Zig-Zag compressor for FACET II witness bunch

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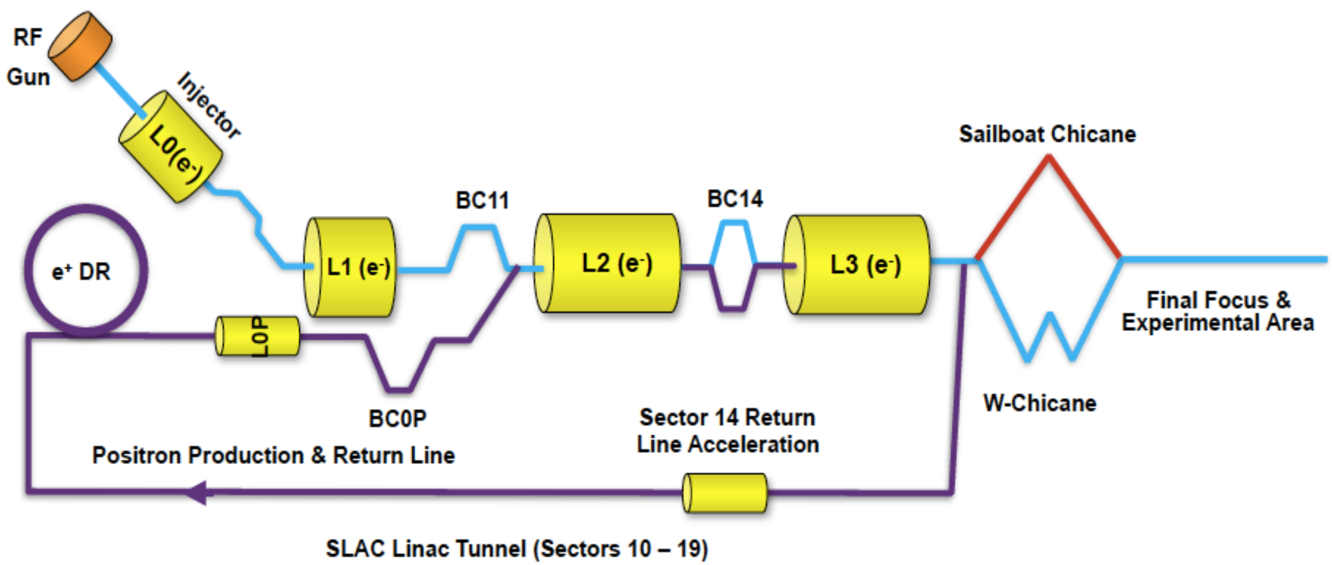
In short

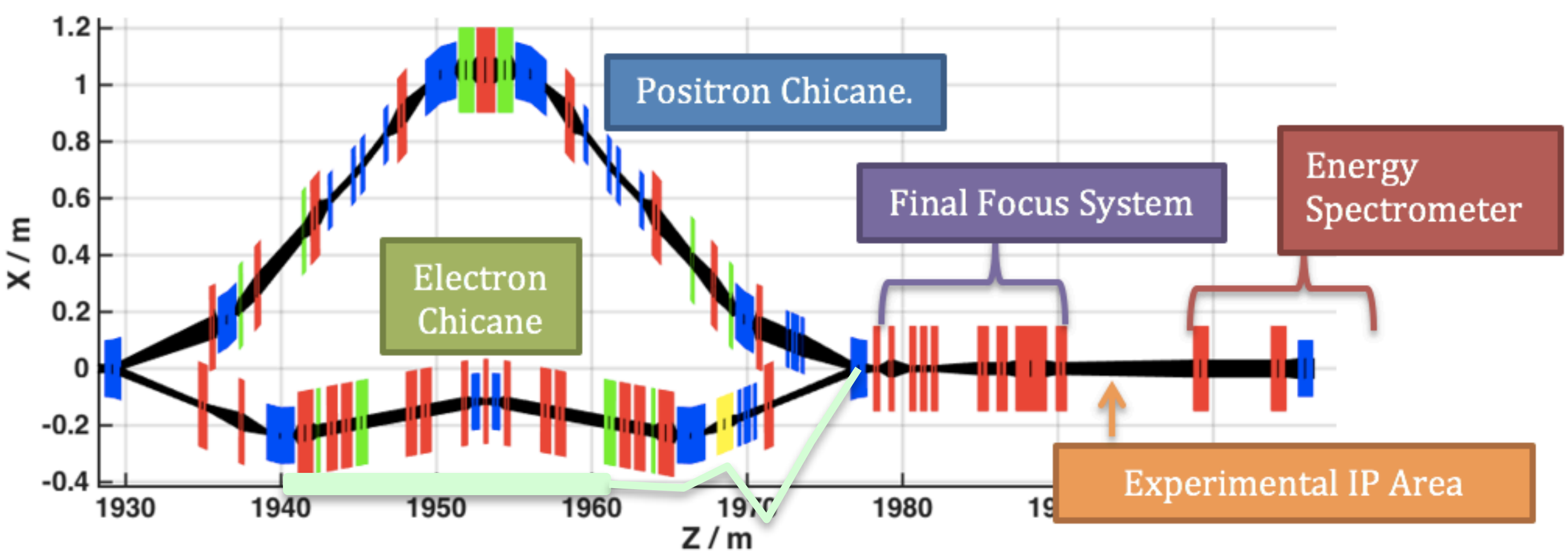
- We propose to develop a system with high compression ratio for a future FACET II facility. The high charge bunch should be compressed more than 30-fold to about 10 kA peak current
- The system will eliminate (or better say, strongly reduce) emittance degradation from CSR in the bunch compressor
  - If necessary, we will explore possibility of suppressing energy spread growth from CSR

External injector for PWFA

- A possibility of injecting a short (fsec) matched low-emittance electron bunch into a PWFA has multiple benefits
  - It can provide for a reliable PWFA with small (e.g. accelerator quality) energy spread
  - Explore "even loading" and high transformer ratio regimes
  - Emulate multi-stage PWFA
  - ….

Just add external injector…





Possible sources of FACET II witness bunch

Option	Dedicated injector	LCLS II
Beam Energy, [GeV]	0.3	4
Bunch Charge , [nC]	0.1/1	0.1
Normalized emittance, [μm]	<1 – 3	<1
Bunch Length, [fsec]	300 – 3,000	~ 200
Peak current, [A]	~ 300	~500

These bunches should be compressed to 10 – to -50 – fold while preserving transverse emittance.
The goal is to compress the witness bunch to about 10 μm (~ 30 fsec) with peak currents from 3 to 10 kA.

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Merger designs for ERLs☆

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Compensating effect of the coherent synchrotron radiation in bunch compressors

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Experimental Observation of Suppression of Coherent-Synchrotron-Radiation–Induced Beam-Energy Spread with Shielding Plates

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Problem

$$\delta x(s_2, z) = \frac{1}{E_0}\int_{s_1}^{s_2} \frac{d[\delta E(z,s)]R_{16}(s,s_2)}{ds}ds \neq 0; \quad (1)$$

$$\delta x'(s_2, z) = \frac{1}{E_0}\int_{s_1}^{s_2} \frac{d[\delta E(z,s)]R_{26}(s,s_2)}{ds}ds \neq 0. \quad (2)$$

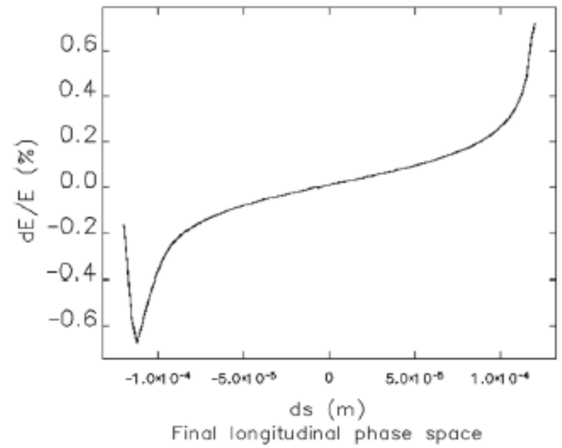
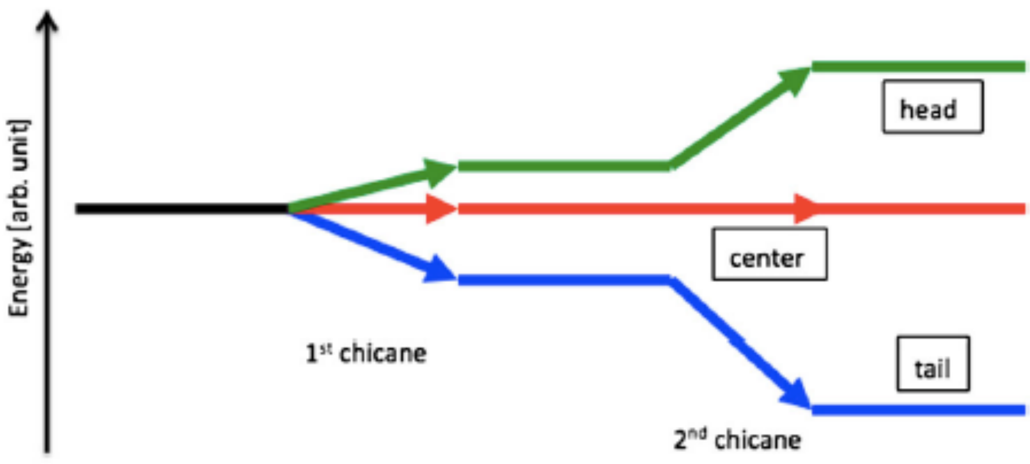


FIG. 4. A typical CSR wakefield induces energy variation along a 1 ps electron bunch. The head and tail of the bunch, respectively, gain and lose energy.



III. TRADITIONAL C-SHAPE CHICANE

TABLE I. eRHIC beam parameters for FEL operation.

Name	Soft x ray	Hard x ray
Energy (GeV)	1.8	10
Bunch charge (nC)	0.2	0.2
Rms bunch length (ps)	1	1
Rms energy spread (keV)	50–200	500
Rms normalized emittance (μm)	0.6	0.2
Undulator period (cm)	1.85	3
Fundamental wavelength (nm)	1	0.1

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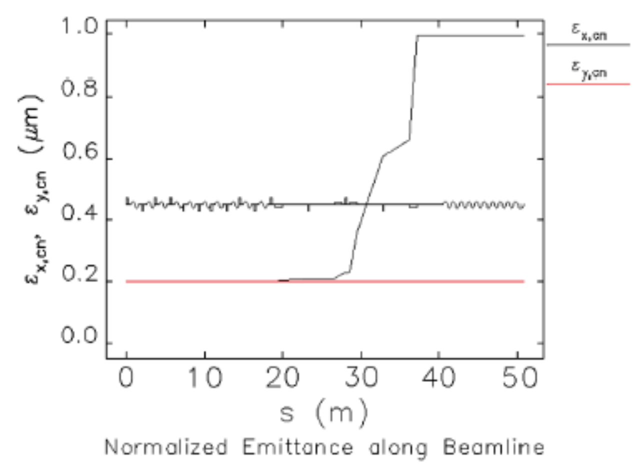


FIG. 3. The evolution of e-beam emittance in the bunch compressor using a single chicane. The blowup of emittance is caused by the CSR effect.

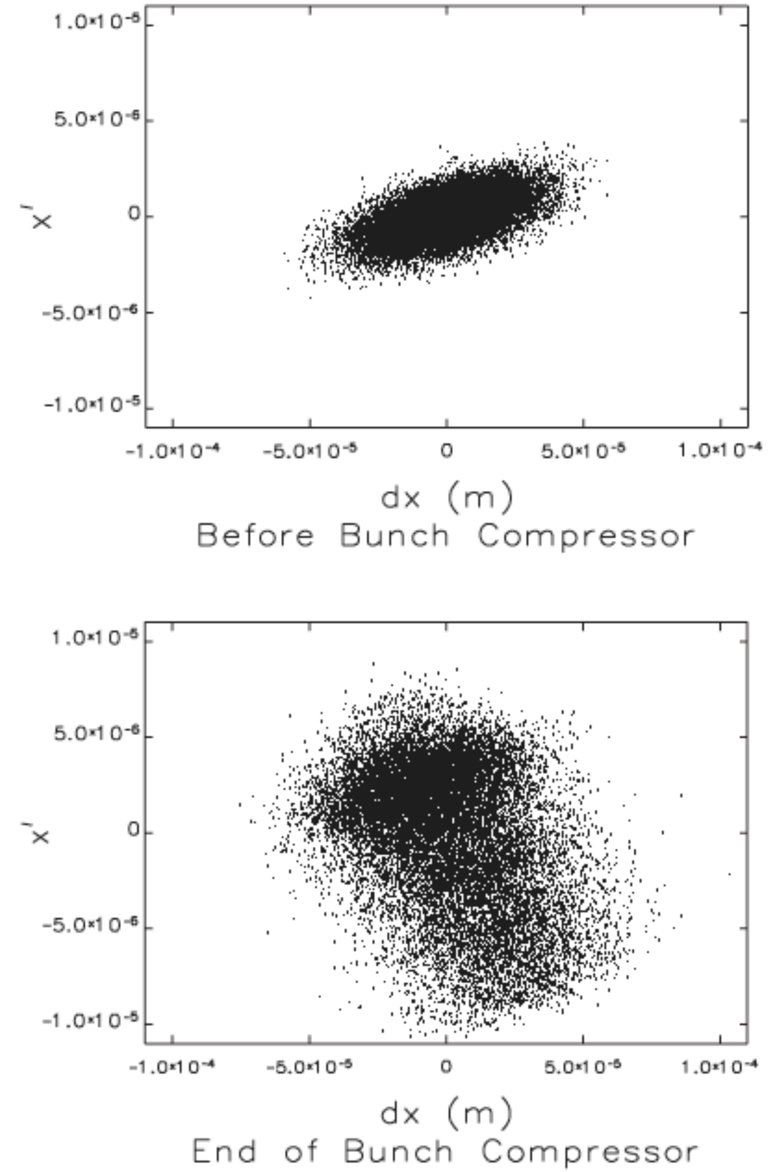
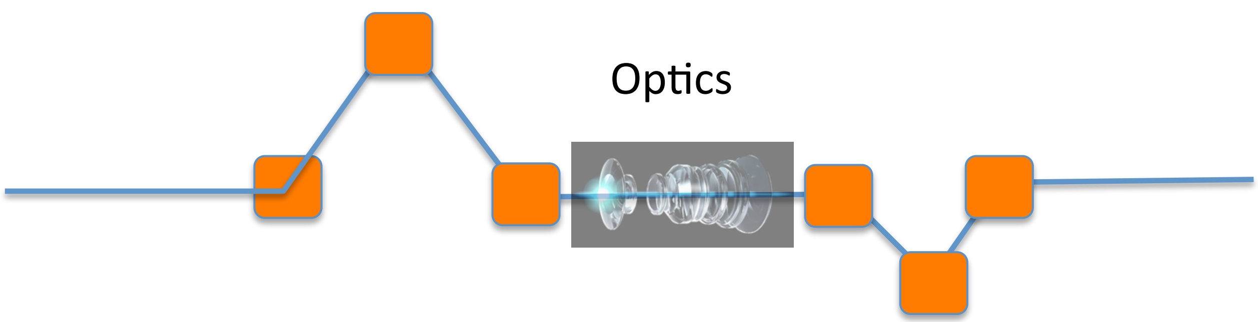


FIG. 5. Phase-space distribution before (top) and after (bo
tom) the bunch compressor. The longitudinal energy variati
induced by CSR wakes is coupled to the coordinate and angu
displacements through R_{16} and R_{26} induced in the chicane. Th
results in smearing of the transverse phase space.

Solution

$$\delta x(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{16}(s, s_2)}{ds} ds = 0; \qquad (1)$$

$$\delta x'(s_2, z) = \frac{1}{E_0} \int_{s_1}^{s_2} \frac{d[\delta E(z, s)] R_{26}(s, s_2)}{ds} ds = 0. \qquad (2)$$



Easy to say, tough to do…

Main points

- First, you have to select relative strength of two buncher legs – the CSR wakefield changes during compression

- Select optimal phase trombone (optics) between two legs
- Optimize beam Twiss parameters at the entrance of the system
- ….. and go in circles few times…

IV. ZIGZAG CHICANE WITH CSR COMPENSATION

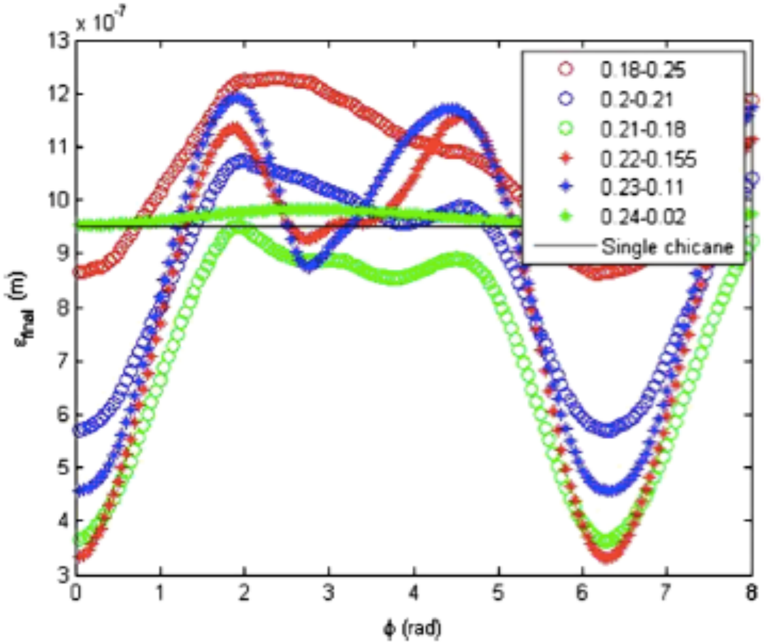


FIG. 7. Horizontal projected normalized emittance as function of the bending angles of the chicanes (listed in the box in the right-upper corner of the graph) and the betatron phase advance between chicanes. The vertical axis is the resulting projected normalized emittance after the bunch compressor. The horizontal axis is the phase advance between two chicanes. The initial normalized emittance before compression is 0.2 μm and the baseline single chicane scheme with a growth factor of 5 is also shown.

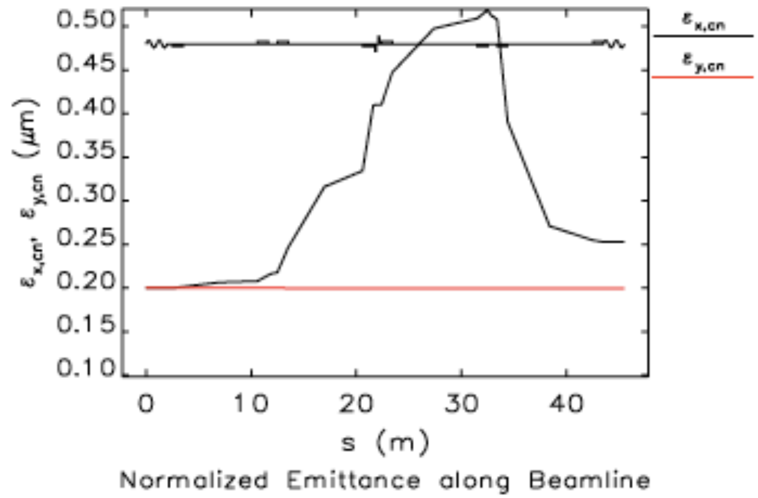


FIG. 9. The emittance growth in the first chicane is largely compensated in the second chicane with careful tuning of all parameters.

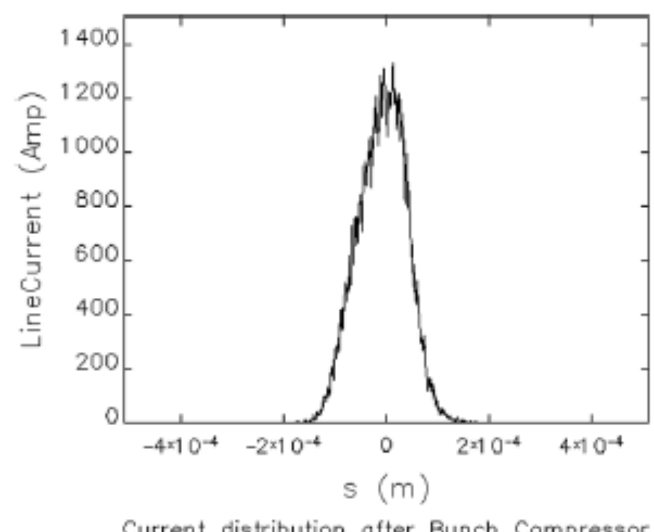


FIG. 10. The current distribution along the bunch at the end of zigzag bunch compressor.

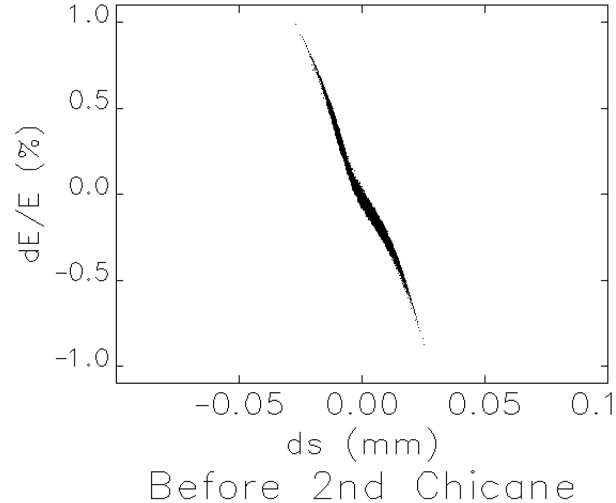
Possible tests: e-bunch in ATF

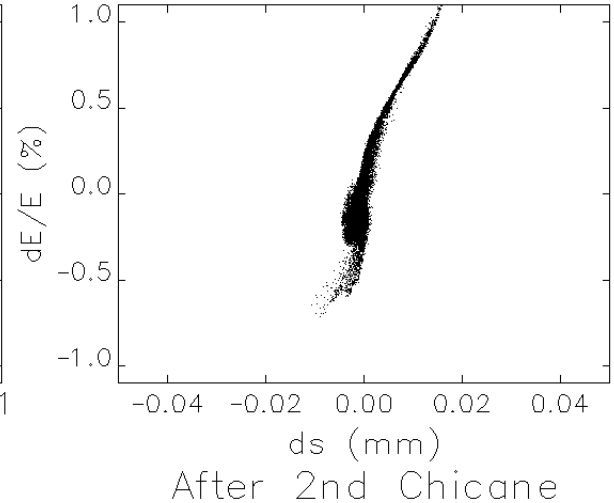
- We have multiple options for bunch compression
- Compressing bunch to ~ 10-20 fs RMS is possible with current ATF and a simple chicane - we plan to start with this simplest option
- If necessary, we will modify system to a proper Zig-Zag chicane compression, which is more robust, emittance-preserving and is suitable for large charges – this is most likely scenario for the injecting bunch

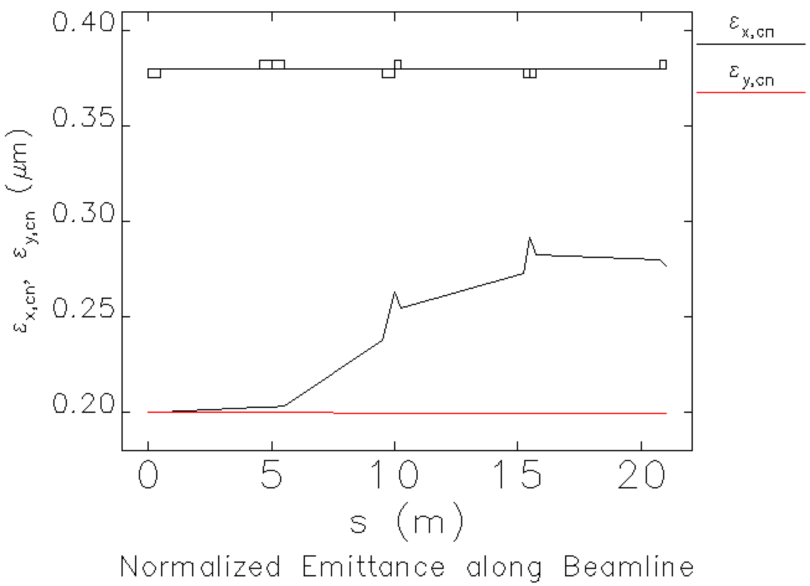
Bunch Compression: existing ATF beam

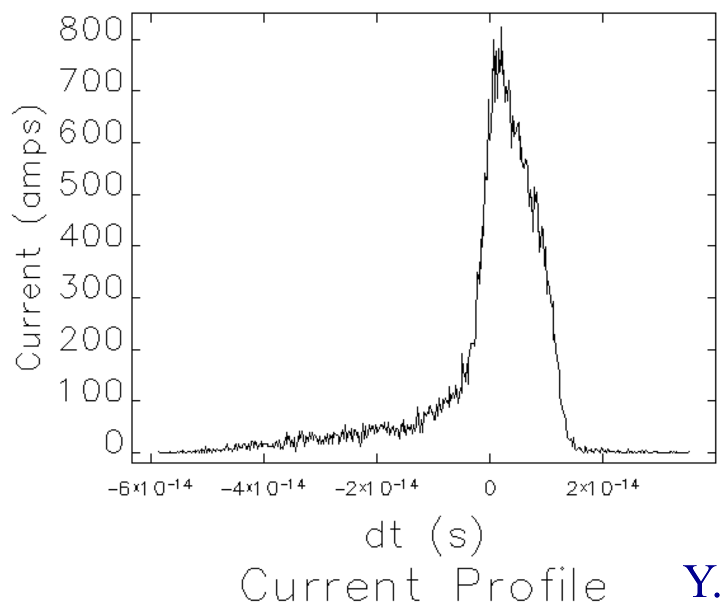
With new Zig-Zag type compressor could be installed in ATF to compress bunches to 12fs

Energy, MeV	**70**
Bunch length, mm	**0.06**
Chirp, m^{-1}	**20**
Bunch length, rms, fsec	**12**





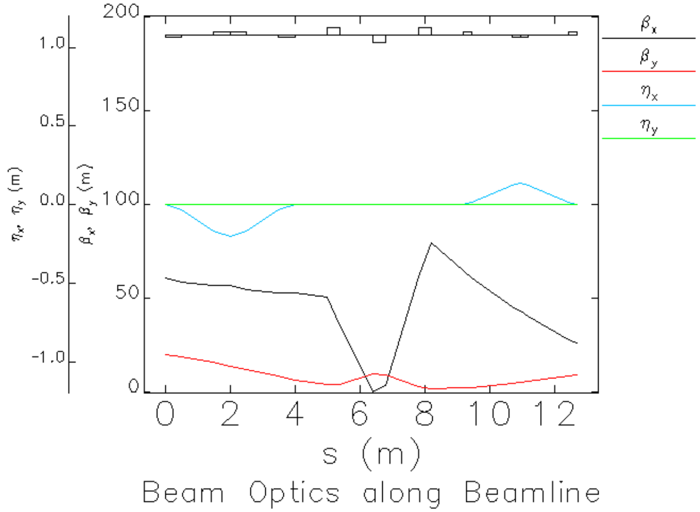




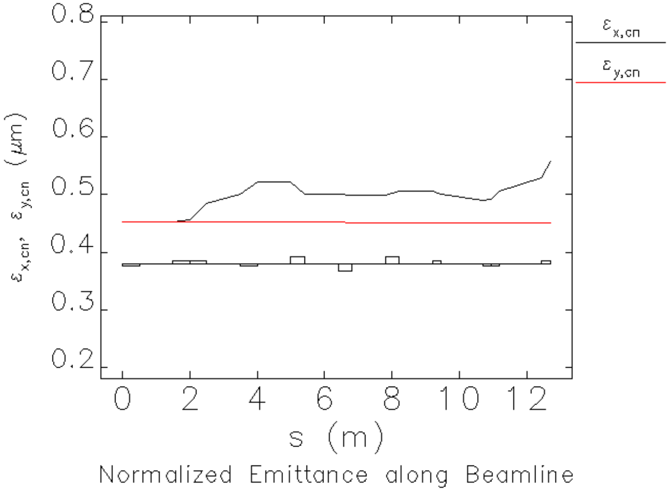
Y. Jing, VL

Future ATF 2

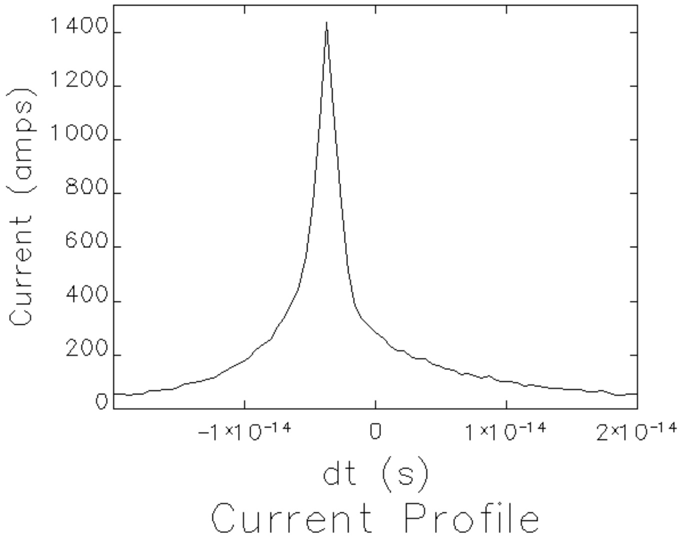
(a)



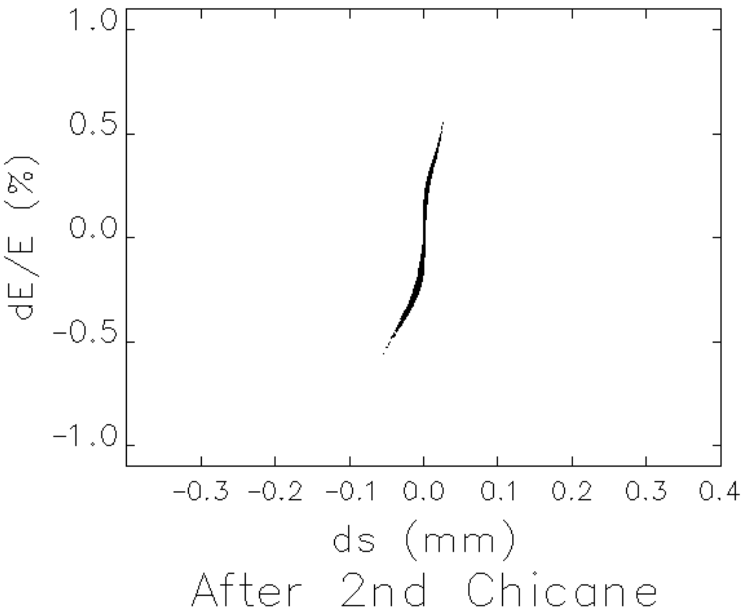
(b)



(c)



(d)



On the fly

- One of the optimization for peak current is to use T566 in the compression beamline
- It allows to remove curvature in the E-t phase space
- I do not have pictures with but this is a relatively standard technique

Conclusions

- We propose to develop a system with high compression ratio for a future FACET II facility.
- The high charge bunch should be compressed more than 30-fold to about 10 kA peak current
- The system will eliminate (or better say, strongly reduce) emittance degradation from CSR in the bunch compressor
- We could conduct p-o-p extperiment at ATF

$$E(s) = E_\mathrm{o} \cdot (1 + \delta(s)) \qquad X' = D(s) \cdot X + \delta(s) \cdot \begin{bmatrix} 0 \\ K_\mathrm{o}(s) \end{bmatrix}$$

$$X(s) = M(s_0|s) \cdot \left\{ X_\mathrm{o} + \int_{s_0}^{s} \delta(s_1) \cdot M^{-1}(s_0|s_1) \cdot \begin{bmatrix} 0 \\ K_\mathrm{o}(s_1) \end{bmatrix} \mathrm{d}s_1 \right\}$$

$$R(s) = \begin{bmatrix} \int_{s_\mathrm{o}}^{s} K_\mathrm{o}(s_1) \cdot \delta(s_1) \cdot m_{12}(s_1|s)\, \mathrm{d}s_1 \\ \int_{s_\mathrm{o}}^{s} K_\mathrm{o}(s_1) \cdot \delta(s_1) \cdot m_{22}(s_1|s)\, \mathrm{d}s_1 \end{bmatrix}.$$

$$E(s) = E_\mathrm{o} \cdot (1 + \delta(s)) \qquad \begin{aligned} \eta(s) &= \int_{s_0}^{s} K_\mathrm{o}(s_1) \cdot m_{12}(s_1|s)\, \mathrm{d}s_1, \\ \eta'(s) &= \int_{s_0}^{s} K_\mathrm{o}(s_1) \cdot m_{22}(s'|s)\, \mathrm{d}s_1. \end{aligned}$$

$$R(s) = \delta(s) \cdot \begin{bmatrix} \eta(s) \\ \eta'(s) \end{bmatrix} - \int_{s_0}^{s} \delta'(s_1) \cdot M(s_1|s) \cdot \begin{bmatrix} \eta(s_1) \\ \eta'(s_1) \end{bmatrix} \mathrm{d}s_1.$$

$$\delta(s) = f(s, \delta_\mathrm{o}, \xi_\mathrm{o}, X_\mathrm{o}, Y_\mathrm{o}), \quad Y^\mathrm{T} = [y, y']$$

$$\begin{aligned} R(s) &= f_1(\delta_\mathrm{o}, \xi_\mathrm{o}, X_\mathrm{o}, Y_\mathrm{o}) \cdot R_1(s) \\ &\quad + f_2(\delta_\mathrm{o}, \xi_\mathrm{o}, X_\mathrm{o}, Y_\mathrm{o}) \cdot R_2(s), \\ R_{1,2}(s) &= \begin{bmatrix} \int_{s_0}^{s} K_\mathrm{o}(s_1) \cdot g_{1,2}(s_1) \cdot m_{12}(s_1|s)\, \mathrm{d}s_1 \\ \int_{s_0}^{s} K_\mathrm{o}(s_1) \cdot g_{1,2}(s_1) \cdot m_{22}(s_1|s)\, \mathrm{d}s_1 \end{bmatrix} \end{aligned}$$

$$R_1(s_f) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad R_2(s_f) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

$$f_1 = \delta_o, \qquad g_1(s) = 1,$$
$$f_2 = f_2(\xi_o), \quad g_2 = s$$

$$\int_{s_0}^{s_f} K_o(s) \cdot m_{12}(s|s_f)\,\mathrm{d}s = 0,$$
$$\int_{s_0}^{s_f} K_o(s) \cdot m_{22}(s|s_f)\,\mathrm{d}s = 0$$

plus two non-trivial conditions of:

$$\int_{s_0}^{s_f} K_o(s) \cdot s \cdot m_{12}(s|s_f)\,\mathrm{d}s = 0,$$
$$\int_{s_0}^{s_f} K_o(s) \cdot s \cdot m_{22}(s|s_f)\,\mathrm{d}s = 0.$$

$$\int_{s_0}^{s_f} M(s|s_f) \cdot \begin{bmatrix} \eta(s) \\ \eta'(s) \end{bmatrix} \mathrm{d}s = 0.$$

It automatically makes two of integrals zero

$$K_o(-s)m_{11}(-s) = -K_o(s)m_{11}(s)$$
$$\Rightarrow \int_{-L}^{L} K_o(s')m_{11}(s')\,ds' \equiv 0$$

$$K_o(-s)(-s)m_{12}(-s) = -K_o(s)(s)m_{12}(s)$$
$$\Rightarrow \int_{-L}^{L} K_o(s')m_{12}(s')s'\,ds' \equiv 0$$

(where $2L$ is the length of the merger) and only two conditions remain:

$$\int_0^L K_o(s') \cdot m_{12}(s')\,ds' = 0, \quad \int_0^L K_o(s') \cdot s \cdot m_{11}(s')\,ds' = 0. \tag{24}$$