Tests of non-linear QED in the collision of electron beams with laser beams

Andreas Ringwald
in collaboration/discussion with
Paola Arias (DESY), Holger Gies (Jena), Axel Lindner (DESY),
Gerhard Paulus (Jena), Javier Redondo (Munich), Andreas Wipf (Jena)

470. WE-Heraeus-Seminar on
Particle Accelerators and High Intensity Lasers
Physikzentrum, Bad Honnef/D, December 13–17, 2010

Motivation

- **Spontaneous pair creation from vacuum**, induced by an **external field**, was first proposed in the context of e^+e^- **pair creation in static, spatially uniform electric field** [Sauter (1931); Heisenberg,Euler (1936); Schwinger (1951); . . .]

  One of the most intriguing non-linear phenomena in quantum field theory
  - theoretically important: beyond perturbation theory
  - eventual experimental observation: probes theory in domain of very strong fields

- Mechanism applied to many problems in contemporary physics:
  - quantum evaporation of black holes [Hawking (1975); Damour,Ruffini (1976); . . .]
  - e^+e^- creation in vicinity of charged black holes [Damour,Ruffini '75; . . .]
  - particle production in early universe [Parker (1969); . . .]
  - particle production in hadronic collisions [Casher, Neuberger, Nussinov (1979); . . .]

- Vacuum in **QED** unstable in a static, spatially uniform electric background field:

⇒ sparks with spontaneous emission of e^+e^- pairs

– observable rate requires extraordinary strong electric field strength, of order

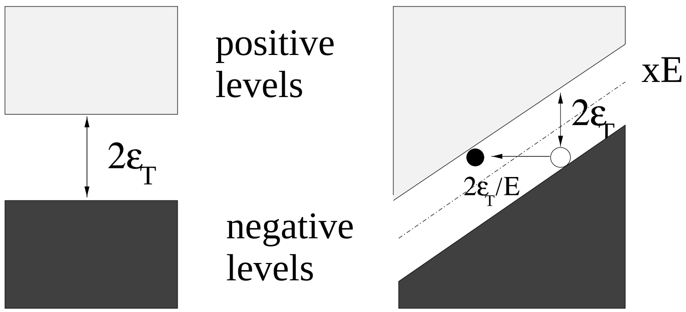
$$\mathcal{E}_c \equiv \frac{m_e\, c^2}{e\, \lambda\!\!\!^{-}_e} = \frac{m_e^2\, c^3}{e\, \hbar} = 1.3 \cdot 10^{18}\ \frac{\mathrm{V}}{\mathrm{m}}$$

[Sauter (1931); Heisenberg, Euler (1936)]

such that

work of field on unit charge e over Compton wavelength $\lambda\!\!\!^{-}_e$	$\approx$	rest energy of e^+e^- pair
$e\, \lambda\!\!\!^{-}_e\, \mathcal{E}_c$	$=$	$m_e\, c^2$

- For $\mathcal{E} \ll \mathcal{E}_c$: [Schwinger (1951)]
  - pair creation: **tunneling**
  - rate: **non-perturbative; exponentially suppressed,**



$$w = \frac{d^4 n_{e^+e^-}}{d^3x\, dt} \propto \exp\left[-\pi \frac{\mathcal{E}_c}{\mathcal{E}}\right] = \exp\left[-\pi \frac{m_e^2 c^3}{\hbar\, e\, \mathcal{E}}\right]$$

- No human-made macroscopic static fields of order $\mathcal{E}_c$ accessible
- Proposals (in early 1970's):
  - critical fields in **nuclear collisions with** $Z_1 + Z_2 \approx 1/\alpha$?

    [Zel'dovich, Popov (1971); Müller, Rafelski, Greiner (1972)]
  - critical fields **at focus**[1] **or at overlap of crossed**[1] **intense lasers**?

    [Bunkin, Tugov (1969); Brezin, Itzykson (1970); Popov (1971);...; Fried *et al.* (2001)]

[1]No pair creation in plane wave.

Pair creation in overlap of crossed laser beams

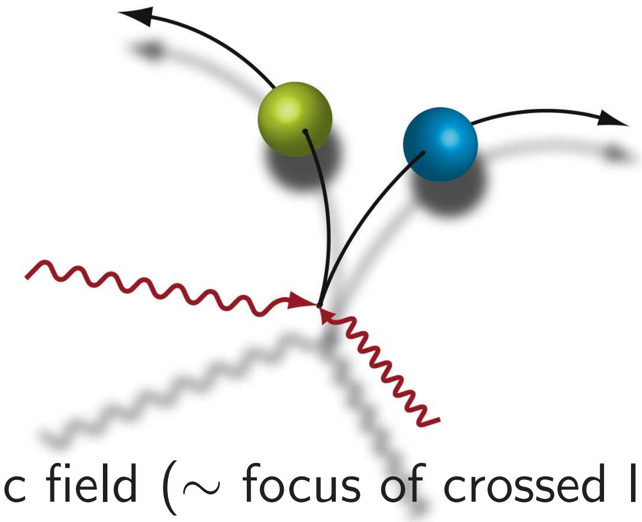


Illustration from [Marklund,Lundin '08]

- In alternating electric field ($\sim$ focus of crossed laser beam)[2],

$$\mathcal{E} \ll \mathcal{E}_c = \frac{m_e^2\, c^3}{e\, \hbar}, \qquad\qquad \hbar\,\omega \ll m_e c^2,$$

rate of spontaneous e^+e^- creation calculable in **semi-classical** manner

[Brezin,Itzykson (1970), Popov (1971)];...]

[2]For more realistic calculation ⇒ talk by Carsten Müller

$$w \equiv \frac{\mathrm{d}^4 n_{e^+e^-}}{\mathrm{d}^3x\,\mathrm{d}t} \simeq \frac{c}{4\,\pi^3 {\lambda\!\!\!^-_e}^4} \times$$

$$\times \begin{cases} \frac{\sqrt{2}}{\pi}\left(\frac{\mathcal{E}}{\mathcal{E}_c}\right)^{\frac{5}{2}} \exp\left[-\pi\,\frac{\mathcal{E}_c}{\mathcal{E}}\left(1-\frac{1}{8}\eta^{-2}+\mathcal{O}(\eta^{-4})\right)\right], & : \quad \eta \gg 1\,, \\ \sqrt{\frac{\pi}{2}}\left(\frac{\hbar\,\omega}{m_e c^2}\right)^{\frac{5}{2}} \sum_{n>2\frac{m_e c^2}{\hbar\omega}} \left(\frac{\mathrm{e}\,\eta}{4}\right)^{2n} \mathrm{e}^{-2\left(n-2\frac{m_e c^2}{\hbar\omega}\right)} \mathrm{Erfi}\left(\sqrt{2\left(n-2\frac{m_e c^2}{\hbar\omega}\right)}\right) & : \quad \eta \ll 1\,, \end{cases}$$

- Dimensionless adiabaticity parameter $\eta\ (\equiv a_0)$,

$$\eta \equiv \frac{e\,\mathcal{E}\,\lambda\!\!\!^-_e}{\hbar\,\omega} = \frac{e\,\mathcal{E}}{m_e c\,\omega}$$

  – **$\eta \gg 1$:** Adiabatic high-field, low-frequency limit agrees with **non-perturbative Schwinger result** for a static, spatially uniform field.
  – **$\eta \ll 1$:** Non-adiabatic low-field, high-frequency limit resembles **perturbative result:** corresponds to $\geq n$-th order perturbation theory, n being the minimum number of quanta required to create an e^+e^- pair: $n \gtrsim 2\,m_e c^2/(\hbar\omega) \gg 1$

- Laser parameters:

Laser parameter				
		Optical	**XFEL**	
		focus: **state-of-art**	design **SASE 5**	focus: **state-of-art**
wavelength	λ	1 μm	0.4 nm	0.4 nm
photon energy	$\hbar\,\omega = \frac{hc}{\lambda}$	1.2 eV	3.1 keV	3.1 keV
max. power	P	1 PW	110 GW	1.1 GW
spot radius (rms)	σ	1 μm	26 μm	21 nm
coherent spike length (rms)	$\triangle t$	500 fs ÷ 20 ps	0.04 fs	0.04 fs
derived quantities				
max. power density	$S = \frac{P}{\pi\sigma^2}$	$3 \cdot 10^{22}\ \frac{\rm W}{\rm cm^2}$	$5 \cdot 10^{15}\ \frac{\rm W}{\rm cm^2}$	$8 \cdot 10^{19}\ \frac{\rm W}{\rm cm^2}$
max. electric field	$\mathcal{E} = \sqrt{\mu_0\, c\, S}$	$4 \cdot 10^{14}\ \frac{\rm V}{\rm m}$	$1 \cdot 10^{11}\ \frac{\rm V}{\rm m}$	$2 \cdot 10^{13}\ \frac{\rm V}{\rm m}$
max. electric field/critical field	$\mathcal{E}/\mathcal{E}_c$	$3 \cdot 10^{-4}$	$1 \cdot 10^{-7}$	$1 \cdot 10^{-5}$
photon energy/e-rest energy	$\frac{\hbar\omega}{m_e c^2}$	$2 \cdot 10^{-6}$	0.006	0.006
adiabaticity parameter	$\eta = \frac{e\,\mathcal{E}\,\lambda\!\!\!^{-}_e}{\hbar\omega}$	$1 \cdot 10^{2}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-3}$

- Minimum necessary peak power for observable effect: [AR (2001)]

	λ	σ	$\triangle t$	$P_{\rm min}$	$S_{\rm min}$	$\mathcal{E}_{\rm min}$
Focused XFEL:	0.1 nm	0.1 nm	0.1 ps	2.5 TW	$7.8 \cdot 10^{27}$ W/cm^2	$1.7 \cdot 10^{17}$ V/m
(≈ "aim")	0.1 nm	0.1 nm	0.1 fs	4.5 TW	$1.4 \cdot 10^{28}$ W/cm^2	$2.3 \cdot 10^{17}$ V/m
Focused XFEL:	0.1 nm	20 nm	0.1 ps	38 PW	$3.0 \cdot 10^{27}$ W/cm^2	$1.1 \cdot 10^{17}$ V/m
(≈ "state-of-art")	0.1 nm	20 nm	0.1 fs	55 PW	$4.3 \cdot 10^{27}$ W/cm^2	$1.3 \cdot 10^{17}$ V/m
Focused optical laser:	1 μm	1 μm	10 ps	49 EW	$1.6 \cdot 10^{27}$ W/cm^2	$7.7 \cdot 10^{16}$ V/m
diffraction limit	1 μm	1 μm	100 fs	58 EW	$1.8 \cdot 10^{27}$ W/cm^2	$8.3 \cdot 10^{16}$ V/m

$\Rightarrow$ Need **tens of EW optical laser** or **TW X-ray FEL**

$\Leftarrow$ Power densities and electric fiels that can be reached with presently available techniques far too small for observable effect (cf. extra table)

- Conceivable **improvements** in **XFEL** technology:
  – X-ray optics, in order to approach diffraction limit $\sigma \gtrsim \lambda$
  – energy extraction, in order to increase power
- Hard to predict whether this goal will be reached before the commissioning of EW-ZW optical lasers ($\gtrsim 2020$?).

Pair creation in overlap of electron beam crossed with laser beam

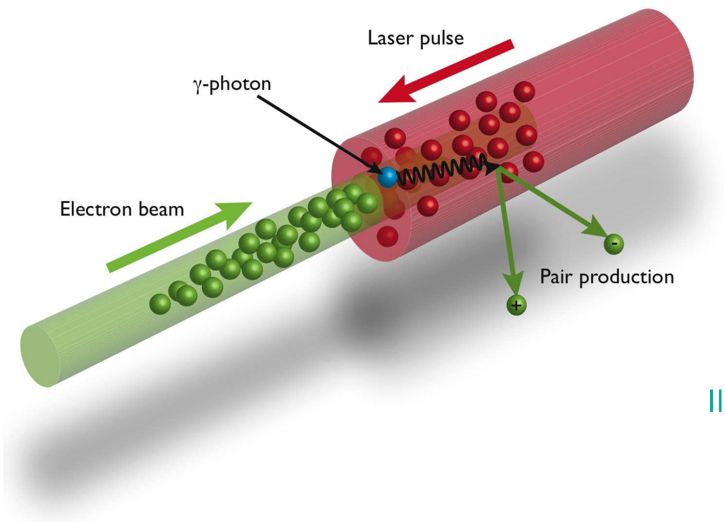


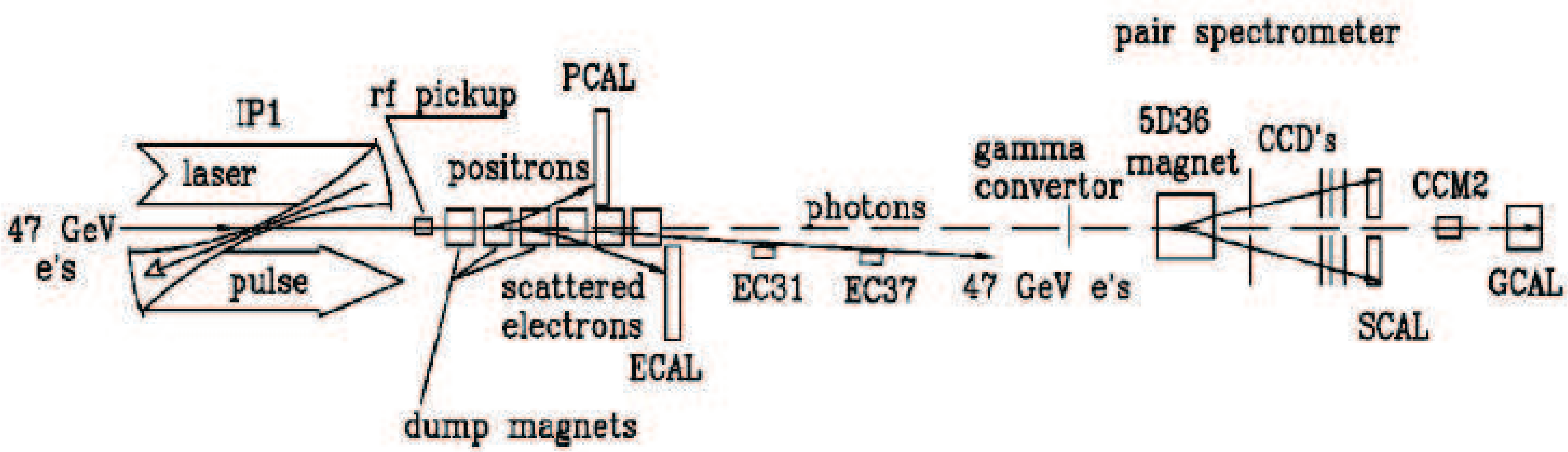
Illustration from [Marklund,Lundin '08]

- Pair creation via[3]
  - direct, Bethe-Heitler like process, $e + n\,\gamma_{\rm L} \to e + e^+e^-$
  - two stage process: [Reiss '62; Nikishov, Ritus '64]
    - ∗ non-linear Compton process, $e + n\,\gamma_{\rm L} \to e + \gamma$, followed by
    - ∗ stimulated, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$ pair production

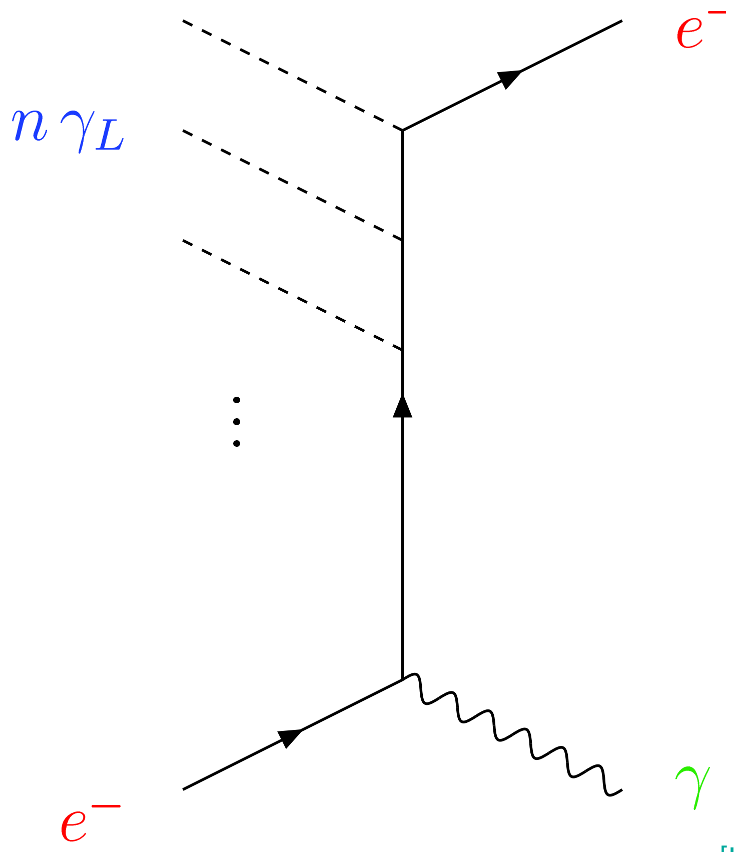
[3] Unified description ⇒ talk by Carsten Müller

- **SLAC E144** studied **non-linear Compton and stimulated pair production** in the collision of a **46.6 GeV electron beam** (the Final Focus Test Beam) with **terawatt photon pulses** of 1053 nm and 527 nm

[Bula et al., PRL 76 (1996) 3116; Burke et al., PRL 79 (1997) 1626; Bamber et al., PRD 60 (1999) 092004]



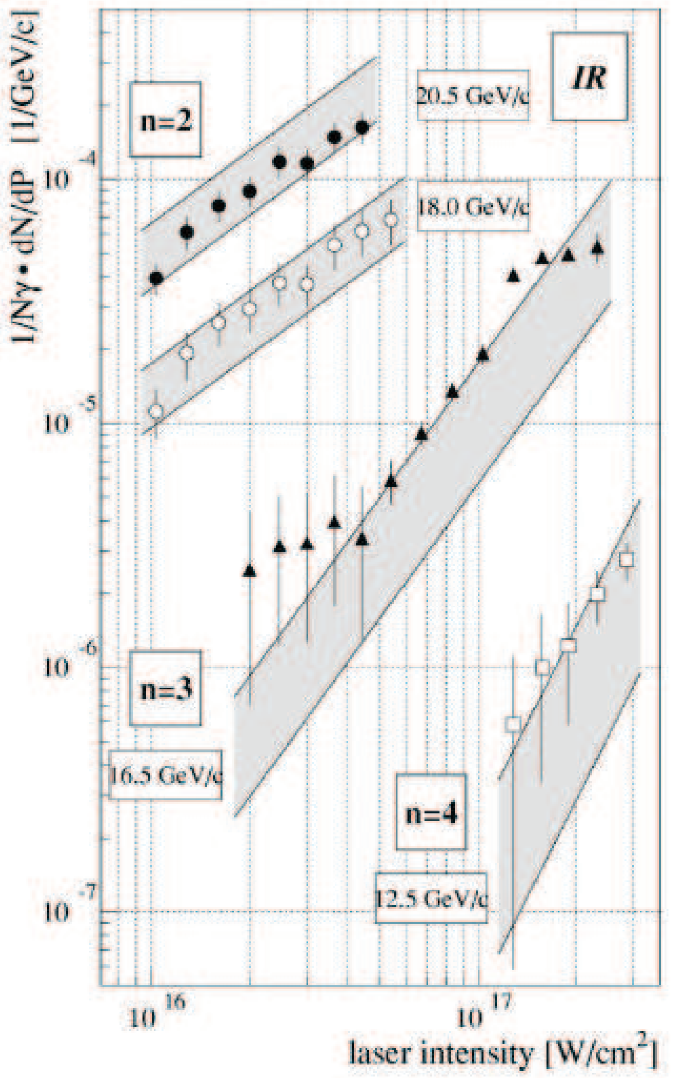
- **Non-linear QED in $e\gamma_{\rm L}$ coll.:**
  adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$
  - **Non-linear Compton**
    $e + n\,\gamma_{\rm L} \to e + \gamma$



[Heinzl]

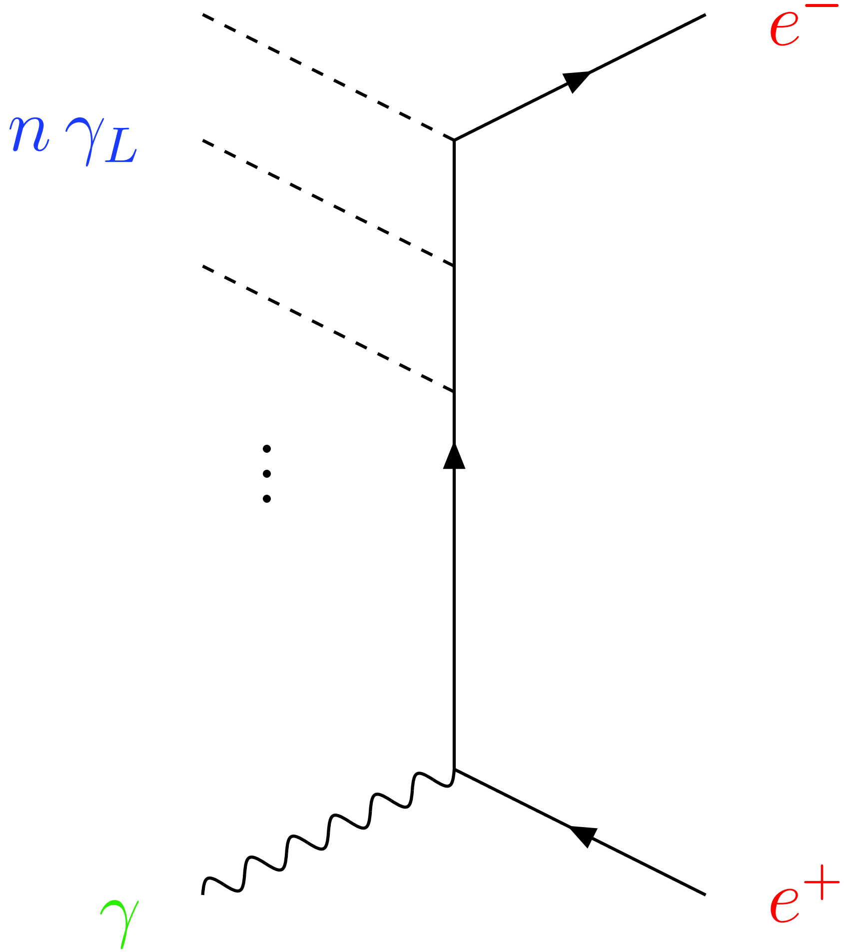
- **Non-linear QED in $e\gamma_{\rm L}$ coll.:**
  adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$

  – **Non-linear Compton**
  $e + n\,\gamma_{\rm L} \to e + \gamma$
  Electron yield,
  $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$



[SLAC E144]

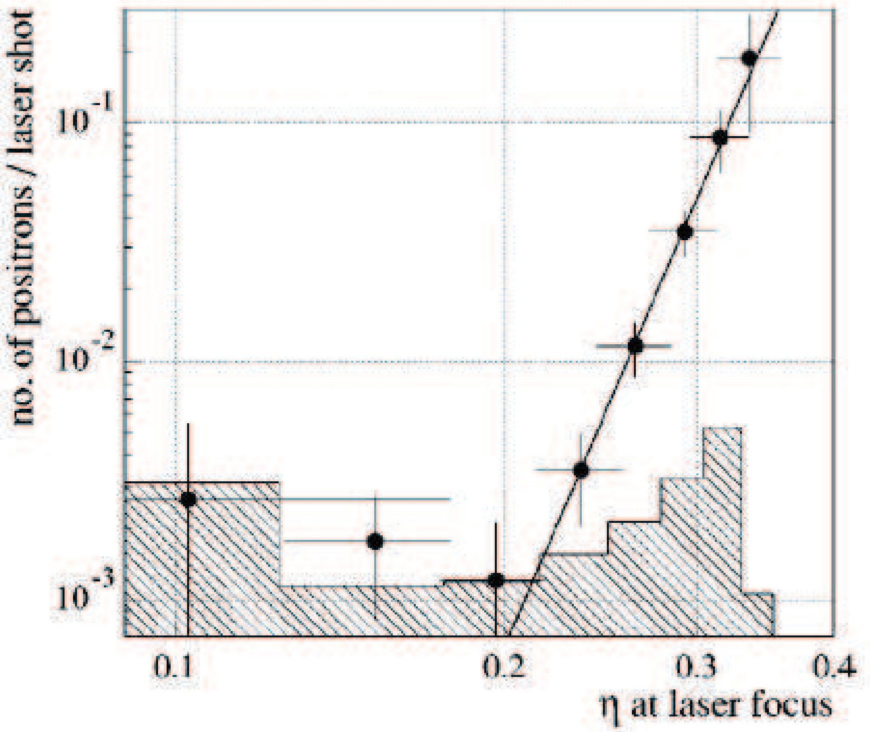
- **Non-linear QED in $e\gamma_{\rm L}$ coll.:** adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$
  - **Non-linear Compton**
    $e + n\,\gamma_{\rm L} \to e + \gamma$
    Electron yield,
    $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$
  - **Pair production:**
    - $\boldsymbol{\eta \ll 1}$**:** stimulated process, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$,



[Heinzl]

SLAC E144: $\eta \ll 1$,

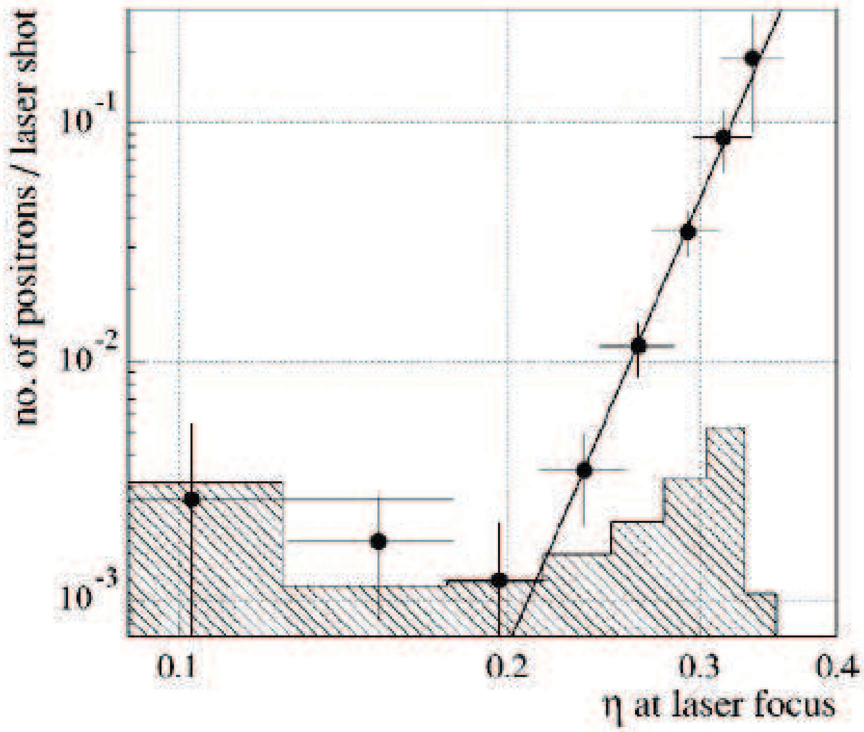
- **Non-linear QED in $e\gamma_{\rm L}$ coll.:** adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$
  - **Non-linear Compton**
    $e + n\,\gamma_{\rm L} \to e + \gamma$
    Electron yield,
    $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$
  - **Pair production:**
    - $\boldsymbol{\eta \ll 1}$**:** stimulated process, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$, positron rate, $R_{e^+} \propto \eta^{2n} \propto I^n$



[SLAC E144]

SLAC E144: $\eta \ll 1$,

- **Non-linear QED in $e\gamma_{\rm L}$ coll.:** adiab. param. $\eta = \frac{e\mathcal{E}}{\omega m_e}$
  - **Non-linear Compton**
    $e + n\,\gamma_{\rm L} \to e + \gamma$
    Electron yield,
    $Y_e \propto \eta^{2(n-1)} \propto I^{n-1}$
  - **Pair production:**
    * $\boldsymbol{\eta \ll 1}$**:** stimulated process, $\gamma + n\,\gamma_{\rm L} \to e^+e^-$, positron rate, $R_{e^+} \propto \eta^{2n} \propto I^n$
    * $\boldsymbol{\eta \gg 1}$**:** non-perturbative process, $R_{e^+} \propto \exp(-8/3\kappa)$, where $\kappa = 2\frac{\omega'}{m_e}\frac{\mathcal{E}}{\mathcal{E}_c}$; however: SLAC E144: $\eta \ll 1$, $\kappa \ll 1$

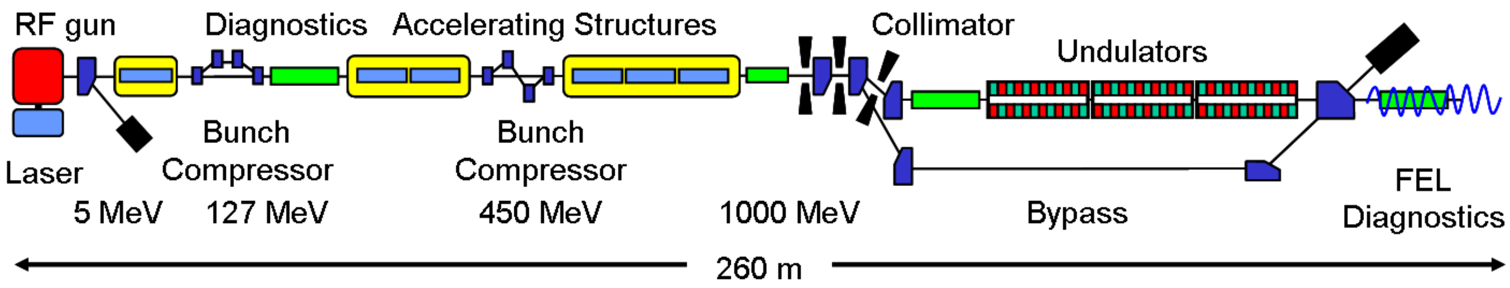


[SLAC E144]

⇒ **Fundamental physics opportunity exploiting multi-GeV e-beams of**

Free Electron Lasers in **VUV to X-Ray Band**

– **FLASH: F**ree Electron **LAS**er in **H**amburg at DESY



– **LCLS: L**inac **C**oherent **L**ight **S**ource at SLAC
– **SCSS: S**Pring-8 **C**ompact **S**ASE **S**ource in Japan
– **European XFEL** in Hamburg/D
– . . .
– **SwissFEL** in Villigen/CH
– **ZFEL** in Groningen/NL

- **Need petawatt laser pulses to probe also $\eta \gg 1$:**

$$\eta = 7.6 \left[\frac{I}{10^{21}\ \mathrm{W/cm^2}}\right]^{1/2} \left[\frac{\lambda_L}{0.4\ \mu\mathrm{m}}\right]$$

LASER	SLAC 144	Required e.g.
Wavelength	527-1064 nm	800 nm
Intensity on target	10^{18} W/cm^2	10^{21} W/cm^2
η (maximum)	0.32	15.38

- **Need $\gtrsim 10$ GeV beam energy to probe $\kappa \lesssim 1$:**

$$\kappa = 0.94 \left[\frac{I}{10^{21}\mathrm{W/cm^2}}\right]^{1/2} \left[\frac{\omega'}{5\ \mathrm{GeV}}\right]$$

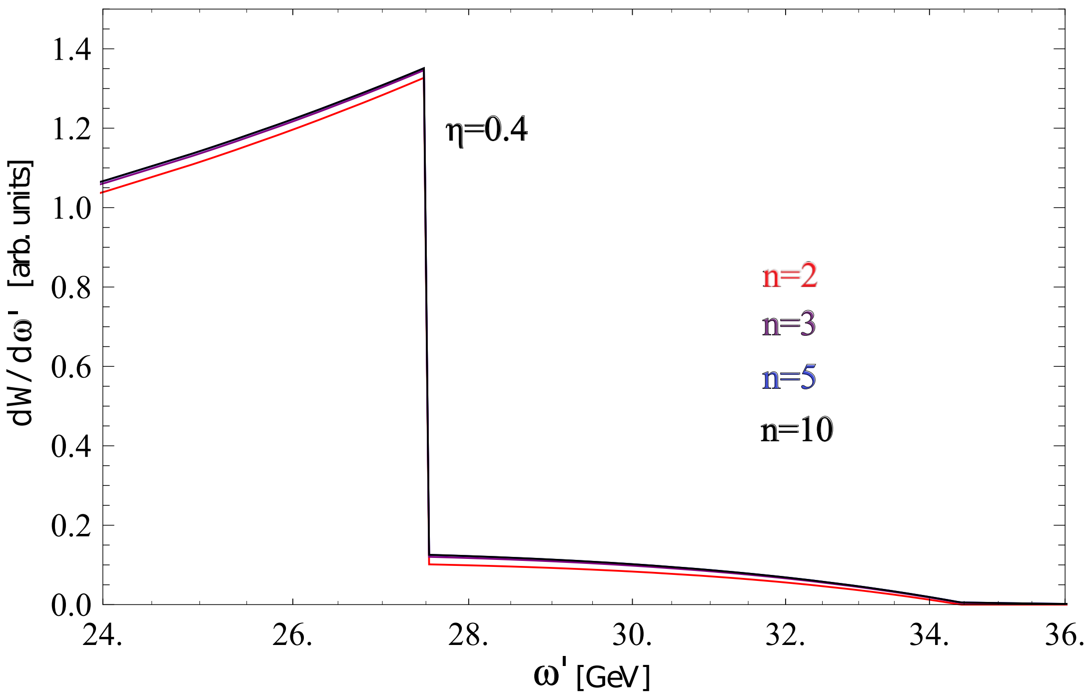
Accelerator	ω' [GeV]	I [W/cm^2]	κ
SLAC	29	10^{18}	0.17
FLASH	0.2	10^{21}	0.03
XFEL	5	10^{21}	0.94

⇒ Crossing FEL electron beam pulses with intense laser pulses allows

– unprecedented studies of non-linear Compton scattering

[...;Harvey,Heinzl,Idlerton '09]

SLAC:



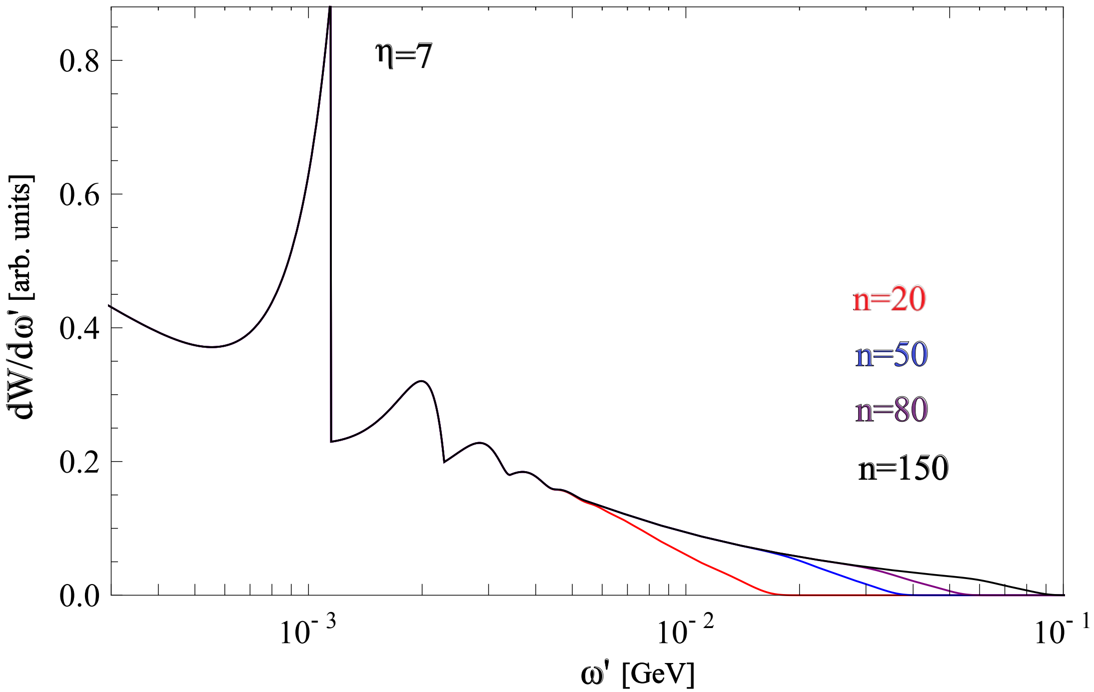
[Arias,Redondo,AR in prep.]

⇒ Crossing FEL electron beam pulses with intense laser pulses allows

– unprecedented studies of non-linear Compton scattering

[...;Harvey,Heinzl,Idlerton '09]

FLASH:



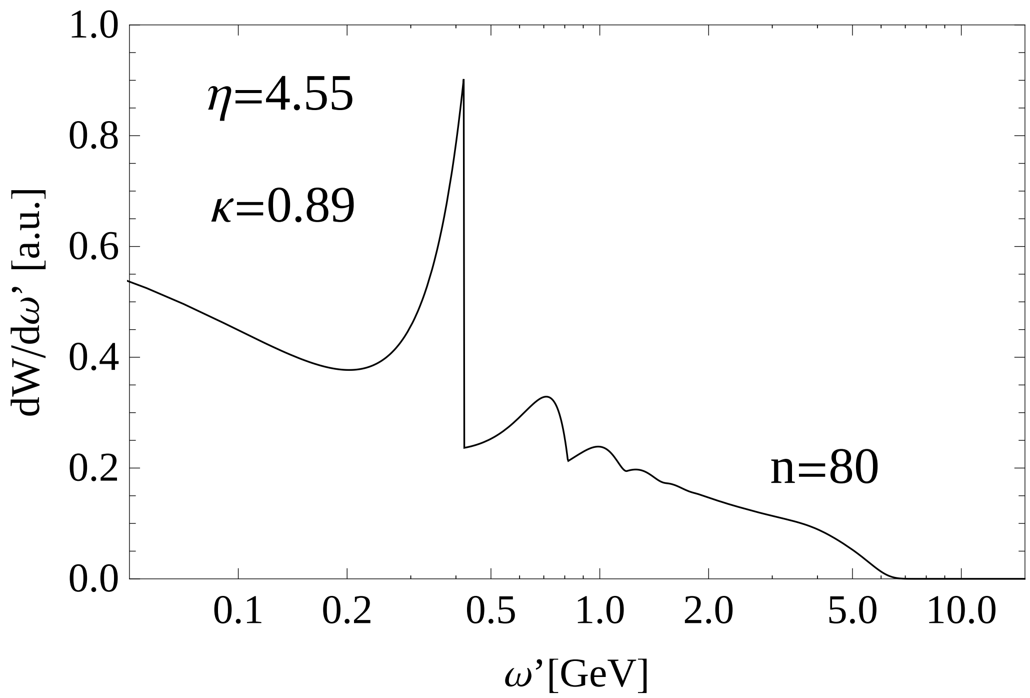
[Arias,Redondo,AR in prep.]

⇒ Crossing FEL electron beam pulses with intense laser pulses allows

– unprecedented studies of non-linear Compton scattering

[...;Harvey,Heinzl,Idlerton '09]

XFEL:



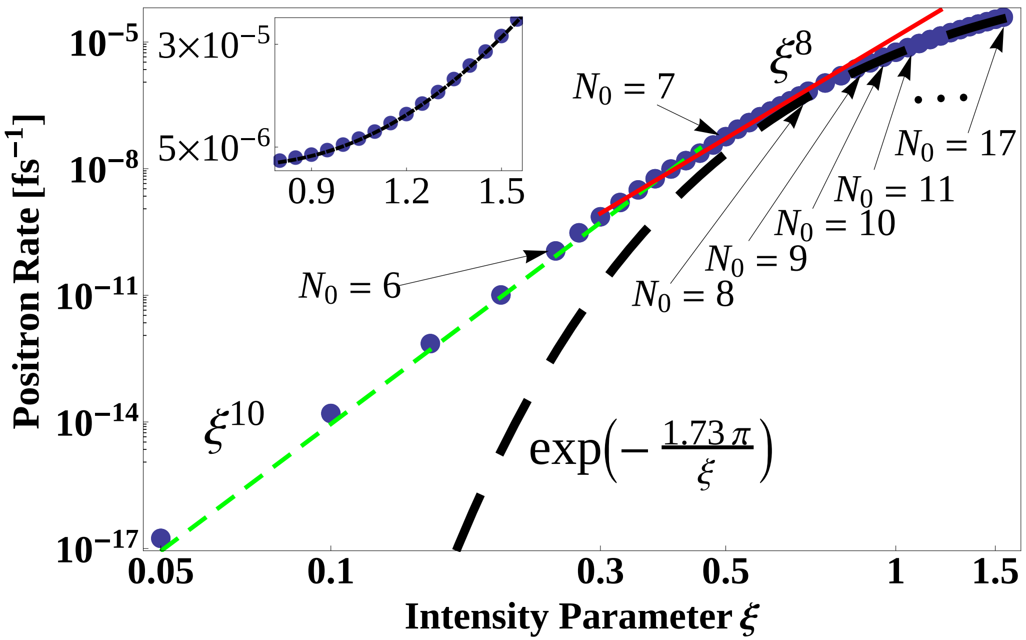
[Arias,Redondo,AR in prep.]

⇒ Crossing FEL electron beam pulses with intense laser pulses allows

– unprecedented studies of non-linear Compton scattering

[...;Harvey,Heinzl,Idlerton '09]

– the first clear experimental observation of non-perturbative, spontaneous pair production [...;Hu,Müller,Keitel '10]



[Hu,Müller,Keitel '10]

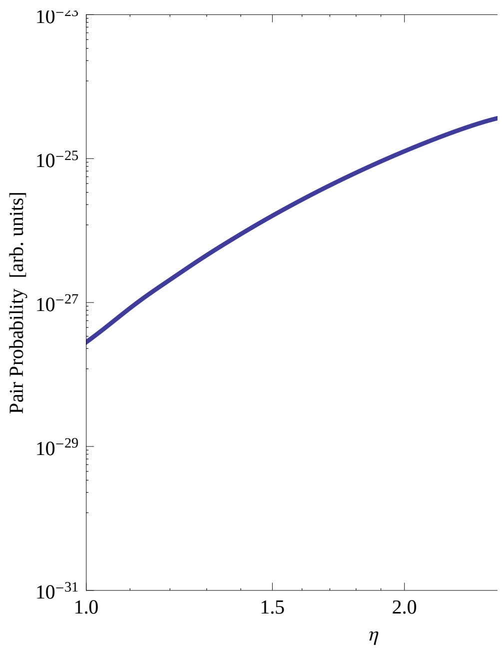
⇒ Crossing FEL electron beam pulses with intense laser pulses allows

– unprecedented studies of non-linear Compton scattering

[...;Harvey,Heinzl,Idlerton '09]

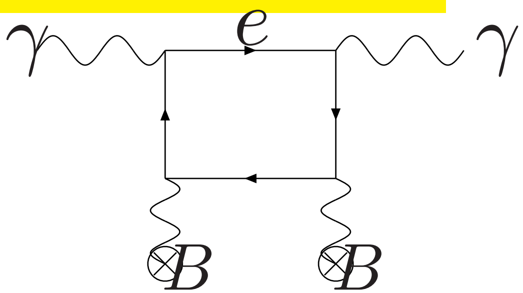
– the first clear experimental observation of non-perturbative, spontaneous pair production [...;Hu,Müller,Keitel '10]

XFEL:



[Arias,Redondo,AR in prep.]

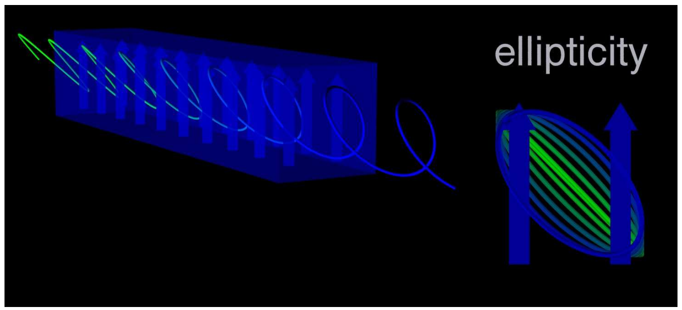
Vacuum magnetic birefringence in QED



$\Rightarrow$ Refractive index in a magnetic field B depends on polarization,

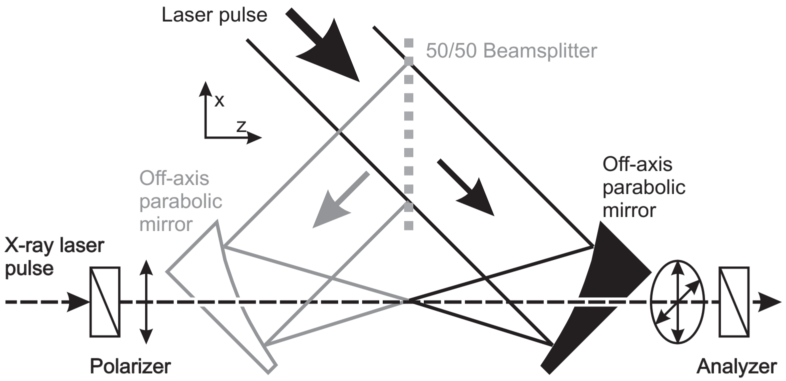
$$\Delta n_{\parallel,\perp} = \left[(7)_{\parallel}, (4)_{\perp} \right] \frac{\alpha}{90\pi} \left(\frac{B}{B_{\rm cr}} \right)^2 ; \qquad B_{\rm cr} = \frac{m_e^2}{e} \simeq 4 \times 10^9 \text{ T}$$

$\Rightarrow$ A linear polarized laser beam entering the magnetic field at an angle θ will turn into a beam with elliptical polarization:



$$\psi_{\rm QED} = 1.0 \times 10^{-17} \left(\frac{\omega}{\rm eV}\right) \left(\frac{\ell}{\rm m}\right) \left(\frac{B}{\rm T}\right)^2 N_{\rm pass} \sin(2\theta)$$

- Experimental possibilities:
  - Optical (eV) laser cavity ($N_{\rm pass} \sim 10^5$) plus macroscopic magnet ($B \sim$ T, $\ell \sim$ m): BMV (Toulouse), OSQAR (CERN), Q&A (Taiwan)
  - X-ray (multi keV) laser ($N_{\rm pass} = 1$) plus
    - macroscopic magnet ($B \sim$ T, $\ell \sim$ m) or [Cantatore *et al.* '91]
    - magnetic field in focal region of crossed petawatt optical laser pulses ($B \sim 10^5$ T, $\ell \sim 10$ μm) [Heinzl *et al.* '06]



Conclusions

- Electron beams of XFELs can be used to study fundamental physics, in particular non-linear and non-perturbative QED processes in crossed electron and high intensity optical laser beams

⇒ Should foresee, at FLASH or XFEL, to install also
  - an intense optical laser
  - a dedicated (single bunches) electron beam line

- Same equipment can also be used for other purposes
  - QED vacuum magnetic birefringence
  - laser plasma booster ⇒ talk by Jens Osterhoff