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Компактные узкополосные источники гамма-излучения на основе нелинейного эффекта Комптона

Сергей Рыкованов

Center for Computational and Data Intensive Science and Engineering
Skolkovo Institute of Science and Technology

Суперкомпьютер «Жорес» для машинного обучения и моделирования основанного на данных

Суперкомпьютер «Жорес» с энергоэффективной гибридной архитектурой:

- 74 вычислительных узла;
- 24 узла с мощными графическими ускорителями (4xNVidia Tesla V100, NVLink + RDMA);
- тензорные ядра для **машинного обучения (глубокое обучение)**;
- потребление энергии: 90 кВатт;
- **производительность 0.5 Пфлоп/с**;
- **система хранения данных 0.5 Пбайт**
- **7-й суперкомпьютер по мощности в России**

«Жорес» - уникальный в России энергоэффективный суперкомпьютер, позволяющий решать широкий круг междисциплинарных задач на стыке ***машинного обучения, наук о данных*** *и* ***математического моделирования*** *в таких областях, как: биомедицина, обработка изображений, разработка и поиск новых лекарств, фотоника, предсказательное тех. обслуживание, разработка новых источников рентгеновского и гамма излучения и т.д.*

ZHORES SUPERCOMPUTER
HIGH PERFORMANCE COMPUTING AND BIG DATA
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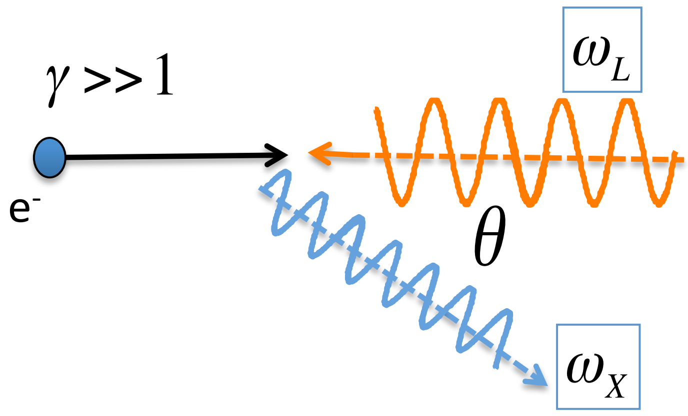
Inverse Compton Scattering (ICS, linear case). Part I



$$a_0 = \frac{eA_L}{mc^2} << 1$$

$$I << 10^{18}\ W/cm^2$$

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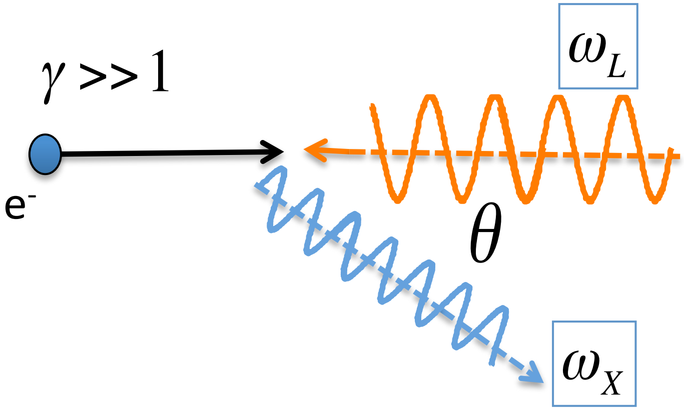
Inverse Compton Scattering (ICS, linear case)



$$a_0 = \frac{eA_L}{mc^2} << 1$$

$$I << 10^{18}\, W/cm^2$$

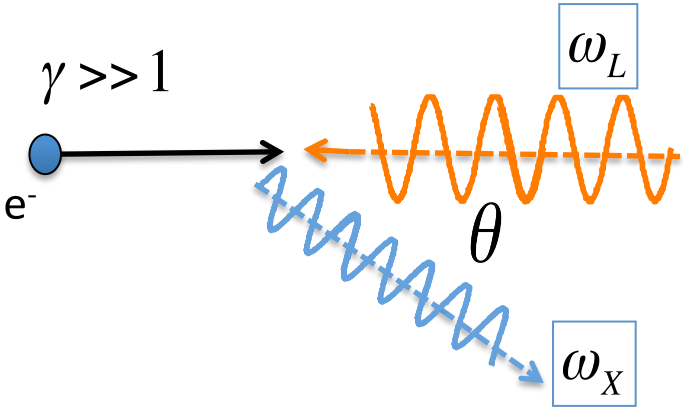
$$\boxed{\omega_X \approx \frac{4\gamma^2 \omega_L}{1 + \theta^2 \gamma^2 + \chi}}$$

$$E_{\max} = 4\gamma^2 \hbar \omega_L$$

$$\theta_{\max} \sim \frac{1}{\gamma}$$

electron recoil $\quad \chi \approx \dfrac{2\gamma \hbar \omega_L}{mc^2}$

Inverse Compton Scattering (ICS, linear case)



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$$E_{\max} = 4\gamma^2\hbar\omega_L$$

$$\theta_{\max} \sim \frac{1}{\gamma}$$

electron recoil $\quad \chi \approx \dfrac{2\gamma\hbar\omega_L}{mc^2}$

Example:

$\gamma = 1000$ (~0.5 GeV e-)

$\hbar\omega_L = 1.55eV$ (~1 um laser)

Max. photon energy:
4 MeV
$\chi \approx 0.5\%$

$\gamma = 40$ (~20 MeV e-)

$\hbar\omega_L = 1.55eV$ (~1 um laser)

Max. photon energy:
10 keV
$\chi \approx 0.02\%$

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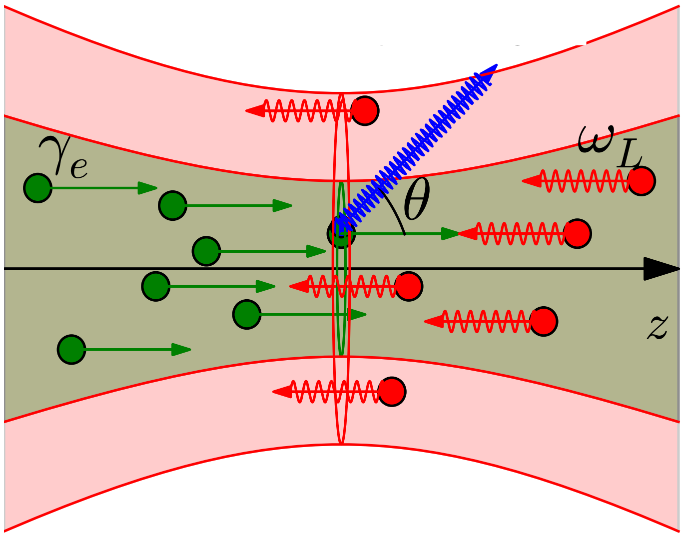
Inverse Compton Scattering is a source of X- and gamma-rays

Collision of an intense laser pulse with an ultra-relativistic (γ>>1) electron beam



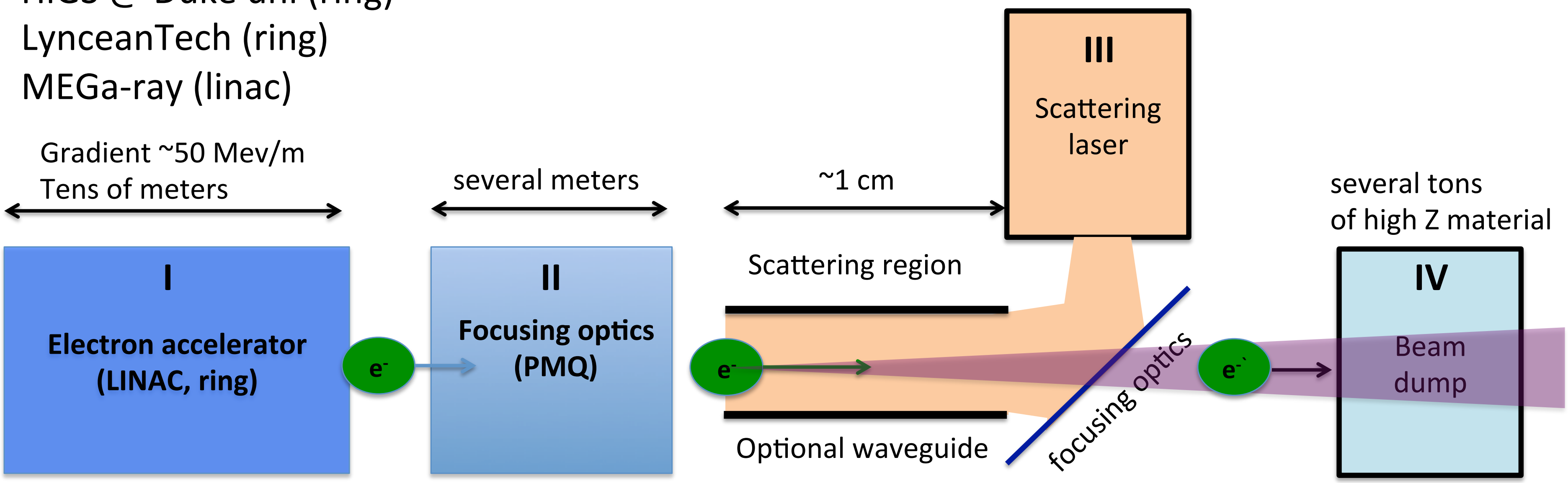
*S.G. Rykovanov, et al, JPHYSB **47**, 234013 (2014)*

- Doppler upshift of laser frequency $\omega_X = 4\gamma^2\omega_L$
- Tunable source
- Extremely short bursts of hard radiation
- Quasi-monochromatic
- Applications: medicine, nuclear physics, materials

Main quality: Spectral brightness = γ-ray yield per bandwidth

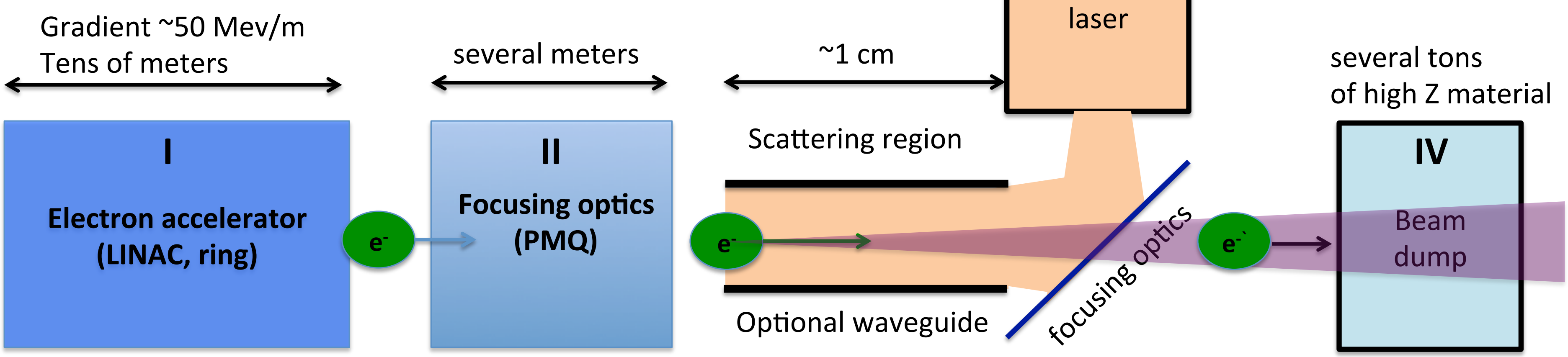
Typical schematics of the ICS source

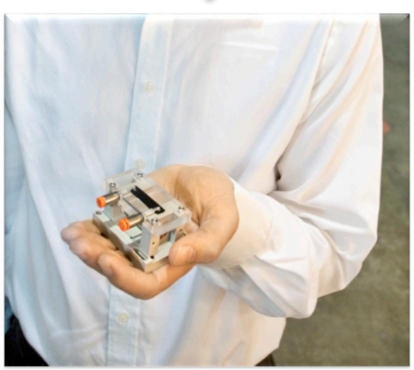
HiGS @ Duke uni (ring)
LynceanTech (ring)
MEGa-ray (linac)

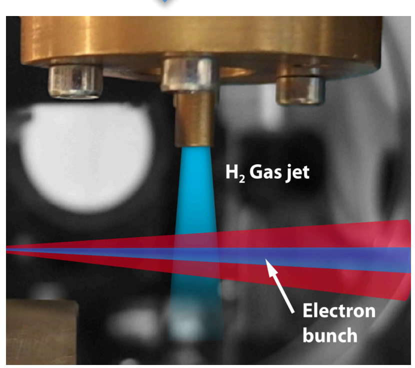


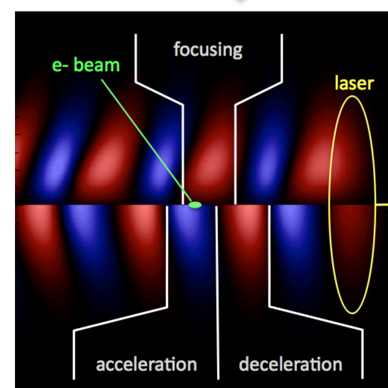
Novel laser-plasma technology allows to decrease the size

HiGS @ Duke uni (ring)
LynceanTech (ring)
MEGa-ray (linac)

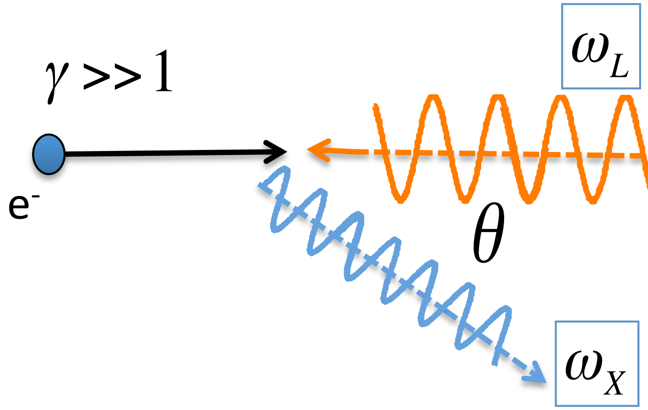








Nonlinear ICS



no restriction on a_0

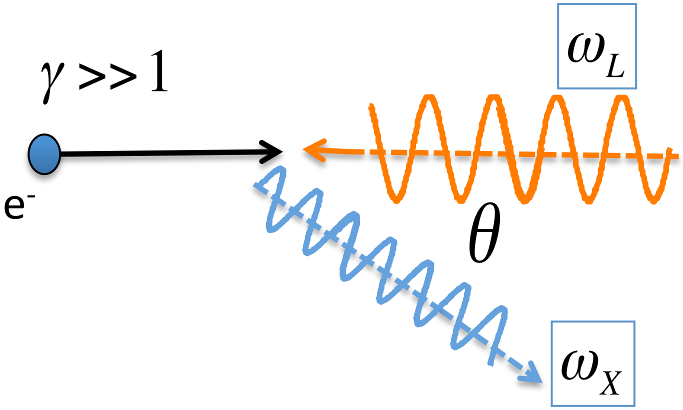
electron is „dressed" by the laser pulse

$$\hbar\omega_X = \frac{4\gamma^2\hbar\omega_L}{1+\gamma^2\theta^2+a_0^2}$$

Total photon yield in natural bandwidth:

$$N_X = N_e\pi\alpha\frac{a_0^2}{1+a_0^2}$$

Nonlinear ICS

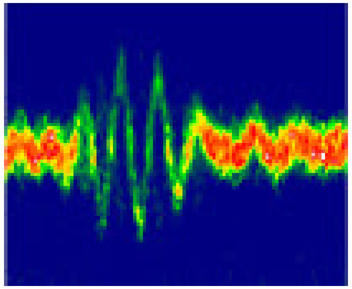


no restriction on a_0

electron is „dressed" by the laser pulse

$$\hbar\omega_X = \frac{4\gamma^2\hbar\omega_L}{1+\gamma^2\theta^2+a^2(t)}$$

Total photon yield in natural bandwidth: $$N_X = N_e\pi\alpha\frac{a_0^2}{1+a_0^2}$$



- Laser pulses ramp on and off smoothly --> time-dependent laser pressure
- Lorentz gamma factor becomes a function of time *γ(t)*
- Generated frequency: $\omega_X(t) = 4\gamma^2(t)\omega_L$

MPIPKS (atto07)

Brief recap on electron motion in a plane EM wave

Case 2. Strong electromagnetic wave

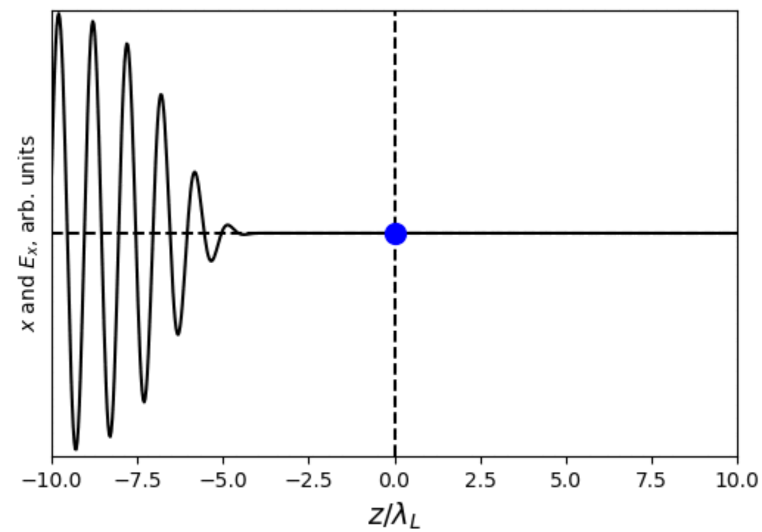
$a_0 = 1$

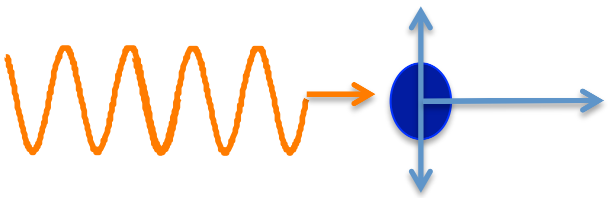
$$\frac{d\vec{p}}{dt} = -e\vec{E} - e\frac{\vec{v}}{c} \times \vec{B}$$

$$E_x = E_0 \cos\left(\omega_L t - k_L z\right)$$

$$u_x = -a_0 \sin(\omega_L t - k_L z)$$

$$u_z = \frac{1}{2}u_x^2 = \frac{a_0^2}{2}\sin^2(\omega_L t - k_l z)$$





Case 2. Strong electromagnetic wave

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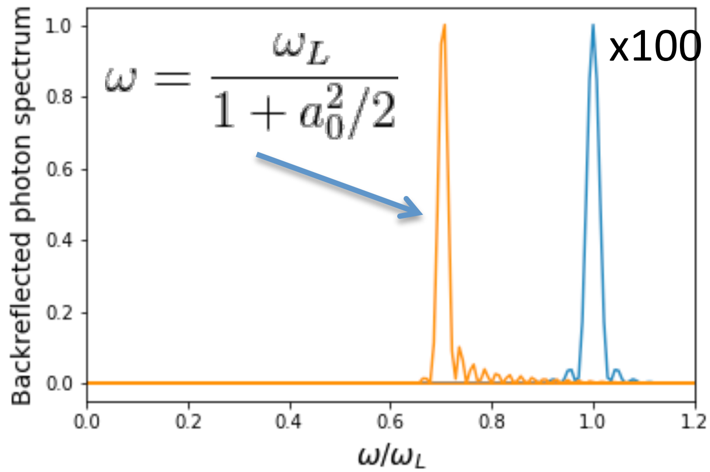
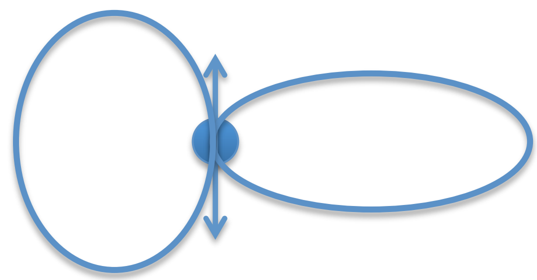
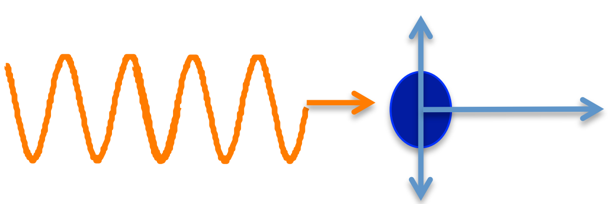
$a_0 = 1$





Angular spectrum



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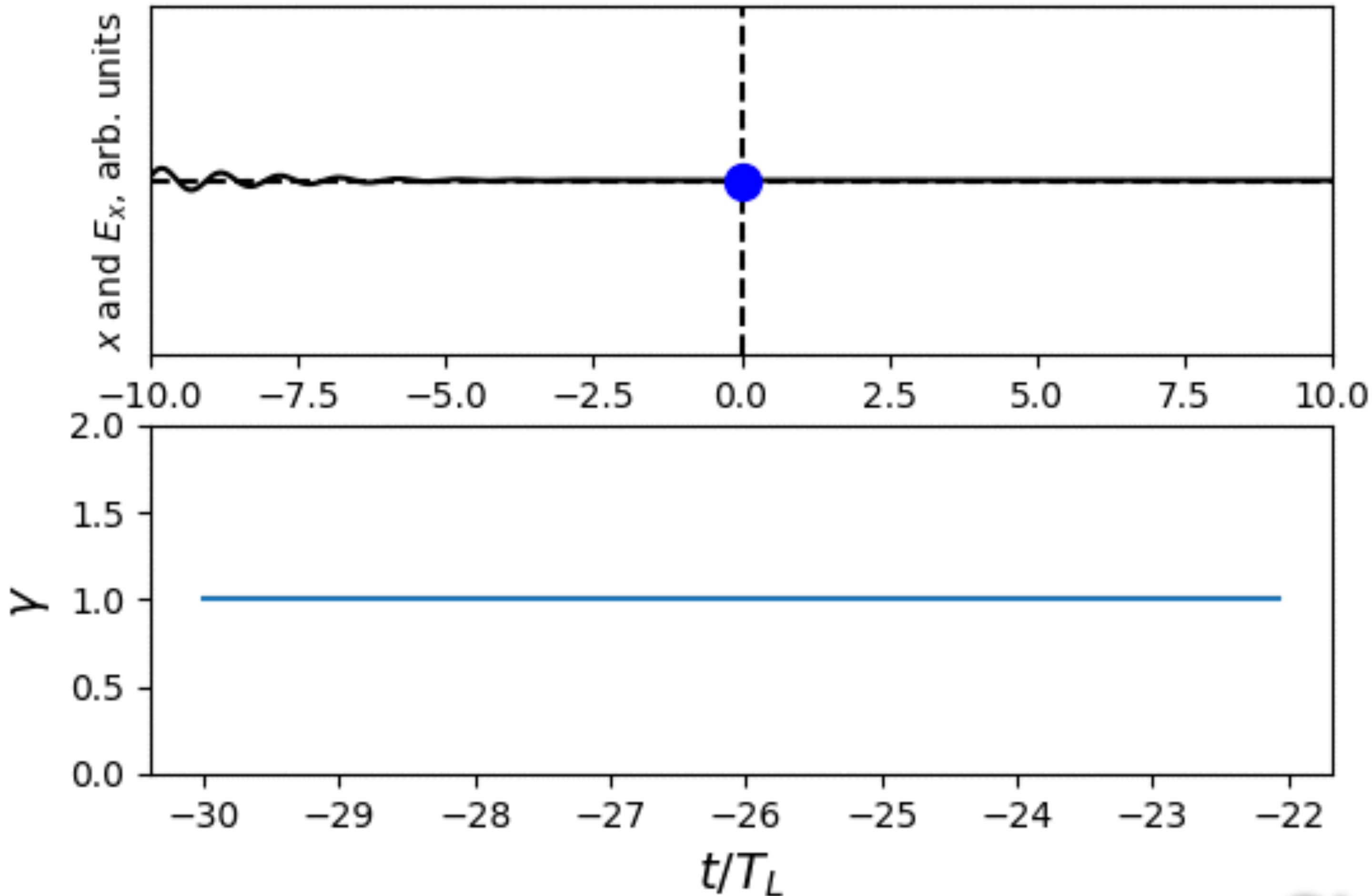
Laser pulse longitudinal shape leads to spectrum broadening



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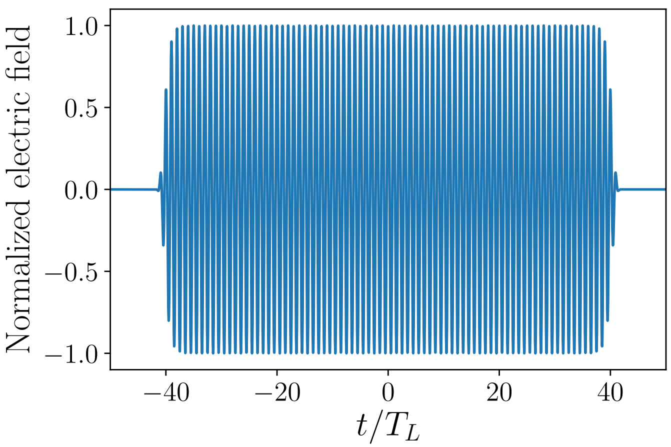
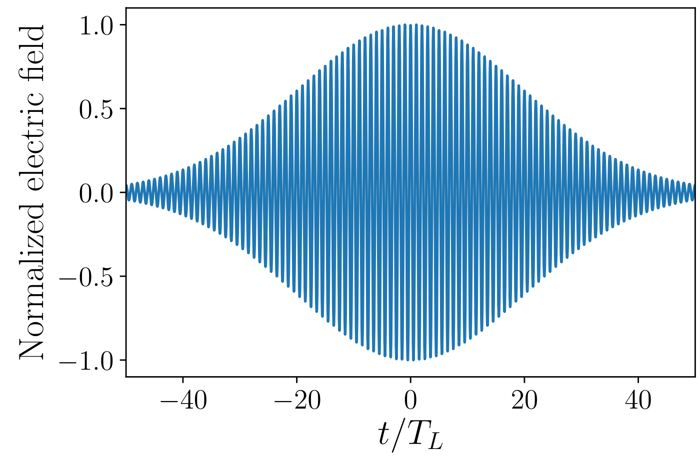
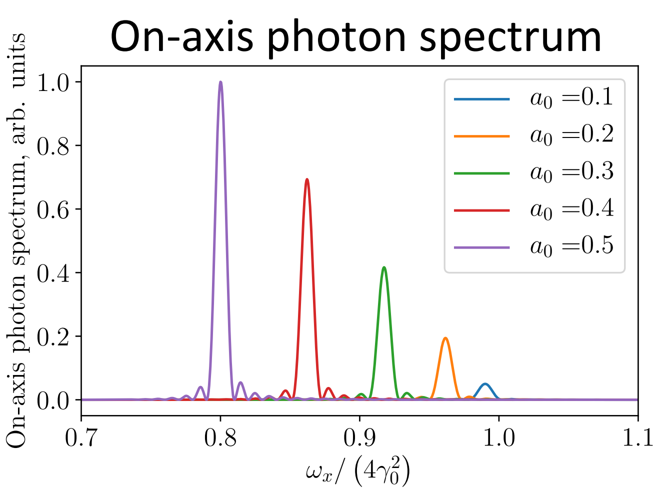
Nonlinear CS: pulse shape leads to broadening

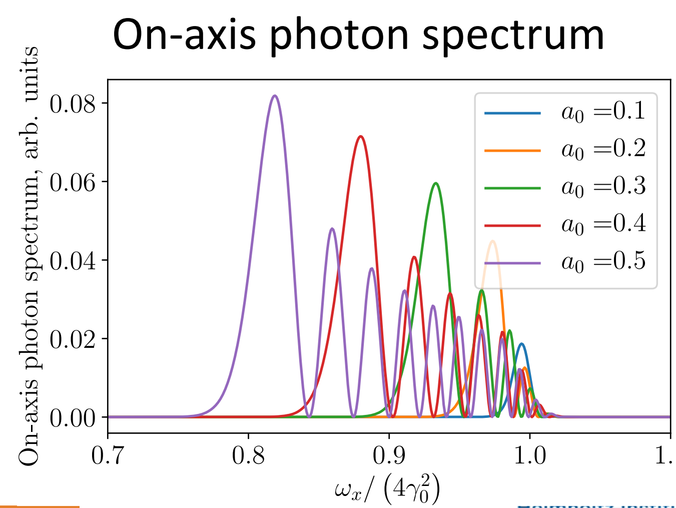
$$\hbar\omega_X = \frac{4\gamma^2\hbar\omega_L}{1+\gamma^2\theta^2+a_0^2}$$

$$N_X = N_e \pi\alpha \frac{a_0^2}{1+a_0^2}$$

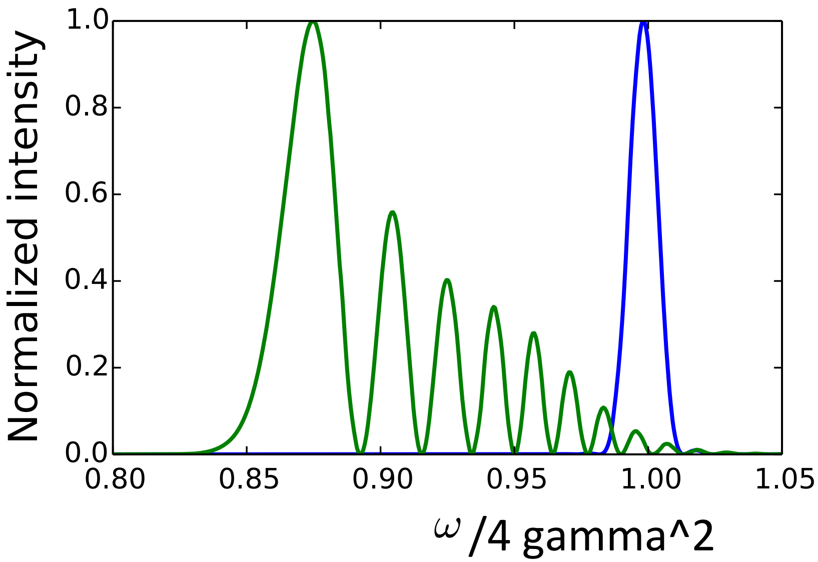


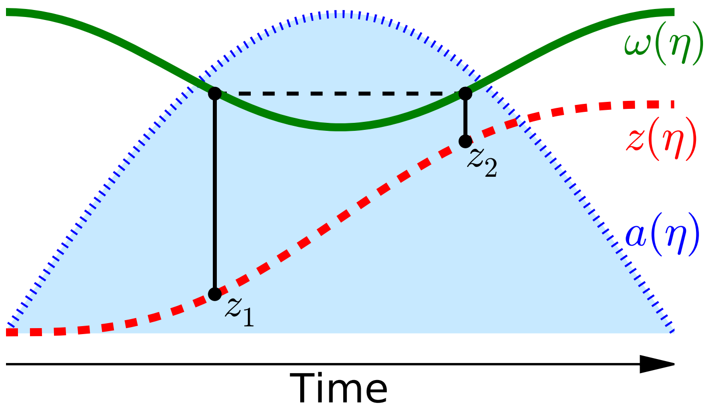






Proper nonlinear chirping





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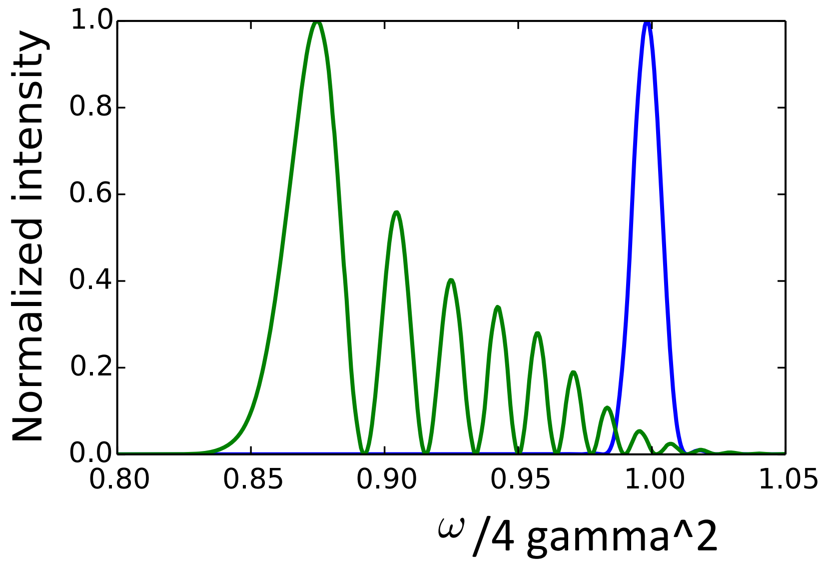
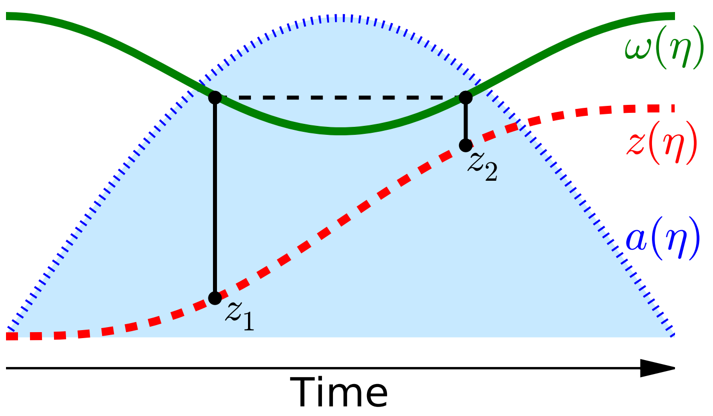
Proper nonlinear chirping





If laser frequency is constant,
the generated frequency is given by:

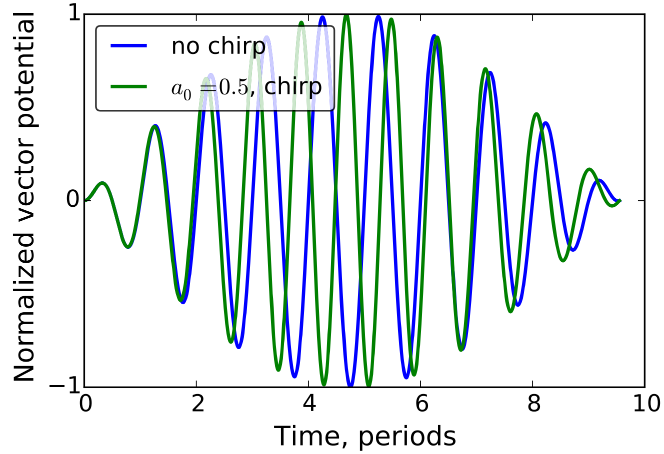
$$\omega(\eta) = \frac{4\gamma^2\omega_L}{1+a^2(\eta)}$$

Why don't we chirp the pulse to exactly compensate the ponderomotive broadening:

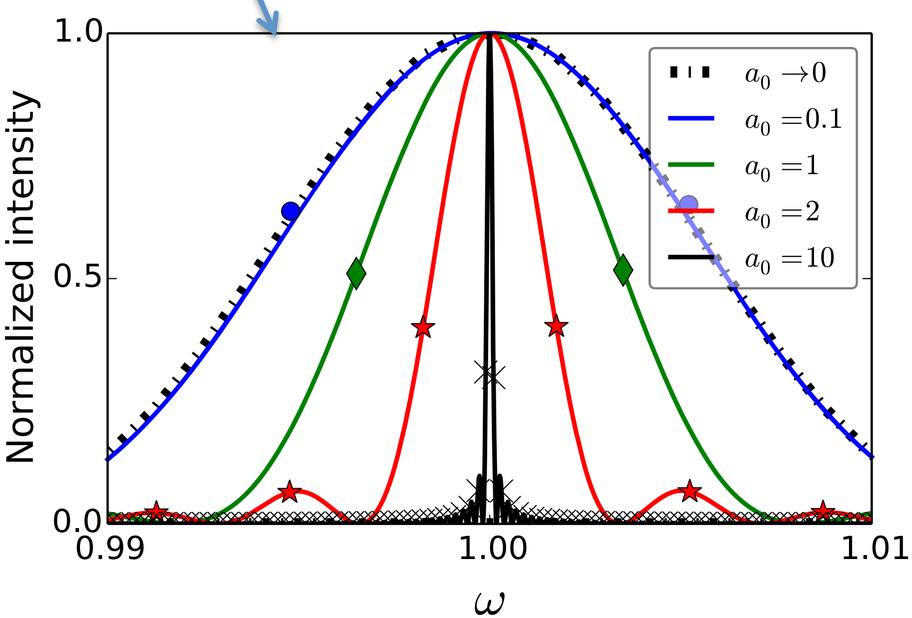
$$\omega(\eta) = \frac{4\gamma^2\omega_L(\eta)}{1+a^2(\eta)} = \frac{4\gamma^2\omega_0\left(1+a^2(\eta)\right)}{1+a^2(\eta)}$$

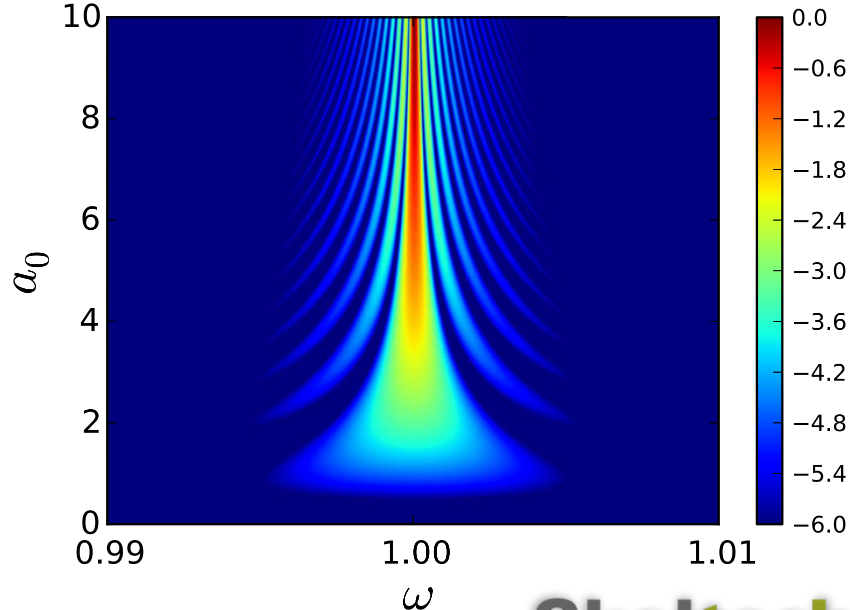
Proper nonlinear chirping totally compensates broadening

Laser pulse



Backscattered spectrum





Proper nonlinear chirping totally compensates broadening

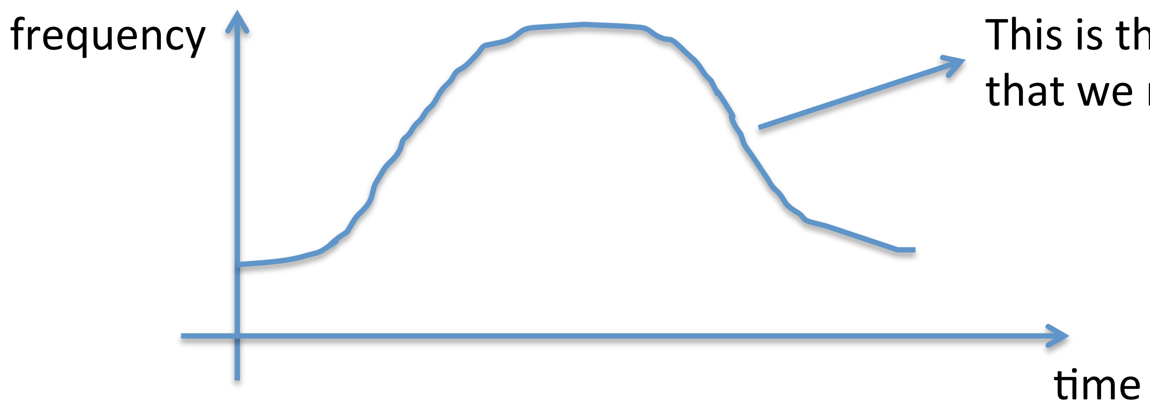
$$\omega(\eta) = \frac{4\gamma^2\omega_L(\eta)}{1+a^2(\eta)} = \frac{4\gamma^2\omega_0\left(1+a^2(\eta)\right)}{1+a^2(\eta)}$$

Great?

But how do we generate such a pulse with nonlinear chirping:

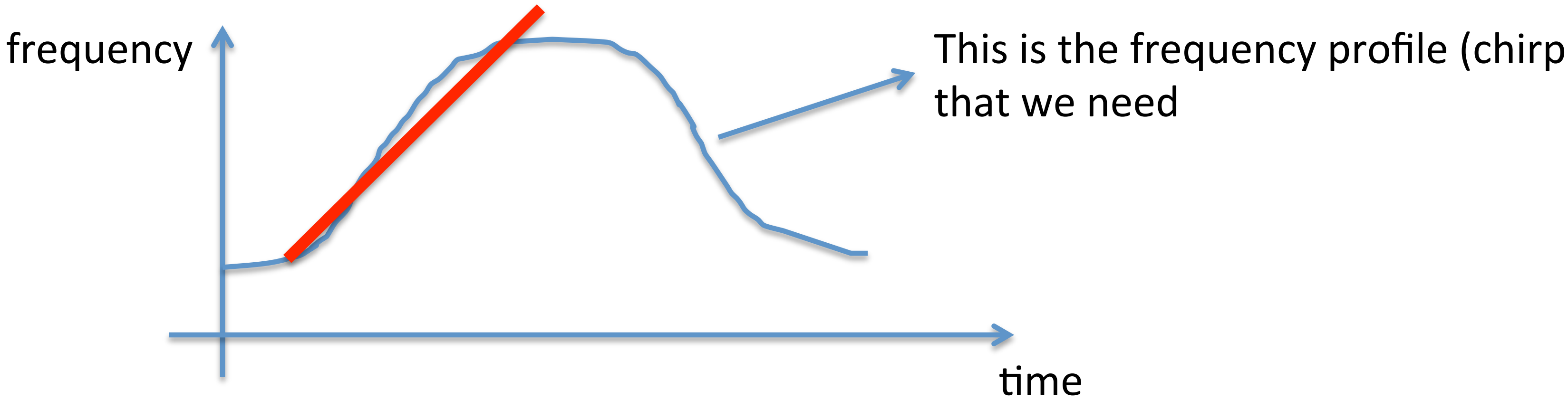
Frequency has to change nonlinearly on the femtosecond scale

Currently not possible.



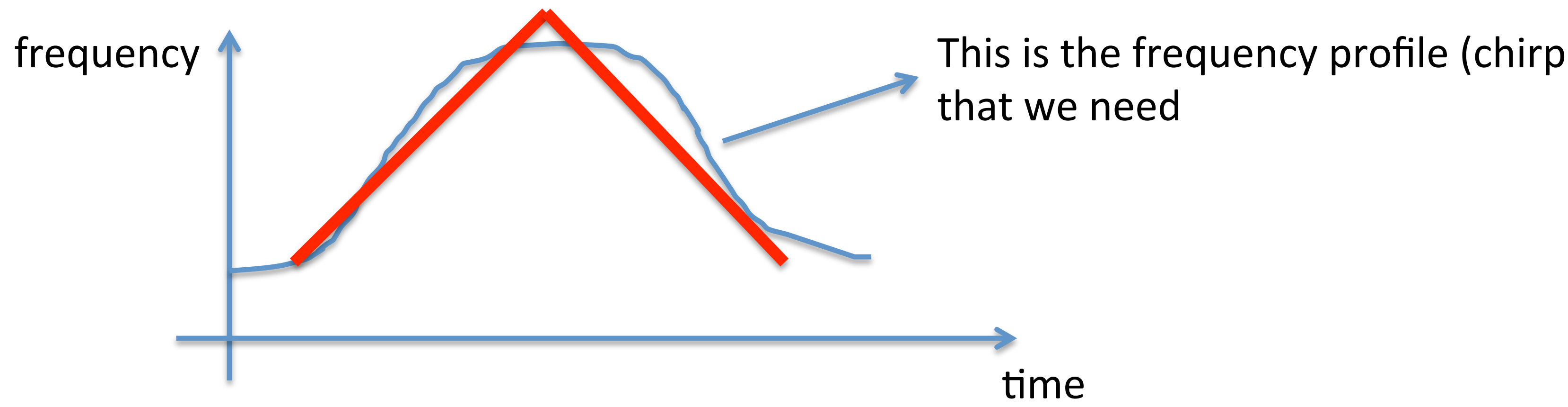
This is the frequency profile (chirp) that we need

Proper nonlinear chirping totally compensates broadening



- Why don‘t we try to use common technology - „linear“ chirp?
- We approximately add **linearly chirped laser pulse** to mimic the nonlinear profile
- But the profile should also have a „downslope“ part - frequency has to go back down
- Any ideas?

Proper nonlinear chirping totally compensates broadening



- Why don‘t we try to use common technology - „linear“ chirp?
- We approximately add **linearly chirped laser pulse** to mimic the nonlinear profile
- But the profile should also have a „downslope“ part - frequency has to go back down
- We just add a **second laser pulse oppositely chirped**

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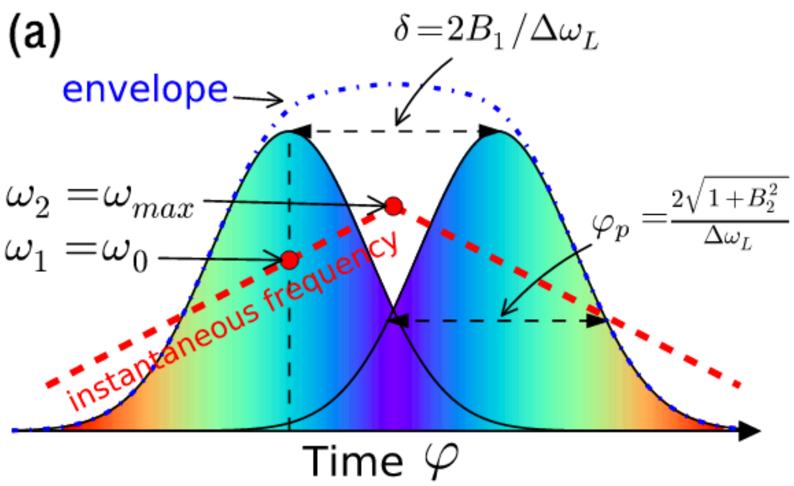
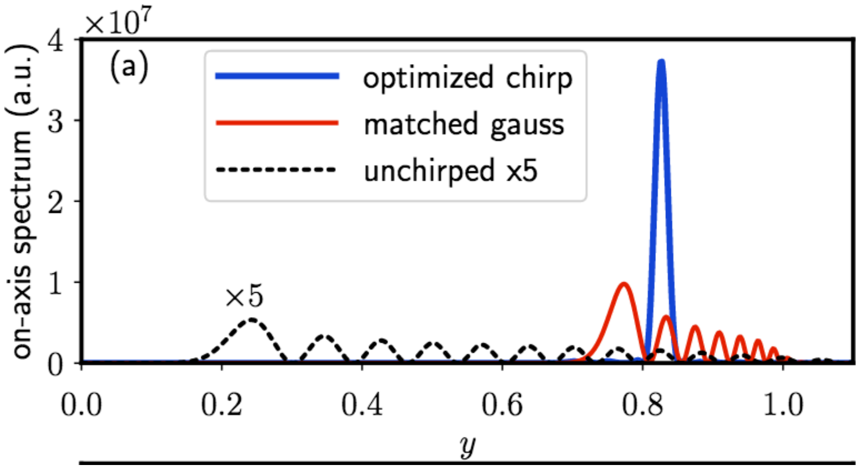
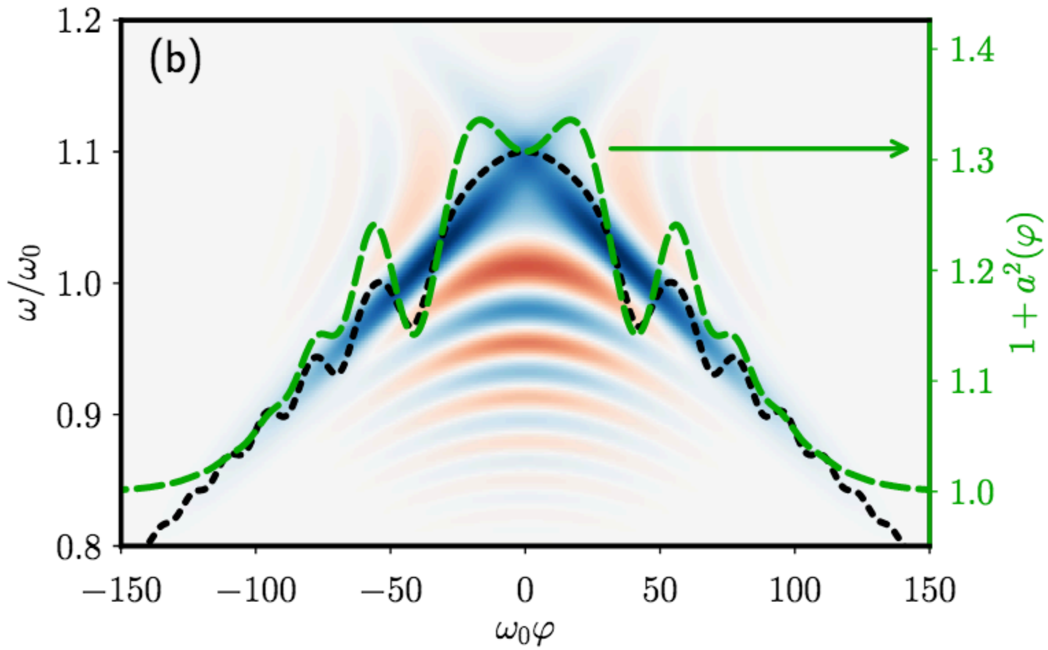
Two oppositely chirped laser pulses







Seipt, Kharin, Rykovanov,
Phys. Rev. Lett. 122, 204802 (2019)

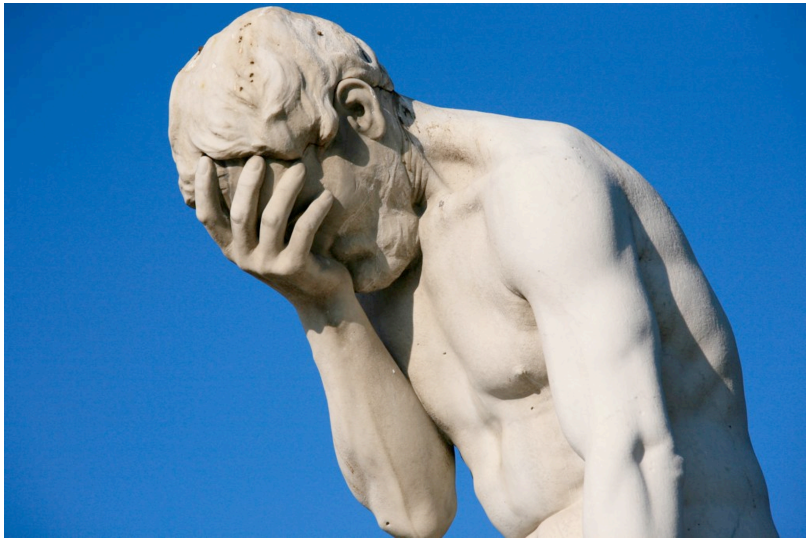
Two oppositely chirped laser pulses

РИА Новости 13 июня в 12:30
Российские физики выяснили, как создать мощнейшие рентгеновские лазеры статья

NewInform 13 июня в 19:46
В России разработали новую методику создания рентгеновского лазера

Вечерняя Москва 13 июня в 23:55
Физики нашли способ создать мощнейшие рентгеновские лазеры

Научная Россия 10 июля в 09:00
Физики из Сколтеха и их зарубежные коллеги выяснили, как повысить мощность рентгеновских лазеров статья



Seipt, Kharin, Rykovanov,
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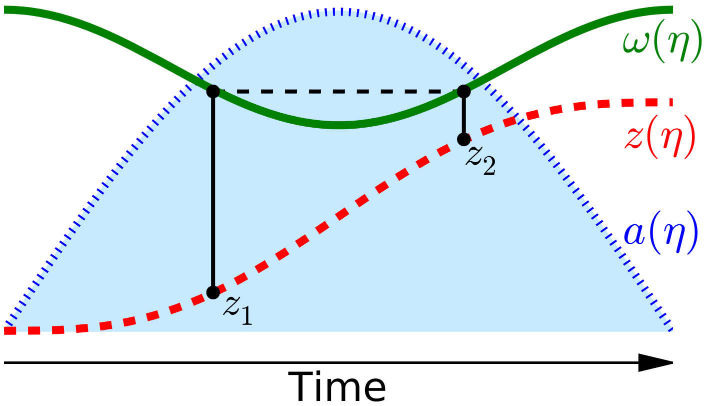
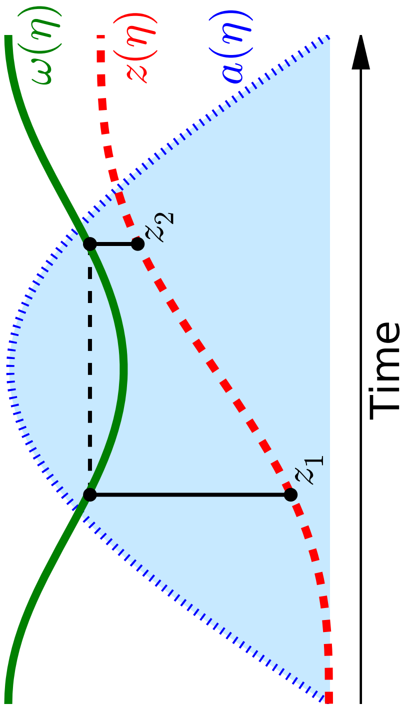
Caustics and catastrophes

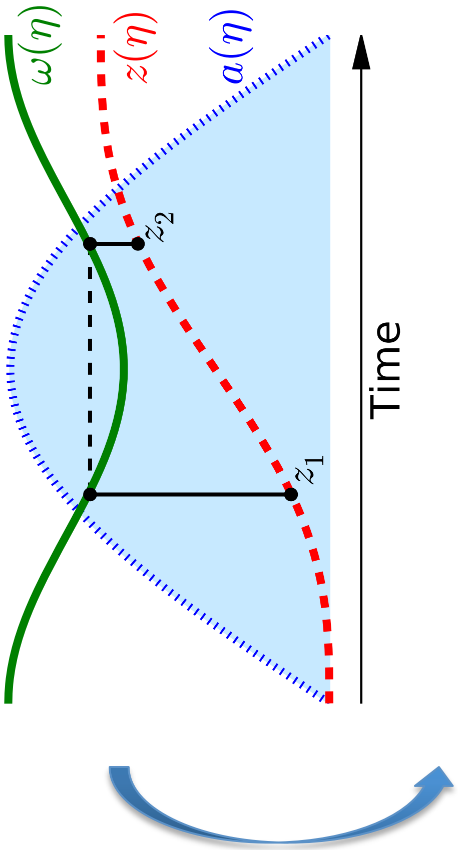
Caustics and catastrophes



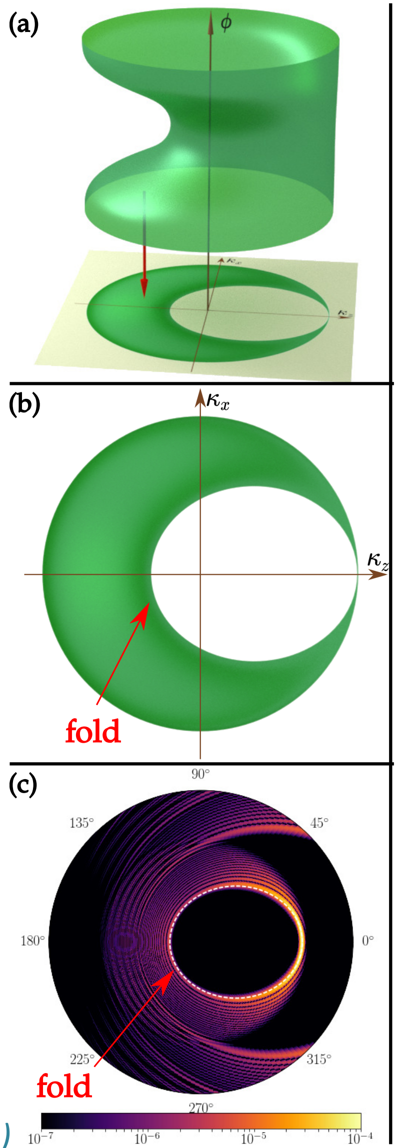
Caustics and catastrophes



Caustics and catastrophes



Caustics and catastrophes



V.Yu. Kharin, D. Seipt, S.G. Rykovanov, Phys. Rev. Lett., 120, 044802 (2018)

FIG. 1. The ray surfaces [stationary phase condition (4)] (a),

Caustics and catastrophes

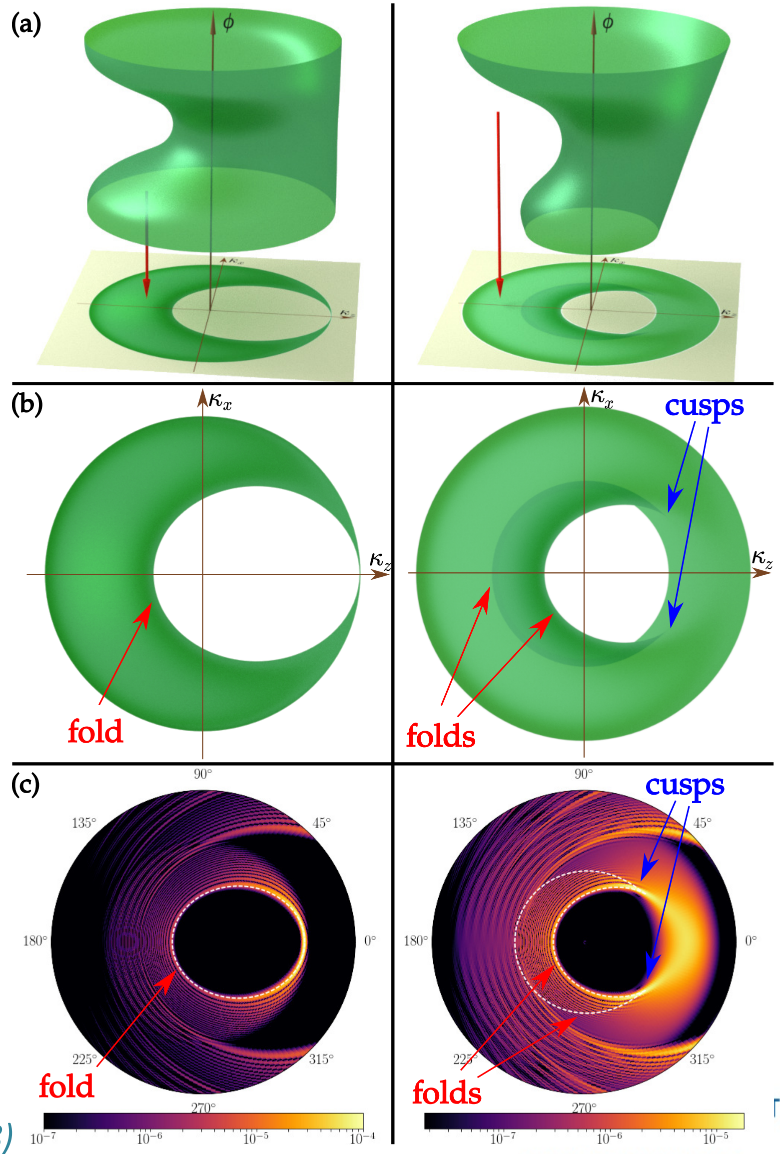
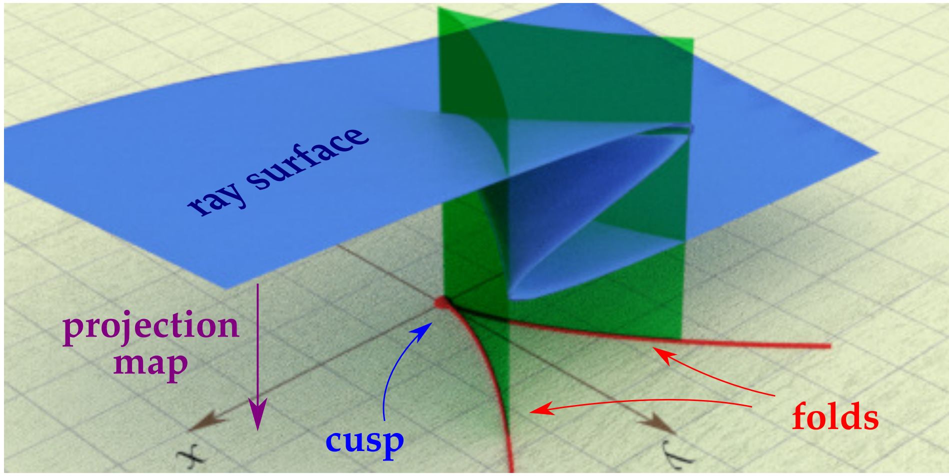
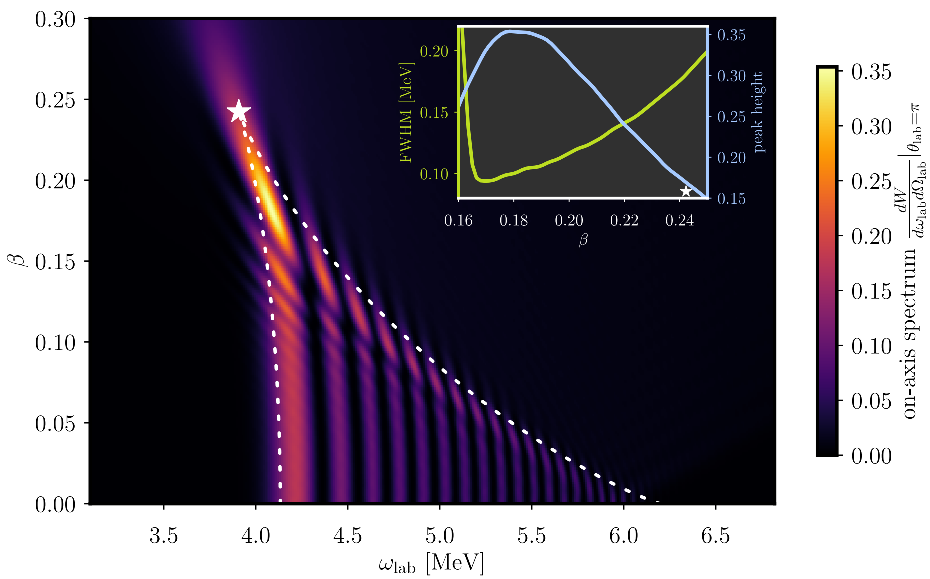


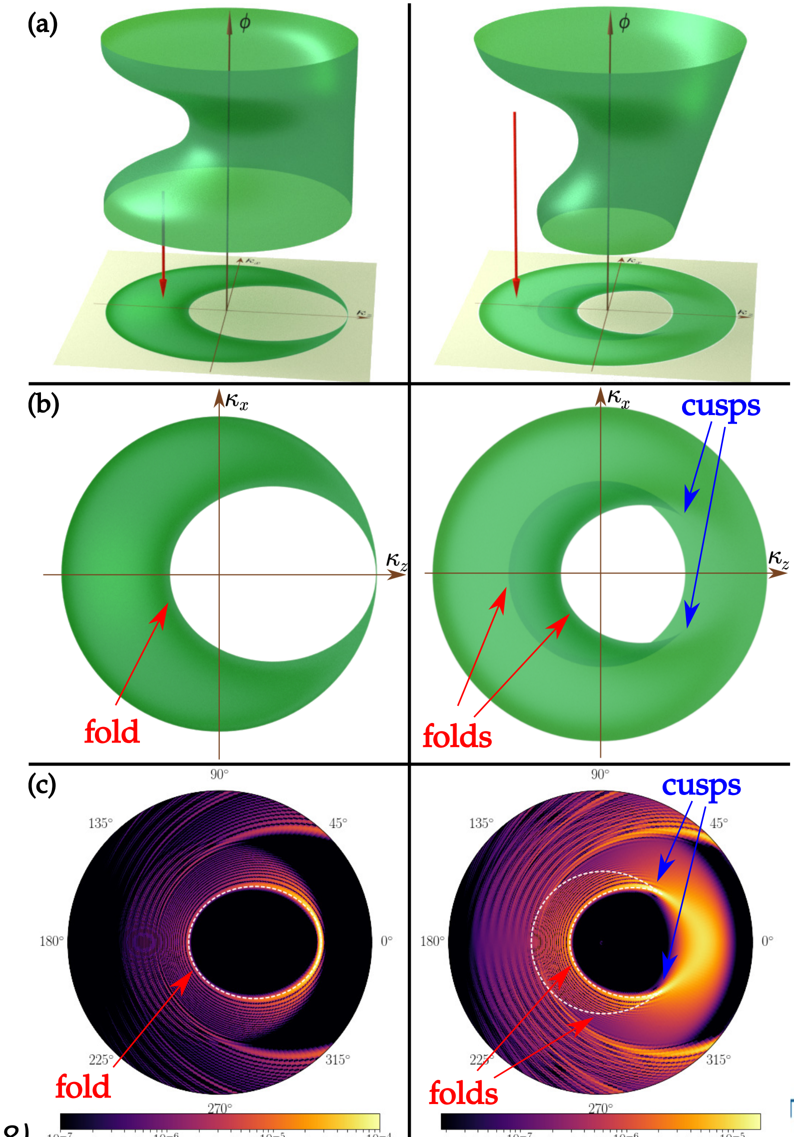
FIG. 1. The ray surfaces [stationary phase condition (4)] (a),

V.Yu. Kharin, D. Seipt, S.G. Rykovanov, Phys. Rev. Lett., 120, 044802 (2018)

Caustics and catastrophes







V.Yu. Kharin, D. Seipt, S.G. Rykovanov, Phys. Rev. Lett., 120, 044802 (2018)

FIG. 1. The ray surfaces [stationary phase condition (4)] (a),

Summary

- Nonlinear Compton Scattering leads to broadening due to the laser pressure. Laser pressure is non-uniform due to the laser pulse temporal envelope -- no pressure on the wings, high pressure in the middle.
- Nonlinear chirping completely removes the broadening
- Two linearly and oppositely chirped pulses can approximately remove the broadening and can lead to significant improvement of existing Compton sources
- Caustics and catastrophes in Compton spectrum lead to bright spots and can be used for photon yield enhancement

References:

Rykovanov et al, Phys. Rev. AB, 19, 030701 (2016)

Seipt, Kharin, Rykovanov, Phys. Rev. Lett., 122, 204802 (2019)

Kharin, Seipt, Rykovanov, Phys. Rev. Lett., 120, 044802 (2018)