Extreme Light-Matter Interactions: Ultra-Relativistic, Radiation-Dominated and QED plasmas

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The Holy Graal of High Field Physics

Schwinger field limit for "breaking the vacuum":
work done over one Compton length = rest electron energy

$$E_S = \frac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm} \rightarrow \boxed{I_S = 4.6 \times 10^{29} \text{ W/cm}^2}$$

at least four orders of magnitude beyond what predicted with proposed exawatt laser technology ...

...luckily, there's interesting unexplored physics and related challenges to be met well before reaching E_S:

radiation friction, pair plasmas, quantum electrodynamics (QED) in high fields (vacuum nonlinearity, cascades, ...)

A common issue: many-particle and collective effects (even in the initial interaction with a single electron or with vacuum!)

Radiation Reaction (*aka* Friction): classical regime

The equation of motion for a charged particle (electron) must be modified to account self consistently for radiation emission i.e. interaction with the self-generated EM field

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) + \mathbf{f}_{\text{rad}}$$

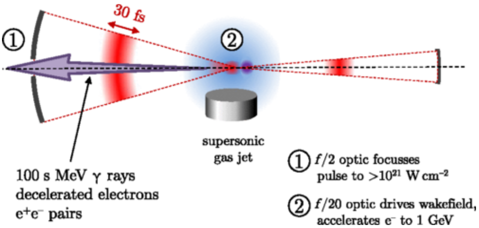
The correct expression of $\mathbf{f}_{\text{rad}}$ is a longstanding problem in classical electrodynamics

“The difficulties [...] touch one of the most fundamental aspect of physics, the nature of an elementary particle [...] the basic problem remains unsolved” (J. D. Jackson)

→ lot of current work on theoretical foundations, technical implementation, effects on dynamics, ...

Radiation Reaction (*aka* Friction): quantum regime

Radiation Reaction (RR) remains an issue also in QED: need to account *all* the relevant processes of interaction with an external field (a many-particle problem)
[see e.g. Di Piazza et al, Rev. Mod. Phys. **84** (2012) 1177 (sec.VI)]

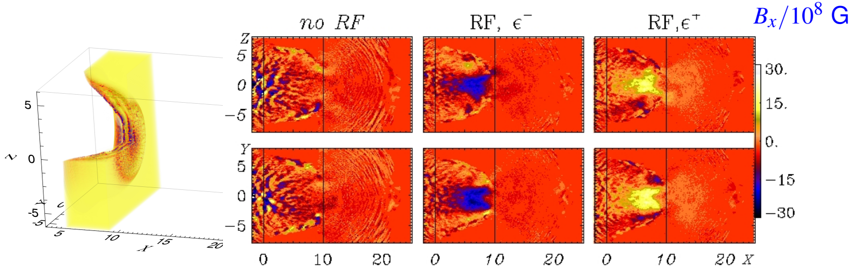


Quantum RR based on discrete photon emission has a stochastic nature which may be evidenced experimentally in all-optical Thomson scattering from GeV electrons at $I \simeq 10^{22}$ W/cm^2

N. Neitz and A. Di Piazza, Phys. Rev. Lett. **111** (2013) 054802
T. G. Blackburn et al, Phys. Rev. Lett. **102** (2014) 015001

Radiation-dominated plasmas

Simulations show radiative losses to play a dominant role in laser-plasma interactions at $I > 10^{23}$ W/cm^2: a laboratory for radiation friction (RF) theory and astrophysical plasmas?

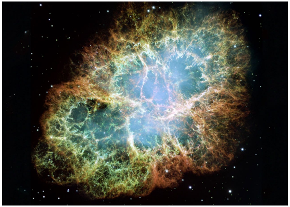


Example: RF induced absorption of EM angular momentum generates ~ 3 GigaGauss magnetic field by "Inverse Faraday Effect" in a plasma

3D simulation; Liseykina, Propuzhenko, Macchi (2015) submitted

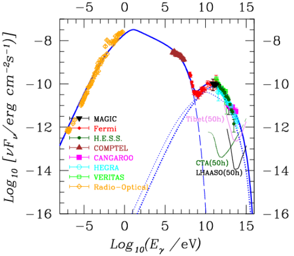
Ultra-relativistic plasmas

High energy plasmas probably exist around the most energetic known objects in the Universe, e.g. the Crab Nebula pulsar



Understanding observations such as γ-ray flaring requires the study of plasmas in high fields and with strong radiation losses, in particular electron-positron pair plasmas

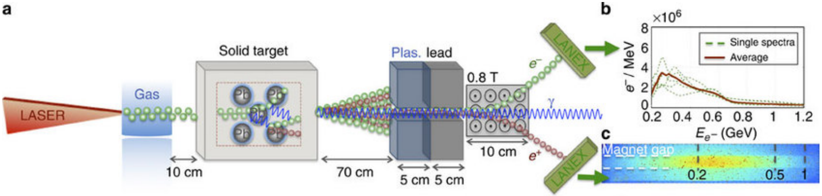
Kohri et al, "Gamma-ray flare and absorption in Crab Nebula: Lovely TeV–PeV astrophysics" Mon. Not. Roy. Astron. Soc. **424** (2012) 2249



Can we study such plasmas in the lab?

Production of pair plasmas from solid targets

Laboratory production of electron-positron pair plasmas via laser-accelerated electrons
$\rightarrow$ Bremsstrahlung in a solid target
$\rightarrow$ pair photo-production in the field of heavy atoms

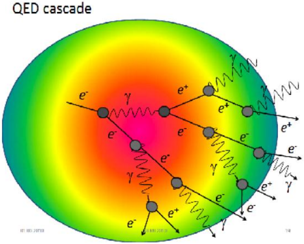


ASTRA-GEMINI laser at RAL (UK): $I = 3 \times 10^{19}$ W/cm^2, $\tau \simeq 42$ fs
Quasi-neutral plasma density: $n_{e\pm} \simeq 10^{16}$/cm^3

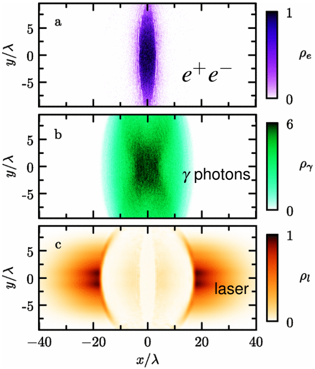
G.Sarri et al, Nature Communications **6** (2015) 6747

Production of pair plasmas in (nearly) *vacuum*

QED cascades from a single electron (or *single photon*) seed in a strong EM field: copious pair production (and ultimate limit on laser intensity?)



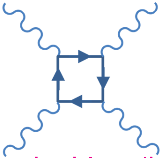
picture by N. Elkina



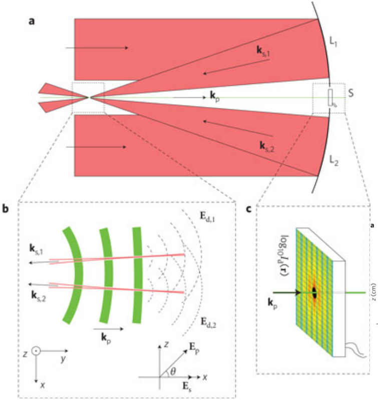
Example: simulated cascades in laser-laser collision at $I \simeq 10^{24}$ W/cm^2 at the edge of ELI capability

[Nerush et al, Phys. Rev. Lett. **106** (2011) 035001]

Probing the nonlinear vacuum



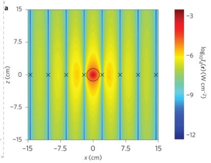
Vacuum is nonlinear because of production of virtual pairs: photon-photon scattering



Proposed matterless double slit interferometry set-up to detect light-by-light diffraction at $I \simeq 10^{24}$ W/cm^2

[King, Di Piazza, Keitel,

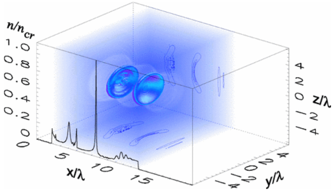
Nature Photonics **4** (2010) 92]

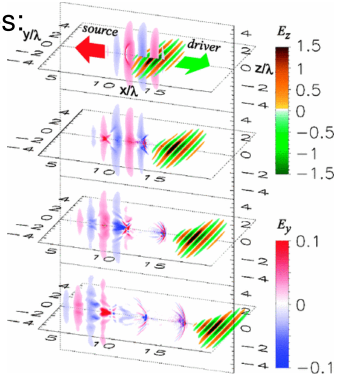


Relativistic plasma optics for intensities $> 10^{24}$ W/cm^2

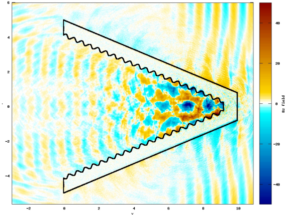
Simulation of “extreme focusing” schemes:

Plasma wakefield as a moving mirror





S.V.Bulanov et al, PRL **91** (2003) 085001



Plasmonic tapered waveguide at high fields

L. Fedeli, A. Sgattoni, A. Macchi, in preparation

Summary and some considerations

ELI-class lasers may allow to study:

- ultra-relativistic, radiation-dominated plasmas (including pair plasmas) with astrophysical (and more) interest for γ-sources
- radiation reaction and QED processes in a high-field, collective regime complementary to the well-investigated high energy sector
- probe the QED vacuum

In addition to laser technology, development and control of relativistic plasma-based optics may allow a further rise of the highest attainable intensity