All-optical source size and emittance measurements of laser-accelerated electron beams

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Helmholtz Institute Jena

3rd NanoAc Workshop Liverpool
07.11.2025

Outline

- Motivation
  - Measuring low emittance and small source sizes of electron beams
- The Optical Grating Method
  - Basic principle and theory
  - Inferring the electron beam source size and emittance
  - Background noise influence
- Lasers @ HI Jena
- Optical Grating Experiment at JETi200

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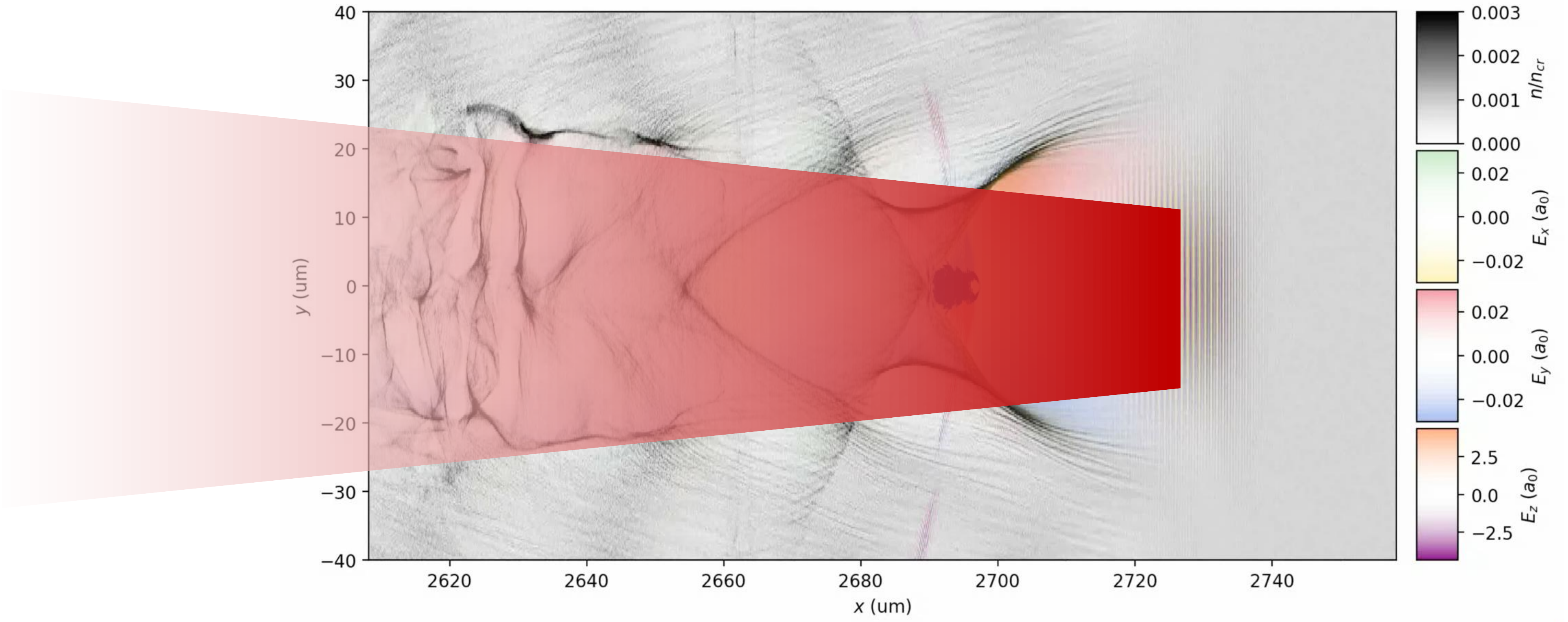
Laser/Plasma Wakefield Acceleration



- Shoot ultraintense laser into gas target: accelerating fields ~ 100 GV/m
- Various mechanisms for injection of electrons into wake bubble
- (Multi-)GeV electron beams after mm ... cm
- Quasi-monoenergetic, small source size, low-emittance, ...

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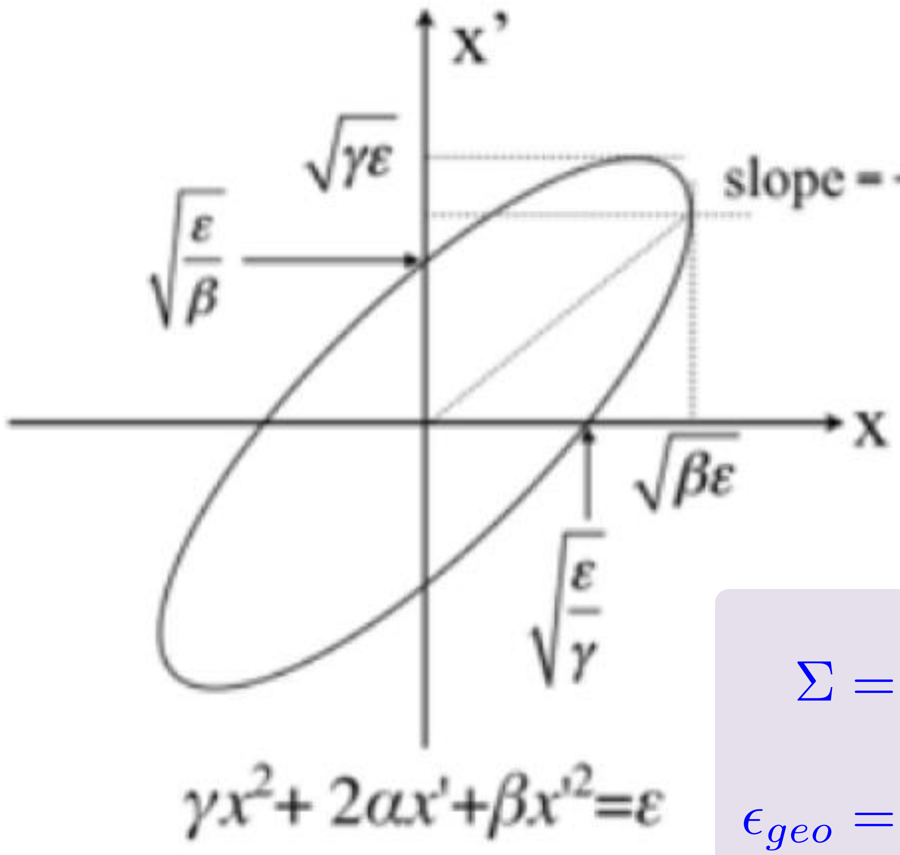
Transverse Beam Emittance

Quality of the transverse beam phase space



$$\Sigma = \begin{pmatrix} \langle x^2 \rangle & \langle x x' \rangle \\ \langle x x' \rangle & \langle x'^2 \rangle \end{pmatrix}$$

$$\epsilon_{geo} = \sqrt{\det \Sigma}$$

Because of focusing fields in bubble:
No correlations at LWFA exit

Geometric emittance

$$\epsilon_{geo} = \epsilon_{rms} = \sigma_x \sigma_{x'}$$

= (source size) x (angular divergence)

Normalized emittance

$$\epsilon_N = \sigma_x \gamma \sigma_{x'}$$

= (source size) x (rms momentum spread)

$$p_x = \gamma v_x = \gamma x'$$

Angular divergence easy to measure.
If we can measure the source size we also have the emittance!

Why a Small Beam Emittance is Important?

- Small emittance → Higher brightness

$$B \propto \frac{I}{\epsilon_{n_x}\epsilon_{n_y}}$$

Beam current

Transverse normalized emittances of the beam

- High brightness is advantageous for:
  - Particle colliders: small emittance beams (high brightness) increases the luminosity
  - As drivers of free electron lasers
  - High quality Inverse Thomson backscattering X- and gamma-ray sources

Plasma photocathode

PRL 108, 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]
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(Received 30 March 2011; published 17 January 2012)

PRL 111, 015003 (2013) PHYSICAL REVIEW LETTERS week ending 5 JULY 2013

Generating High-Brightness Electron Beams via Ionization Injection by Transverse Colliding Lasers in a Plasma-Wakefield Accelerator

F. Li,[1] J. F. Hua,[1] X. L. Xu,[1] C. J. Zhang,[1] L. X. Yan,[1] Y. C. Du,[1] W. H. Huang,[1] H. B. Chen,[1] C. X. Tang,[1] W. Lu,[1,2,*] C. Joshi,[2] W. B. Mori,[2] and Y. Q. Gu[3]
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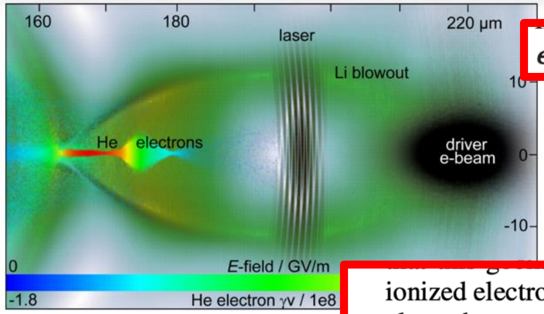
(Received 14 January 2013; published 2 July 2013)



$\epsilon_n \approx 3 \times 10^{-8}$ m rad,

ionized electrons in the transverse plane and localizes them along the propagation axis of the wake leading to an electron beam with a normalized emittance of 8.5 and 6 nm in

Emittance Measurements

- Quadrupole scans: high accuracy but not single shot
- Pepper pots: developed for LINACs but are limited for low emittances
  Salgado et al., arXiv:2412.09971 (under review)
- **Optical grating method (source size measurement → emittance)**

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 012803 (2021)

Characterizing ultralow emittance electron beams using structured light fields

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(Received 2 July 2020; accepted 6 January 2021; published 20 January 2021)

Optical Grating Method

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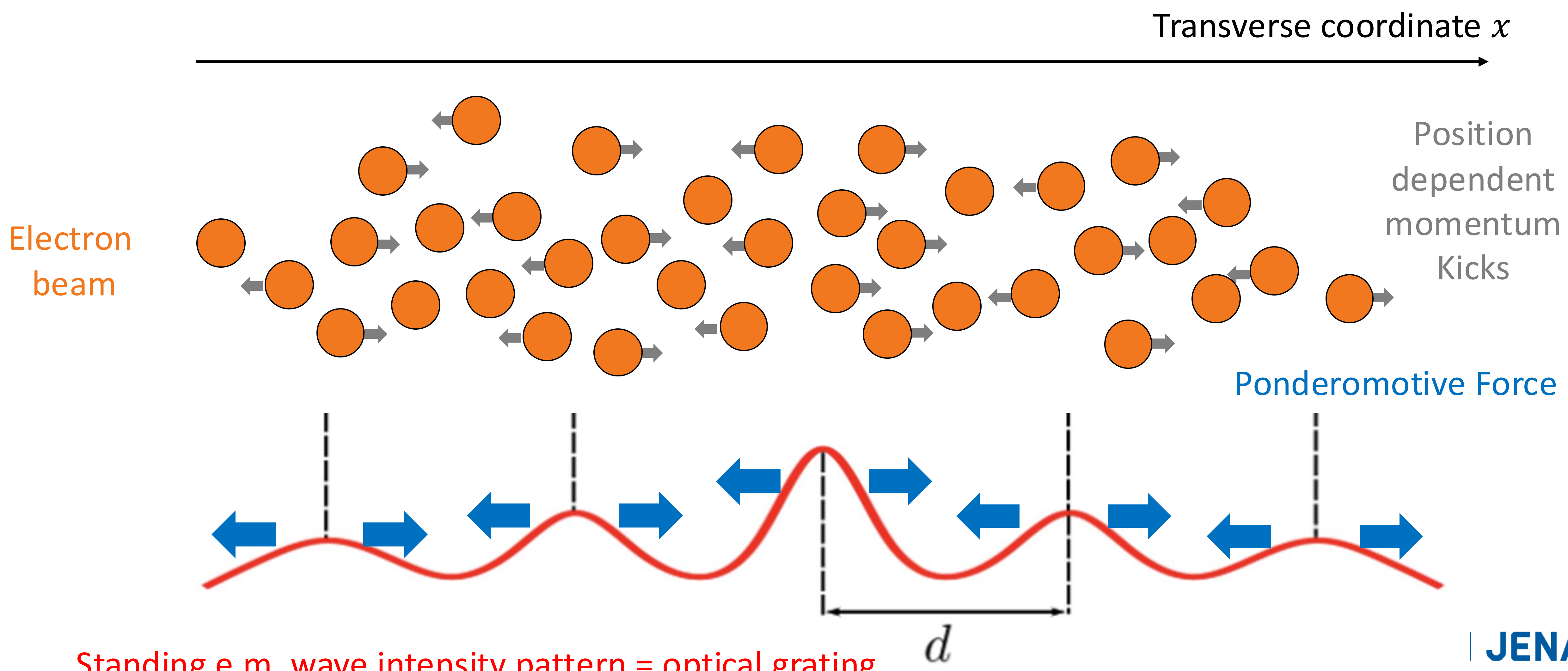
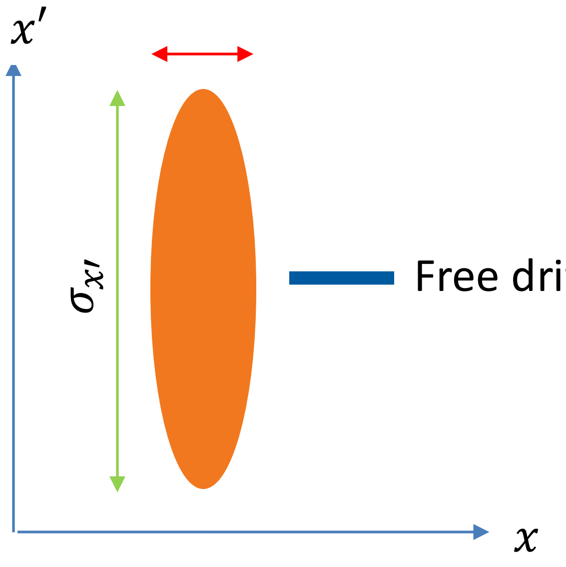
Optical Grating Concept in a Nutshell

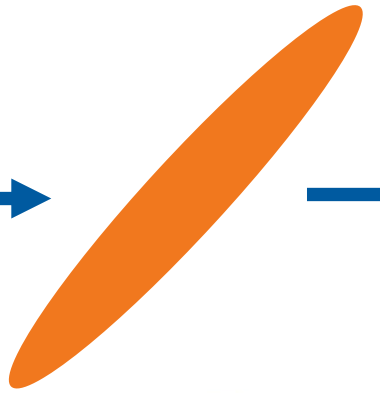


Standing e.m. wave intensity pattern = optical grating

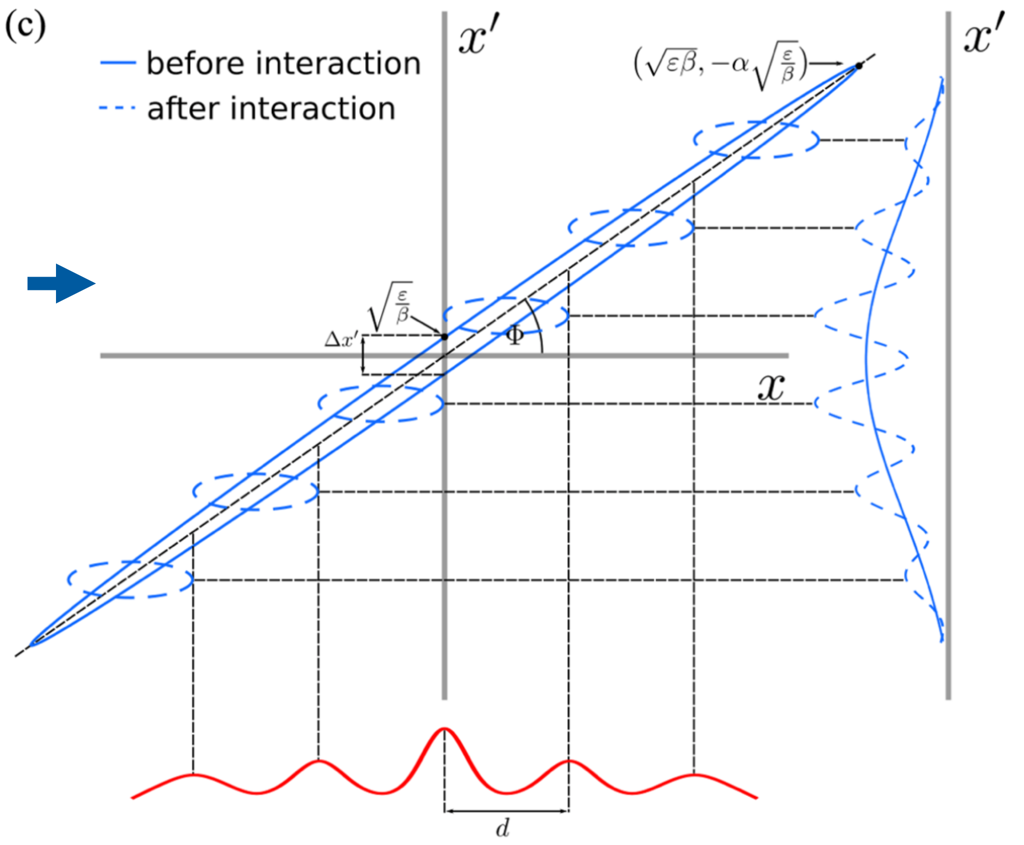
Optical Grating Concept in More Detail



Free drift

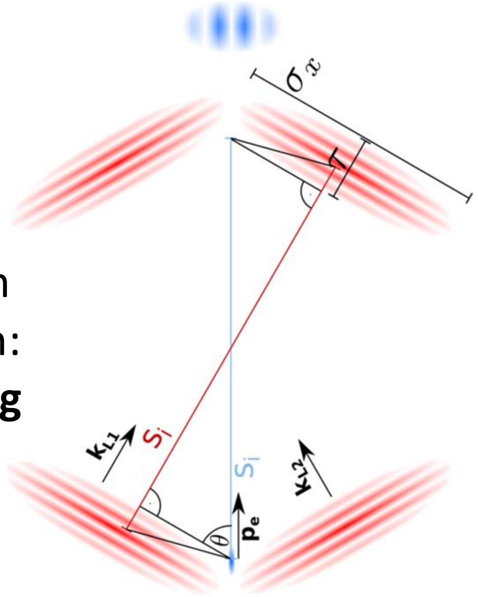


Ponderomotive scattering



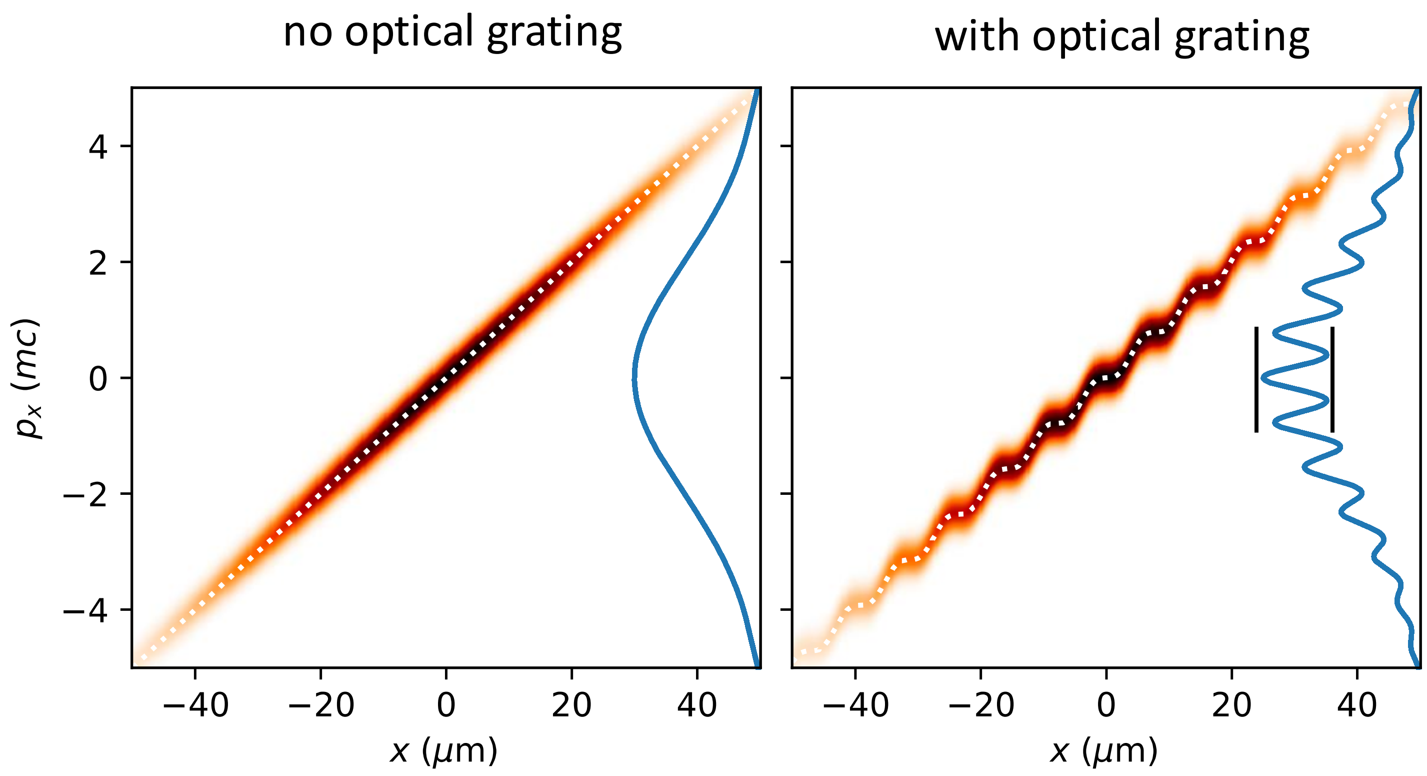
Source = end of LWFA

Two crossed laser beams form a standing wave pattern: **Optical grating**



Electrons are ponderomotively scattered off the standing wave: **Optical grating**
→ periodic modulation of the phase space

Emittance Measurement with Optical Grating



- Momentum distribution translates into spatial distribution
- Measure modulation strength (peak-to-valley ratio)
- Infer source size from p-v-r using theoretical model
- Requires precise knowledge of experimental parameters
  - Drift length between source and grating
  - Optical grating wavelength λ_G
  - Grating strength (intensity)

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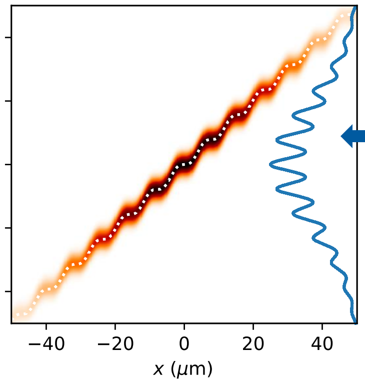
Theory Prediction for Modulation Strength

- Model transverse phase space distribution $n(x, p_x)$ as Gaussians, apply momentum kicks
- Observation in far field:
- Modulation on screen = momentum spectrum
- Modulation strength function $F(p_x)$ → integrate over x, normalize

$\delta p(x) = U \sin k_G x$



$$\mathcal{F}(p_x) = \frac{1}{N_0}\int dx\, n(x,p_x) = \int \frac{d\eta}{\sqrt{2\pi}} \exp\left\{-\frac{[\eta - \alpha \sin(k_G\sigma_x\eta + k_G L p)]^2}{2}\right\}$$

$$\alpha = \frac{LU}{\sigma_x} = \frac{(\text{drift length}) \times (\text{strength of ponderomotive kick})}{(\text{source size})}$$

- Laser grating switched off: $\alpha \to 0, \quad F \to 1$

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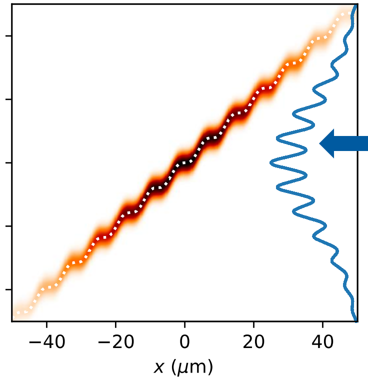
Perturbation Analysis and Inference of σ_x

- Perturbation theory for small α



$$\mathcal{F}(p_x) = 1 + \underbrace{k_G \sigma_x \alpha}_{\text{Intensity factor}} \, e^{-\frac{(k_G \sigma_x)^2}{2}} \underbrace{\cos k_G L p_x}_{\text{Periodic density modulations}}$$

$$= \kappa = k_G L U = \frac{I}{I_0}$$

- Theoretical prediction for peak-to-valley ratio to compare with measured values R_M

$$R_T = \frac{\max_{p_x} F(p_x)}{\min_{p_x} F(p_x)} \simeq 1 + 2\,\kappa\, e^{-2\pi^2 \left(\frac{\sigma_x}{\lambda_G}\right)^2} \leftrightarrow R_M$$

- Depends on 3 parameters: κ, σ_x, λ_G, infer σ_x if other two are known

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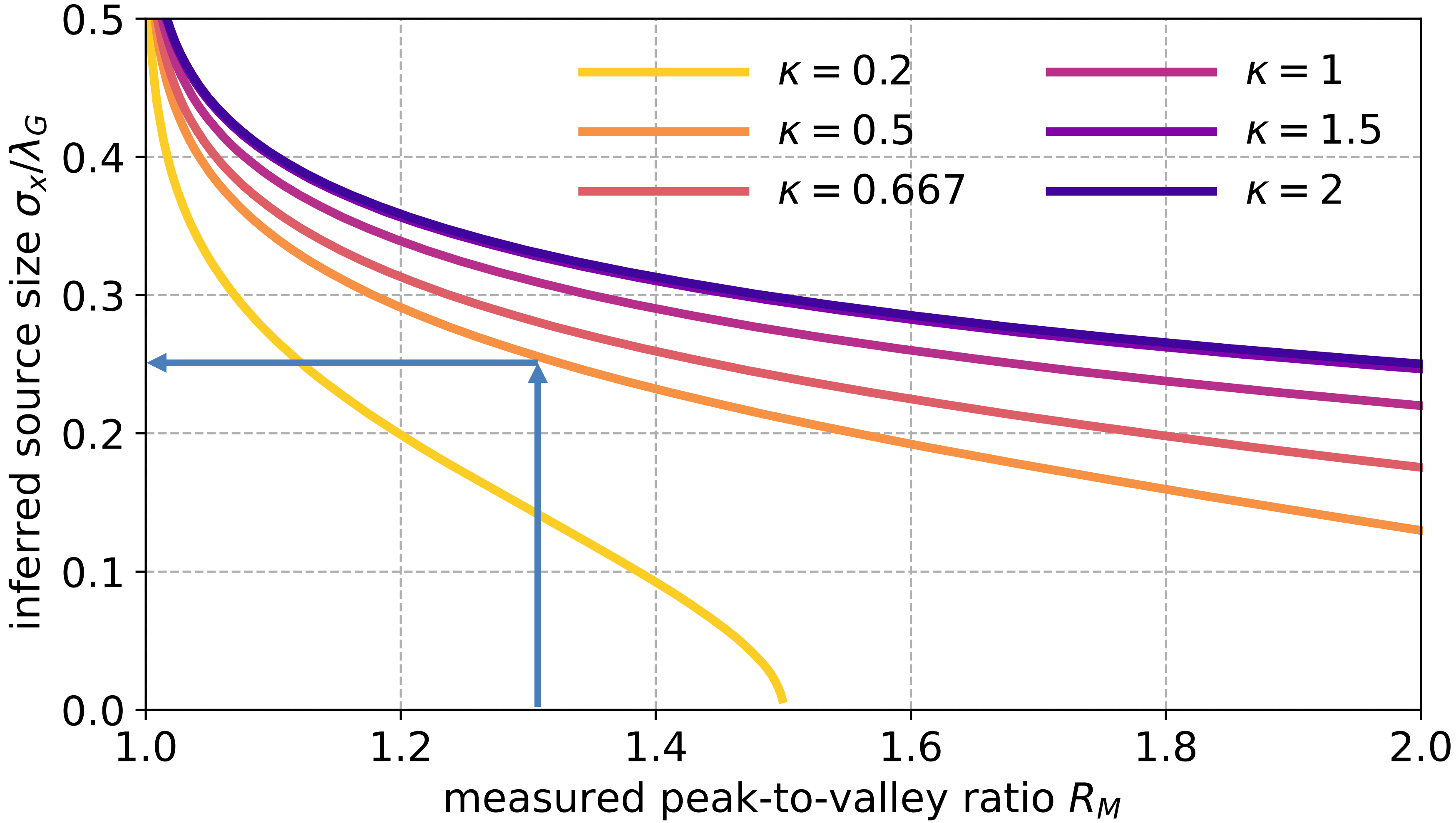
Source Size Inference Beyond Pert-Theory

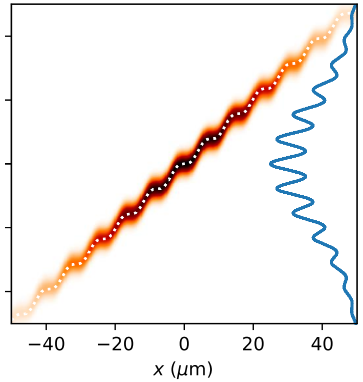
- Laser grating wavelength λ_G
- Grating strength κ



What is the Optimum Grating Strength?

$$\kappa = \frac{I}{I_0}$$

Grating strength parameter



Naively: optimum = largest peak-to-valley ratio at $\kappa = 1$

$\kappa = 1 \leftrightarrow$ horizontal tangents

$$I \sim I_0 \left[\frac{10^{18}\mathrm{W}}{\mathrm{cm}^2}\right] \propto \lambda_L^2[\mu\mathrm{m}] \frac{\gamma^2 \lambda_G^2}{z_{\mathrm{drift}}\, c\, t_{\mathrm{int}}}$$

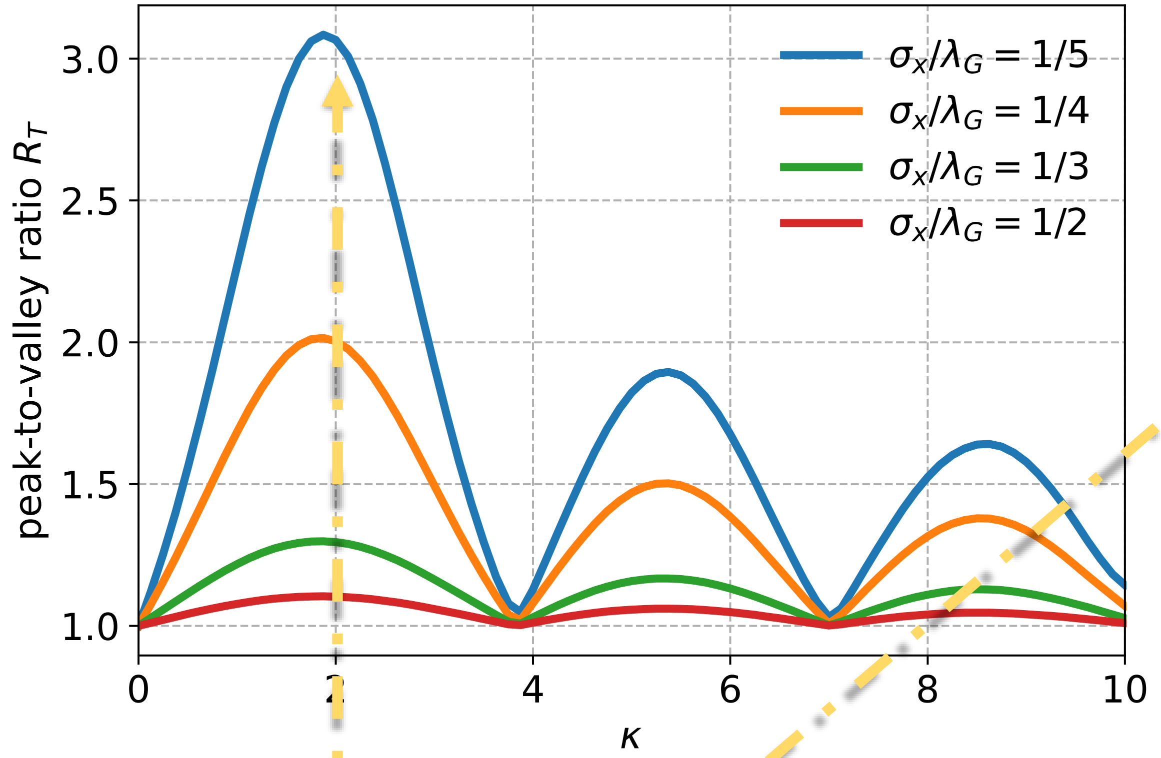
Matched intensity depends on experimental geometry

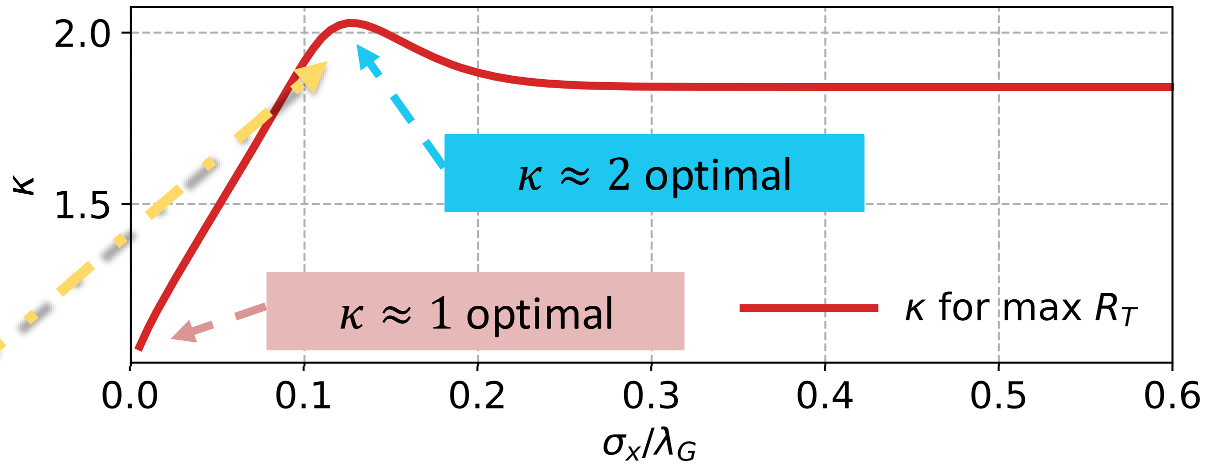
What happens if we cannot match correctly the grating intensity during an experiment?

$\lambda_G, z_{\mathrm{drift}}$, … can be measured easily

I hence κ is very hard to determine experimentally

How precisely do we need to know κ?



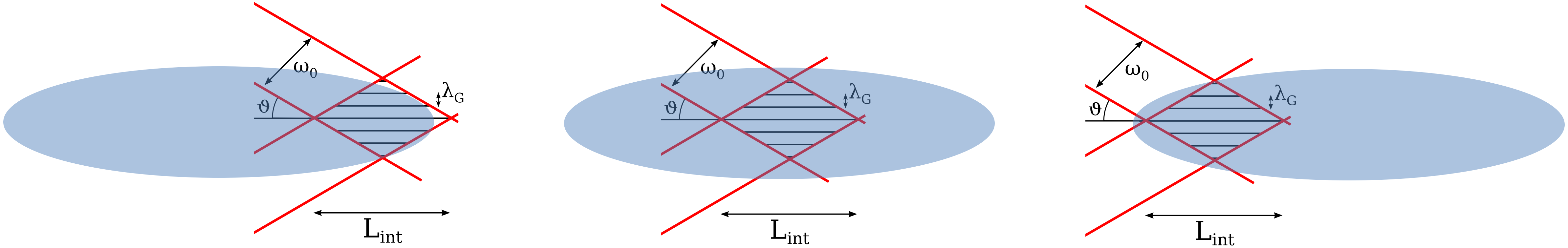


$\kappa \approx 2$ gives maximum peak-to-valley ratio for source size $> 0.1\lambda_G$

Even if kappa not known experimentally, we can use $\kappa = 2$ to perform the analysis → upper bound for inferred source size σ_x

Effect of Unmodulated Background

Depending on the temporal overlap, the grating does not interact with the entire electron beam
→ Some electrons are unmodulated, contributing to background noise



$$P_M \sim [(1-\nu_B)\max\mathcal{F} + \nu_B]N_0$$

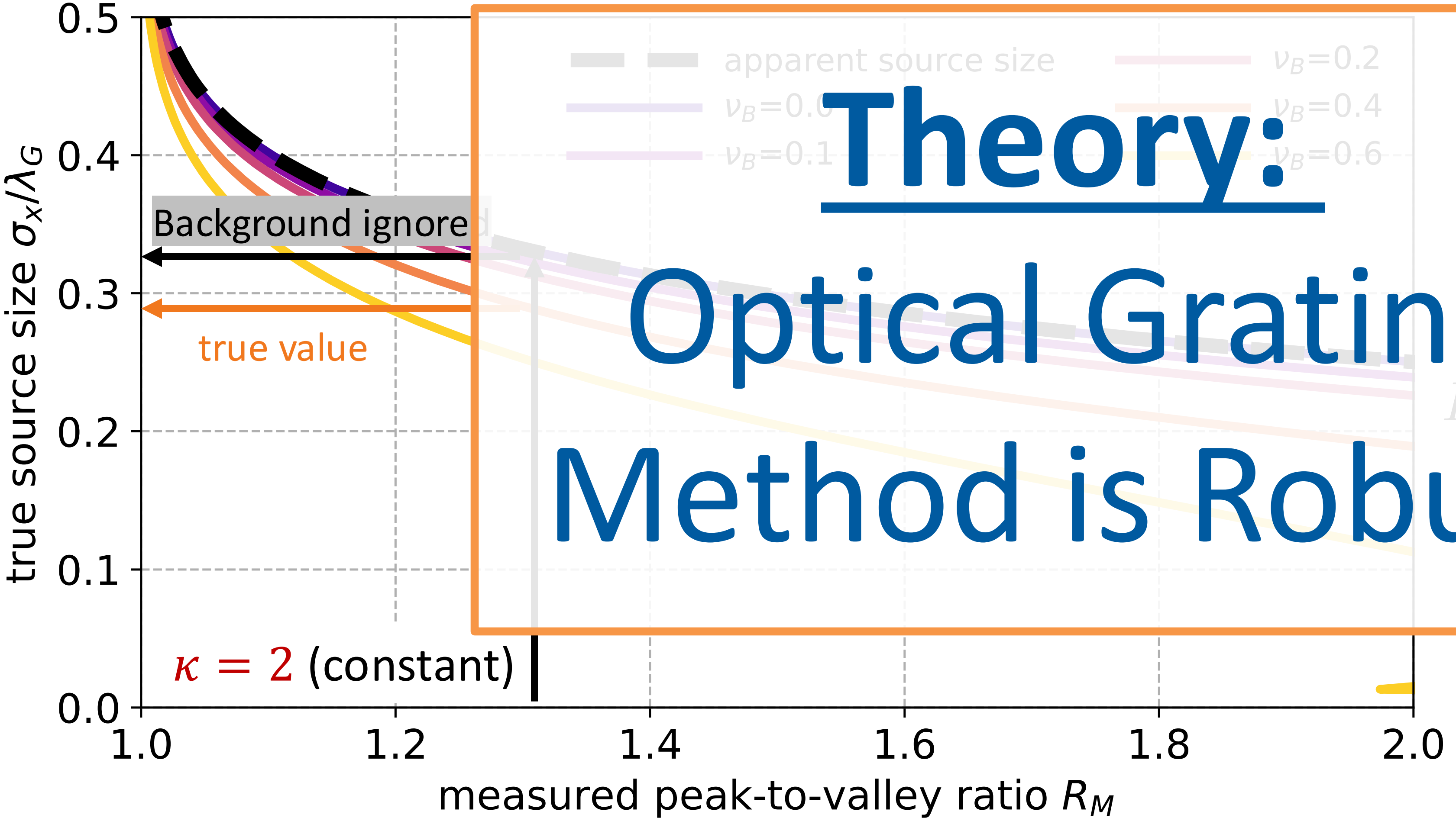
$$V_M \sim [(1-\nu_B)\min\mathcal{F} + \nu_B]N_0$$

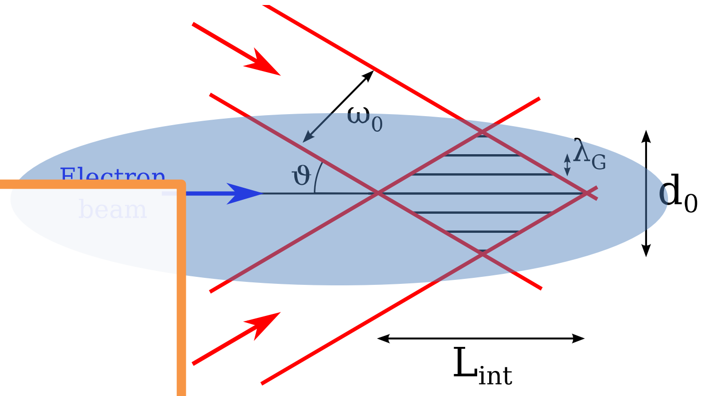
Include the effects of the background noise
ν_B = fraction of unmodulated electrons

$$R_M = \frac{P_M}{V_M} = \frac{\max\mathcal{F} + \frac{\nu_B}{1-\nu_B}}{\min\mathcal{F} + \frac{\nu_B}{1-\nu_B}}$$

Peak-to-valley ratio including background
Effects (unmodulated electrons)

Effect of Unmodulated Electron Background





Theory:

Optical Grating Method is Robust

$$R_M = \frac{P_M}{V_M} = \frac{\max \mathcal{F} + \frac{\nu_B}{1-\nu_B}}{\min \mathcal{F} + \frac{\nu_B}{1-\nu_B}}$$

When ignoring the background in the inference the source size is **overestimated:**

True emittance is smaller than quoted value

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High Intensity Lasers @ HI Jena

JETi ONE

ATHENA

NIR option

Wavelength:	800 nm
Energy:	2 mJ
Pulse duration:	3 fs - 30 fs

SWIR option via OPA + NDFG

Wavelength:	1.1 µm – 7 µm
Energy:	1 mJ – 5 µJ
Pulse duration:	few-cycle

JETi200

Wavelength:	800 nm
Energy on target:	5 J
Pulse duration:	17 fs
Peak power:	300 TW

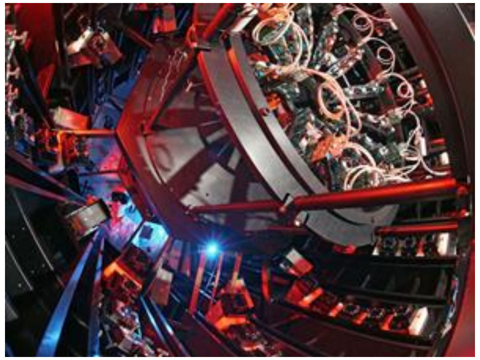
Short pulse NIR probing system

Wavelength: 750 nm

Energy: 200 µJ

Pulse duration: < 5 fs

POLARIS



Wavelength:	1030 nm
Energy on target:	16 J (54 J)
Pulse duration:	100 fs
Peak power:	160 TW (500 TW)

Short pulse probing system

Wavelength: 800 nm

Energy: 20 µJ

Pulse duration: 11 fs

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HI Jena Extension (2022) & TAF project

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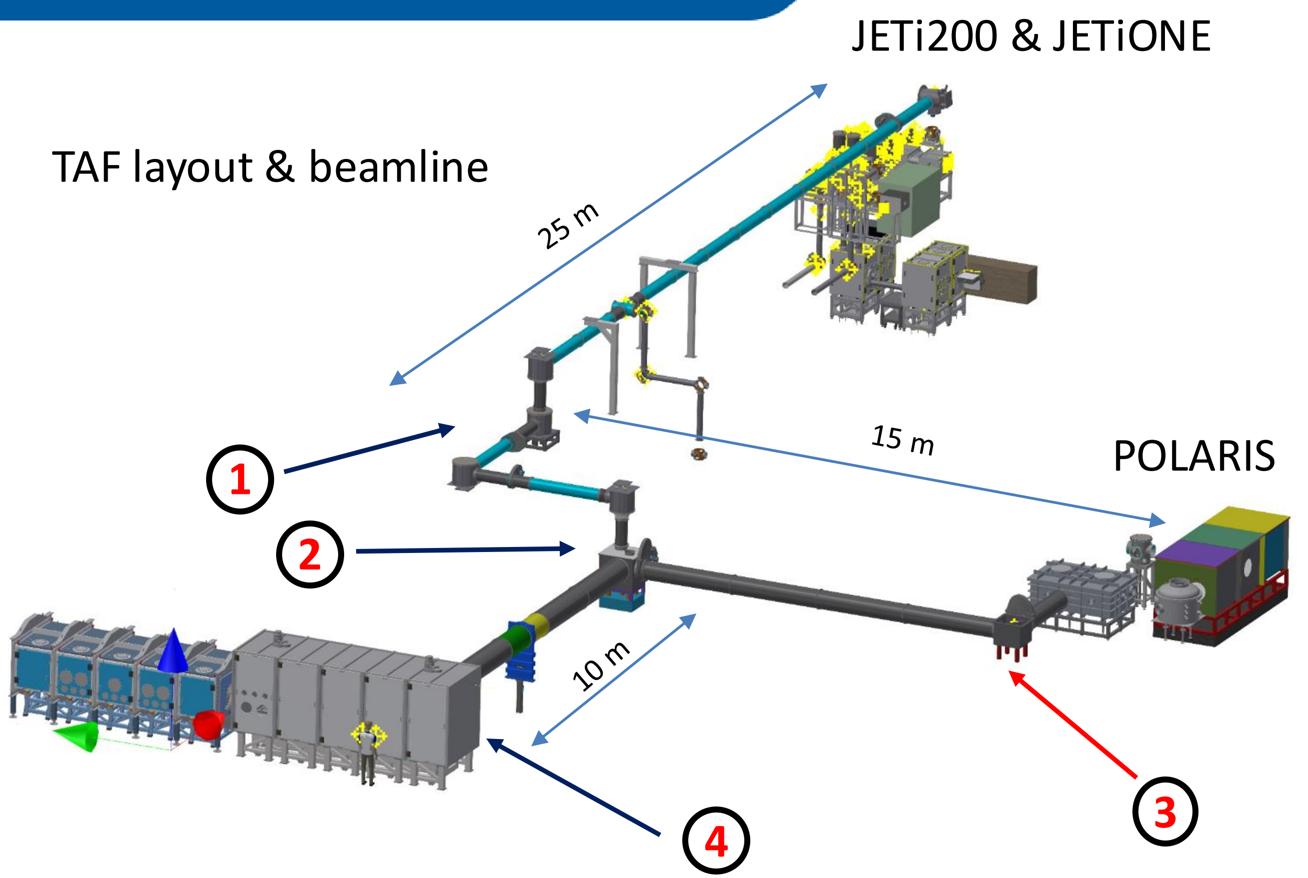
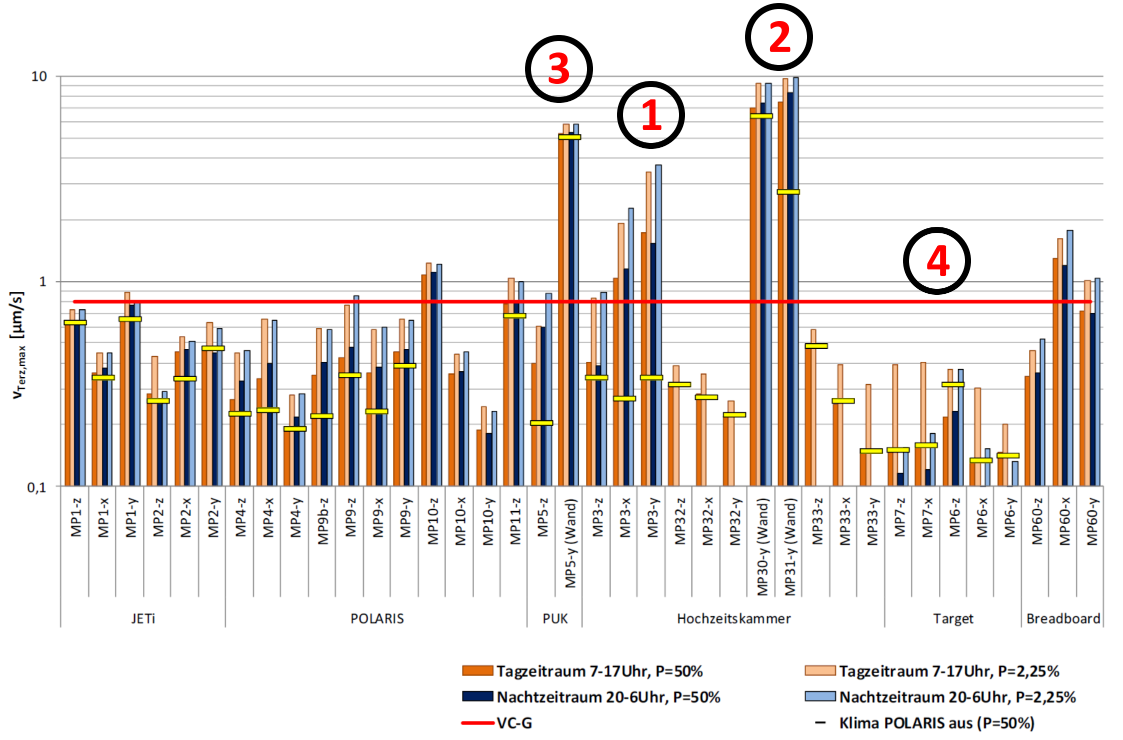
Beam Transport & Stablity Analysis



1. JETi200 Periscope (~ 3m)
2. JETi200 turning chamber above wedding chamber (~ 3 m)
3. POLARIS turning chamber (~ 5 m above ground)
4. Beam shaping chamber (~ 6 m x 2m x 1.5 m)



VC-G: strongest criteria for REM und TEM with sub-Ångström resolution.

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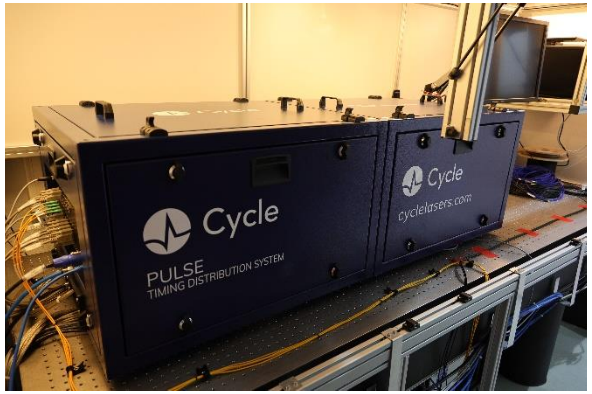
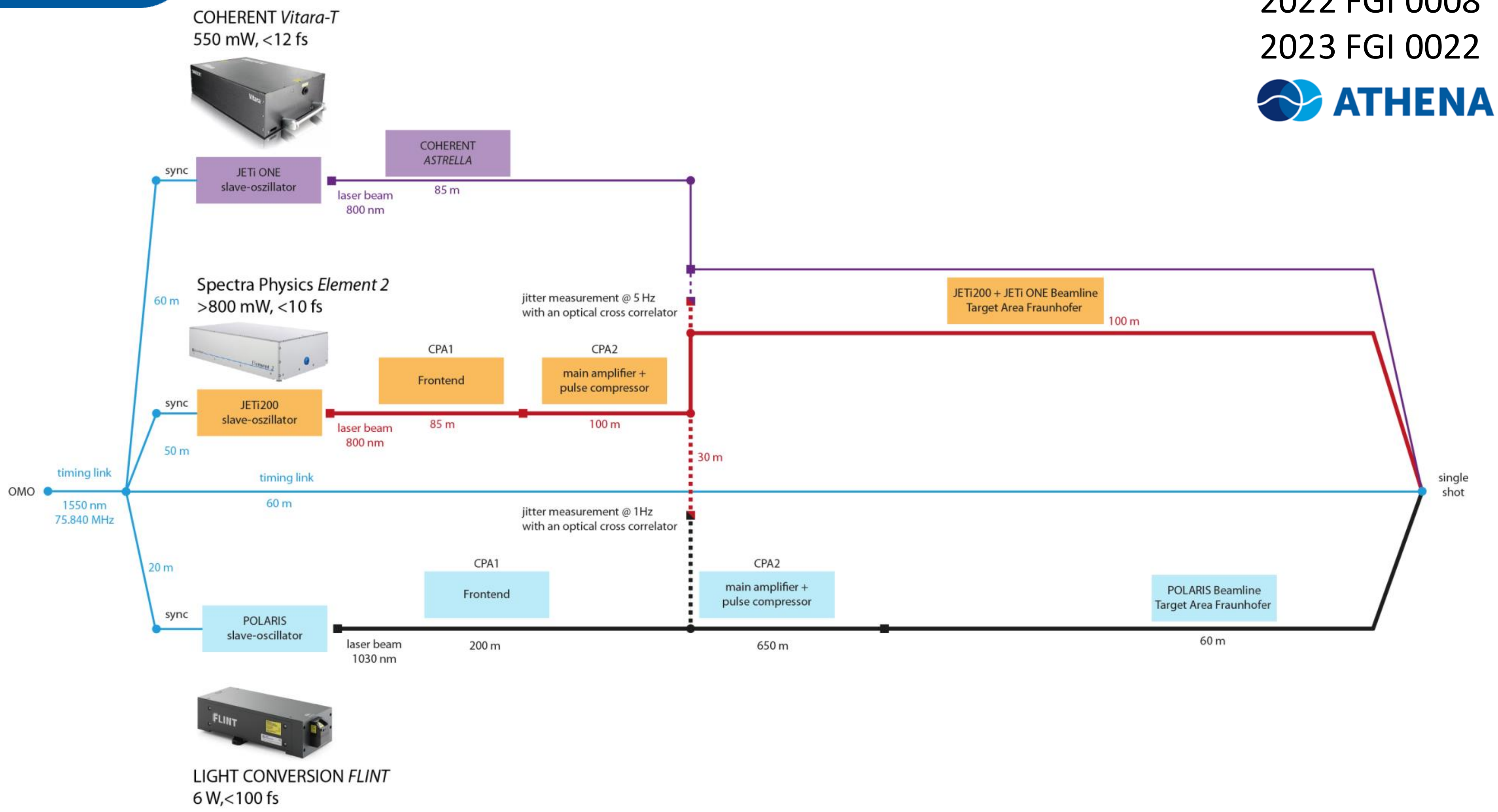
TAF Timing System at HI Jena

2022 FGI 0008
2023 FGI 0022



Temperature stabilized platform for low noise optical master oscillator.



- First flagship experiments in 2027
- **Temporal (~10s fs) and spatial overlap (< 3 µrad) crucial**

OSAT: December 2024

Optical Grating Experiment at JETi200

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Setup for Optical Grating Experiment

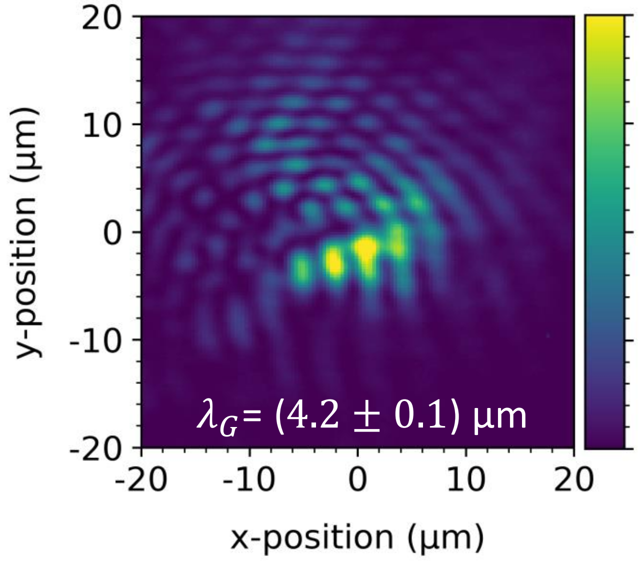
JETi200 laser

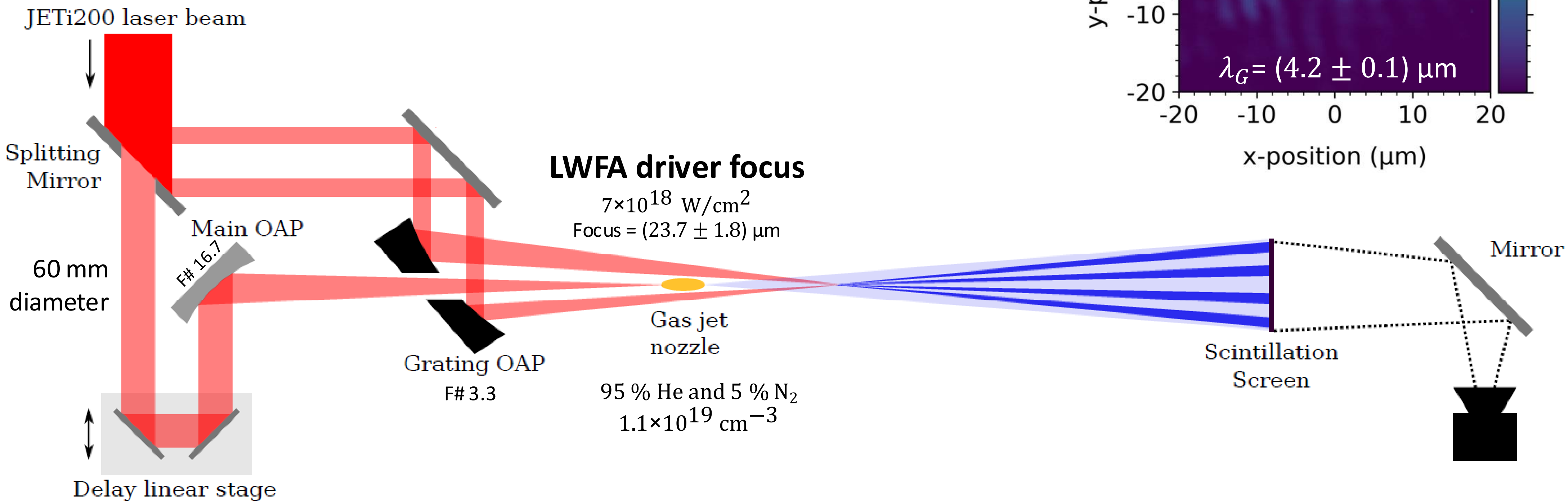
- Energy = 7.2 J (before compressor)
- 800 nm wavelength center
- Pulse duration = 23 fs

Ring laser focus

Focus = (23.7 ± 1.8) µm

Optical Grating





Interaction Time and I_0

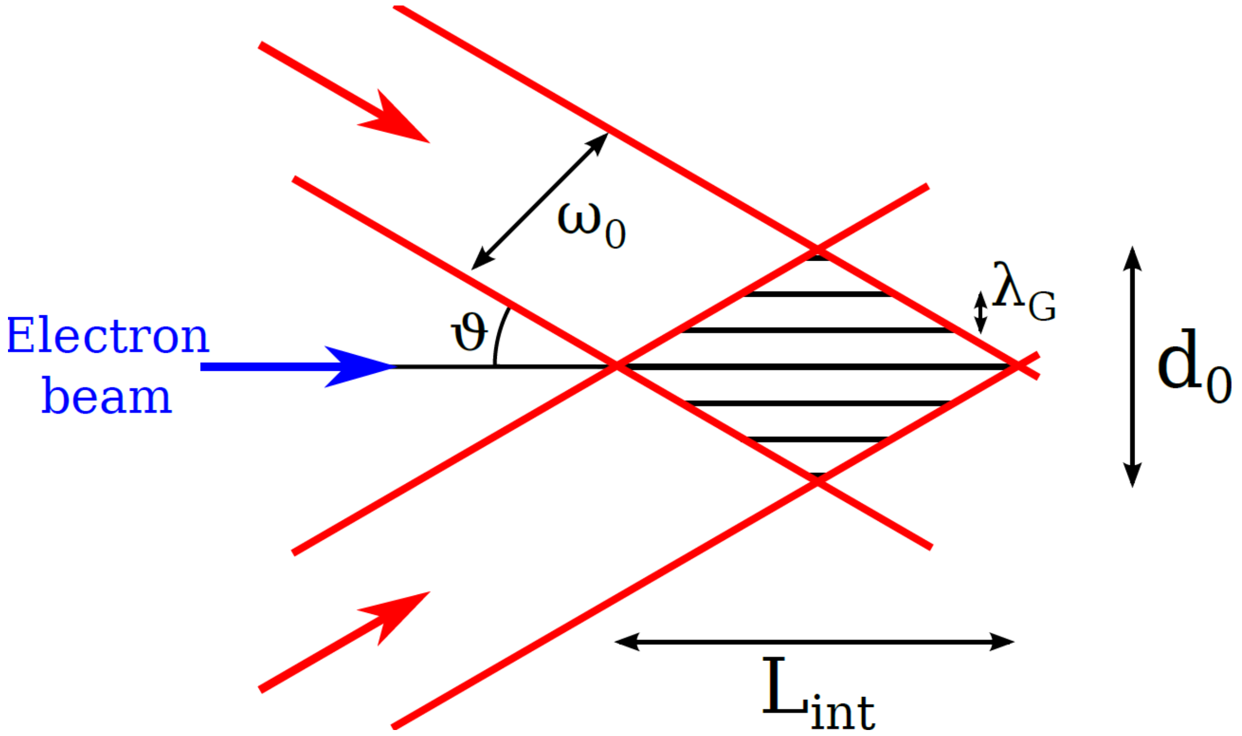
Defined by the experiment geometry

$$t_{int} = \frac{L_{int}}{c}$$

Having a crossing angle $\vartheta = 5.5°$,

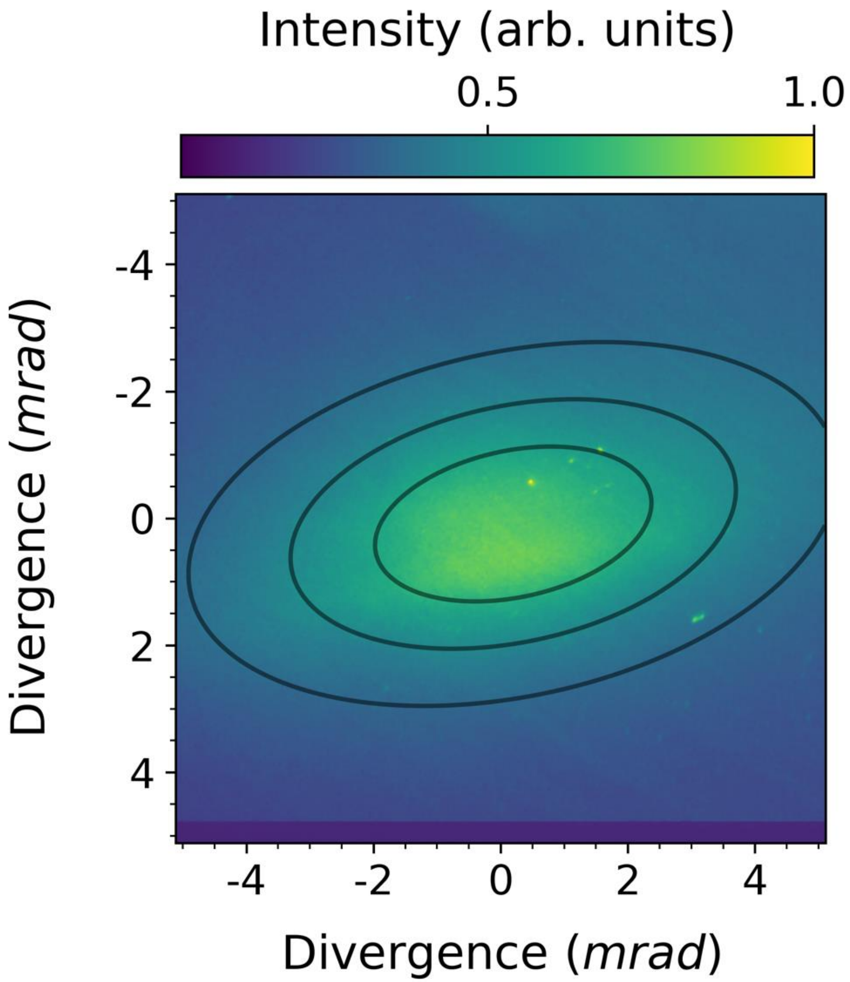
and $L_{int} = \frac{d_0}{\tan\vartheta} \approx 208\ \mu\text{m}$

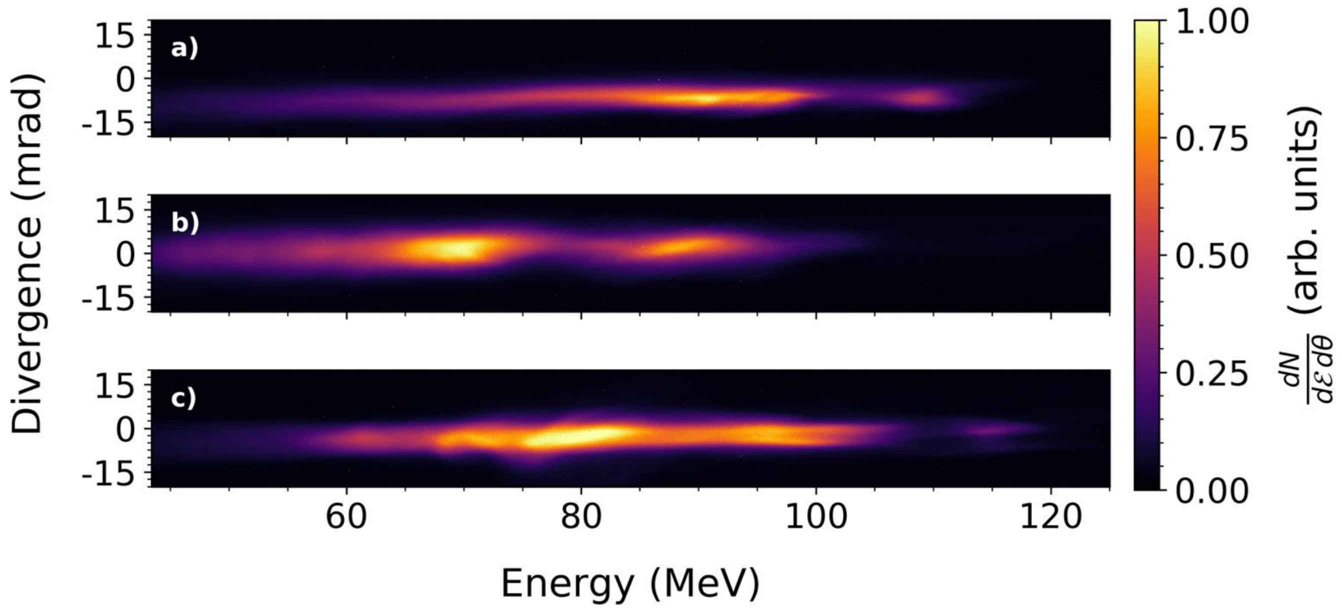
$$t_{int} \approx 582\ \text{fs}$$



For $\kappa = 2$: $I_0 = 6.4 \times 10^{18}\ \text{W/cm}^2 / t_{int}[\text{fs}] \approx 10^{16}\ \text{W/cm}^2$

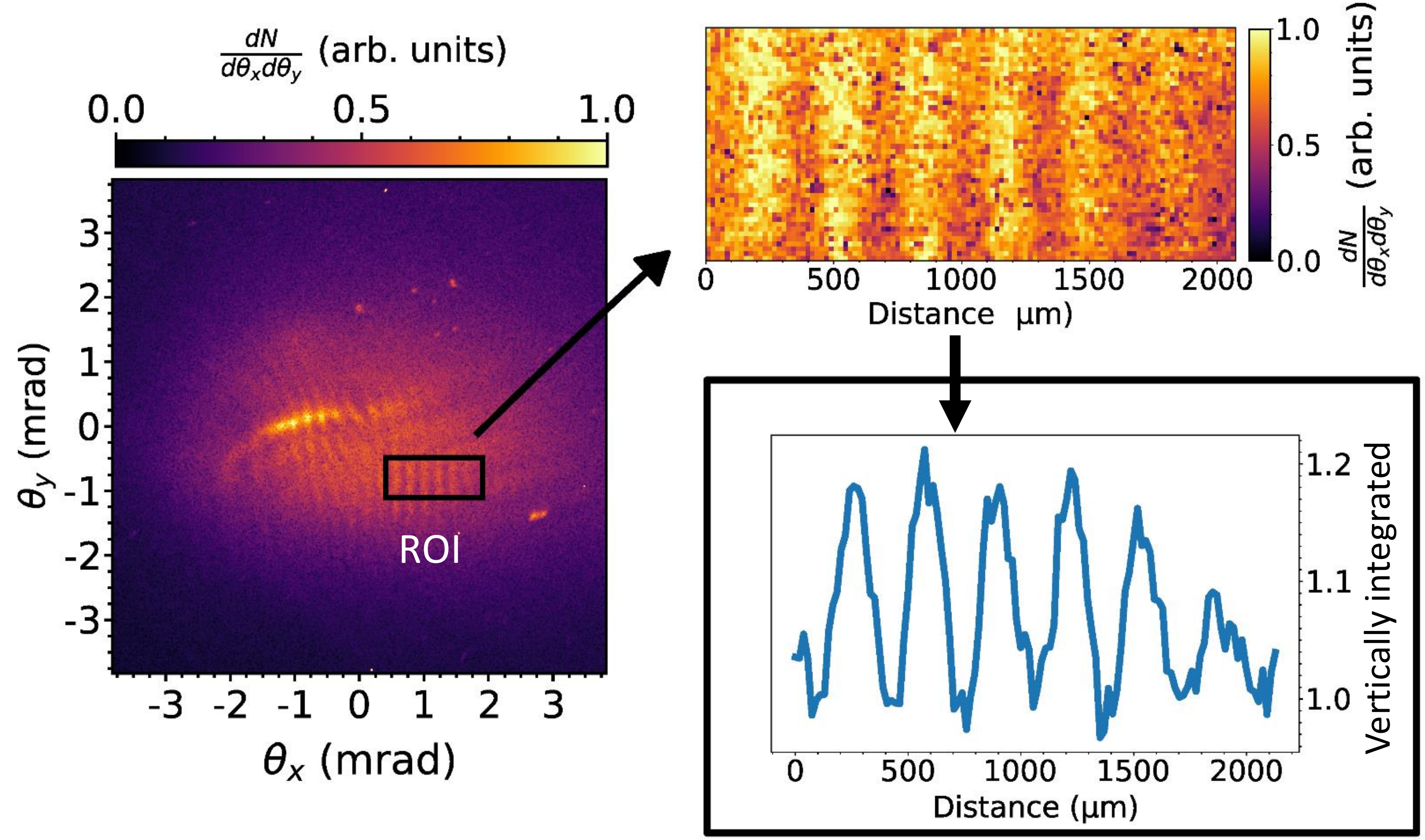
Electron Beam Characteristics





Property	Value
Beam charge	(5.6 ± 0.7) pC
Beam divergence	(2.6 ± 0.4) mrad
Mean energy	73 MeV
Average energy spread	(27.3 ± 4.8) %
Weighted mean Lorentz factor	143

Signal Modulation on the Electron Beam



Total of 184 shots analyzed

Distance between fringes = (330.1 ± 6.6) µm

Experimental peak-to-valley ratio: $R_M = 1.09 \pm 0.04$

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Source Size and Emittance from Experiment

$\boldsymbol{\kappa} = \mathbf{2}$
(strongest modulation depth, upper limit)

$\sigma_x \approx (1.7 \pm 0.2)$ µm

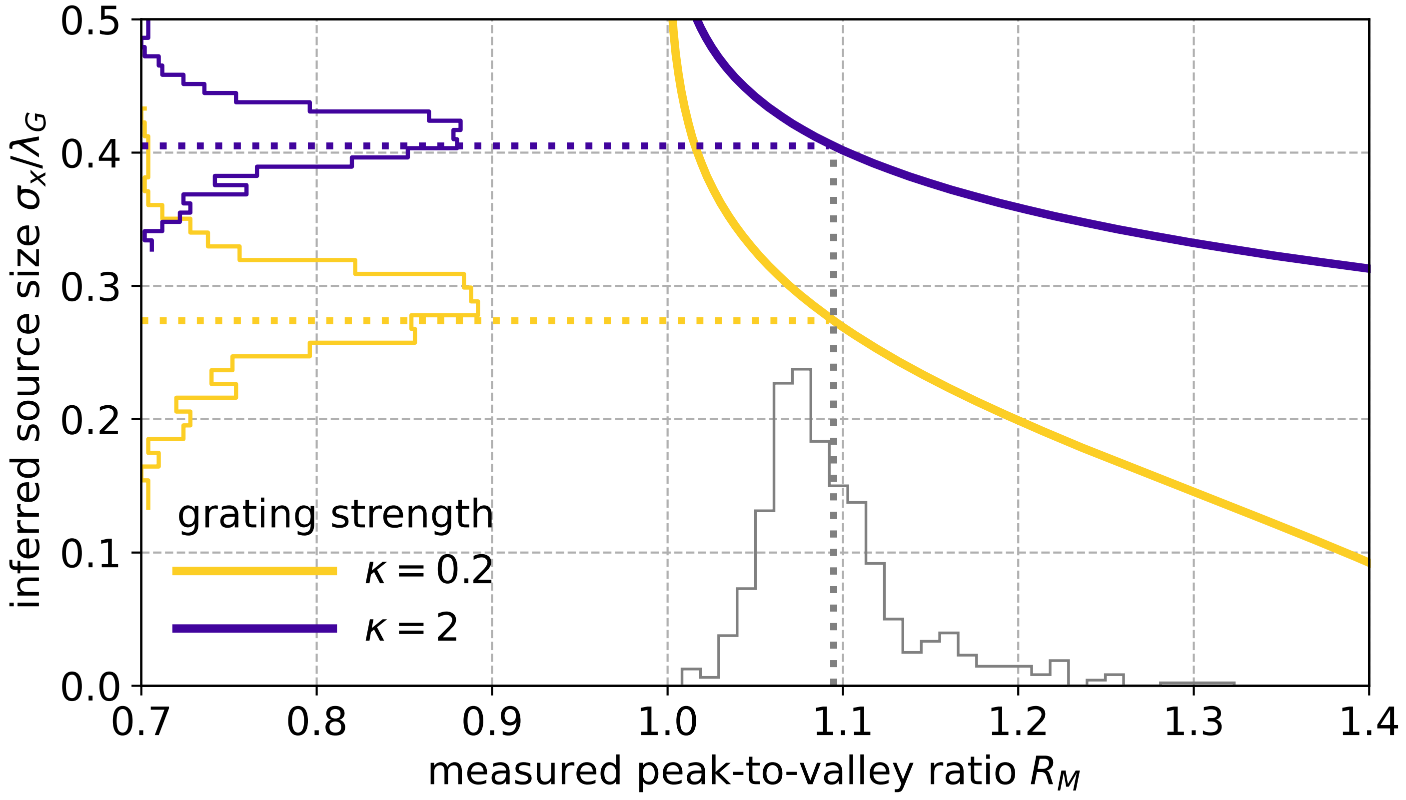
$\epsilon_{\mathrm{rms}} = (4.4 \pm 0.9) \times 10^{-3}\ \pi$ mm mrad

Values are comparable with quadrupole scan results used with LWFA accelerators.

$\boldsymbol{\kappa} = \mathbf{0.2}$
(smaller modulation depth)

$\sigma_x \approx (1.2 \pm 0.4)$ µm

$\epsilon_{\mathrm{rms}} = (3.1 \pm 1.2) \times 10^{-3}\ \pi$ mm mrad



Source size and geometric emittance depends only weakly on the precise grating strength modulation depth

From pepper-pot analysis:
PP $\epsilon_{\mathrm{rms}} \approx 26 \times 10^{-3}\ \pi$ mm mrad

Conclusions

- Developed and demonstrated all-optical single-shot emittance measurement
- Experimental demonstration at JETi200
- Theory for modulation strength allows inference from measured beam modulations
- No precise knowledge of grating intensity? Upper bounds for emittance!
- Systematic robustness of the method w.r.t. to background
- Capability of characterizing electron beams with small source sizes and ultra-low emittances in single shots

Optical Grating Theory: A. Seidel et al., PRAB 24, 012803 (2021).
Optical Grating Experiment: F. C. Salgado et al., PRAB 27, 052803 (2024).
Pepper-Pot Limitations: F. C. Salgado et al., arXiv:2412.09971.

BACKUP

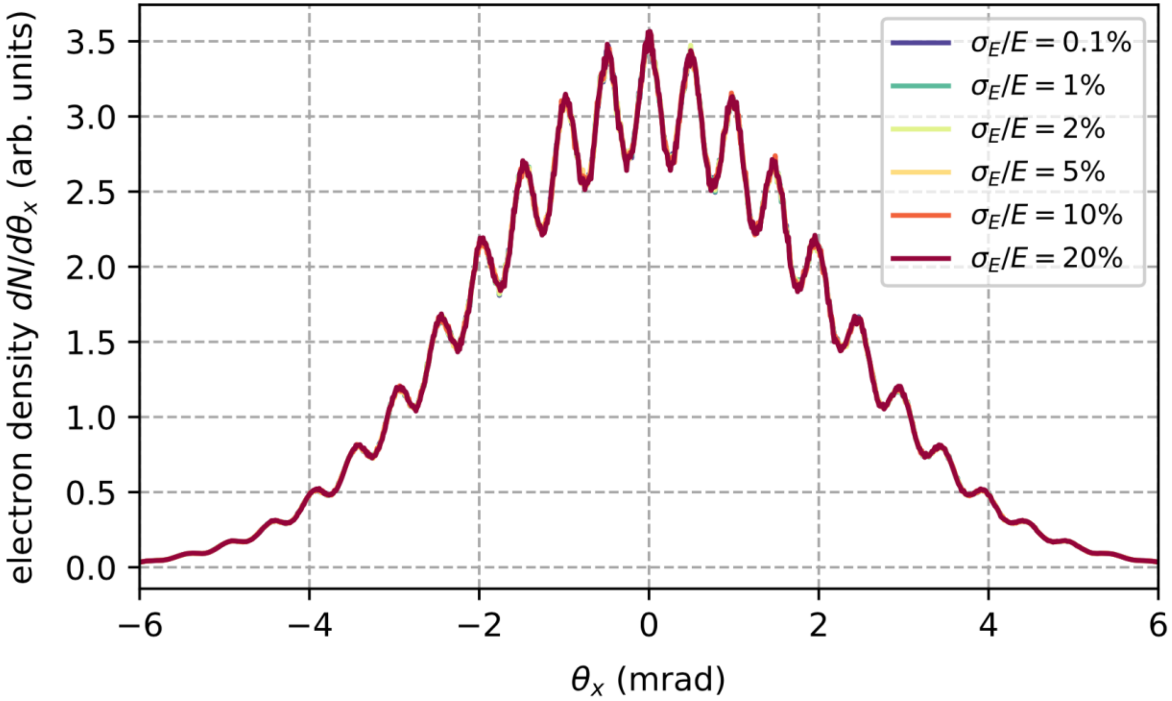


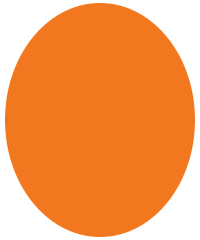
FIG. 11. Simulated effects of different electron beam energy spreads σ_E/E on the peak-to-valley modulations after interaction with the laser grating. No detectable difference in the modulated signal is observed, indicating that the variation in energy spread does not significantly impact the modulation.

Modulation Strength Theory

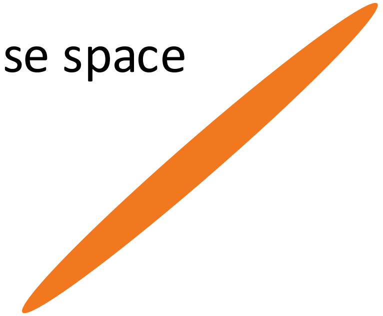
Model transverse phase space distribution as Gaussians

- End of LWFA: Uncorrelated phase space

$$n(x,p_x) = n_0 \exp\left\{-\frac{x^2}{2\sigma_x^2} - \frac{p_x^2}{2\sigma_p^2}\right\}$$



- Just before laser grating: Correlated tilted phase space



$$n(x,p_x) = n_0 \exp\left\{-\frac{(x - Lp_x)^2}{2\sigma_x^2} - \frac{p_x^2}{2\sigma_p^2}\right\}$$

Free drift with drift parameter

$$L = \frac{z_{drift}}{\gamma}$$

- Laser grating: Instantaneous momentum kick $\delta p(x)$

$$n(x,p_x) = n_0 \exp\left\{-\frac{[x - L(p_x + \delta p(x))]^2}{2\sigma_x^2} - \frac{[p_x + \delta p(x)]^2}{2\sigma_p^2}\right\}$$

Ponderomotive kick

$$\delta p(x) = U \sin k_G x$$