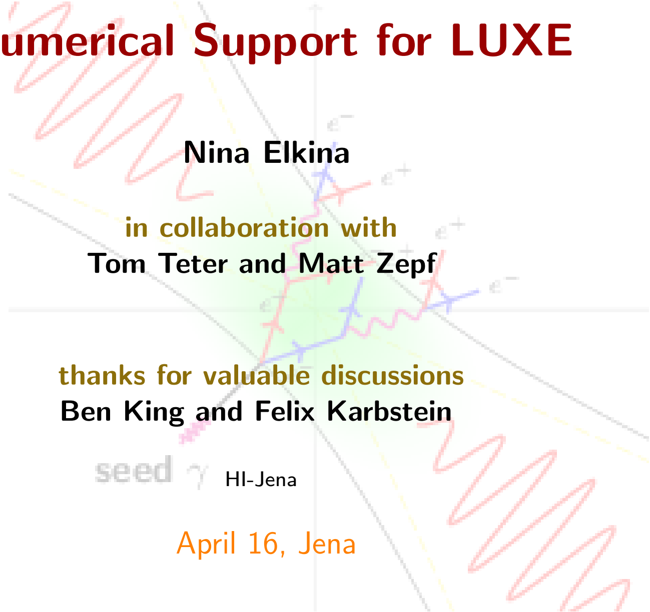
Numerical Support for LUXE

Nina Elkina

in collaboration with
Tom Teter and Matt Zepf

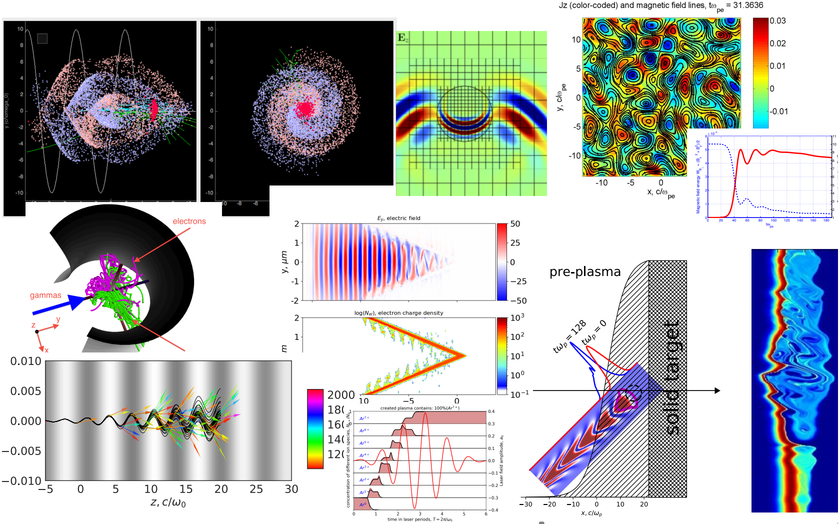
thanks for valuable discussions
Ben King and Felix Karbstein



HI-Jena

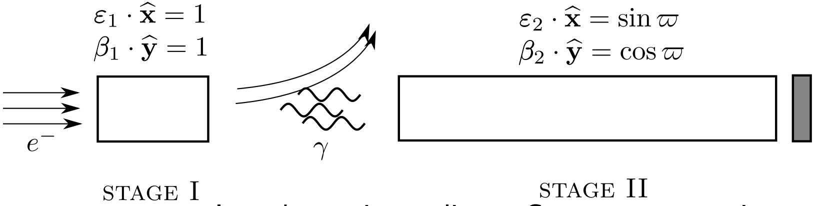
April 16, Jena

Plasma simulations at HI-Jena



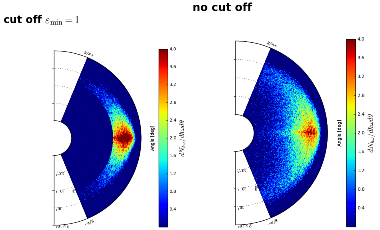
do we want anot

scattering simulation (vacuum birefringence) [1]



stage I: make γ via nonlinear Compton scattering

stage II: measure refractive indexes experienced by γ



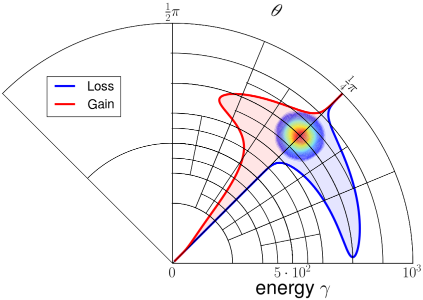
[1]B. King, N. Elkina, Vacuum birefringence in high-energy laser-electron collisions,Phys. Rev. A 94, 062102, 2016

features of PIC-ANTARES code

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\gamma m}\cdot\frac{\partial}{\partial \vec{r}} + \vec{F}\cdot\frac{\partial}{\partial \vec{p}}\right) f(\vec{r},\vec{p},t)$$

$$= \underbrace{\int d^3k\, w_{rad}^{\vec{E},\vec{B}}(\vec{k},\vec{p}+\vec{k})\, f(\vec{r},\vec{p}+\vec{k},t)}_{\textbf{GAIN}} - \overbrace{f(\vec{r},\vec{p},t)\int d^3k\, W_{rad}^{\vec{E},\vec{B}}(\vec{k},\vec{p}}^{\textbf{LOSS}}$$

- Specific features of PIC-ANTARES code
- Descent event generators
- polarization effects
- norm-conserving integrators
- Adaptive mesh and particles

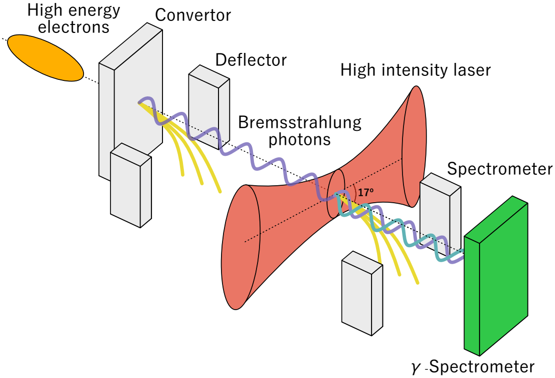


Plan

- overview of LUXE
- update on bremstrahlung spectrum
- lessons from SLAC-144
- Measure Laser Pulse with Compton scattering

LUXE and SLAC

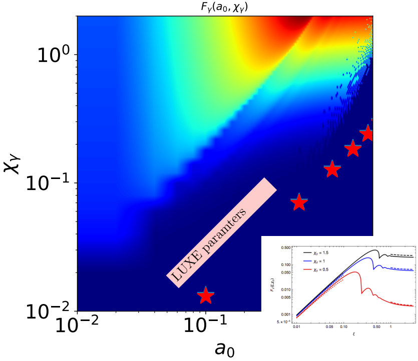
	λ	I, a_0	ε_e	ε_γ	χ_e/χ_γ	a_0
SLAC	527 nm	$10^{18} W/cm^2$	47 GeV	29.2GeV	0.3/0.2	0.3
LUXE	800 nm	$10^{20} W/cm^2$	17.5 GeV	17.5 GeV (?)	0.80109	4-6



matching perturbative/non-perturbative QED

$$\Gamma = \frac{\alpha m_e^2}{4\omega_i} F_\gamma(a_0, \chi_\gamma),$$

$$F_\gamma(\xi_0, \chi_\gamma) = \sum_{n>n_0}^{\infty} \int_1^{v_n} \frac{dv}{v\sqrt{v(v-1)}} \Big[2J_n^2(z_v) - \\ - \xi^2(2v-1)(J_{n+1}^2(z_v) + J_{n-1}^2(z_v) - 2J_n^2(z_v)) \Big]$$



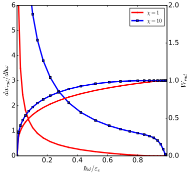
First order processes (with polarization effects)[2]

$$\frac{dW_\gamma}{d\varepsilon_\gamma} = \frac{-\alpha m^2}{\varepsilon_e^2}\left\{ Ai_1(x) + \left[\frac{g(\phi)}{x} + \chi_\gamma\sqrt{x}\right] Ai'(x)\right\}, \quad (1)$$

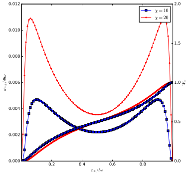
$$\frac{dW_e}{d\varepsilon_e} = \frac{+\alpha m^2}{\varepsilon_\gamma^2}\left\{ Ai_1(x) + \left[\frac{g(\phi)}{x} - \chi_\gamma\sqrt{x}\right] Ai'(x)\right\}, \quad (2)$$

where polarization effects are in $g(\phi) = 2\cos^2\phi + 1$

photon emission

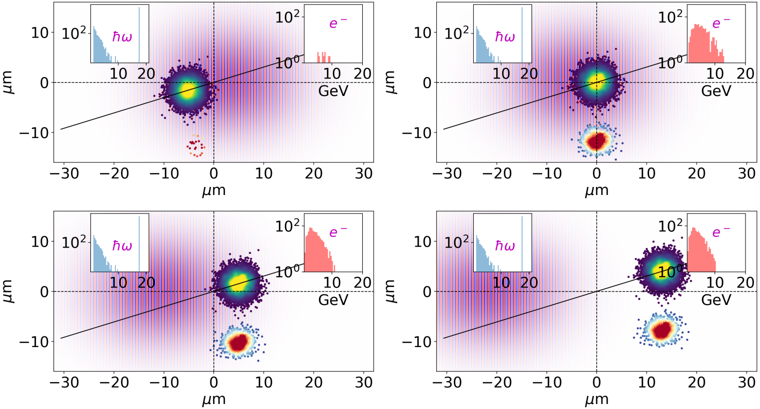


pair production



[2] B. King, N. Elkina, H. Ruhl, Photon polarization in electron-seeded pair-creation cascades, PhysRev. B, 2013 Elkina&Fedotov, 2011

Setup $\theta = 17^o$, $a_0 = 6$, $\hbar\omega = 17.5 GeV$, [3]



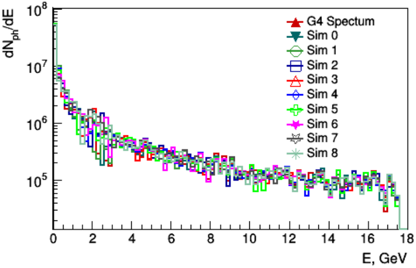
[3]partially simulated on Hemera cluster

Bremstrahlung spectra, e^{-}: 17.5 GeV (GEANT4)

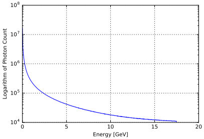
4

Tom&Evgenii's simulation

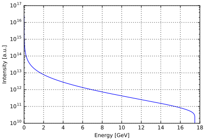
Sasha's Simulation



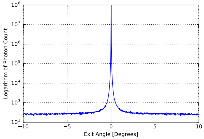
Geant4



Tsai76:

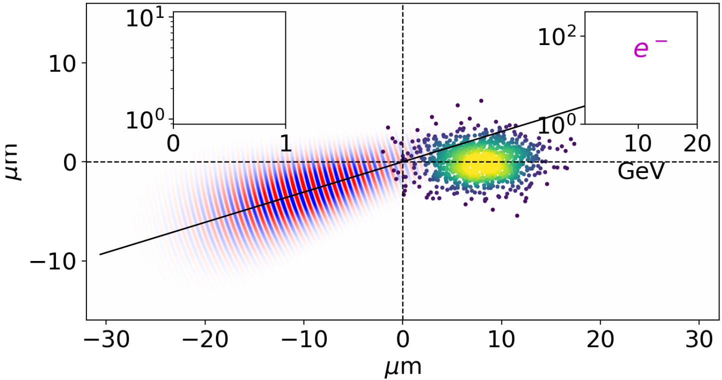


Angular distribution



4 O. Borysov, slides Dec.13, 2018

Pair yield depends strongly on laser pulse structure



Homework: SLAC144

SLAC-R-666

Study of Nonlinear QED Effects in Interacations of Terawatt Laser with High Energy Electron Beam*

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Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94309

DOE/ER/3072-55
October 27, 1989

PROPOSAL FOR AN EXPERIMENTAL STUDY OF NONLINEAR COMPTON SCATTERING

R.C. FERNOW, H.G. KIRK, and J. ROGERS
Brookhaven National Laboratory
I.J. BIGIO, N.A. KURNIT, and T. SHIMADA
Los Alamos National Laboratory
K.T. McDONALD,† D.P. RUSSELL, and M.E. WALL
Princeton University

Журнал экспериментальной и теоретической физики
Т. 47 *1964* *Вып. 3(9)*

КВАНТОВЫЕ ПРОЦЕССЫ В ПОЛЕ ЭЛЕКТРОМАГНИ... ПОЛЯРИЗОВАННОЙ ПО КРУГУ...

Н. Б. Нарожный, А. И. Никишов, В. И. ...

Рассмотрено влияние поля поляризованной по кругу электром... произвольной интенсивности на ход различных квантовых проце... вероятность и интенсивность излучения фотона электроном, вероятн... ния пары фотоном и вероятность распада $\pi \to \mu + \nu$ в поле этой волны... для вероятностей более просты, чем соответствующие выражения для л... ризованной волны, и дают возможность детально исследовать промежу... засть, лежащую между теорией возмущений и областью постоянного по... ние этой промежуточной области позволяет, в частности, качественно судит... ния неоднородного поля на процессы. Подробно рассмотрены зависимости... ностей от частоты волны при фиксированной напряженности поля и распреде... по числу поглощенных из поля фотонов.

A Study of High Field Quantum Elec... Collision of High Energy Electrons wit...

Glenn A. Horton-Smith

Stanford Linear Accelerator C...
Stanford University
Stanford, CA 94309

SLAC-Report-529
July 1998

A Numeric Integration Program to Simulate Nonlinear QED Processes in Electron-Laser or Photon-Laser Collisions

Christian Bula

Joseph Henry Laboratories, Princeton University,
Princeton, New Jersey 08544

June 1997, Version 1.0
(this is file /afs/slac/www/exp/e144/ps/nidoc.ps)

Abstract

This document describes a program to simulate nonlinear QED processes in collisions between a cylindrical electron or photon beam with a focused, high intensity laser pulse. The simulated processes are nonlinear Compton scattering, multiphoton Breit-Wheeler and multiphoton trident pair production in a circularly or linearly polarized laser field. The yield and spectra of final state particles are calculated by numerically integrating the differential reaction rates for these processes over space and time in the beam-laser interaction region. The program allows for an interaction geometry that includes arbitrary crossing angle between the two beams as well as a not diffraction limited spot for the laser beam. Variations of the effective crossing angle between laser and beam particles introduced by the focused laser beam are taken into account in the attenuation of the particle beam as it passes through the laser field in the simulation. In addition to calculating the final states of primary interactions, the program also simulates further (secondary) interactions of reaction products and the laser field. The speed of the simulation was ... in the program development and several methods to reduce the require... presented. The document concludes with a detailed description of ... options, input parameters and instructions for program installation...

Reconstruction of Laser Pulse at SLAC

1. Laser diagnostics [Shmakov's PhD thesis]
   - laser energy: measured by a leakage monitor behind mirror
   - pulse duration: single shot autocorrelation , streak camera
   - focal spot: attenuated refocused pulse equivalent target method after interaction
2. Particle side [Horton's PhD thesis]
   - Cerenkov monitors to measure forward going photons
   -

Nonlinear Compton scattering

$$\frac{dW_n(\omega')}{d\omega'} = \frac{e^2 m^2 n_e}{16\pi\varepsilon^2}\Bigg\{ -4J_n^2(z) + a_0^2\left(2 + \frac{u^2}{1+u}\right)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right]\Bigg\}$$

where $u = \frac{k_\mu k'^\mu}{k_\mu p'^\mu} \simeq \frac{\omega'}{\varepsilon - \omega'}, \quad u_1 = \frac{2k_\mu p^\mu}{m^2} \simeq 2\frac{\varepsilon\omega_0(1-\cos\alpha)}{m^2}$

energy of scattered photon

$$\omega'(\theta) \simeq \varepsilon \cdot \frac{u_1}{(1+u_1) + \gamma^2\theta^2}$$

maximum at $\theta = 0$

$$\omega'_{\max} \simeq \varepsilon \cdot \frac{u_1}{(1+u_1)}, \quad \varepsilon = \gamma m_e c^2$$

1st harmonics+mass shift

first harmonic with mass shift $\overline{m}^2 = m^2(1+a_0^2)$

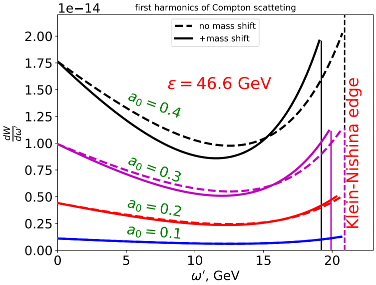
$$\frac{dW_1(\omega')}{d\omega'} = \frac{e^2 m^2 n_e}{16\pi\varepsilon^2} = \Bigg\{ a_0^2 \overbrace{\left[2 + \frac{u^2}{1+u} - 4\frac{u}{u_1}\left(1 - \frac{u}{u_1}\right)\right]}^{\text{Klein-Nishina term}} - a_0^4 \frac{u}{u_1}\left(1 - \frac{u}{u_1}\right)\left[1 + \frac{u^2}{1+u} - \frac{u}{u_1}\left(1 - \frac{u}{u_1}\right)\right.$$

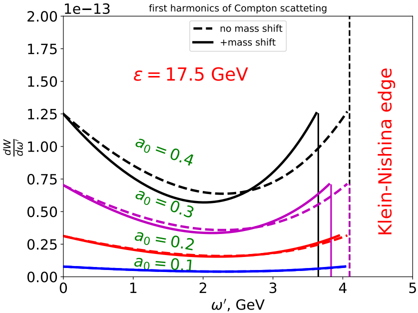
true Klein-Nishina (no mass shift)

$$\frac{dW(\omega')}{d\omega'} = \frac{e^2 m_e^2 n_e}{16\pi\varepsilon^2} a_0^2 \left\{2 + \frac{u^2}{1+u} - \frac{4u}{u_1}\left(1 - \frac{u}{u_1}\right)\right\}$$

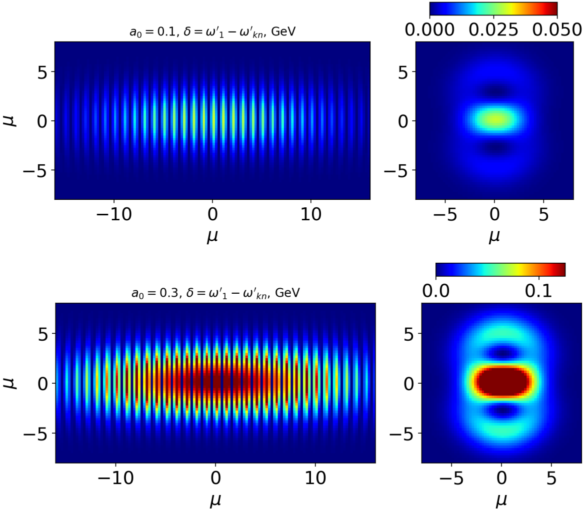
$$\text{where} \quad u \simeq \frac{\omega'}{\varepsilon - \omega'}, \quad u_1 \simeq 2\frac{\varepsilon\omega_0(1-\cos\alpha)}{m^2}$$

Laser diagnostic in a linear regime





Relative difference for Gaussina-like pulse [5]



[5] Narozhny Fofanov, 2000

Summary&Conclusion

- Luxe requires to improve our numerical tools to deal with
  - low statistics because
  - local crossed field approximation
  - predict experimental observables
- Two major sources of uncertainty
  - Initial bremstrahlung spectrum
  - laser focus parameter
- Mapping laser field strength with near-linear regime of Compton scattering