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SIMULATION STUDIES OF LASER COOLING FOR THE GAMMA FACTORY PROOF-OF-PRINCIPLE EXPERIMENT AT THE CERN SPS

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Abstract

The Gamma Factory proof-of-principle (GF PoP) experiment at the Super Proton Synchrotron (SPS) at CERN aims at demonstrating laser cooling of high energy Li-like Pb^{79+} in a synchrotron. First, we present laser cooling simulations with realistic laser and beam parameters of the GF PoP experiment at the SPS. Furthermore, we investigate the expected cooling performance for a Fourier-limited laser pulse and compute the performance metrics, such as emittance reduction. These metrics are then compared to intra-beam scattering (IBS) growth rates to determine the cooling feasibility. Lastly, the angular spread of the outgoing gamma rays is investigated.

INTRODUCTION

The GF PoP experiment at the SPS intends to demonstrate the ability to control the excitation of partially stripped ions in a high-energy synchrotron through head-on interaction with a laser beam. The GF PoP experiment might open the door for possible implementation into a machine like the LHC to produce high energy photons [1, 2]. Atomic physics studies that can be made possible by using these high-energy photon beams can be found in Ref. [3, 4]. Additionally, this technique reduces the beam emittances and, therefore, increases a collider's luminosity. More detailed information about laser cooling can be found in Ref. [5].

The GF PoP experiment will use the $2s \rightarrow 2p_{1/2}$ transition of Li-like Pb ions. There have already been simulation studies on the feasibility of the GF PoP experiment, most of which were performed by A. Petrenko, e.g. see Ref. [6]. The simulations in this paper build on the previous work using a new implementation in the Xsuite framework [7]. This beam-tracking code is being actively developed at CERN with multi-purpose accelerator physics in mind. This enables the study of cooling along with heating effects such as Intra-Beam Scattering (IBS) and Space Charge effects (SC).

METHOD AND PARAMETERS

The GF PoP experiment was simulated in Xsuite assuming a linearized representation for the SPS optics [8], i.e., only defined by a one-turn transport matrix that embeds the transverse and longitudinal tunes and a newly implemented laser cooling element [9] which models the turn-by-turn interaction of the ion beam with a pulsed laser. The excitation probability for laser cooling with a Fourier-limited pulsed laser in Xsuite is calculated using the optical Bloch equations with damping, which provide the steady-state solution for the population of the excited state as detailed in [10, 11]. This approach does not consider any polarization of the laser light. In the case of a successful excitation, the ion energy is reduced due to the spontaneous emission of a photon. The amount of energy reduction is determined by the Doppler-boosted excitation energy of the ion and the random emission angle. Any transverse heating due to emission in the horizontal or vertical direction was not considered because the transverse kicks are small ($\approx$ 12 prad). Cooling rates were assessed by monitoring the emittance and energy spread while tracking. This tracking did not involve heating effects like SC or IBS, which will be discussed separately. Table 1 summarizes the laser parameters necessary for simulations and the beam and Twiss parameters at the interaction point [6]. These parameters establish the experimental setup and conditions for the GF PoP experiment at the SPS, serving as the basis for subsequent simulations of the laser cooling performance. Further details regarding the optical system can be found in Ref. [12].

COOLING RATES

The cooling rate is found in tracking simulations by fitting the first 50 ms of the emittance (or relative momentum spread) time evolution to an exponential function $\epsilon(t) = \epsilon_0 \exp(-c_r t)$, where $\epsilon(t)$ is the emittance at time t, ϵ_0 is the initial emittance, and c_r represents the cooling rate. Laser cooling acts primarily in the longitudinal plane by reducing the energy spread of the beam. However, if there is dispersion at the interaction point, the cooling can also be coupled to the transverse plane by dispersive cooling [13]. Reducing the momentum of a particle in a dispersive region will shift its orbit, which affects its betatron amplitude. To reduce the betatron amplitude in a region with positive dispersion, the momentum must be reduced at a horizontal position $x < 0$. For laser cooling, this can be done by displacing the beam relative to the center of the laser beam. A parametric sweep was performed in the simulation to determine the optimal displacement of the ion beam relative to the laser beam to cool horizontally. The results are shown in Fig. 1, which shows that laser cooling is a versatile tool that provides the flexibility to select the amount of longitudinal and horizontal cooling by adjusting the horizontal orbit of the beam relative to the laser beam. The SPS's optimal horizontal displacement for horizontal cooling is −1.24 mm. Therefore, this value was chosen in the simulations of the horizontal cooling

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Table 1: Parameters of the GF PoP Experiment

Parameter	**Value**
Laser Parameters	
Wavelength (λ)	1031 nm (1.2 eV)
RMS relative band spread (σ_λ/λ)	2×10^{-4}
Single pulse energy at IP (E)	5 mJ
Laser waist radius at IP	1.3 mm
Collision angle (θ_L)	2.6 degrees
Fourier-limited pulse width (σ_t)	2.74 ps
Twiss Parameters at the Interaction Point	
β_x, β_y	54.47 m, 44.40 m
α_x, α_y	-1.55, 1.32
D_x	2.4 m
D_{p_x}	0.09
Machine Parameters	
Transverse tunes (Q_x, Q_y)	26.299, 26.249
Synchrotron tune (Q_s)	0.00628
Ion Beam Parameters	
Ion species	$^{208}Pb^{79+}$
Ion mass (m)	193.687 GeV/c^2
Mean energy (E)	18.652 TeV
Mean Lorentz factor (γ)	96.3
Number of ions per bunch (N)	0.9×10^8
RMS relative energy spread (σ_E/E)	2×10^{-4}
Normalized transverse emittances (ϵ_n)	1.5 mm mrad
RMS bunch length (σ_z)	6.3 cm
Excited state lifetime	76.6 ps
Ion excitation energy $\hbar\omega_0$ [14, 15]	231 eV

for the GF PoP experiment, shown in Fig. 2. Optimal longitudinal cooling isn't at zero offset due to dispersion. The laser is tuned to interact with high-energy particles, which are more prevalent for positive x due to the positive dispersion. Vertical cooling, which is not considered here, can be achieved by introducing coupling between horizontal and vertical planes. Additionally, by changing the beam's energy, the laser can cause longitudinal blow-up, which can mitigate IBS.

INTRA-BEAM SCATTERING

The IBS growth rates can be translated to an exponential increase of the emittance or root-mean-square dp/p [16, 17], which can be compared to the exponential decay due to cooling. The fact that for short time intervals, the emittance evolution due to IBS is described by an exponential allows for a direct comparison with the exponential reduction due to cooling, thus determining whether the beam is in a cooling-dominated or IBS-dominated regime. The IBS growth rates have been computed using the Bjorken-Mtingwa model [18] and the parameters from Table 1 using xibs [17], which is an IBS module within Xsuite [7]. The horizontal emittance

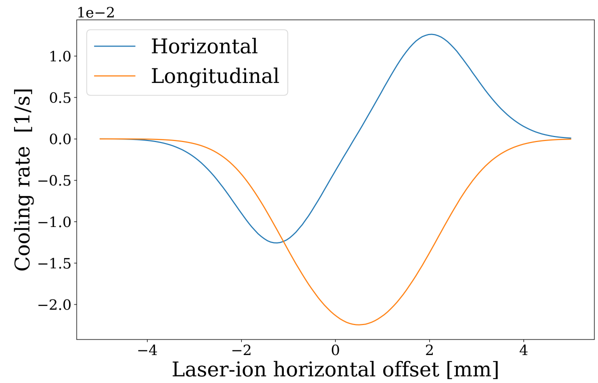

Figure 1: Cooling rate as a function of laser-ion horizontal offset for Pb^{79+} ions. The blue line represents the horizontal cooling rate, while the orange line indicates the longitudinal cooling rate.

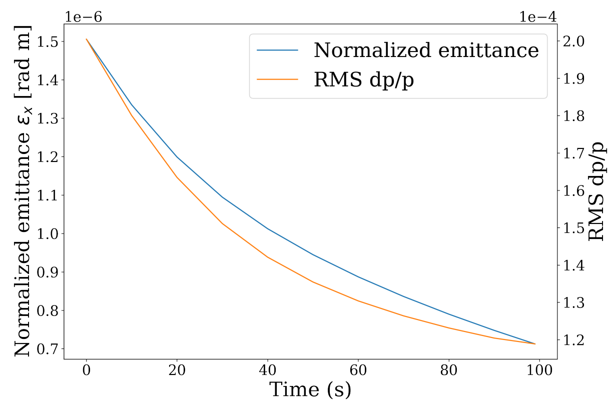

Figure 2: Time evolution of normalized horizontal emittance (blue line) and relative momentum spread dp/p (orange line) for optimized horizontal cooling in the SPS.

and longitudinal IBS growth rates have been computed for a range of normalized emittance and momentum spreads and then compared against the cooling rates, which are assumed to be constant. Figure 3 shows the points where the growth rates from IBS are equal to the cooling rates for horizontal emittance, solid blue line, or momentum spread, dashed blue. The plot also shows the time evolution of the laser cooling process with the red dot indicating the assumed initial beam parameters, and each black arrow indicates a time step of 10 s. Following the arrows, one can see the laser cooler can reduce the emittance and momentum spread by almost 50%. Initially, the cooling rate is large enough to overcome the IBS growth rates, and cooling is expected to stop when the beam reaches the cooling-IBS equilibrium after about 90 s.

PHOTON PRODUCTION

For maximum photon generation, the laser-ion offset was set to 0 according to Fig 1. The estimated number of photons produced from a Li-like Pb^{79+} beam using the laser from the GF PoP experiment is shown in Table 2, which shows that the laser can excite 14.1% of the ions. This corresponds

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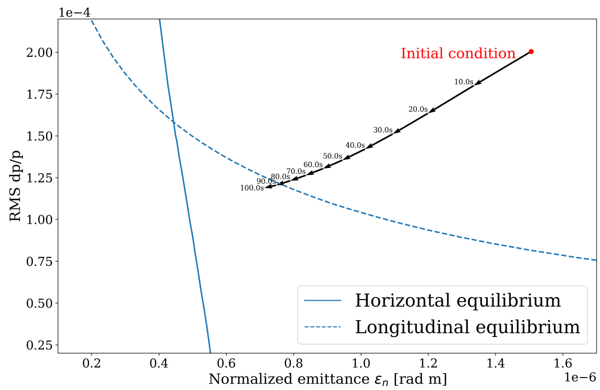

Figure 3: Time evolution of the root-mean-square momentum spread and normalized emittance for the optimized horizontal cooling in the GF PoP experiment. The red dot indicates the beam before cooling. Each arrow represents 10 seconds of cooling. The solid blue line indicates the equilibrium between horizontal cooling and IBS growth rates, and the dashed line for the longitudinal plane.

to a photon intensity of 1.27×10^7 photons per bunch for a single passing by the laser. The Doppler-shifted laser photon energy must match the ion's excitation energy. The Doppler frequency shift is computed using the Lorentz transformation between the two reference frames, according to

$$\omega' = (1 + \beta \cos\theta)\gamma_L \omega \approx 2\gamma_L \omega, \tag{1}$$

where ω' is the photon frequency in the ion-rest frame, θ is the photon-ion angle, γ_L the Lorentz factor, ω is the frequency in the lab frame, and the small angle approximation was used. The Eq. (1) shows that the photon frequency in the ion-rest frame ω' is $2\gamma_L$ times larger than the frequency ω in the lab frame. The Lorentz transformation also affects the angular spread of the photons that are emitted by the excited ions. In the comoving frame of the ion, the emission is equally probable in every direction. However, in the lab frame, the photons will be emitted with angular spread $\theta_e \sim 1/\gamma_L$, which means that the small angle approximation can also be applied to the Doppler frequency shift of the emitted photons. To determine the energy of the photons after spontaneous emission, the Doppler shift is applied to the excitation energy of the ion, which will give another factor of $2\gamma_L$. Consequently, the energy of the emitted photon is enhanced by a factor $4\gamma_L^2$ compared to the photons produced by the laser. For example, this factor would be $\approx 10^8$ for LHC beams [19].

The distribution of photons produced from the GF PoP experiment is shown in Fig. 4 for two cases: the case where the divergence of the ion beam is neglected, in orange, and the case that also considers the ion from which the photon was emitted and its traveling angle. As expected, taking this into account the total distribution of photon angles is wider. In the case of a cooled ion beam, the angular spread will be smaller, and the angular spread of the ions will contribute less to the angular spread of the outgoing photons.

Table 2: Photon Production Parameters

Parameter	**Value**
Number of ions per bunch [20]	0.90×10^8
Fraction of excited particles	14.1‰
Number of emitted photons per bunch	1.27×10^7
Laser wavelength	1.2 eV (1031 nm)
Ion excitation energy $h\omega_0$	231 eV
Maximum emitted photon energy	44 keV

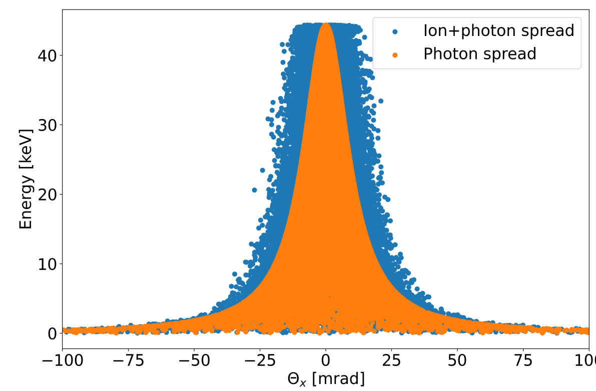

Figure 4: Energy distribution of photons produced by the GF as a function of scattering angle θ for Pb^{79+} ions.

CONCLUSION

The simulations in this study focus on the laser cooling of Li-like Pb^{79+} in the GF PoP experiment. In particular, horizontal cooling is maximized by finding the optimal laser-ion beam displacement to profit from the large horizontal dispersion at the interaction point. This optimal horizontal cooling setup is used for a long simulation of the laser cooling performance without any heating effects. The resulting cooling rate is compared against the computed IBS growth rates to determine the equilibrium between the laser cooling and the emittance blow-up from IBS. The results show that the GF PoP will be able to achieve an appreciable decrease in emittance before the cooling reaches an equilibrium with IBS. Lastly, simulations were performed to estimate the intensity of the produced photon beams and their energy distribution.

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REFERENCES

[1] M. W. Krasny, "Gamma Factory Proof-of-Principle Experiment LETTER OF INTENT Gamma Factory Study Group," CERN, Tech. Rep., 2019.

[2] M. W. Krasny, "Gamma Factory," in *The Future of the Large Hadron Collider: A Super-Accelerator with Multiple Possible Lives*, 2024, pp. 297–303.

[3] D. Budker *et al.*, "Atomic physics studies at the Gamma Factory at CERN," *Annalen der Physik*, vol. 532, no. 8, p. 2 000 204, 2020.

[4] D. Budker, M. Gorchtein, M. W. Krasny, A. Pálffy, and A. Surzhykov, "Physics Opportunities with the Gamma Factory," *Annalen Phys.*, vol. 534, no. 3, p. 2 200 004, 2022.

[5] L. Eidam, O. Boine-Frankenheim, and D. Winters, "Cooling rates and intensity limitations for laser-cooled ions at relativistic energies," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 887, pp. 102–113, 2018.

[6] M. W. Krasny, A. Petrenko, and W. Płaczek, "High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams," *Progress in Particle and Nuclear Physics*, vol. 114, p. 103 792, 2020. doi:10.1016/J.PPNP.2020.103792

[7] G. Iadarola, "Xsuite: a flexible python toolkit for beam dynamics," in *Presented at the 15th International Particle Accelerator Conf. (IPAC'24), Nashville, Tennessee, USA, May 2024, this conference.*, 2024.

[8] *CERN Accelerator Models*. https://acc-models.web.cern.ch/acc-models/

[9] P. Kruyt, D. Gamba, and G. Franchetti, "Advancements and Applications of Cooling Simulation Tools: A Focus on Xsuite," in *Proc. COOL'23*, 2023.

[10] M. Auzinsh, D. Budker, and S. Rochester, *Optically polarized atoms: understanding light-atom interactions*. Oxford University Press, 2010.

[11] H. J. Metcalf and P. der Straten, *Laser cooling and trapping*. Springer Science & Business Media, 1999.

[12] A. Martens *et al.*, "Design of the optical system for the gamma factory proof of principle experiment at the CERN Super Proton Synchrotron," *Physical Review Accelerators and Beams*, vol. 25, no. 10, p. 101 601, 2022.

[13] I. Lauer *et al.*, "Transverse laser cooling of a fast stored ion beam through dispersive coupling," *Physical review letters*, vol. 81, no. 10, p. 2052, 1998.

[14] V. A. Yerokhin and A. Surzhykov, "Energy levels of core-excited 1s2l2l states in lithium-like ions: Argon to uranium," *Journal of Physical and Chemical Reference Data*, vol. 47, no. 2, 2018.

[15] X. Zhang, N. Nakamura, C. Chen, M. Andersson, Y. Liu, and S. Ohtani, "Measurement of the QED energy shift in the 1 s 2 2 p 3/ 2–1 s 2 2 s 1/ 2 x-ray transition in Li-like Pb 79+ 208," *Physical Review A*, vol. 78, no. 3, p. 32 504, 2008.

[16] S. Nagaitsev, "Intrabeam scattering formulas for fast numerical evaluation," *Physical Review Special Topics - Accelerators and Beams*, vol. 8, no. 6, 2005. doi:10.1103/PhysRevSTAB.8.064403

[17] F. Soubelet, S. Kostoglou, and K. Paraschou, "Development of numerical tools for intra-beam scattering modelling," in *Presented at the 15th International Particle Accelerator Conf. (IPAC'24), Nashville, Tennessee, USA, May 2024, this conference.*, 2024.

[18] J. D. Bjorken and S. K. Mtingwa, "Intrabeam scattering," *Part. Accel.*, vol. 13, no. FERMILAB-PUB-82-47-THY, pp. 115–143, 1982.

[19] M. W. Krasny, "Gamma Factory," in *The Future of the Large Hadron Collider: A Super-Accelerator with Multiple Possible Lives*, 2024, pp. 297–303.

[20] Z. Citron *et al.*, "Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC Chapter coordinators: A. Andronic," Tech. Rep., 2019, pp. 90–53.