# SIMULATION OF PHASE SHIFTERS BETWEEN FEL AMPLIFIERS IN COHERENT ELECTRON COOLING<sup>\*</sup>

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#### Abstract

Coherent electron Cooling (CeC) [1] is a proposed advanced beam cooling method that has the potential of reducing the ion beam emittance in significantly shorter amount of time compared to existing cooling methods. A high gain FEL, composed of three permanent magnet helical wigglers, is acting as an amplifier of the ion's signals picked up by electron beam in CeC. A self-consistent simulation which takes the space and possible phase shifts between wigglers into account is crucial in determining the performance of the FEL. The authors developed an algorithm based on the well-used GENESIS [2] code to treat the propagation of particles and radiations in between wigglers and predicted the FEL performance with different beamline layouts. The authors will present their simulation setup and results.

### **INTRODUCTION**

The CeC beamline (Figure 1) consists of low energy beam transport (where electron beam is prepared and accelerated to a total energy of 14.6 MeV), a dogleg section to transport the beam to a common section where the electron beam is co-propagating with the hadron beam. In the common section, the electron beam is picking up information from hadron beam in modulator section (consists of four quadrupoles for beam optics tuning). Then the information is amplified in the FEL section and reacts back to the hadron beam with proper phase adjustment to cool the hadron beam, i.e., to reduce the hadron beam's energy spread and phase space areas. The performance of the CEC is highly dependent on the FEL gain and phase preservation. Thus, a self-consistent simulation of the FEL section is crucial in determining the required electron beam properties and in predicting the machine setups to characterize the cooling.

The FEL section consists of three helical wigglers composed of permanent magnets. The magnetic length for each wiggler is about 250 cm while the wigglers are separated by a drift space of about 42 cm. A schematic drawing of the detailed FEL can be found in Fig. 2 [3]. In between two wigglers, a three pole C-type chicane is used to properly delay the phases of the electron beam (to match with the phases of the radiation fields) and potentially to change the gain of the FEL and thus to adjust the cooling time of the CeC. In the following section of this paper, the authors will explain a method to simulate the three wigglers together with the drifts in between wigglers. The authors will examine how to maximize the beam-field matching using the phase shifter. The authors will also discuss how this study is affecting the understanding of the gain and performance of the cooling.







# FEL SIMULATION SETUP

The authors used GENESIS for the FEL process simulation. It is to our interest that the pondero-motive phases could be adjusted so that the relative phasing between the electron beam and the laser fields could be varied and FEL gain of signal could be studied under various beamline setups. In order to simulate such effect, the phase needs to be changed in a small fraction of the radiation wavelength. In GENESIS, the drifts and chicane models all result in integer steps of the radiation wavelength (tracking results are calculated and exported in steps of the radiation wavelength). Thus, for our study, the distributions of both electrons and fields at the end of each wiggler needs to be exported and reused as inputs for next section of wiggler simulation.

A transport which calculates the phase shifting for both particles and fields is fulfilled with external C++ code which reads in the binary files (.dpa and .dfl files) and generates new binary files with proper phase propagated in between the wiggler gaps. The electron beam parameters used in GENESIS for the studies in this paper is listed in Table 1 [4].

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Table 1: Beam Parameters used in GENESIS Sin	nulat	ions
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Beam energy (MeV)	14.66
Beam current, peak (A)	50
Norm. emittance (mm-mrad)	5
Momentum spread ( $\sigma_p/p$ )	$1 \times 10^{-3}$
Undulator period (cm)	4
Radiation wavelength (µm)	30

In the GENESIS setup, we sliced the electron bunch into 400 slices and each slice contains 16384 macro particles. We generated random shot noises in GENESIS and simulated the evolution of the bunch along with the EM wave "with" and "without" a small  $\delta$ -function-like perturbation, which is located at the middle of the bunch, i.e., slice # 200.

The FEL response on the perturbation was calculated by subtracting it from the bunching factor in the presence of perturbation ("with") and in the case of the pure shot noise ("without"). Being the difference between two complex numbers, such a FEL response is a complex function, i.e., it is described both by the amplitude, and the phase. In the following section, we will discuss our treatment of such FEL responses for the drifts in between wigglers.

#### PHASE SHIFTER MODEL AND RESULTS

As mentioned above, in between two wigglers, there is a C-type chicane which delays the electron bunch to adjust the pondero-motive phase between particles and fields. We exported the particle and field distribution at the end of each wiggler. Shifting particle distribution is rather simple, since it is merely to modify the complex bunching factor by exp(ikx), where k is the wave number of the radiation.

The manipulation on radiation field, however, must take into account that the envelope is changing over the distance, i.e., Rayleigh length is not infinity. In the code, we fulfill this phase shift on fields by performing shifts in the 2D Fourier transformed EM fields. To be more specific, we shifted the EM fields transversely and then performed 2D Fourier transform. After we added the phase shifts, we performed inverse Fourier transform and shifted the EM fields transversely back to where they were.

By doing this, we considered the longitudinal variance of the EM fields. Figure 3 shows evolution of the gain (amplification of the perturbation stated above) of the signal in the FEL under two different phase shifter settings. The phase shifter strength is converted to microns, where 0  $\mu$ m indicates the electrons and the radiation fields are perfectly in phase at the entrance of next wiggler. On the other hand, when we shifted the electrons with respect to the fields by 6  $\mu$ m, about 1/5 of the wavelength, the gain of signal in the FEL drops from 100 to about 80. A full-blown study of the 2D parametric space (two phase shifters between three wigglers) can be seen in Figure 4, which indicates that we have the ability to tune the gain of CeC FEL to cover a wide range ( $\sim 60 - 120$ ) by varying the phase shifter settings. In reality, a 77-ampere current in the phase shifter is correspondent to shifting the beam by entire wavelength and we will have 10% margin in power supplies to tune the FEL gain by adjusting phase shifters [5].



Figure 3: Evolution of gain of a perturbation in existence of shot noise in CeC FEL. When phase shifter is set to perfectly align the electrons and radiation, the gain ( $\sim 100$ ) is higher than the gain when the phase shifter is shifting the electrons by 1/5 of the radiation wavelength ( $\sim 80$ ).



Figure 4: A 2D scan of phase shifter setup results in changing the gain of FEL amplification by a factor of two ( $\sim 60-120$ ), which could be easily distinguishable by the change of cooling time of CeC.

If we compare the electron envelope in the FEL for two cases: a) three wigglers with phase shifters; b) one continuous long wiggler, we could find that the longitudinal variation of EM fields may play a important role, i.e., our Rayleigh length is not significantly larger than the drift space in between wigglers. Detailed study of the causes of this difference is underway. The electron envelope for both cases can be found in Figure 5.



Figure 5: Electron envelope at 6 m in the CeC FEL for one continuous wiggler (top) and three wigglers separated by a  $\sim$ 0.4-m drift space (bot), suggesting the longitudinal variation of radiation could affect the shape of electron envelope, thus affecting the FEL gain the hadron beam sees if not sitting on the top of the curve.

# CONCLUSION

We modelled CeC FEL section while taking the drift space in between wigglers into account. The simulation results suggest that by varying the strengths of phase shifters, we can control the FEL gain in a relatively wide range ( $\sim 60 - 120$ ). The change in the electron envelope may arise from the limited Rayleigh length of the radiation, and we are currently studying this connection.

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