ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB266

SIMULATION STUDIES OF PLASMA CASCADE AMPLIFIER*

J. Ma†, G. Wang, V. N. Litvinenko[1], Brookhaven National Laboratory, Upton, New York, USA
[1]also at Stony Brook University, Stony Brook, New York, USA

Abstract

Plasma cascade amplifier (PCA) is an advanced design of amplifier for the coherent electron cooling (CeC) experiment in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). Woking principle of PCA is the new plasma cascade micro bunching instability occurring in electron beams propagating along a straight trajectory. PCA is cost effective as it does not require separating electron and hadron beams. SPACE, a parallel, relativistic 3D electromagnetic Particle-in-Cell (PIC) code, has been used for simulation studies of PCA.

INTRODUCTION

CeC [1-3] is a promising technique for the rapid cooling of high-energy high-intensity hadron beams. A CeC system consists of three main sections: the modulator, the amplifier, and the kicker. In the modulator, hadrons induce density modulation in the electron beam through Coulomb force. The density modulation is then amplified in the amplifier. In the kicker, the electron beam interacts with the hadrons, correcting their energies towards the nominal value, which results in cooling of the hadron beam. There are various implementations of the CeC amplifier. In this paper, we present simulation studies of the PCA [4]. Working principle of PCA is the new plasma cascade instability (PCI) [5-6] occurring in electron beams propagating along a straight trajectory.

Figure 1 illustrates the layout of a CeC system with the PCA, where solenoids are used to focus the electron beam transversely. As a result, the plasmas frequency is modulated to excite the PCI, and to amplify the density modulation induced by hadrons in the modulator.

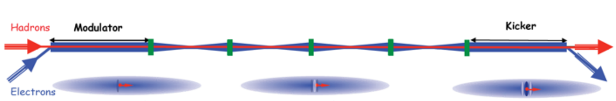

Figure 1: Layout of a CeC system with the PCA.

We have used the SPACE code [7] for simulation studies. SPACE is a parallel, relativistic, three-dimensional (3D), electromagnetic (EM) Particle-in-Cell (PIC) code, which has been used in the simulation studies for the mitigation effect by beam induced plasma [8], the modulation process in CeC [9-12], and the cooling performance of CeC with free electron laser (FEL) amplifier [13-16]. The SPACE code simulation results have been benchmarked with the analytical solution to the modulator problem [17].

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† jma1@bnl.gov

PERIODIC PCA

We have performed simulations of 4-cell periodic PCA to study the performance of PCA. Electron beam parameters in the simulations are listed in Table 1 and are relevant to the CeC experiment at BNL RHIC. A transverse Kapchinsky-Vladimirsky (KV) distribution has been applied to the electron beam in the simulation study. Note that the KV emittance is 4 times of the traditionally defined root mean square (RMS) emittance.

Table 1: Electron Beam Parameters for Periodic PCA

Beam energy, γ	28.5
Peak current, A	100
Normalized KV emittance, mm mrad	8

Figure 2 shows the transverse beam size evolution in a 4-cell PCA and the amplification of the initial density modulation at the frequency of 25 THz.

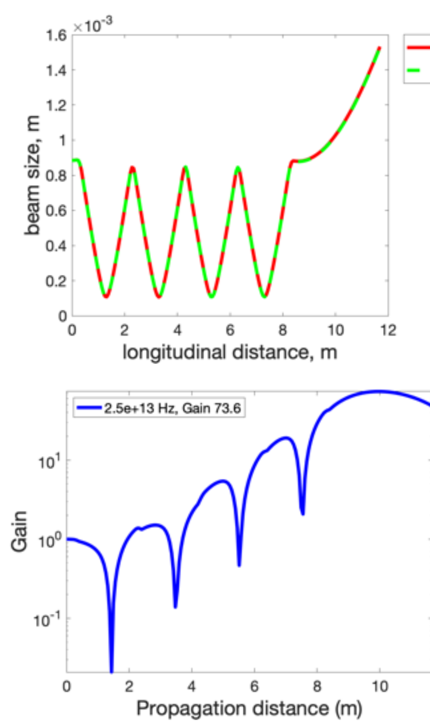

Figure 2: Evolution of transverse RMS beam size (top) and growth of initial density modulation at 25 THz (bottom) in a 4-cell periodic PCA followed by a drift.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB266

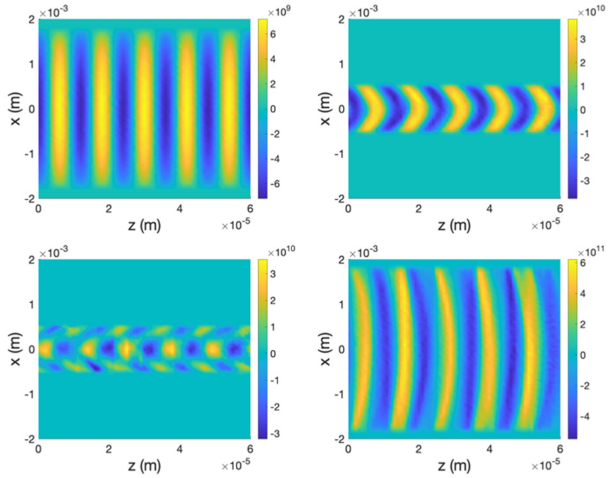

Figure 3: 2D plot of density modulation at 25 THz at the entrance of PCA (top left), slightly before the waist of second cell (top right), slightly after the waist of second cell (bottom left) and at the exit of PCA (bottom right).

The 2D plot in Fig. 3 reveals more details in the evolution of the density modulation through the PCA. When the electron beam is focused by the solenoids, electrons at the transverse edge fall behind the central electrons, as they experience stronger solenoid field. After the electron beam passes the waist of the second PCA cell, several transverse modes appeared. At the exit of PCA, we have observed the amplification of density modulation.

REALISTIC PCA

The simulation study has been performed for the realistic PCA based on the CeC experiment at BNL RHIC. Figure 4 shows the layout of the CeC system installed at BNL RHIC, where the 4 PCA cells are not evenly distributed.

We have designed 3 cases of electron beam parameters for the realistic PCA, and the parameters are listed in Table 2. The evolution of the transverse beam size for the three cases is presented in Fig. 5, as well as the corresponding PCA gain. While all 3 cases provide sufficient PCA gain, we have selected case 2 as our primary option based on our experience in the CeC experiment at BNL RHIC.

For case 2 with electron beam peak current 75A, we have performed a series of sensitivity studies to investigate the dependence of PCA performance on various beam parameters.

Table 2: Electron Beam Parameters for Realistic PCA

	Case 1	Case 2	Case 3
Beam energy, γ	28.5	28.5	28.5
Peak current, A	50	75	100
Normalized KV emittance, mm mrad	5	7	8

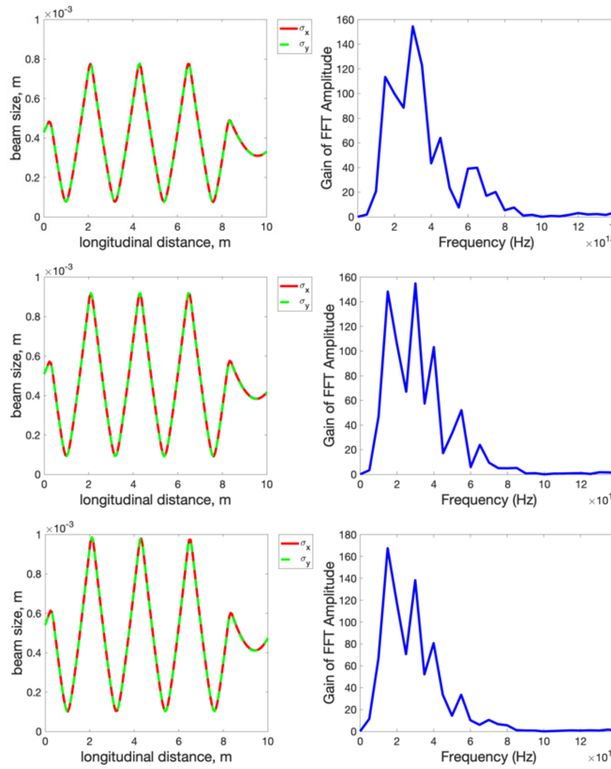

Figure 5: Evolution of transverse RMS beam size (left) and amplification spectrum (right) in a 4-cell realistic PCA for electron beam peak current 50A (top), 75A (middle) and 100A (bottom).

Figure 6 shows the dependence of PCA performance on electron beam emittance for peak current 75A. While normalized KV emittance 7 mm mrad gives sufficient PCA gain, 10 mm mrad reduces the amplification significantly, and 20 mm mrad leads to very little gain in PCA.

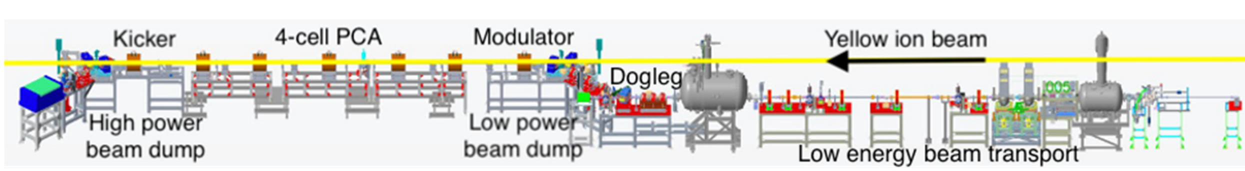

Figure 4: PCA-based CeC system installed at BNL RHIC. The electron beam is generated in a 1.25 MV superconducting radio frequency (SRF) photo-electron gun, accelerated to 14.56 MeV, and merged to co-propagate with the 26.5 GeV/u ion beam circulating in RHIC's yellow ring.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB266

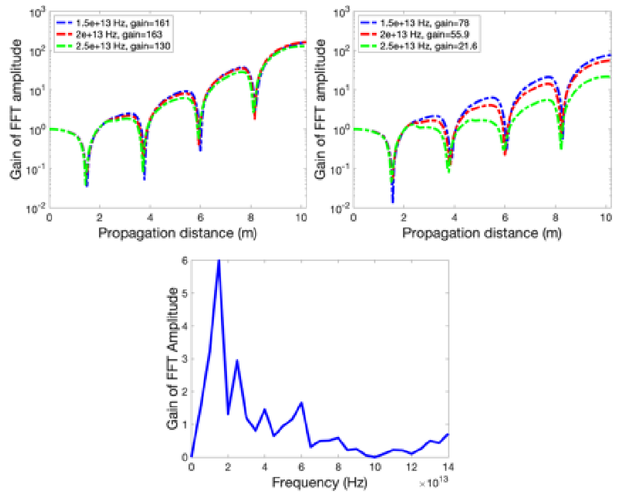

Figure 6: PCA amplification for electron beam peak current 75A and normalized KV emittance 7 mm mrad (top left), 10 mm mrad (top right) and 20 mm mrad (bottom).

Figure 7 presents the dependence of PCA amplification on electron beam energy spread for peak current 75A. Energy spread as low as 2e-4 provides sufficient PCA gain, and energy spread of 4e-4 is still acceptable for a reasonable PCA amplification. However, energy spread of 8e-4 reduces PCA gain dramatically.

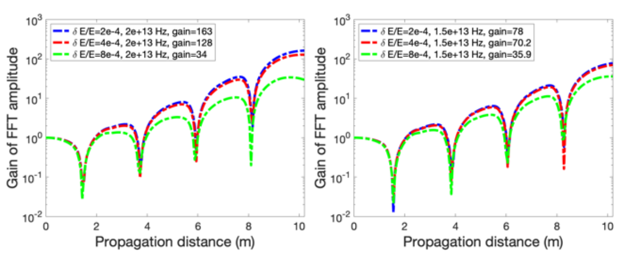

Figure 7: Dependence of PCA amplification on energy spread for electron beam peak current 75A and normalized KV emittance 7 mm mrad (left) and 10 mm mrad (right).

The dependence of PCA gain on the electron beam initial β function is shown in Fig. 8. Changing initial β function by 10% is acceptable, as it provides more than factor of 100 amplification for peak current 75A and normalized KV emittance 7 mm mrad.

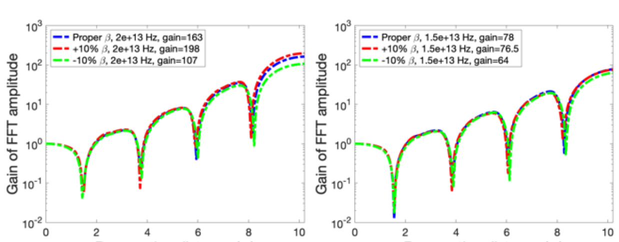

Figure 8: Dependence of PCA amplification on initial β function for electron beam peak current 75A and normalized KV emittance 7 mm mrad (left) and 10 mm mrad (right).

The sensitivity study for the realistic PCA gives us more understanding about the performance of the PCA and provides us the required electron beam parameters in the CeC experiment at BNL RHIC. The simulation study of realistic PCA can be applied to the simulations of PCA-based CeC to predict the cooling rate [18].

EIC PCA

The BNL RHIC will be upgraded to the future Electron-Ion Collider (EIC). We have performed numerical simulations of the PCA designed for the EIC cooler. Table 3 lists the electron beam parameters for the EIC PCA. Compared with the realistic PCA in the CeC experiment, EIC PCA requires higher beam energy, higher peak current and lower emittance. The length of each PCA cell is increased to 20 meters in the EIC PCA design.

The EIC PCA simulation results, shown in Fig. 9, have demonstrated that we can achieve enough amplification at the frequency as high as 1 PHz, which will provide sufficient cooling to satisfy the requirement of hadron beam luminosity in the EIC.

Table 3: Electron Beam Parameters for EIC PCA

Beam energy, γ	275
Peak current, A	250
Normalized KV emittance, mm mrad	2

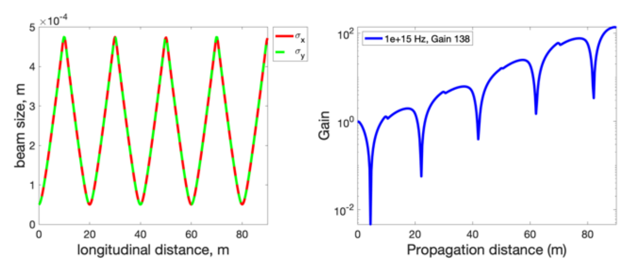

Figure 9: Evolution of transverse RMS beam size (left) and amplification of initial density modulation at 1 PHz (right) in the PCA designed for future EIC.

CONCLUSION

We have presented the simulation studies of the PCA for the CeC system, including the periodic PCA, the realistic PCA for the CeC experiment at BNL RHIC and the proposed PCA for the future EIC at BNL. Sensitivity study has been performed to characterize the dependence of PCA performance on various beam parameters and to provide requirement of beam parameters for the CeC experiment.

The simulation results have demonstrated that the PCA can achieve sufficiently high gain with proper setup, which is necessary for the cooling of hadrons in the kicker section of the CeC system.

The simulation study will continue to support the CeC experiment at BNL RHIC and the design of the future EIC.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB266

REFERENCES

[1] Y. S. Derbenev and V. N. Litvinenko, “FELs and High-energy Electron Cooling”, in *Proc. FEL'07*, Novosibirsk, Russia, Aug. 2007, paper TUCAU01, pp. 268-275.

[2] V. N. Litvinenko, “Coherent Electron Cooling”, in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper FR1GRI01, pp. 4236-4240.

[3] V. N. Litvinenko and Y. S. Derbenev, “Coherent Electron Cooling”, *Phy. Rev. Lett.*, vol. 102, p. 114801, Mar. 2009. doi:doi.org/10.1103/PhysRevLett.102.114801

[4] V. N. Litvinenko *et al.*, “Plasma-Cascade Micro-Bunching Amplifier and Coherent Electron Cooling of a Hadron Beams”, 2018. arXiv:1802.08677

[5] V. N. Litvinenko *et al.*, “Plasma-Cascade Instability”, *Phys. Rev. ST Accel. Beams*, vol. 24, p. 014402, Jan. 2021. doi:10.1103/PhysRevAccelBeams.24.014402

[6] V. N. Litvinenko *et al.*, “Plasma-Cascade Instability- Theory, Simulations and Experiment”, 2019. arXiv:1902.10846

[7] K. Yu and R. Samulyak, “SPACE Code for Beam-Plasma Interaction”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 728-730. doi:10.18429/JACoW-IPAC2015-MOPMN012

[8] J. Ma *et al.*, “Simulation of Beam-induced Plasma for the Mitigation of Beam-Beam Effects”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 734-736. doi:10.18429/JACoW-IPAC2015-MOPMN015

[9] J. Ma *et al.*, “Simulation Studies of Modulator for Coherent Electron Cooling”, *Phys. Rev. ST Accel. Beams*, vol. 21, p. 111001, Nov. 2018. doi:10.1103/PhysRevAccelBeams.21.111001

[10] J. Ma, “Numerical Algorithms for Vlasov-Poisson Equation and Applications to Coherent Electron Cooling”, Ph.D. thesis, Department of Applied Mathematics and Statistics, Stony Brook University, Stony Brook, New York, USA, 2017.

[11] J. Ma, G. Wang, and V. N. Litvinenko, “Simulations of Modulator for Coherent Electron Cooling”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2953-2956. doi:10.18429/JACoW-IPAC2018-THPAF005

[12] J. Ma *et al.*, “Modulator Simulations for Coherent Electron Cooling”, in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 816-819. doi:10.18429/JACoW-NAPAC2016-WEPOA55

[13] J. Ma, G. Wang, and V. N. Litvinenko, “Simulations of Coherent electron Cooling with Two Types of Amplifiers”, *Int. J. Mod. Phys. A,* vol. 34, no. 36, p. 1942029, Dec. 2019. doi:10.1142/S0217751X19420296

[14] J. Ma, G. Wang, and V. N. Litvinenko, “3D Start-to-End Simulations of the Coherent Electron Cooling”, in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3329-3332. doi:10.18429/JACoW-IPAC2019-WEPTS092

[15] J. Ma, G. Wang, and V. N. Litvinenko, “Simulations of Coherent electron Cooling with Free Electron Laser Amplifier and Plasma-Cascade Micro-Bunching Amplifier”, in *Proc. ICAP'18*, Key West, Florida, USA, Oct. 2018, pp. 52-58. doi:10.18429/JACoW-ICAP2018-SUPAF06

[16] J. Ma, G. Wang, and V. N. Litvinenko, “Simulations of Cooling Rate and Diffusion for Coherent Electron Cooling Experiment”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2957-2960. doi:10.18429/JACoW-IPAC2018-THPAF006

[17] G. Wang and M. Blaskiewicz, “Dynamics of ion shielding in an anisotropic electron plasma”, *Phys. Rev. E*, vol. 78, p. 026413, Aug. 2008. doi:10.1103/PhysRevE.78.026413

[18] J. Ma, G. Wang, and V. N. Litvinenko, “Simulations of Cooling Rate for Coherent Electron Cooling with Plasma Cascade Amplifier”, presented at *IPAC'21*, Campinas, SP, Brazil, May 2021, paper WEPAB265, this conference.