Start-To-End Simulations for the European XFEL

Martin Dohlus, Igor Zagorodnov

- 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

Address http://www.desy.de/xfel-beam/

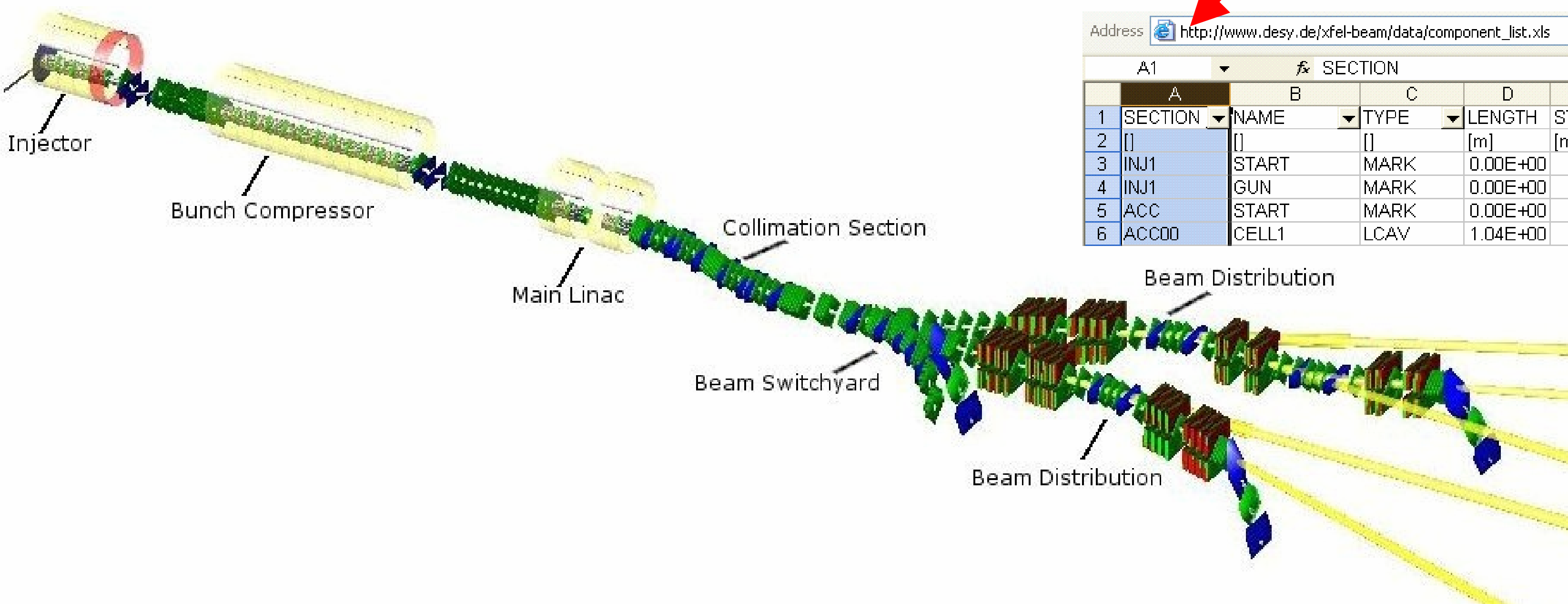
European XFEL Beam Dynamics Group Home Page

MAD file | **List Of Components**

Address http://www.desy.de/xfel-beam/data/component_list.xls

A1 fx SECTION

	A	B	C	D	E	
1	SECTION	NAME	TYPE	LENGTH	STRENGTH	E1/I
2	[]	[]	[]	[m]	[m^(1-n)/MV]	[rad
3	INJ1	START	MARK	0.00E+00	0.00E+00	0.0
4	INJ1	GUN	MARK	0.00E+00	0.00E+00	0.0
5	ACC	START	MARK	0.00E+00	0.00E+00	0.0
6	ACC00	CELL1	LCAV	1.04E+00	1.05E+01	0.0



click in the picture to go to the descriptions of the single parts

Papers, Talks, Meetings | **Start-to-End Simulations** | **XFEL Project Website** | **Links and Codes**

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

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)

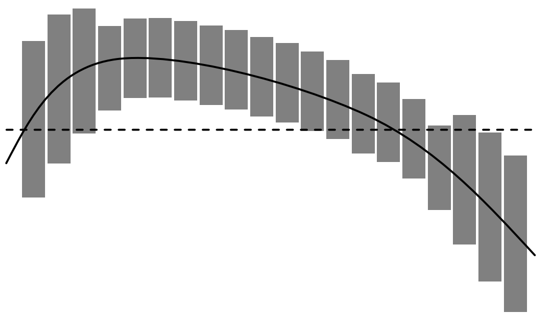
drift,

transport as defined by linear optics (design),

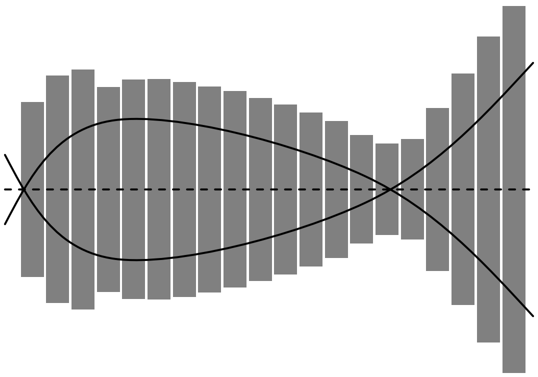
matching

ASTRA: rz space charge model

3d: slices & centroids

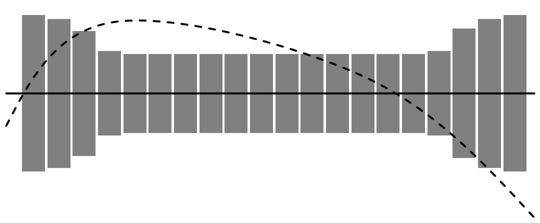


ASTRA rz-model for s.c. calculation



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)

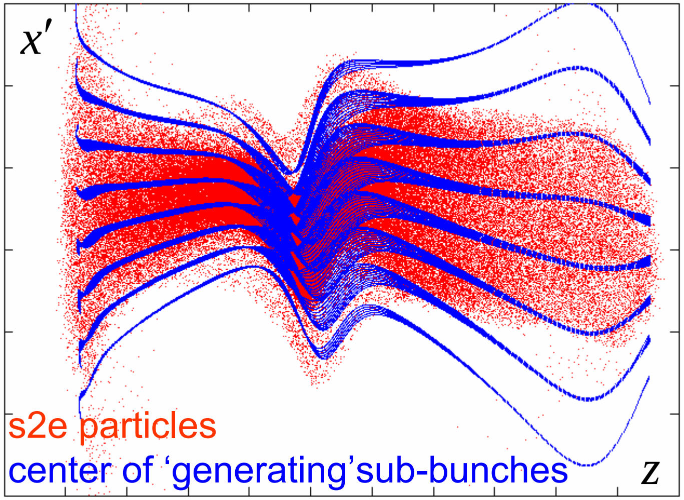
CSRtrack

projected or 1d-CSR model:

particles distribution → smooth 1d current → 1d longitud. field → 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



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

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

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

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

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

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

with:

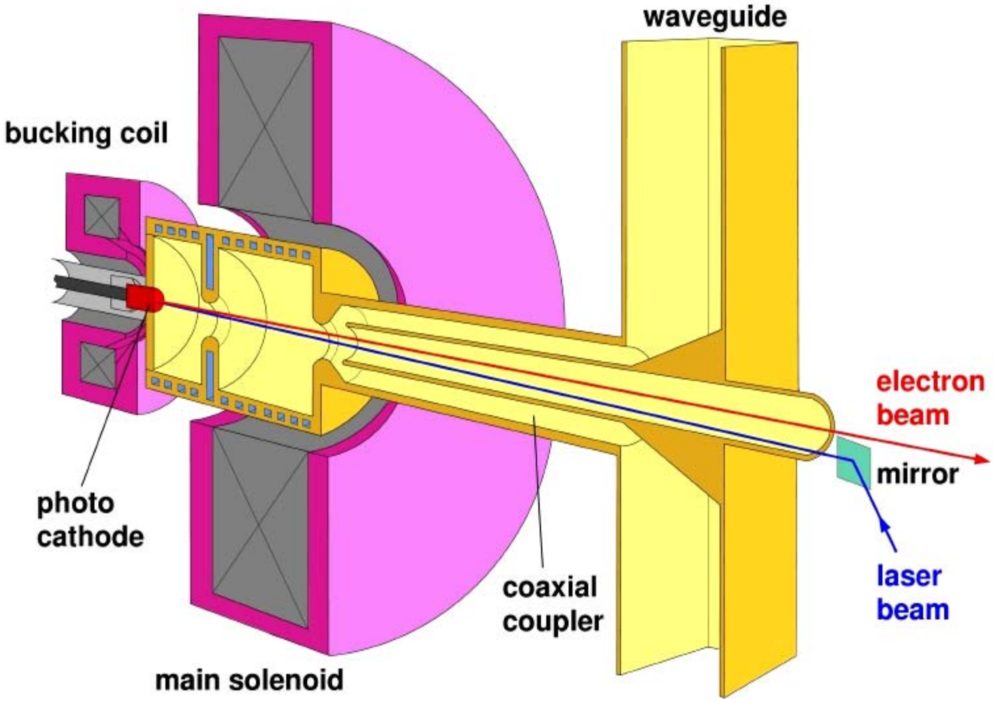
$$\sigma_r(z) = \sqrt{\frac{\varepsilon_n}{\gamma(z)}\beta_{\text{twiss}}(z)}$$

ε_n = normalized design emittance

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

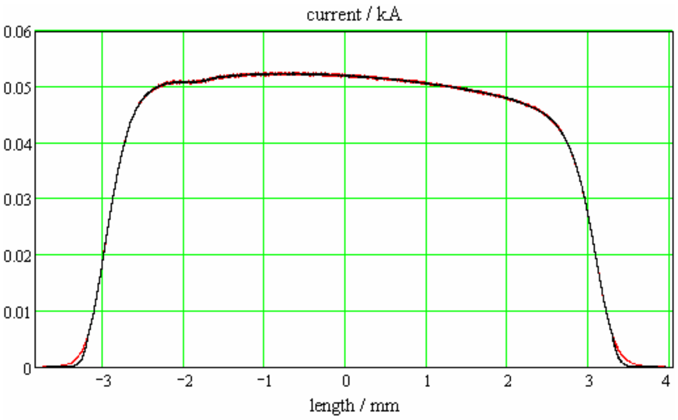
β_x, β_y = beta function

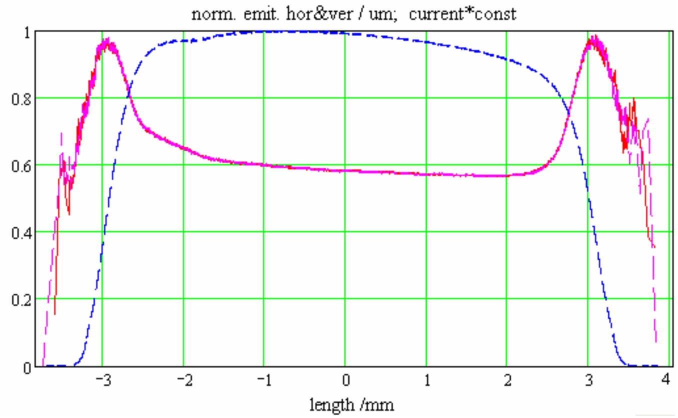
gun



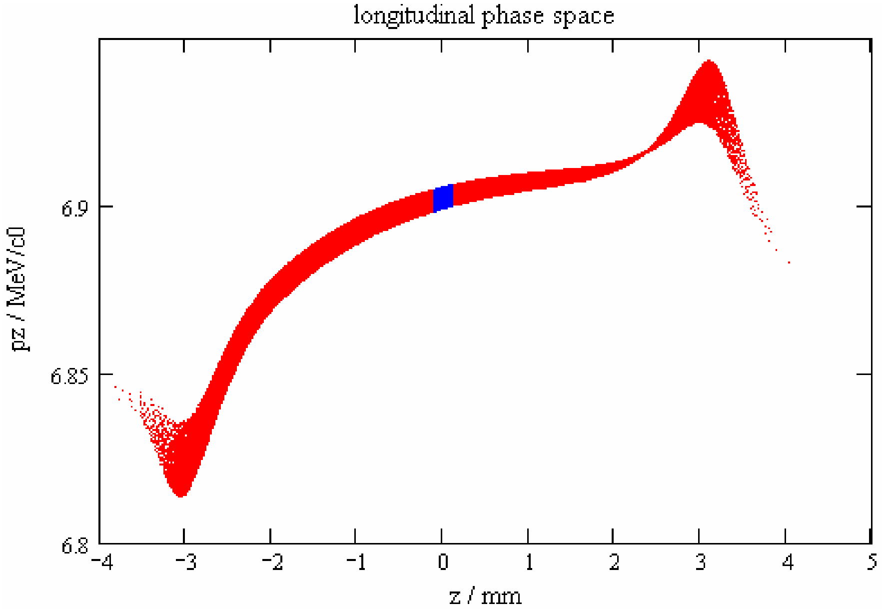
ASTRA simulation
“black box”
(ASTRA input from K.Flöttmann)

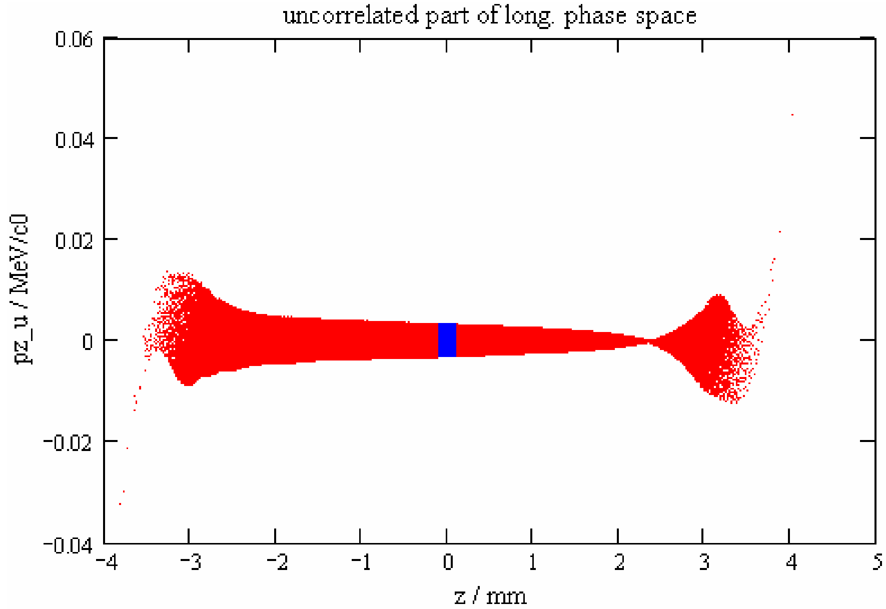
1nC, 200000 particles



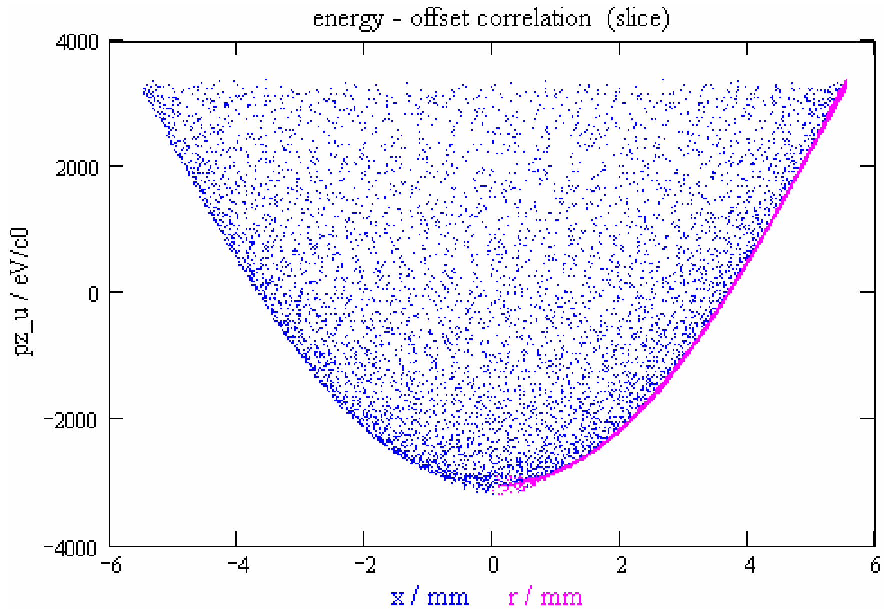


energy-offset correlation after gun

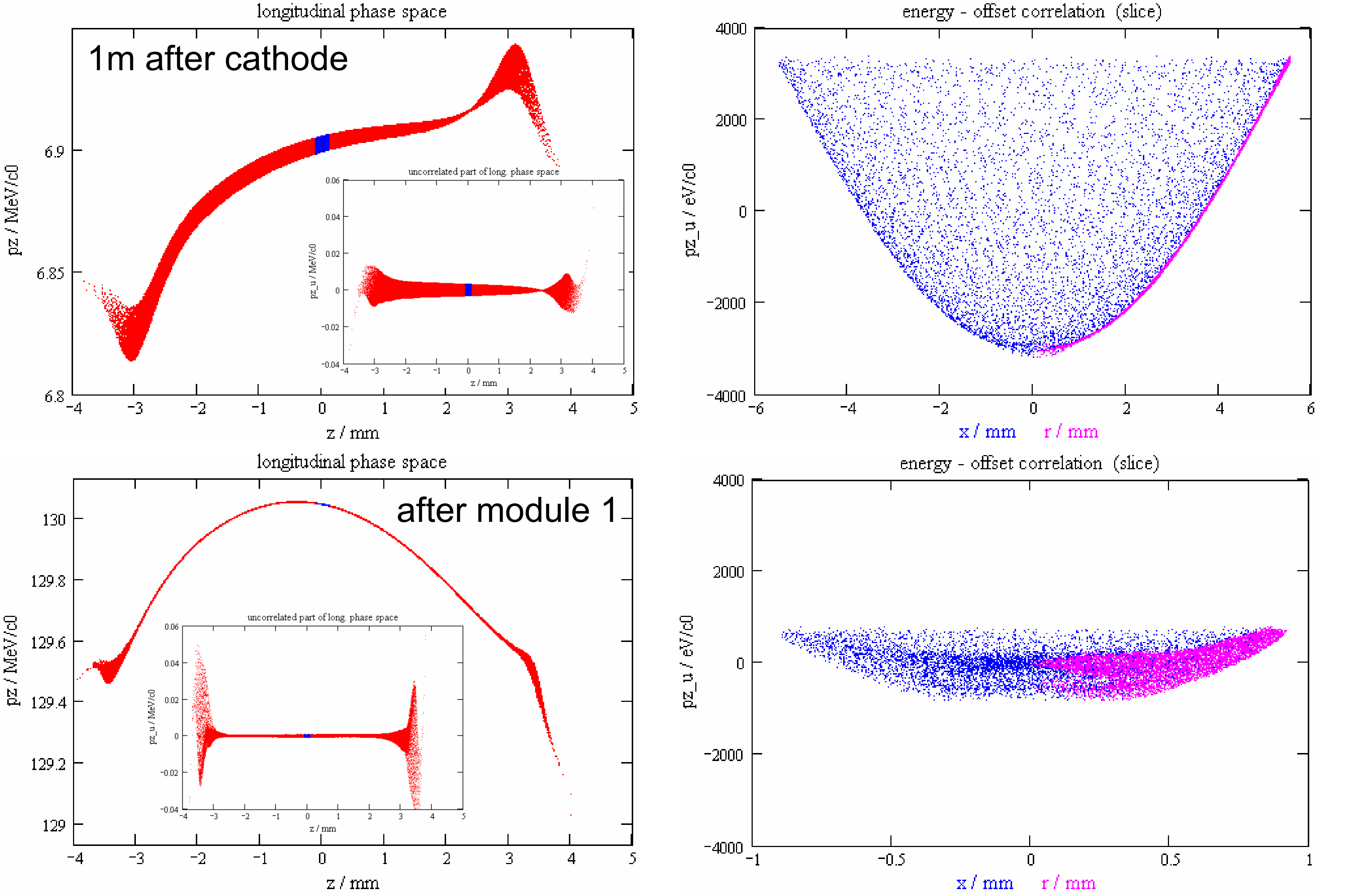




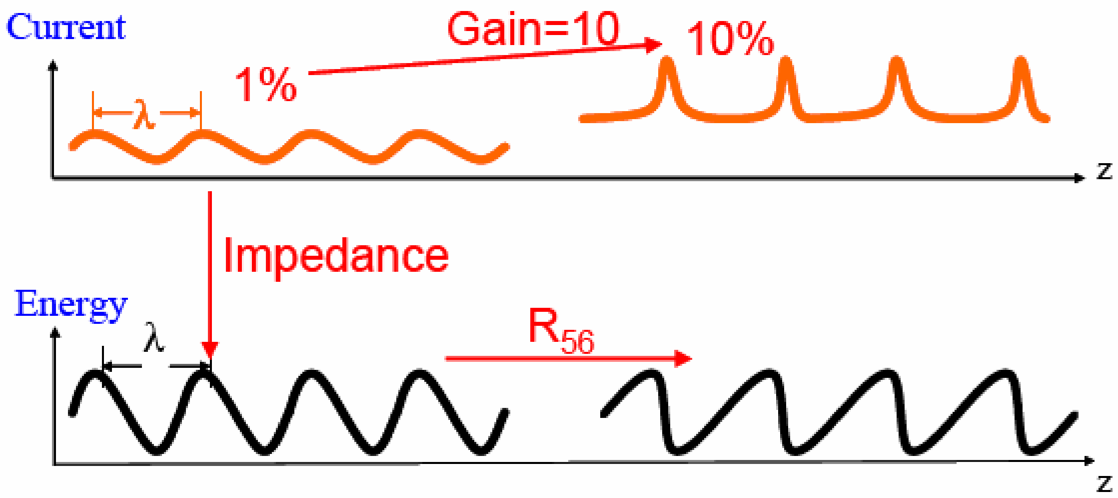
energy-offset correlation
1m after cathode



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

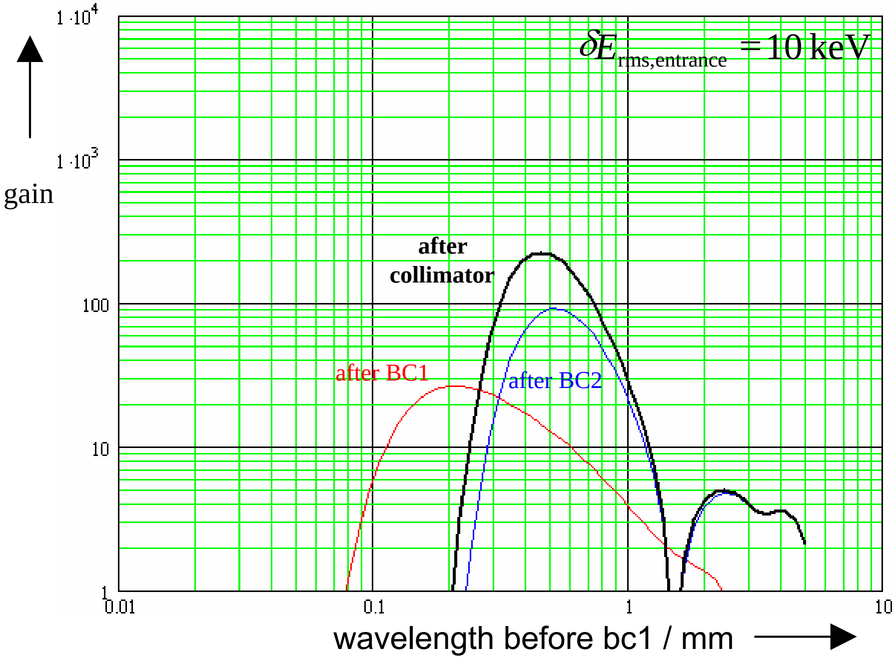
impedances (steady state):

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

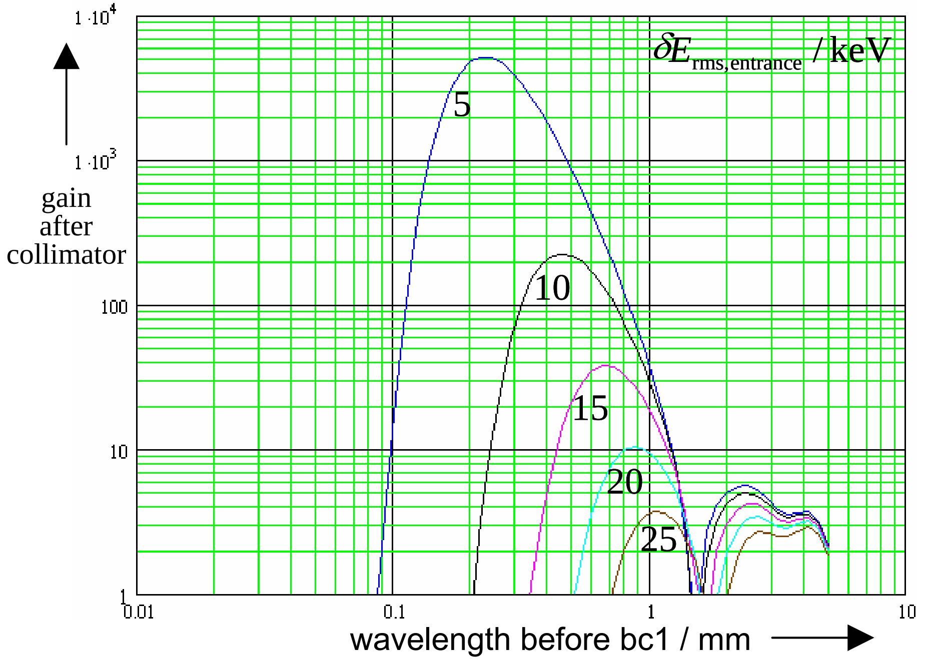
$$Z'_{CSR}\left(k,R_{curv}\right) \approx Z_0\frac{\Gamma(2/3)}{2\pi}\sqrt[3]{\frac{k}{3iR_{curv}^2}}$$ “CSR-instability”

gain curves of μ-bunch “instability”

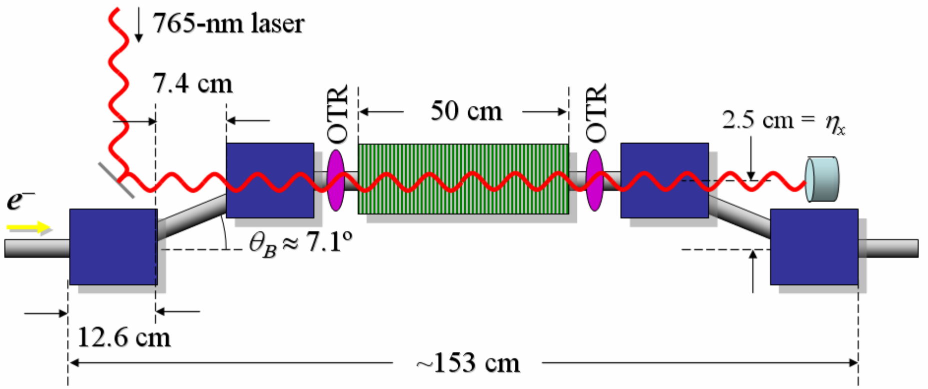
contributions of the sub-sections of the linac for an uncorrelated energy spread of 10 keV



overall gain for different uncorrelated energy spreads



‘laser heater’ System (LCLS layout)



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

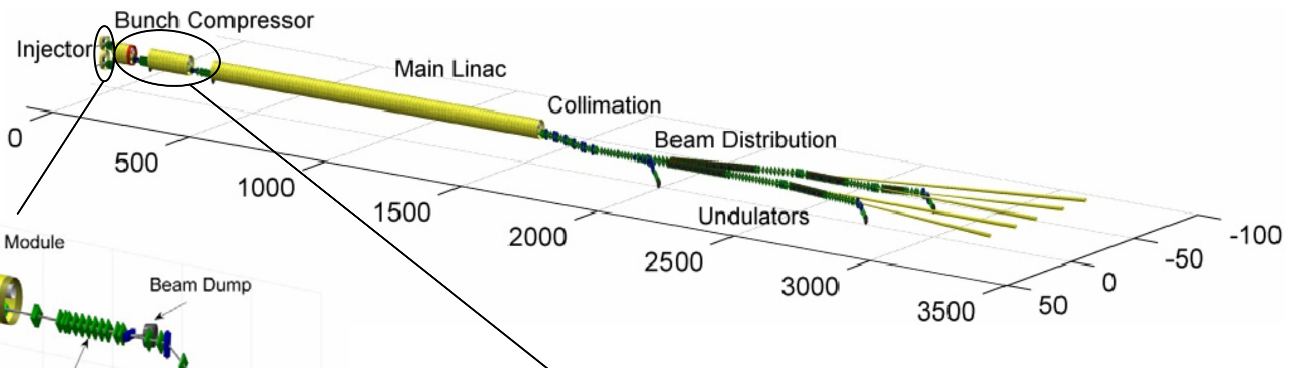
3) s2e simulations:
avoid artificial instability
N_{s2e} << number of electrons → use smoothing techniques

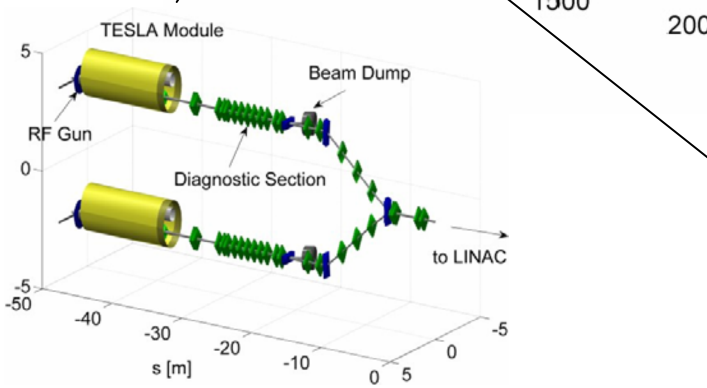
1d methods: adaptive filtering techniques

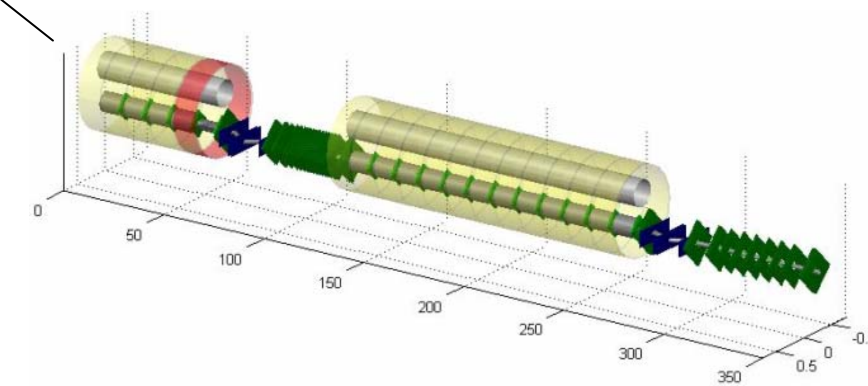
ASTRA: resolution of longitudinal mesh for calculation of space charge field

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

European XFEL, segmentation

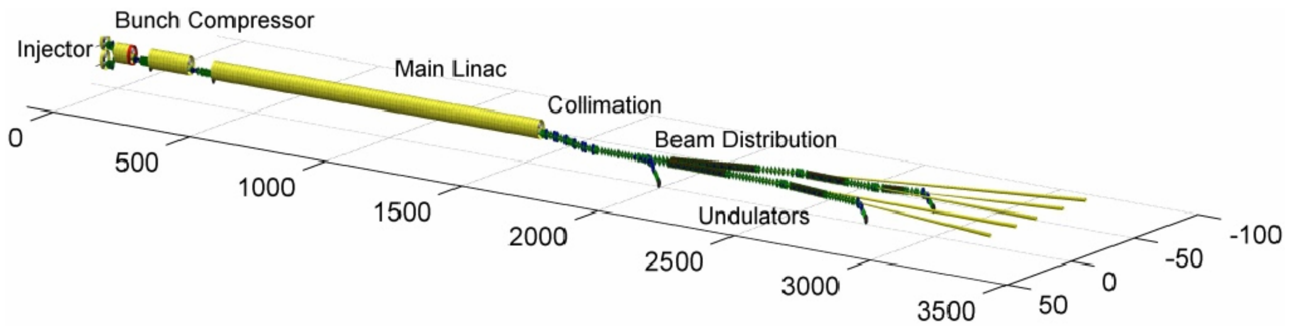






gun → 1nC ~50A ~7MeV
1 x module → 130MeV
dogleg
4 x module + 2 x module-3rd → 500MeV
bc1 → ~1kA
12 x module → 2GeV
bc2 → ~5kA
main linac → 17.5GeV
collimator
beam distribution … undulators …

European XFEL, segmentation



130 MeV · 500 MeV · 2 GeV

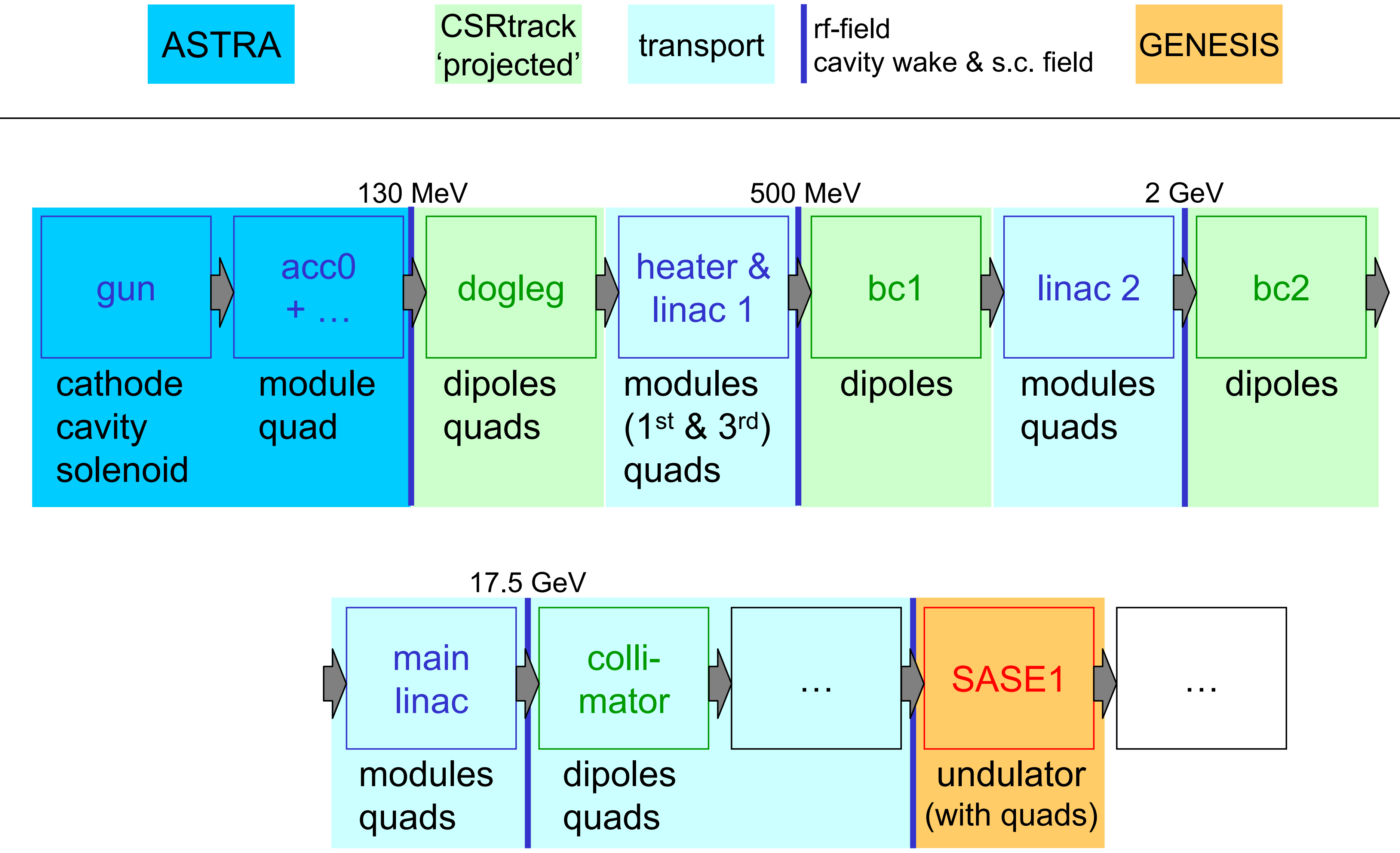
- **gun**: cathode, cavity, solenoid
- **acc0 + …**: module, quad
- **dogleg**: dipoles, quads
- **heater & linac 1**: modules (1^{st} & 3^{rd}), quads
- **bc1**: dipoles
- **linac 2**: modules, quads
- **bc2**: dipoles

17.5 GeV

- **main linac**: modules, quads
- **colli-mator**: dipoles, quads
- **…**
- **SASE1**: undulator (with quads)
- **…**

rf, dispersion

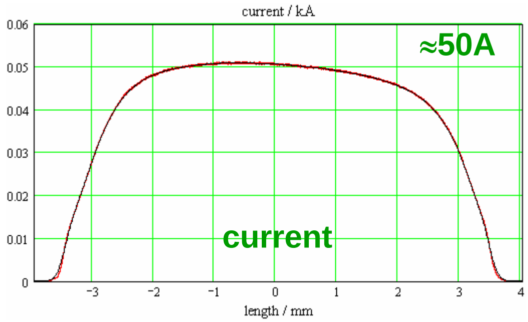
method 1 - fast

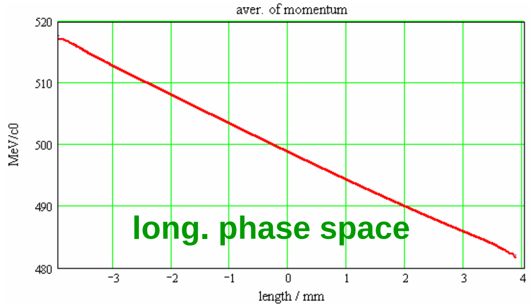


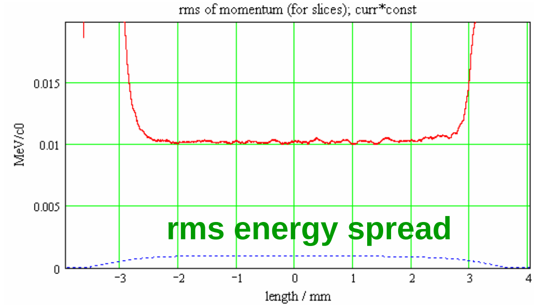
method 1

before BC1

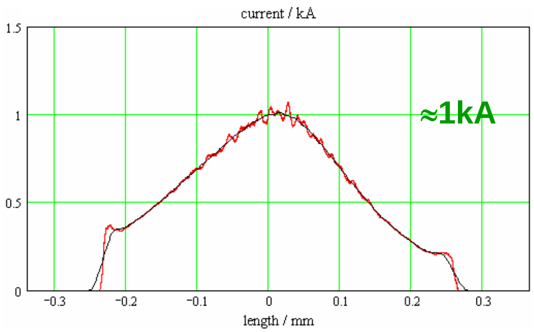
1.3GHz: 442.85 MV 1.42 deg
3.9GHz: 90.63 MV 143.35 deg

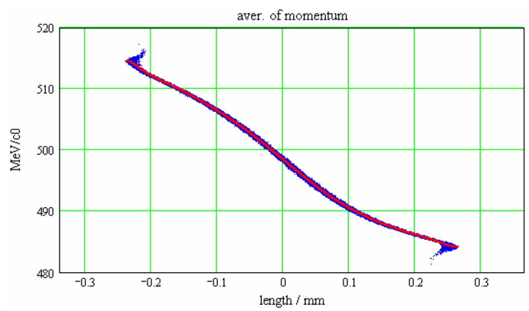


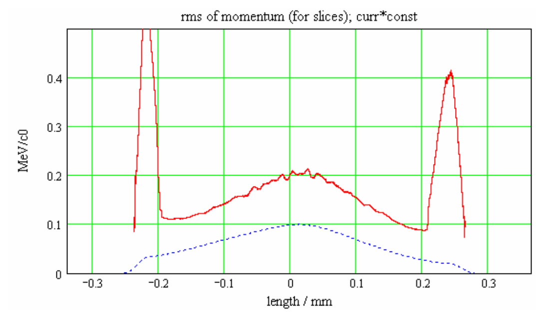




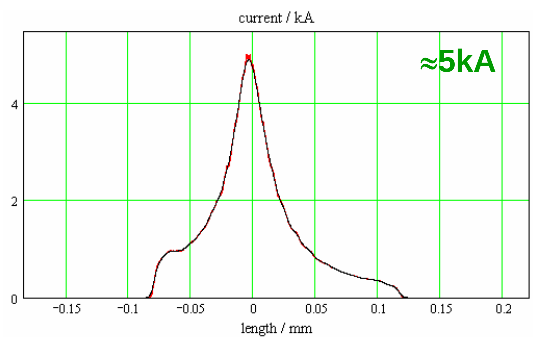
after BC1

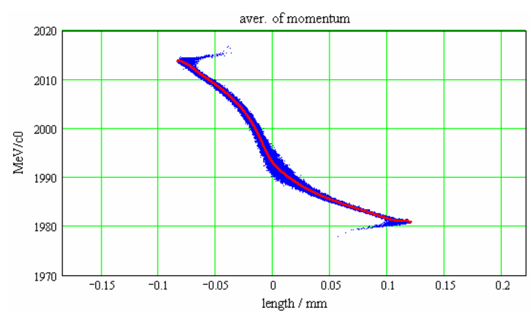


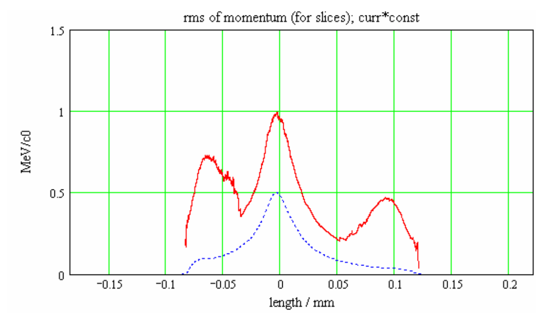




after BC2

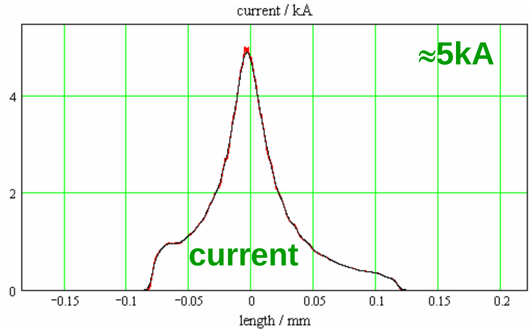


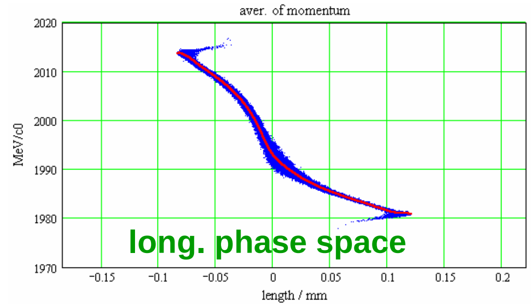


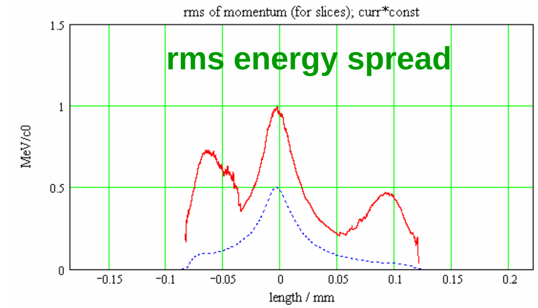


method 1

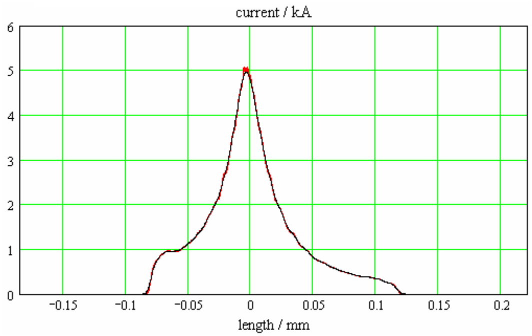
after BC2

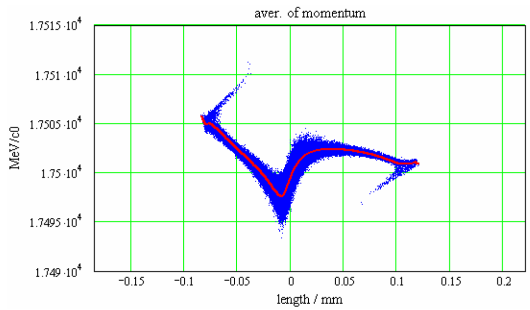


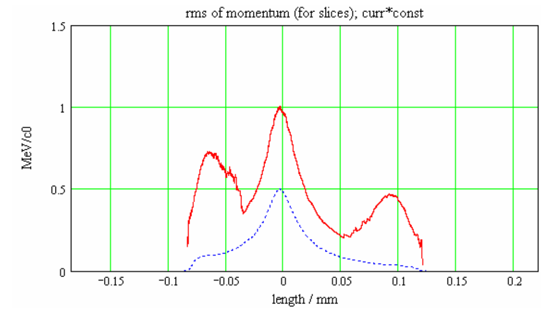


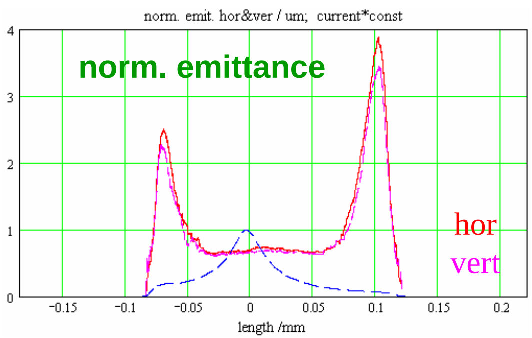


after collimator

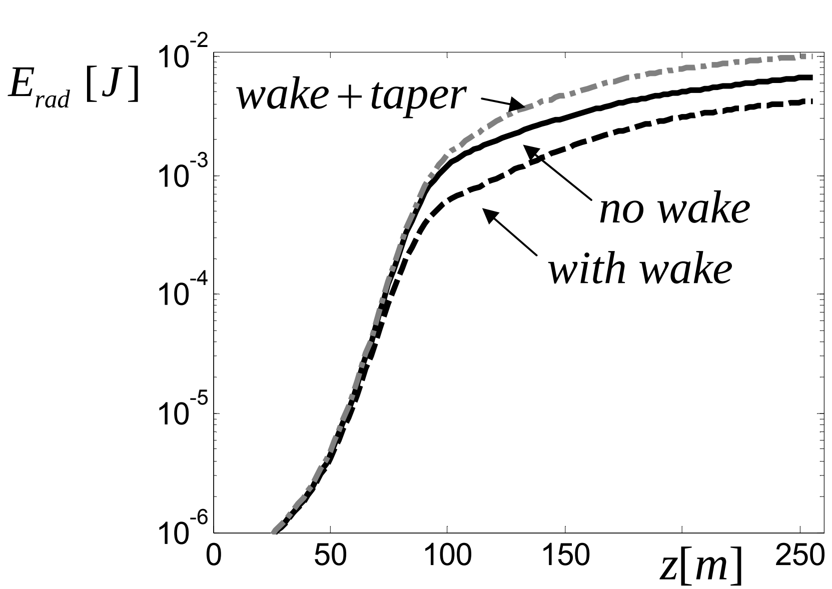


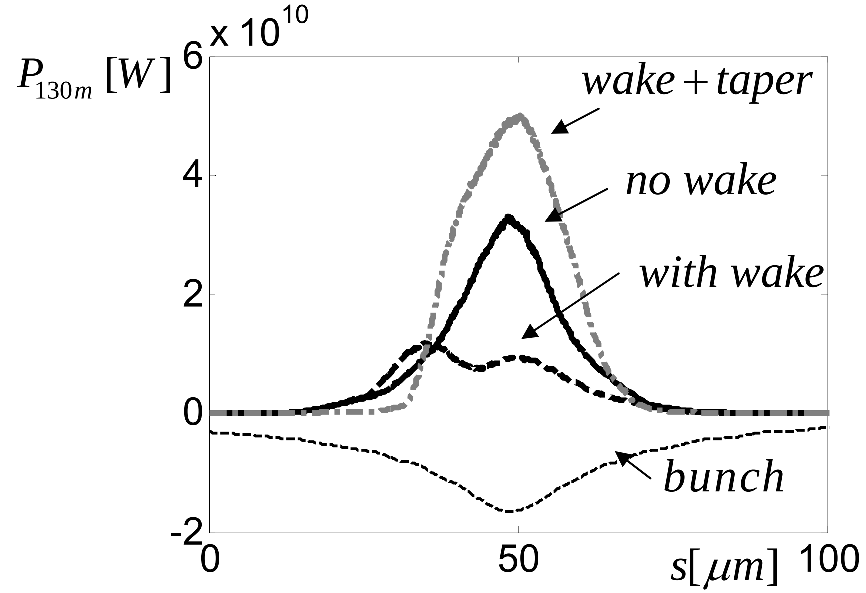




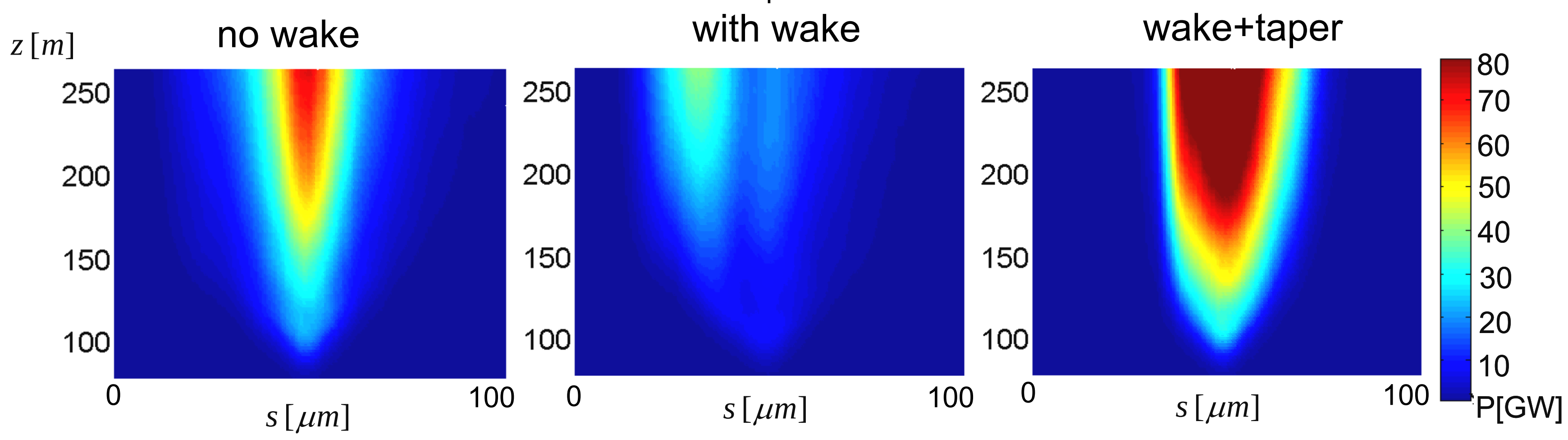


method 1 – GENESIS

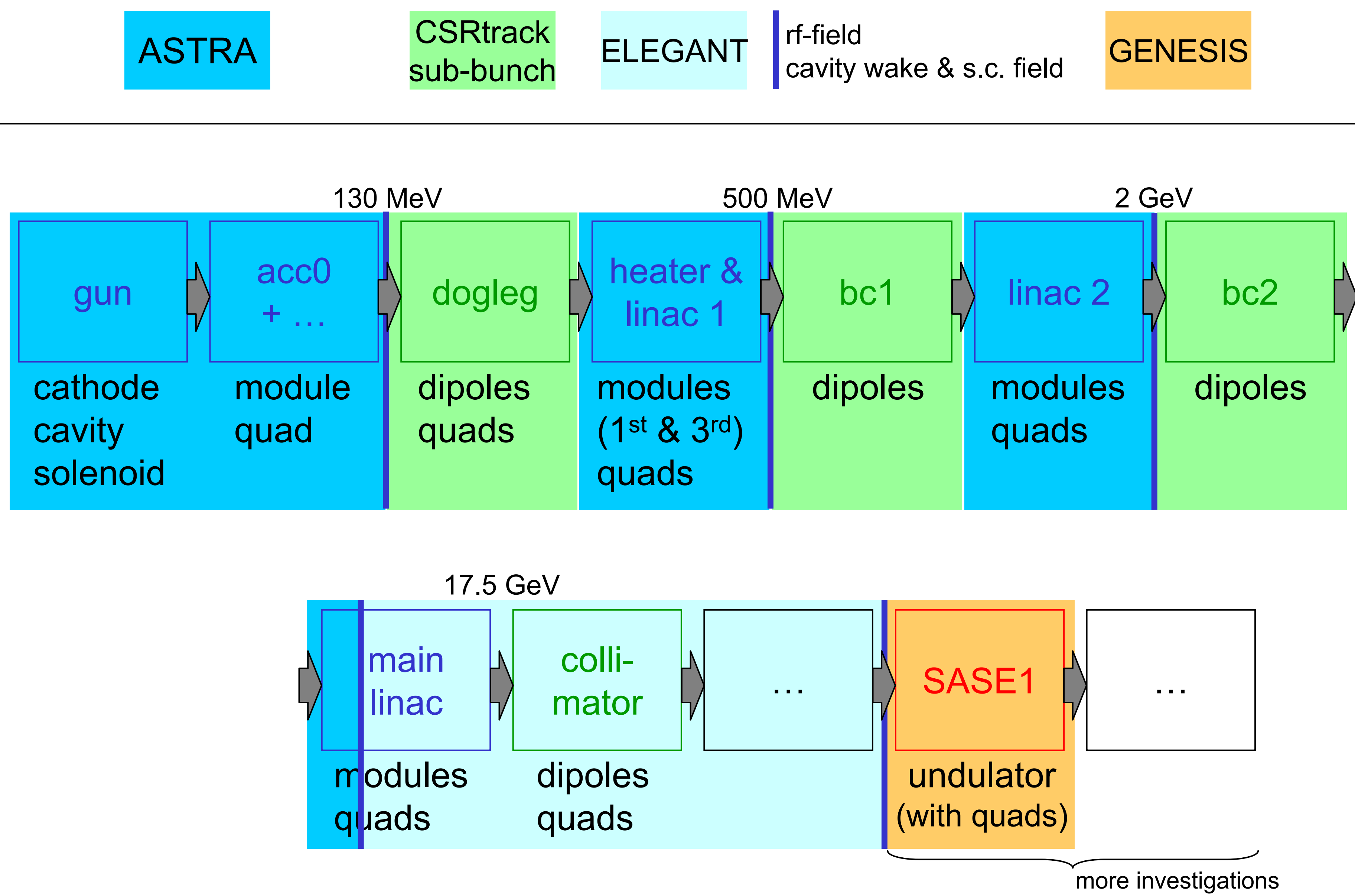




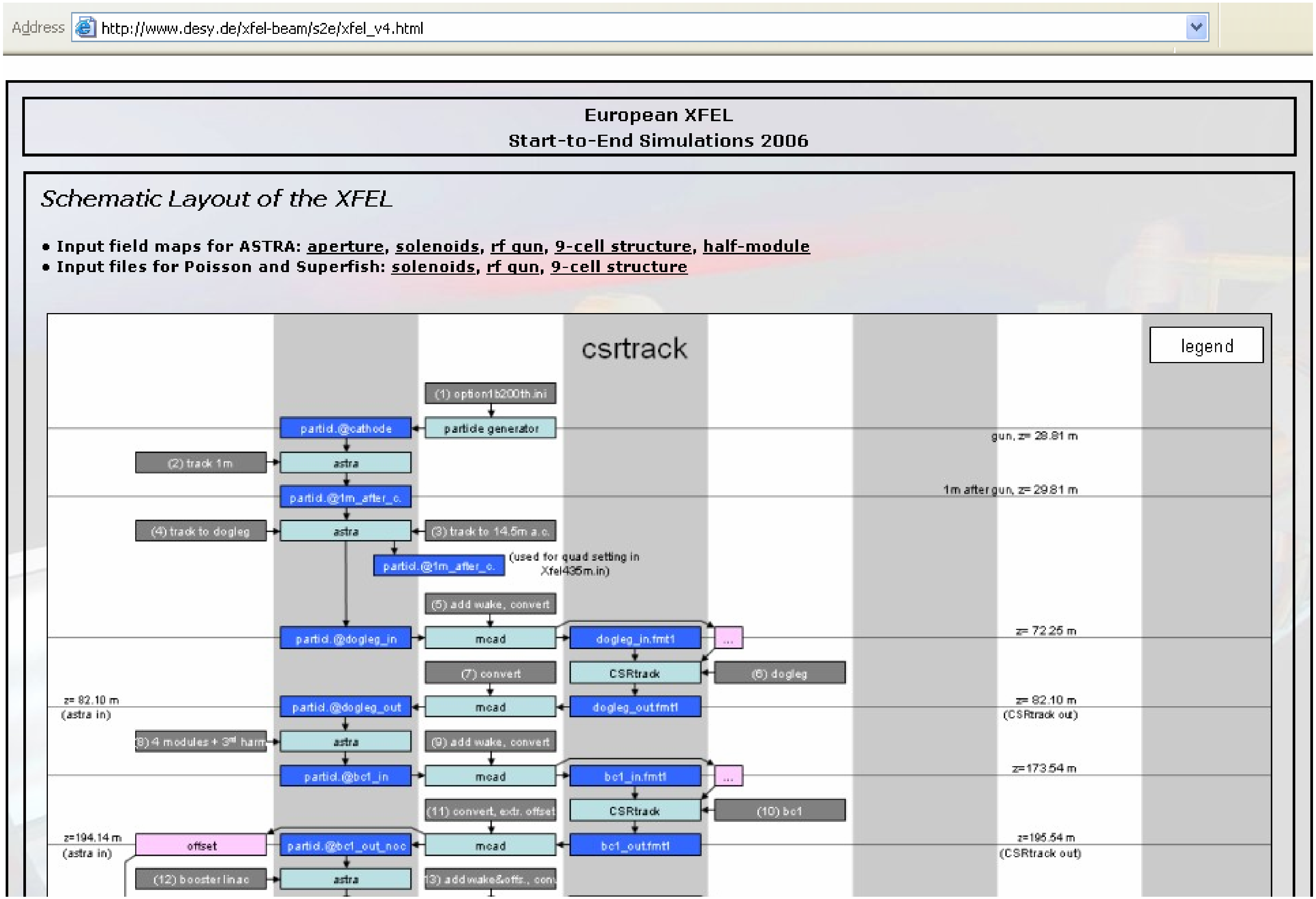
the radiation power at z=130m



method 2 - reference

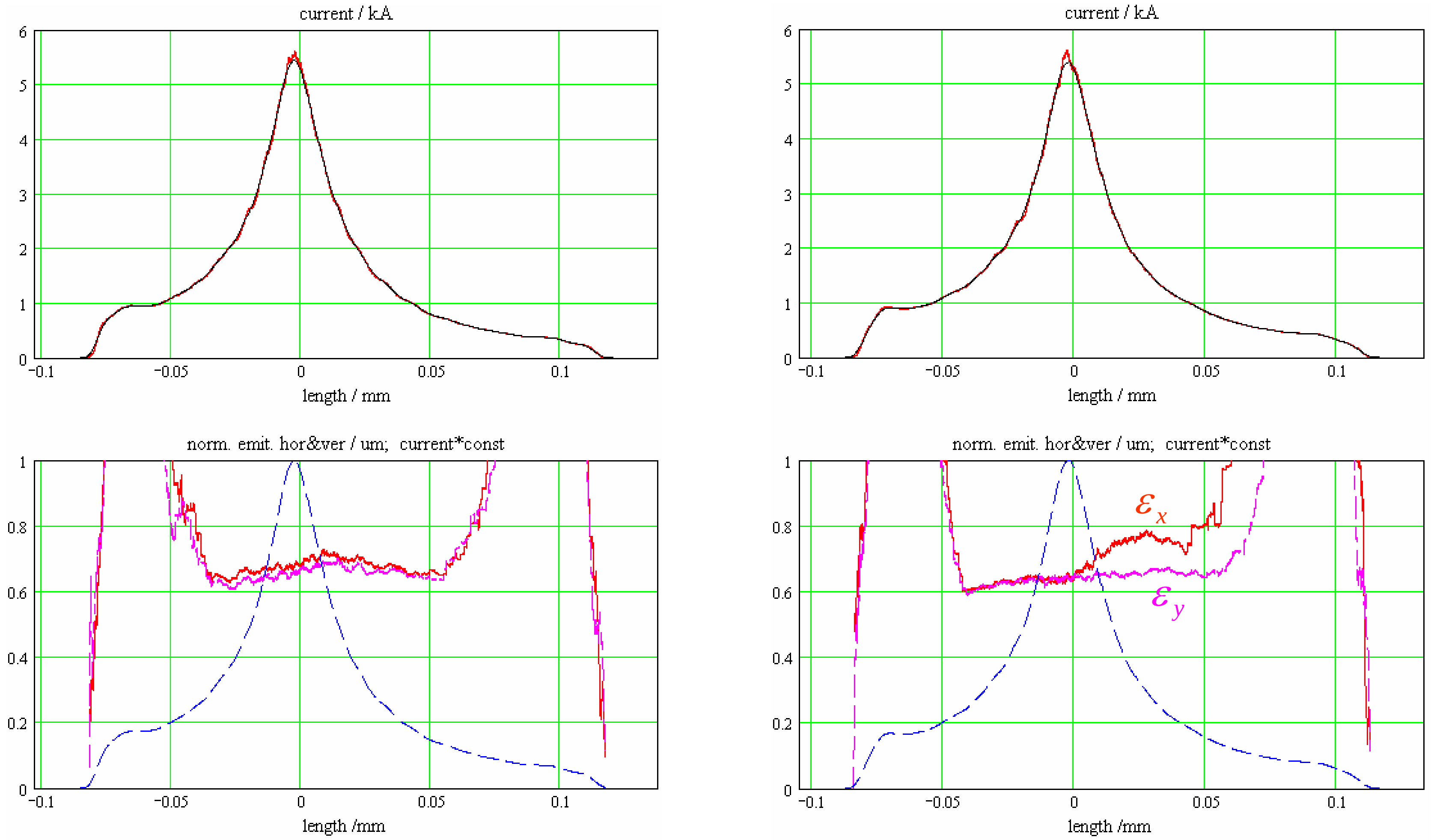


method 2


Address
http://www.desy.de/xfel-beam/s2e/xfel_v4.html
European XFEL
Start-to-End Simulations 2006
Schematic Layout of the XFEL
• Input field maps for ASTRA: aperture, solenoids, rf gun, 9-cell structure, half-module
• Input files for Poisson and Superfish: solenoids, rf gun, 9-cell structure
csrtrack
legend
(1) option1b200th.ini
particle generator
partid.@cathode
gun, z= 28.81 m
(2) track 1m
astra
partid.@1m_after_c.
1m after gun, z= 29.81 m
(4) track to dogleg
astra
(3) track to 14.5m a.c.
partid.@1m_after_c.
(used for quad setting in Xfel435m.in)
(5) add wake, convert
partid.@dogleg_in
mcad
dogleg_in.fmt1
...
z= 72.25 m
(7) convert
CSRtrack
(6) dogleg
z= 82.10 m
(astra in)
partid.@dogleg_out
mcad
dogleg_out.fmt1
z= 82.10 m
(CSRtrack out)
(9) add wake, convert
astra
partid.@bc1_in
mcad
bc1_in.fmt1
...
z=173.54 m
(11) convert, extr. offset
CSRtrack
(10) bc1
z=194.14 m
(astra in)
offset
partid.@bc1_out_noc
mcad
bc1_out.fmt1
z=195.54 m
(CSRtrack out)
(12) booster linac
astra

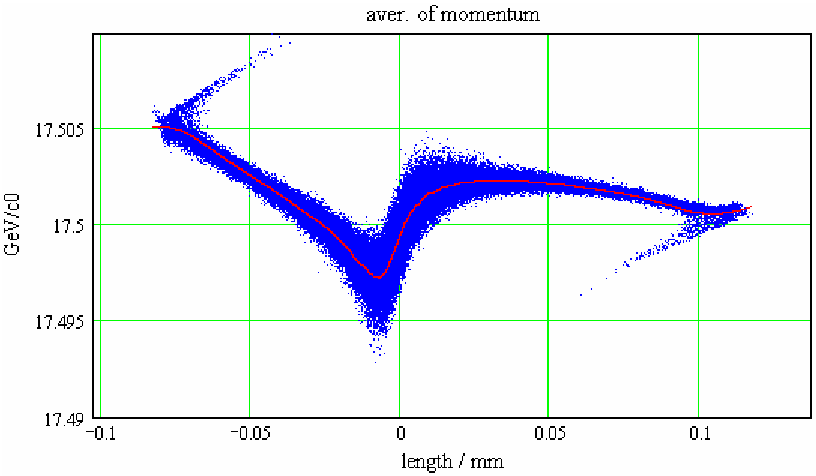
method 1 method 2

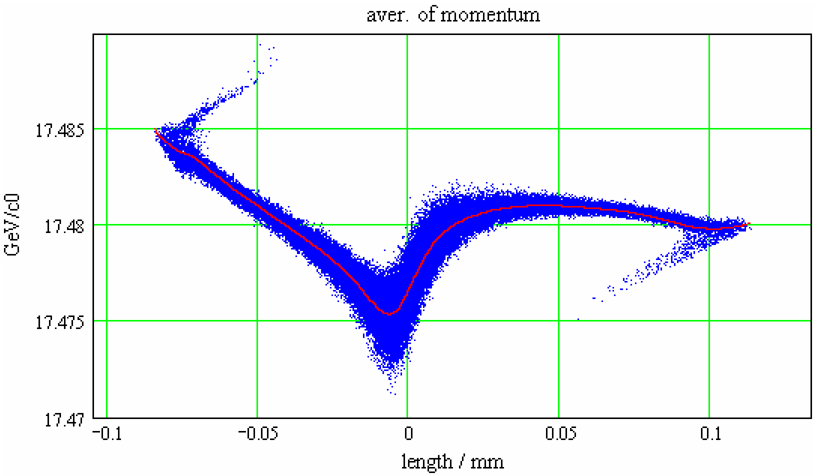
current & slice emittance

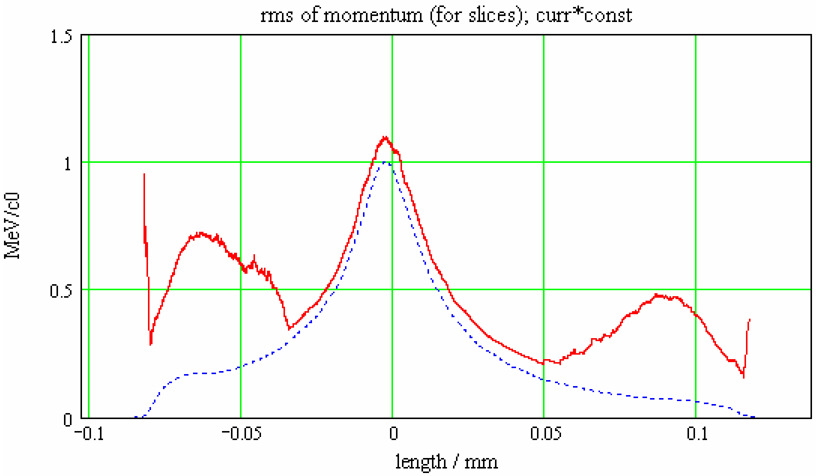


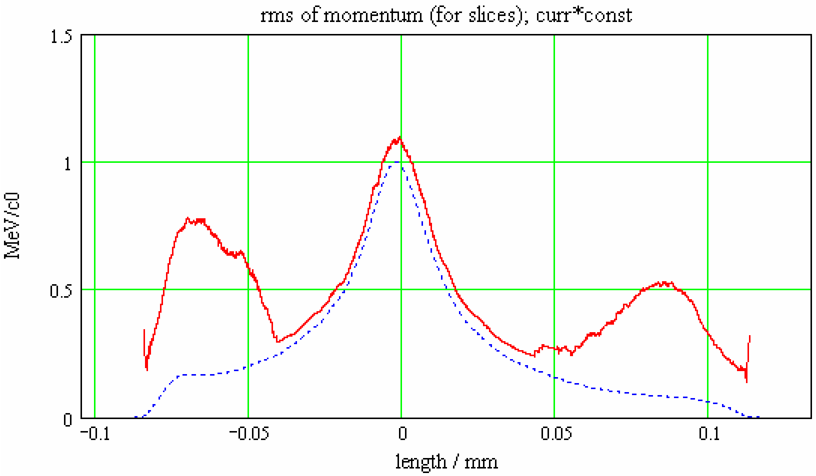
method 1 method 2

long. phase space





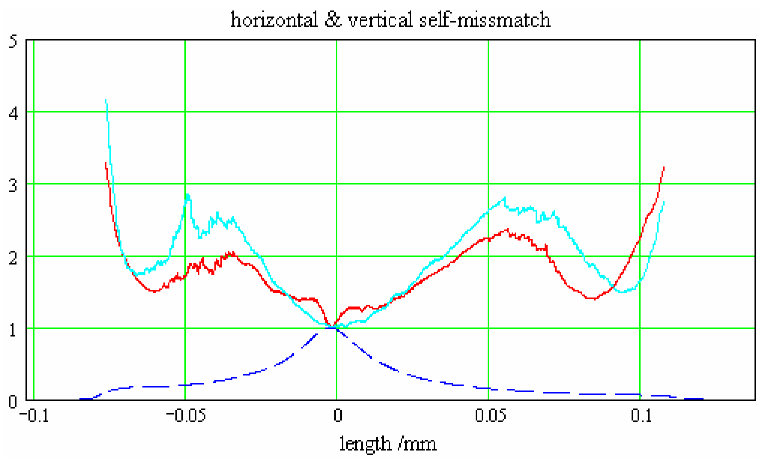


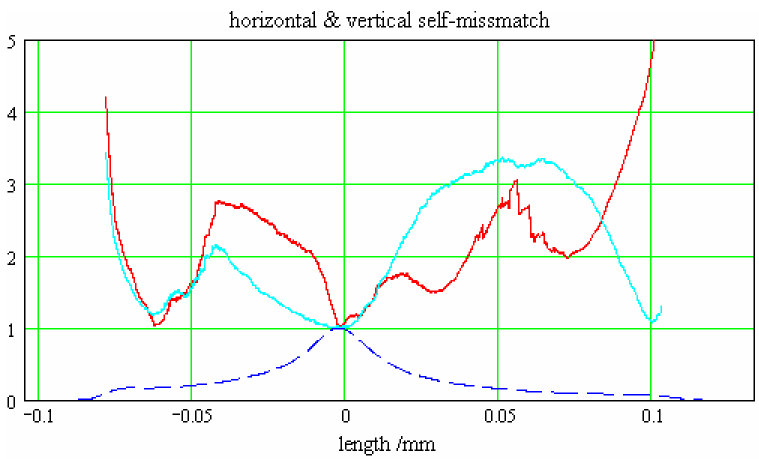


method 1 method 2

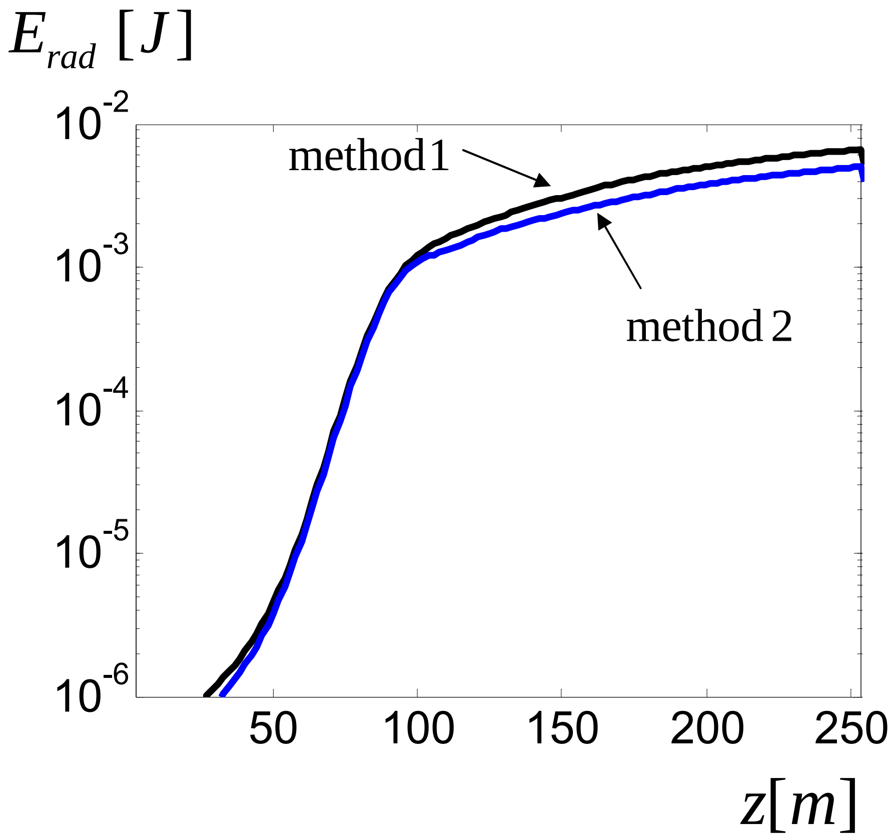
slice miss-match parameter with respect to the slice with the peak current

(self-miss-match)

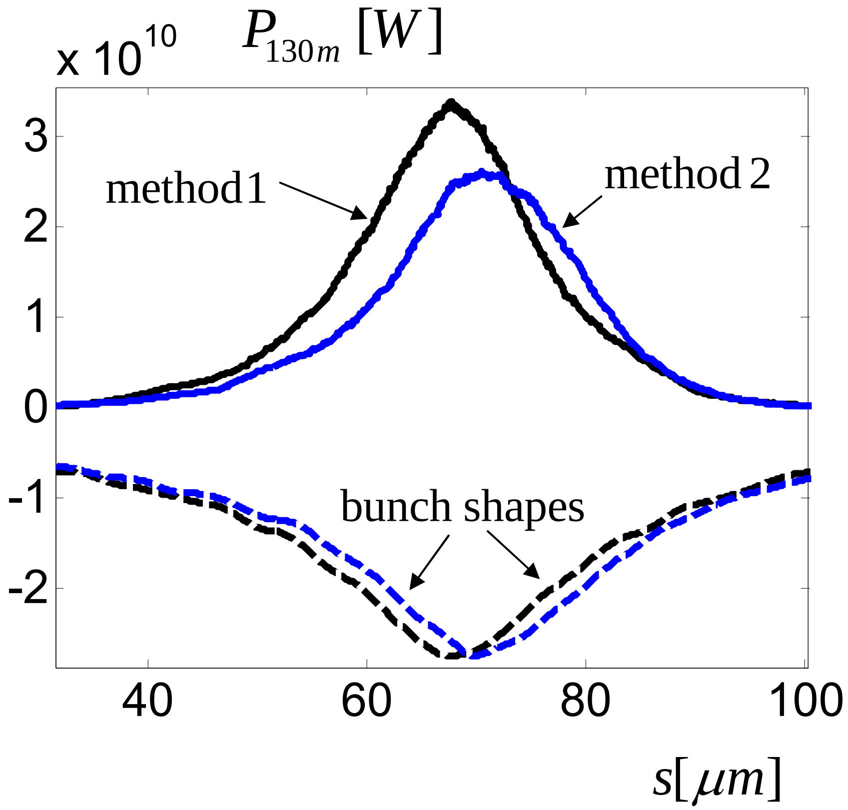




GENESIS: method 1 vs. method 2

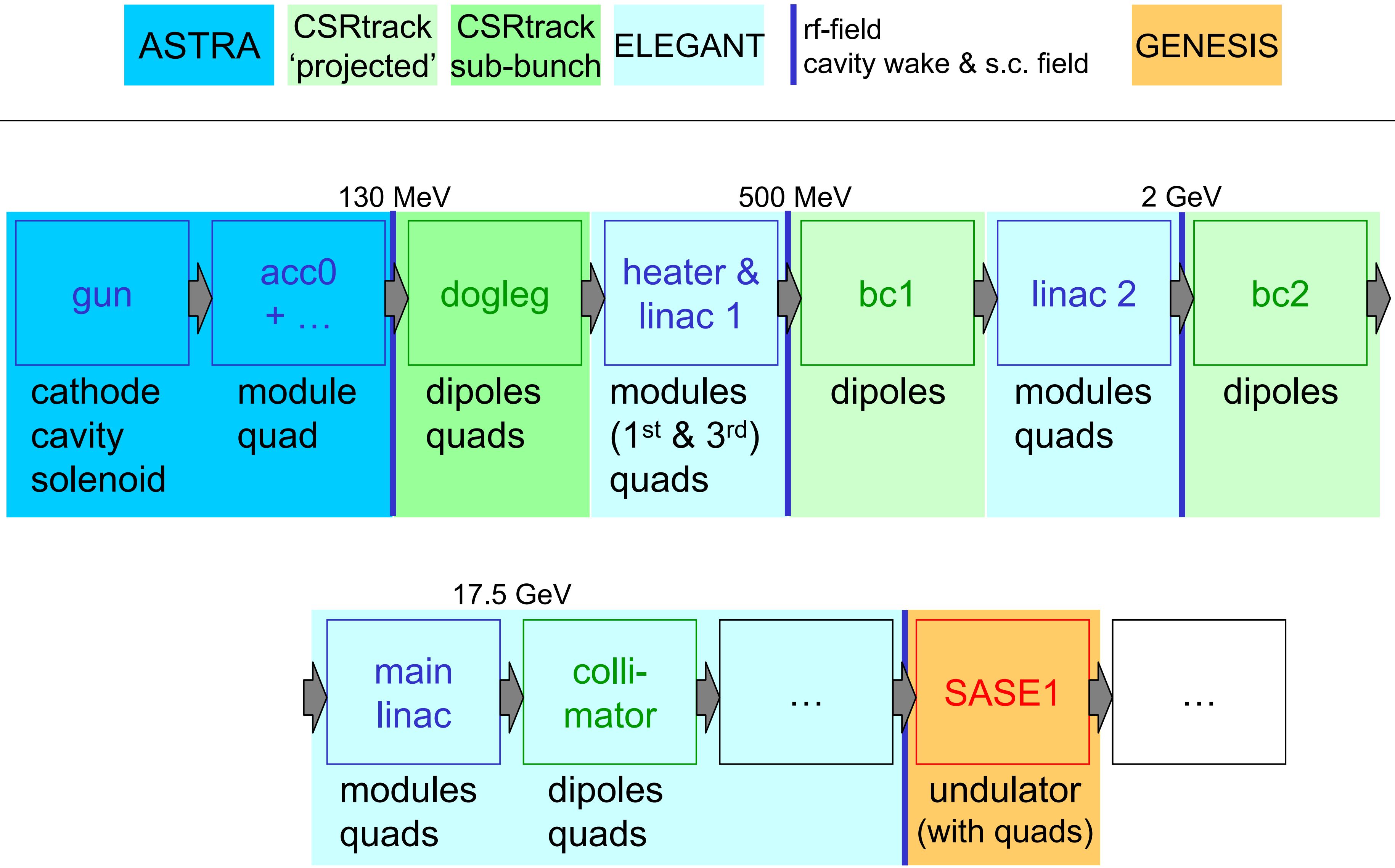


the radiation energy along the undulator



the radiation power along the bunch at z=130m

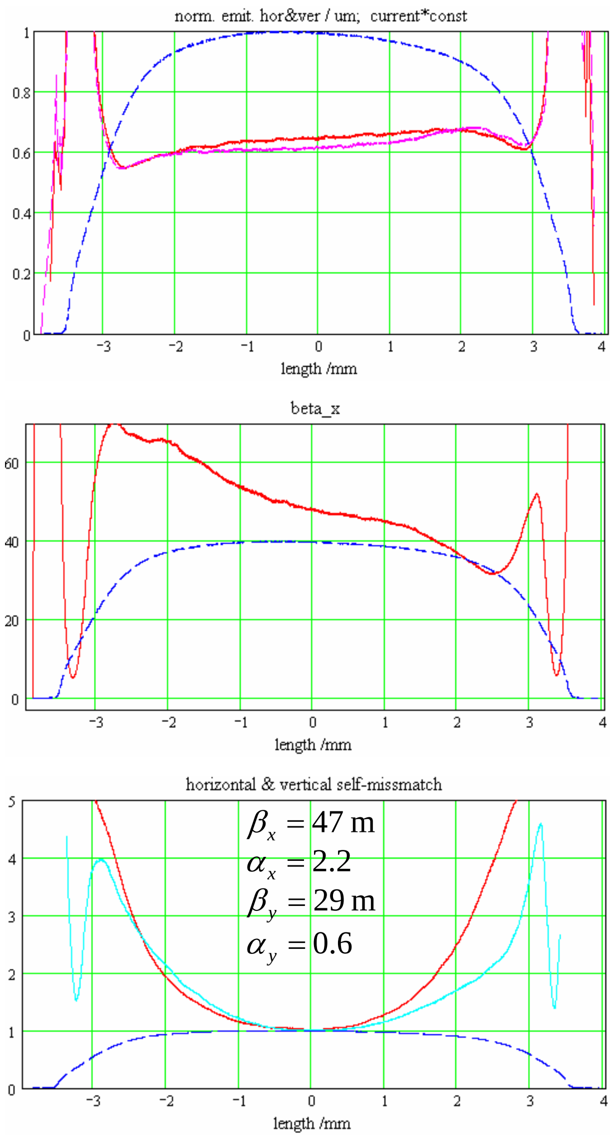
method 3 – accurate&effcient (to be done)



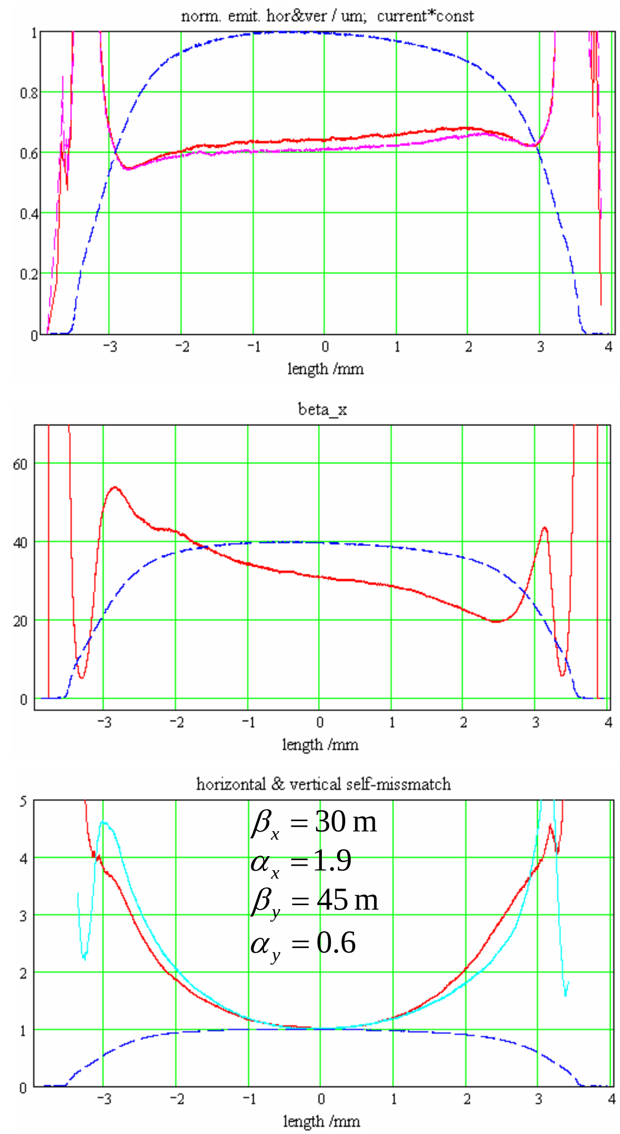
ASTRA (method 2) vs. ELEGANT (method 3)

linac before bc1

ASTRA



ASTRA without s.c.



ELEGANT