Radiation Properties of Tapered X-Ray Free Electron Lasers

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Presentation Outline

Motivation

Why tapering for hard X-ray FELs?

What are the requirements on the radiation from high power X-FELs?

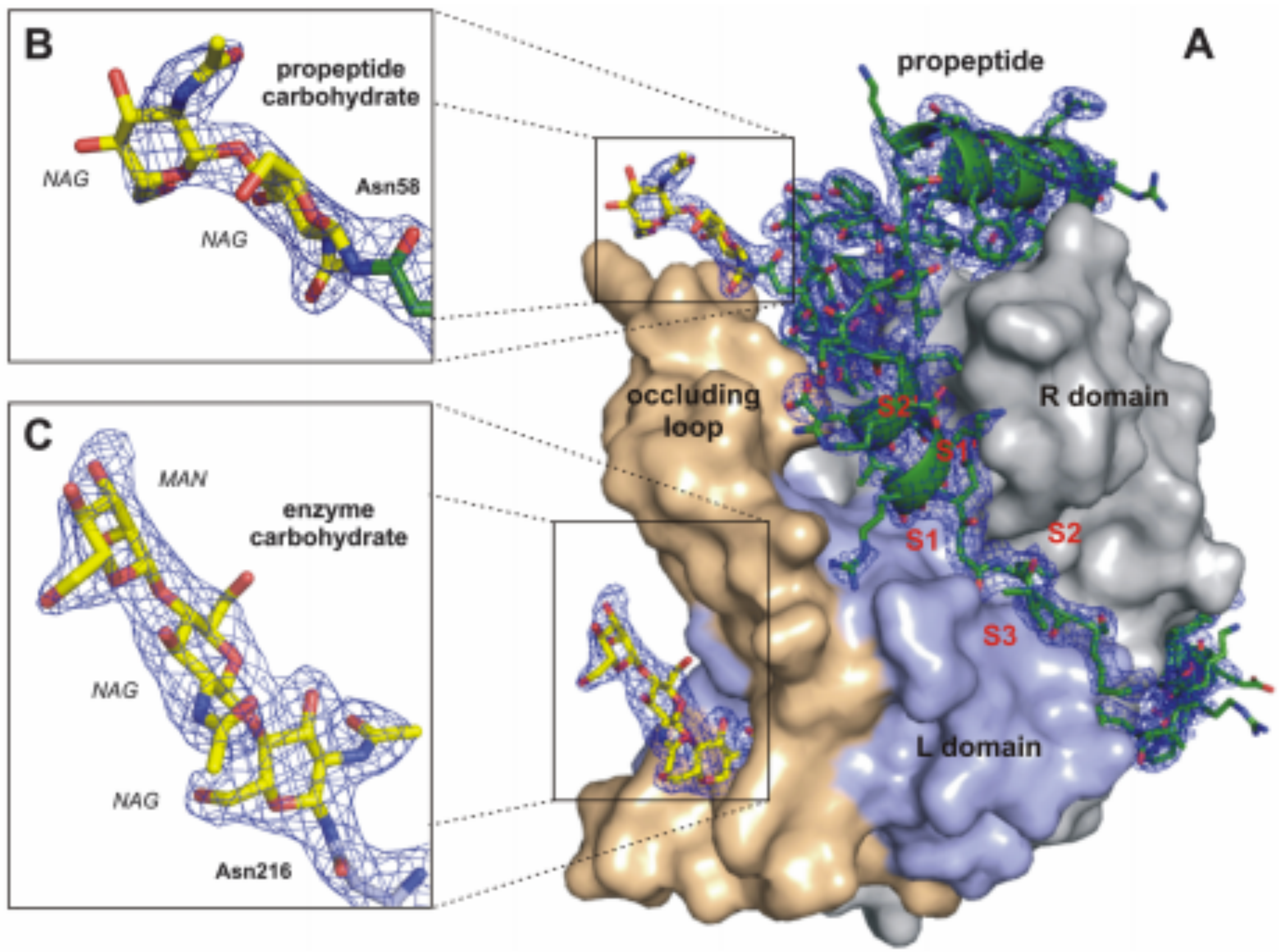
Why do we need to study the radiation properties of tapered hard X-ray FELs?

Tapered X-FELs: Physical Examples and Radiation Properties

Conclusion & Future Work

Pushing the imaging frontier

Redecke et al., Science 339, 6116, (2012)



2.1 A resolution

Trypanosoma brucei cysteine protease cathepsine B

Single Molecule Imaging Goal
20 fs - 20 mJ - 2020

Angstrom scale X-ray diffraction experiments have been performed successfully at LCLS

Resolution improves with higher photon energy & shorter pulse duration reduces radiation damage

Achieving ~ 20 fs pulses with 2 x 10^{13} photons/pulse allows single molecule imaging

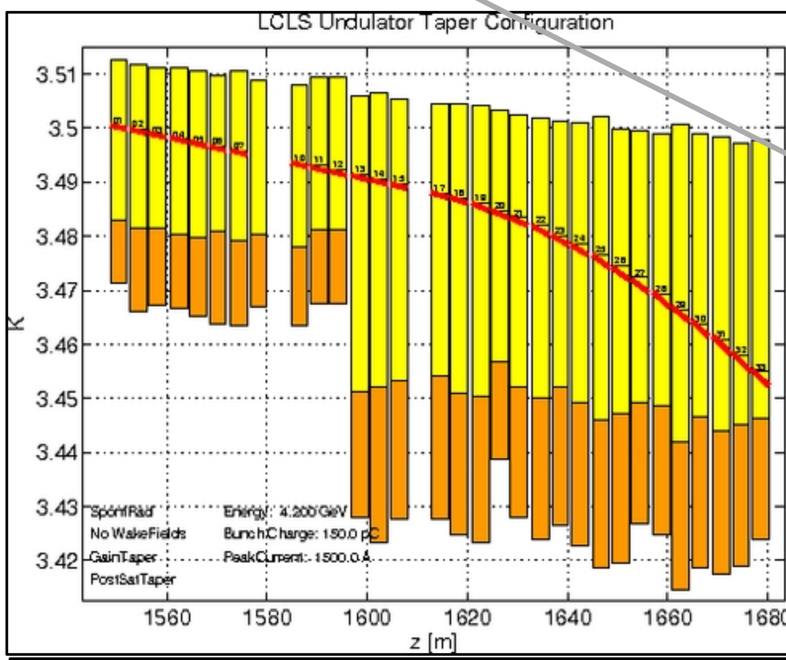
Need TW X-FELs

Why tapering as a path to TW?

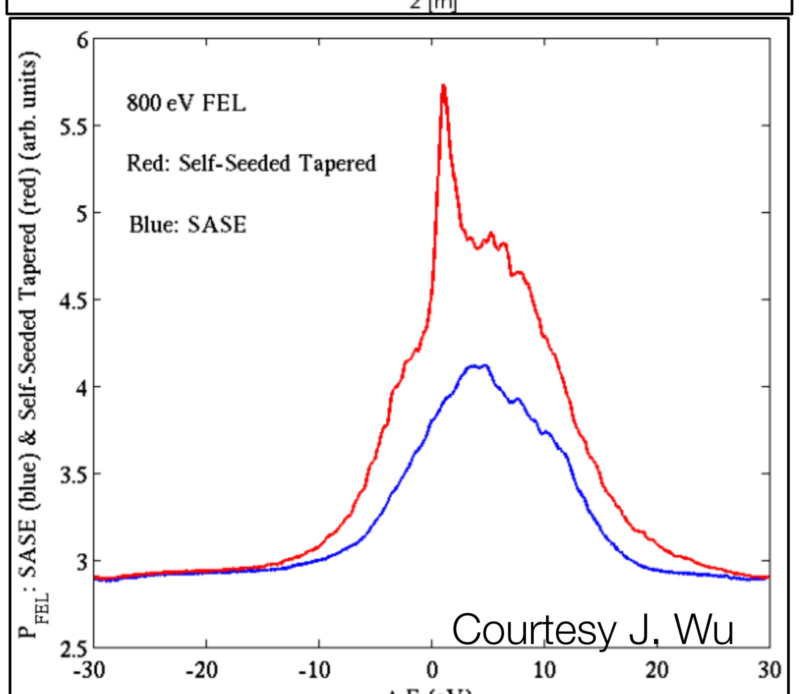
TABLE I: GENESIS Simulation Parameters

Parameter Name	NCU Value
Beam Energy E_0	13.4 GeV
Beam Peak Current I_{pk}	4000 A
Bunch Length t_b	16.4 fs
Normalized Emittances $\epsilon_{x,n}/\epsilon_{y,n}$	0.3/0.3 μ m
Undulator Period λ_w	32 mm
Undulator Parameter K	3.2
Radiation Wavelength λ_r	1.5 Å
Peak radiation power input P_{in}	5 MW
FEL parameter ρ	7.361×10^{-4}

LCLS

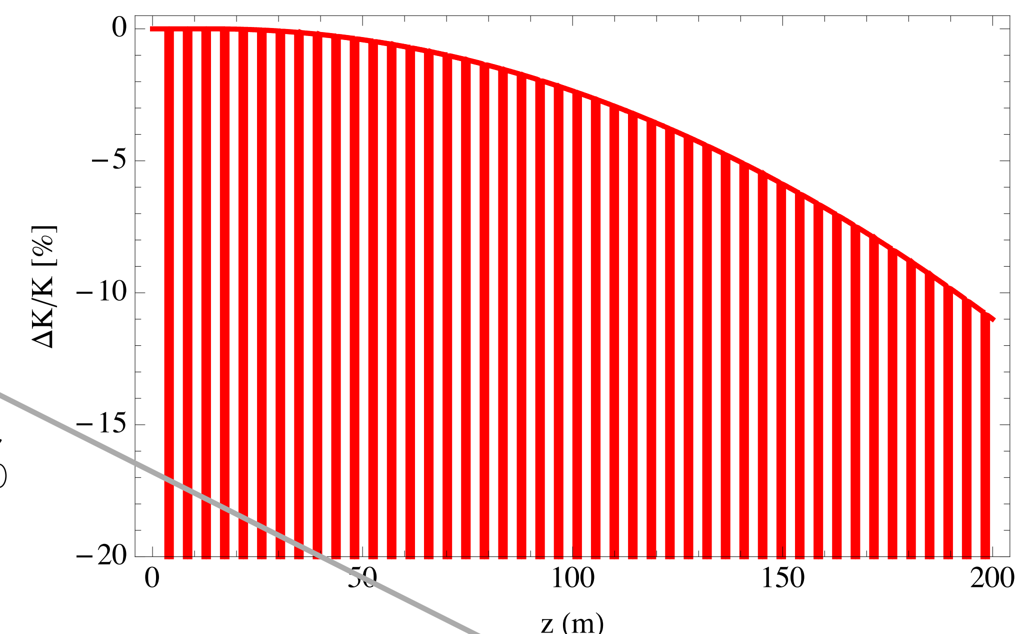


$$\frac{\Delta K}{K} \sim 0.8\%$$

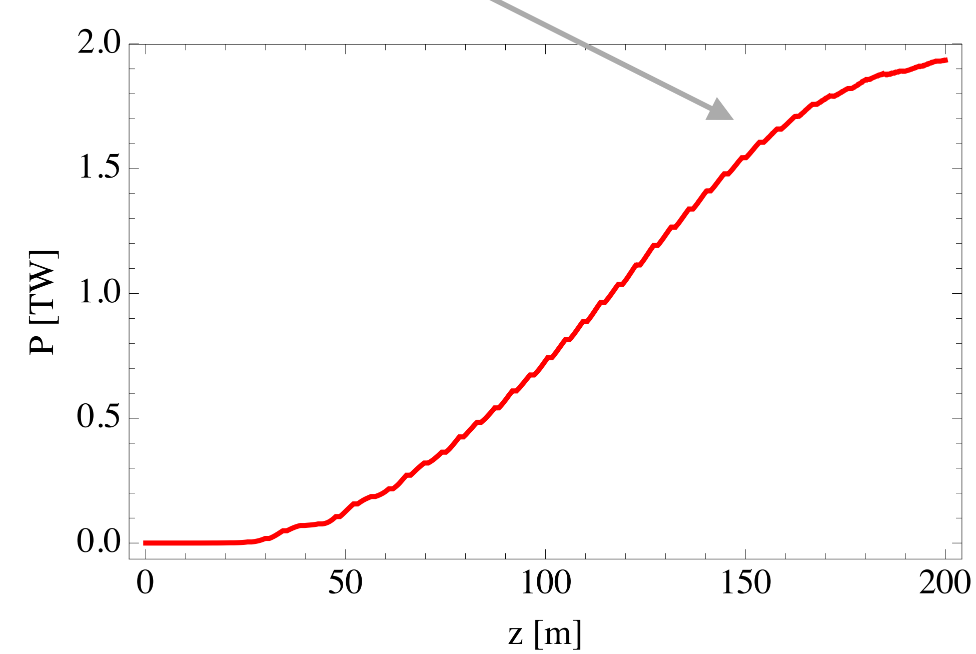


$$\frac{P_{out}}{P_{sat}} \sim 2-3$$

LCLS-II

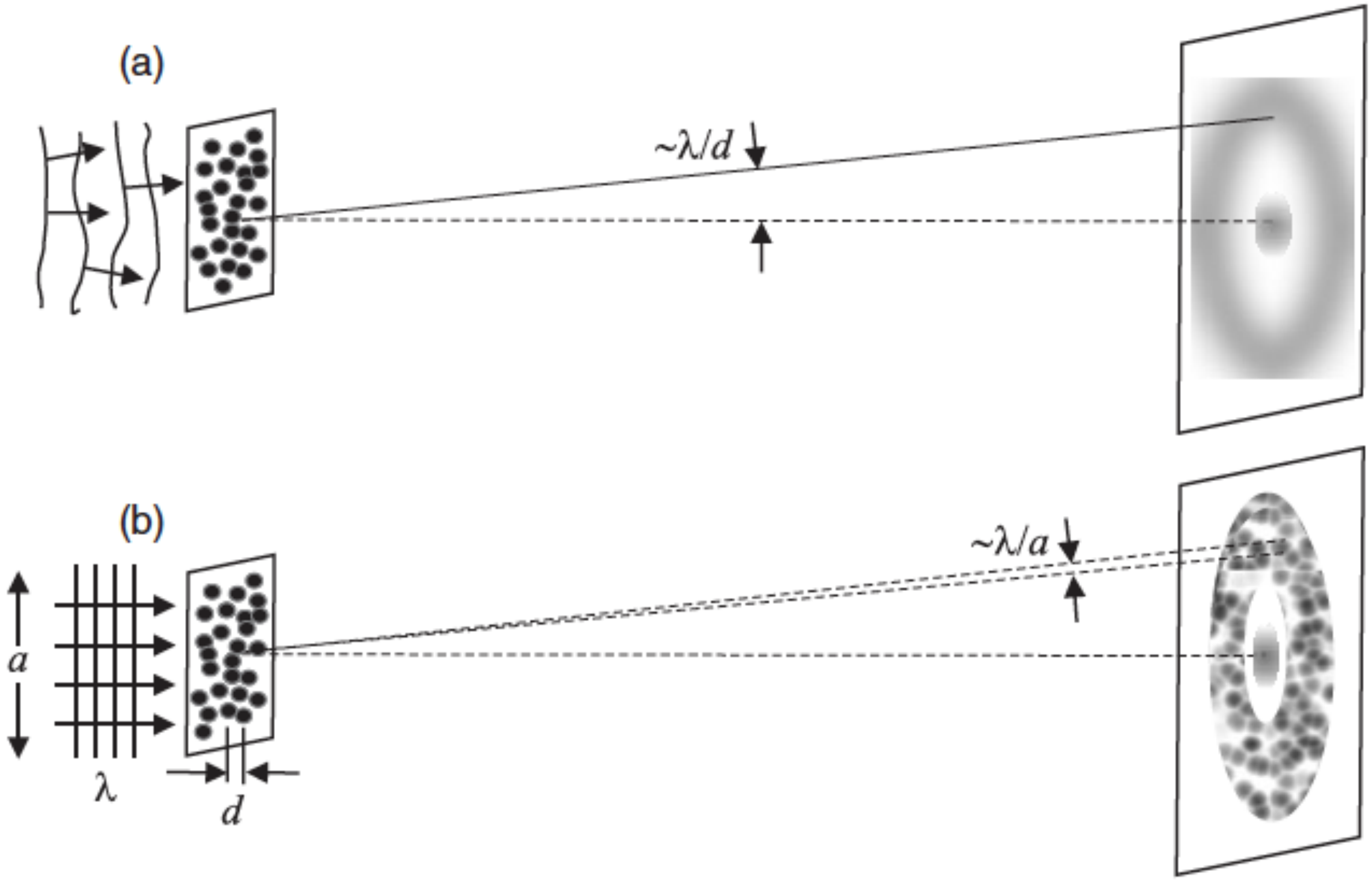


$$\frac{\Delta K}{K} \sim 10-20\%$$



$$\frac{P_{out}}{P_{sat}} \sim 20-100$$

Can we get to TW power and achieve the right coherence/ spectral properties for imaging?



Incoherent Scattering gives statistical average of electron density in sample

Coherent Scattering gives exact measurement (after phase retrieval) of electron density

V. D. Veen, J.F. Pfeiffer, J. Phys. Condens. Matt. **16** 5003-5030, (2004)

Goal:
Characterize the radiation from tapered hard X-ray FELs and determine its applicability in future coherent X-ray diffraction imaging experiments

Presentation Outline

Motivation

Radiation Properties

What is the physical system we studied? How are the optimal taper profiles obtained?

How does the radiation profile evolve in the tapered X-FELs?

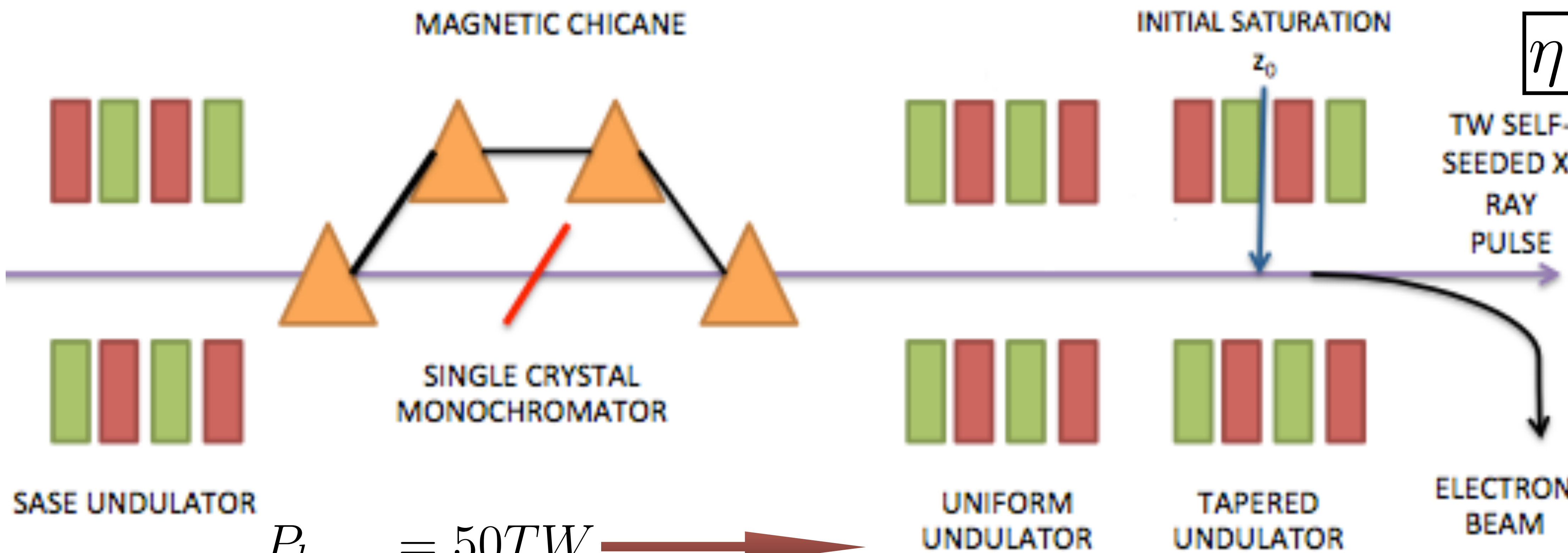
What are the coherence properties and mode structure of the radiation?

Conclusion & Future Work

Self-Seeding + Tapering =TW + Longitudinal Coherence

Gaussian Seed $P_{rad,0} = 5MW$ → $P_{rad} > 1TW$

$\eta > 2\%$



$P_{beam} = 50TW$ →

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FEL parameter ρ	7.361 $\times 10^{-4}$

Taper profile $a_w(z) = a_w(z_0)(1 - c \times (z - z_0)^d)$

Optimization performed over z_0, c, d using GENESIS for maximum output power

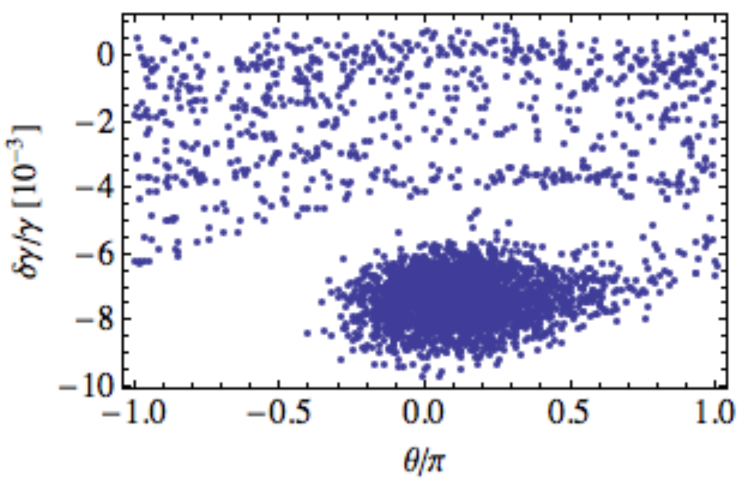
Typical values: $z_0 < L_{sat}$ d ~ 2
taper strength ~ 10-20 %

Y. Jiao, *et al*, Phys. Rev. ST Accel. Beams, vol. 15, p. 050704, May 2012

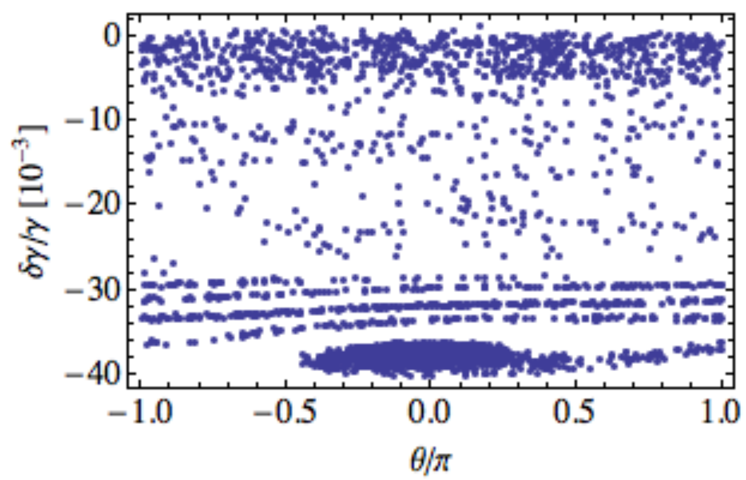
Optimized Tapering Simulations: Transverse Effects

Detrapping -> Reduced Guiding -> Increased Diffraction

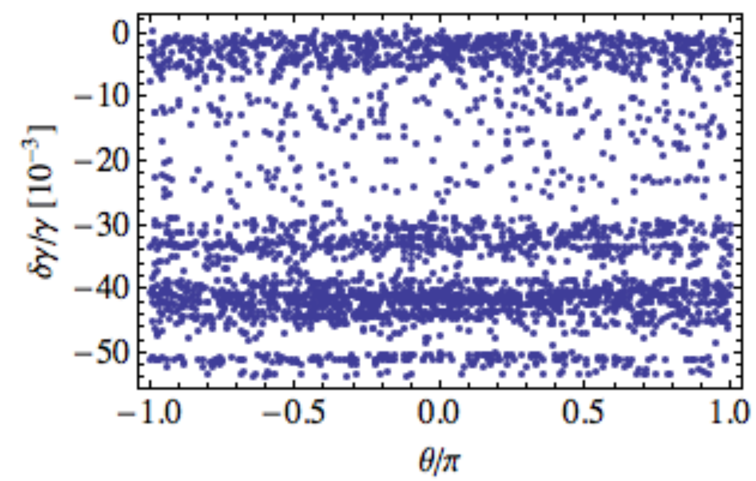
z = 50m

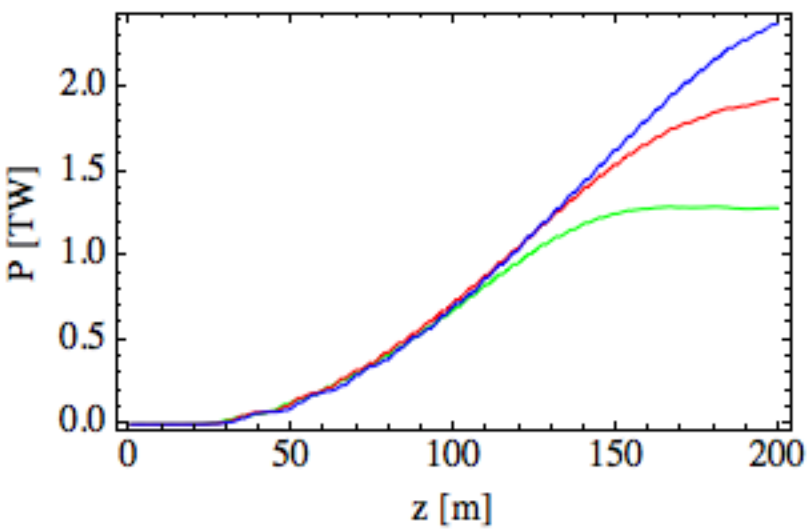


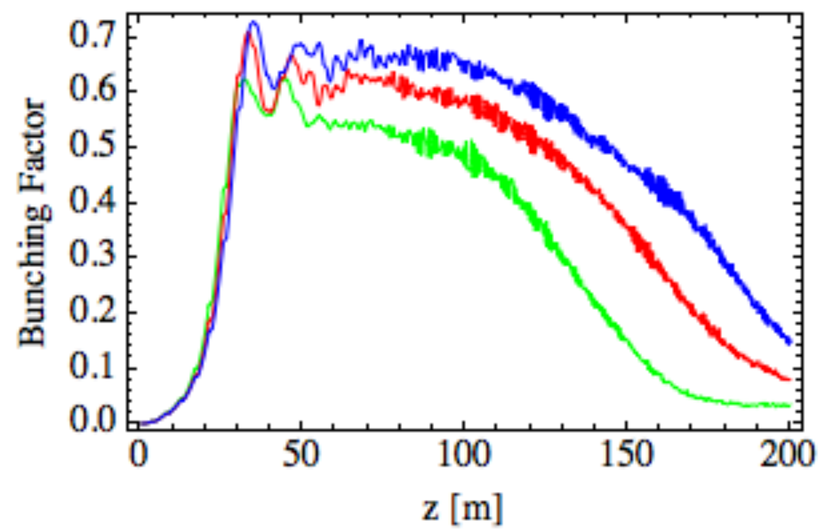
z = 120m



z = 180m

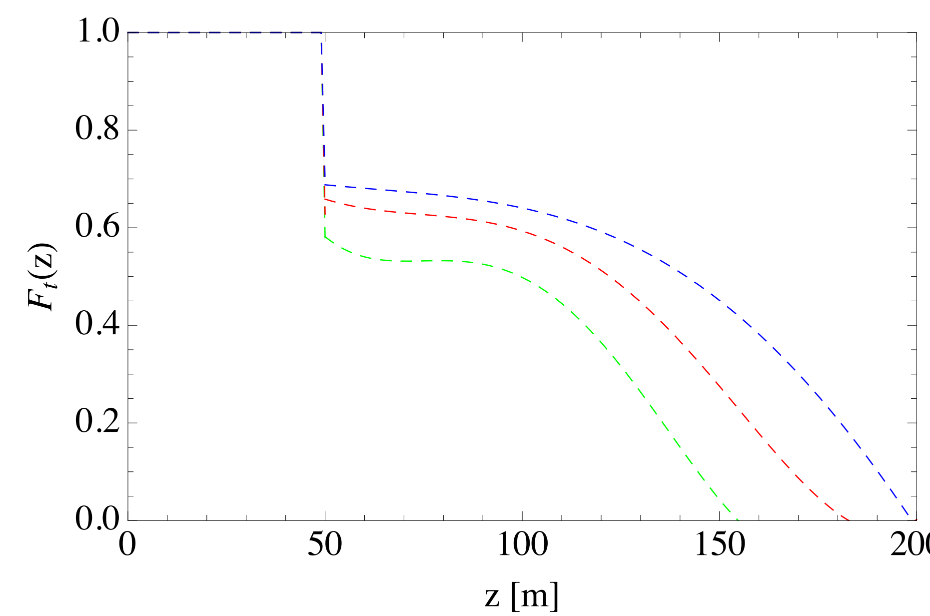


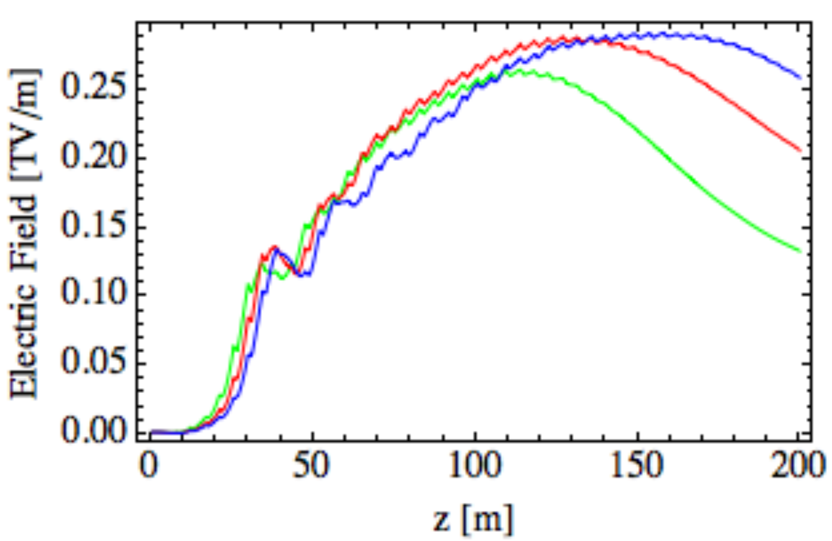


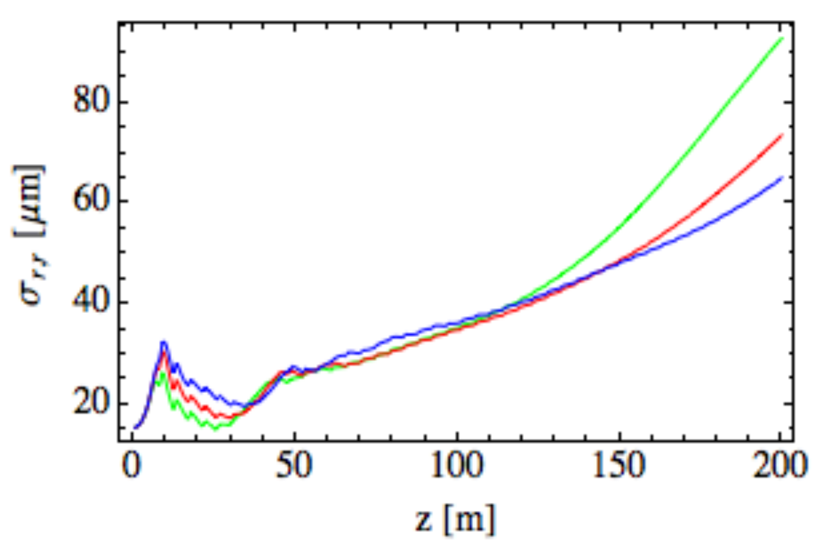


$$n = 1 + \frac{\omega_{p,0}^2}{\omega_s^2}\frac{r_{b,0}^2}{r_b^2}\frac{a_w}{2|a_s|}[JJ]\left\langle \frac{e^{-i\Psi}}{\gamma} \right\rangle$$

D. Prosnitz, A. Szoke, V.K. Neil, Phys. Rev. A., vol. 24, p. 1436, 1981





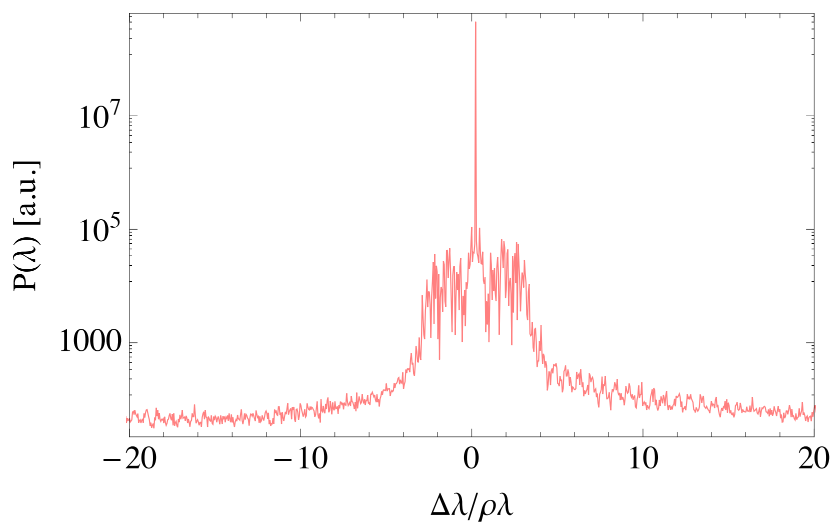


Transverse electron distribution

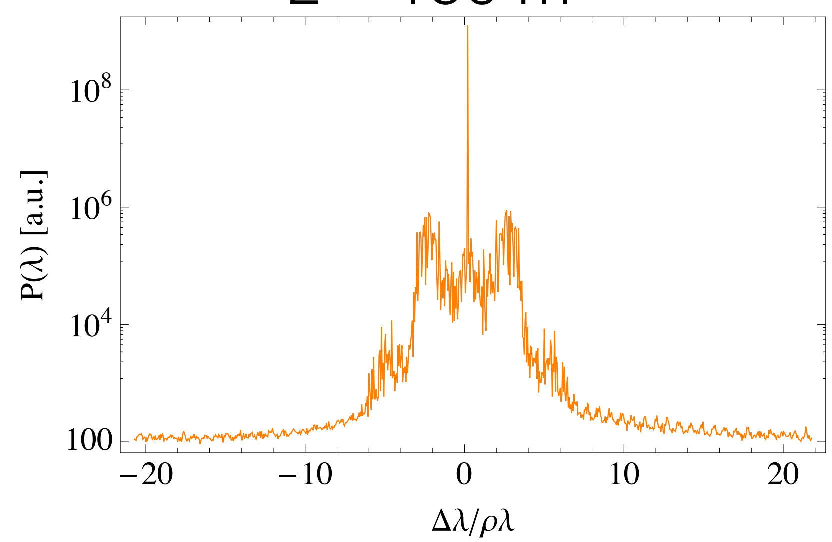
Gaussian Parabolic Uniform

Longitudinal Effects
Spectral Profile and Sideband instability

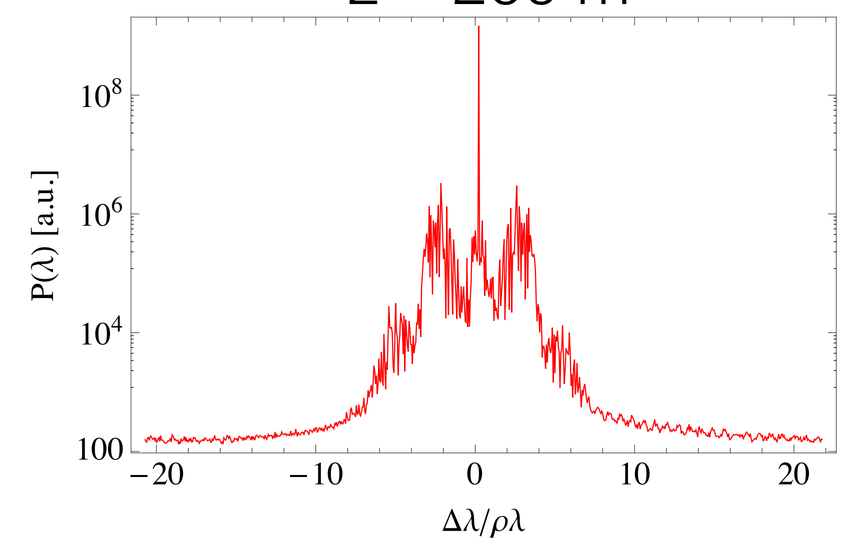
Parabolic at z=75

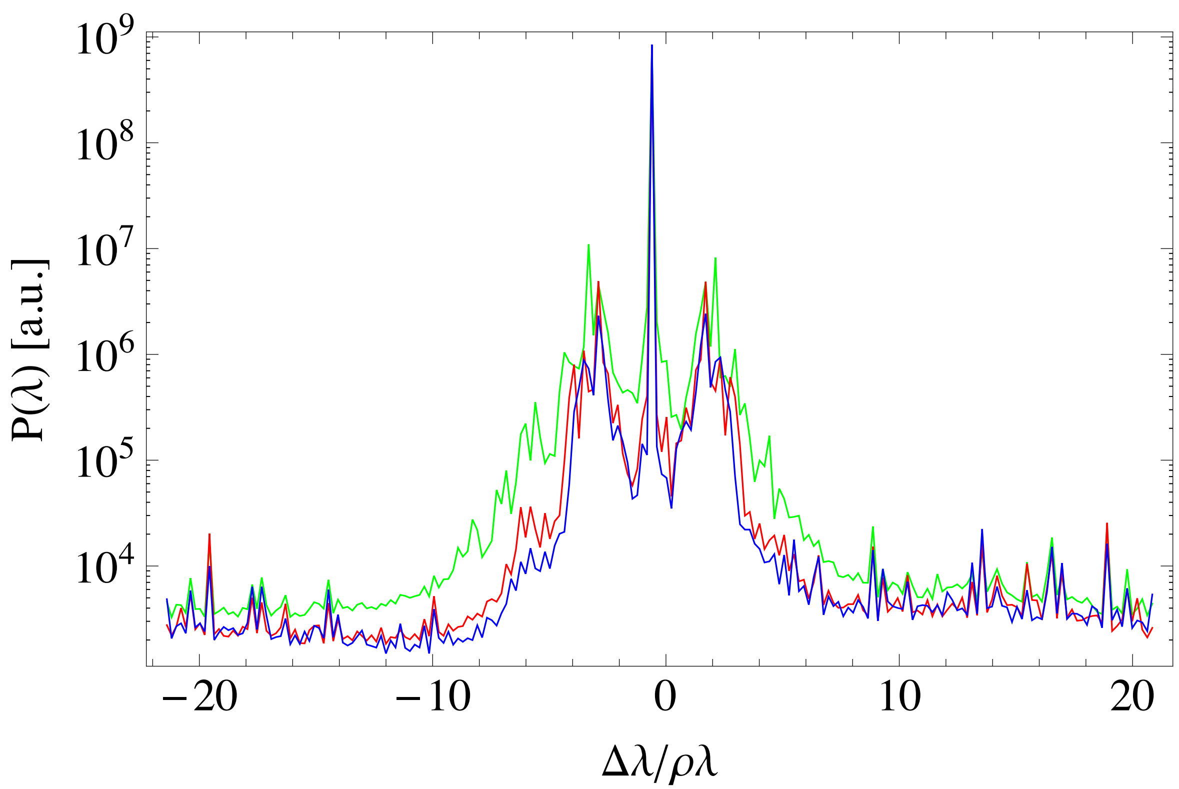


z = 150 m



z = 200 m





Gaussian Parabolic Uniform

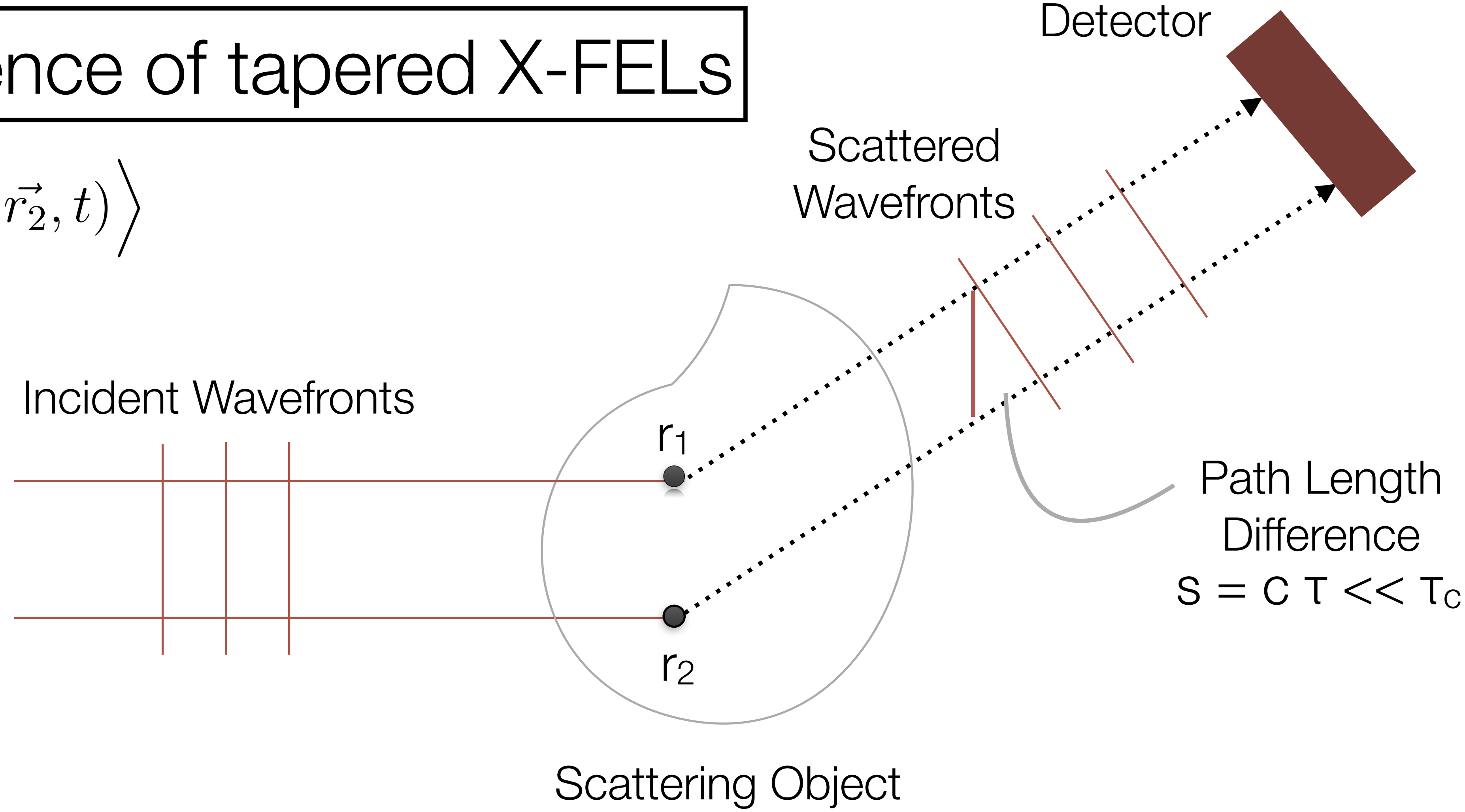
Electron detrapping & sideband growth causes saturation in output power of tapered TW X-FEL

Transverse Coherence of tapered X-FELs

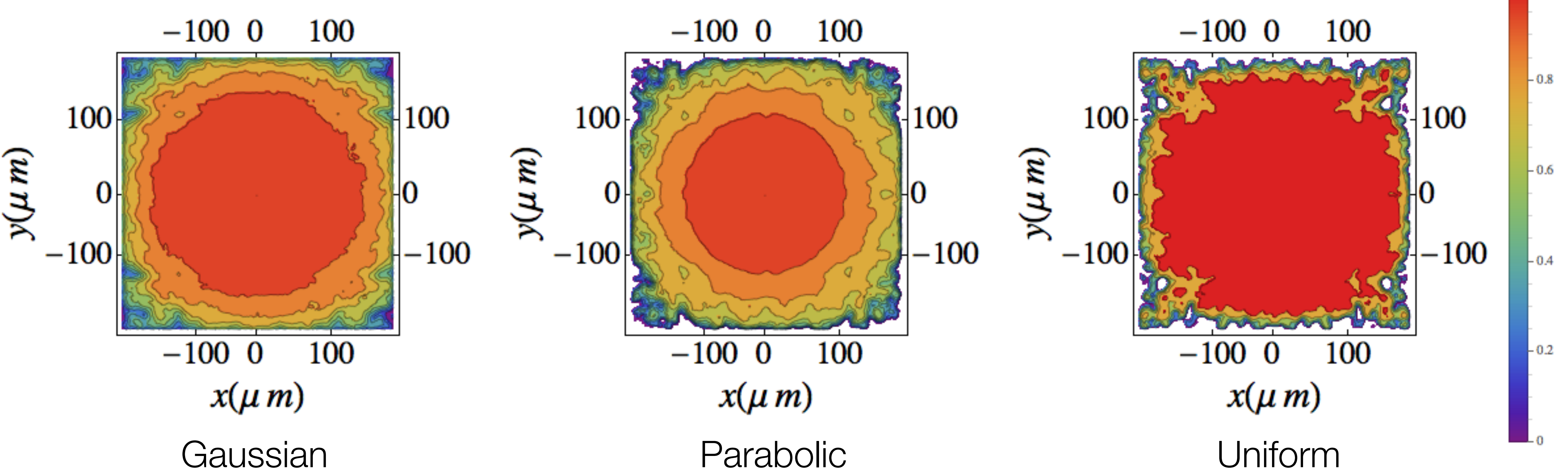
$$\Gamma_{12}(\tau) = \left\langle \vec{E}(\vec{r_1}, t+\tau)\vec{E}^*(\vec{r_2}, t) \right\rangle$$

$$J_{12} \equiv \Gamma_{12}(0)$$

$$\mu_{12} = \frac{J_{12}}{\sqrt{J_{11}J_{22}}}$$

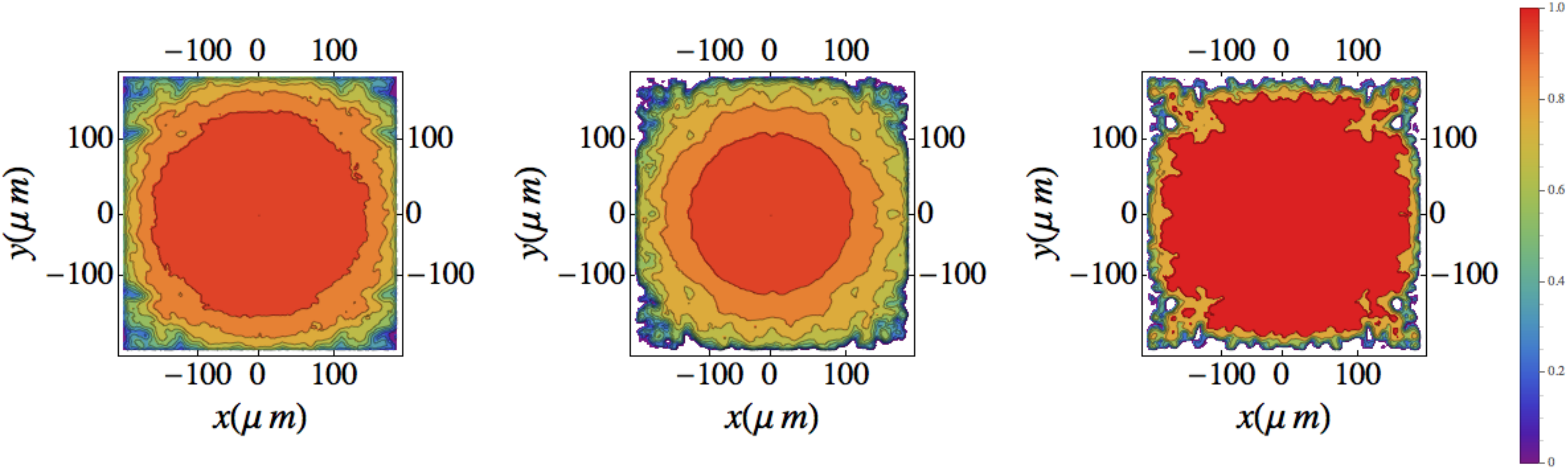


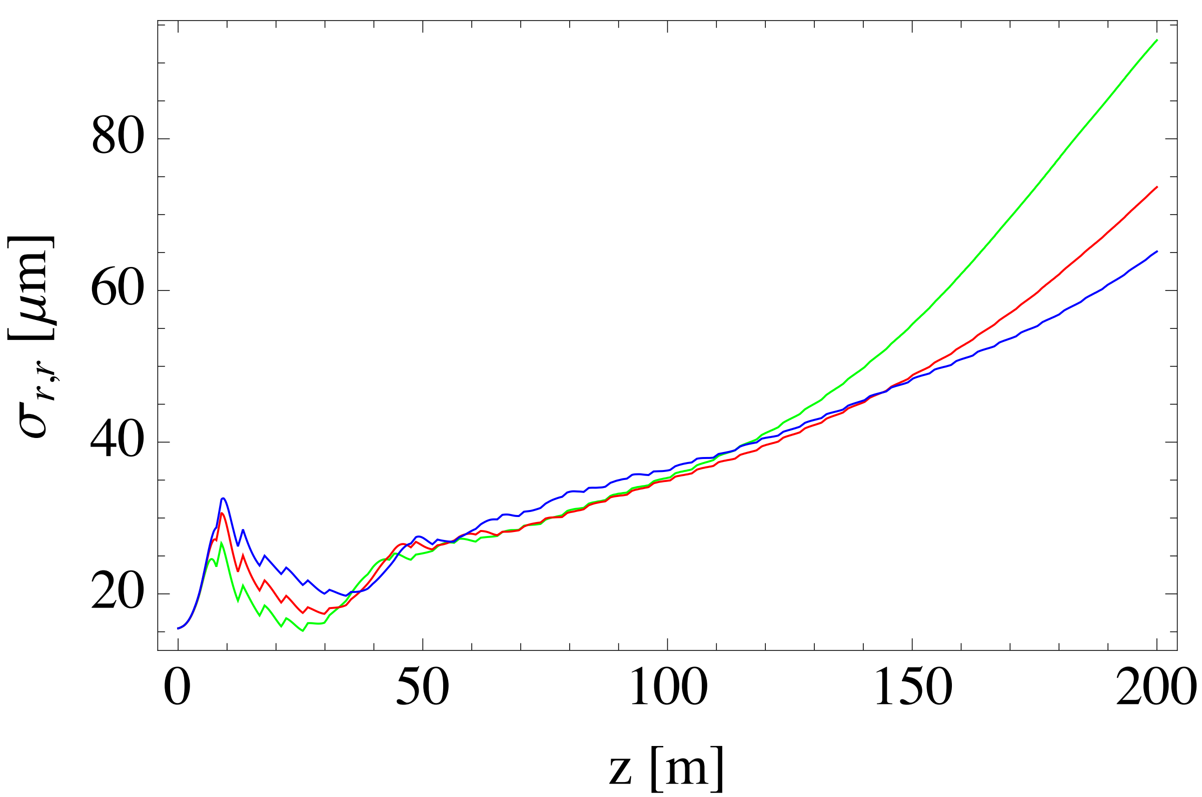
Modulus of complex coherence factor at undulator exit (z=200m) for NCU LCLS-II parameters



Coherence area >> Radiation spot size

$$A_{coh} = \int \mu_{12} \mathrm{d}A >> \pi \sigma_r^2$$

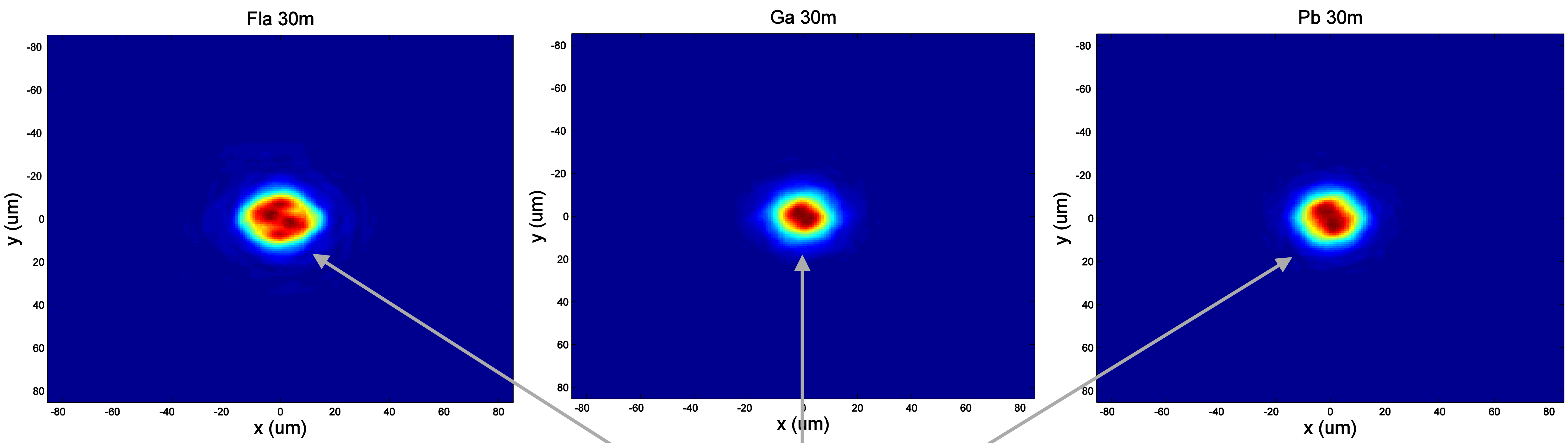




Transverse electron distribution

Gaussian Parabolic Uniform

What is the mode structure of tapered X-FELs?

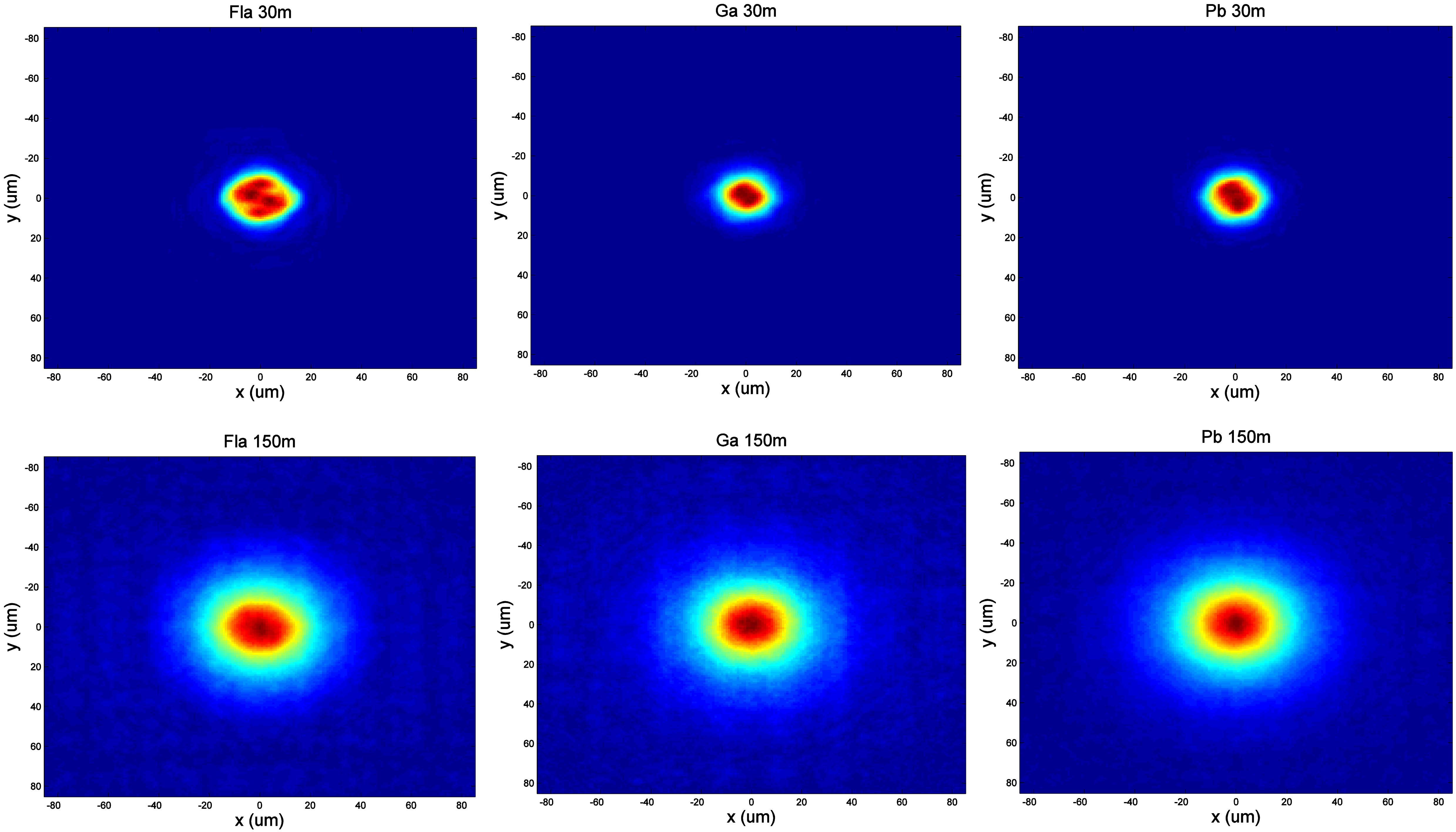


Higher order mode structure in radiation field

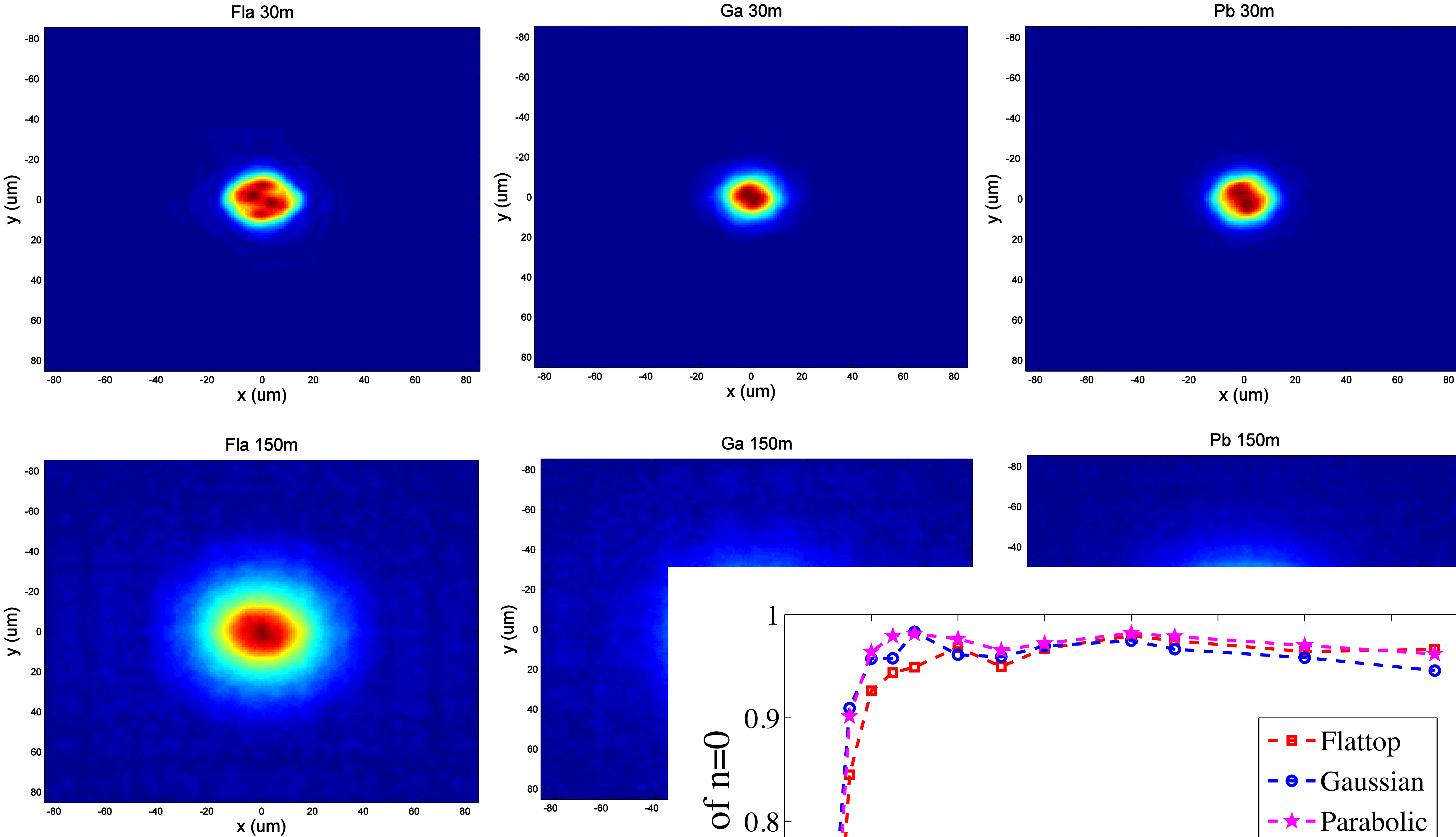
Electric Field expansion in complete set of Laguerre-Gaussian Modes

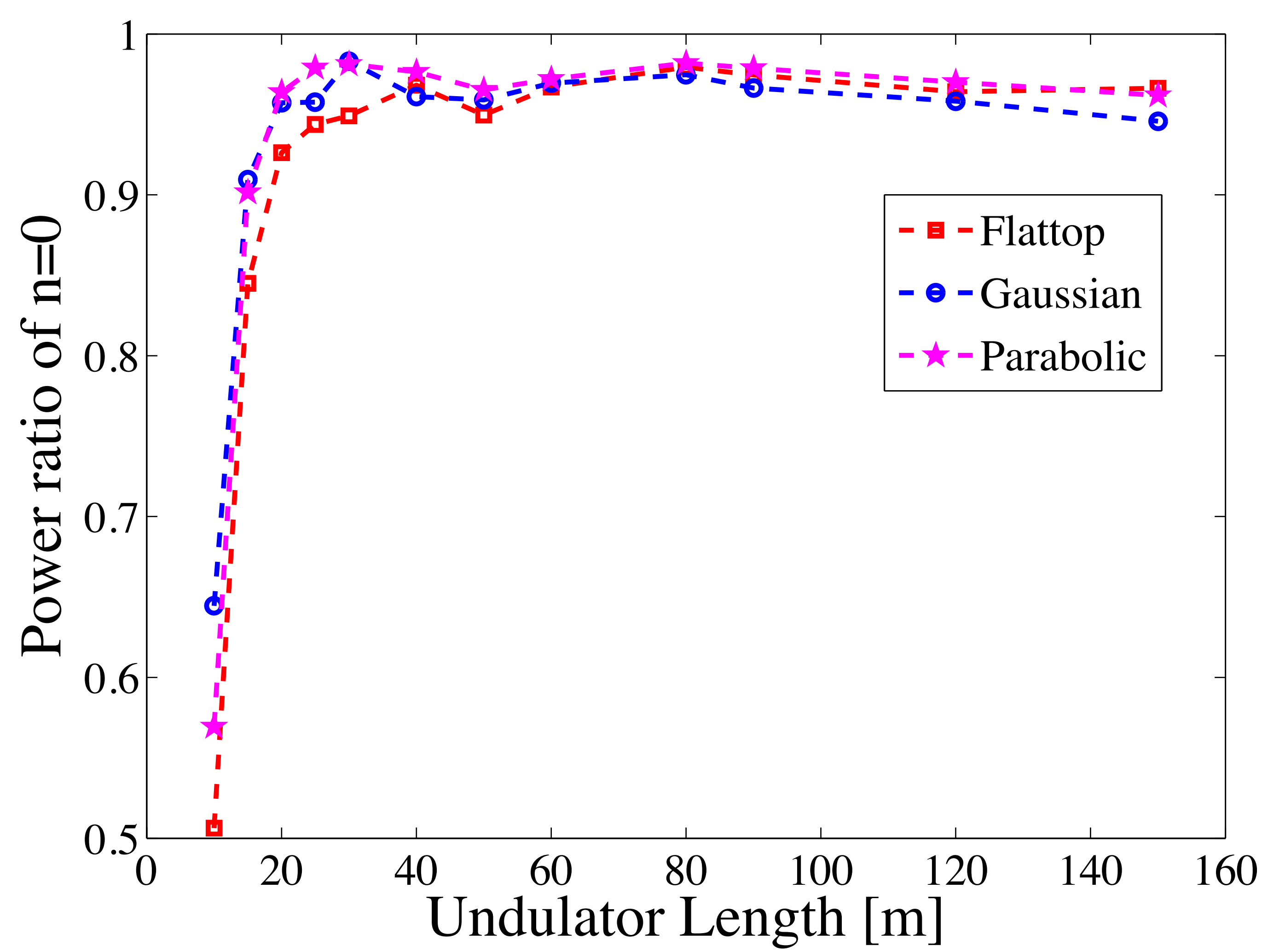
$$E(r) = \sum_{n=0}^{\infty} a_n e^{-\zeta r^2/2} L_n\left(R(\zeta) r^2\right)$$

$$a_n = \int_0^{\infty} E(r) L_n(\Re[\zeta] r^2) e^{-\zeta^* r^2/2} \mathrm{d}(L_n(\Re[\zeta] r^2))$$



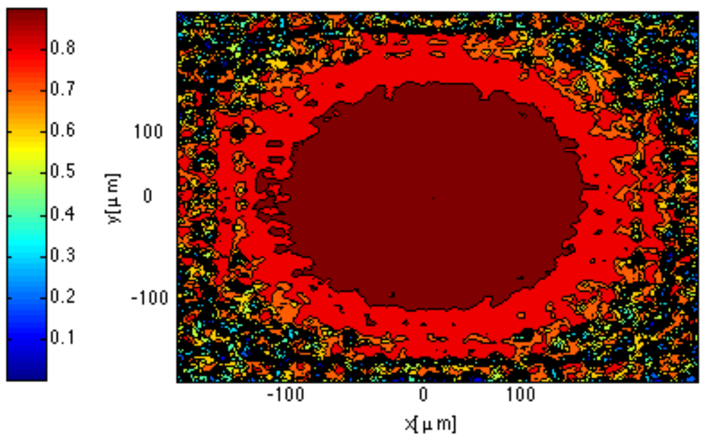
Structures washed out by diffraction and FEL interaction post-saturation





More than 90 % of power in fundamental mode indicates very good transverse coherence

Superconducting Undulator



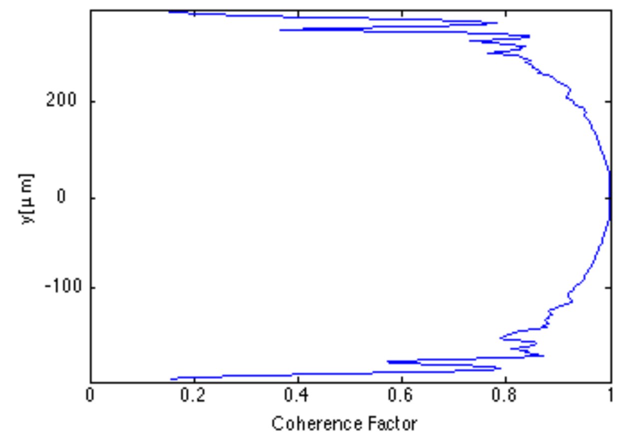
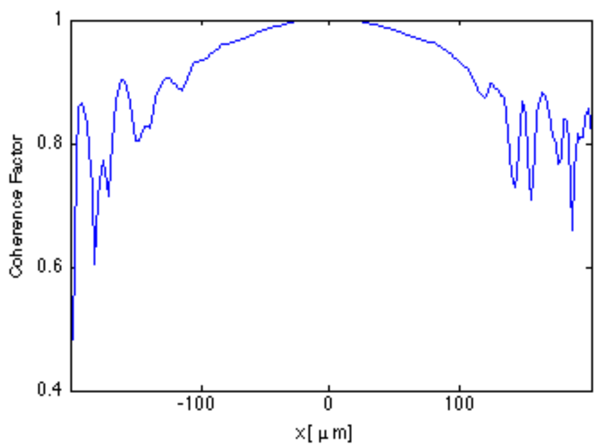
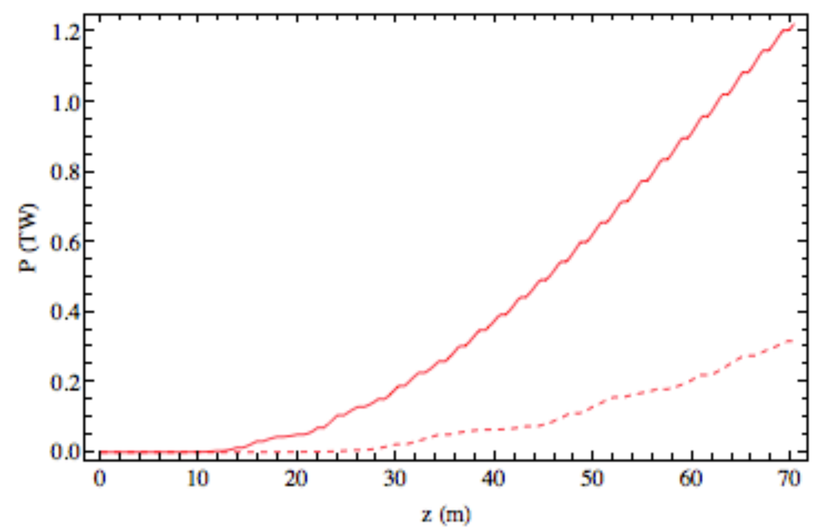


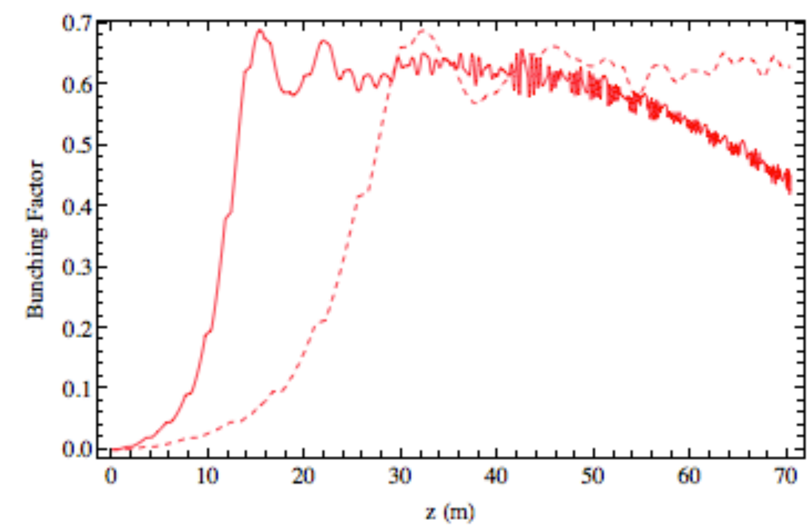
TABLE I: GENESIS Simulation Parameters

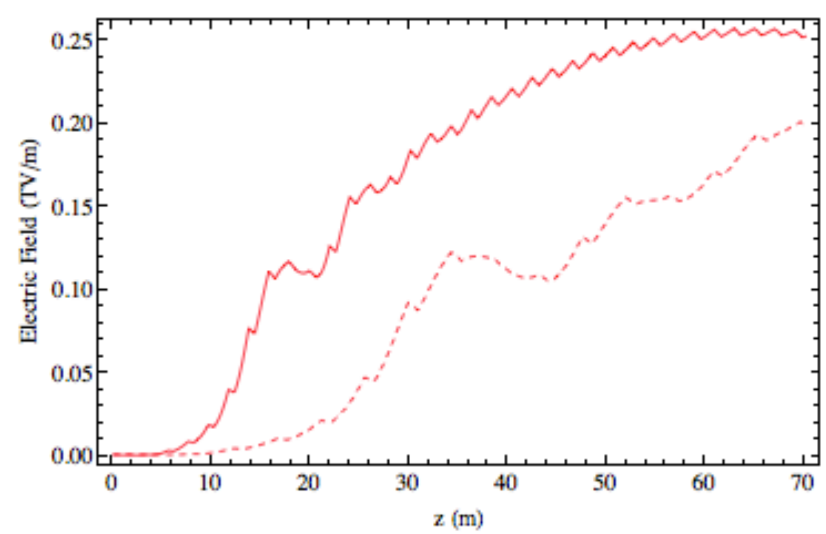
Parameter Name	SCU Value
Beam Energy E_0	7.2 GeV
Beam Peak Current I_{pk}	4000 A
Normalized Emittances $\epsilon_{x,n}/\epsilon_{y,n}$	0.3/0.3 μ m
Undulator Period λ_w	19 mm
Normalised Undulator Parameter a_w	2.44
Radiation Wavelength λ_r	3.24 Å
Peak radiation power input P_{in}	5 MW
FEL parameter ρ	9.898 $\times 10^{-4}$

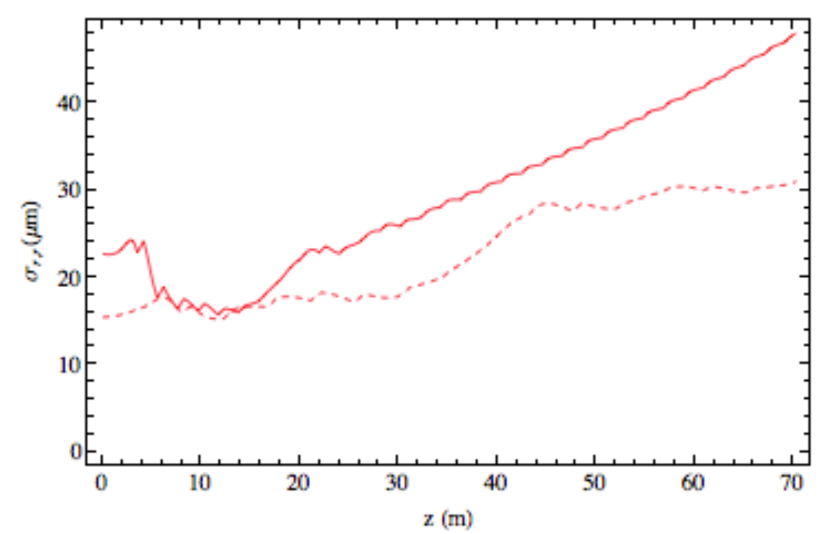


$$A_{coh} = \int \mu_{12} \mathrm{d}A >> \pi \sigma_r^2$$









Presentation Outline

Motivation

Radiation Properties

Conclusion & Future Work

What have we learned from this study?

Conclusions & Future Work

- X-ray FELs in the TW power region are required to push the frontiers of bio-imaging
- Tapering + Self-seeding is a promising strategy for achieving TW power levels with good longitudinal coherence
- The radiation properties and transverse coherence of tapered X-FELs has been analysed and we determined it sufficient for coherent X-ray diffraction applications

- Start to end simulations of optimised tapered X-FELs at TW power levels
- Analytical studies of particle detrapping and its relation to taper strength in TW tapered X-FELs

Acknowledgments

The authors would like to thank Dr. S. Reiche for useful advice and reference to past work on the subject of transverse coherence in an X-FEL

References

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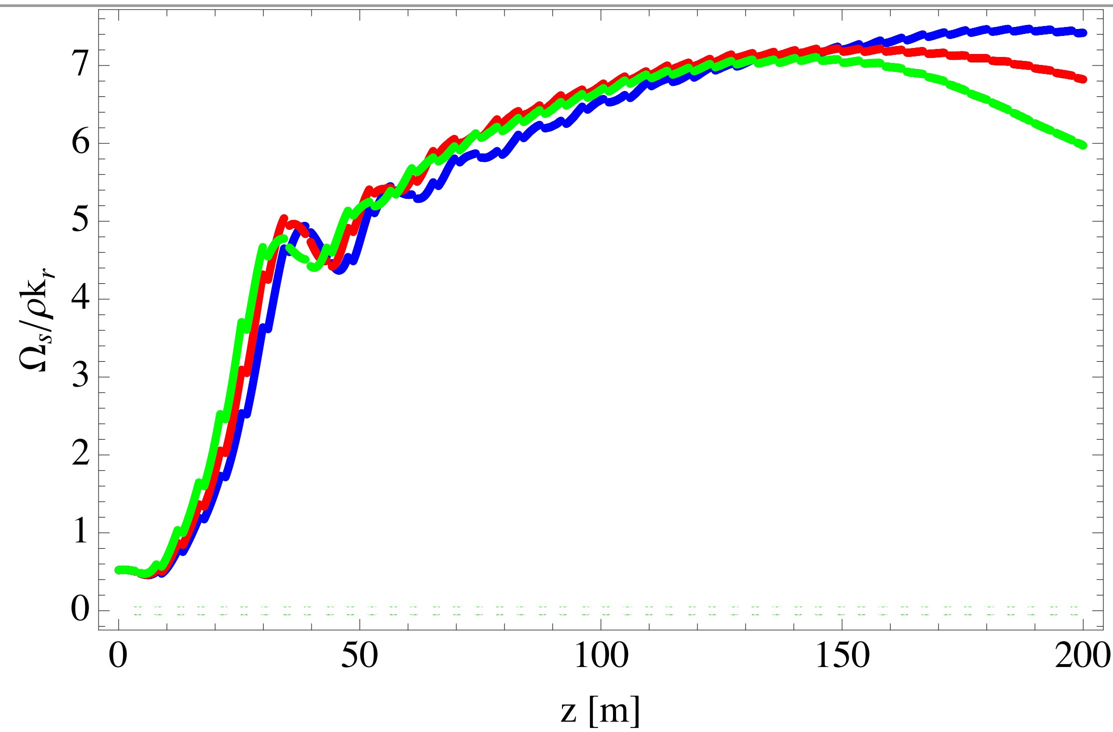
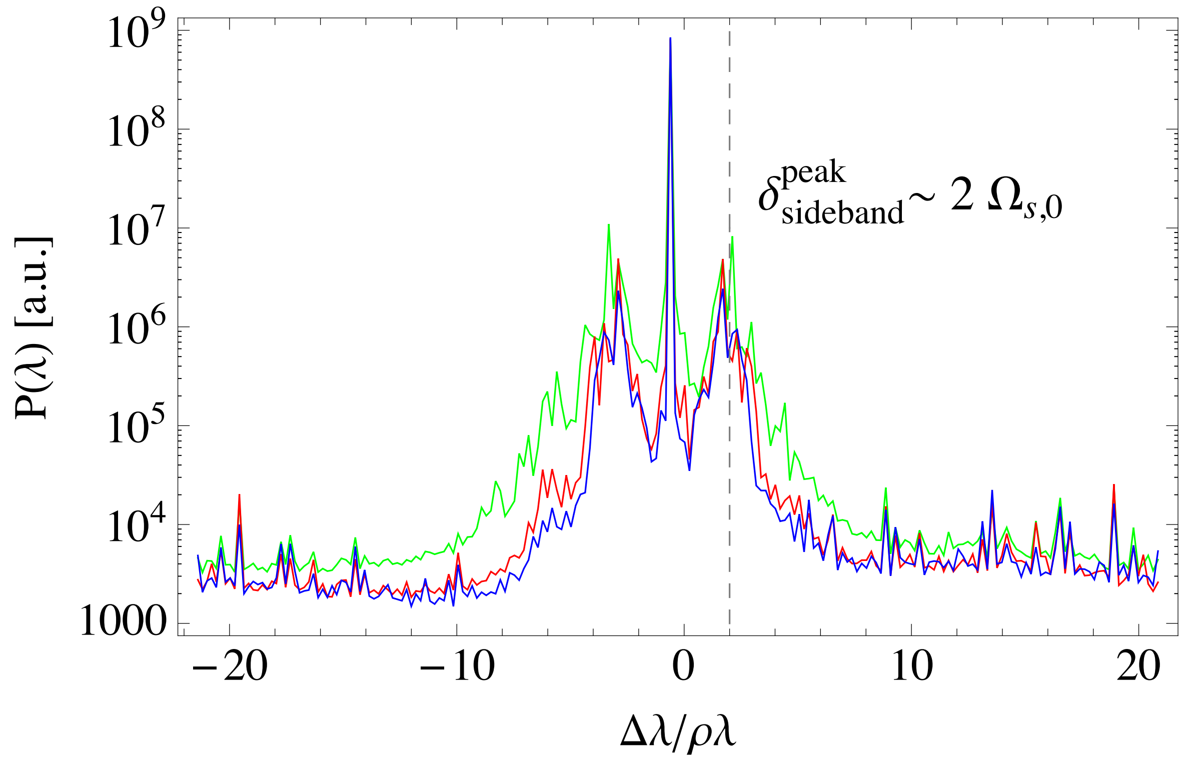
Longitudinal Effects
Spectral Profile and Sideband instability





Gaussian Parabolic Uniform

$$\frac{P_{sideband,max}}{P_{peak}} \sim 0.3\% - 1\%$$

Sideband Intensity reduced for flatter transverse electron distribution

$$\int_{sidebands} P(\lambda)d\lambda = \begin{cases} 1 & \text{Gaussian} \\ 0.4 & \text{Parabolic} \\ 0.3 & \text{Uniform} \end{cases}$$

Mode Decomposition Calculations

Output E field from GENESIS and compute coefficients for different ζ

$$a_n = \sum_{m_1} \sum_{m_2} \tilde{E}\left(\Delta x m_1, \Delta y m_2\right) \exp\left(\frac{-\zeta}{2} r^2\right) L_n\left(R(\zeta) r^2\right) R(\zeta) \Delta x \Delta y,$$

Choose ζ such that fundamental mode dominates FEL interaction i.e. minimises κ

$$\kappa = \sum_{n=1}^{\infty} |a_n| / |a_0|$$

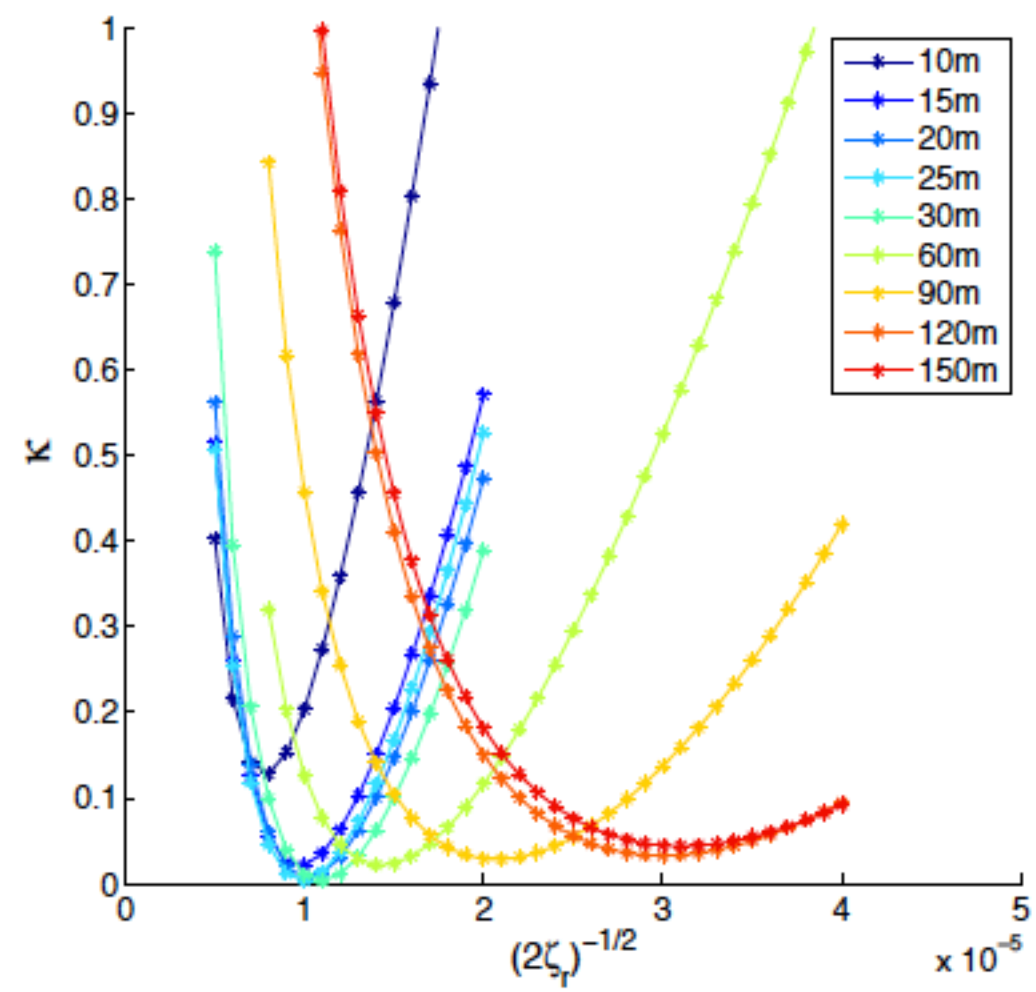


Fig. 2. κ varies with $R(\zeta)$