Optical Diagnostics for Extreme Beam Conditions

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OUTLINE

Terminology: **Optical**: mostly visible, but some stretch (UV – THz)
Extreme: $\sigma_r, \varepsilon \le$ μm , $\sigma_z \sim \lambda$, $\chi \approx 1$, DR > 10^5

Emphasis: Diagnostic methods that are generally applicable (linacs, synchrotrons, PWAs), simple, low cost, minimally invasive and potentially single shot.

Observables:

- **Beam size**
  1) Imaging using the single particle function (SPF) of incoherent ($\lambda \ll c\Delta\tau$) beam associated radiation, e.g. OTR, OSR, phosphorescence
    a. OTR SPF dependence on beam size
    b. Low energy OTR calculations of SPF + new algorithm which includes $\Delta\lambda$
    c. OSR Line spread function
    d. LSYO scintillator, 1 micron measurement

  2) High dynamic range imaging : DR ~10^6
    a) DMD imaging
    b) measurements of PSF with/wo DMD

  3) RMS beam size measurements using interference methods
    a) ODRI from two slits separated longitudinally
    b) OSR from two pinholes separated transversely (1D or 2D)
    c) OSRI from multiple slit diffractive element, optical and UV

OUTLINE (continued)

- **Emittance (transverse)**

  Size + divergence measurement techniques applicable to beams with high space charge

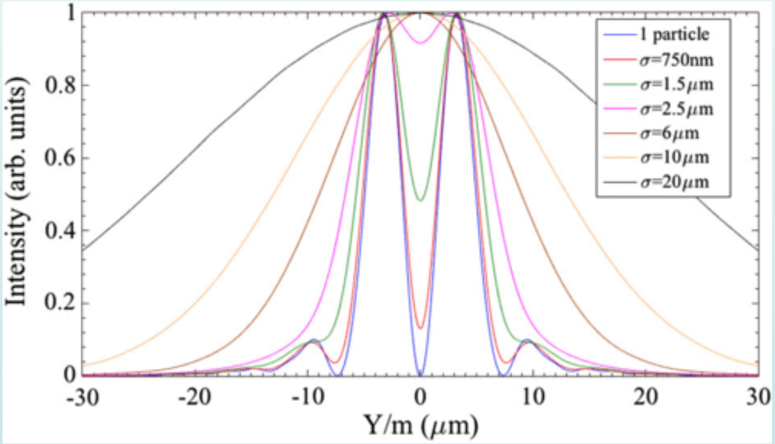
  a) modified quad scan (beam size + divergence vs 1/f) → <rr'> → $\epsilon_{rms} \leq 1\ \mu m$,

  b) OPSM methods (optical pepper pot technique) using OTR
    1- optical pinhole scanning / mechanical and electronic scanning with DMD
    2- micro-lens array method (single shot)

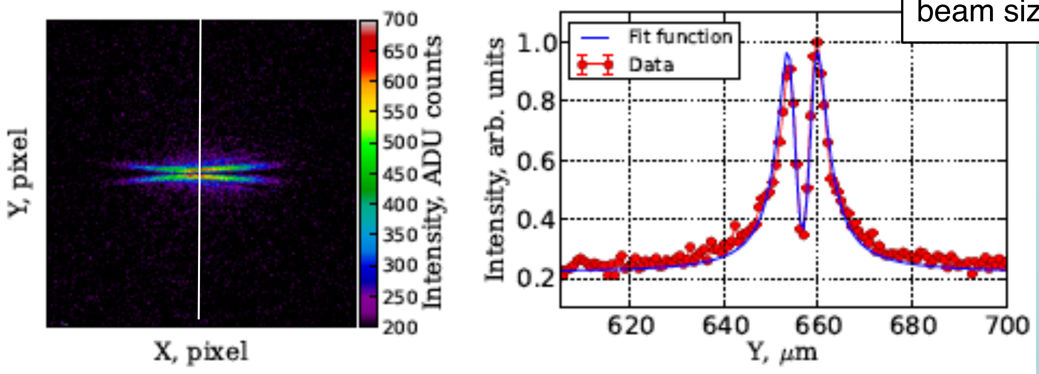
- **Bunch length:** single shot, use coherent optical radiation $(\lambda \geq c\Delta\tau)$, e.g. CTR and CDR

  Angular/spatial distribution (SPF) imaging, $cT \sim \lambda = (1\ \mu m$ -1 mm)

Using the Single particle Function (SPF) of OTR to measure very small (submicron) beams*



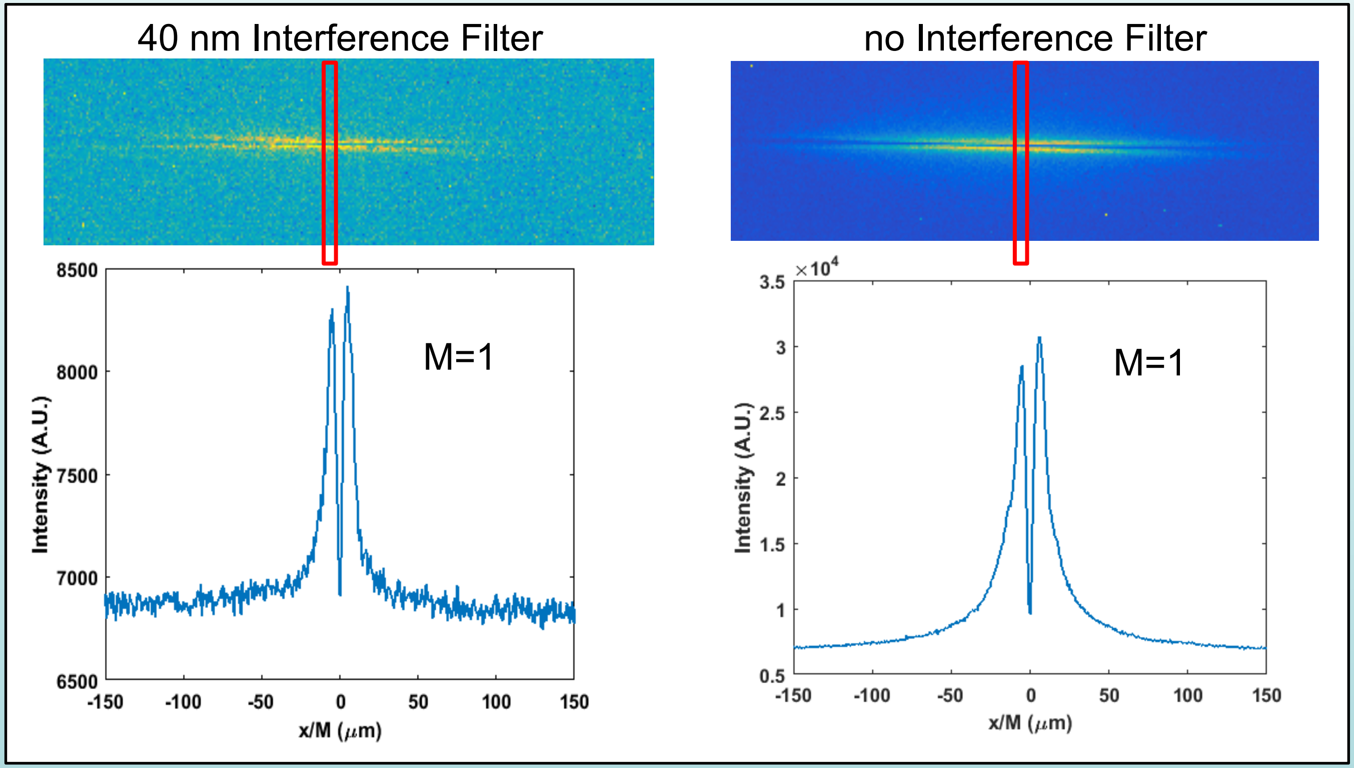
OTR image
KEK ATF2
e beam
1.3 GeV



minimum measured vertical beam size: $0.754 \pm 0.034\ \mu$m

*K. Kruchinin, et. al., Proc. of IBIC13; Journal of Appl. Physics, Conf. 517 (2014).

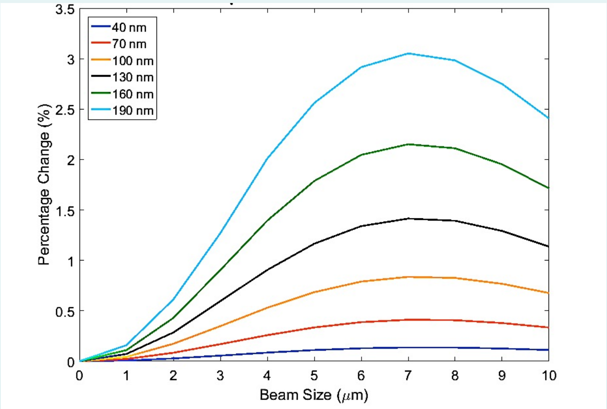
High resolution images indicate that large bandpass may be tolerable without significantly deteriorating visibility

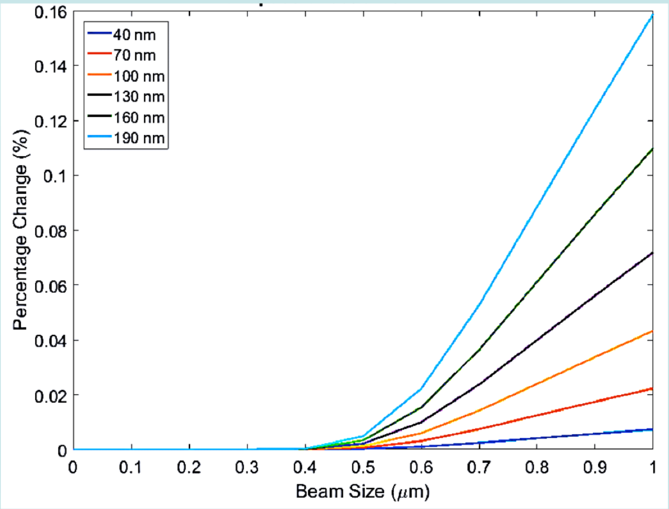


40 nm Interference Filter

no Interference Filter

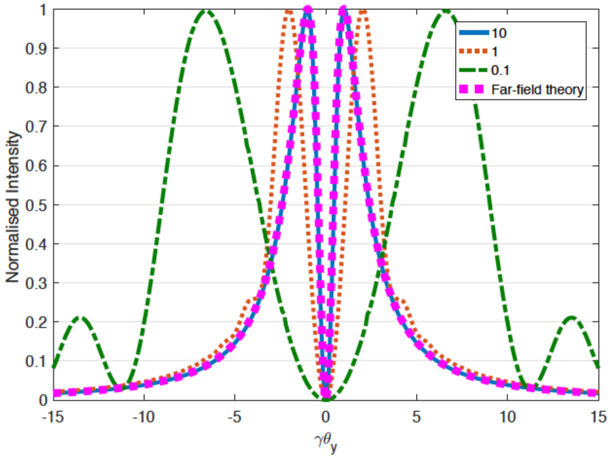
Study of Effect of Bandpass on OTR SPF Minimum



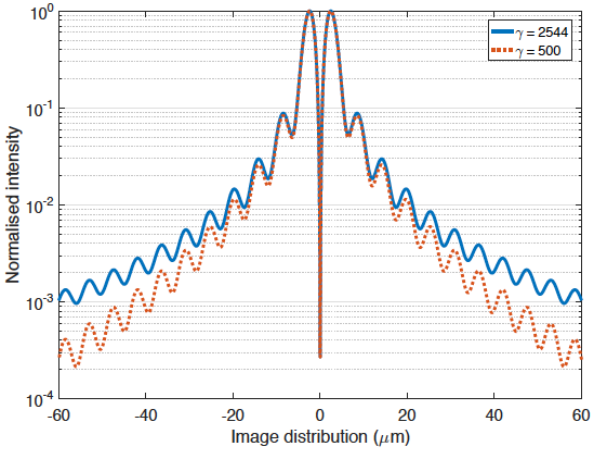


Energy Scaling in OTR Calculations: Reduces Computational Requirements*

Comparison of OTR Angular Distributions for different distances from source in unit of $\gamma^2\lambda$

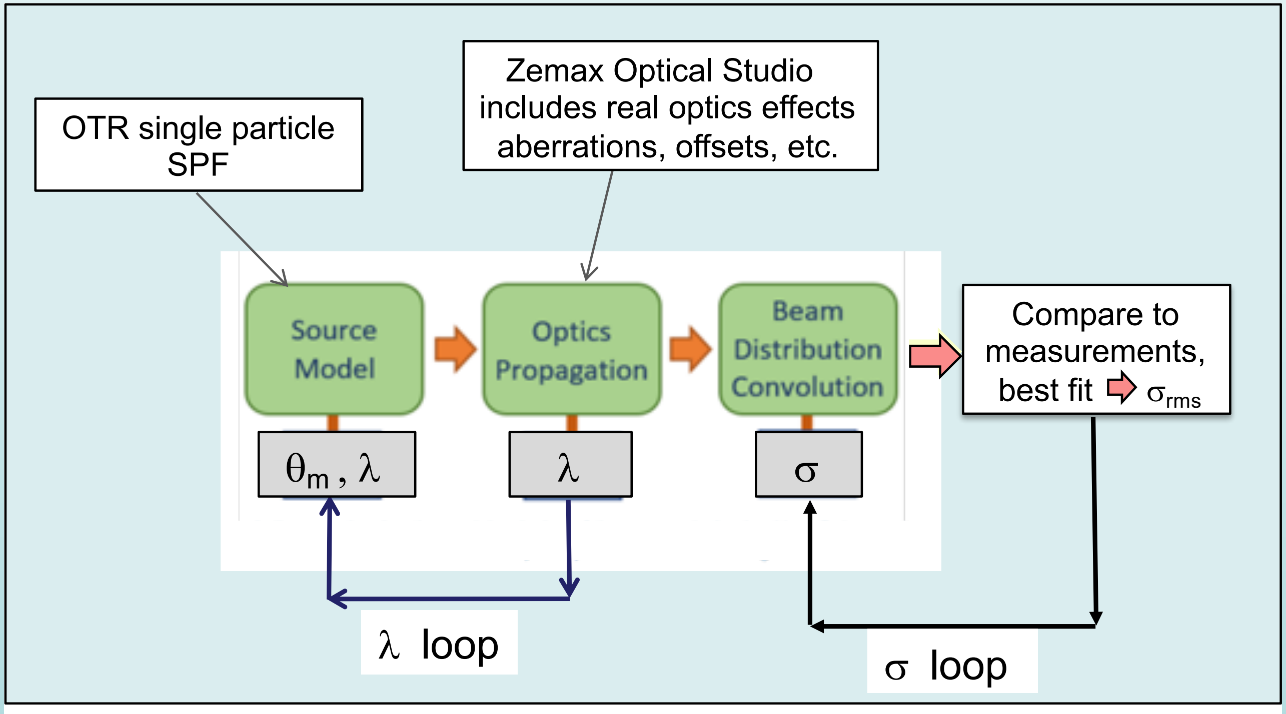


Comparison of OTR SPFs for 250 MeV and 1.3 GeV electrons



*See: J. Wolfenden, et. al., paper **WEPAF036** for more details

Theory Based Algorithm to Determine Beam Size using OTR single particle SPF*



OTR single particle SPF

Zemax Optical Studio includes real optics effects aberrations, offsets, etc.

Source Model

Optics Propagation

Beam Distribution Convolution

Compare to measurements, best fit ⇨ σ_{rms}

θ_m , λ

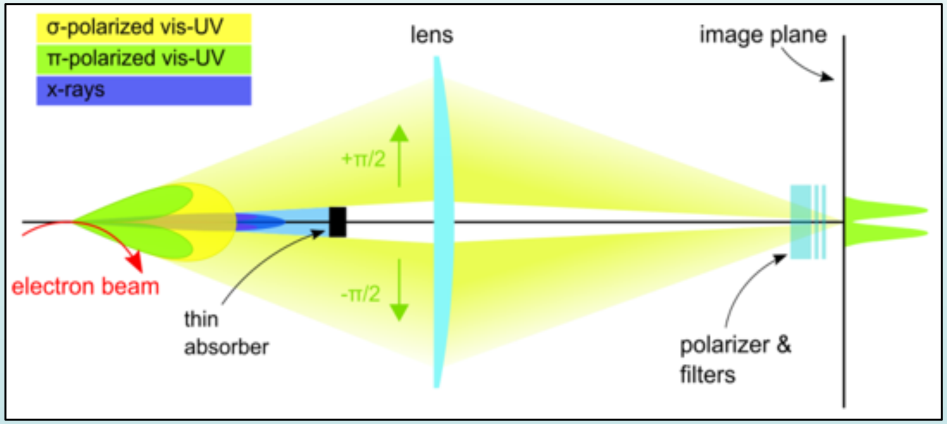
λ

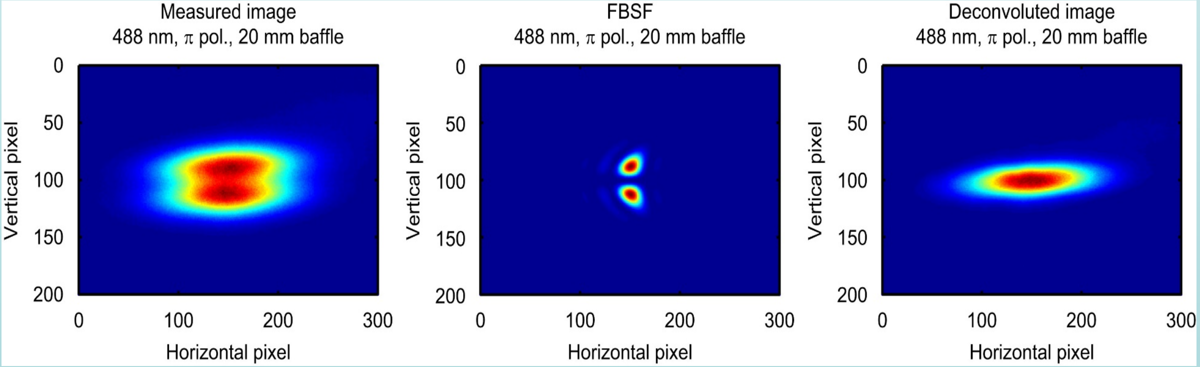
σ

λ loop

σ loop

Beam Size determination by deconvolution of the OSR SPF or “filament beam spread function” (FBSF)*

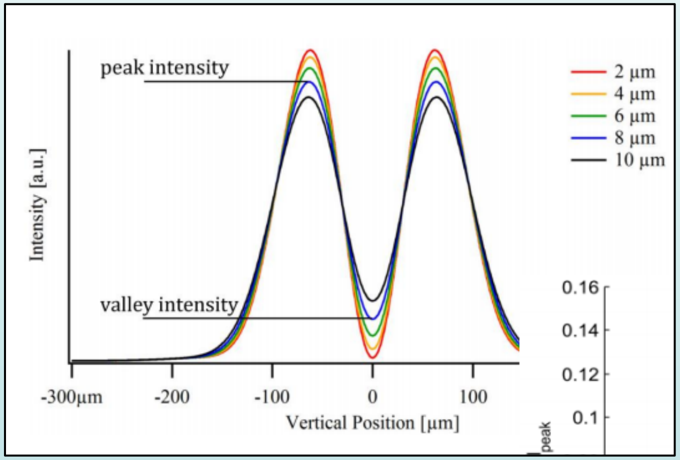


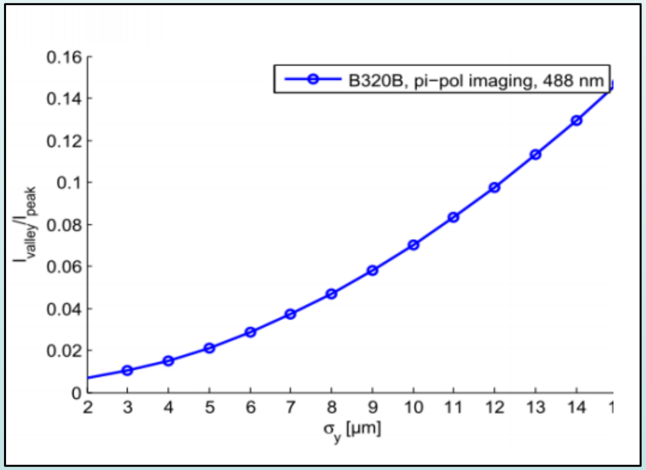


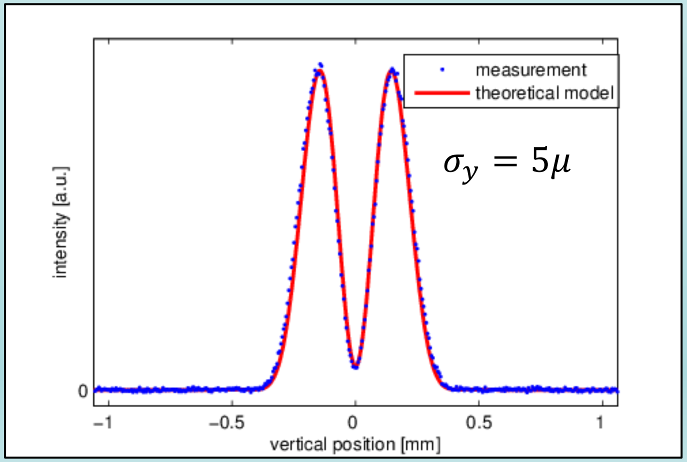
*A. Andersson, 60th ICFA Advanced Beam Dynamics Workshop **FLS2018**, Shanghai March 5-9.

Beam size: OSR SPF

Resolving vertical beam sizes < 5 μm using Visibility and Shape of Pi polarized SPF







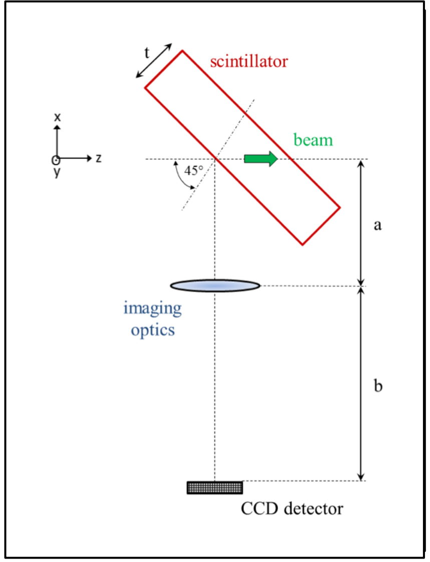
$$\sigma_y = 5\mu$$

Beam Size: Scintillator SPLF

High Resolution Scintillator Studies using Single Particle (Line Spread)Function*

Micrometer beam size experiment at MAMI**

Experimental Setup



a = 27.54 mm

b = 1155.46 mm

→ M = 41.95

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

thickness t = 200 μm

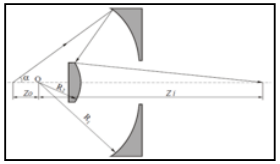
supplier: *OmegaPiezo*

Imaging Optic: Schwarzschild Objective:

- 2 concentric spherical mirrors
- aplanatic (corrected for spherical aberrations)

f = 26.90 mm

NA = 0.19 (nominal)

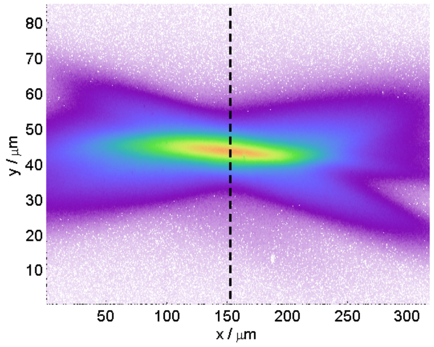


** G. Kube, S. Bajt, A.P. Potylitsyn, et. all., Proc. IBIC2015, Melbourne, Australia

*G. Kube, DESY, Workshop on Emittance Measurements, ALBA, Jan 2018

Beam size determination via Convolution of Gaussian with Scintillator SPF

Measured beam image (λ = 420 nm)



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)

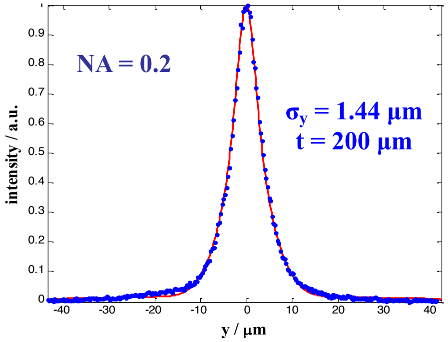
→ Schwarzschild objective (used in experiment)

replaced by paraxial lens with same f and NA

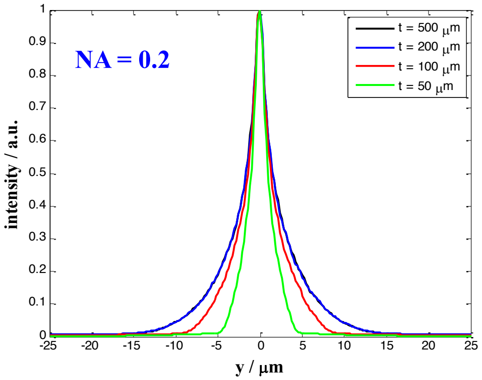
→ non-sequential ray tracing for 10^8 rays at LYSO peak emission wavelength λ = 420 nm

→ single particle source function (SPF)

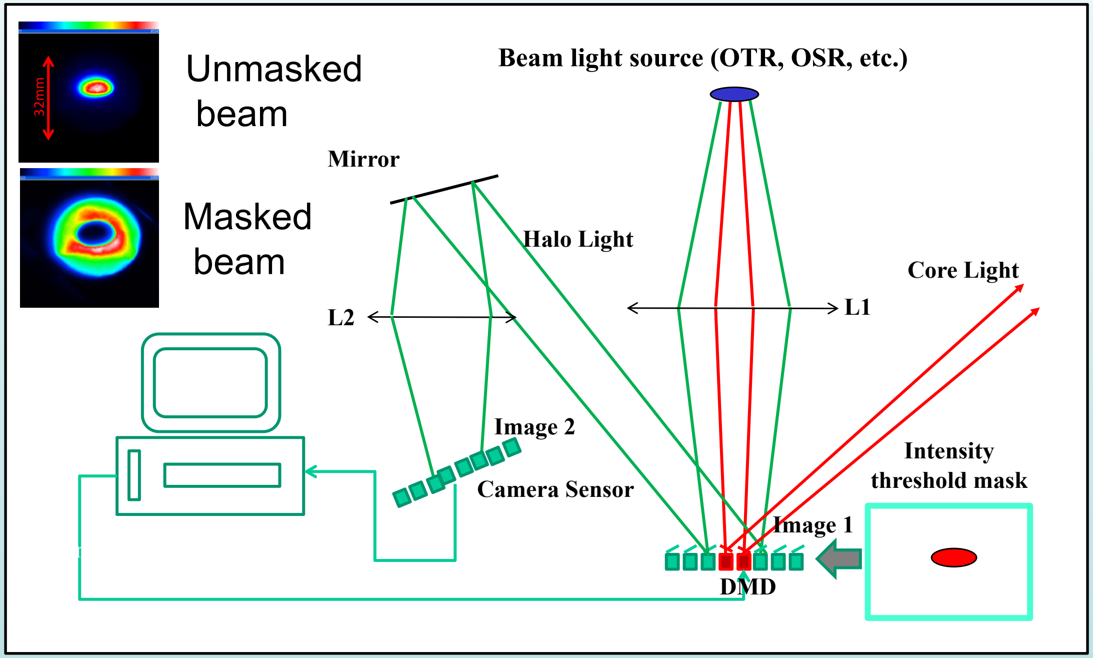
Convolution of SPF with 2D-Gaussian model for beam



To improve resolution reduce **t**



High Dynamic Range Imaging system using DMD *



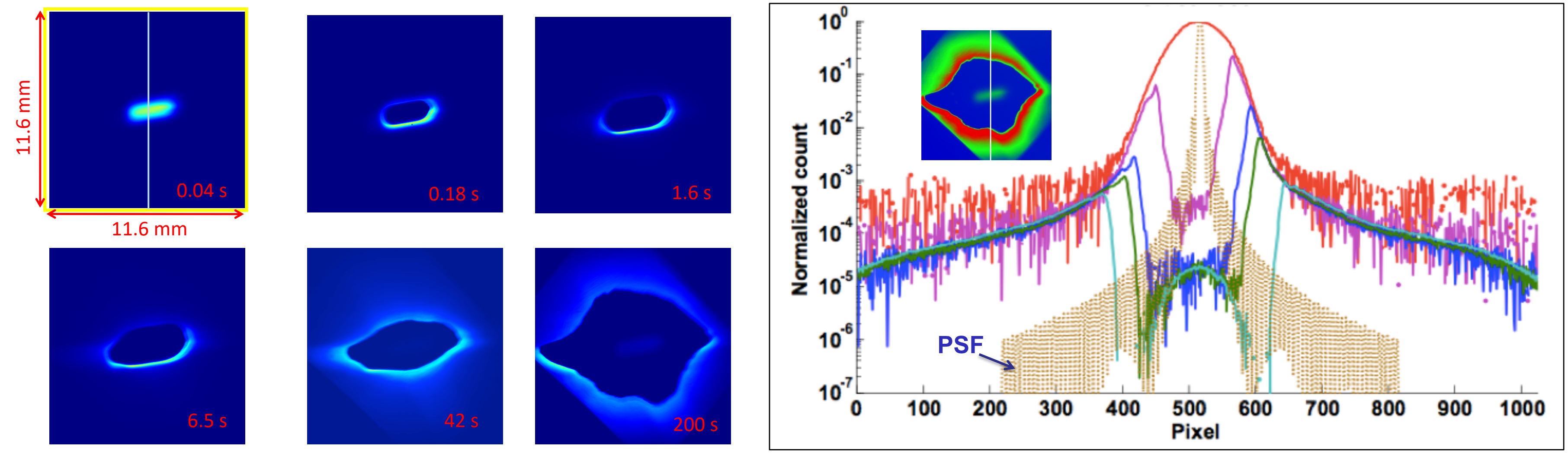
Advantages/ Disadvantages

1. Each mask only requires limited DR image
2. Most scattered light from the core is eliminated - extinction ~10^3
3. Core and Halo can be monitored at same time

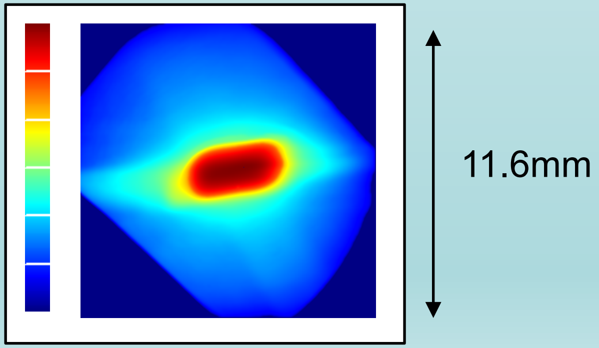
H. Zhang, R. Fiorito, et. al. PRSTAB, 2012; J. Egberts and C. Welsch, JINST, 2010

Halo Imaging of JLAB CW beam with OSR and DMD*

(I = 0.63 mA, 4.68MHz, 135pc/micropulse, λ= 654nm x 90nm , ND=0.4)



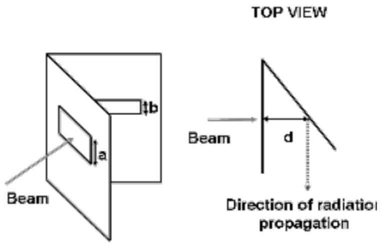
Reconstructed
HDR image

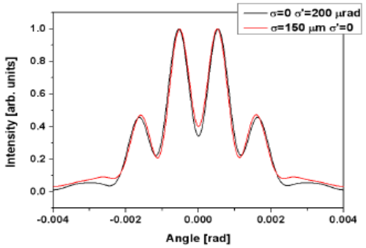


*R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc. IPAC12

Optical Diffraction Radiation Interferences: sensitive to σ, σ' *

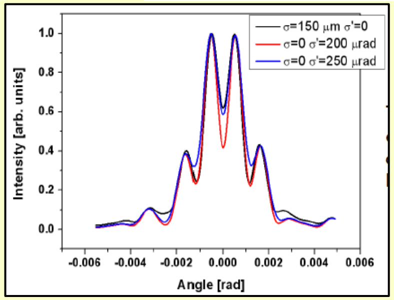
ODRI from two collinear slits





N.B. : slit separation, $L \ll L_{coh} \sim \gamma^2 \lambda$

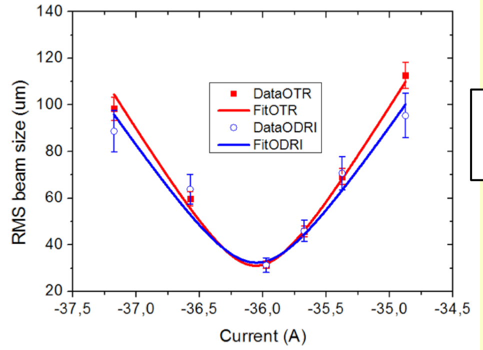
ODRI from two non-collinear slits



A 50 μm offset between the slits removes the mixing between σ, σ'

1 GeV
20 pulses
200 pC/pulse
10 Hz
2 s CCD integration time
=> **80 nC** integrated charge

Quad scan and emittance determination using ODRI data



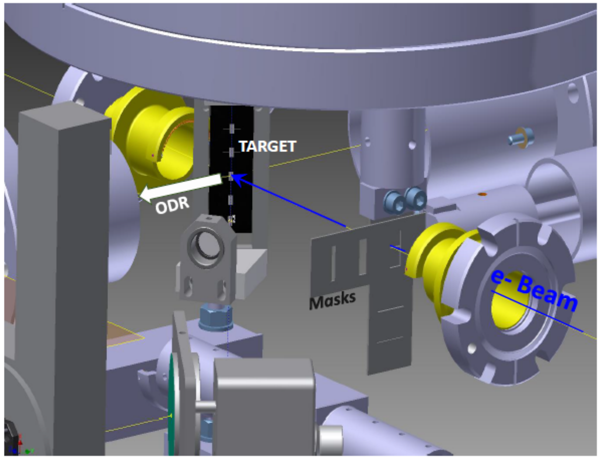
ε_{y_ODRI}=(2.23±0.85) mm-mrad
ε_{y_OTR}= (2.37±0.46) mm-mrad

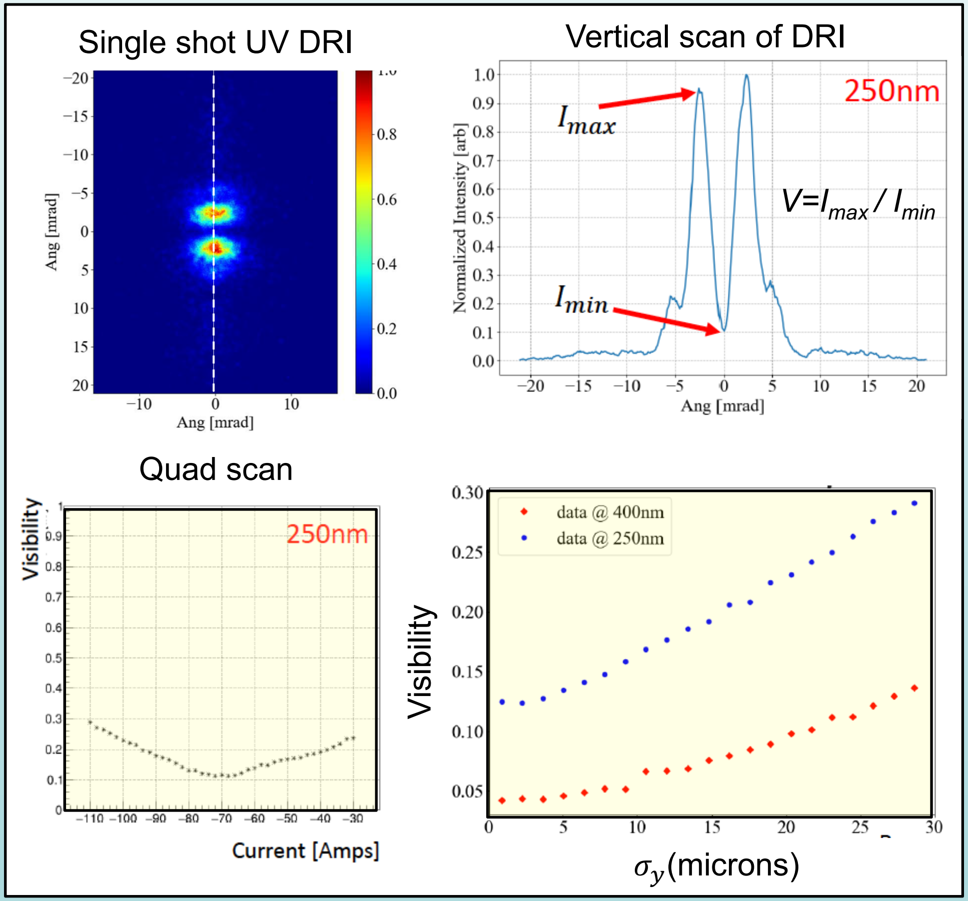
*A. Cianchi., et al. New Journal of Physics 16.11 (2014)

Beam Size DRI, Bergamaschi

UV DRI Experiments at KEK- ATF2*

Diffraction Radiation interference (DRI) from target slit (49.57 µm) and mask slit (100 µm) observed in visible (400nm) and UV (250nm) thanks to intensified cameras




Single shot UV DRI

Vertical scan of DRI

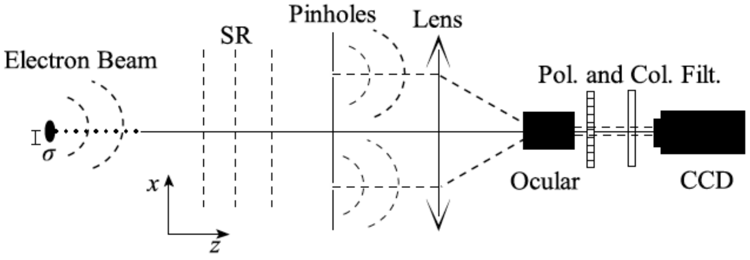
Quad scan

*M. Bergamaschi[1,2], A. Aryshev[3], P. Karataev[1], R. Kieffer[2], T. Lefevre[2], S. Mazzoni[2]

CLIC Workshop 2018, CERN, 23rd January 2018

Beam Shape Reconstruction using OSR interferometry*

OSRI beam size measurement along direction of pinholes**



$$I = I_0 \left\{ \frac{J_1\left(\frac{2\pi a x}{\lambda f}\right)}{\left(\frac{2\pi a x}{\lambda f}\right)} \right\}^2 \times \left\{ 1 + V \cos\left(\frac{2\pi D x}{\lambda f}\right) \right\}$$

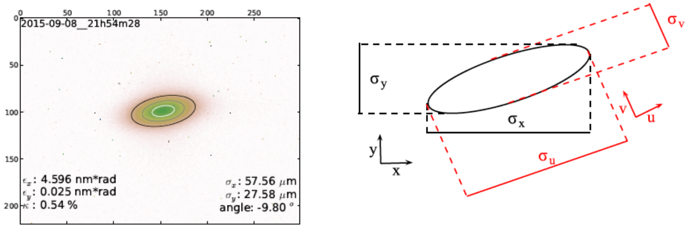
$$\boxed{\sigma_x = \frac{\lambda L}{\pi D} \sqrt{\frac{1}{2} \ln \frac{1}{V}}}$$

I_0: Intensity
a: Pinholes radius
λ: SR wavelength
f: Focal distance of the optical system
D: Pinholes distance
V: Visibility
L: Distance from the source

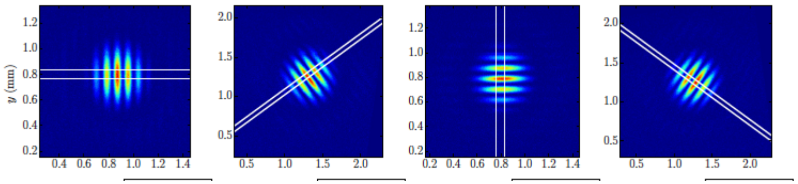
**T. Mitsuhashi, Proc. of IPAC15

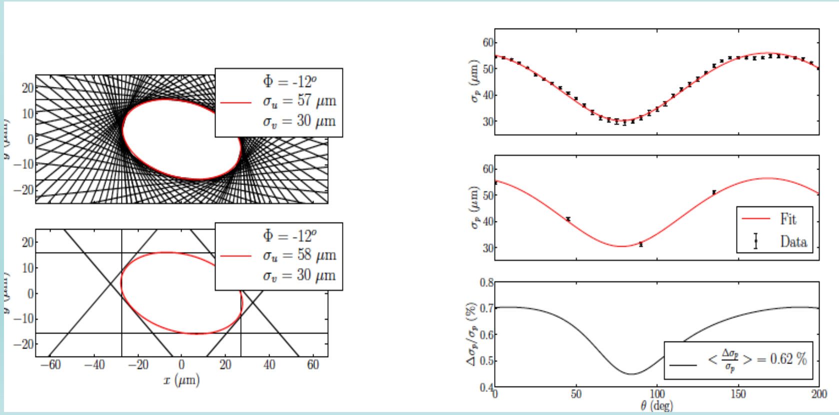
*L. Torino, Workshop on Emittance Measurements, ALBA, Jan. 2018

Rotating Double Slits: 2D Reconstruction of Beam Shape + Tilt

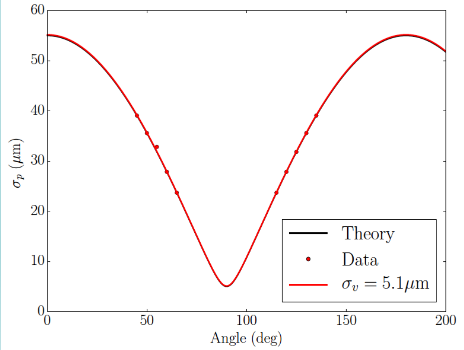


Rotation of pinholes allows measurement of projections of beam parallel and perpendicular to pinhole axis



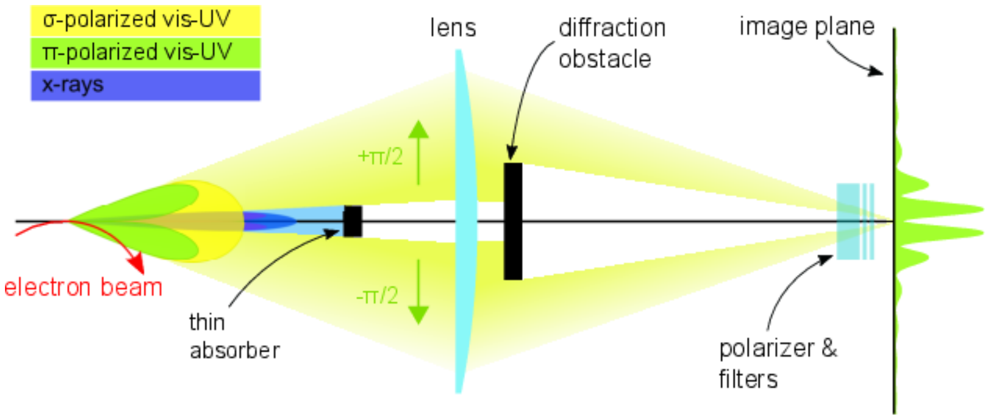


Theoretical fit produces good estimate of small beam sizes with fewer data points



Beam Size OSRI Andersson

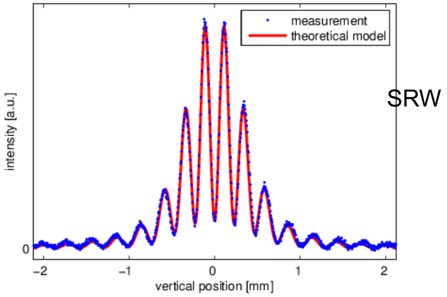
OSRI Use of Diffraction Obstacle to Resolve a Vertical Beam size < 3 μm*



This **diffractometer** method was implemented at the SLS (TIARA collaboration): $\sigma_y = 4.7 \pm 0.1$ μm**

now being used routinely at MAXIV

[**J. Breunlin et al, "Methods for measuring sub-pm rad vertical emittance at the Swiss Light Source", Nucl. Instrum. Meth. A 803, 55 (2015)]

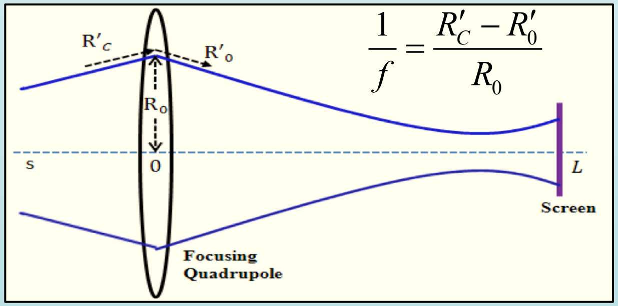


*A. Andersson, 60th ICFA Advanced Beam Dynamics Workshop, **FLS2018**, Shanghai March 5-9.

Novel Quad Scan Method to Determine the rms Emittance of a Space Charge Dominated Beam*

Method:

- Measure rms beam size (σ) and rms divergence (σ') at least two values of magnetic focusing strengths (1/f).
- Use envelop equation to compute cross-correlation term in the equation for the rms emittance: { e.g. $\varepsilon = \sqrt{<x^2><x'^2> - <xx'>^2}$ } in terms of (σ,σ')



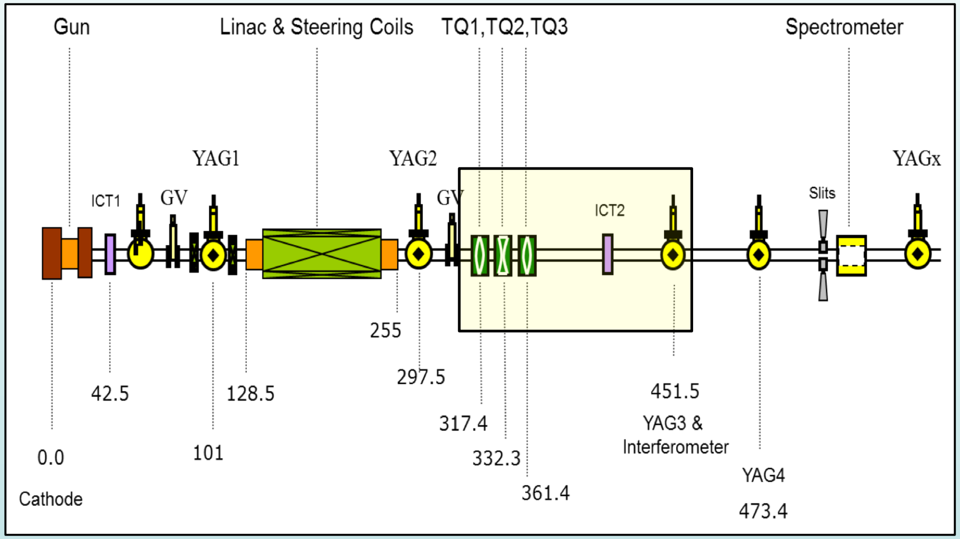
$$\frac{1}{f} = \frac{R'_C - R'_0}{R_0}$$

Advantages:

- Doesn't need a complete quadrupole or solenoid scan
- Multiple (σ,σ') data pairs increase statistical accuracy of measurement
- Works for space charge or emittance dominated beams

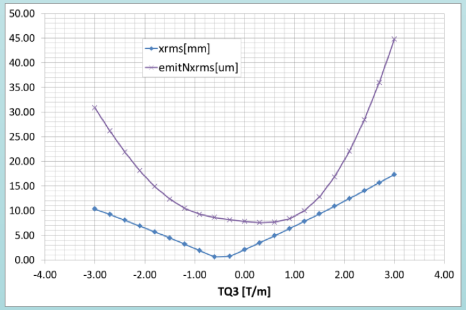
*K. Poorrezaie, R. Fiorito, et. al., PRAB 2013

Experiments/Simulations at ANL (AWA) to Validate New Method*



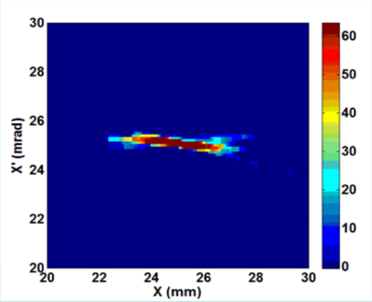
Results to date:

OPAL simulations



e_x = 8 - 9 micron

Tomography



e_x = 8.4 micron

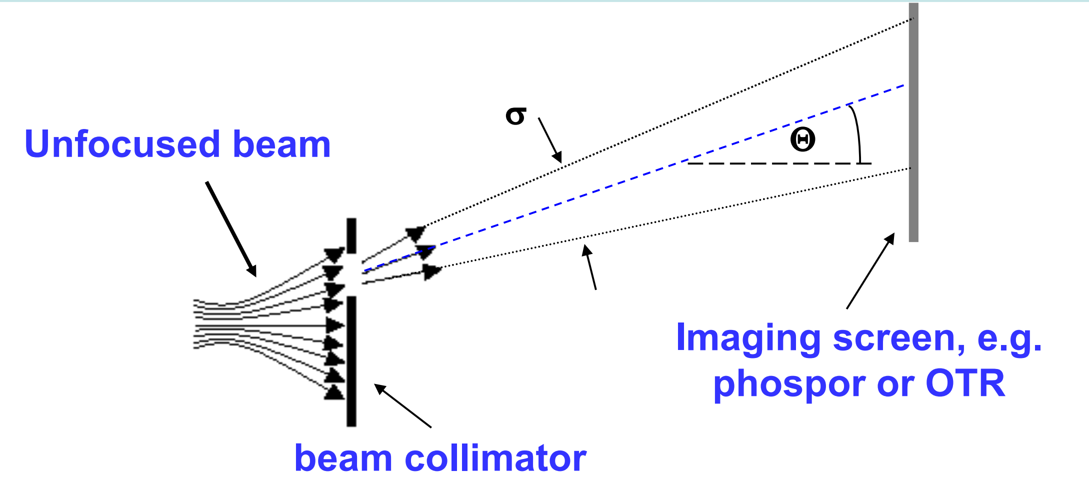
* R. Fiorito, et. al. Proc. IPAC17

Optical Phase Space Mapping: optical replica of the standard pepper pot collimator method

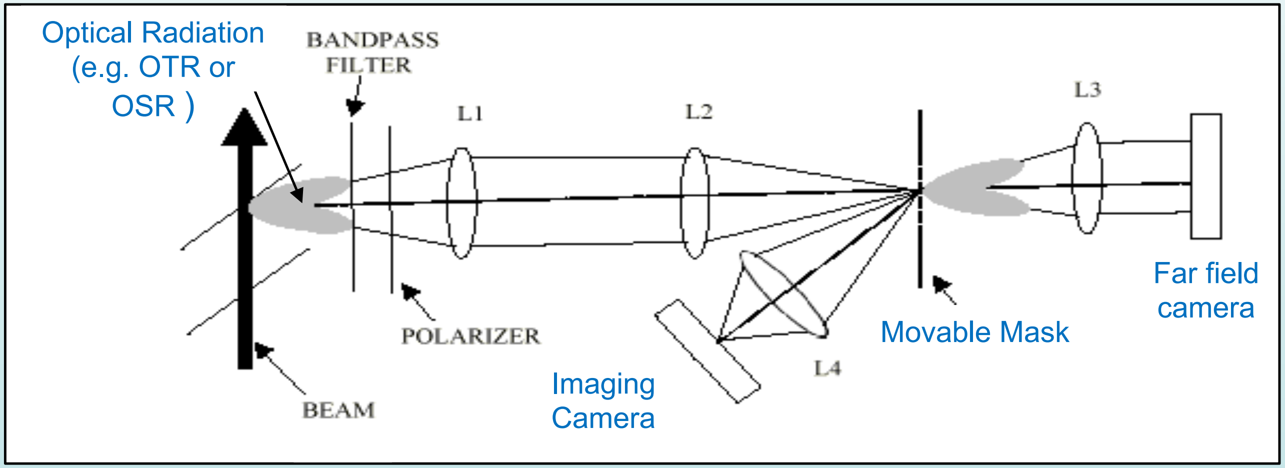
Advantages:

- No physical collimation of beam particles necessary
- Minimally invasive (OTR) to non invasive (ODR, OSR)
- Only optical considerations needed
- Zemax can be used to optimize design

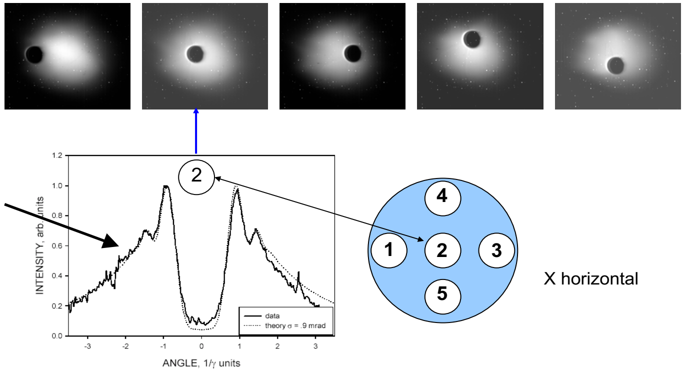
Standard PSM



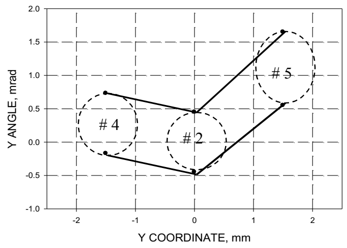
Optical phase space mapping demonstrated with a fixed and movable pinhole masks*



OTRI angular distrib. pattern gives local divergence & trajectory angle

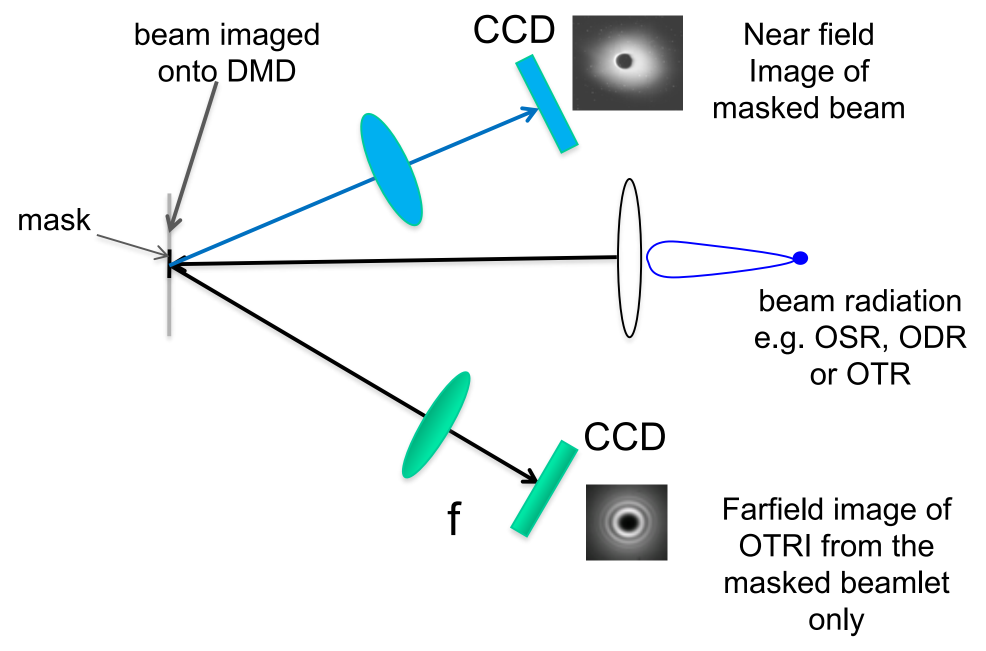


Vertical y , y' Optical Phase Space Map from 1 mm Pinhole Scan



* G. Le Sage, R. Fiorito, et. al., PRAB (1999); R. Fiorito, et. AIP Conf. Proc. 648, (2002);

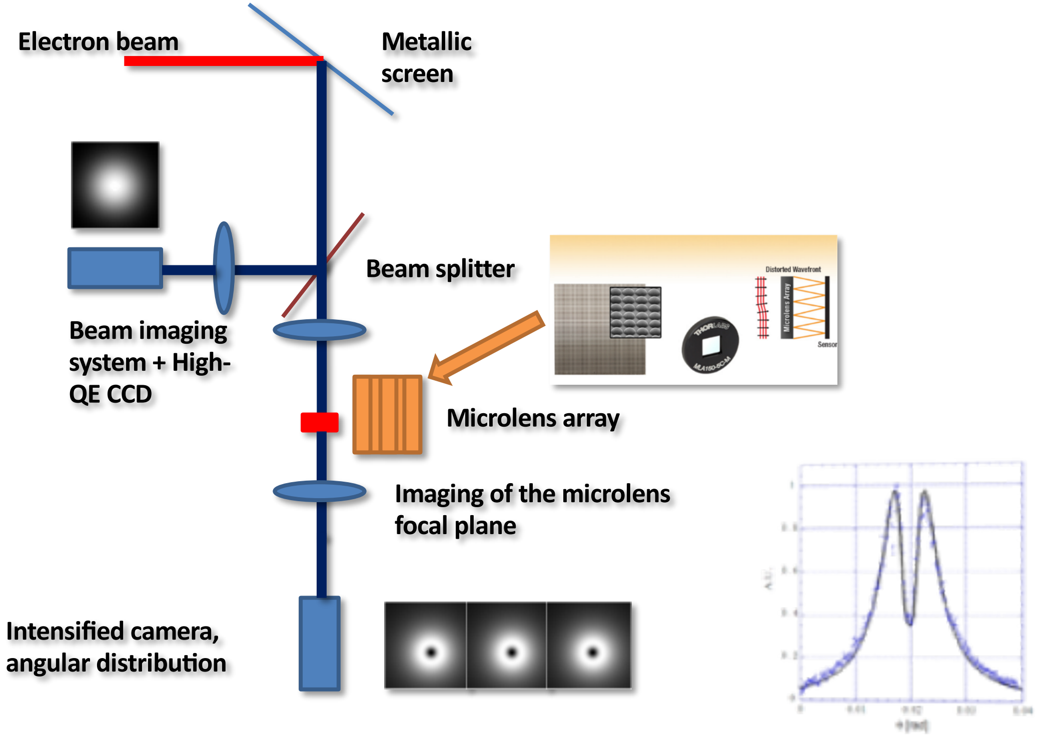
Current Work: Optical Phase Space Mapping with a Programmable mask using DMD



Status and Plans

- implement Zemax to model DMD based OPSM system
- study effects of mask size, shape on resolution of the imaging system (PSF);
- build and test performance of OPSM at a real accelerator using OTR or OSR.

OPSM Emittance Measurement Using a Micro-lens Array *



Electron beam

Metallic screen

Beam splitter

Beam imaging system + High-QE CCD

Microlens array

Imaging of the microlens focal plane

Intensified camera, angular distribution

Cianchi, A., et al. "Transverse emittance diagnostics for high brightness electron beams." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 865 (2017): 63-66.

*A. Cianchi, Workshop on Emittance Measurements, ALBA, Jan. 2018

Novel Bunch Length Monitor Using Angular/Spatial Distributions of Coherent Diffraction Radiation*

- Spectra of CTR and CDR typically used as a measure of bunch length
- Angular and Spatial Distributions of CDR also sensitive to bunch length

$$\frac{dI^{CDR}_{bunch}}{d\Omega} \approx N_e^2 \int_{\Delta\omega} \frac{d^2 I_e^{DR}}{d\omega\, d\Omega} S_z(\sigma_z,\omega)\, d\omega$$

Spectral-Angular Distribution of DR from a single electron

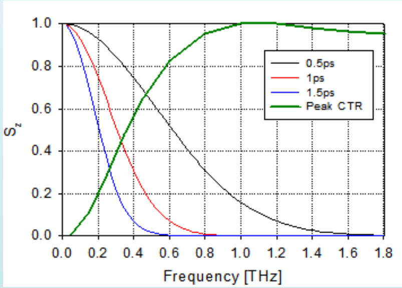
Longitudinal form factor

* A. Shkvarunets and R. Fiorito, PRSTAB, (2008).

Bunch Length: CDR SPF

Advantages of CDR Imaging Bunch Length Monitor:

- No wide band spectral measurements or Fourier transformations necessary
- Single Shot
- Non invasive
- Simple to experimentally implement



Procedure:

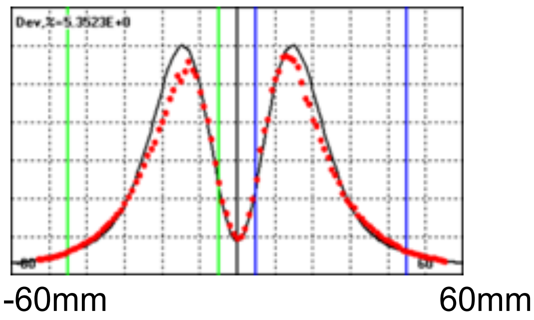
- Choose the size and shape of the radiator so that CDR intensity is sensitive to the range of bunch sizes under investigation (*1/Δω ~ Δτ*)
- Use theory/ simulation code to predict the frequency integrated AD and SPF
- Use appropriate imaging optics and detector to view AD and SPF e.g. for pico-fsec bunches use GHz-THz transmissive optics and pyroelectric sensor
- Fit measured images to theory to measure rms bunch length

Angular Distribution Experiment Confirmation

Scans of AD of CTR and CDR from 100 MeV RF Injector Linac (PSI- SLS)

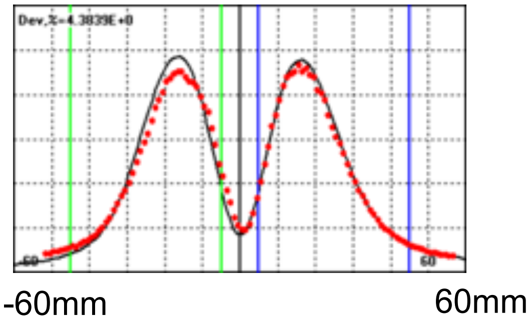
CTR from plate

Pbu-0



CDR from Slit

Pbu-0



Method	Bunch Compressor Tune	T(ps) single Gaussian fit
AD CDR	PBU-0	0.8
E-O technique	PBU-0	0.75
AD CDR	PBU+3	1.0
E-O technique	PBU+3	1.0

R. Fiorito, et.al. Proc. of DIPAC 2007

CDR Spatial Distribution Measurements

Advantages:

1- Less interference from upstream sources, especially at high energy where $L \approx \gamma^2 \lambda$ large (e.g. 40 km for 1 THz at 20 GeV)

2- More intense than angular distribution (more photons per pixel)

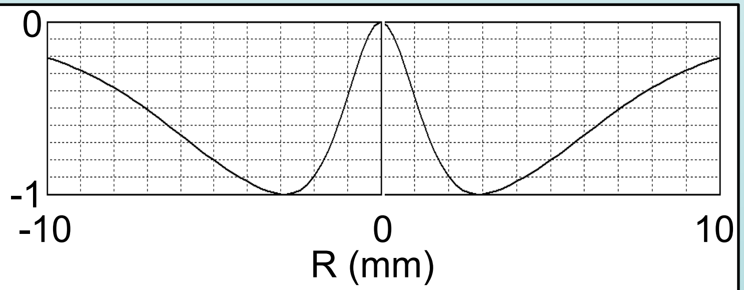
3- Easier to focus and setup optics

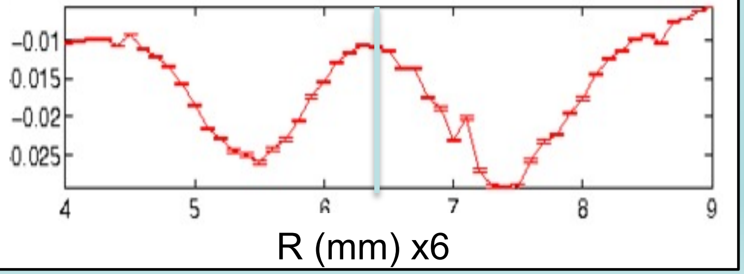
Results: SLAC-FACET (April 2016)

Theoretical (inverted) horizontal scan of CDR from FACET (20 GeV)

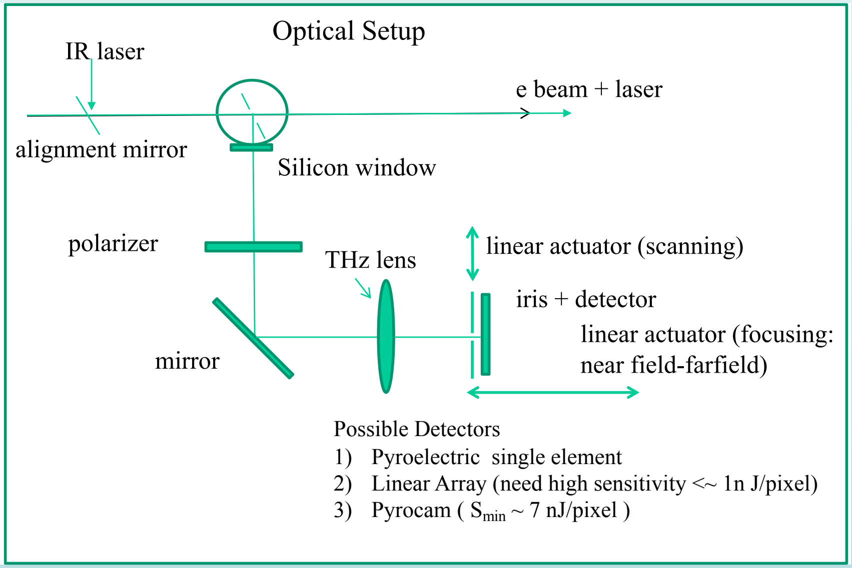
cdT = 25 micron
Q = 0.6 nC
$\sigma = 150\ microns$

Peak to peak separation of experimental scan is almost 2 X theory => focusing error→ Need follow up experiment to check



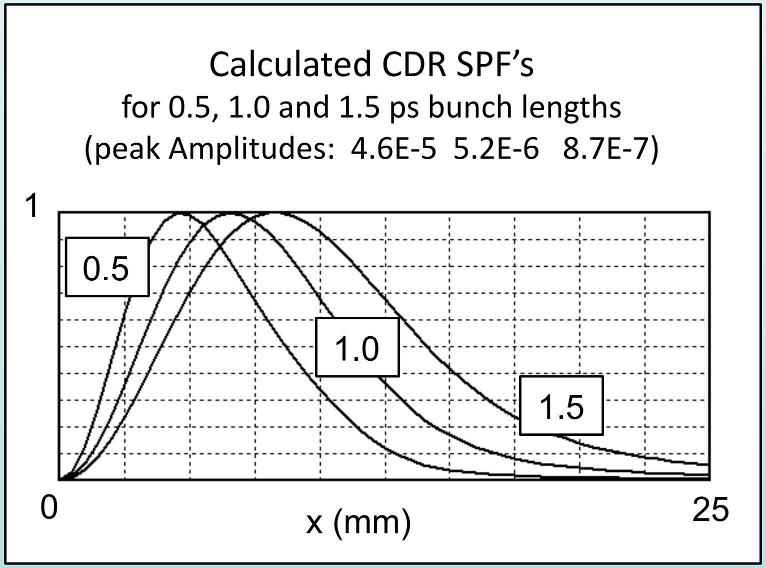


CDR Imaging Experiment in Preparation at PSI's SwissFEL (330 MeV)*



Possible Detectors

1) Pyroelectric single element
2) Linear Array (need high sensitivity <~ 1n J/pixel)
3) Pyrocam (S_{min} ~ 7 nJ/pixel)



*See: J. Wolfenden, et. al., paper **WEPAF035** for more details

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**** Information on EU sponsored PhD Training Networks and Fellowships***
see: University of Liverpool - Exhibit Hall – Table 400