IX International Symposium
RREPS-11
RADIATION from RELATIVISTIC ELECTRONS in PERIODIC STRUCTURES

Inorganic Scintillators for Particle Beam Profile Diagnostics of high brilliant and high energetic Electron Beams

Gero Kube
DESY / MDI
gero.kube@desy.de

- Motivation: Coherent OTR and Beam Diagnostics
- Scintillating Screen Resolution Studies
- Coherent Radiation and Scintillators
- Outlook

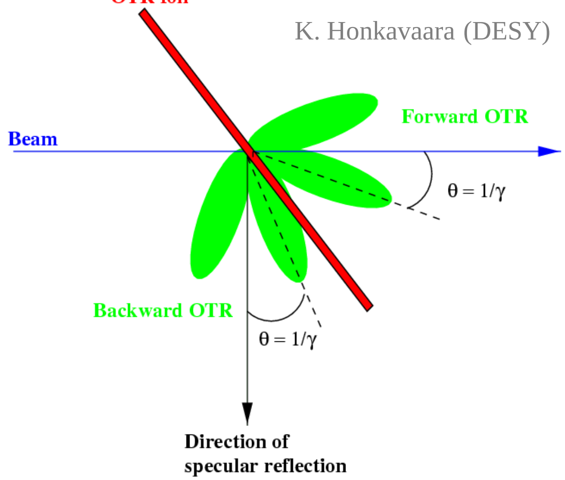
OTR Transverse Beam Profiling

- advantages of Optical Transition Radiation (OTR) beam diagnostics
  - single shot measurement → study of shot-to-shot fluctuations in linac
  - full transverse (2D) profile information
  - linear response → neglecting coherent effects (!)
  - broad selection of available detectors
  - simple and robust setup geometry

    → imaging the beam via OTR in backward direction

courtesy:

K. Honkavaara (DESY)



- nowadays standard method for emittance measurements, beam matching, etc.

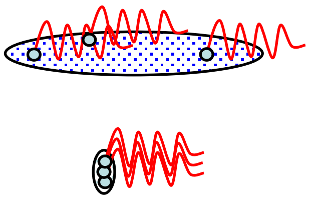
  - in use at nearly all electron linacs
  - OTR monitors replaced formerly used scintillation screens

Breakdown of OTR Beam Profiling

courtesy: S. Wesch (DESY)

- method relies on incoherent radiation of individual bunches
  - incoherent addition of Point Spread Function (PSF)
    - → reflects transverse charge distribution

- origin of coherent (optical) radiation
  - overall bunch length σ_t ~ 1 fs
    - → superposition of fields (interference effects)
    - → enhancement of emitted intensity



long bunch ($\lambda<\sigma_t$)

short bunch ($\lambda>\sigma_t$)

$$\frac{I_{coh}}{I_{incoh}} \approx N \cdot \left|F(\vec{k})\right|^2 \quad \text{with} \quad F(\vec{k}) = \int \mathrm{d}\vec{x}\, \rho_n(\vec{x}) \cdot e^{-i\vec{k}\cdot\vec{x}}$$

bunch form factor

  - micro-structures inside bunch with σ_{MS} ~ 1 fs

number of electrons N large (~10^9) → only small fraction has to contribute

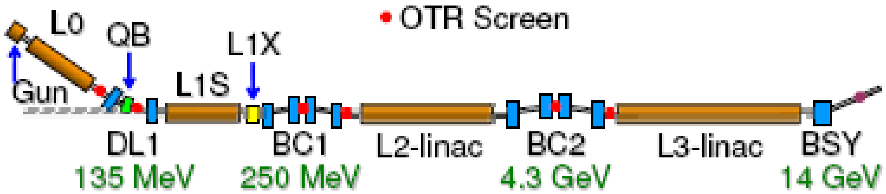
➡ no image of beam profile!

→ COTR on purpose @ APS: A.H. Lumpkin et al., Phys. Rev. Lett. **86** (2001) 79

Unexpected COTR @ LCLS

R. Akre et al., Phys. Rev. ST Accel. Beams **11** (2008) 030703   H. Loos et al., Proc. FEL 2008, Gyeongju, Korea, p.485.

- Linac Coherent Light Source (LCLS) @ SLAC

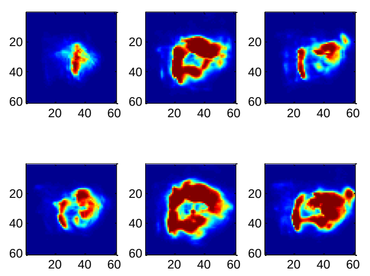


- uncompressed beam, OTR behind BC1
- σ_t = 2.4 ps (rms)
- scan of quad QB → intensity varies by factor 4 ($\sigma_{x,y}$ increased by 25 %)

comparison with incoherent level → only fraction of $3 \cdot 10^{-5}$

- OTR monitor observation with BC1, BC2 switched on

- OTR 12



- OTR 22

- strong shot-to-shot fluctuations
- doughnut structure
- change of spectral contents

measured spot is no beam image!

courtesy: S. Wesch (DESY)

- interpretation of coherent formation in terms of “Microbunching Instability”

E.L. Saldin et al., NIM **A483** (2002) 516   Z. Huang and K. Kim, Phys. Rev. ST Accel. Beams **5** (2002) 074401

COTR Observations

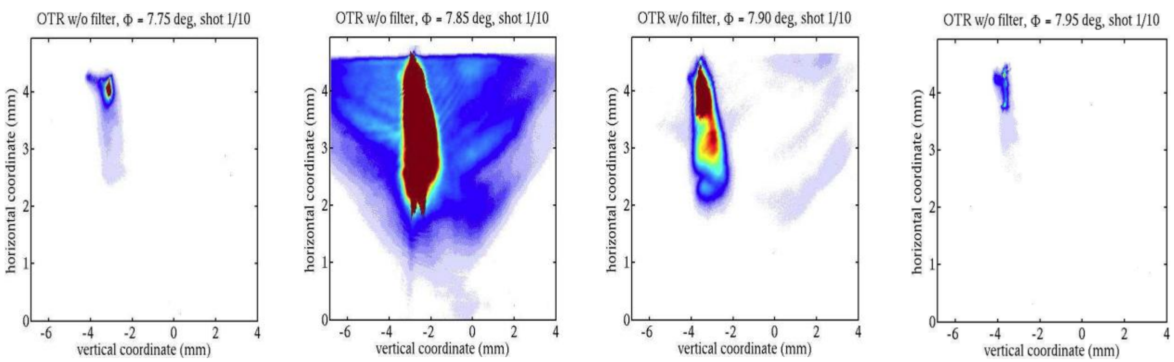
- APS (Argonne, USA)
  - in operation
  - A.H. Lumpkin et al., Phys. Rev. ST Accel. Beams **12** (2009) 080702
- NLCTA (SLAC , USA)
  - in operation
  - S. Weathersby et al., Proc. PAC 2011, New York, USA, p.1.
- FLASH (DESY Hamburg, Germany)
  - in operation
  - S. Wesch et al., Proc. FEL 2009, Liverpool, UK, p.619.
  - C. Behrens et al., Proc. FEL 2010, Malmö, Sweden, p.311.
- FERMI (ELETTRA , Italy)
  - commissioning
  - S. di Mitri, private communication
- SACLA (Spring-8 , Japan)
  - commissioning
  - talk by H. Tanaka @ FEL 2011, Shanghai, China, August 2011

- summary of COTR effects
  - S. Wesch and B. Schmidt, Proc. DIPAC 2011, Hamburg, Germany, p.539.

Consequences

- LCLS: coherent emission compromise use of OTR as reliable beam diagnostics
  - wire scanner for transverse beam diagnostics instead of OTR monitors

- FLASH: COTR observed after modifications to linearize longitudinal phase space



SMATCH screen before FLASH undulator

- **COTR also expected for the E-XFEL**

- alternative schemes for transverse profile diagnostics
  - TR at smaller wavelengths (EUV-TR): L.G. Sukhikh et al., Proc. DIPAC 2011, Hamburg, Germany, p. 544.
  - possibility of transverse beam size diagnostics using PXR: A.S. Gogolev et al., this conference
  - **screen monitors:**

    widely used at hadron accelerators, nearly no information available for high energy electron machines

    B.Walasek-Höhne and G.Kube, Proc. DIPAC 2011, Hamburg, Germany, p. 553

⟹ **ongoing R&D projects @ DESY**

Inorganic Scintillators

- properties
  - radiation resistant → widely used in high energy physics, astrophysics, dosimetry,…
  - high stopping power → high light yield
  - short decay time → reduced saturation

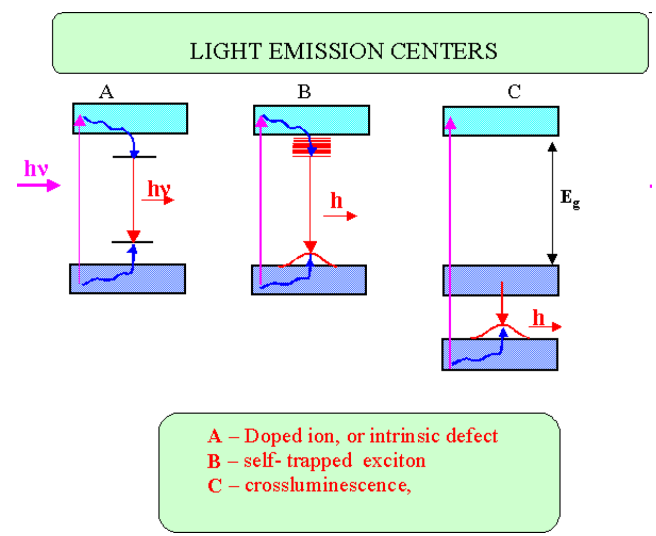
- generation of scintillation light
  - energy conversion (characterstic time 10^{-18} – 10^{-9} sec)

    Formation of el. magn. shower. Below threshold of e^+e^- pair creation relaxation of primary electrons/holes by generation of secondary ones, phonons, plasmons, and other electronic excitations.
  - thermalization of seconray electrons/holes (10^{-16} – 10^{-12} sec)

    Inelastic processes: cooling down the energy by coupling to the lattice vibration modes until they reach top of valence resp. bottom of conduction band.
  - transfer to luminescent center (10^{-12} – 10^{-8} sec)

    Energy transfer from e-h pairs to luminescent centers.
  - photon emission (> 10^{-10} sec)

    radiative relaxation of excited luminescence centers



http://crystalclear.web.cern.ch/crystalclear/

Requirements for Beam Diagnostics

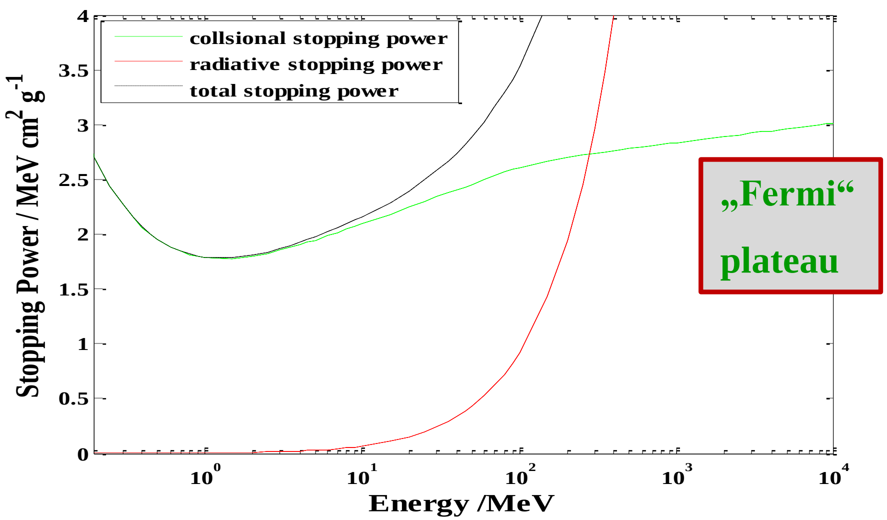
- high spatial resolution

→ influences on light generation process

- light generation in thin target (thickness / $X_0 \approx 10^{-2}$)

→ energy **deposition** of importance

→ ignore radiative stopping power



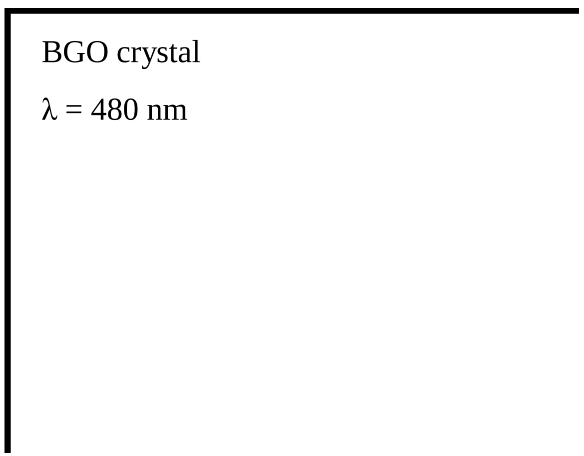
- Fermi plateau: cancellation of incoming particle field by induced polarization field of electrons in medium

→ saturation range $R_\delta = \frac{\hbar c}{\hbar \omega_p}$ ω_p: plasma frequency

- low signal distortion

→ light propagation

- light generated inside scintillator has to cross surface



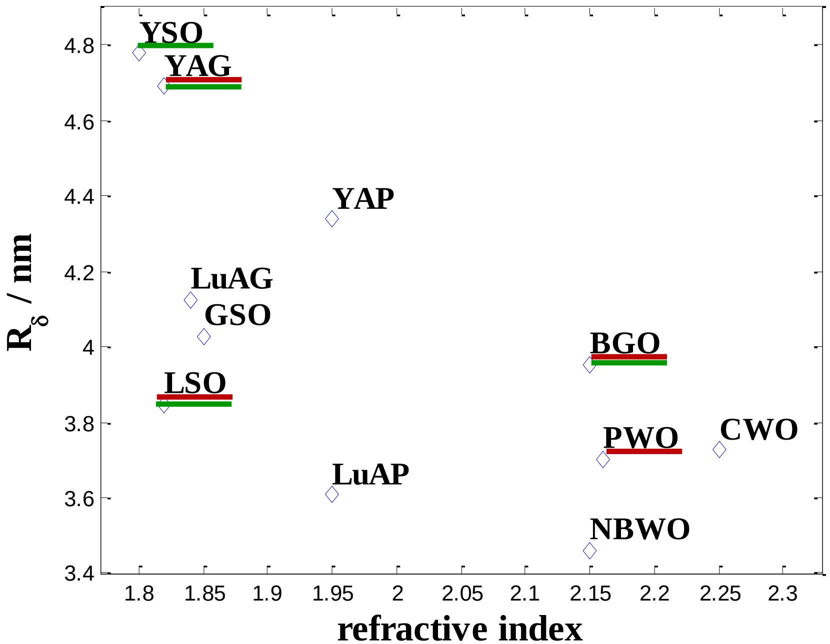
→ refractive index n

- inorganic scintillotors: **high n**

→ large contribution of total reflection

→ **influence on observation geometry**

Scintillator Material Properties



	ρ / g/cm^3	ħω / eV	λ_{max} / nm	yield / 1/keV	n @ λ_{max}	R_δ / nm
BGO	7.13	49.9	480	8	2.15	3.95
PWO	8.28	53.3	420	0.1	2.16	3.70
LSO:Ce	7.1	51.3	420	32	1.82	3.85
YAG:Ce	4.55	42.1	550	11	1.82	4.69
LuAG:Ce	6.76	47.8	535	14	1.84	4.12
YSO:Ce	4.45	41.3	420	9.2	1.80	4.78

- series of measurements

October 2009

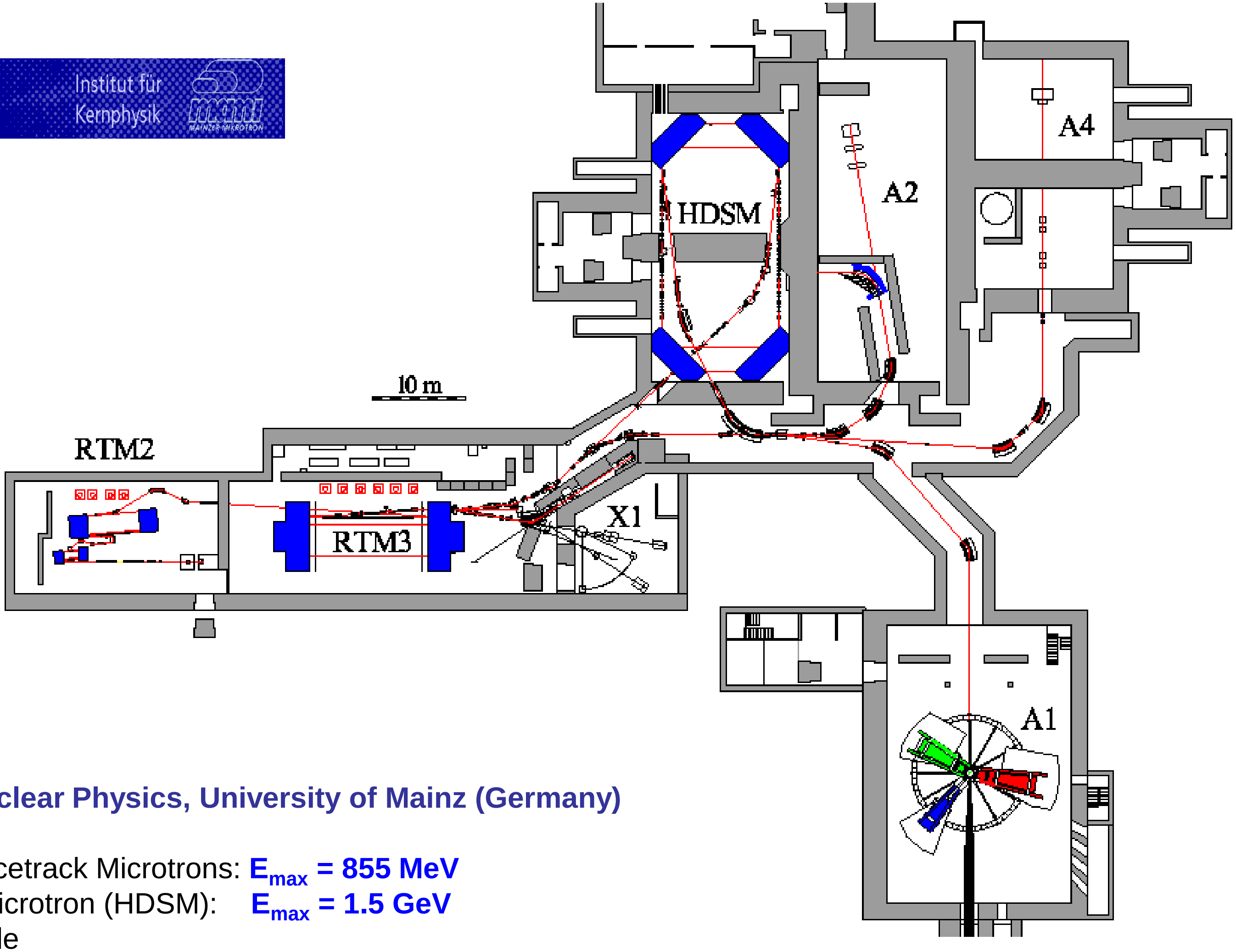
- BGO 0.5 mm
- PWO 0.3 mm
- LYSO:Ce 0.8 mm, 0.5 mm (Prelude 420)
- YAG:Ce 1.0 mm, 0.2 mm, powder
- Al_2O_3 1.0 mm (ceramic)

March 2011

- BGO 0.3 mm
- LYSO:Ce 0.3 mm (Prelude 420, CRY-19 (?))
- YAG:Ce 0.3 mm
- LuAG:Ce 0.3 mm
- YSO:Ce (?) 0.3mm (CRY-18)

Mainz Microtron MAMI

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Institut für Kernphysik
MAINZER MIKROTRON

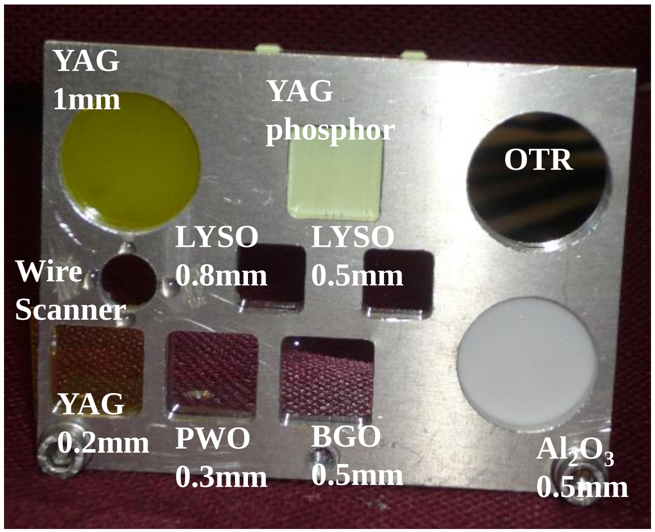


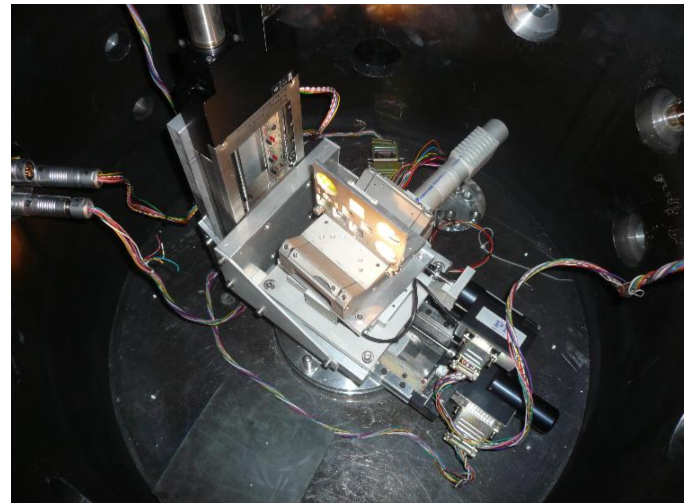
Institute of Nuclear Physics, University of Mainz (Germany)

3 cascaded Racetrack Microtrons: E_{max} = 855 MeV
double-sided Microtron (HDSM): E_{max} = 1.5 GeV
100 % duty cycle
polarized electron beam (~ 80%)

Experimental Setup

- target





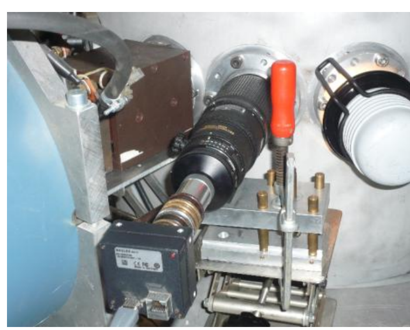
- observation geometry

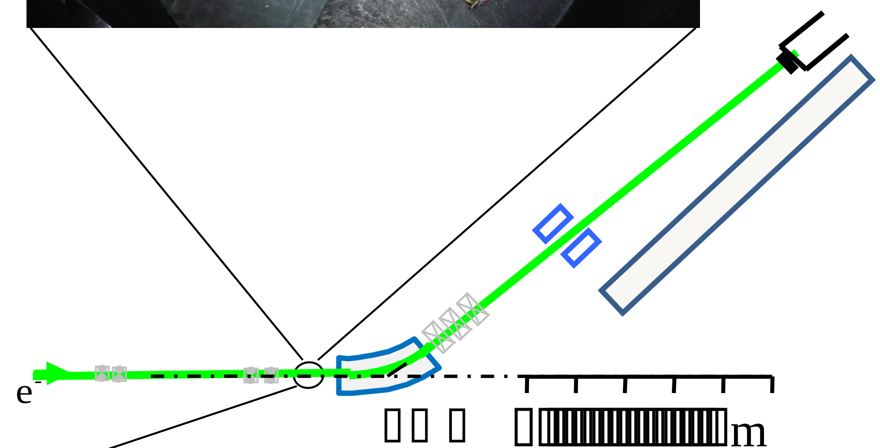
-22.5° w.r.t. beam axis

camera: BASLER A311f

659 x 494 pixel

pixel size 9.9µm x 9.9µm



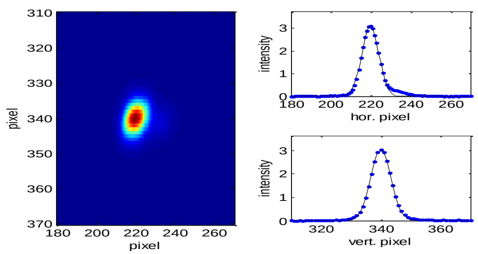


- X1 beamline

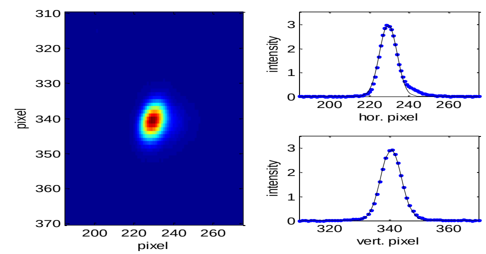
Beam Images

- *measurement and analysis:* I = 46 pA 5 signal and 1 background frame

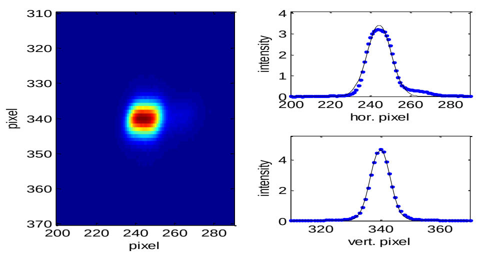
- LYSO:Ce (0.5mm)



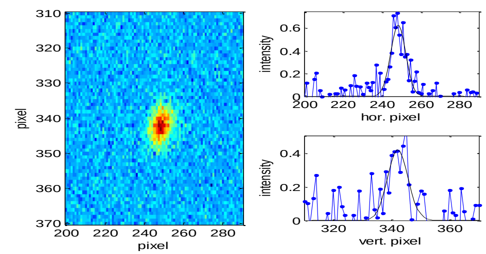
- BGO (0.5mm)



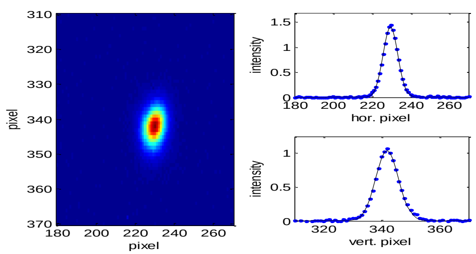
- LYSO:Ce (0.8mm)



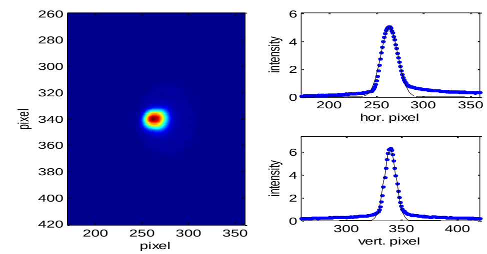
- PWO (0.3mm)



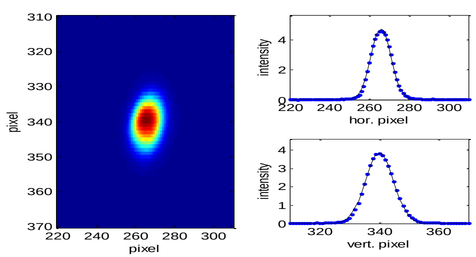
- YAG:Ce (powder)



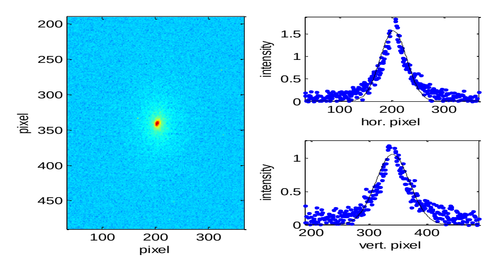
- YAG:Ce (1mm)



- YAG:Ce (0.2mm)



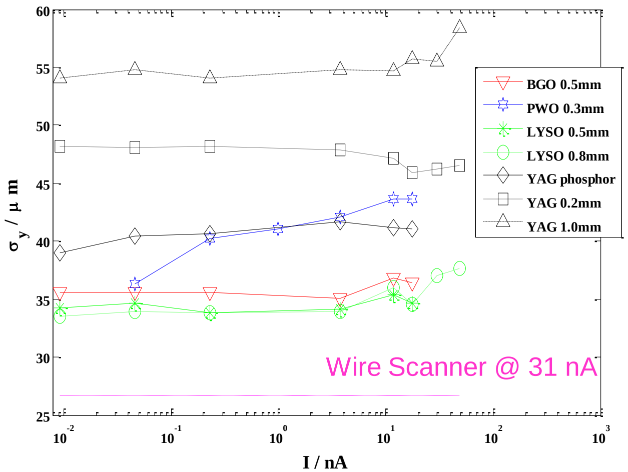
- Al_2O_3 (0.5mm)

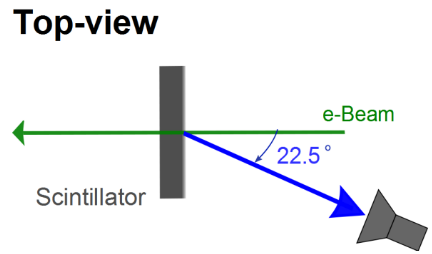


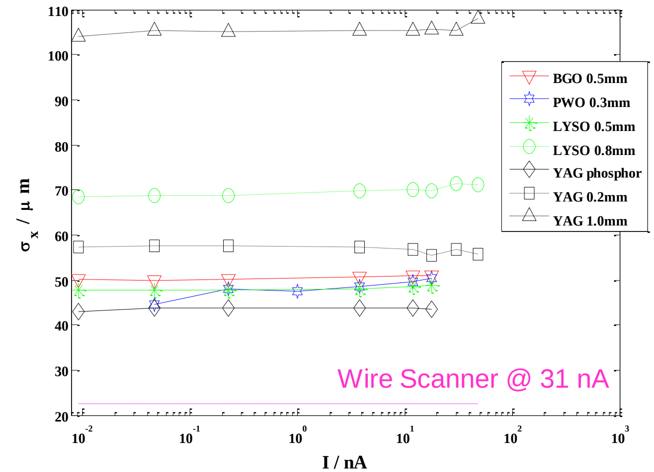
different scale !

Spatial Resolution

- experiment 2009

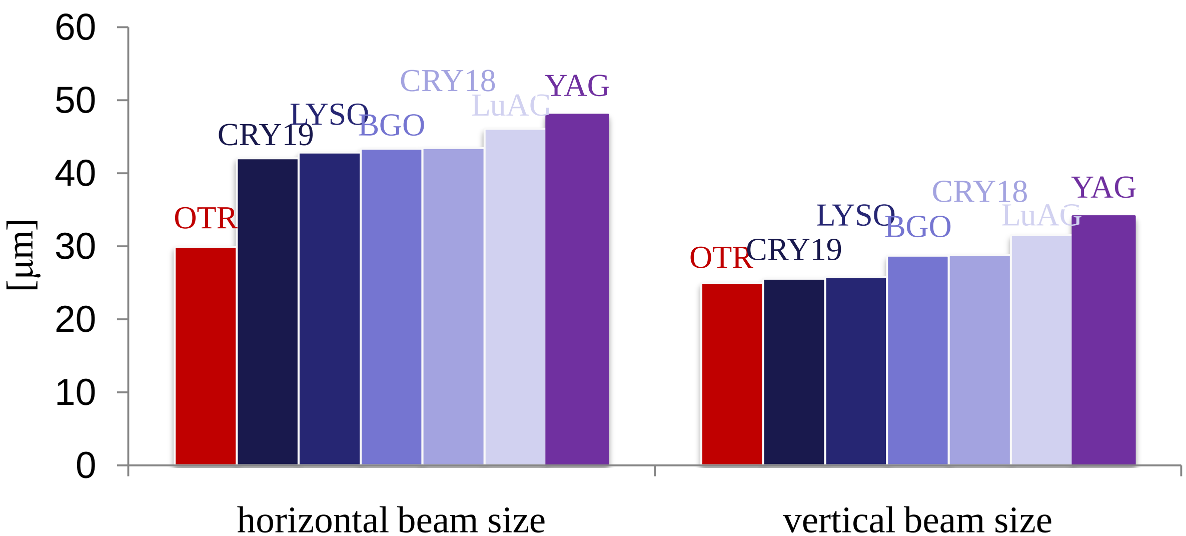






- experiment 2011

G. Kube et al., Proc. IPAC'10, Kyoto (Japan), 2010, p.906



favorite materials

BGO and LYSO

⇒ dependency on observation geometry

Observation Geometry

- beam diagnostics

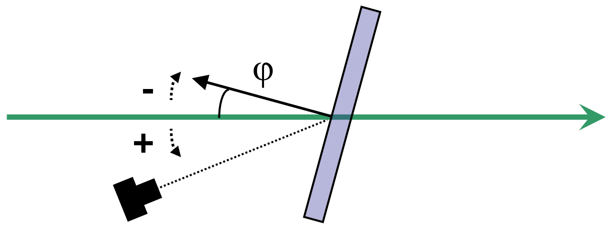
  → popular OTR-like observation geometry:

45°tilt of screen

observation under 90°

→ **turns out to be bad!**

- scintillator tilt versus beam axis

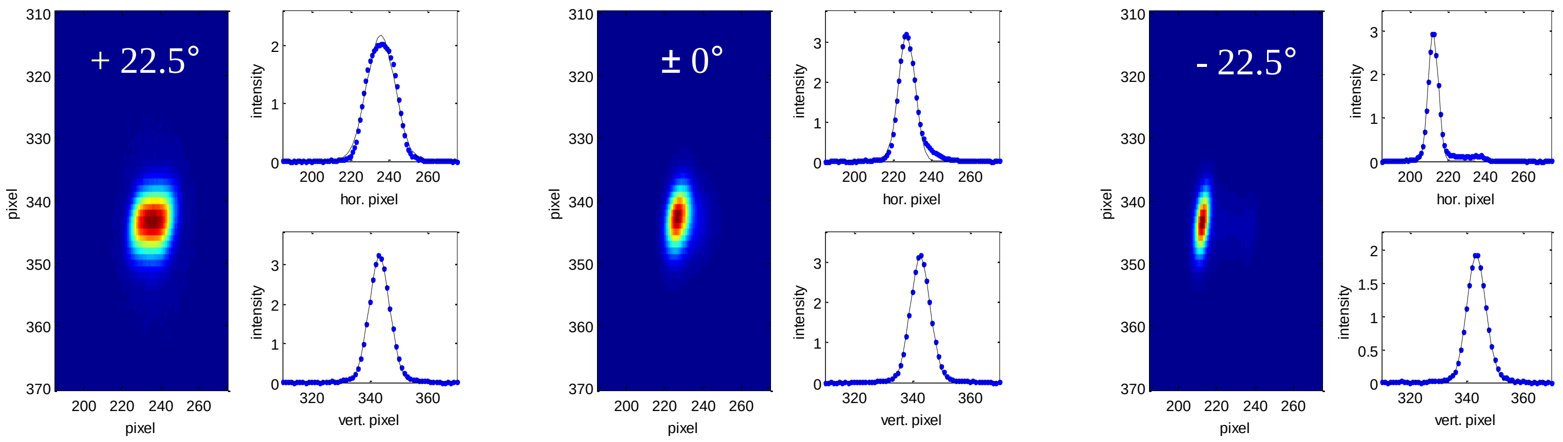


BGO crystal

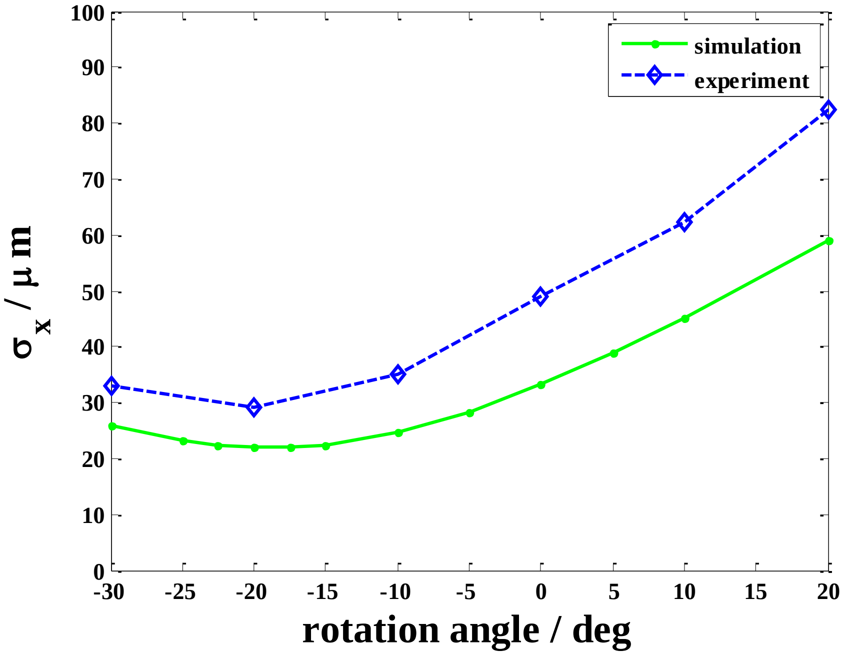
micro-focused beam

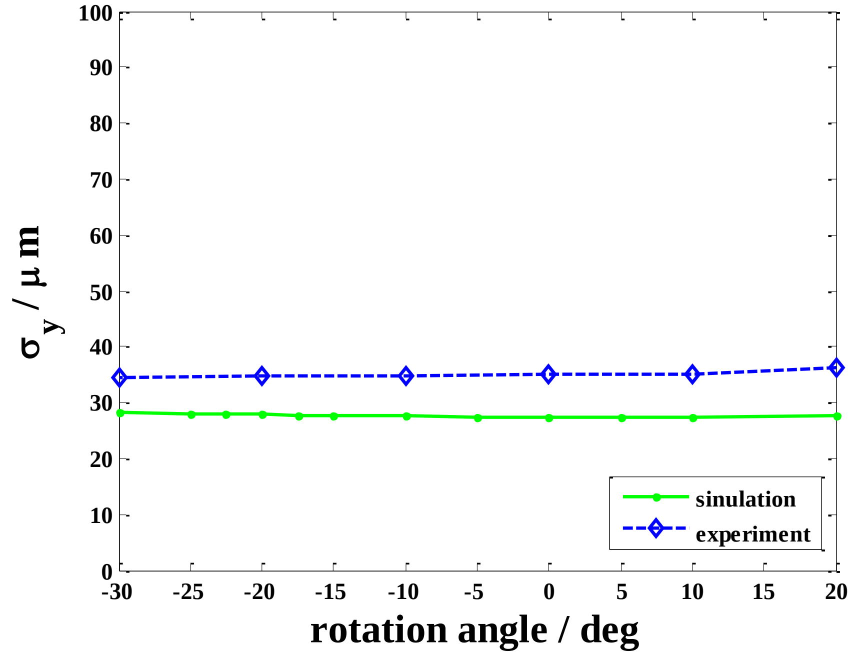
I = 3.8 nA

- measured beam spots



Comparison





- satisfactory agreement between simulation and measurement

  → simulation reproduces observed trend in beam size

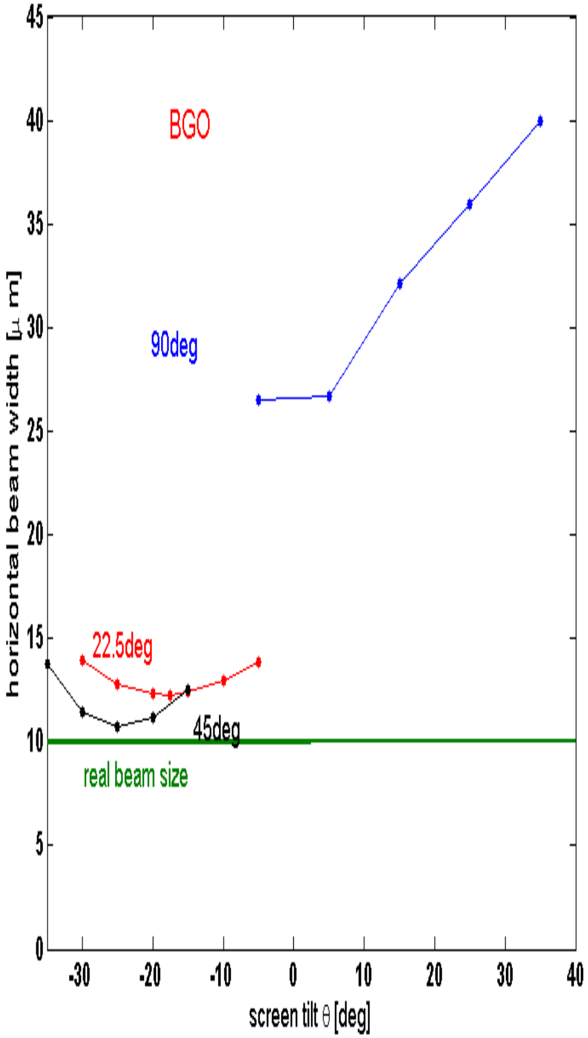
- measured beam size systematically larger than simulated one

  → effect of extension radius not included in calculation → increase in PSF

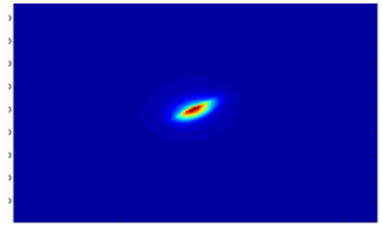
G. Kube, C. Behrens, and W. Lauth, Proc. IPAC 2010, Kyoto, Japan, p.906.

Observation Geometry Influence

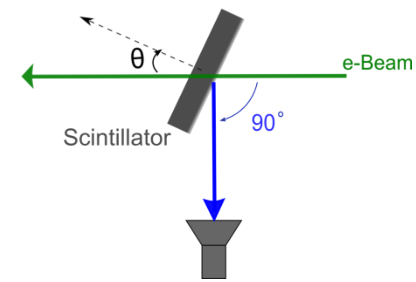
- comparison observation geometry



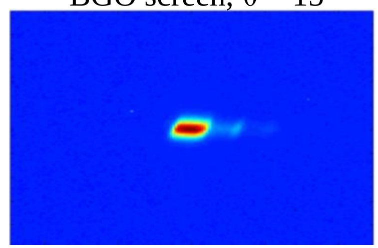
OTR screen



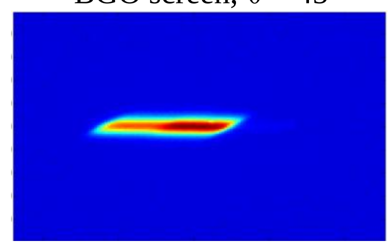
Top-view



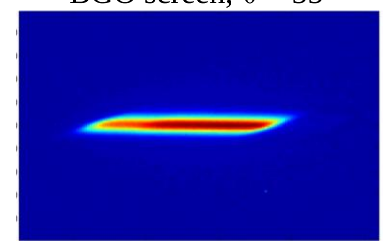
BGO screen, θ = 15°



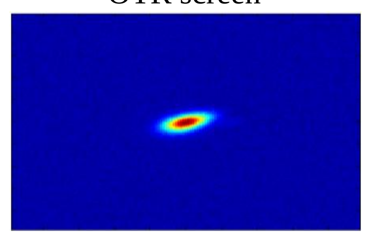
BGO screen, θ = 45°



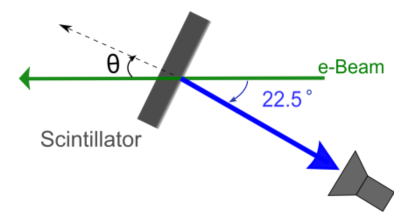
BGO screen, θ = 55°



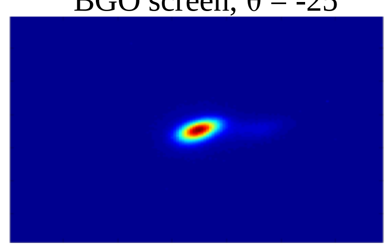
OTR screen



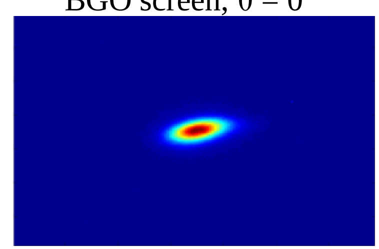
Top-view



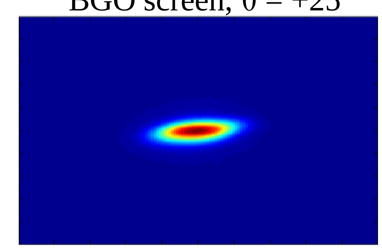
BGO screen, θ = -25°



BGO screen, θ = 0°



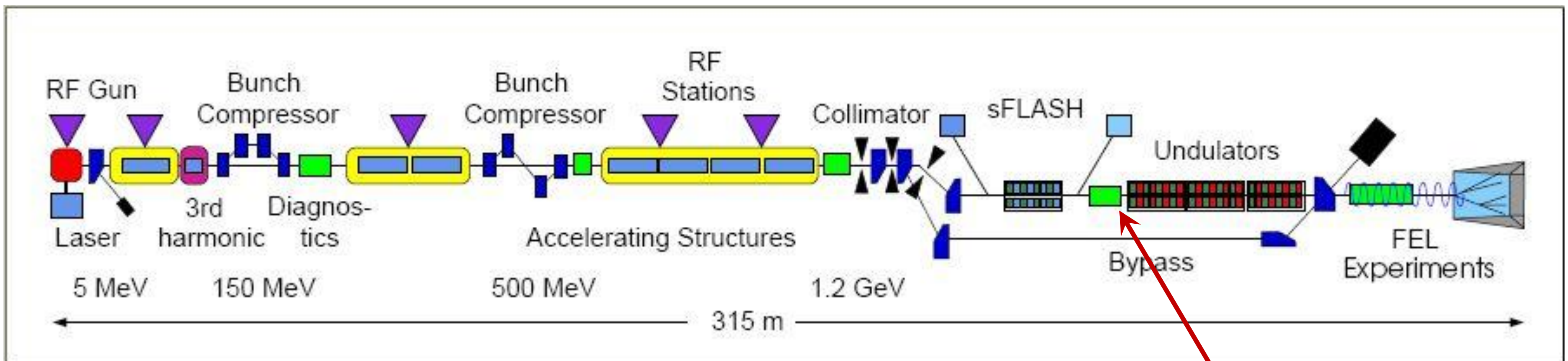
BGO screen, θ = +25°



COTR at Screens

- OTR generation at scintillation screen
  - boundary between scintillation screen and vacuum
    - → (C)OTR generation
    - → may be reflected to camera

- test experiment at FLASH (DESY Hamburg)

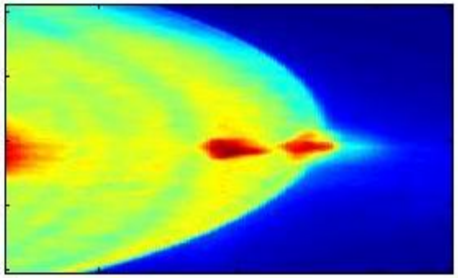


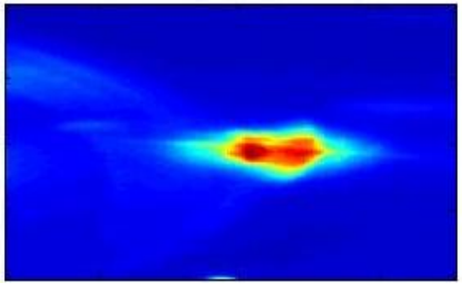
max. beam energy	**1.25 GeV**
min. lasing wavelength	**4.12 nm**
typical photon pulse energy	**> 100 µJ**
typical bunch charge	**1 nC**
normalized emittance	**~ 2 mm mrad**

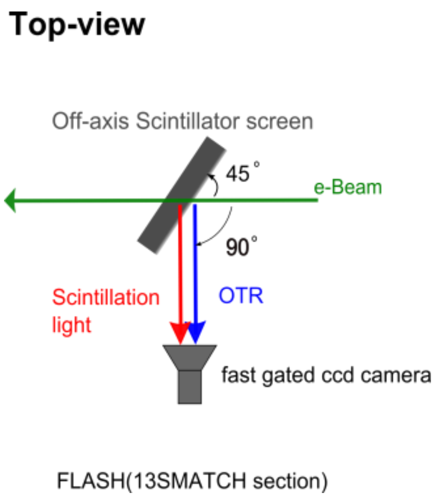
- **LuAG:Ce** and **OTR** screen
  - → location prone to Microbunching Instability
  - → observation under 90°

Observation and Suppression

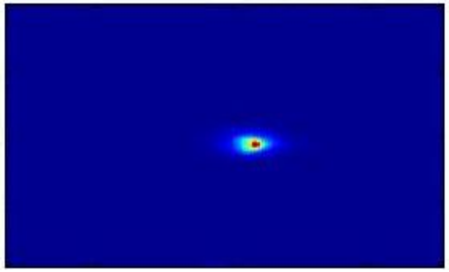
- **coherent radiation observation**
  - Al coated Si OTR screen
    → COTR and coherent SR
  - LuAG screen
    → COTR and scintillation light







- **temporal suppression of coherent radiation**
  - **basic idea:** OTR emission is instantaneous process, scintillation light emitted with delay
    → fast optical shutter
    → read-out with gated camera: camera time delay ≥ scintillation light decay time

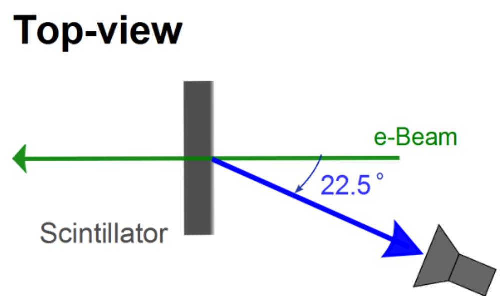


- LuAG screen, 100ns time delay
  → only scintillation light

M. Yan et al., Proc. DIPAC 2011, Hamburg, Germany, p.440.

Outlook

- principle of temporal suppression works
  - observation of pure scintillation light for beam profile determination
  - fast optical switch realized with image intensifier
    - → expensive optical camera systems (about 20 kEUR)
    - → decrease of image resolution
- investigation of spatial suppression
  - no direct reflection of COTR
  - improving influence of observation geometry
    - → influence of Cherenkov radiation ???



additional open points

- influence of luminescent centers on resolution
  - → different dopands, different concentration ?
- screen saturation

saturation at high intensities (> 0.04 pC/cm^2) observed for YAG:Ce screens (A. Murokh et al., Proc. PAC 2001, 1333)

→ material properties of interest: band gap , scintillation decay time

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