Fundamental Physics at Free Electron Lasers.

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Physics of fundamental Symmetries and Interactions - PSI2013
Paul-Scherrer-Institut, Villigen, CH
8-12 September 2013

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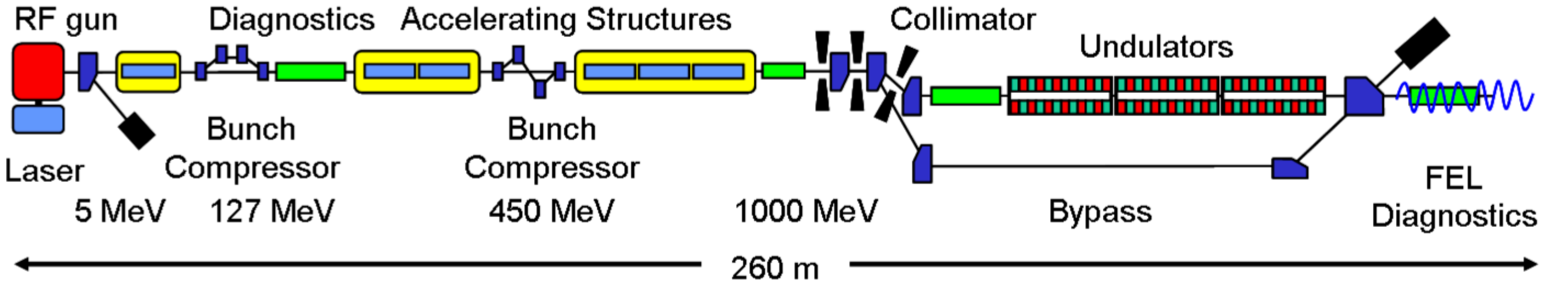
Introduction

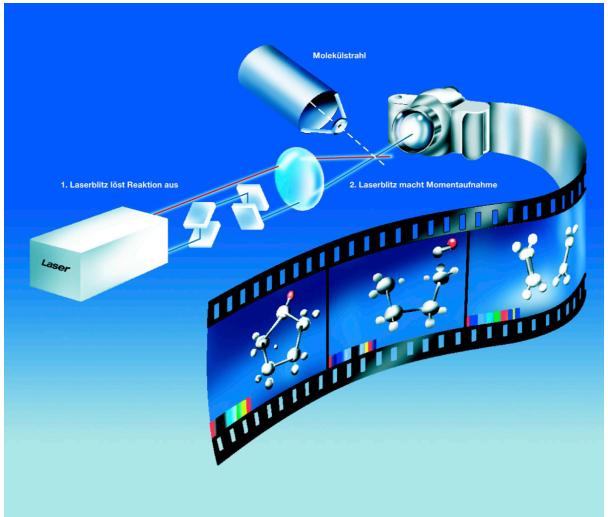
- World-wide a number of Free Electron Lasers (FELs) in VUV to X-ray band in operation/commissioning/construction/planning
  - FLASH: Free Electron Laser in Hamburg at DESY

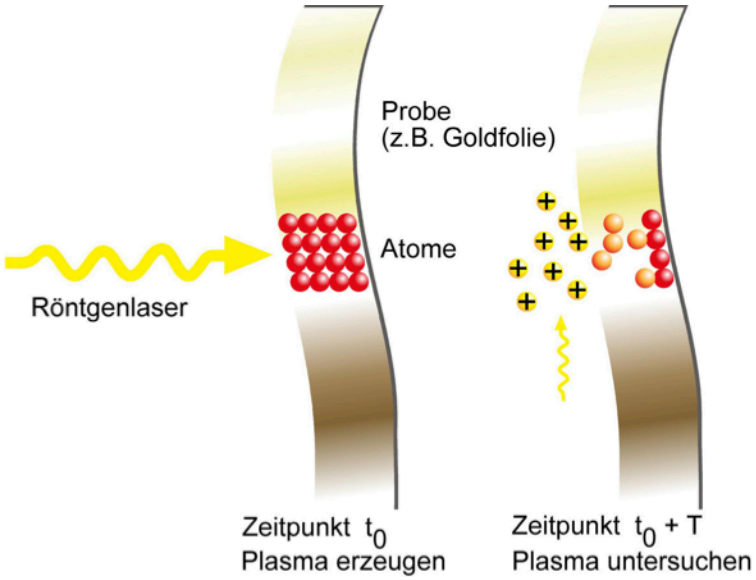


  - LCLS: Linac Coherent Light Source at SLAC
  - SCSS: SPring-8 Compact SASE Source in Japan
  - European XFEL: European X-ray Free Electron Laser in Hamburg
  - ...
  - SwissFEL at PSI
  - ZFEL in Groningen

Introduction

- **>** Photon beam characteristics:
  - High power
  - Short pulse length
  - Narrow bandwidth
  - Spatial coherence
  - Tunable wavelength
- **>** Applications:
  - Atomic and molecular physics
  - Condensed matter physics
  - Material science
  - Structural biology
  - Chemistry
  - Plasma physics



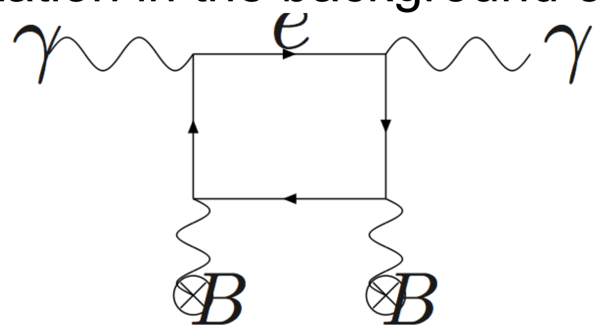


Introduction

- FEL applications in fundamental physics?
- Will discuss in this talk:
  - Non-linear and non-perturbative QED
    - Vacuum magnetic birefringence
    - Non-linear Compton processes and pair creation from electron beam crossed with laser beam
  - Searches for very weakly interacting light particles
    - Axions and axion-like particles
    - MeV-GeV scale hidden or dark photon

Vacuum magnetic birefringence

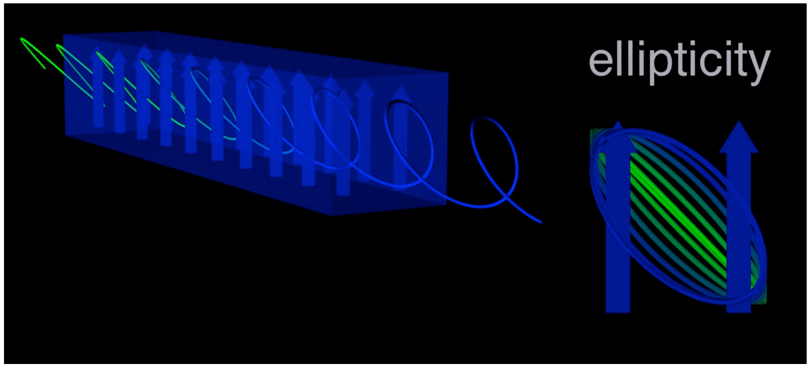
- QED vacuum polarization in the background of a magnetic field:



- Refractive index depends on polarization:

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

- A linear polarized laser beam entering a dipole magnetic field at an angle θ will turn into a beam with elliptical polarization:

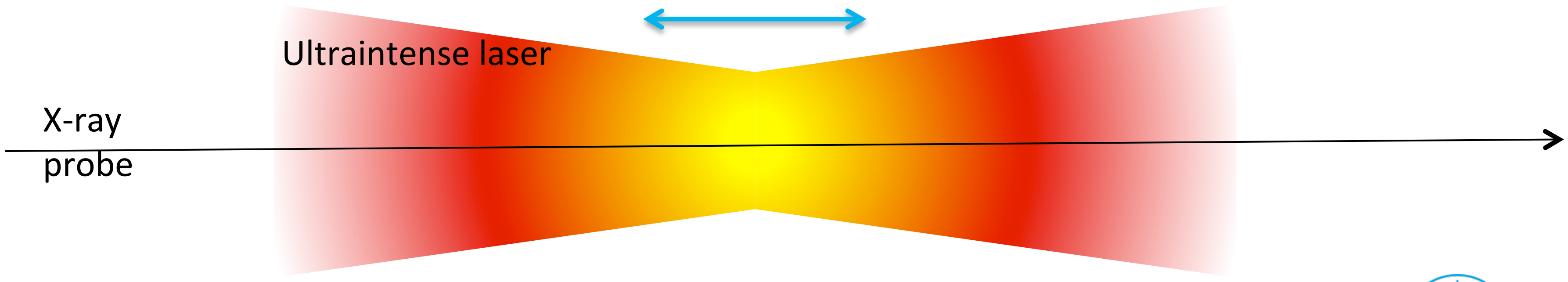


Vacuum magnetic birefringence

- Ellepticity:

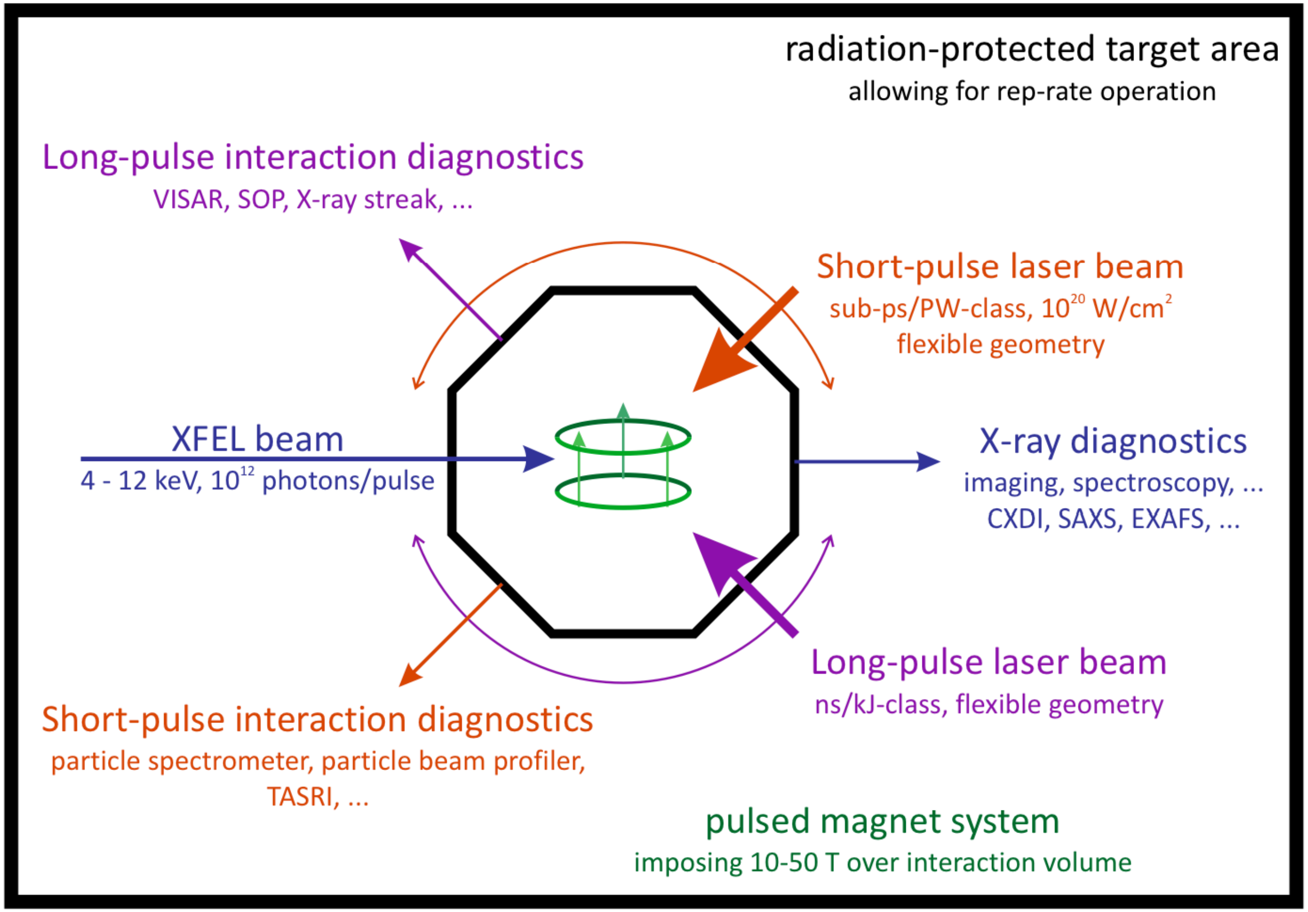
$$\psi_{\text{QED}} = 1.0 \times 10^{-17} \left(\frac{\omega}{\text{eV}}\right) \left(\frac{\ell}{\text{m}}\right) \left(\frac{B}{\text{T}}\right)^2 N_{\text{pass}} \sin(2\theta)$$

- Experimental possibilities:
  - Optical (eV) laser cavity ($N_{\text{pass}} \sim 10^5$) plus macroscopic magnet ($B \sim \text{T}, \ell \sim \text{m}$):
    - BMV (Toulouse, France)
    - PVLAS (Ferrara, Italy)
  - X-ray (multi keV) laser ($N_{\text{pass}} = 1$) plus
    - macroscopic magnet ($B \sim \text{T}, \ell \sim \text{m}$) or [Cantatore et al. '91]
    - magnetic field in focal region of crossed petawatt ($B \sim 10^5\,\text{T}, \ell \sim 10\,\mu\text{m}$) optical laser pulses [Heinzl,Liesfeld,Amthor,Schwoerer,Sauerbrey,Wipf '06]



Vacuum magnetic birefringence

> Opportunity at Helmholtz International Beamline for Extreme Fields (HIBEF) at the European XFEL



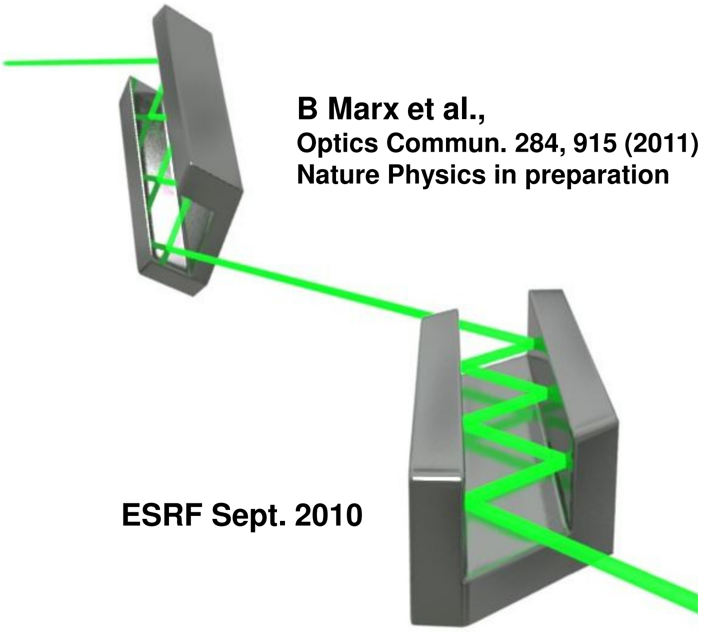
[Schlenvoigt,Schramm,Cowan for the HIBEF User-Consortium `13]

Vacuum magnetic birefringence

> Required sensitivity in ellipticity ($\sim 10^{-10}$) can be achieved exploiting newly developed channel cut crystal polarimetry:

Polarimeter set-up

- **A n-reflection channel-cut as polarizer and a second n-reflection channel-cut as analyzer**

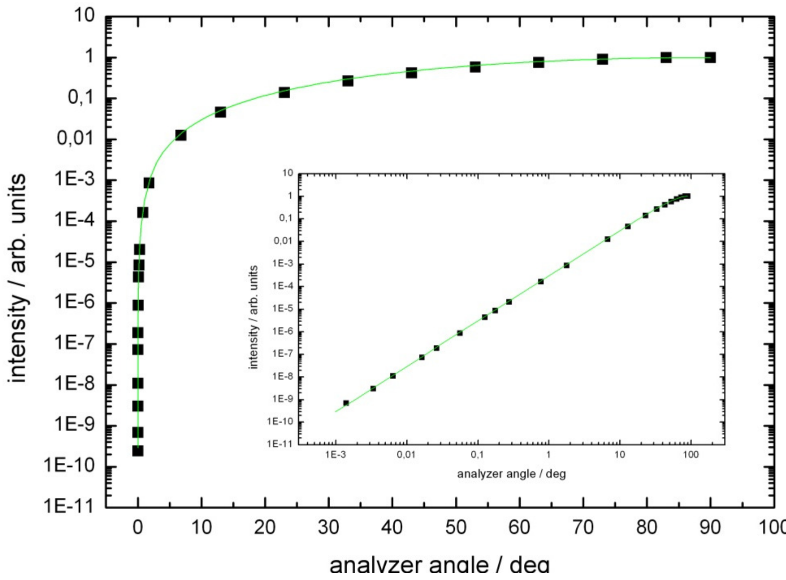


B Marx et al.,
Optics Commun. 284, 915 (2011)
Nature Physics in preparation

ESRF Sept. 2010

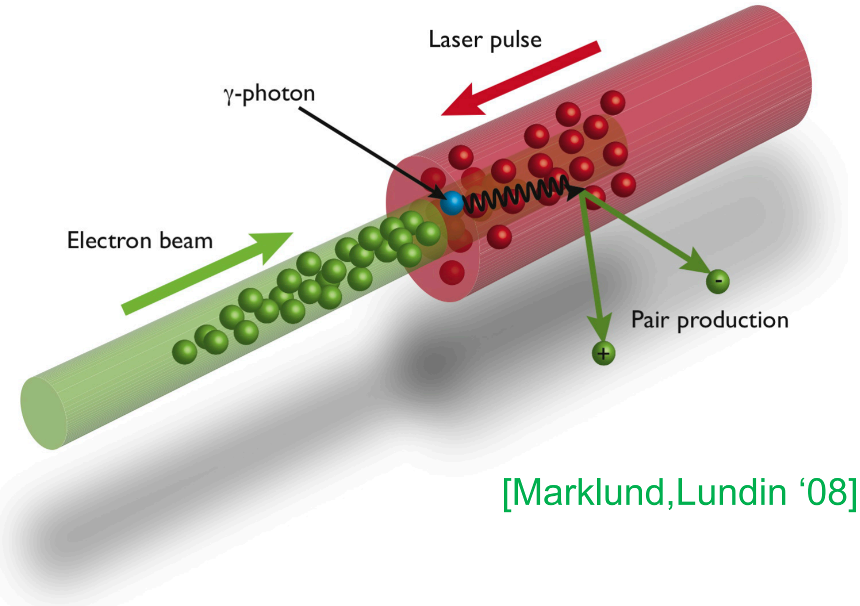
	4 reflections	6 reflections
400 – 6.5 keV	1.5E-9	2.4E-10
800 – 12.9 keV	9.0E-9	7.6E-10

- **Measurements performed at the ESRF in Grenoble**
- **Highest polarization purity of X-rays up to date (δ_0=2.4·10^{-10})**



[Zepf: PIF13]

Pair creation from electron beam crossed with laser beam



[Marklund,Lundin '08]

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

Pair creation from electron beam crossed with laser beam

- Non-linear QED in $e^-\gamma_L$ collisions:
  adiabaticity parameter $\eta \equiv e\mathcal{E}/\omega m_e$

  $\eta \ll 1:$ perturbative regime

  $\eta \gg 1:$ non-perturbative regime

  - Non-linear Compton $e^- + n\gamma_L \to e^- + \gamma$

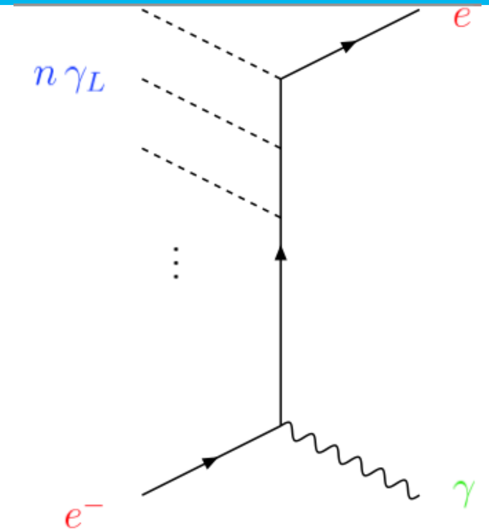
    Electron yield: $Y_e \propto \eta^{2(n-1)} n \propto I^{n-1}$

  - Pair production:

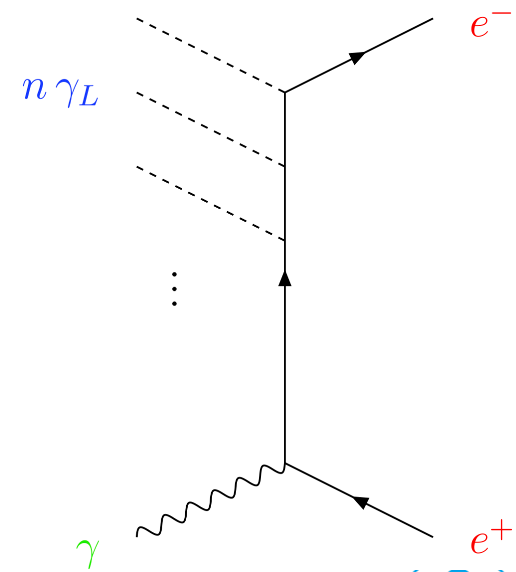
    $\eta \ll 1:$ stimulated process, $\gamma + n\gamma_l \to e^+e^-$

    Positron rate: $R_{e^+} \propto \eta^{2n} \propto I^n$

    $\eta \gg 1:$ non-perturbative
    process, $R_{e^+} \propto \exp(-8/(3\kappa))$,
    where $\kappa = 2(\omega'/m_e)(\mathcal{E}/\mathcal{E}_{\rm cr})$
    $\mathcal{E}_{\rm cr} = m_e^2/e$



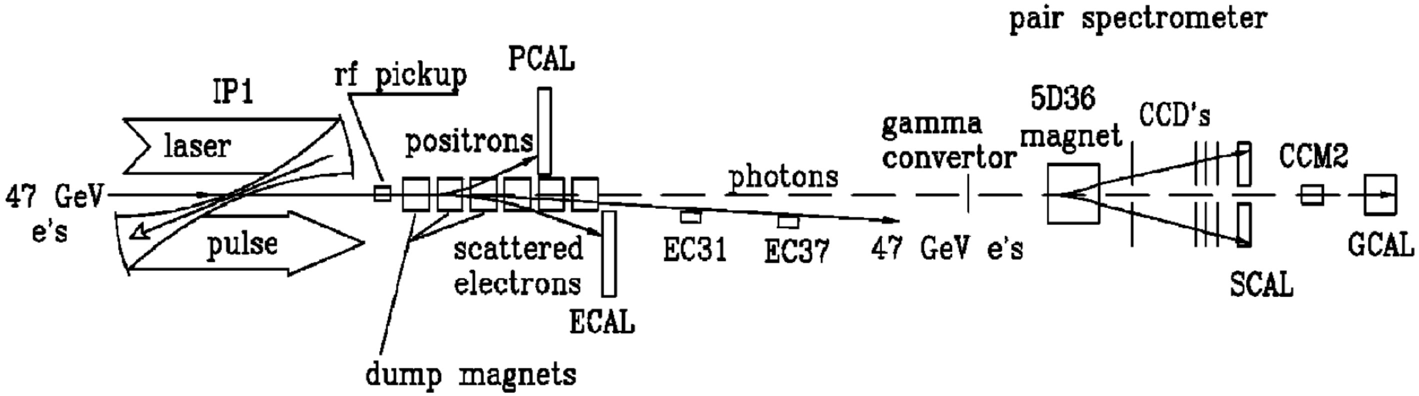
[Heinzl]



Pair creation from electron beam crossed with laser beam

- 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]



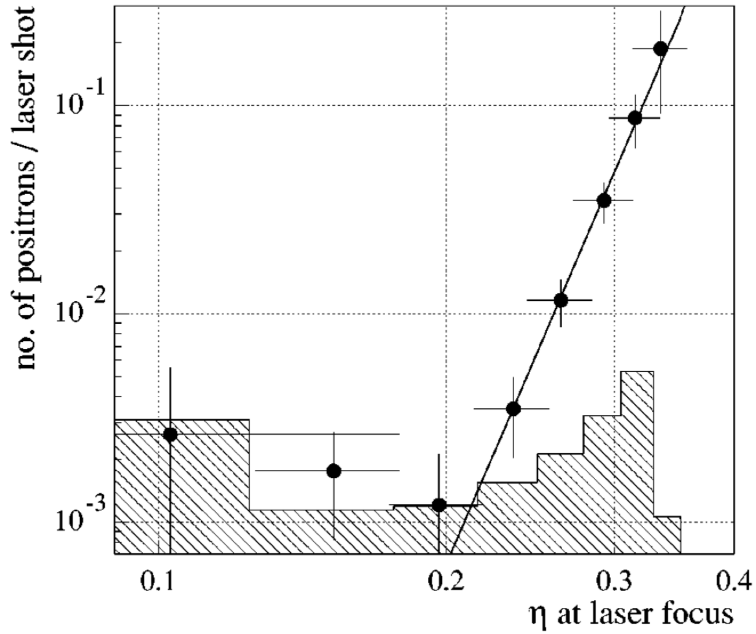
- Laser intensitivity was not enough to enter non-perturbative regime:

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

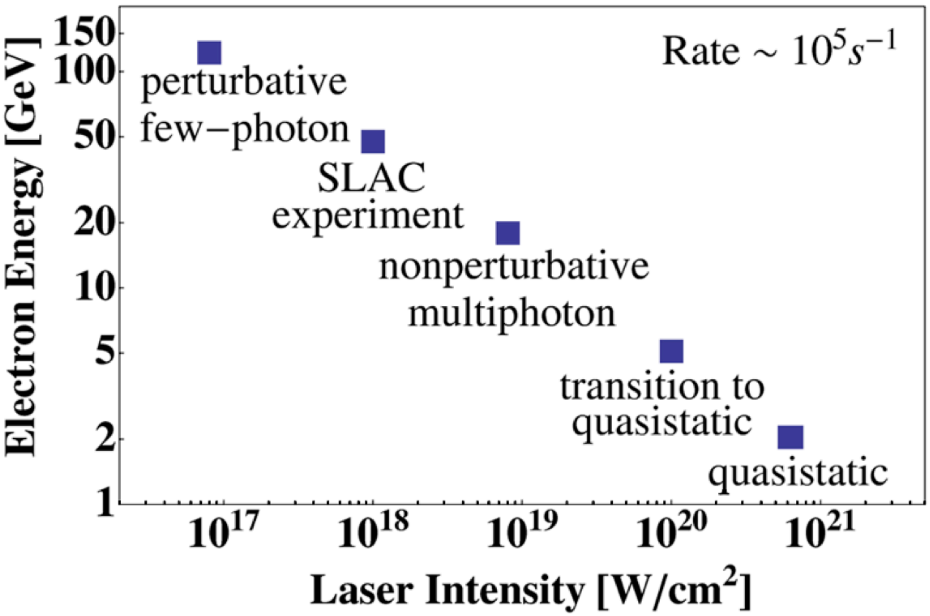
LASER	SLAC 144	Required e.g.
Wavelength	527-1064 nm	800 nm
Intensity on target	10^{18} W/cm^2	10^{21} W/cm^2
η (maximum)	0.32	15.38

Pair creation from electron beam crossed with laser beam

> SLAC 144: perturbative rise of positron rate



[Bamber et al. (SLAC 144) '99]



[Hu,Müller,Keitel '10]

> Opportunity exploiting electron beams of FELs, in particular of FLASH and European XFEL, in combination with high intensity optical lasers

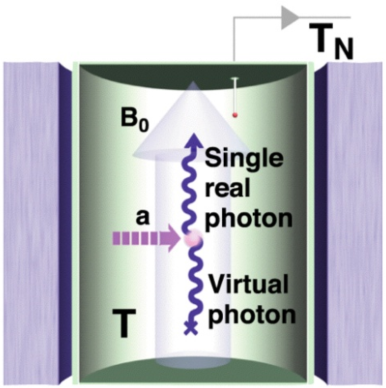
Axions and axion-like particles

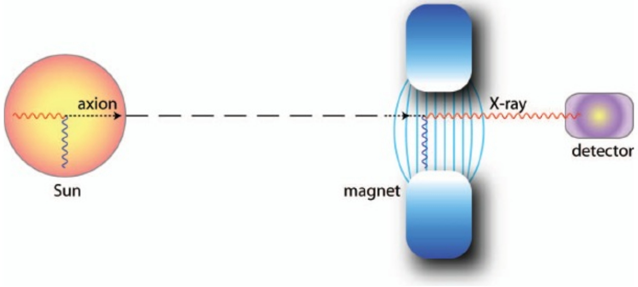
- Axions
  - are predicted in the course of one of the most attractive solutions of the strong CP problem: particle excitations of the dynamical theta parameter [Peccei,Quinn '77; Weinberg '78; Wilczek '78]
  - occur as low energy remnants in many extensions of the standard model, notably in top-down motivated models from string theory; the latter very often feature also axion-like particles (ALPs) (e.g. [Cicoli,Goodsell,AR])
- Axions and ALPs are good candidates for cold dark matter if their characteristic scale ("decay constant") is large, $f_A \gtrsim 10^9\,\mathrm{GeV}$, and their mass is small, $m_A \ll 1\,\mathrm{eV}$ [Preskill et al '83; Abbott,Sikivie '83; Dine,Fischler '83;...; Arias et al '12]
- Coupling to photons has form $\mathcal{L} \supset -\frac{g_{A\gamma}}{4} A\, F_{\mu\nu}\tilde{F}^{\mu\nu}$, with strength

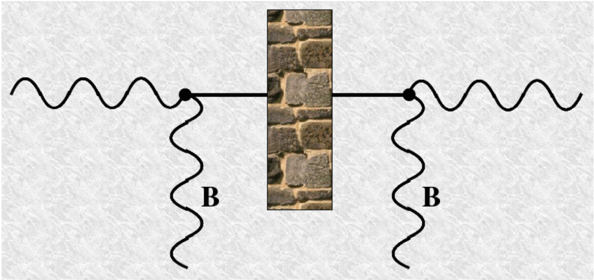
$$g_{A\gamma} \sim \frac{\alpha}{2\pi f_A} \sim 10^{-12}\ \mathrm{GeV}^{-1} \left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)$$

Axions and axion-like particles

- Most sensitive laboratory probes are based on axion or ALP photon conversion in strong magnetic (electric) fields
  - Haloscopes: direct detection of DM axions/ALPs [Sikivie '83]
  - Helioscopes: detection of solar axions/ALPs [Sikivie '83]
  - Light-shining-through-a-wall: production and detection of ALPs [Anselm '85; van Bibber et al '87]



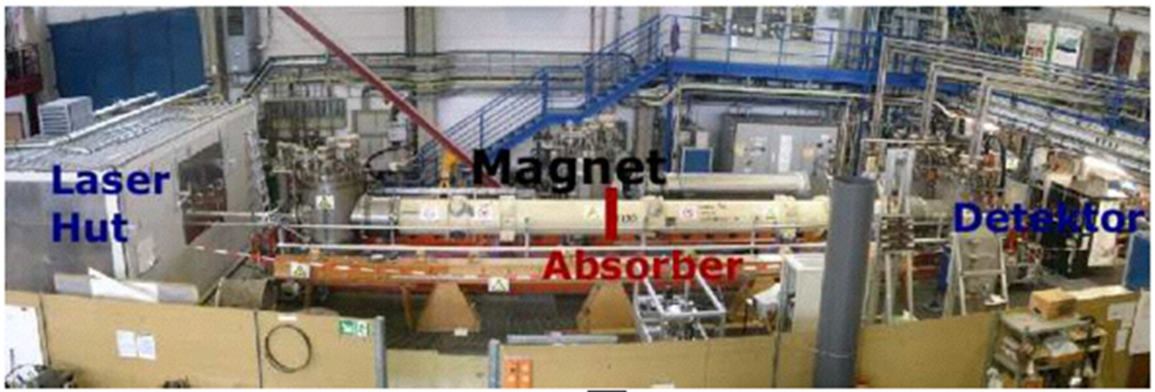




Light-shining-through-a-wall searches

- Most sensitive until now: Any Light Particle Search I (ALPS-I) at DESY
  - One superconducting HERA dipole (5 T)
  - 1.2 kW cw green (2.3 eV) laser
  - CCD camera

[Ehret et al (ALPS-I) '10]

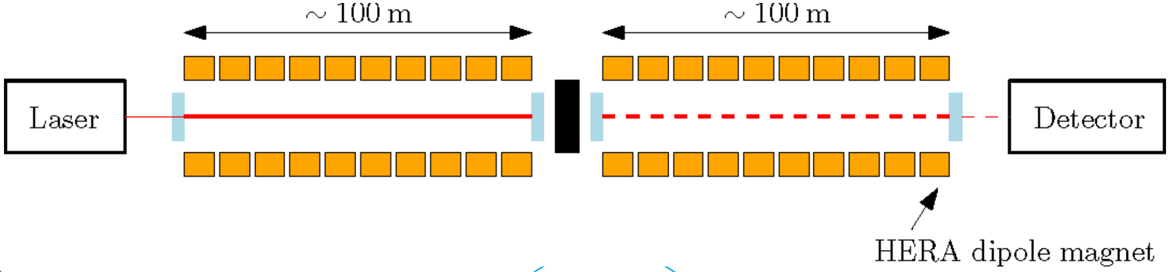


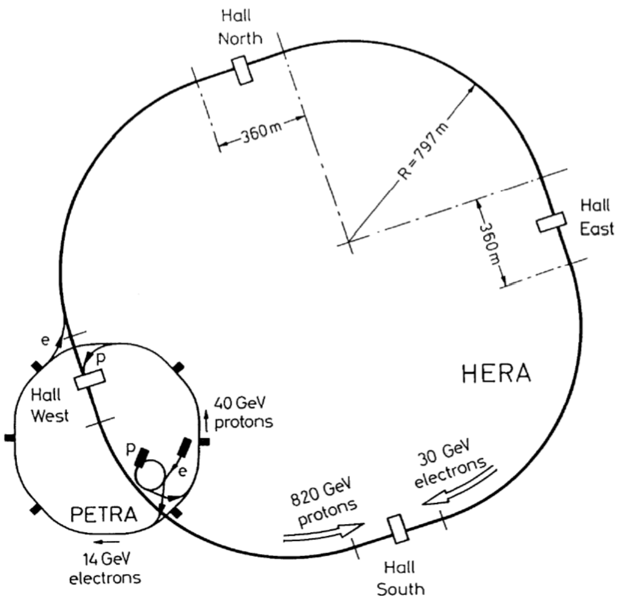
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

Light-shining-through-a-wall searches

> Presently being set up: ALPS-II at DESY (data taking planned for 2017)

- 10 + 10 superconducting HERA dipoles
- 150 kW infrared (1.17 eV) laser light stored before wall; resonant regeneration behind wall
- Transition Edge Sensor

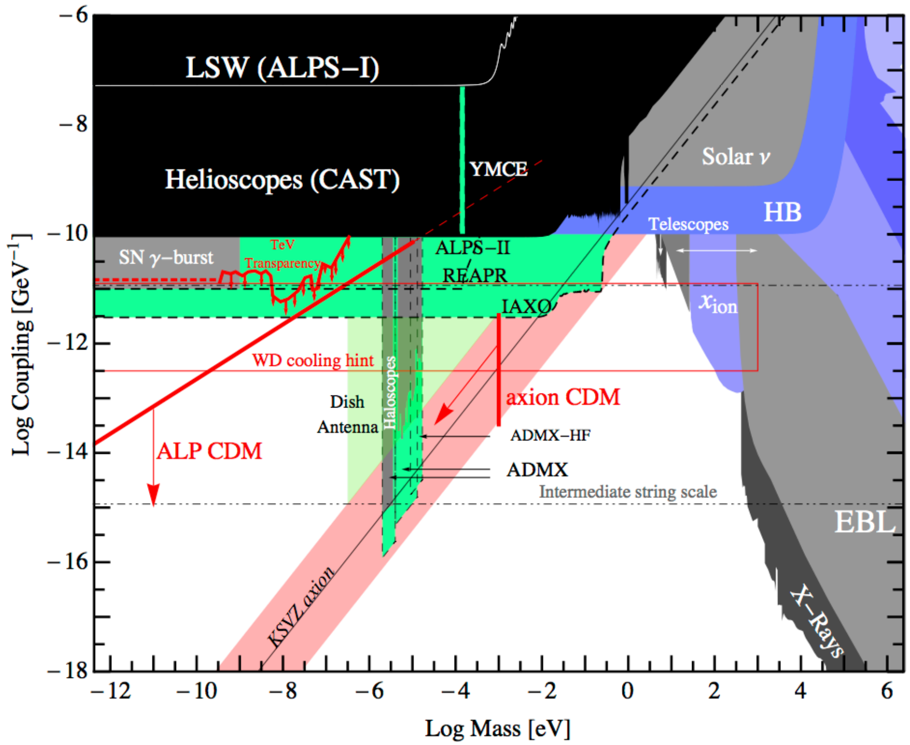




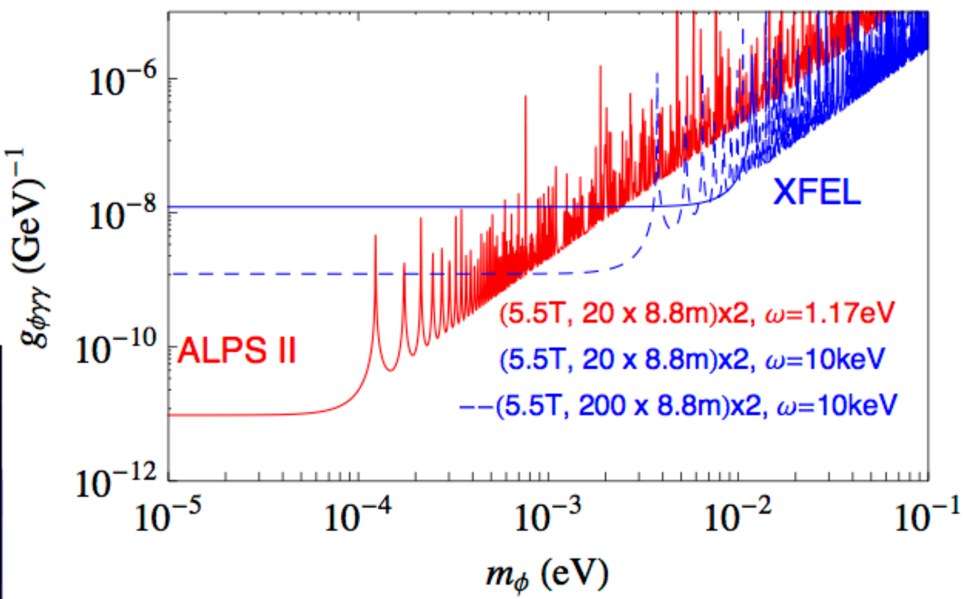
[Bähre et al (ALPS-II) TDR '13]

Light-shining-through-a-wall searches

- X-ray LSW can not compete, at low masses, with optical LSW, because always only single pass, time averaged photon flux quite low



adapted from [Hewett et al '12]



[Arias,AR '10]

- Accessible parameter space at large masses, beyond ALPS-II, deeply excluded by helioscope CAST

MeV-GeV scale hidden (dark) photon

> Occurs in well motivated extensions of the standard model, notably in brane-world scenarios from string theory

> May explain

- $(g-2)_\mu$ anomaly [Pospelov ‘08]
- DM `anomalies´ [Arkani-Hamed et al. ‘08; Pospelov,Ritz ‘08;...]
  - in direct detection (DAMA, CoGeNT, CRESST, CDMS vs. XENON) and
  - in cosmic rays (PAMELA, FERMI, AMS)

if DM charged under hidden U(1)

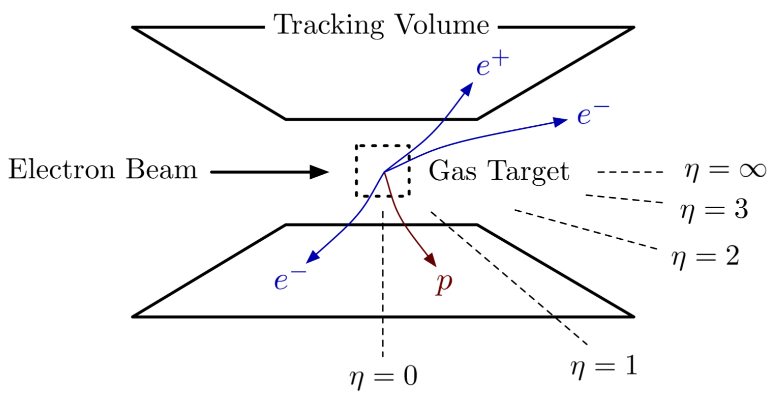
> Can be checked in beam dump and other fixed-target experiments with intense electron beams [Reece,Wang ‘09; Bjorken,Essig,Schuster,Toro ’09; Andreas,Niebuhr,AR ‘12]

> New experiments performed/commissioned/funded/proposed/designed in Mainz at MAMI (A1 Collaboration) and MESA facility, and at JLab (APEX, DarkLight, HPS)

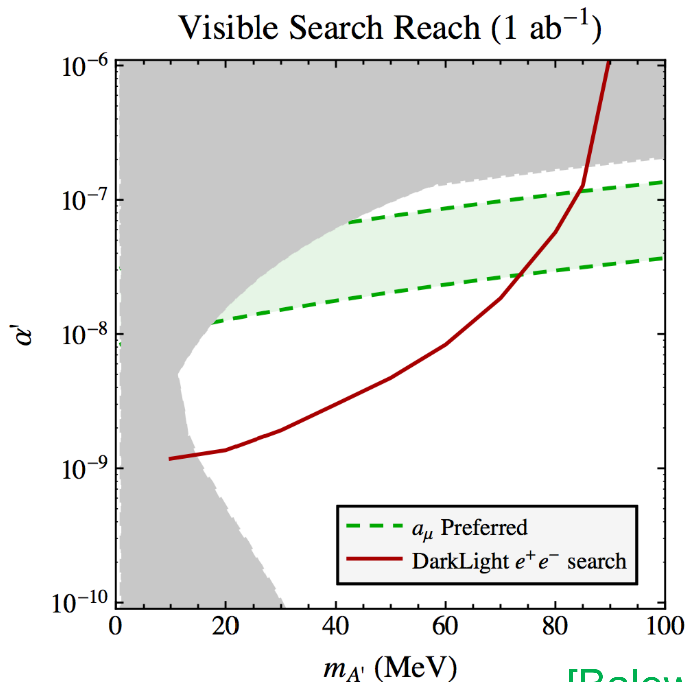
DarkLight at JLab FEL

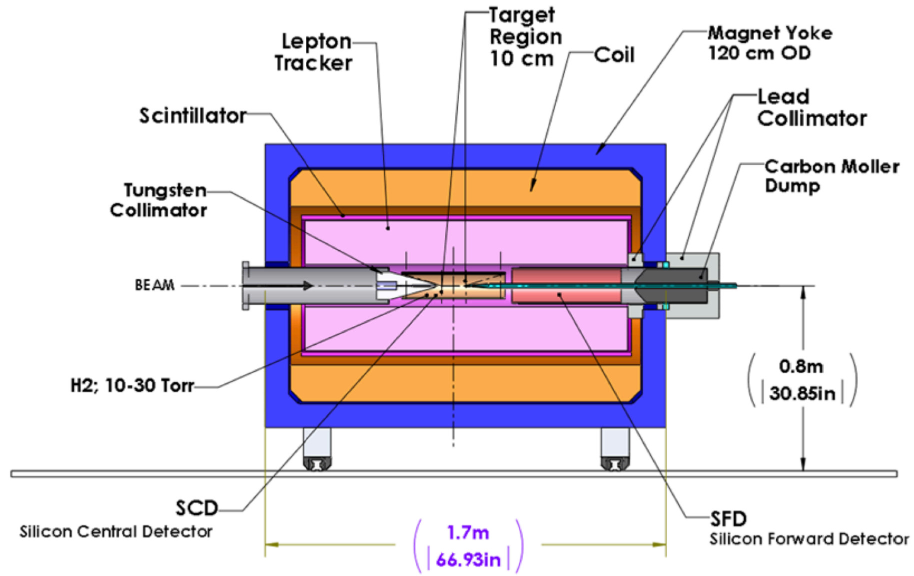
- Internal gas experiment exploiting JLab FEL electron beam (10 mA, 140 MeV) surrounded by compact magnetic spectrometer to search for hidden photons via their decays into lepton pairs,

$$e^- + p \to e^- + p + A' \to e^- + p + e^- + e^+$$



[Freytsis,Ovanesyan,Thaler '09]

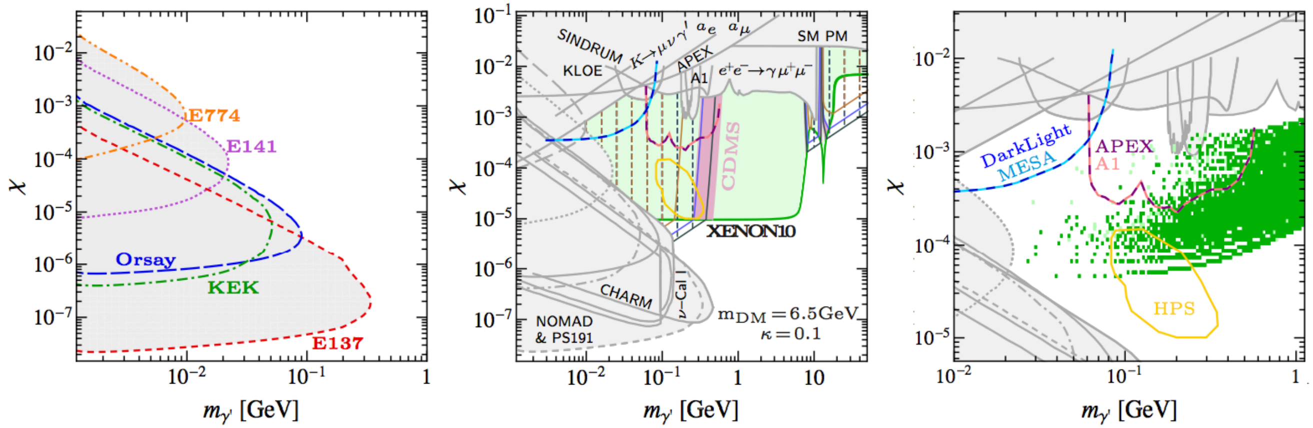




[Balewski et al '13]

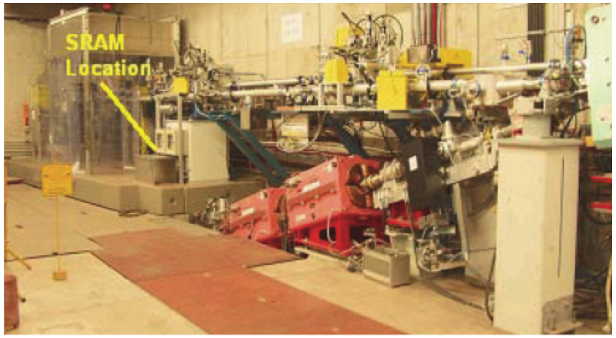
Beam dump searches at FLASH or XFEL?

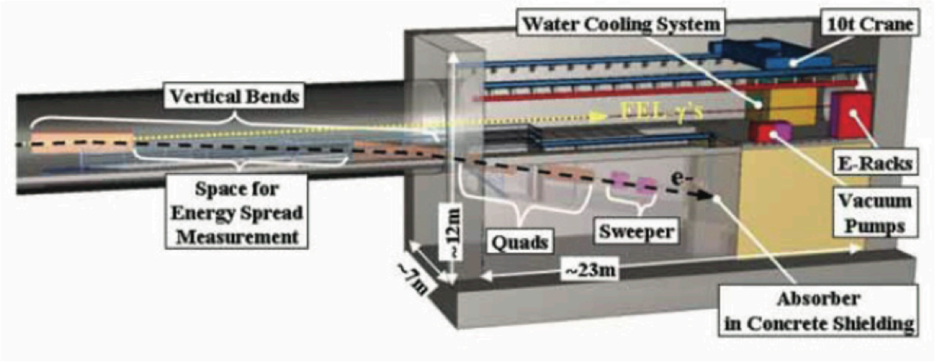
- Parasitic use of spent electron beams at FEL facilities could open further unexplored parameter space



[Andreas,Goodsell,AR '13]

- Not possible at FLASH or European XFEL:





Conclusions

> FELs can be used to study fundamental physics; most promising

- vacuum magnetic birefringence using X-rays as probe, high intensity optical laser to produce the strong magnetic field
- non-linear and non-perturbative QED processes in crossed electron and high intensity optical laser beams
- searches for sub-GeV scale hidden particles in electron beam fixed target experiments

> Should foresee

- to install also an intense optical laser as in the HIBEF at the European XFEL
- to install also a bypass for the electron beam
- to make also the spent electron beam accessible