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PREPARATIONS FOR INSTALLATION OF THE DOUBLE EMITTANCE-EXCHANGE BEAMLINE AT THE ARGONNE WAKEFIELD ACCELERATOR FACILITY*

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Abstract

Preparations to upgrade the single EEX beamline at the Argonne Wakefield Accelerator (AWA) facility to a double EEX beamline are underway. The single EEX beamline recently demonstrated exchange-based longitudinal bunch shaping (LBS) which has numerous applications including high energy physics linear colliders, X-ray FELs, and intense radiation sources. The exchange-based method can generate arbitrary LBS in the ideal case but has limitations in the real case. The double EEX beamline was proposed as a means to overcome the limitations of single EEX due to transverse jitter and large horizontal emittance. In this paper, we present the current status of beamline design and installation and simulation results for the planned experiments: collinear wakefield acceleration with tailored beams and tunable bunch compression without the double-horn feature.

DOUBLE EEX BEAMLINE AT AWA

The Argonne Wakefield Accelerator (AWA) is an accelerator facility dedicated for future accelerator R&D [1]. This facility consists of three RF photoinjector beamlines for carrying out future accelerator research; wakefield applications [2-4], beam manipulation [5], field emission study [6] etc. The main beamline has a 1.5 cell RF gun generating a very high charge beam (up to 100 nC for single bunch) and 6 accelerating cavities to accelerate the beam up to 70 MeV. Downstream of the beamline is a flexible experimental area including a straight section and a single emittance exchange (EEX) beamline.

The EEX beamline was recently used to demonstrate property exchange and longitudinal profile shaping (LPS) [5]. Although the experiment was successful, the single EEX beamline has two important limitations [7] for practical usage. First, the single EEX beamline exchanges the (typically) large longitudinal emittance for the small transverse yet most applications benefit from a small transverse emittance. Second, both initial timing and energy jitters become a horizontal offset jitter after the single EEX beamline.

These limitations can be overcome with a double EEX beamline where a second EEX beamline is added after the first (Fig. 1). The first EEX exchanges transverse and longitudinal phase spaces; this enables the manipulation of the longitudinal phase space by altering the transverse beam properties in the middle section. Afterward, the second EEX exchanges these phase spaces again to return the emittances. Upstream longitudinal jitters become transverse jitters after the first EEX, but go back to longitudinal jitters after the second one [7,8].

The double EEX (DEEX) beamline at the AWA is going to have two double dogleg type EEX beamlines [5] with ~3 m separation for the transverse manipulation using quadrupoles and masks. Each dogleg uses 20 degree bending angle and 1.5 m separation between dipoles. The dispersion of the dogleg is ~0.77 m, and the corresponding deflecting cavity (TDC) strength needed is 1.3 m^{-1}. This beamline also has many YAG screens for transverse measurements, ICTs for the charge level, and two TDCs for longitudinal diagnostic. A single dipole magnet is followed by each TDC to measure the longitudinal phase space. Approximately a 1-m space is reserved at the upstream, middle, and downstream of the double EEX beamline for various EEX applications (e.g. THz radiation [9], wakefield applications [10], etc.).

In the remainder of the paper, we present a study of the CSR-effect in EEX and some preliminary simulation results for applications.

CSR SUPPRESSION IN DOUBLE EEX BEAMLINE

CSR is a well-known limitation for dispersive beamlines (e.g. chicane) and it comes as no surprise that it strongly impacts the DEEX beamline which consist of eight dipole magnets with large bending angles and (some) applications that require a high charge beam. We have found a simple method to partially suppress the CSR-effect for some applications [11], but we still have significant emittance growth along the beamline [7].

Figure 1: AWA drive beamline configuration with a double EEX beamline.

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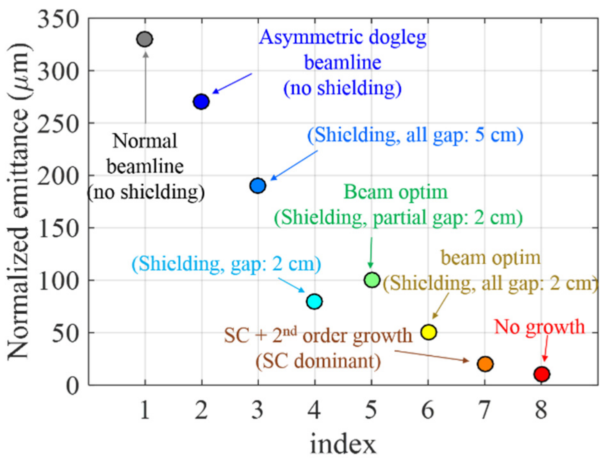

Figure 2: Final horizontal emittance after the double EEX beamline. The 5-nC beam is accelerated up to 50 MeV.

We studied three methods to reduce emittance growth from CSR: (1) asymmetric dogleg, (2) shielding, and (3) transverse beam tuning, summarized in Fig. 2. The y-axis is the final horizontal emittance after the DEEX beamline and each color corresponds to each trial. Start-to-end simulations are used (GPT [12]) to simulate the beam transport, and CSR is included using the CSR-module from Ref. [13]. A 5-nC beam is accelerated to 50 MeV with four accelerating RF cavities, which provides a normalized horizontal emittance at the end of the linac of 10 µm. This is the initial emittance to DEEX. This emittance increases to ~30 µm after the DEEX due to nonlinear fields from magnets and cavities and space-charge effect but without CSR. Once CSR is included, the final emittance increases from 30 µm to 330 µm, demonstrating that CSR is the major factor limiting DEEX.

The first method studied to suppress the CSR effect was the asymmetric dogleg method that uses two different angles for the two doglegs in the EEX beamline [11]. Although it is effective in suppressing the CSR effect on the LPS, the final emittance is still enhanced to 270 µm. Since this method requires a long space compared to identical doglegs and the suppression was not effective enough, we dropped this option for the current DEEX design.

The second method studied used to suppress the CSR-effect uses two shielding plates to suppress CSR (CSR shielding [14,15]). We compared cases where the shielding gap was applied to the entire DEEX beamline to ones where the gap was only applied at key locations. When the gap is applied to the entire beamline, a 5-cm gap reduced the final emittance from 330 µm to 190 µm whereas a 2-cm gap reduced it to 70 µm. This is because the 5-cm gap only cuts a small portion of low-frequency CSR spectrum [16]. Since it is difficult to apply the 2-cm gap to entire beamline, due to the beam transport, we choose to apply it only in the dipole vacuum chambers use our normal 5 cm gap in the rest of the DEEX beamline. This point is labeled "partial gap" in Fig. 2.

Finally, we studied a third method to suppress the CSR-effect that uses transverse beam tuning. When CSR increases the longitudinal emittance in the bend, it becomes entangled with the horizontal beam properties (e.g. beam size, slope, and emittance). Therefore, it is possible to minimize the CSR effect by tuning the transverse beam property [7]. Figure 2 shows the 2-cm gap for the entire beamline generated 70 µm without beam tuning. However, when the 2-cm gap is combined with the tuning method, the emittance is further decreased to 50 µm.

Our beamline design will use the partial gap (2 cm) combined with the tuning method to achieve 100 µm for the high charge case (5 nC). This design is very effective at suppressing the CSR-effect at low charge (~100 pC). The emittance of 1.05 micron is increased to 1.75 micron without shielding while the current design can suppress it to 1.15 micron. It is possible to preserve the emittance with 1-cm gap for the whole beamline or 2-cm gap for the whole beamline with a low bending angle (5 degree) [7].

PRELIMINARY RESULTS OF DOUBLE EEX APPLICATIONS

In this section, we present preliminary simulations and/or experiment results for two DEEX applications. The first application uses LPS to achieve a high transformer ratio, and the second application is bunch compression to overcome several disadvantages of the chicane compressor.

Current Profile Shaping

Collinear type wakefield accelerators are attractive options for the XFEL or other linac-based light sources since these accelerators may provide a high gradient and low construction cost compared to conventional accelerating cavities [17]. One obstacle to realize it is the transformer ratio, defined by the ratio of the maximum decelerating field inside the drive beam to the maximum accelerating field behind the drive beam. Since this factor is related to the efficiency of the wakefield acceleration, it is important to achieve a high value.

Beam with symmetric current profiles are limited to a transformer ratio of 2 [18], but asymmetric current profiles (e.g. triangle) can achieve a high transformer ratio (greater than 2) [19]. Various asymmetric profiles were recently demonstrated at AWA [5] and a high transformer ratio from a quadratic profile was also measured very recently [20]. This experiment demonstrated that we can achieve a transformer ratio of ~5.1 which is even higher than previous record (3.5) with shaping by another method [21].

We plan to demonstrate the shaping using the double EEX beamline. At the same time, we are going to prove the relationship between the current profile and the transformer ratio as predicted by theory. The final goal in terms of transformer ratio is more than 10.

Particle tracking simulations support the feasibility of this experiment. The DEEX beamline can generate various current profiles listed in Ref. [18] and [19]. Since the longitudinal phase space measurement is available at AWA [20], we can observe the wakefield pattern for

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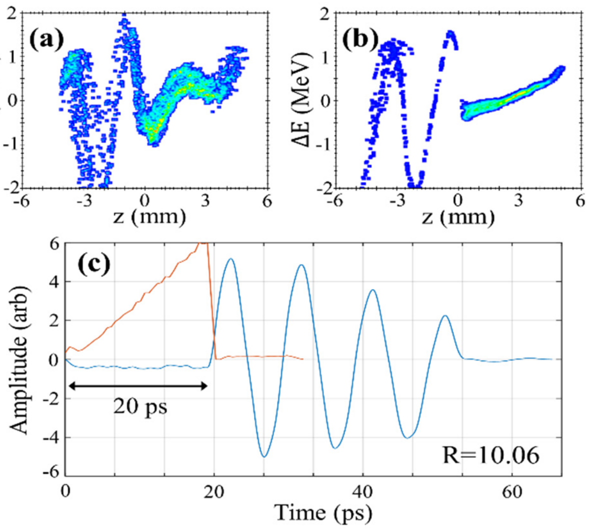

Figure 3: Reconstructed longitudinal phase space of (a) triangle and (b) special head-and-triangle drive beam with a long witness beam. (c) Wakefield pattern estimated from the simulated current profile. Estimated transformer ratio is 10 (ideal is 12).

different drive profiles as shown in Fig. 3. In this figure, (a) and (b) show reconstructed longitudinal phase spaces from different current profiles. The structure introduced in Ref. [10] is used for the simulation, and these are S2E simulation results. The transformer ratio can be calculated from the measured longitudinal phase space or a numerical estimation from the measured current profile, as illustrated in Fig. 3(c).

By optimizing the head shape of the triangle profile, transformer ratio of 10.06 is achieved in simulation and it is very close to the ideal value of 12 under this condition.

EEX as Bunch Compressor

While the magnetic chicane is clearly today's state-of-the-art bunch compression system [22] it still has a few minor limitations. First, a chicane compressor requires a negative longitudinal incident chirp since the momentum compaction of the chicane and the chirp together determine the compression ratio. Therefore, changing the compression ratio is not easy. Second, the strong compression normally generates a double-horn feature on the current profile that can affect the performance of the XFEL as well as radiation safety. Finally, it is necessary to remove this energy chirp after the chicane with a dechirping beamline or operating a linac off-phase.

An EEX compressor may be able to overcome these limitations. While the chicane relies on the path-length difference of different energies, compression using EEX uses the transverse focusing and the transverse-to-longitudinal exchange. Ref. [22] presents preliminary simulations to show the advantages from EEX compressors. Since the compression ratio is determined by the horizontal focusing in the middle section (shown in Fig. 1), the compression ratio is easily tunable; even bunch lengthening and bunch shaping are possible. Second, the transverse focusing cannot introduce double horn features for initially smooth phase space. Even though the double horn feature is introduced by the kink on the initial longitudinal phase space, it may be cancelled by third order momentum kick from a single octupole magnet. Finally, the longitudinal chirp at the exit of the DEEX beamline depends on the quadrupole setting in the middle section again. Both negative and positive chirps can be generated and be controlled in reasonable range.

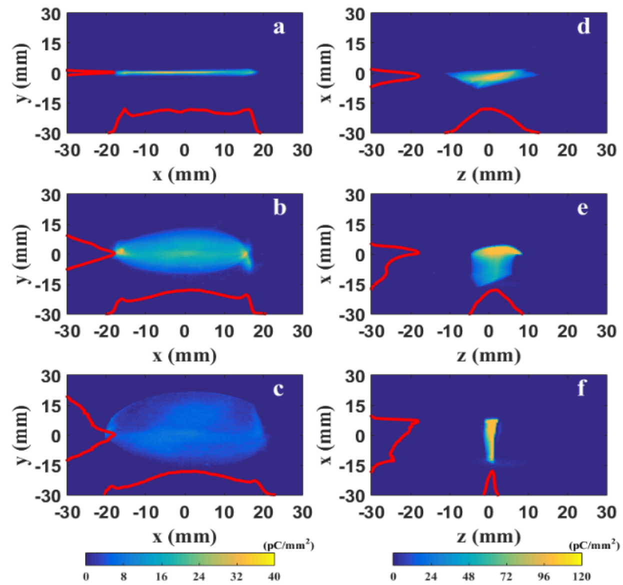

Figure 4: (a-c) Electron-beam images at the YAG screen after a single EEX, showing the impact of an upstream quadrupole, Q1. (a-c) show transverse image as Q1 was set to (a) –0.7 T/m, (b) 0 T/m, and (c) +0.7 T/m. (d-f) utilize a deflecting cavity to measure bunch length, with Q1 set to (d) –0.5 T/m, (e) 0 T/m, and (f) +0.5 T/m.

The tunable compression ratio described above was partially demonstrated during the single EEX shaping experiment last year. When the quadrupole in front of the EEX beamline focused/defocused the beam vertically (shown in Fig. 4 (a-c)), the horizontal beam size after the EEX beamline does not change (a-c) while the bunch length changed from 1.4 mm to 5.0 mm (d-f). Compared to the zero quadrupole case (3.2 mm), negative and positive quadrupole gradients compressed and lengthened the bunch length.

We plan to demonstrate this tunable compression ratio using the double EEX beamline. Based on the simulation, we expect to see the bunch length shorter than 0.05 mm. Also, we plan to explore other advantages, double horn and chirp control, during this experiment.

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CONCLUSION

We presented the current status of the double EEX (DEEX) upgrade at AWA. A DEEX beamline is a powerful phase space manipulator and it has numerous applications. We introduced preliminary simulation results for two promising applications: shaping and compression. Various EEX applications will soon be demonstrated at AWA. On the other hand, the DEEX beamline at AWA has a big emittance growth issue due to (1) many dipole magnets, (2) large bending angles and (3) high charge applications. We explored three simple methods to suppress CSR effects, and CSR shielding combined with beam matching is the most promising method found so far but we are still exploring other avenues to handle CSR in the EEX beamline.

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