Report of 2019 External CeC Review (September 9 & 11, 2019)

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Introduction

The first attempt to demonstrate CeC at RHIC was hampered by excessive 10 THz intensity noise of the electron beam, exceeding the shot noise power by about a factor of 300. The CeC group has identified the source of this noise and demonstrated a way to suppress it. This proposal aims to demonstrate CeC again over the next two years using the Plasma Cascade Instability (PCI) as broadband amplifier.

The external review of the plans for the continuation of the Coherent electron Cooling (CeC) demonstration experiment at RHIC was held on Sep 9 and 11, 2019 via a telecon.

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Charge questions

1. **Is the experiment as described in the proposal technically sound and are the goals achievable? -- Yes, with some comments and reservations.**

Committee comments:

Committee Member 1: The experiment is challenging, with many parameters and a delicate balance between the beam noise, beam cooling and diffusion. This proposal is a "high-risk/high-reward" type of an experiment. The experimental goals correspond to sequential milestones with not many activities that can be performed in parallel (during the experimental run). Some of the initial milestones, such as the low-noise electron beam and the PCA gain, can be demonstrated without ion beam.

Committee Member 2: The proposed experiment is technically well motivated and there is a good likelihood that the advertised goals will be achieved. There is no guarantee, however, as the experiment is complex delving into the issues of the high frequency electron bunch noise with a number of sources, none of which are accounted for in the simulations presented at the level "beyond any doubt". There is a good case being made that important lessons will be learned from the experiment, including for beam physics beyond CeC.

Committee Member 3: The existing study results are not enough for answering this question with full confidence. Additional studies are needed.

A definite YES would imply:

1. A thorough understanding of the physics in all the processes involved in PCA CeC
2. Convincing numerical modeling of the processes
3. Diagnostic tools that have been validated by simulation

Committee Member 4: The first three steps of the plan for Run 20 are clearly feasible and should succeed. Observation of the ion imprint is less certain, since it is at present unclear if other noise sources will be amplified and hide the imprint. Availability of the proposed time-resolved diagnostic beamline will significantly improve understanding and control of the beam properties and, therefore, understanding of the experimental outcomes.

Committee Member 5: The proposal is technically sound, but it is too early to say if the experiment will be successful. There are significant risks in the quality of the electron beam needed for PCA and the ability to measure both the initial beam quality and induced effects in the IR. In particular it is critical to be able to measure the shot noise level of the beam, especially if the imprint effect is not seen immediately. This is a difficult problem in general, and particularly in the mid-IR. Investing in additional methods to determine the true shot noise level, if available, would reduce risk. Additional simulations looking at potential instabilities and noise sources throughout the beam line could reduce some risk. Measuring the shot noise level is critical to understanding results,

Additional comments: The noise control makes the proposed PCA CeC experiment a very challenging yet very important experiment. Noise in high-intensity e-beam is intrinsically an extremely challenging and interesting topic in the accelerator community, in all aspects of theory, simulation and experiment. Yet it plays a critical role, as shown by Run 18, for CeC with any type of amplifier (including the on-going study of microbunching-based amplifier) to work properly.

A lot of knowledge can be gained from the CeC experiment. For example, the failed detection of imprint in Run 18 enabled the team to recognize the importance of noise in the e-beam. Since then they made much progress in (1) understanding the source of noise and noise suppression, (2) developing noise diagnostics and measurement, and (3) developing theoretical and numerical understanding of PCA as amplifier.

This progress motivates the team to make the proposal for the next PCA experiment of CeC.

With all their efforts for the PCA studies, there are still several additional steps from an UNCONDITIONAL YES to Charge Question 1. These steps (as listed below) are extremely hard to do, because of the intrinsic difficulties in noise study, but that is exactly the challenges inherent in the proposal.

(1) Simulation of imprint on realistic e-beam as propagated from the gun, and then the PCA amplification of this imprint

Measuring the imprint---goal for Run 20---requires the knowledge of the imprint made by an ion on the e-bunch (transported from the gun), with the realistic distribution and micro-bunch noise of the e-bunch. Because of the inherent difficulties in simulation of noise, the current studies did patchwork for simulations and did not study the imprint on a realistic beam. Even though a more realistic simulation could be much harder than their existing studies, it could probably be done (as proposed during this review) by using a slice of an e-bunch from IMPACT-T and studying the imprint of one ion and its amplification, along with the original noises in the e-beam. Sensitivities can be further studied for the realistic beam.

(2) Simulation of e-beam development, with coherent microbunching structures or incoherent shot noise, from the gun to the modulator, and then finally to the kicker

It's necessary to propagate the e-beam up to the kicker (for the case without the imprint). This is because for the diffusion calculation, the two density perturbations at the kicker---(1) the amplified imprint and (2) the original but amplified shot noise in the e-beam (without imprint)---impact the ion dynamics via two separate terms. For PCA without saturation, these two perturbation sources add linearly in the e-beam density. The amplitude of the 2nd perturbation at the kicker can then be obtained only by the start-to-end simulation for the e-beam originated from the gun. For this amplitude, its value at the kicker is not the product of its value at the modulator and the PCA gain, because both energy and density perturbation at the modulator work together and get amplified in PCA---this interplay results in the final amplitude at the kicker.

(3) The requirement of imprint measurement on sensitivity of IR detector, and how does the current IR detector meet the requirement.

This was not one of the homework questions, but understanding the diagnostics and its sensitivity is crucial for a successful measurement of noise.

(4) Noise control studies by MDM measurement, and its comparison with simulation of this measurement

The achievement of the team in noise suppression is shown by modulation-demodulation (MDM) measurements, which show how noise can be suppressed by tuning of optics knobs. But these data were not compared with noise suppression simulations. The agreement of the measurement and simulation would give confidence for both, in the noise suppression measurement (especially the MDM diagnostics) and the capability of simulating noise level. The answer from the team (slide 24 for Homework Q&A) indicates such comparison is currently not available. Our impression is that they have a good grasp of noise suppression, but without comparison of simulation with experiment, it's not on solid ground yet.

The team has accumulated ample knowledge, experience and expertise in the CeC studies. Their existing experimental apparatus and the availability of ion beam in RHIC made them in better position to do the next experiment than other research groups. However, these additional steps are necessary but very hard to do, and any small progress toward that direction will be a welcome contribution to the accelerator community. Probably the suggestions/advices from the community could also be helpful for the team to make the steps forward. Considering this is an exploring experiment, without complete information it could still be fine to go ahead. Completing the additional steps can only help the team to avoid "unexpected" results and reduce the chance of "after-thoughts".

2. Is the electron beam quality sufficient to make the experiment possible?

Yes, it appears that the emittance, energy spread, and peak current are sufficiently good for the PCI to be observed over a broad range of wavelengths. The macro-parameters of the electron beam have been already demonstrated at the level needed for the experiment. However, the impact of e-beam quality on the experiment lies in how the e-beam impacts the imprint propagation, and how the shot noise in the e-beam impacts the ion dynamics at the kicker via diffusion. The current study did not use the e-beam distribution from the electron gun for the imprint study. The team has reported that in the modulator, an idealized KV-distribution beam is used to simulate the actual e-beam from the gun, this study needs to be done for an e-beam with realistic distribution from the gun. Also, the shot noise in the e-beam at the kicker was not studied by propagating the e-beam from the gun to the kicker. A complete conclusion to this question can only be made when such detailed studies are done.

3. Are the beam dynamics and cooling simulations sufficiently complete?

The team responded well to their lack of success in observing statistically meaningful imprint from the ion beam in the electron beam during Run 18 and came up with a number of new simulation efforts in order to explain the negative result. There exists a patchwork of various simulations and numerous codes, given the complexity of the experiment. However, it does not live to the highest confidence level of "start-to-end" style simulations and there is still a place for improvement in tying up various pieces and codes into a single coherent framework.

The simulations presented to us have concentrated on modeling of PCI using the SPACE code. These appear to be reliable and to include the essential physics, which provides convincing evidence that PCI is a real phenomenon. However, these simulations are not integrated with simulations of the upstream systems and thus do not appear to reflect noise sources in the band of frequencies subject to strong amplification by PCI. Hence, it is hard to be certain that amplification of noise in the beam will not overwhelm the amplification of the ion imprint, particularly since the latter has a very short length scale that is not as strongly amplified as longer scale perturbations.

The dogleg in front of the modulator is a risk to drive dispersive MBI from both CSR and shot noise. Simulations have confirmed that CSR driven MBI is not a worry, but simulating shot-noise driven MBI is more difficult. Full one-to-one particle simulations to check potential for MBI could decrease the risk of a surprise noise source.

Additional comments are embedded in our answers to Questions 1 and 2.

4. Is there a good likelihood that the experiment succeeds, and should it proceed?

It is unclear whether amplification of the ion imprint will be observed, since this hinges on questions of possible amplification of residual noise in the electron beam. Only experiments will provide a definitive answer to this issue. Even if the answer is negative, further understanding of such noise and its amplification is a subject of broad interest in the accelerator field, and is by itself sufficient reason to perform the experiments.

5. Are there any additional preparations (simulations, diagnostics, etc.) that should be performed?

The team has indicated that having a dedicated diagnostic beamline is needed for accurate evaluation of electron beam. Such diagnostics with a resolution of ~ 1 psec could be built in one year and would allow for fine-tuning and the comprehensive evaluation of the electron beam. The committee agrees that is should be pursued if at all possible.

The committee recommends to couple the SPACE code with full simulations of the injector, i.e., of the gun, linac, and transport line leading up to the modulator. Rather than attempting to simulate the entire beam from the injector with SPACE, this may be done by taking slices from the simulated beam at the entrance to the modulator. (2) Perform simulations to provide the total system (injector plus PCA section) gain curve (gain vs wavelength) for modulations imposed at the exit of the gun, including instabilities driven by shot noise. (3) Use simulations of the gun with one macro-particle per electron to determine the noise spectrum of the beam at the exit of the gun.

The committee recommends to direct the team's attention to addressing our 4 additional comments to question 1.

6. Additional Comment

Given that this proposal is the only CeC experimental effort at present, it seems to the committee that it would be favorable, if the team interacted more strongly with the rest of the CeC community.

Homework questions (as sent to project team on 09/10/19)

The committee would like to thank the team for their thorough and expedient answers to our multiple homework questions. Slide # in our questions refer to the following presentation:

https://indico.bnl.gov/event/6709/sessions/3340/attachments/24497/36267/CeC_experiment_final.pdf

Answers can be found here:

https://indico.bnl.gov/event/6709/sessions/3342/attachments/24525/36316/QA.pdf

1. Slide 38 shows the experimental goals for the requested Runs 20 and 21. Please show the milestones and the means of demonstrating these milestones. For the proposed PCA experiment in Run 20, how will the imprint be measured? Is there going to be an IR detector (or MDM) placed next to the dipole after the kicker? Any additional beam diagnostics that the group feels they should have available for the proposed runs but cannot afford or not enough time? What would they be? How would these additional capabilities help with better control/understanding of the experiment's parameters and with demonstrating the milestones?

2. Slide 25 shows simulation results of an initial imprint of ion on an ideal Gaussian bunch being propagated through PCA. Is it possible to simulate an ion imprint on a realistic electron bunch obtained from simulation of the bunch starting from the gun, and see how such imprint propagate through the PCA?

3. For the simulated RHIC performance (Slide 26), please send us the electron and ion bunch parameters used in the simulations (bunch charges (e, ion), bunch length (electrons), PCA bandwidth). On the same slide (#26), the length of the amplified imprint of an ion is shown as 3.75 microns. However, the PCA gain is considerably higher at longer wavelengths; e.g., at 25 microns it is about 100 vs less than 10 at ~5 microns and below. Why shouldn't we expect amplification of residual noise at longer wavelengths (between 10 and 80 microns) to overwhelm the amplification of the ion imprint?

4. Synchronization of the imprint in the e-beam and the ion particle is important for ion beam cooling by CeC. Difference in energy between an ion and its imprint in the e-beam when traveling through the amplifier could cause their slippage in the kicker. What requirement does the synchronization set on the correlated energy spread? Does the correlated energy spread (sigma_E vs. z), , shown in slide 34 and 35, meet the requirement? Does this correlated energy spread have any impact on the observation in slide 15 for the FEL amplifier? Or any impact on the prediction in slide 26 for the PCA amplifier?

5. Run 18: The measured FEL intensity signal of Fig. 17 (of the writeup) is said to be "at least 100 times smaller" than simulated. Is the noise due to PCI alone sufficient to explain this? Also, for Run 18, apart from measuring the bunch lengthening as shown in slide 15, were there any measurements of other ion beam properties, such as energy spread, etc? That would serve as cross checks for quantitative understanding of what's happening.

6. Was the FEL saturated in Run 18? In the report for the CeC Review, it's said (on page 22) the saturation is very unlikely especially considering the FEL signal was reduced intentionally by 10 times for the imprint experiment. On the other hand, on page 63, it's said the saturation happens when the gain exceed 700. Even though in Run 18 the FEL gain is 50 to 100, the initial microbunching amplitude is 15-20 fold higher. Does this cause FEL to saturate? What would be the saturation situation for PCA amplifier?

7. The laser was eliminated as a possible source of the THz structure in the bunch. Can you say a few words about the laser time profile (i.e. are you using pulse stacking to make the laser pulse long?). What effect does it have on the simulated/expected performance of the CeC?

8. There is a patchwork of various simulations and numerous codes given the complexity of the experiment. It's unclear if this patchwork amounts to "start-to-end" or sufficient level of confidence in the upcoming experiment. Please comment. What are the key knobs in your upcoming experiment given what you learned to maximize the cooling rate? Has a start-to-end simulation been performed from the gun, through the PCA channel to the kicker? What is the gain curve for amplification of noise/modulations originating in the gun, including CSR effects in the dogleg?

9. Our understanding is that PCI has still not been convincingly benchmarked against the experiment to give full confidence in the overall system performance. Please comment. Given this consideration, are the Run plans presented still on an overly-optimistic schedule (e.g. for the time it will take to progress to complete understanding of all the culprits)?

10. What kind of transverse distribution was assumed in PCA simulations? How well does this match the measured distribution? How sensitive is the amplification to the type of distribution?

11. In slide 29, the bunch shift in energy by 0.6*sigma_delta will change the cooling behavior. Is sigma_delta here the slice energy spread or correlated energy spread?

12. In slide 16, it shows a 15-to-20-fold increase of noise level (or microbunching amplitude) in the electron beam, or 300-fold increase in THz power, when the e-beam passes through LEBT. This seems to explain the puzzle shown in slide 15 for Run 18: the absence of imprint signal and the observed bunch lengthening. Is the absence of imprint signal caused by the low signal-to-noise ratio? Could it also be related to FEL saturation so the imprint didn't get amplified as much as expected? Is the FEL saturated or not for such highly microbunched beam? Is the heating of the ion beam caused by the much larger (than expected) diffusion from ion beam interacting with the more severe microbunched electron beam in the kicker?

13. With the newly understood cause (i.e., high-amplitude noise in e-beam) for the puzzle in slide 15, can one simulate the Run 18 experiment and reproduce results of bunch lengthening rate as shown in slide 15? Such detailed quantitative understanding should include factors such as the diffusion of ions with a highly microbunched e-beam, imprint of ion on a realistic beam transported from the gun, and with electron-ion phase-shift due to the actual correlated energy spread in the e-bunch… Such realistic study will also be important for the success of the proposed PCA experiment.

14. Both cooling and diffusion are required for the ion dynamics shown in slide 14 (for FEL amplifier) and in slide 26 (for PCA amplifier). The cooling force calculations are given in detail in the CeC Review Report and references, however, the diffusion studies may be less available. For the FEL amplifier, the diffusion treatment can be found in Gang Wang's paper " On the evolution of ion bunch profile in the presence of longitudinal coherent electron cooling" (https://arxiv.org/abs/1905.03373). For the PCA amplifier, where can one find the reference for the diffusion resulting from ions interacting with clusters imprinted by other ions in the e-beam, as well as diffusion from ions interacting with the amplified microbunching in the original electron beam?

15. Noise control is critical for the success of the proposed PCA experiment for CeC. Noise behavior is studied by measurement using MDM and simulations. Comparison of MDM signal and simulation will help to validate both MDM as a noise detecting tool and the simulation for producing physical results instead of numerical artifacts. Can the simulations, such as SPACE or IMPACT-T, which give promising results in noise control in slide 16, be used to validate the measured dependence of MDM signal on optics settings in slide 19? Or at least show the similar trend?

16. Are there any assumptions about the transverse phase advance between the modulator and kicker? Do you have to assume the phase advance is such that electrons/hadrons return to the same transverse position, or does the PCA create a density sheet with the beam radius?

17. Slide 31 appears to show small gain (<10) if the emittance is as large as 5um. Will it still be possible to observe cooling with that low gain?

18. The 0.023% = 3keV energy spread at 100A seems quite small by LCLS injector standards (admittedly not a great standard!). What is the compression factor to reach 100A? Has this energy spread been measured? What is the risk if the energy spread is 2X or 3X larger?

19. The dogleg in front of the modulator looks like a risk to drive dispersive MBI. Vladimir mentioned that simulations do not show any MBI, but is it understood theoretically why this is so? With small energy spread, MBI at um scales is possible. As with PCI, it is easy to miss MBI in simulations.

20. Measuring the shot noise level appears critical to understanding results. Are there ways of determining the shot noise level besides scaling with peak current? e.g. inserting a thing foil to scatter electrons or a chicane at the end for phase mixing, or…?

21. In the modulator there is slippage between the ions and electrons both due to the 0.1% difference in gamma, and also slippage of the ions relative to each other due to the energy spread. (What is the energy spread? Similar to 0.1%?) Is there any gain to having a shorter modulator to reduce slippage?

22. Perhaps it is beyond the scope of this review, but we are curious if the MBI-CeC can also be demonstrated with very small chicanes that can be corrected by an energy offset. It seems unlikely, but perhaps not so unlikely that it shouldn't be checked.