UNIVERSITY OF GOTHENBURG

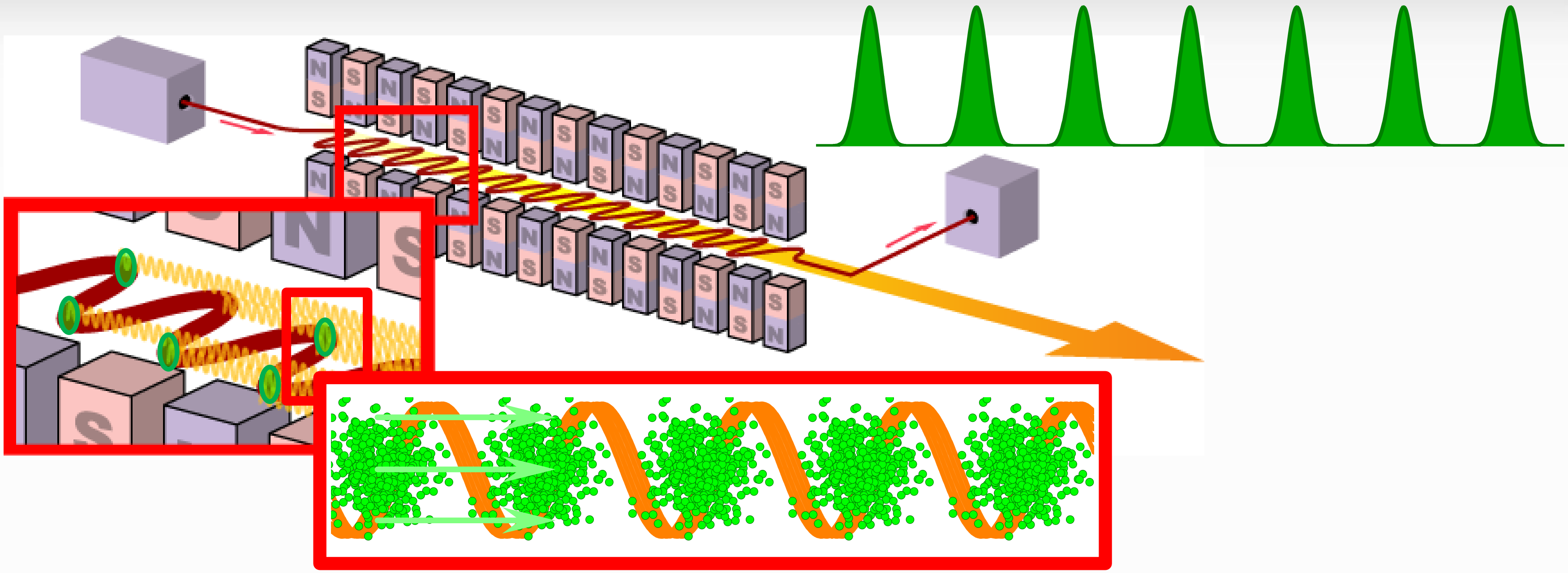
UPPSALA UNIVERSITET

B. I. Stepanov Institute of Physics
National Academy of Sciences of Belarus

GENERATION OF MULTI-CYCLE MILLIJOULE PULSES BY A SINGLE-PASS THz FEL

Ruslan Chulkov, Vitaliy Goryashko, and Vitali Zhaunerchyk

APPROACH



We consider an approach in the form:

- super-radiant FEL source
- planar undulator (K~1)
- prebunched electron beam
- singe-pass interaction geometry

We would like to have:

- central frequency: 5-15 THz
- relative spectral bandwidth: <10%
- output pulse energy: >1 mJ
- spatial properties: diffraction-limited Gaussian beam

OUTLINE

- ? total charge of the electron bunch
- ? number of micro-bunches
- ? bunching factor
- ? bunching period
- ? bunch focusing conditions
- ? electron energy spread
- ? undulator length

parameter space being under consideration

electron energy	**20 MeV**
bunch charge	**0.5; 1.1 nC**
total bunch energy	10; 22 mJ
number of microbunches	1 - 16
electron energy spread, rms	**0 - 2%**
bunch emittance, rms	**0-4 mm·mrad**

β_0 -function	0.6 - 20 m
undulator magnetic field	**0.3 T**
undulator period, λ_u	**50 mm**
number of periods	12
resonant frequency	**~10 THz**
effective Fresnel number, N_F	0.009 – 0.3

THE MODEL

$$\frac{dC_{m,n}(z,\omega)}{dz} = \frac{1}{4S_{m,n}}\int \vec{J}(\vec{r},\omega)\left(\Psi^{x}_{m,n}\right)^{*} dS$$

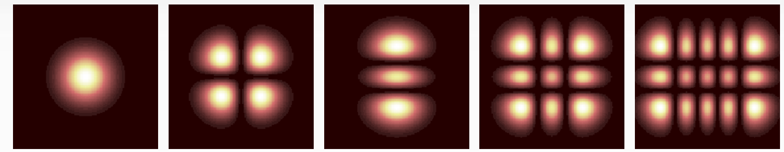
IFT

DFT

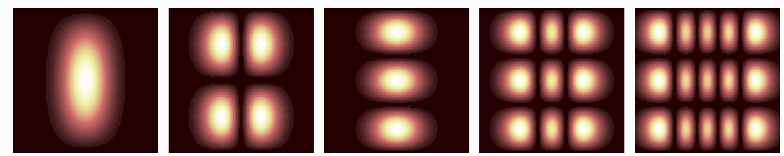
$$\vec{E}^{x}(\vec{r},\omega) = \sum_{m,n} C_{m,n}(z,\omega)\Psi^{x}_{m,n}$$

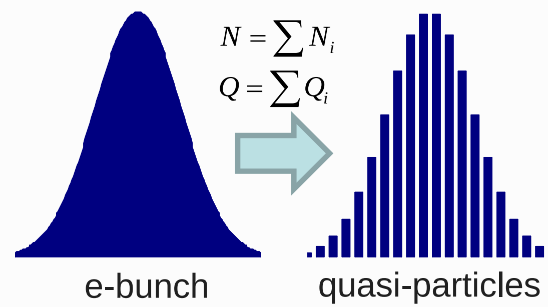
$$\frac{d\vec{\upsilon}_i}{dz} = \mathrm{F}\left\{\vec{r}_i^{\,0}, \vec{\upsilon}_i^{\,0}, \vec{A}_U, \gamma_i\right\} \qquad \frac{d\gamma_i}{dz} = -\frac{e}{m_e c^2}\vec{\upsilon}_i \cdot \vec{E}^{x}(\vec{r}_i, t_i)$$

free-space HG modes



hybrid modes of a slab waveguide





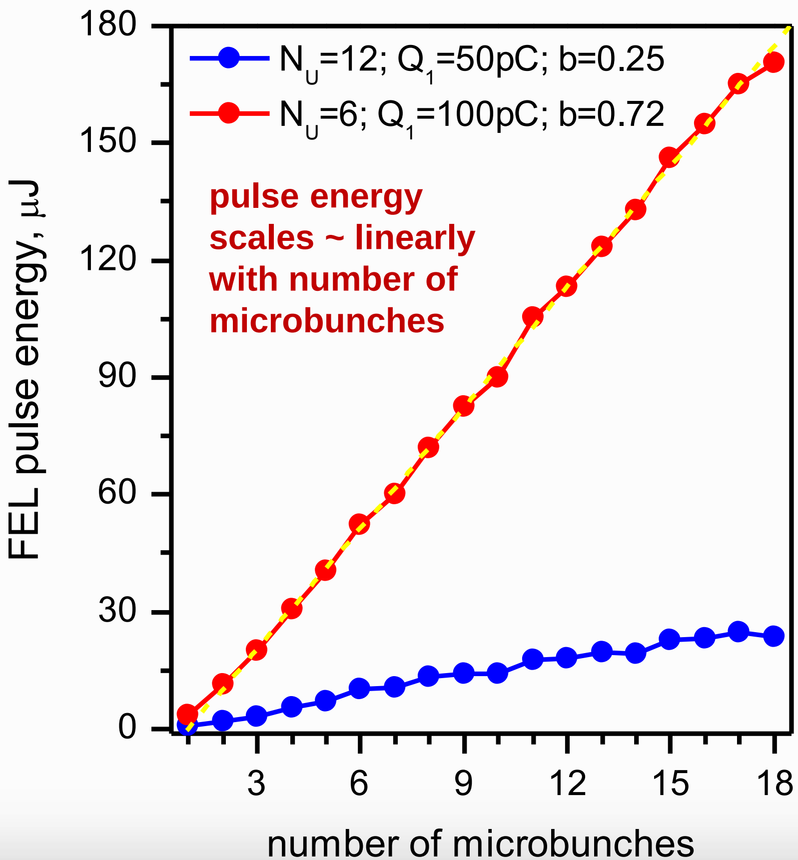
- **field integration over the ponderomotive potential period**
- **optical field decomposing onto a complete set of orthogonal modes $\Psi_{m,n}$**
- **quasi-particle approach for the electron bunch interaction**
- **model takes into account statistical properties of the electron bunch**
- **approximations: paraxial, linear polarization**

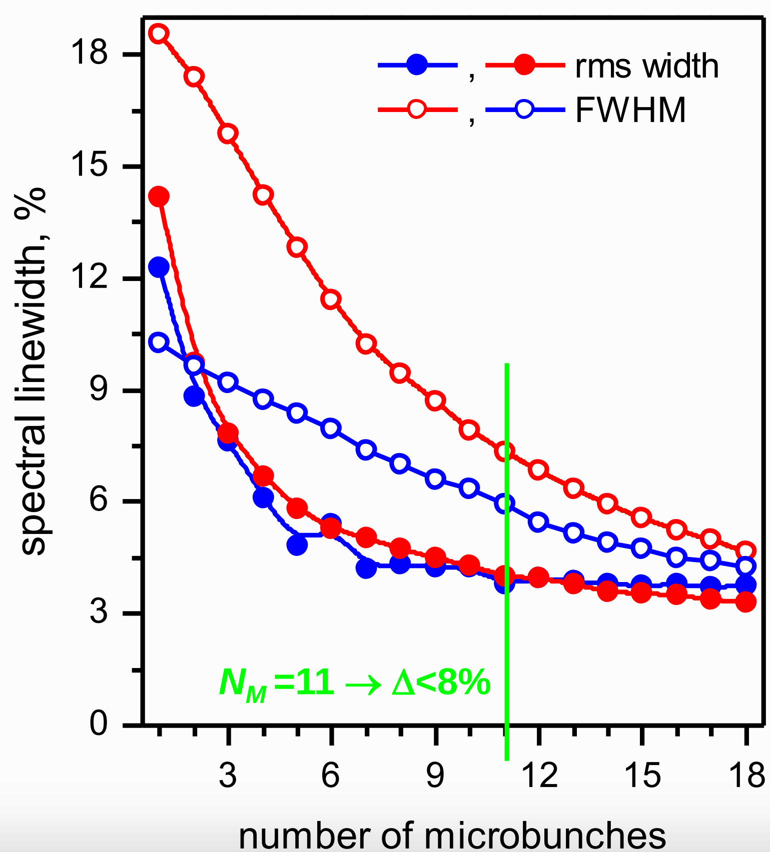
Y. Pinhasi, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 475 (2001), 147.
V. Zhaunerchyk et al., PRST - Accel. Beams, 15 (2012), 050701.
R. Chulkov, et al., PRST – Accel. Beams, 17, 050703 (2014).
B.W.J. McNeil, et al., PRST – Accel. Beams, 6 (2003), 070701.

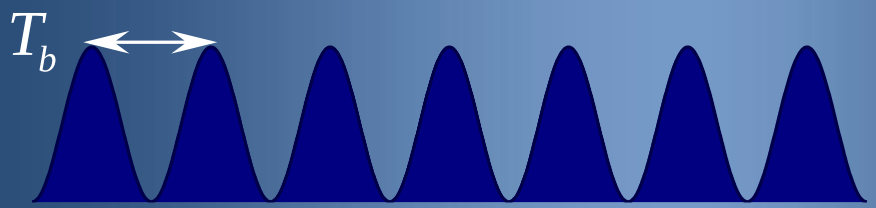
TEST CASE. FEL PULSE ENERGY & SPECTRAL WIDTH

A. Gover, Phys. Rev. Spec. Top. Accel. Beams 8 (2005) 030701

Parameter	No bunching	Single bunch	Periodic bunching
$\Delta\omega$	$1/N_w$	$1/N_w$	$1/N_M$
W_q	N	N_b^2	$N_M N_b^2$
$dW_q/d\omega$	N	N_b^2	$N_M^2 N_b^2$
P_q	N	N_b^2	N_b^2
$dP_q/d\omega$	N	N_b^2	$N_M N_b^2$







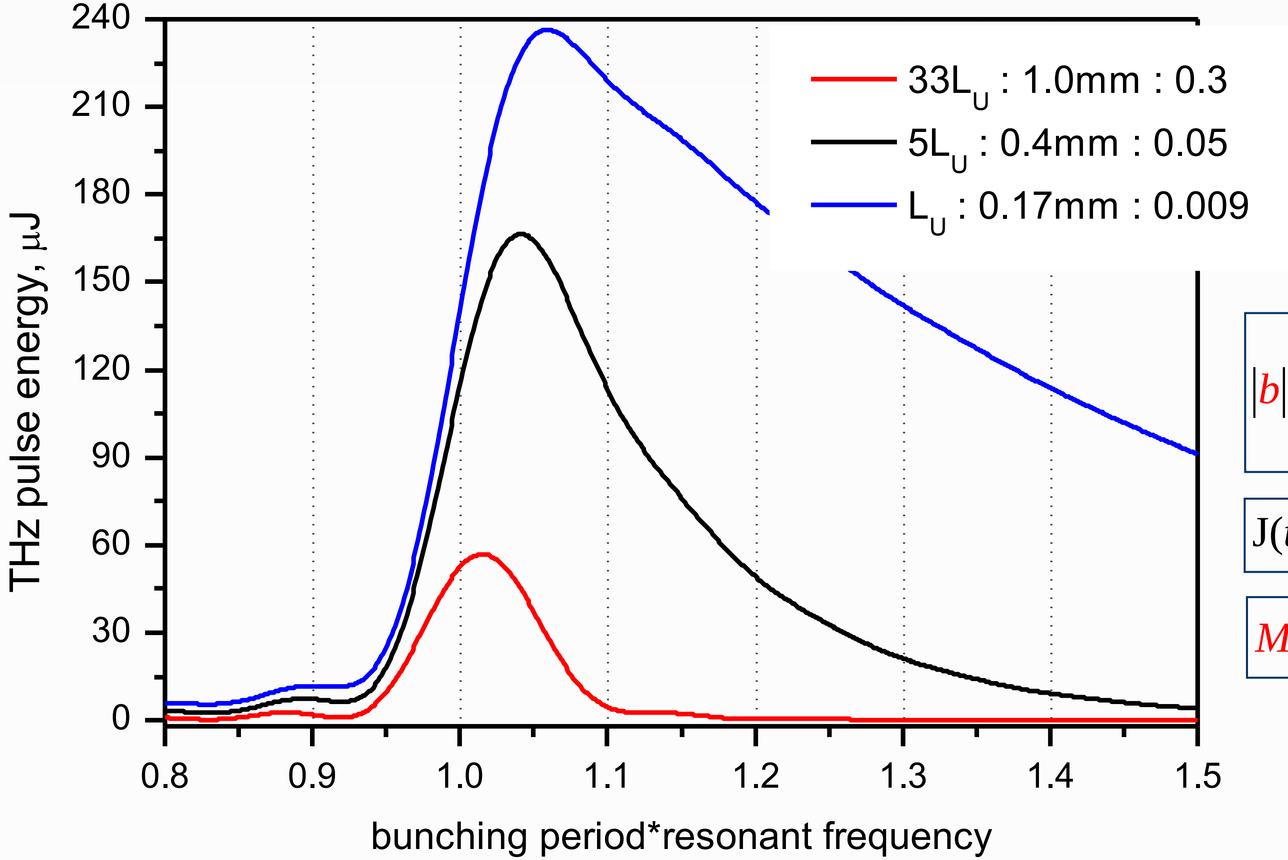
BUNCHING FACTOR 0.25

$$J(t) = J_0 \cos^2\left(\pi t / T_b\right)$$

KNOWN SEMI-ANALITICAL MODEL. THz PULSE ENERGY

E.L. Saldin, et. al., Nuclear Instruments and Methods in Phys. Research A 539 (2005) 499–526.

resonant frequency: **9.7 THz** bunch energy: **10 mJ**



Fresnel number:

$$N_F = \frac{k_{res} r_{rms}^2}{\lambda_u N_u} = \frac{k_{res} \beta_0 \varepsilon}{\lambda_u N_u \gamma_0}$$

$$|b|^2 = \frac{\int J(t) \exp(i\,\omega_{res} t)\, dt}{\int J(t)\, dt}$$

$$J(t) = J_0 \left(1 + M \cos(2\omega_{res} t)\right)$$

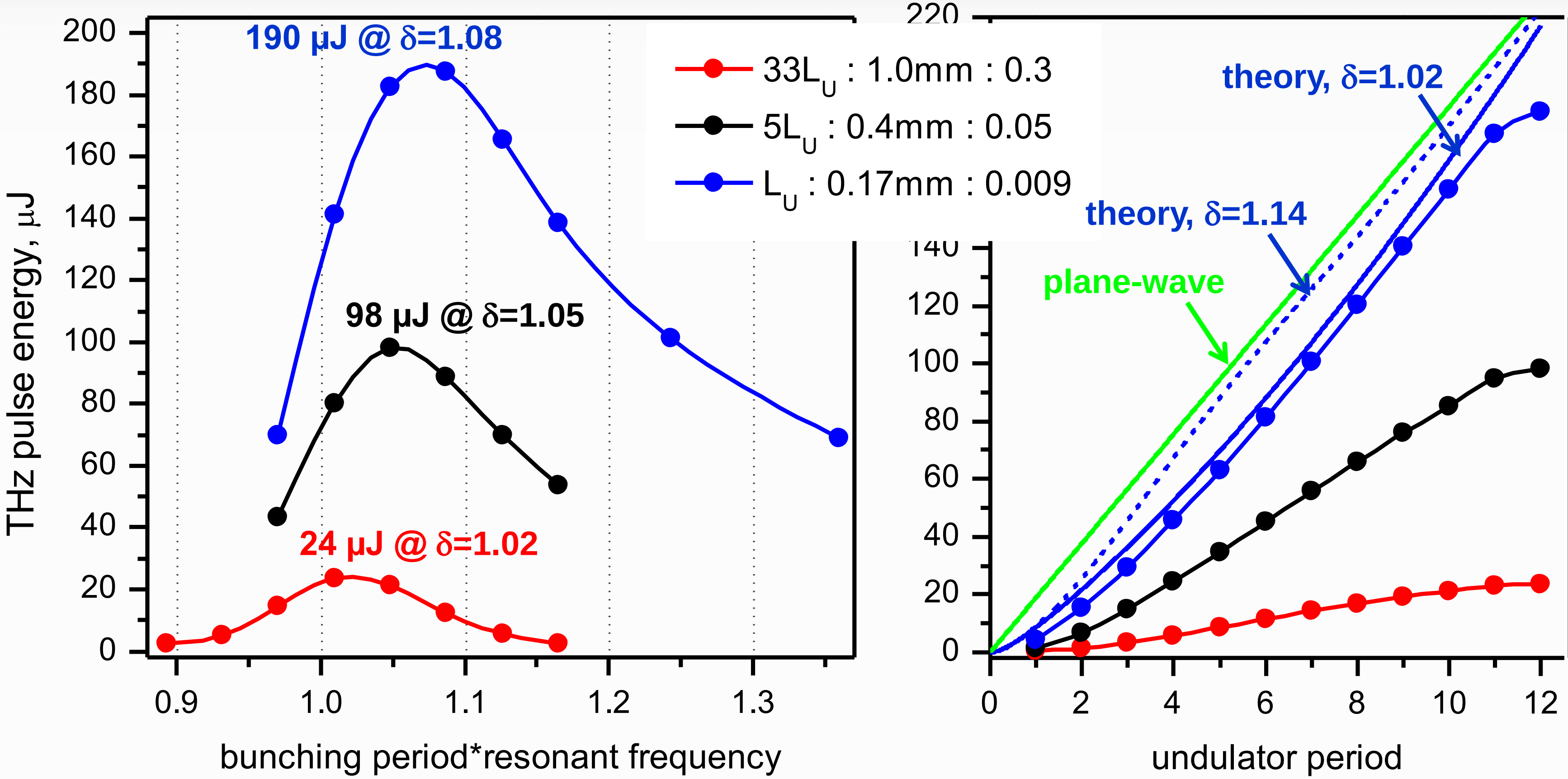
$$M = 4|b|^2 = 1$$

e-beam narrowing → enhancement of the light energy

→ progressive shift in an optimal bunching period

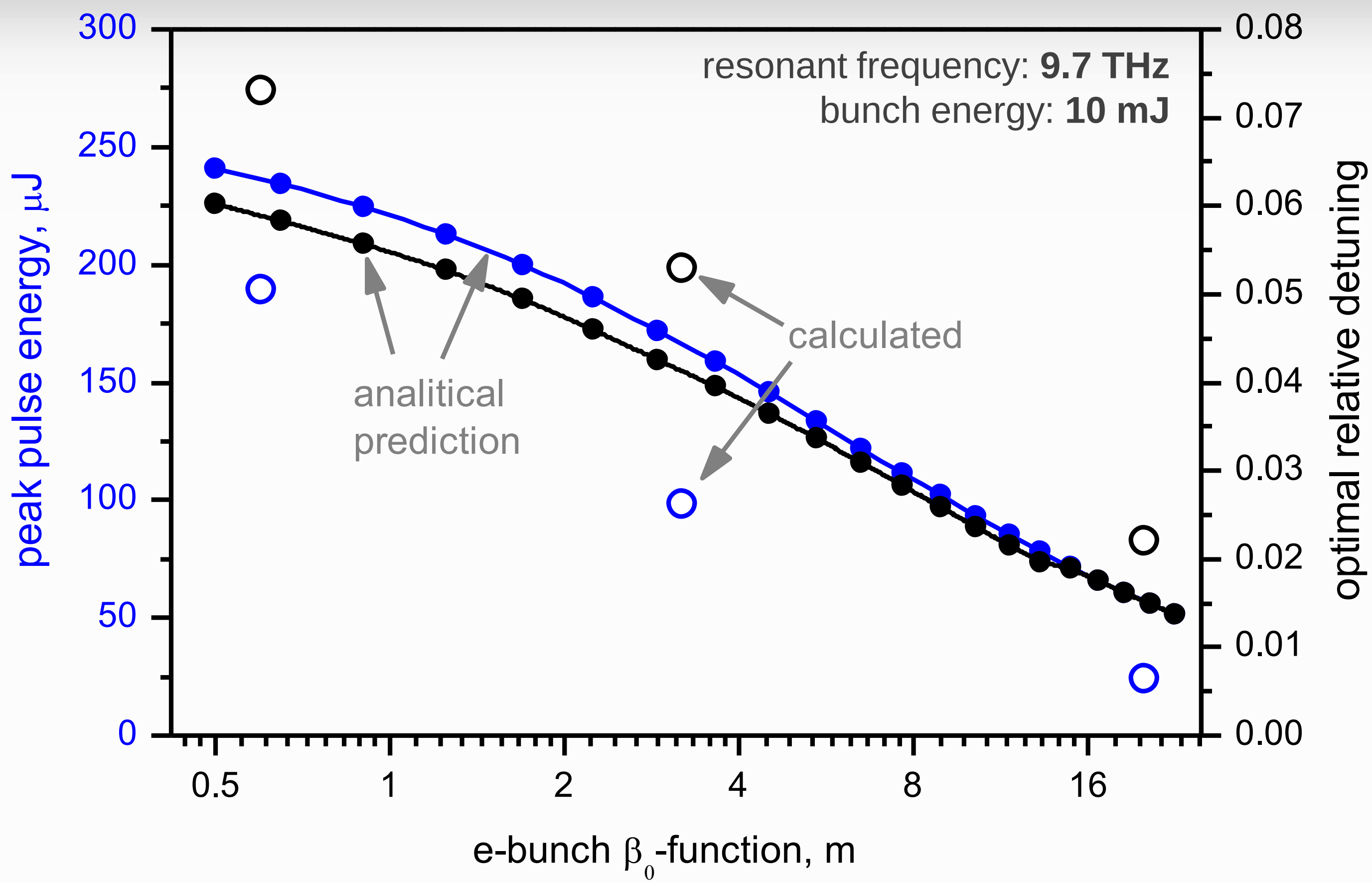
NUMERICAL SIMULATION. THz PULSE ENERGY

resonant frequency: **9.7 THz** bunch energy: **10 mJ**



both the theory and numerical data predict nonlinear dependence of the light energy on N_U
probable cause: change in the optimal detuning as N_U increases

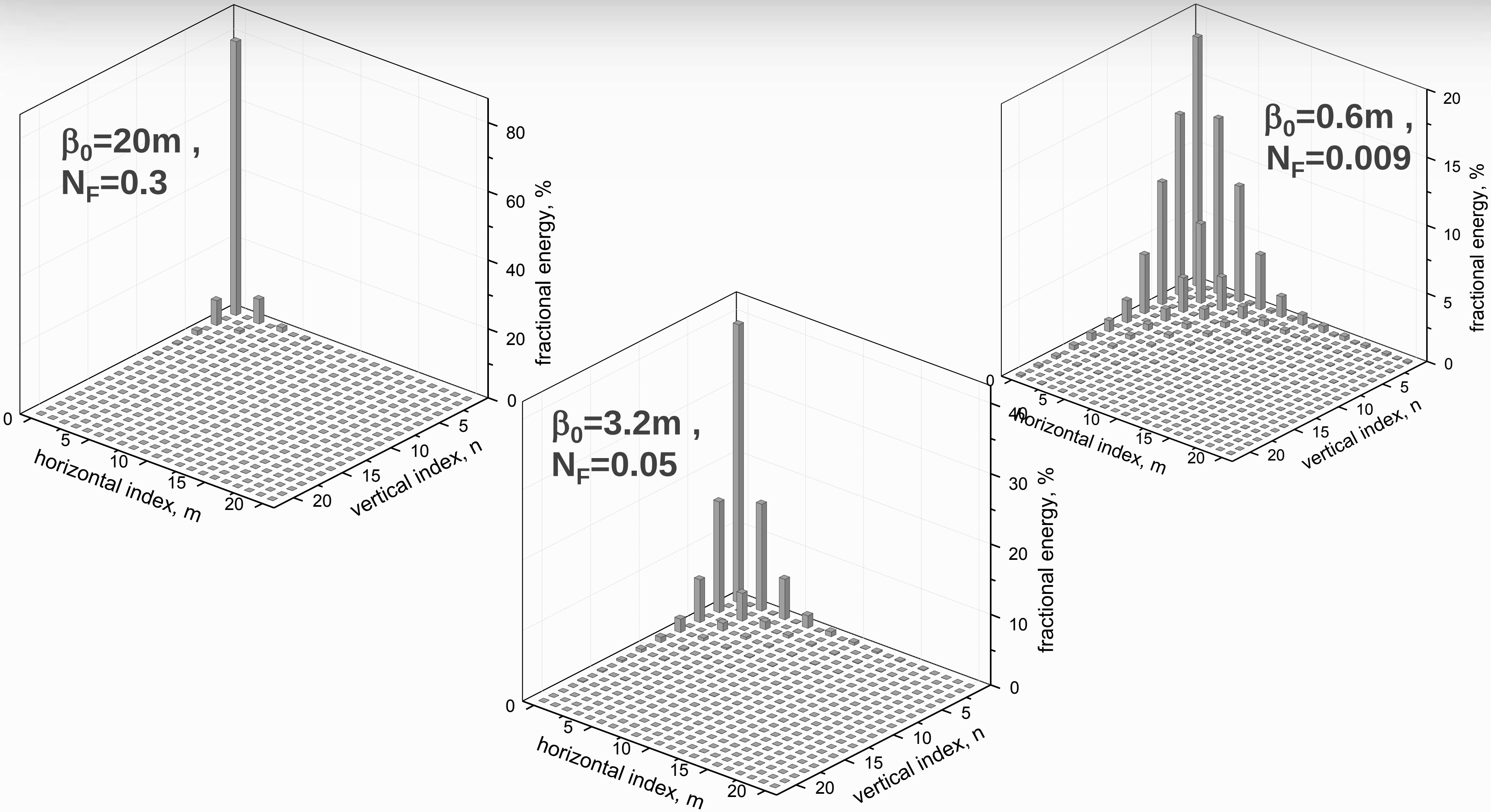
THEORY VS CALCULATIONS. THz PULSE ENERGY



difference in peak pulse energy: 0.8^X-0.4^X of the theoretically expected energy
in optimal detuning: 1.2^X-1.5^X of the theoretically expected value

probable cause: depletion and spread of the electron energy

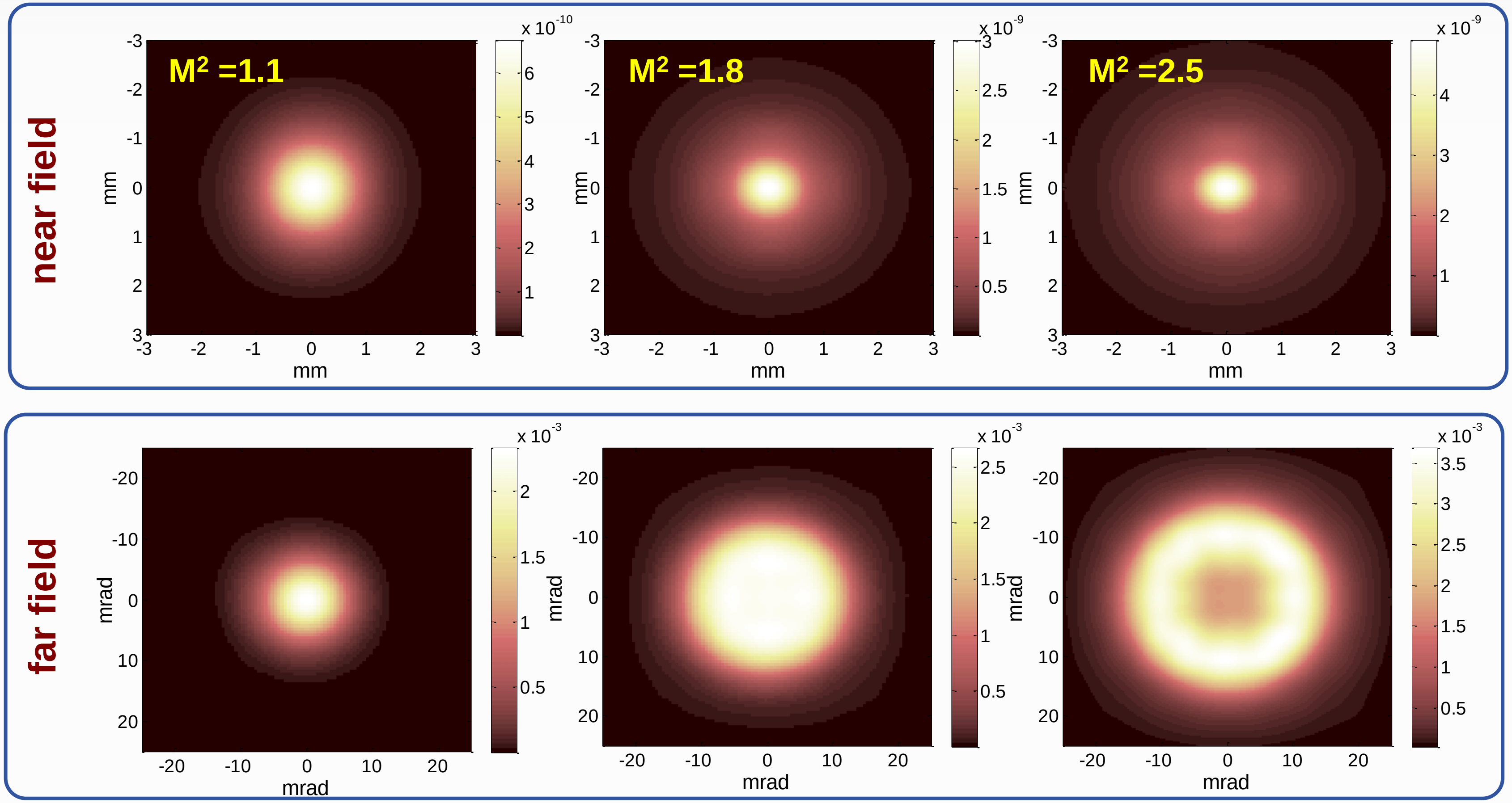
THz MODE COMPOSITION VS FRESNEL NUMBER



decrease in N_F → excitation of high-order modes→ increase in radiation spatial divergence

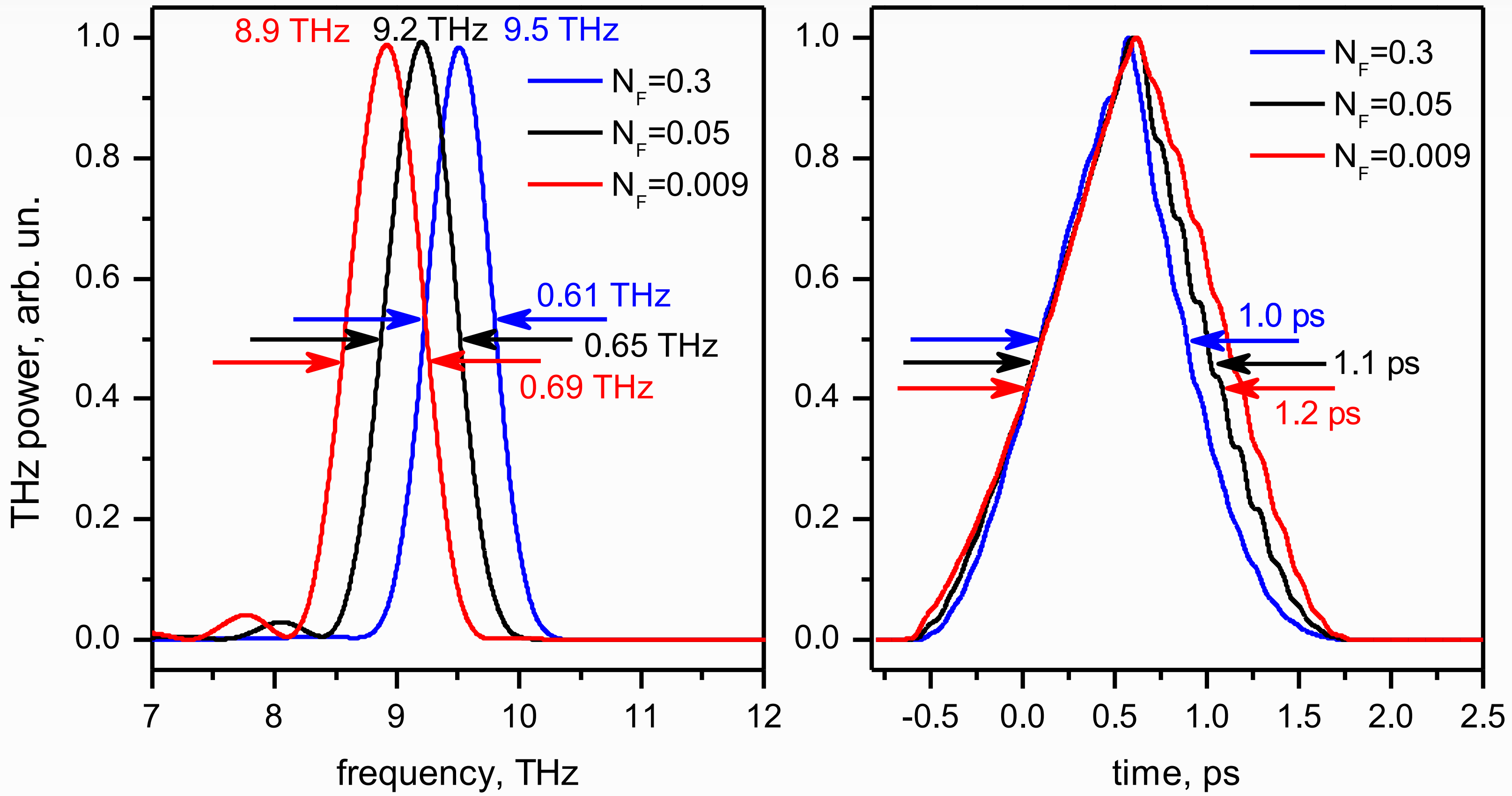
LIGHT BEAM VS FRESNEL NUMBER

β_0=20m , N_F=0.3 β_0=3.2m , N_F=0.05 β_0=0.6m , N_F=0.009



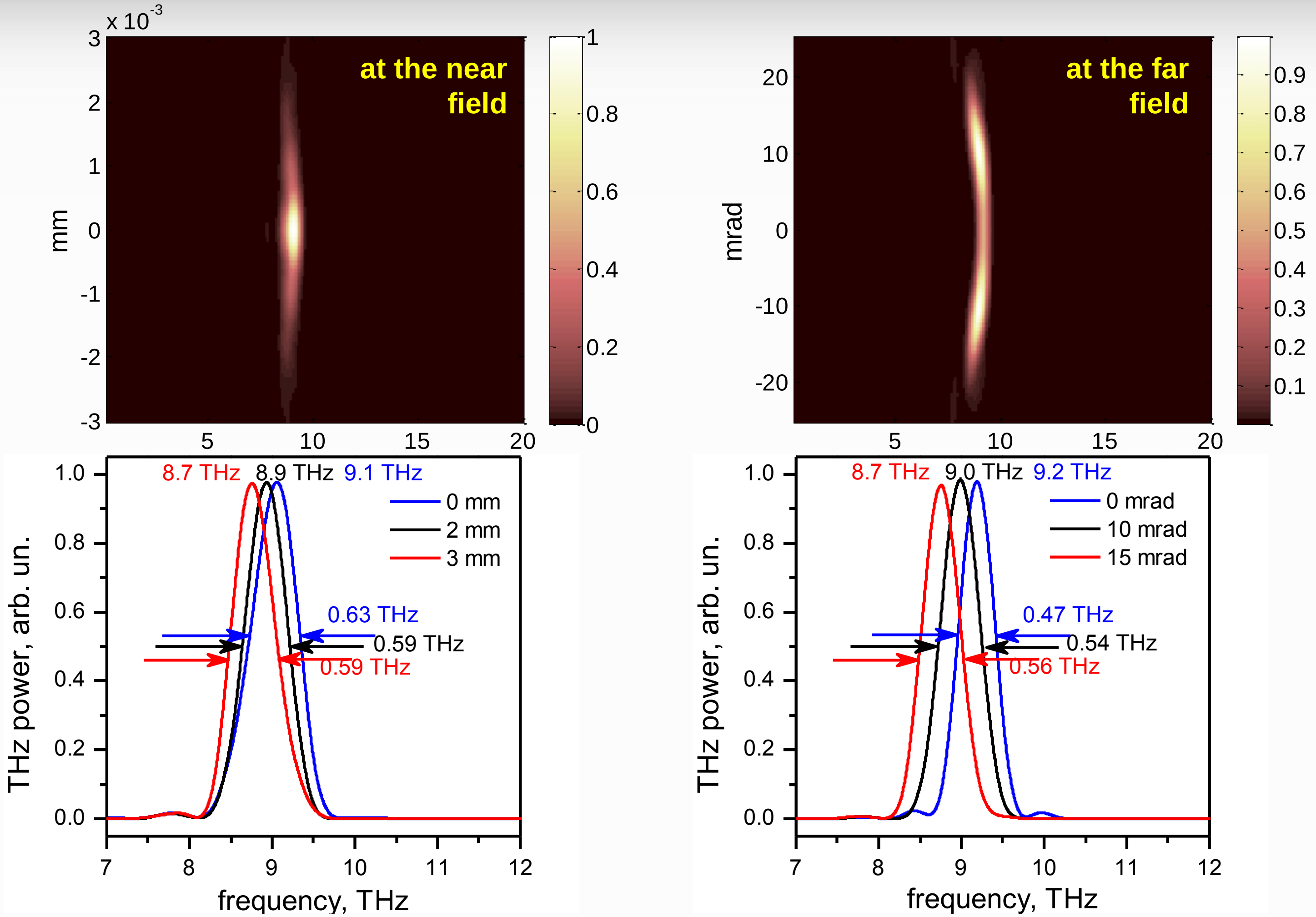
light beam quality gets degraded only ~2 times when N_F decreases by >30 times

SPECTRA & PULSE PROFILES VS FRESNEL NUMBER



FEL spectrum shift towards the low-frequency side with decrease in the Fresnel number

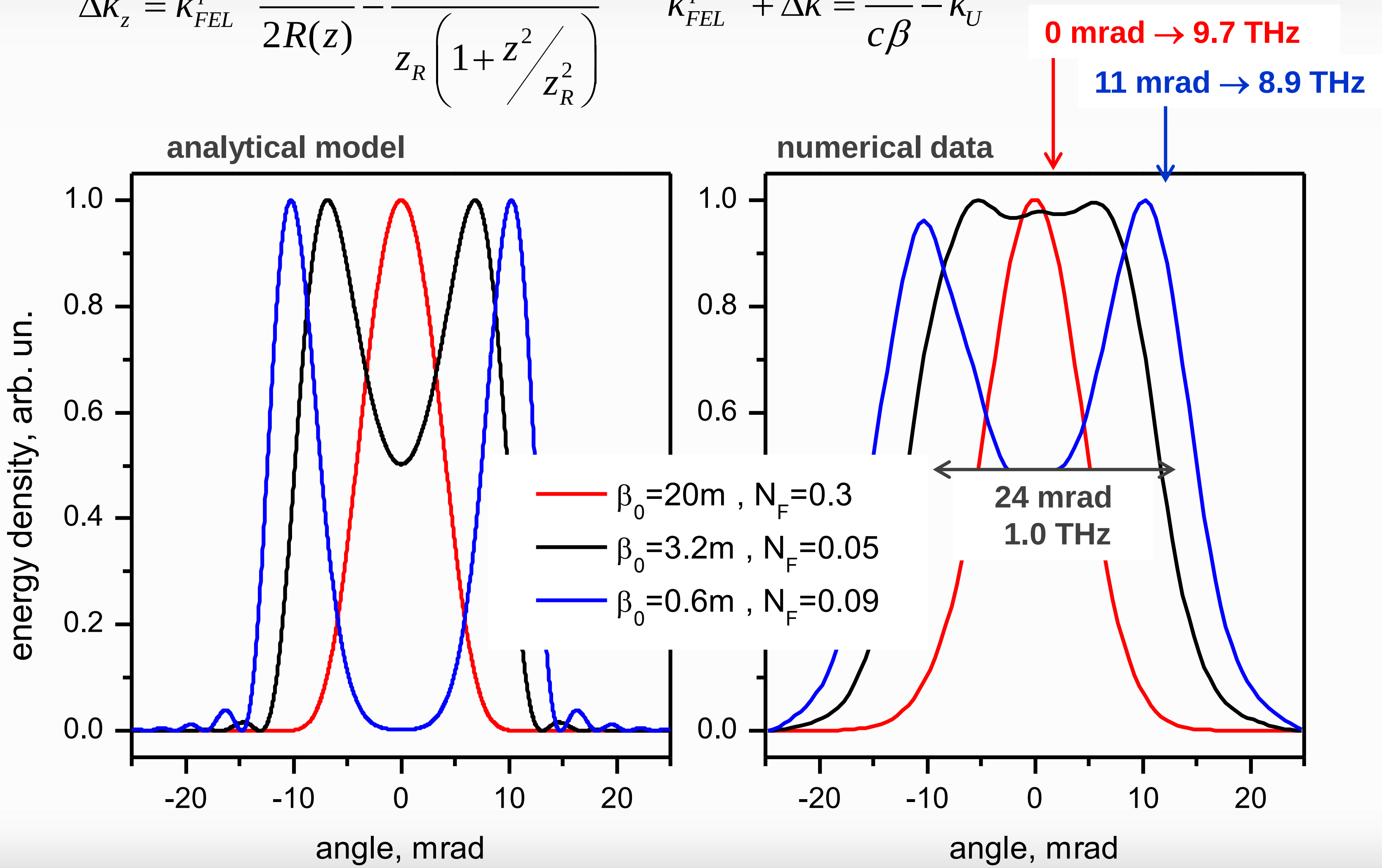
SPATIALLY-RESOLVED THz SPECTRA. N_F=0.009



high-spatial harmonics of the THz radiation are enriched by low-frequencies

THEORY VS CALCULATIONS. FAR FIELD

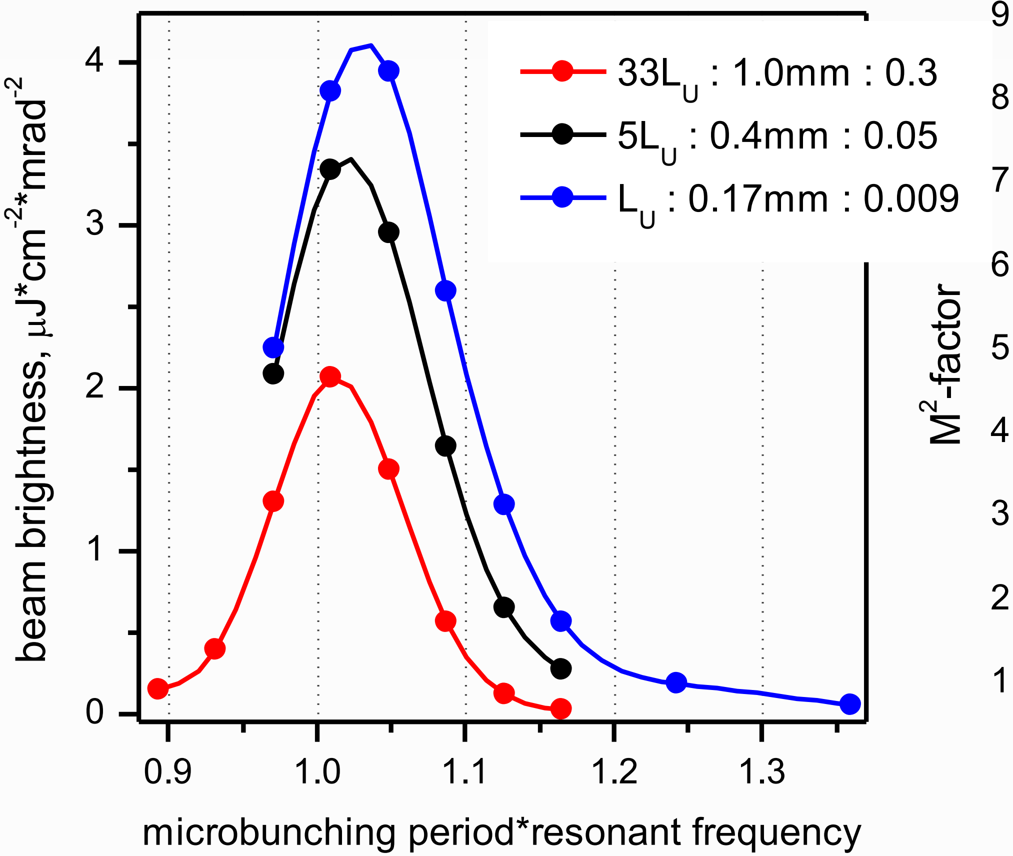
$$\Delta k_z = k_{FEL}^{plane} \frac{r^2}{2R(z)} - \frac{m+n+1}{z_R\left(1+ z^2 \big/ z_R^2\right)} \qquad k_{FEL}^{plane} + \Delta k = \frac{\omega}{c\beta} - k_U$$

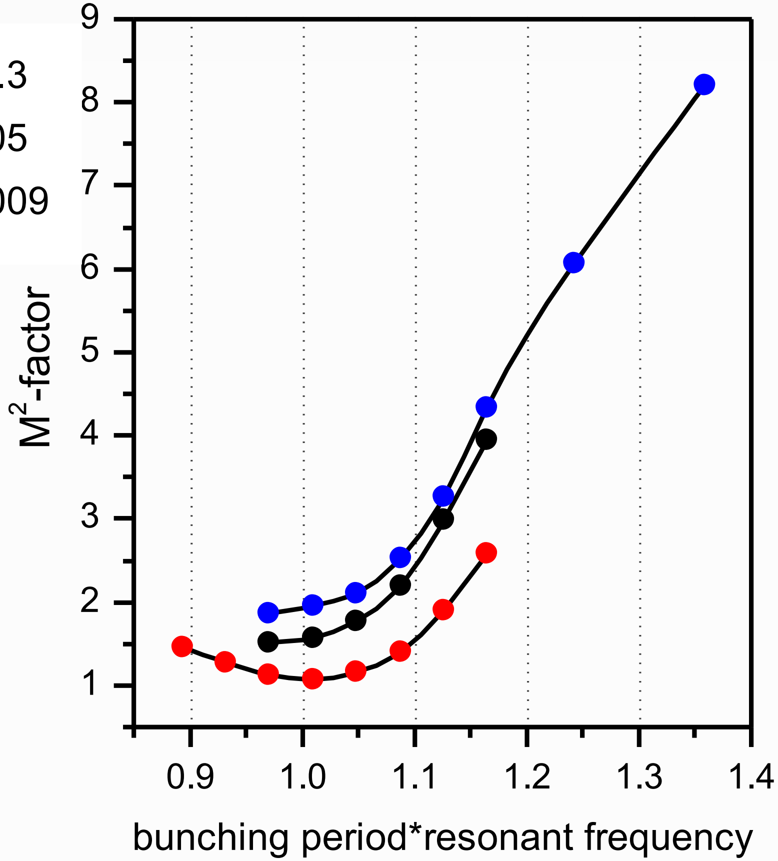


THz BEAM SPATIAL QUALITY AND BRIGHTNESS

$$B = \frac{E_{THz}}{\pi w_0^2 \pi \theta_0^2} = \frac{E_{THz}}{\lambda_{res}^2 \left(\bar{M}^2\right)^2} = \left\langle \frac{\mu J}{cm^2 mrad^2} \right\rangle$$

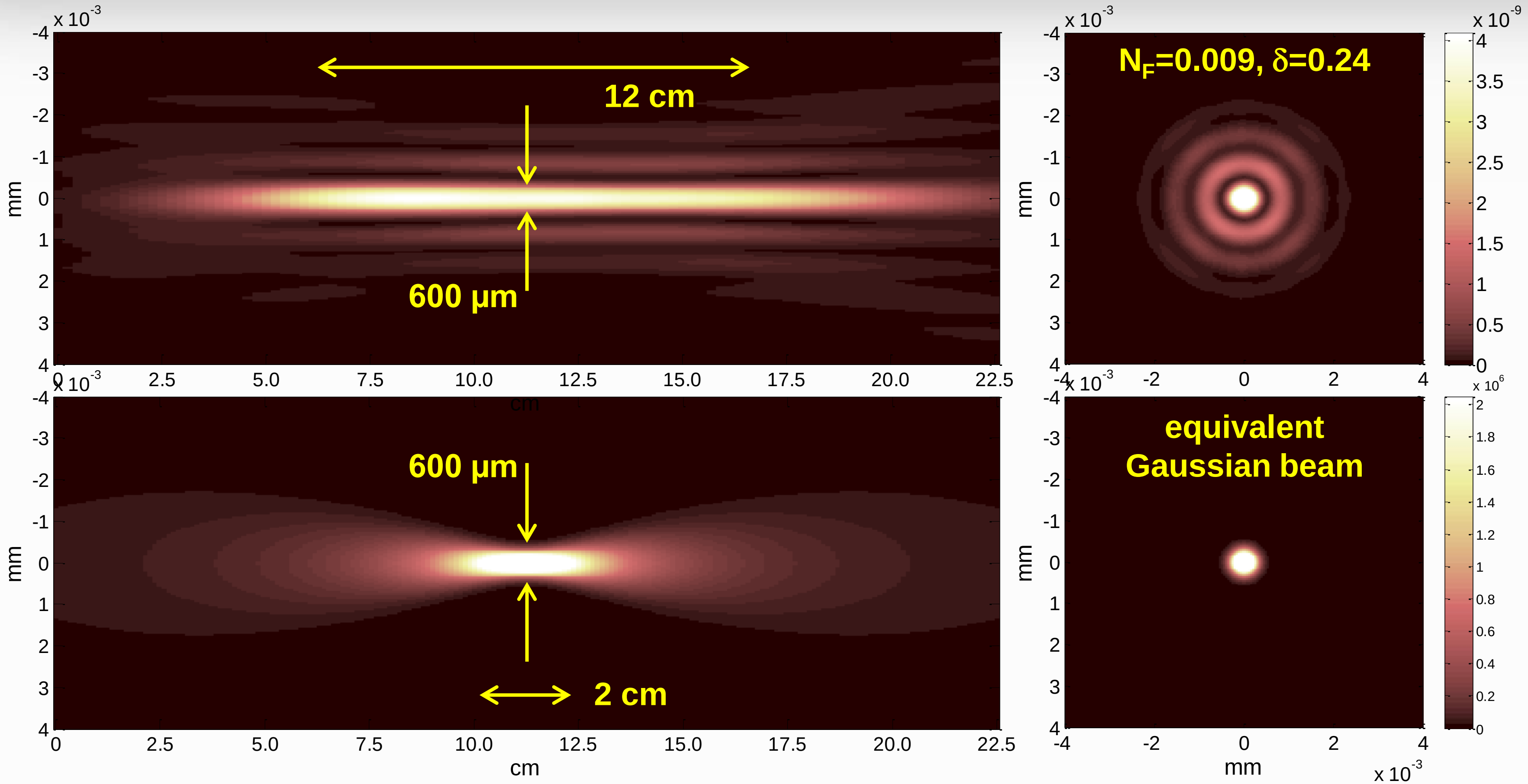
$$\bar{M}^2 = \frac{\int P(\omega) M^2(\omega) \mathrm{d}\omega}{\int P(\omega) \mathrm{d}\omega}$$





tight focusing of the e-bunch ensures greater brightness of the THz beam despite its worse spatial quality

THz BEAM WITH THE EXTENDED FOCUS



I. Minin, O. Minin, Active MMW/Terahertz Security System Based on Bessel Beams, ISRN Optics 2013, 285127.

H. Meng, et al., The Generation of Bessel Beam and Its Application in Millimeter Wave Imaging, J. Infrared Milli. Terahz. Waves 35 (2014), 208–217.

A. Bitman, et al., Computed tomography using broadband Bessel THz beams and phase contrast, Opt. Lettt. 36 (2014), 1925-1928.

THz COHERENT TOMOGRAPHY: BESSEL vs GAUSSIAN

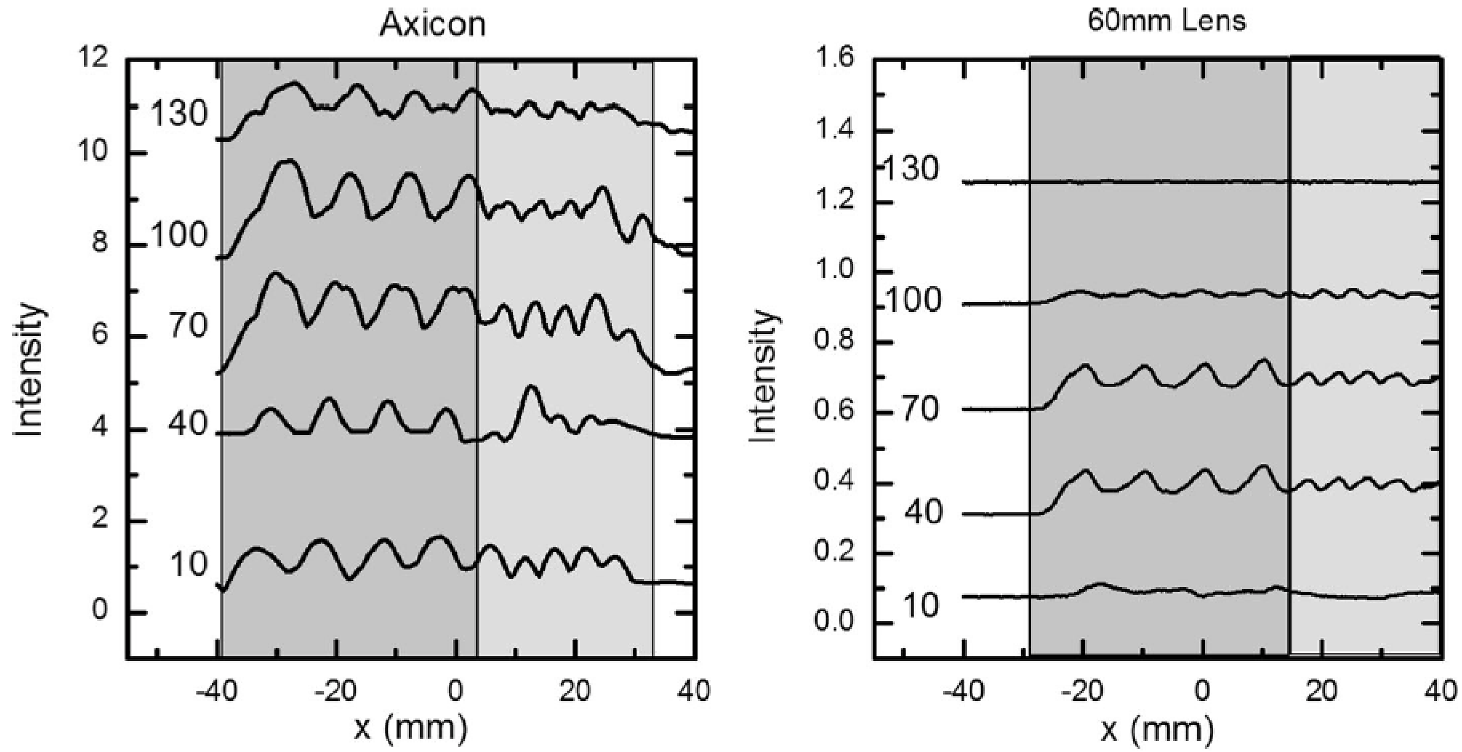
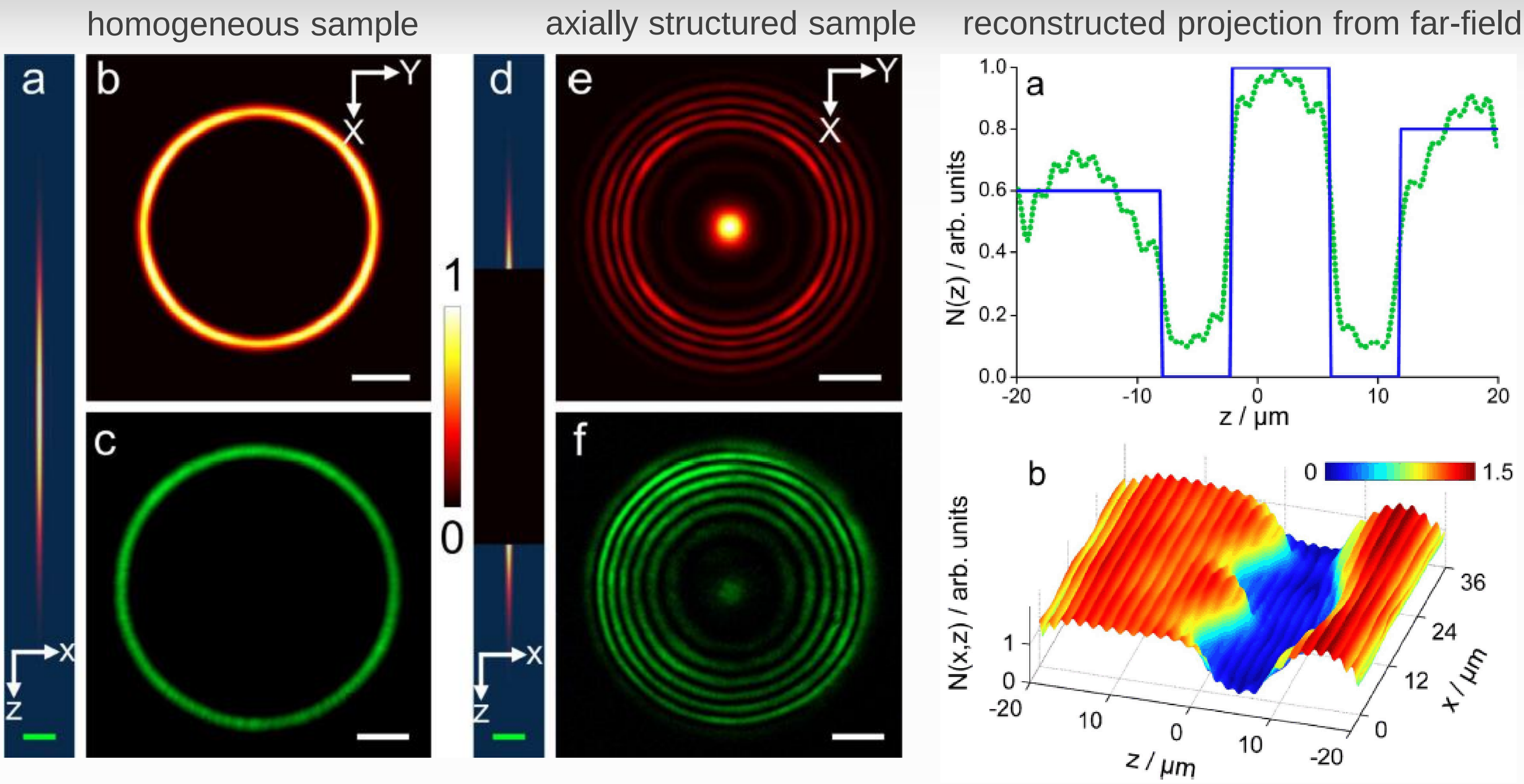


Fig. 5 Scan of a line array consisting of 4 mm metal stripes with 4 mm gaps (dark grey, left side of the individual images) and 2 mm metal stripes with 2 mm gaps (light grey, right side of the images), showing the resolution of (a) the axicon imaging system in comparison to (b) a lens imaging system, at depths of 10 mm, 40 mm, 70 mm, 100 mm and 130 mm.

reproduced from: **S.F. Busch, et al., Focus free terahertz reflection imaging and tomography with Bessel beams, J. Infrared Milli. Terahz. Waves 36 (2015), 318–326.**

enables objects to be imaged in situations in which their distance from the source is uncertain
allows for 3D objects with a single 2D raster scan

NONLINEAR SPECTROSCOPY WITH BESSEL BEAMS

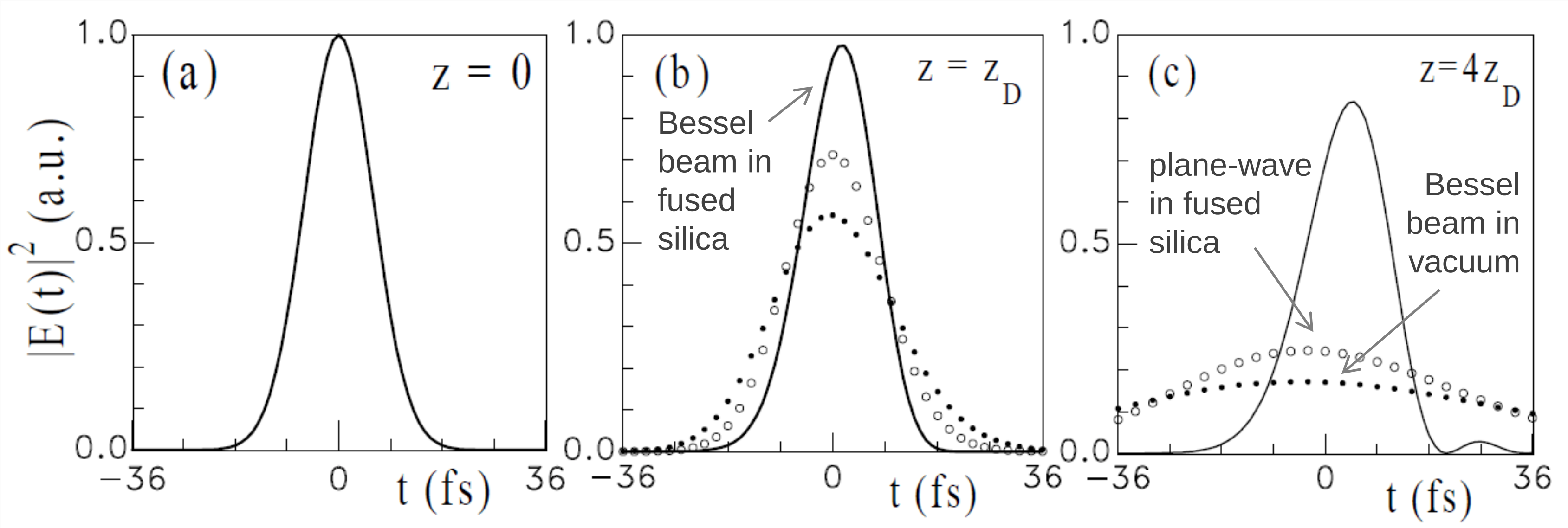


reproduced from: **S. Heuke, et al., Bessel beam CARS of axially structured samples, Nature Scient. Rep. 5, 10991 (2015).**

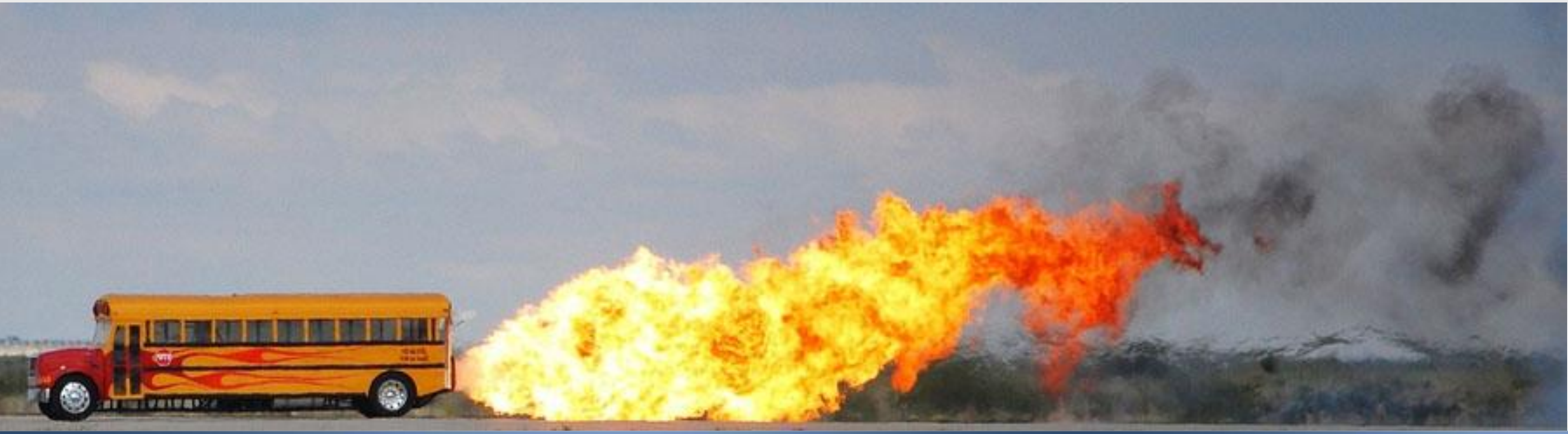
a single diffraction pattern yields sufficient information to retrieve the depth profile of axially structured samples
potential for 3D imaging at scanning the Bessel beam in xy-direction over the sample plane

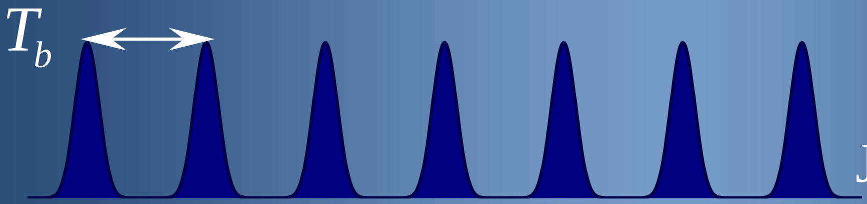
DISPERSION-FREE PROPAGATION OF BESSEL PULSES

reproduced from: **M.A. Porras, Diffraction-free and dispersion-free pulsed beam propagation in dispersive media, Opt. Lett. 26, 1364-1366 (2001). (Bessel beam central frequency: 300 THz)**



effects of material group-velocity dispersion and diffraction can mutually cancel
possible applications: ultrafast spectroscopy; pump-probe experiments





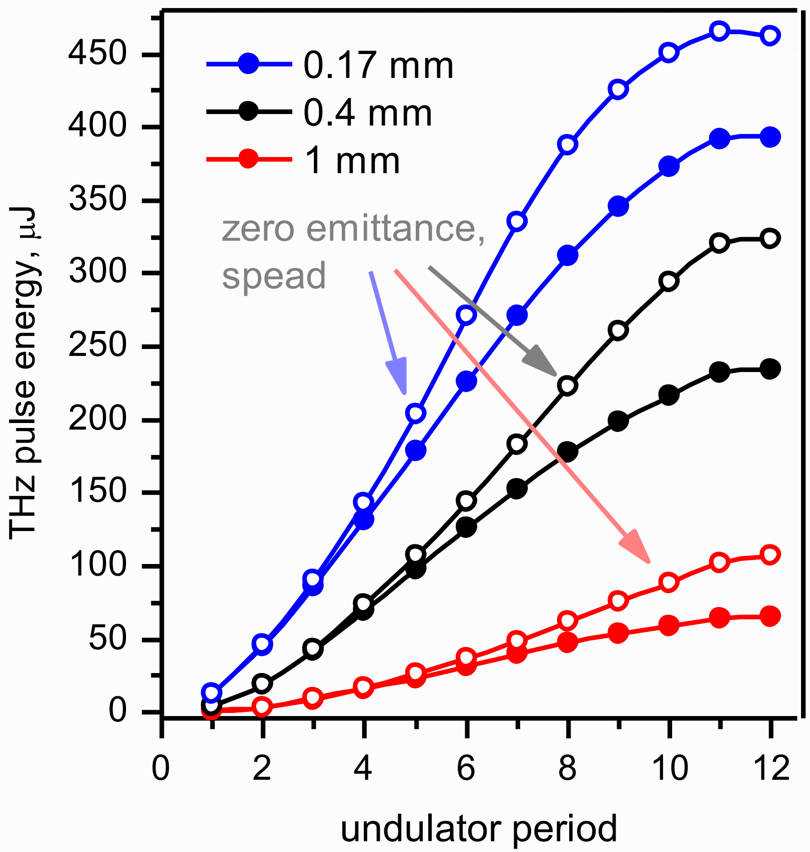
BUNCHING FACTOR 0.72

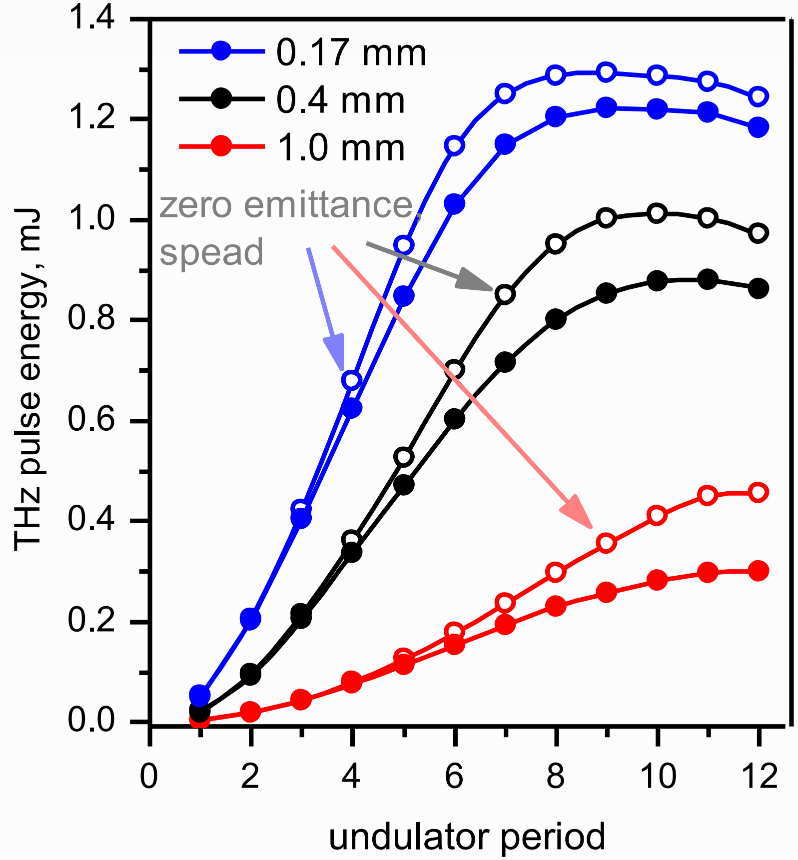
$$J(t) = \left\{ J_0 \cos^2\left(\frac{2\pi t}{T_b}\right) sgn\left[\cos\left(\frac{\pi t}{T_b}\right)\right]\right\}_{positive}$$

THz PULSE ENERGY VS BUNCH WIDTH

bunch charge	0.5 nC
bunch energy	10 mJ

bunch charge	1.1 nC
bunch energy	22 mJ

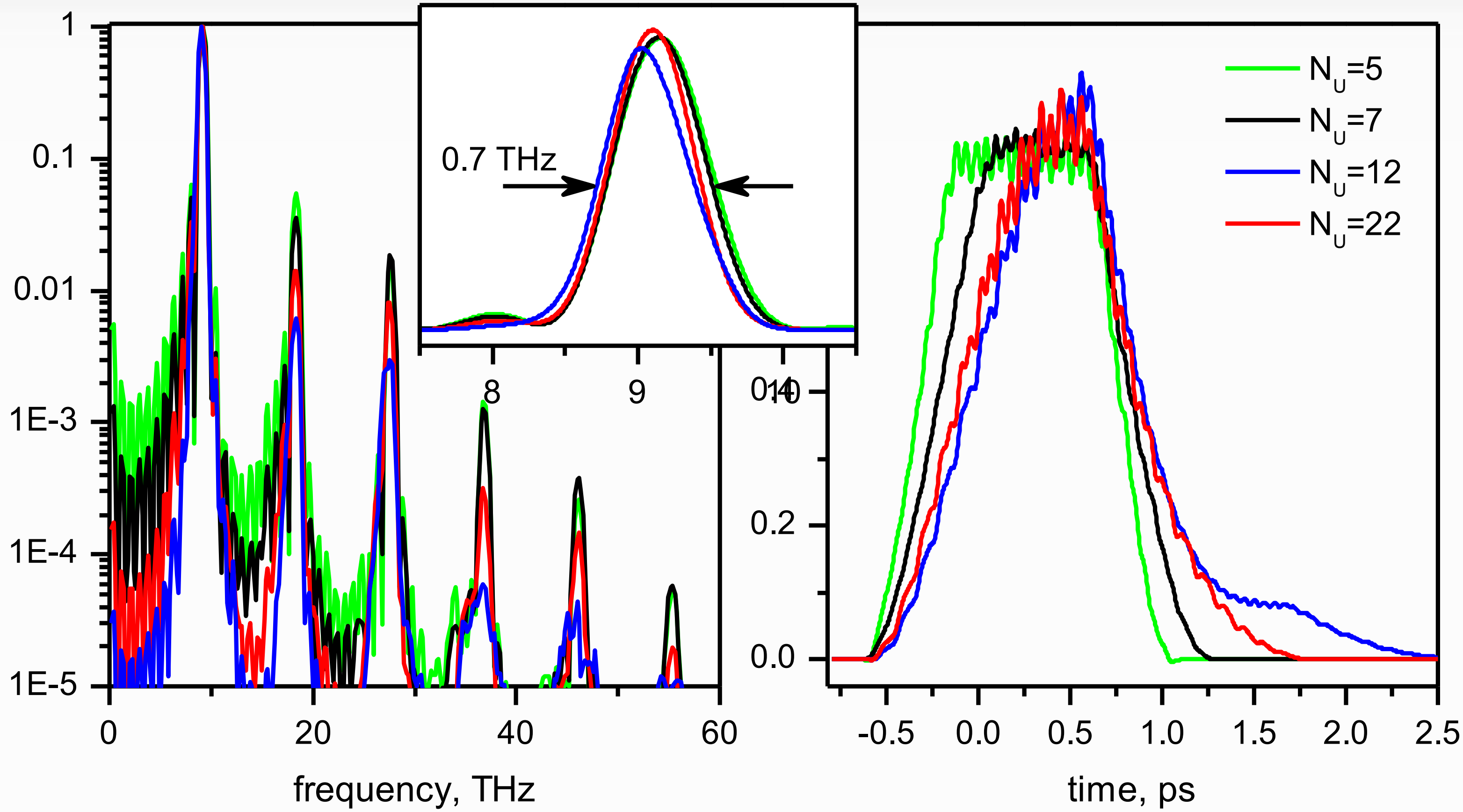




~400 μJ (>450 μJ) @ Q=0.5 nC

>1200 μJ (~1300 μJ) @ Q=1.1 nC

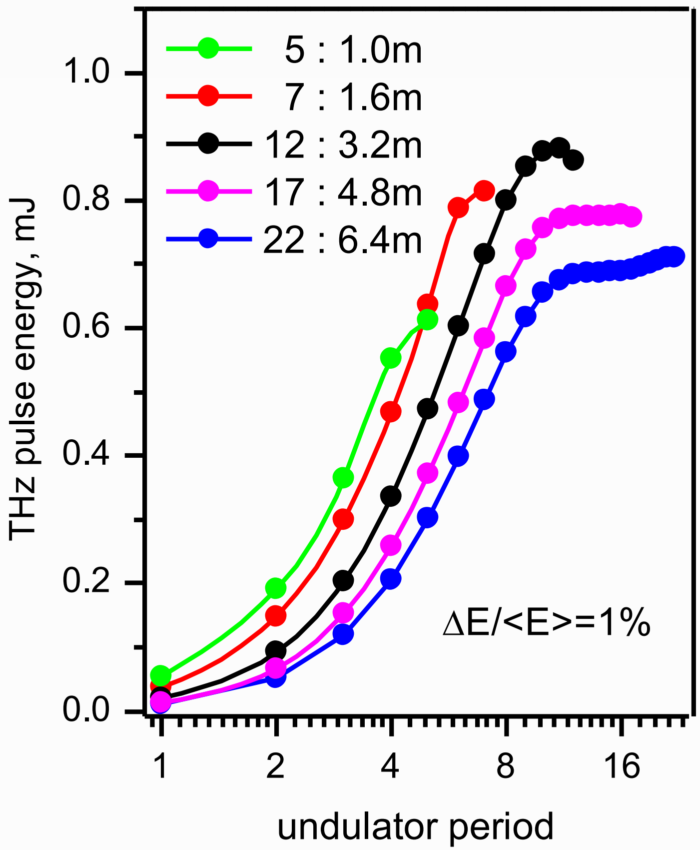
EFFECT OF THE UNDULATOR LENGTH. N_F=0.05

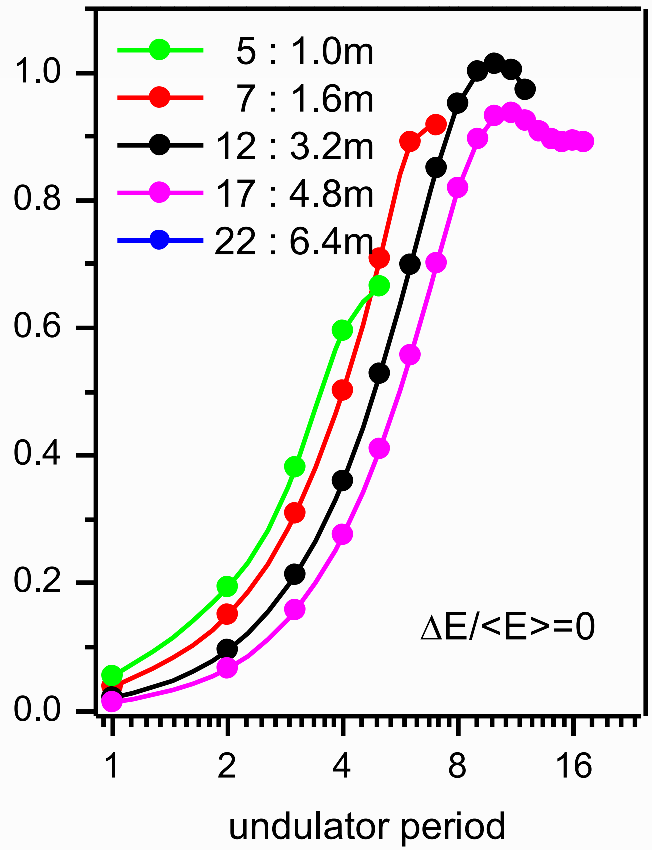


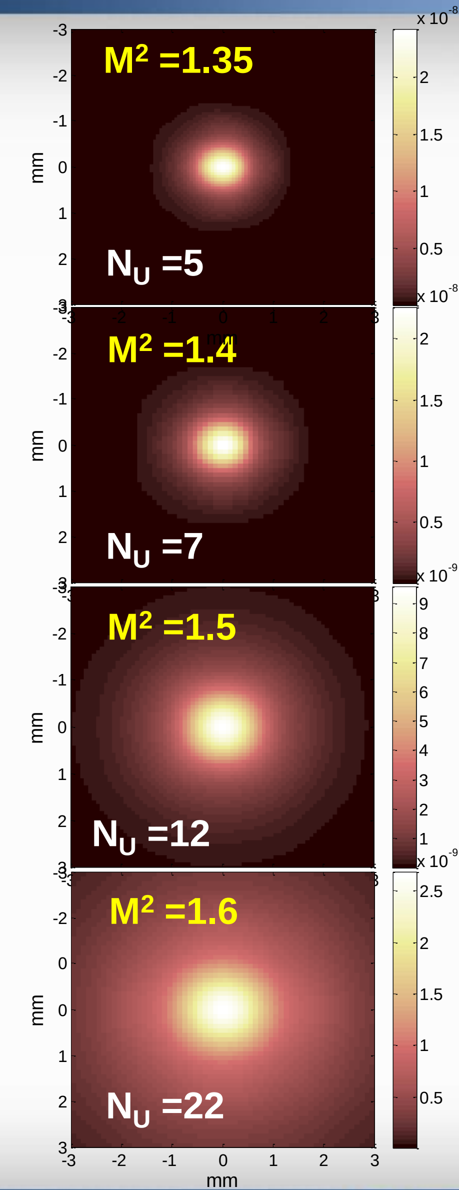
contribution of the higher-order harmonics is enhanced for short undulators
spectral width of the THz pulse is fairly insensitive to number of the undulator periods

EFFECT OF THE UNDULATOR LENGTH. N_F=0.05

broad bunch and long undulator or a narrow bunch and short undulator?



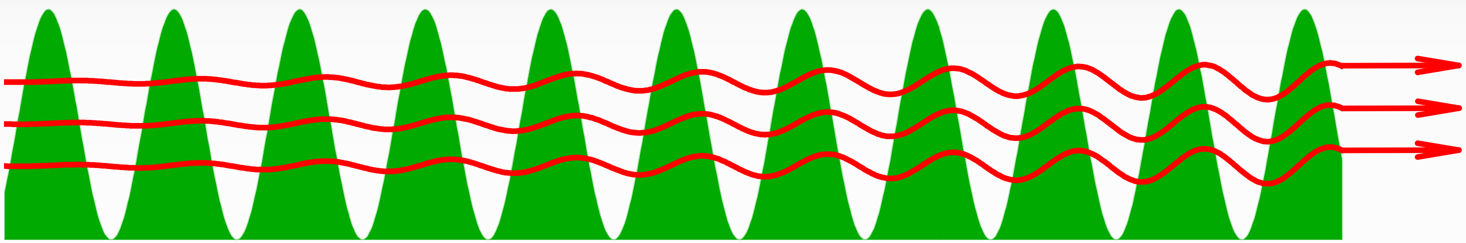




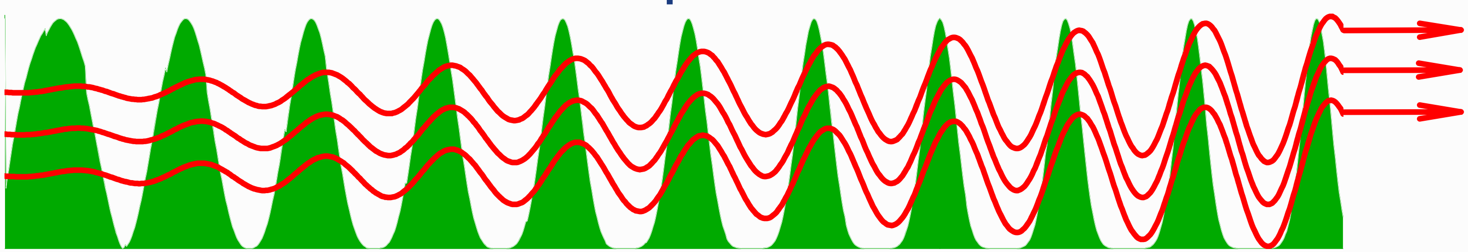
N_U=9-12 is the optimal number of undulator periods for N_F=0.05
pulse energy dependence on N_U is essentially nonlinear

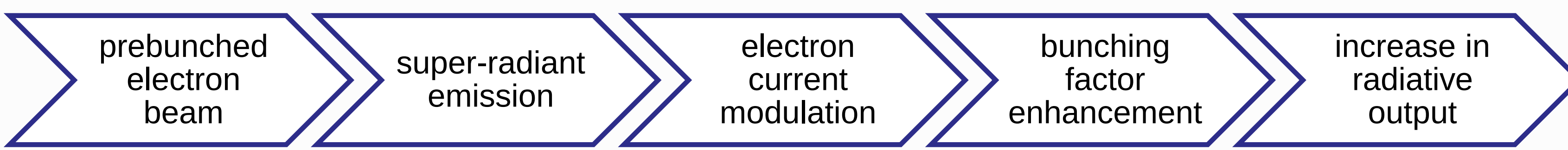
STIMULATED SUPER-RADIANCE

super-radiant case



stimulated super-radiant case

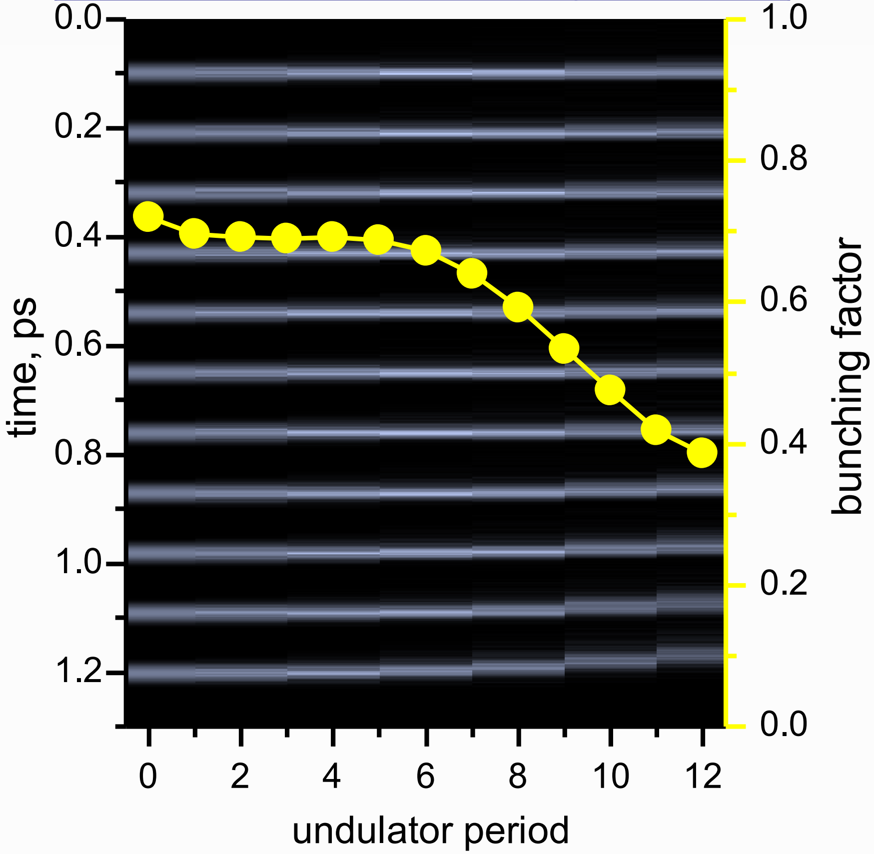


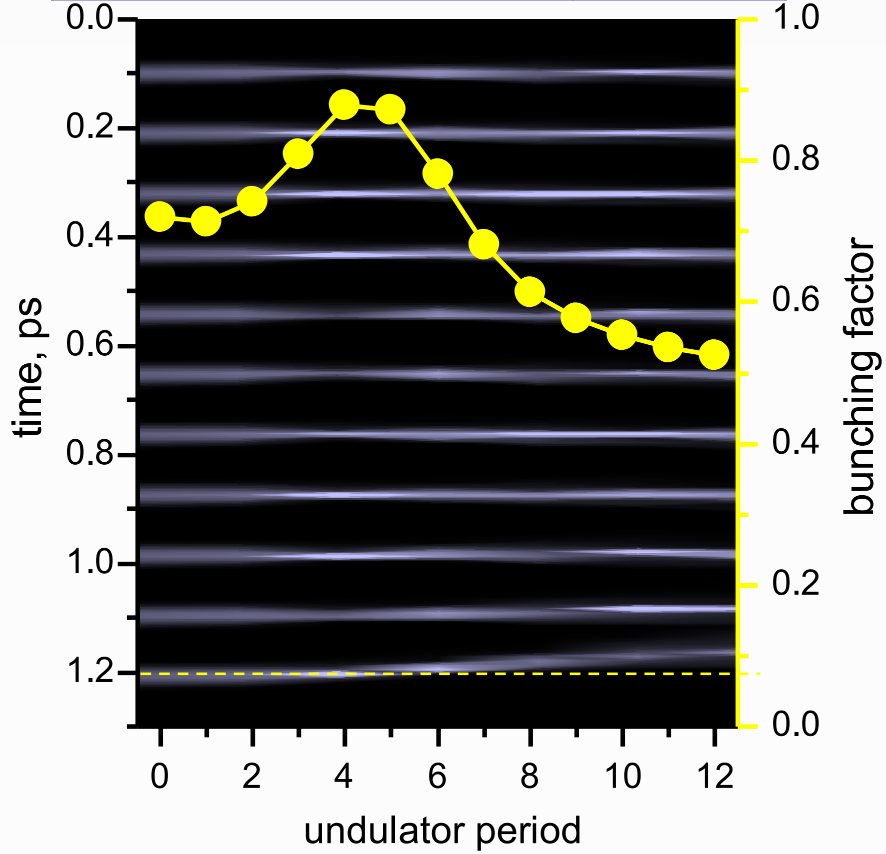


ELECTRON ENERGY DEPLETION

bunch charge	0.5 nC
electron energy spread	1%
bunch emittance, rms	2 mm·mrad

bunch charge	1.1 nC
electron energy spread	0
bunch emittance, rms	0

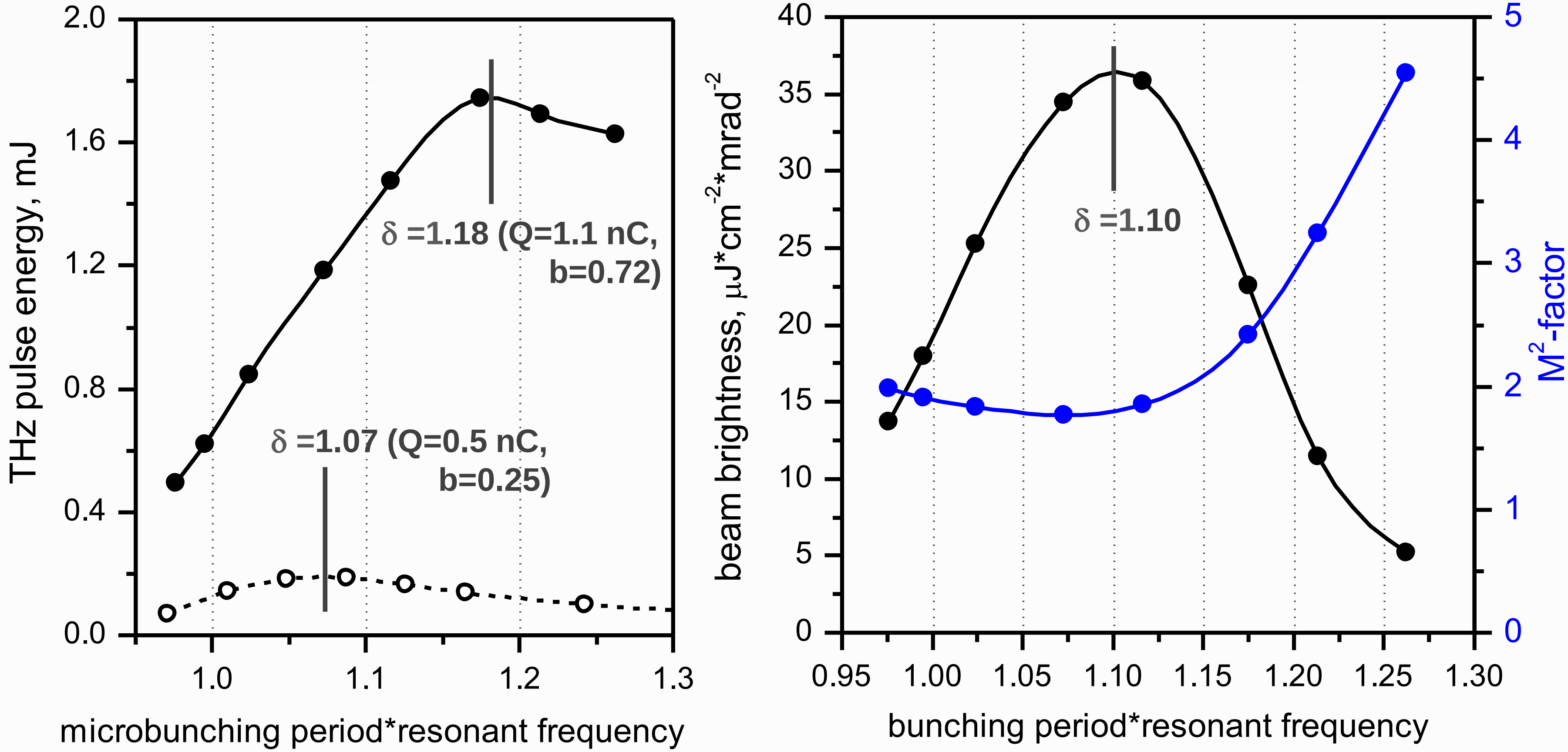




interaction with SACSE promotes the electron bunching enhancement
the enhancement is further destroyed due to spread and depletion in electron energy

EFFECT OF THE BUNCHING PERIOD. $N_F=0.009$

peak pulse energy: 1.7 mJ @ δ=1.18; output beam brightness: 36 μJ/cm²/mrad² @ δ=1.10

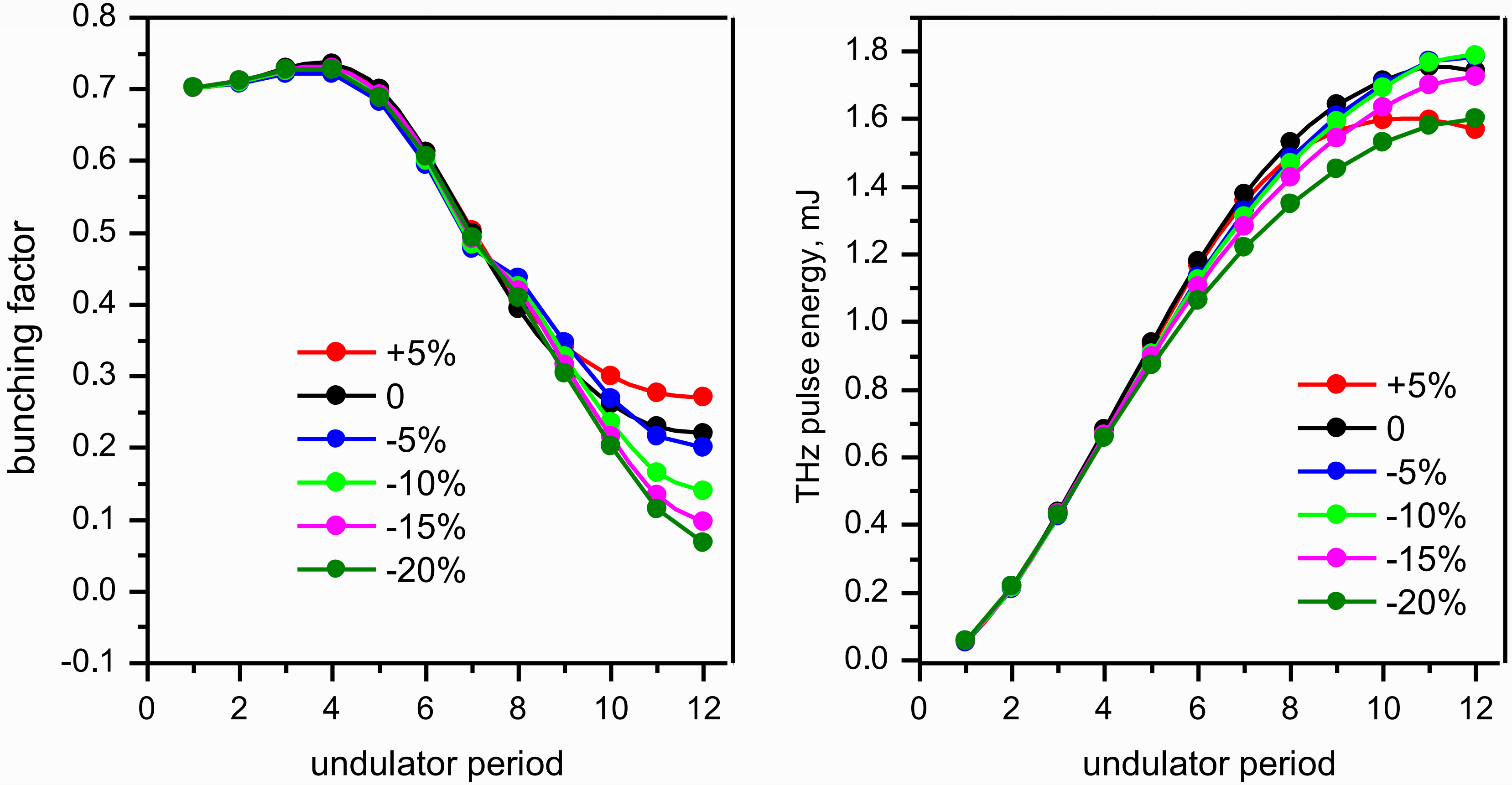


cause of the shift in the optimal bunching period with increase in the bunch charge and bunching factor

TAPERED UNDULATOR. N_F=0.009

N.M. Kroll, et al., IEEE J. Quant. Electr. 17 (1981), 1436. Down-shift tapering of B_U:

- phase velocity of the ponderomotive wave slows down relative to the e-beam velocity
- electrons, trapped into the slowing down buckets, are forced to emit more efficiently
- requirement: tight bunching + high light intensity

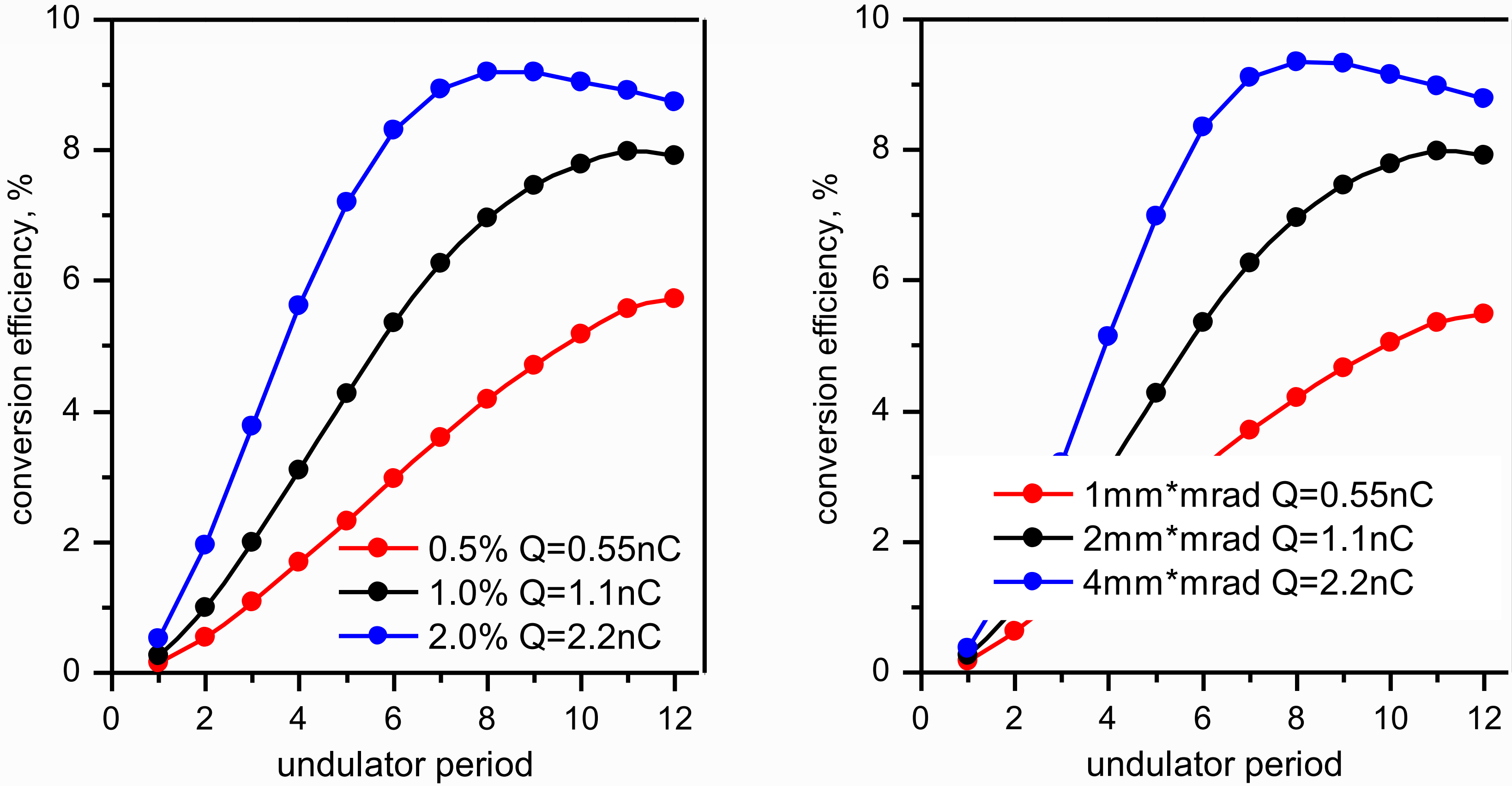


no essential positive effect on FEL pulse energy in our conditions

EFFECT OF THE ENERGY SPREAD AND EMITTANCE

low energy spread with low bunch charge or high energy spread with high bunch charge?

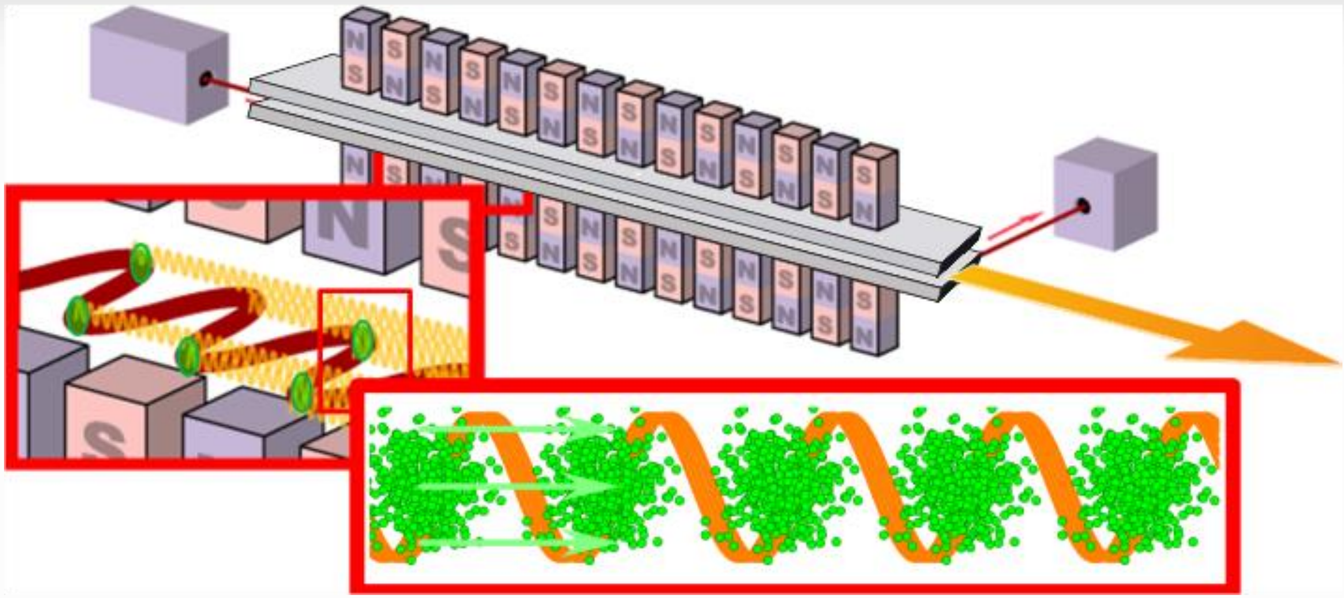
low emittance with low bunch charge or high emittance with high bunch charge?



up-scaling the bunch charge is preferable despite degradation in energy spread and emittance

FEL SOURCE WITH A PLANE WAVEGUIDE

WAVEGUIDED FEL SOURCE



Incorporating an optical waveguide:

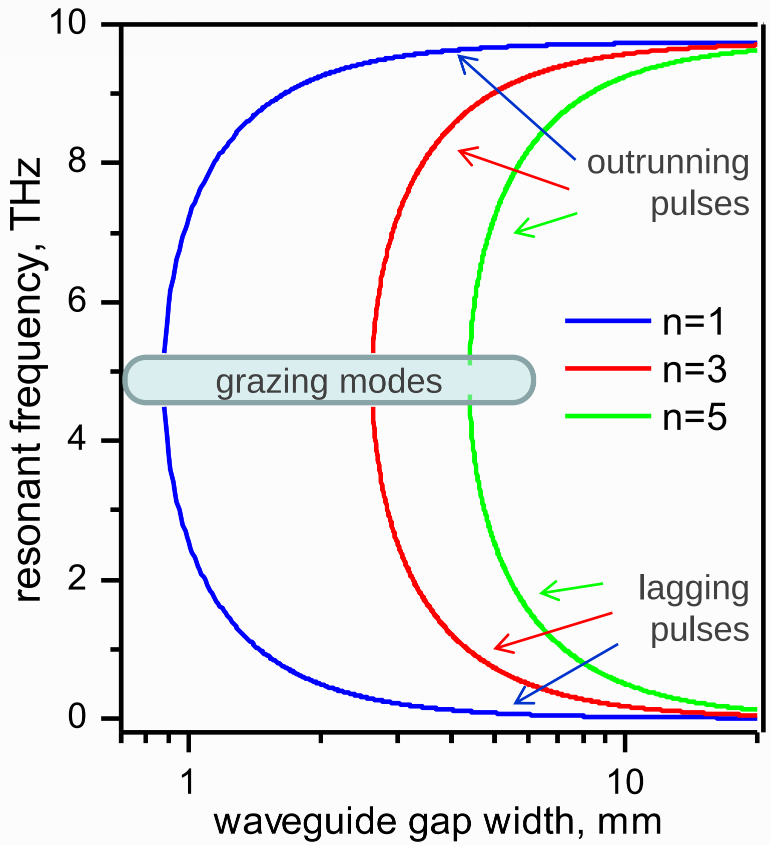
- prevents diffraction defocusing
- enhances THz light intensity
- potential for THz power increase due to SACSE effect

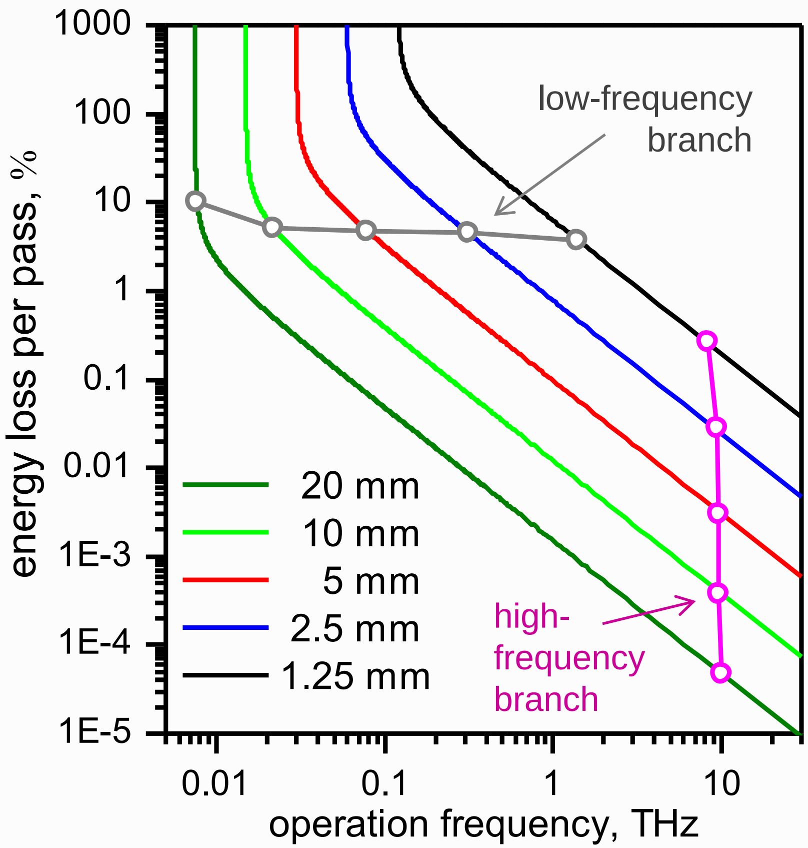
- additional radiative losses due to resistance of the waveguide wall material?
- pulse broadening due to the group velocity dispersion?

EXCITATION CONDITIONS FOR GUIDED MODES

waveguide gap, b	2.5; 5; 10; 20 mm
material of waveguide walls	AISI 304 Cr-Ni Stainless Steel

magnetic permeability of waveguide walls	1.008
conductivity of waveguide walls	1390 kS

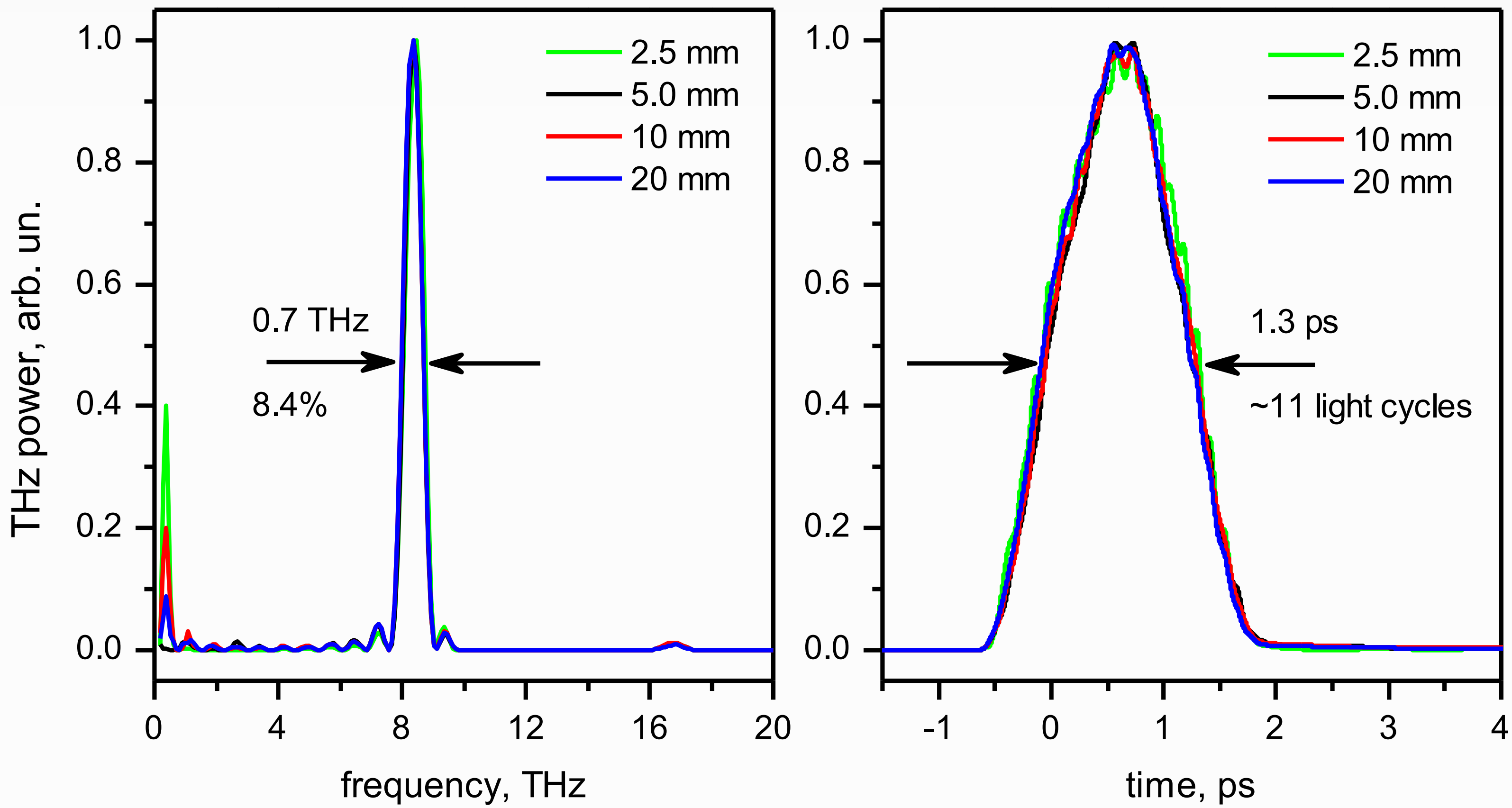




fundamental mode energy loss over undulator pass: 4-10% for low FB; <1% for high FB

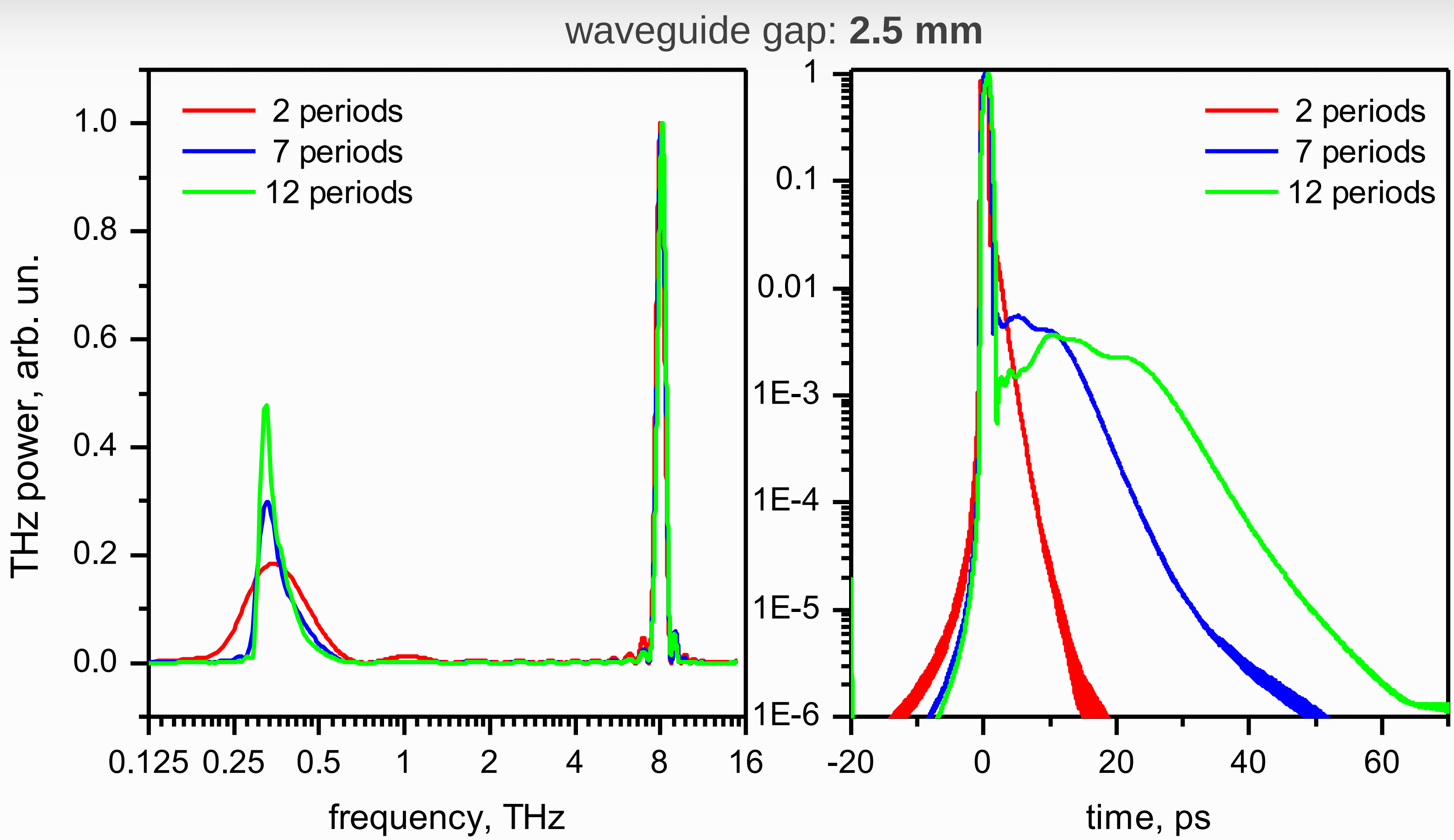
THz SPECTRA & PULSE PROFILES VS WAVEGUIDE GAP

resonant frequency: **9.7 THz** bunch energy: **10 mJ** bunch radius: **140 μm**



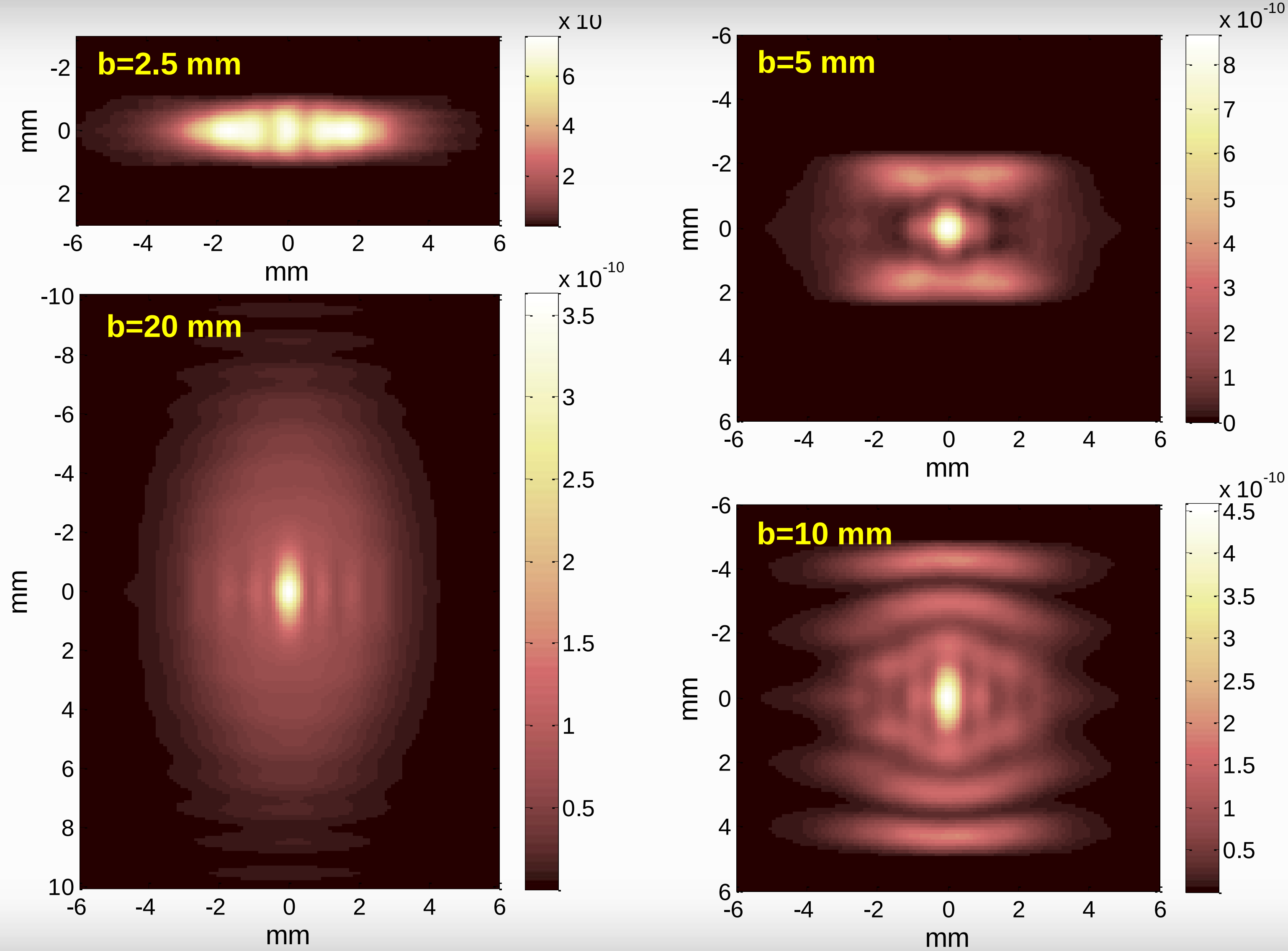
contribution of the low FB is an order of the magnitude less than that of the high FB
THz pulse broadening due to GVD in the waveguide is negligible

LOW-FREQUENCY BRUNCH CONTRIBUTION



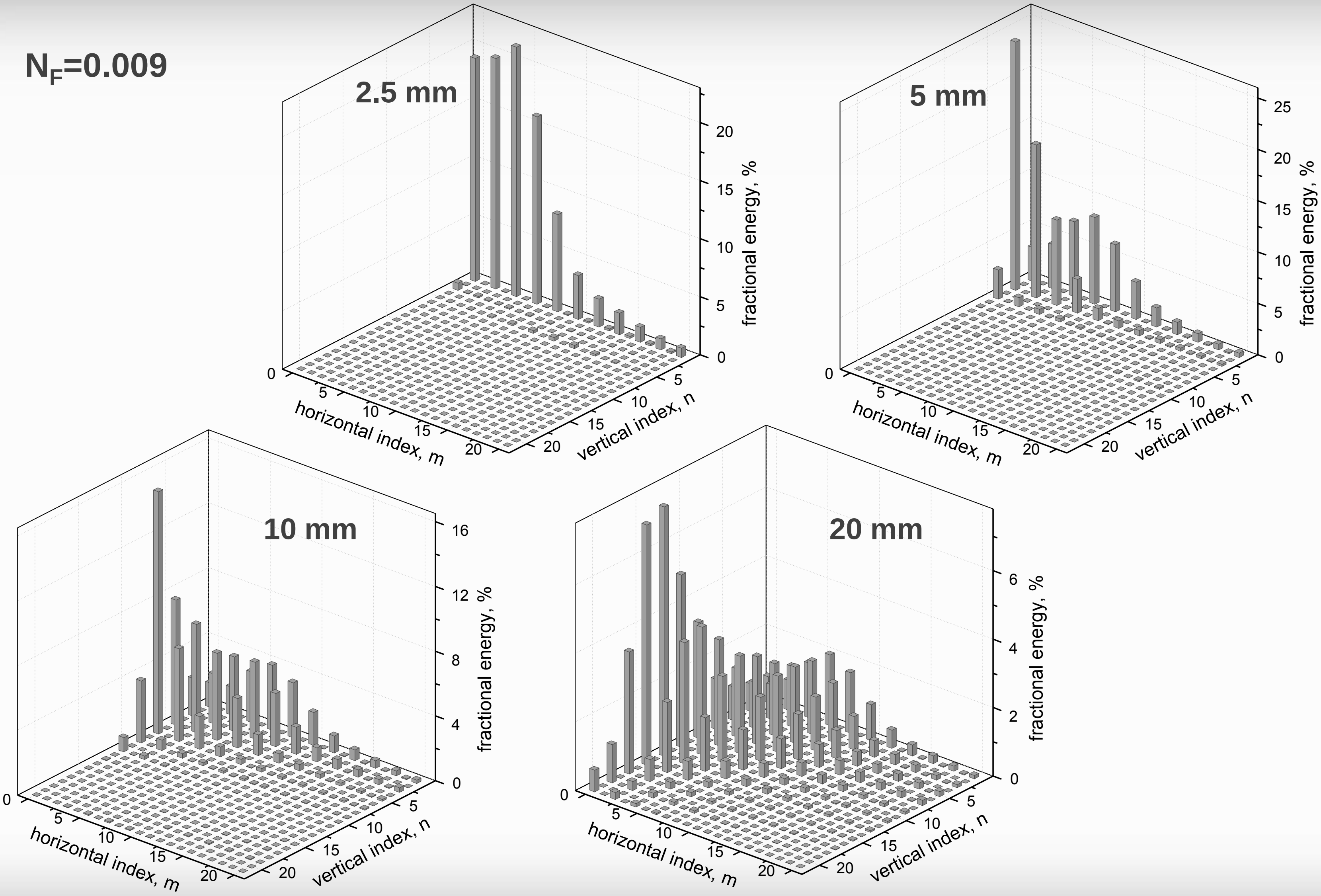
effect of the LFB reveals itself as a low intensity plato at the pulse end
the plato width increases with the undulator length

EFFECT OF THE WAVEGUIDE GAP. NEAR FIELD



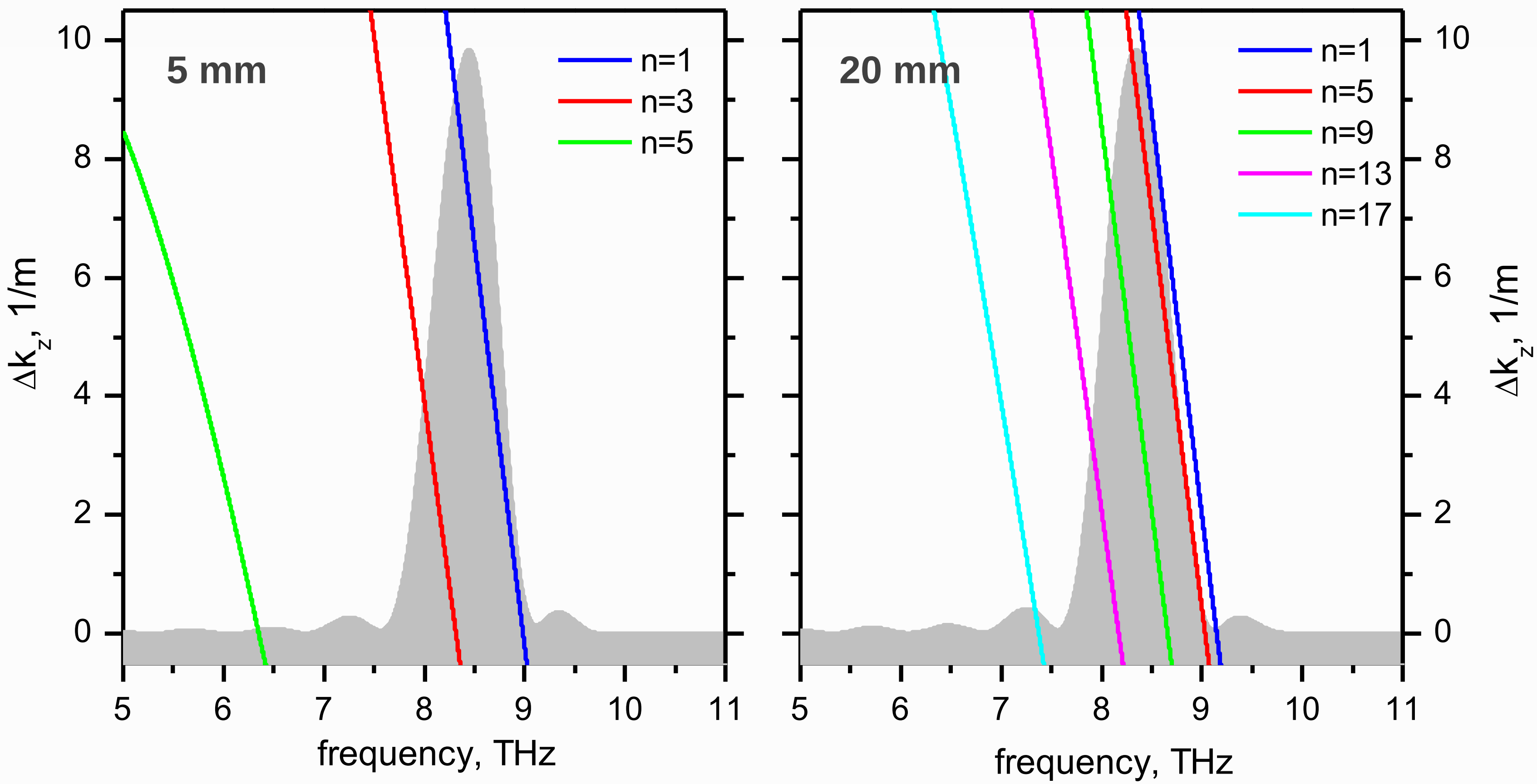
EFFECT OF THE WAVEGUIDE GAP. MODE COMPOSITION

N_F=0.009



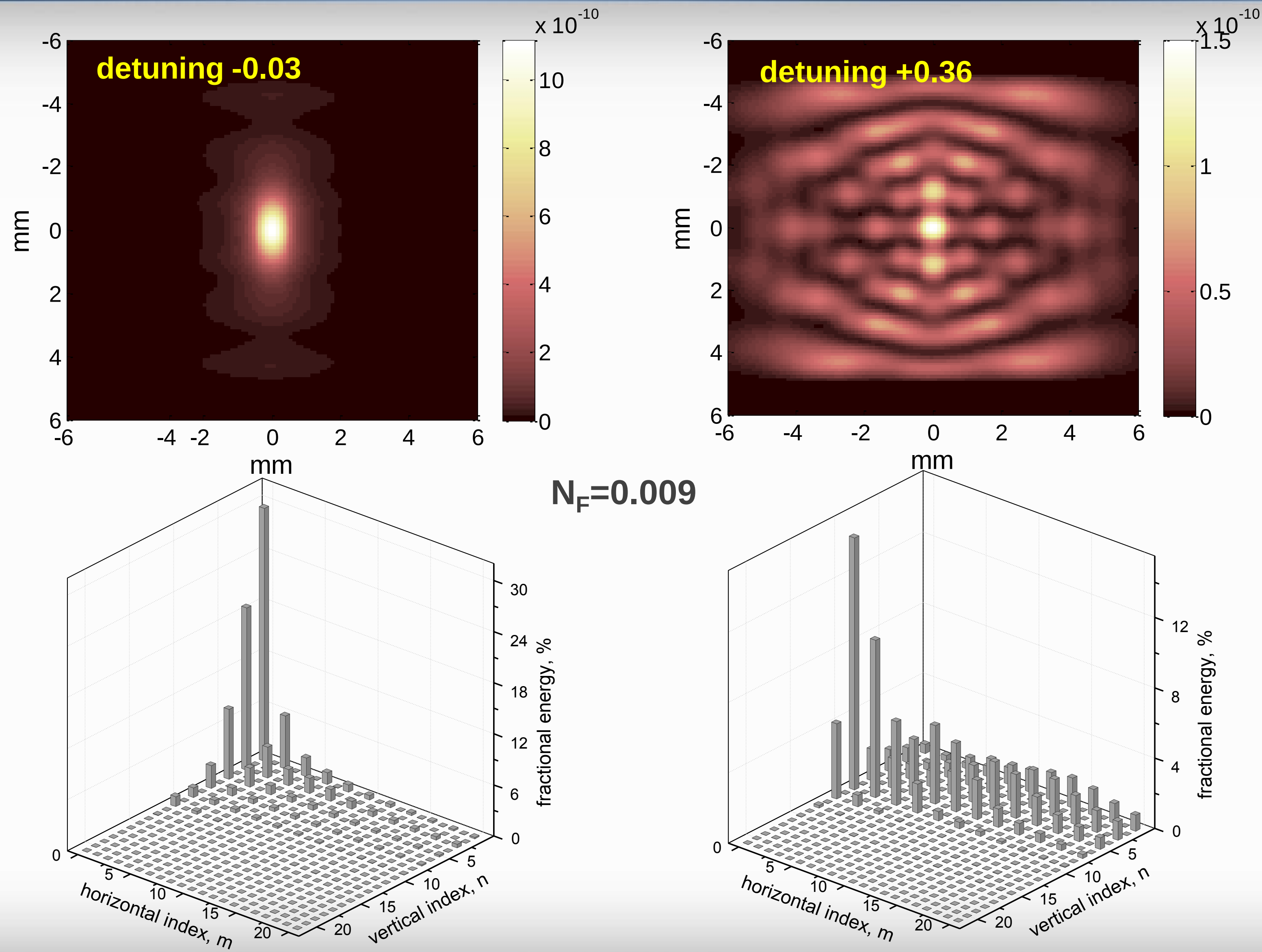
RESONANT CONDITIONS IN AN FEL WAVEGUIDE

N_F=0.009 $\Delta k_z = k_{wavegide} - k_{FEL}^{plane}$ $k_{FEL}^{plane} = \dfrac{\omega}{c\beta} - k_U$ $k_{waveguide} = \sqrt{\left(\omega/c\right)^2 - \left(\pi n/b\right)^2}$



untermode frequency decreases with the increase in the waveguide gap

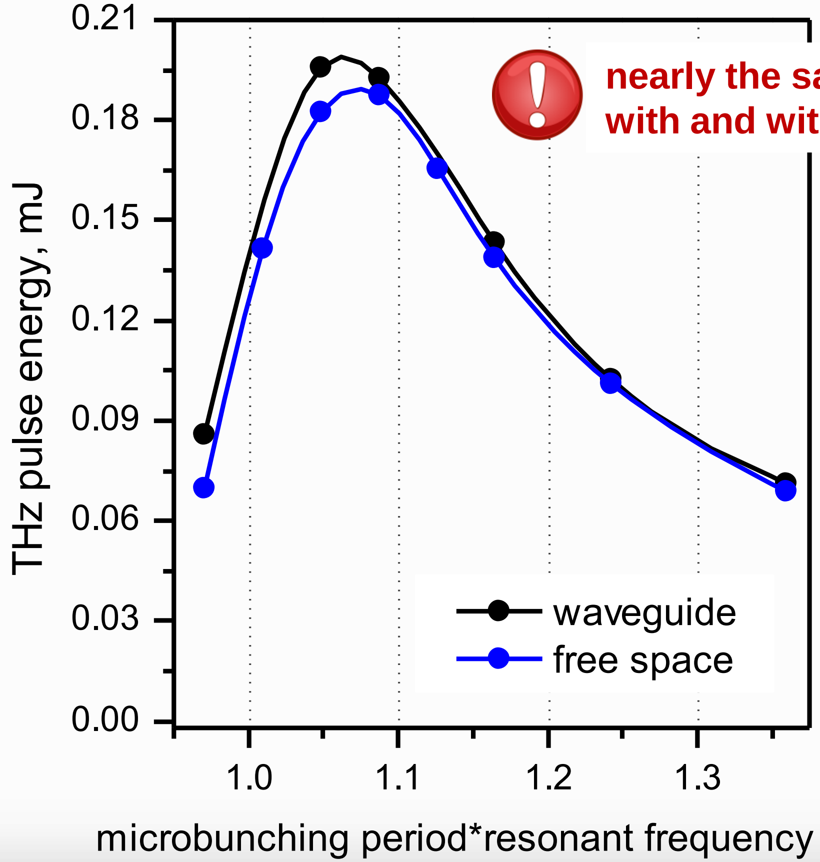
THE DETUNING EFFECT. NEAR FIELD



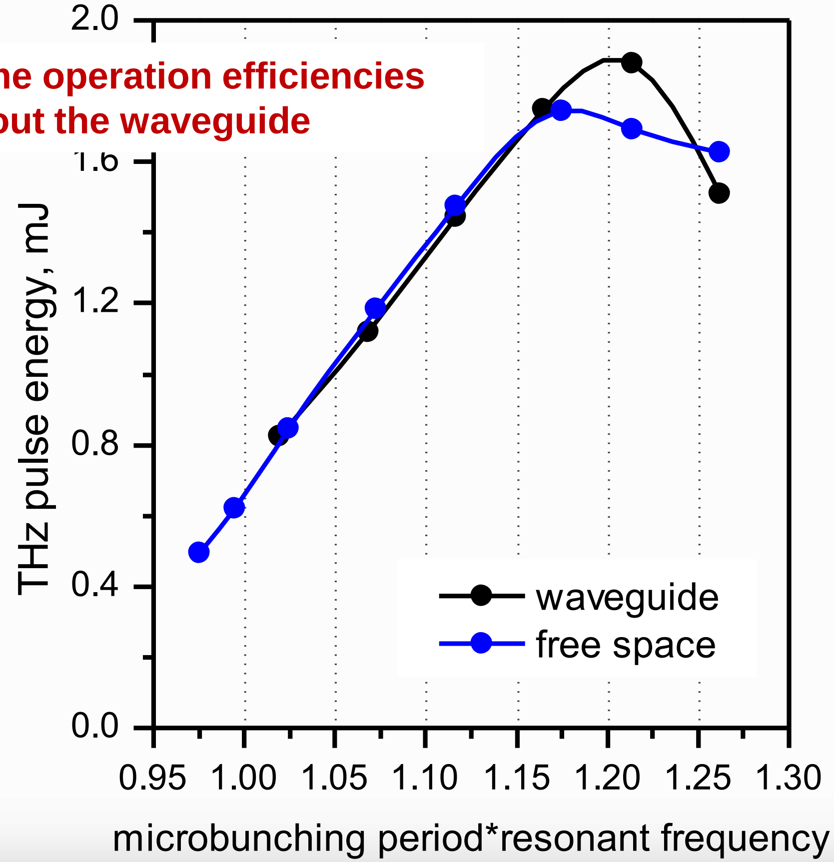
THz PULSE ENERGY

bunching factor	0.25
bunch charge	0.5 nC
bunch energy	10 mJ
guide gap	10 mm

bunching factor	0.72
bunch charge	1.1 nC
bunch energy	22 mJ
guide gap	2.5 mm



nearly the same operation efficiencies with and without the waveguide



SUMMARY

- the free-space and waveguided linear undulator geometries of the single-pass multi-cycle THz light source driven by a prebunched electron beam have been considered numerically; both the undulator types ensure nearly the same operation efficiencies at ~10 THz;
- for the electron bunch, comprising 11 micro-bunches each with the emittance of 2 mm·mrad, energy spread of 1%, and charge of 100 pC, the FEL pulses with energy of up to 1.6 mJ is feasible at the conversion efficiency of 7% and spatial beam quality of less than 3;
- within the parameter space considered, the optimal number of the undulator periods was found to be 9 – 12;
- tight focusing of the electron bunches when the β_0-function value is comparable to the undulator length can be recommended as it enhances both the pulse energy and beam brightness;
- up-scaling the bunch charge is preferable despite degradation in the energy spread and emittance.

RECOMMENDED PARAMETERS

optimum at:

- number of micro-bunches: 10 ÷ 12
- detuning of bunching period : 0.1 ÷ 0.2
- bunch focusing conditions: $\beta_0 = L_U$
- number of undulator periods: 9 ÷ 12

for:

- electron energy: 20 MeV
- electron energy spread: 0.5 ÷ 1% (rms)
- bunch charge: 0.5 ÷ 4 nC
- bunch emittance: 1 ÷ 4 mm·mrad
- undulator period: 5 cm
- undulator parameter: K~1