DIAGNOSTICS FOR ULTRA-LOW EMITTANCE BEAMS*

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Abstract

The achievement in recent years of beams with vertical emittance of a few pico-meter-radians in a number of electron storage rings has presented challenges for diagnostics capable of beam size measurements in this regime. A number of different approaches have been developed for various machines, e.g., laserwire, interferometer, Shintake monitor, coded aperture, compound refractive lens. This presentation will review and compare the different methods, and discuss their strengths, weaknesses, ultimate limitations, and the situations where they might be appropriate; and consider possible future directions.

LOW-EMITTANCE BEAMS

The current generation of low-emittance lepton rings in operation or construction, a few of which are listed in Table 1, have converged to a remarkable extent to a similar set of parameters: vertical emittances of 3-30 pm-rad, energies of one to a few GeV. The beam sizes over most of their rings are in the range of a few to 10 μm, being squeezed down to a few tens of nm at the interaction point in the case of colliders or collider study machines. (Note: the SuperB collider in Italy is being designed to serve both as a collider and as a 3rd-generation light source.)

Table 1: Some Ultra-Low Emittance Machines

Machine	ε_y (pm-rad) (min)	σ_y (μm) at monitor source point	Beam Energy (GeV)
Swiss Light Source	3	~6	2.4
ESRF	<2 (goal)	<10	6.03
Diamond	1.7	6	3
CesrTA (low-energy)	10-20	~10	2.085
ATF/ ATF2	~5-25	~4 (37 nm at FF)	1.3
SuperB LER / HER	~5	~9 (36 nm at IP)	4.18 / 6.7
Super-KEKB LER / HER	~10	~10 (48 / 62 nm at IP)	4 / 7

It is a challenge at these machines to measure vertical beam sizes on the order of microns in most places (tens of nm at the final focus of the ATF2 or interaction points of the B factories). Methods developed for measurements in this regime will be discussed in the next sections.

SR MONITORS

First we will consider beam size monitors based on measurements of the photons (visible or x-ray) generated by the passage of the beam through a bending magnet. Such monitors can be considered purely passive, using only photons that would have been generated anyway by the beam.

SR Imaging: Diffraction Limit on Resolution

The traditional resolution limit of an imaging system with a circular lens or aperture is given by the Rayleigh criterion:

$$\delta = 1.22\frac{\lambda L}{w} \quad (1)$$

where λ is the wavelength used, *w* is the diameter of the lens or other limiting aperture, whichever is smaller, and *L* is the distance from the object to the lens or aperture[1]. In this case, two objects separated by a distance δ lie just on each other's first Airy disk diffraction minimum. (Note that sometimes this is written with the focal length *f* in place of *L*; usually *f* is close to *L* in order to get a good magnification *M*, where $M = f/(f-L)$.) Another useful definition is to consider the width of the point-spread function due to an aperture. For a circular aperture, the intensity of the diffraction pattern in the small-angle approximation is the Airy pattern:

$$I = I_0\left[J_1\left(\frac{\pi}{\lambda}\frac{w}{L}y\right)\bigg/\left(\frac{\pi}{\lambda}\frac{w}{L}y\right)\right]^2 \quad (2)$$

where J_1 is a Bessel function and *y* is the position coordinate in the source plane. (Note that the diffraction pattern here is expressed as projected in the plane of the source; it could equivalently be, and often is, expressed in terms of its projection on the image plane, where *L* becomes the distance from the rear aperture to the image plane and *y* the vertical position in that plane. For our purposes here it is more convenient to consider its expression in the source plane, so that we can estimate the minimum theoretical measurable beam size for a given aperture and wavelength regardless of details of the detection system.) For a rectangular slit of width (height) *w*, and a distance to source *L*, the diffraction pattern is of the form

$$I = I_0\left[\sin\left(\frac{\pi}{\lambda}\frac{w}{L}y\right)\bigg/\left(\frac{\pi}{\lambda}\frac{w}{L}y\right)\right]^2 \quad (3)$$

where, again, *y* is the position coordinate in the source plane.

Next, one force fits a Gaussian to the point-spread function (PSF) (Eq. 2 or 3), and treats the width of the

Gaussian as a smearing term, σ_s, to be taken in quadrature with the beam size:

$$\sigma_m = \sqrt{\sigma_s^2 + \sigma^2} \quad (4)$$

where σ_m is the measured beam size and σ is the true beam size. In this case,

$$\sigma_s \approx 0.4 \frac{\lambda L}{w} \quad (5)$$

(The coefficient is a little bit larger than 0.4 for the circular aperture, and a little bit smaller for the rectangular aperture, but they both round off to 0.4.) This is about a factor of 3 smaller than the Rayleigh criterion (Eq. 1). In any event, both the Rayleigh criterion and the point-spread function width definitions are in common use in the literature.

Now, let's suppose that any mechanical apertures can be made as large as needed, so that the limiting angular aperture is determined by the opening angle of the synchrotron radiation. For a beam of energy *E* GeV, going through a dipole magnet with bending radius ρ, the natural limit of radiation spread at wavelength λ in the vertical direction is[2]:

$$\sigma_\psi = \begin{cases} 1.07[3\lambda/(4\pi\rho)]^{1/3} & ; \quad \lambda >> \lambda_c \\ 0.64/\gamma & ; \quad \lambda \approx \lambda_c \\ 0.58[3\lambda\gamma/(4\pi\rho)]^{1/2} & ; \quad \lambda << \lambda_c \end{cases} \quad (6)$$

Where λ_c is the critical wavelength. Substituting w/L = ~$2\sigma_\psi$ in Eq. 5, it can be seen that unless we have the freedom to change the energy of the beam or the bending radius of the source bend, the resolution will in principle be limited, ultimately, by the detection wavelength.

As a practical matter, the simplest type of system, based on readily-available visible-light optics (where, generally, $\lambda >> \lambda_c$), does not usually have the resolution needed to image the small beam sizes seen at ultra-low-emittance machines. For example, for a 3 GeV beam (γ=5871), with a source bend radius of 30 m, the smearing function σ_s becomes ~50 μm when imaging at 400 nm. Conversely, to get a σ_s of order 10 μm, when λ = 400 nm, would require ρ ~ 25 cm.

On the other hand, if one images using x-rays, better resolution is in principle achievable. For example, for the same *E* = 3 GeV and ρ = 30 m machine, if λ = 1 nm (1.24 keV x-rays), σ_s = ~2 μm. At λ = 10 nm (12.4 keV), σ_s = ~0.2 μm. Several efforts in this direction have been taken over the years.

X-ray imaging: Pinhole Optics

The simplest imaging system, especially for x-rays, is a pinhole or slit camera, and such systems have been installed at several machines. For pinhole optics, the resolution is a balance between the diffraction limit (hole too small) and geometric blurring (hole too large). An analytic approximation for optimizing the aperture size given these two constraints has been published and used at the ESRF[3][4]. A more detailed approach has been taken at Diamond[5], by calculating the Fresnel diffraction pattern due to the pinhole for a point source evenly illuminating the pinhole, over the spectrum seen by the detector. A Gaussian is then fit to the resulting PSF at the detector screen to calculate a smearing function, with additionally the detector resolution added in quadrature. In this way, a σ_s at the source of 6.4 μm has been achieved, and beam sizes of ~6 μm have been measured. It is expected that with further optimization of the pinhole size and improvement in the detector resolution, a σ_s of 2.9 μm can be achieved, with the majority of that resolution being limited by the $CdWO_4$ screen used for detection (which contributes 2.6 μm to the overall resolution in quadrature) and not by the pinhole itself (which contributes 1.33 μm). Incidentally, the peak of the x-ray spectrum after 1 mm Al window and 9 m air path is at 28 keV, so this is a relatively hard spectrum.

Focused imaging can use a larger aperture, not being limited by geometric smearing concerns, and hence can provide better resolution. The next two subsections will look at focused x-ray imaging systems.

X-ray imaging: Fresnel Zone Plate

The Fresnel Zone Plate (FZP) behaves similarly to a lens, needing a monochromator to avoid chromatic aberration. It consists of concentric alternating bands of open and filled regions, with the radius r_n of boundary *n* given by:

$$r_n \approx \sqrt{nf\lambda} \quad (7)$$

Where *f* is the focal length at wavelength λ. Constructive interference produces a focal point at the center, plus higher orders away from the center. Using the relationship between radius and zone width, the Rayleigh criterion for the FZP can be written as:

$$\delta = 1.22 \Delta r_N \quad (8)$$

Where Δr_N is the width of the outermost zone. To provide meaningful contrast at a few keV, typically one or more microns of thickness is needed in the masking material (typically gold or tantalum). The limit of resolution of the FZP is then determined by how thin an empty zone can be created in a mask of such thickness. In recent years zone plates with depth/width aspect ratios of 20 in their outer rings (zone width 45 nm, depth 900 nm) have been reported used up to 8 keV for x-ray microscopy. Consequently, the practical resolution limit does not need to be determined by lens fabrication issues but by the SR divergence angle, at least up to the several keV range.

At the ATF, a double lens telescope using two FZPs has constructed, with a resolution of less than 1 μm at an x-ray energy of 3.22 keV[7]. The optical magnification is 20, and the detector is an x-ray CCD with 24 mm x 24 mm pixels, and a mechanical shutter to limit the exposure time to 20 ms. With this system, two-dimensional beam images can be taken, and beams with σ_y = 6 μm and σ_x = 50 μm have been measured.

X-ray imaging: Refractive Optics

The FZP, due to limitations of the thickness of the mask material that can be used, is limited to lower-energy x-rays (~1 to several keV). If one has a much higher-energy x-ray source, in the few tens of keV, then it becomes possible to consider the use of refractive optics. Such a system, demonstrated at the ESRF[4], uses aluminium or beryllium lenses with rotational parabolic lens surfaces[8], which are *convex* lenses due to the index of refraction being below 1 in the x-ray range. However, due to the index of refraction being only slightly below 1, it is necessary to use a stack of many such lenses to get a usable focal length. The outer aperture of such a system is determined by the radius where half the x-rays are absorbed in the increasingly-thick lens as one moves away from the axis. The aluminum lenses at the ESRF have a Rayleigh diffraction limit of ~0.5 μm at 35 keV. The focal length is 3.25 m, and the magnification is 2.8, so the resolution of the detector would become the limiting factor if not less than 1.4 μm. However, the minimum possible expected beam size is ~7 μm (at 1 pm-rad emittance) or about 20 μm at the detector ($CdWO_4$ scintillator), so this should not be a problem.

Next we consider some non-imaging monitors: the SR interferometer, and the vertical polarization monitor, both of which operate in the visible-light regime. We will then look at a sort of "hybrid" monitor, the X-ray coded aperture monitor.

SR Non-Imaging: SR Interferometer

The SR interferometer, developed by T. Mitsuhashi at KEK[7], is based on the same principle as Michelson's stellar interferometer: using the smearing of an interference pattern by the finite size of a beam (or angular size of a star) to measure the extent of the source. For a two-slit interferometer, the complex degree of spatial coherency is the Fourier transform of the source intensity profile. For a Gaussian beam, the size is given as a function of visibility (peak-valley modulation) γ:

$$\sigma = \frac{\lambda}{\pi}\frac{L}{D}\sqrt{\frac{1}{2}\ln\left(\frac{1}{\gamma}\right)} \qquad (9)$$

where D is the separation between the slits. Generally, the horizontal polarization component of SR is used, since it has a higher intensity than the vertical.

The limitation on the beam size measurement becomes determined by how high a visibility one can measure, with the practical limit somewhere around or above 90%. The other limit is how far apart the slits can be separated; if there are no other physical aperture limits, *D/L* can typically be made larger than the *w/L* appearing in the equation for imaging resolution (Eq. 5). If a visibility γ of 0.9 is taken as the limit, and the slit separation is taken as $4\sigma_\psi$, then the resolution limit of the interferometer is about an order of magnitude better than that of an imaging system. Beam sizes below 5 μm have been measured at the ATF, using reflective optics to avoid chromatic aberration of the objective lens over the filter bandpass[10].

SR Non-Imaging: Vertical Polarization Monitor

The vertical polarization monitor, developed at the Swiss Light Source[11], is essentially an interferometer, but using the vertical polarization component. This is weaker than the horizontal polarization component, but the PSF has a natural zero on axis due to phase reversal there, at all wavelengths, so one can in principle use a wider bandwidth. The double-lobed structure of the vertical polarization component provides a "natural" double-slit interferometer, even with no slits or limiting aperture. No slits are used at PSI, so to analyze the visibility of the vertical polarization pattern they calculate the point-response function for different origin positions, using a Kirchhoff integral over the aperture (which includes a cold finger at the center of mirror). In this way they can calculate the visibility for different-sized beams.

The resolution limit of the vertical polarization monitor is in principle similar to that of the SR interferometer. Beam size measurements of ~6 mm have been demonstrated at the Swiss Light Source.

"Hybrid": X-ray Coded Aperture

The x-ray coded aperture monitor uses another astronomy technique, this time from x-ray astronomy: the use of multiple apertures in a pseudo-random pattern to create an image on the detector of the beam profile convolved with the mask pattern. Reconstruction of the beam profile requires simulation of the full diffraction and absorption characteristics of mask, plus detector response, over the detected spectrum, for each point in the source This is done by propagating the wavefronts from the points in the source distribution to the detector via a Kirchhoff integral over the mask, taking into account transmission and phase shifts through the mask materials. No monochromator is used, so it is a broad-spectrum measurement. The pseudo-random pattern gives a relatively flat spatial frequency response (good for reconstruction), and the large effective aperture enables single-shot measurements. Resolutions are somewhat better than a pinhole camera (some peak-valley ratios contribute to this).

Single-shot resolutions (statistics dominated) of ~10 micron beams with single-shot resolutions of ~2 microns have demonstrated at CesrTA[12]. It is also expected to be able to measure 4 micron beams (+/- 2 microns single-shot) at the ATF2, and it is planned to use a x-ray coded aperture imaging monitor at SuperKEKB.

OTR/ODR MONITORS

OTR Monitor

Optical Transition Radiation (OTR) is radiation emitted when a charged particle passes through the boundary of two surfaces with different dielectric constants, such as vacuum and metal. In the backward direction, the light travels as if "reflected" from the metal surface. In the forward direction, it travels along beam axis[13][14]. The radiation is peaked like 1/γ, like SR, but the measurement aperture can be placed much closer to the source, since it doesn't have to be located downstream of a bend from the source.

The beam can be imaged using this radiation, with a spatial resolution of 2 microns achieved in the visible range (550 nm) using backward transition radiation[15]. Imaging in EUV (13.5 nm) has been proposed for submicron single-shot diagnostics[16]. The double-lobed structure of the point-spread function may also be used for visibility measurements, in a manner similar to the vertical polarization monitor, with sub-micron resolution expected at the ATF2[17][18].

ODR Monitor

If a charged particle beam goes through a slit in a conducting screen, the electric field of the beam polarizes the screen surface, which emits radiation in the direction of specular reflection, called Optical Diffraction Radiation (ODR). It is similar to OTR, but with a hole in the middle, so is non-destructive (as long as the slit edges are clear of the beam tails). The radiation produces an interference pattern similar to that of an SR interferometer, with the vertical polarization component being sensitive to beam size, and it can be used as a beam size diagnostic[19]. It has been tested at the ATF extraction line, with sensitivity to beam sizes down to 14 microns demonstrated at visible wavelengths[20].

Tests at CesrTA are planned to push the wavelength frontier, with sub-micron resolution hoped for[21]. Shorter wavelength are more sensitive to beam size, but produce fewer photons, so a balance is needed to optimize the single-shot resolution. A target slit will be installed in the CesrTA ring, with a 640 μm-wide slit that is expected to measure 16 μm beam sizes at 500 nm wavelength. It is then planned to try a 120 μm-wide slit at 100 nm (EUV), for an expected resolution limit of 3 μm, with possible future extension to x-ray wavelength for further reduction in resolution limit.

LASER WIRE MONITORS

Laser Wire: Focused Waist

The focused-waist laser-wire monitor measures beam size by sweeping a focused laser beam across a bunch, and measuring the inverse-Compton-scattering photons created as a function of laser position. The resolution is determined by the size of laser waist where the beam intersects it:

$$\sigma_{measured} = \sqrt{\sigma_{waist}^2 + \sigma_{beam}^2} \qquad (10)$$

While straightforward in principle, it is important to make sure the waist is properly focused, pulse-to-pulse variations are minimized and understood during the scan, etc. Measurements at the ATF extraction line managed a laser waist of 2.2 +/- 0.2 microns, and measured beam sizes of 2.91 +/- 0.15 microns[22]. Measurements at the ATF2 have gone down to 4.8 +/- 0.3 microns; the laser wire monitor is being moved to a new location in the ATF2 to test with beam sizes below 1 micron[23].

Laser Wire: Shintake Monitor

The Shintake monitor is a variant on the laser wire: instead of scanning a single focused beam, an interference pattern is created between two crossed laser beams in the beam pipe, and the electron beam passes through the interference pattern[24][25]. The interference fringes act like laser wires, and by scanning the phase of the fringes and measuring the depth of modulation of the variations in inverse-Compton photons generated as the beam passes through and between the fringes, the beam size can be measured. Measurement of beams 860 +/- 40 nm in size has been demonstrated at the ATF2 final focus, with a goal at the ATF2 of measuring 37 nm beam sizes[26]. Many technical challenges in equipment stabilization, alignment and background reduction have been met to make this possible[27], and as a result it is expected to achieve 10% statistical and 6% systematic errors for a 1-minute measurement at the 37 nm beam size[28]. This is the highest resolution beam monitor out there at the moment.

LARGE ANGLE BEAMSTRAHLUNG MONITOR

The Large Angle Beamstrahlung Monitor (LABM) is not strictly a pure beam size monitor, but rather it measures the *differences* in sizes, positions, etc. of two colliding beams. It uses the light generated as two bunches focus each other, which is similar to short-magnet SR. Beamstrahlung is also polarized as SR is, with the polarization pattern around the edges of a bunch depending on the relative size, offset, etc. of its collision partner bunch[29][30].

The LABM has undergone preliminary tests at CESR, and it is planned to install a full set of diagnostics for both beams at SuperKEKB to monitor the collision geometry there. Tests are also planned at DAΦNE[31].

SOME COMMENTS AND THOUGHTS FOR THE FUTURE

In considering the needs of low-emittance tuning, it seems likely that single-shot measurements may become more necessary for beam tuning, especially in colliders that push the margins of stability all the time, but not exclusively at colliders, either. As beam sizes become smaller and smaller, the effects of orbit variations over the measurement period becomes more important to disentangle.

For photonic monitors, single-shot measurement generally implies a wide spectral acceptance (no monochromator), to maximize the usable photon flux. This usually means a lot more work is needed understand the system. Simple analytical formulas don't work, and lots of detailed numerical crunching is needed to properly analyze the data.

Detectors have not been touched on here too much, but there will be a growing need to develop high-resolution, high-energy, and high-speed detectors. High resolution wil be needed to minimize the amount of path length required for magnification, as the available path length is often limited. Efficiency at high-energy is needed for detection at shorter wavelengths, which are needed for better resolution. High-speed detectors are needed for single-shot measurements.

Finally, in considering possible directions for the future, some obvious extrapolations come to mind (some already being evaluated by various people), such as: the use of x-ray reflective (grazing incidence) optics for imaging with greater spectral bandwidth for single-shot focused imaging without chromatic aberration; the development of an x-ray interferometer for higher precision integrated measurements; and using lasers of shorter wavelength in a Shintake monitor to go below even the tens of nm range.

Considering the power of going to shorter wavelengths, it is also conceivable that gamma-ray monitors may need to be developed at some point if beam sizes continue to shrink.

Finally, one has to wonder if there is not something else out there that has been completely missed so far, perhaps something completely different from what has yet been developed. Let's think!

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