

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

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LUNI FREBURG

**DESY. LUXE** 

### OUTLINE

#### LUXE = "Laser Und XFEL Experiment"

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

## LUXE: LASER UND XFEL EXPERIMENT

#### What is LUXE?

- New experiment planned in Hamburg using
  - European XFEL accelerator
  - High-power laser
- Documentation:



- Letter of Intent published in Sept. 2019: https://arxiv.org/abs/1909.00860
- Conceptual Design Report (CDR) about to be published
- Multi-purpose experiment
  - It offers a range of new measurements and a variety of detector technologies is needed to accomplish the physics goals
- Collaboration
  - •Not yet formally founded collaboration (process started)
  - •CDR includes authors from 29 institutions

#### **CONCEPTUAL IDEA OF LUXE EXPERIMENT**



X

# SCIENTIFIC MOTIVATION

## **QUANTUM ELECTRODYNAMICS**

- Relativistic field theory of electrodynamics
  - $\bullet$  Perturbation theory in terms of coupling constant  $\alpha$
- World's most precisely tested theory
  - •Anomalous magnetic dipole moment (g-2) of electron:
    - At leading order
    - $O(\alpha)$  correction calculated by Schwinger (1947):
    - State-of-the-art calculations includes terms  $O(\alpha^5)$
    - Precision better than 10<sup>-9</sup>!
  - •Anomalous magnetic dipole moment of muon shows interesting tension
    - New experiment at FNAL ("Muon g-2") => ~factor 4



Sin-Itiro Tomonaga

Julian Schwinger Richa

Richard P. Feynman

 $\mathbf{X}$ 



R. Feynman on QED: *"the price of gaining such an accurate theory has been the erosion of our common sense."* 

#### **DESY.** LUXE

#### THE VACUUM

### The Vacuum

#### **Classical Theory:**

- "space devoid of matter"
- "space-time region where all elements of stress-energy tensor are zero"
   → no momentum, energy, particles or

fields



vacuum

#### Quantum (Field) Theory:

- "state with lowest energy"
- average is zero, but variance non-zero
- vacuum consists of virtual particles
  - $\rightarrow$  can be charged, couple to fields



#### With LUXE we want to boil the

### VACUUM INSIDE STRONG FIELD

What happens if we now put the vacuum inside a strong field?



Vacuum boils if field large enough to create real pairs: "critical field" = work by field over

#### **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:

$$\begin{split} \mathfrak{L} &= \frac{1}{2} \left( \mathfrak{E}^2 - \mathfrak{B}^2 \right) + \frac{e^2}{h c} \int_{0}^{\infty} e^{-\eta} \frac{\mathrm{d} \eta}{\eta^3} \left\{ i \eta^2 \left( \mathfrak{E} \mathfrak{B} \right) \cdot \frac{\cos \left( \frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i (\mathfrak{E} \mathfrak{B})} \right) + \mathrm{konj}}{\cos \left( \frac{\eta}{|\mathfrak{E}_k|} \sqrt{\mathfrak{E}^2 - \mathfrak{B}^2 + 2i (\mathfrak{E} \mathfrak{B})} \right) - \mathrm{konj}} \\ &+ |\mathfrak{E}_k|^2 + \frac{\eta^2}{3} \left( \mathfrak{B}^2 - \mathfrak{E}^2 \right) \right\} \cdot \\ \left( \mathfrak{E}_k \right| = \frac{m^2 c^3}{e \hbar} = \frac{1}{n^{137^4}} \frac{e}{(e^2/m c^2)^2} = \, \, \mathrm{Kritische \ Feldstärke^4.} \end{split}$$

Z.Phys. 98 (1936) no.11-12, 714-732 (translation at arXiv:physics/0605038

### THE CRITICAL FIELD

#### **Presence of strong external field:**

 work by field over Compton wavelength > than two rest masses of particles→ critical field (aka "Schwinger limit")

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



#### 1) Field-Induced Pair Creation:

• pair production from vacuum  $P \propto exp \left( -\pi \frac{\varepsilon_{cri}}{\varepsilon} \right)$ 

$$exp\left(-\pi \frac{\varepsilon_{crit}}{\varepsilon}\right)$$

2) Modified Compton Spectrum:

Schwinger 1951

electron becomes "dressed" => larger effective m<sub>e</sub>



### STATIC ELECTRIC FIELD VS LASER FIELD

• Pair production in a constant static field via tunneling ("Schwinger process")

$$\Gamma_{\text{Schwinger}} \propto \left(\frac{\mathscr{E}_S}{\mathscr{E}_{\text{cr}}}\right)^2 \exp\left[-\pi \frac{\mathscr{E}_{\text{cr}}}{\mathscr{E}_S}\right]$$

Pair production in plane wave laser: asymptotic result

$$\Gamma_{\rm BW} \propto \left(\frac{\mathscr{E}_{\rm L}}{\mathscr{E}_{\rm cr}}\right)^2 \exp\left[-\frac{8}{3}\frac{1}{\gamma_e(1+\cos\theta)}\frac{\mathscr{E}_{\rm cr}}{\mathscr{E}_{\rm L}}\right]$$

### PARTICLE BEAM AND LASER



```
\sim 10^{22} > State-of-the-art laser needed (~10 PW)
```

 $\sim_{10^{20}}$  · Can use well-tested laser technology ( $\sim$ 100 TW

~10 GeV beams can reach Schwinger limit in rest frame with current laser tech

1 GeV

10 GeV

### **CROSS SECTION OF QED PROCESSES**

- Perturbative QED valid
  - •For n photons: n vertices =>
  - •With it follows:
- If 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 and
  Since cannot expand perturbatively



High-energy (relativistic) photon

## **ABSORBING LIGHT WITH LIGHT**



**DESY, LUXE** 

### MAIN PROCESSES OF INTEREST



High energy electron or photon interacts with laser

•Also higher order process "trident":  $e^- + n \gamma_L \rightarrow e^- e^{+i e^- i}$ 

- •E144 experiment probed  $e^- + n \gamma_L$  process in perturbative regime
- •LUXE first to directly probe  $\gamma + n \gamma_L \rightarrow e^{+i e^{-i}}$

#### LUXE IN CONTEXT



- LUXE has good chance to be first to actually break into regime
- And only experiment proposed to directly explore photon-laser interactions

#### **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  $e^- + n \omega_L \rightarrow e^- e^{+i e^- i}$ 

• Saw the power-law increase with  $\xi^{2n}$  but did not reach the critical field



#### E144 IN THE NEWS...

DIE MATEIT WICCEN	The New York Times	Corriere della Sera domenica 21 settembre 1997 19	Murrock, 1. Oktober 1997 - Nr. 227 69 FORSCHUNG UND TECHNIK
DIE CEII WISSEIN		L'importante risultato ottenuto a Stanford	Materie aus Licht erschaffen
Nr. 42 17. Oktober 1997. Seite 17			Amerikanischen Physikern gelingt technischer Durchbruch
	ARCHIVES   1997	Dalla luce è nata la materia	Was bisher nur theoretisch vorausgesagt wurde, hat ein Team von 20 Physikern erstmals im Experiment direkt beshachtet: die Erschefflung von Materia zur schun Lichteinkon. Das
Das Sein und das Nichts, früher das angestammte Thema der Philosophen, wird heute in Teilchenbeschleunigern näher untersucht	Scientists Use Light To Create Particles	Dana luce e llata la llateria	Experiment gelang am Stanford-Teilchenbeschleuniger in Kalifornien.
	By MALCOLM W. BROWNE SEPT. 16, 1997	Como prodisso Finstein	Die Umwandlung von Materie in Licht oder   Die Physiker führten eine Serie derartiger Ex-
ann die Ouantenmechanik ver- standen werden?" So fragte pro- mentare Partikel auf nahezu Lichtge- ber der dagegen unvermutet viel über das	A TRAILBLAZING experiment at the Stanford Linear Accelerator Center in	Come precisse ranstem	andere Energieformen ist nichts Neues. Ein be- sonders zerstörerisches Beispiel dafür sind Atom- sonders zerstörerisches Beispiel dafür sind Atom- ben bei der datue in der
Auture-Herausgeber John Mad- aufeinandergeschossen werden, zerstieben wieder zu John Maddor' Bemerkung über dox, "Was die Biologie angeht, so verfugt sie zu einem wahren Trümmerhaufen wieder zu John Maddor' Bemerkung über	California has confirmed a longstanding prediction by theorists that light beams colliding with each other can good the ampty vacuum into creating comething out	di LANFRANCO BELLONI	suchten Ereignisse (Physical Review Letters, 79, 1626; 1997) und Science, 277, 1202; 1997).
jeder über Erfahrungen aus erster Hand - Energie und neuen Teilchen. Dahei entste Denn genaugenommen ist in Stanlord die vom Fußpilz über die Verdauung his zur hen auch kurzlebige "virtuelle" Lachtteil. Materie nicht aus Licht, sondern vielmehr	of nothing.	Stanford hanno festeggiato la na- fascio laser iniziale se questo sufficien-	1932, als der Physiker Carl Andersen das Positron entdeckte, das positiv geladene Antiteilchen des
sonschaft in der Presse auch so gut weg-, materielle Partikel formen können. menprällenden Lichtstrahlen erzeugten le- tatate Maddox, Brinze man dagegen auf in Stanford dagegen wurden reale diglich ein "kritisches" elektromagneti-	In a report published this month by the journal Physical Review Letters, 20	A scita in laboratorio della prima temente intenso. In opportune condizioni, viene con-	negativ geladenen Elektrons. Treffen ein Elektron und ein Positron aufeinander, lösen sie sich in überrascht. Es handle sich nicht um einen Durch-
einer Dinnerparty das Gespritch auf die Lichtblitze aufeinandergeschussen. Mittels schus Feld, das die Entstellung je eines Quantenmechanik, so bekomme man be- einer trickreichen Versuchsanordnung Elektron-Positron-Paares aus dem purch	physicists from four research institutions disclosed that they had created two tiny	vicinati di fasci di luce. Facendo centrata una quantità di energia in un	einem Energiebhtz aut. Nun ist Physikern, wie bereits kurz gemeldet, erstmals der ungekehrte vorten gebungen gemeldet, erstmals der ungekehrte
stenfalls Antworten we etwar. Nichts sei so sicher, wie Newton gedacht habe, oder onstel Sckunde so viel Energie in einen Wie hat man sich so etwas vorzustellen? auch mutie extranoliert Überhaubt nichts millfärdstel Quadratzentimeter, wie die ze- Dazu muß man ein wenig ausholen. Doon	specks of matter an electron and its antimatter counterpart, a positron by	impulsi di fotoni si è assistito alla pie di elettroni e anti-elettroni, sulla ba-	in Elektronen und Positronen umzuwandeln. Elektronen und Positronen umzuwandeln.
sei sicher. "Was not tut, sind Experimente, die die Bedeutung dieses Fachgebietes de- Zeit verbrauchen. Eine der stärksten La- letztlich nur deshalb möglich, weil in der	colliding two ultrapowerful beams of radiation.	materia, più precisamente di coppie di che regola le reciproche trasformazioni	ber in Beschleuniger-Experimenten. Werden Teil- meint, technisch sei in Stanford ein toller Erfolg chen wie beispielsweise Protonen und Antiproto-
monstrieren und ins allgemeine Bewuist- zein heben", forderte Maddox. Amerikanischen Posidern ist nun ein Unschärferelation fest. daß bezimmtr zu-	American physicists, Dr. Gregory Breit and Dr. John A. Wheeler, But more than	elettroni e di antielettroni. È questo è, fra materia ed energia. appunto, la prima volta che accade. Si è così avuta la prima creazione di	nen aufeinander geschossen, so können sie beim Zusammenprall in einen Energieblitz aufgehen.
solches Experiment gelungen. Zwanzig sammenhängende Größen eines subato- Wissenschaftler von vier amerikanischen maren Partikels (etwa dessen Ort und Ge-	six decades passed before any laboratory could pump enough power into colliding	Come spiegavano i libri di testo, se si materia dalla luce, ha commentato uno oriera luno scontro frontale fra un elet- dei portavoce dell'esperimento condot-	Dieser Energieblitz enthält manchmal kurzlebige Lichtteilchen, aus denen dann Elektron-Positron- kehrt, zweille heute niemand mehr.
Universitäten wandelten am Linearbe- schleuniger in Stanford, Kalifornien, enst- zekteurige Licht in Matrie um ein Work A 7 Zeitkdauer) nicht gleichzeitig scharf defi- nieft werden. Diese merkwindige Pfüzig	beams of radiation to conjure up matter from nothingness. The Stanford	trone e un anti-elettrone, si provoca to a Stanford da una squadra di una	lebigen Lichteilchen virtuelle Photonen im
das ein wenig an die Erschaffung der Welt durch göttliche Hand erinnert. Suzusagen WVarum gitt ganz allgemein – also auch im Vakuum. Der sogenannte leere Raum darf daher	accelerator finally provided enou	ticella di materia con quella di anti-ma-	lichen Lichtweilchen. Virmelle Photonen entstehen nur für einen kurzen Moment in einem starken
aus bloßem Nichts Materie zu erzeugen, nicht exakt leer sein, sonst müßlen darin das blieb bislang der Bibel oder der Ur- kentitheorie werbehalten. Nun ist führer	Dr. Adrian C. Melissinos of <b>DUICITUC</b> Home News Journals Topics Careers	tro consiste in un paio di fotoni o parti- tro consiste in un paio di fotoni o parti-	clektrischen Feld in der Nähe eines geladenen Teilchens. Im Experiment am Stanford-Beschleu- Universungen, Annliche Bedingungen finden sich im Universungen, Annliche Bedingungen finden sich im
Schöpfungsakt endlich auch vor Zeugen gelungen. IST schärfungen pickt ein kann. Tatsachlich gleicht also das Vakuum in	experiment was produced by a tr	celle di luce, che si allontanano dal luo- considerò sul piano teorico la possibile produzione di coppie di elettroni e po-	niger in Kalitomien wurden die Elektron-Posi- tron-Paare estmals nicht aus viruellen, sondern bei handelt es sich um extrem dichte
Verglichen mit dem Gotteswerk (oder LOC Wahrheit einem See, in dem unablässig eben dem leig bang), nimmt sich das Er- erbeit der Leis keinen handlich im Mittel erbeit der Leis keinen handlich im Stender	of the needed energy, even thous	le traiettorie della particella e dell'anti- sitroni in seguito all'urto fra due fotoni particella iniziale prima della sponto reali. La traduzione pratica dell'idea	Jass gewonntellen Findenhein geschaftet. Lasst gewonntellen Findenhein geschaftet. Lasst gewonntellen Findenhein geschaftet. Schwiedkung unter der Wirkung der
ford allerdings bescheiden aus: Nach insge- samt rund vierjähriger Arbeit hatten sie <b>Atvarage</b> uull. Wenn allerdings in einem derart For- delnden Nichts zwei Lichtblitze mit Wacht	most powerful.	frontale, sono nella direzione est-ovest, teorica ha richiesto qualche decennio,	Der Durchbruch gelang einem Toam aus zwan- muten, dass Neutronensterne eine strakes Magnetich baben An ihrer Oberfläche könsten
gerade einmal rund einhundert Elektro- nen - sowie deren Antiteikhen, die Po-	But the opposing beam of ra	dalla loro annichilazione della come pure lo svinippo un tecnologie sofisticate, e	zig Wistenschaftern von vier annerkanischen för- schungsinstituten. För das aufwendige Experi- ment beschlete die Gungen autwiendige Experi-
stronen – erzeugt. Mit dieser Ausbeute, für Partikelpaar zum sprung von der mögi- die in Stanford mehrere Billionen Watt verheit wurden, ließe sich nicht einnal ein Amerikanische Schwirzlich zu sich das vorzustellen? bit is	drawn from electrons whizzing d	si allontanano nella dire- zione nord-sud in senso virtuosismo da parte de-	Photonen. In einem ersten Schrift verwendete sie Die Physiker erholfen sich deshalb von ihren
Taschenlämpehen zum Glühen bringen. Eine verheerende Energiebilanz Aber es Physiker schufen auch. Immerhin ist das ein Sujet, das Phy- sikstudenten erst in den böheren Seme-	beam.	opposto. E i fotoni gene- gli sperimentatori di Staaford che hanno do	DISCOVER MAGAZINE - DECEMBER 1997
gen ja auch mehr uns Prinzipelle Ausre- ner Energie laßt sich Materie verstoffil- chen. Welch eins Symbolkraft steekt in die-	The paths of colliding electrons : G Science 29 Aug 1997:	punto due, e non uno so-	Let There Be Matter
sem Akt. aus reinem Licht erzeugung aus dem Nichts sich zwai in den niesenhaften Detektoren der Teilchenphy-	complicated as those choreograp Vol. 277, Issue 5330, pp. 1202 DOI: 10.1126/science.277.5330.1202	lo, per rispettare la fon- damentale legge della precisione sia gli impulsi	
Mensch namlich schon vormehr als funtzer Jahren gemeistert - mit verheerenden Aus- wirkumen Die Atomosche dange die Schladbert kische Anwendungen scheidert die Schladbert	2	conservazione della laser iniziali sia gli im-	by Jeffrey Winters
te aller Welt die plötzliche Umwandlung nicht", nieint denn auch Adrian Melissinos von Materie in Energie, gemäß der simplen bedauernd.	Subscribe for just €1 a wee Article Figures & Data Info & Metrics eLett	ers pre i libri di testo spicga-	
Gleichung E = mc <sup>2</sup> (die Masse einen Kör- pers multipliziert mit der Lichtgeschwin- diekeit in Orustraumit dessen Einer Jahren der Steaten Ge- hert Dumit Laun num besnehensen der	······	avrebbe dovuto essere	
Albert Einstein, der diese berihnteste Formel der Physik 1905 erstmals veröffent-	Turning matter into light, heat, and other forms of energy is nothing new, as	e. Facendo urtare fra lo-	Latert 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-easts
Ichte, ahnte noch nichts von der gewalti- gen Sprengkraft, die sich dahinter verbirgt. Harmose schiebe zum Ender suiner Aus- warum sie until zwi. Nathlich konnten die	Stanford Linear Accelerator Center (SLAC) has demonstrated the inverse	ro, lungo la direzione positroni (cioè di antic-	hines because atoms in its core fuse, transforming a sliver of matter into light. And when particles of matter and antimatter
fuhrungen: "Es ist nicht ausgeschlossen, Stanforder Erkenntnisse auch beim Bau daß bel Körpern, deren Energieinhalt in zukünftiger Beschleumiger sein (sofern	process—what University of Rochester physicist Adrian Melissinos, a	ticolarmente energici, era prevista la fica negli esperimenti di fisica delle alte	neet, they annihilate each other in a blaze of energy.
hohem Maße veränderlich ist (z. B. bei den Geld dafür vorhaufen ist). Zudern interes- Radiumsalzen), eine Präfung der Theorie seinens wirdt "Eine erzendiges Echlein, serniellen der Welt sandte extrem kurze tronsesterene bhliche Präferse wermu	spokesperson for the group, calls "the first creation of matter out of light."	n formata da un elettrone e da un anti- loro particelle accelerate.	But like any equation, E=mc2 works in both directions, at least theoretically. That is, it should be possible to convert energy nto matter. Now a team of physicists has accomplished just that; they have transmuted light into matter. "We're able to turn
schlitzung, Nicht bei den Radiumsahzen, Lichtpulse aus Um einen zweiten, nuch en- sondern in Hiroshima wurde die Theorie ergiereicheren Strahl zu erzeugen, lenkten erzeugung aus dem Nichts ist philoso-	the 1 September <i>Physical Review Letters</i> , the researchers describe how the	y elettrone che si allontanano in senso Ben diversa e la situazione ricreata in opposto lungo la direttiva est-ovest. California dove la produzione delle	optical photons into matter," says Princeton physicist Kirk McDonald, coleader of the team. "That is quite a technological
bewiesen. Nun, ein weiteres halbes Jahr- hundert später, wird in Stanford Materie den feingebündelten Elektronenstrahl, der verbaren zum den sicherformer, im Stenforder Russforder Berkforden und den Schleren die Under under her den sicher späteren den sicher den Schleren und den sicher der Under stenden sich under under sicher die Under under sicher der Under die under under sicher der Schleren die Under sicher der Schleren de	collided large crowds of photons together so violently that the interactions snawned particles of matter and antimatter: electrons and positrons	La previsione teorica dell'effetto ri- coppie è avvenuta per opera dei soli fo- sale arli anni Trenta, ma solo la teorio- toni che sono le particelle costituenti la	cap.
stall Zerstörung demonstnert, Werden die Wie Progongbälle auf einen Lastwagen Kosmos dereinst aus einer Energiefluktua- Physiker um Adrian C. Melissinos ebenso praliten die Lichtteilchen auf die Elektro- tion im Vakuum entstanden ist.	(antielectrons).	logia odierna è stata in grado di trasfor- luce dove almeno uno dei quali deve	If 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 energythe Big Bang. And physicists who smash atoms together have witnessed the conversion
in die Geschichte eingehen wie Robert nen und wurden mit noch mächtigerem Das Mißverhältnis zwischen (Energie-) Oppenheimer und seine Los-Alamos- Greef und seine Los-Alamos- Ungehehrung die Gebehrung zum Aufwand und (Materie-) Ausbeate im Stan-		esperimento reale. cioè deve esistere per una brevissima	of energy into matter"virtual" photons that flit in and out of existence just long enough to spawn the particles of exotic
Die Fachleute winken ab: An Einsteins sche Gammastrahlung, die mit dem nach- gen, wie begrenzt die Moglichkeiten der Formel zweiße schon lange niemand mchr; sten Laserputs kollisiere.	Gamma photon Laser	A Stanford namo sparati inipulatila. Inanote of temps for accupative por	shotons arise as part of a complex chain of events starting with a collision of two particles of matter. Until now, no one had
und daß sich Licht in Materie umwandeln Adrian Melissinos stöhnt noch heute, steins berühmter Formel mittlerweile die lasse, sei schne öfters bewiesen wurden, wenn er an die Sensibilität dieses Fuer- hafte Ereiten einen gewähligen Lichtbilitz		Rimbalzando come palline lanciate in gioco soltanto dei fotoni reali o ordi-	nrecuy created matter from fight. "Back in 1934 physicists realized that it would be possible to do this in principle," says McDonald, "But it just wasn't technically feasible."
Dennoch gelang is Staford ein Dennoch deuting konnte die Juster und verster eine met deut gegenten mit dem grefekting gehen bereiten deuting durch einem an mit dem grefekting gehen bereiten deuting durch einem an mit dem grefekting gehen bereiten deuting durch einem an einem staford ein bereiten deuting durch einem an einem staford eine	Electron	contro una Ferrari in corsa, l'energia nari, offrendo così la dimostrazione dei fotoni incidenti ha subito un au- pratica di un fenomeno previsto da lun-	By the early 1990s, McDonald and his colleagues had all the technological pieces in place to conduct such an experiment.
her vorzuweisen hatte, waren eber indirek- te Ergebnisse, sozuszien Abfallprodukte der genauso wie den morgendlichen er erzegen, die noch nicht einmal die Masse der Brobe genauso wie den morgendlichen eine Brobelisten einer Altona zusammenbringen. Das Zer-	pair	mento e di conseguenza si è passati dal- la luce laser incidente, situata nella fre- ne di energia elettromagnetica si è riu-	The key piece was a laser capable of packing a tremendous amount of energy into a small space. The laser that McDonald in collaborators use at Stanford execution watts of paymer enough to light every home in North America But
wie sie in den Hochenergiezentren Cern in aufheizu. Wicht nur in der Essterik ist auch naturgesetzlich allemal einfacher zu Genf oder Desy in Hamburg gang und eben alles mit allem verbunden.		quenza del visibile, a raggi gamma di sciti quindi a ricavare della materia,	ather than drain the national electric grid, the laser takes a rather ordinary amount of energy and compresses it into a pulse
		fotoni gamma, riflessi all'indietro, a lo- quasi da libro di testo, della famosa for-	or 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 saucezed
		ro volta si scontrano con i fotoni del mula einsteiniana.	ogether, the energy is still only about a millionth of what's needed to make matter.

### WHY IS STRONG-FIELD QED INTERESTING?

- Relevant to numerous phenomena in our Universe
  - Astrophysics: Hawking radiation, surface of neutron stars (magnetars), cosmic ray propagation
    - •Condensed matter and atomic physics (Z>137)
    - •Accelerator physics: high energy e<sup>+</sup>e<sup>-</sup> colliders
    - •Transition from perturbative to non-perturbative regime

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

• And ..... what could be more exciting than probing quantum physics in a new regime!?

•M. Peskin at Snowmass 20/21: "...the motivation of exploring the regime is very strong"

### **ANALOGY TO HAWKING RADIATION**

- Energy needed to create on-shell e<sup>+</sup>e<sup>-</sup> pair:
- Grav. Field near the event horizon:
- Schwarzschild radius . =>
- Energy to separate pair:



H. Murayama

 $\rightarrow$ 

#### Hawking radiation possible if virtual pair becomes real, i.e.

# 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, ...





X

#### THE EUROPEAN XFEL

#### **View along L3 accelerator section and undulator**









#### **EUROPEAN XFEL INAUGURATION**





#### **Operating since September 2016**

DESY. LUXE

### THE EUROPEAN XFEL

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**DESY. LUXE** 



### LOCATIONS IN EU.XFEL TUNNEL

#### • Location at EU.XFEL:

- Annex of shaft building XS1: at end of electron accelerator
- Was build for 2<sup>nd</sup> EU.XFEL fan foreseen for later (>2029)
- 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)



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#### SCHEMATIC VIEW: BEAM EXTRACTION AND TRANSFER



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#### **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 µs: kicks bunch at end of bunch train)



 $\times$ 

annex

#### 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



#### **XS1 BUILDING**



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### LASER TECHNOLOGY







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© 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."
- Use Ti:Sa laser with 800 nm wavelength (E=1.55 eV)
- Energy focussed strongly in both time and space => high intensity
- Experiment has two phases:
  - Initially 40 TW (phase-0), later 350 TW (phase-I)

### LASER PARAMETERS

- Repetition rate: 1 Hz
- Pulse length 30 fs
- Collision angle: 17.2 degrees



Laser intensity:

Parameter	Phase-0	Phase-0	Phase-I	
Laser energy after compression [J]	1	10		
Percentage of laser in focus [%]				
Laser focal spot size $w_0$ [µm]	>8	>3	>3	
Peak intensity [10 <sup>19</sup> W/cm <sup>2</sup> ]	1.9	13.3	120	
Peak intensity parameter ξ	3.0	7.9	23.6	
Peak quantum parameter χ:				
E <sub>beam</sub> =16.5 GeV	0.56	1.50	4.5	
E <sub>beam</sub> =14.0 GeV	0.48	1.28	3.8	- [

with

E<sub>L</sub>: energy (J) ∆t: pulse length (s) : focus area (m<sup>2</sup>)

intensities achieved by de-focussing laser or stretching pulse

#### LASER BEAMLINE



#### LASER DIAGNOSTICS



•Need 3D characterization of laser: energy, pulse length and spot size

•Goal: 5% on intensity => plan many (partially redundant) measurements

# PARTICLE DETECTORS AND PHYSICS MEASUREMENTS

#### e-laser mode



- Goal: Detection of electrons, positrons and photon fluxes and measure their energy spectra
- Particle fluxes vary between ~0.01 e<sup>+</sup> and 10<sup>9</sup> (e<sup>-</sup> and  $\gamma$ ) per laser shot!
- Use technologies adapted to respective fluxes of signal and background

### DETECTORS

- High rate regions:
  - Cerenkov detectors
  - Scintillator screens
- Low rate regions
  - Silicon pixel detectors
  - High granularity calorimeters

Two complementary technologies used in each case for cross-calibration, reduction of syst. uncertainties



#### **E-LASER MODE: COMPTON SCATTERING**



#### • Expect ~10<sup>9</sup> electrons and photons per laser shot

• Chose detectors that can cope with this high rate => Cherenkov & Scintillator

### **CHERENKOV DETECTOR**



### **SCINTILLATOR SCREEN**



**DESY. LUXE** 

### **COMPTON-EDGE SHIFT**

#### **Compton energy spectrum modified:**

• Compton edges shifted to lower energies as electrons acquires an effective mass:





=> Goal: measure these edges

### **COMPTON-EDGE ANALYSIS: RECONSTRUCTION**



- Gaussian laser pulse: superposition of different  $\xi \rightarrow$  edges overlay in spectrum
- Position and shape of edges sensitive to dependence of nonlinear Compton cross-section on  $\xi$
- Edge reconstruction vis Finite Impulses Response Filter (FIR)  $\rightarrow$  max. in response = edge position

#### **COMPTON-EDGE ANALYSIS: SIMULATED RESULT**



• First harmonic kink position (edge of maximum  $\xi$ ) as a function of  $\xi_{max}$  compared to theory prediction

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### **PHOTON DETECTION SYSTEM**



Three detector technologies

- Spectrometer with scintillator screens behind converter
  - Measure flux and energy spectrum
- Backscattering calorimeter
  - Measure flux
- •Gamma profiler (sapphire)
  - Measure location

### **PHOTON SPECTROMETER**

- Up to 10<sup>9</sup> photons per bunch crossing with ~GeV energies
- Energy spectrum measurement
  - Spectrometer with scintillators behind converter
  - Energy resolution <2%



#### **PHOTON ENERGY MEASUREMENT**



#### **Alternative way to reconstruct Compton edges**

### **PHOTON FLUX**

- Up to 10<sup>9</sup> photons per bunch crossing with ~GeV energies
- Flux measured with
  - Spectrometer
  - Backscattering calorimeter (lead glass blocks)







#### **GAMMA PROFILER**

- When using polarized laser, expect angular spectrum of photons to depend on  $\xi$  for and distance from IP of 6m:
  - Parallel: m, Perpendicular: m
  - Ellipticity is independent measure of laser intensity parameter



• Measurement of 5 m provides constraint: for  $\xi>2$ 

#### **Positron Detection: e-laser mode**



#### -laser mode



#### **Provides most direct test of Schwinger limit**

#### **ELECTRON AND PHOTON LASER MODE**



Very different e- rate in e-laser and photon-laser modes
 nood to change detector technology when photon laser run s

need to change detector technology when photon-laser run starts

### PAIR PRODUCTION



- Three methods for producing pairs
  - Compton photons inside same laser pulse => largest rate
  - Bremsstrahlung photons produced upstream => highest E
  - Compton photons produced upstream (E=9 GeV)



10

18

E (GeV)

16

14

12

### PAIR PRODUCTION



#### • Expected event rates

- Electron-laser mode: 10<sup>-2</sup>-10<sup>4</sup> e<sup>+</sup>e<sup>-</sup> pairs
- Photon-laser mode: 10<sup>-3</sup>-1 e<sup>+</sup>e<sup>-</sup> pairs

#### Need good background rejection and good linearity

• Silicon pixel tracker and high granularity calorimeter

### TRACKER



#### Four layers of ALPIDE silicon pixel sensors

- Sensors developed for ALICE tracker upgrade
  - Pitch size: 27 x 29 μm<sup>2</sup> => spatial resolution ~5 μm
- •With tracking:
- •Background: <0.1 event per bunch crossing



N. Tal Hod, A. Santra (Weizmann I)

### HIGH GRANULARITY CALORIMETER



- •20 layers of 3.5 mm thick tungsten plates
- Silicon or GaAs sensors (5x5 cm<sup>2</sup> pads, 320 µm thick), Moliére radius 8 mm
- Readout via FLAME ASIC (developed for FCAL)
- Resolutions: ,

Independent measure of energy via position and calorimeter => N<sub>particle</sub>

### **BSM PHYSICS**

- Three ideas being explored at present
  - 1. Use high photon flux from strong-field Compton process for beam dump type experiment => neutral particles that couple to photons (axion-like particles)





*G. Perez, Y. Soreq et al., to be published* 

#### DESY. LUXE

### SENSITIVITY TO AXION-LIKE PARTICLES

#### Photons dumped on beam dump

- Converted to axion-like particles (ALP, ) via Primakoff effect
  - Sensitivity to masses of m(a)~100 MeV
- •ALPs decay to photons after some lifetime  $\boldsymbol{\tau}$



- •Measure energies and angles =>
- •Also determine lifetime by reconstructing decay point
- Could use e.g. calorimeter with good pointing resolution (tbd)
  - E.g. SplitCal by SHiP looks good (JINST 13 (2018), no. 02, C02041)



### SENSITIVITY TO AXION-LIKE PARTICLES

- Sensitivity estimated for 1 year assuming no background
  - This still needs to be verified!!!
- Competitive with other ongoing and planned experiments
  - •e.g. similar to FASER2



### **CONCLUSIONS AND OUTLOOK**

- Exciting opportunity to explore QED in new regime using European XFEL and high power laser
  - Observe transition from perturbative to nonperturbative regime of QED
  - Parasitically use for BSM physics
- Goal is installation in 2024 during extended shutdown planned for European XFEL
  - Conceptual design report will be released within the next week
  - Interesting detector technologies used, optimized for physics goals
  - Reviews starting
- We welcome new collaborators

S. Weinberg (03/2019): "*My* advice is to try crazy ideas and innovative experiments. Something will come up."



## BACKUP

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### **GOALS OF THE LUXE EXPERIMENT**

#### **Probe QED in a new regime**

- Measure interaction of real photons with electrons and photons at or beyond the Schwinger limit, thereby probing a new strongly coupled regime of quantum physics
- Measure non-perturbative production of e<sup>+</sup>e<sup>-</sup> pairs from light
- Make precision measurements of ey and yy interactions in a transition from the perturbative to the non-perturbative regime of QED
- Use strong-field QED process to design sensitive search for new particles beyond the SM that couple to photons

### **SILICON DETECTORS**





#### ALPIDE pixel detectors

- Developed by ALICE collaboration
- Staves of 27 cm length; sensor size 1.5x1.5 cm<sup>2</sup>
- Achieve full coverage with two staves placed next to each other
- •Pixel size: 27 x 29 μm<sup>2</sup> => Spatial resolution ~5 μm
- Plan to use four layers staggered behind each other
- Redundant tracking possible, important for beam background rejection

N. Hod (Weizmann Inst.)

### CALORIMETERS



- 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

### **HIGH-ENERGY PHOTON FLUX**



- Simulation of converter using Geant4
  - Tungsten Target with 0.01  $X_0$  (35 µm) => 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



dN/dE | 10

10

E (GeV)

6

~10%:

#### **PHOTON ENERGY MEASUREMENT**



#### **GENERAL OVERVIEW: XS1 BUILDING**



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## PAIR PRODUCTION PROCESS

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

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

• Pair production in plane wave laser: asymptotic

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

 Good agreement between full calculation and asymptotic result for and







### LUXE PARAMETER SPACE: THEORY VIEW



#### LUXE will probe three different regimes as the laser intensity is varied

- Dedicated teams for calculations and simulations contributing to LUXE
- All results based on custom simulations (A. Hartin, UCL)
  - Cross-checks by other theorists involved ongoing (Gothenburg, Plymouth, Skoltech, MEPHI, Jena)

#### **BSM SENSITIVITY**



**DESY.** LUXE

### **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

#### SNOWMASS SESSION: HIGH FIELD PHYSICS WITH INTENSE ELECTRON AND LASER BEAMS

Contribution list Timetable Oct. 7 <sup>th</sup> 2020						>
		🕂 Print	PDF	Full screen	Detailed view	Filter
13:00	Schwinger field physics				М	ichael Peskin 🥝
	Zoom 20					13:00 - 13:10
	SLAC E-320 experiment	Sebastian Meurer		stian Meuren		
	Zoom 20					13:10 - 13:15
	LUXE experiment				Beat	e Heinemann
	Zoom 20					13:15 - 13:20
	One-sliders					Ø
	Zoom 20					13:20 - 13:23

More interesting issues concern modeling and emergent behavior:

The pairs in the e+e- plasma created by Schwinger fields are produced coherently. What is the effect of this quantum coherence ? Are there prominent plasma modes enhanced by this effect ? Is there nonlinear pattern formation ?

This is an unexplored regime, so we should expect surprises.

Fascinating nonlinear phenomena arise from coherent effects in high-harmonic X-ray generation and from spinodal decomposition in alloys and polymer solutions. Why not here?

Thus, the motivation to explore the  $\chi > 1$  regime is very strong.

M. Peskin

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#### https://indico.fnal.gov/event/44870/sessions/16264/#20201007