Characterization of the optical performance of high resolution beam imaging systems

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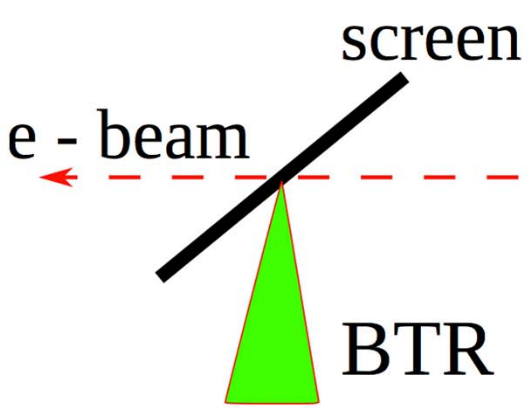
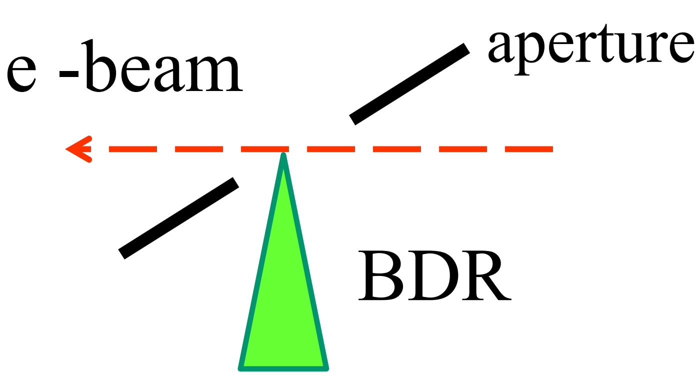
Goal: use the shape the PSF's of OTR and ODR, to perform very high resolution (submicron) beam imaging



- Transition radiation (TR) appears when a charged particle crosses a boundary between two media with different dielectric constants.
- The resolution is determined by the source dimensions induced by a single particle plus distortion caused by the optical system (diffraction of OTR tails)

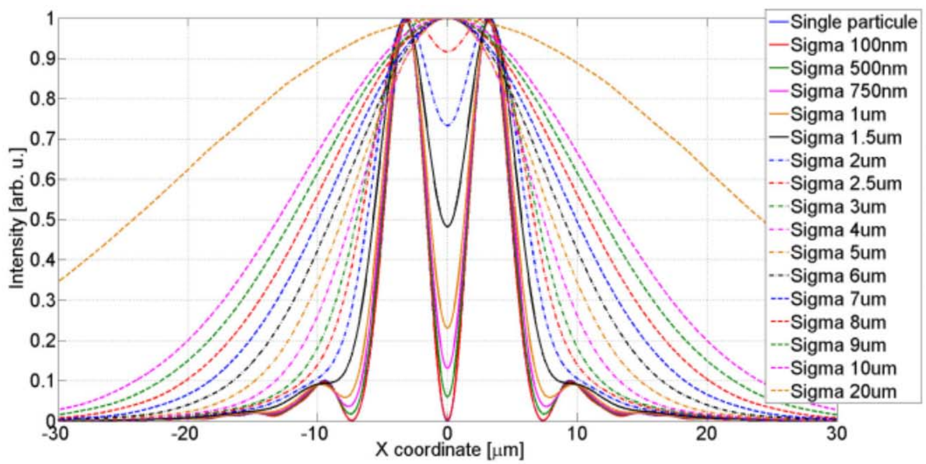


- Diffraction Radiation (DR) appears as particle passes through an aperture
- Resolution similarly limited by shape of PSF and distortion due to optics

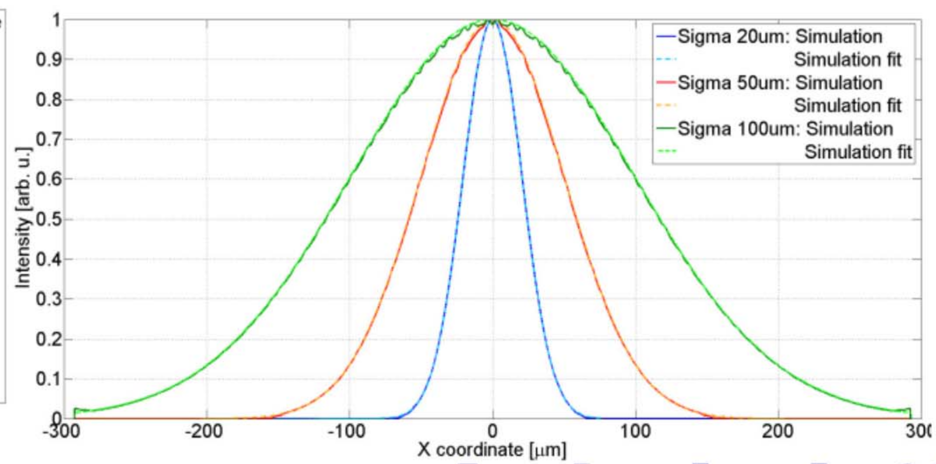
OTR Beam Imaging

- The OTR PSF is a source generated by a single electron projected by an optical system onto a camera;
- The measured image of a beam is a convolution of the inherent single particle OTR PSF and **the PSF of the optics** used to do the imaging with the beam distribution

OTR PSF imaging



Classical imaging



State of the Art:

1- Karataev et. al. have used low dynamic range imaging + Zemax simulations to propagate OTR field generated by a single electron point source to image plane of an optical imaging system (i.e. uses theoretical model of OTR source field)

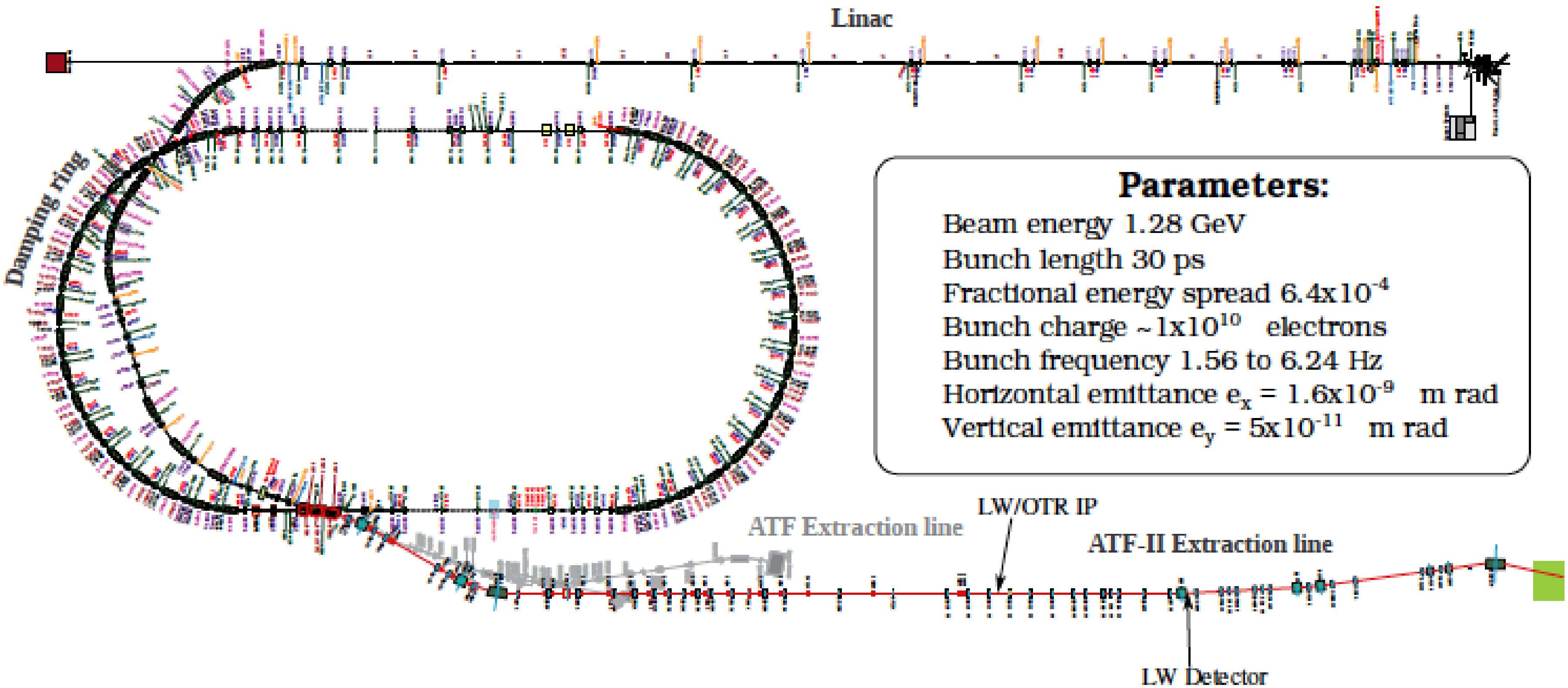
2- They then deconvolve the OTR PSF from the measured (1 micron KEK electron beam) to infer the actual beam size with submicron resolution (limited by the optics effects which are modeled and incorporated into Zemax and the dynamic range of the imaging method (presently about 1000).

Next Step:

a) separately measure the optical system's PSF so we can deconvolve it from the data to begin with and compare with Zemax.

b) Use high dynamic range imaging (>10^5) attainable using a digital masking technique we have developed) to improve the accuracy and resolution of the beam size measurement.

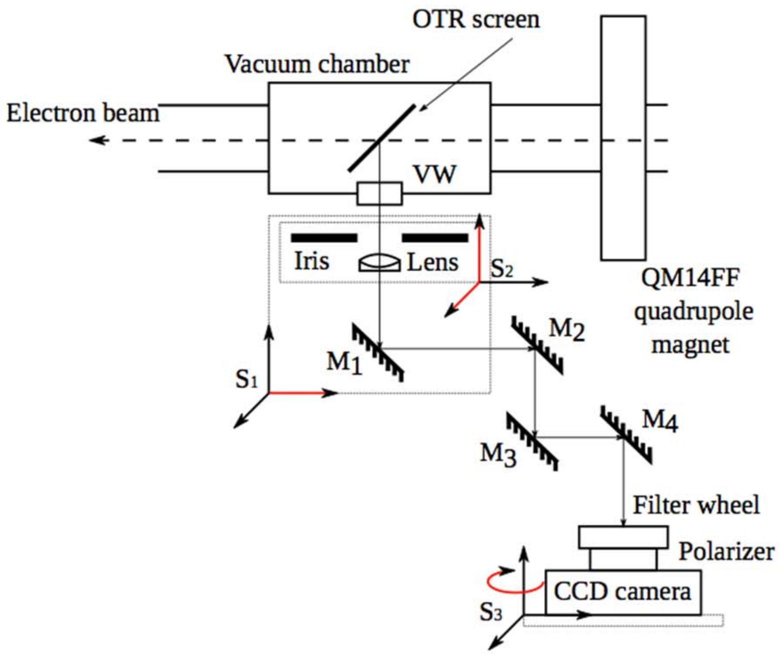
KEK: Accelerator Test Facility

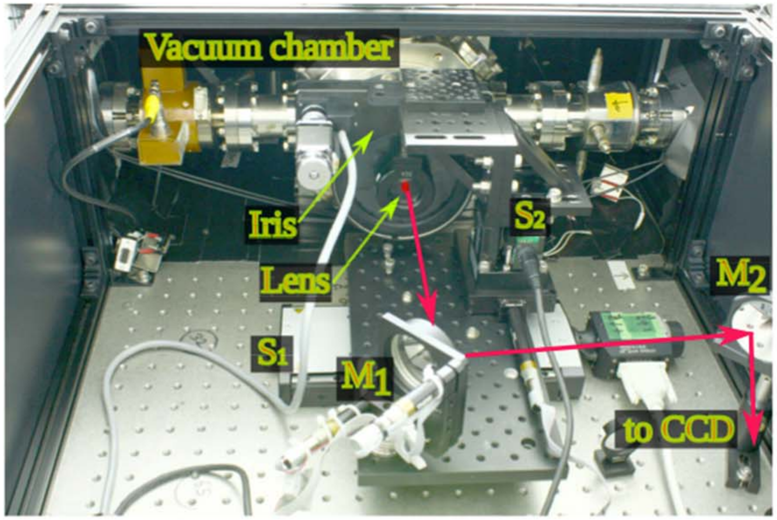


G. White, et la., ATF Collaboration, Physical Review Letters 112, 034802 (2014)

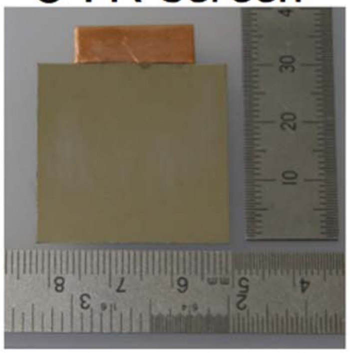
Vertical emittance	12 pm
Beam size in the OTR (design)	1.0 μm
Beam size in the OTR (meas.)	0.75 μm

Experimental Setup





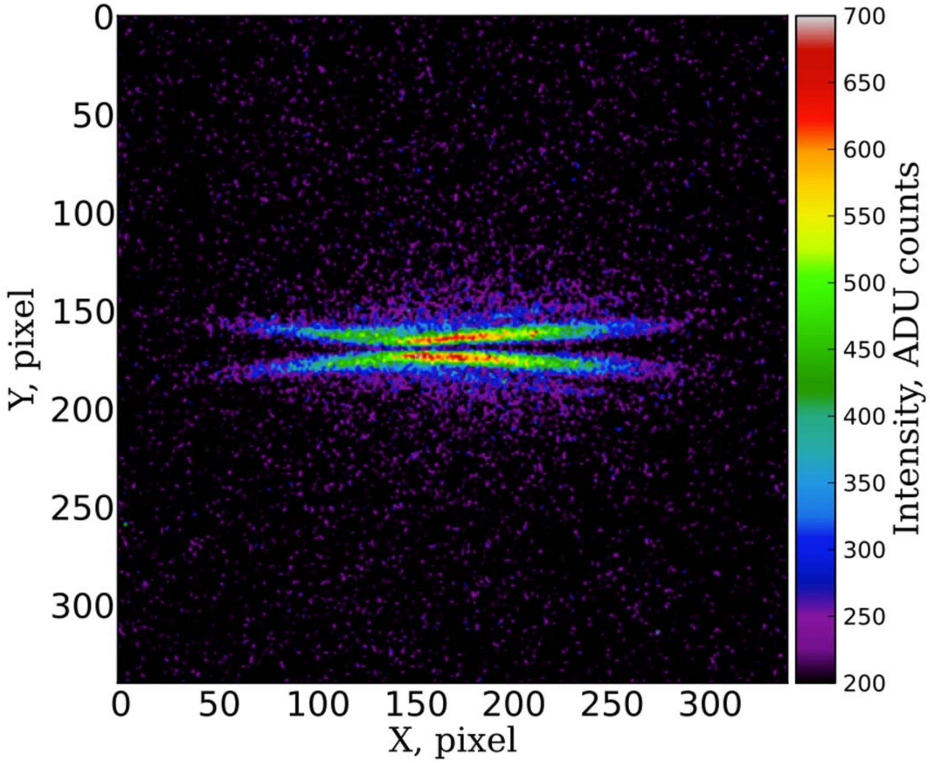
OTR screen



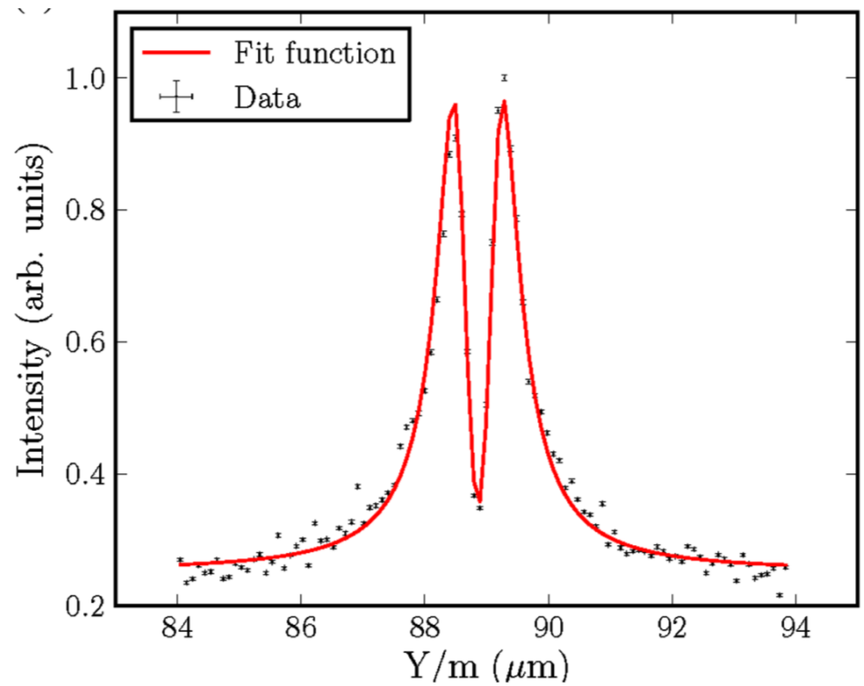
0.3×30×30 mm aluminized silicon

- Lens - "CVI Laser Optics" cemented achromat, f=120mm, ø=30mm
- CCD Camera - SBIG-ST8300M with 5.4 μm pixel size, 3352×2532 pixel array and ~50% quantum efficiency

Example of OTR image measured with linear polarizer and 550±20 nm band pass filter*



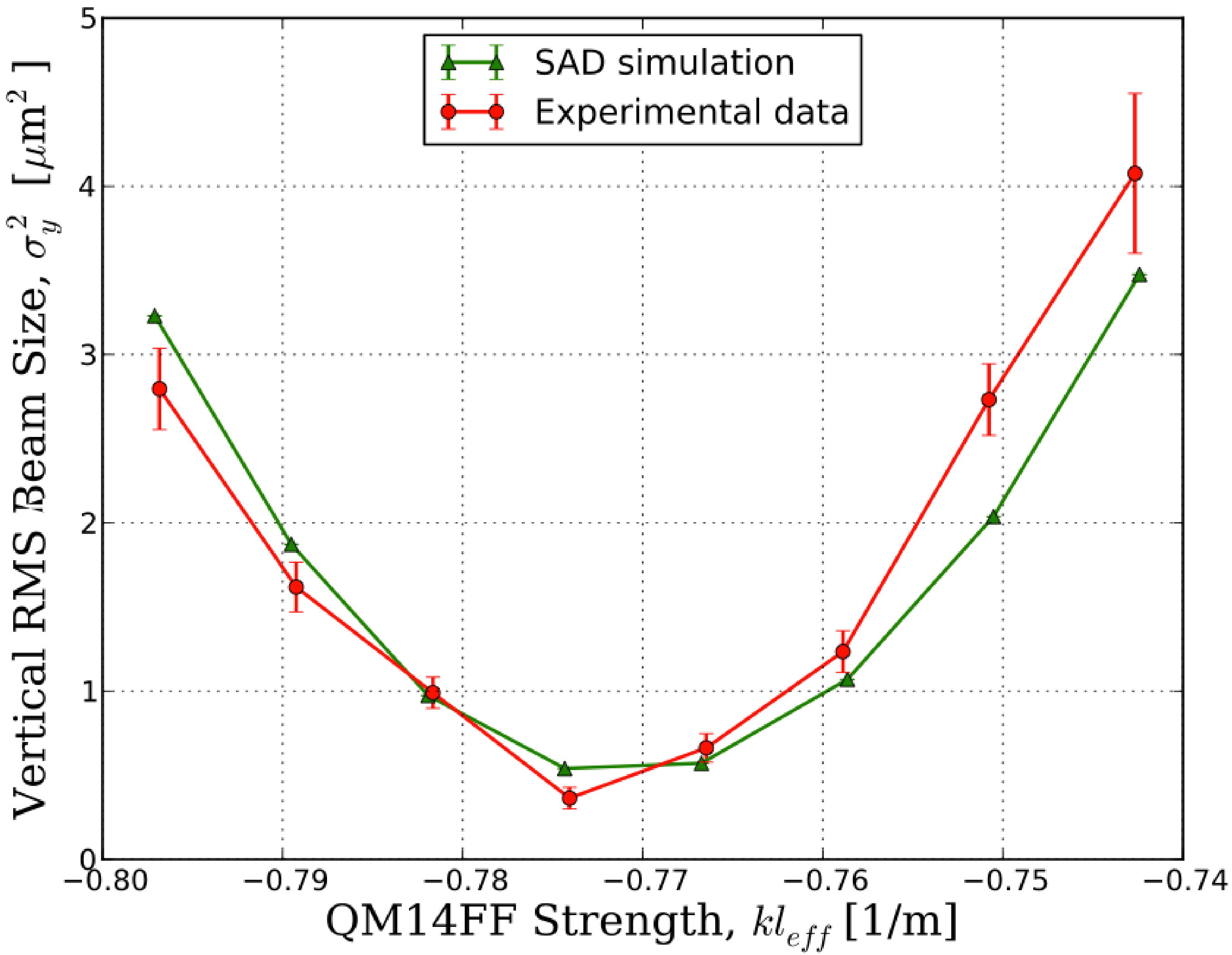
Vertical Line Scan



*** P. Karataev, et al., Physical Review Letters 107, 174801 (2011).**

Comparison of the OTR and Laser-wire measurements

Minimum measured beam size was: $0.754 \pm 0.034\ \mu m$

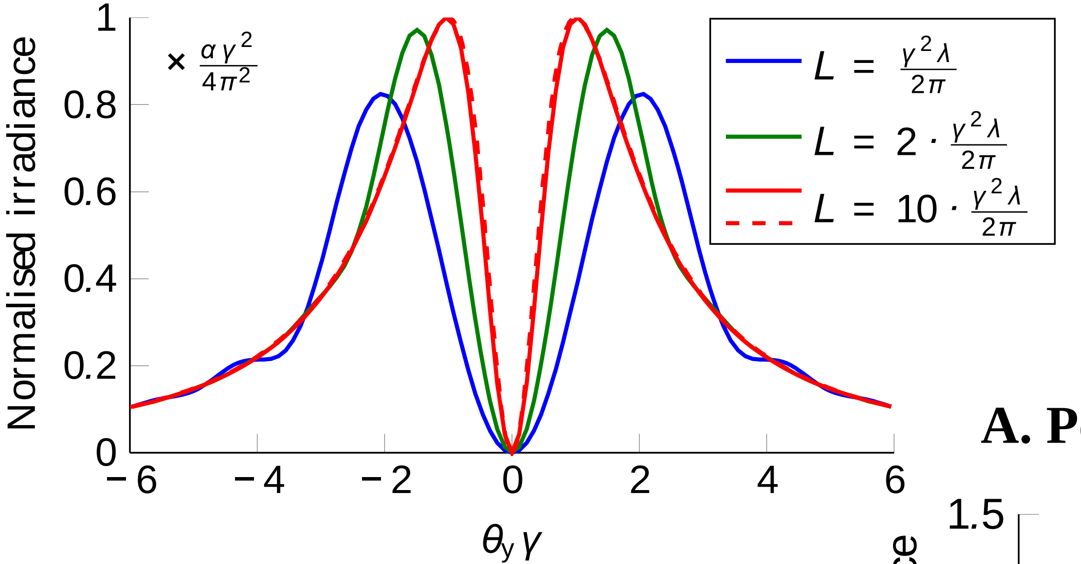


ZEMAX

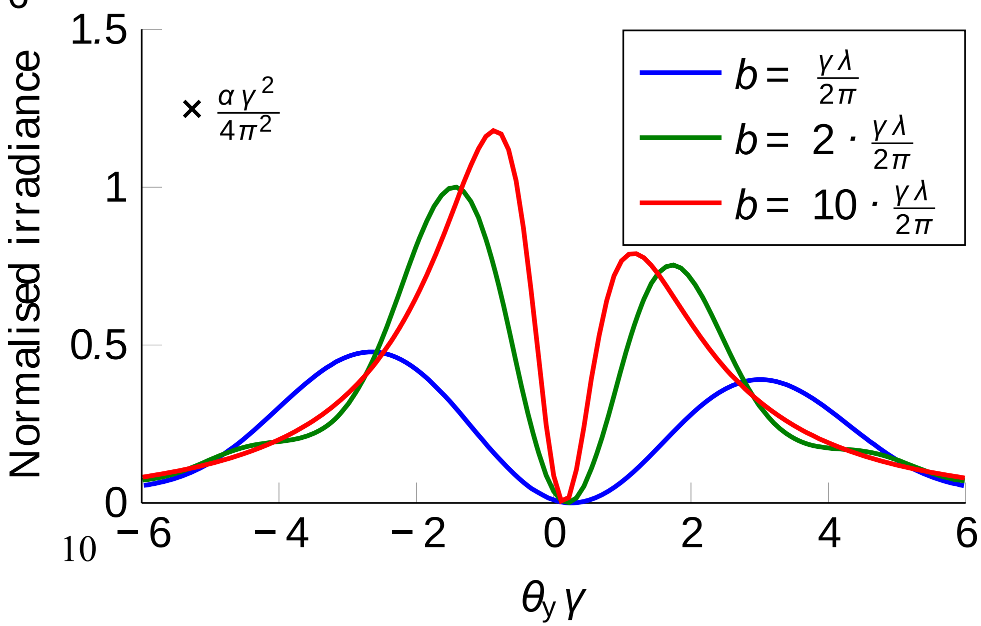
- **Readily available commercial optical design software: standard tool to conceptualize, design, optimize, analyze and tolerance optical systems;**
- **Physical Optics Propagation (POP): ZEMAX mode that propagates the wavefront surface by surface;**
- **In POP the wavefront is modeled with an array (the resolution defines the wavelength)**
- **The initial field distributions of source need to be known: these are calculated using Maxwell's Equations for a relativistic charge in free space;**
- **The array propagates between the surfaces -> a transfer function is computed at each surface;**
- **If the initial sources is known, simulation of any source is possible, i.e. TR, DR, ChR, SR, etc.**

Verification of the code

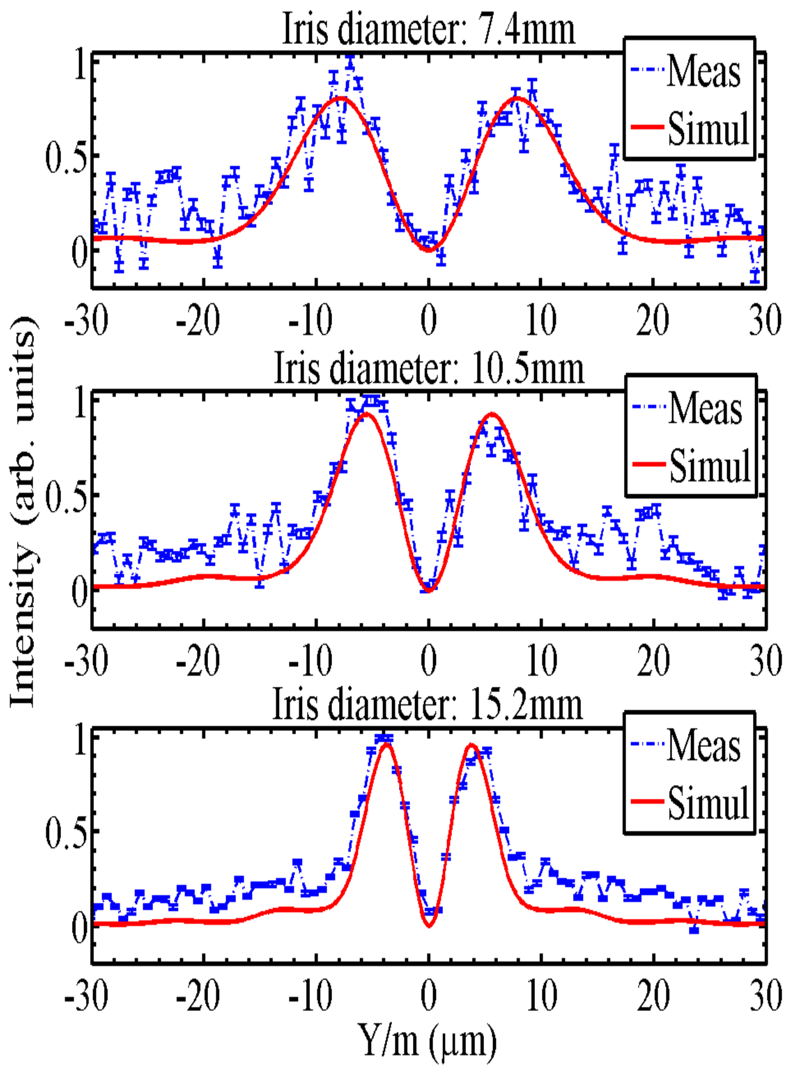
TR in the pre-wave zone
V. Verzilov, Physics Letters A 273 (2000) 135



TR from a tilted target
A. Potylitsyn, NIM B 145 (1998) 169



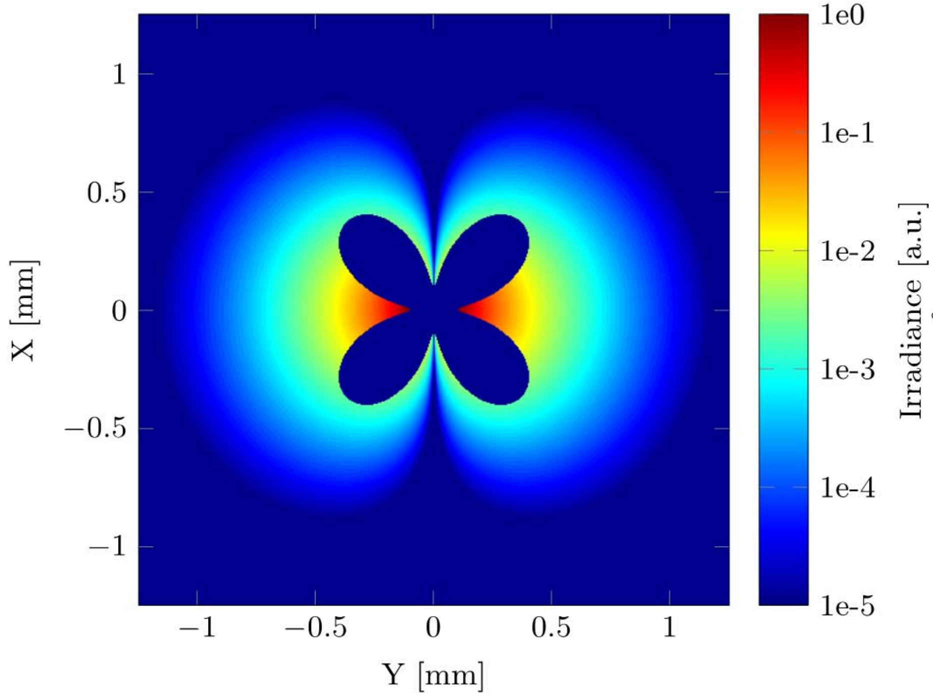
Comparison of the experimental results with ZEMAX simulations



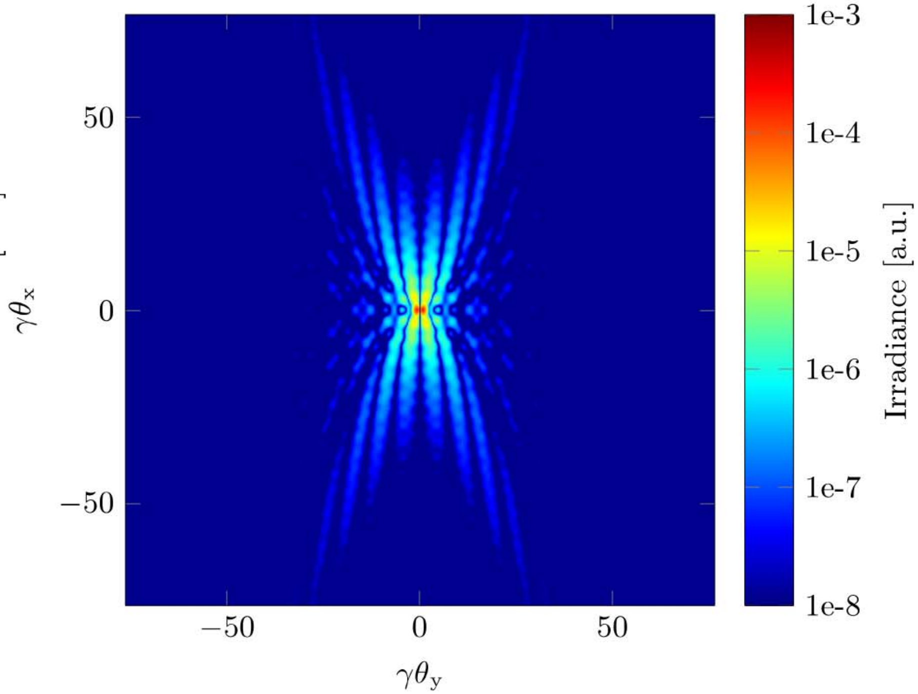
Investigation of the diffraction effect due to Iris

ZEMAX: capable of predicting distributions of ODR from arbitrary shaped aperture

Source Distribution



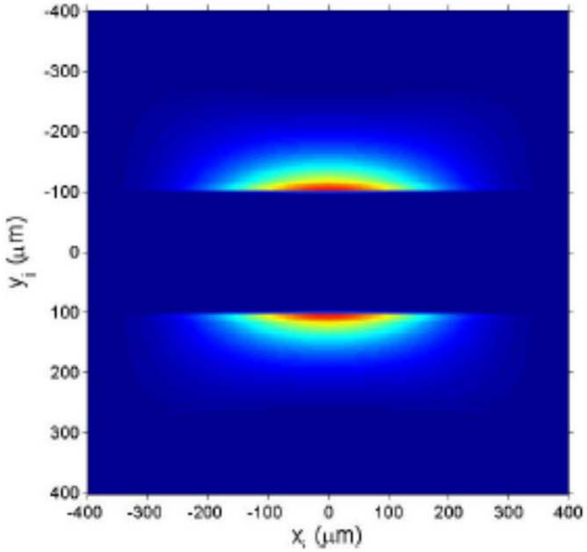
Angular distribution



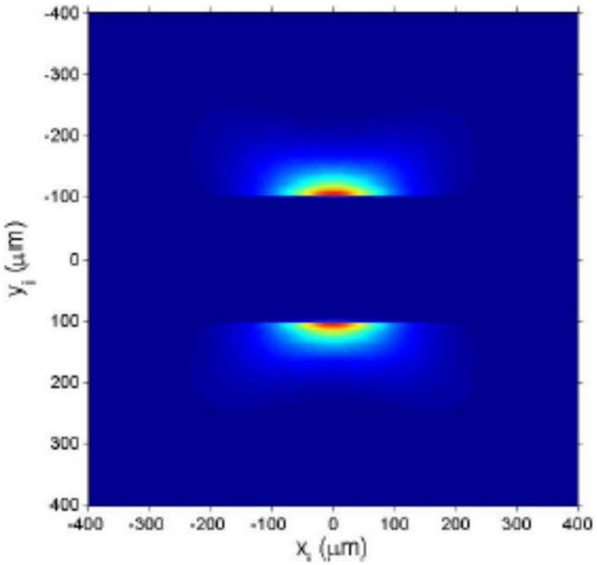
Theory: Restoration of Beam Profile from Source Image of ODR*

($\gamma = 2500$; $\lambda = 0.5$m; $\theta = 0.1$)

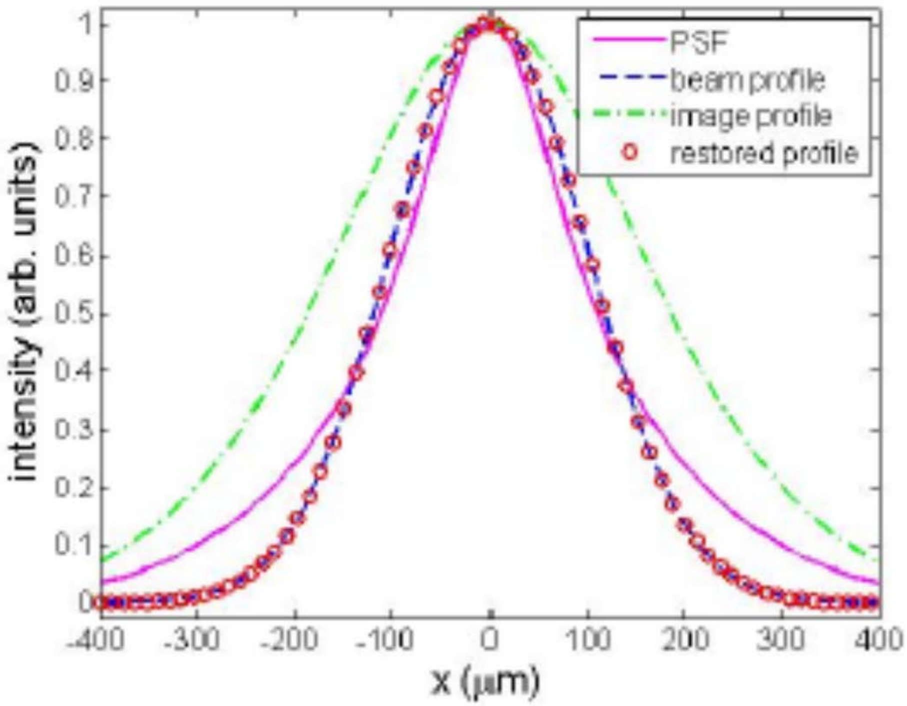
ODR Distribution from Gaussian Beam



PSF



Vertical Profiles



*D.Xiang, et. al. PRSTAB 2007

Plans: High Dynamic Range PSF Measurements

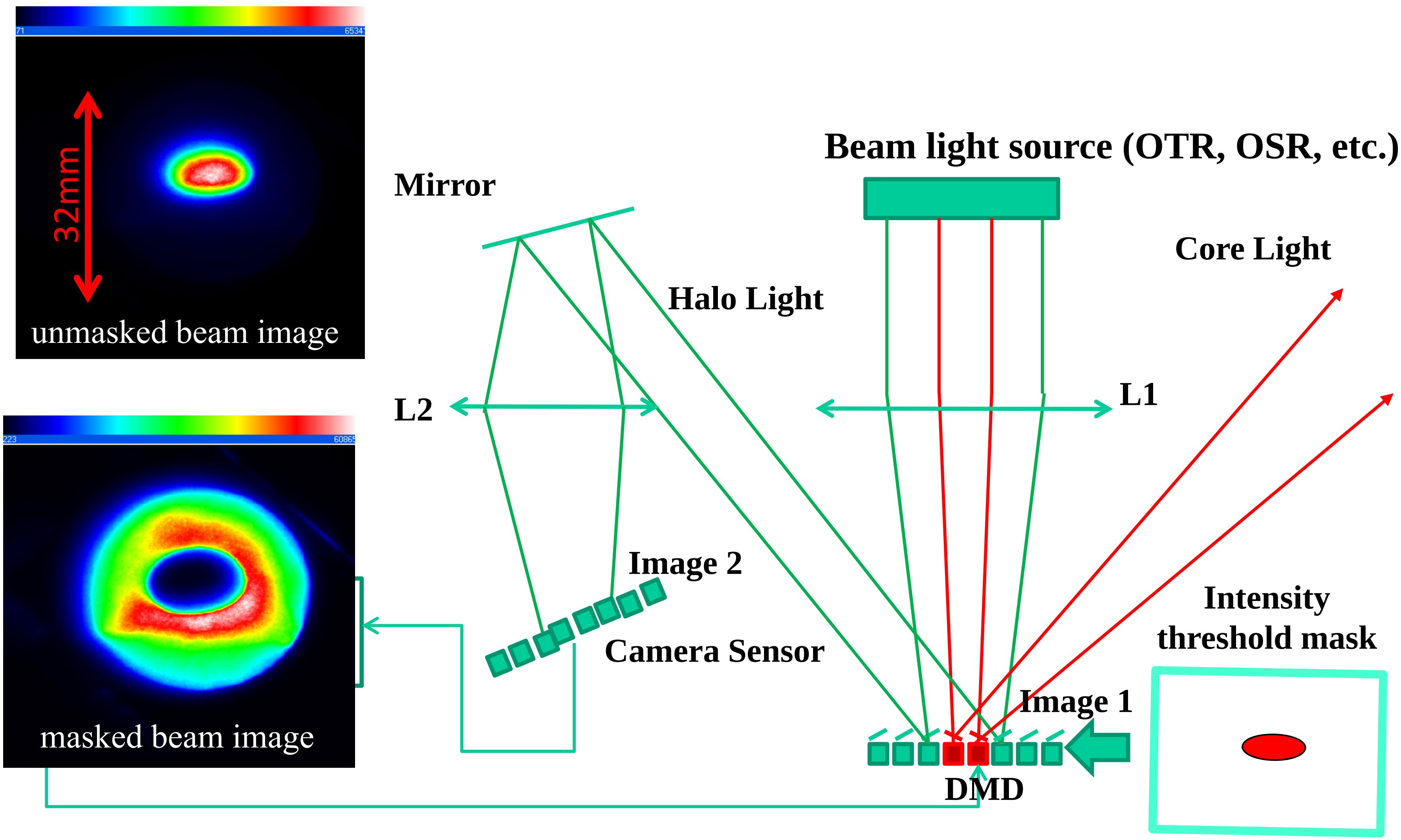
Proposed steps

1) HDR measurment of PSF of Optical system using lab Point Source

2) HDR measurment of PSF of OTR and ODR (with Compare measurements of PSFs to theory and Zemax

GOAL: Deconvolve PSFs from measured OTR, ODR source distribution to obtain beam profile with higher accuracy

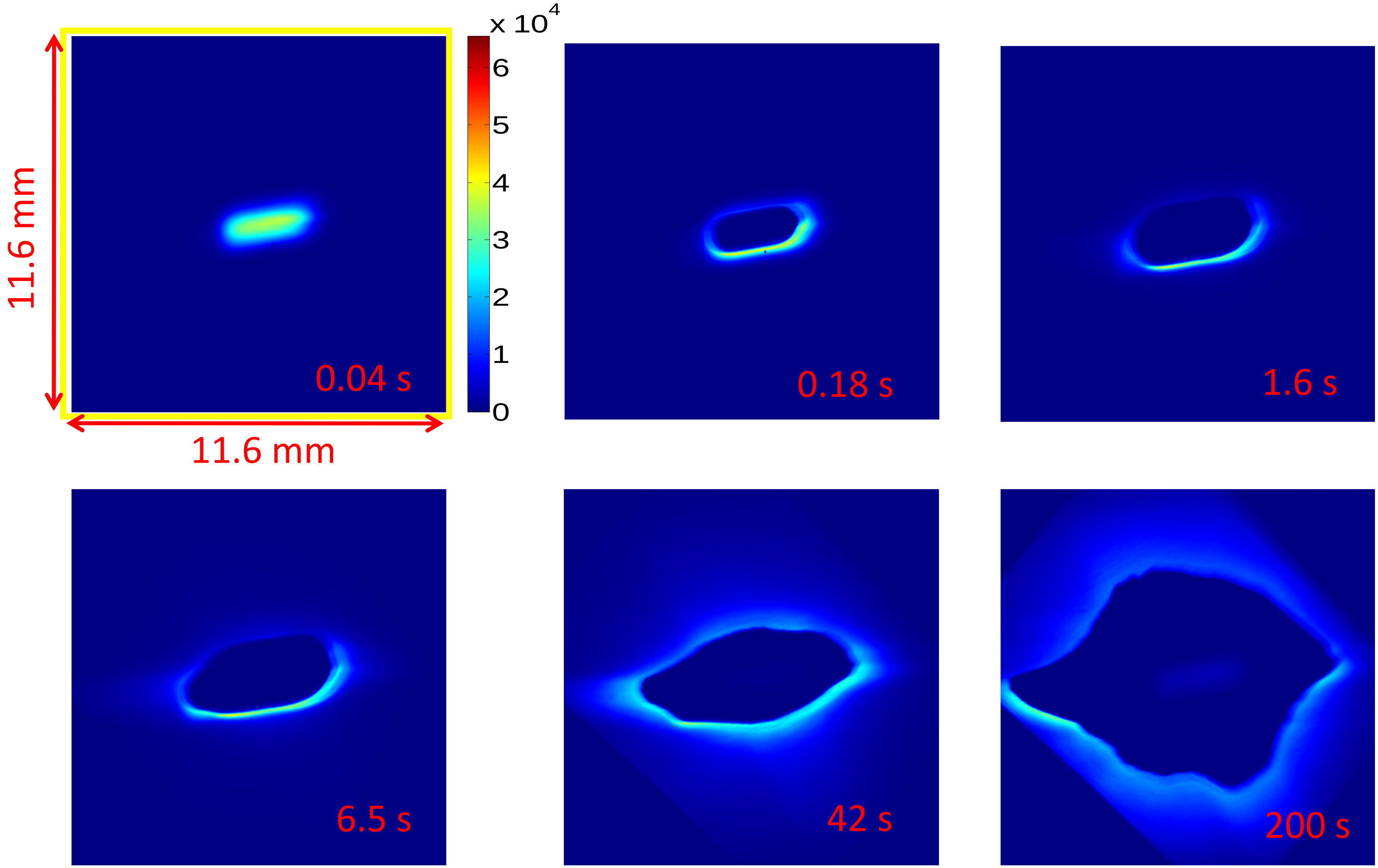
DMD Based HDR Beam Imaging*



*H. Zhang, et. al. Phys. Rev. ST Accel. and Beams (2012)

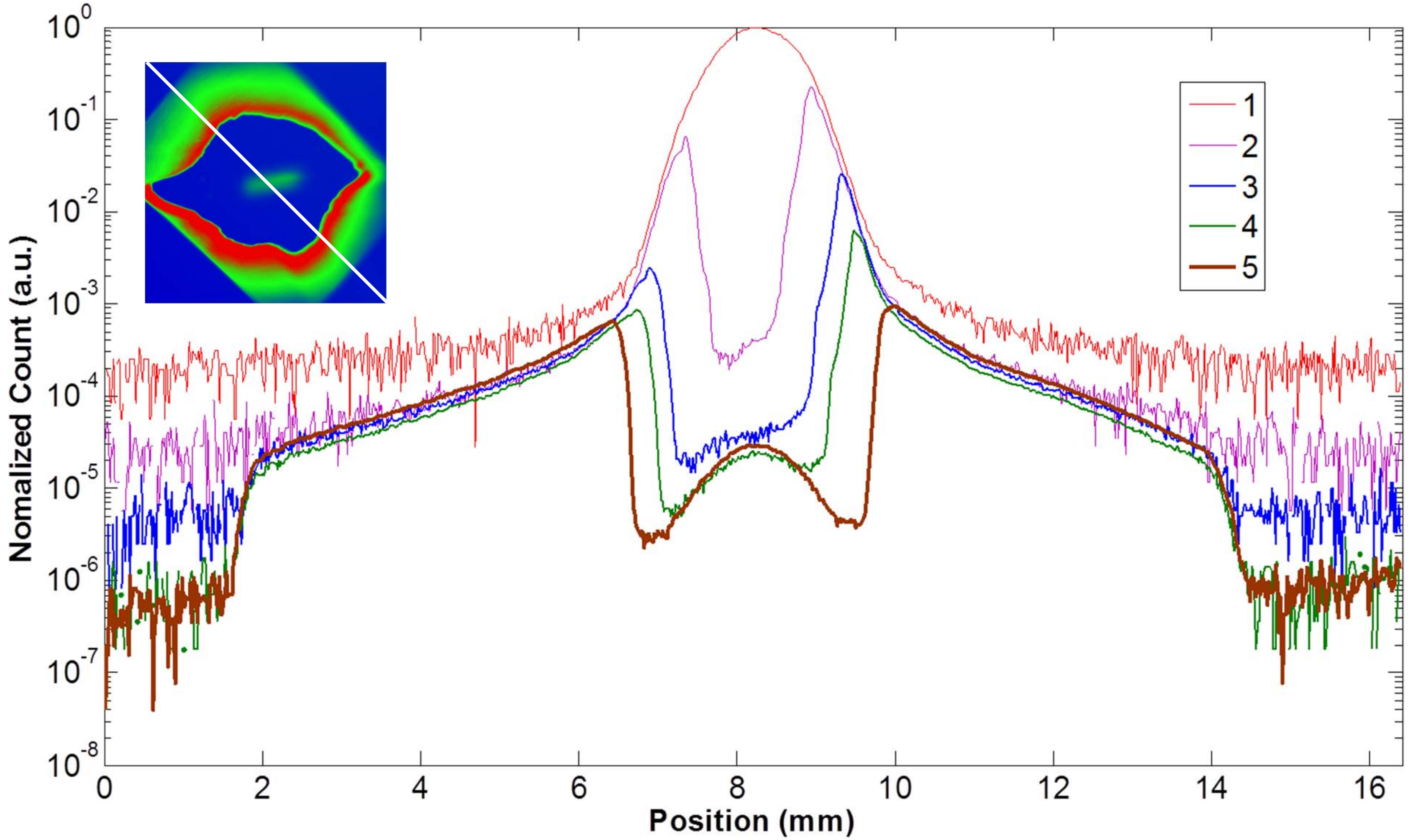
OSR Beam Halo Imaging of JLAB ERL using DMD threshold mask*

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



*R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

Measurement of Dynamic Range of imaging system

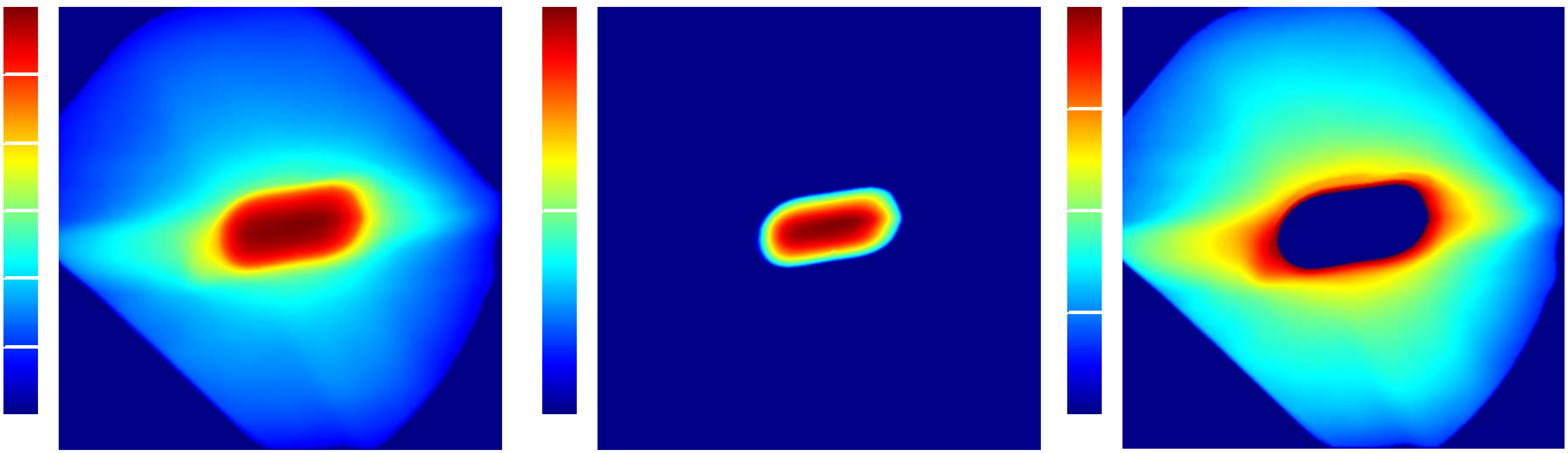


R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

Reconstructed intensity distribution $I(x,y)$ and calculated total radiant energy E_{Total}

Assume $I(x,y) \sim J_{beam}(x,y)$ => $E_{total} \sim Q_{beam}$

$(1-10^{-6})\, I_{max}$ | $(1-10^{-2})\, I_{max}$ | $(10^{-2}-10^{-6})\, I_{max}$



$$E_{Total} \equiv \int_S I(x,y)\,dxdy$$

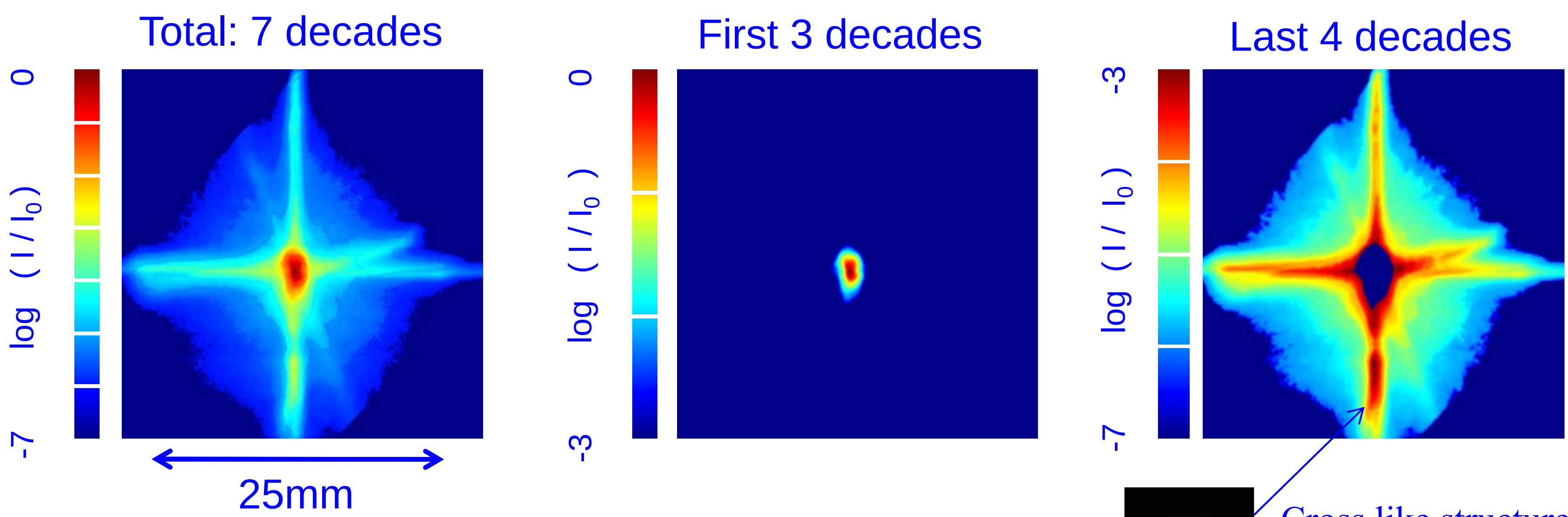
$$E \sim 0.99\, E_{Total}$$

$$E \sim 0.01\, E_{Total}$$

R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

High Dynamic Range OSR Image of the SLAC/SPEAR3 stored beam dominated by PSF of Optical Beamline*

(I_b = 349 mA; beam size: 150 x 60 microns)



Cross like structures due to diffraction of OSR from rectangular masks in optical diagnostic beam line

*R. Fiorito et. al. Proc. of BIW12; H. Zhang, et. al. Proc. of IPAC 12

First Steps of Optics Characterization

1) develop laboratory method to characterize and improve (minimize) the PSF due to optical effects using a laser generated point source

- Diffraction
- Chromatic Aberration
- Spherical Aberration
- Light Scattering

2) compare measured optical PSF to Zemax simulation incorporating characteristics of the laser point source and candidate optics designs for submicron beam imaging.

Optics Characterization

Point Source Creation

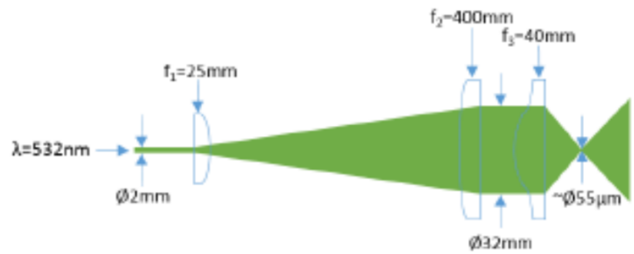


Figure 1: Optical system used to create the point source.

The optical system used to create the point source consists of a 16x magnification telescope and an aspheric focusing lens. The M^2 of the laser was measured at (1.28±0.06), which we used at a later stage for reference.

A profile scan was performed by tracking a knife edge through the beam. The intensity was measured using a lens to collect the light onto a CCD. By taking these measurements at various points throughout the beam waist, the size and position of the beam waist minimum could be determined.

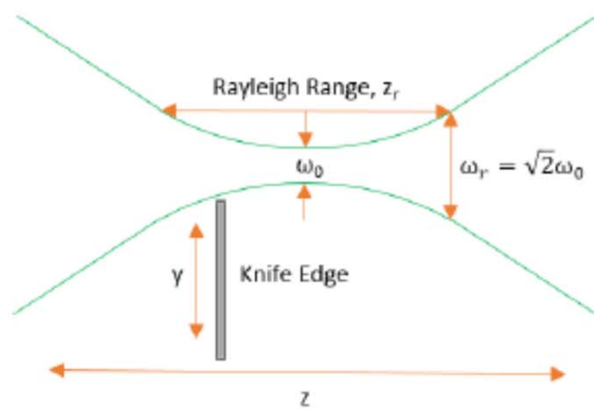


Figure 2: A demonstration of how the knife edge scan was performed.

Summary and Experimental Plans

a- **Create a laser point source** using optics developed for creating laser wires (r~1 micron) (poster by J. Wolfenden).

b- **Measure the PSF of candidate optics imaging systems for ATF/KEK with HDR**, e.g. optics that may be placed entirely outside the ATF vacuum chamber, as well as an optical system incorporating a digital micromirror array for high dynamic range imaging.

2- **Use Zemax to simulate the PSF** of each of the above optical setups in order to compare with data, understand and optimize the performance of these optical systems.

3- M**easure point like* and larger beam sizes using OTR and ODR** at KEK's ATF accelerator.

*(i.e. the ATF electron beam size can be focused to <~1 micron, which is less than the FWHM of the theoretically predicted OTR and ODR PSFs)

4 - **Compare the characteristics (visibility) of the measured, theoretical and simulated PSF of OTR and ODR** to optimize the optics

5- **Deconvolve the PSFs from measurements** of small beams to push the resolution limit to below 100 nm.