Resolution Studies of inorganic Scintillation Screens for high energetic and high brilliant Electron Beams

Gero Kube, Christopher Behrens (DESY),
Werner Lauth (IKP, Mainz)
gero.kube@desy.de

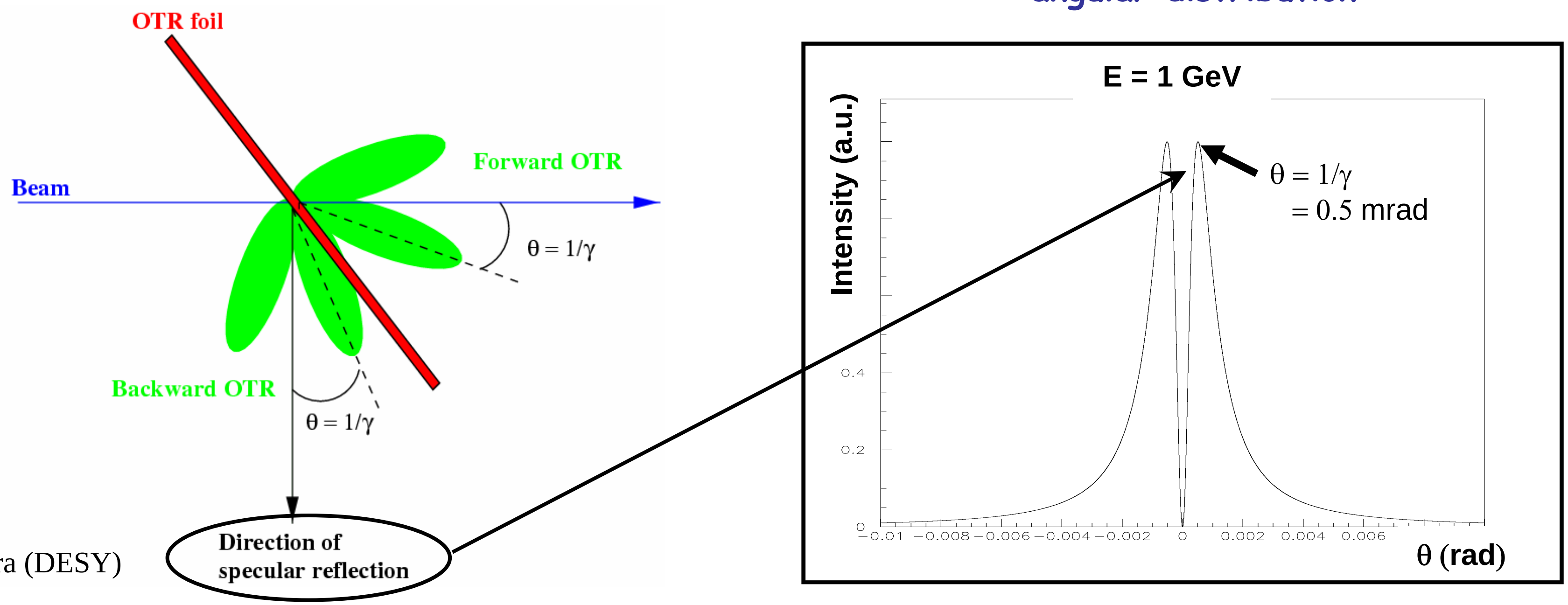
- Introduction
- Results of Test Experiment @ MAMI
- Outlook

DESY
HELMHOLTZ GEMEINSCHAFT

Standard Diagnostics in Linacs: OTR

- transition radiation: electromagnetic radiation emitted when a charged particle crosses boundary between two media with different optical properties
- visible part: Optical Transition Radiation (OTR)
- beam diagnostics: backward OTR (reflection of virtual photons)
  typical setup: image beam profile with optical system
  → beam image and measurements of beam shape and size

angular distribution



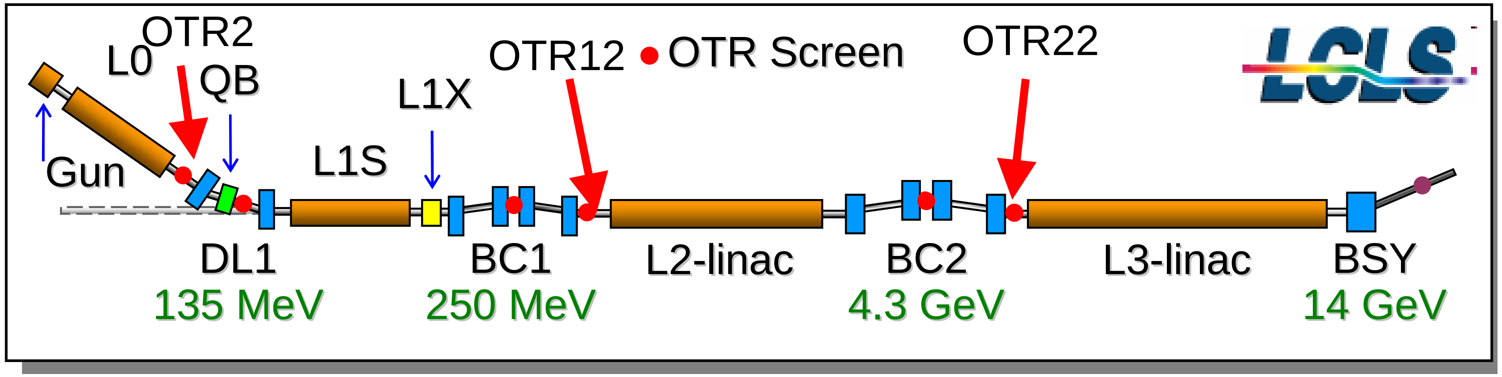
courtesy:

K. Honkavaara (DESY)

OTR Diagnostics: Pitfalls

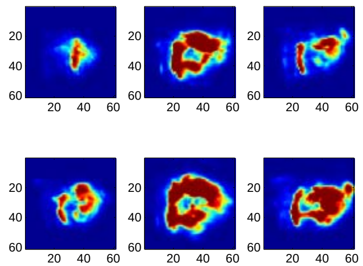
- Linac Coherent Light Source (LCLS) @ SLAC

courtesy: H. Loos (SLAC)

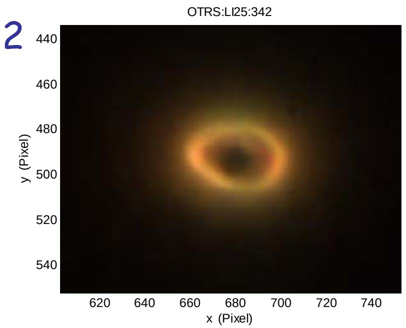


- OTR monitor observation with BC1, BC2 switched on

  - OTR 12



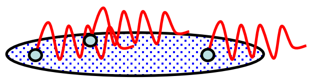
  - OTR 22



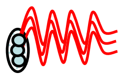
⇒ measured spot is no beam image

- interpretation: coherent OTR (COTR) emission

  → strong compression in bunch compressors



long bunch ($\lambda<\sigma_z$)



short bunch ($\lambda>\sigma_z$)

➡ in the meantime COTR also at FLASH

Consequences & Alternatives

- LCLS: coherent emission compromise use of OTR as reliable beam diagnostics

    → wire scanners for transverse beam diagnostics instead of OTR

- profile diagnostics based on transition radiation

    reduce coherent effects: observation at smaller wavelength

    → **EUV/XUV transition radiation imaging**

    (in collaboration with Tomsk Polytechnic University, Russia and Institut für Kernphysik, Mainz University)

    1.) spectral range of coherent emission ?

    2.) EUV/XUV optics expensive and difficult to handle

- profile diagnostics based on different physical processes

    - **wire scanners** → in preparation for dedicated positions @ XFEL

    - **luminescent screen monitors** → widely used at hadron accelerators
nearly no information for high-energy electron machines

⟹ **motivation for test experiment**

Inorganic Scintillators

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

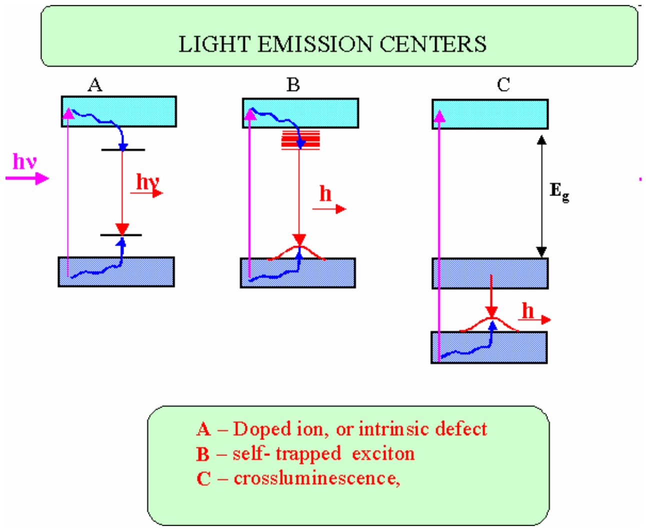
- generation of scintillation light
  - energy conversion (characterstic time $10^{-18} – 10^{-9}$ sec)

    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/

Implication on Transverse Resolution

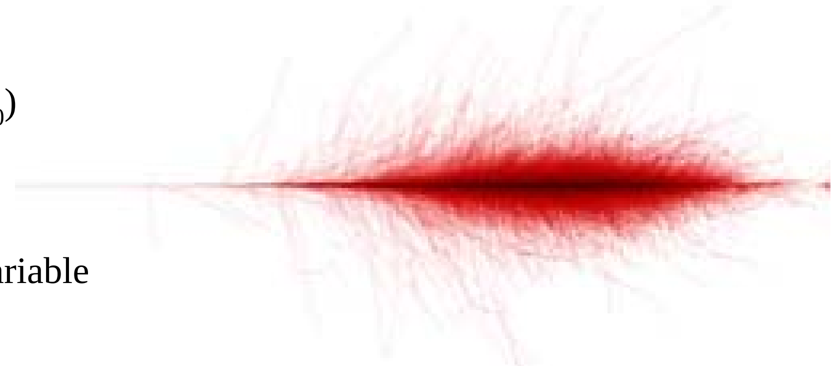
Which effects may affect transverse resolution ?

- light generation: energy conversion → transverse range of ionization
- light propagation → total reflection at scintillator surface

energy conversion

- „thick target“ : formation of electromagnetic shower

  (thickness in the order of radiation length X_0)



F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

- transverse shower dimension: ***Molière radius*** as scaling variable

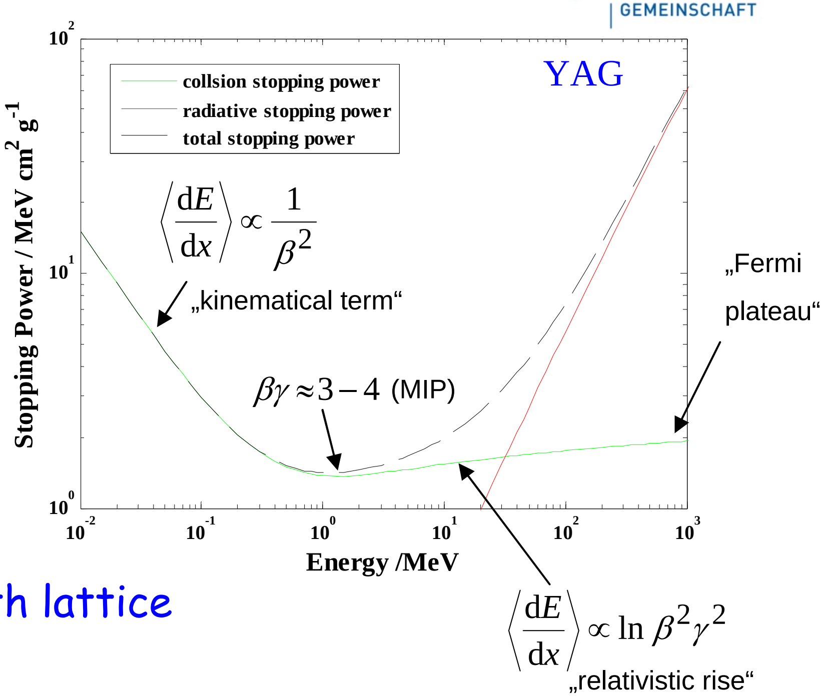
  → containing 90% of shower energy

$$R_M \approx 0.0265\ X_0 (Z + 1.2)$$

X_0 : radiation length, Z : atomic number

Implication on Transverse Resolution

- energy loss
  - Bethe-Bloch (collision)
  - Bremsstrahlung (radiative)



- energy deposition in "thin target"
  - ignore radiative contribution

    - thickness / $X_0 \approx 10^{-2}$

    - small amount of re-absorption in material

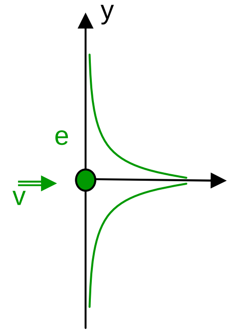
- ionization: interaction of particle em. field with lattice
  - particle field

    virtual photons, in classical picture transverse evanescent waves
  - relativistic rise

    incease of transverse field extension
  - Fermi plateau

    cancellation of incoming particle field by induced polarization field of electrons in medium

    → saturation range as scaling variable R_δ



$$\vec{E} \propto e^{-y/y_0}$$

with $y_0 = \lambda\!\!\!^{-}\, \beta_m \gamma_m$

$$\beta_m = \beta\sqrt{\varepsilon(\omega)}$$

Implication on Transverse Resolution

- extension radius
  - limiting value:

$$R_\delta = \frac{c}{\omega}\sqrt{1-\varepsilon(\omega)}$$

ε(ω): complex dielectric function

  - approximation as free electron gas (Drude model)

$$R_\delta = \frac{\hbar c}{\hbar \omega_p}$$

ω_p: plasma frequency

$$\hbar\omega_p = 28.816\sqrt{\rho\langle Z/A\rangle}\ \text{eV}$$

- light propagation
  - light generated inside scintillator has to cross surface

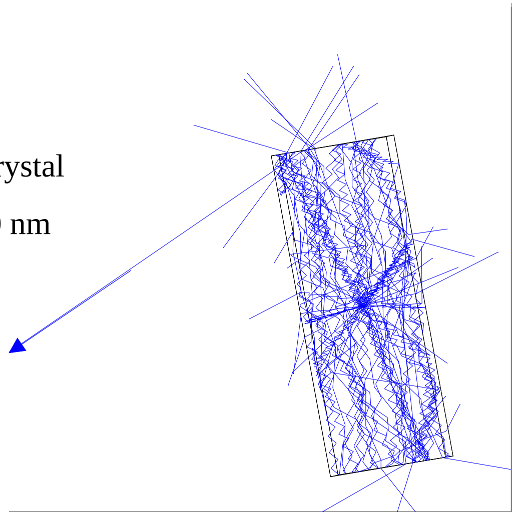
refractive index n

inorganic scintillators

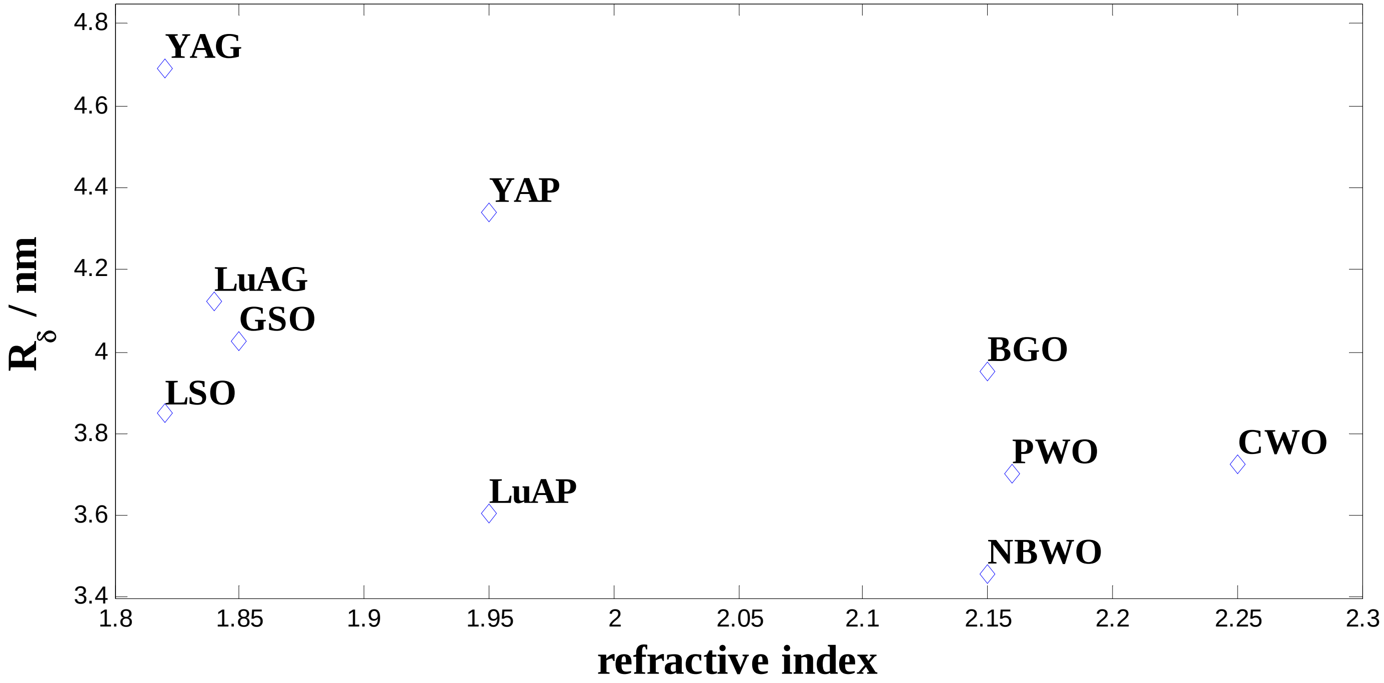
→ high n, i.e. large contribution of total reflection

BGO crystal

λ = 480 nm



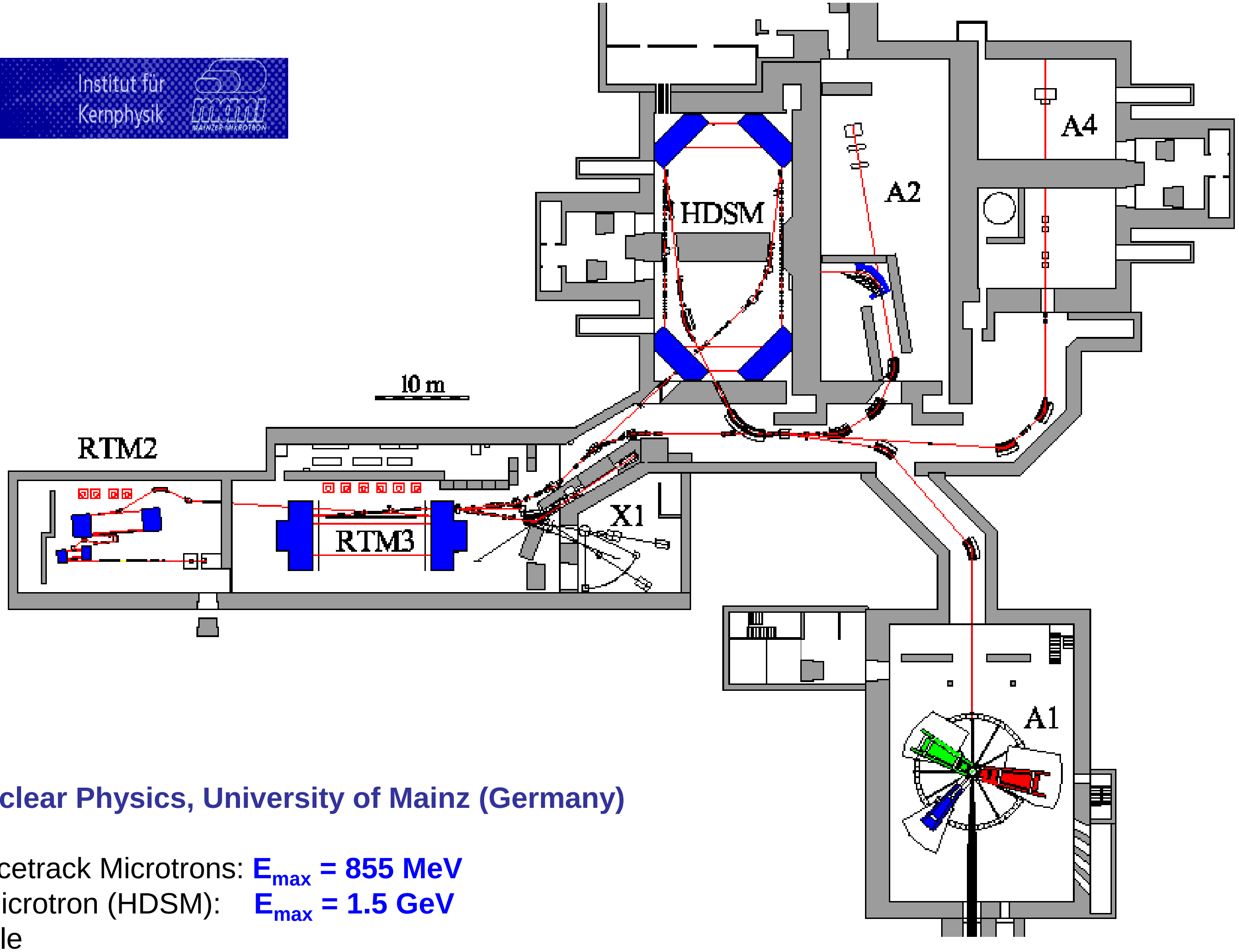
Scintillator Material Properties



- scintillators under investigation
  - BGO: 0.5 mm
  - PWO: 0.3 mm
  - LYSO: 0.8 mm, 0.5 mm (Prelude 420)
  - YAG: 1.0 mm, 0.2 mm, phosphor

	ρ [g/cm^3]	$\hbar\omega_p$ [eV]	R_M [cm]	λ_{max} [nm]	yield [1/keV]	n @ λ_{max}	R_δ [nm]
BGO	7.13	49.9	2.23	480	8	2.15	3.95
PWO	8.28	53.3	2.00	420	0.1	2.16	3.70
LSO:Ce	7.1	51.3	2.08	420	32	1.82	3.85
YAG:Ce	4.55	45.5	2.77	550	11	1.95	4.34

Mainz Microtron MAMI

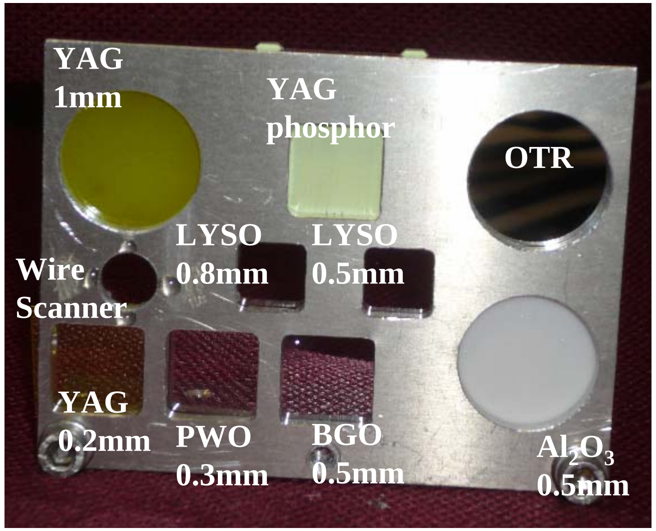


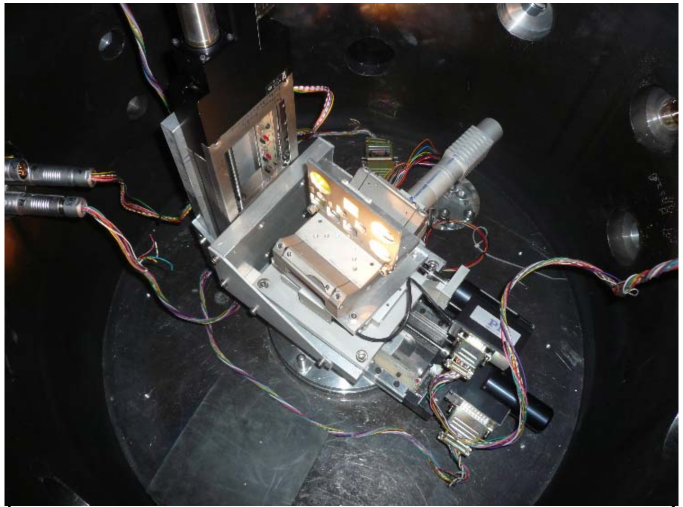
Institute of Nuclear Physics, University of Mainz (Germany)

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





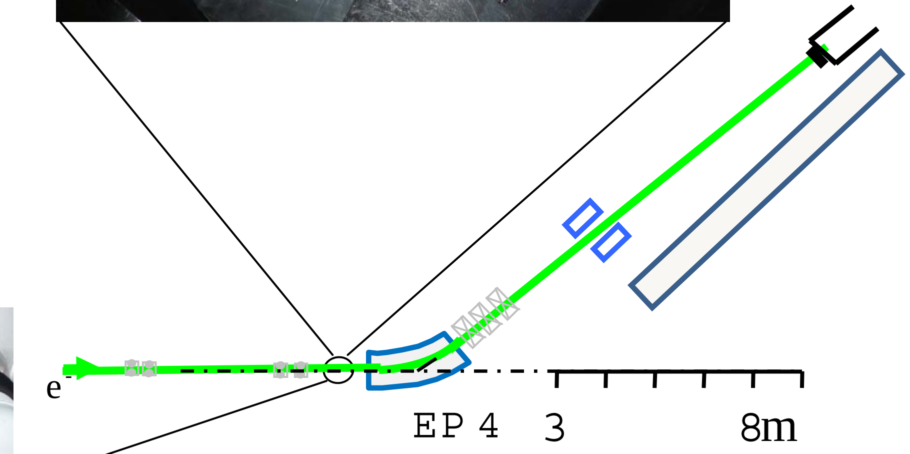
- observation geometry

-22.5° w.r.t. beam axis

camera: BASLER A311f

659 x 494 pixel

pixel size 9.9µm x 9.9µm



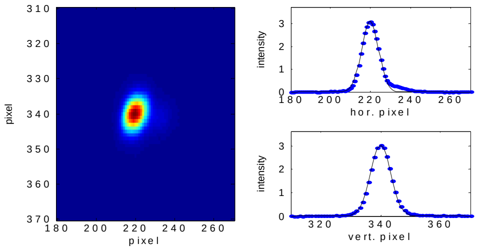
- X1 beamline

Beam Images

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

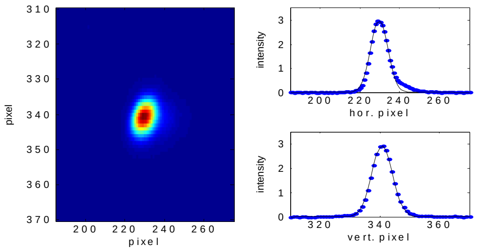
LYSO:Ce

(0.5mm)



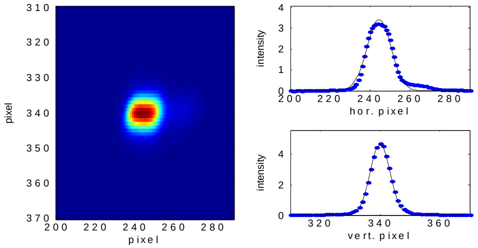
BGO

(0.5mm)



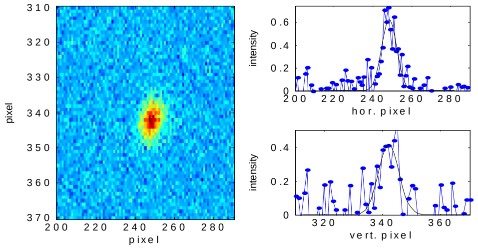
LYSO:Ce

(0.8mm)



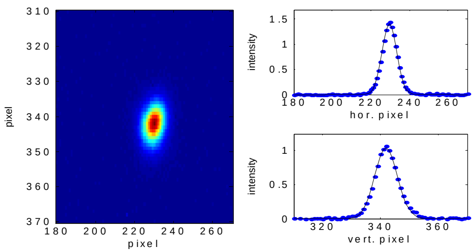
PWO

(0.3mm)



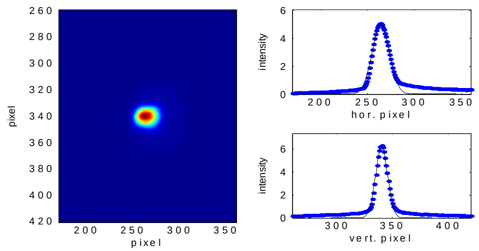
YAG:Ce

(powder)



YAG:Ce

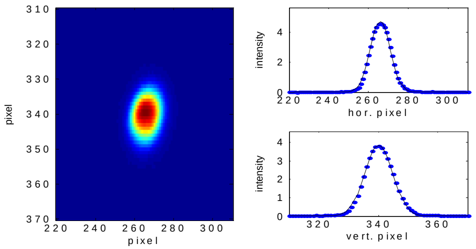
(1mm)



different scale !

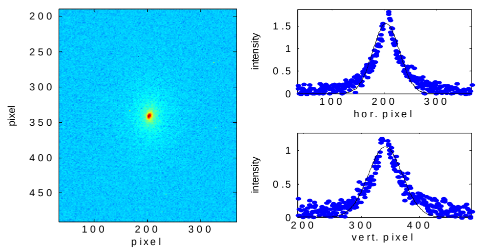
YAG:Ce

(0.2mm)



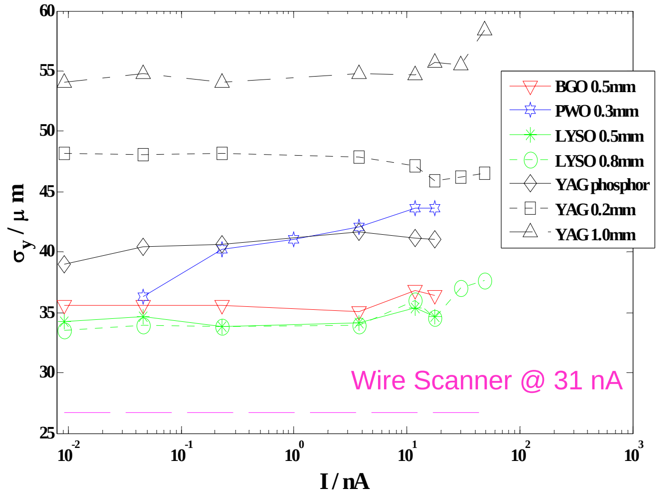
Al_2O_3

(0.5mm)

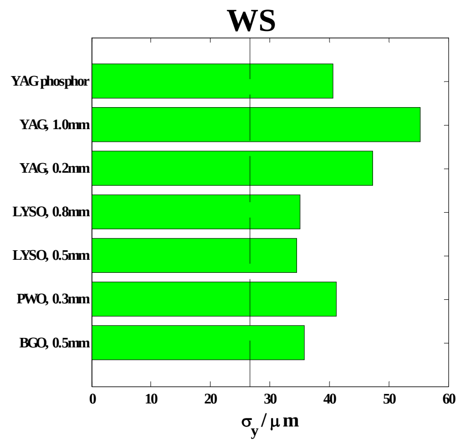


Results

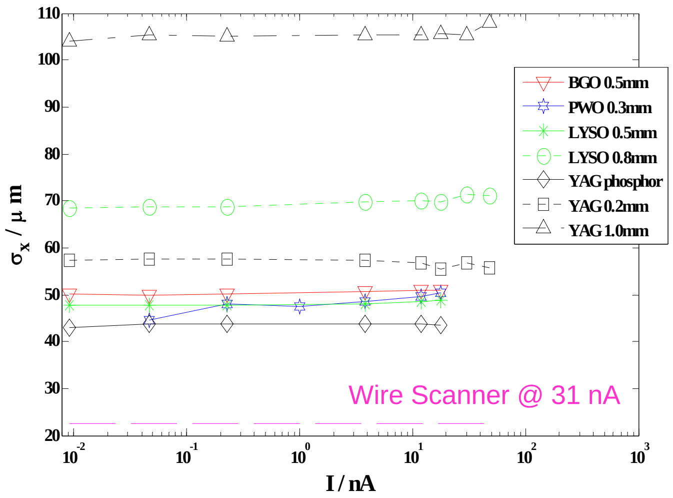
- vertical beam size

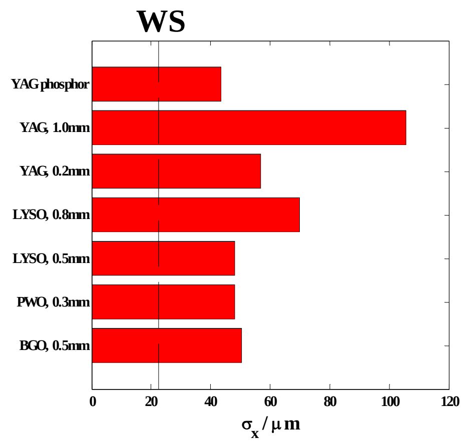


- mean values



- horizontal beam size

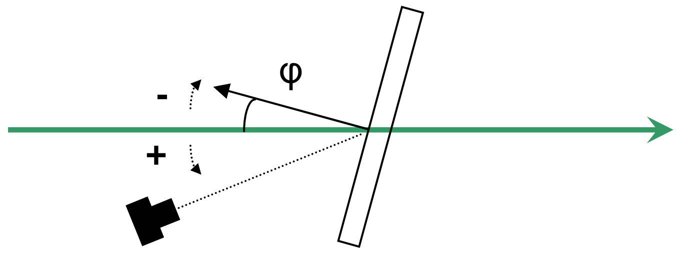




⟹ dependency on observation geometry

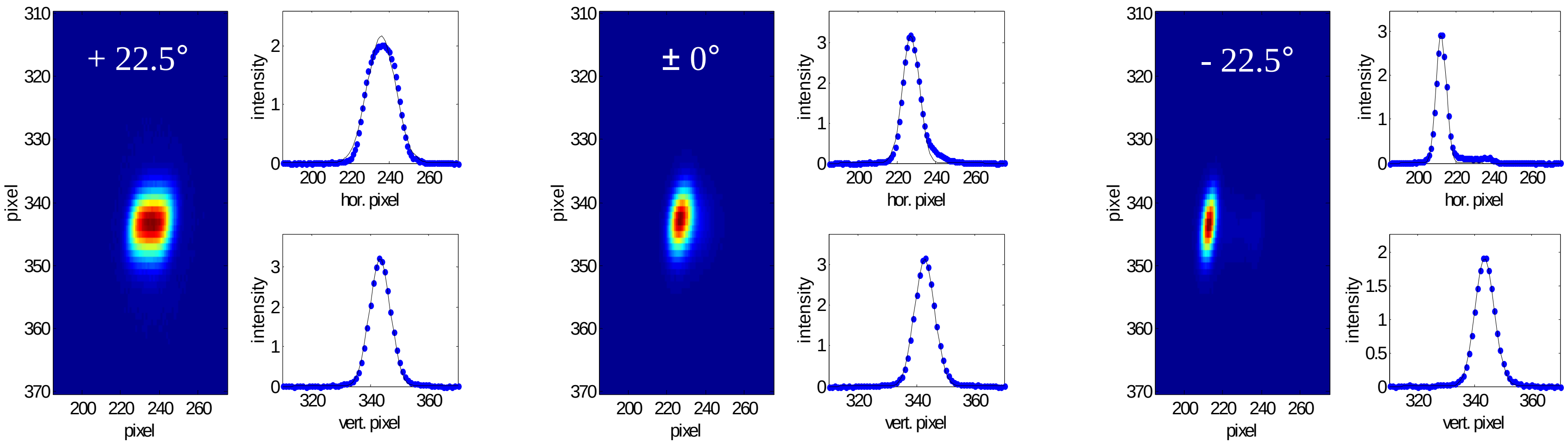
Observation Geometry

- beam diagnostics
  - → popular OTR-like observation geometry:
    - 45°tilt of screen
    - observation under 90°
- scintillator tilt versus beam axis

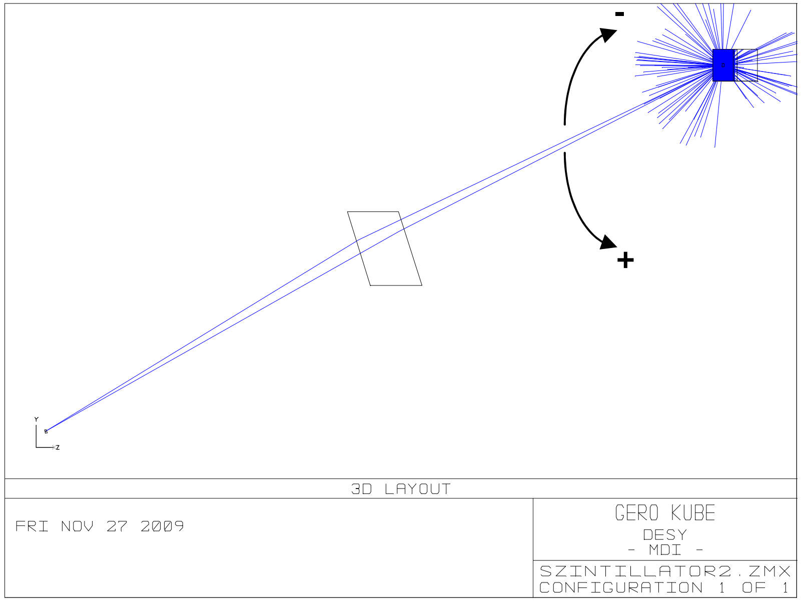


- BGO crystal
- micro-focused beam
- I = 3.8 nA

- measured beam spots



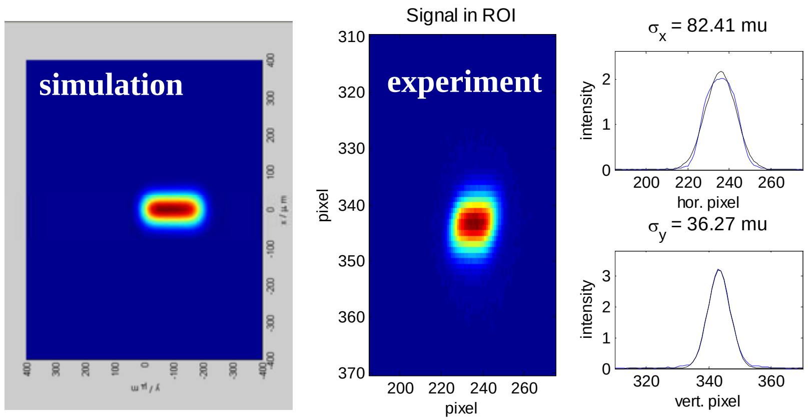
Simulation of Light Propagation



Analysis:

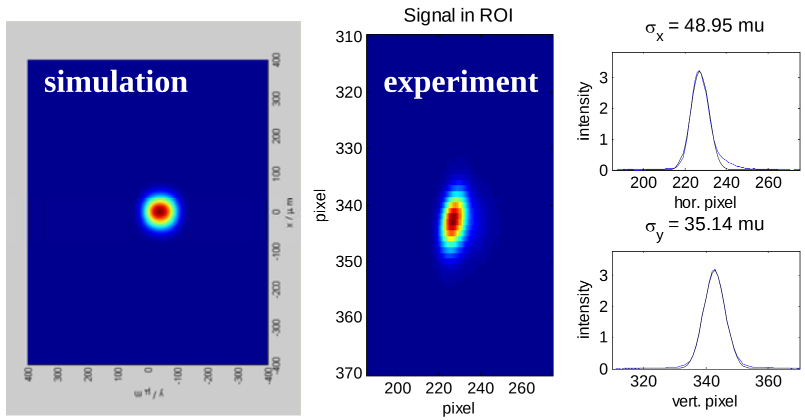
- ZEMAX calculation of 2-dim PSF
- calculation of 2-dim beam profile
- convolution of PSF and beam profile
- horizontal / vertical projection of resulting distribution
- determinatiuon of 2nd moment (standard deviation)

+ 22.5°

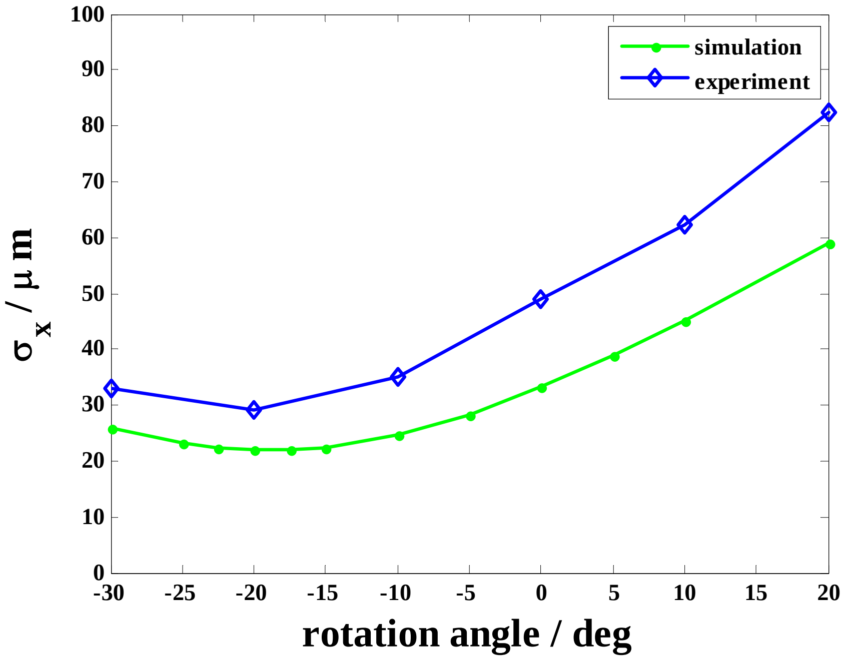


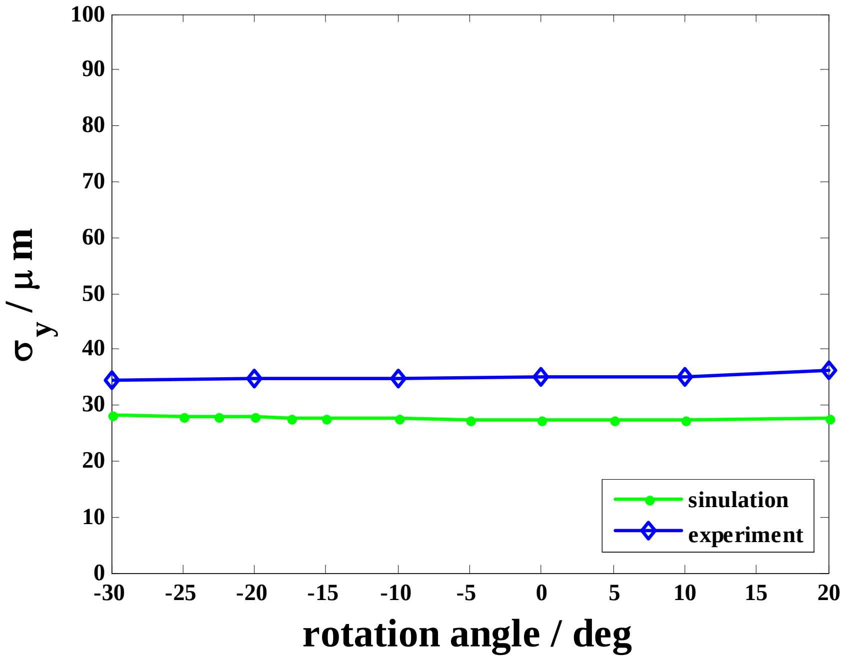
different scale !

0°



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

- results summarized in IPAC'10 proceedings: G. Kube, C. Behrens, W. Lauth, MOPD088

Future Plans

- continue search for optimum scintillator material
- direct comparison with OTR diagnostics
- influence on observation geometry for different materials (and thicknesses)
    - → new test experiment @ MAMI, March 2011
- COTR generation at scintillators
    - → contribution of M. Yan

open points

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

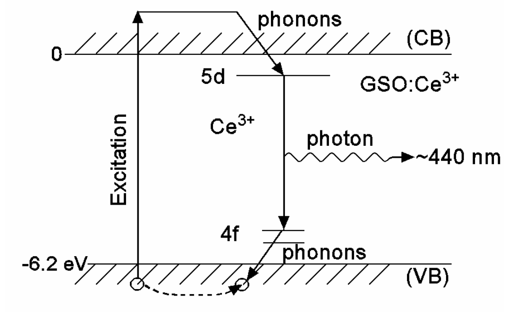
saturation at high intensities (> 0.04 pC/cm^2) observed for YAG:Ce screens (A. Murokh et al., Proc. PAC 2001, 1333)

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

Luminescent Types

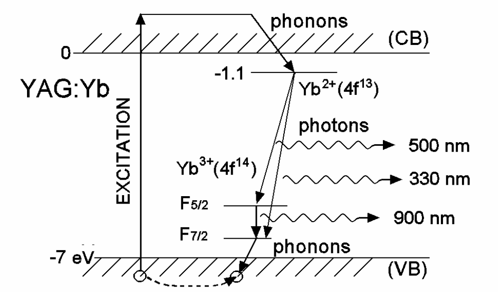
- Exciton luminescence: BGO, …

  Ionization/excitation by radiation creates unbound e-h pairs or bound e-h pairs called excitons. Excitons can move rather freely in crystals, caught at impurities, defects, and so on, and the STE (self-trapped excitons) gives luminescence upon radiative recombination.



- Dopant luminescence: GSO:Ce, …

  Radiative recombination of STE at dopant (activator) ions.

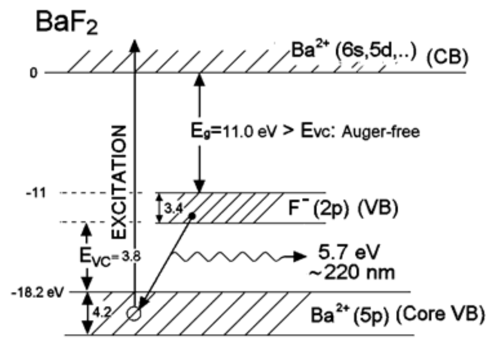


- Charge-transfer luminescence

  Belongs to exciton luminescence. Due to charge transfer where initial and final states are different, selection rules for EM transition are loosened, thereby enhancing transition probability.

- CVL (Core-valence luminescence, Cross luminescence)

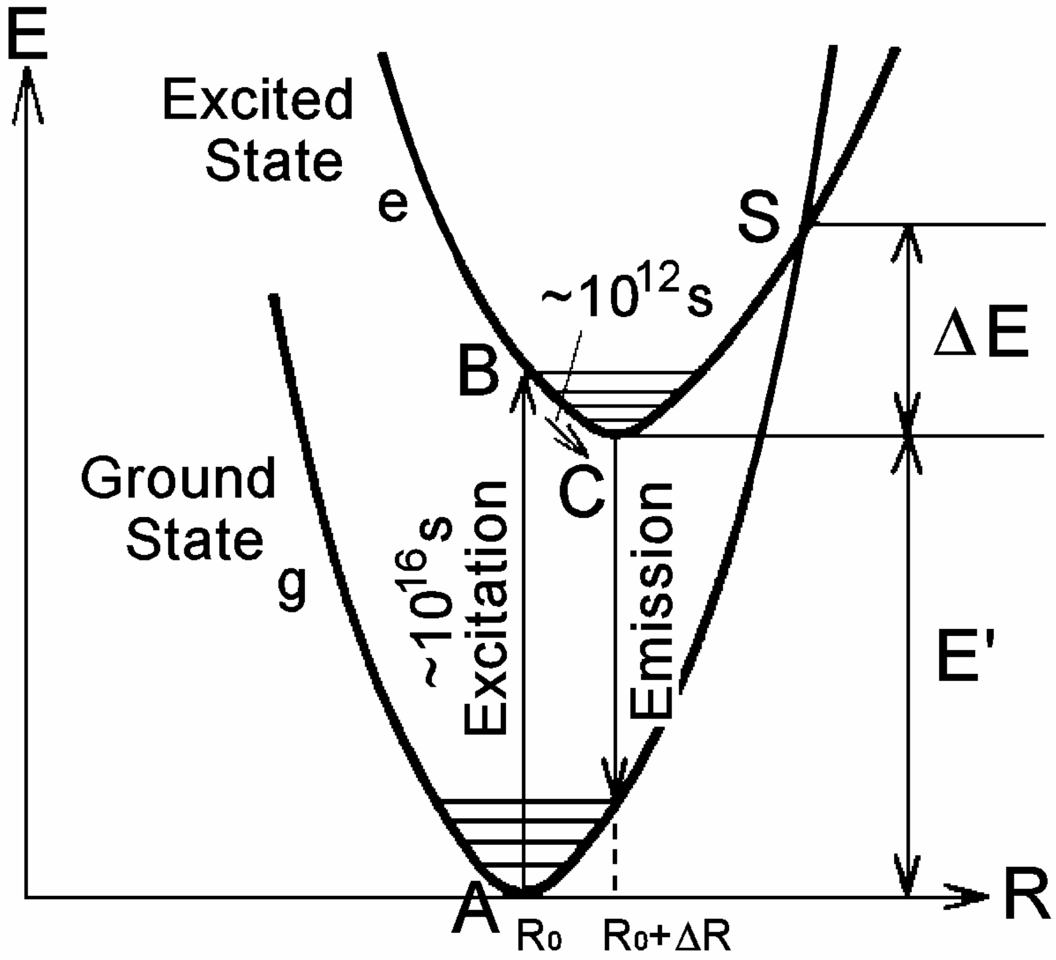
  After excitation of the core-valence electron, an electron in the valence band recombines with the resultant hole radiatively. To avoid Auger process, $E_{VC} < E_g$ is necessary.
  BaF_2, CsF, LiF,…..



M. Kobayashi (KEK): Introduction to Scintillators

Luminescence

- luminescence in configurational coordinate diagram



M. Kobayashi (KEK):
Introduction to Scintillators

R = inter-atomic distance between ground state of ligand atom and the excited state of luminescence centre atom