Simulation of sub 10 fs low charge beam generation at PITZ

H. Qian

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HELMHOLTZ ASSOCIATION

DESY

Outline

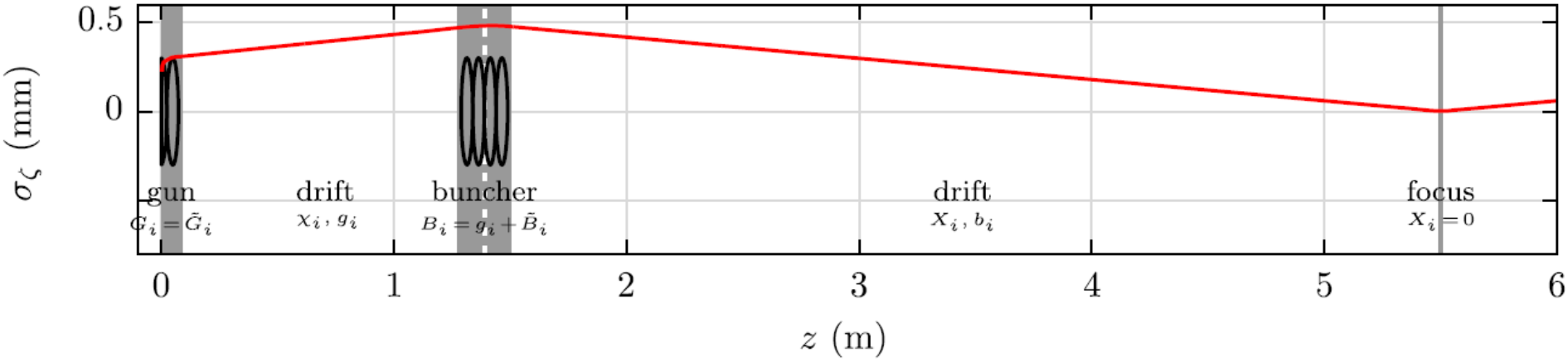
- Introduction to stretch mode velocity bunching at REGAE
- Application to PITZ
- Outlook

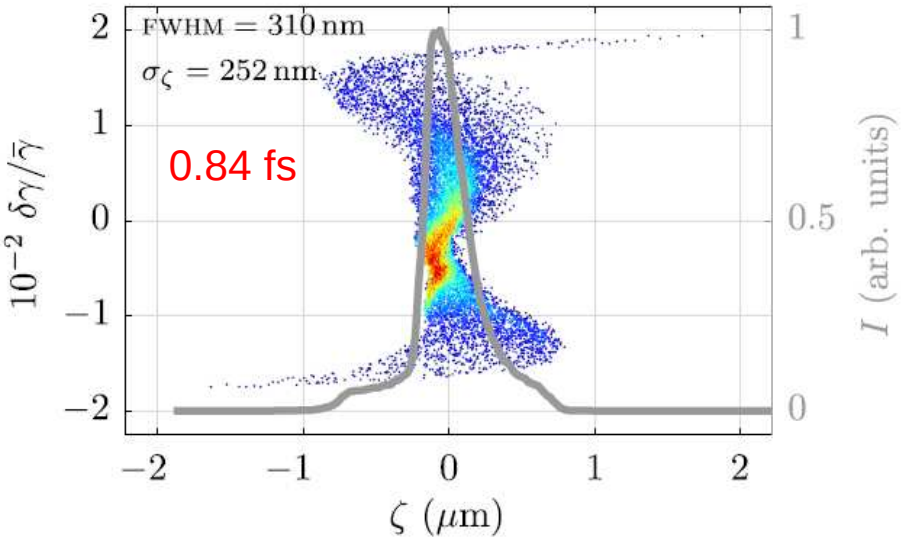
PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 120102 (2015)

Linearization of the longitudinal phase space without higher harmonic field

Benno Zeitler,[1,*] Klaus Floettmann,[2] and Florian Grüner[1]

[1]*Center for Free-Electron Laser Science and Department of Physics,*





Introduction to velocity bunching

- Longitudinal dispersion in a drift

$$\Delta z = \Delta z_0 + R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \ldots$$

$$where\ \delta = \Delta\gamma / \gamma$$

$$when\ \gamma >> 1,\ R_{56} = L/\gamma^2,\ T_{566} = -1.5R_{56},\ U_{5666} = 2R_{56}$$

- Energy chirp: energy correlation with slice position in the bunch

$$\delta = \delta_0 + a_1\Delta z_0 + a_2\Delta z_0^2 + a_3\Delta z_0^3 + \ldots$$

$$\delta_0 : uncorrelated\ energy\ spread, or\ slice\ energy\ spread$$

- Velocity bunching

$$\Delta z = R_{56}\delta_0 + (1 + a_1R_{56})\Delta z_0 + (\ldots)\Delta z_0^2 + (\ldots)\Delta z_0^3 + \ldots$$

- Limit of velocity bunching
  - Slice energy spread
  - Nonlinear energy chirp
  - Nonlinear longitudinal dynamics

Example:
Gamma = 10, L= 2 m, R56~20 mm

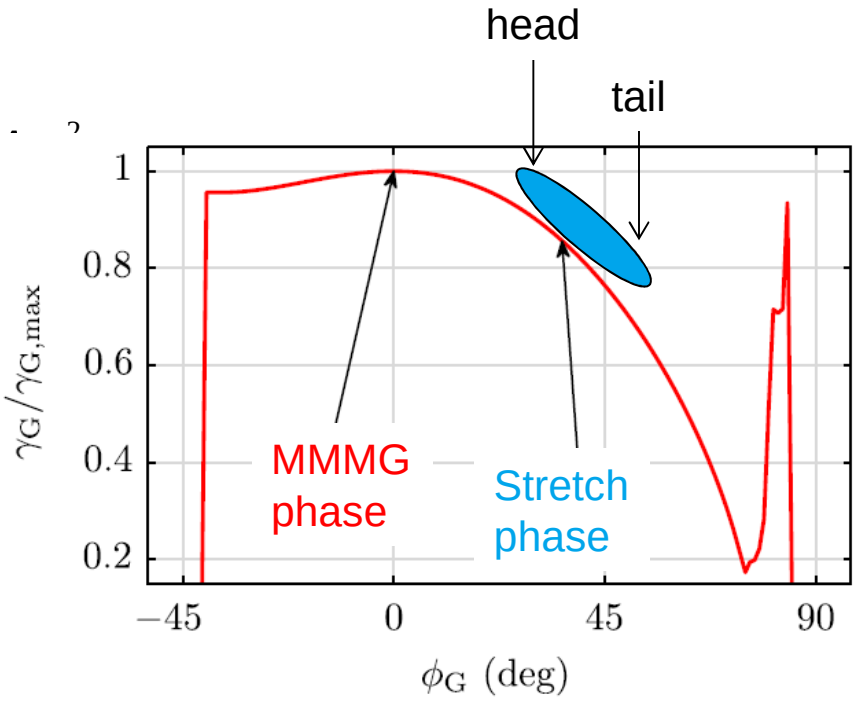
Slice energy spread: 1e-5 → 0.7 fs
Nolinear energy chirp: 1deg→1e-4→10 fs
Nonlinear dynamics: σt=1ps→ 23 fs

Introduction to nonlinear chirp compensation

- Harmonic cavity

$$E_k = eV_{RF}\cos(k_{RF}\Delta z_0 + \theta_0) = -E_0 + A_1 z + \dots$$

$$a_2 \propto A_2 \propto V_{cav} k_{RF}^2 \propto \frac{V_{cav}}{n^2}(nk_{RF})^2$$

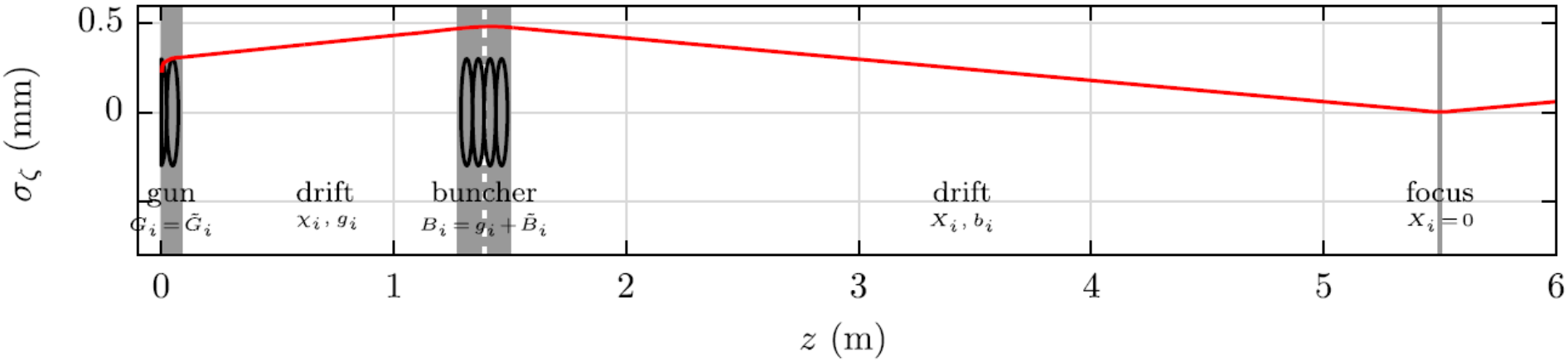


- Stretch mode to reduce nonlinar curv

$$\delta = \delta_0 + a_1\Delta z_0 + a_2\Delta z_0^2 + a_3\Delta z_0^3 + \dots$$

$$= \delta_0 + \frac{a_1}{n}(n\Delta z_0) + \frac{a_2}{n^2}(n\Delta z_0)^2 + \frac{a_3}{n^3}(n\Delta z_0)^3 + \dots$$

$$= \delta_0 + \frac{a_1}{\Lambda}\Lambda z' + \frac{a_2}{\Lambda^2}\Lambda z'^2 + \frac{a_3}{\Lambda^3}\Lambda z'^3 + \dots$$



REGAE stretch mode formulas

- Energy chirp after buncher

$$\gamma(\zeta_C) = \hat{\gamma}(\zeta_C) + \Delta\gamma(\zeta_C)$$
$$= \underbrace{A_0}_{\bar{\gamma}} + \underbrace{A_1\zeta_C + A_2\zeta_C^2 + A_3\zeta_C^3 + \cdots}_{\delta\gamma},$$

- Bunch compression after a drift

$$\zeta(z) = \chi_1(z)\zeta_C + \chi_2(z)\zeta_C^2 + \chi_3(z)\zeta_C^3,$$

with the coefficients χ_i defined by

$$\chi_1(z) = 1 + (z - z_0)[\eta_1 A_1]$$
$$\chi_2(z) = (z - z_0)[\eta_1 A_2 + \eta_2 A_1^2]$$
$$\chi_3(z) = (z - z_0)[\eta_1 A_3 + 2\eta_2 A_1 A_2 + \eta_3 A_1^3].$$

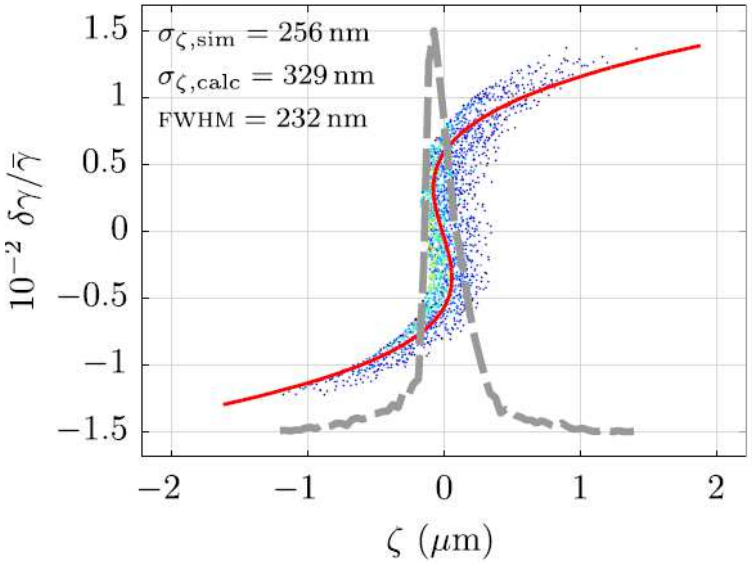
1st order compression:
X1=0
1 knob needed, e.g. scan buncher phase only

2nd order compression:
X1=0, X2=0 (A2>0)
2 knobs needed, e.g. scan buncher phase & amplitude

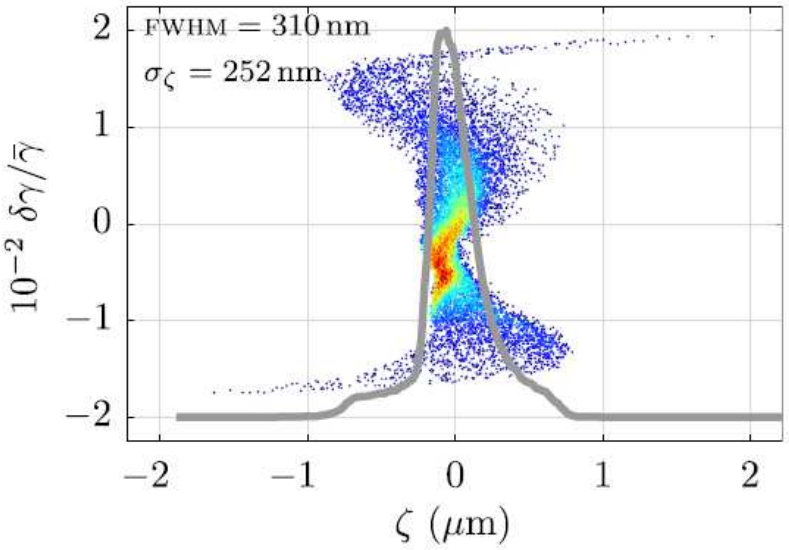
3rd order compression:
X1=0, X2=0 (A2>0), X3=0
3 knobs needed, e.g. scan buncher phase & amplitude, + gun phase

REGAE simulations

Case	Method	Space charge	E_G (MV/m)	ϕ_G (deg)	E_B (MV/m)	ϕ_B (deg)	E_{kin} (MeV)	$\sigma_\zeta(z_F)$ (μm)	$\sigma_t(z_F)$ (fs)
(i)	simulation	no	100.00	34.13	21.66	−111.99	3.12	0.19	0.63
(iv)	simulation	no	100.00	38.00	21.77	−104.15	3.25	0.11	0.38
(iv)	simulation	50 fC	100.00	42.00	21.63	−97.42	3.32	0.24	0.80



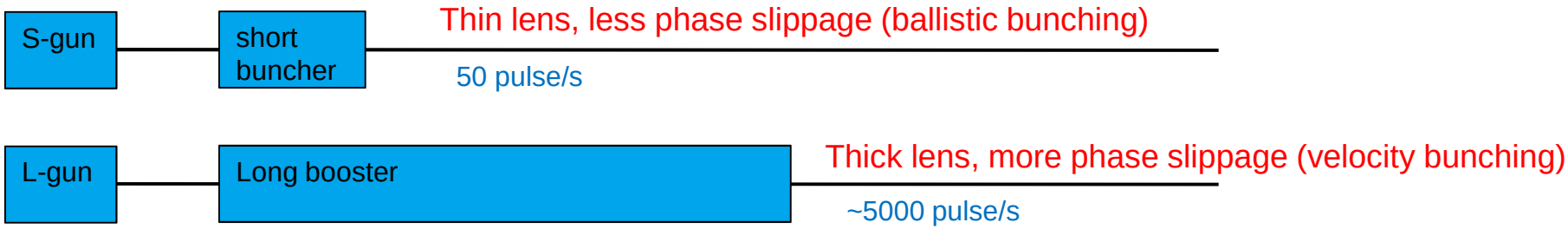
2nd order compression
No space charge



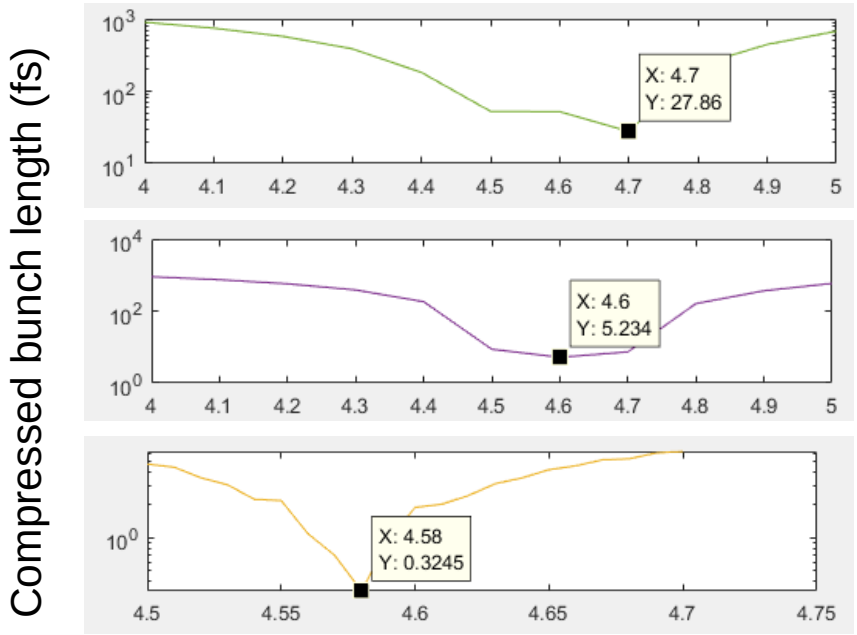
3rd order compression
With space charge

Apply REGAE technique to PITZ

- Comparison between REGAE and PITZ



- Analytical simulations for PITZ (Gun 60MV/m, 45 deg +MMMG)



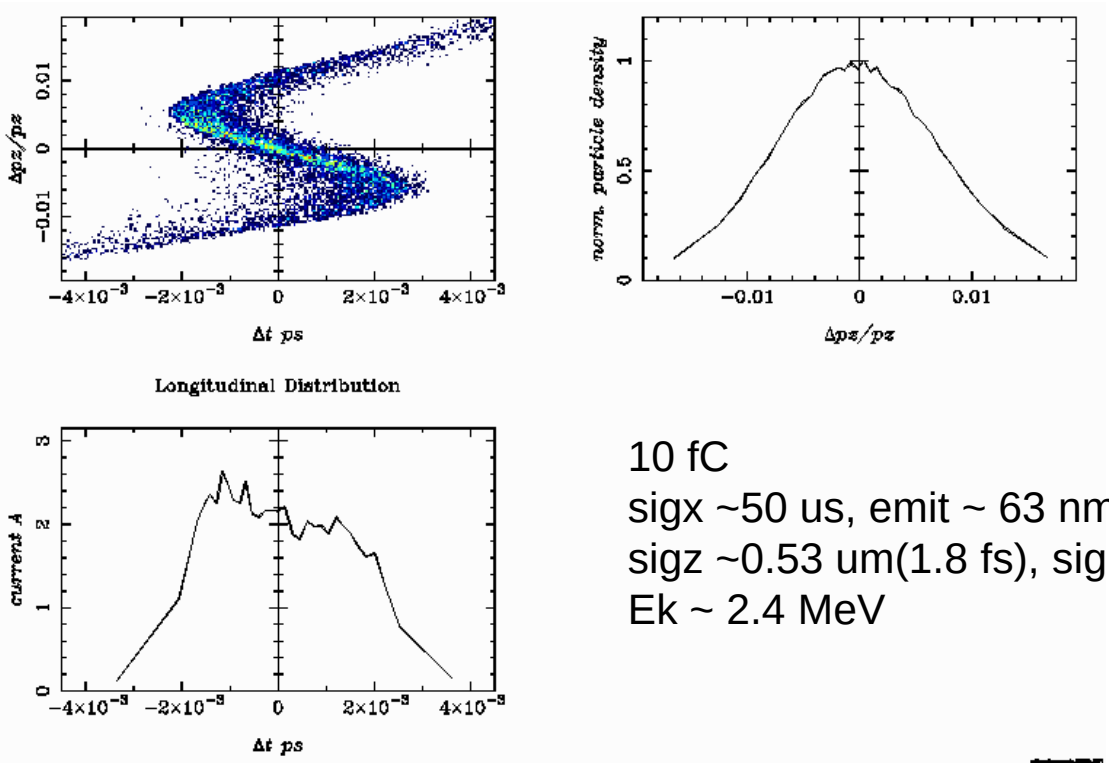
Booster scan step size: 0.1 MV/1deg

Booster scan step size: 0.1 MV/0.1deg

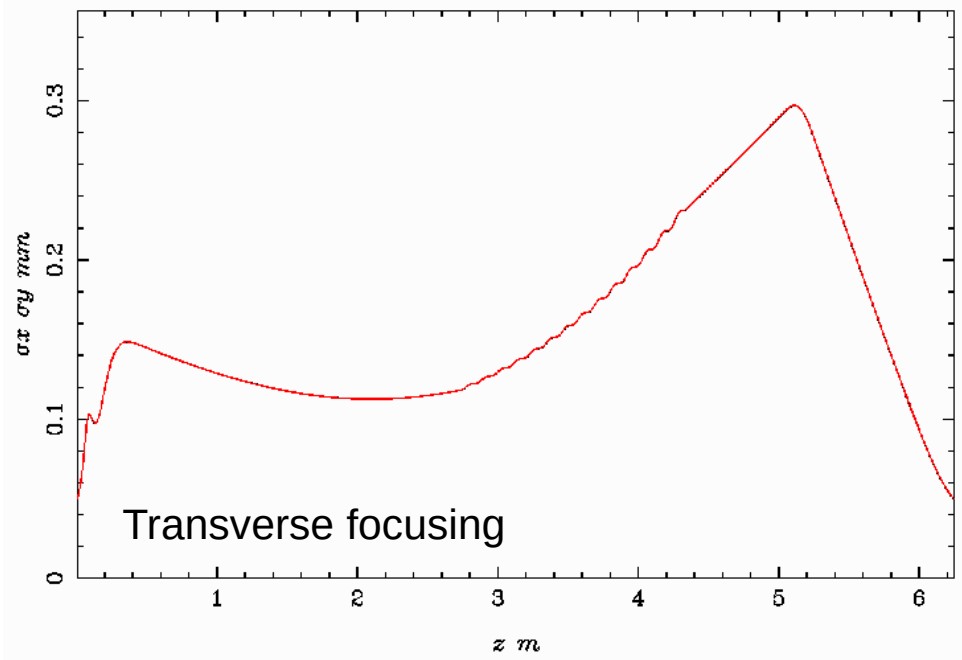
Booster scan step size: 0.01 MV/0.01deg

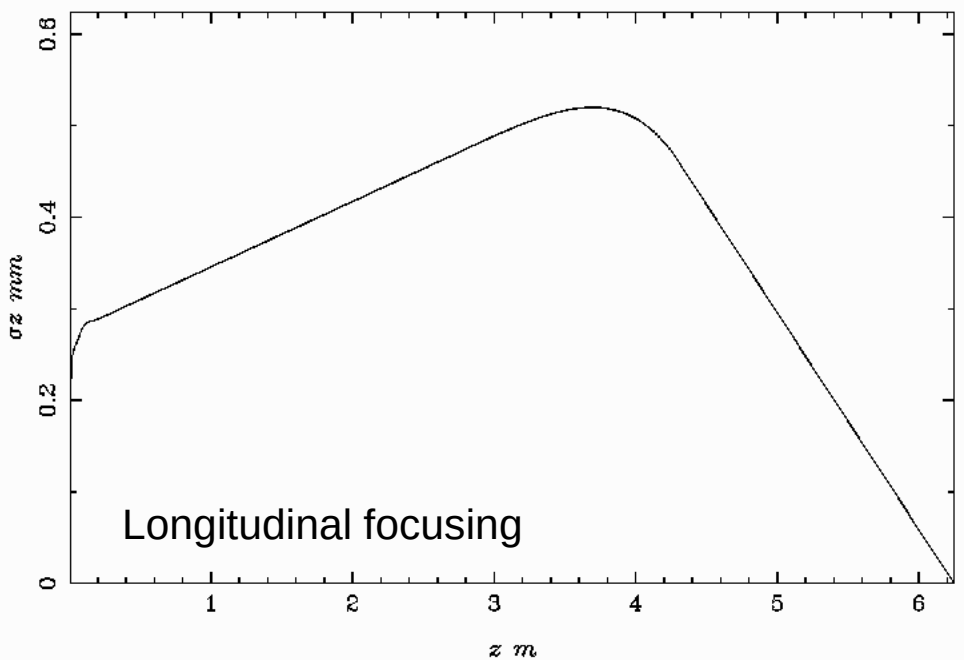
ASTRA Simulations

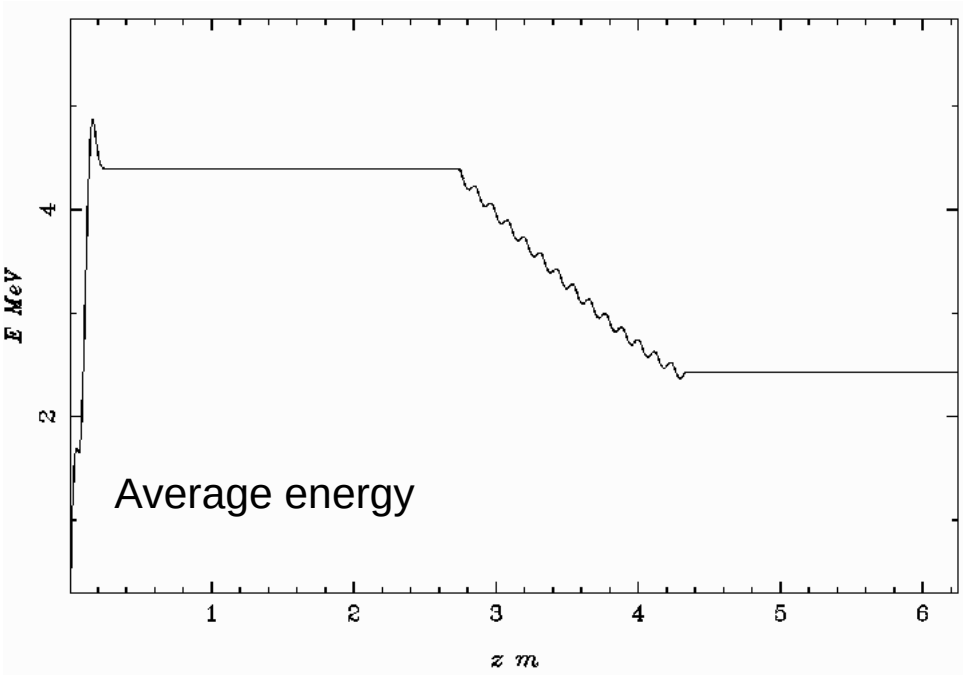
- With both longitudinal and transverse focusing
  - Laser: FWHM 2ps, BSA 200 um, 60 nm.rad thermal emittance
  - Gun: 60 MV/m, 45 deg + MMMG
  - Booster: 5.1 MV/m, -122.30 deg
  - Focusing position: around Plasma cell location

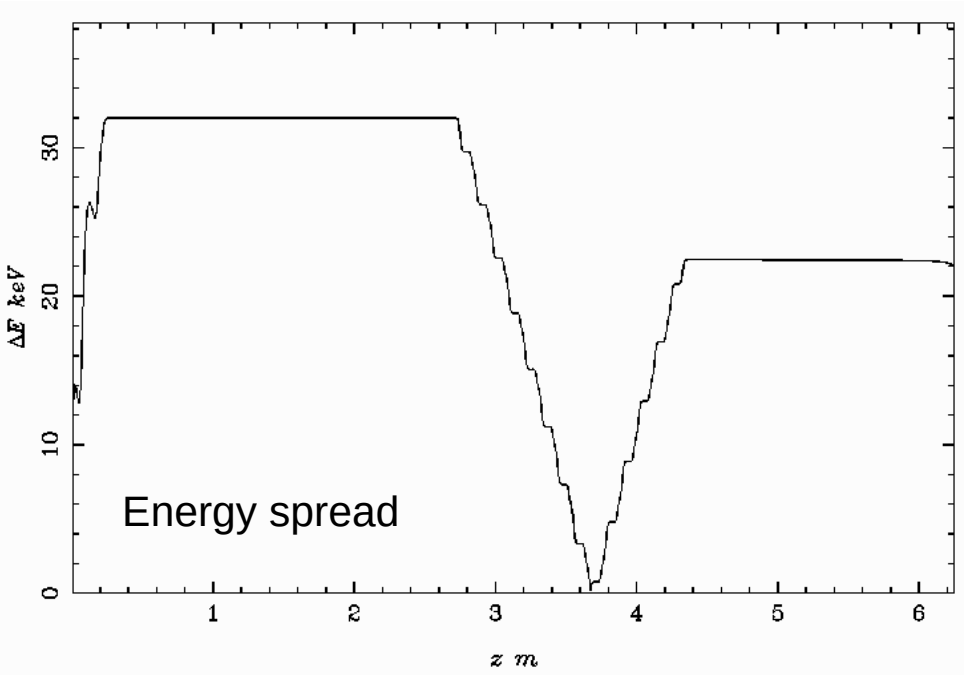


10 fC
sigx ~50 us, emit ~ 63 nm.rad
sigz ~0.53 um(1.8 fs), sigE ~22 keV
Ek ~ 2.4 MeV


σx σy mm
0
0.1
0.2
0.3
1
2
3
4
5
6
z m
Transverse focusing


σz mm
0
0.2
0.4
0.6
1
2
3
4
5
6
z m
Longitudinal focusing


E MeV
2
4
1
2
3
4
5
6
z m
Average energy


ΔE keV
0
10
20
30
1
2
3
4
5
6
z m
Energy spread

Outlook

- Refine optimizations
- Investigate jitter sensitivity
- Investigate short bunch diagnostics
- Investigate short bunch applications