Imaging of Charged-Particle Beams with OTR and ODR

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I. Introduction

II. Optical Transition Radiation (OTR)
   - OTR results with electrons
   - OTR point-spread function (PSF) aspects
   - OTR results with protons, hadrons

III. Optical Diffraction Radiation (ODR) as a nonintercepting (NI) beam-size monitor.
   - ODR near-field experimental results (APS, CEBAF)
   - ODR model results for Gamma=1000, 46000

IV. Summary
The charged-particle beam transverse size and profiles are part of the basic characterizations needed in accelerators to determine beam quality.

A basic beam imaging system includes:

- conversion mechanism (scintillator, optical or x-ray synchrotron radiation (OSR or XSR), Cherenkov radiation (CR), optical transition radiation (OTR), undulator radiation (UR), and optical diffraction radiation (ODR).
- optical transport (lenses, mirrors, filters, polarizers).
- imaging sensor such as CCD, CID, CMOS camera, with or without intensifier and/or cooling.
- video digitizer.
- image processing software.
• OTR can be used for beam size/profile, position, divergence, energy, relative intensity, bunch length info.

A.H. Lumpkin et al., NIM A296, 150 (1990)
Optical Transition Radiation Interferometry (OTRI) Calculations

Coherent Spectral-Angular Distribution from a Macropulse,

- Number of Photons per Unit Frequency and Solid Angle

\[ \frac{d^2N}{d\omega d\Omega} = \left| r_{\perp,\parallel} \right|^2 \frac{d^2N_1}{d\omega d\Omega} I(k) \bar{\zeta}(k) \]

Single Particle OTR Spectral-Angular Distribution

\[ \frac{d^2N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \left( \theta_x^2 + \theta_y^2 \right) \]

\[ \left( \gamma^{-2} + \theta_x^2 + \theta_y^2 \right)^2 \]

\[ E = 220 \text{ MeV} \quad \sigma_{x', y} = 0.2 \text{ mrad} \]

From D. Rule and A. Lumpkin, PAC’01
Wartski Interferometer Phase Term

\[ I(k) = 4 \sin^2 \left( \frac{kL}{4} \left( \gamma^{-2} + \theta_x^2 + \theta_y^2 \right) \right) \]

\[ L = \text{foil separation distance} \]

\[ k_x = k \sin \theta \cos \phi = k \sin \theta_x \approx k \theta_x \]
\[ k_y = k \sin \theta \sin \phi = k \sin \theta_y \approx k \theta_y \]
\[ k_z = k \cos \theta \approx k = \omega / c \]

\[ \theta^2 = \theta_x^2 + \theta_y^2 << 1 \quad \text{(relativistic case)} \]

From D. Rule and A. Lumpkin, PAC’01

\[ E = 220 \text{ MeV, } \sigma_{x',y'} = 0.2 \text{ mrad} \]
\[ L = 6.3 \text{ cm, } \lambda = 537 \text{ nm} \]
OTRI Calculations (cont.)

Coherence Function

\[ \Im(k) = N + N_B \left( N_B - 1 \right) |H(k)|^2 \]

Fourier Transform of Charge Form Factors

\[ H(k) = \frac{\rho(k)}{Q} = g_x(k_x)g_y(k_y)F_z(k_z) \]

\( Q = \text{total charge of macropulse} \)

Bunching fraction = \( f_B = \frac{N_B}{N} \)

Note: The coherence function reduces to just the number of particles, \( N \), when the number of microbunched particles, \( N_B \) is zero.

From D. Rule and A. Lumpkin, PAC'01
Schematic Layout for APS Accelerators

Layout of Nonintercepting Beam Diagnostics in the APS

- **Storage Ring (7 GeV, 1104 m circumference)**
  - 360 BPMs
  - 1 DCCT, 1 FCM
  - 1 BM/(OSR + XSR) Port
  - 1 Undulator Radiation (UR)
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- **Injector Synchrotron (0.32-7 GeV, 368 m circumference)**
  - 80 BPMs
  - 1 FCM
  - 3 Optical Synchrotron Radiation (OSR) ports
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- **Linear Accelerator**
  - 1-4 OSR ports

- **Accumulator Ring (325 MeV)**
  - 16 BPMs
  - 2 PCMs
  - 2 OSR Ports
  - 2 Striplines (Tune)
  - 1 Loss Monitor

- **Low Energy Undulator Test Line (LEUTL)**
  - 8 BPMs
  - 1 FCM
  - 1 Loss Monitor

- **Low Energy Transport 1**
  - 8 BPMs
  - 1 FCM
  - 1 Loss Monitor

- **Low Energy Transport 2**
  - 8 BPMs
  - 1 FCM
  - 1 Loss Monitor

- **Beam Dump**

- **Test Line**
  - 2 BPMs
  - 1 ODR Test Station

- **Bending Magnet**

- **Undulator**

- **OSR, XSR**

- **UR**

- **High Energy Transport**
  - 12 BPMs
  - 1 FCM
  - 1 Loss Monitor
  - 1 ODR Monitor (proposed)
7-GeV Test with OTR at APS

\[ \varepsilon_x = 1300 \, \mu\text{m} \times 50 \, \mu\text{rad} = 65 \, \text{nm rad.} \]

Lumpkin et al., PAC07
Lebedev evaluated OTR resolution in 1996 and Castellano et al. paper in 1998 points out an OTR PSF that has polarization feature. But they calc. about $12\lambda$ (FWHM) for total width and 0.1 rad collection angle.

- Polarization effects on beam image size observed in ODR and OTR in 2007 in collaboration with JLAB.
- Dao Xiang et al. in PRST-AB (2007) calc. PSF for OTR and ODR.
- OTR polarization effects reported for A0PI beam sizes at BIW10.
- KEK OTR experiment in 2005 did not use polarizer.
- KEK OTR experiment in IPAC10 does use polarizer and PSF structure.
• Newly installed Al-coated Si wafer used with 5-µA Tune beam (250 µs at 60 Hz). Polarization effects seen on $\sigma_{x,y}$.

**Total Intensity, ND1.0**
- $\sigma_x$: 150 µm, $\sigma_y$: 161 µm

**V-pol**
- $\sigma_x$: 127 µm
- $\sigma_y$: 166 µm

**H-pol.**
- $\sigma_y$: 134 µm
- $\sigma_x$: 155 µm

• OTR image size sensitive to polarization via PSF or ?
Polarized OTR Image Effects

- Perpendicular OTR component has smaller image than total OTR image by about 20 µm at 150-350 µm sizes.

Vertically Pol. OTR used for x size

Schematic of the induced currents that generate radially polarized OTR when a charge distribution strikes a metal surface.

A. Lumpkin et al., BIW10
Because of diffraction, the image of point source is not a point but ring pattern which is determined by the OTR point spread function. For a simple model like below, the PSF would be proportional to:

\[ f^2(\theta_m, \gamma, \zeta) = \left[ \int_0^{\theta_m} \frac{\theta^2}{\theta^2 + \gamma^{-2}} J_1(\zeta \theta) d\theta \right]^2 \]

\( \theta_m \) is the maximum acceptance angle of the lens, \( R_l \) is the radius of the lens, \( \theta = R_l / a, \) \( \zeta = k R_i / M, \) \( M = b / a \) is the magnification factor

With parameters \( M = 1, \theta_m = 0.1 \) 
\( E = 4 \text{GeV}, \lambda = 500 \text{nm}, \) the image of a single electron is shown

C. Liu et al., JLAB
Properties of PSF

- Not sensitive to energy
- Sensitive to acceptance angle
- Horizontal polarizer reduce PSF by \( \frac{y}{\sqrt{x^2 + y^2}} \)

With a mask blocking rays with angle smaller than \( \theta_1 \), PSF will be

\[
f^2(\theta_m, \gamma, \varsigma) = \left[ \int_{\theta_1}^{\theta_m} \frac{\theta^2}{\theta^2 + \gamma^{-2}} J_1(\varsigma \theta) d\theta \right]^2
\]

C. Liu et al., JLAB
MATLAB OTR PSF Calculations

- 14.3 MeV, \( M=1 \), \( \lambda=500 \) nm, \( \theta_{\text{max}}=0.010 \), \( \sigma=25 \) µm
- This version with convolutions implemented at FNAL.

Total PSF

\[ \text{Hpol PSF} \]

\[ \text{Vpol PSF} \]

At Image plane

\[ X \]

\[ Y \]
PSF Convolved

- $14.3 \text{ MeV}, M=1, \lambda=500\text{nm}, \theta_{\text{max}}=0.010, \sigma = 25 \mu\text{m}$

Original Sigma = 25
Total PSF Sigma = 33.1772
HorPol-HorProj PSF Sigma = 38.0076
HorPol-VerProj PSF Sigma = 29.3867
• 14.3 MeV, M=1, λ=500 nm, θ_{max}=.010, sigma = 10 µm

Original Sigma = 10
Total PSF Sigma = 22.5904
HorPol-HorProj PSF Sigma =  NA
HorPol-VerProj PSF Sigma = 16.627
- KEK staff used vertical polarizer and small beam to observe PSF and suggested potential use of structure.

Figure 3: CCD image of the OTR taken with linear polarizer and 500 nm optical filter (a) and two image projections: horizontal (b) and vertical (c).

Equation: \[
f(x) = a + \frac{b}{1 + [c(x - \Delta x)]^2} \left[ 1 - e^{-2\sigma^2} \cos[c(x - \Delta x)] \right] \quad (1)
\]

where \(a\), \(b\), \(c\), \(\sigma\), and \(\Delta x\) are free parameters of the fit function, namely: \(a\) is the vertical offset of the distribution with respect to zero which included a constant background; \(b\) is the amplitude of the distribution; \(c\) is the distribution width; \(\sigma\) is the smoothing parameter dominantly defined by the beam size; and \(\Delta x\) is the horizontal offset of the distribution with respect to zero.
• It seems the OTR PSF polarization effect is a symmetric difference in image size around the total PSF size in the model, while the JLAB data are strongly asymmetric in effect magnitude.
• Postulate this anomalous aspect is due to the induced current distribution as revealed through polarized OTR.
• Such strong asymmetry also seen in the ODR data and simulations. Perpendicular component is better.
• The broken A.D. symmetry at low gamma should be in the PSF calc. model.
• Five OTR stations in beamlines at Fermilab after feasibility evaluated by Lumpkin and Scarpine (PAC03).

Scarpine, Lumpkin, Tassoto, PAC05,7
OTR Station at Fermilab

V.E. Scarpine and A. H. Lumpkin
Example with 120-GeV Protons

- Intense beams imaged before the NUMI target.

First NuMI OTR Images

- OTR just upstream of target
- $9.4 \times 10^{12}$ 120 GeV protons/spill
- 8.4 $\mu$m Kapton + 0.17 $\mu$m Al foil
- Foil in beam $\sim$45 minutes at various intensities

Courtesy of V. Scarpine
Initial success on imaging 120 GeV protons @10^{13} ppp.
Model of OTR Divergence Effects

• Both single-foil and two-foil effects considered.
Antiprotons (Pbars) were less intense than proton beams, but still can be imaged in a transport line.
OTR Works for Intense Relativistic Hadrons, What About Heavy Ions (HI)?

- Is there sufficient charge crossing the interface so OTR could be detectable? Use $Q^2$ and $\beta^2$ dependencies.
- Can the thin foil survive the areal charge density levels? (Beamline exit windows and stripper foils do).
- 120-GeV protons, up to $10^{13}$ in a 10-µs batch in 1mm x 1mm spot on aluminized Kapton (6 µm). Screen survived 6 months in beam at Fermilab.
- Look at lobe angle like 80-keV electrons? Or other.
- Use ICCD, cooled CCD, or CMOS cameras to boost sensitivity to low signals.
- Use Forward OTR; with annular mirror? Out of stripper foil?
- What beam intensity levels used at GSI (and LHC)?
Proposed OTR Application to Heavy Ions

- Consider applying technologies and concepts for ions.
- Take advantage of charge state for OTR generation.

For a non-relativistic charge Q, traveling with velocity v, the spectral energy density of transition radiation is,

\[ W(\omega) = \frac{4 Q^2 \beta^2}{3\pi c}, \]

where \( \beta = \frac{v}{c} \) and c is the speed of light.

Ginzburg and Tsyovich, (1984)

Hypothesize \( Q^2 = (Ze)^2 \) where Z is the ion charge state and e is the magnitude of electron charge.

More than a “gedanken” experiment!
Table I. Comparison of various particle beam cases and estimated OTR photons generated for ions (Preliminary).

<table>
<thead>
<tr>
<th>Part.</th>
<th>E(MeV)</th>
<th>Q</th>
<th>β</th>
<th>γ</th>
<th>Y(ph/e)</th>
<th>N</th>
<th>Mult.</th>
<th>Photon #</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^-</td>
<td>0.080</td>
<td>1</td>
<td>0.63</td>
<td>1.15</td>
<td>2x10^{-6}</td>
<td>4x10^{11}</td>
<td>1</td>
<td>7x10^{5}</td>
<td>*Int.</td>
</tr>
<tr>
<td>e^-</td>
<td>150</td>
<td>1</td>
<td>0.99</td>
<td>300</td>
<td>2x10^{-3}</td>
<td>6x10^{9}</td>
<td>-</td>
<td>1x10^{7}</td>
<td>yes</td>
</tr>
<tr>
<td>p^+</td>
<td>120x10^{3}</td>
<td>1</td>
<td>0.99</td>
<td>129</td>
<td>10^{-3}</td>
<td>10^{11}</td>
<td>-</td>
<td>10^{8}</td>
<td>CID</td>
</tr>
</tbody>
</table>

MeV/u

<table>
<thead>
<tr>
<th>Part.</th>
<th>E(MeV)</th>
<th>Q</th>
<th>β</th>
<th>γ</th>
<th>Y(ph/e)</th>
<th>N</th>
<th>Mult.</th>
<th>Photon #</th>
<th>CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar^+</td>
<td>11.4</td>
<td>10</td>
<td>0.15</td>
<td>1.01</td>
<td>10^{-6}</td>
<td>10^{10}</td>
<td>5.3</td>
<td>5x10^{4}</td>
<td>*Int.</td>
</tr>
<tr>
<td>U^+</td>
<td>11.4</td>
<td>28</td>
<td>0.15</td>
<td>1.01</td>
<td>10^{-6}</td>
<td>10^{11}</td>
<td>42</td>
<td>4x10^{6}</td>
<td>*Int.</td>
</tr>
<tr>
<td>U^+</td>
<td>300</td>
<td>73</td>
<td>0.65</td>
<td>1.21</td>
<td>10^{-6}</td>
<td>10^{9}</td>
<td>5329</td>
<td>5x10^{6}</td>
<td>*Int.</td>
</tr>
</tbody>
</table>

*Use intensifier for gain and the gating feature. More discussions later today. Also the ion intensity increases projected for FAIR look even better for photon numbers. The Multiplier (Mult.) column is the estimated scaling with Q^2\beta^2.
ODR Basics

- Diffraction radiation is produced when a charge moving at constant velocity *passes nearby* a boundary between media with different dielectric constants.

- Diffraction radiation (DR) is produced by the interaction between the EM fields of the traveling charge and the conducting screen.
  *the image charge currents radiate, ODR is radially polarized.*

- The extension of the electromagnetic field of a relativistic particle is a flat circle of diameter $\frac{\gamma \lambda}{2\pi}$.

- The radiation intensity is:
  $$ I \propto e^{-\frac{2\pi a}{\gamma \lambda}} $$

- DR impact parameter is:
  $$ \frac{\gamma \lambda}{2\pi} \rightarrow \text{if } a \geq \frac{\gamma \lambda}{2\pi} \text{ No radiation} $$
  $$ \text{if } a \approx \frac{\gamma \lambda}{2\pi} \text{ DR} $$
  $$ \text{if } a \ll \frac{\gamma \lambda}{2\pi} \text{ TR} $$

Enrica Chiodroni
LNF - INFN
Possible Beam Diagnostics

Diffraction Radiation Observables
- Near field (at or near target) intensity
- Far field angular distribution
- Polarization
- Frequency spectrum
- Interference between radiation from 2 sources

These can be combined to measure potentially
- Beam size
- Beam position
- Beam divergence
- Energy

Recent measurements at KEK, APS, FLASH, CEBAF
Interest at other labs: BNL
Further ODR Studies Proposed

- Path to test near-field imaging on 10-µm size at 23 GeV.
## ODR Demonstrations

<table>
<thead>
<tr>
<th>Technique, Near or Far field</th>
<th>Beam Energy (GeV)</th>
<th>Beam size (μm)</th>
<th>Charge</th>
<th>Detector</th>
<th>Div. (μrad)</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slit in plane, F</td>
<td>1.2</td>
<td>10-14</td>
<td>1 nC</td>
<td>PMT, scan</td>
<td>1.5</td>
<td>KEK</td>
</tr>
<tr>
<td>Slit in plane, F</td>
<td>0.68, 0.90</td>
<td>85**</td>
<td>30 nC</td>
<td>Cooled CCD</td>
<td>80</td>
<td>INFN/FLASH</td>
</tr>
<tr>
<td>Single plane, N</td>
<td>7</td>
<td>1300</td>
<td>3 nC</td>
<td>CCD</td>
<td>70</td>
<td>APS/ANL</td>
</tr>
<tr>
<td>Single plane, N</td>
<td>4.5</td>
<td>120</td>
<td>80 μC</td>
<td>CCD</td>
<td></td>
<td>FNAL/CEBAF</td>
</tr>
<tr>
<td>Slit in plane, N</td>
<td>0.90</td>
<td>200</td>
<td>30 nC</td>
<td>Cooled CCD</td>
<td>80**</td>
<td>FNAL/INFN</td>
</tr>
<tr>
<td>Two planes, F</td>
<td>0.90</td>
<td>89</td>
<td>30 nC**</td>
<td>Cooled CCD</td>
<td>150</td>
<td>INFN/FLASH</td>
</tr>
<tr>
<td>Two-1/2 Planes</td>
<td>1.2, 0.9</td>
<td>10, 90</td>
<td></td>
<td>Cooled CCD</td>
<td></td>
<td>KEK, INFN</td>
</tr>
</tbody>
</table>
ODR is a Potential Nonintercepting Diagnostic for GeV Lepton Beams and TeV Hadron Beams

- At left, schematic of ODR generated from two vertical planes (based on Fig.1 of Fiorito and Rule, NIM B173, 67 (2001). We started with a single plane.
- At right, calculation of the ODR light generated by a 7-GeV electron beam for $d = 1.25$ mm in the optical near field based on a new model (Rule and Lumpkin).

\[ a/2 = d \sim \gamma \lambda / 2\pi \]
An Analytical Model has been Developed by D. Rule for ODR Near-Field Distributions Based on the Method of Virtual Quanta

- We convolved the electron beam’s Gaussian distribution of sizes $\sigma_x$ and $\sigma_y$ with the field expected from a single electron at point $P$ in the metal plane (J.D. Jackson)

$$\frac{dI}{d\omega}(u, \omega) = \frac{1}{\pi^2} \frac{q^2}{c} \left( \frac{c}{v} \right)^2 \alpha^2 N \frac{1}{\sqrt{2\pi\alpha^2}} \frac{1}{\sqrt{2\pi\alpha^2}} \times$$

$$\int \int dx dy \ K_1^2(\alpha b) e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{y^2}{2\sigma_y^2}},$$

where $\omega =$ radiation frequency, $v =$ electron velocity $\approx c =$ speed of light, $q =$ electron charge, $N$ is the particle number, $K_1(\alpha b)$ is a modified Bessel function with $\alpha = 2\pi/\gamma\lambda$ and $b$ is the impact parameter.

APS Test Summary

- Electron beam energy = 7GeV, $\gamma = 13,699$
- Bunch intensity $\sim 1.9 \times 10^{10}$ (3 nC)
- Beam sizes: $\sigma_x = 1375$ μm, $\sigma_y = 200$ μm
- Typical impact parameter $\sim 5 \sigma_y$
- Wavelength $\lambda \sim 0.4$-0.8 μm
- Sensitive to horizontal offsets of 50-100 μm
- Sensitive to beam size changes of 20%
7-GeV Test at APS

Lumpkin et al., PRST-AB (Feb. 2007)
Perpendicular ODR Polarization Component Gives More Direct Representation of Beam Size.

- Quadrupole current scan provides beam-size scan.

- ODR size tracks OTR or bunch real size
- ODR/OTR ratio function of ODR PSF

ODR Also Has Good NI Beam-Position Sensitivity Using Orthogonal Polarization Component

- OTR and ODR Image Centroid versus Horizontal rf BPM values are linear.

- ODR also BPM
CEBAF Beam Offers Extended Parameter Space to Test an NI Beam-size Monitor for Operations.

- CEBAF beam size is 10 times smaller and the charge is 1000 times greater than APS case. What are background sources?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APS</th>
<th>CEBAF</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>7</td>
<td>1- 5</td>
<td>5, 250</td>
</tr>
<tr>
<td>X Beam size (μm)</td>
<td>1300</td>
<td>100-150</td>
<td>300, 30</td>
</tr>
<tr>
<td>Y Beam size (μm)</td>
<td>200</td>
<td>100-150</td>
<td>15, 2</td>
</tr>
<tr>
<td>Current (nA)</td>
<td>6</td>
<td>100,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Charge/ 33 ms (nC)</td>
<td>3</td>
<td>3,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

A. Lumpkin et al., PAC07
Basic ODR images at 10 µA CW

Polarization Component effects are very clear in ODR.

Hpol.: Double lobe

Total: $\sigma_x = 996 \, \mu m$

Vpol.: $\sigma_x = 609 \, \mu m$
• Effects of vertical polarizer and 550x10 nm Bandpass filter on ODR profile size are shown.

• ODR size tracks OTR and flying wire (FW) size, better V-pol. and 550nm filter
Further ODR Studies Proposed

- Path to test near-field imaging on 10-µm size at 23 GeV.
Proposed FACET test at 23 GeV

- New parameter space for ODR tests provided at FACET.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APS</th>
<th>CEBAF</th>
<th>ILC</th>
<th>FACET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>7</td>
<td>1-5</td>
<td>5, 15, 250</td>
<td>23</td>
</tr>
<tr>
<td>X Beam size (μm)</td>
<td>1300</td>
<td>80-100</td>
<td>300, 150, 30</td>
<td>10</td>
</tr>
<tr>
<td>Y Beam size (μm)</td>
<td>200</td>
<td>80-100</td>
<td>15, 8, 2</td>
<td>10</td>
</tr>
<tr>
<td>Current (nA)</td>
<td>6</td>
<td>100,000</td>
<td>50,000</td>
<td>30</td>
</tr>
<tr>
<td>Charge/ 33 ms (nC)</td>
<td>3</td>
<td>3,000</td>
<td>10,000</td>
<td>3</td>
</tr>
</tbody>
</table>

- FACET parameters more similar to ILC parameter.
- Scaling from APS test at 7 GeV indicates signals OK.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APS</th>
<th>FACET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge (nC)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rep, rate (Hz)</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>Beam size (um)</td>
<td>1300 x 200</td>
<td>10 x 10</td>
</tr>
<tr>
<td>$\gamma \lambda/2\pi$ (mm)</td>
<td>1.4</td>
<td>4.6</td>
</tr>
<tr>
<td>5 sigma-y (mm)</td>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>CCD</td>
<td>8 bit</td>
<td>12 bit</td>
</tr>
</tbody>
</table>
ODR model: FACET Case

- **Vertical polarization component, lambda= 800 nm, IP= 100, 50 µm. Curves for 10, 20, 35, 50,100 µm.**

- **Better sensitivity predicted for IP=50µm (≈5σ_r)**
Parallel polarization component shows beam-size effect at 10-µm regime. Curves for 10, 20, 35, 50, 100 µm.

H-Pol “valley” also sensitive to bunch size
• More sensitive with IP=50µm (small $\sigma_x$)
• New OTR converter using aluminized Kapton for the 20-mm aperture was prepared at Fermilab Thin Films lab by Eileen Hahn. About 1500 Angstroms of Al deposited by evaporation method on a stretched 6-µm thick Kapton film for CEBAF experiments. (possibly for GSI).

• New ODR converter was prepared by sputtering a 600 Angstrom Al coating on a 300-µm thick Si wafer cut for <100> plane. (Possibly use same type at FACET.)
Deconvolution of Profile

- ODR Point spread function (PSF) may be defined for optical system so can deconvolve from observed image.

- Beam profile and not only size and position can (potentially) be measured with NI ODR!!

• NML examples for beam-size monitor for $\sigma_x=200 \, \mu m$ (L) and $400 \, \mu m \pm 20\%$ (R) with $\sigma_y=200 \, \mu m$, $d = 5 \sigma_y$, and $\gamma=1000$. 

Courtesy of C.-Y. Yao, ANL
ODR Model Shows Wavelength Effect

- Examples for beam-size monitor for \( \sigma_x = 400 \pm 20\% \) \( \mu m \) with \( \sigma_y = 400 \mu m \), \( d = 12 \sigma_y \), and \( \gamma = 1000 \). \( \lambda = 0.8 \mu m \) (left) and 10 \( \mu m \) (right).

Perpendicular Polarization

Courtesy of C.-Y. Yao, ANL
ODR Model Shows Beam-size Effects

- LHC examples for beam-size monitor for $\sigma_x=800 \text{ µm}$ and varying $d$ from 4.8-8 mm (L), and with $\sigma_x=800 \text{ µm} \pm 20\%$, $\sigma_y=800 \text{ µm}$, $d = 6 \sigma_y$, $\lambda=1.0 \text{ µm}$, and $\gamma=7500$ (R).

Perpendicular Polarization

Legend: $\sigma_x$ symbol: simulated, line: Gaussian fitted.

Courtesy of C.-Y. Yao, ANL
SUMMARY

• Extensive experience with OTR imaging of relativistic leptons and some with hadrons provides base for diagnostic applications.

• OTR polarization effects need to be elucidated, and the microbunching instability COTR discussed Monday is a challenge for imaging bright beams. (Mitigation options).

• OTR imaging seems to have potential for intense, non-relativistic heavy ion beams in many GSI-FAIR cases. Follow-up needed.

• Demonstrations of ODR imaging for leptons done in several labs and parameter sets. Further tests at FACET and NML proposed.

• Modeling done for ODR imaging of hadrons in principle, but not very practical in rings, possibly in transport lines.

• The future still remains bright for imaging techniques for charged-particle beam diagnostics.
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