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EMPOWERING A BROAD AND DIVERSE COMMUNITY IN BEAM DYNAMICS SIMULATIONS WITH XSUITE

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Abstract

Xsuite is a Python toolkit for modelling and simulation of particle accelerators, which has been developed at CERN together with collaborators from other institutes over the past four years. The code has reached a mature development stage and has become the workhorse for several studies and applications, allowing the gradual replacement of legacy tools like Sixtrack, COMBI, PyHEADTAIL. This contribution provides an overview of the code capabilities and illustrates examples in different areas of accelerator science, including low-energy hadron rings for medical applications, high-intensity hadron accelerators, high-energy hadron and lepton colliders.

INTRODUCTION

CERN has been the birthplace of many accelerator physics software tools that have become standard in the community, such as MAD-X [1], Sixtrack [2], Sixtracklib [3], COMBI [4], and PyHEADTAIL [5]. These tools represent years of effort and expertise in their respective domains. However, as increasingly complex studies are needed, the limitations of these legacy tools have also become apparent. Adding new features, for example to allow accurate modelling of lepton accelerators, has proved challenging. Interfacing between these tools to perform simulations including different effects has been difficult, as these codes were often been built independently, and were not designed with extensibility in mind—this often implies using ad-hoc scripts and text files to pass information between the tools. Furthermore, increasingly, hardware acceleration of beam dynamics studies using Graphical Processing Units (GPUs) has been of interest, with many simulations being well suited for it. However, the legacy tools do not provide this option, and retrofitting it would be cumbersome, if not impossible.

In response to these issues, the Xsuite [6] project was started in 2021, with aim of creating a Python-based toolkit, where collective effects and GPU acceleration are supported out of the box. Since then, a large array of functionalities has been included in Xsuite, such as optics design and matching, lattice design, collimation and particle-matter interaction, and various collective effects such as impedances, beam-beam effects, space charge, intra-beam scattering, and electron cloud. Thanks to Xsuite, studies can leverage the state-of-the-art scientific computing and data visualisation tools available in the Python ecosystem. Xsuite provides the functionality of the many previous tools within its packages, enabling a seamless integration of different physical phenomena in a single simulation: e.g., in Fig. 1 we show an integrated visualisation of the beam within the aperture

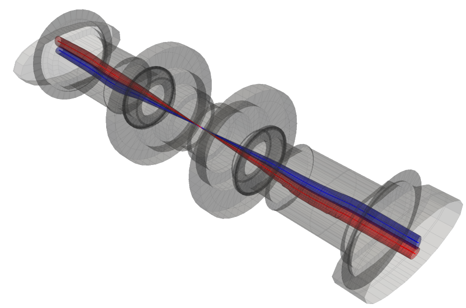

Figure 1: A visualisation of the beam envelopes and the apertures at the LHC IP1 (the Atlas Experiment) created with of Xsuite.

model of the LHC obtained using Xsuite. Built-in support for GPU acceleration, as well as multithreaded tracking, allows for a considerable speed-up in most simulations. By design, Xsuite can be extended by the user; notably, extensions that leverage GPU acceleration can be achieved with relative ease.

XSUITE DESIGN, EVOLUTION AND COMMUNITY

Xsuite is structured as a suite of Python packages, each focusing on distinct functionality [7].

- **Xtrack** is the main engine of Xsuite, where thin and thick tracking maps are implemented, together with lattice modelling capabilities, and optics calculation and matching tools.
- **Xpart** is used to generate different kinds of particle distributions matched to the beamline optics.
- **Xfields** provides support for collective effects: beam-beam, space charge, electron cloud.
- **Xwakes** provides support for calculation of wakefields and impedances, and for beam dynamics simulations including these effects.
- **Xcoll** simulates particle-matter interactions in collimators and other beam-intercepting devices [8].
- **Xdeps** provides support for deferred expressions, flexible multi-objective optimizers for matching, and a tabular data explorer [9].
- **Xobjects** provides a vendor-agnostic way to write multithreaded and GPU-accelerated code [9].

The Xsuite approach uses an orthogonal architecture to split the software into independent modules, enhancing scalability, easing feature development, and lowering the learning curve for users and developers—in fact, it often empowers users to actively contribute as developers. Adopting agile principles, Xsuite emphasizes user feedback, continuous testing, and a rapid release cycle, with updates multiple times per month to meet the evolving needs of the community.

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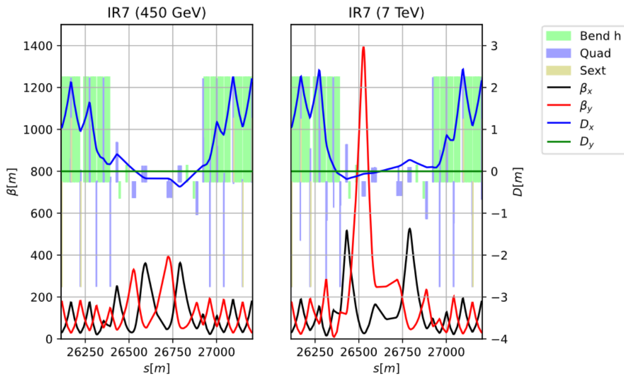

Figure 2: Optics in the betatron collimation insertion at different stages of the tested cycle.

The adoption of Xsuite has exceeded expectations, with over 30 contributors and more than 130 active users worldwide to date. Its versatility has led it to be applied in a wide array of accelerator facilities, spanning CERN, Fermilab, BNL, GSI, KEK/J-PARC, medical facilities and studies (HIT, MedAustron, NIMMS), as well as light sources. The software has been mentioned about 200 times in the IPAC24 proceedings, and used in tutorials at accelerator schools such as the Joint Universities Accelerator School (JUAS), the US Particle Accelerator School (USPAS), and CERN Accelerator Schools (CAS).

EXAMPLE APPLICATIONS

Due to its ease of use and open nature, Xsuite has enabled a number of diverse applications. In the present article we showcase some of them; others can be found in past contributions [6, 10] or in other articles of these proceedings, e.g. [11–14].

HL-LHC Cycle Design and Tests

Xsuite has been adopted as a go-to tool for offline studies of many beam dynamics phenomena at CERN. However, its potential to be employed to generate configurations for accelerator operation is increasingly of interest, in order to replace MAD-X as a standard tool for lattice modelling, survey, optics calculations, knob generation, etc.

To this end, in 2024 Xsuite was for the first time used to develop a full machine cycle to test optics solutions (visualised in Fig. 2) and corrections strategies in view of the HL-LHC upgrade, which was successfully tested at the LHC during Machine Development sessions [15]. The development of this cycle required optics matching, the design of the squeeze functions to smoothly change the optics during acceleration and at top energy, the generation of knobs for controlling crossing angle and separation bumps at the collision points and of knobs for the correction, tunes, chromaticity, and coupling throughout the cycle. A link with the LHC Control Software Architecture (LSA, [16]) system was also developed.

This, in conjunction with other experiences of Xsuite being used in the control room for machine development

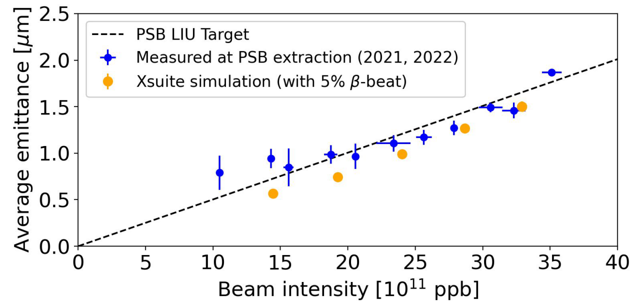

Figure 3: Comparison of PSB beam brightness between Xsuite simulation and measurement. Courtesy of T. Prebibaj.

studies [17], shows the potential of using it in the accelerator-operation context. While relying on a modern and supported tool has clear advantages, there are also less tangible ones: e.g. the opportunities it could create for synergy and overlap between the teams that design future accelerators and those that operate the current ones.

Simulation of Multi-Turn Injection to CERN PSB

The Proton Synchrotron Booster (PSB), first synchrotron of the LHC injector chain, receives hydrogen ions (H^-) from the upstream Linac4. These ions undergo multi-turn charge-exchange injection, during which their electrons are stripped, leaving only protons. The protons are then accelerated to 2 GeV before being transferred either to the ISOLDE facility or to the CERN Proton Synchrotron (PS).

A wide range of beam dynamics effects in the PSB have been modelled with Xsuite and included in tracking simulations used to characterize and optimize the machine's beam performance [18]. Figure 3 presents the beam brightness of LHC-type beams in the PSB, comparing measurements from 2021 and 2022 with Xsuite simulations. These simulations involved tracking realistic 6D particle distributions and combined several important beam dynamic effects: multi-turn injection, scattering at the injection foil, edge focusing and eddy currents in the pulsed injection chicane magnets, double-harmonic RF capture and acceleration, dynamic beta-beating and correction, and space charge effects (modelled with a self-consistent 2.5D Particle-in-Cell algorithm).

Multi-Species Tracking for Medical Applications

The simultaneous use of mixed helium and carbon ion beams in particle therapy presents a unique opportunity to combine precise tumour irradiation with carbon ions and real-time range verification using helium ions. This approach leverages the distinct properties of the two species—helium ions' extended range compared to carbon ions at the same energy per nucleon—and their nearly identical charge-to-mass ratios (q/m), which allow them to be accelerated together in the same ring. This capability enhances treatment precision while minimizing additional radiation exposure to healthy tissues. Implementing this dual-species strategy requires meticulous synchronization during beam generation, acceleration, and extraction, making advanced simulation tools essential for feasibility studies and optimization.

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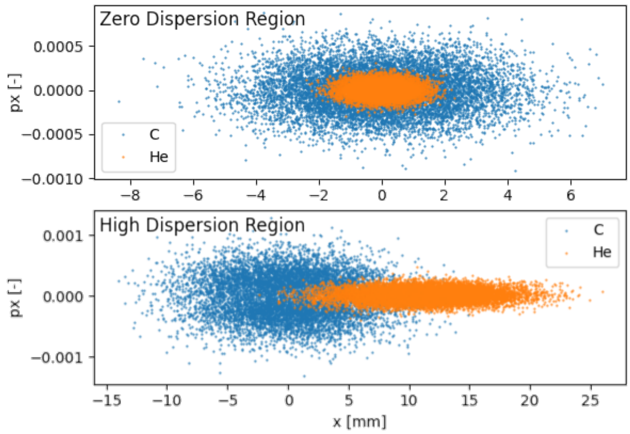

Figure 4: Demonstration of the phase space of the mixed $^4He^{2+}$ and $^{12}C^{6+}$ beam accelerated to 400 MeV/u in regions of different dispersion in the generic PIMMS lattice. Courtesy of M. Kausel.

Renner *et al.* [19] and Kausel *et al.* [20] employed Xsuite to analyse the feasibility of this scheme with $^4He^{2+}$ and $^{12}C^{6+}$ ions in a PIMMS-like synchrotron at MedAustron. This was possible as Xsuite allows 6D tracking of ions with a q/m varied across the beam. In the former [19], a slow extraction scheme was studied, where Xsuite's 6D tracking capabilities facilitated the modelling of third-order resonant extraction processes, allowing optimizing the parameters to achieve a consistent fluence ratio of ion species. In the latter study [20], Xsuite supported the feasibility evaluation of a double multi-turn injection scheme for mixed beam generation: this method involves sequentially injecting helium and carbon ions into a synchrotron. Xsuite simulations highlighted the challenges posed by differences in injection energy and phase-space distributions. An example of the phase space of such a mixed beam is visualised in Fig. 4.

Experimental Region Modelling in Lepton Colliders

Potential future collider projects are currently being considered at CERN, often using studies conducted with Xsuite. One such project is the next-generation lepton machine, FCC-ee, which shares synergies with the current state-of-the art lepton collider SuperKEKB in Tsukuba, Japan—especially when it comes to their experimental regions, due to their nano beam schemes, and high crossing angles.

The modelling of the SuperKEKB experimental solenoid was accomplished using Xsuite [21], which demonstrated the challenges in adapting complex lattice structures for comprehensive simulation, and the result is visualised in Fig. 5. SuperKEKB's interaction region (IR) includes a shared solenoids affecting both the Low Energy Ring (LER) and High Energy Ring (HER), which partially overlaps with the final-focus quadrupole and other magnetic elements, requiring precise modelling of its magnetic field and beam dynamics. Originally designed in the SAD (Strategic Accelerator Design [22]) framework, the lattice was converted to Xsuite using the custom SAD2XS tool, which preserved key features like solenoid slicing and coupling representations.

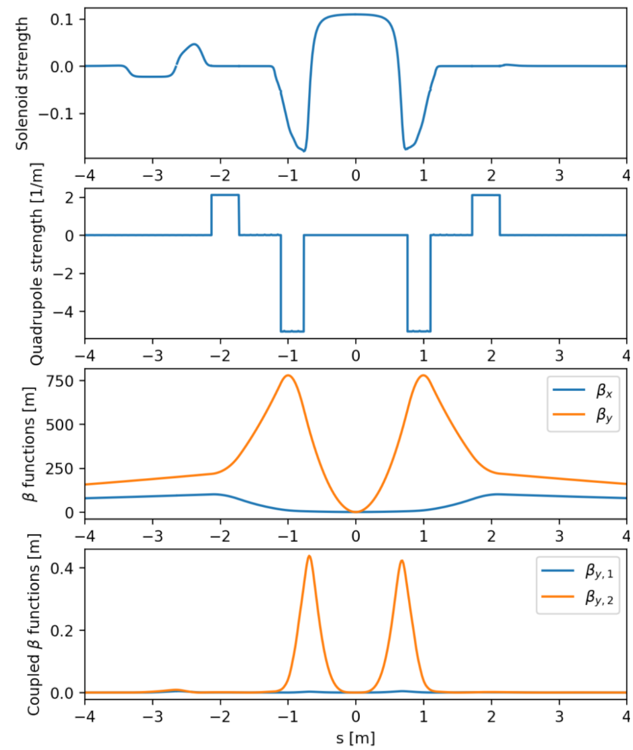

Figure 5: Optics functions and magnet strengths at the IP within the BELLE-II solenoid of SuperKEKB. Courtesy of J. Salvesen.

The solenoid's magnetic field geometry was divided into multiple slices, each with reference frame transformations to account for relative alignments between the solenoid and the magnets. Derived from BELLE-II field maps, these adjustments ensured realistic simulations of the solenoid's impact, obtaining accurate effects on key quantities like orbit, beta functions and linear coupling terms. Xsuite's flexibility allowed iterative optics matching and troubleshooting, easily addressing residual coupling and alignment differences between SAD and Xsuite models, coming from different models of the magnetic elements used in two code. The tool also handled effects like synchrotron radiation, enabling accurate modelling of beam dynamics, dynamic aperture, equilibrium emittances, momentum acceptance, collimation. Further studies involving beam-beam and wakefields are already planned.

CONCLUSIONS

Xsuite has been developed as a modern, Python-based toolkit designed to enable ambitious accelerator physics studies. Its modular architecture, built-in GPU acceleration, and a vibrant community have enabled it to be used for a wide range of applications, from medical accelerators to complex beam dynamics studies for future colliders, and even in operational contexts. The ongoing development of collective effect models, driven by the requirements of cutting-edge projects, further exemplify the role that such a versatile tool can have in the accelerator physics community.

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