Advanced Optical Diagnostics

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Accelerator Diagnostics Based on CPB Radiations

Emphasis: High Power Beams (for light sources or colliders) for tune up (mildly intercepting) and full operation (non intercepting)

Goal: Fast (near real time), simple, robust monitors for injector and accelerators

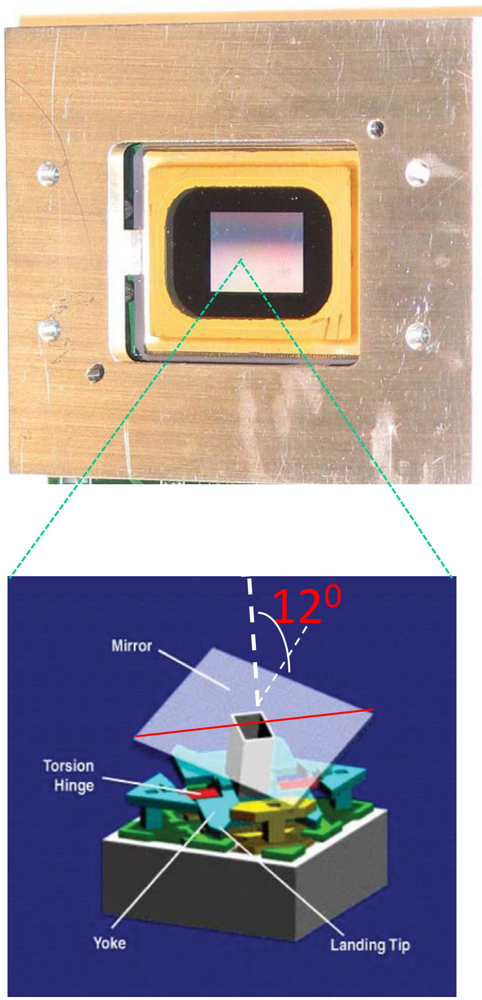
Approach: employ beam based radiation, e.g. OTR, OSR,… combined with innovative optical techniques

Present and Proposed Activities:

1. High dynamic range (HDR) (>10 (6)) beam/ halo imaging using OSR OTR, etc. (CI,SLAC,CERN)
2. HDR/high resolution OTR and ODR beam imaging (CI, PSI, RHUL)
3. Noninvasive single shot bunch length monitor using coherent diffraction radiation (CI, PSI, U. Dundee)
4. Optical phase space mapping (CI)
5. Emittance and energy spread monitors using optical synchrotron radiation interferences (FERMI@Trieste)

1. High Dynamic Range Beam/Halo Imaging with a Digital Micro-mirror Device*

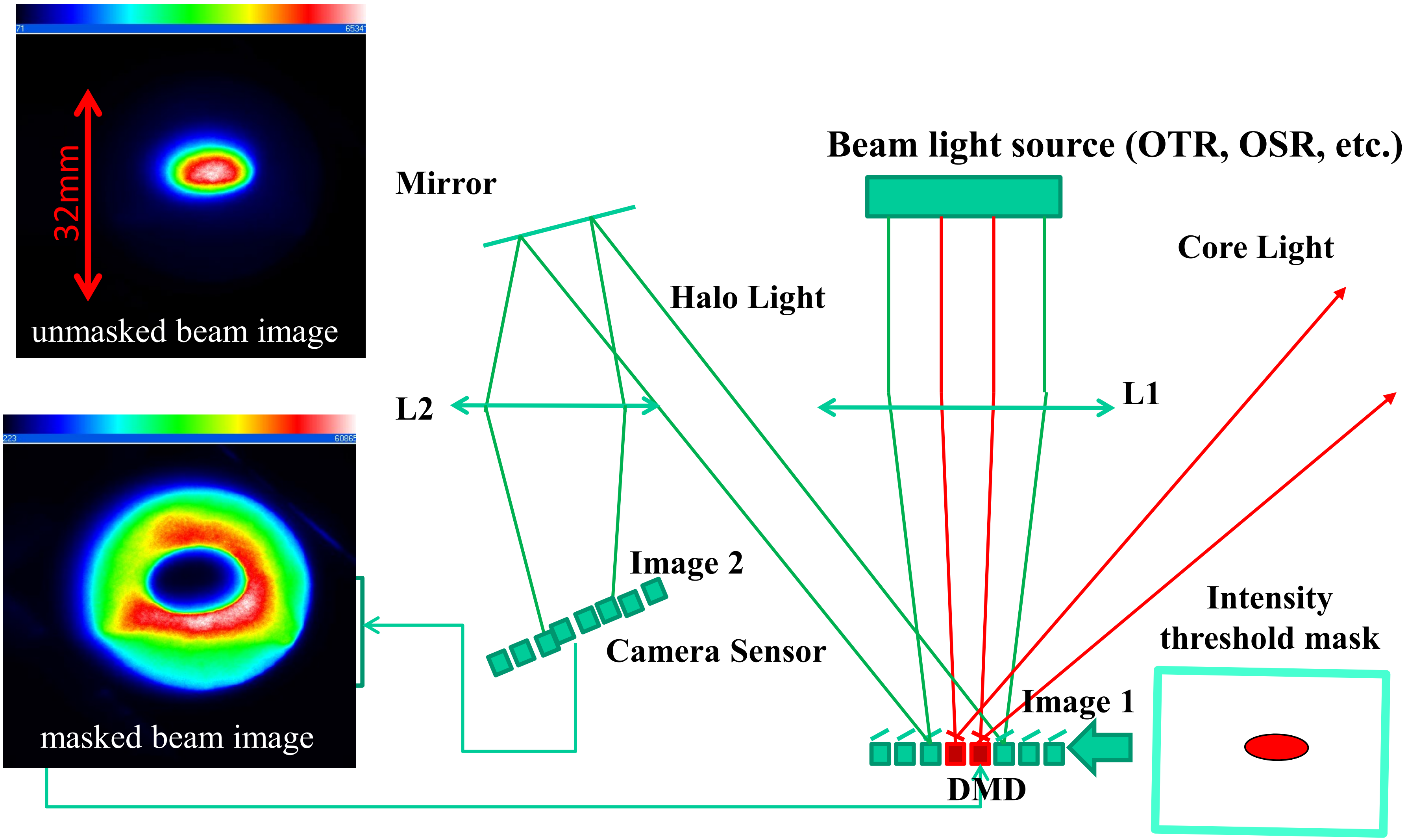
*DLP™ Texas Instruments Inc.



Array dimensions: 14 x 10 mm
Pixels: 1024 x 768,
Pixel dimension: 14x14 μicrons
Switching rate: 9600 fps
Individual pixel addressable

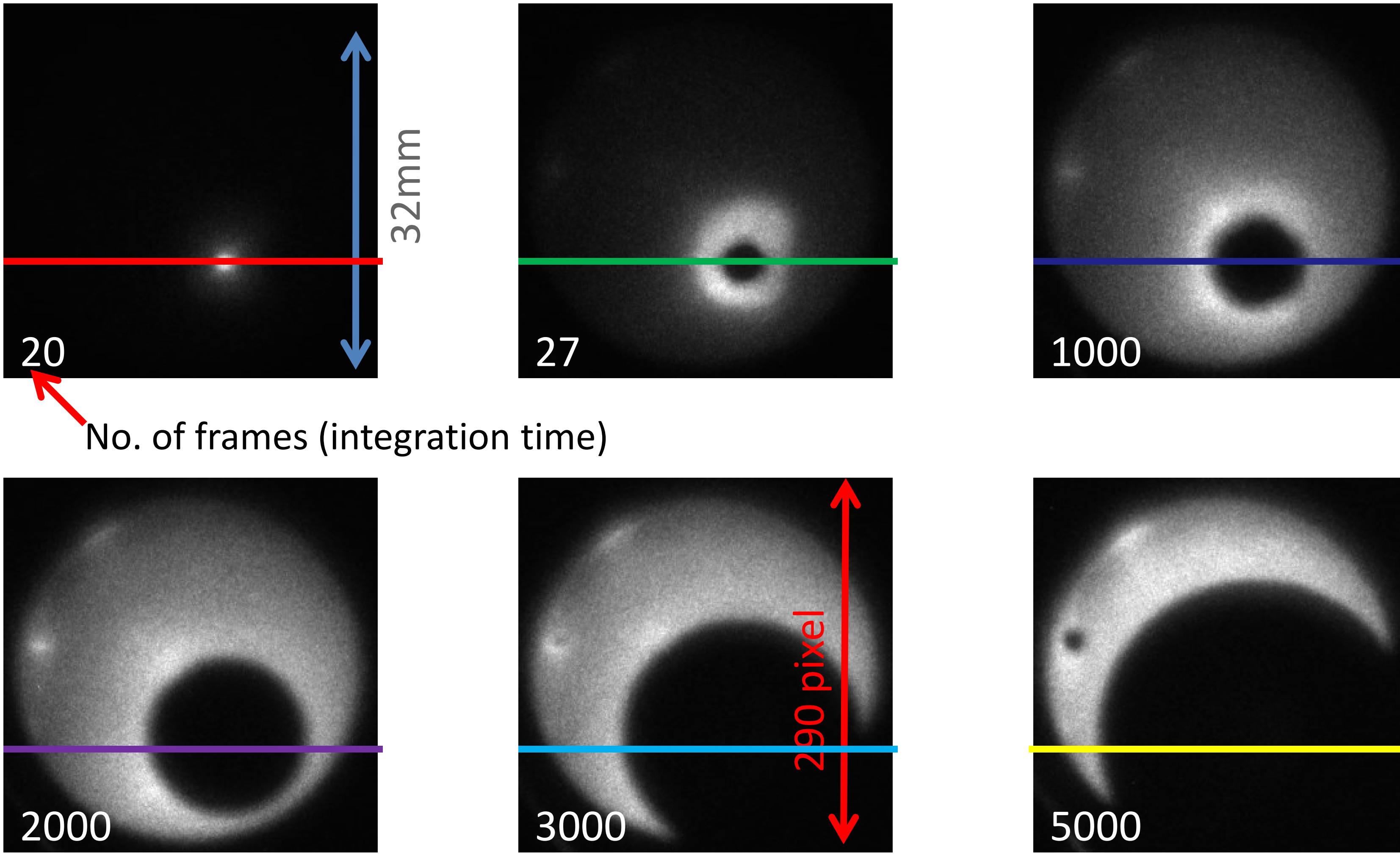
Uses: 1-Spatial light modulator
2-Adaptive optical Mask

Optical Technique for Beam Halo Imaging*

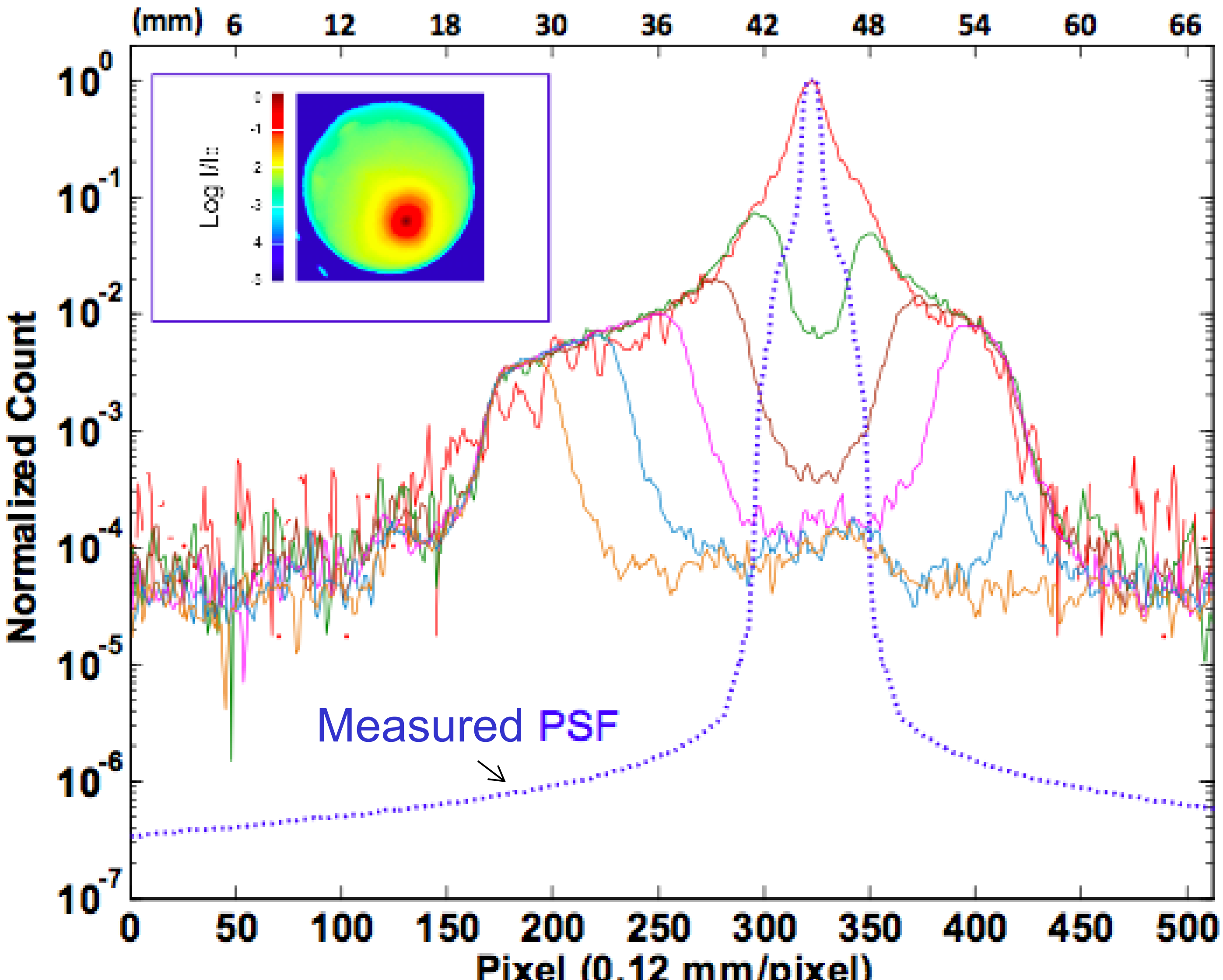


*H. Zhang, et. al. Phys. Rev. ST Accel. and Beams (2012)

Dynamic range measurement of imaging system using DMD as an optical mask with phospor screen (21mA ebeam)

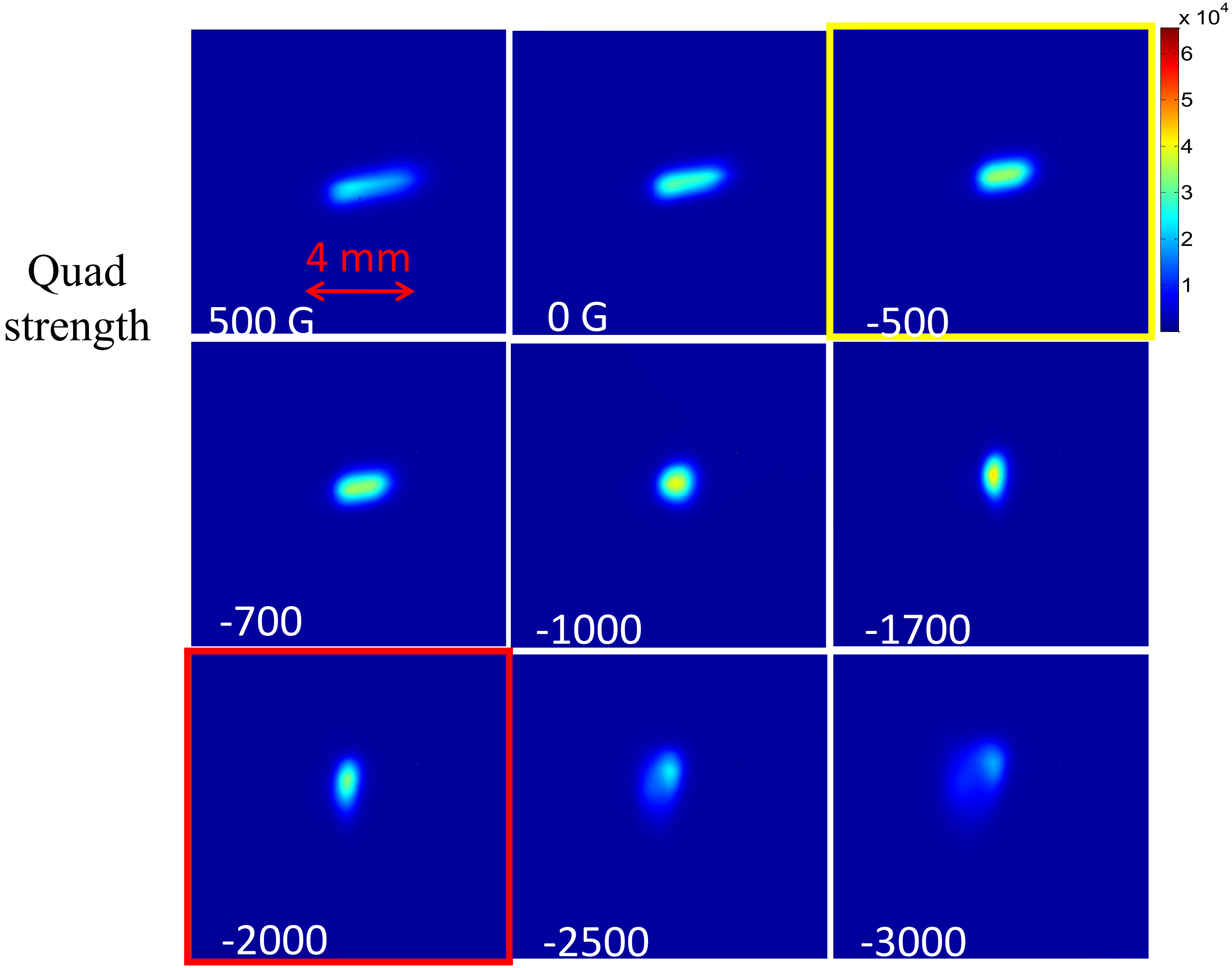


Dynamic Range and Point Spread Function Measurements for UMER



OSR Quad Scan with Tune-up Beam

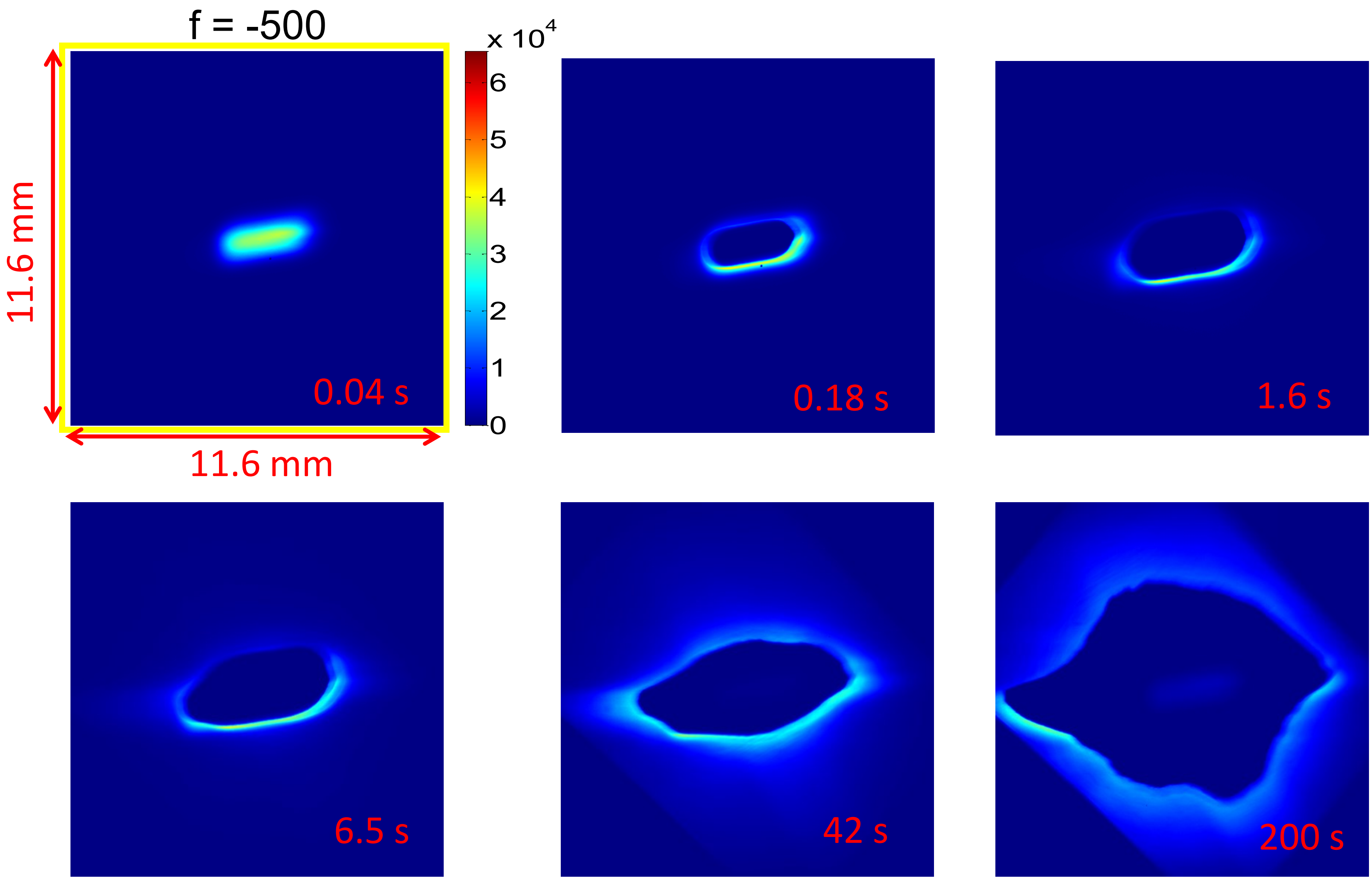
(E=135 MeV, I= 0.32mA: 2Hz rep-rate, 250μs macro, 4.68MHz micro, 135pC/micro)



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

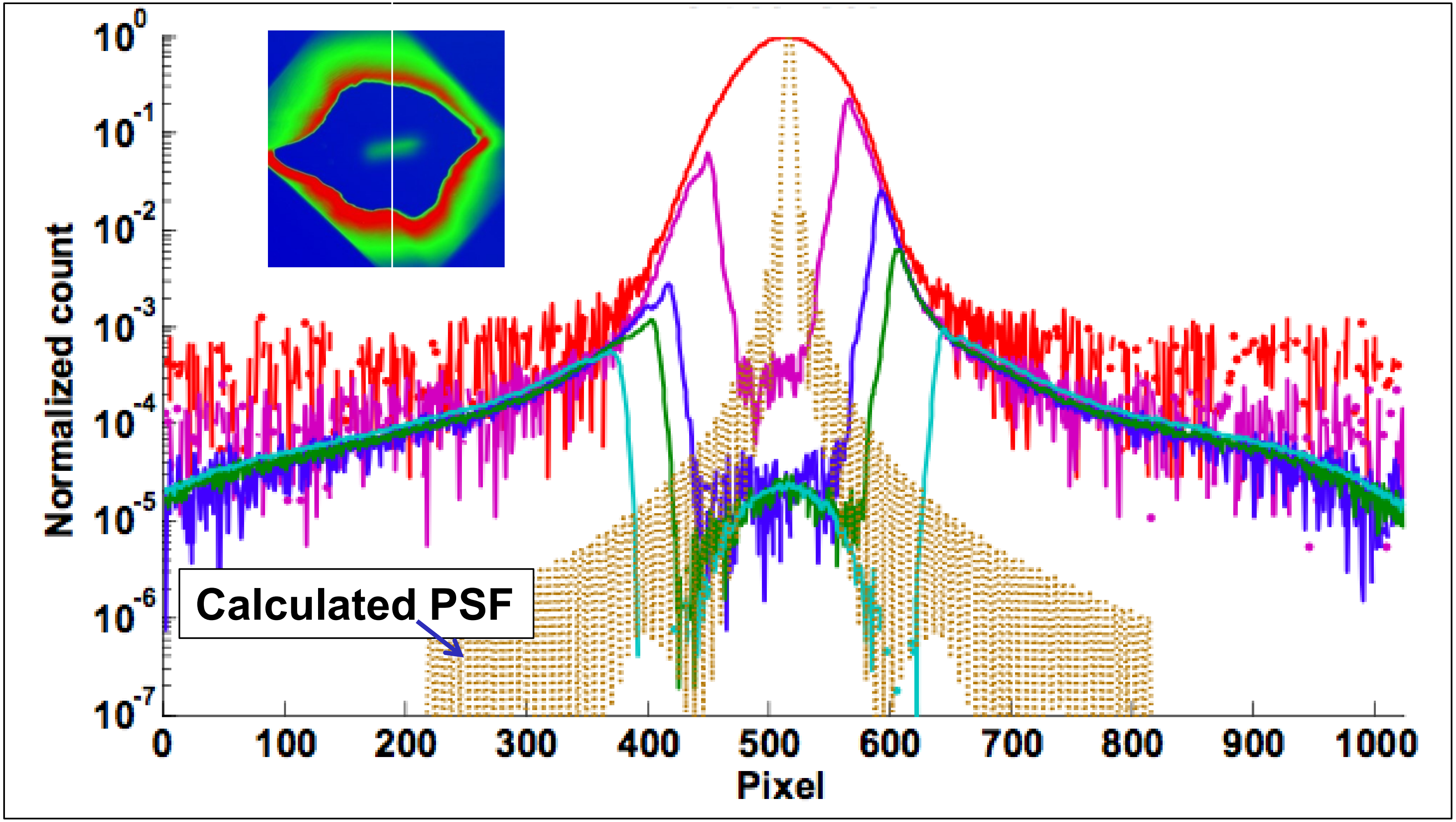
OSR Beam Halo Imaging of JLAB ERL using DMD threshold mask*

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



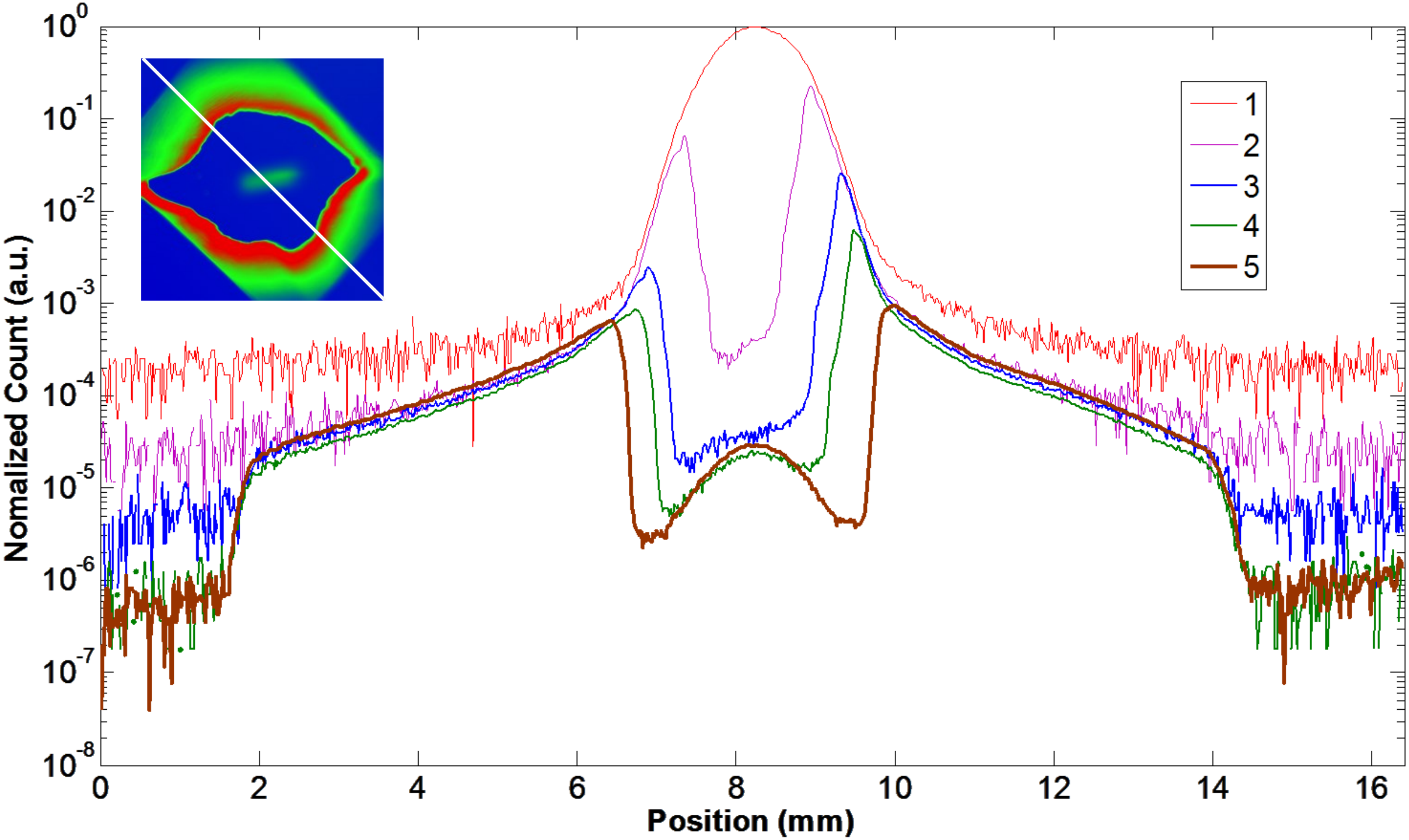
*R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

Dynamic Range Plots of Beam Along with Calculated PSF From Diffraction from Primary Aperture (slit)



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

Measurement of Full Dynamic Range of Imaging System

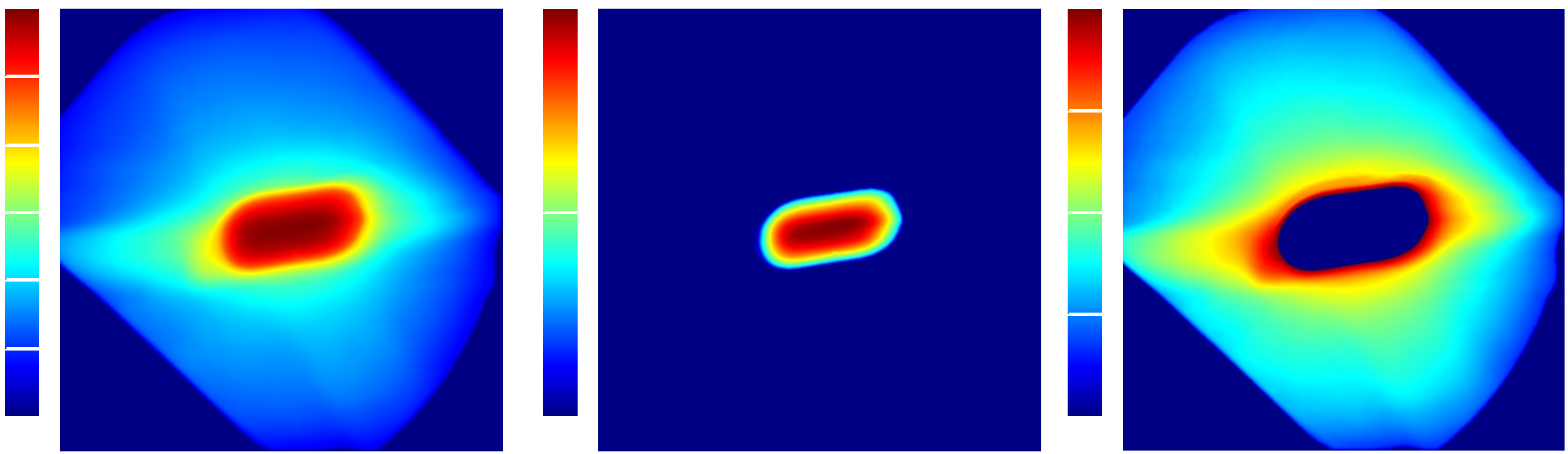


R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

Reconstructed intensity distribution $I(x,y)$ and calculated total radiant energy in core and halo

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

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



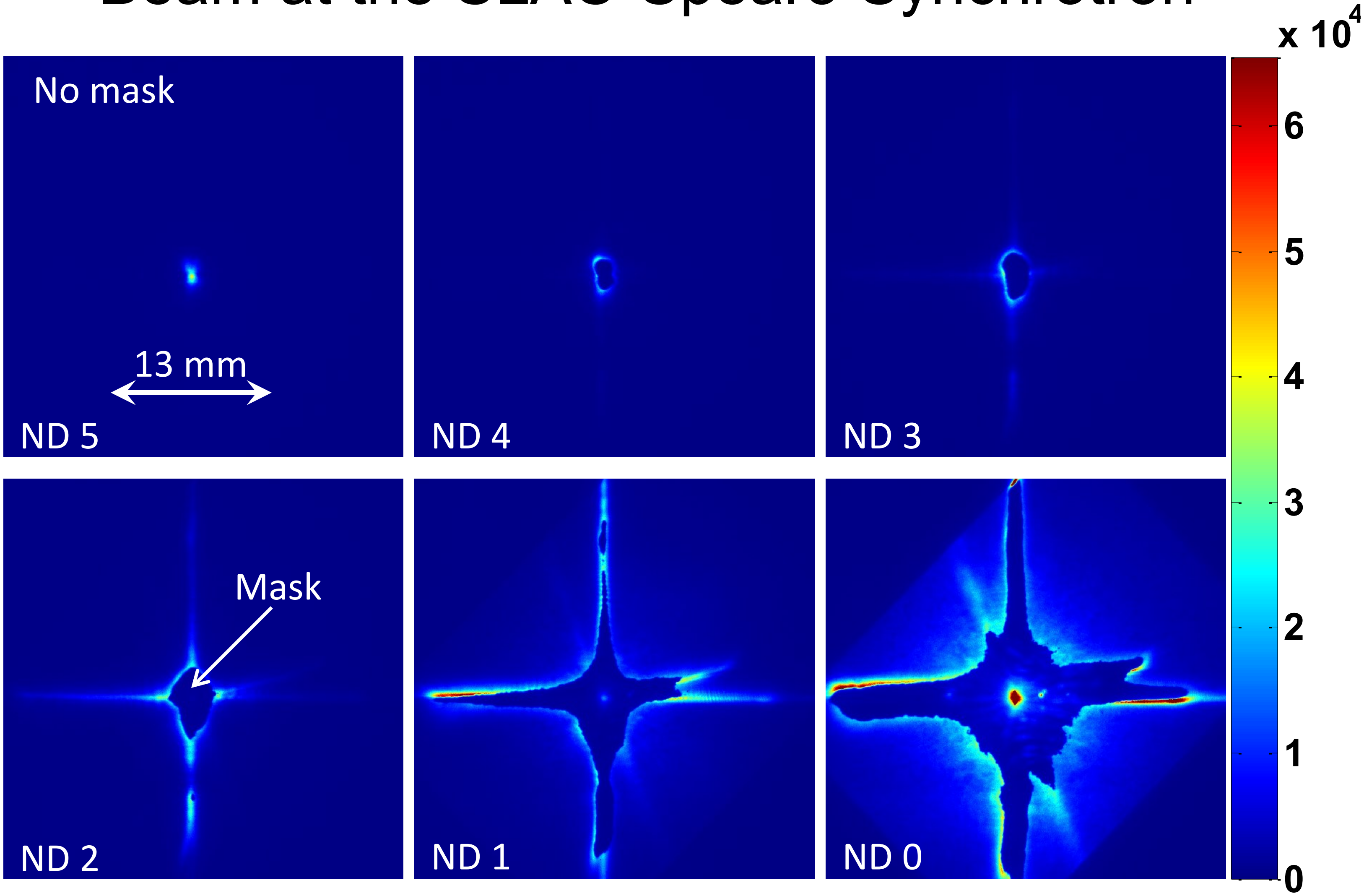
$$E_{Total} \equiv \int_S I(x,y)\,dxdy$$

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

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

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

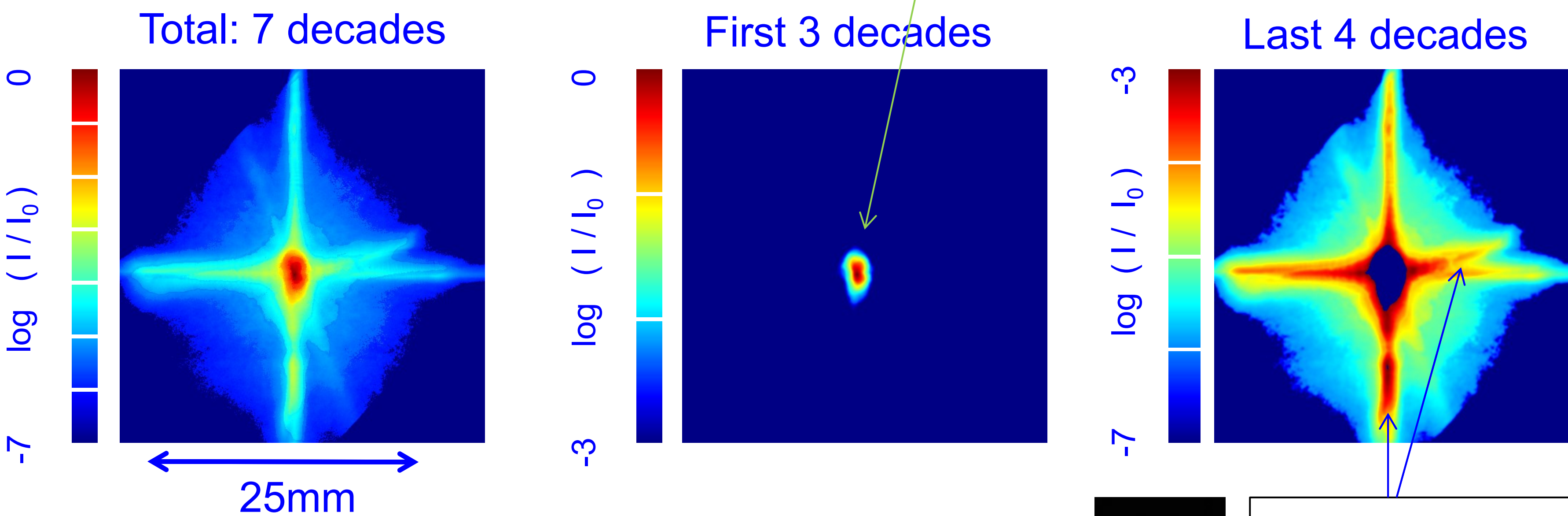
High Dynamic Range Imaging of the 349 mA Stored Beam at the SLAC-Spear3 Synchrotron

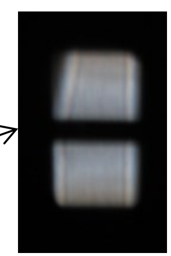


Integration time: 2ms

Reconstructed High Dynamic Range OSR Image of the SLAC/SPEAR3 stored beam with "halo" dominated by diffraction from blocking apertures

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





Measured aperture function at 1st lens in diagnostic beam line

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

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

Advancements and applications of HDR imaging with DMD

1- Develop simulation code to predict OSR PSF from measured Aperture Function- test with SPEAR 3 data or other (e.g. Diamond) OSR beam line
2- Compare 1 to Zeemax simulations
3- Repeat 1,2 for LHC conditions; build test stand to do HDR imaging on LHC in 'parasitic mode' either on bench optics or in tunnel; measure the PSF LHC optical synchrotron line; compare to Zeemax.
4- Investigate Fourier filtering of PSF to "remove finite aperture effect" test at intense OSR source (SPEAR3, Diamond, ..)
5- Incorporate Lyot optics and/or apodizing filters created with high speed DMD processor (dithered gray scale apertures) to further improve the PSF and the DR, e.g. by filtering out diffraction effects from first objective and mask

2) High Dynamic Range/High Resolution OTR and ODR Beam Profile Imaging

Present state of the art of OTR beam size measurements:

Deconvolution of the measured PSF of OTR from measured OTR source distribution and Zeemax code calculations that include real transmissivity of the optical transport have produced submicron beam size measurement.

Proposed next steps

1) HDR measurement of OTR PSF using DMD technique - could provide even greater measurement accuracy and shed light on the limits to OTR beam size measurement.

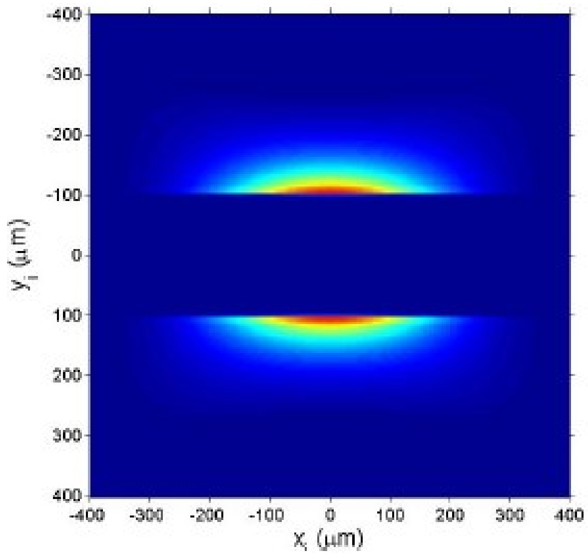
2) HDR measurment of PSF of ODR (with DMD)
3) Compare measurement of PSF of ODR to theory*
4) Deconvolve PSF from measured source distribution to obtain beam profile

*Xiang et. al. PRSTAB 2007

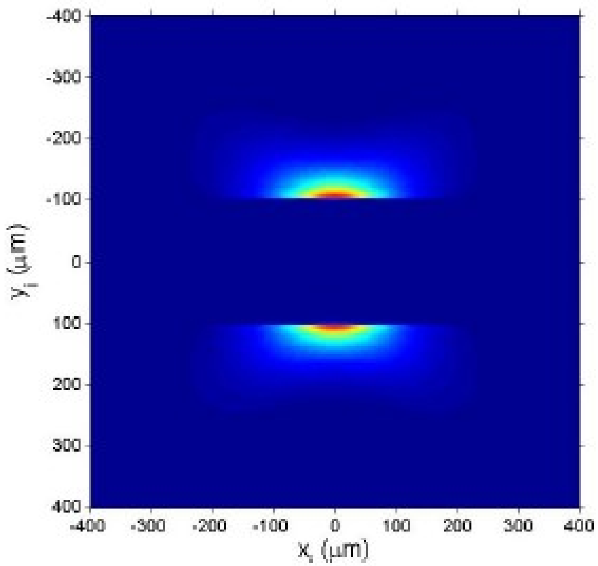
Theory: Restoration of Beam Profile from Source Image of ODR*

(γ = 2500; λ = 0.5m; θ = 0.1)

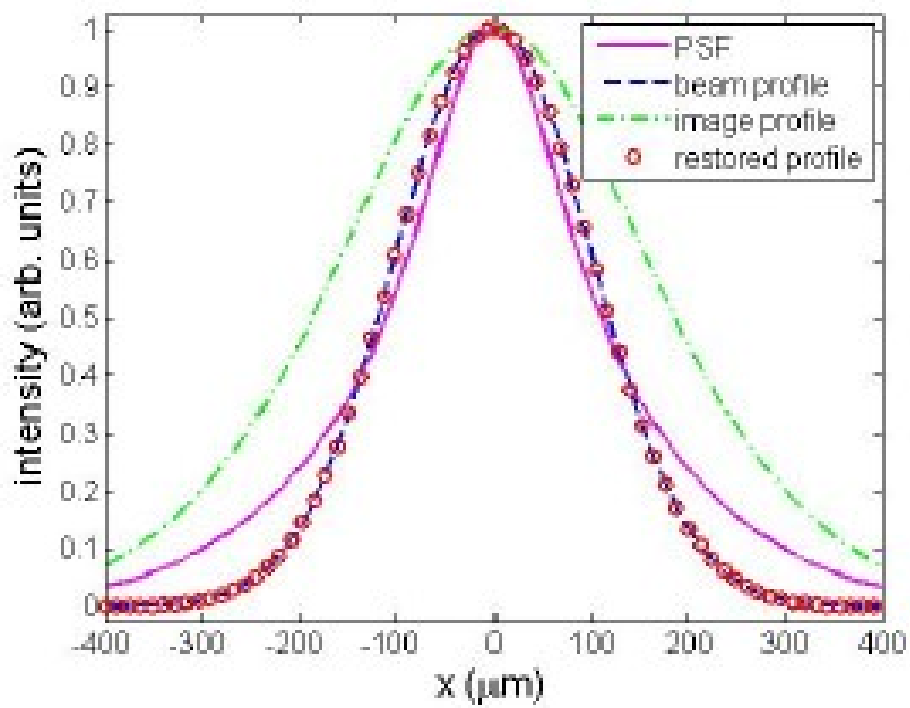
ODR Distribution from Gaussian Beam



PSF



Vertical Profiles

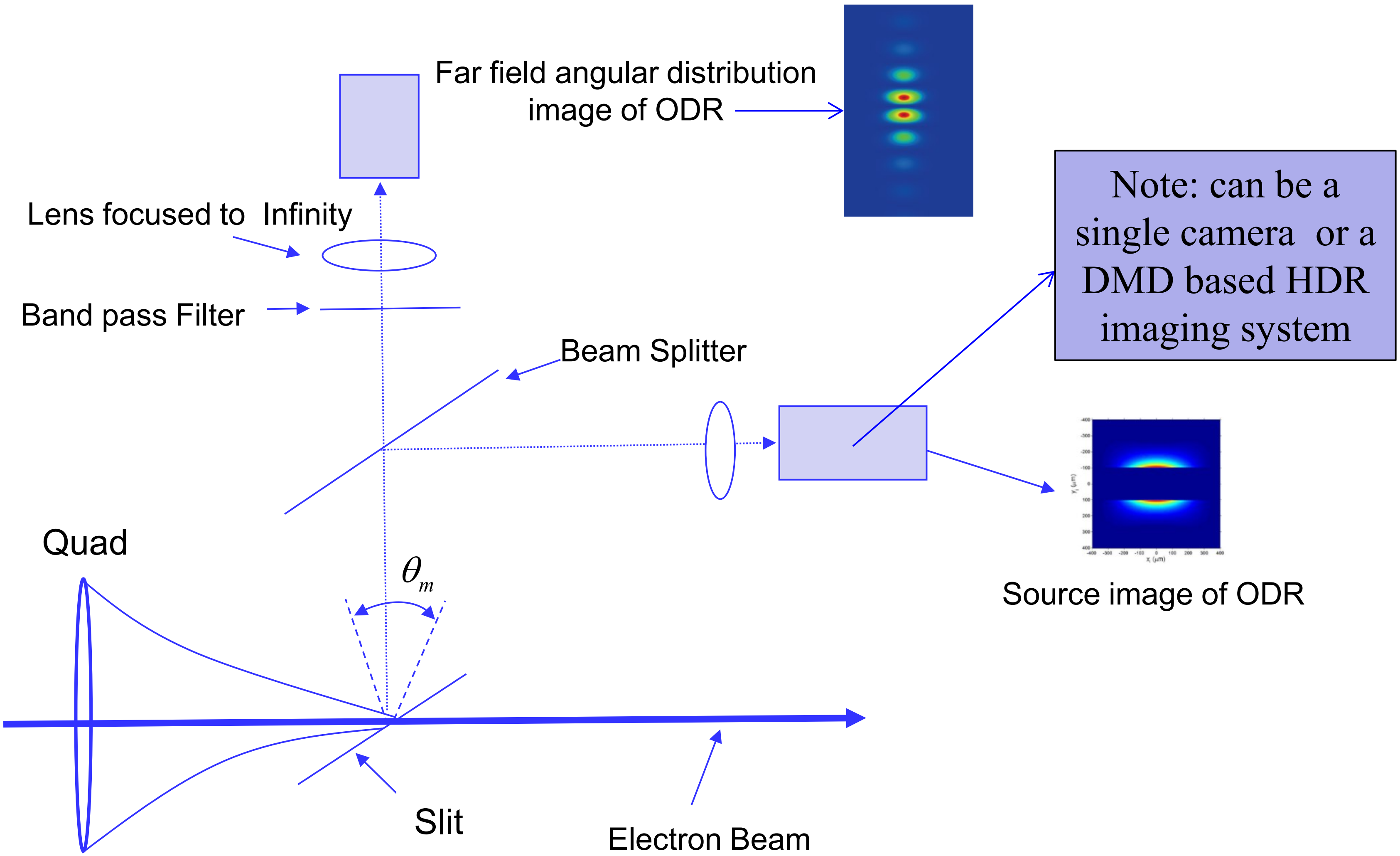


*D.Xiang, et. al. PRSTAB 2007

Proposed collaboration with CI, RHUL, KEK – CERN? PSI ?

1) Measure and verify theoretically predicted PSF of ODR using 10 micron beam at KEK using high dynamic range (HDR) DMD technique
2) Make HDR measurement of PSF of OTR at same time (use two radiators) and compare to previous measurements and Zeemax code calculations.
3) Expand beam and use calculated and measured PSF's to deconvolve profile from measured ODR source field distribution (using high DR technique); compare to OTR beam profile again using HDR imaging at KEK and PSI (3 GeV - SFEL); do simulations to study resolution of source imaging method to beam size and offset (OBPM)
4) Optional: simultaneously use far field ODR or ODRI pattern to measure beam size.

Proposed Experimental Setup for Simultaneous Imaging of Far field Angular Distribution and Source Distribution of ODR



Special equipment available for proposed experiments

1- DMD array with ALP 4.1 high speed processor (already on hand at CI)

2- Apogee Instruments 16 bit, cooled CCD and control software
(can be borrowed on approval from UMD)

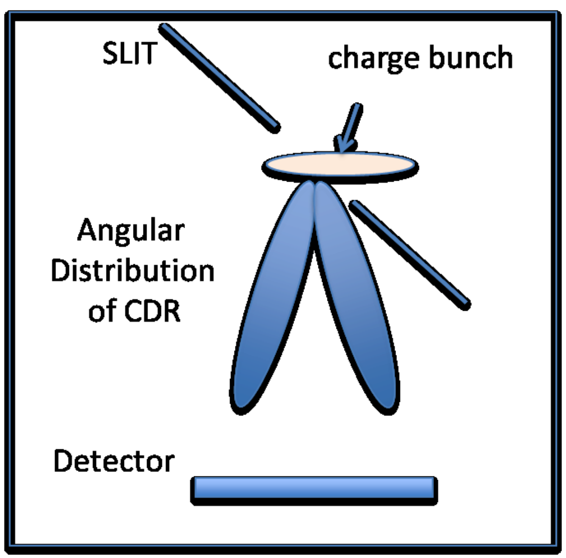
3- PIMAX I gated, intensified CCD and pulse timing generator
(UMD)

Non invasive Bunch Length Diagnostic using Angular Distribution of Coherent Diffraction Radiation

$$\frac{d^2 I_{bunch}^{DR}}{d\Omega} \approx N_2 \int_{\Delta\omega} \frac{d^2 I_e^{DR}(\gamma,\omega,a)}{d\omega d\Omega} S_z(\sigma_z,\omega)\, d\omega$$

Spectral-Angular Distribution of DR from single electron calculable for any shape, size (a) radiator*

Longitudinal form factor depends on Bunch Length



Advantages of the method:

1) no spectral measurements needed
2) single shot capability
3) can be applied to measure any bunch length

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

New Method Uses Angular Distribution to Determine Bunch Length*

(simple, single shot, low cost)

Frequency Dependent AD of CDR projected at point p

$$J(\omega, p)$$

Bunch longitudinal form factor

$$S_z(\omega) = \left| \int_{z1}^{z2} \rho(z) \exp(i\omega z / V) dz \right|^2$$

longitudinal bunch distribution

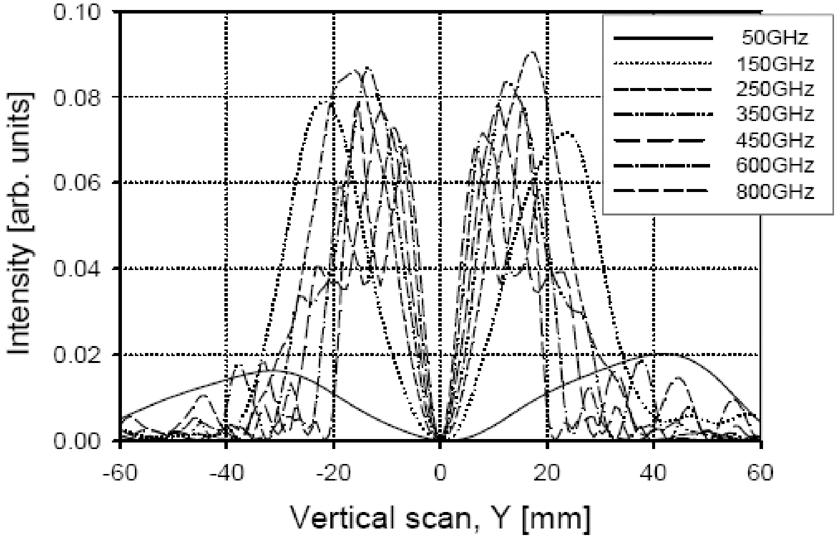
Broad band projected AD distribution of CTR from a bunch measured at point p

$$W(p) = \int_{\omega 1}^{\omega 2} J(\omega, p) S_z(\sigma_z, \omega) d\omega$$

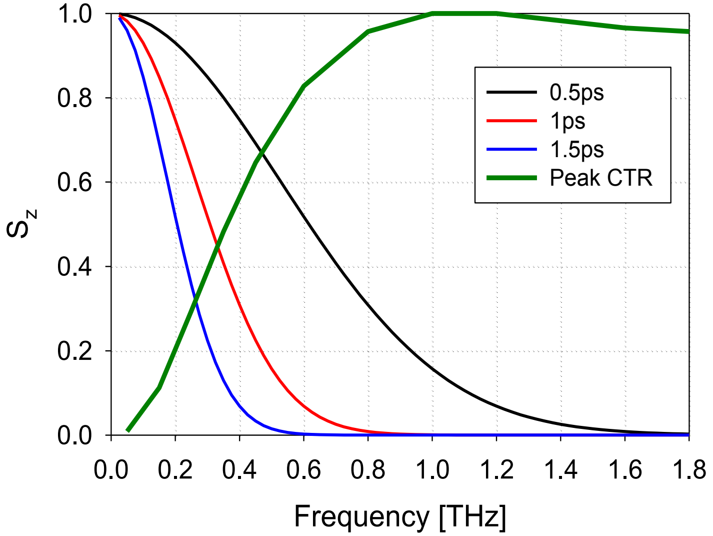
*R. Fiorito, et. al. Proc. of DIPAC 07

Example: Angular Distribution of CDR from Finite Disk, E=100 MeV

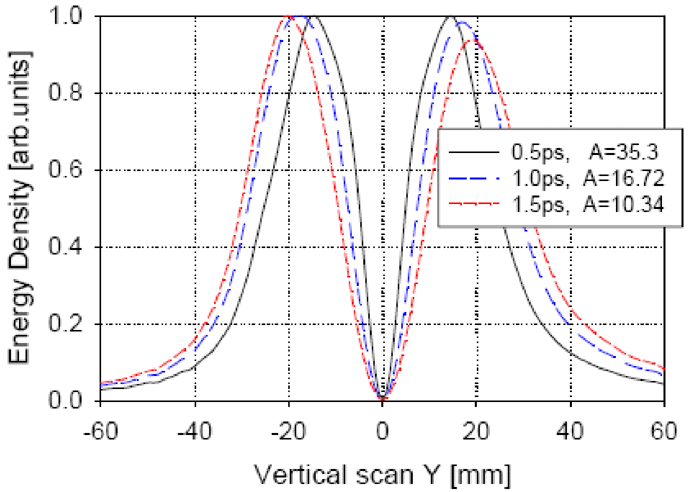
Projected Angular Distributions, J(ω,p)



Bunch Form factors for various pulse widths and CTR spectrum



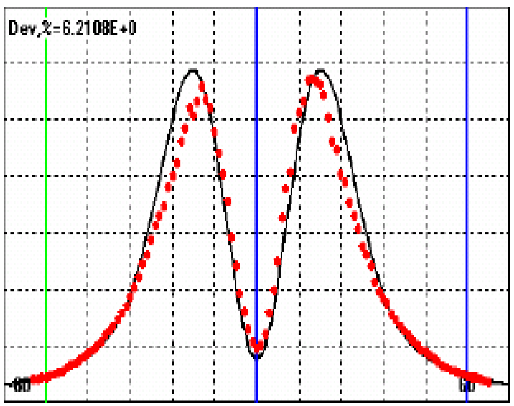
Frequency Integrated Broad Band Power, W(p) for various pulse widths



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

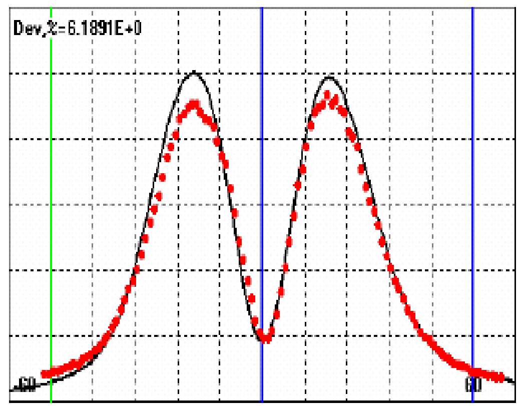
Proof of Principle Experiment perform at Paul Scherrer Institute's 100 MeV LINAC using scanning Golay cell*

CDR from rectang. plate



-60mm +60m

CDR from Slit



-60mm +60mm

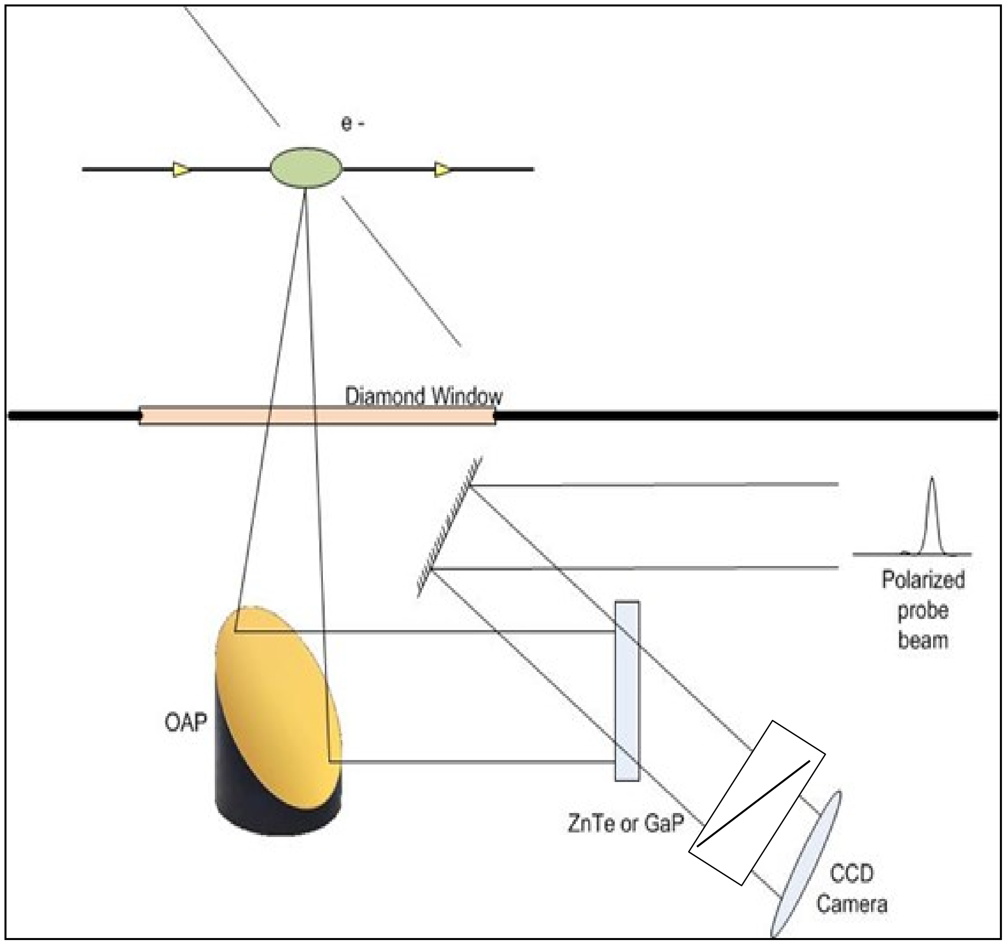
Single Gaussian bunch fits

Method	Tune	T(ps)
AD CTR/CDR	PBU-0	0.7
E-O technique	PBU-0	0.75
AD CTR/CDR	PBU+3	1.0
E-O technique	PBU+3	1.0

*R. Fiorito, et. al. Proc. of DIPAC 07

Proposed electro optic single shot imaging of CDR AD

(uses modification of THz imaging system developed and successfully use at PSI*)



*Sutterlein and Schlott 2009

Conventional Bunch Length Measurement Techniques employing CTR or CDR uses direct spectroscopy or Fourier transform interferometry to deduce the bunch form factor -> bunch length

Scanning Fourier Transform autocorrelation: measures spectrum of CTR

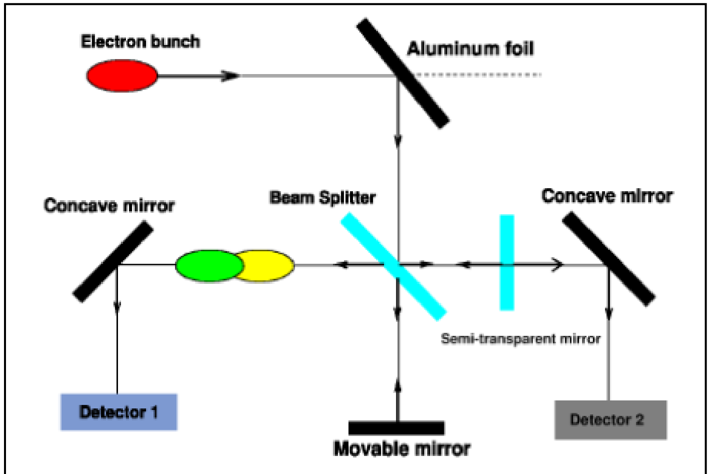
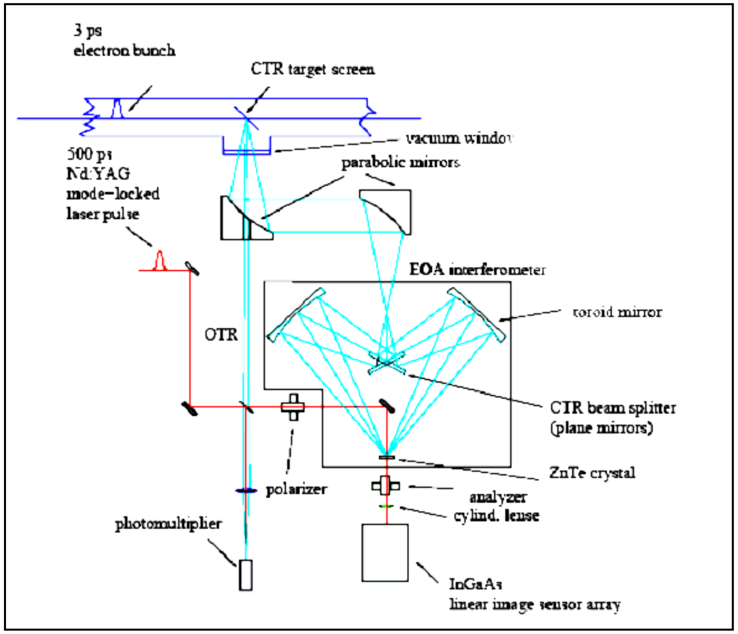


FIG. 1. (Color) Michelson interferometer. Detector 1 is used to record the autocorrelation function. Detector 2 is a reference detector used to normalize the autocorrelation function.

D. Mihalcea, et. al., PRSTAB 9, 082801 (2006)

Single shot CTR autocorrelator



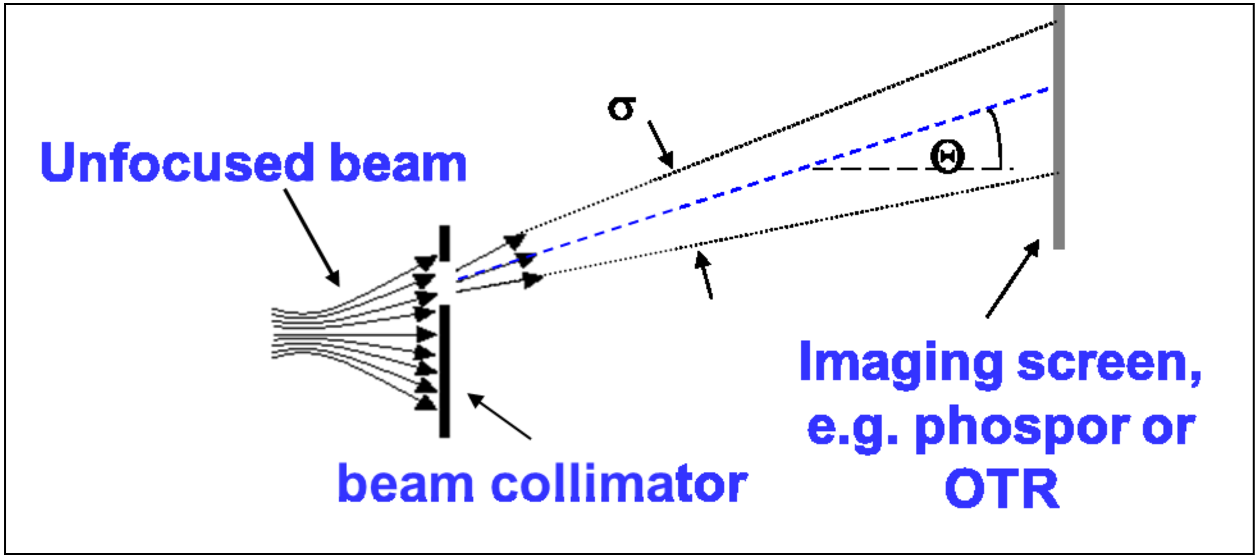
D. Suettertlein, PhD. Thesis, Swiss Light Source 100 MeV Injector Linac

Additional Topics

3) Optical phase space mapping (OPSM)*- the optical equivalent of the pepper pot technique

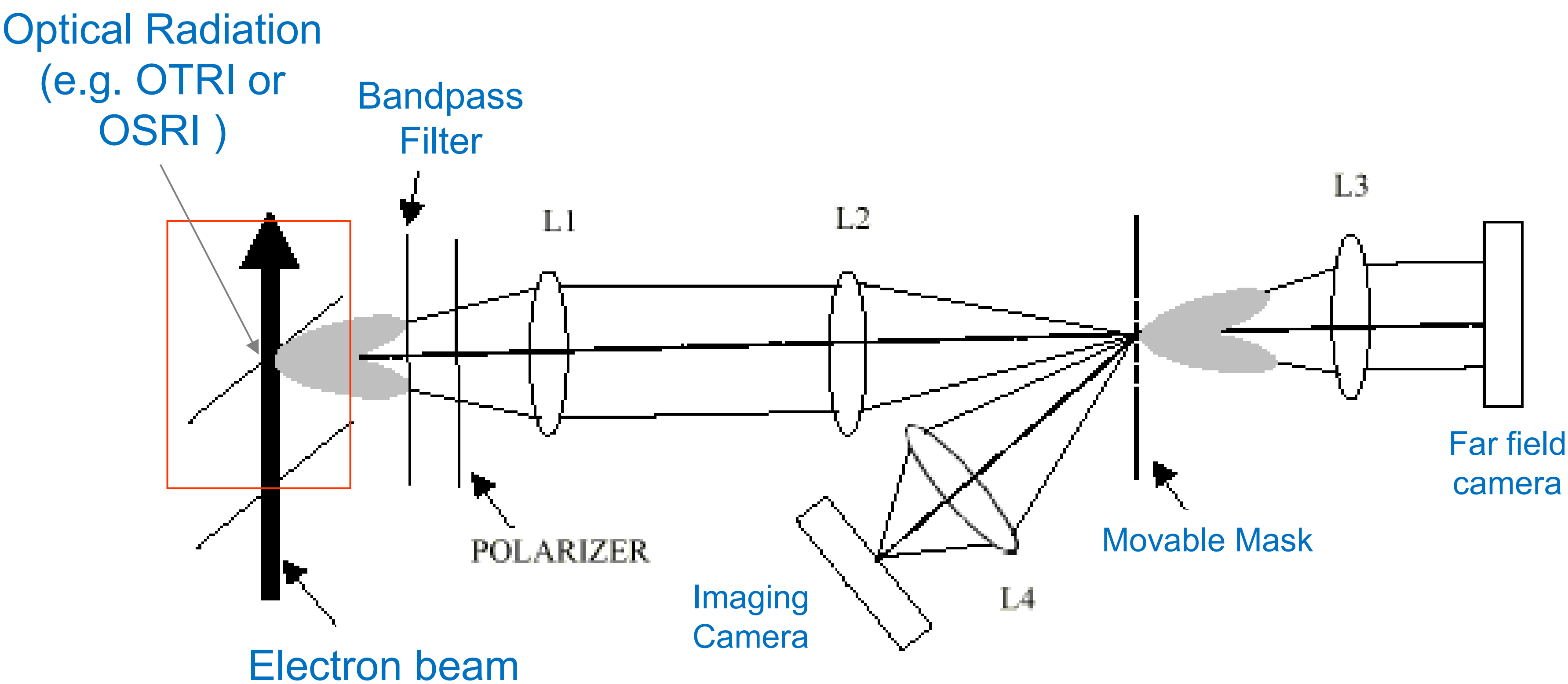
Conventional PSM: uses collimator (slits or pinholes) to segment the beam into beamlets, whose angular trajectories and angular spreads are measured as a function of position within the beam to make a PSM

Problems: *Not practical for high energy beams - collimation doesn't work - beams too small; requires drift space and imaging screens in the beam line.*



* R.B. Fiorito, A.G. Shkvarunets, and P.G. O'Shea, AIP Conf. Proc. No. 648, (2002).

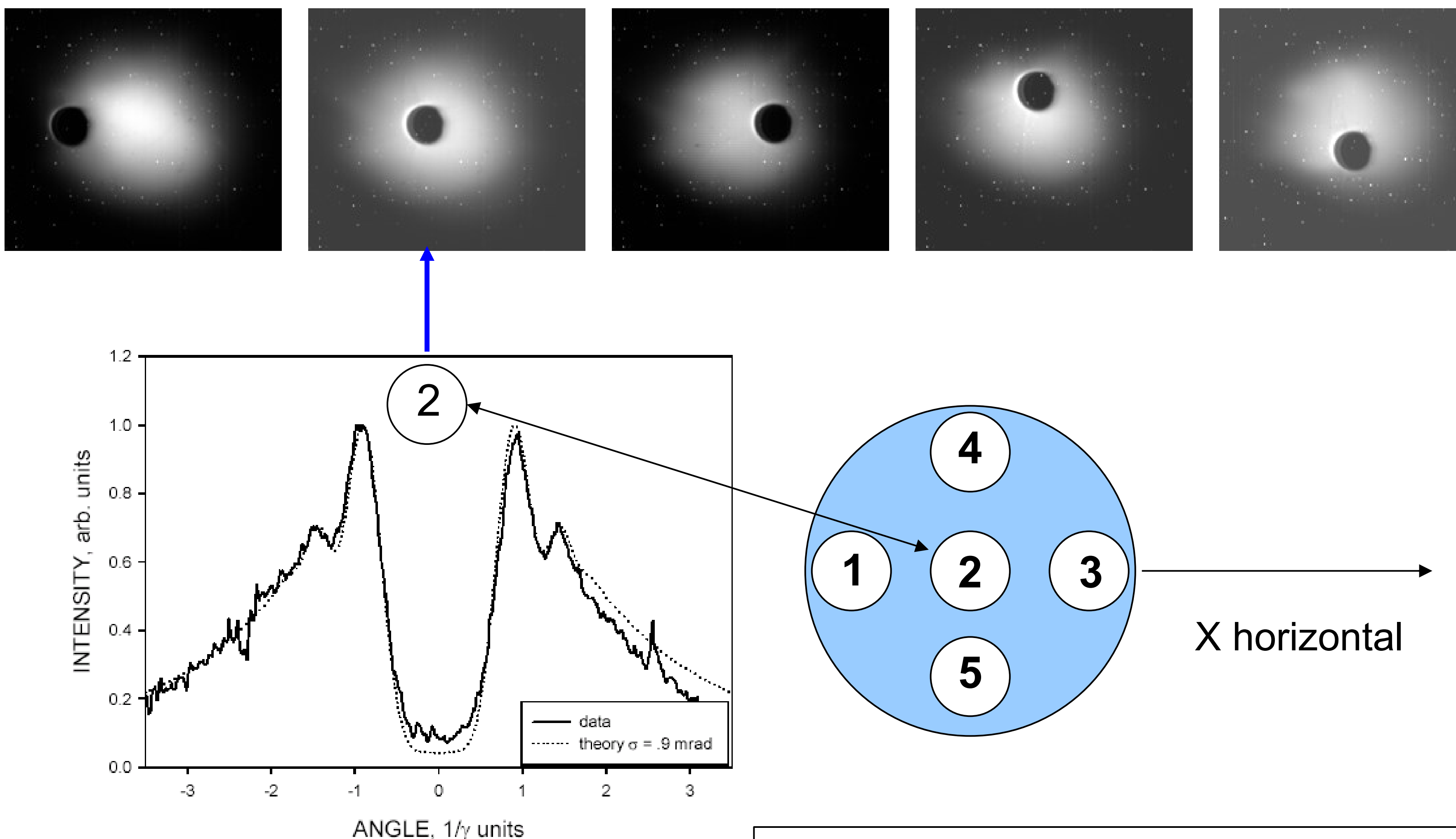
OPSM: uses optical mask to segment beam associated radiation to measured beam divergence and trajectory angle measurements as a function of position within the beam image at one position in space *



Applications: 1) separate out core and halo emittance
2) create phase (trace) space map of beam

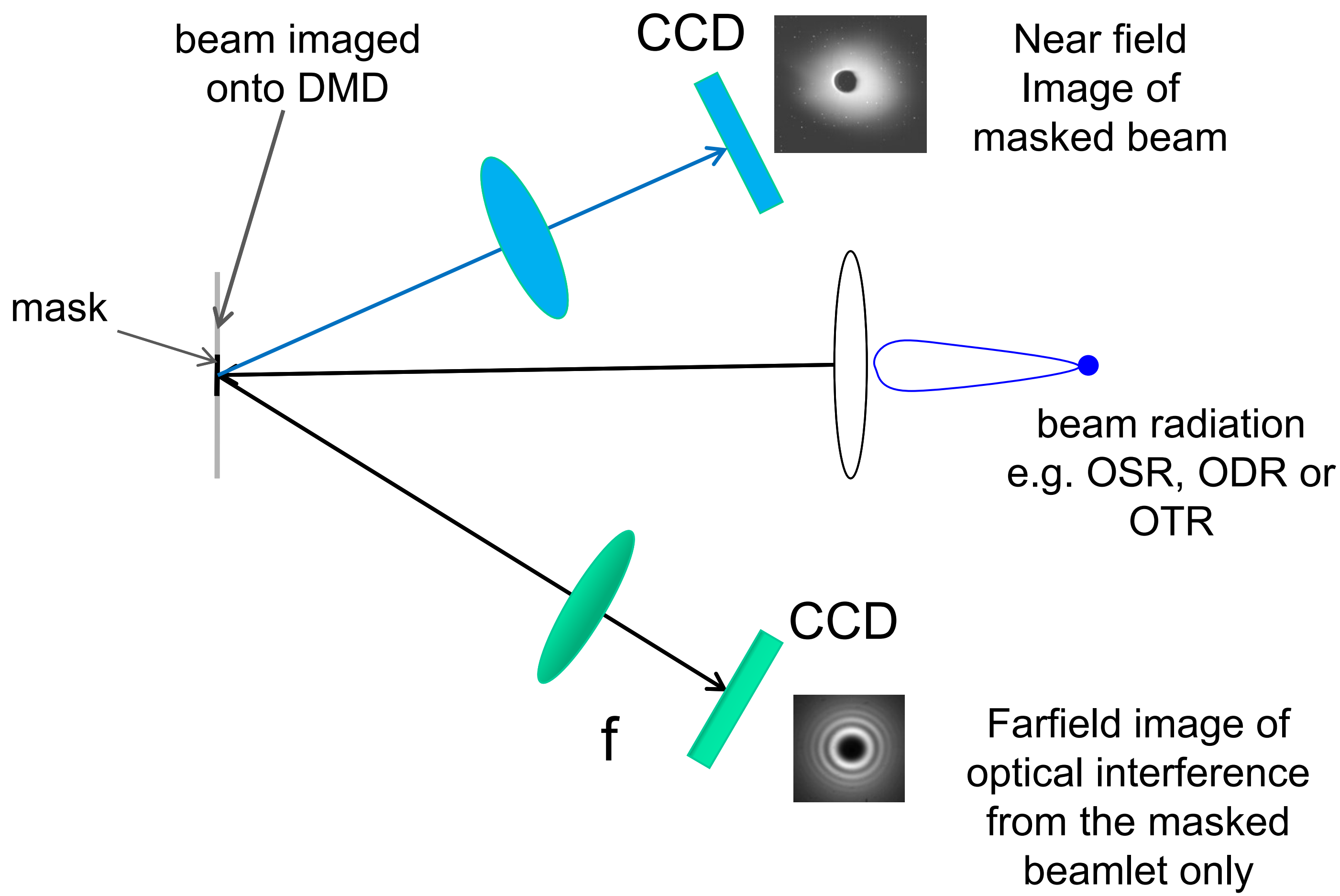
Proof of principle experiment using OTR and a scanning pinhole mask

Done at 95 MeV linac at NPS- Monterrey CA*



R. Fiorito, et. AIP Conf. Proc. 648, (2002)

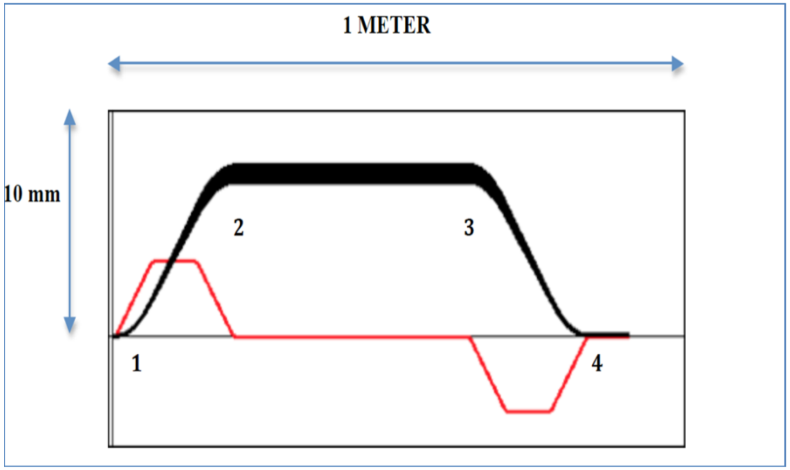
New Concept: Optical Phase Space Mapping using a DMD



Potential Applications: 1) separate out core and halo emittances
2) create trace space maps

Non Invasive Emittance and Energy Spread Monitor using OSR Interferences

Diagnostic Mini chicane Design with (1,2) 'S' and (2,3) ' U' Interferometers

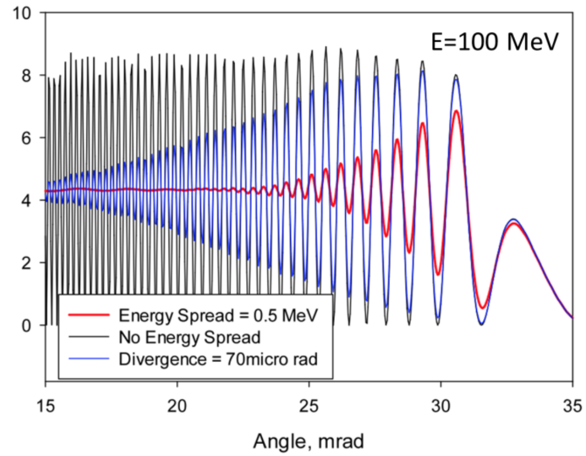


Properties of Chicane:

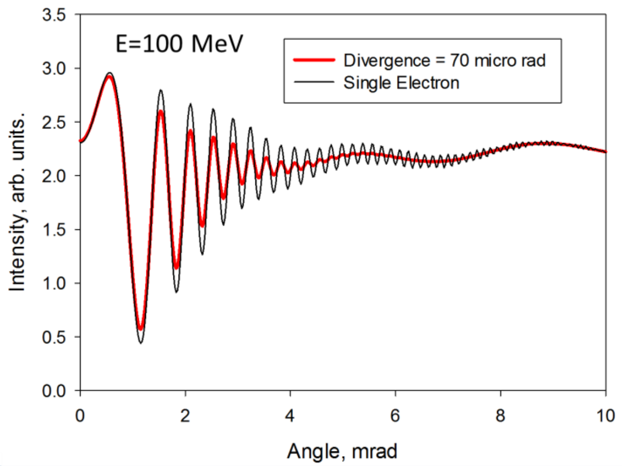
B (100MeV) = 0.12 Tesla
B(285 MeV) = 0.35 Tesla

L @magnet = 100 mm
L (2,3) = 600 mm
Angle deflection = 35 mrad

OSR Interferences from (1,2) shows sensitivity to dE/E
(due to large angular dispersion)



OSR Interferences from (2,3) shows sensitivity to divergence
(and essentially no sensitivity to dE/E)



Optics to Observe Optical Synchrotron Radiation Interferences