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ADVANCEMENTS AND APPLICATIONS OF COOLING SIMULATION TOOLS: A FOCUS ON Xsuite

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Abstract

This paper presents recent advancements in cooling simulation tools in Xsuite, which is a new particle accelerator simulation code developed at CERN. An electron cooling module, based on the Parkhomchuk model, has been implemented and benchmarked against Betacool using parameters of the LEIR e-cooler at CERN. Additionally, a laser cooling module has been implemented, capable of simulating various laser pulse types, including Fourier-limited and continuous wave lasers. This module is applied to the Super Proton Synchrotron (SPS) with the aim of simulating the Gamma Factory proof-of-principle experiment (PoP) at CERN. First results are presented.

INTRODUCTION

The goal of this paper is to present the electron cooling and the laser cooling module of Xsuite and their respective advantages compared to other tracking codes. Xsuite is a collection of Python packages for multi-particle simulations for particle accelerators. It has been under development at CERN since 2021 and it has the capability to run on both CPUs and GPUs [1]. As for electron cooling, two currently available codes that also incorporate the Parkhomchuk model of electron cooling [2, 3] are Betacool [4, 5] and JSPEC (JLab Simulation Package for Electron Cooling) [6, 7]. The main advantage that Xsuite provides over Betacool is that it is under active development, whereas Betacool is no longer active. In comparison to JSPEC, Xsuite offers GPU capability and offers a wide variety of features beyond electron cooling, including synchrotron radiation, beam-beam effects, electron cloud, etc.

As for laser cooling, the Xsuite module is the first publicly available code that simulates laser cooling in particle accelerators with a great level of detail. While Betacool does offer laser cooling capabilities, it does not have an elaborate excitation scheme like Xsuite. The main goal of the new Xsuite module is to provide tools for simulating the beam cooling in the Gamma Factory [8–12], which is part of the Physics Beyond Colliders (PBC) study at CERN that aims to generate intense beams of scattered photons. Before the implementation of the Gamma Factory in the Large Hadron Collider (LHC), a proof-of-principle (PoP) experiment is intended to be carried out in the Super Proton Synchrotron (SPS). The laser cooling module of Xsuite will be a key tool in simulating these two cases.

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ELECTRON COOLING

This work is an expansion of the electron cooling simulation tools developed by N. Biancacci and A. Latina, which were initially used for simulating the impact of IBS on low-intensity cooled beams in LEIR [13, 14]. The electron cooling module of Xsuite has been benchmarked with BETACOOL for the CERN accelerator LEIR (Low Energy Ion Ring) [15]. The benchmark compares the implementation of the Parkhomchuk model in both codes. The first part of the benchmark is done by comparing the time evolution of the emittance. The second part compares the cooling force as a function of the velocity difference between the circulating beam particles and the electrons. The electron cooler parameters are displayed in Table 1. The blue curve in Fig. 1, labeled as SC=0, represents the emittance comparison for a lead coasting beam in LEIR at 18 GeV/c. Here, SC=0 indicates that the space charge effect of the electron beam is inactive. The cooling force comparison is displayed in Fig. 2. The benchmark shows that Xsuite and Betacool produce compatible results for the time evolution of the emittance as well as for the cooling force as a function of the velocity difference. Additionally, the same benchmark was successfully performed for coasting beams in ELENA at 35 MeV/c [16], utilizing the electron cooler parameters provided in [17, 18]. Lastly, the module proved valuable in clarifying the magnetic field straightness requirements for the new AD electron cooler [19].

Table 1: LEIR Electron Cooling Simulation Parameters [20]

Parameter	Value
Electron beam radius	25 mm
Cooler length	3 m
Magnetic field strength	0.07 T
Transverse temperature	10 meV
Longitudinal temperature	1 meV
Current	0.6 A
β_x / β_y in the cooler	5/5 m

Initially, the benchmark between Xsuite and Betacool failed when the electron beam space charge was included. The Xsuite module incorporates two components of the electron beam space charge. Firstly, it incorporates an energy

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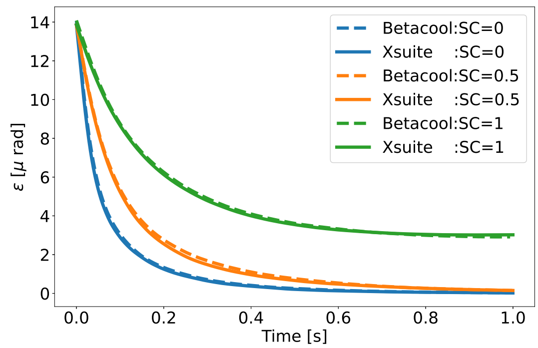

Figure 1: Comparison of cooling performance between the Parkhomchuk model in Xsuite and Betacool in LEIR at 18 GeV/c. The graph shows the time evolution of the transverse horizontal emittance. The value of SC indicates the magnitude of the space charge effects of the electron beam, where 0 indicates no space charge effects and 1 indicates the theoretical space charge of the electron beam, with no neutralisation from rest gas ions or similar.

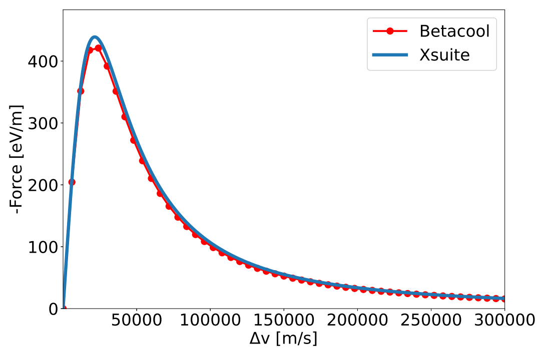

Figure 2: Comparison of longitudinal cooling force between the Parkhomchuk model in Xsuite and Betacool for a lead beam in LEIR at 18 GeV/c. The dependence of the longitudinal component of the cooling force on the relative velocity difference is displayed.

offset based on the location of the electron along the electron beam radius, assuming a uniform electron distribution with hard edges. Secondly, a collective rotation of the electron beam is implemented. Both these aspects of the electron beam space charge are described in [21]. The discrepancy between the two codes was eventually resolved by rectifying two minor bugs in the Betacool code and by disabling an undocumented and unclear effect that is implemented in Betacool only. After implementing these three changes, the cooling rates with space charge effects are in agreement, as can be seen in Fig. 1. The undocumented effect implemented in Betacool acts on the local electron temperature due to the electron beam rotation, but no reference for this effect was found. This remains to be investigated.

LASER COOLING

In addition to the electron cooler, a laser cooling module is also being developed in Xsuite. Laser cooling is a well-established technique for cooling atoms in traps, and it is recently also being explored experimentally in synchrotrons [22, 23]. First, lasers excite atoms, causing them to emit photons in a random direction, which on average reduces momentum in the direction of the incoming laser pulse. To narrow the momentum spread, laser cooling leverages on the narrow bandwidth of lasers and the large Doppler shift of the laser frequency when colliding head-on with charged atoms circulating in the storage ring. By carefully adjusting the laser frequency, it is possible to selectively interact with high-energy particles only, while leaving low-energy particles unaffected.

The laser cooling module is currently capable of using two different types of laser pulses: a Fourier-limited pulse and a continuous wave laser. Here, the focus will be on the continuous wave laser. The laser cooling process consists of two parts: excitation and spontaneous emission. The model that is being used for the excitation will be discussed first and then the model of spontaneous emission.

Excitation

The governing equations for this scenario are the optical Bloch equations with damping, which are described in [24, 25]. The excitation probability can be obtained by finding the steady-state solution of the population of the excited state. A graphical representation of this solution is shown in Fig. 3, which depends on three parameters:

1. Γ is the decay rate of the excited state.
2. $\Delta = \omega_l - \omega_0$ is the detuning, which is the difference between the frequency of the laser light and the frequency corresponding to the transition to the excitation state.
3. Ω_R is the Rabi frequency, which quantifies the laser-ion coupling strength.

Each particle in the beam will correspond to a different position in the excitation map, based on its parameters. In particular, the detuning is different for each particle because all the ions have different energies and momenta, which means that they experience a different laser frequency due to a different Doppler shift. The laser cooling module of Xsuite computes Ω_R, Γ, and Δ for every particle crossing the laser cooler element and employs the excitation map shown in Fig. 3 to assign it an excitation probability.

Spontaneous Emission

The current model for spontaneous emission remains consistent across various laser pulse types. Firstly, when an ion becomes excited, it loses energy because of the quasi head-on collision with the photon. Secondly, the ion will emit a photon in a random direction, which causes it to gain or lose energy based on the outcome of the random event. Lastly, a Lorentz transformation is applied to transform from the co-moving frame of the ion to the lab frame. The whole emission process is assumed to be instantaneous, which is a valid approximation, for example, for the ions considered in the Gamma Factory proof of principle experiment: Li-like $^{208}_{82}\mathrm{Pb}^{79+}$, with an excited-state lifetime of 76.6 ps [26],

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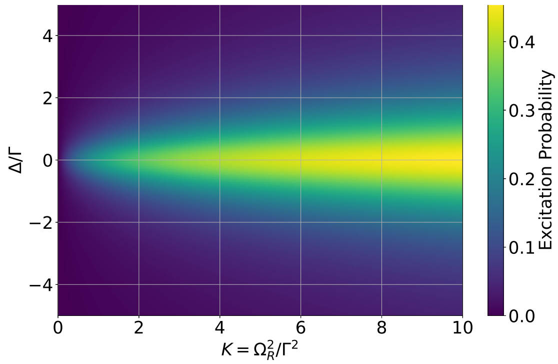

Figure 3: Steady-state solution for excited state population vs. detuning-to-decay rate ratio (vertical axis) and saturation parameter $K = \Omega_R^2/\Gamma^2$ (horizontal axis). Color indicates the ratio of the number of excited ions to the total number of ions.

which is much shorter than the SPS revolution period, which is 23 µs [27].

Laser Cooling Results

Preliminary simulations have already been performed by A. Petrenko for the Gamma Factory proof-of-principle experiment in the SPS [28, 29]. The difference between his simulations and the ones in this paper is the type of laser that is used. The simulations in this paper make use of a CW-laser, whereas the previous results were performed with a Fourier-limited pulse. Aside from that, the same simulation parameters were used, which are provided in Table 2. The current simulation utilized coasting beams and did not account for heating effects like Intra-beam scattering (IBS) and beam space charge. The primary focus of the analysis was the time evolution of the number of excited particles, as depicted in Fig. 4. This plot also illustrates the evolution of the RMS momentum spread. It is noteworthy that both the number of excited particles and the RMS momentum spread decrease together. Indeed, the simulation parameters were tuned such that only particles with a large $\Delta p/p$ experience momentum reduction through interaction with the laser cooler. As the high-momentum particles have their momentum reduced, the excitation process diminishes, ultimately halting the cooling process, as no ions with a matching momentum are left in the beam. This is confirmed by looking at the momentum distribution at the start and end of the simulation, which is shown in Fig. 5. Particles with large $\Delta p/p$ have indeed experienced momentum reduction, and there is an accumulation of particles with a momentum offset of $\Delta p/p = 3 \times 10^{-4}$. The absence of heating effects in the simulation exacerbates this accumulation.

CONCLUSIONS

An electron cooling module based on the Parkhomchuk model was developed in Xsuite and successfully benchmarked against Betacool. During the benchmarking process, two minor bugs were found in the electron beam space charge

Table 2: Gamma Factory PoP Simulation Parameters

Ion excited freq. ω_0	3.5×10^{17}	s^{-1}
Excited time τ [26]	76.6×10^{-12}	s
Fractional $\Delta p/p$	3.0×10^{-4}	
Relativistic γ	96.3	
Excited decay Γ	1.31×10^{10}	s^{-1}
$K = \Omega_R^2/\Gamma^2$	7.17 ± 0.01	

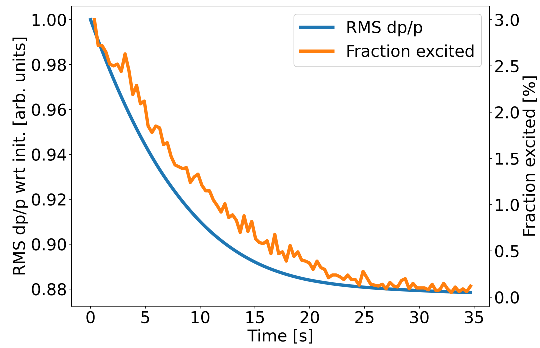

Figure 4: Time evolution of RMS $\Delta p/p$ and the fraction of excited particles in the accelerator. Left vertical axis: RMS $\Delta p/p$ relative to the initial value ($\Delta p/p = 3 \times 10^{-4}$). Right vertical axis: Fraction of excited particles. Horizontal axis: Elapsed time.

module of Betacool and these have been fixed. An undocumented effect of the electron beam space charge rotation of the transverse temperature of the electrons was found in the Betacool implementation, which still needs to be understood. The version of Betacool with these changes can be found in [30]. The electron cooling module of Xsuite will form a powerful tool with the possibility to include effects such as IBS and space charge, and thus will be a comprehensive tool for simulating all machines with electron coolers at CERN. A laser cooling module was also developed in Xsuite, which has the capability of using different laser pulses, including

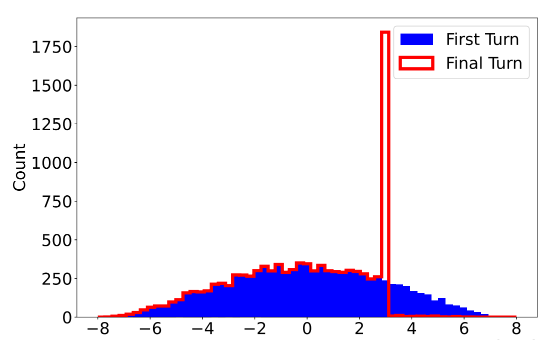

Figure 5: Comparison of histograms for $\Delta p/p$ at the first and final turn of the beam in the simulation. The blue histogram represents the first turn, while the red histogram represents the distribution of $\Delta p/p$ at the end of the simulation.

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Fourier-limited and continuous wave lasers. The module is still under testing. First results show that the physics of the process is captured by the implementation. The next aim is the simulation of the SPS PoP experiment.

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