Beam Dynamics Studies for the PITZ Undulator

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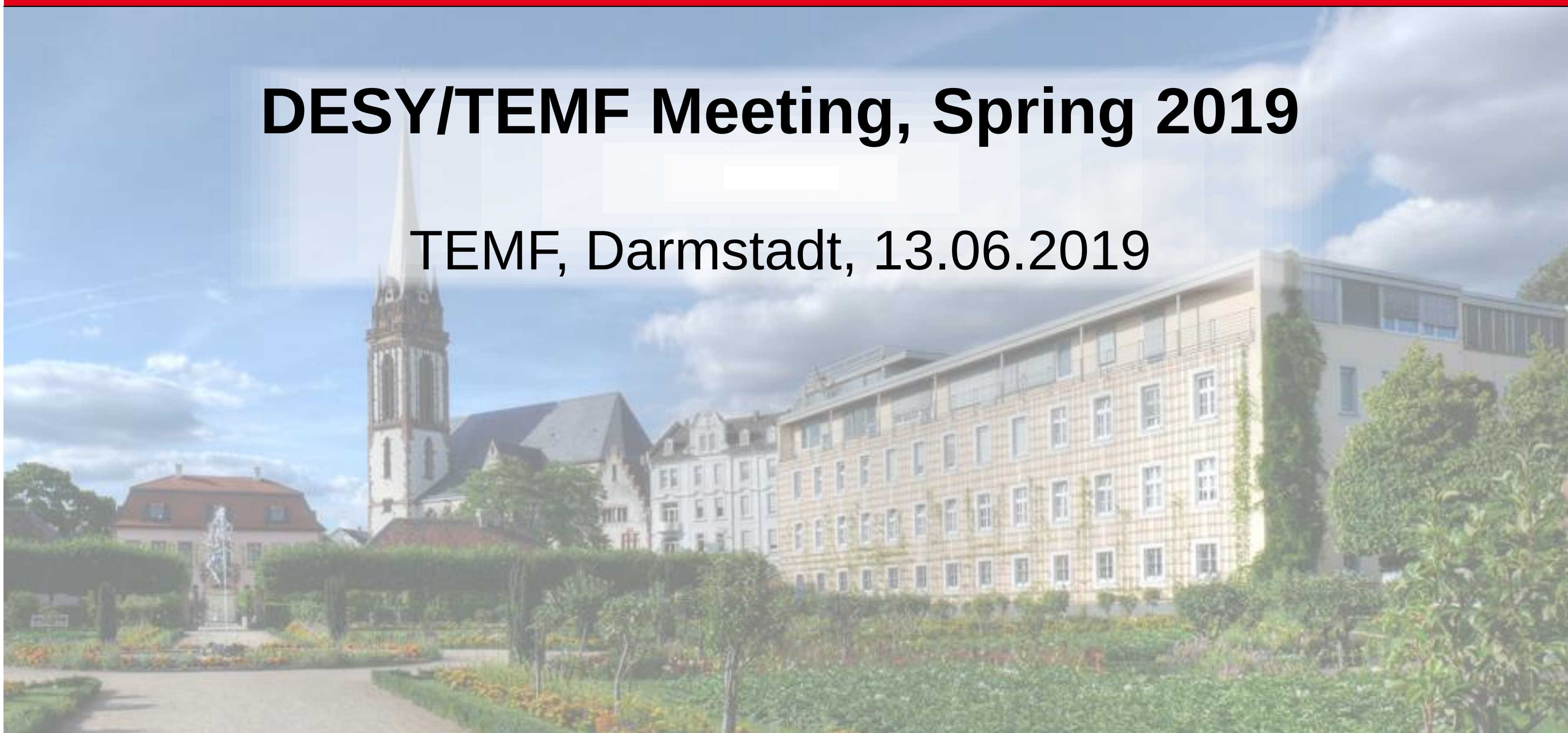

Structure

I. Introduction

II. Numerical Models

  i. 2D Undulator Model

  ii. Space Charge Models and Codes

III. Simulation Results

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Introduction
THz SASE FEL at DESY PITZ

Motivation:

Development of a high power, tunable THz source for European XFEL

⇒ THz radiation at $\lambda \sim 100\ \mu\mathrm{m}$, $\sim 6\ \mathrm{ns}$ pulse length, and $\sim 38\ \mathrm{MW}$ peak power

THz-FEL Parameters:

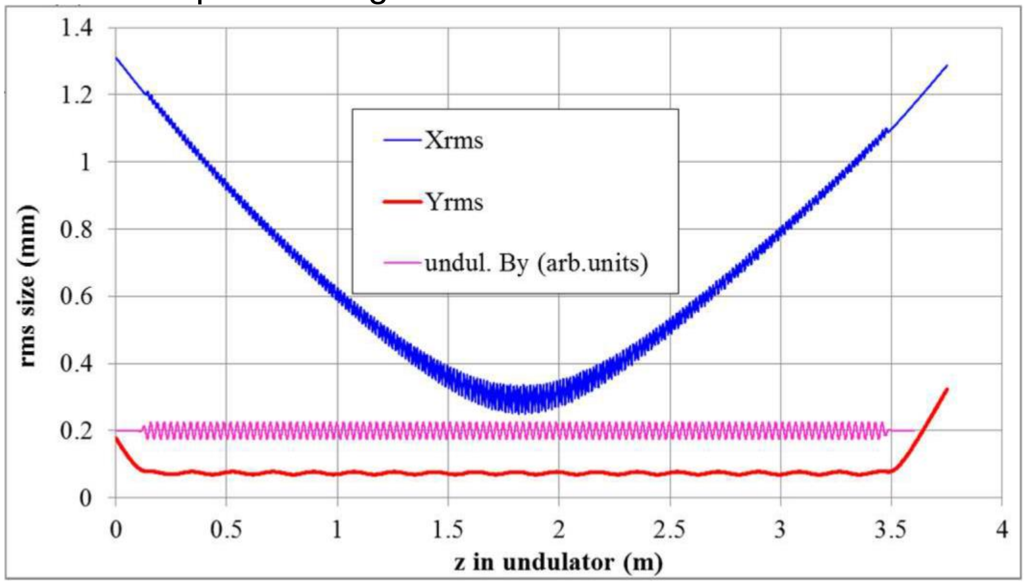
- Bunch charge $Q_b \sim 4\ \mathrm{nC}$
- Beam energy $E_b \sim 16.7\ \mathrm{MeV}$
- Und. length $L_u \sim 3.4\ \mathrm{m}$
- Und. period $\lambda_U \sim 3\ \mathrm{cm}$

Challenge:

Transport of SC dominated beam

⇒ SC beam dynamics simulation

Astra Space Charge Simulation of Beam in Undulator



Source: M. Krasilnikov at ICAP 2018

Further Information:

M. Krasilnikov et al., „Start-to-End Simulations of THz SASE FEL Proof-of-Principle Experiment at PITZ", ICAP'18, Key West

Numerical Models

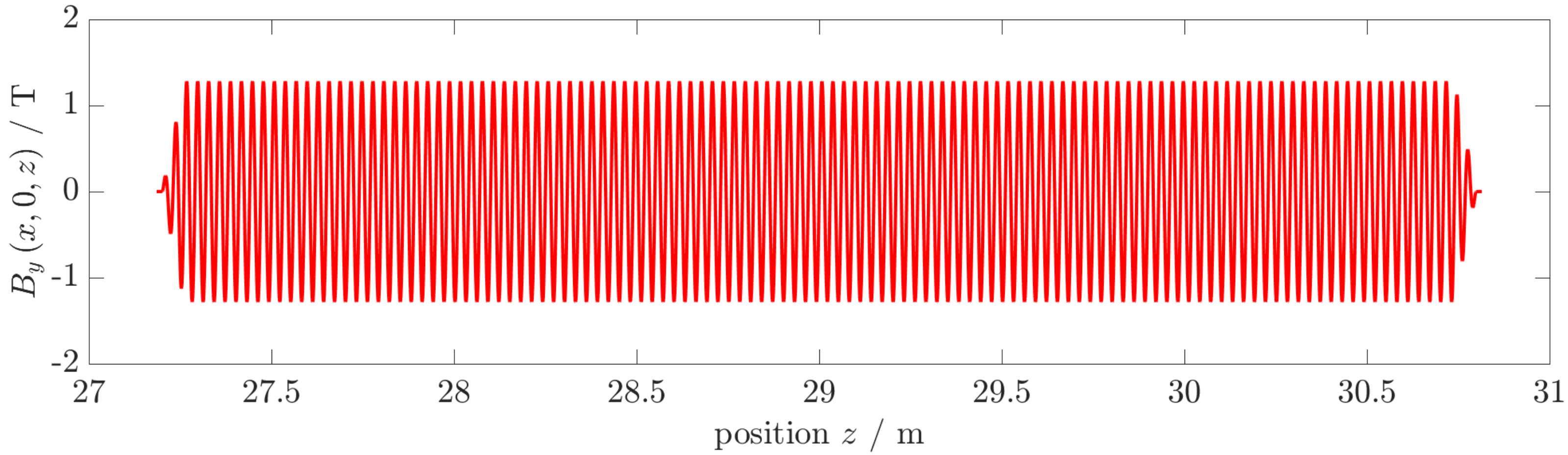
2D Undulator Model

Analytic 2D Undulator Field Model:

$$\vec{B}(\vec{r}) = B_0(z)\, cosh\left(\frac{2\pi}{\lambda_u}\, y\right)\, sin\left(\frac{2\pi}{\lambda_u} z\right)\, \vec{e}_y + B_0(z)\, sinh\left(\frac{2\pi}{\lambda_u} y\right)\, cos\left(\frac{2\pi}{\lambda_u} z\right) \vec{e}_z$$

with period $\boldsymbol{\lambda_u = 3\ \mathrm{cm}}$, total length $\boldsymbol{L_u = 120\ \lambda_u}$, and tapered $\boldsymbol{0\ \mathrm{T} \leq B_0(z) \leq 1.28\ \mathrm{T}}$

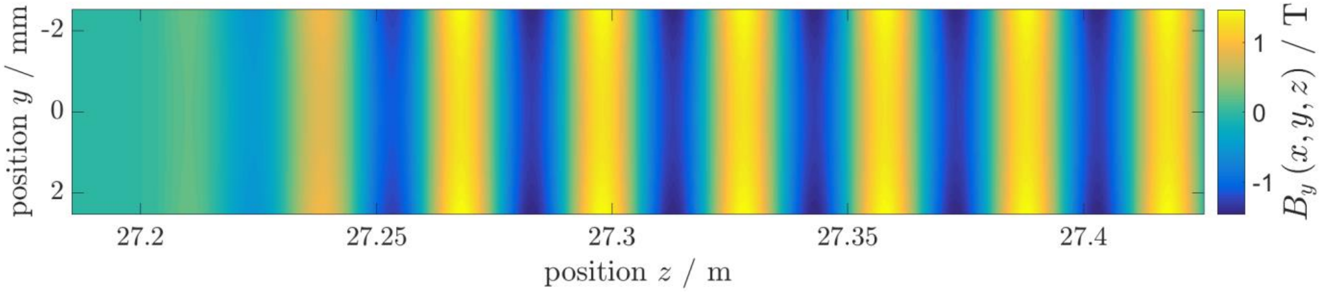
2D Undulator Field on Axis:



Numerical Models
Idealized 2D Undulator

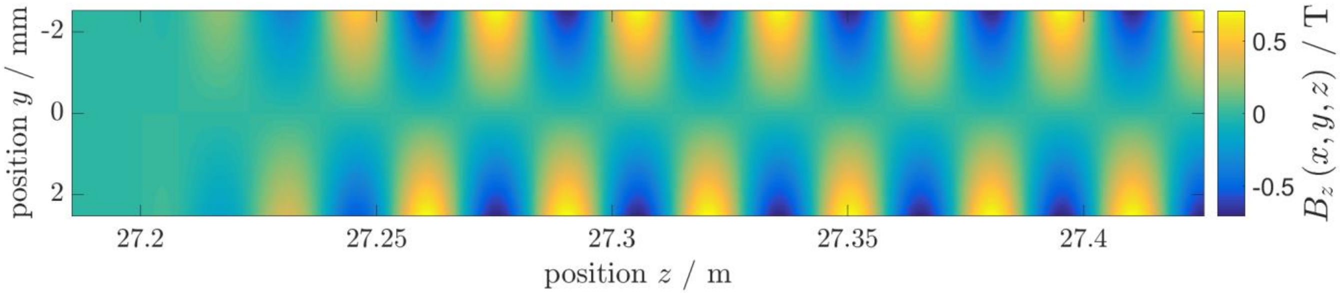
Periodic field map w. tapering:

$\Rightarrow B_y(x, y, z)$



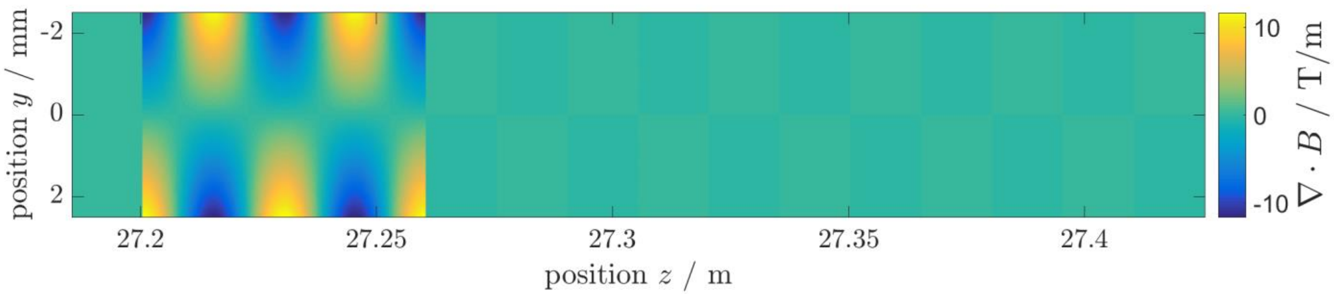
Focusing in y:

$\Rightarrow B_z(x, y, z)$



Linear tapering:

$\Rightarrow \vec{\nabla} \cdot \vec{B} \neq 0$



Numerical Models
2D Undulator Model

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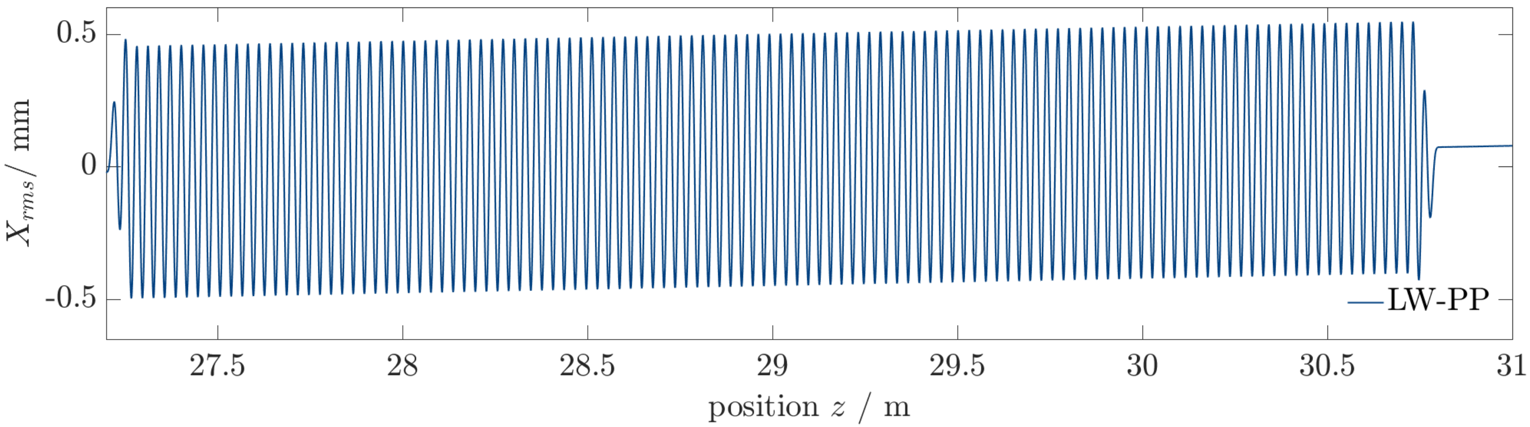
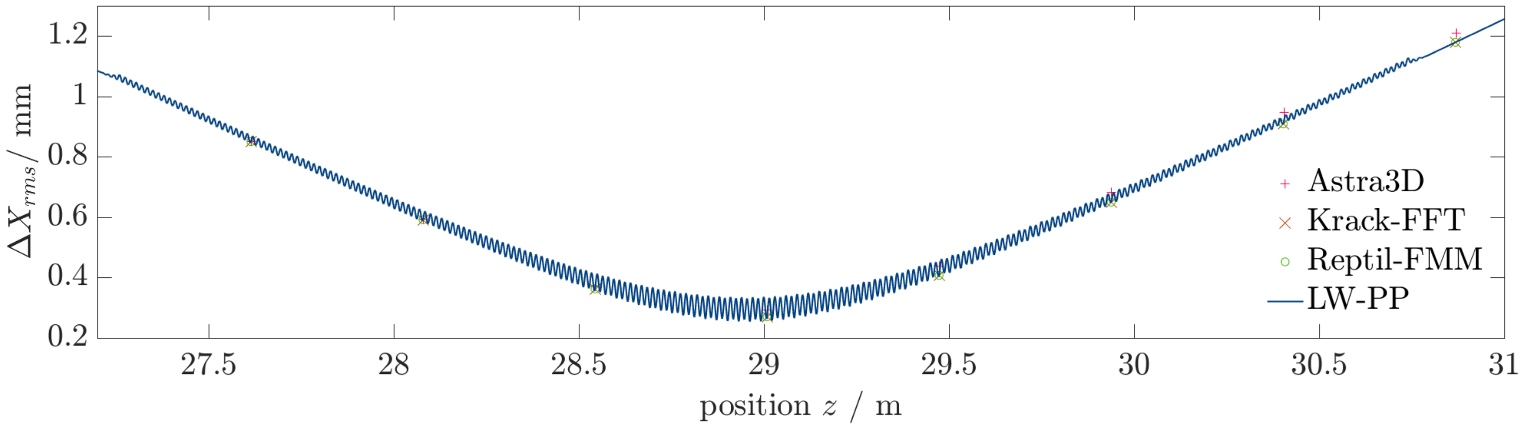
Beam Dynamics in the Undulator w/o SC:

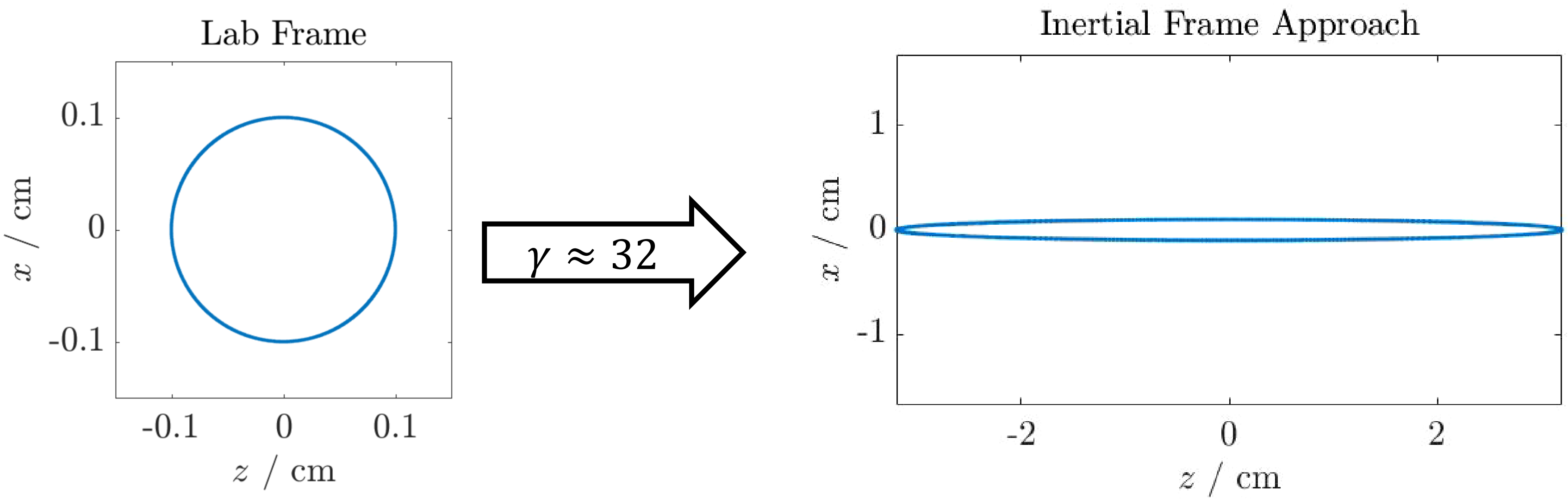




Numerical Models
Space Charge Models and Codes

Inertial Frame Approach:

Electrostatic solver in bunch „rest“ frame
⇒ Approximation exact if $\beta = \text{const.}$ and $\Delta\beta = 0$
⇒ Missing effects: Non-inertial frame, velocity dispersion, radiation
⇒ Codes: Astra3D (PIC-FFT), Krack (PIC-FFT), TEMF-Code (PP), REPTIL (FMM)



Numerical Models
Space Charge Models and Codes

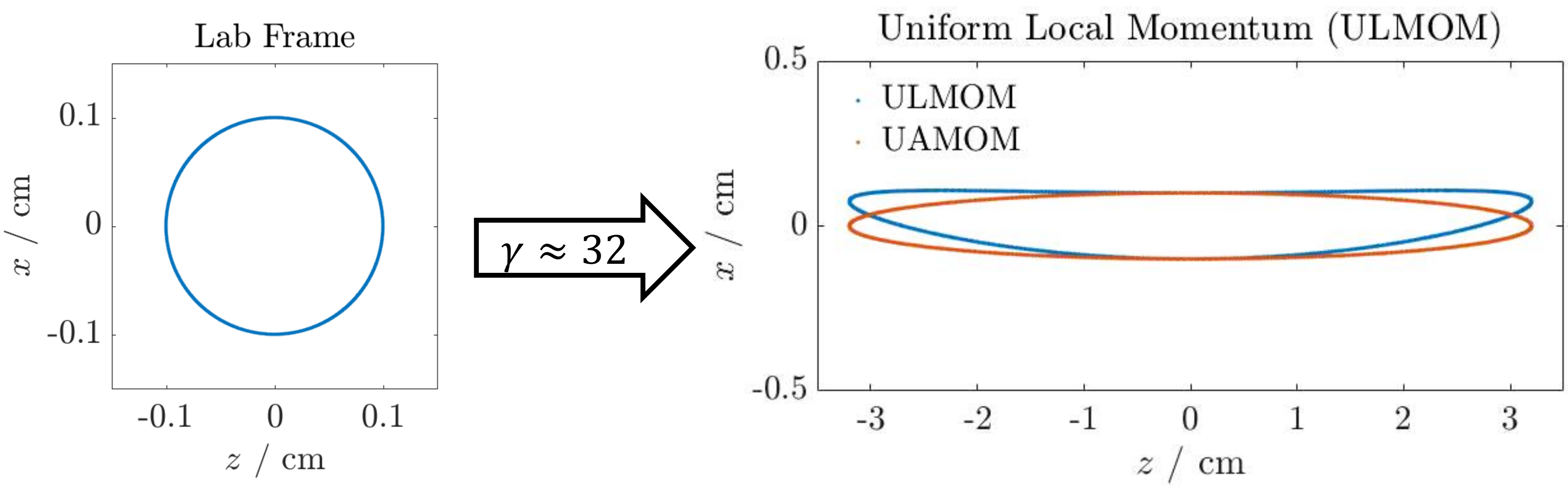
Local Inertial Frame Approach:

Electrostatic solver for local particle frame

⇒ Approximation exact if $\beta_{particle} = const.$

⇒ Missing effects: Nonlinear trajectory, radiation

⇒ Codes: TEMF-Code (PP), “REPTIL (w. energy binning)”



Numerical Models
Space Charge Models and Codes

Liénard-Wiechert Approach:

Full electromagnetic solver

⇒ Evaluation of time-retardation $|\vec{r_i} - \vec{r_j}| = c\,(t_i - t_j)$

⇒ Liénard-Wiechert fields include radiation

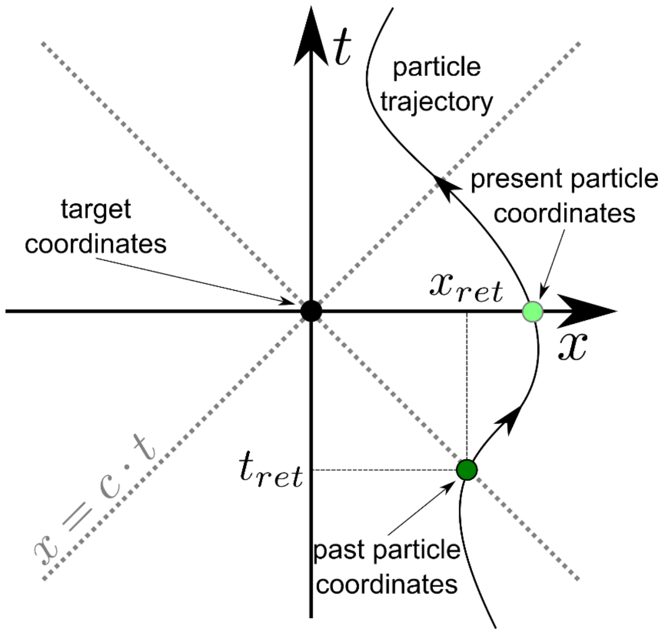
⇒ Codes: TEMF-Code (PP)

For $t_j < t_0$ rigid bunch initialization:

$$\Rightarrow z_j(t_j) = z_j(t_0) - c\,\beta_z(t_0)\,(t_0 - t_j)$$

Radiation Off:

⇒ Setting $\frac{d\vec{\beta}}{dt} = 0$ neglects radiation field



Simulation Results
Retardation and Radiation Effects

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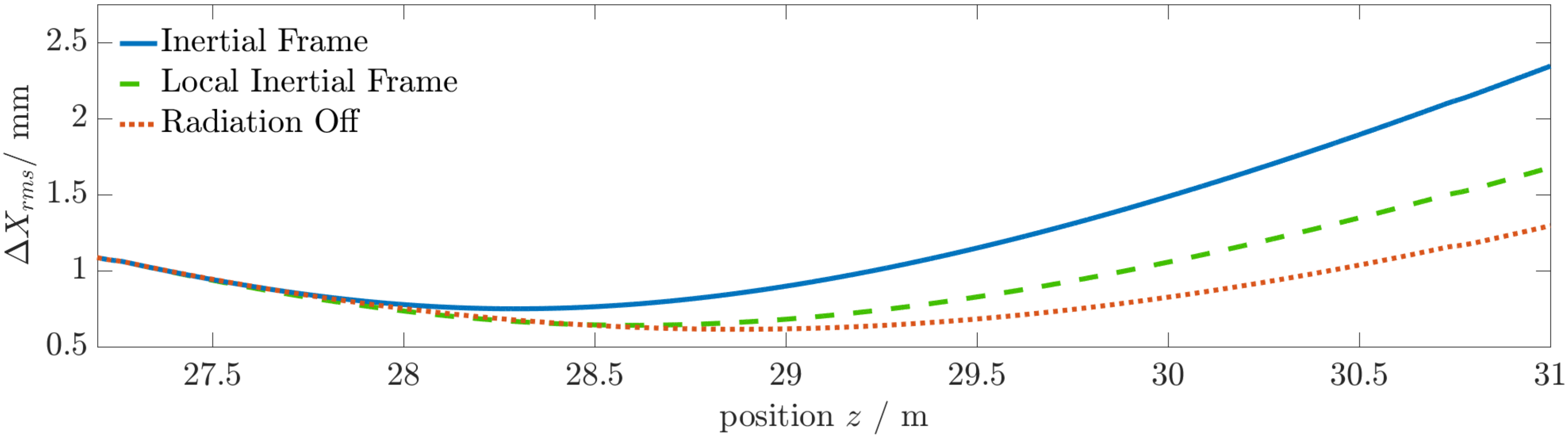
Transversal Bunch Size Growth:



- Bunch size ΔX_{rms} for IF model larger than for LIF model
  $\Rightarrow$ Artificial increase of static space charge effects
- Bunch size ΔX_{rms} for RO smallest
  $\Rightarrow$ Static space charge effects not dominating

Simulation Results
Retardation and Radiation Effects

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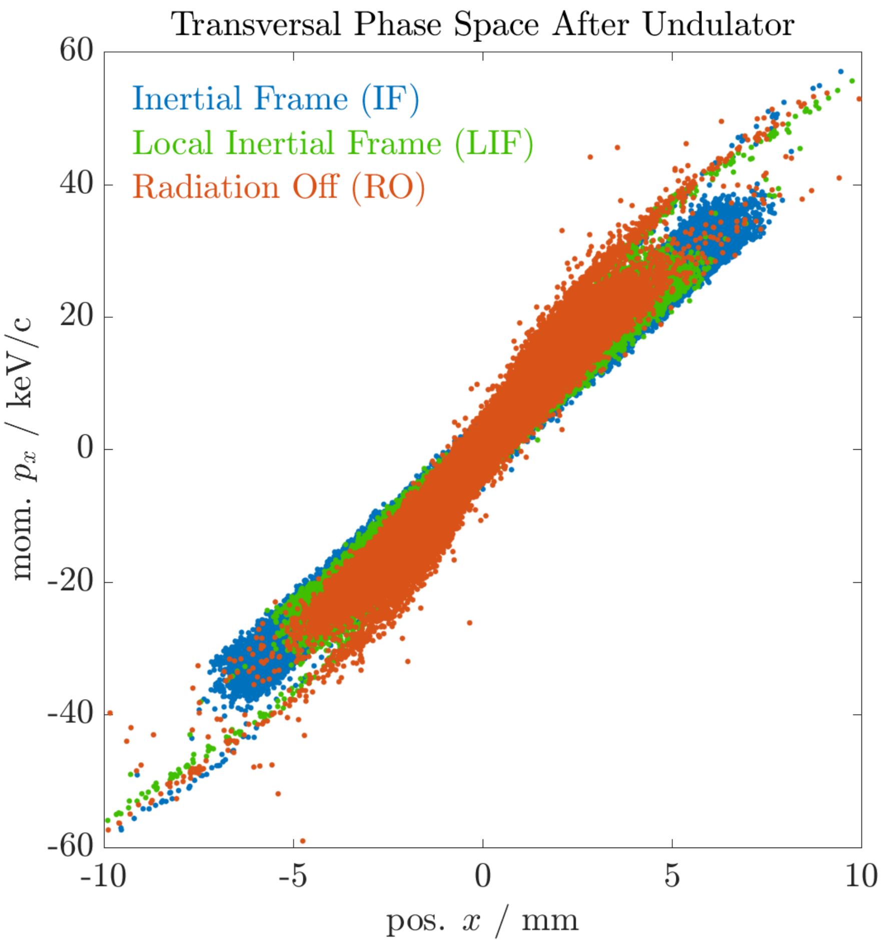
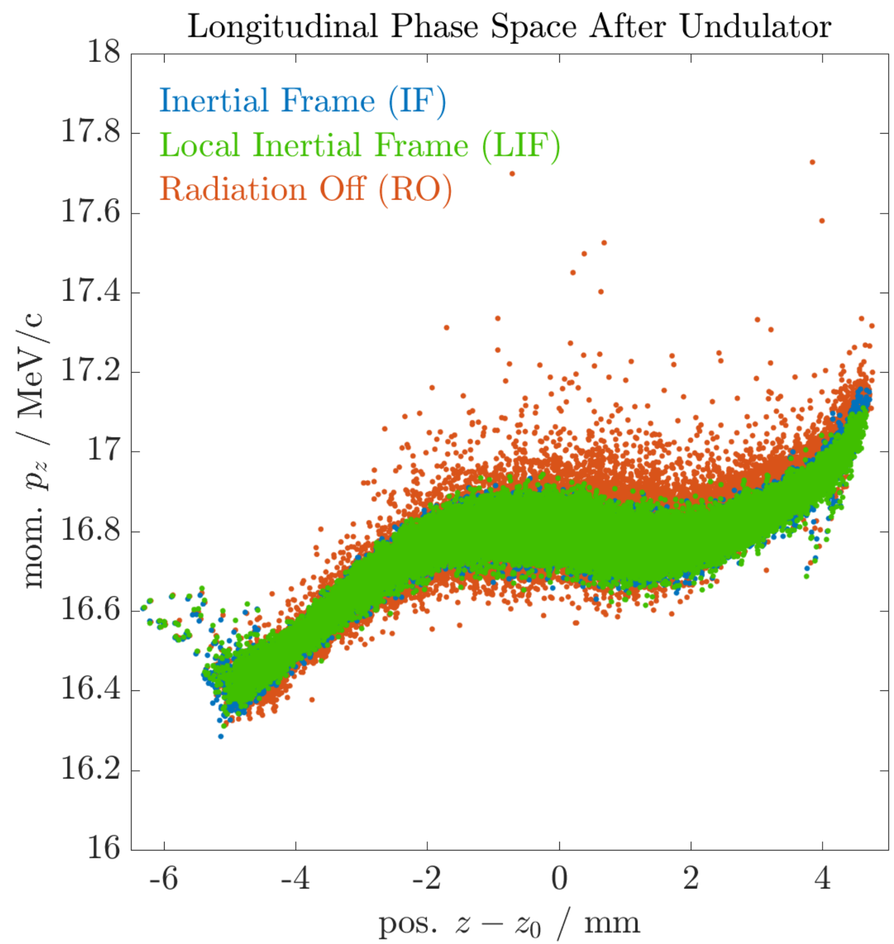
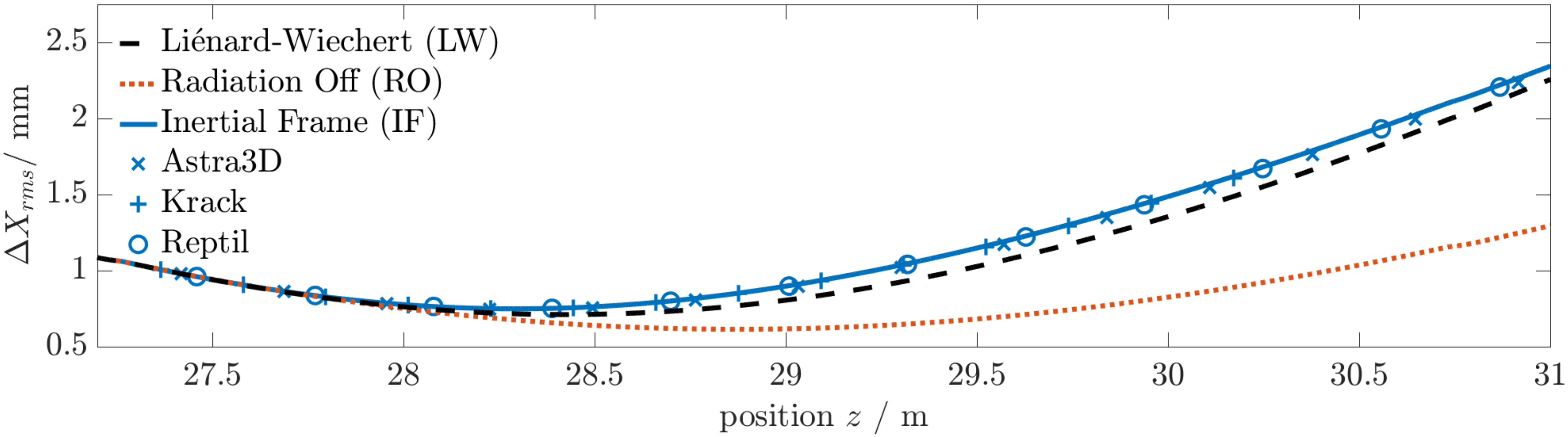




⇒ Inertial frame approaches overestimate static space charge field

Simulation Results
Retardation and Radiation Effects

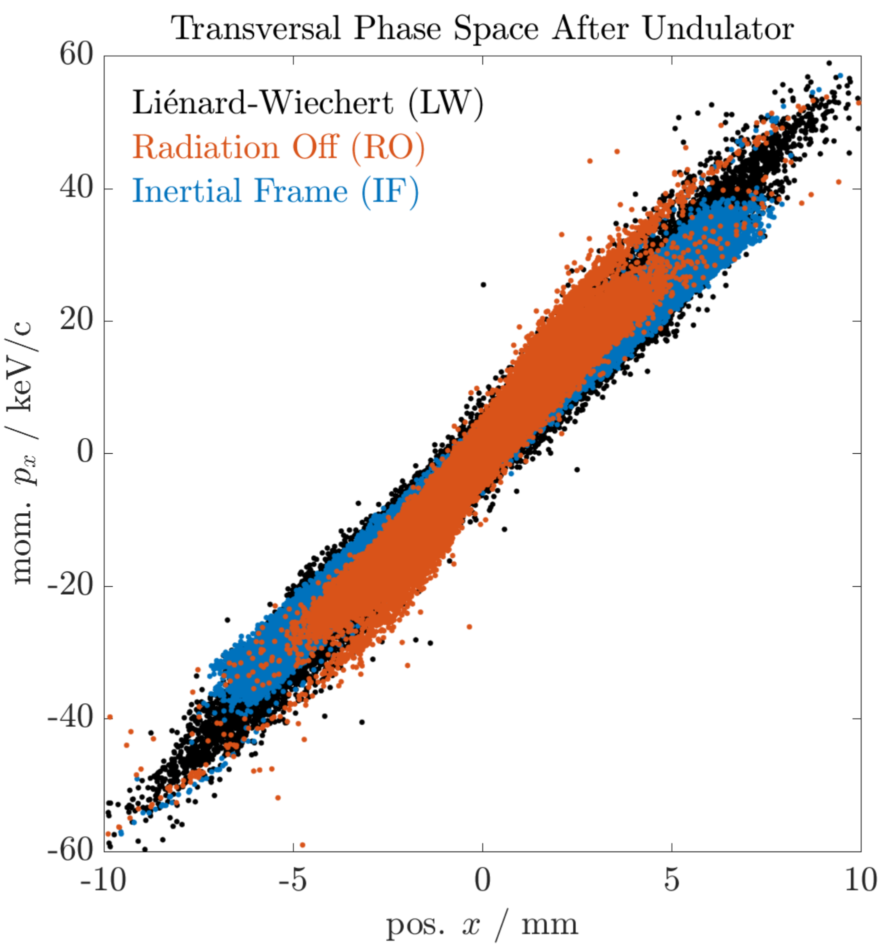
Transversal Bunch Size Growth:

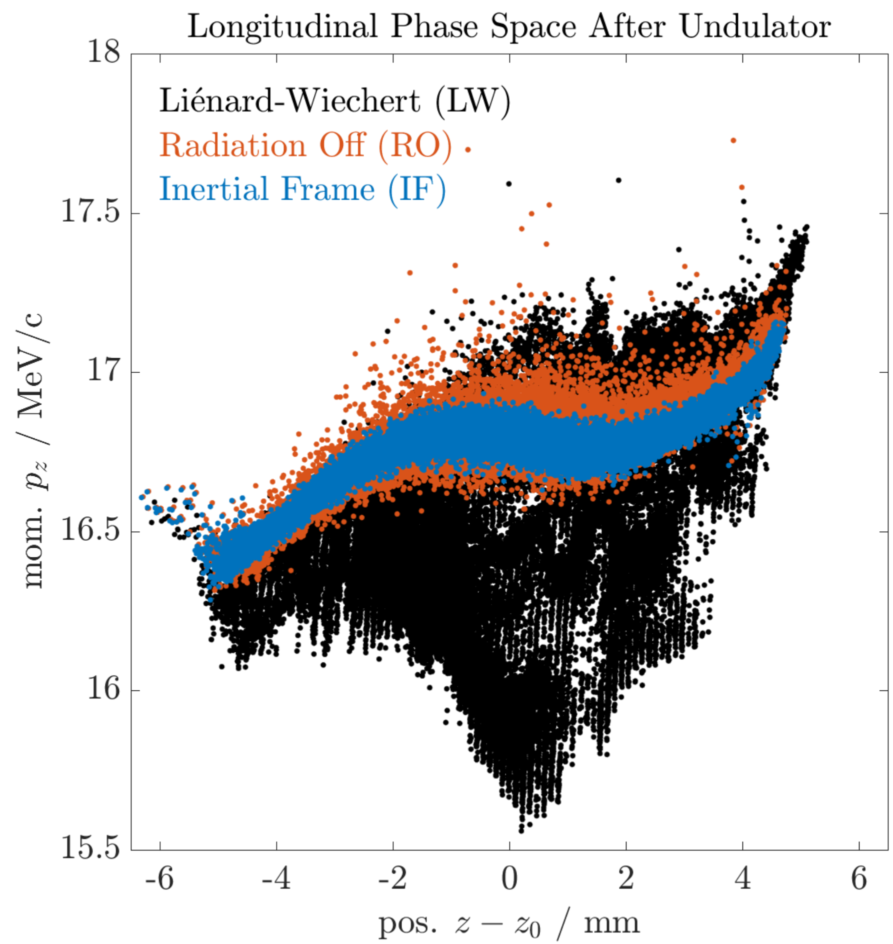


- Good agreement of IF, Astra3D, Krack and Reptil simulations
- Small difference in ΔX_{rms} between IF and LW in bunch size
- Bunch size for RO significantly smaller than for LW

  ⇒ Radiation leads to higher emittance

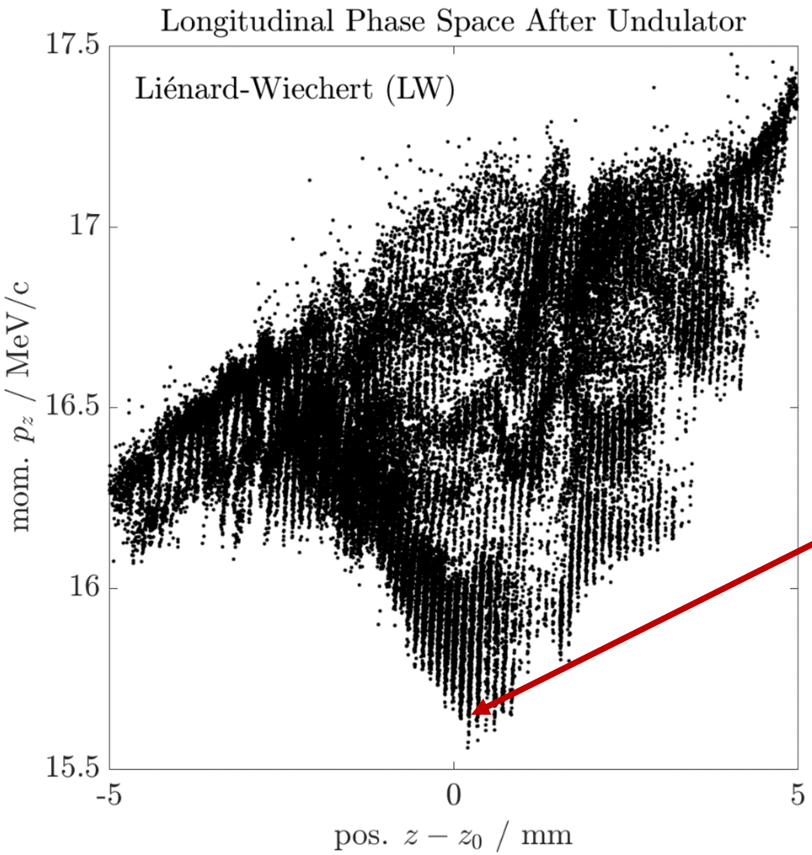
Simulation Results
Retardation and Radiation Effects





⇒ Radiation fields dominate space charge beam dynamics

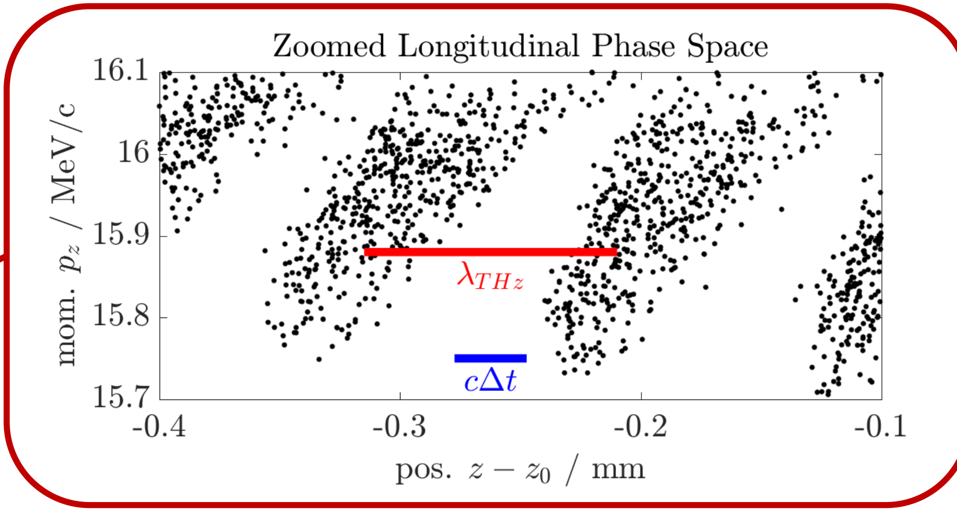
Simulation Results
Retardation and Radiation Effects



Longitudinal Bunching:

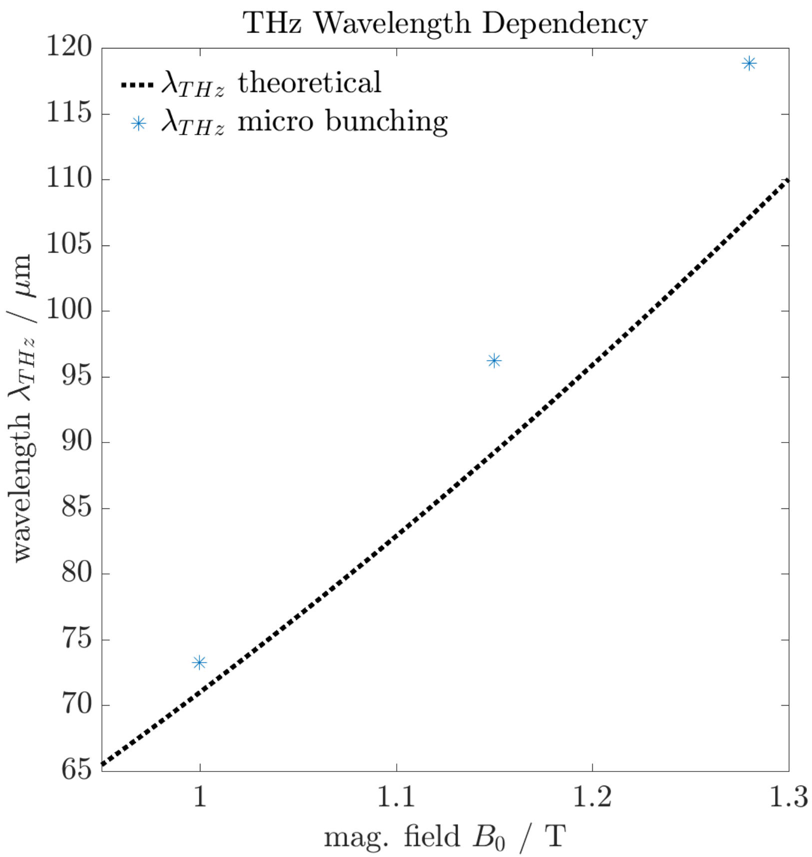
THz-Wavelength $\lambda_{THz} = \frac{\lambda_U}{2\,\gamma^2}\left(1 + \frac{K^2}{2}\right) \approx 105\ \mu\text{m}$

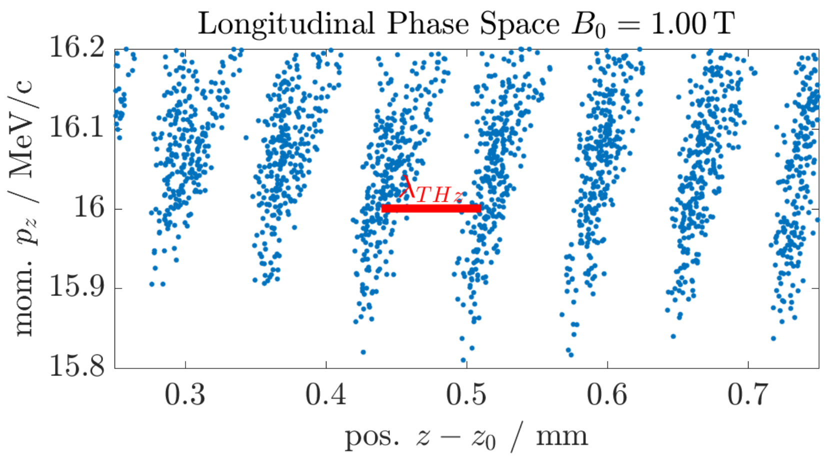
Micro-bunching consistent with λ_{THz}

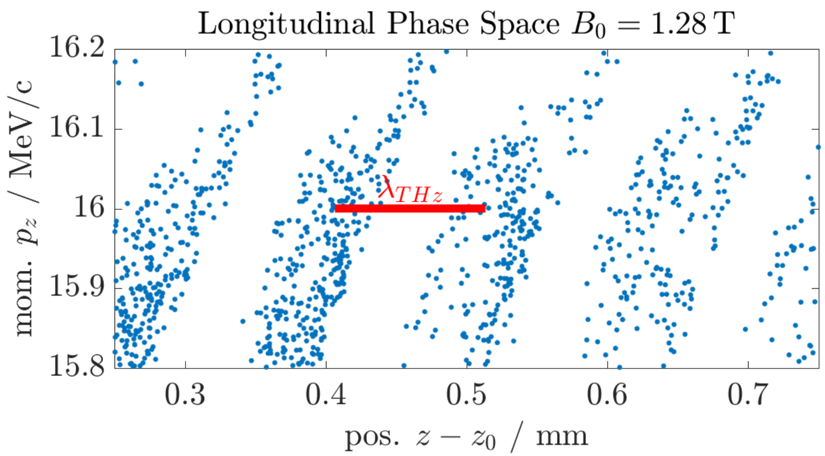


Simulation Results
Retardation and Radiation Effects

THz-Wavelength Dependency:







Simulation Results
Retardation and Radiation Effects

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Particle Bunch at Undulator Exit:

Quantity	LW-model	IF-model	Rel. Dev.
Δx_{rms}	3.1 mm	3.1 mm	$+0.5\%$
Δy_{rms}	2.6 mm	2.6 mm	-0.9%
Δz_{rms}	2.2 mm	2.2 mm	-2.3%
δE_{rms}	347.4 keV	95.7 keV	-72.5%
ϵ_x	$17\,\pi$ mrad mm	$13\,\pi$ mrad mm	-24.6%
ϵ_y	$10\,\pi$ mrad mm	$7\,\pi$ mrad mm	-30.5%
ϵ_z	$1366\,\pi$ mrad mm	$282\,\pi$ mrad mm	-79.4%

- IF-model provides reasonable estimate for bunch size
- IF-model underestimates transversal emittance
- Strong deviation for energy spread and long. emittance

Simulation Results
Retardation and Radiation Effects

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Radiation Field:

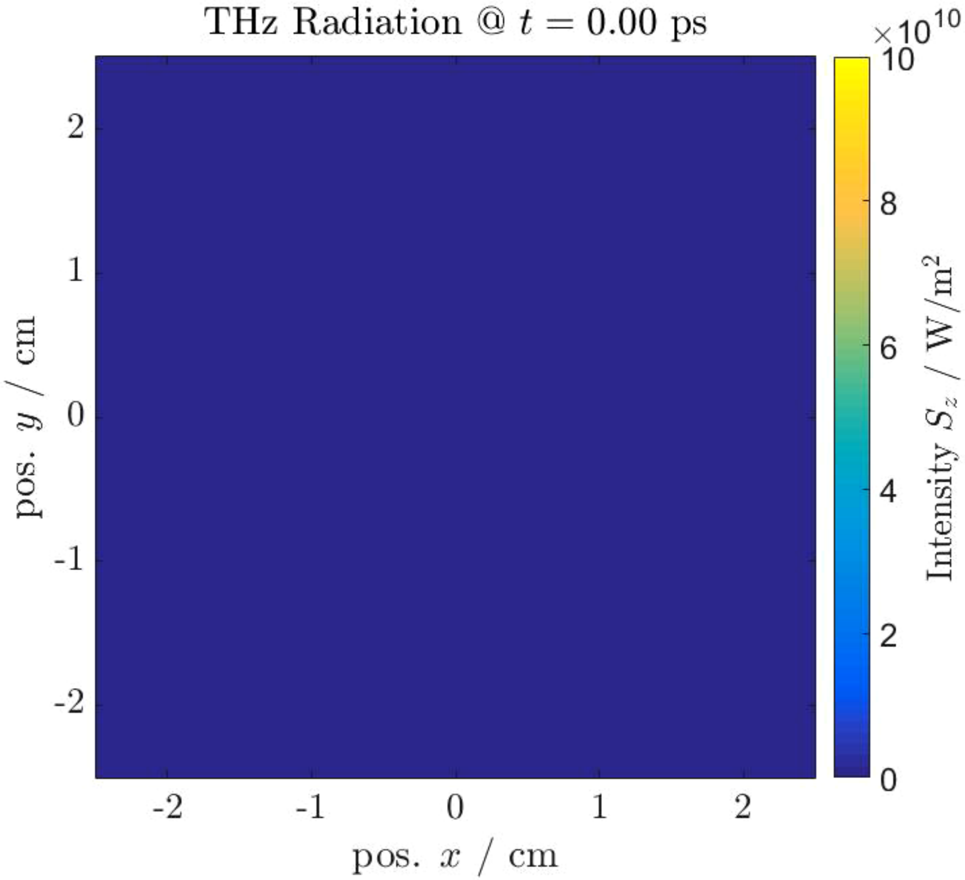
Screen at $z = 30.8\ \mathrm{m}$

Spatial res. $\Delta x = 100\ \mu\mathrm{m}$
($\lambda_{THz} \approx 105\ \mu\mathrm{m}$)

Temporal res. $\Delta t = 0.1\ \mathrm{ps}$
($T_{THz} \approx 0.35\ \mathrm{ps}$)

$\Rightarrow$ Memory limitation for Δt

… work in progress



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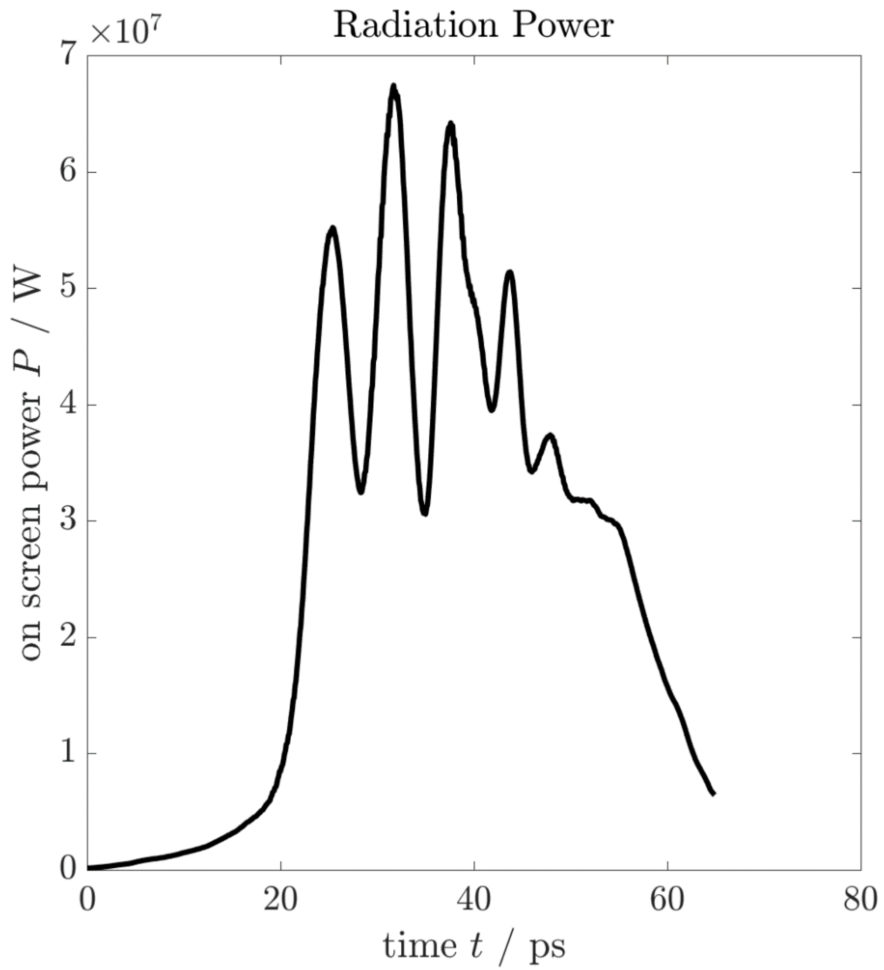

Summary & Outlook

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Summary:

- Liénard-Wiechert simulations of THz-FEL undulator with $\mathrm{N} \leq 100\mathrm{k}$ particles
- Inertial frame models overestimate static space charge effects
- Radiation effects dominate space charge beam dynamics
- Astra3D, Krack, and Reptil provide reasonable estimates for beam size, but cannot reproduce momentum space (no general statement)

Outlook:

- Validation of Liénard-Wiechert simulations with CST EM-PIC
- Implementation of realistic undulator field map
- Study of bunch parameters: charge, size, etc…
- Approximation of particle world lines ⇒ red. LW-code memory requirements
- Approximation of retardation & retardation effects in Reptil ⇒ red. runtime

…thanks to M. Krasilnikov for the provided data.