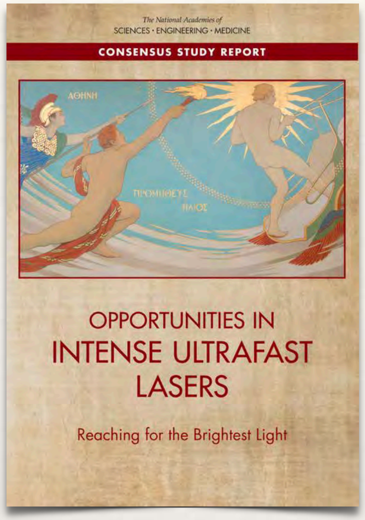
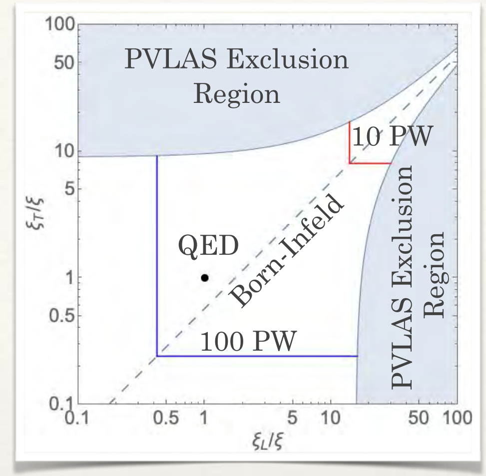


Precision measurement at the petawatt level and above: new frontiers via collaboration



Fundamental Physics

Wendell T. Hill, III

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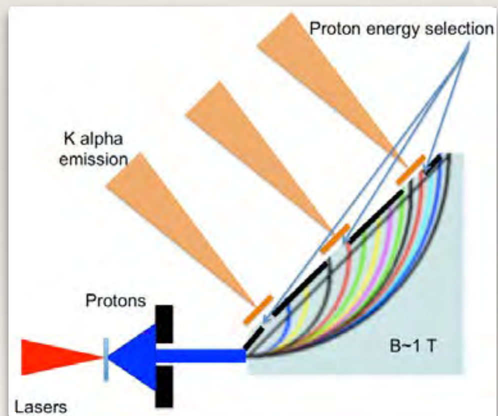
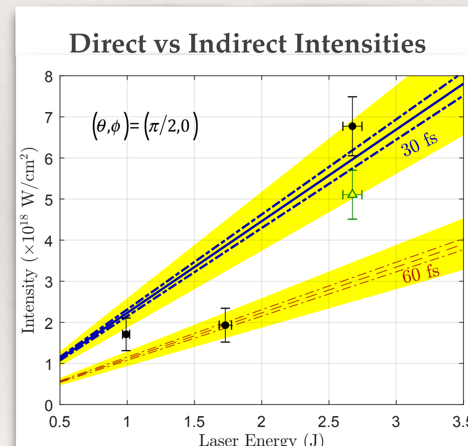
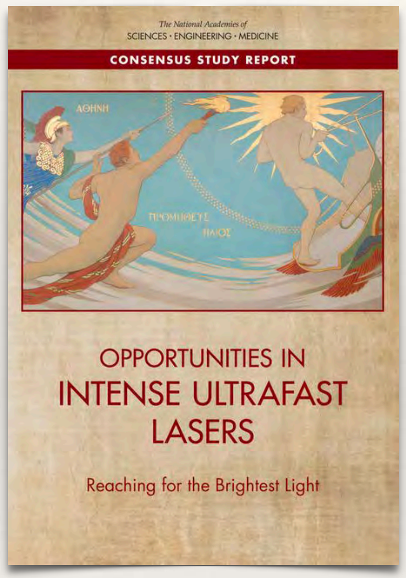


New Technologies



Diagnostics

Needs



Conclusion 1: The science is important. ⋯

Conclusion 2: Applications exist in several areas. ⋯ Science is a main application of high-intensity lasers, and all applications of high-intensity lasers rely on the fundamental science of high-intensity laser-matter interactions.

Conclusion 5: The US has lost its previous dominance. ⋯ Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs.

Recommendation 1: The Department of Energy should create a broad national network ⋯ as the cornerstone of a national strategy to support science, applications, and technology of intense and ultrafast lasers.

Recommendation 5: Agencies should create programs for U.S. scientists and engineers that include mid-scale infrastructure, project operations in high-intensity laser science in the United States, development of key underpinning technologies; and engagement in research at international facilities such as Extreme Light Infrastructure.

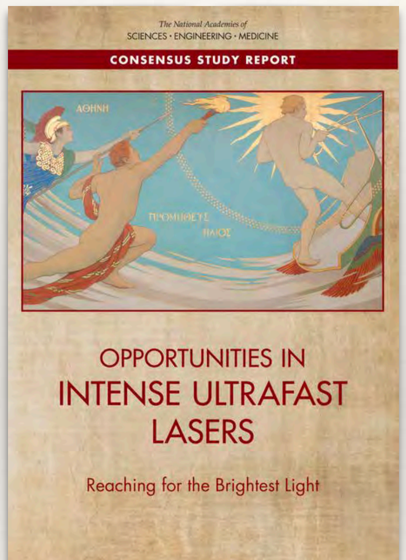
https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

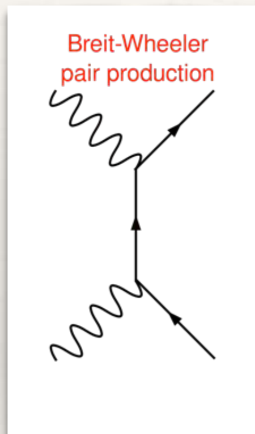
Outline

- Precision Measurement with high statistics (many shots)
- Potential collaborative studies
    - quantum vacuum via photon-photon scattering
    - time history of proton acceleration
    - diagnostic tools
- Summarize

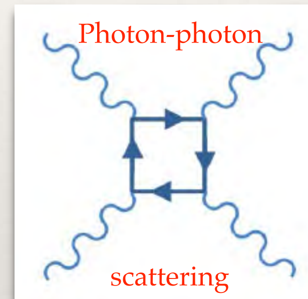
Fundamental Physics

Studying the nature of the quantum vacuum





"The physics case for QED experiments using intense lasers has two general justifications. First, many basic QED processes have not yet been observed or have not been observed in sufficiently clean experiments to allow for detailed comparison with QED predictions. Second, many extensions of the standard model predict as yet unobserved particles/fields. If such particles exist, they typically modify the vacuum polarizability and can therefore have observable consequences on QED processes. Therefore, measurement of fundamental QED processes can, when carefully compared to theory, constitute a search for physics beyond the standard model."

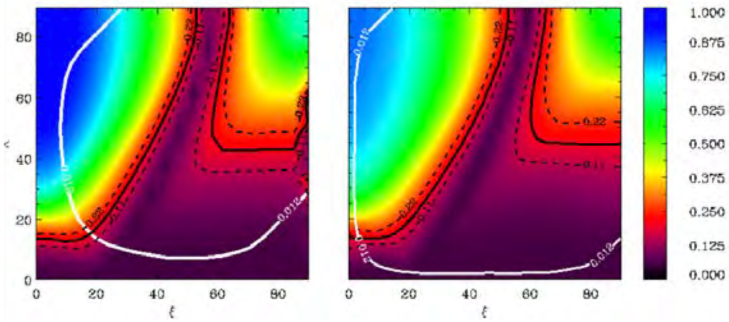


https://www.nap.edu/catalog/24939/opportunities-in-intense-ultrafast-lasers-reaching-for-the-brightest-light

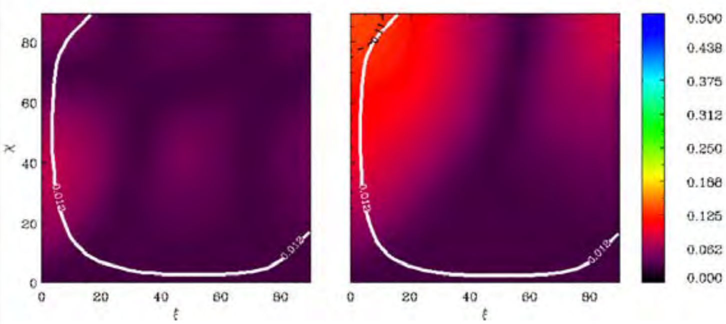
The quantum vacuum

$$\mathcal{L} = -\mathcal{L}_0 + \xi_L \mathcal{L}_0^{\,2} + \left(7/4\right)\xi_T \mathcal{G}^2$$

Evidence for vacuum birefringence from the first optical-polarimetry measurement of the isolated neutron star RX J1856.5–3754



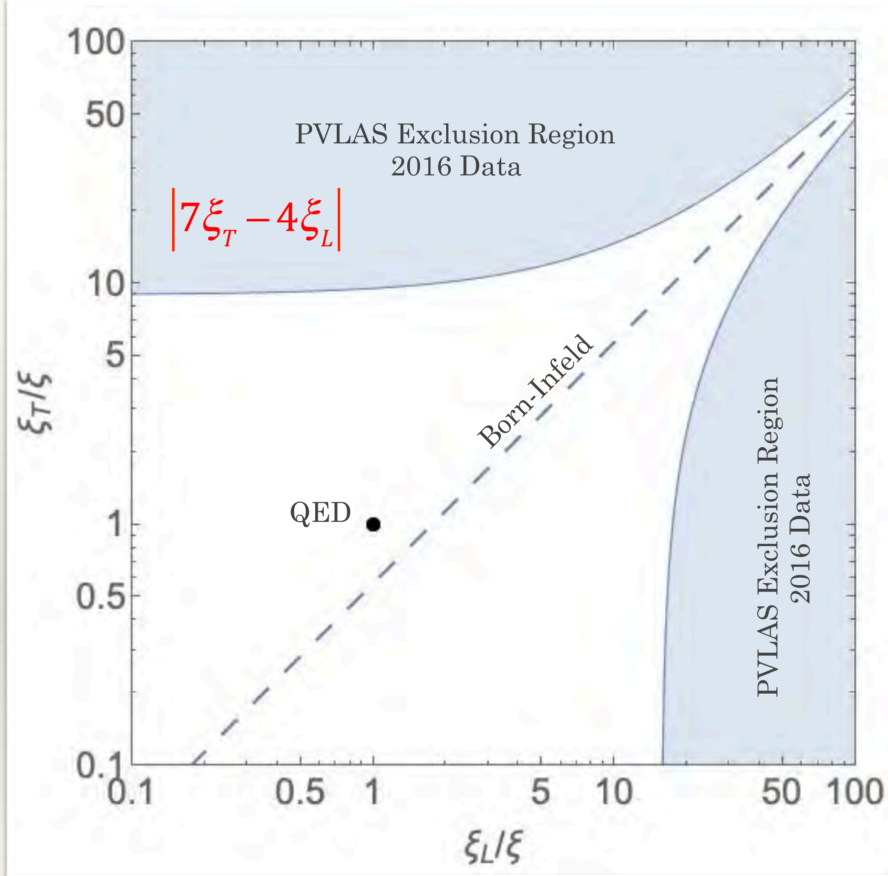
Polarization degree with vacuum polarization



Polarization degree without vacuum polarization

MNRAS **465**, 492–500 (2017).

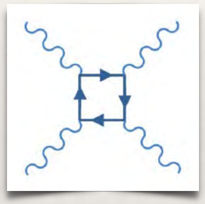
Parameter space where nonlinear response of the vacuum is expected



Updated from Hill and Roso, J Phys.: Conf. Series **869**, 012015 (2017)

The quantum vacuum photon-photon scattering

Limits to single-shot observation for a 3σ measurement
(from Tommasini *et al.*, Springer Series in Chem. Phys. **106** (2014)

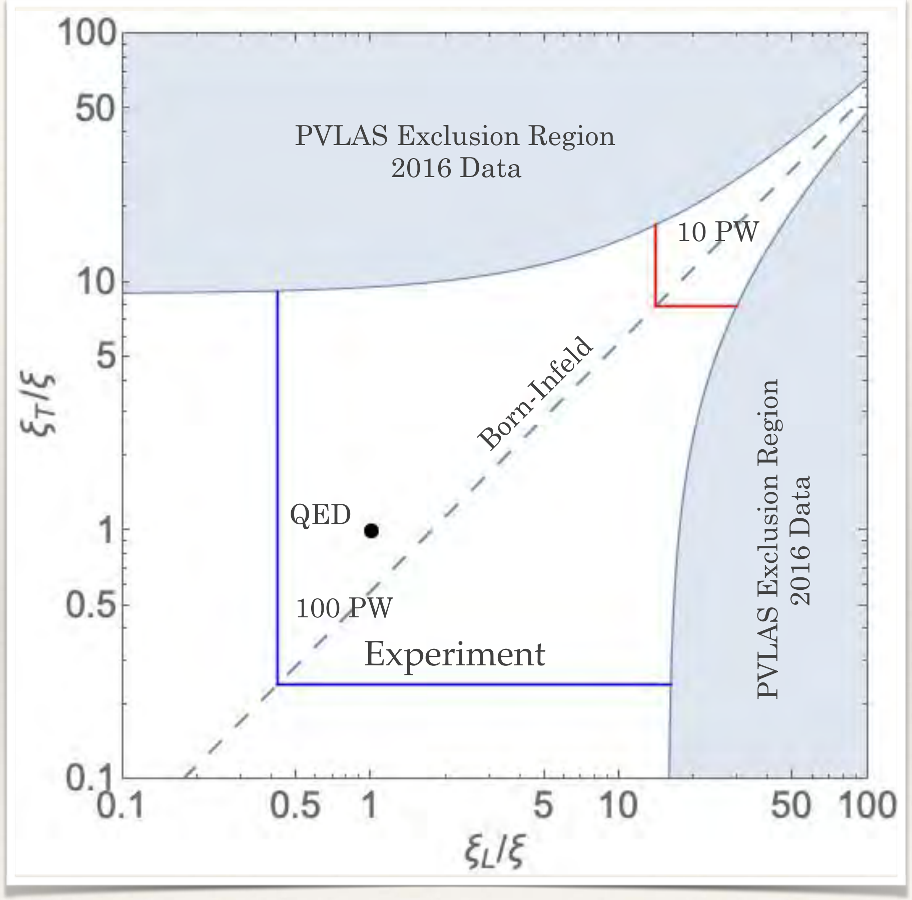


Power (PW)	Limit $\xi_L / \xi^{(QED)}$	Limit $\xi_T / \xi^{(QED)}$
1	4.0×10^2	2.3×10^2
10	24	14
100	0.42	0.24

Collecting multiple shot increases sensitivity

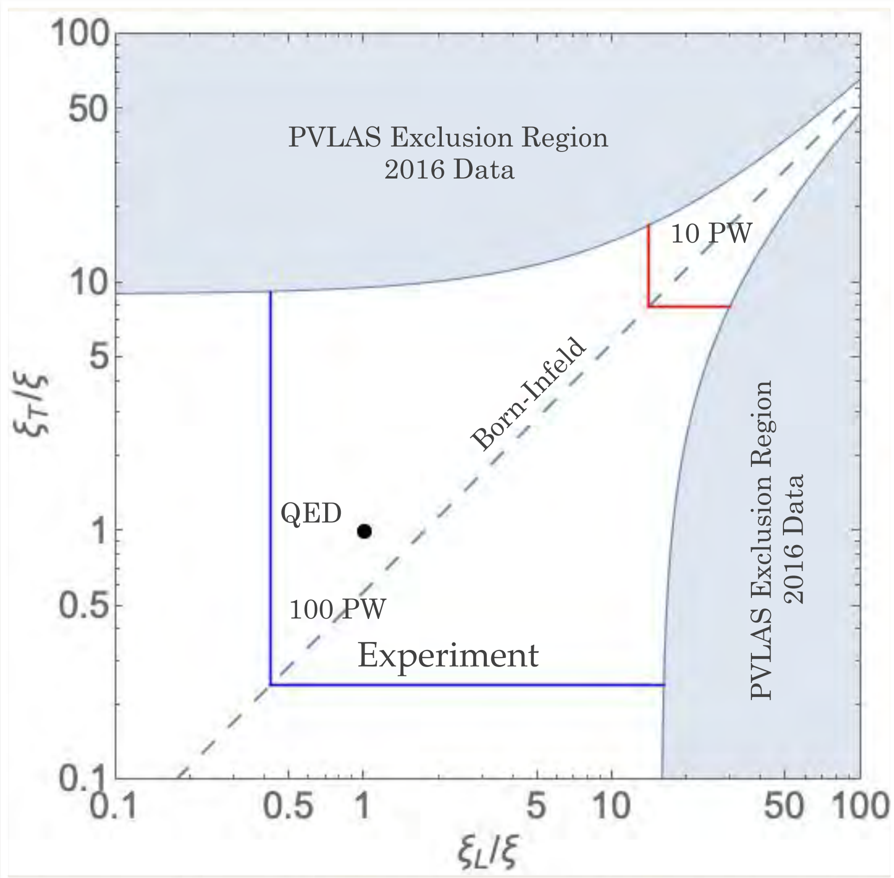
The expected number of events is:

- $\propto N$ with $\sigma_N \propto \sqrt{N}$
- $N \sim 5$k puts a 1 PW laser in the range of a 100 PW single-shot laser

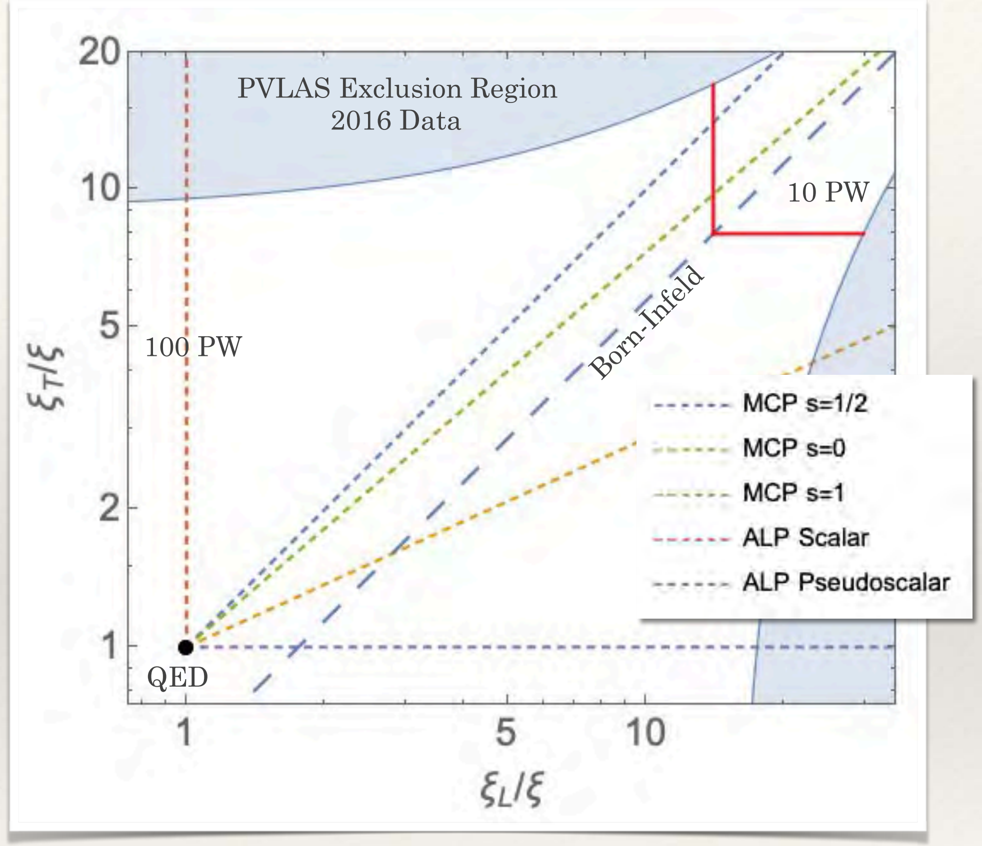


Updated from Hill and Roso, J Phys.: Conf. Series **869**, 012015 (2017)

Parameter space where nonlinear response of the vacuum is expected



Updated from Hill and Roso, J Phys.: Conf. Series **869**, 012015 (2017)



After Tommasini *et al* . Springer Series in Chemical Physics **106**, 137 (2014)

What ELI enables in the near term

What can be enabled by a US-ELI collaboration?

Name/Location	Energy (J)	Peak Power (PW)	Pulse Width (fs)	Rep Rate (Hz)
HAPLS/ELI Beamlines	30	1	30	10
ATON (CPA)/ELI Beamlines	2000	10	130	1/5 min
ELI-NP	210	2 × 10	21	0.017

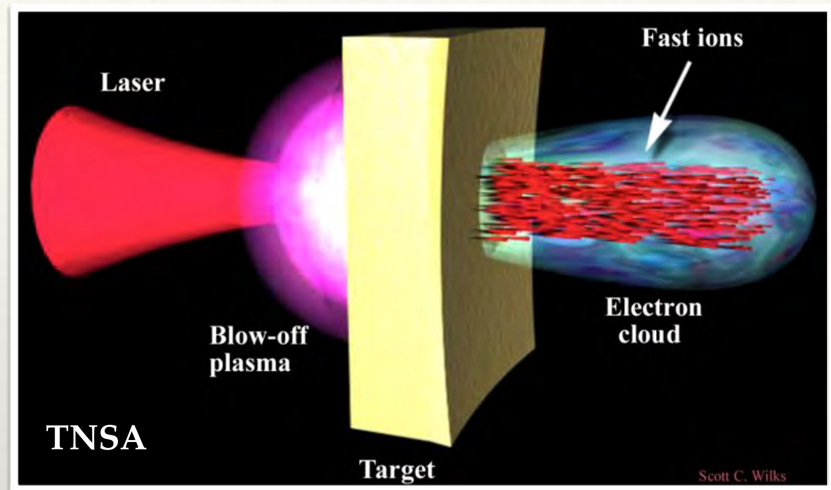
HAPLS/ELI Beamlines → 36,000 shots/hr

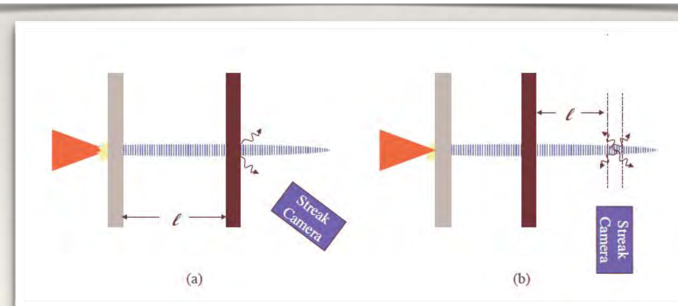
ATON (CPA)/ELI Beamlines → 12 shots/hr

⟹ High repetition rate lasers enable physics that can be probed on a singles-shot basis to be be probed when thousands of shots are taken.

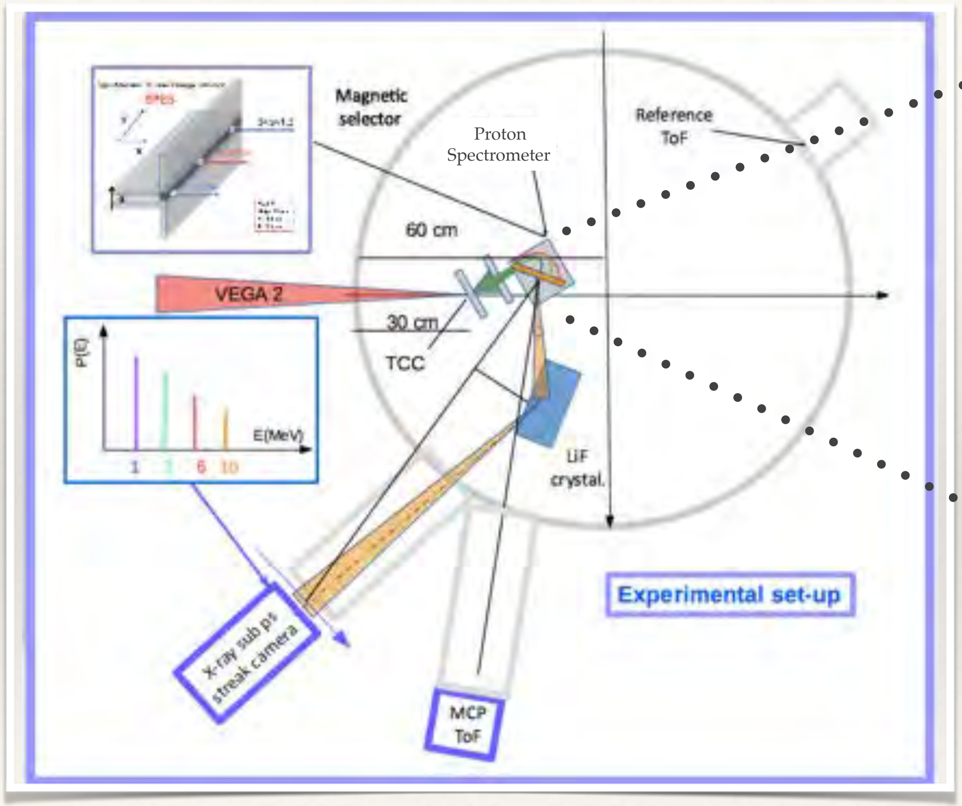
Technology: proton acceleration

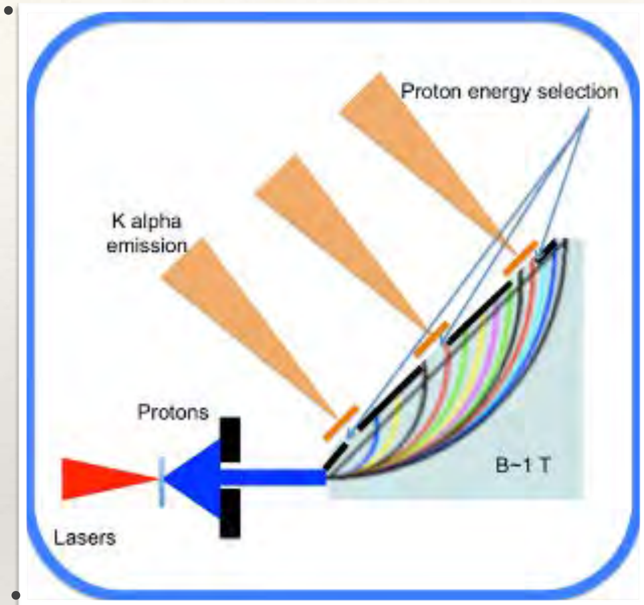
- Laser-driven ion sources hold promise for many technological advances:
  - medical applications; novel secondary sources such as fast neutron sources; direct application for equation of states studies, etc.
- Laser-driven ion sources are promising for a number of reasons:
  - Compact; high particle flux (when high rep rate lasers are employed); provide access to femtosecond time-domain information; etc.
- What new could the US-ELI collaboration enable?
  - High rep rates ⇒ time-history studies.





Time-history measurements





Prototype magnetic selector with parallel tracers, enabling energy-selected K_α radiation, captured by an X-ray streak camera, to measure the proton time-history.

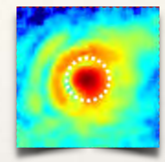
Precision experiments: need for diagnostics

I. Accurate knowledge of the intensity in the focus.
II. An ultra-sensitive way to assess the particle density in the focal volume.

- Requirements for a suitable technique for (I) include:
  - able to operate at full laser power and at background chamber pressures;
  - sensitive to changes in beam parameters that can lead to intensity degradation (e.g., chirp, divergence, Strehl ratio, etc.);
  - minimally intrusive and able to coexist with the primary experiment and
  - single-shot capable, proving intensity assessment in realtime.
- Requirements a suitable technique for (II) include:
  - 1, 2 and 4 from I plus,
  - it must be sensitive enough to detect a single particle in the focal volume ($\sim 2\pi\, w_0{}^2 z_R$).

Possible approaches: nonlinear Thomson scattering

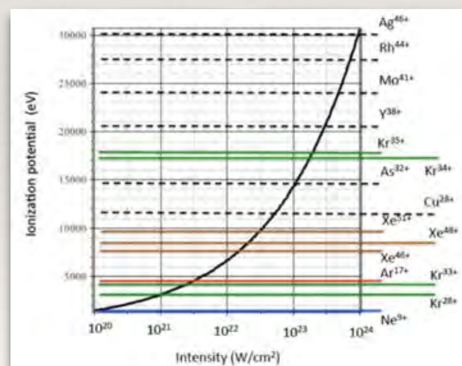
- Indirect approaches, e.g., from spatial images of the focal spot:
  - not a real time approach and thus not sensitive to beam parameter changes;
  - has never been tested against a direct approach.

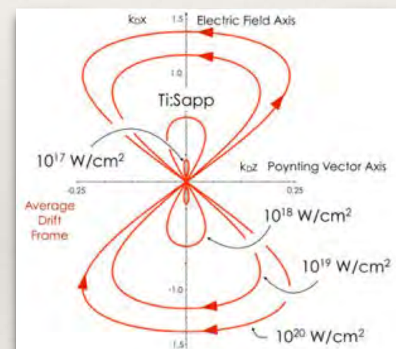


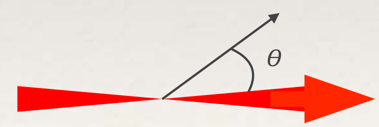
$$I = \frac{C_{pk}/C_{pulse}}{\Delta t_{eff} A}$$

- Direct approaches:
  - Relativistic, nonlinear Thomson scattering (RTS)
    - Wavelength shifts of the incident light: Sarachick & Schappert, Phys. Rev. D **1** (1970); Chen, *et al.*, Nature **396** (1998)]; Tarbox, *et al.*, JOSA B **32** (2015);
    - Angular distribution of the radiation: Harvey,Phys. Rev. Accel. Beams **21** (2018)
    - Appearance intensity for inner-shell tunnel ionization: Ciappina, *et al.*, Phys. Rev. A **99** (2019)

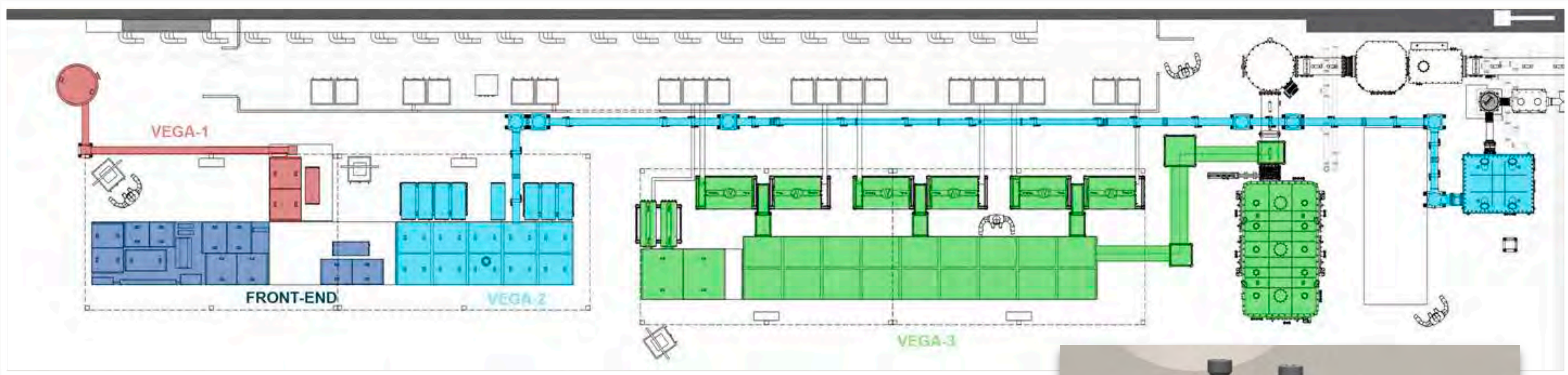
$$\lambda_r^{(n)} = \frac{\lambda_0}{n}\left[1+\frac{r_0\lambda_0^2\left(1-\cos\theta\right)}{2\pi m_e c^3} I_p\right]$$







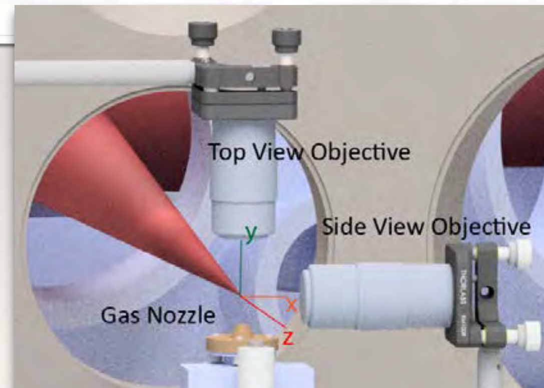
Centro de Láseres Pulsados (CLPU) VEGA Laser



https://www.clpu.es/en/facilties-vega-features

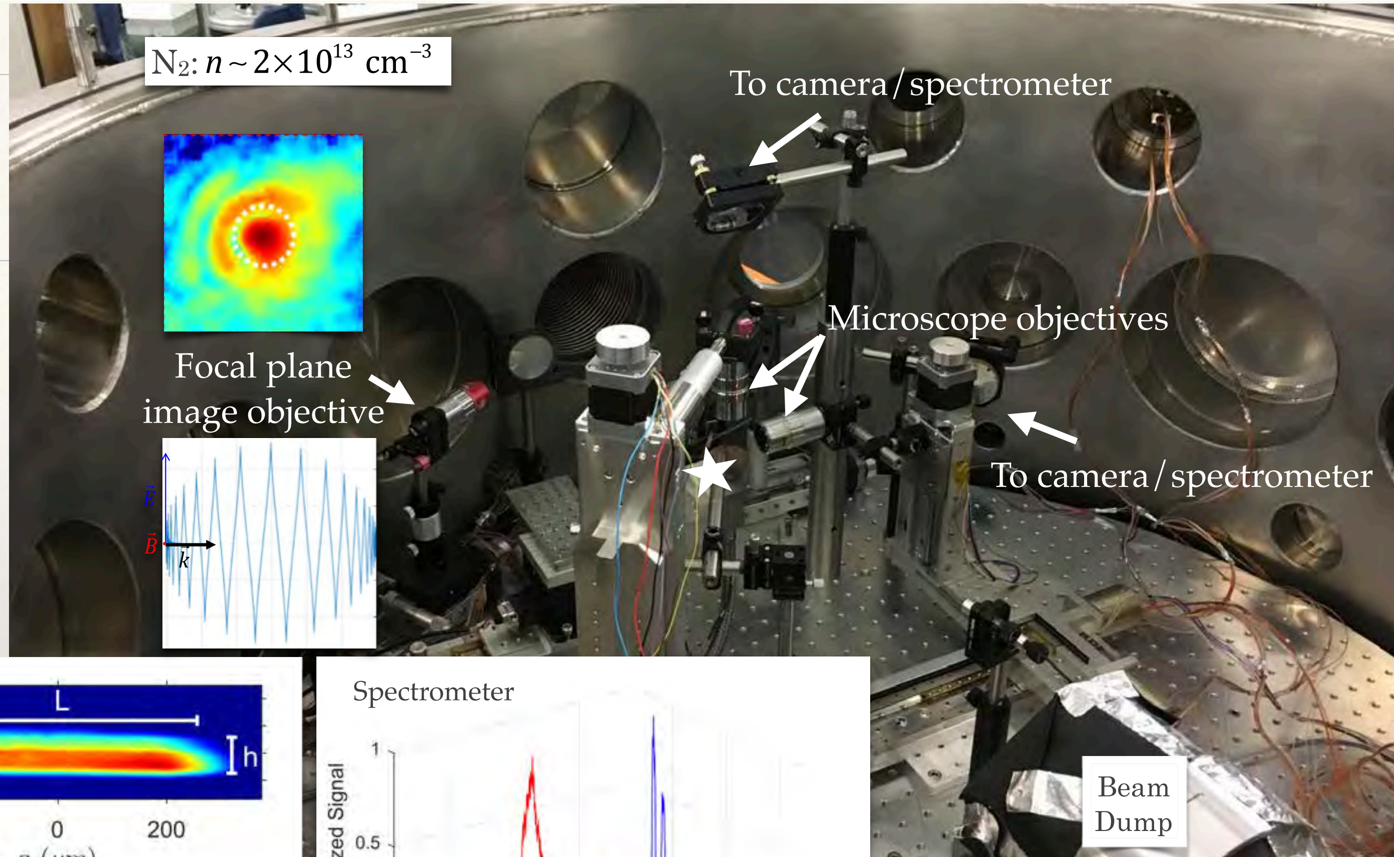
	Peak Power	Energy/shot	Duration/pulse	Rep. Rate	Central @
VEGA 1	20 TW	600 mJ	30 fs	10 Hz	800 nm
VEGA 2	200 TW	6 J	30 fs	10 Hz	800 nm
VEGA 3	1 PW	30 J	30 fs	1 Hz	800 nm

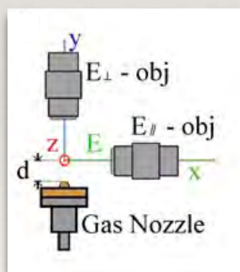
$f/13 \rightarrow 22\ \mu m$, $10^{18}\ W/cm^2 < I_p < 10^{19}\ W/cm^2$

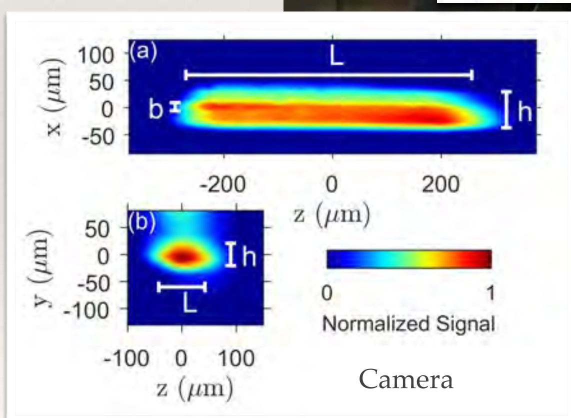


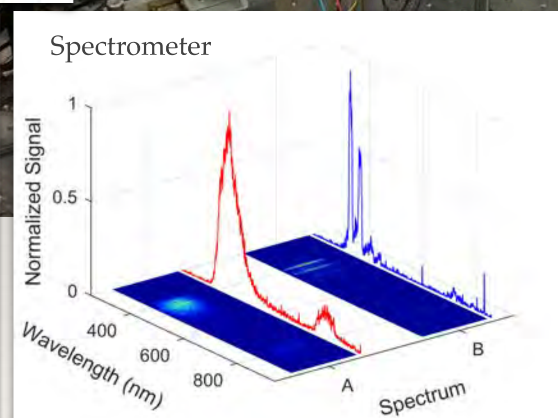
RTS experiment

- Electrons generated via ionization up to 5 e^-/N.
- RTS signal captured with two microscope objectives and sent to camera or spectrometer that was gated.
- Image focal plane



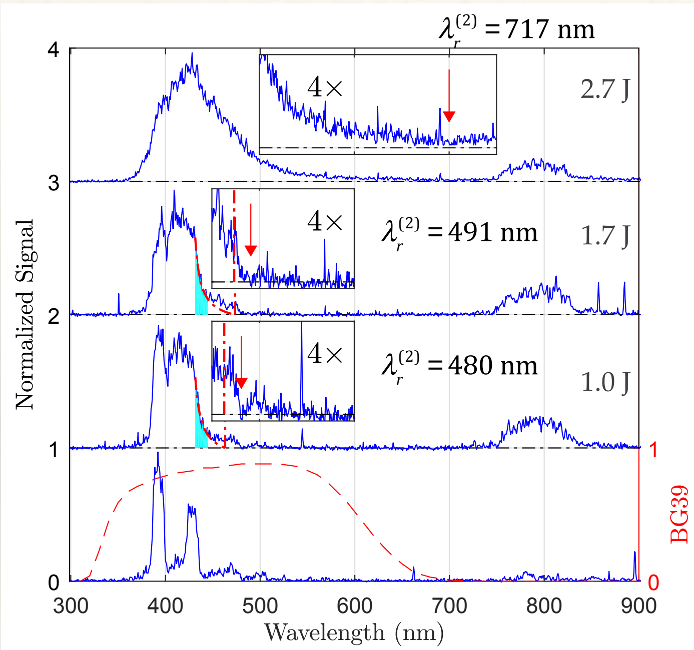


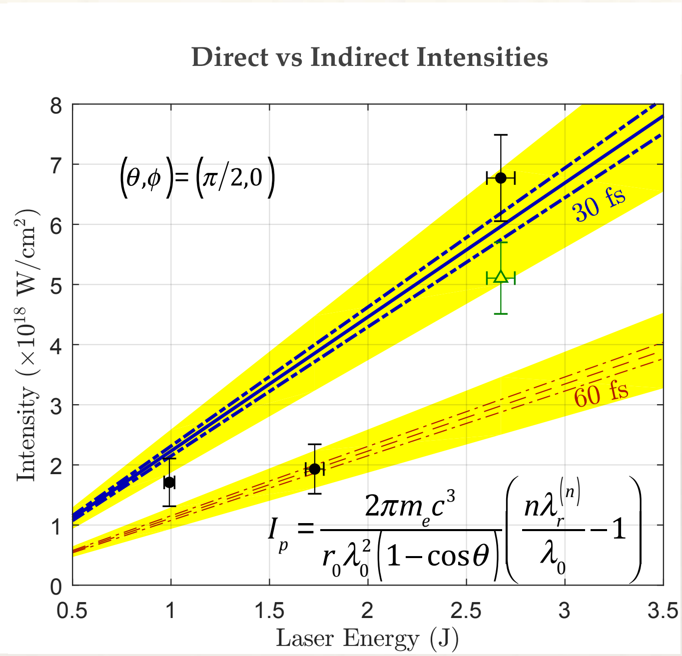


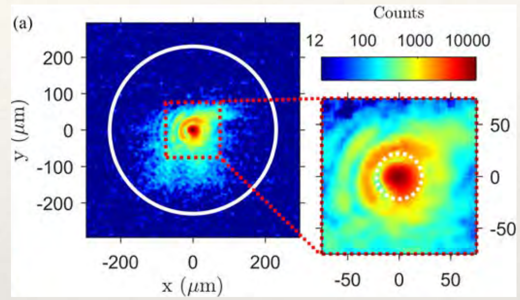


He, *et al.*, Opts. Ex. **21**, 30020

RTS Results Between 1 - 7×10^{18} W/cm^2







$I_{\mathrm{pk}}^{\mathrm{Im}}(\Delta t) = \frac{U C_{\mathrm{pk}}}{T_{\mathrm{eff}} C_{\mathrm{sum}} A_{\mathrm{pix}}}$; $U =$ pulse energy

$C_{\mathrm{pk}} =$ peak count; $T_{\mathrm{eff}} = \int g(t)\,dt$

$C_{\mathrm{sum}} = \sum$ inside white circle

$A_{pix} =$ camera pixel area

He, *et al.*, Opts. Express 21, 30020 (2019)

Pressure monitor

PRL 109, 253903 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Measuring Extreme Vacuum Pressure with Ultraintense Lasers

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(Received 8 June 2012; revised manuscript received 4 October 2012; published 20 December 2012)

We show that extreme vacuum pressures can be measured with current technology by detecting the photons produced by the relativistic Thomson scattering of ultraintense laser light by the electrons of the medium. We compute the amount of radiation scattered at different frequencies and angles when a Gaussian laser pulse crosses a vacuum tube and design strategies for the efficient measurement of pressure. In particular, we show that a single day experiment at a high repetition rate petawatt laser facility such as Vega, that will be operating in 2014 in Salamanca, will be sensitive, in principle, to pressures p as low as 10^{-16} Pa, and will be able to provide highly reliable measurements for $p \gtrsim 10^{-14}$ Pa.

DOI: 10.1103/PhysRevLett.109.253903 PACS numbers: 42.62.−b, 07.30.Dz, 41.60.−m, 52.38.−r

$$P_e = N_\gamma^{(n)}\left[\frac{\pi}{4c_n}\frac{1}{\Delta t r_L}\frac{1}{f}\frac{k_B T}{\eta}\frac{1}{\alpha}\frac{\sqrt{c\tau}}{w_0\lambda_0}\left(\frac{m_e c^2}{r_0 E}\right)^{3/2}\right] \rightarrow \begin{cases} \geq 9\times10^{-15}\ \text{mbar for } w_0 \sim 2\ \mu\text{m @ 5hr} \\ \geq 9\times10^{-16}\ \text{mbar for } w_0 \sim 20\ \mu\text{m @ 5hr} \end{cases}$$

- ✔ This model suggests a sensitivity to pressures in the right ball park.
- ✕ It will take hours to reach this sensitivity.

Summary

- An engagement in international laboratories is critical to keep US at the forefront of intense-field and ultrafast physics — this is only possible with agency support and the redevelopment of a community;
  - The time is ripe for a host of fundamental studies and technology development
    - The quantum vacuum and proton acceleration are two examples;
  - High repetition rate lasers are key to investigating the underlying physics, which is critical if we are to be ready to exploit 10^{24} W/cm^2 — e.g., High Power Laser Sci. Eng. **7**, e4 (2019);
    - Developing *in situ* diagnostic tools capable of operating at high rep rate and single shot is one example.
- US laser technologists have made key contributions to lasers in ELI; it time to support teams of US investigators as users of these facilities.
- Similar situation holds for international attosecond user facilities.