Advanced Bunching Scheme at REGAE

Linearization of the longitudinal phase space without higher harmonic field

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LAOLA. is a collaboration of

Outline

> REGAE

  > Time-resolved electron diffraction

  > LAOLA@REGAE: External injection project

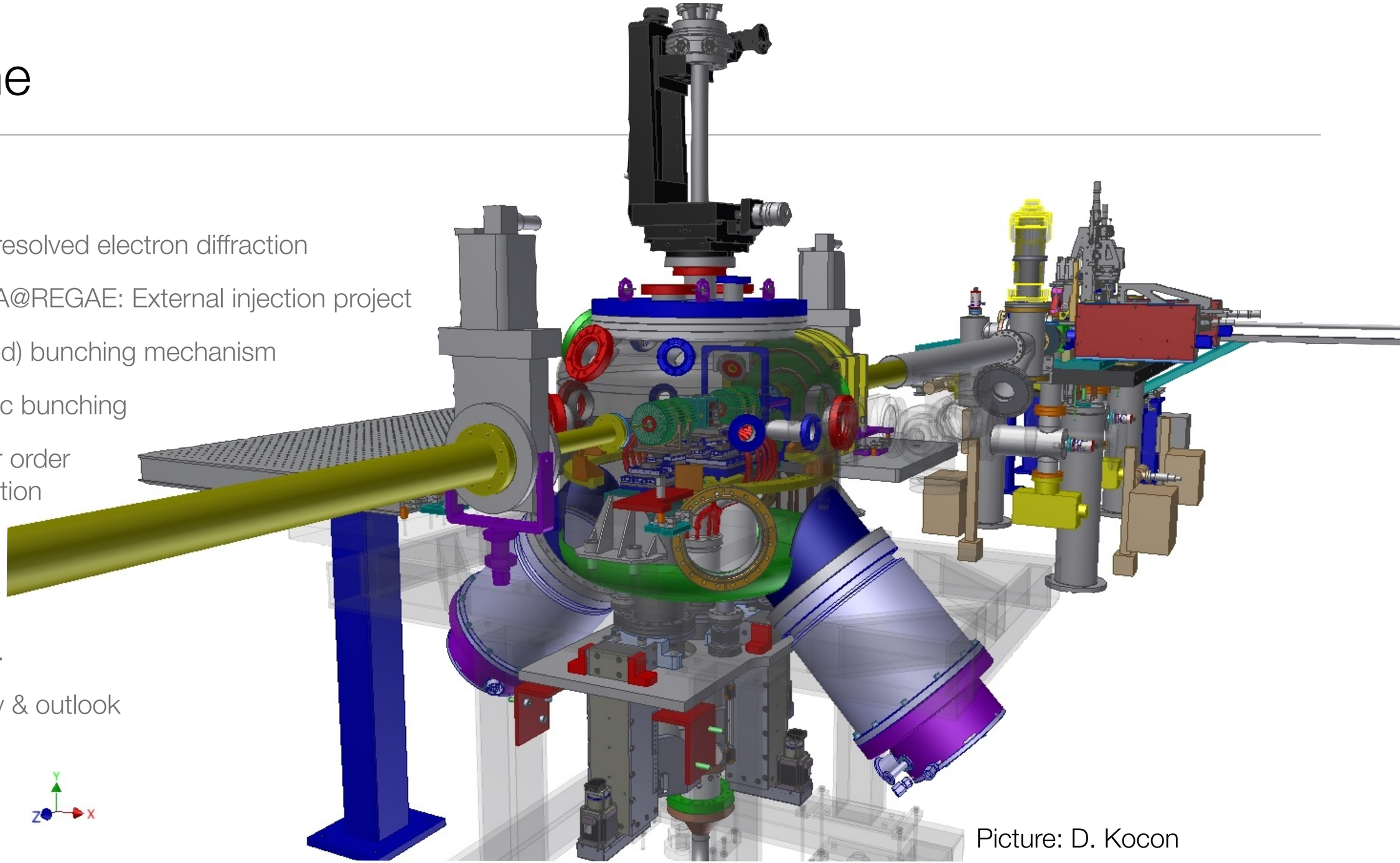
> (Advanced) bunching mechanism

  > Ballistic bunching

  > Higher order correction

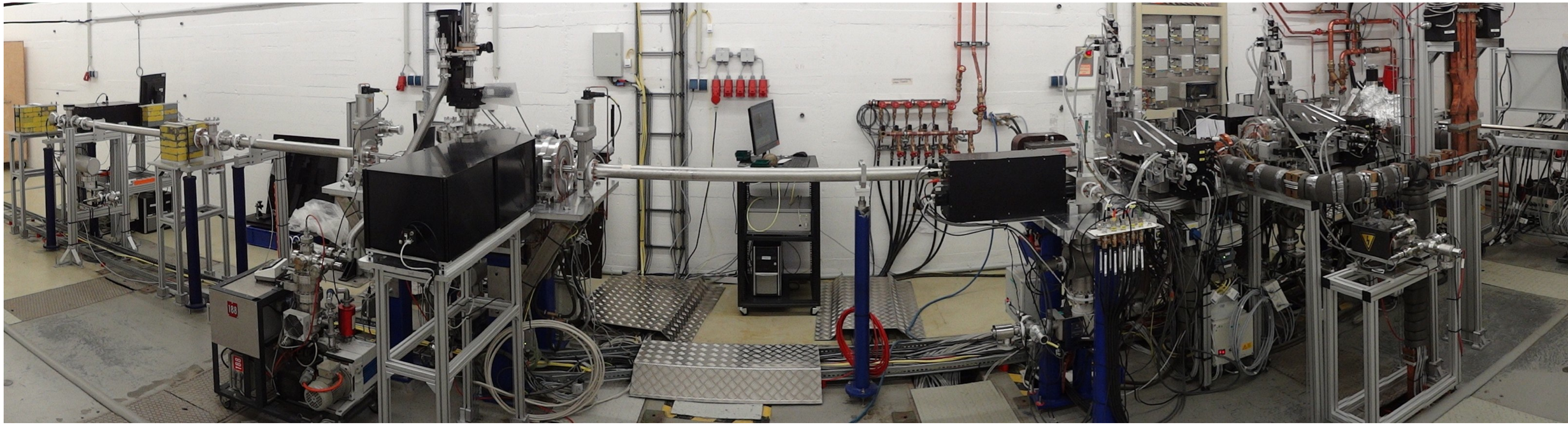
> Results…

> Summary & outlook



Picture: D. Kocon

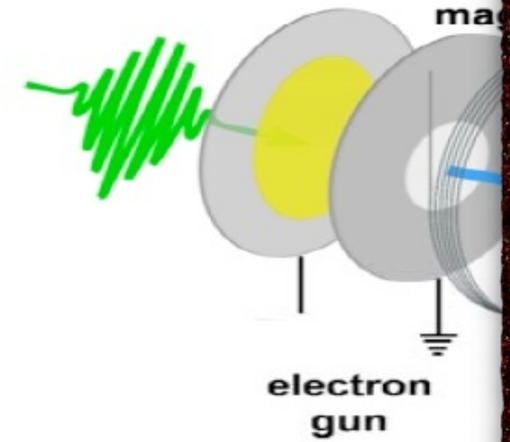
REGAE: Relativistic Electron Gun for Atomic Exploration

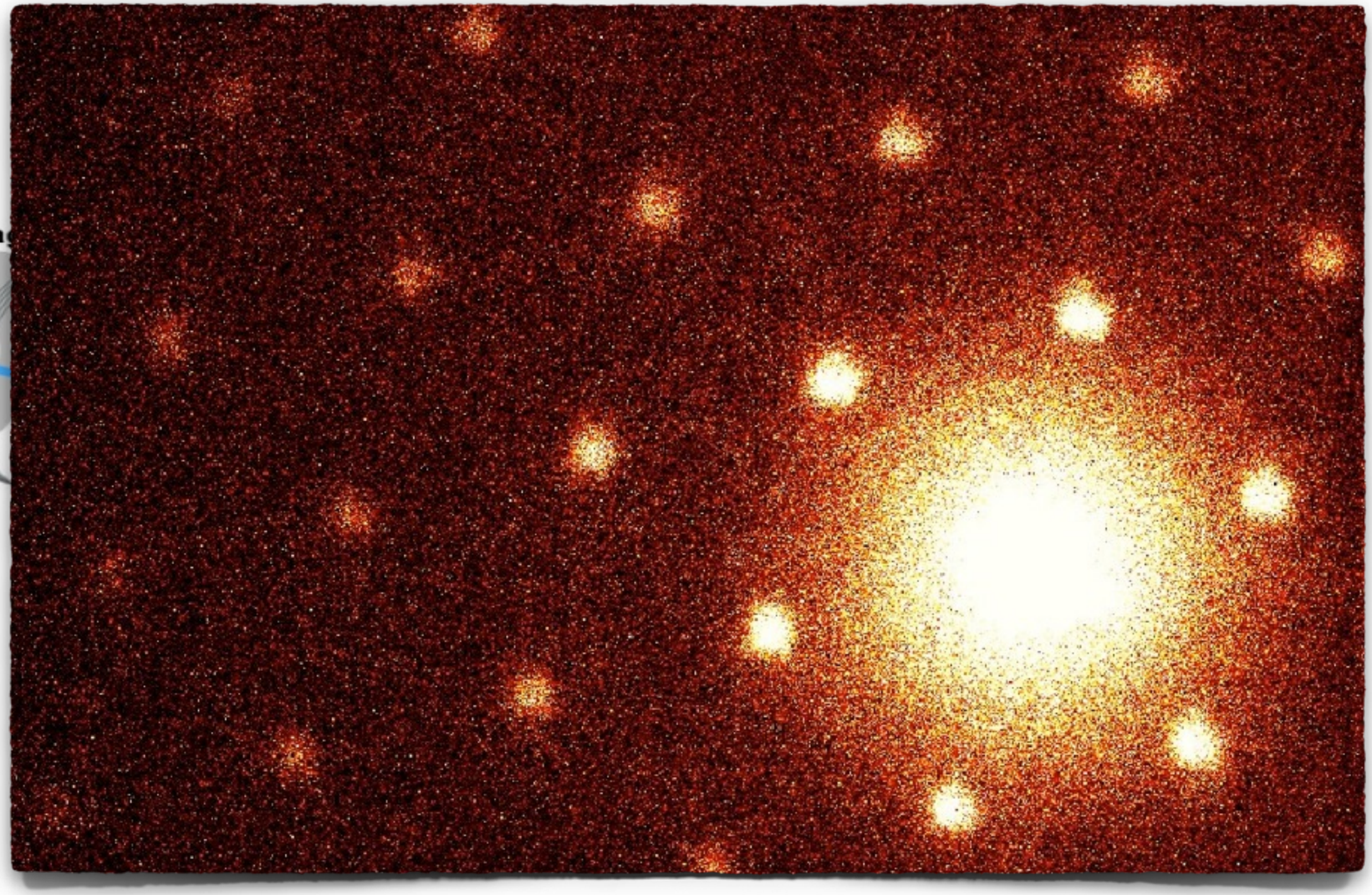


Average Energy	5.6 MeV
Energy Spread	10 keV
Bunch Charge	100 fC
Bunch Length	<10 fs (rms)
Beam Size	600 µm (rms)
Transv. Emittance	0.03 π mm mrad

REGAE: Time-resolved Electron Diffraction

> „Design goal“





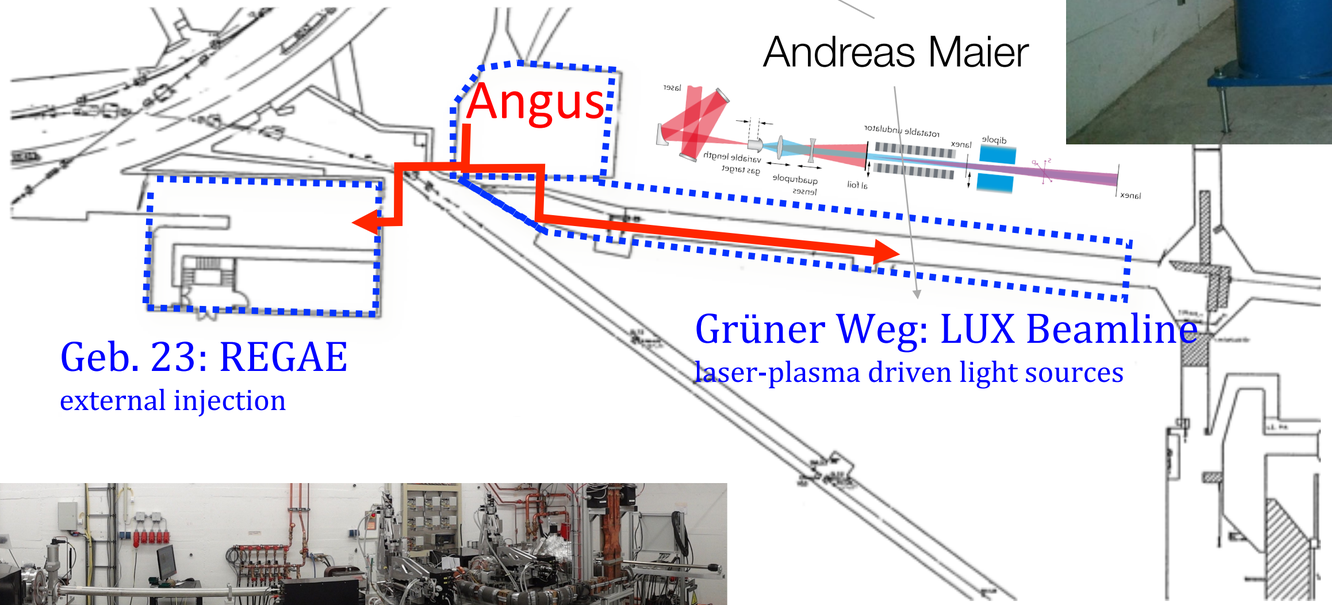
Courtesy by
Group of R.J.D. Miller

LAOLA@REGAE (& LUX Project)

Geb. 22: New Laserlab

ANGUS, a new 200 TW laser

Andreas Maier

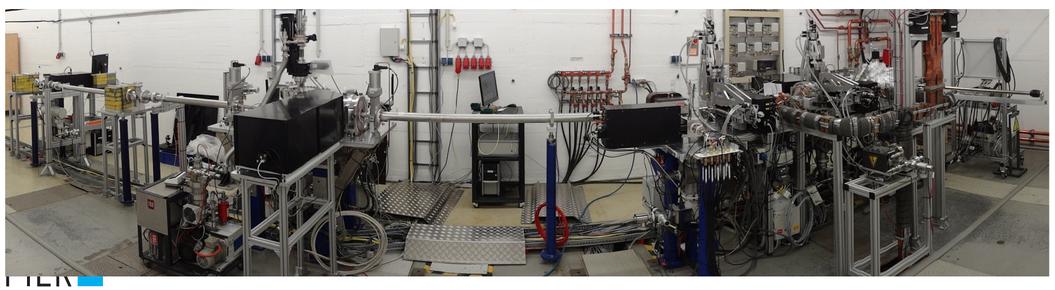


Grüner Weg: LUX Beamline

laser-plasma driven light sources

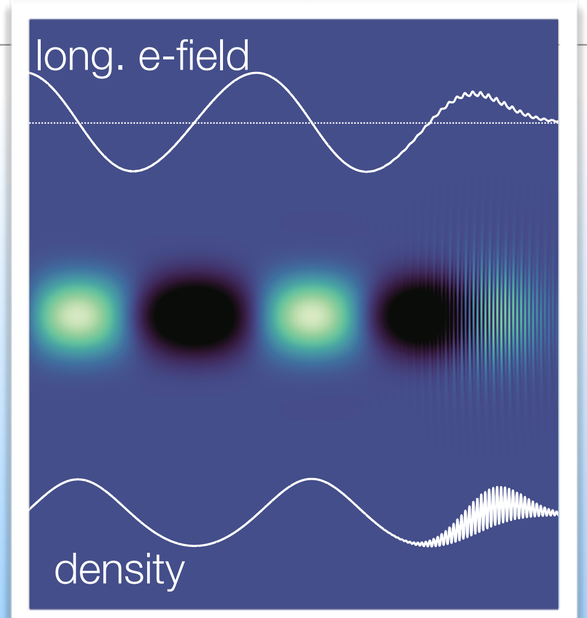
Geb. 23: REGAE

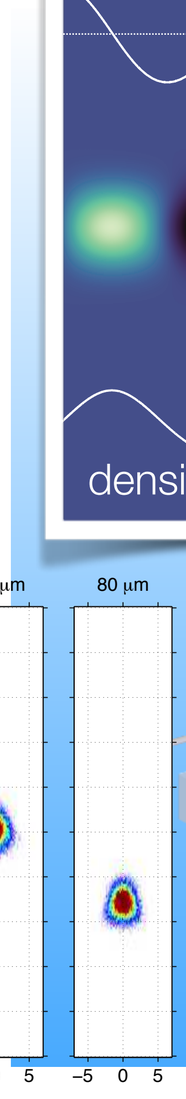
external injection

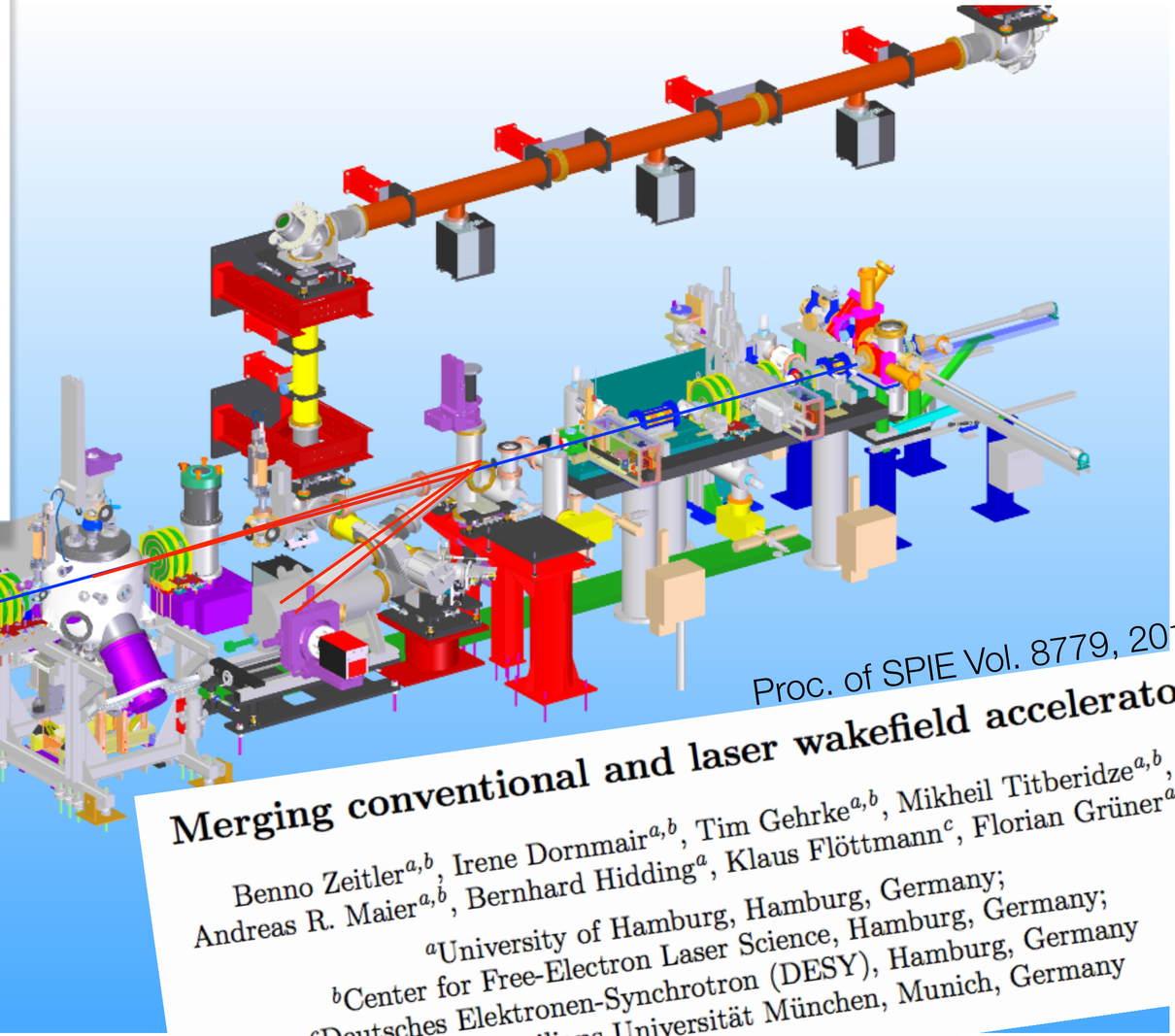


LAOLA@REGAE: External Injection

- Goal: Mapping the wake
  - REGAE: Conventional electron gun
  - ANGUS: 200 TW laser
  - Laser-pump, electron-probe experiment







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Merging conventional and laser wakefield accelerators

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& contribution at EAAC2013

Simulations: I. Dornmair, S. Jalas

LAOLA. PIER

REGAE

> Relevant parameters:

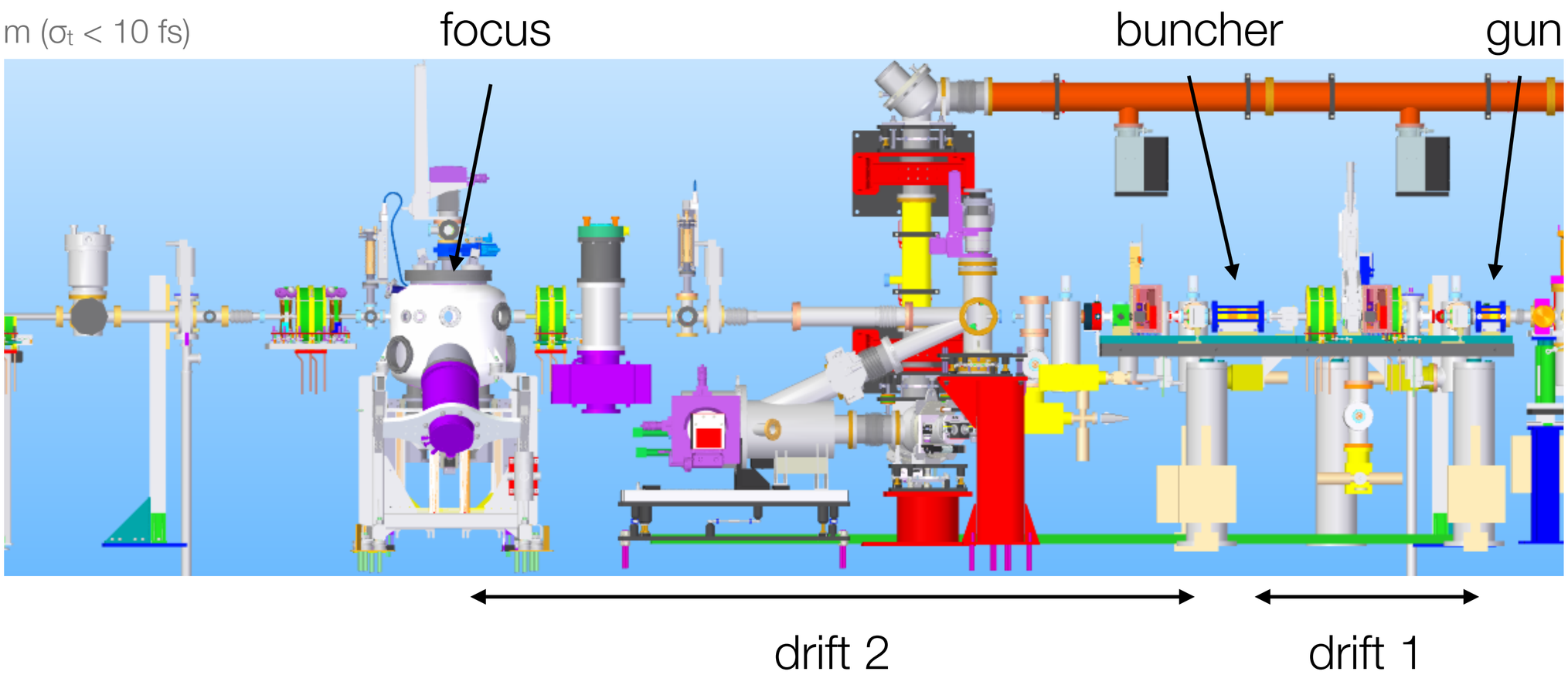
  > Electron gun: $E_G \leq 120$ MV/m, $z_G = 0$ m

  > Buncher: $E_B = 10..40$ MV/m, $z_B = 1.3$ m

  > Focus: $z_F = 5.5$ m ($\sigma_t < 10$ fs)

  > Drift 1: ~1 m

  > Drift 2: ~4 m



Ballistic Bunching: REGAE

> Zero-crossing of buncher cavity

> Linear correlated energy spread

> +Drift: Longitudinal focusing

> Result: Bunch length <10 fs

> But…

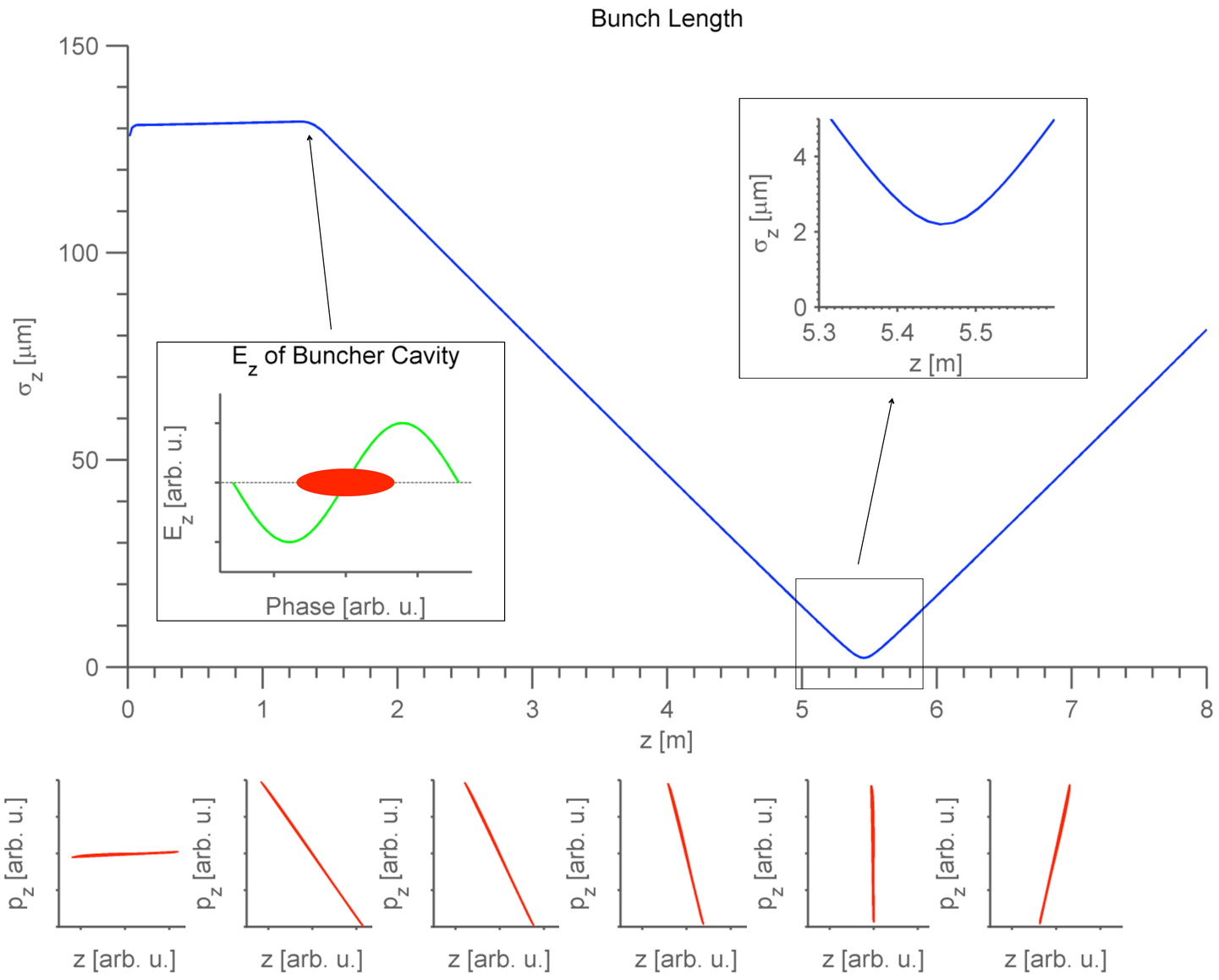
> Low energy (~5 MeV)

> Low charge (~100 fC)

> Limit(s) of bunch length?

> Space charge repulsion

> Phase space curvature



Ballistic Bunching: Phase Space Curvature

> Basic concept:

> Linear correlated **velocity** spread

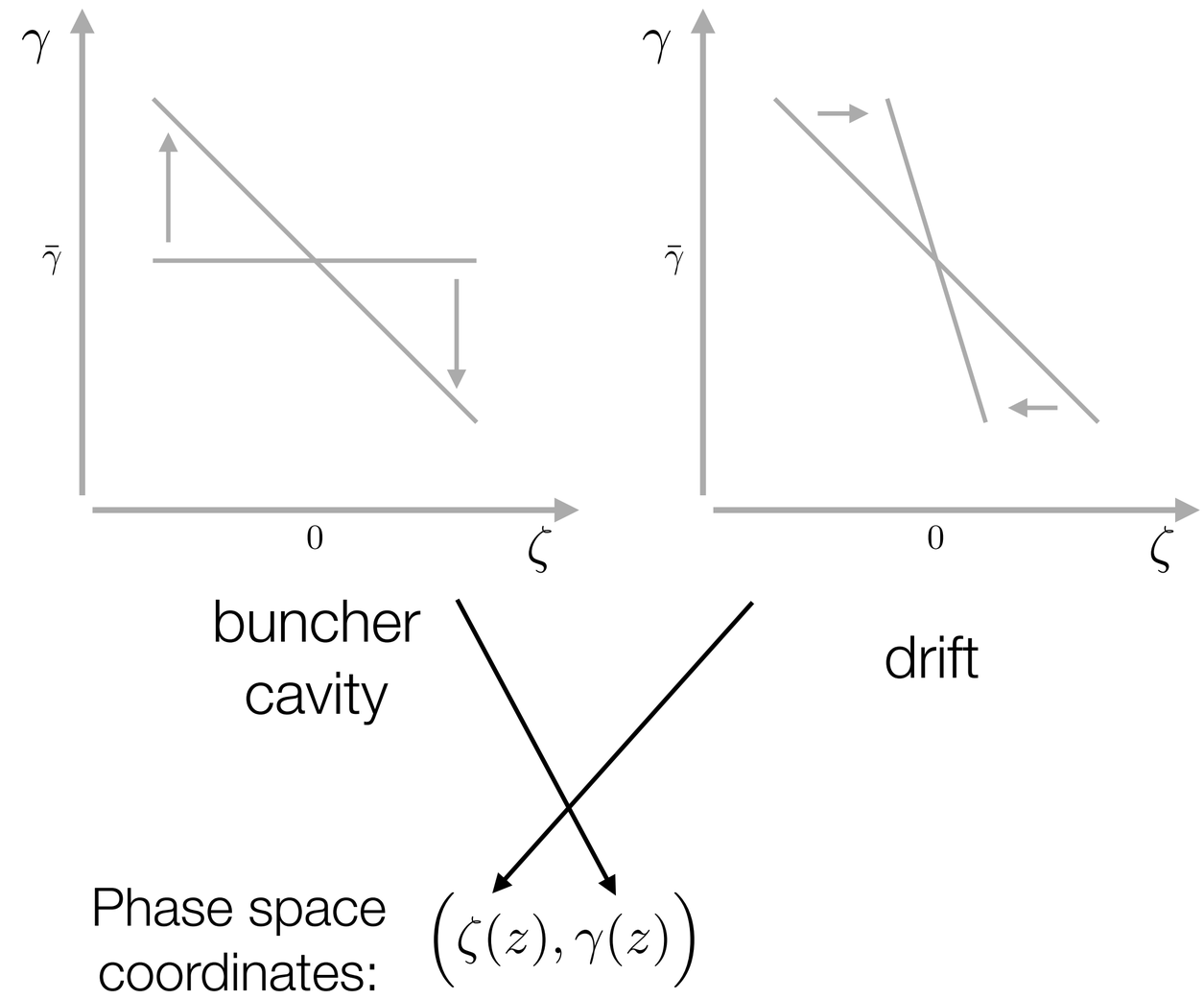
> Free drift leads to longitudinal focus

> Note: Drift changes ζ, cavity changes γ

> But… zero crossing of cavity:

> Linear correlated **energy** spread

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$$



Ballistic Bunching: Phase Space Curvature

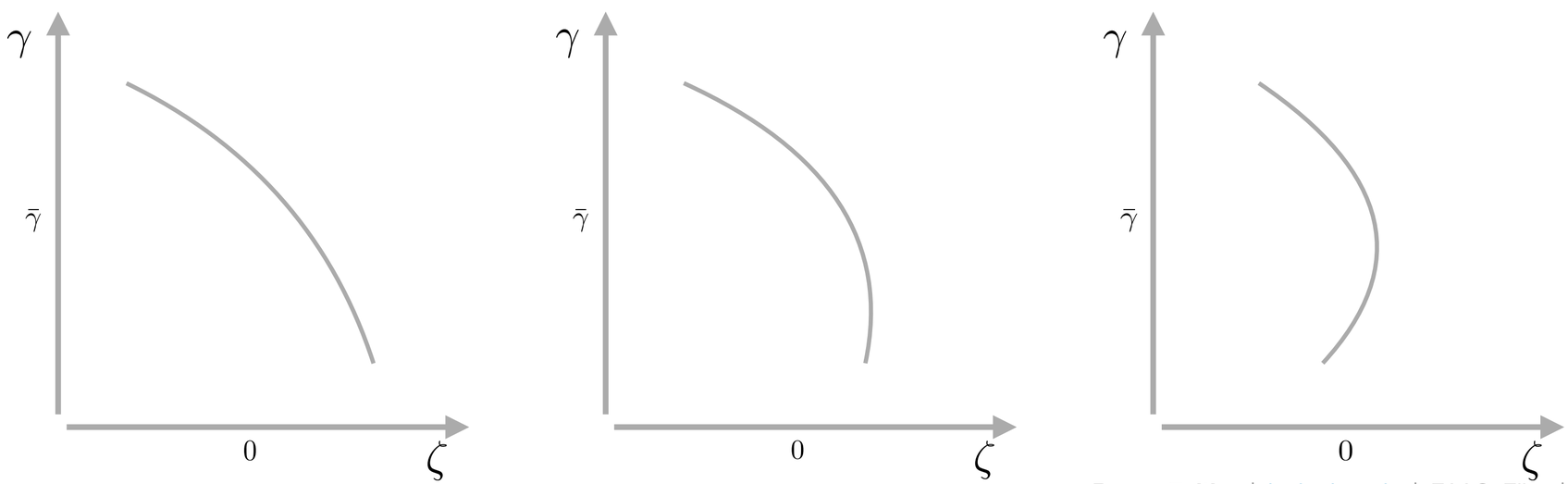
> Consequence?

> Curvature due to drift!

$$\Delta\zeta(z) = \Delta v \cdot \big(t(z) - t(z_0)\big) = \frac{1}{\beta}\Delta\beta(\gamma) \cdot (z - z_0)$$

$$= \frac{1}{\bar{\beta}}\left[\frac{\mathrm{d}\beta}{\mathrm{d}\gamma}\Big|_{\bar{\gamma}} \cdot \delta\gamma + \frac{1}{2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\gamma^2}\Big|_{\bar{\gamma}} \cdot (\delta\gamma)^2 + \frac{1}{6}\frac{\mathrm{d}^3\beta}{\mathrm{d}\gamma^3}\Big|_{\bar{\gamma}} \cdot (\delta\gamma)^3 + \cdots\right]_{z_0} \cdot (z - z_0)$$

$$= \Bigg[\underbrace{\frac{1}{\bar{\gamma}^3\bar{\beta}^2}}_{\eta_1(\bar{\gamma})} \cdot\delta\gamma + \underbrace{\frac{2 - 3\bar{\gamma}^2}{2\bar{\gamma}^6\bar{\beta}^4}}_{\eta_2(\bar{\gamma})} \cdot (\delta\gamma)^2 + \underbrace{\frac{2 - 5\bar{\gamma}^2 + 4\bar{\gamma}^4}{2\bar{\gamma}^9\bar{\beta}^6}}_{\eta_3(\bar{\gamma})} \cdot (\delta\gamma)^3 + \cdots\Bigg]_{z_0} \cdot (z - z_0)$$



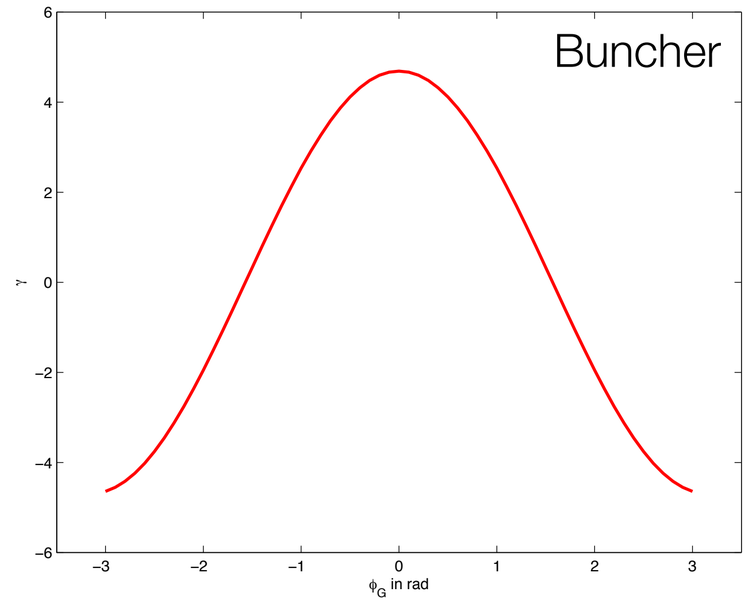
Ballistic Bunching: Phase Space Curvature

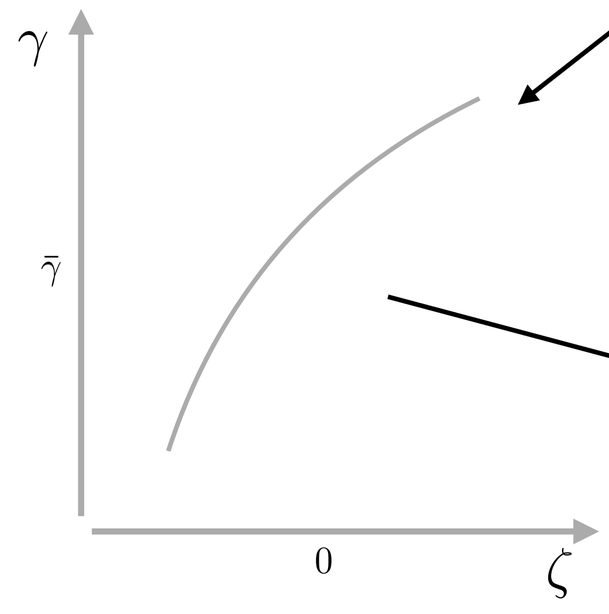
> But: Linear correlated **energy** spread?

> Only to first order

> General description… curved

> Polynomial/Taylor expansion





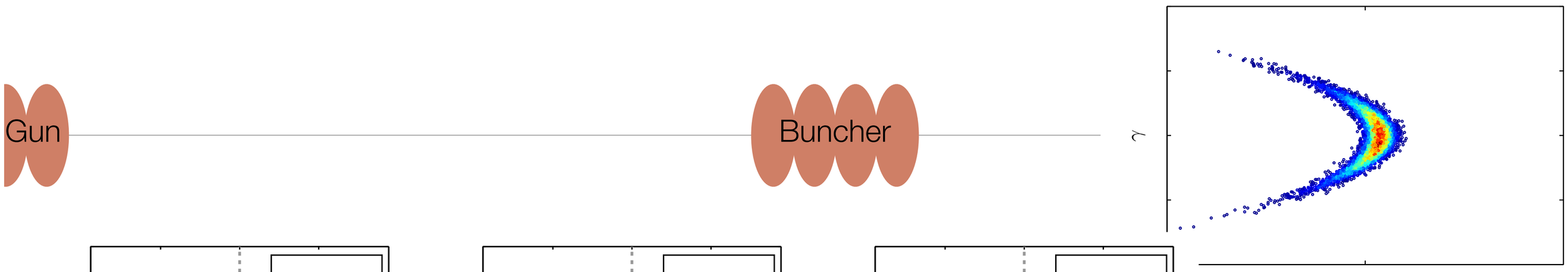
$$\gamma(\zeta_0) = \underbrace{A_0}_{\bar{\gamma}} + \underbrace{A_1\zeta_0 + A_2\zeta_0^2 + A_3\zeta_0^3}_{\delta\gamma(\zeta_0)}$$

Phase Space Linearization

> Simplified problem:

  > Curvature only from cavities

  > No non-linear evolution in drift



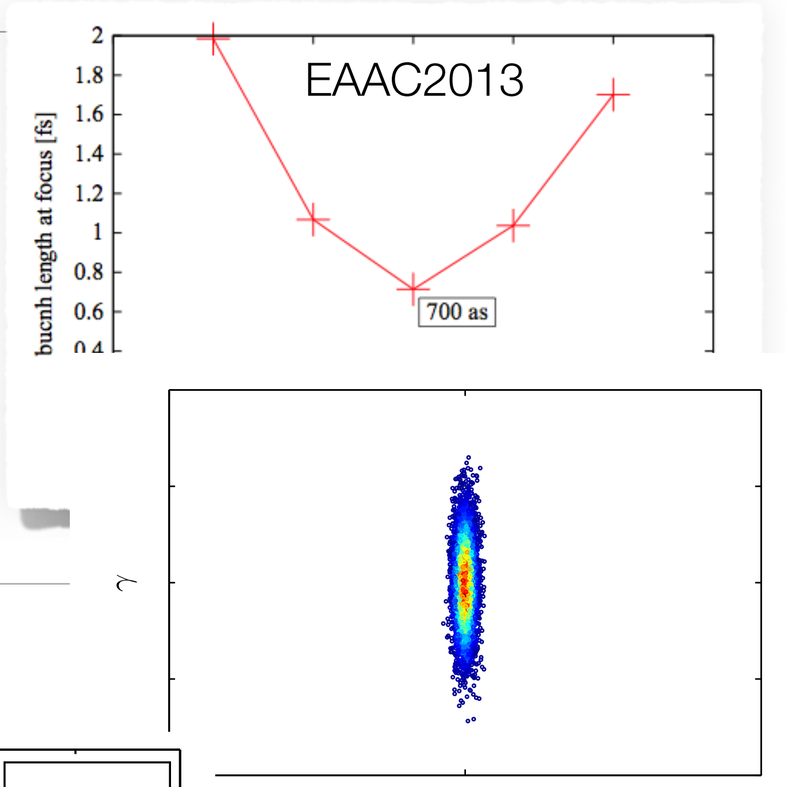
Phase Space Linearization

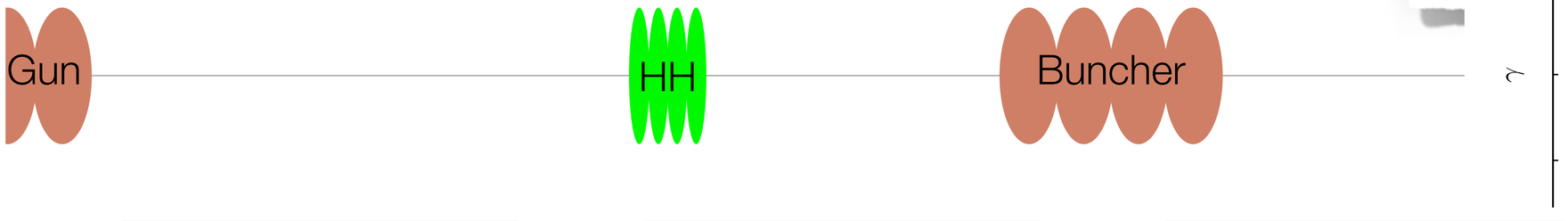
> Solution 1: 3rd harmonic cavity

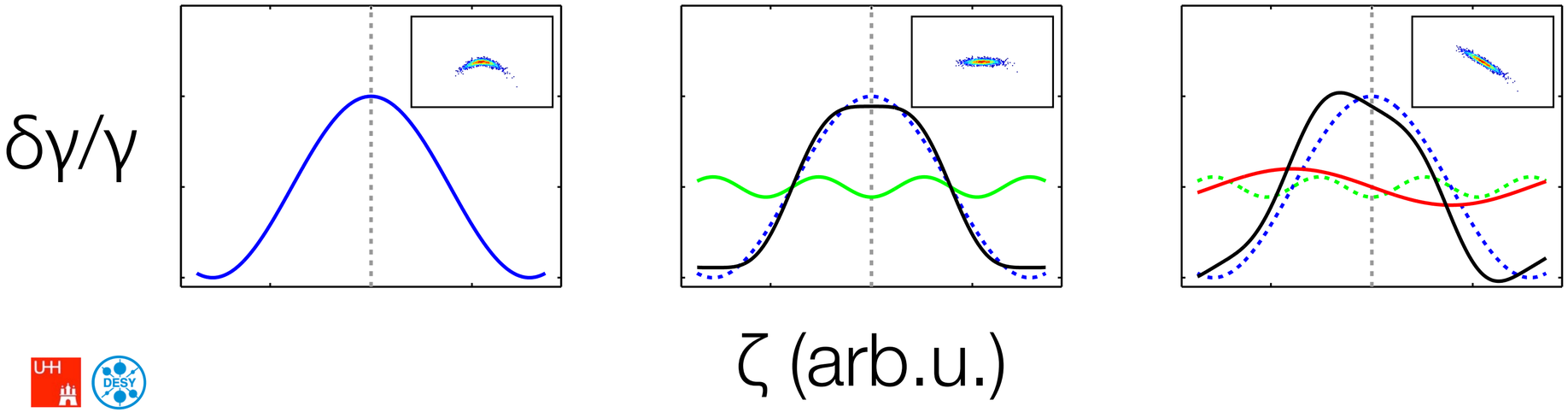
> (Fourier series: Plateau by summation of uneven frequencies)

> Works: 700 as (K. Floettmann, Nucl. Instr. Meth. Phys. Res. A, Vol. 740, 2014)

> No space & money: X-band structure…







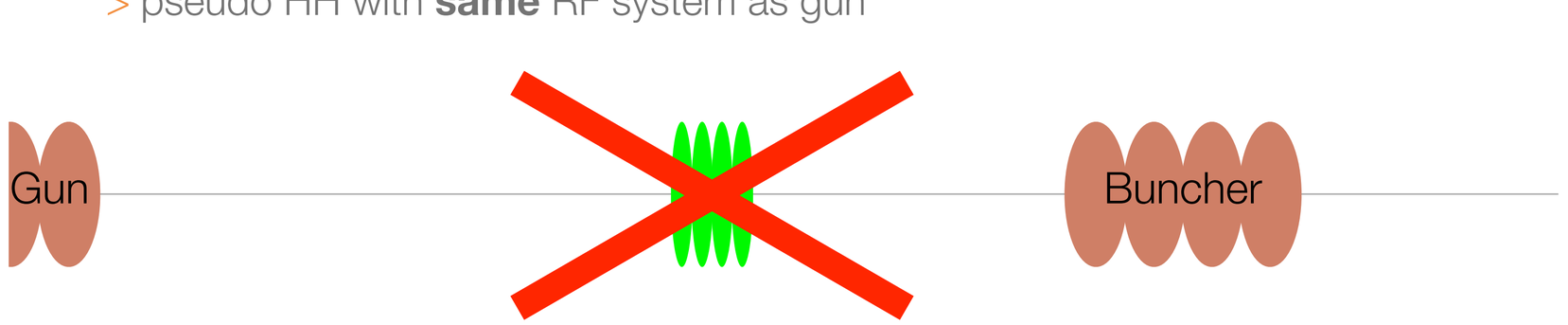
Phase Space Linearization

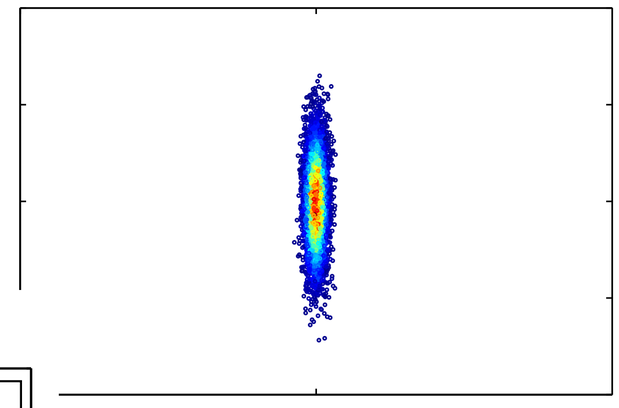
> Solution 2: Stretcher mode

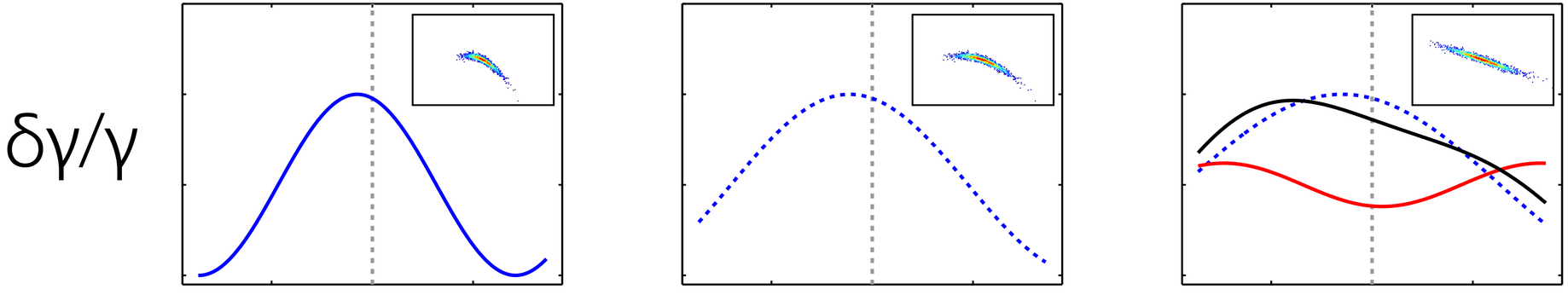
> Gun settings: (far) off-crest

> Beam expansion between gun and buncher

> pseudo HH with **same** RF system as gun







Stretcher Mode: Method

> Analytic description of bunch dynamics in gun, drift(s) & buncher in phase space

> Third order polynomial in ζ ⟶ three coefficient-equations X_i

> Four free parameters (cavity fields & phases)

$$\zeta_z = \zeta_B + \Delta\zeta(z) = X_1\zeta_B + X_2\zeta_B^2 + X_3\zeta_B^3$$

$$X_1 := 1 + (z - z_B) \cdot [H_1 S_1 \cdot]$$

$$X_2 := (z - z_B) \cdot [H_1 S_2 + H_2 S_1^2]$$

$$X_3 := (z - z_B) \cdot [H_1 S_3 + 2H_2 S_1 S_2 + H_3 S_1^3]$$

$S_i = a_i + B_i$: Sum of γ-Coefficients

$H_i = \eta_i(a_0 + B_0)$

> Optimization with Astra (and Matlab):

> Seed parameters from analytical method

> Longitudinal rms emittance: measure for nonlinearities

> Match minimum of emittance and bunch length

> Two parameters ⟶ buncher phase/amplitude

ϵ_1, …MS

> Note: Publication with referees (PRSTAB)

Linearization of the longitudinal phase space without higher harmonic field

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Accelerator applications like free-electron lasers, time-resolved electron diffraction, and advanced accelerator concepts like plasma acceleration desire bunches of ever shorter longitudinal extent. However, apart from space charge repulsion, the internal bunch structure and its development along the beamline can limit the achievable compression due to non-linear phase space correlations. In order to improve such a limited longitudinal focus, a correction by properly linearizing the phase space is required. At large scale facilities like FLASH at DESY or the European XFEL a higher harmonics cavity is installed for this purpose. In this paper another method is described and evaluated: Expanding the beam after the electron source enables a higher order correction of the longitudinal focus by a subsequent accelerating cavity which is operated at the same frequency as the electron gun. The elaboration of this idea presented here is based on a ballistic bunching scheme, but can be extended to bunch compression based on magnetic chicanes. The core of this article is an analytic model describing this approach, which is verified by simulations, predicting possible bunch length below 1 fs at low bunch charge. Minimizing the energy spread down to $\sigma_E/E < 10^{-5}$ while keeping the bunch long is another interesting possibility, which finds applications e.g. in time resolved transmission electron microscopy concepts.

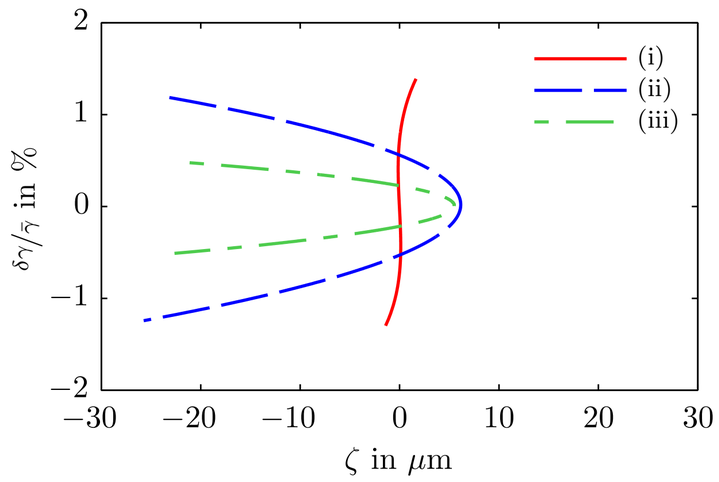
Applications: Second Order

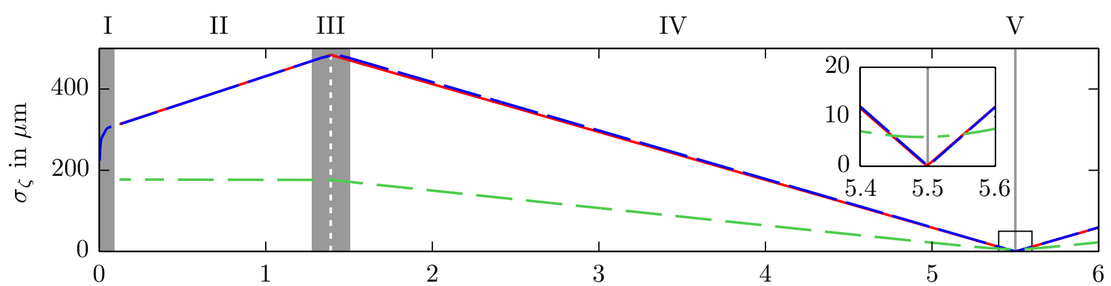
> Comparison of theory and simulation: case (i)

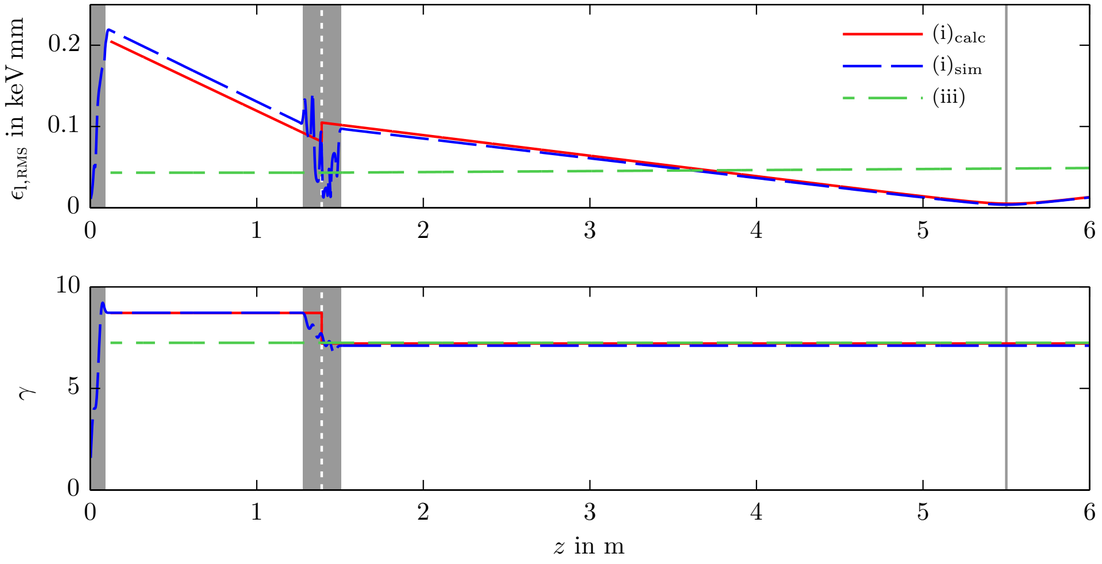
> Calc & sim: E_G = 100.0 MV/m, ϕ_G = 34.1 deg
Calc: E_B = 21.2 MV/m, ϕ_B = -109.3 deg
Sim: E_B = 21.7 MV/m, ϕ_B = -112.0 deg

> Standard bunching scheme: case (iii)

> Calc: E_G = 70.0 MV/m, ϕ_G = 0.0 deg
Calc: E_B = 6.6 MV/m, ϕ_B = -90.0 deg







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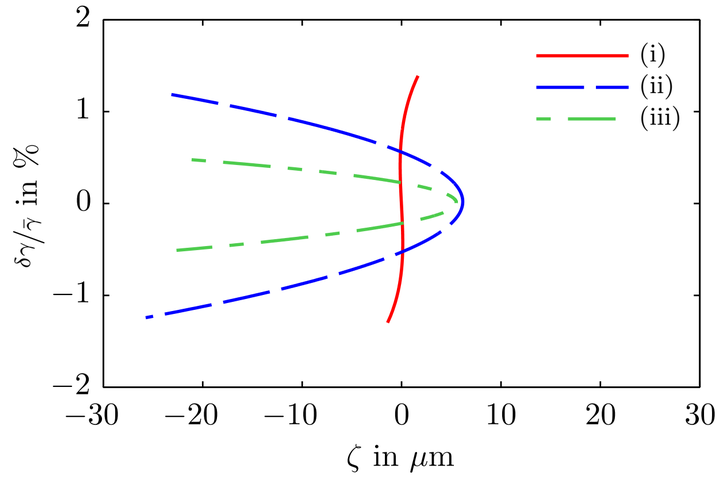
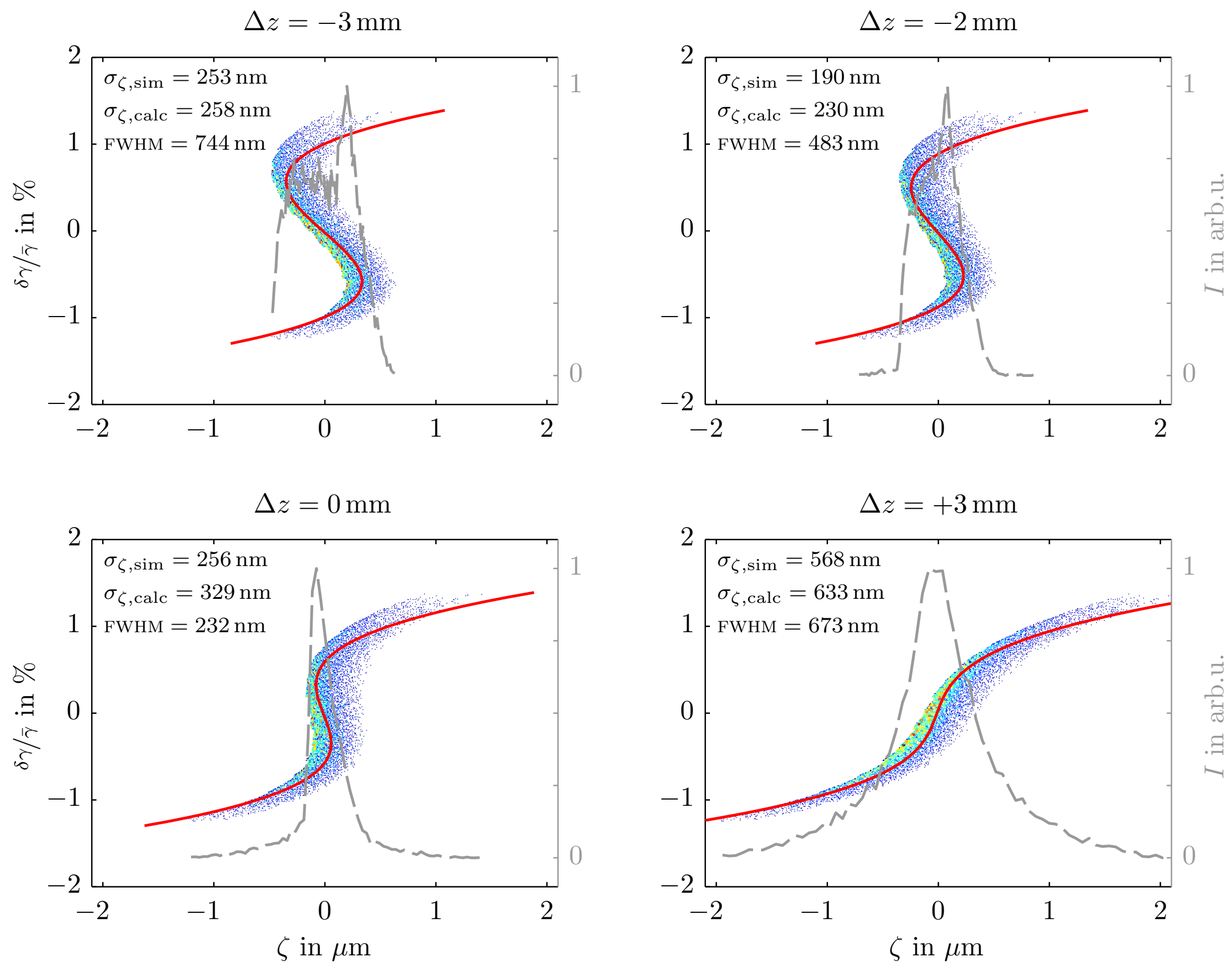




Applications: Third Order

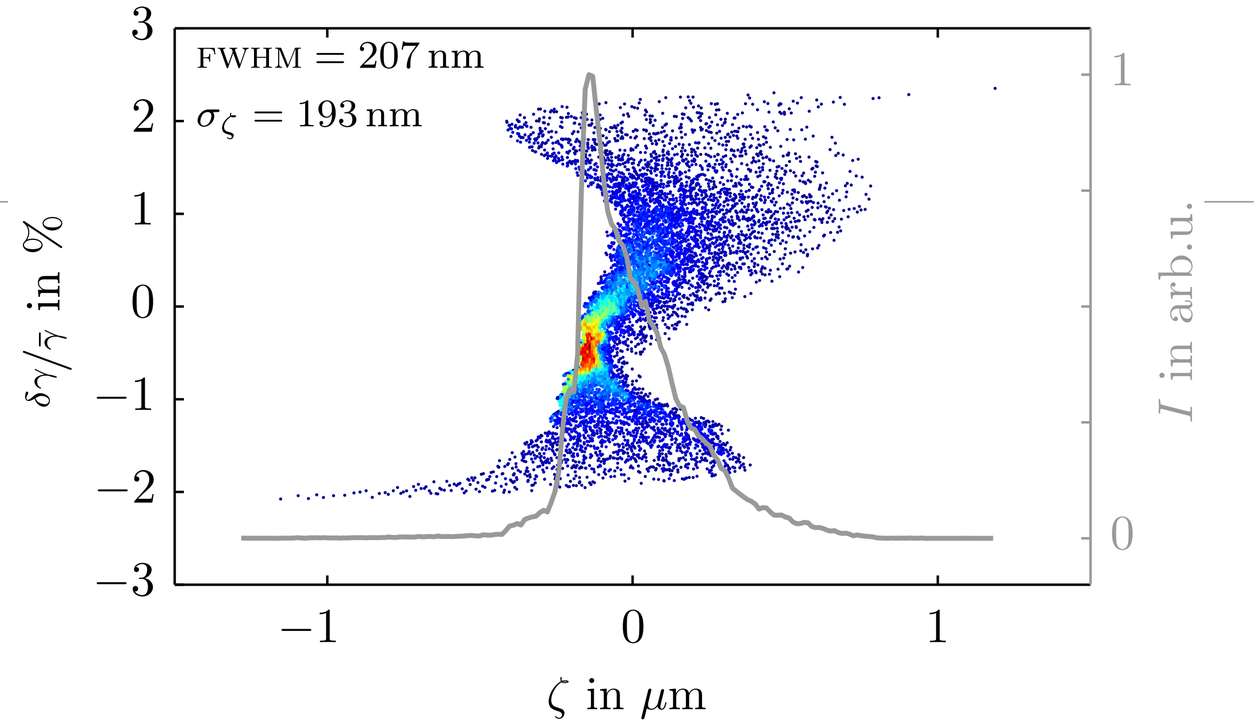
> Use of gun phase ϕ_G

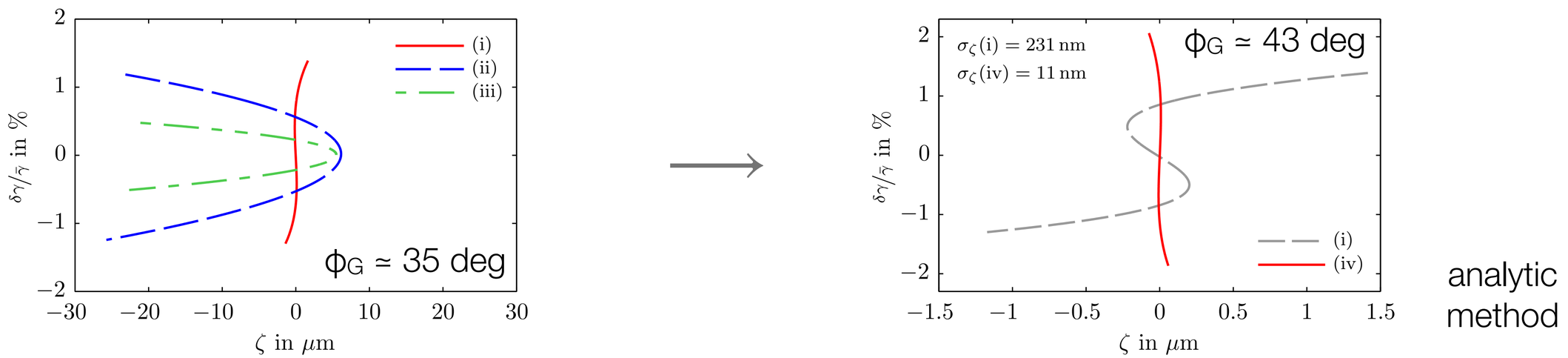
> Gun: E_G = 120.0 MV/m, ϕ_G = 44.3 deg
Buncher: E_B = 29.3 MV/m, ϕ_B = -97.5 deg

> Q = 50 fC

> E_{kin} = 3.7 MeV

> σ_ζ = 175 nm ≙ 580 as





Applications…

> How about…

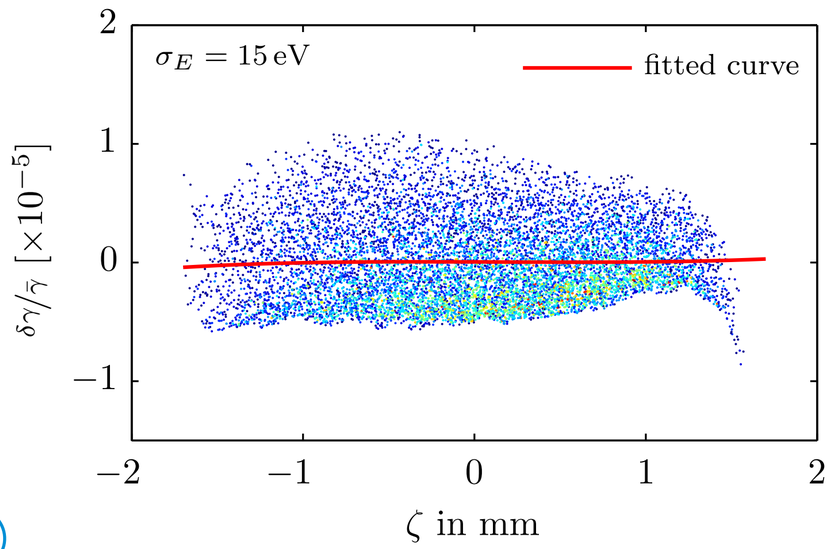
> Gun: E_G = 100.0 MV/m, ϕ_G = 45.7 deg
Buncher: E_B = 14.1 MV/m, ϕ_B = -69.9 deg

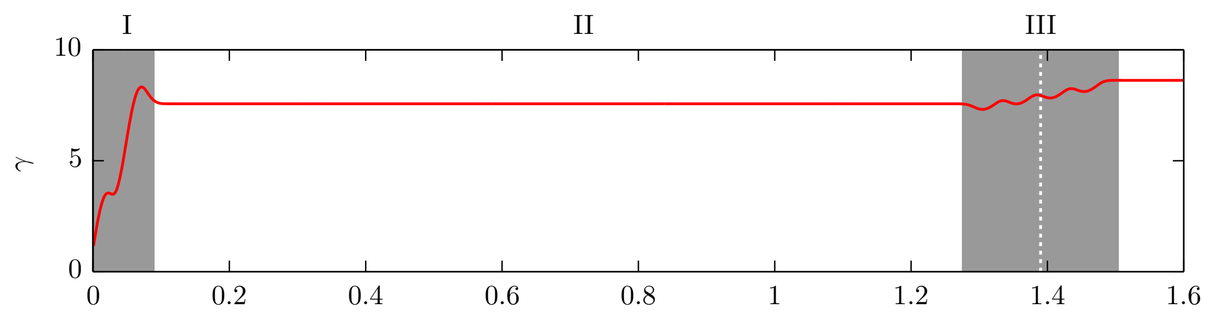
> Q = 50 fC

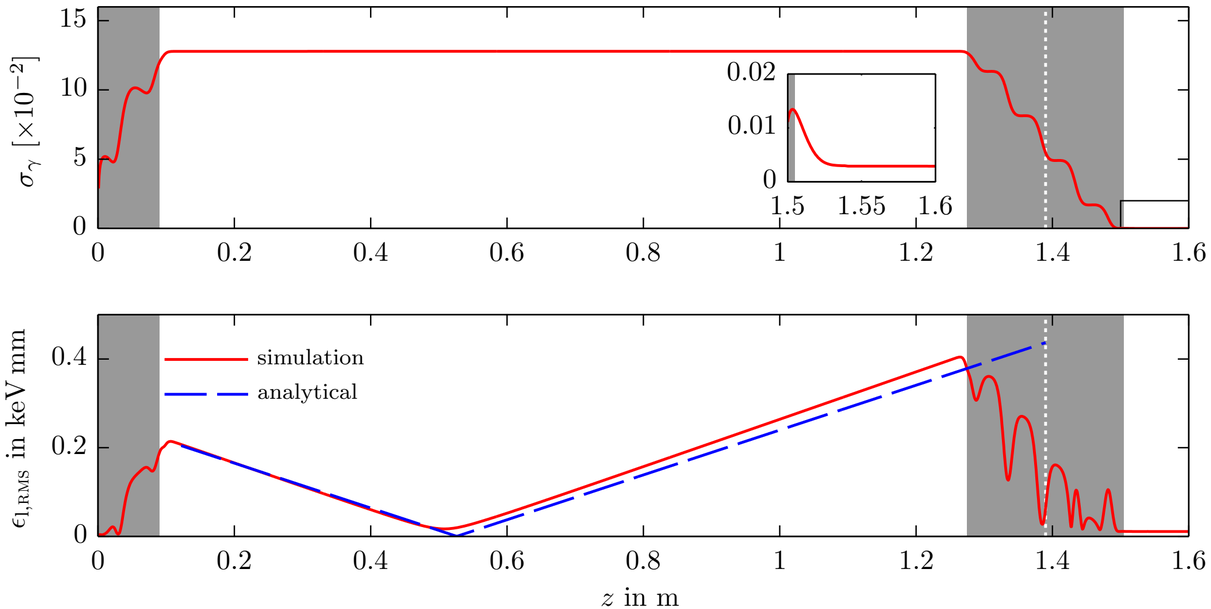
> E_{kin} = 3.9 MeV, σ_{Ekin} = 15 eV

> Relative energyspread: $4 \cdot 10^{-6}$

> Accelerating phase







Summary & Outlook

> Summary

> Basic concept of ballistic bunching

> Correction of curvature w/o 3rd harmonic structure

> Stretcher mode

> Sub-fs bunches at REGAE

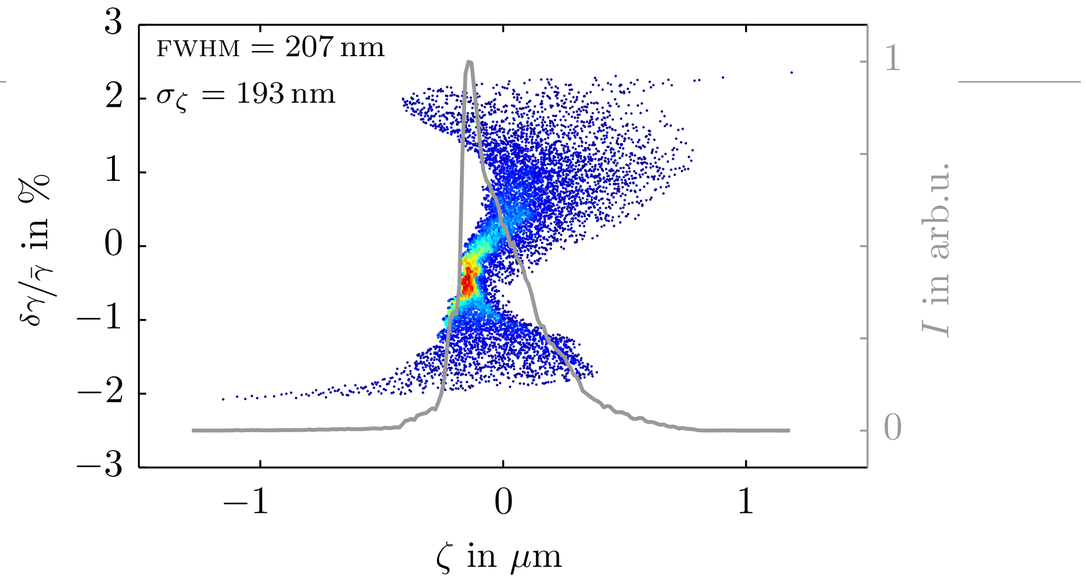
> Energy spread compensation

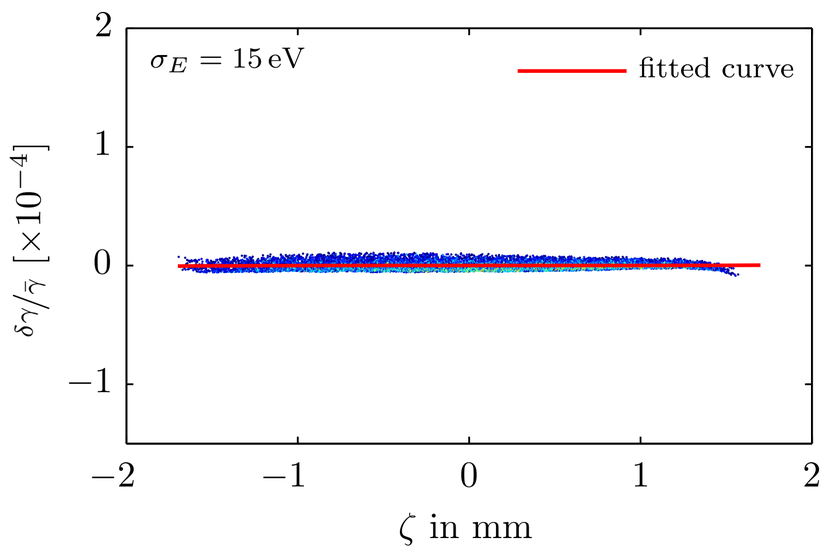
> Outlook

> Concept applicable… now

> But, how to measure?

> Concept could be adapted to other machines





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