Joint ARIES-ADA Workshop on ‘Scintillation Screens and Optical Technology for transverse Profile Measurements‘

Krakow, April 1 - 3, 2019

Profile Measurements with Scintillators: Requirements and Applications at Accelerators

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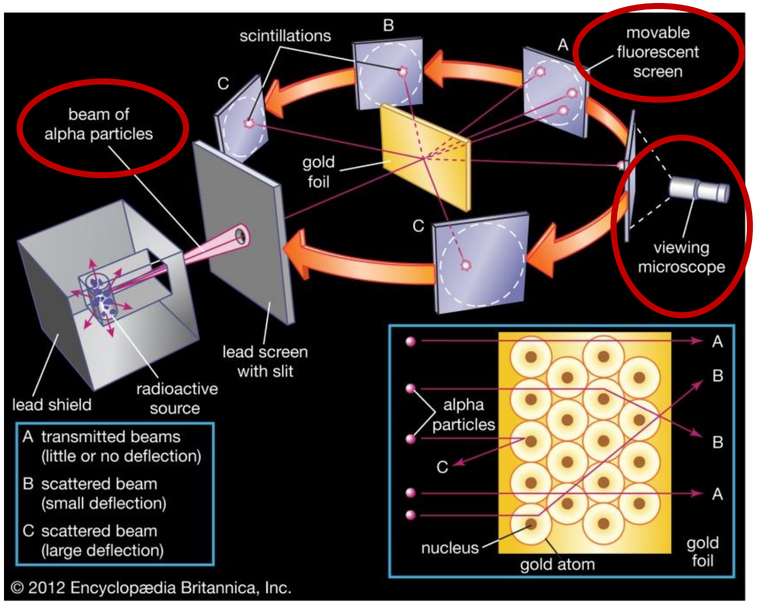
- Introduction
- Profile Measurements with Scintillators
- Stability and Resolution
- Summary and Outlook

Introduction

- historical screen monitor
  - Geiger–Marsden experiments (Rutherford gold foil experiment)
    - → series of experiments: 1908 – 1913

      atom contains nucleus where all positive charge and most of mass is concentrated
  - setup of 1913 experiment

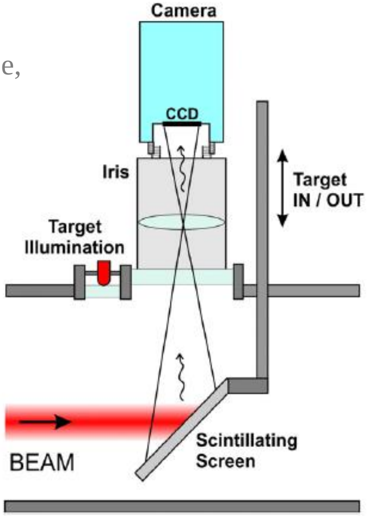
    H. Geiger, E. Marsden, Philosophical Magazine **25** (1913) 604.
    - → particle beam (α particles)
    - → viewing optics (photon counting)
    - → moveable screen (ZnS)



- present screen monitor for beam diagnostics
  - particle beam → $e^{\pm}$, p, heavy ions, (γ)…
  - optics (+ detector) → imaging
  - scintillating screen ➡ main goal of this workshop

(with cameras & optics)

B. Walasek-Höhne and G. Kube, Proc. DIPAC‘11, Hamburg (Germany), p.553



Scintillators for Beam Diagnostics

- workshop on *'Scintillating Screen Applications in Beam Diagnostics'*
  - GSI Helmholtz Centre for Heavy Ion Research, Darmstadt (Germany)

    February 14-15, 2011

    → https://www-bd.gsi.de/ssabd/

- properties of good scintillator

  B. Walasek-Höhne et al., IEEE Trans. Nucl. Sci. **59** (2012) 2307.

  - sufficient efficiency in energy conversion into light
  - large dynamic range
  - emission spectra matched to spectral response of photon detector

  } intensity

  - good linearity between incident particle flux and light output
  - good spatial resolution
  - short decay time for reduction of saturation effects

  } reproducibility / resolution

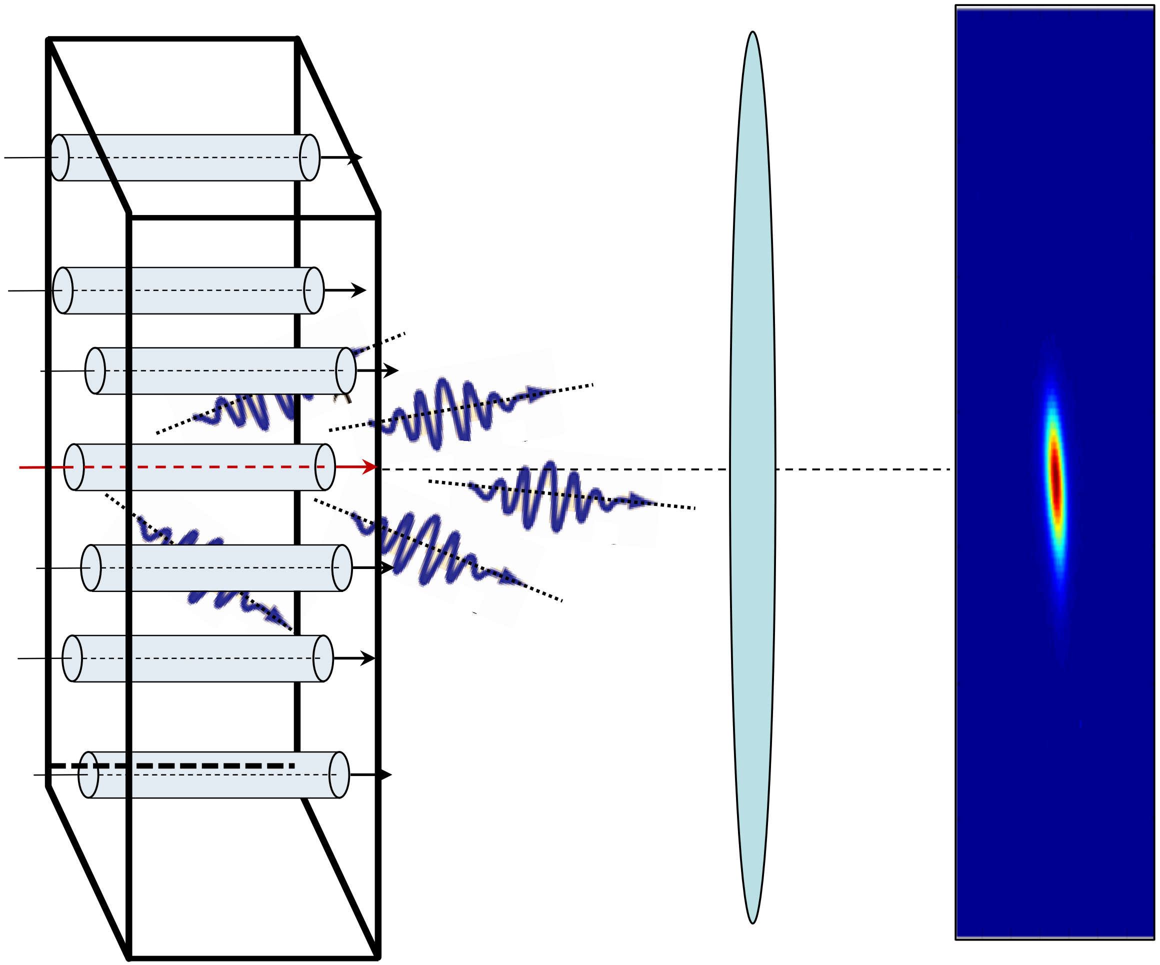
  - good mechanical and thermal stability
  - high radiation hardness to prevent material damages

  } stability

- properties affected by
  - scintillator material
  - beam

➡ bring together experts from different fields

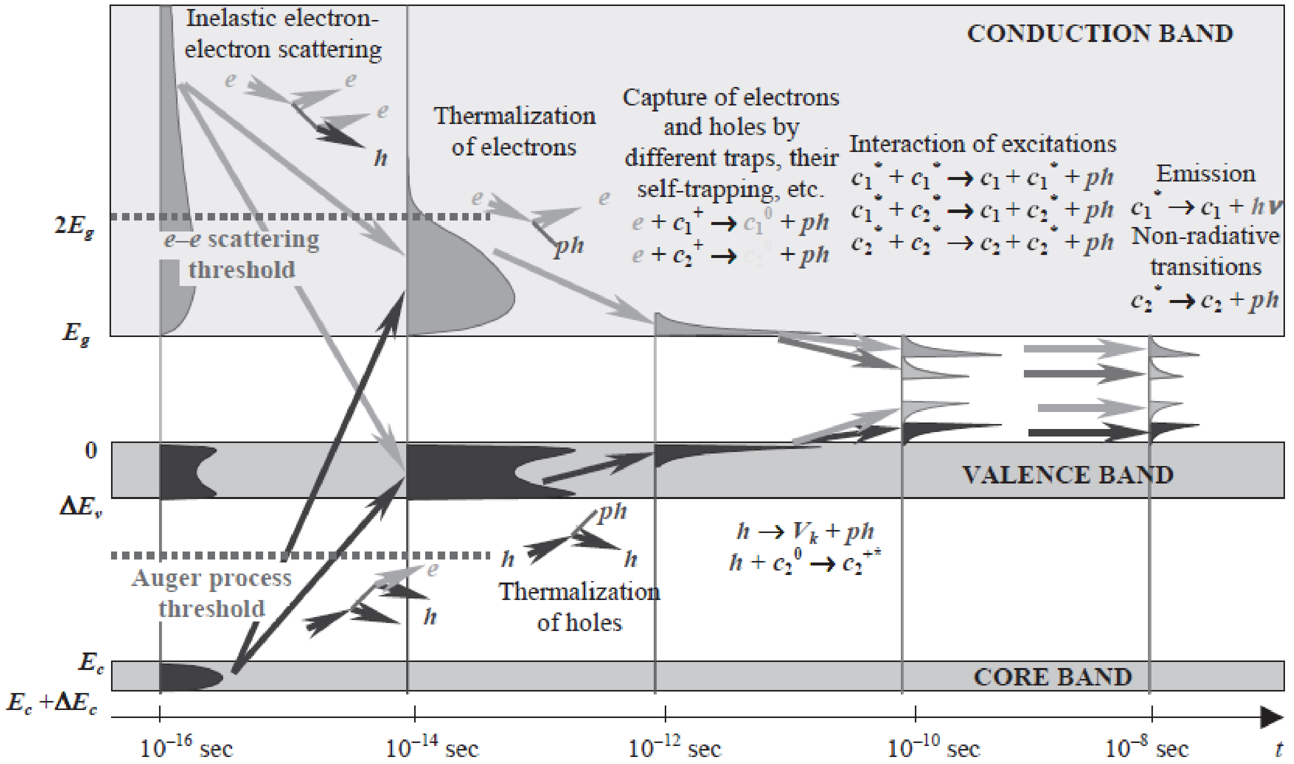
Beam Image Generation



- particle crosses scintillator
  - formation of ionization channel
- light emission from channel
  - isotropic emission
  - light has to cross boundary between scintillator / vacuum
- imaging with lens onto detector
  - image of channel

    → diameter O(nm)
- superposition of channel images
  - beam image generation

Scintillation Light Generation



A.N. Vasil‘ev, Proc. SCINT’99,

Moscow (Russia), 1999, p.43

- multi-stage process
  - energy conversion → generation of “hot” electronic excitations
  - thermalization → phonon emission: transform T_{kin} of excitations in heat
  - localization → excitation interaction with defects/impurities
  - transfer to luminescent centers → migration of relaxed excitons
  - radiative relaxation → emission of scintillation light

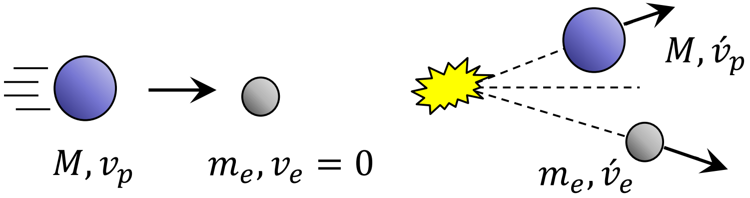
particles (mainly)

scintillator material

Stage 1: Beam

- charged particle interaction with target material (scintillator)
  - inelastic scattering (impact ionization)
- fundamental difference between light / heavy particles
  - “heavy” particles: $A \geq 1$ → p, α, ions,…
  - “light” particles → $e^{\pm}$
- energy transfer from beam particle to scintillator shell electron
  - simple (non-relativistic) kinematical consideration:

    maximum energy transfer → head-on collision



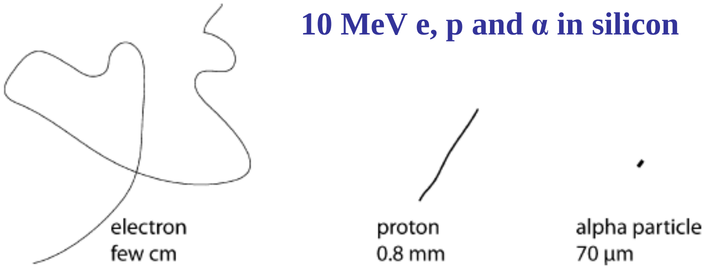
$$\boxed{\frac{\Delta E_{max}}{T_{kin}} = 4\frac{m_e M}{(m_e + M)^2}}$$

- heavy particles $\xrightarrow{M \gg m_e} 4\frac{m_e}{M}$ ***proton beam:*** $\frac{\Delta E_{max}}{T_{kin}} \sim \frac{1}{500}$

  small energy transfer in single collision

- light particles $\xrightarrow{M = m_e} 1$

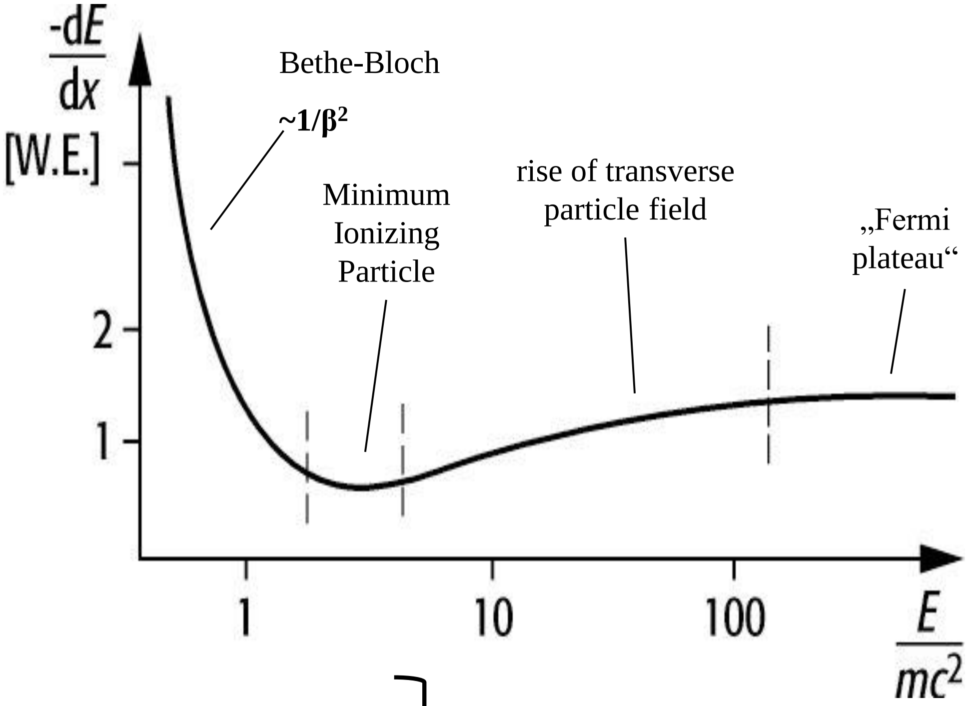
  large angular deviations possible due to large energy transfer


10 MeV e, p and α in silicon

Stage 1: Energy Loss and Range

- collisional stopping power
  - general form

$$\boxed{-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{{Z_p}^2}{\beta^2}\ln(a\beta^2\gamma^2)}$$



- heavy particles
  - especially ion beams…

→ large Z_p (projectile charge)

→ low β (Bethe-Bloch regime)

➡ high energy loss

➡ short particle range (even < scintillator thickness)

} screen stability (mechanical + signal reliability)

- light particles (relativistic e± beams)

→ $Z_p = 1$

→ $\beta \approx 1$ (Fermi plateau)

➡ curved trajectories (ionization channels)

➡ radiative energy loss (Bremsstrahlung)

} resolution broadening

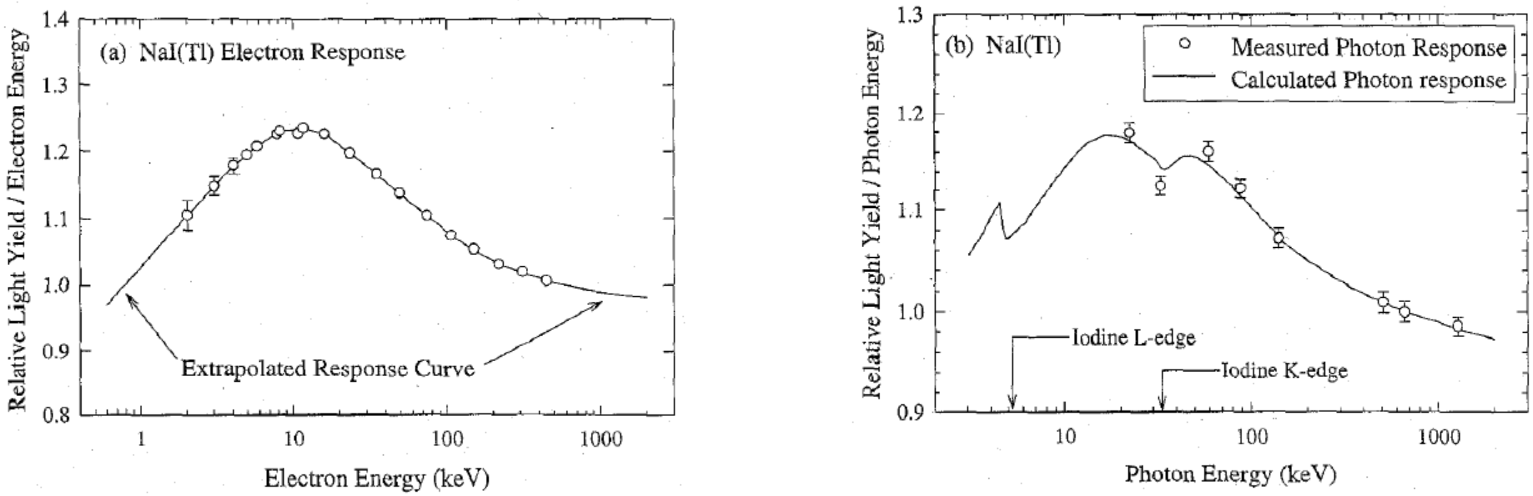
Comment: γ-Response of Scintillators

- scintillators used for γ-ray beam profile measurements
  - X-ray converter for CCDs → e.g. for pinhole camera

➡ difference in scintillator response between ***charged particles*** and ***photons***

- charged particle response
  - collisional stopping power
    → several interactions (especially heavy particles)
    → mainly with outer shell electrons

- photon response
  - photo effect
    → single interaction, predominantly with inner shells
    → complex cascade structure



B.D. Rooney and J.D. Valentine, IEEE Trans. Nucl. Sci. **44** (1997) 509

- smooth electron response
- photon response with substructure

Stage 2-5: Scintillator Material

- stages 2-5 strongly depend on physical processes inside scintillator
  - next talk → Weronika Wolszczak: *Introduction to Scintillator Physics*

- scintillator screens for beam diagnostics
  - powder screens: **P11** (ZnS:Ag), **P20** ([Zn,Cd]S:Ag), **P43** (Gd_2O_2S:Tb), **P46** ($Y_3Al_5O_{12}$:Ce), **P47** ($Y_2Si_5O_5$:Tb), …
    - → deposition of luminescence powder on glass metal base
    - → high sensitivity, good linearity
    - → resolution limited by grain size
  - ceramic screens: ZrO_2:Al, ZrO_2:Mg, ZrO_2:Y, Al_2O_3, Al_2O_3:Cr (**Chromox**), AlN, BN, …
    - → manufactured by sintering of powder
    - → moderate light yield
    - → good radiation hardness, better thermo-mechanical properties
  - inorganic crystals: CsI:Tl, YAG ($Y_3Al_5O_{12}$:Ce), BGO ($B_4Ge_3O_{12}$), LYSO ($Lu_{1.8}Y_{0.2}SiO_5$:Ce) , CWO ($CdWO_4$), …
    - → good light yield
    - → degradation effects under high current beam irradiations
    - → good resolution

B. Walasek-Höhne, C. Andre, P. Forck, E. Gütlich, G. Kube, P. Lecoq, and A. Reiter, IEEE Trans. Nucl. Sci. **59** (2012) 2307

Scintillator Material: Review

- fluorescent screens until late 1960's
  - ZnS (fixed on metallic substrate by inorganic binder)
    - → high conversion efficiency, suffered from radiation damage, high outgassing (binder)
  - quartz, monocrystalline sapphire, ruby, lithium glass
    - → low efficiency & expensive
- chrome-activated radiation resistant alumina phosphor
  - produced by anodizing Al in an electrolyte containing Cr ions (LBL)

R.W. Allison et al., UCRL-19270 (1969)

- chrome-doped alumina ceramics (CERN 1974)
  - AF-225 Rouge (Desmarquest & C.E.C, France)
    - → ruby-like emission spectrum, high efficiency, good vacuum compatibility
    - → quality of Al_2O_3:Cr depending on supplier
- Chromox CERN type 6

C.D. Johnson CERN-PS-90-42 AR

  - small R&D project with Andermann & Ryder Ltd. (UK)
    - → 99.4% Al_2O_3, 0.5% Cr_2O → better thermal properties
- inorganic scintillators
  - CsI:Tl

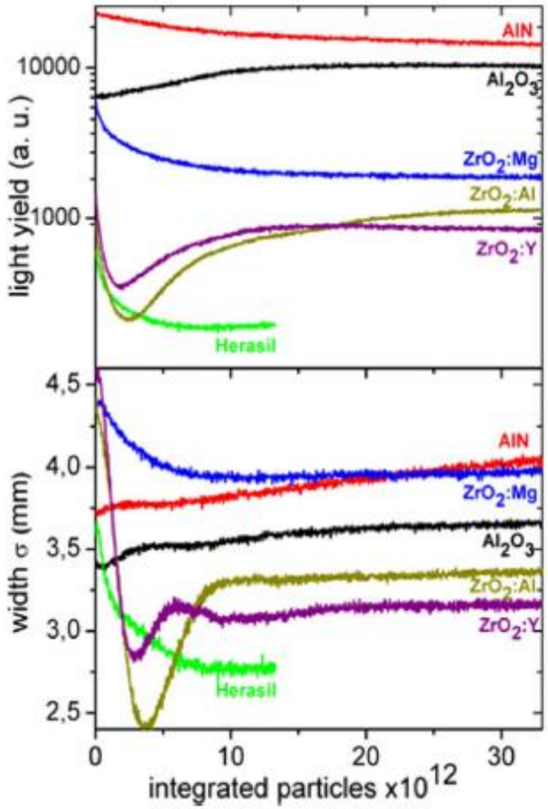
J. Camas et al., Proc. PAC'93 (1993) 2498

  - YAG:Ce → *high resolution monitor*

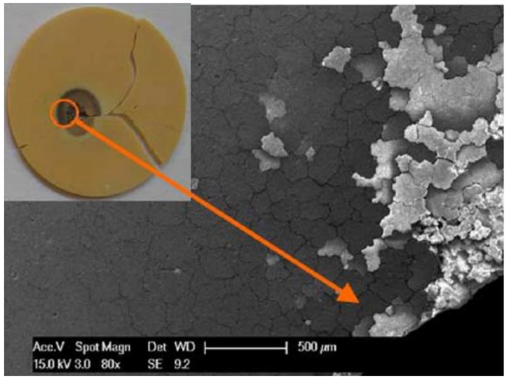
W.S. Graves et al., Proc. PAC'97 (1997) 1993

Scintillator Material Influence

- hadron machines
  - stability is critical
    - → extensive studies of scintillator properties @ GSI
  - change of scintillator properties under irradiation

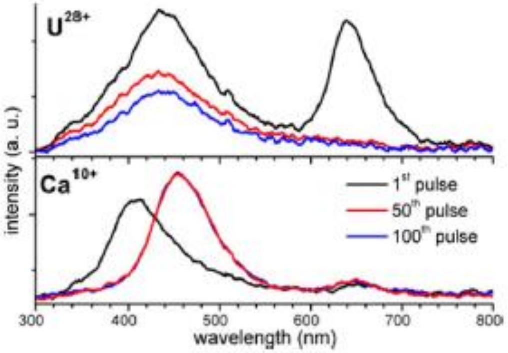


B. Walasek-Höhne et al., IEEE Trans. Nucl. Sci. **59** (2012) 2307



electron microscopy image of irradiated ZrO_2:Mg

- change of spectrum under irradiation



quartz glass

(Herasil)

- studies with p beams

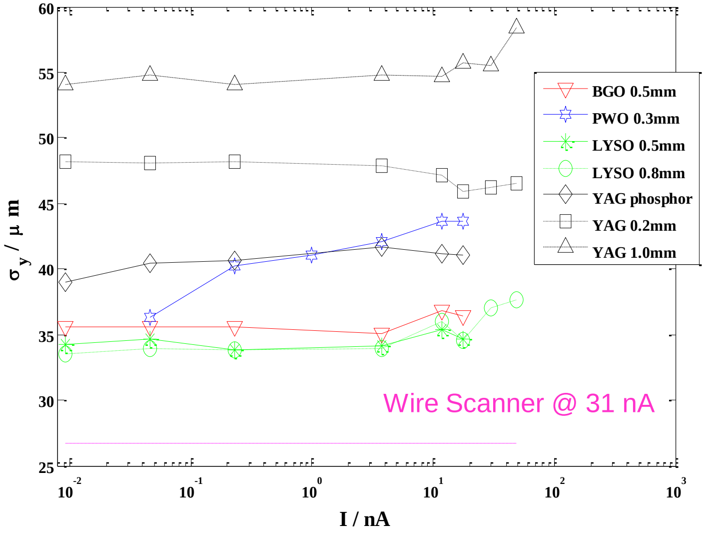
S. Burger et al., Proc. IBIC’16, Barcelona, Spain (2016), MOPG78, p.268.

➡ resolution uncritical (mm beams)

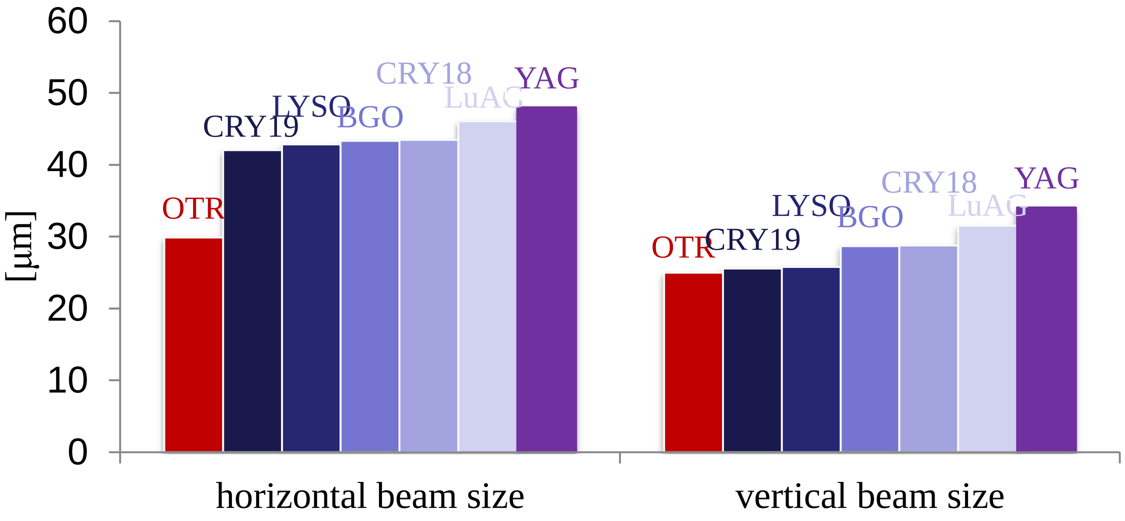
absolute size measurement questionable

Scintillator Material Influence

- electron machines
  - resolution is critical → studies of scintillator properties @ Mainz Microtron MAMI (Univ. Mainz, Germany)
    - 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)
    - 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)



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

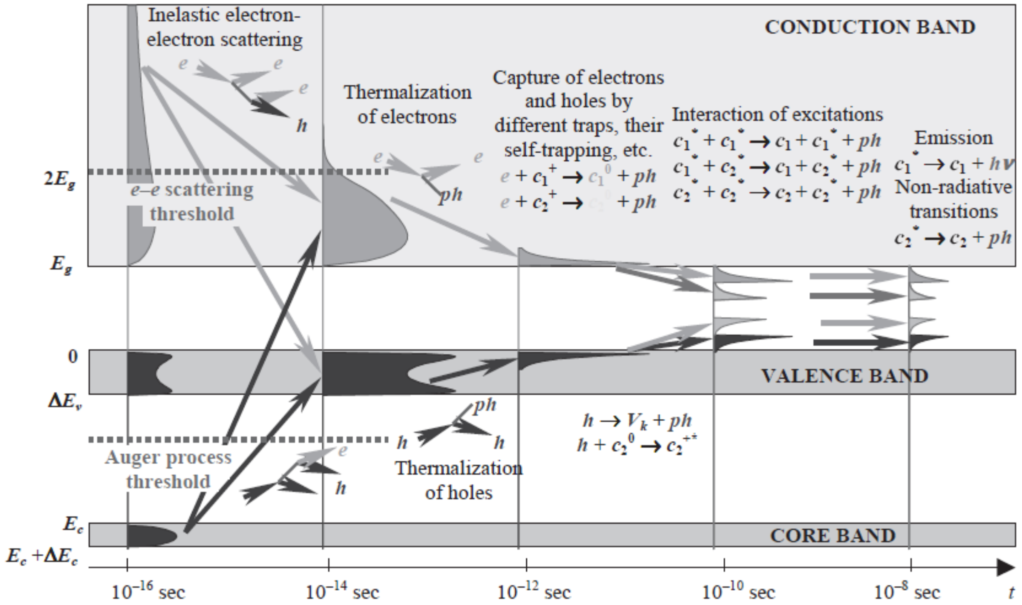


G. Kube et al., Proc. IPAC'12, New Orleans (USA), 2012, p.2119

➡ LYSO:Ce showed best spatial resolution

Scintillator Material: Resolution

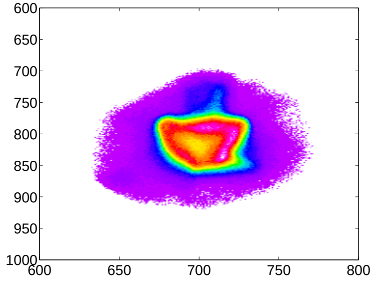
- influence of scintillator material on resolution
  - which stage defines resolution properties ?

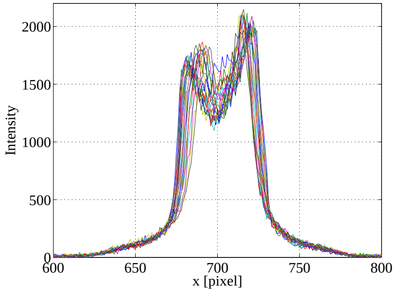


A.N. Vasil‘ev, Proc. SCINT’99,

Moscow (Russia), 1999, p.43

- stability / reliability for e-beams



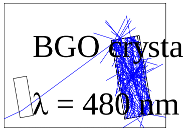


- possible parameters influencing spatial resolution
  - → diameter of primary ionization channel (how defined?)
  - → mobility of excitation carriers
  - → …

?

→ talk tomorrow

Resolution and Observation Geometry



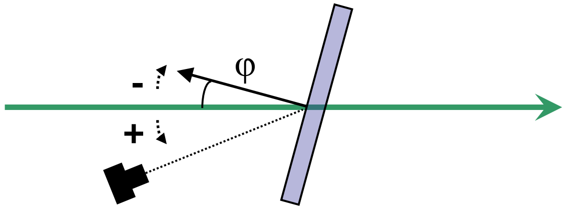
- light propagation from scintillator to detector
  - light generated inside scintillator has to cross boundary

    → refractive index $\boxed{n}$
  - inorganic scintillators: **large *n***

    → large contribution of total reflection

    → **influence on observation geometry**

- experiment: scintillator tilt vs. beam axis

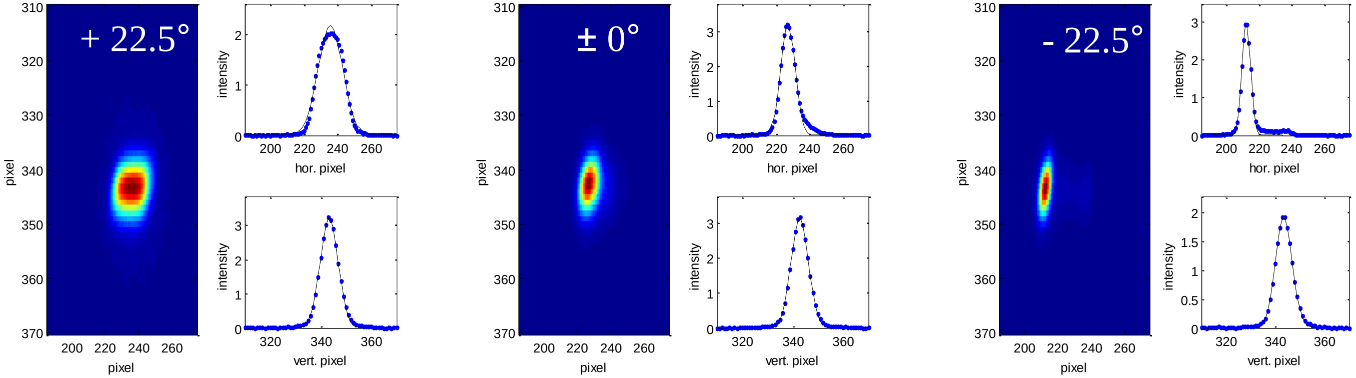


BGO crystal

micro-focused electron beam

I = 3.8 nA

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

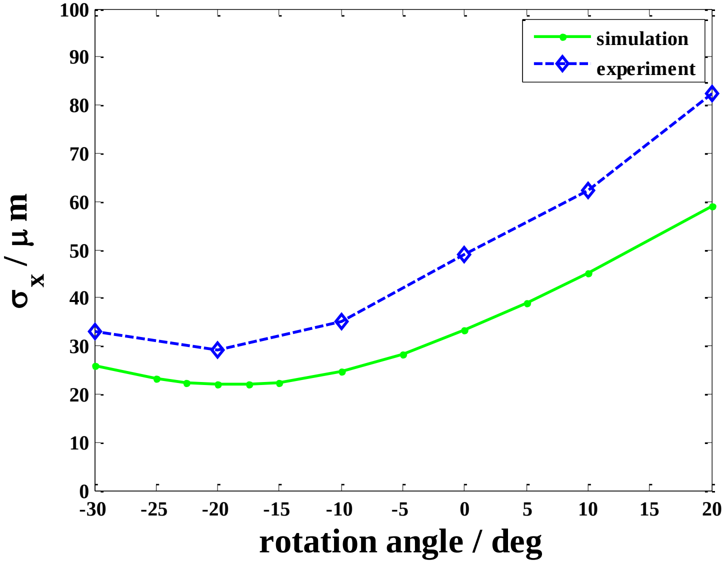


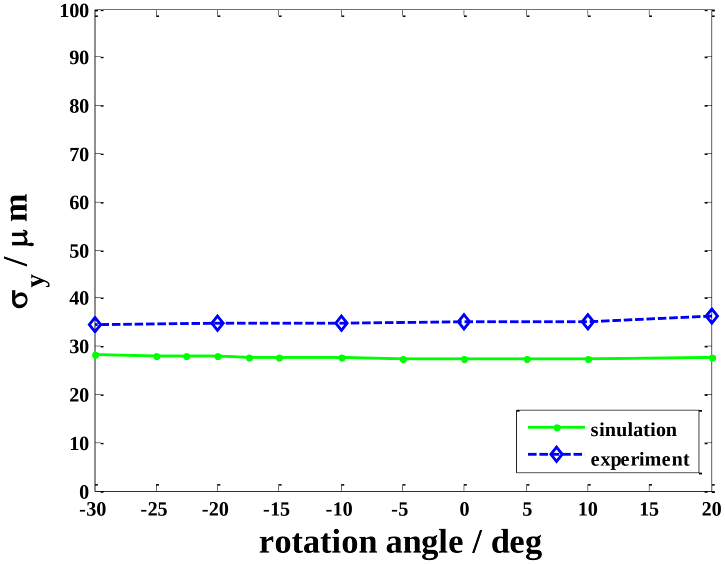
Observation Geometry Model

- light propagation in scintillator

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

  - simple ZEMAX model → light generated by line source, scintillator characterized by n





  - satisfactory agreement between simulation and measurement

    → simulation reproduces observed trend in beam size

  - measured beam size systematically larger than simulated one

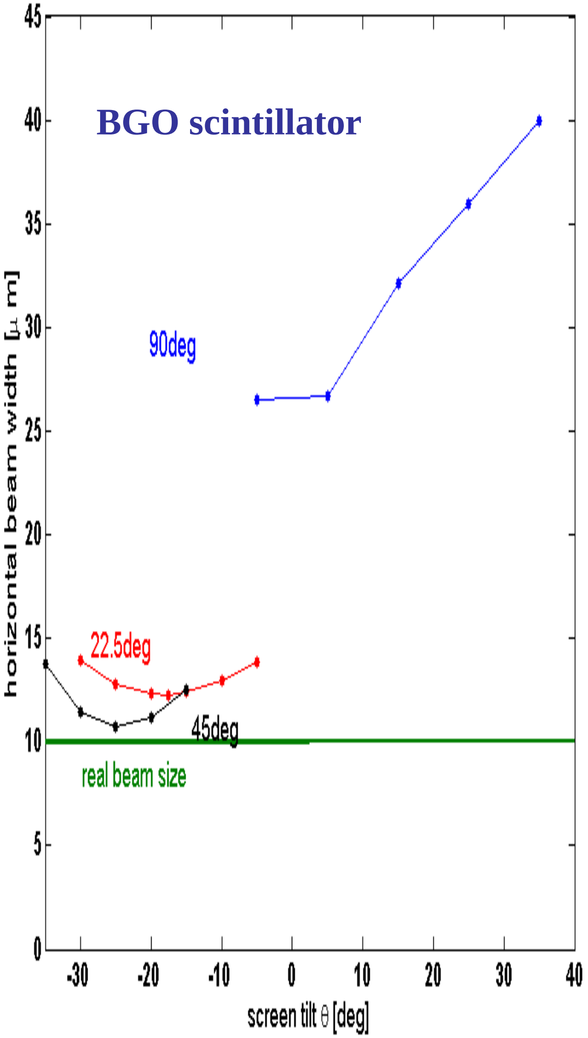
    → effect of scintillator material properties not included in calculation → increase in PSF

- geometrical model

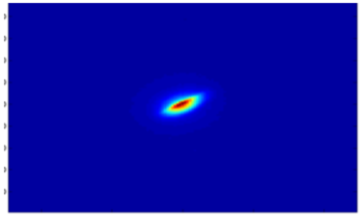
  R. Ischebeck et al., Phys. Rev. ST Accel. Beams **18** (2015) 082802

Observation Geometry Influence

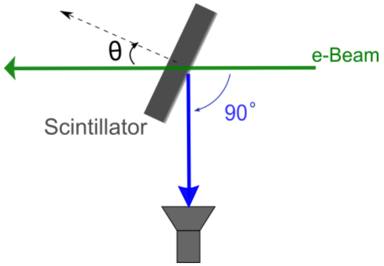
- comparison observation geometry



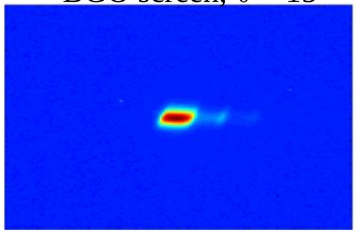
OTR screen



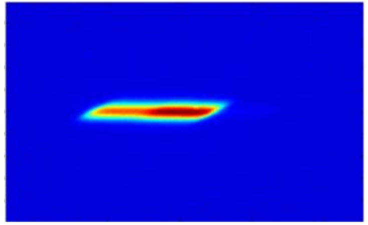
Top-view



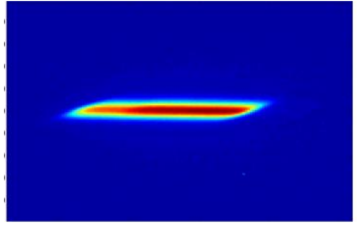
BGO screen, θ = 15°



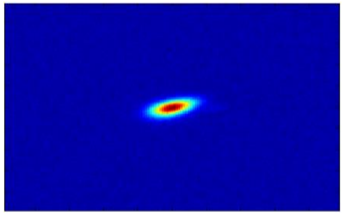
BGO screen, θ = 45°



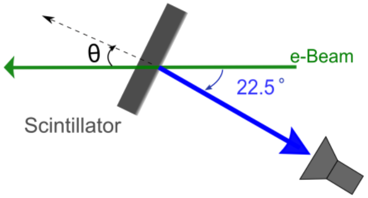
BGO screen, θ = 55°



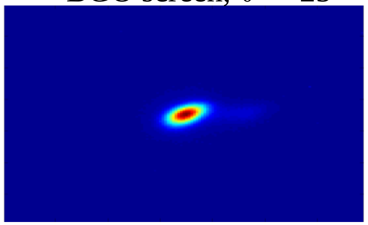
OTR screen



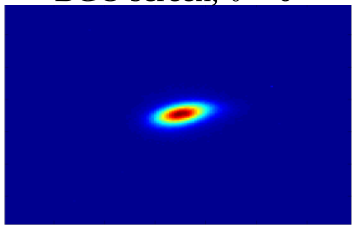
Top-view



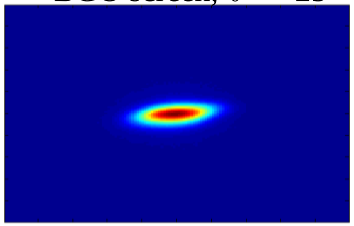
BGO screen, θ = -25°



BGO screen, θ = 0°



BGO screen, θ = +25°



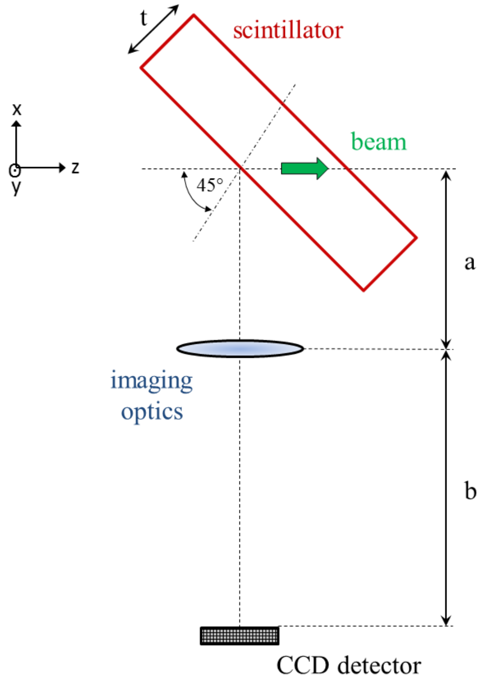
G. Kube et al., Proc. IPAC’12, New Orleans, USA (2012) p.2119

Exploring the Resolution Limits

- micrometer beam size experiment

  G. Kube et al., Proc. IBIC‘15, Melbourne, Australia (2015) p.330

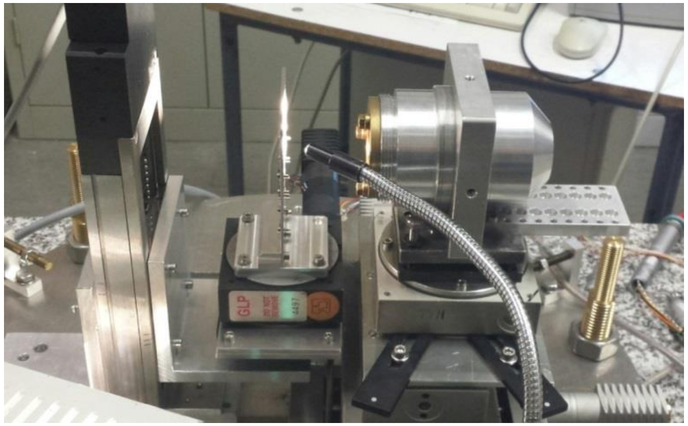
  - experimental scheme



$a = 27.54$ mm

$b = 1155.46$ mm

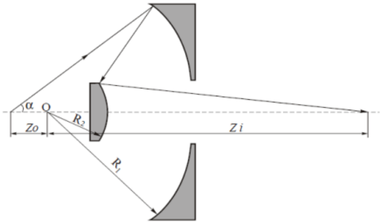
→ $M = 41.95$



Target: LYSO scintillator ($Lu_{2(1\text{-}x)}Y_{2x}SiO_5$:Ce)

thickness t = 200 μm

supplier: *OmegaPiezo*



Schwarzschild Objective:

→ 2 concentric spherical mirrors

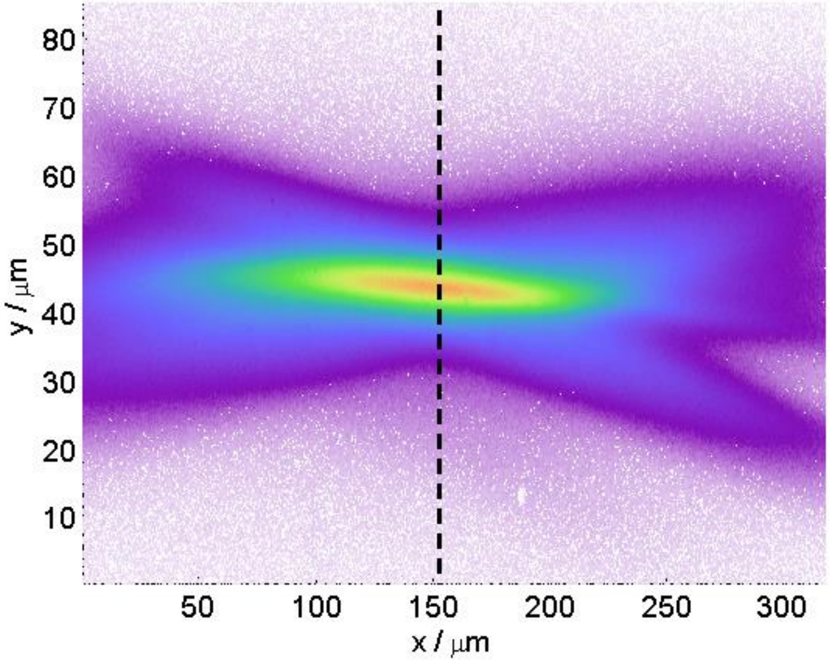
→ aplanatic (corrected for spherical aberrations)

f = 26.90 mm

NA = 0.19 (nominal)

Micrometer Beam Size Measurement

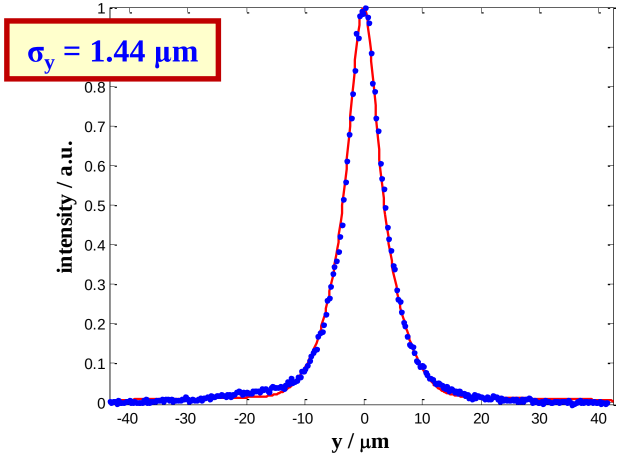
- measured beam image



- horizontal beam profile
  - → affected by OTR-like 90° observation geometry
- vertical beam profile
  - → affected by depth-of-focus

restriction: analysis only along vertical cut

- **analysis**: scintillator model in Zemax©
  - → light emission from single electron represented by line source in LYSO crystal with isotropic light emission
  - → scintillator properties described by n(λ)
  - → Schwarzschild objective replaced by paraxial lens with same f and appropriate NA
  - → non-sequential ray tracing for 10^8 rays at LYSO peak emission wavelength λ = 420 nm
    - → single particle resolution function (SPF)
  - → SPF convolution with 2D-Gaussian (beam profile)
  - → vertical cut and comparison



Summary and Outlook

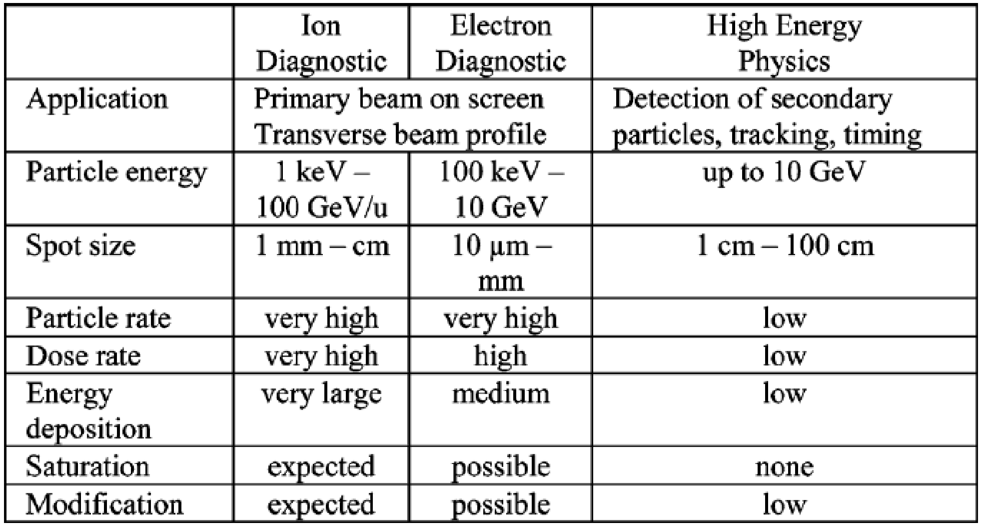
- scintillators are versatile tool for beam diagnostics
  - measurement of different beam parameters
    - → intensity, position, transverse shape & size

- light generation in scintillator
  - complicated multi-stage process
  - influenced by
    - → particle beam properties
    - → scintillator physics

- impact of scintillator properties
  - beam profile diagnostics
    - → ***stability*** and ***resolution***
  - influence difficult to predict

- dream
  - a priori knowledge of scintillator influence
  - perhaps this workshop is step in right direction
    - → hope for fruitful discussions…

- different accelerators with different conditions



	Ion Diagnostic	Electron Diagnostic	High Energy Physics
Application	Primary beam on screen Transverse beam profile		Detection of secondary particles, tracking, timing
Particle energy	1 keV – 100 GeV/u	100 keV – 10 GeV	up to 10 GeV
Spot size	1 mm – cm	10 µm – mm	1 cm – 100 cm
Particle rate	very high	very high	low
Dose rate	very high	high	low
Energy deposition	very large	medium	low
Saturation	expected	possible	none
Modification	expected	possible	low

B. Walasek-Höhne et al., IEEE Trans. Nucl. Sci. **59** (2012) 2307

- acknowledgment
  - thanks to Beata, Peter and the GSI team for excellent organisation !!!