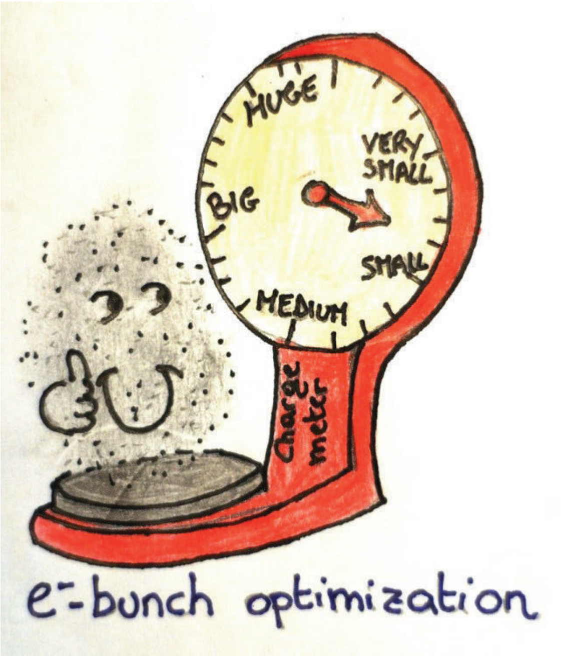
SHORT BUNCH, LOW CHARGE OPERATION AT THE EUROPEAN XFEL USING DIFFERENT LONGITUDINAL PHOTO~CATHODE LASER SHAPING DISTRIBUTIONS



Barbara Marchetti
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Outline

- Introduction about fully coherent and/or extremely short x-rays radiation pulses
- Simulations of the compression of 20pC e-bunches at the European XFEL
  - Description of the method used to find the accelerator parameters
  - Results of fast 3D simulations using different longitudinal photo-cathode laser shaping
- Conclusions and outlook

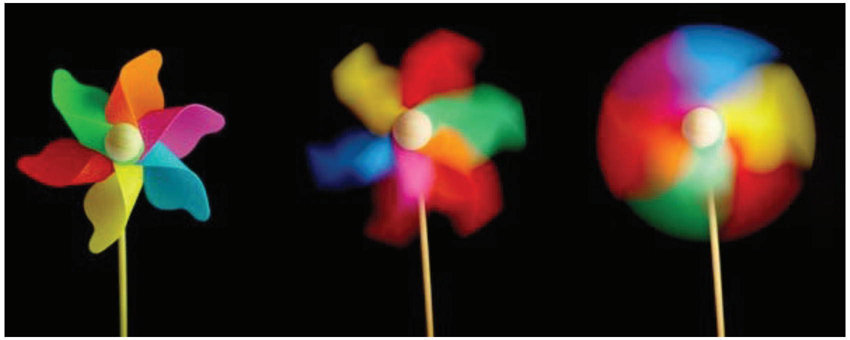
X-rays FELs challenges

Short pulses

Longitudinal coherence

X-rays FELs challenges

Short pulses

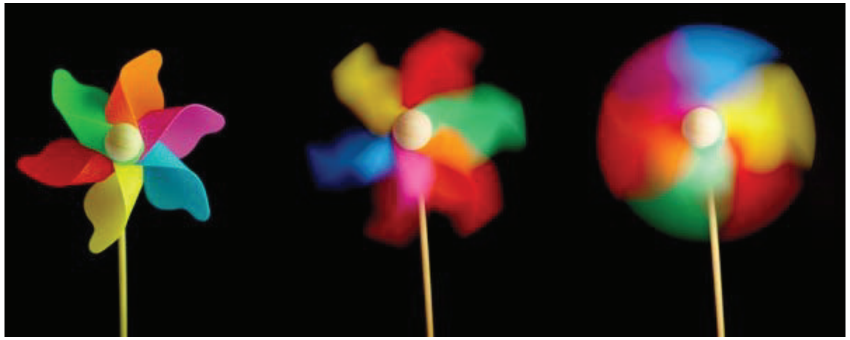


Short exposure time

Longitudinal coherence

X-rays FELs challenges

Short pulses



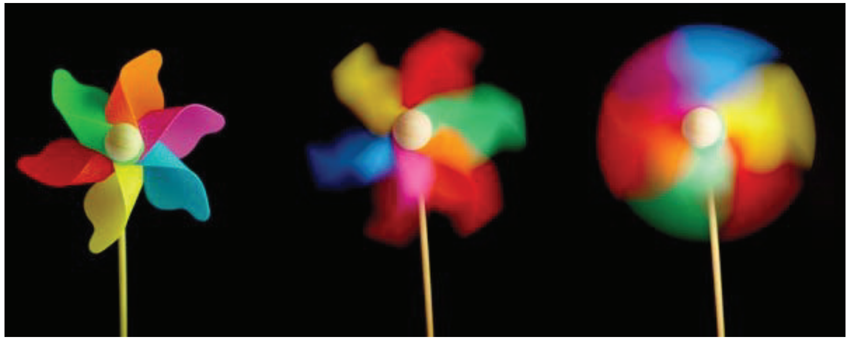
Short exposure time

Preserve samples

Longitudinal coherence

X-rays FELs challenges

Short pulses



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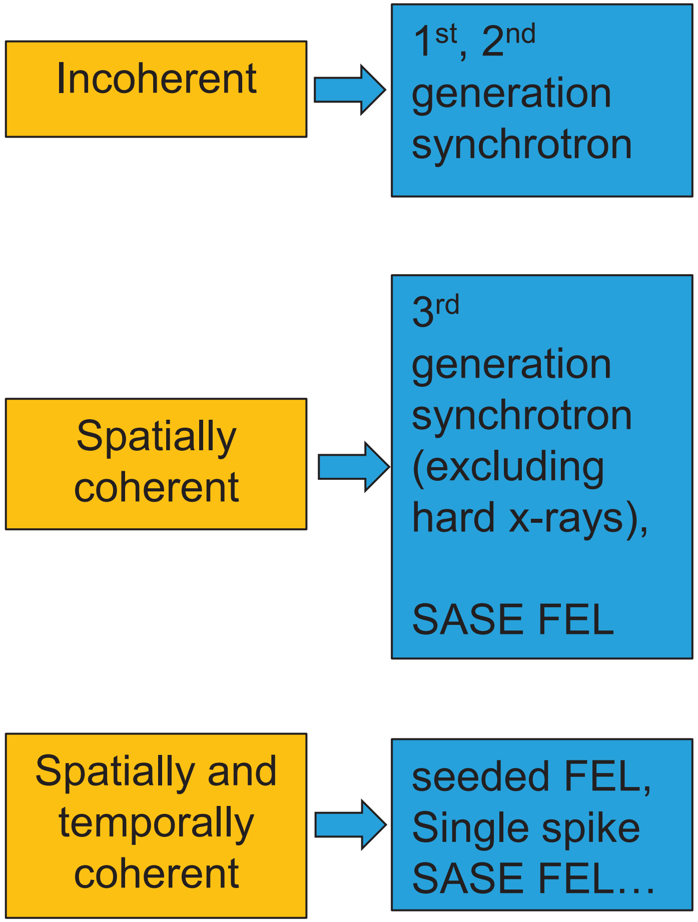
Longitudinal coherence

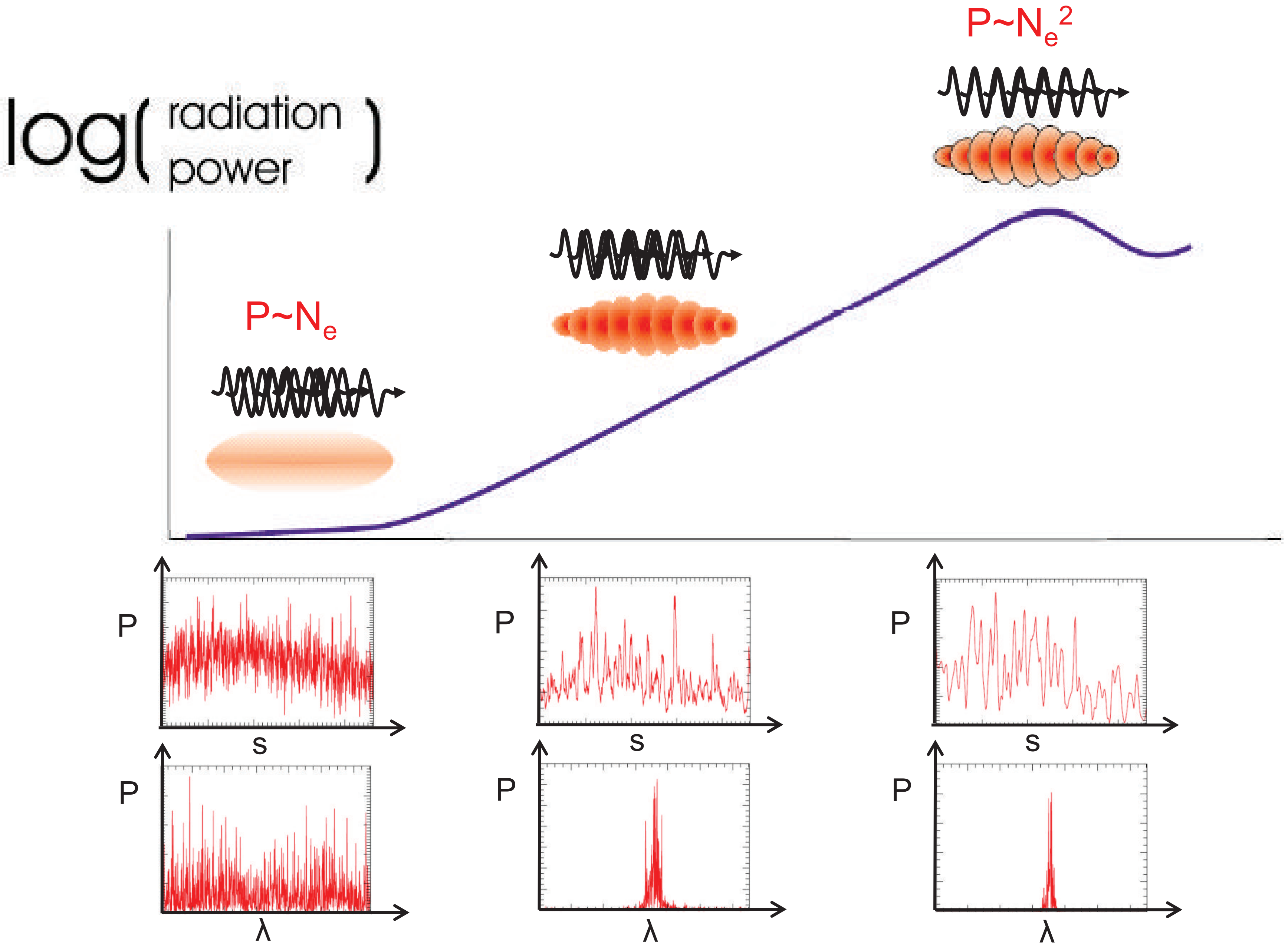


Incoherent → 1^{st}, 2^{nd} generation synchrotron

Spatially coherent → 3^{rd} generation synchrotron (excluding hard x-rays), SASE FEL

Spatially and temporally coherent → seeded FEL, Single spike SASE FEL…

Lack of longitudinal coherence in SASE FEL



Methods to produce fully coherent and/or extremely short x-ray radiation pulses

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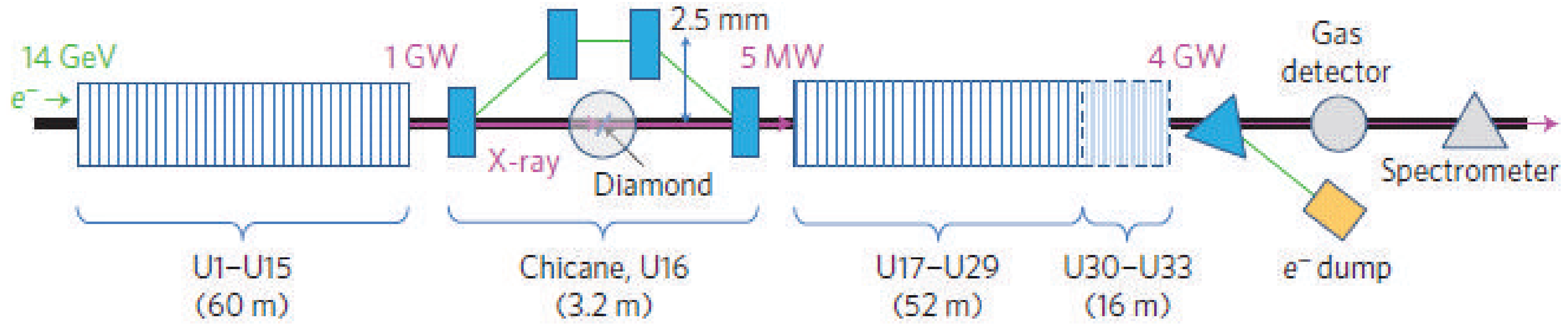

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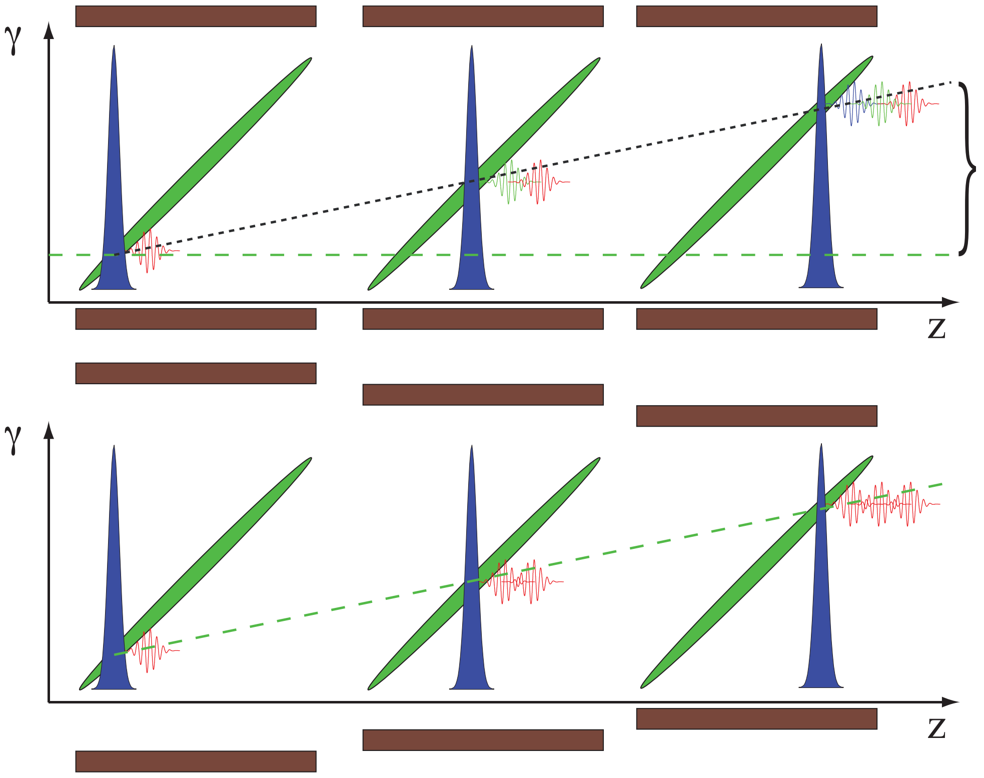

- L. Gianne Emission
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  Undulato 01
- E. Saldin sion FEL with
  energy-c neration of
  attosecor cs -
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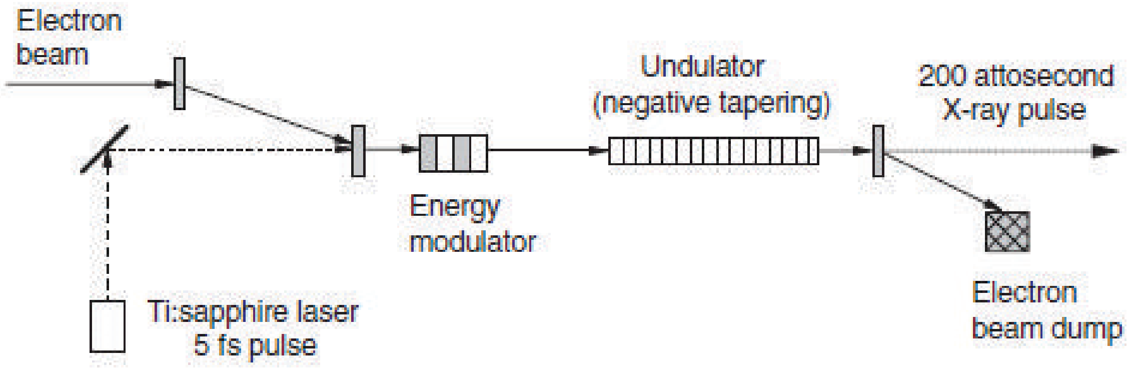

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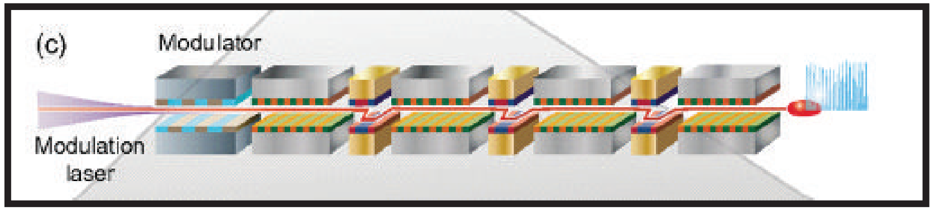

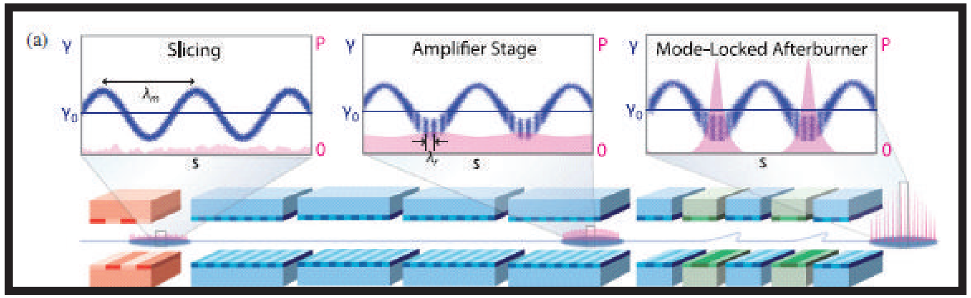

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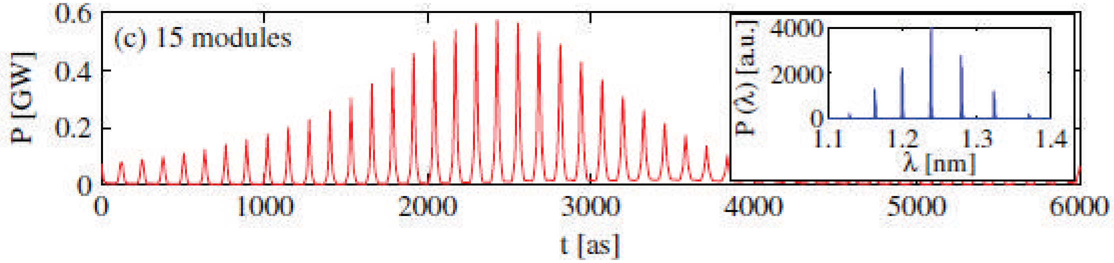

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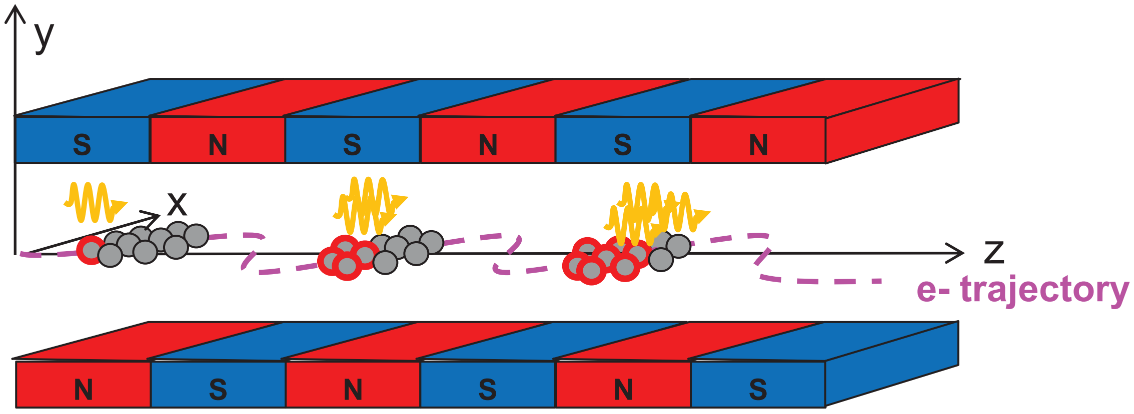
- Single spike SASE FEL: → Long. coherent radiation pulses, minimum length limited by cooperation length
  - S. Reiche et al., 2008. Nuclear Instruments and Methods in Physics Research A 593, 45-48.
  - J. B. Rosenzweig et al., 2008. Nuclear Instruments and Methods in Physics Research A 593, 39-44.
  - Y. Ding et al., 2009. Physical Review Letters 102, 254801.
  - L. Wang et al., 2011. Proceedings of IPAC2011.

Cooperation Length



N_w = number of undulator periods
λ = resonant wavelength

The radiation propagates faster than the electron (it “slips” by λ per undulator period); thus electrons communicate with the ones in front only if their separation is less than the total slippage S:

$$S=N_w\lambda.$$

The Cooperation Length is defined as the slippage in one power gain length

$$\boxed{L_c = \frac{\lambda}{4\pi\rho}}$$

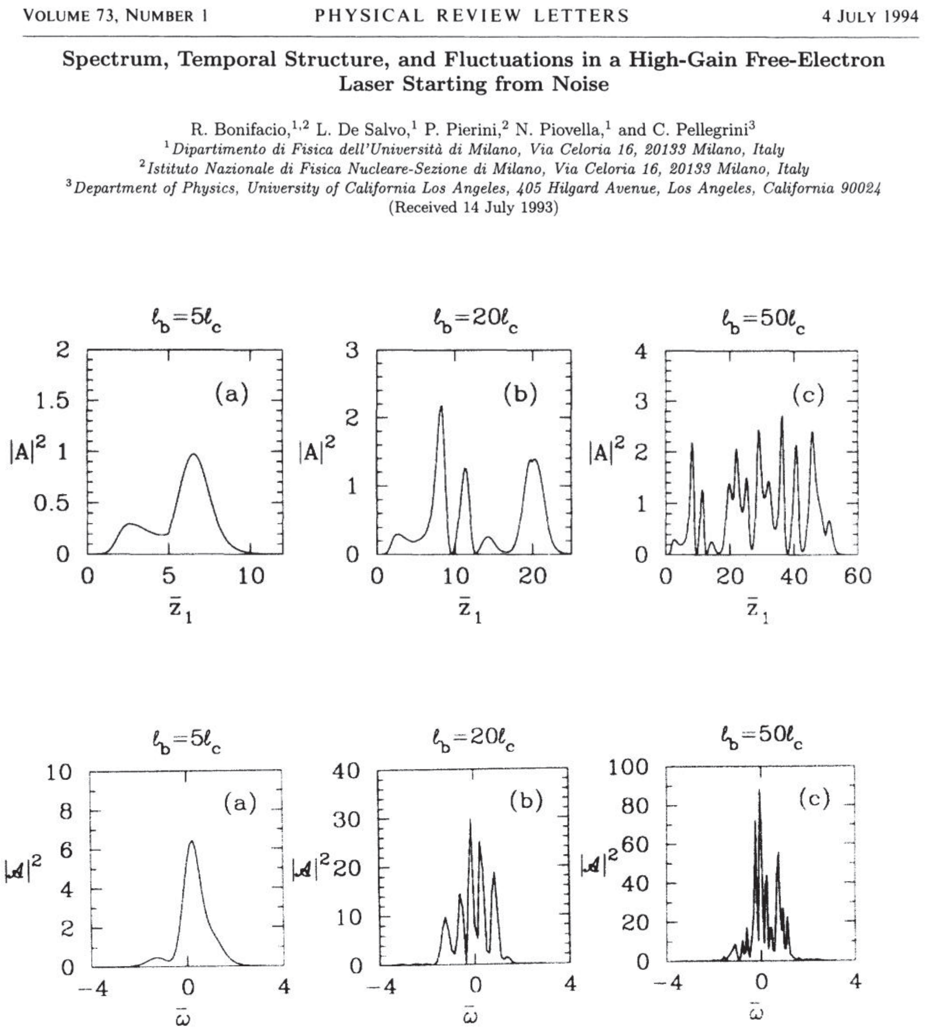
ρ = Pierce parameter

Single spike condition in SASE FELs

$L_b \leq 2\pi L_c$ → single spike regime
L_b = bunch length
L_c = cooperation length

Number of the spikes:

$$N_s = \frac{L_b}{2\pi\, L_c}$$



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Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]
[1] *Dipartimento di Fisica dell'Università di Milano, Via Celoria 16, 20133 Milano, Italy*
[2] *Istituto Nazionale di Fisica Nucleare-Sezione di Milano, Via Celoria 16, 20133 Milano, Italy*
[3] *Department of Physics, University of California Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90024*
(Received 14 July 1993)

Short pulses operation and choice of the laser parameters

- In order to fulfill the single spike condition (or get as close as possible to it) the charge of the electron bunch must be small (sub pC or few tens of pC) and it is necessary to work at the maximum compression point (or very close to it).

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- In order to fulfill the single spike condition (or get as close as possible to it) the charge of the electron bunch must be small (sub pC or few tens of pC) and it is necessary to work at the maximum compression point (or very close to it).
- The working point deeply different from the nominal XFEL working point that has been already extensively studied [*I. Zagorodnov, M. Dohlus, 2011. PRSTAB 14, 014403*] and that has to fulfill mainly the ultra-high brilliance request

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- In *I. Zagorodnov, Ultra-short low charge operation at FLASH and the European XFEL Proceeding of FEL 2010* has been underlined that the use of a similar approach for the ultra-short low charge operation ends up into strong stability requirements for the RF-jitter.

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- The use of a short electron bunch at the gun exit helps to relax the RF tolerances.

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- The use of a shorter e-bunch at the gun exit helps to relax the RF tolerances.
- The European XFEL facility is foreseen to have a unique type of photo-cathode laser, whose prototype is currently installed at PITZ [*I. Will, G. Klemz, 2008. Generation of flat-top picosecond pulses by coherent pulse stacking in a multicrystal birefringent filter. Optics Express 16 14922*]. This laser allows to tune the longitudinal flat-top shape of the pulse up to 20ps FWHM. The shortest feasible laser profile is a Gaussian having a FWHM of about 2 ps.

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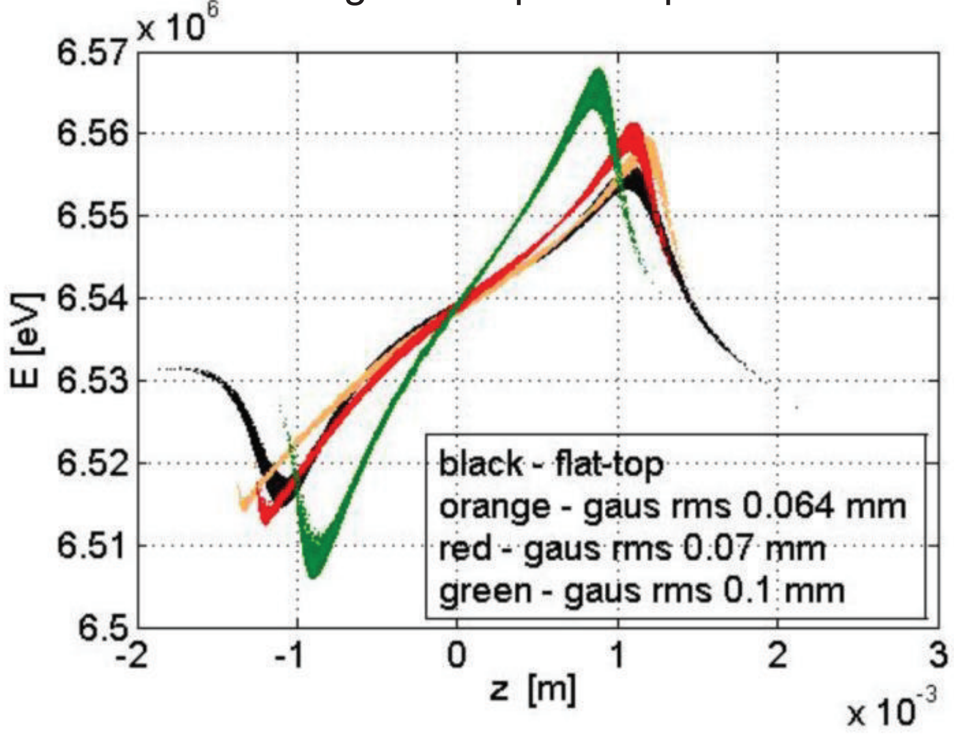
- The use of a shorter e-bunch at the gun exit helps to relax the RF tolerances.
- The European XFEL laser allows to tune the longitudinal flat-top shape of the pulse up to 20ps FWHM. The shortest feasible laser profile is a Gaussian having a FWHM of about 2 ps.
- In the present work we will present the compression of a 20pC electron bunch for single spike operation in the hard x-rays (0.26 nm) using different longitudinal photo-cathode laser shapes shorter than the nominal XFEL working point.

Input beams

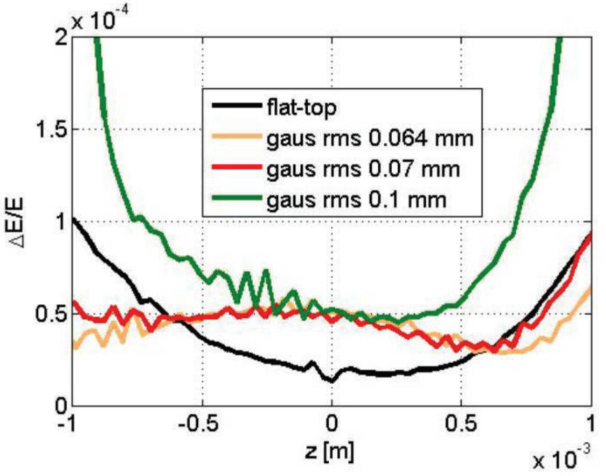
Longitudinal phase space



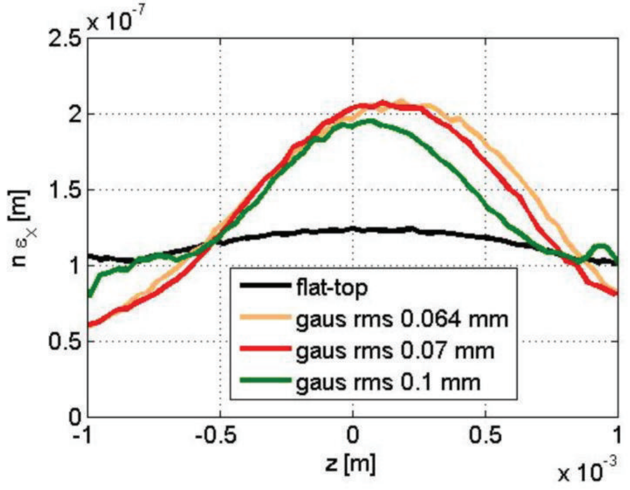
Flat top laser pulse
2/5.4\2 ps,
Transverse rms 0.11 mm

Gaussian laser pulse
2.1 ps FWHM
transverse rms 0.1-0.07-0.064 mm

Slice energy spread

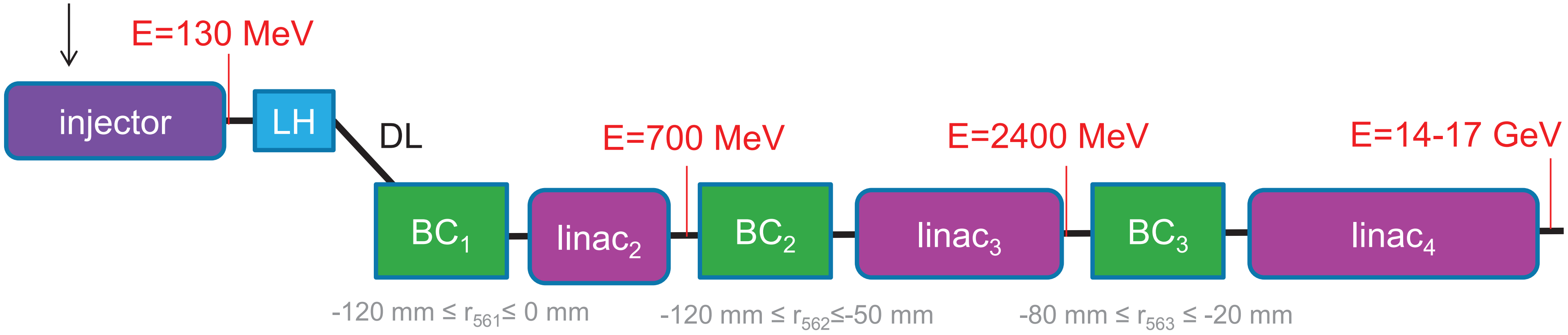


Normalized slice emittance

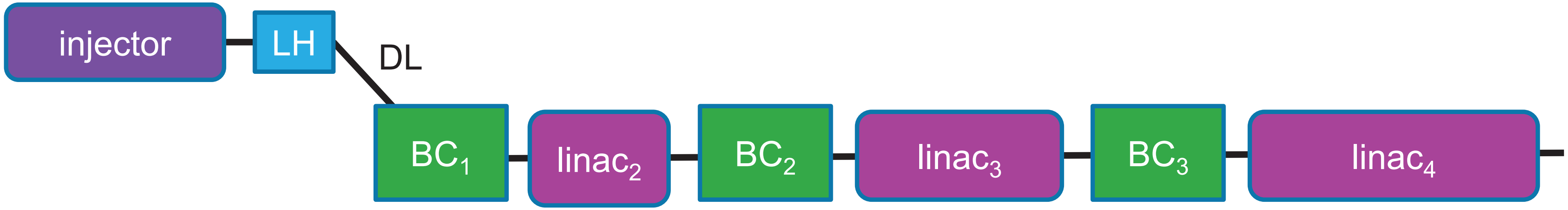


European XFEL layout

- Photocathode RF gun, 1.6 cell L-band normal conducting having 60 MV/m peak E_{field} at the Cs_2Te cathode
- TESLA accelerating cavity, 1.3 GHz
- TESLA 3.9 GHz cavity



Analytical guess of the required energy deviation at the exit of the injector



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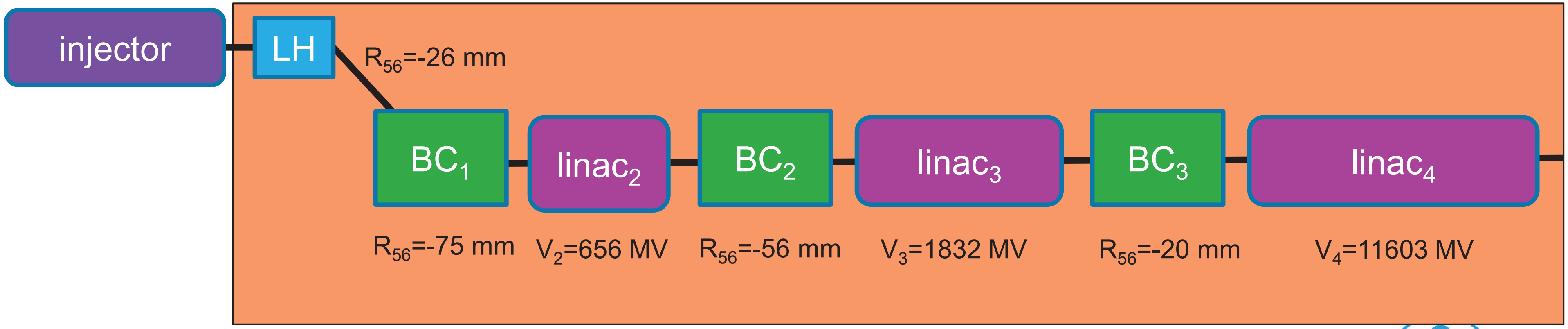


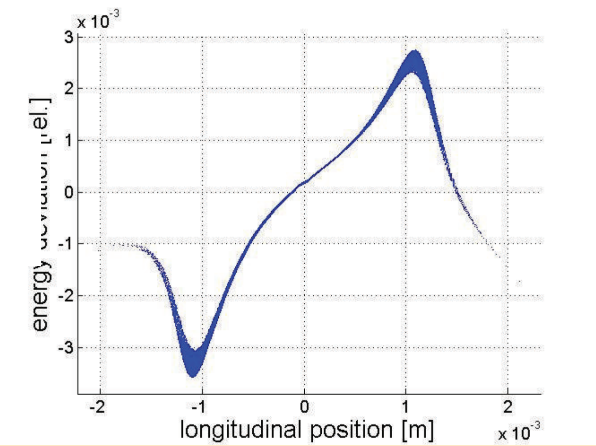
Analytical guess of the required energy deviation at the exit of the injector

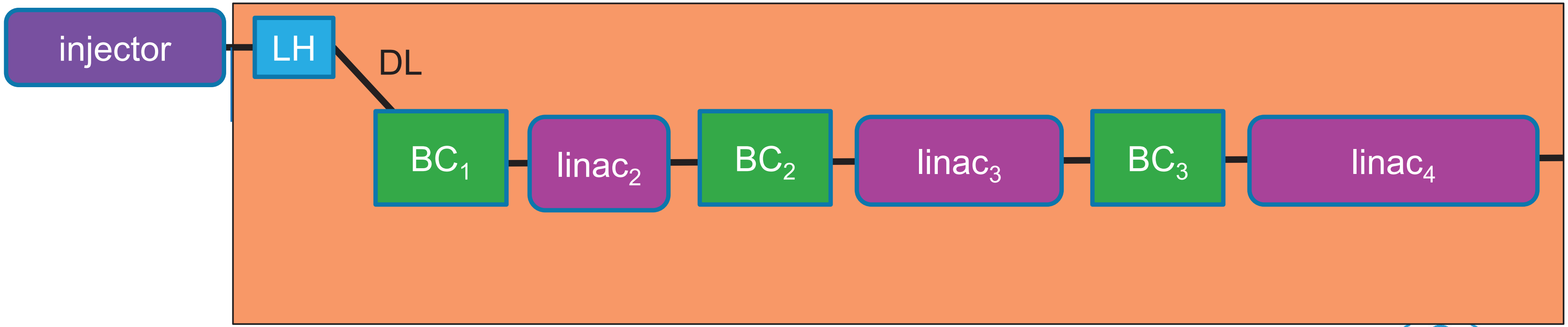
Energy of the particle at position s

$$\delta(s) \equiv \frac{E_0(s) - E_{ref}}{E_{ref}} \approx \delta'(0)s + \frac{\delta''(0)}{2}s^2 + \frac{\delta'''(0)}{6}s^3$$

Energy deviation at position s

Energy of the reference particle





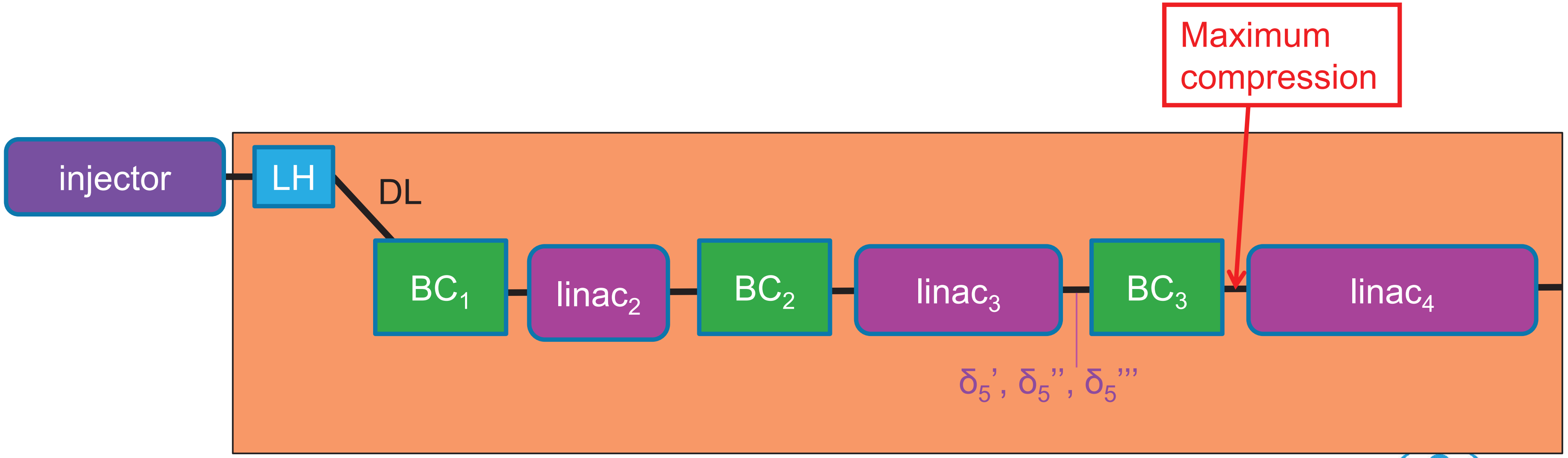
Analytical guess of the required energy deviation at the exit of the injector

Longitudinal “matching conditions” (K. Flöttmann et al., 2001. Generation of Ultrashort Electron Bunches by cancellation of nonlinear distortions in the longitudinal phase space. TESLA FEL Report 2001-06.):

$$\delta'_5 = -\frac{1}{R_{56}}$$

$$\delta''_5 = -2(\delta'_5)^2 \frac{T_{566}}{R_{56}}$$

$$\delta'''_5 = \frac{6}{R_{56}}\left[-(\delta'_5)^3 U_{5666} + 2\delta'_5 \frac{T_{566}^{\,2}}{R_{56}}\right]$$



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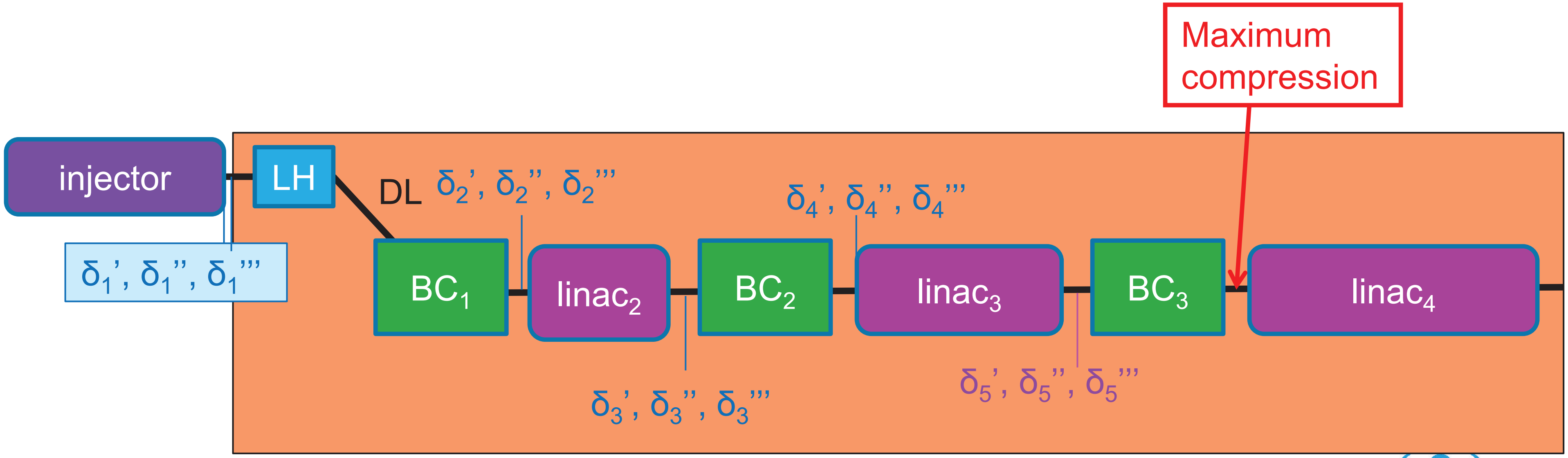
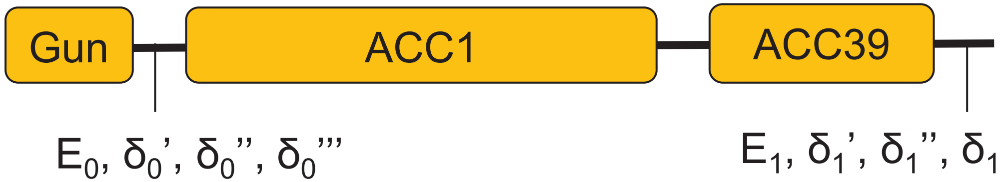


Calculation of the setup of the injector

δ_1', δ_1'' and δ_1''' are known

Injector scheme:



Gun

ACC1

ACC39

E_0, δ_0', δ_0'', δ_0'''

E_1, δ_1', δ_1'', δ_1'''

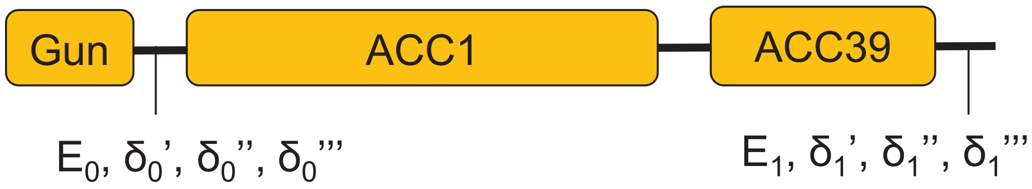
Calculation of the setup of the injector

δ_1', δ_1'' and δ_1''' are known

↓

δ_0', δ_0'' and δ_0''' are calculated by fitting the ASTRA output at the gun exit

Injector scheme:



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↓

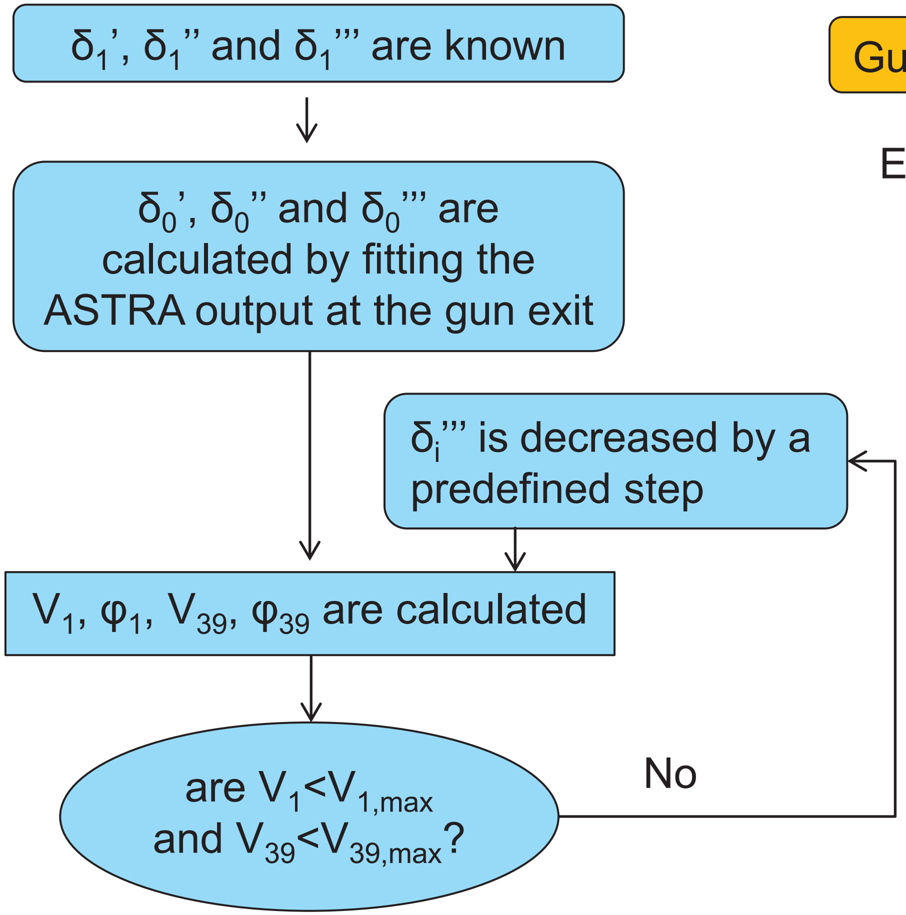
V_1, φ_1, V_{39}, φ_{39} are calculated

Injector scheme:

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & -k & 0 & -nk \\ -k^2 & 0 & -(nk)^2 & 0 \\ 0 & k^3 & 0 & (nk)^3 \end{pmatrix} \begin{pmatrix} X_{11} \\ Y_{11} \\ X_{1n} \\ Y_{1n} \end{pmatrix} = \begin{pmatrix} E_1 - E_0 \\ E_1\delta'_1 - E_0\delta'_0 \\ E_1\delta''_1 - E_0\delta''_0 \\ E_1\delta'''_1 - E_0\delta'''_0 \end{pmatrix}$$

$$\begin{aligned} X_{11} + iY_{11}e^{i\phi_{11}} &= V_{11}e^{i\phi_{11}} \\ X_{1n} + iY_{1n}e^{i\phi_{1n}} &= V_{1n}e^{i\phi_{1n}} \end{aligned}$$

Calculation of the setup of the injector



δ_1', δ_1'' and δ_1''' are known

δ_0', δ_0'' and δ_0''' are calculated by fitting the ASTRA output at the gun exit

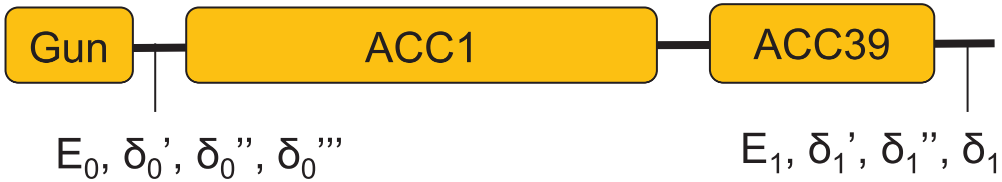
δ_i''' is decreased by a predefined step

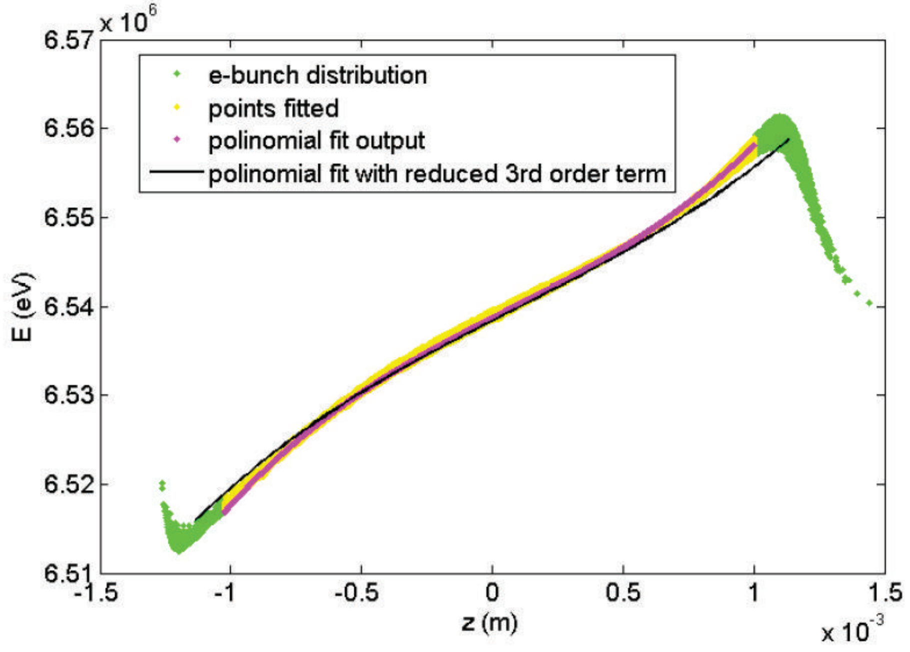
V_1, φ_1, V_{39}, φ_{39} are calculated

are $V_1<V_{1,max}$ and $V_{39}<V_{39,max}$?

No

Injector scheme:





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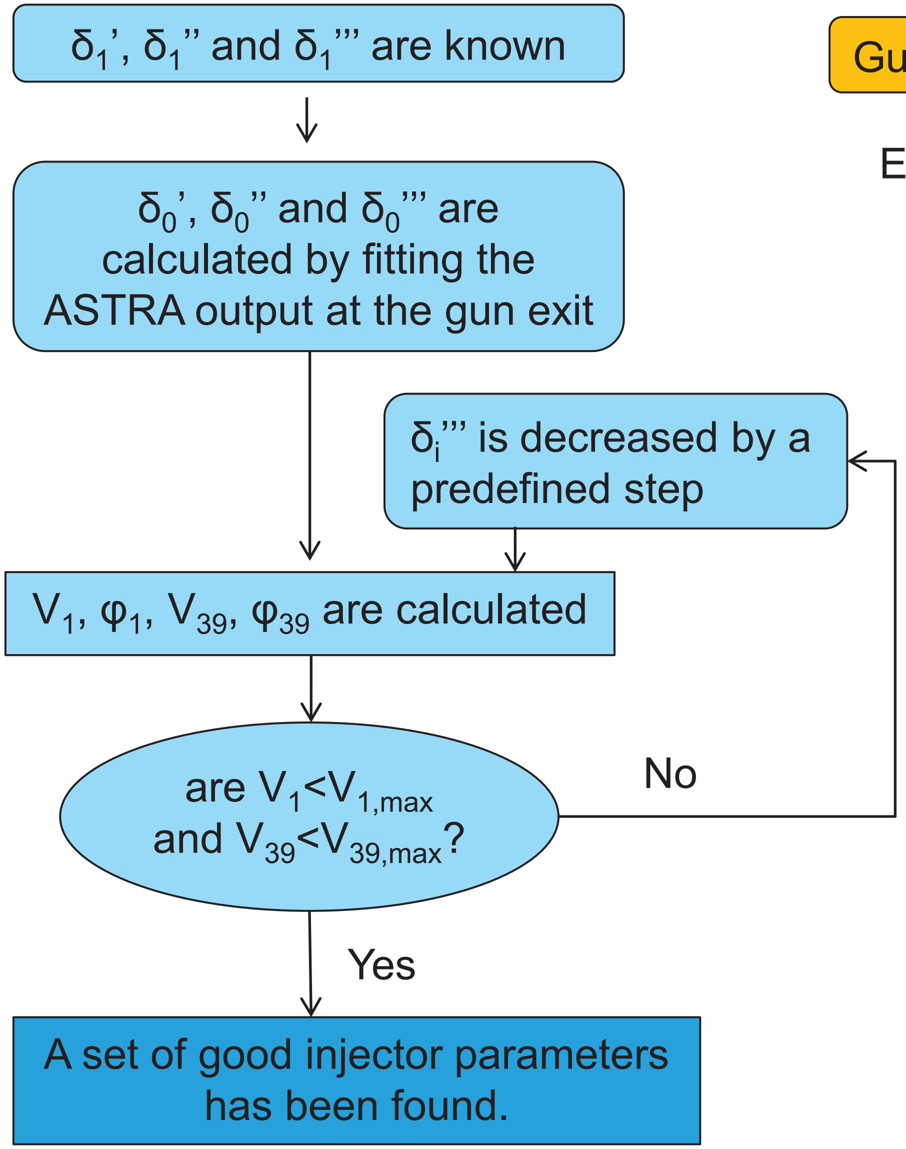


δ_1', δ_1'' and δ_1''' are known

δ_0', δ_0'' and δ_0''' are calculated by fitting the ASTRA output at the gun exit

δ_i''' is decreased by a predefined step

V_1, φ_1, V_{39}, φ_{39} are calculated

are $V_1<V_{1,max}$ and $V_{39}<V_{39,max}$?

No

Yes

A set of good injector parameters has been found.

Injector scheme:

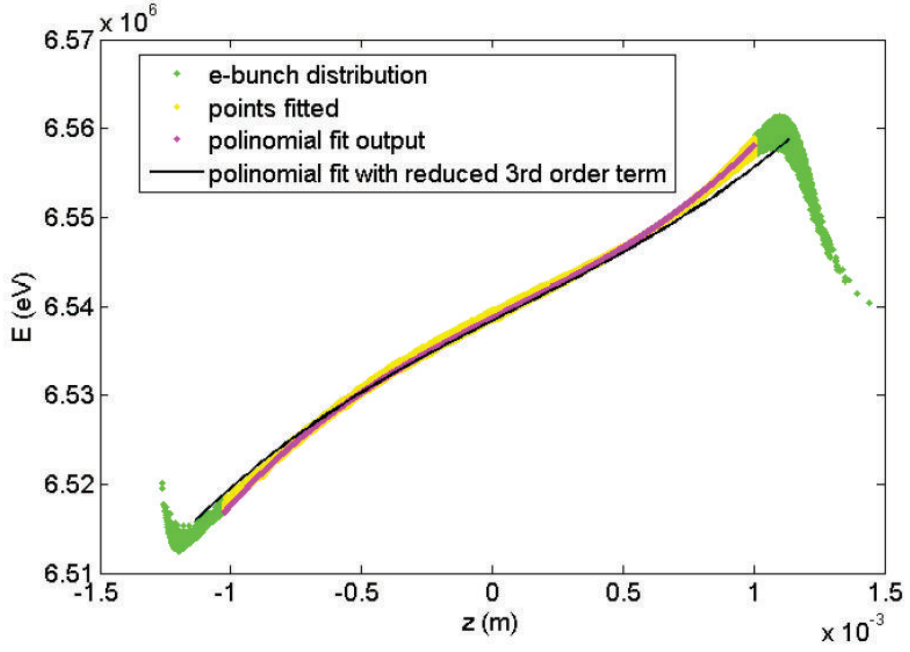
Gun

ACC1

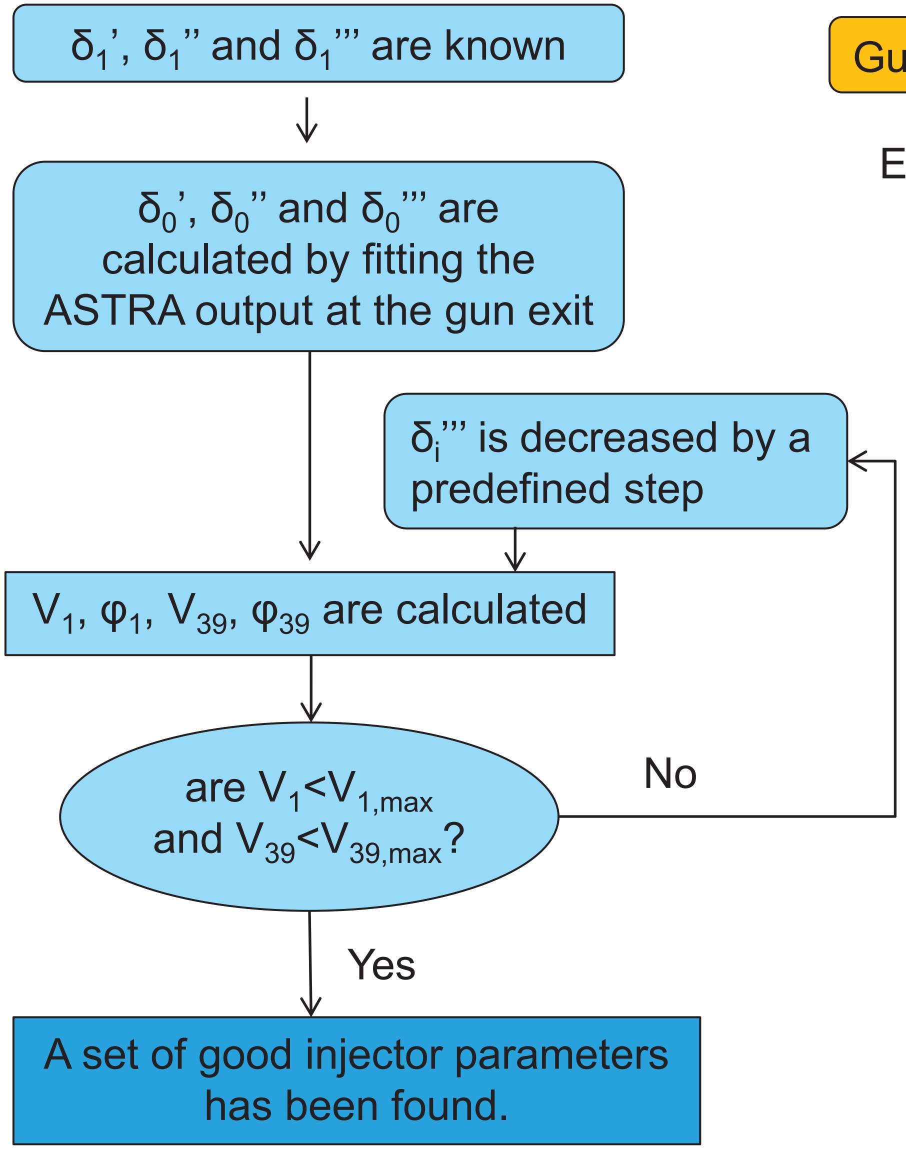
ACC39

E_0, δ_0', δ_0'', δ_0'''

E_1, δ_1', δ_1'', δ_1'''



Calculation of the setup of the injector


δ_1', δ_1'' and δ_1''' are known

δ_0', δ_0'' and δ_0''' are calculated by fitting the ASTRA output at the gun exit

δ_i''' is decreased by a predefined step

V_1, φ_1, V_{39}, φ_{39} are calculated

are $V_1<V_{1,max}$ and $V_{39}<V_{39,max}$?

No

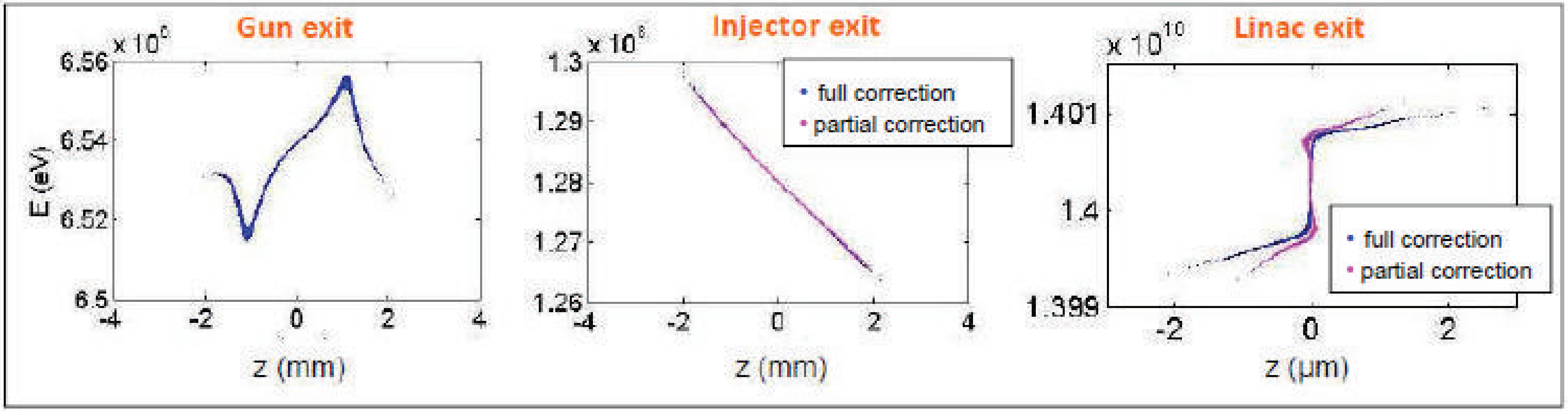
Yes

A set of good injector parameters has been found.

Injector scheme:

The procedure is repeated for slightly different δ_1' values. The initial longitudinal phase space obtained by ASTRA is tracked including RF-wakes in linac1, linac2 and linac3 and the best δ_1' is chosen in order to maximize the local peak current in the central slice of the e-bunch.

Calculation of the setup of the injector



Fast 3D simulations procedure

- **ASTRA** (tracking with 3d space charge, DESY, K. Flöttmann) in the **injector**;
- **CSRtrack** (tracking through dipoles, DESY, M. Dohlus, T. Limberg) in the **LH**, **DL** and **BCs**
- **Linear transport matrices** multiplication in the **linac sections**;
- **RF-wakefields and longitudinal space charge along the linac sections** have been added analytically (I. Zagorodnov, M. Dohlus, Phys. Rev. ST Accel. Beams 14, 014403 (2011)).

Results (maxV_1=180 MV, maxV_{39}=40 MV)

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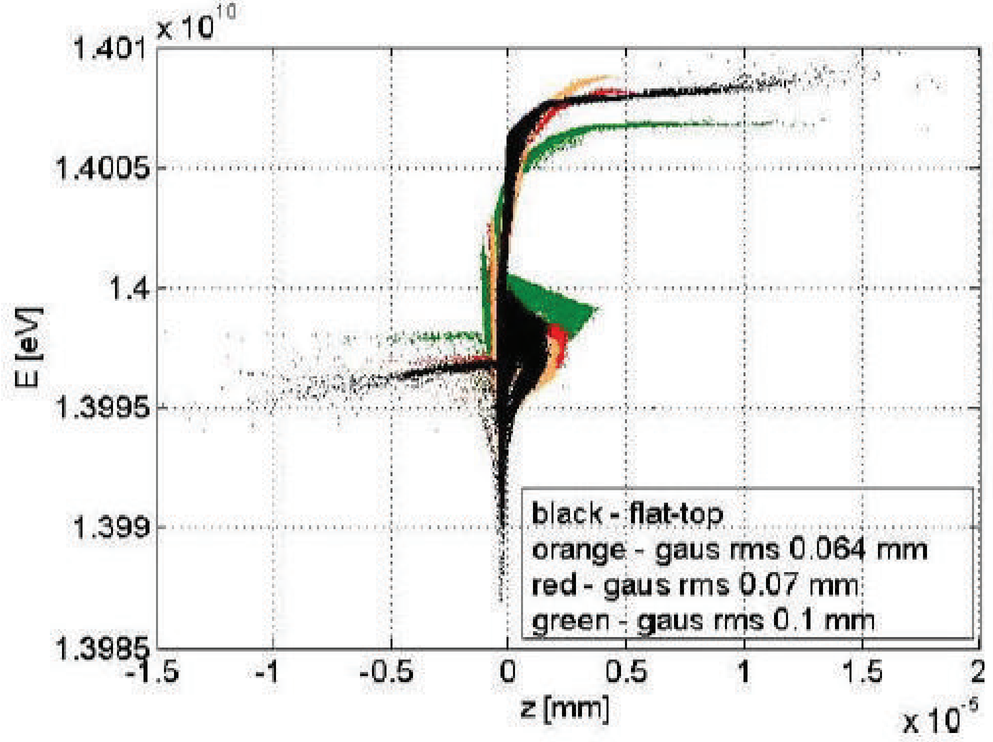
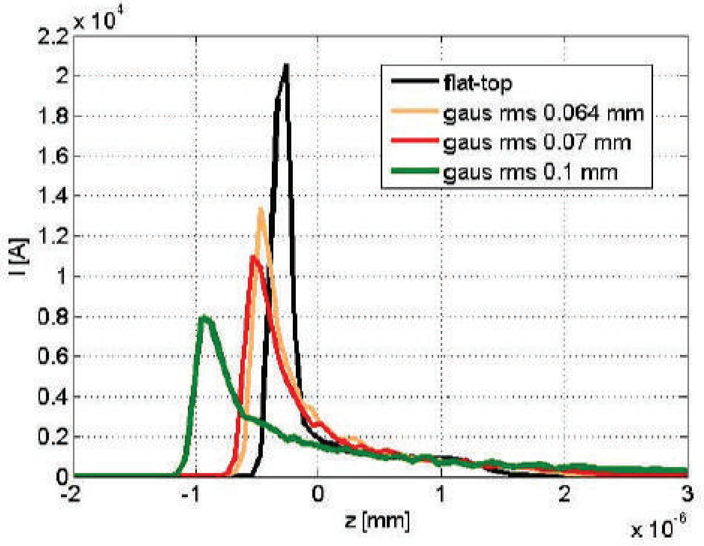




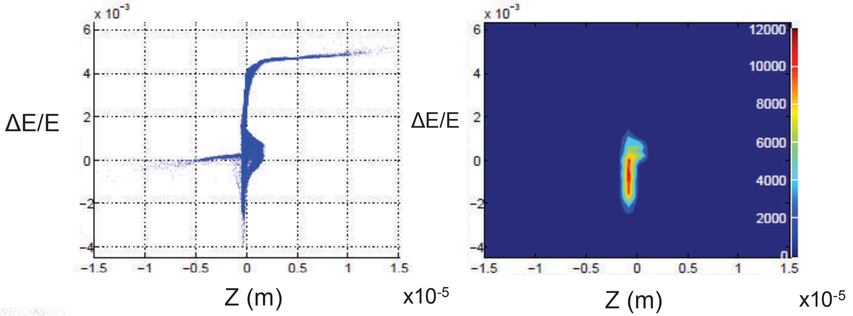
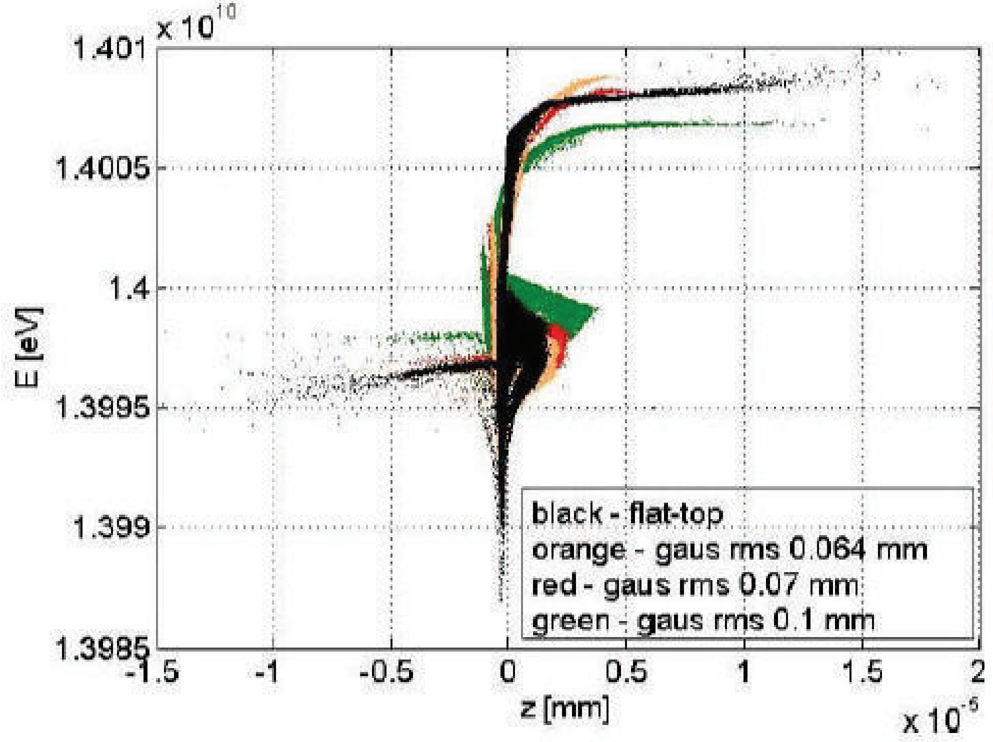


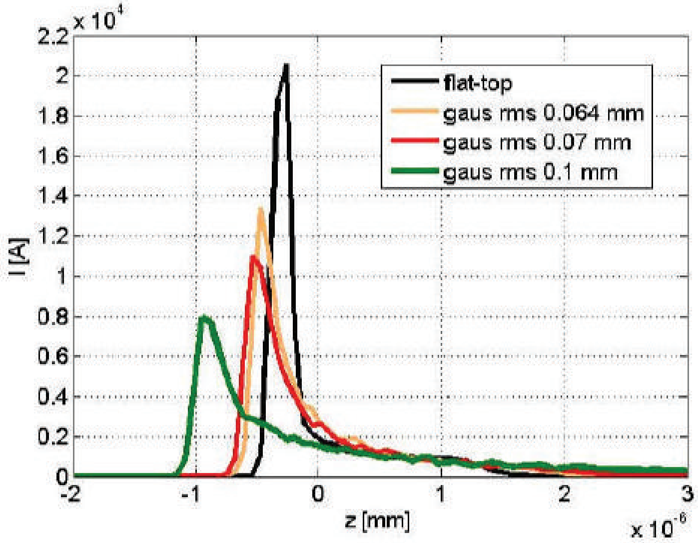
Table 2. Summary of the projected parameters at the exit of the linac for the different input distributions.

Input distr.	$n\epsilon_x$ (μ m)	$n\epsilon_y$ (μ m)	Energy spread (*relative*)	FWHM (*fs*)
Flat-top	0.16	1.11	$2.53 * 10^{-4}$	0.74
Gaus rms 0.064 mm	0.224	0.964	$2.67 * 10^{-4}$	0.934
Gaus rms 0.07 mm	0.21	0.92	$2.33 * 10^{-4}$	1.14
Gaus rms 0.1 mm	0.19	0.804	$1.44 * 10^{-4}$	1.44

Results (maxV_1=180 MV, maxV_{39}=40 MV)

B. Marchetti et al. accepted by Physics Procedia





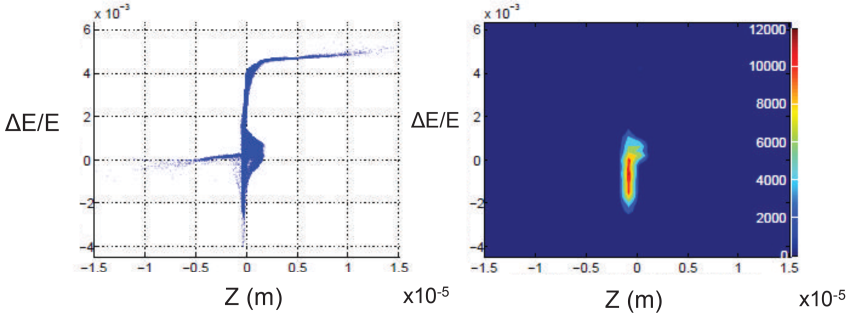
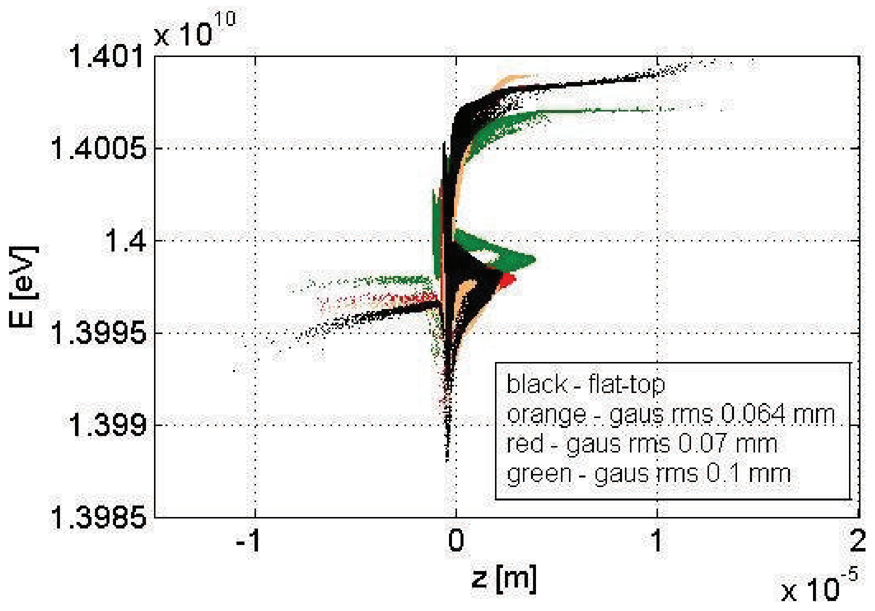
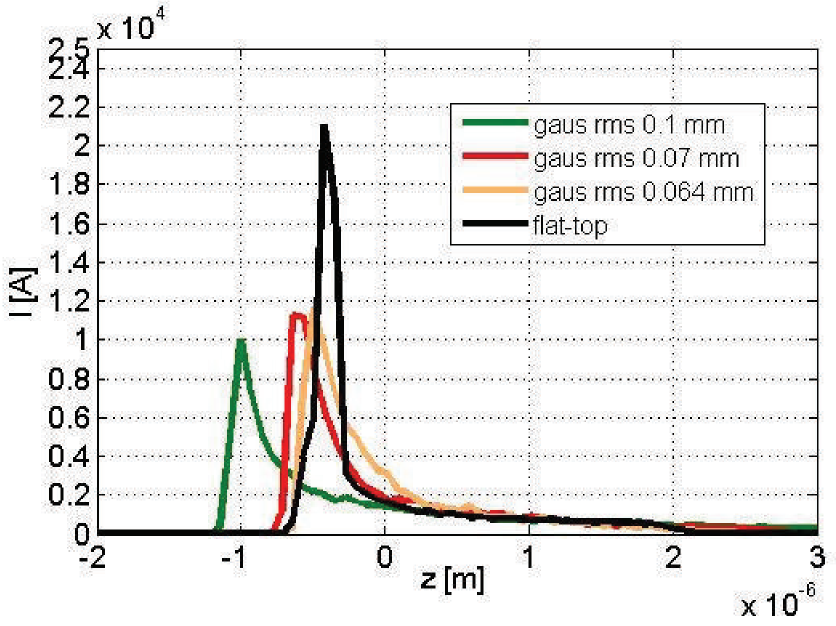


Table 1. Summary of the partial compression factors for the different input distributions.

Input distr.	*DL*	*BC*$_0$	*BC*$_1$	*BC*$_2$
Flat-top	1.3	2.8	7	329
Gaus rms 0.064 mm	1.3	2.1	9.5	259
Gaus rms 0.07 mm	1.3	2.1	9.6	195
Gaus rms 0.1 mm	1.3	2.1	9.6	122

Results (maxV$_1$=150 MV, maxV$_{39}$=30 MV)

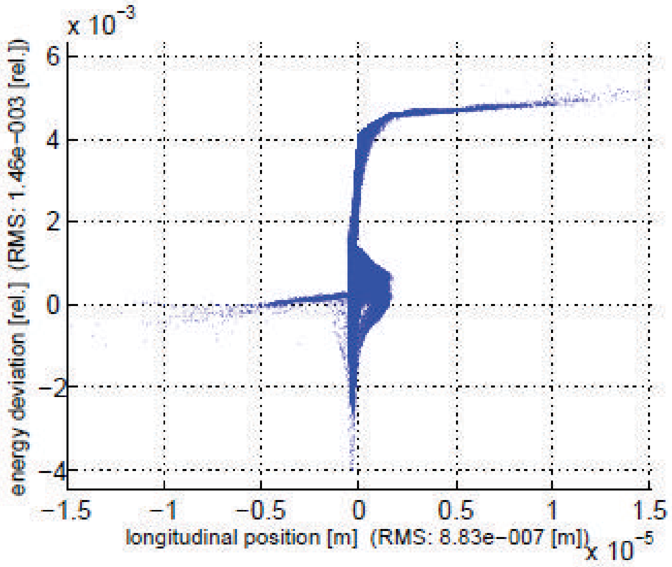


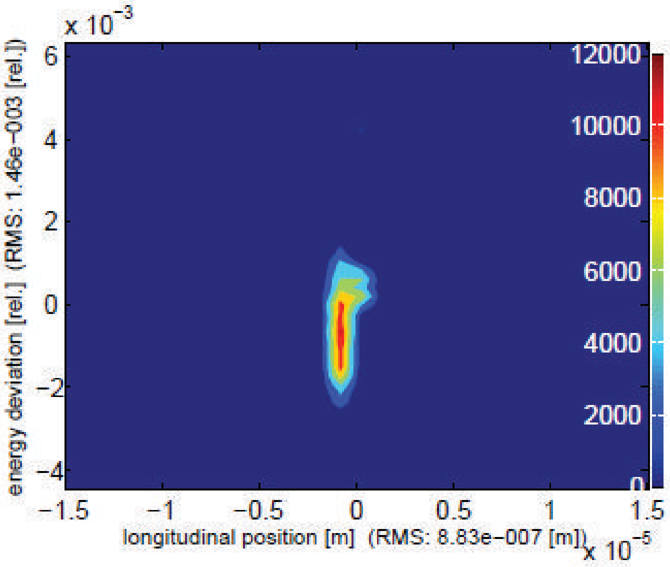


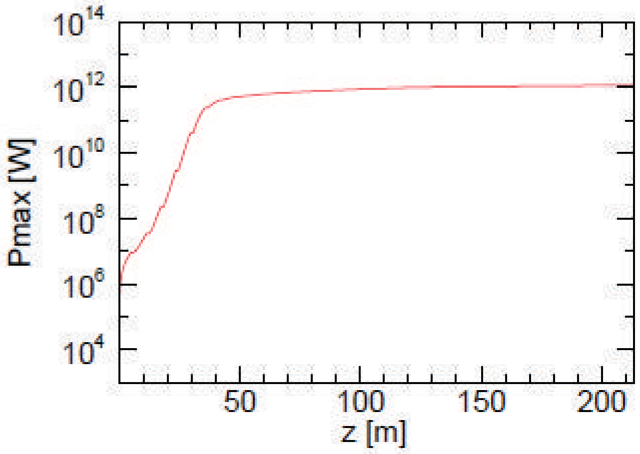
	$n\varepsilon_x$ [mm*mrad]	$n\varepsilon_y$ [mm*mrad]	ΔE [rel]	Long. FWHM [fs]
Flat-top	0.29	0.94	$2.29*10^{-4}$	0.43
Gauss 0.064 mm	0.31	0.77	$2.67*10^{-4}$	1.13
Gauss 0.07 mm	0.29	0.73	$2.12*10^{-4}$	1.05
Gauss 0.1 mm	0.28	0.67	$1.36*10^{-4}$	1.11

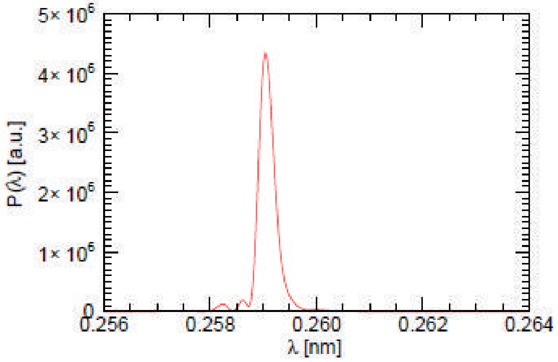
Radiation

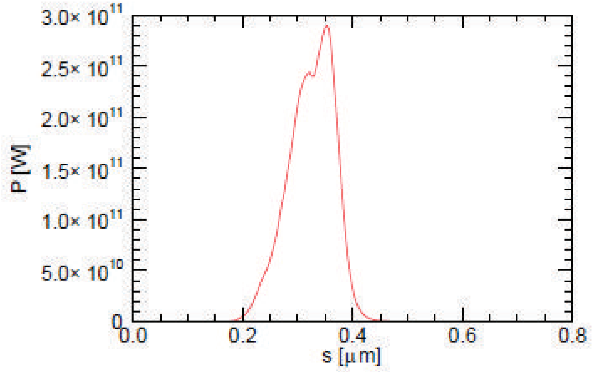
Period [mm]	40
Magnetic Field [T]	1.14
K	4.27
E-bunch energy	14
Wavelength [nm]	2.6







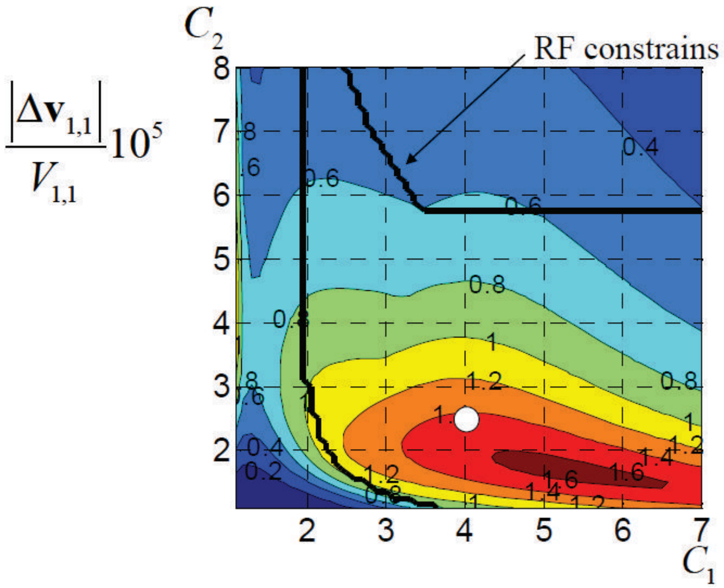




RF tolerances

The RF-jitter that affects most the compression comes from ACC1.

Tolerances on jitter of ACC1 to have 10% variation of the compression factor using a 20ps long flat-top (20pC charge):



Proceedings of FEL2010, Malmö, Sweden

WEOBI2

ULTRA-SHORT LOW CHARGE OPERATION
AT FLASH AND THE EUROPEAN XFEL

Igor Zagorodnov
DESY, Hamburg, Germany

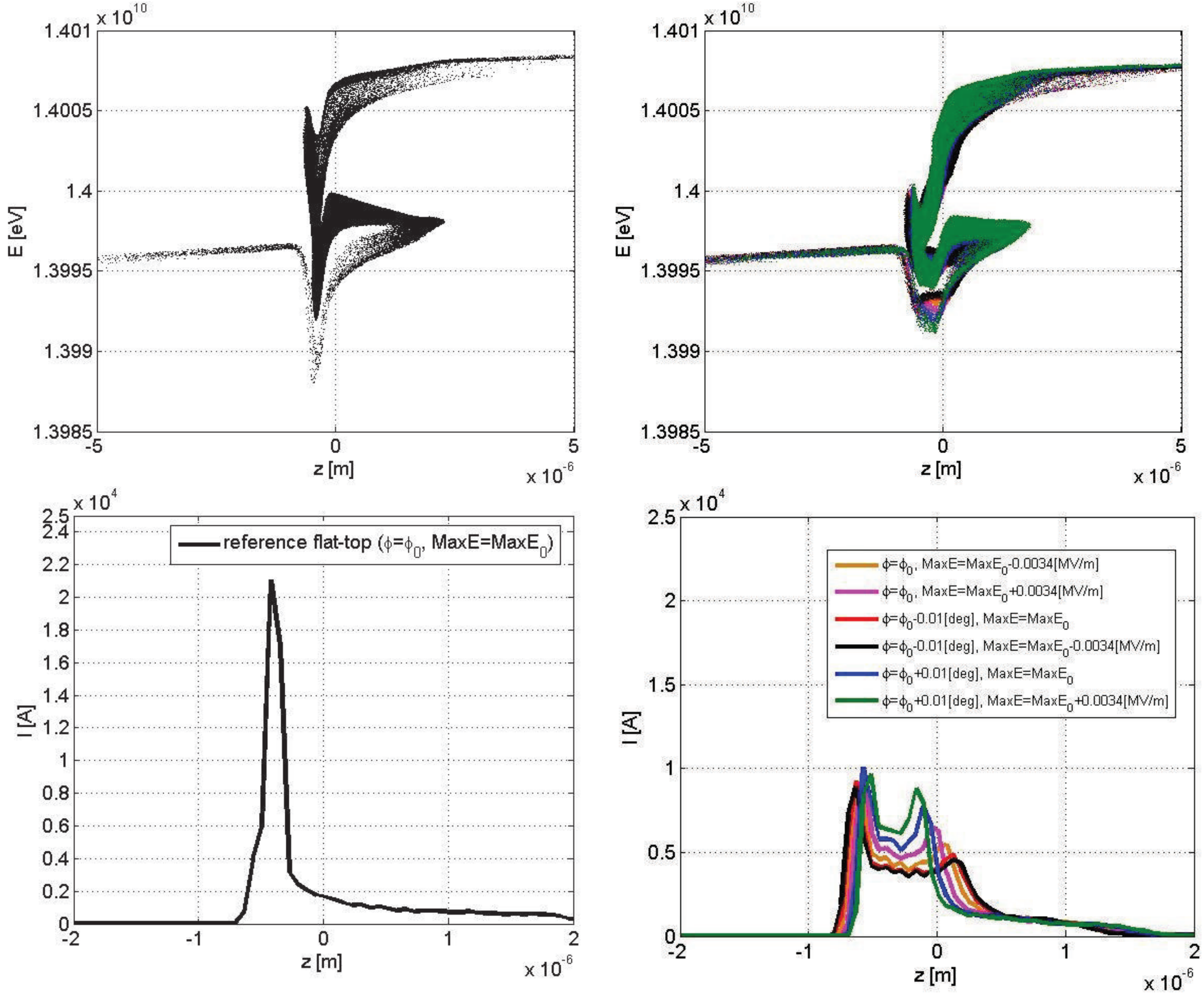
Tolerances on jitter of ACC1 for the simulated short flat-top:

$$\frac{|\Delta v_{1,1}|}{V_{1,1}} = 5.4\text{e-}005$$

RF tolerances – effect of the jitter of ACC1

Instability in the
current profile
for:

Δφ=+/- 0.01 deg
ΔmaxE=+/- 0.01%



Limits of the presented simulations

- The transverse space charge in the linac1 has not been yet included.
- The transport between the exit of linac3 and the entrance of the undulator has been neglected
- In the simulations using Genesis the wakefields in the undulator and the longitudinal SC have not been included.

Conclusions and outlook

- A working point for the European XFEL delivering a single spike radiation pulse at 0.26 nm wavelength has been discussed using fast 3D start to end simulations. This configuration presents an e-bunch already fairly short at the gun exit in order to relax the RF tolerances.
- Full 3D simulations are foreseen using this setup in order to confirm or correct the result. In particular we expect that the inclusion of the 3D space charge force in the linac may impact the total emittance and the slice energy spread of the beam.
- In order to tune the machine settings the full characterization of the electron bunch at the gun exit (in particular the knowledge of its longitudinal phase space distribution) is crucial. Experimental measurements to characterize the e-bunch properties at the exit of the gun are feasible at the PITZ facility at DESY, Zeuthen site, where the same laser and gun of the XFEL facility are present together with the possibility to fully characterize the electron bunch both in the transverse and longitudinal phase space.

Acknowledgements

- I would like to thank Igor Zagorodnov, Mikhail Krasilnikov, Martin Dohlus, Sven Reiche, Frank Stephan, Juliane Roensch Schulenburg and Marie Rehders and in general the group of "Ultra-short pulses at FLASH" for profitable clarifications and discussions.

Thank you for the attention !