Experimental Studies on Coherent Synchrotron Radiation in the Emittance Exchange Line at the Fermilab A0 Photoinjector

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Abstract

Future accelerators will employ advanced beam conditioning systems such as emittance exchangers to manipulate high brightness beams. Coherent synchrotron radiation (CSR) in the dipoles could limit the performance of the emittance exchanger. In this paper, we report the experimental studies on measuring CSR and its effects on the beam at the A0 photoinjector in the emittance exchange line. After reporting the CSR power measurements, we report on the diagnostic scheme based on a weak skew quad in the emittance exchange line to study the CSR effects on the beam and other beam dynamics.

INTRODUCTION

Phase-space manipulation of high-brightness beams will play a crucial role in future accelerators. One such phase-space manipulation involves exchanging the longitudinal emittance with the transverse emittance of the beam. The ability to exchange emittance is useful in free electron lasers where the transverse emittance needs to be very small. The RF gun typically produces a beam with a smaller longitudinal emittance compared to the transverse emittance (typically $\sim 1\mu$m). Thus exchanging the transverse and longitudinal emittance not only gives a beam with a smaller transverse emittance, but also a larger longitudinal emittance, which reduces undesirable effects like microbunching instability [1]. Moreover, by adding a transverse mask to the incoming beam, 100 femtosecond bunches can be generated using the emittance exchange principle [2].

The emittance exchange line (EEX) consists of a TM_{110} rf cavity sandwiched by doglegs. The scheme is based on a variation of the original scheme proposed by Cornacchia, where the cavity was at the center of a chicane. A crucial advantage of the new scheme is the output emittances are uncoupled after the exchange[3]. Neither schemes take into account the finite length of the cavity, space charge effects, coherent synchrotron radiation (CSR) and wakefields.

When an electron bunch goes through a magnetic bend, it generates synchrotron radiation. When the wavelength of the synchrotron radiation is comparable to the bunchlength, then the radiation becomes coherent and is called as CSR. Since the CSR is coherent radiation, the intensity of such radiation goes as N^2, where N is the number of particles in the bunch.

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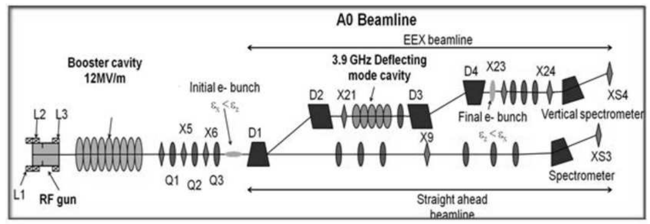

Figure 1: Experimental Setup of the A0 photoinjector facility. The quad before the dipole D3 is a skew quad.

Also, the bunch loses energy due to CSR leading to an energy spread on the bunch. The power loss due to CSR can be expressed as: $P = \frac{N^2 x e^2}{\epsilon_0 \rho^{2/3} \sigma_z^{4/3}}$, where N is the number of particles, x is 0.0279, ρ is the bending radius ,σ_z is the bunch length, and e is the charge of electron. Therefore, the shorter the bunch at the dipole, the larger the power loss due to CSR [4]. There are other effects as well: the radiation from the tail of the bunch can catch up with the head of the bunch and interact leading to an energy spread within the bunch. The energy spread is then converted to transverse emittance growth when the bunch exits the bend.

Recently, a skew quadrupole was installed before the third dipole in the EEX beamline to study CSR effects. In this work, we present experimental results from operating the EEX line with the skew quad on. This work was motivated by the work at SLAC that used a skew quad to study CSR effects in a bunch compressor[5].

EXPERIMENTAL SETUP

The emittance exchange facility consists of a L-band RF gun followed by a superconducting booster cavity, which accelerates the e-beam to 14 MeV. After acceleration, the beam is steered and focused using the dipoles and the quads (Q1 Q2 Q3). The beam then can either continue straight to XS3 or could be bend into the dogleg. In our experiments, the beam is sent through the doglegs (D1 D2 D3 D4) to the spectrometer (XS4). Between the doglegs is the 3.9 GHz deflecting mode cavity, which was switched on/off in our study. When the bunch passes through the dogleg, CSR is expected to be more pronounced at dipole 3. So, we installed optics to collect the radiation coming out of the port at D3. The light is collimated using an off axis parabolic mirror onto a plane mirror. The reflected light is then directed either to a pyrometer (for power measurement) or to an interferometer (to measure bunch length) [4].

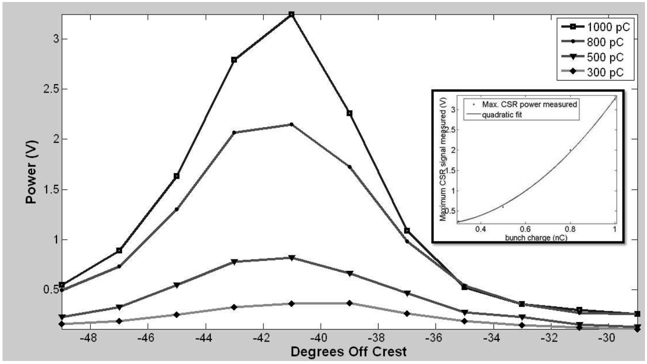

Figure 2: Experiment: CSR Power measurement at dipole 3 as a function of 9-cell phase. Maximum power is observed at 41 degrees off crest. The number of bunches was 10. Increasing the number of bunches saturated the pyro.

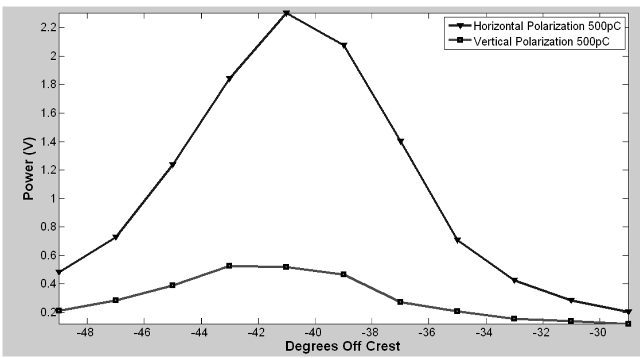

Figure 3: Experiment: For CSR, the horizontally polarized component has approximately 5 times more power than the vertical one. The charge was 500 pc and the number of bunches was 40.

EXPERIMENTAL RESULTS

CSR Power measurements

Synchrotron radiation is predominantly horizontally polarized. Since we bend the beam horizontally, synchron radiation gets multiplied by the bunch form factor and N^2. By installing a polarizer (FIR), we measured the effect of polarization and found that the power is 5 times more in the horizontal direction. Theoretically, the horizontal polarization carries 7 times more power than the vertical. The discrepancy may be due to the finite geometry of the beam pipe cutting off some radiation and also that the radiation is not focussed to a small spot at the detector. We also found that the power increases quadratically with charge as expected. This is shown in Figure 2. Comparison between charges with fixed bunches poses a limitation because the pyrometer gets saturated for higher charge at lower number of bunches. The number of bunches we chose was 10 to prevent the pyro from saturating at 1nC.

Beam dynamics

At the skew quad, the particle get a y kick proportional to its x-position, $y' = \frac{x}{F}$ where F is the focal length of the skew quad. This kick is converted to a y-position change at the screen: $y_{screen} = R_{34} y'_{quad}$. In terms of r.m.s. quantities, as long as the β_y at the screen is small, the y-beamsize, $\sigma_{y_{screen}} = \frac{\sigma_{x\,quad}}{K}$ where K is a constant and $\sigma_{xquad} = \sqrt{x_{\beta quad} + (\eta\delta)^2}$ where η is the dispersion and δ is the energy spread.

WITH 5-CELL OFF: If the beam size at the skew quad is dominated by dispersion (like in a bunch compressor)and assuming linear chirp ($\delta = hz_{in}$), we can write: $\sigma_{y_{screen}} = \frac{hz_{in}}{K}$. After cancelling dispersion, the y-position is proportional to incoming bunch length.In our setup, the dispersion is cancelled by using the last three quads after the X23 screen station.

WITH 5-CELL ON: If the 5-cell is on and when the RF chirp is zero (at minimum energy spread), then we can write $\sigma_{y_{screen}} = \frac{\sqrt{{x_0}^2 + L{x'_0}^2}}{K}$, where L is the length of the doglgeg drift, because the beam size at the skew quad is now dominated by the β_x. From EEX transport equations: we can write $\delta_{out} = \frac{-x_0}{\eta} - \frac{Lx'_0}{\eta}$ Also, for a single particle going through a dogleg, $x_{quad} = x_0 + Lx'_0$. Hence, we can write $x_{quad} = \delta_{out}\eta$. In summary, when the chirp is zero and with the 5-cell on, the y-beam size maps the outgoing energy profile:$y_{screen} = \frac{\delta_{out}\eta}{\kappa_0}$ where κ_0 is a constant of proportionality. Thus the skew quad acts like a vertical spectrometer. Here we have made a thin-lens approximation for the 5-cell and have ignored effects like space charge.

Simulations

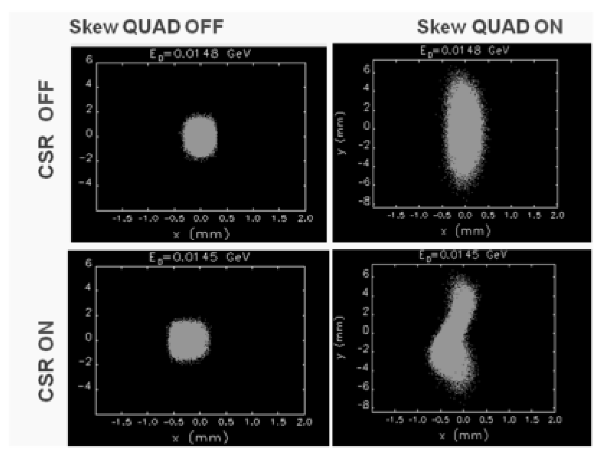

Figure 4: Simulation: elegant showing the effect of CSR and skew quad at X24. Due to CSR, the head particles gets higher energy leading to a transverse offset. The 5-cell was switched off.

We used $BeamLattice$ and $elegant$ programs to study the effect of skew quad on beam dynamics. After optimizing the betafunction using *elegant*, we turned on CSR effects in *elegant* by introducing CSRSCBEND and CSRDRIFT elements. The results are shown in Figure 4. CSR modulates the energy by accelerating the head which then modifies the transverse position of the particles when they come out of the bend. Space charge could also show a similar behavior.

EXPERIMENTAL RESULTS

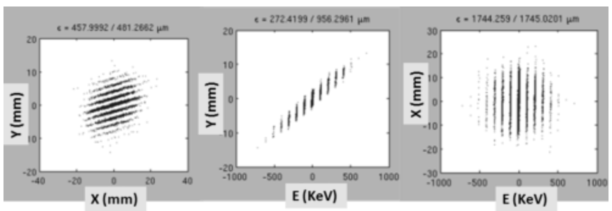

Figure 5: Simulation:Beam lattice program showing the effect of skew quad with slits in and 5 cell on.

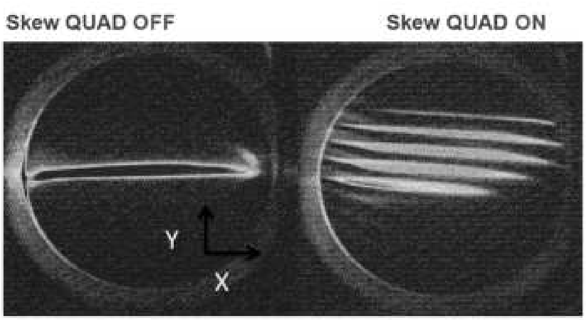

Figure 6: Experiment:When the slis are in at X3 and the 5-cell turned on, the skew quad projects the energy spectrum on the screen when the chirp is zero

5-cell turned on In order to study the effect of skew quad on the emittance exchange line, we switched on the 5-cell with the horizontal slits inserted at X3. When the slits are inserted, the transverse modulation gets transfered to longitudinal phase space leading to a energy and time modulation [2]. Hence at X23, the beam image has no modulation. But, when the skew quad was turned on, the modulation effects are visible in the y-direction. This is shown in Figure 6. This can be explained as follows: As mentioned before, when the chirp is zero (at minimum energy spread), the x-beamsize at the skew quad is dominated by β_x and hence the skew quad projects the x-modulation in y at the screen. Any chirp then shows itself as the slit orientation at X23. However, the x-modulation at the skewquad is proportional to the energy modulation at the output of the 5-cell. Hence, the skew quad can be used to measure the energy spectrum of the beam.

CONCLUSION AND FUTURE WORK

In this work, we have reported on CSR measurements and the effect of skew quad on the dogleg line with the 5-cell turned on and off. We plan to study CSR effects on the bunch with the 5-cell on at larger chirp. This is will not only increase the CSR self-effect but also reduce the beamsize at the screen for convenient beamsize measurements.

ACKNOWLEDGMENTS

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