LUXE physics case and plans

Matthew Wing (UCL / DESY)
on behalf of LUXE collaborators

- Science motivation
- Overall setup, accelerator and laser
- [Detectors: see next two talks from Maryna and Sasha]
- Outlook and summary
- Summary

35th FCAL Collaboration Meeting — DESY, 19 September 2019

Introduction

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

Letter of Intent for the LUXE Experiment

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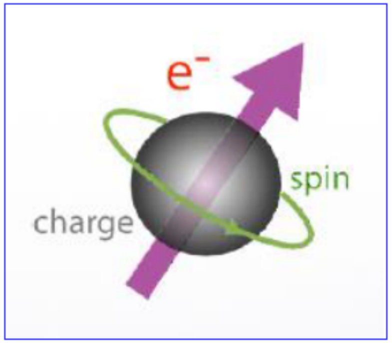
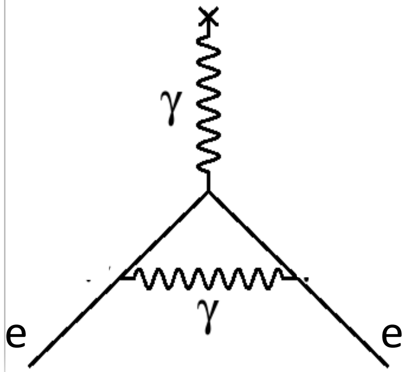
DESY-19-151
arXiv:1909.00860

Science motivation

Reminder: Quantum electrodynamics

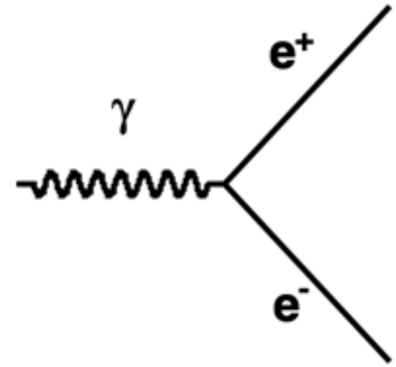


- Relativistic field theory of electrodynamics
- Perturbation theory in terms of coupling constant α
- World's most precisely tested theory
  - Anomalous magnetic dipole moment (*g*−2) of electron:
    - Zero at leading order, first corrections calculated by Schwinger (1947)
    - Based on precise measured and calculated (includes terms of 5th order: α^5) values, extract $1/\alpha = 137.035\ 999\ 084\ (21)$
    - 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

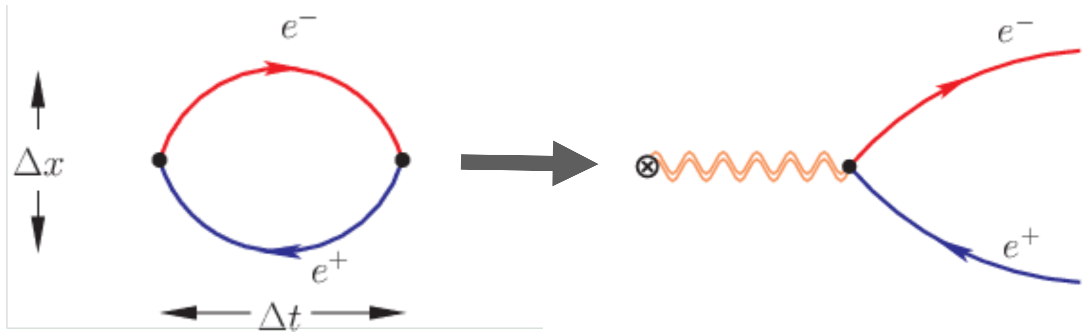
$$E_{\mathrm{crit}} = \frac{mc^2}{e \lambdabar_C} = \frac{m^2 c^3}{e\hbar} = 1.3 \times 10^{16} \ \ \mathrm{V/cm}$$

Why explore strong field QED ?

- Relevant to numerous phenomena in our Universe
  - Astrophysics:
    - Hawking radiation, surface of neutron stars (magnetars), early Universe
  - Condensed matter and atomic physics (nuclei with $Z > 137$)
  - Accelerator physics: high energy e^+e^- colliders
- Main goals:
  - Testing theoretical predictions in novel regime
    - Gain deeper understanding of quantum physics
  - Measure transition from perturbative to non-perturbative regime
    - Could teach us about other non-perturbative regimes, e.g. understanding confinement [Gribov, hep-ph/9902279]
- Schwinger field has never been reached experimentally in clean environment
  - Exciting to be the first to explore this … we might be surprised what we find!

The Schwinger process

J. Schwinger: *On Gauge Invariance and Vacuum Polarization*, Phys. Rev. 82 (1951) 664



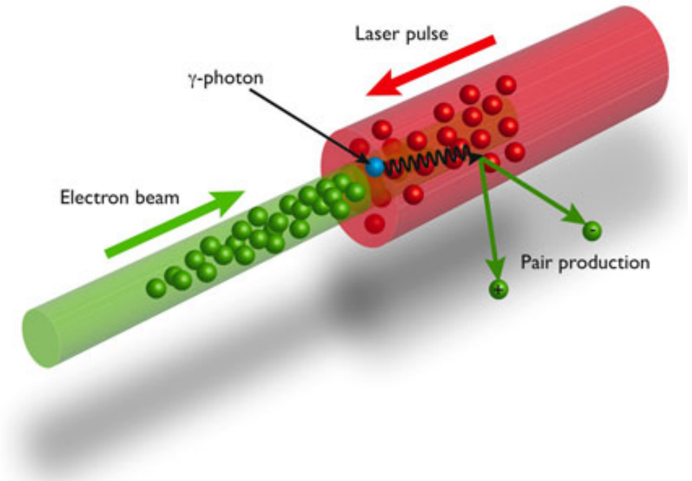
- Simple picture of photon in electric field:
  - The EM force is $F = e\varepsilon$
  - Energy needed to separate e^+e^- pair: $E = F \cdot d_{min}$
  - Heisenberg: $\Delta t \geq \hbar/\Delta E \Rightarrow \Delta t_{min} = \hbar/(2mc^2)$

    $\Rightarrow$ minimum distance: $d_{min} = 2c\Delta t_{min} = \hbar/mc = \lambda_c$
  - Virtual pair becomes real if $E = F \cdot d_{min} = \hbar e\varepsilon/mc > 2mc^2$

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

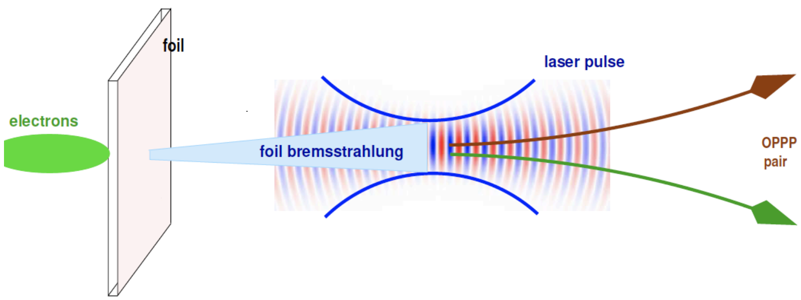
Laser and particle beam interactions

- Use laser to generate electric field
- Use high energy electron beam, also for source of photons



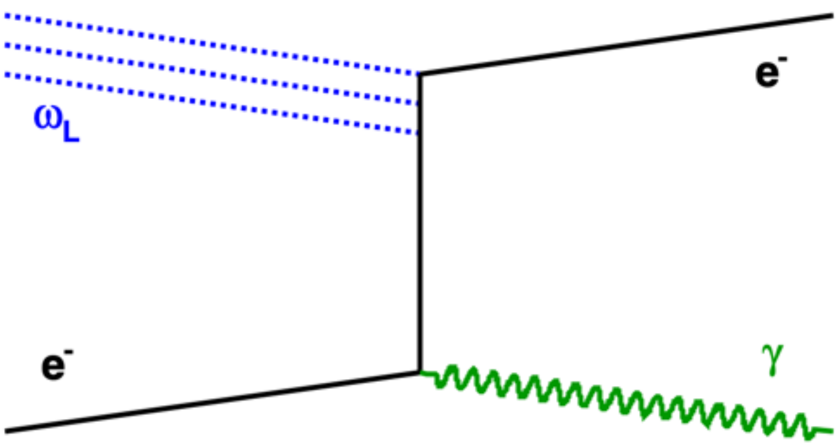
$$\xi = \frac{e\,\epsilon_L}{m_e\,\omega_L\,c} \qquad \chi = \frac{E_{\rm beam}(1-\cos\alpha)}{m_e\,c^2}\frac{\epsilon_L}{\epsilon_{\rm crit}} \sim \gamma_e \frac{\epsilon_L}{\epsilon_{\rm crit}}$$

- Laser power required to reach Schwinger field (*χ ~ 1*):
  - Raw laser intensity, *I = 2×10*^{29} *W/cm*^{2}
    - Way beyond current technology
  - EU.XFEL, $E_e \approx$ *10 GeV*: *I ≈ 10*^{20} *W/cm*^{2}
    - Use well-test laser technology
  - ELI-NP, $E_e \approx$ *1 GeV*: *I ≈ 10*^{22} *W/cm*^{2}
    - State-of the art laser needed

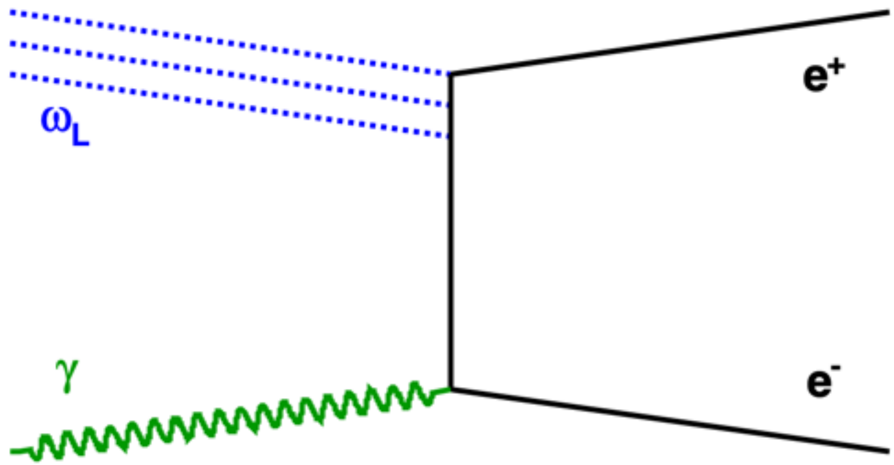


Main processes of interest

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



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



- High energy electron or photon interacts with laser
  - Also higher order processes $e^- + n\omega_L \to e^-e^+e^-$
  - Via two steps ($e^- + n\omega_L \to e^- + \gamma$ and then $\gamma + n\omega_L \to e^+e^-$) or one step

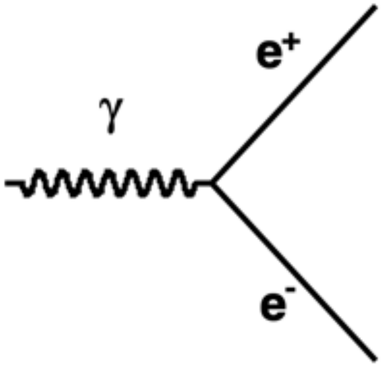
Cross section for QED processes

- In perturbative QED
  - For n photons, $\sigma \sim \alpha^n$
  - With $\alpha \sim e^2 \sim \xi^2$, it follows: $\sigma \sim \xi^{2n}$
- If $\xi \gtrsim 1$ all orders can contribute ~equally $\Rightarrow$ cannot truncate series
  - All-order calculation needs to be performed (hard)
- Example for asymptotic result for $\xi \gg 1$ and $\chi < 1$: $\sigma \sim \chi e^{-8/(3\chi)}$
  - Since $\chi \sim \sqrt{\alpha}$ cannot expand perturbatively
  - Result not proportional to powers of α

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

Pair production process

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

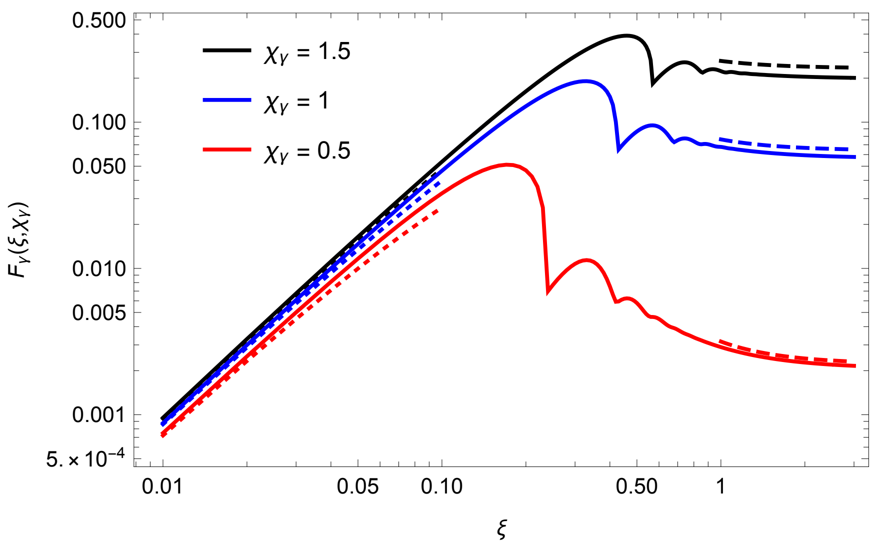


$$\Gamma_{\mathrm{SPP}} \propto \exp\left(-\pi \frac{m_e^2}{e|\mathbf{E}|}\right)$$

- Pair production in plane wave laser: asymptotic result

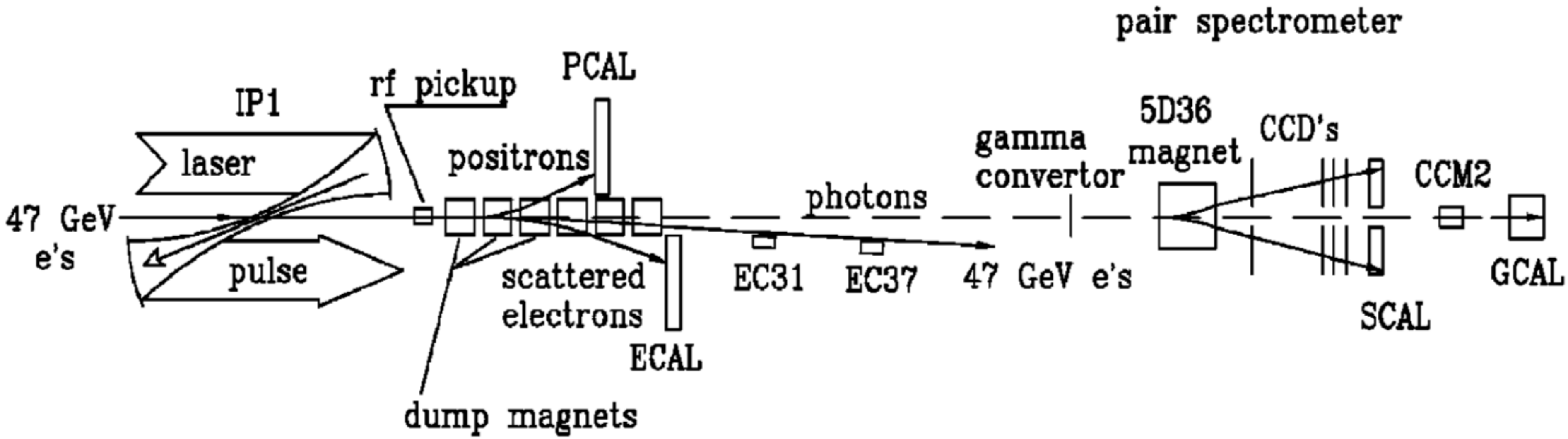
$$\Gamma_{\mathrm{OPPP}} \to \frac{3}{16}\sqrt{\frac{3}{2}}\,\alpha\, m_e\,(1+\cos\theta)\;\frac{|\mathbf{E}|}{\mathrm{E}_c}\exp\left[-\frac{8}{3}\frac{1}{1+\cos\theta}\frac{m_e}{\omega_i}\frac{\mathrm{E}_c}{|\mathbf{E}|}\right]$$

- Good agreement between full calculation and asymptotic result for *ξ « 1* and *ξ > 1*



A. Hartin, A. Ringwald, N. Tapia,
Phys. Rev. **D 99** (2019) 036008

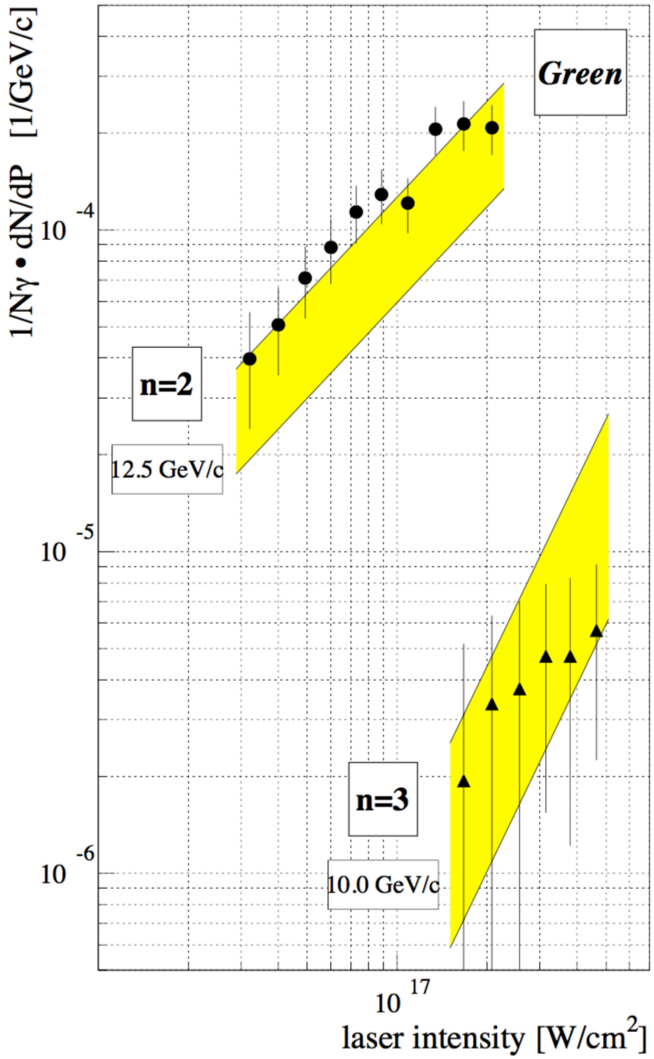
E144 experiment at SLAC

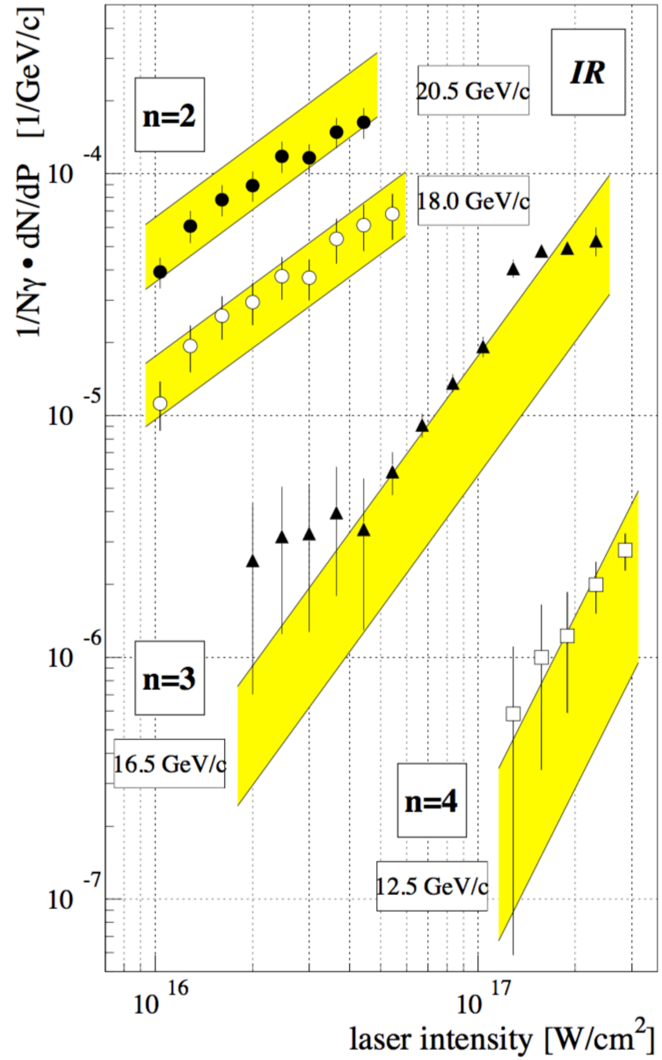


- Used *46.6 GeV* electron beam (Final Focus Test Beam) with 5×10^{9} electrons per bunch up to *30 Hz*.
- Terawatt laser pulses with intensities of $\sim 0.5 \times 10^{18}\ W/cm^{2}$ and frequency of *0.5 Hz* for wavelengths *1053 nm* and *527 nm*.
- Electron bunch and laser collided with 17° crossing angle.

E144 Coll., C. Bamber et al., Phys. Rev. **D 60** (1999) 092004;
T. Koffas, "Positron production in multiphoton light-by-light scattering", PhD thesis, University of Rochester (1998), SLAC-R-626.

E144 experiment results



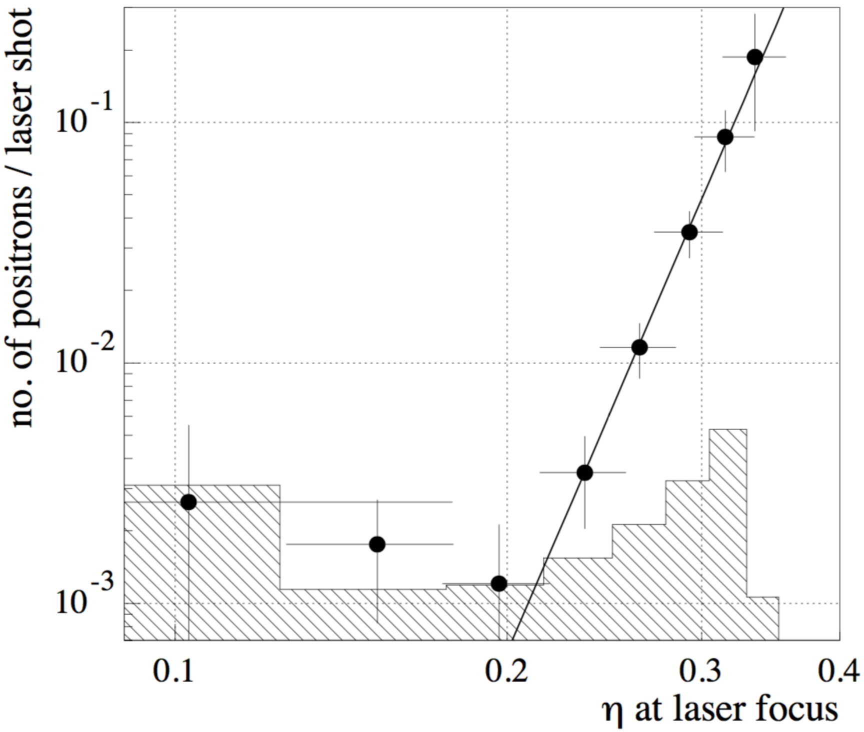


Data on non-linear Compton scattering compared to simulation

E144 experiment results

E144 achieved $\xi < 0.4$ and $\chi < 0.25$

- Measured non-linear Compton scattering with $n = 4$ photons absorbed and pair production with $n = 5$ photons absorbed
- **Observed strong rise ~ ξ^{2n} but not asymptotic limit**
- Measurements well described by theory
- Large uncertainty on the laser intensity
- **Did not achieve the critical field**



E144 in the news

DIE ZEIT WISSEN
Nr. 42 17. Oktober 1997. Seite 17

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

Warum ist etwas?

Amerikanische Physiker schufen erstmals Materie aus reinem Licht

Von Ulrich Schnabel

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 energy to do it.

Dr. Adrian C. Melissinos of the University of Rochester, a spokesman for the group, said in an interview that the weaker of the two light beams used in the experiment was produced by a trillion-watt green laser. That in itself fell far short of the needed energy, even tho... most powerful.

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

The paths of colliding electron... complicated as those choreogr...

RESEARCH NEWS PHYSICS

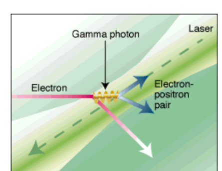
Conjuring Matter From Light

David Ehrenstein
+ See all authors and affiliations

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

Article Figures & Data Info & Metrics

Turning matter into light, heat, and other forms of energy is n... nuclear bombs spectacularly demonstrate. Now a team of ph... Stanford Linear Accelerator Center (SLAC) has demonstrated... process—what University of Rochester physicist Adrian Melis... spokesperson for the group, calls "the first creation of matter... the 1 September *Physical Review Letters*, the researchers des... collided large crowds of photons together so violently that th... spawned particles of matter and antimatter: electrons and p... (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.

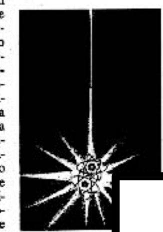
Come spiegavano i libri di testo, se si opera uno scontro frontale fra un elettrone e un anti-elettrone, si provoca una reciproca annichilazione della particella di materia con quella di anti-materia. Il risultato del drammatico incontro consiste in un paio di fotoni o particelle di luce, che si allontanano 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 energici, 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, situata nella frequenza del visibile, a raggi gamma di rimbalzo 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 una ventina 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 allineare e sincronizzare con la massima precisione sia gli impulsi laser iniziali sia gli impulsi degli elettroni accelerati. Ma, come recita un detto locale, le cose ...



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.

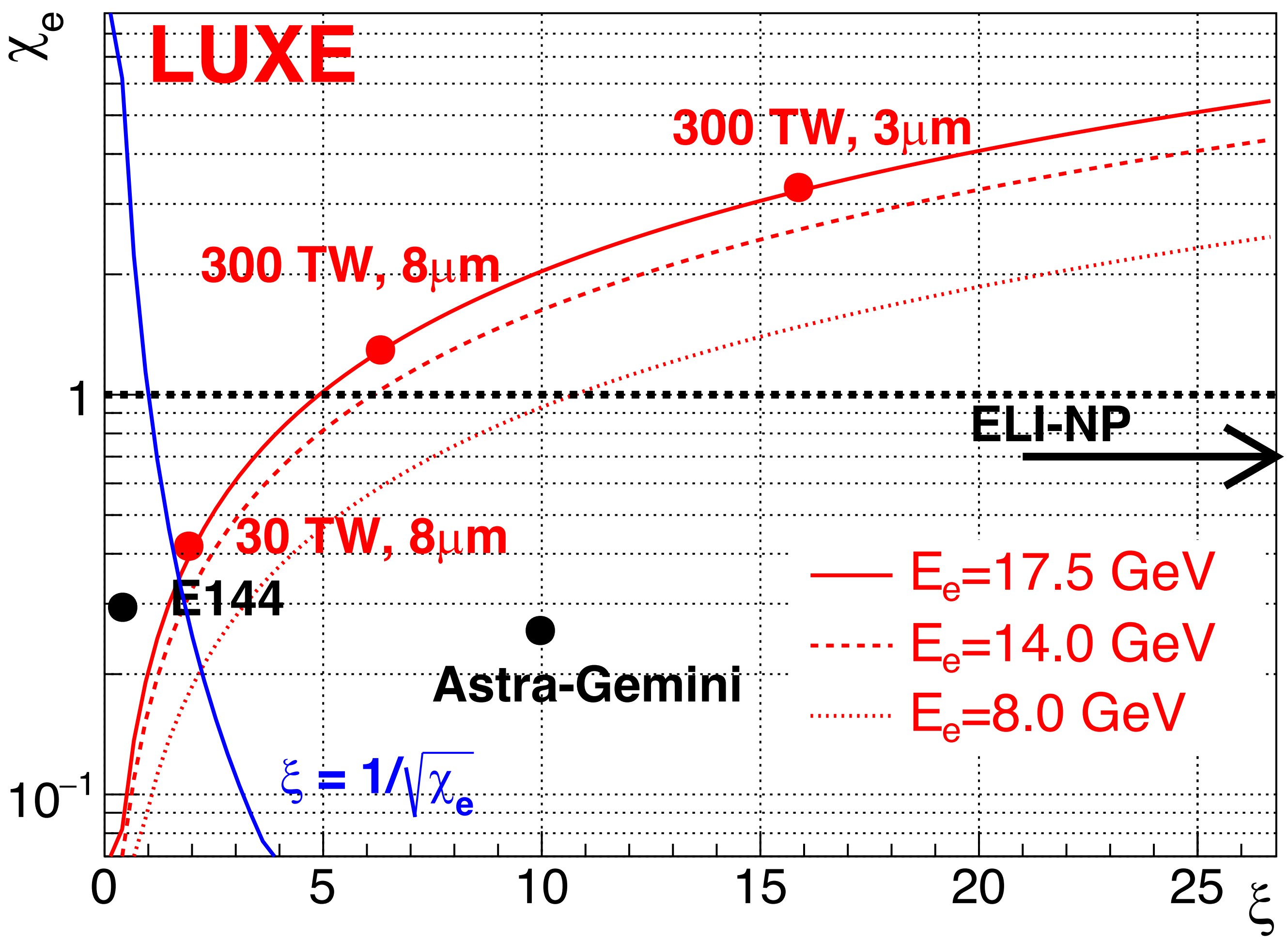
Die Umwandlung von Materie in Licht oder andere Energieformen ist nichts Neues. Ein besonders zerstörerisches Beispiel dafür sind Atombomben. Aber auch bei der Kernspaltung in ...

Die Physiker führten eine Serie derartiger Experimente durch, die mehrere Monate dauerten. Sie analysierten danach Tausende von Kollisionen und fanden dabei mehr als hundert der gesuchten Ereignisse ...

Laser gegen Elektronenstrahl

Erkenntnisse für Astronomie

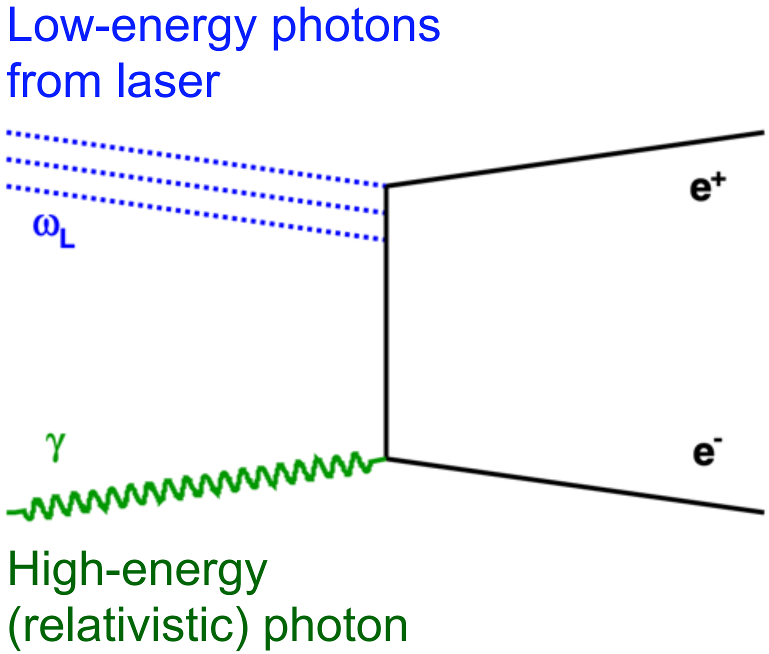
Parameter space

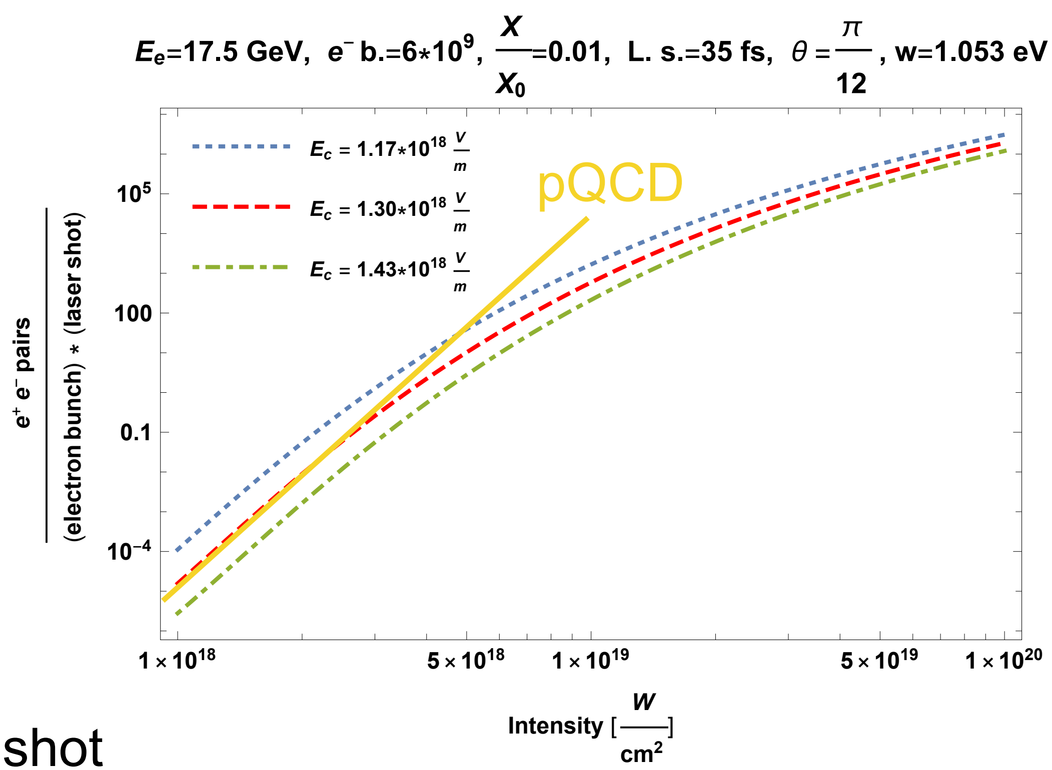


$$\xi = \frac{e\,\epsilon_L}{m_e\,\omega_L\,c}$$

$$\chi_i = \frac{E_i(1-\cos\alpha)}{m_e\,c^2}\,\frac{\epsilon_L}{\epsilon_{\rm crit}}$$

Absorbing light with light





Prediction for rate of positrons per shot

$\xi \ll 1 \quad : \quad R_{e^+} \propto \xi^{2n} \propto I^n$ Perturbative regime: strong rise, follows power-law

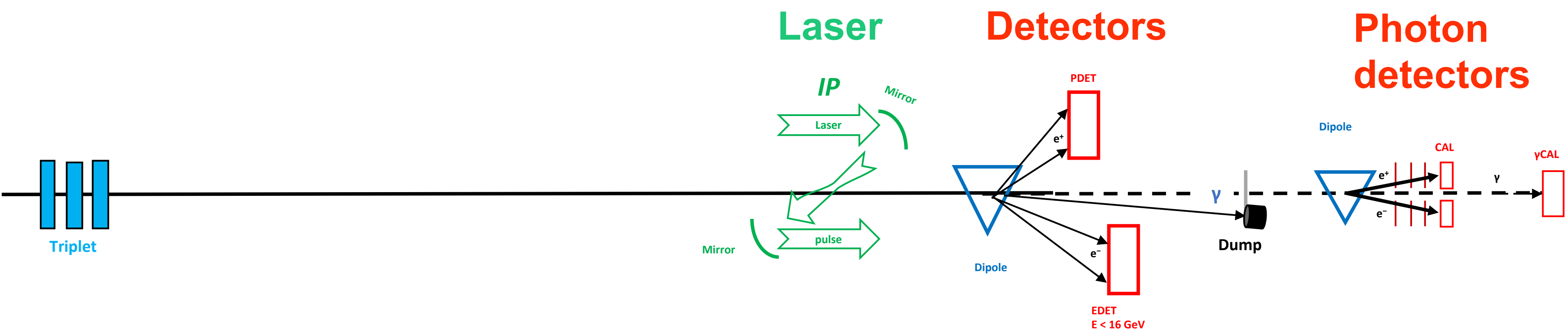
$\xi \gg 1 \quad : \quad R_{e^+} \propto \chi \exp(-8/(3\,\chi))$ Non-perturbative regime: departure from power-law

A. Hartin, A. Ringwald, N. Tapia,
Phys. Rev. **D 99** (2019) 036008

Overall setup, accelerator and laser

Electron–laser collisions

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



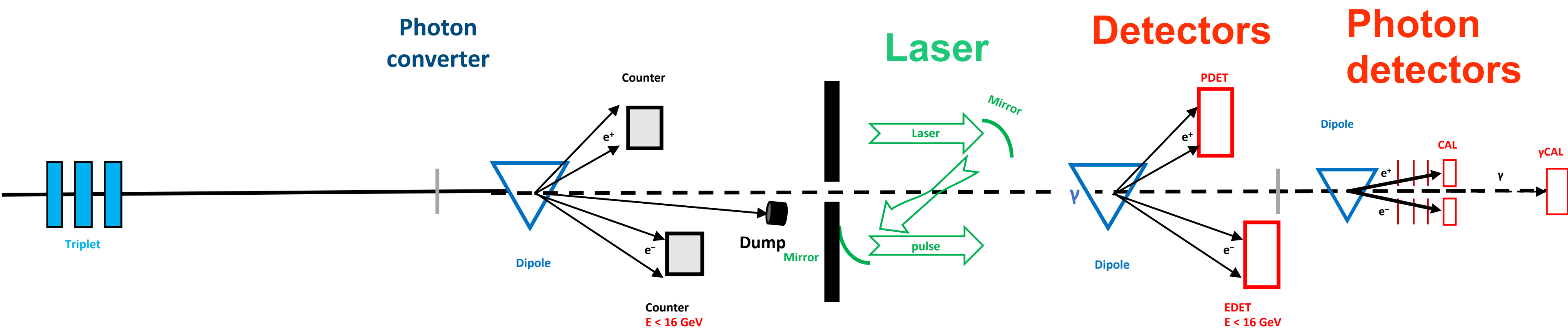
Dipole and detectors to measure $e^{+}e^{-}$ pairs

Kicker and triplet to select single bunch and focus it

Electron–laser interaction area

Photon–laser collisions

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



Dipole and detectors to remove $e^{+}e^{-}$ pairs and monitor photon flux

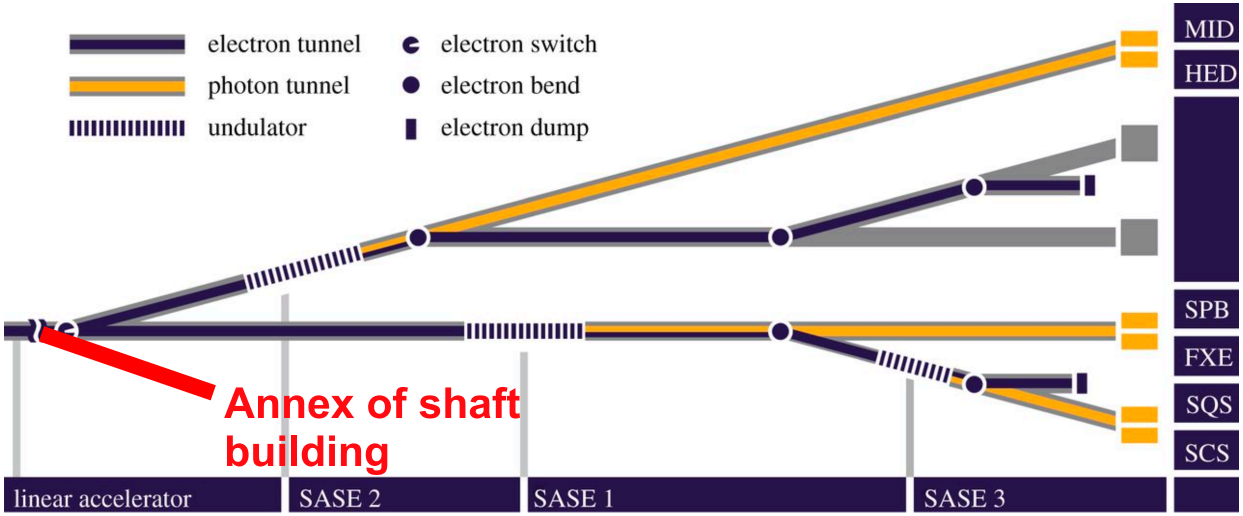
Dipole and detectors to measure $e^{+}e^{-}$ pairs

Kicker and triplet to select single bunch and focus it

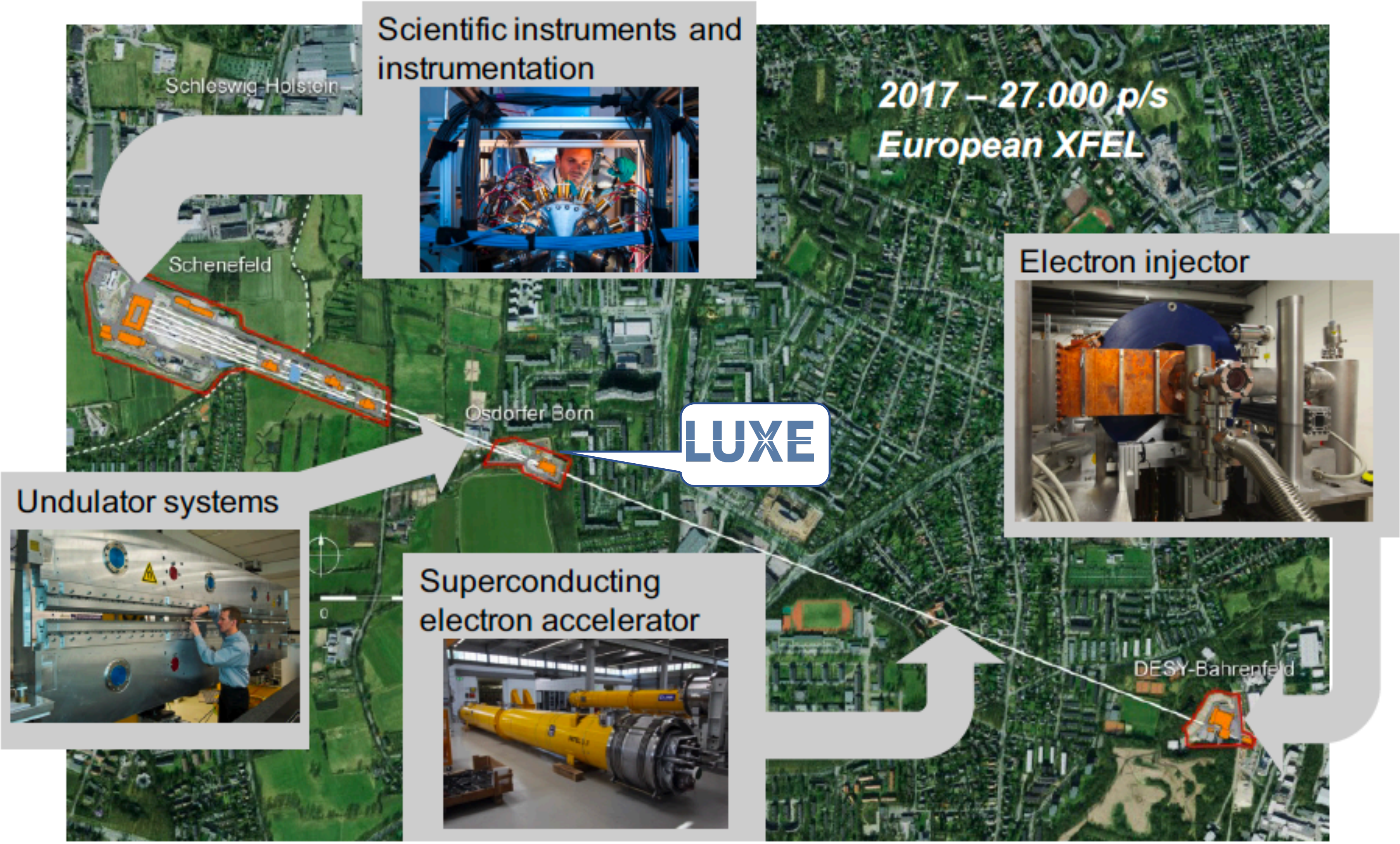
Photon–laser interaction area

Locations in the EU.XFEL tunnel

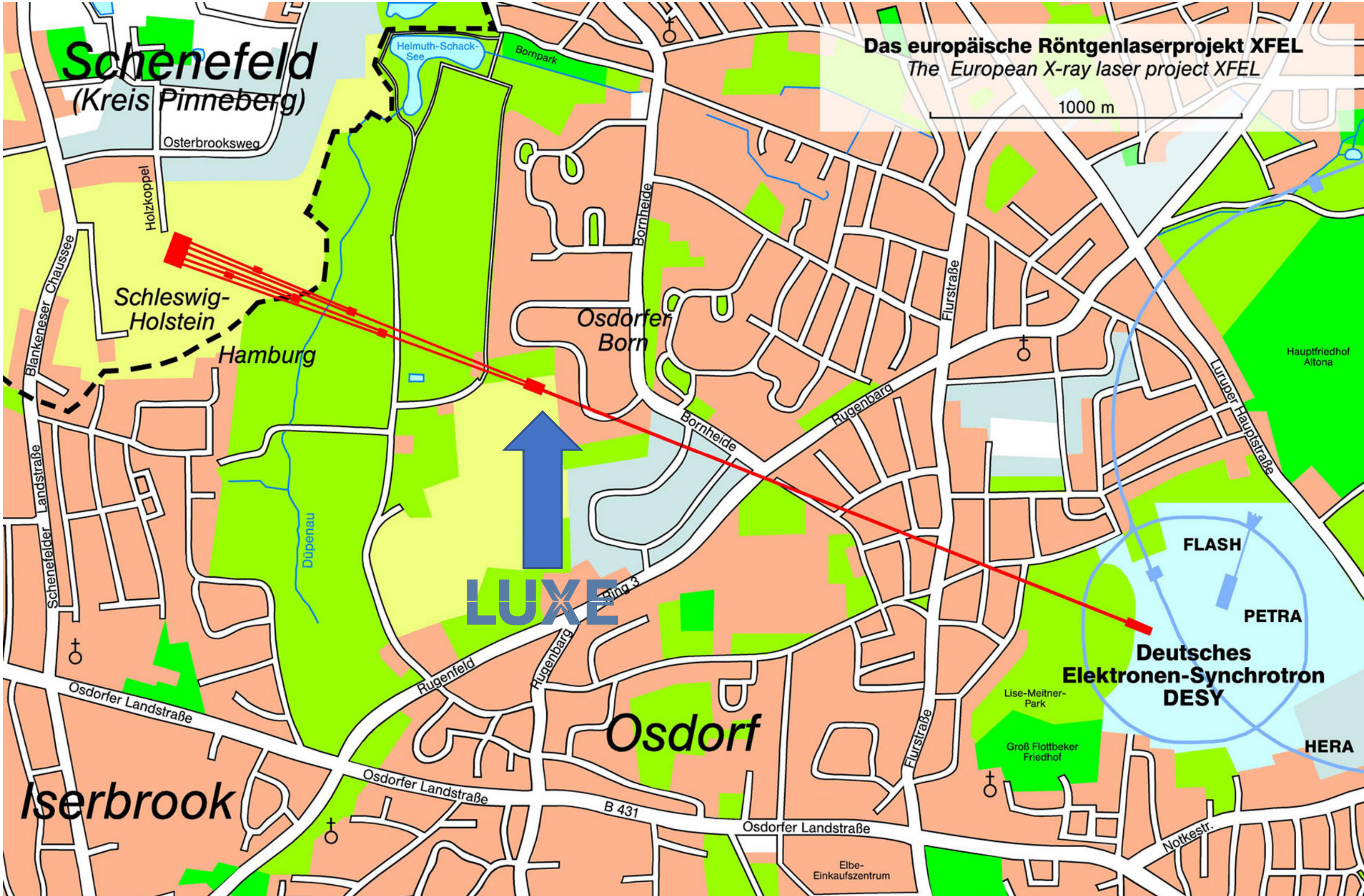
- Location at EU.XFEL:
  - Annex of shaft building XS1: at end of electron accelerator
  - Was built for 2nd EU.XFEL fan foreseen for later (late 2020s)
- Design aims to have no impact on photon science programme
  - Use only 1 of the 2700 bunches in bunch train (kicked out by fast kicker magnet)



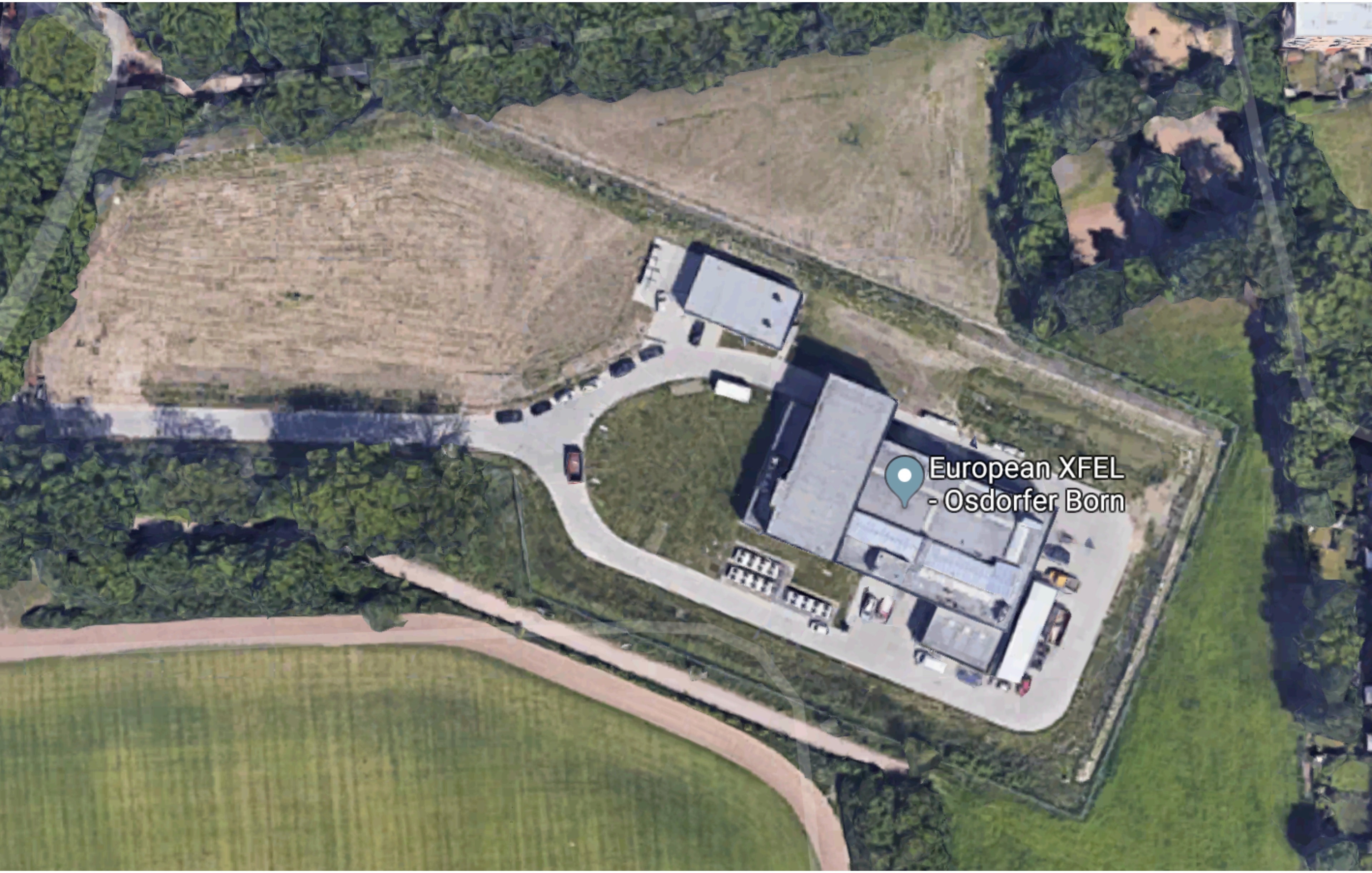
Location


Scientific instruments and instrumentation
Schleswig-Holstein
2017 – 27.000 p/s
European XFEL
Schenefeld
Electron injector
Osdorfer Born
LUXE
Undulator systems
Superconducting electron accelerator
DESY-Bahrenfeld

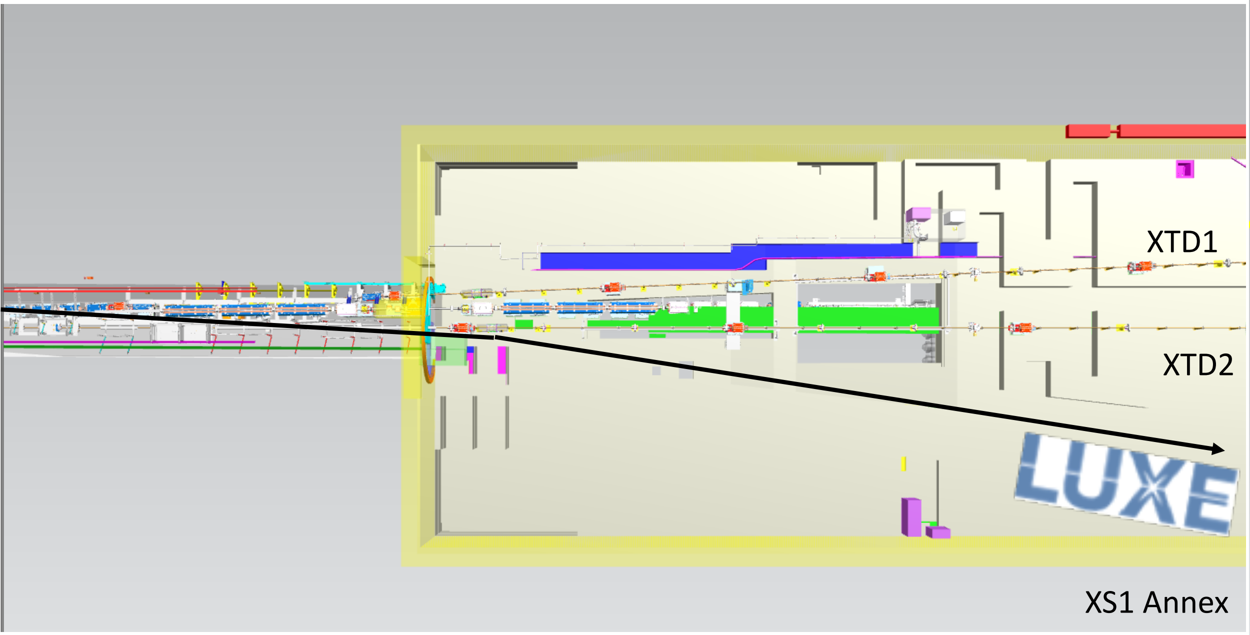
Location

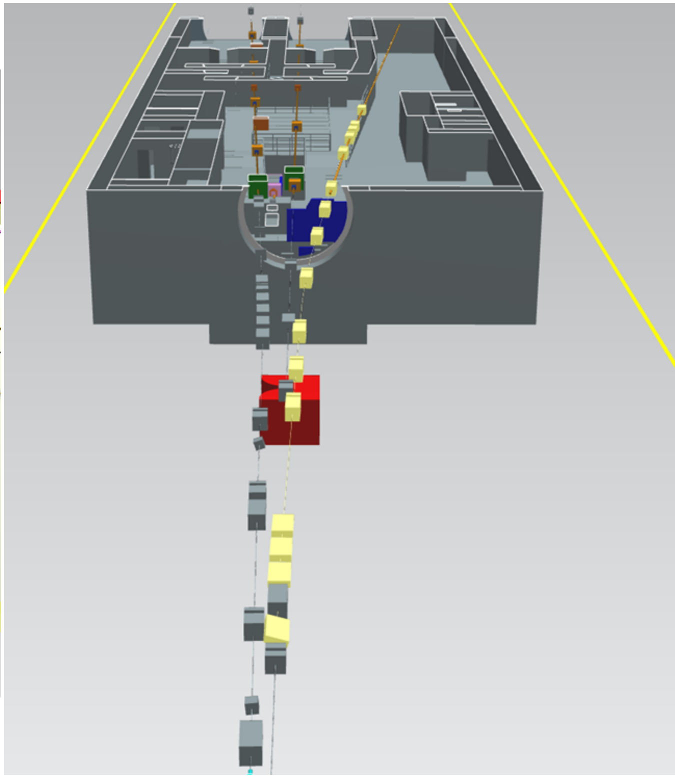

Das europäische Röntgenlaserprojekt XFEL
The European X-ray laser project XFEL
1000 m
Schenefeld
(Kreis Pinneberg)
Osterbrooksweg
Holzkoppel
Helmuth-Schack-See
Bornpark
Schleswig-Holstein
Hamburg
Blankeneser Chaussee
Osdorfer Born
Bornheide
Flurstraße
Rugenbarg
Luruper Hauptstraße
Hauptfriedhof Altona
Düpenau
LUXE
Ring 3
Rugenfeld
FLASH
PETRA
Deutsches Elektronen-Synchrotron DESY
HERA
Lise-Meitner-Park
Groß Flottbeker Friedhof
Schenefelder Landstraße
Osdorfer Landstraße
Osdorf
Iserbrook
B 431
Notkestr.
Elbe-Einkaufszentrum

Location



Schematic view: beam extraction and transfer



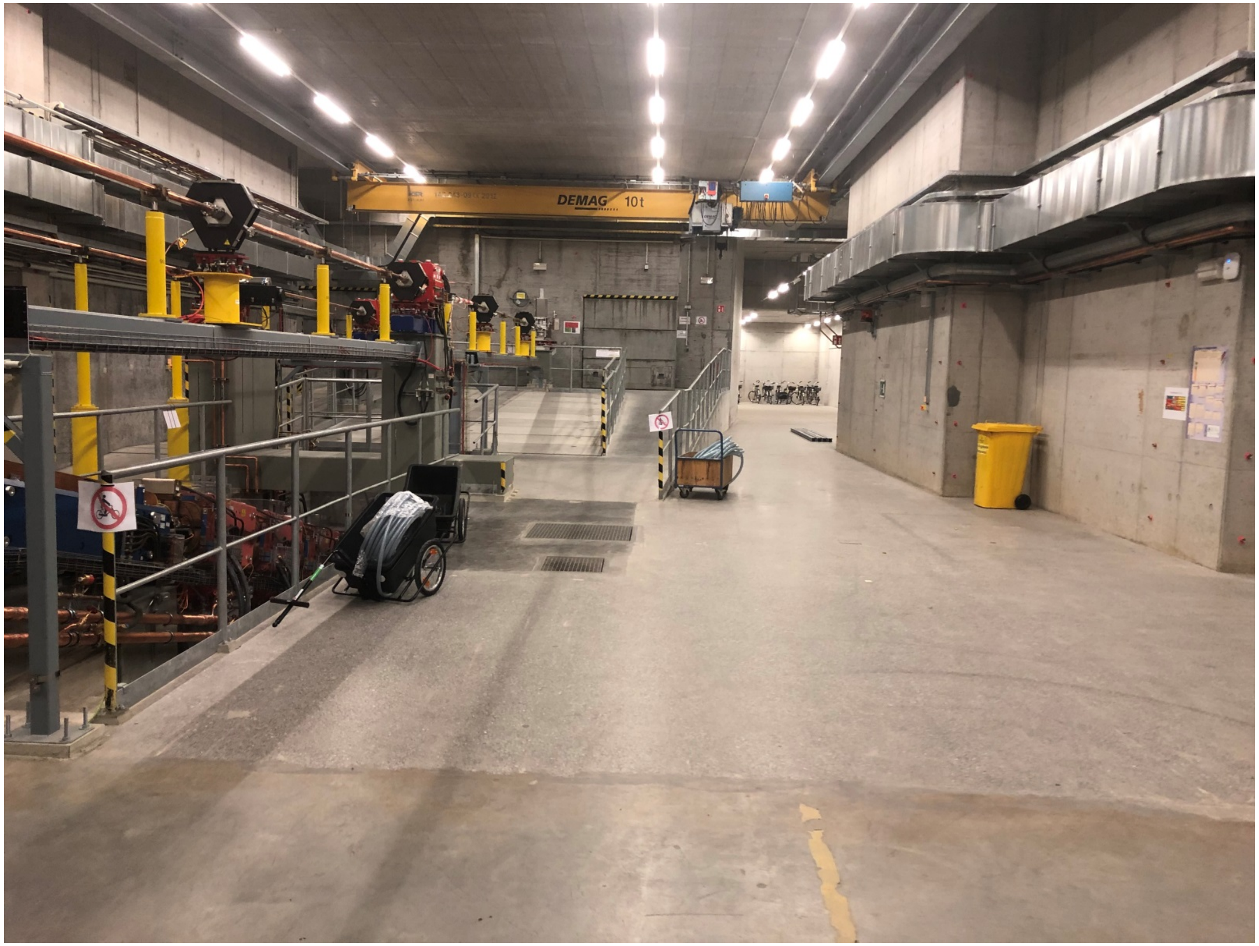


XS1 annex area

Shaft located at end of linear accelerator of European XFEL

Annex dimensions:

- 60 m long
- 5.4 m wide
- 5 m high

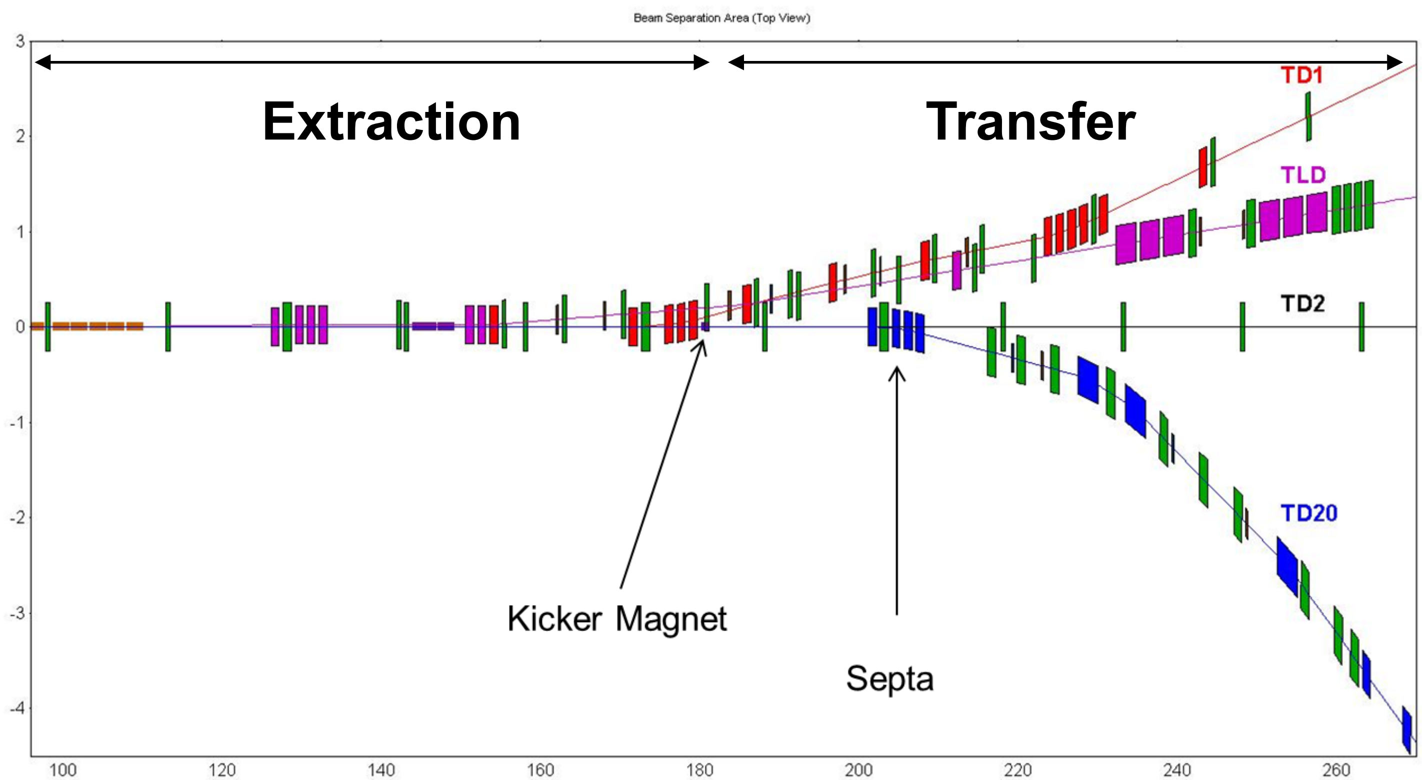


Beamline layout

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

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

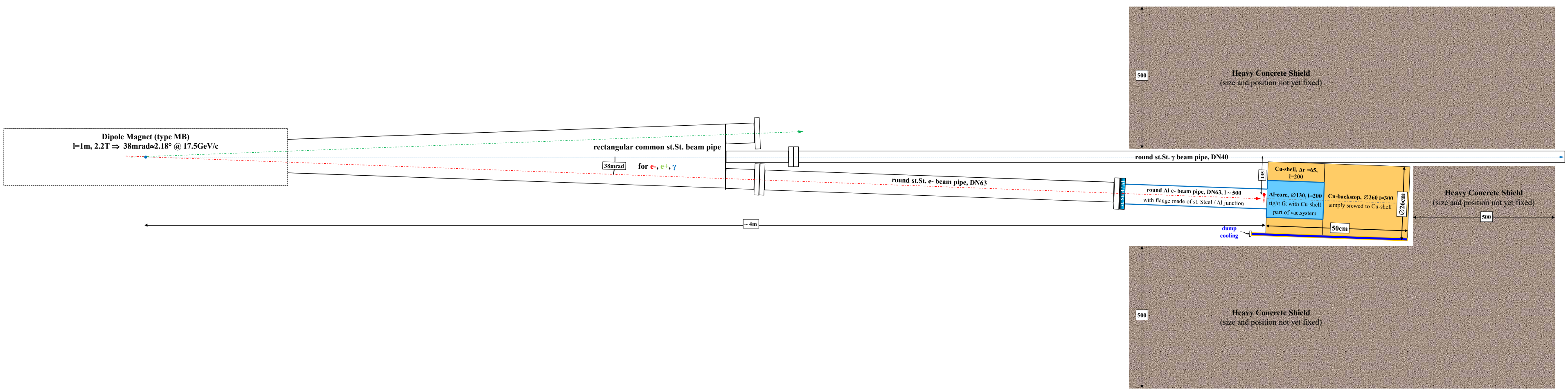
Installation requires: 5 weeks for extraction; 7 weeks for transfer line



F. Burkart, W. Decking

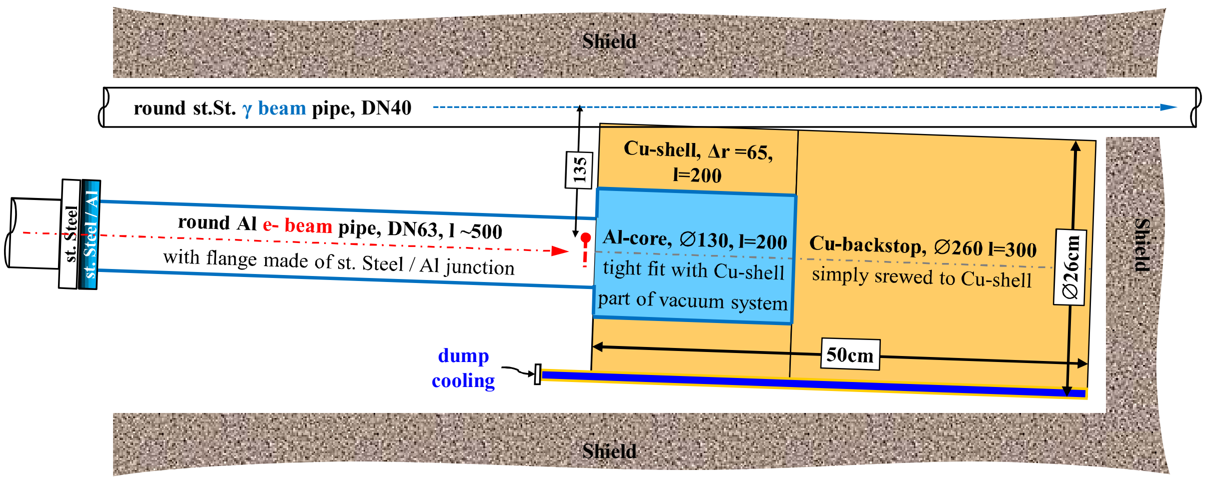
Beam dump

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



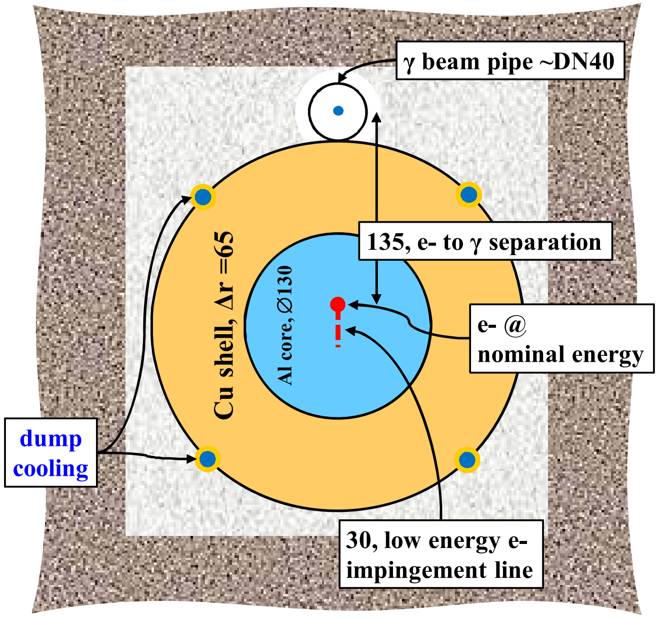
Beam dump

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



Longitudinal Cut

lenghts without units are in mm



Front View

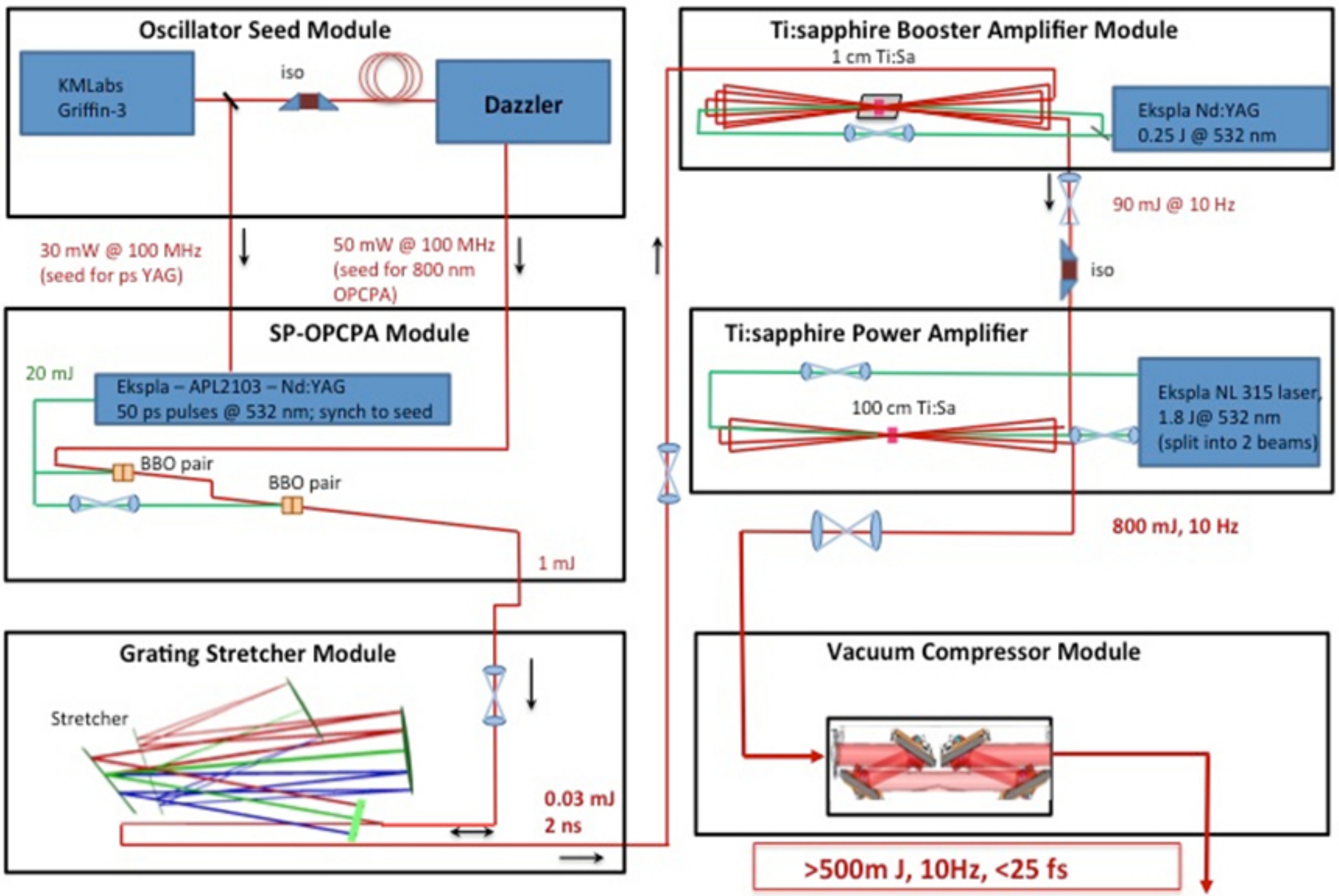
lenghts without units are in mm

Laser beam

Parameter	Initial	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: **E_e = 17.5 GeV** **E_e = 14.0 GeV**	 **0.41** **0.32**	 **1.3** **1.0**	 **3.3** **2.6**

Lower intensities achieved by de-focussing laser or stretching pulse

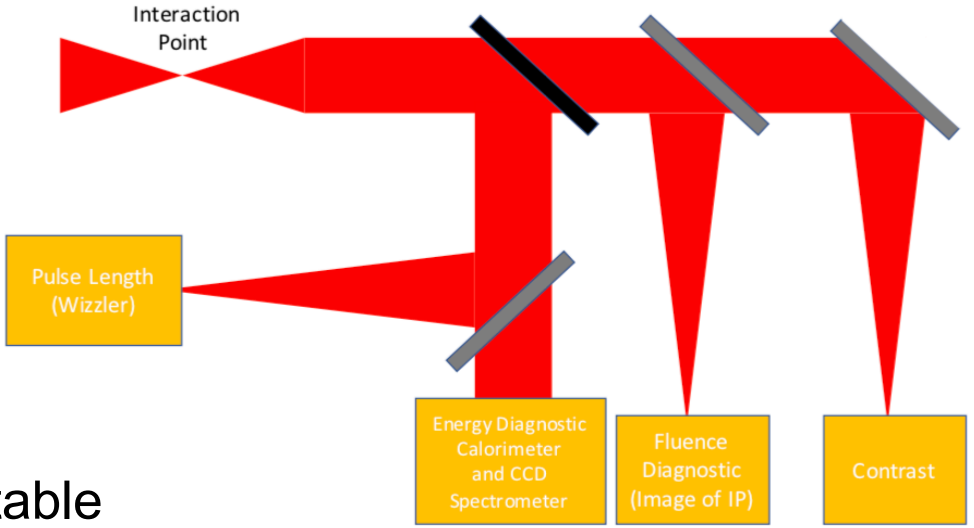
Laser design



I. Pomerantz, G. Sarri,
M. Zepf 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



Tentative time scale

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

Summary

- LUXE is an experiment to test what happens when high energy electrons or photons observe an intense laser field.
- LUXE will probe quantum physics in new regime of high intensity QED using a tiny 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 37 scientists (12 institutions from 4 countries) performed feasibility study.
  - Release a “Letter of Intent” on the arXiv.

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)

Thanks to Beate Heinemann whose seminar slides I used