High Intensity Laser Matter Interaction

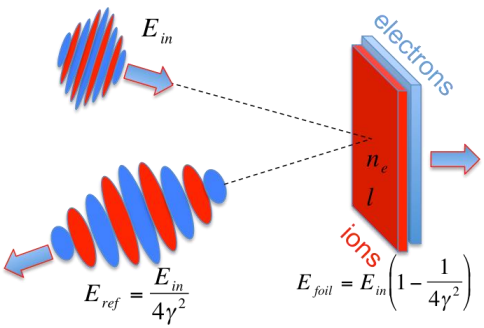
S. S. Bulanov,

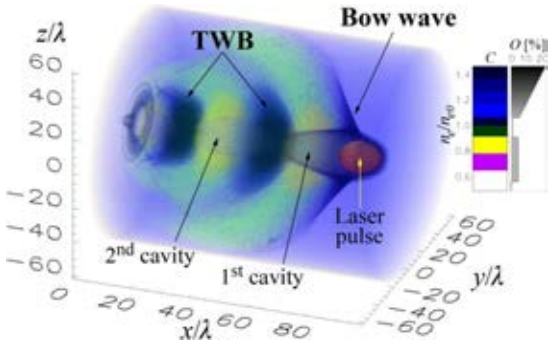
S. Steinke, E. Esarey, W. P. Leemans

Lawrence Berkeley National Laboratory

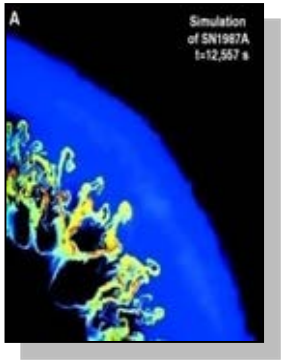
Short focal length PW-class Lasers allow for the study of different and novel plasma physics effects

Electron and Ion Acceleration

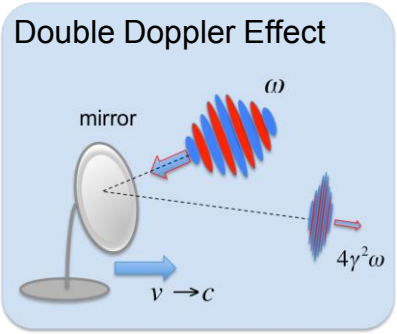




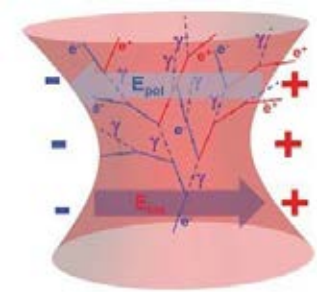
Relativistic Astrophysics



Relativistic Flying Mirrors



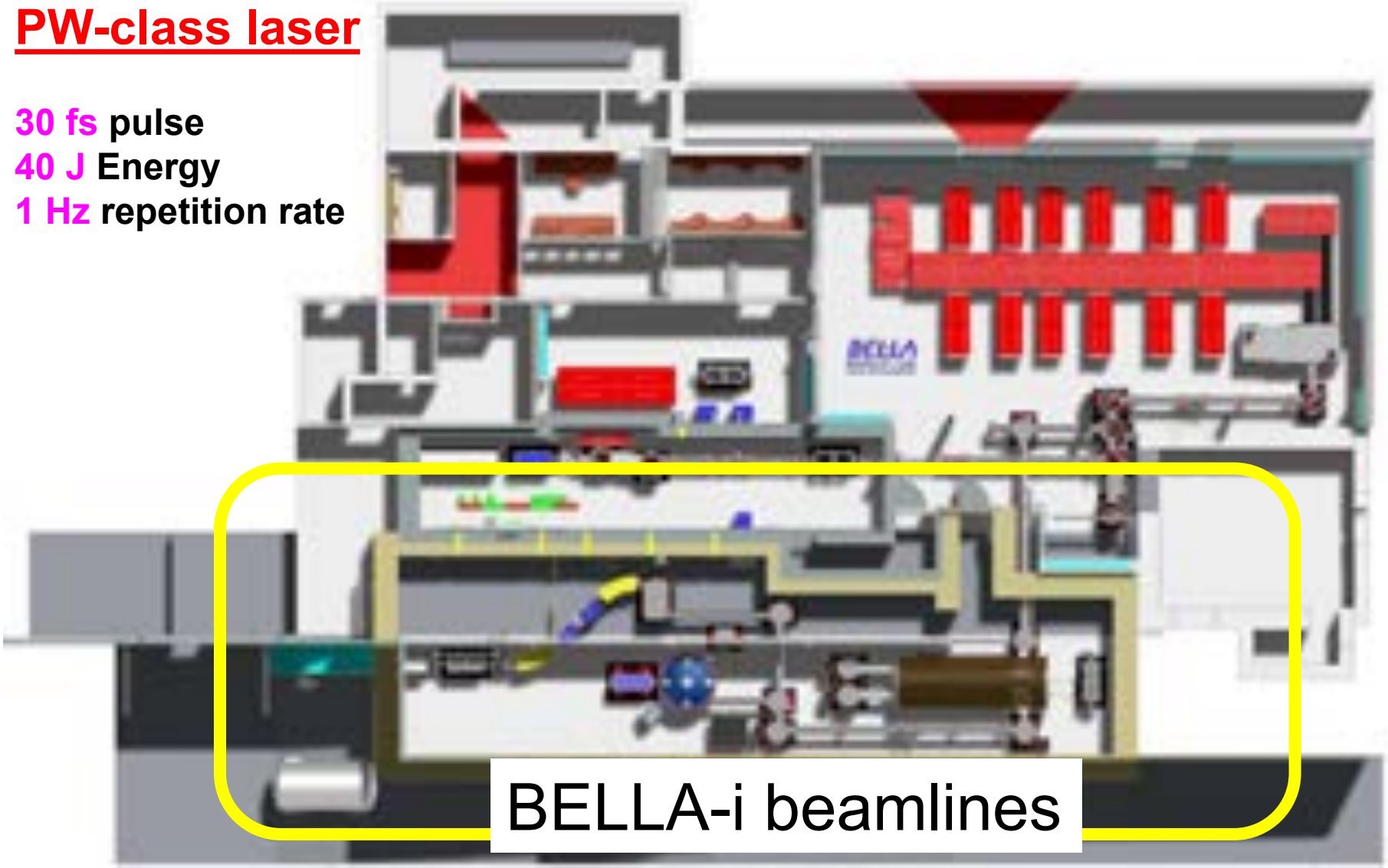
High Intensity Particle Physics



BELLA-i beamlines: expand the facility by adding short focal length capability – ultra-high intensity

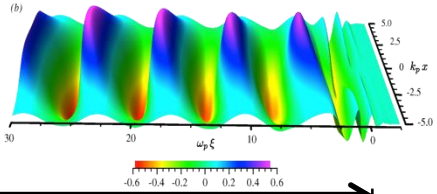
PW-class laser

30 fs pulse
40 J Energy
1 Hz repetition rate

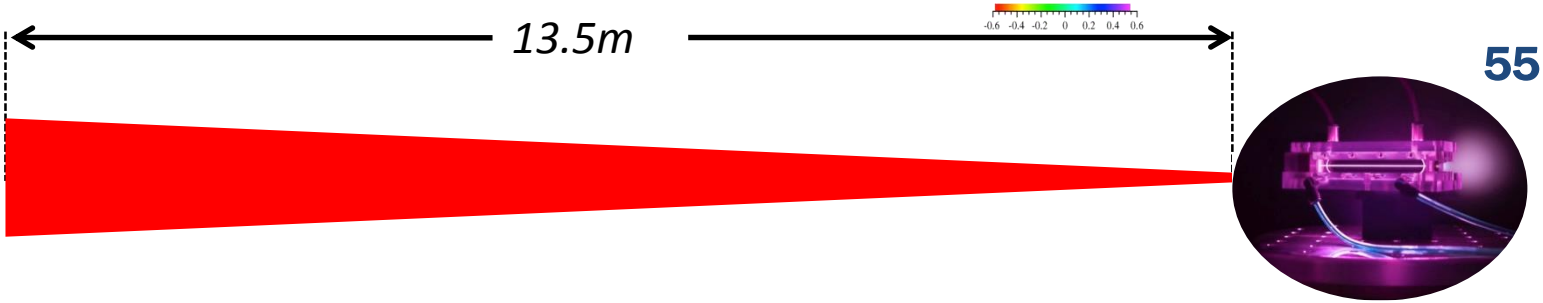


For electron acceleration, BELLA is focused with long focal length. For ions (etc.) it requires short focal length and plasma mirrors

Electron acceleration



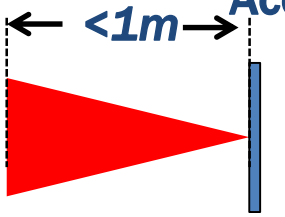
Intensity ~1.5×10^{19} Wcm^{-2}
Acc. fields ~10-50GV/m



55 micron spot

High Intensity physics

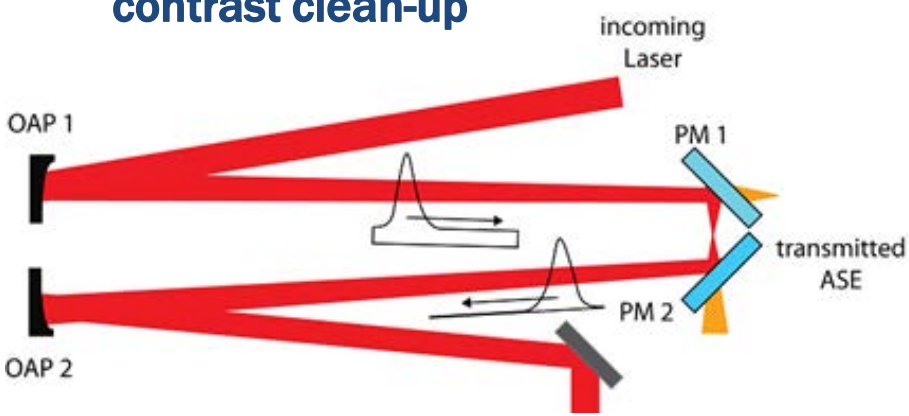
Intensity ~$3\text{-}5\times10^{21}$ Wcm^{-2}
Acc. fields ~TV/m



4-5 micron spot

+

Plasma mirror technology for contrast clean-up



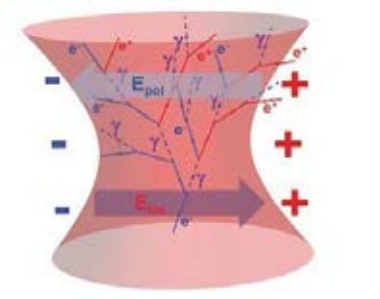
Short focal length PW-class Lasers allow for the study of different and novel plasma physics effects

Electron and Ion Acceleration

Relativistic Astrophysics

Relativistic Flying Mirrors

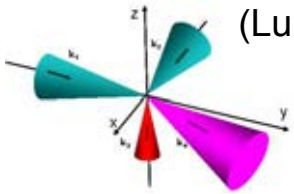
High Intensity Particle Physics

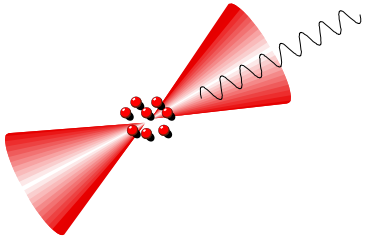


The processes typical for High Intensity Particle Physics

Birefringent e.m. vacuum (Rozanov, 1993)

4-wave mixing
(Lundström et al, 2006)

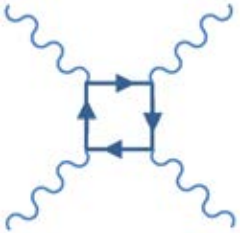




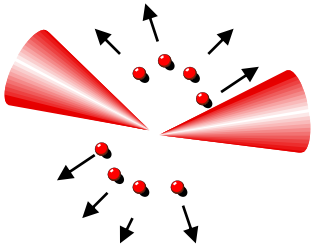
High order harmonic generation through quantum vacuum interaction
(Di Piazza, Hatsagortsyan,
C. H. Keitel, 2005
Fedotov & Narozhny, 2006)

High Intensity

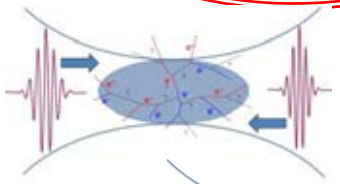
Particle Physics

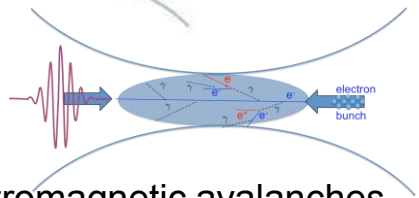


Photon-photon scattering
via relativistic mirrors
(Koga et al (2012))

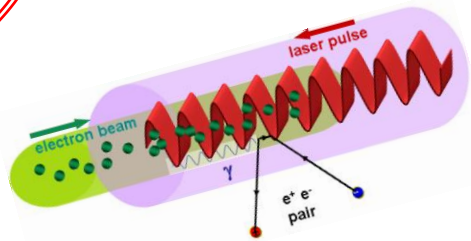


Electron positron pair production from vacuum (Schwinger, 1951)





- Electromagnetic avalanches
- Electromagnetic cascades



Mulitphoton Compton and Breit-Wheeler processes
A. I. Nikishov, V. I. Ritus (1964);
Bula et al (1996); Burke et al (1997)

New physics opportunities at the intersection of quantum field theory and high intensity

- Nonperturbative Quantum Field Theory

- Matter in extreme conditions

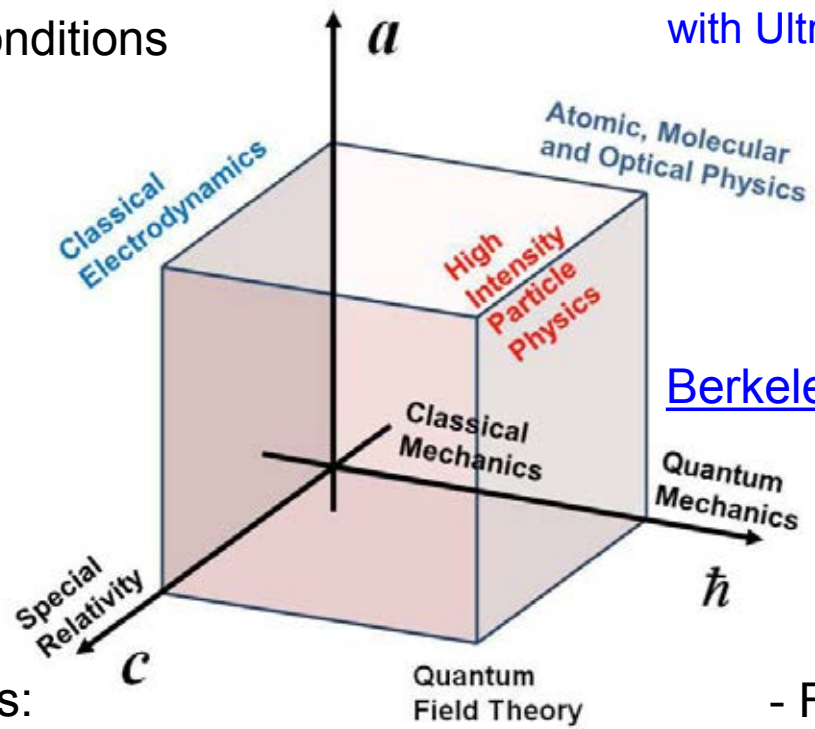
- Electromagnetic Cascades

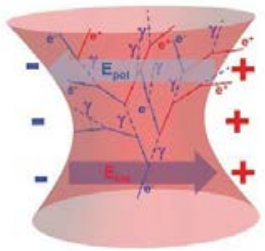
- Electromagnetic Avalanches

- Ultimate Laser Intensity Limit

- Next generation lasers:
  - day-to-day operation
  - new laser-matter interaction applications

Workshop on
"Nonlinear QED Phenomena
with Ultra-Intense PW-class Lasers"
LBNL, May 2012





Berkeley Cube

- Future γγ colliders

- Future lepton colliders

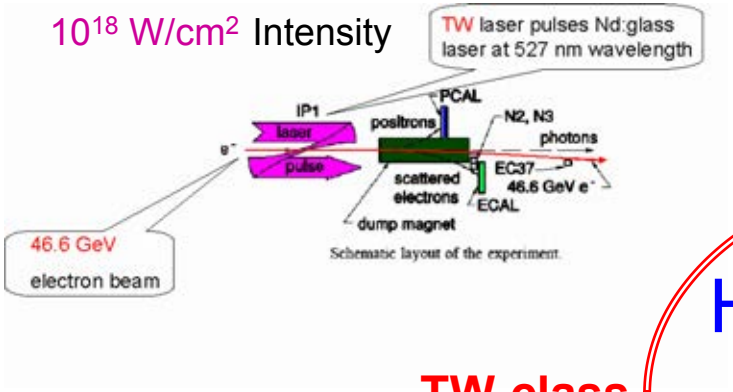
- Various astrophysical phenomena

High Intensity Particle Photon Interactions

Ultra-high intensities are needed for Particle Physics studies

SLAC experiments E144 (1996)

10^{18} W/cm^2 Intensity



Schematic layout of the experiment.

High Intensity Particle Physics

EW-class lasers ?

ELI
(under construction)

multi PW-class lasers

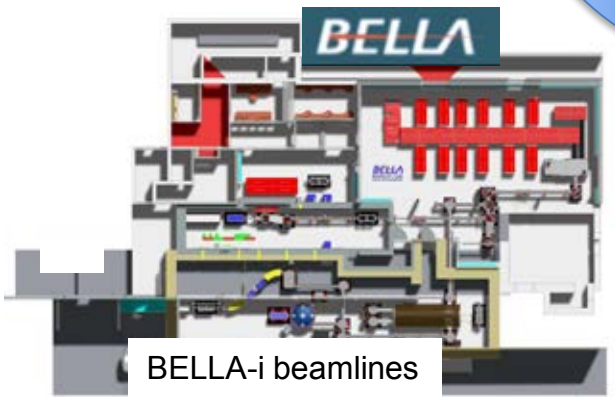
~10^{23} W/cm^2 Intensity
~100 fs pulse
~kJ Energy

TW-class lasers

proposed

~10^{22} W/cm^2 Intensity
30 fs pulse
40 J Energy

operational



BELLA-i beamlines

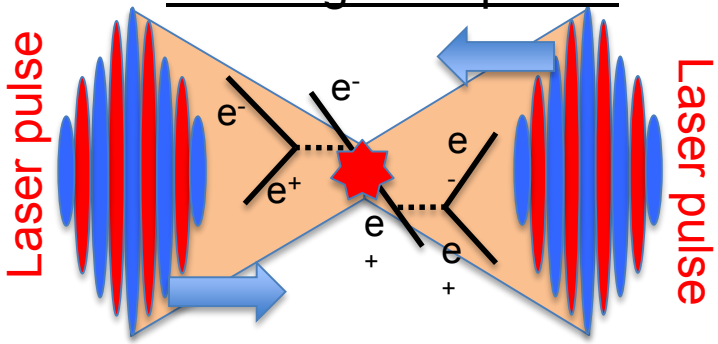
PW-class lasers

Particle Acceleration, Future collider studies, High Field Science

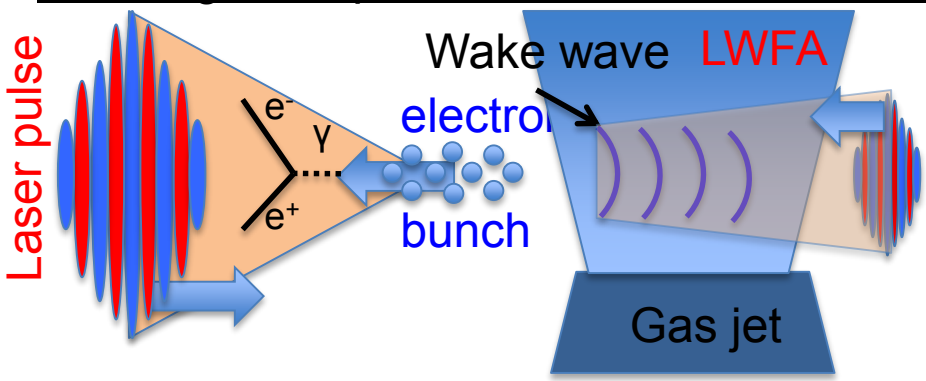
High Field Science, Particle Acceleration Laboratory Astrophysics & Hadron Therapy

Use of relativistic electron beams enables the study of nQED effects with PW-lasers

Colliding laser pulses



Colliding laser pulse and an electron beam



1. Radiation effects become dominant

$$I_{rad} = 3.5 \times 10^{23}\ \mathrm{W/cm^2}$$

2. QED effects become dominant

$$I_Q = 5.5 \times 10^{24}\ \mathrm{W/cm^2}$$

1. Schwinger limit

$$I_S = 2.3 \times 10^{29}\ \mathrm{W/cm^2}$$

1. Radiation effects become dominant

$$I_{rad} = 2 \times 10^{20}\ \mathrm{W/cm^2} \quad + \quad E_e = 10\ \mathrm{GeV}$$

$$I_{rad} = 4 \times 10^{21}\ \mathrm{W/cm^2} \quad + \quad E_e = 0.5\ \mathrm{GeV}$$

2. QED effects become dominant

$$I_Q = 10^{21}\ \mathrm{W/cm^2} \quad + \quad E_e = 10\ \mathrm{GeV}$$

$$I_Q = 4 \times 10^{23}\ \mathrm{W/cm^2} \quad + \quad E_e = 0.5\ \mathrm{GeV}$$

3. QED cascade

$$I_C = 10^{23}\ \mathrm{W/cm^2} \quad + \quad E_e = 10\ \mathrm{GeV}$$

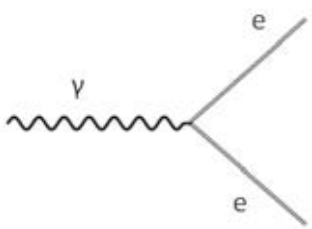
$$I_C = 5 \times 10^{23}\ \mathrm{W/cm^2} \quad + \quad E_e = 0.5\ \mathrm{GeV}$$

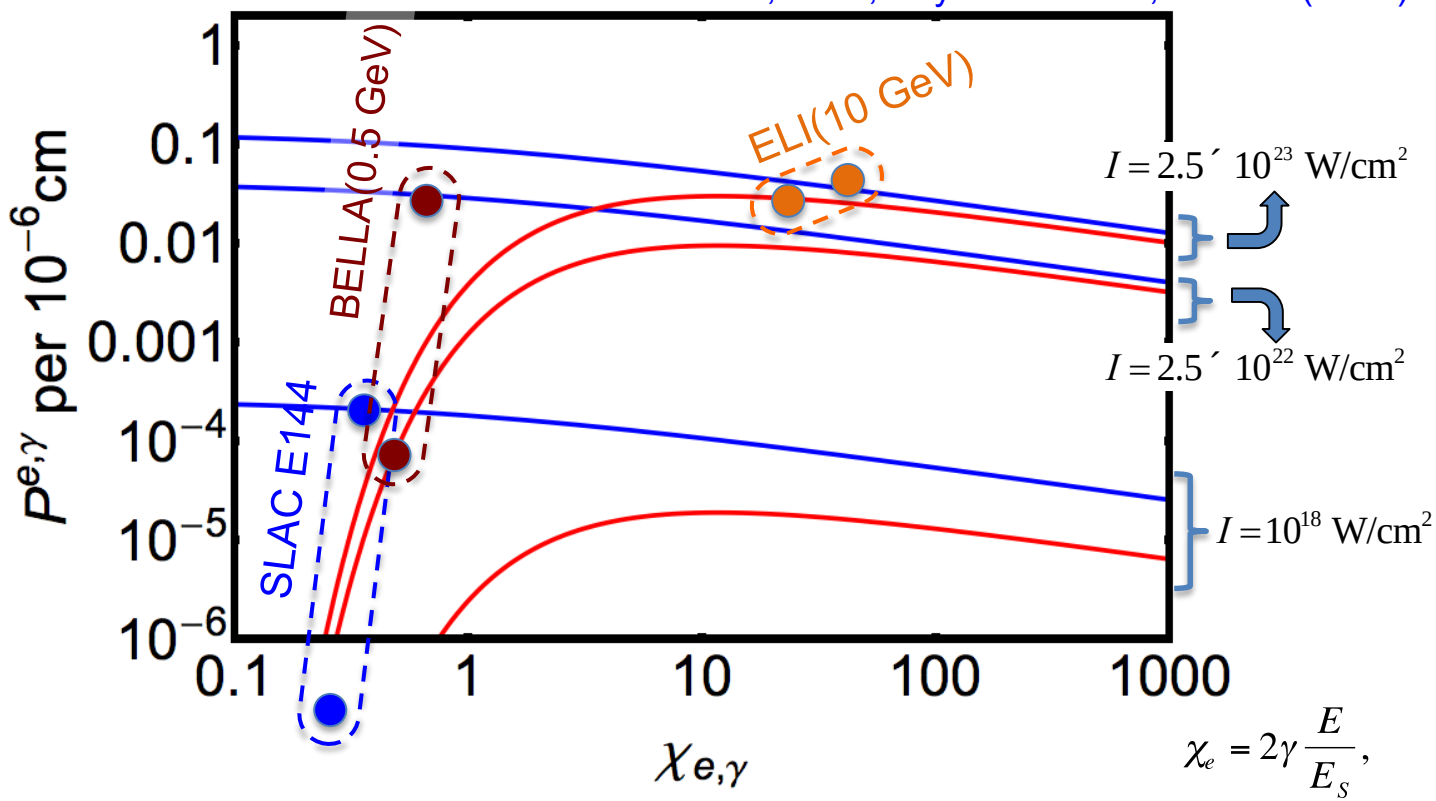
Electromagnetic cascades: high event rates for PW lasers colliding with e-beams

LBNL: S. S. Bulanov, et al., Phys. Rev. A 87, 062110 (2013)

Multiphoton Compton effect

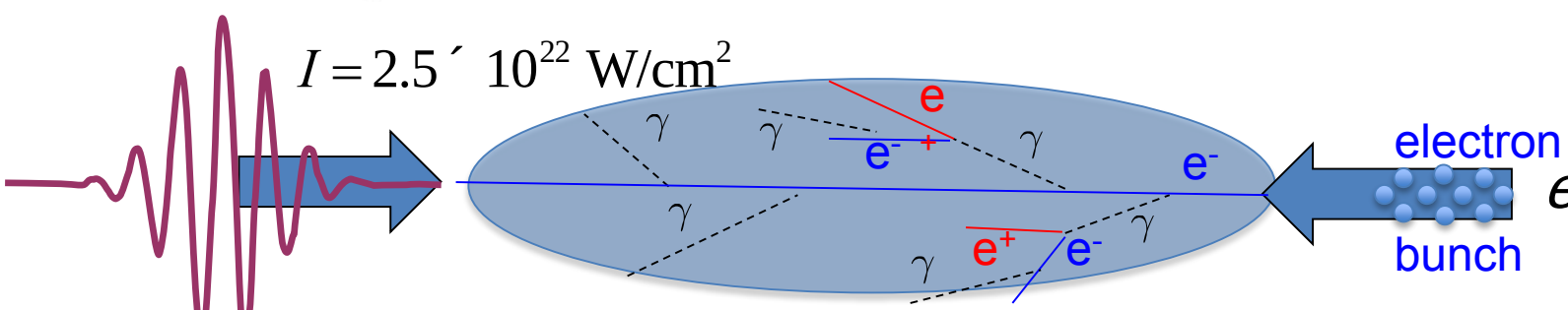
Multiphoton Breit-Wheeler effect





$$\chi_e = 2\gamma \frac{E}{E_S},$$

$$\chi_\gamma = 2\frac{\hbar\omega}{mc^2}\frac{E}{E_S},$$



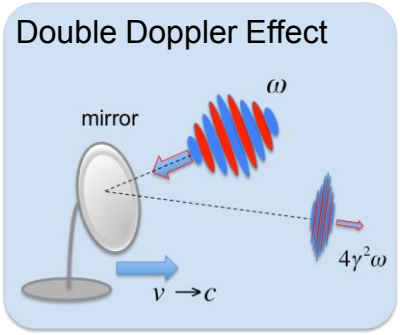
$$e_e^0 = 0.5\,\text{GeV}$$

Short focal length PW-class Lasers allow for the study of different and novel plasma physics effects

Electron and Ion Acceleration

Relativistic Astrophysics

Relativistic Flying Mirrors



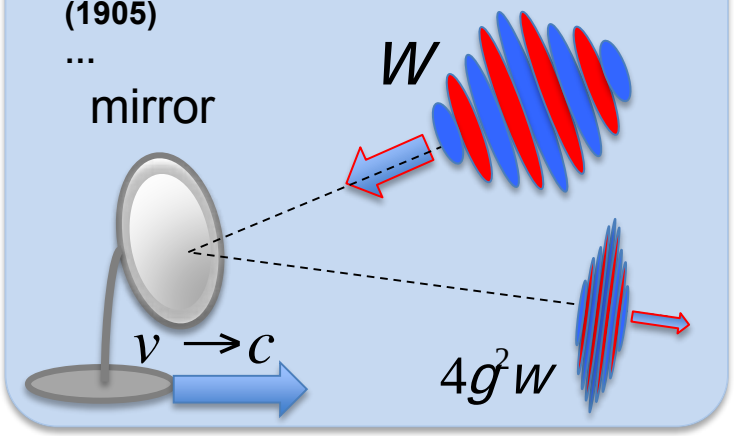
High Intensity Particle Physics

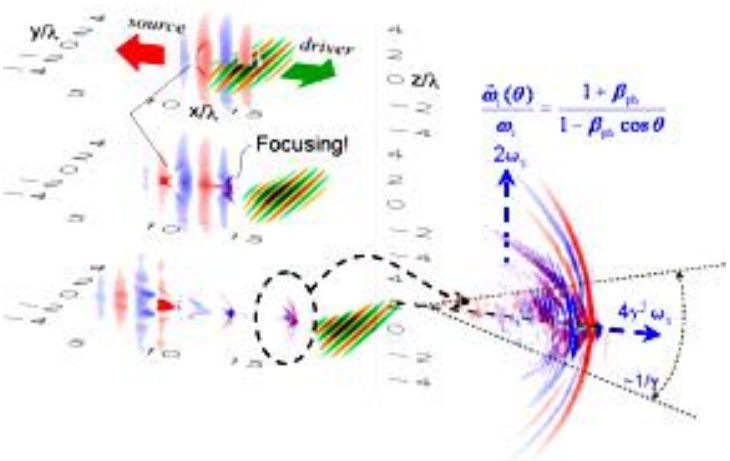
Electromagnetic Pulse Intensification and Shortening by Flying Mirror formed in laser-plasma interaction

Double Doppler Effect

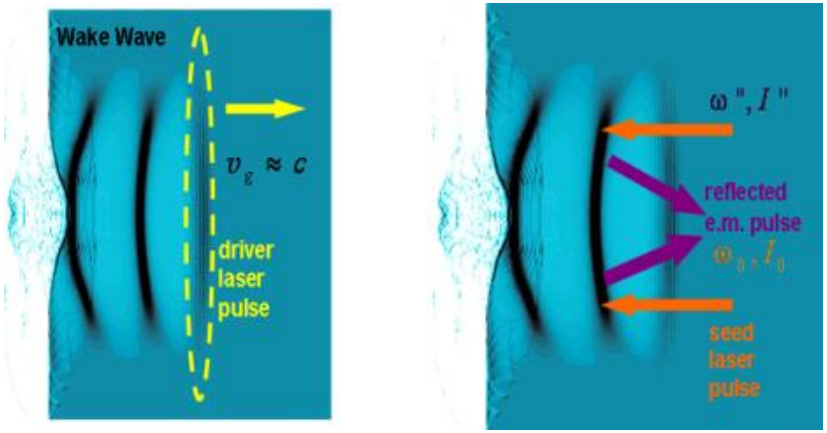
A. Einstein, Ann. Phys. (Leipzig) 17, 891 (1905)

...





Paraboloidal relativistic mirrors are formed by the wake wave left behind the laser driver pulse



S.V.Bulanov, T. Esirkepov, T. Tajima, Phys.Rev.Lett. 91, 085001 (2003)

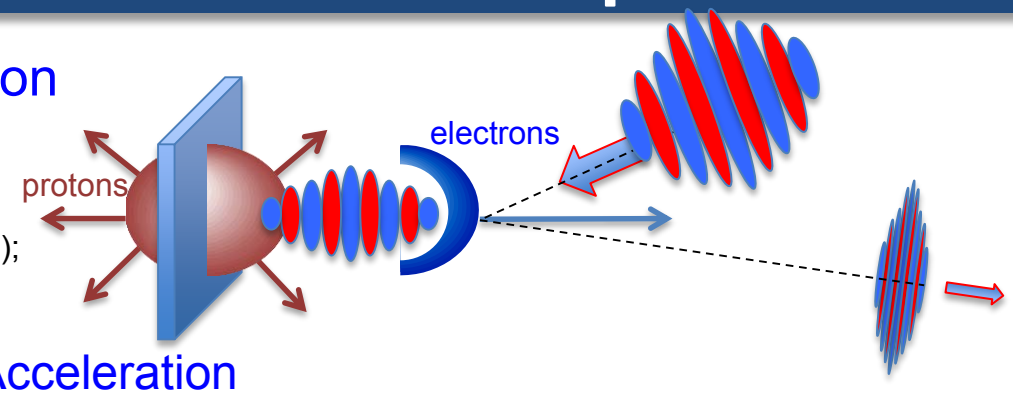
The maximum intensification for the reflection at spherical plasma wake wave:

$$I_r \sim g^4 I_0$$

Relativistic Flying Mirrors are Generated using the Laser Driven Ion Acceleration Setup

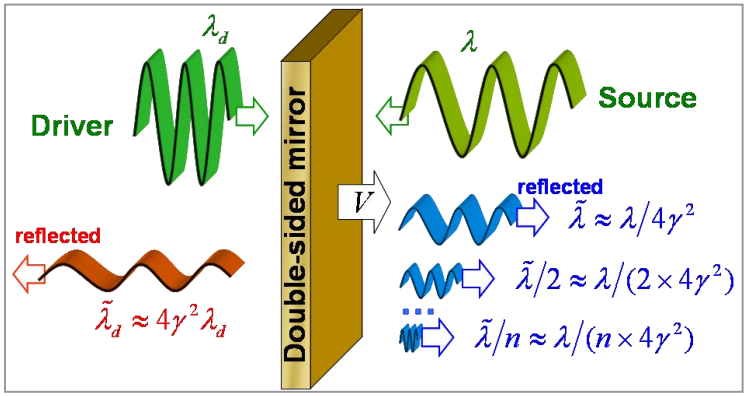
Flying Mirror from Coulomb Explosion

V.V. Kulagin, et al., Phys. Rev. Lett. **99,** 124801 (2007);
D. Habs, et al., Appl. Phys. B **93**, 349 (2008);
J. Meyer-ter-Vehn, H.-C. Wu, Eur. Phys. J. D **55,** 433 (2009);
H.-C. Wu, et al., Phys. Rev. Lett. 104, 234801 (2010).



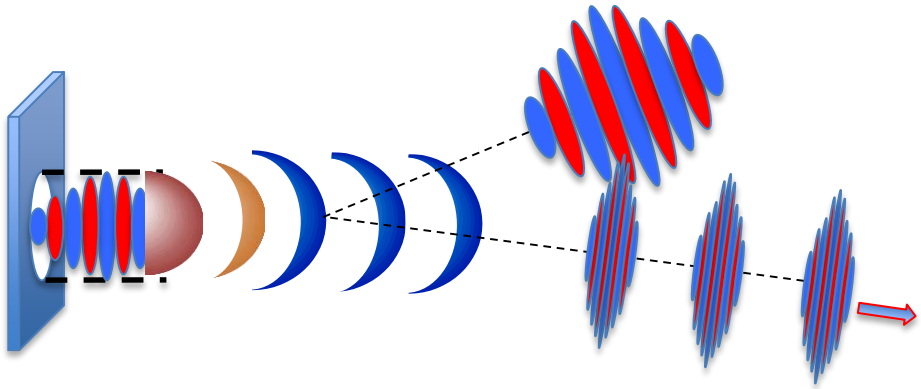
Flying Mirror from Radiation Pressure Acceleration

T.Zh. Esirkepov, et al., Phys. Rev. Lett. 103 (2009) 025002.



Flying Mirror from multiple electron layers (Directed Coulomb Explosion)

S. S. Bulanov, et al., Phys. Lett. A **374**, 476 (2010).



Summary: new PW-class facilities provide access to new regimes of accelerator science and applications

High intensity particle physics

- Nonlinear QED: Mulitphoton Compton and Breit-Wheeler processes
- EM cascade/pair production in backscatter from 0.5 GeV beam

Flying mirrors: coherent, ultrashort pulse x-rays

- Underdense plasmas: highly nonlinear wake
- Overdense plasmas: electron sheets from RPA

Relativistic astrophysics: magnetic reconnection and collisionless shock waves are closely related to the physics of laser-ion acceleration

Challenges

Theory

-Beyond the plane wave approximation
-Finite size effects
-Beyond the external field approximation
-Electromagnetic Cascades and Avalanches
- Ultimate limit for attainable laser intensity

-Physics beyond the Standard Model

Experiment

- Uncharted region in the parameter space of the Standard Model
- Electromagnetic Cascades and Avalanches
-Test bed for future detector techniques
-Test bed for interactions at future colliders

Facilities

-PW-class laser facilities: radiation dominated regime of interaction, multiphoton Compton and Breit-Wheeler processes, electromagnetic cascades
-multi PW-class laser facilities: electromagnetic cascades and avalanches

Question

Q: What types of detectors are needed to detect the nQED effects?

A: In principle, detectors such as charged particle tracking, EM calorimeters, of the type being used at LHC and other big accelerators, can be used. However, an extremely high flux of electrons, positrons, and photons can be an issue for these detectors, which needs to be addressed. Moreover the detectors that will be able to detect nQED effects in high intensity laser interaction with charged particles need to be developed for the next generation of lepton and photon-photon colliders. This fact makes the high intensity laser facilities an ideal testbed for novel detector concepts and detector techniques.