Start-To-End Simulations for the European XFEL

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- description of European XFEL beam line
- technical aspects of simulation

  matching / codes / tools

- gun
- μ-bunch "instability"

  laser heater / technical aspects of simulation

- European XFEL – segmentation (for simulation)
- method 1 (fast)
- method 2 (reference)
- method 3 (efficient & accurate) – to be done

European XFEL, description, s2e home page

s2e simulation: technical aspects

rf settings: phase and amplitude settings are very sensitive
wakes & space charge effects change longitudinal
profile significantly!
$\rightarrow$ iterative optimization

matching: real
artificial

steering

bunch: 1nC, ~50A (initial)

simulation: s2e particles (ASTRA-generator & gun simulation)
$N_{s2e} \approx 200000$
try to track these particles; avoid conversions to
other distributions (if possible);

simulation tools

ASTRA: on-axis-tracking, rz-space charge, rf, magnets,
no wakes

CSRtrack: non-linear motion effects,
1d CSR model, sub-bunch models

GENESIS: time dependent 3d FEL code

ELEGANT: rf, magnets, wakes,
no space charge, 1d CSR model

utility programs

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format conversion: ASTRA / CSRtrack / sdds

some simple manipulations of longitudinal phase space:
   add cavity wakes (based on point particle wakes,
         asymptotic fit to ECHO calculations),
   add space charge wakes (semi analytic model)

some simple manipulations of transverse phase space:
(transport matrices)
   drift,
   transport as defined by linear optics (design),
   matching

ASTRA: rz space charge model

3d: slices & centroids
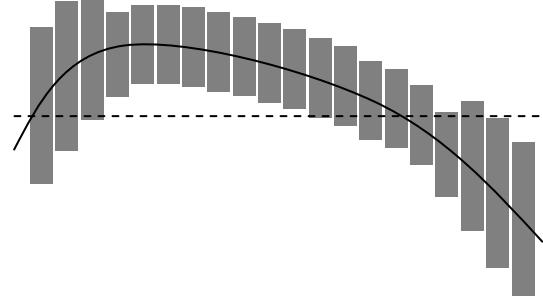
ASTRA rz-model for s.c. calculation
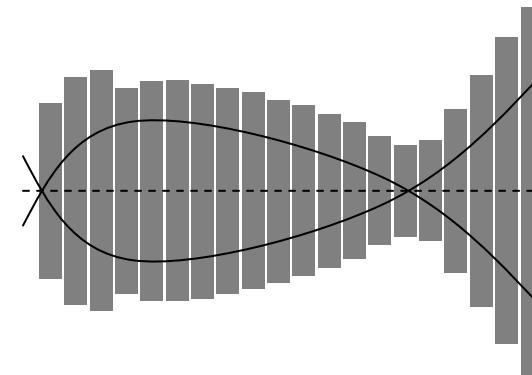
charge density is underestimated

1) extract centroid offsets
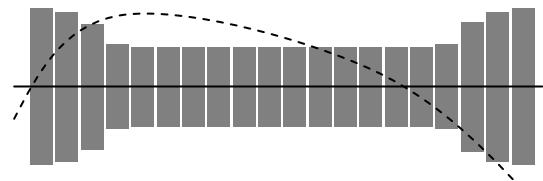
2) ASTRA tracking of particles with
   extracted centroid offsets

3) transport centroid offsets (matrix)

4) restore new particle coordinates
   (add centroid offset)

remark: 3d space charge models create more noise (or need more particles)

CSRtrack

projected or 1d-CSR model:

particles distribution $\rightarrow$ smooth 1d current $\rightarrow$ 1d longitud. field $\rightarrow$ particle energy
low numerical effort

sub-bunch model:

1) create distribution of 'generating' 3d-sub-bunches
   $N_g \approx 100000$; ($x, x', y=0, y'=0, z, p_z, q$)
2) combine s2e-particles and 'generating' bunches
3) set charges of s2e-particles in combined
   distribution to zero
4) CSRtrack: self consistent tracking
   ~10^1h on linux cluster with 20 cpu-s (64bit)
5) extract coordinates of s2e particles

x'

s2e particles
center of 'generating' sub-bunches
z
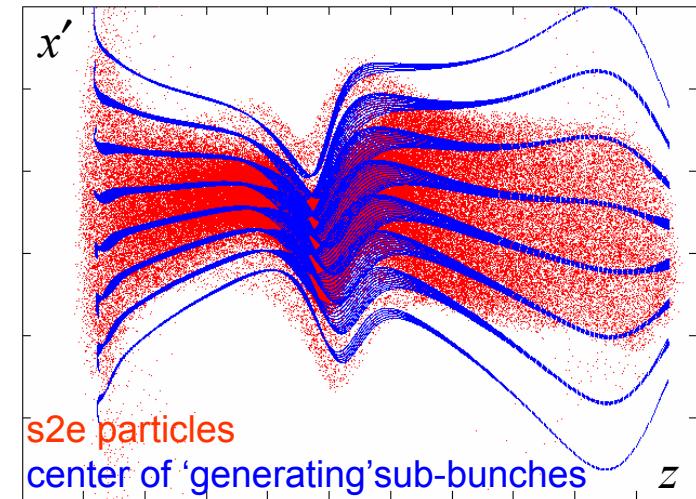
projected vs. sub-bunch:

1d model sufficient for centroid motion & projected emittance;
XFEL: slice effects are weak;
       uncorr. energy spread dominated by laser heater

semi analytic space charge model

steady state space charge impedance:

R_{pipe} = radius of beam pipe
σ_r = rms width of round gaussian beam
γ = Lorentz factor

$$\mathbf{E}(x, y, z, k) = \mathbf{E}(x, y, k, \sigma_r, R_{pipe}, \gamma) \cdot \exp(-ikz)$$

$$Z'_{sc}(k, \sigma_r, R_{pipe}, \gamma) = \frac{\int \mathbf{u}_z \cdot \mathbf{E}(x, y, k, \sigma_r, R_{pipe}, \gamma) \psi(x, y) dx dy}{\int \psi(x, y) dx dy}$$

$\psi(x, y)$ = transverse profile (round, rms width σ_r)

e.g. free space, $k\sigma_r/\gamma \ll 1$: $Z'_{sc}(k, \sigma_r, R_{pipe}, \gamma) \approx \dfrac{iZ_0 k}{2\pi\gamma^2} \ln\left(\dfrac{\gamma}{k\sigma_r}\right)$

$$Z_{sc}(k, a \to b) = \int_a^b Z'_{sc}(k, \sigma_r(z), R_{pipe}, \gamma(z)) dz$$

with:

ε_n = normalized design emittance

$$\sigma_r(z) = \sqrt{\frac{\varepsilon_n}{\gamma(z)} \beta_{twiss}(z)}$$

$$\beta_{twiss}(z) \approx \sqrt{\frac{\beta_x(z)^2 + \beta_y(z)^2}{2}}$$

β_x, β_y = beta function

gun
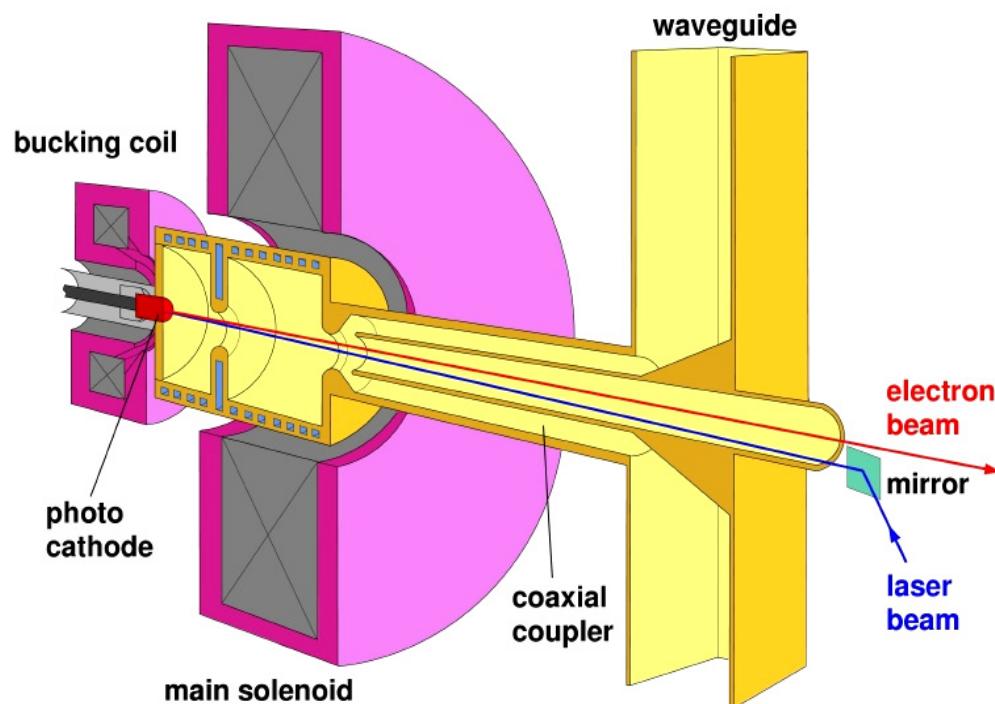
ASTRA simulation
"black box"
(ASTRA input from K.Flöttmann)

1nC, 200000 particles
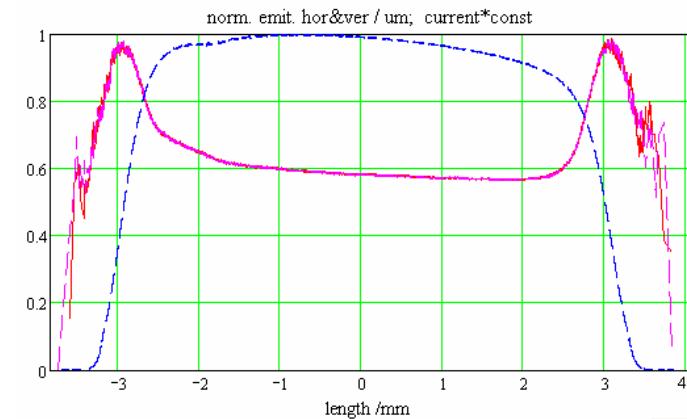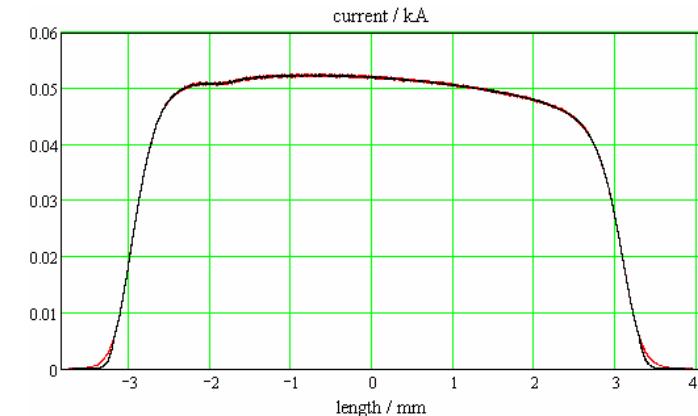
energy-offset correlation after gun

longitudinal phase space

uncorrelated part of long. phase space

energy - offset correlation (slice)
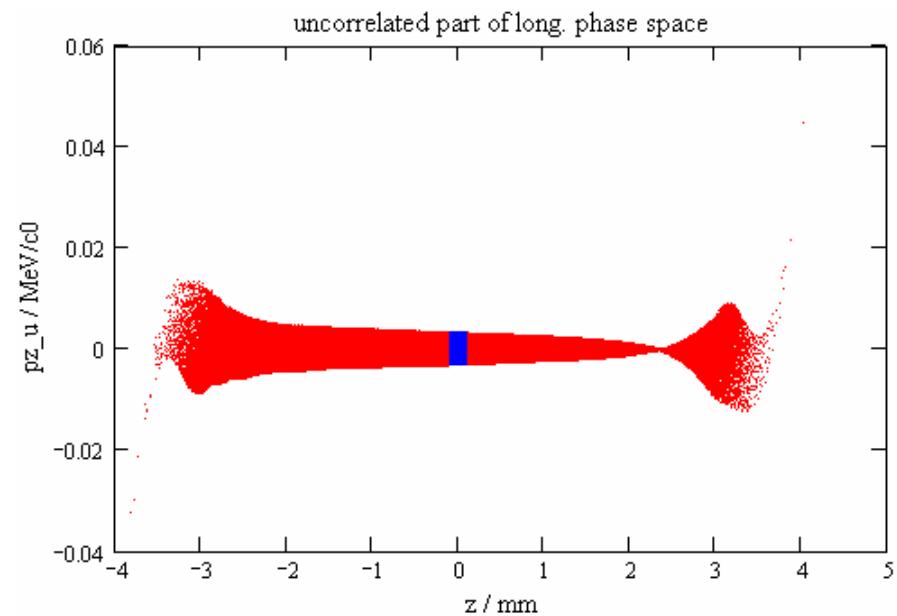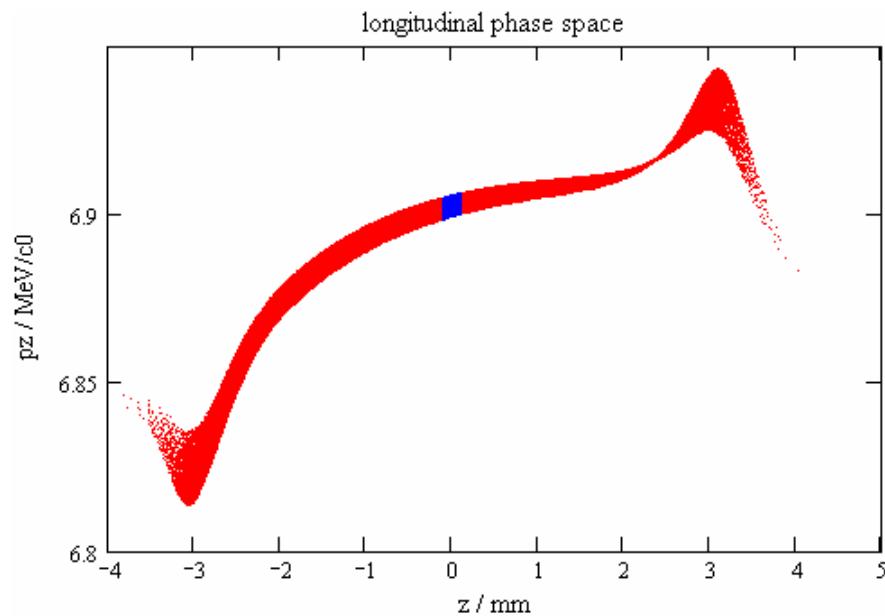
energy-offset correlation
1m after cathode
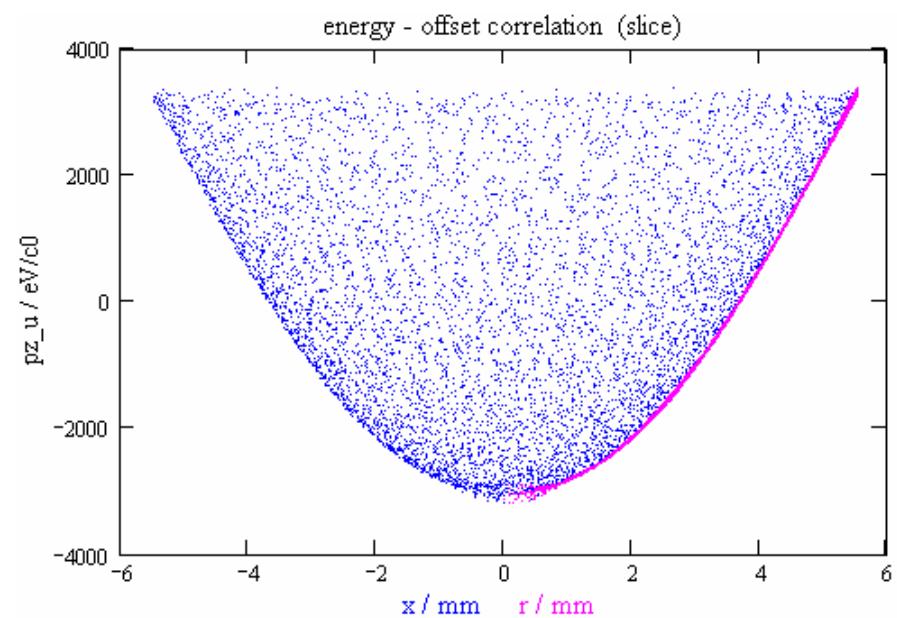
energy-offset correlation
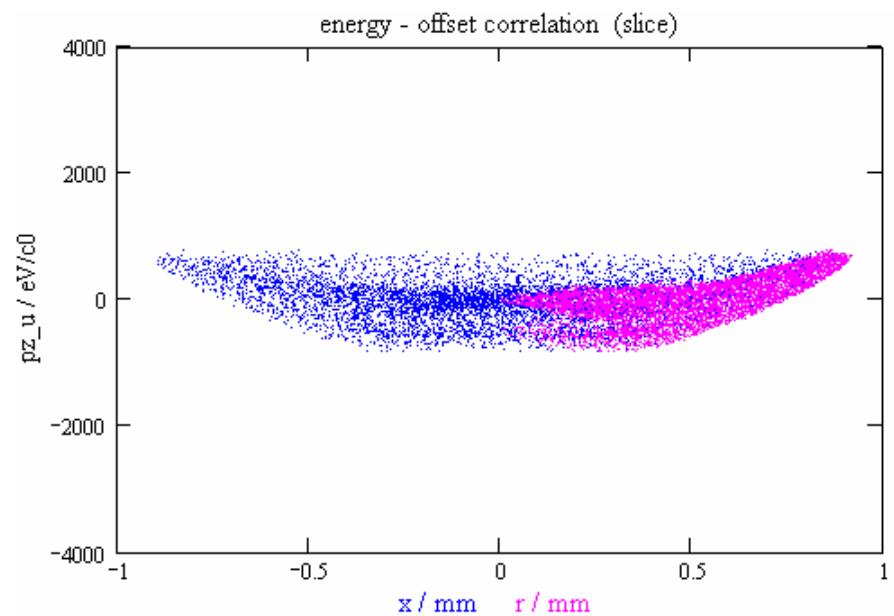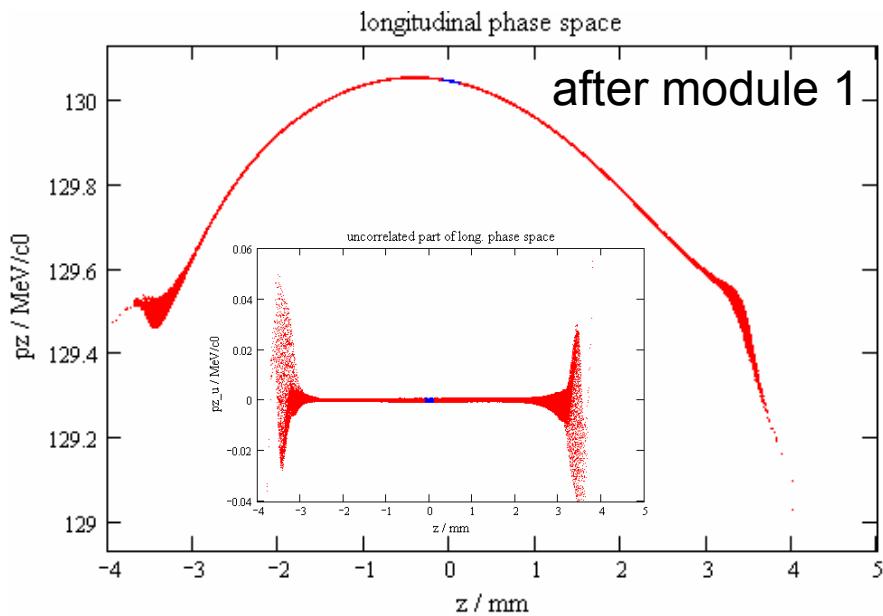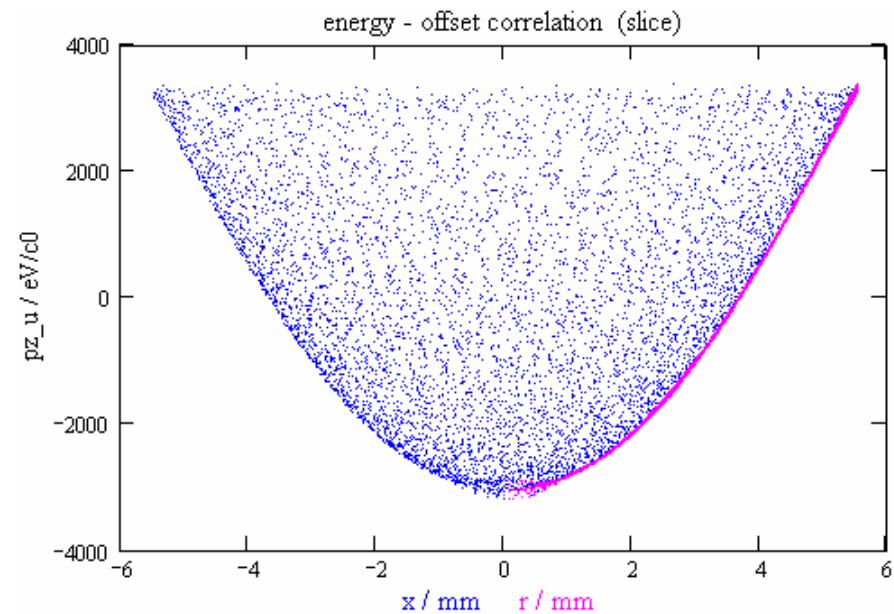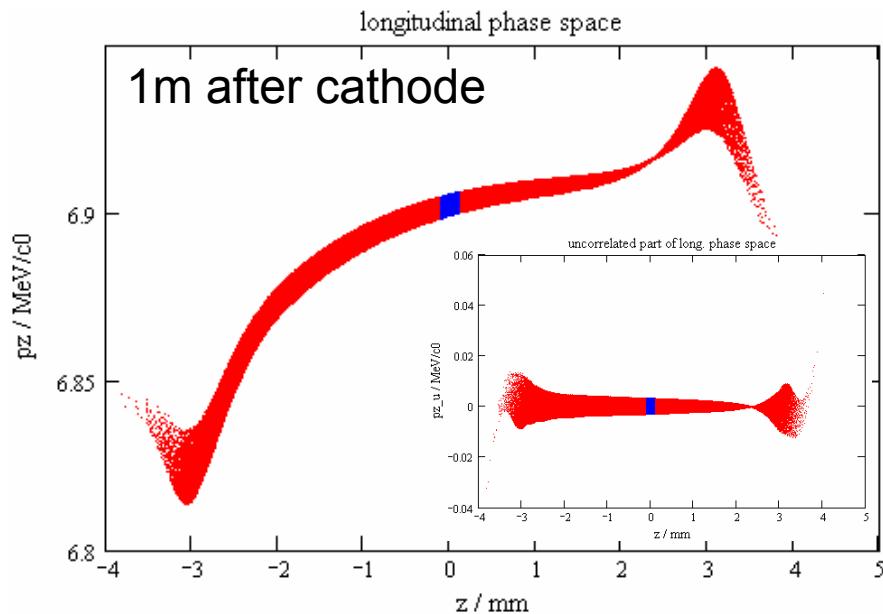
μ-bunch "instability"
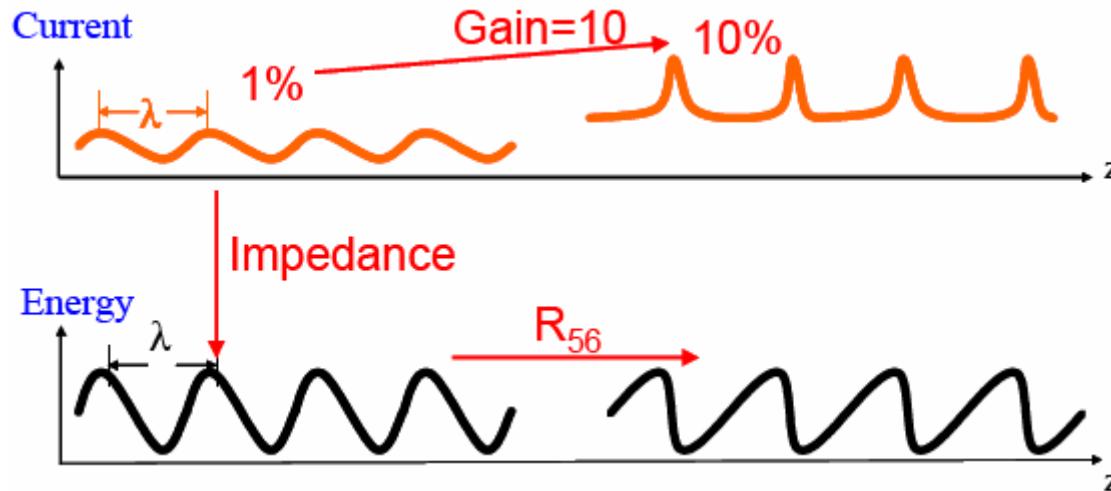
picture from
Z. Huang, J.Wu: Microbunching instability due to bunch compression
http://icfa-usa.jlab.org/archive/newsletter/icfa_bd_nl_38.pdf

impedances (steady state):

$$Z'_{sc}\left(k,\sigma_r,R_{pipe},\gamma\right) \approx \frac{iZ_0 k}{2\pi\gamma^2}\ln\left(\frac{\gamma}{k\sigma_r}\right) \quad \text{(free space, } k\sigma_r/\gamma \ll 1) \quad \text{"SC-instability"}$$

$$Z'_{CSR}\left(k,R_{curv}\right) \approx Z_0 \frac{\Gamma(2/3)}{2\pi}\sqrt[3]{\frac{k}{3iR_{curv}^2}} \quad \text{"CSR-instability"}$$

gain curves of µ-bunch "instability"

contributions of the sub-sections of the linac for an uncorrelated energy spread of 10 keV

$$\delta E_{rms,entrance} = 10\,keV$$

gain

after collimator

after BC1   after BC2

wavelength before bc1 / mm ⟶
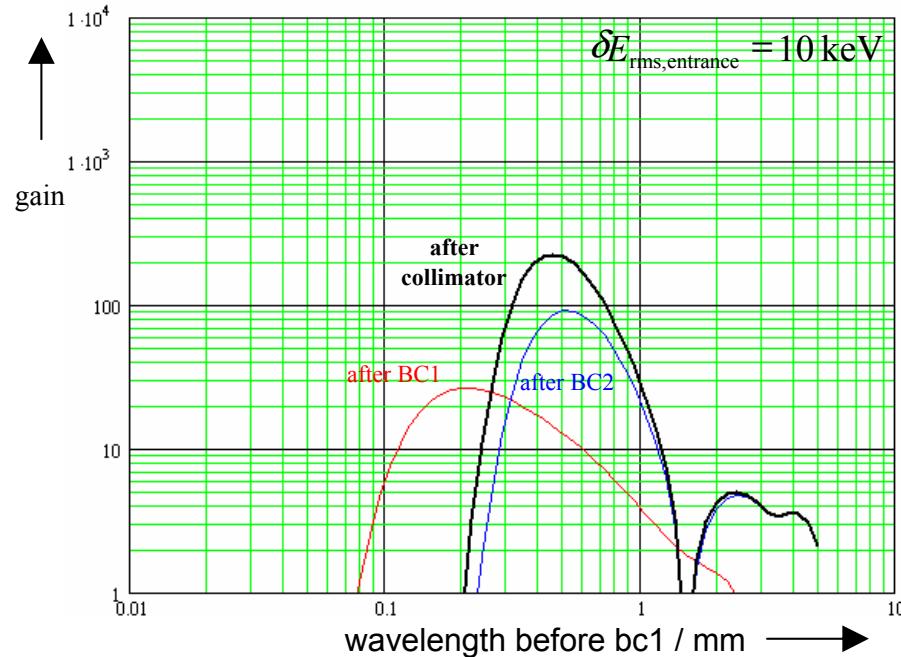
overall gain for different uncorrelated energy spreads

$$\delta E_{rms,entrance} / keV$$

gain after collimator

5

10

15

20

25

wavelength before bc1 / mm ⟶
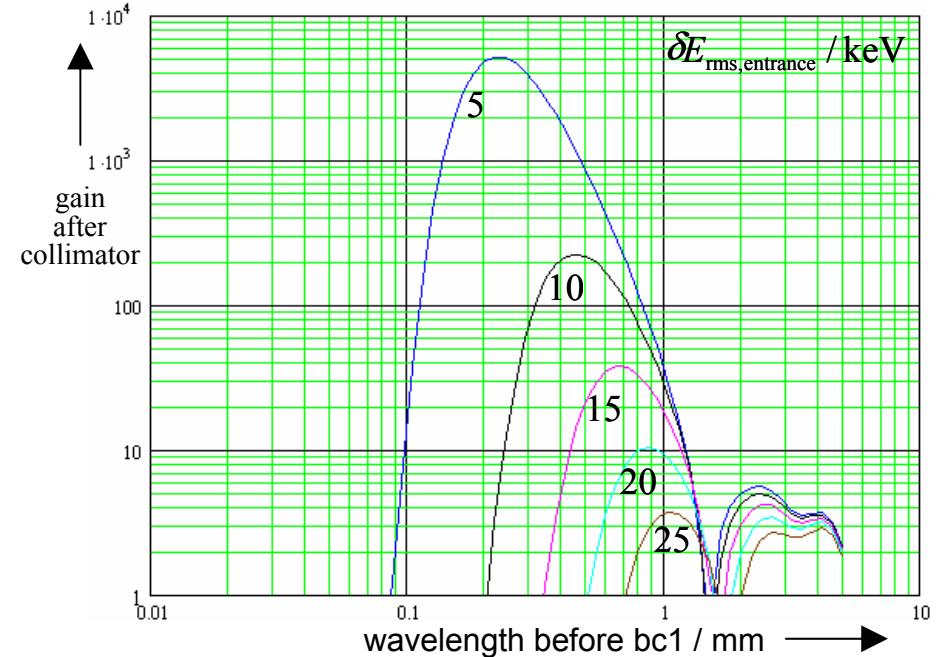
'laser heater' System (LCLS layout)

↓ 765-nm laser

7.4 cm

OTR ⟵ 50 cm ⟶ OTR

2.5 cm = η_x

e^-

$\theta_B \approx 7.1°$

12.6 cm

~153 cm
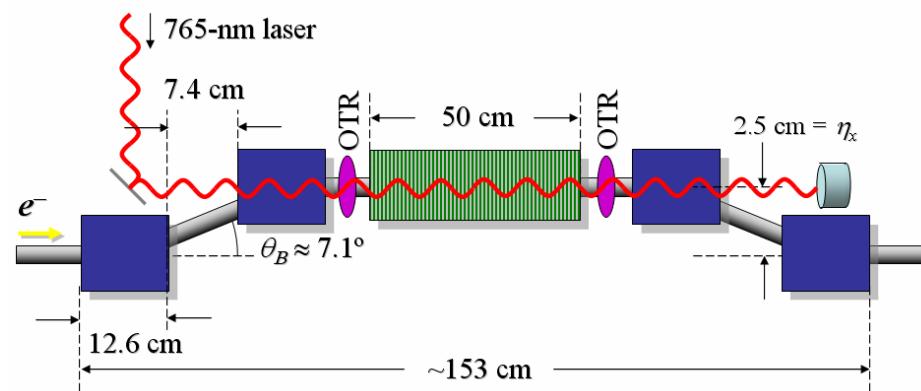
μ-bunch "instability", numerical aspects

1) μ-bunch-gain calculations are not subject of full s2e simulations

2) → separate investigations

CSR: integral equation method (limited applicability)
projected method: modulated beam, 1- and 2-stage compression
SC: impedance + r56

3) s2e simulations:

avoid artificial instability

N_{s2e} << number of electrons → use smoothing techniques

1d methods: adaptive filtering techniques

ASTRA: resolution of longitudinal mesh for calculation of
space charge field

CSRtrack sub-bunch-method: use of 'generating' sub-bunches

European XFEL, segmentation
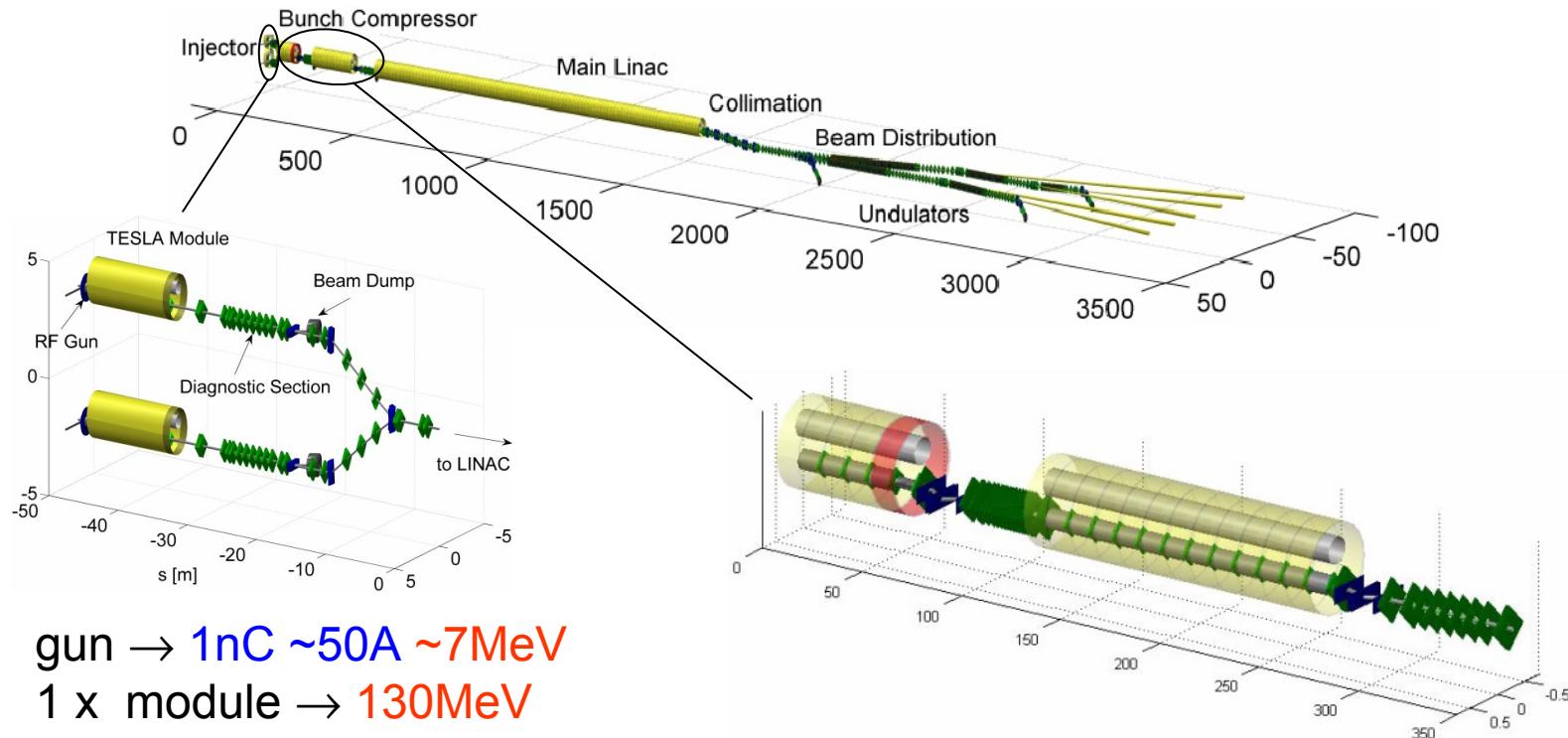
gun → 1nC ~50A ~7MeV
1 x module → 130MeV
dogleg
4 x module + 2 x module-3rd → 500MeV
bc1 → ~1kA
12 x module → 2GeV
bc2 → ~5kA
main linac → 17.5GeV
collimator
beam distribution … undulators …

European XFEL, segmentation

	130 MeV			500 MeV		2 GeV
gun	acc0 + …	dogleg	heater & linac 1	bc1	linac 2	bc2
cathode cavity solenoid	module quad	dipoles quads	modules (1st & 3rd) quads	dipoles	modules quads	dipoles

	17.5 GeV				
main linac	colli-mator	…	SASE1	…
modules quads	dipoles quads		undulator (with quads)	

rf, dispersion

method 1 - fast

ASTRA | CSRtrack 'projected' | transport | rf-field cavity wake & s.c. field | GENESIS

130 MeV   500 MeV   2 GeV

| gun | acc0 + … | dogleg | heater & linac 1 | bc1 | linac 2 | bc2 |
| cathode cavity solenoid | module quad | dipoles quads | modules (1st & 3rd) quads | dipoles | modules quads | dipoles |

17.5 GeV

| main linac | colli-mator | … | SASE1 | … |
| modules quads | dipoles quads | | undulator (with quads) | |

method 1

before BC1

1.3GHz: 442.85 MV   1.42 deg
3.9GHz: 90.63 MV 143.35 deg
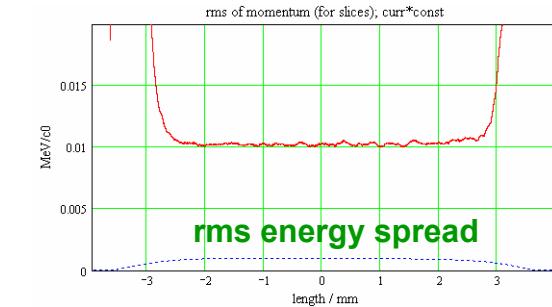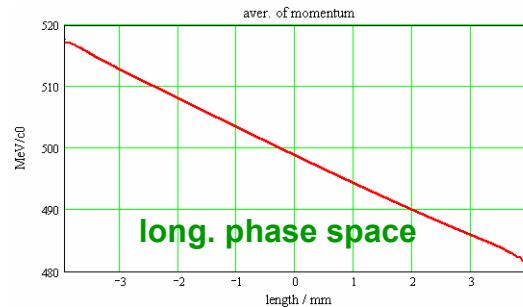
≈50A

current

long. phase space

rms energy spread

after BC1

≈1kA

after BC2

≈5kA

method 1

method 1 – GENESIS

the radiation power at z=130m

TESLA-FEL Report 2005-10: Impact of Undulator Wake-Fields and Tapering on the European X-Ray FEL Performance
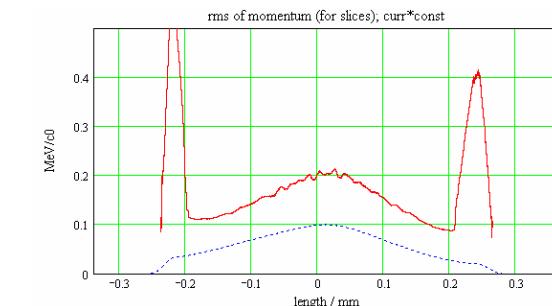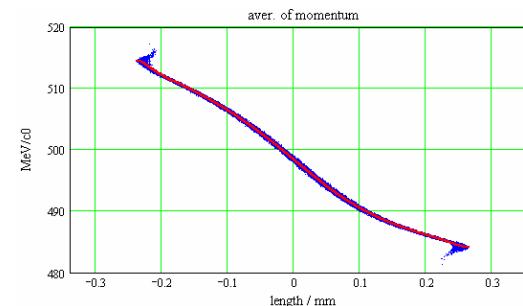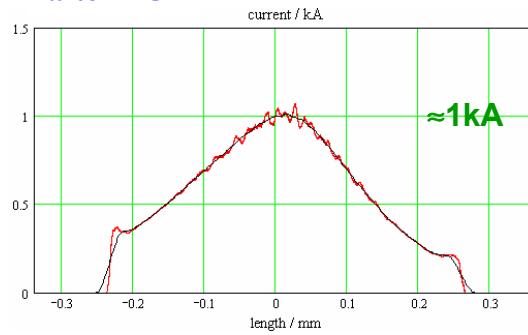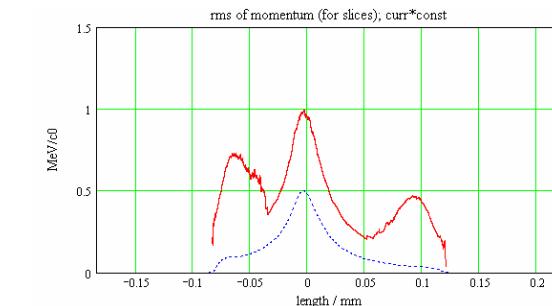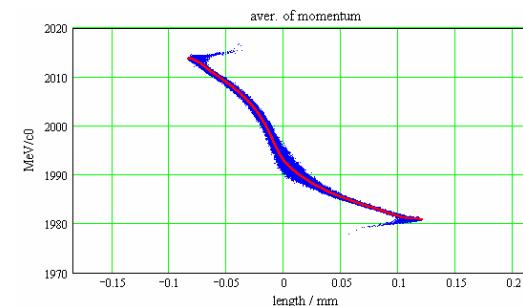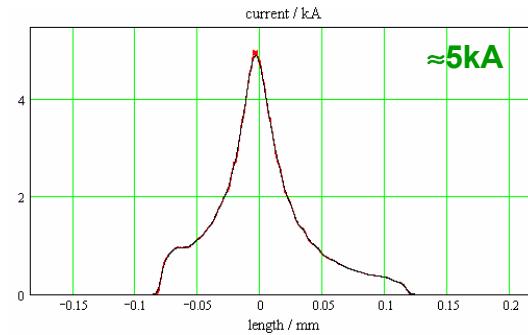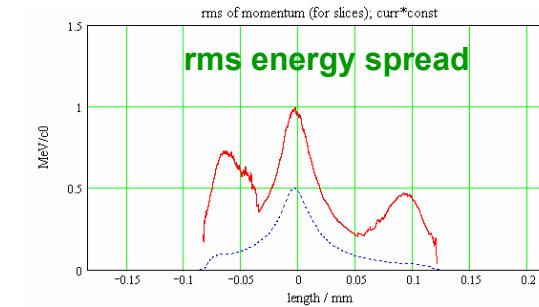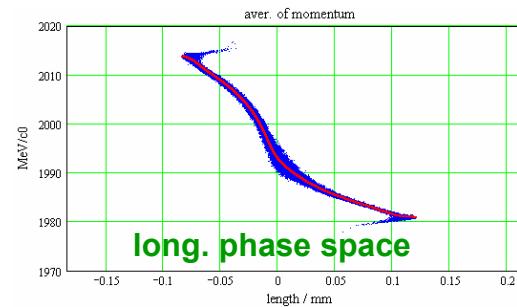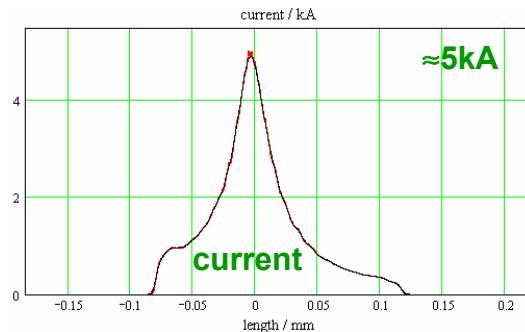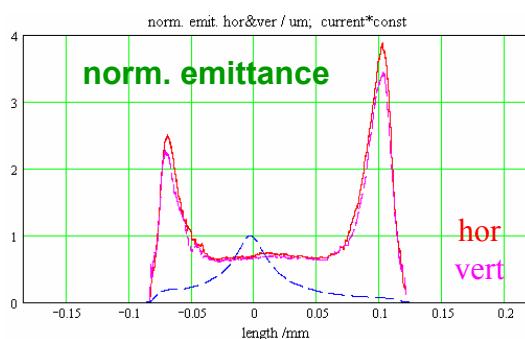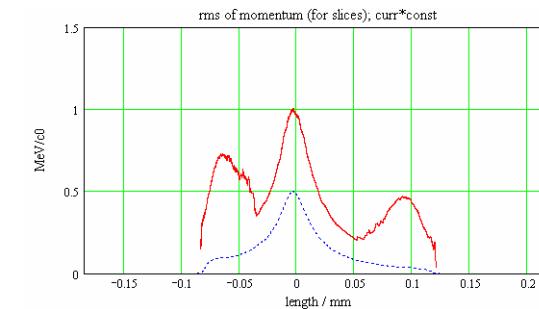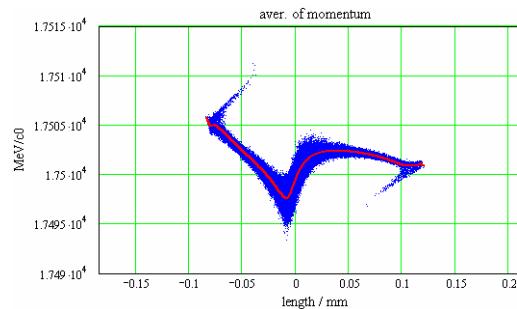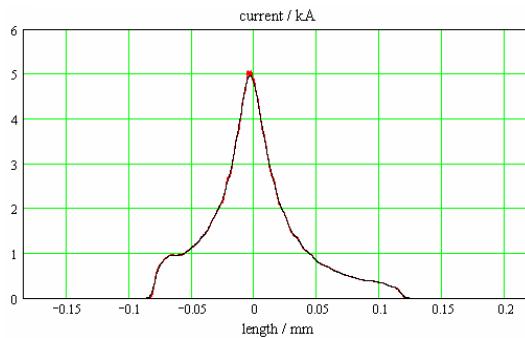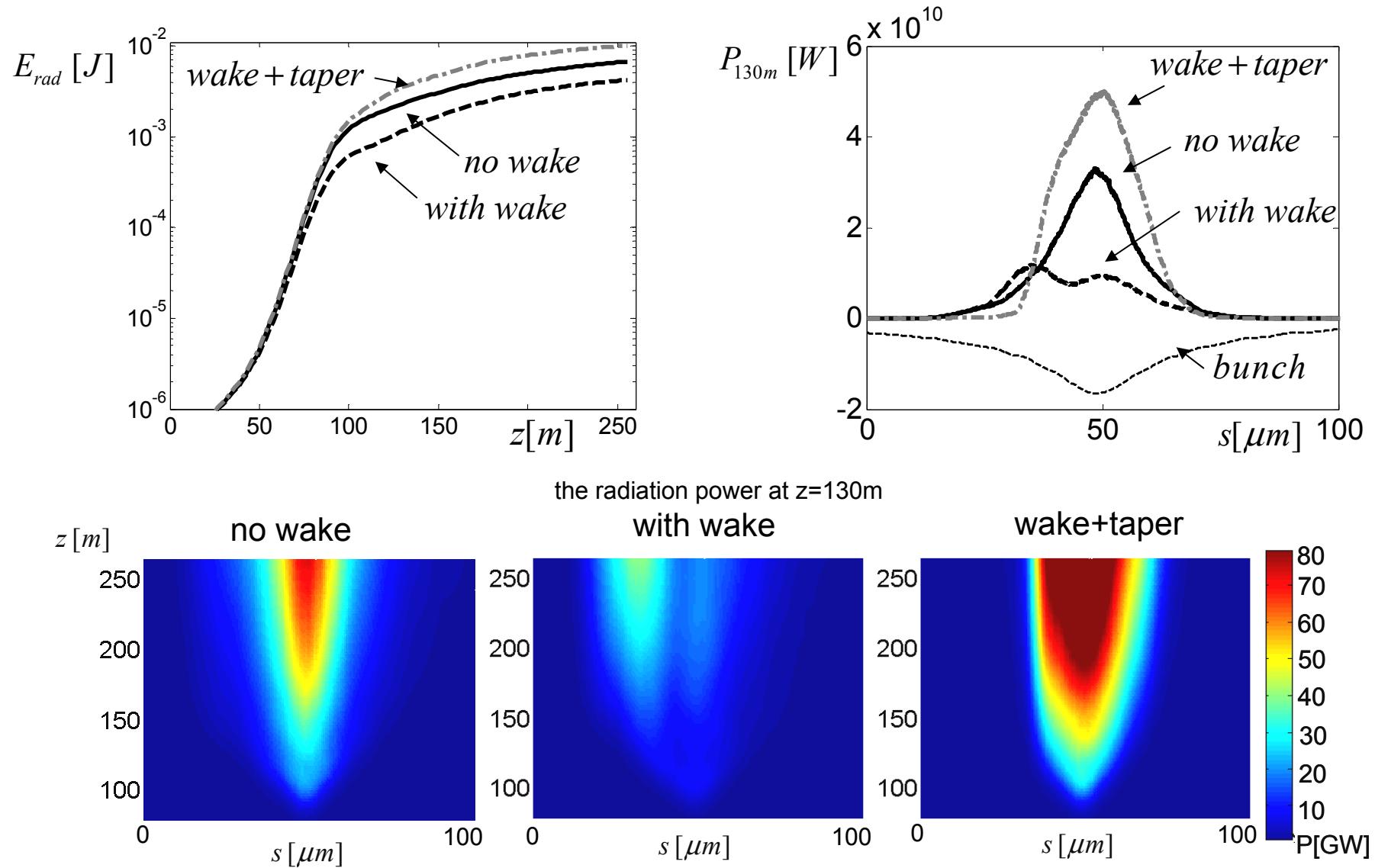
method 2 - reference

| ASTRA | CSRtrack sub-bunch | ELEGANT | rf-field cavity wake & s.c. field | GENESIS |

130 MeV   500 MeV   2 GeV

gun → acc0 + … → dogleg → heater & linac 1 → bc1 → linac 2 → bc2 →

| cathode cavity solenoid | module quad | dipoles quads | modules (1st & 3rd) quads | dipoles | modules quads | dipoles |

17.5 GeV

→ main linac → colli-mator → … → SASE1 → …

| modules quads | dipoles quads | | undulator (with quads) | |

more investigations
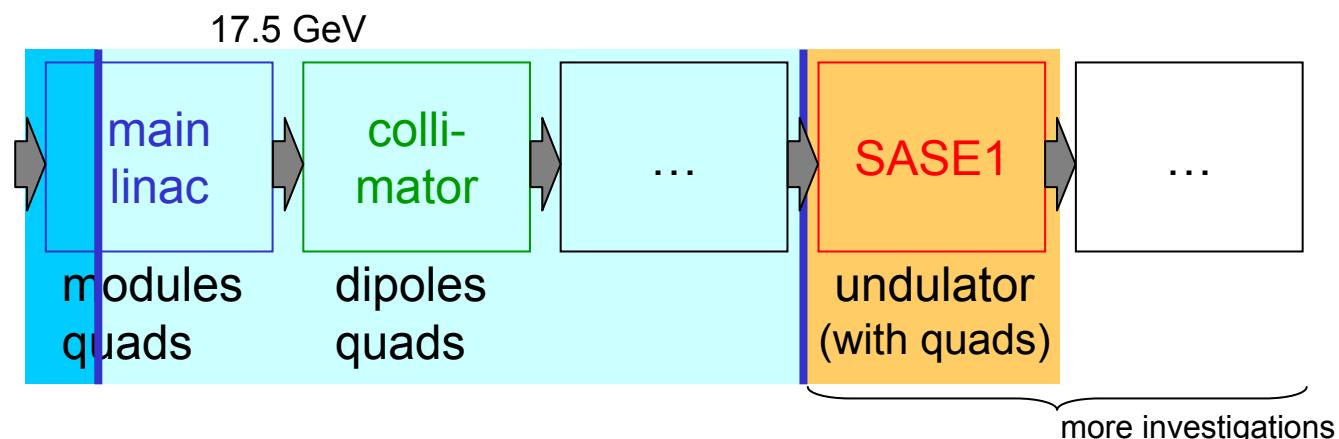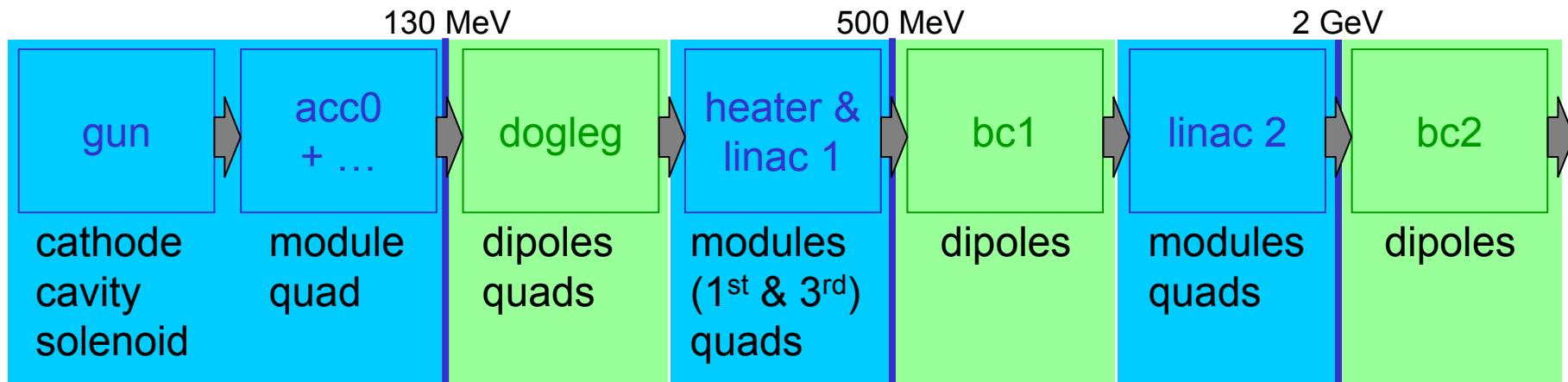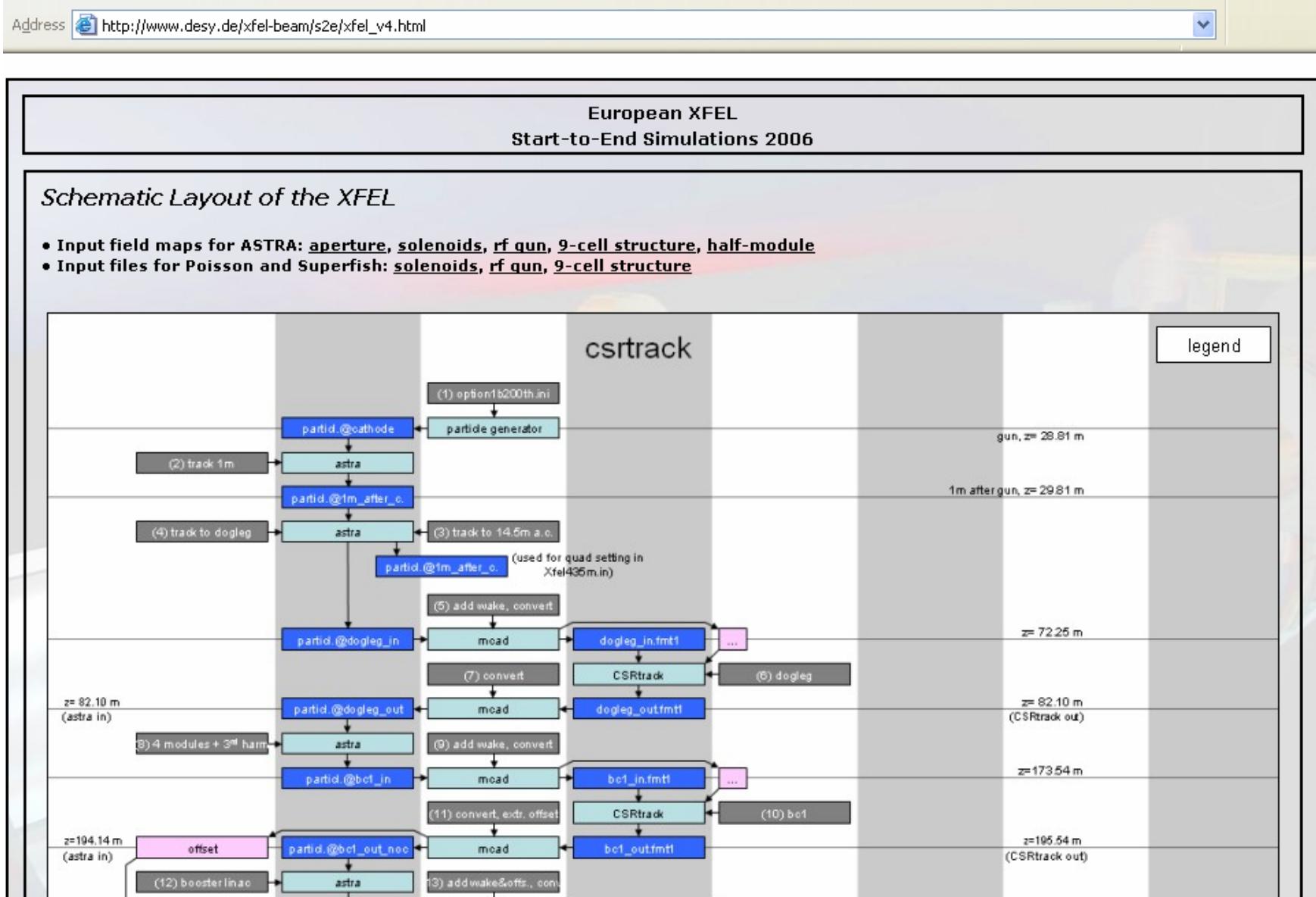
method 2

method 1   method 2

current & slice emittance
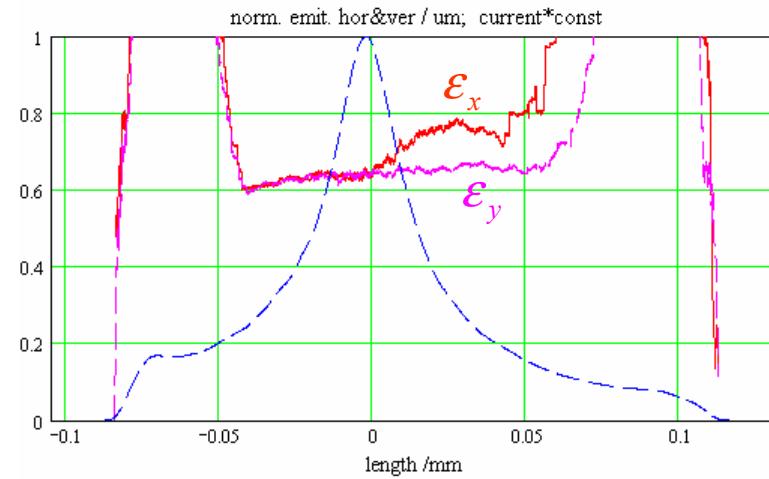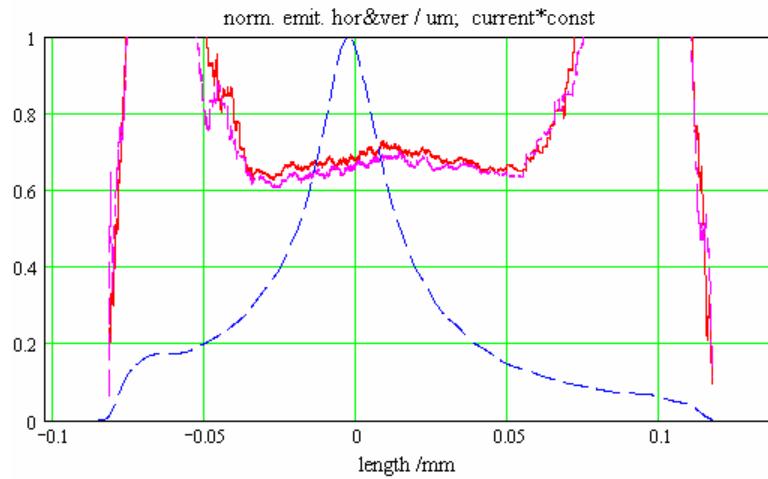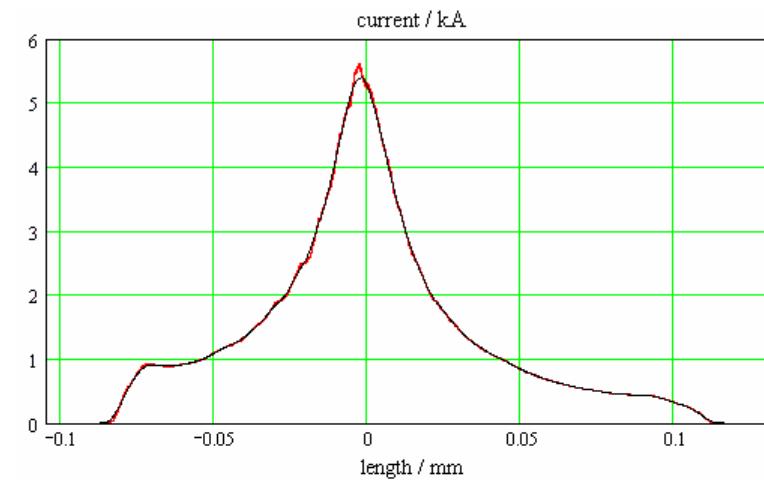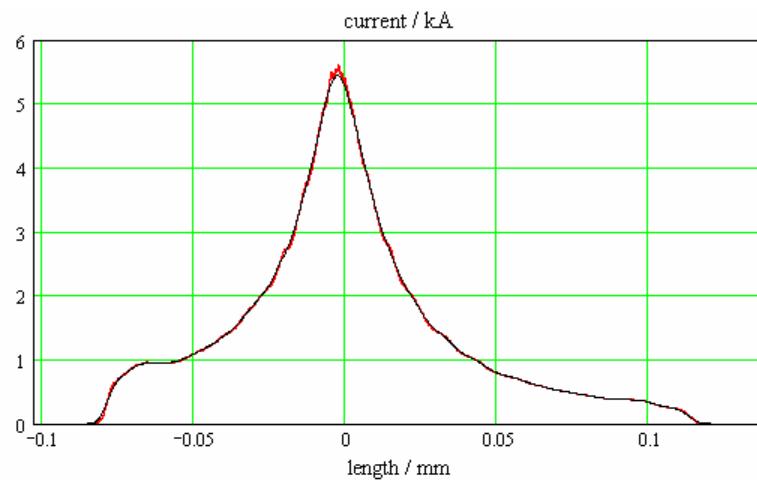
method 1

method 2

## long. phase space
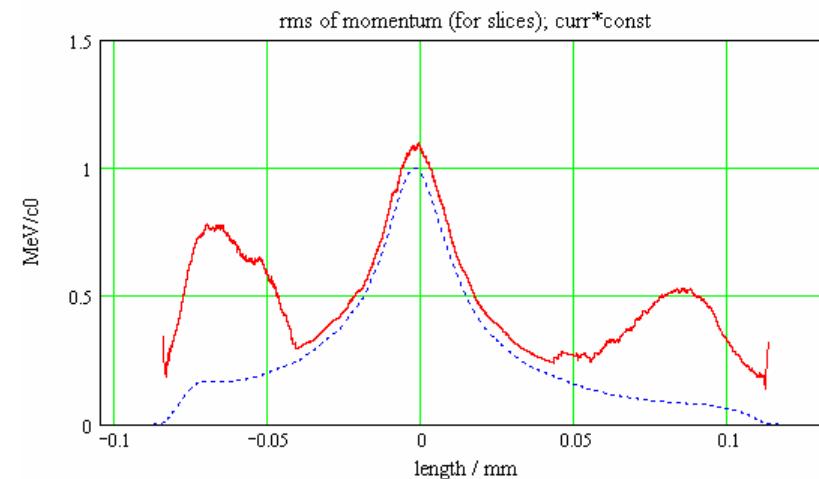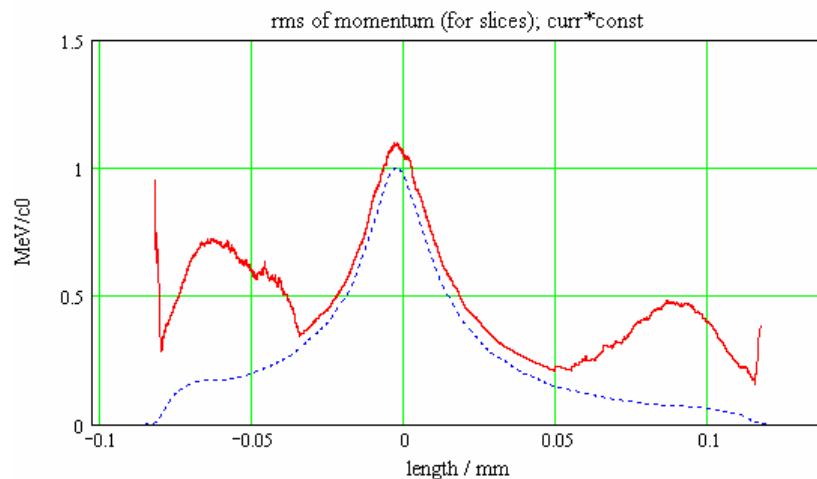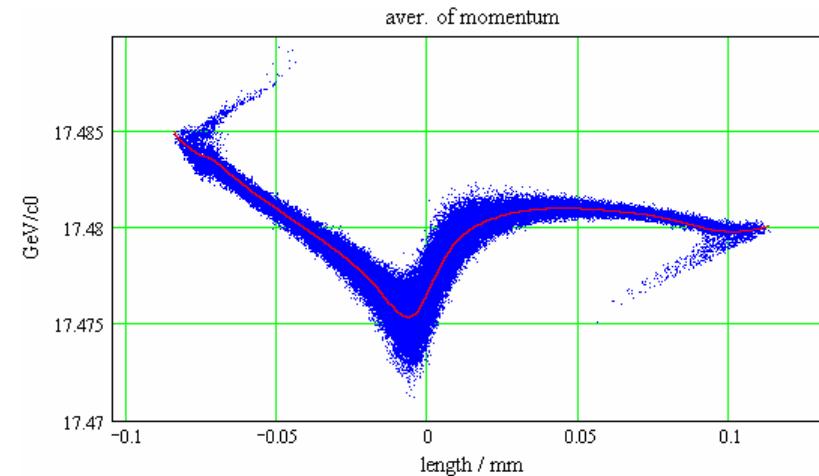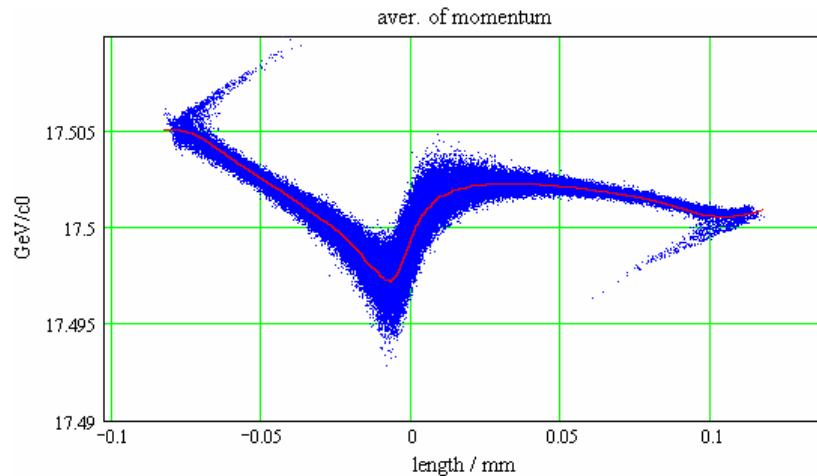
method 1

method 2

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slice miss-match parameter with respect to the slice with the peak current

(self-miss-match)

horizontal & vertical self-missmatch

horizontal & vertical self-missmatch
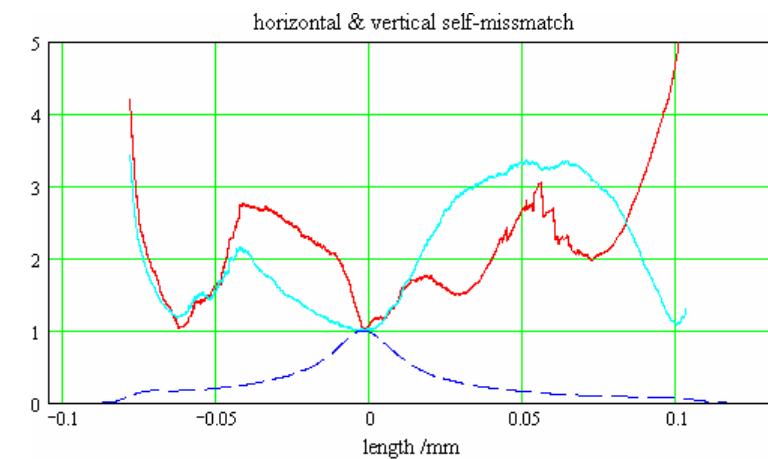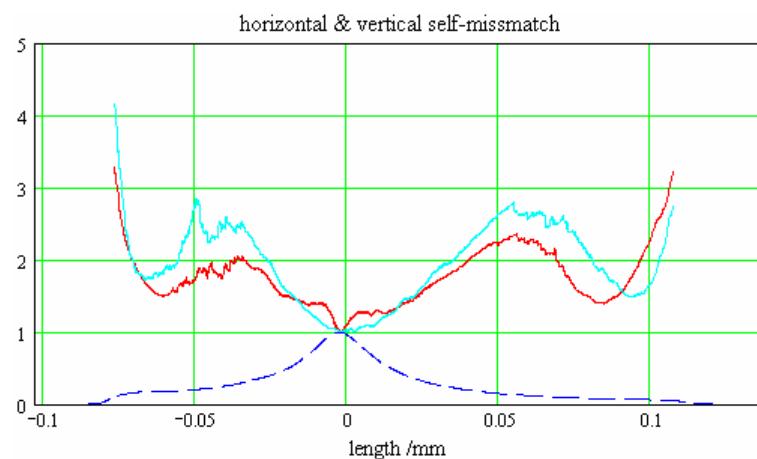
GENESIS: method 1 vs. method 2
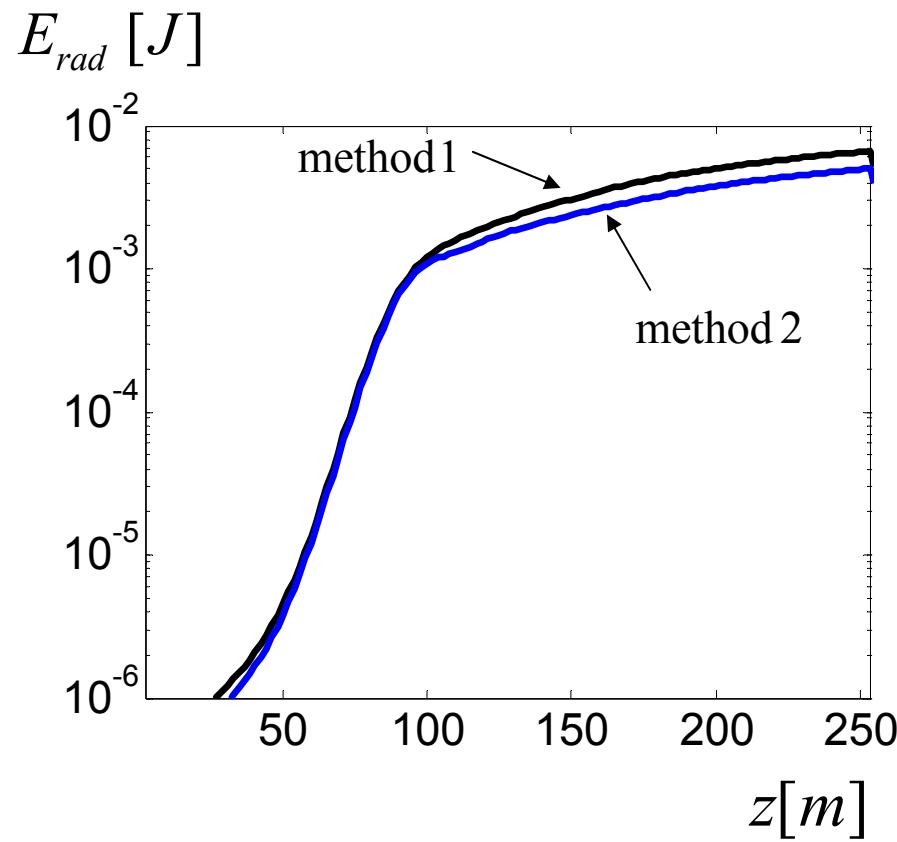
the radiation energy along the undulator
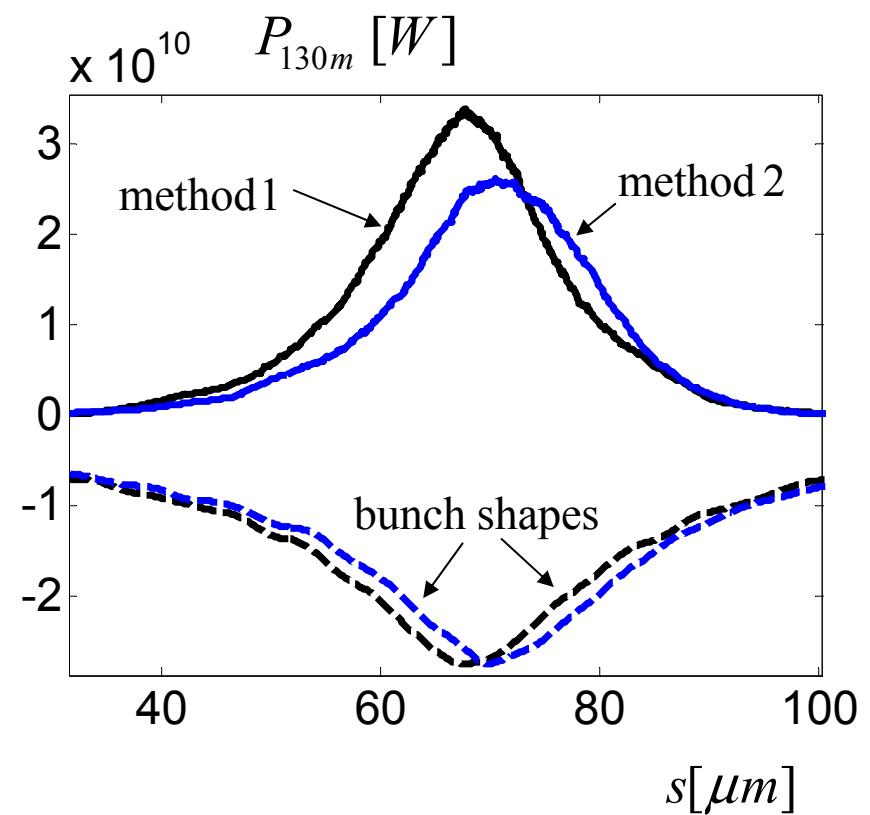
the radiation power along the bunch at z=130m

method 3 – accurate&effcient (to be done)

ASTRA (method 2) vs. ELEGANT (method 3)

linac before bc1

ASTRA
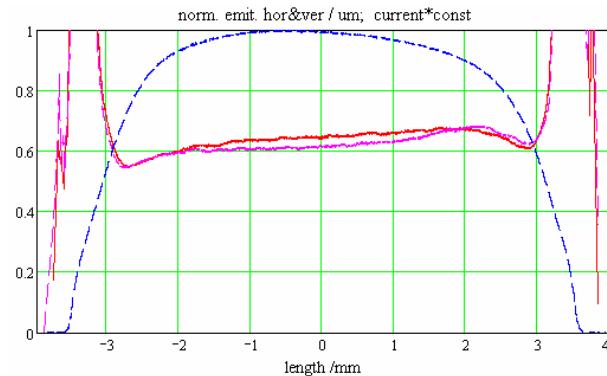
ASTRA without s.c.

ELEGANT

For the bottom-right panels:

ASTRA:
$$\beta_x = 47 \text{ m}$$
$$\alpha_x = 2.2$$
$$\beta_y = 29 \text{ m}$$
$$\alpha_y = 0.6$$

ASTRA without s.c.:
$$\beta_x = 30 \text{ m}$$
$$\alpha_x = 1.9$$
$$\beta_y = 45 \text{ m}$$
$$\alpha_y = 0.6$$

ELEGANT:
$$\beta_x = 30 \text{ m}$$
$$\alpha_x = 2.0$$
$$\beta_y = 45 \text{ m}$$
$$\alpha_y = 0.6$$