UNIVERSITY of ROCHESTER

LABORATORY FOR
LASER ENERGETICS
UNIVERSITY OF ROCHESTER

Overview on tests and applications of strong-field QED with multi PW lasers

Antonino Di Piazza

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Outline

- The electromagnetic interaction
- The quantum vacuum and the critical fields of QED
- Strong-field QED in an intense laser field
- Radiation reaction in a nutshell
- Vacuum-polarization effects in a nutshell
- Flying-focus beams: a new tool to study strong-field QED
- The multipetawatt laser facility NSF OPAL
- Conclusions
- Reviews on strong-field QED:
  1. A. Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)
  2. B. King and T. Heinzl, High Power Laser Sci. Eng. **4**, e5 (2016)
  3. T. G. Blackburn, Rev. Mod. Plasma Phys. **4**, 5 (2020)
  4. F. Karbstein, Particles **3**, 39 (2020)
  5. A. Gonoskov et al., Rev. Mod. Phys. **94**, 045001 (2022)
  6. A. M. Fedotov et al., Phys. Rep. **1010**, 1 (2023)

The electromagnetic interaction

- Quantum electrodynamics (QED) is the relativistic quantum theory describing the interaction among electric charges
- By considering the lightest electric charges, electrons and positrons, the basic scales of QED are obtained by combining the electron charge e and mass m, together with c and $\hbar$:

Strength: $\alpha=e^2/4\pi\epsilon_0\hbar c=7.3\times10^{-3}$ (Fine-structure constant)	Energy: $mc^2=0.51\ \mathrm{MeV}$ (Electron rest energy)
Length: $\lambda_C=\hbar/mc=3.9\times10^{-11}\ \mathrm{cm}$ (Compton wavelength)	Electromagnetic field: $E_{cr}=m^2c^3/\hbar\|e\|=1.3\times10^{16}\ \mathrm{V/cm}$ $B_{cr}=m^2c^3/\hbar\|e\|=4.4\times10^{13}\ \mathrm{G}$ (Critical fields of QED)

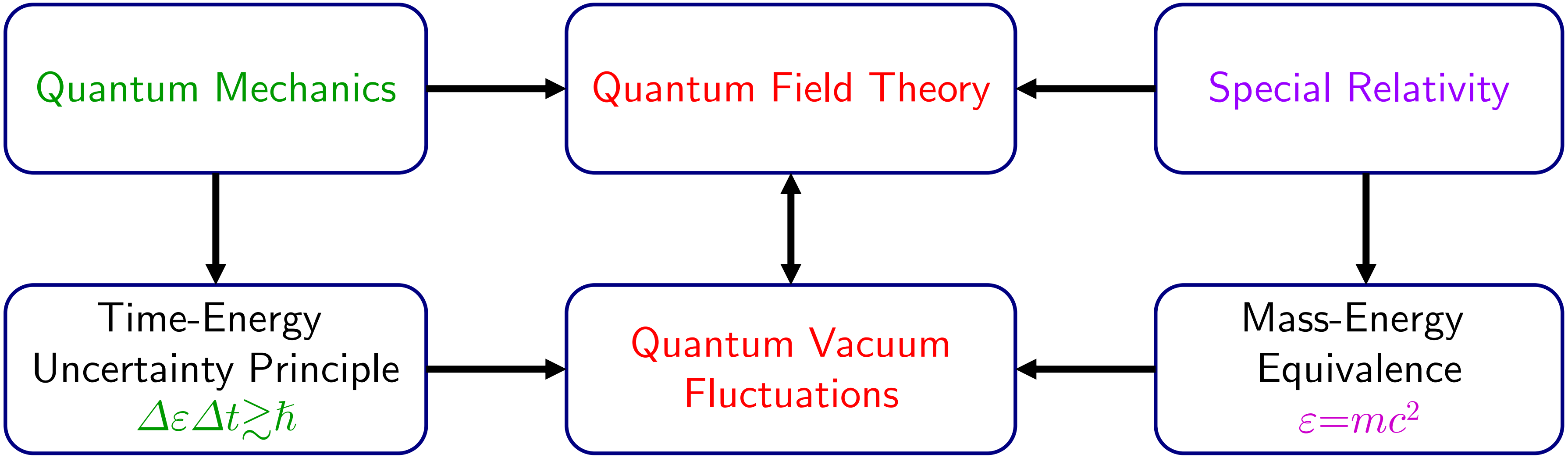
- Critical laser intensity of QED:

$$I_{cr}=cE_{cr}^2=4.6\times10^{29}\ \mathrm{W/cm^2}$$

World-record intensity: $10^{23}\ \mathrm{W/cm^2}$ (Yoon et al. 2021)

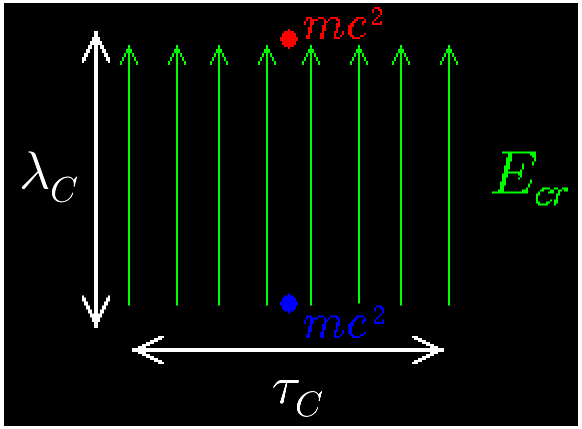
The quantum vacuum and the critical fields of QED

- The vacuum state is the lowest-energy state of the theory, where no particles are present
- In quantum field theory
  - "Fluctuations" of particles-antiparticles are present in the vacuum
  - They cover a very short distance and annihilate again after a very short time (in the case of electrons and positrons $\lambda_C=\hbar/mc\sim10^{-11}$ cm and $\tau_C=\lambda_C/c=\hbar/mc^2\sim10^{-21}$ s, respectively)



- Physical meaning of the critical fields:

$$|e|E_{cr} \times \frac{\hbar}{mc} = mc^2$$



- Vacuum instability and electromagnetic cascades (Bell et al., PRL 2008, Bulanov et al., PRL 2010, Fedotov et al., PRL 2010)
- The interaction energy of a Bohr magneton with a magnetic field of the order of B_{cr} is of the order of the electron rest energy
- In the presence of background electromagnetic fields of the order of the critical ones a new regime of QED, the strong-field QED regime, opens:

  1. where the properties of the vacuum are substantially altered by the fields
  2. where a tight interplay unavoidably exists between collective (plasma-like) and quantum effects
  3. which is unaccessible to conventional accelerators because it requires coherent fields

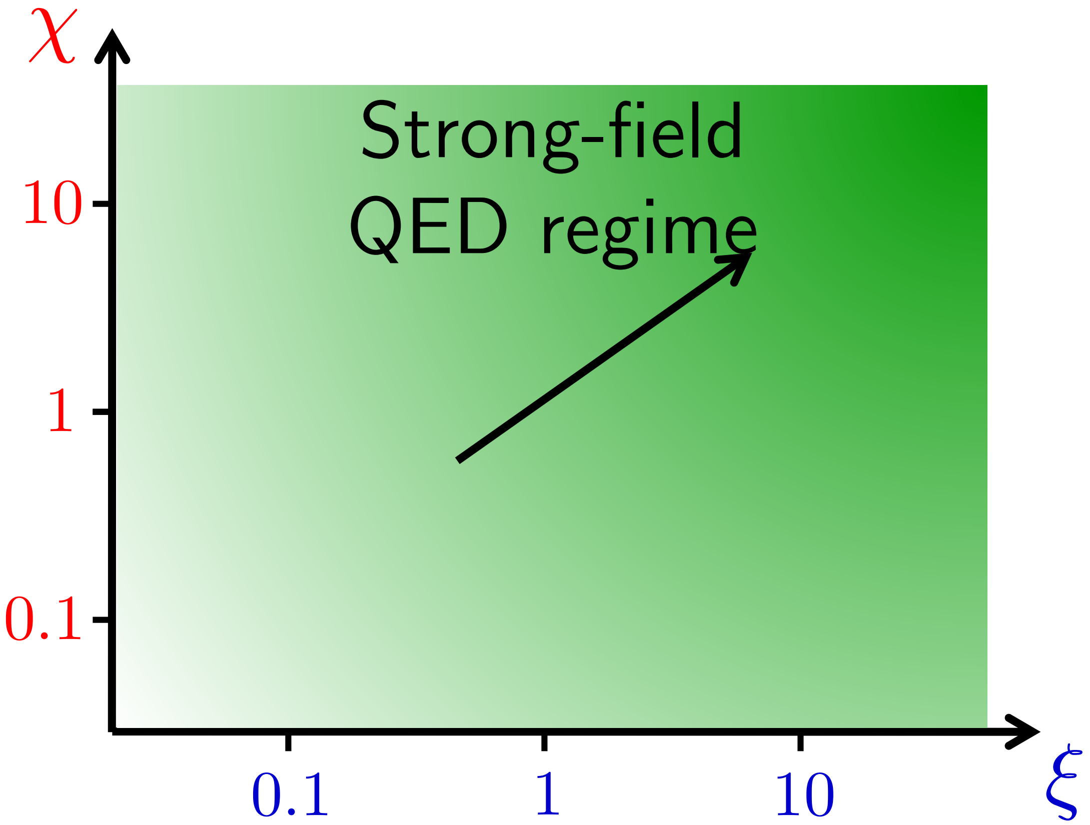
Strong-field QED in an intense laser field

- An electron with energy ε collides head-on with a plane wave with amplitude E_L and angular frequency ω_L (wavelength λ_L)

- The physical observables depend on the two Lorentz- and gauge-invariant parameters

$$\xi = \frac{1}{2\pi}\frac{|e|E_L\lambda_L}{mc^2} = \frac{|e|E_L\lambda_C}{\hbar\omega_L}$$

$$\chi = \frac{E_L}{E_{cr}}\bigg|_{\text{rest frame}} \approx \frac{2\varepsilon}{mc^2}\frac{E_L}{E_{cr}}$$



Optical laser technology

Optical laser technology ($\hbar\omega_L \sim 1$ eV, $\lambda_L \sim 1$ μm)	Energy (J)	Pulse duration (fs)	Spot radius (μm)	Intensity (W/cm^2)
Experiments (Astra Gemini, CoReLS)	10	40	2.5	4×10^{20}
Facilities (APOLLON, ELI Beamlines, ELI-NP, ZEUS etc...)	$10\div100$	$10\div20$	1	$10^{21}\div10^{22}$
Record intensity (CoReLS, 2021)	50	20	1.1	1.1×10^{23}
Future projects (NSF OPAL)	2×500	20	1.3	5×10^{23}

Electron accelerator technology

Electron accelerator technology	Energy (GeV)	Beam duration (fs)	Spot radius (μm)	Number of electrons
Conventional accelerators (SLAC)	50	3×10^3	1	4×10^{10}
Laser-plasma accelerators (LBNL)	7.8	35	40	3×10^7

Message: Present technology allows for the experimental investigation of strong-field QED

$$\xi = 7.5\frac{\sqrt{I_L[10^{20}\ \mathrm{W/cm^2}]}}{\hbar\omega_L[\mathrm{eV}]}$$

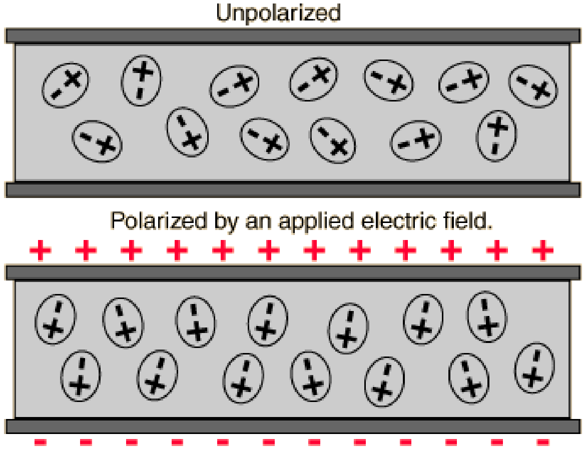
$$\chi = 5.9\times10^{-2}\,\varepsilon[\mathrm{GeV}]\sqrt{I_L[10^{20}\ \mathrm{W/cm^2}]}$$

Radiation reaction in a nutshell

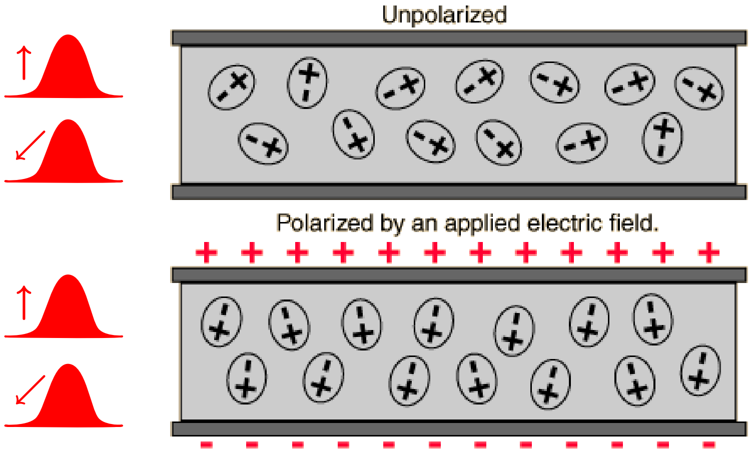
Units with $\epsilon_0=\hbar=c=1$

- Accelerated electric charges emit electromagnetic radiation (relativistic Larmor formula, s is the electron's proper time) $$\frac{d\mathcal{E}}{dt} = -\frac{2}{3}\frac{e^2}{4\pi}\frac{du^\mu}{ds}\frac{du_\mu}{ds}$$
- The exact dynamics of the electron in an external field includes the effects of this energy loss (and of the related momentum loss)
- By adding an extra force to the Lorentz equation due to the field produced by the electron itself, one can obtain the Lorentz-Abraham-Dirac (LAD) equation $$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{2}{3}\frac{e^2}{4\pi}\left(\frac{d^2u^\mu}{ds^2} + \frac{du^\nu}{ds}\frac{du_\nu}{ds}u^\mu\right)$$
- The LAD equations features physical inconsistencies (runaway solutions, violation of causality) essentially due to the Schott term
- Landau and Lifshitz noticed that within classical electrodynamics a "reduction of order" can be carried out: $$\frac{du^\mu}{ds} \approx \frac{e}{m}F^{\mu\nu}u_\nu \text{ in } \frac{2}{3}\frac{e^2}{4\pi}\left(\frac{d^2u^\mu}{ds^2} + \frac{du^\nu}{ds}\frac{du_\nu}{ds}u^\mu\right)$$
- One obtains the Landau-Lifshitz (LL) equation $$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{2}{3}\frac{e^2}{4\pi}\left[\frac{e}{m}(\partial_\alpha F^{\mu\nu})u^\alpha u_\nu - \frac{e^2}{m^2}F^{\mu\nu}F_{\alpha\nu}u^\alpha + \frac{e^2}{m^2}(F^{\alpha\nu}u_\nu)(F_{\alpha\lambda}u^\lambda)u^\mu\right]$$
- Experiments on radiation reaction in intense laser fields: Cole et al., 2018, Poder et al., 2018, Los et al., 2024

Vacuum-polarization effects in a nutshell



- Due to the presence of the virtual electron-positron pairs, the vacuum according to QED behaves as a birefringent medium
- Dichroic/absorptive effects come into play when pair production becomes sizable
- For fields with wavelengths much larger than the $\lambda_C \approx 3.9\times10^{-7}\ \mu\mathrm{m}$, vacuum-polarization effects are local
- They can be described as if the vacuum features two refractive indexes depending on the mutual polarization of polarizing and probe fields



- Examples of vacuum refractive indexes for a background electromagnetic field $(\boldsymbol{E}, \boldsymbol{B})$ and a probe propagating along the direction $\boldsymbol{n}$ and polarized either along $\boldsymbol{\mathcal{E}}$ or along $\boldsymbol{\mathcal{B}}$ ($I_{cr} \sim 10^{29}\ \mathrm{W/cm^2}$)

$$\boldsymbol{\mathcal{E}} = \boldsymbol{E} - (\boldsymbol{n}\cdot\boldsymbol{E})\boldsymbol{E} + \boldsymbol{n}\times\boldsymbol{B}$$

$$n_{\mathcal{E}} = 1 + \frac{4\alpha}{90\pi}\,\frac{(\boldsymbol{n}\times\boldsymbol{E})^2 + (\boldsymbol{n}\times\boldsymbol{B})^2 - 2\boldsymbol{n}\cdot(\boldsymbol{E}\times\boldsymbol{B})}{I_{\mathrm{cr}}}$$

$$\boldsymbol{\mathcal{B}} = \boldsymbol{B} - (\boldsymbol{n}\cdot\boldsymbol{B})\boldsymbol{B} - \boldsymbol{n}\times\boldsymbol{E}$$

$$n_{\mathcal{B}} = 1 + \frac{7\alpha}{90\pi}\,\frac{(\boldsymbol{n}\times\boldsymbol{E})^2 + (\boldsymbol{n}\times\boldsymbol{B})^2 - 2\boldsymbol{n}\cdot(\boldsymbol{E}\times\boldsymbol{B})}{I_{\mathrm{cr}}}$$

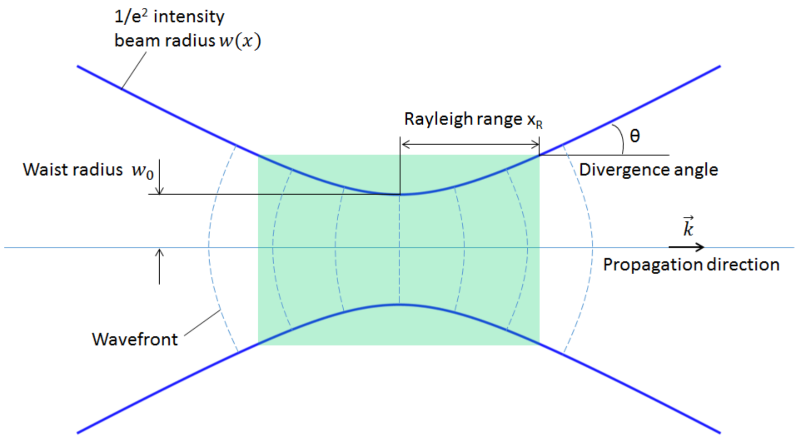
A limitation of Gaussian beams for SFQED

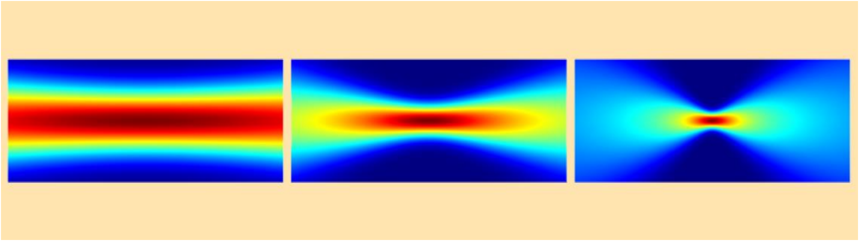
- The expressions of the classical and quantum nonlinearity parameters show that strong-field QED effects benefit from high laser intensities

$$\xi = \frac{1}{2\pi}\frac{|e|E_L\lambda_L}{mc^2} = \frac{|e|E_L\lambda_C}{\hbar\omega_L}$$

$$\chi = \left.\frac{E_L}{E_{cr}}\right|_{\text{rest frame}} \approx \frac{2\varepsilon}{mc^2}\frac{E_L}{E_{cr}}$$

- Interesting effects, like radiation reaction and vacuum birefringence, also depend on how long particles experience strong fields
- Gaussian laser beams feature an intrinsic limitation: at a given power, the more one focuses the beam to increase the intensity, the shorter becomes the longitudinal region where the field is strong





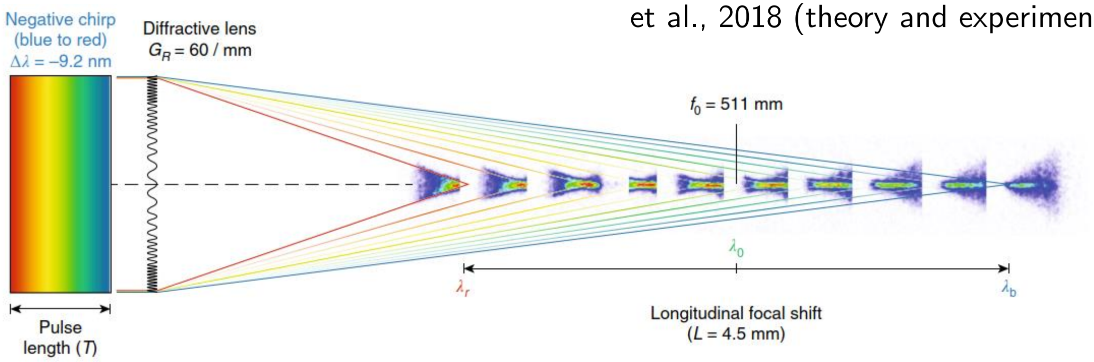
$$E_y(t,\boldsymbol{r}) = B_z(t,\boldsymbol{r}) = E_0\frac{e^{-r_\perp^2/w^2(x)}}{w(x)}\sin\left[\omega(t-x) - \frac{\omega x r_\perp^2}{x^2+x_R^2} + \psi_0\right]$$

$$r_\perp = \sqrt{y^2+z^2}, \quad w(x) = w_0\sqrt{1+\frac{x^2}{x_R^2}}, \quad x_R = \frac{\omega w_0^2}{2}$$

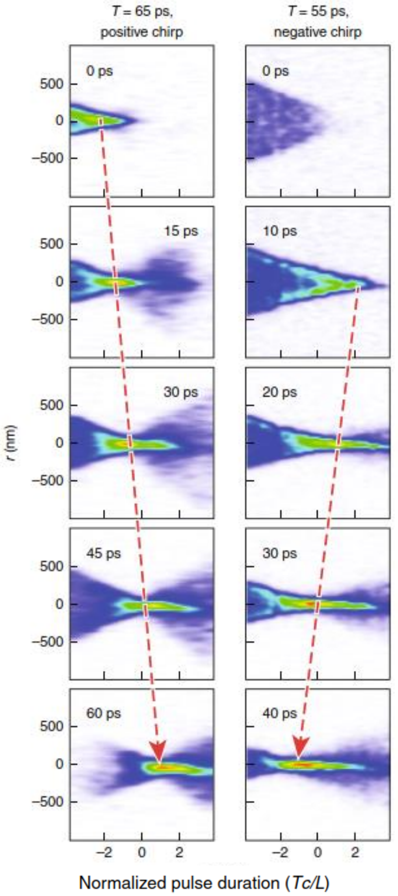
Flying-focus beams

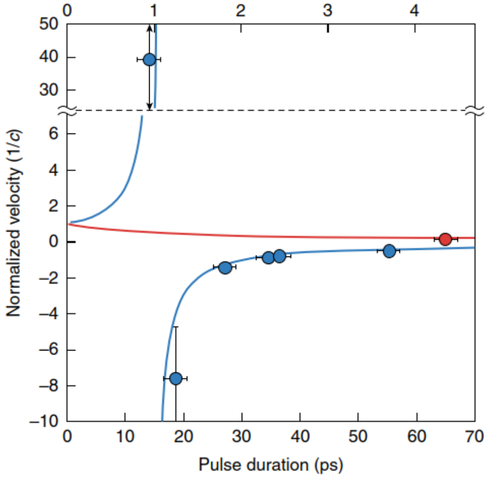
- One can overcome the limitation of a Gaussian beam and control the focal position by using, e.g., a chirped pulse (the frequency content of the pulse depends on time) and a chromatic lens (different frequencies are focused at different points)

Saint-Marie et al., 2017 (theory) and Froula et al., 2018 (theory and experiment)

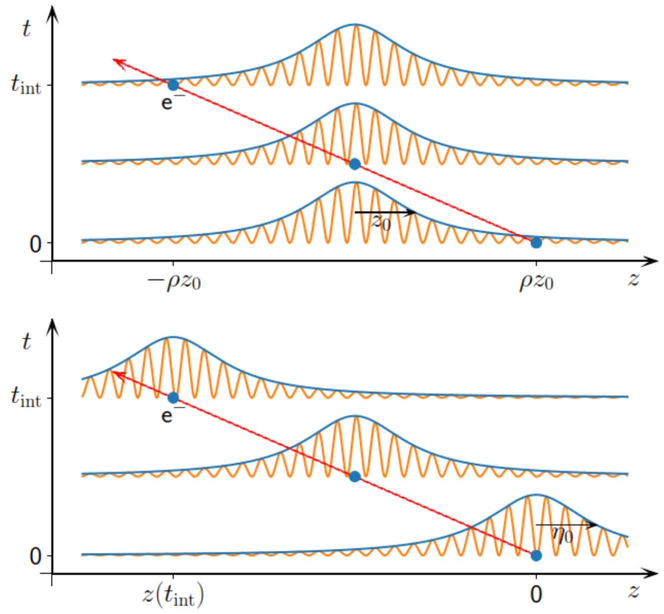


- The velocity of such a “flying-focus” pulse can be controlled, can be either positive or negative and the case $v_f \approx -1$ was demonstrated experimentally
- To sustain the pulse over a long length high energies are required





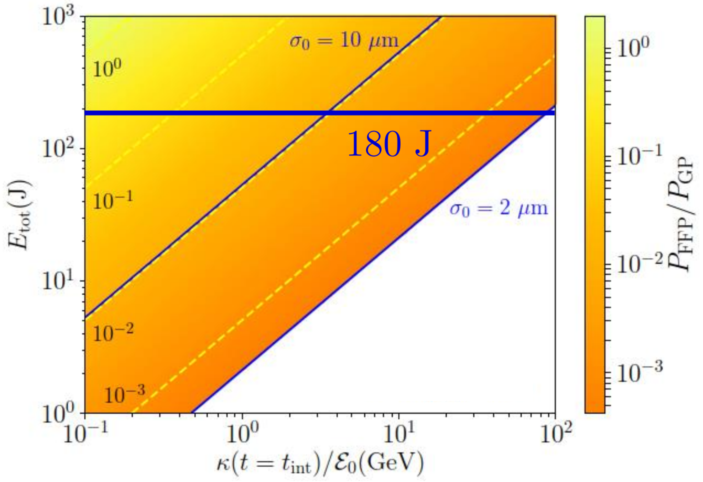
- The idea of using a flying-focus pulse with focus moving at the speed of light in the opposite direction of the phase velocity can be exploited in different contexts



- Classical radiation reaction sizable at relatively low laser powers (Formanek et al. PRA 2022)
- Energy loss due to radiation reaction:

$$\varepsilon(t) \approx \frac{\varepsilon_0}{1+\frac{4\varepsilon_0}{3m} r_e \omega_0^2 \int_0^t g^2(t')\xi^2(t')dt'} = \frac{\varepsilon_0}{1+\kappa(t)}$$

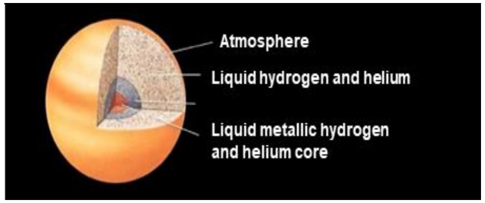
- The energy loss depends on the laser energy per unit surface ($\kappa(t) \sim \xi_0^2 t$)
- A flying-focus allows for the same energy losses than a Gaussian beam but at much lower power
- Numerical results for $t_{\rm int} = 100$ ps (corresponding to $\sim$ 60,000 oscillations)



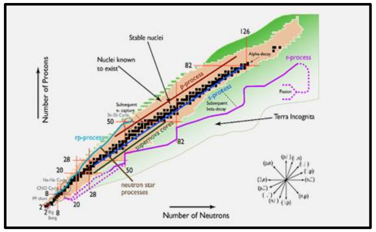
- Similar conclusions hold for vacuum-polarization effects

NSF OPAL: a laser design project funded by NSF and guided by the most pressing scientific questions in the four research areas

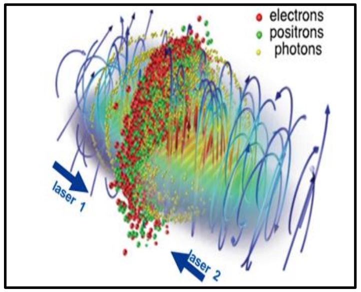
Laboratory Astrophysics and Planetary Physics (LAPP)



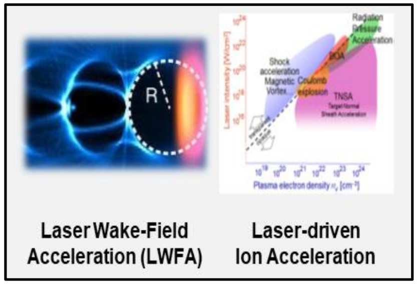
Laser-Driven Nuclear Physics (LDNP)



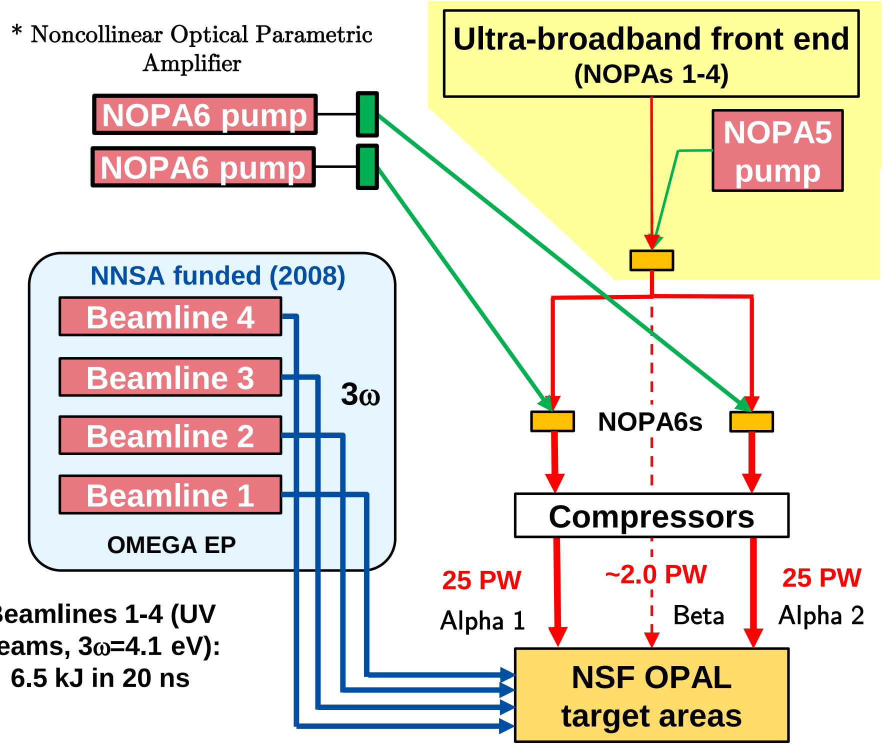
High-Field Physics and Quantum Electrodynamics (HFP/QED)



Particle Acceleration and Advanced Light Sources (PAALS)



Laser system



* Noncollinear Optical Parametric Amplifier

Ultra-broadband front end (NOPAs 1-4)

NOPA5 pump

NOPA6 pump

NOPA6 pump

NOPA6s

Compressors

~2.0 PW Beta

25 PW Alpha 1

25 PW Alpha 2

NNSA funded (2008)

Beamline 4

Beamline 3

Beamline 2

Beamline 1

OMEGA EP

3ω

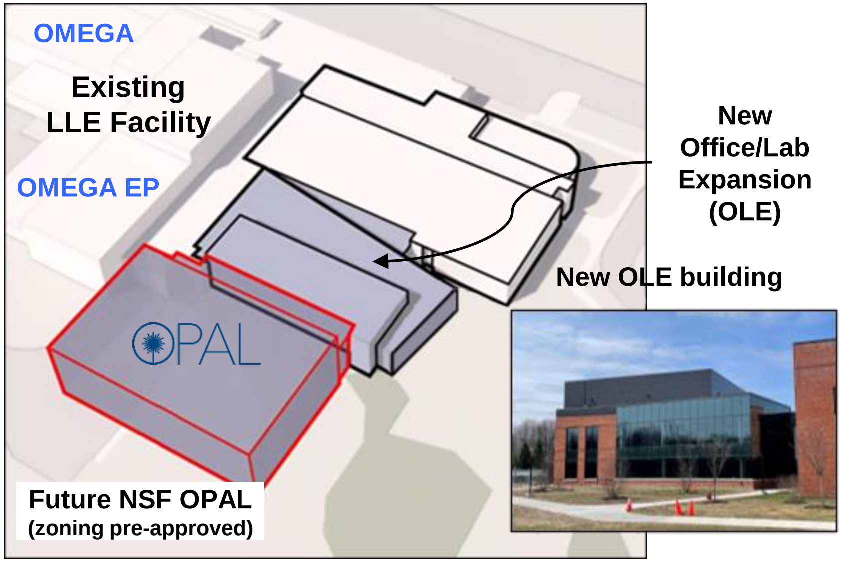
NSF OPAL target areas

Beamlines 1-4 (UV beams, 3ω=4.1 eV): 6.5 kJ in 20 ns

Alpha 1-2 (ω=1.4 eV): 500 J in 20 fs

Beta (ω=1.4 eV): < 50 J in 20 fs

Construction site



New Office/Lab Expansion (OLE)

New OLE building

The two buildings would house NSF OPAL, plus labs and offices for new research

Conclusions

- Modern lasers offer a unique possibility to access new extreme regimes of interaction of light with matter and can be used as a new tool, alternative to conventional accelerators, for investigating fundamental physics and quantum electrodynamics in still uncharted regimes
- Flying-focus beams are laser beams where the focus moves with controllable velocity
- We have proposed to exploit the unique properties of flying-focus beams as a tool to test strong-field effects like radiation-reaction and vacuum-polarization effects under controlled conditions at relatively low laser powers/intensities
- NSF has awarded funding to design NSF OPAL: a two, 25-PW laser system at the LLE for investigating plasma physics, nuclear physics, strong-field QED etc...

A post-doc position is available in my group at the University of Rochester starting at any time

If you are interested, please contact me at
a.dipiazza@rochester.edu