eurizon

European network for developing new horizons for RIs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

European XFEL

X-ray FEL pulse characteristics from the 6 GeV driver

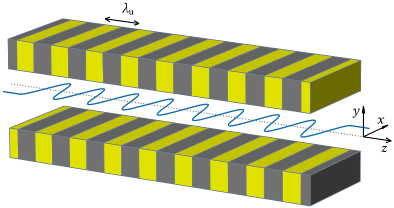
Eurizon 2020+ workshop on FEL linac driver and FEL physics applications

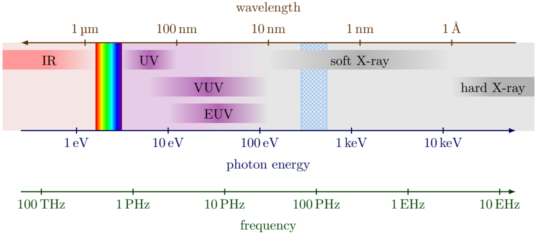
Fabian Pannek

European XFEL

January 2024

FEL driven by 6 GeV electron beam





spectral ranges according to ISO-21348:2007

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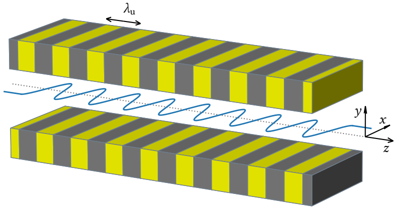

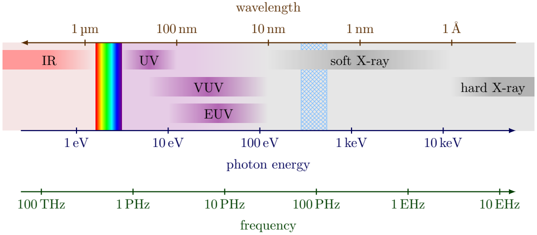

- 85 % of the earth crust is made up of oxides
- molecules containing oxygen: new dissociation pathways and dynamics
- ferroelectricity, high temperature superconductivity, spin transitions

- 250 eV to 1 keV (5 nm to 1.2 nm):
  - 3d transition metals, oxides
  - organic materials, hybrid structures

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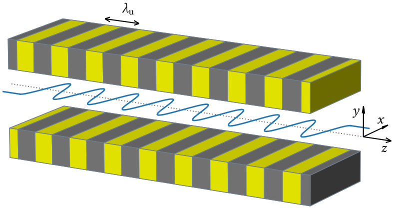

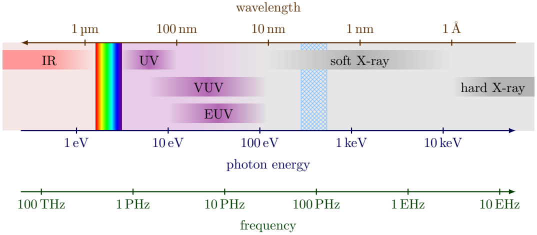

- 85 % of the earth crust is made up of oxides
- molecules containing oxygen: new dissociation pathways and dynamics
- ferroelectricity, high temperature superconductivity, spin transitions
- battery research

- 250 eV to 1 keV (5 nm to 1.2 nm):
  - 3d transition metals, oxides
  - organic materials, hybrid structures
- down to 50 eV (25 nm):
  - Li and B
  - two photon exciatations of C-, N-, O-edges

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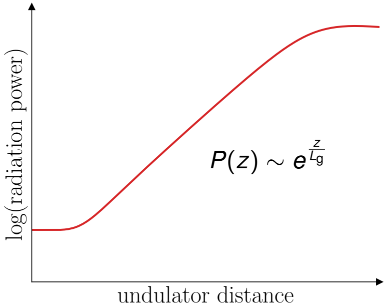
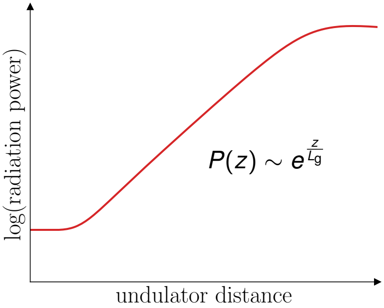
1D approximation: Exponential Growth Regime



gain length describes FEL power growth

1D approximation: Exponential Growth Regime



gain length describes FEL power growth

$$L_{g0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{FEL}} = \frac{\gamma}{\sqrt{3}}\left[\frac{I_A}{I_e}\frac{\sigma_{x,y}^2}{\pi}\frac{\lambda_u}{\widehat{K}^2}\right]^{1/3}$$

γ_r: beam energy

I_e: current

$\sigma_{x,y}$: rms beam size

λ_u: undulator period

$\widehat{K}$: undulator strength $\propto B\lambda_u$

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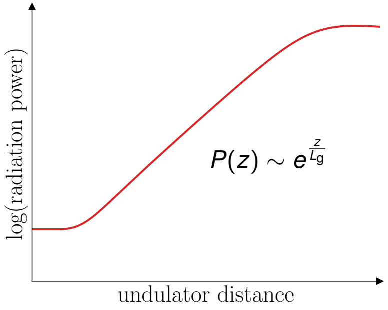

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1D $\rightarrow$ diffraction, energy spread, angular spread?

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  - based on 19 fitting coefficients:

$$\Lambda = a_1 X_d^{a_2} + a_3 X_\varepsilon^{a_4} + a_5 X_\gamma^{a_6} + a_7 X_\varepsilon^{a_8} X_\gamma^{a_9} + a_{10} X_d^{a_{11}} X_\gamma^{a_{12}} + a_{13} X_d^{a_{14}} X_\varepsilon^{a_{15}} + a_{16} X_d^{a_{17}} X_\varepsilon^{a_{18}} X_\gamma^{a_{19}}$$

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Analytical Study: Electron Beam Parameters

- Parameters used for analytical study:

Parameter	Symbol	Value
energy	E	6 GeV
rms energy spread	σ_E	2 MeV
current	I_e	5 kA
emittance (normalized)	ε_n	0.3 mm mrad
average beta function	β_{avg}	20 m
rms beam size	$\sigma_{x,y}$	23 µm

Technical Contraints for Planar Undulator

- radiation wavelength: $\lambda_\ell = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$
- $K \propto \lambda_u B$
- maximum magnetic field depends on:
  - gap size per period length g/λ_u
  - material
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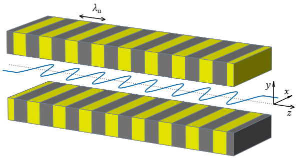

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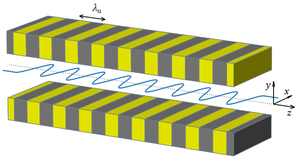

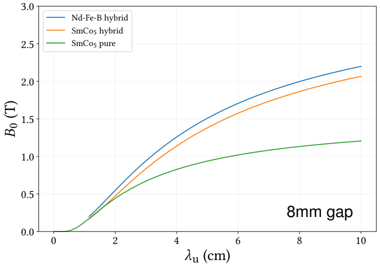

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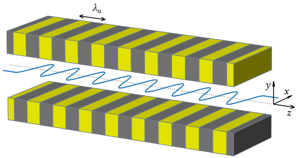

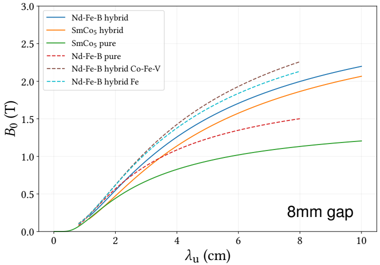

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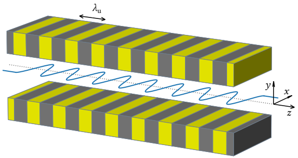

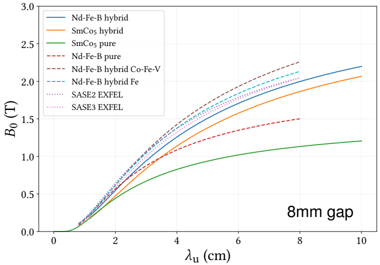

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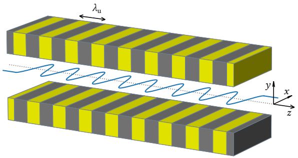

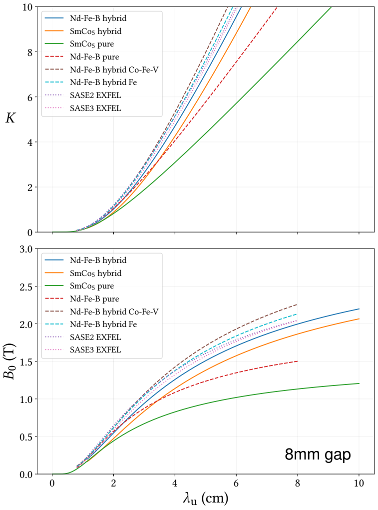

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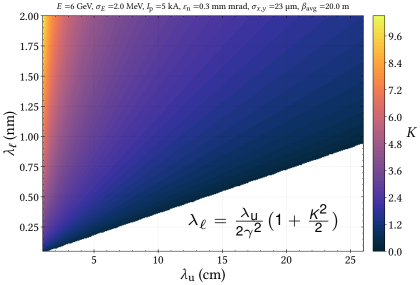
Wavelength Range: lower limit



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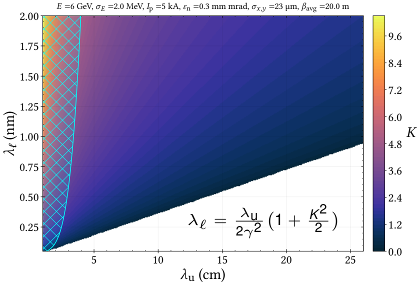

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  - cyan: Nd-Fe-B hybrid Fe, 8 mm gap

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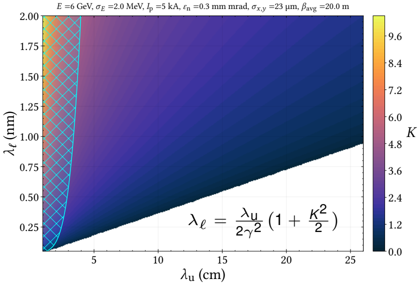

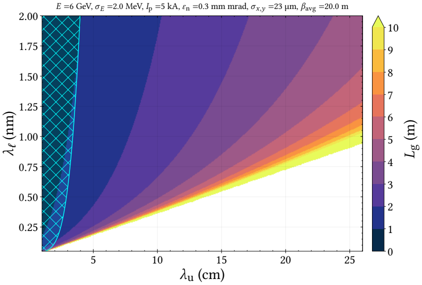

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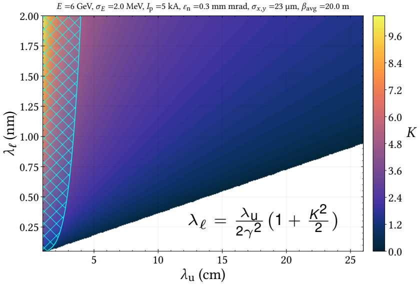

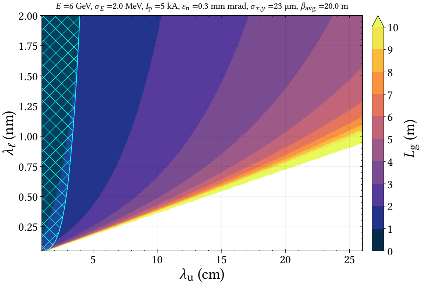

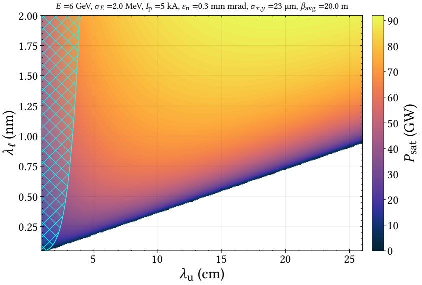

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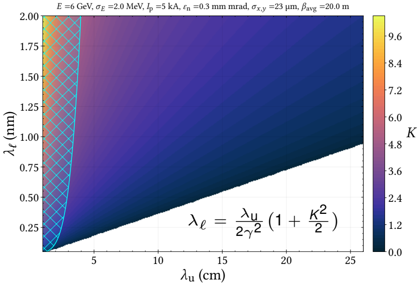

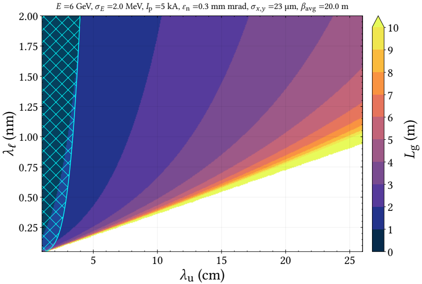

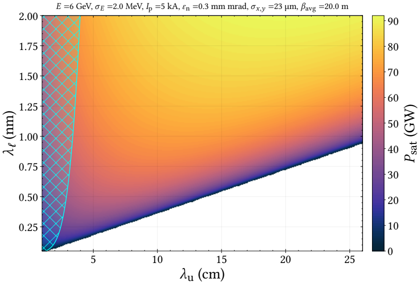

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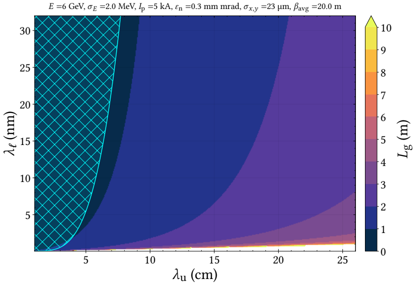
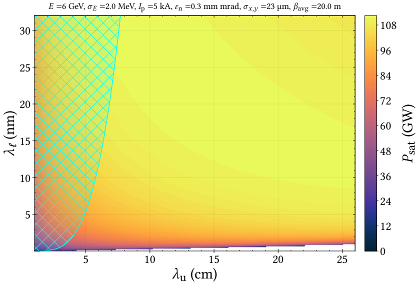
- 6 GeV $\rightarrow$ high power in soft X-ray regime

Wavelength Range: Soft X-ray and EUV

- Undulator period length λ_u
  - limits smallest possbile λ_ℓ
  - small λ_u benefits small gain length
  - technical limit for B-field if λ_u too small
  - affects saturation power
  - compromise $L_g \longleftrightarrow P_{sat}$





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- Undulator period length λ_u
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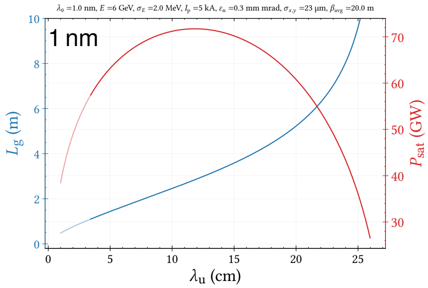

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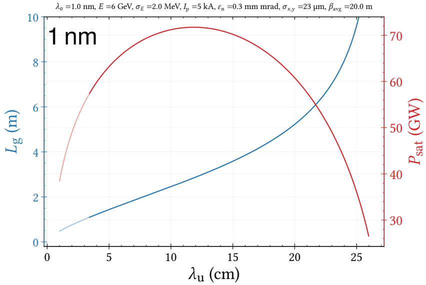

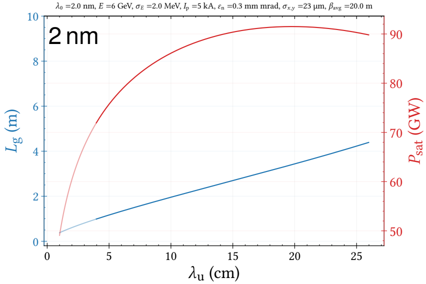

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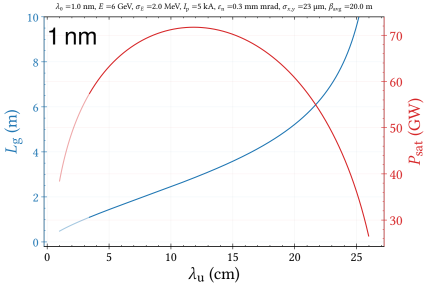
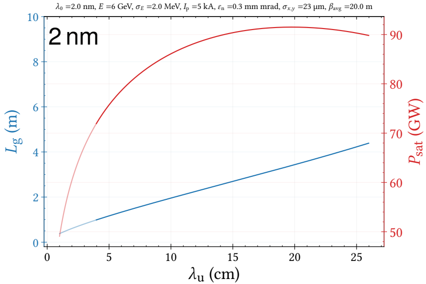
- λ_u for wavelengths from 1 nm to 25 nm
- $\lambda_u = 13\,\text{cm}$
  - maximum P_{sat} at shortest wavelengths
  - within 10 % of max P_{sat} at longer wavelengths





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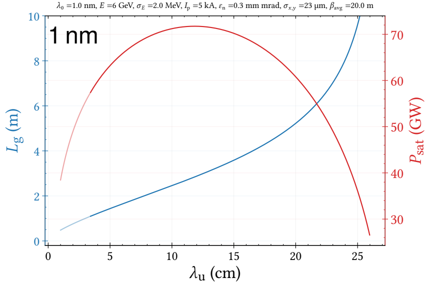

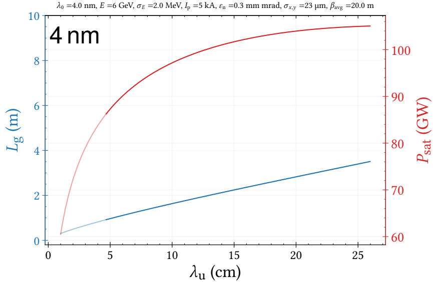

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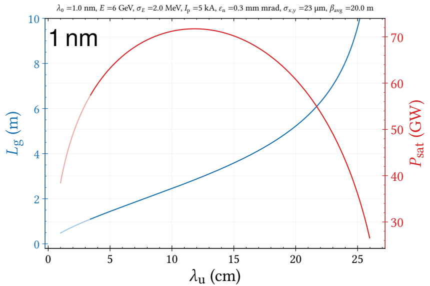

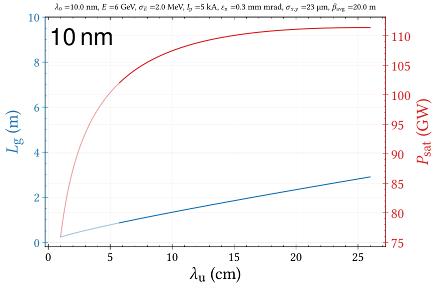

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- λ_u for wavelengths from 1 nm to 25 nm
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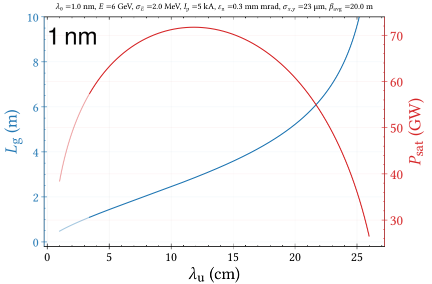
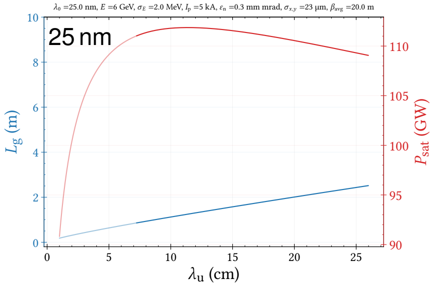
  - $P_{sat} \sim 70\,\text{GW}$ to $110\,\text{GW}$
  - $L_g \sim 3.1\,\text{m}$ to $1.4\,\text{m}$





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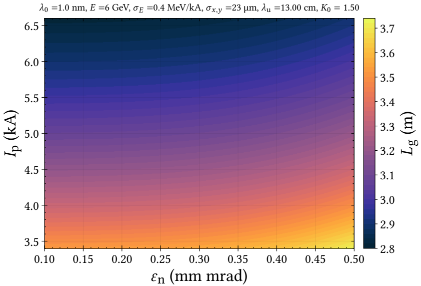
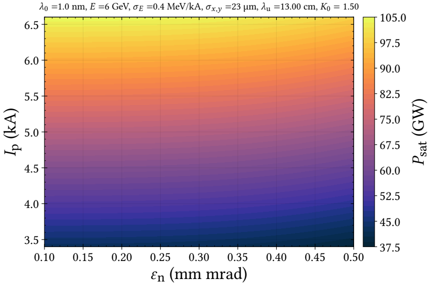
Sensitivity to Current and Emittance: 1 nm

- scaled energy spread with current:
  - 2 MeV at 5 kA, ± 0.4 MeV/kA
- $\sigma^2_{x,y} = \beta_{avg}\varepsilon_n/\gamma$
  - kept $\sigma_{x,y}$ constant by adjusting β_{avg}





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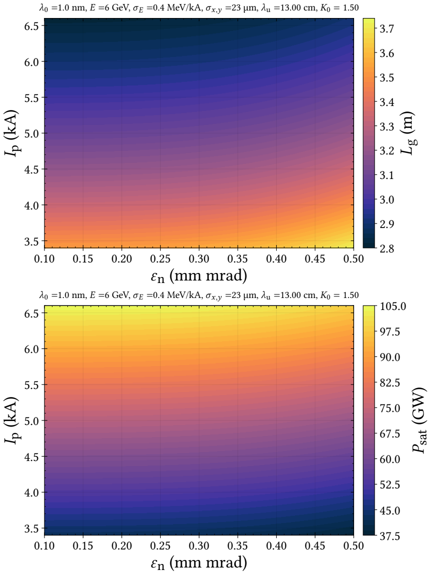
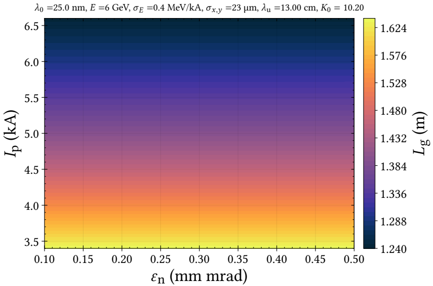
- $\sigma_{x,y}^2 = \beta_{\text{avg}} \varepsilon_{\text{n}} / \gamma$
  - kept $\sigma_{x,y}$ constant by adjusting β_{avg}
- scales with current as $L_{\text{g}} \propto I_{\text{e}}^{-1/3}$
- emittance $\rightarrow$ angular spread
  - spread in resonance wavelength

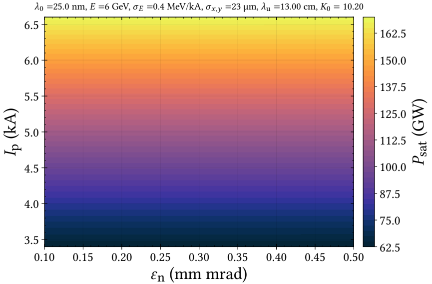


Sensitivity to Current and Emittance: 25 nm

- scaled energy spread with current:
  - 2 MeV at 5 kA, ±0.4 MeV/kA
- $\sigma^2_{x,y} = \beta_{avg}\varepsilon_n/\gamma$
  - kept $\sigma_{x,y}$ constant by adjusting β_{avg}



- scales with current as $L_g \propto I_e^{-1/3}$
- emittance → angular spread
  - spread in resonance wavelength
  - less severe at larger wavelengths



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GENESIS1.3 FEL code

- GENESIS1.3, v4 by Sven Reiche
  - https://github.com/svenreiche/Genesis-1.3-Version4
- time-dependent, 3D
- entire bunch and field is kept in memory
- based on the Slowly Varying Envelope Approximation (SVEA)
  - equations of motion are Undulator-Period Averaged (UPA)
- coordinate system is based on slices
  - electron bunch consists of slices
- photon field
  - calculated with the same longitudinal granularity
  - transversely: rectangular grid

FEL Beamline Lattice

- planar undulators
- undulator period length $\lambda_{\mathrm{u}} = 13\,\mathrm{cm}$
- undulator segments, 0.42 m space inbetween
  - quadrupole to focus electron beam
  - diagnostics
- undulator segment length 2.08 m (16 periods)
  - $\sim$ 1 power gain length
  - undulator tapering

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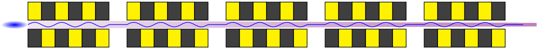
Undulator Tapering

- resonance condition:

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad , \qquad K \propto \lambda_u B$$



- electron bunch loses energy along FEL undulator beamline
- compensation of the electron energy loss necessary
- undulator tapering to preserve resonance condition
- undulator strength K should be decreased along the undulator

Undulator Tapering

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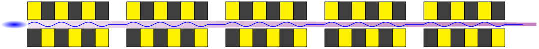

- electron bunch loses energy along FEL undulator beamline
- compensation of the electron energy loss necessary
- undulator tapering to preserve resonance condition
- undulator strength K should be decreased along the undulator
- optimize K-values of individual radiator segments for maximum power output
  - here for simplicity based on time-independent scan simulations

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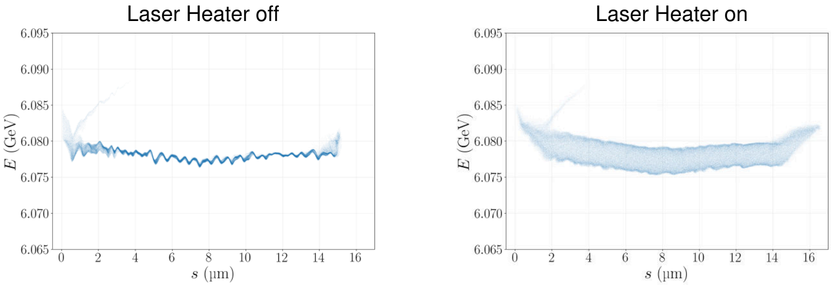
S2E: Beam parameters



- microbunching instability suppressed by laser heater
- laser heated electron distribution is used in the following

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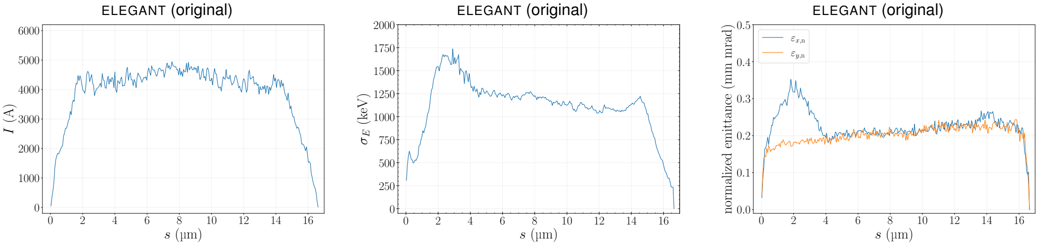
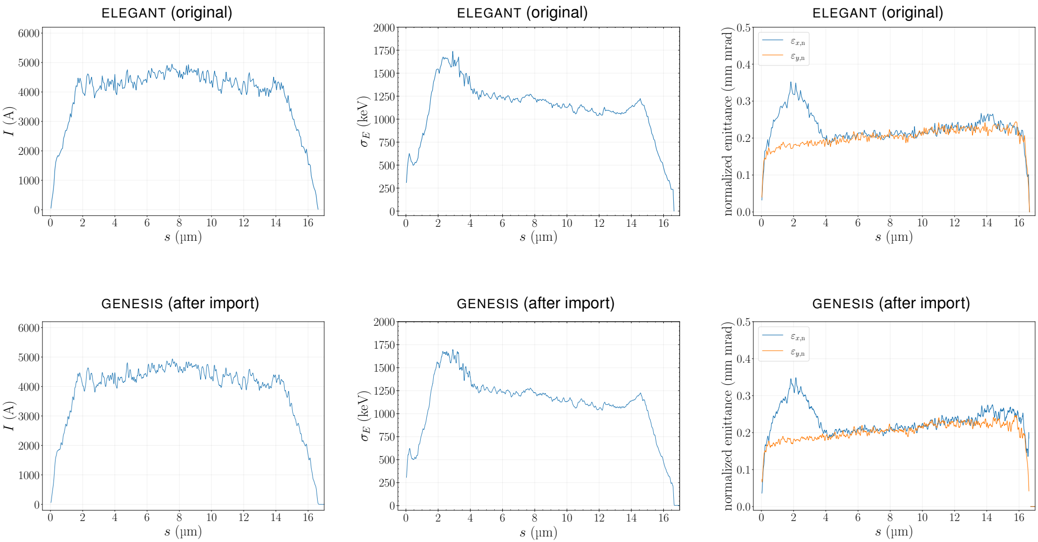
Beam parameters



Beam parameters



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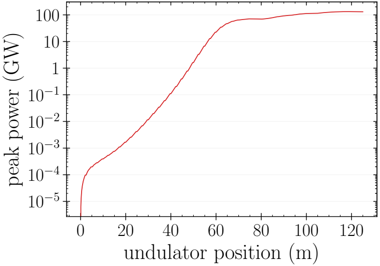
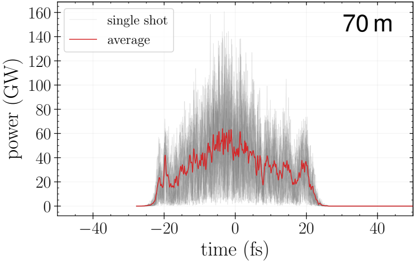
FEL Performance at 1 nm



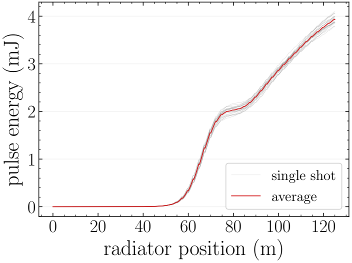


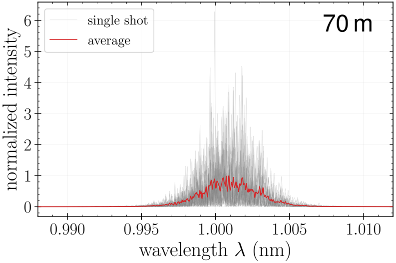
25 shots

no tapering

$z_{\text{sat}} \sim 70\,\text{m}$

$P_{\text{sat}} \sim 70\,\text{GW}$





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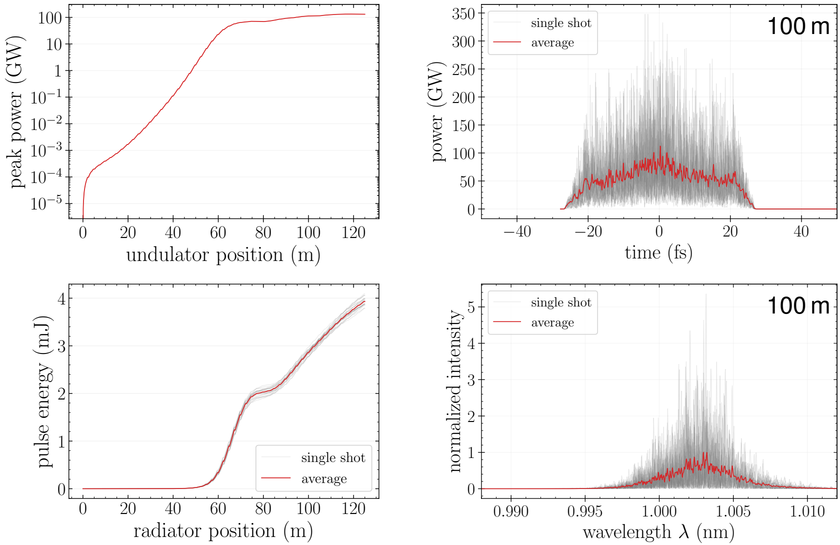

25 shots

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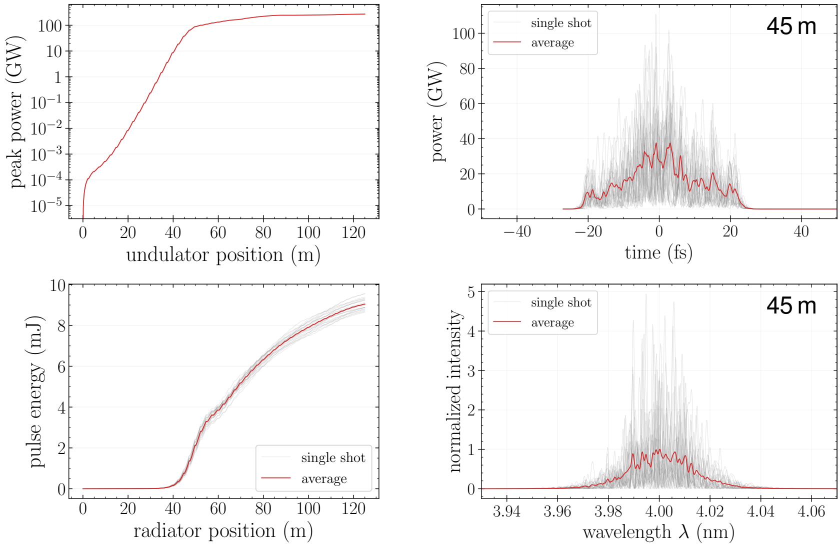
FEL Performance at 4 nm



25 shots

no tapering

$z_{\mathrm{sat}} \sim 50\,\mathrm{m}$

$P_{\mathrm{sat}} \sim 100\,\mathrm{GW}$

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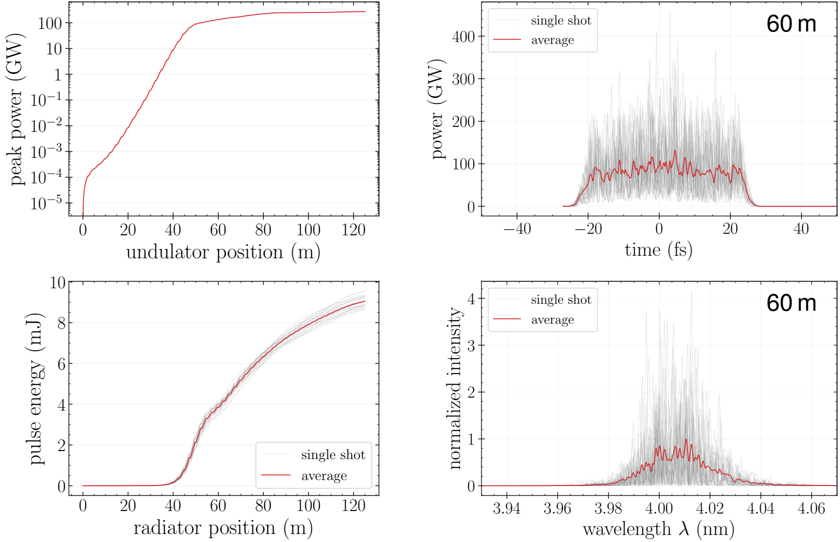

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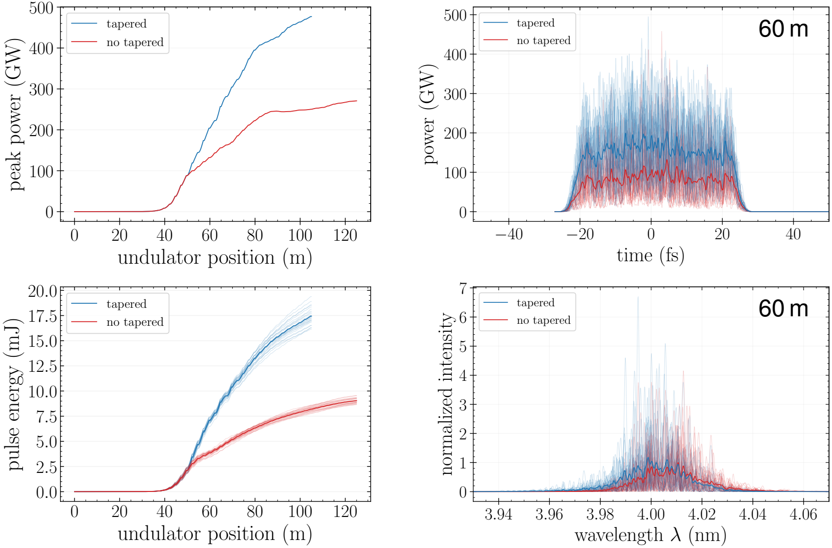
FEL Performance at 4 nm: Undulator Tapering



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tapering

2 x power

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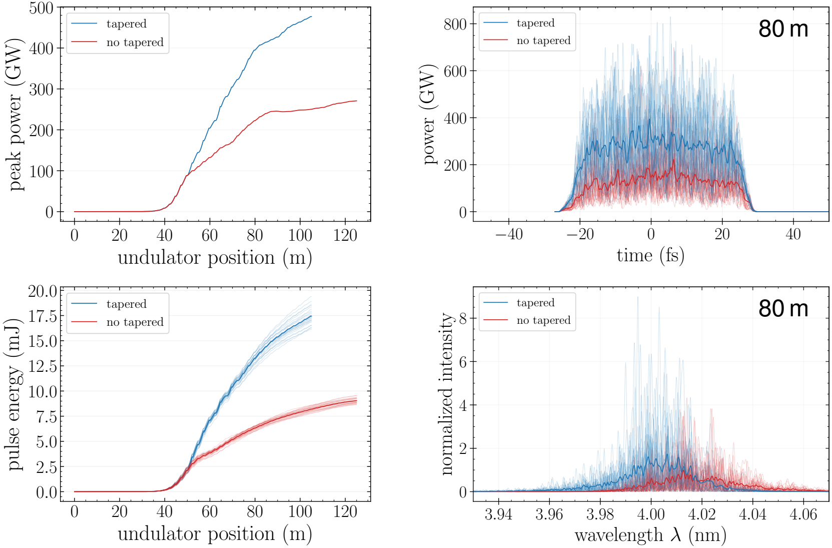

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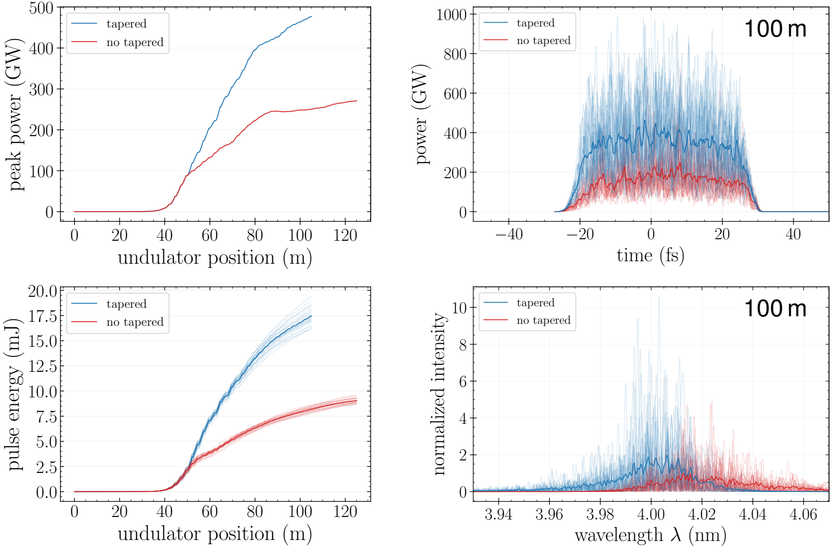

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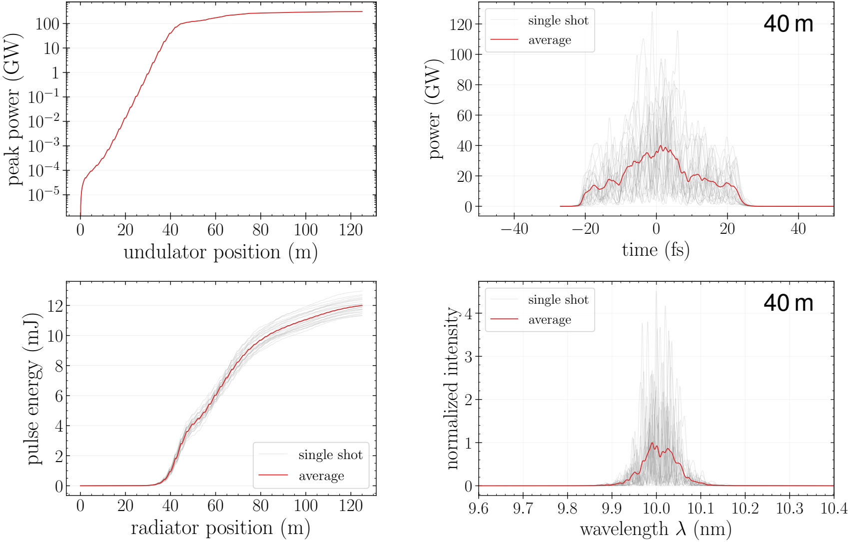
FEL Performance at 10 nm



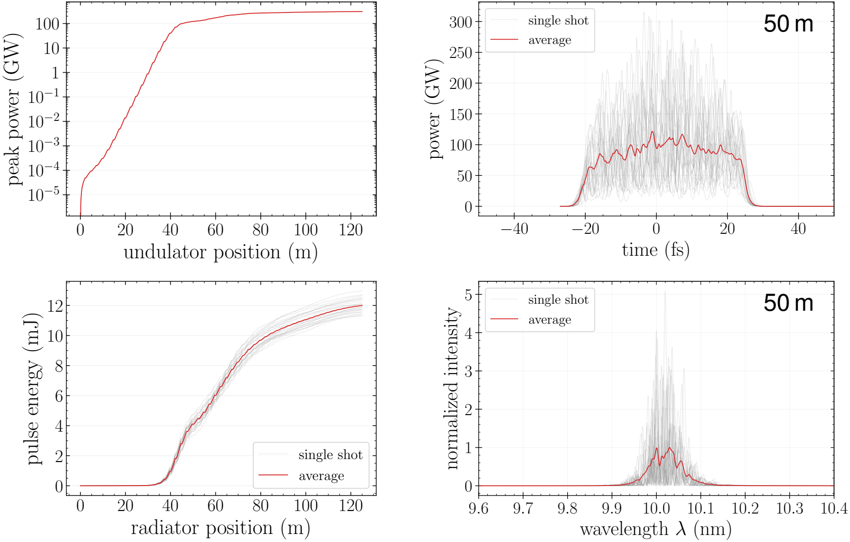
25 shots

no tapering

$z_{\mathrm{sat}} \sim 45\,\mathrm{m}$

$P_{\mathrm{sat}} \sim 100\,\mathrm{GW}$

FEL Performance at 10 nm



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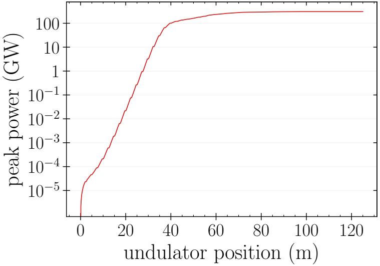
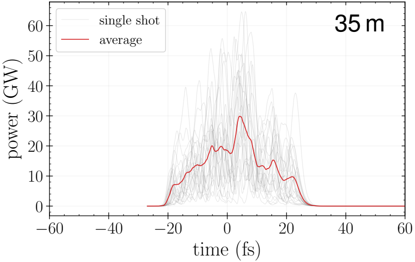
FEL Performance at 25 nm



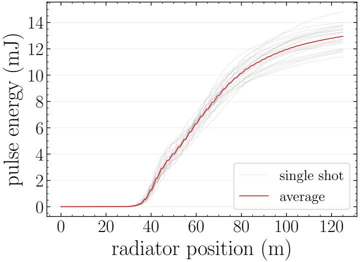


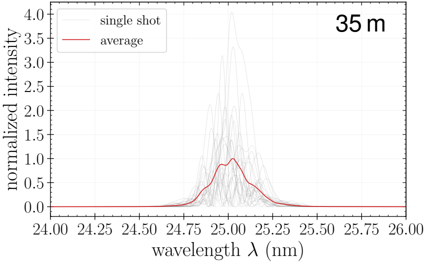
25 shots

no tapering

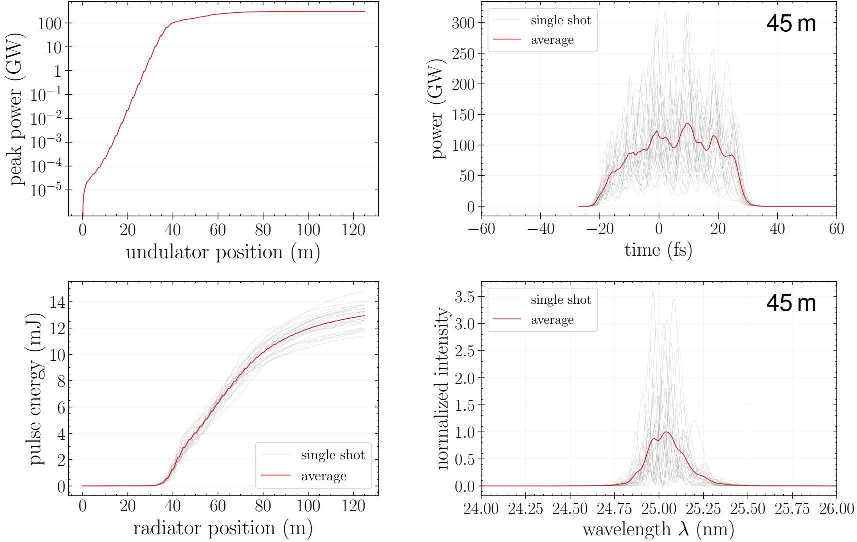
$z_{\text{sat}} \sim 40\,\text{m}$

$P_{\text{sat}} \sim 100\,\text{GW}$





FEL Performance at 25 nm



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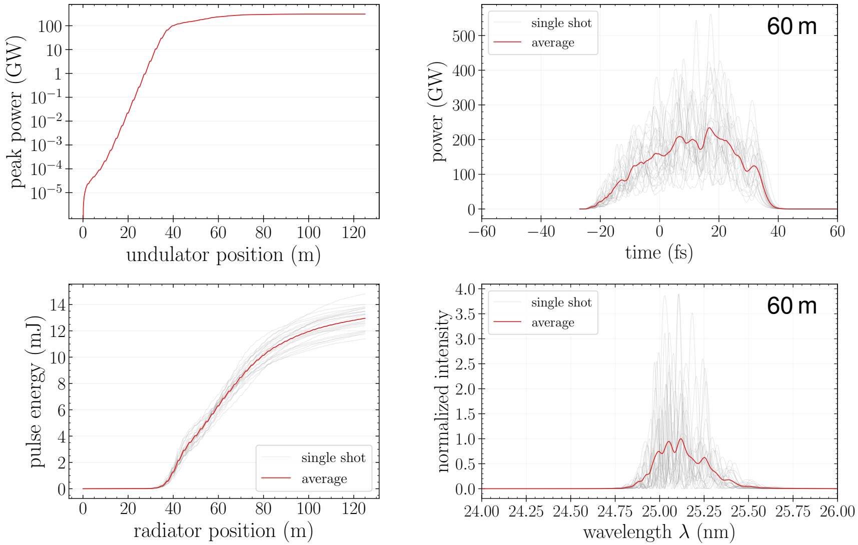

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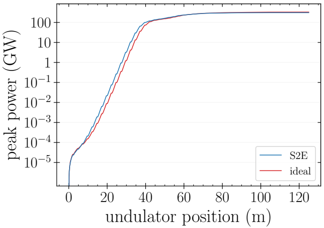
Ideal Simulations

- compared to S2E simulations:
  - Gaussian distribution
  - lower energy: $\sim$ 6.08 vs 6 GeV
  - higher emittance: $\sim$ 0.2 vs 0.3 mm mrad
  - larger energy spread: $\sim$ 1.2 vs 2 MeV
- slightly higher gain in S2E simulations

25 nm



Ideal Simulations

European XFEL — eurizon, European network for developing new horizons for RIs

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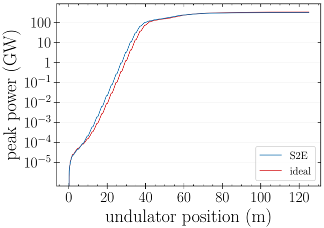
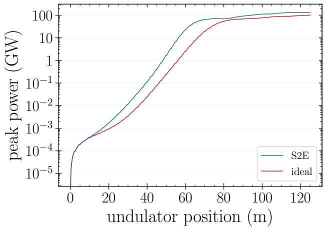
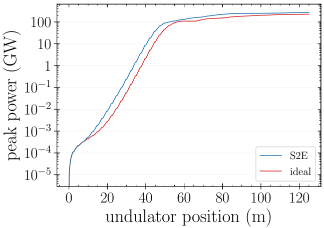


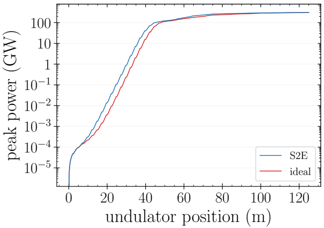
1 nm



4 nm



10 nm



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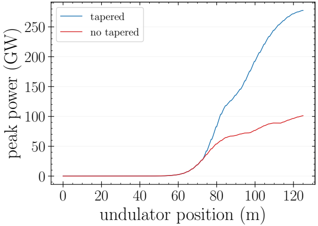
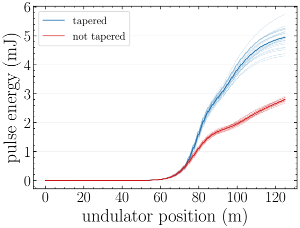
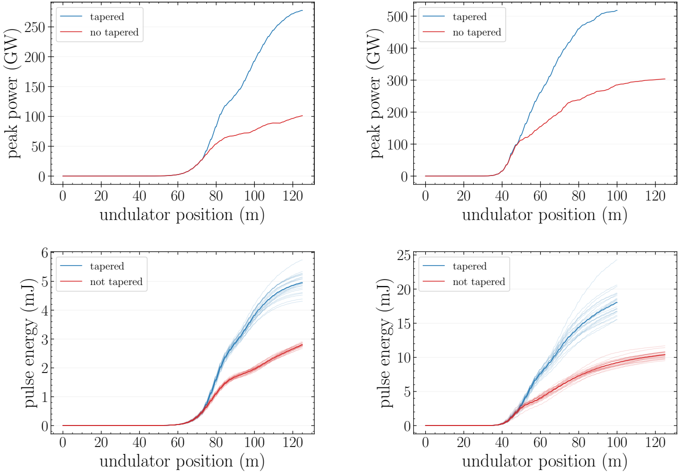
1 nm



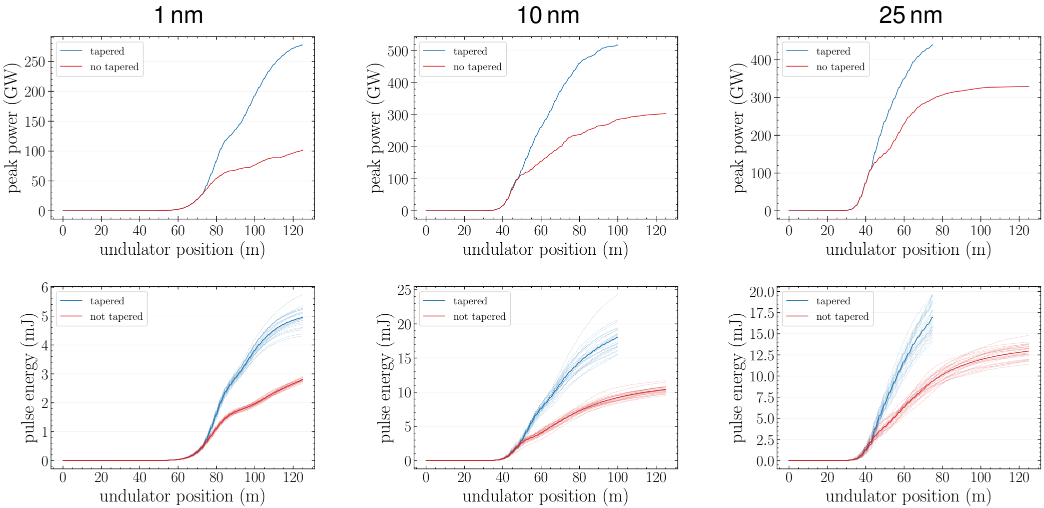


Ideal Simulations: Tapering 1 nm, 10 nm, 25 nm

1 nm 10 nm



Ideal Simulations: Tapering 1 nm, 10 nm, 25 nm



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- FEL with $\sim$ 100 m undulator beamline
- wavelength from 1.2 nm to 25 nm $\rightarrow$ photon energy from 50 eV to 1 keV
- SASE pulses with peak power in 70 GW to 100 GW range
- SASE pulses with pulse energy in 2 mJ to 6 mJ range
- factor $\sim$ 2 improvement is expected with undulator tapering

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- Analytical: sensitivity to current and emittance
- Ideal Simulations: 1 nm
- Ideal Simulations: 10 nm
- Ideal Simulations: 10 nm
- Ideal Simulations: 25 nm
- Transverse Coherence

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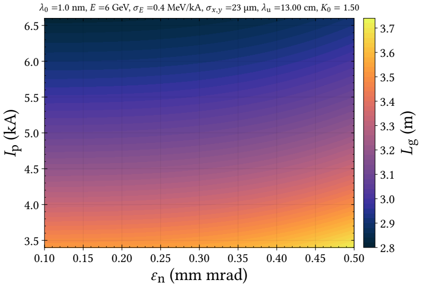
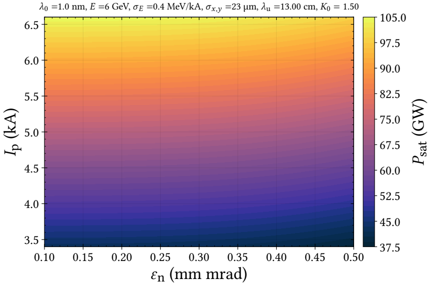
Sensitivity to Current and Emittance: 1 nm

- scaled energy spread with current:
  - 2 MeV at 5 kA, ± 0.4 MeV/kA
- $\sigma^2_{x,y} = \beta_{\text{avg}} \varepsilon_{\text{n}} / \gamma$
  - kept $\sigma_{x,y}$ constant by adjusting β_{avg}
  - β_{avg} ranges from 12 m to 60 m





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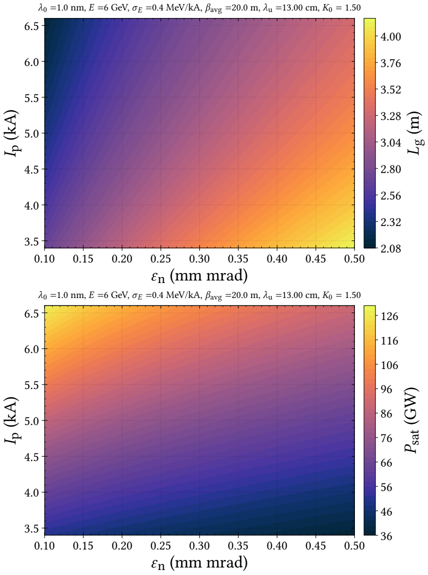

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Sensitivity to Current and Emittance: 25 nm

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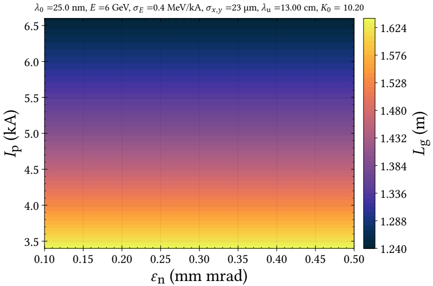
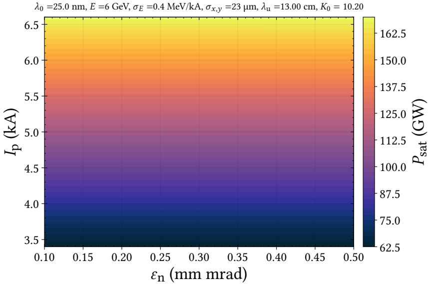
  - β_{avg} ranges from 12 m to 60 m





Sensitivity to Current and Emittance: 25 nm

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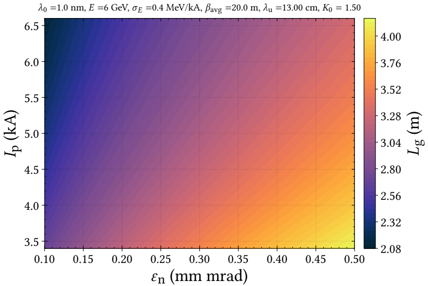
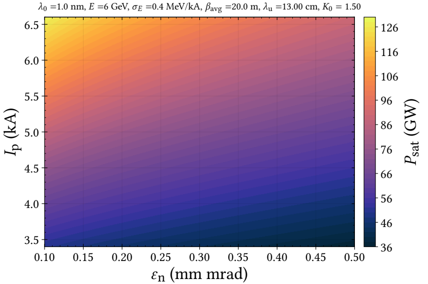


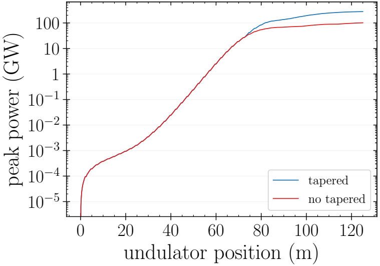


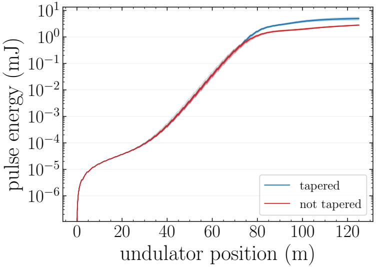
Ideal Simulations: Electron Beam Parameters

- GENESIS1.3, v4 simulations based on ideal Gaussian electron distributions
- Parameters used for ideal simulations:

Parameter	Symbol	Value
energy	E	6 GeV
rms energy spread	σ_E	2 MeV
peak current	I_e	5 kA
emittance (normalized)	ε_n	0.3 mm mrad
average beta function	β_{avg}	20 m
rms beam size	$\sigma_{x,y}$	23 µm
rms bunch length	σ_e	6 µm

Ideal Simulations: 1 nm





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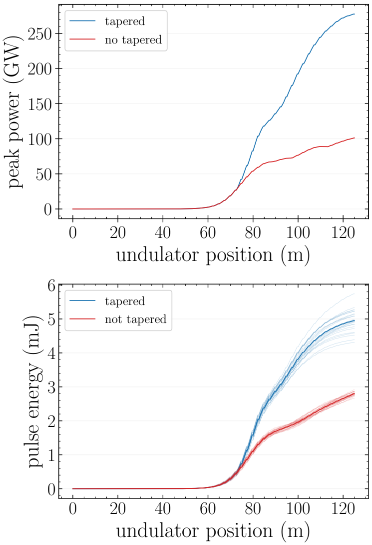
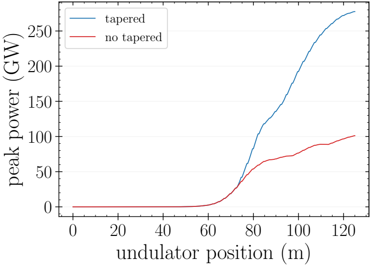
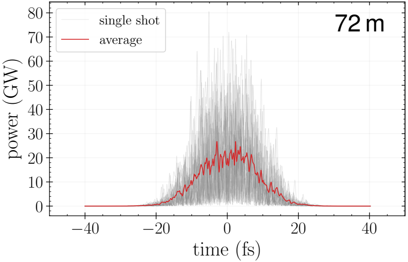
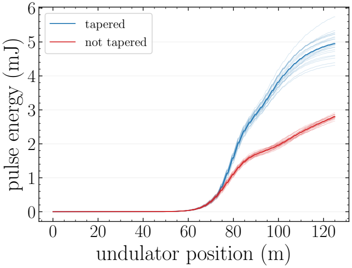
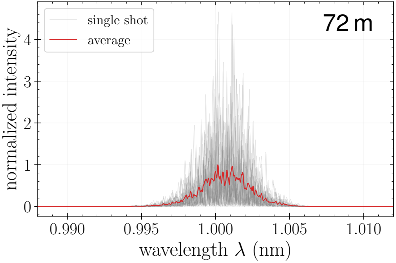


Ideal Simulations: 1 nm









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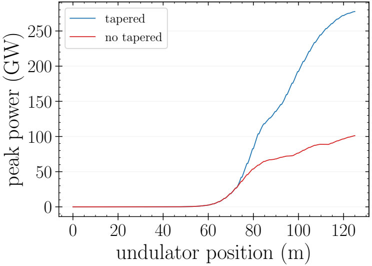

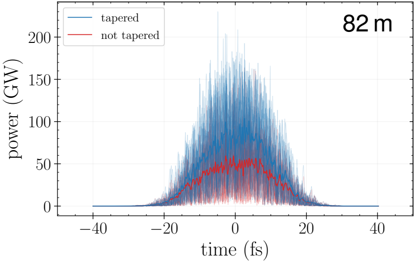

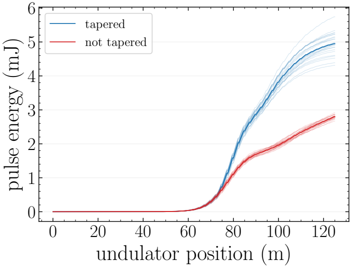

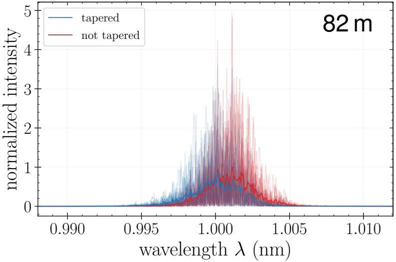

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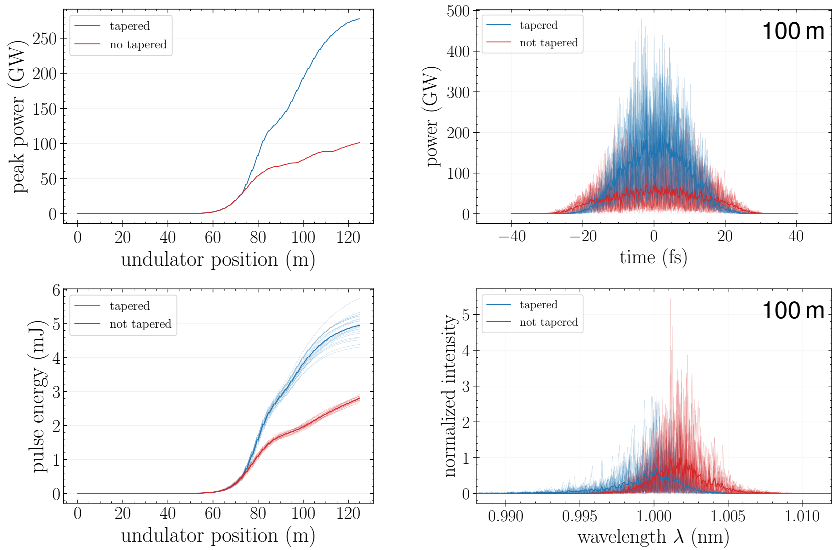
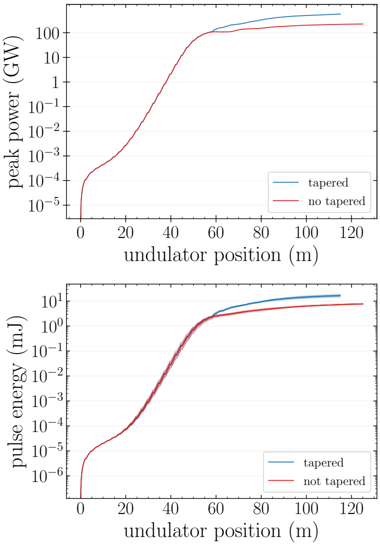


Ideal Simulations: 4 nm



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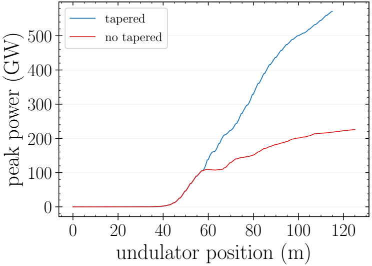

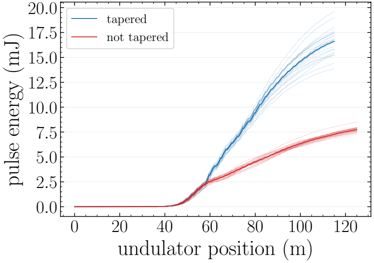

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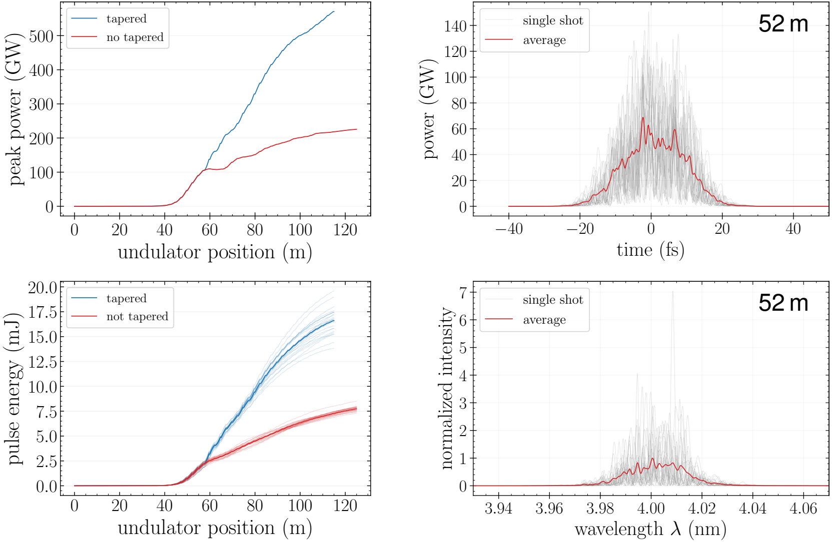

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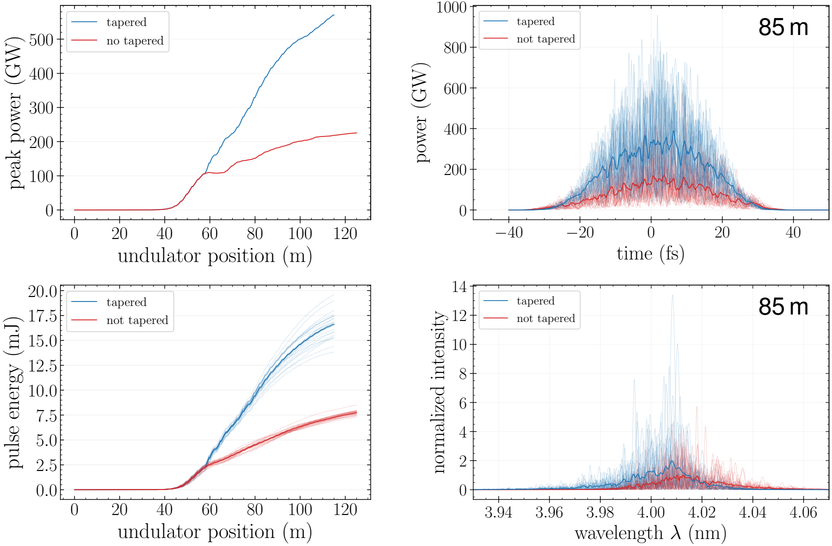

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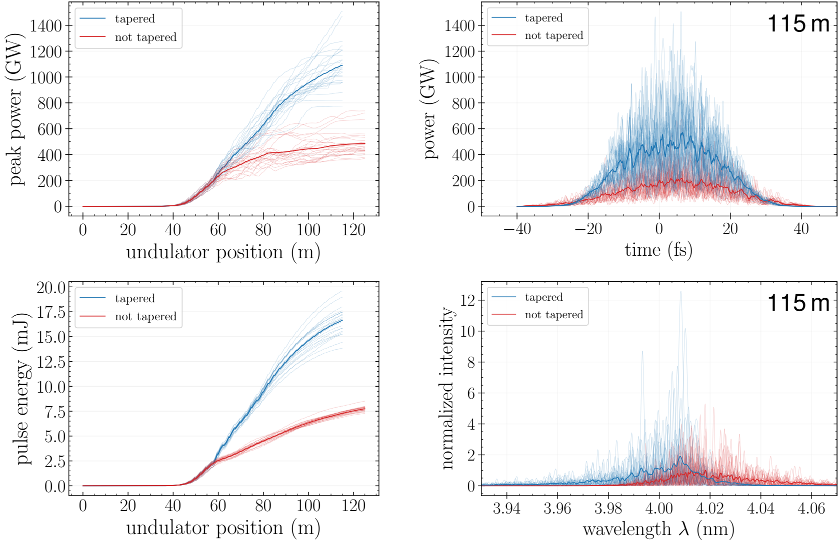

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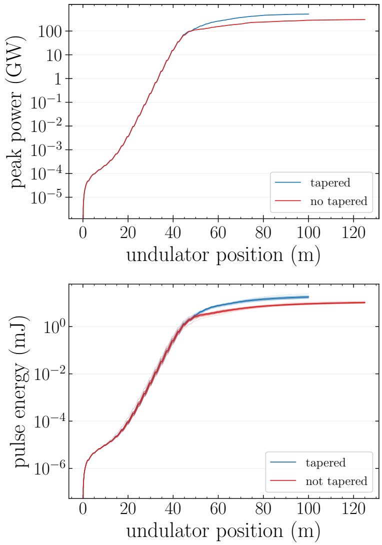

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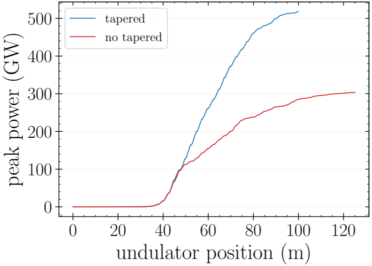
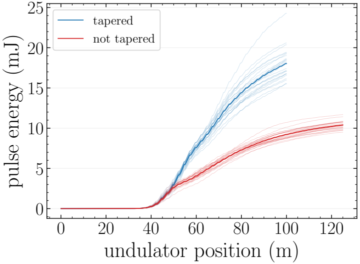
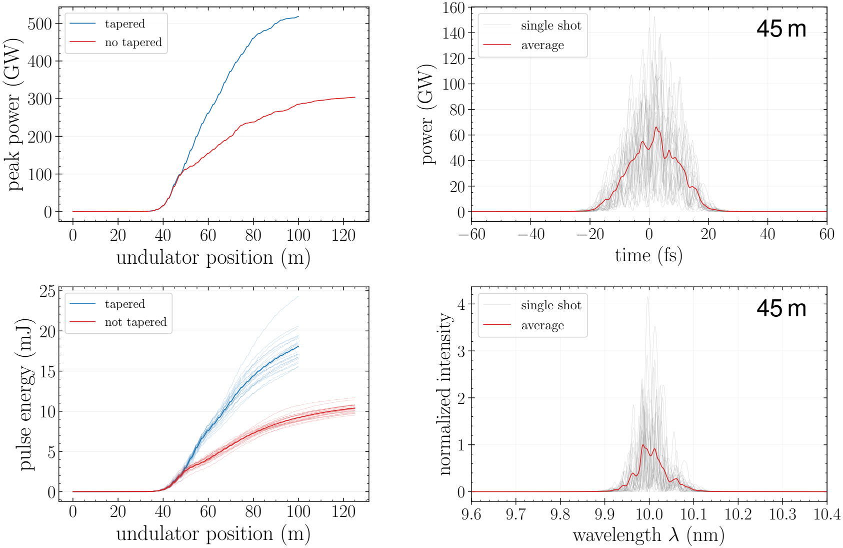




Ideal Simulations: 10 nm

European XFEL
eurizon
European network for developing new horizons for RIs



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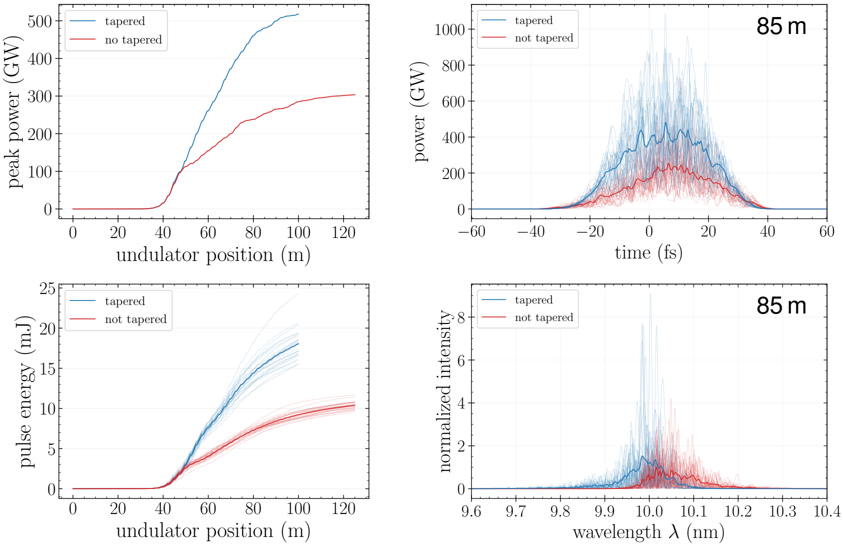

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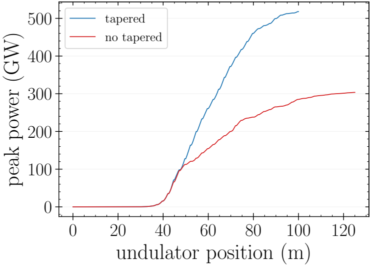
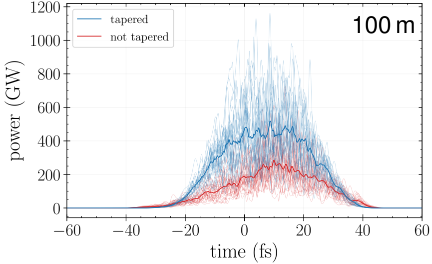
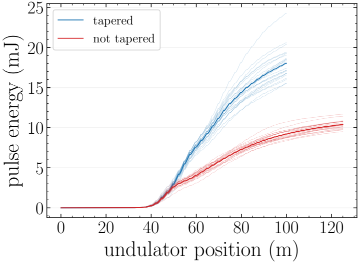
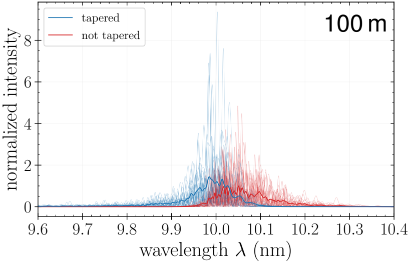
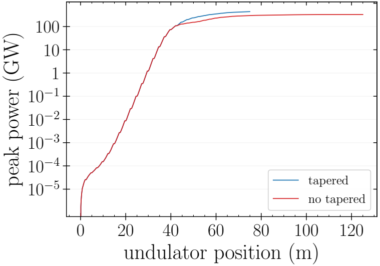


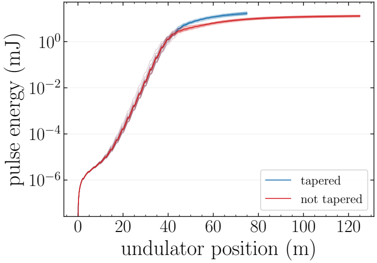






Ideal Simulations: 25 nm





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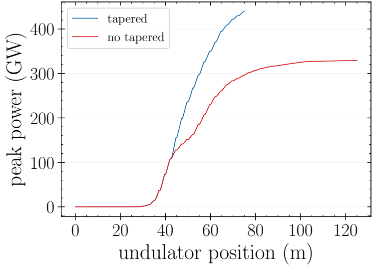

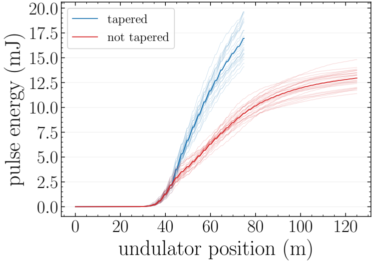

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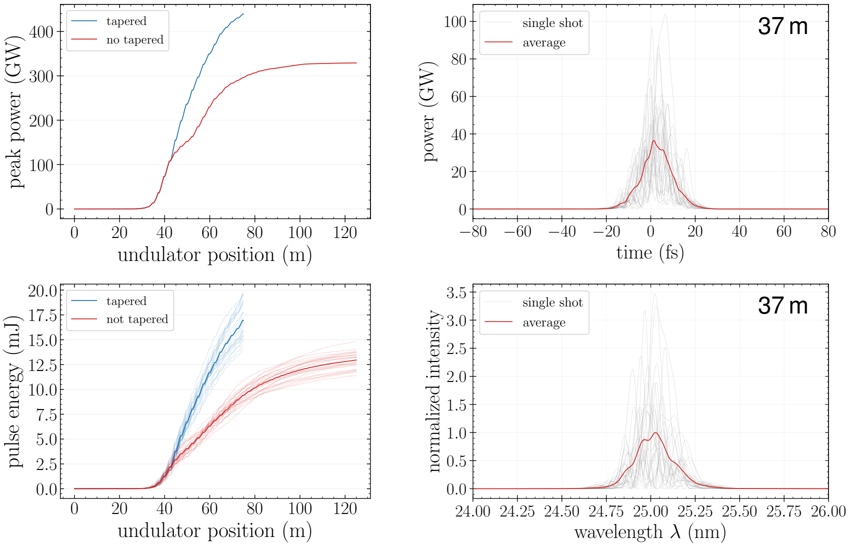

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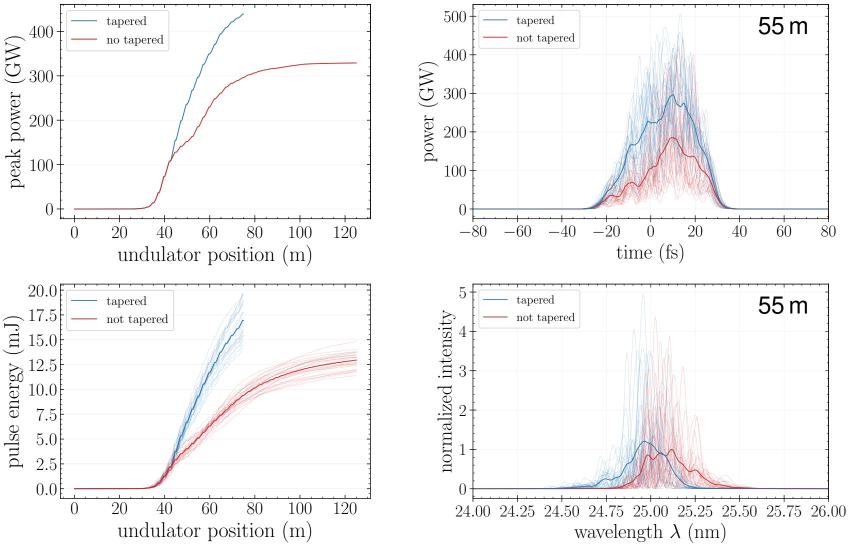

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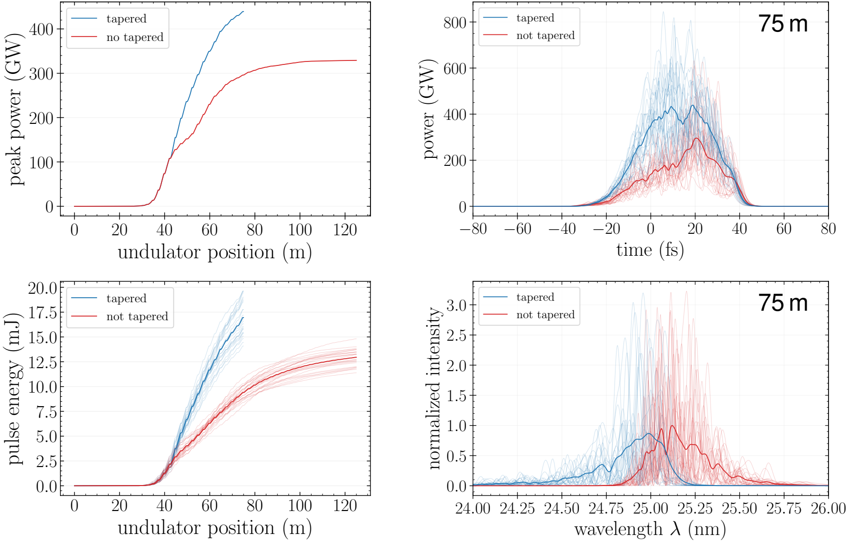

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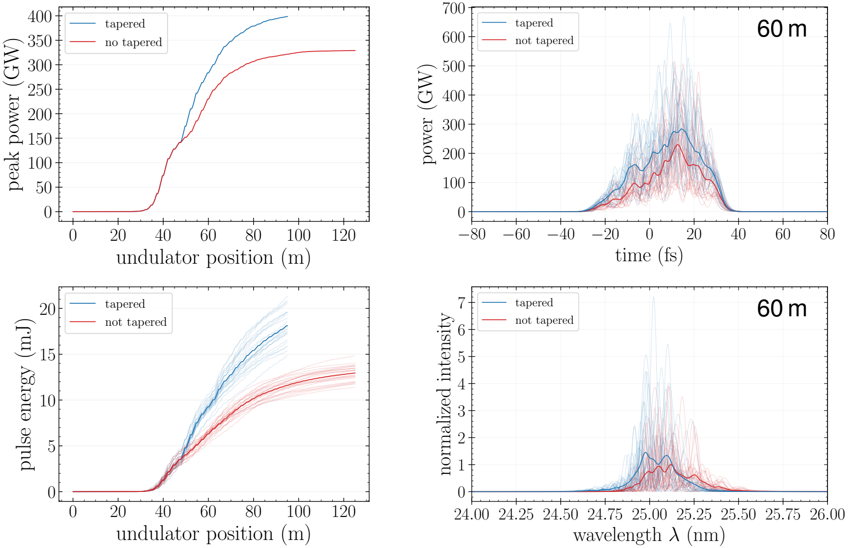

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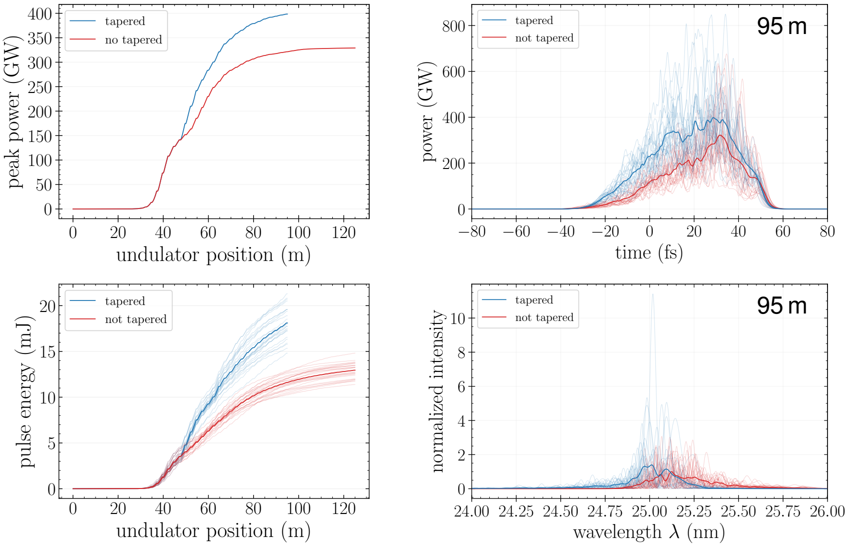
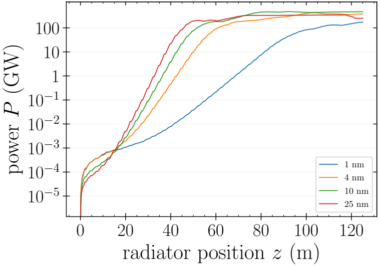
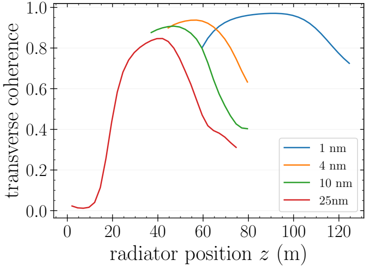


Transverse Coherence

- maximum coherence before saturation
  - end of linear regime
- depends on $2\pi\varepsilon/\lambda_\ell$
- untapered, ideal simulations with 0.6 mm mrad
  - 1nm: $2\pi\varepsilon/\lambda_\ell = 0.32$
  - 4nm: $2\pi\varepsilon/\lambda_\ell = 0.08$
  - 10nm: $2\pi\varepsilon/\lambda_\ell = 0.032$
  - 25nm: $2\pi\varepsilon/\lambda_\ell = 0.013$





see also e.g. E.L. Saldin et al.: Coherence properties of the radiation from X-ray free electron laser, 2007

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