Advanced Optical Diagnostics for Charged Particle Beams

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Radiation from Charged Particle Beams

Transition radiation: produced when a charge particle with constant velocity passes through an interface between media, with different dielectric constants e.g. vacuum to metal foil or dielectric slab

Diffraction radiation: produced as a charged particle passes near a medium with a different dielectric constant

Synchrotron radiation: produced as a particle is accelerated in magnetic field

Virtual Photon Theory*: provides a powerful paradigm to visualize and calculate the properties of these and other types of radiation from relativistic charged particles

Main Concept: EM field due to a moving charged particle seen by observer in lab looks like a plane wave which interacts with its surroundings similar to a real photon

E.G. TR; reflection and refraction of virtual photons

DR: diffraction of v.p’s;

SR: compton scattering of v.p’s

Landau and Lifshitz ‘Clas. Thy of Fields’; C. Brau: ‘Electromagnetic Thy’
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*

*DLPTM 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*

Beam light source (OTR, OSR, etc.)

Mirror

Halo Light

Core Light

L2

Image 2

Camera Sensor

DMD

Image 1

Intensity threshold mask

unmasked beam image

masked beam image

32mm

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

No. of frames (integration time)

- 20 frames
- 27 frames
- 1000 frames
- 2000 frames
- 3000 frames
- 5000 frames

32mm

290 pixel
Dynamic Range and Point Spread Function Measurements for UMER
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 )

Measurement of Dynamic Range of imaging system

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

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

$$E_{Total} \equiv \int_{S} I(x,y) dx dy$$

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

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

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

\( I_b = 349 \text{ mA}; \) beam size: 150 x 60 microns

Total: 7 decades
First 3 decades
Last 4 decades

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

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 measurement 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*
\((\gamma = 2500; \lambda = 0.5\text{m}; \theta = 0.1)\)

*D.Xiang, et. al. PRSTAB 2007
Proposed collaboration with CI, RHUL, KEK and 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)

4) Optional: simultaneously use far field ODR pattern to measure beam size.
Proposed Experimental Setup for Simultaneous Imaging of Far field Angular Distribution and Source Distribution of ODR

- Lens focused to Infinity
- Band pass Filter
- Beam Splitter
- Far field angular distribution image of ODR
- Source image of ODR

Note: can be a single camera or a DMD based HDR imaging system
Special equipment available for proposed experiments
(upon request from UMD)

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

2- Apogee Instruments 16 bit, cooled CCD and control software

3- PIMAX I gated, intensified CCD and pulse timing generator
Non invasive Bunch Length Diagnostic using Angular Distribution of Coherent Diffraction Radiation

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

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

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

\[ S_z(\omega) = \left| \int_{z_1}^{z_2} \rho(z) \exp(i \omega z / V) dz \right|^2 \]

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
Projected Angular Distributions, $J(\omega, p)$

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 performed at Paul Scherrer Institute’s 100 MeV LINAC using scanning Golay cell*

CDR from rectang. plate

CDR from Slit

Single Gaussian bunch fits

<table>
<thead>
<tr>
<th>Method</th>
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<tr>
<td>AD CTR/CDR</td>
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<td>E-O technique</td>
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<td>AD CTR/CDR</td>
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*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
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.

**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

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)
does not show sensitivity to dE/E
due to large angular dispersion

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