21].

FIXED TARGET EXPERIMENTS

BDSIM has been used to model a number of fixed target beamline experiments at CERN, particularly in the North Area. For kaon studies in the M2 beam line, the AMBER experiment uses Cherenkov (CEDAR) detectors for particle identification. To improve the beam quality at the CEDAR, BDSIM showed a large, low-divergence beam for was the most efficient for tagging, and by putting the whole beamline under vacuum and modifying the beam optics, a factor 3 gain in kaon rate could be achieved [22]. Also in the North Area, BDSIM was used to model the K12 beamline to the NA62 experiment showing that the choice of gas in their CEDAR Cherenkov detectors impacted beam divergence and subsequent beam transport beyond the detector [23]. The T9 & T10 beamlines were modelled as part of this study [24].

SHADOWS was a proposed beam dump experiment in the CERN North Area alongside the PA42/K12 beam line aiming to search for feebly interacting particles. The rate, composition, and evolution of the beam and backgrounds were studied in a BDSIM model [25]. It was observed that on-axis background mostly missed the SHADOWS acceptance, but low energy muons were non-negligable. To mitigate this, a dedicated sweeping system consisting of magnetised iron blocks reduced the muon background by a factor of 120 [26].

Outside of CERN, BDSIM has been used to assess how changes to a target station will impact the proton beamline at the High Intensity Proton Accelerator (HIPA) cyclotron at the Paul Scherrer Institut (PSI), Switzerland [27]. BDSIM was benchmarked against MCNP6 with agreement in power deposited in the model's target and collimators shown to within 1%. Further studies related experimental data to Monte Carlo power deposition and loss calculations, with losses being identified as controllable [28].

LIGHT SOURCES

In the European XFEL, BDSIM indicated sources of beam losses in efforts to match experimental measurements of relatively high radiation doses in diagnostic undulator sections, with a wirescanner shown to contribute a non-negliable dose [29]. A later study tracked photon distributions of synchrotron radiation (SR) with good agreement seen with measured data [30]. It was concluded that lower energy SR dominates downstream undulator dose while upstream undulator dose is dominated by high energy electron losses.

The FEL technique of using a slotted foil in bunch compressor to produce short radiation pulses will cause an increased particle loss rate due to scattering from the foil. BDSIM was used to characterise the impact of a slotted foil on the radiation dose in the front section of one of the undulators [31]. It was shown that the foil could lead to catastrophic radiation dose rates in the undulators, with permanent damage in as little as 41 hours of machine running.

BDSIM has been recently used to model collimation in the Diamond-II upgrade [32]. The collimators are critical to a proposed beam killing method of turning off RF cavities and capturing the beam with a few tens of turns. To model their performance, accurate collimator geometry was included in a BDSIM model, converted from CAD engineering files to GDML with the pyg4ometry package [33]. Results show that even when accounting for thermal diffusion processes, the collimator would melt for all materials modelled.

MEDICAL ACCELERATORS

At ULB, Belgium, a number of studies of IBA's Proteus® One and Proteus® Plus proton therapy systems have been conducted. In a comparison between experimental data and start-to-end simulations in BDSIM, an absolute error in degrader transmission of less than 0.5 % was observed across all degraded beam energies [34]. In the same comparison, the error on the depth-dose profile in a water phantom agreed within 2 %. In a comparison between MCNPX and a coupling of BDSIM & FISPACT-II, activation rates were estimated of shielding in the proximity the energy degrader of the Proteus® One model [35]. An optimisation study of the Proteus® Plus system showed that the inclusion of a beam stopper in the fixed-beamline nozzle could improve the deliverable dose rate by up to a factor of 3 [36].

In a model of PSI Gantry 2, a new optics and collimation configuration was benchmarked against measurement taken in clinical scenarios, with predicted transmission showing a factor of 6 improvement [37]. A proton beam line for the TATTOOS radioisotope target station was designed with BDSIM, with results demonstrating that a high-power beam split by a unique beam splitter is safe to operate without significant losses [38]. BDSIM was used to demonstrate a proposed momentum cooling technique by using a wedge in the energy selection system that reduced the momentum spread without introducing substantial beam losses [39]. It was shown that with a gantry design incorporating such a wedge would gain almost a factor of 100 in transmission.

LhARA, the Laser-hybrid Accelerator for Radiobiological Application is a proposed novel 2-stage accelerator for radiobiology research in the UK [40]. BDSIM has been instrumental to the LhARA design process, evaluating it's performance in in start-to-end tracking studies of its Stage 1 beam line, the Stage 2 FFA injection and extraction lines, and LhARA's end station dose rate estimations [40,41]. Particle tracking through LhARA's novel gabor lens devices has also been demonstrated based on prototype experiments [42].

At the SC200 proton therapy facilty in Hefei, China, a proposed design for a novel intensity suppression scheme using two collimators was proposed and verified using BDSIM [43]. The study simulated proton transport in a start-to-end model including the gantry beamline and treatment nozzle. Collimation caused beam size changes, deliberately impacting subsequent optics and reducing beam intensity. In a separate performance study of a degrader design, BDSIM highlighted an improvement in transmission rates of between 36 and 70% due to a decreased beam emittance growth from the degrader [44].

NOVEL & OTHER ACCELERATORS

Other highlighted applications of BDSIM include the design and performance assessment of the AWAKE electron spectrometer [45], modelling of the magnetic lattice of the nuSTORM accelerator used in neutrino-nucleus scattering physics studies [46], and beam halo tracking, collimation, and loss modelling in MAGIX at MESA [47].

REFERENCES

[1] L. J. Nevay *et al.*, "BDSIM: An accelerator tracking code with particle-matter interactions", *Comput. Phys. Commun.*, vol. 252, p. 107200, 2020. `doi:10.1016/j.cpc.2020.107200`

[2] BDSIM website: `http://www.pp.rhul.ac.uk/bdsim`

[3] S. Agostinelli *et al.*, "Geant4 - A Simulation Toolkit", *Nucl. Instrum. Meth. A*, vol. 506, pp. 250-303, 2003.

[4] S. T. Boogert *et al.* "Beam delivery simulation (BDSIM): A Geant4 based toolkit for diagnostic and loss simulation", in *Proc. of IBIC'13*, Oxford, UK, 2013, pp. 799-802. `doi:10.18429/JACoW-IPAC2015-MOPJE078`

[5] W. Shields *et al*, "Progress & Developments of Beam Delivery Simulation (BDSIM)", presented at IPAC'24, Nashville, TN, USA, May 2024, paper WEPR69, this conference.

[6] V. Rizzoglio *et al.*, "On the accuracy of Monte Carlo based beam dynamics models for the degrader in proton therapy facilities", *Nucl. Instrum. Meth. A*, vol. 898, pp. 1-10, 2018. `doi:10.1016/j.nima.2018.04.057`

[7] B. Pilicer *et al.* "Study of Muon Backgrounds in the CLIC Beam Delivery System", in *Proc. of IPAC'15*, Richmond, VA, USA, pp 2075-2078. `doi:10.18429/JACoW-IPAC2015-TUPTY032`

[8] A. Aloev *et al.*, "CLIC Muon Sweeper Design", *arXiv:1603.00005v1*, Feb 2016.

[9] R. M. Bodenstein *et al.*, "Investigation of CLIC 380 GeV post-collision Line", in *Proc. IPAC'19*, Melbourne, Australia, pp 528-531. `doi:10.18429/JACoW-IPAC2019-MOPMP038`

[10] N. Fuster-Martínez *et al.*, "Beam halo collimation studies and measurements at the Accelerator Test Facility ATF2", *Nucl. Instrum. Meth. A*, vol. 917, pp. 31-42, 2019.

[11] L. Nevay *et al.*, "LHC collimation and energy deposition studies using beam delivery simulation (BDSIM)", in *Proc. IPAC'16*, Busan, Korea, pp 3101-3103. `doi:10.18429/JACoW-IPAC2016-WEPOY047`

[12] S. Walker *et al.*, "Precision modelling of energy deposition in the LHC using BDSIM", in *Proc. IPAC'19*, Melbourne, Australia, pp. 723-726. `doi:10.18429/JACoW-IPAC2019-MOPRB064`

[13] FASER Collaboration, "Technical Proposal FASERν", *arXiv:2001.03073v1*, Jan. 2020.

[14] A. Abramov *et al.*, "Development of collimation simulations for the FCC-ee", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1718–1721. `doi:10.18429/JACoW-IPAC2022-WEPOST016`

[15] A. Abramov *et al.*, “Studies of layout and cleaning performance for the FCC–ee collimation system”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 356–359. `doi:10.18429/JACoW-IPAC2023-MOPA128`

[16] A. Abramov *et al.*, “Collimation simulations for the FCC-ee”, *JINST*, vol. 19, p T02004, 2024.

[17] M. Boscolo *et al.*, “The status of the interaction region design and machine detector interface of the FCC-ee”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 256–259. `doi:10.18429/JACoW-IPAC2023-MOPA091`

[18] A. Abramov *et al.*, “Revised collimation configuration for the updated FCC-hh layout”, in *Proc. HB’23*, Geneva, Switzerland, Oct. 2023, pp. 495-498. `doi:10.18429/JACoW-HB2023-THBP18`

[19] Q. Xiu *et al.*, “Design of interaction region and MDI at CEPC”, in *Proc. eeFACT2016*, Daresbury, UK, 2016, pp. 53-56. `doi:10.18429/JACoW-eeFACT2016-TUT1AH2`

[20] W. Xu *et al.*, “Estimation of the radiation backgrounds in the CEPC vertex detector”, *Radiat. Detect. Technol. Methods.*, vol. 6, pp. 170–178, 2022.

[21] D. Babusci *et al.*, “$\gamma\gamma$-physics at KLOE/KLOE-2”, *Int. J. Mod. Phys. Conf. Ser.*, vol. 35, p. 1460395, 2014.

[22] F. Metzger *et al.*, “Kaon beam simulations employing conventional hadron beam concepts and the RF separation technique at the CERN M2”, *J. Phys.: Conf. Ser.*, vol. 2687, p. 052023, 2024. `doi:10.18429/JACoW-IPAC2023-TUPM070`

[23] G. L. D’Alessandro *et al.*, “Studies for the K12 high-intensity kaon beam at CERN”, in *Proc. IPAC2021*, Campinas, SP, Brazil, pp. 3049-3052. `doi:10.18429/JACoW-IPAC2021-WEPAB186`

[24] G. L. D’Alessandro *et al.*, “Implementation of CERN secondary beam lines T9 and T10 in BDSIM”, *J. Phys.: Conf. Ser.*, vol. 1350, p. 012095, 2019.

[25] W. Baldini *et al.*, “SHADOWS - Search for Hidden And Dark Objects With the SPS, Expression of Interest”, *arXiv.2110.08025*, Oct. 2021.

[26] F. Stummer *et al.*, “Conceptual design of the magnetised iron block system for the SHADOWS experiment”, *J. Phys.: Conf. Ser.*, vol. 2687, p. 022030, 2024.

[27] M. H. Tahar *et al.*, “Proton beamline Simulations for the high intensity muon beamline at PSI”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 2036–2039. `doi:10.18429/JACoW-IPAC2022-WEPOTK006`

[28] M. H. Tahar *et al.*, “Probing the losses for a high power beam”, *Nucl. Instrum. Meth. A*, vol. 1046, p. 167638, 2023.

[29] S. Liu *et al.*, “Study of possible beam losses after post-linac collimation at European XFEL”, in *Proc. IPAC’18*, Vancouver, BC, Canada, May 2018, pp. 4092-4095. `doi:10.18429/JACoW-IPAC2018-THPMF022`

[30] S. Liu *et al.*, “Undulator Radiation Dose Caused by Synchrotron Radiation at the European XFEL”, *J. Phys.: Conf. Ser.*, vol. 1350, p. 012037, 2019.

[31] A. Potter *et al.*, “Studies of particle losses from the beam in the EU-XFEL following scattering by a slotted foil”, in *Proc. IPAC2021*, Campinas, SP, Brazil, pp. 1681-1684. `doi:10.18429/JACoW-IPAC2021-TUPAB125`

[32] H. Ghasem *et al*, “Collimator study for the Diamond-II storage ring”, presented at IPAC’24, Nashville, TN, USA, May 2024, paper TUPG19, this conference.

[33] S. D. Walker, *et al.*, “pyg4ometry: A Python library for the creation of Monte Carlo radiation transport physical geometries”, *Com. Phys. Com.*, vol. 272, p. 108228, 2022.

[34] C. Hernalsteens *et al.*, “A novel approach to seamless simulations of compact hadron therapy systems for self- consistent evaluation of dosimetric and radiation protection quantities”, *Europhys. Lett.*, vol. 132, p. 50004, 2021. `doi:10.1209/0295-5075/132/50004`

[35] E. Ramoisiaux *et al.*, “Self-consistent numerical evaluation of concrete shielding activation for proton therapy systems”, *Eur. Phys. J. Plus*, vol. 137, p. 889, 2022. `doi:10.1140/epjp/s13360-022-02960-9`

[36] E. Gnacadja *et al.*, “Optimization of proton therapy eye-treatment systems toward improved clinical performances”, *Phys. Rev. Research*, vol. 4, p. 013114, 2022. `doi:10.1103/PhysRevResearch.4.013114`

[37] V. Maradia *et al.*, “A new emittance selection system to maximize beam transmission for low-energy beams in cyclotron-based proton therapy facilities with gantry”, *Med Phys.*, vol. 48, pp. 7613–7622, 2021. `doi:10.1002/mp.15278`

[38] M. Hartmann *et al.*, “Design of the 590 MeV proton beamline for the proposed TATTOOS isotope production target at PSI”, *J. Phys.: Conf. Ser.*, vol. 2420, p. 012105, 2023. `doi:10.1088/1742-6596/2420/1/012105`

[39] V. Maradia *et al.*, “Demonstration of momentum cooling to enhance the potential of cancer treatment with proton therapy”, *Nat. Phys.*, vol. 19, pp. 1437–1444, Jul. 2023. `doi:10.1038/s41567-023-02115-2`

[40] G. Aymar *et al.*, “LhARA: The Laser-hybrid Accelerator for Radiobiological Applications”, *Front. Phys.*, vol. 8, 2020. `doi:10.3389/fphy.2020.567738`

[41] W. Shields *et al*, “The Laser-hybrid Accelerator for Radiobiological Applications (LhARA): An Update Towards the Conceptual Design”, presented at IPAC’24, Nashville, Tennessee, USA, May 2024, paper THPR54, this conference.

[42] T. Nonnenmacher *et al*, “Anomalous Beam Transport through Gabor (Plasma) Lens Prototype”, *Appl. Sci.*, vol. 11, p. 4357, 2021. `doi:10.3390/app11104357`

[43] Man-Fen Han *et al*, “Study of intensity suppression in a gantry beamline for SC200 proton therapy system”, *J. Nucl. Sci. Technol.*, vol. 56, no. 12, 2019. `doi:10.1080/00223131.2019.1641445`

[44] Man-Fen Han *et al*, “Investigation of combined degrader for proton facility based on BDSIM/FLUKA Monte Carlo methods”, *Nucl. Sci. Tech.*, vol. 29, p. 134, 2018. `doi:10.1007/s41365-022-01002-4`

[45] L. Deacon *et al*, “A spectrometer for proton driven plasma accelerated electrons at AWAKE - recent developments”, in *Proc. IPAC’16*, Busan, Korea, May 2016, pp. 2605-2608. `doi:10.18429/JACoW-IPAC2016-WEPMY024`

[46] L. Alvarez Ruso *et al*, “Neutrinos from Stored Muons (nuSTORM)”, *arXiv*, 2022.

[47] B. Ledroit and K. Aulenbacher, “Collimation of target induced halo following MAGIX at MESA”, 2019 *J. Phys.: Conf. Ser.*, vol. 1350, p. 012138. `doi:10.1088/1742-6596/1350/1/012138`