Photon Physics at ELI-Beamlines User Facility

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ELI-Beamlines

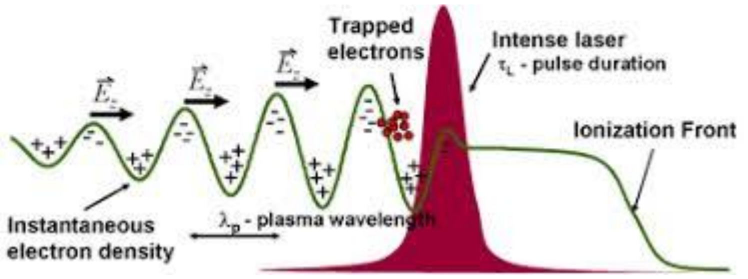
New Vistas in Photon Physics in Heavy-Ion Collisions, EMMI Workshop, Krakow 21st September 2022

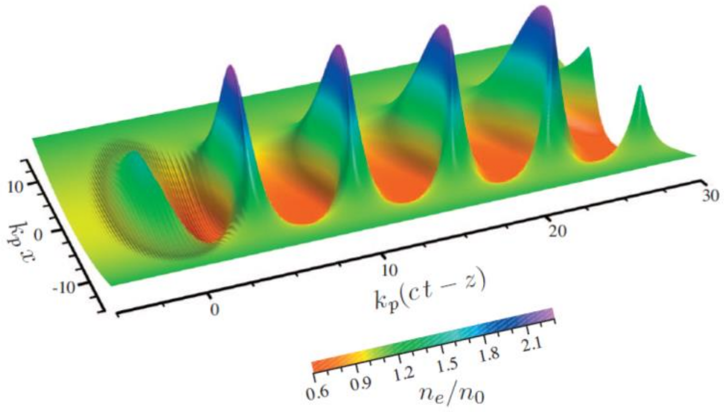
- Laser Wakefield Acceleration
- ELI-Beamlines User Facility
- ELI-ELBA all-optical laser-electron collider at ELI-Beamlines
- ALFA kHZ electron accelerator

LASER WAKEFIELD ACCELERATION

TAJIMA AND DAWSON'S IDEA IN 1979

The use of plasma as an accelerating medium to avoid breakdown and achieve stronger gradients was already discussed in 50s [1].
In 1979, Tajima and Dawson proposed to accelerate electron beams in the wake of a laser pulse propagating inside a plasma [2].
They predicted GV/cm accelerating gradients by focusing a laser pulse down to 10^{18} W/cm^2 in a 10^{18} cm^{-3} plasma.





[1] V. I. Veksler, "Coherent principle of acceleration of charged particles", Proceedings of the CERN Symposium on High Energy Accelerators and Pion Physics, vol. 1. Geneva, 1956. Pages 80–83
[2] T. Tajima and J. M. Dawson, "Laser Electron Accelerator", Phys. Rev. Lett. 43, 267 (1979)

ELECTRON INJECTION IN THE PLASMA WAVE

The electron injection in the plasma accelerating cavity plays a crucial role in the quality of the produced beams. It can be controlled by means of overlapping laser pulses [1], ionization of high-Z gases [2], longitudinal density tailoring [3], or a combination of them [4].

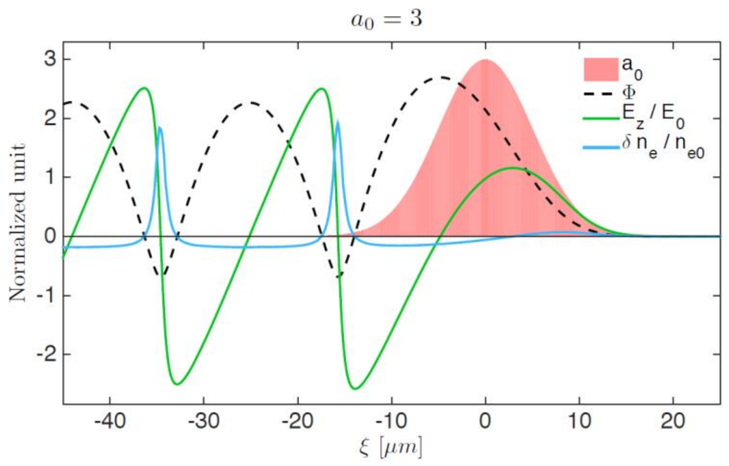


Figure 1.5: Non-linear wakefield quantities for $a_0 = 3$: Normalized laser amplitude a, plasma potential φ, longitudinal electric field E_z/E_0 and density perturbation $\delta n_e/n_{e0}$ on axis in the co-moving coordinate system.

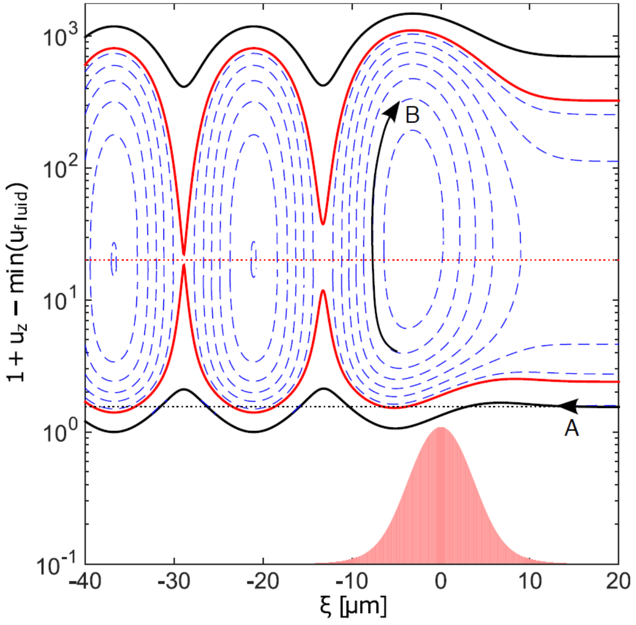


Figure 1.6: Phase space of a plasma wave in the co-moving coordinates driven by a laser pulse with $a_0 = 3$, $\tau_0 = 30$ fs in a plasma with a background electron density $n_e = 5 \times 10^{18}$ cm^{-3}. The laser pulse is plotted without vertical scale just to indicate its location. Trapped orbits (dashed blue lines), separatrix (red line) and fluid orbit (black line) are represented.

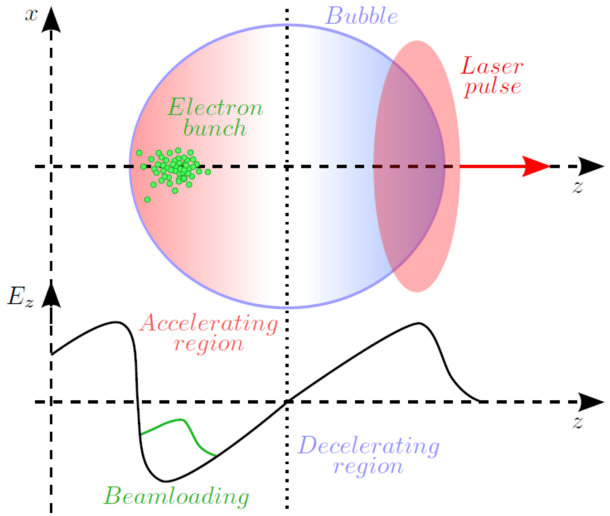


Figure 1.8: Representation of the wakefield in the bubble regime and illustration of the beam-loading effect. The laser pulse propagating in the z-direction drives a bubble with accelerating field (red gradient) for $z < 0$ and decelerating field (blue gradient) for $z > 0$. Injected electrons (green dots) distort the electric field in the bubble (in green).

Figures from the Ph.D. thesis of E. Guillaume "Control of electron injection and acceleration in Laser-Wakefield Accelerators" Ecole Polytechnique (2015)

[1] J. Faure et al., "Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses", Nature 444, 737 (2006)
[2] A. Pak et al., "Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes", Phys. Rev. Lett. 104, 025003 (2010); C. McGuffey et al., "Ionization Induced Trapping in a Laser Wakefield Accelerator", Phys. Rev. Lett. 104, 025004 (2010)
[3] S. V. Bulanov et al., "Particle injection into the wave acceleration phase due to nonlinear wake wave breaking", Phys. Rev. E R5257 (1998); A. J. Gonsalves et al., "Tunable laser plasma accelerator based on longitudinal density tailoring", Nature Physics 7, 862 (2011)
[4] C. Thaury et al., "Shock assisted ionization injection in laser-plasma accelerators", Sci. Rep. 5, 16310 (2015)

LIMITS OF LASER WAKEFIELD ACCELERATION

Laser wakefield acceleration is limited by different physical processes.
After being focused, the laser diffracts, losing intensity and worsening the plasma cavity. The **diffraction length** can be estimated by:

$$L_{diff} = 2\pi \frac{\omega_0}{\omega_p} \lambda_p$$

This effect can be compensated by self-focusing or external guiding in pre-formed plasma channels. The **laser pump depletion** happens when the laser driver loses enough energy to not be able anymore to drive the wakefield. It can be estimated by equating the laser energy to the energy left in the wake wave [1]:

$$L_{depl} = \left(\frac{\omega_0}{\omega_p}\right)^2 \lambda_p \times \begin{cases} \frac{2}{a_0^2} & \text{for} \quad a_0 \leq 1. \\ 1 & \text{for} \quad a_0 \gg 1. \end{cases}$$

Since the electrons travel faster than the plasma wave, after some distance they outrun the accelerating phase of the wave, entering a decelerating phase. This distance is called **dephasing length**:

$$L_{deph} = \left(\frac{\omega_0}{\omega_p}\right)^2 \lambda_p \times \begin{cases} 1 & \text{for} \quad a_0 \leq 1. \\ \frac{4}{3}\sqrt{a_0} & \text{for} \quad a_0 \gg 1. \end{cases}$$

Finally, beam loading occurs when the electric field of the injected electrons is strong enough to cancel the accelerating field [2]:

$$N_{max} = \frac{n_p A_b E_z}{k_p E_{CWB}} \simeq 5 \cdot 10^{14} \frac{E_z}{E_0} A_b(cm^2) \sqrt{n_o[10^{18} cm^{-3}]}$$

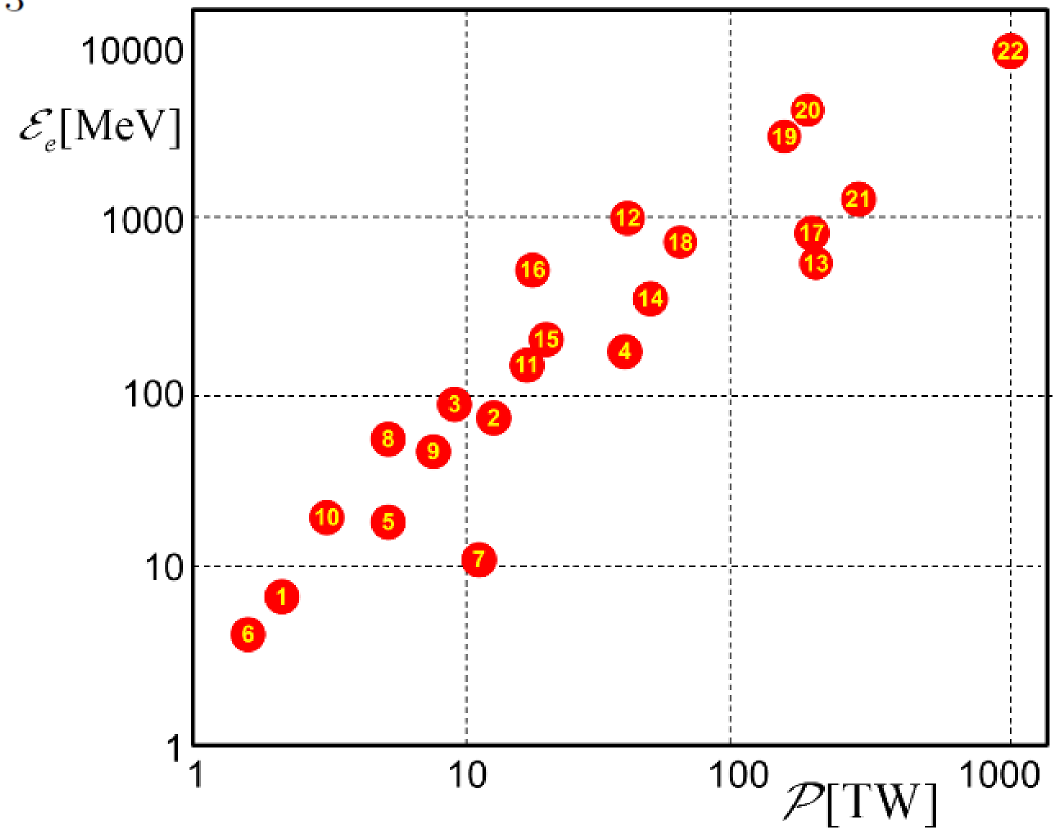
[1] S. V. Bulanov et al., “Nonlinear depletion of ultrashort and relativistically strong laser pulses in an underdense plasma” Phys. Fluids B: Plasma Physics 4(7)1935 (1992); E. Esarey et al., “Nonlinear pump depletion and electron dephasing in laser wakefield accelerators”, Proceedings of the Advanced Accelerator Concept Workshop, 737, 578 (2004)
[2] T. Katsouleas et al., “Beam loading in plasma accelerators”, Part. Accel., 22, 81 (1987)

LASER WAKEFIELD ACCELERATION SCALING LAWS

Under ideal conditions, the energy and the charge of the electron beam can be estimated by the following expressions [1]:

$$\Delta E[GeV] \simeq 1.7 \left(\frac{P_L[TW]}{100}\right)^{1/3} \left(\frac{1}{n_p[10^{18}cm^{-3}]}\right)^{1/3} \left(\frac{0.8}{\lambda_L[\mu m]}\right)^{4/3}$$

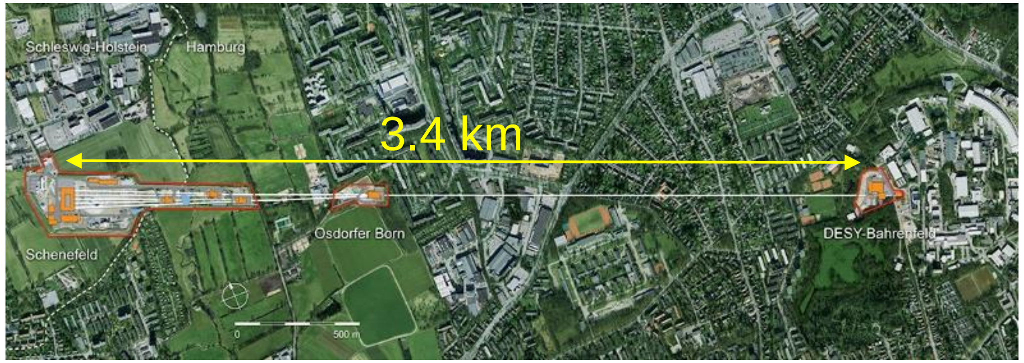
$$C[pC] \simeq 400 \frac{\lambda_L[\mu m]}{0.8} \sqrt{\frac{P_L[TW]}{100}}$$



[1] *W. Lu et al. "Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime", Phys. Rev. ST Accel. Beams, 10, 061301 (2007)*

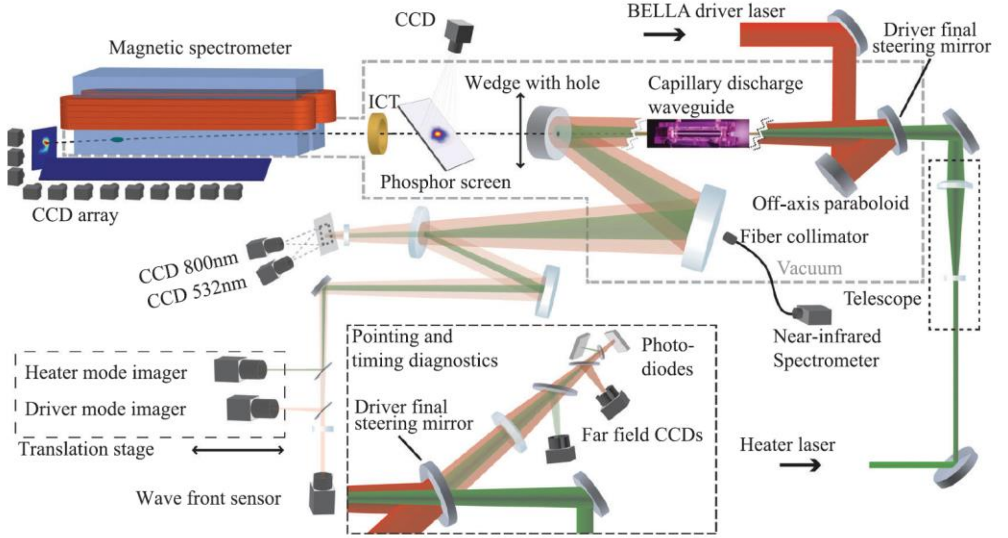
HIGHEST ENERGY LASER WAKEFIELD ACCELERATOR (SO FAR)

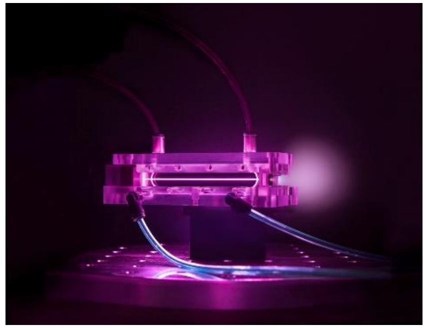
STATE OF THE ART CONVENTIONAL ACCELERATOR



- European XFEL, Schenefeld, Germany
- **17.5 GeV**, 1 nC/pulse, 3×10^4 pulse/s
- **3.4 km long** [1]

STATE OF THE ART LASER WAKEFIELD ACCELERATOR





- Berkeley Laboratory, USA
- **7.8 GeV**, 5 pC / 6 GeV, 62 pC
- **20 cm, facility 10s meters** [2]

[1] https://www.xfel.eu/facility/overview/facts_amp_figures/index_eng.html
[2] A. J. Gonsalves et al., "Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide", Phys. Rev. Lett. 122, 084801 (2019)

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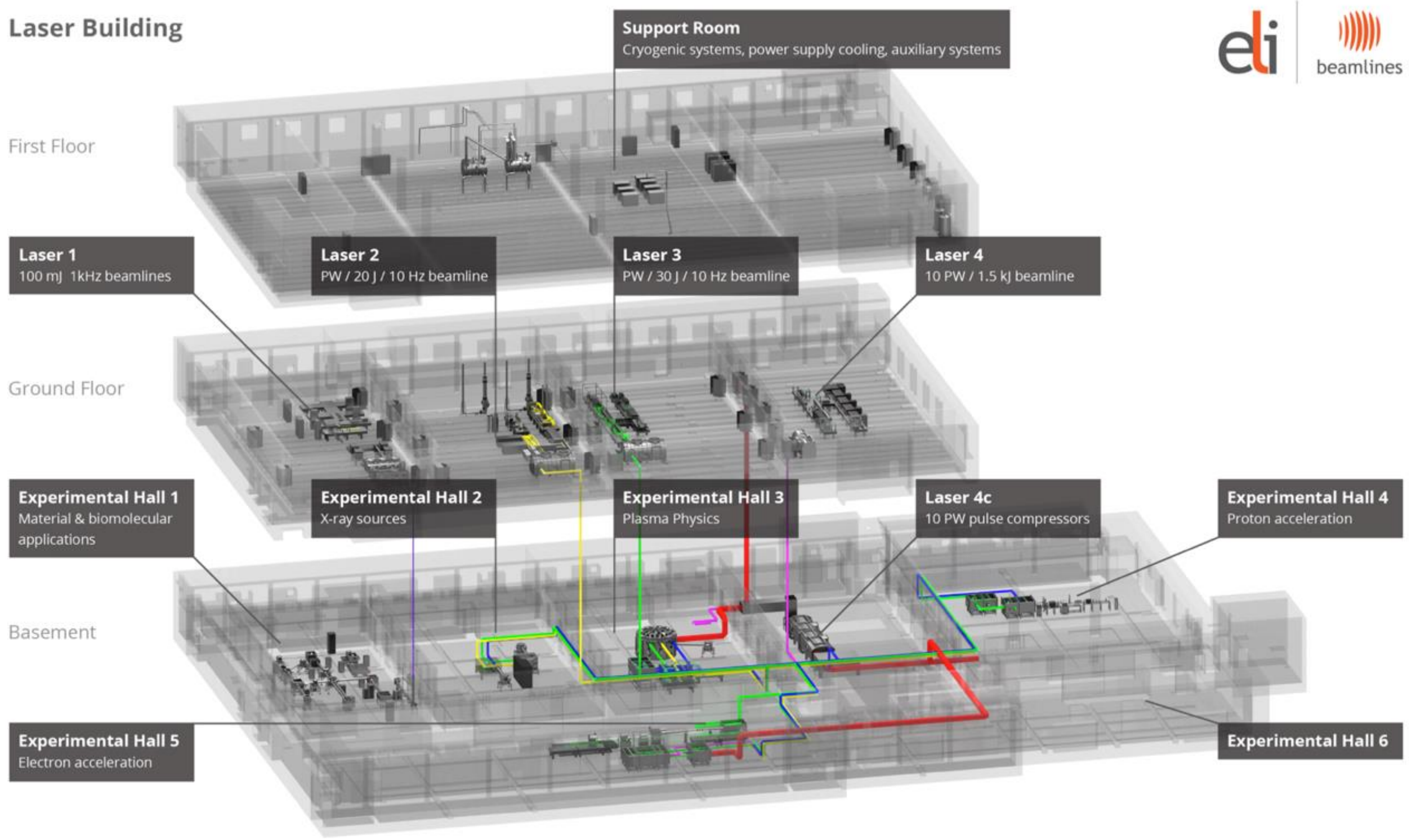
ELI-BEAMLINES USER FACILITY

ELI-BEAMLINES FACILITY IN DOLNI BREZANY (CZECH REPUBLIC)



Laser Driven Secondary Sources: Photons (infrared, XUV, X-ray, Gamma), Electrons, Protons & Ions

ELI-BEAMLINES LASERS

Synchronization within <100 fs by master facility clock

L1 – ALLEGRA

Technology
- OPCPA
- Circular
- Gaussian
- Synchronized probe beam

Parameters

Nominal	Current
100 mJ	55 mJ
1 kHz	1 kHz
15 fs	15 fs

Expected Electron Energy
10-100 MeV

L2 – DUHA

Technology
- OPCPA
- Circular
- Flat-top
- Synchronized mid-IR pulse

Parameters

Nominal	Current
J	WORK
10s Hz	IN
<40 fs	PROGRESS

Expected Electron Energy
0.1-1 GeV

L3 – HAPLS

Technology
- Ti:Sapphire, DPSSL
- Square, 250x250 mm^2
- Flat-top

Parameters

Nominal	Current
30 J	13 J
10 Hz	3.3 Hz
30 fs	30 fs

Expected Electron Energy
1-10 GeV

L4 – ATON

Technology
- Nd:glass
- Square, 550x550 mm^2
- Flat-top
- Longer beams (ns and ps)

Parameters

Nominal	Current
1.5 kJ	WORK
1/min	IN
150 fs	PROGRESS

Expected Electron Energy
10-100 GeV

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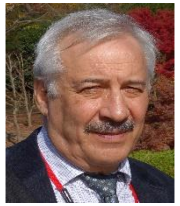
IN-HOUSE LWFA TEAM



S. Bulanov

Department of Radiation Physics and Electron Acceleration

X-Ray sources

J. Nejdl

LUIS Beamline

A. Molodozhentsev

HiFi

S. Bulanov

Electron Acceleration

Laser Systems

B. Rus

Technology Infrastructure

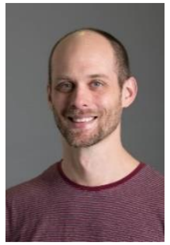
P. Bakule

Monte Carlo group

R. Versaci

G. Grittani
- Coordination
- User Experiments

C. Lazzarini
- ALFA End-Station
- High power laser propagation & optical diagnostics

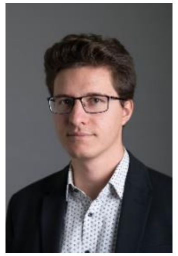


M. Nevrkla
- High power laser guiding
- Laser-plasma diagnostics
- Gas Targets design & development

L. Vilanova
- Electron-EM interaction
- Counter-propagation set-up
- Diagnostics for non-linear QED experiments

F. Vitha (Ph.D. Student)
- DAQ
- LWFA automation

Ilya Zymak
- Electron beam diagnostics
- Radiation damage testing



S. Lorenz (Ph.D. student)
- CFD simulations
- Gas targets design & development
- Gas target tomography

J. Sisma (Ph.D. student)
- High power laser guiding
- Optical design

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CURRENT COLLABORATORS & PROSPECTIVE USERS

ELI-ELBA REVIEW 2020

- **H. Milchberg**
- **G. Sarri**
- **M. Kando**
- **A. Maier**
- **S. Karsch**
- **S. Steinke**

LASER-DRIVEN VHEE RADIOTHERAPY

- **Industrial Technology Research Institute (Taiwan)**
- **J. Cvek, L. Knybel (Fakultni Nemocnice Ostrava)**
- **M. Favetta (Policlinico di Bari)**

RADIATION TESTING

RADNEXT

CERN

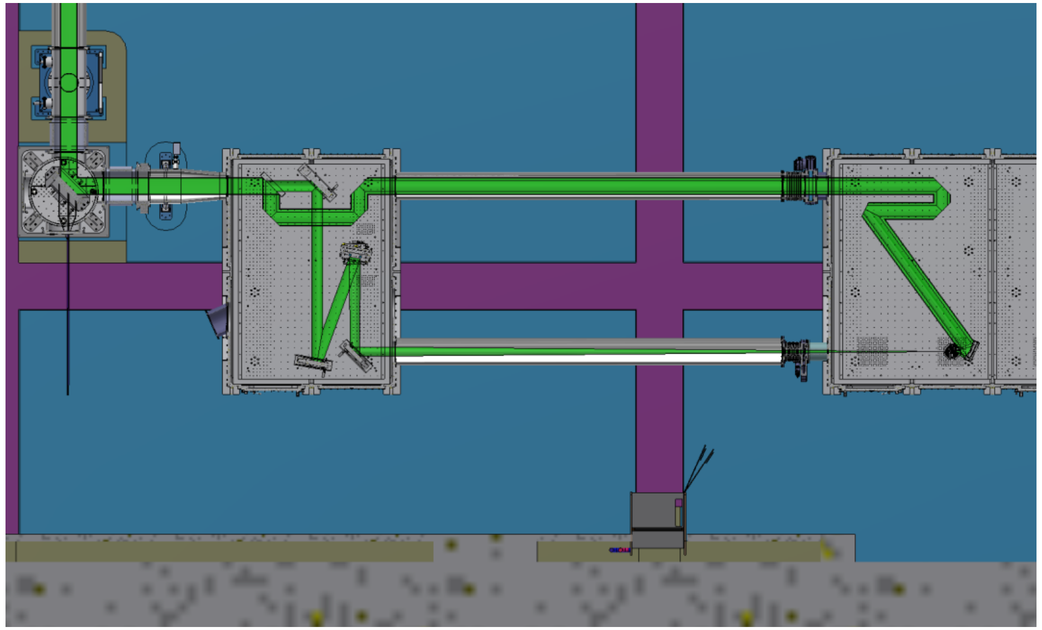
ELI-ELBA USER CONFERENCES 2020-2021

2 panels (Colliding LWFA beams with PW lasers, kHz Electron Acceleration in Near Critical Density Plasmas)
5-10 invited contributions per panel, >300 Registered users, avg. 50 users/presentation

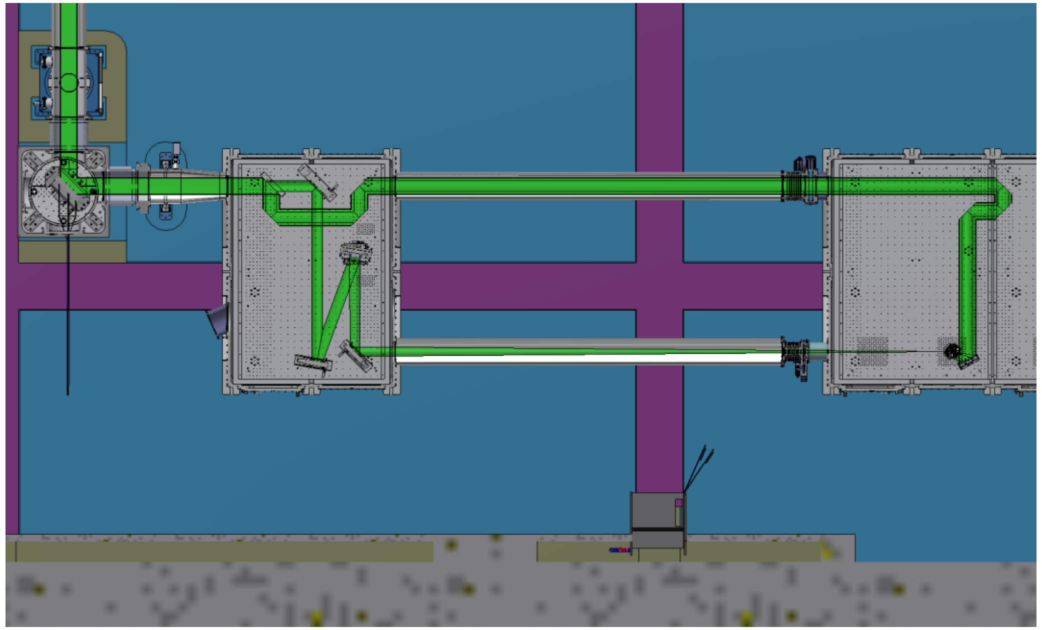
ELI-ELBA ALL-OPTICAL COLLIDER AT ELI-BL

ELI-ELBA all-optical GeV electron PW laser collider

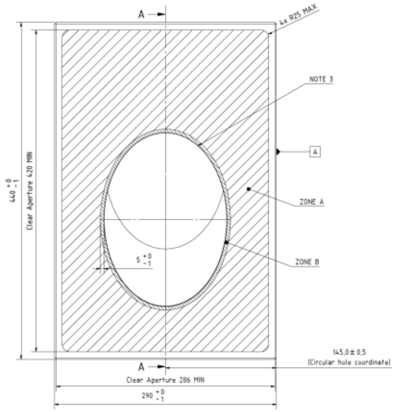
Head-on Configuration

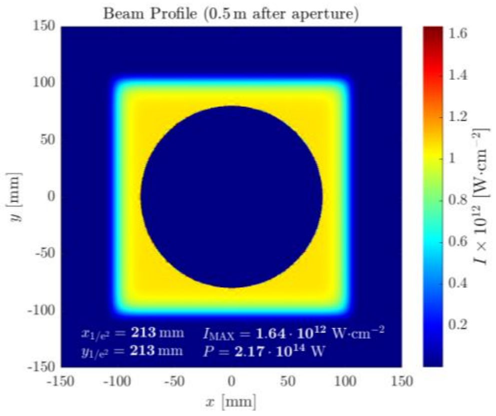


Off-axis Configuration



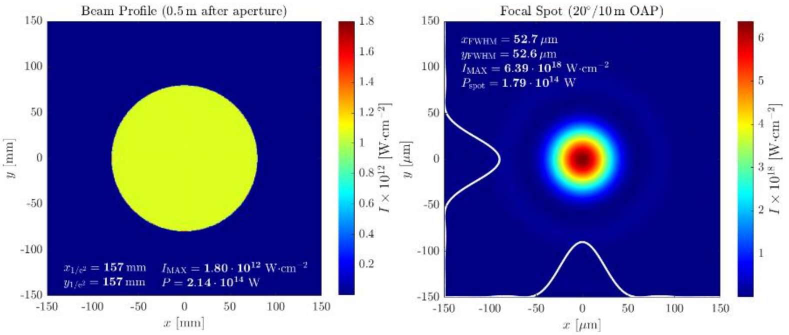
Key Technology is 50:50 Wavefront Splitting to enable high temporal synchronization of the LWFA beam and the CP laser





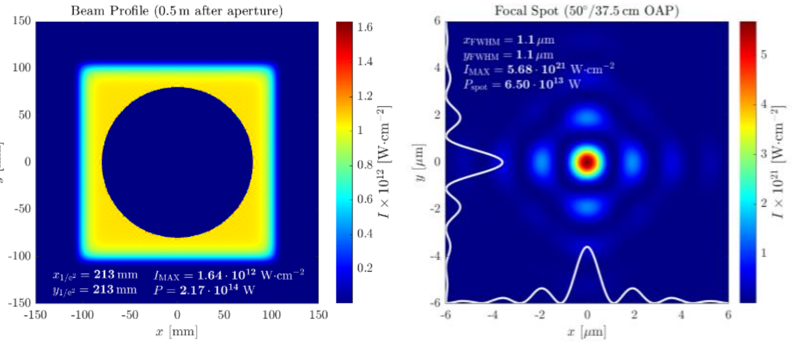
ELI-ELBA design parameters

Design of electron accelerator



Electron energy ≈ 200 MeV/J

Design of counter-propagating laser



	Parameter	Current L3 Performance	Nominal L3 performance
LASER	Laser energy before WS splitting	13 J	30 J
	Laser time duration	27 fs	30 fs
	Repetition Rate	3.3 Hz	10 Hz
	Laser Wavelength	800 nm	800 nm
ELECTRON	Laser Energy for LWFA	> 5 J	> 10 J
	Electron beam energy (mean of QME peak)	> 1 GeV	> 2 GeV
	Energy spread (FWHM)	< 20%	< 20%
	Electron beam charge in QME peak	> 25 pC	> 40 pC
	Electron beam divergence	< 2 mrad	< 2 mrad
	Electron beam pointing stability	< 2 mrad	< 2 mrad
CP LASER	Laser Energy for Collider Laser	> 5 J	> 10 J
	Focal number	1.5	1.5
	Focal length	375 mm	375 mm
	Focal spot FWHM	< 2 µm	< 2 µm
	Peak intensity	> 1.5 x 10^{21} W/cm^2	>3 x 10^{21} W/cm^2
	Collision angle	0° and 40°	0° and 40°

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ELI-ELBA Current Status and Plan

- Electron acceleration line installed
- Counter Propagation line procured, waiting for delivery, installation completed by March 2023
- Set-up accommodates different wavefront splitters configuration, so the split ratio could be changed depending on user requirements
- Involvement of user for experimental diagnostics, data analysis and modeling is key to success

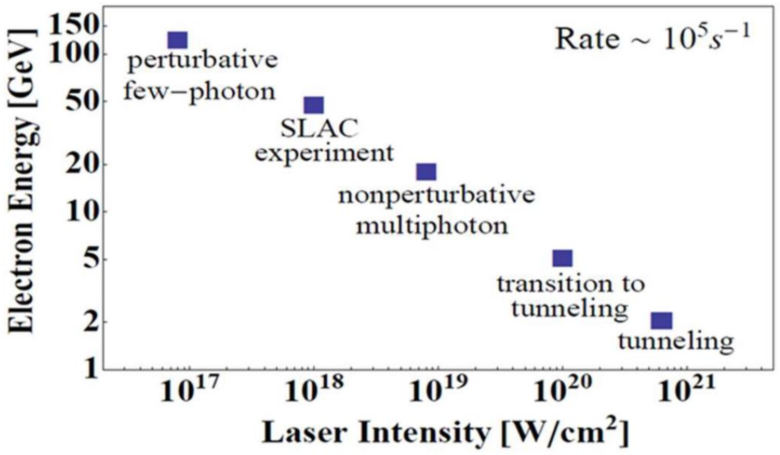
First Light (Spring 2022)

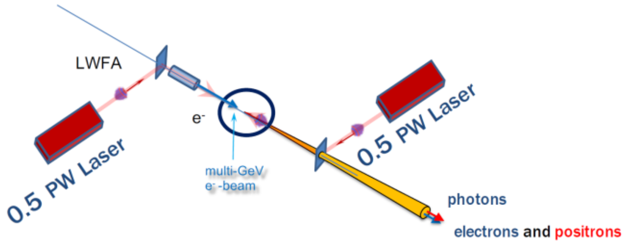
LWFA Accelerator (Autumn 2022)

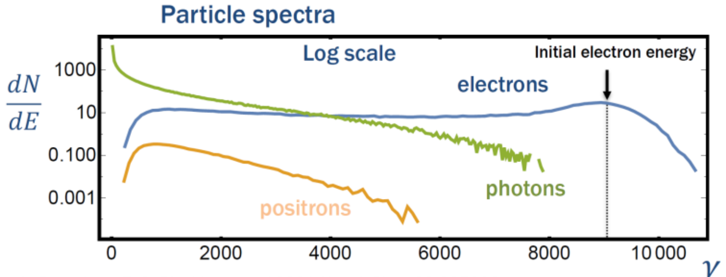
Laser Electron Collider (2023)

Proposed potential user experiments at ELI-ELBA (from User Conference 2021)

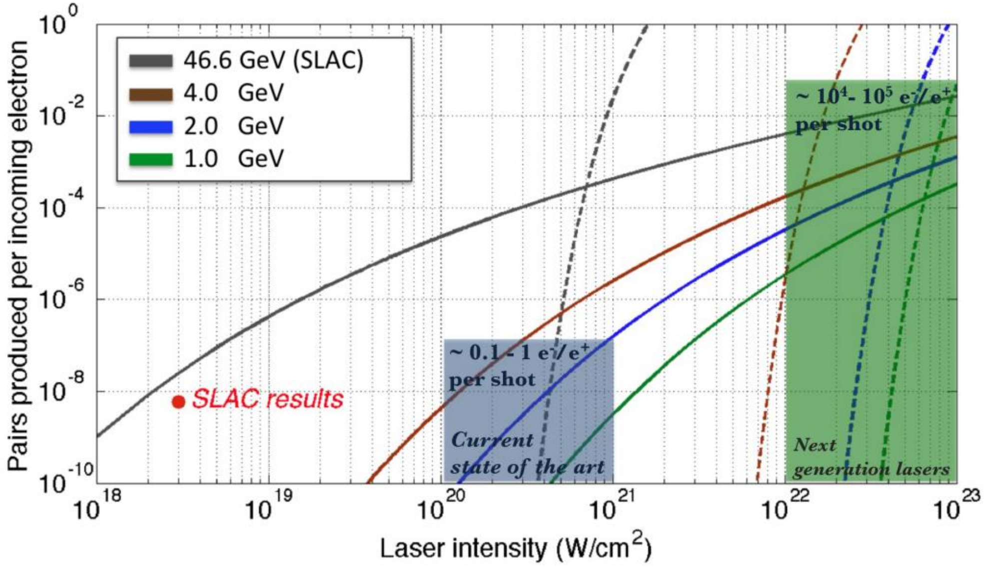
- Testing semi classical spin models and relativistic Kapitza Dirac
- Testing quantum radiative reaction including stochastic effects
- Testing all optical pair production in the tunneling regime
- Testing local constant field approximation including new class violation
- Generating polarized lepton beams and a meter for laser pulses

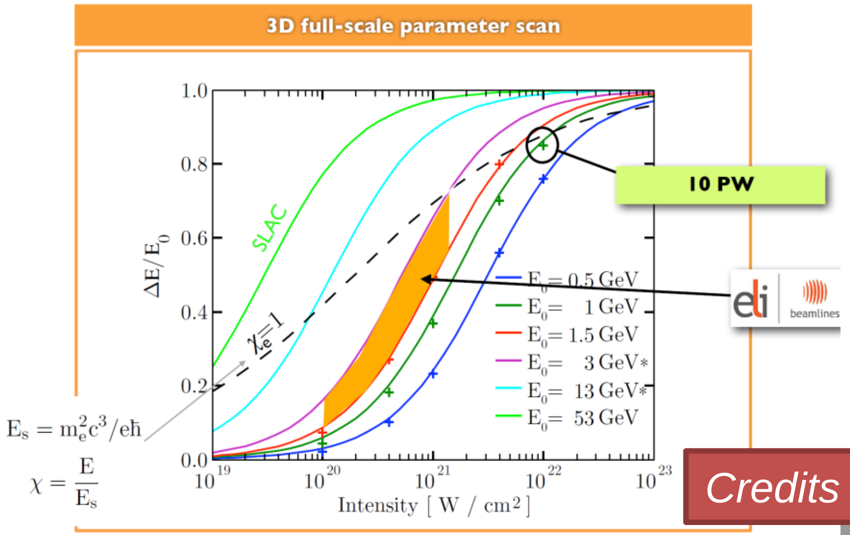






code Ptarmigan: T. G. Blackburn *et al* 2021 *New J. Phys.* 23 085008





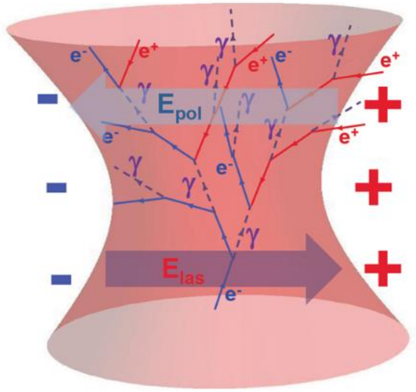
Credits to C. H. Keitel, L. Silva, G. Sarri, S. S. Bulanov

Extreme Field Limits:

QED Vacuum as Nonlinear, Dispersive and Dissipative Medium

Towards studying of nonlinear QED effects with high power lasers.
Radiation dominated & QED regimes in the high intensity
electromagnetic wave interaction with charged particles & vacuum.

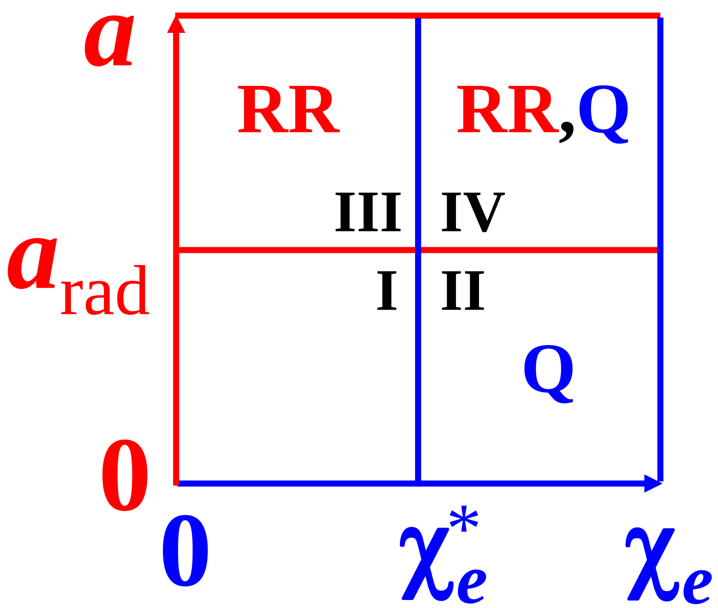
$$E_S = \frac{m_e^2 c^3}{e\hbar} \qquad I_S = c\frac{E_S^2}{4\pi} \approx 10^{29}\,\frac{W}{cm^2}$$



Schwinger (Sauter, Bohr,…) field

Courtesy of S.V. Bulanov

4 regimes



Dimensionless amplitude

$$a = eE/m_e\omega c$$

At $a=a_{rad}$ emitted energy becomes equal to the energy received from EM wave.

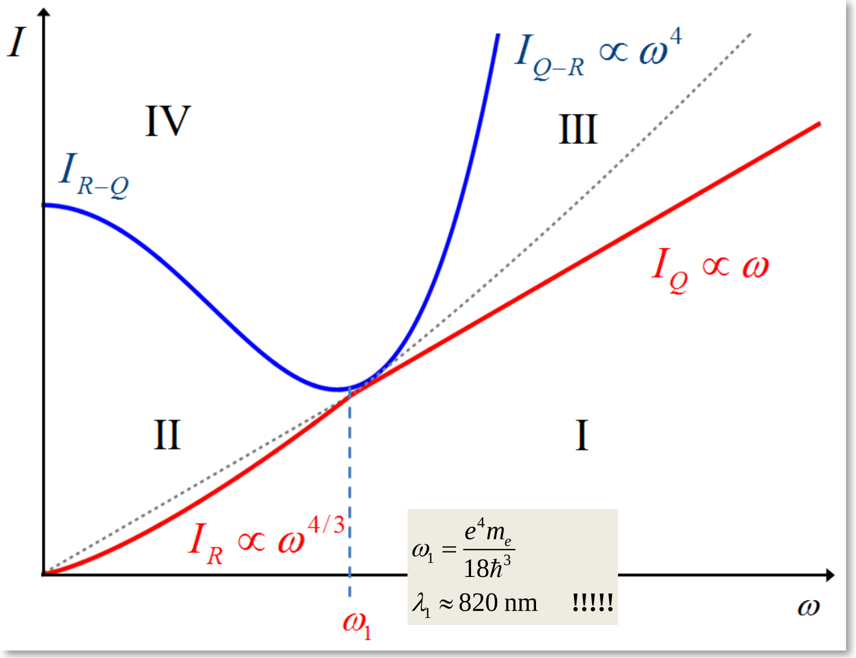
$$a_{rad} = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3} \qquad r_e = \frac{e^2}{m_e c^2}$$

When the recoil of the emitted photon is significant, the emission probability is characterized by χ_e parameter (Lorentz and gauge invariant)

$$\chi_e = (\gamma_e/E_S)[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2]^{1/2}$$

At $\chi_e > \chi_e^* \approx 1$ the QED effects come into play

Courtesy of S.V. Bulanov



$$I_R = \frac{m_e^4 c^5 e^2}{144\pi\hbar^4}\left(\frac{\omega}{\omega_1}\right)^{4/3} = 3.8\times10^{23}\left(\frac{\omega}{\omega_1}\right)^{4/3}\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_Q = \frac{m_e^4 c^5 e^2}{144\pi\hbar^4}\left(\frac{\omega}{\omega_1}\right) = 3.8\times10^{23}\left(\frac{\omega}{\omega_1}\right)\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_{R-Q} = \frac{m_e^4 c^5 e^2}{9\pi\hbar^4} = 5.6\times10^{24}\frac{\mathrm{W}}{\mathrm{cm}^2}$$

$$I_{Q-R} = 87\frac{c^5\hbar^8\omega^4}{e^{14}} = 8.2\times10^{21}\left(\frac{\omega}{\omega_1}\right)^4\frac{\mathrm{W}}{\mathrm{cm}^2}$$

Curves $I_R(w)$, $I_Q(w)$ and $I_{R-Q}(w)$, $I_{Q-R}(w)$ subdivide (I, w) plane to 4 domains:

I) Relativistic electron - EM field interaction with neither radiation friction nor QED effects

II) Electron - EM wave interaction is dominated by radiation friction

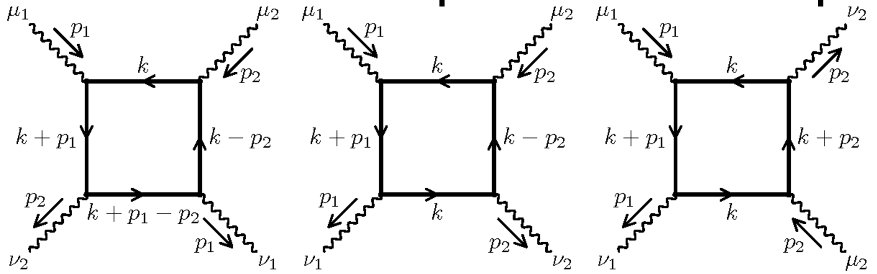
III) QED effects important with insignificant radiation friction effects

IV) Both QED and radiation friction determine radiating charged particle dynamics in the EM field

SVB, T. Zh. Esirkepov, M. Kando, J. Koga, K. Kondo, and G. Korn, *Plasma Phys. Rep.* 41, 1-51 (2015)

Courtesy of S.V. Bulanov

In the QED, photon-photon scattering occurs via creation-annihilation of virtual electron-positron pairs by two initial photons followed by annihilation of the pairs into final photons



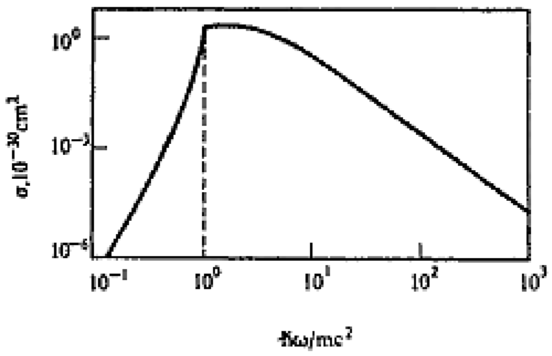
R. Karplus and M. Neuman, Phys. Rev. 83, 776 (1951)

ATLAS Collaboration, Nature Physics 13, 852 (2017)

Dependence of the photon-photon scattering cross section on the photon frequency (assume that)

$$\omega_1 = \omega_2 = \omega_\gamma$$

$$\sigma_{\gamma\gamma} = \begin{cases} \left(\dfrac{973}{10125\pi}\right)\alpha^2 r_e^2 \left(\dfrac{\hbar\omega_\gamma}{m_e c^2}\right)^6 & \text{for } \hbar\omega_\gamma << m_e c^2 \\ \left(\dfrac{3}{12\pi}\right)^2 \alpha^2 r_e^2 \left(\dfrac{m_e c^2}{\hbar\omega_\gamma}\right)^2 & \text{for } \hbar\omega_\gamma >> m_e c^2 \end{cases}$$



Courtesy of S.V. Bulanov

Electron-positron pair creation via the Breit-Wheeler process has the cross section

$$\sigma_{\gamma\gamma\to ep} = \frac{1}{2}\pi r_e^2 (1-\beta_e^2)\left\{(3-\beta_e^4)\ln\left(\frac{1+\beta_e}{1-\beta_e}\right) - 2\beta_e(2-\beta_e^2)\right\}$$

where

$$\beta_e = \sqrt{1 - 2m_e^2c^4/\hbar^2\omega_1\omega_2(1-\cos\varphi)}$$

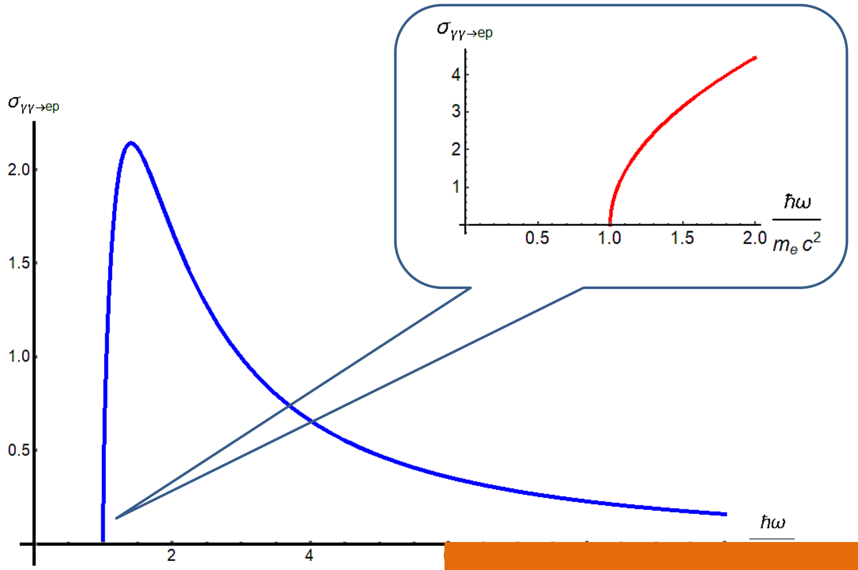
is Lorentz invariant

Near the threshold when $\beta_e \leq 1$

$$\omega_1\omega_2(1-\cos\varphi) \geq 2m_e^2c^4/\hbar^2$$

the cross section is given by

$$\sigma_{\gamma\gamma\to ep} = \pi r_e^2\sqrt{\frac{1}{\beta_e} - 1}$$



Courtesy of S.V. Bulanov

G. Breit and J. A. Wheeler, Physical Review 46, 1087 (1934)
X Ribeyre, E d'Humi`eres, S Jequier and V T Tikhonchuk, PPCF 60, 104001 (2018)

Synergic Cherenkov-Compton Radiation

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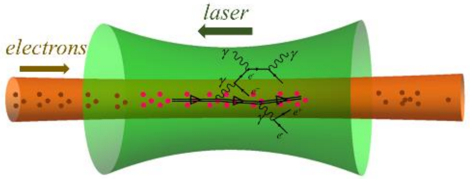
A. J. Macleod, A. Noble, and D. A. Jaroszynski, Cherenkov Radiation from the Quantum Vacuum, Phys. Rev. Lett. 122, 161601 (2019);
S. V. Bulanov, P. V. Sasorov, S. S. Bulanov, G. Korn, Synergic Cherenkov-Compton radiation, Phys. Rev. D 100, 016012 (2019)
I I Artemenko, E N Nerush, and I Yu Kostyukov, Quasiclassical approach to synergic synchrotron–Cherenkov radiation in polarized vacuum, New J. Phys. 22 093072 (2020)

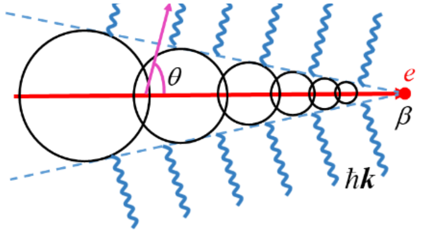


$$\gamma_0 > \gamma_{Ch} = \frac{1}{\sqrt{2\Delta n_\pm}} = \sqrt{\frac{45\pi E_S^2}{\alpha(11\pm 3)E_0^2}} \approx 30\sqrt{\frac{I_S}{I_0}}$$

The laser intensity $I_0 = cE_0^2/4\pi$ in the focus region of 10 PW laser is equal to 10^{24} W/cm^2;

$I_S = cE_S^2/4\pi \approx 10^{29} W/cm^2$, i. e. the Cherenkov radiation threshold is exceeded for the electron energy above 10 GeV.

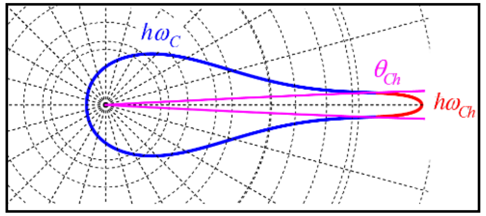
The Cherenkov cone with the angle $\theta_{Ch} = 2\sqrt{\varepsilon_\pm I_0 / I_S}$ in the focus of 10 PW laser is $\approx 2\times10^{-5}$.



The photon invariant mass

$$\mathbf{p}_0 + \hbar\mathbf{k}_0 = \mathbf{p} + \hbar\mathbf{k},$$
$$m_e c^2\gamma_0 + \hbar\omega_{\gamma,0} = m_e c^2\gamma + \hbar\omega_\gamma,$$
$$\mathbf{k} = \frac{\mathbf{k}}{|\mathbf{k}|c} n_\pm \omega$$

$$\mu_{\parallel,\perp}^2 = -\alpha m_e^2 \begin{cases} \left[\frac{11\pm 3}{90\pi}\chi_\gamma^2 + i\sqrt{\frac{3}{2}}\frac{3\pm 1}{16}\chi_\gamma \exp\left(-\frac{8}{3\chi_\gamma}\right)\right] & \text{for } \chi_\gamma \ll 1 \\ \left[\frac{5\pm 1}{28\pi^2}\sqrt{3}\Gamma^4\left(\frac{2}{3}\right)(1-i\sqrt{3})(3\chi_\gamma)^{2/3}\right] & \text{for } \chi_\gamma \gg 1 \end{cases}$$



At the high photon energy end, when $\chi_\gamma = \frac{E_0}{E_S}\frac{\hbar(\omega + k_x c)}{m_e c^2} > 1$, the vacuum polarization effects and the Cherenkov radiation weaken.

As a result, the photons with the energy above $\hbar\omega_\gamma = m_e c^2 E_S /$ … in the radiation. For 10 PW laser parameters this energy is 10…

Courtesy of S.V. Bulanov

Kinematics of SCCS

Following to **V. L. Ginzburg (1940)** we describe the kinematics of electron-photon interaction in QED vacuum as

$$\mathbf{p}_0 + \hbar\mathbf{k}_0 = \mathbf{p} + \hbar\mathbf{k}, \quad m_e c^2\gamma_0 + \hbar\omega_{\gamma,0} = m_e c^2\gamma + \hbar\omega_\gamma$$

with $\gamma_0 = \sqrt{1 + p_0^2 / m_e^2 c^2}$, $\gamma = \sqrt{1 + p^2 / m_e^2 c^2}$, $\mathbf{p} = p_{\parallel}\mathbf{e}_x + p_{\perp}\mathbf{e}_y$, and $\mathbf{k} = |\mathbf{k}|(\cos\theta\,\mathbf{e}_x + \sin\theta\,\mathbf{e}_y)$

In medium with $n \neq 1$ the wave frequency ω and wave vector $\mathbf{k}$ are related to each other as $\mathbf{k} = \frac{\mathbf{k}}{|\mathbf{k}|c} n_\pm \omega$.

The photon energy is

$$\hbar\omega_\gamma = g \pm \sqrt{g^2 + 2s\hbar\omega_0\left(\frac{m_e c^2\gamma_0 + p_{\parallel,0}c}{n_\pm^2 - 1}\right)}$$

where s is the number of photons and

$$g = \frac{(p_{\parallel,0}c - s\hbar\omega_0)n_\pm\cos\theta - m_e c^2\gamma_0 - s\hbar\omega_0}{n_\pm^2 - 1}$$

When the function g is positive and $s\hbar\omega_0 \ll m_e c^2/\gamma_0$ the photon energy can be found to be

$$\hbar\omega_{Ch} \approx 2g + s\hbar\omega_0\left(\frac{m_e c^2\gamma_0 + p_{\parallel,0}c}{2(n_\pm^2 - 1)}\right)$$

This corresponds to the Cherenkov radiation.

In the opposite limit, when $g < 0$, in the limit $s\hbar\omega_0 \gg m_e c^2/\gamma_0$ the Compton scattering mode frequency is given by

$$\hbar\omega_C \approx \frac{s\hbar\omega_0(m_e c^2\gamma_0 + p_{\parallel,0}c)}{(p_{\parallel,0}c - s\hbar\omega_0)n_\pm\cos\theta - m_e c^2\gamma_0 - s\hbar\omega_0}$$

In the limit In the limit $s < s_m$, where $s_m, = m_e c^2 / 4\hbar\omega_0\gamma_0$ the photon energy equals $\hbar\omega_C = 4s\hbar\omega_0\gamma_0^2$; at $s > s_m$, we have $\hbar\omega_C = m_e c^2\gamma_0^2$.

Courtesy of S.V. Bulanov

Cherenkov Radiation

Condition of Cherenkov radiation,

$$s\hbar\omega_0 \;\square\; \frac{\sqrt{m_e^2c^4 + p_{\square,0}^2c^2} - p_{\square,0}cn_{\pm}\cos\theta}{1+n_{\pm}\cos\theta}$$

The electron energy should be large enough to have

$$\gamma_0 > \gamma_{Ch} = \frac{1}{\sqrt{2\Delta n_{\pm}}} = \sqrt{\frac{45\pi E_S^2}{\alpha(11\pm 3)E_0^2}} \approx 30\sqrt{\frac{I_S}{I_0}}$$

Here the laser intensity $I_0 = cE_0^2/4\pi$ in the focus region of 10 PW laser is approximately equal to 10^{24} W/cm^2;
$I_S = cE_S^2/4\pi \approx 10^{29}$ W/cm^2, i. e. the Cherenkov radiation threshold is exceeded for the electron energy above 10 GeV.
The Cherenkov cone with the angle $\theta_{Ch} = 2\sqrt{\varepsilon_{\pm}I_0/I_S}$ in the focus of 10 PW laser it is approximately equal to 2×10^{-5}.

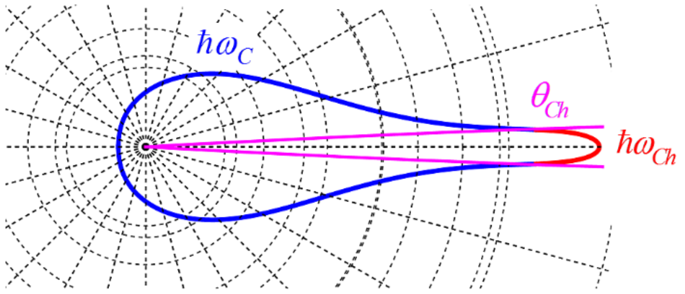
The rate of the energy loss due to the Cherenkov radiation friction force along the electron trajectory is

$$\frac{dE_e}{dx} = -\frac{e^2}{c^2}\int_{v_e n/c>1}\left(1-\frac{c}{v_e n_{\pm}}\right)\omega d\omega \approx -\frac{e^2}{\lambdabar_C^2}\varepsilon_{\pm}\left(\frac{E_0}{E_S}\right)^2$$

Integration is done over the region where $v_e n_{\pm}/c > 1$.
The formation length is given by

$$l_{Ch} \approx \lambdabar_C\gamma_e \quad (\lambdabar_C = \hbar/m_e c = 3.8\times10^{-11}\,\text{cm})$$

It is approximately equal to 2×10^{-5}.
Traversing the laser focus region the electron emits 0.2 photons.
For the electric charge of the LWFA electron bunch of 100 pC we obtain 10^4 photons.



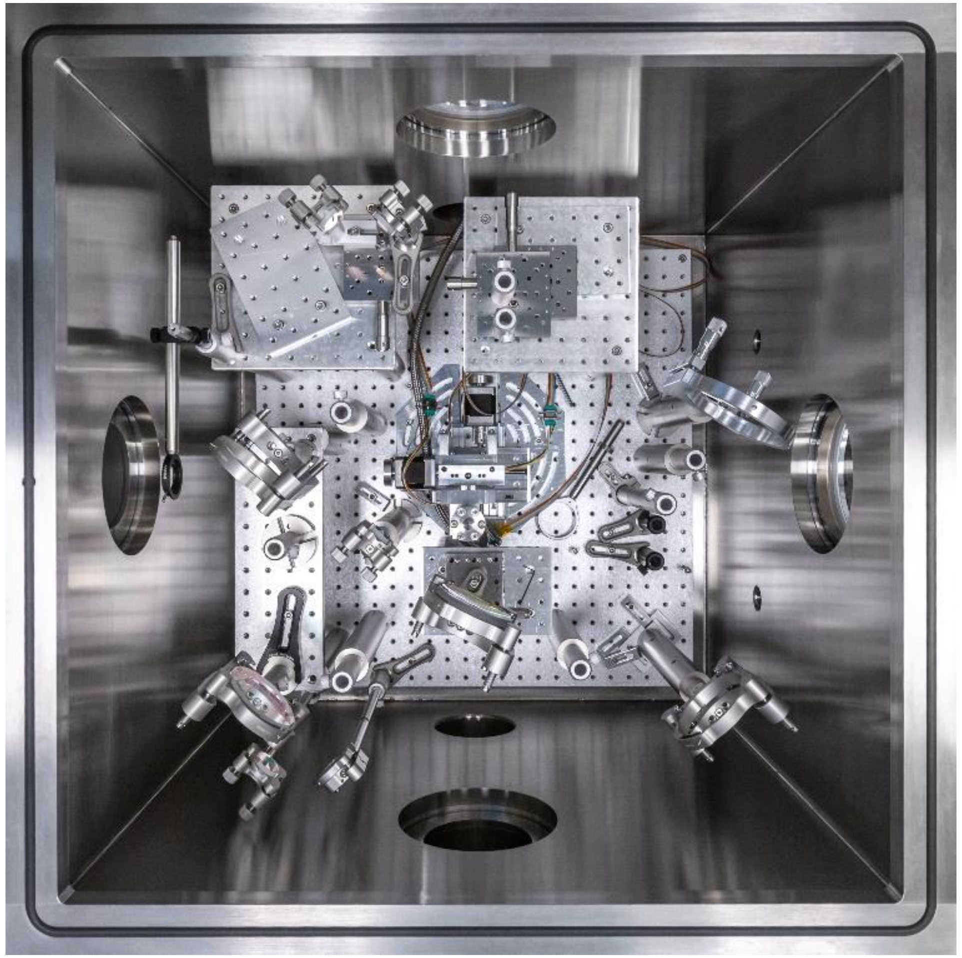
Angle distribution of the energy logarithm for photon radiated by the SCCRS mechanism. Blue color used for Compton scattering and red color for the Cherenkov radiation. Magenta lines show the Cherenkov cone.

I. E. Tamm and I. M. Frank, Comptes Rendus de l'Accademie des Sciences de l'USSR 14, 109 (1937)

Courtesy of S.V. Bulanov

ALFA kHz ELECTRON ACCELERATOR

Towards Watt-class laser electron accelerators



THANK YOU FOR YOUR ATTENTION

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