Комптоновские источники для экспериментов по нелинейной квантовой электродинамике

Сергей Рыкованов (Сколтех)
Александр Федотов (МИФИ)
Игорь Костюков (ИПФ РАН)

Основная идея

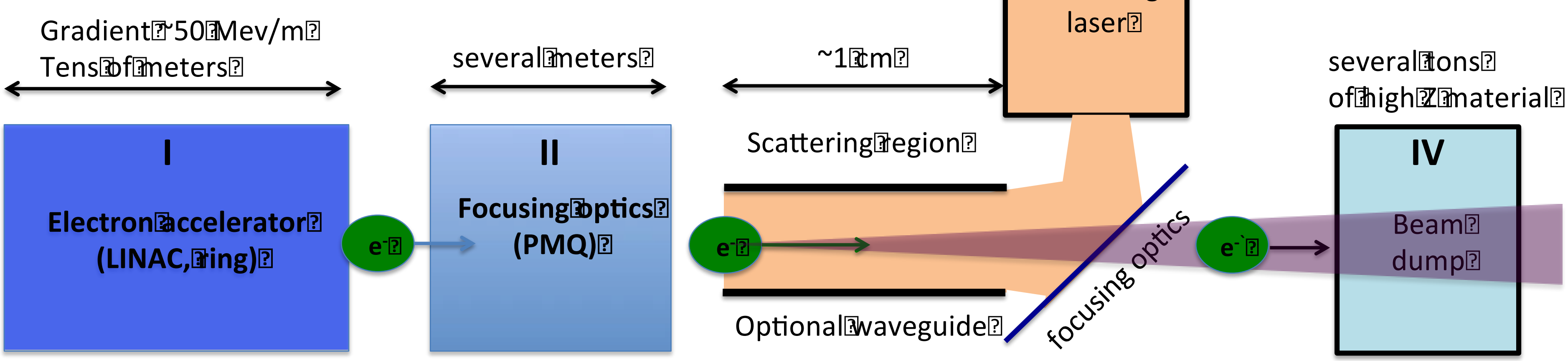
Размещение мощного (мульти-тераваттного / петаваттного) лазера рядом с ускорителем для комптоновского источника:

→ Значительное увеличение выхода комптоновских фотонов за счет нелинейности

→ Фундаментальные эксперименты по нелинейной КЭД

Typical schematics of the ICS source

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



Nonlinear Compton Scattering can increase photon yield by several orders of magnitude

- All contemporary sources are based on linear Compton Scattering (1 electron scattered on 1 photon)
- "Weak" laser pulses are used a_0<=0.01
- Nonlinear Compton Scattering (a_0 ~ 1) (theoretically) allows to increase photon yield by several orders of magnitude
- **Next we will discuss Nonlinear Compton Scattering and methods to significantly increase the photon yield independent of accelerator system**

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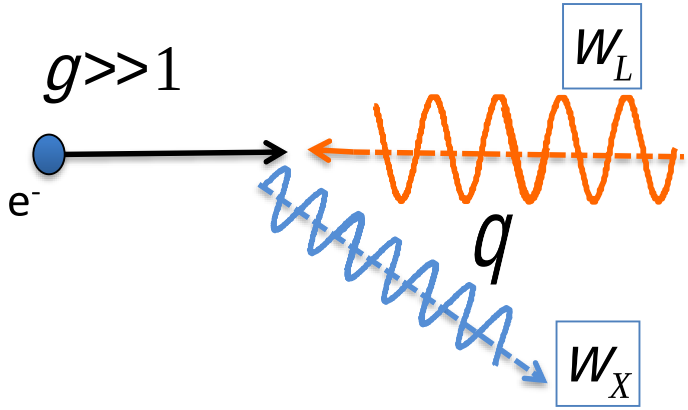
Nonlinear ICS



no restriction on a_0

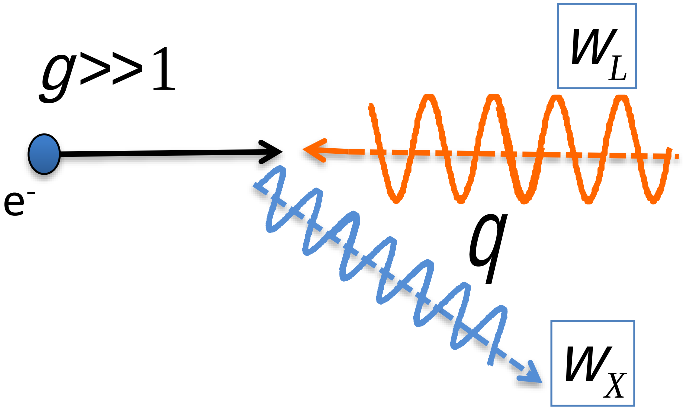
electron is „dressed“ by the laser pulse

Linear: $$\hbar\omega_L + \varepsilon_e = \hbar\omega_X + \varepsilon'_e$$ Energy-momentum conservation

Non-Linear: $$n\hbar\omega_L + \tilde{\varepsilon}_e = \hbar\omega_X + \tilde{\varepsilon}'_e$$ Energy-momentum conservation + angular momentum conservation

- Generation of harmonics (same as in magnetic undulator)
- Harmonics can carry well-defined Orbital Angular Momentum (OAM)

Nonlinear ICS



no restriction on a_0

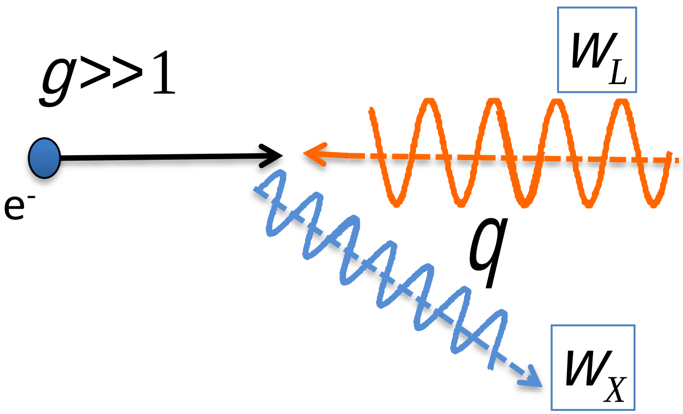
electron is „dressed“ by the laser pulse

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

Total photon yield in natural bandwidth:

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

Nonlinear ICS



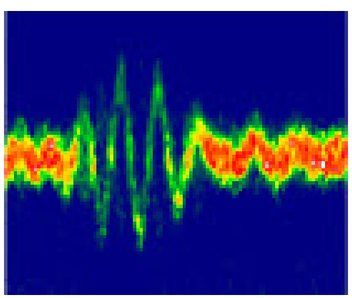
no restriction on a_0

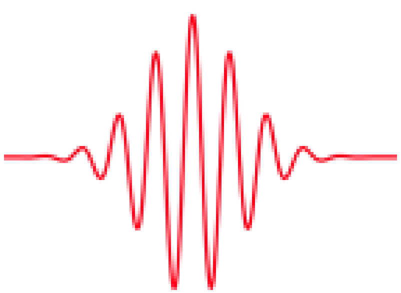
electron is „dressed“ by the laser pulse

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

Total photon yield in natural bandwidth:

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

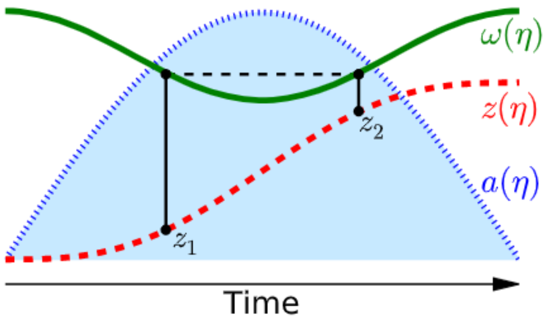




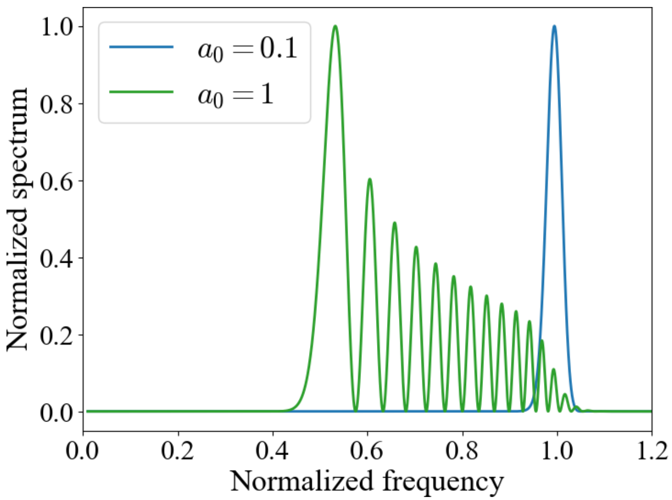
- Laser pulses ramp on and off smoothly --> time-dependent laser pressure
- Lorentz gamma factor becomes a function of time *γ(t)*
- Generated frequency: $w_X(t) = 4g^2(t)w_L$

MPIPKS (atto07)

Ponderomotive broadening

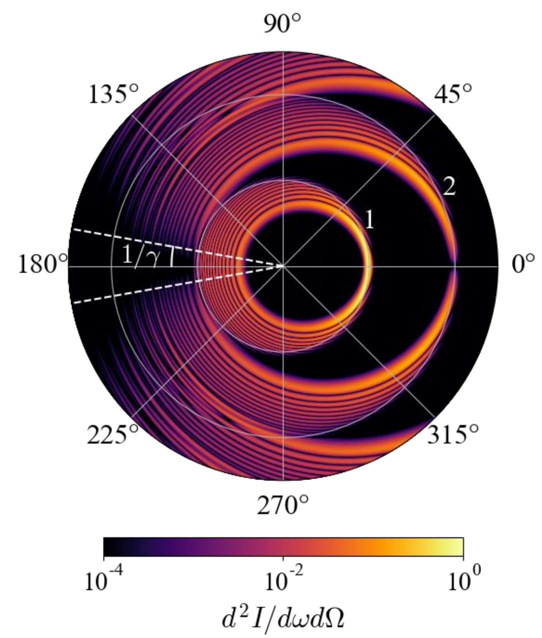


S.G. Rykovanov, et al, PRAB 19 (2016): 030701

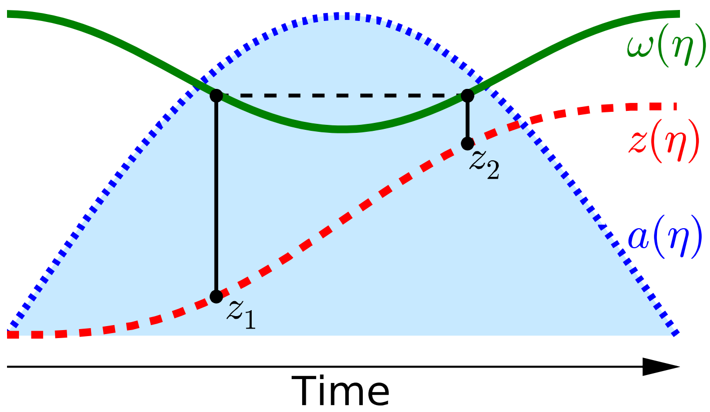


$$\omega_n(\eta) = \frac{4\gamma^2 n\omega_0}{1 + a(\eta)^2/2}$$

Ponderomotive broadening destroys the monochromaticity of Compton photon source and severely limits its applicability



Proper nonlinear chirping

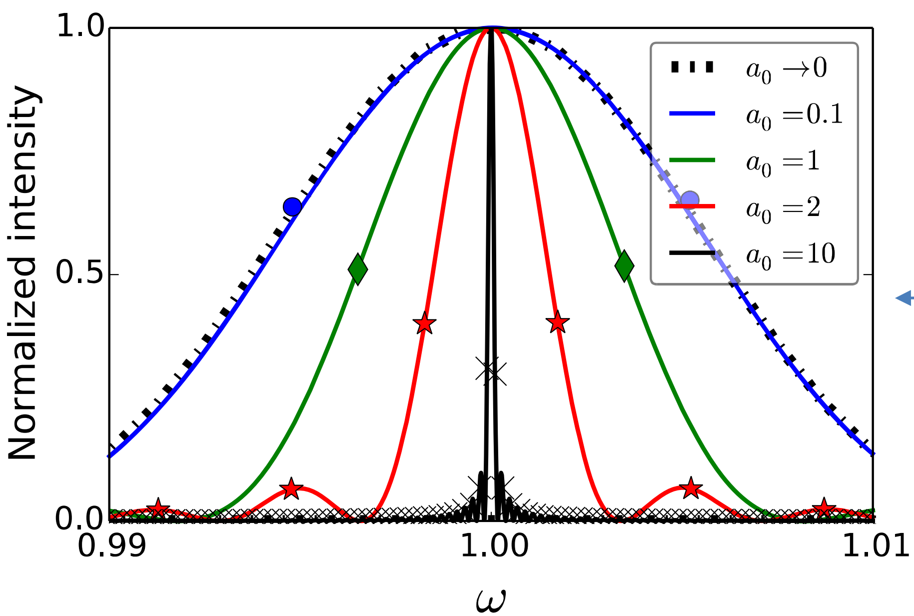


If laser frequency is constant,
the generated frequency is given by:

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

Why don‘t we chirp the pulse to exactly compensate the ponderomotive broadening:

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



backscattered spectrum

*S.G. Rykovanov, et al, PRAB **19**, 030701 (2016)*

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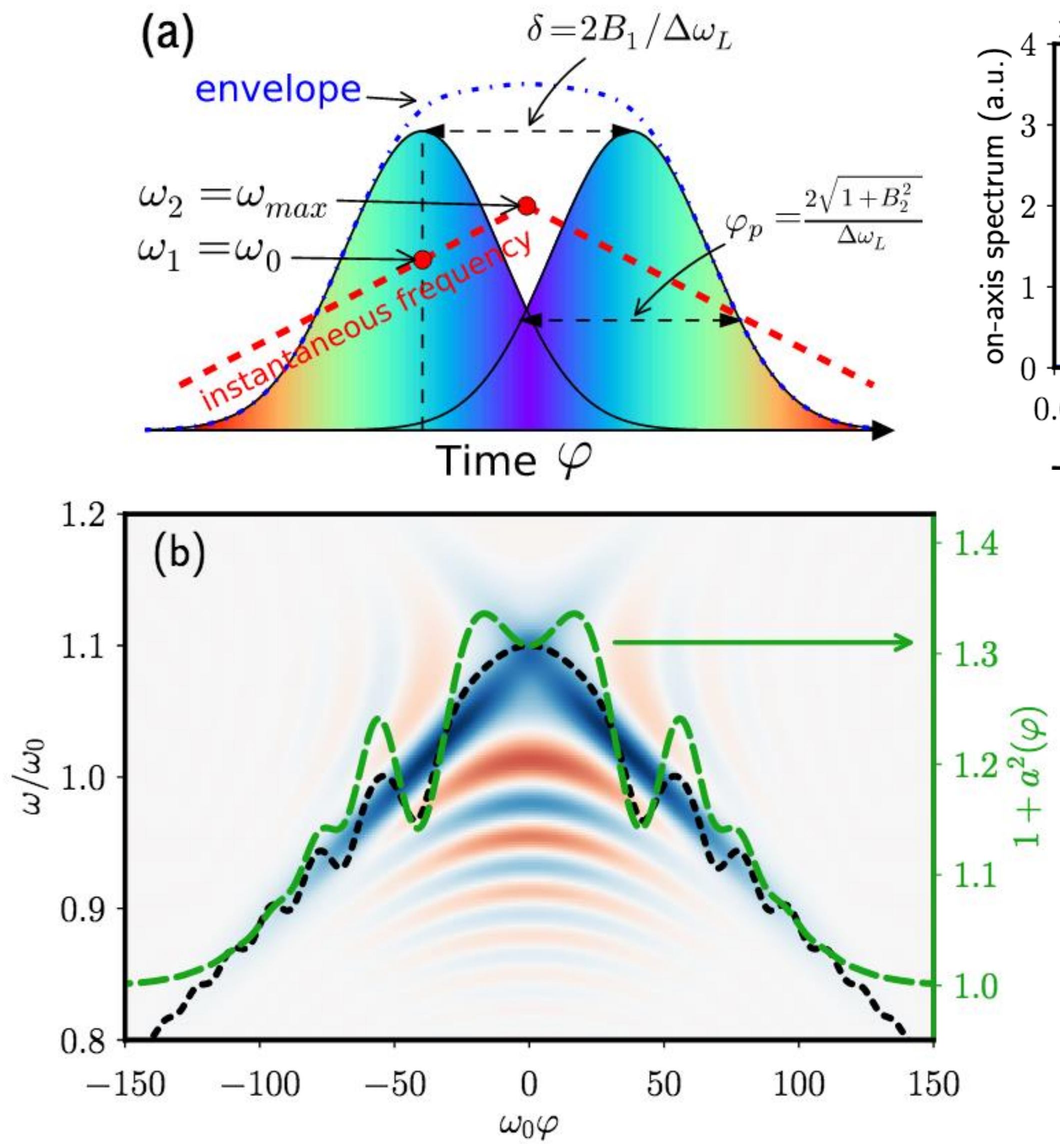
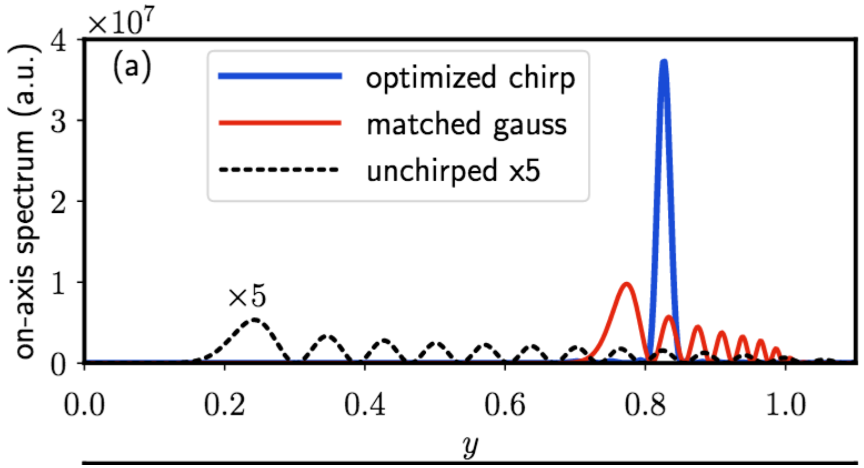
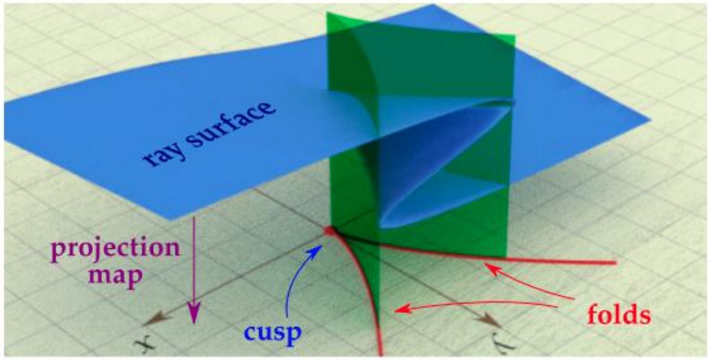
Two oppositely chirped laser pulses





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

Theory of singularities of differentiable projection maps (catastrophe theory)

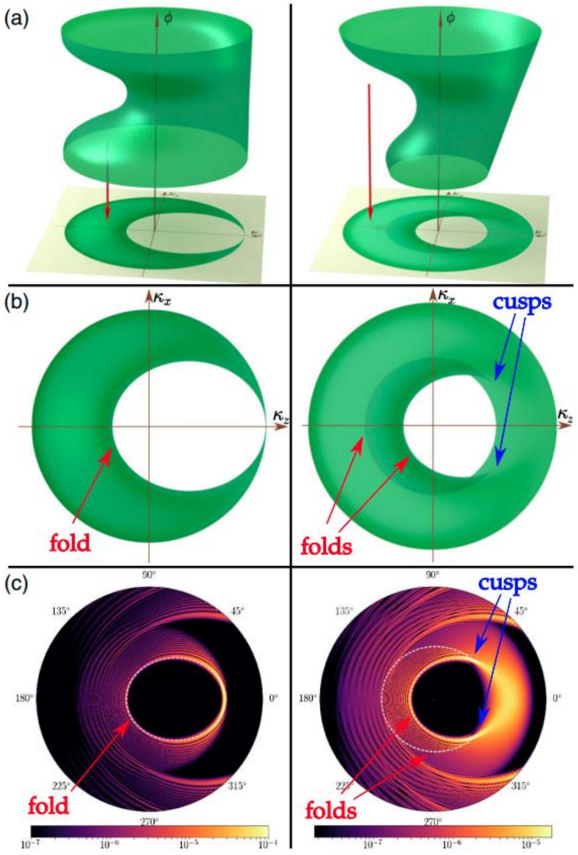


V. Yu. Kharin, et al. PRL 120.4 (2018): 044802

$$\frac{d^2 I}{d\omega d\Omega} = \kappa \frac{\omega^2}{4\pi^2} \left| \int_{-\infty}^{\infty} d\phi \;\; \mathbf{n} \times [\mathbf{n} \times \mathbf{u}] \, e^{i\omega(\phi + z - \mathbf{n}\cdot\mathbf{r})} \right|^2$$

Apply catastrophe theory to the stationary phase picture.

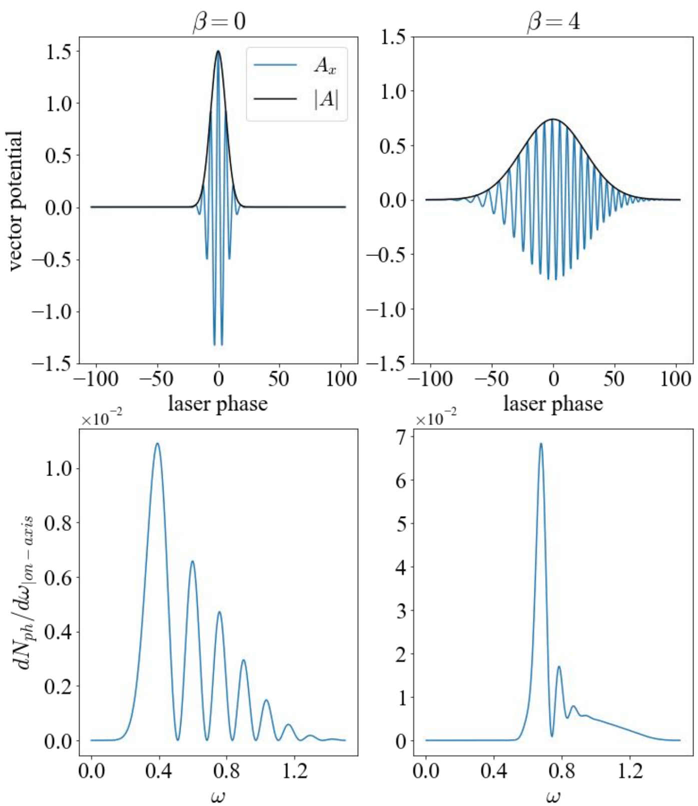
Narrow spectral peaks could be found in the vicinity of spectral caustics.

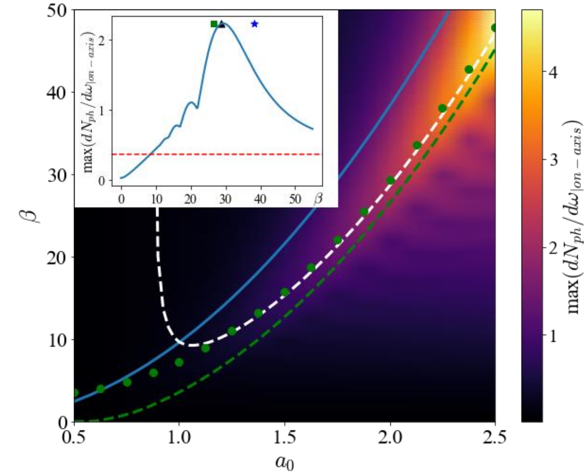


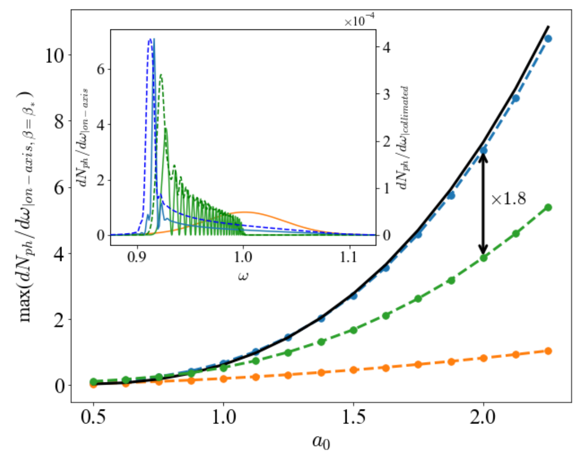
V. Yu. Kharin, et al. PRL 120.4 (2018): 044802

Optimal linear chirp in the spectral domain

$$\tilde{A}(\omega) = \sqrt{2\pi}\, a_0 \tau \exp\left[-\frac{\tau^2}{2}(\omega-\omega_0)^2(1-i\beta)\right]$$







$a_0 = 2$

$\tau = 6\pi$

$\beta_{opt} \approx 48$

$\omega_0 = 1.55\,\mathrm{eV}$

$\tilde{\tau} = 8\ \mathrm{fs}$

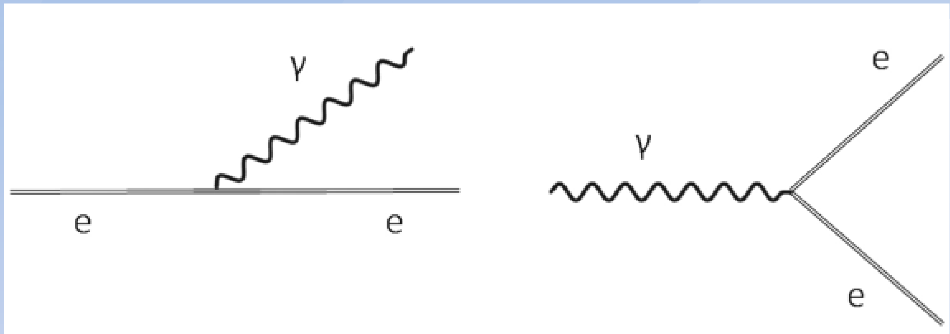
$\beta^{(2)} \approx 3072\ \mathrm{fs}^2$

Увеличение выхода фотонов

- Весьма нехитрыми (линейными) манипуляциями со спектром лазерных импульсов мультитераваттных и петаваттных систем можно **на несколько порядков** увеличить выход комптоновских фотонов по сравнению с линейным режимом
  - Минус: малая скважность (repetition rate)
  - Плюс: большая яркость в одном выстреле

НЕЛИНЕЙНОЕ КОМПТОНОВСКОЕ РАССЕЯНИЕ: ОСНОВНЫЕ ПАРАМЕТРЫ

$$a_0 = \frac{eE}{mc\omega_L} \propto \sqrt{I_L}$$ нормированная напряженность лазерного поля



$$e^- + n\hbar\omega \rightarrow e^- + \gamma$$

излучение фотонов (комптоновское рассеяние)

$$\gamma + n\hbar\omega \rightarrow e^- + e^+$$

фоторождение пар

$a_0>1$ ($n>>1$) – нелинейный режим комптоновского рассеяния

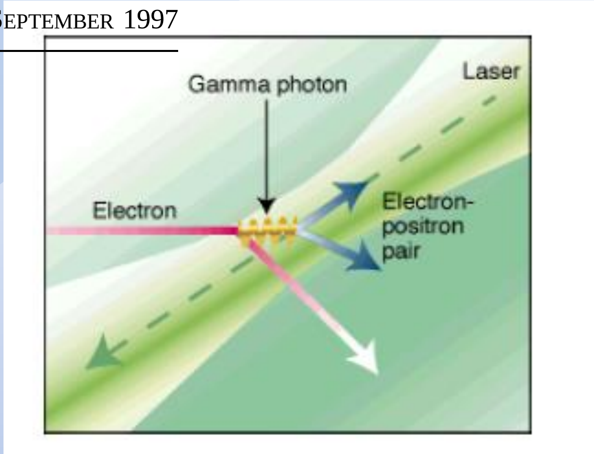
$$\chi_{e,ph} = \frac{1}{a_S}\sqrt{(\varepsilon_{e,ph}\mathbf{E} + \mathbf{p}_{e,ph} \times \mathbf{B})^2 - (\mathbf{p}_{e,ph} \cdot \mathbf{E})^2}$$

$\chi>1$ – квантовый режим (эффект отдачи и зависимость от спина)

НЕЛИНЕЙНОЕ КОМПТОНОВСКОЕ РАССЕЯНИЕ: ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ

SLAC E144 ЭКСПЕРИМЕНТ

VOLUME 79, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1997



Positron Production in Multiphoton Light-by-Light Scattering

D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

A signal of ~10^6 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC.

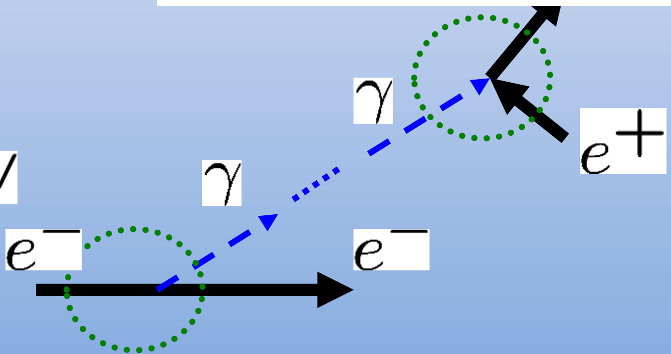
Laser:

$$\lambda = 0.527\mu\text{m}$$

$$I \approx 1.3 \times 10^{18}\text{W/cm}^2$$

$$\varepsilon_\gamma = 29.2\text{GeV}$$

$$N_{e+}/\text{lasershot} \approx 0.2$$



a_o ~< 1, слабонелинейный режим

D.L.Burke, *et al.*, Phys. Rev. Lett. **79**, 1626 (1997).
C.Bamber, *et al.*, Phys. Rev. D **60**, 092004(1999).

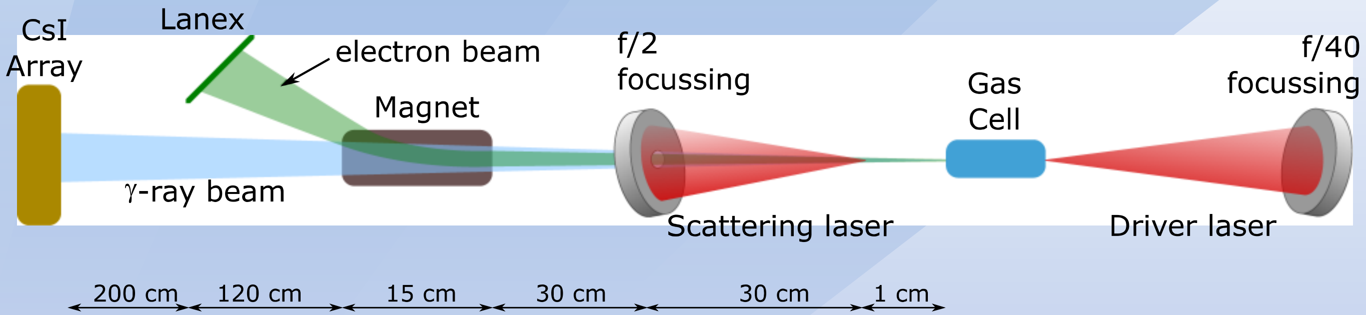
ЛАЗЕРНО-ПЛАЗМЕННАЯ СХЕМА

PHYSICAL REVIEW X **8**, 031004 (2018)

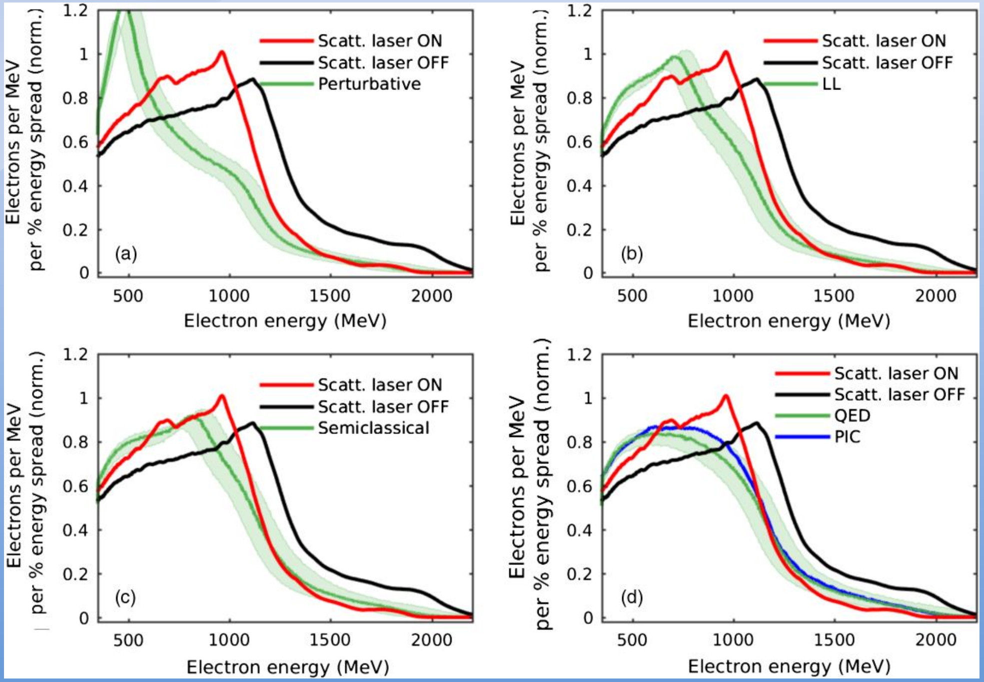
Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser

K. Poder,[1,†] M. Tamburini,[2] G. Sarri,[3,*] A. Di Piazza,[2] S. Kuschel,[4,5] C. D. Baird,[6] K. Behm,[7] S. Bohlen,[8] J. M. Cole,[1] D. J. Corvan,[3] M. Duff,[9] E. Gerstmayr,[1] C. H. Keitel,[2] K. Krushelnick,[7] S. P. D. Mangles,[1] P. McKenna,[9] C. D. Murphy,[6] Z. Najmudin,[1] C. P. Ridgers,[6] G. M. Samarin,[3] D. R. Symes,[10] A. G. R. Thomas,[7,11] J. Warwick,[3] and M. Zepf[3–5]

(a)



a_0 ~ 7, нелинейный режим, низкая точность измерений



SLAC E320 ПРОЕКТ

E-320: Probing Strong-field QED at FACET-II

13 ГэВ + 17 ТВт

FACET-II PAC Meeting

October 28, 2020

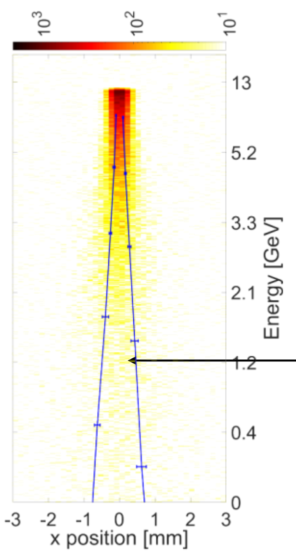
Sebastian Meuren
(for the E-320 collaboration)

Stanford PULSE Institute

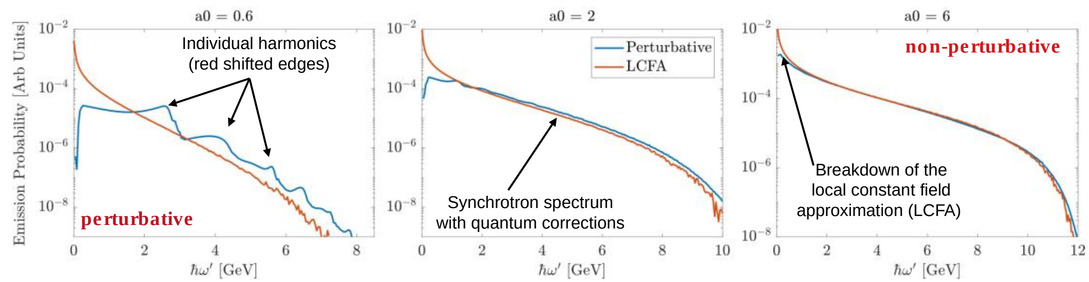
SLAC NATIONAL ACCELERATOR LABORATORY

Current simulations: *Nielsen*
Initial simulations: *Tamburini & Vranic*
Perturbative (E-144 code): *Holtzapple*

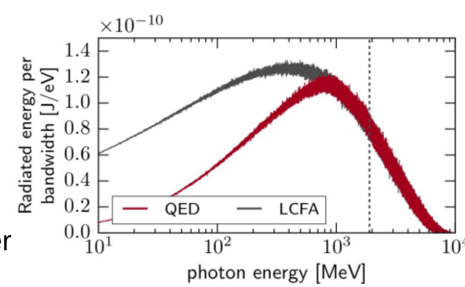
- **2021 (spring)**: calibrate detectors, measure backgrounds, access perturbative regime: a_0 1 (~10^{18} W/cm^2)
- **2021 (summer)**: observe the transition to nonperturbative laser-electron interactions: a_0 5 (10^{19} W/cm^2)

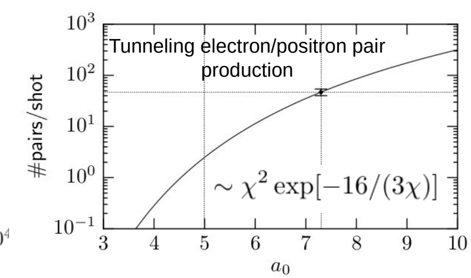


Detector response:
Mir-Ali Hessami & Storey



- **2021 (winter)**: quantum radiation reaction (electrons emitting n 5 photons)
- **2021 (winter)**: QED vacuum breakdown: a_0 10 (2x10^{20} W/cm^2)





- **2022 (spring)**: LCFA breakdown requires Compton / pair spectrometer (*Naranjo & Rosenzweig*)

Sebastian Meuren (for the E-320 collaboration) 3

LUXE ПРОЕКТ

Eur. Phys. J. Spec. Top. (2021) 230:2445–2560
https://doi.org/10.1140/epjs/s11734-021-00249-z

THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

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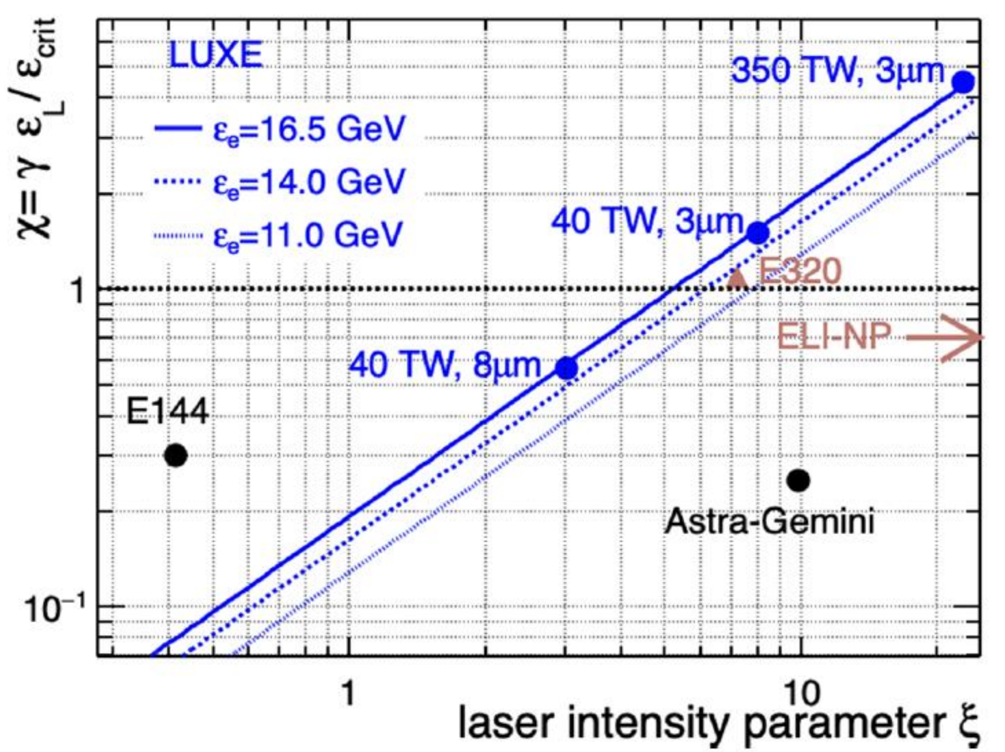
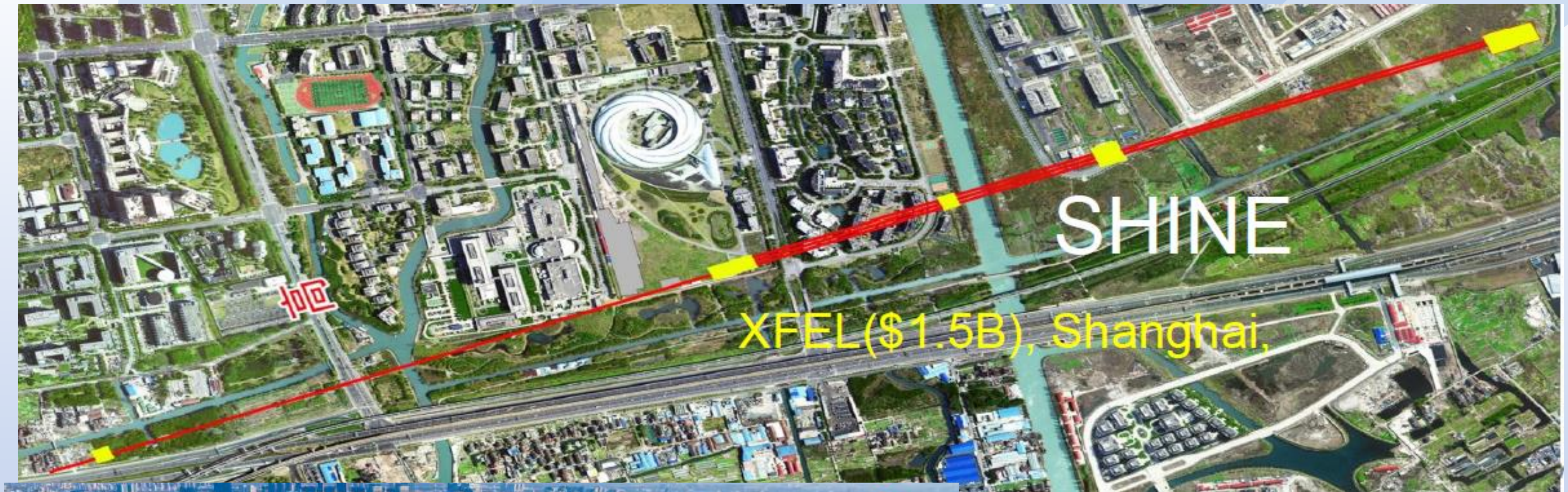
Conceptual design report for the LUXE experiment

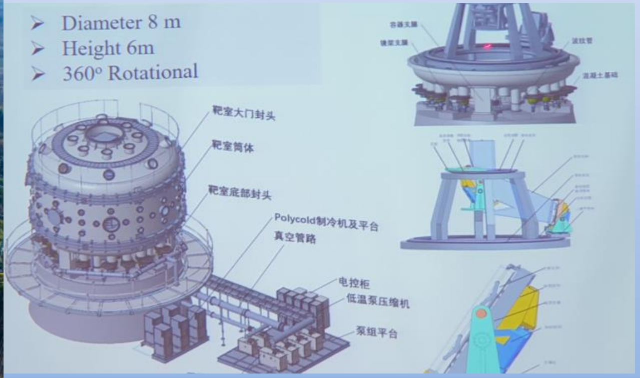
H. Abramowicz[1], U. Acosta[2,3], M. Altarelli[4], R. Aßmann[5], Z. Bai[6,7], T. Behnke[5], Y. Benhammou[1], T. Blackburn[8], S. Boogert[9], O. Borysov[5], M. Borysova[5,10], R. Brinkmann[5], M. Bruschi[11], F. Burkart[5],

Abstract This Conceptual Design Report describes LUXE (Laser Und XFEL Experiment), an experimental campaign that aims to combine the high-quality and high-energy electron beam of the European XFEL with a powerful laser to explore the uncharted terrain of quantum electrodynamics characterised by both high energy and high intensity. We will reach this hitherto inaccessible regime of quantum physics by analysing high-energy electron-photon and photon-photon interactions in the extreme environment provided by an intense laser focus. The physics background and its relevance are presented



SHINE ПРОЕКТ (КИТАЙ)





XFEL + 100 ПВт лазер (SEL – Station of Extreme Light)

Выводы и предложения

Один из проектов КИ предусматривает 3 лазерные станции. Одну из станций можно оснастить мощной лазерной системой (мульти-ТВт или суб-ПВт) для исследования нелинейного режима комптоновского рассеяния.

1-й этап: исследование методов значительного увеличения выхода фотонов
2-й этап: исследование эффектов реакции излучения, исследование границ применимости приближений плоской волны и постоянного скрещенного поля
3-й этап: сильно-полевая КЭД, генерация электрон-позитронных пар, (200 ТВт система)

Приложения сильно-нелинейного режима комптоновского источника: генерация короткого импульса гамма-квантов с высокой яркостью и широким спектром для исследования быстропротекающих процессов в one-shot режиме.

КОМПТОНОВСКИЙ ИСТОЧНИК В НЦФМ

Один из проектов КИ предусматривает 3 лазерные станции. Одну из станций можно оснастить мощной лазерной системой (мульти-ТВт или суб-ПВт для исследования нелинейного режима комптоновского рассеяния.

1-й этап: исследование эффектов реакции излучения, исследование границ применимости приближений плоской волны и постоянного скрещенного поля

2-й этап: сильно-полевая КЭД, генерация электрон-позитронных пар,
(200 ТВт система)

Приложения сильно-нелинейного режима комптоновского источника:
генерация короткого импульса гамма-квантов с высокой яркостью и широким спектром для исследования быстропротекающих процессов в one-shot режиме.

Использование технологии CafCA позволяет генерировать сверхкороткие оптические импульсы. Это может быть интересно для исследования «неизлучающих» режимов взаимодействие электронов с лазерным полем, а также режимов, где не работает приближение плоской волны.

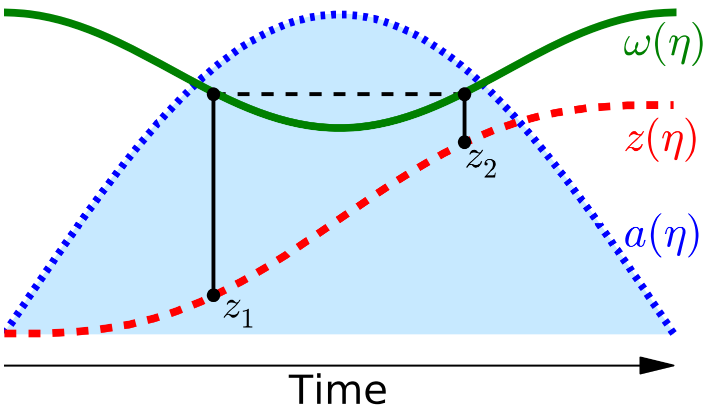
СубПВТ ЛАЗЕРНАЯ СИСТЕМА PEARL

W = 24 Дж,
T = 43 фс,
P ~ 0.56 ПВт,
λ = 0.911 мкм
Laser Phys. Lett. 4, 421 (2007).

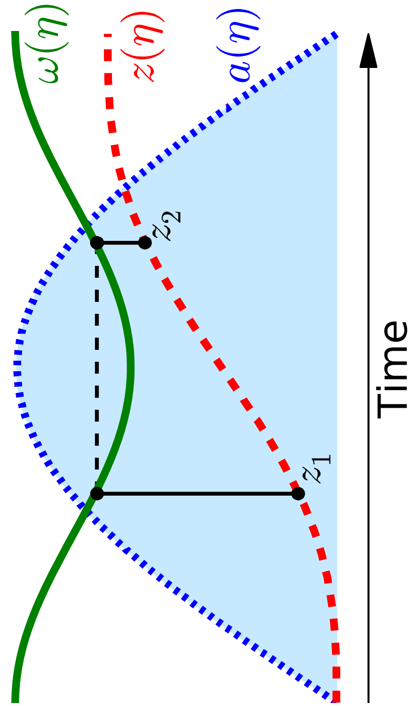
CafCA метод:
T = 11 фс,
P ~ 1.5 ПВт,
Opt. Express 29, 28297 (2021).

Caustics and catastrophes

Caustics and catastrophes



Caustics and catastrophes



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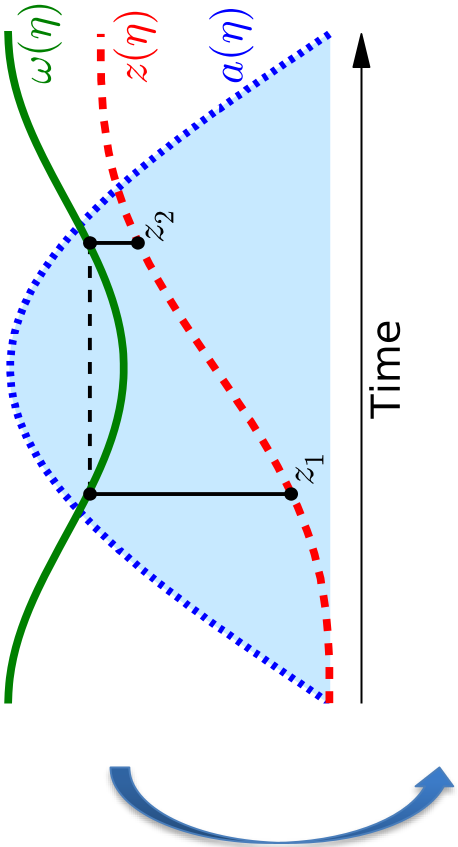
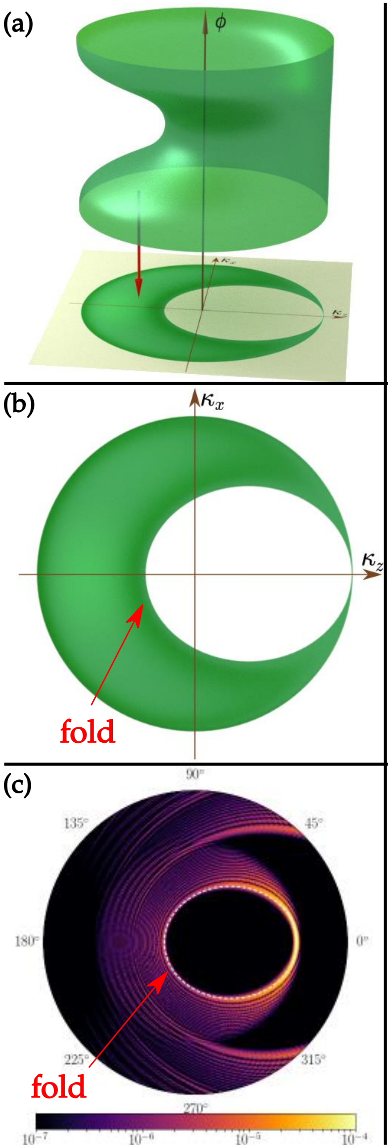
Caustics and catastrophes



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

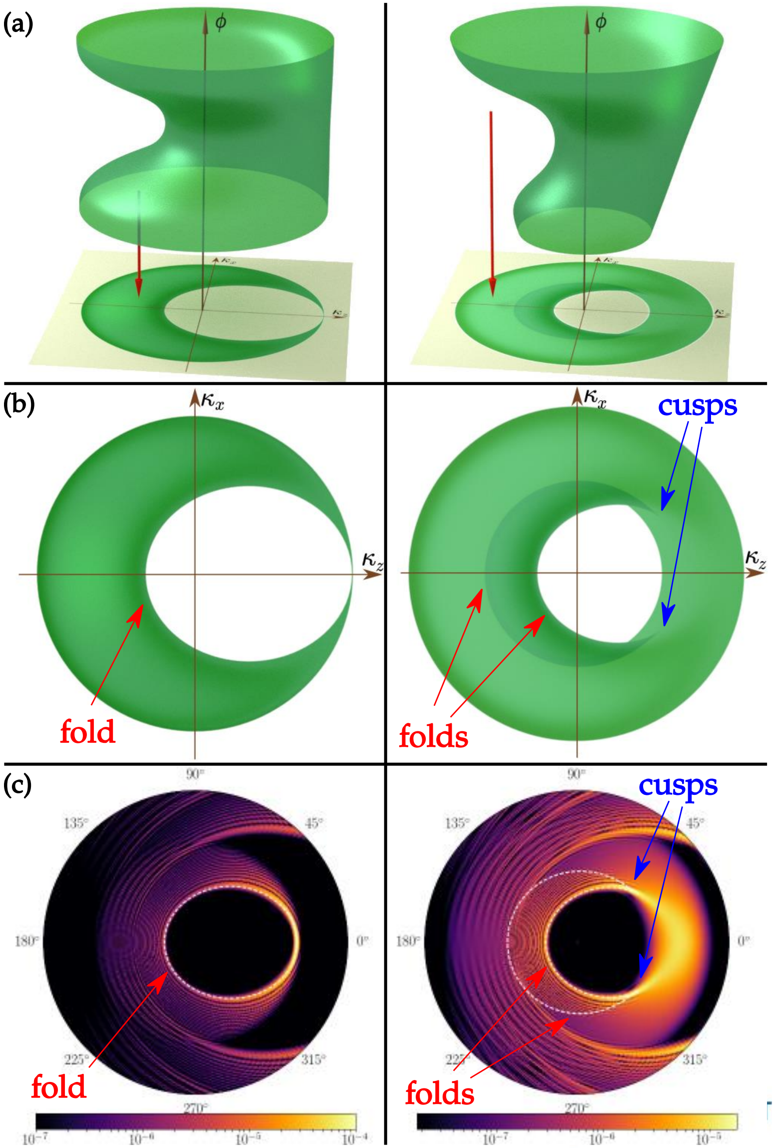
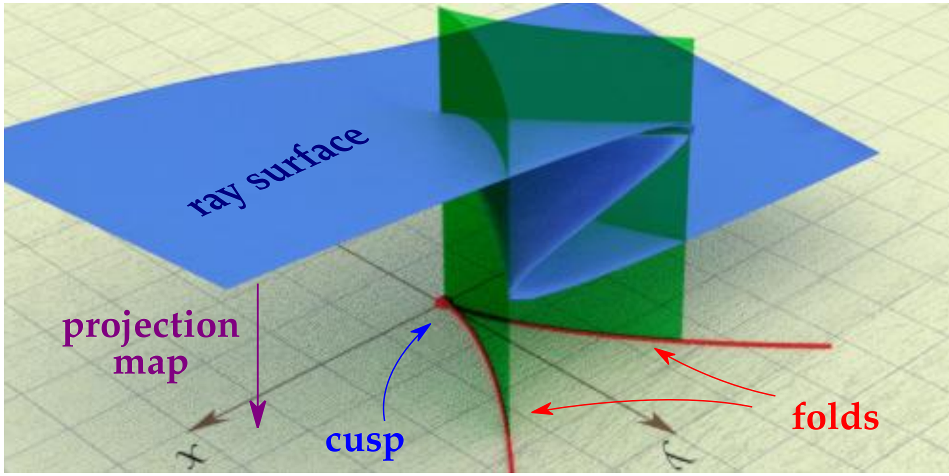
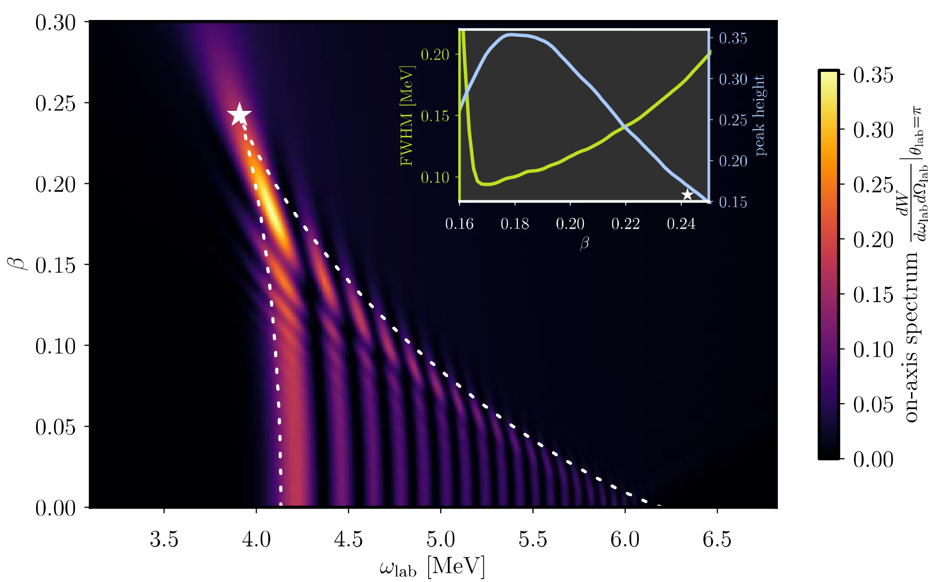


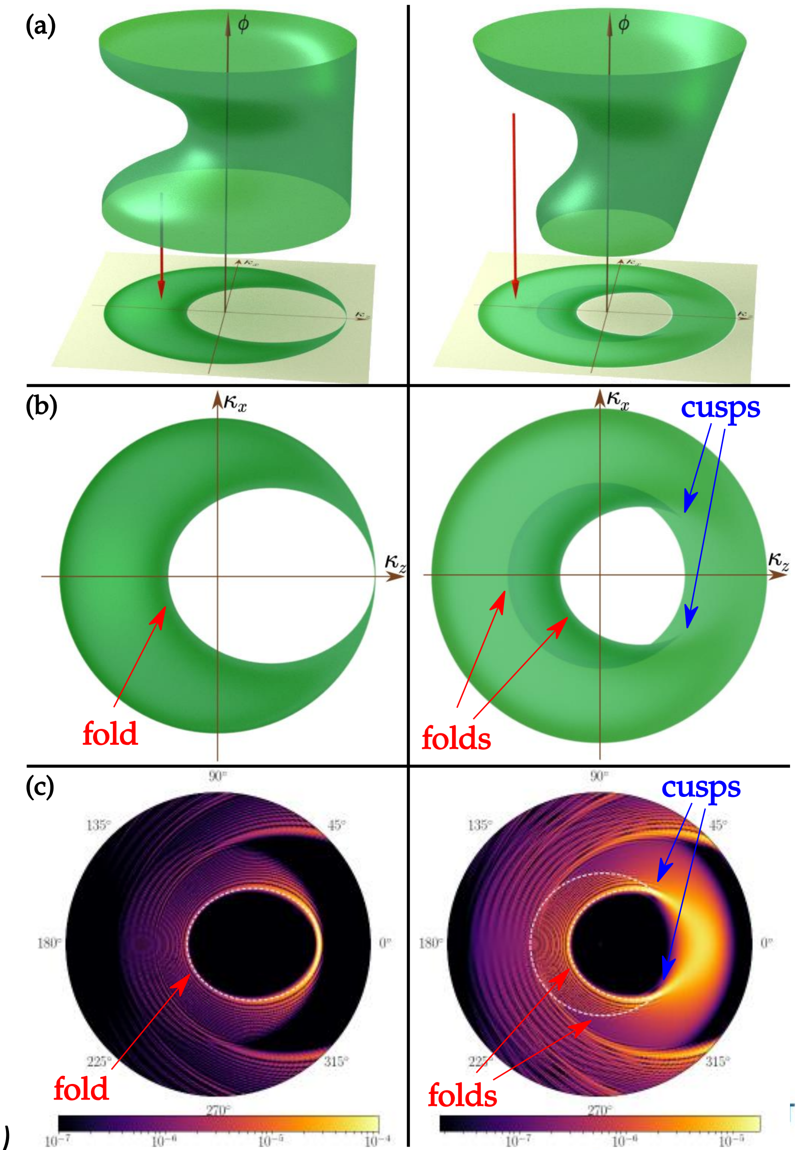
FIG. 1. The ray surfaces [stationary phase condition (4)] (a),

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)

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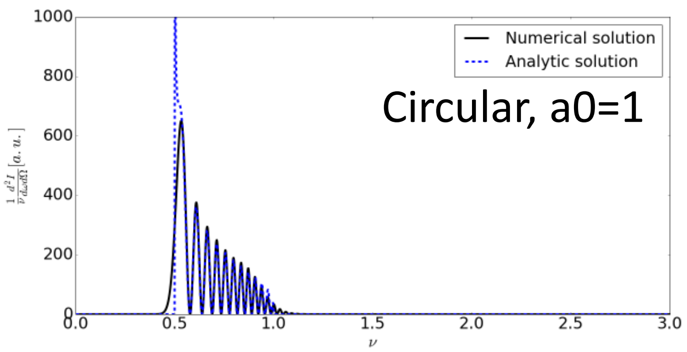
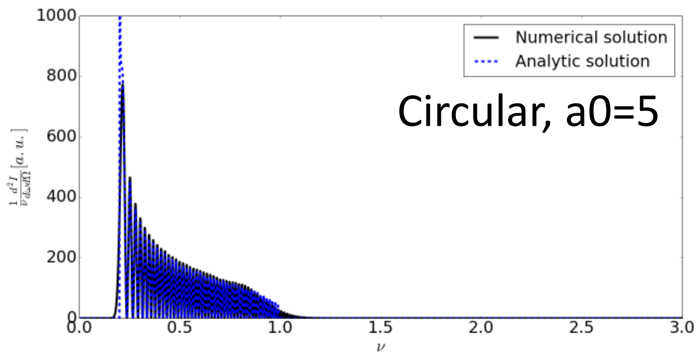
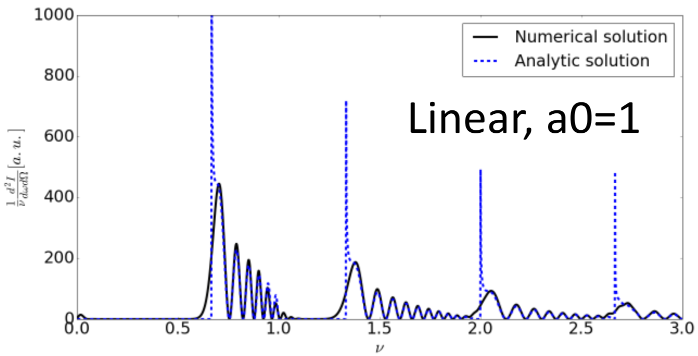
FIG. 1. The ray surfaces [stationary phase condition (4)] (a),

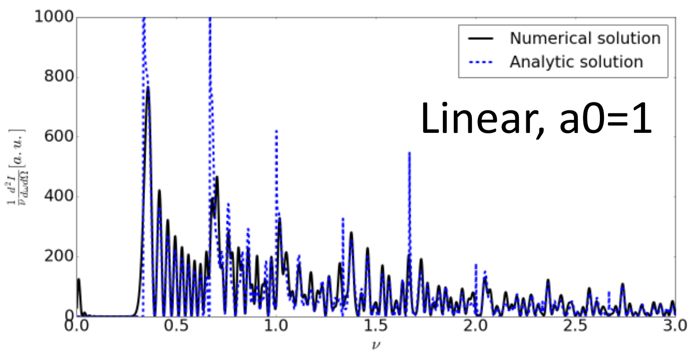
Generation of harmonics

- Linear (a0<<1) Compton scattering is a source of narrow bandwidth gamma-rays
- One can significantly increase photon yield by increasing a_0 for rectangular pulses
- Temporally shaped laser pulses lead to ponderomotive broadening in the spectrum
- Linear polarization leads to harmonics on axis, circular – no harmonics on axis (backscatter)
- Nonlinear chirping can compensate broadening, but hard to do experimentally
- Linear chirping is “easy“ to implement

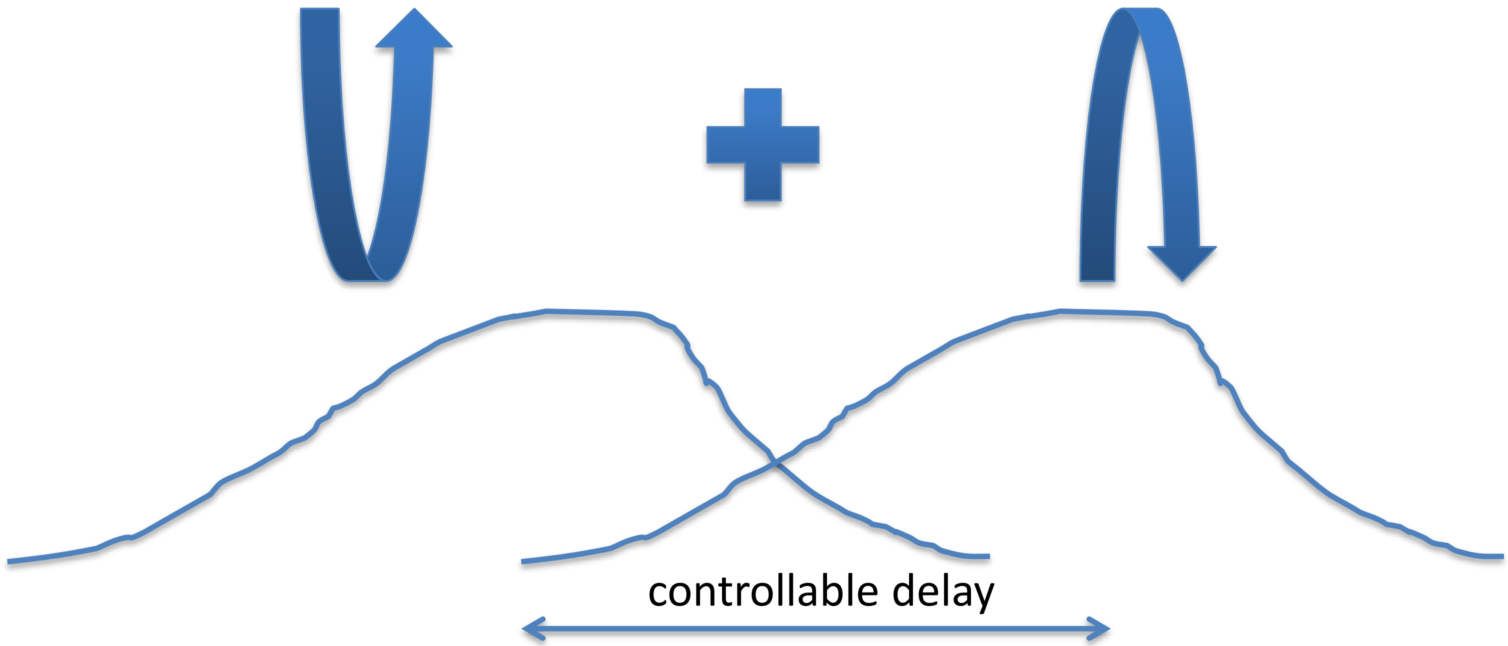


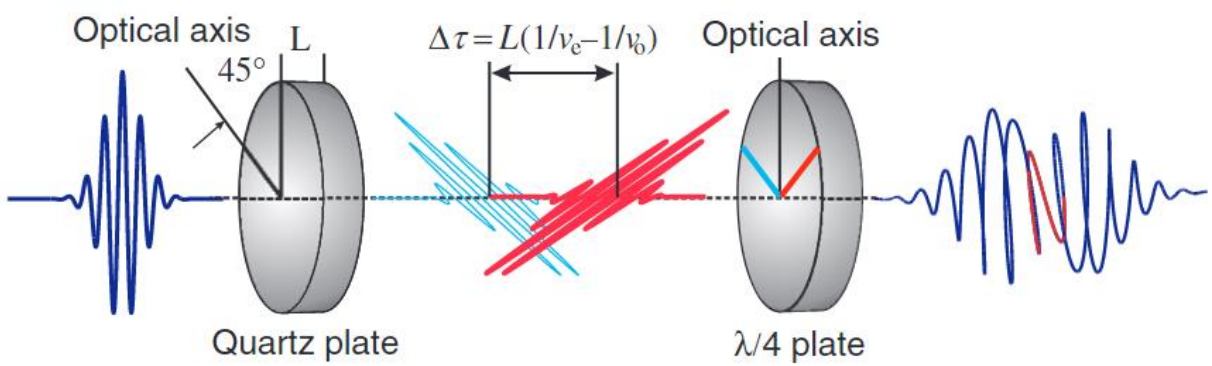






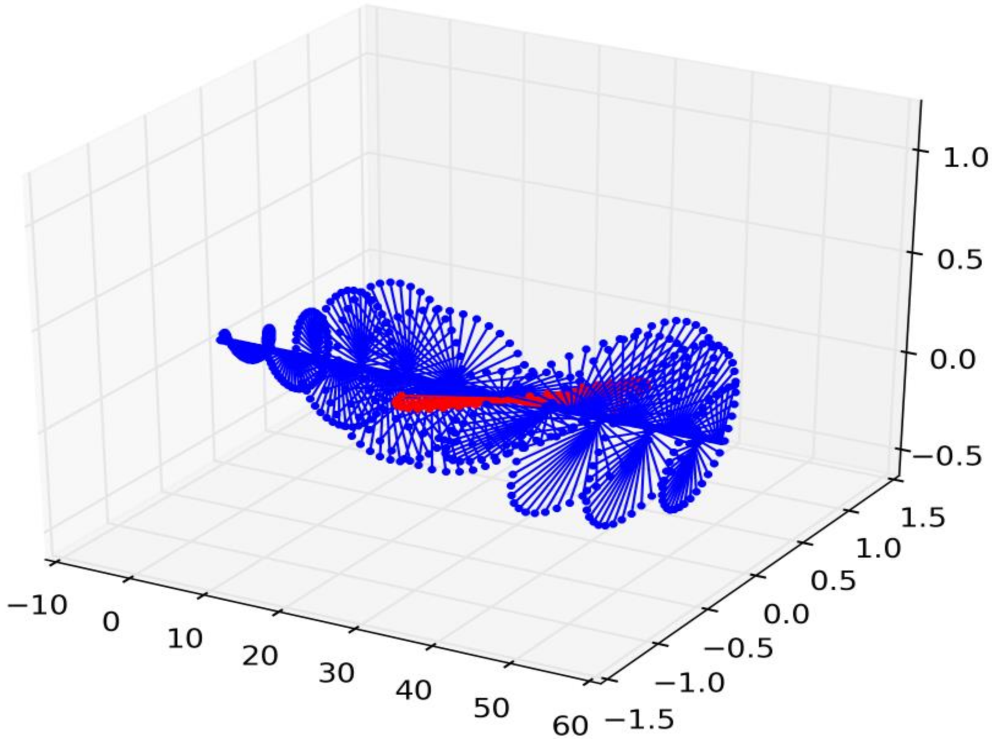
Polarization gating technique





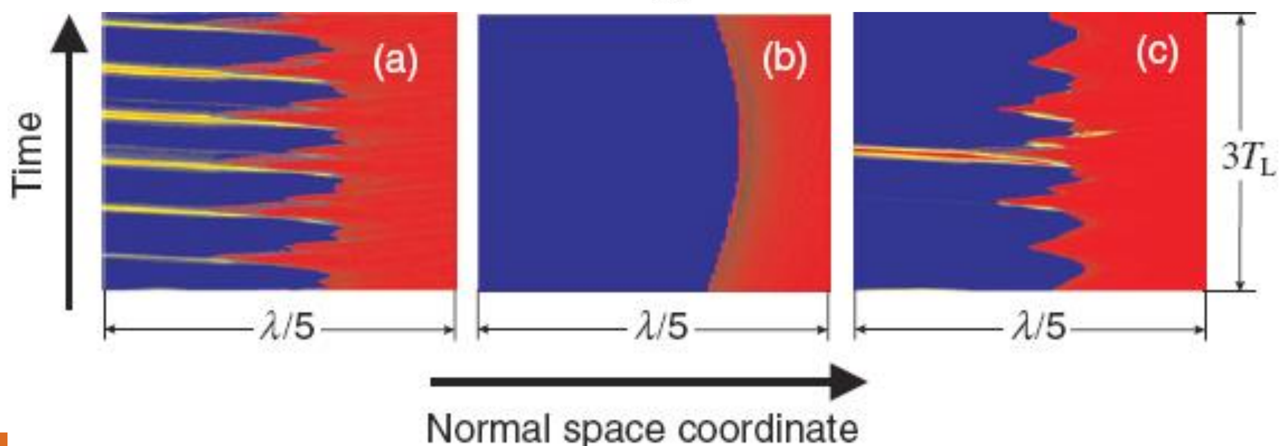
S.G. Rykovanov, et al, New Journal of Physics 10, 025025 (2008)

Polarization gating technique in surface harmonics



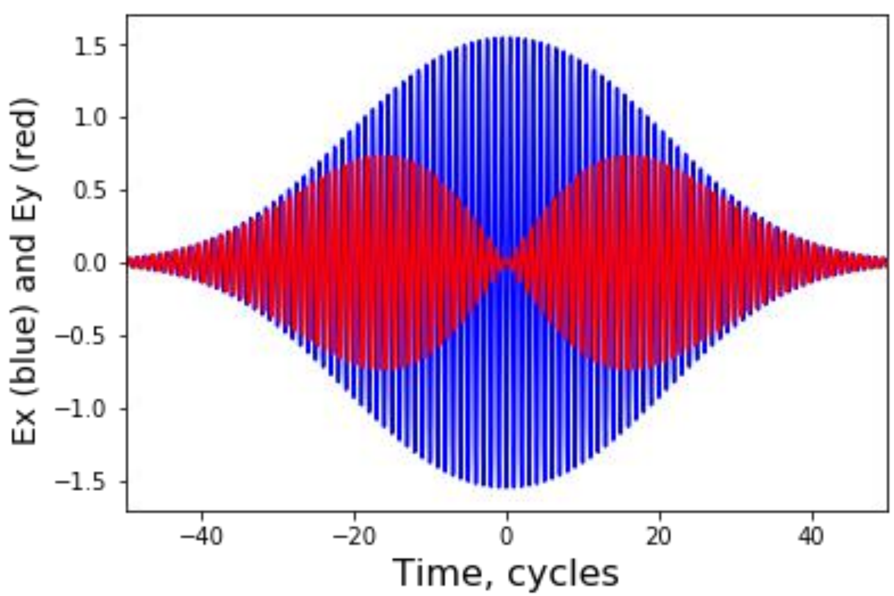
S.G. Rykovanov, et al, New Journal of Physics 10, 025025 (2008)

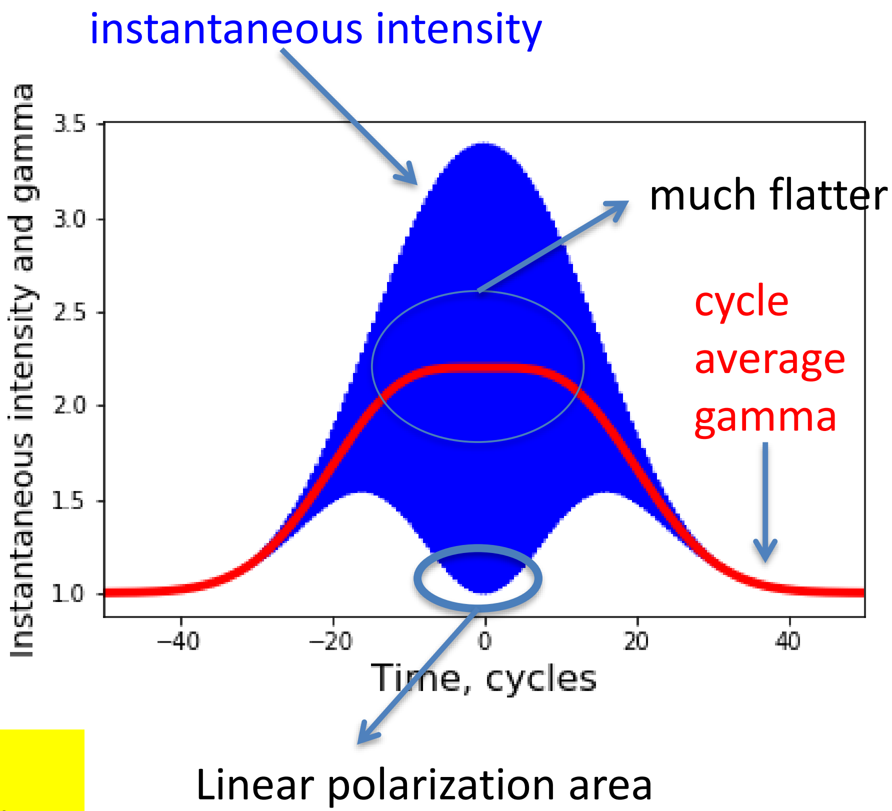
Mark Yeung, J Bierbach, E Eckner, **S Rykovanov**, S Kuschel, A Sävert, M Förster, **C Rödel**, GG Paulus, S Cousens, M Coughlan, B Dromey, M Zepf, Phys. Rev. Lett. 115, 193903 (2015)



PG technique in Compton Scattering

- Circular – no harmonics (at beginning and the end of the pulse)
- Linear – harmonics (near the middle of the pulse depending on the delay)
- Polarization gating – harmonics are only generated near the middle of two pulses where the polarization is linear

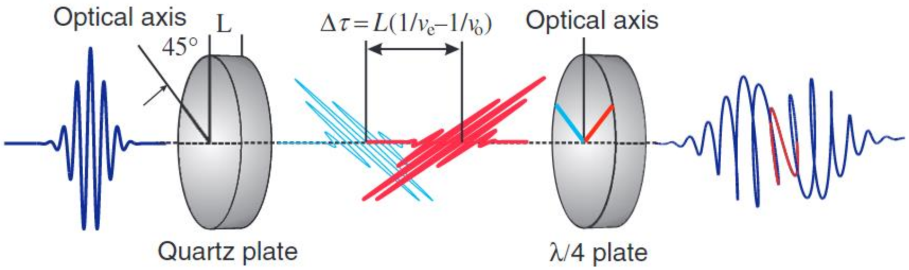




Two beneficial effects:

1. Flatter electron gamma factor at peak intensity
2. Linear polarization only near the peak intensity

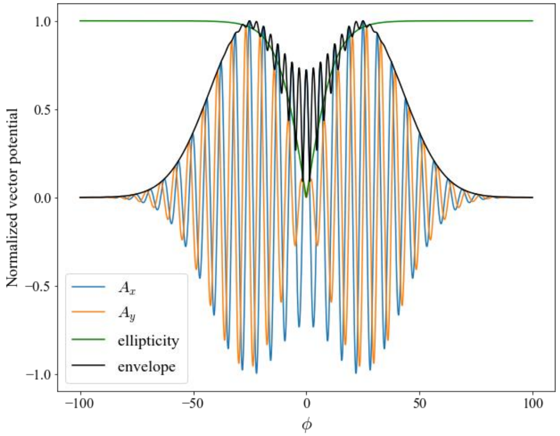
Polarization gating technique



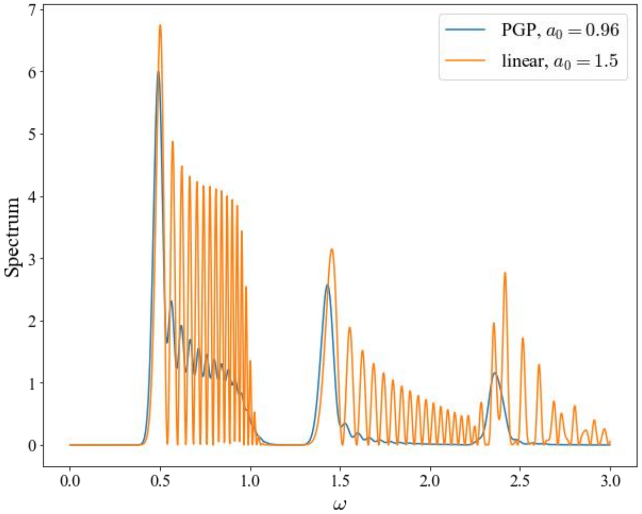
S.G. Rykovanov, et al, New Journal of Physics 10, 025025 (2008)

$$\phi = t - z, \qquad \delta = \pi n$$

$$\mathbf{A}_\perp = \frac{a_0}{2} e^{i\phi} \left(g\left(\phi - \frac{\delta}{2}\right) \varepsilon_+ + g\left(\phi + \frac{\delta}{2}\right) \varepsilon_- \right) + c.c.$$



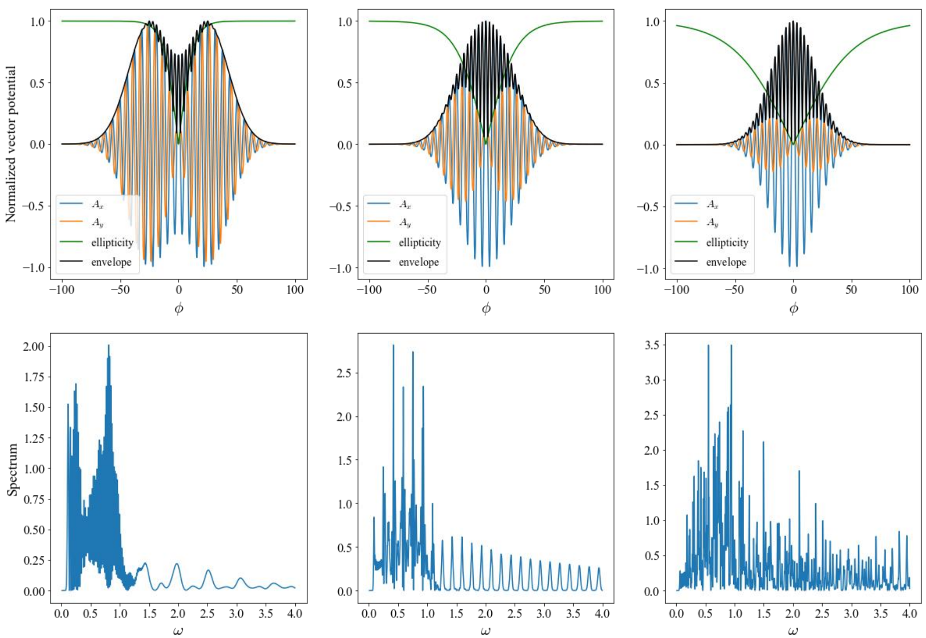
Laser pulse with time-varying ellipticity – a simple method to avoid ponderomotive broadening in harmonics spectrum

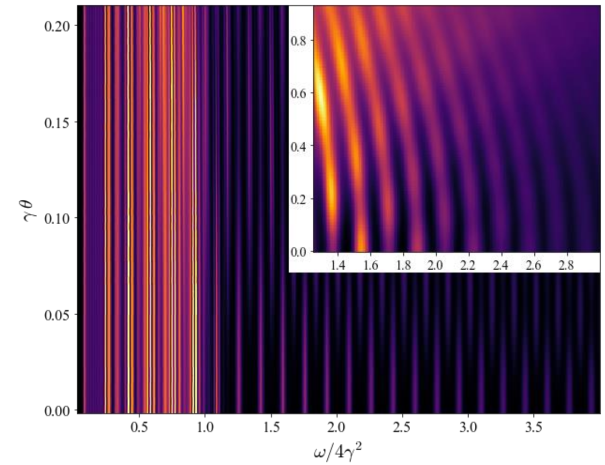


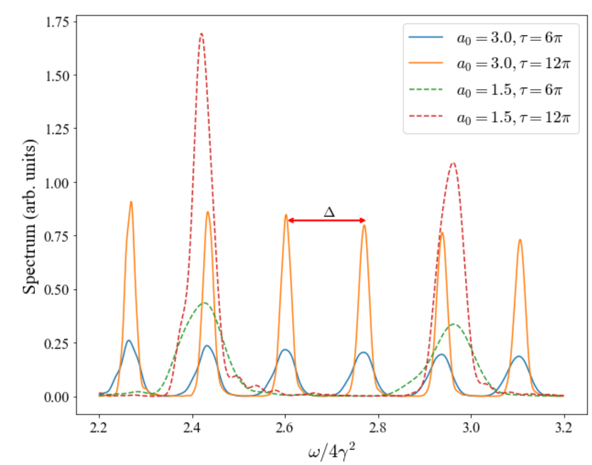
- For high intensities harmonics start to overlap into complete disarray
- On-axis harmonics are not emitted for circular polarization

Gamma comb

Choosing optimal delay between the circular pulses leads to a nice comb in gamma region (observed in angular distribution as well). Properties of this comb are governed by strength and length of the incident pulse.

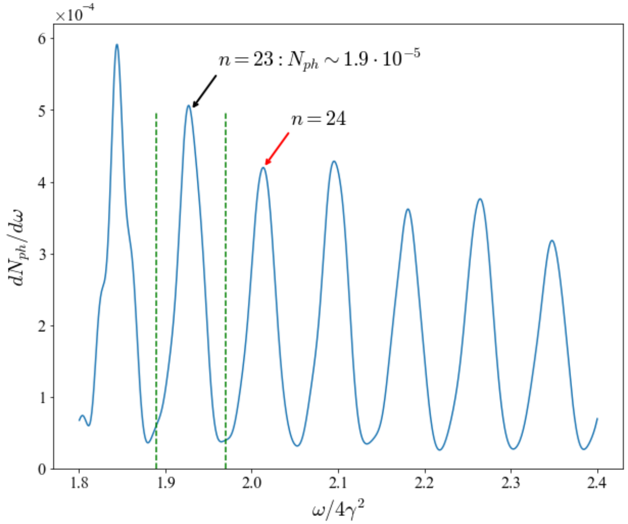






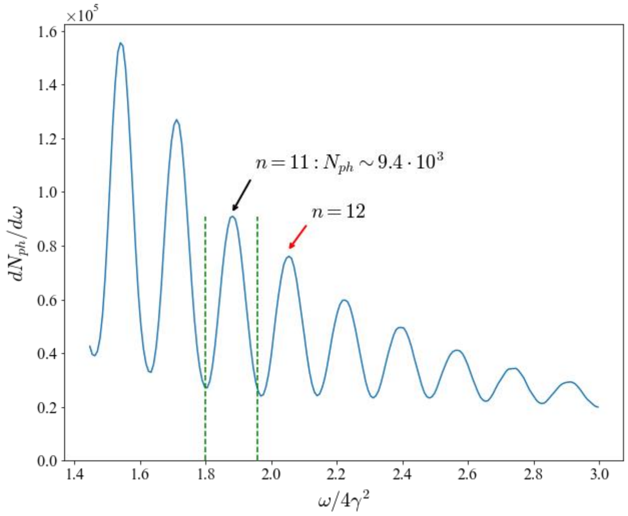
Photon yield

- Plane wave with gaussian temporal envelope ($a_0 = 3, \tau =$



Due to collimation angle even harmonics are also present

- Laser pulse ($a_0 = 2, \tau = 30\pi$),
- realistic electron beam (10^8 electrons, $\gamma = 529, \epsilon_n \approx 0.15$ mm mrad, $\sigma_r \approx 1.4\ \mu$m, $\sigma_\theta \approx 0.19$ mrad, $\delta E \approx 1\%$),
- $\theta_{col} = 0.2/\gamma$



The effect could be observed experimentally

M. Valialshchikov, V. Yu. Kharin, S.G. Rykovanov, accepted to Phys. Rev. Lett.
https://arxiv.org/abs/2011.12931

Notable Compton gamma-ray sources

Facility	Gamma-ray photon energy [MeV]	Intensity (ph/s)	Collimated spectrum width [%]	Repetition rate [MHz]	Technology
HIGS (Duke university, in operation)	1-100	Full intensity: $10^8 – 4*10^9$ Collimated intensity: $\sim 6*10^6 – 2.5*10^8$	5	5.6	Storage ring: 0.24-1.2 GeV FEL: 1060-190 нм (1.17-6.53 eV)
HIGS-2 (planned?)	2-12	Full intensity: $10^{11} – 10^{12}$ Collimated intensity estimate: $5*10^8 – 5*10^9$	<0.5	5.6	Same as above + IR Laser with Fabri-Perrot cavity
newSubaru (Hyogo University, Japan, in operation)	1.7-76	Full intensity: $\sim 4*10^7$ Collimated intensity: $\sim 10^5$	1-2	500 198 bunches, each with rep.rate 2.53	Storage ring: 0.974-1.5 GeV Laser: Nd:YVO_4 (1064 nm + 532 nm) CO_2 (10.59 nm)
ELI-NP (under construction)	0.2-19.5	Collimated intensity: $8*10^8$	<0.5	10^{-4}	Linear accelerator 180-750 MeV Laser: Yb:Yag 515 нм, 2.3 eV
Project in LBNL (conceptual design?)	~1-10	Full intensity (10 Hz): $\sim 10^9$-10^{10} Collimated: $\sim 10^8$-10^9	2-10	10^{-5} (current tech.) >10^{-3} (tech. in development)	Laser wakefield acceleration

Notable Compton gamma-ray sources: possible extreme push in intensity?

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Project in LBNL (conceptual design?)	~1-10	**Collimated intensity:** **10^{10} -- 10^{11}**	2-10	10^{-5} (current tech.) >10^{-3} (tech. in development)	Laser wakefield acceleration

Conclusion

- **Nuclear Photonics** is new and perspective multi-disciplinary science area
- **Nuclear Photonics** describes methods of generation of intense monochromatic gamma-ray sources and their interaction with matter
- Billions of dollars invested world-wide in Nuclear Photonics (US, EU, China, Japan and others), several new facilities under construction
- Plasma based gamma-ray sources are very compact and can potentially compete with HIgS facility + they have intrinsic short duration (~10 fs)
- Sources based on Linear Compton Scattering can offer ~10^8 photons/sec having 1-5% bandwidth and 1-100 MeV photon energies
- Nonlinear Compton Scattering can potentially increase the photon yield up to ~10^{12} photons/sec for the same photon beam parameters
- *One can generate gamma beams carrying spin and orbital angular momentum*
- *What are the applications of the gamma comb?*
- *On-going discussion: What are new applications?*

Review article in press: DOI: 10.3367/UFNe.2021.03.038960

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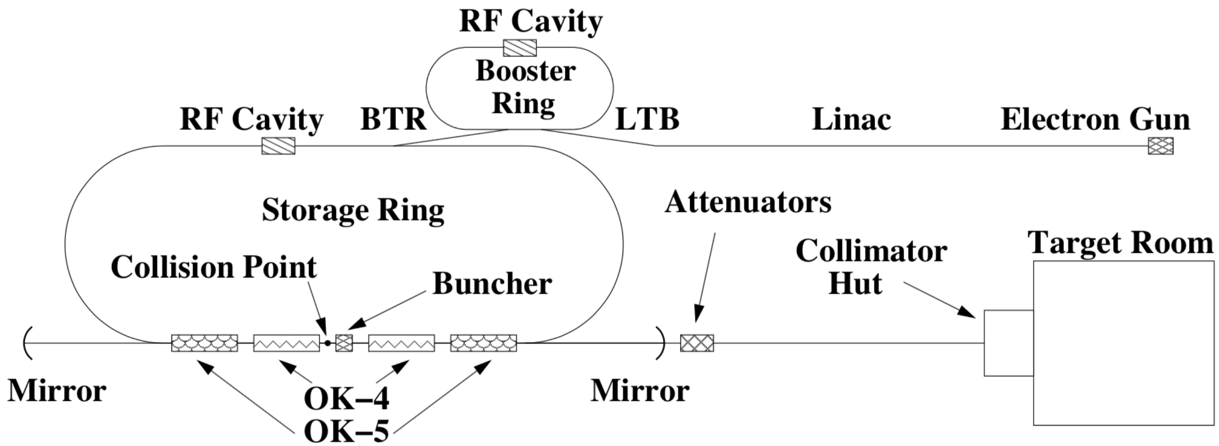
Duke University (HIgS facility)

Уникальная установка основанная на обратном эффекте Комптона, работает как Центр Коллективного Пользования с ~2000 года

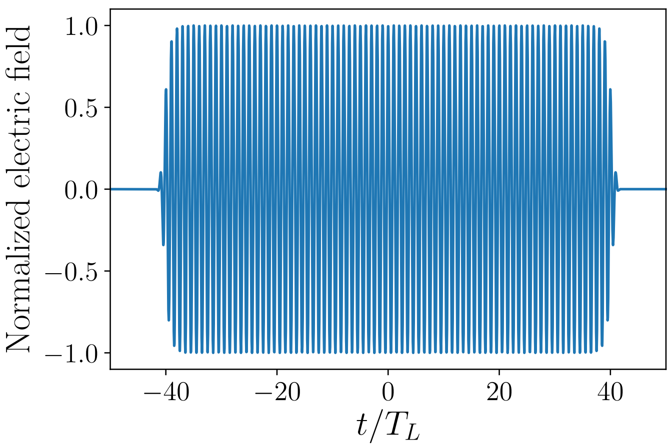
0.18–1.2 GeV e-



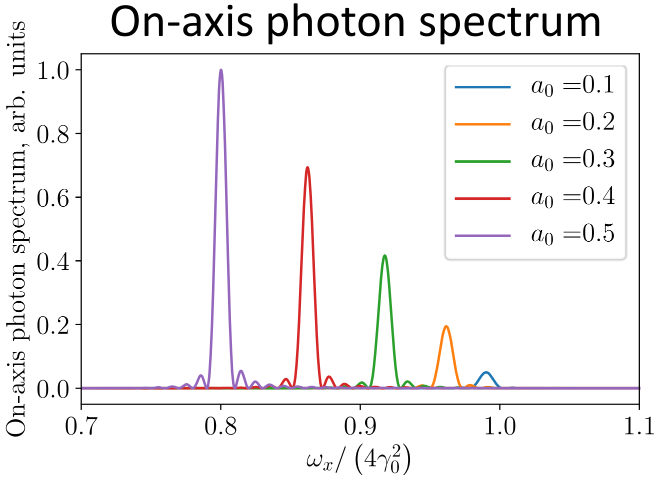
HIGS flux performance table for high-flux, quasi-CW operation, DFELL/TUNL, November, 2017 (Version 2.4).

HIGS Flux Performance Projection		Total Flux [g/s] CW Operation Two-Bunch (*)	Collimated Flux ($\Delta E_\gamma / E_\gamma$ = 5% FWHM) (#), (@)	FEL λ [nm]	Comment Linear Pol. with OK-4 Circular Pol with OK-5
No-loss Mode: E_γ < ~16 MeV					
E_γ = 1 – 2 MeV	(E_e = 237 – 336 MeV)	1 x 10^8 – 4 x 10^8	6 x 10^6 – 2.4 x 10^7	1064	Linear and Circular (a), (b)
E_γ = 2 – 2.9 MeV	(E_e = 336 – 405 MeV)	4 x 10^8 – 1 x 10^9	2.4 x 10^7 – 6 x 10^7	1064	Linear and Circular (a), (b)
E_γ = 2 – 3 MeV	(E_e = 288 – 353 MeV)	2 x 10^8 – 6 x 10^8	1.2 x 10^7 – 3.6 x 10^7	780	Linear and Circular (a), (b)
E_γ = 3 – 5.4 MeV	(E_e = 353 – 474 MeV)	6 x 10^8 – 2 x 10^9	3.6 x 10^7 – 1.2 x 10^8	780	Linear (a), (b)
E_γ = 3 – 6.3 MeV	(E_e = 353 – 512 MeV)	6 x 10^8 – 3 x 10^9	3.6 x 10^7 – 1.8 x 10^8	780	Circular (a), (b)

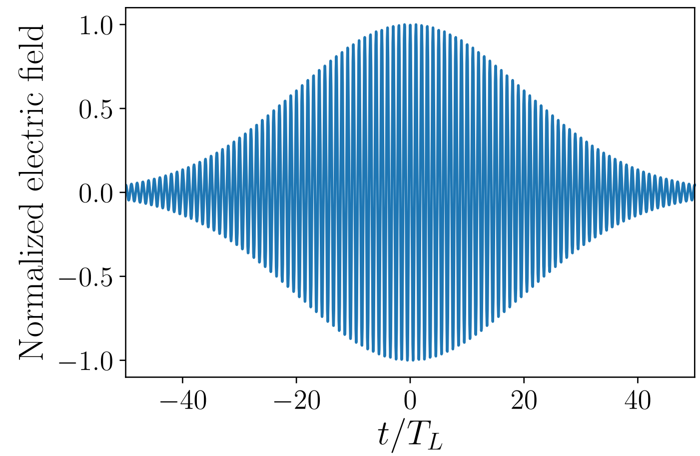
$$\hbar\omega_X = \frac{4\gamma^2\hbar\omega_L}{1+\gamma^2\theta^2+a_0^2}$$



On-axis photon spectrum



$$N_X = N_e p a \frac{a_0^2}{1+a_0^2}$$



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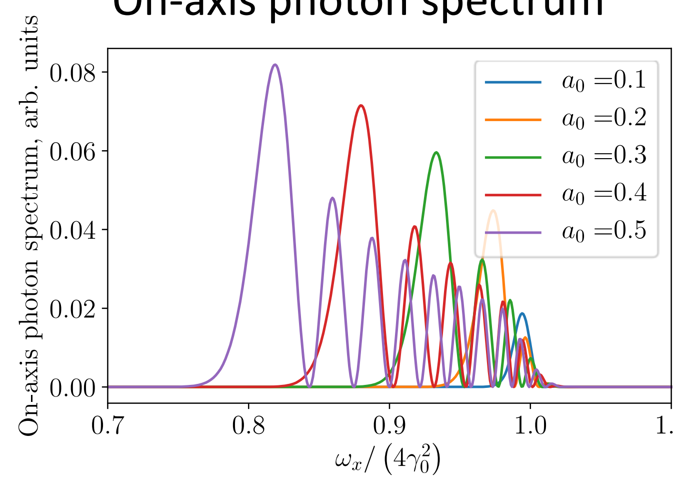
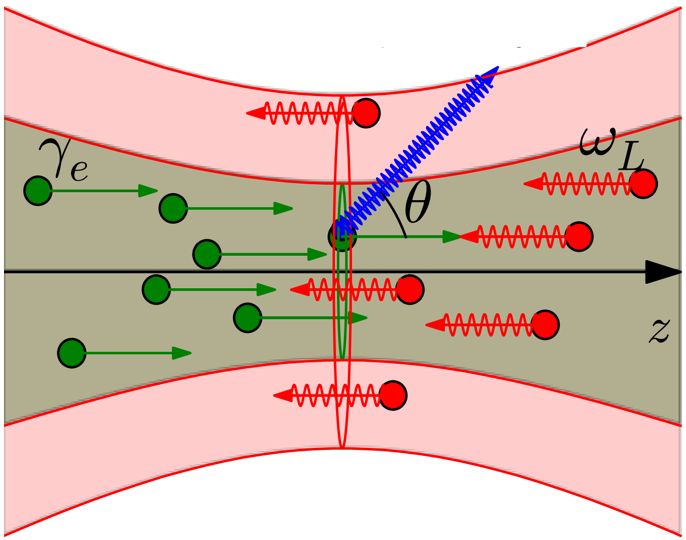


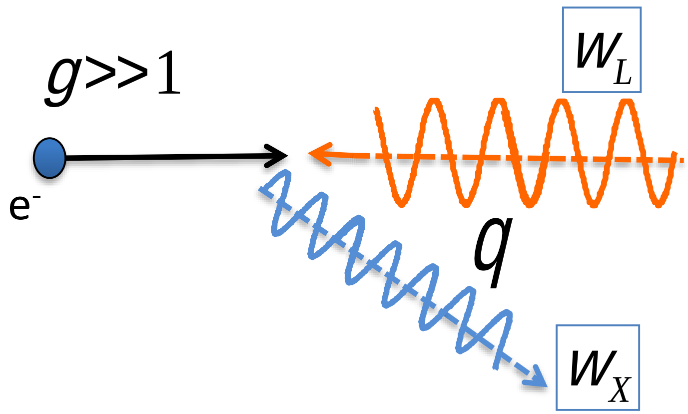
Collision of an intense laser pulse with an ultra-relativistic (γ>>1) electron beam



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

- Doppler upshift of laser frequency $w_X = 4g^2 w_L$
- Tunable source
- Extremely short bursts of hard radiation
- Quasi-monochromatic
- Applications: medicine, nuclear physics, materials
- Nuclear Resonant Fluorescence : nuclear spectroscopy

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



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

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

$$W_X » \frac{4g^2 W_L}{1 + q^2 g^2 + c}$$

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

$$q_{max} \sim \frac{1}{g}$$

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

Example:

$g = 1000$ (~0.5 GeV e-)

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

Max. photon energy:
4 MeV
$c » 0.5\%$

$g = 40$ (~20 MeV e-)

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

Max. photon energy:
10 keV
$c » 0.02\%$

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Brief recap on electron motion in a plane EM wave

Case 2. Strong electromagnetic wave

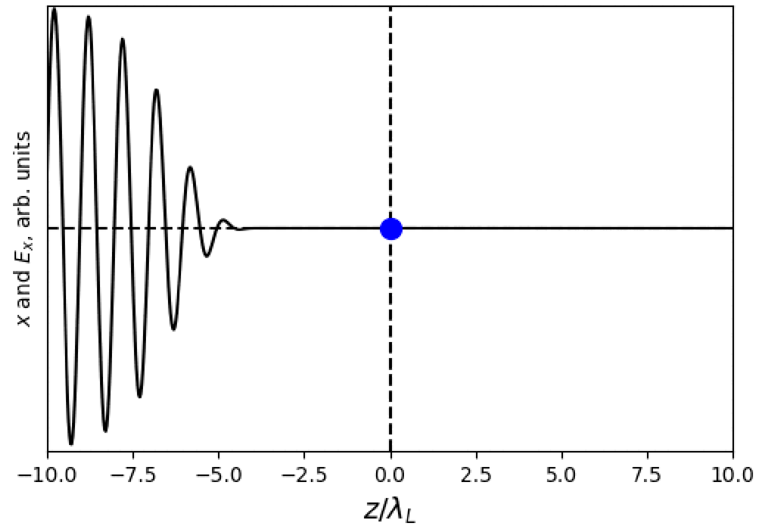
$a_0 = 1$

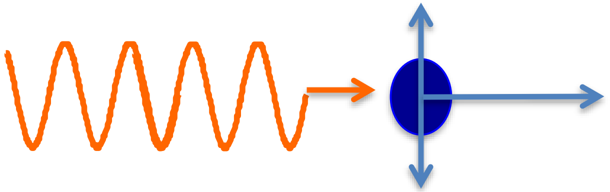
$$\frac{d\vec{p}}{dt} = -e\vec{E} - e\frac{\vec{v}}{c} \times \vec{B}$$

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

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

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





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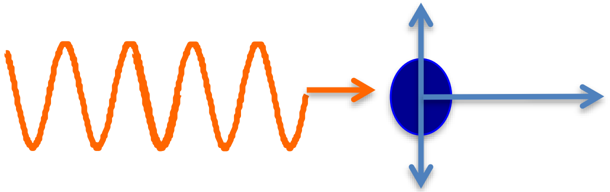

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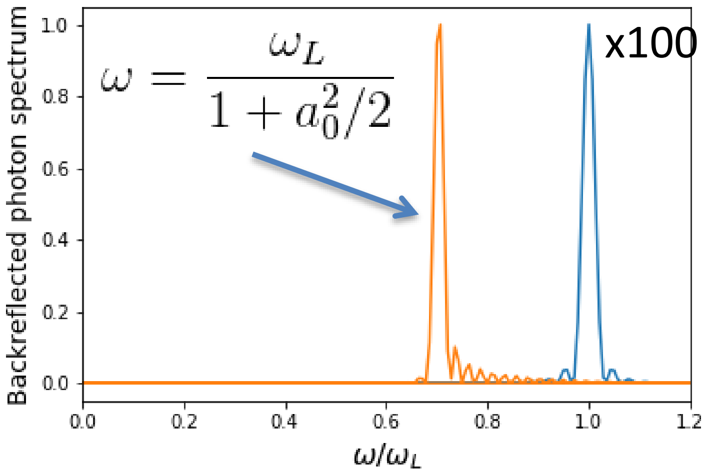
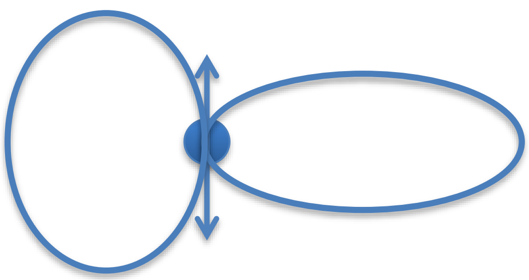
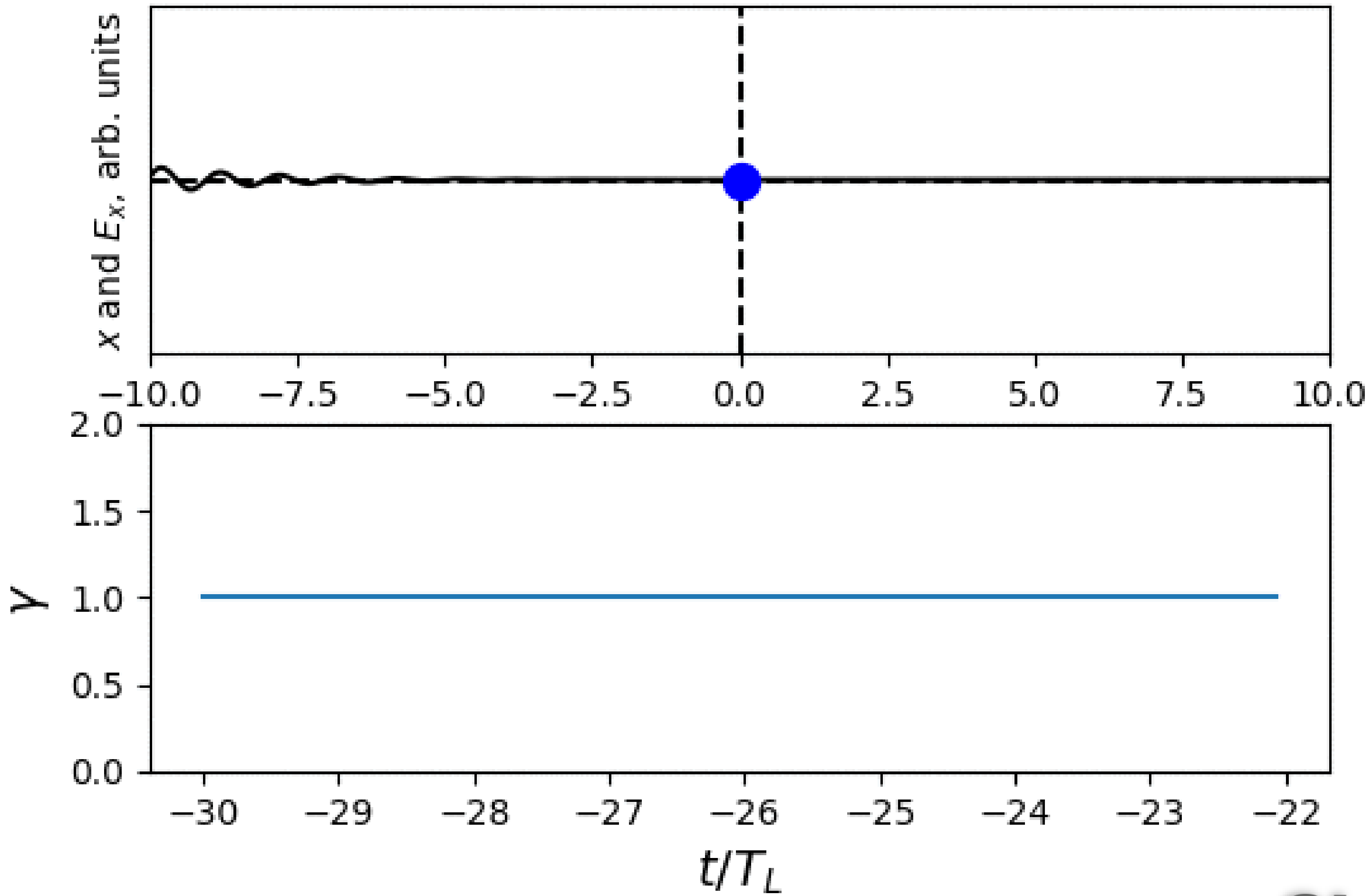




Angular spectrum

Laser pulse longitudinal shape leads to spectrum broadening



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