ANALYSIS OF EXPERIMENTAL RESULTS INVESTIGATING SHIELDING FOR COHERENT SYNCHROTRON RADIATION MITIGATION

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Abstract

An experiment was conducted at Argonne Wakefield Accelerator to evaluate the efficacy of shielding plates with varying gap sizes on the suppression of coherent synchrotron radiation (CSR) effects in a compression environment. The longitudinal phase spaces upstream and downstream of the compression beamline were measured with three different shielding gap sizes. Although the results were broadly consistent with expectations, several issues require further clarification, including beam stability and nonlinear stretch and shortening under strong CSR fields. The analysis was performed using the 1D longitudinal tracking code, BELT, and included both CSR and space-charge effects. We present the analysis results.

INTRODUCTION

Coherent Synchrotron Radiation (CSR) often has adverse effects, inducing nonlinear energy spread and transverse emittance growth. Although CSR effects on the beam depend on various factors, including the bending angle and current profile, previous studies have demonstrated that the vacuum-chamber geometry is also an important factor [1–3]. This effect is often referred to as CSR shielding. To date, studies of CSR shielding have mainly focused on demonstrating the shielding effect itself. Further study in a realistic compression environment is necessary to exploit this mechanism for beam-quality preservation.

To experimentally study CSR shielding in a compression environment, a chicane-like beamline was constructed at the Argonne Wakefield Accelerator (AWA). The first campaign encountered several issues associated with the large R_{56} of the beamline ($\approx$ 0.45 m) and the resulting sensitivity to the α-BBO crystal setup [4]. In the second campaign, we addressed the issues identified during the first run and measured longitudinal phase spaces affected by CSR for various shielding-gap sizes.

The measurement results show the expected shielding-gap-dependent changes in the longitudinal phase spaces. However, clear signs of machine instability prevent us from drawing firm conclusions directly from measurements. To better understand the collected data and prepare the third campaign, we performed an analysis using a one-dimensional tracking code, called BEam Longitudinal Tracking (BELT) [5]. This lightweight code was used to model the chicane-like beamline at the AWA facility.

We first briefly introduce the experiment setup, which was described in our earlier publication [4], and discuss the experiment results. We then present the simulation results from the BELT code and discuss the issues encountered during the analysis.

MEASUREMENT OF CSR EFFECTS ON A BEAM WITH VARIABLE SHIELDING

The experiment was conducted at the AWA facility using a reversed-chicane beamline [4]. As shown in Fig. 1, the beamline consists of two identical doglegs and two quadrupoles that flip the phase space, allowing the two identical doglegs to operate like a chicane. This layout has a large R_{56} of 0.45 m [4]. Each dipole in the reversed chicane is equipped with a tunable parallel-plate shielding gap. Longitudinal phase-space diagnostics are available both upstream and downstream of the reversed chicane, allowing the CSR-induced changes to the beam to be measured across the chicane.

During the experiment, bunches with charges of 1-2 nC and a nominal energy of approximately 44 MeV were prepared. The variable shielding-gap was scanned sequentially from 3 cm to 2 cm and then to 1 cm. The 3 cm gap measurement was repeated to assess measurement consistency. At each gap size, the measurement was repeated with a horizontal slit (50 mm×2 mm) installed upstream of the chicane. This slit reduces the total bunch charge by blocking the beam in the vertical direction while minimally perturbing the horizontal or longitudinal phase spaces. This low-charge case was used as the reference corresponding to the CSR-off case in the simulations. The measured phase space images are displayed in Fig. 2.

From Fig. 2, it is clear that the CSR-induced energy modulation strongly depends on the shielding-gap size. Although the overall structure follows the typical steady-state CSR wake pattern [6], the distance between the energy-loss trough and the trailing energy plateau decreases as the shielding gap is reduced. This behavior is expected from the suppression of low-frequency components of the CSR wake by parallel-plate shielding [1]. In contrast, small energy modulations originating from α-BBO setup errors become more pronounced as the gap is reduced. At this stage, it is unclear whether these modulations originate from laser-system instability or from modulation amplification through a mechanism similar to microbunching instability [7].

Although the results show the expected shielding-gap-dependent changes, they also show clear signs of machine instability. The measurement began with the 3 cm gap, and

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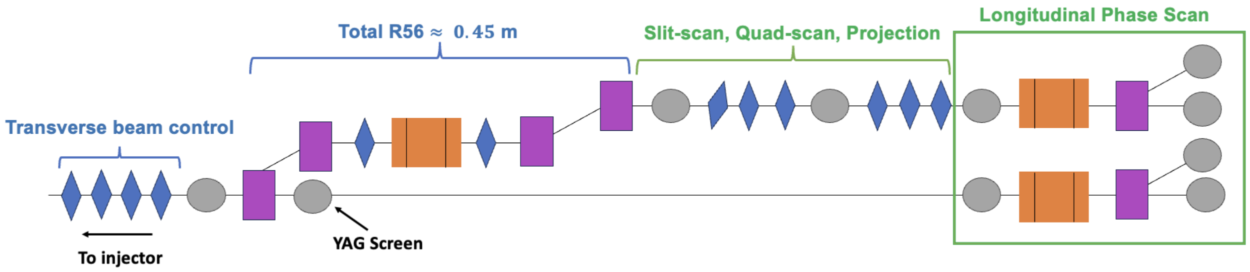

Figure 1: Beamline layout for the CSR measurement. Blue diamonds are quadrupoles, purple rectangles are rectangular dipoles, orange boxes are transverse deflecting cavities, and grey circles are diagnostic stations, including slits and YAG screens.

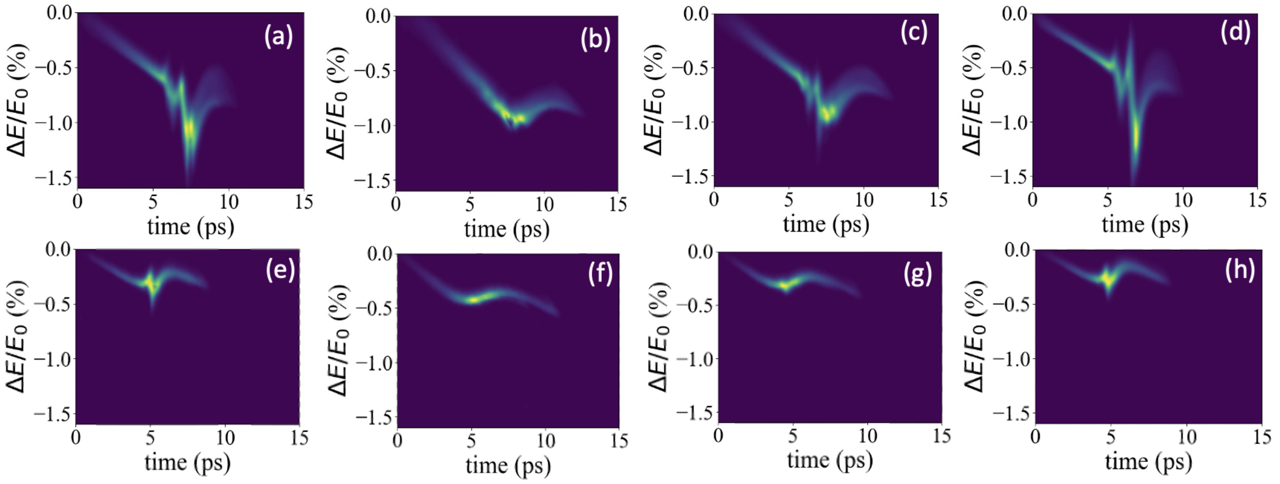

Figure 2: Measured longitudinal phase-spaces. The first row shows longitudinal phase spaces with shielding-gap sizes of 3 cm (repeat measurement), 3 cm, 2 cm, and 1 cm, respectively. The second row shows the corresponding measurement with a 2-mm slit. Each column uses the same shielding-gap size for the two rows.

the gap was then reduced. After one complete set of measurements, the 3-cm gap measurement was repeated as a consistency check. As shown in Fig. 2 (a) and (b), the two 3 cm gap measurements show significantly different bunch lengths and energy spreads. The modulation associated with the α-BBO mismatch is also more pronounced in the repeat measurement. Panel (e) and (f) show the corresponding results with the 2 mm slit, which significantly reduces the bunch charge. However, differences in the observed bunch length and modulation remain even in these reduced-charge cases. It is worth noting that there are 45 minutes gap between each measurement. Therefore, laser-system instability could be one possible cause of the observed differences.

These results identify several issues that needs to be investigated or addressed before the next campaign. Further analysis is also required to determine whether the observed trends originate primarily from the laser instability or the shielding effect itself.

ANALYSIS USING 1D LONGITUDINAL TRACKING SIMULATION

We chose one-dimensional longitudinal tracking as the primary analysis tool because of its convenience and the limited availability of transverse beam information, such as transverse beam size along the chicane and the incident transverse phase spaces. In particular, the BELT code was selected because it can include parallel-plate shielding effects and it supports backward tracking. The original plan was to apply backward tracking to the longitudinal phase spaces measured with the 2 mm slit. However, these beams still exhibited significant CSR effects and therefore could not be treated as CSR-off cases. We therefore adopted the longitudinal phase space measurement upstream of the chicane as the input for forward tracking. The 1.78 nC case was selected to extract the longitudinal correlation curve. The measured phase space used for this input is shown in Fig. 3.

To model the reverse chicane in the BELT code, four 30 cm dipoles, each providing a bending angle of 20°, were placed next to each other. The R_{56} of the first and third dipoles were set to 0.006 m, while those of the second and fourth dipoles' were set 0.225 m. This configuration approximates the longitudinal transport through the reversed chicane while retaining the R_{56} evolution and CSR contribution from each dipole. The drifts and quadrupoles were ignored in this one-dimensional model because they do not directly generate CSR and their contributions on longitudi-

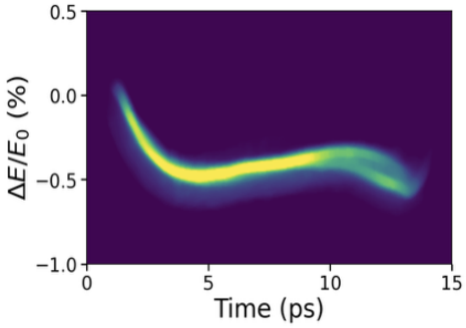

Figure 3: Measured longitudinal phase-space upstream of the chicane.

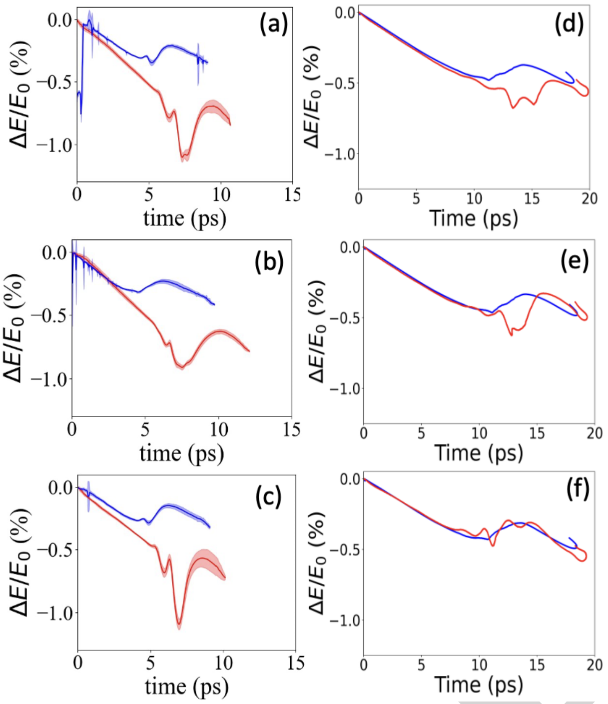

Figure 4: Longitudinal phase-spaces from measurements and simulations. Red and blue curves correspond to without and with a 2 mm slit. The left and right columns show measured and simulated correlations, respectively. The rows correspond to shielding-gap sizes of 3 cm, 2 cm, and 1 cm from top to bottom.

nal dynamics is negligible. The three shielding-gap sizes from the experiment were then simulated.

Figure 4 compares correlation curves from the experiment (left column) with the simulation results (right column). The red and blue curves correspond to the cases without and with the 2 mm slit, respectively. In the BELT simulations, the slit case was modeled by reducing the bunch charge from 1.78 nC to 0.45 nC.

From the simulated results, several shielding-gap-dependent features can be observed. First, the distance between the trough and plateau decreases as the shielding-gap is reduced. Second, in the 3 cm gap case, there are three troughs followed by a plateau due to α-BBO mismatch (see panel d). Third, as the shielding-gap is reduced, the third trough merges with the trailing plateau and eventually disappears. Similar trends are also observed in the experimental results shown in the left column. This agreement indicates that the observed changes are, at least in part, shielding-gap-dependent.

On the other hand, the simulation results also show a large discrepancies from the measurements in term of bunch length and energy spread. A similar discrepancy is observed in the reduced charge case. Possible sources include calibration errors of upstream and downstream longitudinal diagnostics, uncertainty in the upstream longitudinal phase space measurement due to space-charge driven evolution from the chicane entrance to the diagnostic location (≈15 m), or loss of information associated with transverse-longitudinal couplings from CSR and a slit necessary for longitudinal diagnostics [8]. The dominant source of this discrepancy is not yet clear.

CONCLUSION

The second campaign of the CSR shielding experiment was carried out in a realistic compressor environment. Although the laser-system instability issues was confirmed during the measurement, the observed changes, along with unique features associated with the α-BBO mismatch, indicate that shielding-gap-dependent effects are present. The analysis also shows that additional care is required for diagnostics calibration and beam alignment through the diagnostic slit. In the next experimental campaign, multi-cycle measurement for different shielding-gap sizes will be necessary to separate shielding effects from shot-to-shot and long-term machine variations.

ACKNOWLEDGMENTS

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