Bunch Compressor Options – preliminary results

FCC injector meeting

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6/10/17

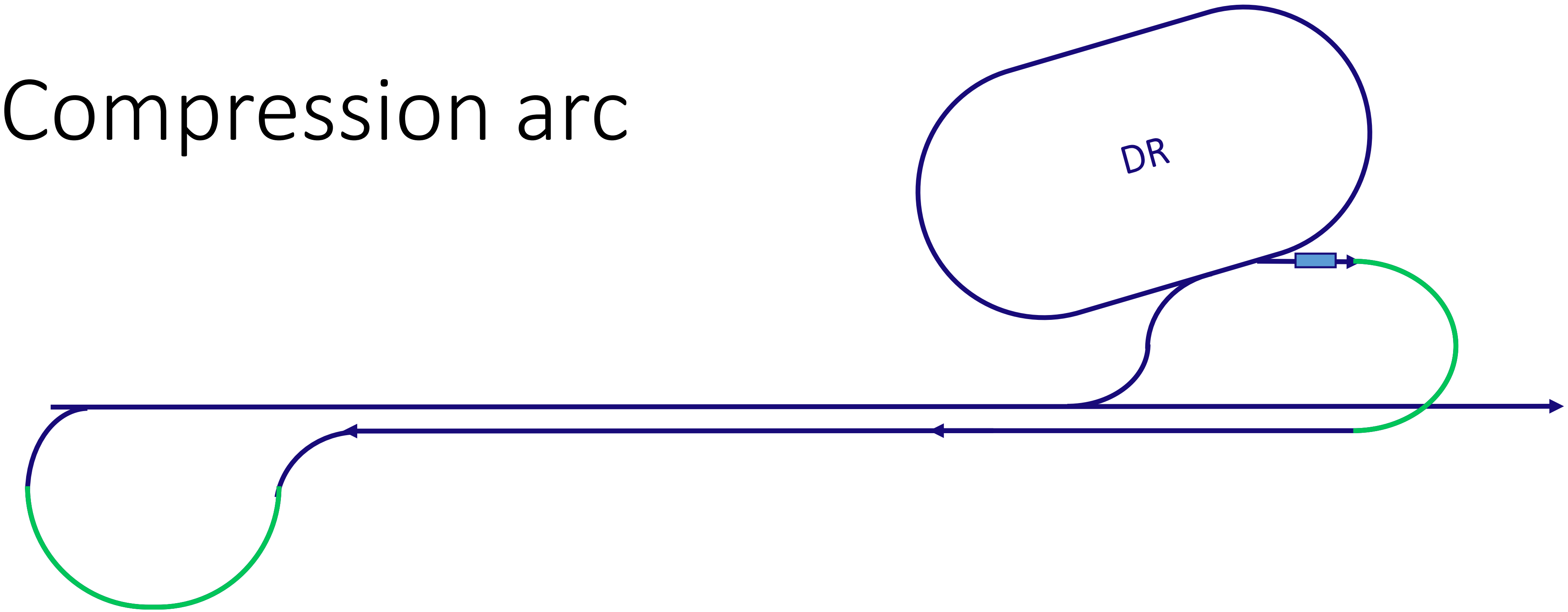
Outline

1. Bunch compressor options
    1. Compression arc
    2. Dogleg designs
2. Turnaround loops
3. CSR cancellation

Bunch Compressor option 1

Compression arc

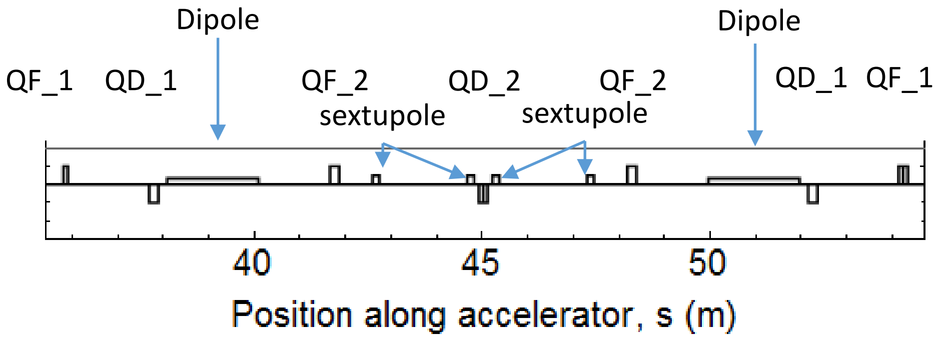
Compression arc



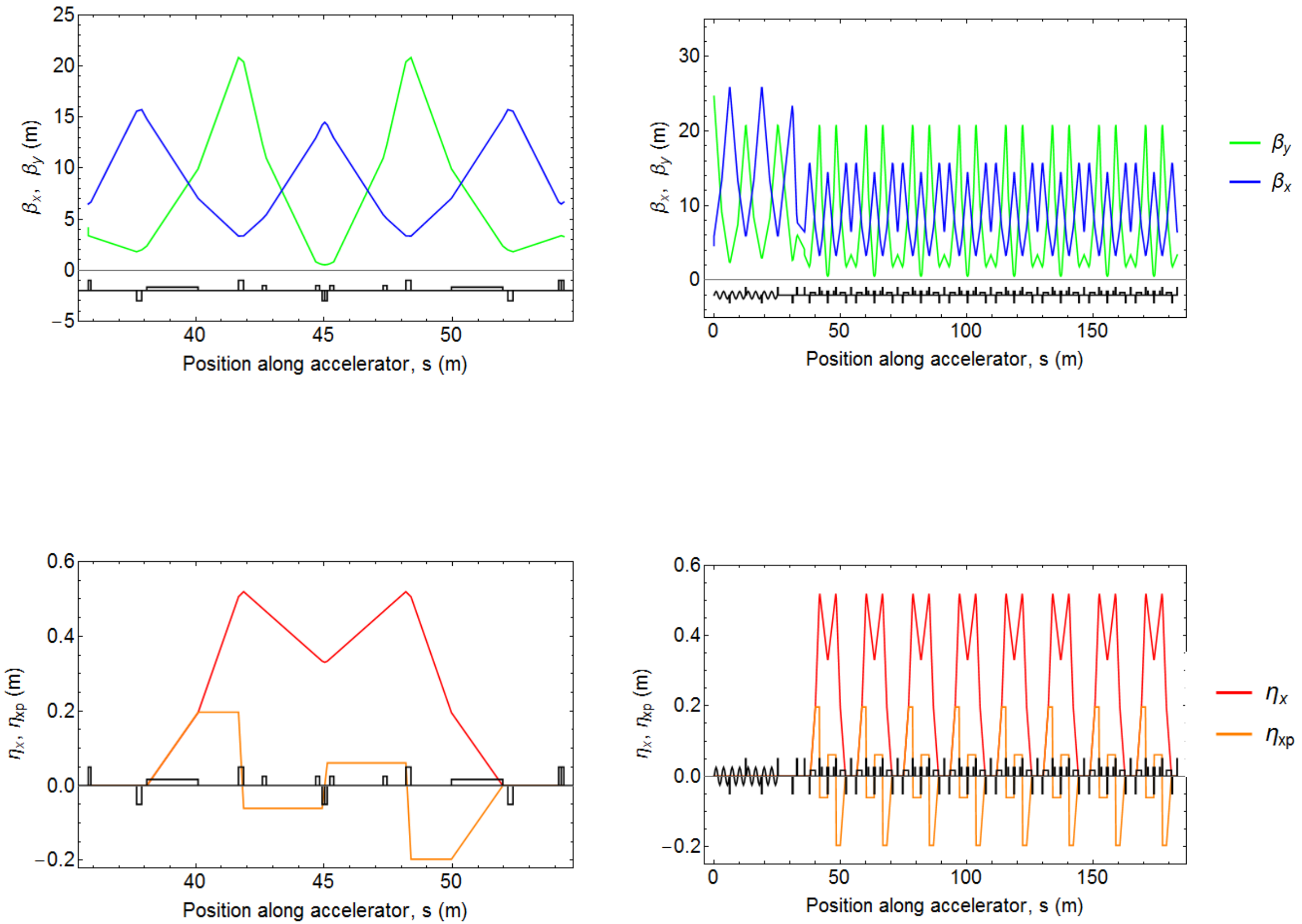
180 deg arc with R56 ≠ 0.

Compression arc

8 cells
22.5° of bending per cell



One cell

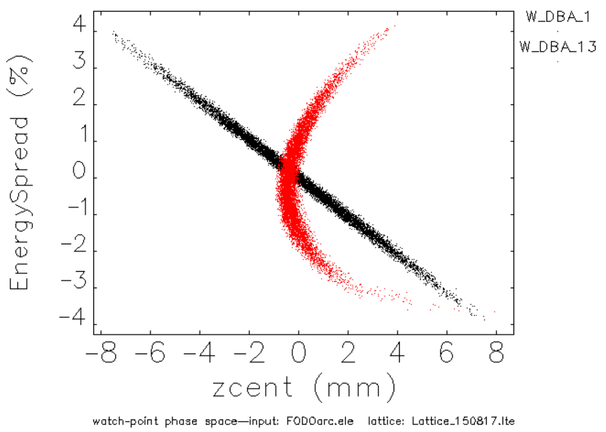


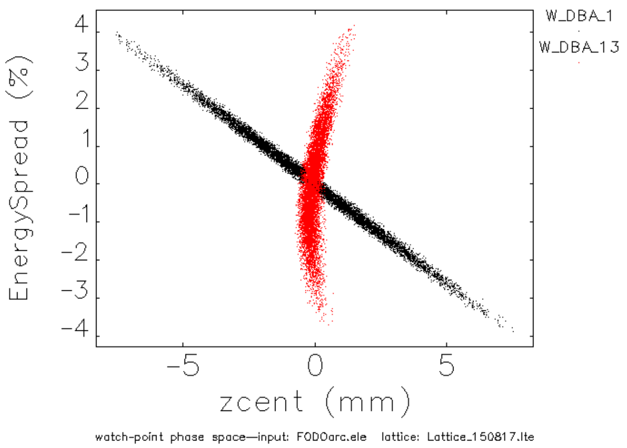
Compression arc

Black = initial distribution
Red = final distribution after compression

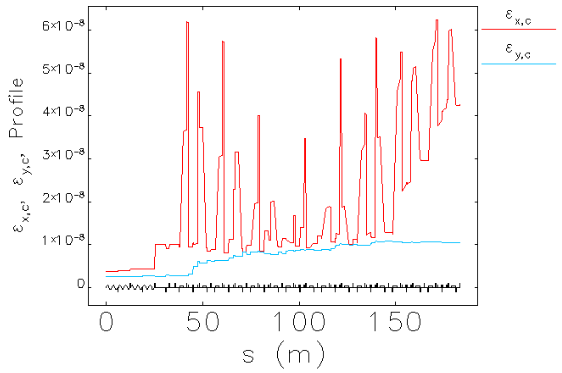
- Energy chirp established by S-band accelerating section
- The second-order terms (from longitudinal dispersion and RF curvature) can be address through the inclusion of sextupoles in the dispersive region.

Without sextupoles	With sextupoles
C = 3.66 R56 = 0.205 m T566 = 2.397 m	C = 7.915 R56 = 0.205 m T566 = 0.556 m





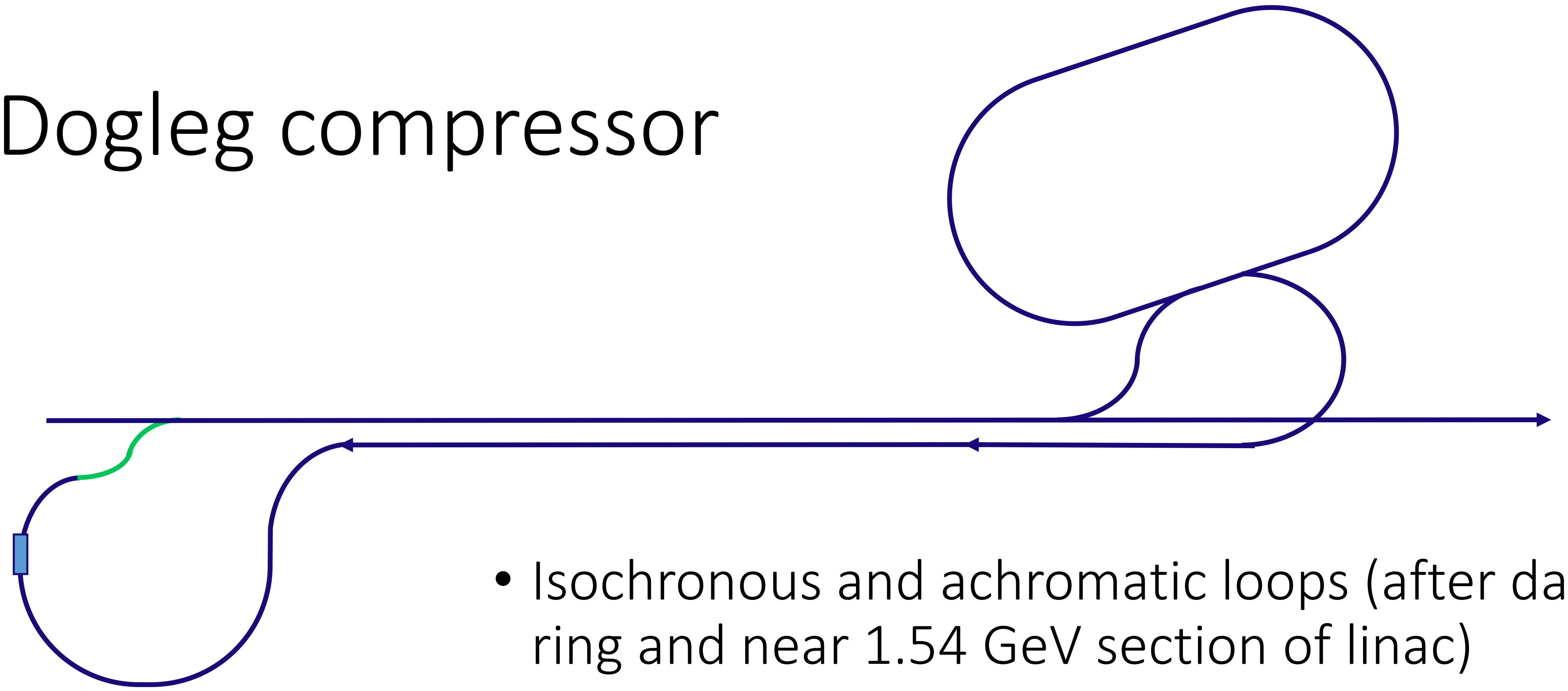
Very large CSR-induced emittance growth from the many dipoles



Bunch Compressor options 2 & 3

Dogleg compressors

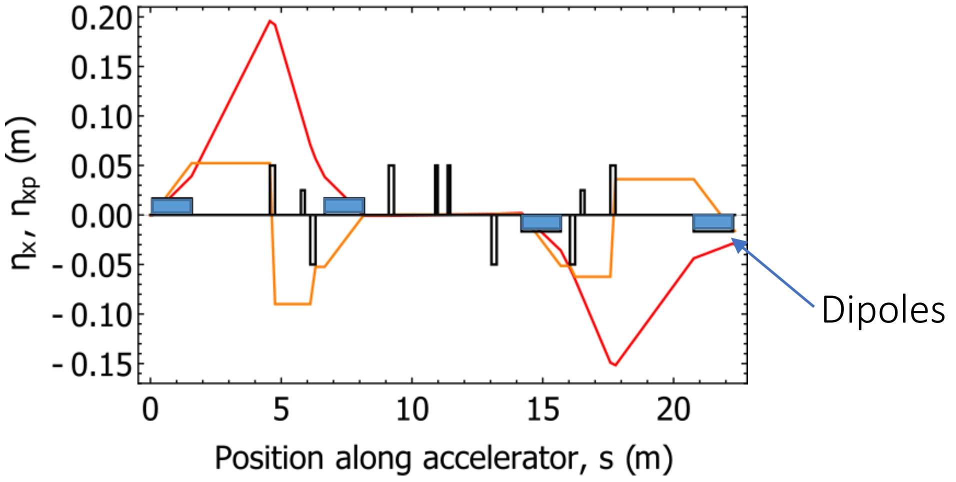
Dogleg compressor



- Isochronous and achromatic loops (after damping ring and near 1.54 GeV section of linac)
- Followed by accelerating structure and dogleg compressor

Two Dogleg designs

Dogleg option 1



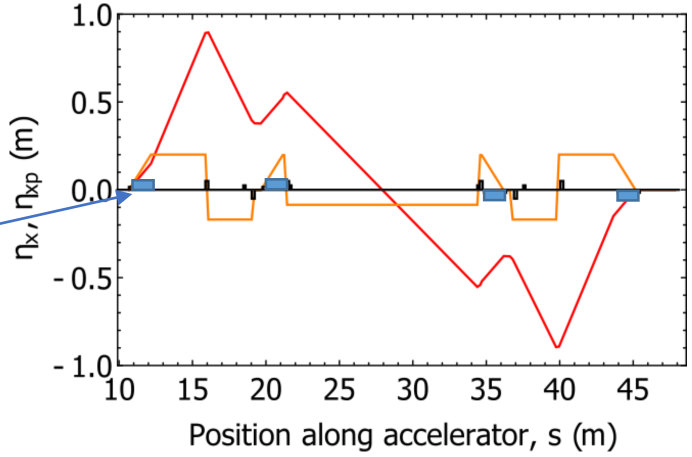
Pros:

- Easier to ensure phase advance of π between sextupoles and dipoles.

Cons:

- Difficult to achieve the R56 value required.

Dogleg option 2



Pros:

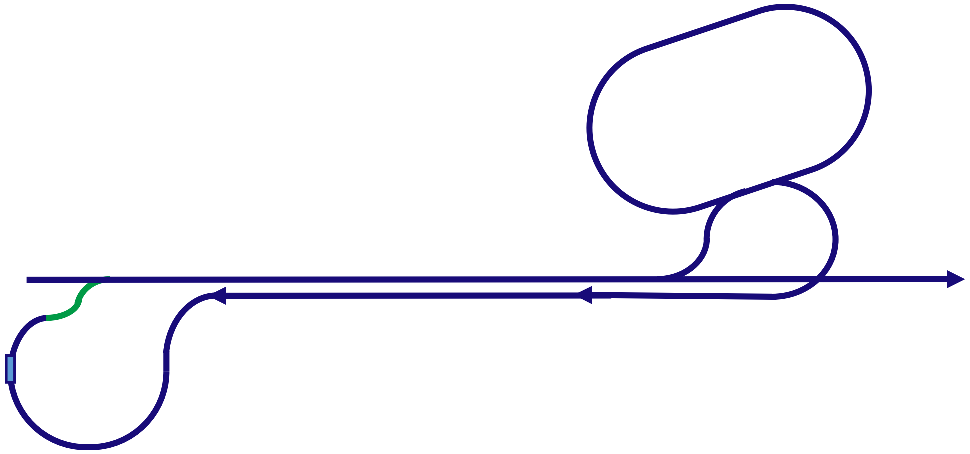
- **Easier to enable a larger R56 value.**

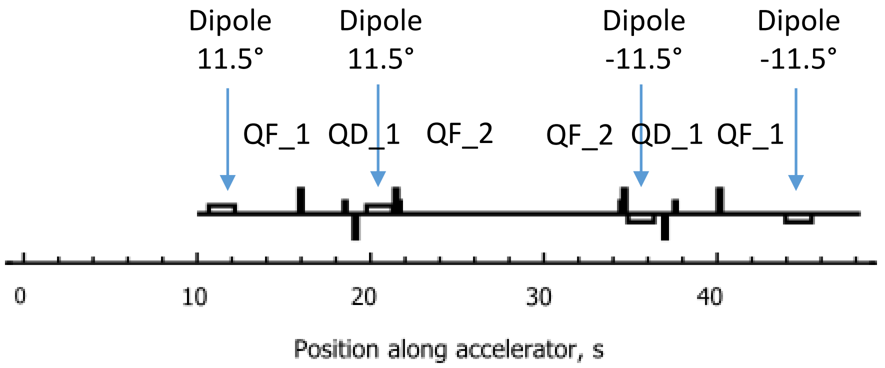
Cons:

- Beta_x and dispersion functions follow each other, making it difficult to ensure phase advance.

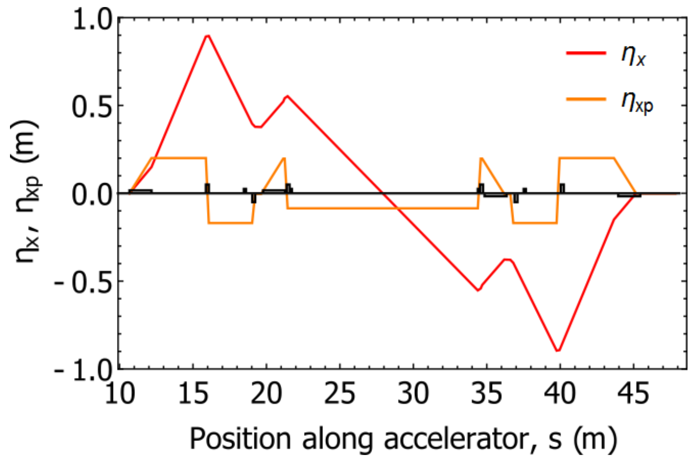
Dogleg 2 design

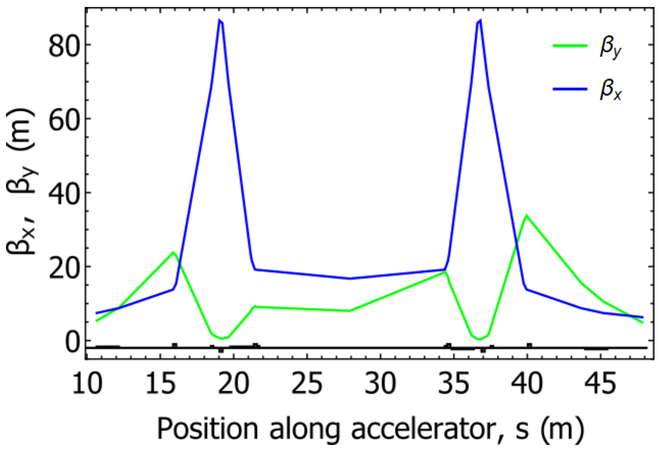
Establishing chirp:
VOLT = 66.257 MV
L = 2.97 m
f = 2.856 GHz
Phase = 180 degrees





"QF_1": QUAD,L=0.2,K1=2.0557
"QD_1": QUAD,L=0.2,K1=-2.1601
"QF_2": QUAD,L=0.2,K1=2.5613

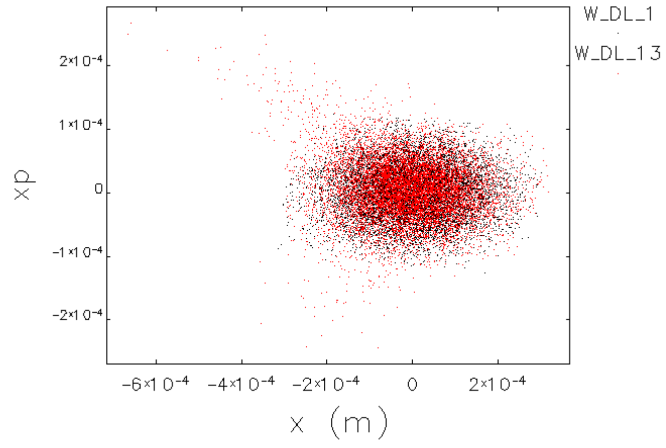


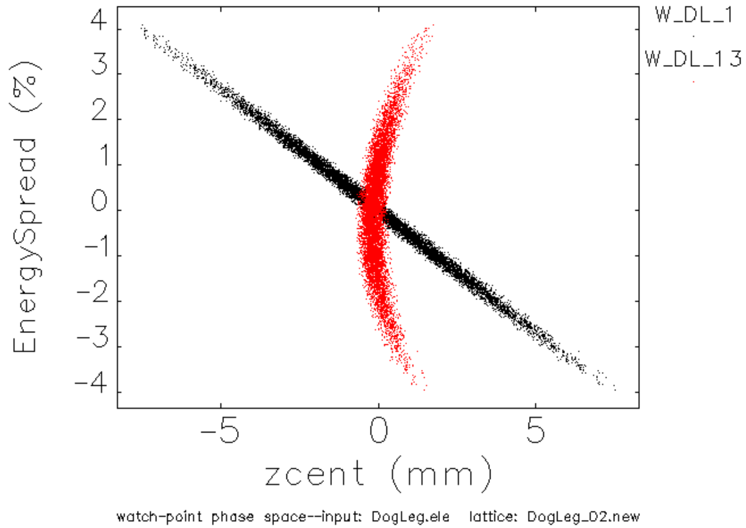


R56 = 190.15 mm
T566 = 0.98 m

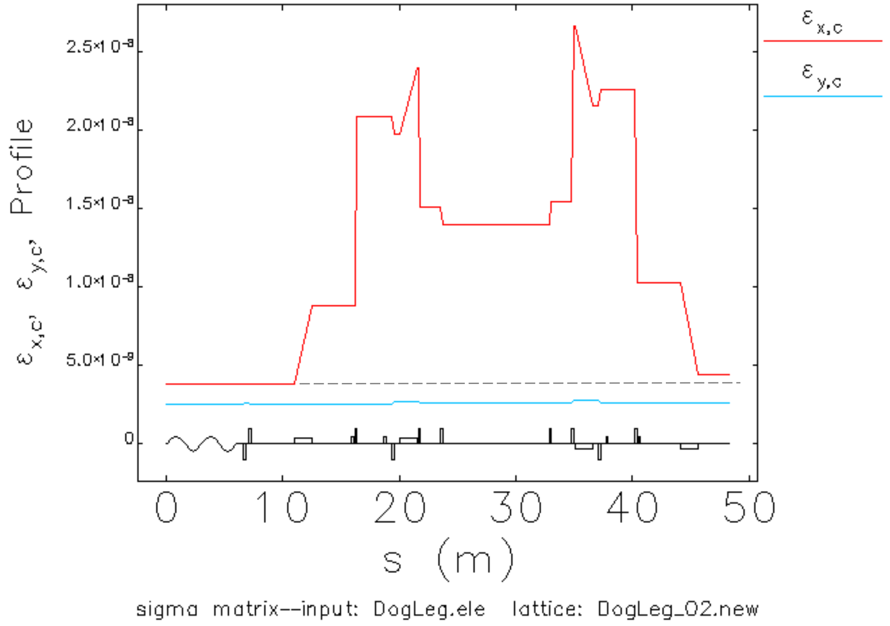
Dogleg 2 design

Black = initial
Red = final

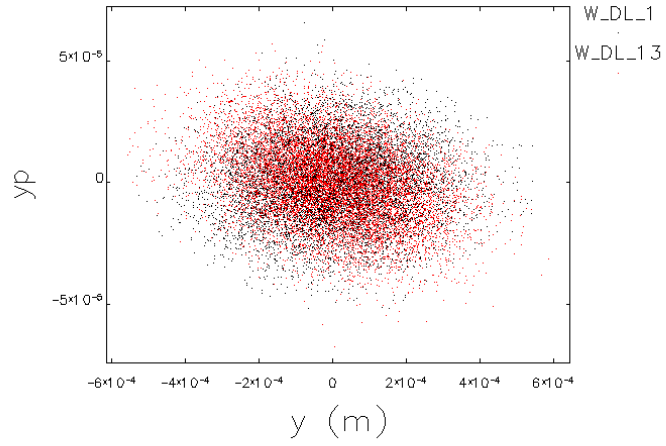




Compression ratio: 8.538



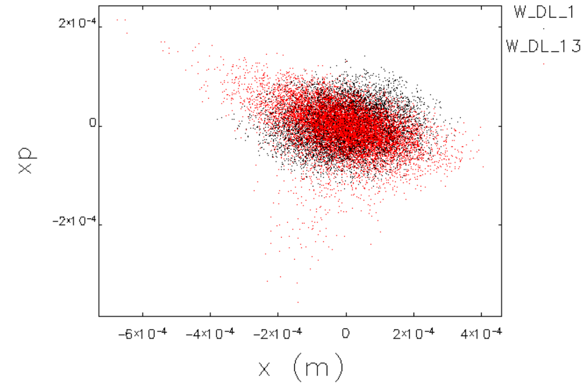
Emittance growth: 17.6 %

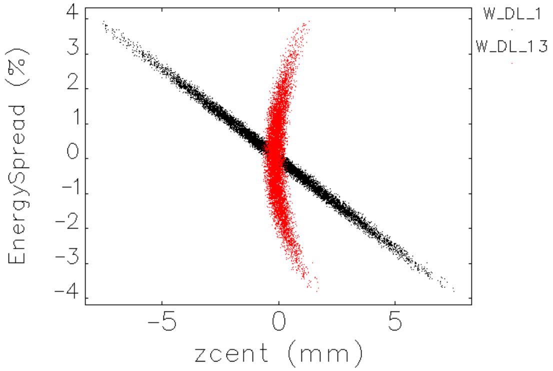


Dogleg compressor - CSR

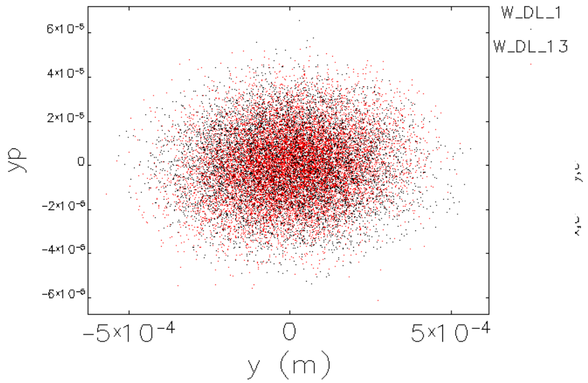
Black = before dogleg
Red = after dogleg

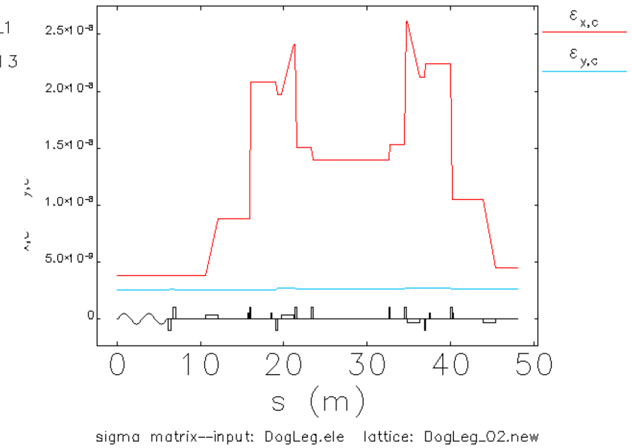
Without CSR



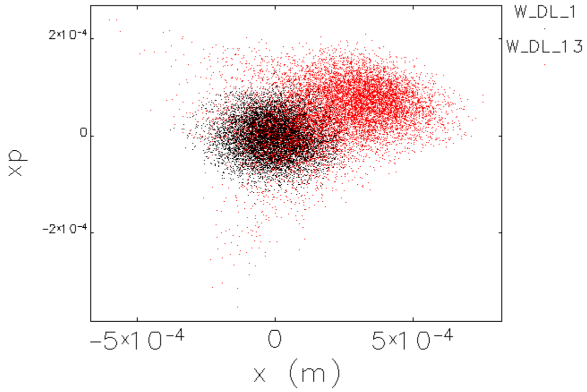


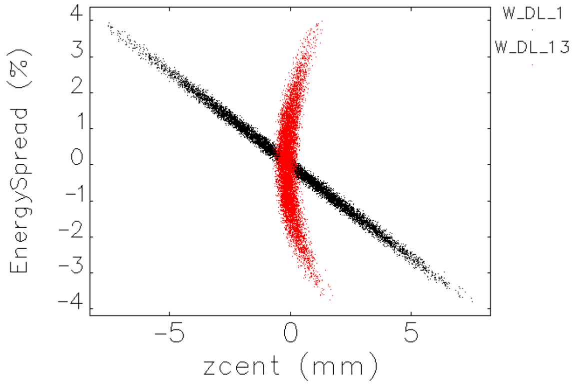
C = 8.537883



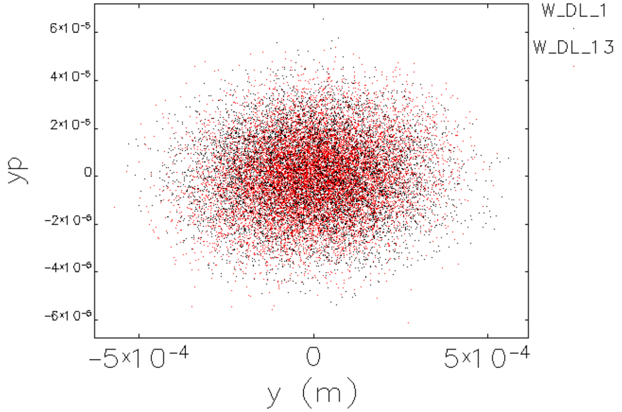


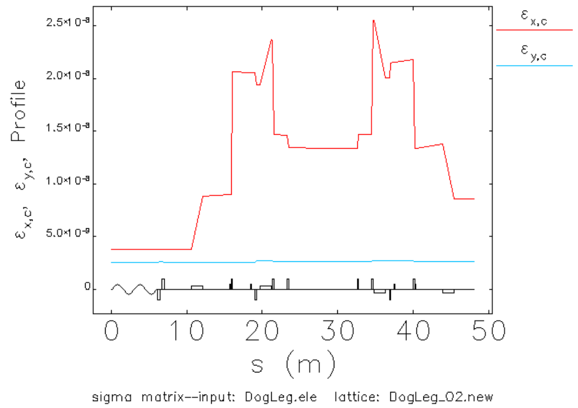
With CSR





C = 8.451488





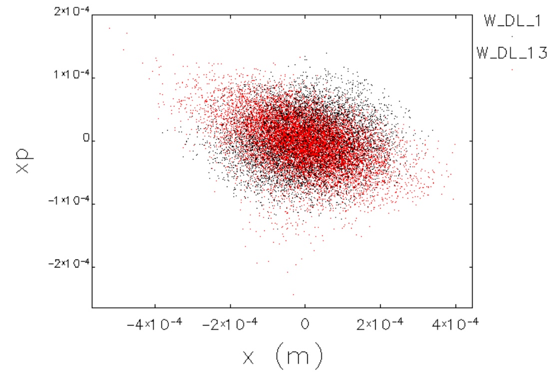
46.6 % increase in horiztonal emittance

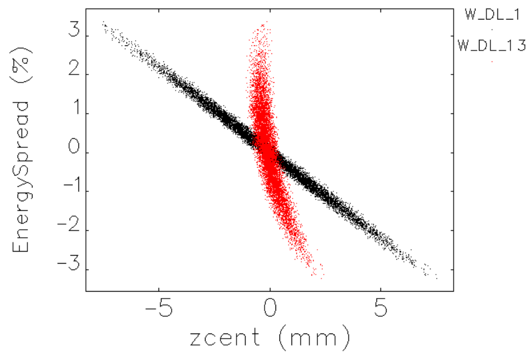
Dogleg compressor - CSR

Black = before dogleg
Red = after dogleg

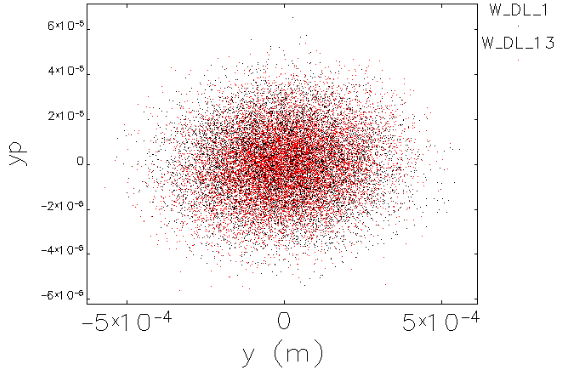
Easing off on the compression

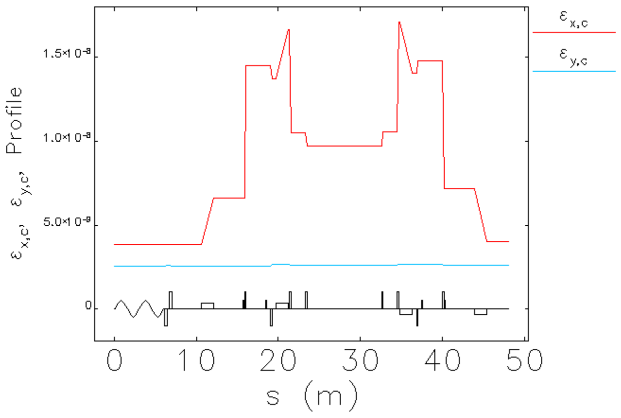
Without CSR



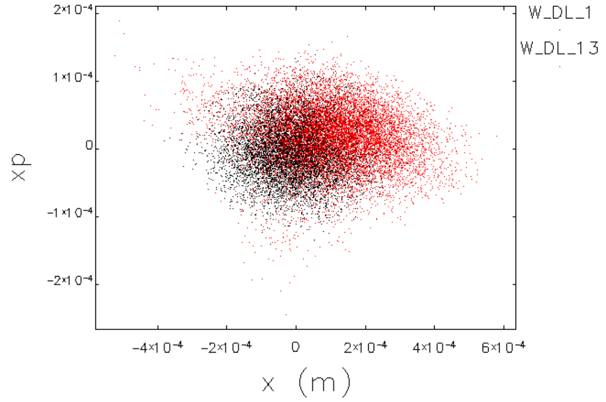


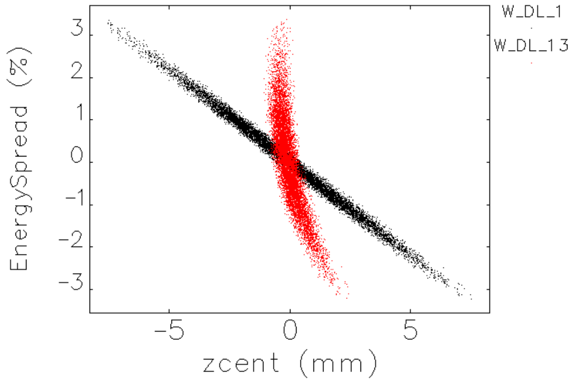
C = 5.398869



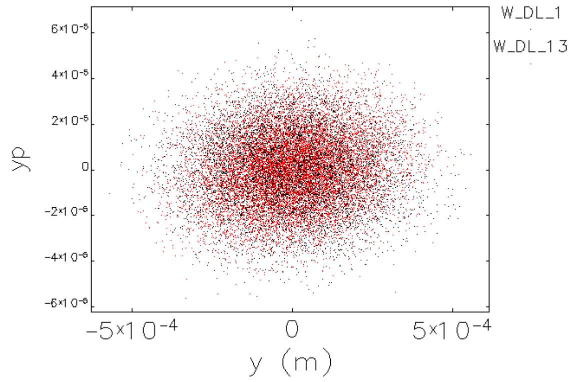


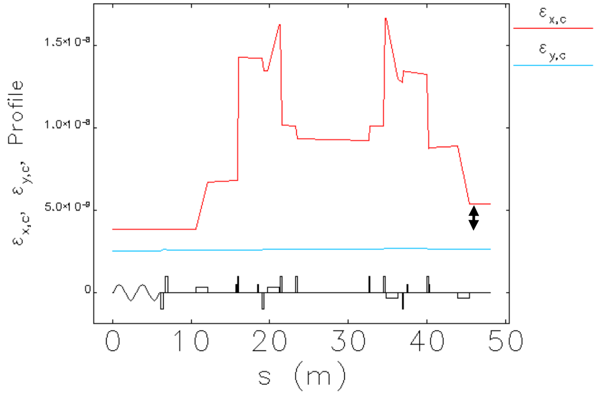
With CSR





C = 5.398501





25.7 % increase in horiztonal emittance

CSR-induced emittance growth estimate

```
Quit[]

In[1023]:= re = 2.8179403227*10^-15 ;
           Nb = 2.66*10^10;
           En = 1.54*10^9;
           γ = 1.54*10^9/(0.511*10^6);
           ϵy = 2.66*10^-9;
           ϵx = 3.9*10^-9;

           θ = 0.200713; (* rad *)
           LB = 1.5; (* m *)
           σzf = 2.*10^-3;
           β = 10;
           α = 0;
           ψ = LB^2 (1+α^2) + 4 β^2 + 4 α β LB;

           ϵN = ϵx γ;

In[932]:= γ
Out[932]= 3013.7

In[933]:= ϵx γ
Out[933]= 8.01644×10^-6

In[934]:= Nb*1.6*10^-19
Out[934]= 4.256×10^-9
```

CSR

In[1036]:= $\left(\frac{\epsilon}{\epsilon 0}\right)$

$$\epsilon\text{growth} = \text{Sqrt}\left[1 + \frac{(0.22)^2}{16}\,\frac{r_e^2 N_b^2}{\gamma\,\epsilon_N\,\beta}\,\psi\left(\frac{\text{Abs}[\theta]^5 L_B}{\sigma_{zf}^4}\right)^{(3/2)}\right]$$

Out[1037]= 57.0815 %

ISR

In[954]:= $$\sigma_{\delta ISR} = \text{Sqrt}\left[\frac{55}{24\,\text{Sqrt}[3]}\,\frac{r_e\,\text{hbar}\,c}{(m\,c^2)^6}\,\frac{E^5 L_B}{\rho}\right]$$

Which equals approx...

In[1038]:= $$\sigma_{\delta ISR} = \frac{1}{L_B}\,\text{Sqrt}[(4.13*10^{-11})\,(\text{En}*10^{-9})^5\,\text{Abs}[\theta]^3]$$

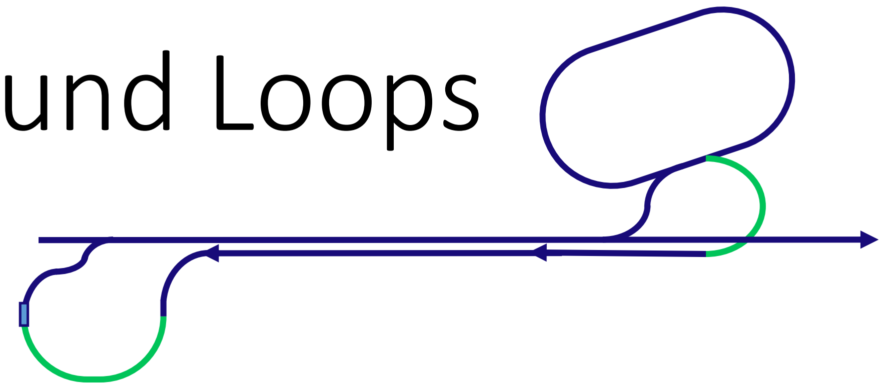
Out[1038]= 1.13383×10^{-6}

Equations from Chao "Handbook of Accelerator Physics and Engineering" 2nd Ed. p 336

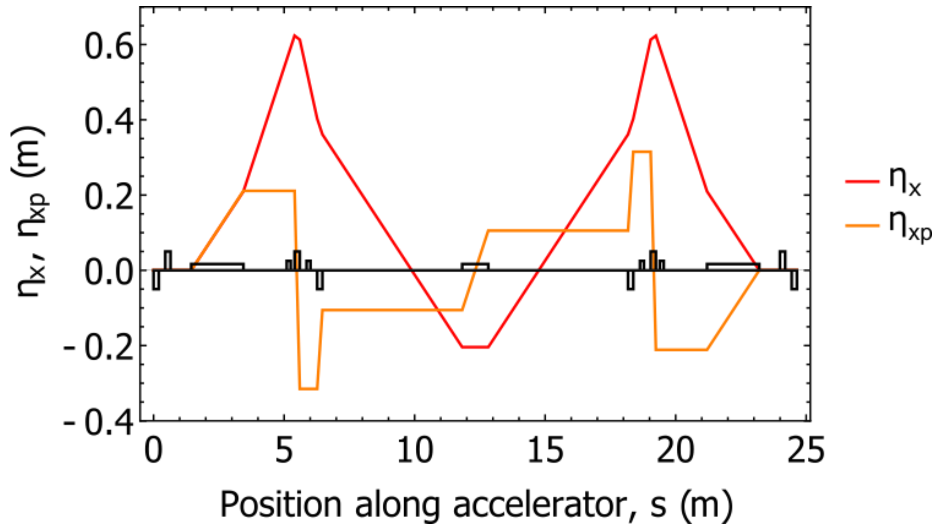
Turnaround loops

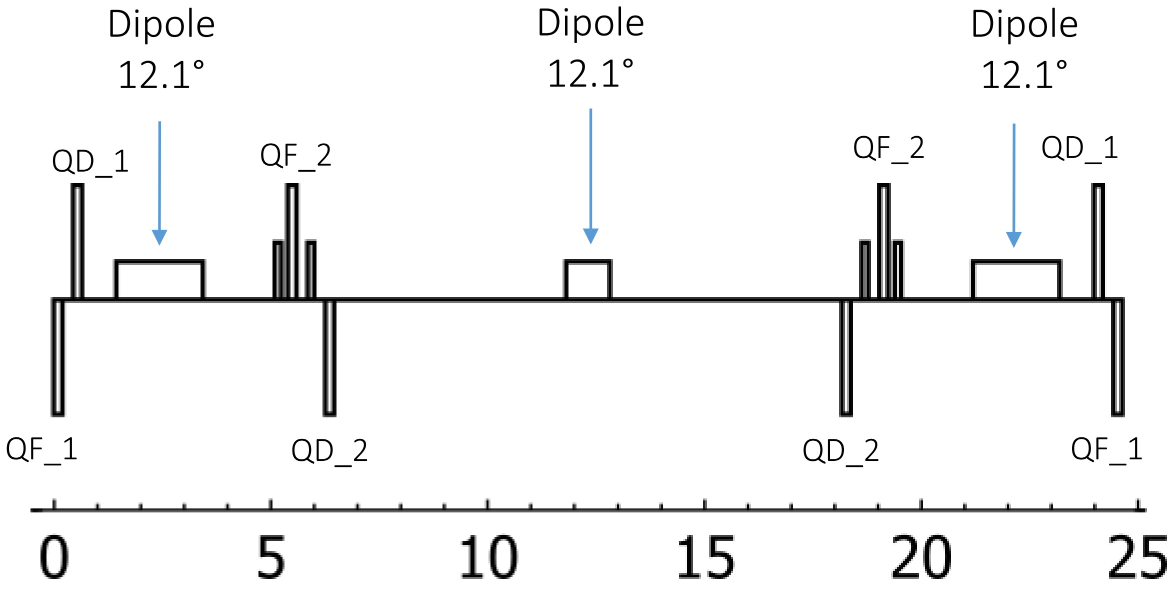
Isochronous and acromatic 180 deg. loops

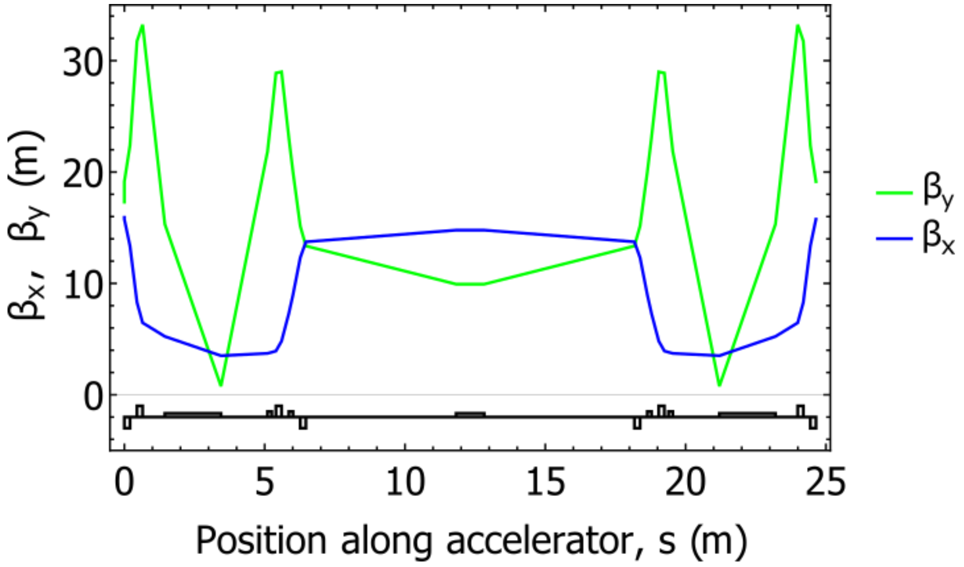
180 Turnaround Loops



5 TBA cells
36.2 degrees per cell

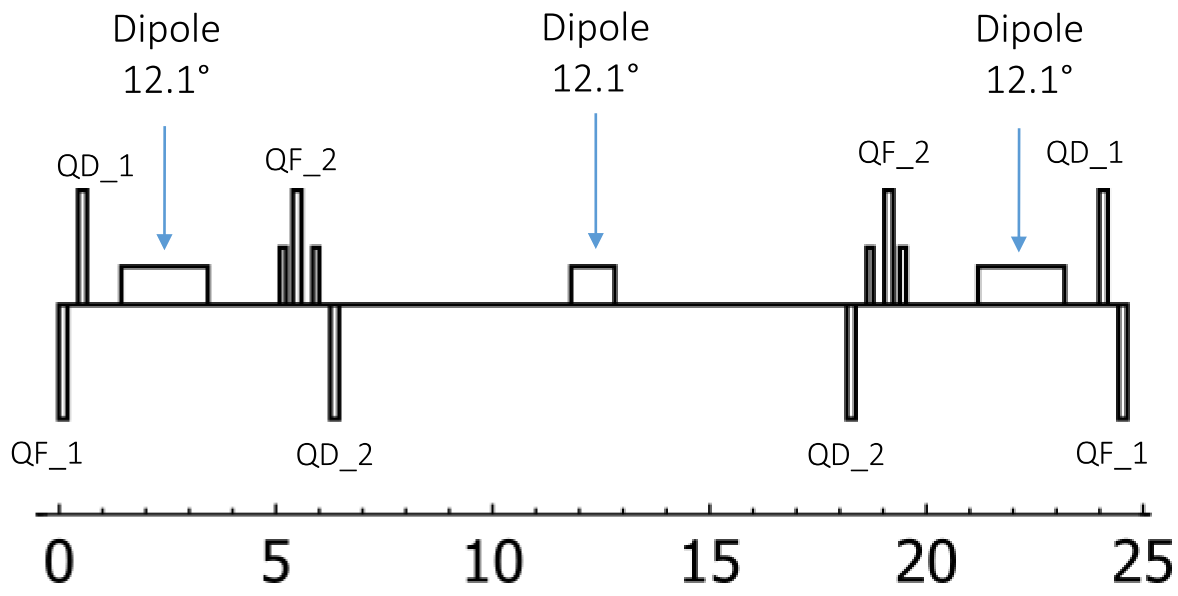


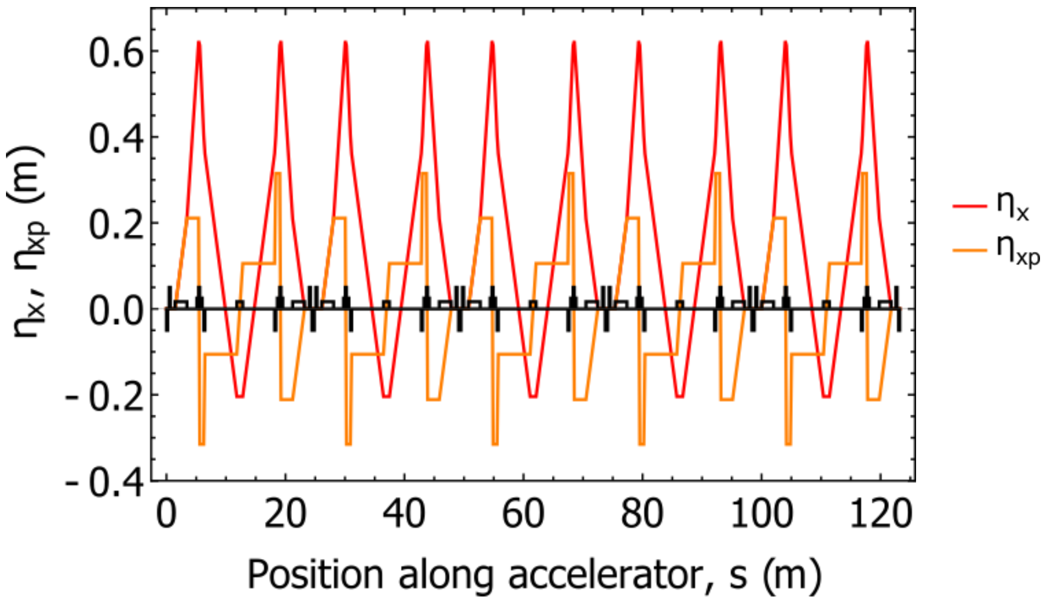


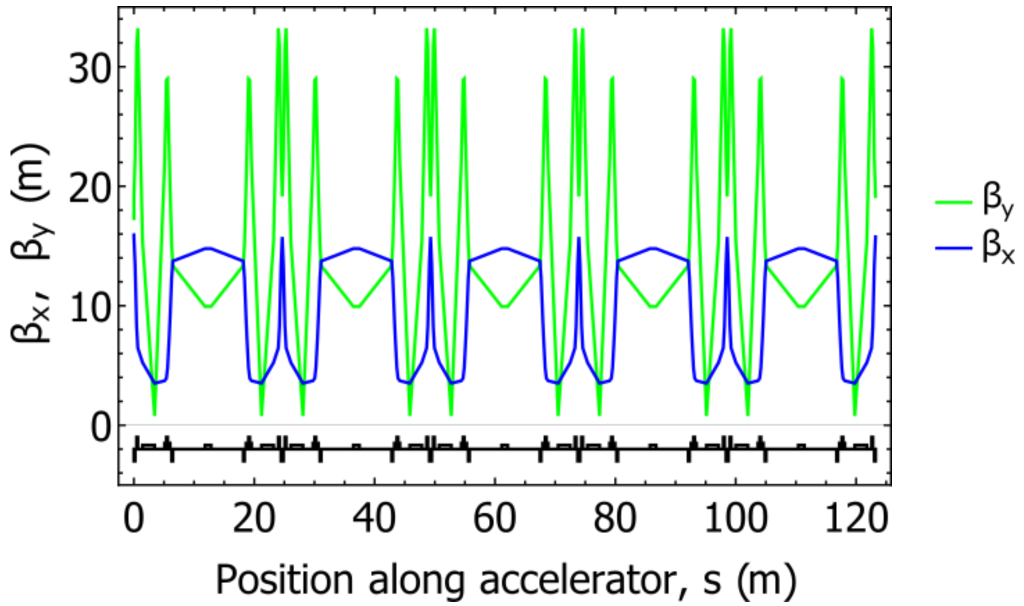


180 Turnaround Loop

5 TBA cells
36.2 degrees per cell

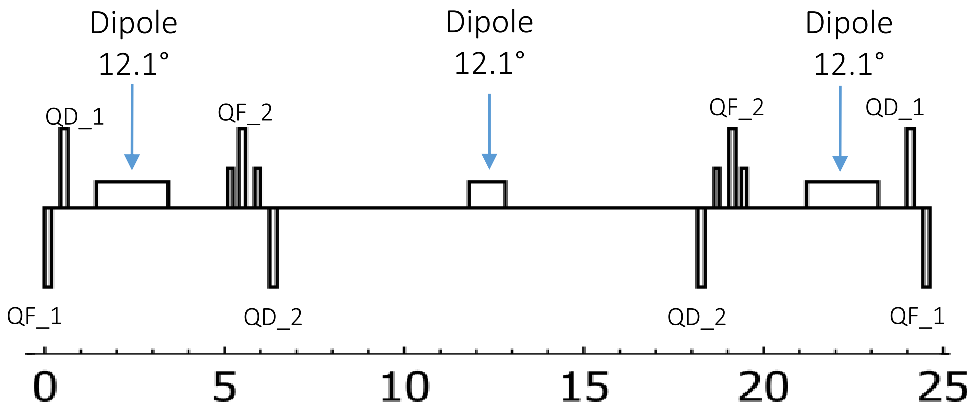


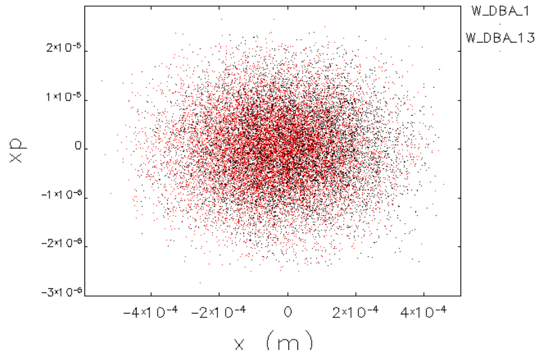


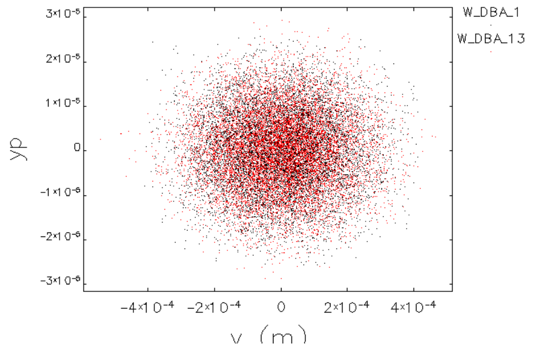


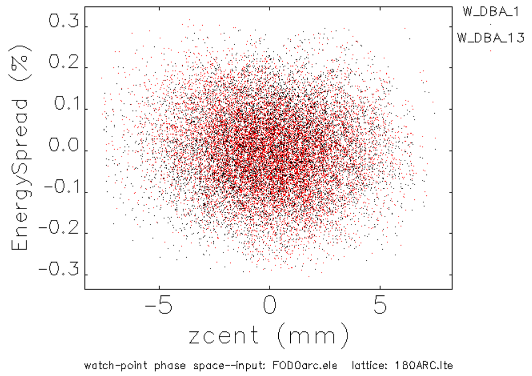
180 Turnaround Loop

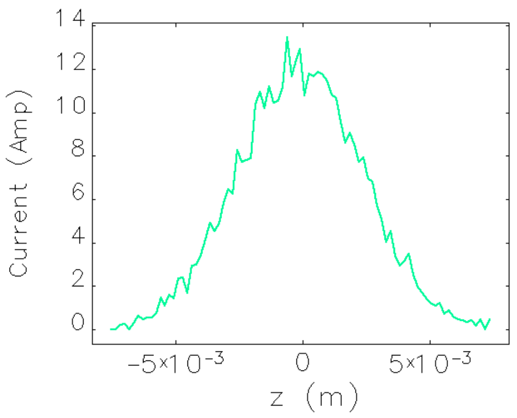
Black = initial distribution
Red = final distribution



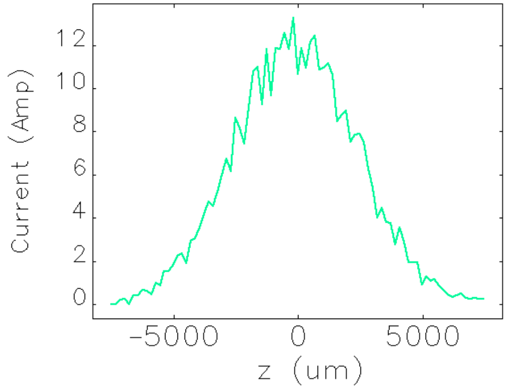








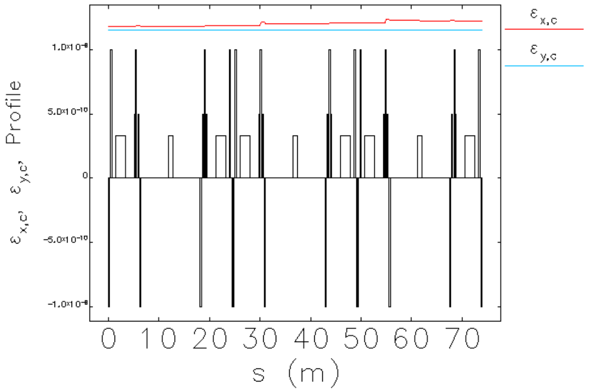
Initial current profile



Final current profile

180 Turnaround Loop

Initial distribution	With CSR	With CSR
	Compression Ratio 1.000016	Compression Ratio 0.9992598
enx 3.550834 mm mrad	enx 3.649786 mm mrad	enx 3.691573 mm mrad
eny 3.466103 mm mrad	eny 3.466121mm mrad	eny 3.465129 mm mrad



CSR has a very small effect

Thoughts on CSR cancellation

… an idea for consideration

CSR kicks

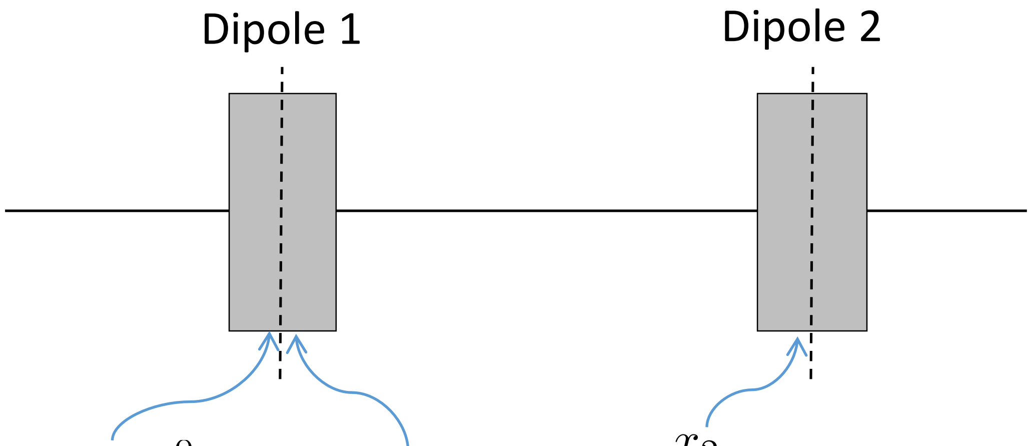
As the bunch passes through dipole, CSR causes a change in energy. The particle starts a betatron oscillation around a new reference trajectory, increasing its Courant-Snyder invariant.

$$X_k = \begin{pmatrix} x_k \\ x'_k \end{pmatrix} = \begin{pmatrix} \rho^{4/3}[\theta cos(\theta/2) - 2sin(\theta/2)] \\ sin(\theta/2)(2\delta + \rho^{1/3}\theta k) \end{pmatrix}$$

where
$$k = \delta_{CSR}\frac{R^{2/3}}{L_b} = 0.2459\frac{r_e Q}{e\gamma\sigma^{4/3}}$$

where δ_{CSR} is from the steady-state solution.

from Y. Jiao et. al (2014) Phys. Rev. ST AB **17** 060701



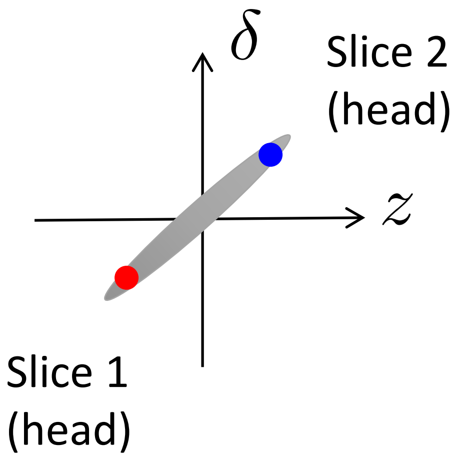
$$x_{1-} = 0, \quad x'_{1-} = 0$$

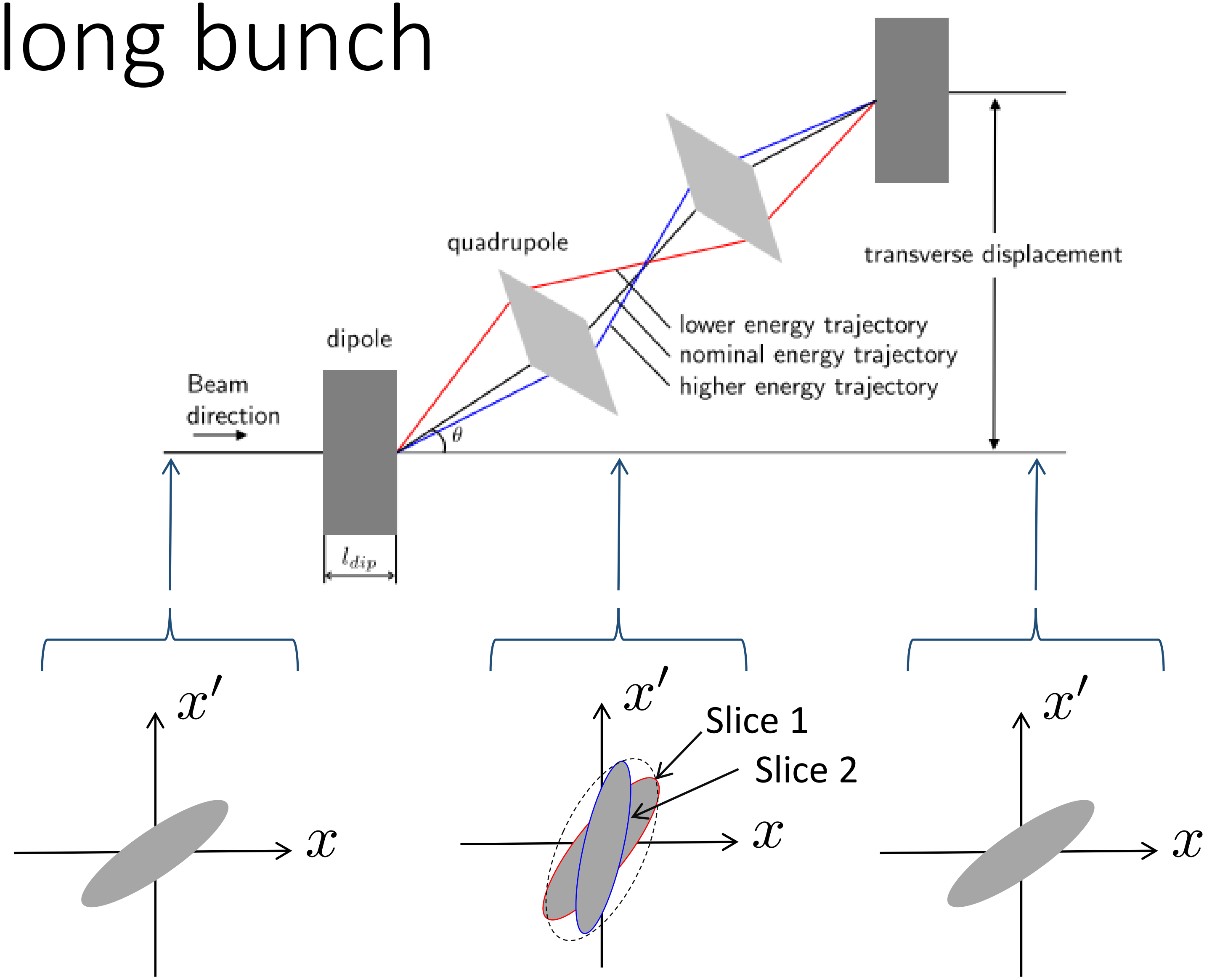
$$x_{1+} = x_{1-} + x_{k1}, \quad x'_{1+} = x'_{1-} + x'_{k1}$$

$$x_{2-}, \quad x'_{2-}$$

$$\begin{pmatrix} x_{2-} \\ x'_{2-} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}[\cos\phi_{12} + \alpha_1 \sin\phi_{12}] & \sqrt{\beta_1\beta_2}\sin\phi_{12} \\ \frac{(\alpha_1 - \alpha_2)\cos\phi_{12} - (1+\alpha_1\alpha_2)\sin\phi 12}{\sqrt{\beta_2\beta_1}} & -\alpha_2\sqrt{\frac{\beta_1}{\beta_2}} \end{pmatrix} \begin{pmatrix} x_{1+} \\ x'_{1+} \end{pmatrix}$$

Slice variations along bunch





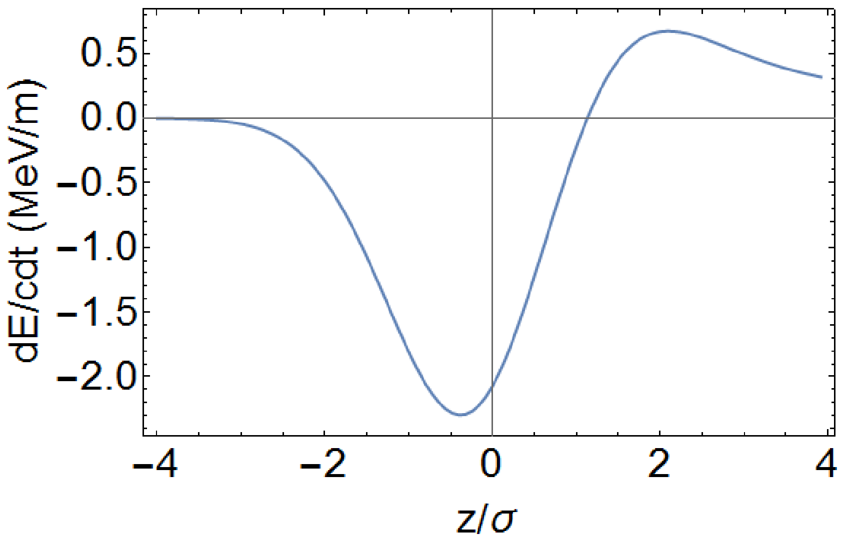
CSR kick cancellation idea

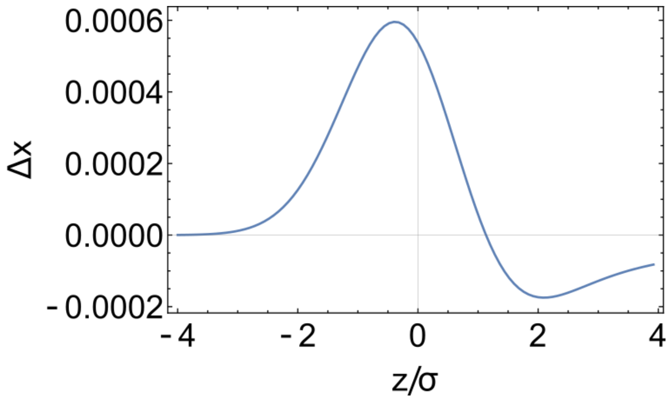
$$X_k = \begin{pmatrix} x_k \\ x'_k \end{pmatrix} = \begin{pmatrix} \rho^{4/3}[\theta cos(\theta/2) - 2sin(\theta/2)] \\ sin(\theta/2)(2\delta + \rho^{1/3}\theta k) \end{pmatrix}$$

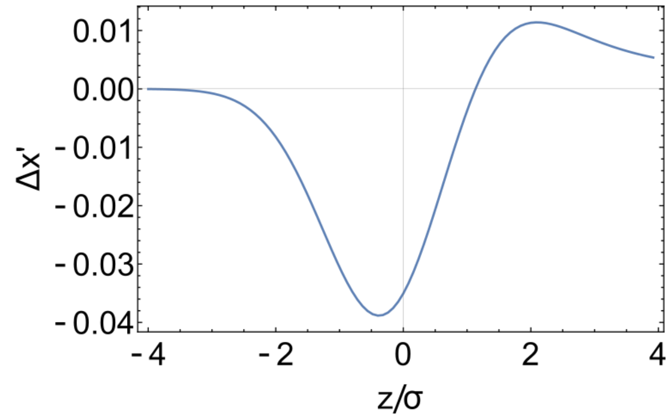
$$k = \delta_{CSR}\frac{R^{2/3}}{L_b}$$

$$\frac{dE}{cdt} = \frac{-2e^2}{4\pi\epsilon_0(3R^2)^{1/3}}\left[\int_{\tilde{z}-z_L}^{\tilde{z}} \frac{d\lambda}{dz}\left(\frac{1}{\tilde{z}-z}\right)^{1/3} dz\right]$$

For a Gaussian bunch







CSR kick cancellation idea

If $\phi_{12} = \pi$

$$\begin{pmatrix} x_{2-} \\ x'_{2-} \end{pmatrix} = \begin{pmatrix} -\sqrt{\frac{\beta_2}{\beta_1}}\rho^{4/3}k[\theta\cos(\theta/2) - 2\sin(\theta/2)] \\ \frac{(\alpha_2-\alpha_1)}{\sqrt{\beta_2\beta_1}}\rho^{4/3}k[\theta\cos(\theta/2) - 2\sin(\theta/2)] - \alpha_2\sqrt{\frac{\beta_1}{\beta_2}}\sin(\theta/2)(2\delta + \rho^{1/3}\theta k) \end{pmatrix}$$

Vary (or can vary) along the length of the bunch

Could be used vary relative strengths of the two parts of the sum.

If $\phi_{12} = \pi/2$

$$\begin{pmatrix} x_{2-} \\ x'_{2-} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}\alpha_1\rho^{4/3}k[\theta\cos(\theta/2) - 2\sin(\theta/2)] + \sqrt{\beta_1\beta_2}\sin(\theta/2)(2\delta + \rho^{1/3}\theta k) \\ \frac{(1+\alpha_1\alpha_2)}{\sqrt{\beta_2\beta_1}}\rho^{4/3}k[\theta\cos(\theta/2) - 2\sin(\theta/2)] - \alpha_2\sqrt{\frac{\beta_1}{\beta_2}}\sin(\theta/2)(2\delta + \rho^{1/3}\theta k) \end{pmatrix}$$

Thanks