ISMA R&D scintillation detectors for high energy physics projects and medical application

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1. History and development reasons
2. Problems and solutions
3. Light collection as the part of technology
4. Scintillation detectors for HEP of development
5. Scintillation detectors for medical application
6. Conclusion
Historical current needs

Single crystalline scintillator is probably the best but the most complex and expensive decisions. Non growth technology as an alternative:

- **50th** - start of both option and ...era of growth domination
- **70th** - ceramics as alternative to the growth
- **2015** – return to composites as an efficient and cheap solution

1950’s - composite

1970’s - ceramics

1950’s - composite

Renaissance of composite technology – the dream or reality?
1. History and development reasons

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6. Conclusion
Composite scintillator – small scintillator particles/granules embedded to immersion gel

Driving force for development is the search of cost efficient solution for many detector designs. There are no any application claiming for lower price!
Composites - what is attractive?

Technical and technology advantages:

- Use of synthesized scintillation powders
- Variable thickness (from 50 micron)
- High spatial resolution
- High uniformity
- Large area any complex shapes
- Commercially available components
- Ready to visualization

Initial problems:

- Low transparent media, light scattering
- Customized design for each customer
- Simulation and optimization for each design
- Particles analysis and presize synthesis
- Light guide output solution for thick detector
Composites - scintillators for customer requirements

Scintillation powder fabrication

- Chemical
  - Sol-gel
  - Precipitation
  - Hydrothermal
  - Other

- Synthesis

- Solid state

- Advantage
  - Easy to obtain
  - High purity

- Drawback
  - Irregular shape
  - Additional milling is required
  - Non uniformity size form 10s of nm

CeO$_2$, GOS:Pr,Ce, GAGG:Ce

Scintillation powder is the main problem for technology
OUTLINE

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Light collection in composites

Granule size selection

Light scattering in heterogeneous system

<table>
<thead>
<tr>
<th>Granule size</th>
<th>Light attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 30 nm Nanoparticles</td>
<td>Granule size significantly less than scintillation wavelength</td>
</tr>
<tr>
<td>~ 100-200 nm</td>
<td>Granule size less than emission wavelength</td>
</tr>
<tr>
<td>300-800 nm</td>
<td>Granule size is comparable with emission wavelength</td>
</tr>
<tr>
<td>&gt; 1000 nm</td>
<td>Large crystal</td>
</tr>
</tbody>
</table>
Light collection in composites

Base requirements for composites

- Refractive index
- Granule shape
- Granule size
- Concentration and distribution uniformity

Monte Carlo simulation should cover at least:

A. Light passage in imaginary cell

B. Simulation of light transport

\[
\tau(L) = \frac{j(L)}{S} = \frac{\beta_1 \beta_2}{\zeta} \chi h \gamma L + \beta_2 \chi h \gamma L \\
(\chi + \frac{\beta_1 \beta_2}{\zeta}) \chi h \gamma L + (\beta_1 + \beta_2) \chi h \gamma L
\]

C. Regular shape

Irregular shape
Composites application

**Spectrometry**
- Composites with large granules size
- Granule size is commensurate with absorbed energy

**X-ray screening**
- Good transparency without pixelation
- Direct application onto CMOS
- Good spatial resolution and uniformity

**Gamma detection**
- High threshold of sensitivity to low gamma

**Neutron detection**
- $^6$Li base detector

**HEP projects**
- CERN
- ILC
- Institute of High Energy Physics
  Chinese Academy of Sciences

**Film, x-ray image @80 keV**
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Composite scintillators application for HEP

<table>
<thead>
<tr>
<th></th>
<th>Scintillation plastic</th>
<th>Scintillation crystal</th>
<th>Composite scintillators</th>
</tr>
</thead>
<tbody>
<tr>
<td>radiation resistance</td>
<td>up to 5 Mrad</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>cover large area</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>cost-efficiency</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Composite scintillator is the alternative to the scintillation plastic but possesses with higher radiation resistance comparable with inorganic crystals.
Ways of improvement of radiation hardness plastic scintillators

Transmission spectra of undoped polystyrene before and after irradiation with 10 MRad dose
(A.D.Bross, A.Pla-Dalmau)

Irradiation induced decrease of light yield in plastic scintillator

Radiation hardness may be improved by:

- shifting of luminescence maximum of plastic scintillator into long-wave region
- increasing of radicals mobility without changes in mechanical properties of plastic scintillator
Improvement of radiation hardness via increasing of radicals mobility

Doping of plastic scintillator polymer base with diffusion amplifier may result in increase of radiation hardness

Introducing of diffusion amplifiers levels dependence of traps formation rate on irradiation dose rate,

but
disimprove the mechanical properties of plastic scintillator

Light yield dependence of plastic scintillator on polyphenyl oxide concentration (diffusion amplifier in polystyrene) under irradiation with 2.8 MRad dose

“Cross-linking” of polymer base is the way to improve the properties of radiation hardness plastic scintillator
Improvement of radiation hardness plastic scintillators

- Shifting of luminescence maximum into the region of transparency
- Introducing of diffusion amplifiers into cross-linked polymer backbone

Increase of radiation hardness threshold up to 10 MRad

<table>
<thead>
<tr>
<th>ID scint.</th>
<th>Light yield, % (rel.)</th>
<th>D1/2, MRad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 Mrad</td>
<td>5 Mrad</td>
</tr>
<tr>
<td>1</td>
<td>80</td>
<td>49</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>59.5</td>
<td>41</td>
</tr>
</tbody>
</table>

P. Zhmurin, ISMA
Development of thin-layer detectors for HEP

Radiation hardness of organic vs inorganic scintillators

Single crystal and composites

Polysterene

Radiation hardness more 100 MRad

Radiation hardness up to 5 MRad

Radiation hardness of oxide based composites is in 20 times higher than scintillation plastic!
Scintillation detectors

- Crystal growth
- Micro-pulling-down crystal fiber growth
- Scintillation ceramics
- Scintillation powders/ granules
- Other

E.Auffray, Cern, February 2009
Composite elements for various loading doses

- Single crystal plates
- Substrate
- WLS fiber
- WLS fiber
- Light guide
- Single crystal granules
- WLS fiber
- Light guide
- Scintillation powder granules

Essential overlapping of YSO:Ce emission spectrum and YAG:Ce absorption spectrum
Radiation hardness of polysiloxanes

Irradiation with electrons ($E_0 = 8.3$ MeV) up to 300 MRad dose

![Sylgard 184](image)

Before irradiation  After 300 Mrad

Irradiation with protons (150 KeV)

![Figure 2](image)

Haiying Xiao et al., Journal of Applied Polymer Science, ·2008

- Loss of transparency is the result of microcracks appearance
- Appearance of microcracks is due to:
  - leaving of the methyl groups
  - formation of an inorganic, silica-like final product, which consists of $\text{SiO}_x$

The possible way to increase of radiation resistance is **hardening of polysiloxane matrix with scintillation granules**
YAGG:Ce as a material for WLS fiber

Decay time Composite Scintillator with YAGG:Ce fiber before and after irradiation with dose of 50 MRad

Decay time, Composite Scintillator element with YAGG:Ce fiber, 22ns

Radiation hardness is more than 100 MRad
Light collection in scintillation layer

WLS fiber – YAG:Ce

Testing scheme

Nonuniformity of composite scintillator

<table>
<thead>
<tr>
<th>L, mm</th>
<th>Counts rate, %</th>
<th>Diffuse refl</th>
<th>Mirror refl</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>101%</td>
<td>102%</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>101.5%</td>
<td>104%</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>98%</td>
<td>103.5%</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>90%</td>
<td>101%</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>81%</td>
<td>96%</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>73%</td>
<td>91.5%</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>65%</td>
<td>86%</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>59%</td>
<td>81%</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>53%</td>
<td>75.5%</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>51%</td>
<td>72%</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>50%</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>48%</td>
<td>69.5%</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>46.5%</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>46.5%</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>49%</td>
<td>71%</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>55.7%</td>
<td>75%</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>65%</td>
<td>81%</td>
<td></td>
</tr>
</tbody>
</table>

Nonuniformity is up to 15% for composite scintillator of 40 mm width
Optical light guide selection

**Quartz glass** and silicone are transparent in the range $\lambda > 400$ nm for doses up to 100 Mrad

**Sapphire** is transparent in the range $\lambda > 350$ nm for doses more than 100 Mrad

**Molding silicone** for optical light guide

<table>
<thead>
<tr>
<th>Scintillation type</th>
<th>Optical light guide</th>
<th>Relative light output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic</td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>YSO:Ce composite</td>
<td>Silicone</td>
<td>250%</td>
</tr>
<tr>
<td>YSO:Ce composite</td>
<td>Quartz</td>
<td>120%</td>
</tr>
<tr>
<td>YSO:Ce composite</td>
<td>Sapphire</td>
<td>50%</td>
</tr>
</tbody>
</table>

We have different materials for composite detectors and we propose optical materials with the best radiation hardness.
Development of thin-layer detectors for HEP

Composite detector

Requirements

✓ Super granularity
✓ Radiation hardness
✓ Decay time not more 20 ns

Available now

✓ Decay time 10-20 ns
✓ LO comparable with polysterene
✓ Radiation hardness >100 MRad
✓ Radiation hard WLS and opto fiber in complect
✓ Cherenkov and scintillation signal simultaneous registration

“Warm” version of calorimeter is possible

Possible designes for “warm” calorimeter

✓ Technology of powder synthesis, ceramics, melting
✓ Crystal WLS fiber growth

Position sensitivity design – coincidence counting
Development of thin-layer detectors for HEP

Future HEP projects

Semiconductor detector is main applicant to HL LHC and new project upgrade today

Future detector – super granularity design

Composites implementation. What we can offer?
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Flexible scintillators for photodetector and CMOS application

<table>
<thead>
<tr>
<th>Grain size, microns</th>
<th>Thickness, mm</th>
<th>Light yield flexible VS crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 40</td>
<td>0.1-0.3</td>
<td>30</td>
</tr>
<tr>
<td>40-120</td>
<td>0.3-0.5</td>
<td>55</td>
</tr>
<tr>
<td>120-200</td>
<td>0.5-1.5</td>
<td>80</td>
</tr>
</tbody>
</table>

Position sensitive flexible scintillators without pixelation

Pixel detectors VS flat panel

Light output of composite scintillators
Transparent flexible scintillators

Experimental data

Ways to increase of transparency
- Granule size
- Granule shape
- Micro light guides and micropixel technology on photoresist base

Correlation of experiment and theory
Medical application

**Advantage of flexible detector**

- High position sensitivity
- Takes a form of organ or tissue under study
- Good spatial resolution
- High uniformity
- Good performance
- Easy production in a variety of shapes

**Transition from flat detectors to flexible ones**
1. There are many materials on the market meeting the main customer requirements on physical parameters.

2. Searching for materials meeting economical and technological requirements is the problem of current interest.

3. Last decade technologies for obtaining radiation detectors alternative to scintillation crystals have been actively developing.

4. Creation of multicomponent scintillation systems is the way for obtaining of cost efficiency detectors.
Thank you!