



Proposal for a new experiment using a Laser and XFEL to test quantum physics in the strong-field regime

Beate Heinemann (DESY and University of Freiburg)

on behalf of LUXE Collaborators

DESY Colloquium, August 27th and 28th 2019

























OUTLINE

LUXE = "Laser Und XFEL Experiment"

- Scientific Motivation
- Accelerator and Laser
- Particle Detection and Simulation Results
- Conclusions



Letter of Intent for the LUXE Experiment

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from draft document, to be released end of this week

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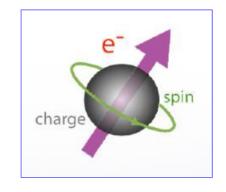


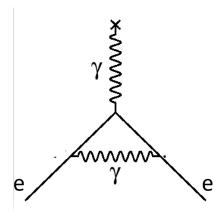
SCIENTIFIC MOTIVATION



REMINDER: QUANTUM ELECTRODYNAMICS

- Relativistic field theory of electrodynamics
- Perturbation theory in terms of coupling constant α
- World's most precisely tested theory
 - Anomalous magnetic dipole moment (g-2) of electron:
 - Zero at leading order => first corrections calculated by Schwinger (1947)
 - Based on precise measured and calculated (includes terms of 5^{th} order: α^5) values, extract $1/\alpha = 137.035~999~070~(98)$
 - Precision better than 10⁻⁹, consistent with other measurements
 - Anomalous magnetic dipole moment of muon shows interesting tension
 - New experiment at FNAL ("Muon g-2") will improve precision by factor 4



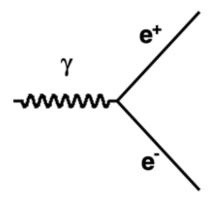




QED: WHAT DO WE NOT KNOW?

What happens if electrons or photons propagate in a very strong field?

•QED expects that vacuum becomes unstable e.g. for nucleus with Z>137. Spontaneous creation of e⁺e⁻ pairs ("boiling of vacuum")



•Historical developments:

- •1930s: Initial discussions of EM in strong field in literature (Sauter, Euler, Heisenberg) => introduction of "critical field"
- •1951: First no-perturbative calculations by Julian Schwinger
- •1990s: E144 experiment at SLAC

$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18} \text{ V/m}$$



HEISENBERG AND EULER: THE CRITICAL FIELD



Folgerungen aus der Diracschen Theorie des Positrons.

Von W. Heisenberg und H. Euler in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

Aus der Diracschen Theorie des Positrons folgt, da jedes elektromagnetische Feld zur Paarerzeugung neigt, eine Abänderung der Maxwellschen Gleichungen des Vakuums. Diese Abänderungen werden für den speziellen Fall berechnet, in dem keine wirklichen Elektronen und Positronen vorhanden sind, und in dem sich das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert. Es ergibt sich für das Feld eine Lagrange-Funktion:

$$\mathfrak{L} = \frac{1}{2} \left(\mathfrak{E}^2 - \mathfrak{B}^2 \right) + \frac{e^2}{h \, c} \int_{0}^{\infty} e^{-\eta} \, \frac{\mathrm{d} \, \eta}{\eta^3} \left\{ i \, \eta^2 \left(\mathfrak{E} \, \mathfrak{B} \right) \cdot \frac{\cos \left(\frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2 \, i \, (\mathfrak{E} \, \mathfrak{B})} \right) + \mathrm{konj}}{\cos \left(\frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2 \, i \, (\mathfrak{E} \, \mathfrak{B})} \right) - \mathrm{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3} \left(\mathfrak{B}^2 - \mathfrak{E}^2 \right) \right\} \cdot \left(\mathfrak{E}_k \right) = \frac{m^2 \, c^3}{e \, \hbar} = \frac{1}{\pi^1 37^{\circ \circ}} \frac{e}{(e^2/m \, c^2)^2} = \pi \, \text{Kritische Feldstärke}^{\circ \circ}. \right)$$



WHY EXPLORE STRONG-FIELD QED?

•Relevant to numerous phenomena in our Universe

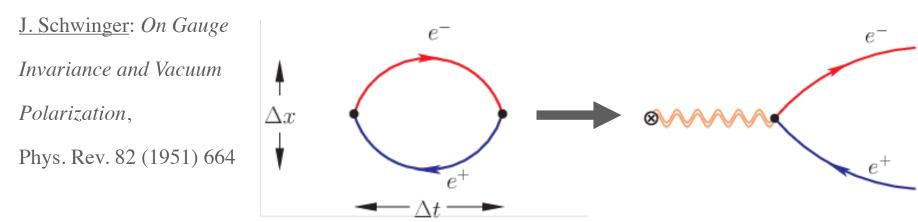
- •Astrophysics:
 - •Hawking radiation, surface of neutron stars (magnetars), early Universe
- •Condensed matter and atomic physics (nuclei with Z>137)
- •Accelerator physics: high energy e⁺e⁻ colliders

•Main goals:

- Testing theoretical predictions in novel regime
 - •gain deeper understanding of quantum physics
- Measure transition from perturbative to non-perturbative regime
 - •could teach us about other non-perturbative regimes, e.g. understanding confinement [Gribov, hep-ph/9902279]
- Schwinger field has never been reached experimentally in clean environment
 - •Exciting to be the first to explore this ... we might be surprised what we find!



THE SCHWINGER PROCESS



Photon in electric field: simplified

- The EM force is $F = e\varepsilon$
- Energy needed to separate e^+e^- pair: $E=Fd_{min}$
- Heisenberg: $\Delta t \geq \frac{\hbar}{\Delta E} = \Delta t_{min} = \frac{\hbar}{2mc^2} = \Delta t_{min} = \Delta t_{m$
- Virtual pair becomes real if $E = F d_{min} = \frac{\hbar e \varepsilon}{mc} > 2mc^2$

$$\Rightarrow$$
Possible if $\varepsilon > \frac{2m^2c^3}{\hbar e} = 2\varepsilon_{crit}$

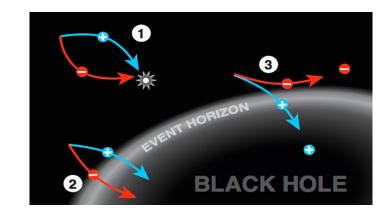
$$P \propto \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2c^3}{\hbar e\varepsilon}\right) = \exp\left(-2\frac{\varepsilon_{crit}}{\varepsilon}\right)$$

NB: full calculation gives π instead of 2



ANALOGY TO HAWKING RADIATION

- Energy needed to create on-shell e⁺e⁻ pair: $\Delta E = 2mc^2$
- Grav. Field near the event horizon: $F = \frac{G_N Mm}{r_S^2}$
- Schwarzschild radius $r_S = \frac{2G_N M}{c^2}$. => $F = \frac{mc^4}{4G_N M}$
- Energy to separate pair: $E=Fd_{min}=\frac{mc^4}{4G_NM}\times\frac{\hbar}{mc}=\frac{\hbar c^3}{4G_NM}$

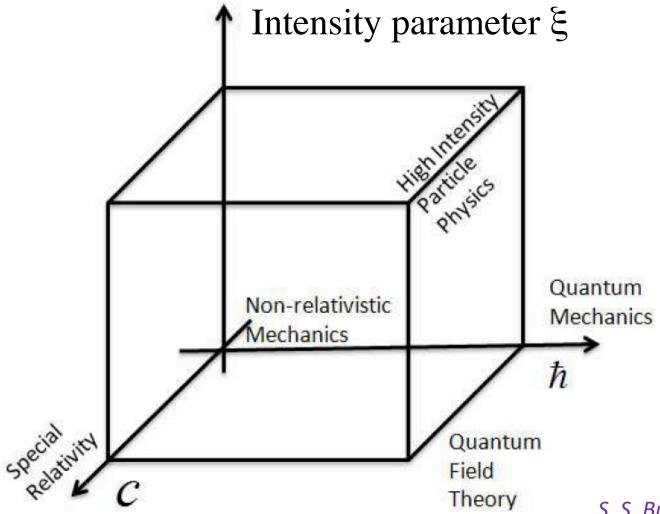


H. Murayama

Hawking radiation possible if virtual pair becomes real, i.e. $\frac{\hbar c^3}{4G_N M} > 2mc^2$



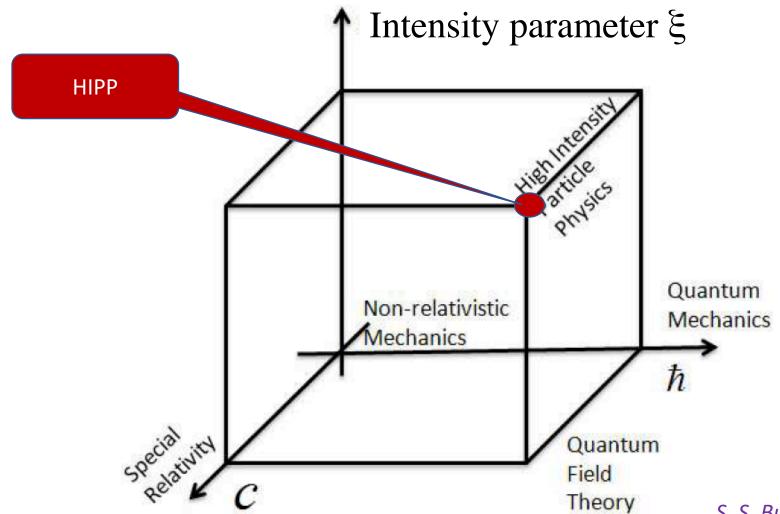
THEORIES ON A CUBE



S. S. Bulanov, W. Leemans et al.



THEORIES ON A CUBE



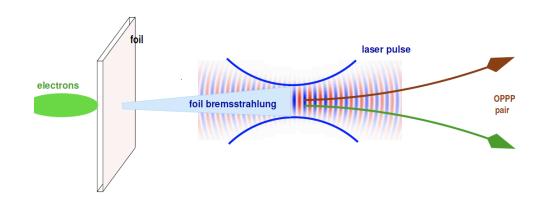
S. S. Bulanov, W. Leemans et al.



LASER AND PHOTON BEAM

- Use Laser to generate electric field
- Use high energy electron beam

$$\xi = \frac{e\varepsilon_L}{m_e \omega_L c} \qquad \qquad \chi \approx \gamma \frac{\varepsilon_L}{\varepsilon_{crit}}$$



- Laser power required to reach Schwinger field $(\chi_{\gamma} \sim 1)$:
 - Non-relativistic photons:

I=2x10²⁹ W/cm²

• EU.XFEL, E_y≈10 GeV: I≈10²⁰ W/cm²

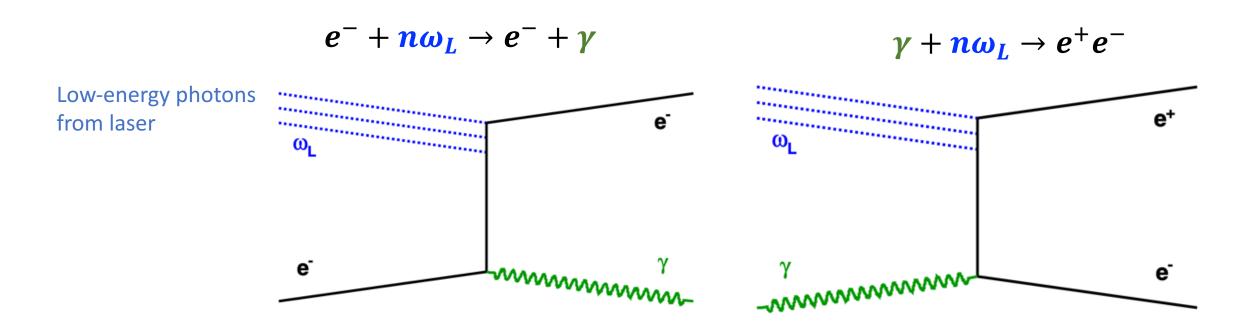
•ELI-NP, E_v≈ 1 GeV:

I≈10²² W/cm²

- => Much beyond currently achievable values
- => Can use well-tested laser technology
- => State-of-the-art laser needed



MAIN PROCESSES OF INTEREST



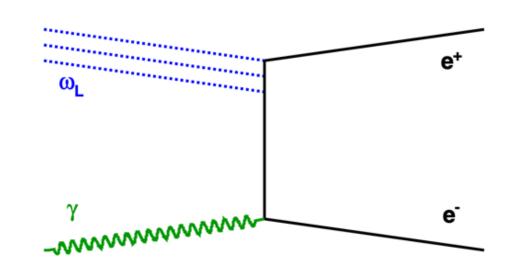
High energy electron or photon interacts with laser

- •Also higher order process $e^- + n\omega_L \rightarrow e^- e^+ e^-$
- Via two steps $(e^- + n\omega_L \to e^- + \gamma)$ and then $\gamma + n\omega_L \to e^+ e^-)$ or one step



CROSS SECTION OF QED PROCESSES

- Perturbative QED valid
 - For n photons $\sigma \propto \alpha^n$
 - •With $\alpha \propto e^2 \propto \xi^2$ it follows: $\sigma \propto \xi^{2n}$
- If $\xi \gtrsim 1$ all orders can contribute ~equally => cannot truncate series any more
 - All-order calculation needs to be performed (which is hard)



- Example for asymptotic result for $\xi \gg 1$ and $\chi < 1$: $\sigma \propto \chi e^{-8/(3\chi)}$
 - Since $\chi \propto \sqrt{\alpha}$ cannot expand perturbatively
 - •Result not proportional to powers of α

Observation of deviation from power-law is the experimental signature of strong QED

PAIR PRODUCTION

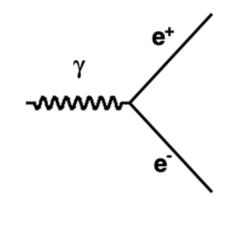
- Process not possible in vacuum in classical **electrodynamics**
- Pair production in a constant static field (Schwinger process)

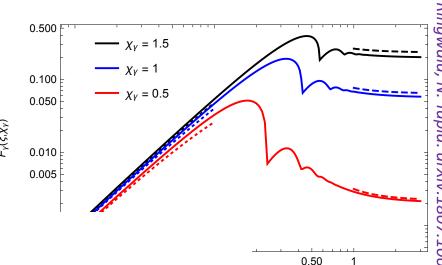
$$\frac{\Gamma_{\rm SPP}}{V} = \frac{m_e^4}{(2\pi)^3} \left(\frac{|\mathbf{E}|}{E_{\rm c}}\right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_{\rm c}}{|\mathbf{E}|}\right) \qquad \propto \exp\left(-\pi \frac{E_c}{|\mathbf{E}|}\right)$$

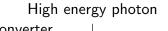
 Pair production in plane wave laser: asymptotic result

$$\Gamma_{\text{OPPP}} \to \frac{3}{16} \sqrt{\frac{3}{2}} \alpha \, m_e \, (1 + \cos \theta) \, \frac{|\mathbf{E}|}{\mathbf{E}_c} \exp \left[-\frac{8}{3} \frac{1}{1 + \cos \theta} \frac{m_e}{\omega_i} \frac{\mathbf{E}_c}{|\mathbf{E}|} \right]$$

 Good agreement between full calculation and asymptotic result for $\xi \ll 1$







High intensity laser beam

PAIR PRODUCTION

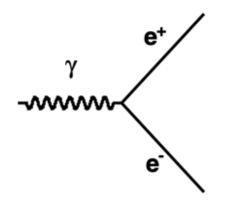
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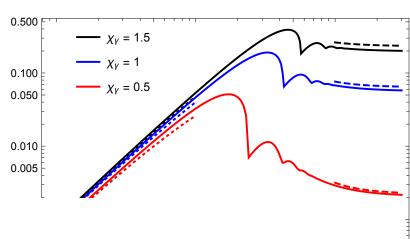
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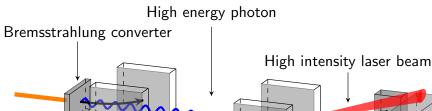
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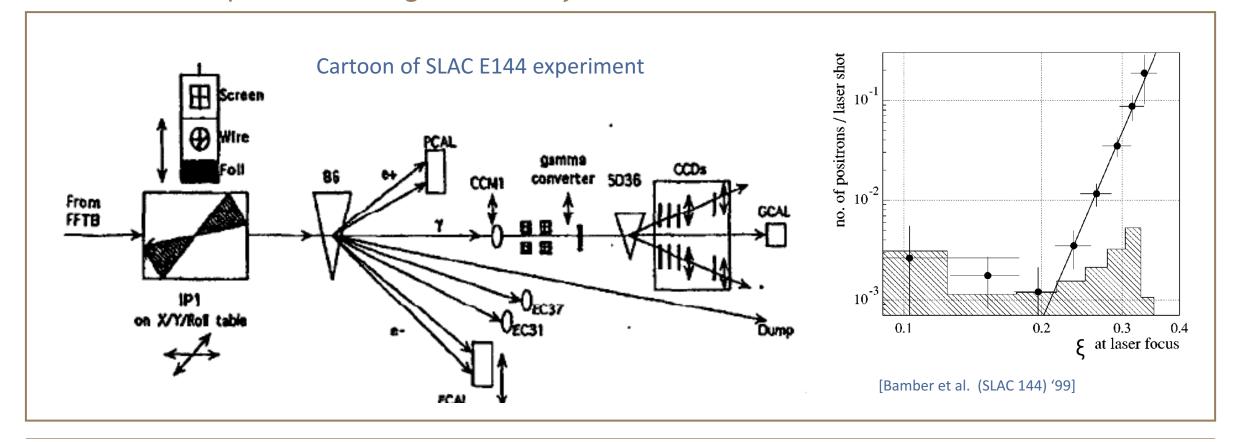


Tapia: arXiv:1807.10670



EXPERIMENT E144 AT SLAC

- Experiment at SLAC in 1990s with E_{beam} =46.6 GeV achieved $\chi \le 0.25$
 - Did observe two-step process $e^- + n\omega_L o e^- e^+ e^-$
 - Saw the expected strong rise with ξ^{2n} but did not reach the critical field



E144 IN THE NEWS...

DIE ZEIT WISSEN

Nr. 42 17. Oktober 1997.

Das Sein und das Nichts, früher das angestammte Thema der Philosophen, wird heute in Teilchenbeschleunigern näher untersucht

sanden serchan't Schapp resanden serchan serchanten serc

solches Experiment gelungen. Zwanzig Wissenschaftler von vier amerikanischen Universitäten wandelten am Linearbe schleuniger in Stanford, Kalifornien, erst schleuniger in Stanford, Kahfornien, erst-mals pures Licht in Materie um, ein Werk, das ein wenig an die Erschaffung der Welt durch göttliche Hund erimert. Sozosagen aus bioßem Nichts Materie zu erzeugen, das blieb bislang der Bibel oder der Ur-knälltheorie vorbehalten. Nun ist dieser Schöpfungsakt endlich auch vor Zeug

Den umgekehrten Prozeß hat der Mensch nämlich schon vor mehr als funfzig Jahren gemeistert – mit verheerenden Au-wirkungen. Die Atombombe demonstrier andere generated reinforce chosen-free and the politheria to the control of the politheria to te aller Welt die plötzliche Umwandlun

wie sie in den Hochenergiezentren Cern in Genf oder Desy in Hamburg gang und

Warum

etwas

Amerikanische

Physiker schufen

erstmals Materie

aus reinem Licht

Von Ulrich Schnabel

sammenhängende Größen eines subato maren Partikels (etwa dessen Ort und Ge schwindigkeit oder auch seine Energie und Zeitdauer) nicht gleichzeitig scharf definiert werden. Dieses merkwürdige Prinzi gilt ganz allgemein – also auch im Vakuum. Der sogenannte leere Raum darf daher nicht exakt leer sein, sonst müßten darin

nicht caskt ker sein, sost millen darin Energie und i bensäuser miglicher Teil chen genau gleich Null sein was bat Ur-schäftigenung nocht ein kann. Tatssellicht gleicht also das Vakeum in Tatssellicht gleicht also das Vakeum in Tatssellicht gleicht also das Vakeum in Bereige und Materie fluktureren hill Moter addieren sich diese Flukturationen stest bro-delnden Nichts zwei Lichtlitze mit Wacht auszummegnellen, dann kann des Ehre-summegnellen, dann kann des Ehre-summegnellen, dann kann des Ehre-partikelpaar zum Sprung von der migli-chen in die reale Eusteler verhelten.

chen in die reale Existenz verhelten. Schwierig, sich das vorzustellen? Ist ei nuch. Immerhin ist das ein Sujet, das Phy sikstudenten erst in den höheren Semi stern zugemutet wird. Und auch die haben ihre liebe Not mit dem Begreifen. Er-schwerend kommt hinzu, daß die Materie erzeugung aus dem Nichts sich zwar in der riesenhaften Detektoren der Teilchenphy-

siker nachweisen läßt, ansonsten jedoch keine sichtbaren Spuren hinterläßt. "Prak tische Anwendungen sehe sch leider nicht", nieint denn auch Adrian Melissinos

The New York Times

ARCHIVES 100°

Scientists Use Light To Create Particles

By MALCOLM W. BROWNE SEPT. 16, 1997

A TRAILBLAZING experiment at the Stanford Linear Accelerator Center in California has confirmed a longstanding prediction by theorists that light beams colliding with each other can goad the empty vacuum into creating something out

In a report published this month by the journal Physical Review Letters, 20 physicists from four research institutions disclosed that they had created two tiny specks of matter -- an electron and its antimatter counterpart, a positron -- by colliding two ultrapowerful beams of radiation.

The possibility of doing something like this was suggested in 1934 by two American physicists, Dr. Gregory Breit and Dr. John A. Wheeler. But more than six decades passed before any laboratory could pump enough power into colliding beams of radiation to conjure up matter from nothingness. The Stanford accelerator finally provided eno

Dr. Adrian C. Melissinos o group, said in an interview that experiment was produced by a of the needed energy, even thou most powerful.

But the opposing beam of ra drawn from electrons whizzing second beam of radiation was a

The paths of colliding electron: complicated as those choreogra

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Conjuring Matter From Light

David Ehrenstein

+ See all authors and affiliations

Science 29 Aug 1997: Vol. 277, Issue 5330, pp. 1202 DOI: 10.1126/science.277.5330.1202

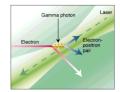
Article

Figures & Data

Info & Metrics

el etters

Turning matter into light, heat, and other forms of energy is nothing new, as nuclear bombs spectacularly demonstrate. Now a team of physicists at the Stanford Linear Accelerator Center (SLAC) has demonstrated the inverse process—what University of Rochester physicist Adrian Melissinos, a spokesperson for the group, calls "the first creation of matter out of light." In the 1 September Physical Review Letters, the researchers describe how they collided large crowds of photons together so violently that the interactions spawned particles of matter and antimatter; electrons and positrons (antielectrons)



Corriere della Sera

DOMENICA 21 SETTEMBRE 1997

L'importante risultato ottenuto a Stanford

Dalla luce è nata la materia Come predisse Einstein

scita in laboratorio della prima temente intenso. materia generata da incontri ravcollidere fra di loro abbondanti

materia, più precisamente di coppie di elettroni e di antielettroni. È questo è, fra materia ed energia. appunto, la prima volta che accade. opera uno scontro frontale fra un clet- dei portavoce dell'esperimento condot-

una reciproca annichilazione della particella di materia con quella di anti-materia. Il risultato del drammatico incon- chibald Wheeler, che, insieme a Gre tro consiste in un paio di fotoni o parti- gory Breit, negli anni Trenta per prime celle di luce, che si allontanano dal luogo dell'impatto in direzione opposta. Se e trajettorie della particella e dell'antiparticella iniziale, prima dello scontro reali. La traduzione pratica dell'idea frontale, sono nella direzione est-ovest, teorica ha richiesto qualche decennio,

allora i fotoni generati dalla loro annichilazione si allontanano nella direzione nord-sud in senso opposto. E i fotoni generati dall'urto sono appunto due, e non uno soo, per rispettare la fondamentale legge della conservazione della quantità di moto. Sempre i libri di testo spicgavano che il fenomeno avrebbe dovuto essere erfettamente reversibie. Facendo urtare fra loro, lungo la direzione

nord-sud, due fotoni pargenerazione di una coppia di particelle, energie quando si fanno urtare fra formata da un elettrone e da un antielettrone che si allontanano in senso opposto lungo la direttiva est-ovest.

sale agli anni Trenta, ma solo la tecnologia odierna è stata in grado di trasformare un esperimento mentale in un

ser ultra-energetici contro un fascio di elettroni accelerati in senso opposto. Rimbalzando come palline lanciate contro una Ferrari in corsa, l'energia dei fotoni incidenti ha subito un aumento e di conseguenza si è passati dalla luce laser incidente, situata nella frero volta si scontrano con i fotoni del mula einsteiniana

Stanford hanno festeggiato la na- fascio laser iniziale se questo sufficien

In opportune condizioni, viene con vicinati di fasci di luce. Facendo centrata una quantità di energia in un collidere fra di loro abbondanti singolo punto, sufficiente a creare copimpulsi di fotoni si è assistito alla pie di elettroni e anti-elettroni, sulla ba creazione di particelle di materia e anti- se della famosa relazione di Einstein che regola le reciproche trasformazion

Si è così avuta la prima creazione d Come spiegavano i libri di testo, se si materia dalla luce, ha commentato uno trone e un anti-elettrone, si provoca to a Stanford da una squadra di una ventina di fisici. Fra questi è anche un fisico di Princeton, seguace di quell'Ar considerò sul piano teorico la possibile produzione di coppie di elettroni e po sitroni in seguito all'urto fra due fotoni

> come pure lo sviluppo di tecnologie sofisticate, anche una buona dose di virtuosismo da parte degli sperimentatori di Stanford che hanno do vuto allineare e sincronizzare con la massima precisione sia gli impulaser iniziali sia gli im pulsi degli elettroni acce lerati. Ma, come recita un detto locale, le cos nascono sempre prima il California. La creazion di coppie di elettroni positroni (cioè di antie lettroni) di solito si ver

ticolarmente energici, era prevista la fica negli esperimenti di fisica delle altloro particelle accelerate.

Ben diversa è la situazione ricreata ir California dove la produzione delle La previsione teorica dell'effetto ri- coppie è avvenuta per opera dei soli fo toni che sono le particelle costituenti luce dove almeno uno dei quali de essere virtuale, come si dice in gerge cioè deve esistere per una brevissim A Stanford hanno sparato impulsi la- frazione di tempo per scomparire p

A Stanford, infatti, sono stati mes in gioco soltanto dei fotoni reali o ordi nari, offrendo così la dimostrazion pratica di un fenomeno previsto da lur go tempo. Dalla enorme concentrazio ne di energia elettromagnetica si è riu quenza del visibile, a raggi gamma di sciti quindi a ricavare della materia rimbalzo particolarmente energetici. I dando una ulteriore dimostrazion fotoni gamma, riflessi all'indietro, a lo-quasi da libro di testo, della famosa fo

Rene Burther Beitung

Mittwoch, I. Oktober 1997 - Nr. 227 69

FORSCHUNG UND TECHNIK

Materie aus Licht erschaffen

Amerikanischen Physikern gelingt technischer Durchbruch

Was bisher nur theoretisch vorausgesagt wurde, hat ein Team von 20 Physikern erstmals met periment direkt beobachtet die Erschaffung von Materie aus echten Lichtteilchen. Das Experiment gelang am Samford-Teilchenbeschleuniger in Kalifornien.

Die Umwandlung von Materie in Licht oder andere Energeformen ist dichts Neues. Ein besonder zustrücherdesse Beigheid daffer auf Alons andere zustrücherdesse Beigheid daffer auf Alons andere der Schaffer und Alons auf Alons auf

eine wie beispielsweie Protonen und Antiproto-nen aufeinander geschossen, so Kunnen sie beim Zustammenprall in einen Energiebitz aufgeben. Dieter Energebeitz ersthätt mannfaml kurzbeitge-Dieter Energebeitz ersthätt mannfaml kurzbeitge-teilspiel Lichtstellen virtuelle Photonen im Gegenautz zu den achten Photonen, den gewühn-lichen Lichtstellen virtuelle Photonen einstehen lichtstellen Virtuelle Photonen einstehen lichtstellen virtuelle Photonen einstehen lichtstellen virtuelle Photonen einstehen zu die Photonen siehen die Stellen-Posi-tielsbens. Im Esperiment am Stanford-Beschleuniger im Kalifornien wurden die Elektron-Posi-tielsbens im Esperiment am Stanford-Beschleuniger im Kalifornien wurden die Elektron-Posi-tielsbens im Esperiment am Stanford-Beschleuniger im Kalifornien wurden die Elektron-Posi-tielsbens im Esperiment am Stanford-Beschleuniger im Kalifornien wurden die Elektron-Posi-

Laser gegen Elektronenstrahl

Der Durchbruch gelang einem Toam aus zwan-eig Wissenschaftern von vier amerikanischen For-schungsinstituten. Für das aufwendige Experinent benötigte die Gruppe extrem ene Photonen. In einem ersten Schritt verwi

Die Physiker führten eine Serie derartiger Ex-perimente durch, die mehrere Monate dauerten. Sie analysierten danach Tausende von Kollisio-nen und Janden dabei mehr als bundert der ge-suchten Ereignisse (Physical Review Letters, 79,

sei aber keine Sensation. Denn an Einsteins be-rühmter Gleichung E = mc, wonach Energie in Masse umgewandelt werden könne und umge-

Erkenntnisse für Astronomie

Die Umwandlung von Licht in Materie wurde möglich, weil die Zusammenstösse der Photonen ein unglaublich starkes elektromagnetisches Felo erzeugten. Ähnliche Bedingungen finden sich im ezzugien, Ahnliche Bedingungen finden sich im Universum wähnscheinlich nar an wenigen Orten, zum Beispiel auf der Überfliche von Neutronensten und der Schaffliche von Neutronensten Universum der Schaffliche Volleit. Die Bei bei der Schaffliche Volleit. Die Schaffliche Volleit. Die Schwerkraft Kollabert. Die Wissenschafter vermuten, dass Neutronensteme ein extrem starkes Mapoeffeld haben. An über Überfläche konnten destalb Prozesse ablaufen, wie sie am Teilchenbeschlossinger in Saunford Gebachte wurden.

Discover

DISCOVER MAGAZINE - DECEMBER 1997 Let There Be Matter

by Jeffrey Winters

halbert Einstein's epochal insight into the equivalence of matter and energy, elegantly expressed as E=mc2, has been

confirmed countless times, most dramatically whenever a nuclear weapon detonates. The process also occurs naturally-a str shines because atoms in its core fuse, transforming a sliver of matter into light. And when particles of matter and antimatter meet, they annihilate each other in a blaze of energy.

But like any equation, E=mc2 works in both directions, at least theoretically. That is, it should be possible to convert energy into matter. Now a team of physicists has accomplished just that: they have transmuted light into matter. "We're able to turn optical photons into matter, says Princeton physicist Kirk McDonald, coleader of the team. "That is quite a technological

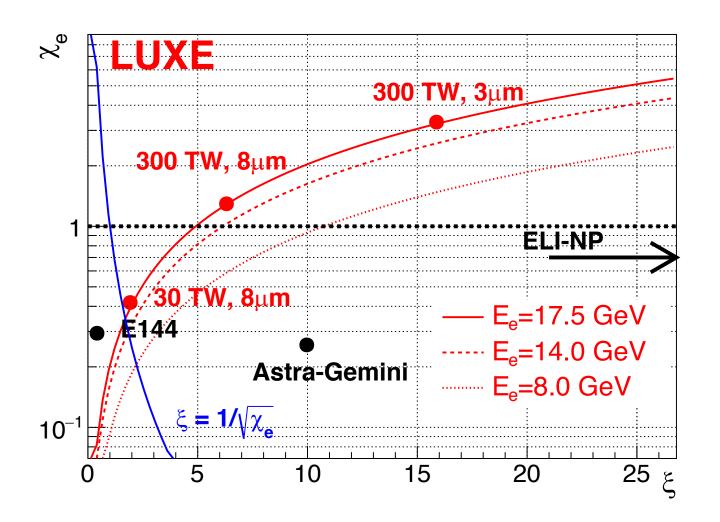
Of course, physicists would have been shocked if they couldn't get energy to convert into matter. After all, the entire univers began with an explosion of energy--the Big Bang. And physicists who smash atoms together have witnessed the conversion of energy into matter--"virtual" photons that flit in and out of existence just long enough to spawn the particles of exotic matter routinely observed in particle accelerators. But such virtual photons aren't under the direct control of physicists; these photons arise as part of a complex chain of events starting with a collision of two particles of matter. Until now, no one had directly created matter from light. "Back in 1934 physicists realized that it would be possible to do this in principle," says McDonald, "But it just wasn't technically feasible."

By the early 1990s, McDonald and his colleagues had all the technological pieces in place to conduct such an experiment. The key piece was a laser capable of packing a tremendous amount of energy into a small space. The laser that McDonald and his collaborators use at Stanford generates a trillion watts of power, enough to light every home in North America. But rather than drain the national electric grid, the laser takes a rather ordinary amount of energy and compresses it into a pulse for about a trillionth of a second. By focusing this pulse on an area of just 16- millionths of a square inch, the physicists bathe a spot with an incredibly intense electromagnetic field. But even with this crowd of high-power photons squeezed together, the energy is still only about a millionth of what's needed to make matter

DESY, LUXE



PARAMETER SPACE



Intensity parameter:

$$\xi = \sqrt{4\pi\alpha} \left(\frac{\mathcal{E}_L}{\omega_L m_e} \right) = \frac{m_e \mathcal{E}_L}{\omega_L \mathcal{E}_{cr}}$$

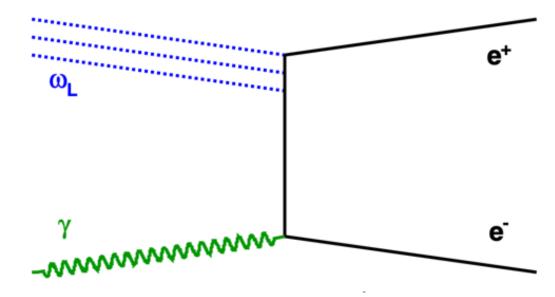
Quantum parameters:

$$\chi_e = (1 + \cos \theta) \frac{E_e}{m_e} \frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

$$\chi_{\gamma} = (1 + \cos \theta) \frac{E_{\gamma}}{m_e} \frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

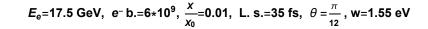
ABSORBING LIGHT WITH LIGHT

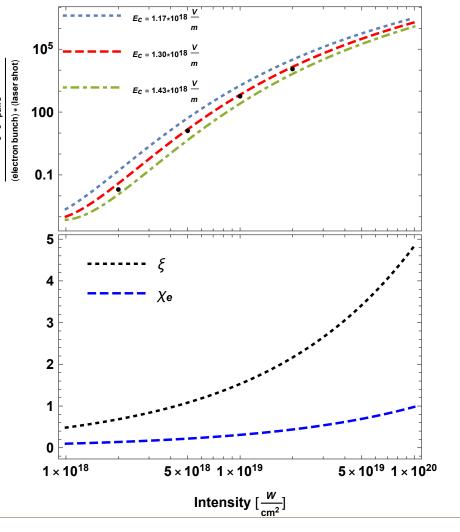
Low-energy photons from laser



High-energy (relativistic) photon

$$\Gamma_{\text{BPPP}} \to \frac{9}{128} \sqrt{\frac{3}{2}} \alpha E_e (1 + \cos \theta)^2 \left(\frac{|\mathbf{E}|}{E_c}\right)^2 \exp \left[-\frac{8}{3} \frac{1}{1 + \cos \theta} \frac{m_e}{E_e} \frac{E_c}{|\mathbf{E}|}\right] \frac{X}{X_0}.$$

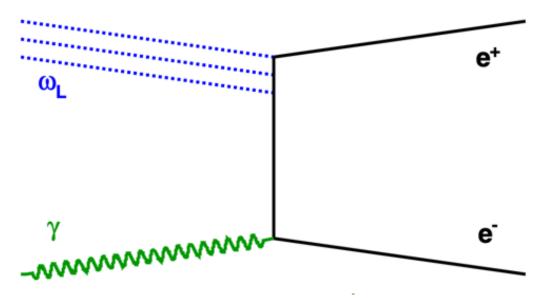






ABSORBING LIGHT WITH LIGHT





 E_e =17.5 GeV, e⁻b.=6*10⁹, $\frac{X}{X_0}$ =0.01, L. s.=35 fs, $\theta = \frac{\pi}{12}$, w=1.053 eV Pert. QED (electron bunch) * (laser shot) e⁺ e⁻ pairs 0.1 A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670, 1×10^{18} 1×10^{20} Intensity [-

Prediction for rate of positrons per laser shot

$$\xi \ll 1$$
: $R_{e^+} \propto \xi^{2n} \propto I^n$

High-energy (relativistic) photon

Perturbative regime: strong rise, follows power-law

$$\xi \gg 1$$
: $R_{e^+} \propto \chi_{\gamma} \exp\left(-\frac{8}{3\chi_{\gamma}}\right)$ Non-perturbative regime: departure from power-law

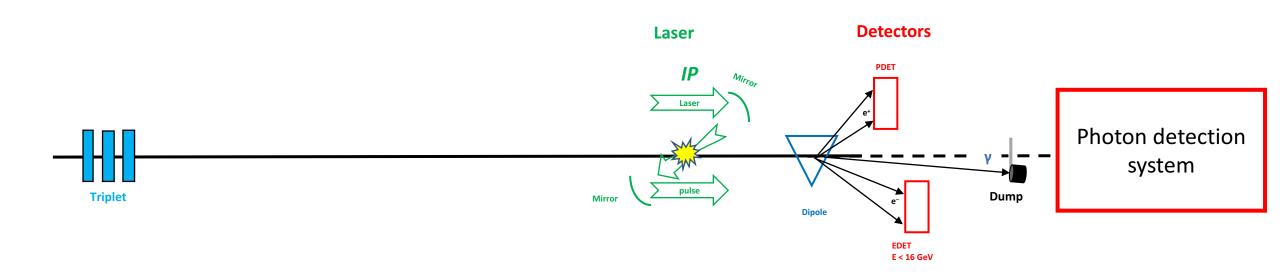


ACCELERATOR AND LASER

X

ELECTRON LASER COLLISIONS

Compton and trident processes: $e^- + n\omega \rightarrow e^- + \gamma$ and $e^- + n\omega \rightarrow e^- e^+ e^-$



Kicker and triplet to select single bunch and focus it

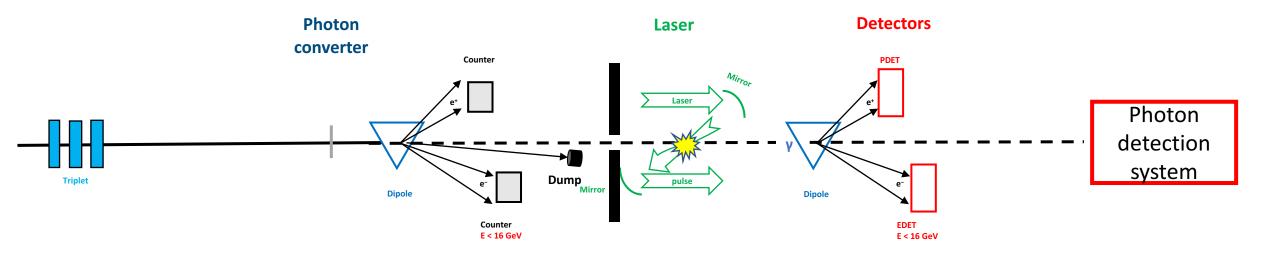
Electron- Laser interaction area

Dipole and detectors to observe e+e- pairs

PHOTON LASER COLLISIONS



Pair production (Breit-Wheeler) process: $\gamma + n\omega \rightarrow e^- + e^+$



Kicker and triplet to select single bunch and focus it

Dipole and detectors to remove e+e- pairs and monitor photon flux

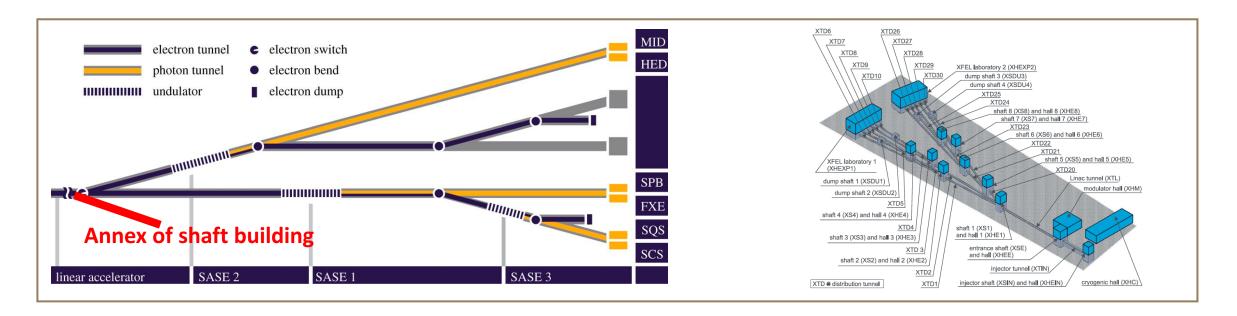
Photon- Laser interaction area

Dipole and detectors to observe e+e- pairs



LOCATIONS IN EU.XFEL TUNNEL

- Location at EU.XFEL:
 - Annex of shaft building XS1: at end of electron accelerator
 - Was build for 2nd EU.XFEL fan foreseen for later (late 2020s)
- Design aims to have no impact on photon science programme
 - •Use only 1 of the 2700 bunches in bunch train (kicked out by fast kicker magnet)

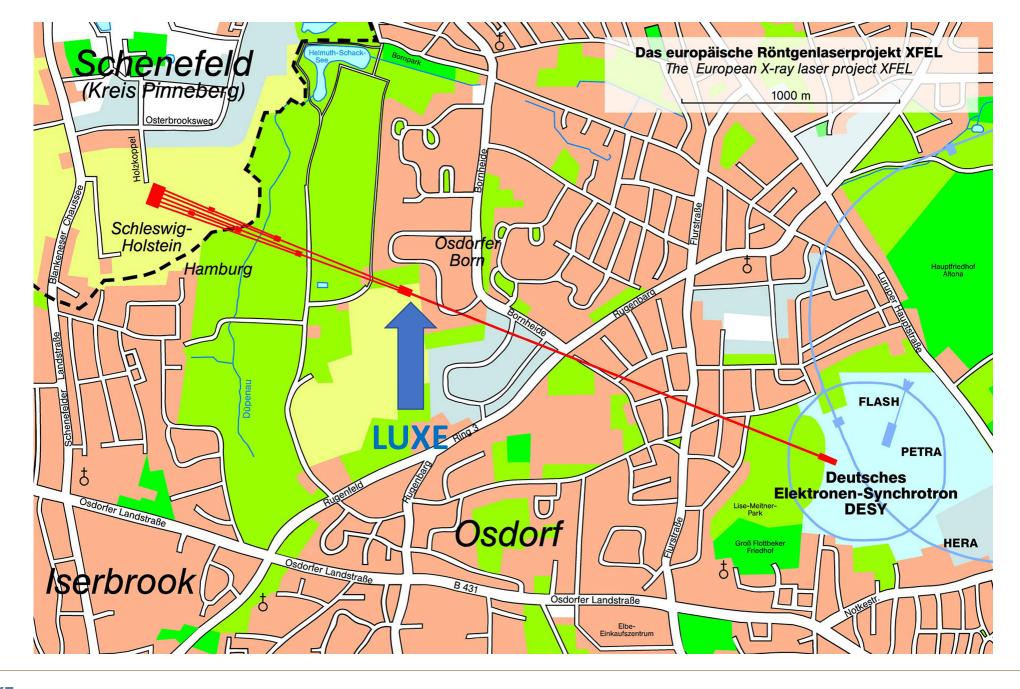




LOCATION





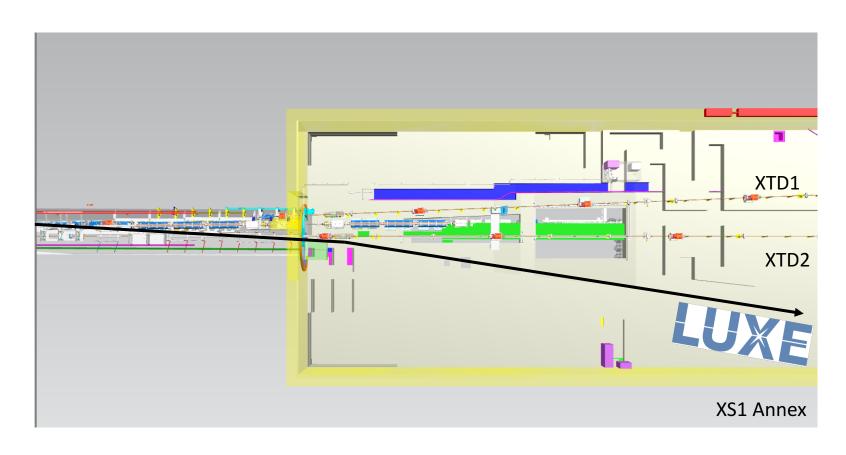


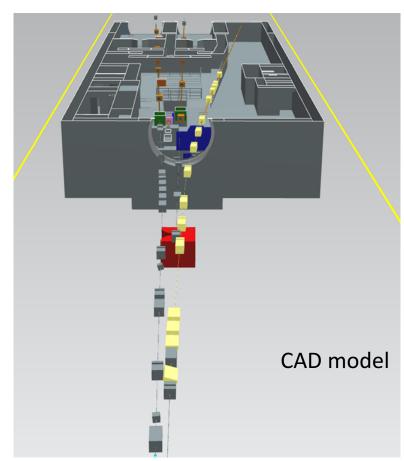






SCHEMATIC VIEW: BEAM EXTRACTION AND TRANSFER





M. Huening, M. Scheer, F. Burkart, W. Decking

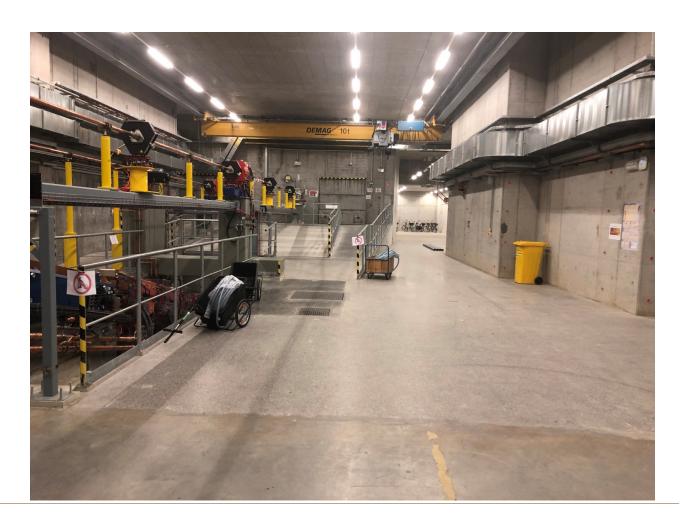


PICTURE OF TUNNEL AT XS1 ANNEX

Shaft located at end of linear accelerator of European XFEL

Dimensions of annex

• 60m long, 5.4m wide, 5m high





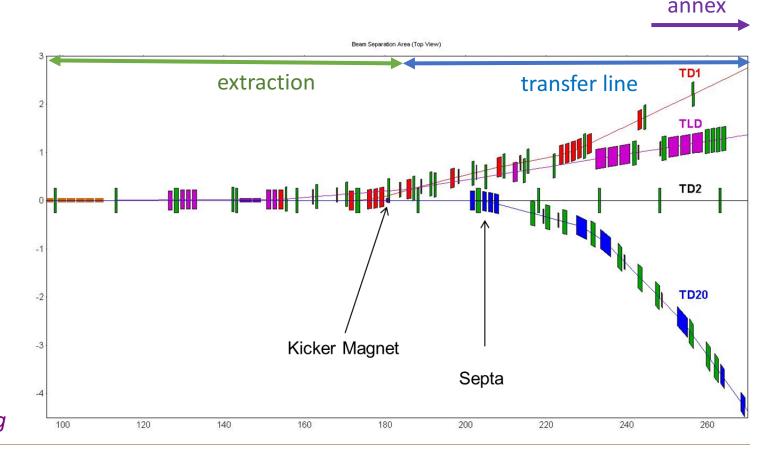
BEAMLINE LAYOUT

Design of magnets for beam extraction and then beam transfer to LUXE

- Most magnets use design already operating today in XFEL.EU
- New fast kicker magnets

Installation requires

- 5 weeks for extraction
- 7 weeks for transfer line



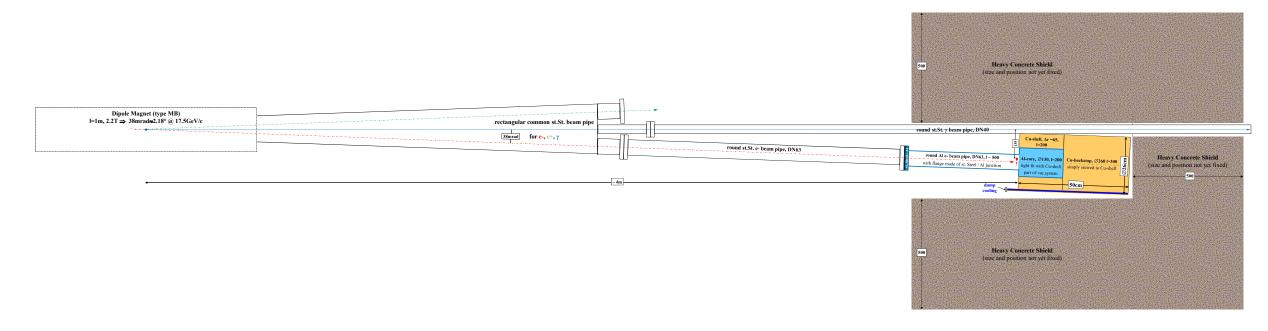
F. Burkart, W. Decking



BEAM DUMP

Beam needs to be safely dumped, design (with radioprotection group) well advanced

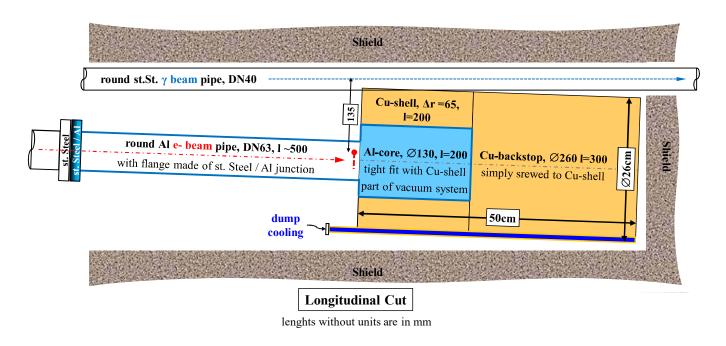
F. Burkart, M. Schmitz (DESY)

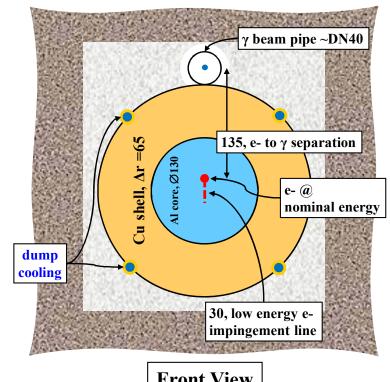




BEAM DUMP

Beam needs to be safely dumped, design (with radioprotection group) well advanced





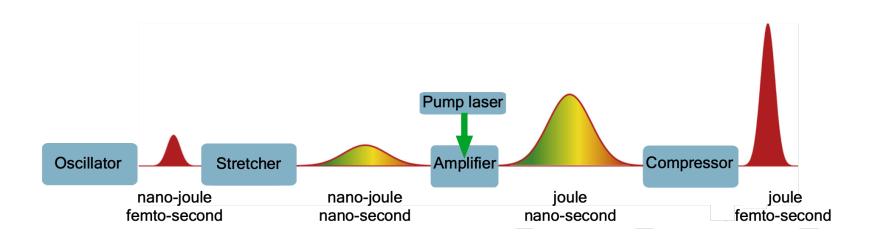
Front View

lenghts without units are in mm

F. Burkart, M. Schmitz (DESY)



LASER TECHNOLOGY









Mahmoud

Donna Strickland

Prize share: 1/4

- Use Chirped Pulse Amplification (CPA) technique
 - Half of the NP 2018 shared by Gerard Mourou and Donna Strickland for "for their method of generating high-intensity, ultra-short optical pulses."
- Ti:Sa laser with 800 nm wavelength
- Energy focussed strongly in both time and space => high intensity



LASER PARAMETERS

Parameter	Initial stage	Stage 1	Stage 2
Laser energy after compression [J]	0.9	9	
Percentage of laser in focus [%]	40	40	
Laser energy on focus [J]	0.36	3.6	
Laser pulse duration [fs]	30	30	
Laser repetition rate [Hz]	1	1	
Laser-beam crossing angle [degrees]	17	17	
Laser focal spot FWHM [μm]	8	8	3
Peak intensity [10 ¹⁹ W/cm ²]	1.6	16	110
Peak intensity parameter ξ	2	6.2	16
Peak quantum parameter χ: Ebeam=17.5 GeV Ebeam=14.0 GeV	0.41 0.32	1.3 1.0	3.3 2.6

Laser intensity:

$$I = \frac{E_L}{\Delta t \pi d^2}$$

with

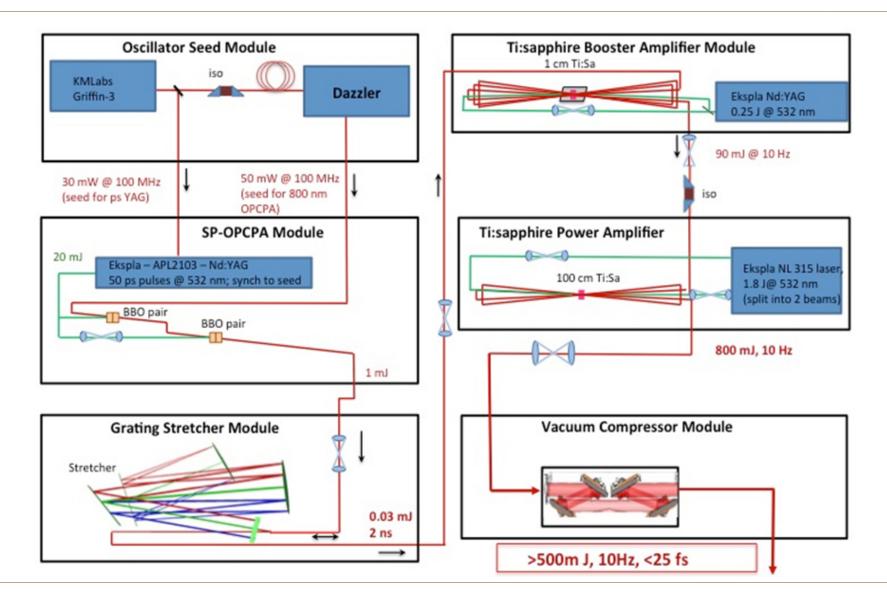
E_L: energy (J)

 Δt : pulse length (s)

 πd^2 : focus area (m²)

Lower intensities achieved by de-focussing laser or stretching pulse

LASER DESIGN

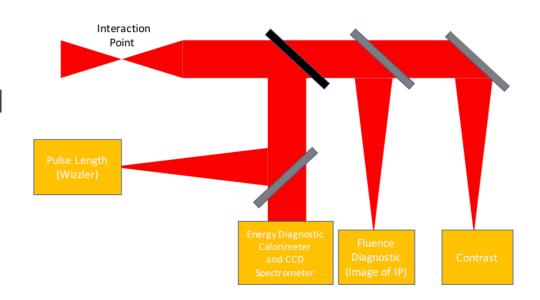


I. Pomerantz (Tel Aviv), G. Sarre (Belfast), M. Zepf (HZI Jena, Jena, Belfast) and others



LASER DIAGNOSTICS

- Aim to control intensity at level of 5-10%
 - Cannot measure it directly
- Several diagnostics measurements planned to measure parameters
 - Energy
 - Fluence (Energy/area)
 - Pulse length
- Laser shots can vary by ~15% for stable laser at this power
 - System can be used to tag intensity of individual shots





PARTICLE DETECTION AND SIMULATION RESULTS

RATES OF PARTICLES

e+laser	Location	particle type	rate for $\xi = 2.6$	rate for $\xi = 0.26$
	e [−] detector	$e^-, E_e < 16 \text{ GeV}$	1.5×10^{9}	6×10^{6}
	e^+ detector	e^+	15.3	< 0.01
	Photon detector	γ	6×10^{10}	1×10^7
	Photon detector (W foil)	e^+ and e^-	6×10^{6}	1×10^4
	Photon detector (W wire)	e^+ and e^-	1.5×10^{5}	1×10^2
			•	

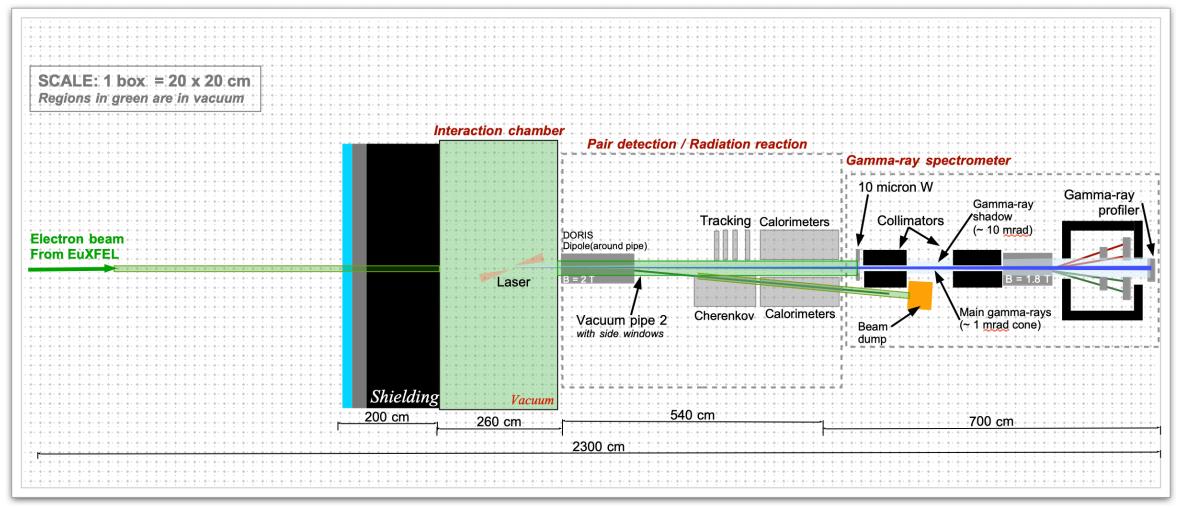
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l .	Location	particle type	rate for $\xi = 2.6$ rate for $\xi = 1.2$
γ+laser	e ⁻ detector behind converter	$e^{-}, E_{e} < 13 \text{ GeV}$	2×10^{7}
	e^+ detector behind converter	e^+	9×10^{4}
	photons after converter	γ	1.3×10^{8}
	e^{\pm} detector behind IP	e^-/e^+	5 1×10^{-2}
	Photon detector	γ	1.3×10^{8}
	Photon detector	e^+ and e^-	160
			-

=> Very different rates of particles => need different technologies

ELECTRON LASER COLLISIONS

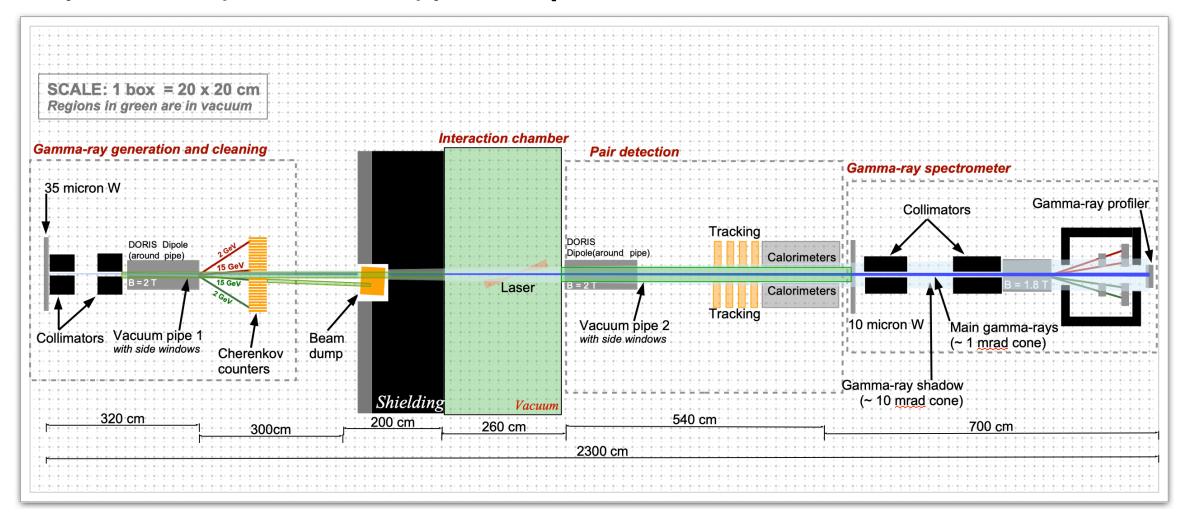
Compton and trident processes: $e^- + n\omega \rightarrow e^- + \gamma$ and $e^- + n\omega \rightarrow e^- e^+ e^-$



X

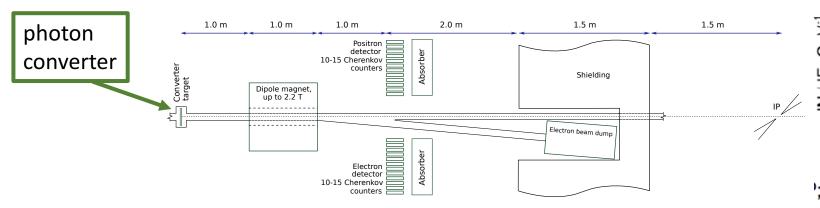
PHOTON LASER COLLISIONS

Pair production (Breit-Wheeler) process: $\gamma + n\omega \rightarrow e^- + e^+$

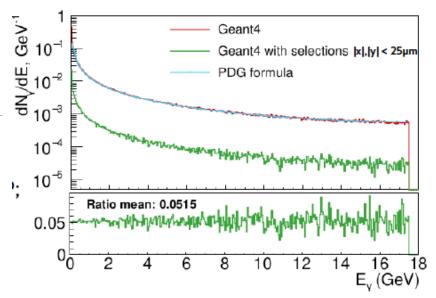


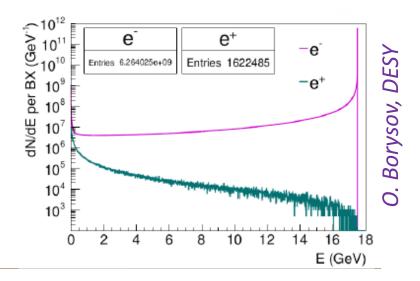


HIGH-ENERGY PHOTON FLUX



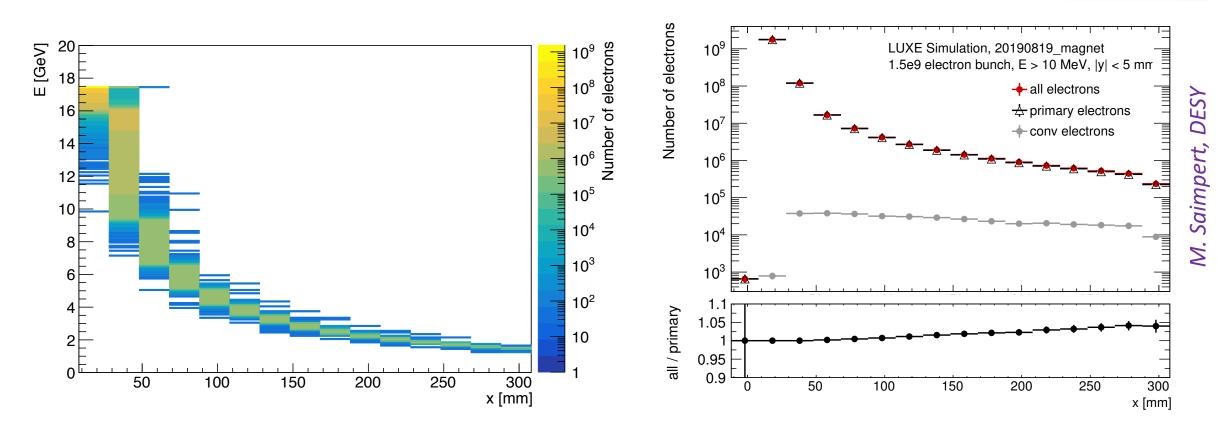
- Simulation of converter using Geant4
 - Tungsten Target with 0.01 X_0 (35 μ m) => 1% at IP
- Spectrum of photon energies important to know
 - Measure by observing electrons and positrons right after dipole magnet
- Particle detection
 - •2T magnet followed by array of Cherenkov detectors measures flux vs impact position => energy spectrum







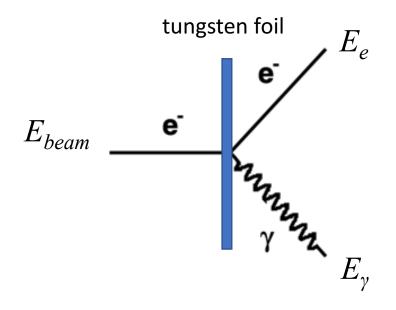
PHOTON FLUX MEASUREMENT: ELECTRONS

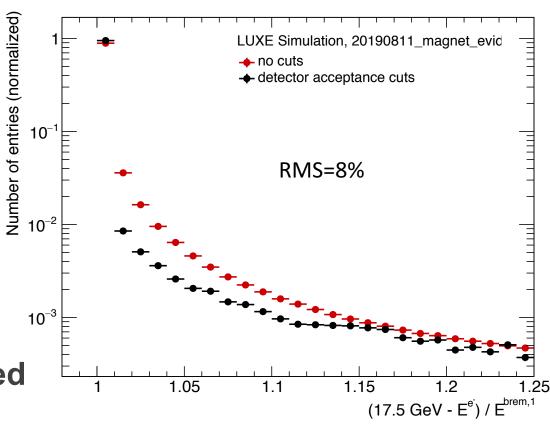


- Electron energy measured based on position behind dipole magnet
- Dominated by primary electrons
 - Contamination of converted electrons small (can estimate based on positron flux)



PHOTON ENERGY MEASUREMENT



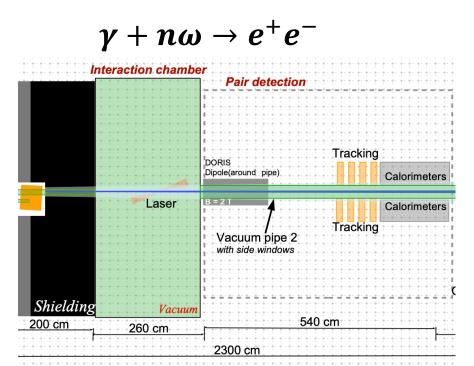


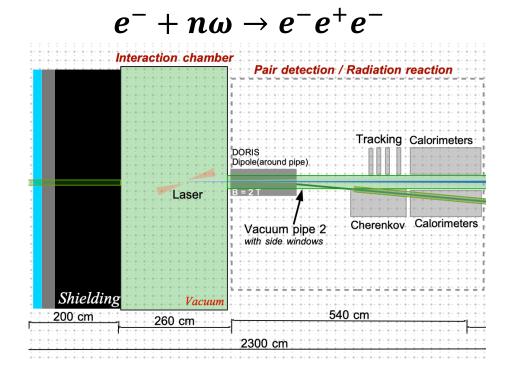
Photon energy determined from measured electron energy to within ~10%:

$$E_{\gamma} = E_{beam} - E_{e}$$



ELECTRON AND POSITRON DETECTORS





Pair production:

• e^+ and e^- rate ~0.01-100 => silicon pixel detectors and calorimeters

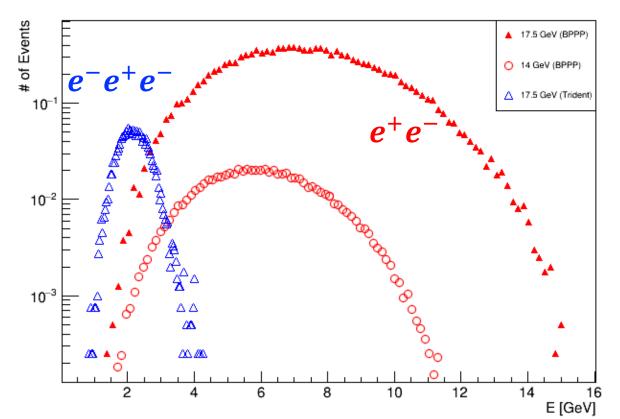
Trident:

- e^+ rate ~0.01-100 => silicon pixel detectors and calorimeters
- e^- rate ~10⁶-10⁹ => Cerenkov counters and calorimeter/absorber

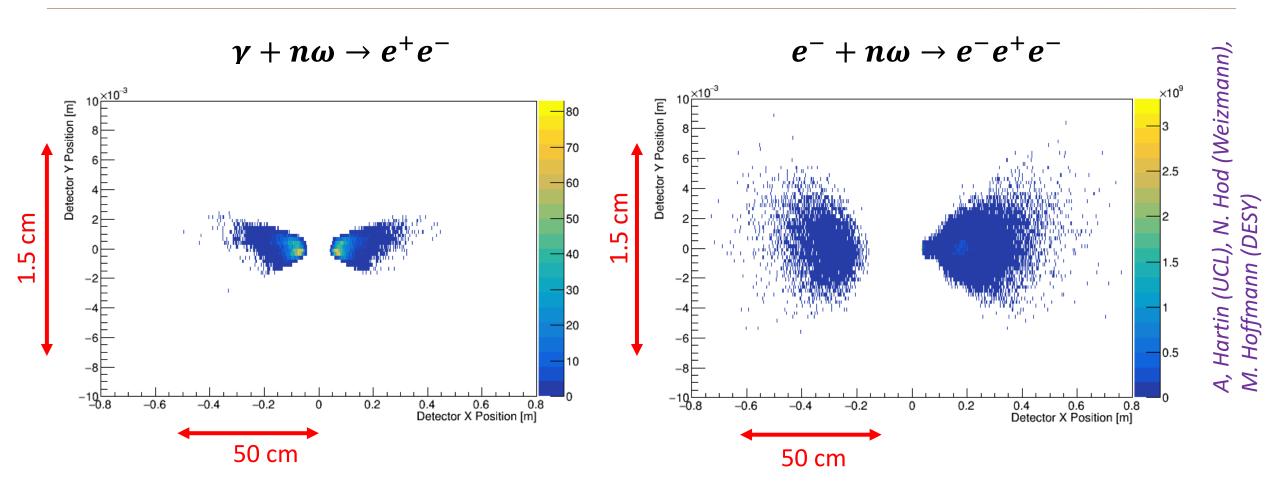
SIMULATION RESULTS

- Monte Carlo simulation of expected signatures used
 - By A. Hartin, UCL
- Energy spectrum ranges between 1 and 15 GeV
 - Energies significantly lower for trident process
- For trident process uses "twostep" process only
 - Calculation of one-step trident ongoing

Positron Energy Spectrum



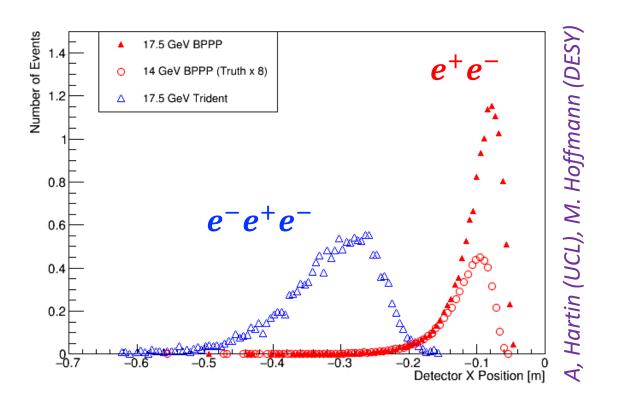
DETECTOR OCCUPANCIES AFTER INTERACTION POINT

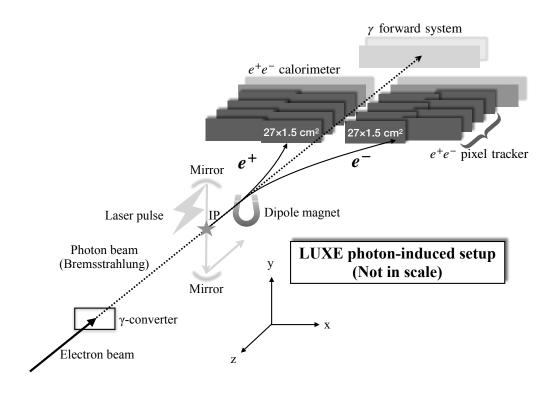


- Vertical direction: very small spread for both processes
- Horizontal direction: particles contained within ~50 cm



HIT POSITION AT FIRST DETECTOR PLANE



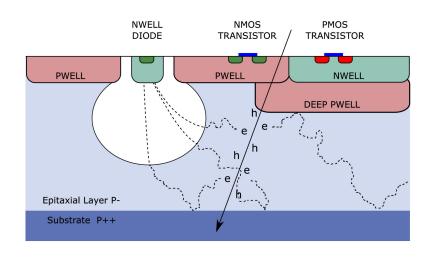


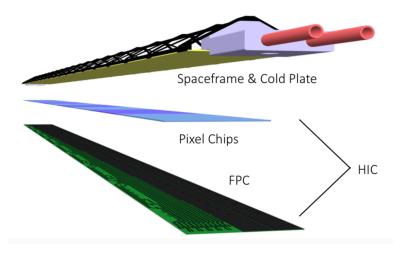
Detectors need to span about ~50 cm to have acceptance >95%:

- $e^- + n\omega \rightarrow e^- e^+ e^-$ process: acceptance ~95%
- $\gamma + n\omega \rightarrow e^+e^-$ process: acceptance >99%



SILICON DETECTORS





ALPIDE pixel detectors

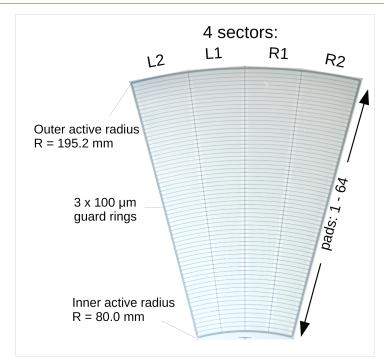
N. Hod (Weizmann Inst.)

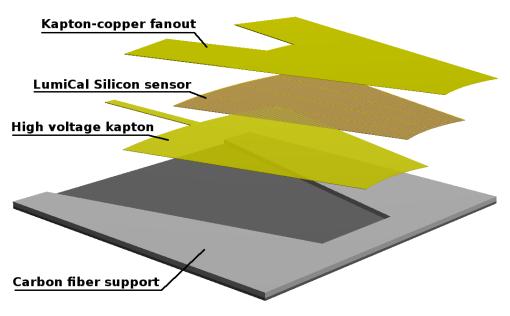
- Developed by ALICE collaboration
- Staves of 27 cm length; sensor size 1.5x1.5 cm²
 - Achieve full coverage with two staves placed next to each other
- •Pixel size: 27 x 29 μm² => Spatial resolution ~5 μm
- Plan to use four layers staggered behind each other

Redundant tracking possible, important for beam background rejection



CALORIMETERS



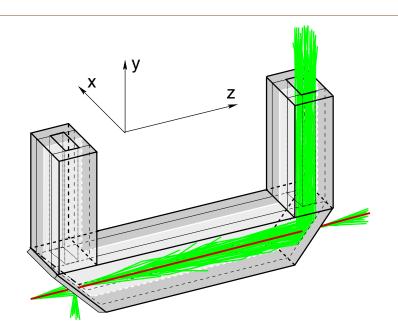


Y. Benhammou, H. Abramowicz, A. Levy (Tel Aviv U)

High granularity silicon Tungsten calorimeter

- Developed for luminosity measurement at linear colliders (LUMICAL)
- •20 tungsten absorber plates (3.5mm), Si layers in gaps (320 µm)
- Geometry adapted to fit needs of LUXE (~50cm long, vertical spread <1mm)
- Moliere radius 8 mm, Prototyped and test beam measurements available

CHERENKOV COUNTERS





Use Cherenkov detectors in high-flux regions

- Use design developed for ILC polarimeters
- •Linearity better than 0.1% over dynamic range spanning 10³
- Threshold of ~10 MeV => robust against background from low energy radiation
- Plan to use array of 15 detectors with cross section of 2x2 cm²

DESY, LUXE



POSITRON RATE VS LASER INTENSITY

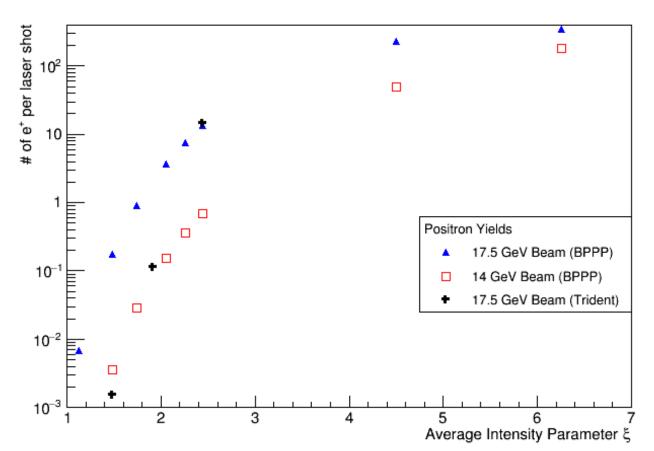
Main result of experiment

Low laser intensity

Encounter power-law behaviour

High intensity

- Should observe deviation from power-law behaviour
- Aim to quantify by extracting coefficient





POSITRON RATE VS LASER INTENSITY

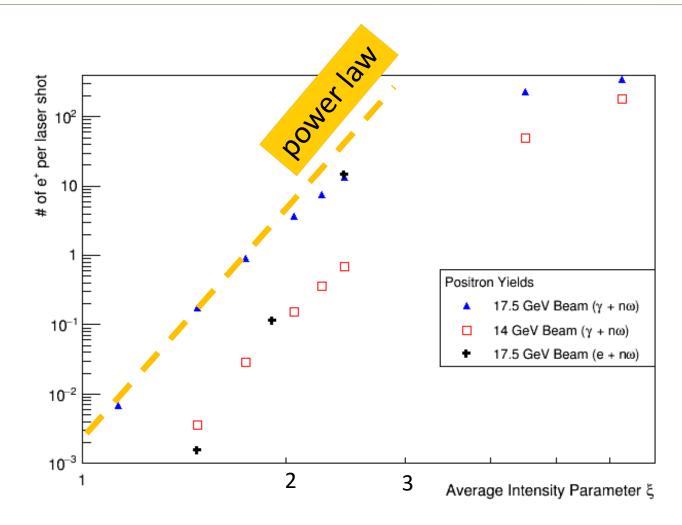
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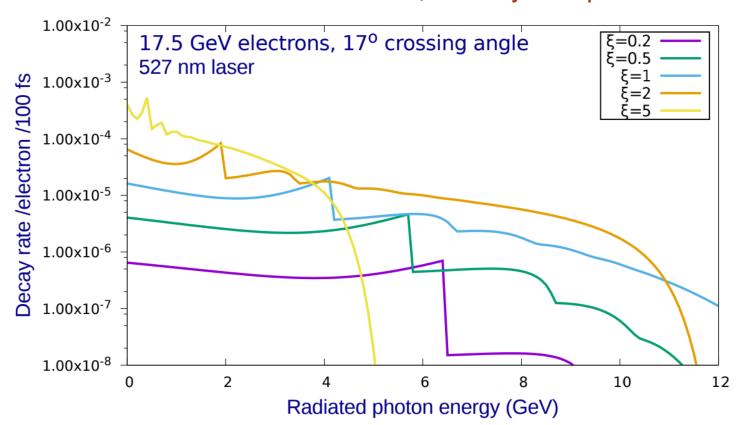
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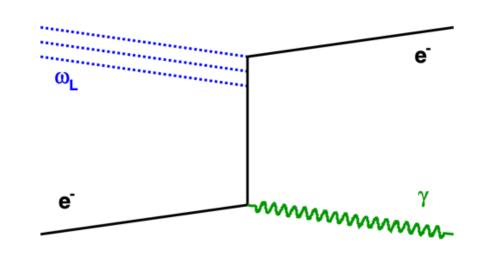




NON-LINEAR COMPTON SCATTERING: $e^- + n\omega_L \rightarrow e^- + \gamma$

HICS for 17 GeV electrons, intensity sweep



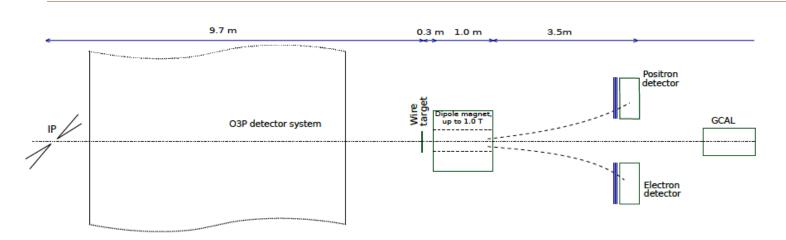


$$p_{\rm i} + k \frac{\xi^3}{2\chi_{\rm i}} \to p_{\rm i}^2 = m^2(1 + \xi^2)$$

A, Hartin (UCL)



NON-LINEAR COMPTON PROCESS

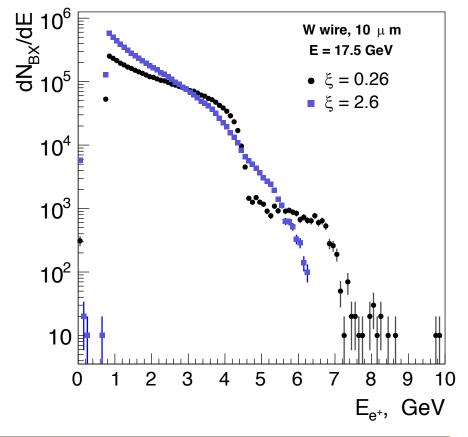


Measure photon flux and energy in "photon detection system"

- Photon flux very high (>10⁷ per laser shot)
- Thin wire to convert photons to e+e- pairs

Compton edges observable in e^\pm energy spectra at low ξ

M. Borysova (Kiev KINR)





TENTATIVE TIME SCALES: 2020 AND BEYOND

- Summer 2020
 - CDR for LUXE experiment (TDR a year later?)
- Nov/Dec 2020
 - Start preparatory work for installation; main installation following year
- 2022-2023: prototype experiment (stage-0)
 - 1st year: electron-laser running
 - 2nd year: photon-laser running
- 2024:
 - Install more powerful laser (~1 PW) and improved laser diagnostics
 - Publish results of stage-0 experiment
- 2025-2027: Data taking with high-power laser (stage-1)
 - Interesting to run at different energies, currents,... configurations
 - Plan to benefit from requirements of other experiments



CONCLUSIONS

- LUXE is an experiment to test what happens when high energy electrons or photons observe an intense laser field
- LUXE will probe quantum physics in new regime of high intensity QED using a minute fraction of European XFEL electron beam
 - Measure several phenomena predicted more than 60 years ago
 - Test quantum field theory in a new regime
- International collaboration of 36 scientists (12 institutions from 4 countries) performed feasibility study
 - Will release a "Letter of Intent" later this week



CONCLUSIONS

- LUXE is an experiment to test what happens when high energy electrons or photons observe an intense laser field
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S. Weinberg: "My advice is to try crazy ideas and innovative experiments. Something will come up."





THANKS!!

DESY directorate:

DESY Strategy Fund funded many of studies presented here

DESY technical groups:

- MVS (Vacuum Modification)
- MIN (Kicker, Beam Dump)
- D3 (radio protection advice)
- MEA (installation and Magnets)
- ZM1 (Construction Input)
- MKK (Power/Water)
- IPP (CAD integration)

DESY divisions

• MXL, MPY, MPY1 (from M), FLC (from FH)





BACKUP SLIDES



STEVEN WEINBERG

Steven Weinberg (03/2019, interview at APS):

Do you think the problems faced by particle physicists today are different from those that you faced as a young scientist?

I do. It was a different situation 50 years ago. Back then, we had experimental data coming out of our ears, and a lot of it didn't seem to fit any pattern. The problems seemed formidable, but there were so many ways to go with new theories. It really was a thrilling time to be a physicist.

Nowadays, it's very hard to think of a challenge that we can get our teeth into. The current puzzles don't offer theorists many opportunities to propose solutions that can be tested experimentally.

Do you have any advice to offer the next generation?

Winston Churchill had a motto at the beginning of World War II: "Keep buggering on." In that spirit, I think it's better to do something than to do nothing. My advice is to try crazy ideas and innovative experiments. Something will come up.



Steven Weinberg, NP 1979



NON-LINEAR COMPTON SCATTERING: $e^- + n\omega \rightarrow e^- + \gamma$

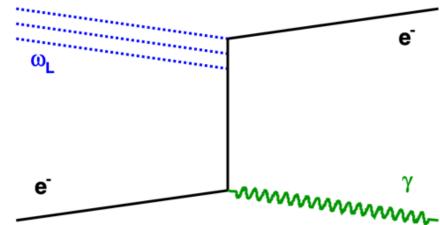
Rate of high-intensity Compton scattering proportional to

$$\sum_{\mathsf{n}} \delta^{(4)} \left[p_{\mathsf{i}} + k \frac{\xi^3}{2\chi_{\mathsf{i}}} + nk - p_{\mathsf{f}} - k \frac{\xi^3}{2\chi_{\mathsf{f}}} - k_{\mathsf{f}} \right]$$

 Even for small n expect shift of Compton edge due to effective increase of electron rest mass

$$p_{\rm i} + k \frac{\xi^3}{2\chi_{\rm i}} \to p_{\rm i}^2 = m^2(1 + \xi^2)$$

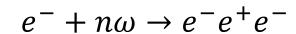
Has never been observed

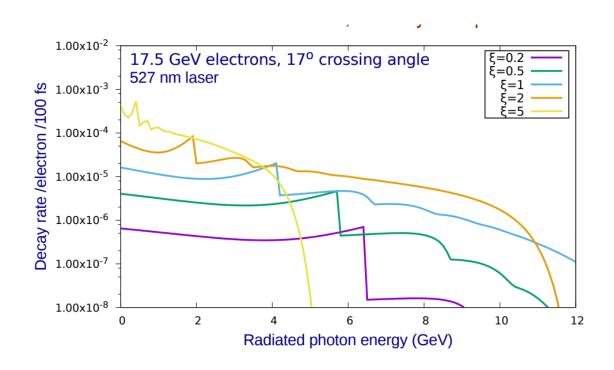




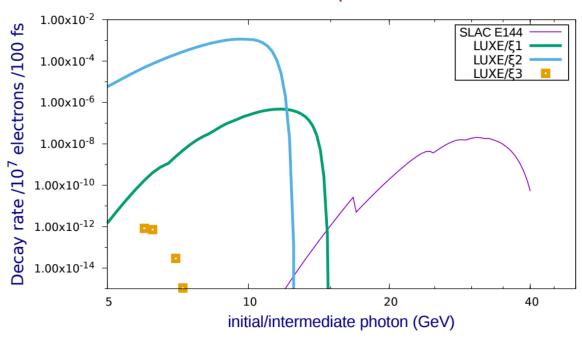
MEASUREMENTS OF MASS SHIFT AND TRIDENTS

$$e^- + n\omega \rightarrow e^- + \gamma$$



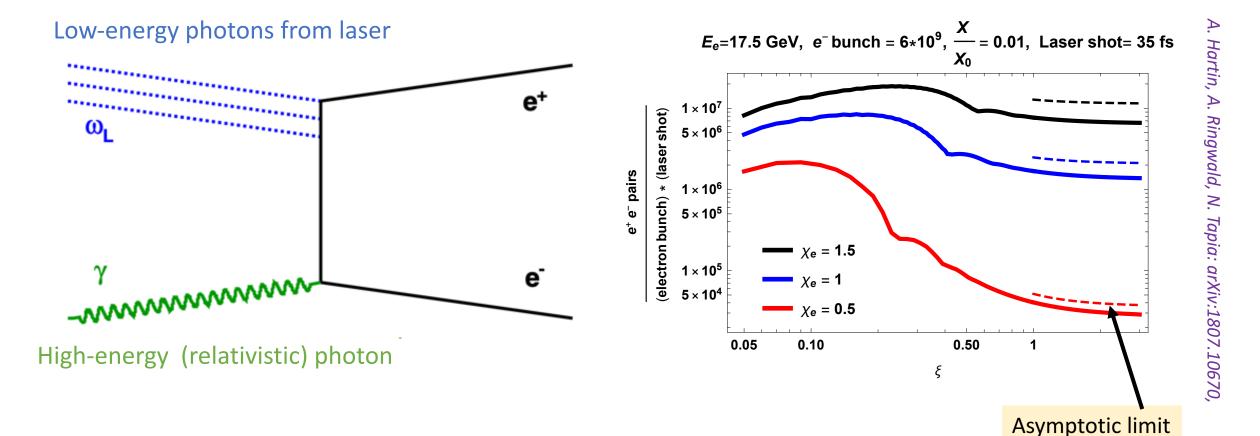


Positron rate for different parameter sets



Plots from A. Hartin, IJMPA 33, 1830011 (2018)

ABSORBING LIGHT WITH LIGHT



- Use spectrum of high energy photons created via Bremsstrahlung
 - •Full calculation agrees with asymptotic limit for $\xi > 1$ and $\chi \lesssim 1$

DESY, LUXE