FACET-II
Facility for Advanced Accelerator Experimental Tests

Machine/physics studies towards FACET-III stability

C. Emma
FACET-II Science Workshop
October 2019
SLAC

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Motivation: Sub-um bunches and stability challenges

- 2-stage compression designs for improved stability:
    - Green field example
    - FACET-II 2-stage example

- Passive CSR compression in wigglers
    - Mega-Amp beams at FACET-II

- Conclusion and future direction of study

Motivation for generating stable, sub-um beams

Science Applications:

- Beam physics towards new operating regimes in existing and next generation X-FELs (BES)
- Beam physics towards collider with suppressed beamstrahlung (HEP)
- Support for high brightness beams from Plasma Wakefield (HEP)
- Gamma ray source based filamentation (NNSA)
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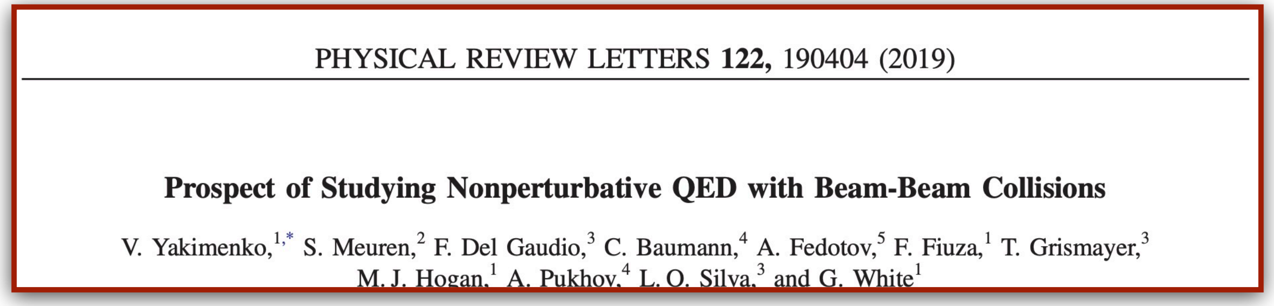
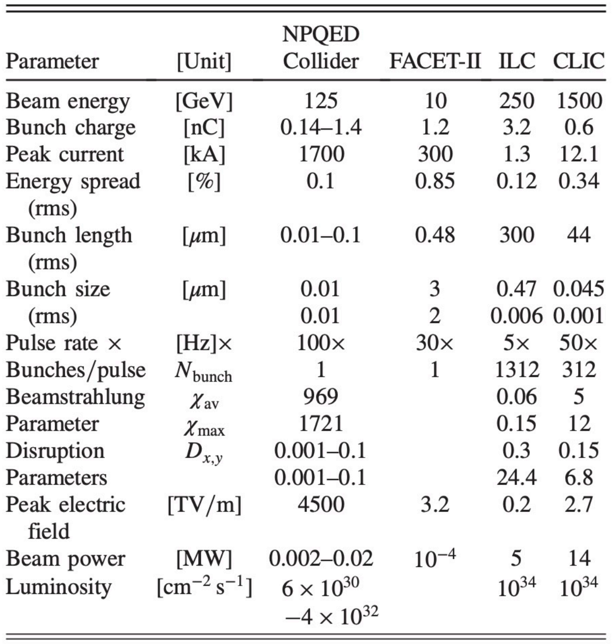


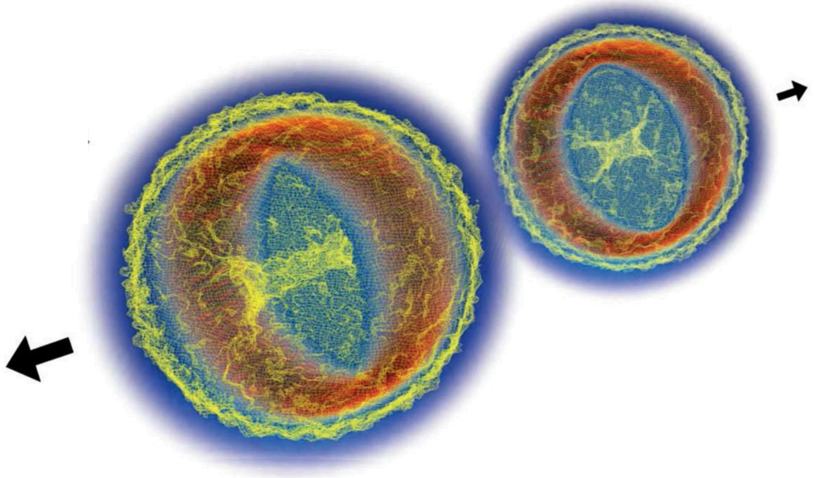
PHYSICAL REVIEW LETTERS **122,** 190404 (2019)

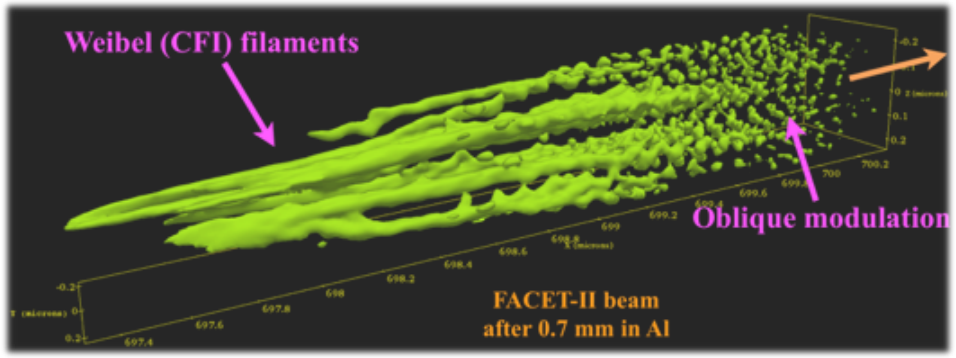
Prospect of Studying Nonperturbative QED with Beam-Beam Collisions

V. Yakimenko,[1,*] S. Meuren,[2] F. Del Gaudio,[3] C. Baumann,[4] A. Fedotov,[5] F. Fiuza,[1] T. Grismayer,[3] M. J. Hogan,[1] A. Pukhov,[4] L. O. Silva,[3] and G. White[1]

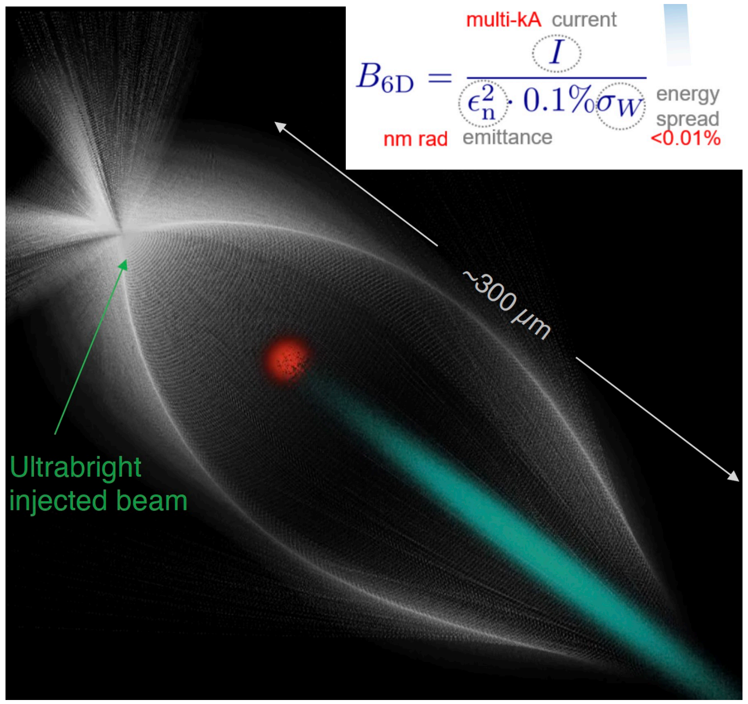


Parameter	[Unit]	NPQED Collider	FACET-II	ILC	CLIC
Beam energy	[GeV]	125	10	250	1500
Bunch charge	[nC]	0.14–1.4	1.2	3.2	0.6
Peak current	[kA]	1700	300	1.3	12.1
Energy spread (rms)	[%]	0.1	0.85	0.12	0.34
Bunch length (rms)	[μm]	0.01–0.1	0.48	300	44
Bunch size (rms)	[μm]	0.01 0.01	3 2	0.47 0.006	0.045 0.001
Pulse rate ×	[Hz]×	100×	30×	5×	50×
Bunches/pulse	N_{bunch}	1	1	1312	312
Beamstrahlung	χ_{av}	969		0.06	5
Parameter	χ_{max}	1721		0.15	12
Disruption	$D_{x,y}$	0.001–0.1		0.3	0.15
Parameters		0.001–0.1		24.4	6.8
Peak electric field	[TV/m]	4500	3.2	0.2	2.7
Beam power	[MW]	0.002–0.02	10^{-4}	5	14
Luminosity	[cm^{-2} s^{-1}]	6×10^{30} -4×10^{32}		10^{34}	10^{34}





S. Corde, yesterday



B. Hidding, yesterday

Motivation for generating stable, sub-um beams

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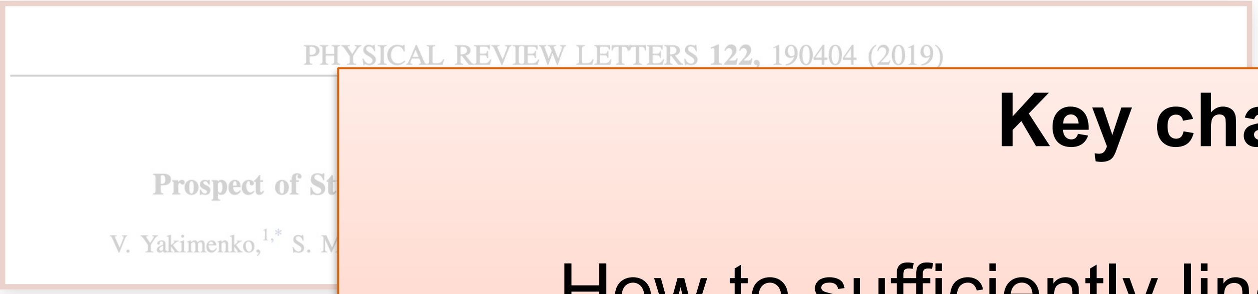

PHYSICAL REVIEW LETTERS 122, 190404 (2019)

Prospect of St

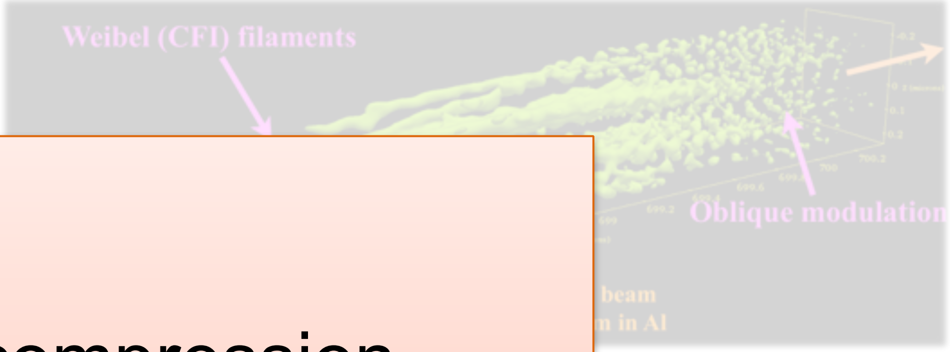
V. Yakimenko,[1,*] S. M

Key challenges:

How to sufficiently linearize the compression

Preserving the longitudinal and transverse beam quality

Ensuring stable and predictable beam delivery



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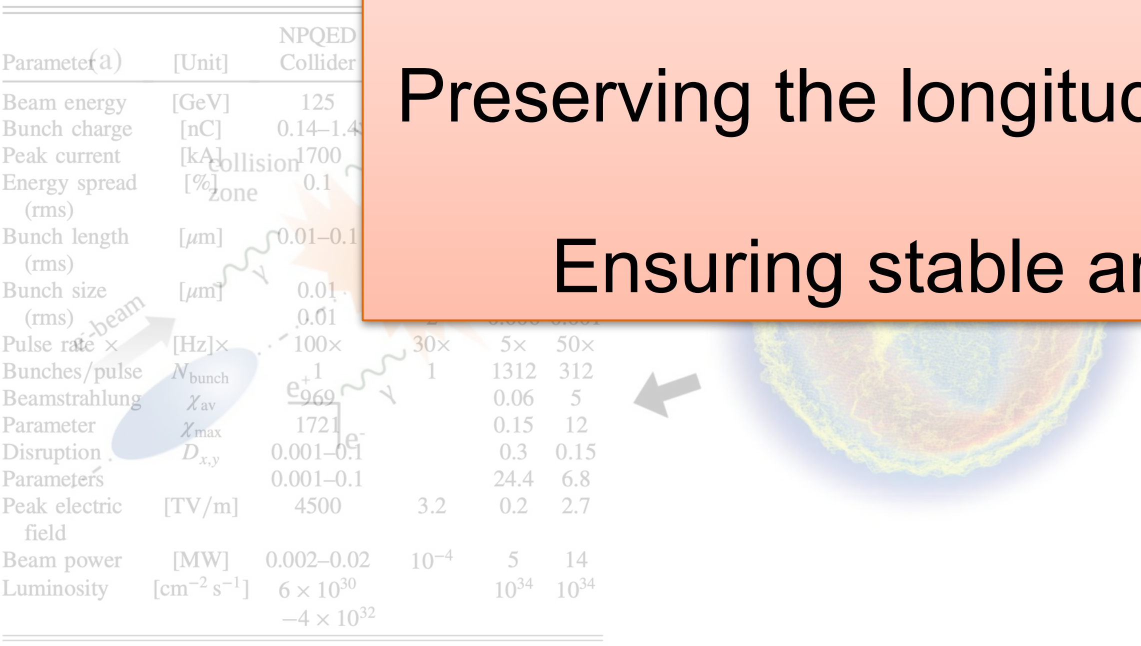

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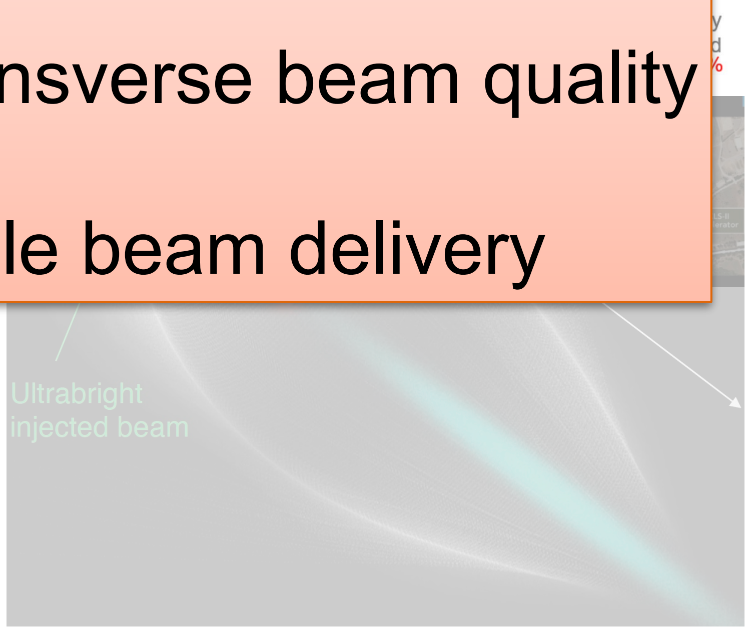

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Motivation for generating stable, sub-um beams

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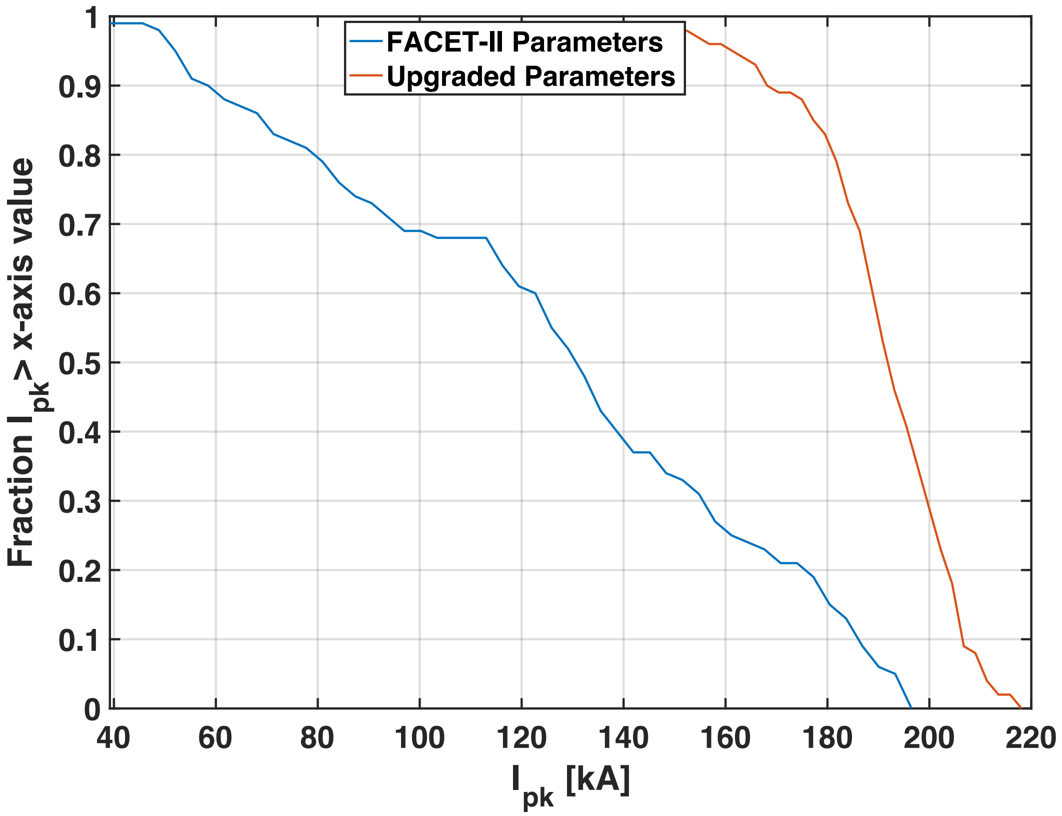


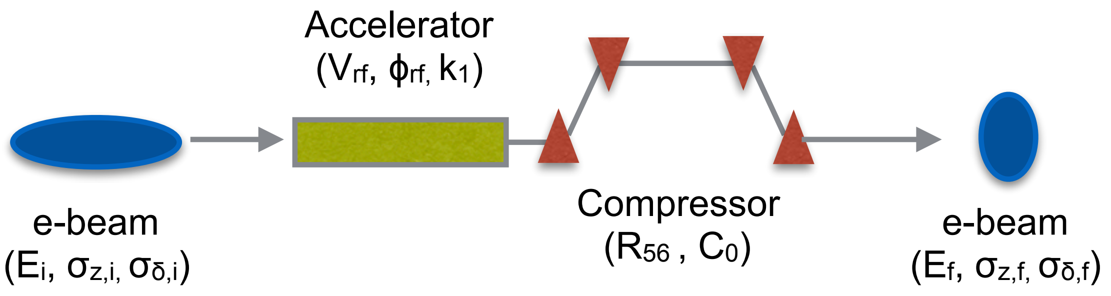
Approaches to improved stability

- Alternating sign multi-stage compression (equivalent to FODO focusing concept)
  - Chirpers: off-crest RF, wakefields, IFEL
  - Compressors: ballistic, chicane, dog-leg, zig-zag, wiggler
- Stabilization from self induced wakes (longer bunch => smaller wake induced chirp)
- Correct treatment of 3D CSR effects

Goal: Design for ~ GeV, 10nm long bunches (10pC, 1MHz CW)
Understanding stability with codes that are benchmarked with 400nm beams at FACET-II

Bunch length jitter in single vs two-stage compression

Single Stage



Accelerator
(V_{rf}, ϕ_{rf}, k_1)

e-beam
(E_i, $\sigma_{z,i}$, $\sigma_{\delta,i}$)

Compressor
(R_{56} , C_0)

e-beam
(E_f, $\sigma_{z,f}$, $\sigma_{\delta,f}$)

For linear compression (Acc. Handbook 4.5):

$$\sigma_{z,f}^2 = \sigma_{z,i}^2(1 + k_1 R_{56})^2 + \sigma_{\delta,i}^2 R_{56}^2 (E_f/E_i)^2 \approx (1 + k_1 R_{56})^2 \sigma_{z,i}^2$$

The bunch length jitter can be written in terms of the phase jitter (assuming $C_0 >> 1$ and $\varphi_{rf} << 1$)

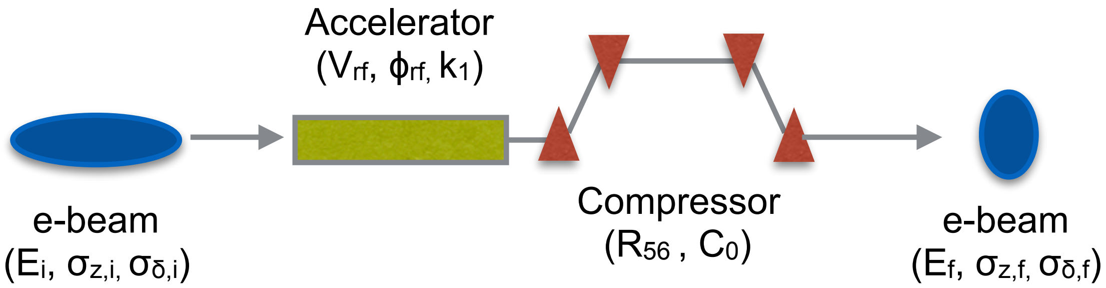
$$\boxed{\frac{\Delta\sigma_{z,f}}{\sigma_{z,f}} = (C_0 \mp 1)\cot\phi_{rf}\Delta\phi_{rf} \approx C_0 \frac{\Delta\phi_{rf}}{\phi_{rf}}}$$

Jitter ∝ C_0

Cannot get stability and short bunches simultaneously

Bunch length jitter in single vs two-stage compression

Single Stage



Accelerator
(V_{rf}, ϕ_{rf}, k_1)

e-beam
(E_i, $\sigma_{z,i}$, $\sigma_{\delta,i}$)

Compressor
(R_{56}, C_0)

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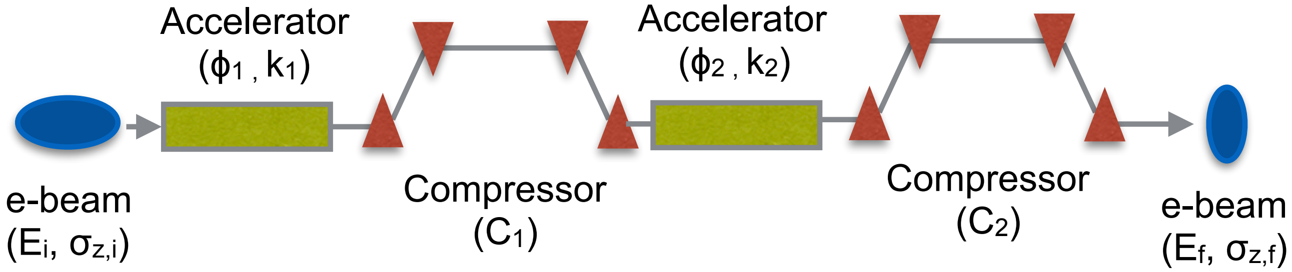
Two-Stage



Accelerator
(ϕ_1, k_1)

Accelerator
(ϕ_2, k_2)

e-beam
(E_i, $\sigma_{z,i}$)

Compressor
(C_1)

Compressor
(C_2)

e-beam
(E_f, $\sigma_{z,f}$)

For two stages, if $C_1, C_2 >> 1$ and $\Phi_1, \Phi_2 << 1$:

$$\frac{\Delta\sigma_z}{\sigma_z} = \left[C_1^2E_1/E_2 - 1/C_2\right]\frac{\Delta\phi_1}{\phi_1} + \left[C_1C_2E_1/E_2 - 1/C_1\right]\frac{\Delta\phi_2}{\phi_2}$$

This provides a condition on C_1, C_2 to minimize the impact of the phase jitter on the bunch length jitter.

$$\boxed{C_2 = \frac{E_2}{C_1^2E_1}}$$

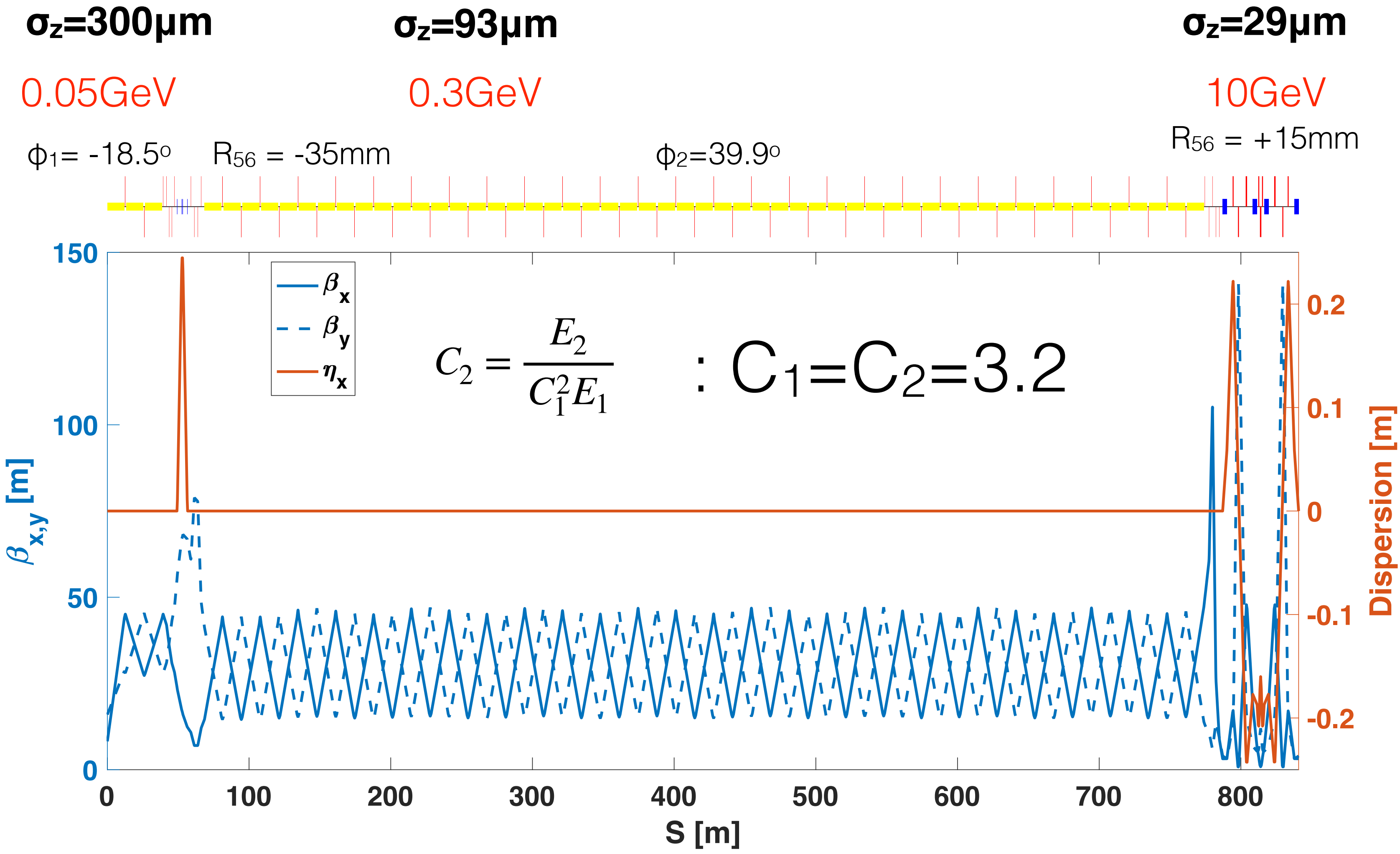
Jitter can be minimized by choosing

(C_1, C_2, E_1, E_2)

Simulations of 2-stage compression for 10 GeV beam

Parameter	Units	Value
RF Freq	f_{rf} (Hz)	2856
On-Crest rf Voltage	V_0 (MV/m)	20
Initial Energy	E_0 (MeV)	50
Stage Energy	$E_{1,2}$ (GeV)	0.3,10
Initial Bunch Length	σ_z (mm)	0.3
Initial Energy Spread	$\delta_{E,i}/E$ (rms, uncorrel.)	3.3E-05
Initial Emittance	$\gamma\varepsilon_{x,y}$ (µm-rad)	0.3
Bunch Charge	Q (pC)	10

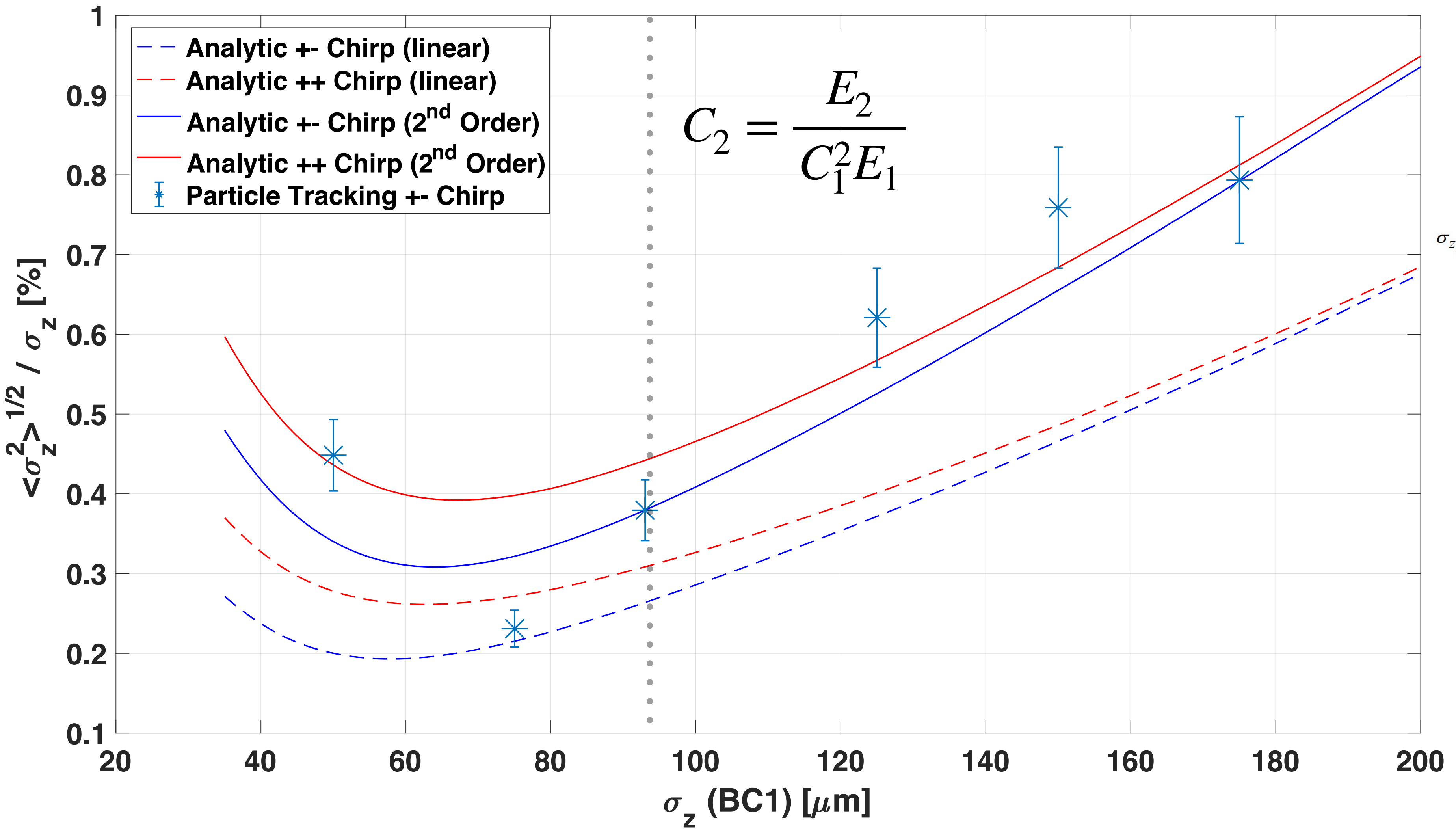
- Apply random jitter to each cavity $\Delta\varphi$ +/- 0.1^{o}
- Track 10^5 MP * 100 random seeds
- rms Bunch length jitter: $\Delta\sigma_z$
- rms Bunch arrival jitter: Δz



$$C_2 = \frac{E_2}{C_1^2 E_1} \quad : C_1 = C_2 = 3.2$$

Tracking simulations include effect of wakefields, RF curvature, nonlinearity in compression beyond simple linear formulas

RF Phase Jitter results



Analytic Formulas

Linear Contribution from 2-stage (LCLS CDR Ch.7):

$$\sigma_{z_2} \approx \sqrt{\left[(1+\alpha_1 k_1)(1+\alpha_2 k_2)+\alpha_2 k_1 E_1/E_2\right]^2 \sigma_{z_0}^2 + \left[\alpha_1 (1+\alpha_2 k_2) E_0/E_1 + \alpha_2 E_0/E_2\right]^2 \sigma_{\delta_0}^2}$$

$$k_2 = -\frac{2\pi}{\lambda}\left(1-\frac{E_1}{E_2}\right)\frac{\sin\left(\varphi_2 + (1+\alpha_1 k_1)\Delta\varphi_1 + \Delta\varphi_2\right)}{\cos\varphi_2}$$

2nd order from non-linear rf & T566 (Acc. Handbook 4.5):

$$\sigma_{z_f}^2 = \frac{E_i^2}{E_f^2} R_{56}^2 \sigma_i^2 + (1 + h R_{56})^2 \sigma_{z_i}^2 + R_{56}^2 (h_2 + r h^2)^2 \zeta$$

$$r = T_{566}/R_{56}$$

For Gaussian: $\zeta = 2\sigma^4$

$$h_2 = -\frac{2\pi^2 e V_0}{\lambda^2 E_f} cos\phi_{rf}$$

- Fix final bunch length at 29μm, vary C_1/C_2 ratio by adjusting φ^1,φ^2
- For more compression scale charge and use L_2 wakes to passively increase chirp to further compress in BC2

Minimum jitter close to analytic formulas.

Wakefields can be used to further shorten bunch length

Possible bunch length jitter tests at FACET-II

σ_z=300µm

L1 - ϕ=-90°

R56 = -46mm

σ_z=46µm

BC11 *E=135 MeV*

L2 - ϕ=54°

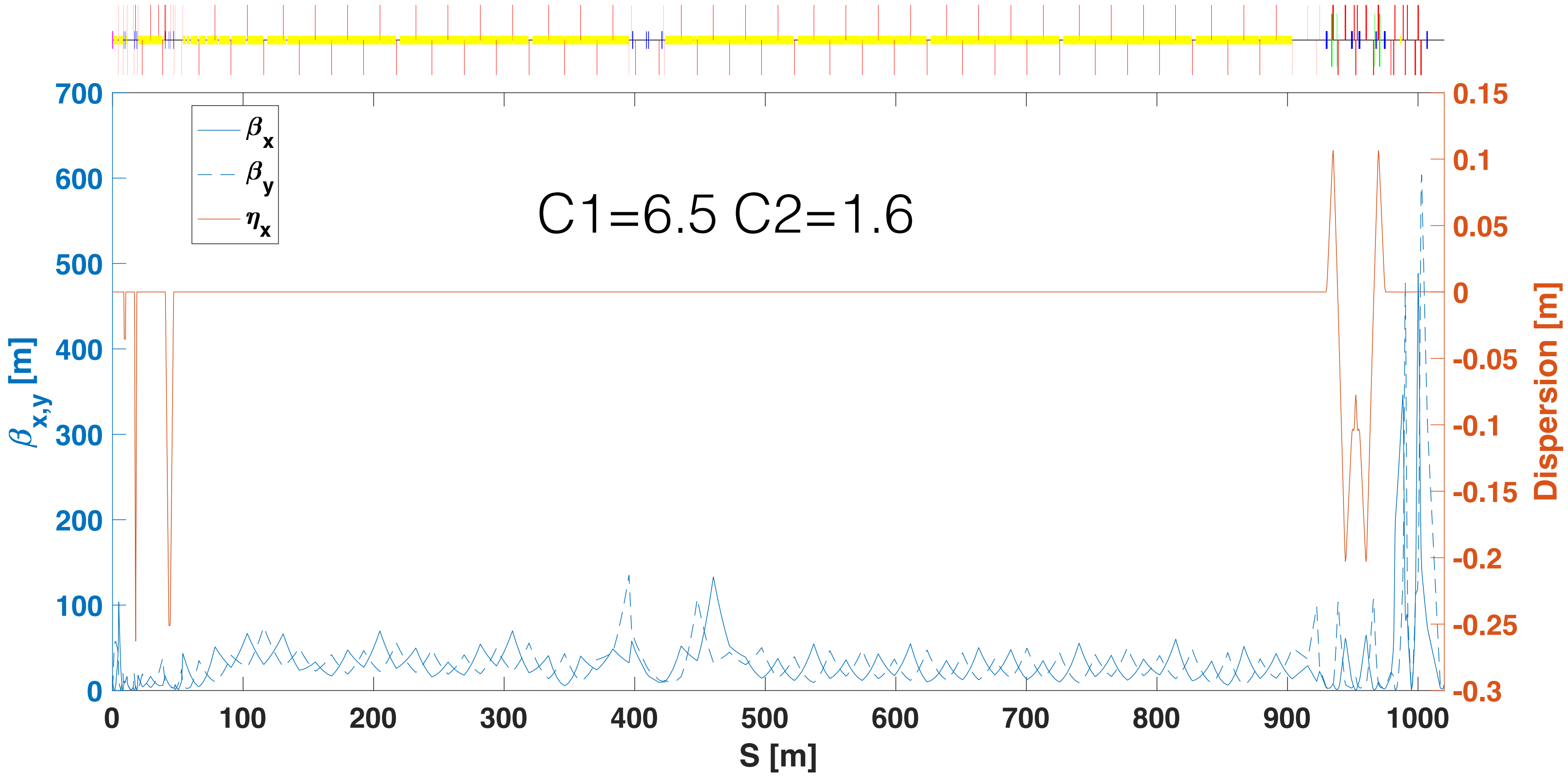
BC14 *OFF*

L3 - ϕ=54°

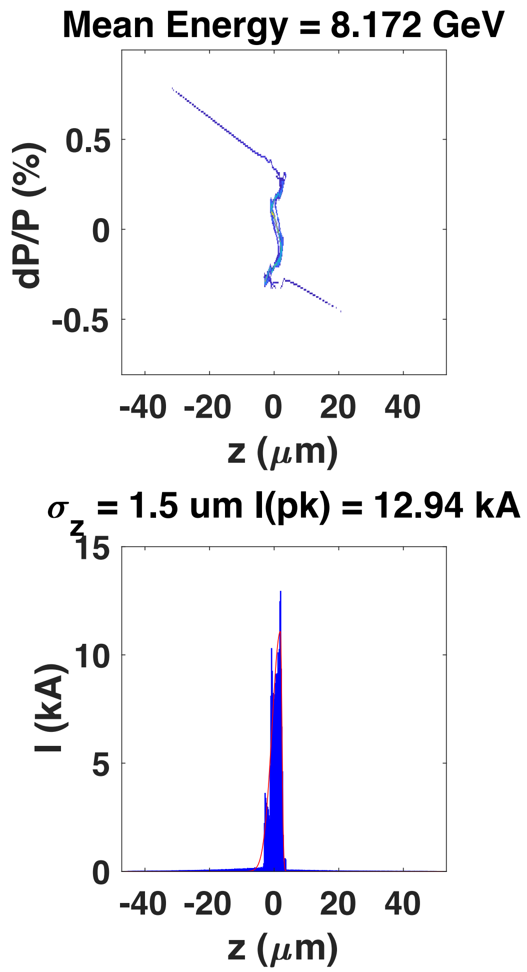
σ_z=28-1.5 µm

BC20 *E=8.2 GeV*

R56 = 5mm



Start-to-end Tracking + ISR, CSR, LSC



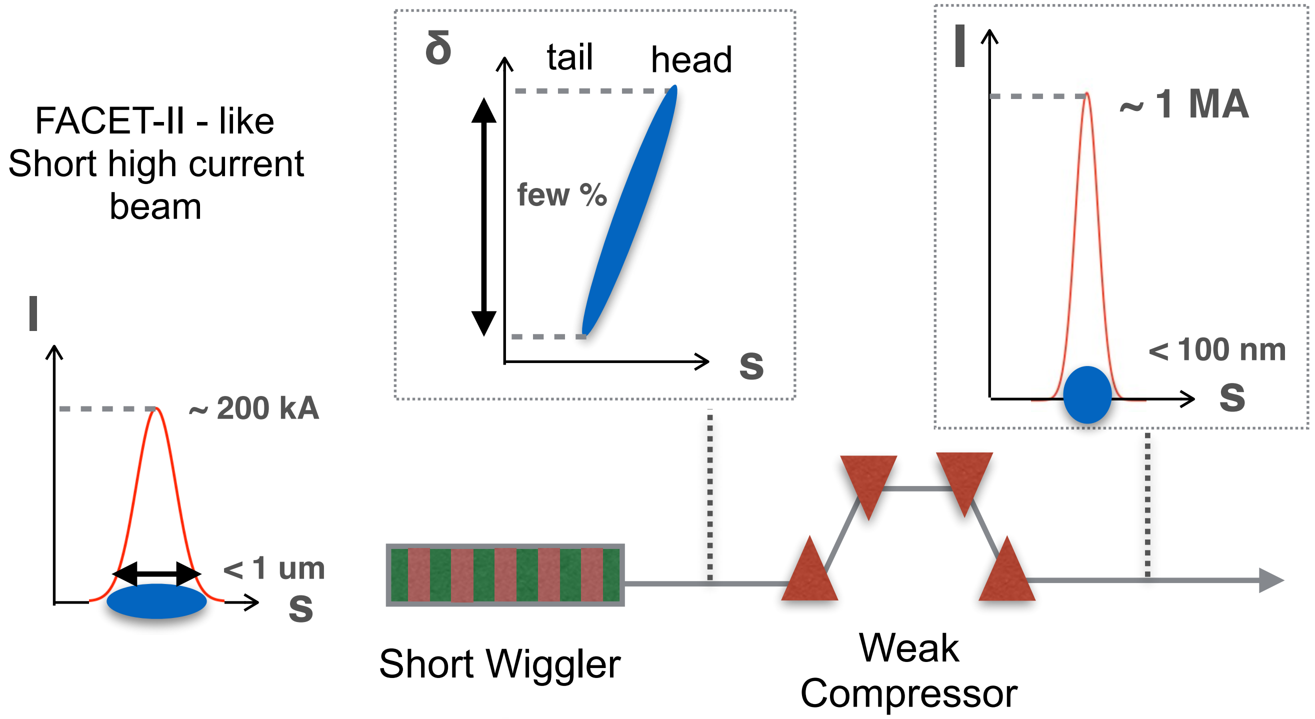
RMS Jitter	2-Stage (RF only)	2-Stage (RF+wakes)	3-stage nominal FACET-II
$\Delta\sigma_z/\sigma_z$ (%)	2.9	3.3	48.4
Δz (µm)	16.1	10.1	30.0

10x reduction in bunch length jitter for two-stage compression compared to nominal FACET-II config with similar bunch length

CSR-based compression for sub 100nm mega Amp beams

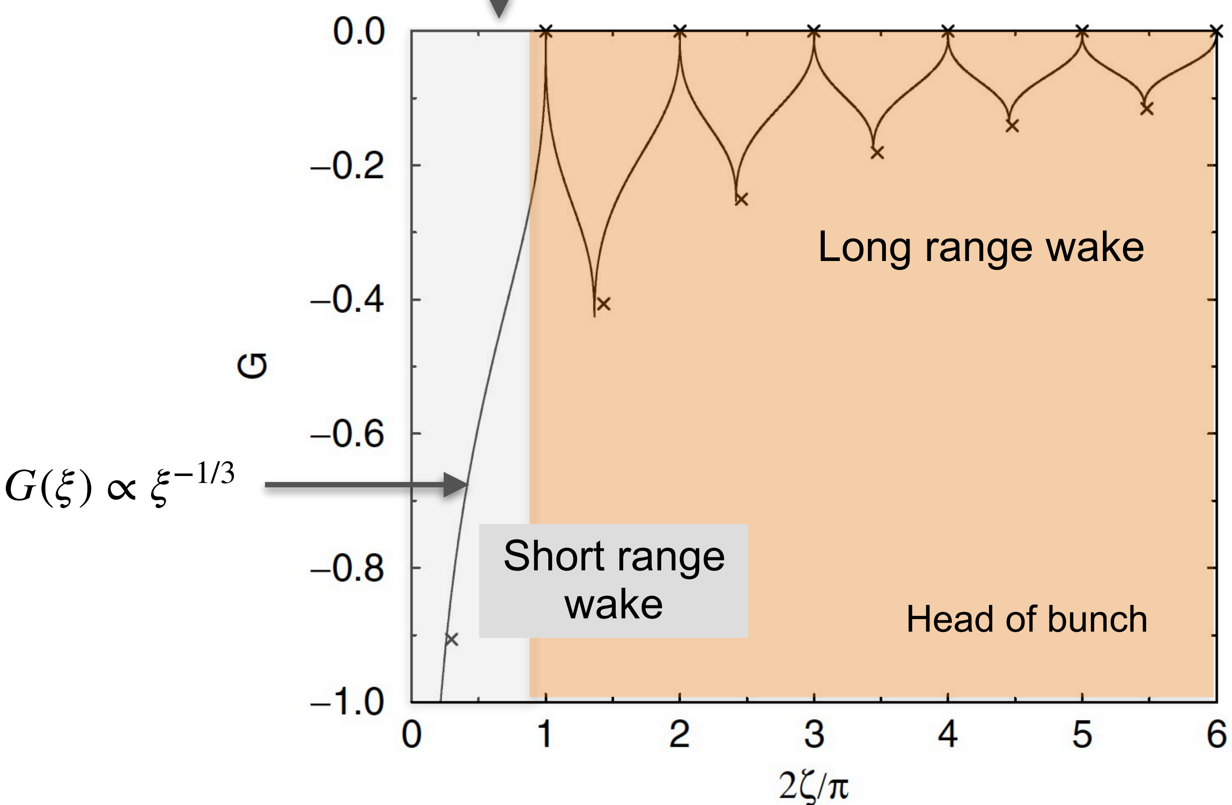
- CSR wake generated by a ***short bunch*** in a ***short wiggler*** applies strong chirp on the beam.
- Strongly chirped bunch through ***weak compressor (-ve R_{56})*** to achieve sub-um bunches
- Experimentally studied at low charge (XLEAP) with data matching theory/ simulations.

Large chirp from passive CSR in wiggler allows strong compression with weak chicane



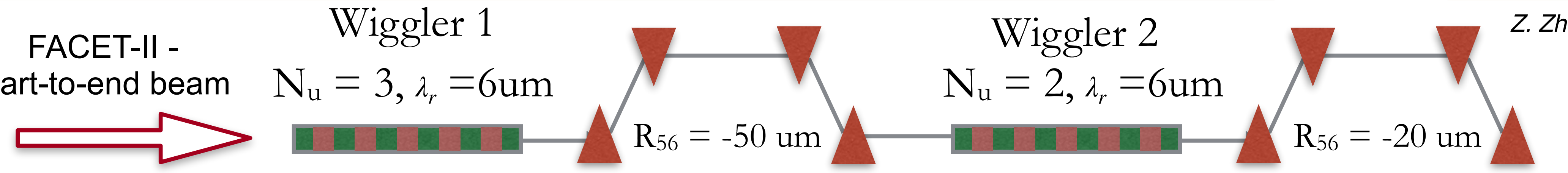
Derbenev, Rossbach, Saldin, Shiltsev, DESY TESLA-FEL Report (1995)

Wu, Raubenheimer, Stupakov, PRSTAB (2003)



Example calculation for FACET-II

Z. Zhang et. al., in preparation



FACET-II - start-to-end beam

Wiggler 1

$N_u = 3$, λ_r =6um

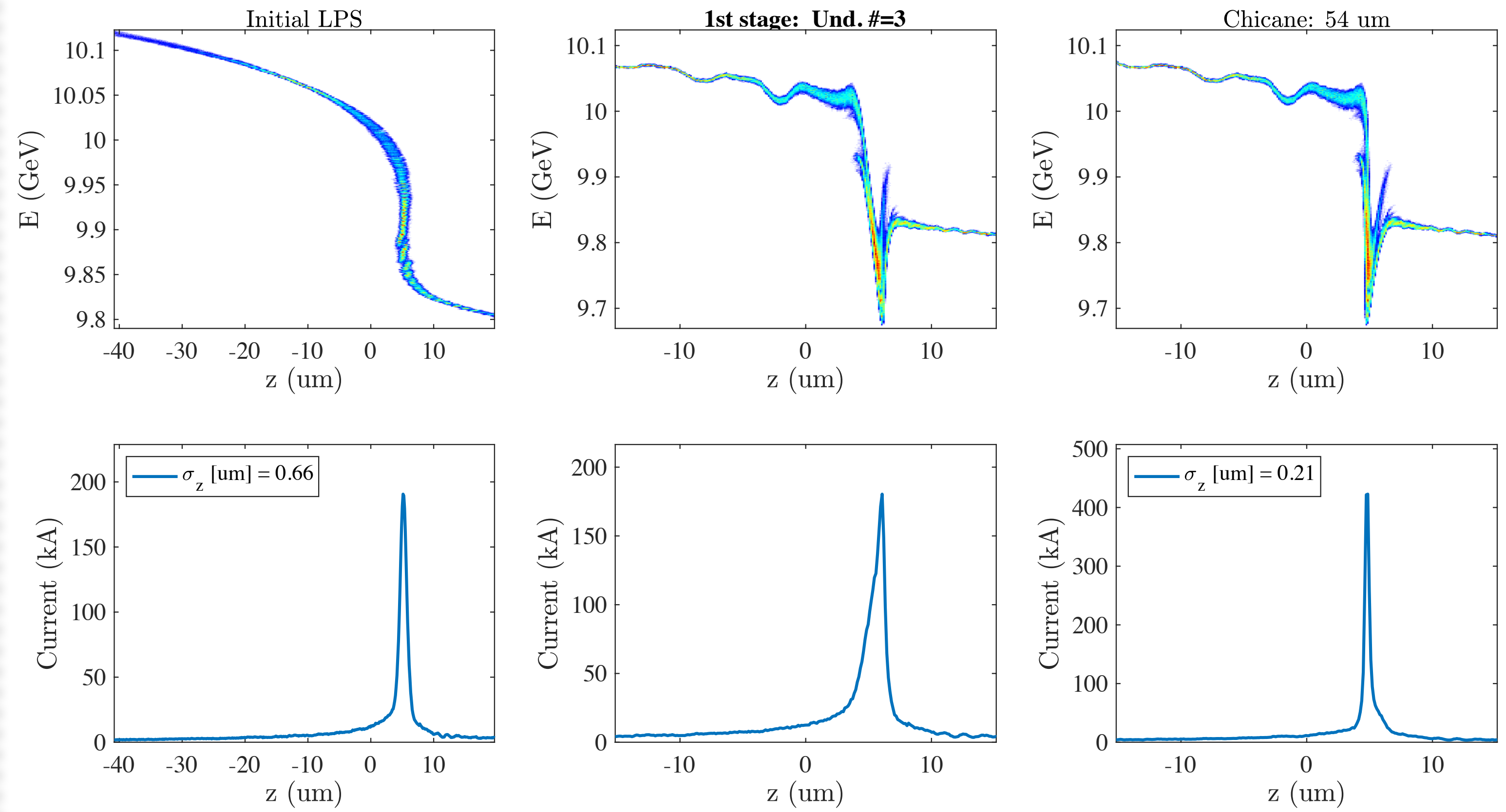
R_{56} = -50 um

Wiggler 2

$N_u = 2$, λ_r =6um

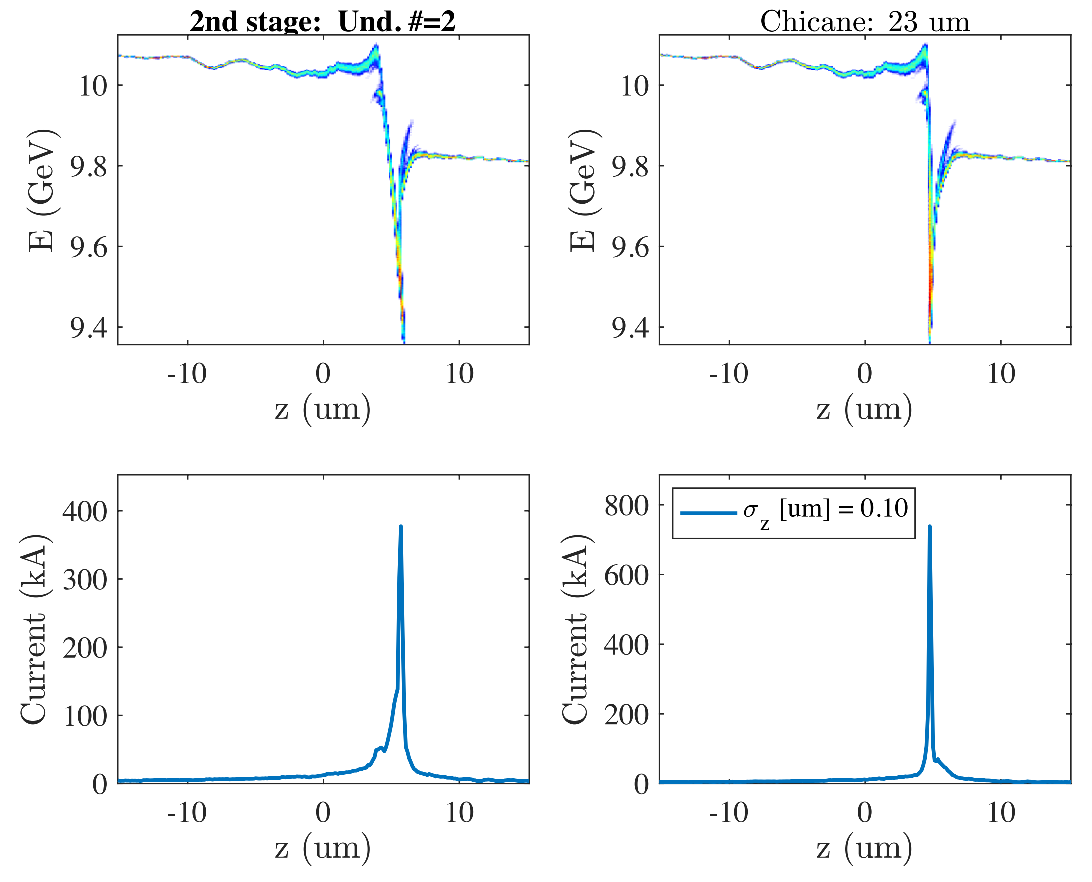
R_{56} = -20 um

Stage 1



- Extreme beam power (~10 PW) can be used to drive short wavelength sub-fs pulse XFEL even with relatively large emittance (~10 um)

Stage 2



Compression of 3-6x achievable with 1-2 stages

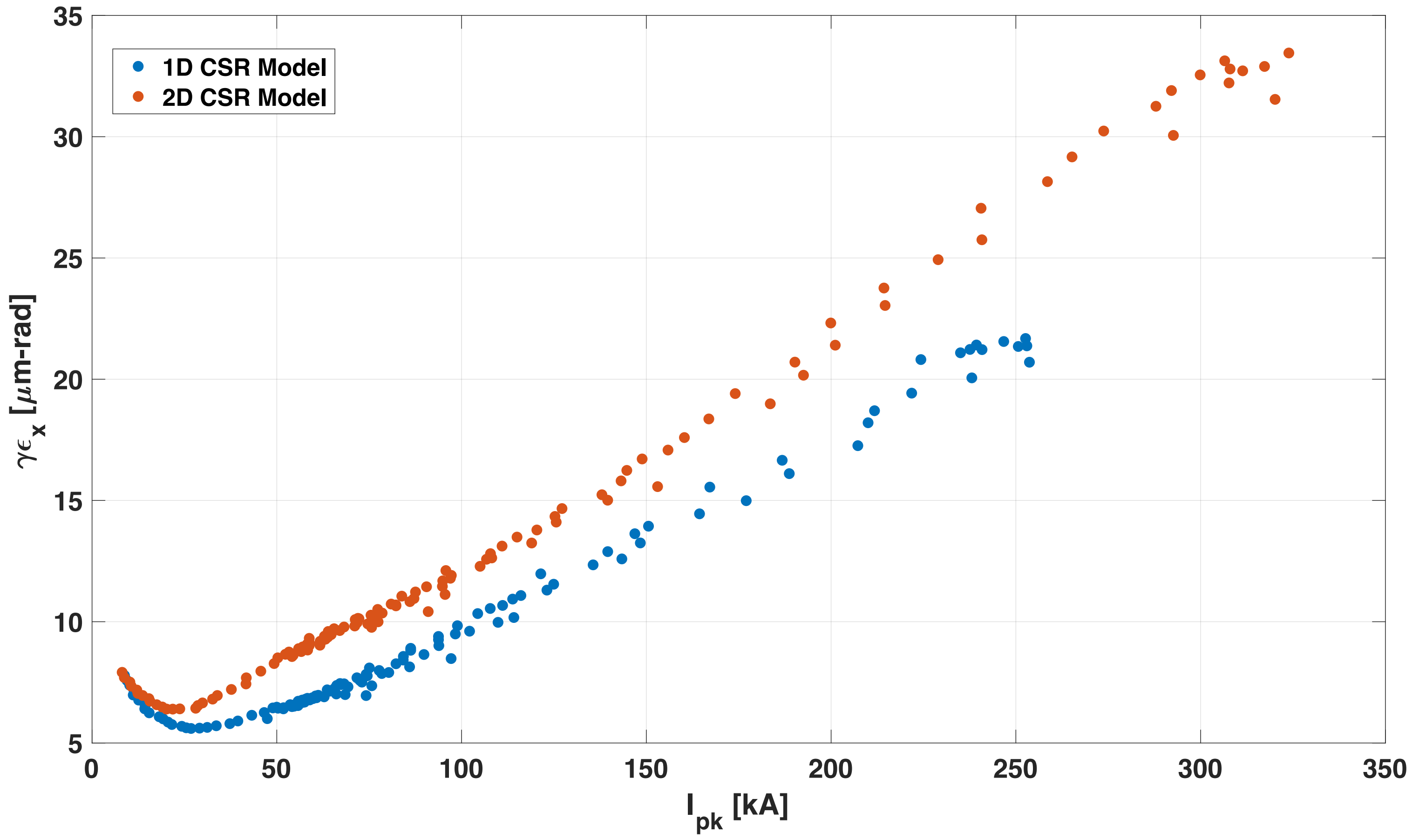
Small physical footprint allows testing at FACET-II

Emittance growth in compressors needs to be evaluated

Theoretical challenges for CSR calculation high current beams

- For FACET-II parameters at full compression show departure between 1D & 2D CSR effects in last BC20 dipole

- Recent theoretical work on 2D-3D CSR is examining these issues, e.g. Y. Cai PRAB 20, 064402 (2017), G. Stupakov, Proc. IPAC TUZZPLS3 (2019)



Study of 2D/3D CSR needed to properly account for high current effects

Extension of theoretical models is in progress

Measurements at FACET-II will provide first comparison between theory and data in this new regime

Summary

- We are studying the science drivers and concepts of extending the compression of particle beams from sub-um down to ~10 nm (with > MA current)

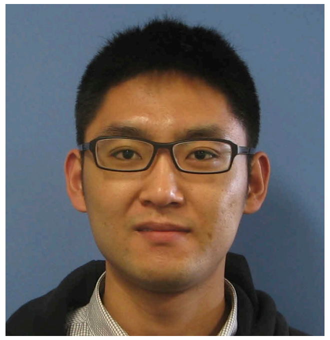
- Key challenges are:
  - How to sufficiently linearize the compression
  - Preserving the longitudinal and transverse beam quality
  - Ensuring stable and predictable beam delivery

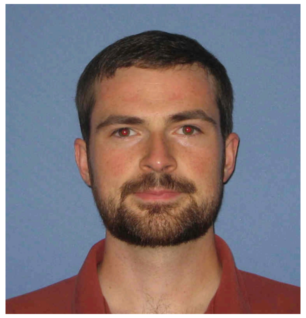
- Specific research programs under study:
  - Correct treatment of 2D/3D-CSR, with time efficient modeling codes which allow for optimization studies
  - Novel approaches to compression, e.g. via high gradient chirp sources like IFELs

- FACET-II will enable testing concepts for extreme compression and provide an opportunity for studying the associated physics and highlighting the major challenges

- This effort will support SLAC’s role as a world leading center for electron accelerator physics and matches SLAC’s annual lab plan by developing technologies for “brighter X-rays for photon science” and “advancing the luminosity and energy frontiers for future colliders”

THANK YOU!



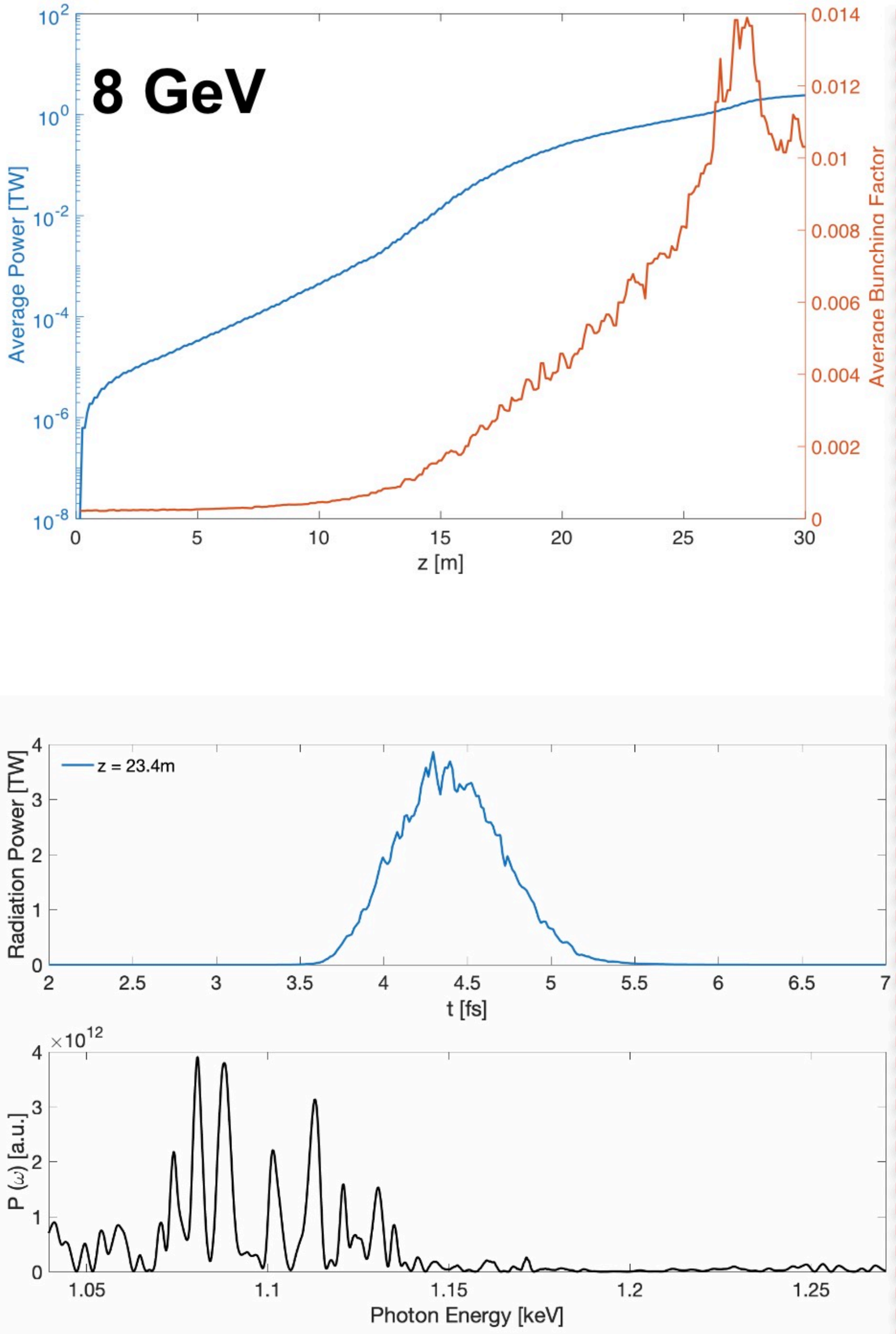


…see you in the future FACET-III Science Workshops

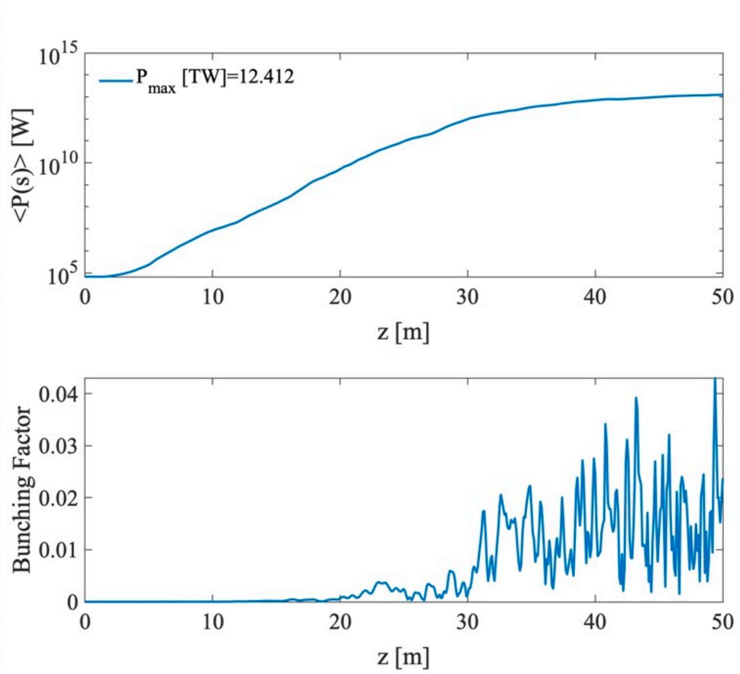
Bonus slides

FEL Simulation for extreme compression of FACET-II beam

Electron Beam	Parameter
Energy	8/15 GeV
Peak Current	1 MA
Emitttance (x,y)	10,50 um/10um
Energy Spread (rms)	350/400 MeV
Beta Function	5 m
Undulator (LCLS-II SXU)	
Period	3.9 cm/5cm
Peak K (planar)	5.5/8.2
Length	30 m
FEL parameters	
Resonant Wavelength	1 nm
Pierce Parameter	4.8/8.4 * 10^{-3}



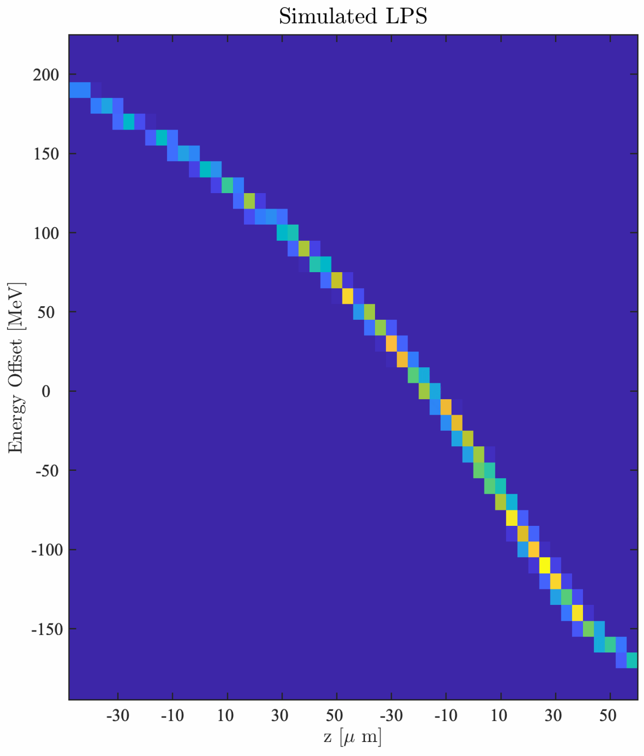
15 GeV



- TW-level output in 20m undulator for both cases.
- B~1% at saturation

Dancing beams @ FACET-II

Single Bunch



Two Bunch