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
**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

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**Angular distribution**

- For $E = 1$ GeV
- $\theta = 1/\gamma = 0.5$ mrad

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**courtesy:**

K. Honkavaara (DESY)
OTR Diagnostics: Pitfalls

- Linac Coherent Light Source (LCLS) @ SLAC

![Linac Diagram](image)

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

in the meantime COTR also at FLASH

long bunch ($\lambda<\sigma_z$)

short bunch ($\lambda>\sigma_z$)

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**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 \(\rightarrow\) widely used in high energy physics, astrophysics, dosimetry,…
  - high stopping power \(\rightarrow\) high light yield
  - short decay time \(\rightarrow\) reduced saturation

- **generation of scintillation light**
  - energy conversion \(\text{(characteristic time } 10^{-18} - 10^{-9} \text{ sec)}\)
    - 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 \(\text{(10^{-16} – 10^{-12} sec)}\)
    - 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 \(\text{(10^{-12} – 10^{-8} sec)}\)
    - Energy transfer from e-h pairs to luminescent centers.
  - photon emission \(\text{ (> 10^{-10} sec)}\)
    - 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 $X_0$)

- transverse shower dimension: Molière radius as scaling variable
  → containing 90% of shower energy

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

$X_0$: radiation length, $Z$: atomic number

F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html
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
    - increase of transverse field extension
  - Fermi plateau
    - cancellation of incoming particle field by induced polarization field
      - of electrons in medium
      - saturation range as scaling variable $R_5$

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Implication on Transverse Resolution

- **extension radius**
  - limiting value:
    \[
    R_\delta = \frac{c}{\omega} \sqrt{1 - \varepsilon(\omega)}
    \]
    \(\varepsilon(\omega)\): complex dielectric function
  - approximation as free electron gas (Drude model)
    \[
    R_\delta = \frac{hc}{\hbar \omega_p}
    \]
  \(\omega_p\): 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
      \(\rightarrow\) high \(n\), i.e. large contribution of total reflection

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Scintillator Material Properties

![Graph showing refractive index vs. R_nm for various scintillator materials including BGO, GSO, LuAG, LSO, LuAP, PWO, CWO, NBWO, YAG, and YAP.]

- **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

<table>
<thead>
<tr>
<th>Scintillator Type</th>
<th>Density (g/cm³)</th>
<th>ħωₚ (eV)</th>
<th>Rₘ (cm)</th>
<th>λ_max (nm)</th>
<th>Yield (1/keV)</th>
<th>n @ λ_max</th>
<th>R₆ (nm)</th>
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</thead>
<tbody>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>49.9</td>
<td>2.23</td>
<td>480</td>
<td>8</td>
<td>2.15</td>
<td>3.95</td>
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<tr>
<td>PWO</td>
<td>8.28</td>
<td>53.3</td>
<td>2.00</td>
<td>420</td>
<td>0.1</td>
<td>2.16</td>
<td>3.70</td>
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<tr>
<td>LSO:Ce</td>
<td>7.1</td>
<td>51.3</td>
<td>2.08</td>
<td>420</td>
<td>32</td>
<td>1.82</td>
<td>3.85</td>
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<tr>
<td>YAG:Ce</td>
<td>4.55</td>
<td>45.5</td>
<td>2.77</td>
<td>550</td>
<td>11</td>
<td>1.95</td>
<td>4.34</td>
</tr>
</tbody>
</table>
Mainz Microtron MAMI

Institute of Nuclear Physics, University of Mainz (Germany)

3 cascaded Racetrack Microtrons: \( E_{\text{max}} = 855 \text{ MeV} \)
double-sided Microtron (HDSM): \( E_{\text{max}} = 1.5 \text{ GeV} \)
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
Beam Images

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

- **LYSO:Ce**
  - (0.5mm)

- **LYSO:Ce**
  - (0.8mm)

- **YAG:Ce**
  - (powder)

- **YAG:Ce**
  - (0.2mm)

- **BGO**
  - (0.5mm)

- **PWO**
  - (0.3mm)

- **YAG:Ce**
  - (1mm)

- **Al₂O₃**
  - (0.5mm)

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Results

- vertical beam size

![Graph showing vertical beam size](image)

- horizontal beam size

![Graph showing horizontal beam size](image)

mean values

![Bar chart showing mean values](image)

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
  - $I = 3.8 \, \text{nA}$

- measured beam spots

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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
- determination of 2nd moment (standard deviation)

![Image of simulation and experiment results at different angles]
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 dopants, different concentration?
- screen saturation
  - saturation at high intensities (> 0.04 pC/cm²) 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, .....
Luminescence

- luminescence in configurational coordinate diagram

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

M. Kobayashi (KEK):
Introduction to Scintillators