BROOKHAVEN NATIONAL LABORATORY

Collider-Accelerator Department

Compensation of CSR in bunch compressor for FACET-II

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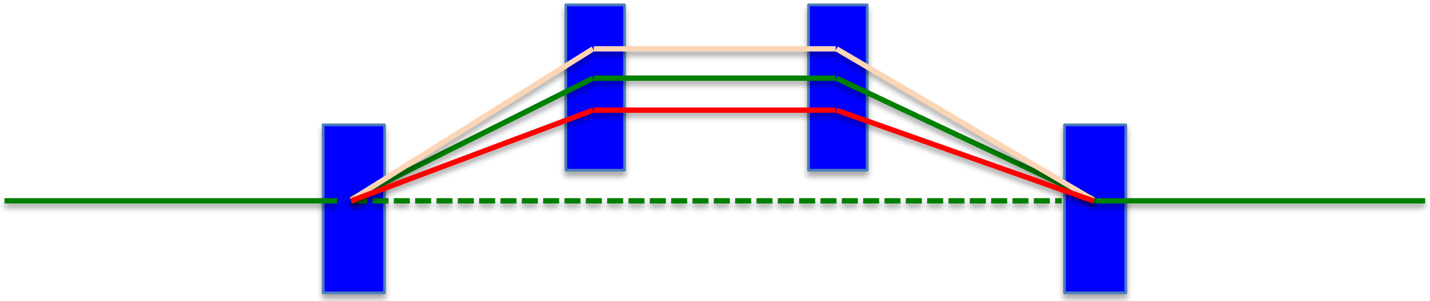
Facet II workshop, SLAC

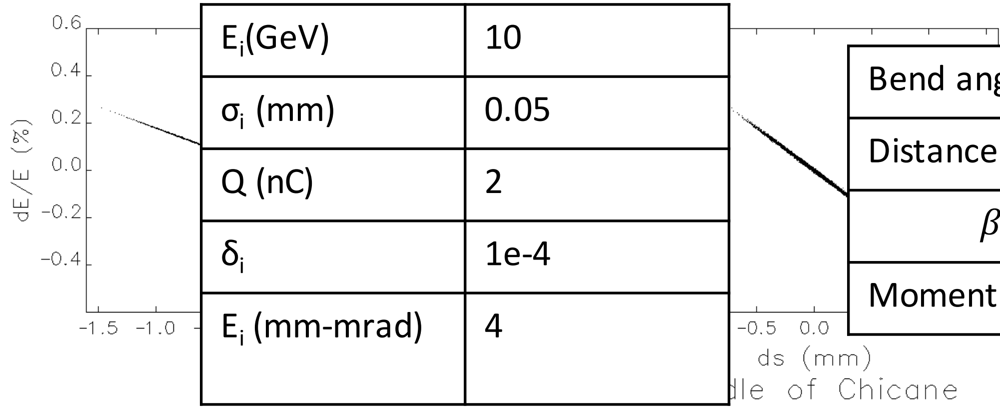
Outline

- Single C-type bunch compressor and performance.
- Options for bunch compressing to reduce CSR effect on beam qualities.
- Two stage bunch compressor with cancelling CSR effect.
- Possible further improvements.
- Summary.

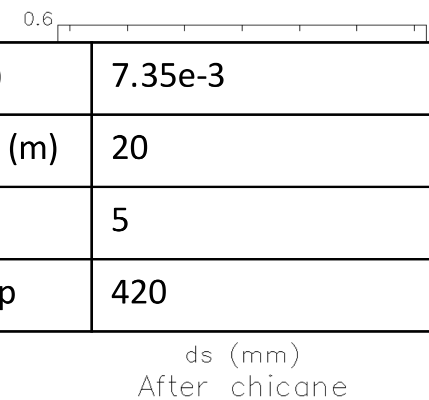
Single C-type bunch compressor

Using dispersive section (dipoles), the pathlengths for different energy particles could be adjusted, i.e, rotation in longitudinal phase space.



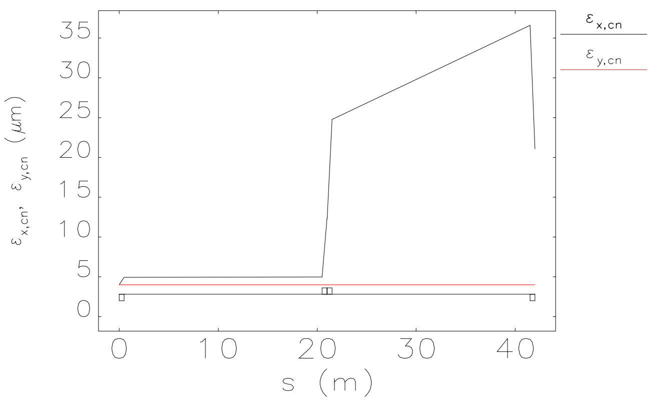


E_i(GeV)	10
σ_i (mm)	0.05
Q (nC)	2
δ_i	1e-4
E_i (mm-mrad)	4

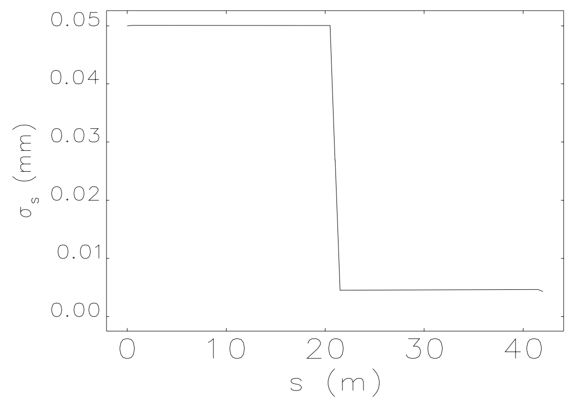


Bend angle (rad)	7.35e-3
Distance dipoles (m)	20
$\beta_i (m)$	5
Momentum chirp	420

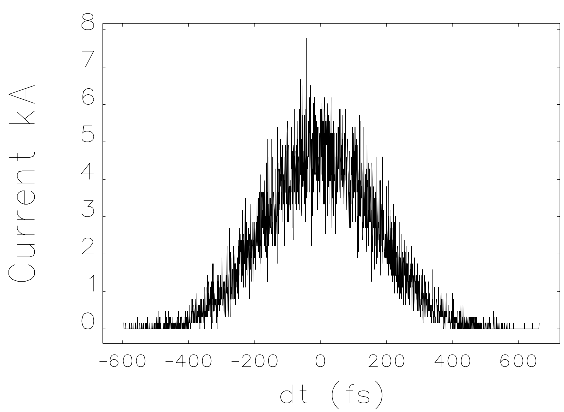
Single C-type BC (cont'd)



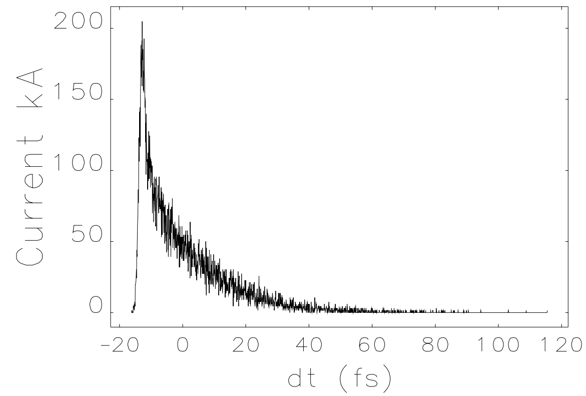
Normalized Emittance along Beamline



Bunch Length along Beamline



Initial Current Profile



Final Current Profile

Emittance blown up 5-fold by CSR.

CSR wakes are calculated in dipoles ("CSRCSBEND") and drifts ("CSRDRIFT") in ELEGANT.

Some techniques can be employed to reduce the CSR.

Compression using recirculating ARCs

Bunch compression done in ARCs where bends have gradually reduced strengths. So that while the bunch length gets shorter, it experiences weaker bends => less CSR effects!

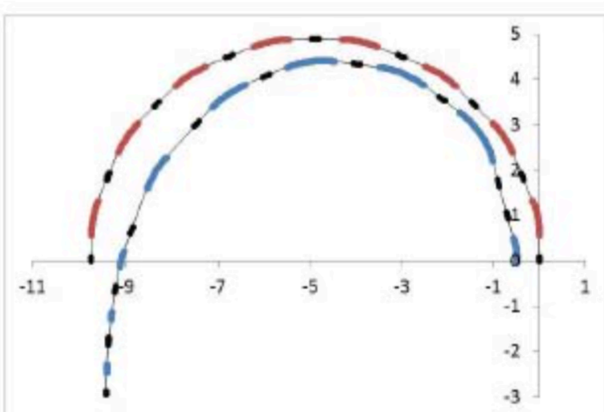


Figure 1: Conventional FO0DO and excitation-modulated compressor layouts. Quadrupoles and beam line in black; conventional line bends in brown, modulated line in blue.

Table 1: Compressor Arc Parameters

	FODO	Modulated
Diameter	9.78 m	8.95 m
# bends	8	9
cell tune	$\nu_x,\nu_y=90^\circ$	$\nu_x,\nu_y=90^\circ$
phase advance	$\nu_x,\nu_y=2,2$	$\nu_x,\nu_y=2.4,2.5$
M_{56}	0.63 m	1.56 m
ε_x^N in/out	0.5/1.86 µm-rad	0.5/0.72 µm-rad
ε_L^N in/out	50/55 keV-psec	50/59 keV-psec

D.R. Douglas, et al., TUPMA034, IPAC15

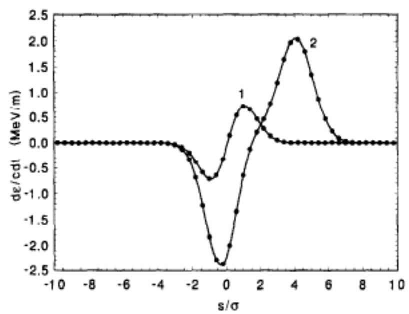
With sophisticated optics tuning (usually with usage of higher order-poles), smaller emittance growth can be achieved.

S.Di Mitri, EPL 109, 62002 (2015)

Why not cancel the CSR?

Emittance spoil due to CSR wakes

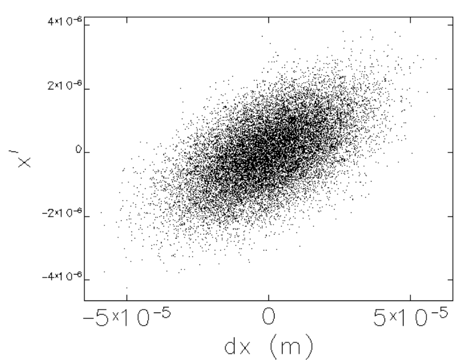
A typical CSR wake looks like:



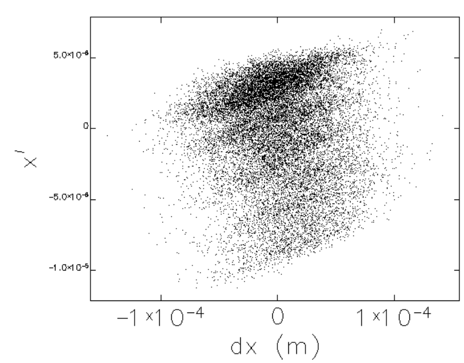
E.Saldin et. Al. NIMA 398 (1997)

CSR wakes change particle energy according to its longitudinal position within a bunch -> induce energy spread.

This results in the change in transverse beam position (x) and divergence (x') through D and D'.



Before Bunch Compressor

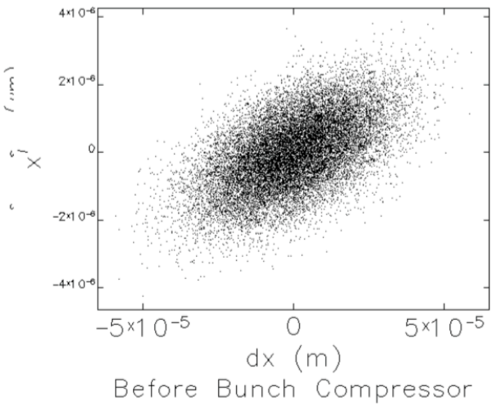


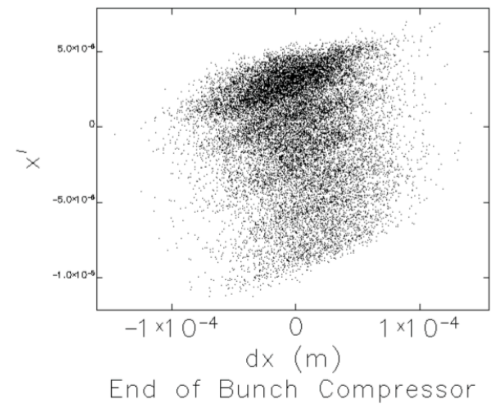
End of Bunch Compressor

Phase space plots show clear evidence of emittance spoil due to the longitudinal – transverse coupling in chicanes.

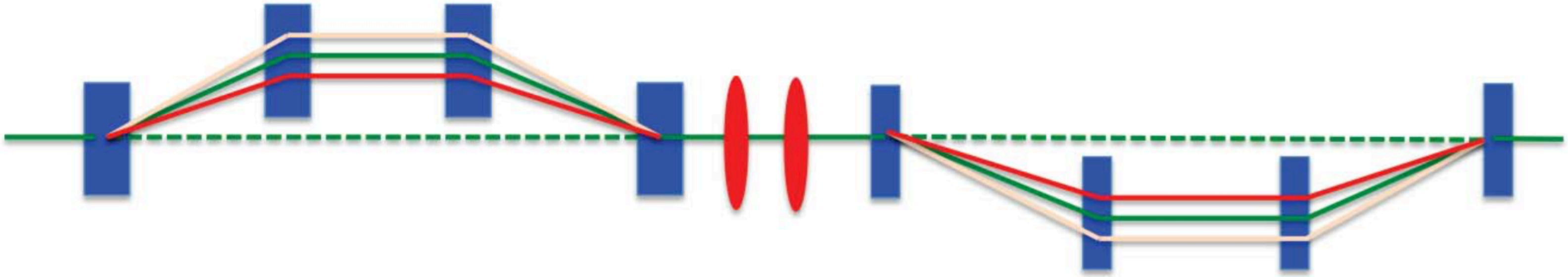
Alternative way -- "cancel" the CSR

To the lowest order, the smearing in the transverse phase space is result of the coordinate and the angular displacement depending on longitudinal position of the particle.





How to remove this? – negative dispersion!



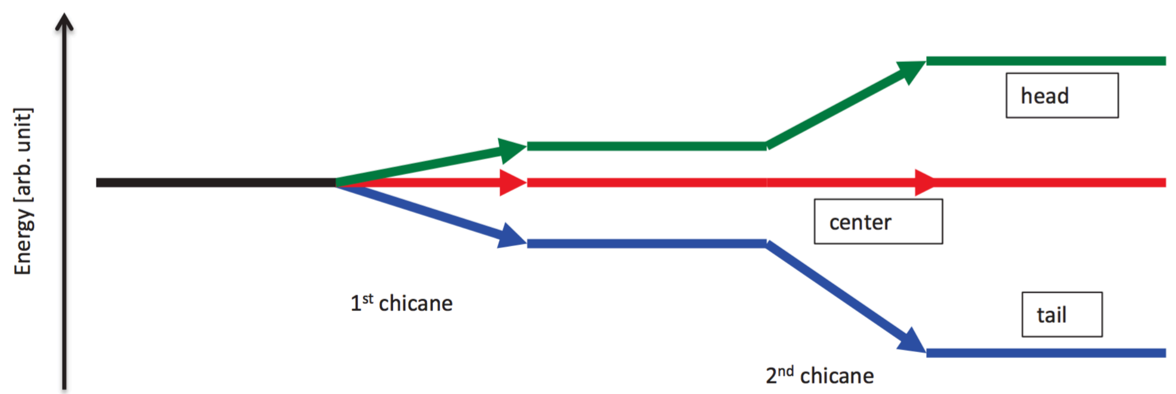
PRSTAB. **16**, 060704(2013)

Cure – two chicanes

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.

Beam energy change diagram along the beam line:



Phase advance between two chicanes can be tuned to realign different longitudinal slices – reduce the overall projected emittance.

Modified S-type BC

Scheme of the 2 chicane BC :

C-type chicane 1 + Phase shifter + C-type chicane 2

= Modified S-type BC

The two C-type chicanes are located at the same energy with opposite bending directions (or can adjust the phase to make it W shape).

By adjusting the phase advance, optics and relative compression strengths of the two chicanes, we wish to maximize the cancellation of the CSR effect.

The total rotation in phase space needs to stay the same. Keep the same desired peak current!

Phase shifter

Phase shifter is done using a matrix element (EMATRIX in ELEGANT) with components as:

$$R_{11} = \sqrt{\frac{\beta_2}{\beta_1}}\left(\cos\psi + \alpha_1 \sin\psi\right)$$

$$R_{12} = \sqrt{\beta_1\beta_2}\,\sin\psi$$

$$R_{21} = -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\psi + \frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}\cos\psi$$

$$R_{22} = \sqrt{\frac{\beta_2}{\beta_1}}\left(\cos\psi - \alpha_1 \sin\psi\right)$$

Simple model without worrying the detailed magnets and optics. Ideal for parameter scan.

with β, α, ψ the optics functions and phase advance at the first and second chicanes respectively.

Modified S-type BC

Scheme of the 2 chicane BC :

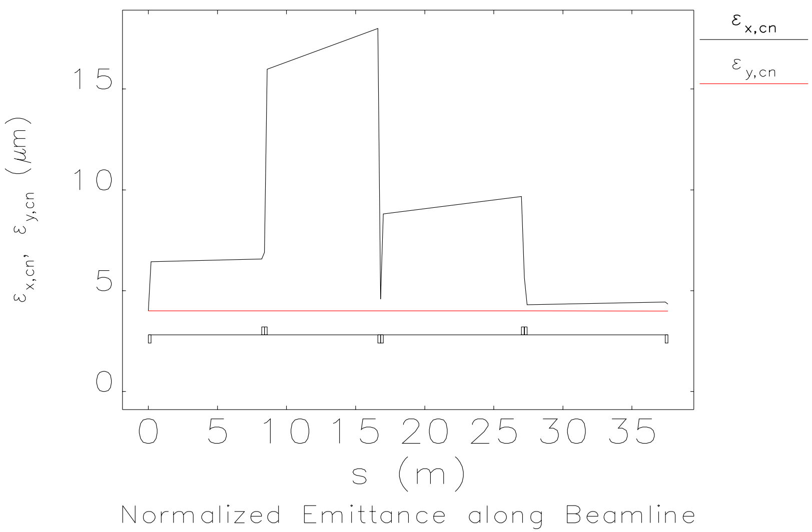
C-type chicane 1 + Phase shifter + C-type chicane 2

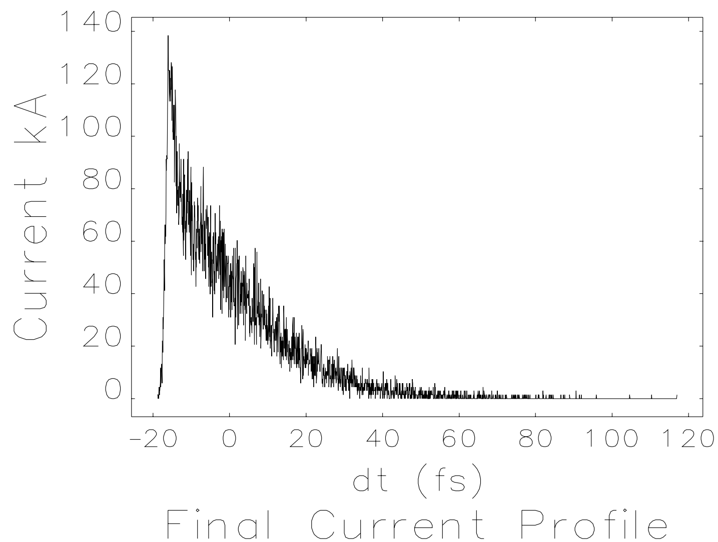
= Modified S-type BC

Bend angle (rad)	0.01
Distance dipoles (m)	8
$\beta_i(m)$	10
α_i	-1

Bend angle (rad)	0.0057
Distance dipoles (m)	10
$\beta_i(m)$	103
α_i	5

Performance- 20 fold compression

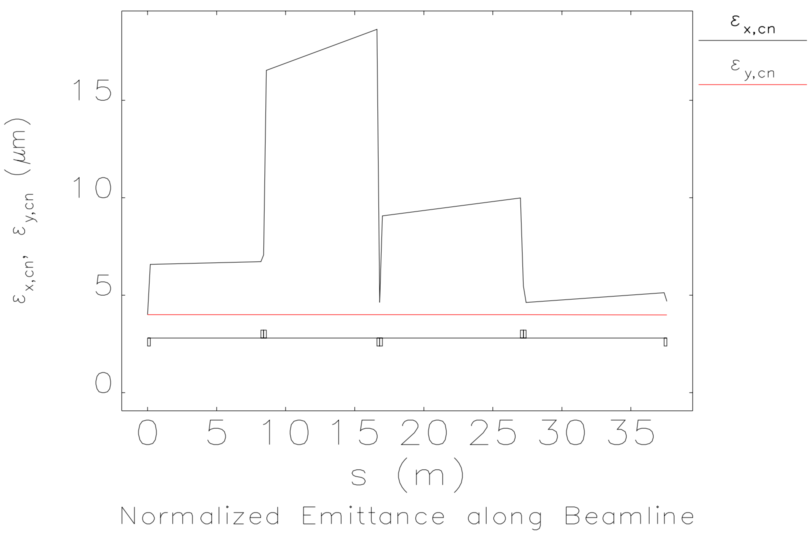


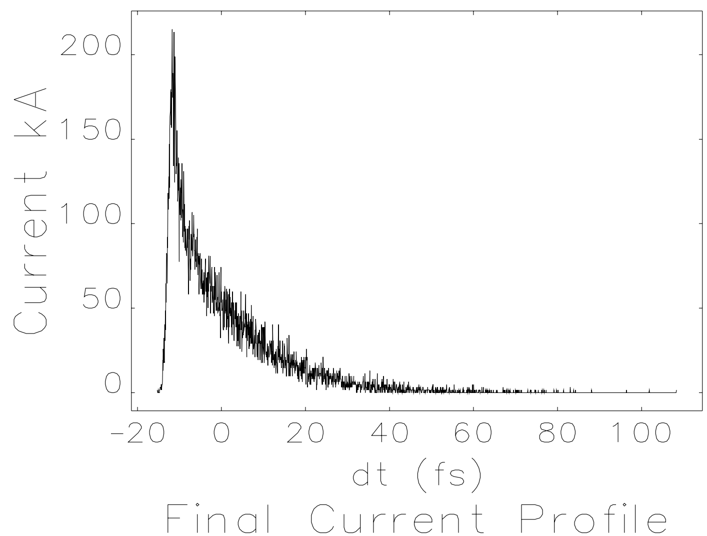


Using the best parameter set, we track particles with Gaussian distribution along the bunching system (CSR, ISR, SR, higher order terms etc. are included, no external wakes considered).

20 fold in compression results in the final emittance of 4.33 um – 8 % growth.

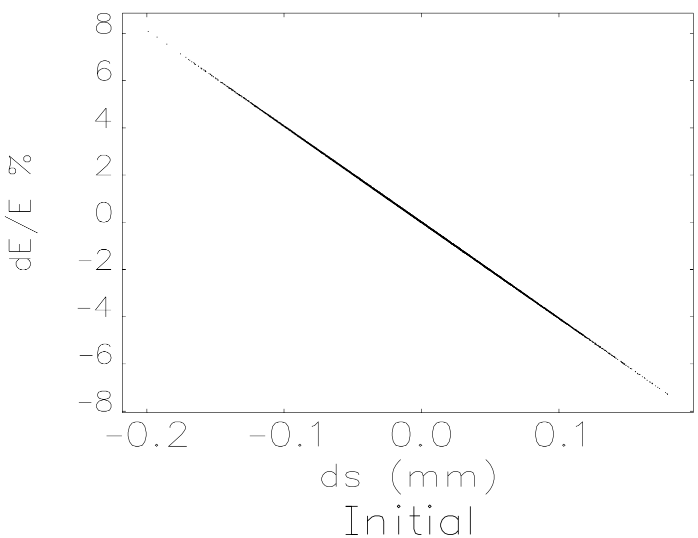
Performance- 30 fold compression

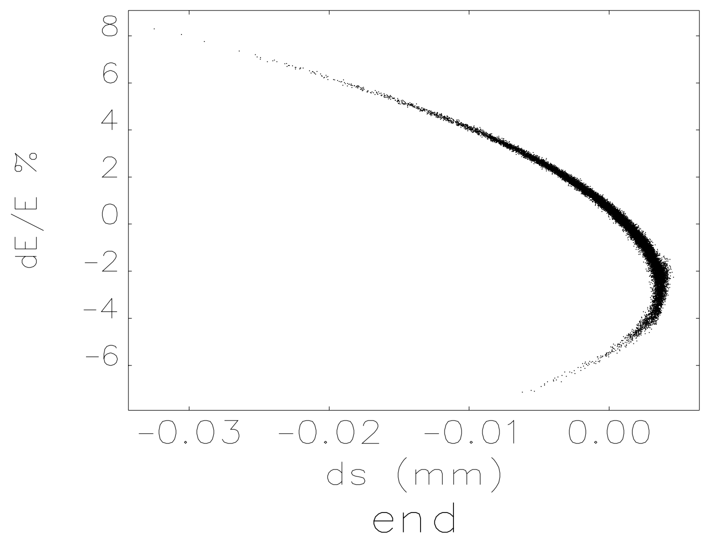




30 fold in compression results in the final peak current > 200k amps. The final emittance is 4.66 um – 16.5 % growth.

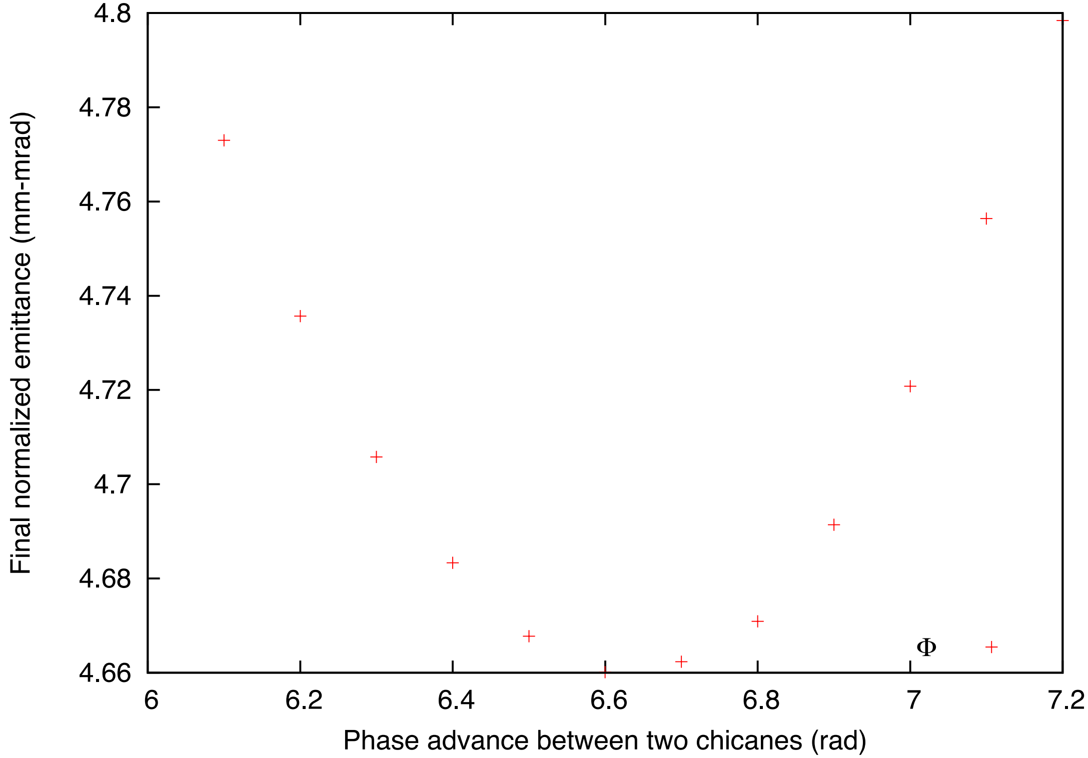
Longitudinal phase space





Close to maximum compression, further rotating in phase space would result in huge emittance growth caused by CSR.

Phase scan



Optimal phase advance is 6.65 rad.

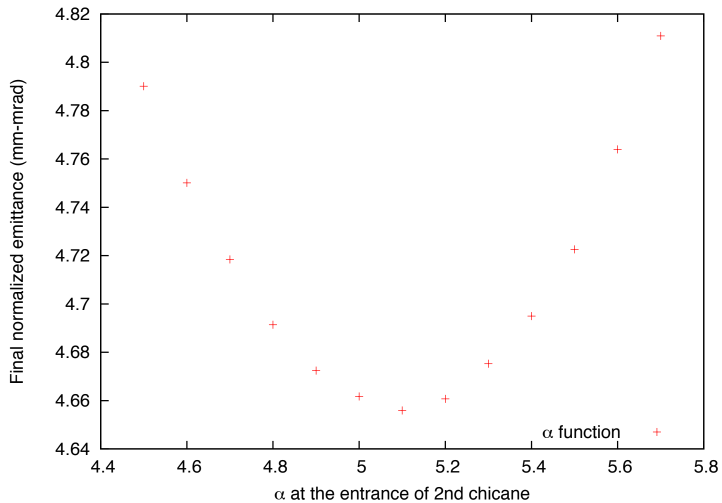
Optimal ratio in strengths (R_{56}) of two chicanes is about 4:1.

Best parameter set reduces the emittance growth to about 16.5%.

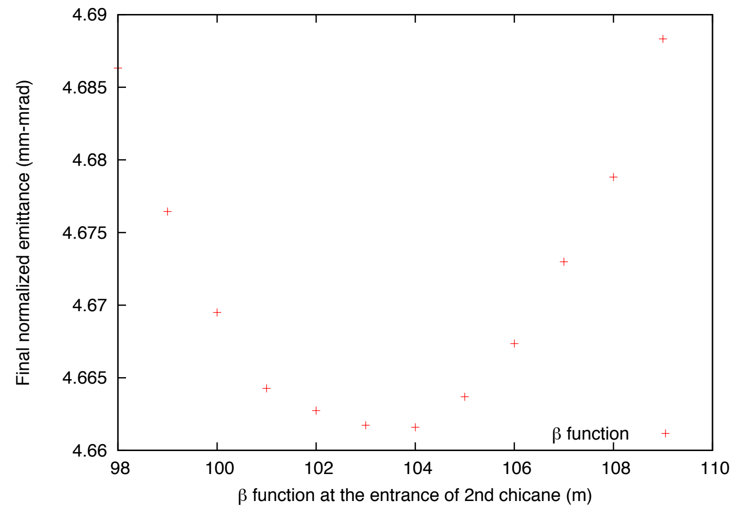
Optics scan

We also scan thru the optics functions (β, α) @ 2nd chicane:

Fix beta, change alpha



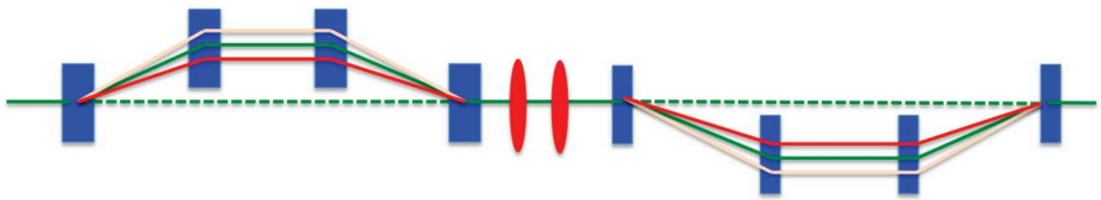
Fix alpha, change beta



Alpha function has stronger effect than beta function. Choosing the proper ratio of compression between two chicanes is the most crucial part in terms of CSR suppression.

Reduce CSR growth further?

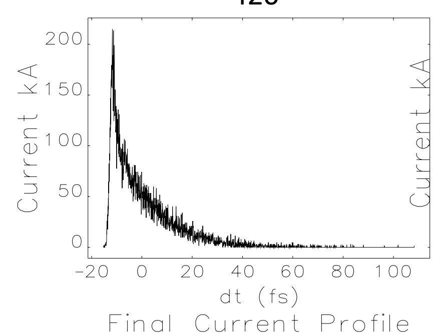
The CSR wakes are largely cancelled with the reverse bending (or proper phase adjustment between chicanes). The CSR can be further reduced with traditional tricks, e.g., by increasing initial beam chirp, we can reduce bend angles further more to reduce CSR.



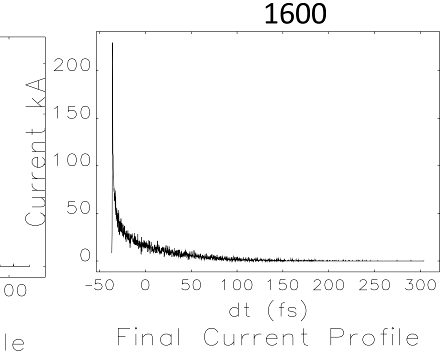
Initial beam chirp increased from 420 to 1600

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

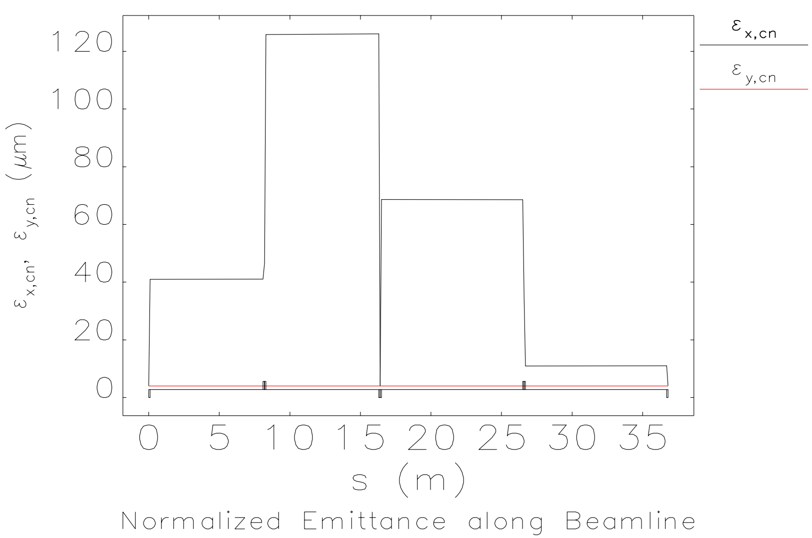
420

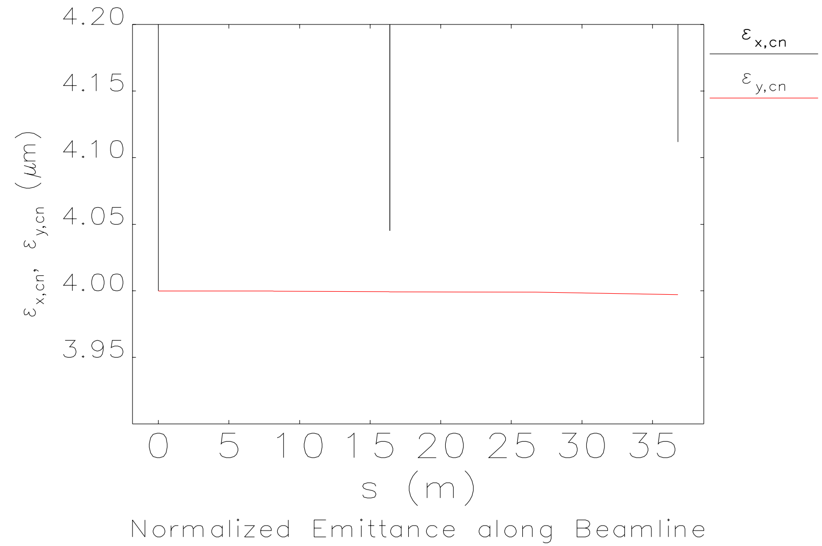


1600



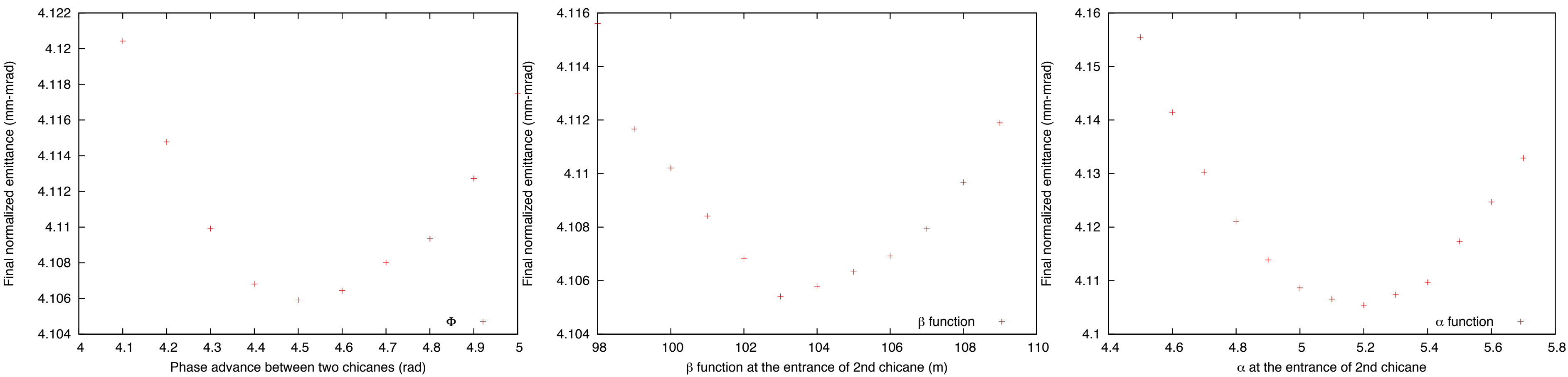
Reduce CSR growth further (cont'd)





CSR induced emittance growth is reduced from 4.66 um to about 4.11 um with higher chirp (420 -> 1600).

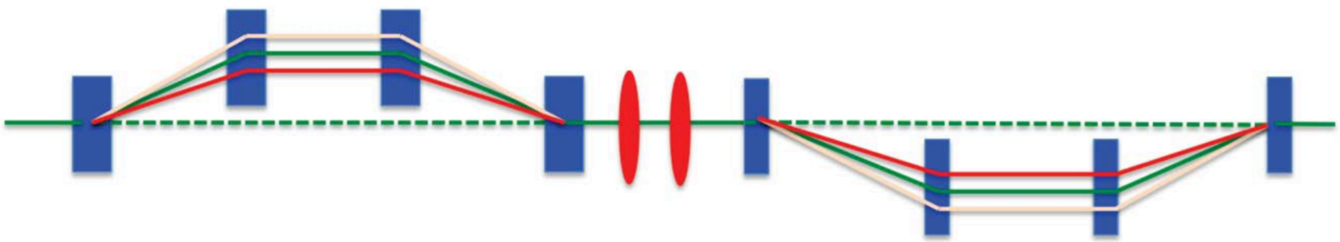
Reduce CSR growth further (cont'd)



Optics can be optimized to further slightly reduce the emittance growth but to this level the effect from matching is not significant.

If higher peak current is desirable, by simply increasing the chirp further to 2000, we have peak current of 350k amps and the final emittance is 4.4 um (without optimizing).

Full parametric space scanning



β_{i1}, α_{i1} θ_1, l_1, l_{d1} $\beta_{i2}, \alpha_{i2}, \phi_{12}$ θ_2, l_2, l_{d2}

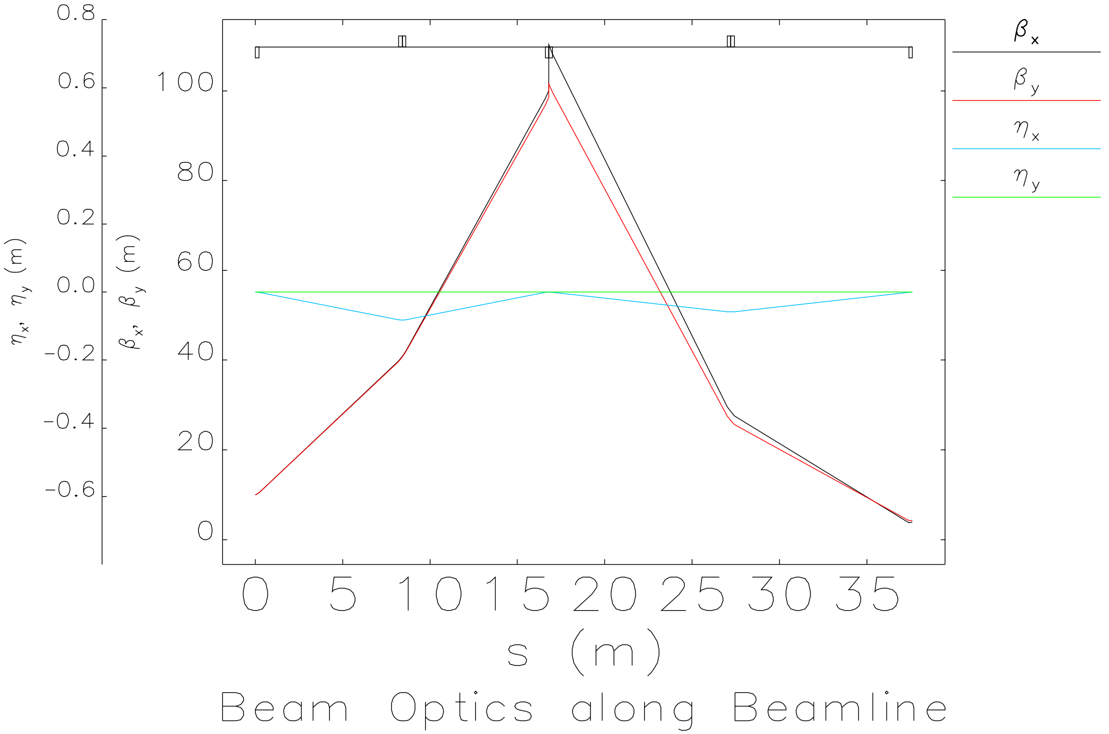
Optics at the entrances of two chicanes and chicane strengths form a set of parametric space for the compression system. A multi-objective (i.e., final peak current and beam emittance) optimizer could be a perfect candidate for improving the system further more in case better beam qualities are desirable. Some faster optimizers (RCDs, Powell's, simplex, etc…) can be employed as online tuning (in exchange of missing global optimum).

Summary

- C-type chicane can be used to compress e- beam to high peak current at FACET-II however the emittance could be blown up by CSR a few folds.
- By introducing an additional chicane (with proper split of compression ratios between two), there is a possibility that the CSR kicks (linear part) can be largely cancelled. Such compressing system can either be a zigzag type (with reverse dispersion) or a W-type (with proper phase advance between chicanes) to satisfy space requirement.
- Future improvements involves full parametric space scan of this well identified system.

Back-up slides

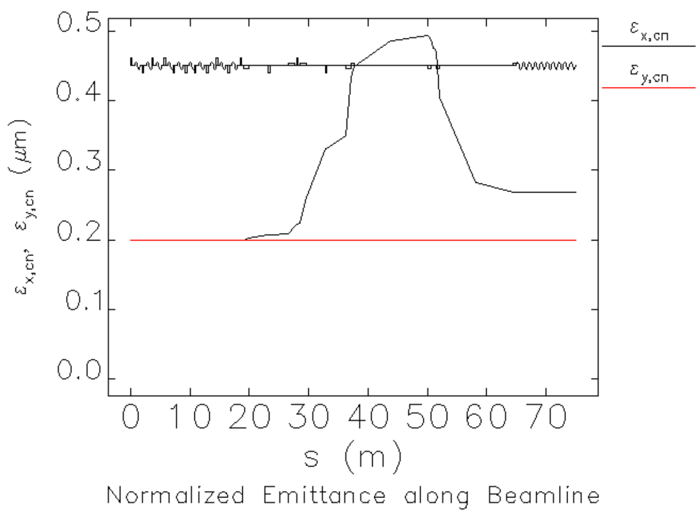
TWISS



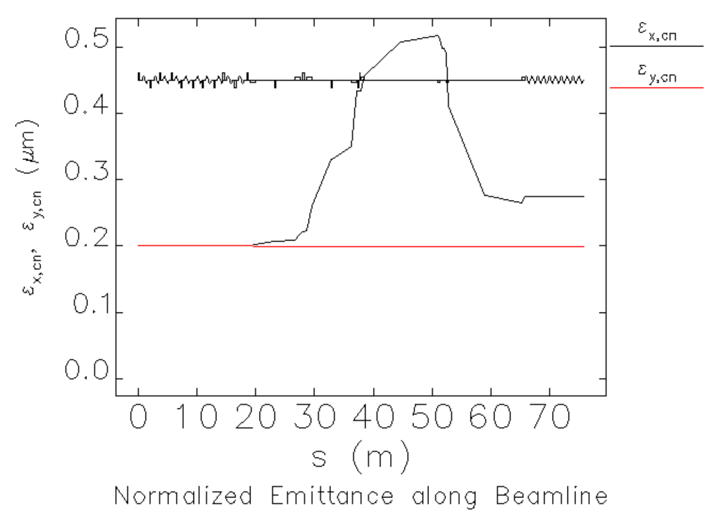
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
η_x, η_y (m)
β_x, β_y (m)
100
80
60
40
20
0
0 5 10 15 20 25 30 35
s (m)
Beam Optics along Beamline
β_x
β_y
η_x
η_y

Real lattice

Our previous results on a similar case (an earlier proposed eRHIC based FEL



Matrix, emit = 0.26 um



Real, emit = 0.266 um

E_f(GeV)	10
σ_f (mm)	0.3
Q (nC)	0.2
δ_i	2e-4