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DESIGN OF A BUNCH COMPRESSOR WITH CSR SUPPRESSION TO ACHIEVE HUNDREDS OF kA PEAK CURRENT

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Abstract

A four dipole magnetic chicane is usually used to compress electron bunch to very short in modern accelerators which requires electron beams to have high peak current. The coherent synchrotron radiation (CSR) originated from the strong bending magnets in the chicane could greatly degrade the quality of the electron beam. In this paper, we present our design for a bunch compressing system with 30 to 100 fold in bunch length reduction and at the mean time suppress the effect of CSR on the e-beam's quality. We discuss and detail the performance of such a compressor for potential FACET-II upgrade.

INTROUDCTION

There are many things in a beam line that could cause degradation of beam qualities (emittance, energy spread, bunch length, etc…). Coherent Synchrotron Radiation (CSR) is one of these notorious effects and it can easily blow up beam emittance by an order of magnitude when beam current is high, i.e., when electron bunch is compressed. What is proposed at FACET2[1] is to compress electron beam to have ultra high beam current ~ hundreds of kA peak current. We designed a compressing scheme to compensate the CSR effect in bending magnets to alleviate emittance growth cause by the CSR effect.

The beam parameters we used are listed in Table.1. To simulate beam dynamics in the bunch compressor when CSR effect exists, we generated 20 million macro-particles and propagated the beam through the beam line in ELEGANT[2]. We implemented Stupakov's model to simulate the CSR effect in dipoles and near-by drift spaces all along the bunch compressor.

Table 1: Parameters for Operational ATF Beam Parameters

Charge, nC	2
RMS bunch length, mm	0.05
RMS energy spread	1e-4
Norm. emittance, um	4
Beam energy, GeV	10
Initial momentum chirp	420

We started using single stage C-shape chicane to compress the electron beam. Ideally, in such a chicane, the paths' lengths, as well as the transit time through the chicane, depend on the particles energy. In combination with the correlated energy spread (chirp), this entails a rotation in longitudinal phase space. The ratio between the uncorrelated and correlated energy determines the maximum bunch compression. A sketch of how a C-shape chicane works is shown in Fig. 1.

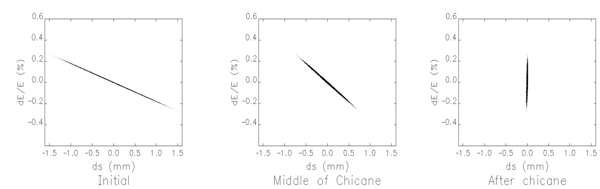

Figure 1: The beam, with an initial energy chirp, rotates and compresses in a C-type chicane.

However, in reality, the deterioration of phase space caused by CSR effects can result from a full rotation. Partial rotation, and under some situations, with an asymmetric compressor layout, assures better performance in reducing emittance growth induced by the CSR effect, and thus results in a beam with a slightly better quality.

In our single C-shape chicane design, we chose a symmetric layout wherein the magnet strengths in four dipoles are equal. The results are shown in Fig. 2. As can be easily seen, the emittance is blown up by 5-fold.

The emittance growth originates mostly from the third and fourth magnets, where the beam is already compressed and the peak current is high. This growth in transverse emittance reflects the fact that the CSR wake depends both on longitudinal position within the bunch, as well as on the azimuth along the beam line. The head of the bunch gains energy while the tail part loses energy.

The coordinate and the angular displacement that depend on beam energy (in dispersive region), i.e., longitudinal position of the particle result in a smearing in the transverse phase space, and also in the growth of the projected emittance. Figure 3 illustrates this smearing effect, comparing the plots of the transverse phase space before and after the chicane.

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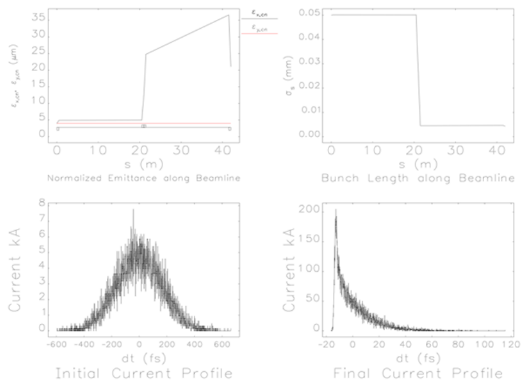

Figure 2: A conventional C-type chicane shows in order to compress the beam to 200 kA peak current, the emittance grows to 5 times after the chicane.

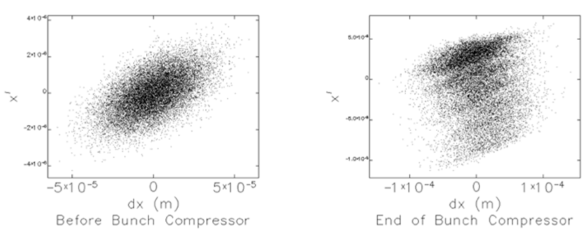

Figure 3: Phase-space distribution before (left) and after (right) the bunch compressor. The longitudinal energy variation induced by CSR wakes is coupled to the coordinate and angular displacements through R16 and R26 induced in the chicane. This results in smearing of the transverse phase space.

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As a remedy for the above problem, i.e., the displacement in the transverse plane due to the longitudinal energy variation induced by CSR wakes, we propose to use two consequent chicanes with reversed bending directions, i.e., a zigzag-type compressor[3]. The opposite signs of the dispersion functions should allow us to decouple the longitudinal and transverse degrees of freedom. By controlling optics between the two reversing chicanes (or not reversing if phase advance between chicanes is tuned to be 180 degree), we can suppress the correlated emittance growth due to photon emission along the dispersive path. Thus, the resulting emittance growth due to CSR effects could be greatly reduced. Since bunch length is shorter, correspondingly CSR wake is stronger in the second chicane, and the energy change also is larger. The cancellation of the CSR effect naturally requires a weaker second chicane compared to the first one. Figure 4 is a sketch of the energy variation caused by CSR wake in a zigzag chicane.

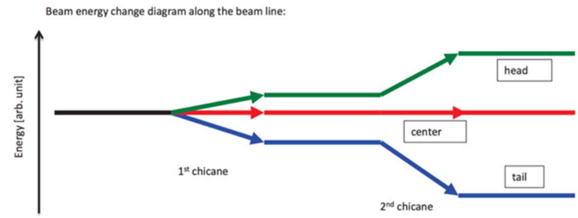

Figure 4: Using two chicanes with opposite bending directions (thus opposite) D and D', it is possible to compensate the emittance growth by cancelling the transverse effects induced by CSR wakes. Change in energy in second chicane is stronger due to stronger wakes – shorter bunch length, thus the bending strength should be smaller. Phase advance between two chicanes can be tuned to realign different longitudinal slices – reduce the overall projected emittance.

In general, for this zigzag chicane setup, we optimize the bending angles of both chicanes to maximize the cancellation of CSR effects in both chicanes, the phase advance and optics functions between chicanes to better align the longitudinal slices to reduce overall emittance. The results are quite satisfying. For a compression of 20-fold in peak current, the overall emittance only grows from 4 um to 4.33 um after the zigzag chicane, that's 8% emittance growth comparing to 5 fold from a single C-type chicane. We show the emittance evolution along the bunch compressor and final current (~ 140 kA) in Fig 5.

Using the same technique, we can increase the compression ratio to 30 fold and the final emittance is 4.66 um, i.e., 16.5% growth with peak beam current > 200 kA. Details shown in Fig. 6.

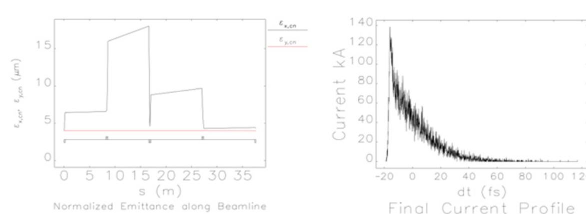

Figure 5: Emittance growth due to CSR effect is largely cancelled in 2nd chicane of a zigzag chicane with optics tuning to align slices in between.

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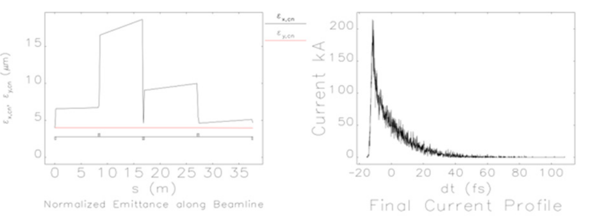

Figure 6: Further increase the compression strength results in a beam with peak current > 200 kA and emittance ~ 4.66 um, 16.5% growth before compression.

As described above, the complete optimization requires a full scan of the optics function in between the chicanes, i.e., optics matching. Figure 7 shows the scanned results of beta function and alpha function at the entrance of second chicane. Alpha function has stronger effect than beta functions on the final emittance. However, choosing the proper ratio of compression between two chicanes (for our case, close to 4:1, as mentioned before, second chicane should be weaker since beam current is higher there) is the most crucial part in terms of CSR suppression.

There are easy ways to further reduce the emittance growth caused by CSR effect. The CSR wakes are already largely cancelled with the reverse bending (or proper phase adjustment between chicanes). The CSR can be further reduced with traditional tricks, e.g., by increasing initial beam chirp, we can reduce bend angles further more to reduce CSR. We tried an example of increasing initial momentum chirp from 420 to 1600 while reducing the bending angles of both chicanes (see Table. 2) to keep the same peak current ~ 200 kA.

Table 2: Zigzag Chicane Setup to Reach ~ 200 kA Peak Current

Chirp	420	1600
1st chicane angle (rad)	0.01	0.0049
2nd chicane angle (rad)	0.0057	0.0022

The final emittance growth drops from 4.66 um to 4.11 um with higher chirp, shown in Fig. 8. Using the exact same chicane layout, by simply increasing the chirp further to 2000, we can compress the electron beam to have peak current of 350 kA with a final emittance of 4.4 um (such emittance could be further optimized using the method described).

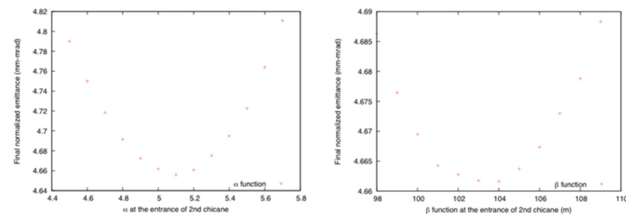

Figure 7: By varying alpha and beta functions at the entrance of second chicane, we are able to further reduce emittance growth by a few percent by aligning difference slice's phase space ellipses.

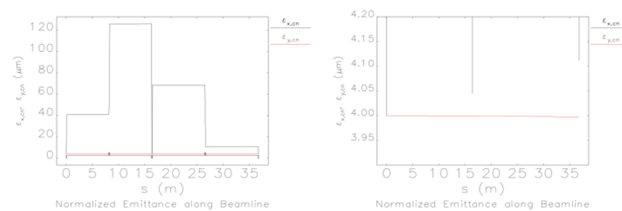

Figure 8: Emittance growth for a 30-fold bunch compressor is < 3% with initial momentum chirp of 1600.

As we depicted above, optics at the entrances of two chicanes and chicane strengths form a set of parametric space for the compression system. In reality, a multi-objective (i.e., final peak current and beam emittance) optimizer could be a perfect candidate for improving the system further more in case better beam qualities are desirable. Some faster optimizers (RCDs, Powell's, simplex, etc…) can be employed as online tuning (in exchange of missing global optimum) tools in operation. We plan to test our findings at FACET in the near future.

CONCLUSION

We found the cause of CSR induced emittance growth in a bunch compressor and compensated the CSR effects by balancing the strengths and optics between two C-shape chicanes. We were able to apply the design to a potential bunch compressor for FACET-II upgrade to achieve a multi-hundred Ampere electron beam with minor emittance growth due to CSR effect.

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