Radiation Sources and their Application for Beam Profile Diagnostics

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- Introduction to Imaging
- Transverse Profile Measurements based on OTR and ODR
- Parametric X-Ray Radiation
- Coherent Radiation Diagnostics and Smith-Purcell Radiation
Size Measurements

- **task**
  - determination of beam profile
    - measurement of characteristical size (rms, …)

- **conventional size measurement**
  - take object and measure

- **difficulties**
  - object extremely small
  - object not directly accessible
    - inside vacuum beam pipe, accelerator environment, …

- **optical imaging**
  - generate replica in comfortable environment
  - adjust replica size (image) to size of measuring device (CCD)

courtesy: J. Amundson (FNAL)
Imaging and Resolution

- **neglect lens imperfections (aberrations)**
  - **diffraction limited** systems → high quality, aberration-free systems

- **fundamental resolution limit**
  - point observer detecting photons from point emitter → location of emission point?

  - uncertainty principle: \( \Delta x \cdot \Delta p_x \approx \hbar \)
  - high resolution: (i) small \( \lambda \) (ii) high NA

- **image of point source**

  - point-like object
  - magnification \( M \)
  - Airy pattern

\[
\Delta x = 0.61 \frac{M\lambda}{\sin \vartheta}
\]
Fundamentals of Image Formation

- **detailed resolution information**
  - requires basic knowledge of image formation

- **simple imaging setup**

- **procedure**
  - calculate image of point source (single particle radiation) → **Point Spread Function (PSF)**
  - image of extended object → 2-dim. convolution of source distribution and PSF
  - resolution → difference between source distribution and image (resp. PSF)

- **PSF calculation**
  - el. field in source plane
  - field propagation from element to element → in frame of scalar diffraction theory
    - (i) source plane – lens input
    - (ii) lens input – lens output
    - (iii) lens output – image plane
  - intensity distribution in the image plane
Fundamentals of Image Formation

- **source field**
  - radiation field → depends on mechanism of radiation generation

- **propagation**
  - scalar diffraction theory
    - (here: from source to lense plane)
      \[
      E_{x_i, y_i}^l(\vec{r}_i, \omega) = -i \frac{e^{ika}}{\lambda a} \cdot e^{i \frac{k}{2a}(x_i^2 + y_i^2)} \int \int d\xi d\eta \, E_{x_i, y_i}^s(\vec{r}_s, \omega) \cdot e^{i \frac{k}{2a}(x_s^2 + y_s^2)} \cdot e^{-i k \frac{x_i y_i}{a}}
      \]
    - aperture boundaries
  - far field (Fraunhofer) approximation:
    \[
    \frac{k}{2}(x_s^2 + y_s^2)_{\text{max}} \ll a
    \]
    \[
    E_{x_i, y_i}^m(\vec{r}_i, \omega) = -i \frac{e^{ika}}{\lambda a} \cdot e^{i \frac{k}{2a}(x_i^2 + y_i^2)} \int \int d\xi d\eta \, E_{x_i, y_i}^s(\vec{r}_s, \omega) \cdot e^{-i(k x_i + k y_i)} \propto \mathcal{F}(E_{x_i, y_i}^s) \quad \left( k_{x,y} = \frac{k x_i y_i}{a} \right)
    \]
  - basis of Fourier Optics

- **thin lens approximation**
  - quadratic phase shift:
    \[
    E_{x_i, y_i}^{l_w}(\vec{r}_i, \omega) = E_{x_i, y_i}^{l_n}(\vec{r}_i, \omega) \cdot e^{-i \frac{k}{2f}(x_i^2 + y_i^2)}
    \]
    with \[
    \frac{1}{f} = \frac{1}{a} + \frac{1}{b}
    \]

- **intensity**
  \[
  \frac{d^2 W}{d\omega d\Omega} = \frac{c}{4\pi^2} \left( |\overline{E}_{x_i}^i(\vec{r}_i, \omega)|^2 + |\overline{E}_{y_i}^i(\vec{r}_i, \omega)|^2 \right)
  \]
Image Formation: Systems Approach

- **Image formation**

  \[ \text{Image} = \text{PSF} \otimes \text{Object} + \text{Noise} \]

  - Point Spread Function (PSF)
    - image of a point source (single particle)
    - characteristic of the imaging instrument
    - deterministic function
  - Noise
    - nondeterministic function
    - described in terms of statistical distributions

- **Systems approach to imaging** (Fourier Optics)

  - „standard“ signal theory
    - 1-dim. signals (in time domain)
    - system analysis with **delta pulse**
  - Imaging
    - 2-dim. signals (in spatial domain)
    - system analysis with **point source**
    - system response: **PSF**
Radiation Generation: Considerations

- radiation generation via particle interaction with matter
  - luminescent screen monitors

- radiation generation via particle electromagnetic field
  - particle electromagnetic field
  - relativistic contraction characterized by Lorentz factor

\[ \gamma = \frac{E}{m_0c^2} \]

\( \gamma \rightarrow \infty: \) plane wave

- \( mc^2 = 0 \text{ MeV} : \) light \( \rightarrow \) „real photon“
- ultra relativistic energies: idealization \( \rightarrow \) „virtual photon“

\( m_p c^2 = 938.272 \text{ MeV} \)
\( m_e c^2 = 0.511 \text{ MeV} \)
Separation of Particle Field

- electromagnetic field bound to particle observation in far field (large distances)

separation mechanisms

- bending of particle via magnetic field
  synchrotron radiation

  ⇒ circular accelerators

linear accelerators: no particle bending!

- diffraction/reflection of particle electromagnetic field via material structures
  exploit analogy between real/virtual photons:
  - light reflection/refraction at surface ↔ backward/forward transition radiation (TR)
  - light diffraction at edges ↔ diffraction radiation (DR)
  - light diffraction at grating ↔ Smith-Purcell radiation
  - light (X-ray) diffraction in crystal ↔ parametric X-ray radiation (PXR) …
**Synchrotron Radiation**

- **circular accelerator:** radiation source available for free
  - bending magnet (wiggler, undulator)

- **non-invasive**

- **strong collimation (vertical)**
  - opening angle: \( \Psi \propto 1/\gamma \)

- **emission over wide spectral range**
  - choice of operational range

  ![Graph showing spectral power density vs photon energy](image)

  \[ h\omega_c = \frac{3}{2} \frac{hc^3}{\rho} \]

  - electron
  - proton

  \( E_{\text{kin}} = 20 \text{ GeV} \)
  \( \rho = 370 \text{ m} \)

- **polarized**
  - define vertical angular divergence

  ![Graph showing radiation field vs angle](image)

- **particle beam diagnostics:** resolution
  - electric field propagation through optical elements → radiation field

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**SR Field: Standard Text Book**

- **source field:** particle field described by Liénard-Wiechert potentials:

\[
\varphi(t) = \left(\frac{-e}{R(1 - \hat{n} \cdot \beta)}\right)_t, \quad \vec{A}(t) = \left(\frac{-e \hat{\beta}}{R(1 - \hat{n} \cdot \beta)}\right)_t
\]

- **field derivation:**

\[
E(t) = -\vec{\nabla} \varphi(t) - \frac{1}{c} \frac{\dot{\vec{A}}(t)}{c}, \quad \vec{H}(t) = \vec{\nabla} \times \vec{A}(t)
\]

\[
\vec{E}(t) = -e \left(\frac{(1 - \hat{n}^2)(\hat{n} - \beta)}{R^2(1 - \hat{n} \cdot \beta)} + \frac{\hat{n} \times \left[\hat{n} \times \beta\right]}{cR(1 - \hat{n} \cdot \beta)^3}\right)_t, \quad \vec{H}(t) = \hat{n} \times \vec{E}(t)
\]


- **neglect velocity term** (far field approximation)

- **Fourier transform:**

\[
\vec{E}(\omega) \approx -\frac{i \omega e}{c R} \int_{-\infty}^{+\infty} d\tau \left[\hat{n} \times \left[\hat{n} \times \beta\right]\right] e^{i\omega(\tau + R(\tau)/c)}
\]

- **special case:** charged particle moving on circular orbit

\[
E_x(\omega) = E_x = A_x \frac{\hbar \omega}{2\hbar \omega_c} \left(1 + \gamma^2 \Psi^2\right) K_{2/3} \left[\frac{\hbar \omega}{2\hbar \omega_c} \left(1 + \gamma^2 \Psi^2\right)^{3/2}\right]
\]

\[
E_y(\omega) = E_y = A_y \frac{\hbar \omega}{2\hbar \omega_c} \gamma \Psi \sqrt{1 + \gamma^2 \Psi^2} \cdot K_{1/3} \left[\frac{\hbar \omega}{2\hbar \omega_c} \left(1 + \gamma^2 \Psi^2\right)^{3/2}\right]
\]

- **analytical field description**

- **comments:**

(i) approximative field description → far field approximation

(ii) emission from single point on orbit → additional contributions: depth of field, orbit curvature

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Synchrotron Radiation Field

- Second representation: starting point again Liénard-Wiechert potentials

\[
\varphi(t) = \left( -\frac{e}{R(1 - \hat{n} \cdot \hat{\beta})} \right), \quad \vec{A}(t) = \left( -\frac{e \vec{\beta}}{R(1 - \hat{n} \cdot \hat{\beta})} \right)
\]

- Fourier transform of potentials:

\[
\varphi(\omega) = -e \int_{-\infty}^{+\infty} \frac{1}{R(\tau)} e^{i\omega(\tau + R(\tau)/c)} d\tau, \quad \vec{A}(\omega) = -e \int_{-\infty}^{+\infty} \frac{\vec{\beta}(\tau)}{R(\tau)} e^{i\omega(\tau + R(\tau)/c)} d\tau
\]

- Field derivation:

\[
\vec{E}(\omega) = -\frac{i\omega e^{+\infty}}{c} \int_{-\infty}^{+\infty} d\tau \left[ \left( \frac{\vec{\beta} - \hat{n}}{R(\tau)} \right) - \frac{ic}{\omega} \frac{\hat{n}}{R^2(\tau)} \right] e^{i\omega(\tau + R(\tau)/c)}
\]

with \( \tau = \int_{0}^{\tau} \frac{dz}{c\beta(z)} = \frac{1}{c} \int_{0}^{\tau} \left[ 1 + \left( \gamma \beta_x \right)^2 + \left( \gamma \beta_y \right)^2 \right] \frac{dz}{2\gamma^2} \)

Knowledge of arbitrary particle orbit: \( \vec{E}(\omega) \) determined

Arbitrary magnetic field configuration: determines orbit and \( \vec{E}(\omega) \)

- Comments:
  (i) exact field description \( \rightarrow \) numerical near field calculation
  (ii) includes depth of field & curvature \( \rightarrow \) no additional contributions, only field propagation
  (iii) free codes available \( \rightarrow \) easy field calculation, even field propagation!

Light Sources: Emittance Diagnostics

emittance  
typical values  $\varepsilon_x = 1\text{-}5 \text{ nm.rad}$ and $1\%$ emittance coupling

example:  $s_{\text{hor}} = 40 \text{ mm}$, $s_{\text{vert}} = 20 \text{ mm}$  (PETRA III @ DESY)

fundamental resolution limit (uncertainty principle)

optical imaging:  $l = 500 \text{ nm}$ and  $D\Psi \approx 1.7 \text{ mrad}$  $D_{\text{vert}} = 145 \text{ mm}$  

diffraction limited

X-ray imaging: focusing optics

reflective optics  
Kirkpatrick-Baez mirrors,…

diffractive optics  
Fresnel zone plates,…

refractive optics  
Compound Refractive Lenses (CRL)

X-ray imaging: non-focusing optics

pinhole camera  
example: Diamond Light Source


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Light Sources: Emittance Diagnostics

**SR interferometer**

T. Mitsuhashi, Proc. of BIW 2004 Knoxville, Tennessee, p.3

USR studies at PETRA III (DESY):

\[ \varepsilon_x = 160 \text{ pm.rad} \quad @ \text{3 GeV} \]

**π-polarisation imaging**


widely applied @ SLS

**coded aperture imaging**


C. Bloomer, "Coded Aperture @ DLS", TUCZB2
Constant Linear Motion

- **source field**
  - point charge with **constant** velocity \( v \) \( \rightarrow \) Liénard-Wiechert fields
    \[
    \vec{E}(t) = -e \left( \frac{1-\beta^2}{R^2 (1 - \hat{n} \cdot \hat{\beta})} \hat{\beta} + \frac{\hat{n} \times \left( \frac{\hat{n} - \hat{\beta}}{cR(1 - \hat{n} \cdot \hat{\beta})} \right)}{cR} \right),
    \]
    \( \vec{H}(t) = \hat{n} \times \vec{E}(t) \)
    no acceleration term

- common representation \( \rightarrow \) cylindrical coordinate system
  \[
  \vec{E}(\rho, \varphi, z, \omega) = \frac{e\alpha}{\pi v} e^{i\omega z} \left( K_1(\alpha\rho) \hat{\rho} - i K_0(\alpha\rho) \hat{z} \right)
  \]
  with \( \alpha = \frac{\omega}{\gamma v} = \frac{2\pi}{\lambda\beta\gamma} \)

- ultra-relativistic particles \((\gamma \gg 1)\)
  - neglect longitudinal field component
  - pure transverse “pancake“ structure
  - radial extension: \( \alpha\rho \approx 1 \)

  \[
  \rho = \frac{\lambda\beta\gamma}{2\pi} \approx \gamma\lambda
  \]
  virtual photon range

- angular distribution

3-dim. theories
D.V. Karlovets and A.P. Potylitsyn, Nucl. Instr. and Meth. B266 (2008) 3738 \ ...........

- separation of field \( \rightarrow \) different radiation sources

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**Transition Radiation**

- **transition radiation**: electromagnetic radiation emitted when a charged particle crosses boundary between two media with different optical properties

- **visible part**: Optical Transition Radiation (OTR)

- **beam diagnostics**: backward OTR
  typical setup: image beam profile with optical system

- **advantage**: fast single shot measurement
  linear response (neglect coherence !)

- **disadvantage**: high charge densities may destroy radiator
  → limitation on bunch number

- **field separation mechanism**
  → reflection at boundary (perfect conductivity)

→ reflected and incident field are the same
OTR Monitor Resolution

- PSF calculation in image plane
  - Field propagation in frame of scalar diffraction theory
    \[ E_{x_i,y_i}^{l}(\vec{r}_i,\omega) = -i \frac{e^{ika}}{\lambda a} \cdot e^{i\frac{k}{2a}(x_i^2+y_i^2)} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dx_s dy_s E_{x_s,y_s}^{l}(\vec{r}_s,\omega) \cdot e^{i\frac{k}{2a}(x_s^2+y_s^2)} \cdot e^{-\frac{a}{4}x_s x_i+y_s y_i} \]

  - Care: screen dimension ↔ field extension \( \gamma \lambda \)
    → might modify radiation properties

- OTR resolution for beam imaging (far field)

  - Resolution definition according to classical optics:
    \[ \Rightarrow \text{first minimum of PSF} \]
    \[ \Rightarrow \text{diameter of Airy disk} \]
    \[ R_{i0} \approx 1.12 \frac{M \lambda}{\theta_m} \]
    - \( M \): magnification
    - \( \theta_m \): lens acceptance angle (NA)
    - \( \theta_m \) determined by optics, not by radiation properties!

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A.P. Potylitsyn, in "Advanced Radiation Sources and Applications", p.149
G. Kube, TESLA-FEL Report 2008-01
G. Stupakov, SLAC-PUB-14758 (2011) …….
**OTR Monitors**

**example: FLASH @ DESY**

![Diagram of OTR Monitors]

- **optical system**
  - | magnification | f / mm | a / mm | b / mm |
  - | 1 | 250 | 500 | 500 |
  - | 0.382 | 200 | 724 | 276 |
  - | 0.25 | 160 | 800 | 200 |

**screen shot: 6 DBC2**

**standard monitors @ e-Linacs**

- **10 keV:** R.B. Fiorito et al., Proc. PAC 2007, p.4006
- **30 GeV:** P. Catravas et al., Proc. PAC 1999, p.2111

**OTR @ hadron accelerators**

- **protons:** O.V. Afanasyev et al., Proc. BIW 2006, p.534
  V.E. Scarpine et al., Proc. BIW 2006, p.473
- **heavy ions:** B. Walasek-Höhne et al., Proc. HB 2012, p.580

K. Honkavaara et al., Proc. PAC 2003, p.2476

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**COTR and possible Mitigation**

unexpected Coherent OTR observation during LCLS commissioning

- strong shot-to-shot fluctuations
- doughnut structure
- change of spectral contents

measured spot is no beam image!

text continues...

interpretation of coherent formation in terms of “Microbunching Instability”

- E.L. Saldin et al., NIM A483 (2002) 516

alternative schemes for transverse profile diagnostics

- short term perspective: scintillating screen monitors
- long term perspective: TR imaging at smaller $\lambda$

proof of principle experiment @ $\lambda = 19.6$ nm:

additional advantage of better resolution

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courtesy:

H. Loos (SLAC)

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E.L. Saldin et al., NIM A483 (2002) 516


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L.G. Sukhikh et al., Proc. IPAC 2012, New Orleans (USA), p. 819

and submitted to PRST-AB
**PSF dominated Imaging**

- **Image formation**
  - standard imaging:
    - minimize PSF contribution → image is true replica of object

- **PSF dominated imaging**
  - object size $\ll$ PSF
    - image dominated by PSF properties
  - non-zero object size
    → smearing out of PSF
    → beam size determination via image contrast
  - resolution below diffraction limit
    → resolve sub-micron beam sizes with optical methods

- **Experimental verification**
  - synchrotron radiation → $\pi$-polarisation imaging
  - OTR → test experiment @ ATF2

\[\text{minimize measured beam size (0.754 ± 0.034) \mu m}\]
**Diffraction Radiation**

- **problem OTR:** screen degradation/damage
  
  → limited to only few bunch operation, no permanent observation

- **Optical Diffraction Radiation (ODR):** non-intercepting beam diagnostics
  
  - DR generation via interaction between particle EM field and conducting screen
    
    → diffraction of „virtual photons“

- **radial field extension**
  
  → radius $\lambda\beta\gamma / 2\pi \approx \lambda\gamma$

- **limiting cases**
  
  \[ a \gg \lambda\gamma : \text{no radiation} \]
  \[ a \approx \lambda\gamma : \text{DR} \]
  \[ a \ll \lambda\gamma : \text{TR} \]

- **comment:** ODR in circular accelerator (CesrTA, Cornell)

**ODR Imaging**

- **PSF calculation in image plane**
  - field propagation in frame of scalar diffraction theory
    - no beam image, illuminated edge of half-plane

- **ODR imaging for beam diagnostics**
  - P. Evtushenko et al., Proc. BIW08, WECOTC01 (2008), p.332
  - (relative) 1D beam size monitor: \( \sigma_x \)
    - (i) Gaussian beam profile
    - (ii) known distance between slit edge and beam center
    - pre-defined ROI: projected 1D intensity profile
    - fit profile with Gaussian distribution \( (\sigma_x) \)
    - cross-calibrate \( \sigma_x \) with OTR beam profiles

- **1D beam position monitor**
  - ODR centroid
  - achieved sensitivity: 50-100 \( \mu \text{m} \)
    - \( \sigma_x = 1.3 \text{ mm}, \) depends on beam size


PSF for vertical polarized ODR from semi-infinite plane

courtesy: P. Evtushenko (JLab)
ODR Angular Distribution

angular distribution dependence

▶ on beam size
▶ on beam offset
  → beam centered in slit aperture
▶ on beam divergence x'
  → interferometric methods

1D beam size determination \( (\sigma_y) \)


▶ very low emittance beam \( (\varepsilon_y = 1.5 \times 10^{-11} \text{ m.rad}) \) @ KEK-ATF, centered in slit
▶ exploit visibility \( I_{\text{min}} / I_{\text{max}} \) of projected vertical polarization component

courtesy: E. Chiadroni (INFN)

sensitive on beam size \( \sigma_y \approx 10 \mu m \)

courtesy:
  P. Karataev (RHUL)
  A. Potylitsyn (TPU)
ODR Interferometry

beam divergence: DR / ODTR interferometer


ODRI: 1D beam size determination @ FLASH (DESY)


- compact double slit arrangement
- both slits with different sizes
  second slit within radiation formation length of first one
- $\sigma_y, \sigma_{y'}$ and offset by complex fit routine

$\lambda = 800$ nm

excellent agreement
**Parametric X-Ray Radiation (PXR)**

- **idea:** higher photon energies $\hbar \omega$
  - better resolution
  - insensitive on coherent effects

- **real photons**
  - X-rays $\leftrightarrow$ Bragg reflection, crystals

- **virtual photons**
  - field separation by Bragg reflection at crystal lattice
  - $\rightarrow$ radiation field: **Parametric X-Ray Radiation (PXR)**

- **crystal periodicity (3D)**
  - discrete momentum transfer (reciprocal lattice vector $\vec{\tau}_{hkl}$)
  - $\rightarrow$ emission of line spectrum

\[
\begin{align*}
\vec{p}_i &= \vec{p}_f + \hbar \vec{k} + \hbar \vec{\tau}_{hkl} \\
\delta E &= \left( \vec{p}_i - \vec{p}_f \right) \cdot \vec{v} = \hbar \vec{k} \cdot \vec{v} + \hbar \vec{\tau}_{hkl} \cdot \vec{v} = \hbar \omega \\
\hbar \omega_{hkl} &= \hbar c \left| \frac{\vec{\beta} \cdot \vec{\tau}_{hkl}}{1 - \sqrt{\varepsilon} \vec{\beta} \cdot \vec{k}} \right| \\
\varepsilon &= 1 - |\chi_0| \\
\text{dielectric constant (}\approx 1) \\
\end{align*}
\]

- **Si crystal**
  - $E = 855$ MeV
  - $\Theta_B = 22.5^\circ$


courtesy: M.J. Winter (Science Photo Library)
**Parametric X-Ray Radiation (PXR)**

- **PXR**: Bragg scattering of virtual photons
  - virtual photon properties retained
  - → double lobe angular distribution

- **radiation generation inside crystal**
  - material properties influence radiation characteristics
  - → angular width:
    \[
    \Delta \theta = \sqrt{\frac{1}{\gamma} + \left(\frac{\hbar \omega_p}{\hbar \omega}\right)^2}
    \]
    plasma energy \(\hbar \omega_p\)
    (Si: 31 eV)

- **background contribution**: real photon diffraction
  - transition radiation from crystal entrance surface
  - → diffracted at crystal planes under same Bragg angle

- **additional contribution to angular distribution**
  - DTR: smaller angular width

radiation amplitude:

\[
A_r = A_{cr} + R_A (A_v - A_{c0})
\]
PXR for Beam Profile Diagnostics

- **advantage of PXR diagnostics**
  - spatial separation from COTR background
    - OTR reflection wrt. surface normal \( \hat{n} \)
    - PXR reflection wrt. reciprocal lattice \( \hat{t} \)

- **proposals**

- **detection scheme (1)**
  - imaging with X-ray optics
    - sensitivity ?

- **detection scheme (2)**
  - X-ray scintillator/detector close to emission point
    - conversion of X-rays to visible light
      - allows usage of standard optics and CCD
    - parallel object and image plane
    - sensitivity, background ?

- **detection scheme (3)**
  - exploit angular distribution
    - requires exact knowledge of shape
      - PXR / DTR interference, …
    - additional background contributions ?

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PXR for Beam Profile Diagnostics

- **direct imaging with pinhole camera**
  - test experiment at SAGA Light Source (Japan)
    - 255 MeV linac beam, $f_{\text{rep}} = 1$ Hz, $I_{\text{avg}} = 7$ nA
    - Si crystal, $t = 20$ μm, (220) reflection @ 11.6 keV
  - OTR beam profile  →  PXR beam profile
    - single shot  →  12600 shots
    - 3.5 h exposure time
  - image plate as detector

- **detector close to emission point**
  - test experiment @ SAGA
    - image plate 55.6 mm from target crystal
    - 1 sec exposure time
    - image plate inside vacuum chamber
    - large background contribution
  - test experiment @ MAMI (Mainz, Germany)
    - scintillator close to target + CCD
    - sensitivity to low, no beam image
PXR Angular Distribution

- **angular distribution measurements**
  
  G. Kube et al., Proc. IPAC 2013, Shanghai, China, p.491

  - test experiment @ MAMI (Mainz, Germany)
    - 855 MeV, $I_{\text{avg}} = 500$ nA
    - use of low-cost X-ray CCD
    - (100)-cut Si-crystal, $t = 50$ μm
    - $\hbar\omega(220) = 16.55$ keV, $\hbar\omega(400) = 23.40$ keV
    - two (out of 6) beam configurations
      
      Config 1: $\sigma_x = 45.7$ μm, $\sigma_y = 42.9$ μm
      
      Config 2: $\sigma_x = 44.7$ μm, $\sigma_y = 796$ μm

  - angular distribution sensitive on beam size

  - observation
    - $\theta_1$ independent on photon energy: $\theta_1 = 0.6$ mrad $\approx 1/\gamma$
    - additional lobes at $\theta_2 \sim 1.8$ mrad

  - interpretation
    - significant DTR contribution
    - additional contribution from diffracted bremsstrahlung ???
Longitudinal Profile Diagnostics

**Coherent Radiation Diagnostics (CRD)**
- standard method for radiation based bunch length diagnostics

long bunch $$(\lambda<\sigma_z)$$
short bunch $$(\lambda>\sigma_z)$$

**basic procedure**
- **principle**: bunch length/shape dependent emission spectrum of coherent radiation

\[
\frac{dU}{d\lambda} = \left( \frac{dU}{d\lambda} \right) \left( N + N(N-1)|F(\lambda)|^2 \right) \text{ with } F(\lambda) = \int_{-\infty}^{+\infty} dz S(z)e^{\frac{2\pi z}{\lambda}}
\]

- measure radiation intensity as function of wavelength in spectral region of interest
  - bunch length determination requires spectral decomposition of intensity
  - intensity-interferometer in THz region (Michelson or Martin-Puplett interferometer)
- Fourier transform
  - **bunch profile and bunch length**
- radiation generation
  - coherent radiation source: synchrotron radiation, transition radiation, diffraction radiation, Smith-Purcell radiation, Cherenkov radiation, …
Coherent Radiation Diagnostics

- **TR, DR or SR based CRD**
  - polychromatic emission spectrum
    - → spectrometer required for spectral decomposition
  - Michelson / Murtin-Puplett interferometers: scanning devices
    - → no single-shot capability

- **single-shot CRD**
  - extension to multi-stage single-shot grating spectrometer


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**pyro-electric line detector**
- 30 channels @ room temperature
- no window, works in vacuum
- fast read out
- sensitivity ~ 300 pJ (S/N=5)

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S. Wesch et al., Proc. BIW’12, Newport News (VA), USA, p.256
Smith-Purcell Radiation

- **idea**: dispersive radiation generation
  - radiation generation and analysis with one device
  - → compact setup, option for single-shot capability

**Smith-Purcell radiation (SPR)**
- field separation
  - → virtual photon diffraction at 1D
    Bravais-structure (grating)
  - → grating provides 1D discrete momentum

**momentum conservation**:
\[
\vec{p}_i = \vec{p}_f + \hbar k + \hbar \mathbf{n} \frac{2\pi}{D} \hat{\nu}
\]
\[
(\vec{p}_i - \vec{p}_f) \cdot \hat{v} = \hbar \omega = \hbar k \cdot \hat{v} + \hbar \mathbf{n} \frac{2\pi}{D} \hat{\nu} \cdot \hat{v}
\]
\[
2\pi \frac{c}{\lambda} = \frac{2\pi}{\lambda} \nu \cos \theta + n \frac{2\pi}{D} \nu
\]
\[
n \lambda = D \left( \frac{1}{\beta} - \cos \theta \right)
\]

→ **SPR dispersion relation**

- **distance dependence**
  - range of el. field: \( \lambda \beta \gamma / 2\pi \)
  - 2D field description: \( \vec{E} \propto e^{-\frac{2\pi \beta}{\lambda \gamma} d} \)
  - intensity scaling: \( I \propto |\vec{E}|^2 \propto e^{-\frac{4\pi \beta}{\lambda \gamma} d} \)

- **SPR identification**
  - dispersion relation: necessary condition
  - distance dependence: sufficient condition
SPR for Bunch Length Diagnostics

proposals


bunch length monitor based on SPR


similar setup

courtesy G. Doucas, V. Blackmore (Oxford)

measurement at 45 MeV, FELIX

critical items

- limited number of points for reconstruction → interferometer: typically about 200 points
- single photon emission spectrum → different model predictions, especially at high γ

Summary

- **radiation physics widely used for beam diagnostics**
  - longitudinal and transverse beam profiles
  - beam divergence, beam energy, …

- **circular accelerators: synchrotron radiation**
  - new 3rd generation light sources with ultra-small beam sizes
    - → X-ray imaging: possibility to measure beam sizes down to μm level

- **linear accelerators: working horse OTR (+ screens), ODR in experimental stage**
  - OTR: invasive measurement, usually resolution of about 10 μm
  - better resolution → smaller wavelengths (EUV), PSF-dominated imaging
  - new 4th generation light sources → coherent emission compromises use of OTR as reliable diagnostics
  - ODR: high resolution measurements via angular distribution → ODRI offers possibility to resolve ambiguities

- **PXR: interesting for X-ray region**
  - still in early experimental stage → first experiments in view of beam diagnostics

- **CRD: bunch length/shape measurements**
  - CTR, CDR, CSR → spectral decomposition with interferometers
  - CSPR → dispersive emission characteristic, but still some open questions…
Outlook

**commercial codes applied to radiation physics**

- TR generation with CST Particle Studio®
  

- OTR/ODR generation and propagation with ZEMAX®
  
  
  
  T. Aumeyr et al., Proc. IPAC 2014, Dresden, Germany, p.3722

**Surface Cherenkov Radiation**

- growing interest → as radiation source
  
- but also for beam diagnostics
  

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- for your attention