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September 13 - 17, 2021

Laser-Particle Collider for High-field High-energy Physics Studies

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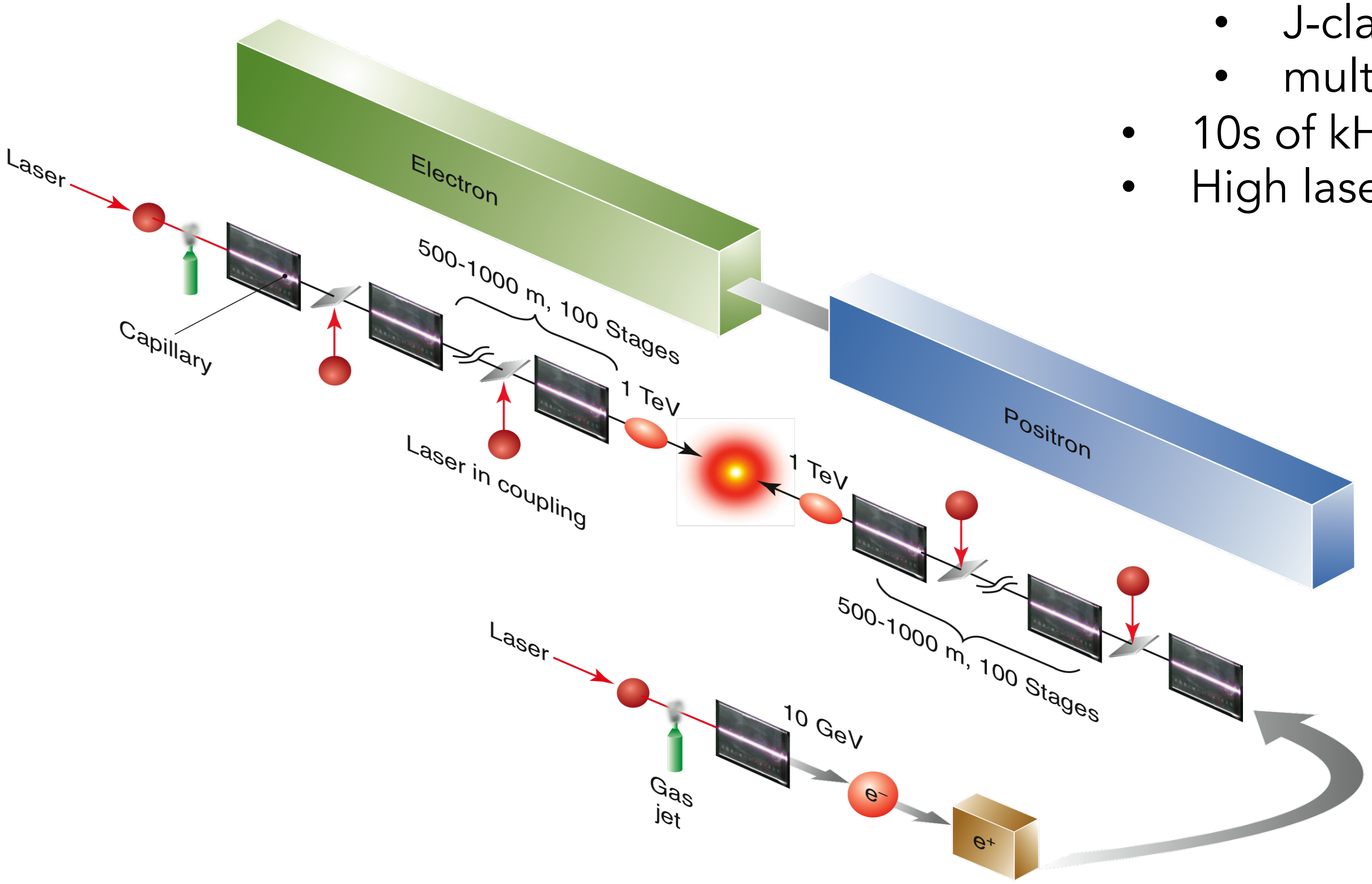
Basic configuration of a laser-plasma linear collider

Linac: staged LPAs

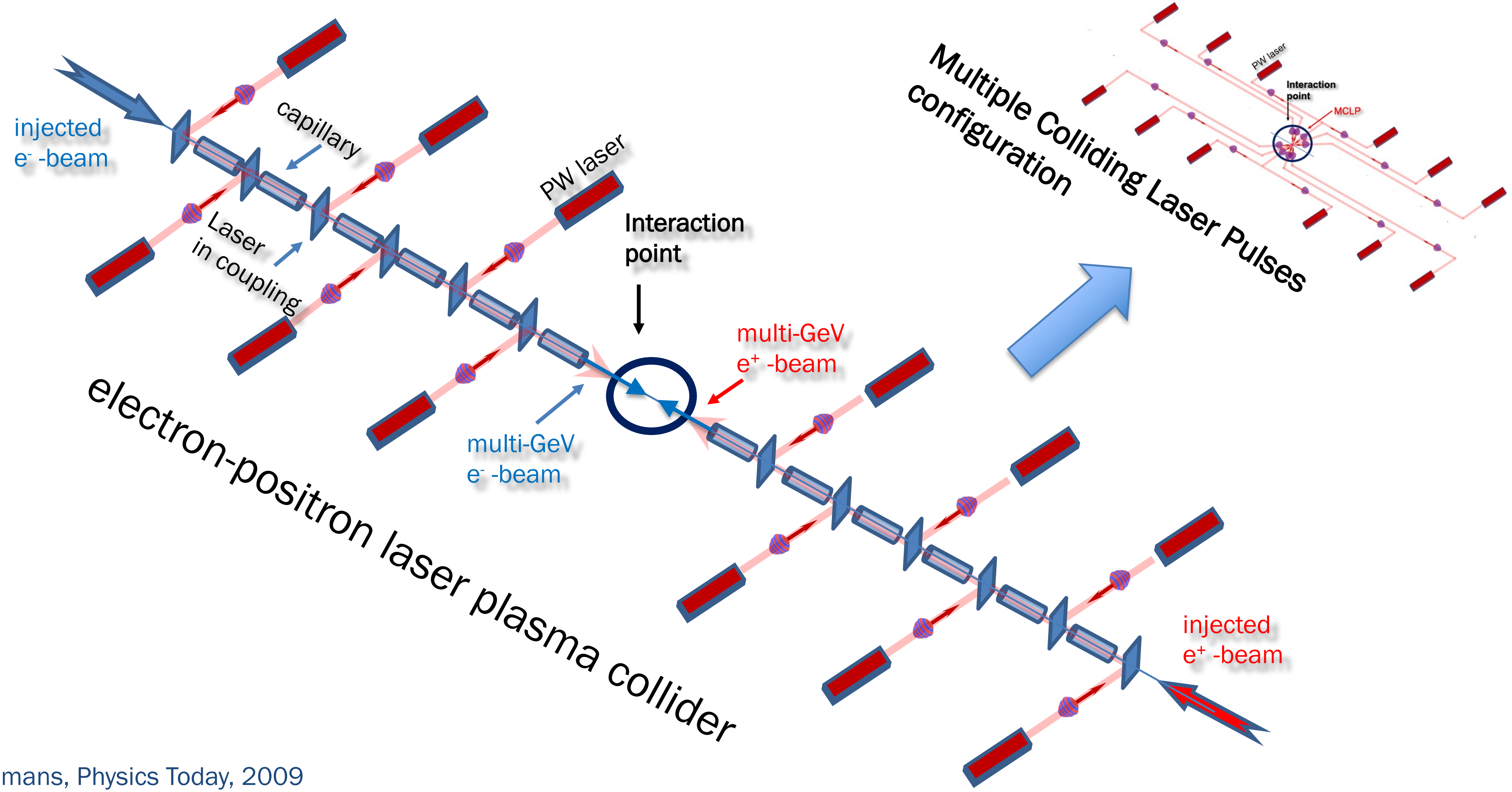


- **Plasma density optimization: n ~ 10^{17} cm^{-3}**
- Staging & laser coupling into plasma channels:
  - J-class laser energy/stage required
  - multi-GeV energy gain/stage
- 10s of kHz rep. rate to achieve luminosity (100s kW)
- High laser efficiency required (tens %)

Leemans & Esarey Phys. Today (2009)

This slide is courtesy of C. B. Schroeder

Plasma based collider can easily be made multi-purpose with minimal adjustments to its configuration



injected e^- -beam

capillary

Laser in coupling

PW laser

Interaction point

multi-GeV e^+ -beam

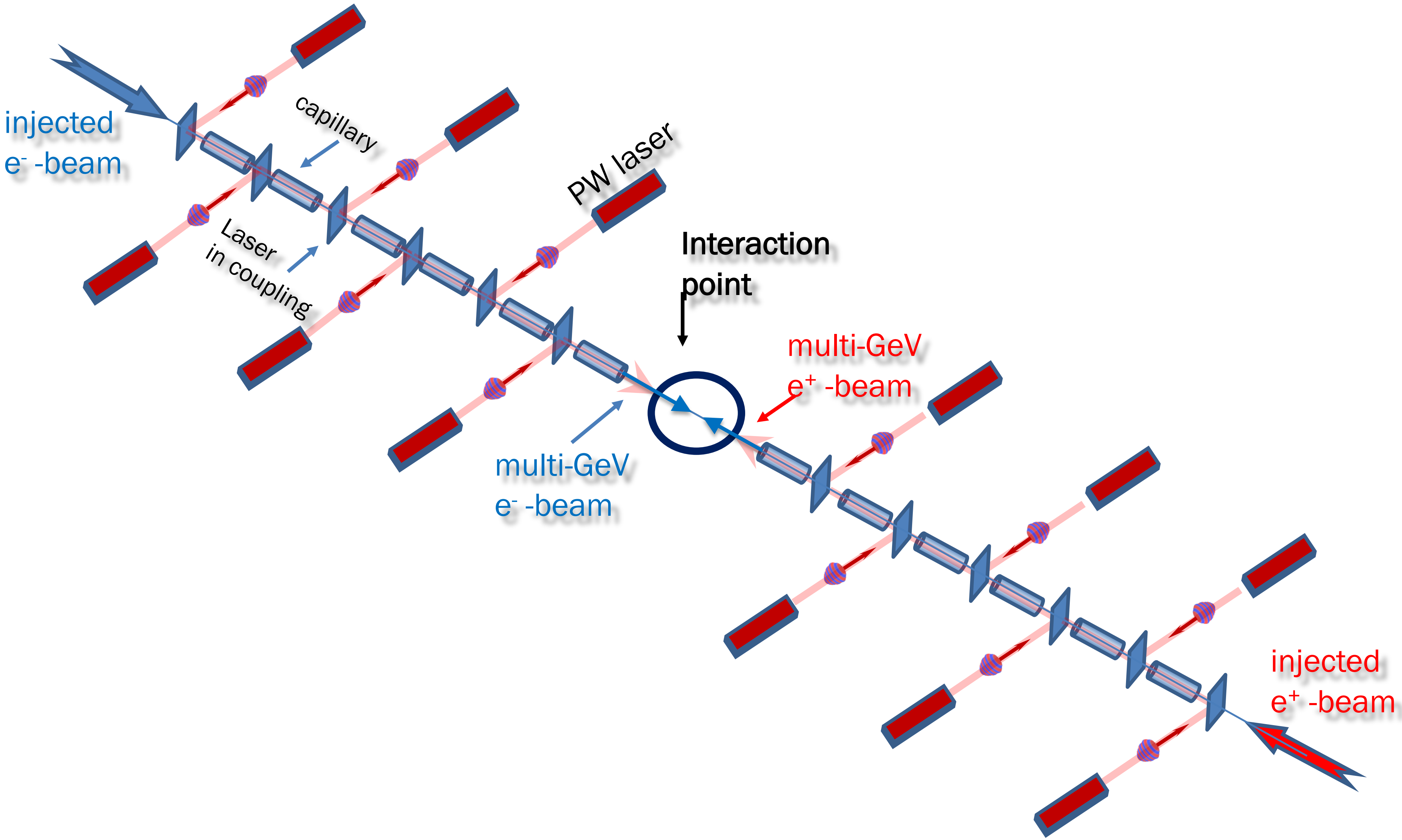
multi-GeV e^- -beam

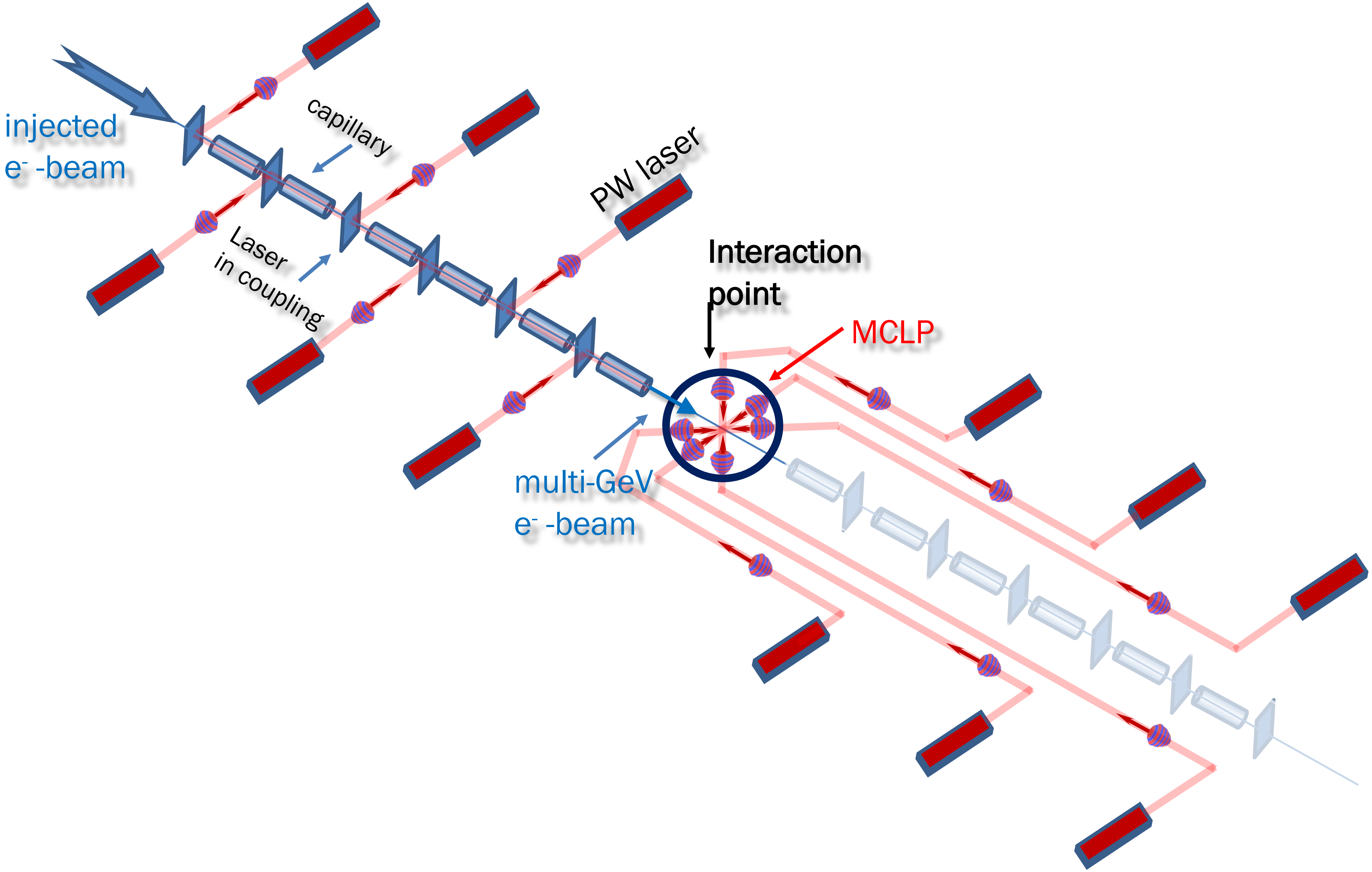
electron-positron laser plasma collider

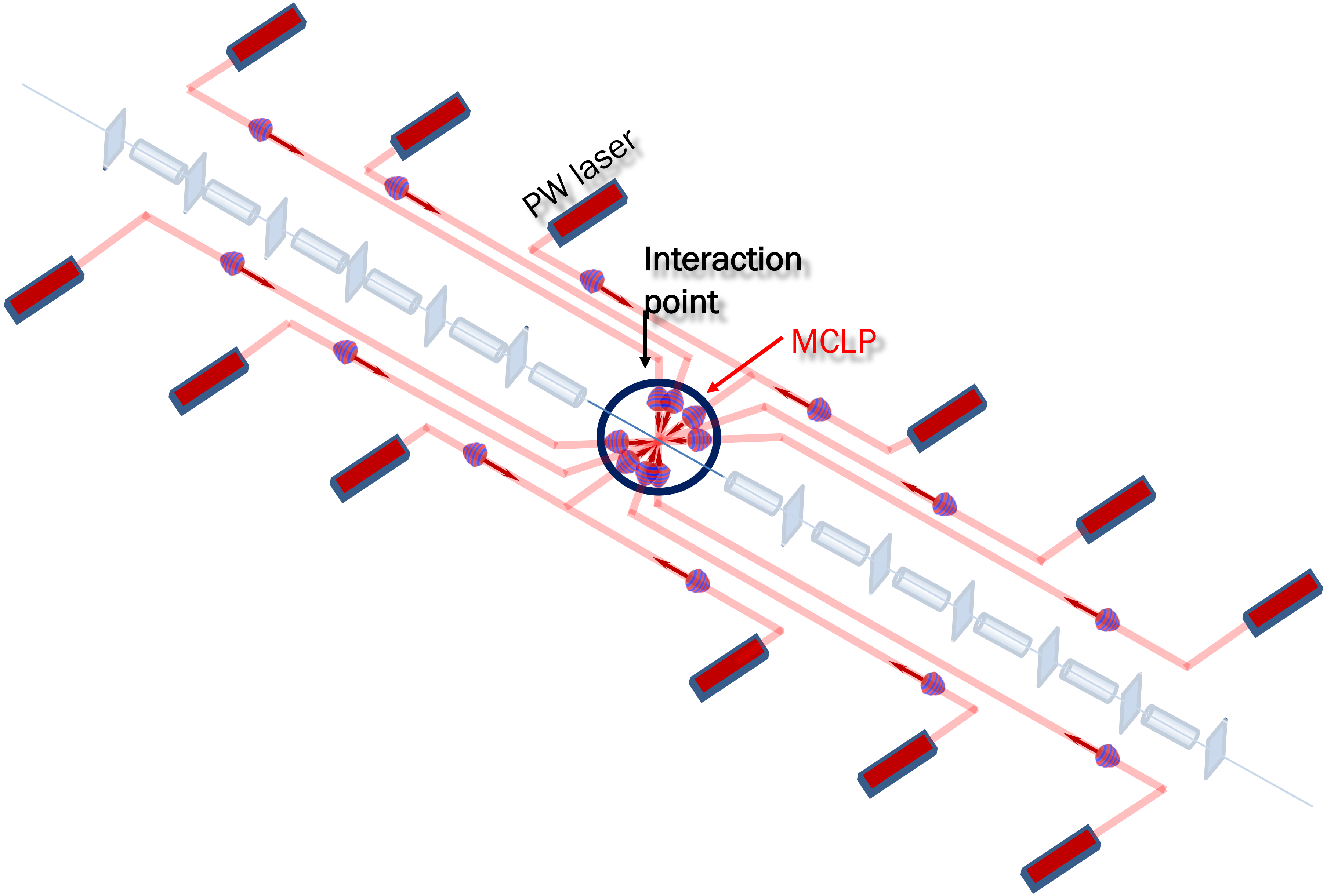
injected e^+ -beam

Multiple Colliding Laser Pulses configuration

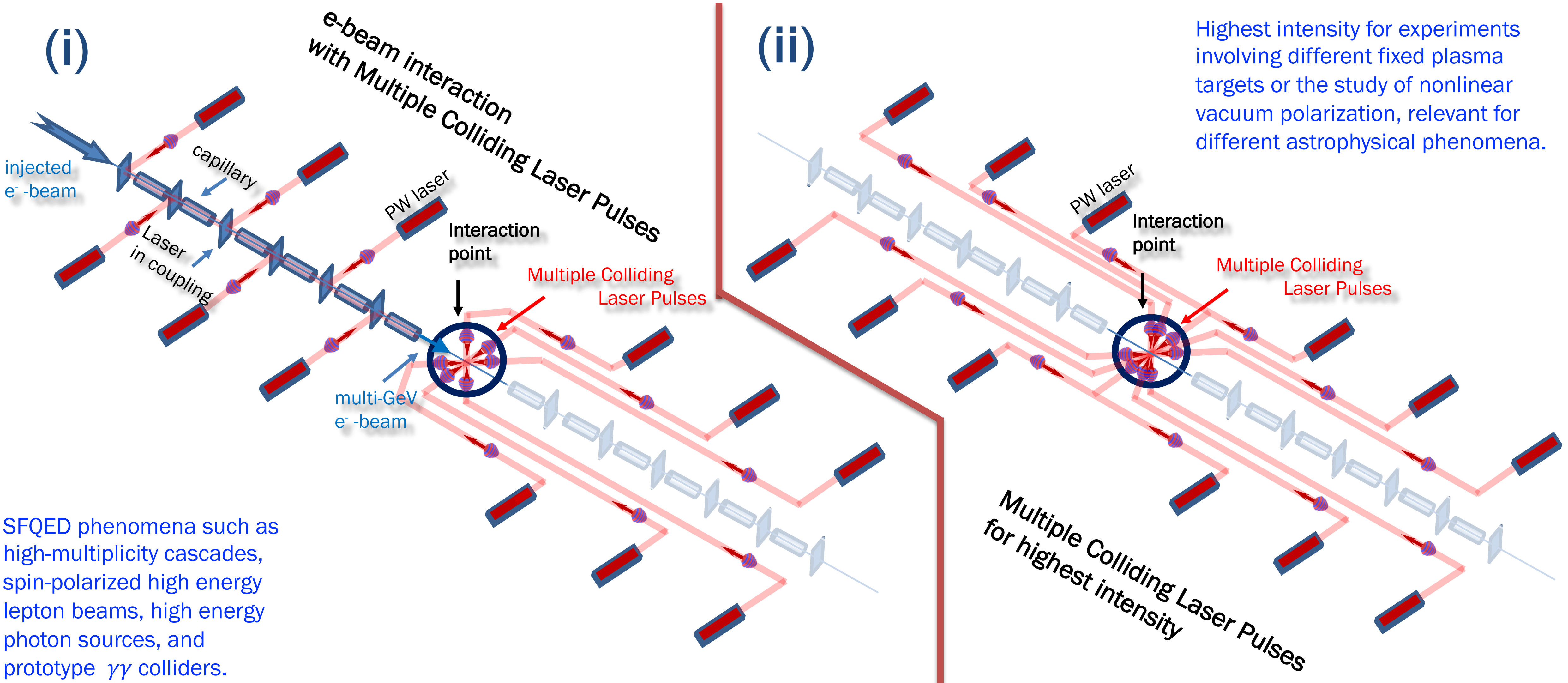
E. Esarey, W. P. Leemans, Physics Today, 2009


injected
e- -beam
capillary
Laser
in coupling
PW laser
Interaction
point
multi-GeV
e+ -beam
multi-GeV
e- -beam
injected
e+ -beam


injected
e^- -beam
capillary
PW laser
Laser
in coupling
Interaction
point
MCLP
multi-GeV
e^- -beam


PW laser
Interaction point
MCLP

Two configurations are possible:
(i) e-beam laser interaction and (ii) laser – laser interaction



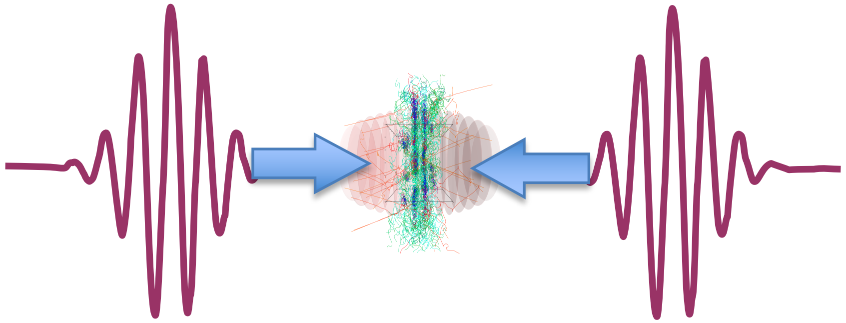
SFQED phenomena such as high-multiplicity cascades, spin-polarized high energy lepton beams, high energy photon sources, and prototype $\gamma\gamma$ colliders.

Highest intensity for experiments involving different fixed plasma targets or the study of nonlinear vacuum polarization, relevant for different astrophysical phenomena.

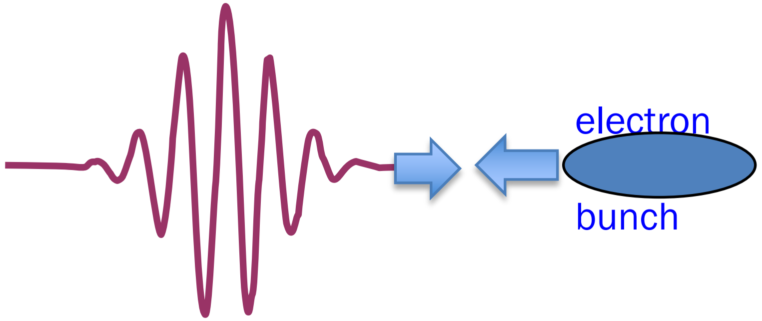
P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, Phys. Plasmas 27, 050601 (2020)

Colliding laser – laser and e-beam – laser provide two principal schemes of the experiments for the study of strong field QED phenomena.

Colliding laser pulses



Colliding laser pulse and an electron beam



A. Gonoskov, T. G. Blackburn, M. Marklund, S. S. Bulanov,
“Charged particle motion and radiation in strong electromagnetic fields”, arxiv.org/abs/2107.02161

(i)

e-beam interact
with Multi

injected
e⁻-beam

(ii)

Highest intensity for experiments
involving different fixed plasma
targets or the study of nonlinear
for
mena.

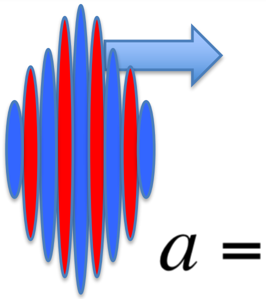
SFQED phen
high-multiplicity cascades,
spin-polarized high energy
lepton beams, high energy
photon sources, and
prototype $\gamma\gamma$ colliders.

Colliding Laser Pulses
ighest intensity

P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, Phys. Plasmas 27, 050601 (2020)

Behavior of particles and fields is characterized by Lorentz invariant parameters

Classical nonlinearity parameter



$$a = \frac{eE}{m\omega c}$$ Electron energy gain over laser wavelength in units of *mc*^{2}

$a = 1$ → Relativistic regime of interaction $\lambda = 1\ \mu m$

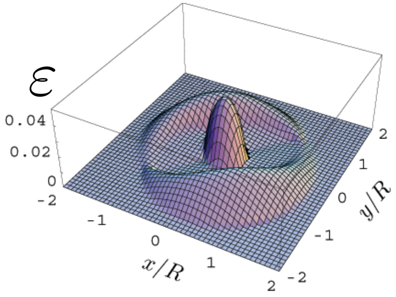
Critical QED field can create an electron-positron pair at Compton length, $\lambda_C = 3.86 \times 10^{-11}$ cm

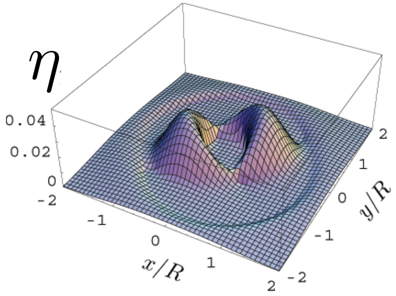
$$E_S = \frac{m^2 c^3}{e\hbar} = 1.32\times10^{16}\ V/cm \quad \rightarrow \quad a_s = \frac{\hbar\omega}{mc^2} = 4.1\times10^5$$

$$n_{e^+e^-} = \frac{e^2 E_S^2}{4\pi\hbar^2 c}\varepsilon\eta \coth\left[\frac{\pi\eta}{\varepsilon}\right]\exp\left[\frac{\pi}{\varepsilon}\right]$$

$$\varepsilon = \frac{1}{E_S}\sqrt{(\mathcal{F}^2+\mathcal{G}^2)^{1/2}+\mathcal{F}} \qquad \eta = \frac{1}{E_S}\sqrt{(\mathcal{F}^2+\mathcal{G}^2)^{1/2}-\mathcal{F}}$$

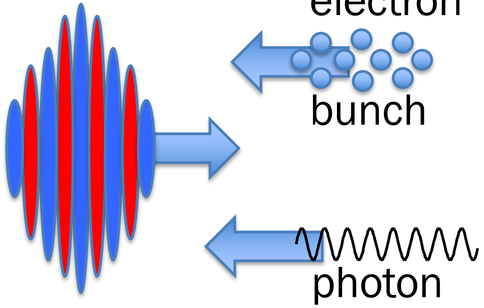
$$\mathcal{F} = (\mathbf{E}^2-\mathbf{B}^2)/2 \qquad \mathcal{G} = \mathbf{E}\cdot\mathbf{B}$$





Behavior of particles and fields is characterized by Lorentz invariant parameters

Quantum Effects



$$\chi_e = \frac{e\hbar\sqrt{(F_{\mu\nu}p^\nu)^2}}{m^3c^4}$$

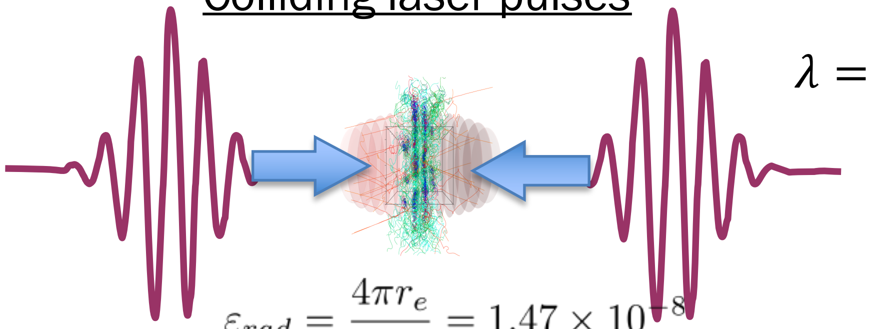
$$\chi_\gamma = \frac{e\hbar\sqrt{(F_{\mu\nu}k^\nu)^2}}{m^3c^4}$$

counter-propagating laser and electron/photon

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

The dependence of the electron energy on the field strength is profoundly different in these two principal interaction schemes, leading to different thresholds

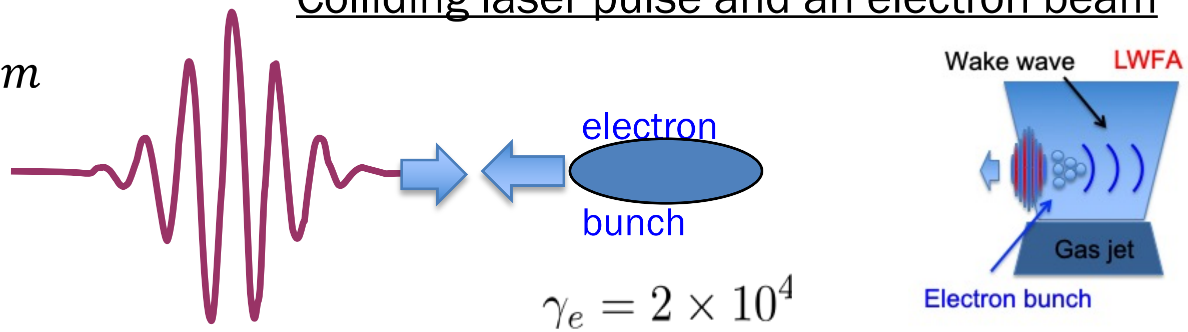
Colliding laser pulses



$$\lambda = 0.8\ \mu m$$

$$\varepsilon_{rad} = \frac{4\pi r_e}{3\lambda_0} = 1.47 \times 10^{-8}$$

Colliding laser pulse and an electron beam



$$\gamma_e = 2 \times 10^4$$

Laser Power:

1-10 PW

1. Radiation effects become dominant

$$a > a_{rad} = \varepsilon_{rad}^{-1/3} = 400$$

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

2. QED effects become dominant

$$a > a_Q = (2\alpha/3)^2 \varepsilon_{rad}^{-1} = 1.6 \times 10^3$$

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

1. Radiation effects become dominant

$$a > a_{rad} = (\omega \tau_{laser} \gamma_e \epsilon_{rad})^{-1/2} = 10$$

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

2. QED effects become dominant

$a > a_Q = (2\alpha/$

$I_Q = 5.8 \times 1$

Laser Power:

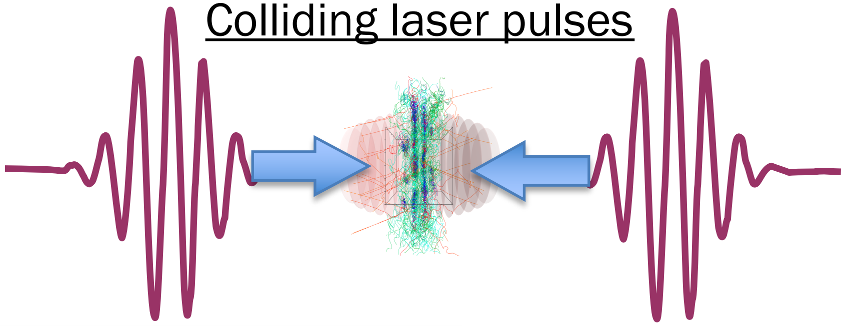
1-10 PW

Marlene Turner
SF QED capabilities at BELLA PW: second beamline overview
Wed, 15/9

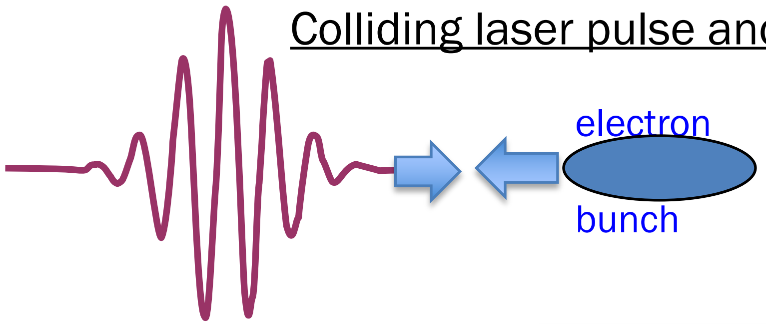
S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, G. Korn, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 660, 31 (2011)*

The dependence of the electron energy on the field strength is profoundly different in these two principal interaction schemes

Colliding laser pulses



Colliding laser pulse and an electron beam

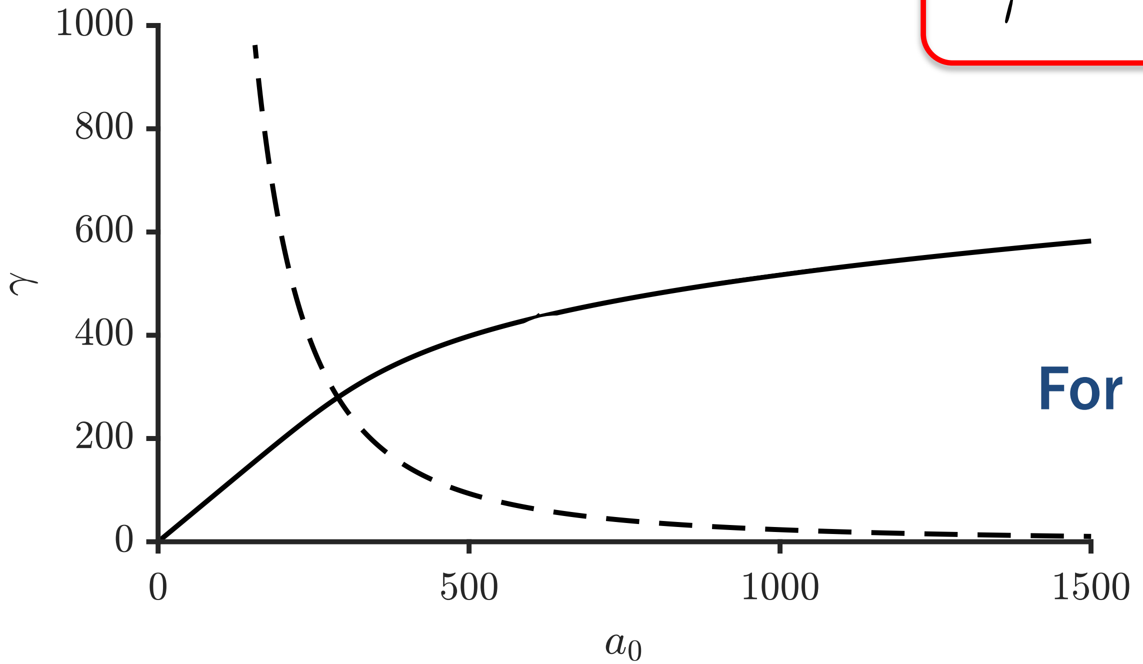


$$\boxed{\gamma \sim (a/\epsilon_{rad})^{1/4}}$$

For $a \gg a_{\mathrm{rad}} = \epsilon_{\mathrm{rad}}^{-1/3}$

$$\varepsilon_{rad} = \frac{4\pi r_e}{3\lambda_0} = 1.47 \times 10^{-8}$$

$$\boxed{\gamma \sim (\epsilon_{rad} a^2)^{-1}}$$



For $p_0 \epsilon_{rad} a^2 \gg 1$

Optimal focusing of laser radiation can be obtained using multiple colliding laser pulses (MCLP)

- Optimal focusing in terms of a dipole wave

I.M. Bassett, Opt. Acta **33**, 279 (1986);
I. Gonoskov et al., PRA **86**, 053836 (2012).

- e^+e^- pair production by MCLP

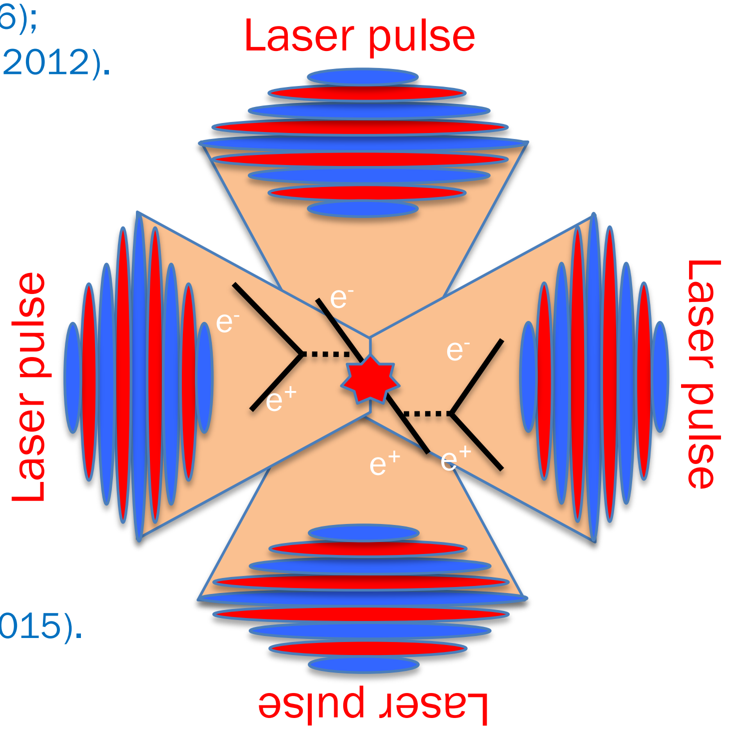
S.S. Bulanov et al., PRL **104**, 220404 (2010);
S.S. Bulanov et al., PRL **105**, 220407 (2010);
A. Gonoskov et al., PRL **111**, 060404 (2013).

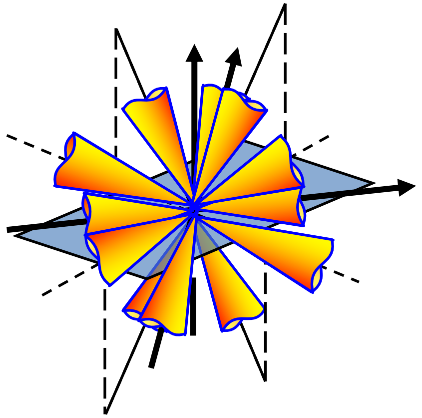
- EM cascades in MCLP

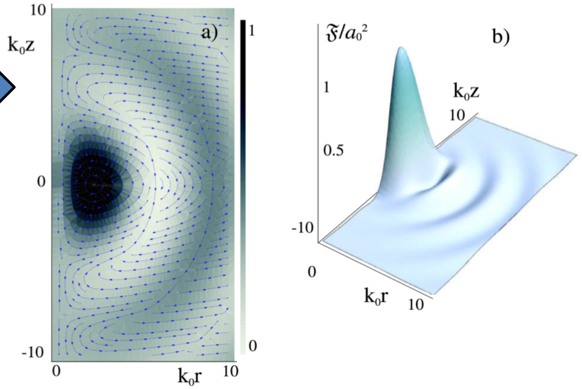
A. Gonoskov et al., PRL **113**, 014801 (2014).
E. G. Gelfer et al., Phys. Rev. A 92, 022113 (2015).
M. Vranic et al., PPCF **59**, 014040 (2017).
Z. Gong et al., PRE **95**, 013210 (2017).

- Directed source of GeV photons

A. Gonoskov et al., Phys. Rev. X 7, 041003 (2017).







- MCLP + e-beam = Basis for studying high-energy high-intensity physics

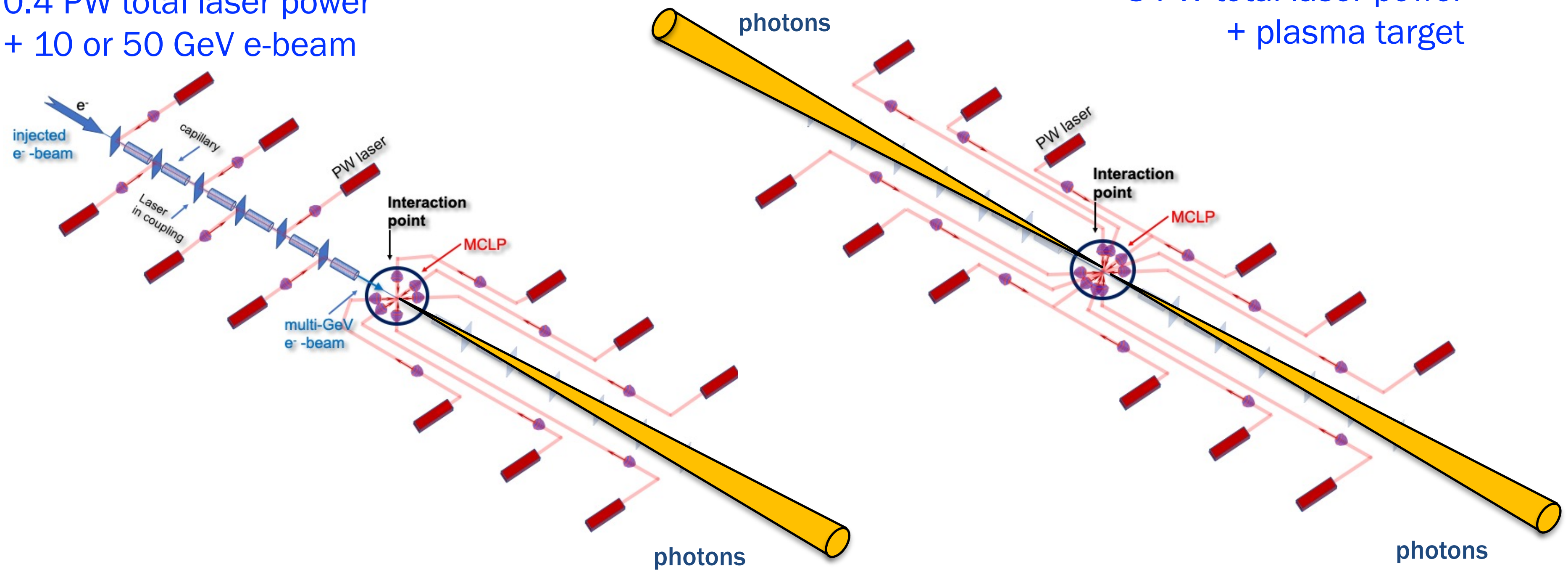
$$a_0 \sim 800\sqrt{\mathcal{P}\,[\mathrm{PW}]}$$

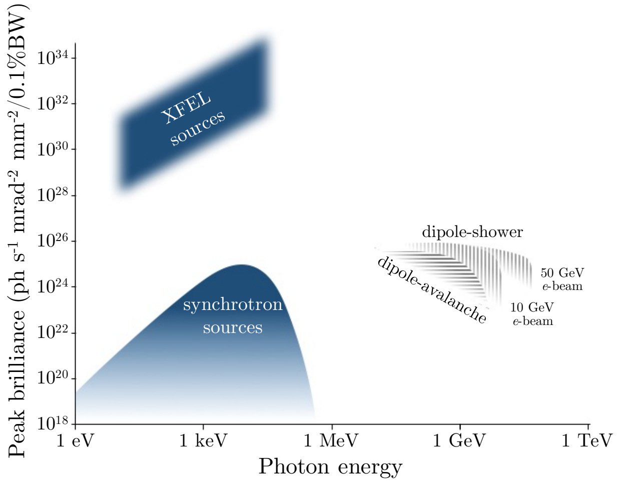
J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

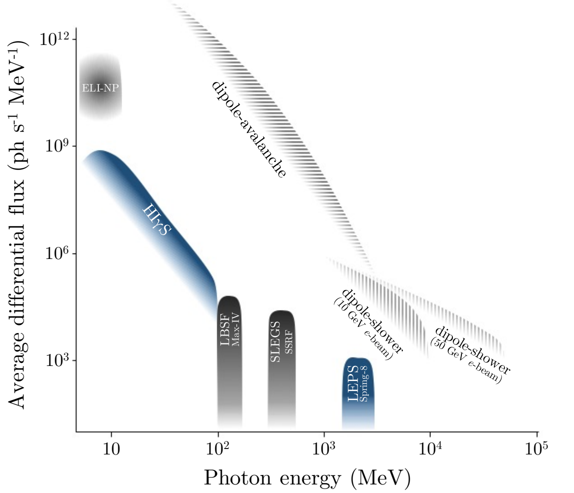
Multiple-Beam laser facility can efficiently produce multi-GeV photon beam with high peak brilliance and high average flux

e-beam interaction with
Multiple Colliding Laser Pulses
dipole-shower:
0.4 PW total laser power
+ 10 or 50 GeV e-beam

Multiple Colliding Laser Pulses
dipole-avalanche:
8 PW total laser power
+ plasma target



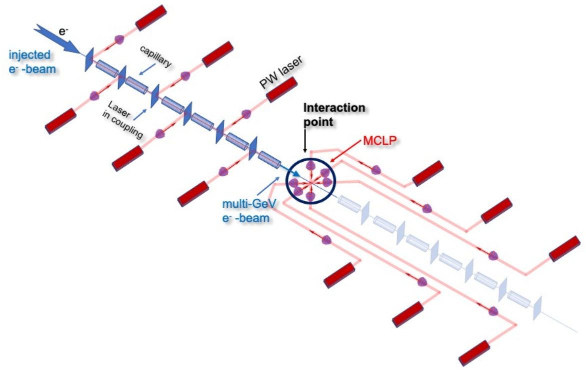


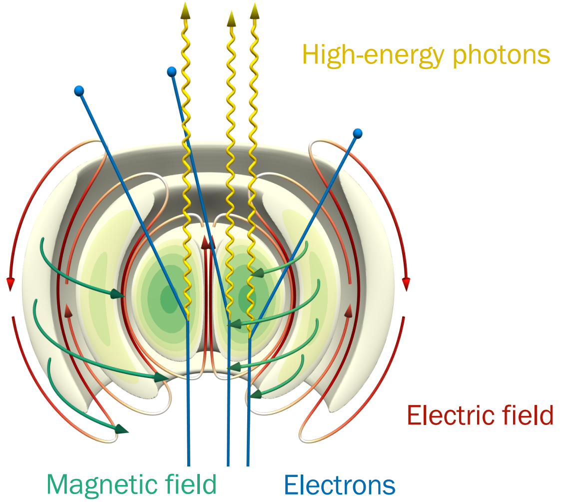


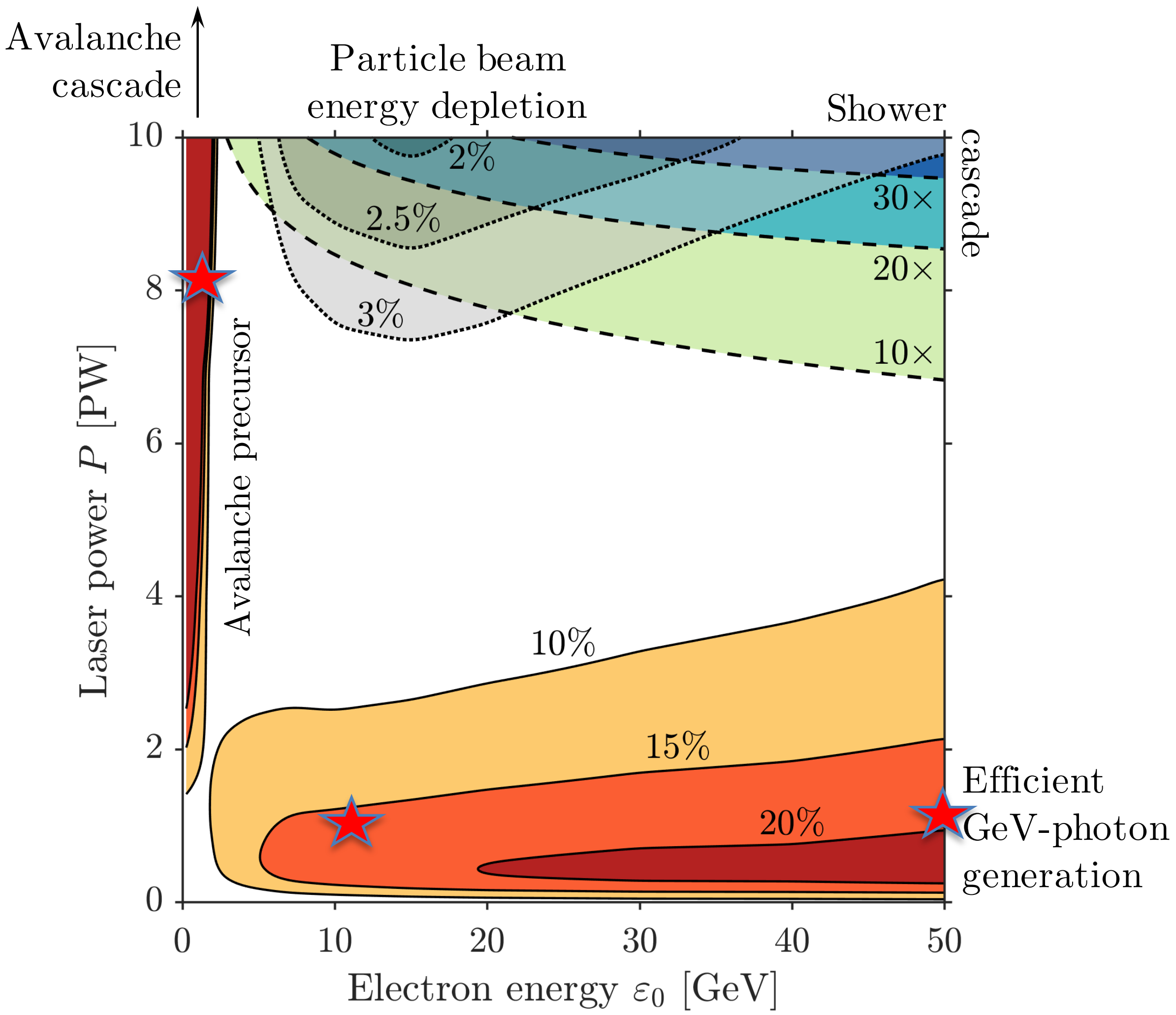
J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

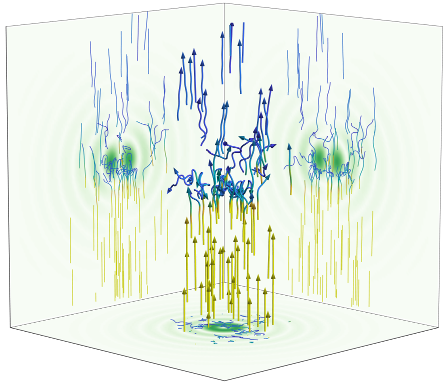
A. Gonoskov, et al, Phys. Rev. X 7, 041003 (2017).

The interaction of a high energy electron beam with MCLP makes assessible different SF QED phenomena





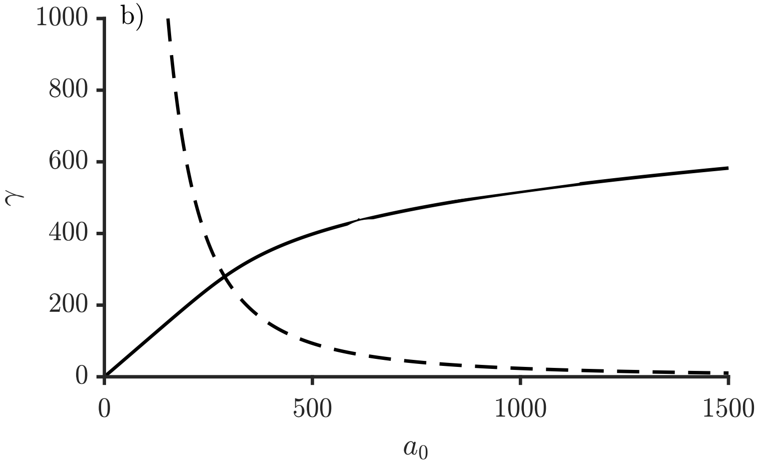




J. Magnusson, et al, Phys. Rev. Lett. 122, 254801 (2019)
J. Magnusson, et al, Phys. Rev. A 100, 063404 (2019)

QED PIC code ELMIS: A. Gonoskov, et al., Phys. Rev. E 92, 023305 (2015)

Extreme e-beam energy depletion gives rise to two distinct populations of photons and electron-positron pairs



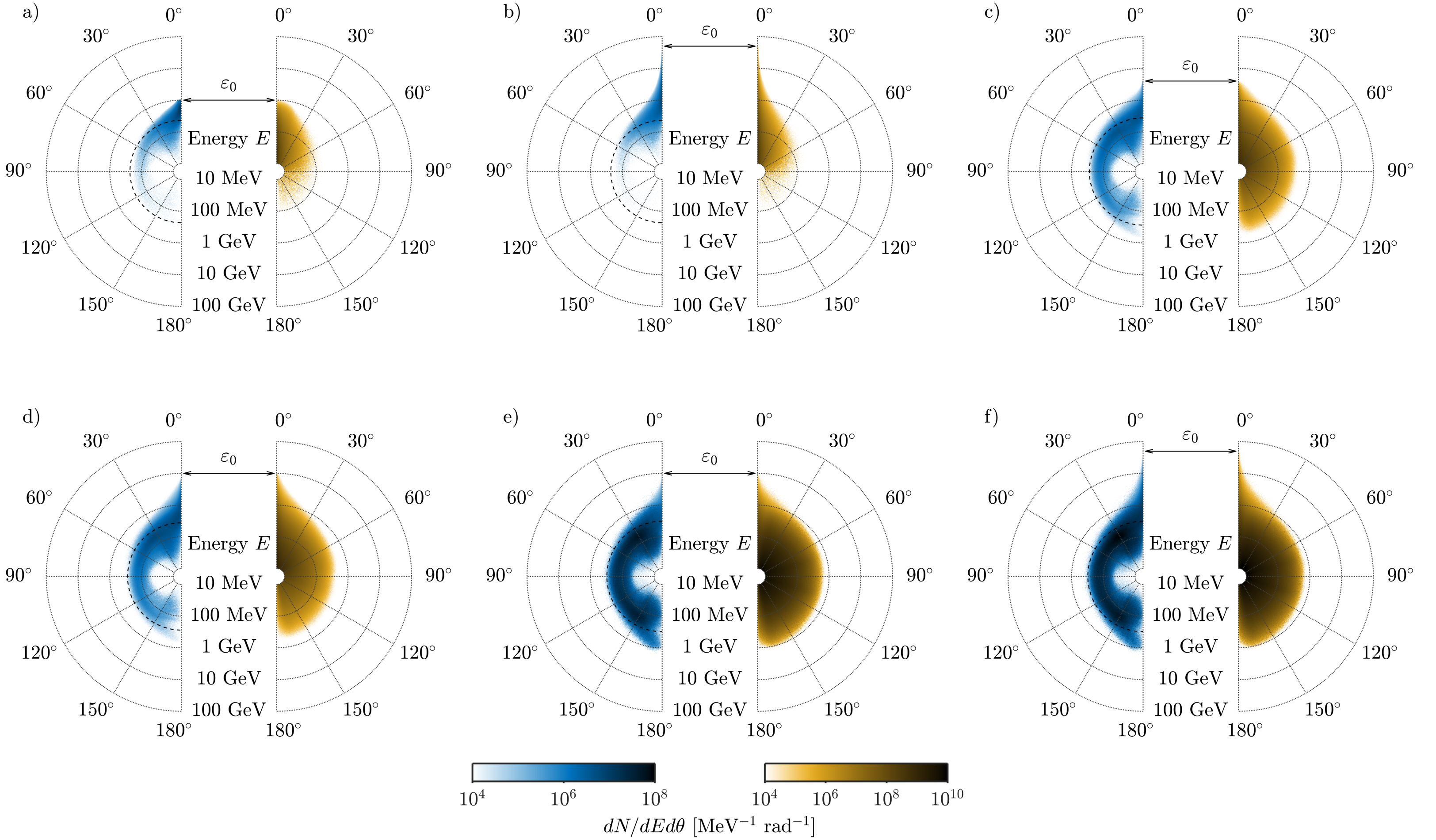
High energies

The high energy photons and electrons are collimated along the electron beam axis

Low energies

There is a near isotropic emission of lower energy photons and electron-positron pairs

Low energy emission come from the (re)acceleration of decelerated electrons and generated pairs



Energy-angle distributions of electrons (blue, left) and photons (yellow, right) emitted from the interaction for six cases of laser power P and initial electron energy ε_0: (a) 1 PW and 1 GeV, (b) 1 PW and 50 GeV, (c) 4 PW and 4 GeV, (d) 4 PW and 10 GeV, (e) 10 PW and 10 GeV, and (f) 10 PW and 50 GeV.

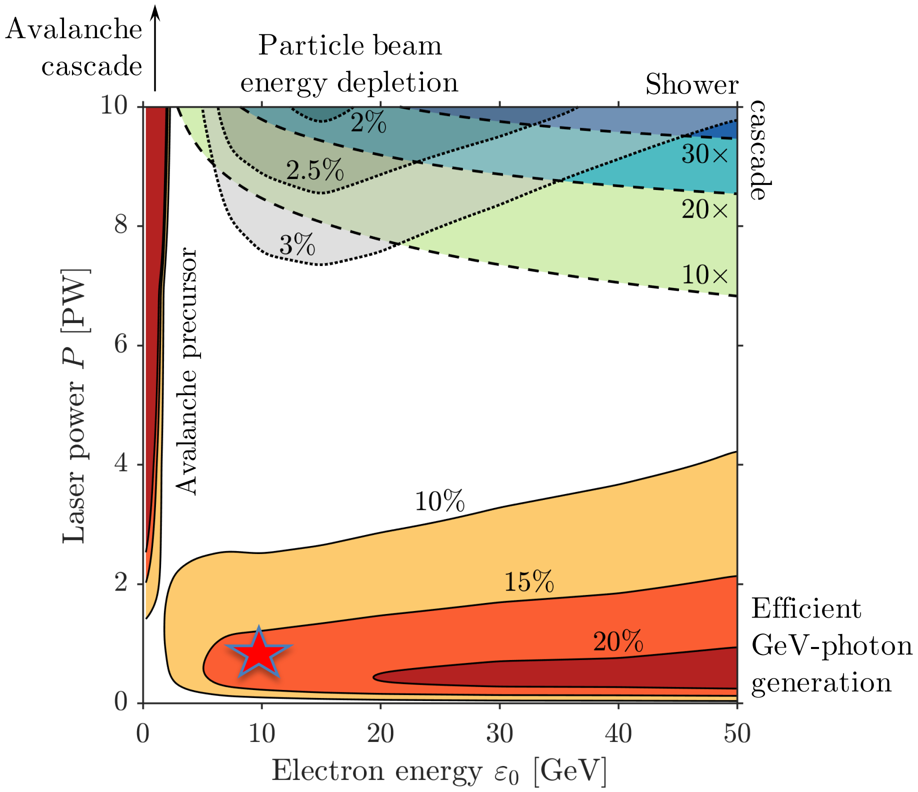
Conclusions

- Optimal for a number of SF QED processes (pair production, EM cascades and avalanches, generation of GeV photons) laser focusing can be realized through the Multiple Colliding Laser Pulses configuration.

- The MCLP configuration when combined with a high energy electron beam provides an effective way of transformation of beam energy into high energy photons.

- The initial electron beam energy and total MCLP power optimal for generation of GeV photons are within reach of PW-class laser facilities.

- The interaction of a high energy electron beam with the MCLP leads to a fast depletion of the electron beam energy.



Thank you!