Parameter study for superradiance and SASE FEL at PITZ

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Estimation of superradiance energy

The spectrum density from a single electron passing an undulator is given by [1]

$$\frac{d^2U_m}{d\Omega d\omega} = \frac{e^2\gamma^2m^2K^2}{4\pi\epsilon_0 c(1+K^2/2)^2} \times \frac{\sin^2(\pi N_u(\omega-\omega_m)/\omega_1)}{\sin^2(\pi(\omega-\omega_m)/\omega_1)} \times |JJ|^2$$

$$JJ = J_n\left(\frac{mK^2}{4+2K^2}\right) - J_{n+1}\left(\frac{mK^2}{4+2K^2}\right), m = 2n+1$$

The width of the spectrum is related to the radiation frequency by

$$\frac{\Delta\omega_m}{\omega_m} = \frac{1}{mN_u}$$

The radiation angle is related to the energy of the electron by

$$\Delta\Omega_m = \frac{2\pi}{\gamma^2}\frac{1+K^2/2}{2mN_u}$$

The total energy of the radiation is

$$U_m(\omega) = \frac{d^2U_m}{d\Omega d\omega}\Delta\Omega_m\Delta\omega_m$$

For the fundamental mode, the radiation from a bunch of N electrons has the total energy of

$$U_\omega = U_0[N + N(N-1)g^2(\sigma_z)]$$

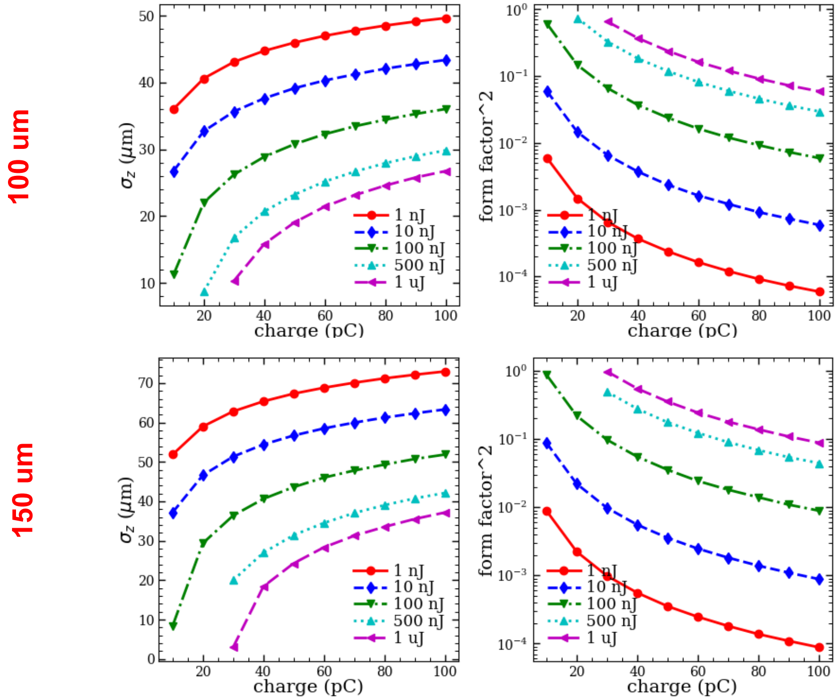
Assuming a Gaussian distribution, the form factor is given by

$$g^2(\sigma_z) = e^{-4\pi^2\sigma_z^2/\lambda_s^2}$$

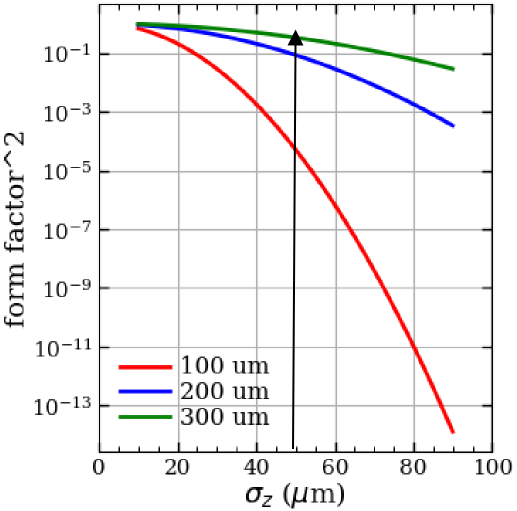
[1] Peter Schmüser, Martin Dohlus, Jörg Rossbach, Chapter 2, Undulator Radiation, **Ultraviolet and Soft X-Ray Free-Electron Lasers, Introduction to Physical Principles, Experimental Results**, Technological Challenges. Springer-Verlag, 2007

Estimation of superradiance energy

- To obtain certain energy, the corresponding bunch length for various charges



Form factor vs bunch length



$$E \propto N + N(N-1)f^2(\sigma_z, \lambda_s)$$

$g^2(\sigma_z) = e^{-4\pi^2\sigma_z^2/\lambda_s^2}$ for Gaussian profile

N number of electrons

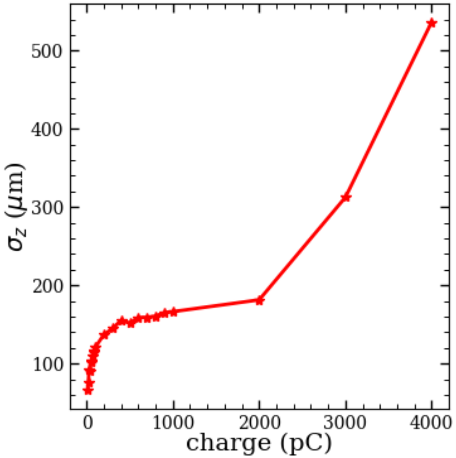
σ_z RMS bunch length

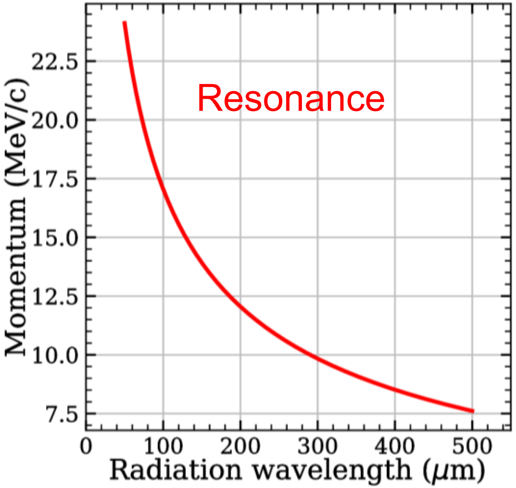
λ_s resonant wavelength

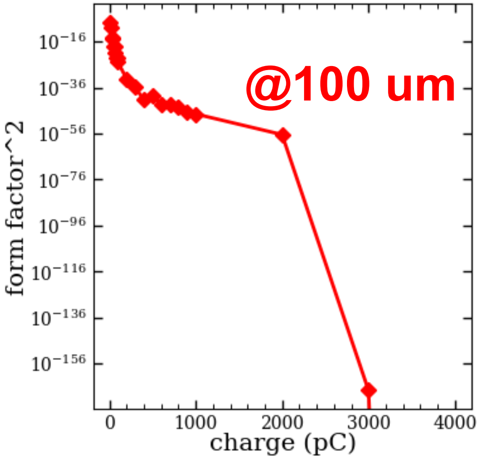
- To get even only **1 nJ at 100 um**, the bunch length needs to be ~**50 um RMS**

Estimation of superradiance energy

- Using the shortest RMS bunch length Anusorn has achieved in his simulations, the radiation energy and form factor are calculated
- The radiation energy is **linearly depending** on the bunch charge, because of the very small form factor, thus no coherent radiation; the radiation energy is also quite small





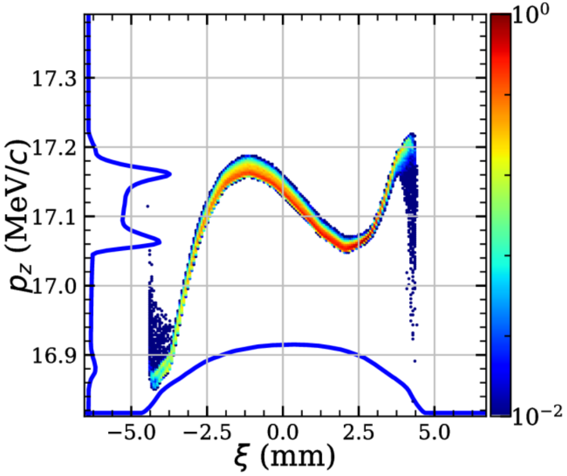


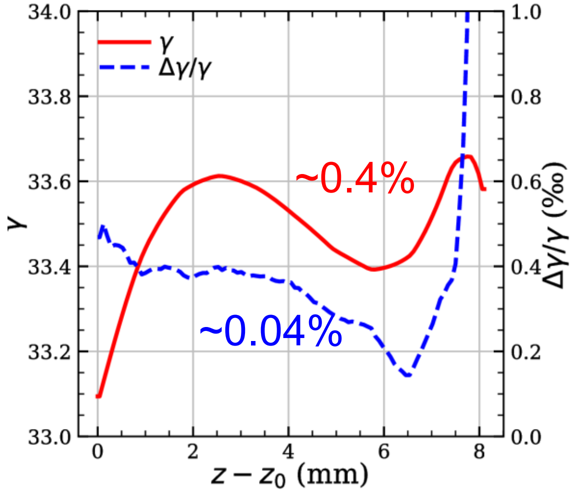
- Besides refining the compression, we may also consider the resonance at a much longer wavelength (maybe sub-THz), in order to get more and measurable radiation

Parameter scan for THz SASE FEL

Norm. emittance: 4 um
Tran. phase space: matched
Long. Dist.: Flattop/Gaussian
Correlated energy spread: 0.5%
Slice energy spread: 0.05%

Scan parameters:
- Bunch charge from 1 nC to 5 nC
- Peak current from 100 A to 500 A





Longitudinal phase space from S2E simulation with Astra

Parameter scan for THz SASE FEL

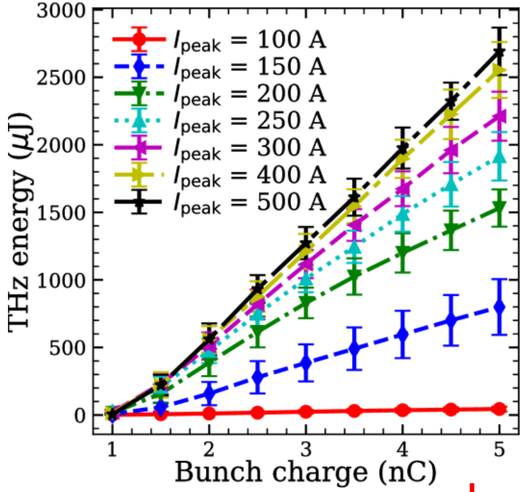
Norm. emittance: 4 um
Tran. phase space: matched
Long. Dist.: Flattop/Gaussian
Correlated energy spread: 0.5%
Slice energy spread: 0.05%

Scan parameters:
Bunch charge from 1 nC to 5 nC
Peak current from 100 A to 500 A

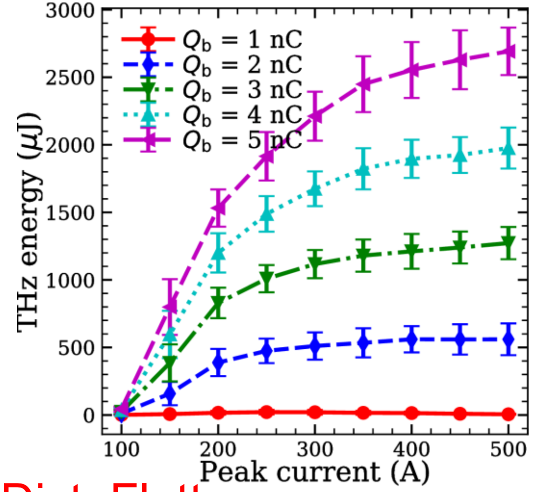
By Genesis 1.3

- **Efficiency or ρ depends on peak current;**
- **Radiation energy $\propto$ e^- beam energy or charge**

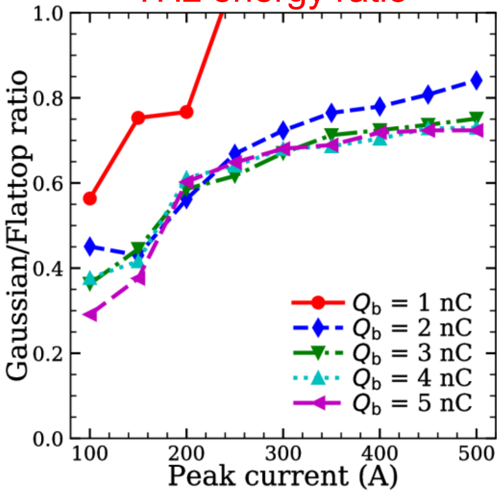
THz energy vs Charge



THz energy vs Current



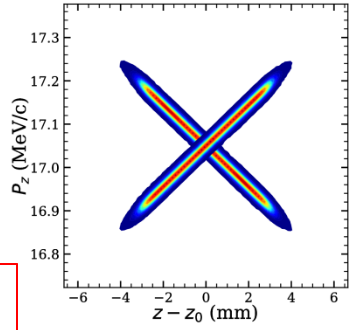
THz energy ratio



Long. Dist: Flattop

Parameter scan for THz SASE FEL

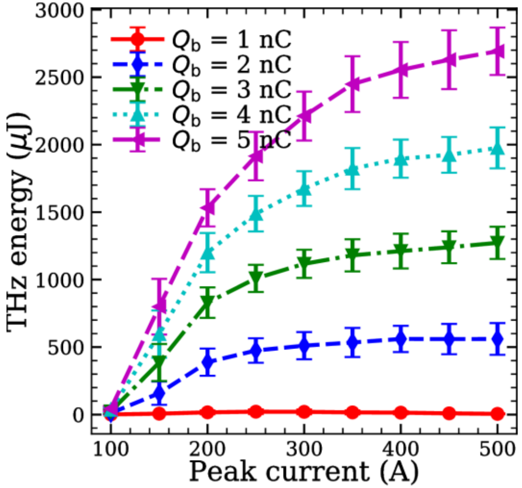
Long. phase space



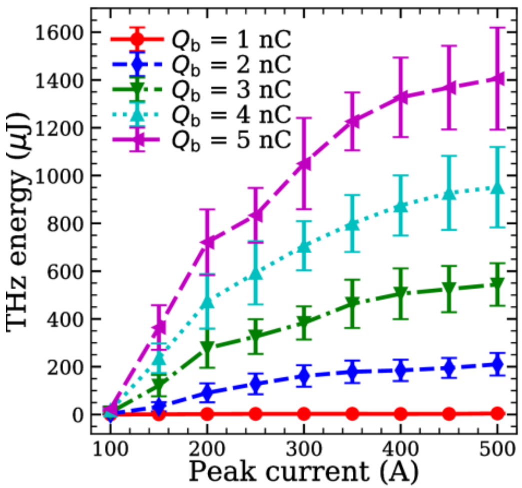
Norm. emittance: 4 um
Tran. phase space: matched
Long. Dist.: Flattop
Correlated energy spread: +/-0.5%
Slice energy spread: 0.05%

Scan parameters:
- Bunch charge from 1 nC to 5 nC
- Peak current from 100 A to 500 A

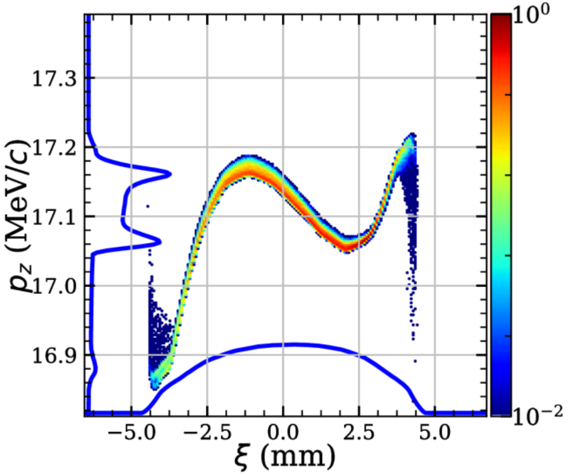
- **A positive energy chirp can almost double the radiation energy**



Positive chirp

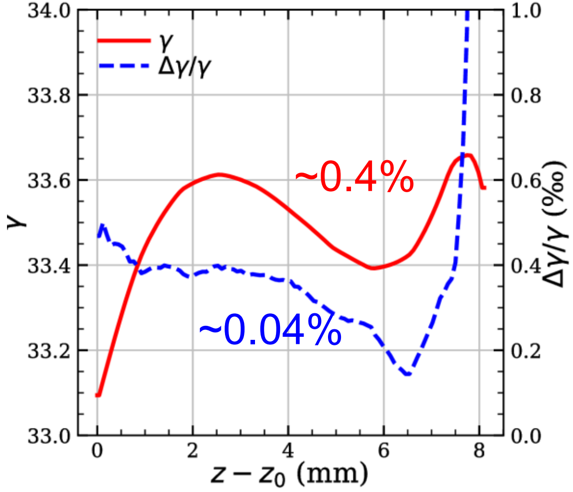


Negative chirp



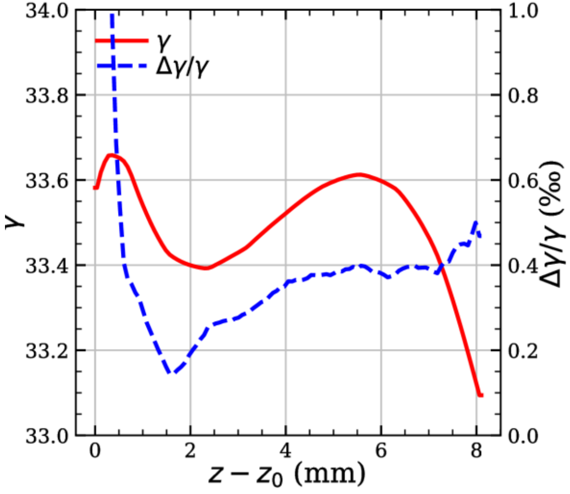
Long. Phase from S2E simul.

Parameter scan for THz SASE FEL



Dist. from S2E simulation

Flipped dist.

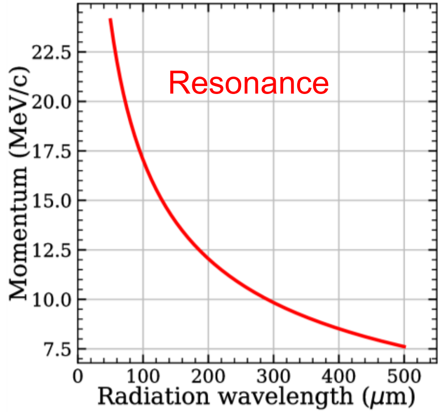


Parameter	Normal dist.	Flipped dist.	Unit
Pulse energy	**493.1±108.8**	**709.1±140.5**	**μJ**
Centre wavelength	**101.8±0.7**	**103.4±0.7**	**μm**
Spectrum width	**2.0±0.4**	**2.5±0.6**	**μm**
Arrival time jitter	**1.5**	**1.1**	**ps**

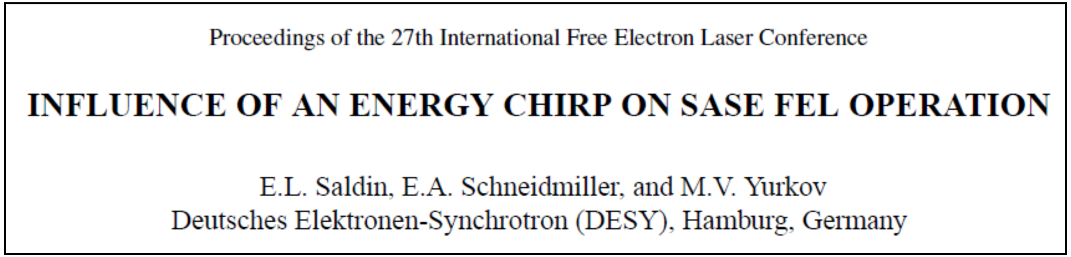
- THz energy increased by 44%

Summary

- For superradiance
  - Shorter bunch length + long / sub-THz radiation wavelength



- For SASE FEL
  - Peak current beyond 200-300 A (depending on the bunch charge) doesn't improve the SASE performance
  - The energy chirp is worth to be investigated further to maximum the THz output



Proceedings of the 27th International Free Electron Laser Conference

INFLUENCE OF AN ENERGY CHIRP ON SASE FEL OPERATION

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Dynamical effects on superradiant THz emission from an undulator

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