



LUXE

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

Birmingham, February 19th 2020





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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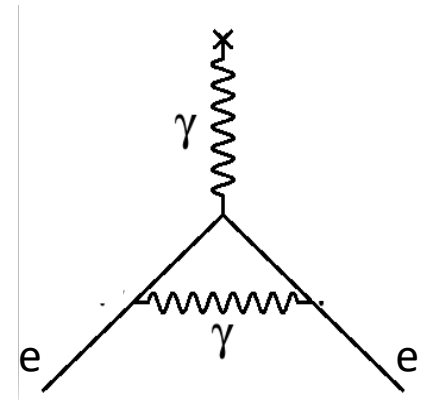
arXiv:1909.00860



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 5th 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?**

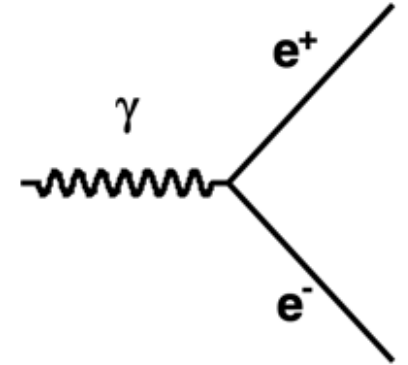
- QED expects that vacuum becomes unstable e.g. for nucleus with $Z > 137$. Spontaneous creation of e^+e^- pairs (“boiling of vacuum”)

- **Historical developments:**

- **1930s:** Initial discussions of EM in strong field in literature (Sauter, Euler, Heisenberg) => introduction of “critical field”

- **1951:** First non-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 Maxwell'schen 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:

$$\Omega = \frac{1}{2} (\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{hc} \int_0^\infty e^{-\eta} \frac{d\eta}{\eta^3} \left\{ i\eta^2 (\mathfrak{E}\mathfrak{B}) \cdot \frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})}\right) + \text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i(\mathfrak{E}\mathfrak{B})}\right) - \text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3} (\mathfrak{B}^2 - \mathfrak{E}^2) \right\}.$$

$$\left(\begin{array}{l} \mathfrak{E}, \mathfrak{B} \text{ Kraft auf das Elektron.} \\ |\mathfrak{E}_k| = \frac{m^2 c^3}{e \hbar} = \frac{1}{„137“} \frac{e}{(e^2/mc^2)^2} = \text{„Kritische Feldstärke“} \end{array} \right)$$

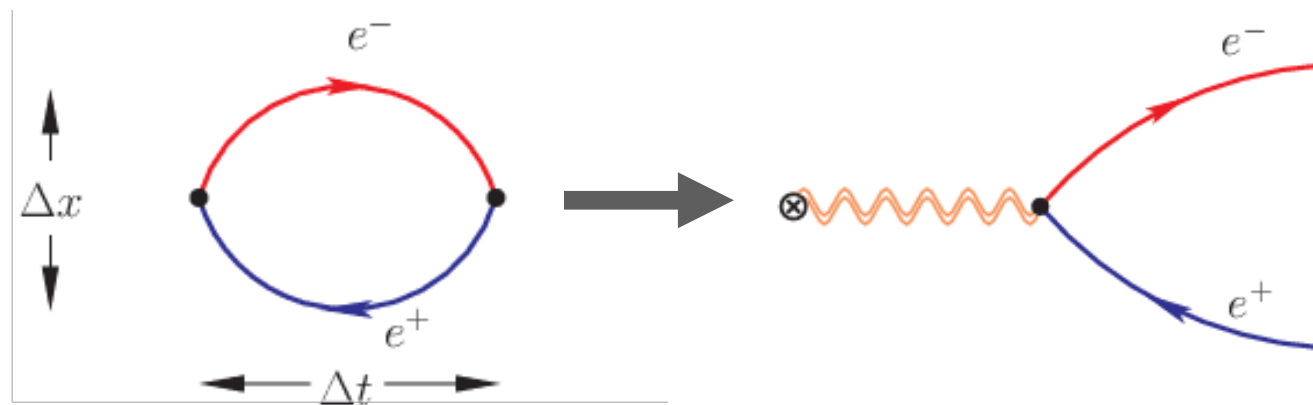
THE SCHWINGER PROCESS

J. Schwinger: *On Gauge*

Invariance and Vacuum

Polarization,

Phys. Rev. 82 (1951) 664



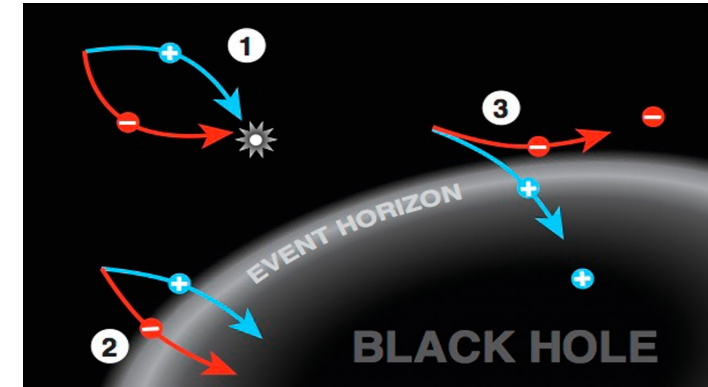
Photon in electric field: simplified

- The EM force is $F = e\varepsilon$
- Energy needed to separate e^+e^- pair: $E = Fd_{min}$
- Heisenberg: $\Delta t \geq \frac{\hbar}{2\Delta E} \Rightarrow \Delta t_{min} = \frac{\hbar}{4mc^2} \Rightarrow$ minimum distance: $d_{min} = 2c\Delta t_{min} = \frac{\hbar}{2mc} = \lambda_c/2$
- Virtual pair becomes real if $E = Fd_{min} = \frac{\hbar e\varepsilon}{2mc} > 2mc^2 \Rightarrow$ possible if $\varepsilon > \frac{4m^2c^3}{\hbar e} = 4\varepsilon_{crit}$

$$P \propto \exp\left(-\frac{d}{\lambda_c}\right) \propto \exp\left(-\pi \frac{\varepsilon_{crit}}{\varepsilon}\right)$$

ANALOGY TO HAWKING RADIATION

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



H. Murayama

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



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

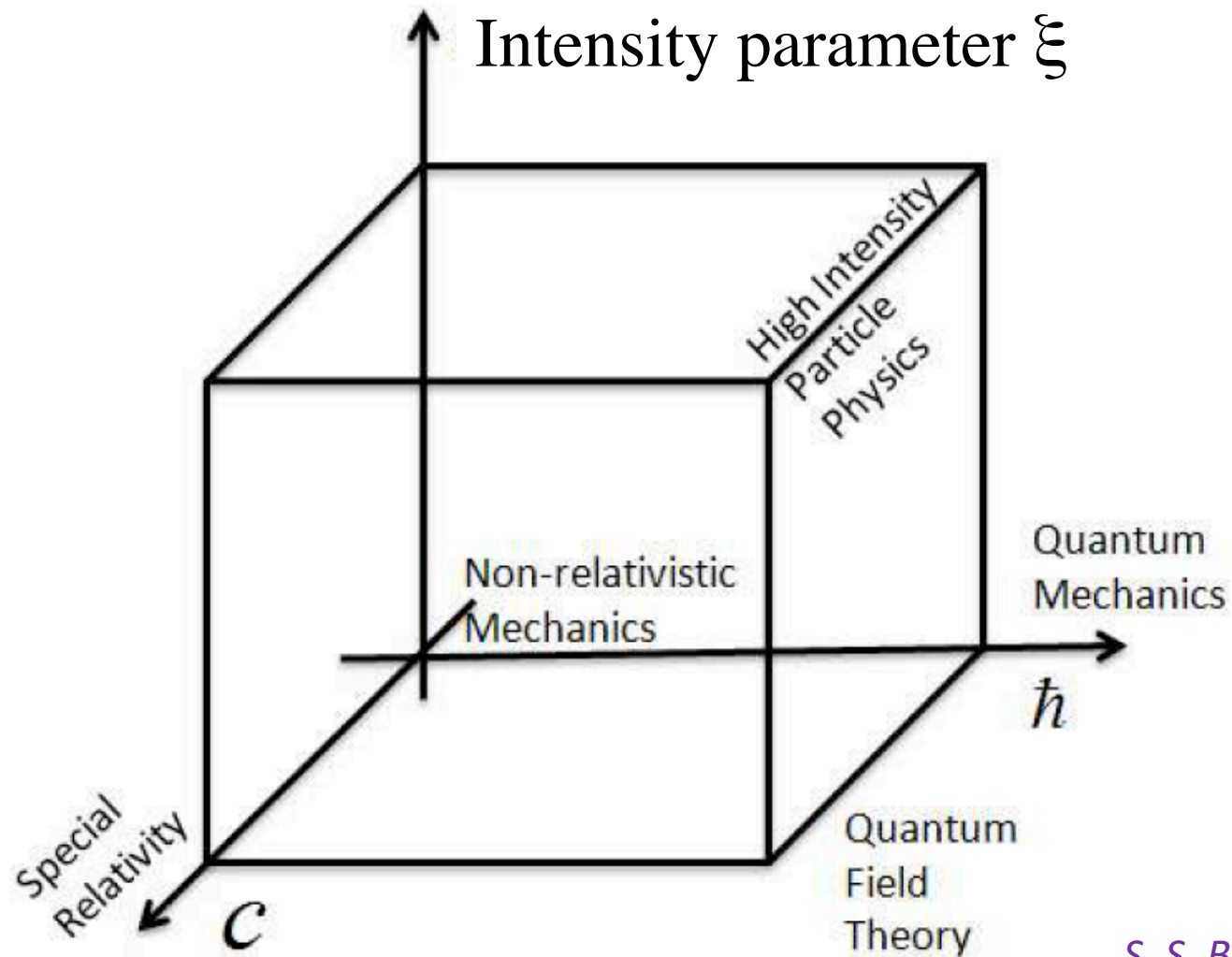
- could teach us about other non-perturbative regimes, e.g. understanding confinement [Gribov, hep-ph/9902279]

- **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!



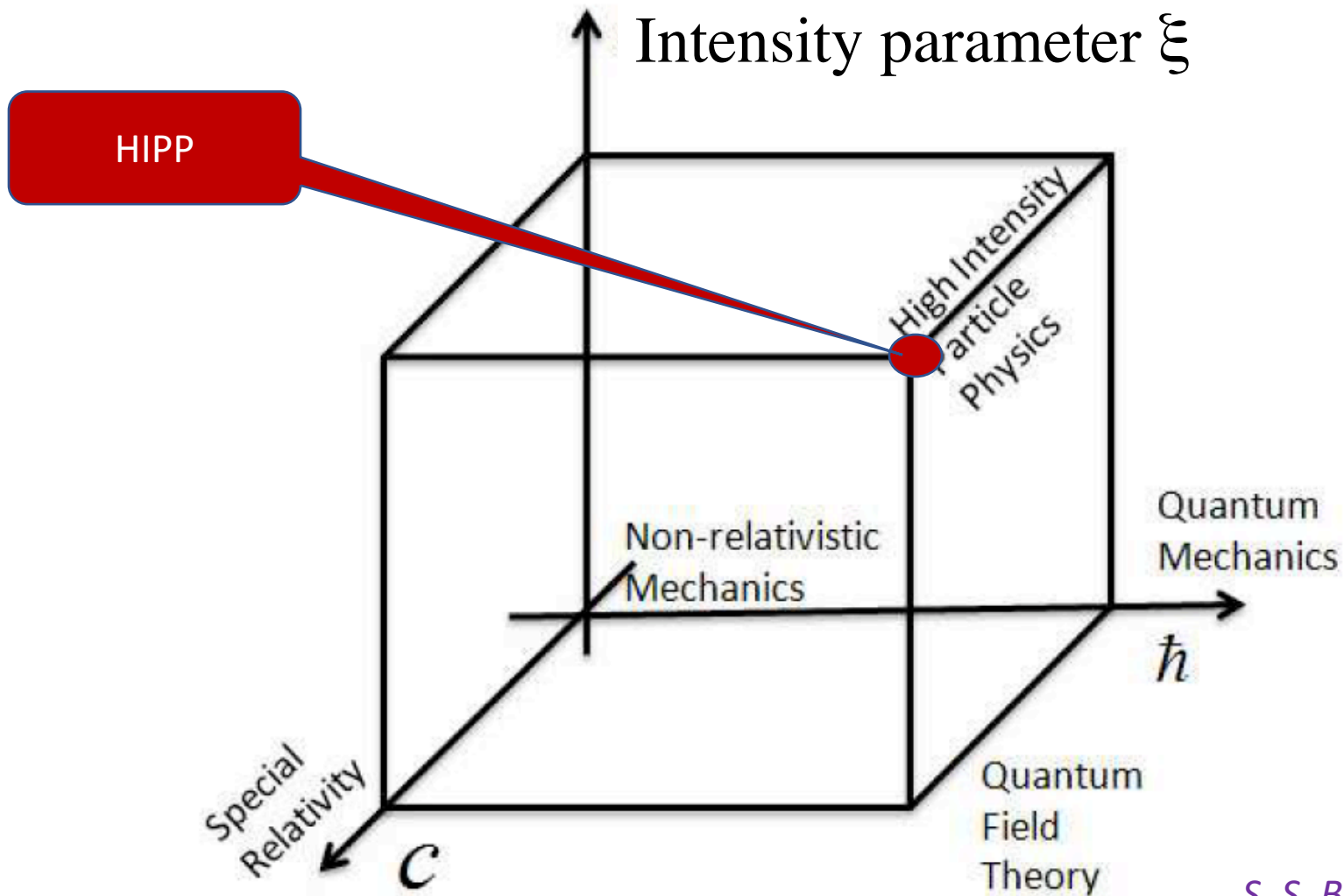
THEORIES ON A CUBE



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



THEORIES ON A CUBE

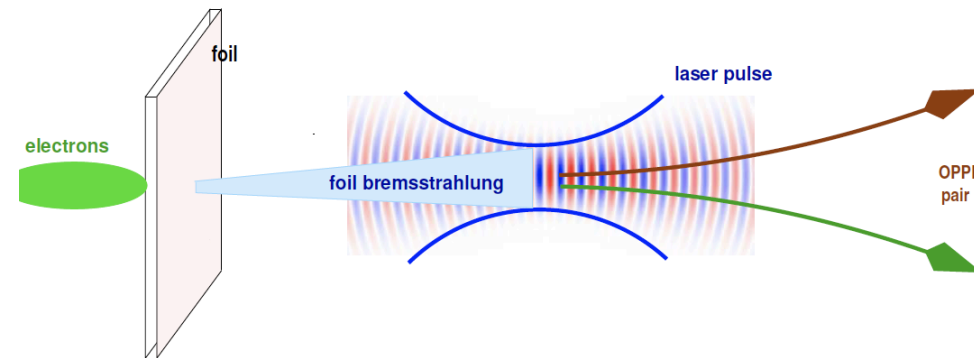


S. S. Bulanov, W. Leemans et al.

LASER AND PHOTON BEAM

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

$$\xi = \frac{e\epsilon_L}{m_e\omega_L c} \quad \chi \approx \gamma \frac{\epsilon_L}{\epsilon_{crit}}$$



- Laser power required to reach Schwinger field ($\chi_\gamma \sim 1$):

- Non-relativistic photons: $I = 2 \times 10^{29} \text{ W/cm}^2$
- EU.XFEL, $E_\gamma \approx 10 \text{ GeV}$: $I \approx 10^{20} \text{ W/cm}^2$
- ELI-NP, $E_\gamma \approx 1 \text{ GeV}$: $I \approx 10^{22} \text{ W/cm}^2$

=> Much beyond currently achievable values

=> Can use well-tested laser technology

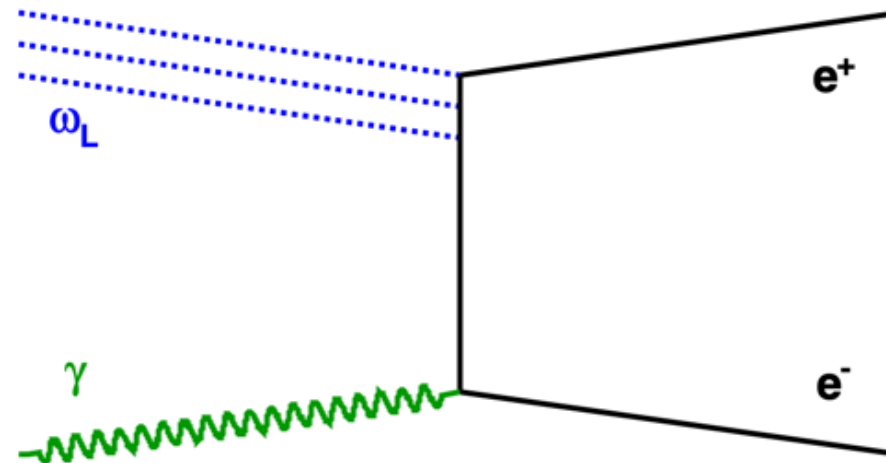
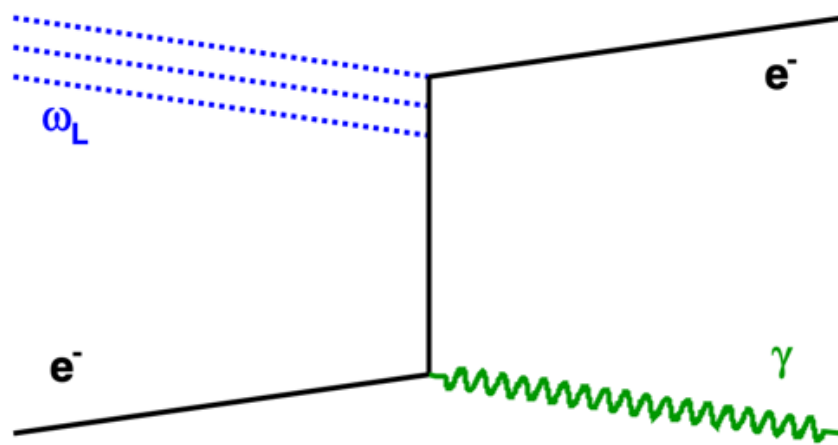
=> State-of-the-art laser needed

MAIN PROCESSES OF INTEREST

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

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

Low-energy photons
from laser

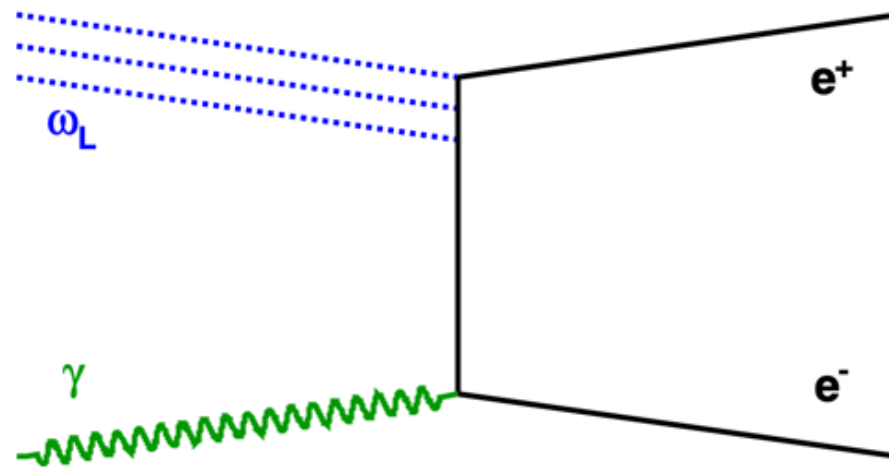


High energy electron or photon interacts with laser

- Also higher order process $e^- + n\omega_L \rightarrow e^- e^+ e^-$
- Via two steps ($e^- + n\omega_L \rightarrow e^- + \gamma$ and then $\gamma + n\omega_L \rightarrow e^+ e^-$) 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 \sim equally \Rightarrow 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

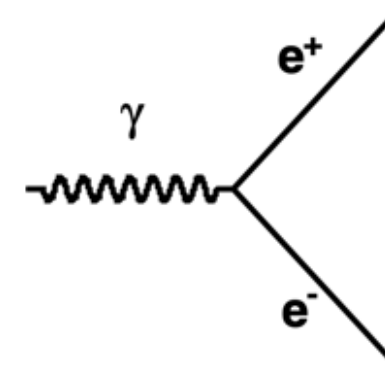


**Observation of deviation from power-law is
the experimental signature of strong QED**

PAIR PRODUCTION PROCESS

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

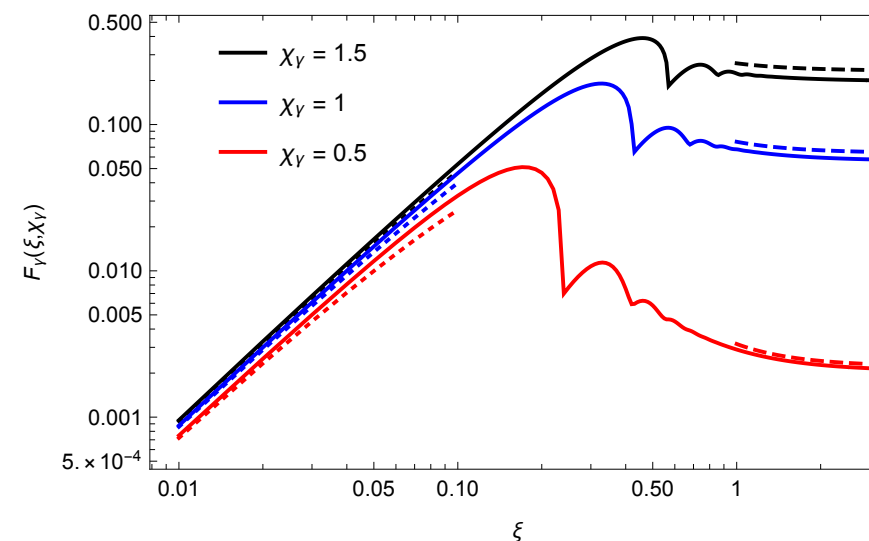
$$\frac{\Gamma_{\text{SPP}}}{V} = \frac{m_e^4}{(2\pi)^3} \left(\frac{|\mathbf{E}|}{E_c} \right)^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_c}{|\mathbf{E}|}\right) \propto \exp\left(-\pi \frac{E_c}{|\mathbf{E}|}\right)$$



- Pair production in plane wave laser: asymptotic result

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

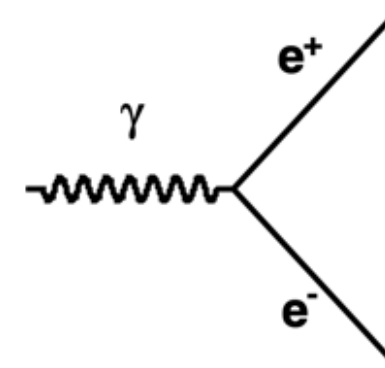
- Good agreement between full calculation and asymptotic result for $\xi \ll 1$ and $\xi > 1$



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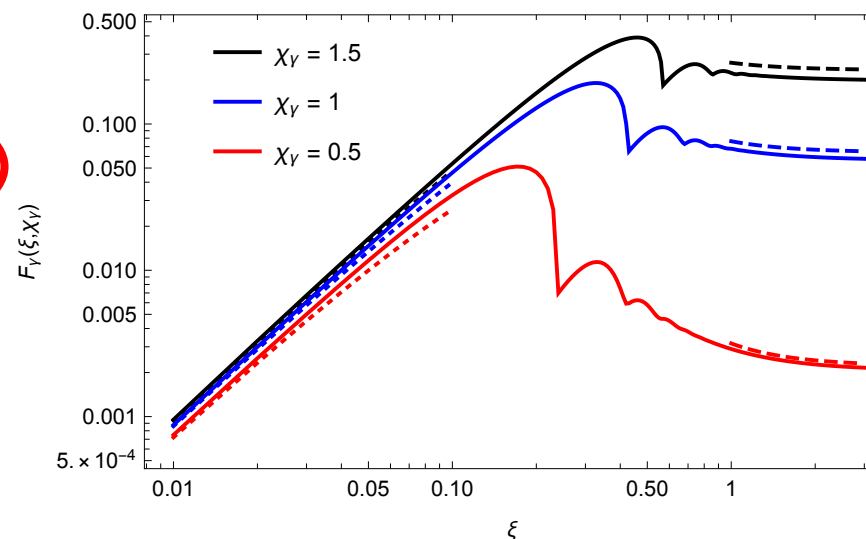
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- Pair production in plane wave laser: asymptotic result

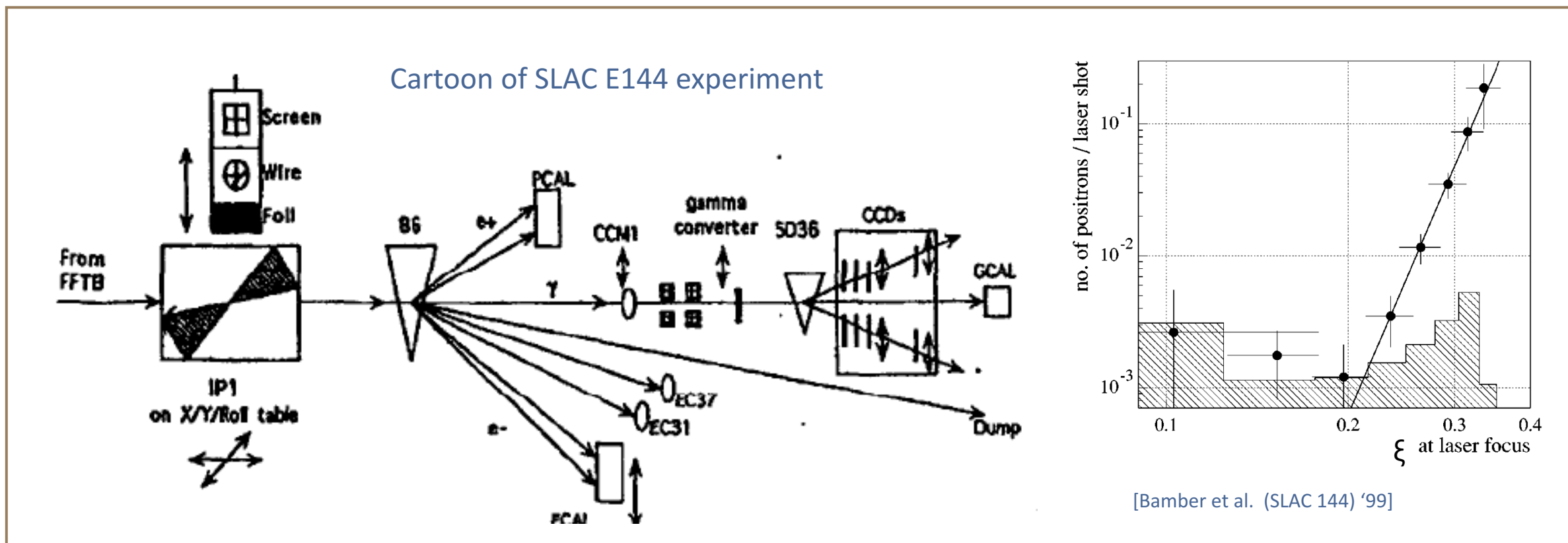
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- Good agreement between full calculation and asymptotic result for $\xi \ll 1$ and $\xi > 1$



EXPERIMENT E144 AT SLAC

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





E144 IN THE NEWS...

DEUTSCHE ZEIT WISSENS
 Nr. 42 17. Oktober 1997. Seite 17

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

Kann die Quantenmechanik verstanden werden? So fragte: programmatisch vor einigen Jahren Nature-Herausgeber John Maddox. „Was die Biologie angeht, so verfügt jeder über Erfahrungen aus erster Hand – vom Fußpilz über die Verdauung bis zur Fortpflanzung. Deshalb kommt diese Wissenschaft in der Presse auch so gut weg.“ Kluge Maddox bringe man dagegen auf einer Dinnerparty das Gespräch auf die Quantenmechanik, so bekomme man bestenfalls Antworten wie etwa: Nichts sei zu schnell, die Welt sei nicht so wie sie scheint, man möge entropieren: Therapeutik nehme sie an. Man soll nicht aufpassen, sondern die Bedeutung dieses Fachgebietes demonstrieren und sie allgemeine Bewusstseinsbahn“ forcieren Maddox.

Amerikanische Physiker an zwei von mehreren Standorten, wählten am Linearbeschleuniger der Stanford-Mittelnormen, erstmalig Licht in Materie um, die Werk, wie ein wenig an die Erfindung der Welt durch göttliche Hand erörtern, Aussagen aus bloßen Nichts Materie zu erzeugen, das sich selbst in Teilchen und Antiteilchen vorfinden. Nur ist dieser Schöpfungsakt endlich auch vor Zeugen möglich.

Verglichen mit dem Gottestoff der Erzeugung der Hochenergiephysiker in Stanford allerdings beschließen zur Nachregulierung der Teilchenbeschleuniger, das gerade einmal rund einhundert Elektrotronen – sowie deren Antiteilchen, die Positronen – erzeugt. Mit dieser Ausbeute, für die in Stanford mehrere Billionen Watt verwendet werden, ließe sich nicht einmal ein Taschengeldspeicher zum Glücken bringen. Eine verheerende Energiebatterie. Aber es geht ja auch mehr um Prinzipielle: Also reiner Energie läßt sich Materie vererben. Welche Wichtige Syntheschritt steckt in diesem Akt?

Die angekündigte Prozedur hat der Mensch nämlich schon vor mehr als fünfzig Jahren gemessen – mit vornehmender Auswirkung. Die Atomkerne demonstrieren in aller Welt die plötzliche Umwandlung von Materie in Energie, gemäß der selbigen Gleichung – die die Masse eines Kernes multipliziert mit der Lichtgeschwindigkeit zum Quadrat ergibt dessen Energie. Albert Einstein, der diese berühmteste Formel der Physik 1905 erstmalig veröffentlichte, ahnte noch nicht von der gewaltigen Springkraft, die sich dahinter verbirgt. Er dachte an die Energie, die aus den Atombomben – als ist nicht abgeschlossen, daß bei Kernen, deren Energieinhalt in beiden Maße veränderlich ist (in beiden Radienmaß), eine Prüfung der Theorie gelang. Nicht nur in der Theorie, sondern in der Natur, denn die Radioaktiven, sondern in Hiroshima wurde die Theorie bewiesen. Nur, ein weiteres halbes Jahrhundert später, wird in Stanford Materie aus Licht erzeugt und damit Schöpferkraft statt Zerstörerenergie demonstriert. Werden die Physiker um Adrian C. Melissinos ebenso in der Theorie, wie in der Natur, Robert Oppenheimer und seine Los-Alamos-Kollegen?

Die Fachleute wanken ab. An Einsteins Formel zweifel schon lange niemand mehr. Doch, ein weiteres halbes Jahrhundert später, wird in Stanford Materie aus Licht erzeugt und damit Schöpferkraft statt Zerstörerenergie demonstriert. Werden die Physiker um Adrian C. Melissinos ebenso in der Theorie, wie in der Natur, Robert Oppenheimer und seine Los-Alamos-Kollegen?

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The New York Times
 ARCHIVES | 1997

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 of nothing.

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 enough power.

Dr. Adrian C. Melissinos of the group, said in an interview that the experiment was produced by a torrent of the needed energy, even though the beams were only a few centimeters most powerful.

But the opposing beams of radiation drawn from electrons whizzing in a second beam of radiation was so powerful that it produced particles.

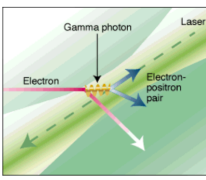
The paths of colliding electrons are complicated as those choreographed by a computer.

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2 ARTICLES REMAINING

Article Figures & Data Info & Metrics eLetters

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 collimated 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 19

**L'importante risultato ottenuto a Stanford
 Dalla luce è nata la materia
 Come predisse Einstein**

di LANFRANCO BELLONI

A Stanford hanno festeggiato la nascita in laboratorio della prima materia generata da incontri ravvicinati di fasci di luce. Facendo collidere fra di loro abbondanti impulsi di fotoni si è assistito alla creazione di particelle di materia e antimateria, più precisamente di coppie di elettroni e di antielettroni. E questo è, appunto, la prima volta che accade.

Come spiegavano i libri di testo, se si opera uno scontro frontale fra un elettrone e un anti-elettrone, si provoca una reciproca annichilazione della particella di materia con quella di antimateria. Il risultato del drammatico incontro consiste in un paio di fotoni o particelle di luce, che si allontanano dal luogo dell'impatto in direzione opposta. Se le traiettorie della particella e dell'antiparticella iniziale, prima dello scontro frontale, sono nella direzione est-ovest, 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 solo, per rispettare la fondamentale legge della conservazione della quantità di moto. Sempre i libri di testo spiegavano che il fenomeno avrebbe dovuto essere perfettamente reversibile. Facendo urtare fra loro, lungo la direzione nord-sud, due fotoni particolarmente energetici, era prevista la generazione di una coppia di particelle, formata da un elettrone e da un anti-elettrone che si allontanano in senso opposto lungo la direttiva est-ovest.

La previsione teorica dell'effetto risale agli anni Trenta, ma solo la tecnologia odierna è stata in grado di trasformare un esperimento mentale in un esperimento reale.

A Stanford hanno sparato impulsi laser 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, sinistralmente fredda del visibile, a raggi gamma di rimbombo particolarmente energetici. I fotoni gamma, riflessi all'indietro, a loro volta si scontrano con i fotoni del

fascio laser iniziale se questo sufficientemente intenso. In opportune condizioni, viene concentrata una quantità di energia in un singolo punto, sufficiente a creare coppie di elettroni e anti-elettroni, sulla base della famosa relazione di Einstein che regola le reciproche trasformazioni fra materia ed energia.

Si è così avuta la prima creazione di materia dalla luce, ha commentato uno dei portavoce dell'esperimento condotto a Stanford da una squadra di un ventotto di fisici. Fra questi è anche un fisico di Princeton, seguace di quell'Archibald Wheeler, che insieme a Gregory Breit, negli anni Trenta per primo considerò sul piano teorico la possibile produzione di coppie di elettroni e positroni in seguito all'urto fra due fotoni reali. La traduzione pratica dell'idea teorica ha richiesto qualche decennio, come pure lo sviluppo di tecnologie sofisticate, e anche una buona dose di virtuosismo da parte degli sperimentatori di Stanford, che hanno dovuto operare in modo lineare e sincronizzato con la massima precisione sia gli impulsi laser iniziali sia gli impulsi degli elettroni accelerati. Ma, come recita un detto locale, le cose nascono sempre prima in California. La creazione di coppie di elettroni e positroni (c'è di anti-elettroni) di solito si verificava negli esperimenti di fisica delle alte energie quando si fanno urtare fra loro particelle accelerate.

Ben diversa è la situazione ricreata in California dove la produzione delle coppie è avvenuta per opera dei soli fotoni che sono le particelle costituenti la luce dove almeno uno dei quali deve essere virtuale, come si dice in gergo, cioè deve esistere per una brevissima frazione di tempo per scomparire poi subito. A Stanford, infatti, sono stati messi in gioco soltanto dei fotoni reali o ordinari, offrendo così la dimostrazione pratica di un fenomeno previsto da lungo tempo. Dalla enorme concentrazione di energia elettromagnetica si è riusciti quindi a ricreare della materia, dando una ulteriore dimostrazione, quasi da libro di testo, della famosa formula einsteiniana.

Neue Zürcher Zeitung Mittwoch, 1. 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 im Experiment direkt beobachtet: die Erschaffung von Materie aus echten Lichtteilchen. Das Experiment gelang am Stanford-Teilchenbeschleuniger in Kalifornien.

Die Umwandlung von Materie in Licht oder andere Energieformen ist nichts Neues. Ein besonders zentralisiertes Beispiel dafür sind Atombomben. Aber auch bei der Kernspaltung in Kernkraftwerken wird Materie in Energie umgesetzt. Erstmals gelang diese Umwandlung im Jahr 1932, als der Physiker Carl Anderson das Positron entdeckte, das positiv geladene Antiteilchen des negativ geladenen Elektrons. Treffen ein Elektron und ein Positron aufeinander, lösen sie sich in einem Energieblitz auf. Nun ist Physikern, wie bereits kurz gemeldet, erstmalig der umgekehrte Vorgang gelungen: Energie in der Form von Licht in Elektronen und Positronen umzuwandeln.

Elektron-Positron-Paare entstanden auch bisher in Beschleuniger-Experimenten. Werden Teilchen wie beispielsweise Protonen und Antiprotonen aufeinander geschossen, so können sie beim Zusammenstoß in einen Energieblitz aufgehen. Dieser Energieblitz enthält manchmal kurzlebige Lichtteilchen, aus denen dann Elektron-Positron-Paare geschaffen werden. Man nennt diese kurzlebigen Lichtteilchen virtuelle Photonen im Gegensatz zu den echten Photonen, den gewöhnlichen Lichtteilchen. Virtuelle Photonen sind nur für einen kurzen Moment in einem starken elektrischen Feld in der Nähe eines geladenen Teilchens zu beobachten. In einem Teilchenbeschleuniger in Kalifornien wurden die Elektron-Positron-Paare erstmals nicht aus virtuellen, sondern aus gewöhnlichen Photonen geschaffen.

Lasert gegen Elektronenstrahl
 Der Durchbruch gelang einem Team aus zwanzig Wissenschaftlern aus vier amerikanischen Forschungsinstituten. Für das aufwendige Experiment benötigte die Gruppe extrem energiereiche Photonen. In einem ersten Schritt verwendeten sie Laser gegen Elektronenstrahl.

Die Umwandlung von Licht in Materie wurde möglich, weil die Zusammenstöße der Photonen ein ungewöhnlich hartes elektromagnetisches Feld erzeugten. Ähnliche Bedingungen finden sich im Universum wahrscheinlich nur an wenigen Orten, zum Beispiel auf der Oberfläche von Neutronensternen. Dabei handelt es sich um extreme dicht Objekte, die entstehen, wenn ein Stern am Ende seiner Entwicklung in einem Schwarzschild kollabiert. Die Wissenschaftler vermuten, dass Neutronensterne ein extrem starkes elektromagnetisches Feld erzeugen, das Teilchenbeschleuniger in Stanford beschaffen wurden. Die Physiker schaffen sich deshalb von ihrer

DISCOVER MAGAZINE - DECEMBER 1997
Let There Be Matter

by Jeffrey Winters

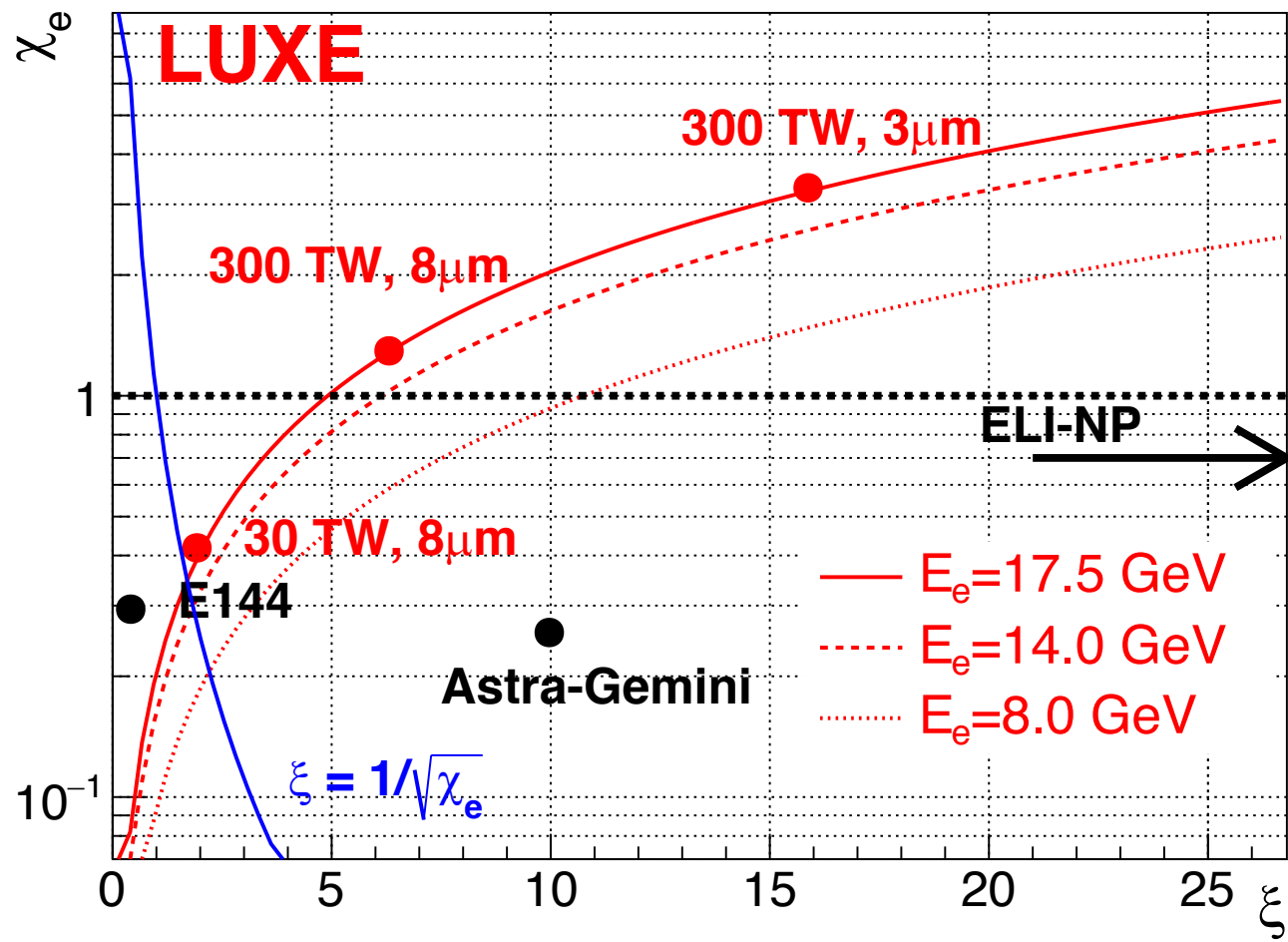
Albert Einstein's epochal insight into the equivalence of matter and energy, elegantly expressed as E=mc², has been confirmed countless times, most dramatically whenever a nuclear weapon detonates. The process also occurs naturally--a bit shines because atoms in its core fuse, transforming a sliver of 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 leap."

Of course, physicists would have been shocked if they couldn't get energy to convert to matter. After all, the entire universe 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."



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:

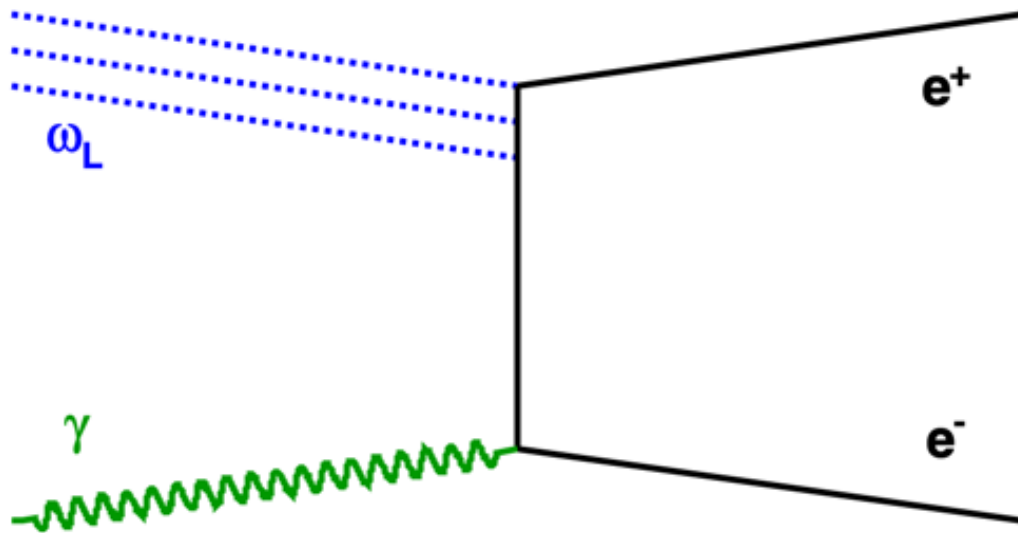
$$\chi_e = (1 + \cos \theta) \frac{E_e}{m_e} \frac{\mathcal{E}_L}{\mathcal{E}_{cr}}$$

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



ABSORBING LIGHT WITH LIGHT

Low-energy photons from laser

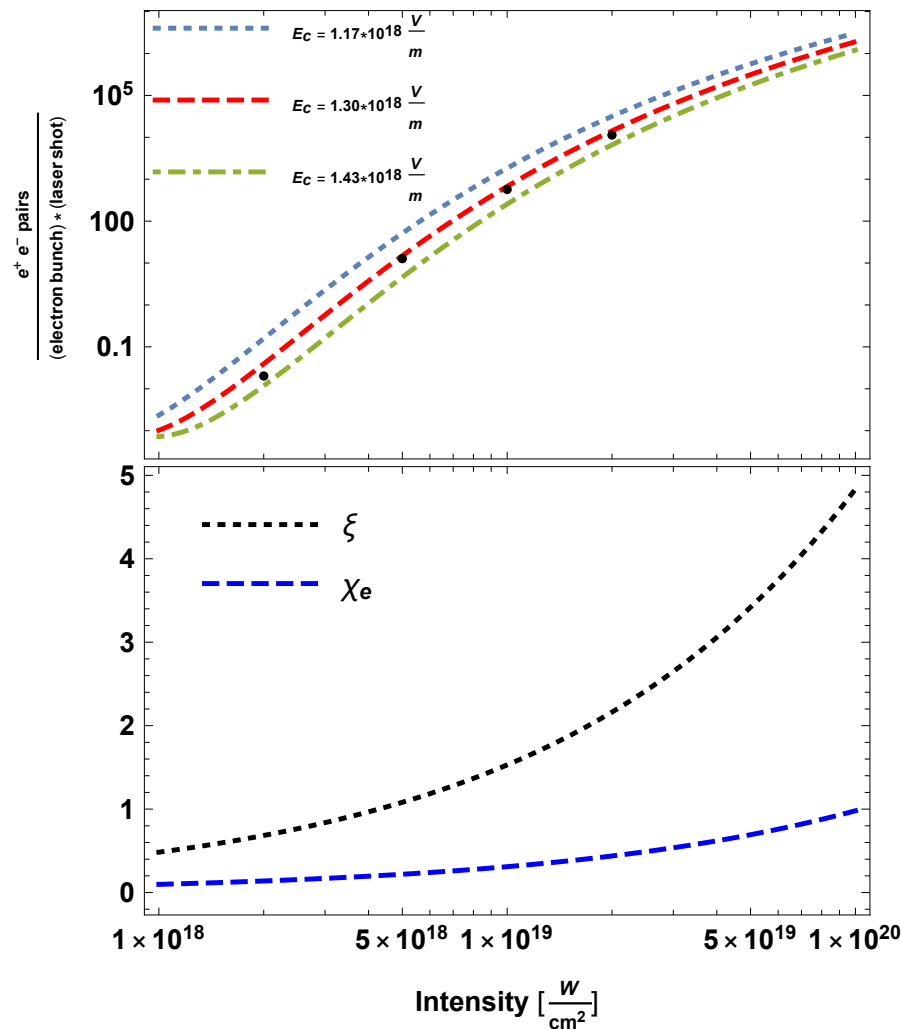


High-energy (relativistic) photon

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

For $N(\omega_L) > 5$: $\sqrt{s} > 2mc^2$

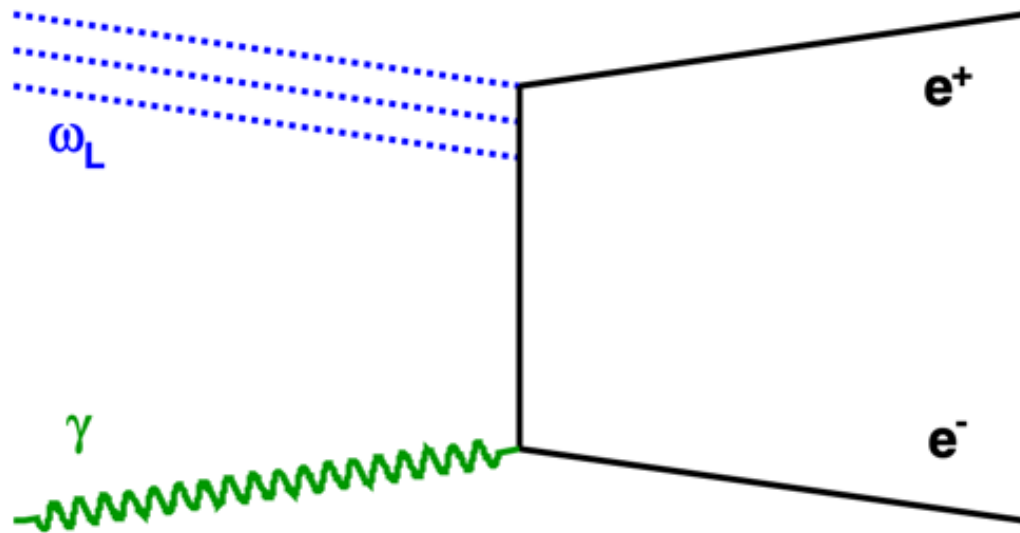
$E_e=17.5 \text{ GeV}$, $e^- \text{ b.}=6 \times 10^9$, $\frac{X}{X_0}=0.01$, $L. \text{ s.}=35 \text{ fs}$, $\theta = \frac{\pi}{12}$, $w=1.55 \text{ eV}$



A. Hartin, A. Ringwald, N. Tapia: arXiv:1807.10670,

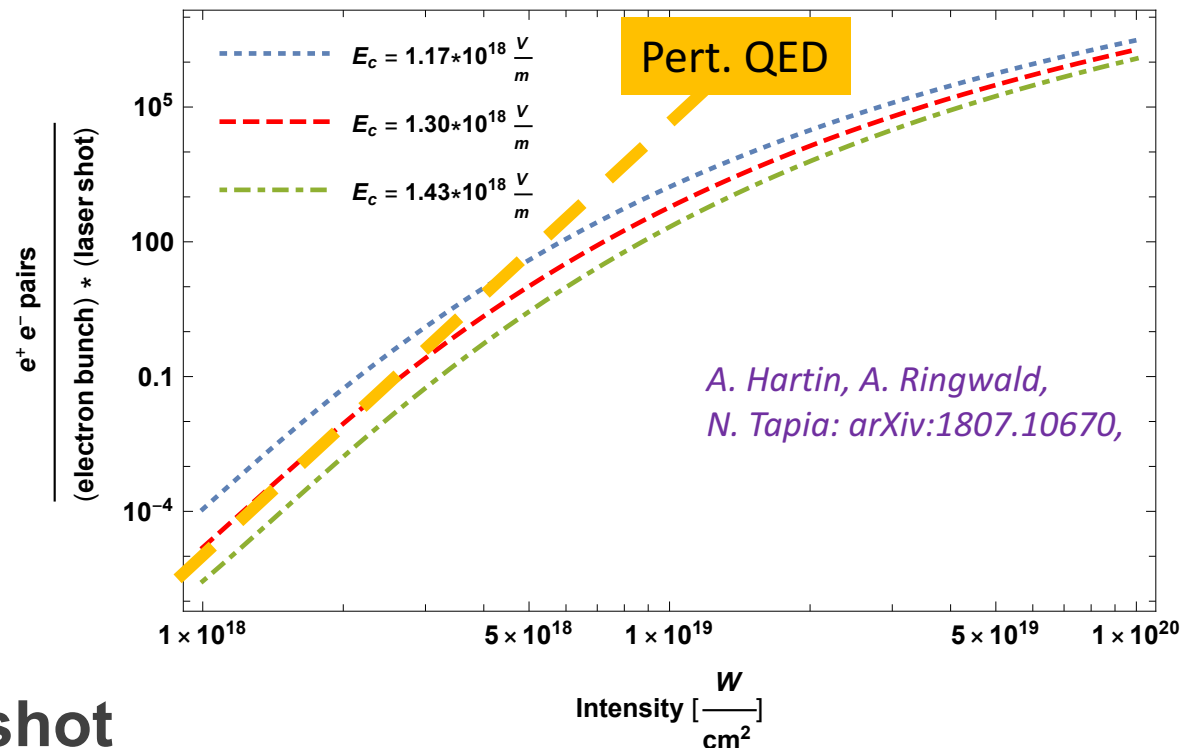
ABSORBING LIGHT WITH LIGHT

Low-energy photons from laser



High-energy (relativistic) photon

$$E_e = 17.5 \text{ GeV}, \quad e^- \text{ b.} = 6 \times 10^9, \quad \frac{X}{X_0} = 0.01, \quad L. \text{ s.} = 35 \text{ fs}, \quad \theta = \frac{\pi}{12}, \quad w = 1.053 \text{ eV}$$



• Prediction for rate of positrons per laser shot

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

👉 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



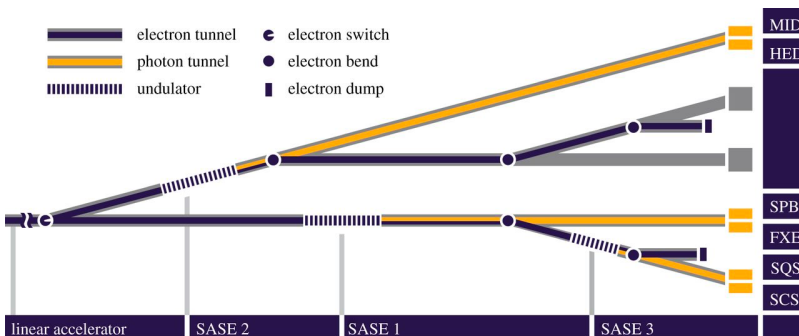
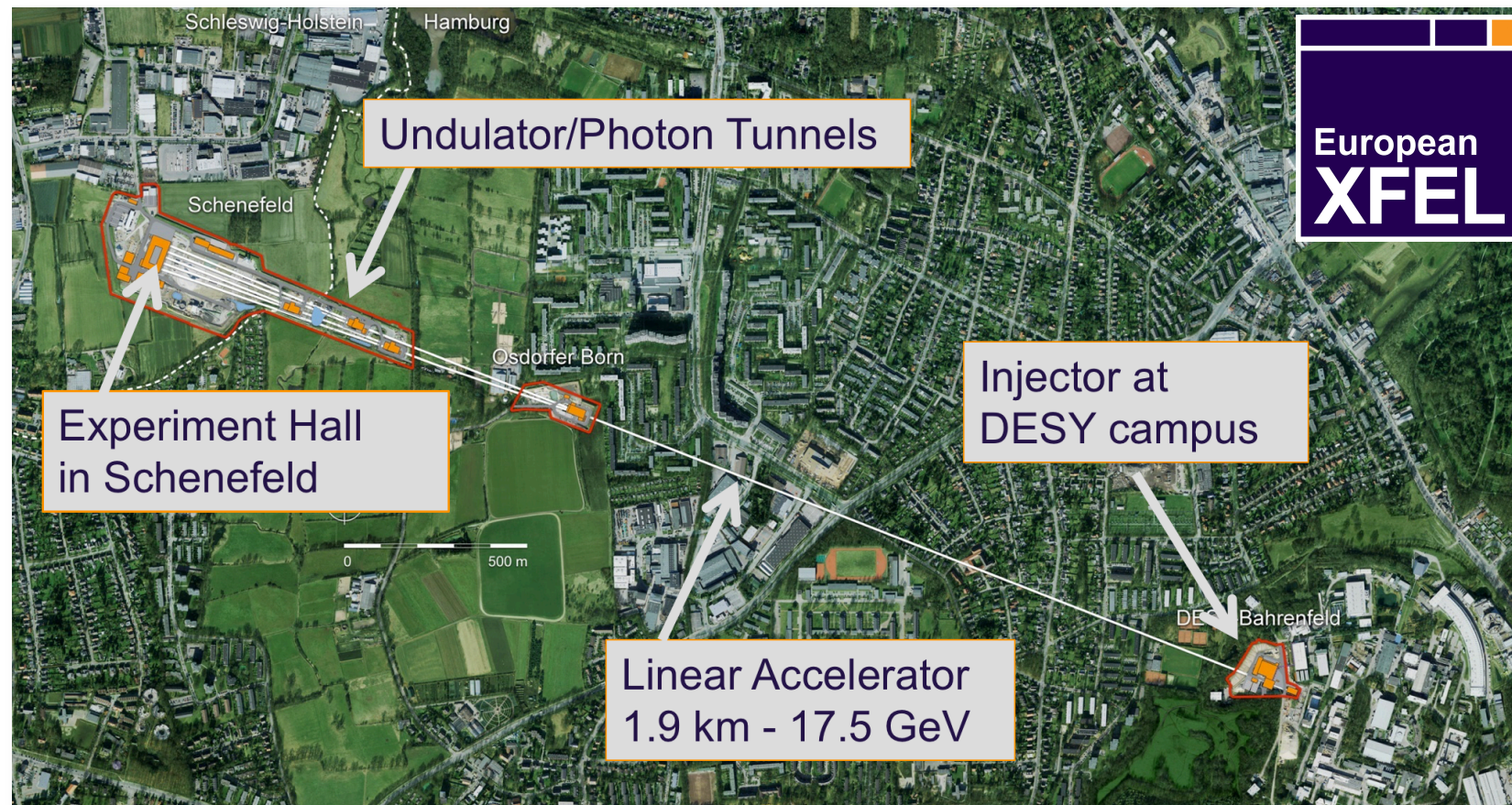
ACCELERATOR AND LASER



THE EUROPEAN XFEL

Electron accelerator:

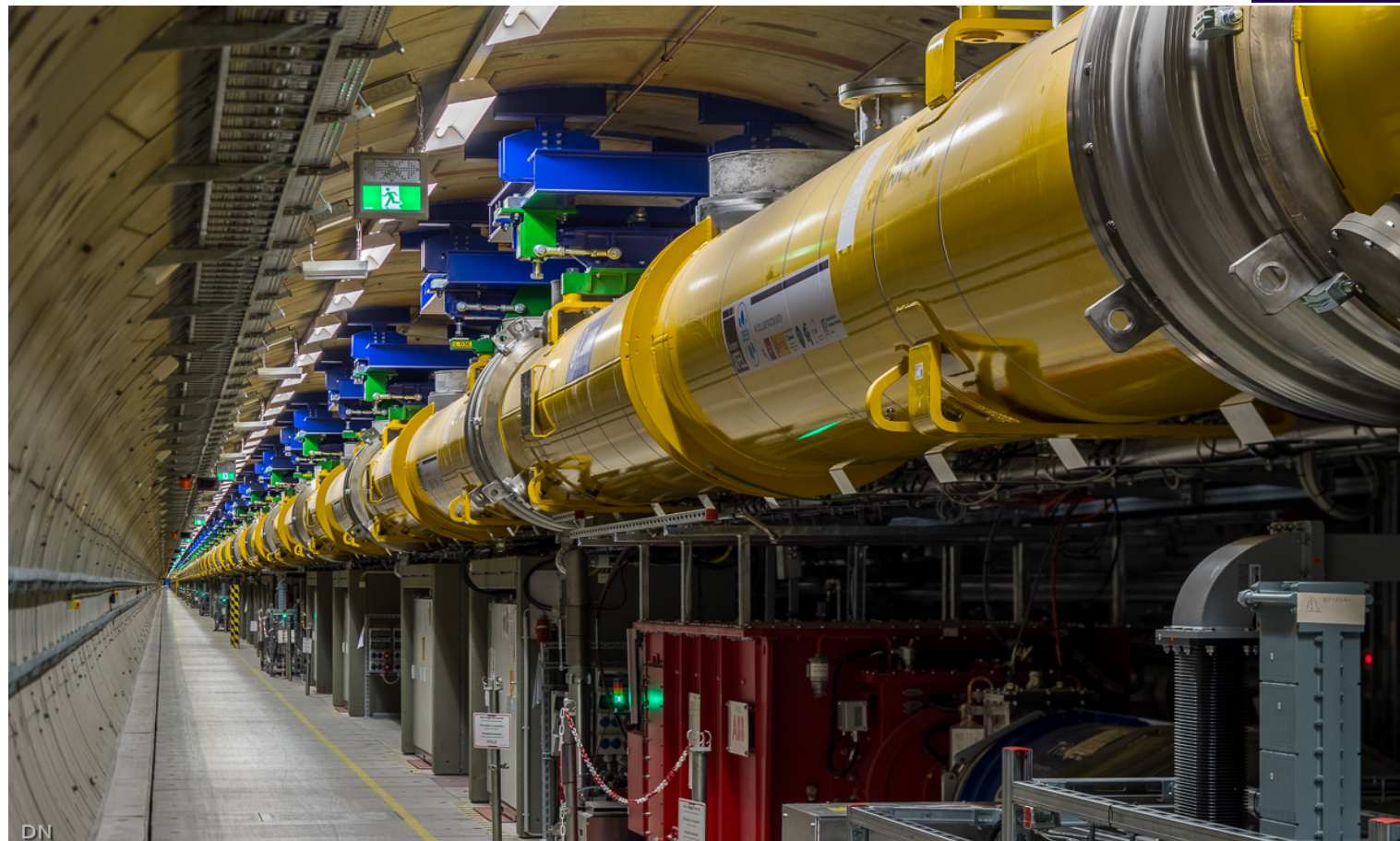
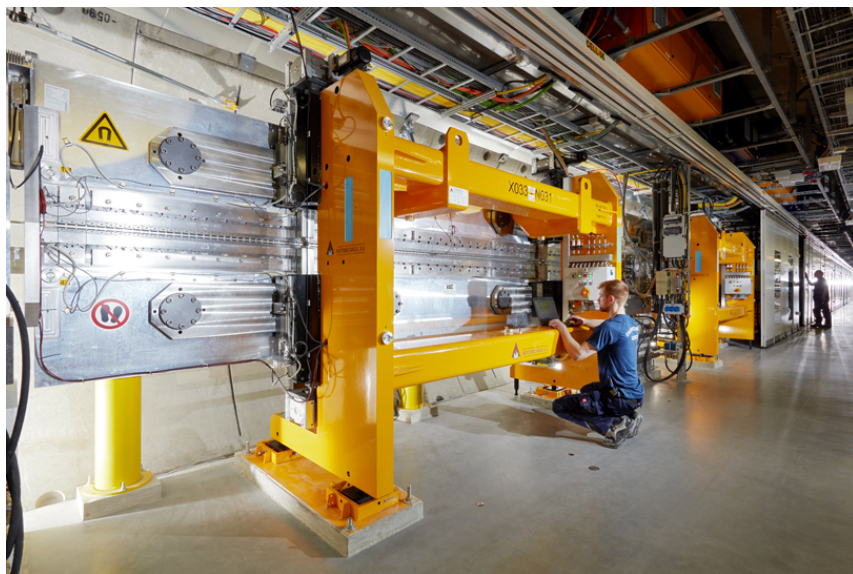
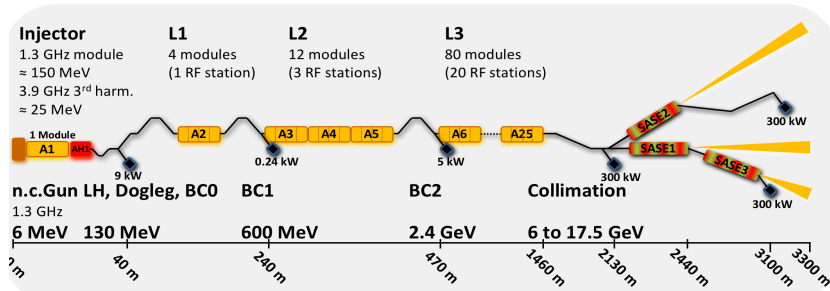
- 2.1 km 17.5 GeV SCRF linear accelerator
- 2700 electron bunches at rate of 10 Hz
- X-ray photons produced in undulators
- Experiments for physics, material science, chemistry, biology, ...





THE EUROPEAN XFEL

View along L3 accelerator section and undulator





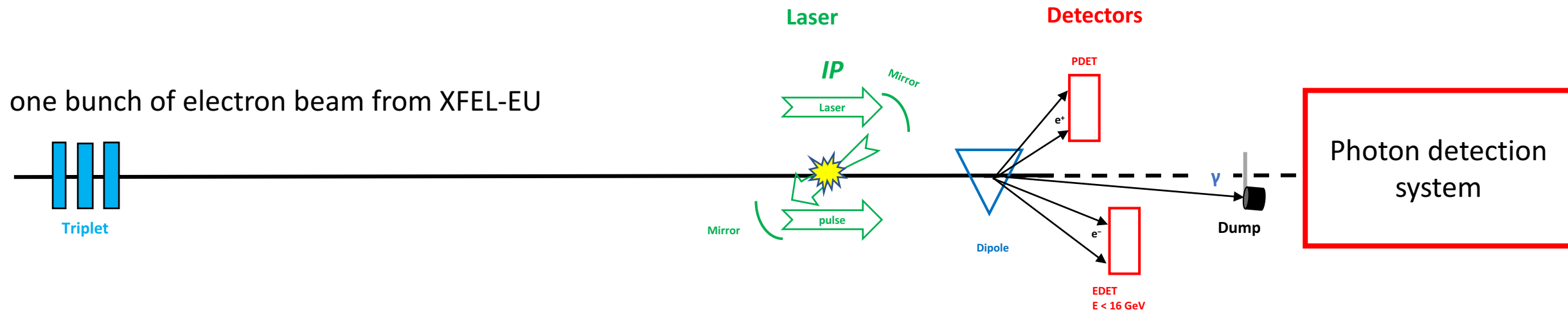
EUROPEAN XFEL INAUGURATION



Operating since September 2016

ELECTRON LASER COLLISIONS

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



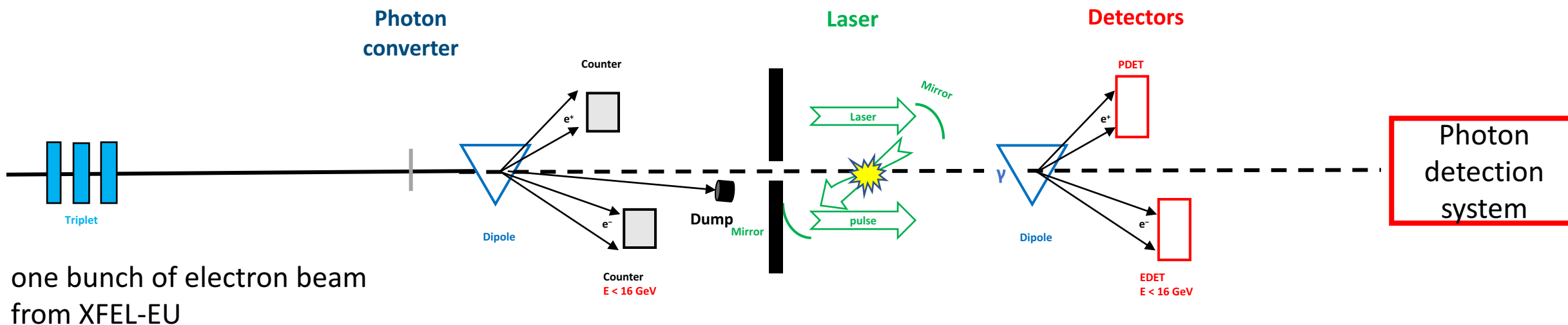
Kicker and triplet to select single bunch and focus it

Electron- Laser interaction area

Dipole and detectors to observe e⁺e⁻ pairs

PHOTON LASER COLLISIONS

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



one bunch of electron beam from XFEL-EU

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



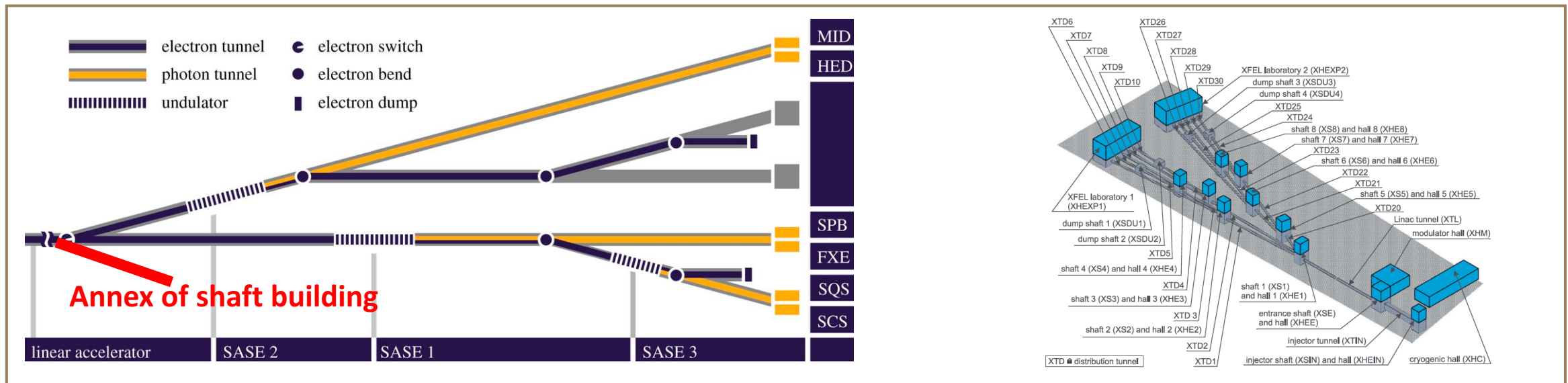
LOCATIONS IN EU.XFEL TUNNEL

- **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

Schleswig-Holstein

Schenefeld

Osdorfer Born

DESY-Bahrenfeld

LUXE

Scientific instruments and instrumentation

2017 – 27.000 p/s
European XFEL

Electron injector

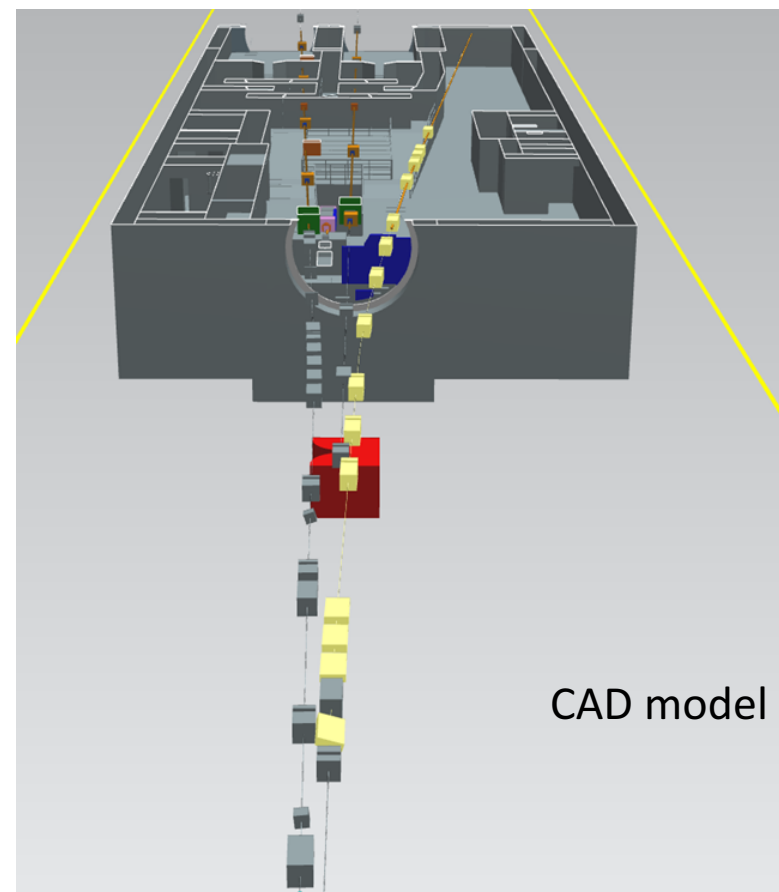
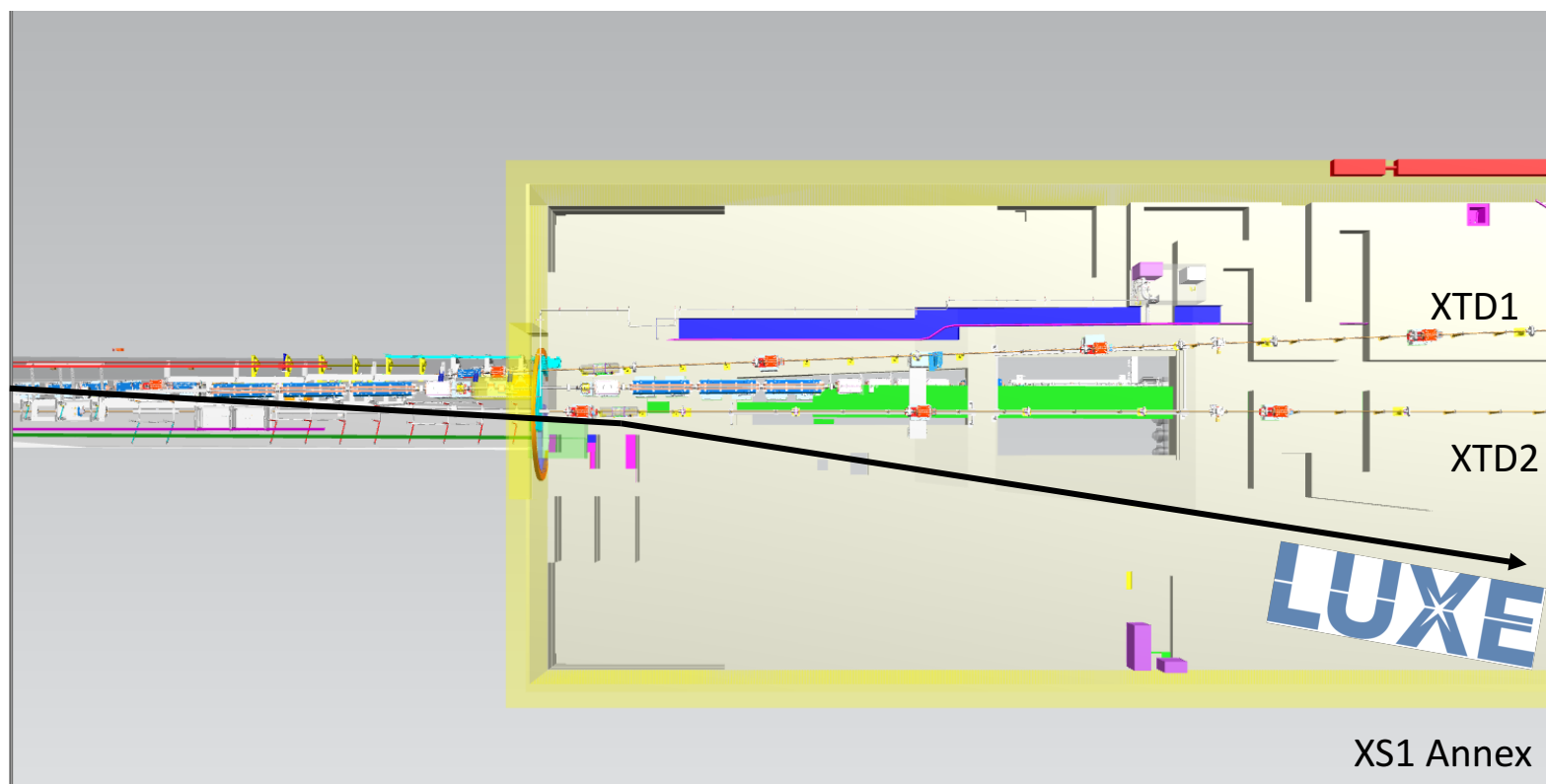
Undulator systems

Superconducting electron accelerator

The image is a composite of an aerial map and several inset photographs. The map shows the layout of the LUXE facility, with various components highlighted in orange and red. Callout boxes with arrows point to these components, providing more detail. The 'Scientific instruments and instrumentation' box shows a person working with a complex array of cables and sensors. The 'Electron injector' box shows a large, cylindrical machine with a blue dome. The 'Undulator systems' box shows a long, horizontal structure with a person standing next to it. The 'Superconducting electron accelerator' box shows a long, yellow cylindrical structure in a large hall. The '2017 – 27.000 p/s European XFEL' text is overlaid on the map. The 'LUXE' logo is also present on the map. The map labels include 'Schleswig-Holstein', 'Schenefeld', 'Osdorfer Born', and 'DESY-Bahrenfeld'.



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

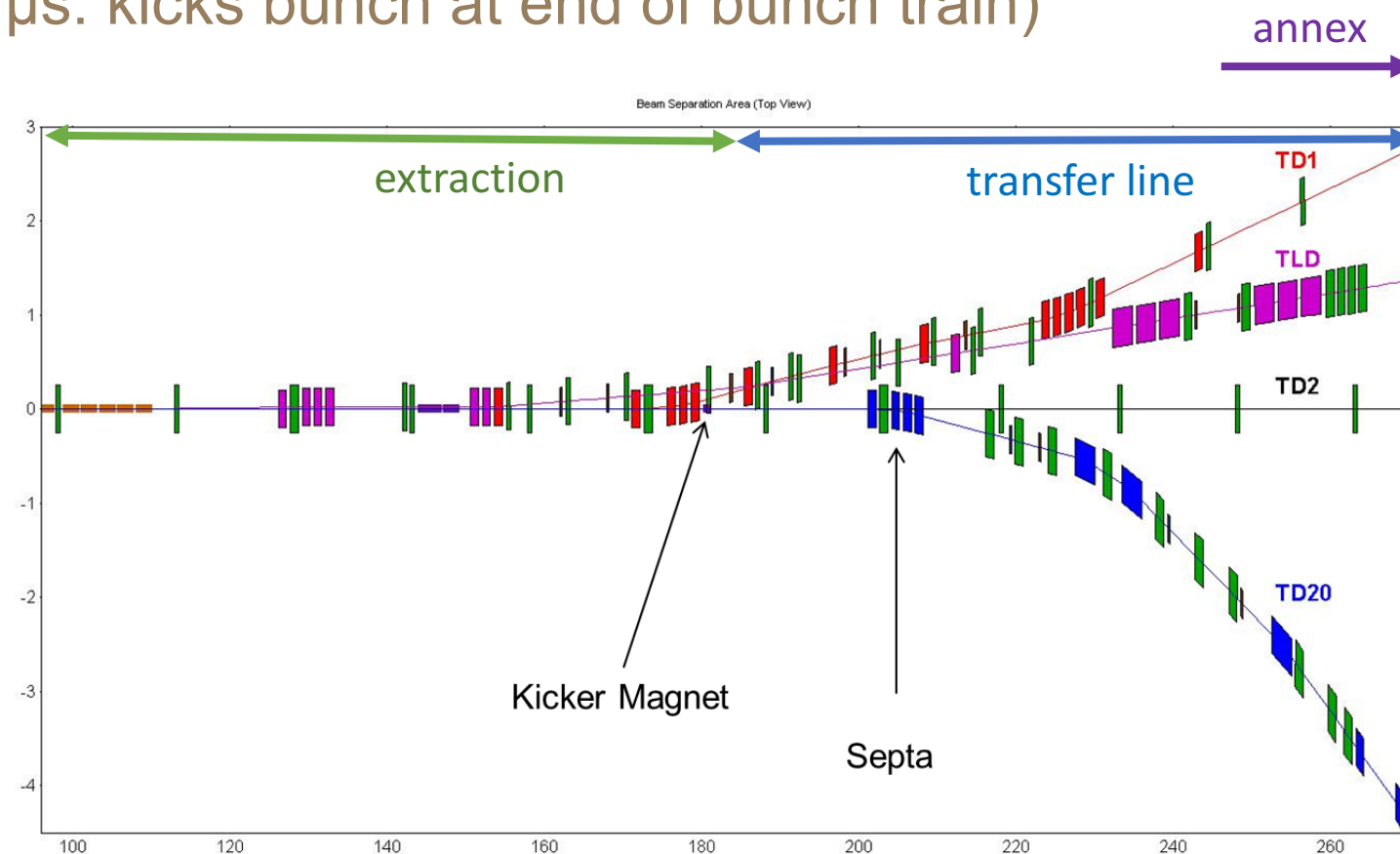
Design of magnets for **beam extraction** and then **beam transfer** to LUXE

- Most magnets use design already operating today in XFEL.EU
- New fast kicker magnets (2 μ s: kicks bunch at end of bunch train)

Installation requires

- 5 weeks for extraction
- 7 weeks for transfer line

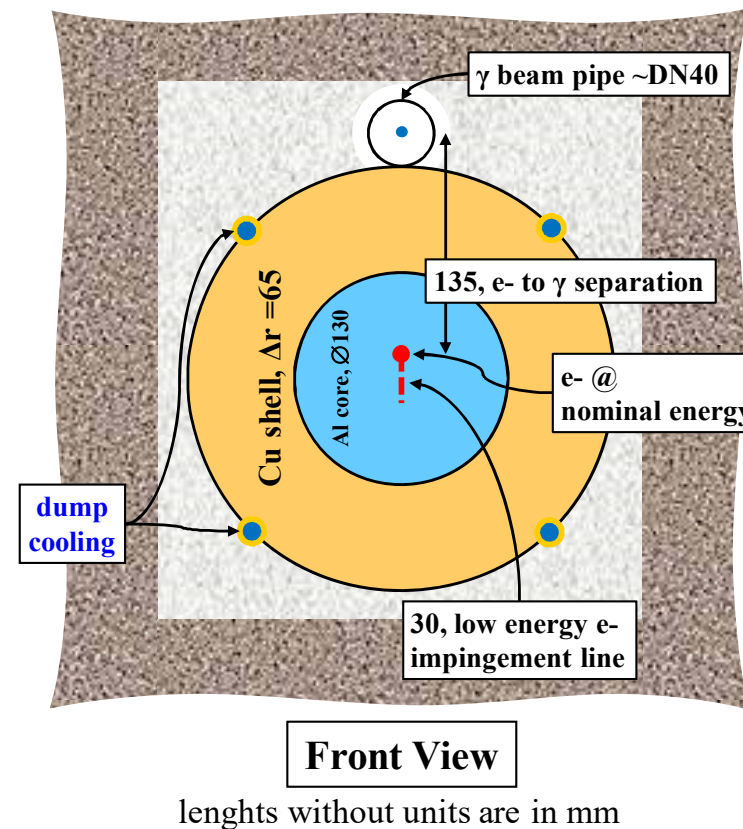
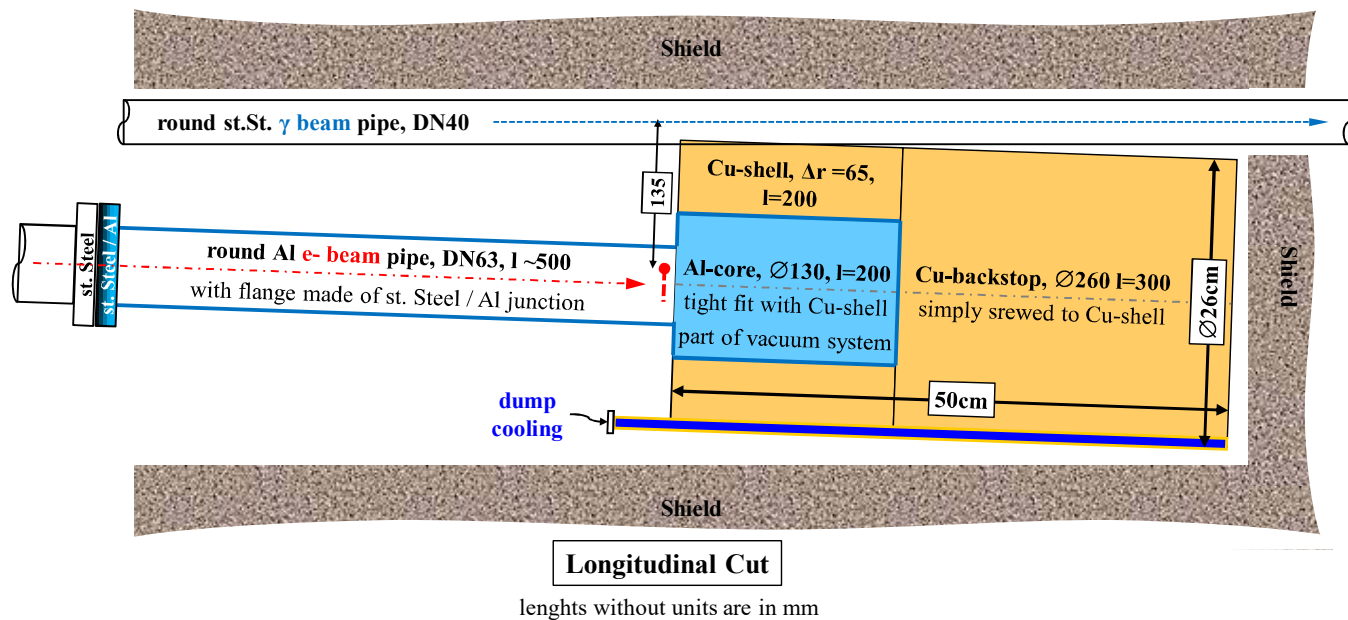
F. Burkart, W. Decking





BEAM DUMP

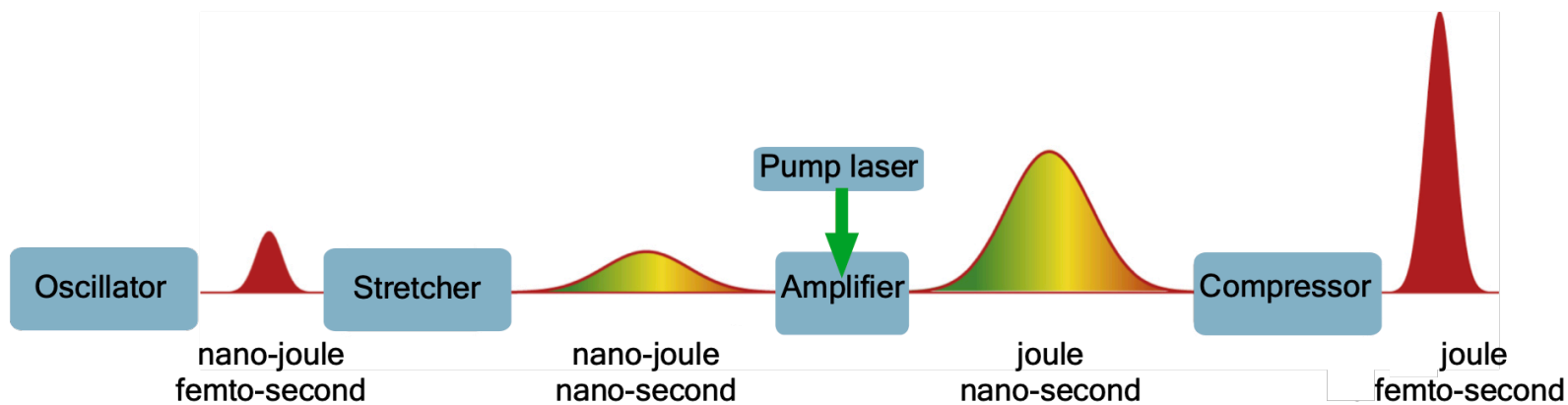
Beam needs to be safely dumped, design (with radioprotection group) well advanced



F. Burkart, M. Schmitz (DESY)



LASER TECHNOLOGY



© Nobel Media AB. Photo: A. Mahmoud
Gérard Mourou
Prize share: 1/4



© Nobel Media AB. Photo: A. 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 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	0.41	1.3	3.3
Ebeam=14.0 GeV	0.32	1.0	2.6

Laser intensity:

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

with

E_L : energy (J)

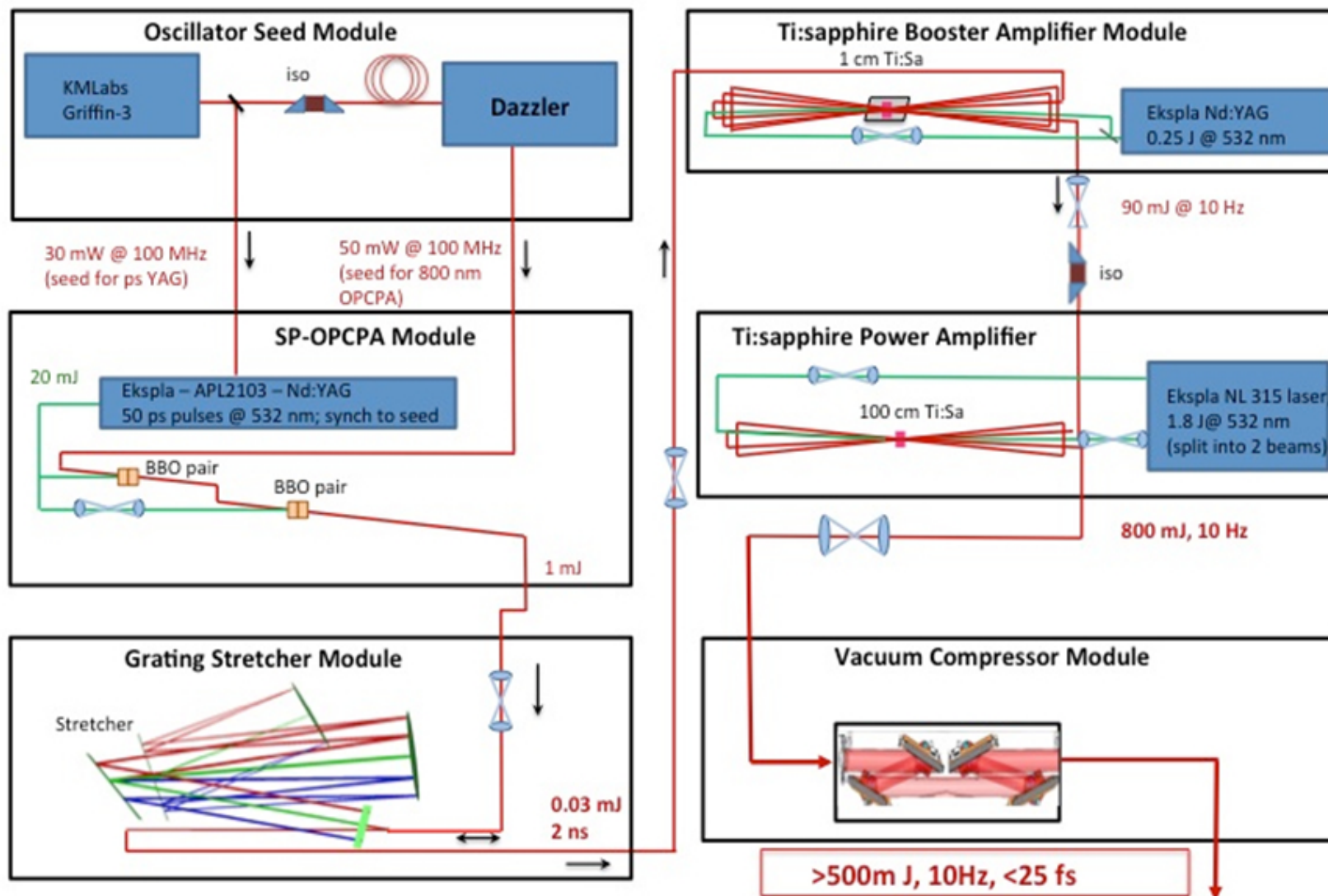
Δt : pulse length (s)

πd^2 : focus area (m^2)

Lower intensities achieved by de-focussing laser or stretching pulse



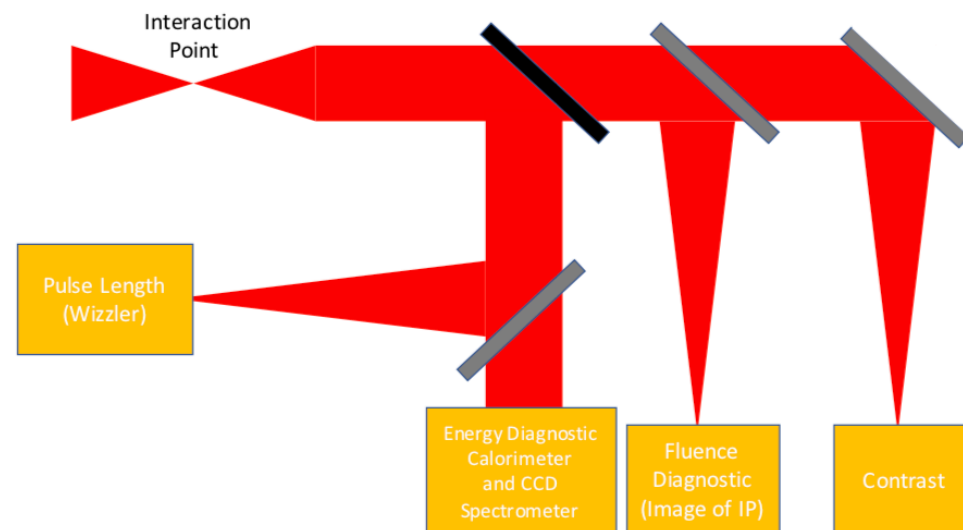
LASER DESIGN



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

M. Borysova, O. Borysov

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

γ +laser

Location	particle type	rate for $\xi = 2.6$	rate for $\xi = 1.2$
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	

$\sim 1000/\mu\text{m}$

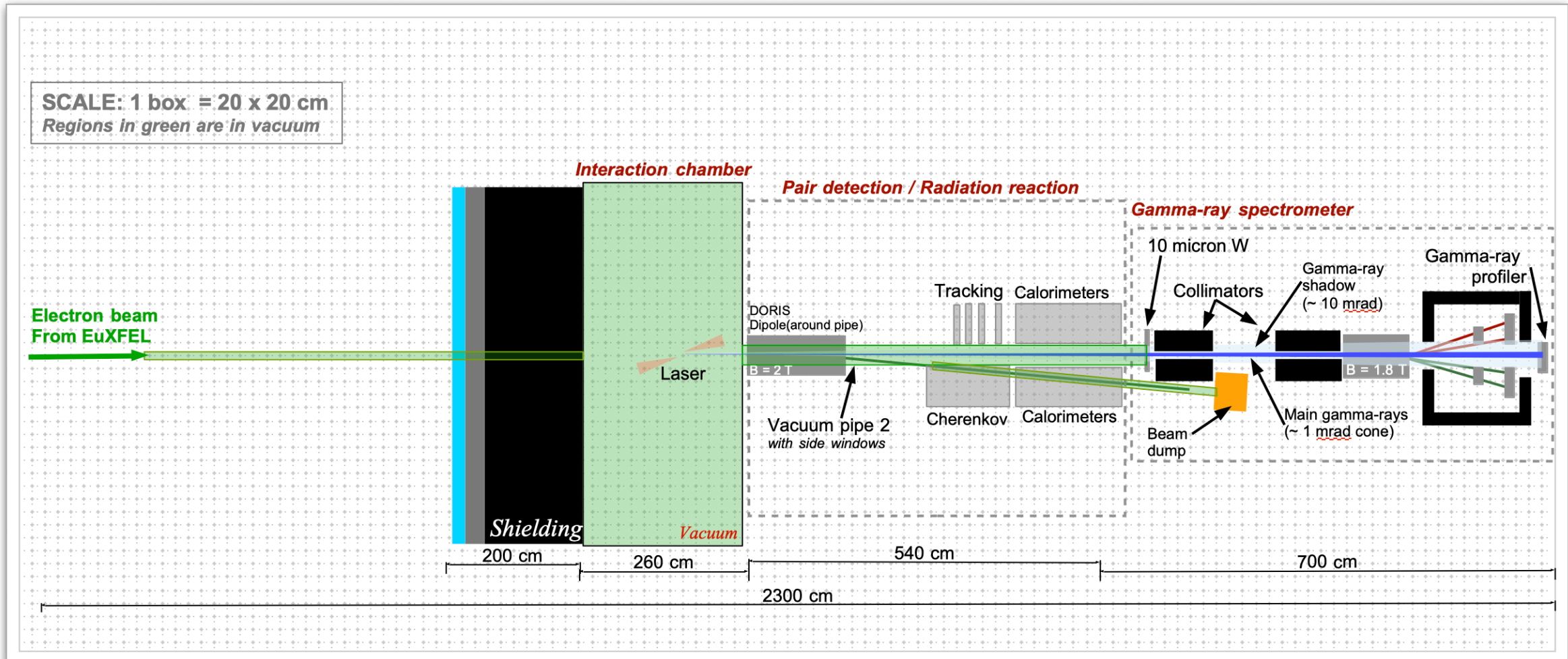
$\sim 0.01/\text{m}$

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



ELECTRON LASER COLLISIONS

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

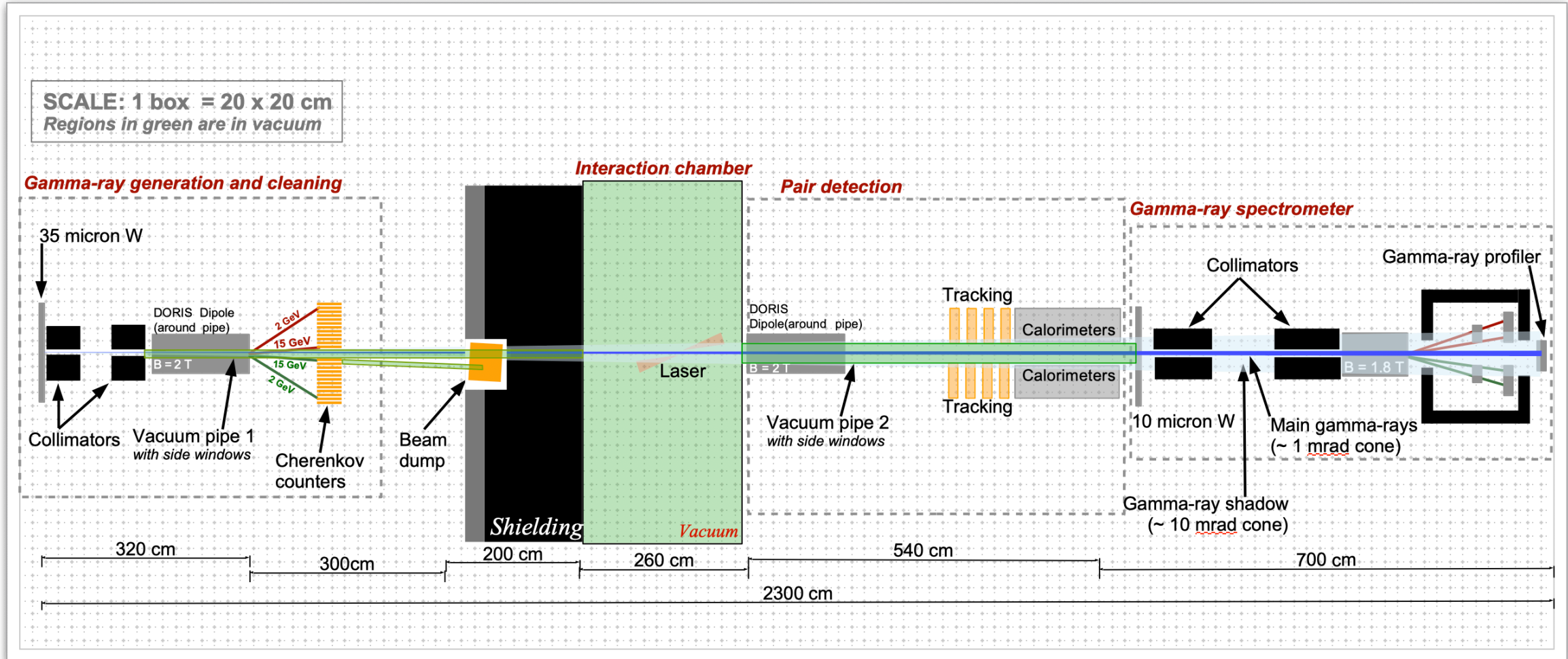


G. Sarre, Belfast

PHOTON LASER COLLISIONS

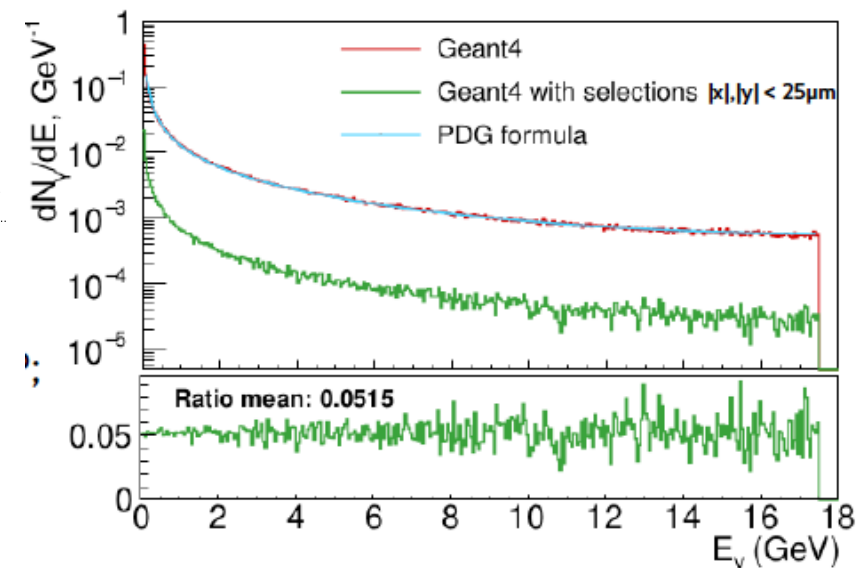
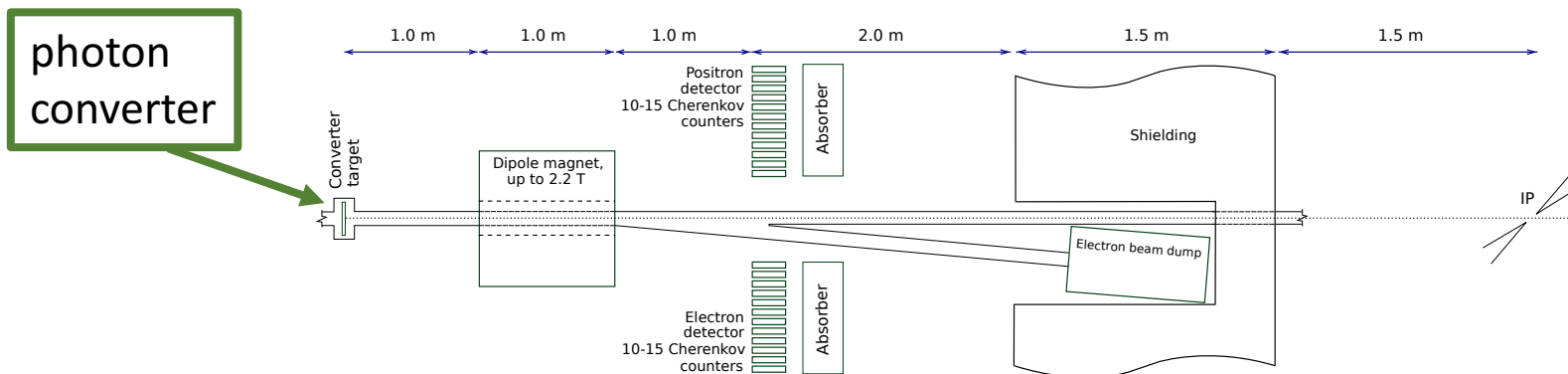


Pair production (Breit-Wheeler) process: $\gamma + n\omega \rightarrow e^- + e^+$



G. Sarre, Belfast

HIGH-ENERGY PHOTON FLUX



- **Simulation of converter using Geant4**

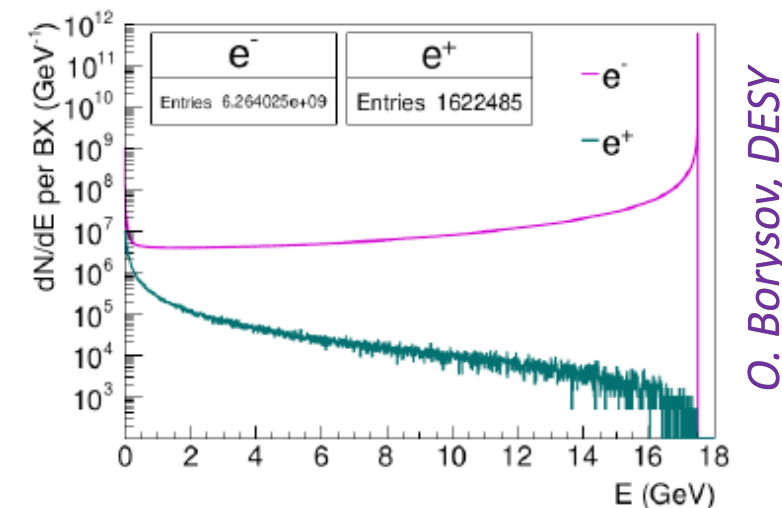
- Tungsten Target with $0.01 X_0$ ($35 \mu\text{m}$) \Rightarrow 1% at IP

- **Spectrum of photon energies important to know**

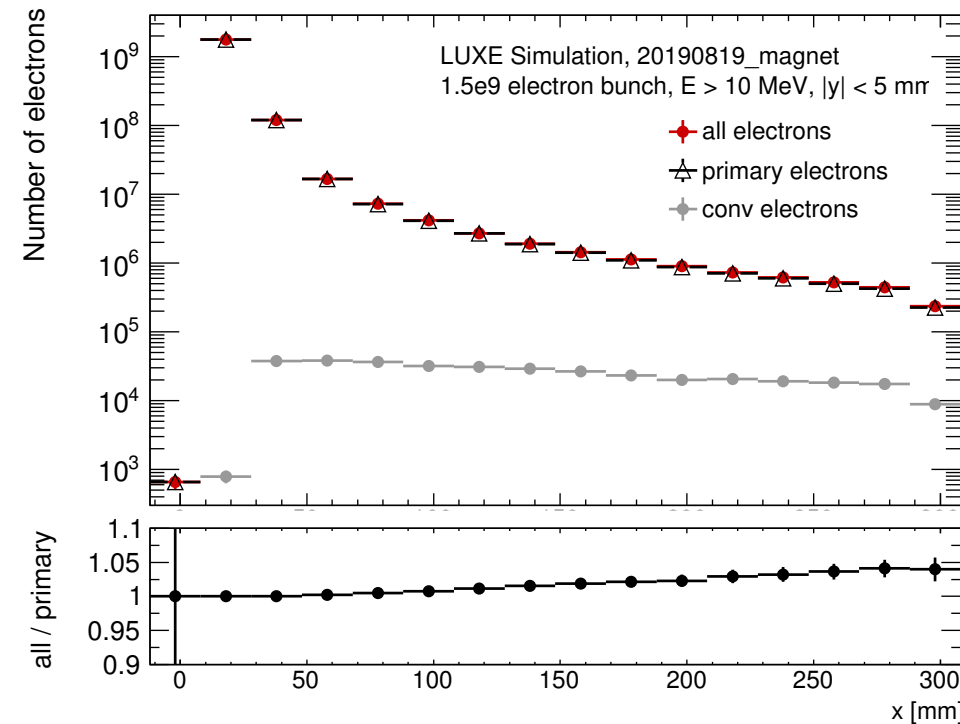
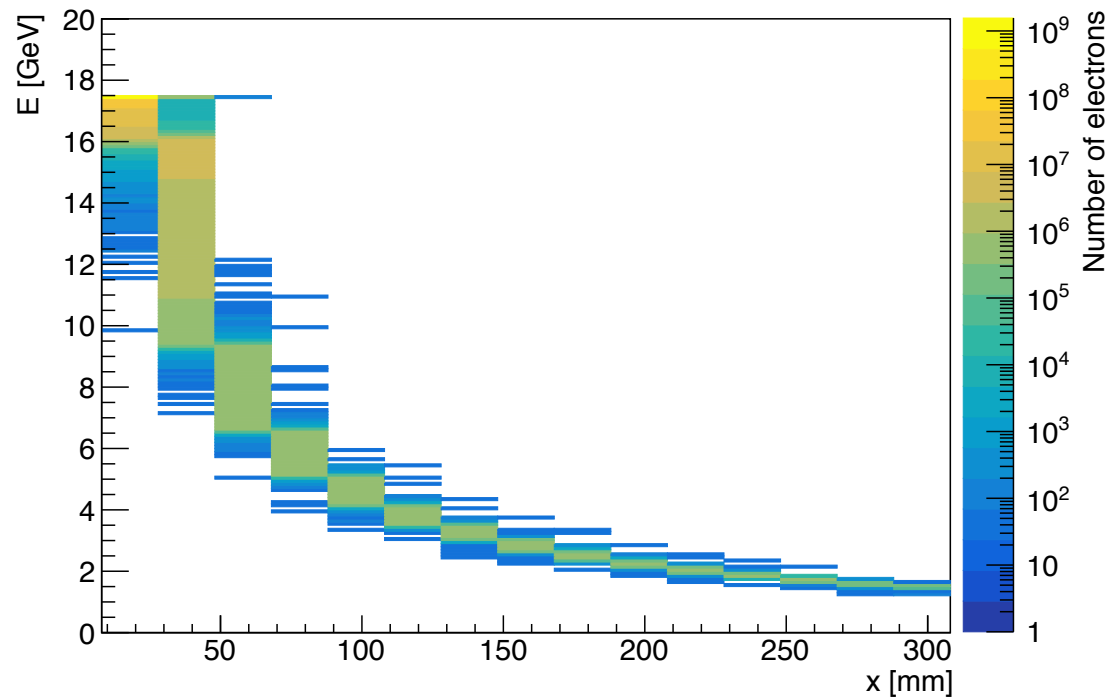
- Measure by observing electrons and positrons right after dipole magnet

- **Particle detection**

- 2T magnet followed by array of Cherenkov detectors measures flux vs impact position \Rightarrow energy spectrum



PHOTON FLUX MEASUREMENT: ELECTRONS

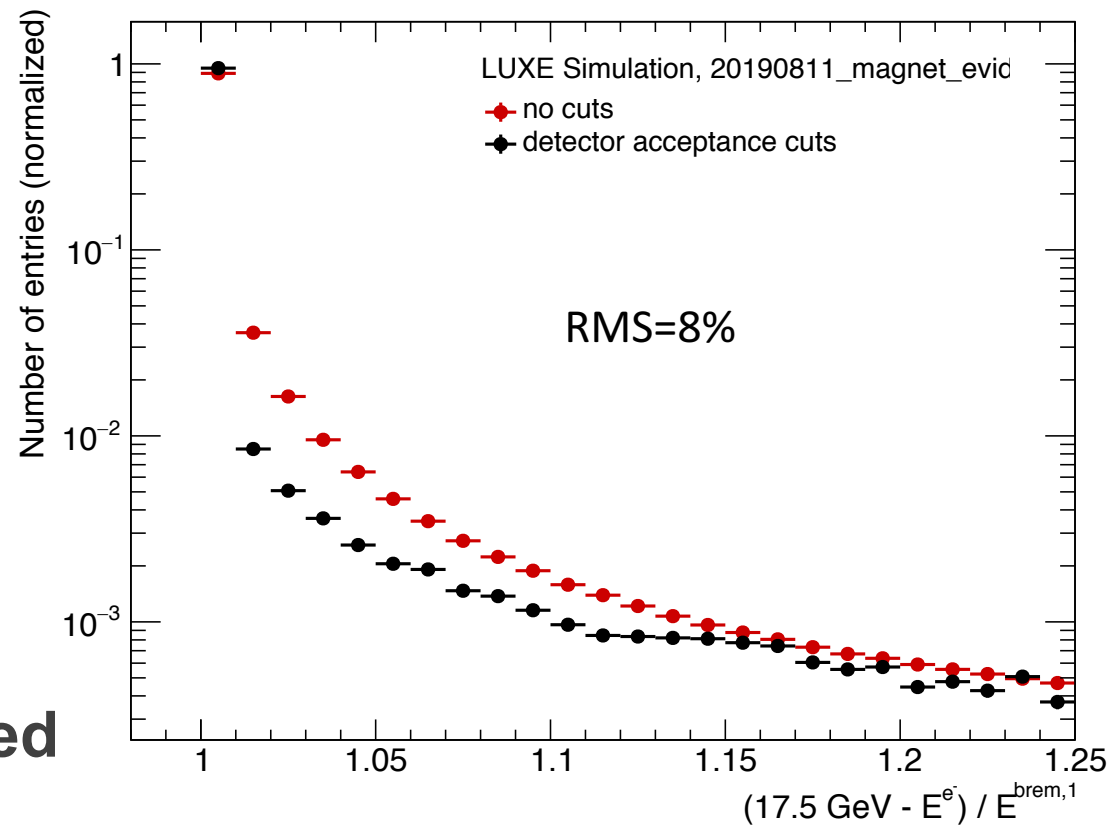
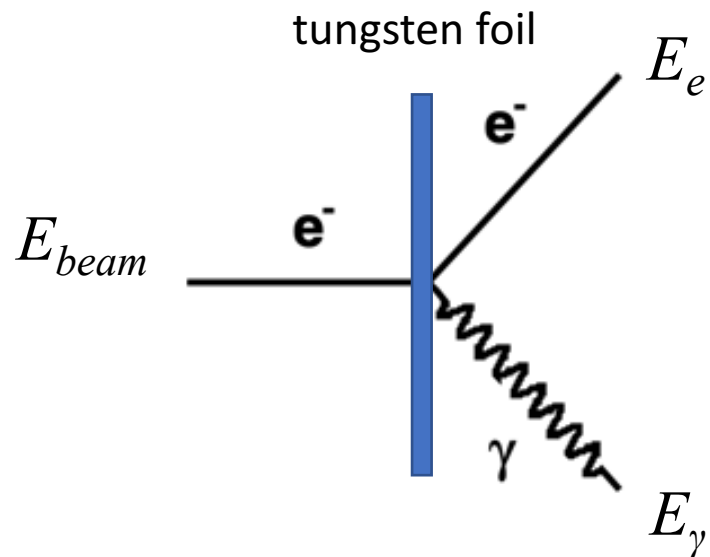


M. Saimpert, DESY

Electron energy measured based on position behind dipole magnet

- Dominated by primary electrons
- Contamination of converted electrons small (estimated from positron flux)
- Electron rates high: $\sim 10^5$ - 10^7 /mm/event

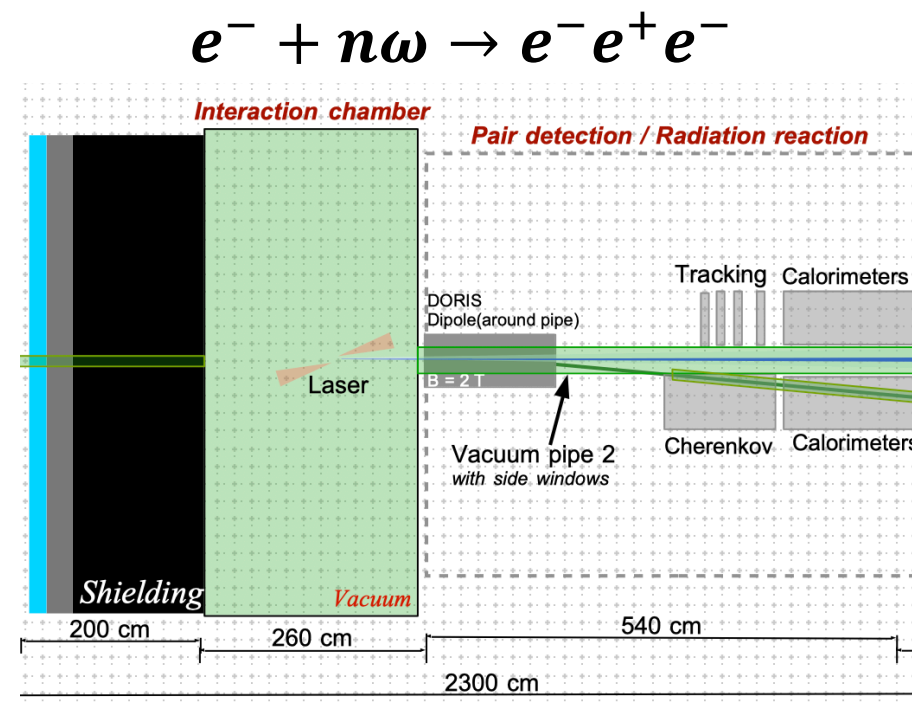
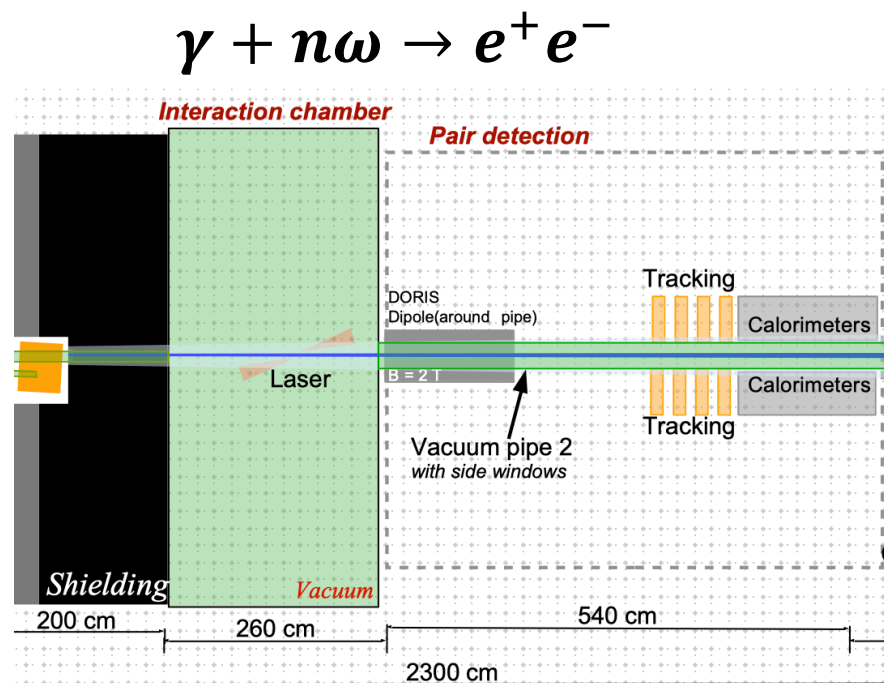
PHOTON ENERGY MEASUREMENT



Photon energy determined from measured electron energy to within $\sim 10\%$:

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

ELECTRON AND POSITRON DETECTORS



- **Pair production:**

- e^+ and e^- rate $\sim 0.01-100 \Rightarrow$ silicon pixel detectors and calorimeters

- **Trident:**

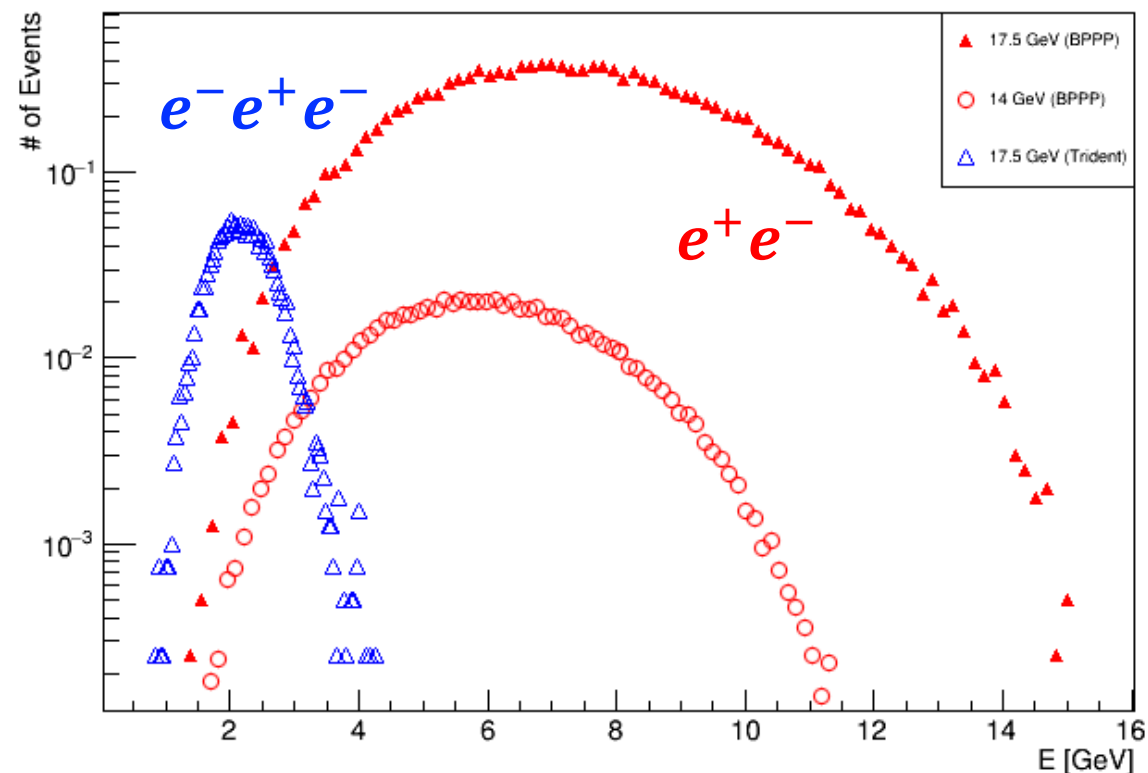
- e^+ rate $\sim 0.01-100 \Rightarrow$ silicon pixel detectors and calorimeters
- e^- rate $\sim 10^6-10^9 \Rightarrow$ Cerenkov counters and calorimeter/absorber



SIMULATION RESULTS

- **Monte Carlo simulation of expected signatures used**
 - *By A. Hartin, UCL*
- **Energy spectrum spans 1-15 GeV**
 - *Energies significantly lower for trident process*
- **For trident process uses “two-step” process only**
 - *Calculation of one-step trident ongoing*

Positron Energy Spectrum

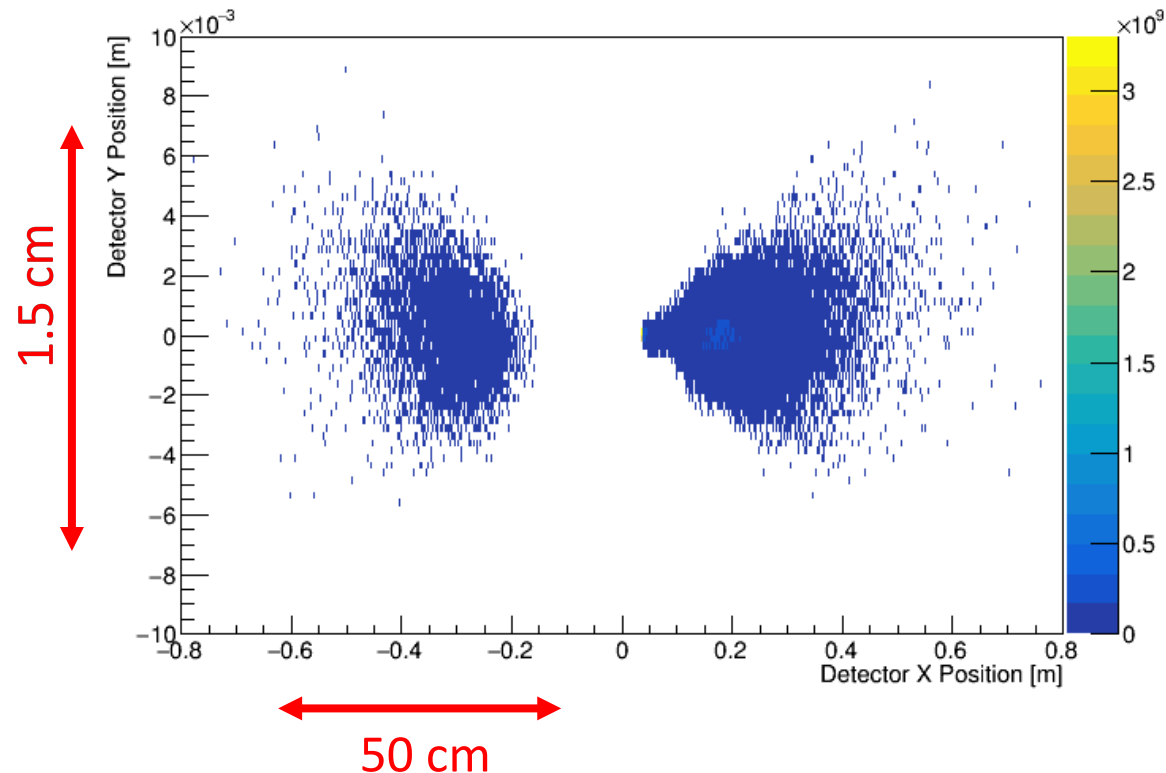
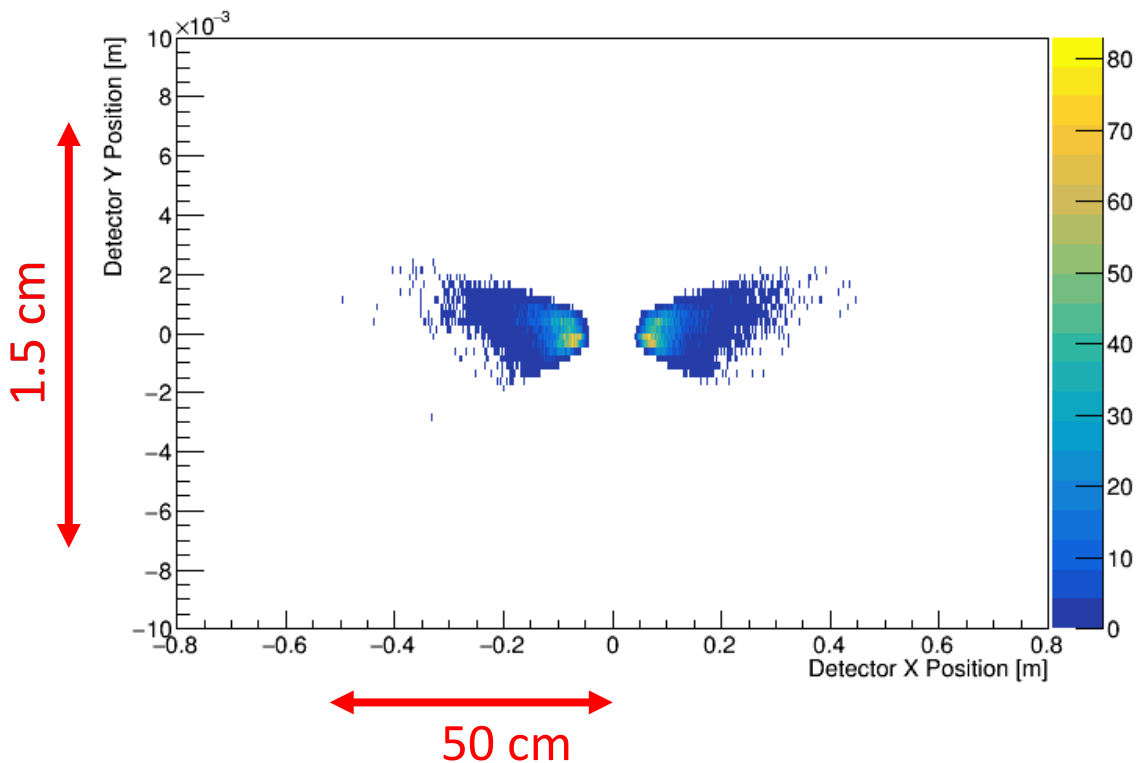


A, Hartin (UCL), M. Hoffmann (DESY)

DETECTOR OCCUPANCIES AFTER INTERACTION POINT

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

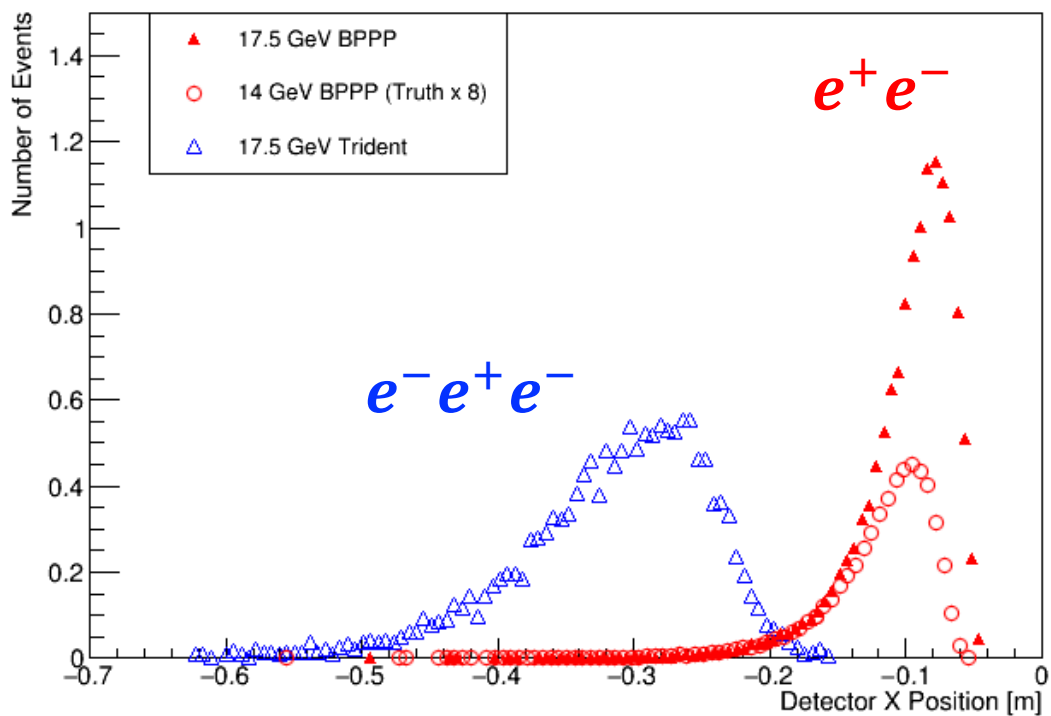
$$e^- + n\omega \rightarrow e^- e^+ e^-$$



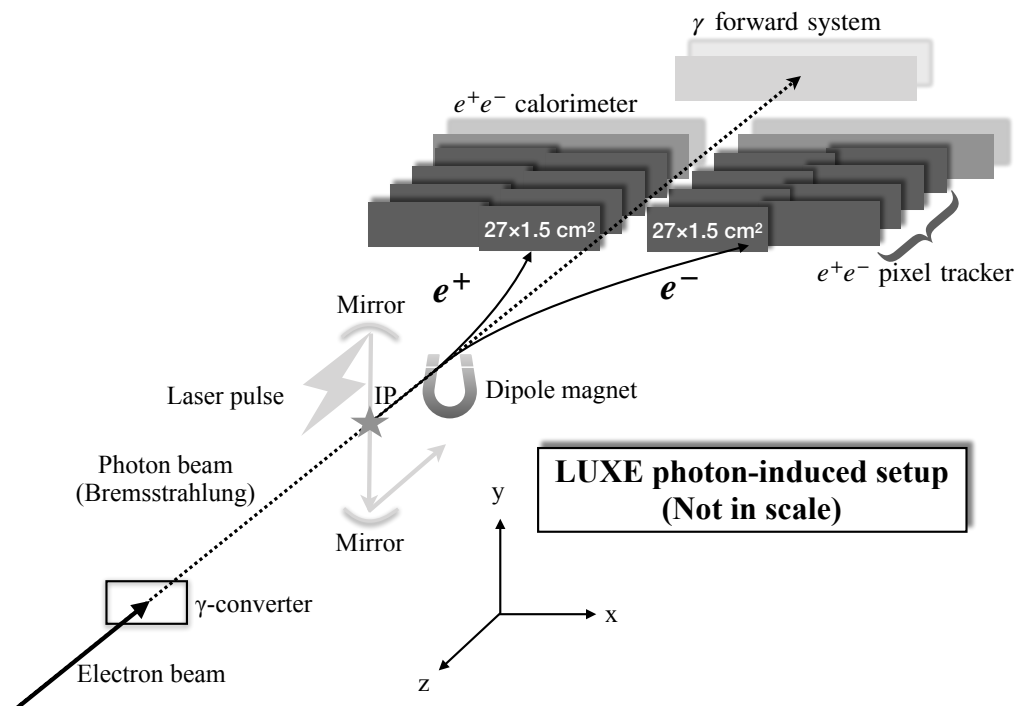
A. Hartin (UCL), N. Hod (Weizmann),
M. Hoffmann (DESY)

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

HIT POSITION AT FIRST DETECTOR PLANE



A, Hartin (UCL), M. Hoffmann (DESY)

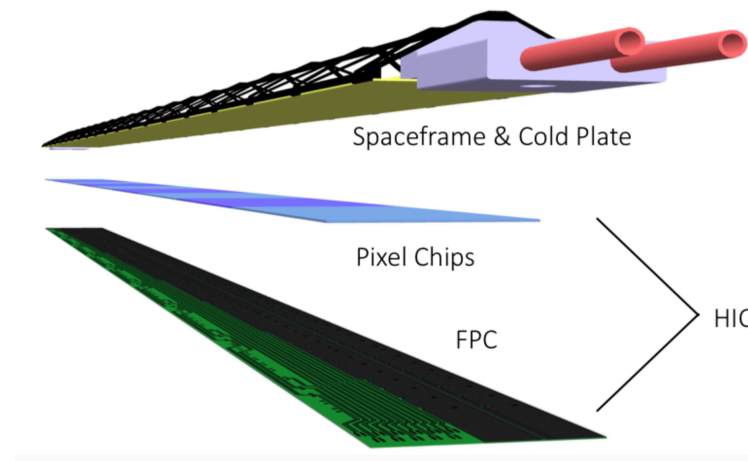
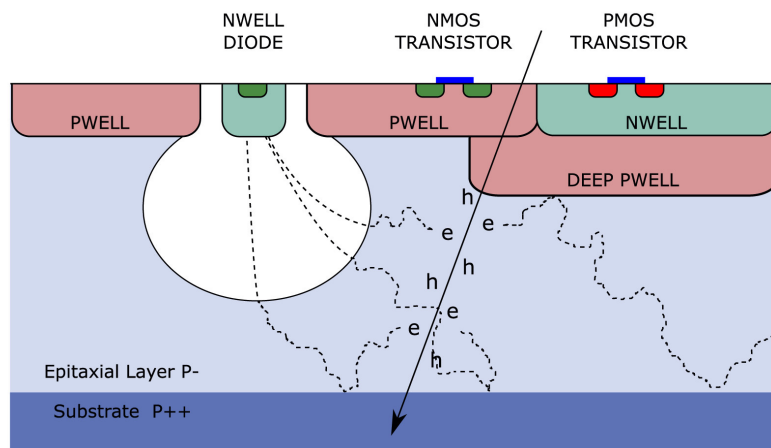


N. Hod (Weizmann Inst.)

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



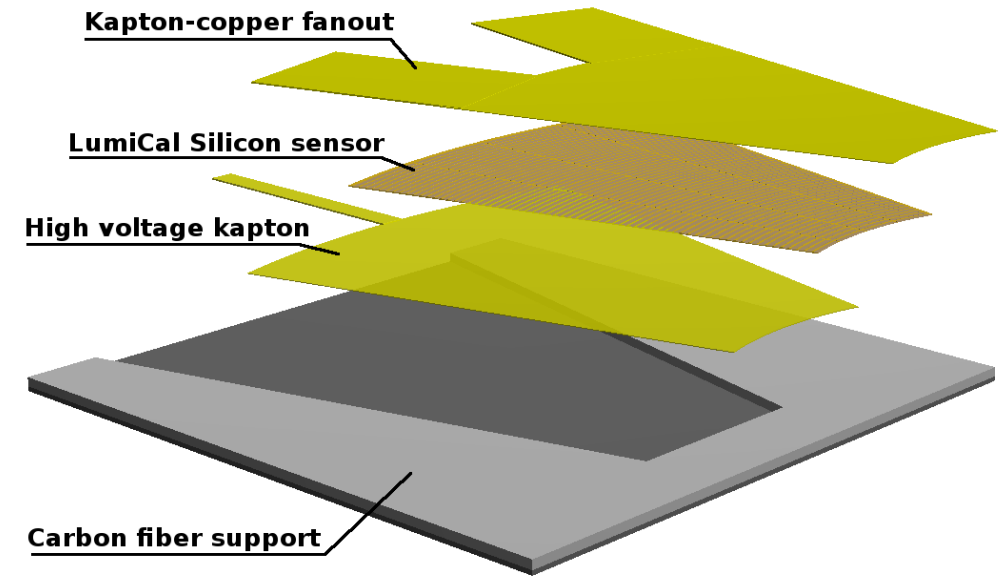
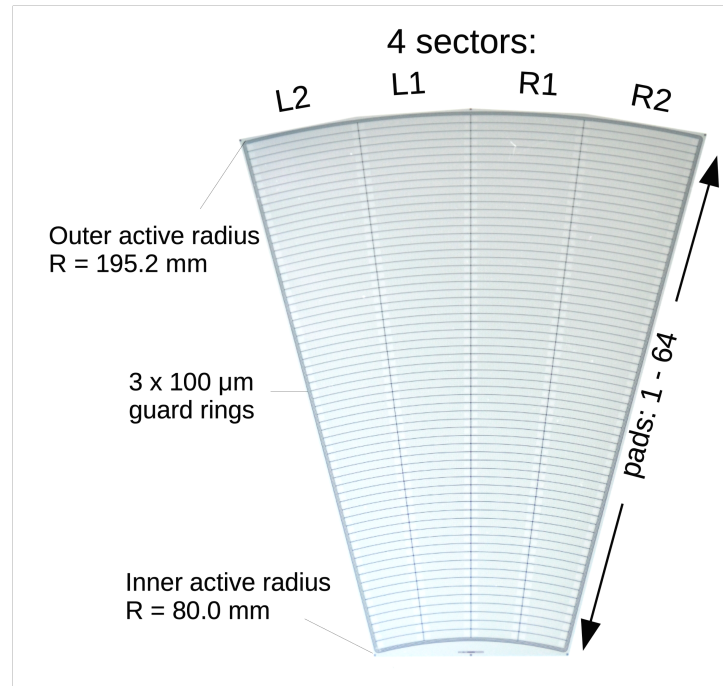
N. Hod (Weizmann Inst.)

ALPIDE pixel detectors

- Developed by ALICE collaboration
- Staves of 27 cm length; sensor size $1.5 \times 1.5 \text{ cm}^2$
 - Achieve full coverage with two staves placed next to each other
- Pixel size: $27 \times 29 \text{ }\mu\text{m}^2 \Rightarrow$ Spatial resolution $\sim 5 \text{ }\mu\text{m}$
- Plan to use four layers staggered behind each other

Redundant tracking possible, important for beam background rejection

CALORIMETERS

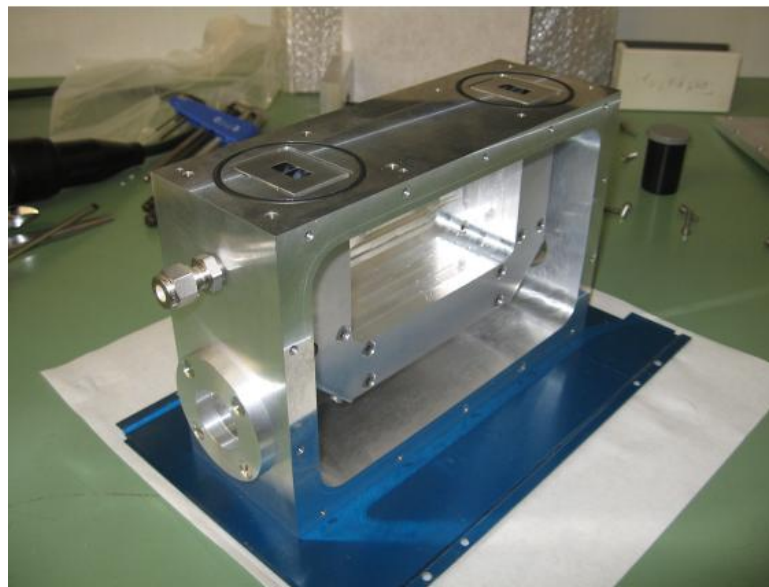
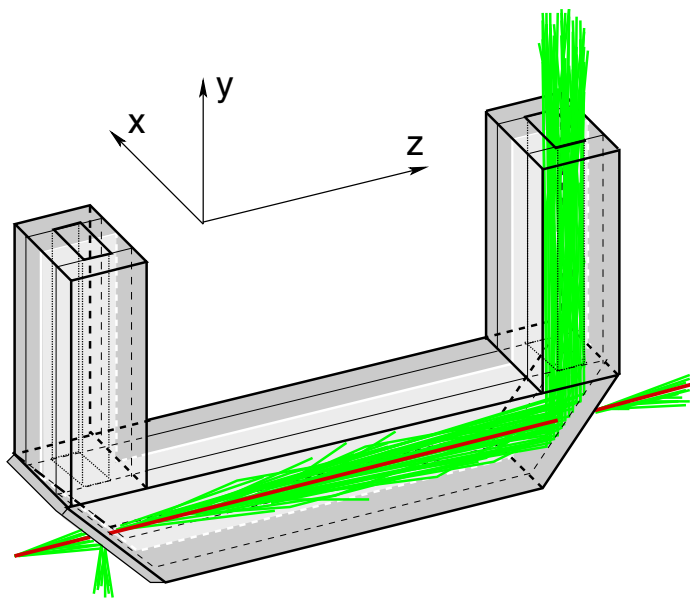


Y. Benhammou, H. Abramowicz, A. Levy (Tel Aviv U)

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



J. List (DESY)

Use Cherenkov detectors in high-flux regions

- Use design developed for ILC polarimeters
- Linearity better than 0.1% over dynamic range spanning 10^3
- Threshold of ~ 10 MeV \Rightarrow robust against background from low energy radiation
- Plan to use array of 15 detectors with cross section of 2×2 cm²

POSITRON RATE VS LASER INTENSITY

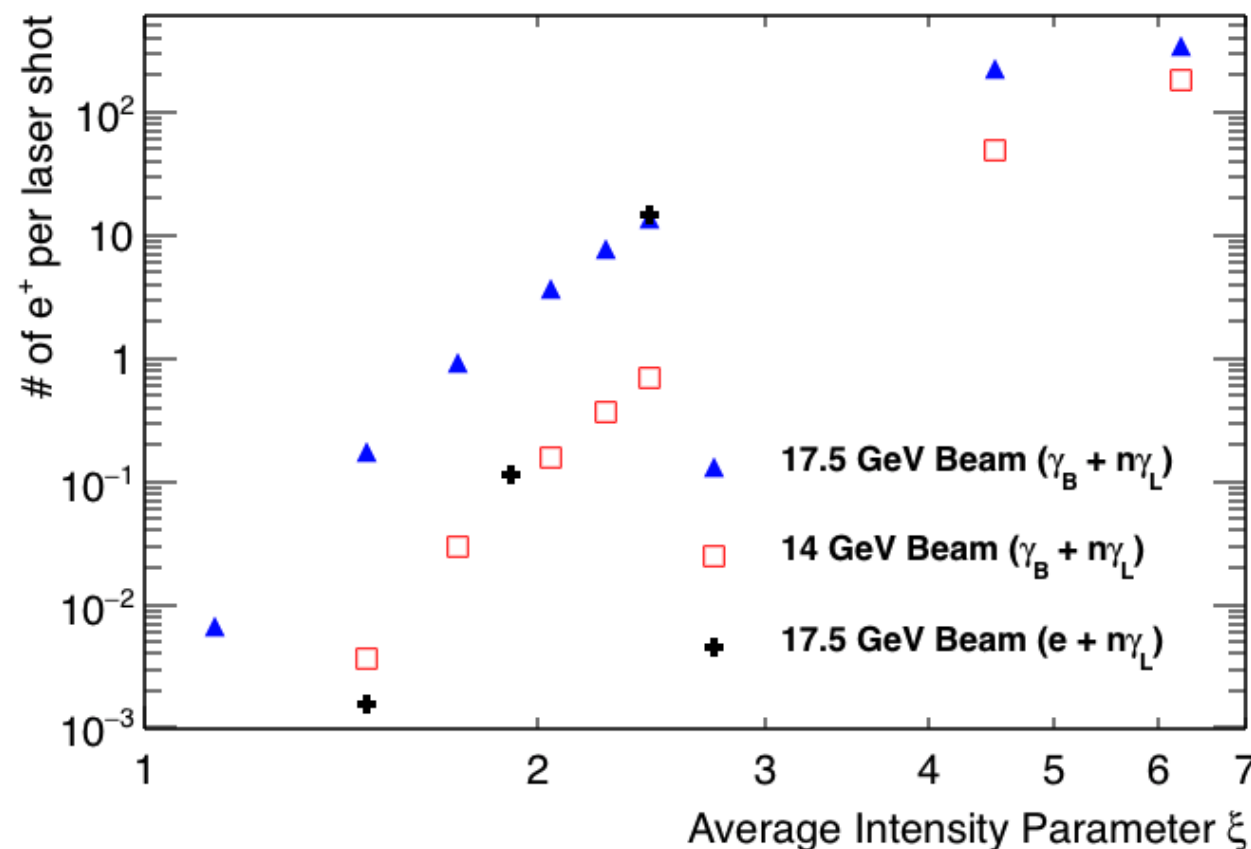
Main expected result of experiment

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

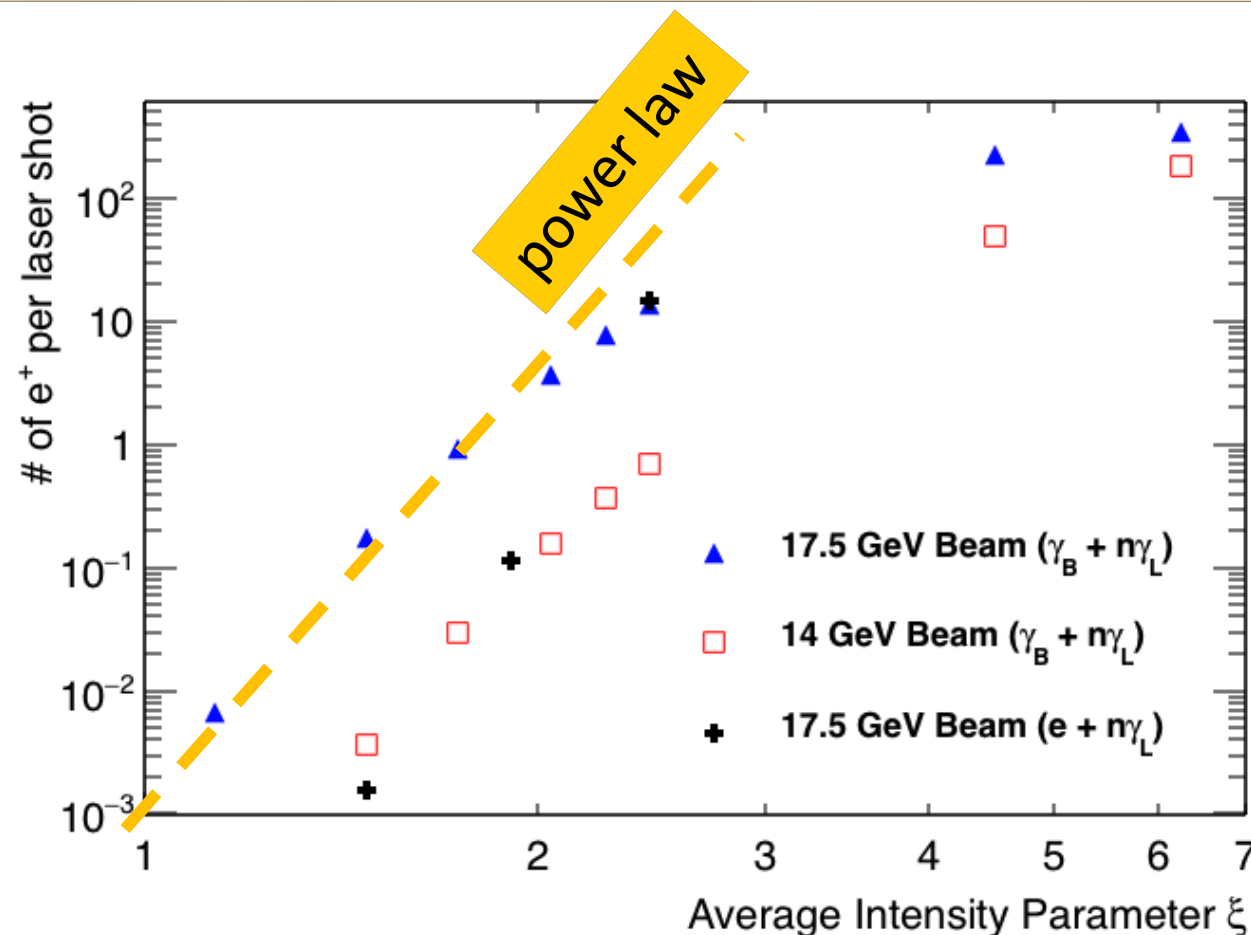
Main expected result of experiment

Low laser intensity

- Encounter power-law behaviour

High intensity

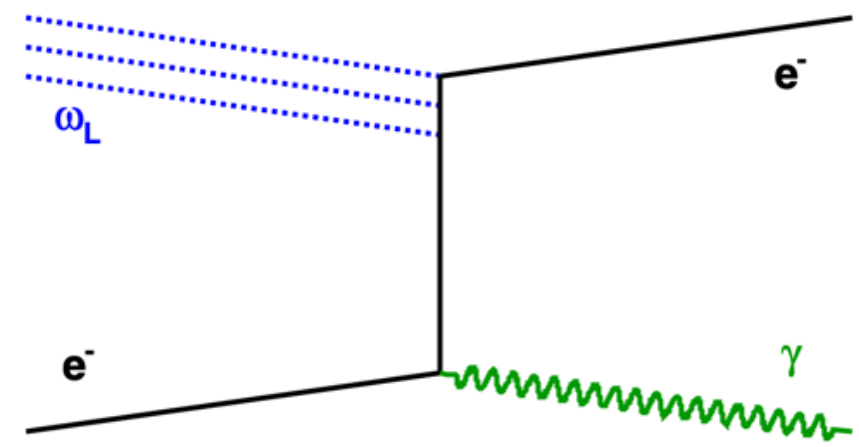
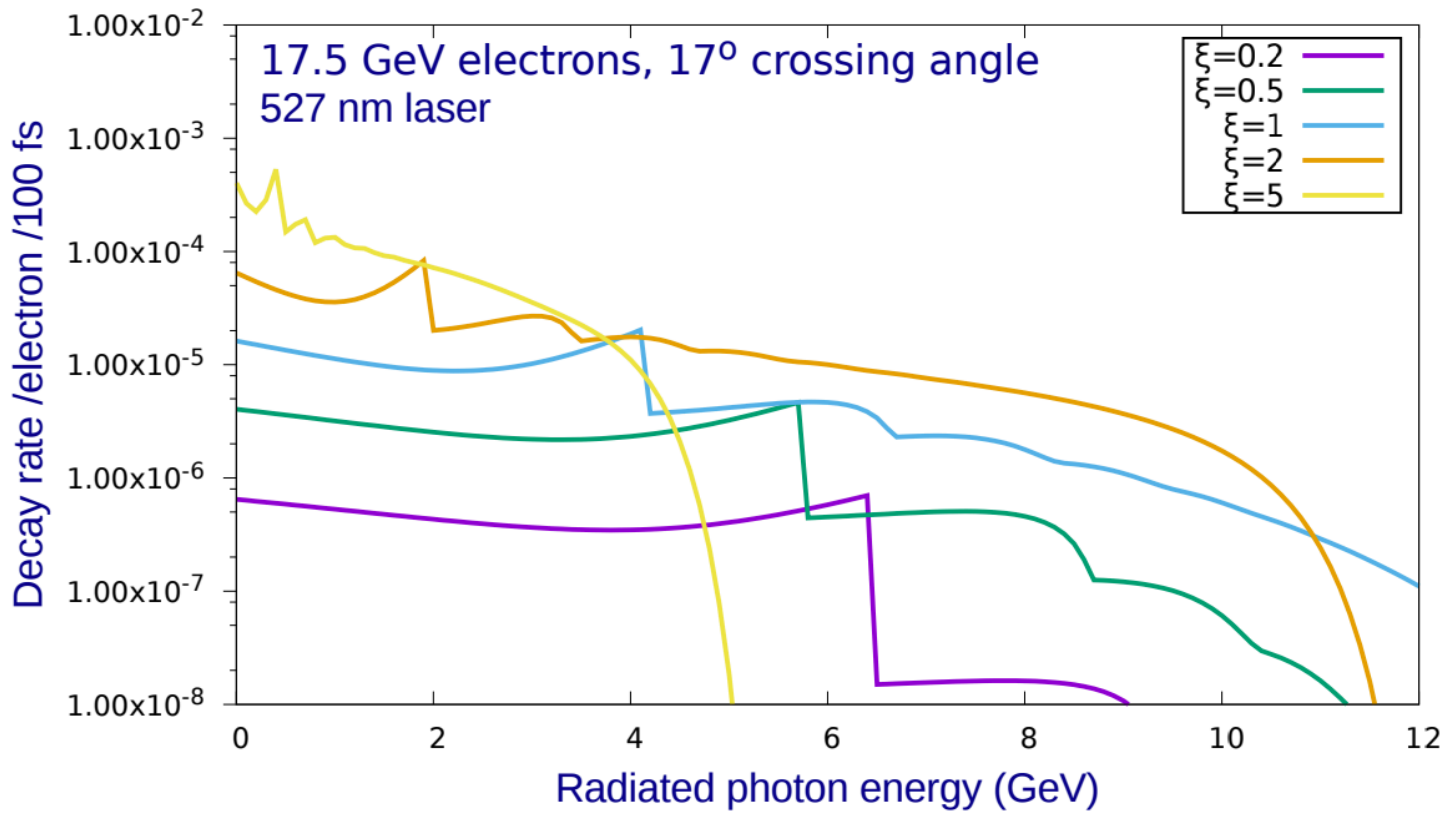
- Should observe deviation from power-law behaviour
- Aim to quantify by extracting coefficient





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

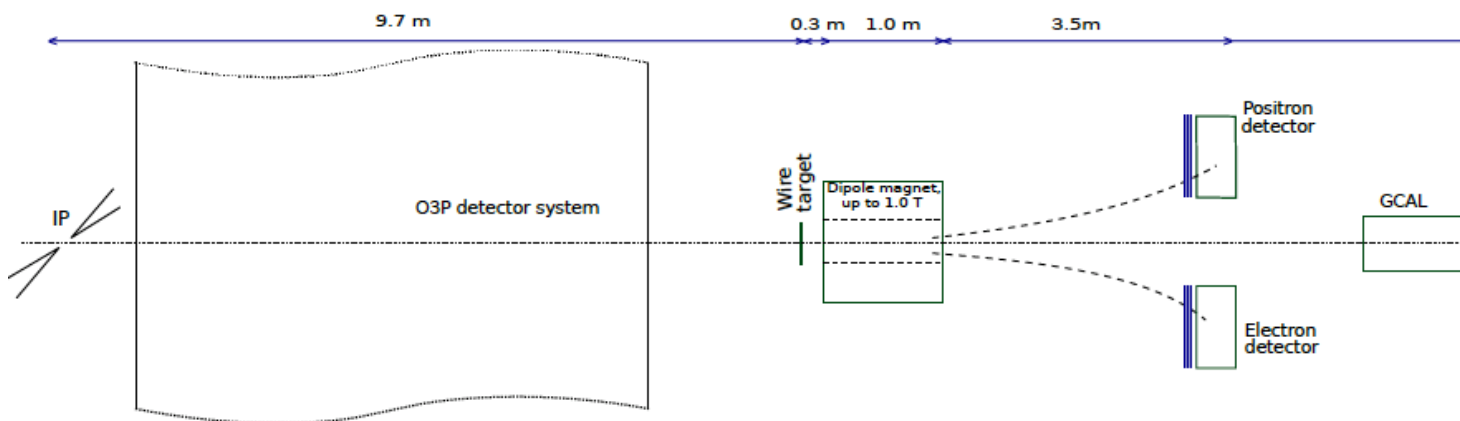
HICS for 17 GeV electrons, intensity sweep



$$p_i + k \frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2 (1 + \xi^2)$$

A, Hartin (UCL)

NON-LINEAR COMPTON PROCESS

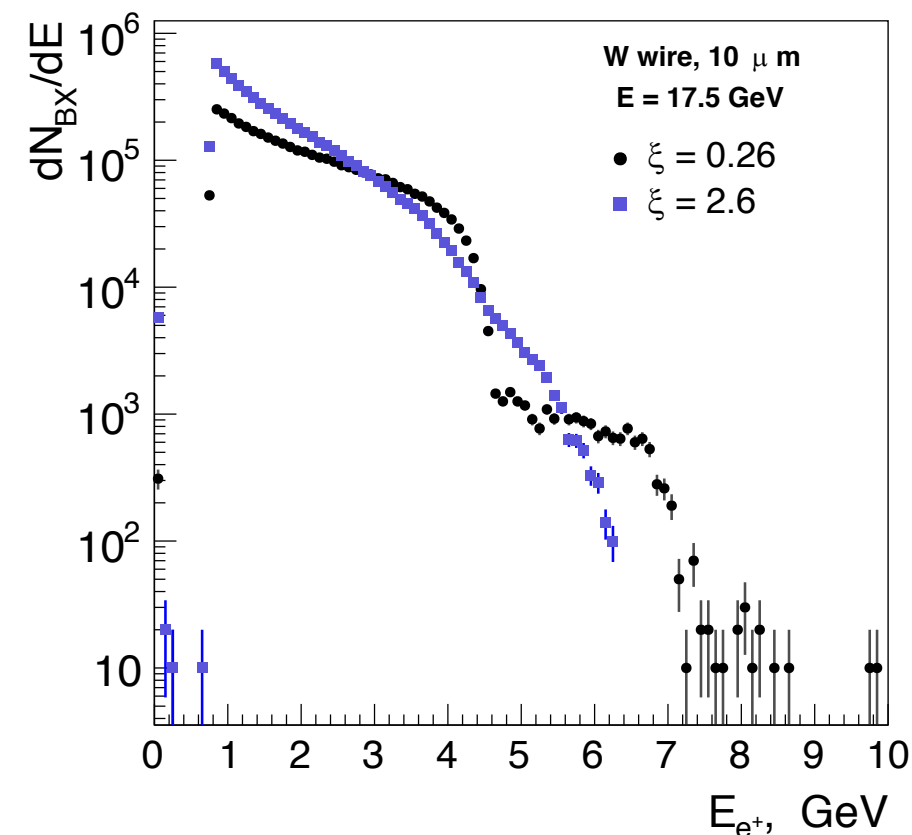


M. Borysova (Kiev KINR)

Measure photon flux and energy in “photon detection system”

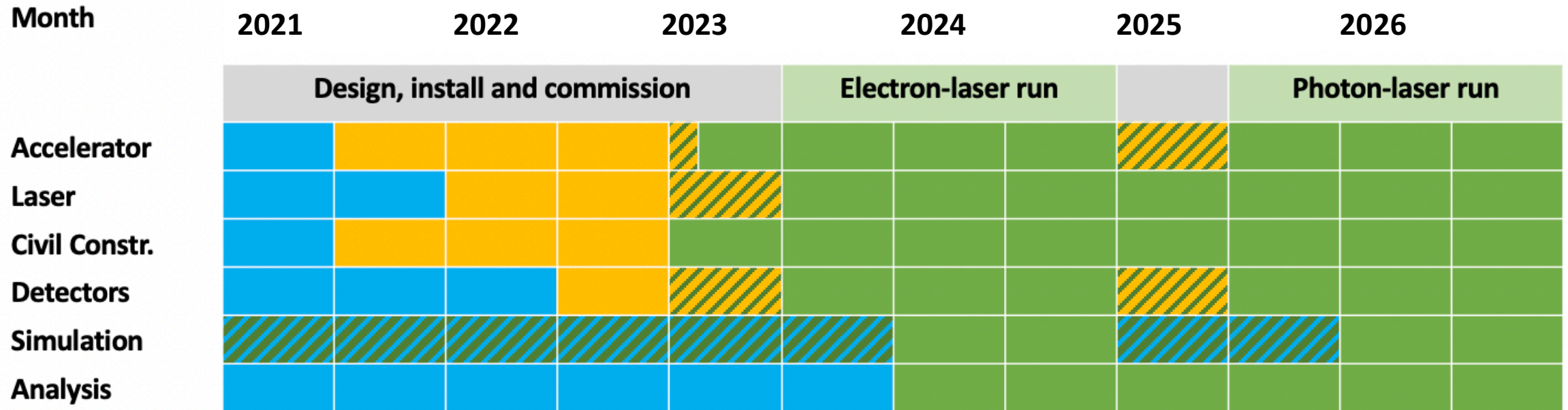
- Photon flux very high ($>10^7$ per laser shot)
- Thin wire to convert photons to e^+e^- pairs

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





TENTATIVE TIME SCALES: 2020 AND BEYOND



- **Fall 2020**
 - CDR for LUXE experiment
- **Nov/Dec 2020**
 - Start preparatory work for installation; main installation following year

CONCLUSIONS

- **LUXE will boil the vacuum 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 performed feasibility study**
 - “Letter of Intent” released in September
- **Only possible in synergy between accelerator, laser and particle physicists**



S. Weinberg: *“My advice is to try crazy ideas and innovative experiments. Something will come up.”*



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 bugging 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

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

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

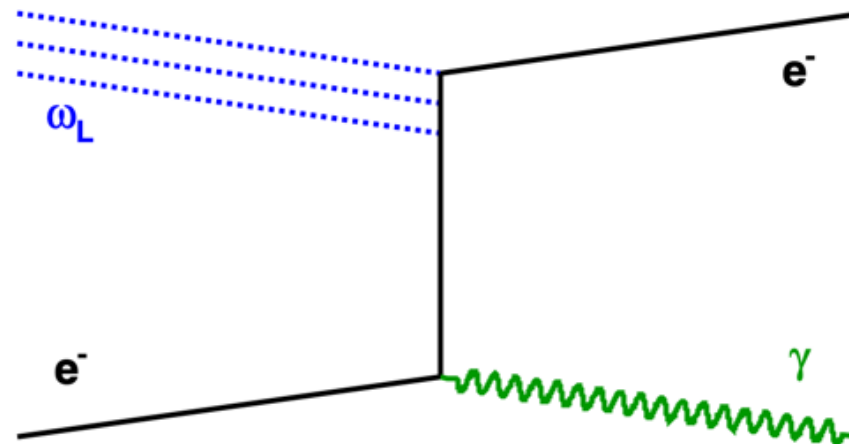
- Rate of high-intensity Compton scattering proportional to

$$\sum_n \delta^{(4)} \left[p_i + k \frac{\xi^3}{2\chi_i} + nk - p_f - k \frac{\xi^3}{2\chi_f} - k_f \right]$$

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

$$p_i + k \frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2 (1 + \xi^2)$$

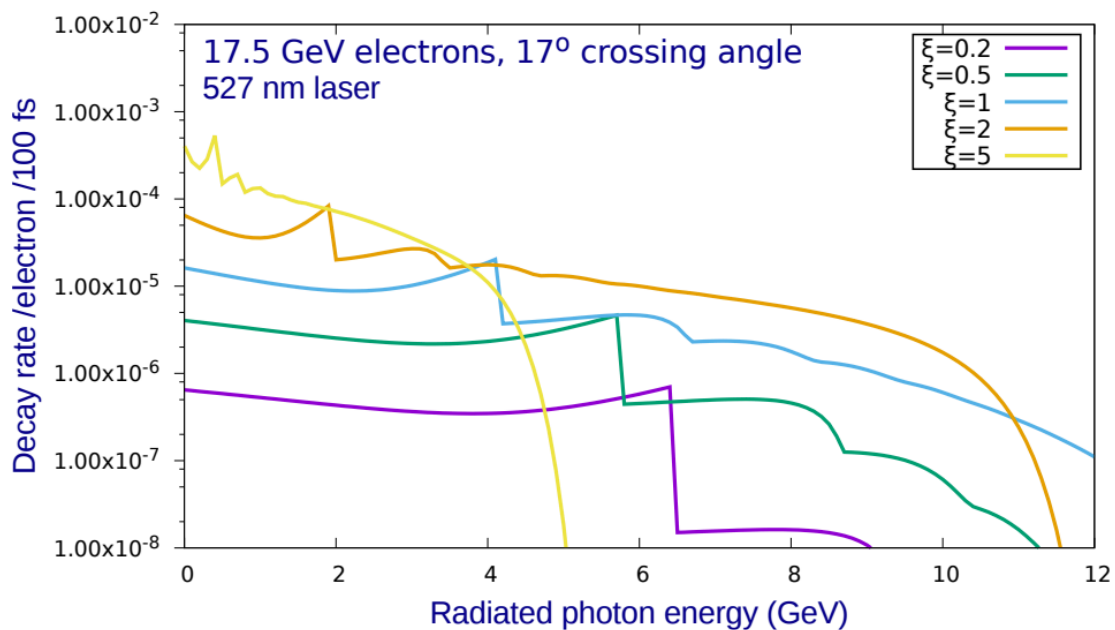
- Has never been observed





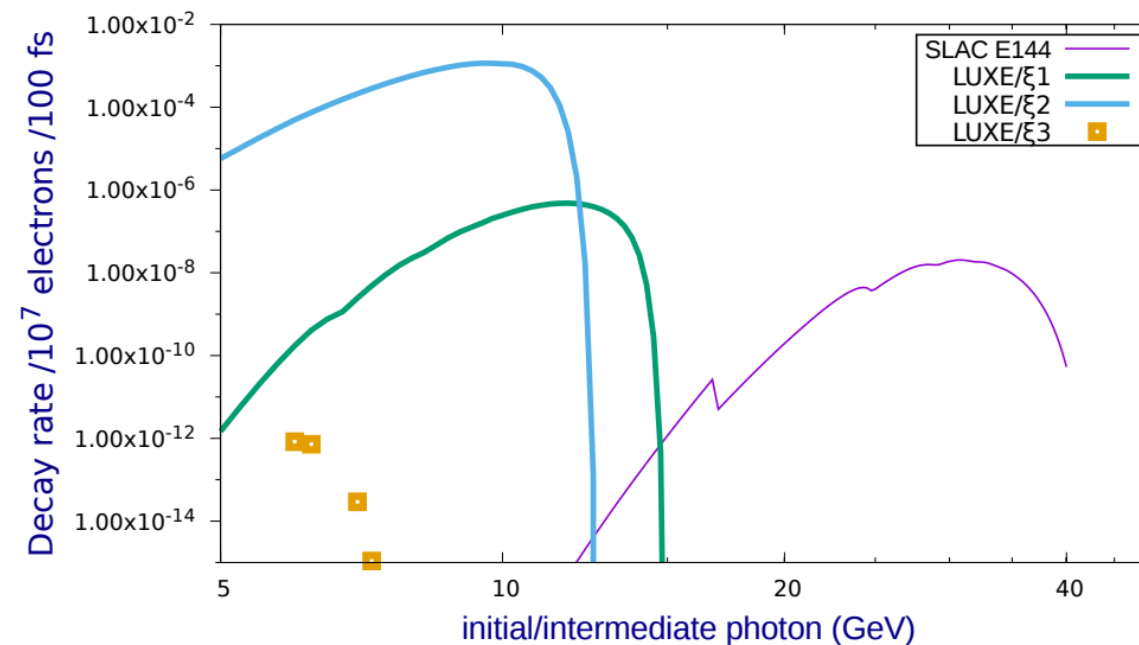
MEASUREMENTS OF MASS SHIFT AND TRIDENTS

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



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

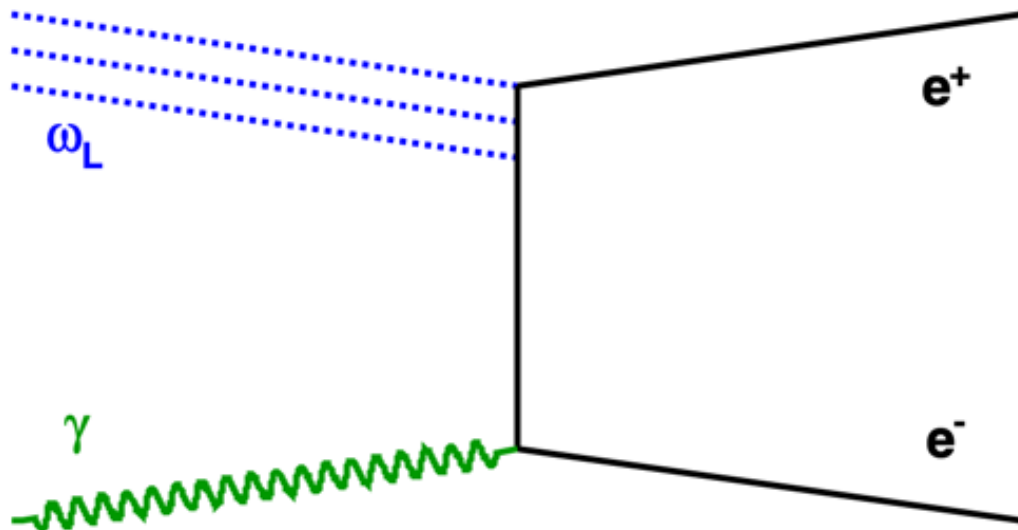
Positron rate for different parameter sets



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

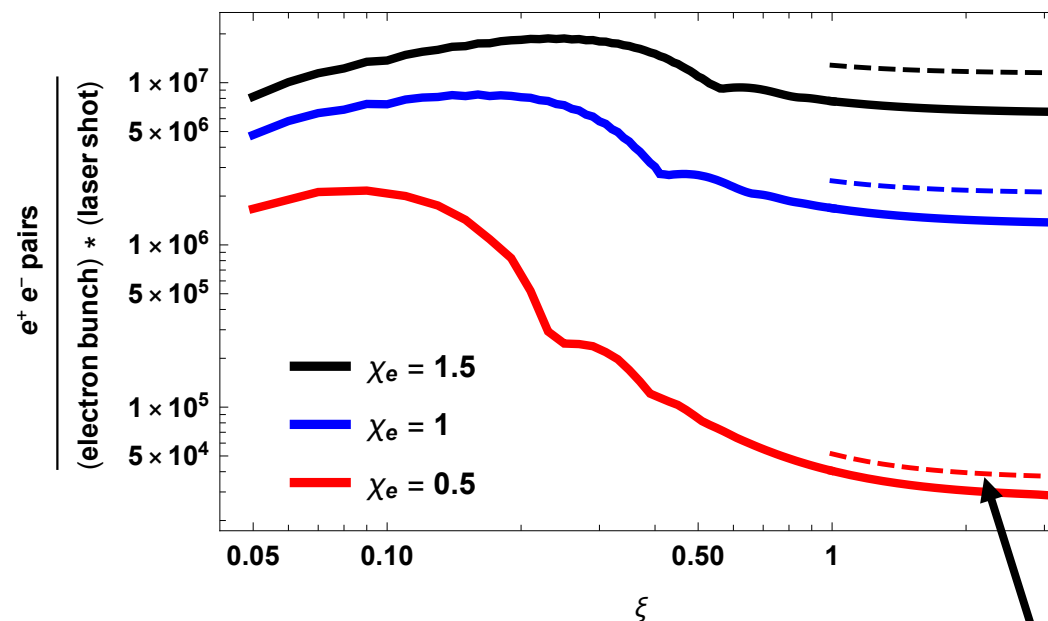
ABSORBING LIGHT WITH LIGHT

Low-energy photons from laser



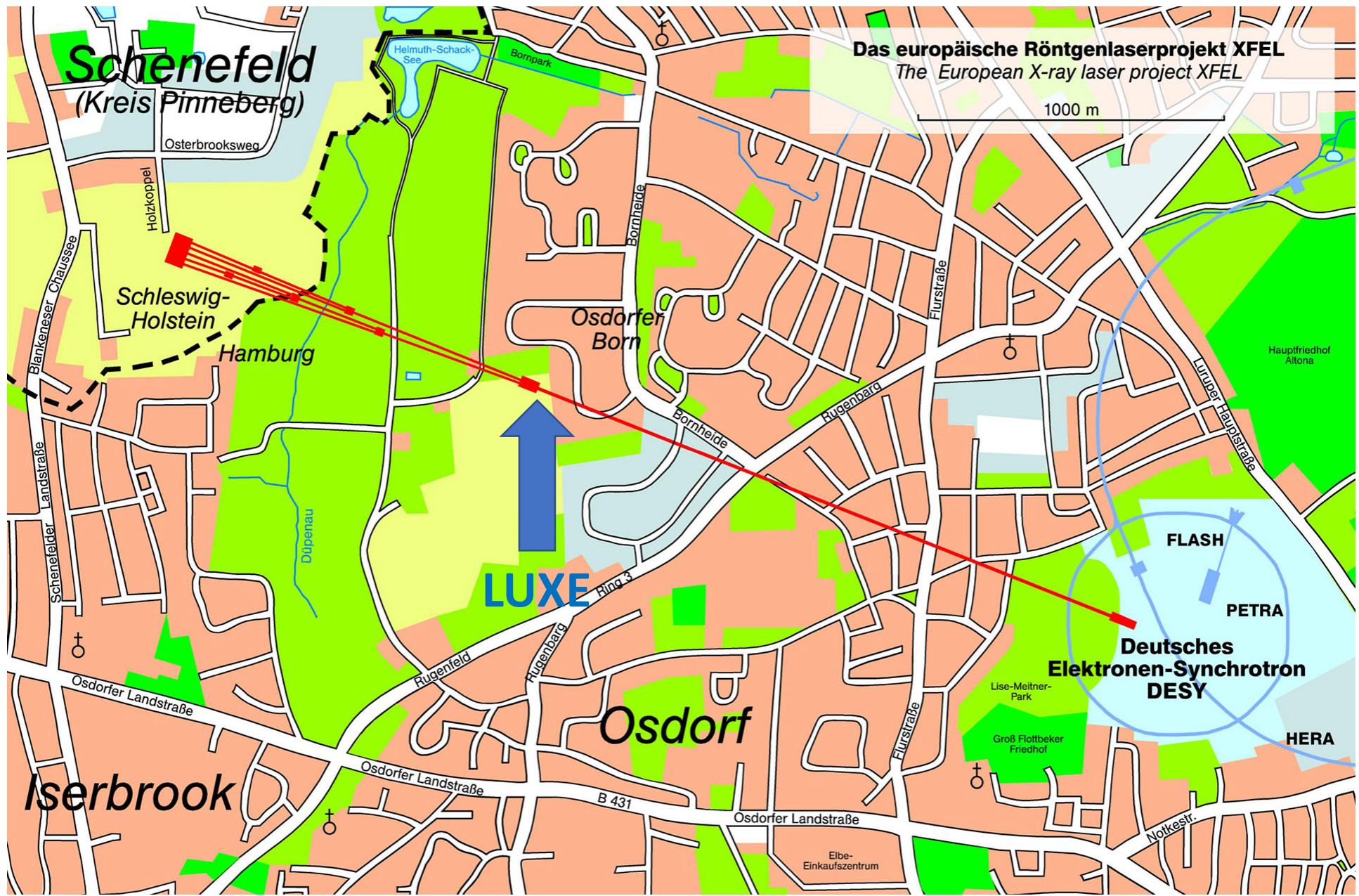
High-energy (relativistic) photon

$E_e=17.5$ GeV, e^- bunch = 6×10^9 , $\frac{X}{X_0} = 0.01$, Laser shot= 35 fs



Asymptotic limit

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







BEAM DUMP

Beam needs to be safely dumped, design well advanced

F. Burkart, M. Schmitz (DESY)

