Title

Enhancing Laguerre-Gaussian Mode Laser Heater Performance: A Review and Analytical Exploration of Intrabeam Scattering

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Publication Date

2023

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I. Abstract

This is a review paper on the Laguerre-Gaussian Mode Laser Heater for Microbunching Instability Suppression in Free-Electron Lasers. The intent is to study the various collective effects that influence Microbunching instability (MBI) in free-electron lasers.

II. Introduction

Microbunching instabilities driven by collective effects in high-brightness electron beams can impair performance in accelerators and free-electron lasers (FELs) [1]. These instabilities arise from the self-interaction of the electron beam through mechanisms like longitudinal space charge forces or coherent synchrotron radiation [2]. They amplify existing density modulations in the beam, which continue to increase in amplitude downstream. A well-established method to suppress microbunching uses a laser heater to induce additional uncorrelated energy spread [3]. However, other collective effects may come into play and further impair these performances in FELs. This review studies those other collective effects that contribute to MBI, which is a considerable challenge in maintaining the quality of the electron beams. Understanding these collective effects to eliminate them would serve as a benefit to the overall purpose of FELs.

III. Methods

Microbunching instabilities (MBI) are the undesirable formation of groups/bunches of particles within the main beam. MBI in free-electron lasers can be influenced by various collective effects beyond the ones mentioned in the provided paper [5]. As referenced in [5], the longitudinal space charge is a significant contributor arising from the mutual repulsion of charged particles within the electron beam. Coherent synchrotron radiation, mentioned in [1–4], is another collective effect that can impact MBI. This phenomenon occurs when the radiation emitted by individual electrons in the beam interferes coherently, leading to additional longitudinal and transverse effects. [1] While covering this material, I was curious about the collective effects, other than the two mentioned, that contribute to the occurrence of MBIs.

A research study was done to find a theoretical formulation of MBI within IBS, using Vlasoc-Fokker-Planck's equation and information about the effects and interactions of Itrabeamscattering [6]. Intrabeam scattering (IBS) is when particles in a beam scatter off of each other due to their similar electromagnetic interactions. This process leads to differentiations of particles within the beams, which ultimately causes the formation of micro bunches. Models utilizing the Fokker-Planck equation are used by simulating the IBS process to predict its effects on beam distribution over time.

To quantitatively begin with, a time-independent probabilities function describing the momentum change of a test particle before and after a collision will derive the VFP equation.

The research is solely interested in the effect of MBI. Therefore, the VFP equation would be linearized, and the friction and diffusion coefficients would be substituted. Particle tracking simulations are then compared to the theoretic formulation to prove the MBI effects from IBS [6].

$$[Log]_x = ln(\frac{q^2}{a^2}) \; ; [Log]_y = ln(\frac{q^2}{b^2})$$

Equation 1: Coulomb Log Factors.

$$\frac{dF}{dt} = (\frac{\partial F}{\partial t})_c$$

Equation 2: Kinetic equation for phase space distribution (presence of collision).

$$\frac{dF}{dt} = -\sum_i \frac{\partial}{\partial p_i}(D_i F) + \frac{1}{2}\sum_{i,j} \frac{\partial^2}{\partial p_i p_j}(D_{ij} F)$$

Equation 3: Combining Equations 1 and 2.

$$f_1(X; s) = f_1(X; 0) - \int_0^s \frac{\partial f_0}{\partial \delta}(\frac{d\delta}{d\tau})_1 d\tau - \int_0^s [\frac{\partial}{\partial \delta}(D_{z,0}(\tau) f_1) + \frac{\partial}{\partial \delta}(D_{z,1}(\tau)\ f_0)]d\tau + \int_0^s [\frac{D_{zz,0(\tau)}}{2}\frac{\partial^2 f_1}{\partial \delta^2} + \frac{D_{zz,1(\tau)}}{2}\frac{\partial^2 f_0}{\partial \delta^2}]d\tau$$

Equation 4: Linearized Vlasoc-Fokker-Planck equation.

Taking Equation 3, and integrating the coefficients over the transverse phase space and linearizing them to be able to analyze the MBI data, Equation 4 is arrived at. Using this function, and substitution of friction and diffusion coefficients, will result in a set of linear integral equations. These semi-analytical calculations that are performed are called "*Completely Integrated Modified Piwinki Formalism"* (CIMP).

ELEGANT is a simulation software package designed for modeling and analyzing charged particle beam transport in accelerators and beamlines, which was used in this research and others to qualitatively analyze particle data.

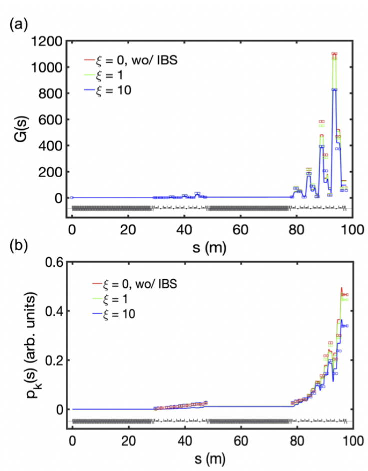

Figure 1: ELEMENT results of gain energy modulation as a function of s. With $\xi = 0\ (no\ IBS), \xi = 1\ (normal\ IBS\ effect),\ \xi = 10\ (enhanced\ IBS\ effect)$

IV. Results and Interpretation

According to the results of the paper both quantitatively and qualively, it can be analyzed that CIMP and ELEGANT give similar data on the IBS growth rates. In Figure 1, we see that the IBS effect is shown especially where the gain is high, close to s = 80 and above. Below s = 80, the effect on MBI is small on the beamline. The squares show the data of the Elegant simulation whereas the line is the CIMP model. It can be determined that both result in agreement with the impact of IBS. IBS impacts the gain of the particle bean, through its microbunching, which results in lower gain. Attempting to minimize IBS would result in higher gain, which is better overall for the performance of FELs.

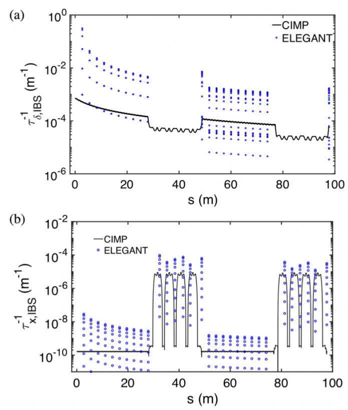

Figure 2: Visual representation of Completely Integrated Modified Piwinki Formalism (CIMP) vs. ELEGANT Data

In Figure 2, it is seen again that the data of CIMP and ELEGANT both agree with each other. The only differentiation is the growth rate for the energy spread, which shows CIMP producing lower data than Elegant.

ELEGANT simulations and the Fully Integrated Modified Piwinski Formalism (CIMP) were used to show IBS and were confirmed through their agreed results.

V. Conclusion

In conclusion, this paper studies the impact of Interbeam Scattering, one of the collective effects that contribute to MBI in electronic beams. By analyzing these collective effects, there can be solutions created to minimize MBIs from occurring, thus improving FEL performance. Future work that can be done, is finding ways to stop IBS from occurring in the first place instead of solving this issue later by using laser heaters that suppress MBIs.

References

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