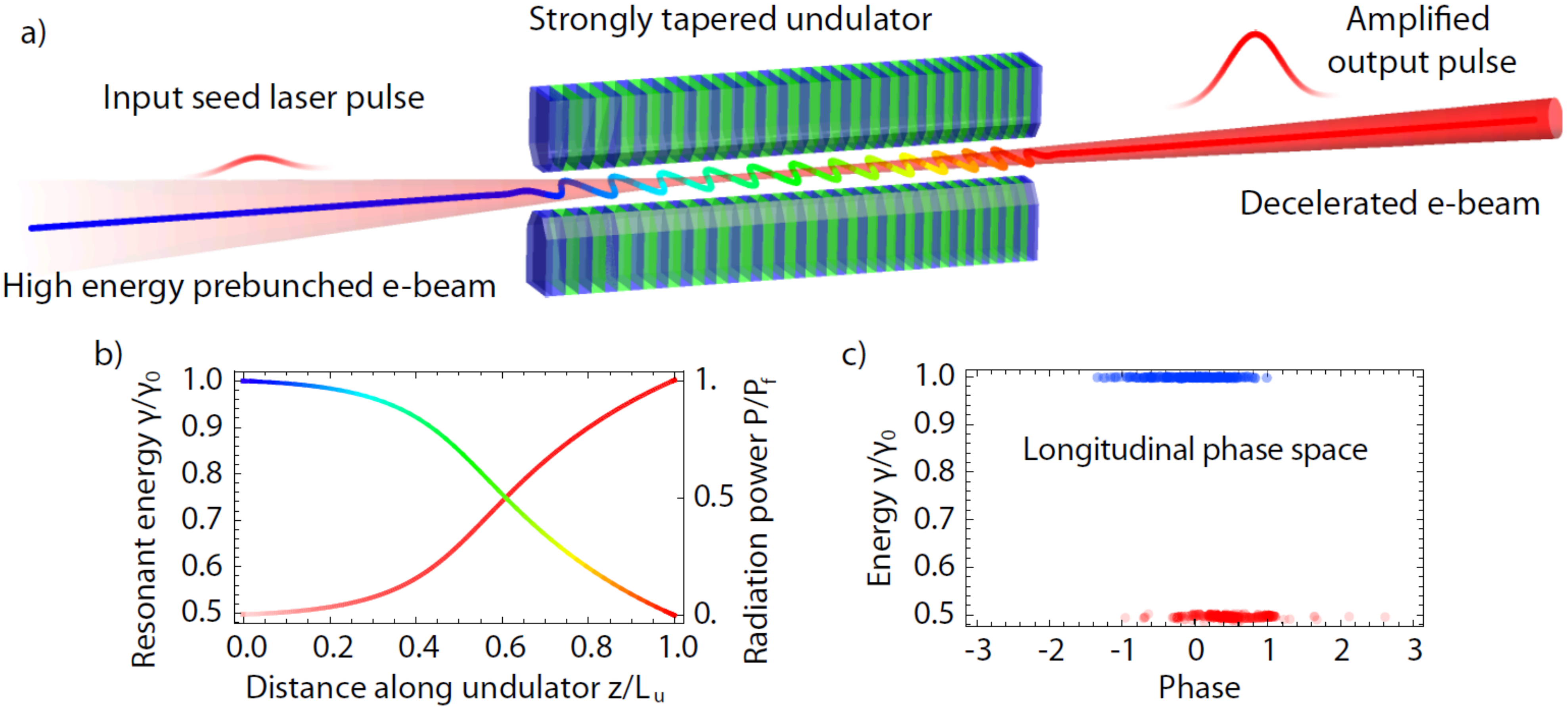
Strongly Focusing Undulator Design for TESSA-266

Youna Park

Outline

- Rubicon IFEL, Nocibur IIFEL, and TESSA-266
- efficiency vs transverse beam size
- Beam size and power output for different quadrupole lattice systems
- Matching the linac and the undulator beam size
- Time-dependent Simulation Result of TESSA-266

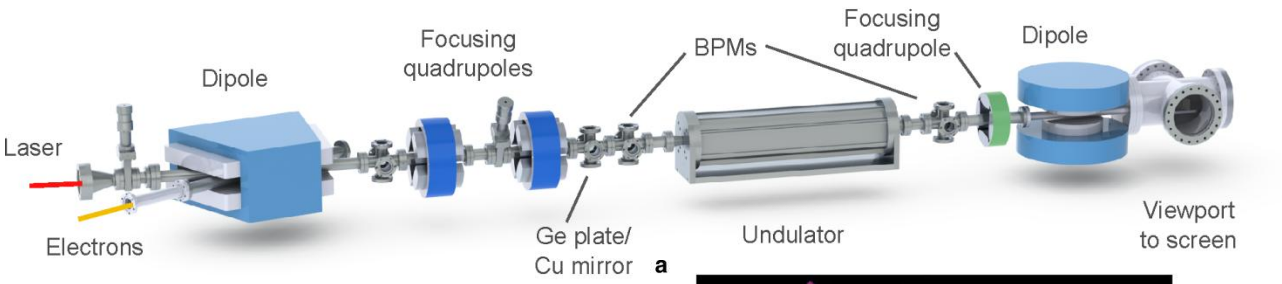
TESSA- Tapering Enhanced Stimulated Superradiant Amplification

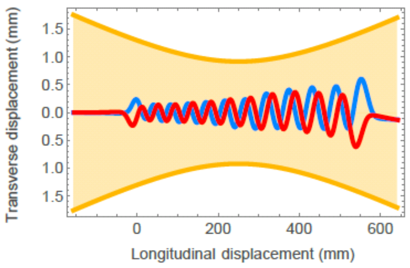


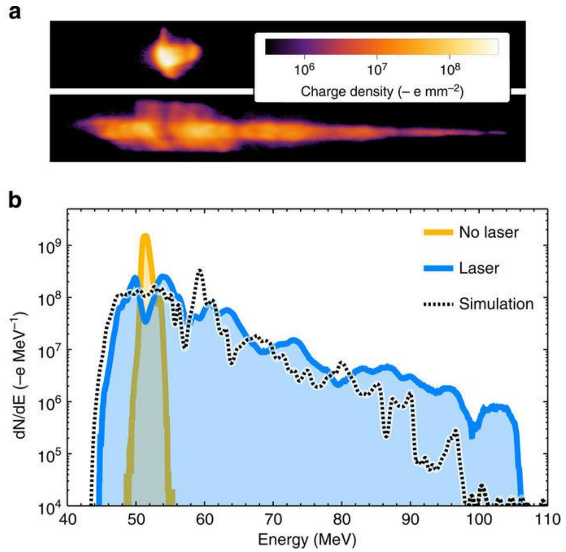
High-quality electron beams from a helical inverse free-electron laser accelerator
Duris, J.; Musumeci, P.; Babzien, M.; et al.
NATURE COMMUNICATIONS Volume: 5 Article Number: 4928 Published: SEP 2014

Rubicon IFEL experiment(BNL)

- First strongly tapered helical undulator, 52MeV -> 92MeV



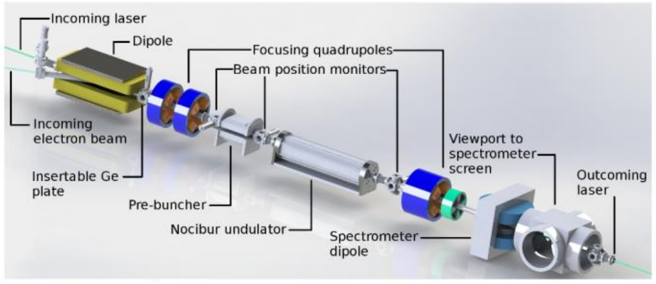




Input e-beam energy	50 MeV
Average accelerating gradient	**100 MV/m**
Laser wavelength	10.3 μm
Laser power	**100-300 GW**
Laser focal spot size (w)	980 μm
Laser Rayleigh range	30 cm
Undulator length	**54 cm**
Undulator period	4 – 6 cm
Magnetic field amplitude	5.2 – 7.7 kG

NOCIBUR IIFEL deceleration experiment(BNL)

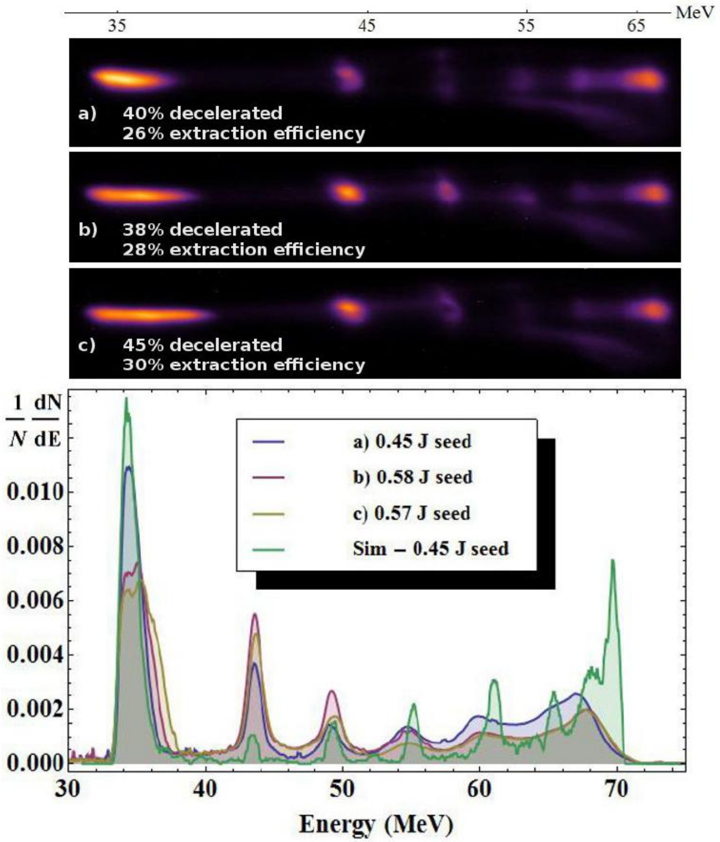
IIFEL Rubicon: IFEL reversed to decelerate electron beams 65->35MeV



High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

N. Sudar, P. Musumeci, J. Duris, I. Gadjev, M. Polyanskiy, I. Pogorelsky, M. Fedurin, C. Swinson, K. Kusche, M. Babzien, and A. Gover

Phys. Rev. Lett. 117, 174801 – Published 19 October 2016



E-Beam energy	65 → 35 MeV
emittance	2 mm-mrad
σxy (waist)	100 μm
Laser Wavelength	10.3 μm
Rayleigh Range	0.3 m
Laser Waist	1 mm
Laser Power	200 GW
E-beam current	100 A
E-beam charge	100 pC
λw buncher	0.05 m (1 period)
Chicane: R56	21 → 59 μm
period tapering	0.06 - 0.04 m
K tapering	2.01 - 1.19

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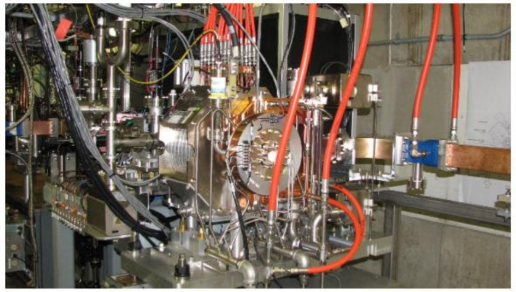
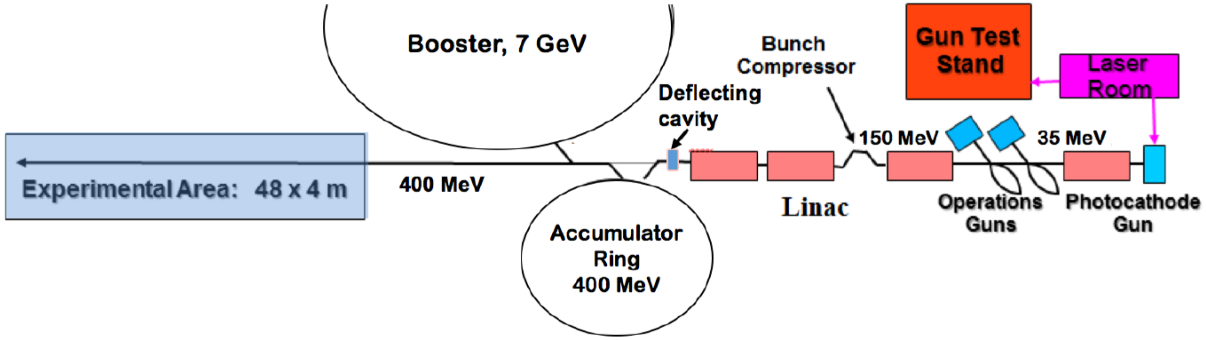
TESSA-266

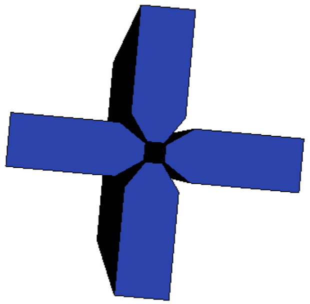


- Higher gain and higher current for radiation measurement
- Injector Linac at Argonne National Laboratory will operate at 375 MeV, 1kA and provide injection for 1.5 minutes in every 2 minutes
- decelerate ebeam for ~10% efficiency in 4 m undulator.
- Significant improvement from <1% efficiency in previous short wavelength FEL.



E-beam Energy	375MeV
Radiation Wavelength	266nm
Emittance	2 um
Seed Power	< 1GW
Energy spread	~.1%?
Peak Current	1 kA
Bunch length (RMS)	50um?

Tapered Helical Undulator:



Halbach helical undulator magnets

Undulator gap will be tapered to satisfy the resonance condition:

Tapering Equation for Helical Undulator: $\frac{dK}{dz} = -2k_w K_l \sin \Psi_r$

k_w = undulator wavenumber

$K_l = \frac{eE_0}{km_e c^2} = \frac{e\lambda}{2\pi mc^2}\sqrt{2Z_0 I_{crit}}$ = laser vector potential

Ψ_r = resonant phase

High Gain Regime:
K_l will be updated every period using
Genesis Informed Tapering (GIT) Simulation by J. Duris, P. Musumeci (UCLA)
https://github.com/ypark39/GIT2018

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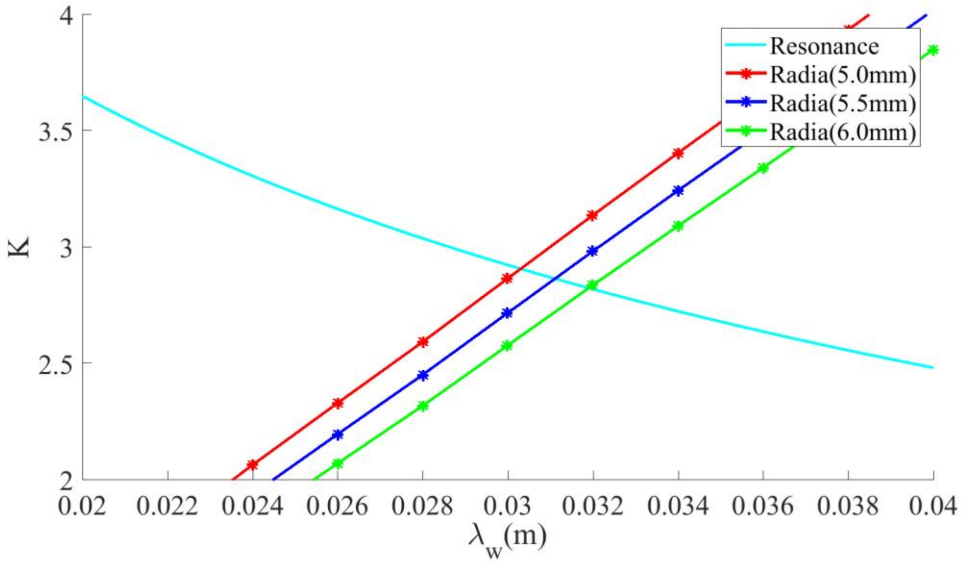
Tapered Helical Undulator:

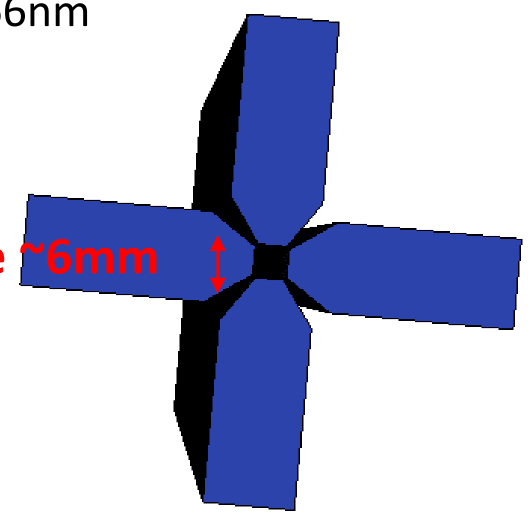
We determined that undulator period of 3.2 cm is the minimum length because :

- Smaller undulator period yields greater power, but smaller period requires smaller beam clearance.
- From Radia simulation we obtained undulator vector potential for different gaps and periods
- Given 6mm as the minimum for beam clearance, 3.2 cm was the smallest undulator period.



Cyan: K vs. λ_u at resonance,
$\gamma_0 = 375$MeV, λ=266nm

Permanent magnets(NdFeB)



efficiency η vs electron beam size

$$\eta(z) = \frac{\chi_1 f_t}{\gamma_0}\left(\frac{K_0}{\gamma_0} E_0 \sin\psi_r z + \frac{f_t \chi_2}{2}\frac{K_0^2}{\gamma_0^2}\sin^2\psi_r z^2\right)$$

f_t = trapping fraction

C. Emma "High efficiency, high brightness X-ray free electron laser pulses via fresh bunch self-seeding and undulator tapering," *UCLA*. ProQuest ID: EMMA_ucla_0031D_15825. Merritt ID: ark:/13030/m5j72b7s(Derivation assumed 1D and constant current, C. Emma 2017)

γ_0 = initial energy

K_0 = initial undulator vector potential parameter

$$\chi_1 = \frac{e}{2m_e c^2}$$

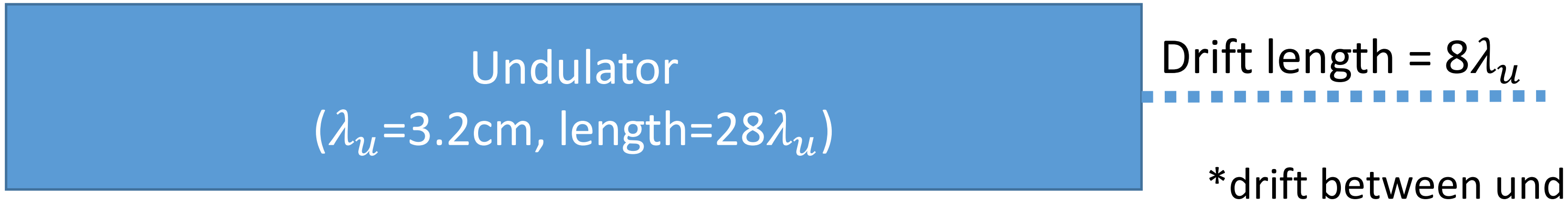
$$\eta \propto \frac{1}{\sigma_e^2}$$

$$\chi_2 = \frac{Z_0 I}{8\pi\sigma_e^2},$$

σ_e = e-beam size

- Derivation assumed constant current
- Optimal beam size based on gain length is unknown due to the emittance and the 3D effects.

Undulator with Natural Focusing, $<\sigma_x>$=76um



*drift between undulators is required for diagnostic purposes and phase shifter

$$M_u = \begin{bmatrix} \cos(k_x z) & \frac{1}{k_x}\sin(k_x z) \\ -k_x \sin(k_x z) & \cos(k_x z) \end{bmatrix}, \quad M_d = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

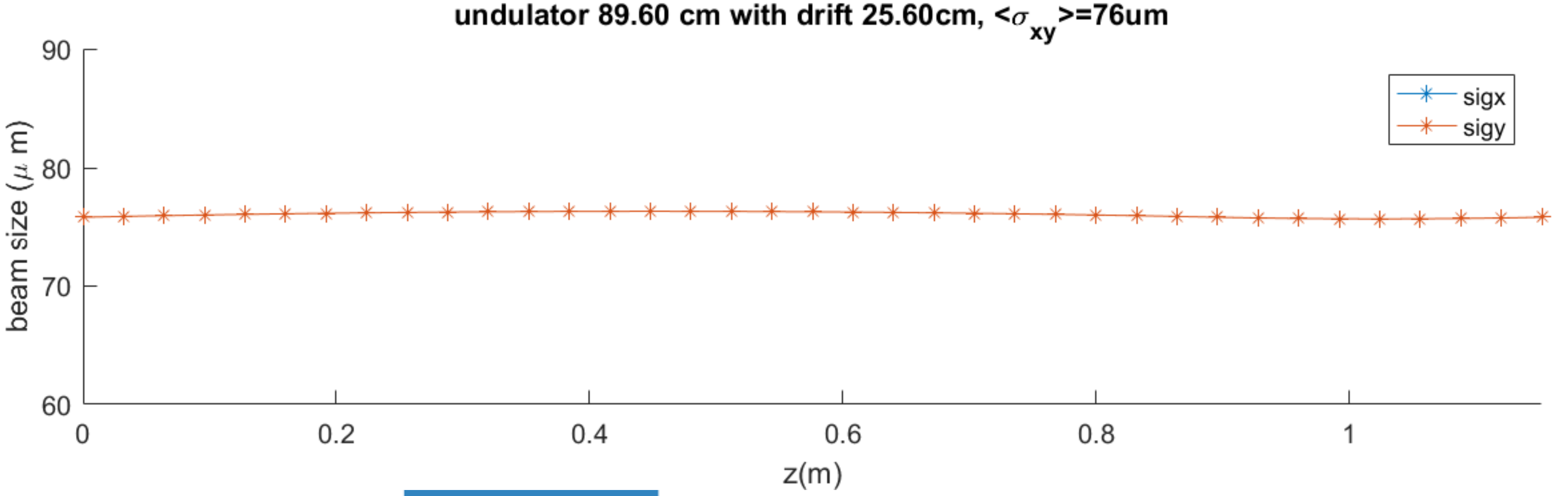
$k_x = \frac{1}{\sqrt{2}} \frac{k_w K}{\gamma_0}$

k_w = undulator wave number

$K = \frac{eB_0}{k_w m_e c}$

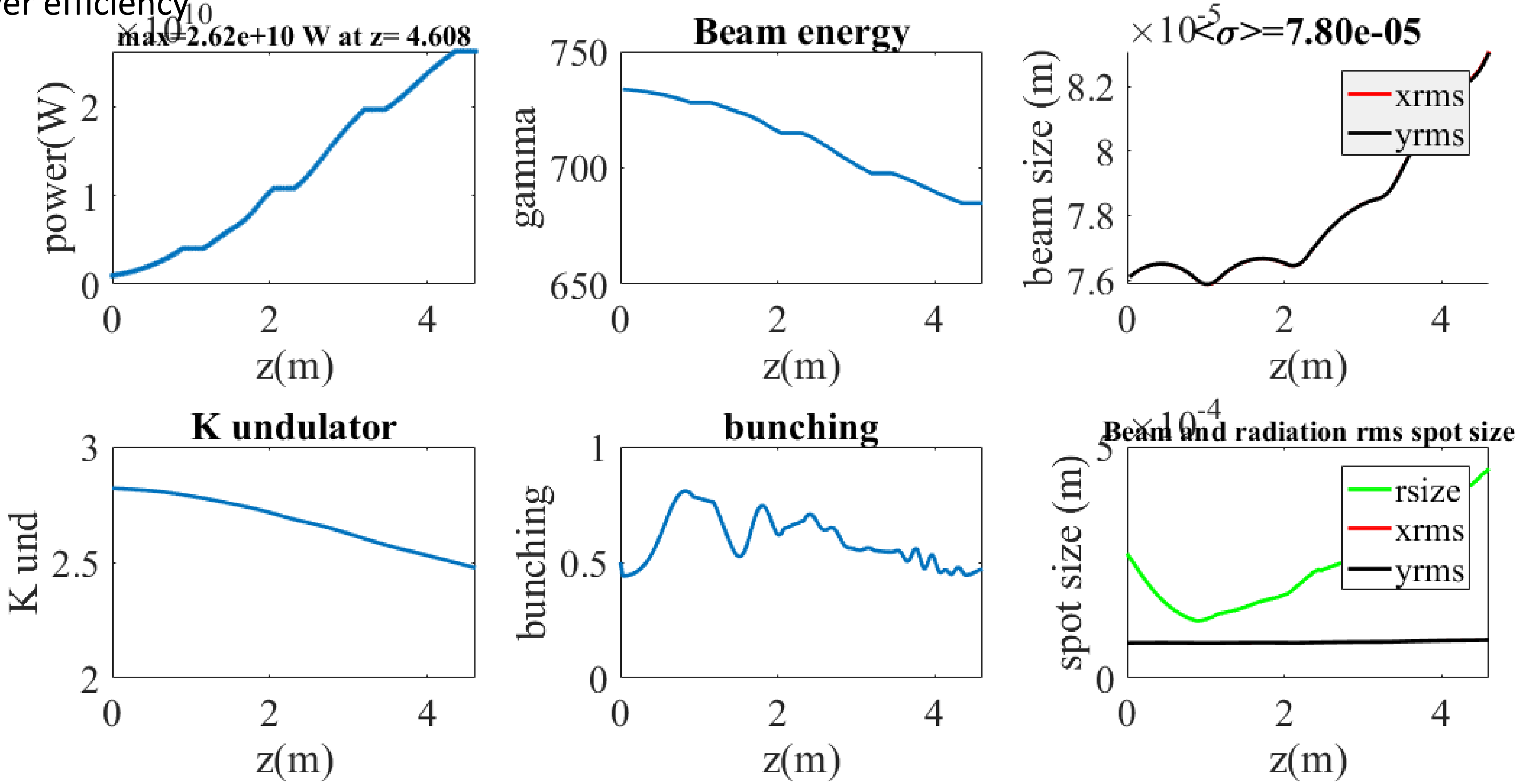
d = drift length

$M_{tot} = M_d M_u$

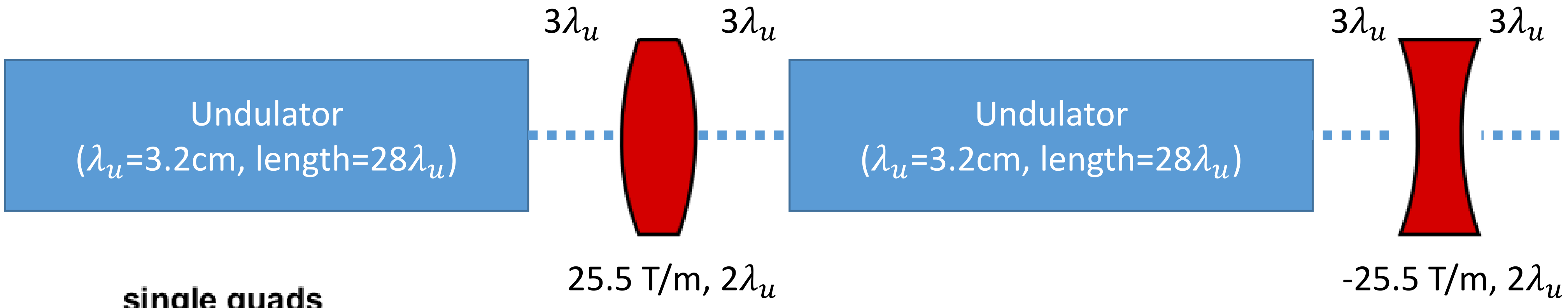


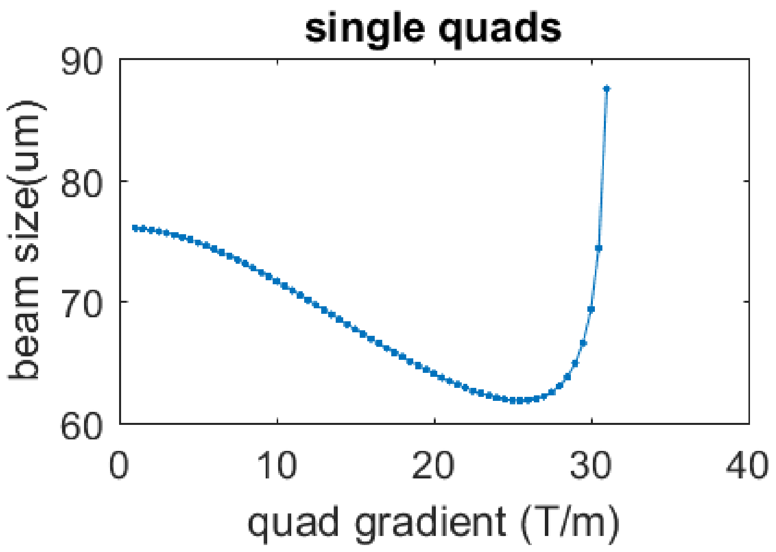
GIT Simulation for Undulator with Natural Focusing

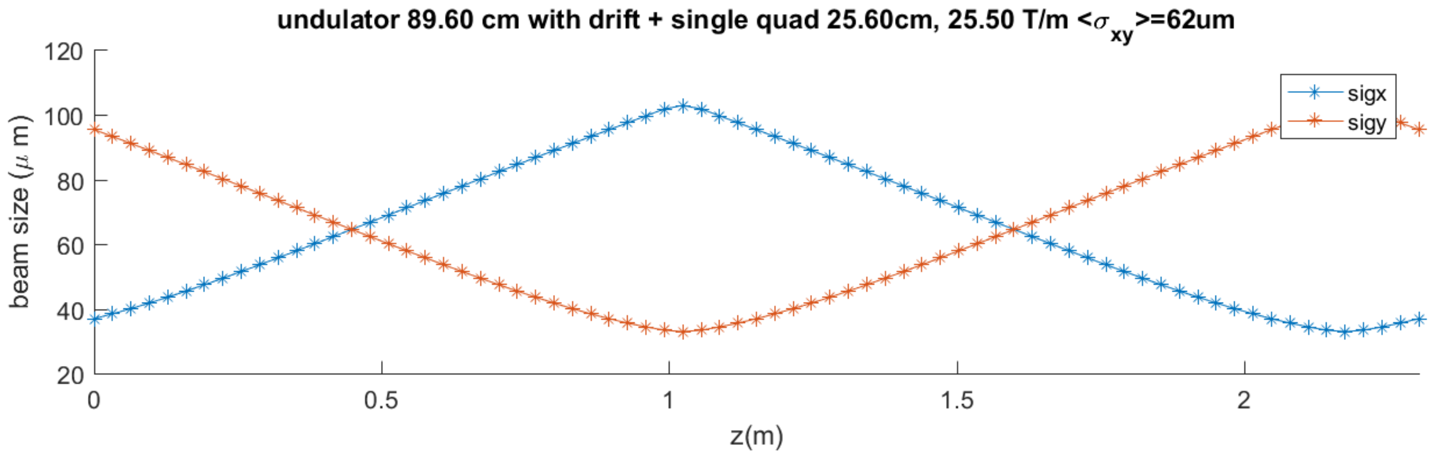
~6.9% power efficiency



Focusing and defocusing quadrupoles alternated, $<\sigma_x>$=62um







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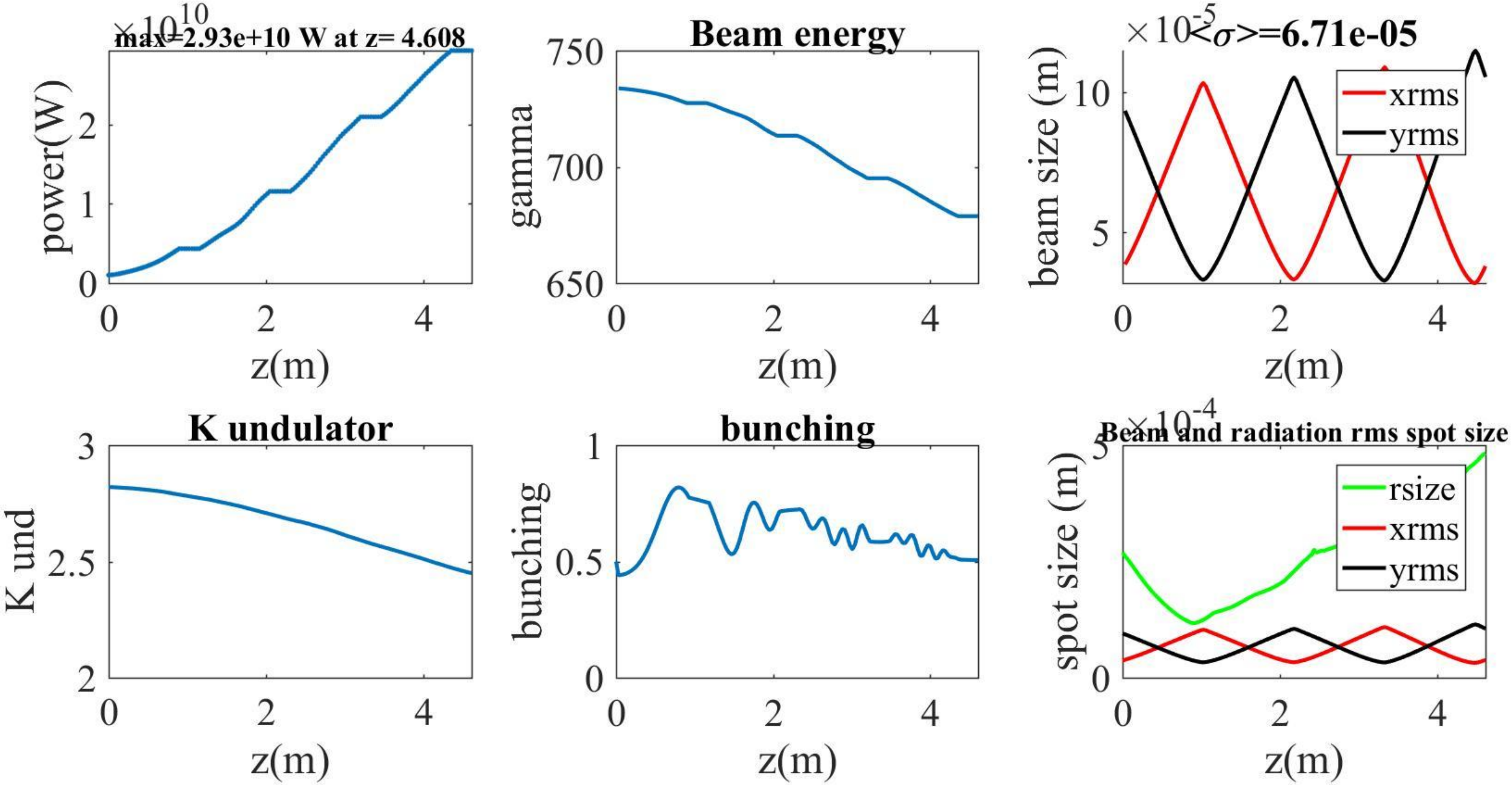
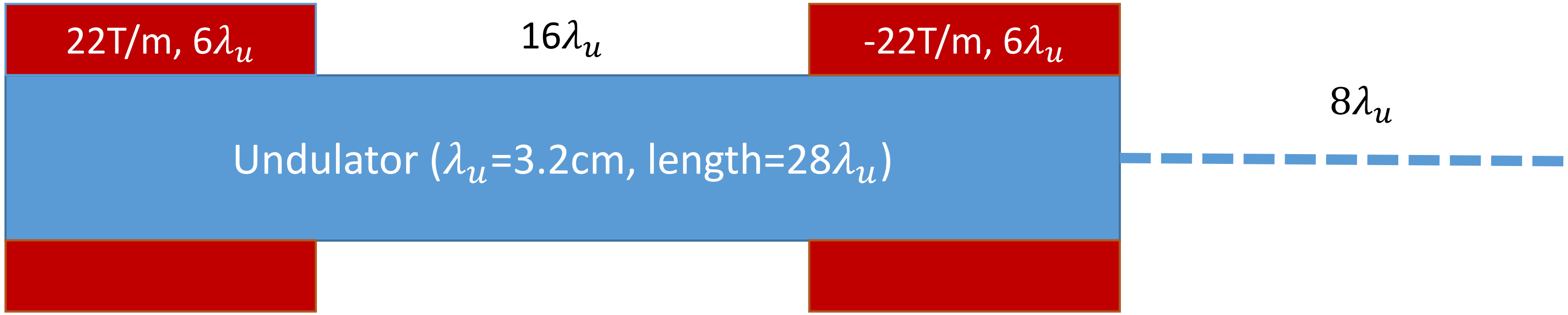
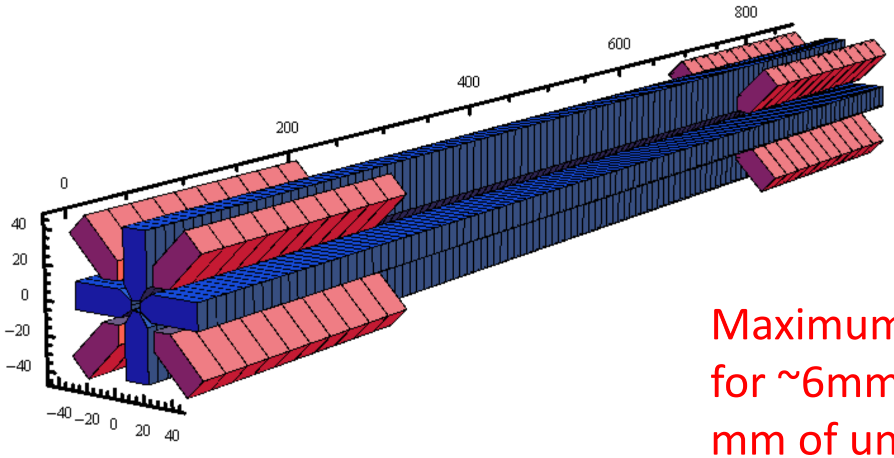
GIT Simulation of Focusing and defocusing quadrupoles alternated

7.8% power efficiency

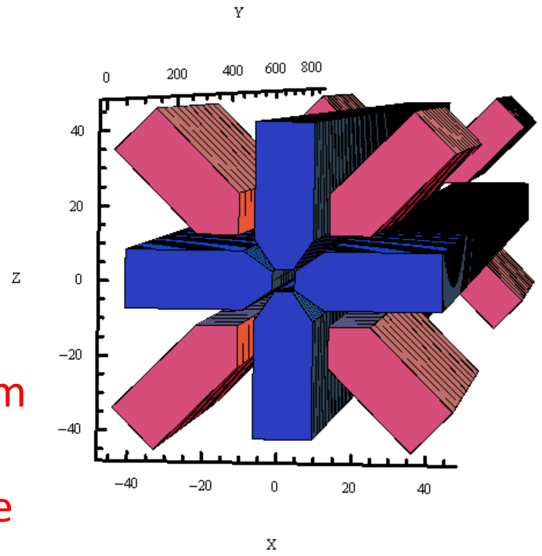


Quads placed around undulator

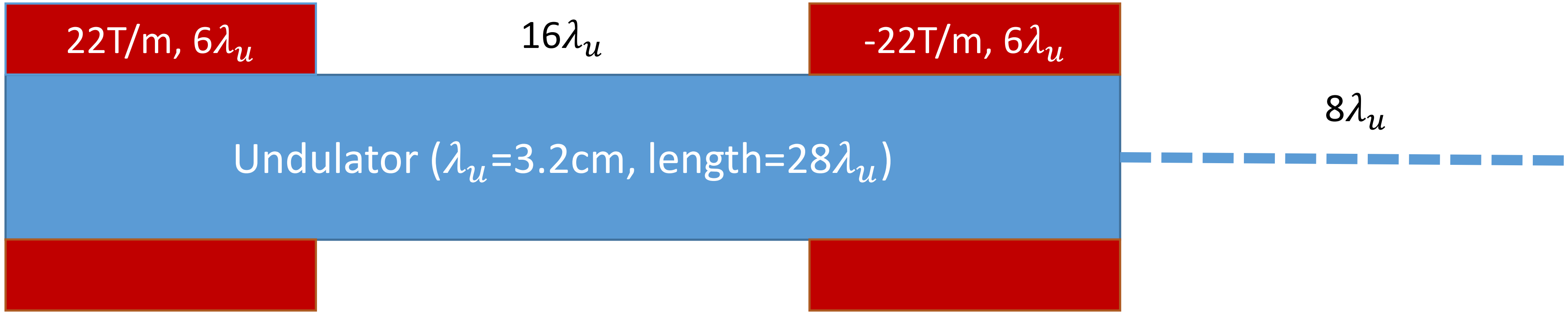




Maximum quad gradient of 22 T/m for ~6mm beam clearance and ~4 mm of undulator holder clearance



Quads placed around undulator



$$M_{u+fq} = \begin{bmatrix} \cos(\sqrt{k_0'}z) & 1/\sqrt{k_0}\sin(\sqrt{k_0'}z) \\ -\sqrt{k_0{}'}\sin(\sqrt{k_0{}'}z) & \cos(\sqrt{k_0{}'}z) \end{bmatrix} \qquad M_{u+dq} = \begin{bmatrix} \cosh(\sqrt{|k_0'|}z) & \frac{1}{\sqrt{|k_0{}'|}}\sinh(\sqrt{|k_0'|}z) \\ \sqrt{|k_0'|}\sinh(\sqrt{|k_0'|}z) & \cosh(\sqrt{|k_0'|}z) \end{bmatrix}$$

$k_0' = k_0 + k_x^2$,

k_0 = focusing strength, k_x = undulator parameter

$$M_{tot} = M_d M_{u+dq} M_u M_{u+fq}$$

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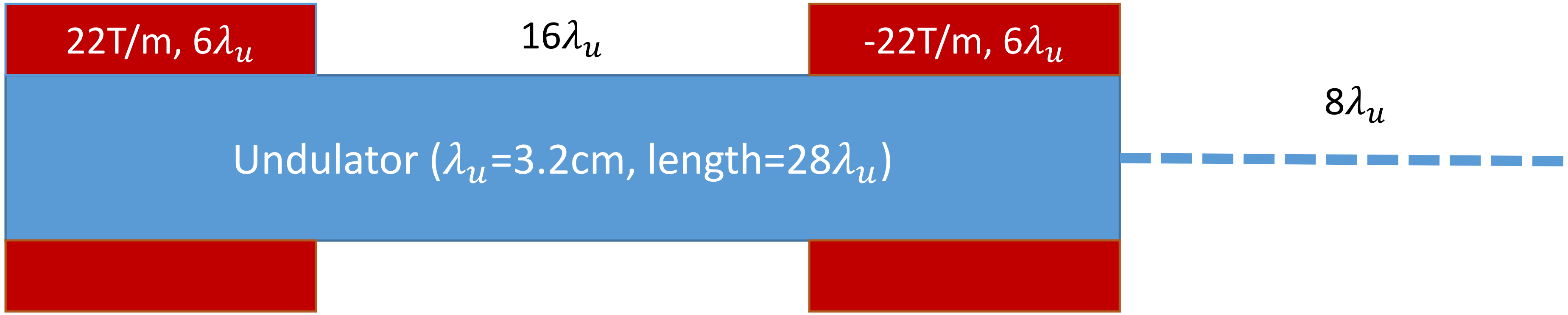
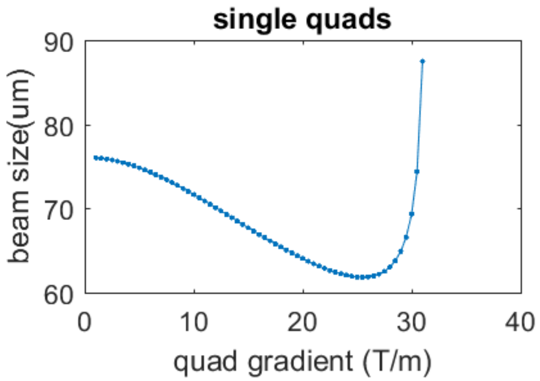
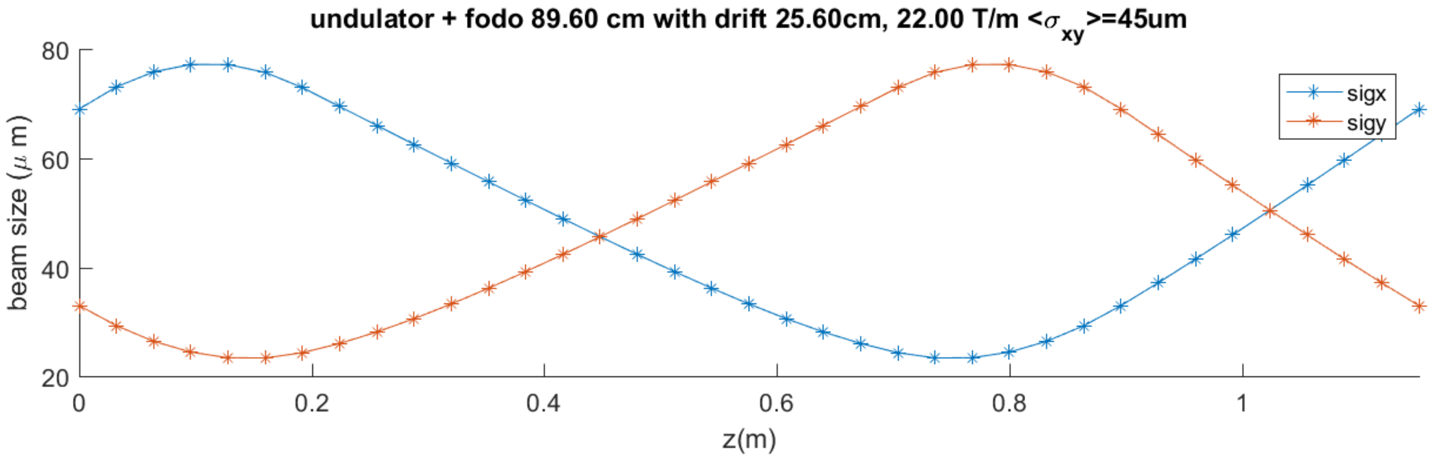
Quads placed around undulator, $< \sigma_x >$=45um

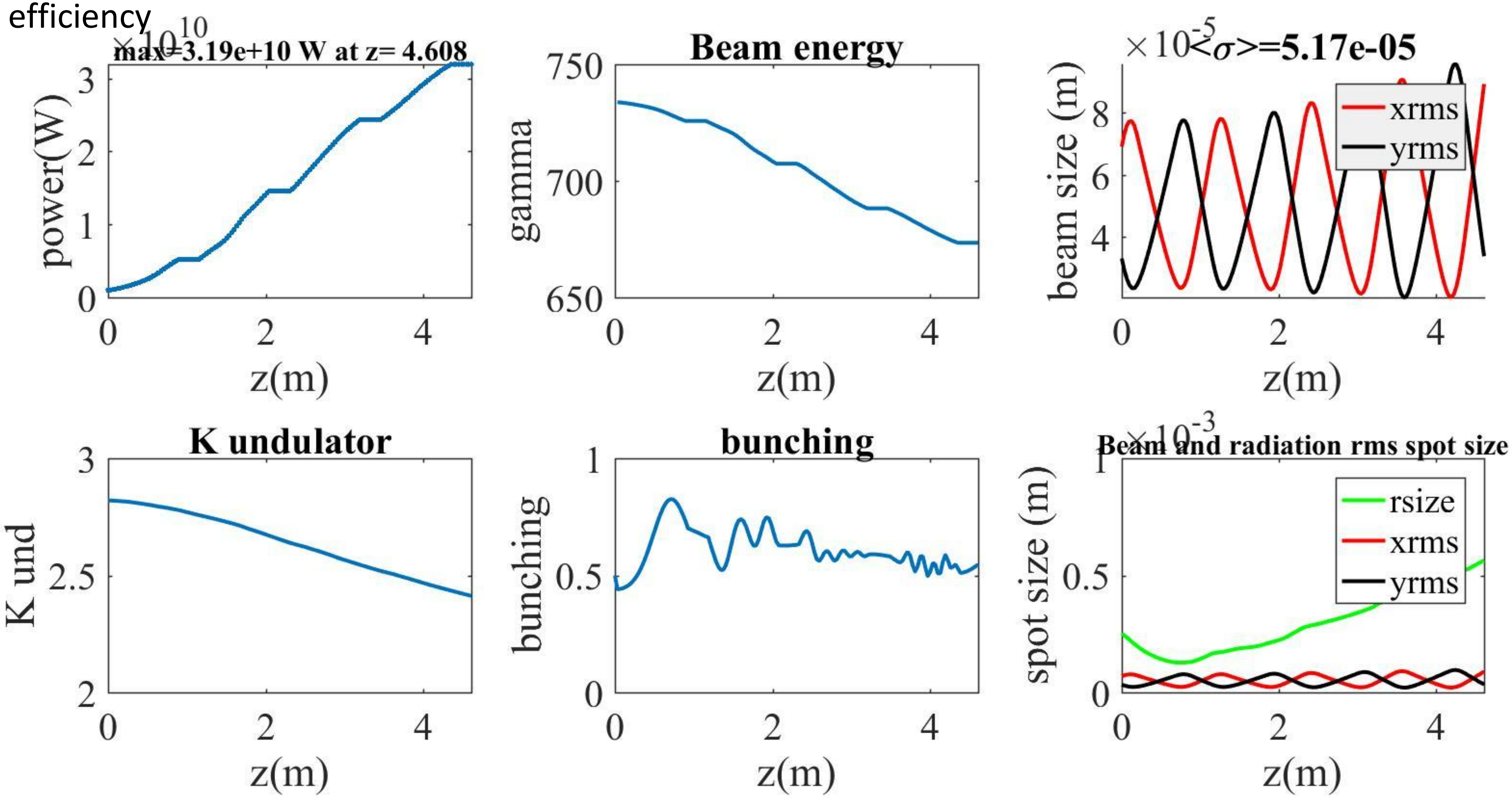




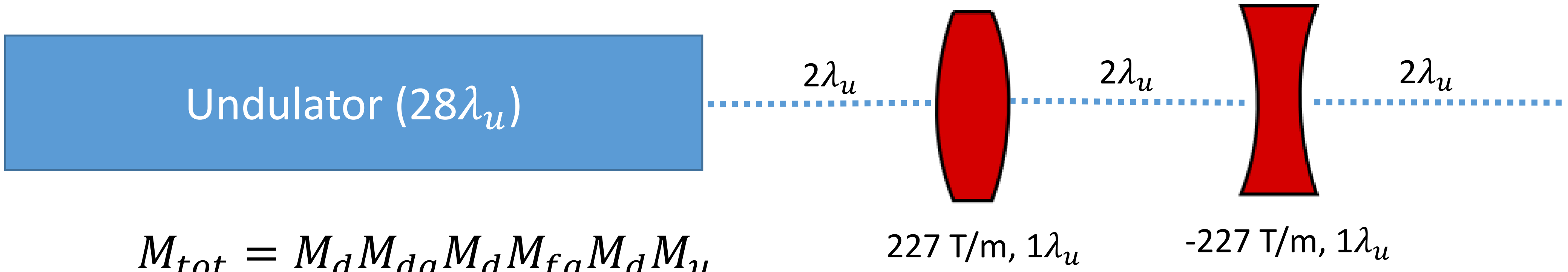


GIT Simulation for quads placed around undulator

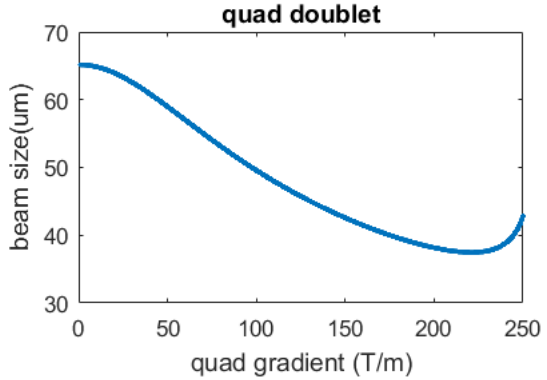
8.5% power efficiency

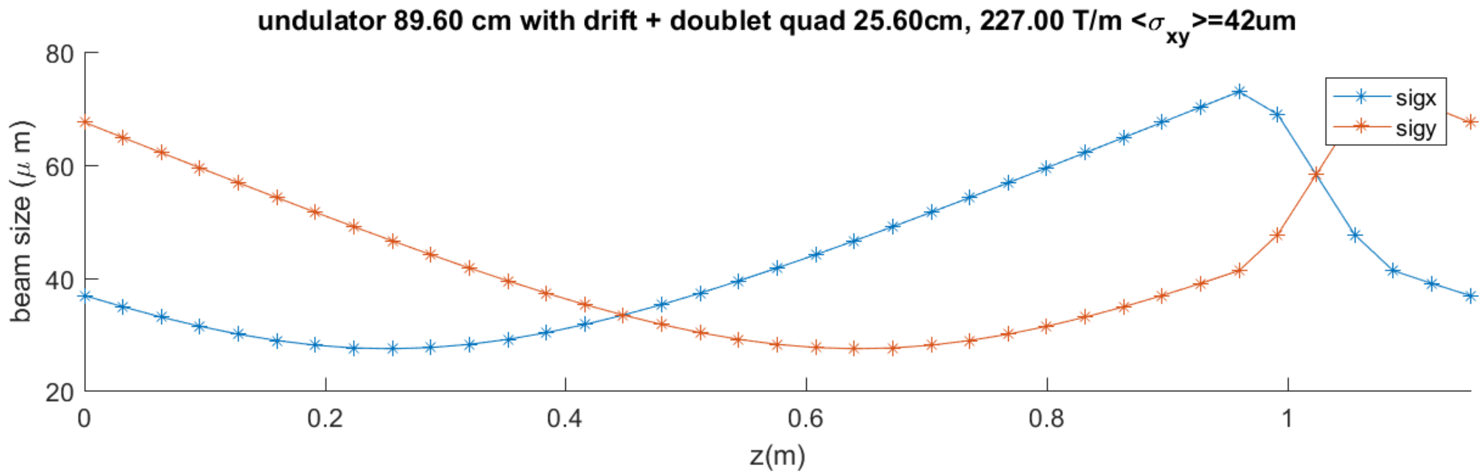


Double quadrupole placed in the drift, $<\sigma_x>$=42um



$$M_{tot} = M_d M_{dq} M_d M_{fq} M_d M_u$$





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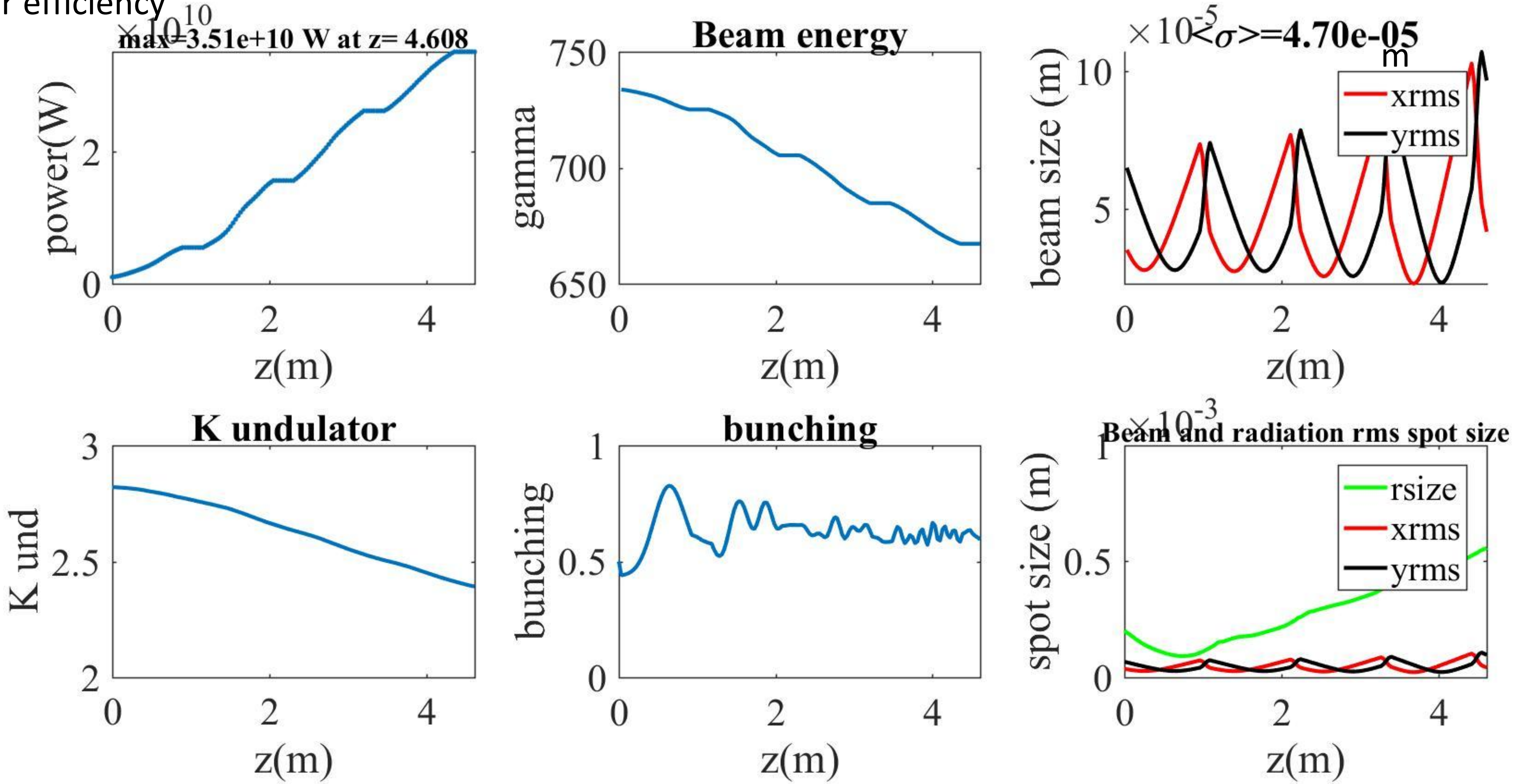
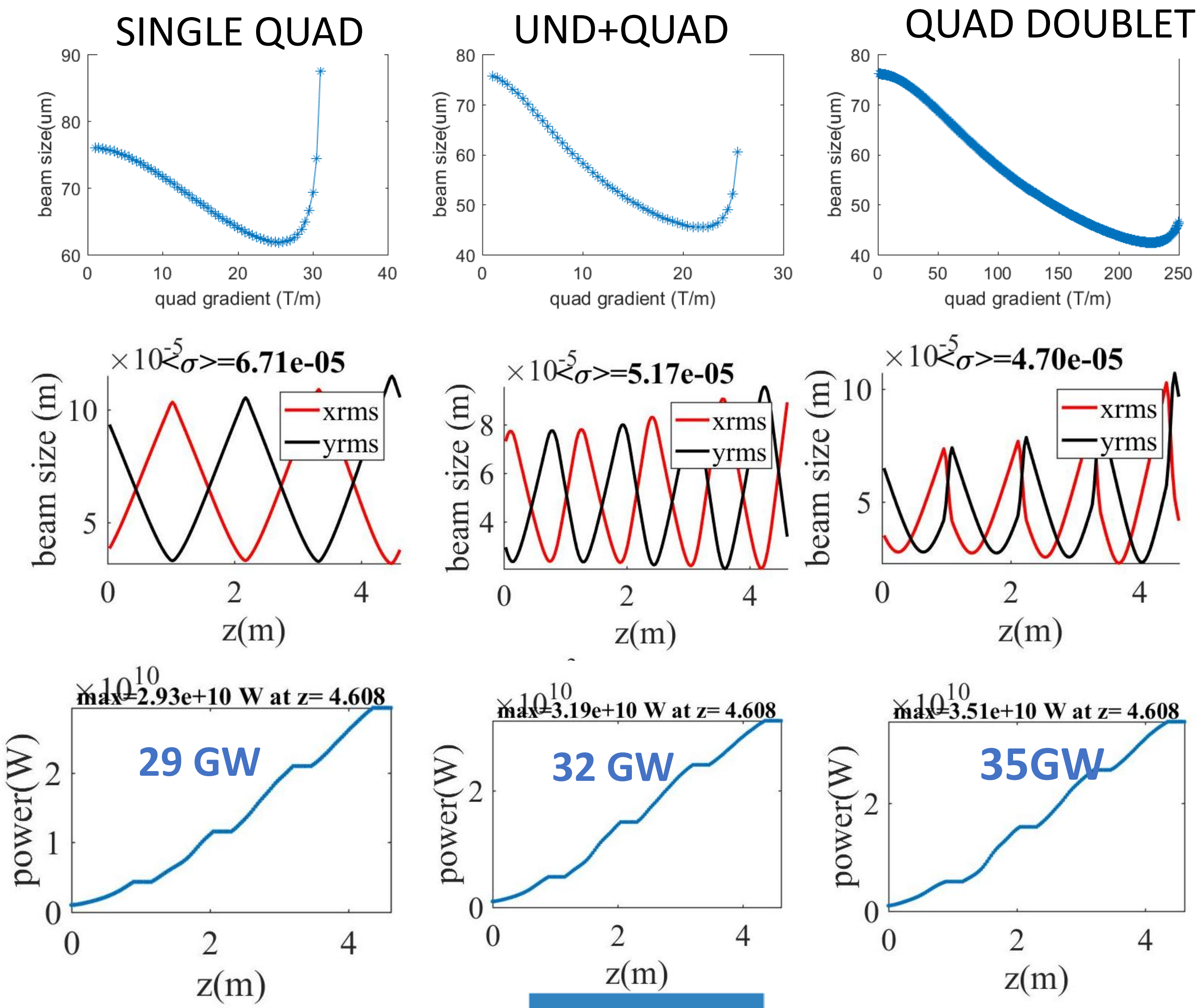
GIT Simulation for double quadrupole placed in the drift

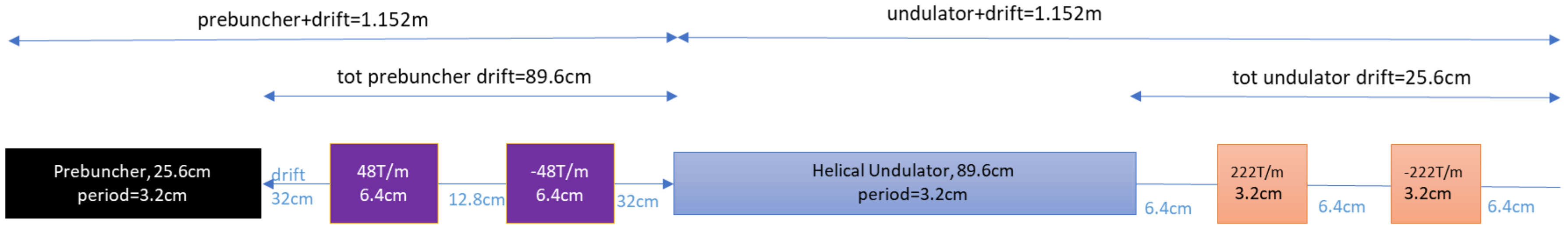
~9.3% Power efficiency



Beam size vs quad gradient for 3 different FODO lattice

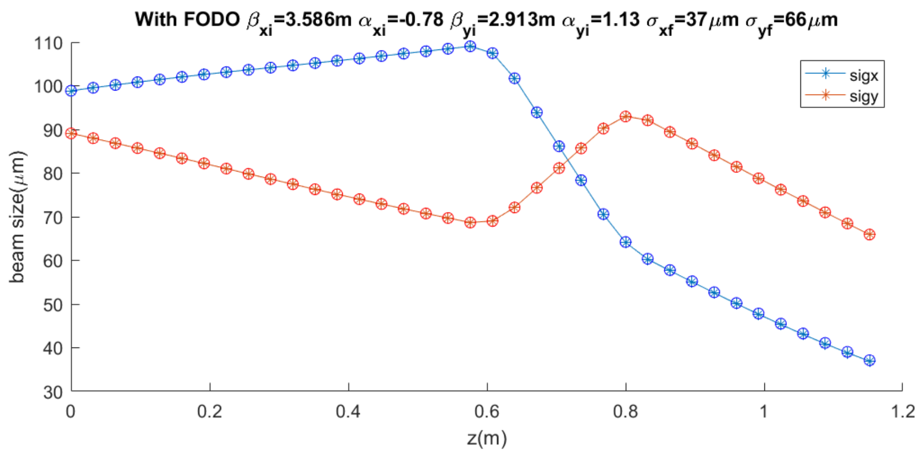


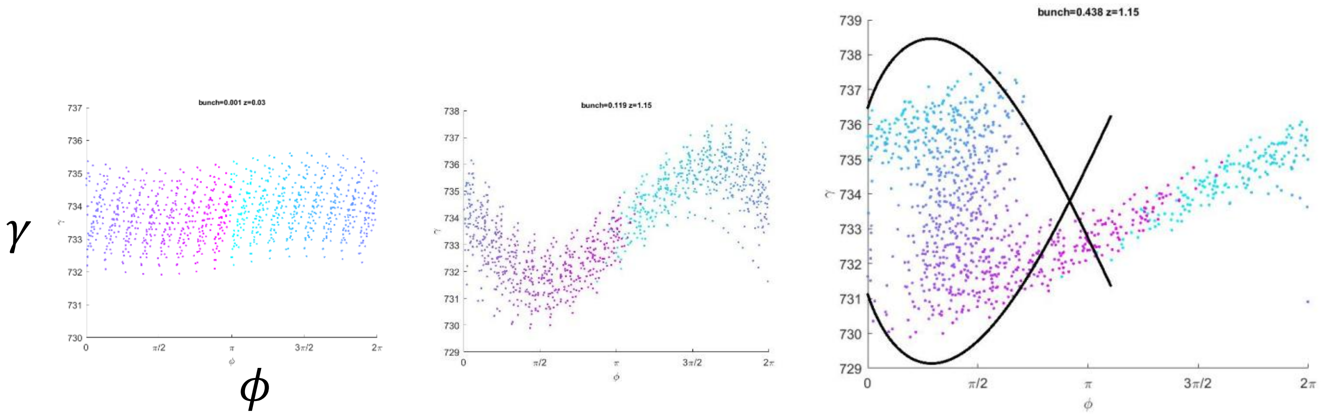
Linac output to undulator



R56buncher=15.1um
phaseshift=0.5

Bunching factor = 0.44

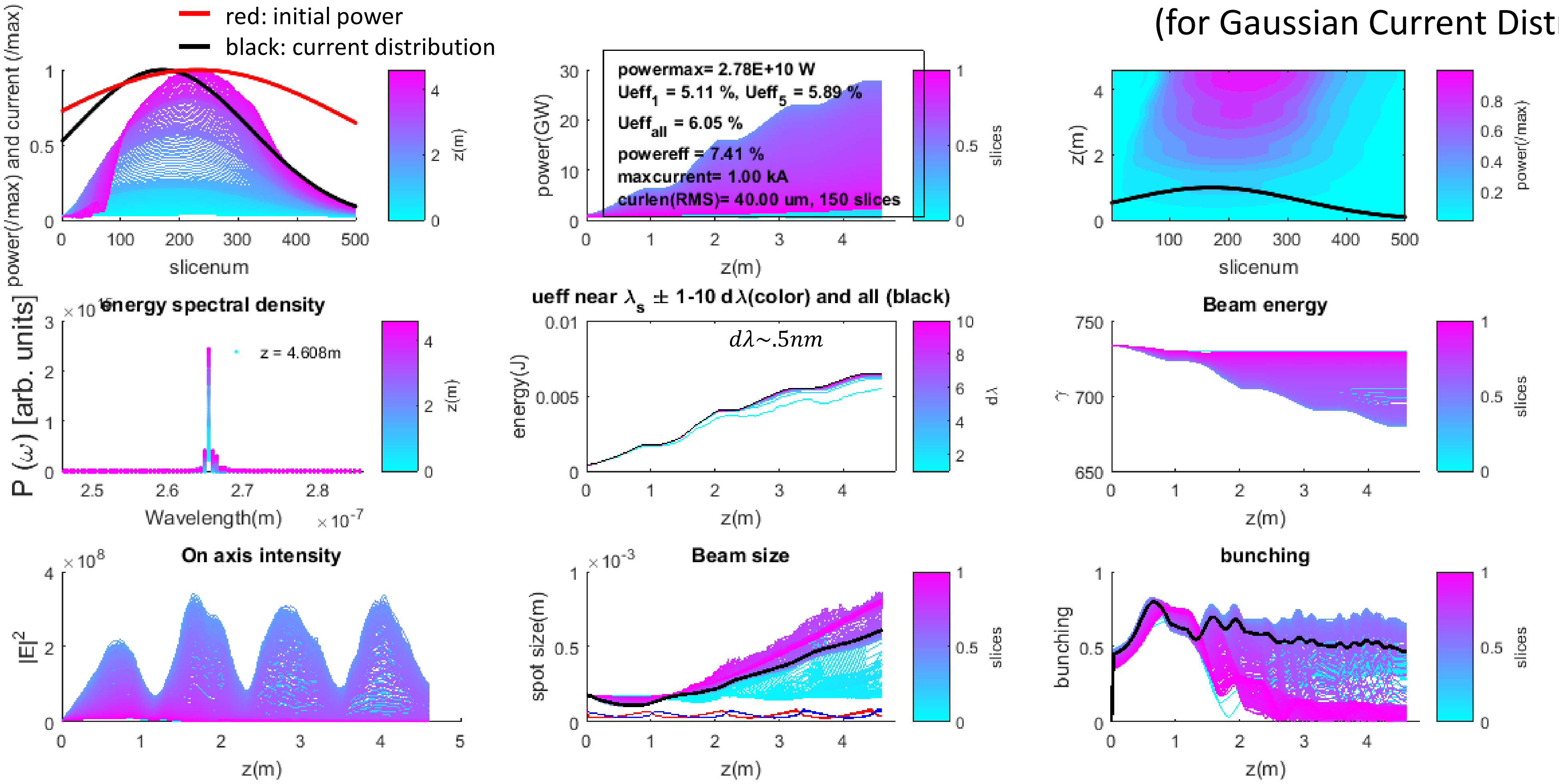




(a) At prebuncher entrance (b) after prebuncher (c) After drift + R56

Time-Dependent Simulation result of TESSA-266, quadrupole doublet

(for Gaussian Current Distribution)



Conclusion

- TESSA-266 is the next step of tapered helical undulator experiment, going from 10um to 266nm.
- In tapered helical undulator, efficiency increases with smaller beam size, need to optimize quadrupole lattice setup
- Three different FODO lattice setup were explored, doublet quads being the best
- The doublet quads setup was also used to match the undulator beam size with the linac

Collaborators:

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Reference

[1] J Duris, A Murokh, and P Musumeci. TESSA. New Journal of Physics, 17(6):063036, 2015.
[2] N. Sudar, P. Musumeci, J. Duris, I. Gadjev, M. Polyanskiy, I. Pogorelsky, M. Fedurin,C. Swinson, K. Kusche, M. Babzien, and A. Gover. High efficiency energy extraction from a relativistic electron beam in a strongly tapered undulator. Phys. Rev. Lett., 117:174801, Oct 2016.
[3] A. Murokh "Challenges and opportunities for an industrial EUV FEL", contributed talk, 2015 EUV Lithography Symposium, October 5-7, 2015, Maastricht, Netherlands