Optical Methods for transverse Beam Profile (Emittance) Diagnostics

Gero Kube
DESY / MDI
gero.kube@desy.de

- Introduction
- Diagnostics for Linacs:
  OTR, ODR, Screens

Accelerator Key Parameters

light source: spectral brilliance

- measure for phase space density of photon flux

$$B = \frac{\text{Number of photons}}{[\text{sec}][\text{mm}^2][\text{mrad}^2][0.1\%\ \text{bandwidth}]}$$

- user requirement: high brightness

  → lot of monochromatic photons on sample

- connection to machine parameters

$$B \propto \frac{N_\gamma}{\sigma_x \sigma_{x'} \sigma_z \sigma_{z'}} \propto \frac{I}{\varepsilon_x \varepsilon_z}$$

- requirements

i) high beam current

- achieve high currents
- cope with high heat load (stability)

collider: luminosity $\mathcal{L}$

- measure for the collider performance

$$\dot{N} = \mathcal{L} \cdot \sigma$$

relativistic invariant proportionality factor between cross section σ (property of interaction) and number of interactions per second

- user requirement: high luminosity

  → lot of interactions in reaction channel

- connection to machine parameters

$$\mathcal{L} \propto \frac{I_1 \cdot I_2}{\varepsilon}$$

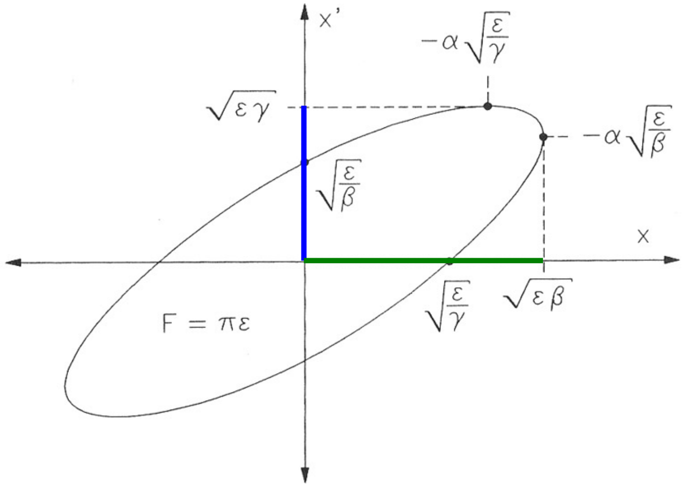
for two identical beams with emittances $\varepsilon_x = \varepsilon_z = \varepsilon$

ii) small beam emittance

- achieve small emittance (task of lattice designer)
- preserve emittance (stability)
- measure small emittance

Beam Emittance (Circ. Accelerator)

- projected area of transverse phase space volume
- emittance ε not directly accessible for beam diagnostics



- beam size $\sigma = \sqrt{\varepsilon\beta}$
- beam divergence $\sigma' = \sqrt{\varepsilon\gamma}$

- dispersion: $\sigma = \sqrt{\varepsilon\beta + (\eta\,\Delta p/p)^2}$ $\sigma' = \sqrt{\varepsilon\gamma + (\eta'\,\Delta p/p)^2}$
- influence of physical process σ_{pp}
- monitor resolution σ_{mon}

radiation generation

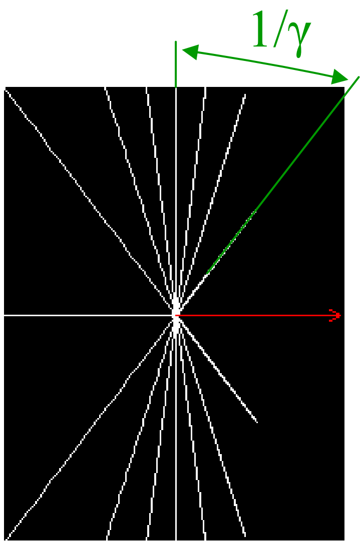
→ measure: beam spot σ_s

→ calculate: $\varepsilon(\beta, \gamma, \eta, \eta', \Delta p/p, \sigma_s, \sigma_{\mathrm{mon}}, \sigma_{\mathrm{pp}})$

Radiation Generation: Considerations

- radiation generation via particle interaction with matter
  - luminescent screen monitors

- radiation generation via particle electromagnetic field
  - particle electromagnetic field
  - relativistic contraction characterized by Lorentz factor



electric field lines in LAB frame

$$\gamma = E / m_0 c^2$$

E : total energy

$m_0 c^2$: rest mass energy

proton: $m_p c^2 = 938.272\ \text{MeV}$

electron: $m_e c^2 = 0.511\ \text{MeV}$

$\gamma \rightarrow \infty$: plane wave

- $mc^2 = 0$ MeV : light → „real photon“
- ultra relativistic energies : idealization → „virtual photon“

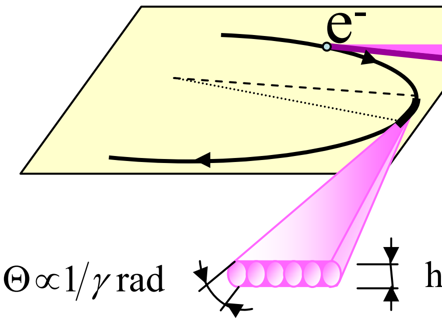
Separation of Particle Field

- electromagnetic field bound to particle
  observation in far field (large distances)
  } separate field from particle

- separation mechanisms
  - bending of particle via magnetic field

    synchrotron radiation

    ⟹ circular accelerators



linear accelerators: no particle bending ???

  - diffraction of particle electromagnetic field via material structures

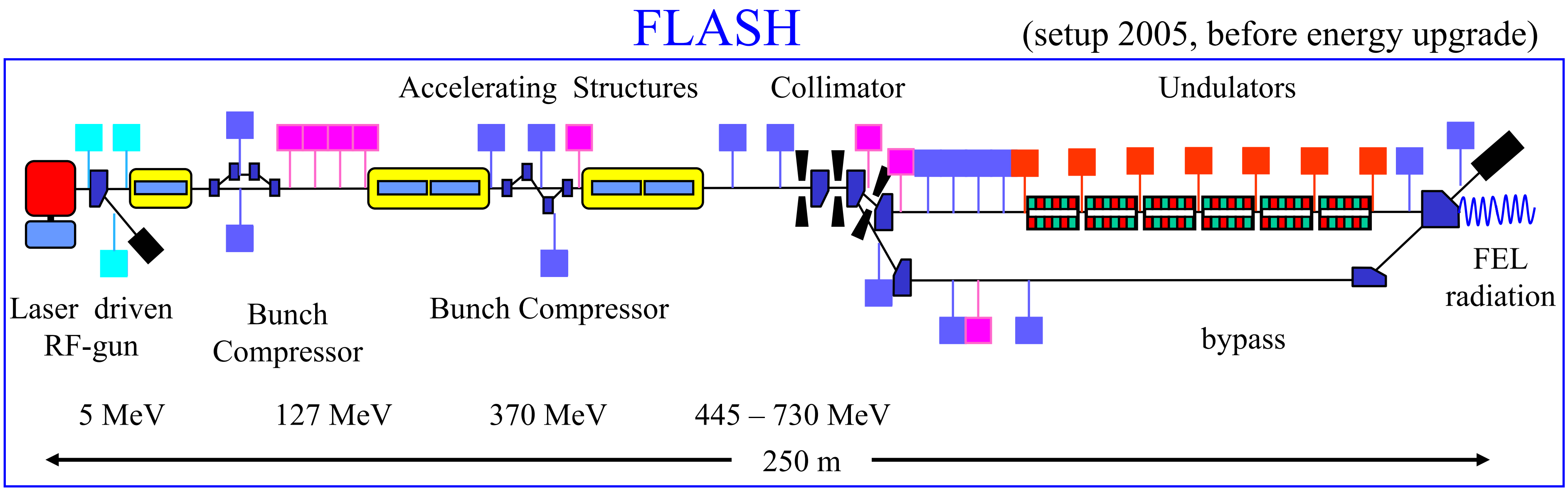
    exploit analogy between real/virtual photons:

    - light reflection/refraction at surface ↔ backward/forward transition radiation (TR)
    - light diffraction at edges ↔ diffraction radiation (DR)
    - light diffraction at grating ↔ Smith-Purcell radiation
    - light (X-ray) diffraction in crystal ↔ parametric X-ray radiation (PXR) …

Outline

- profile monitors at linear accelerators
  - experience from FLASH @ DESY
  - of special interest for the European XFEL @ DESY
  - standard: Optical Transition Radiation (OTR) based monitors
  - trends: Optical Diffraction Radiation (ODR) based monitors
  - pitfalls: comments on coherent radiation production
- luminescent screen monitors
  - beam tests @ MAMI: October 2009
- (high resolution profile monitors at circular accelerators)
  - trends in synchrotron radiation based diagnostics
- (synchrotron radiation for proton beam diagnostics)

Trans. Profile Diagnostics @ FLASH



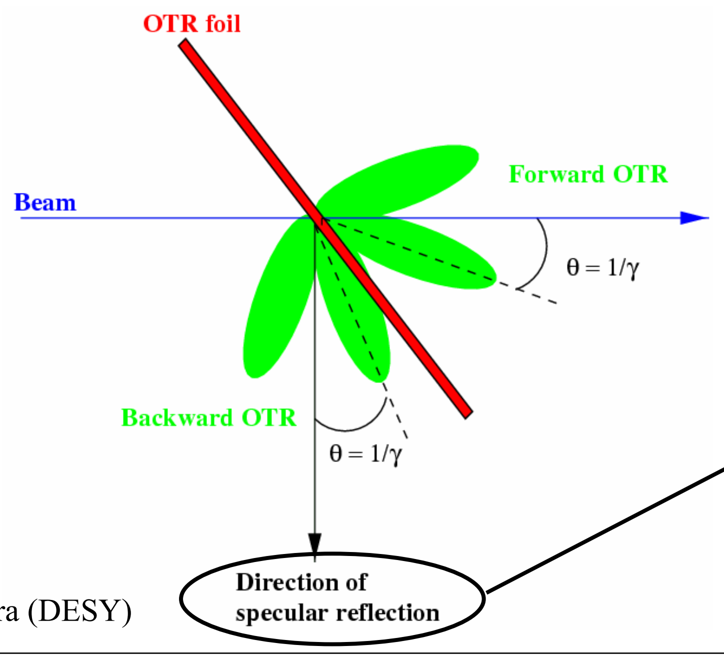
transverse beam profile monitors:

- 3 Ce:YAG screens
- 8 OTR + WS stations
- 16 OTR stations
- 7 WS stations (hor.+ vert.)

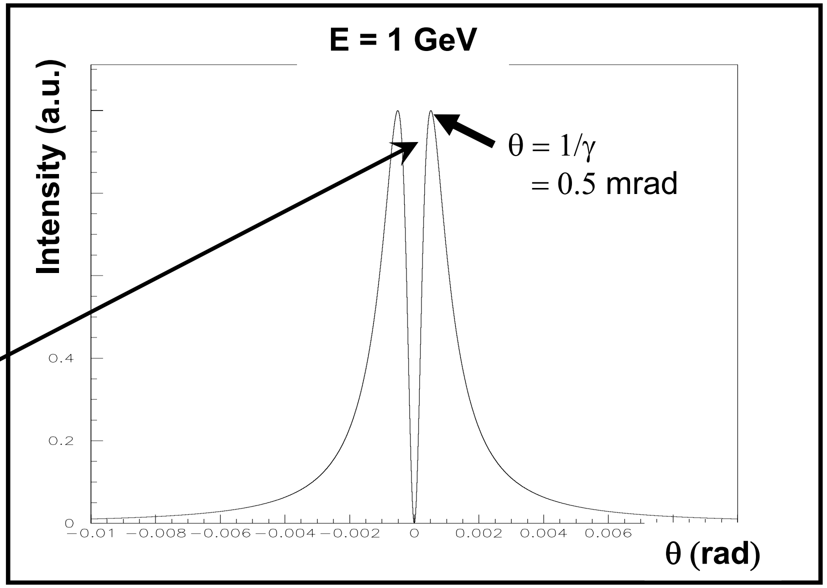
courtesy: K. Honkavaara (DESY)

Optical Transition Radiation

- 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
- advantage: fast single shot measurement, linear response (neglect coherence !)
- disadvantage: high charge densities may destroy radiator



angular distribution

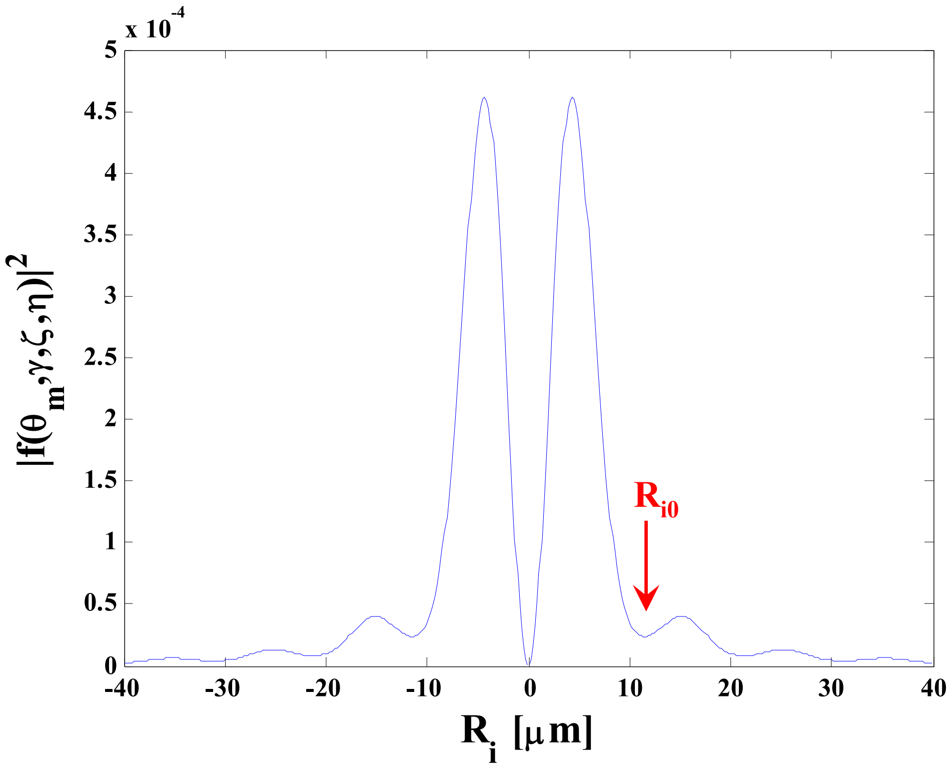


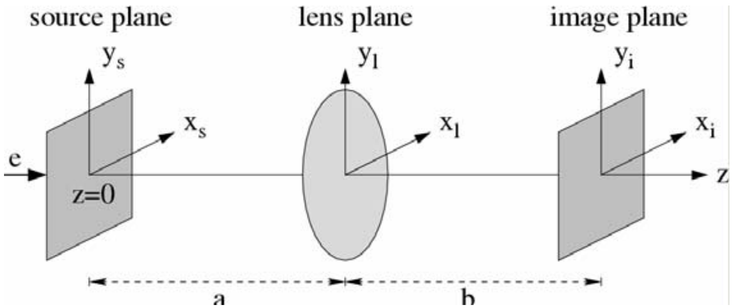
courtesy:
K. Honkavaara (DESY)

OTR Monitor Resolution

- calculation of point spread function in image plane

G. Kube, TESLA-FEL Report 2008-01





- parameters of calculation

E = 1 GeV
λ = 500 nm
f = 250 mm
a = b = 500 mm (1:1 imaging)
lens-Ø = 50.8 mm

- OTR resolution
  - resolution definition according to classical optics:

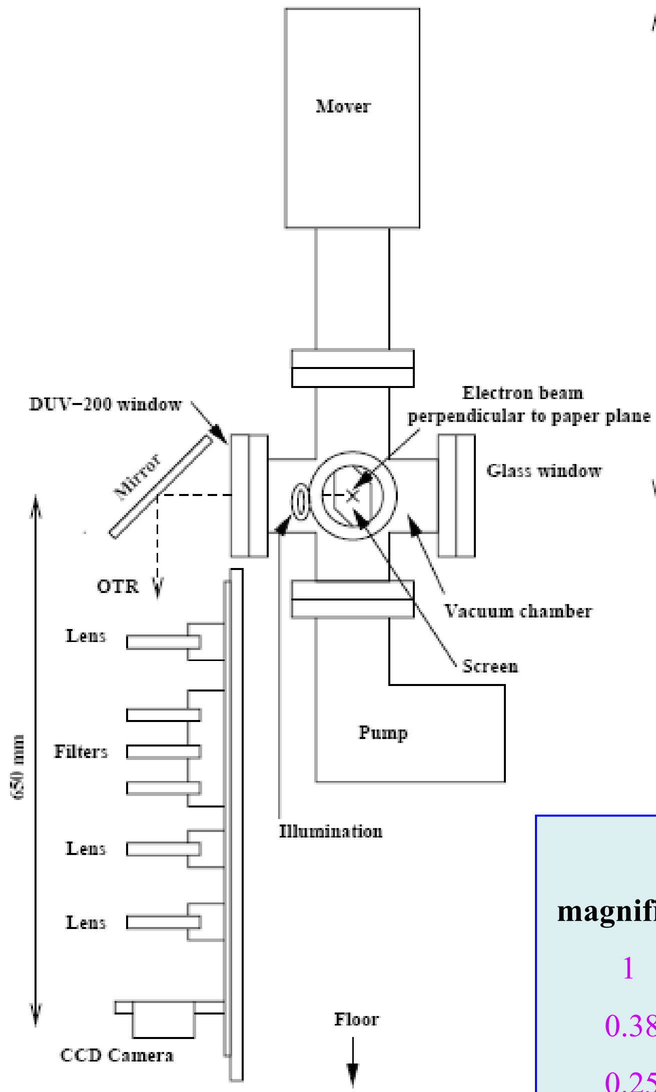
⟹ first minimum of PSF (→ diameter of Airy disk)

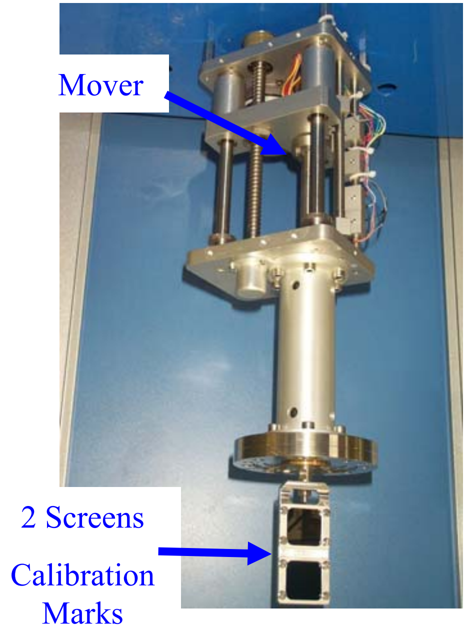
$$R_{i0} \approx 1.12 \frac{M\lambda}{\theta_m}$$

M: magnification

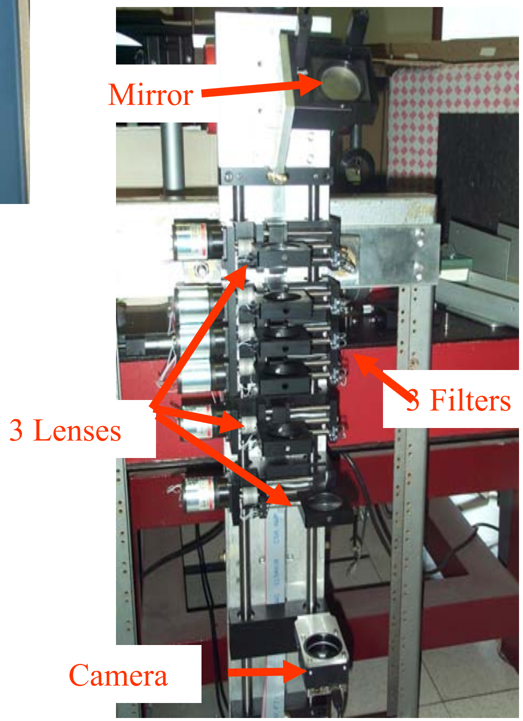
θ_m: lens acceptance angle

OTR Monitors at FLASH





K. Honkavaara et al.,
Proc. PAC 2003, p.2476



optical system

magnification	f / mm	a / mm	b / mm
1	250	500	500
0.382	200	724	276
0.25	160	800	200

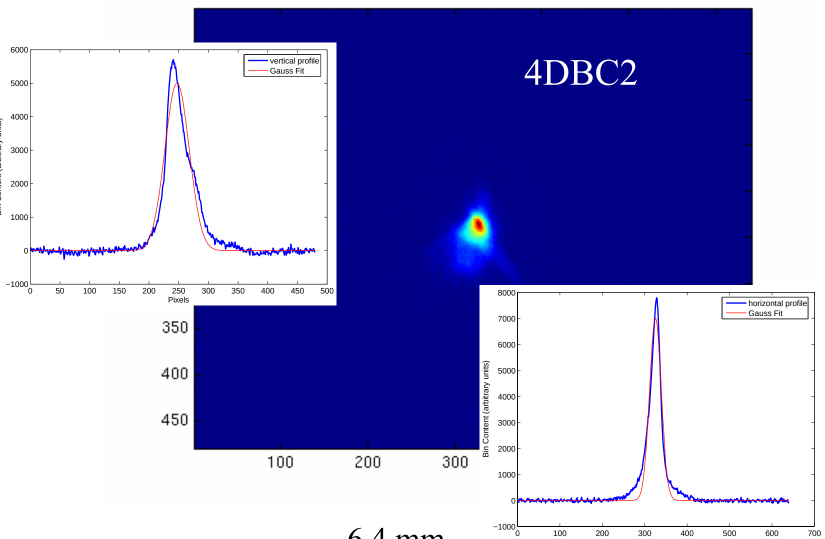
OTR Monitors at FLASH

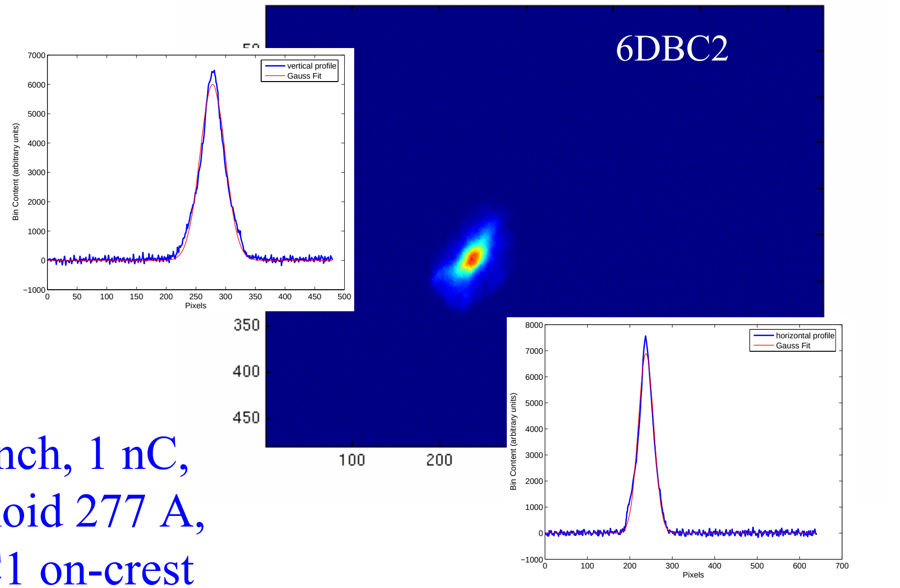
Emittance Measurement Setup at the Injector

courtesy: K. Honkavaara (DESY)

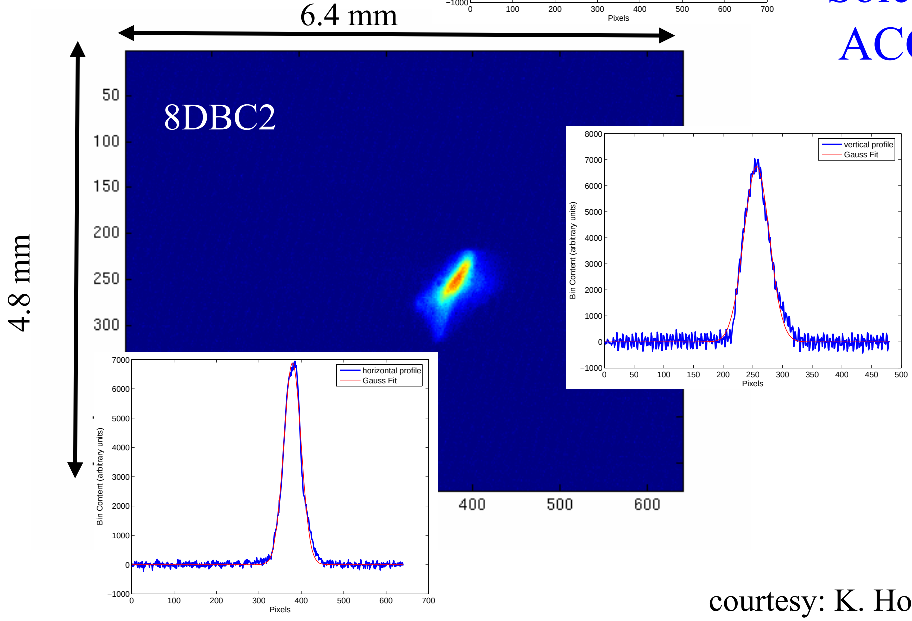
4 OTR+WS stations in a FODO lattice

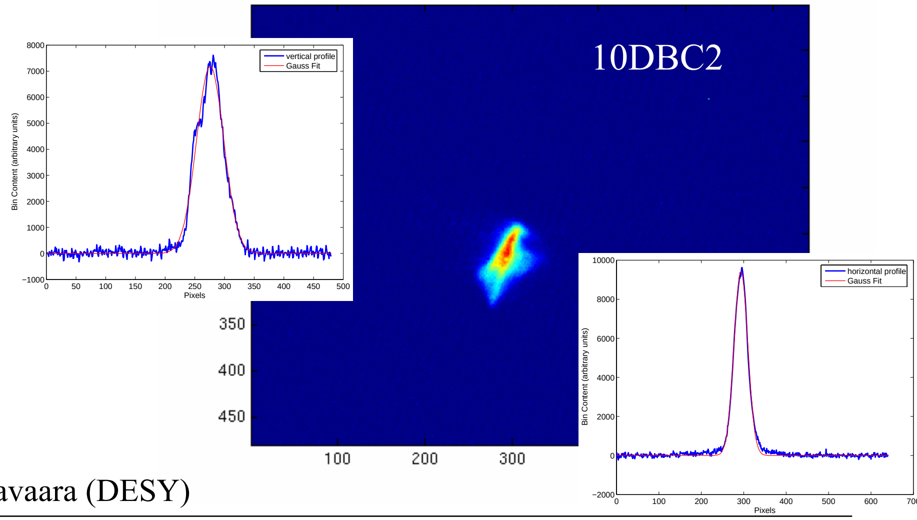
Example of Beam Images (matched)





1 bunch, 1 nC,
Solenoid 277 A,
ACC1 on-crest





courtesy: K. Honkavaara (DESY)

Optical Diffraction Radiation (ODR)

- problem OTR: screen degradation/damage

  → limited to only few bunch operation, no permanent observation

- ODR: excellent candidate to measure beam parameters parasitically

  - DR generation via interaction between the EM fields of the moving charge and the conducting screen

    → diffraction of "virtual photons"

  - extension of EM field of a relativistic particle is flat circle

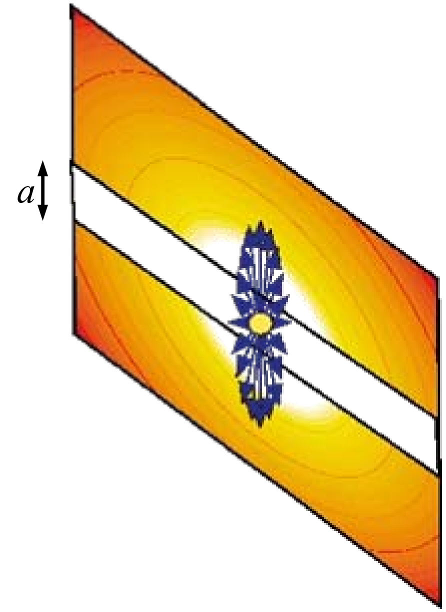
    → radius $\lambda\beta\gamma/2\pi$

  - radiation intensity scales proportional to $|E|^2$:

$$I \propto e^{-a/h_{int}} \quad \text{with } h_{int} = \frac{\lambda\beta\gamma}{4\pi}$$

  - dependency on impact parameter h_{int}:

$$a >> h_{int} \; : \; \text{no radiation}$$
$$a \cong h_{int} \; : \; \text{DR}$$
$$a << h_{int} \; : \; \text{TR}$$



Principle of ODR Diagnostics

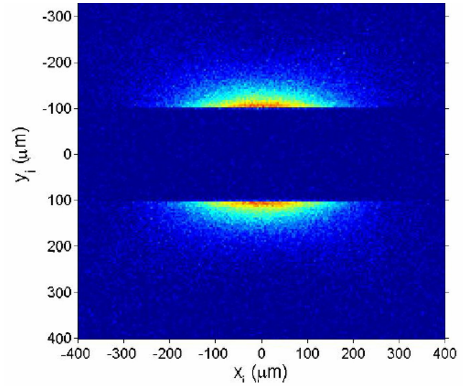
- imaging with ODR: no beam image, illuminated slit

  → seems not suitable for beam diagnostics

  nevertheless, attempts to use ODR imaging:

  A. Lumpkin et al., Proc. BIW 2008, TUPTPF061

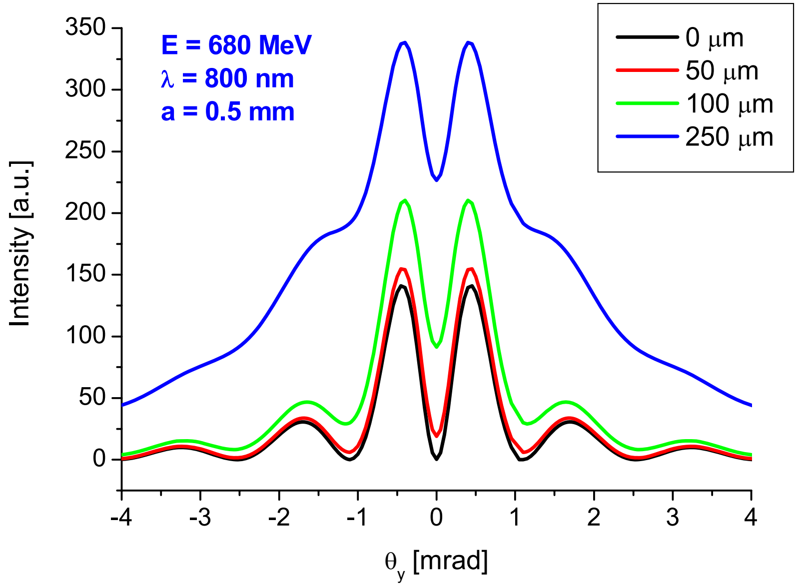
D. Xiang et al., PRST AB 10, 062801 (2007)



- exploit ODR angular distribution:

  visibility of interference fringes can be used to determine transverse size of a bunch of electrons crossing the slit

  → increasing σ_y both the peak intensity and the central minimum increase

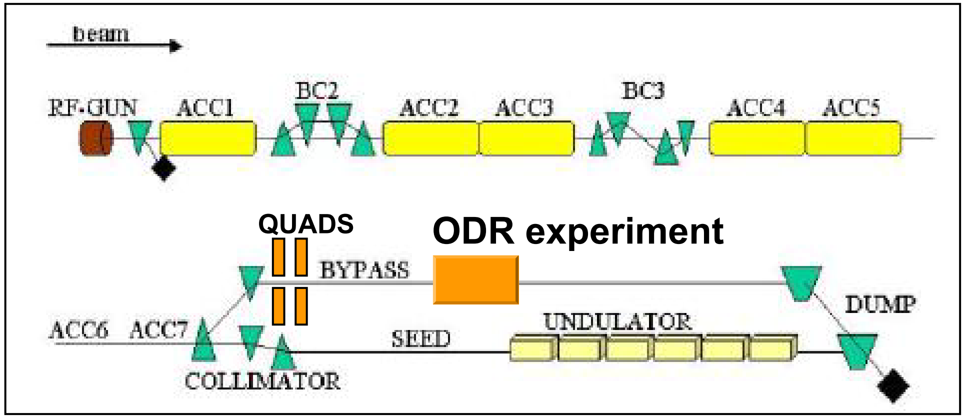


courtesy: E. Chiadroni (INFN)

- research project @ FLASH

ODR Experimental Setup @ FLASH

- overview

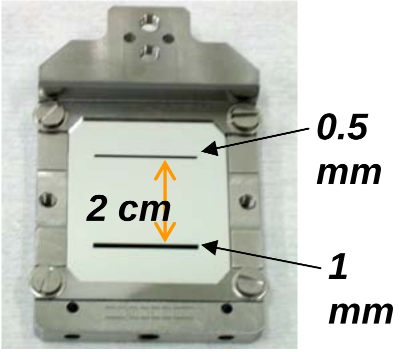


- high energy, up to *1 GeV*
- long bunch trains, up to 800 bunches per macro-pulse
- repetition rate 5 Hz
- good long term stability
- small transverse emittance, ~ 2 mm mrad

- target

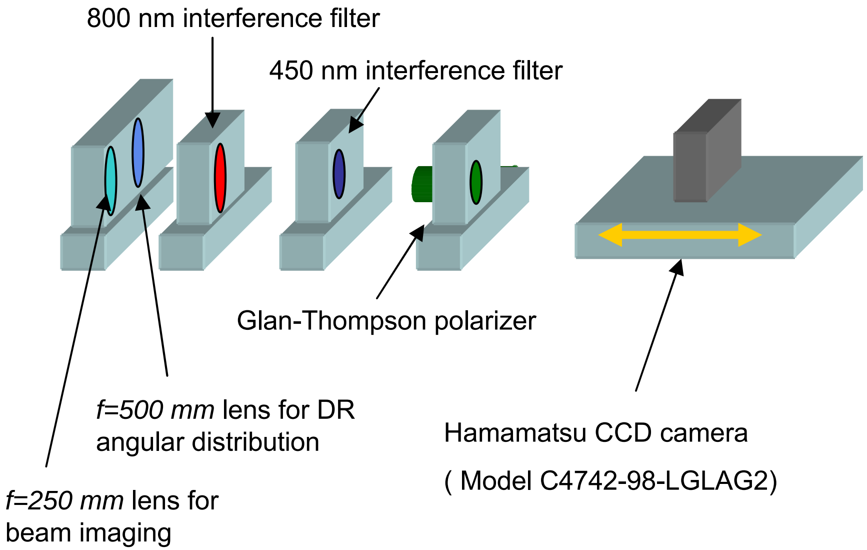
realized with **lithographic technique:**

starting from silicon nitride wafer, opening slit by means of chemical etching.



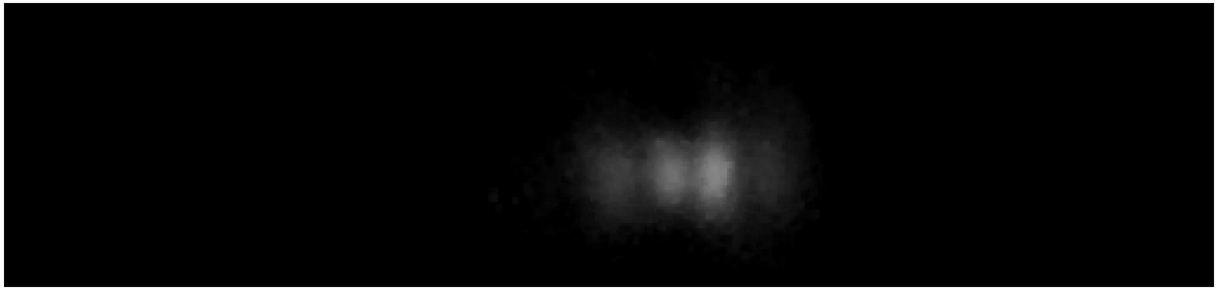
Al deposition enhances reflectivity more than a factor of 2

- optical system



ODR Evidence

- CCD image



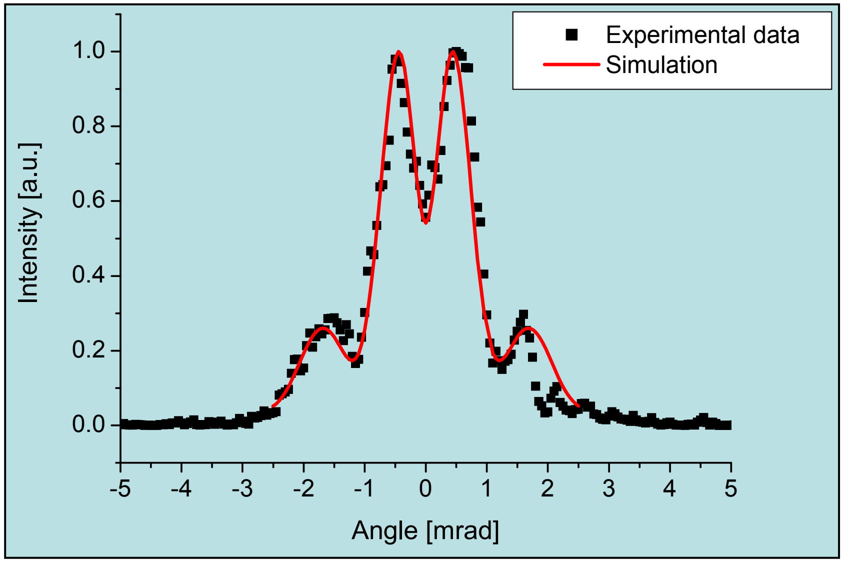
Beam transport optimization

- 0.7 nC
- 25 bunches
- 2 s exposure time
- E_{beam} (nominal) = 680 MeV
- 800 nm filter and polarizer in

- comparison

Simulation parameters:

- a = 0.5 mm
- Gaussian distributed beam
- σ_y = 80 µm
- σ'_y = 125 µrad
- E_{beam} = 610 MeV



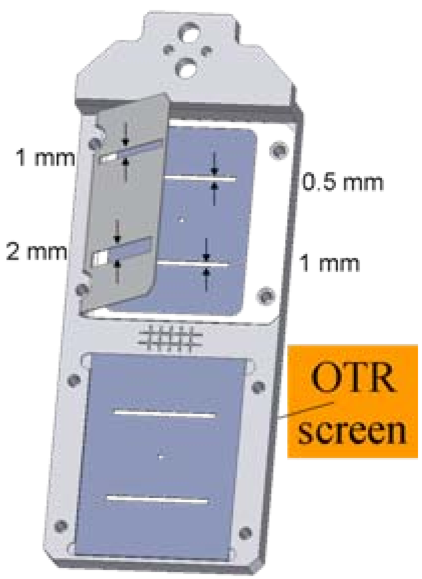
E. Chiadroni, M. Castellano, A. Cianchi, K. Honkavaara, G. Kube, V. Merlo, F. Stella,
Non-intercepting electron beam transverse diagnostics with optical diffraction radiation at the DESY FLASH facility
NIM B 266 (2008) 3789–3796 *and* ***Proc. of PAC 2007, p.3982***

ODR Interferometry (ODRI)

- reduction of synchrotron radiation background

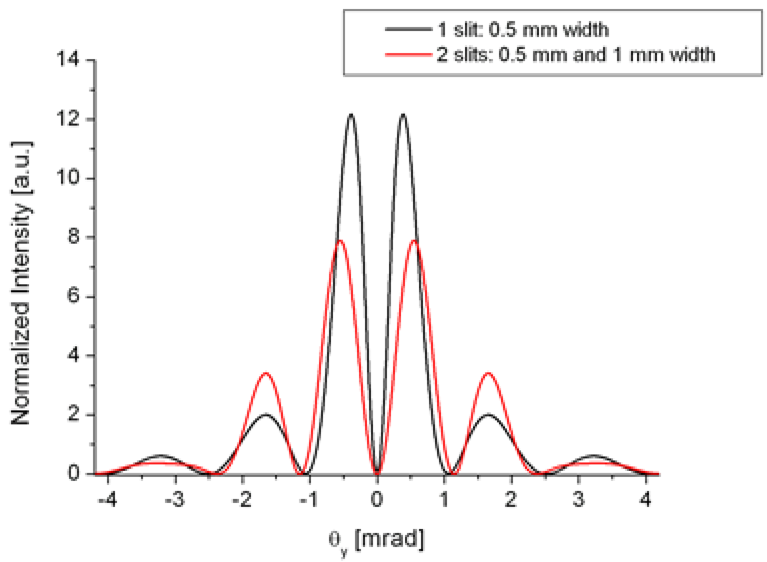
courtesy: E. Chiadroni (INFN)

→ stainless steel shield in front of ODR screen with larger cut



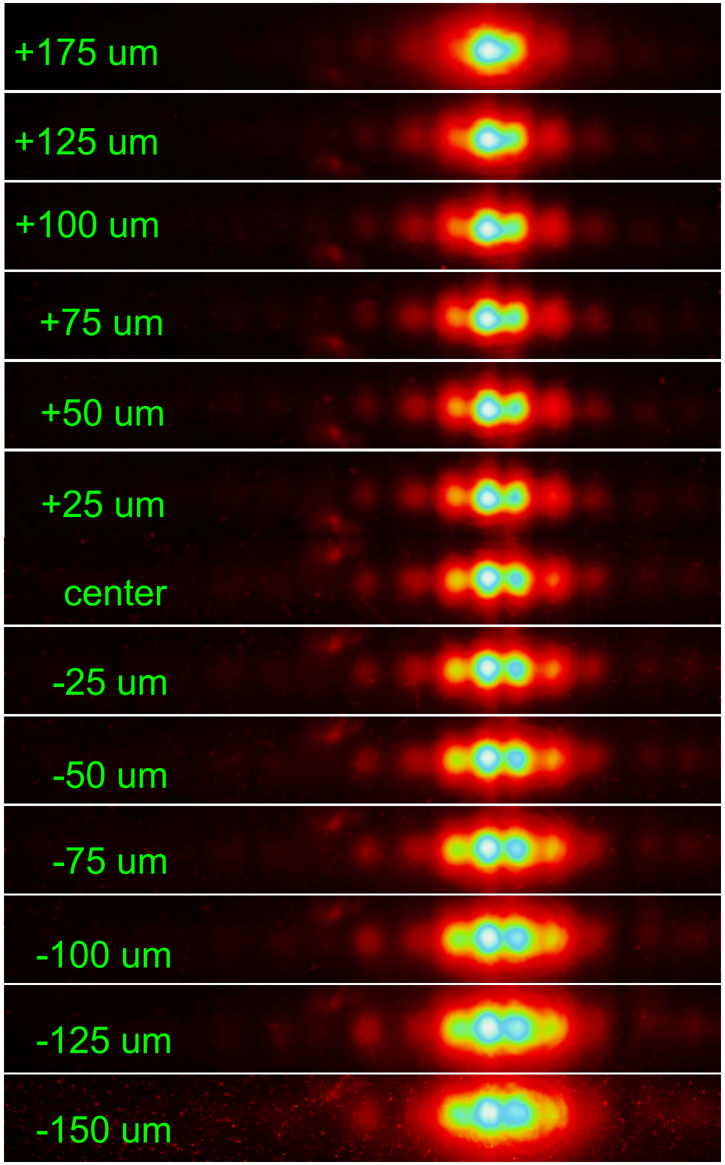
In the case of a wavelength of 800 nm and 1 GeV beam energy the 1 mm cut is not large enough to prevent the production of ODR in the forward direction, reflected by the screen and interfering with the backward ODR produced by the screen itself.

An ODR analogous of the Wartski interferometer used for OTR, with the difference that in this case the two interfering amplitudes are different in intensity and angular distribution



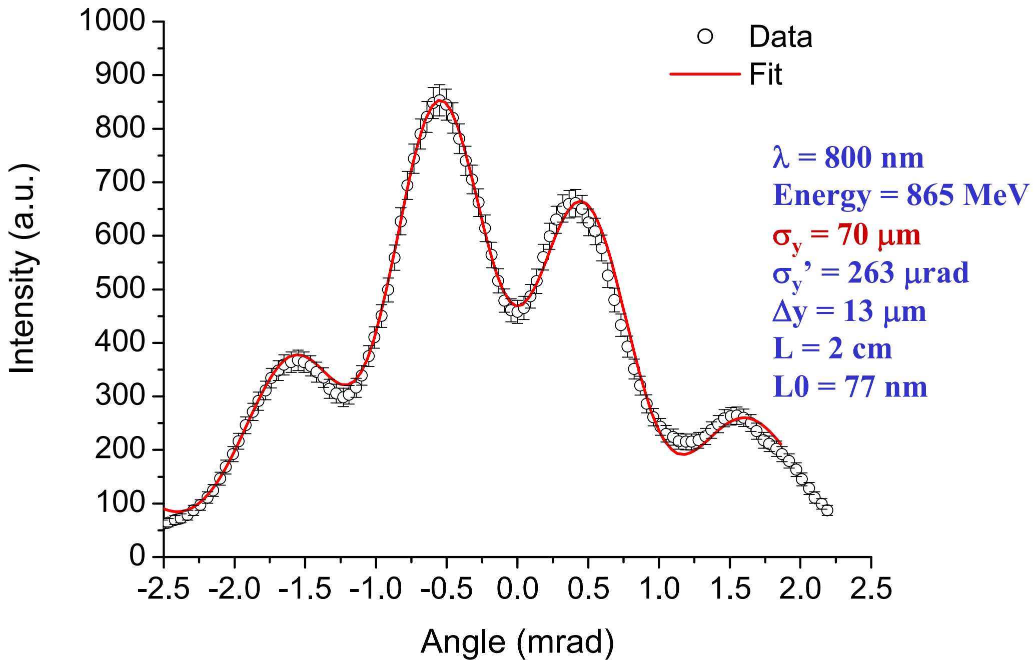
Single particle going through the center of both slits with 900 MeV energy and 800 nm wavelength

ODRI Measurements



courtesy: E. Chiadroni (INFN)

- transverse scan within the slit
- fit of ODRI angular distribution



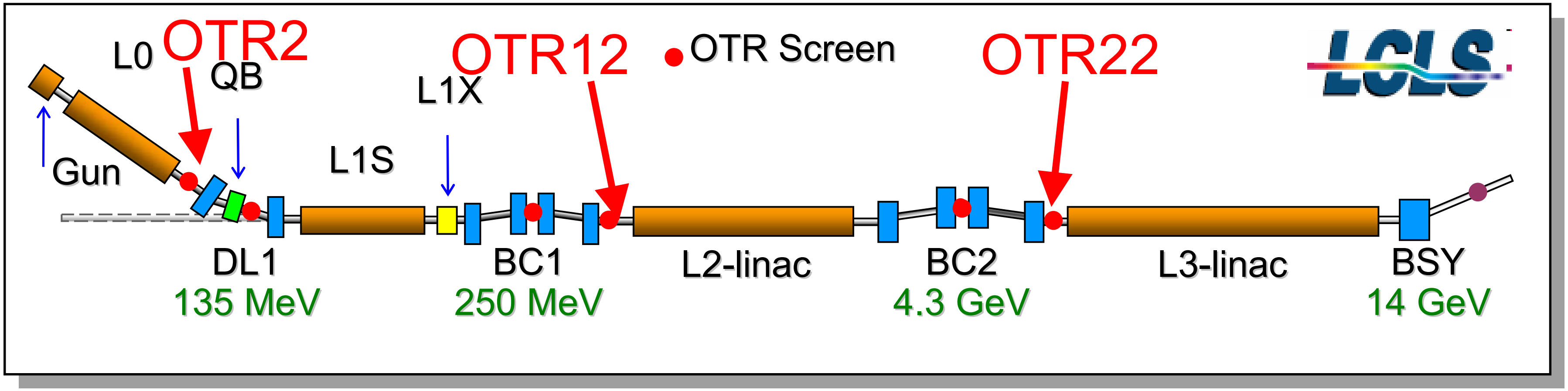
E. Chiadroni, M. Castellano, A. Cianchi, K. Honkavaara, G. Kube,
Optical diffraction radiation interferometry as electron transverse diagnostics
Proc. DIPAC 2009, p.151

⇒ activities to explore ODRI properties will continue this year after redesign of target and optics

OTR/ODR Diagnostics: Pitfalls

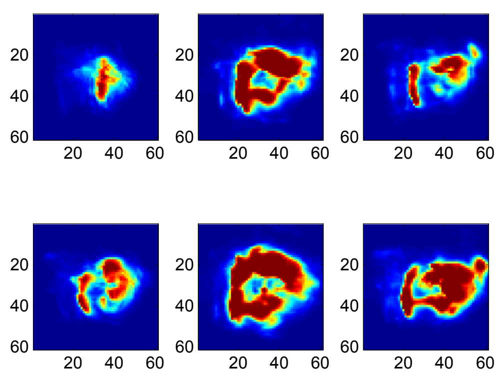
- Linac Coherent Light Source (LCLS) @ SLAC

courtesy: H. Loos (SLAC)

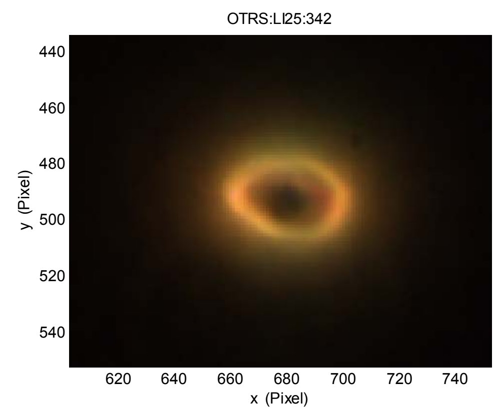


- OTR monitor observation with BC1, BC2 switched on

  - OTR 12



  - OTR 22



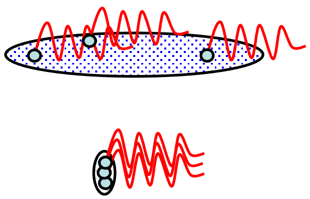
⟹ measured spot is no image of beam

Coherent OTR (COTR)

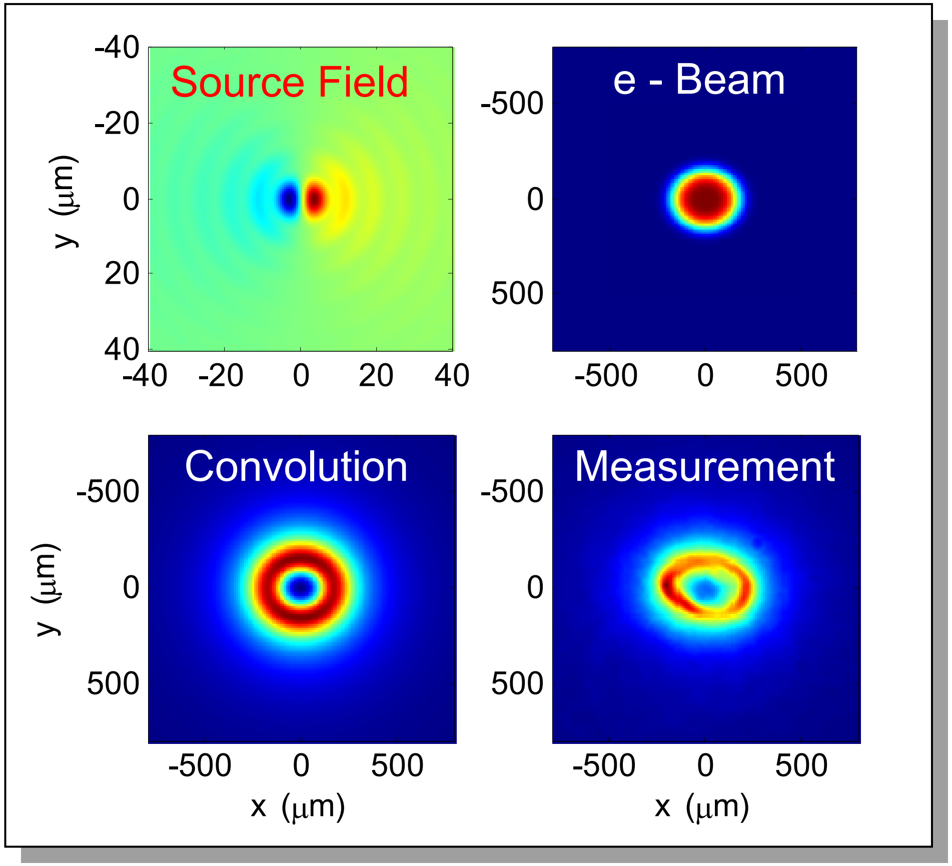
- interpretation: coherent OTR emission

  → strong compression in bunch compressors

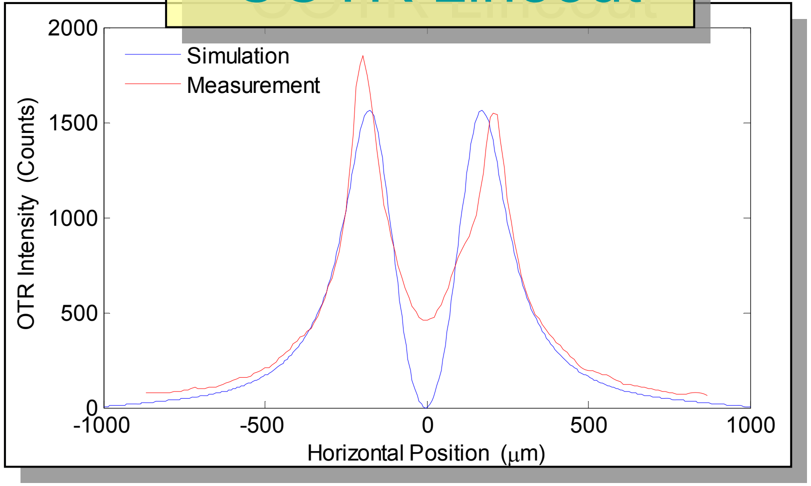
- simulation



H. Loos et al., Proc. FEL 2008, p.485



OTR22, 250 pC, 4.3 GeV
10 µm bunch length
100 µm rms beam size
Super-Gaussian



Consequences

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

  → wire scanners for transverse beam diagnostics instead of OTR

- XFEL: experience from FLASH

  → no COTR observation in standard operation

…better to be prepared in advance…

- alternative schemes for transverse profile diagnostics
  - **ODRI**

    coherent effects may also appear → possibility to extract information from angular distribution ???
  - **TR at smaller wavelengths (EUV-TR)**

    test experiment performed March 2010
  - **screen monitors**

    widely used at hadron accelerators, nearly no information available 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

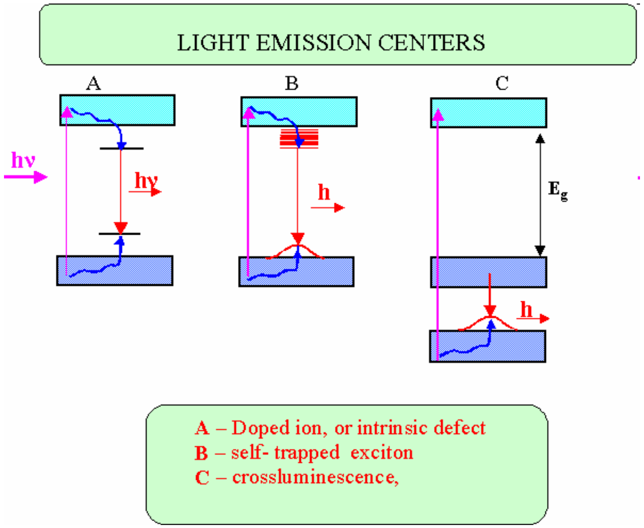
- generation of scintillation light
  - energy conversion (characterstic time $10^{-18} – 10^{-9}$ sec)

    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

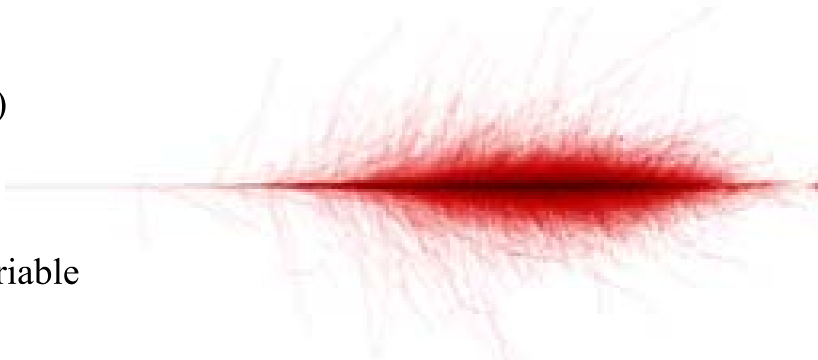
Which effects may affect transverse resolution ?

- 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

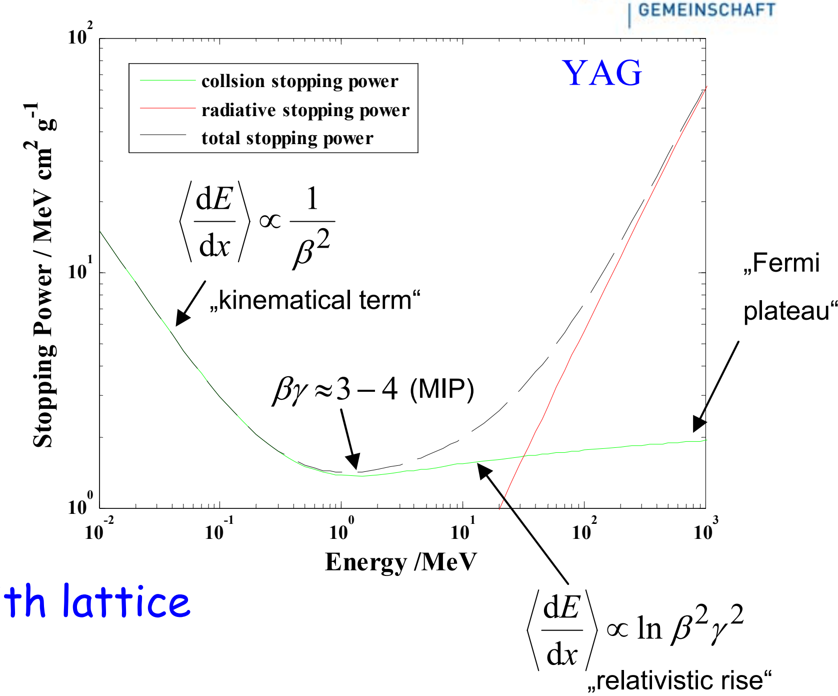
Implication on Transverse Resolution

- 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



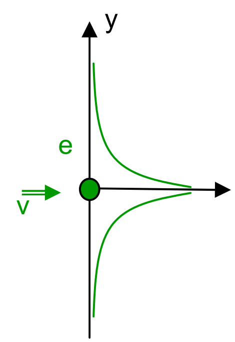
- ionization: interaction of particle em. field with lattice
  - particle field

    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

    $\rightarrow$ saturation range as scaling variable R_δ



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

with $y_0 = \lambdabar \beta_m \gamma_m$

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

Implication on Transverse Resolution

- extension radius
  - limiting value:

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

$\varepsilon(\omega)$: 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

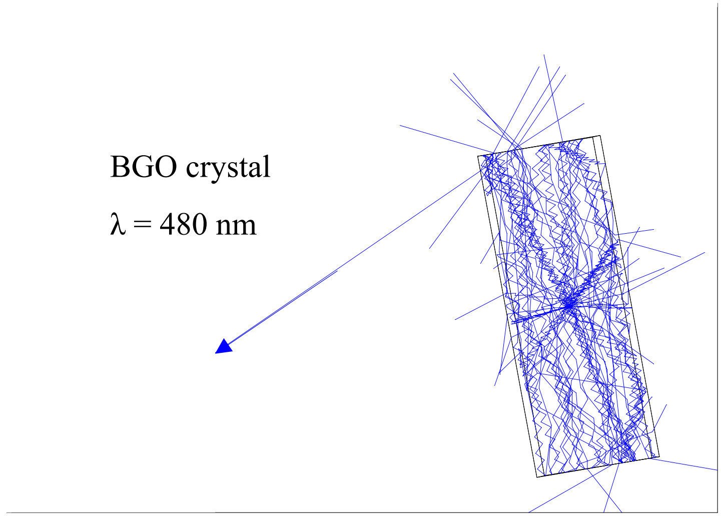
refractive index n

inorganic scintillators

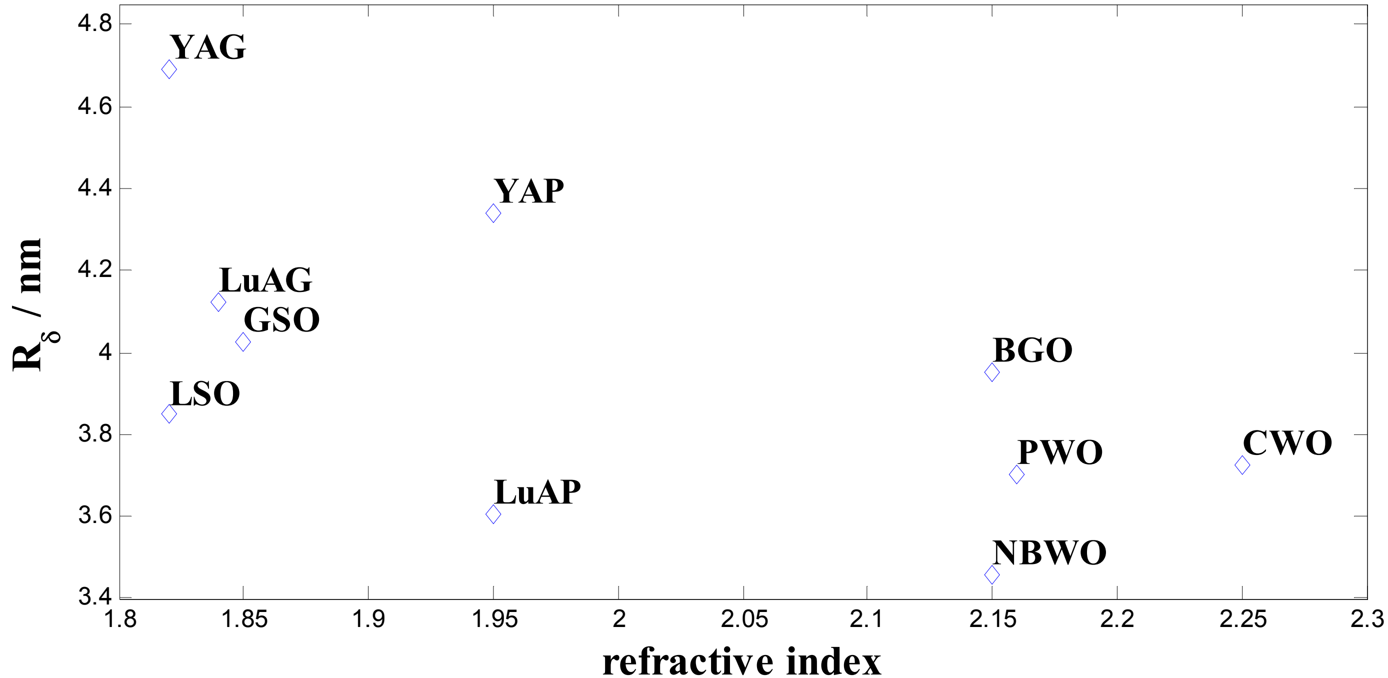
→ high n, i.e. large contribution of total reflection

BGO crystal

λ = 480 nm



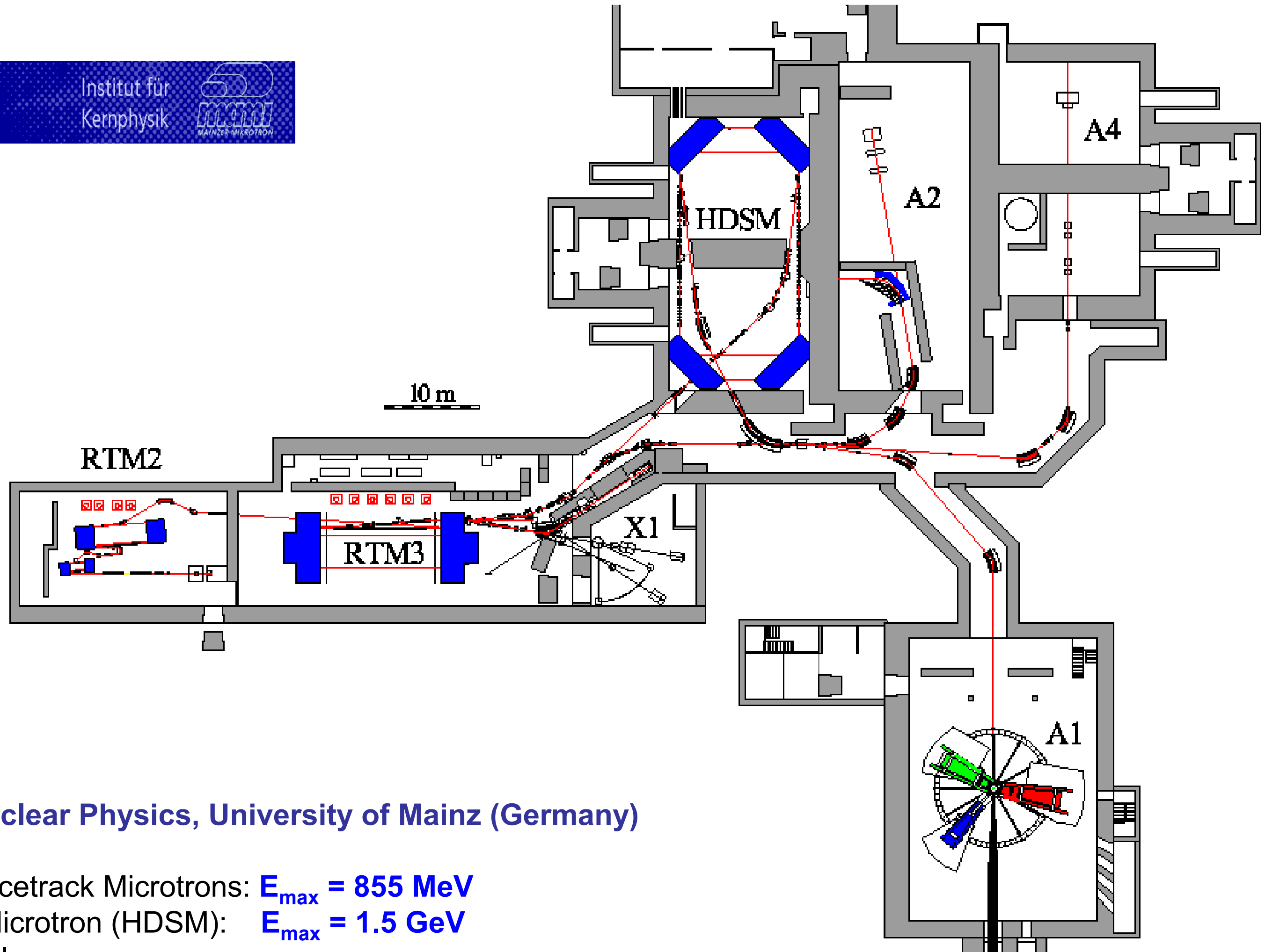
Scintillator Material Properties



- 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

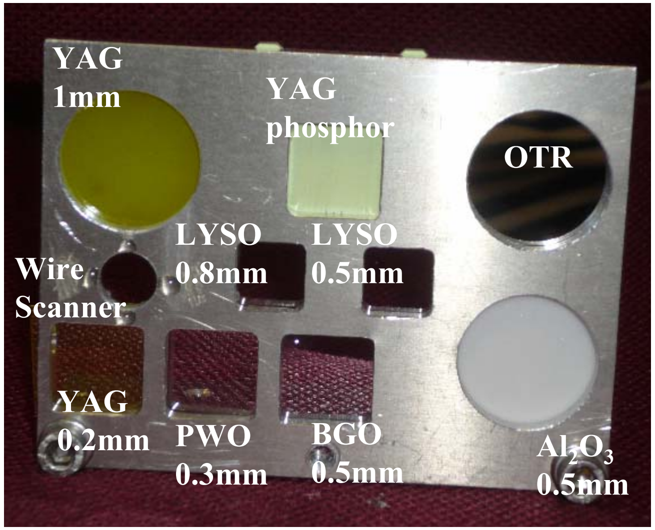


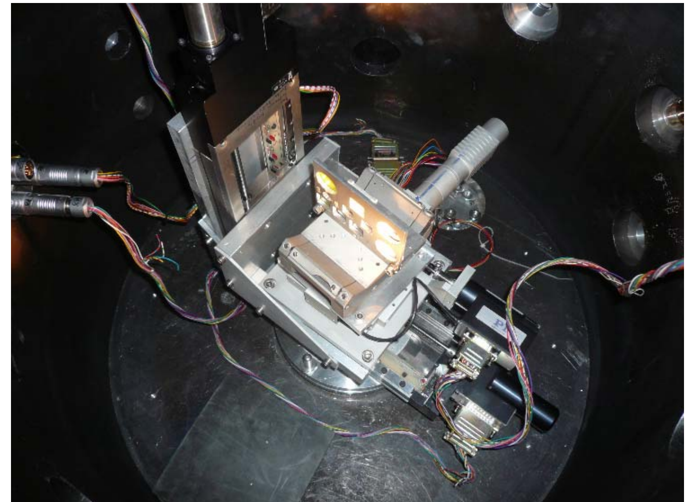
Institute of Nuclear Physics, University of Mainz (Germany)

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





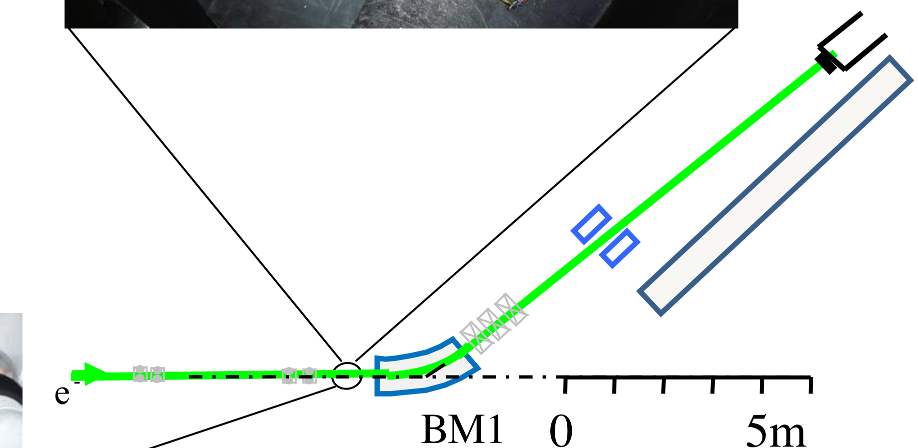
- observation geometry

-22.5° w.r.t. beam axis

camera: BASLER A311f

659 x 494 pixel

pixel size 9.9µm x 9.9µm

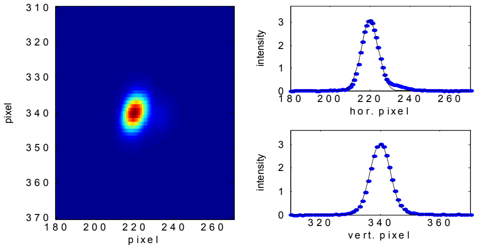


- X1 beamline

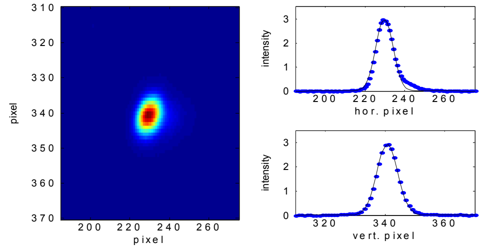
Beam Images

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

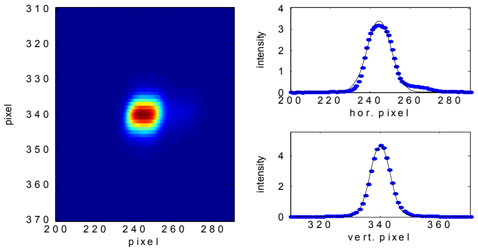
LYSO:Ce (0.5mm)



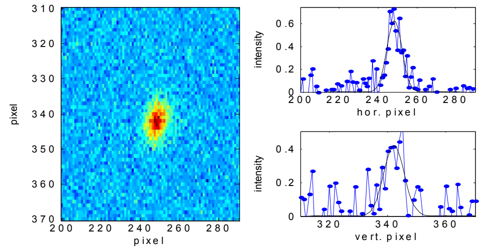
BGO (0.5mm)



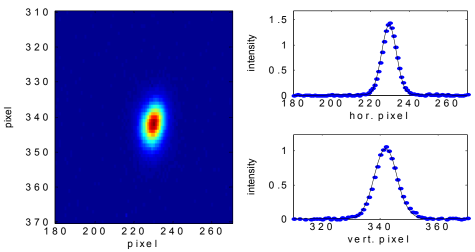
LYSO:Ce (0.8mm)



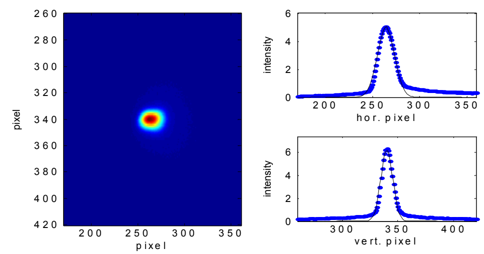
PWO (0.3mm)



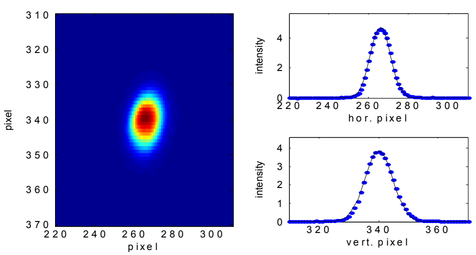
YAG:Ce (powder)



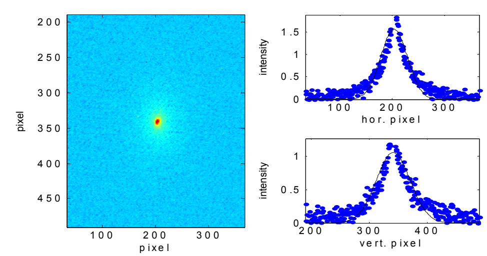
YAG:Ce (1mm)



YAG:Ce (0.2mm)



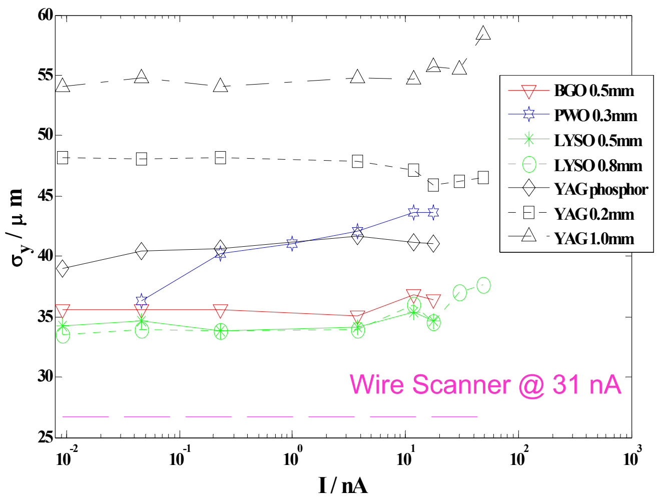
Al_2O_3 (0.5mm)



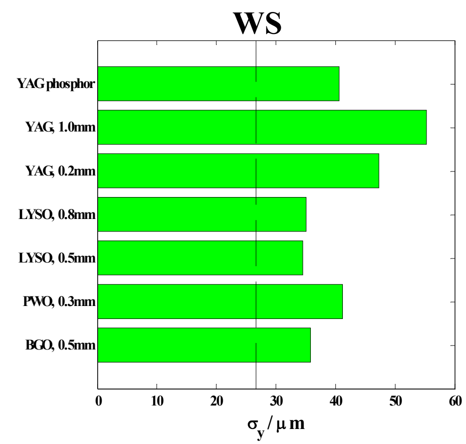
different scale !

Results

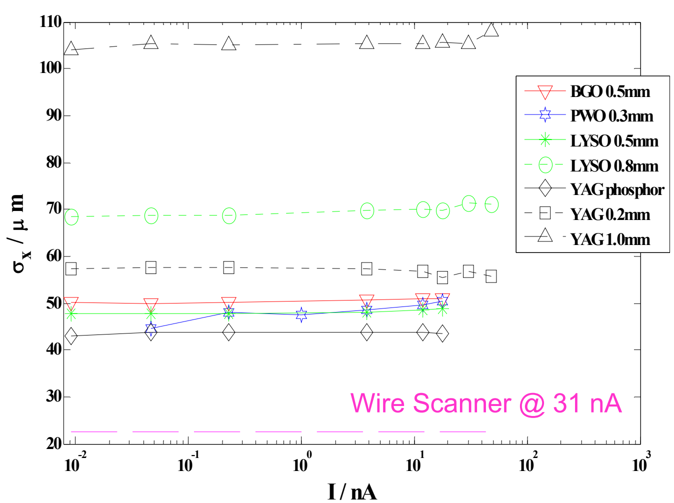
- vertical beam size

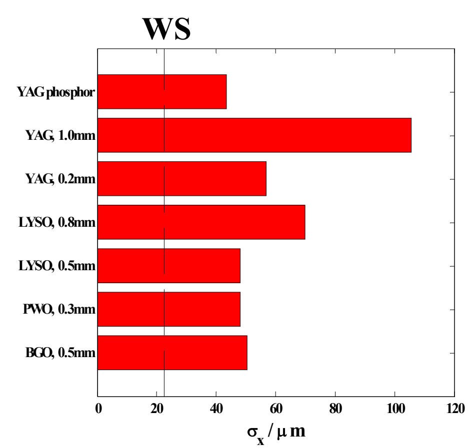


- mean values



- horizontal beam size





⇒ dependency on observation geometry

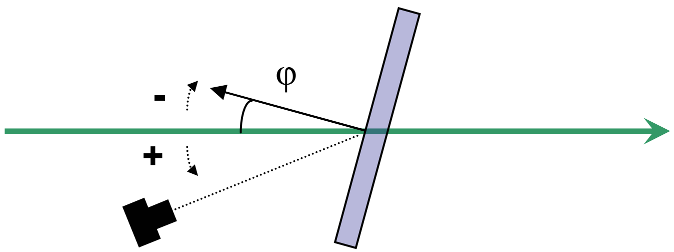
Observation Geometry

- beam diagnostics

  → popular OTR-like observation geometry:

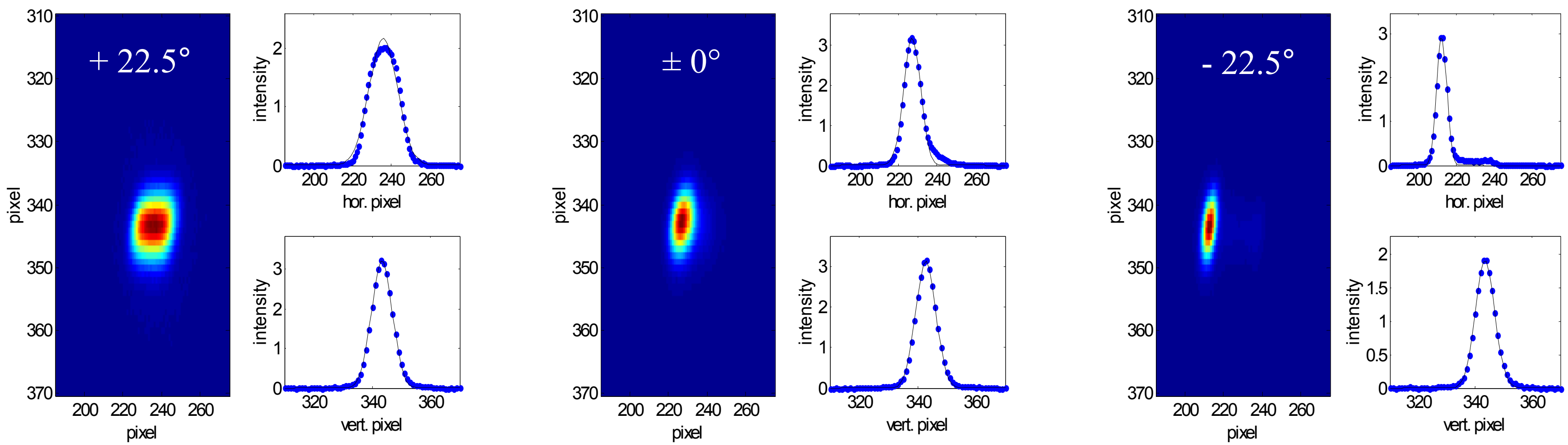
  - 45°tilt of screen
  - observation under 90°

- scintillator tilt versus beam axis

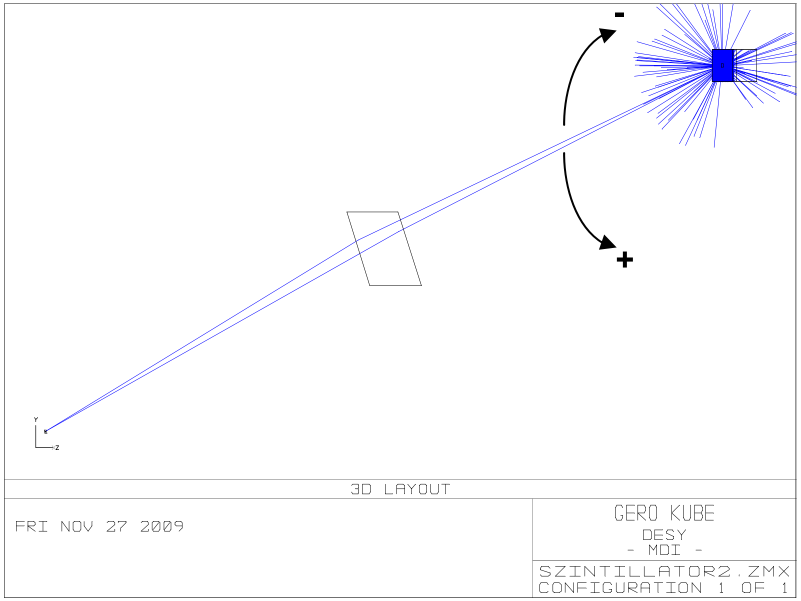


  - BGO crystal
  - micro-focused beam
  - I = 3.8 nA

- measured beam spots



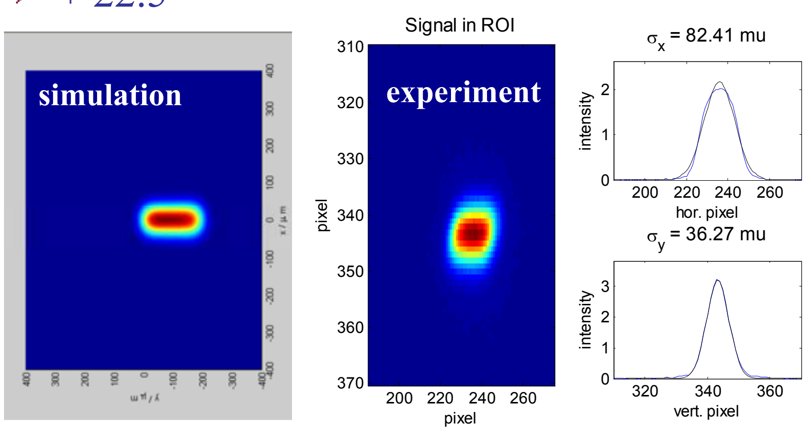
Simulation of Light Propagation



Analysis:

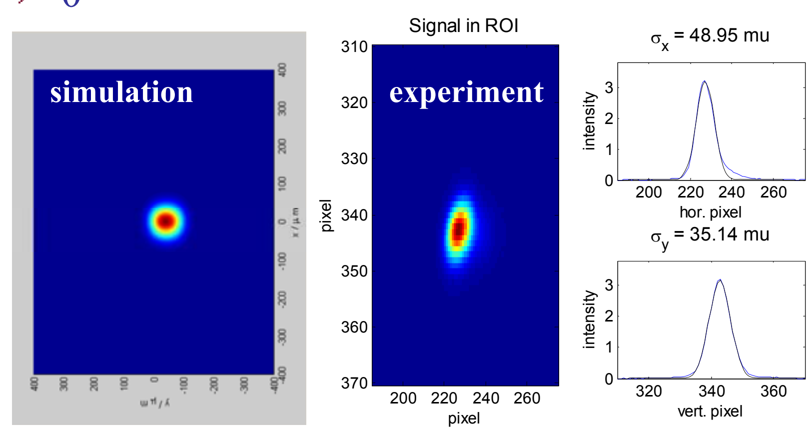
- ZEMAX calculation of 2-dim PSF
- calculation of 2-dim beam profile
- convolution of PSF and beam profile
- horizontal / vertical projection of resulting distribution
- determinatiuon of 2nd moment (standard deviation)

+ 22.5°

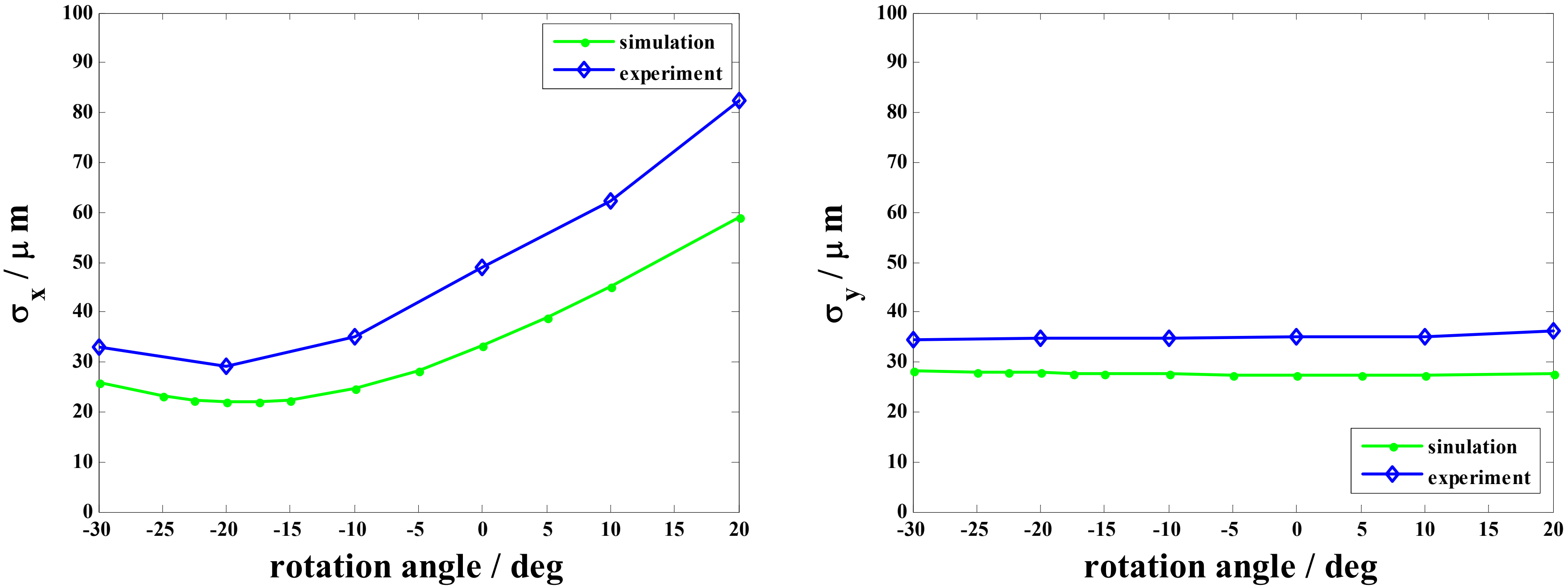


different scale !

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

- improve simulation to include effect of energy conversion
- continue search for optimum scintillator material

  → CRY-19 (Crytur) has promising properties similar to LYSO
- systematic studies of influence of scintillator thickness
- influence on observation geometry for different materials and thicknesses

⟹ **order of new screen materials in preparation**

open point

- 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