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APPLICATIONS AND OPPORTUNITIES FOR THE EMITTANCE EXCHANGE BEAMLINE

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Abstract

Emittance exchange (EEX) provides a powerful method for controlling the longitudinal phase space distribution using the relatively simpler methods of transverse control. An EEX beamline was installed at the Argonne Wakefield Accelerator (AWA) facility in 2015. Several experiments important to wakefield acceleration, such as a high transformer ratio from shaped bunches, have already been demonstrated. A on-going program to seek new opportunities for the EEX beamline including beam's temporal profile shaping, THz radiation generation, time-energy correlation control, diagnostics uses of EEX, etc is underway. In this paper, we present the status of this program and discuss potential applications.

EMITTANCE EXCHANGE

Emittance exchange (EEX) is a unique beam manipulation method for exchanging the transverse and longitudinal phase spaces. The concept was first introduced in 2002 by M. Cornachia and P. Emma [1] with an incomplete exchange, and was subsequently modified to give a complete exchange in 2006 by K.-J Kim et al. [2]. A thorough and intuitive description of how EEX works is given in appendix A of Ref. [3]. The A0 photoinjector at Fermialb was the first facility to demonstrate the exchange of emittance [4], as well as the first to generate a bunch train [5]. These achievements provided new opportunities for phase space manipulation and inspired various new applications.

Early applications of EEX seeked to generate small transverse emittances. The idea was to make one of the transverse emittance extremely small (e.g. $\varepsilon_y \gg \varepsilon_x$) by a flat beam transform (FBT) [6] and then exchange the large emittance (ε_y) with the small longitudinal emittance ($\varepsilon_y \gg \varepsilon_z$) by using the EEX beamline. This emittance repartition would be a feasible application for a linear collider without damping rings. At the same time, it can ease the stringent transverse emittance requirements for linac based light sources such as XFEL and XFELO [2].

In addition to repartitioning, EEX provided a new way to control the longitudinal beam properties. Researchers started to work on utilizing this new opportunity and published many theory and simulation papers beginning in 2010. For example, a multi-slit was applied to the beam to generate multiple transverse beamlets, and EEX successfully converted it to a longitudinal bunch train [5]. Similarly, there were other concepts to extend this capability to X-ray generation such as Ref. [7-9]. At that time, a similar concept for triangular bunch generation arose [10]. Here, a transverse mask was applied to the beam to shape the electron beam's transverse distribution so that EEX converts it to a triangular longitudinal profile. Follow-up work continued to improve the quality of the method [3, 11]. It was finally demonstrated in 2016 at Argonne Wakefield Accelerator (AWA) facility [12].

AWA's EEX R&D program has two purposes: to experimentally demonstrate and improve EEX methods at the AWA facility and to explore new applications for EEX. This paper describes the most recent research taking place at the AWA facility and shows the potential benefits that EEX can provide to the Accelerator community.

ARGONNE WAKEFIELD ACCELERATOR FACILITY

The AWA facility installed and commissioned an EEX beamline in 2015 [13]. After the shutdown of the A0 photoinjector facility, the AWA facility currently has the only operating EEX beamline in the world. More recently, the AWA facility upgraded this beamline to a double EEX beamline, that is well equipped with diagnostics, to extend our EEX capability and research scope.

The upgraded EEX beamline is shown in Fig. 1 and its detailed parameters are listed in Table 1. This beamline consists of four sections: matching, 1st EEX, middle matching, and 2nd EEX. At the end of each EEX beamline, we have diagnostics for measurement of both the transverse and longitudinal phase spaces.

In addition to the EEX beamline, the AWA facility also has other complimentary capabilities enabling various proof-of-principle experiments vital to beam control [14]. These capabilities have been demonstrated through many collaborations with the AWA group and strongly support EEX R&D at AWA facility.

Table 1: The AWA Facility Operational Parameters and the EEX Beamline Design Parameters

AWA facility parameters	**Value**	**Unit**
Operational charge	0.01-100	nC
Laser spot radius	0.1-12	mm
Laser pulse length (FWHM)	0.3-10	ps
Maximum beam energy	62	MeV
EEX beamline parameters	**Value**	**Unit**
Bending angle	20	degree
Dipole-to-dipole	1.5	m
Dispersion of dogleg	0.7	m
R56 of dogleg	0.3	m

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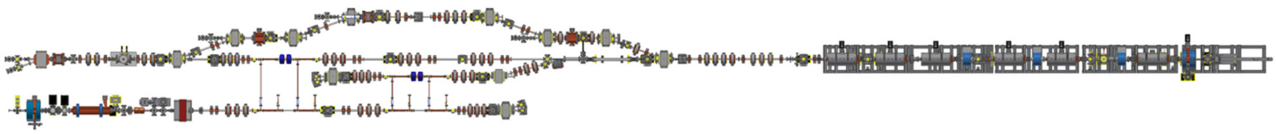

Figure 1: Beamline layout of the AWA facility. The uppermost beamline is the double EEX beamline.

AWA RESEARCH 1: REPARTITIONING

Working in collaboration with NIU, Hiroshima university and KEK, the AWA group plans to demonstrate 6D emittance repartitioning. As described in Ref. [15], the initial photoinjector emittance of (45, 45, 10) µm for x, y, and z directions could be repartitioned to satisfy the ILC emittance requirement (10, 0.04, 2.5E5) µm using the FBT with high emittance ratio and followed by an EEX. So far, the FBT was successfully demonstrated at the AWA facility with a 1 nC charge and the best emittance ratio measured was 110 [16].

In the next step, we plan to send this flat beam into the EEX beamline to demonstrate 6D repartitioning. A flat beam will be generated using a magnetized beam and three skew quadrupoles located at the exit of the linac (see Fig. 1). The four quadrupoles located after the skew quadrupoles are used to match the beam's transverse condition into the EEX beamline. Both transverse and longitudinal phase space measurements areavailable at the entrance and exit of the EEX beamline.

AWA RESEARCH 2: LONGITUDINAL PROFILE SHAPING

As already described in the earlier section, the EEX beamline exchanges the transverse and longitudinal phase spaces. This implies another capabilitiy: any transverse distribution can be converted into a longitudinal distribution. This capability enables new and better quality longitudinal phase space control. As the first example, we will show profile shaping methods the AWA group is currently working on.

There are two types of longitudinal profile shaping. One creates discretely modulated profiles (i.e. bunch train generation for tunable coherent radiation generation) and the other creates continuously shaped profile (e.g. a triangular profile for high transformer ratio [17]).

Discrete Modulation

Bunch train generation requires a discrete transverse modulation to be converted into a discrete longitudinal density modulation. Applying the multi-slit [5] is the easiest way to generate a discrete density modulation, but it loses 50% of the charge. To avoid this charge loss issue and increase the tunability, several methods are being considered and some of them have been tested.

The micro-lens array can be used to generate a dot-patterned electron beam distribution. This dot-pattern at the cathode can be imaged to the entrance of the EEX beamline, where the EEX converts it to a bunch train [18]. Here the spacing between the micro bunches can be easily tuned by rotating the micro-lens array or the imaging ratio.

The same result can be accomplished using an array of small cathodes (similar to Ref. [7]). Here the cathode array generates a dot-pattern beam. Then conversion process is the same as in the MLA case. A group at LANL is currently testing various field emission cathode arrays partially for this purpose [19]. These cathodes are under test at Argonne Cathode Test stand (ACT) which is a small L-band beamline located in the AWA facility [20].

A more recent concept for generating a bunch train use transverse wigglers [21]. A transverse wiggler imparts a transverse momentum modulation to the transverse phase space and the EEX beamline converts this modulation into a longitudinal density modulation. Here the micro bunch length and spacing can be independently tuned by the incident beam's convergence (controlled with quadrupole magnets) and the wiggler field strength (controlled by the gap of the wiggler).

Continuous Profile Shaping

Continuous profile shaping can be accomplishedwith methods similar to those just described. Masking can shape the transverse profile into any shapes [12], and the imaging of a transversely shaped laser on the photocathode or a field emitter array can generate them too.

Continuous and arbitrary profiles can also be generated using nonlinear magnets. A series of nonlinear magnets can make a polynomial relationship between the initial and final particle coordinates. This polynomial correlation can be used to create various downstream profiles. If the initial transverse profile is close to quadratic, a single sextupole magnet can convert this profile into a triangle profile (see. Fig. 2).

Another recent concept under study is using transverse wigglers. Since the wiggler gives a sinusoidal modulation to the transverse momentum, each modulation from the wigglers works as the basis for arbitrary correlation as we can see from Fourier expansion. The concept is numerically confirmed and introduced in this proceeding [22].

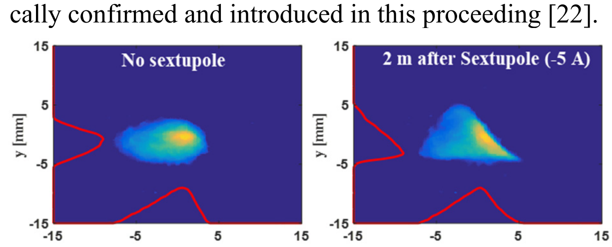

Figure 2: Transverse beam images measured at the 3 m downstream of a sextupole magnet. A vertically symmetric profile is converted to a triangular profile by the sextupole.

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AWA RESEARCH 3: COMPRESSION

The next capability of the EEX beamline we describe is another example of longitudinal control, bunch compression. Prevous work by LANL [23] and ANL [24] explored the feasibility of bunch compression using EEX. We recently revisited this concept but concentrated on establishing capabilities beyond the compression as done with a chicane.

Chicane compression only provides bunch compression given an incident chirp. Since it does not change particle's longitudinal momentum, chirp control is required both before and after the chicane. On the other hand, EEX based bunch compression controls both particle's longitudinal position and momentum [25] as described below.

The EEX compressor enables tunable compression. Quadrupole magnets before the EEX are used to control the transverse distribution and therefore determine the longitudinal properties after the EEX. An incident chirp is not required for the compression while transverse focusing compresses the bunch longitudinally. Simulaton studies have shown that if the transverse emittance is small enough, EEX can generate sub-fs long bunches [26].

The EEX compressor also enables tunable chirp control. The quadrupoles before the EEX can control the slope of the transverse phase space. This change of the slope results in a change of the longitudinal chirp after the EEX. Thus, an EEX compressor does not require additional chirp control using linac phase or dechirper.

The tunable compression from the EEX compressor enables applications that need tunable longitudinal (energy or density) modulations [27]. As an example, double-EEX beamline [24, 28] which consists of two EEX beamline with a transverse manipulation section in the middle. The longitudinal modulation of an incident beam is converted to a transverse dmoulation by the first EEX. Next, middle section uses quadrupoles to tune the modulation. Finally, the second EEX beamline converts the transverse modulation to either a density or energy modulation depending on the application.

Similarly, the tunable chirp enables application for the XFELO. The XFELO requires extremely small energy spread (~1E-5) due to its spectral acceptance. At the same time, it requires a bunch length of ~0.5 ps which requires bunch compression (bunch length out of the injector is typically a few to tens of ps). While conventional methods require appropriate adjustment of linac phase for chirp control, harmonic cavities for linearity, chicanes for compression, and dechirper for chirp removal [29], the EEX compressor only requires harmonic cavities for linearity control [30]. Moreover, even those can be taken out as discussed in the next section.

AWA's recent study showed promising simulation results meeting both the length and energy requirements of the XFELO [30]. We currently have an emittance growth issue originated due to CSR, so more optimization work is underway to suppress the CSR effect sufficiently.

AWA RESEARCH 4: LINEARITY

The previous sections focused on control of one-dimensional characteristics, such as profile and bunch length. In this section, we focus on two-dimensional control. We introduce two examples: correction of nonlinearities in longitudinal phase space and the generation of arbitrary longitudinal correlations.

A nonlinearity in longitudinal phase space can induce unwanted features degrading the beam quality. The double-horned profile after a strong compression is one of the most well-known examples of this nonlinearity [31]. In this case, a third-order component in the longitudinal phase space is transformed into an S-shape in the phase space by a strong compression. This S-shape gives rise to two spikes (a.k.a the double-horn) that appear at each end of the density profile.

The simplest way to suppress the double horn profile is linearizing the phase space which has traditionally done with a high harmonic RF cavities. In the double-EEX beamline, the double-horn profile can be corrected with a single octupole magnet. Recent simulation results support this idea [32], and the AWA plans to demonstrate the concept experimentally by the end of this year.

A second example of nonlinearity correction is for the XFELO application where harmonic cavities apply a time-dependent sinusoidal longitudinal momentum kick. The role of harmonic cavities in the XFELO beamline can be replaced by a single sextupole magnet in the double-EEX beamline. More details are covered in Ref. [30]

Another recent work at the AWA is the generation of arbitrary correlation. As mentioned earlier for the bunch train generation application, transverse wigglers can provide an arbitrary correlation between transverse position and momentum [22]. This means that it can be used to either linearize the phase space or add a desired nonlinearity on the phase space. If an EEX beamline is followed by this wiggler system, the control of nonlinearity can be applied to the longitudinal phase space. The AWA group is currently developing this method and looking for applications.

AWA RESEARCH 5: DIAGNOSTICS

In this section, we introduce an application utilizing the longitudinal-to-transverse exchange. While transverse-to-longitudinal property conversion provides new applications based on easy to control longitudinal properties, longitudinal-to-transverse exchange enables ultra-high resolution longitudinal diagnostics [33].

Two representative measurement methods of longitudinal properties are bunch length measurement using a deflecting cavity and energy measurement using a dipole spectrometer. A correlation generated by the deflecting cavity or dipole magnet enables these measurements, but it also limits the resolution due to the contribution from the original transverse components (e.g. finite transverse beam size). This is why the transverse emittance limits the resolution of these representative methods.

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On the other hand, the resolution of EEX-based measurement of the same longitudinal properties is not limited by the transverse coordinates because of the exchange. Thus, the resolution limit only comes from higher-order components in the beamline and collective effects such as CSR. If one can properly suppress these effects, the resolution reaches ~10 as for time and <1 keV for energy. The AWA group is working on the design of the diagnostic system and exploring its achievable resolution. Preliminary results [33] already show the measurement case for the beam condition cannot be measured by deflecting cavity with the power level to the one used for EEX.

CONCLUSION

EEX is a new beam manipulation method and its applications have yet to be fully explored. It enables new limits of the longitudinal beam manipulation which is usually limited due to the short duration of the beam moving speed of light or correlation. There have been interesting EEX applications introduced to accelerator community in last two decades. The AWA group is currently exploring even more applications to exploit the full potential of EEX. It is not discussed in this proceeding, but many hurdles that needs to be overcome were discovered while studying these applications. The AWA group is also working on these issues (e.g. timing and energy jitter [34] and emittance growth from CSR [35] etc) to go beyond proof-of-principle experiments.

We invite accelerator scientists to think about possible benefits they can get by applying EEX to their research. We hope EEX enables a step up to the next level of accelerator development for future accelerators.

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