High energy physics studies at PW-class laser and advanced accelerator linear collider facilities

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High-power lasers are able to generate strong electromagnetic fields, which can probe different regimes of charged particle interactions.

**Charge particle motion and radiation in strong electromagnetic fields** A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod. Phys. (2022)
Strong Field Quantum Electrodynamics describes the phenomena in strong EM fields in the environments where the field strength is large relative to the QED critical field. Laser fields may provide both strong electromagnetic fields and generate high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.

- Nonperturbative Quantum Field Theory
- Matter in Extreme conditions
- Next generation lasers
  - Day-to-day operation
  - New applications
- Future lepton colliders
- Future yy colliders
- Various astrophysical phenomena

Laser fields may provide both strong electromagnetic fields and generate high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.


- Electron positron pair production from vacuum (Schwinger, 1951)
- Electromagnetic avalanches (Bell&Kirk, 2008)
- Electromagnetic cascades (Bella et al, 2006)

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

4-wave mixing (Lundström et al, 2006)

Interaction point physics at future TeV class lepton colliders (Yakimenko et al, 2019)

Birefringent e.m. vacuum (Rozanov, 1993)

- Multiphoton Compton and Breit-Wheeler processes
  - A. I. Nikishov, V. I. Ritus (1964);
Sources of strong fields and why focus on lasers?

1. The magnetic fields surrounding compact astrophysical objects, such as pulsars, magnetars and black holes.

2. The boosted, collective Coulomb fields of ultrarelativistic, dense lepton bunches, as found at the final focus of conventional particle accelerators.

3. The electric fields around high-Z nuclei.

4. The coherently summed, nuclear electric fields observed by ultrarelativistic leptons travelling through a crystal along an axis of symmetry.

5. The electromagnetic fields produced by focusing of high-power lasers.

Acceleration of particles and generation of new sources of radiation is a major part of the scientific case for new high-power laser facilities. Since the regimes of these applications will be affected or even dominated by the interplay between collective plasma effects and strong field quantum processes, it is of paramount importance that such studies become an integral part of the scientific program.

Moreover, the architecture of such laser accelerator facilities makes it natural to study SFQED on-site.

P. Zhang, et al, PoP 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 \( mc^2 \)

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

\[ E_S = \frac{m^2 c^3}{eh} = 1.32 \times 10^{16} \text{ V/cm} \]

\[ a_s = \frac{\hbar \omega}{mc^2} = 4.1 \times 10^5 \]

Quantum Effects

\[ \chi_e = \frac{eh}{m^3 c^4} \sqrt{(F_{\mu\nu}p^\nu)^2} \]

\[ \chi_y = \frac{eh}{m^3 c^4} \sqrt{(F_{\mu\nu}k^\nu)^2} \]
The interaction of a multi-GeV electron beam with a PW class laser pulse will produce photons and electron-positron pairs.

Charged particle motion and radiation in strong electromagnetic fields, A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod. Phys. (2022)
What can be expected in terms of positron and photon production by high intensity lasers?

Number of positrons produced in high-intensity laser-plasma interactions. For laser-electron beam interactions (open circles), the energy of the electron beam is noted in brackets. Points marked with asterisks indicate experimental results from LWFA electron-beam interactions with high-Z foils; in these cases the laser power is not indicated.

Brightness of radiation emitted in high-intensity laser interactions with electron beams (open circles) or plasma targets (filled circles), as well as in non-laser strong-field environments, as (1-2) measured in recent experiments and (3-) predicted by simulations.

Charged particle motion and radiation in strong electromagnetic fields, A. Gonoskov, T. G. Blackburn, M. Marklund, and S. S. Bulanov, Rev. Mod.Phys. (2022)
How higher electromagnetic field strength can be achieved?

Multi-PW and Multiple-beam laser facility is expected to reach new regimes of SFQED
Two configurations are possible: (i) e-beam laser interaction and (ii) laser – laser interaction

(i) e-beam interaction with Multiple Colliding Laser Pulses

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

(ii) PW laser

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

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

$a_0 \sim 800 \sqrt{P} \ [\text{PW}]$


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


Multi-PW and Multiple-beam laser facility can be turned into an LPA-based collider

- Average laser power requirement determined by luminosity goal
- Maximize charge/bunch to reduce average laser power requirements
- To reach luminosity $\sim 10^{34} \text{s}^{-1} \text{cm}^{-2}$ requires tens of kHz repetition rates (100s kW average laser power)

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

Geddes et al., arXiv:2208.13279 (2022)
Multi-PW and Multiple-beam laser facility can be turned into an LPA-based collider, which needs a demonstration facility at intermediate energy.
20-80 GeV LPA-based Collider Design and Possible Applications

Electron source:
- Photocathode
  - 15 um length
  - Polarized electron beam
  - 0.1 um emittance
- Plasma injector
  - under development

Positron source:
- nC electron beam
- 10 MeV photons via Thomson scattering
- High-Z target
- Damping ring
- 0.1 um emittance

Beam delivery system
- ~100 m
- ~10 m

Electron accelerator

Positron accelerator

**TABLE I**: High-level IP parameters for $\sqrt{s} = 40$ GeV $e^+ e^-$ LPA-based collider.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>200 pC</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>15 um</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1 kHz (upgrade to 25 kHz)</td>
</tr>
<tr>
<td>Spot size at IP</td>
<td>50 nm</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$4 \times 10^{30}$ cm$^{-2}$s$^{-1}$ (upgrade to $1 \times 10^{32}$ cm$^{-2}$s$^{-1}$)</td>
</tr>
</tbody>
</table>

**Laser-plasma based production and acceleration of muons:**
(i) Testing muon acceleration technologies

**QCD:**
(i) Precision $\alpha_s$ measurement
(ii) Measurements to improve simulation modeling
(iii) New QCD measurements: e.g., jet substructure
(iv) New tests of QCD factorization and universality of hadronization effects

**Beyond SM:**
(i) Milli-charged particles
(ii) Axion-like particles
(iii) Low mass resonances decaying to hadronic final states

**Strong Field QED:**
(i) High energy electron/positron/photon interactions with intense EM fields
(ii) Beam delivery system and interaction point limitations due to strong fields

**γγ, ep, ee collider studies**
μ acceleration
proton acceleration
Can LPA-based Collider be reconfigured for different types of studies?

The principal scheme of the advanced accelerator linear collider demonstration facility at intermediate energy with possible reconfiguration into $\gamma\gamma$ collider and electron-ion collider

ANA – advanced and novel accelerator
Conclusions

- Multi-PW and Multi-beam laser facilities are optimal for the study of a number of SF QED processes (pair production, EM cascades and avalanches, generation of GeV photons).

- 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, such as BELLA, ZEUS, and ELI (BL and NP).

- Realizing the challenge of a TeV collider based on advanced and novel accelerating (ANA) techniques will only be possible with a sustained, decades-long R&D effort.

- Intermediate facilities such as a 20-80 GeV collider will be required to demonstrate key accelerator technologies and subsystems that are compatible with the ANA technology. With sufficient science motivation, such a machine could be pursued, enabling key components to be tested on the path to a TeV collider.
The presentation was based on the following papers:


Thank you!