

INVESTIGATION OF POSSIBLE CSR INDUCED ENERGY SPREAD EFFECTS WITH THE A0 PHOTOINJECTOR BUNCH COMPRESSOR*

R. P. Fliller III[#], H. Edwards, G. Kazakevich, R.M. Thurman-Keup, J. Ruan, Fermilab, Batavia, IL 60510, U.S.A.

T. Koeth, Rutgers University, Piscataway, NJ 08854, U.S.A.

Abstract

The bunch compressor of the A0 Photoinjector at Fermilab was removed this past spring to install a transverse to longitudinal emittance exchange experiment. Prior to its removal questions arose about the possibility of observing the effects of Coherent Synchrotron Radiation on the compressed beam. The energy spread of the beam with and without compression was measured to observe any changes. Various beam charges were used to look for square law effects associated with CSR. No direct observation of CSR in the compressor was attempted because the design of the vacuum chamber did not allow it.

In this paper we report the results of these experiments and comparison with simulations using ASTRA and CSRTrack. The results are also compared with analytical approximations.

INTRODUCTION

The A0 photoinjector is undertaking an experiment to do a proof of principle transverse to longitudinal emittance exchange.[1] This exchange utilizes a deflecting mode RF cavity between two doglegs to produce the exchange. When performing such an exchange, all sources of emittance growth must be understood. The low energy of the A0 beam, 16 MeV, and the compressed bunch mean that Coherent Synchrotron Radiation (CSR) might be a concern for the experiment.

In this paper we discuss measurements done with the A0 bunch compressor prior to its decommissioning to understand any effects of CSR on the A0 beam. These measurements are compared with analytical approximations and simulations using the CSRTrack code.[2] Measurements of CSR in the spectrometer bending magnet are also presented to verify the existence of CSR.

COHERENT SYNCHROTRON RADIATION

CSR occurs when a short bunch passes through a dipole magnet and the radiation from the tail of the bunch interacts with the front of the bunch. A majority of the bunch loses energy, but a portion of the head gains energy. Transverse emittance growth can also occur as

particles do not strictly follow the orbits dictated by the dispersion function because of the energy loss.

The electron bunch radiates a total power of

$$P = \frac{\Gamma(\frac{5}{6})}{6^{1/3} 4\pi^{3/2} \epsilon_0} \frac{(Ne_0)^2 c}{\sigma_s^{4/3} R^{2/3}} + \frac{Ne_0^2 c \gamma^4}{R^2} \quad (1)$$

where σ_s is the bunch length, R is the bending radius, N is the number of electrons, and γ is the relativistic factor. The first term represents the coherent power loss and is the dominant term. The second term is the incoherent power loss and is negligible in our case. The effects of vacuum pipe shielding are ignored in this expression.

Saldin has a model for CSR effects on the electron beam that assumes the transverse size of the bunch can be neglected.[3] The criterion for this is the Derbenev criterion.[4]

$$\frac{\sigma_x^{3/2}}{\sigma_s R} \ll 1 \quad (2)$$

Our compressed beam does not meet the Derbenev criterion so this model does not apply. Three dimensional simulations are needed to model the effects.

A0 BUNCH COMPRESSOR

The layout of the A0 photoinjector has been described in many publications.[5] An RF gun followed by a 12MV/m superconducting cavity accelerates the electron beam to a maximum energy of 16 MeV. A chicane type bunch compressor can be used to compress the electron bunch from 1.5 mm to 0.3 mm. The compression is achieved by operating the booster cavity off crest. This lowers the beam energy to 12.3 MeV. A quadrupole transport channel follows the compressor. A spectrometer bends the beam 45 degrees into the beam dump. Prior to the dump, a screen can be used to image the beam and provide a momentum spread measurement.

The vacuum chamber of the compressor did not allow installing any detectors to measure the radiation. There was no open port on the spectrometer vacuum chamber to measure radiation during the time the bunch compressor was installed. Subsequently, a crystalline quartz window was installed on the spectrometer and measurements of the radiation were performed using a pyroelectric detector.

SIMULATIONS

Simulations were done to compare the effects of CSR on the electron beam. Astra was used to simulate all straight sections of the beamline.[6] CSRTrack was used

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[#]fliller@fnal.gov

to simulate the bunch compressor and the spectrometer sections of the beamline. CSRTrack simulations were run with and without CSR effects turned on. This was done to separate out the CSR effects

BEAM MEASUREMENTS

In order to investigate the effect of CSR on the electrons, we measured the momentum profile of the beam under three conditions, 16 MeV uncompressed, 12.3 MeV uncompressed, and 12.3 MeV compressed. The 12.3 MeV uncompressed beam was chirped for compression but the compressor was turned off. For each of those conditions three charges were used, up to 2.7nC/bunch to look for effects that scale with the charge.

Prior to each measurement the beam was focused on the screen. The horizontal spot size was limited by the 0.33m of dispersion generated by the spectrometer.

16 MeV

Figure 1 shows a typical profile of a 16 MeV, 2.88 nC beam after the spectrometer. Also shown are simulations with and without CSR. The profile corresponds to an RMS energy spread of 81 keV, or 0.5%. We show the data with the highest charge since the CSR effects scale as Q^2 .

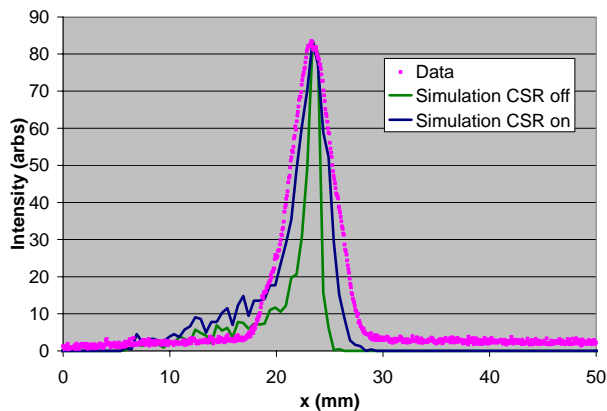


Figure 1: Beam profile after spectrometer for 16 MeV beam (pink). The blue and green lines are simulations with and without CSR. Lower energy is to the right. The energy scale is 47.8keV/mm.

The green trace is a simulation without CSR. It predicts a smaller energy spread than was measured. The blue trace includes CSR in the spectrometer and has an increase of 8keV in the energy spread and 9% growth in the transverse emittance. The CSR simulation more closely matches the data.

The beam in this case satisfies the Derbenev criterion and so Saldin's model is applicable. It predicts an energy spread increase of 4 keV and a 12% emittance growth. This is also consistent with the growth seen in the simulation without CSR compared to the data.

At the time of these measurements it was not possible to measure the CSR directly. These measurements will be discussed in the next section.

12.3 MeV Uncompressed

Next we measured the case where the beam was chirped for compression, but the bunch compressor was turned off. In this way we can disentangle effects not due to the compression itself. The booster cavity was operated at -41 degrees off crest to chirp the bunch. The beam energy was 12.3 MeV.

Figure 2 shows the beam profile after the spectrometer for the chirped and uncompressed beam and a bunch charge of 2.8nC. The RMS energy spread of the beam is 363 keV. This increased spread is from the chirp.

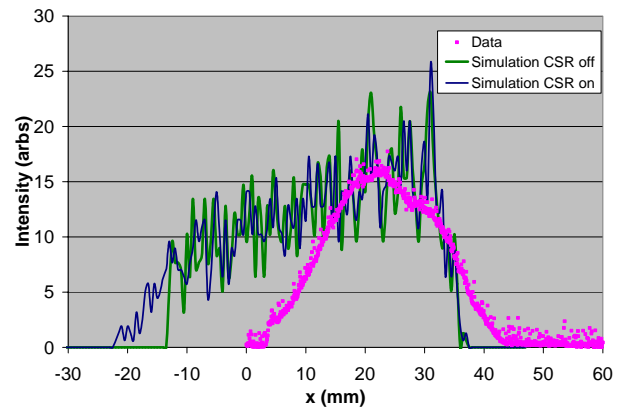


Figure 2: Beam profile after spectrometer for chirped and uncompressed beam (pink). The blue and green lines are simulations with and without CSR. The edge at 3mm is the end of the viewing screen. Lower energy is to the right. The energy scale is 37.2keV/mm.

The simulations show a larger energy spread than the beam, and a much broader profile. The additional spread in the simulation comes from the chirping in the booster cavity. Turning on the CSR shows no additional effects on the beam in the simulations. From this we may conclude that CSR has little effect of the chirped and uncompressed beam.

12.3 MeV Compressed

The final case tested was a fully compressed beam. The compressor shortens to bunch to 0.3mm FWHM at maximum compression. [7]

Figure 3 shows a beam profile after the spectrometer for the chirped and uncompressed beam and a bunch charge of 2.6 nC. The beam profile changes after the spectrometer as a result of compression, however the rms energy spread is same as in the uncompressed case.

Simulations of the profile are qualitatively similar to the data. However there is little evidence of any effects of CSR effects in the simulation. The agreement between the simulations and the data is not increased substantially by adding CSR effects.

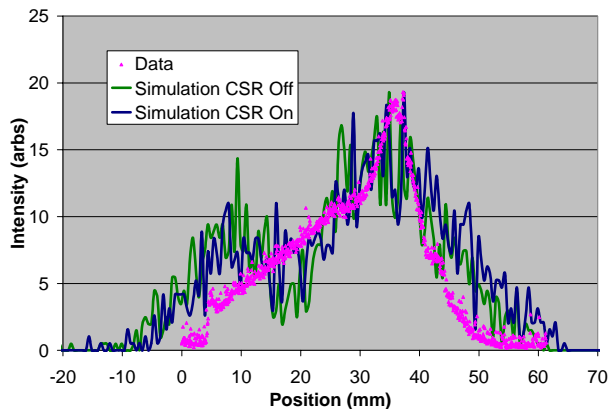


Figure 3: Beam profile after spectrometer for compressed beam (pink). The blue and green lines are simulations with and without CSR. The edge at 4mm is the end of the viewing screen. Lower energy is to the right. The energy scale is 37.2keV/mm.

SYNCHROTRON RADIATION MEASUREMENTS

At the time that the beam energy spread measurements were made, it was impossible to measure the synchrotron radiation at the spectrometer. During a shutdown to install the transverse to longitudinal emittance exchange experiment, a quartz window was added to the 22 degree port on the spectrometer vacuum chamber. This allowed us to measure the synchrotron radiation using a pyroelectric detector.

As Equation 1 shows, the coherent radiation power scales as $\frac{Q^2}{\sigma_s^{4/3}}$ and is independent of the beam energy.

We measured the radiated power at the spectrometer as the charge was varied. With each change in the charge, the bunch length was measured using a streak camera. We measured at 12.3 MeV and 16 MeV to investigate energy effects. The 12.3MeV was chirped to see what CSR was emitted by the chirped but uncompressed beam. The results are plotted in Figure 4.

The black line is a linear fit to the data taking into account both beam energies. The beam at 12.3 MeV was exhibiting 100 keV energy jitter during the

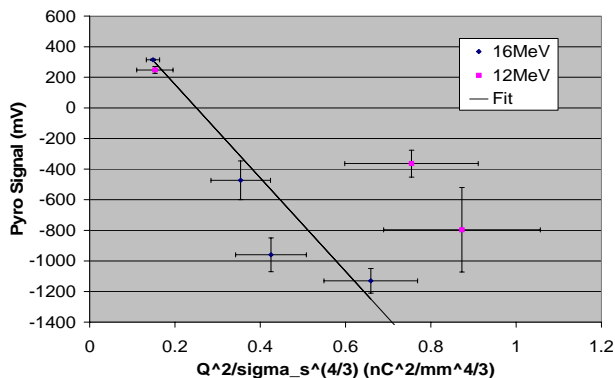


Figure 4: Pyroelectric Detector response vs. $\frac{Q^2}{\sigma_s^{4/3}}$. The black line is a linear fit.

measurements. This would affected the bunch length measurement and is the cause of the large horizontal error bars. Nevertheless, the general trend is consistent with Coherent Radiation being emitted in the spectrometer dipole magnet for uncompressed beams.

CONCLUSION

We have performed measurements of Coherent Synchrotron Radiation at the A0 Photoinjector. The data show that CSR is emitted by uncompressed beams in the spectrometer magnet. Measurements of CSR in the compressor were not possible because the compressor vacuum chamber was not designed for it, and no window was in place on the spectrometer when the bunch compressor was installed.

In addition we measured the effect of CSR on the energy spread of the beam by comparing to simulations with CSR effects turned on and off. This shows that CSR has some effect on the energy spread of the beam for 16MeV uncompressed beams with small energy spread. For the compressed and chirped but uncompressed beam the effects are not apparent from this analysis.

Nevertheless the effects of CSR can be seen at the A0 Photoinjector. This will have an effect on our Transverse to Longitudinal Emittance Exchange experiment. This is discussed in other papers at this meeting.[1] Future plans to study CSR include obtaining a Shottky detector for more sensitive analysis, and possibly measuring the energy changes along the length of the bunch using a deflecting mode cavity.

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