Progress of a Superradiant THz FEL source at the PITZ facility

Natthawut Chaisueb,

PPS meeting, DESY, Zeuthen

Outline of the Talk

1 PITZ beamline

2 Tunable THz source at PITZ

3 Angular flux density of undulator radiation

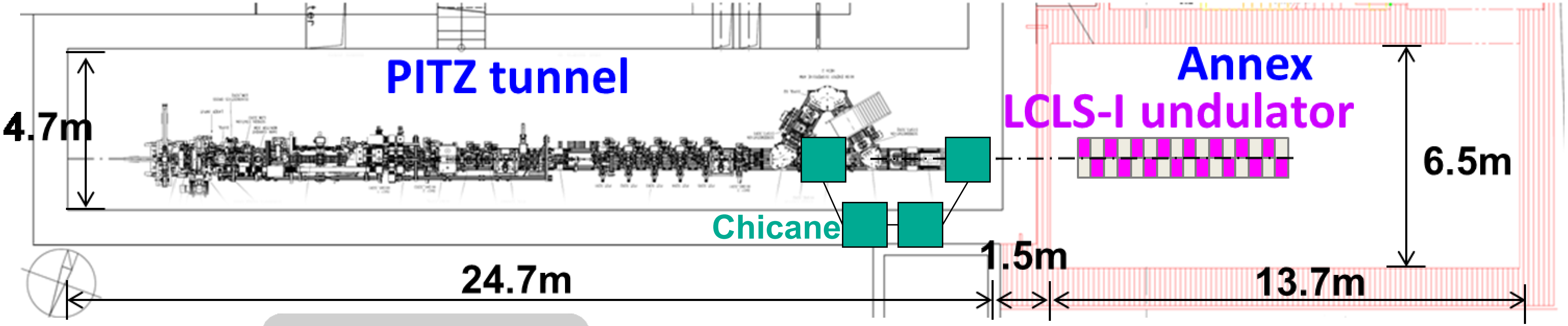
4 Benchmark of SPECTRA and theory

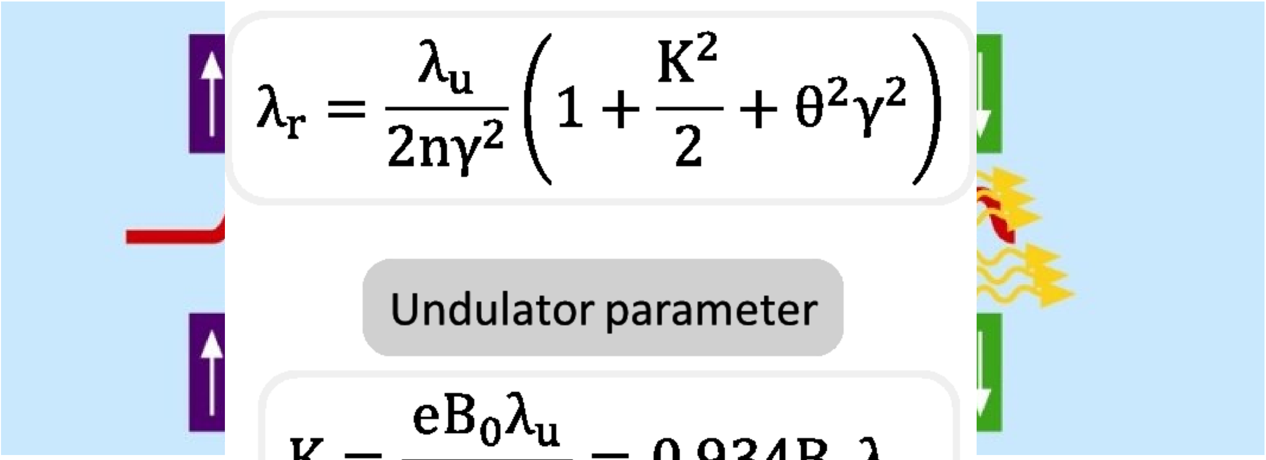
5 Bunch length VS bunch charge

6 Energy spread VS bunch charge

PITZ beamline

LCLS-I undulator





Radiation wavelength

$$\lambda_r = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

Undulator parameter

$$K = \frac{eB_0\lambda_u}{2\pi m_e c} = 0.934 B_0 \lambda_u$$

Properties	LCLS undulator
Type	planar
K-value	3.58
Undulator length	3.42 m
Vacuum chamber size	11 mm x 5 mm
Magnetic field	1.28 T
Period length	30 mm

Tunable THz source at PITZ

Beam energy and harmonic number

$$\lambda_r = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \theta^2\gamma^2\right)$$

Harmonic number: 1, 3, 5,…

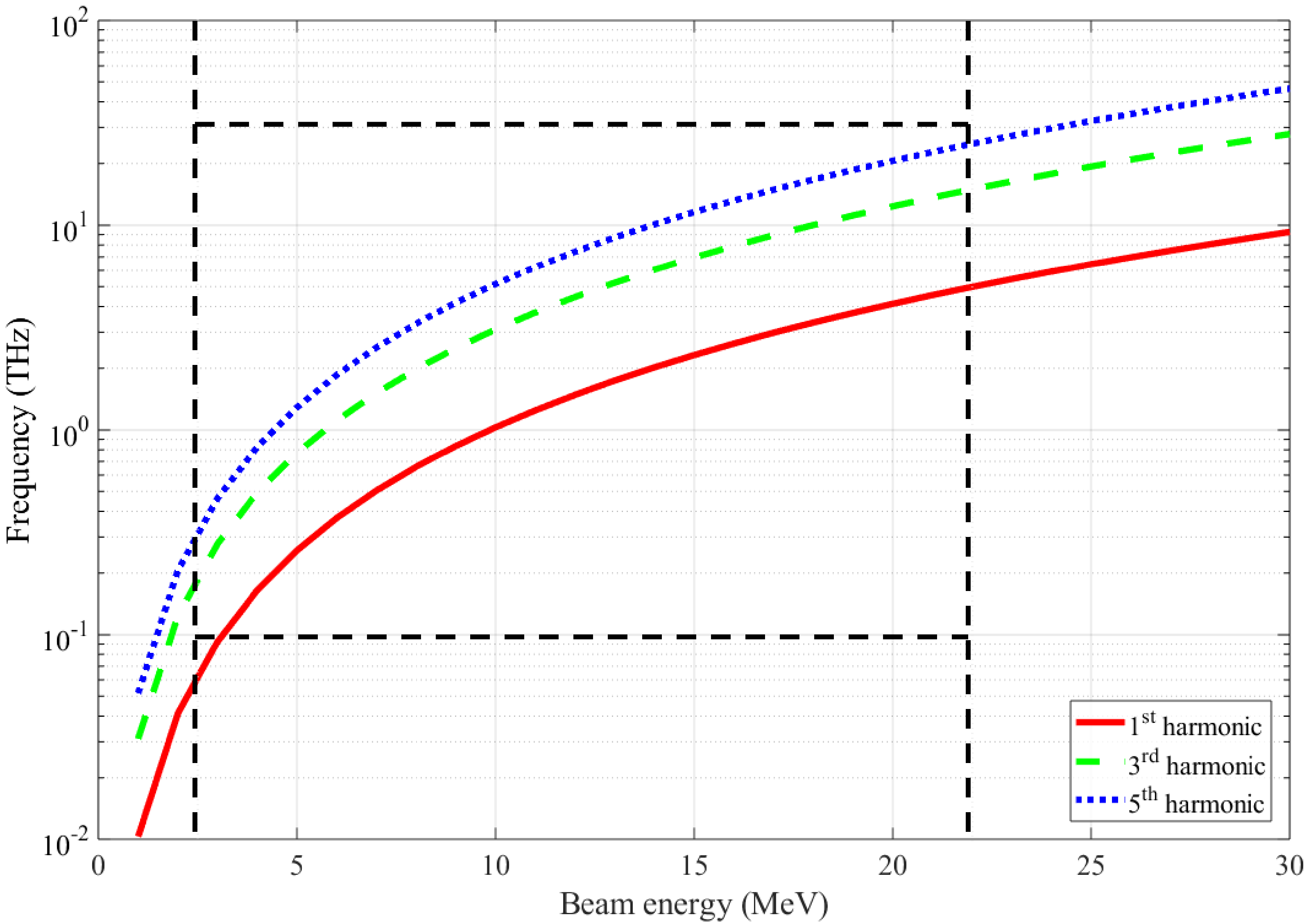
Beam energy at PITZ: 2.5 – 22 MeV

THz range: 0.1 – 30 THz

1st harmonic: 0.1 – 5 THz (3 – 22 MeV)

3rd harmonic: 0.2 – 15 THz

5th harmonic: 0.3 – 25 THz



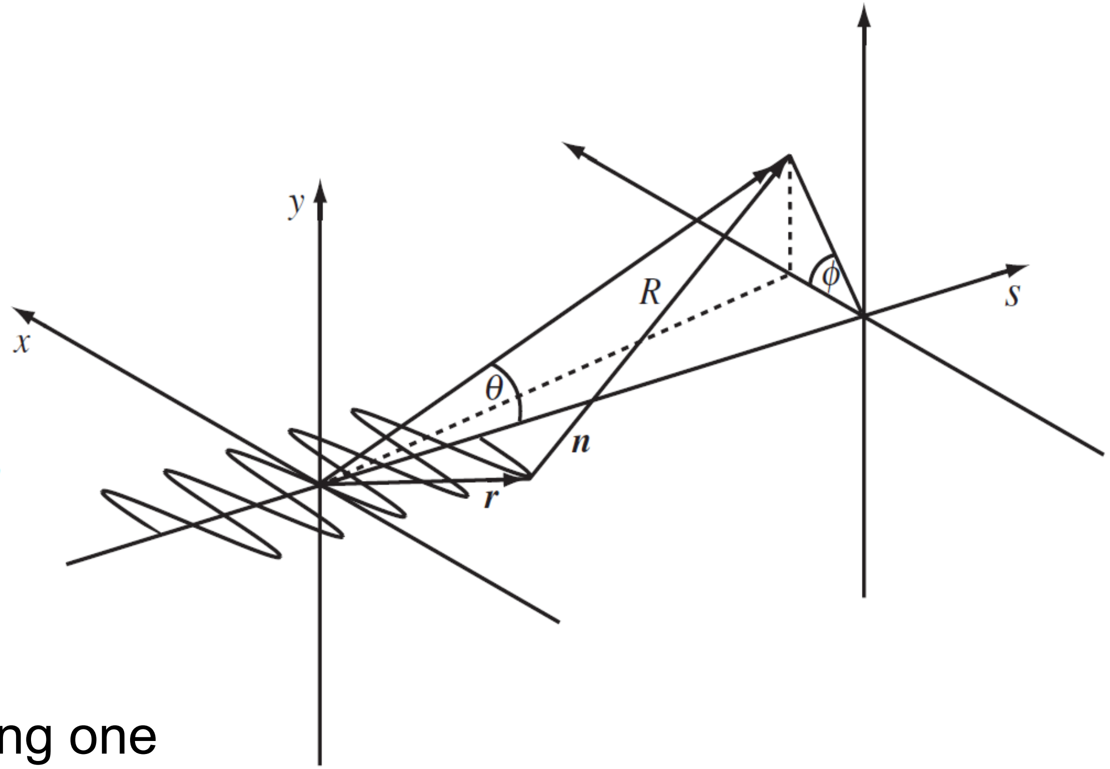
Angular flux density of undulator radiation

The Poynting vector gives the energy flow per unit area per unit time.

$$\boldsymbol{S} = \frac{1}{\mu_0}(\boldsymbol{E} \times \boldsymbol{B}) = \epsilon_0 c^2 (\boldsymbol{E} \times \boldsymbol{B}) = \epsilon_0 c E^2 \boldsymbol{n} = \frac{\boldsymbol{d^2W}}{\boldsymbol{dAdt}}$$

$$\text{A solid angle} = \boldsymbol{d\Omega} = \frac{\boldsymbol{dA}}{\boldsymbol{R^2}}$$

$$\text{Fourier transform } E(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E(\omega) e^{-i\omega t} \, d\omega$$



The spectral angular energy radiated by an electron during one passage through the undulator.

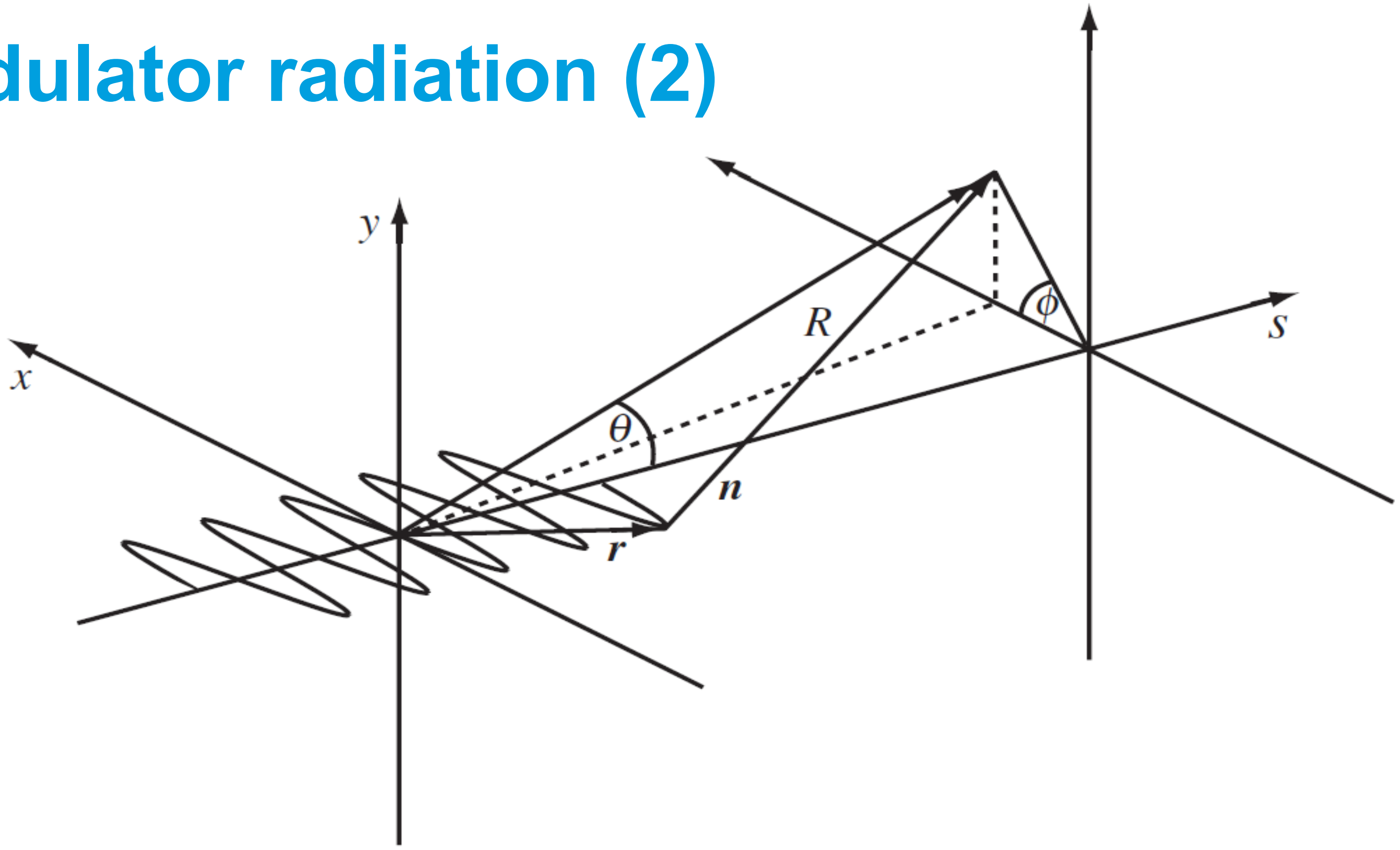
$$\frac{d^2W}{d\Omega d\omega} = 2\varepsilon_0 c R^2 \left|E(\omega)\right|^2$$

R is the displacement from the radiated point to the observer

Angular flux density of undulator radiation (2)

The spectral angular energy

$$\frac{d^2W}{d\Omega d\omega} = 2\varepsilon_0 c R^2 \left|E(\omega)\right|^2$$



- On axis undulator radiation:
  - θ=0 and Φ=0
  - Only odd harmonics: 1, 3, 5,…
  - Horizontal polarization
- Planar undulator has only a verticle magnetic field.
- Far field approximation: *R* >>> *r,* the observation angle is kept constant.

The spectral angular energy on-axis for a single electron

$$\left.\frac{d^2W}{d\Omega\, d\omega}\right|_{\theta=0} = \frac{e^2 N^2 \gamma^2}{4\pi\epsilon_0 c} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K)$$

Angular flux density of undulator radiation (3)

The spectral angular energy on-axis
for a single electron

$$\left.\frac{d^2W}{d\Omega\, d\omega}\right|_{\theta=0} = \frac{e^2N^2\gamma^2}{4\pi\epsilon_0 c} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K)$$

The lineshape function

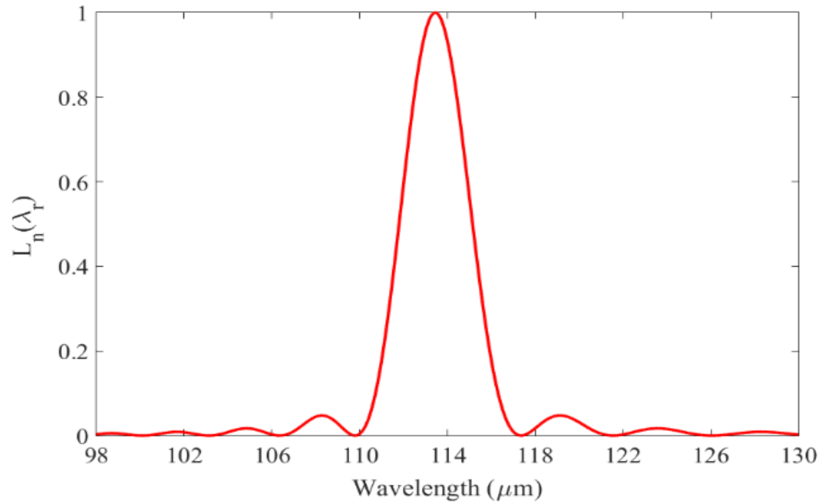
$$L\left(\frac{N\Delta\omega}{\omega_1}\right) = \left[\frac{\sin\left(N_u \pi\Delta\omega/\omega_1\right)}{N_u \sin\left(\pi\Delta\omega/\omega_1\right)}\right]^2$$

- The interference of the radiated wave from the undulator magnet with N periods
- It is proportional to the spectral intensity.

The multiplicative factor

$$F_n = \left(J_{(n+1)/2}(Z) - J_{(n-1)/2}(Z)\right)^2$$

It is related with the radiated power transferred from the fundamental harmonic to the higher harmonics.



characteristics of the lineshape function for the first harmonic.

Angular flux density of undulator radiation (4)

The spectral angular energy on-axis
for a single electron

$$\left.\frac{d^2W}{d\Omega\, d\omega}\right|_{\theta=0} = \frac{e^2N^2\gamma^2}{4\pi\epsilon_0 c} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K)$$

$$\left.\frac{d^2W}{d\Omega\, d\omega}\right|_{\theta=0} \xrightarrow{\times \frac{N_e}{t}} \left.\frac{d^2P}{d\Omega\, d\omega}\right|_{\theta=0} \xrightarrow{P\, =\, \hbar\omega\dot{N}} \left.\frac{d^2\dot{N}}{d\Omega\, d\omega/\omega}\right|_{\theta=0}$$

The angular flux density on-axis [photons/s/mrad^2/0.1%BW]

$$\left.\frac{d\dot{N}}{d\Omega}\right|_{\theta=0} = \frac{e^2N^2\gamma^2}{4\pi\epsilon_0 c}\frac{I_b}{e}\frac{2\pi}{h} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K)\,\frac{\Delta\omega}{\omega}$$

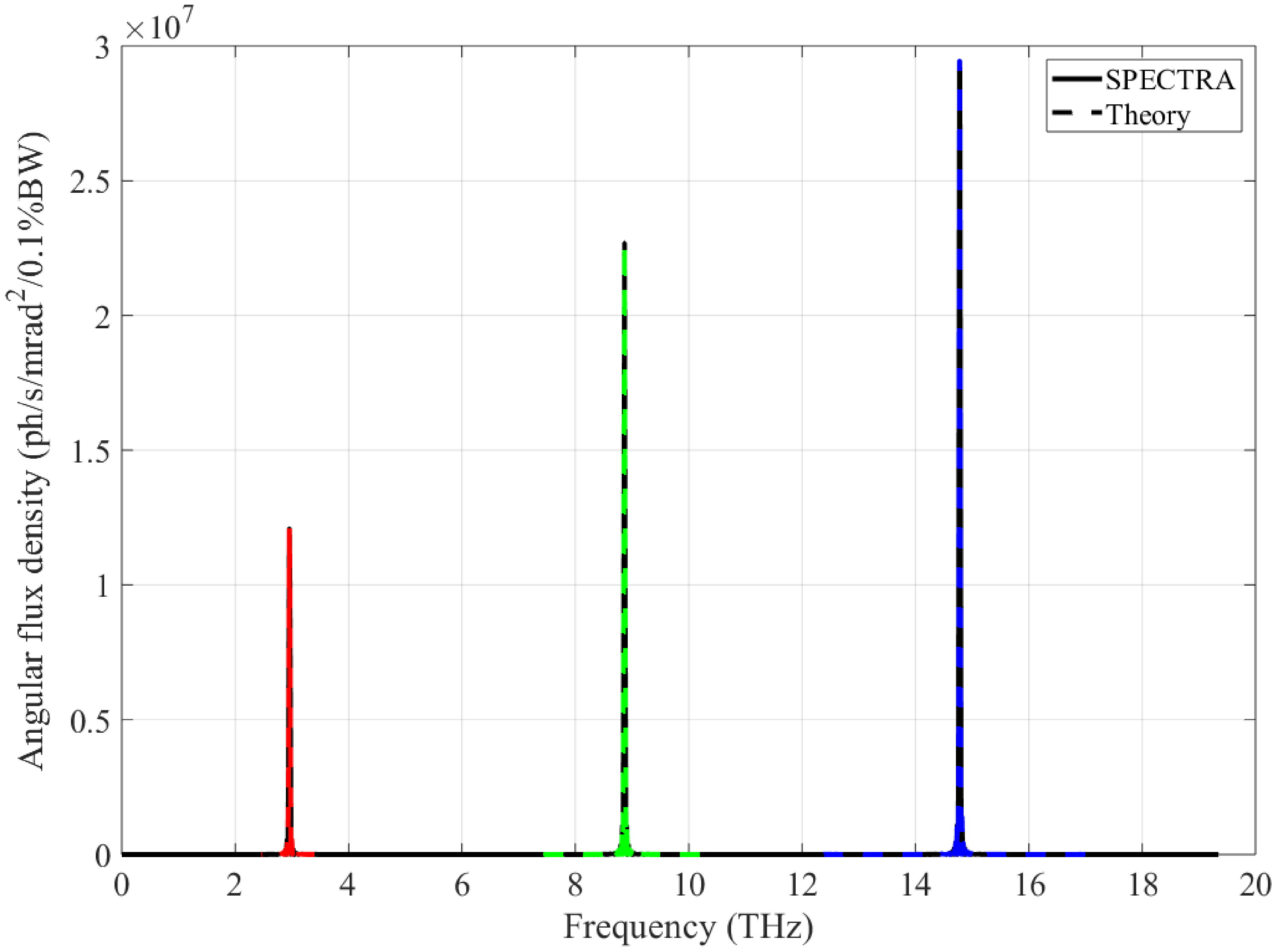
SPECTRA program

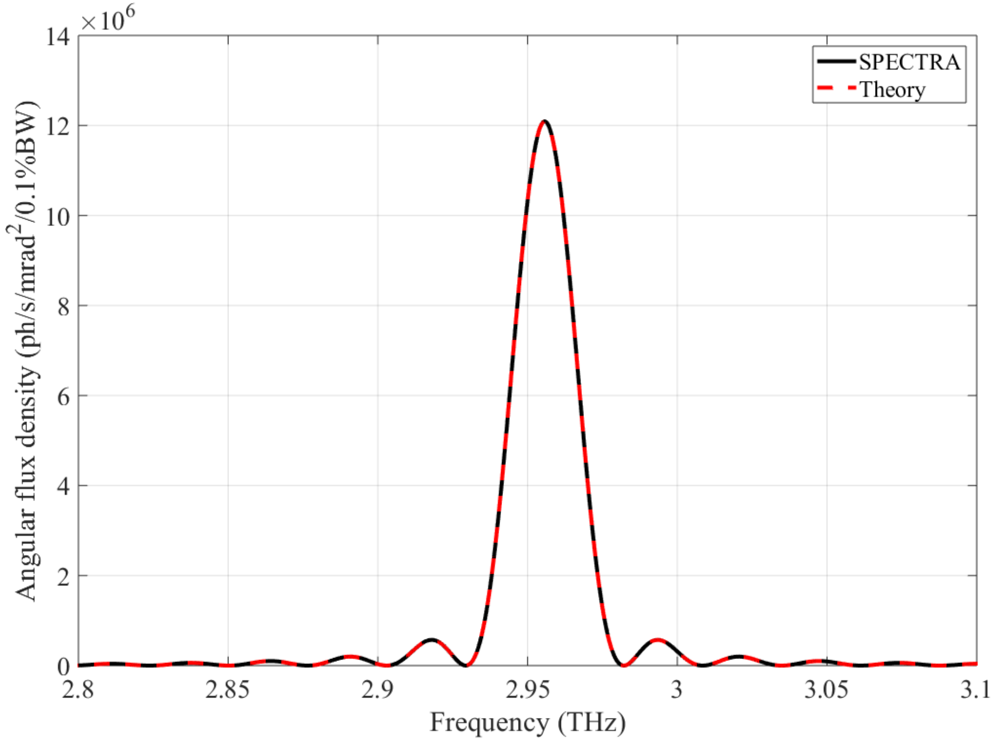
- Optical properties of synchrotron radiation
- Various filters and convolution of detector’s resolution
- Energy spread and finite emittance of the electron beam
- Rectangular, circular or doughnut-shaped apertures

[1] James A Clarke, The Science and Technology of Undulators and Wigglers

Benchmark of SPECTRA and theory

Angular flux density of first three harmonics





Pulse energy

Superradiant undulator radiation

The spectral angular energy on-axis for a single electron

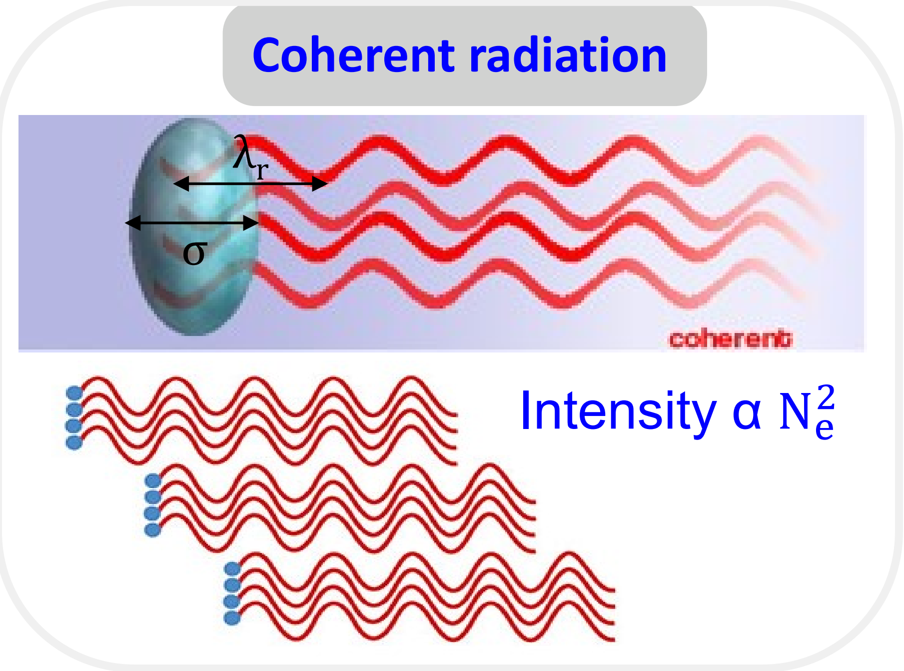
$$\left.\frac{d^2W}{d\Omega\, d\omega}\right|_{\theta=0} = \frac{e^2N^2\gamma^2}{4\pi\epsilon_0 c} L\left(\frac{N\Delta\omega}{\omega_1}\right) F_n(K)$$

Radiation energy of a single electron

$$W_{1e} = \frac{d^2W}{d\Omega d\omega}\Delta\Omega\Delta\omega$$

Solid angle = $\Delta\Omega = \frac{2\pi}{\gamma^2}\frac{1+K^2/2}{2nN_u}$

Fractional bandwidth = $\frac{\Delta\omega}{\omega} = \frac{1}{nN_u}$



Pulse energy of an electron bunch

$$W_{tot} = W_{1e}N_e\left[1+\left(N_e-1\right)f(\omega)\right]$$

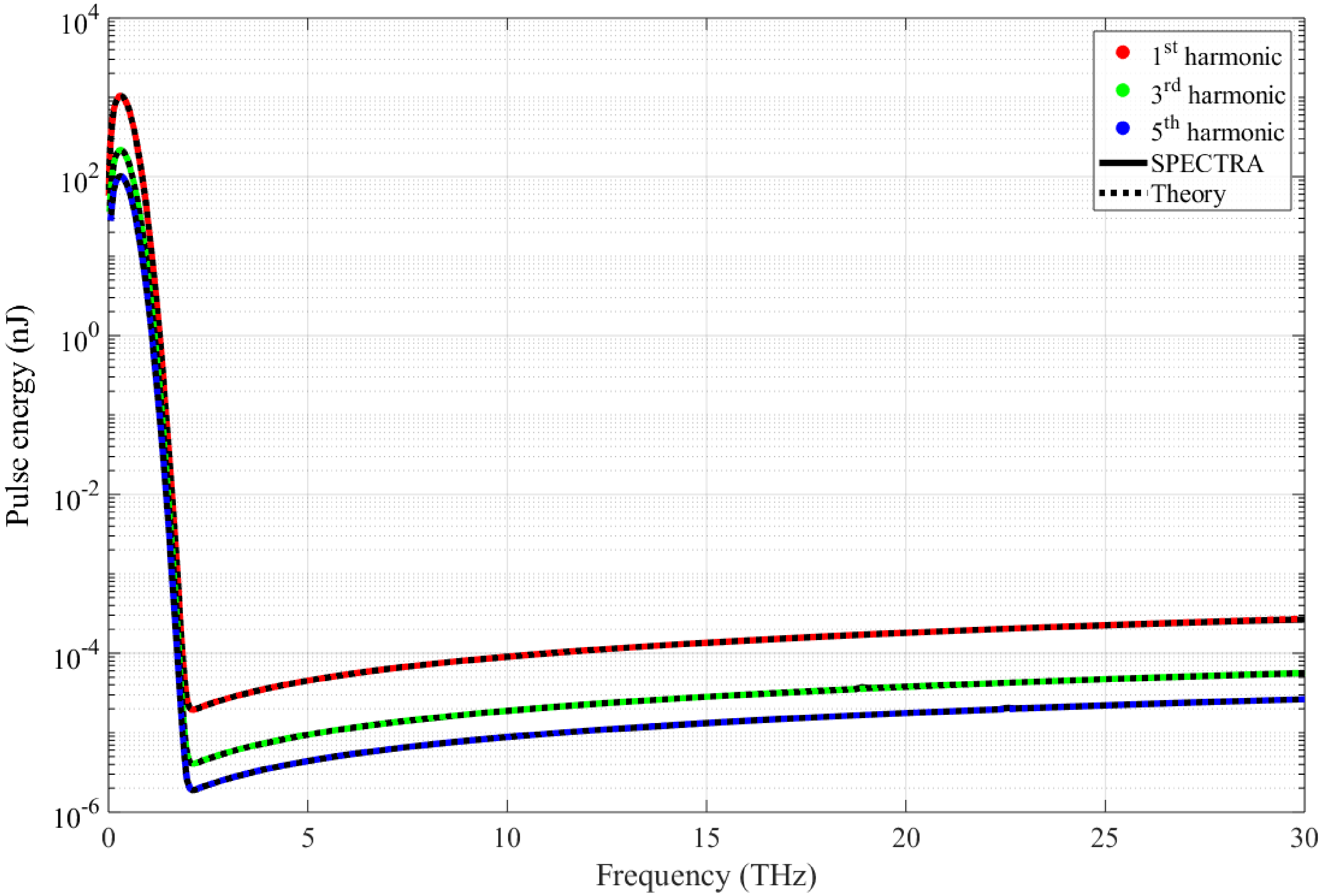
Longitudinal Gaussian form factor

$$f(\omega) = e^{-(\omega\sigma_z/c)^2} = e^{-(2\pi\sigma_z/\lambda_r)^2}$$

Peter Schmüser, Martin Dohlus, Jörg Rossbach, Ultraviolet and Soft X-Ray Free-Electron Lasers, Introduction to Physical Principles, Experimental

Benchmark of SPECTRA and theory

Pulse energy



SPECTRA result

The angular flux density on-axis [photons/s/mrad²/0.1%BW] $\frac{d\dot{N}}{d\Omega}$

The spectral energy on-axis for a single electron $\frac{dW}{d\omega}$

Energy of a single electron by integrating over all frequency W_{1e}

Pulse energy of an electron bunch

$$W_{tot} = W_{1e} N_e \left[1 + \left(N_e - 1\right) f(\omega)\right]$$

Effects of emittance and energy spread

Beam envelope

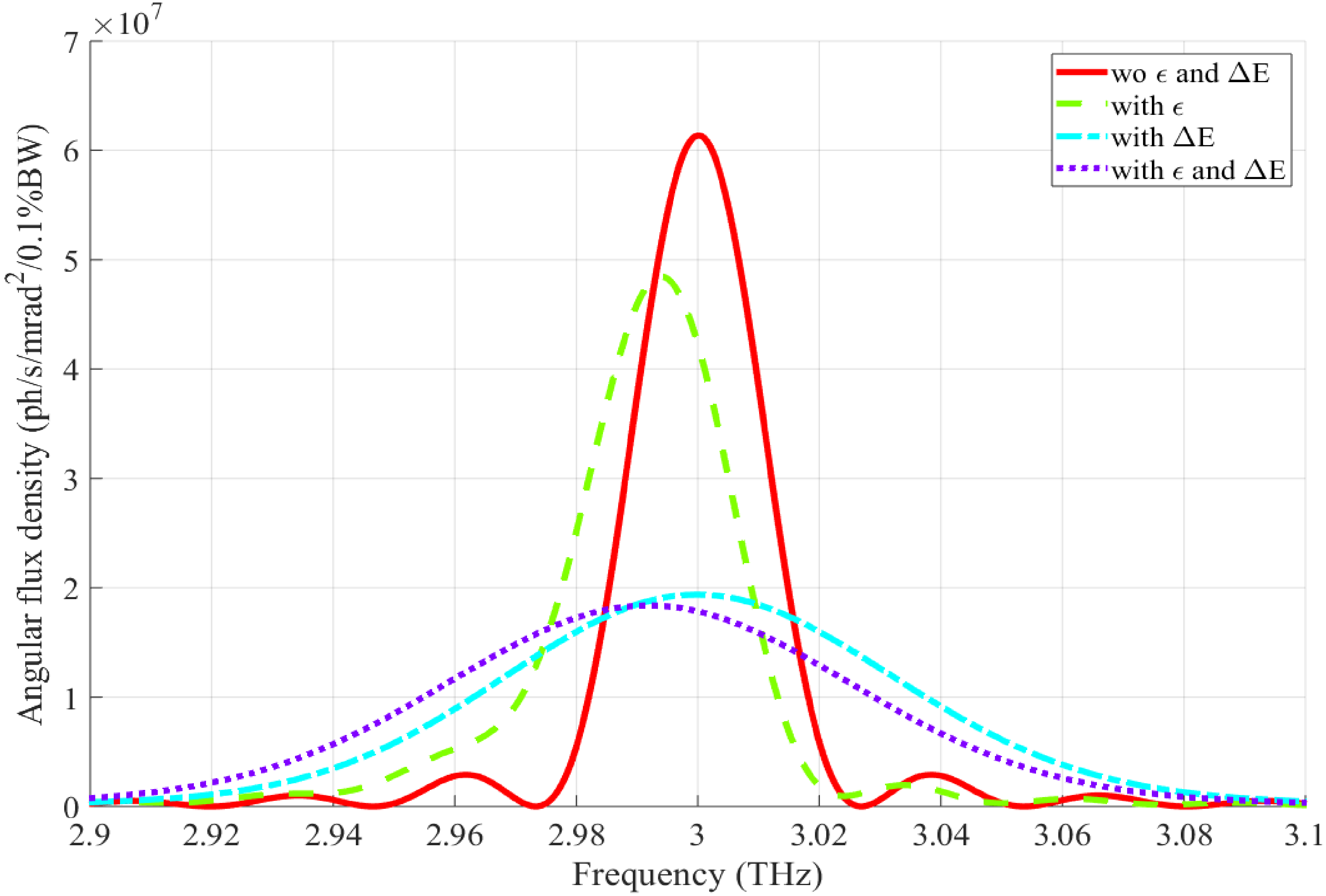
$$\sigma = \left[\epsilon\left(\beta_0 - 2\alpha_0 l + \frac{1+\alpha_0^2}{\beta_0} l\right) + \left(\frac{\sigma_E}{E}\right)^2 \left(\eta_0^2 + \eta_0'^2 l^2\right)\right]^{1/2}$$

The effect due to the finite electron-beam emittance and energy spread is described as a beam envelope.

The beam envelope is taken into account by a two-dimensional electron distribution.

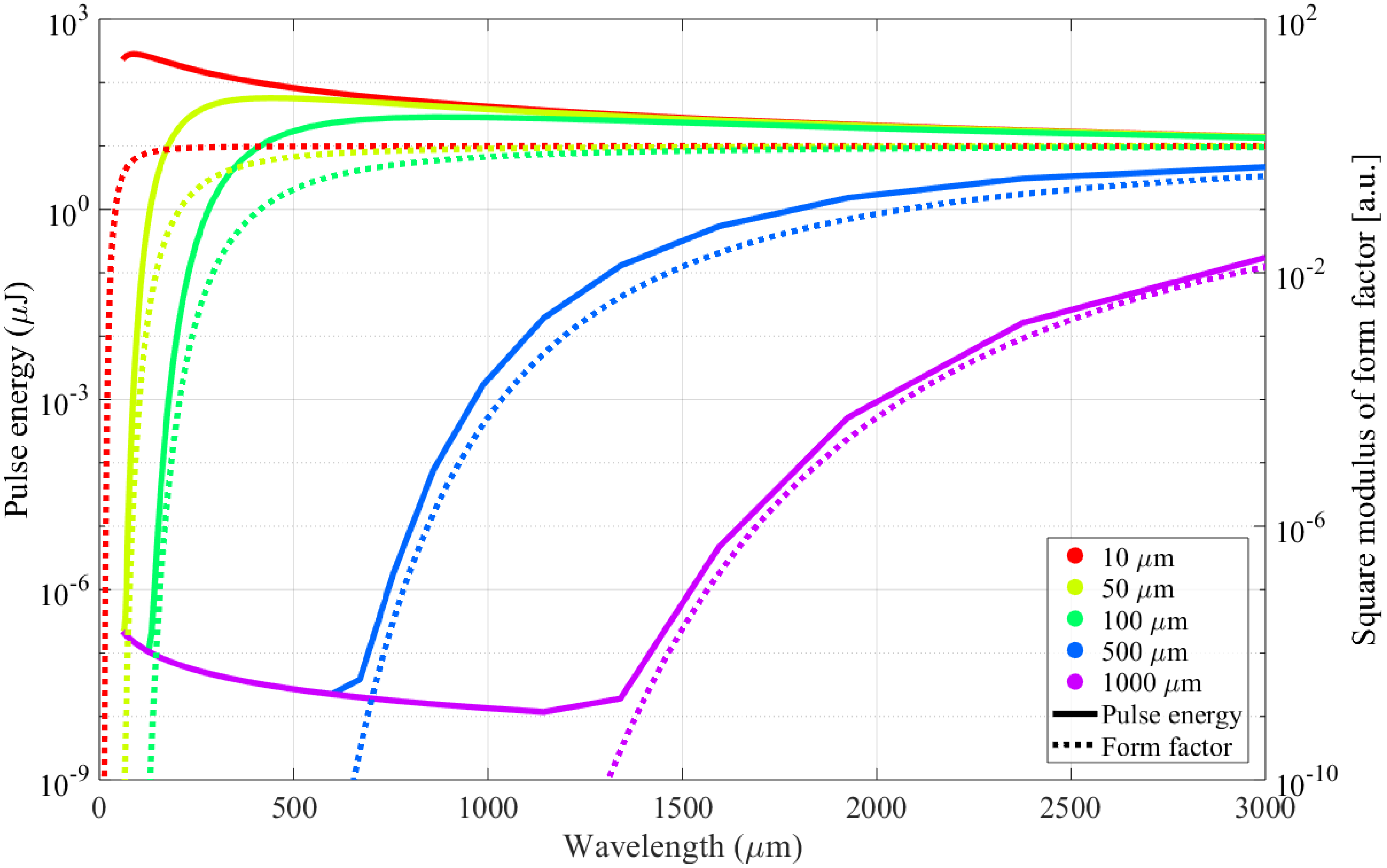
Emittance = 5 mm.mrad
Energy spread = 0.5%

The energy spread of the electron beam causes a broad bandwidth.



Electron Bunch Length

Pulse energy and form factor



Observed position = 0.6 m
Bunch charge = 500 pC
Emittance = 5 mm.mrad
Correlated energy spread = 0.5%
First harmonic

Scan parameters:
Beam energy = 3 – 22 MeV
Bunch length = 10, 50, 100, 500, 1000 µm

The pulse energy and form factor drop at wavelength shorter than their bunch length.

An electron beam with shorter bunch length generates undulator radiation with a broader spectrum and higher pulse energy.

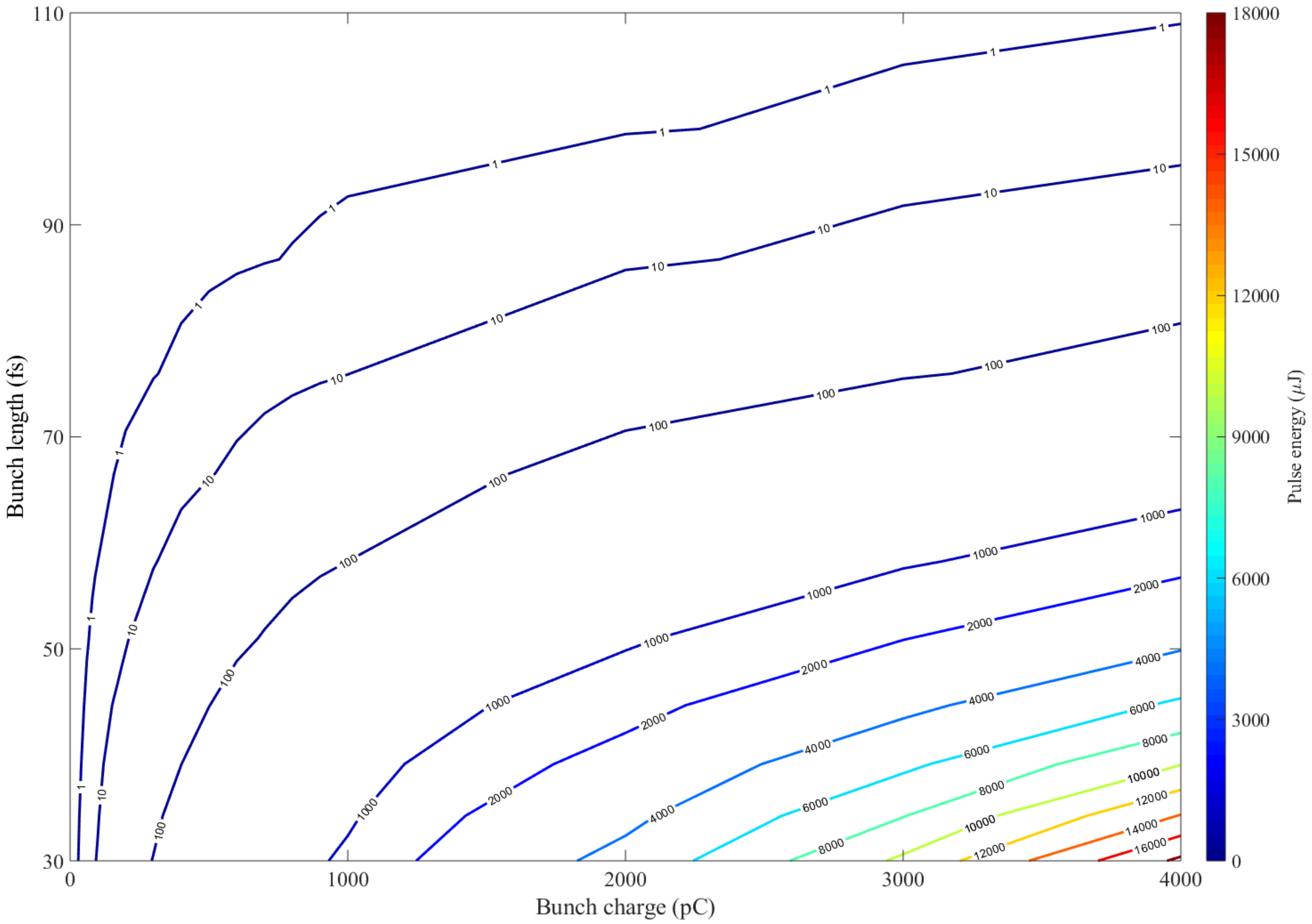
Bunch length VS bunch charge

First harmonic at 5 THz

Beam energy = 22 MeV (5 THz)
First harmonic
Observed position = 0.6 m
Emittance = 5 mm.mrad
Correlated energy spread = 0.5%

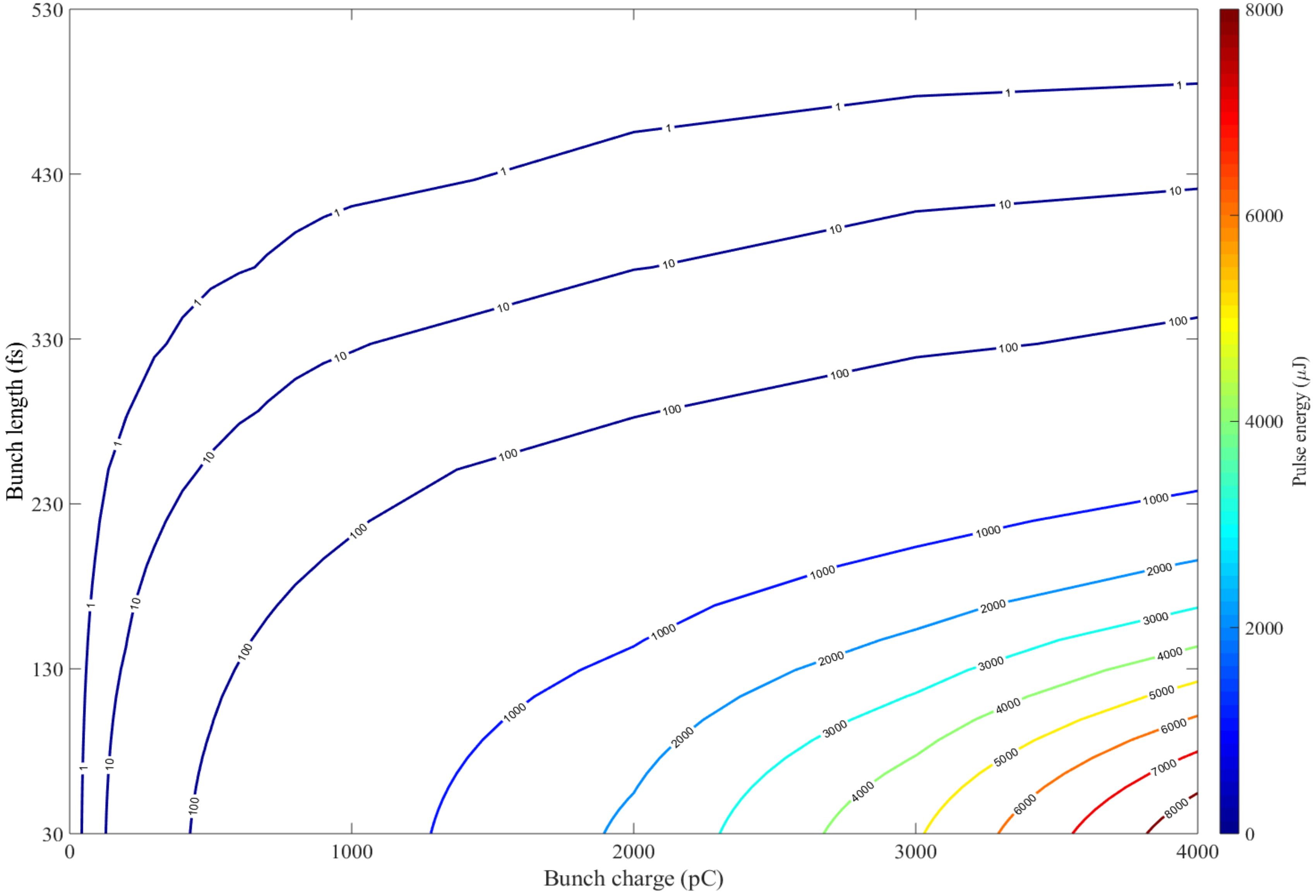
Scan parameters:
Bunch charge = 10 – 4000 pC
Bunch length = 30 – 5000 µm

Result
Highest pulse energy = 18 mJ
Pulse energy of 1 mJ: 30 – 60 fs
1 – 4 nC
Pulse energy of 1 µJ: 30 – 110 fs
30 – 4000 pC



Bunch length VS bunch charge

First harmonic at 1 THz



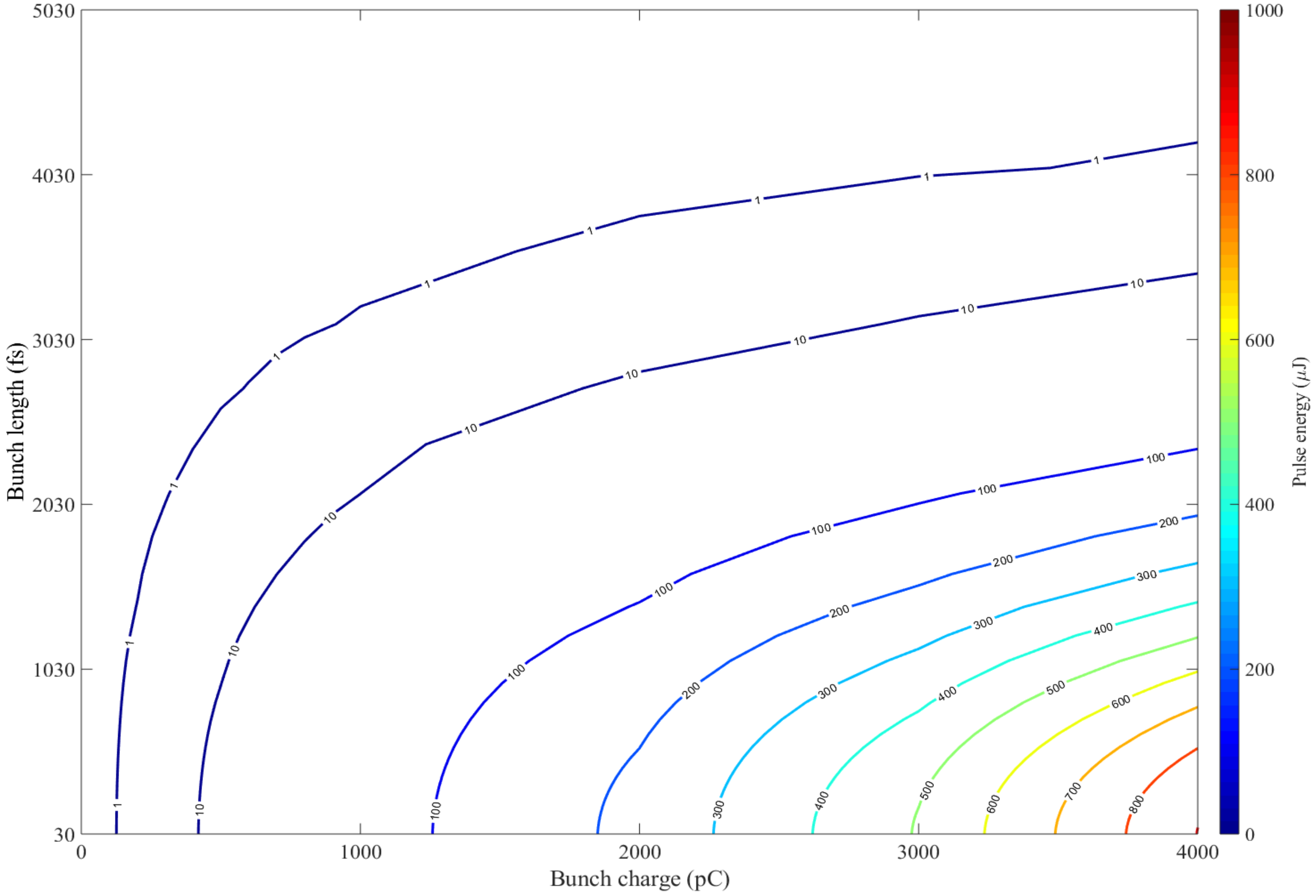
Beam energy = 10 MeV (1 THz)
First harmonic
Observed position = 0.6 m
Emittance = 5 mm.mrad
Correlated energy spread = 0.5%

Scan parameters:
Bunch charge = 10 – 4000 pC
Bunch length = 30 – 5000 μm

Result
Highest pulse energy = 8 mJ
Pulse energy of 1 mJ: 30 – 230 fs
1.3 – 4 nC
Pulse energy of 1 μJ: 30 – 480 fs
50 – 4000 pC

Bunch length VS bunch charge

First harmonic at 0.1 THz



Beam energy = 3 MeV (0.1 THz)
First harmonic
Observed position = 0.6 m
Emittance = 5 mm.mrad
Correlated energy spread = 0.5%

Scan parameters:
Bunch charge = 10 – 4000 pC
Bunch length = 30 – 5000 μm

Result
Highest pulse energy = 800 μJ
Pulse energy of 1 mJ: -
Pulse energy of 1 μJ: 30 – 4000 fs
100 – 4000 pC

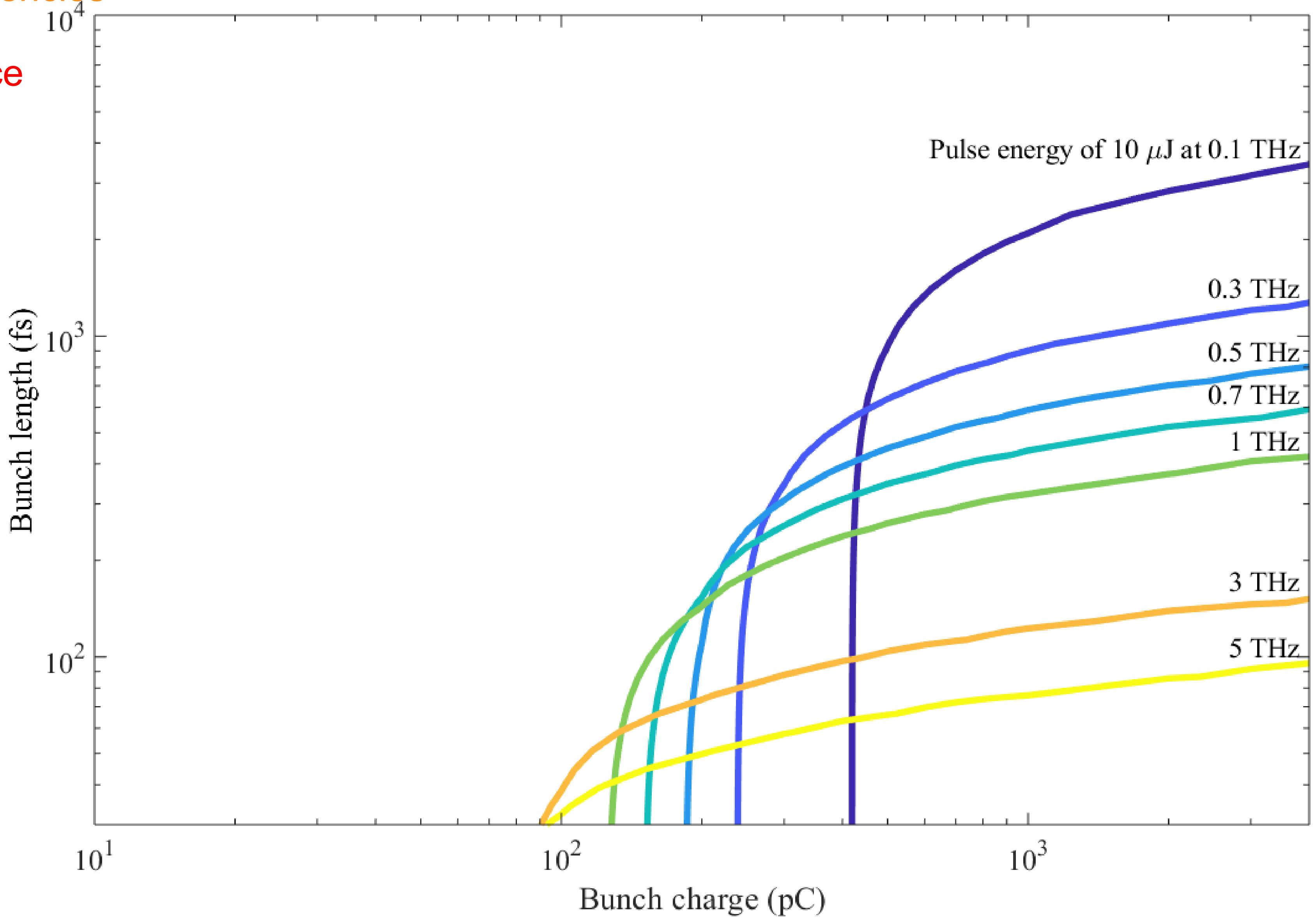
Pulse energy of 10 μJ

First harmonic with possible frequencies

TECHNICAL NOTE: Terahertz Science at European XFEL, April 2018:
minimum pulse energy of 10 μJ at all frequencies

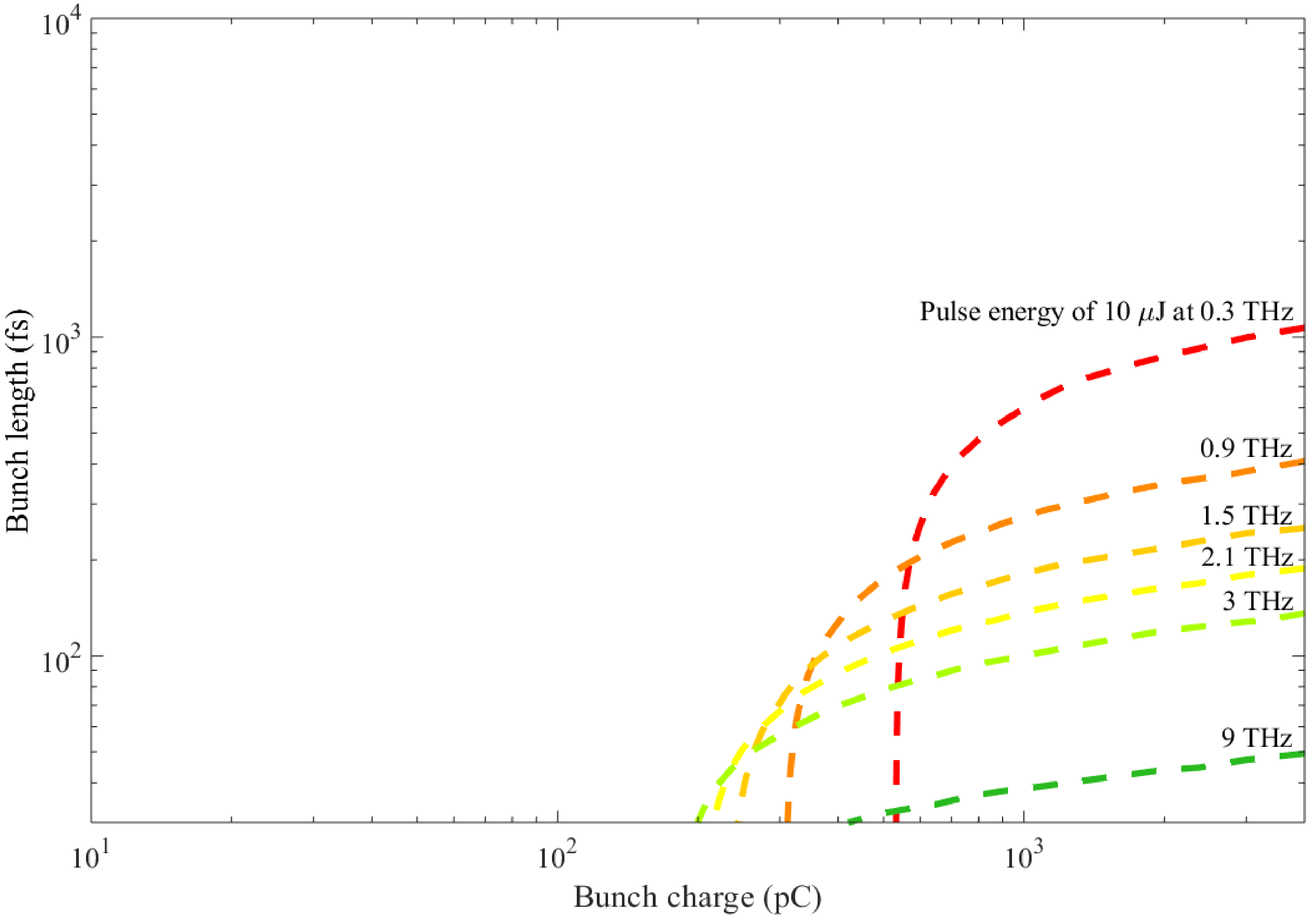
First harmonic
Beam energy = 3 – 22 MeV
Frequency = 0.1 – 5 THz

Result
Possible longest bunch length and lowest bunch charge:
0.1 THz = 3300 fs, 400 pC
0.3 THz = 1200 fs, 230 pC
0.5 THz = 800 fs, 180 pC
0.7 THz = 600 fs, 150 pC
1 THz = 400 fs, 120 pC
3 THz = 147 fs, 90 pC
5 THz = 95 fs, 90 pC



Pulse energy of 10 µJ (2)

Third harmonic with possible frequencies



Third harmonic
Beam energy = 3 – 17 MeV
Frequency = 0.3 – 9 THz

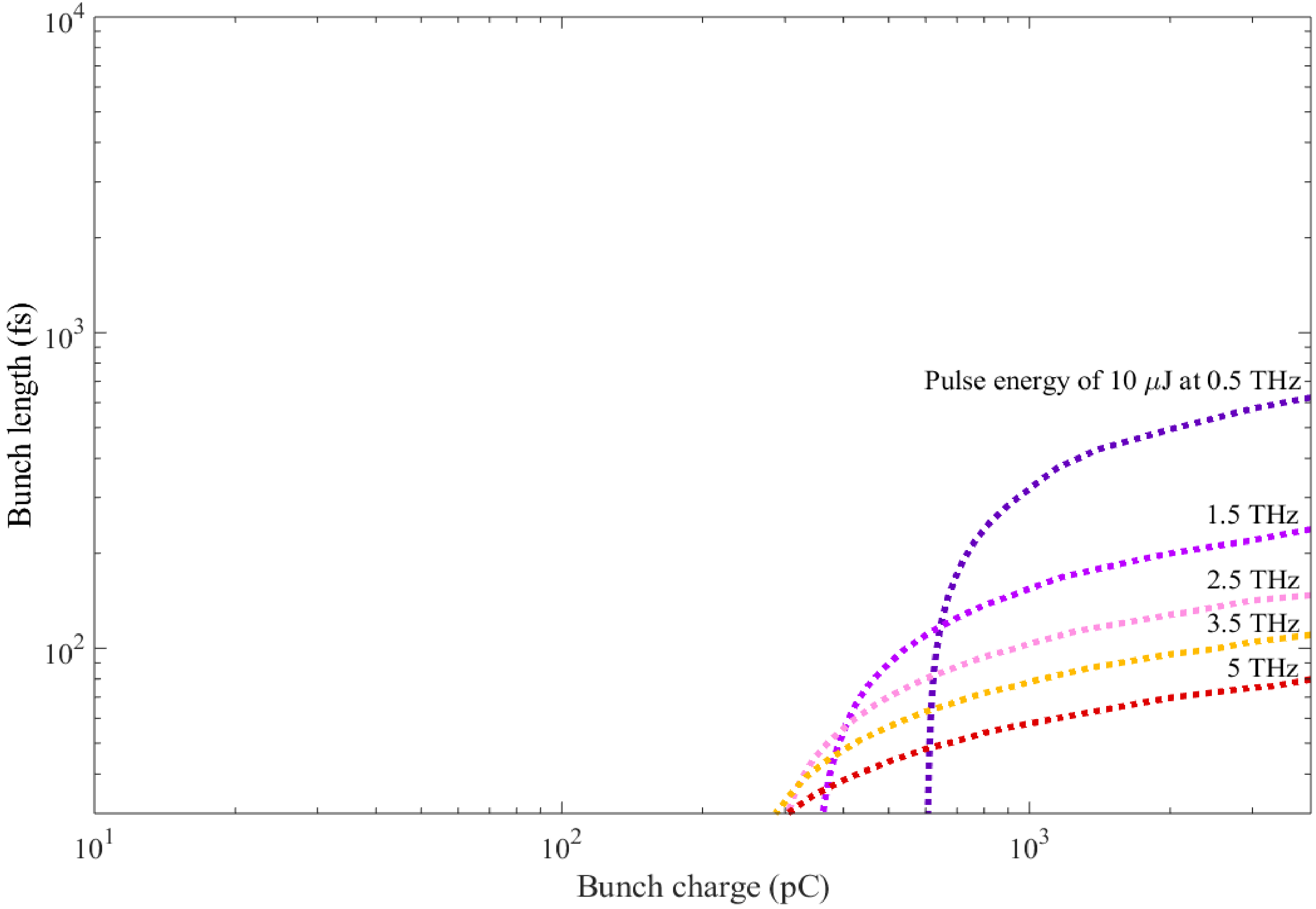
Result
Possible longest bunch length and lowest bunch charge:
0.3 THz = 1000 fs, 510 pC
0.9 THz = 400 fs, 300 pC
1.5 THz = 270 fs, 230 pC
2.1 THz = 200 fs, 210 pC
3 THz = 130 fs, 200 pC
9 THz = 50 fs, 410 pC

Pulse energy of 10 μJ (3)

Fifth harmonic with possible frequencies

Fifth harmonic
Beam energy = 3 – 10 MeV
Frequency = 0.5 – 5 THz

Result
Possible longest bunch length and lowest bunch charge:
0.5 THz = 600 fs, 600 pC
1.5 THz = 230 fs, 370 pC
2.5 THz = 150 fs, 300 pC
3.5 THz = 110 fs, 300 pC
5 THz = 80 fs, 300 pC

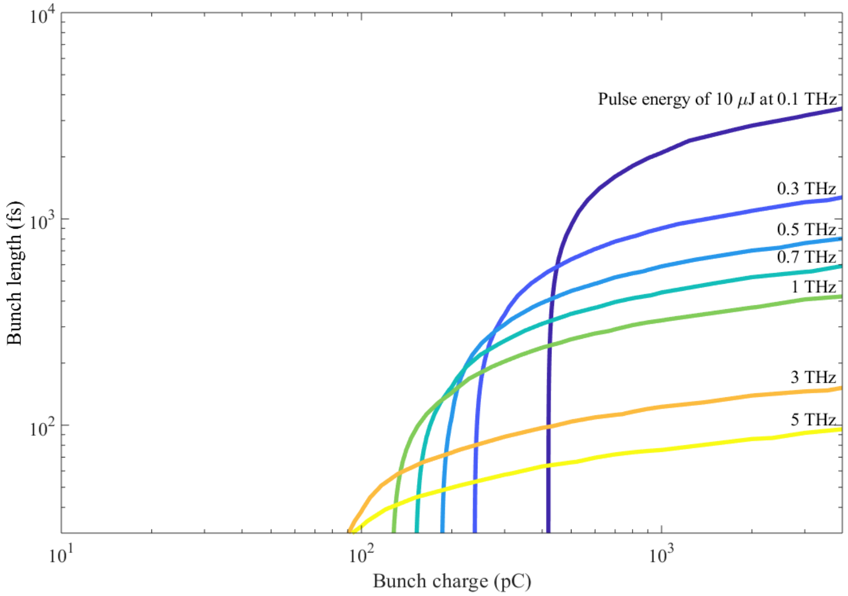


Pulse energy of 10 μJ (4)

First three harmonics with possible frequencies

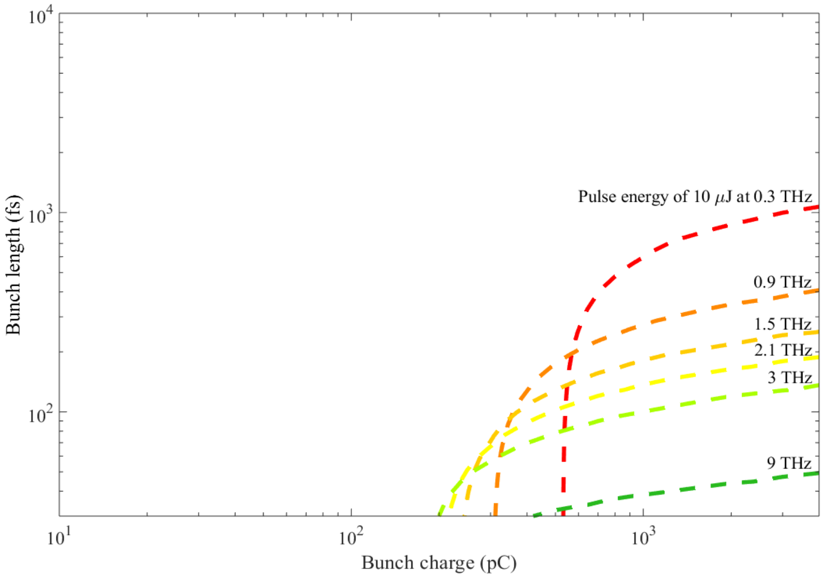
First harmonic

Beam energy = 3 – 22 MeV
Frequency = 0.1 – 5 THz
Longest bunch length = 95 – 3300 fs
Lowest bunch charge = 90 – 400 pC



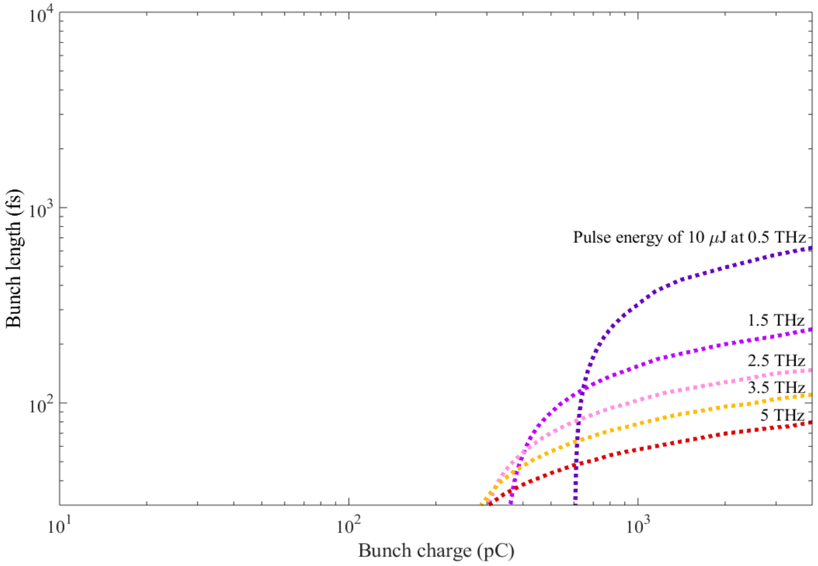
Third harmonic

Beam energy = 3 – 17 MeV
Frequency = 0.3 – 9 THz
Longest bunch length = 50 – 1000 fs
Lowest bunch charge = 200 – 510 pC



Fifth harmonic

Beam energy = 3 – 10 MeV
Frequency = 0.5 – 5 THz
Longest bunch length = 80 – 600 fs
Lowest bunch charge = 300 – 600 pC

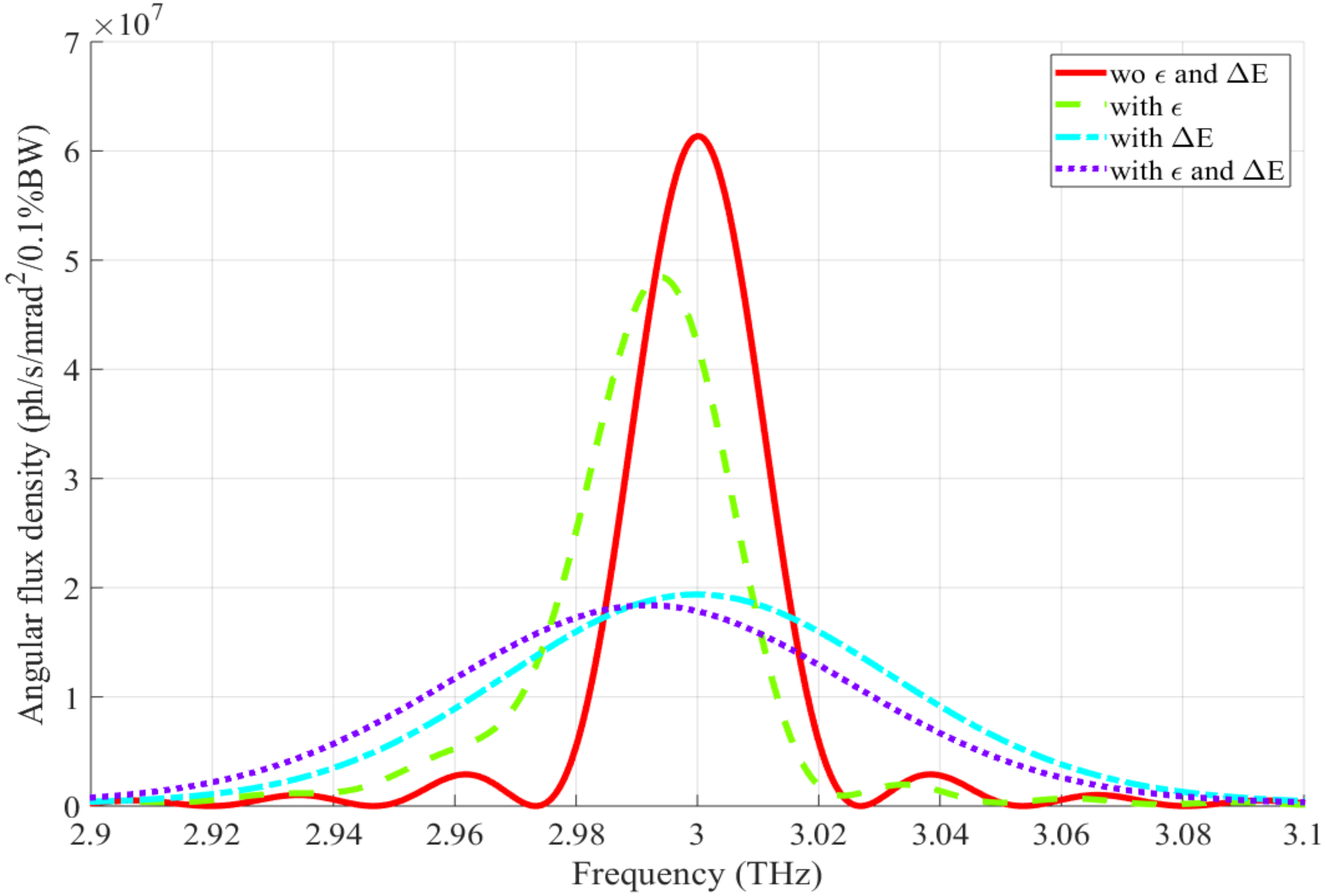


Energy spread VS bunch charge

Band-pass filter

Band-pass filter

- For selecting specified frequencies in the THz range to get high spectral resolution.
- Relative bandwidth: 15 - 20%
- Peak transmission: 84 - 97%
- The filters are fabricated from thin metal foil with holes.
- Configuration of the holes depends on the required wavelength.

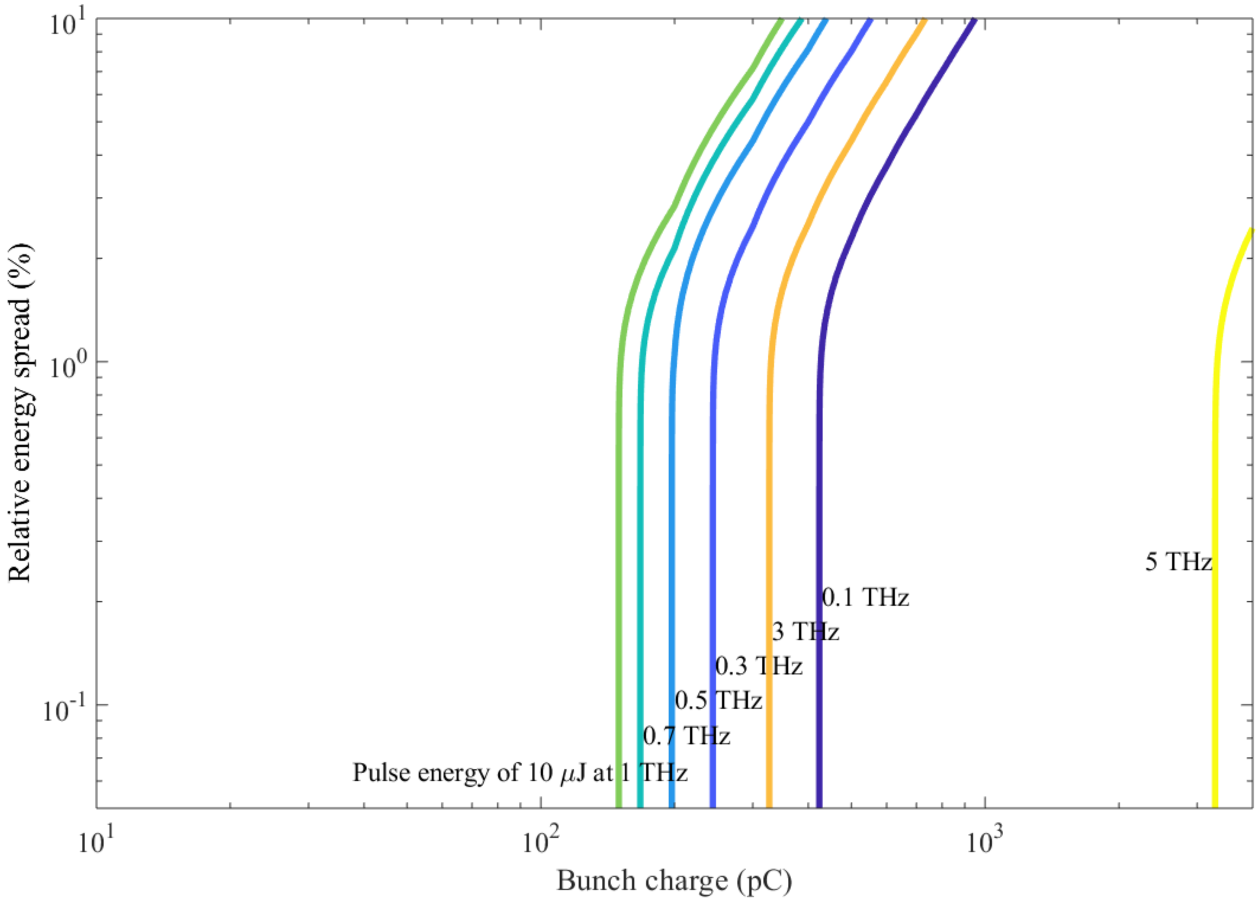


Band-pass filter of 10%
= 2.85 – 3.15 THz for the central frequency of 3 THz.

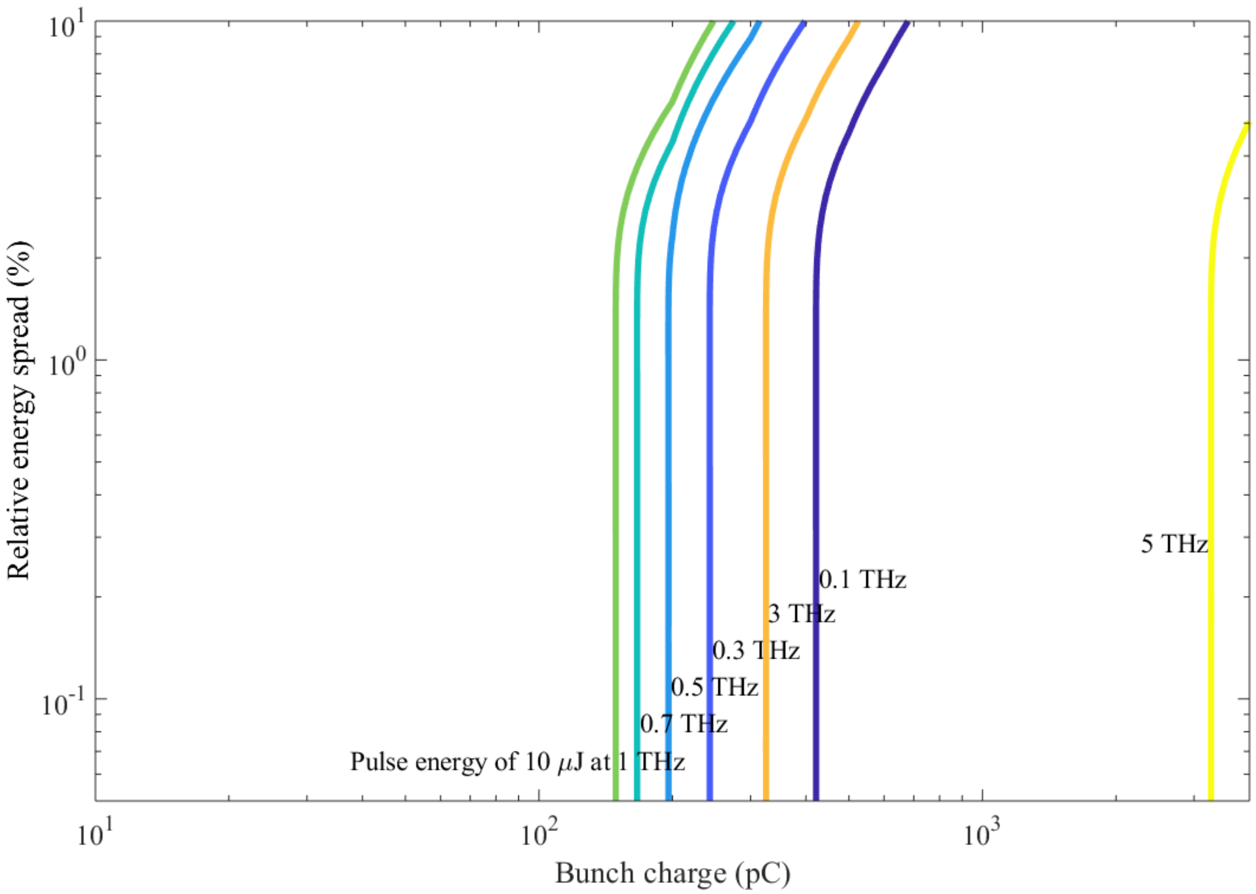
Energy spread VS bunch charge

First harmonic for bunch length of 90 fs with band-pass filter

Band-pass filter of 10%

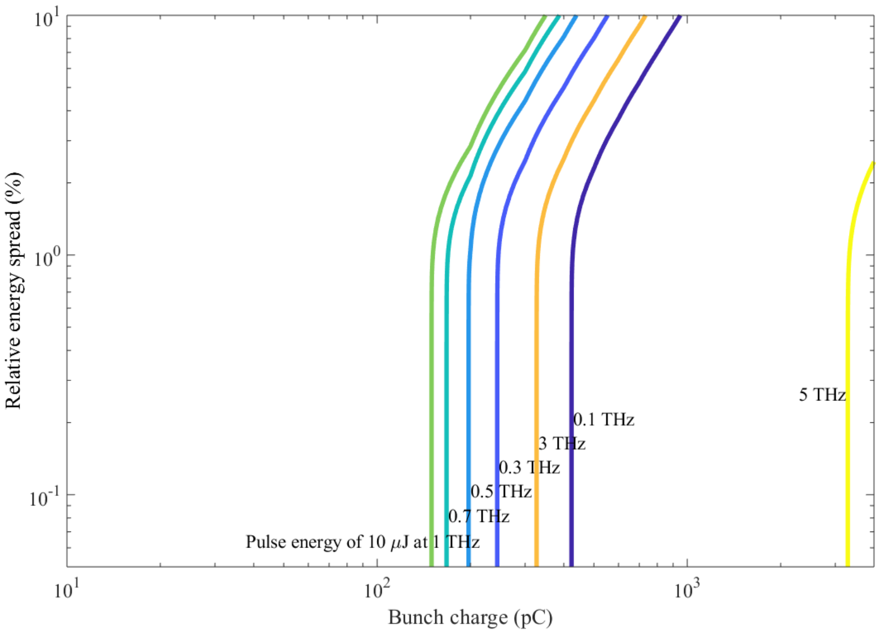


Band-pass filter of 20%

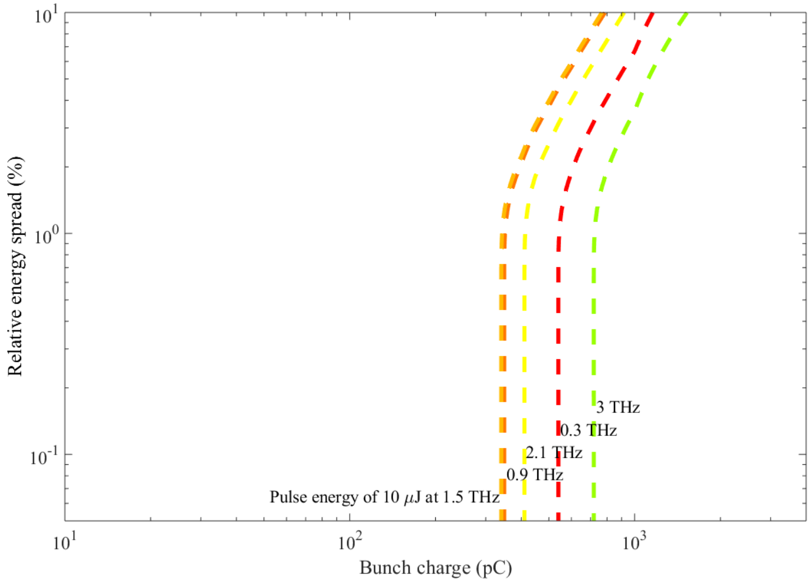


Energy spread VS bunch charge

First three harmonics for bunch length of 90 fs with band-pass filter 10%

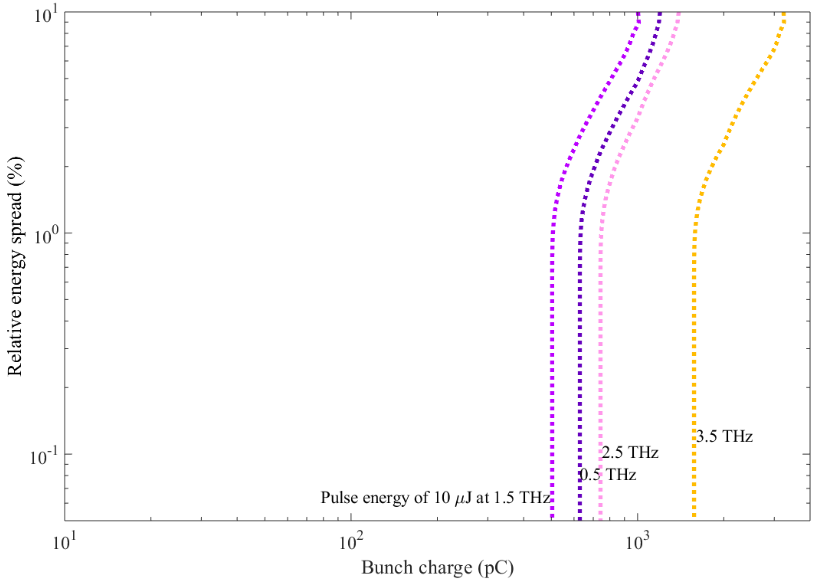


1st harmonic



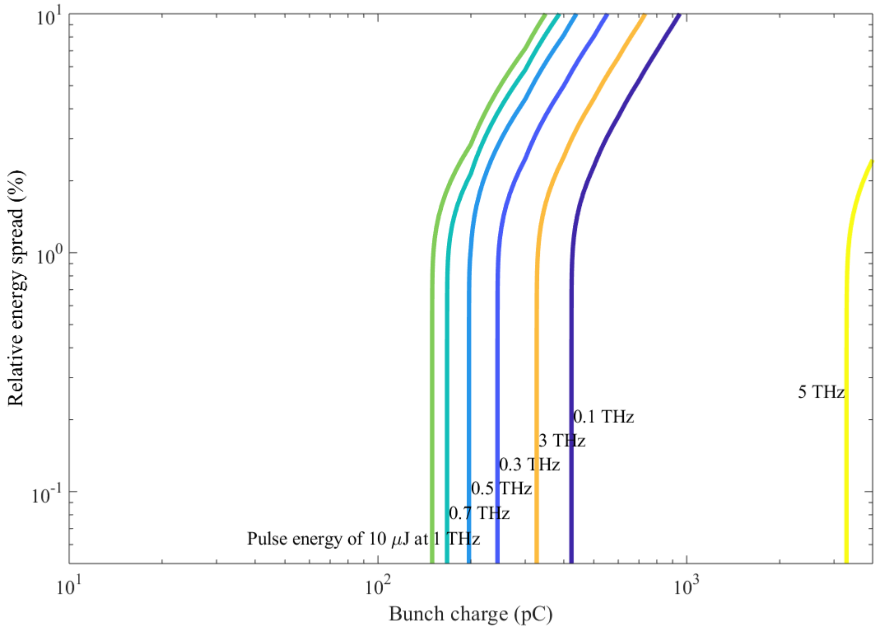
3rd harmonic

5th harmonic

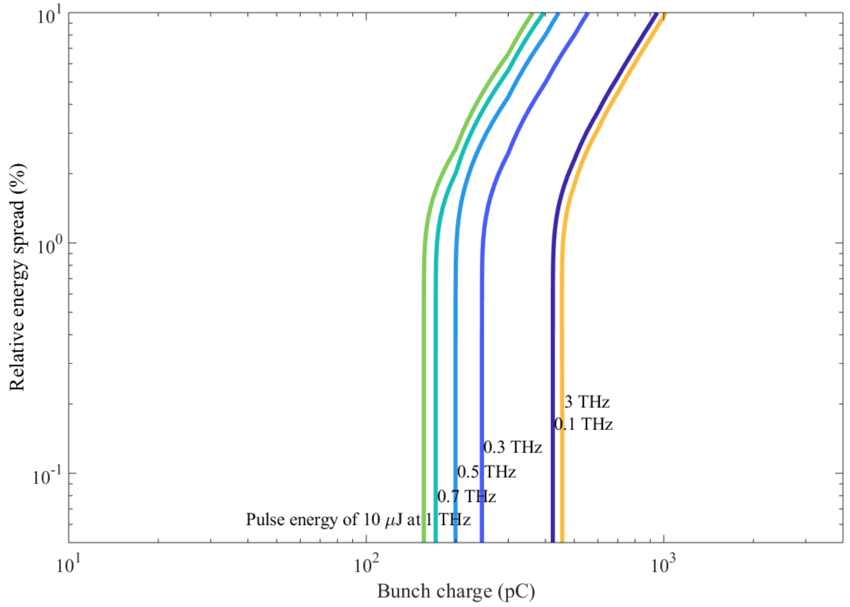


Energy spread VS bunch charge

First harmonics with band-pass filter 10% for various bunch lengths

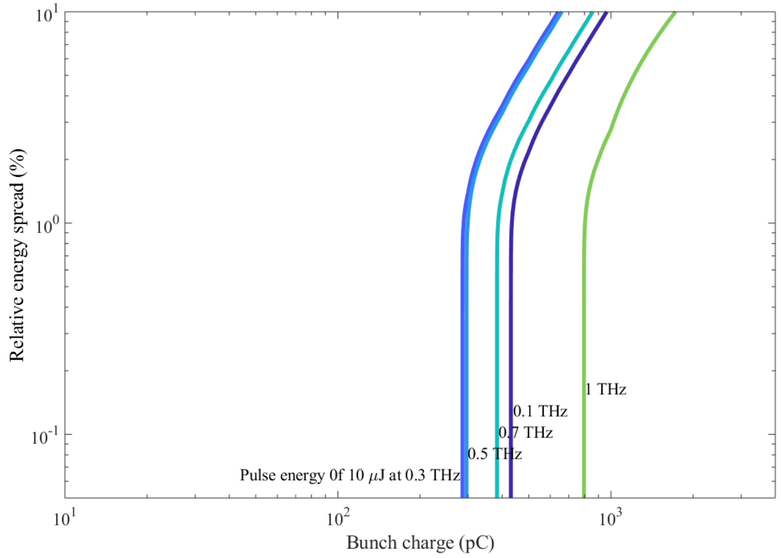


90 fs



100 fs

300 fs



Summary and outlook

Summary

- Superradiant undulator radiation including emittance and energy spread was performed.
- The radiation frequency of 0.1 – 5 THz with the pulse energy of 10 µJ can be achieved for electron beam energy of 3 – 22 MeV at the fundamental harmonic.
- The radiation frequency of 5 – 9 THz with the pulse energy of 10 µJ can be reached at third harmonic.
- Energy spread should not exceed than 1%.

Outlook

- Transverse properties of radiation include vacuum chamber of undulator magnet

Thank you