Когерентное спонтанное излучение фотоинжекторных электронных сгустков

А.В. Савилов[1,2]

Данная презентация опирается на работы, проведенные в соавторстве со следующими коллегами:

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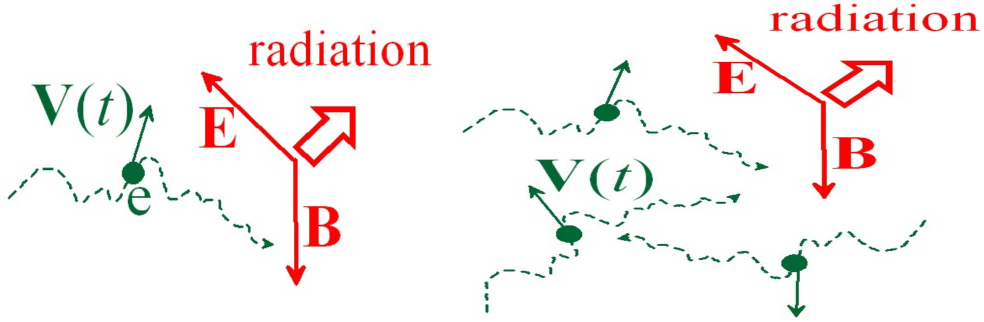
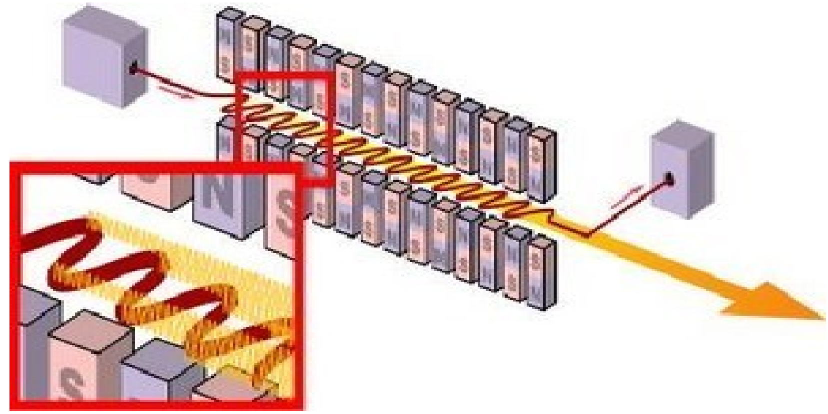
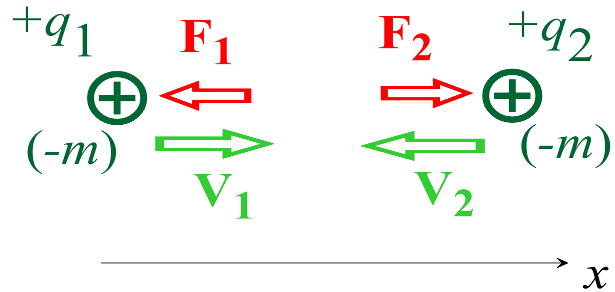
OUTLINE



1. Спонтанный и индуцированный режимы излучения

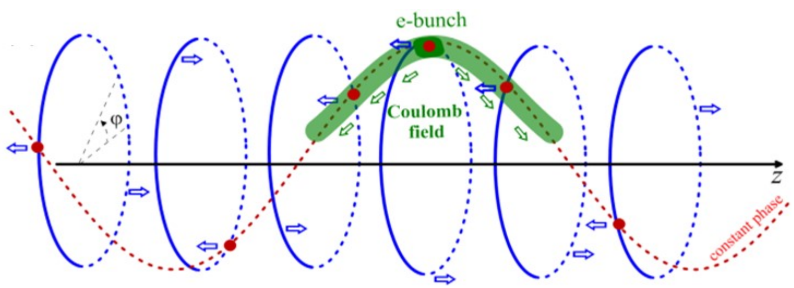


2. Ондуляторное излучение



3. Ондуляторное излучение
в режиме отрицательной массы

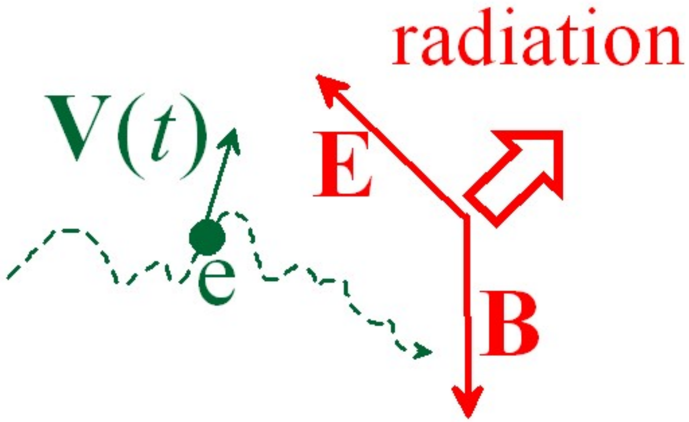
4. Циклотронное излучение



Radiation: energy conservation

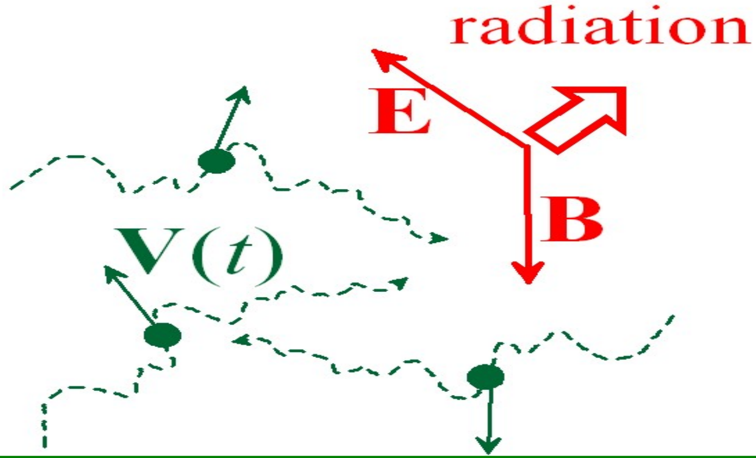
The averaged work of the radiated field under the source should be negative (the wave electric field should decelerate the particle):

$$\int \mathbf{jE}\ dV < 0$$



$$e\langle \mathbf{V}\,\mathbf{E} \rangle_t < 0$$

Spontaneous emission from a single particle (or a small electron bunch)

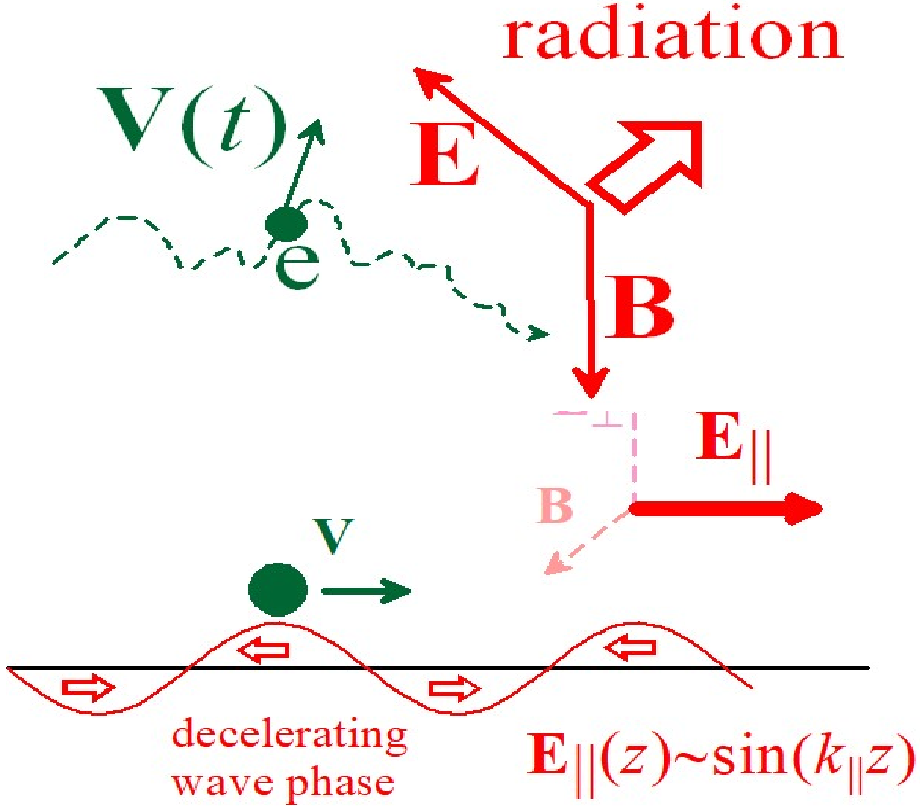


$$e\left\langle \langle \mathbf{V}\,\mathbf{E} \rangle_t \right\rangle_{\substack{\text{all}\\ \text{particles}}} < 0$$

Induced emission from an ensemble of particles (*the wave provides the "proper" organization of this ensemble*)

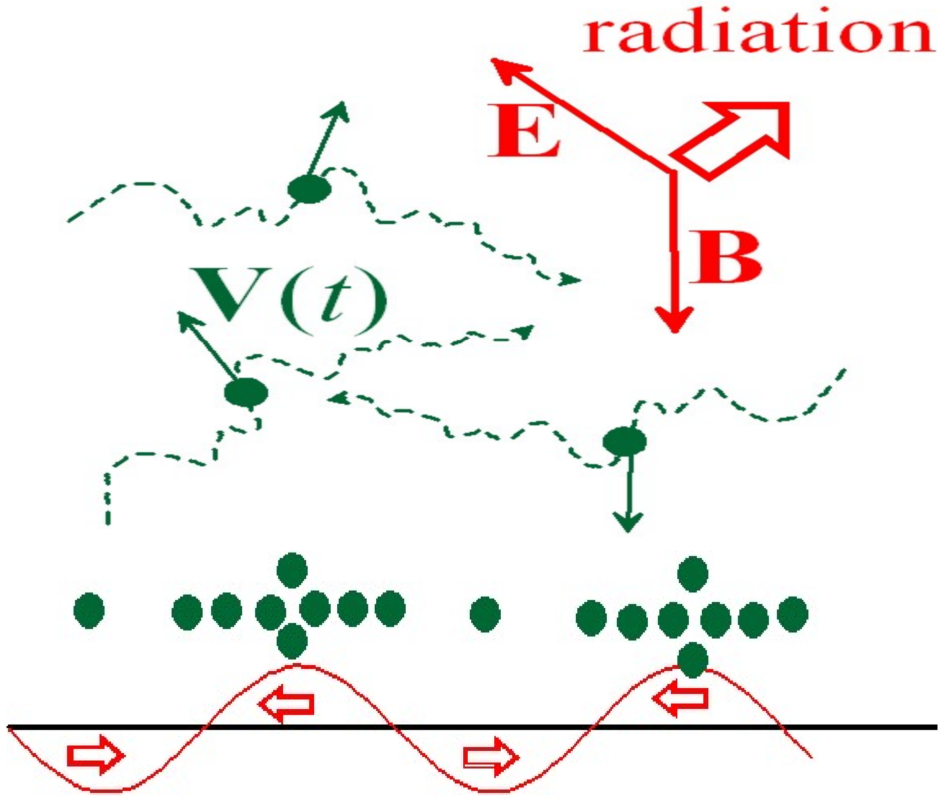
Спонтанное и индуцированное излучение заряженных частиц

Spontaneous emission
from a single particle.



$$e\left\langle \mathbf{V}\,\mathbf{E} \right\rangle_t < 0$$

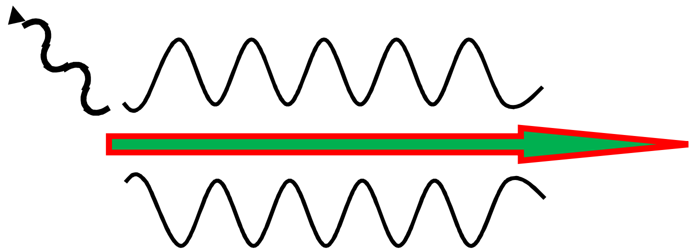
Induced emission
from an ensemble of particles.

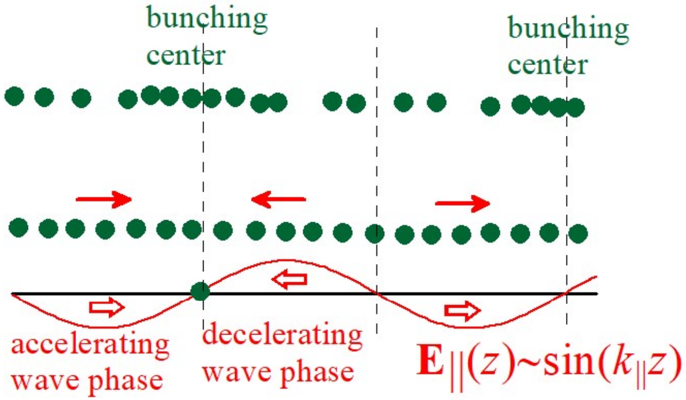


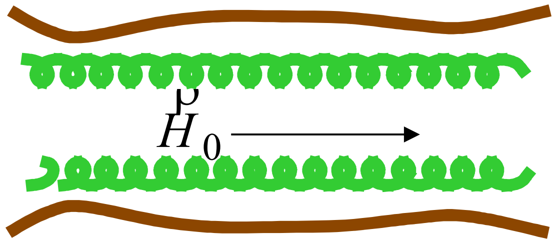
$$e\left\langle \left\langle \mathrm{V}\,\mathbf{E} \right\rangle_t \right\rangle_{\substack{\text{all}\\ \text{particles}}} < 0$$

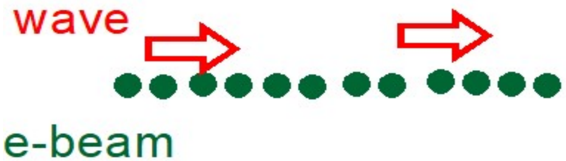
Электронные мазеры и лазеры – индуцированное излучение

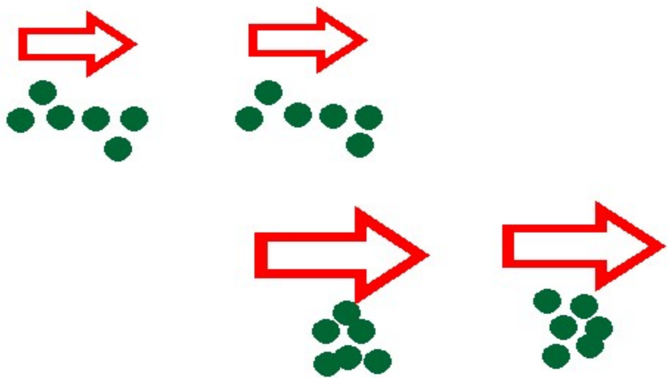
Ла́зер (от англ. *laser*, акроним от ***l**ight **a**mplification* *by **stimulated** **e**missionof **r**adiation* «усиление света посредством вынужденного излучения»)

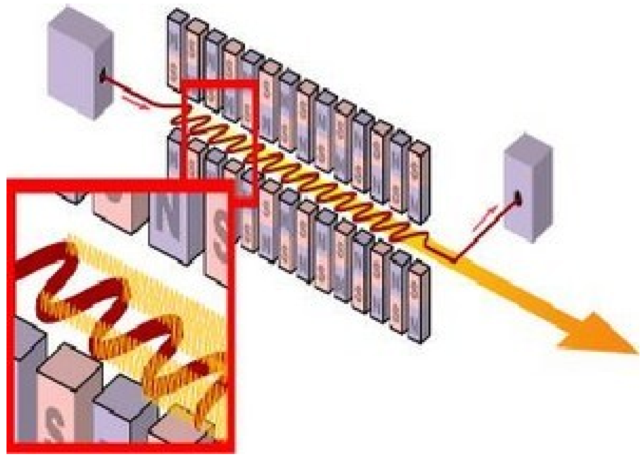


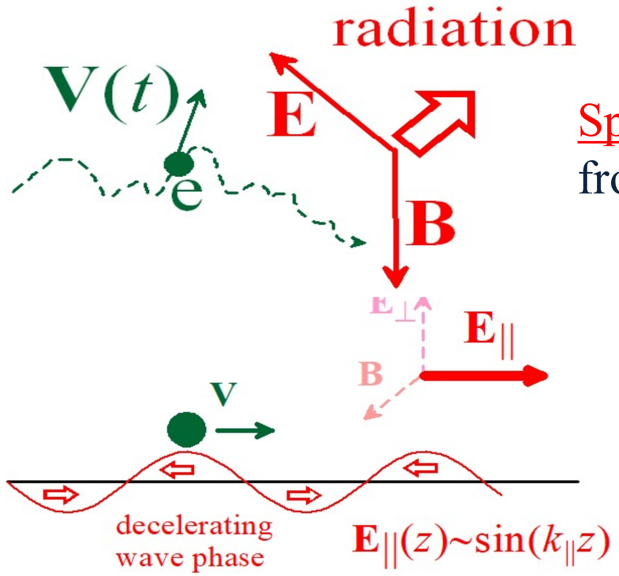








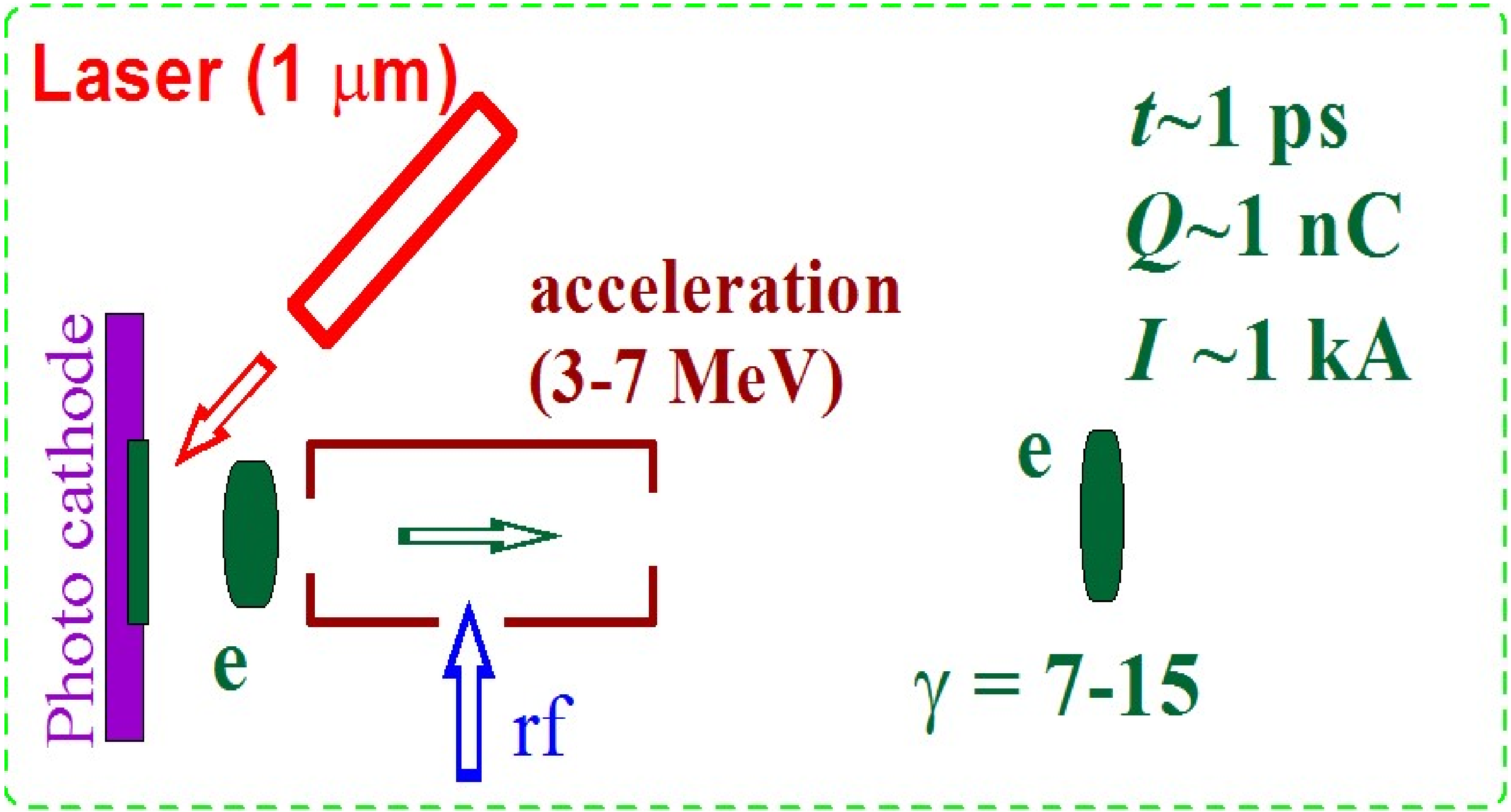




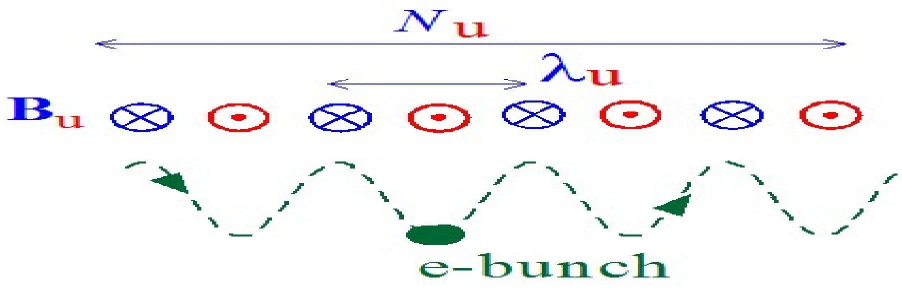
Spontaneous emission from a single particle.

- Ginzburg, V.L. On radiation of microradiowaves and their absorption in air. Akad. Nauk SSSR 1947
- Motz, H. Applications of the radiation from fast electron beams. J. Appl. Phys. 1951.

Photo-injector e-bunch

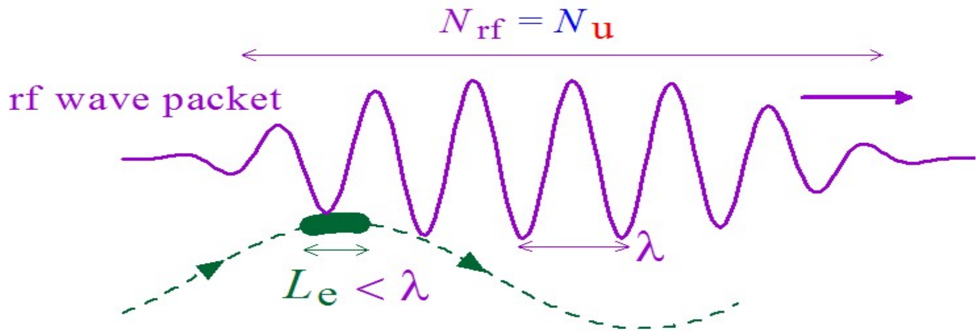


Powerful source of THz radiation based on spontaneous coherent emission from a short photo-injector e-bunch



Spontaneous coherent **undulator emission** from a short (shorter than radiation wavelength) "ready-for-use" e-bunch.

1 ps e-bunch
➔bunch length = 0.3 mm
➔ ➔radiation frequency ~ 1 THz

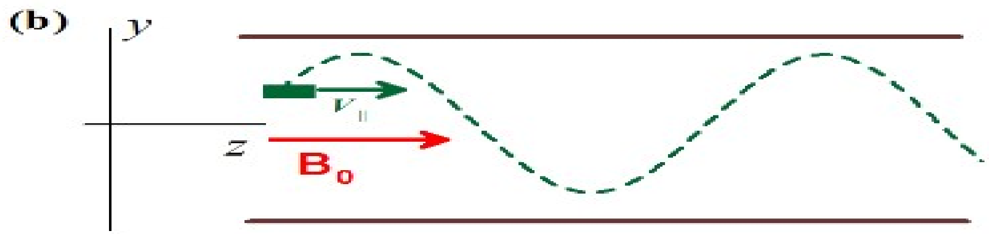


5 MeV e-bunch ➔

$\gamma \sim 10$ ➔ $\lambda_u \sim 3$ cm

$$\lambda \approx \lambda_u / \gamma^2$$

$\lambda \sim 0.3$ mm $f \sim 1$ THz



Cyclotron radiation:

$\lambda \sim 0.3$ mm *B= 2-3 T*

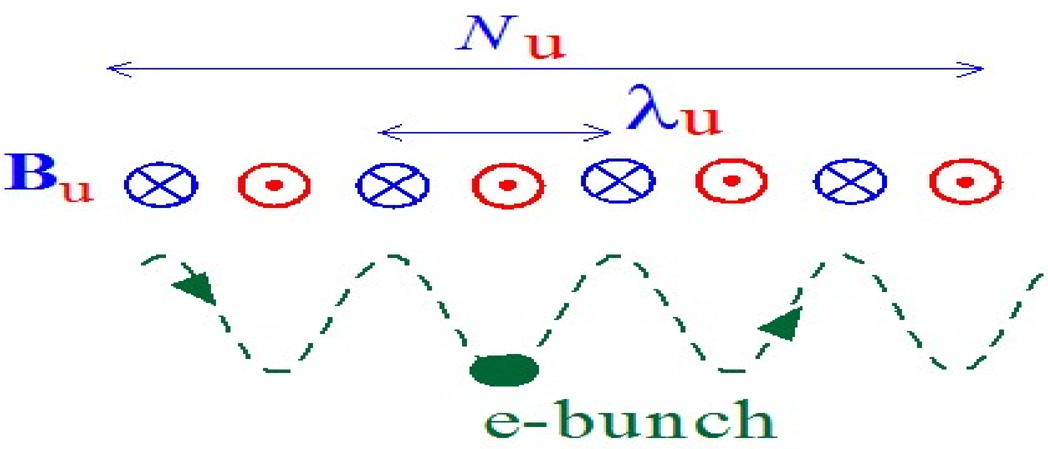
MOTIVATION: creation of a powerful source of coherent THz radiation

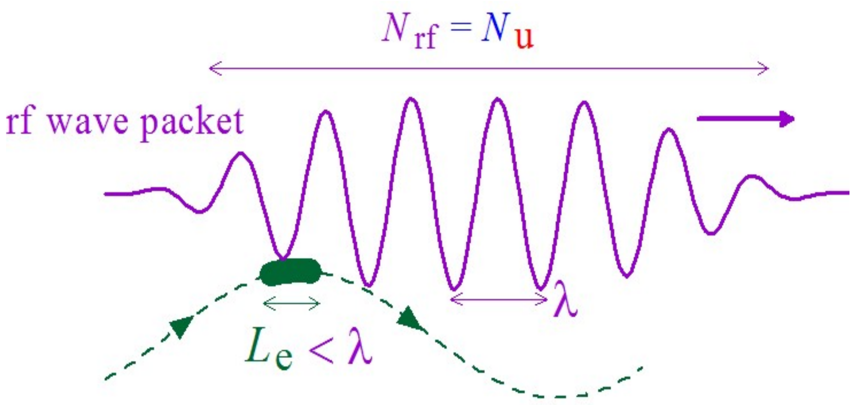
* Very simple system:
- no feedback system is required
- electron bunching process is not needed ➔ relatively short radiation region

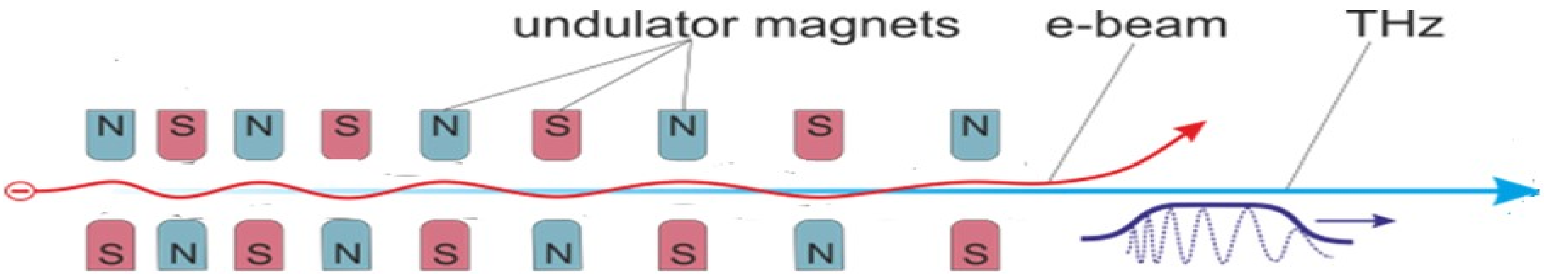
* Fixed phase of the THz signal

* Photo-injector electron source can be easily synchronized with other sources (for instance, sinchronization of the THz source and the X-ray FEL in pump-probe experiments can be easily provided)

* Possibility for changing («chirping») the frequency during a single rf-wave pusle

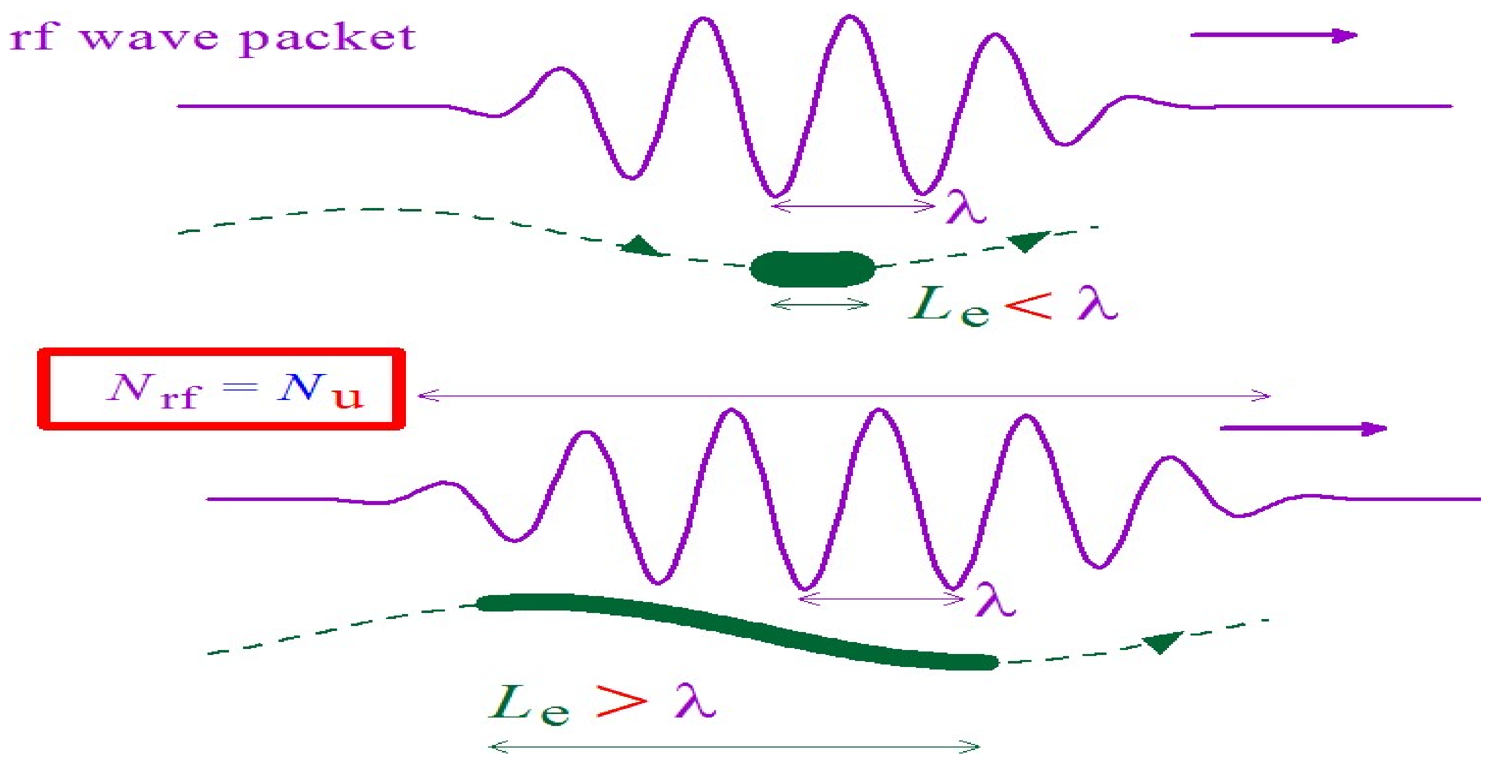




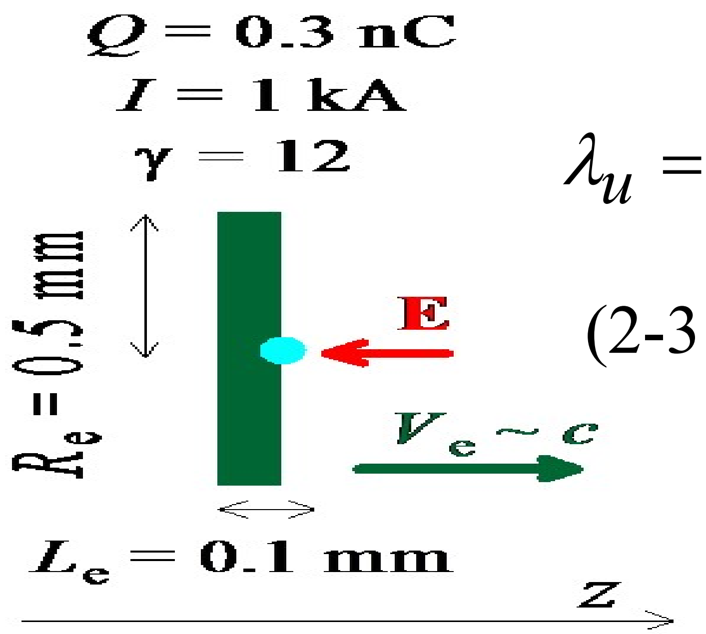


Formation of ultra-short pulses: Coulomb repulsion

The number of circles of the radiated wave packet
(= the number of "operating" undulator periods)
is limited by the **Coulomb repulsion**



Coulomb repulsion of a photo-injector e-bunch



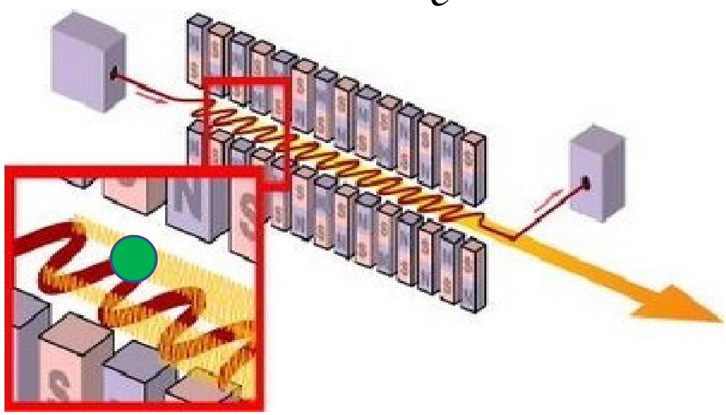
$\lambda_u = 2.5cm$

(2-3 THz)

Estimations: $Z = 4\lambda_u = 10cm$

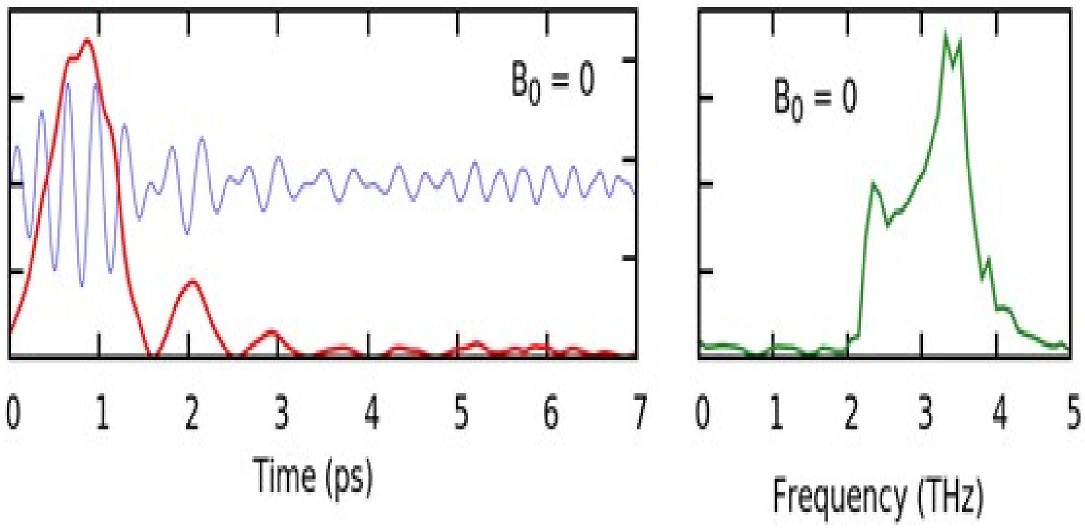
Energy spread: $\frac{\delta\gamma}{\gamma} \approx 10\%$

Elongation: $\frac{\delta L_e}{L_e} \approx 100\%$

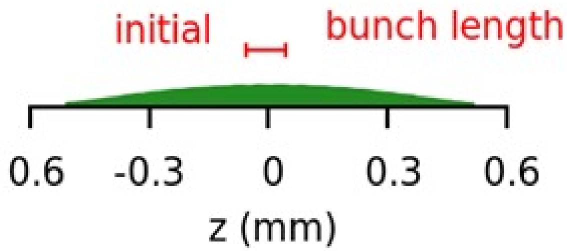


Numerical simulations:

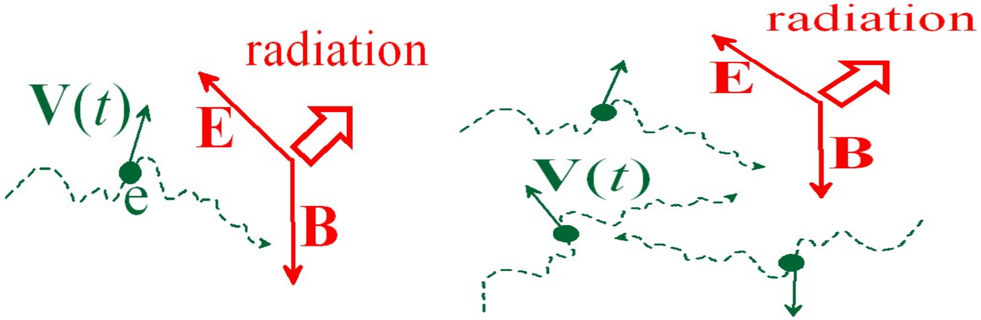
electric field of the radiated signal, power and spectrum.



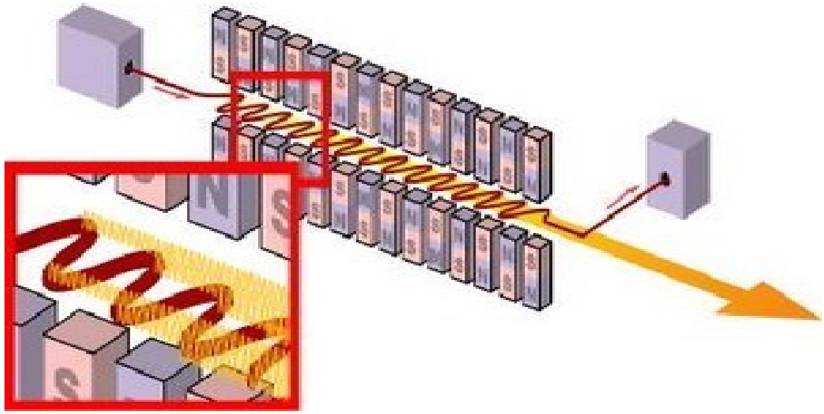
The e-bunch after a 60 cm trip.



OUTLINE



1. Спонтанный и индуцированный режимы излучения



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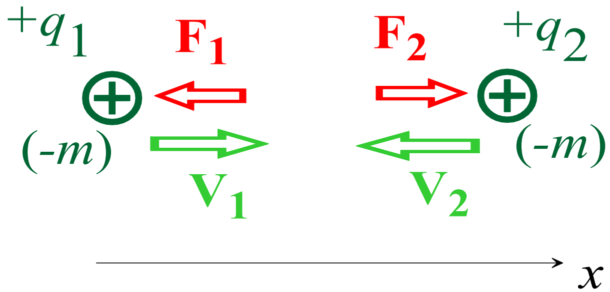

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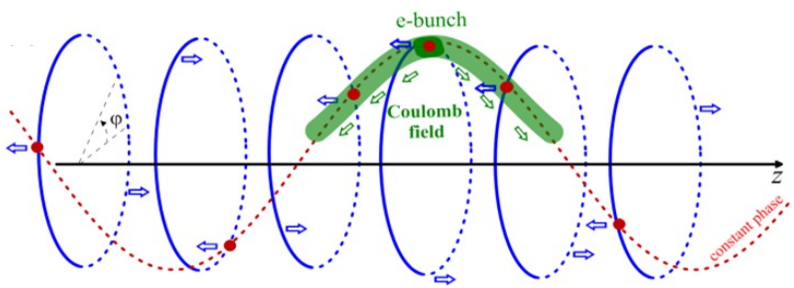


4. Циклотронное излучение

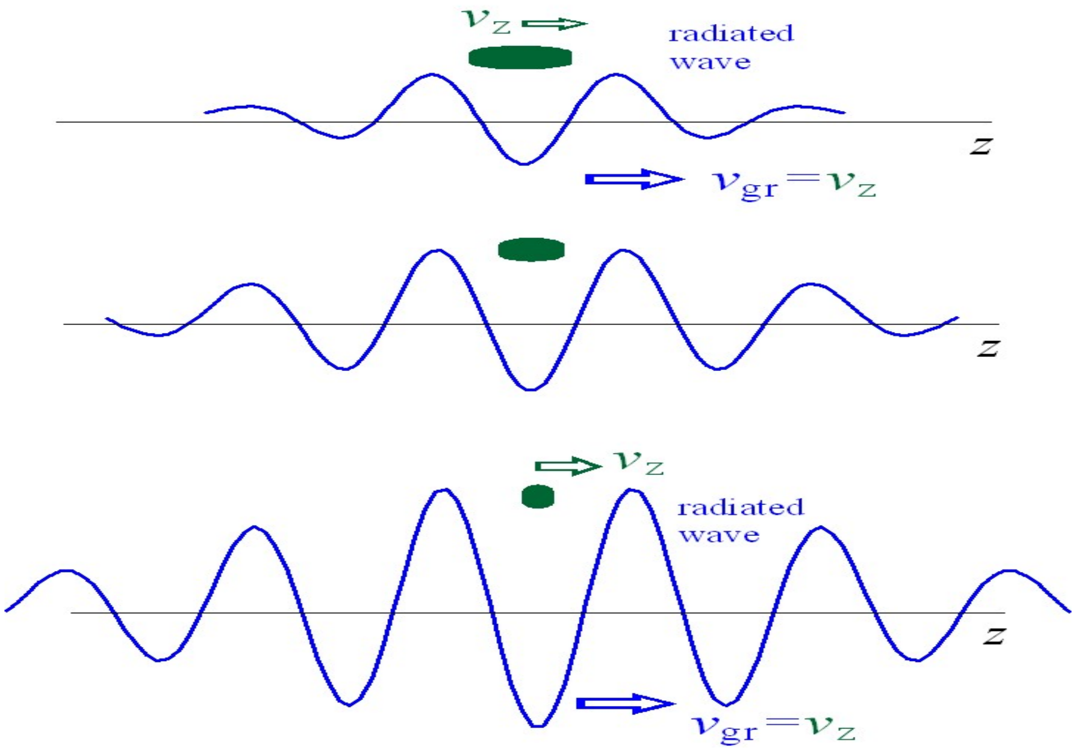
APPLIED PHYSICS LETTERS **110**, 263508 (2017)

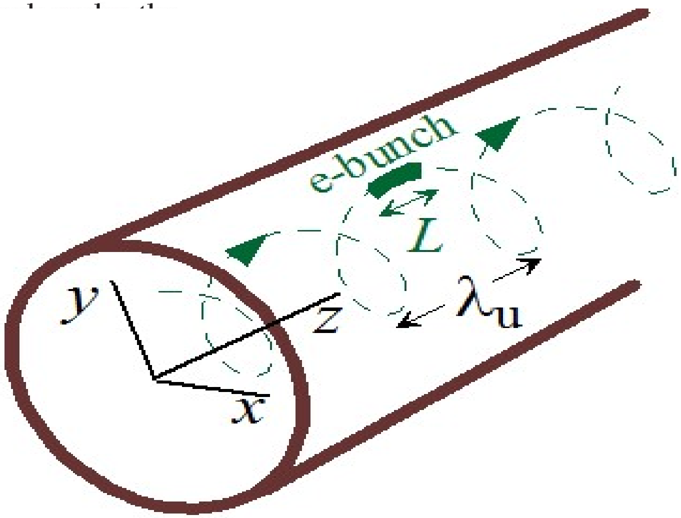
Super-radiative self-compression of photo-injector electron bunches

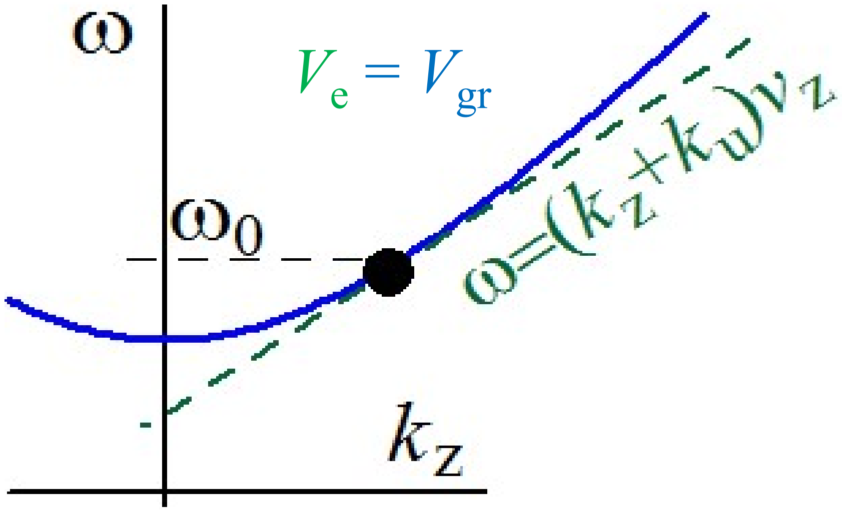
I. V. Bandurkin, Yu. S. Oparina, and A. V. Savilov
Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia

(Received 31 March 2017; accepted 17 June 2017; published online 30 June 2017)

It is shown that the spontaneous undulator super-radiation from a short (shorter than the radiation wavelength) electron bunch can result in a significant axial compression of th
effect of the rf field of the radiated wave. This "self-compression" can be used to
source of electromagnetic radiation based on the bicolor spontaneous coherent ra
dense electron bunches. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/





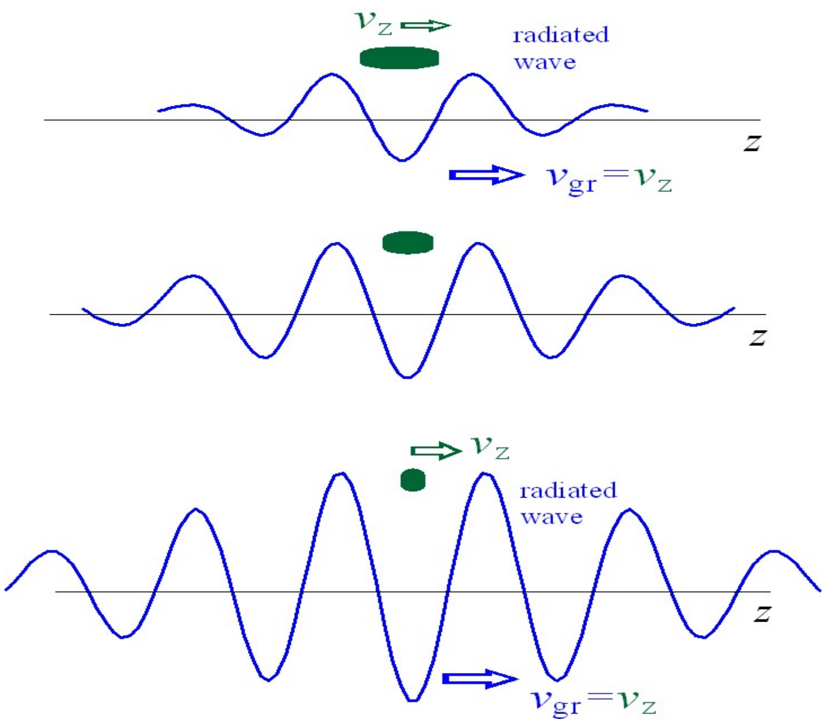


E-bunch length = 1-2 mm (several ps)

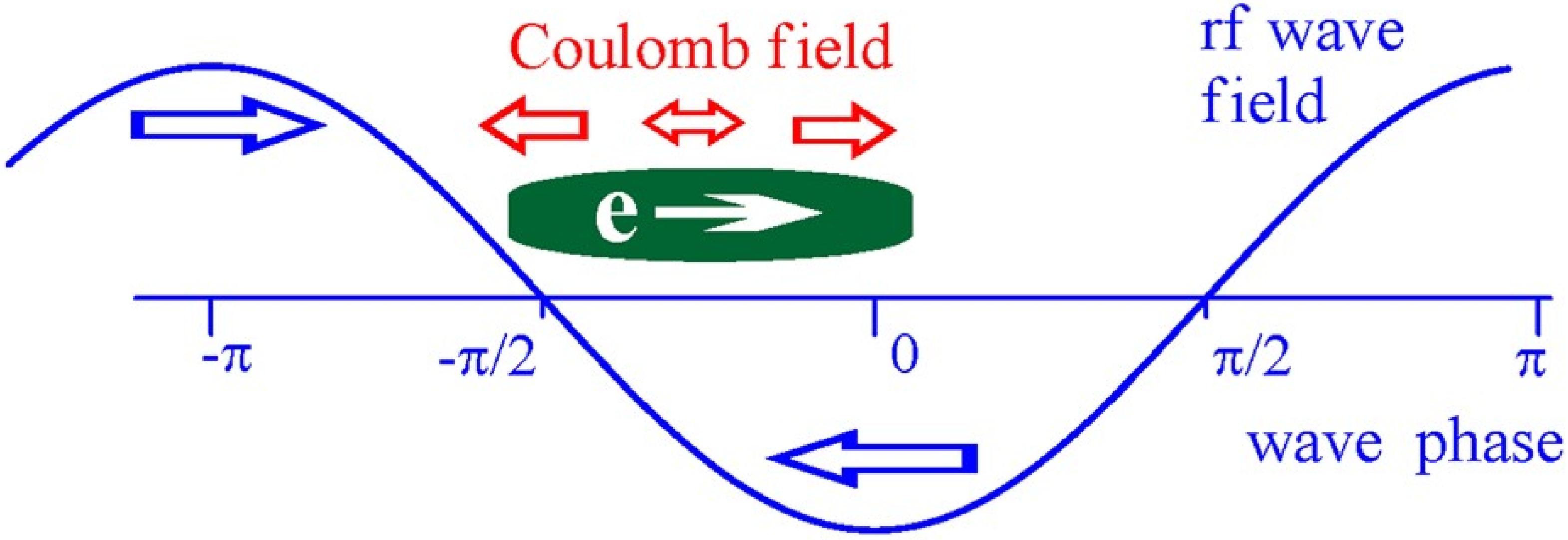
Radiation wavelength – several mm.

Super-radiation self-compression of a short dense e-bunch

Spontaneous undulator radiation of a long-wavelength ($\lambda > L_e$) wave leads to the self-compression of the bunch in the field of the radiated wave.



$$L_e = \lambda/4$$



KARAT simulations:

transformation of the e-bunch in the process of the undulator emission of the compressing wave

$L_0 = 0.9$ mm (3 ps)

$R = 1$ mm

$\gamma = 7$ (3 MeV)

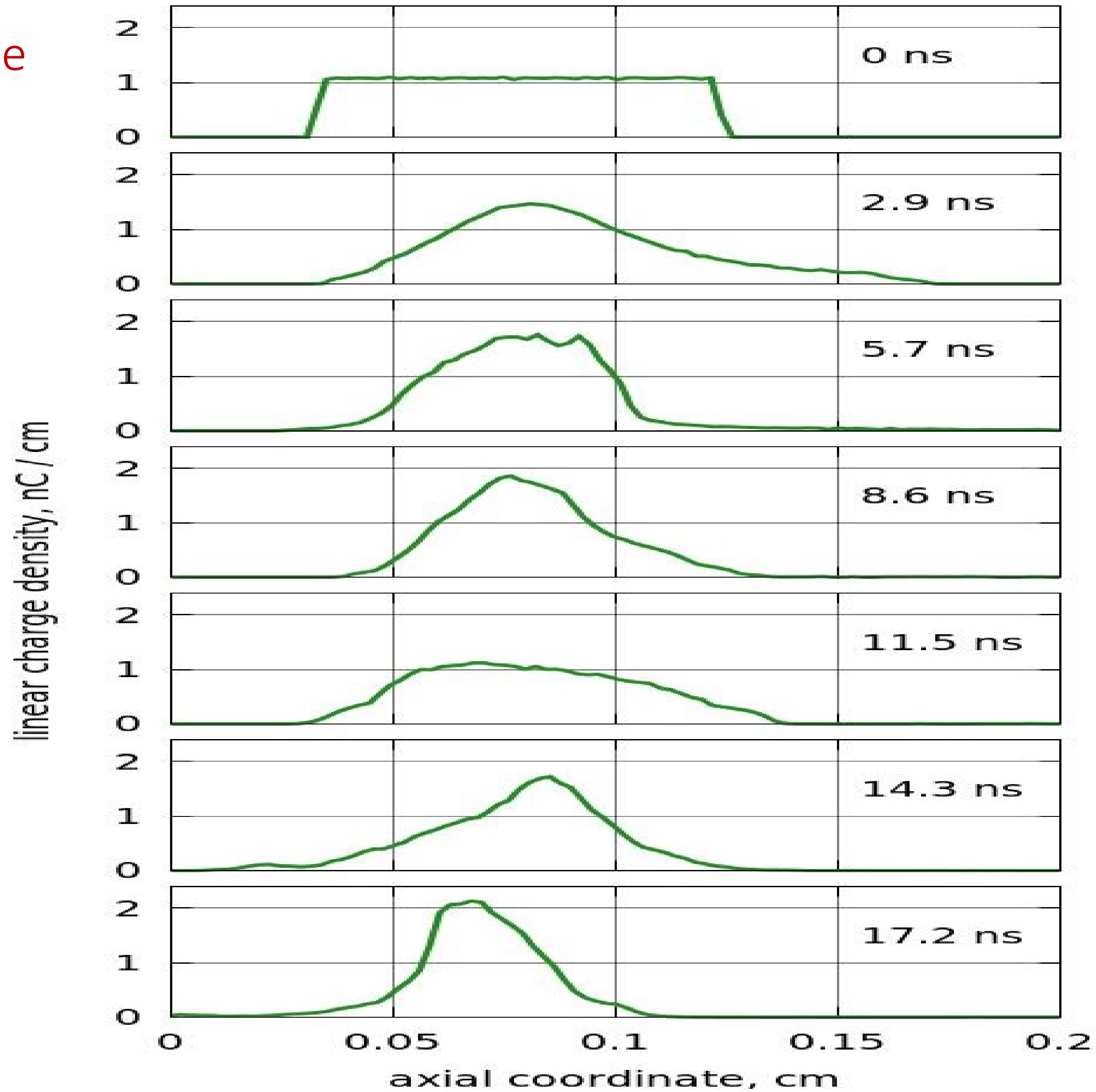
$d_u = 6$ cm $K_u = 0.7$

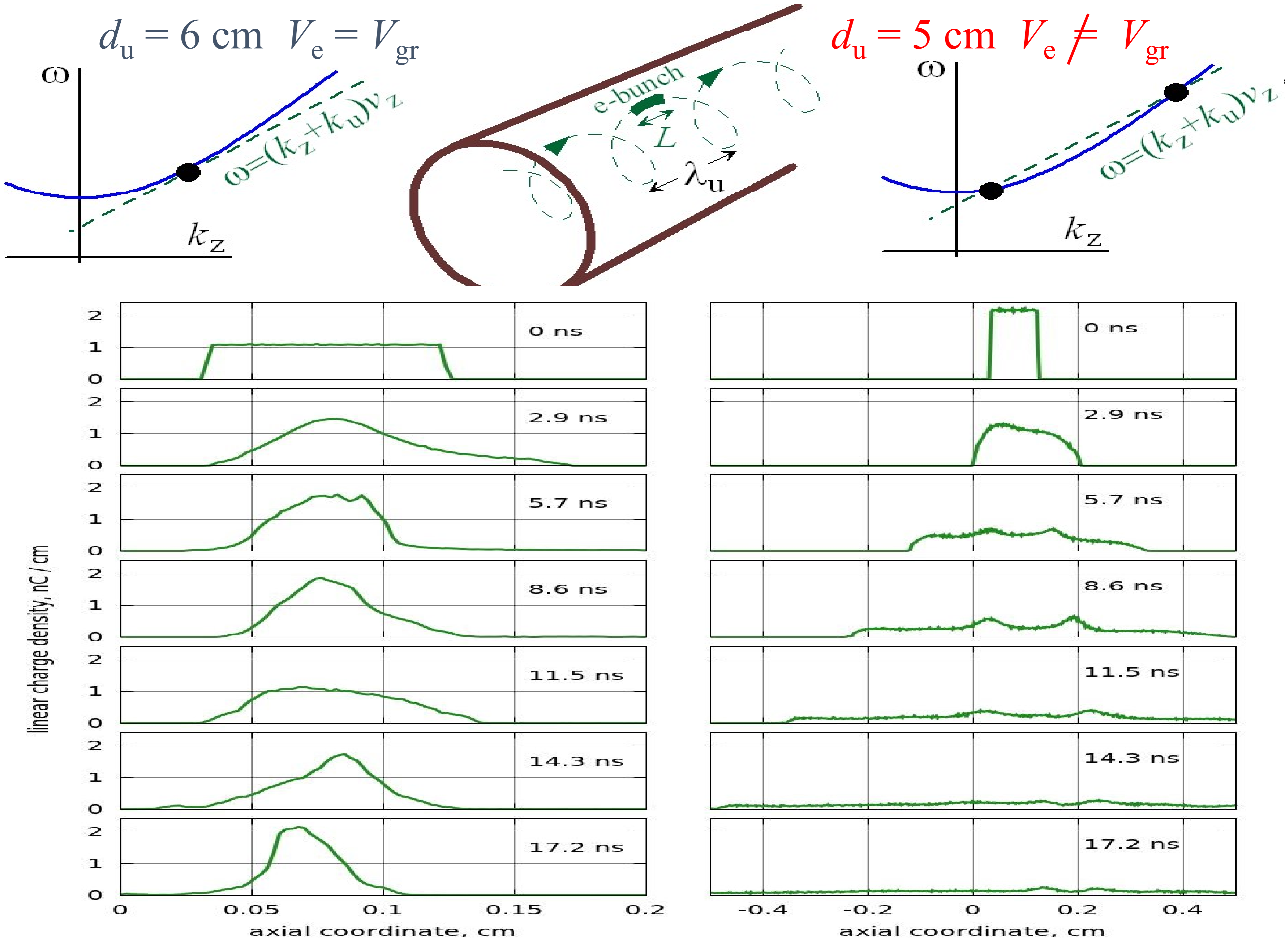
Q= 0.1 nC

Radiated wavelength = 1.8 mm

Waveguide diameter = 6 mm

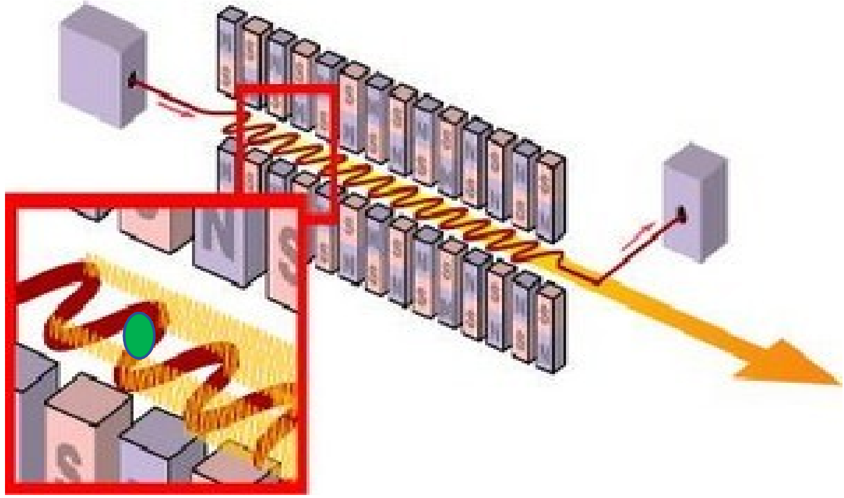
Axial distributions of the charge density at various moments of the time





$d_u = 6$ cm $V_e = V_{gr}$
$d_u = 5$ cm $V_e \neq V_{gr}$
ω
k_z
$\omega=(k_z+k_u)v_z$
e-bunch
L
λ_u
0 ns
2.9 ns
5.7 ns
8.6 ns
11.5 ns
14.3 ns
17.2 ns
linear charge density, nC / cm
axial coordinate, cm

Undulator radiation of ultra-short pulses



Physics of Plasmas ARTICLE scitation.org/journal/php

Coherent super-radiative undulator emission of ultra-short THz wave pulses

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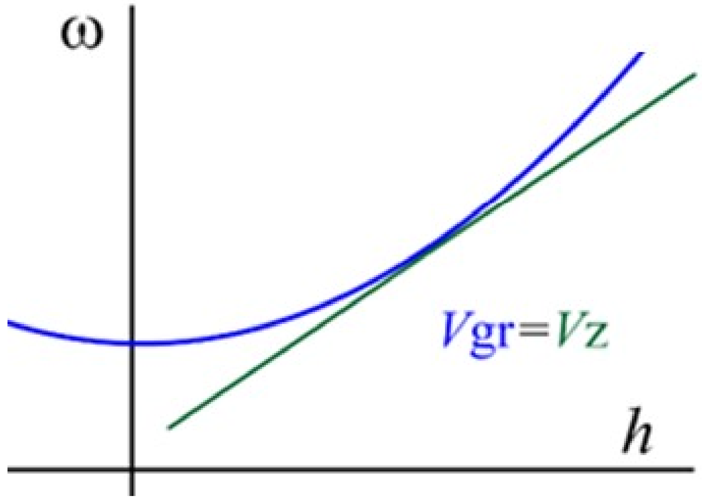
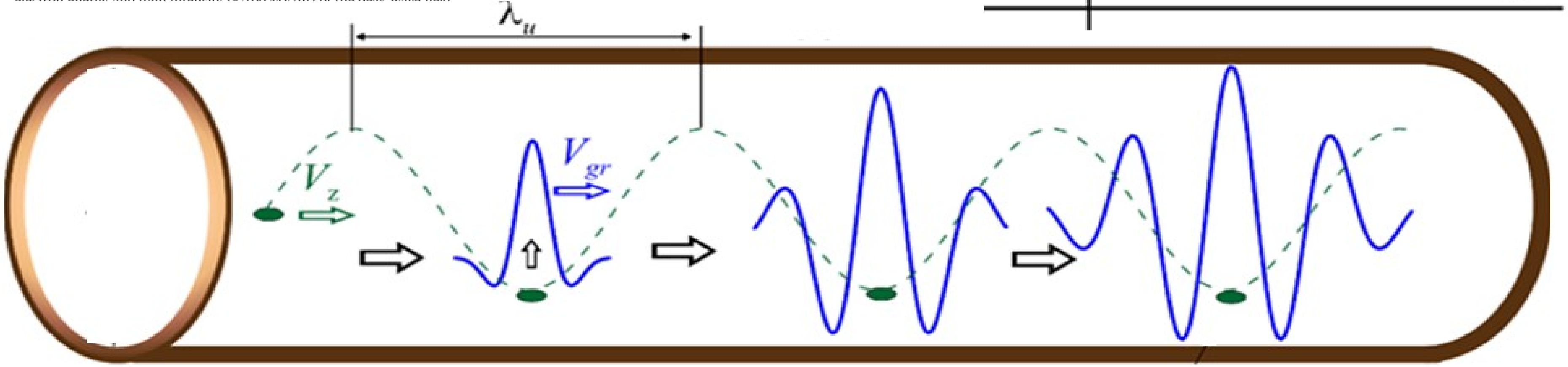
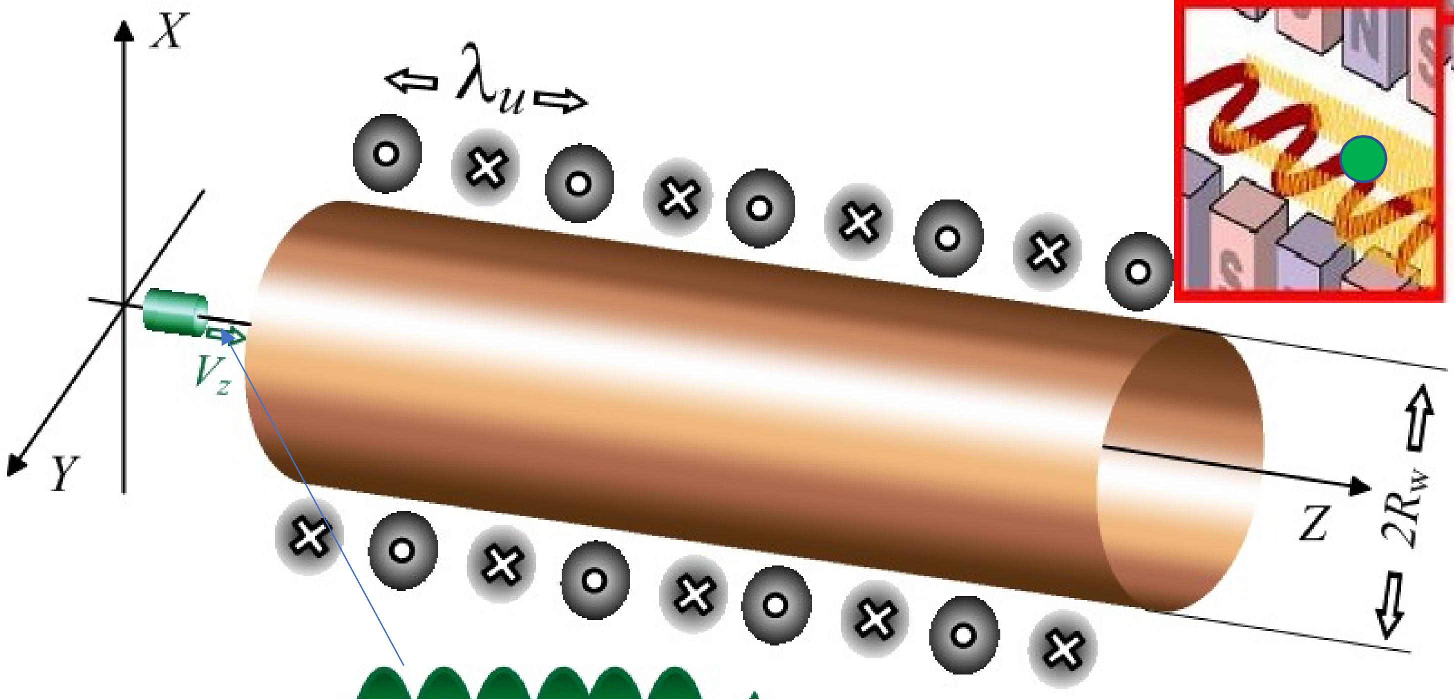
ABSTRACT

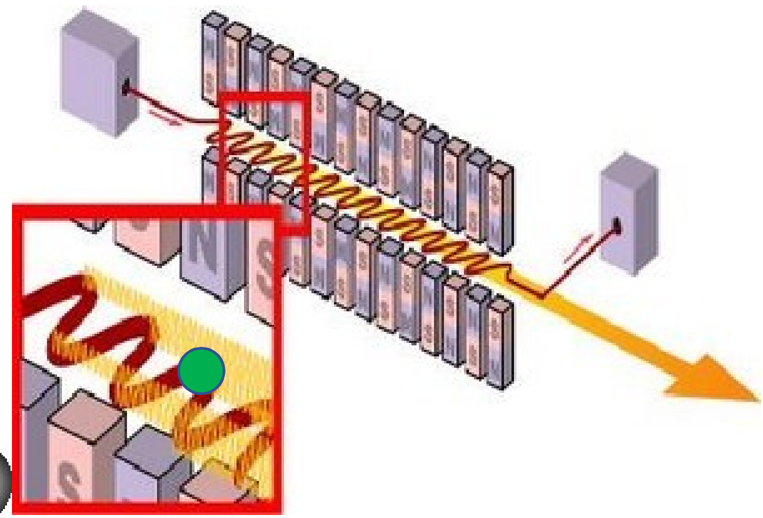
We study spontaneous coherent super-radiative undulator emission in the terahertz frequency range from a short (as compared to the wavelength of the radiated wave), dense electron bunch. Since the group velocity of the wave is close to the bunch velocity, this is a process of spontaneous radiation followed by amplification of a single wave cycle. Despite the Coulomb repulsion of electrons inside the bunch, its compactness, which is necessary to ensure the spontaneous coherent character of the radiation process, is provided by the compression of the bunch under the action of its own radiation fields. As a result, formation of an ultra-short (several cycles long) powerful wave packet occurs when the bunch moves through several undulator periods with high (~20% in optimized profiled systems) efficiency of extraction of the electron energy and high intensity (~100 MV/m) of the peak wave field

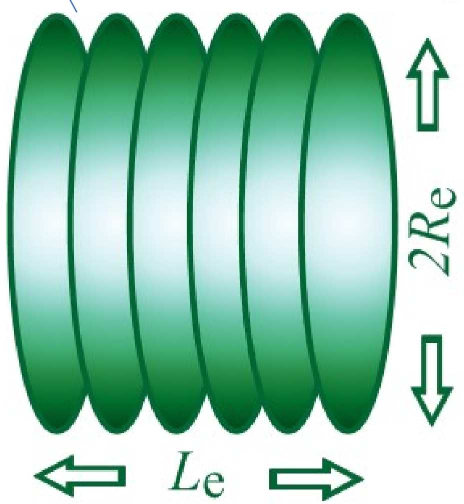




SCR process







I. V. Bandurkin, I. S. Kurakin, and A. V. Savilov, “Compression of a photoinjector electron bunch in the negativemass undulator,” *Phys. Rev. Accel. Beams*, vol. 20, p. 020704, 2017

Longitudinal Coulomb field inside a bunch:

- bunch is a set of charged disks.

Electron-wave interaction:

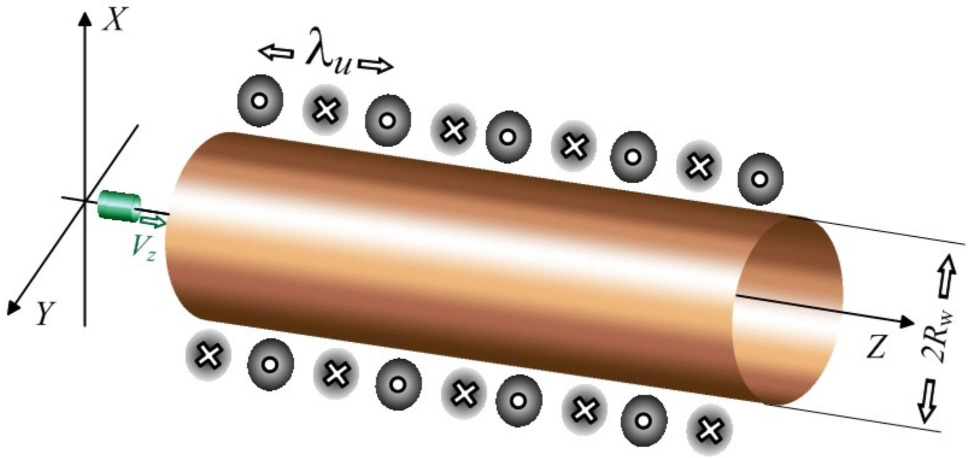
- bunch is a set of macro particles.

SCR process

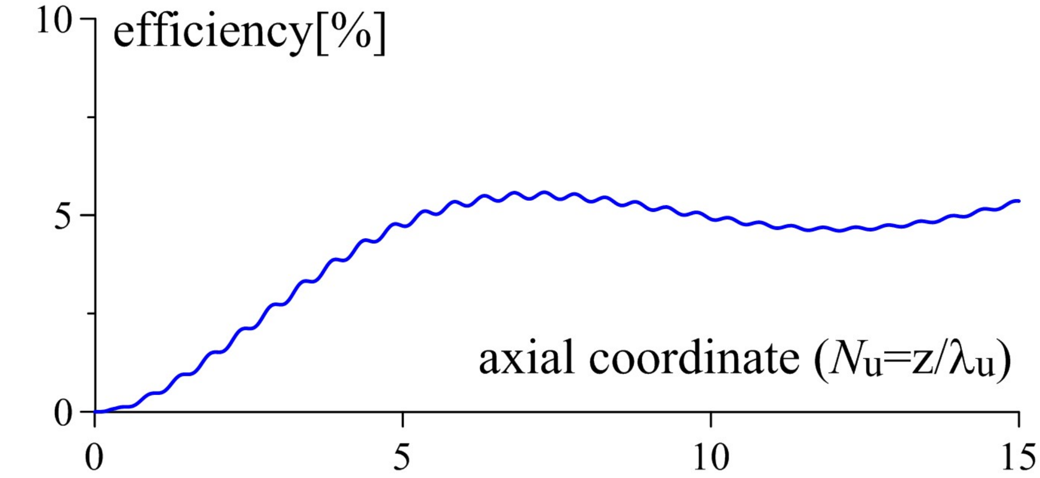
We consider the radiation of the bunch with
- initial duration 1.2 p*
- transverse size 4 mm
- total bunch charge is 0.5 nC
- energy 5 MeV (γ=11)

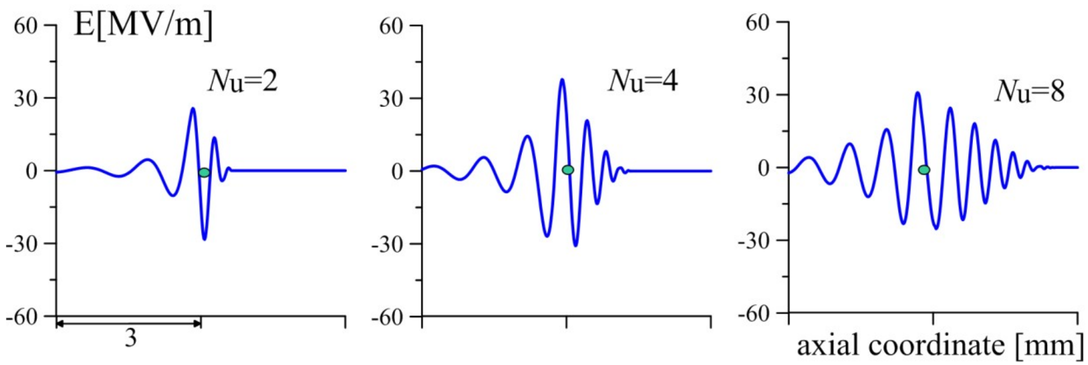
In the undulator with
- undulator parameter K=0.7
- period of 10 cm.

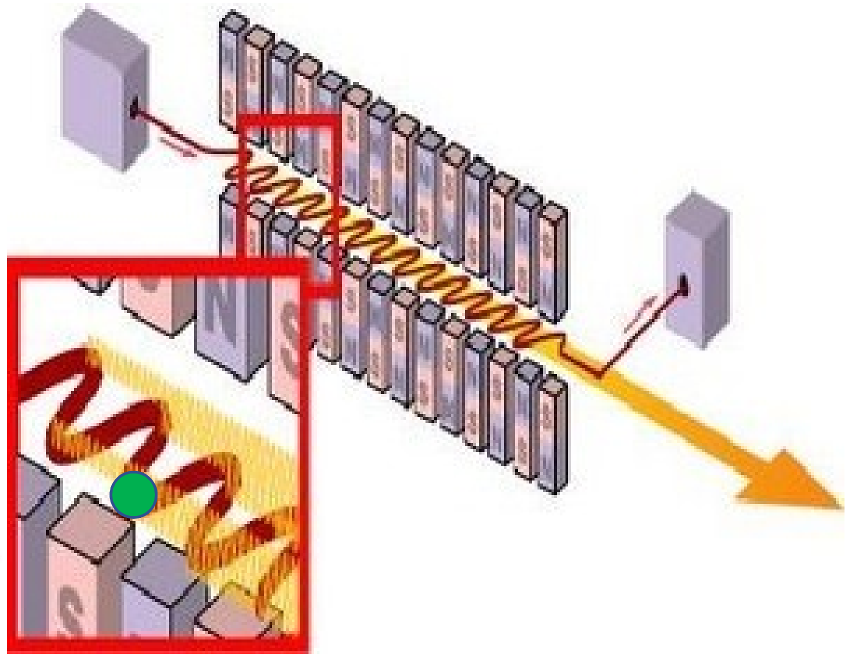
Optimal waveguide radius 3.25 mm.



*The bunch length (0.36 mm) is approximately one-fourth part of the characteristic wavelength of the radiated wave packet determined by Doppler up-shift of the undulator period.

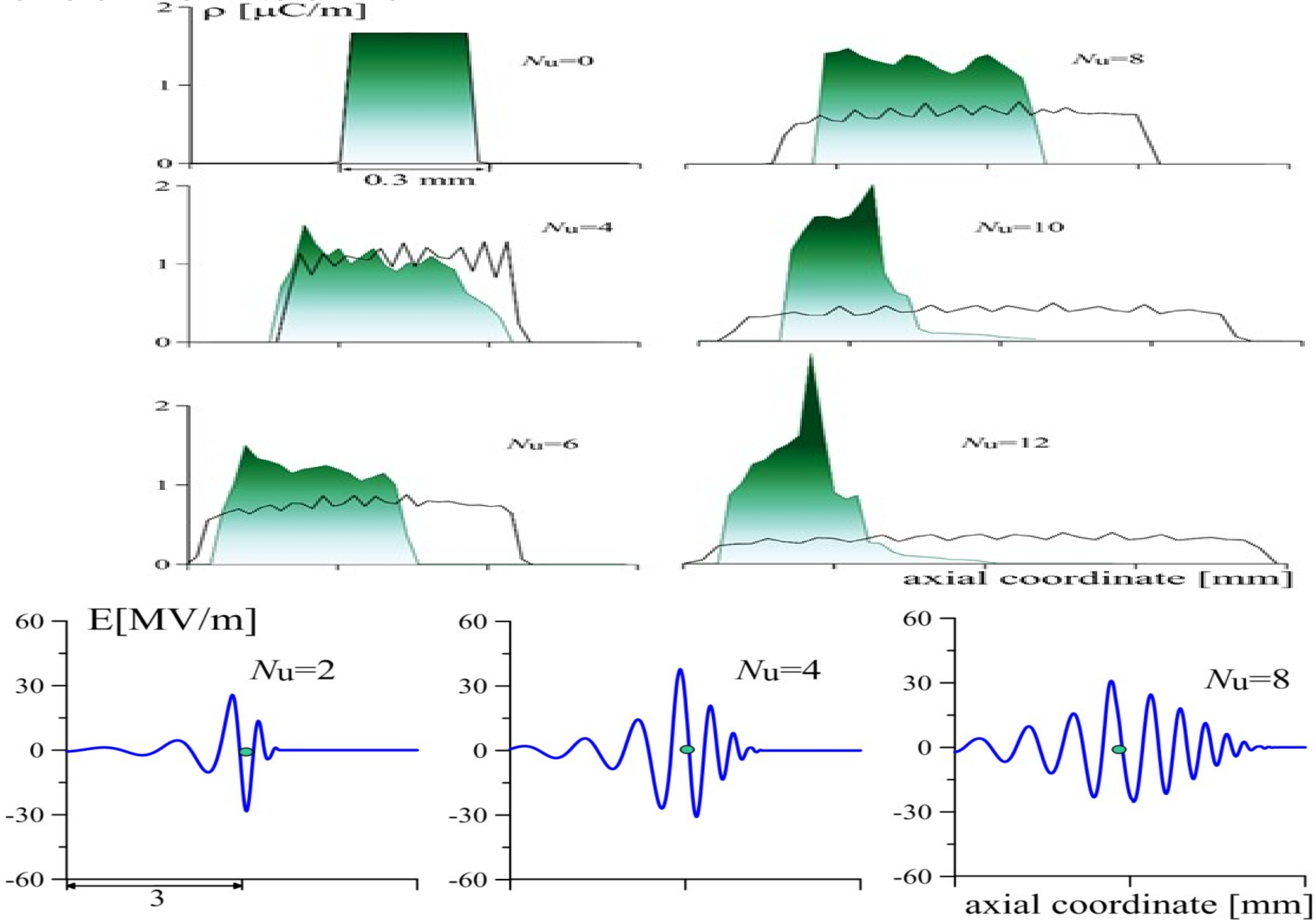




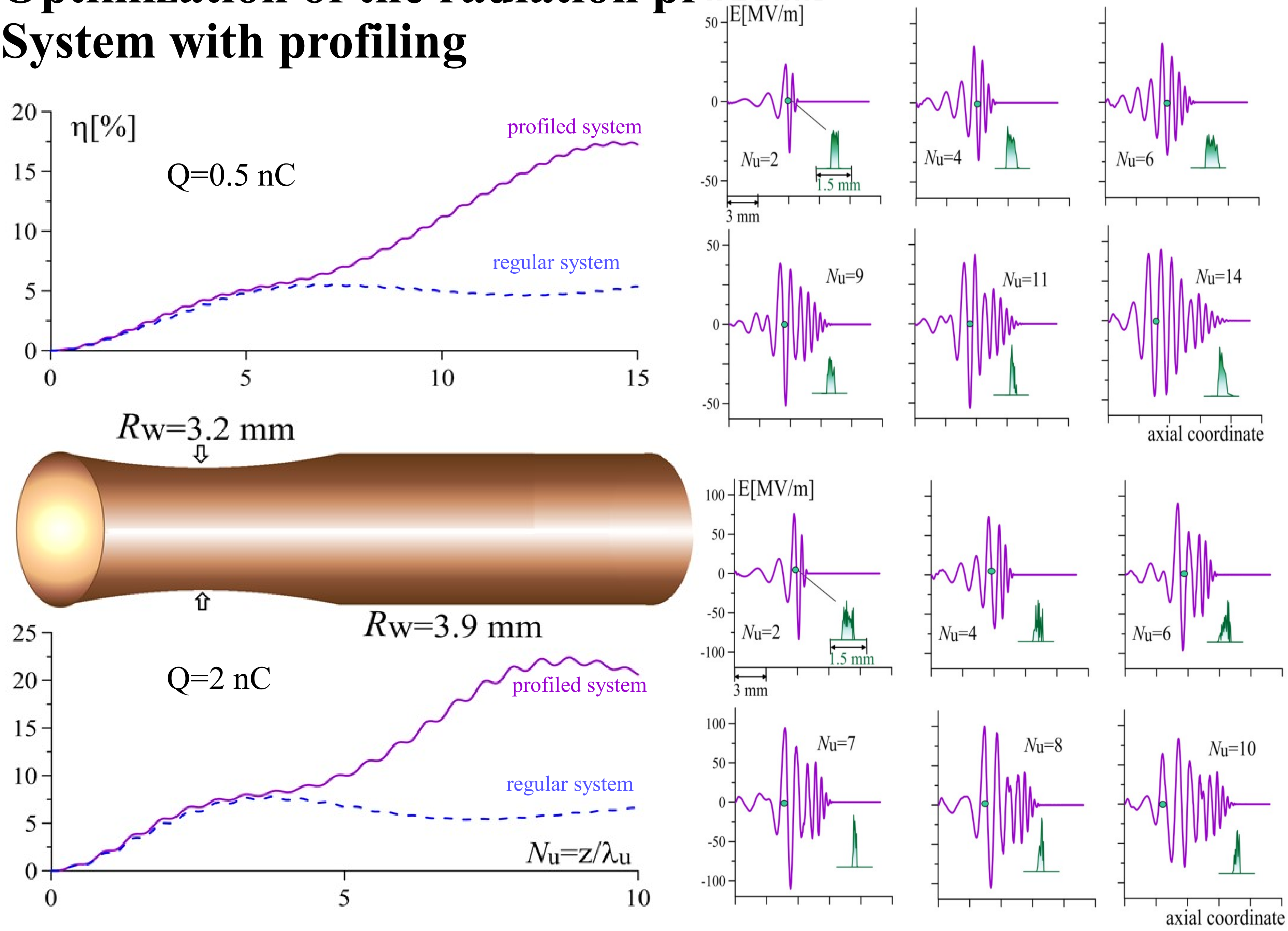


Super-radiative self-compression of the electron bunch

Dynamics of the charge density inside the bunch. The linear charge versus the axial coordinate after the electron bunch passes N_u undulator periods. Black curves: only the Coulomb field is taken into account. Green fills: both the radiated and Coulomb fields are taken into account.



Optimization of the radiation process. System with profiling



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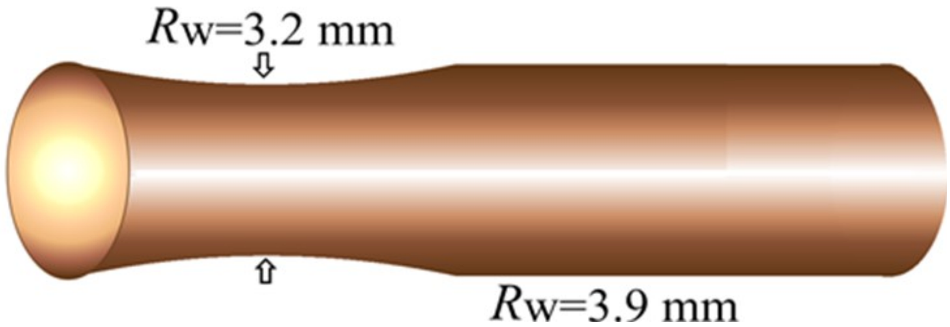
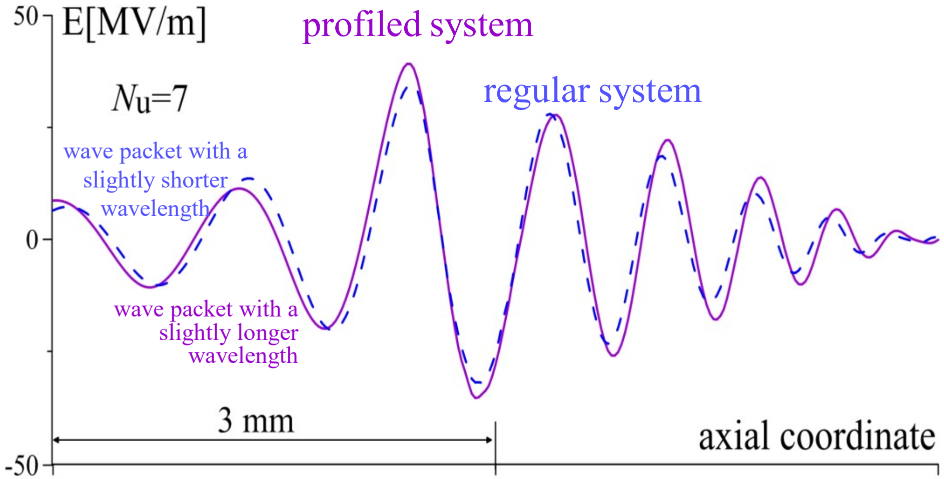
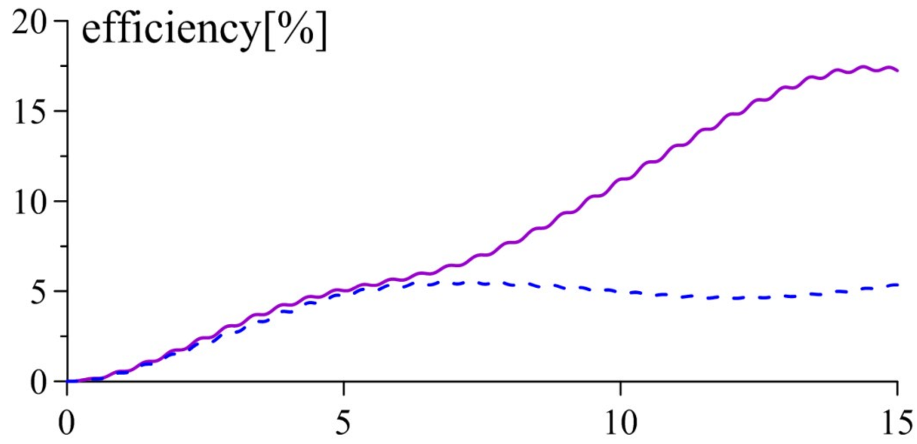
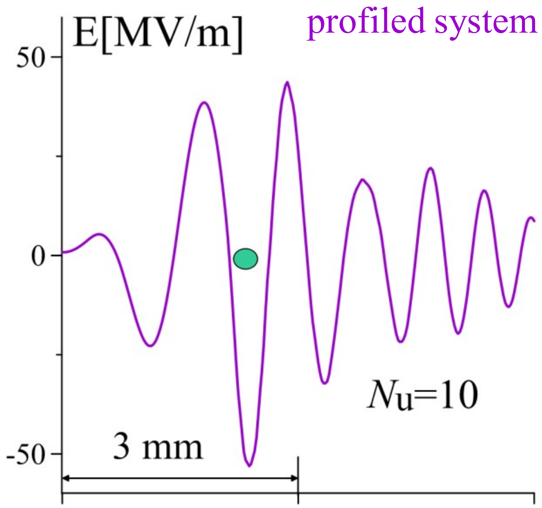
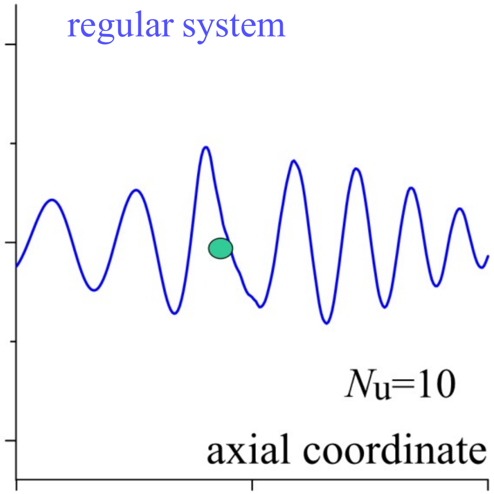










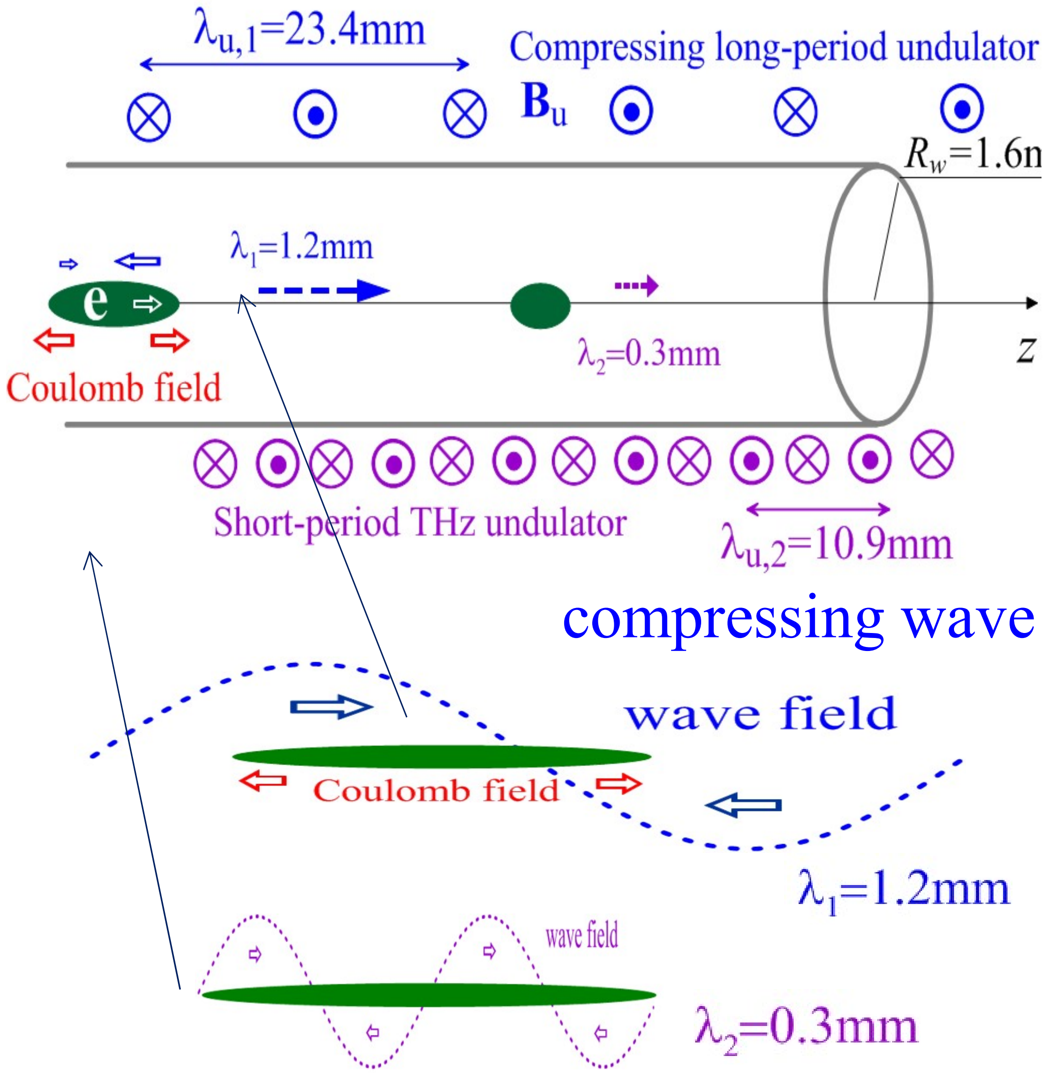
In the both cases, the electron efficiencies and the shapes of the radiated wave pulses are very similar at the point corresponding to the end of the profiled section. However, beyond this point, the behavior of the radiation processes becomes different. In the regular system, the electronic efficiency starts to decrease as the coordinate grows, whereas in the irregular waveguide, we see the second stage of the growth of the electron efficiency. As a result, a significantly more intense wave pulse is generated in the case, where the profiled section is used. In the case of using an input section with a smaller radius, a wave packet with a slightly longer wavelength is formed.

Two-wave process in two undulators

super-radiation of the long-wavelength compressing wave ➔

e-bunch self-compression ➔

short-wavelength radiation



Physics of Plasmas ARTICLE scitation.org/journal/php

EDITORS' SUGGESTION

Spontaneous super-radiative cascade undulator emission from short dense electron bunches

Cite as: Phys. Plasmas **26**, 113105 (2019); doi: 10.1063/1.5123551
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Published Online: 11 November 2019

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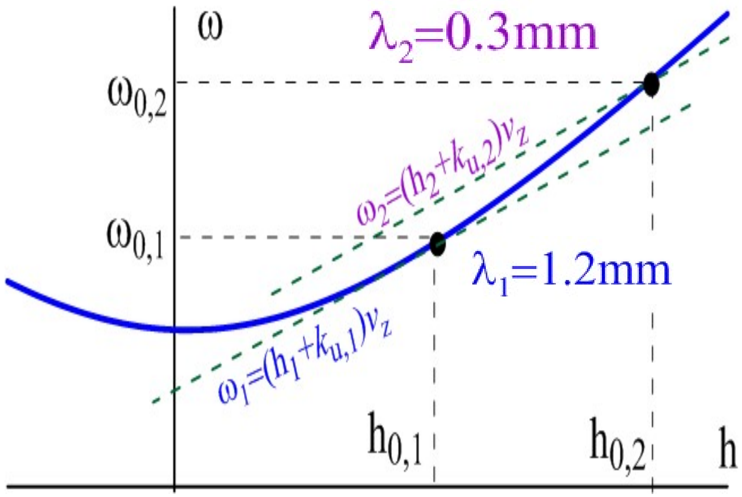
ABSTRACT

We propose to use super-radiative self-compression of a short dense electron bunch to provide the cascade two-undulator regime of spontaneous emission from the bunch. At the first stage of this cascade, the spontaneous super-radiative emission of a relatively long-wavelength wave results in compression of the bunch by the radiated field. This results in high-efficiency spontaneous radiation of a short-wavelength wave at the second stage. According to the simulations performed for electron bunches with the parameters typical for modern photoinjectors, the cascade regime ensures radiation in the subterahertz frequency range with efficiencies from 10% (in regular systems) up to 30%–50% (in profiled systems).

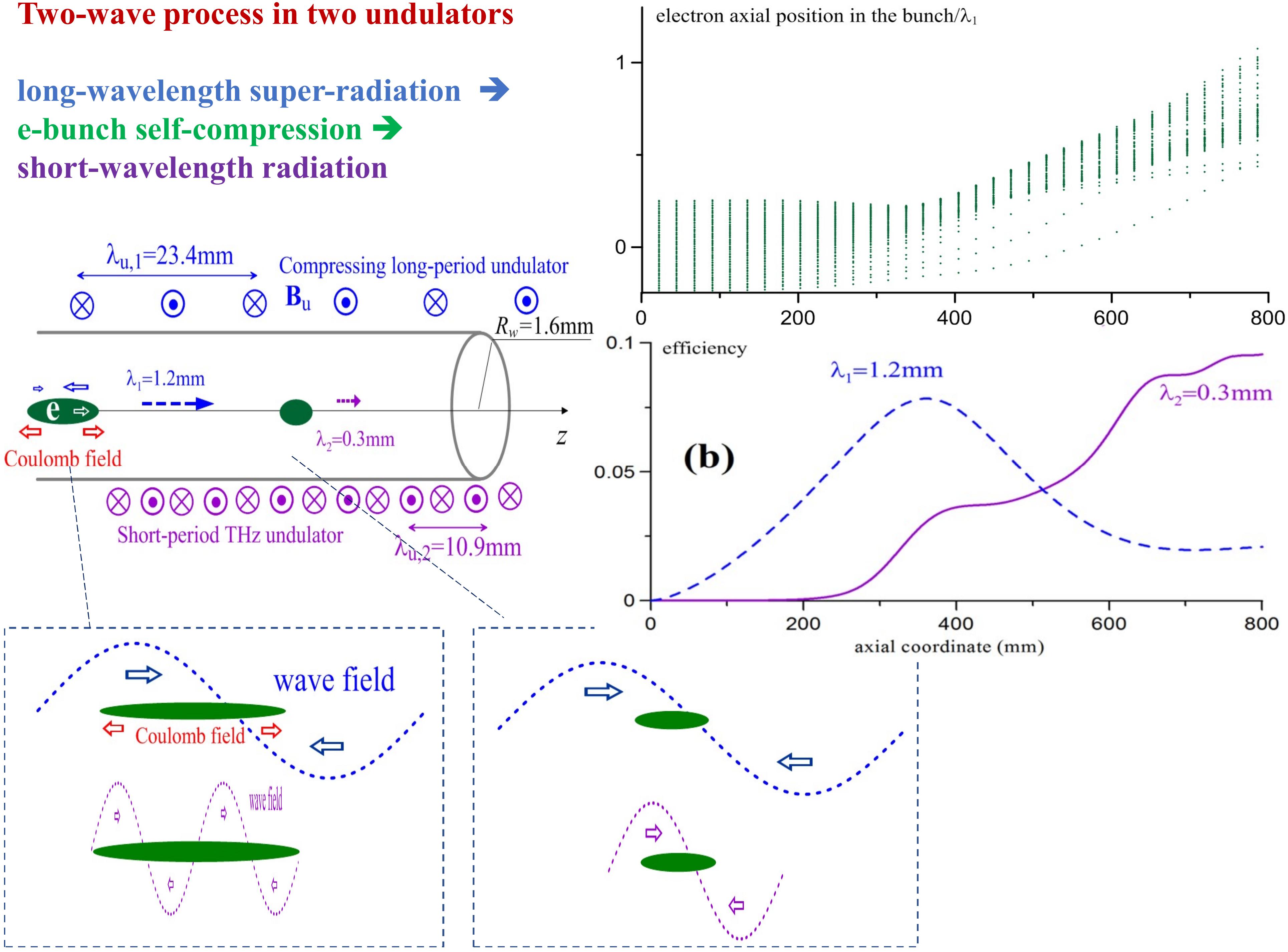


E-beam: 3 MeV, 0.1 nC

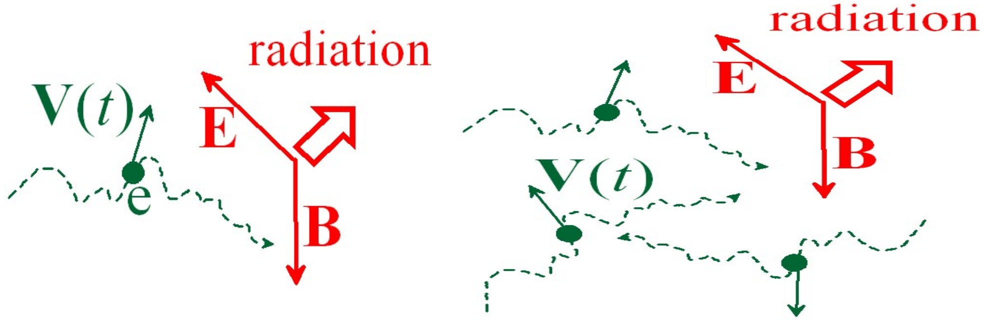
$L = 0.5*\lambda_1 = 0.6$ mm (2 ps)

Two-wave process in two undulators

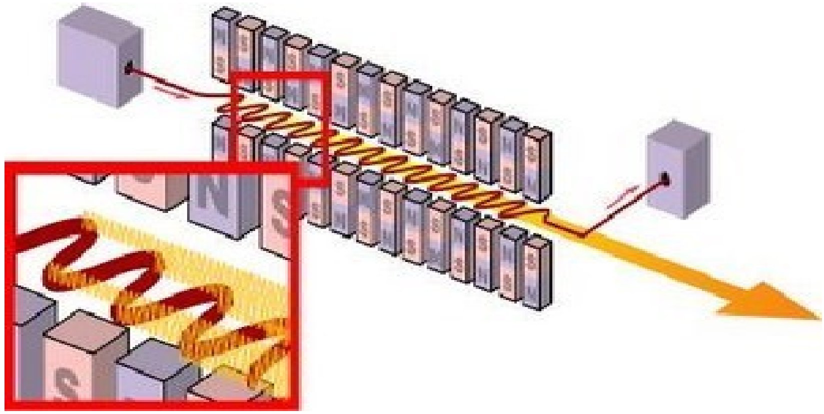
long-wavelength super-radiation ➔
e-bunch self-compression ➔
short-wavelength radiation



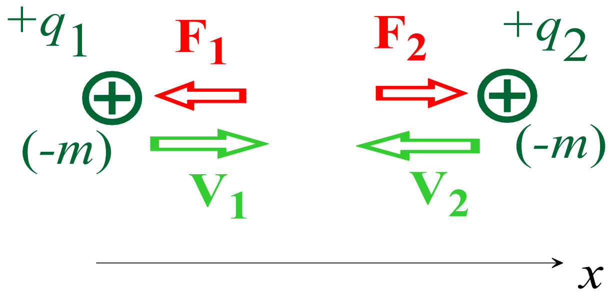
<u>OUTLINE</u>



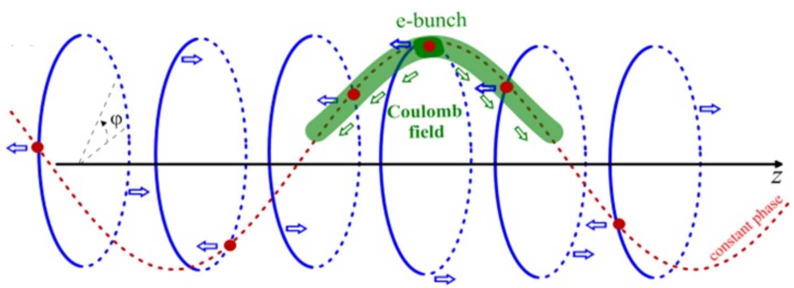
1. Спонтанный и индуцированный режимы излучения



2. Ондуляторное излучение



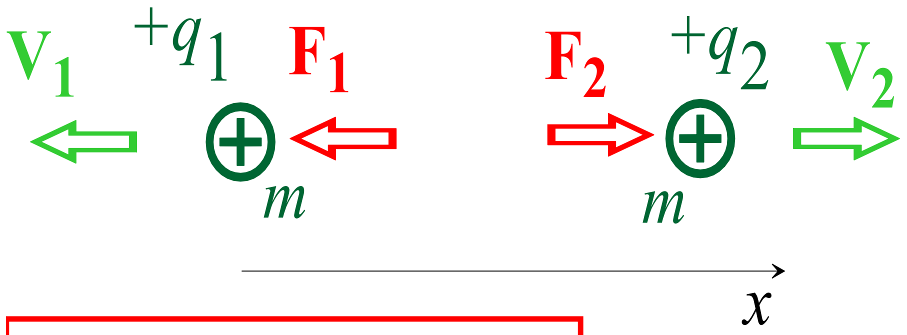
<u>3. Ондуляторное излучение в режиме отрицательной массы</u>



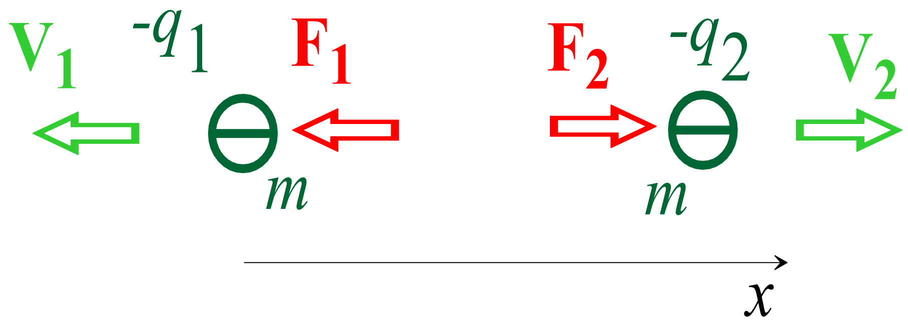
4. Циклотронное излучение

Positive and negative mass

Coulomb repulsion of two positive (two negative) charges.

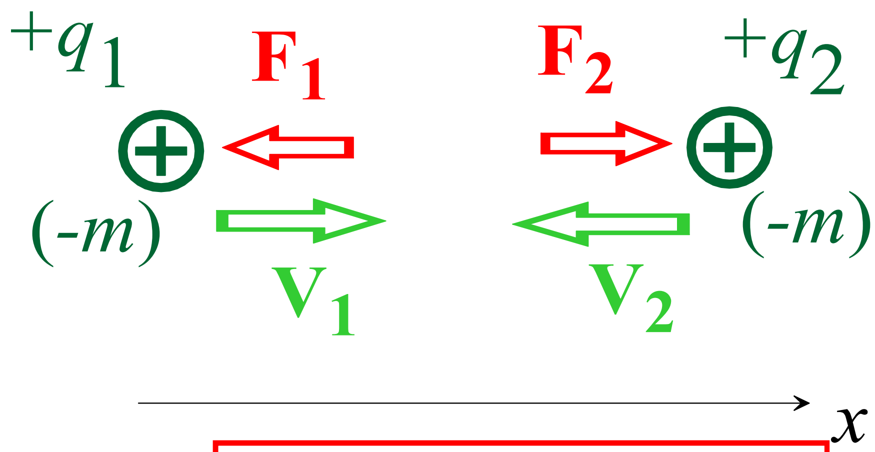


$$\frac{d^2x}{dt^2} = \frac{dV}{dt} = \frac{F}{m}$$



$$\mathbf{F}_1 < 0 \Rightarrow V_1 < 0$$

$$\mathbf{F}_2 > 0 \Rightarrow V_2 > 0$$



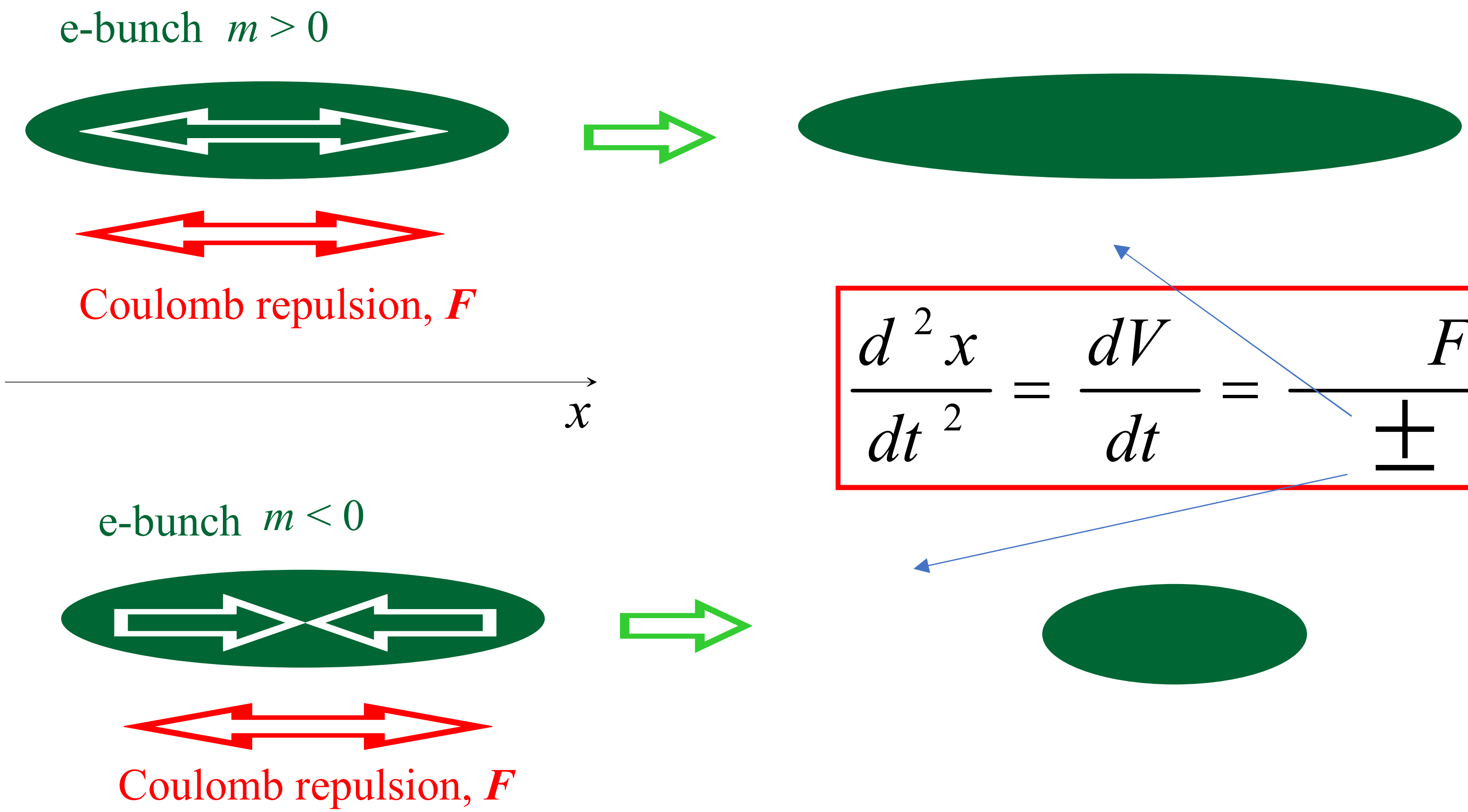
$$\frac{d^2x}{dt^2} = \frac{dV}{dt} = \frac{F}{(-m)}$$

$$\mathbf{F}_1 < 0 \Rightarrow V_1 > 0$$

$$\mathbf{F}_2 > 0 \Rightarrow V_2 < 0$$

Two positive (two negative) charges are attracted !!!

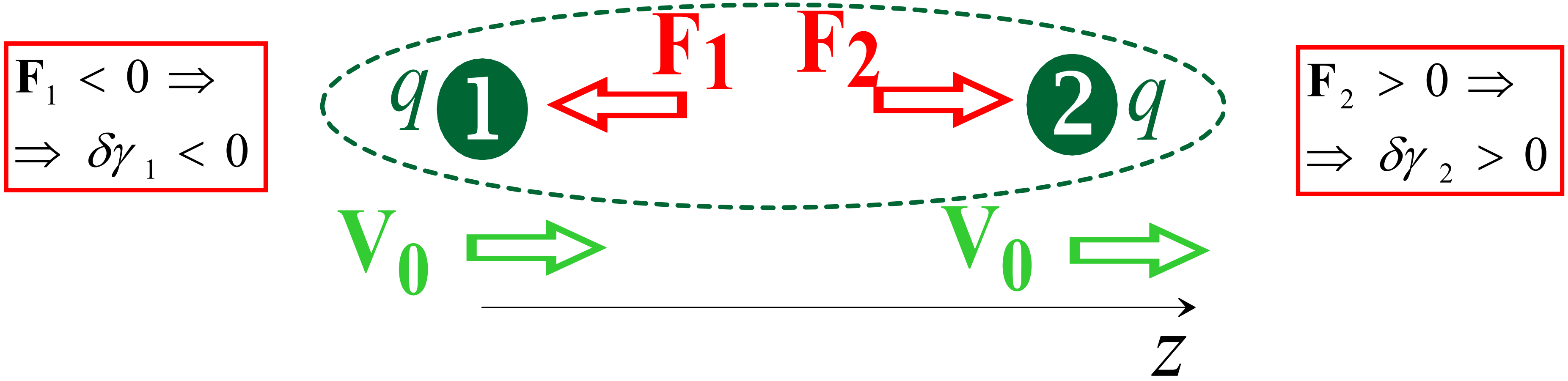
Positive and negative mass



$$\frac{d^2x}{dt^2} = \frac{dV}{dt} = \frac{F}{\pm\ m}$$

Negative-mass electrons are attracted !!!

Relativistic electron bunches



$$Energy = mc^2\gamma$$

$$mc^2 \frac{d\gamma_{1,2}}{dt} = F_{1,2} \times V_z \qquad \frac{dz_{1,2}}{dt} = V_z = V_0 + \frac{\partial V_z}{\partial \gamma} \times (\gamma_{1,2} - \gamma_0)$$

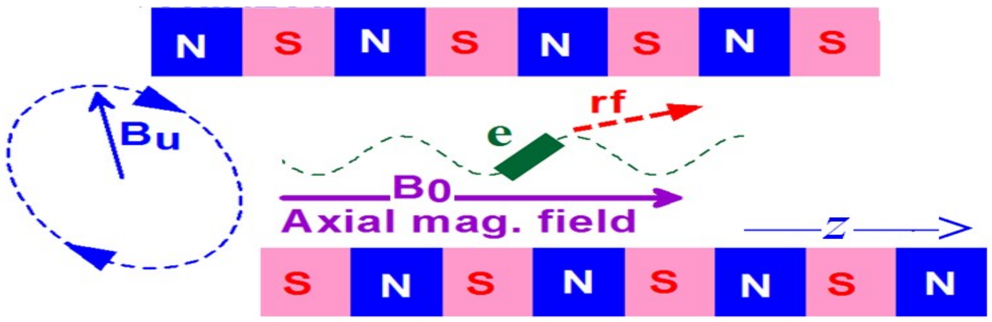
Evolution of the bunch length, z_2-z_1

$$\frac{d}{d(ct)}(z_2 - z_1) = \mu \times (\gamma_2 - \gamma_1)$$

is determined by the difference in energies of the two particles

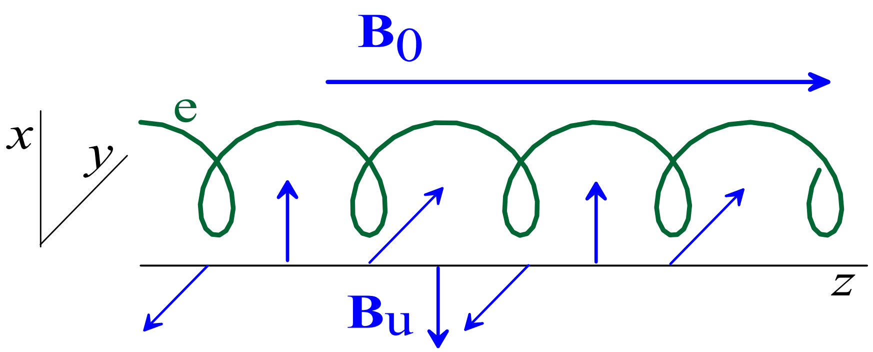
$$\mu = \frac{1}{c}\frac{\partial V_z}{\partial \gamma}$$

Helical undulator with axial magnetic field



$$\mathbf{B}_u = -\mathbf{x}_0 B_u \sin(h_u z) + \mathbf{y}_0 B_u \cos(h_u z) + \mathbf{z}_0 B_0$$

$$p_+ = \gamma (V_x + iV_y)/c \qquad Z = h_u z$$



$$\frac{dp_+}{dZ} = K_u \exp(iZ) + i\frac{\Omega_c}{\Omega_u} p_+$$

$$p_+ = \frac{-iK_u}{1 - \Omega_c/\Omega_u} \exp(iZ)$$

$$\frac{V_{\text{und}}}{c} = \frac{K}{\gamma} \times \frac{1}{\Delta}$$

$$\Delta = 1 - \Omega_c/\Omega_u = F(\gamma, V_z)$$

$$K_u = eB_u / mh_u$$

Undulator factor (norm. undulator magnetic field)

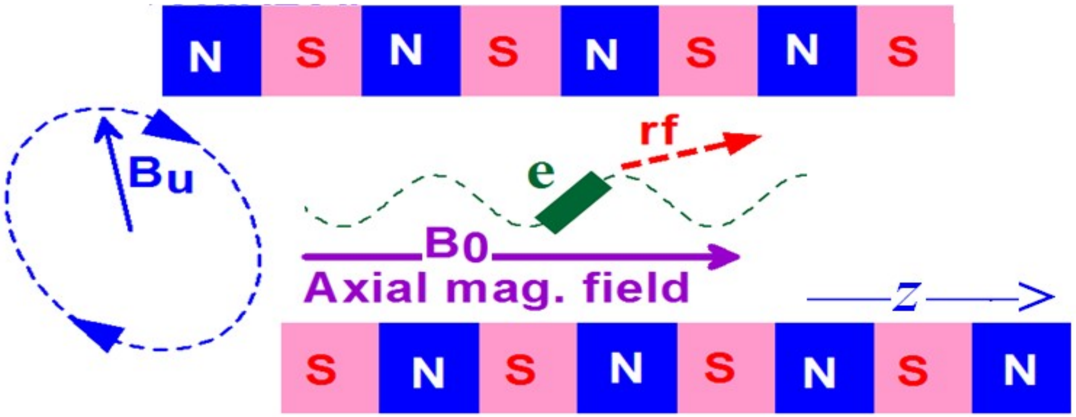
$$\Omega_c = \frac{eB_0}{mc\gamma}$$

Free electron cyclotron oscillations

$$\Omega_u = h_u V_z$$

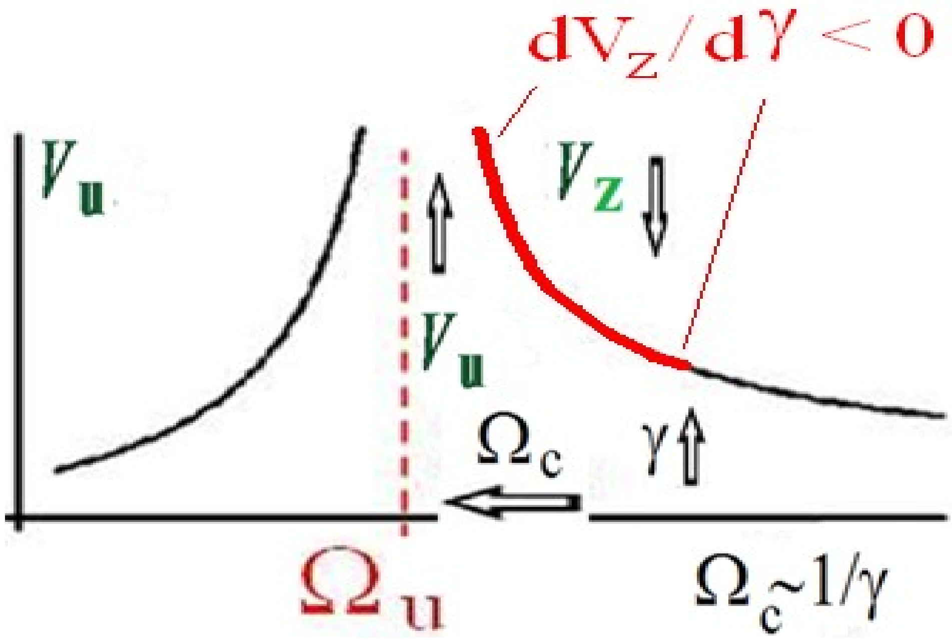
Forced electron oscillations in periodic undulator field

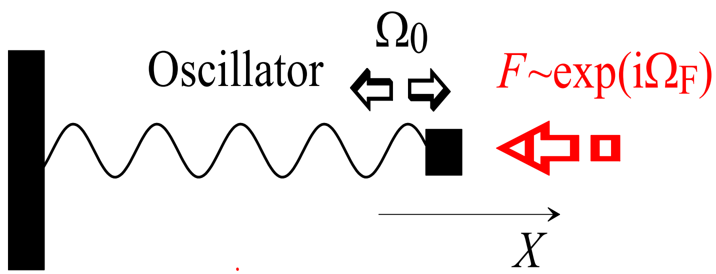
Negative-mass regime in an undulator with axial magnetic field

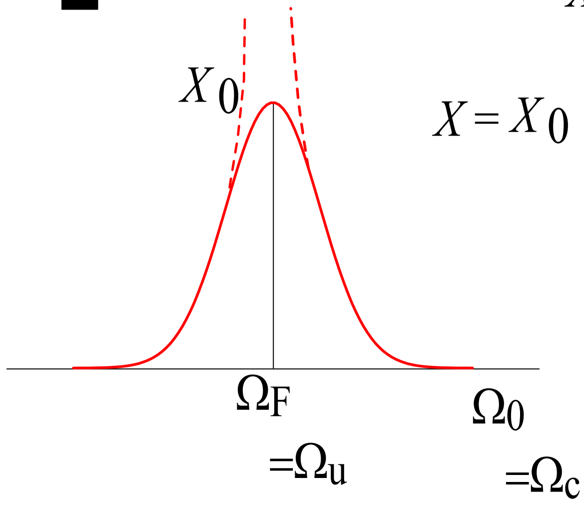


$$\frac{d^2X}{dt^2} + \Omega_0^2 X = F_0 \exp(i\Omega_F t)$$

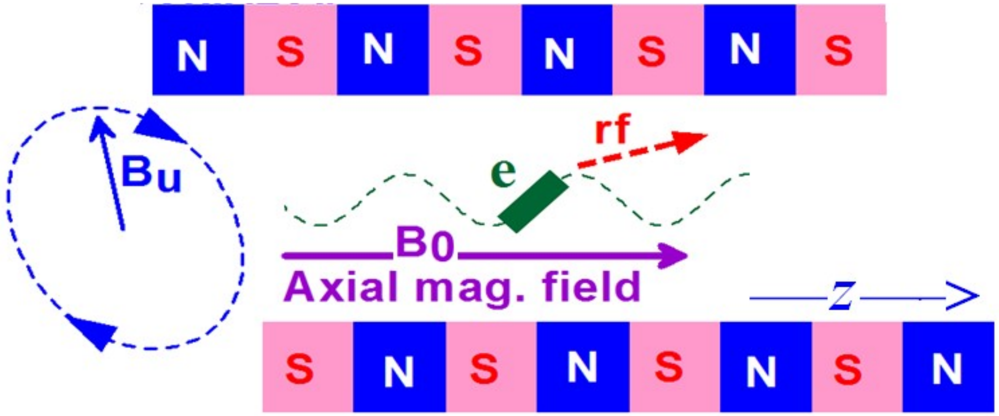
Velocity of undulator oscillations vs the electron cyclotron frequency

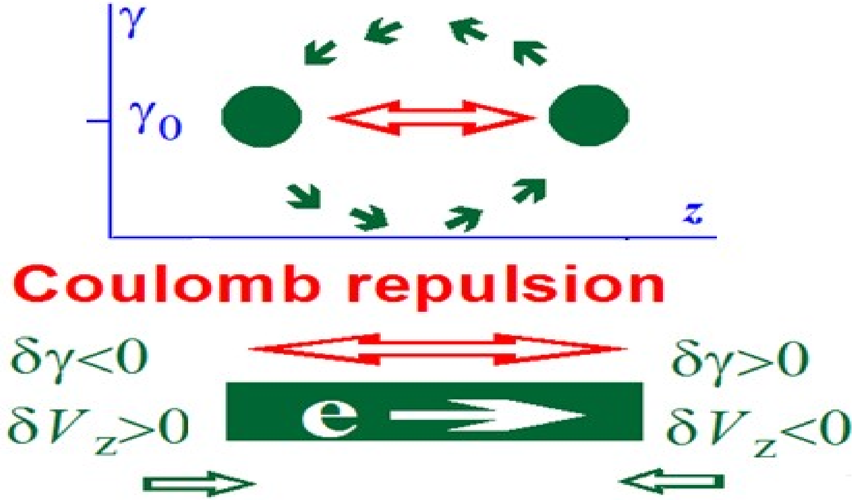




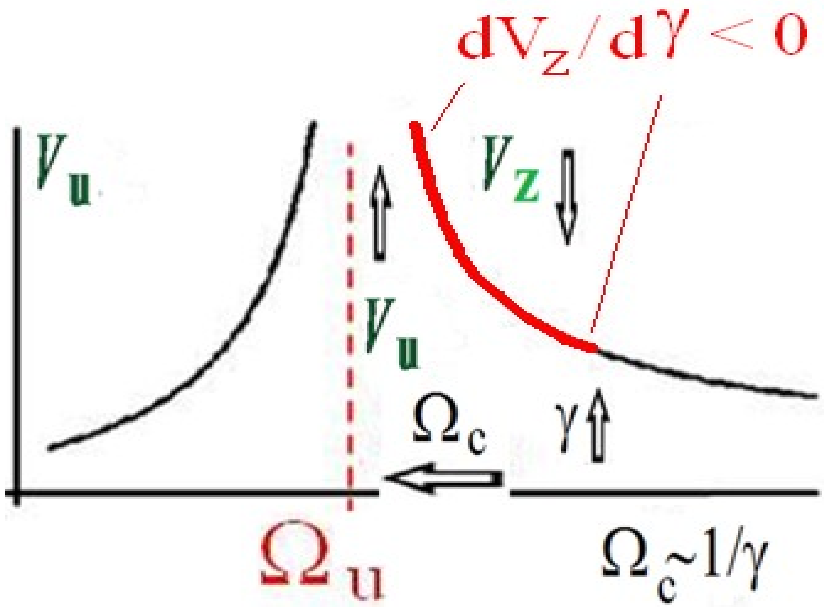


Negative-mass regime in an undulator with axial magnetic field





Velocity of undulator oscillations vs the electron cyclotron frequency



Negative-mass regime:

$$\frac{1}{c}\frac{dV_z}{d\gamma} = \frac{1 + K^2/\Delta^3}{\gamma^3} < 0$$

$$\Delta < 0 \quad (\Omega_c > \Omega_u)$$

$$|\Delta| < K^{2/3}$$

Undulator velocity: $\gamma V_u / c = K / \Delta$

Undulator frequency $\Omega_u = h_u V_{||}$

Cyclotron frequency $\Omega_c = eB_0 / \gamma mc$

Resonance mismatch: $\Delta = 1 - \Omega_c / \Omega_u$

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 020704 (2017)

EDITORS' SUGGESTION

Compression of a photoinjector electron bunch in the negative-mass undulator

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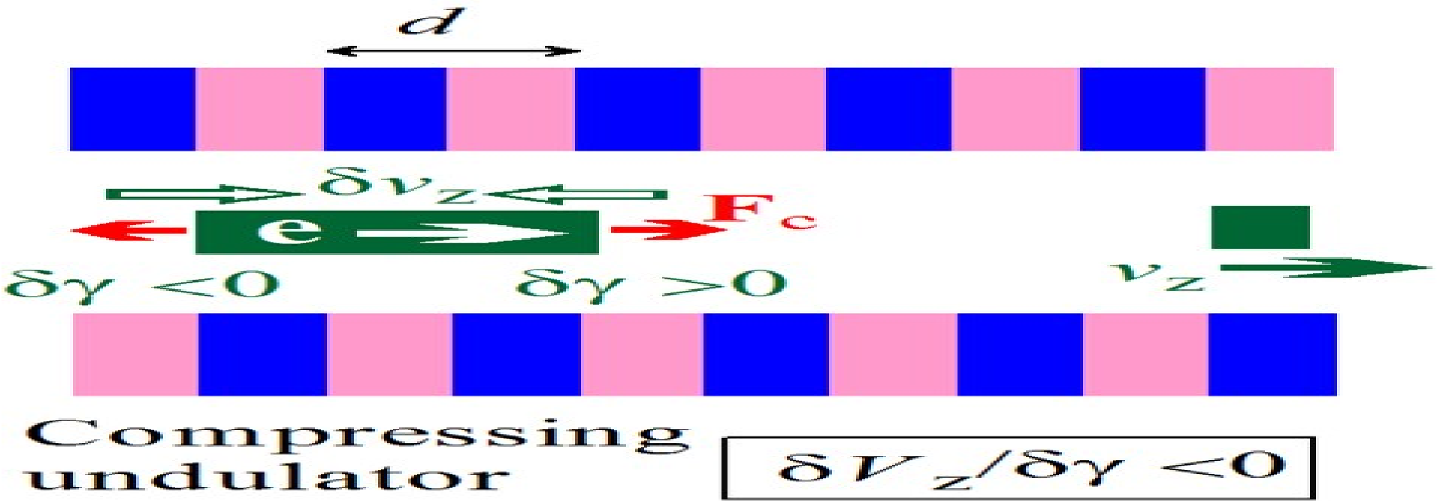
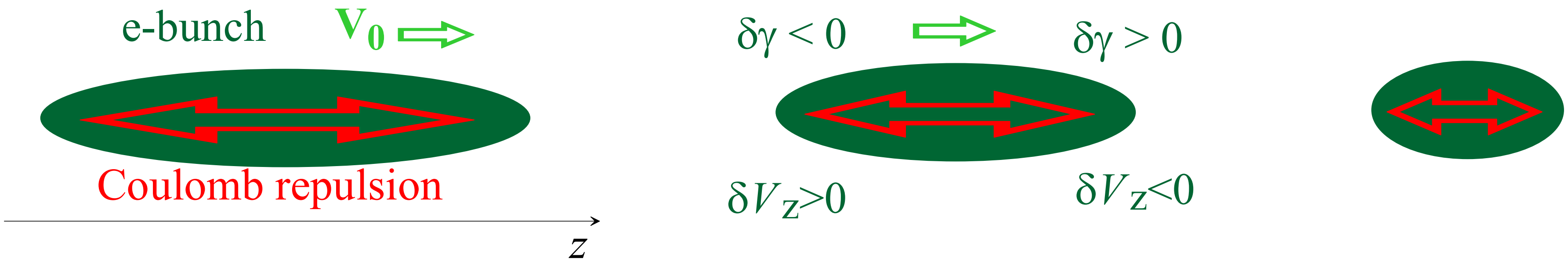
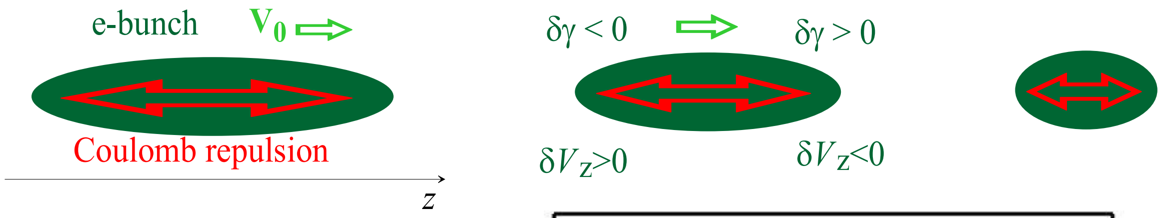
[2]*Lobachevsky Sate University of Nizhny Novgorod, 603950, Russian Federation*
(Received 9 November 2016; published 15 February 2017)

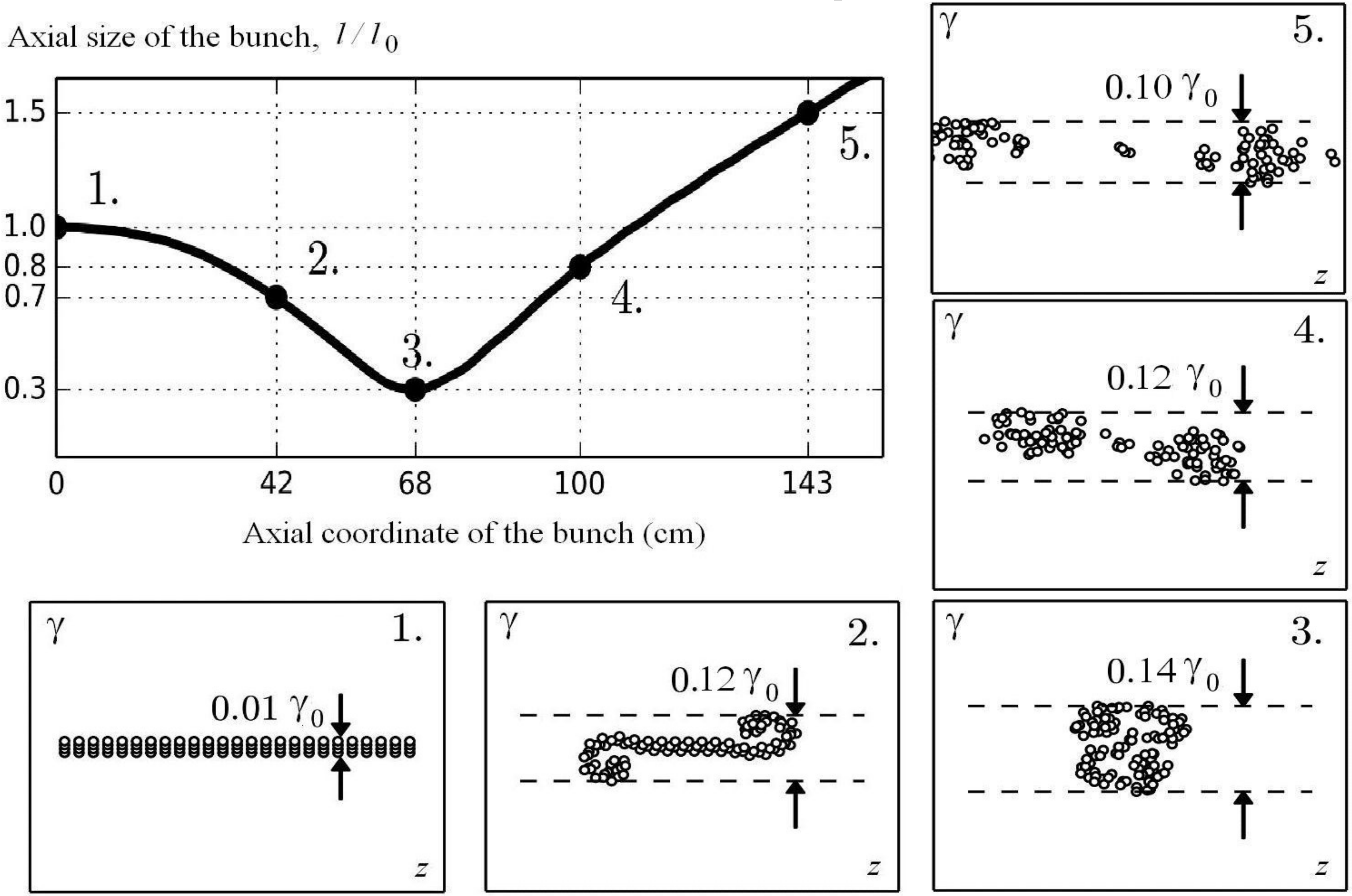




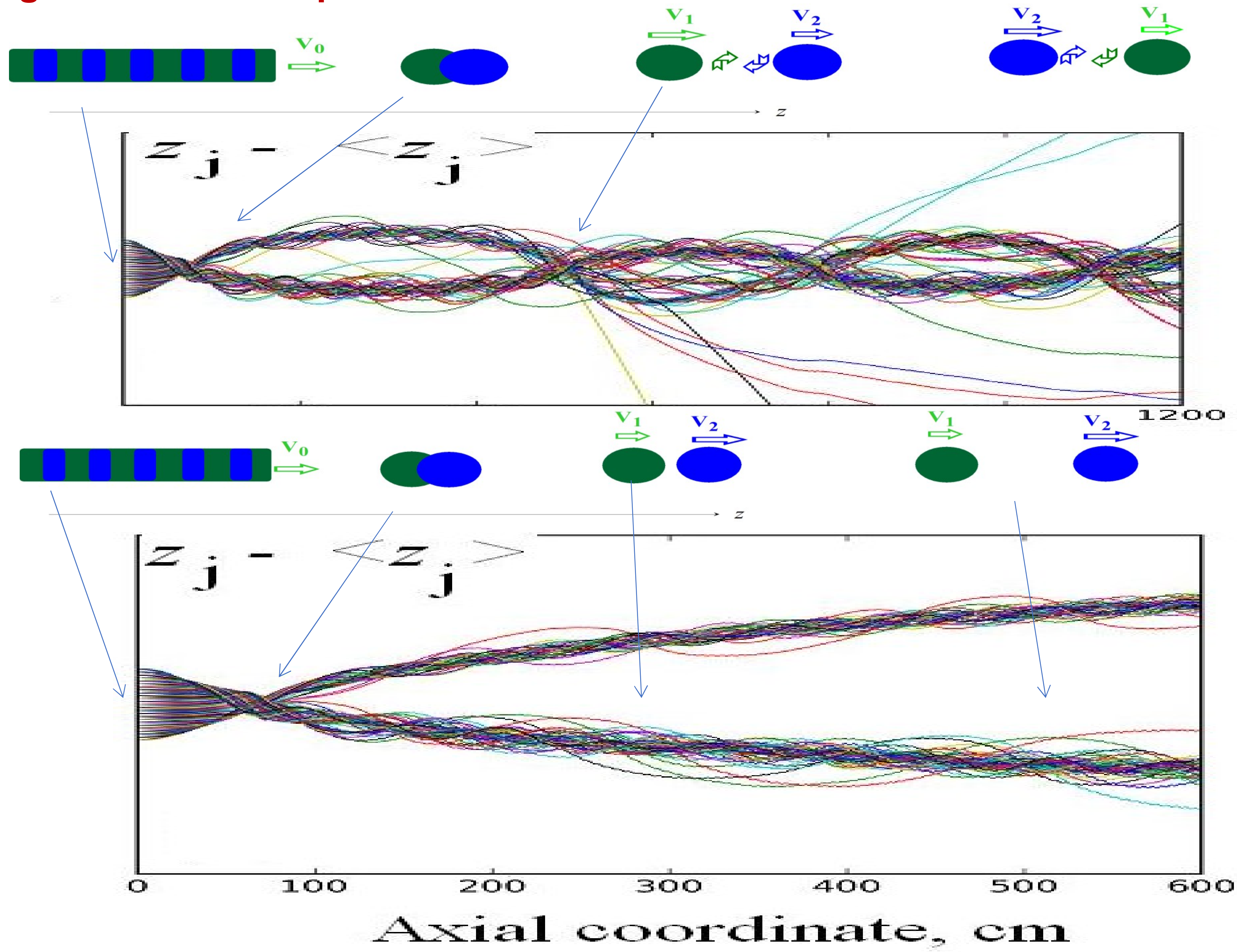
Compression of an electron bunch
under the effect of its own Coulomb field

Negative-mass compression of a 0.3 nC 1 mm e-bunch

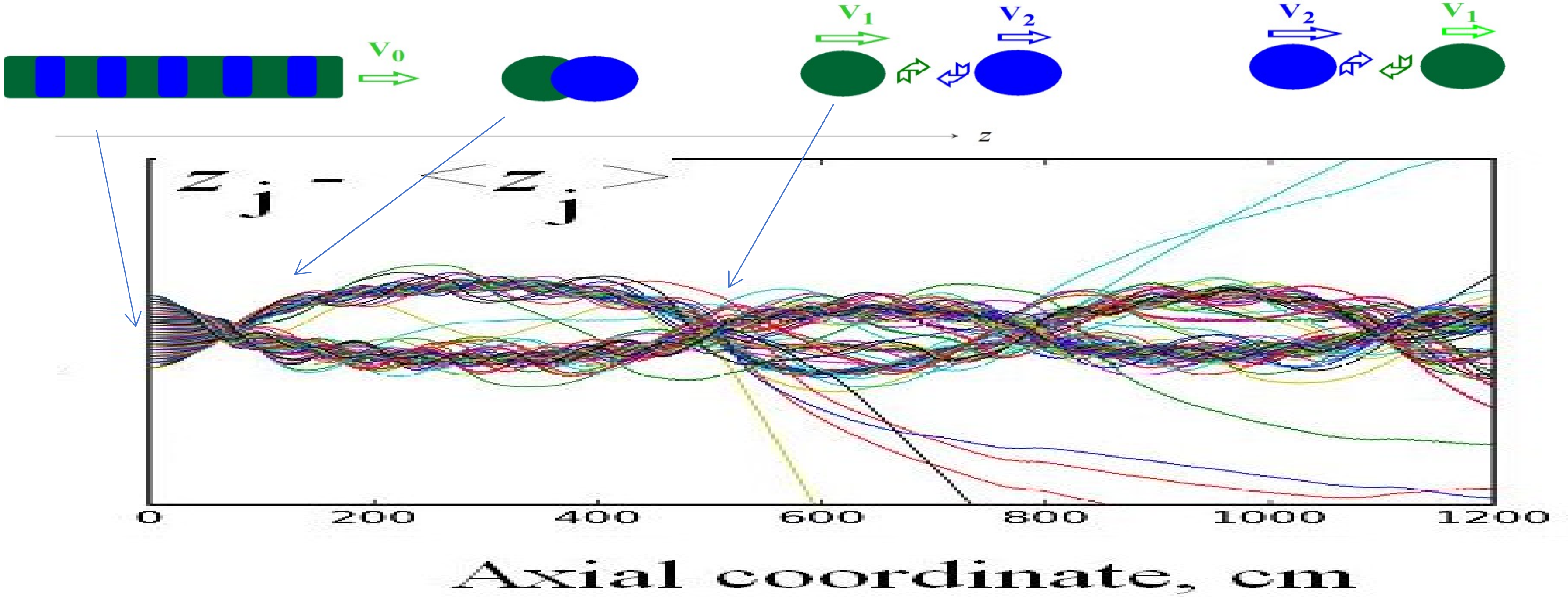




Negative-mass compression of a 0.3 nC 1 mm e-bunch



Negative-mass compression of a 0.3 nC 1 mm e-bunch

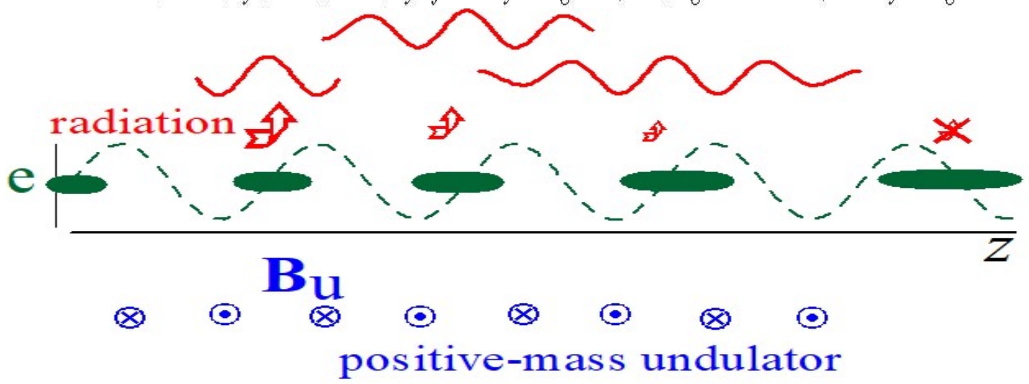


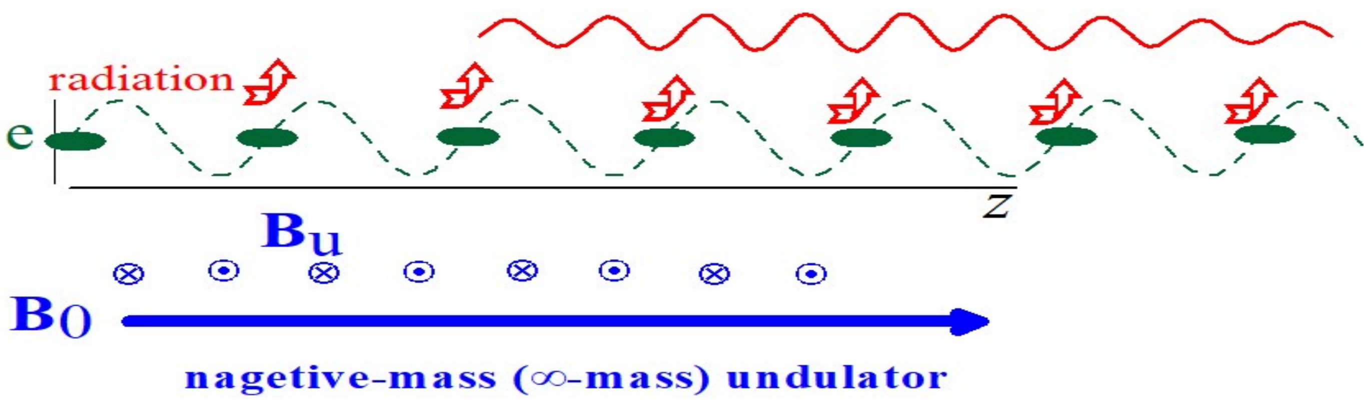
Numerical simulations of the negative-mass-undulator THz FEM

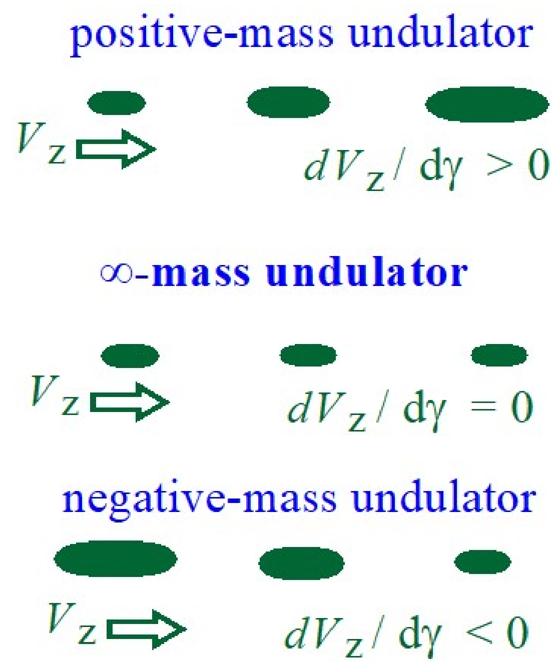
APPLIED PHYSICS LETTERS 107, 163505 (2015)

Negative-mass mitigation of Coulomb repulsion for terahertz undulator radiation of electron bunches

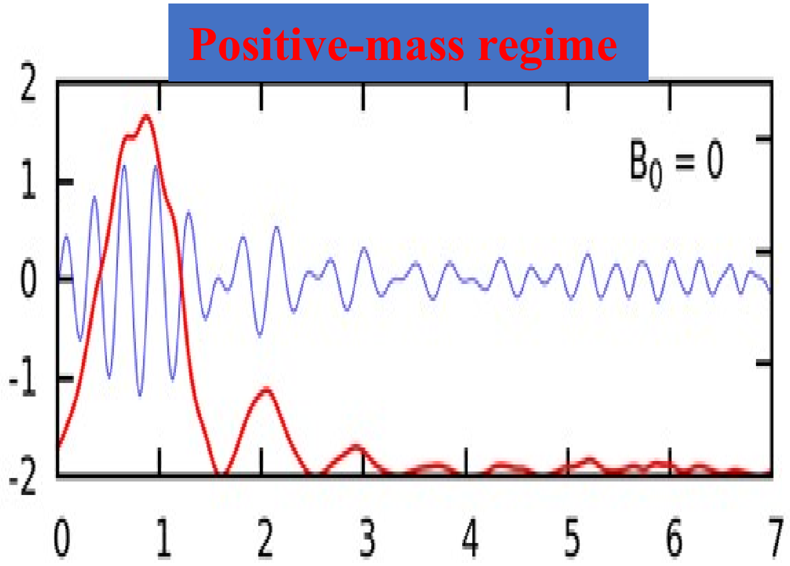
N. Balal,[1] I. V. Bandurkin,[2] V. L. Bratman,[1,2] E. Magory,[1] and A. V. Savilov[2,3]
[1]*Ariel University, Ariel 40700, Israel*
[2]*Institute of Applied Physics, Russian Academy of Sciences, 46 Ulyanov St., Nizhny Novgorod 603950, Russia*
[3]*Lobachevsky State University of Nizhny Novgorod, 23 Gagarin Avenue, Nizhny Novgorod 603950, Russia*

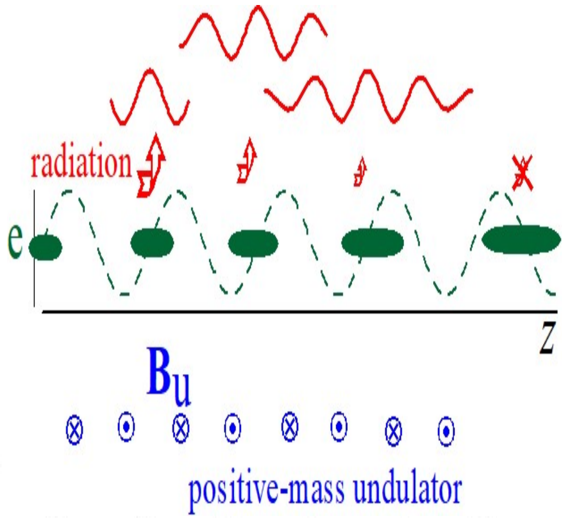




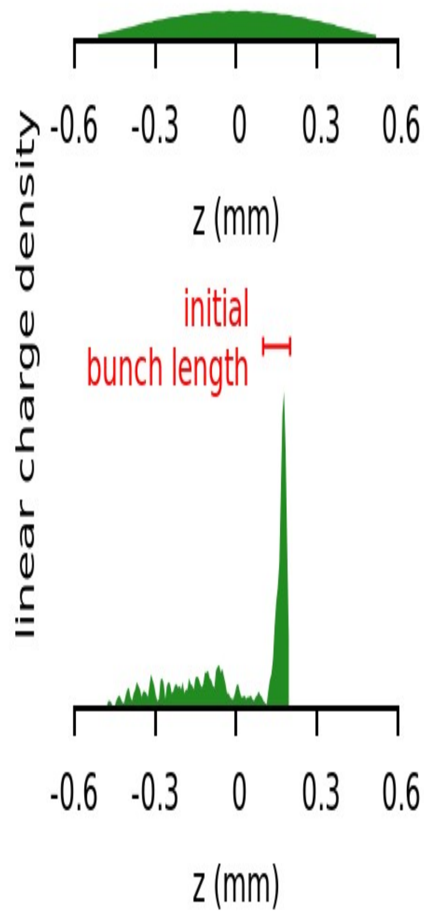


Electric field of the radiated signal, power and spectrum.

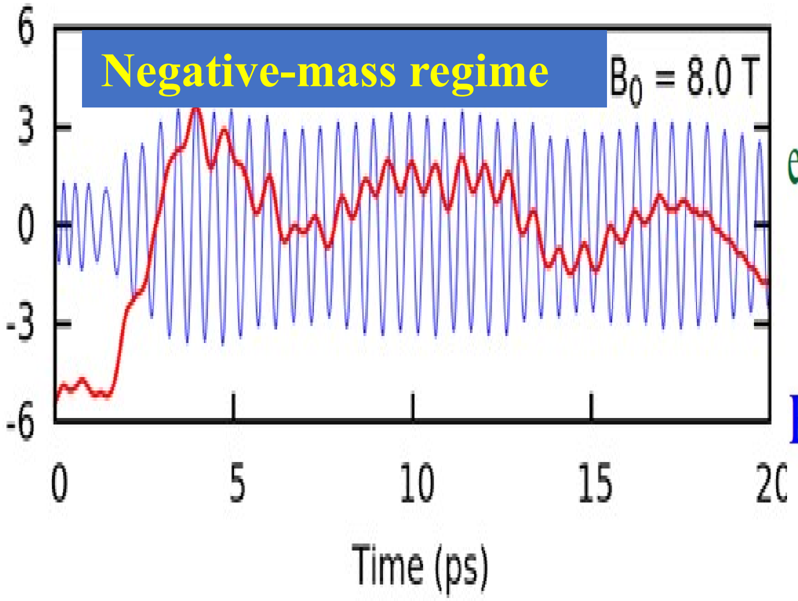


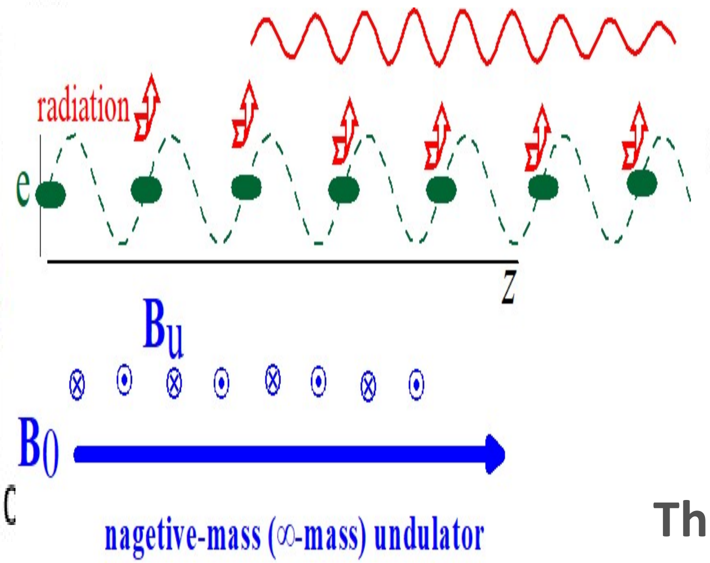


The bunch after a 60 cm trip (B_0=0).



The resonant value of the guiding field is B = 5 T.

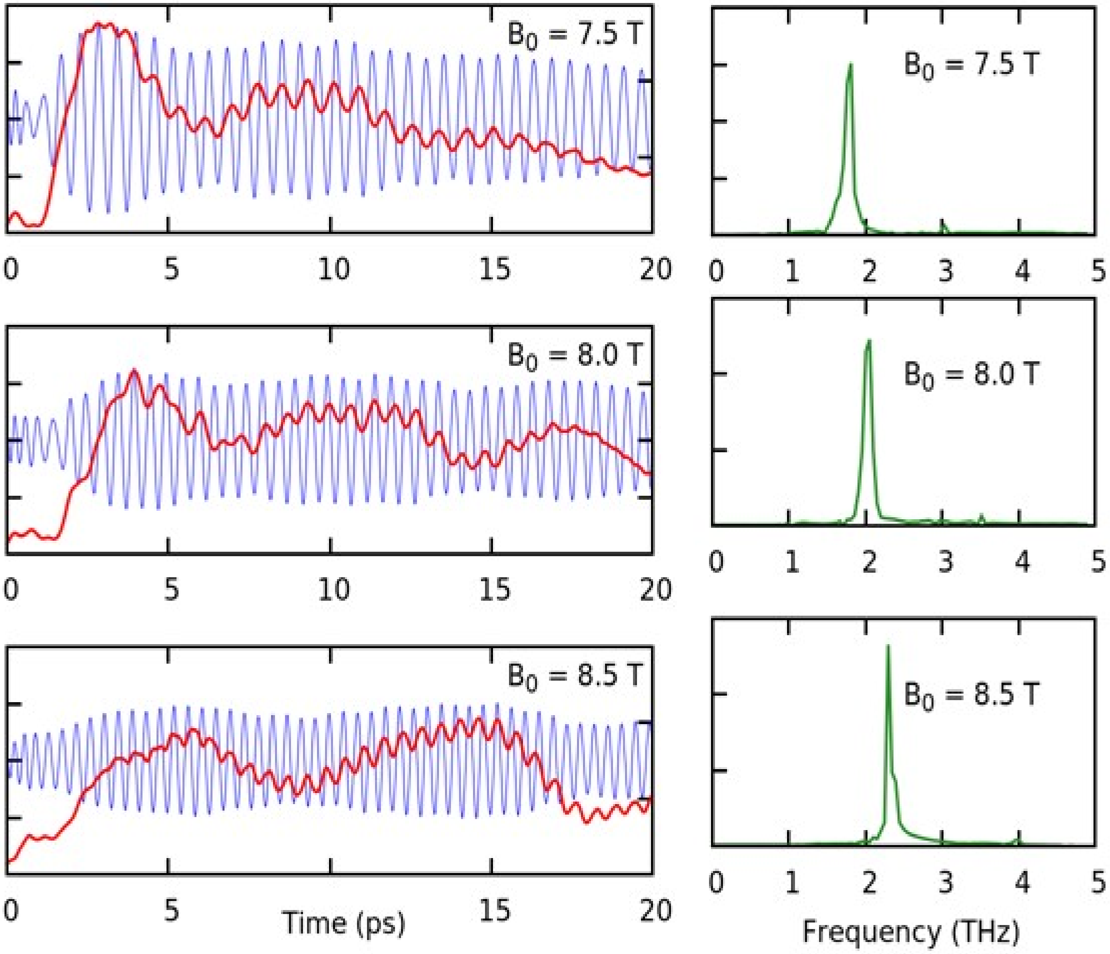




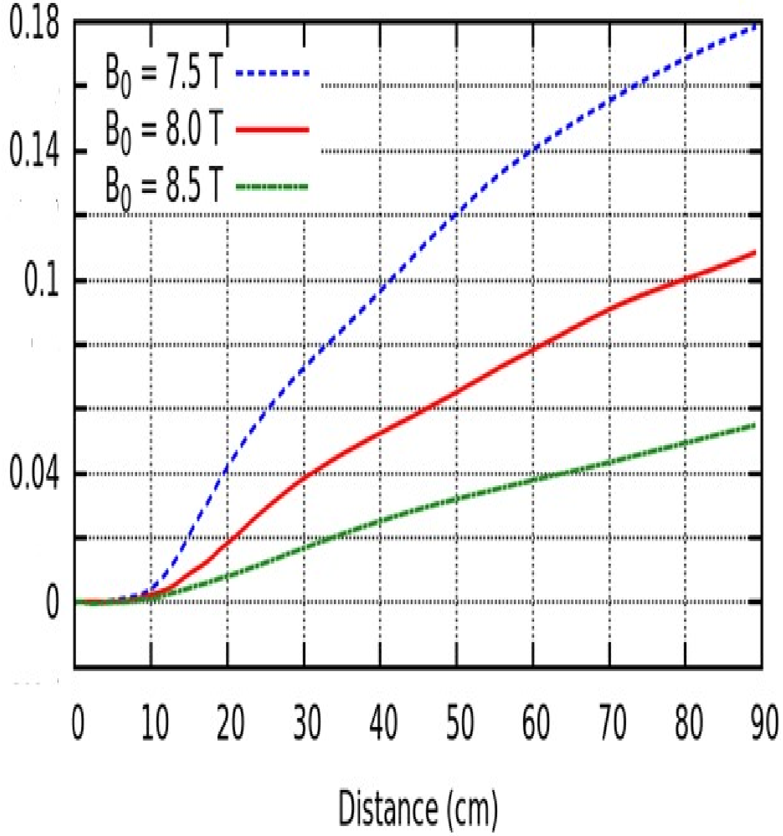
The bunch after a 90 cm trip (B_0=8 T).

Negative-mass undulator emission at various axial magnetic fields

Electric field of the wave, power and frequency spectrum.



Averaged loss of the electron energy (electron efficiency) vs the axial coordinate



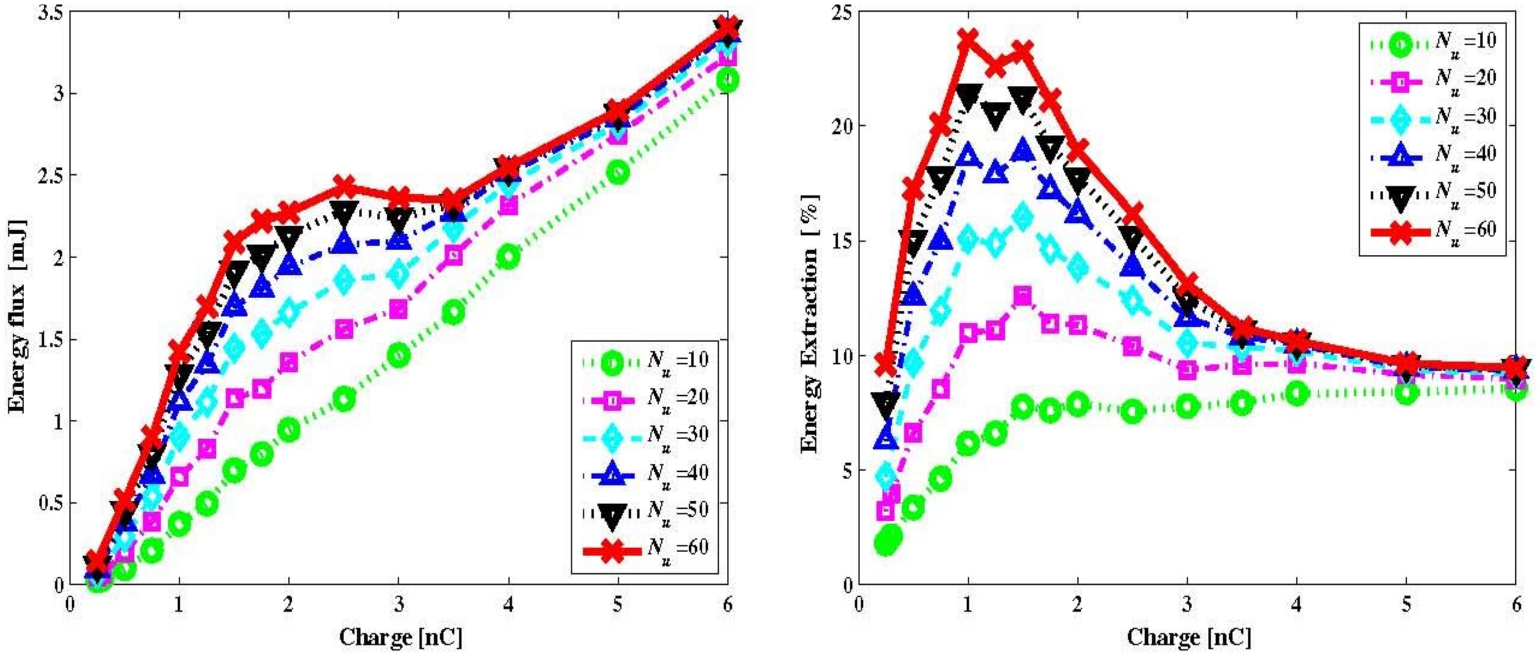
The total bunch energy loss after of approximately 1 meter trip in the negative-mass regime ~10%.

This corresponds to an average power of the order of 10 MW in the 20 ps forward-radiated THz pulse.

A change in the axial magnetic field (7.5-8.5 T) provides frequency tuning in the range 1.7-2.3 THz.

Negative-mass undulator emission efficiency vs the e-bunch charge

The electron efficiency stays over 10% at giant (several nC) e-bunch charges!



(a) (b)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 050704 (2016)

Energy enhancement and spectrum narrowing in terahertz electron sources due to negative mass instability

Yu. Lurie,[1,*] V. L. Bratman,[1,2] and A. V. Savilov[2]
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(Received 10 March 2016; published 26 May 2016)

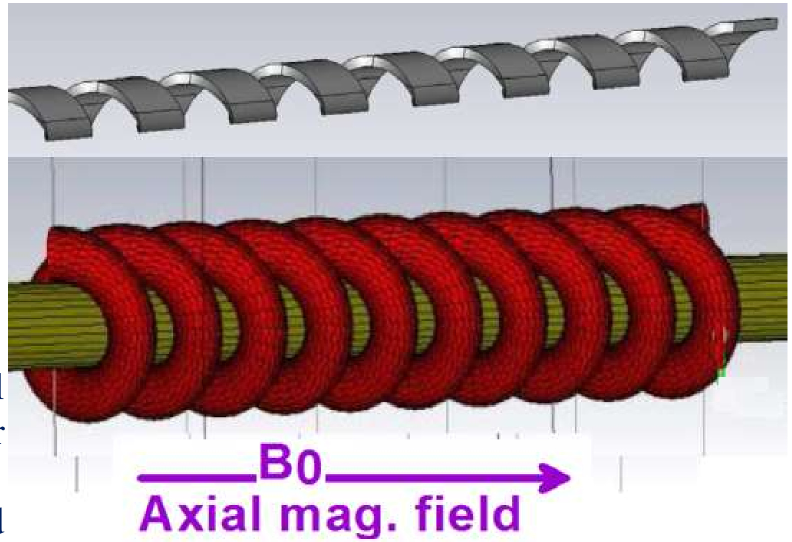
Helical undulator with a strong axial magnetic field

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 122401 (2017)

Helical undulator based on partial redistribution of uniform magnetic field

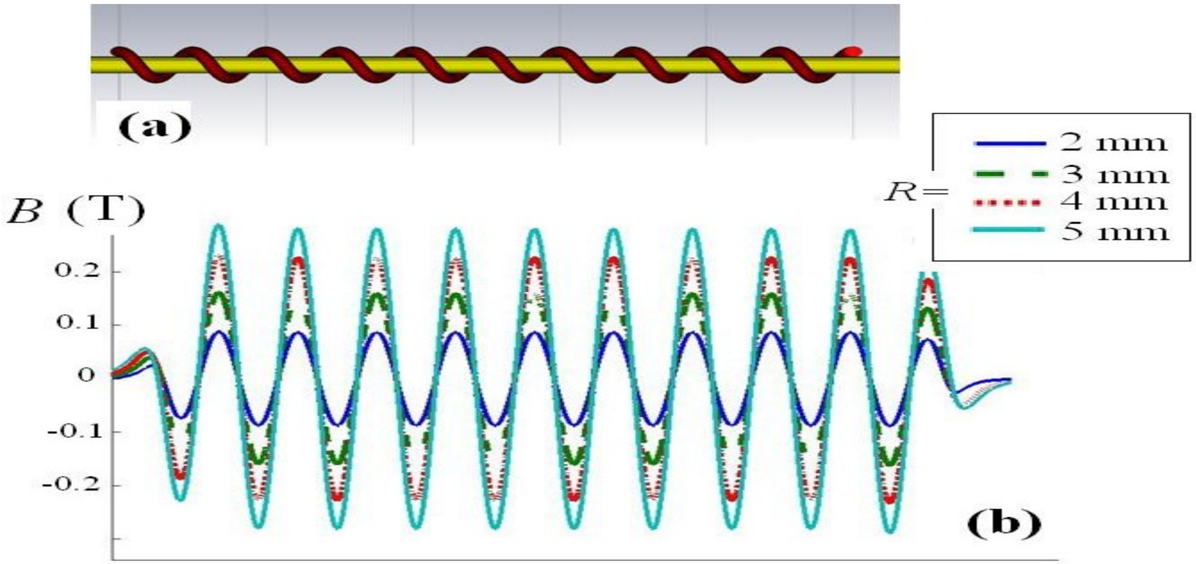
N. Balal,[1] I. V. Bandurkin,[2,*] V. L. Bratman,[1,2] and A. E. Fedotov[2]
[1]*Ariel University, 40700 Ariel, Israel*
[2]*Institute of Applied Physics, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia*
(Received 9 August 2017; published 19 December 2017)

A new type of helical undulator based on redistribution of magnetic field of a solenoid by ferromagnetic helix has been proposed and studied both in theory and experiment. Such undulators are very simple and efficient for promising sources of coherent spontaneous THz undulator radiation from dense electron bunches formed in laser-driven photo-injectors.



A large guiding magnetic field can be used to obtaining the helical undulator field. It can be done by insertion of periodic conducting or magnetic structures into a solenoid.

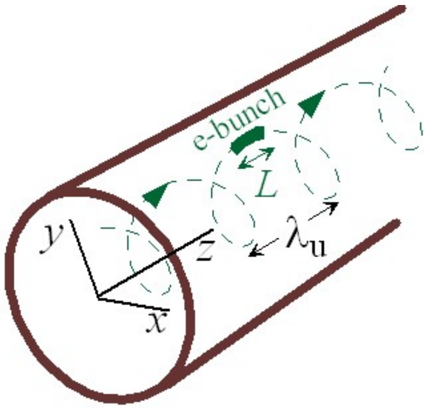
Simple copper or iron helices can be placed inside a pulsed solenoid for obtaining a helical undulator field. For example, an iron helix with a period of 2.5 cm and an inner diameter of 10 mm wound of a wire with a radius of 3 mm and mounted into the solenoid with a uniform field of 8 T, provides the needed undulator parameter K=0.45 .

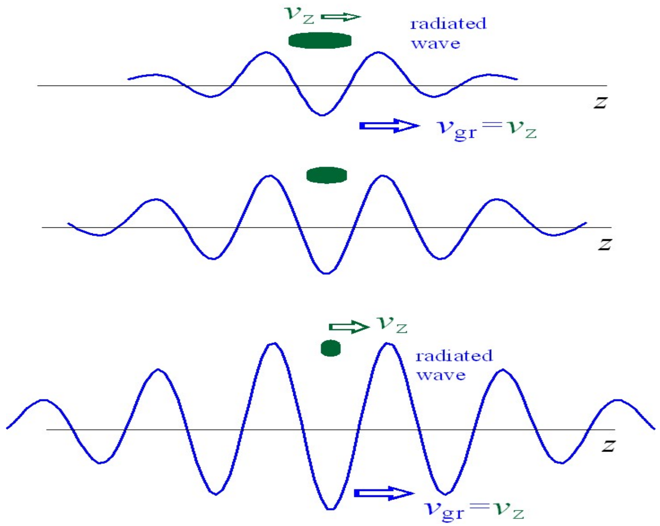


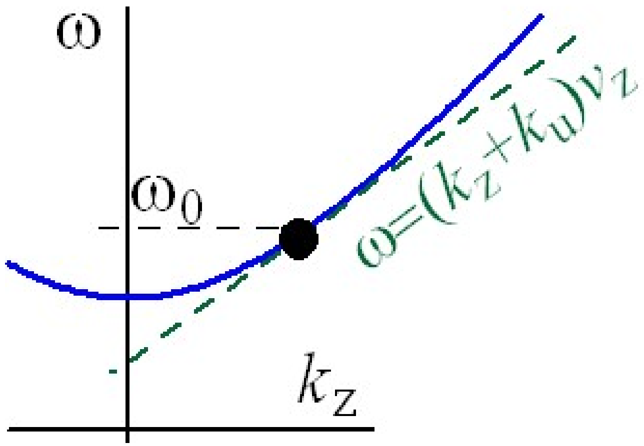
a) iron wire in the form of helix wound on cylindrical copper waveguide with outside diameter 10 mm and placed inside the solenoid with strong guiding field,

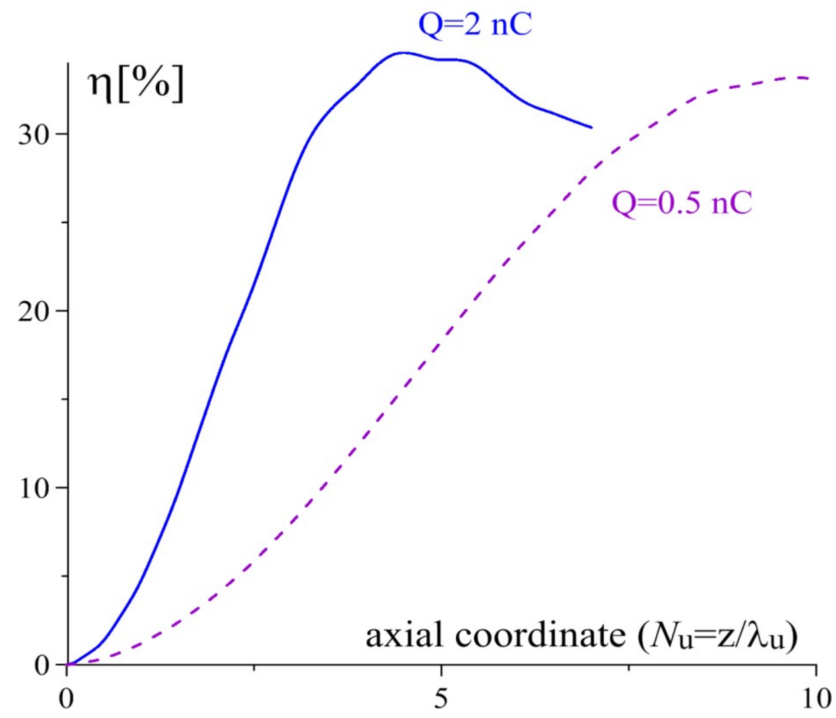
b) axial distributions of transverse undulator fields

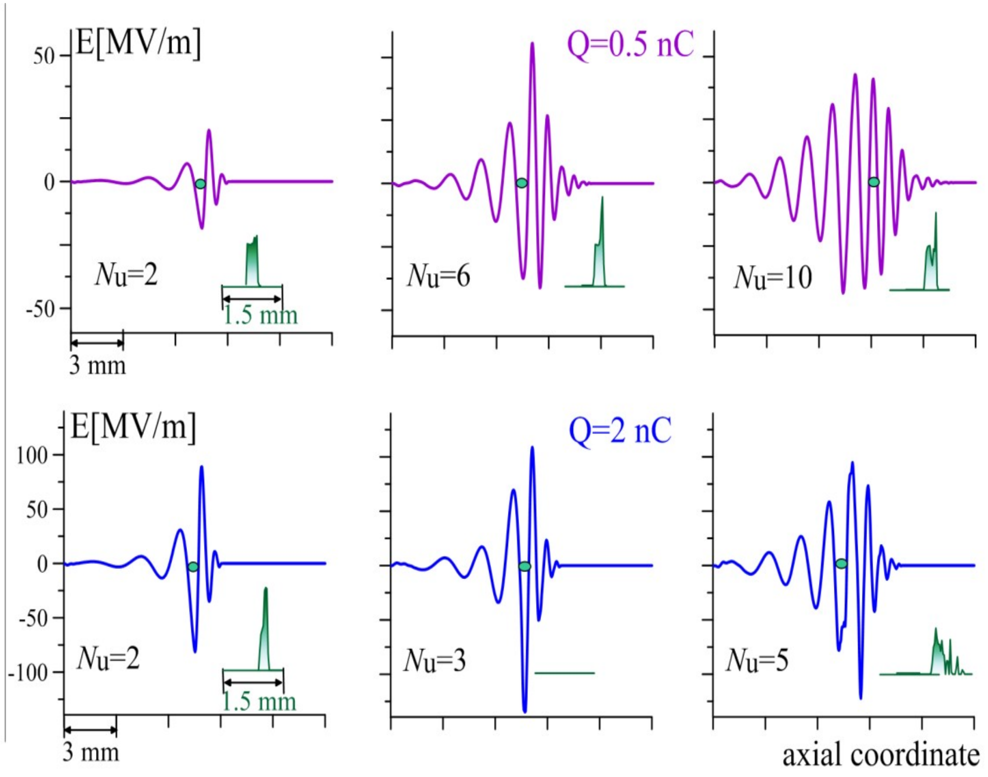
Super-radiation of a short wave pulse



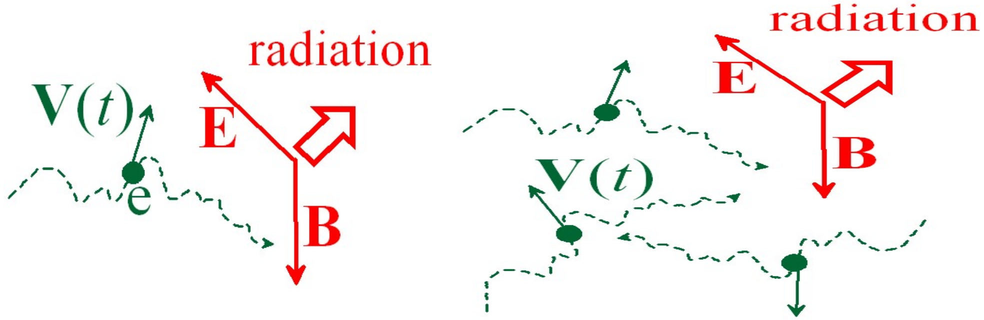




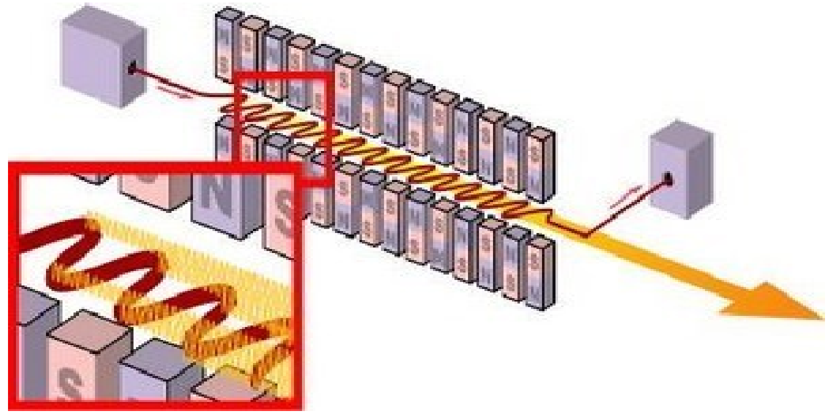




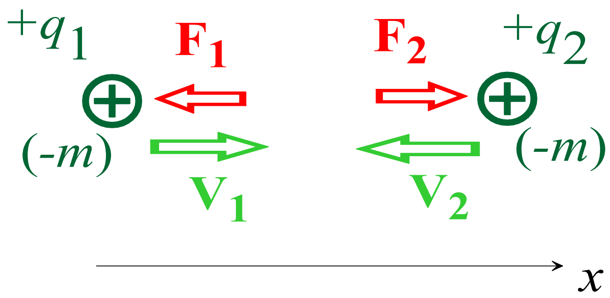
OUTLINE



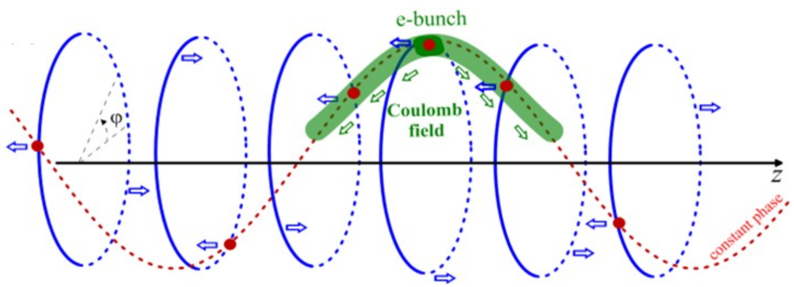
1. Спонтанный и индуцированный режимы излучения



2. Ондуляторное излучение

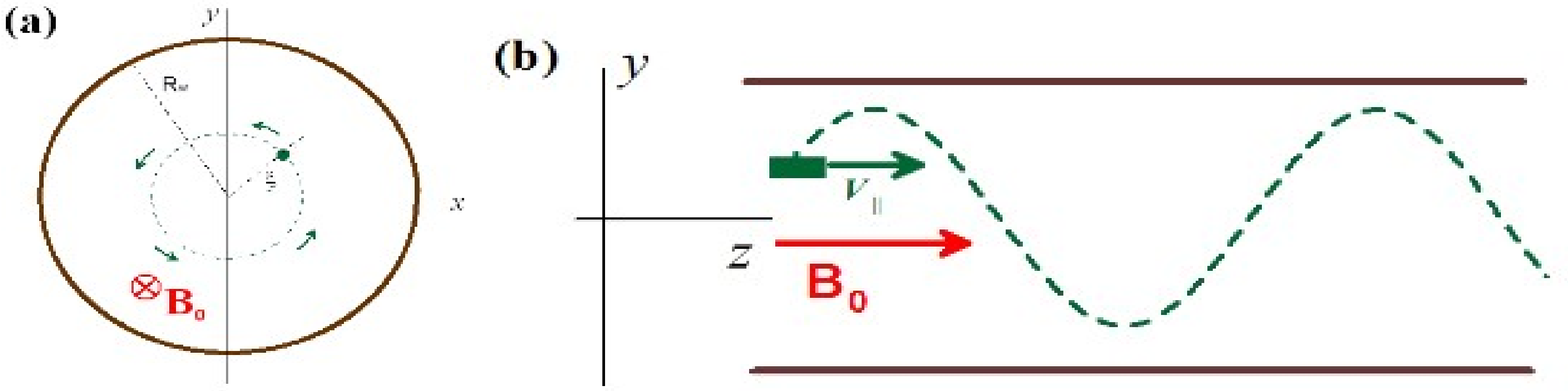


3. Ондуляторное излучение в режиме отрицательной массы

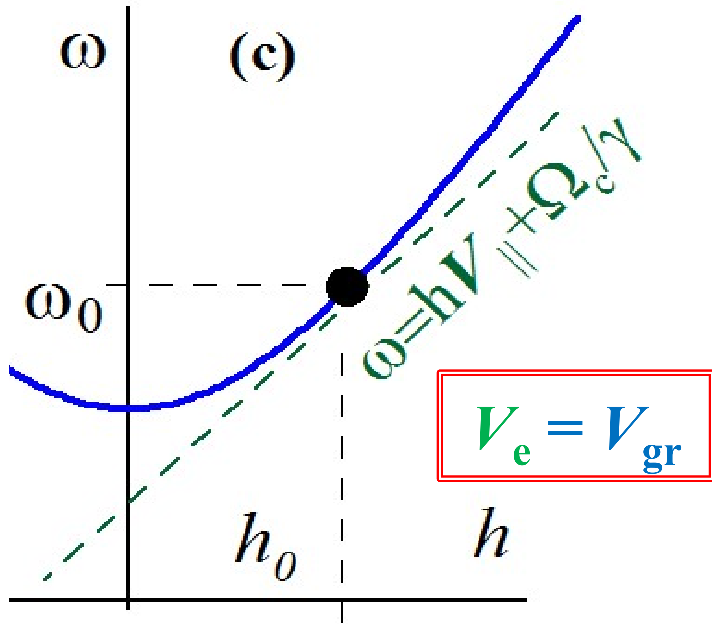


4. Циклотронное излучение

Spontaneous coherent **cyclotron** radiation



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 030701 (2019)



Spontaneous superradiant sub-THz coherent cyclotron emission from a short dense electron bunch

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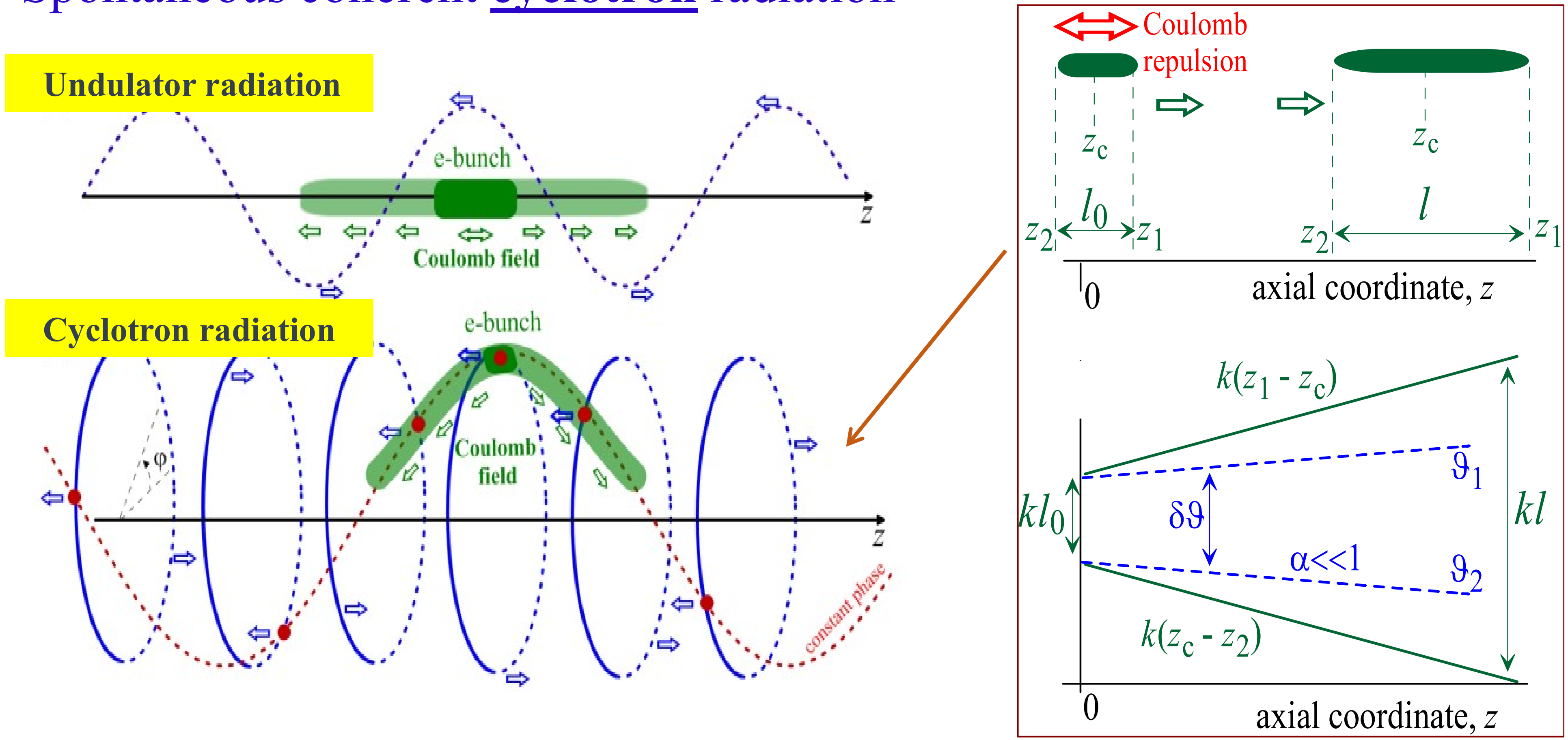
Short dense electron bunches produced by modern photoinjectors are attractive from the viewpoint of the realization of powerful and effective sources of subterahertz radiation based on the spontaneous coherent mechanism of emission. This type of emission is realized if the effective phase size of the bunch with respect to the radiated wave is small enough. Therefore, the repulsion of particles caused by a strong Coulomb field inside the dense electron bunch strictly limits the duration of the radiation process due to the increase in the bunch length. We show that this problem can be solved by using the cyclotron mechanism of the spontaneous radiation due to the effect of compensation of the Coulomb repulsion in the phase space.

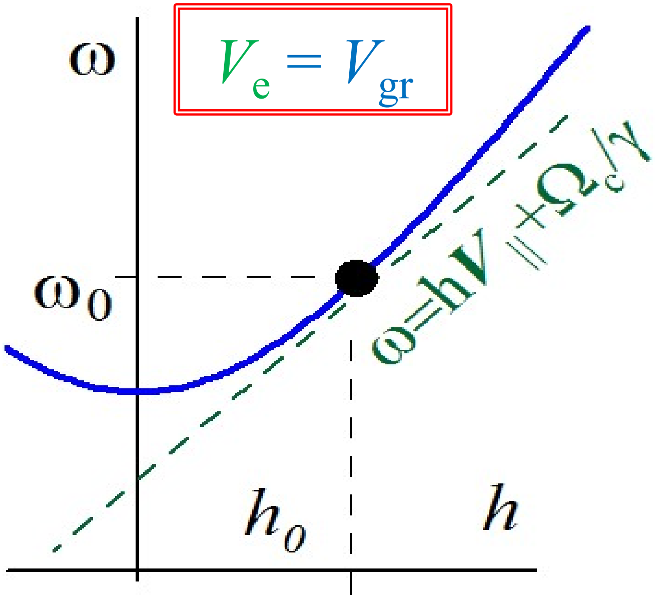
Spontaneous coherent **cyclotron** radiation



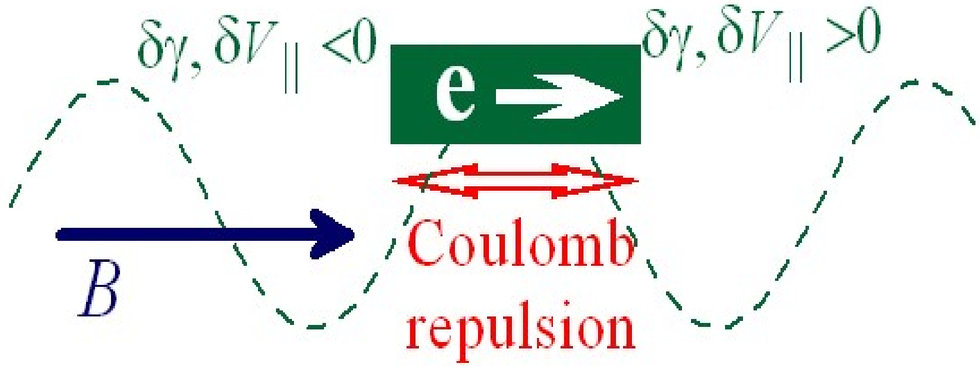
The repulsion of particles caused by a strong Coulomb field inside the dense electron bunch leads to the increase in the bunch length.

This problem can be solved by using the cyclotron mechanism of the spontaneous radiation due to the effect of compensation of the Coulomb repulsion in the 2-D phase space.

Spontaneous coherent **cyclotron** radiation

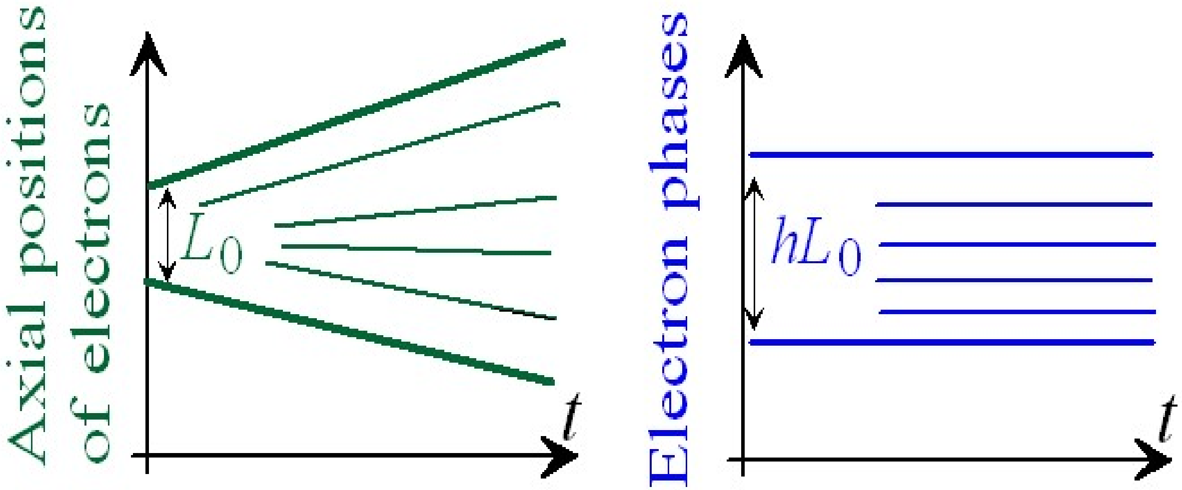


$$\omega - hV_{\parallel} - \frac{\Omega_c}{\gamma} = \frac{d\theta}{dt} = \omega - hV_{\parallel} - \frac{\Omega_c}{\gamma}$$

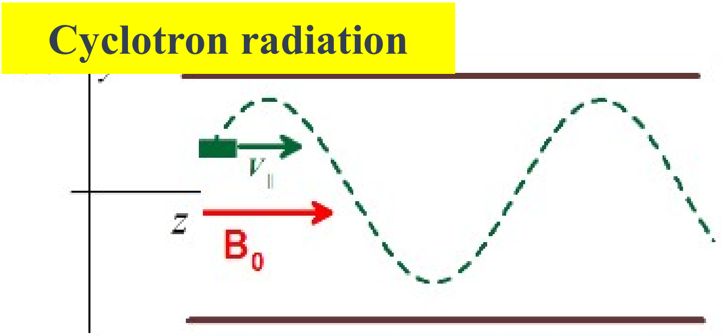


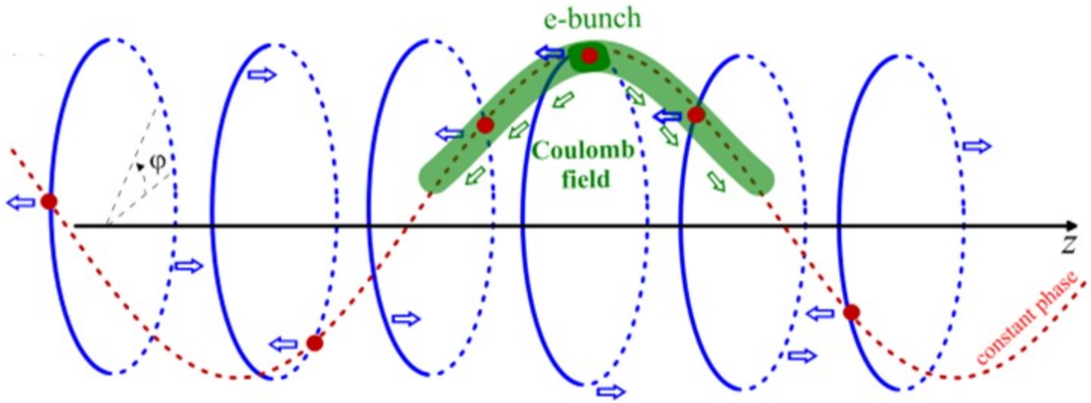
In the case of the cyclotron maser, Coulomb repulsion leads to increase of the axial size of the bunch, and there is no mechanism compensating this repulsion.

However, the phase size of the e-bunch in respect with the radiated wave stays constant. Thus, the spontaneous radiation does not stop.



Spontaneous coherent **cyclotron** radiation





Electron phase with respect to the wave

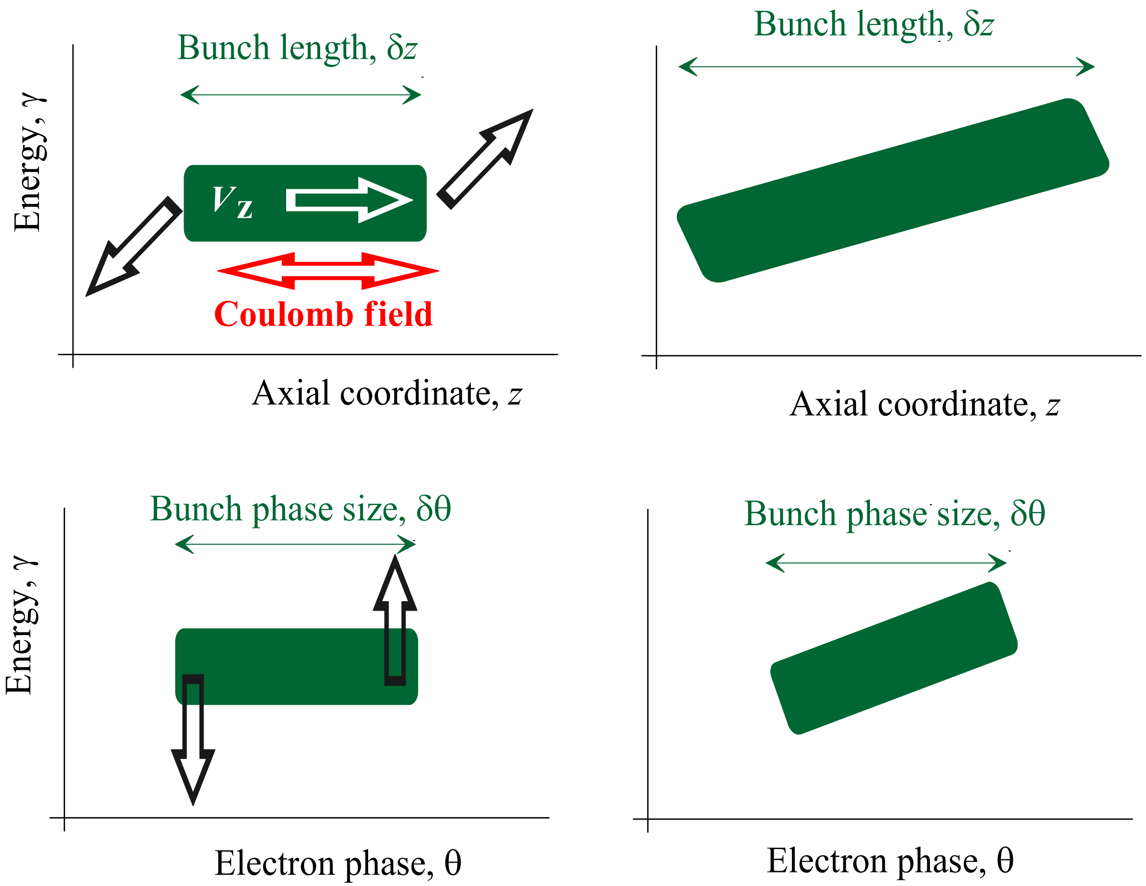
$$\theta = \varphi + hz - \omega t \quad , \quad \varphi = \int \Omega_c dt$$

Bunch length ≠ bunch phase size

$$\delta\theta = h\delta z + \delta\varphi$$

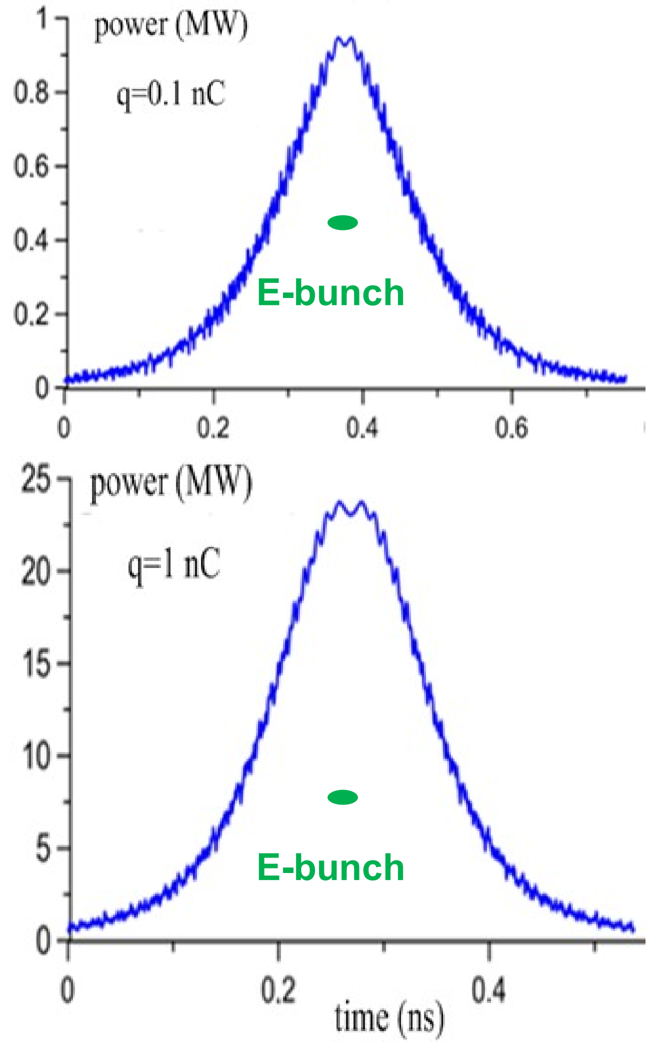
The curve (rotating helix)
of the constant phase

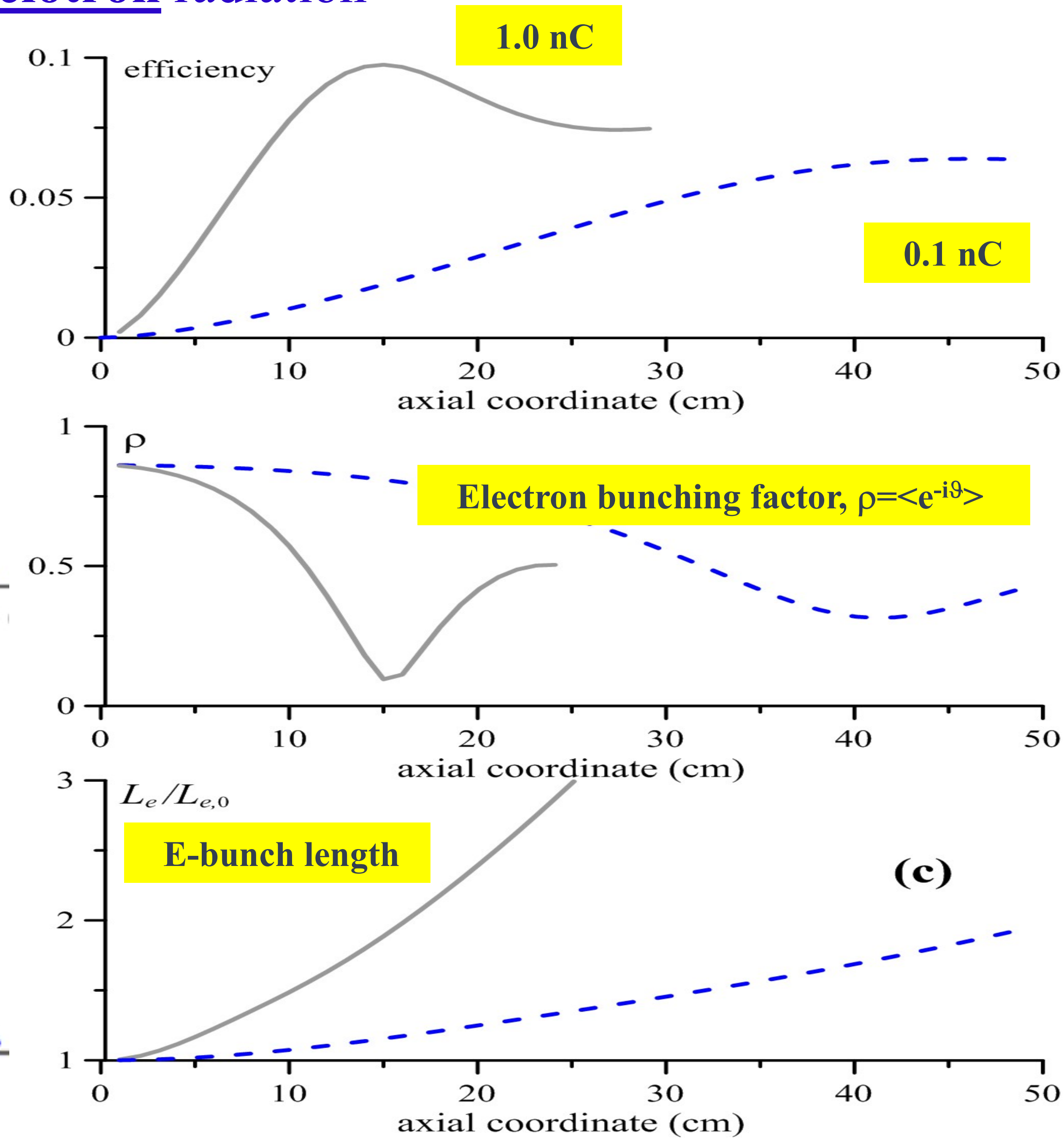
$$\varphi(z) = -hz$$



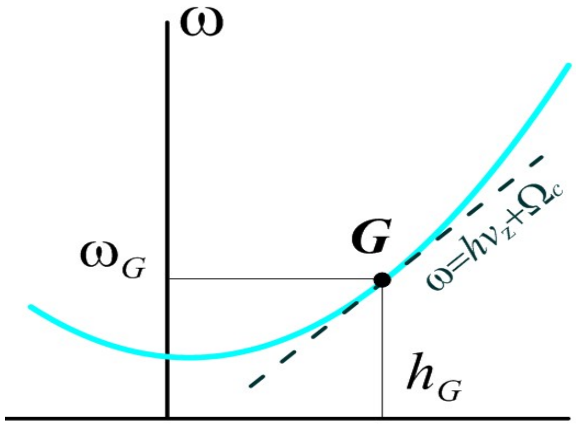
Spontaneous coherent **cyclotron** radiation

Frequency = 0.5 THz
E-bunch length = 0.15 mm (λ/4)
E-bunch: 6 MeV, 0.1 – 1.0 nC
Magnetic field = 2.7 T



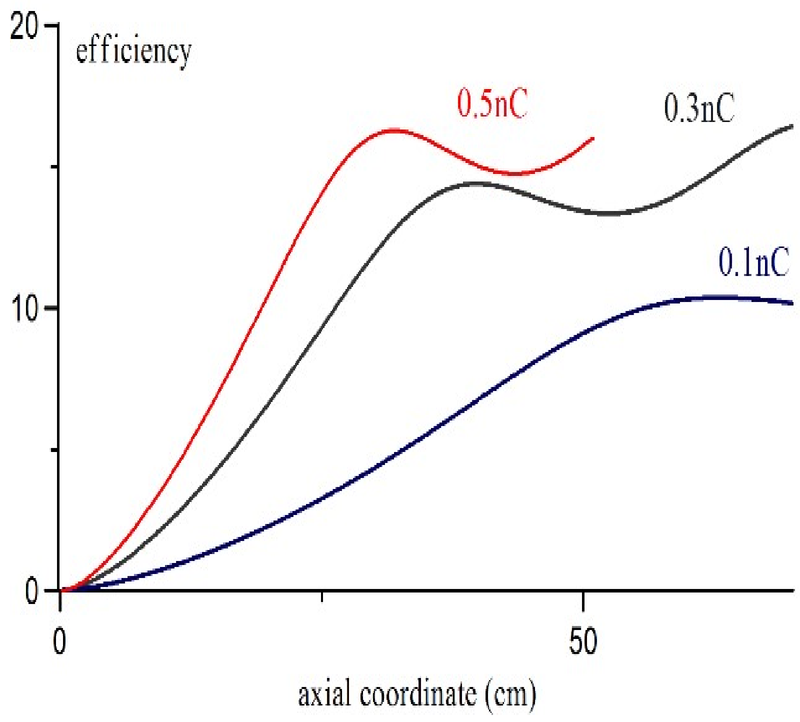


Spontaneous coherent super-radiative emission

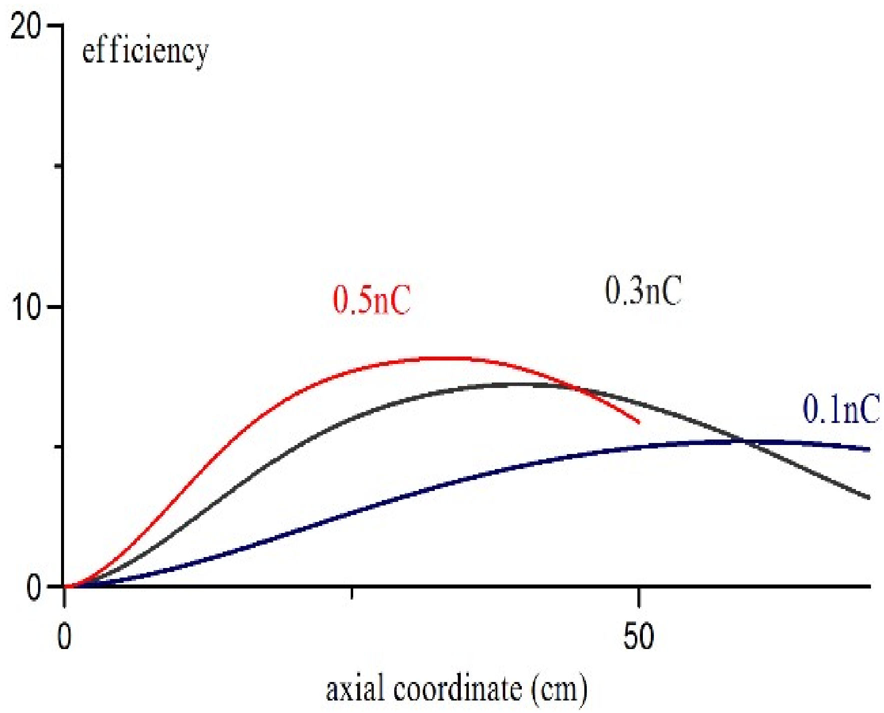


Frequency : 400 GHz (0.75 mm)	
Beam Energy	6.MeV ($\gamma = 13$)
Beam Radius	0.5 mm
Beam Duration	0.25 ps (0.075 mm)
Transverse velocity	$\beta_\perp = 0.06816$ $(1/\gamma \approx 0.0769)$
Waveguide:	$R = 2$ mm

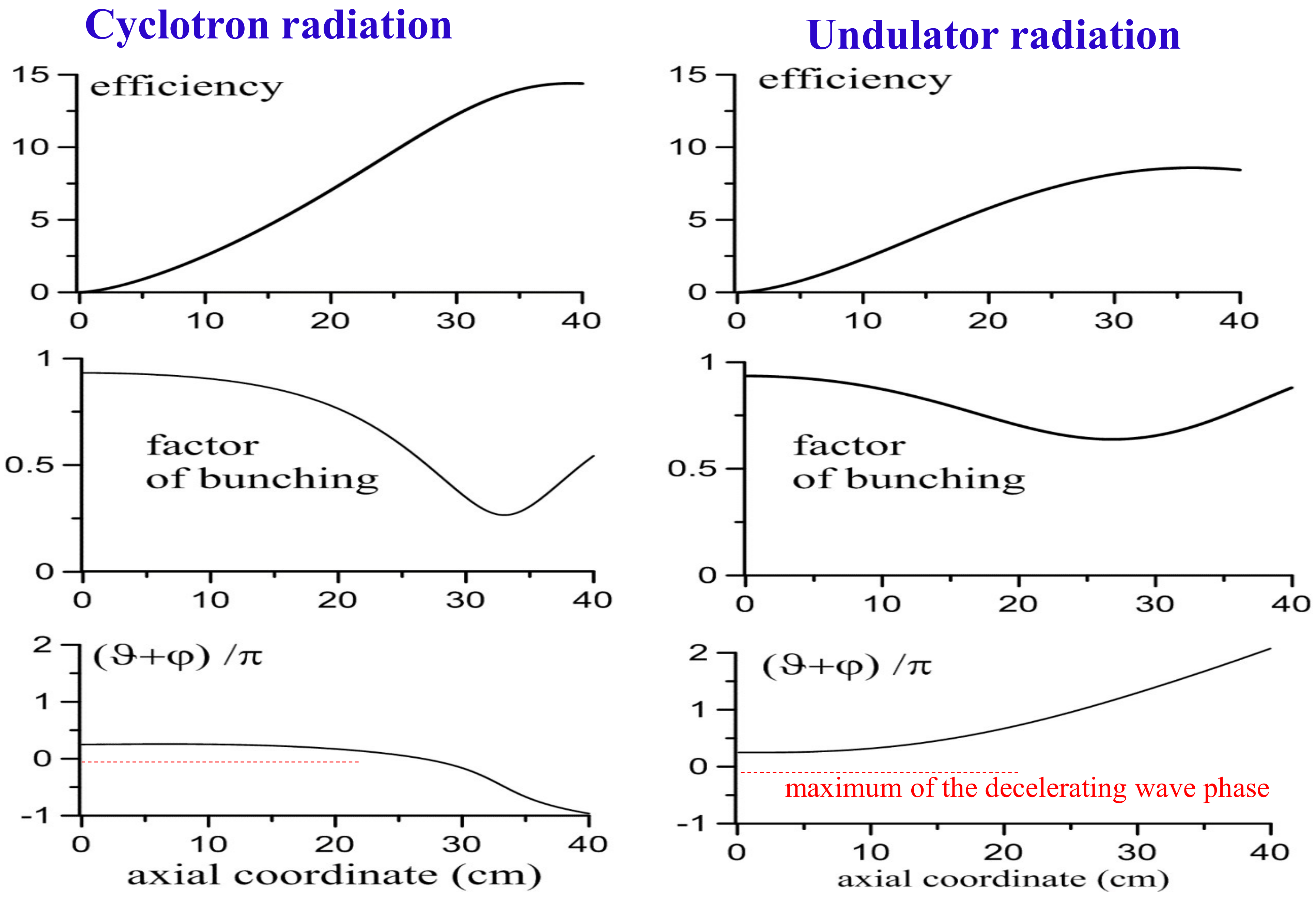
Cyclotron radiation



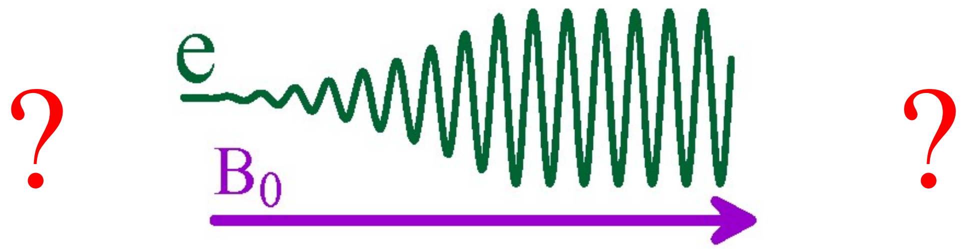
Undulator radiation

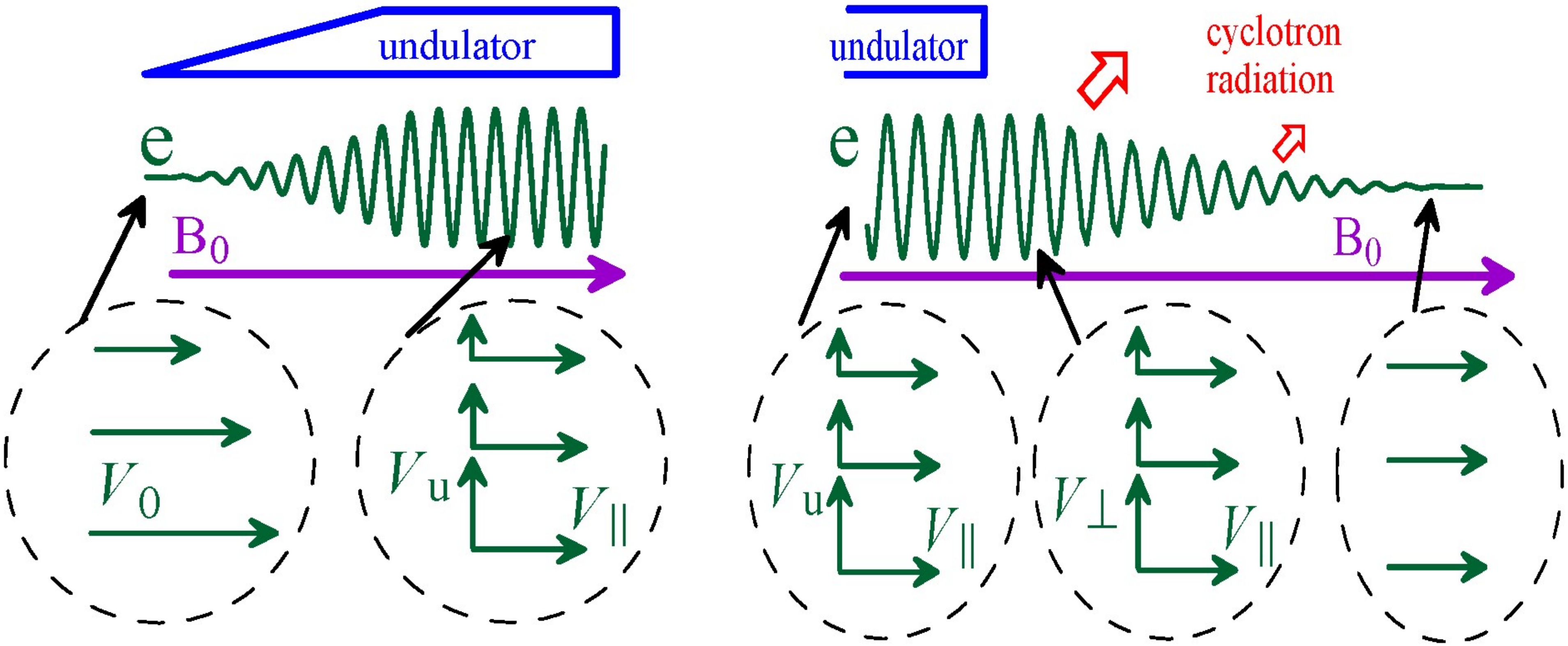


Spontaneous coherent super-radiative emission



Spontaneous coherent **cyclotron** radiation
– e-beam formation





APPLIED PHYSICS LETTERS **105**, 073503 (2014)

Cyclotron-undulator cooling of a free-electron-laser beam

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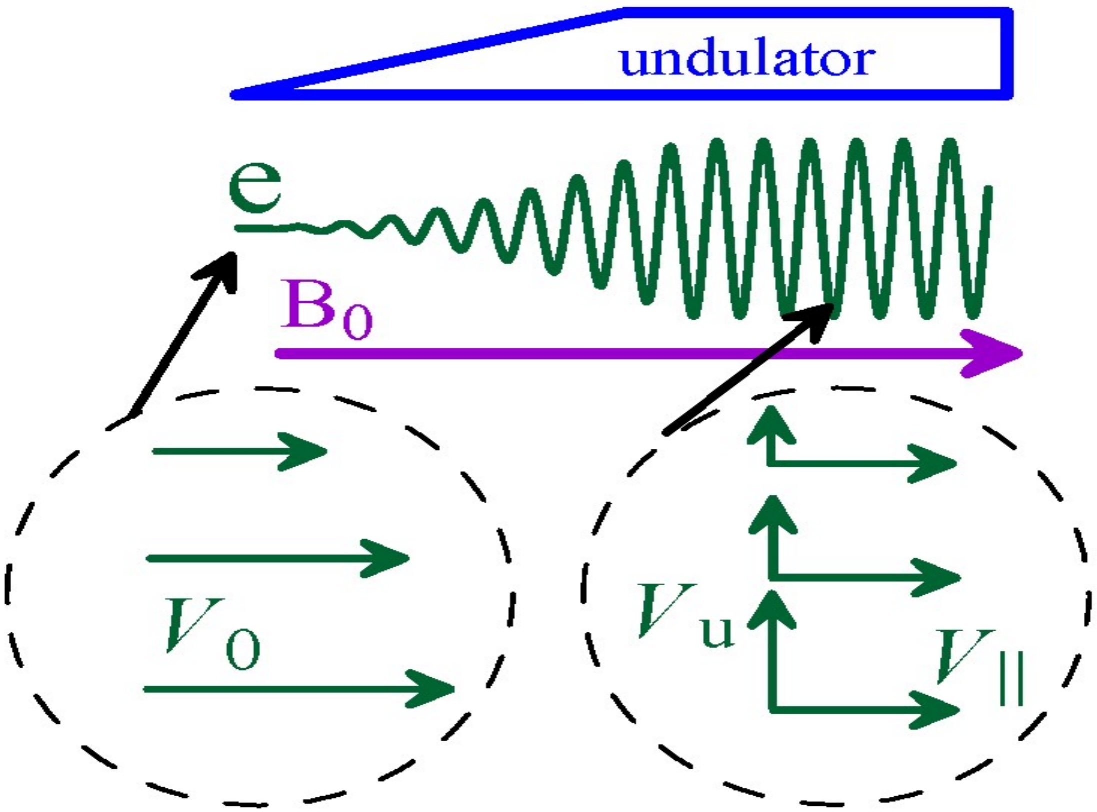
We propose methods of fast cooling of an electron beam, which are based on wiggling of particles in an undulator in the presence of an axial magnetic field. We use a strong dependence of the axial electron velocity on the oscillatory velocity, when the electron cyclotron frequency is close to the frequency of electron wiggling in the undulator field. The abnormal character of this dependence (when the oscillatory velocity increases with the increase of the input axial velocity) can be a basis of various methods for fast cooling of moderately relativistic (several MeV) electron beams. [http://dx.doi.org/10.1063/1.4893455]

Regime of ~~negative~~ **infinite** mass

$$\frac{1}{c}\frac{dV_z}{d\gamma}=\frac{1+K^2/\Delta^3}{\gamma^3}=0$$



Spread in initial energy does not lead to the spread in the axial velocity
(“axial cooling”)

$$\omega = h\boxed{V_{||}} + \Omega_e$$

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 110702 (2015)

Cyclotron radiation cooling of a short electron bunch kicked in an undulator with guiding magnetic field

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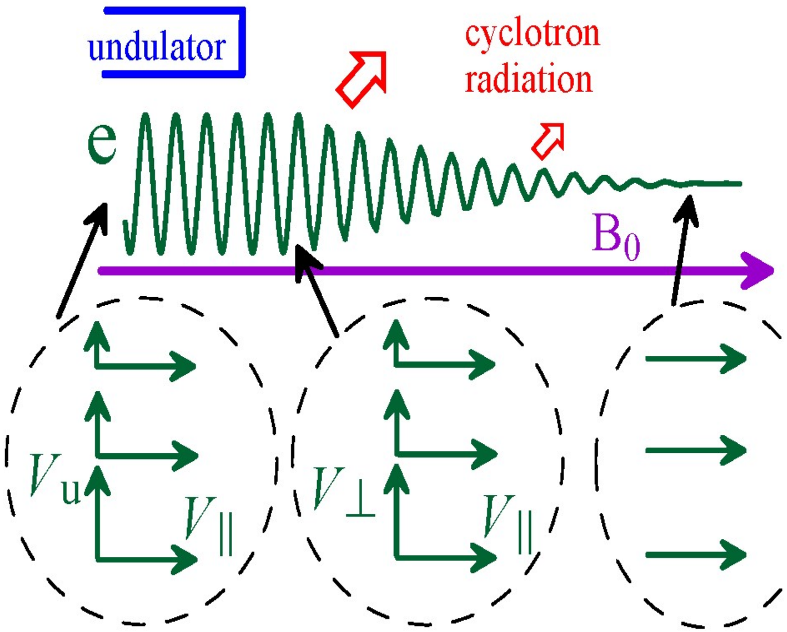
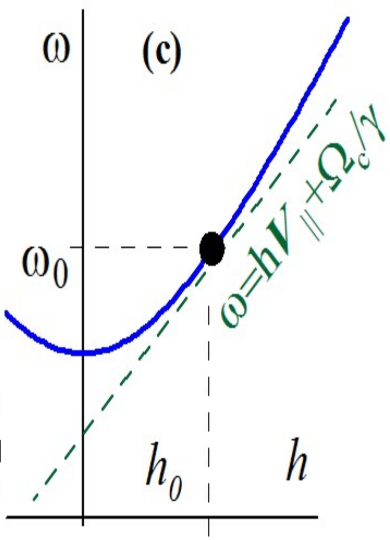
We propose to use of an undulator with the guiding axial magnetic field as a "kicker" forming a bunch of electron gyro-oscillators with a small spread in the axial velocity. The cyclotron emission from the bunch leads to losing oscillatory velocity of electron gyrorotation, but it does not perturb the axial electron velocity. This effect can be used for transformation of minimization of the spread in electron axial velocity in the undulator section into minimization of the spread in electron energy in the cyclotron radiation section.





$$V_e = V_{gr}$$

1. Infinite-mass undiulator kicking: spread in initial energy does not lead to the spread in the axial velocity ("axial cooling")

$$\omega = h V_{\|} + \Omega_e$$

2. Group resonance condition: radiation does not lead to the spread in the axial velocity

$$\frac{d\beta_{\|}}{dz} = \frac{d}{dz}\left(\frac{p_{\|}}{\gamma}\right) = \frac{d\gamma}{dz} \times \frac{\beta_{gr} - \beta_{\|}}{\gamma}$$

3. Group resonance condition: the most effective radiation process (super-radiation).

4. Group resonance condition: the Coulomb repulsion does not lead to an increase in the phase size of the e-bunch (see above)

Spontaneous coherent emission if the negative-mass undulator: the total bunch energy loss after of approximately 1 meter trip in the negative-mass regime ~10%.

Radiation frequency = 2 THz:
5.5 keV/ 0.3 nC / 0.1 mm e-bunch
Undulator period = 2.5 cm
Axial magnetic field = 8 T
Radiation: 10 MW, 20 ps, over 10^{-4} J.

Radiation frequency = 0.4 THz:
5.5 keV/ 0.3 nC / 0.5 mm e-bunch
Undulator period = 10 cm
Axial magnetic field = 2 T
Radiation: 1.5 MW, 150 ps, 10^{-4} J.

Electron bunch motion in the negative-mass undulator can be used also to compress e-bunch axial length by a factor of 5 (no radiation, just due to the Coulomb ~~repulsion~~ attraction of electrons).

Spontaneous coherent cyclotron emission: the total bunch energy loss after of 20-40 cm radiation section ~ 5-10%.

Radiation frequency = 0.5 THz:
5.5 keV/ 0.1 nC / 0.3 mm e-bunch
Axial magnetic field = 2.7 T
Radiation: 30-500 MW, 100 ps, ~10^{-4} J.

Self-compression of an electron bunch due to the super-radiation of a long-wavelength wave:

nC e-bunches can be compressed down to "THz" lengths, and their axial size can be stabilized at trip lengths ~ several meters.

No axial magnetic field is required.

However, an additional short-period undulator is needed to provide the THz radiation with an efficiency of 10-30 %.