Multilevel Optimization of FELs

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Multilevel Optimization of FELs

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   FLASH
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6. Transverse Dynamics

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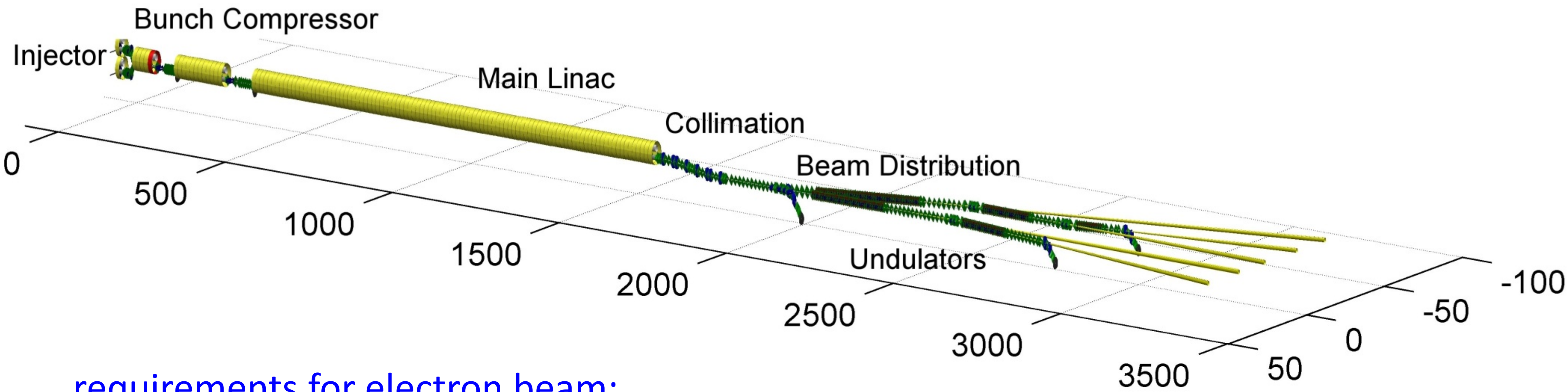
1. Introduction
the FEL



requirements for electron beam:

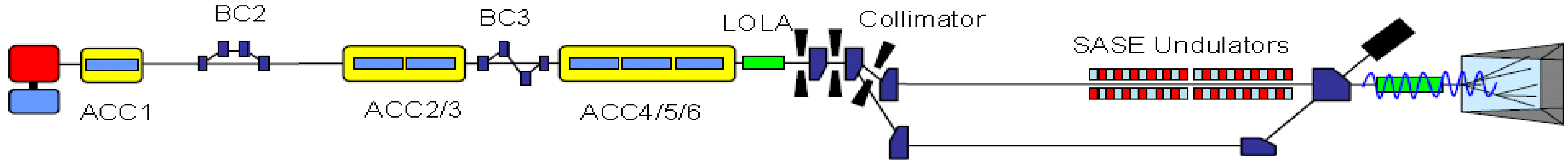
short wavelength → high energy
narrow spectrum → small energy spread, small wakes
short pulses → short electron bunches
short undulators → small gain length → low emittance, high peak current, overlapp of photon and particle beam
stability of spectrum and pulse

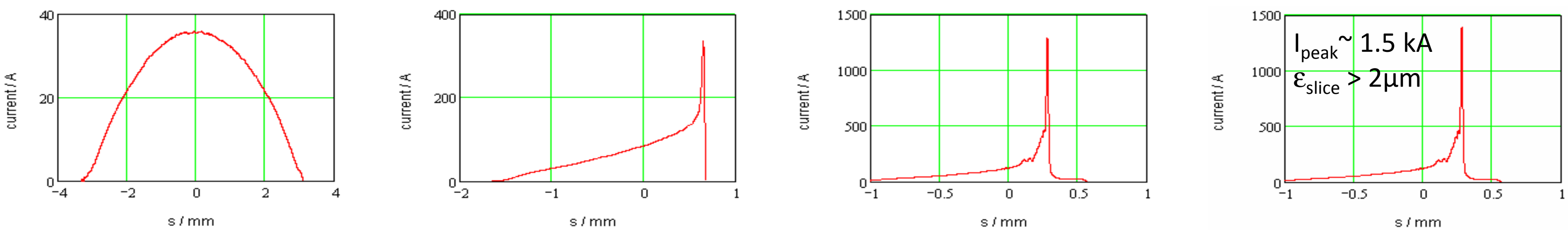
demanding requirements for all components:

gun, bunch compression system,
main accelerator, collimator and beam distribution, undulators,
diagnostics, feedbacks, …

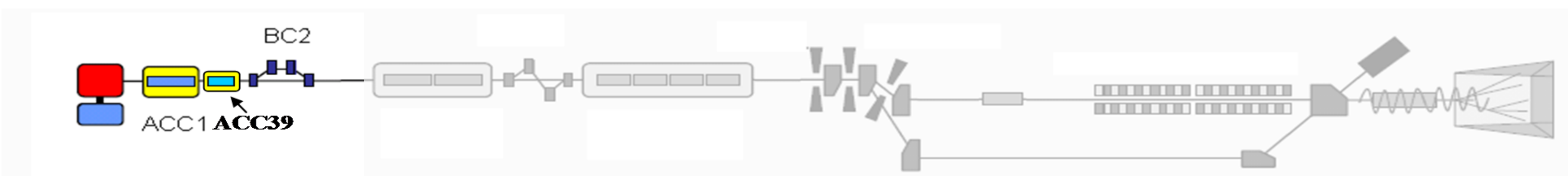
2. Example
FLASH – bunch compression (BC) working point

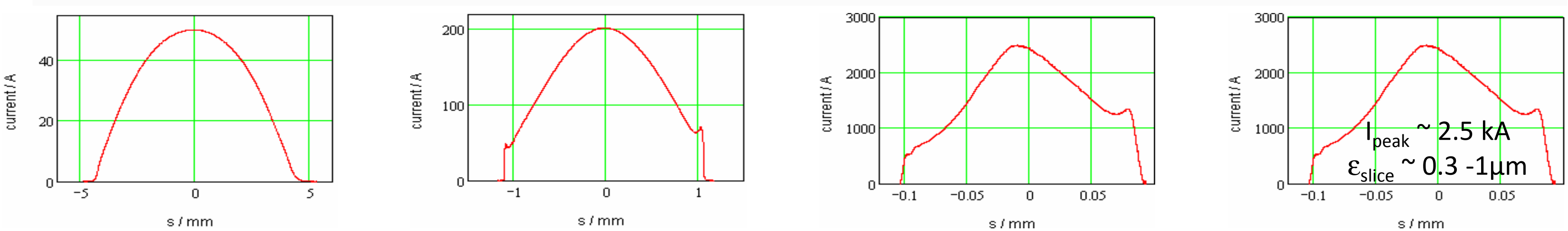
rollover compression, Q = 0.5 nC 2008





linearized compression, Q = 1.0 nC 2010

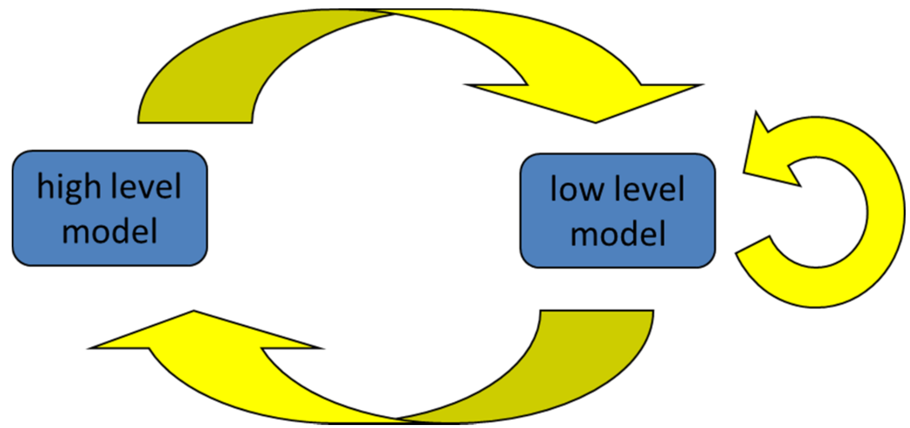




3 amplitudes, 3 phases, 2 dispersion parameters

2. Example

FLASH – multilevel optimization → BC-working point



FLASH I
simulation methods (looking for working points)

1d analytical solution without collective effects
(8 macroparameters -> 6 RF settings)

initial guess

↓

1d tracking with space charge and wakes
~ **seconds** (1 cpu)
- → accelerator low level
- → compressor low level

~ 5 iterations

↓

quasi 3d tracking with all collective effects
~ **30 min** (1 cpu)
- → accelerator "medium" level
- → **CSRtrack** "medium" level

~ 5 iterations

↓

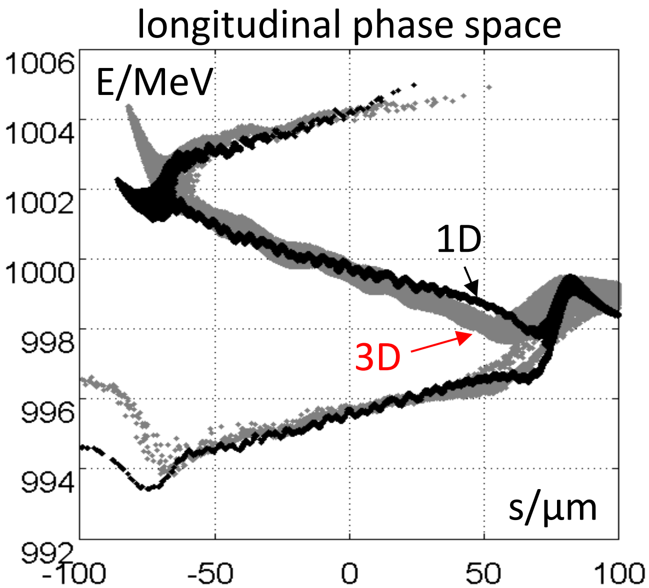
3d tracking with all collective effects
~ **10 h** (46 cpu-s)
- → **Astra** "high" level
- → **CSRtrack** "medium" level

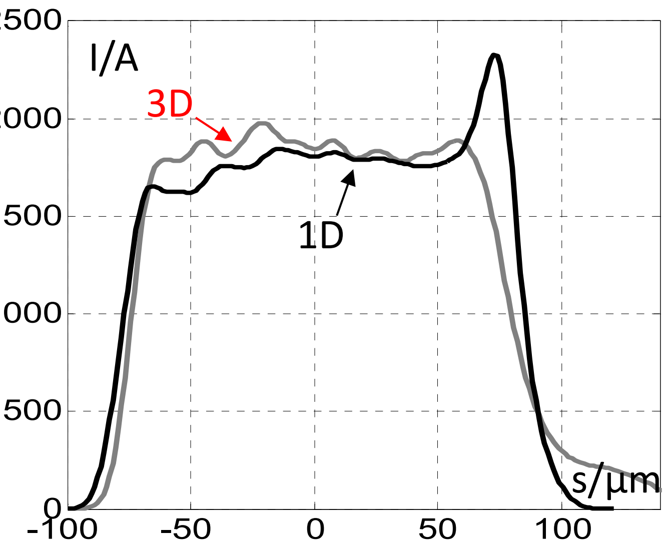
final result

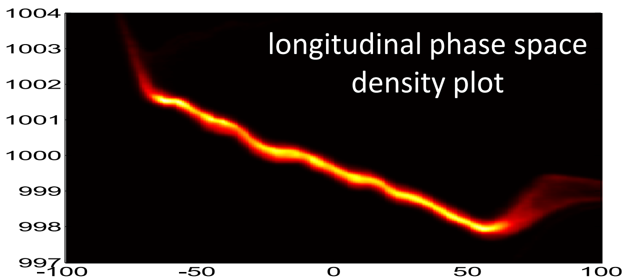
2. Example

FLASH – multilevel optimization ⟶ BC-working point

linearized compression: Q = 1.0 nC, compression factor ≈ 40
simulation with wakes, SC- and CSR-fields



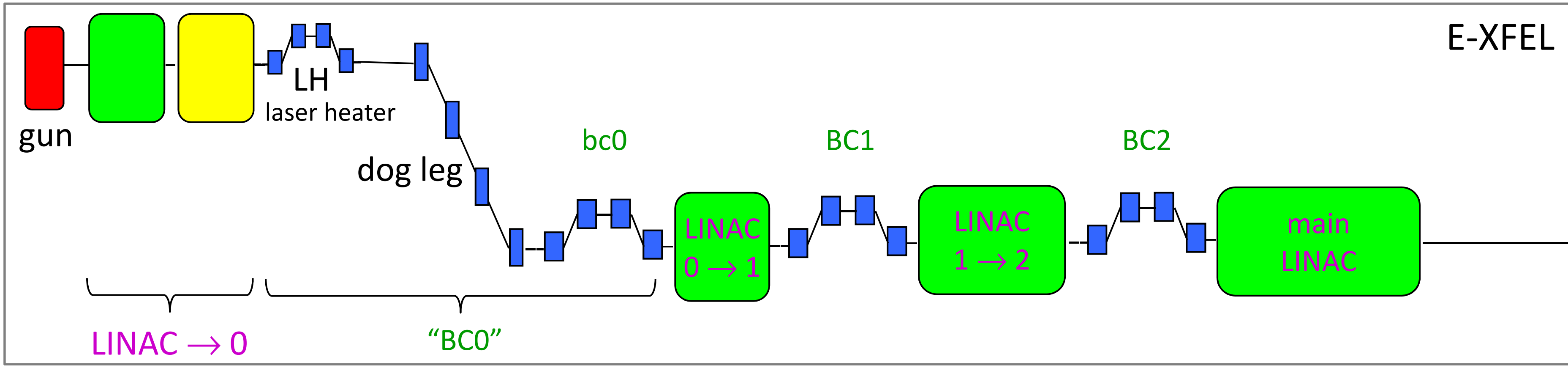


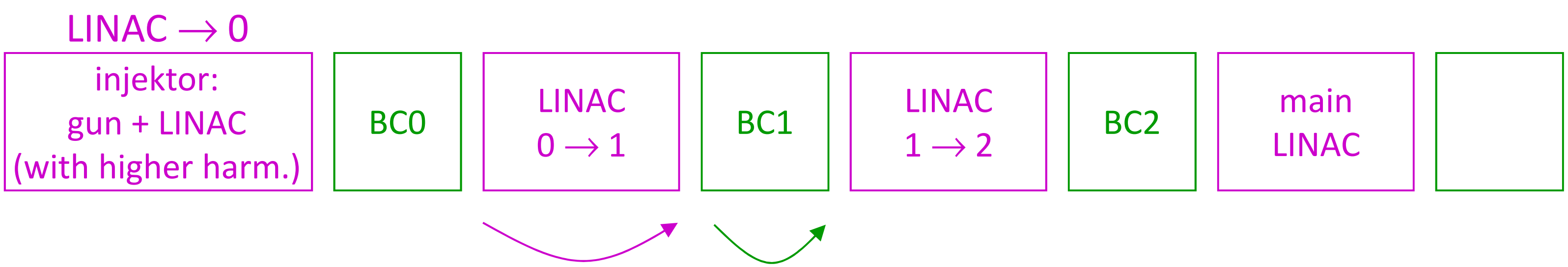


from Igor Zagorodnov, DESY

3. Low Level: Calculation of BC Working Points

simplification (no energy spread, no self effects)





energy step

$s_\nu \to s_\nu$

$\mathcal{E}_\nu \to \mathcal{E}_\nu + L(s_\nu)$

position step

$s_\nu \to s_\nu + D(\mathcal{E}_\nu)$

$\mathcal{E}_\nu \to \mathcal{E}_\nu$

polynomial representation of $L(s)$ and $D(\mathcal{E})$

truncated recursion of polynomials $\longrightarrow$ total compression to stage n

3. Low Level: Calculation of BC Working Points

compression factor, compression parameters

total compression to stage n: $C_n(s) = \left(\frac{d}{ds} S_n(s) \right)^{-1}$

with
s = initial long. position
S_n = long. position after stage n

f.i. two stage compression:

$$\begin{pmatrix} \mathcal{E}_0 \\ \mathcal{E}_1 \\ C_0 \\ C_1 \\ C_1' \\ C_1'' \end{pmatrix} = f\left(A_0, \varphi_0, A_0^{(h)}, \varphi_0^{(h)}, A_1, \varphi_1, \psi_0, \psi_1 \right)$$

BC energies: $\mathcal{E}_0$, $\mathcal{E}_1$

compression factors: C_0, C_1

higher derivatives of total compression: C_1', C_1''

working point parameters = $\mathbf{y}$

LINAC parameters = $\mathbf{x}$ (amplitudes and phases)

compressor parameters $= \mathbf{p}$ (magnet strengths or R_{56})

short: $\mathbf{y} = f(\mathbf{x}, \mathbf{p})$

inverse function can be calculated: $\mathbf{x} = g(\mathbf{y}, \mathbf{p})$

3. Low Level: Calculation of BC Working Points
criteria and constraints

here begins physics:

choice and optimization of working point parameters $\mathbf{y}$

BC energies

compression factors

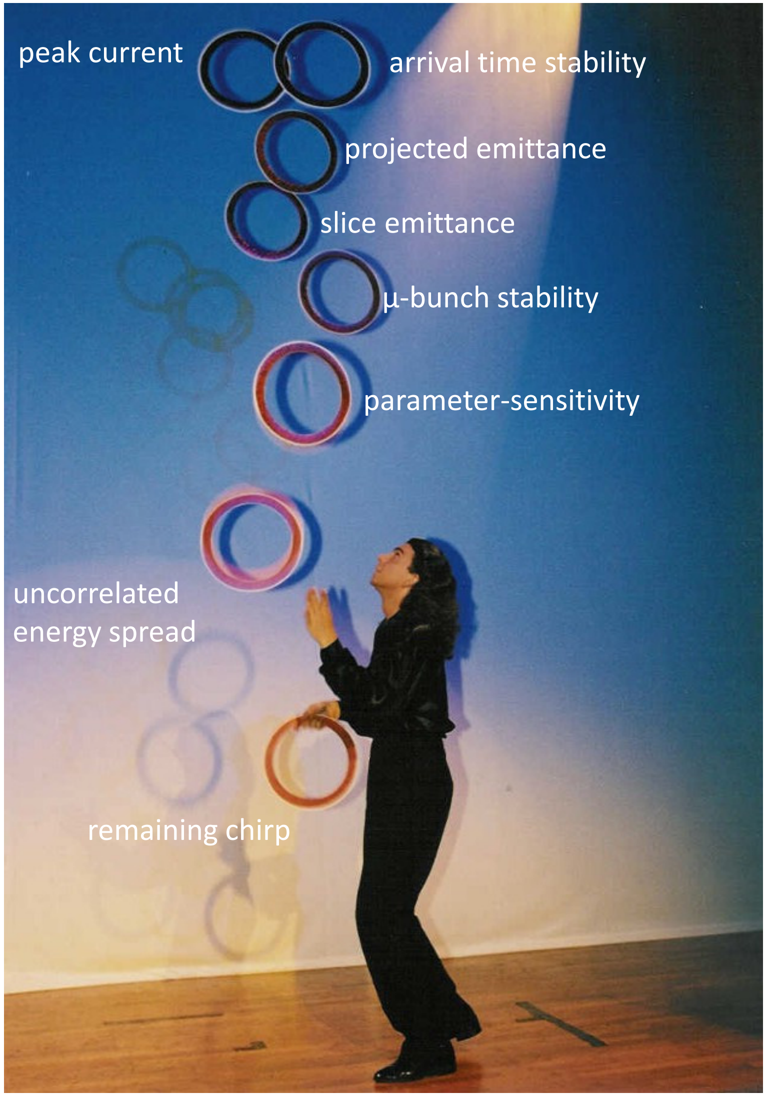
higher derivatives
of total compression

and

compressor parameters $\mathbf{p}$

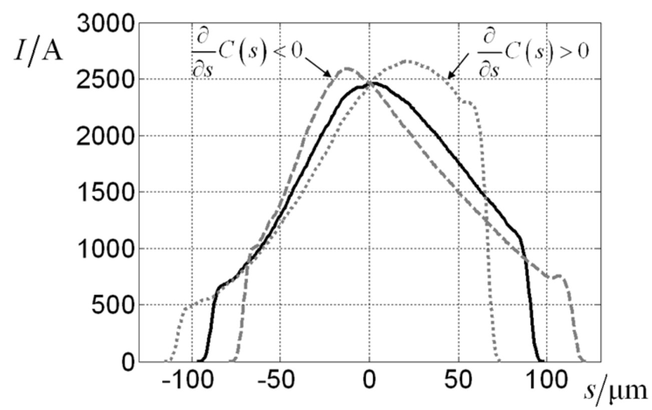
f.i. strength of BC,
deflection angle, or R_{56}

many criteria



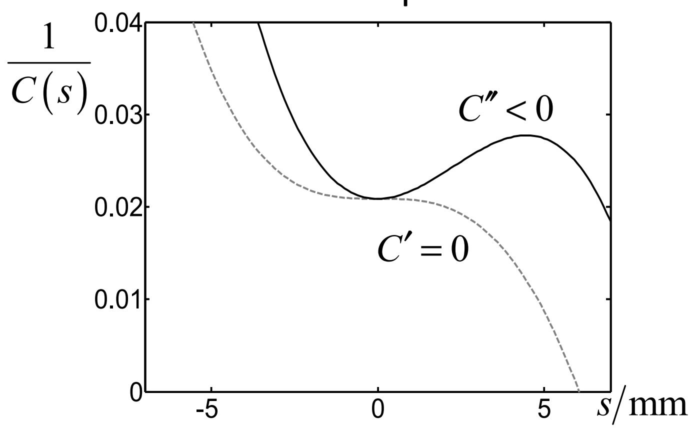
3. Low Level: Calculation of BC Working Points
criteria and constraints

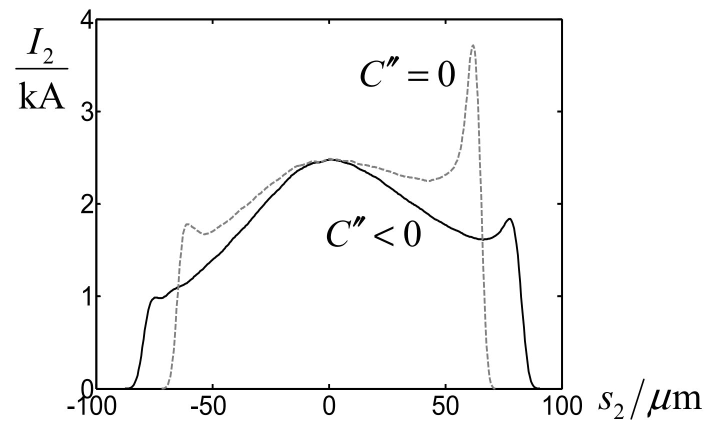
f.i. derivatives of total compression
can be used to control the bunch shape



C'
bunch center

inverse compression





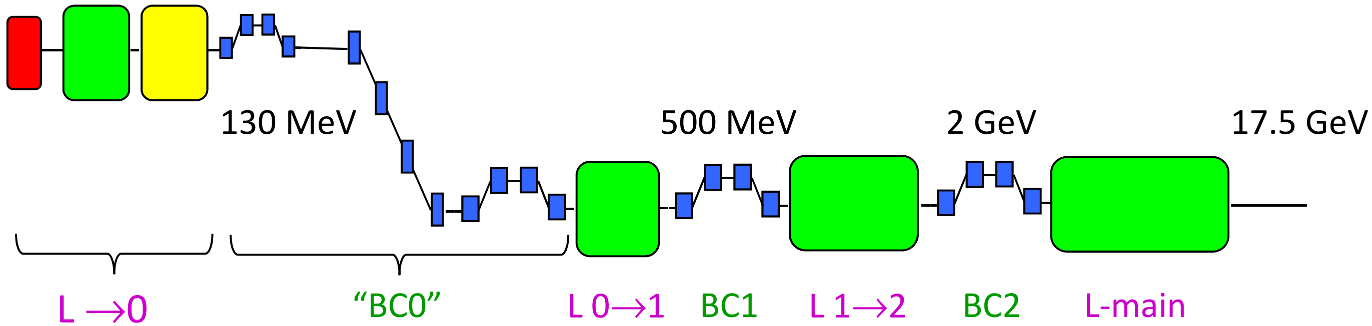
C''
bunch tails

2. Example

E-XFEL – BC working point

1 nC → 5 kA, total compression = 100

three stage compression (E-XFEL)

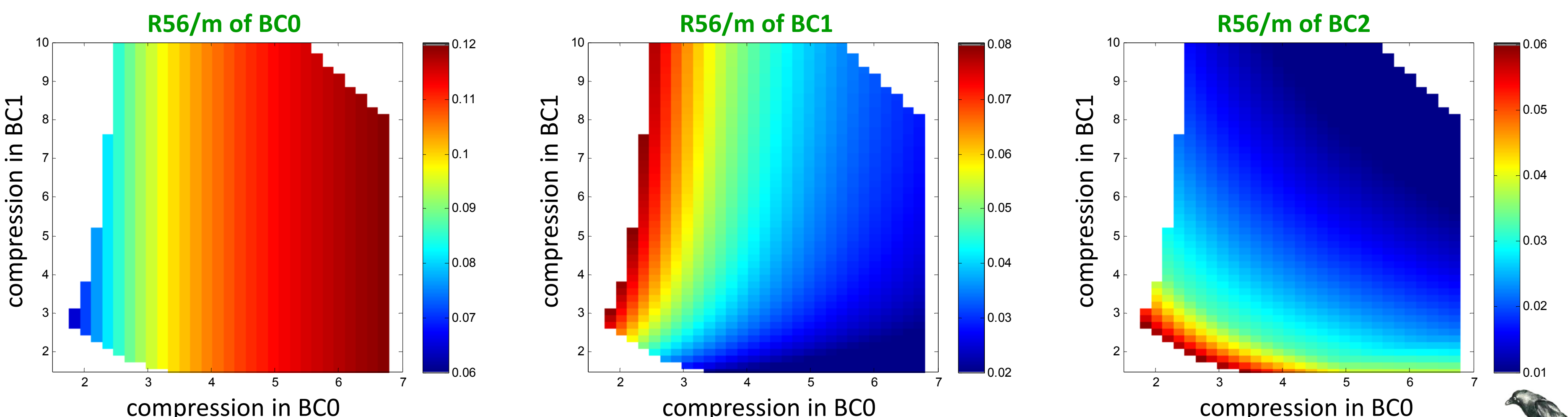


BC energies: pre defined

compression factors: free, but total compression fixed (=100)

higher derivatives of total compression: pre defined (=0)

compression parameter: R56, criterion = maximal chirp, constraints from RF, BC, maximal $\Delta\mathcal{E}$



2. Example

XFEL – BC working point 1 nC $\rightarrow$ 5 kA, total compression = 100

charge sensitivity

R56 sensitivity

rf **sensitivity**: amplitude sensitivity $A_n \rightarrow A_n + \delta A_n$

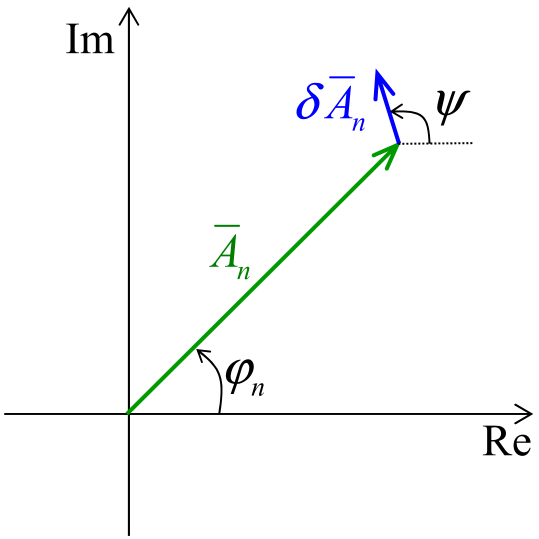
phase sensitivity $\varphi_n \rightarrow \varphi_n + \delta\varphi_n$

complex sensitivity $\bar{A}_n \rightarrow \bar{A}_n + \delta\bar{A}_n$

(amplitude and phase together)

$$S_n = \max_{\psi} \left| \frac{\delta C}{C} \frac{\bar{A}_n}{\delta \bar{A}_n} \right|$$

with $\delta\bar{A}_n = \delta A_n \exp(i\psi)$



rms rf sensitivity

(all amplitudes and phases together)

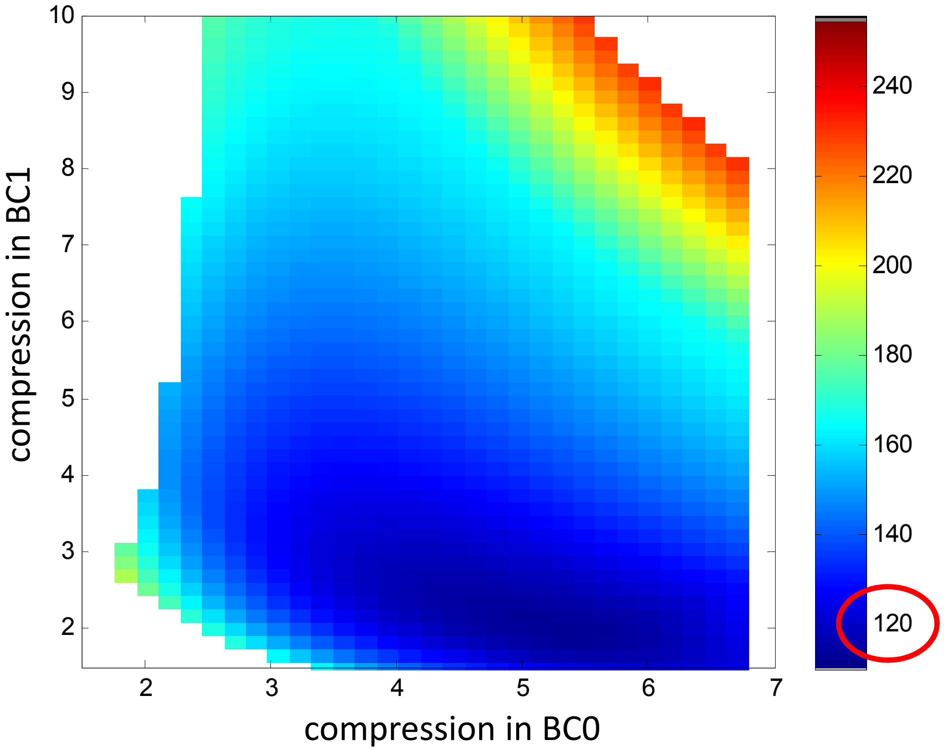
$$S_{\text{rms}} = \sqrt{\sum S_n^2}$$

2. Example

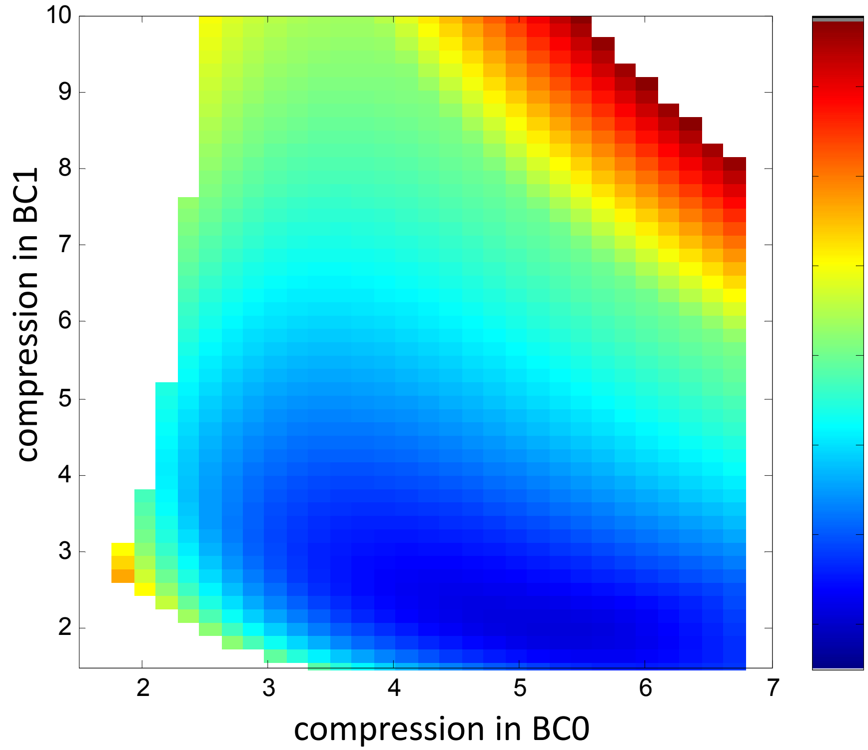
XFEL – BC working point

1 nC → 5 kA, total compression = 100

complex sensitivity L→0



rms sensitivity

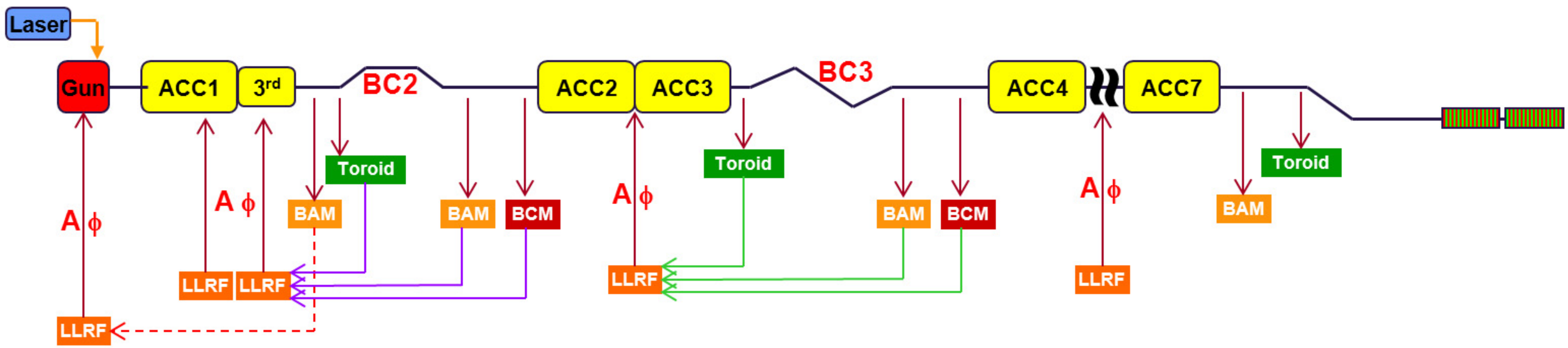


this is essentially the L→0 picture!

f.i. $S_0 = 120$ and $\left|\dfrac{\Delta C}{C}\right| < 0.1$ $\rightarrow \left|\dfrac{\Delta A_0}{A_0}\right| < \dfrac{0.1}{120} \approx 0.00083$

required amplitude stability of L→0

Fast Longitudinal Feedbacks at FLASH



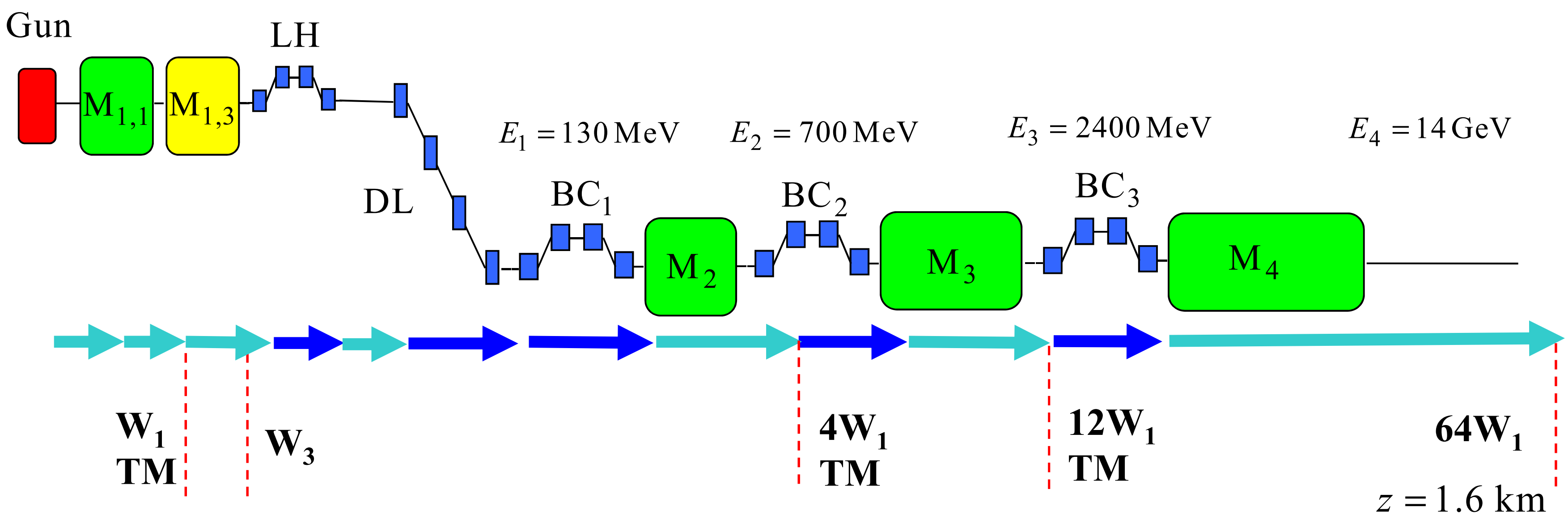
Beam Based Feedbacks:

- BAM before BC2 corrects phase in RF-Gun
- BAM and BCM after BC2 simultaneously correct amplitude and phase in ACC1 and 3rd harmonic
- BAM and BCM after BC3 correct amplitude and phase in ACC23

from Holger Schlarb, DESY

4. Two Level Optimization of BC Working Point
high level simulation

Full 3D simulation method (**200 CPU, ~10 hours**)



ASTRA (tracking with 3D SC) since 2011: ASTRA with wakes

CSRtrack (tracking with CSR, “projected” model)

W1 = wake of TESLA module

W3 = wake of 3rd harmonic module

TM = transverse matching to the design optics

4. Two Level Optimization of BC Working Point
find WP parameters of high level simulation

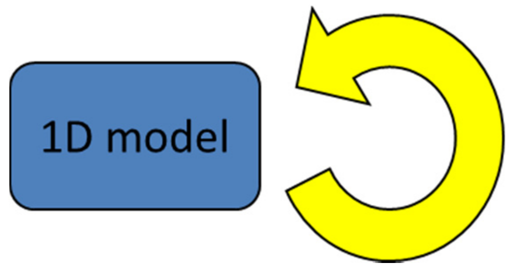
$\mathbf{y}$ = working point parameters (energy, compression + derivatives)

$\mathbf{x}$ = LINAC parameters (amplitudes and phases)

$\mathbf{p}$ = compressor parameters (magnet strengths or R56)

no self-effects: $\mathbf{y} = f(\mathbf{x},\mathbf{p})$

$\mathbf{x} = g(\mathbf{y},\mathbf{p})$



fast scan to find the working point $\mathbf{y},\mathbf{p}$

with self-effects: $\mathbf{y} = f_Q(\mathbf{x},\mathbf{p},Q)$ Q = bunch charge

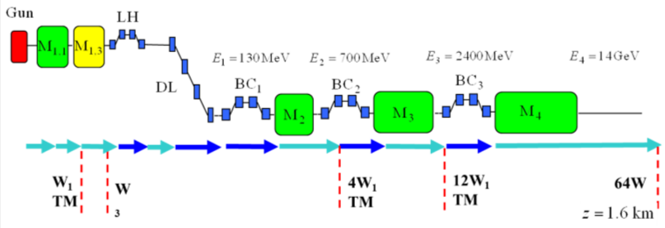
$$\mathbf{y} = f_Q(\mathbf{x}_n,\mathbf{p},Q) + f(\boxed{\mathbf{x}_{n+1}},\mathbf{p}) - f(\mathbf{x}_n,\mathbf{p})$$

fix point iteration to find LINAC parameters

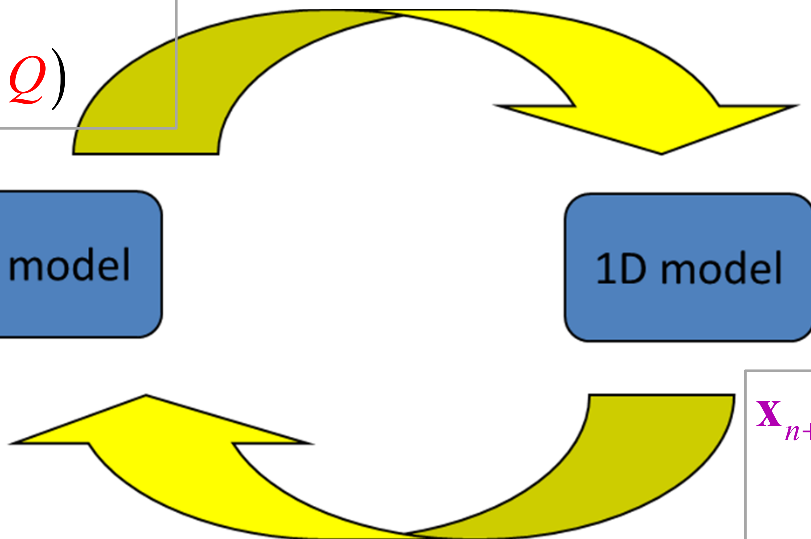
4. Two Level Optimization of BC Working Point

find WP parameters of high level simulation

Full 3D simulation method (**200 CPU, ~10 hours**)



$$\mathbf{y}_n = f_Q\left(\mathbf{x}_n, \mathbf{p}, Q\right)$$



$$\mathbf{x}_{n+1} = g\left(\mathbf{y} - \mathbf{y}_n + f\left(\mathbf{x}_n, \mathbf{p}\right), \mathbf{p}\right)$$

↑

(use low level inverse function)

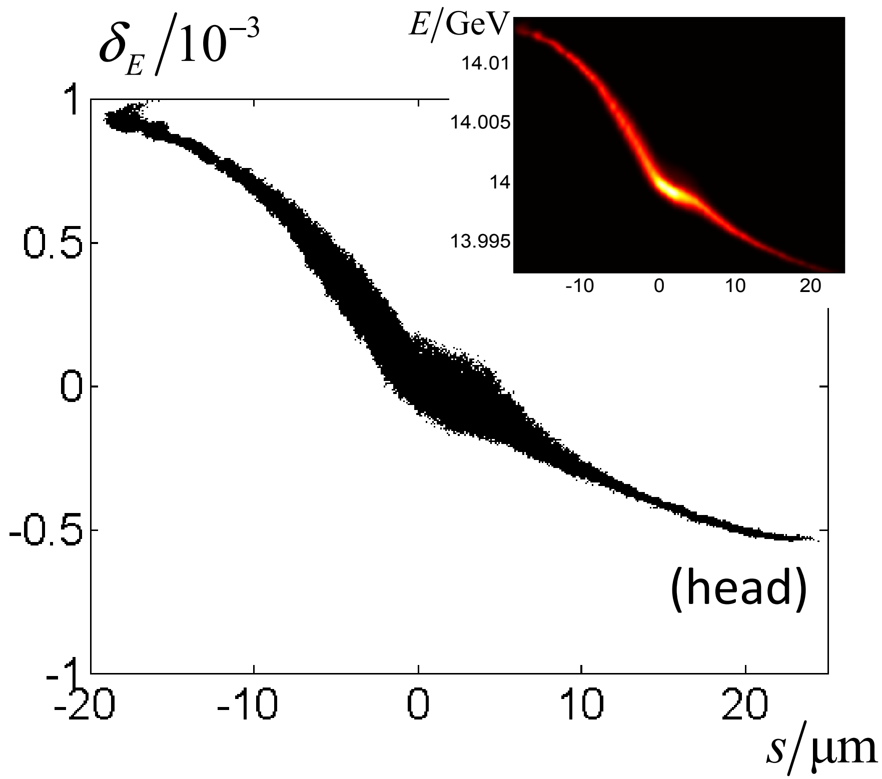
scheme from

I.Zagorodnov, M.Dohlus: A Semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects, Phys. Rev. STAB, 2011.

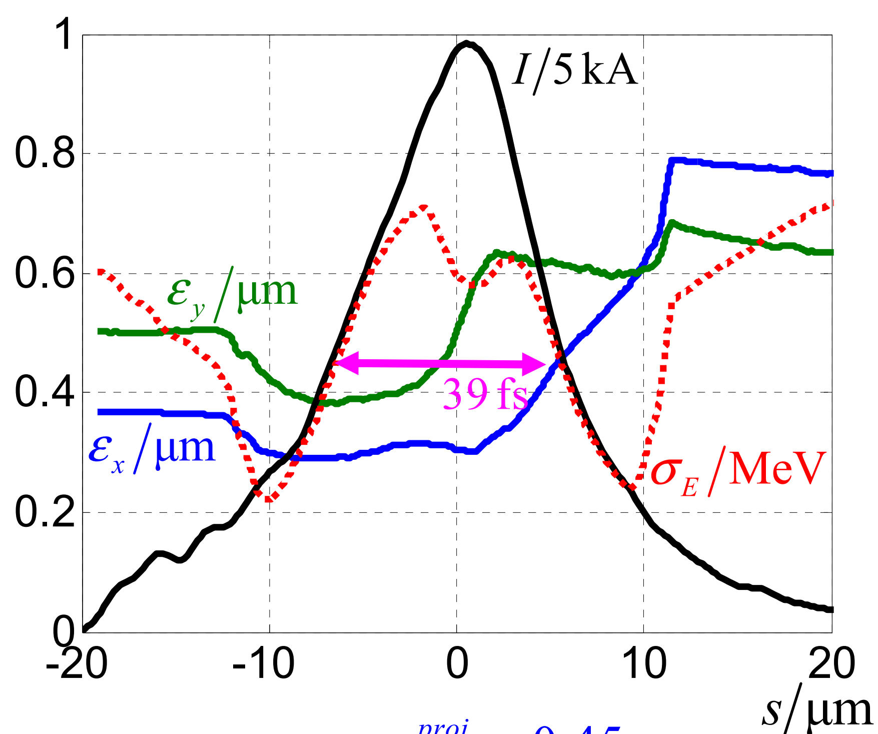
2. Example
E-XFEL – BC working point

f.i. Q = 250 pC $\rightarrow$ 5 kA   compression factor $\approx$ 400

longitud. phase space



current, emittance, energy spread

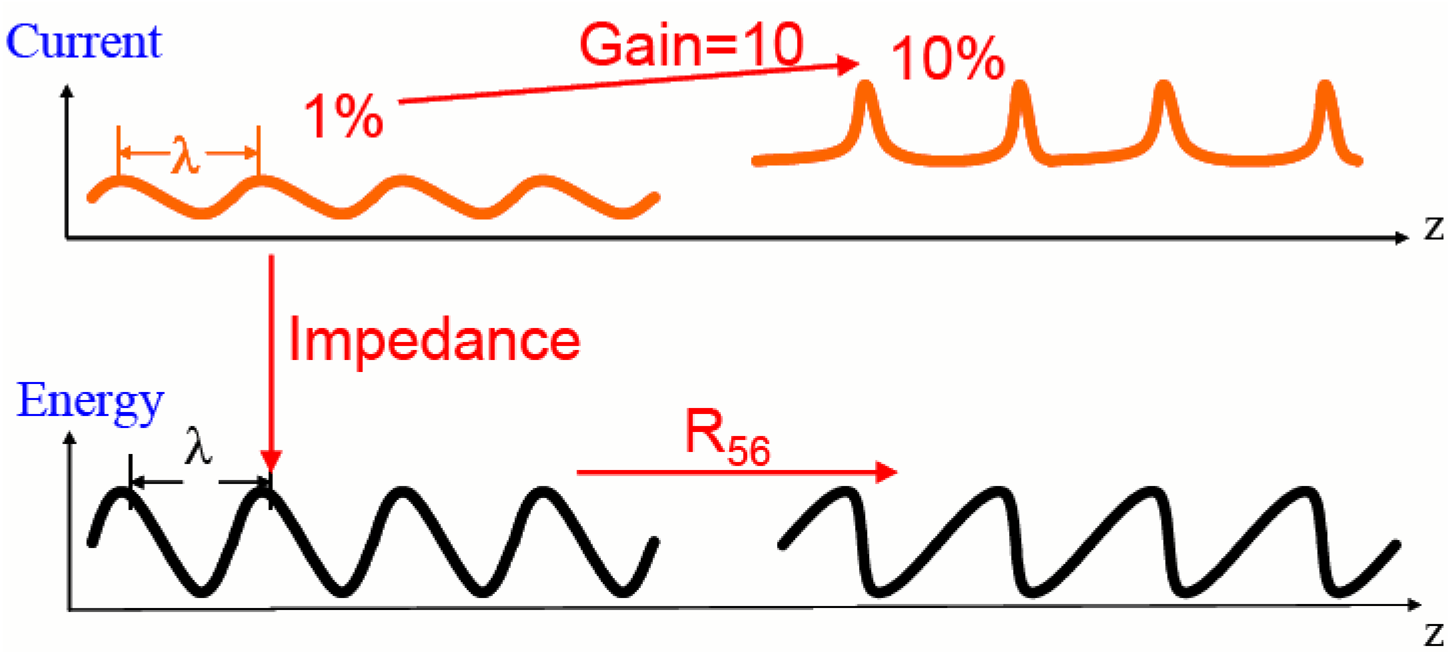


$\varepsilon_x^{proj} = 0.45\ \mu\mathrm{m}$

$\varepsilon_y^{proj} = 1.5\ \mu\mathrm{m}$

from Igor Zagorodnov, DESY
1st meeting of EXFEL accelerator consortium

5. Micro-Bunching
amplification mechanism

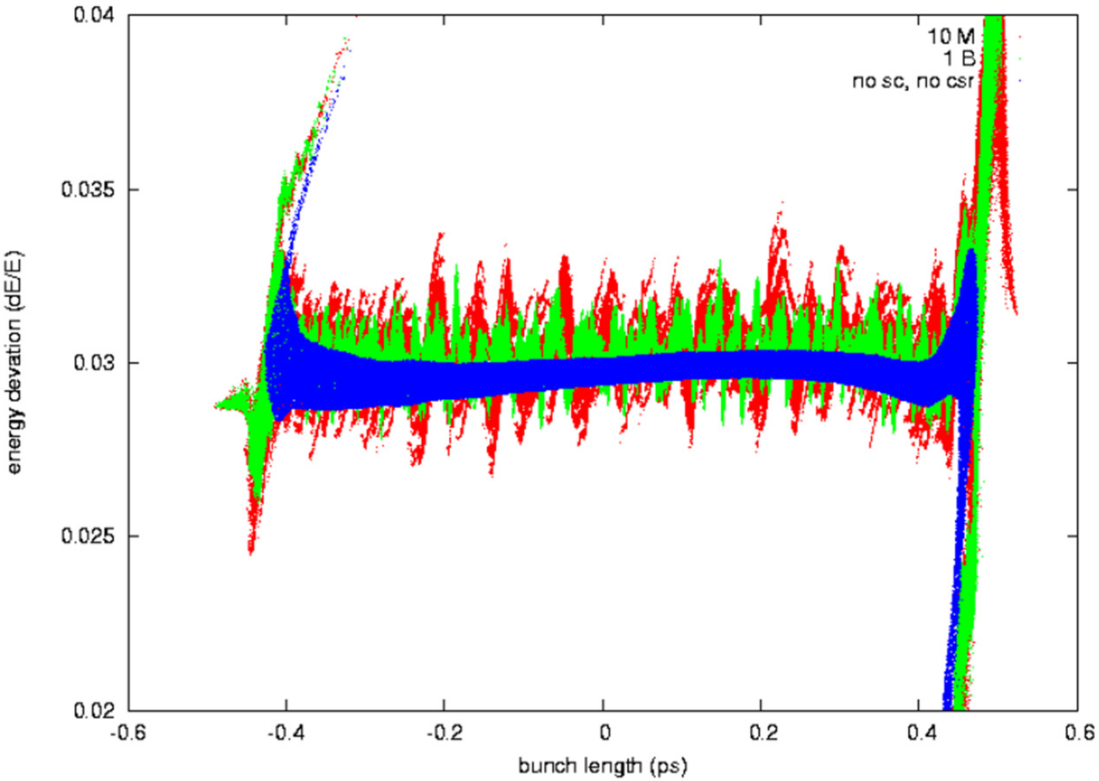


5. Micro-Bunching
"high" level

Ji Qiang
Lawrence Berkeley National Laboratory
Microbunching Instability Workshop
Oct. 6-8, Berkeley, USA, 2008

Large Scale Simulation Is Needed

Final Longitudinal Phase Space Distribution w/o SC and CSR
(Using **10M** and **1B** particles)

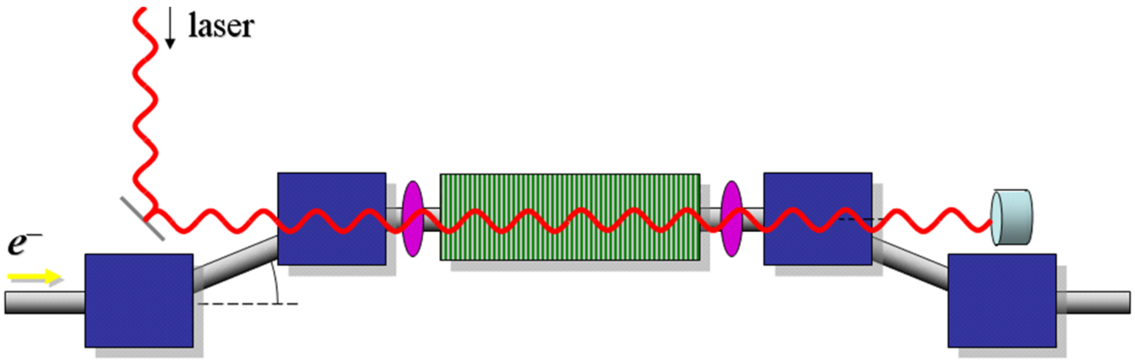


no sc, no csr
with, 1E7 particles
with, 1E9 particles

5. Micro-Bunching

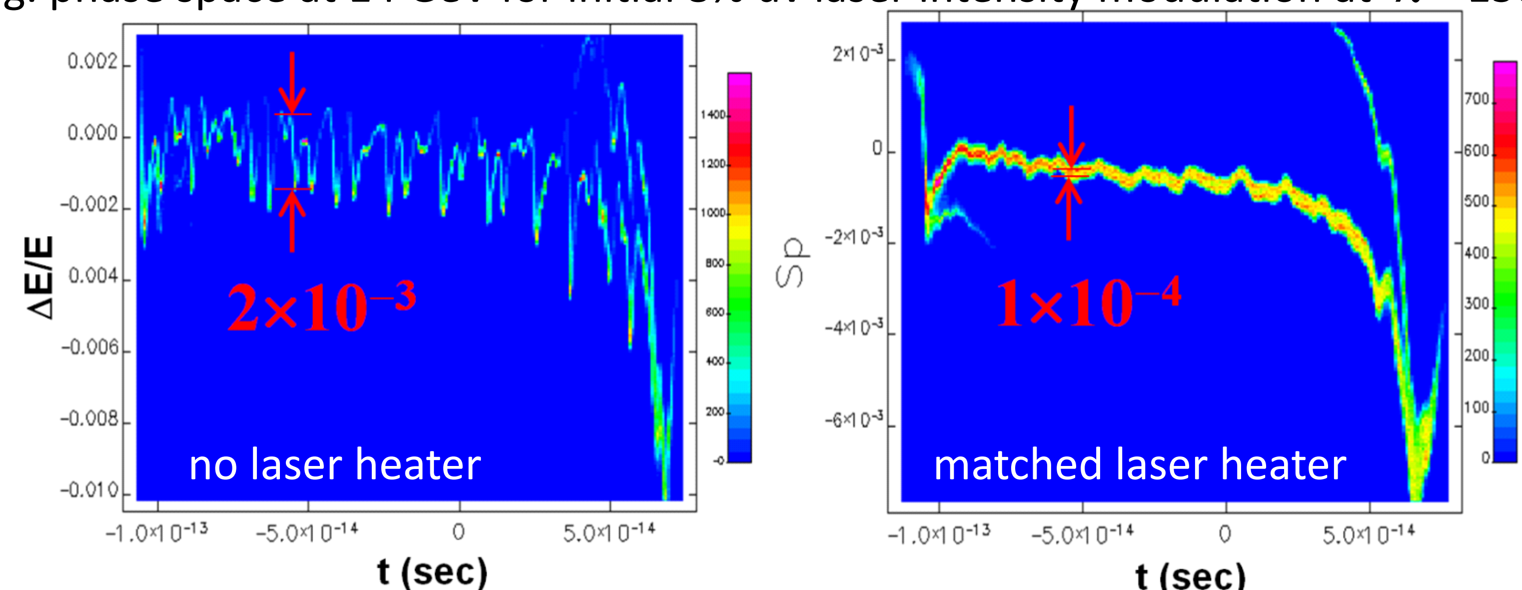
increase slice energy spread ⟶ reduced micro-bunching

laser heater:



Example LCLS:

final long. phase space at 14 GeV for initial 8% uv laser intensity modulation at λ = 150nm



courtesy P. Emma

5. Micro-Bunching
low level: linear gain model

integral equation method: $G(z) = G^{(0)}(z) + \int_0^z K(z,\tilde{z})G(\tilde{z})d\tilde{z}$

Heifets,Stupakov: PhysRev ST, 064401 2002
Huang, Kim: PhysRev ST, 074401 2002

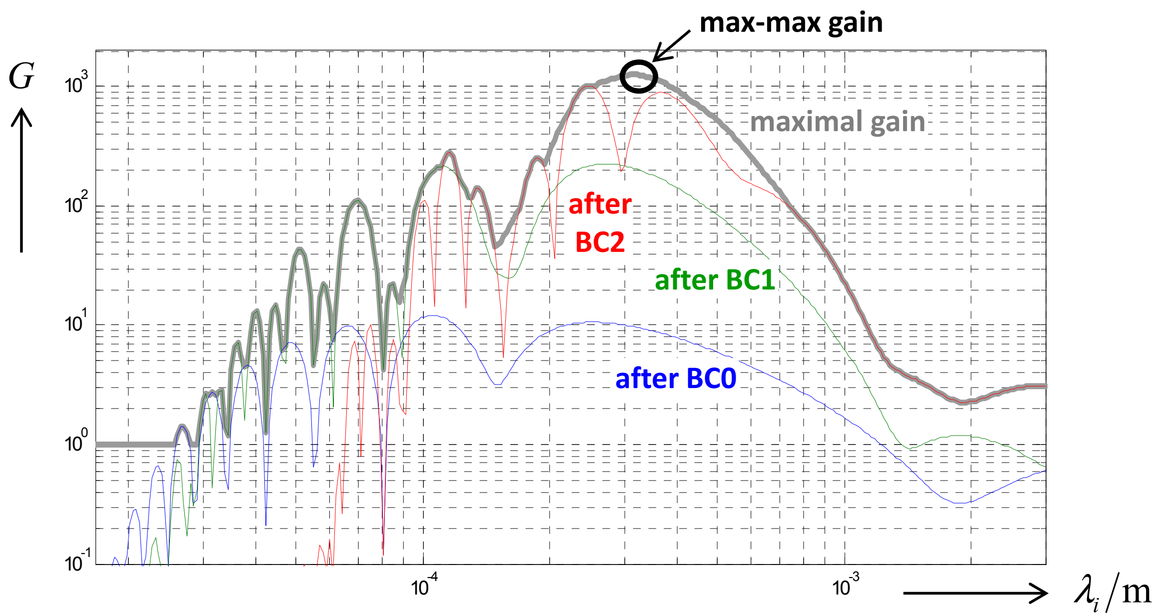
$G = \frac{\tilde{I}(z)}{I(z)}\frac{I(0)}{\tilde{I}(0)}$ gain factor, amplification of **relative** modulation

$z =$ length along linac

$\lambda_i =$ wavelength of initial density modulation

$K =$ kernel depends on **impedance**, current, optics, rf settings,
spectrum of uncorrelated **energy spread**, … ← **laser heater**

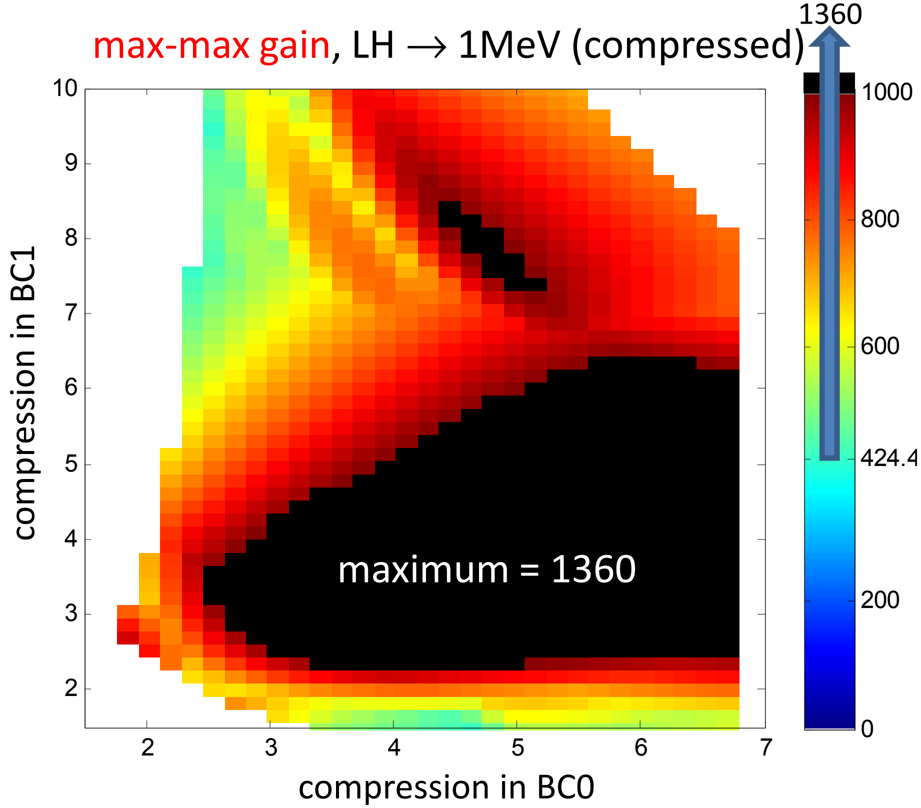
example:
E-XFEL

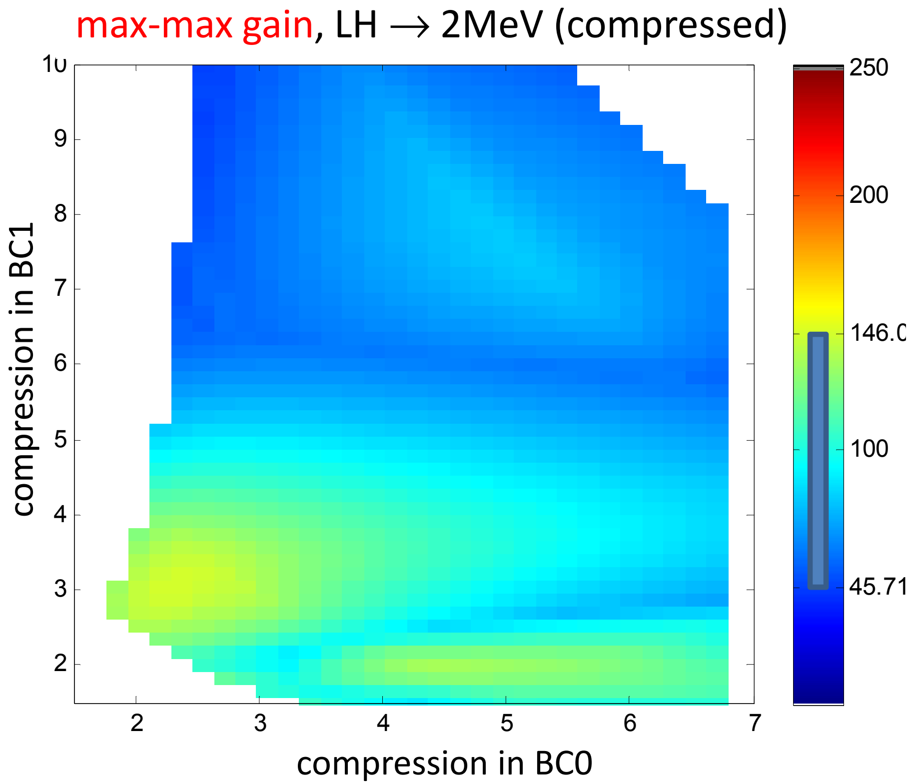


5. Micro-Bunching

example: E-XFEL

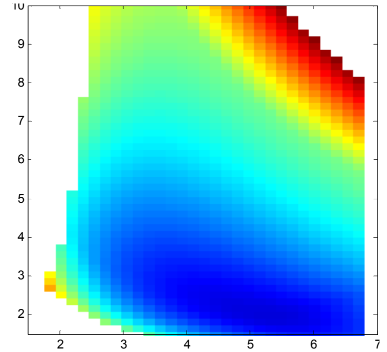
1 nC $\rightarrow$ 5 kA, total compression = 100



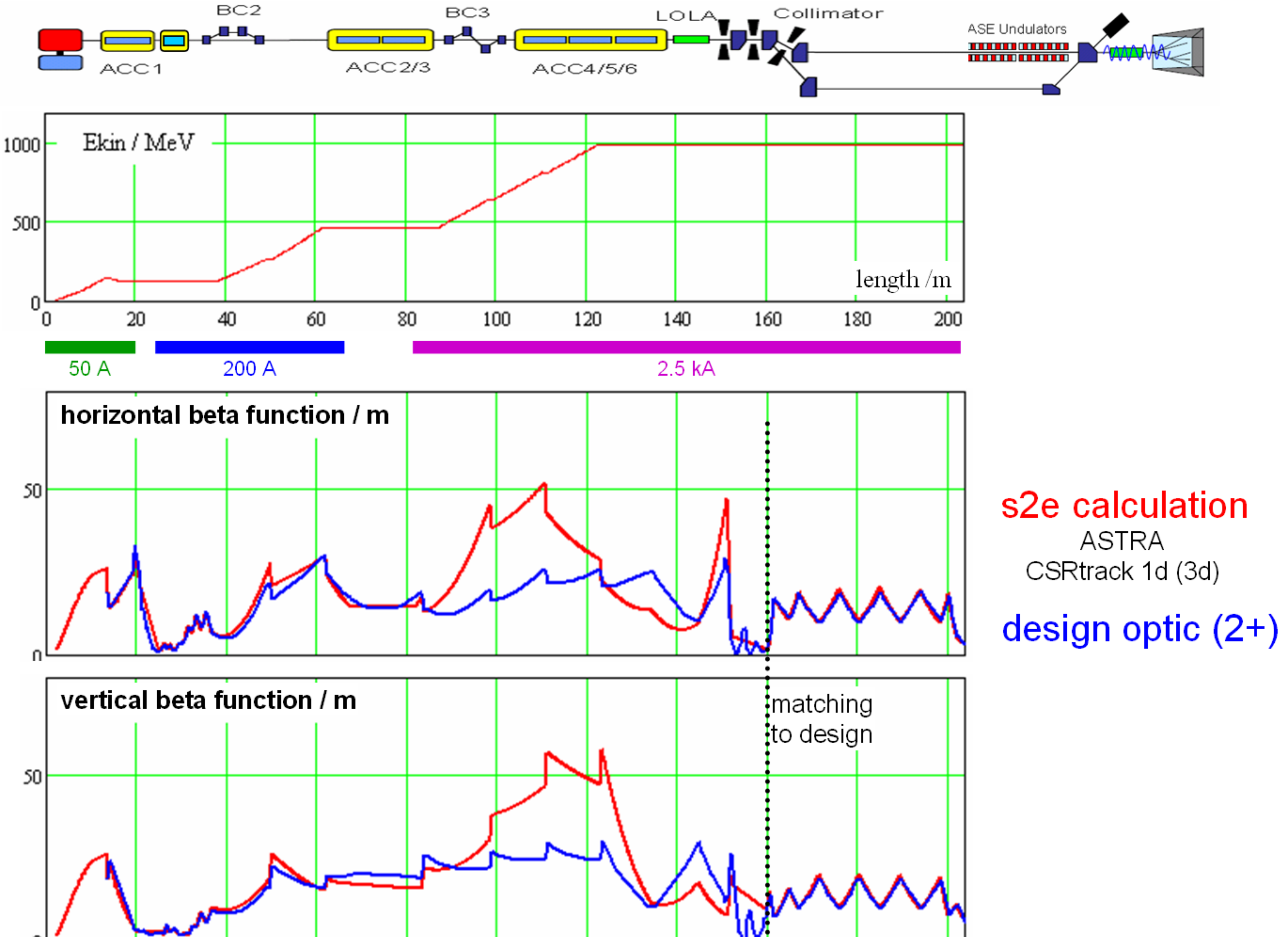


rms rf sensitivity:

$$S_{\text{rms}} = \sqrt{\sum S_n^2}$$

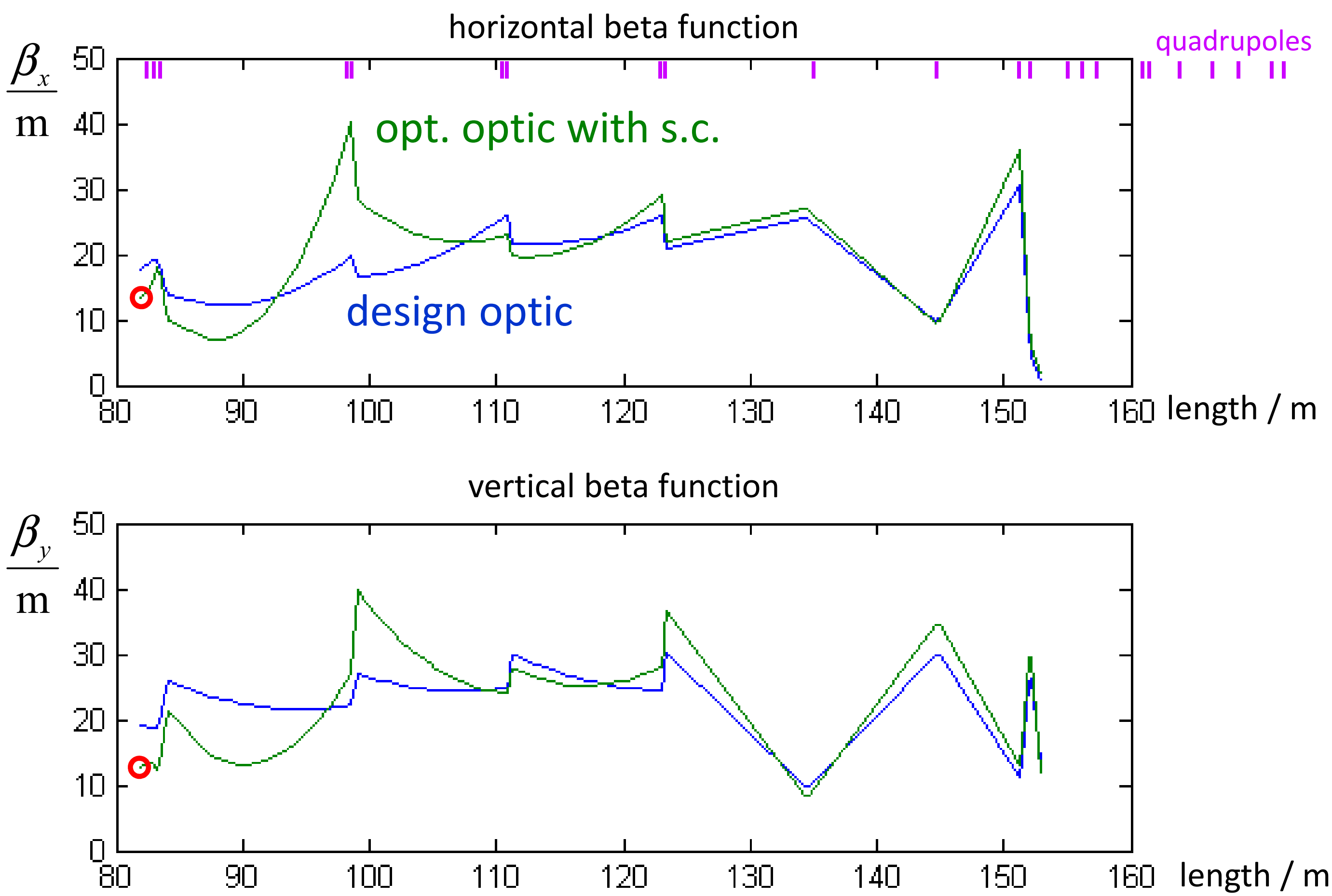


6. Transverse Dynamics
example: FLASH 2008



6. Transverse Dynamics

optimization: change quadrupole settings to approximate design optic



optics after BC3
(s2e simulation)
deviates from design

fast optimization with low level model

6. Transverse Dynamics
a low level model

transverse EoM: $\frac{d}{dz}\begin{pmatrix} x \\ x' \end{pmatrix} = \mathbf{M}\begin{pmatrix} x \\ x' \end{pmatrix} + \begin{pmatrix} 0 \\ F_x / v_\parallel p_\parallel \end{pmatrix}$ with $\mathbf{M} = \begin{pmatrix} 0 & 1 \\ k_x & -p'_\parallel / p_\parallel \end{pmatrix}$

k_x hor. focusing strength

F_x hor. SC force

$v_\parallel, p_\parallel$ long. velocity, momentum

2nd order momenta: $c_{xx} = \langle x, x \rangle \quad c_{xx'} = \langle x, x' \rangle \quad c_{x'x'} = \langle x', x' \rangle \quad \mathbf{C} = \begin{pmatrix} c_{xx} & c_{xx'} \\ c_{xx'} & c_{x'x'} \end{pmatrix}$

momenta tracking: $\mathbf{C}' = \mathbf{MC} + \mathbf{CM} + \frac{1}{v_\parallel p_\parallel}\begin{pmatrix} 0 & \langle F_x, x \rangle \\ \langle F_x, x \rangle & 2\langle F_x, x' \rangle \end{pmatrix}$

low level momenta tracking: $\mathbf{C}' = \mathbf{MC} + \mathbf{CM} + \frac{f_x}{v_\parallel p_\parallel}\begin{pmatrix} 0 & c_{xx} \\ c_{xx} & 2c_{xx'} \end{pmatrix}$

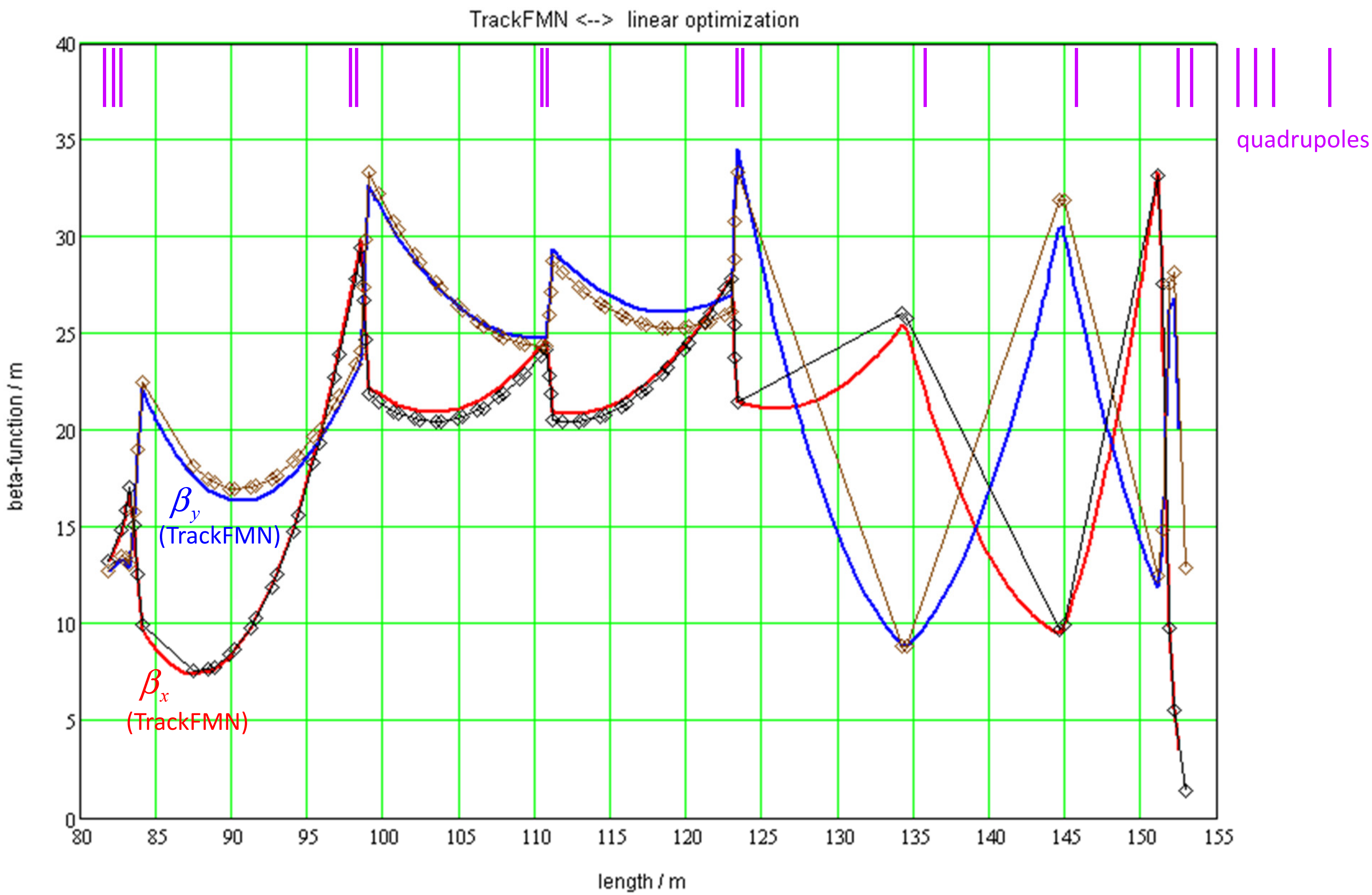
approximation „effective linear force“: $F_x \approx f_x x$ with $\langle F_x, x \rangle = f_x \langle x, x \rangle$

coefficient $f_x = f_x(I, c_{xx}, c_{yy}, \cdots)$ for a gaussian distribution

Sacherer: RMS Envelope Equations with SC, CERN/SI/Int. DL/70-12 18.11.1970

6. Transverse Dynamics

comparison: “high” level (TrackFMN) with low level



red/blue = TrackFMN = tracking with **xy space charge solver**

brown/black diamonds = **low level momenta tracking**

7. Conclusion

high numerical effort for “high level” physical models

even these models are not gauged (to the very end), but they are successful

also much simpler models (low level) are successful

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optimization and tuning:

complicated goal because of difficult tradeoff between different effects

with self effects:
tuning of BC working point and optics is necessary

both is feasible with multi level computations