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MEASUREMENT OF THE INCOHERENT DEPTH OF FIELD EFFECT ON HORIZONTAL BEAM SIZE USING A SYNCHROTRON LIGHT INTERFEROMETER

M. J. Boland, AS, Clayton, Victoria, Australia
J. Corbett, SLAC, Menlo Park, CA, USA
T. Mitsuhashi, KEK, Tsukuba, Ibaraki, Japan

Abstract

The electron beam size as measured using synchrotron light in a circular accelerator is influenced by the incoherent depth of field effect. This effect comes about due to the instantaneous opening angle of the emitted synchrotron radiation (SR) and the acceptance angle of the SR light monitor beamline. Measurements were made using a visible light interferometer at the visible light beamlines in three circular accelerators at ATF, SPEAR3 and AS. The first order spatial coherence of the beam was measured and from that the horizontal beam size was calculated. The data is compared with a theory of synchrotron radiation with and without the horizontal incoherent field depth effect.

INTRODUCTION

The work in the paper covers in more detail the horizontal theory presented in Ref. [1]. If we accept the theory of the coherence of SR given in Ref. [2,3], then the highly relativistic motion of electrons in a storage ring results in temporal squeezing at the point of photon emission. From the observers frame of reference, this gives the appearance of a small cusp in the trajectory which – in the visible part of the spectrum – effectively forms a diffraction limited window from which the SR emerges. Each single electrons emits pencil of light having approximately the same opening angle in vertical and horizontal (precisely speaking the vertical distribution has π component so a small difference exists) which is then occupied by a single mode of 1 photon (or vacuum when photon number is zero). The opening angles of the pencils of light are $(\lambda/\rho)^{1/3}$ in both for vertical and horizontal.

The independent electrons in the bunch emit this pencil of light with a probability roughly proportional to the fine structure constant $\alpha = 1/137$. According to quantum physics, a fraction of a photon does not exist, leaving the situation that only one electron in every 137 electrons emits one single photon. The observed intensity downstream is the incoherent summation of these pencils of light. In an light source storage ring there are a lot of electrons in the bunch, so the SR is still very bright. One single photon mode in a pencil of light is coherent, so an interferogram created by a double slit interferometer must have a contrast of exactly 1 for many observations of individual photons emitted by single electrons. So, if this pencils of light illuminate a double slit downstream, as shown in Fig. 1, the following situations emerge in the horizontal case.

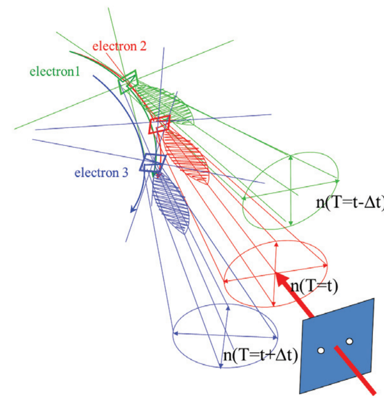
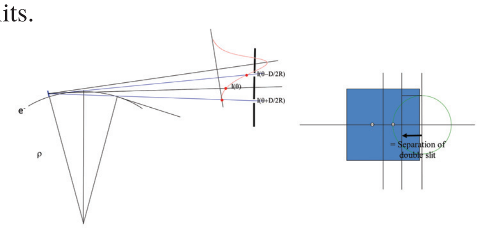
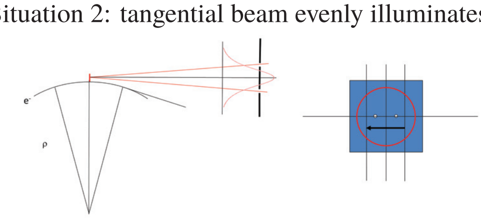


Figure 1: Photon emission from an electron beam in storage ring bending magnet.

Situation 1: beam upstream of tangent starts to illuminates slits.



Situation 2: tangential beam evenly illuminates slits.



Situation 3: beam downstream of tangent last illumination of slits.

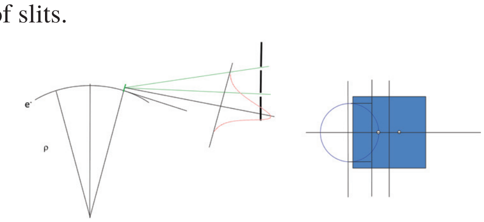


Figure 2: Horizontal sweeping of beam over double slits.

Situation 1 in following figure shown pencil of light start to illuminate the one of double slit, full noon illumination

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in situation 2, and end of illumination in situation 3. The contrast of interferogram for each case is modulated by intensity imbalance factor for each position of pencil against the double slit. Only in full noon illumination case does is the intensity balanced in each slit.

Each individual light source has a Gaussian shaped profile,

$$\frac{\exp\left[\frac{-[x-\rho\{1-\cos(\theta)\}]^2}{2\sigma^2}\right]}{\sigma\sqrt{2\pi}}. \tag{1}$$

Where σ denotes beam size and the term $x-\rho\{1-\cos(\theta)\}$ term is the displacement of centre of Gaussian distribution represented by ρ and θ, which is the rotation of the axis of the pencil of light along the bending radius ρ. Then apparent beam profile is calculated by integrating over θ thus,

$$\int \frac{\exp\left[\frac{-[x-\rho\{1-\cos(\theta)\}]^2}{2\sigma^2}\right]}{\sigma\sqrt{2\pi}} d\theta. \tag{2}$$

Then the real part of spatial coherence by this apparent distribution is given by,

$$\gamma_h(D) = \iint \frac{2\sqrt{I_1\left(\theta+\frac{D}{2R}\right)I_2\left(\theta-\frac{D}{2R}\right)}}{I_1\left(\theta+\frac{D}{2R}\right)+I_2\left(\theta-\frac{D}{2R}\right)} \cdot I(\theta)\cdot\frac{\exp\left[\frac{-[x-\rho\{1-\cos(\theta)\}]^2}{2\sigma^2}\right]}{\sigma\sqrt{2\pi}}\cdot\cos\left(\frac{2\pi D x}{R\lambda}\right)d\theta dx. \tag{3}$$

In here the term

$$\frac{2\sqrt{I_1\left(\theta+\frac{D}{2R}\right)I_2\left(\theta-\frac{D}{2R}\right)}}{I_1\left(\theta+\frac{D}{2R}\right)+I_2\left(\theta-\frac{D}{2R}\right)}\cdot I(\theta), \tag{4}$$

denotes intensity imbalance between each of the slits, and $I(\theta)$ is intensity scale factor at θ given by,

$$I(\theta) = \frac{\xi(\theta)}{\xi(0)}, \tag{5}$$

where $\xi(\theta)$ is intensity distribution of pencil of light in horizontal plane. A plot of the observed change in the visibility of the interferogram with the intensity imbalance ratio is shown in Fig. 3.

For physical reasons, the spatial coherence at $D = 0$ must be 1, the necessary condition to check Eq. 5 is whether $\gamma_h(0) = 1$ or not. Numerical integration of equation Eq. 5 shows that if $\gamma_h(0) = 0.999999998$ the integration range chosen is sufficient. We cannot simply check if this condition is satisfied mathematically, we must also check if this is the case physically by doing the experiment. Three sets of experimental data measured at ATF, AS and SPEAR3 all seem to support this theory.

EXPERIMENTAL RESULTS

Three set of experimental data are presented to verify the afore mentioned theory. Each machine on which the measurements were performed have approximately the same bending radius but quite different beam sizes.

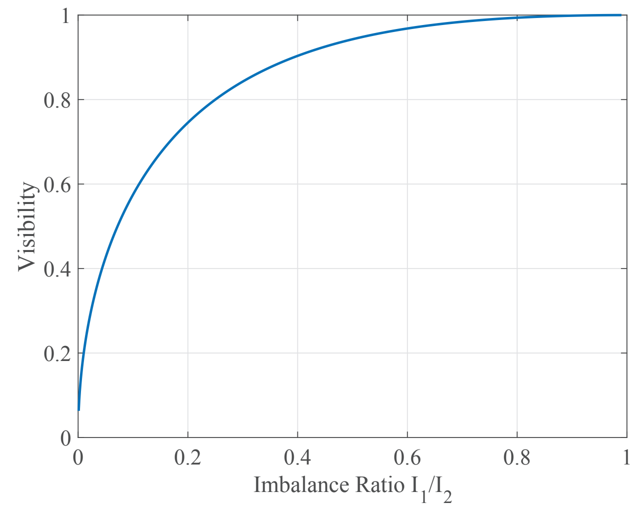

Figure 3: Change in visibility with imbalance ratio.

ATF

The initial results that led to the curiosity of the incoherent field depth effect were measured at the Accelerator Test Facility (ATF) in 1998. These data show the largest effect of the experimental results presented here due to the small beam size less than 40 μm. The small beam sizes at ATF where in fact one of the motivations for developing the SR interferometer monitor, since conventional visible optics can only resolve down to approximately 50 μm beam sizes.

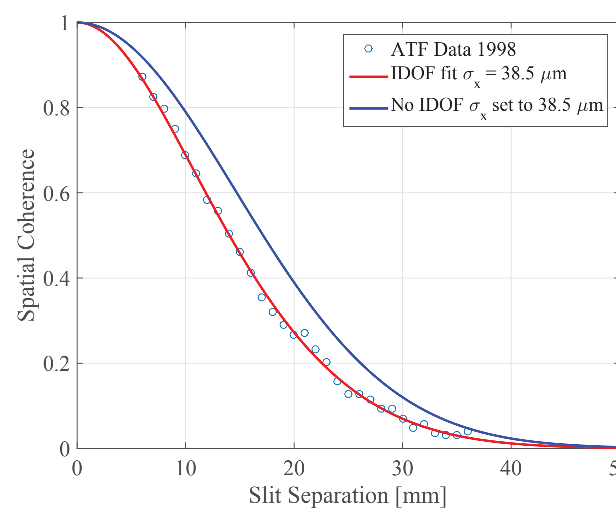

Figure 4: ATF data from 1998.

AS

The Australian Synchrotron (AS) is a third generation 3 GeV electron storage ring light source with a bending radius of 7.59 m and the beam size at the optical diagnostic beamline is twice the size of the ATF. According to the lattice parameters measured using LOCO [4] the horizontal beam size at the source point is 87 μm. Fitting the IDOF theory

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to the measured data gives beam size of 88.0 μm, while the curve without the IDOF effect for a beam size of 88.0 μm does not agree with the data as shown in Fig. 6. If a theoretical curve without the IDOF effect is fit to the data, the beam size is determined to be around 8% larger at 94.8 μm – in strong disagreement with the lattice parameters. The beta function at the optical beamline source point would have to be 20% larger than the nominal to explain the effect. Fig. 5 shows a comparison between the two fits and, although it is difficult to distinguish between the two curves, the IDOF fit residuals are half the value of those without the IDOF effect included.

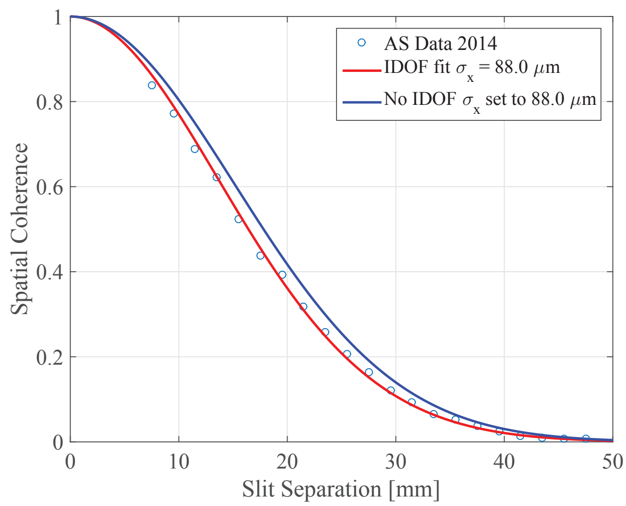

Figure 5: AS data from January 2014.

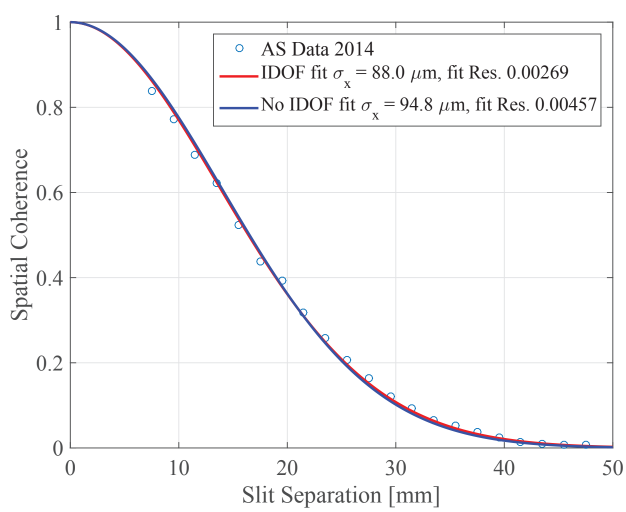

Figure 6: AS fit comparison, IDOF fit has smaller residuals.

SPEAR3

The SPEAR3 data show the smallest effect since beamline has the largest source point and the bending radius is approximately the same as AFT and AS. Nonetheless there is a distinguishable difference and the IDOF theory gives a better fit to the data. The beam size of 132.7 μm is consistent with the value expected from the nominal lattice. A recent reduction in the horizontal emittance in SPEAR3 in 2015 warrants new a new data set with the smaller beamsize.

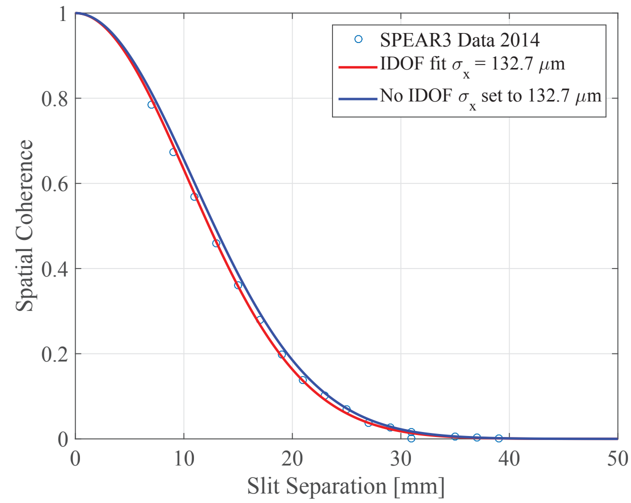

Figure 7: SPEAR3 data from March 2014.

CONCLUSIONS AND FURTHER WORK

The theory of the incoherent field depth effect seems to be supported by measurements made with visible light interferometers at the ATF, AS and SPEAR3 storage rings. The effect is larger for smaller beam sizes (and for larger bending radius) and is not easily explained by errors in the storage ring lattice parameters, for example. There are plans to remeasure SPEAR3 using the new lower emittance lattice which has reduced the beam size by around 15%. Measurements will also be performed on the newly installed interferometer at the LHC, which has a bending radius of almost one thousand times that of smaller light sources.

REFERENCES

[1] T. Mitsuhashi, "Recent Trends in Beam Size Measurements using the Spatial Coherence of Visible Synchrotron Radiation", THYC2, *These Proceedings*, IPAC'15, Richmond, USA (2015).

[2] T. Mitsuhashi, "Beam Profile and Size Measurement by SR Interferometers", in *Beam Measurement*: Proceedings of the Joint US-CERN-Japan-Russia School on Particle Accelerators, Editors S-i. Kurokawa, S.Y. Lee, E. Perevedentsev and S. Turner, p. 399–427, World Scientific, Singapore (1999).

[3] K.-J. Kim, "Characteristics of Synchrotron Radiation", AIP Conf. Proc. **184**, 565 (1989). http://dx.doi.org/10.1063/1.38046

[4] J. Safranek, "Experimental determination of storage ring optics using orbit response measurements", NIMA, 388, 27 (1997).