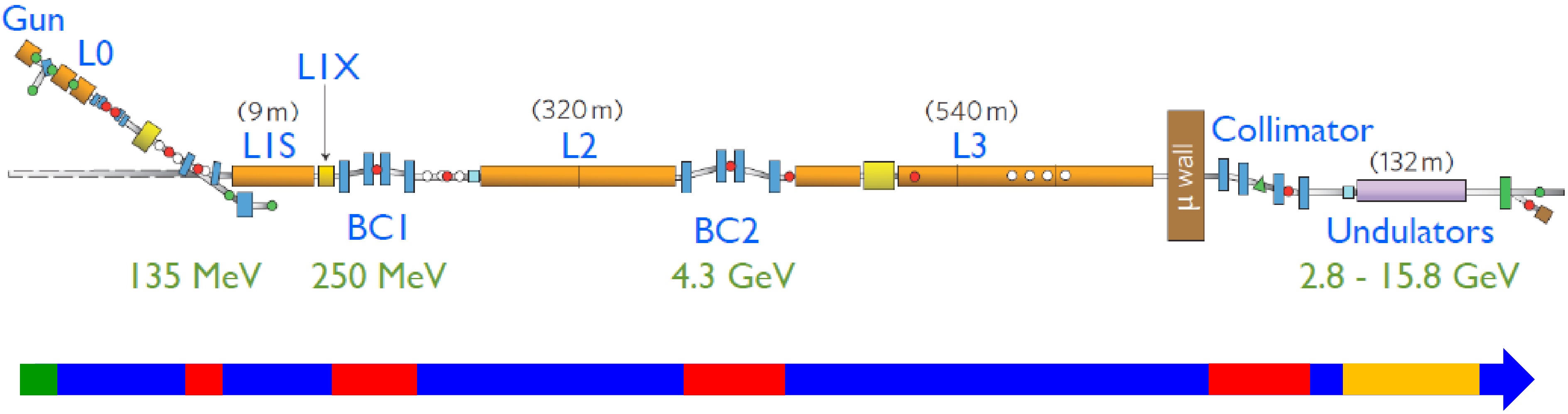
Fast Simulation of FEL Linacs with Collective Effects

M. Dohlus
IPAC 2018

A typical X-FEL



gun environment
photo cathode
cavity, solenoid,
drift …

straight
cavity,
quadrupole,
drift …

dispersive
bend,
quadrupole,
drift …

FEL
undulator,
quadrupole,
wakes …

Linacs
diagnostics
transport …

chicanes
collimators
dog legs …

FEL interaction

“accelerator”

4 Types of Problems

gun environment
photo cathode
cavity, solenoid,
drift …

cathode physics
self-fields ~ external fields
assumption for self fields:
„SC“ or Maxwell

Parmela, Astra, GPT, CST-PS,
Impact, Opal,…

interface

“accelerator”

straight
cavity,
quadrupole,
drift …

Astra, GPT, …

dispersive
bend,
quadrupole,
drift …

external fields > self fields
standard approaches:
„SC“ for straight part,
1D-CSR for non-straight part

Elegant,
Impact, Opal, Ocelot, Xtrack, …

CSRtrack, …

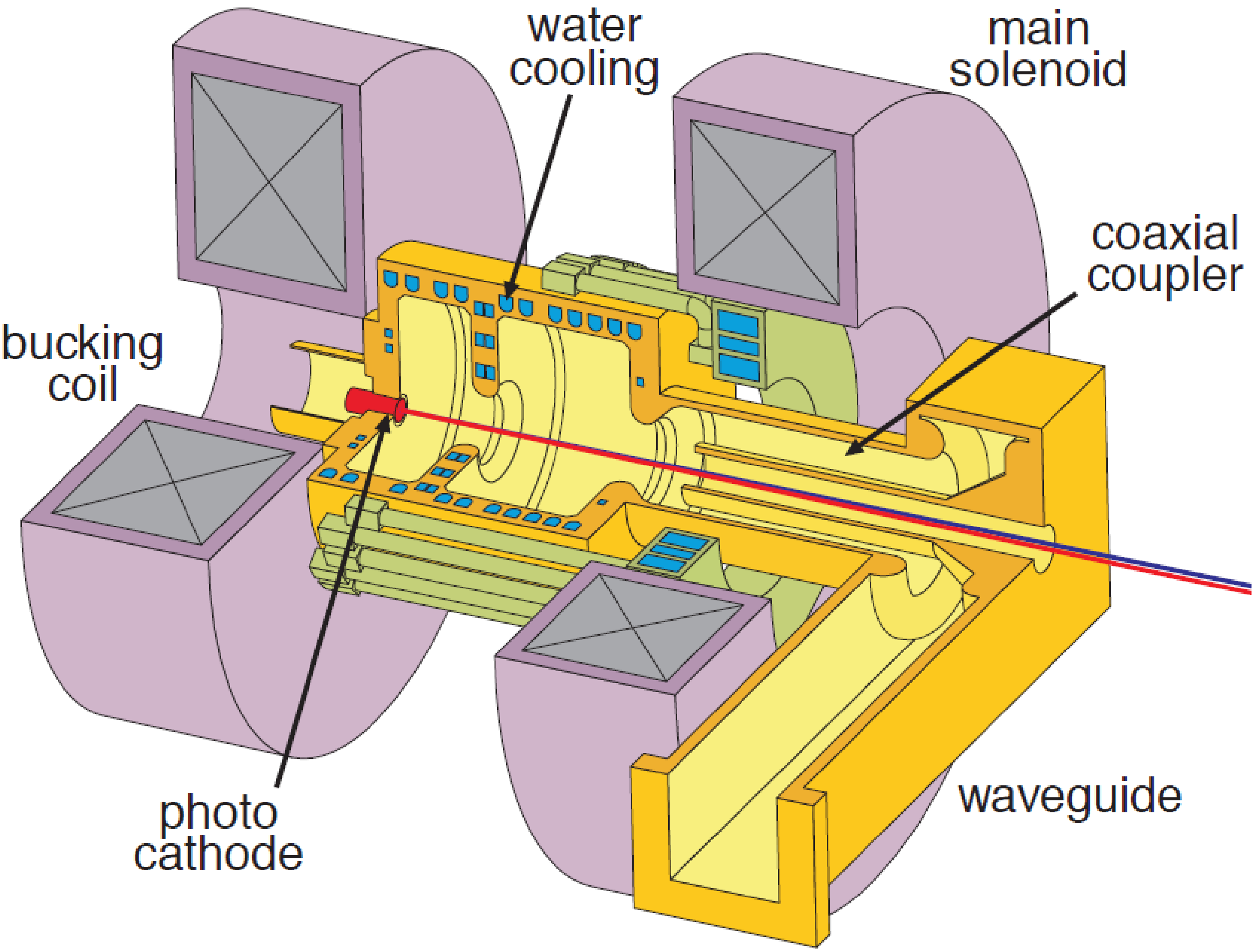
interface

FEL
undulator,
quadrupole,
wakes …

FEL effects
slippage & wave propagation
mono- or multi-frequent

Genesis, Alice,
Fast, Ginger, …

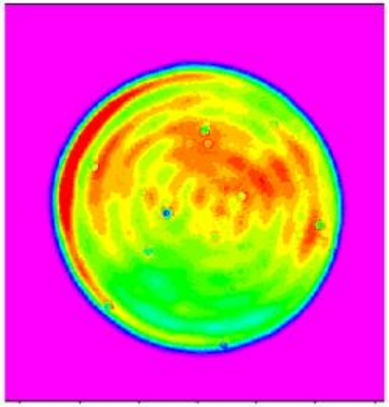
About EM-Fields: Gun



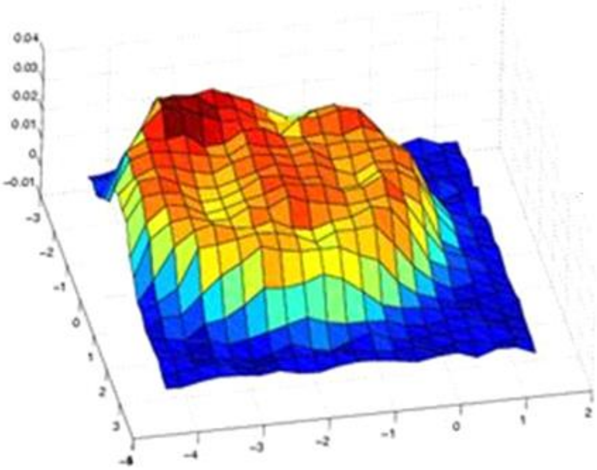
emission model → cathode distribution

Laser (transverse & time)
quantum efficiency (transverse)

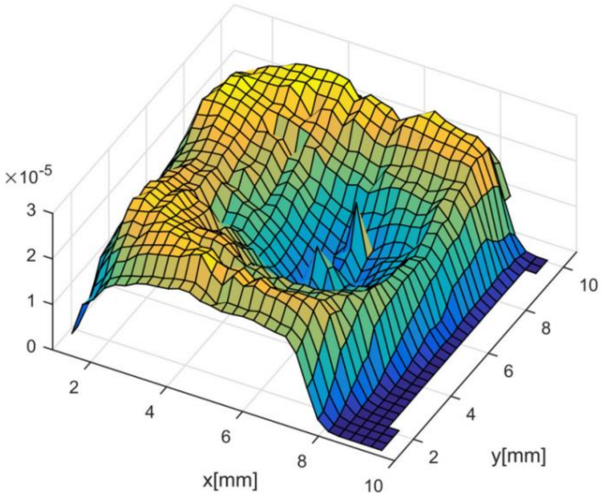
Laser



X



QE map



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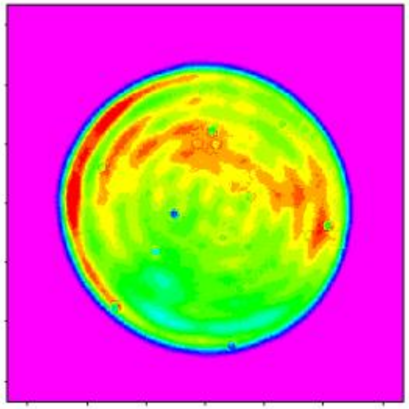
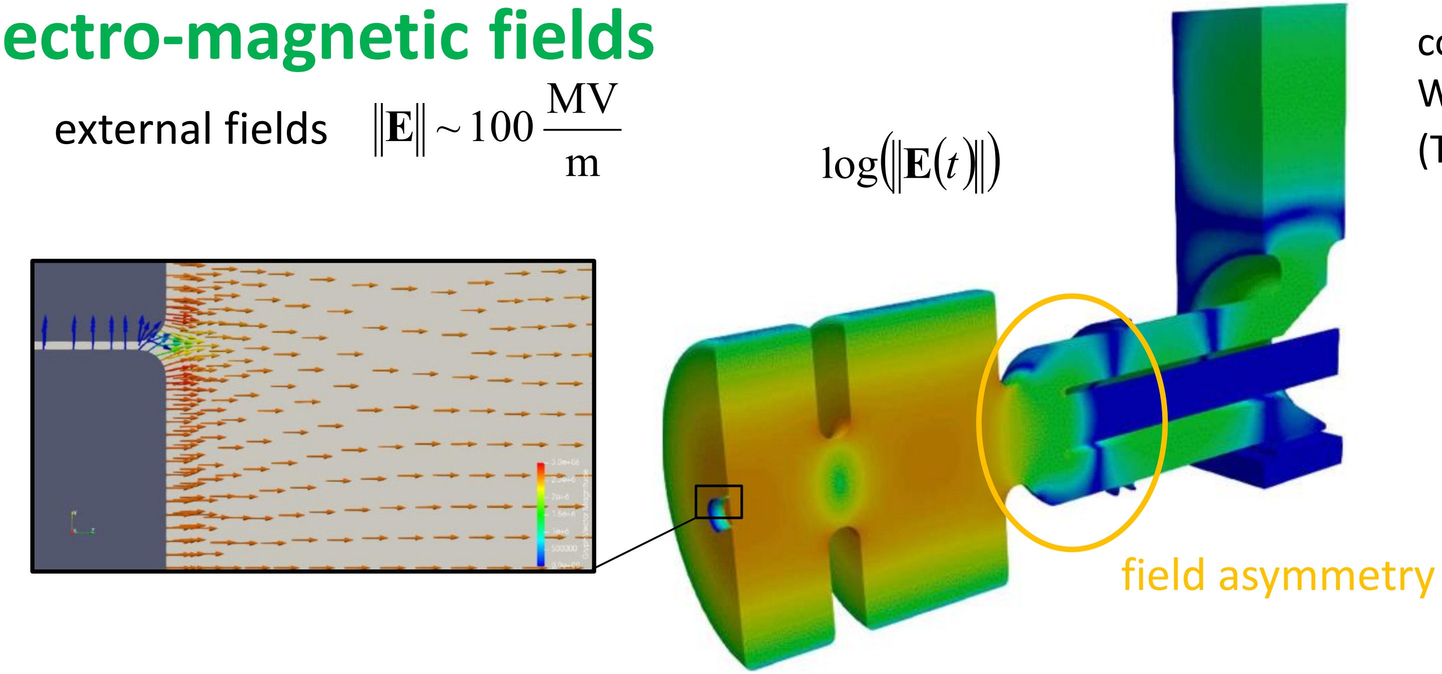
Charge density



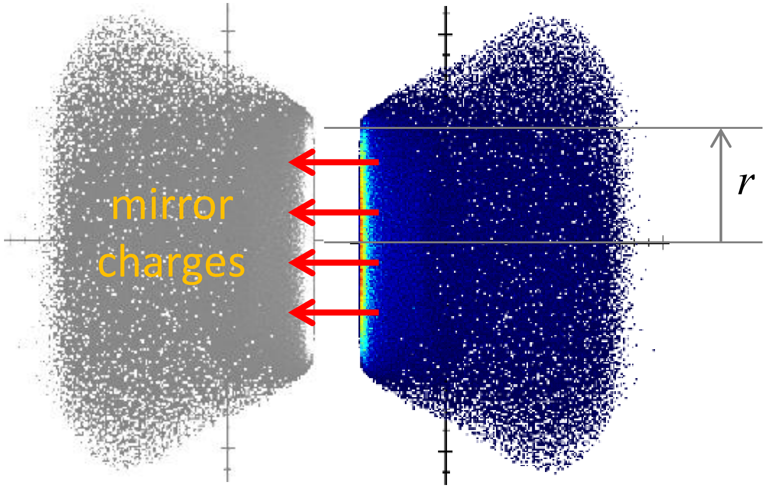
electro-magnetic fields

external fields $\|\mathbf{E}\| \sim 100\,\frac{\mathrm{MV}}{\mathrm{m}}$

courtesy
W. Ackermann
(TUD-TEMF)

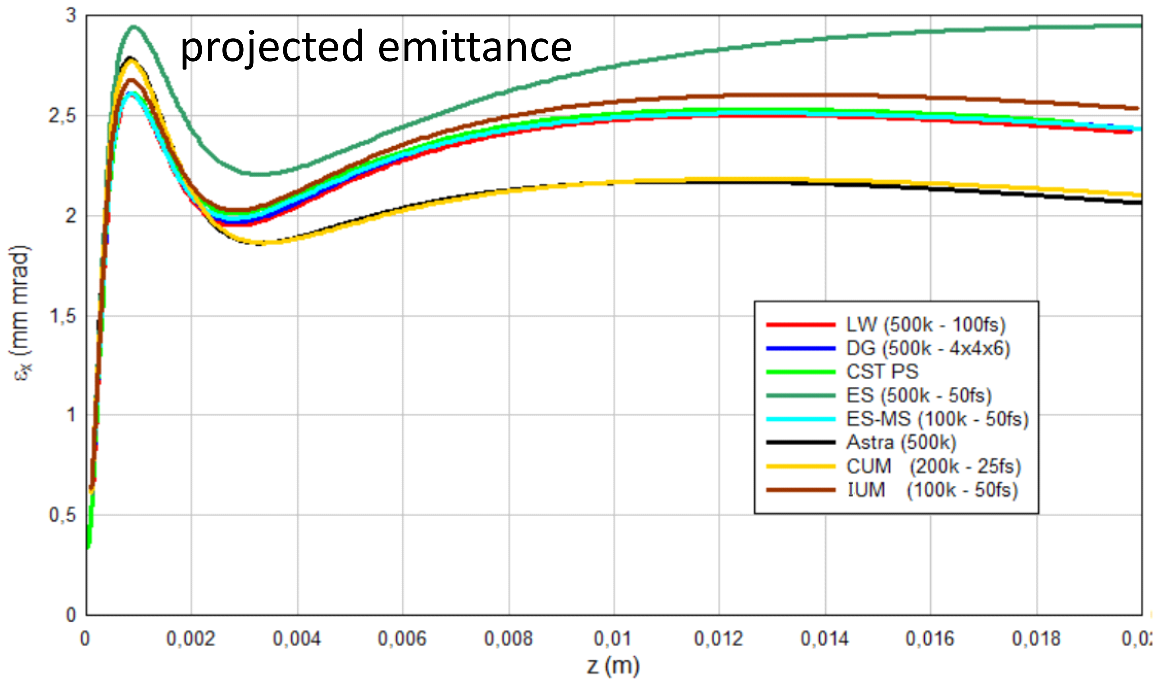


self fields $E_z \sim \frac{Q}{\varepsilon_0}\frac{1}{\pi r^2}$



same order of magnitude

tracking with different types of self fields

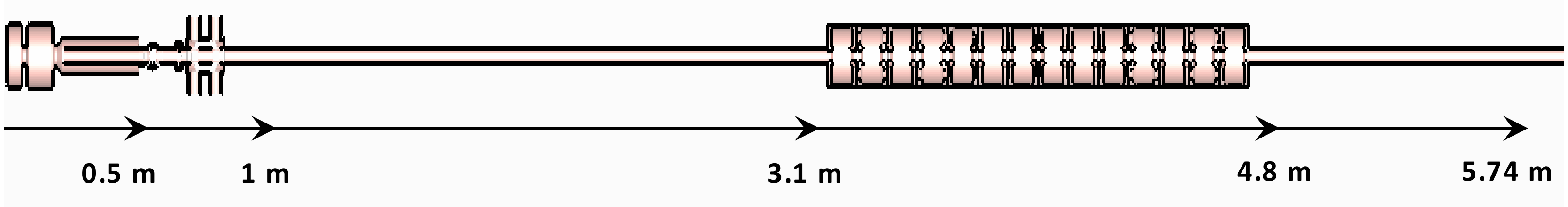


courtesy
E. Gjonaj (TUD-TEMF)

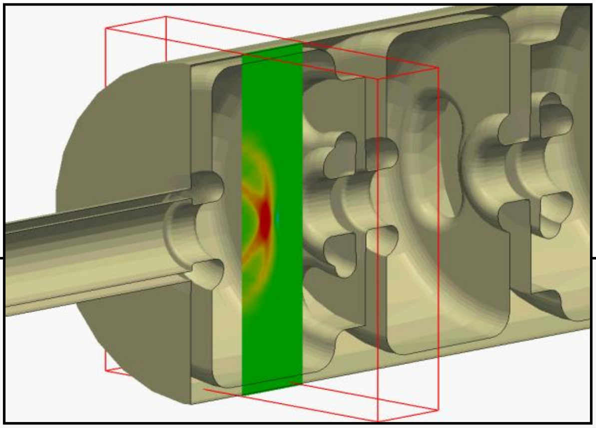
LW	Lienert Wiechert	**full Maxwell**
DG		
CST	CST particle studio	
ES	electro static approximation	static
ESMS	electro-static and magneto-static approximation	
Astra	collective uniform motion approach	uniform motion
CUM	**collective uniform motion** approach	
IUM	individual (per particle) uniform motion approach	

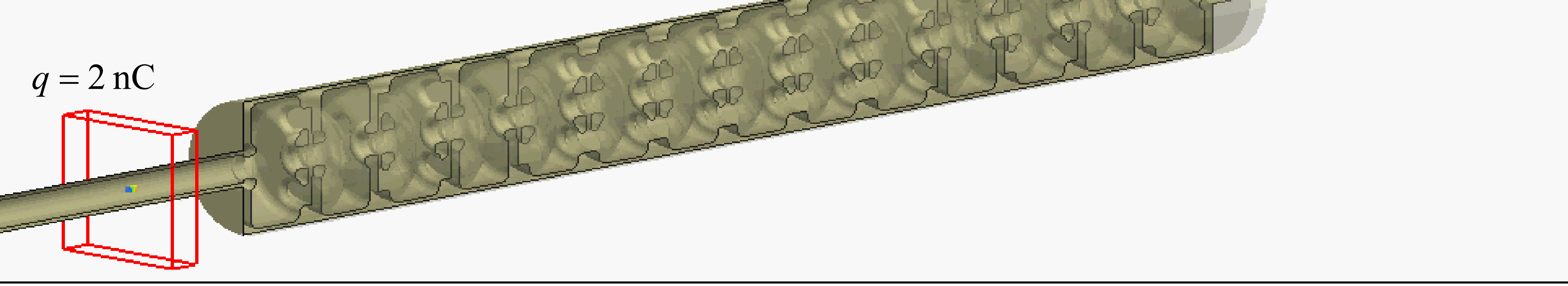
About EM-Fields: First Straight Section

(PITZ at DESY, Zeuthen)

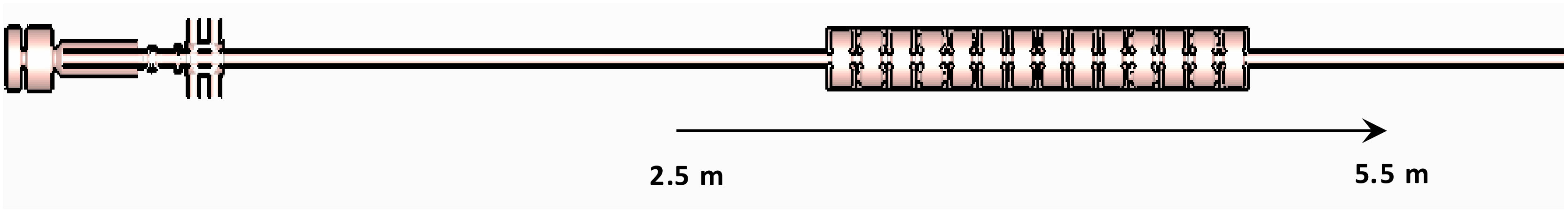


full Maxwell	**collective uniform motion**
PBCI	**Astra**
grid $\Delta = 50\ \mu\mathrm{m}$	
mesh-cells ~ 300×10^6	
time-steps ~ 10^5	
simulation time ~ 1 .. 3 day	~ minutes
parallel computing	scalar computing

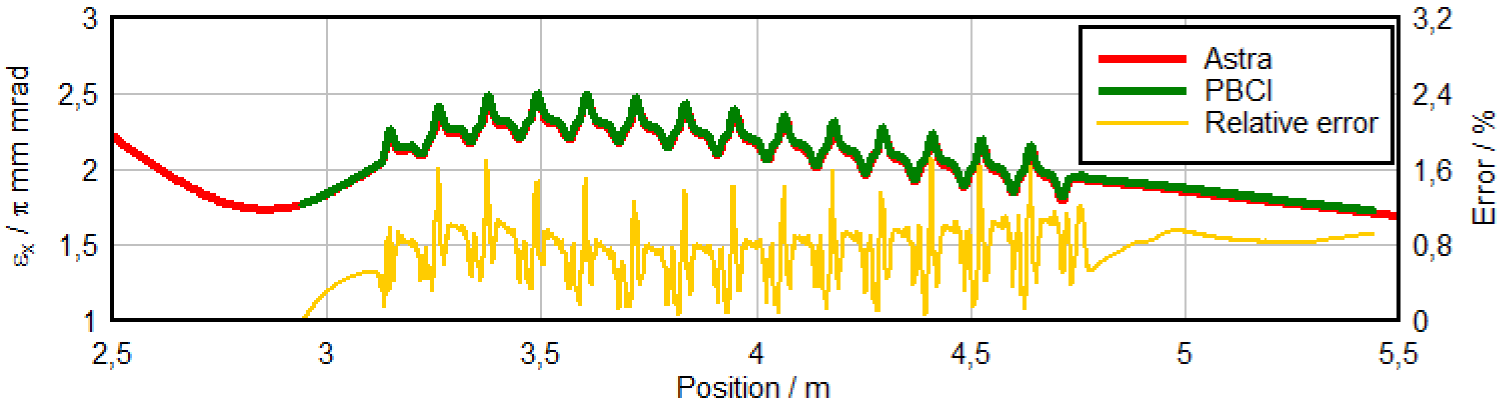




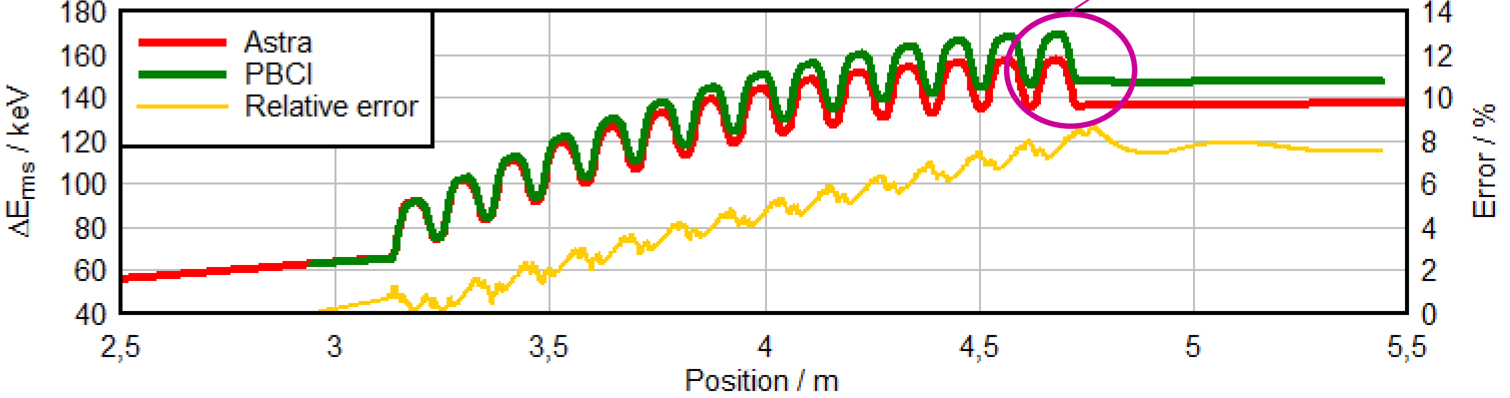
courtesy E. Gjonaj (TUD-TEMF)



projected emittance



energy spread



difference is caused by wakes !

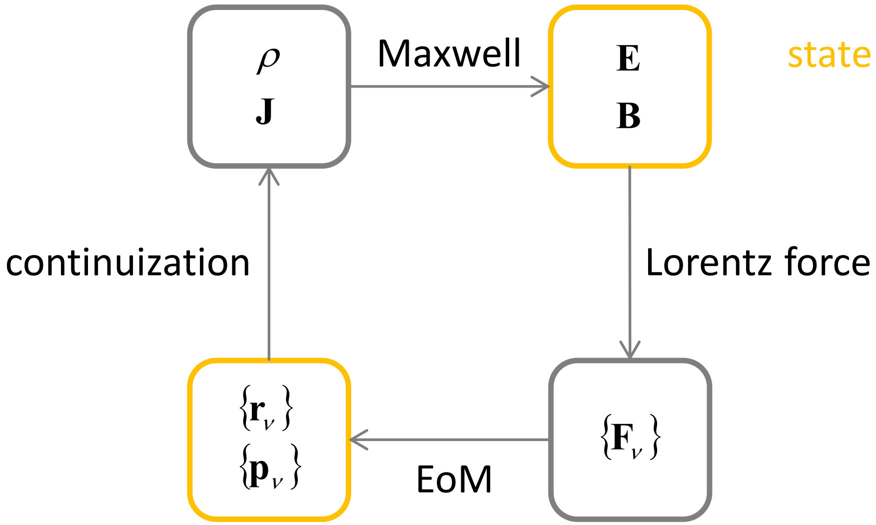
courtesy E. Gjonaj (TUD-TEMF)

About EM-Fields: Maxwell vs. CUM

time domain solver

domain = field-volume

time step by Courant criterion ~ 1µm/c



effort is very high

$$\sim \frac{\text{length of beamline}}{\text{length of bunch}} < 1\text{E}3 \dots 1\text{E}6$$

(dispersion free, window & parallel)

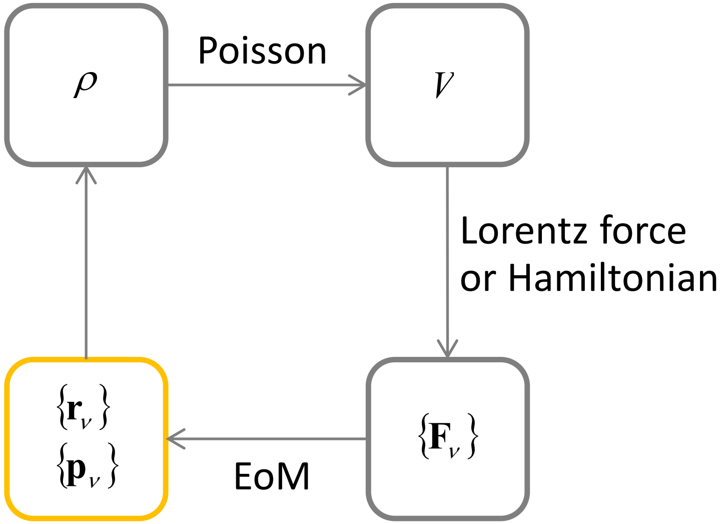
state quantities

collective uniform motion

“frozen” bunches

domain = bunch-volume

time step ← variation of ext. fields ~ 1cm/c



moderate effort

About Tracking: General vs. Adopted

general purpose tracking

no assumption about fields

any spatial and time dependency

any ratio of self- to external fields

difficult step width control

fine steps in fringe fields

applications

strong self fields

gun

or validation of adopted tracking

adopted tracking

generic description of external fields

field regions with hard boundaries

f.i. $\mathbf{B}(x, y, z, t) = \nabla \times (\mathbf{e}_z A(x, y))$

tracking between boundaries in large steps

special steps at boundaries (edges)

applications

weak self fields

cavities and magnets above 10 MeV

very effective

remarks

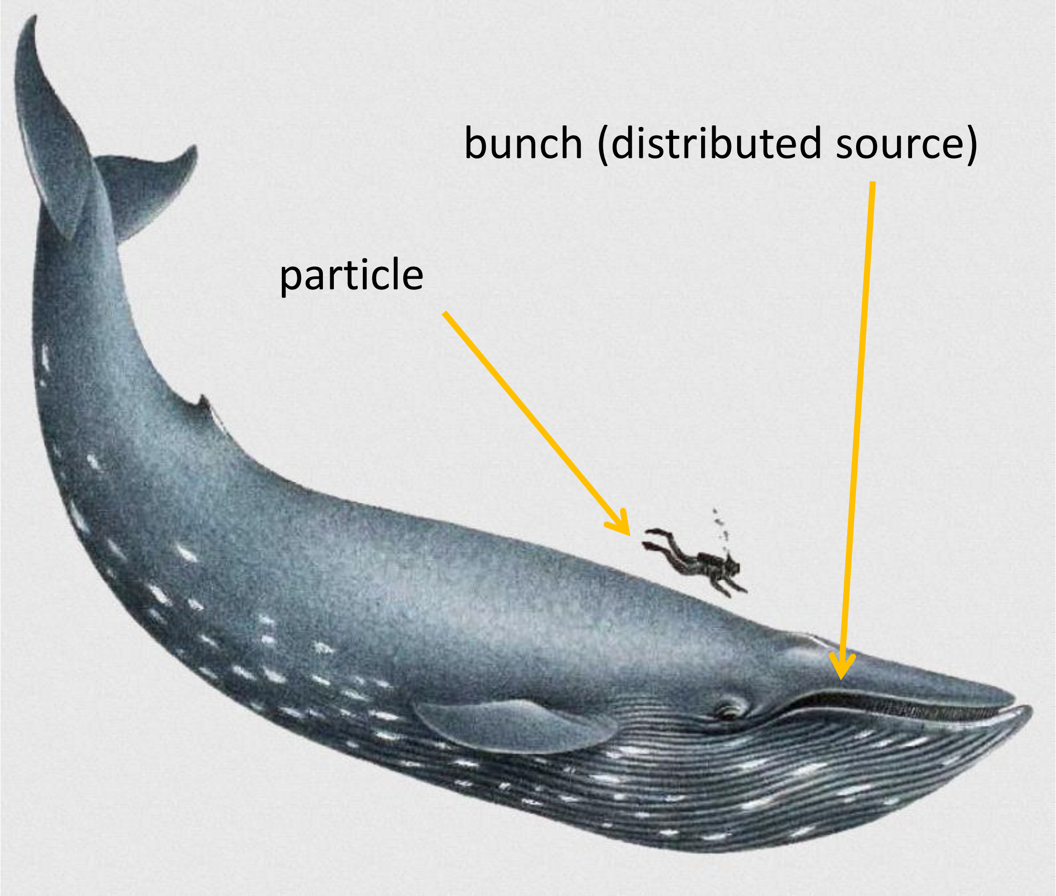
gun: needs cathode and emission model
external fields by field maps → general tracking method
self fields by CUM or even Maxwell, large effort for Maxwell
interplay of self- and external fields is crucial (emittance compensation)
computation and optimization is time consuming

gun and “accelerator” are computed separately

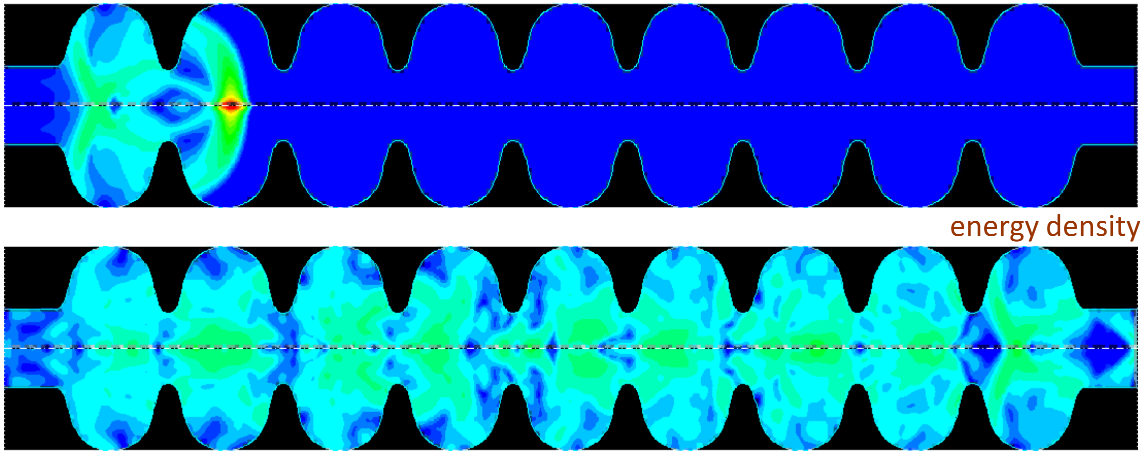
straight sections: self fields by CUM + wakes
generic external fields → adopted tracking method
very effective computation (per length)

to be considered: **wakes** (geometry, resistivity of chamber)
CSR (trajectory, ... chamber)

Wakes



wakes are pre-calculated solutions



energy density

source particle $\mathbf{r}_s(t) = x_s\mathbf{e}_x + y_s\mathbf{e}_y + ct\mathbf{e}_z$ with charge q_s creates fields $\mathbf{E}$, $\mathbf{B}$

test particle $\mathbf{r}_t(t) = x_t\mathbf{e}_x + y_t\mathbf{e}_y + (ct - s)\mathbf{e}_z$ gets integrated kick $\Delta\mathbf{p}$

$$\boxed{\mathbf{w}(x_s, y_s, x_t, y_t, s) = \frac{\Delta\mathbf{p}}{q_s q_t}}$$

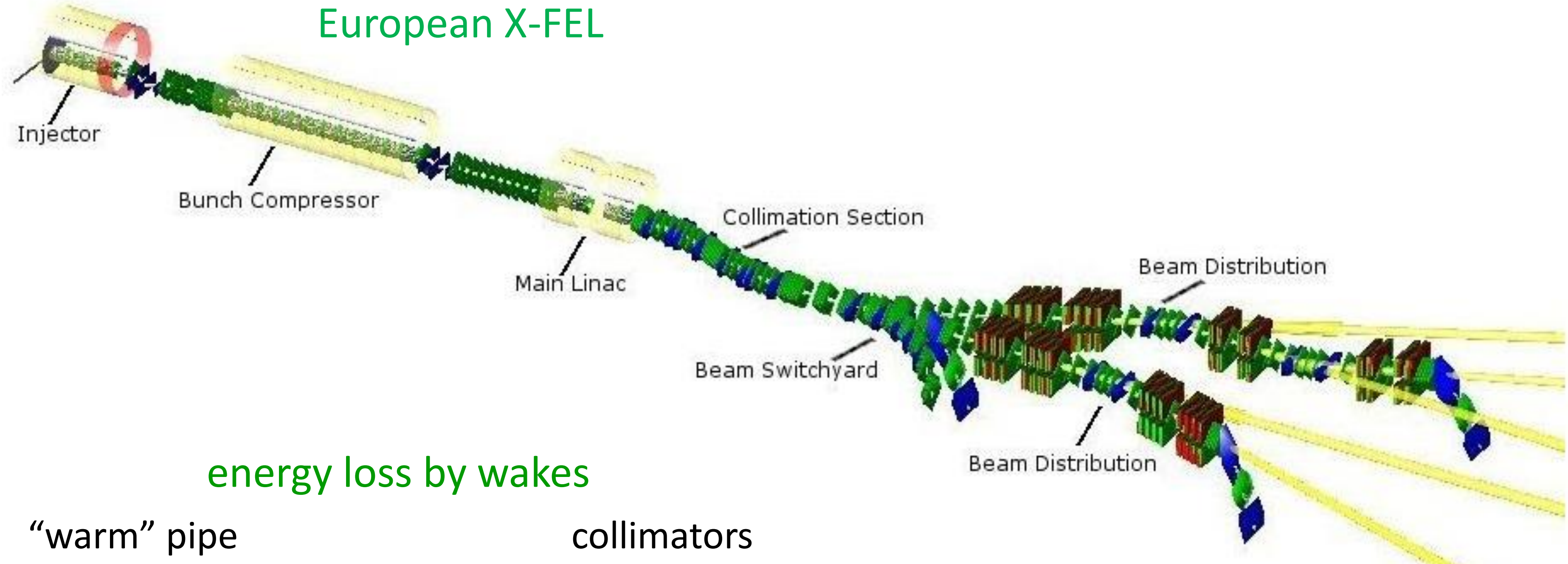
short & long range wakes

monopole and dipole wakes in structures with symmetry of revolution !!!

longitudinal and transverse wakes offset-independent

impedance/wake data base

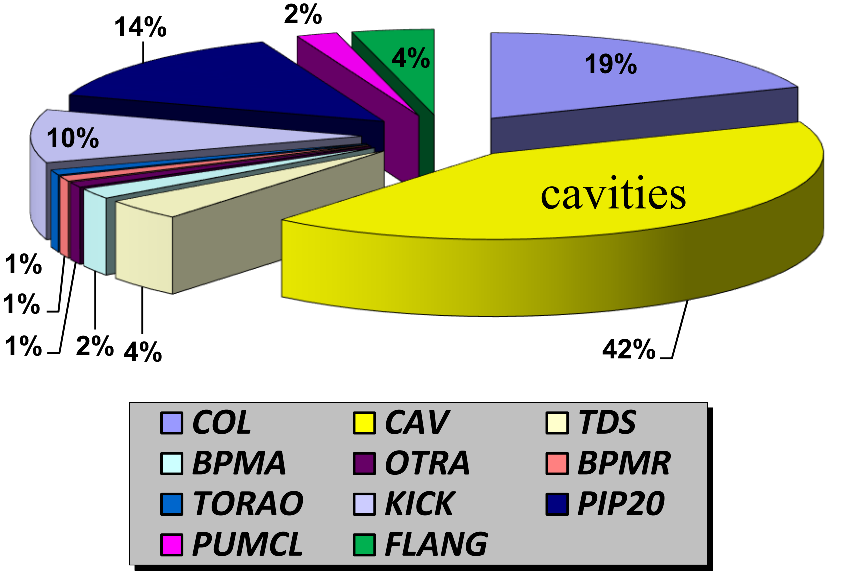
European X-FEL



energy loss by wakes

“warm” pipe

collimators



about 2000 components:
824 cavities (including TDS)
500 flanges
220 BPMs (5 types)
78 pumps
20 OTR screens
7 collimators
5 BAMs
3 kickers
warm pipes, …

remarks

wakes can be "collected" over some length

update of transverse wakes: length << betatron wavelength

update of longitudinal wakes: length << wavelength of longitudinal oscillations
before dispersive sections

wake updates are fast compared to SC updates, but less often

accelerator:

effects due to transverse wakes are minor

effects due to longitudinal wakes are essential → long. phase space and compression

in undulator:

longitudinal wake causes energy loss

tapering

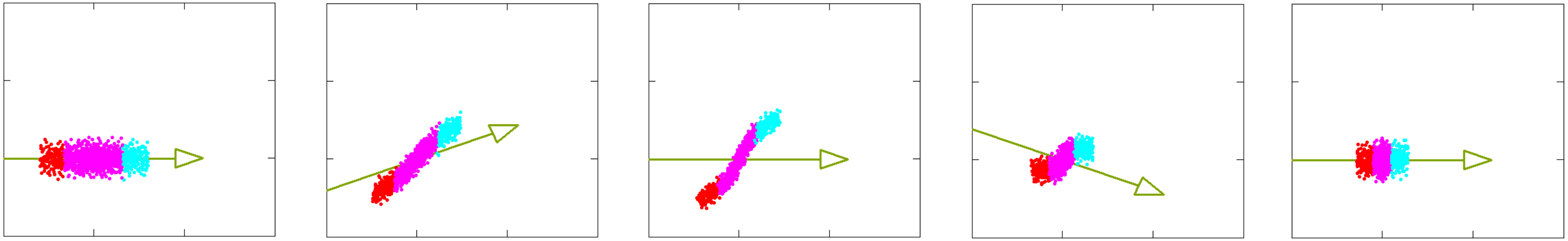
FEL codes use a wake per length (averaged for a typical section)

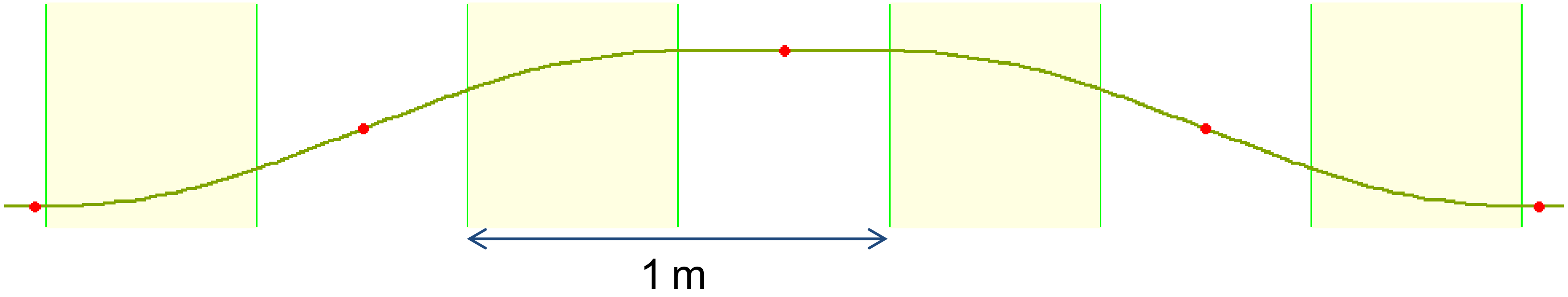
transient wakes can be used for dispersive sections (→ **1D CSR model**)

CSR Effects in Chicanes

do not try this at home: 1nC → 5 kA @ 500 MeV

without self-interaction





CSR Effects in Chicanes

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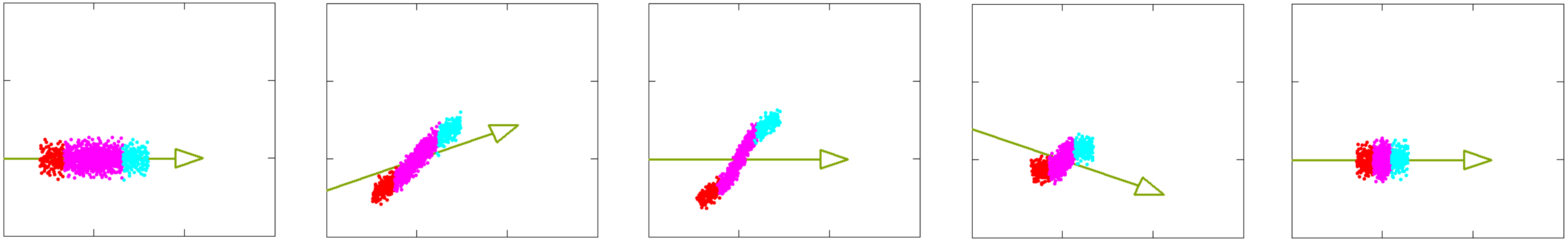
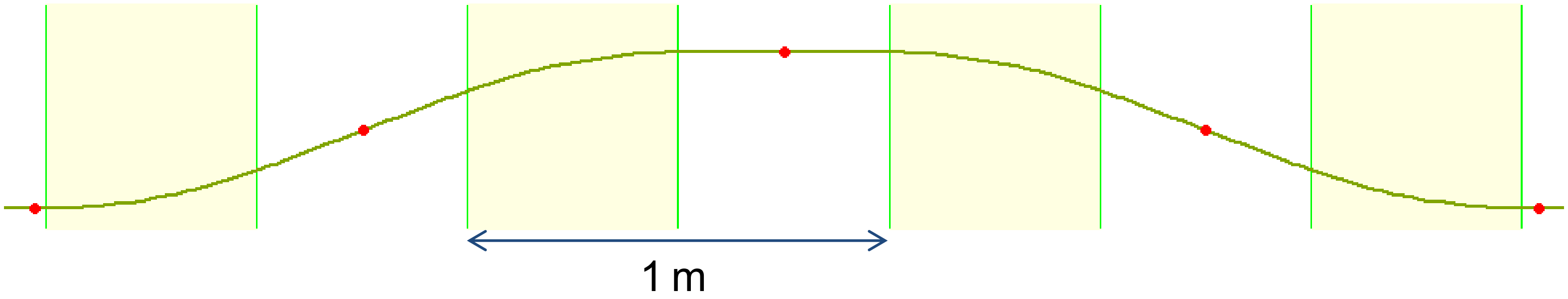
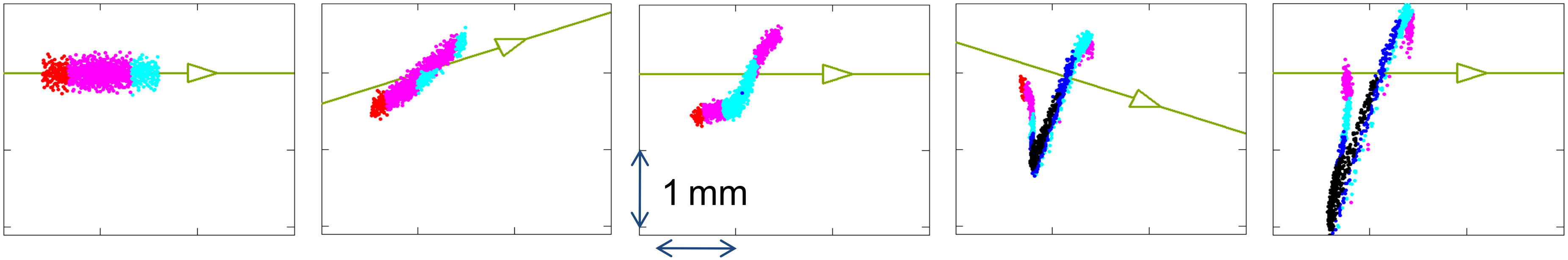
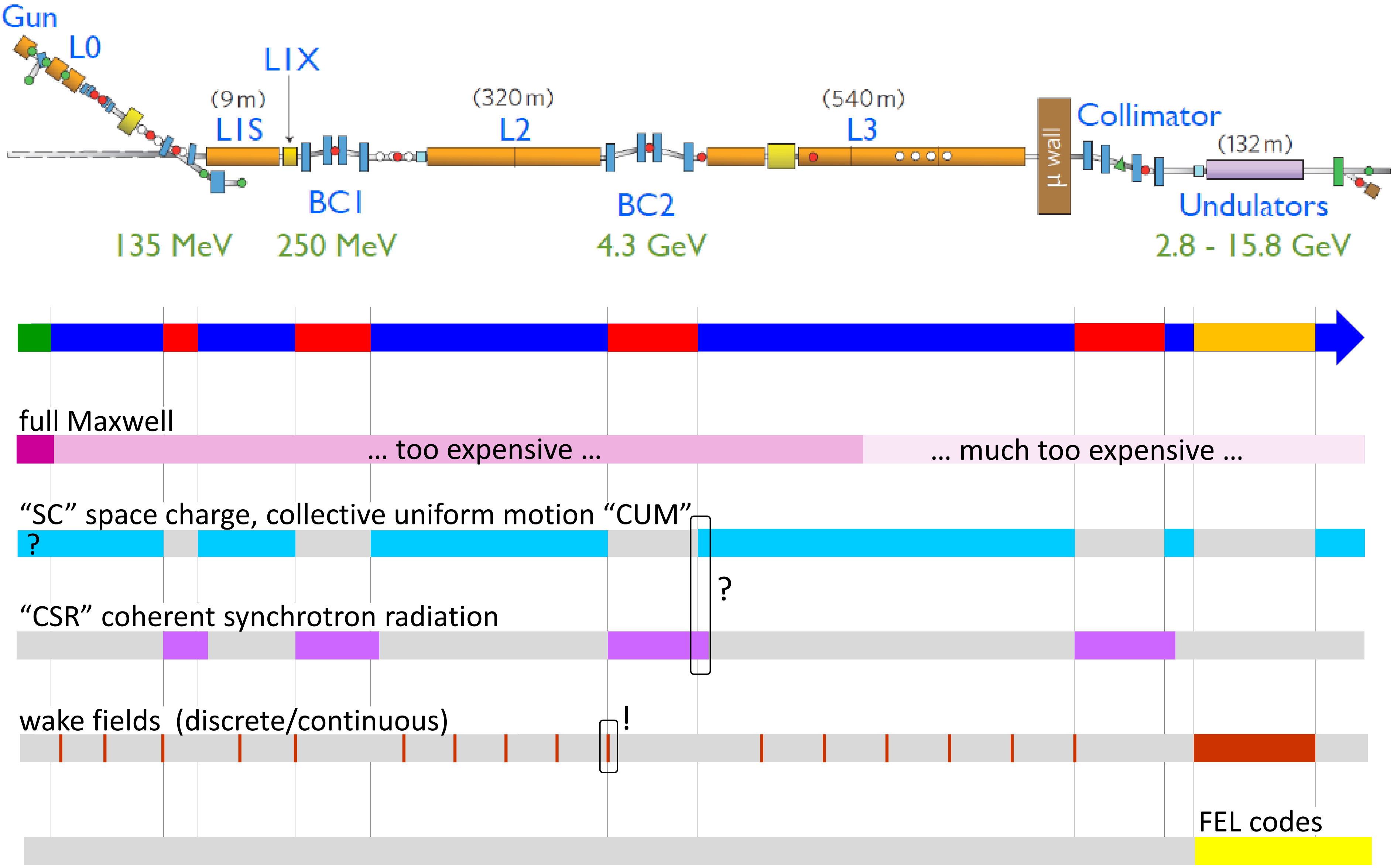




with self-interaction



Interplay for Start-to-End Simulations



full Maxwell

… too expensive …

… much too expensive …

“SC” space charge, collective uniform motion “CUM”

?

?

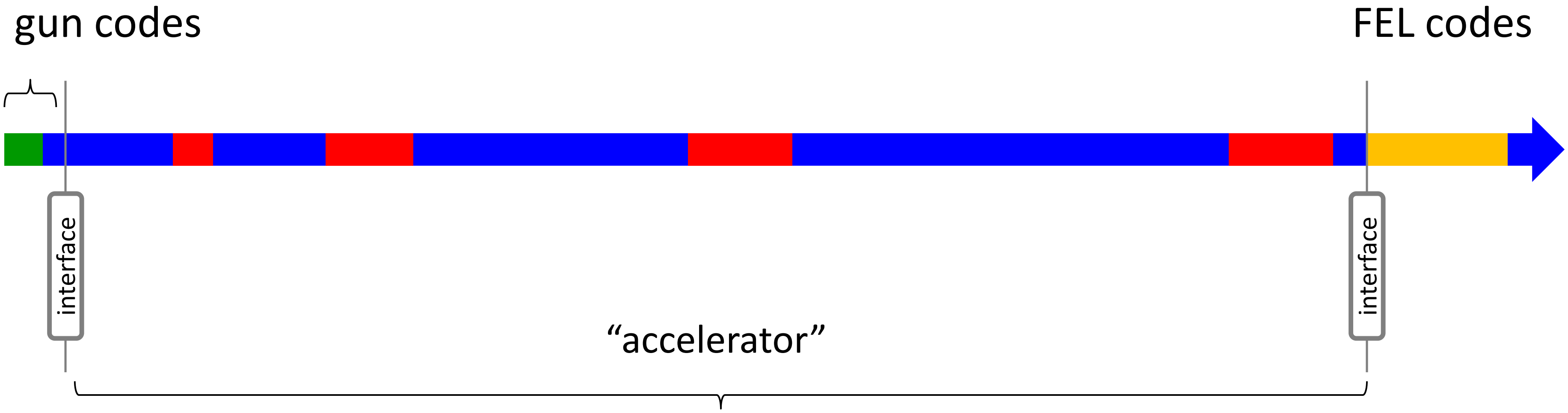
“CSR” coherent synchrotron radiation

wake fields (discrete/continuous)

!

FEL codes

The Standard Approach



Impact, Opal, Ocelot, Xtrack, …

CUM + adopted

wakes

1D CSR

parallel implementations

Considered Effects of Standard Approach

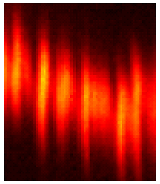
precise **longitudinal dynamics** (compression)

longitudinal profile
peak current
correlated & un-correlated energy spread
BCs: parallel plate shielding (perfect conducting)

transverse self effects

transverse shape
emittance
SC optics, mismatch & self-mismatch

micro-bunching



start-up from shot-noise needs “full particle” simulation and high spatial resolution

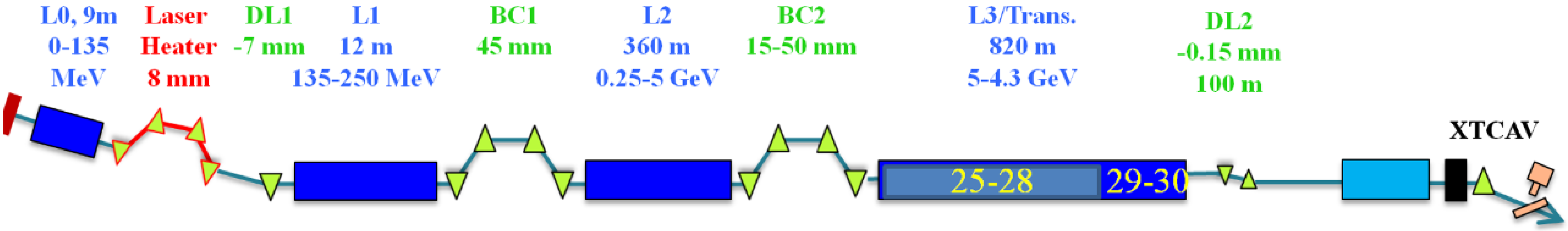
identify critical wavelength
increased emittance and energy spread
effect of laser heater

micro-bunching with full-particle-simulation

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 054402 (2017)

Start-to-end simulation of the shot-noise driven microbunching instability experiment at the Linac Coherent Light Source

J. Qiang,[1,*] Y. Ding,[2,†] P. Emma,[2] Z. Huang,[2] D. Ratner,[2] T. O. Raubenheimer,[2]
M. Venturini,[1] and F. Zhou[2]



L0, 9m
0-135
MeV

Laser
Heater
8 mm

DL1
-7 mm

L1
12 m
135-250 MeV

BC1
45 mm

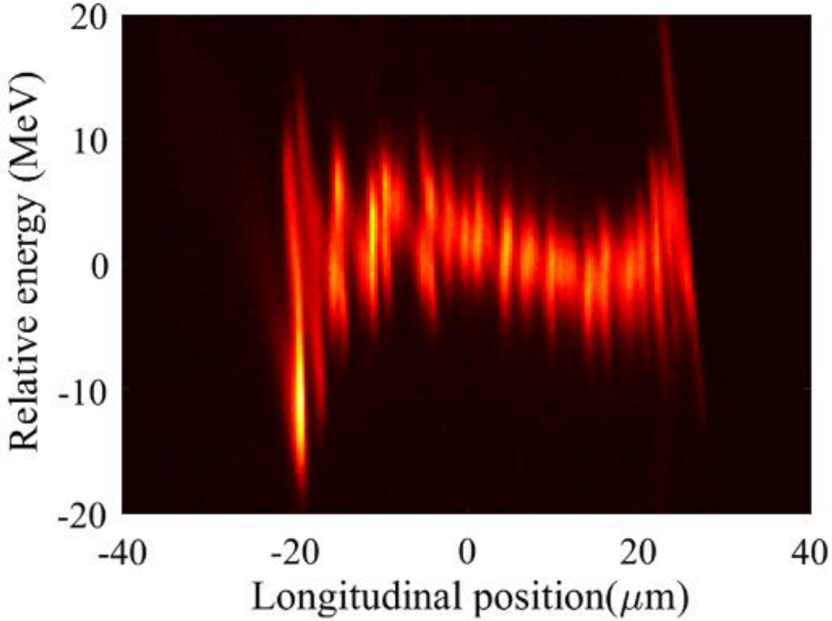
L2
360 m
0.25-5 GeV

BC2
15-50 mm

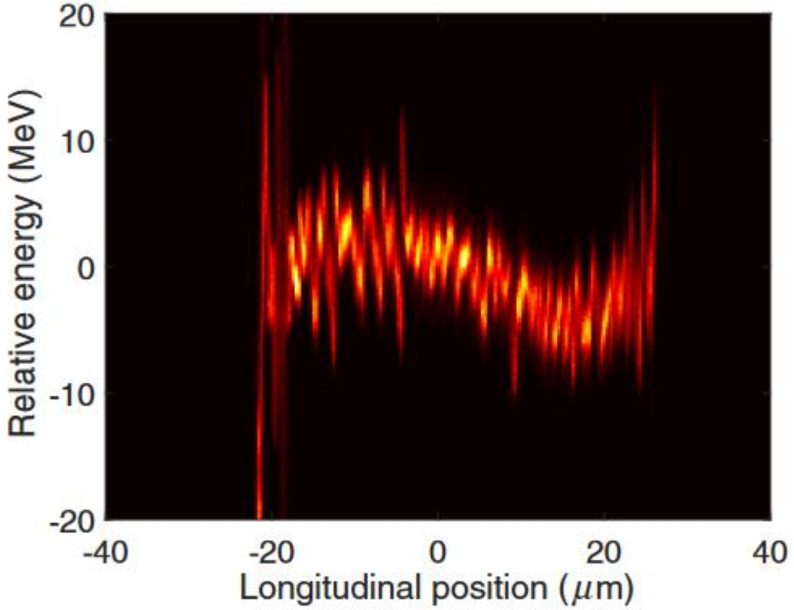
L3/Trans.
820 m
5-4.3 GeV

DL2
-0.15 mm
100 m

XTCAV



(a) measurement



(b) simulation

180pC
1kA
LH off

Missing Effects of Standard Approach

3D CSR model

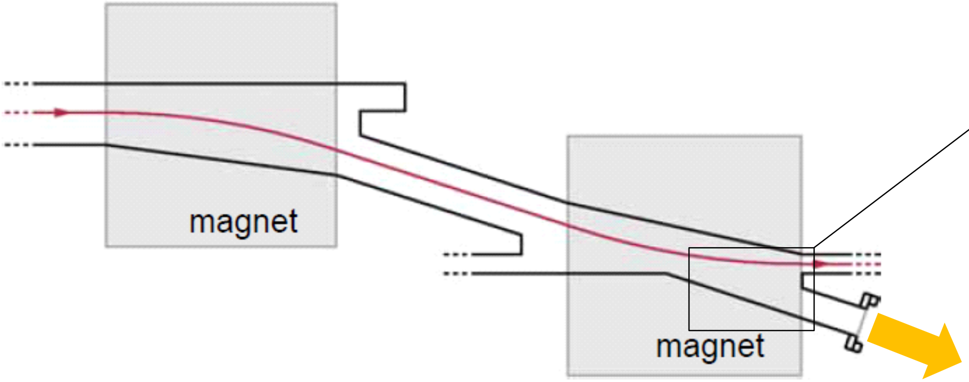
density(x,y,s)
force vector (x,y,s)
consistent treatment of “SC” + “CSR”

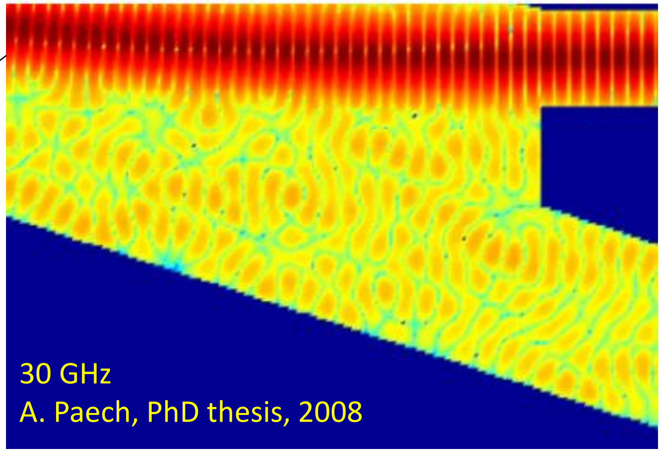
1D CSR model

density(s)
long. force (s)

BC chambers: CSR + resistive wall effects in

energy loss → beam dynamics
→ heating
radiation





A. Paech, PhD thesis, 2008

Lighter Approaches and Special Methods

3D beam & 1D forces: (as Elegant or Xtrack)

1D self effects (**long. SC impedance**,
wakes,
1D CSR)
3D beam & tracking

applicability of longitudinal SC impedance: $\gamma z_c >> \sigma_\perp$

z_c is characteristic length (bunch length or scale of micro-bunching)

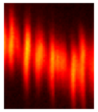
this condition is usually good fulfilled after the first cavities for the rest of the machine, if there is no micro-bunching

in straight sections after the first cavities the longitudinal shape is nearly frozen

light trackers: (as LiTrack or Rftweak) with 1D beam & tracking

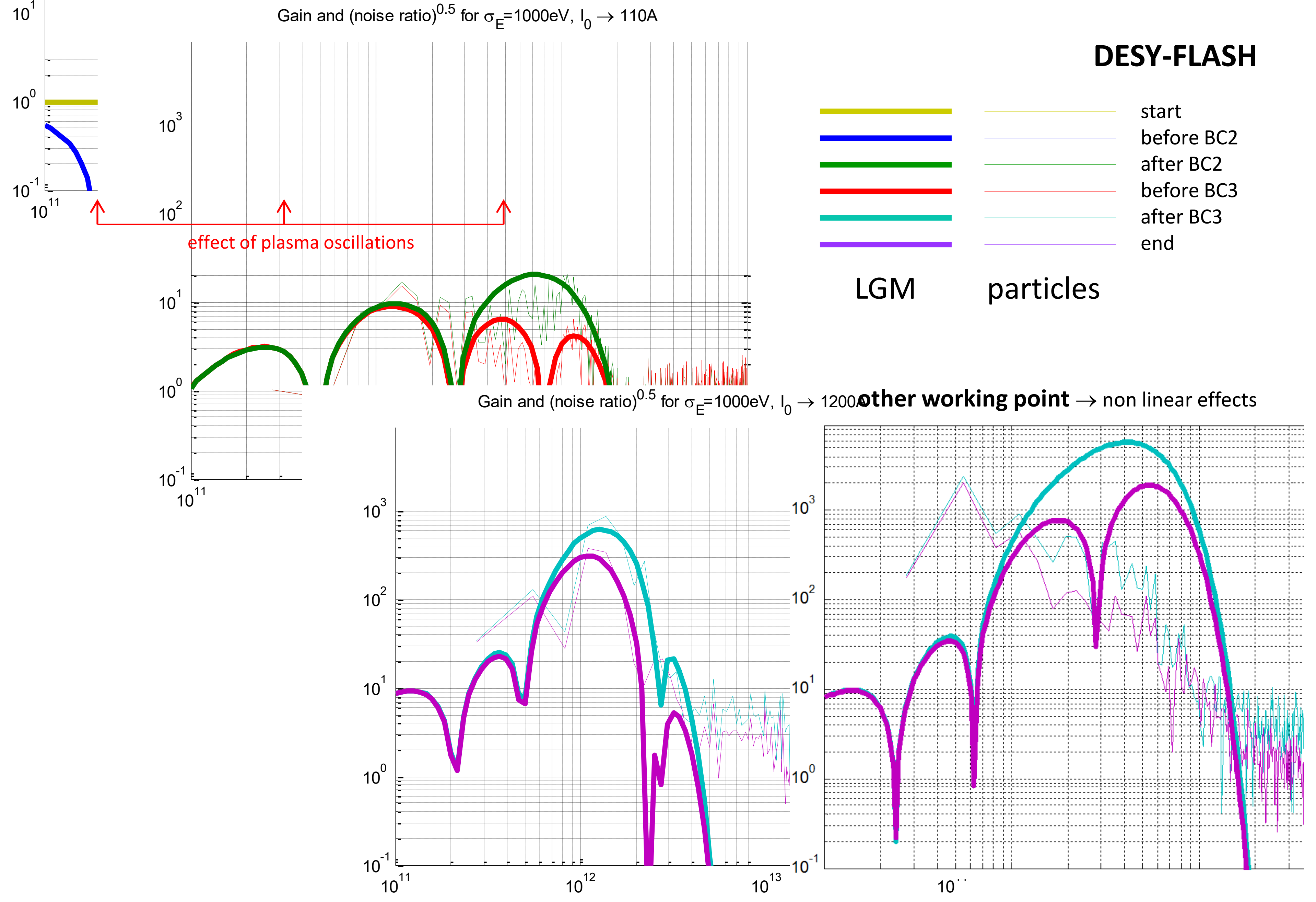
discrete model (with effective impedance) for straight sections,
pre-calculated wake-tables for dispersive sections (CSR)
$\rightarrow$ tool for control room

micro-bunching (special):



<table>
<tr><th>1D particles</th><th>LGM (linear gain model)</th></tr>
<tr><td>one macro particle per electron
shot noise
$\{z_\nu , p_{z\nu}\}$
dynamics in longitudinal phase space</td><td>continuous 6d phase space
coasting beam + periodic perturbation
$F(\mathbf{r},\mathbf{p}) = F_0(\mathbf{r},\mathbf{p}) + f(\mathbf{r},\mathbf{p})$
dynamics in full phase space</td></tr>
<tr><td>initial z-distribution = arbitrary</td><td>initial z-perturbation = harmonic</td></tr>
<tr><td colspan="2">initial energy distribution = arbitrary, z-independent</td></tr>
<tr><td></td><td>initial transverse phase space = gaussian</td></tr>
<tr><td colspan="2">1d space charge impedance
1d wakes</td></tr>
<tr><td></td><td>1d CSR</td></tr>
<tr><td>particle tracking</td><td>integral equation</td></tr>
<tr><td>phase space
non-linear effects
(as saturation and harmonics)</td><td>gain
linear</td></tr>
</table>

example: gain (LGM) and noise (particles) vs. initial frequency

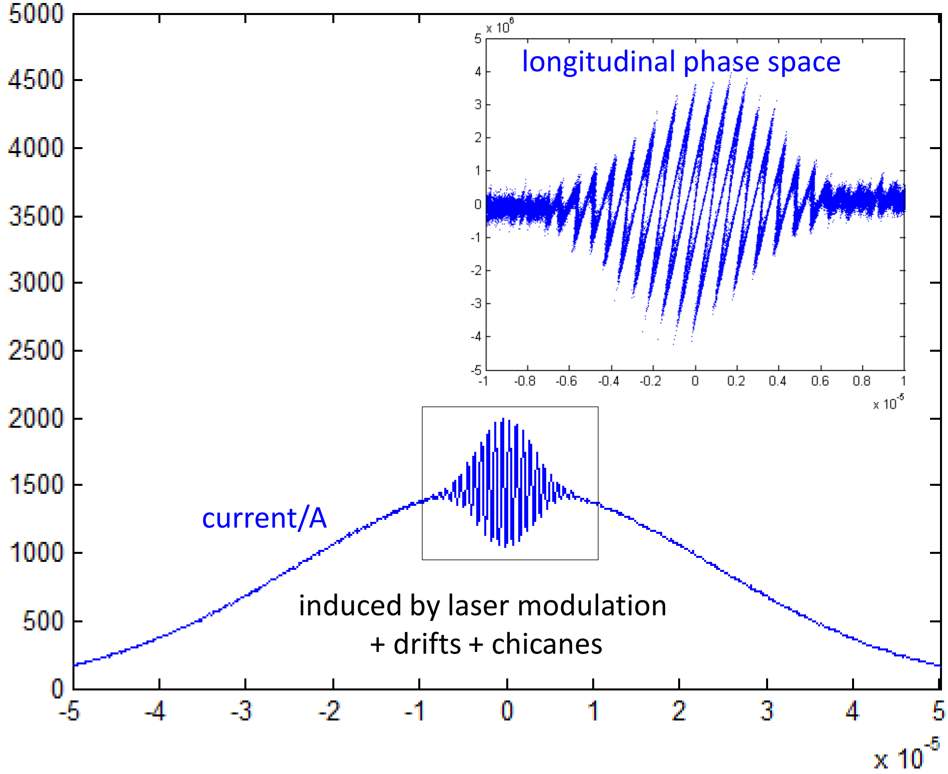


DESY-FLASH

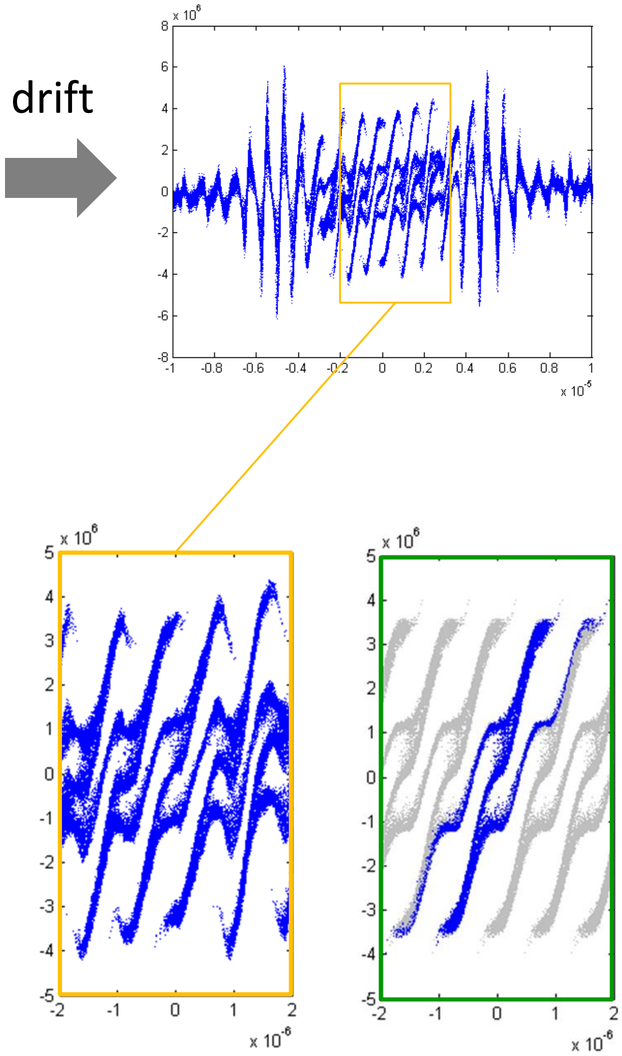
effect of plasma oscillations

other working point → non linear effects

Lighter Approaches and Special Methods



induced by laser modulation
+ drifts + chicanes



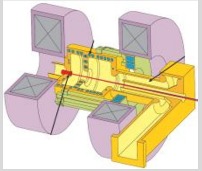
periodic distributions + CUM

full simulation with 300pC
periodic simulation with 4pC

Finally, Computation Times

scalar

parallel



CUM
$L<1m$, $N_p \sim 10^{6}$

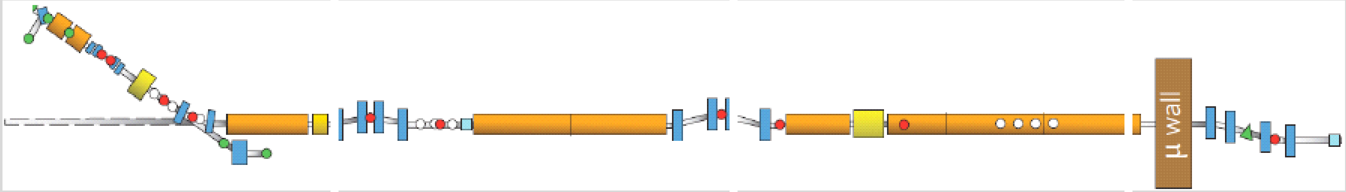
Maxwell, TD
$L<1m$, $N_p \sim 10^{6}$

1 s

1 min

1 h

1 d



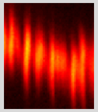
light tracker
(1d)

Maxwell, TD
$L\sim 1m$, $N_p \sim 10^{6}$

standard approach
$L\sim 10^{3}$ m, $N_p \sim 10^{6}$

standard approach
$L\sim 10^{3}$ m, $N_p \sim 10^{9}$

micro-bunching



LGM