Scintillating Screen Applications in Beam Diagnostics

Workshop Summary

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Gero Kube, DESY Hamburg

The workshop on "Scintillating Screen Applications in Beam Diagnostics" organized by DESY, GSI and HIT and recently held at GSI gave a possibility to exchange ideas, to report on recent developments and to communicate experiences.

It provided the opportunity to continue and enhance discussions with the experts from different accelerator facilities, material science and suppliers.

- **two days**
- **more than 50 participants**
- **more than 15 institutes**
- **website: http://www-bd.gsi.de/ssabd**

Motivation

There is a long history of scintillator applications in particle detection. Traditionally used in physics, scintillators today serve many purposes in science and engineering (e.g. medicine, geophysics, beam diagnostics…).

Scintillators are installed in all accelerator laboratories around the world.

→ In hadron and low energy electron machines scintillators are mainly used for transversal beam profile determination.

→ In modern LINAC-based light sources the interest in scintillators was recently revived when coherent effects were discovered that spoil the standard OTR measurements.

Outline

- General introduction to scintillating materials
- Scintillation mechanism
- Applications in beam diagnostics
- Experience at hadron machines
- Experience at electron machines

Scintillators

Scintillation: the process in which energy deposited in a material, e. g. by a charged particle, is converted into photons

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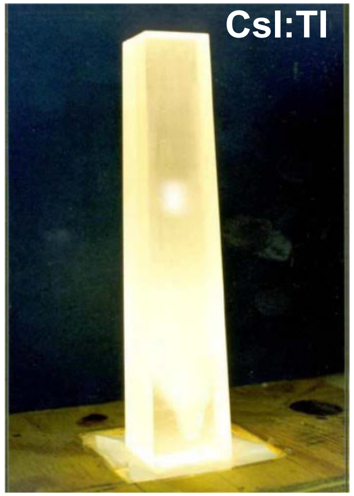
Physical state:

- Solid



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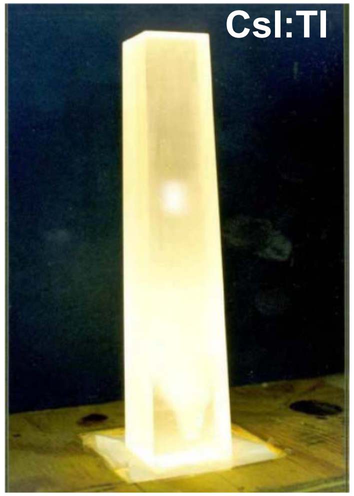

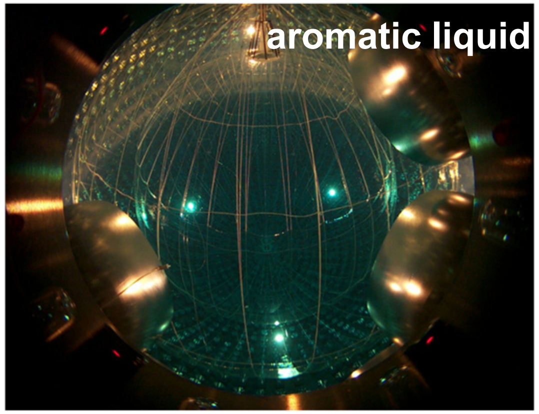

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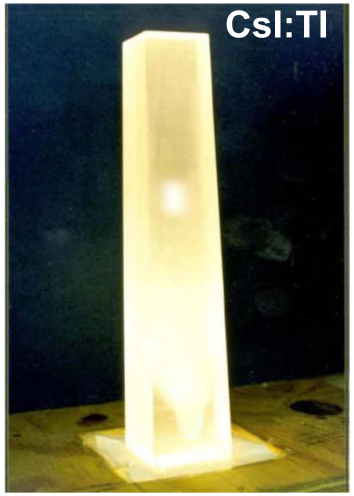

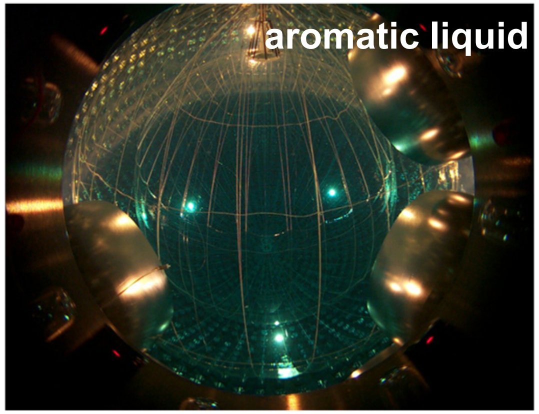

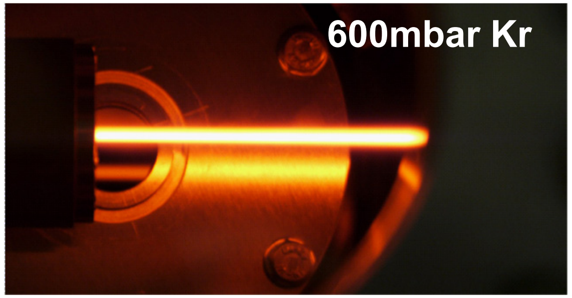

F. Becker WEOD1

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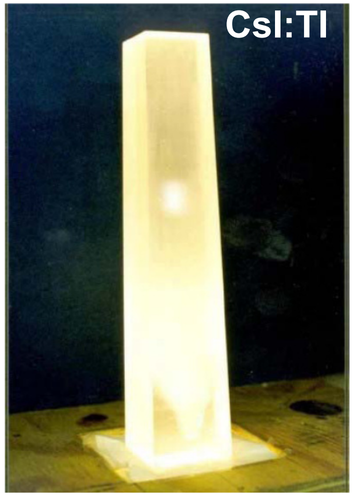
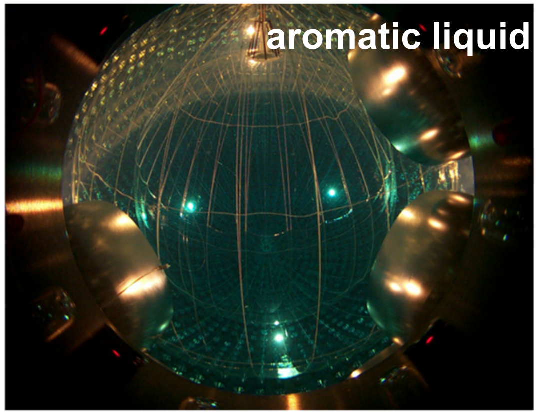
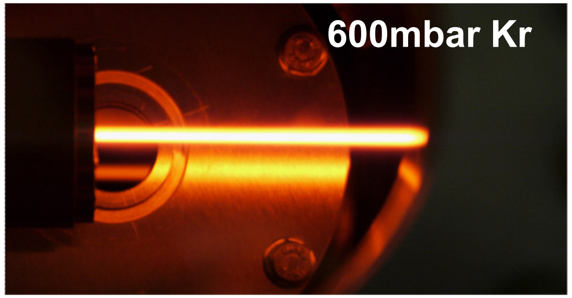


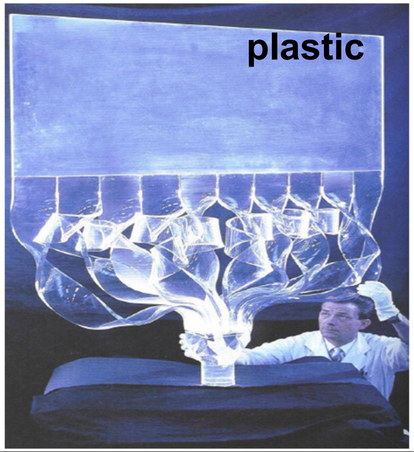




F. Becker WEOD1

Composition:

- Organic



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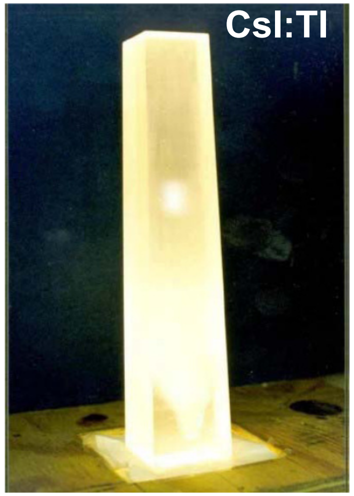

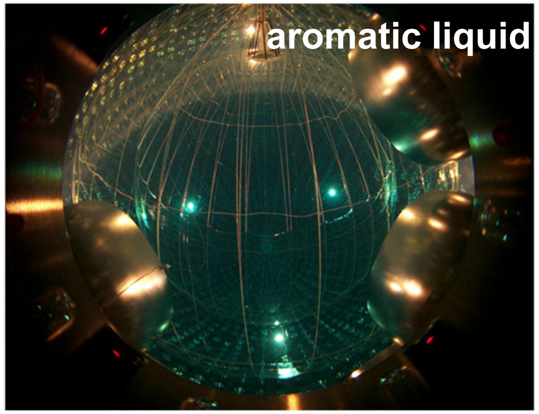

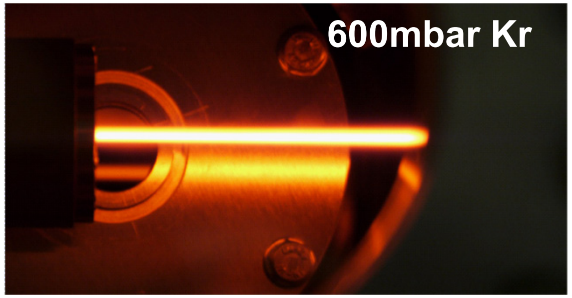

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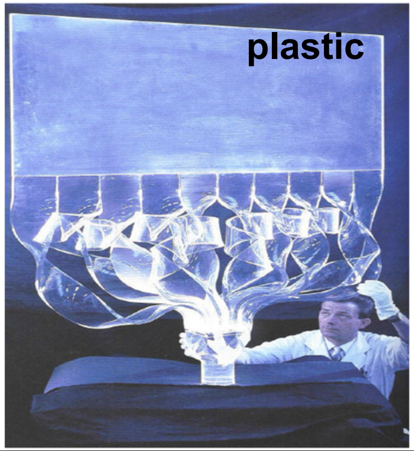
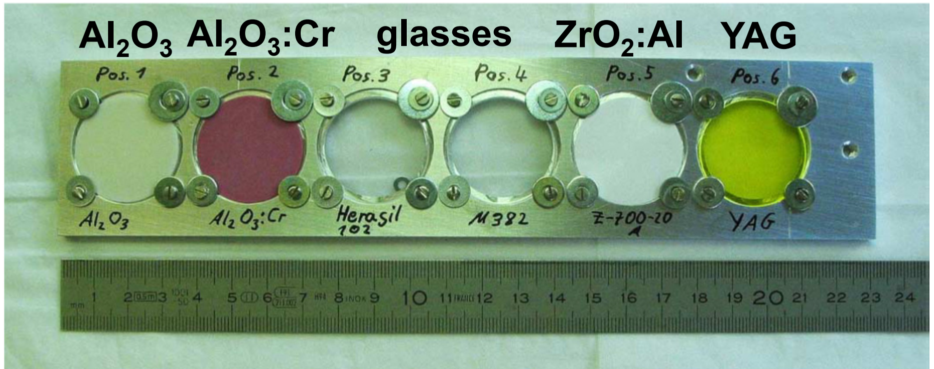
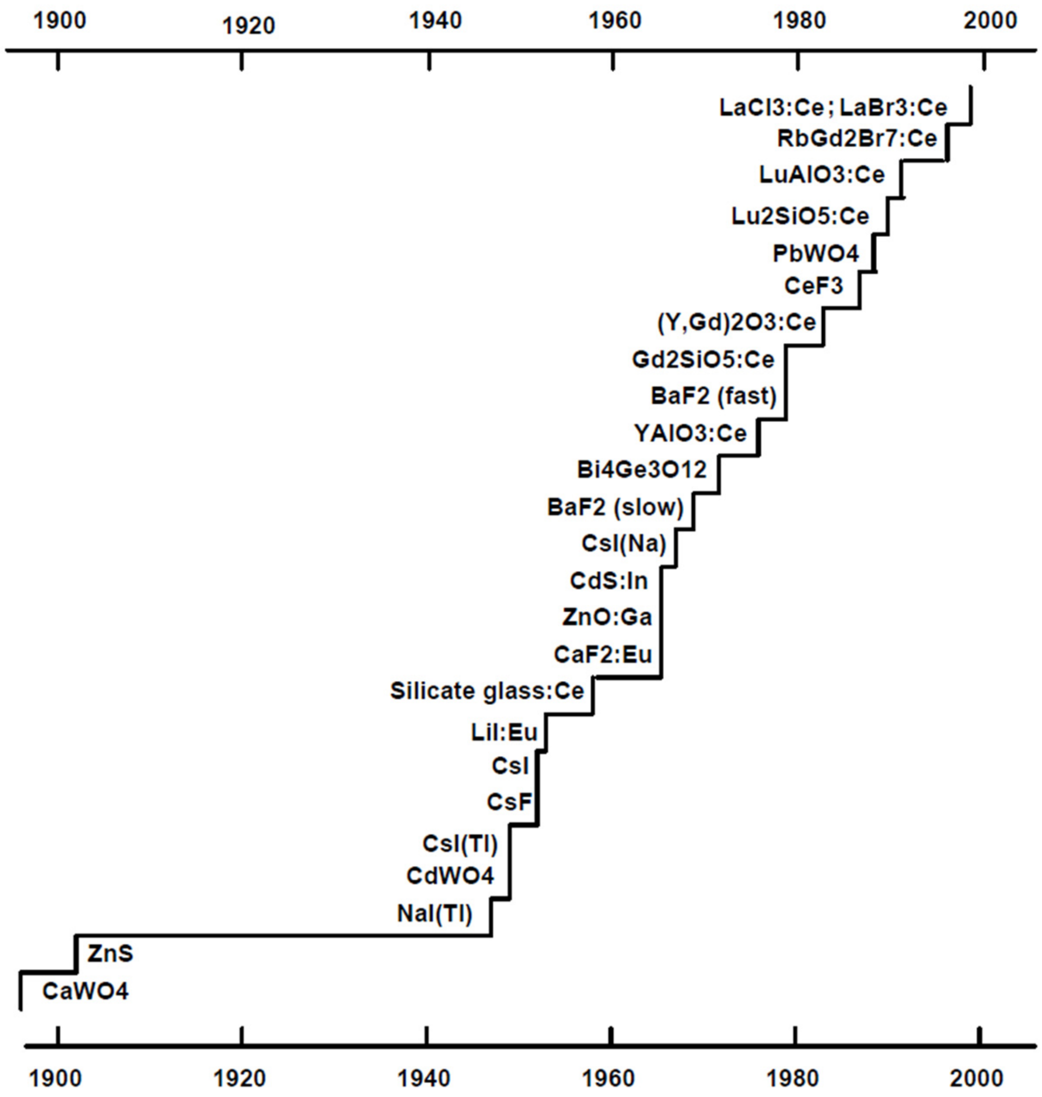




History of scintillator discovery



[M. J. Weber, J. Lumin. 100, 2002]

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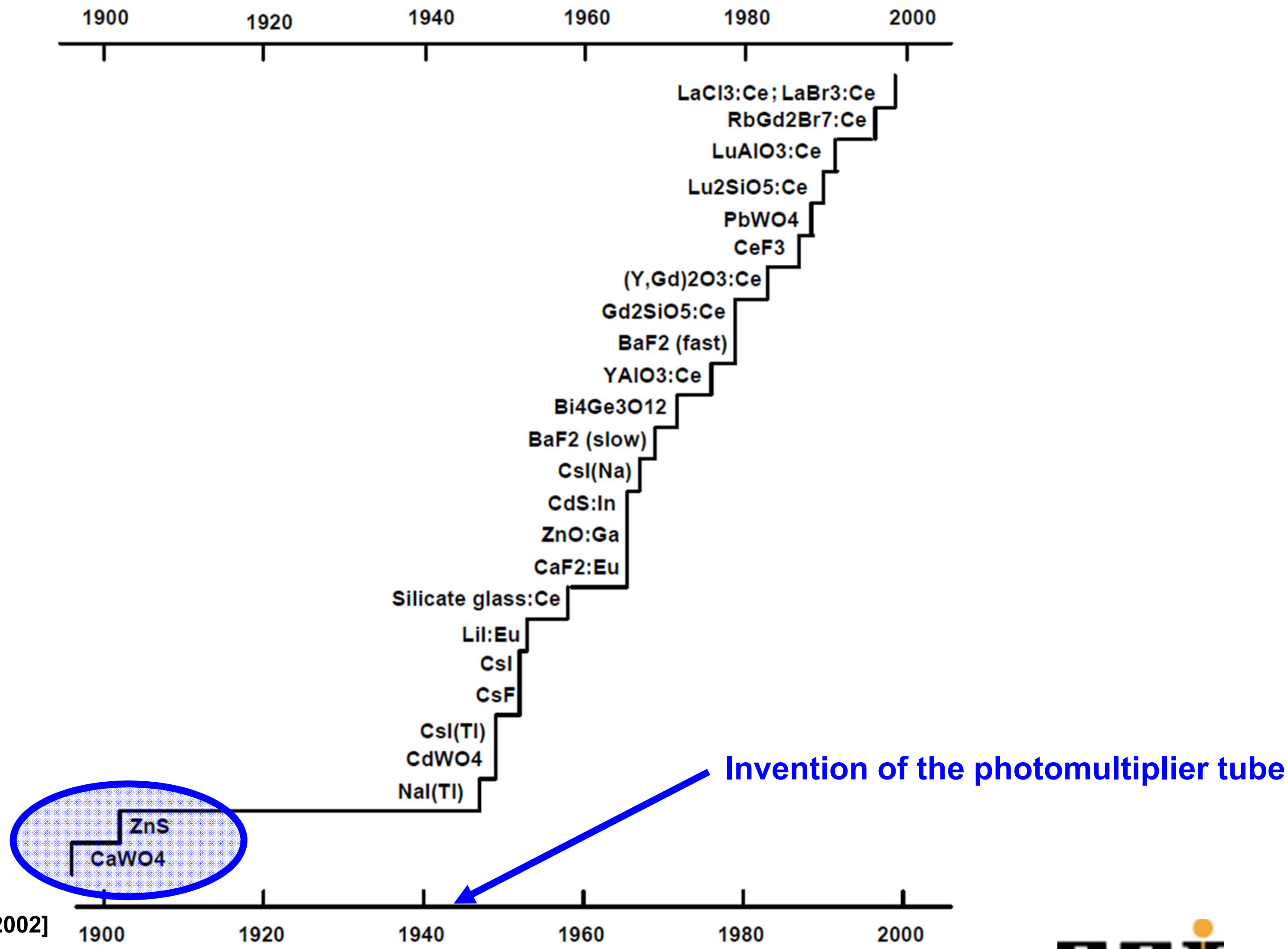

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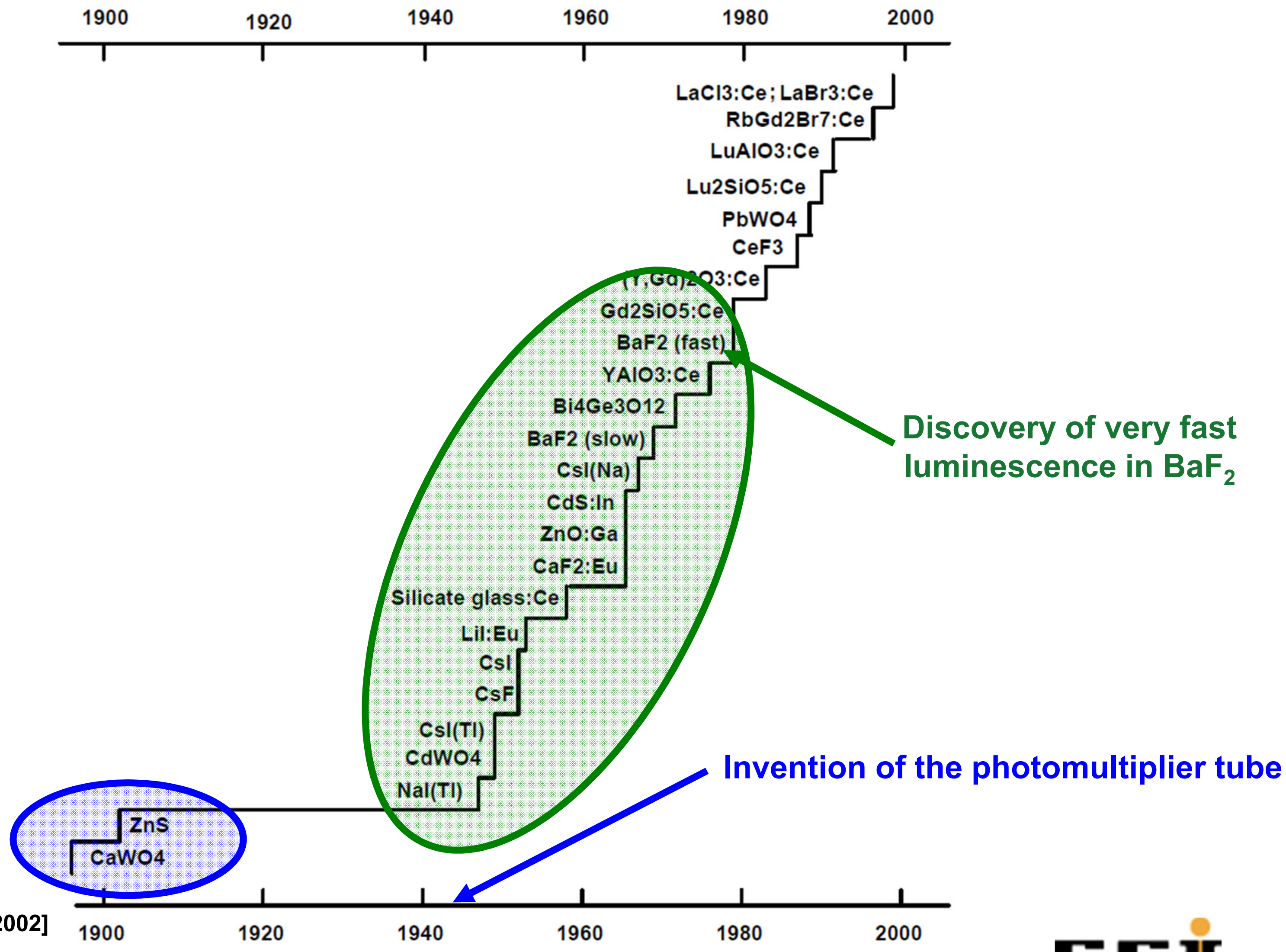

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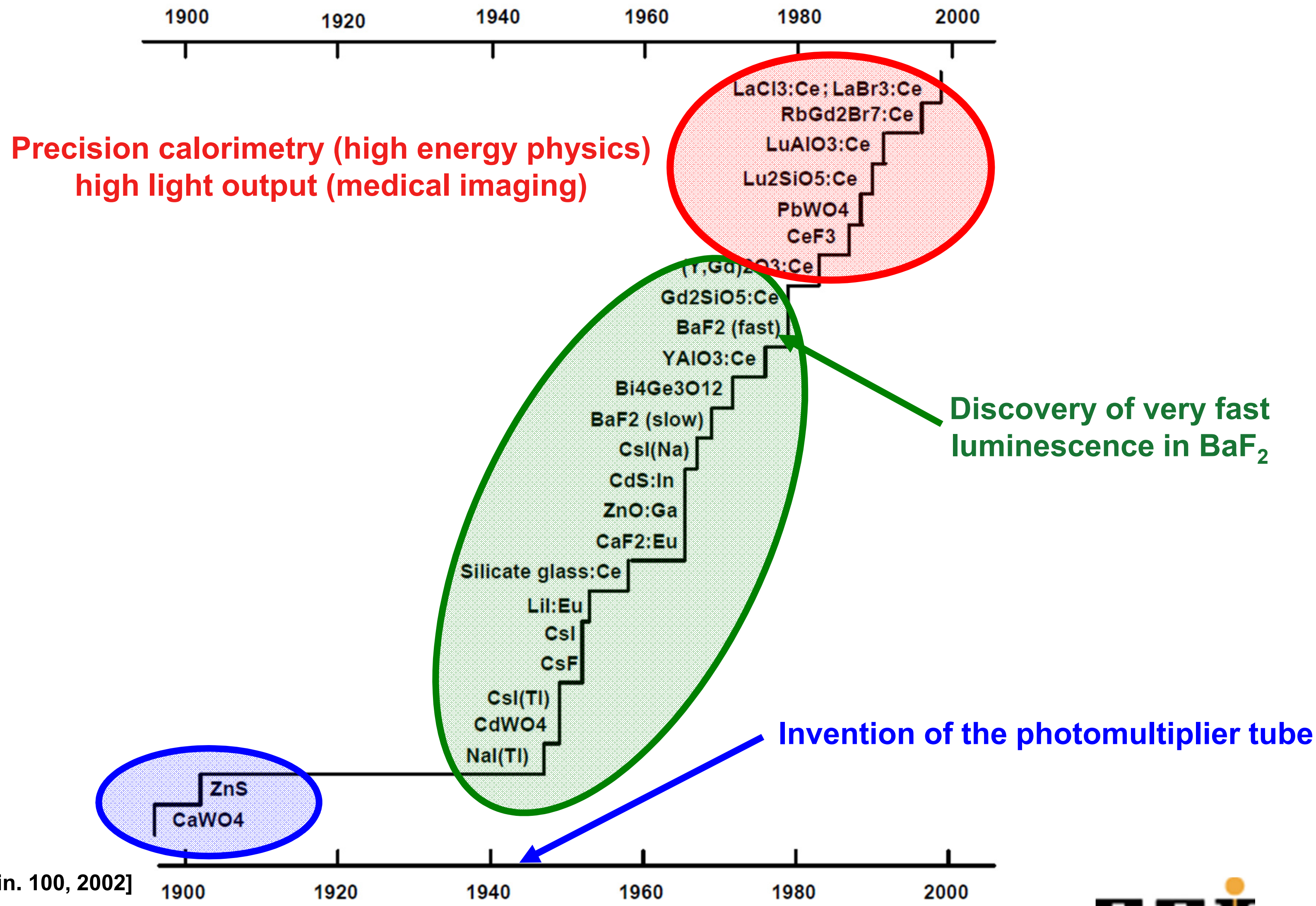

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- **Scintillation mechanism**
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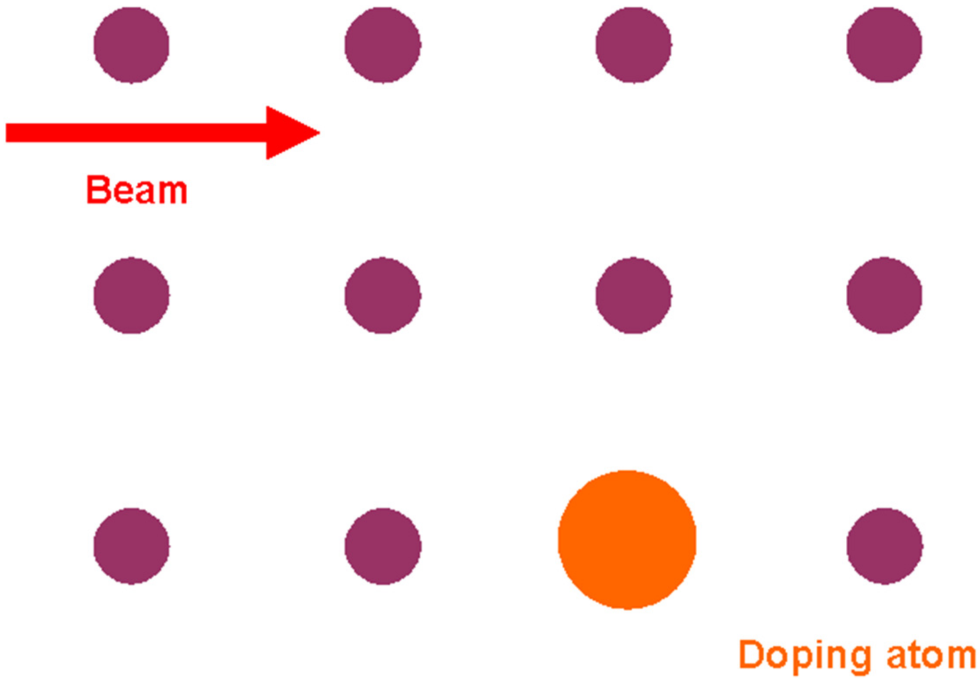
Scintillating process - general

Interaction steps within the scintillation process

• beam (electron, ions)



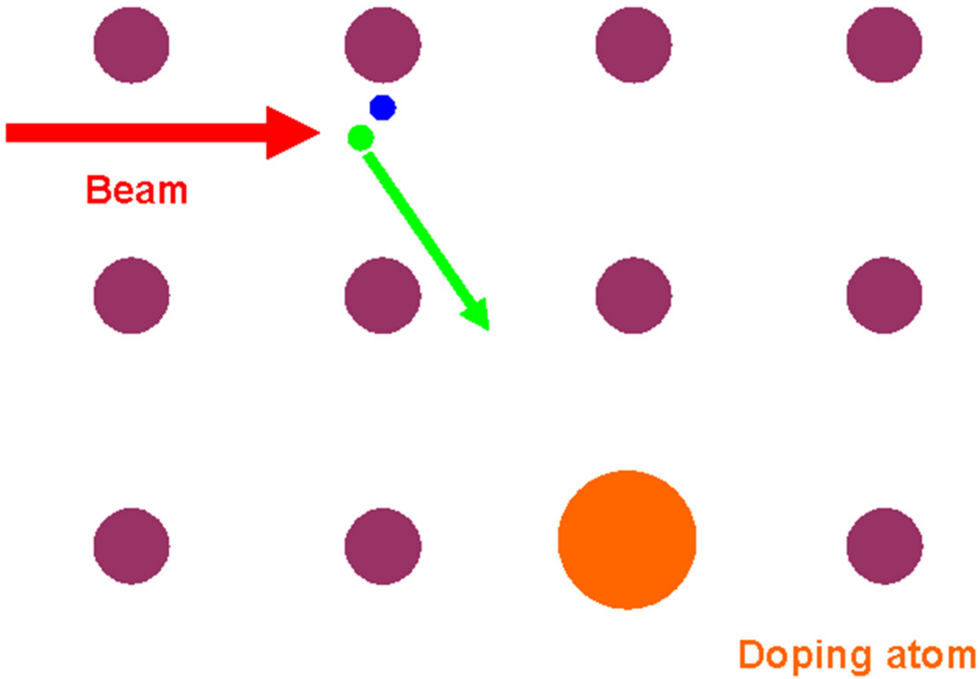
Scintillating process - general

Interaction steps within the scintillation process

- beam (electron, ions)

creation of hot electrons +

deep holes



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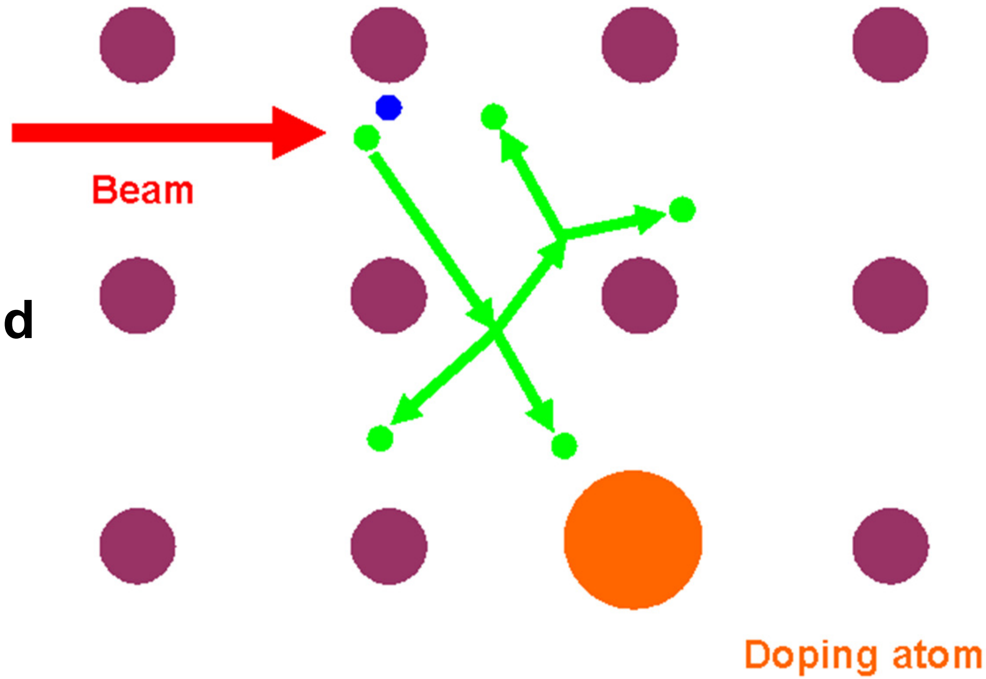
• **multiplication:**

electron – electron scattering and

Auger process

• **thermalization:**

electron – phonon coupling



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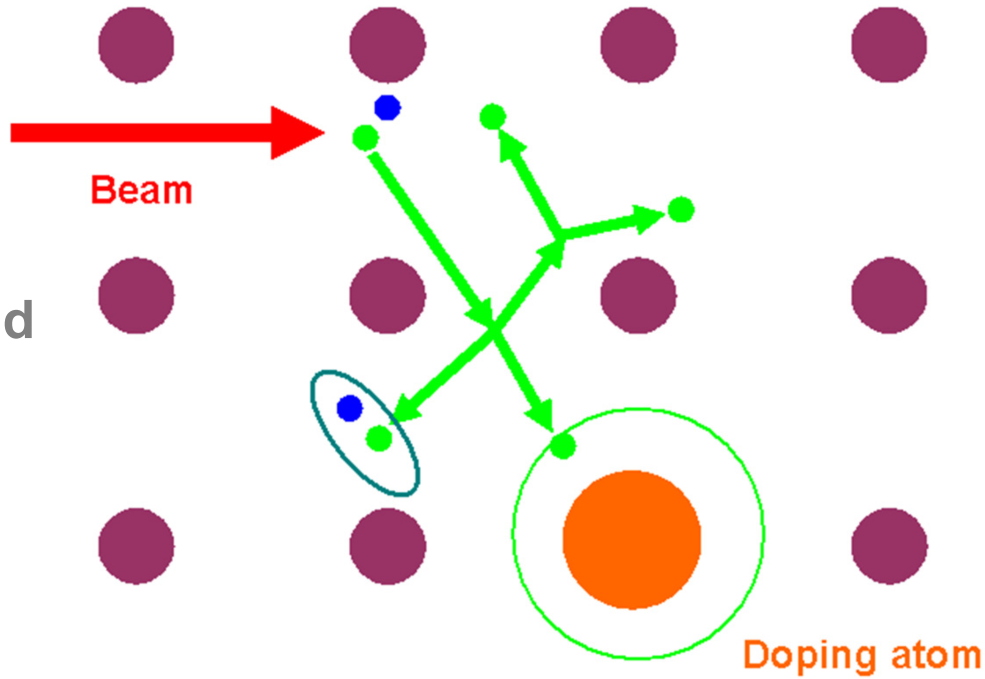

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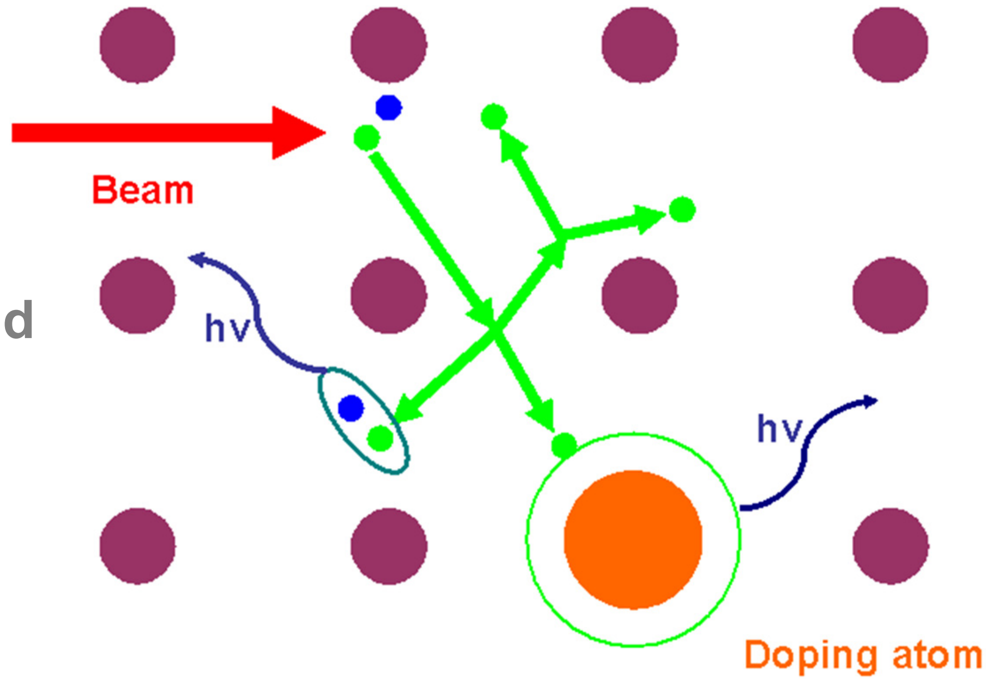
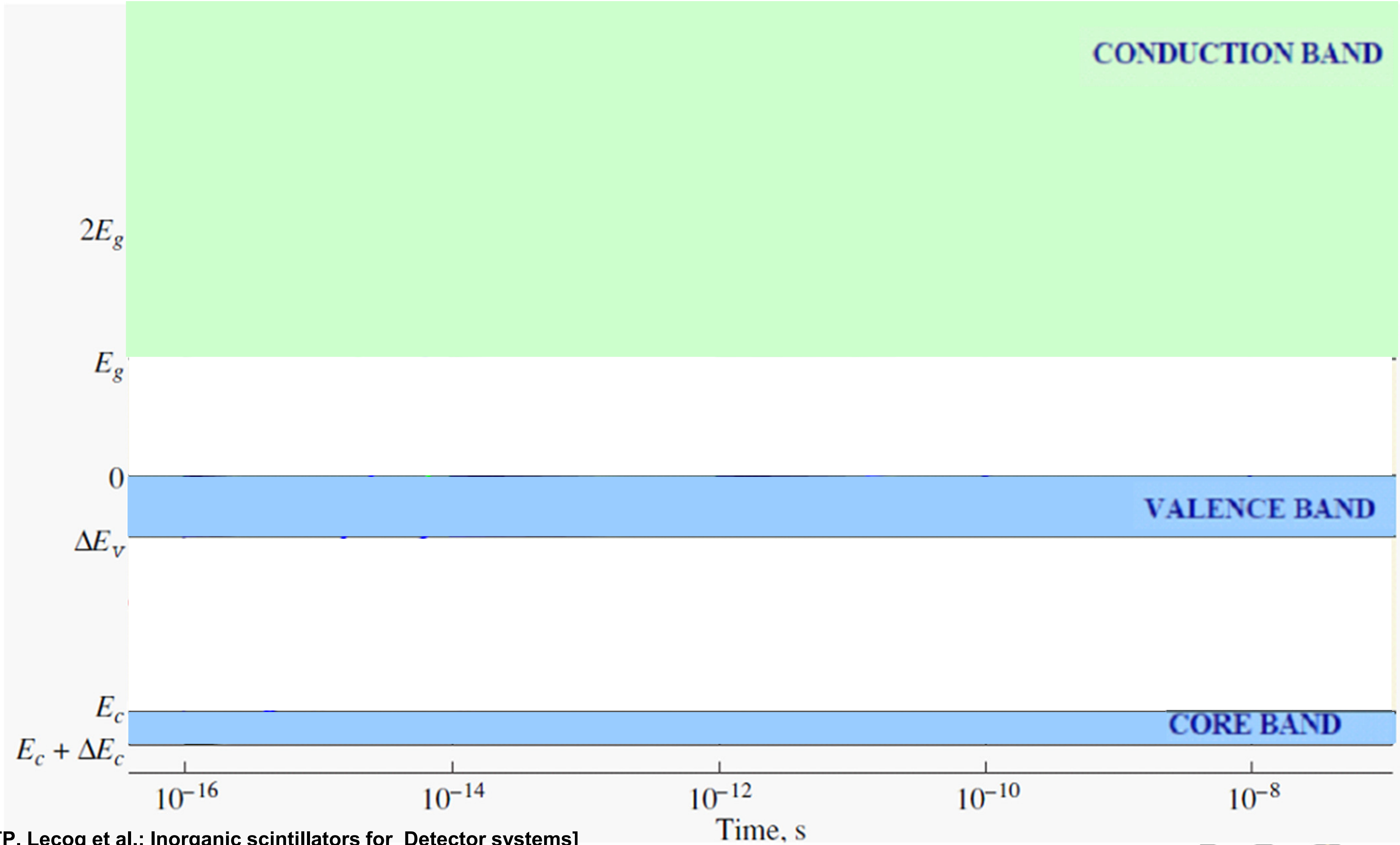
- **decay via photon emission**



Relaxation of electronic excitations



[P. Lecoq et al.: Inorganic scintillators for Detector systems]

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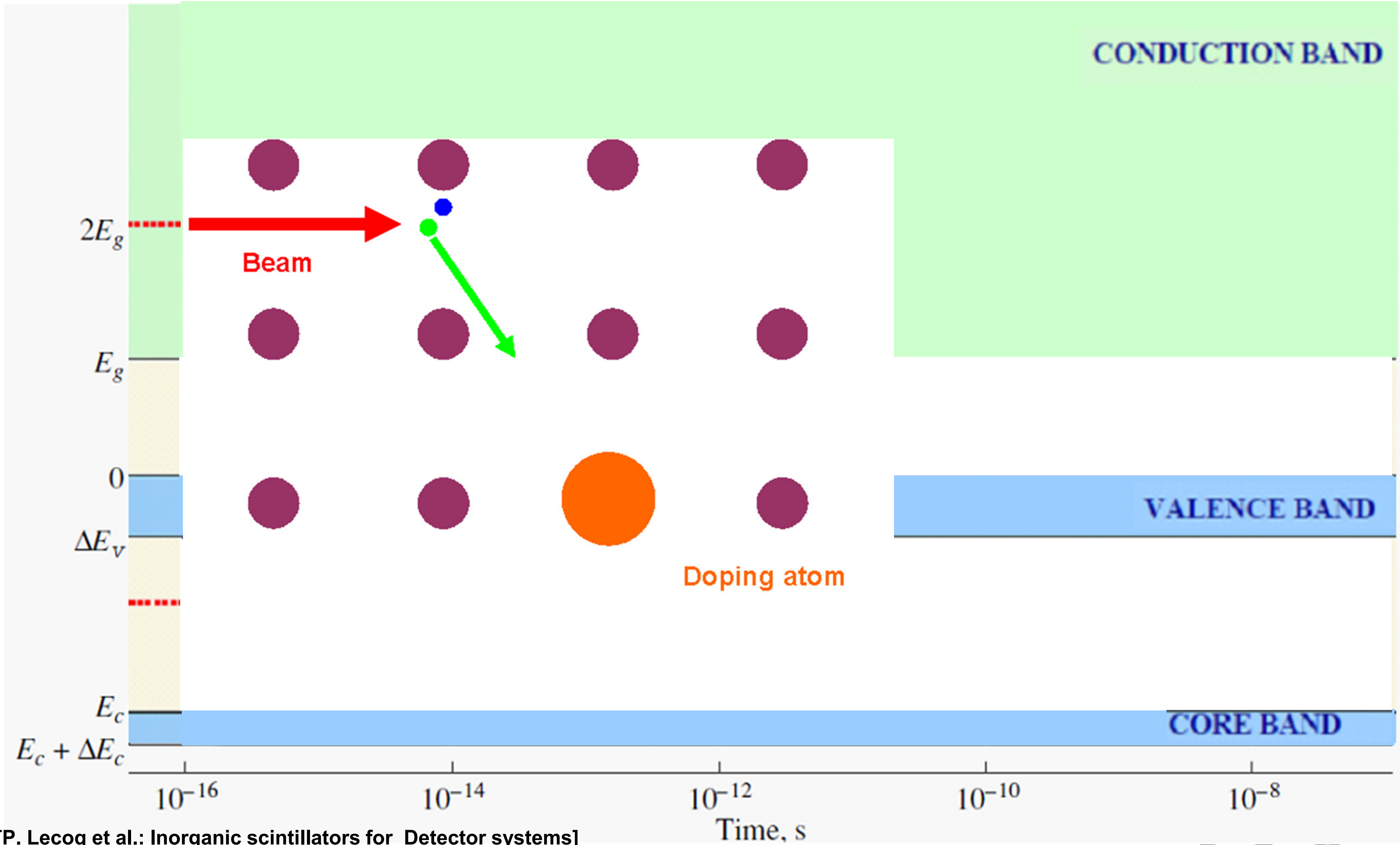

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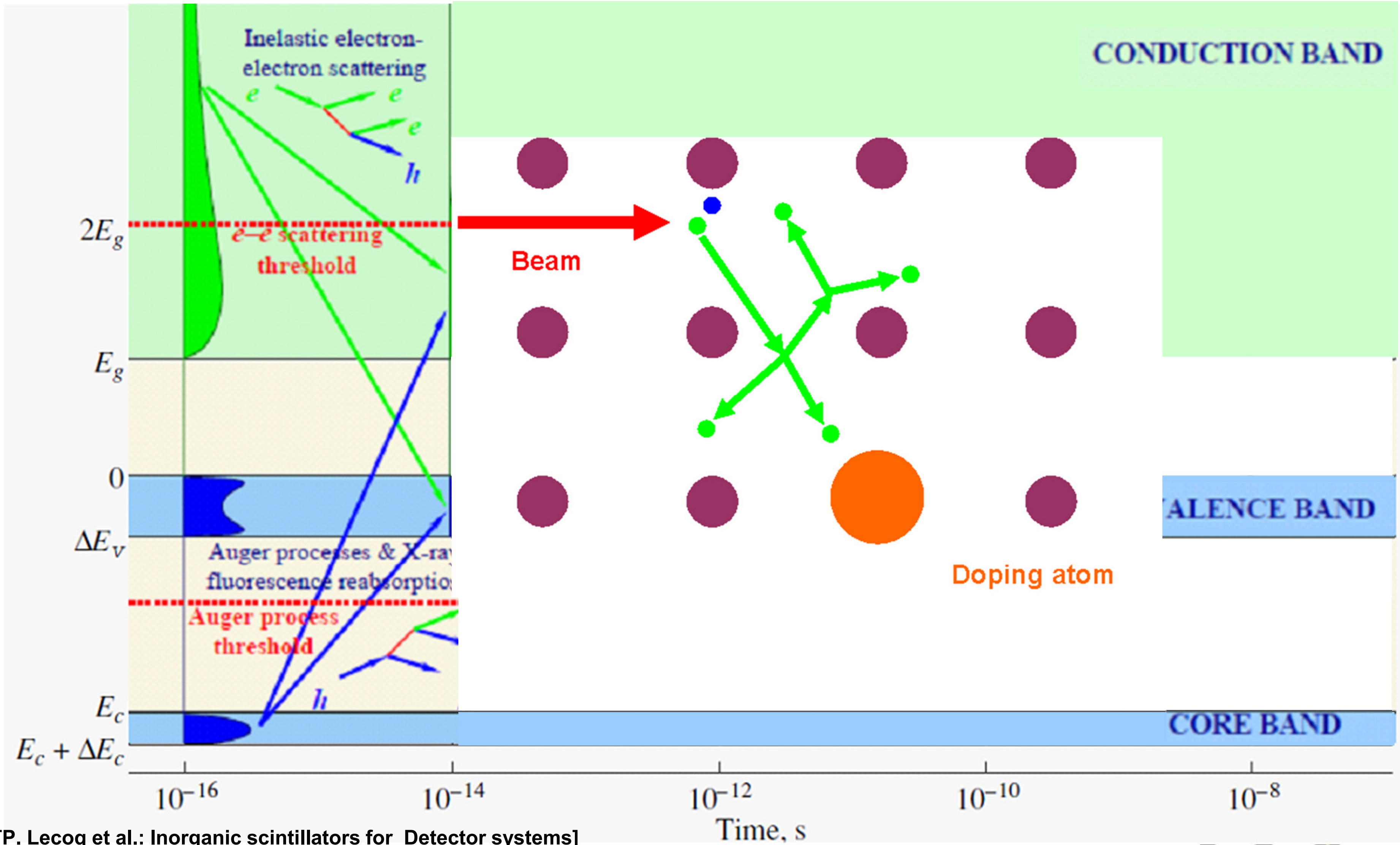

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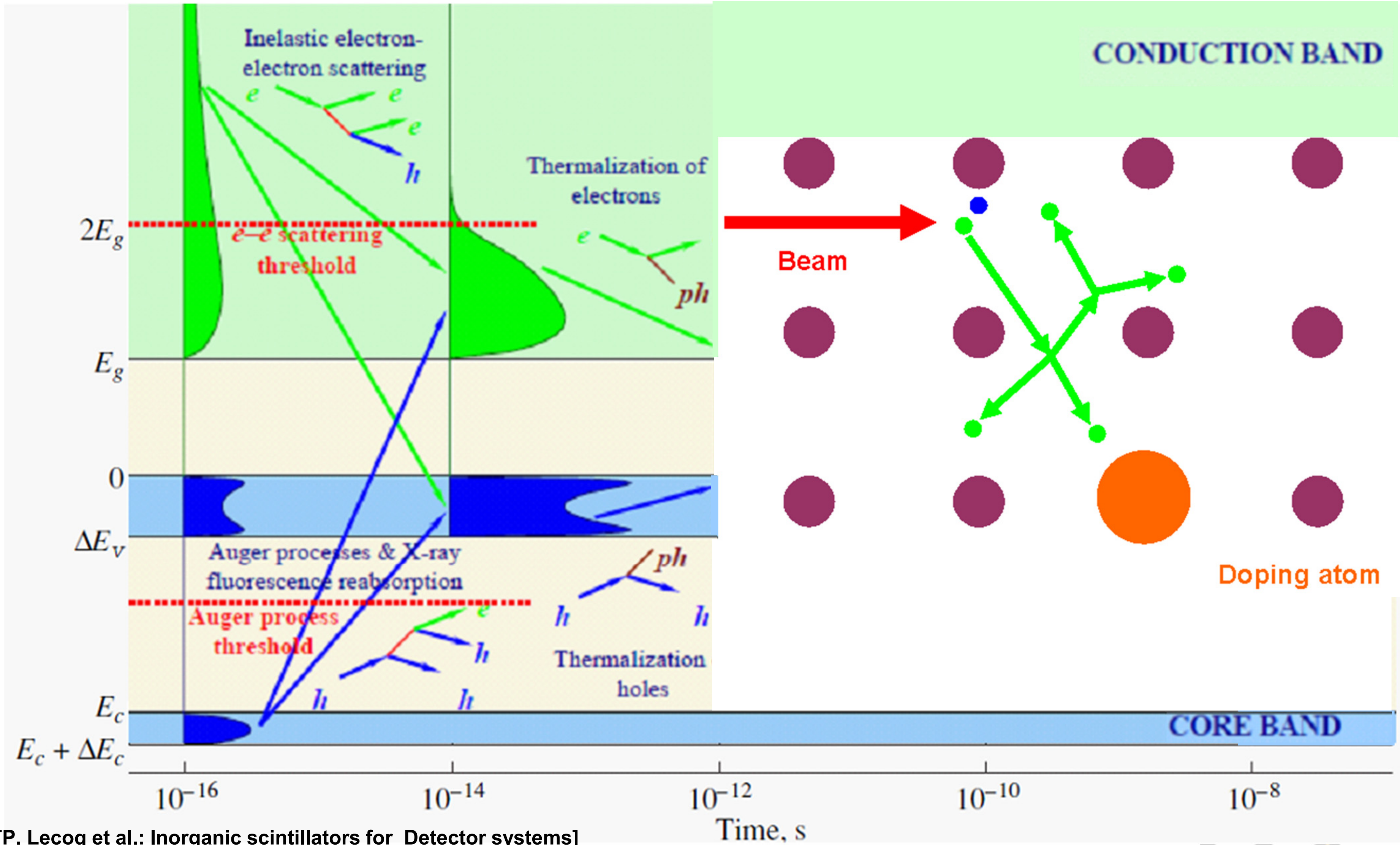

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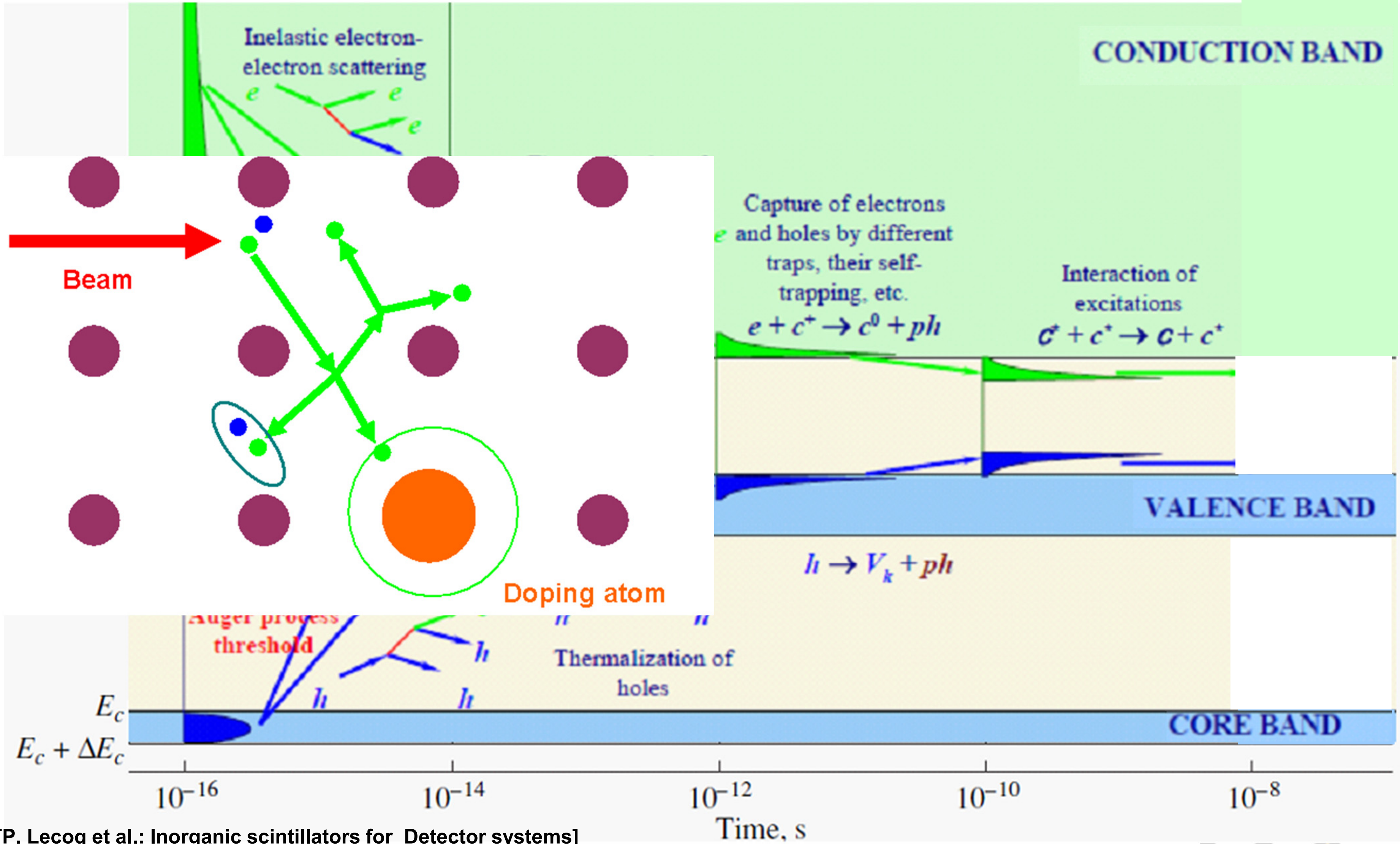

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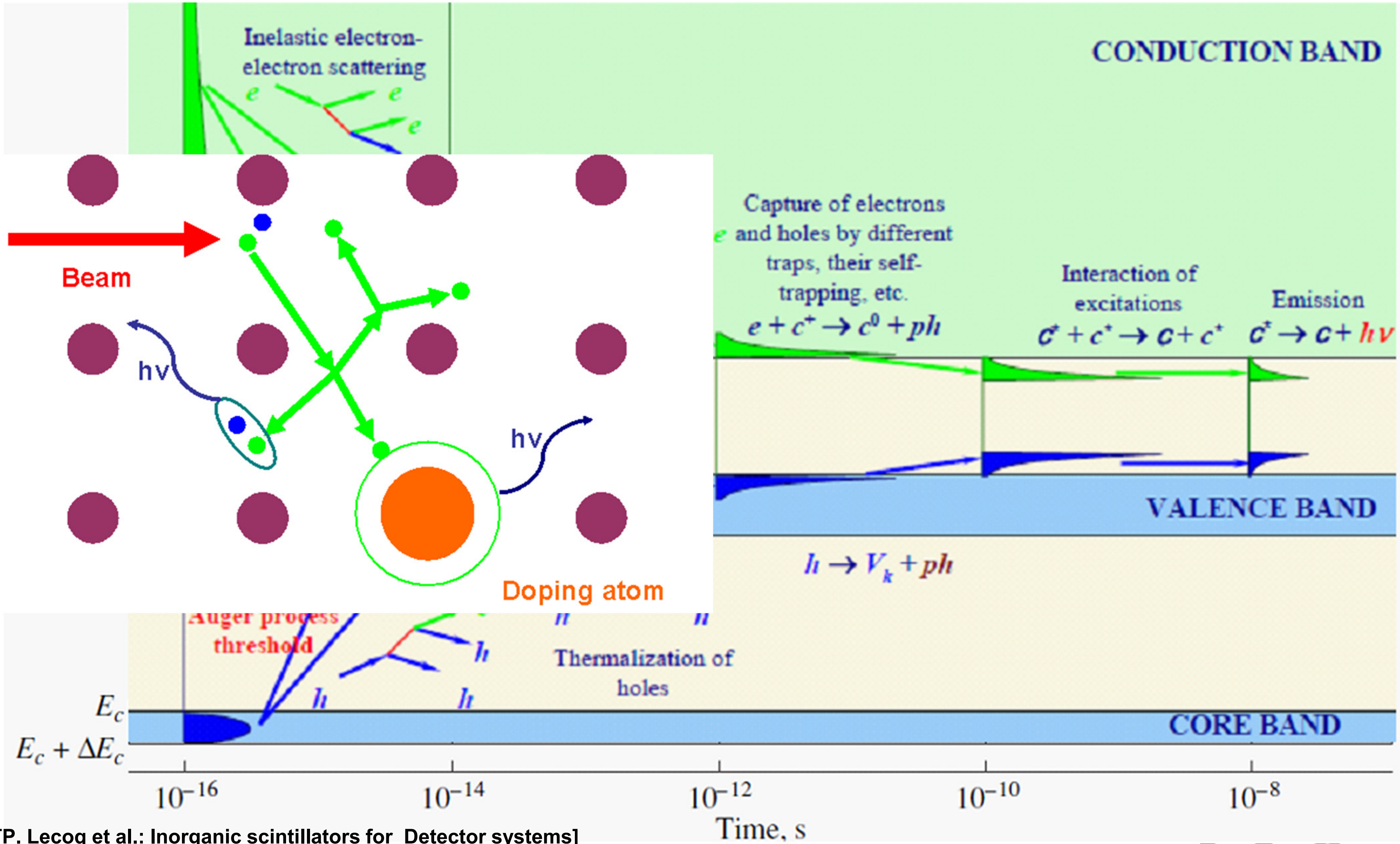

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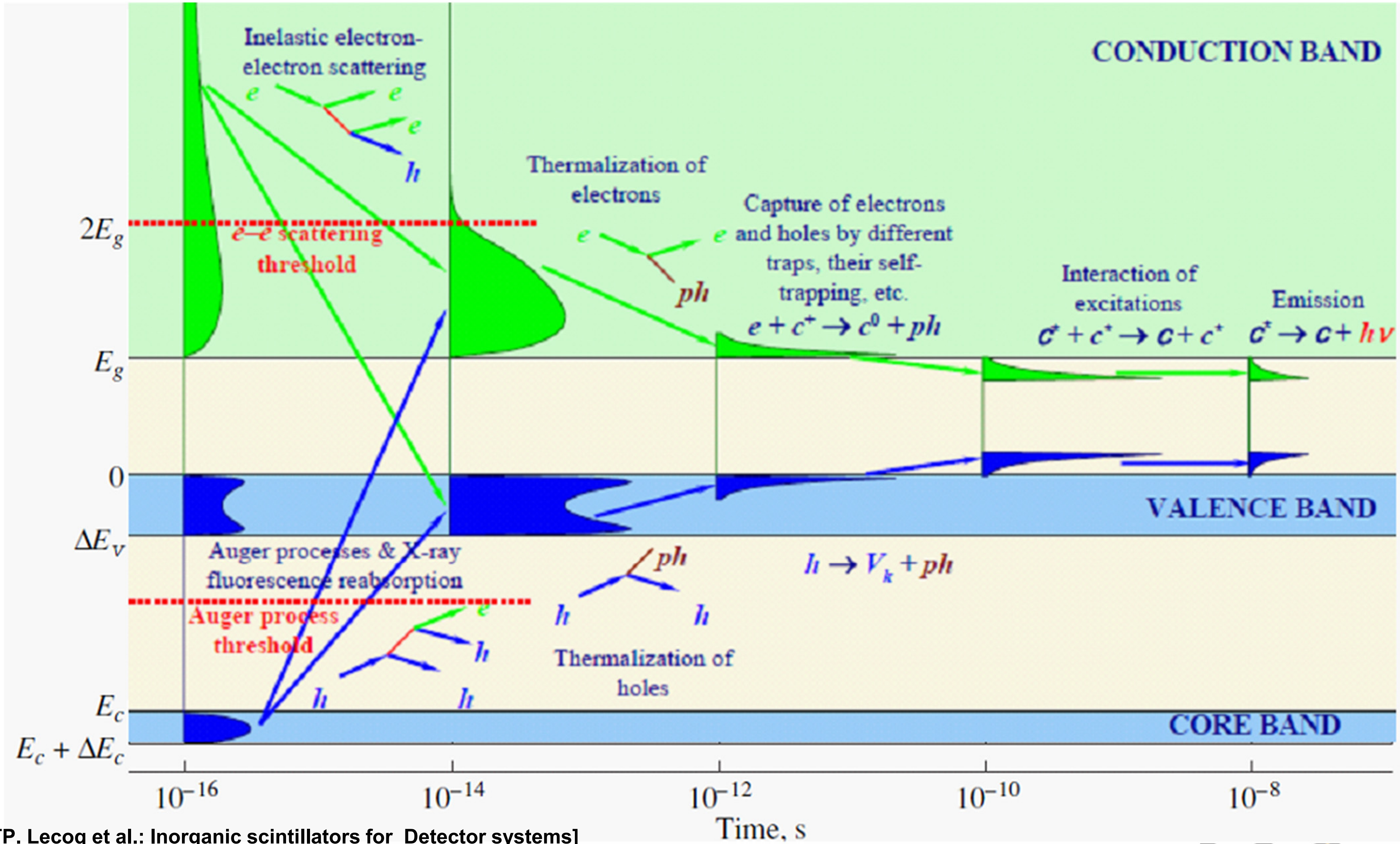

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Scintillation efficiency

Scintillation efficiency

$$\eta = (E_{dep}/\beta E_g) \cdot S \cdot Q$$

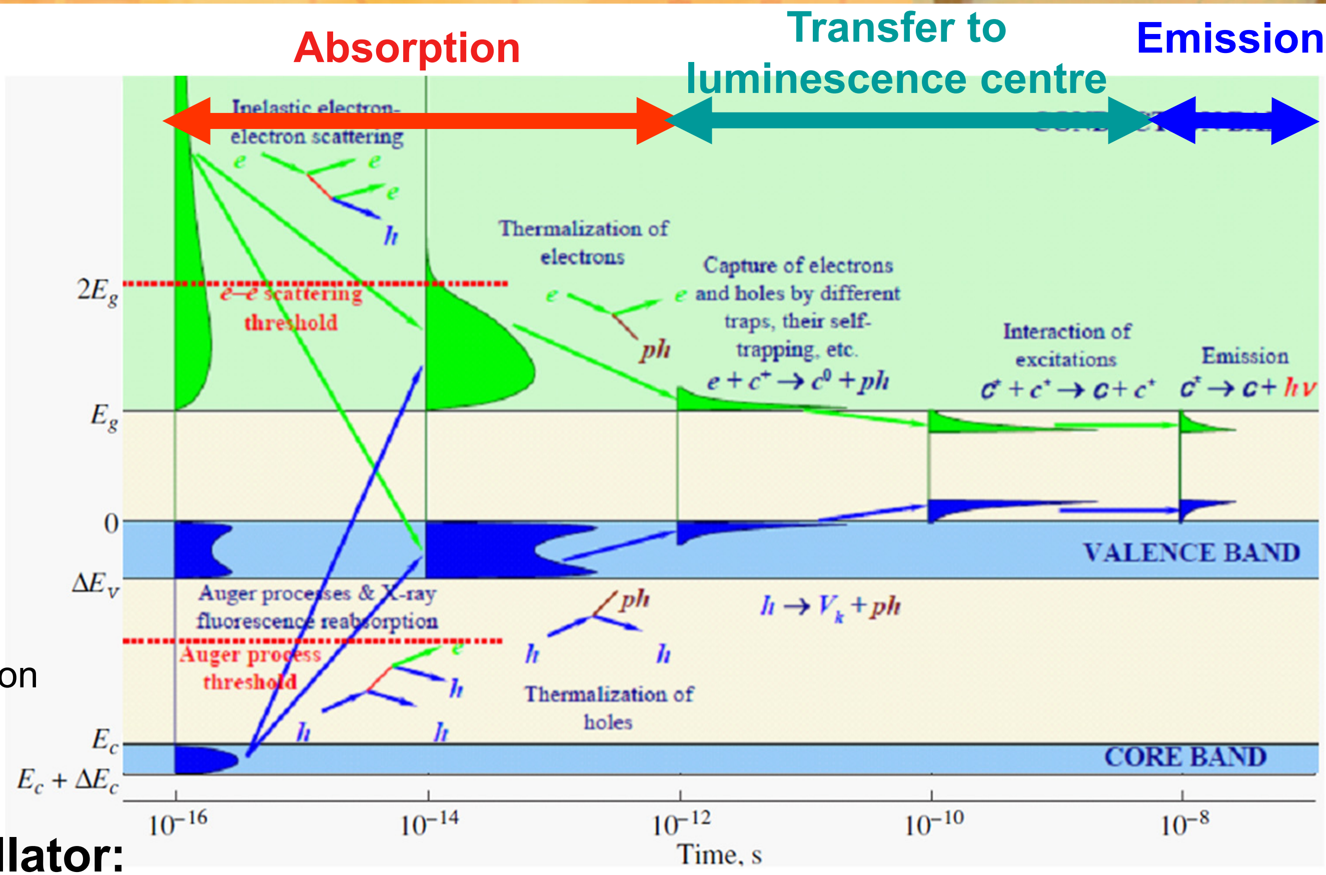
E_{dep}- deposited energy

βE_g – energy to create electron-hole pair

Energy efficiency

$$\eta_e = (E_{hv}/\beta Eg) \cdot S \cdot Q$$

E_{hv}- energy of scintillation photon



Example of good scintillator:

For materials having transfer and luminescence efficiencies **S** and **Q** near unity and a scintillation photon energy approaching the one of the band gap, the energy efficiency should be ~25-30%

[P. Lecoq: Inorganic scintillators for Detector systems]

Scintillation efficiency of various scintillators

Material	Phonons/MeV	Wavelength (nm)	Efficiency (%)
Intrinsic			
CsI	2000	315	0.8
Self-activated			
$CdWO_4$	15000	480	3.6
Bi_4GeO_{12}	8200	480	2.1
Activated			
NaI:Tl	38000	415	11.3
CsI:Tl	65000	540	13.7
LYSO:Ce	25000	240	7.4
YAG:Ce	16000	512	3.9

Limiting factors

Complicated scintillation process is influenced by many factors:

Temperature: thermal quenching is related to electron-phonon interactions and radiationless processes.

Concentration: interaction between luminescence centers increases with their concentration in the material. Energy migration through nonradiative energy transfer can take place if concentration is high enough.

Impurities: e.g. killer ions can compete with active ions and limit the scintillation efficiency.

Local density-induced quenching: relaxation of electronic excitation can lead to the formation of nanometric scale regions containing several electronic excitation separated by short distance.

[P. Lecoq: Inorganic scintillators for Detector systems]

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- General introduction to scintillating materials
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- **Applications in beam diagnostics**
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Bandwidth of applications

- huge application range for inorganic scintillators

very simplified comparison of scintillator usage

	Ions	Electrons	"normal" usage
particle energy	1 keV -100 GeV/u	100 keV -10 GeV	till 10 GeV (PANDA)
spot size	1 mm - cm	10 µm - mm	1 – 100 cm
counts per pulse	10^4 -10^{13}	10^7-10^{10}	< 10^6
counts rate	high	high	medium
energy deposition	very large	medium	low
saturation effects	expected	possible	none
material modification	expected	possible	no

Scintillator characteristics of interest

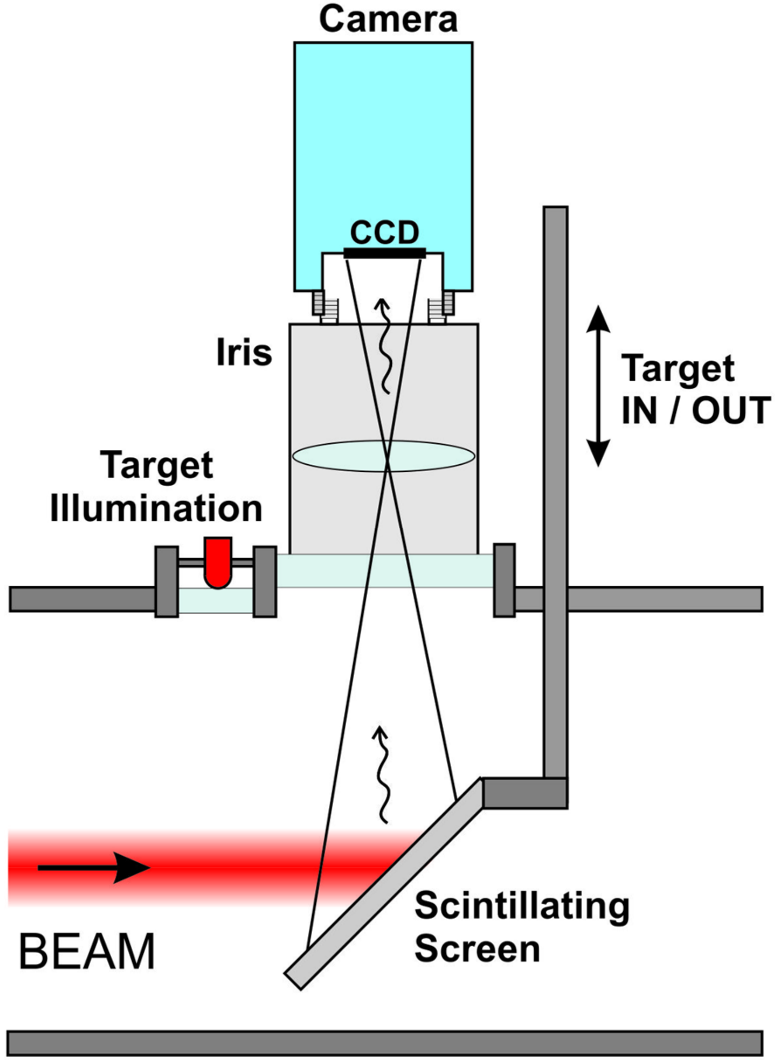
- high efficiency for energy conversion
- high dynamic range and good linearity between the incident particle flux and the light output
- emission spectra matches to the spectral response of light detector
- no absorption of the emitted light to prevent artificial broadening by the stray light inside the material
- fast decay time, to enable observation of possible time dependent beam size variations
- good mechanical and thermal properties
- high radiation hardness to prevent damages

[P. Forck: JUAS Lecture]
[P. Strehl: Beam Instrumentation and Diagnostics]

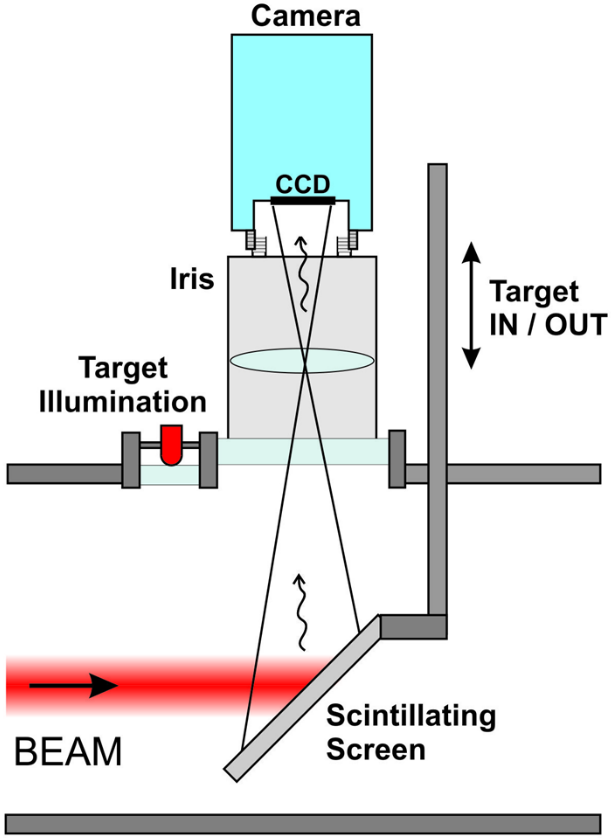
Applications in beam diagnostics

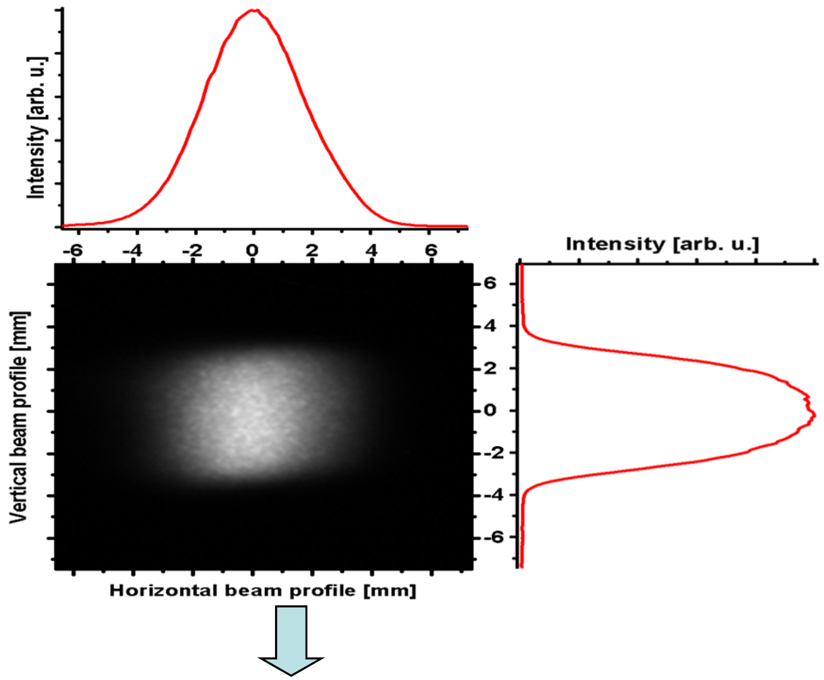
Scintillating screens are widely used in accelerator facilities for transversal beam profile and precise single shot emittance measurements

- simple, reliable profile measurement system
- used for beam alignment
- most direct way of beam observation: complete 2D information



Profile measurements

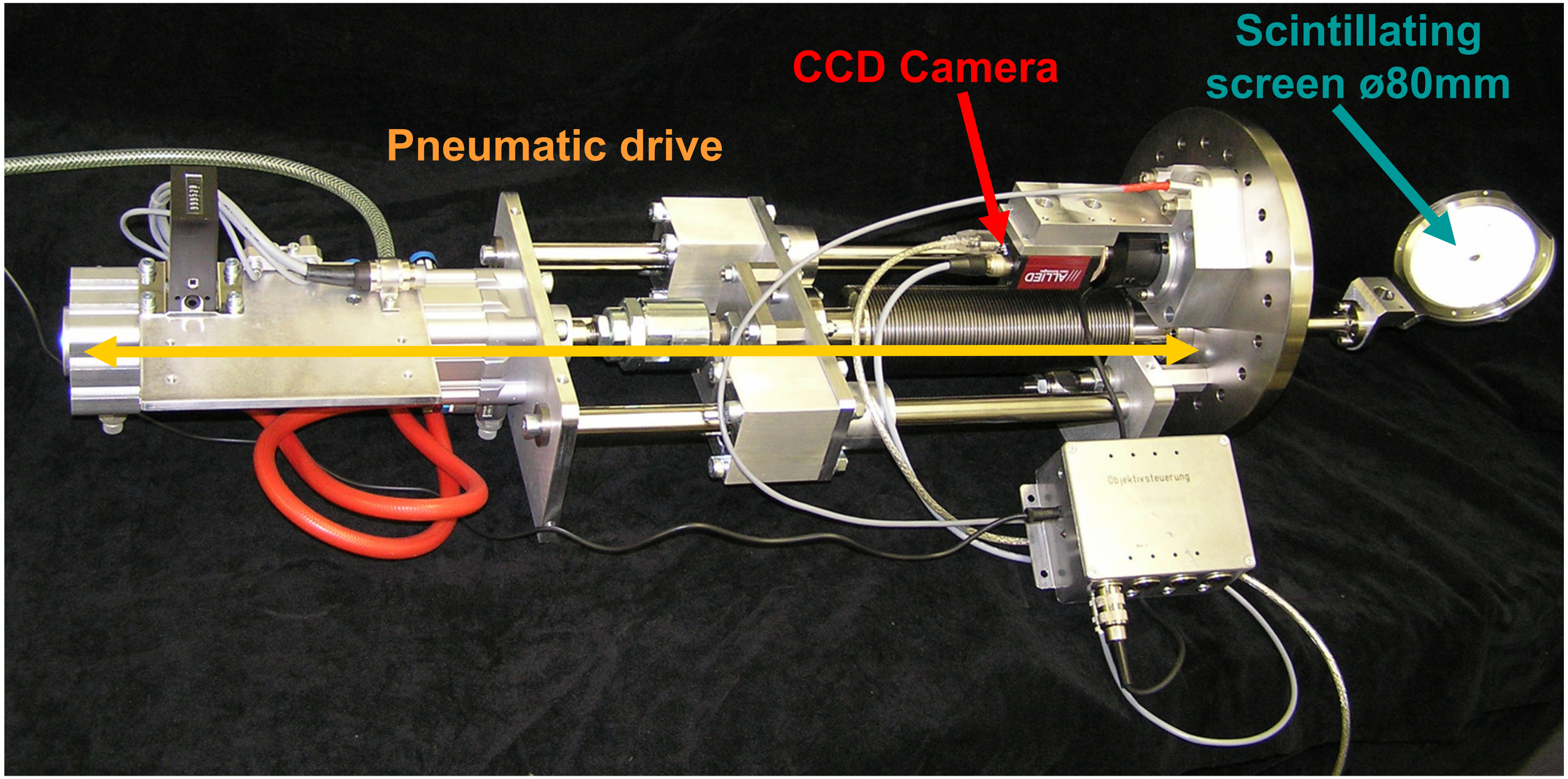




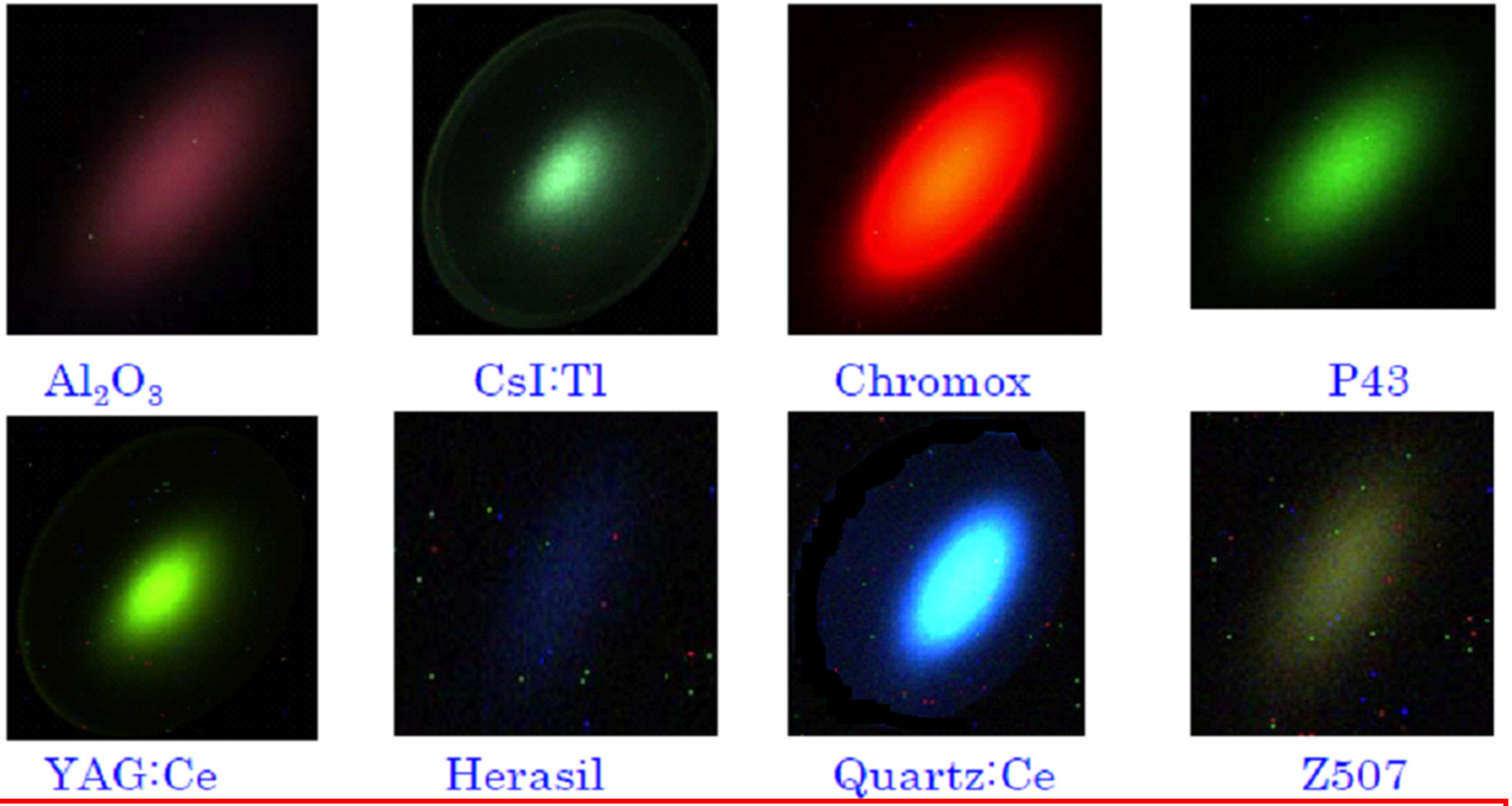
From the projection:

- light yield (integral)
- centre of projection
- beam width
- asymmetry
- peakness

Typical realization from HIT



Examples for beam profiles

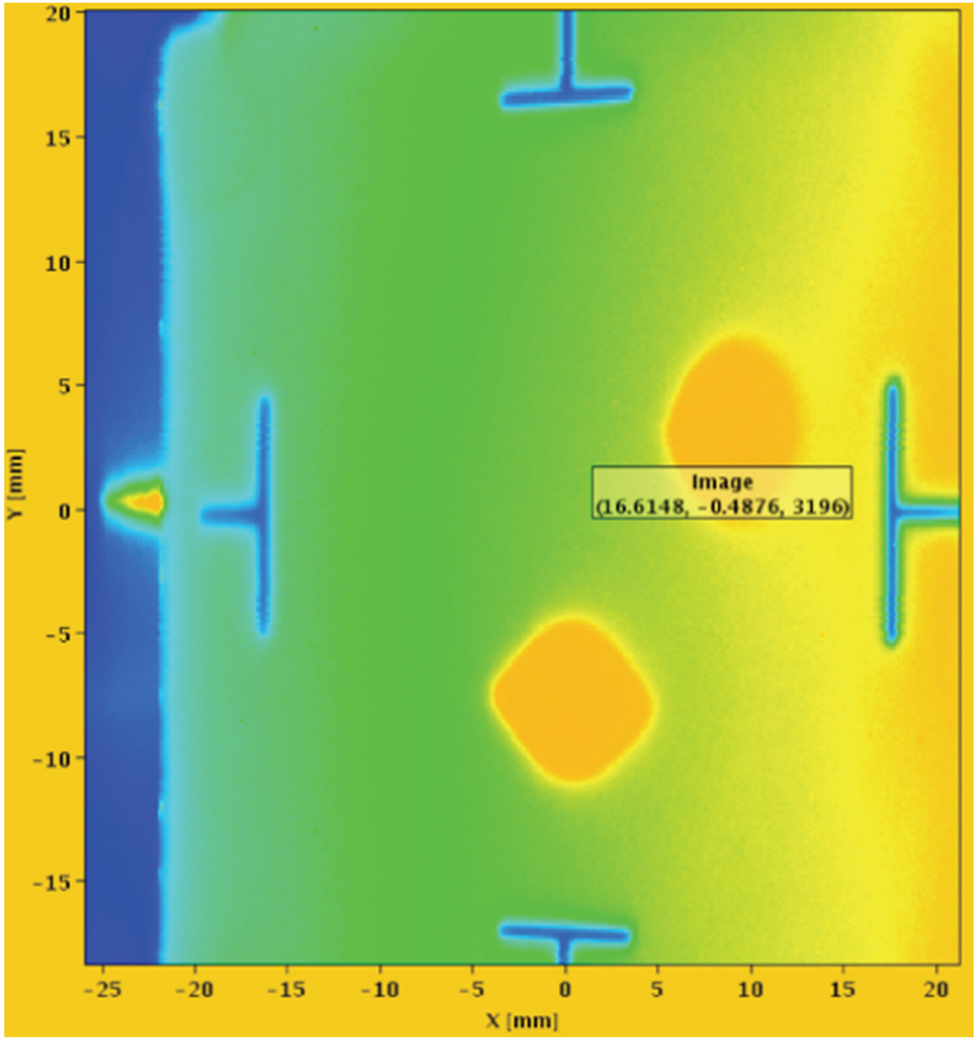


Light emitted by different scintillators during 300MeV/u Uranium beam irradiation observed with colour camera

[B. Walasek-Höhne, GSI]

Screen at LHC

Chromox screen at LHC, protons at 450 GeV



[U. Raich, CERN, CAS Lecture]

[E. Bravin, CERN, Workshop]

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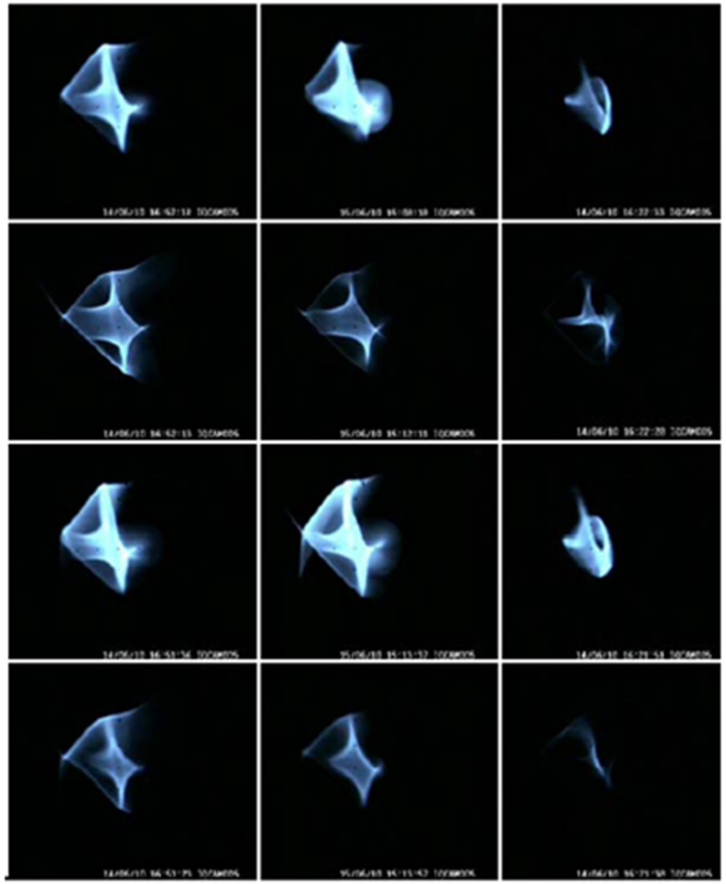

Uex = 15 kV @ KBr

Ion beam spot at GSI ECR ion source during microwave frequency tuning

[J. Mäder, GSI, Workshop]

Typical screen materials

Materials used in beam diagnostics applications

Name	Material	Max. emission	Decay time
BGO	$Bi_4Ge_3O_{12}$	480 nm	300 ns
LYSO	$Lu_{1.8}Y_{0.2}SiO_5$:Ce	397 nm	41 ns+slow
YAG	$Y_3Al_5O_{12}$:Ce	512 nm	100 ns
P43	Gd_2O_2S:Tb	545 nm	1 ms
P47	$Y_2Si_5O_5$:Tb	400 nm	100 ns
Chromox	Al_2O_3:Cr	700 nm	1 ms

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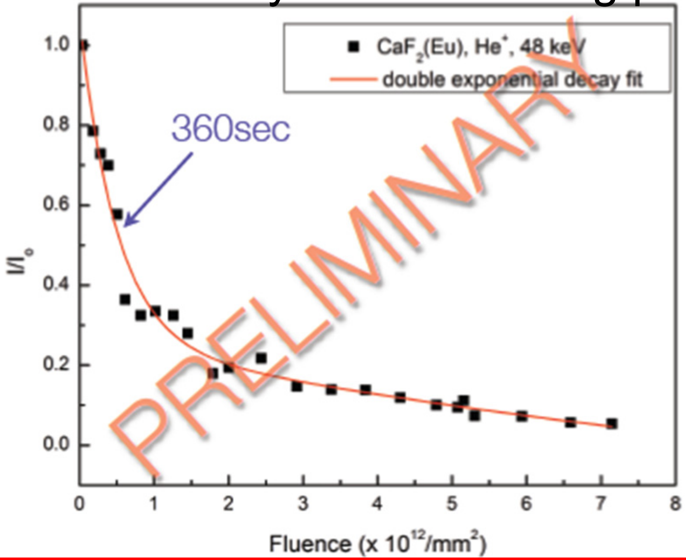
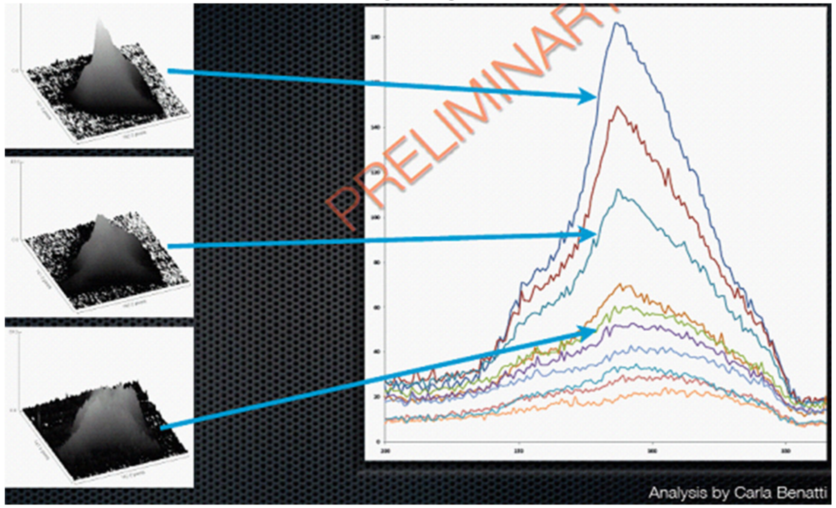
Screens for low energetic ion beams

Particles are completely stopped in the screen material, deposition of energy and charge in material may lead to heating problems and electrical charging





Beam parameters: He^+, 1 nA at 48keV, 1.3 h

light output vs. fluence

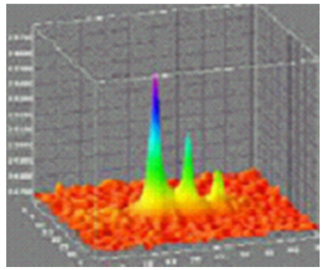
→ 2-component damage mechanism (fast, slow)

light emission distribution changes

→ crucial for profile and pepper-pot emittance measurements!

[G. Perdikakis, NSCL/MSU, Workshop]

Sensitivity: CsI:Tl is sensitive enough for $2 \cdot 10^5$ H^+ at 200 keV

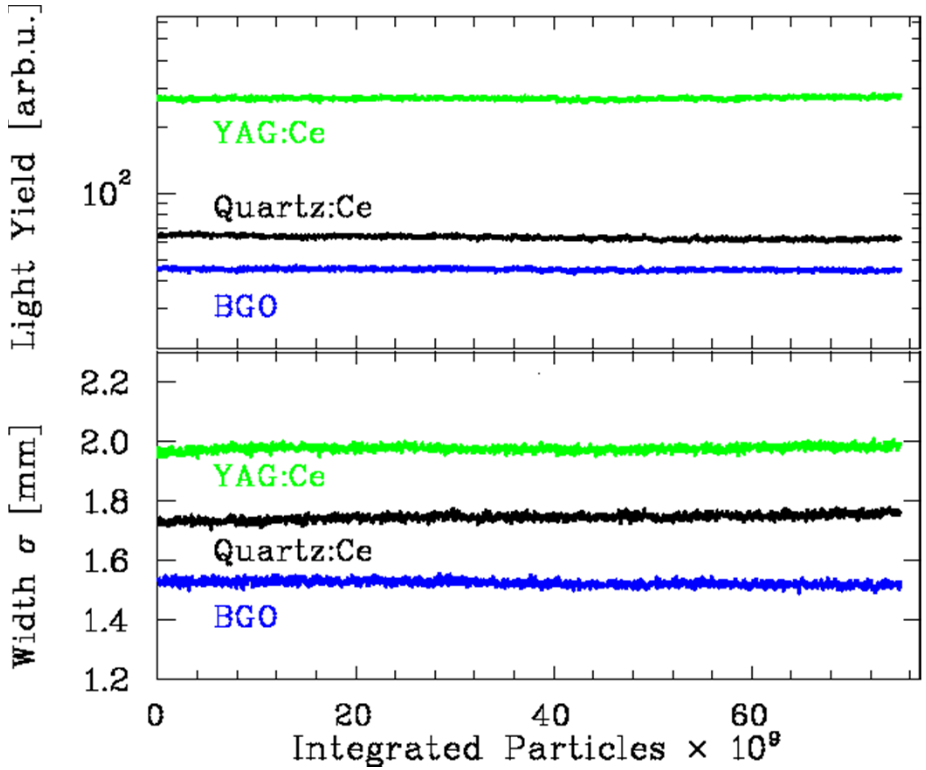


[P. Finacchiaro, INFN-LNS, Workshop]

[J. Harasimowicz et al., Rev. of Scient. Instr. 81]

Screens at low currents

Systematical studies at different ion species with energies up to **11.4 MeV/u** and beam currents from some **nA** to some **mA**



Purpose built scintillators applicable for low currents

→ different image reproduction

→ but reproducible behaviors

→ different width reading of 25%

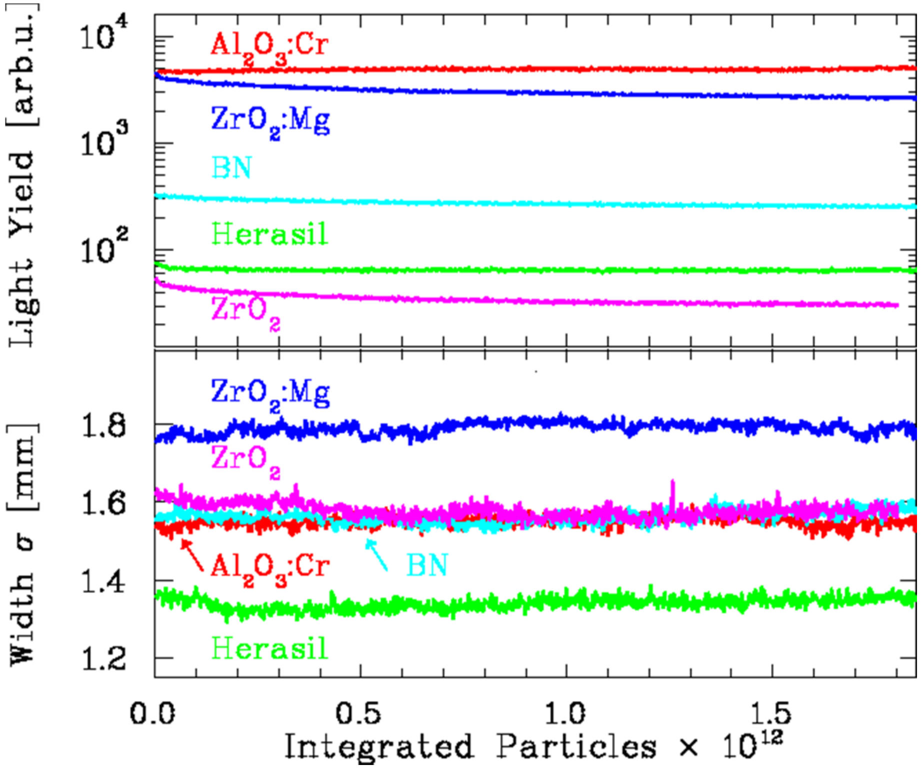
→ not suitable for higher currents

Beam parameters: $^{12}C^{2+}$, 11.4 MeV/u, $5 \cdot 10^6$ ppp in 100 μs, **~17 nA**, 1500 pulses

Average temperature: 23°C (backside)

[E. Gütlich (GSI) et al., IEEE Transact. on Nucl. Science]

Screens at medium currents



Only ceramics can survive irradiation with medium and high current ion beams

→ different image reproduction

→ but reproducible behavior

→ different light yield and width reading

→ light yield does not correlate with beam width

→ different beam shape

Beam parameters: $^{40}Ar^{10+}$, 11.4 MeV/u, $2\cdot10^9$ ppp in 100 µs, **~30 µA,** 1000 pulses

Average temperature: ~47°C (backside of ZrO_2:Mg)

[E. Gütlich (GSI) et al., IEEE Transact. on Nucl. Science]

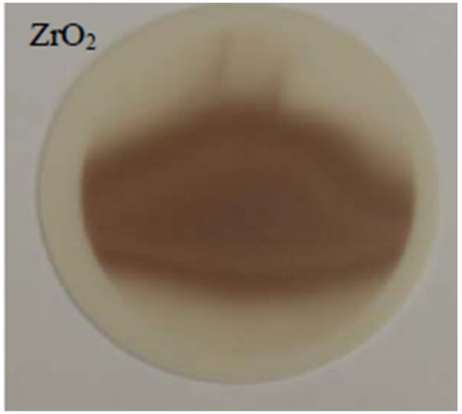
Screen coloration

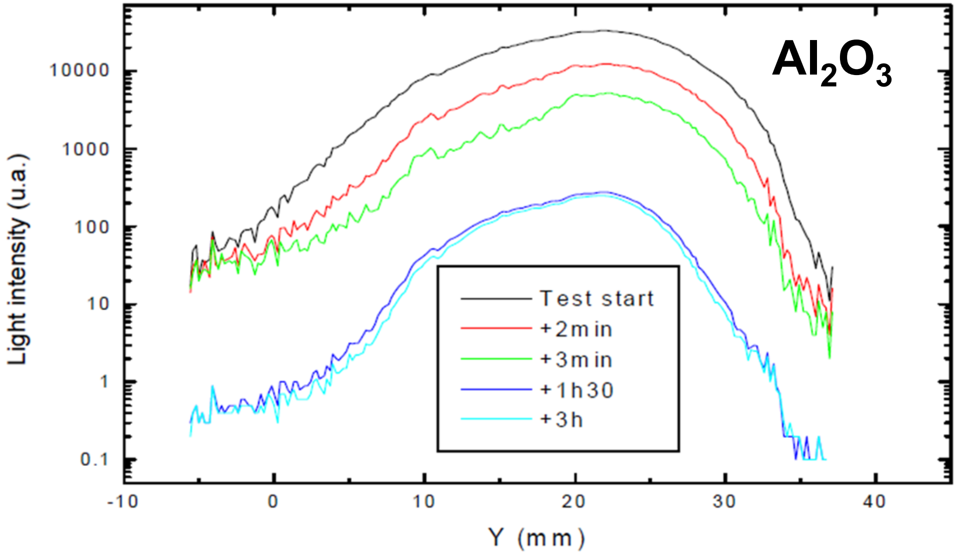
Different materials showed different behavior during irradiation

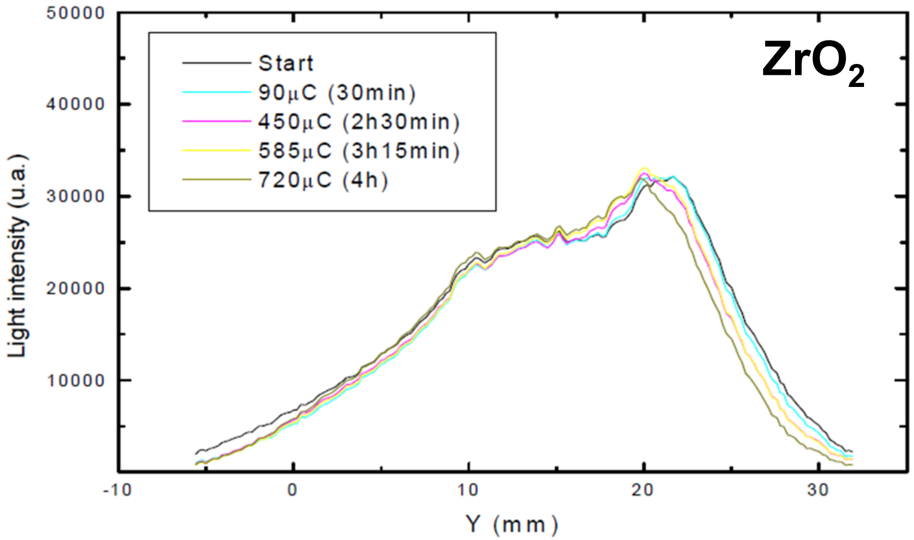
→ standard used Chromox was fading with time (not shown)

→ Al_2O_3 light yield decreased with time

→ ZrO_2 very stable behavior although coloration of surface





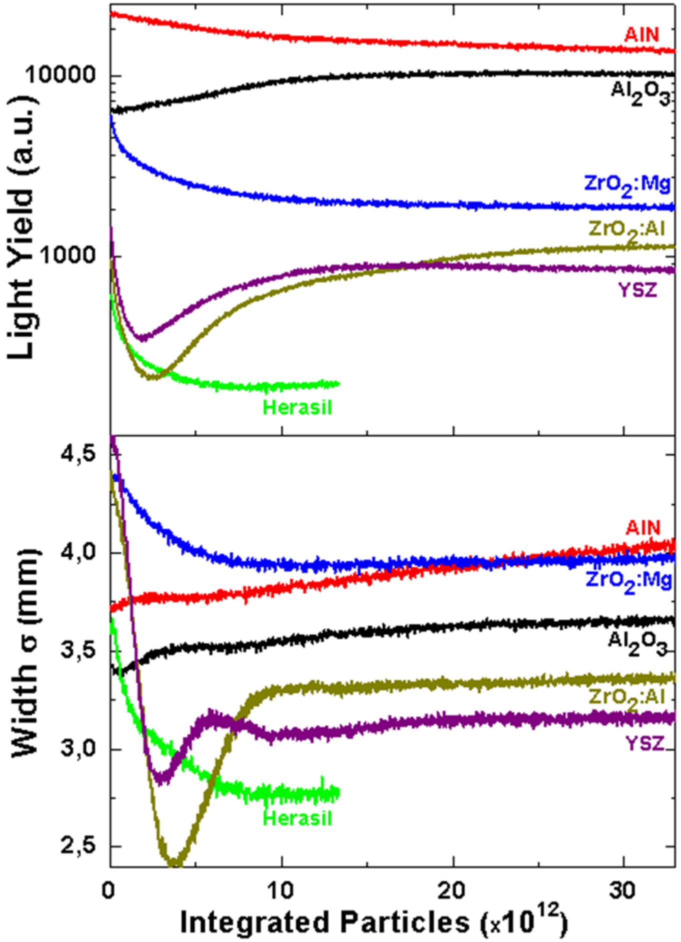


Beam parameters: Pb^{54+}, 4.2 MeV/u, **100 µA** , 60 µs

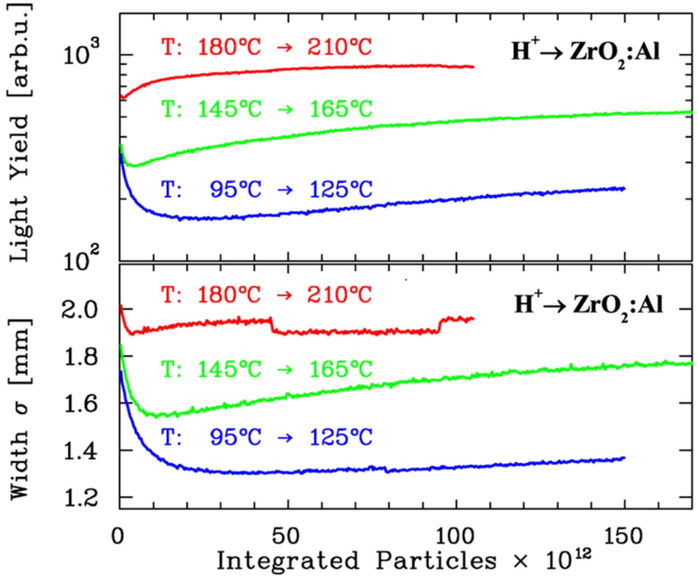
[C. Bal, CERN, DIPAC2005]

[E. Bravin, CERN, Workshop]

Screens at high currents



→ light yield and profile width depend on material
→ different dynamical behavior
→ reasons: material modification and temperature dependency
→ strong material modifications

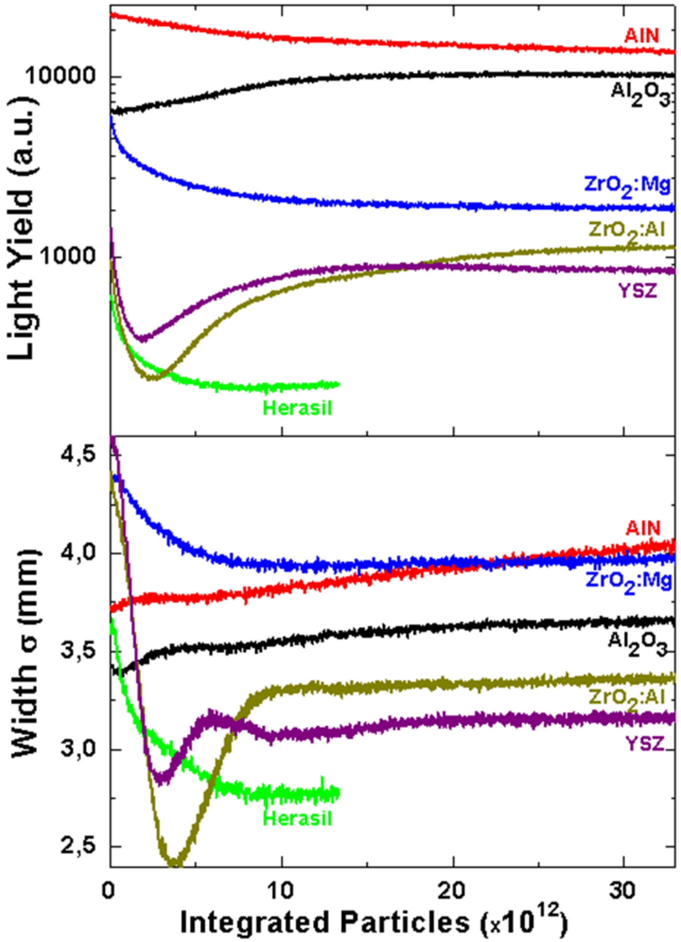


Beam parameters: H^+, 4.8 MeV/u, $3.5 \cdot 10^{11}$ ppp in 4 ms, **260 µA,** 300-500 pulses

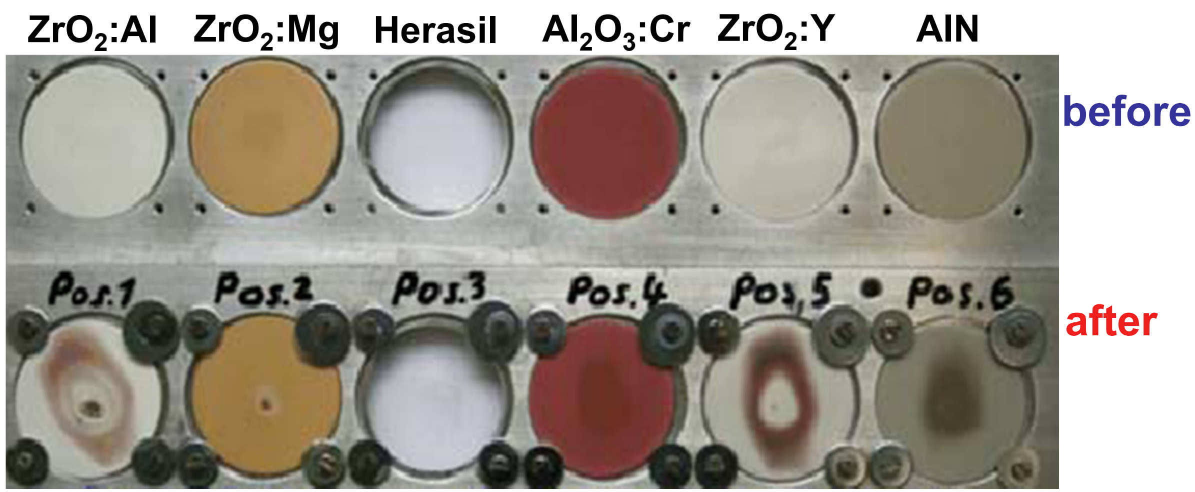
Beam parameters: Ar^{10+}, 11.4 MeV/u, $3.3 \cdot 10^{10}$ ppp in 0.2 ms, **260 µA,** 1000 pulses
Average temperature: ~200°C (backside of Al_2O_3)

[E. Gütlich (GSI) et al., IEEE Transact. on Nucl. Science]

Screens at GSI – high currents



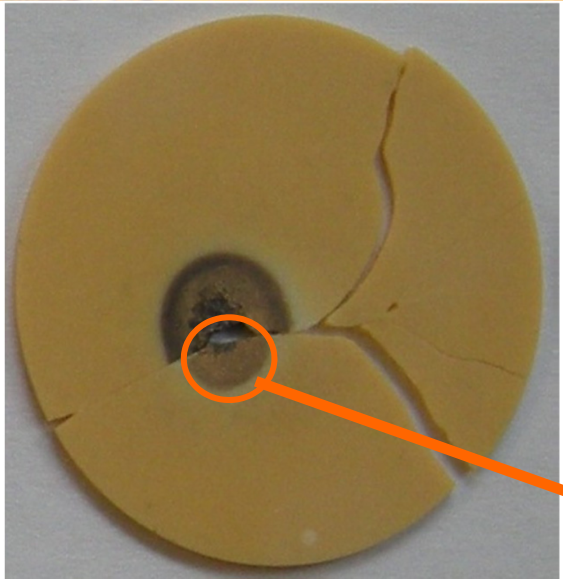
- → light yield and profile width depend on material
- → different dynamical behavior
- → reasons: material modification and temperature dependency
- → strong material modifications

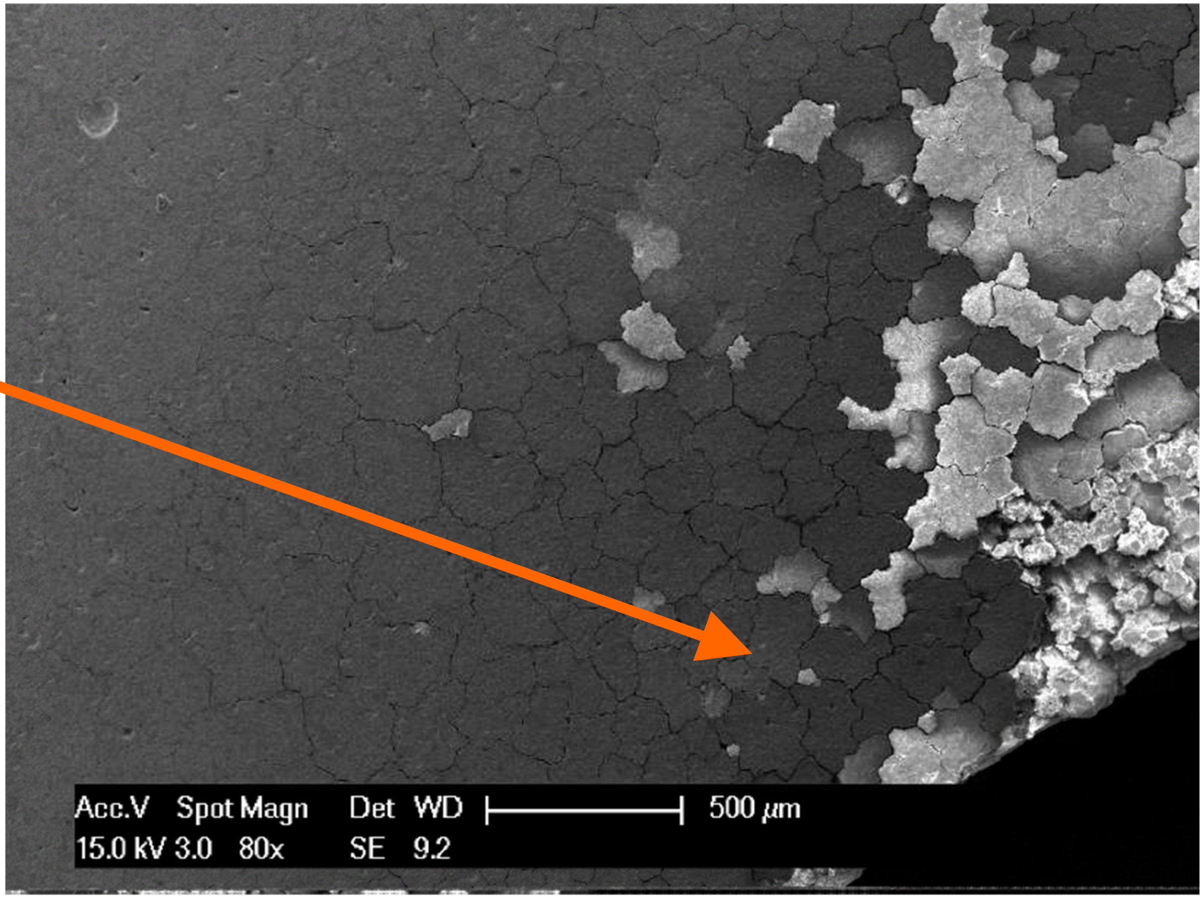


Beam parameters: Ar^{10+}, 11.4 MeV/u, $3.3 \cdot 10^{10}$ ppp in 0.2 ms, **260 μA,** 1000 pulses
Average temperature: ~200°C (backside of Al_2O_3)

[E. Gütlich (GSI) et al., IEEE Transact. on Nucl. Science]

Damages due to heating e.g. ZrO_2:Mg





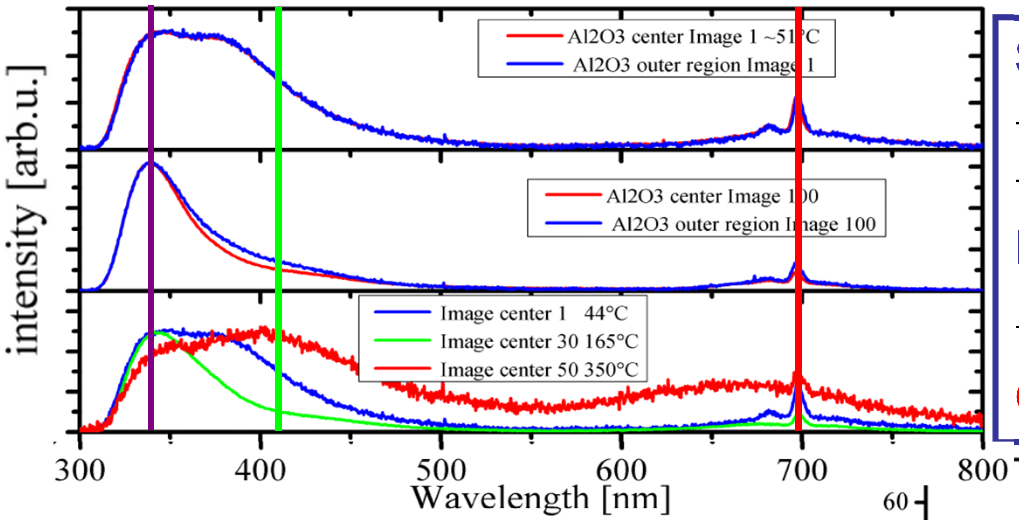
Phase transformation
(monoclinic → tetragonal)

→ volume expansion (3-5%)
→ micro-cracks in material

[R. Krishnakumar, GSI]

Spectroscopic studies - Al_2O_3

Wavelength spectra and image reproduction for Al_2O_3



Spectrum influenced by:

→ material modification by ions

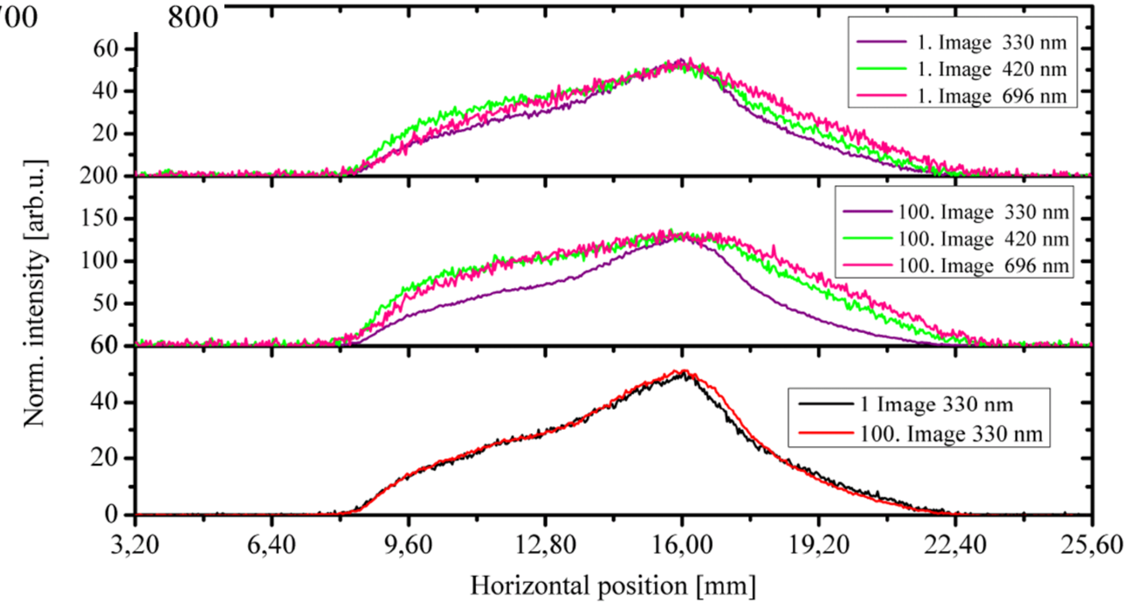
→ temperature

But:

→ some transitions are less sensitive

Goal: Find right wavelength interval!

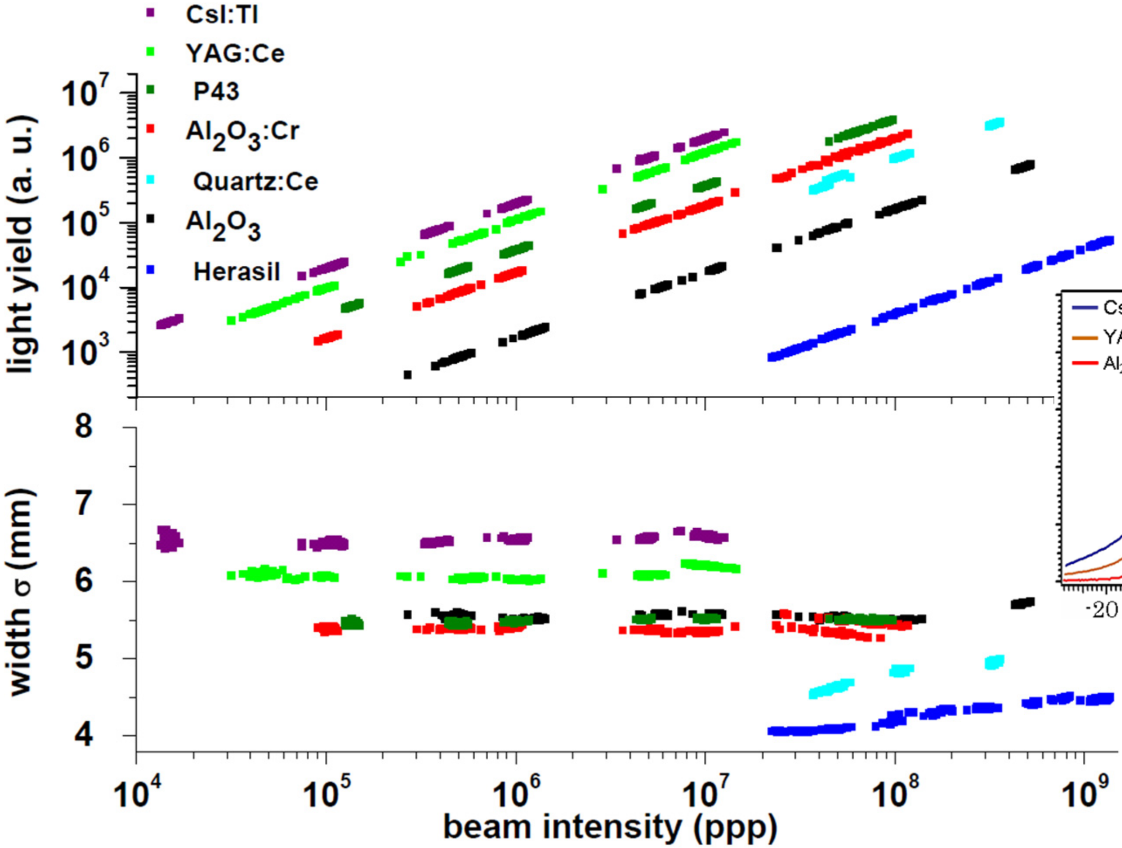
Beam parameters: Ca^{10+}, 4.8 MeV/u, $5 \cdot 10^{10}$ ppp in 3.3 ms, **30 μA,** 100 pulses



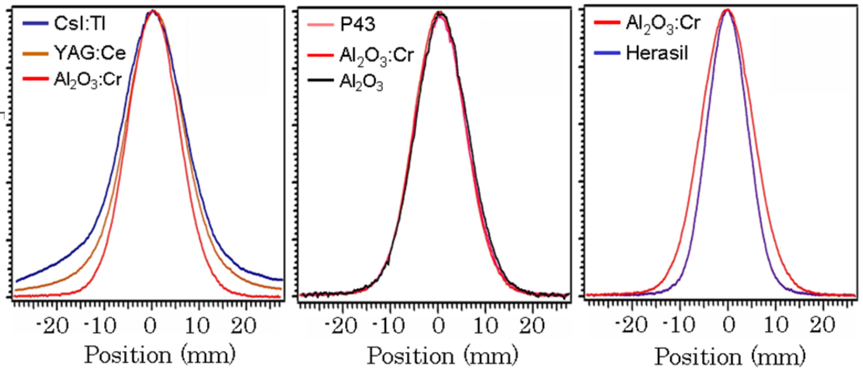
[E. Gütlich et al., MOPD57]

Screens for high energetic ion beams

Due to low energy deposition (dE/dx) in material, ceramics are compared with purpose built scintillators



→ light yield and profile width depend on material
→ different beam shape
→ very linear behaviors

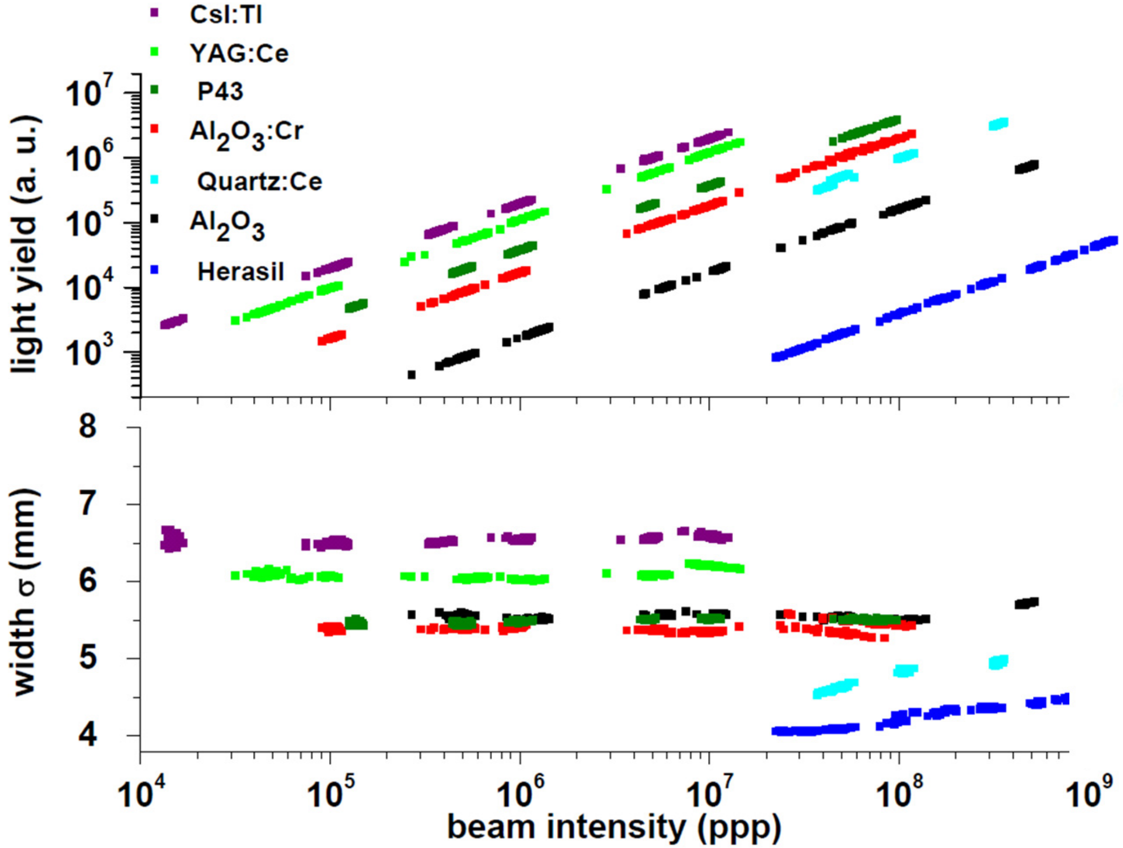


Beam parameters: U, 269 MeV/u, 10^4 – 10^9 ppp, 300 ms pulse length

[P. Forck et al., MOPD53]

Screens for high energetic ion beams

Due to low energy deposition (dE/dx) in material ceramics could be compare with purpose built scintillators



→ light yield and profile width depend on material
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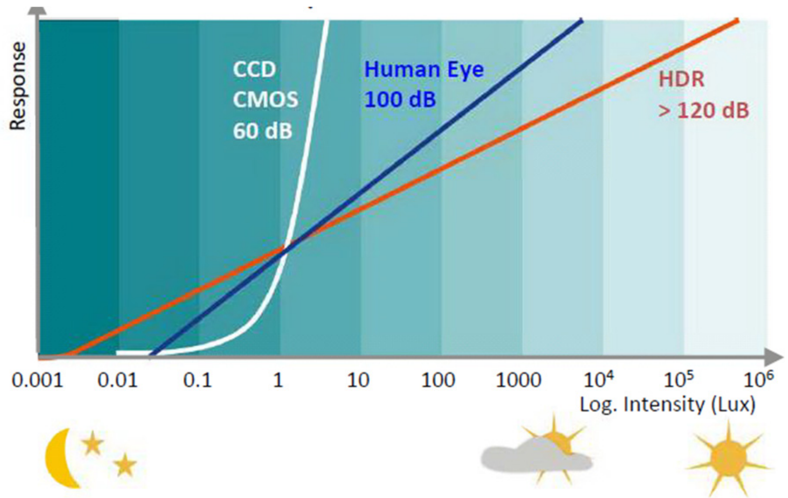


we need higher dynamic range for

- **DAQ**
- **scintillators**

Beam parameters: U, 269 MeV/u, 10^4 – 10^9 ppp, 300 ms pulse length

[P. Forck et al., MOPD53]

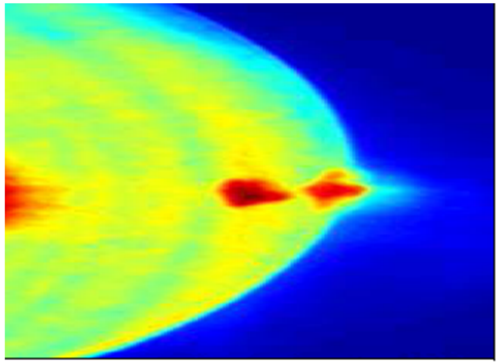
Outline

- General introduction to scintillating materials
- Scintillation mechanism
- Applications in beam diagnostics
- Experience at hadron machines
- **Experience at electron machines**

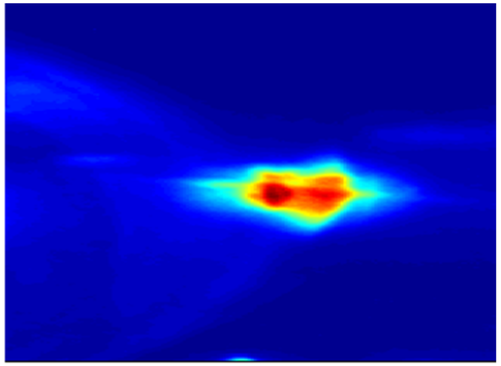
Electron machines

Optical Transition Radiation (OTR) diagnostics fail because of coherent effects

→ profile diagnostics based on scintillating screens is needed



(a) OTR screen



(c) LuAG screen

S. Wesch WEOA01

[M. Yan et al., TUPD59]

FLASH, electrons at 700 MeV, 0.5 nC

Electron machines

Optical Transition Radiation (OTR) diagnostics fail because of coherent effects

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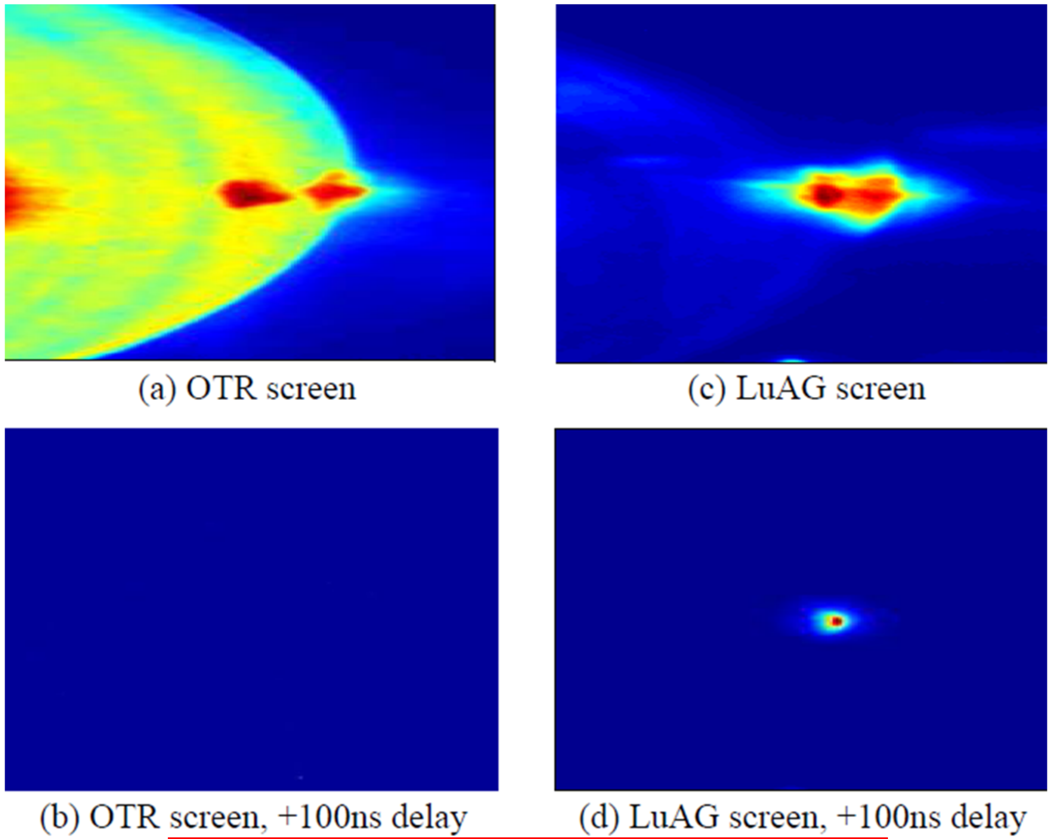
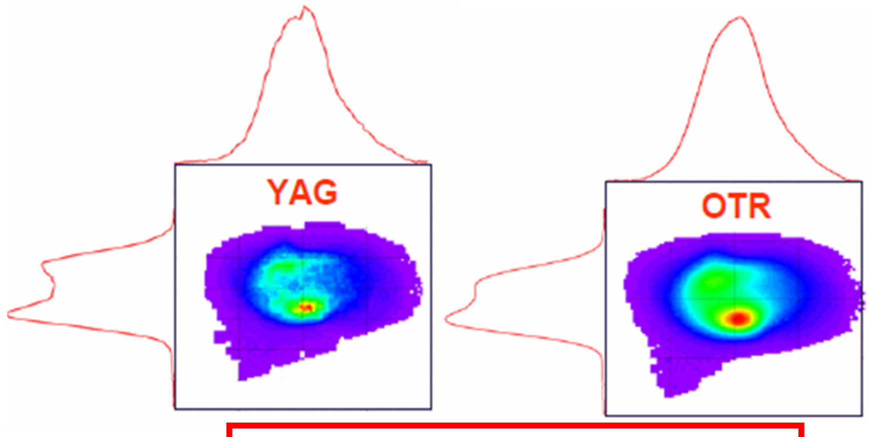


S. Wesch WEOA01

[M. Yan et al., TUPD59]

FLASH, electrons at 700 MeV, 0.5 nC

Comparison with OTR

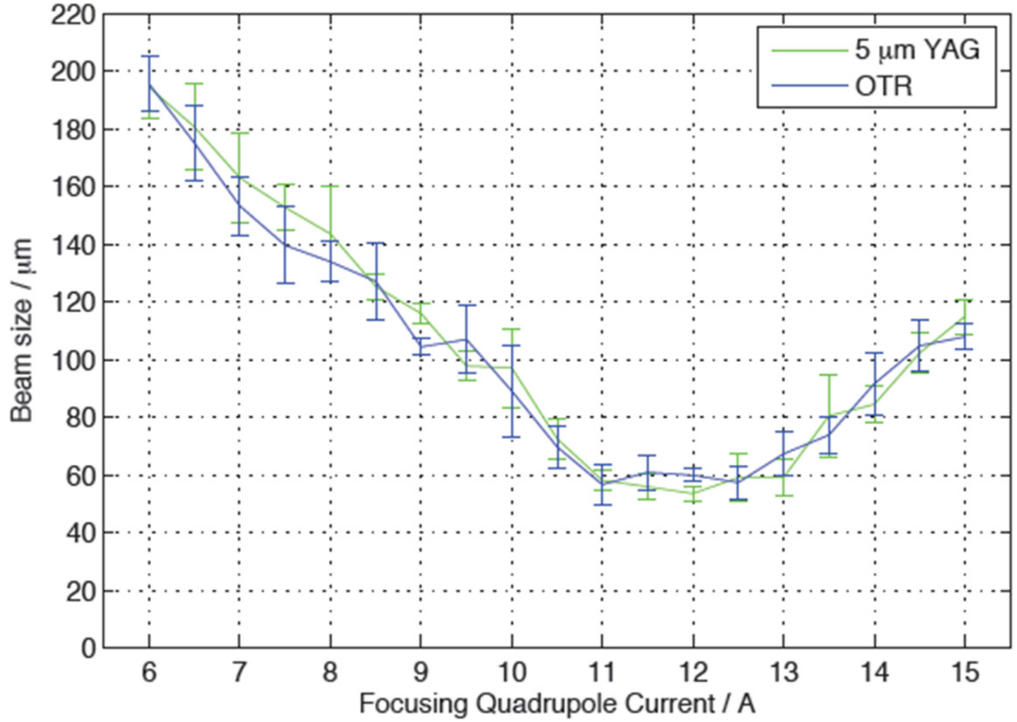


Beam parameters: electrons, momentum 24.5 MeV/c, 1 nC

YAG screen shows detailed structure of beam during one bunch

→ due to low light yield of OTR averaging of several bunches in necessary.

[S. Rimjaem, PITZ, et al., TUPD54]



Beam parameters: electrons at 130 MeV, 200 pC

comparison to beam size measurement with OTR shows good agreement down to 60 µm rms

[R. Ischebeck, PSI, Workshop]

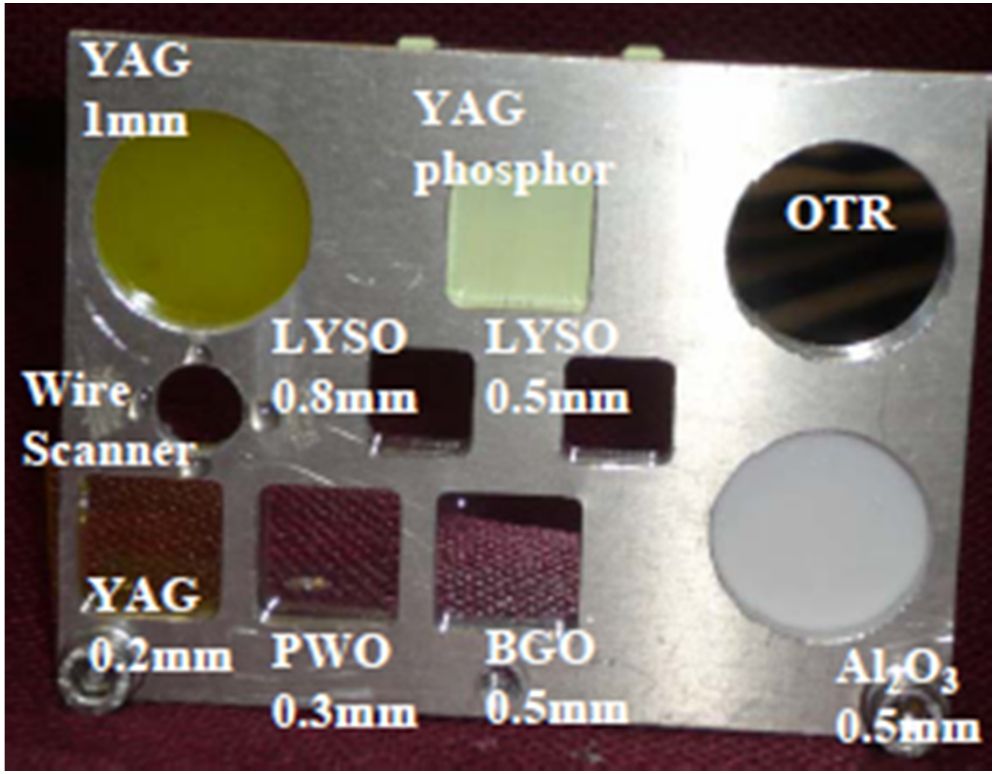
Electron machines

Optical Transition Radiation (OTR) diagnostics fail because of coherent effects

→ profile diagnostics based on scintillating screens is needed

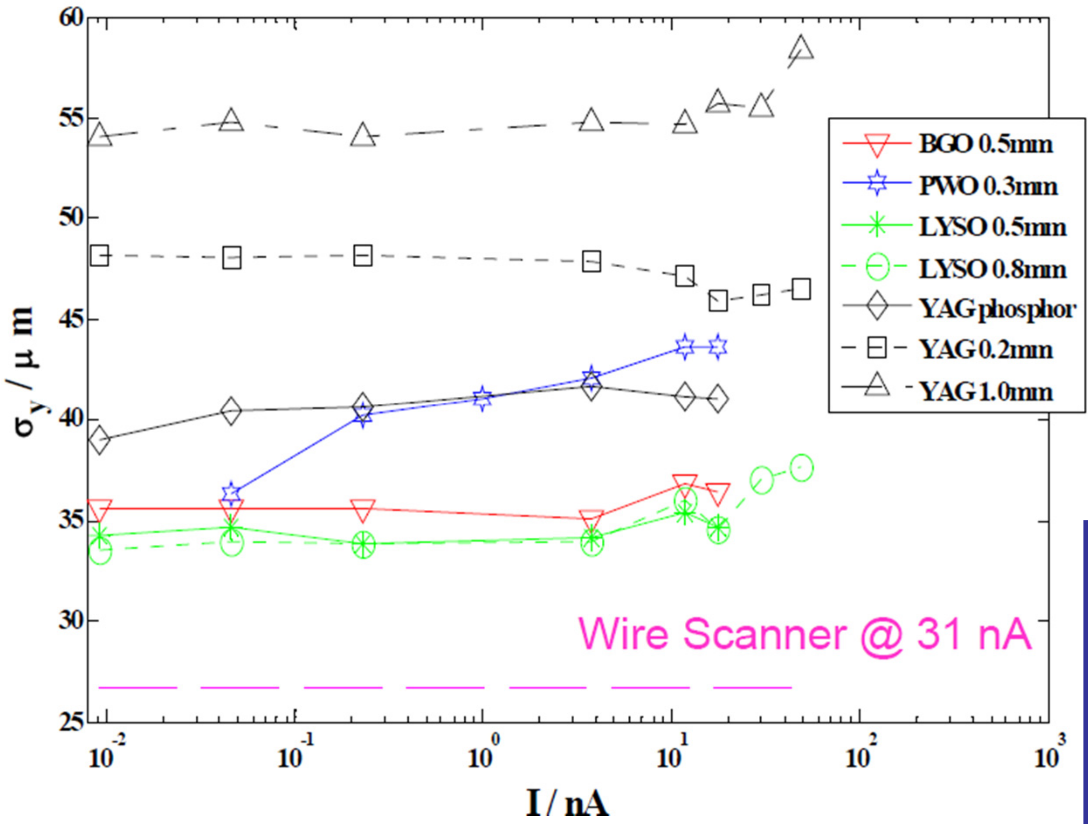
→ ongoing search for optimum scintillator material

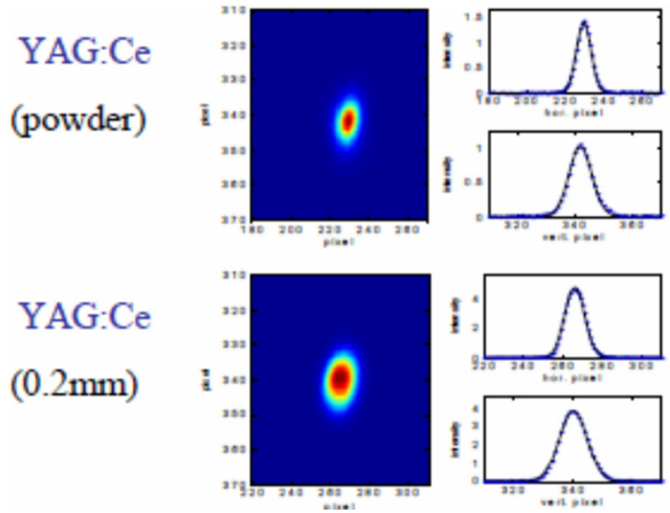
→ influence of observation geometry for different materials (and thicknesses)



[G. Kube (DESY) et al., IPAC2010]

Electron machines - MAMI



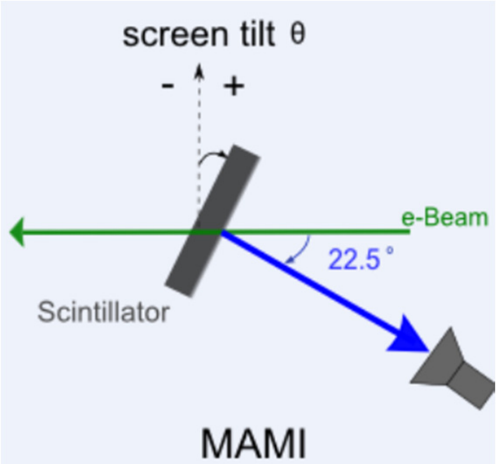


→ different image reproduction
→ but reproducible behavior
→ beam profile readings depend on material
→ beam profile reading of YAG:Ce depends on material thickness

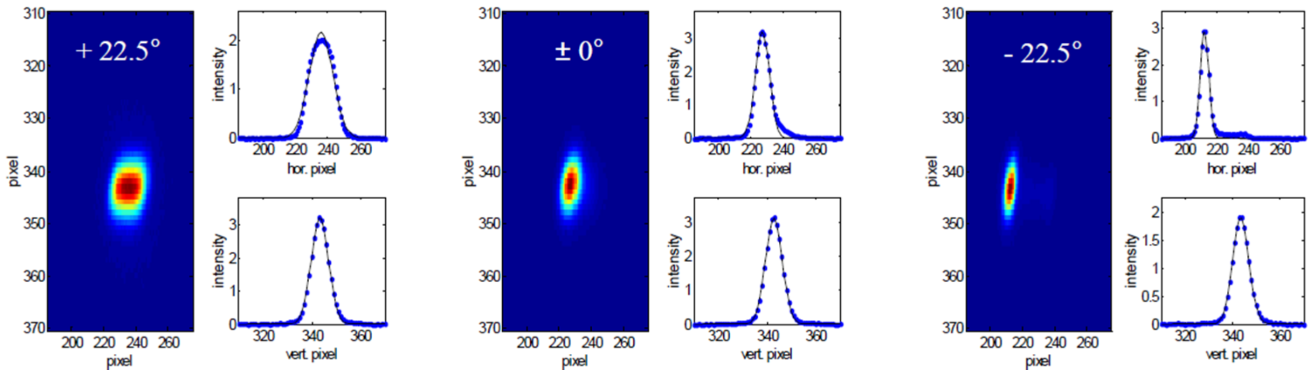
Beam parameters: electrons at 855 MeV, 10^{-2} – 50 nA

[G. Kube (DESY) et al., IPAC2010]

Investigation of detector geometry



Variation of the screen angle influence the measured size



Beam parameters: electrons at 855 MeV, 3 nA

ZEMAX simulations

→ propagation of light through material influences detected image

→ satisfactory agreement between simulation and measurement **[G. Kube (DESY) et al., IPAC2010]**

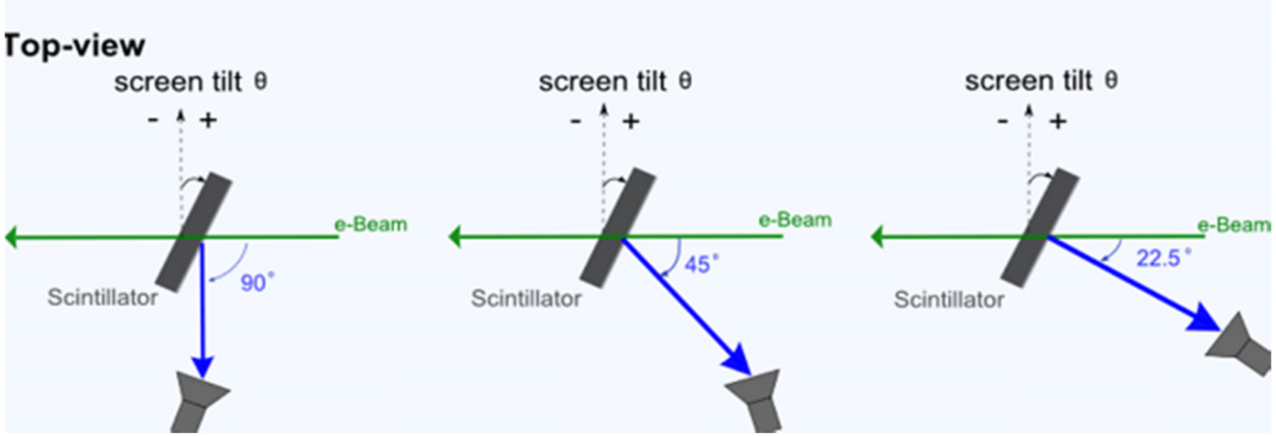
→ an optimum screen tilt angle exists

Further improvement of the resolution of the system by simulations:

- observation geometry
- screen tilt
- screen material
- thickness of the screen
- focal plane

[M. Yan (U. of Hamburg) et al., TUPD59]

Example – observation geometry

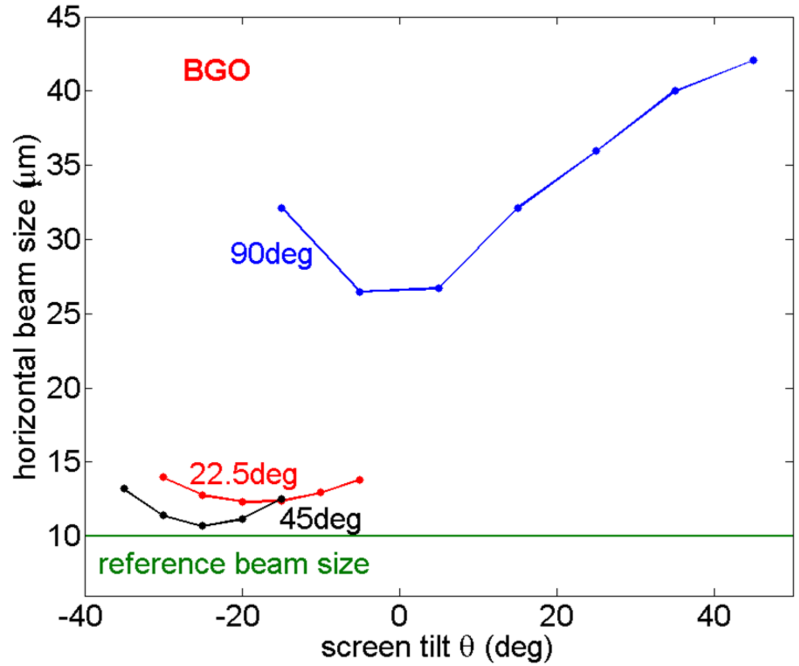


Assumptions:

- line light source emitting isotropically, located inside the BGO crystal with the width of 10 µm
- total10^8 rays at BGO peak emission wavelength 480 nm was traced

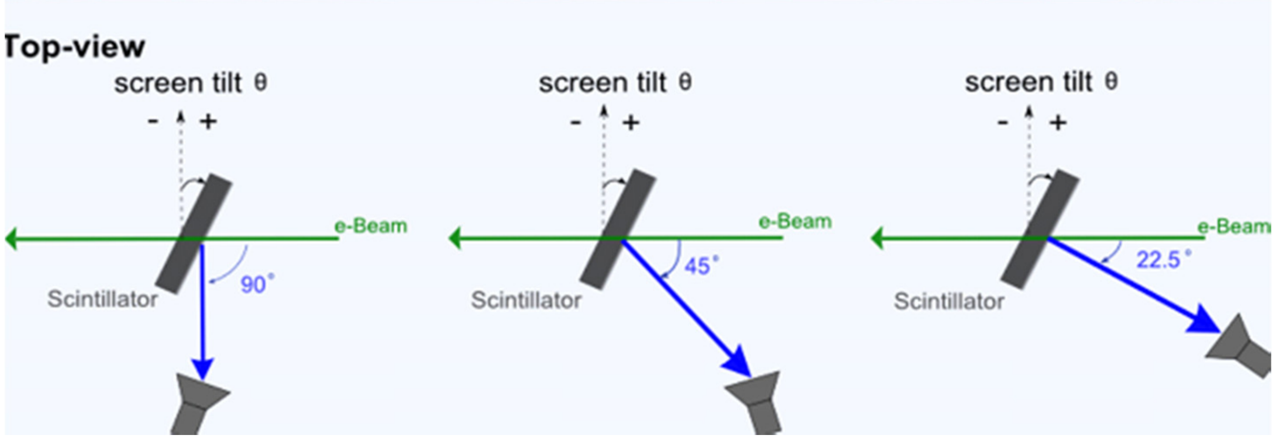
→ placing detector under 45° with respect to the beam axis seems to offer the best resolution

→ an optimum screen tilt angle exists



[M. Yan (U. of Hamburg) et al., TUPD59]

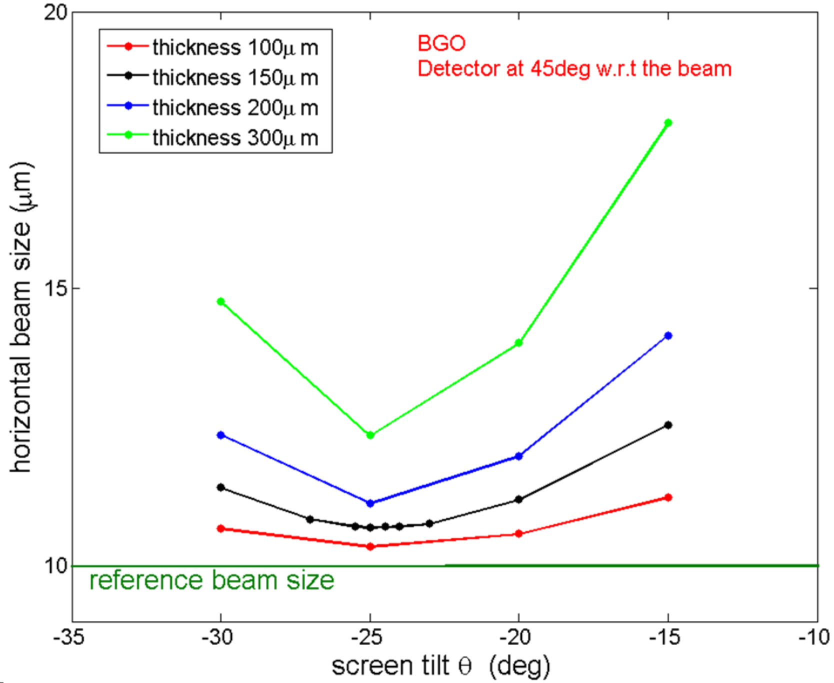
Example – material thickness



Assumptions:

- line light source emitting isotropically, located inside the BGO crystal with the width of 10µm
- total10^8 rays at BGO peak emission wavelength 480 nm was traced

→ thickness of screen influences the resolution
→ thicker scintillation screen shows worse resolution
→ the optimum screen tilt angle is not affected by the thickness of the scintillation screen



[M. Yan (U. of Hamburg) et al., TUPD59]

Conclusions

Scintillation is a complicate process which can be influence by several factors

like e.g. temperature, concentration or impurities in material

- **still searching for a stable solution**

  → the different materials represent different shapes for the same beam

  → scintillators degrade (especially for low-energy ion beams)

  → can we understand (predict) the damage mechanism?

- **no "ideal" scintillator material**

  → most appropriate material varies from application to application

  purpose build scintillators in electron machines

  ceramics in hadron machines

response of various scintillating materials depend on many parameters such as energy, intensity, particle species and time structure of the beam

- **correct observation geometry** can significant improve the resolution

- support from **Crystal Clear Collaboration**

Acknowledgment

Thank you for your attention!

more details can be found on webpage of "Scintillating Screen Applications in Beam Diagnostics" Workshop http://www-bd.gsi.de/ssabd