INTENSITY IMBALANCE OPTICAL INTERFEROMETER BEAM SIZE MONITOR*

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Abstract

The technique of measuring the beam size in a particle accelerator with an optical interferometer with the Mitsuhashi apparatus is well established and one of the only direct measurement techniques available. However, one of the limitations of the technique is the dynamic range and noise level of CCD cameras when measuring ultra low emittance beams and hence visibilities close to unity. A new design has been successfully tested to overcome these limitations by introducing a known intensity imbalance in one of the light paths of the interferometer. This modification reduces the visibility in a controlled way and lifts the measured interference pattern out of the noise level of the CCD, thus increasing the dynamic range of the apparatus. Results are presented from tests at the ATF2 at KEK and on the optical diagnostic beamline at the Australian Synchrotron storage ring.

OPTICAL INTERFEROMETRY

The Mitsuhashi apparatus [1] for measuring the first order spatial coherence of a beam of charged particles that emit synchrotron radiation is well established and used on many accelerators. The technique samples two parts of the diverging visible light beam using a double slit type configuration.

Using a focussing mirror the beams from each slit are brought together to form an interference pattern that is recorded with a CCD camera. A mirror is currently used to focus the beams since mirrors can be constructed with a larger aperture and with better roughness and dig-scratch performance than a lens of the same aperture. A parabolic mirror can be made with relatively few aberrations drawing on the experience of astronomical mirrors for telescopes. In essence to start to construct an interferometer the first step is to build a telescope to image the beam. Once a good optical path has been established the interferometer components can be added step by step to construct the Mitsuhashi apparatus for measuring the first order spatial coherence. A narrow bandpass filter is added to simplify the analysis, for example $\omega = 500$ nm, $\Delta\omega = 10$ nm. A polariser is used to select the σ-mode of the synchrotron radiation so as to distinguish it from the π-mode which produces a interference pattern with a phase shift that washes out the interferogram. If more intensity is needed for low beam currents it is possible to use a wider bandpass filer of 80 nm to increase the light, however the analysis of the data will have to take this into account.

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A typical example of an interference pattern produced with the Mitsuhashi apparatus is shown in Fig. 1:

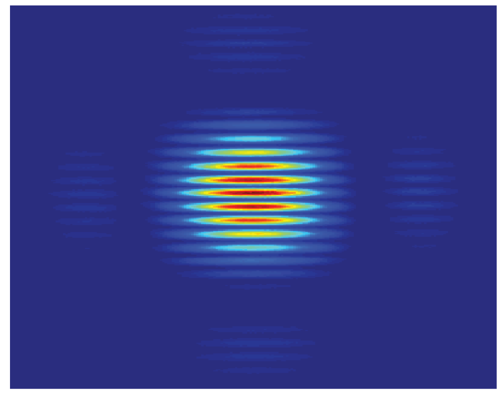

Figure 1: A typical interference pattern created by the Mitsuhashi apparatus for measuring beam sizes.

LIMITATIONS OF A CONVENTIONAL INTERFEROMETER

In modern accelerators where the vertical emittance is being pushed lower and lower, towards sub-picometre radian level, the beam size becomes very small and is highly spatially coherent. This means that the visibility of the interference pattern is very close to unity and the troughs dip down into the noise floor of the CCD that is recording the pattern. As a consequence the Mitsuhashi apparatus is practically limited by the signal to noise ratio of the CCD camera. At ATF2 optical beamline in the injection area the beam size was measured by the interferometer to be 5 μm with an error of less than 1 μm [2], which was mostly due to the CCD noise. The CCD by Hamamatsu [3] is one of the best performing on the market, with a low noise level and a very linear response across the range required for the interferometer, so a modification of the technique was required to improve the performance at very high spatial coherence.

INTENSITY IMBALANCE TECHNIQUE

The intensity distribution of the interference pattern created by light of wavelength λ passing through a double slit of hieght a, slit separation D and a distance R from the source with a certain polarisation is given by [2]

$$I(y) = I_0 \mathrm{sinc}\left(\frac{2\pi a}{\lambda R} y\right)^2 \left[1 + |\mathcal{V}| \cos\left(\frac{2\pi D}{\lambda R} y + \phi\right)\right],$$

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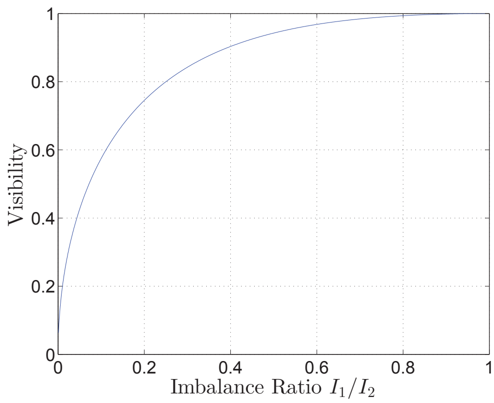

Figure 2: Visibility plotted again the imbalance ratio $\rho = I_2/I_1$ in the interferometer.

where the visibility $\mathcal{V}$ is related to the complex degree of coherence by a factor involving the intensity of each beam I_1 and I_2 given by

$$\mathcal{V} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}|\gamma|.$$

In most cases one can assume $\mathcal{V} = |\gamma|$ since for $I_1 \approx I_2$ this assumption is valid. For a symmetrical visible radiation fan with the interferometer sampling the beam at the top and bottom of the optical axis, it can be assumed that the intensity is the same at each slit opening. Figure 2 shows that for an imbalance of up to 10% the visibility only changes by less than 1%.

This leads to two situations; one where the intensity is imbalanced due to the beam or beamline conditions; the where an imbalance is introduced in a controlled way, i.e. the intensity imbalance interferometer. An optical flat with the top half fully transmissive and the bottom half with an attenuation coating can be introduced to create the imbalance and reduce the visibility for a given beam size. The true beam size can then be determined as follows by correcting the measured visibility to the complex degree of coherence using the imbalance ratio $\rho = I_2/I_1$

$$|\gamma| = \mathcal{V}\frac{(1+\rho)}{2\sqrt{\rho}},$$

and then computing the beam size from the Fourier pair of the visibility distribution using (again following [2])

$$\sigma_y = \frac{\pi D}{\lambda R}\sqrt{\frac{1}{2}\ln\left(\frac{1}{|\gamma|}\right)}.$$

Using this method with a value of $\rho = 0.2$ gives a visibility reduction of 0.745 and achieves the aim of lifting the fringes in the interference pattern above the noise. The following section demonstrates the intensity imbalance technique using beam size measurements from ATF2 at KEK.

ATF2 MEASUREMENTS

Light is extracted just after the injection point of the ATF2 damping ring using a mirror that captures the light symmetrically above and below the optical axis. The beam is then reflected out of the tunnel and onto an optical hutch on the roof of the damping ring and directed into the interferometer on the optical table as shown in Fig. 3.

Firstly the beam size was measured using the standard interferometer and the slit size varied to check the distribution of the visibility function. Using the 20 mm slit separation the visibility was quite high around 0.95, so the imbalance method could be put to good use. Figure 4 shows the interferogram for the balanced interferometer, while Fig. 5 shows the interferogram from the intensity imbalanced measurement.

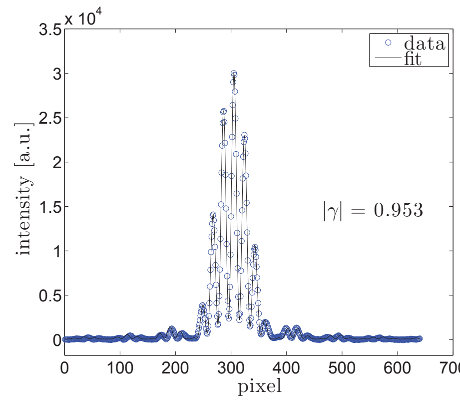

Figure 4: Interferogram from the balanced interferometer with a slit separation of 20 mm.

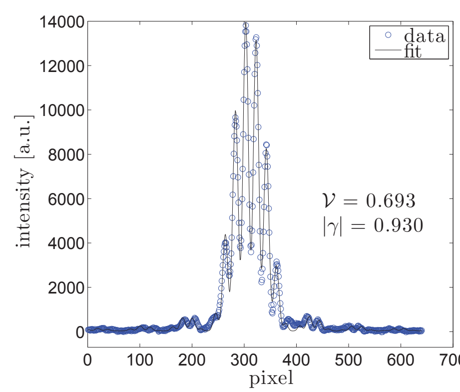

Figure 5: Interferogram from the balanced interferometer with a slit separation of 20 mm also showing the visibility corrected to derive the complex degree of coherence.

The fit to the interferogram produces some inconsistent beam sizes as seen in Table 1, indicating a problem with the signal to noise or a shot to shot beam size variation.

The measurements were repeated using the intensity imbalance setup and as expected the visibility was reduced (compare Fig. 4 and Fig. 5). When the complex degree

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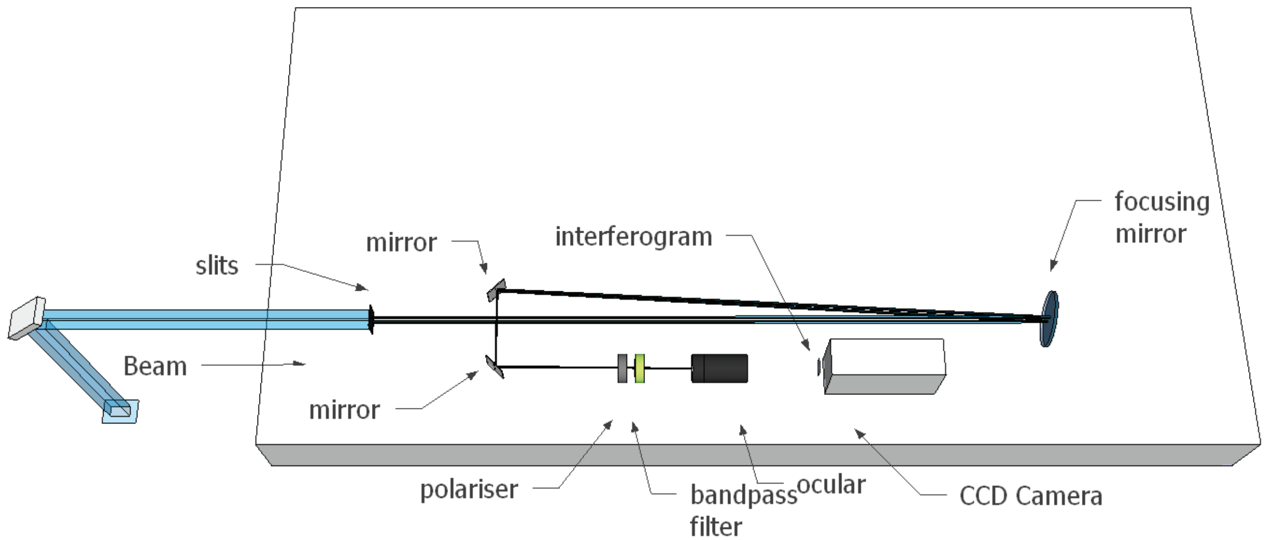

Figure 3: The currently used configuration of the Mitsuhashi aparatus interferometer as used at the ATF2 at KEK (March 2012).

Table 1: Summary of ATF2 Balanced Interferometer Measurements

slit separation (mm)	$\lvert\gamma\rvert$	σ_y (µm)
20	0.953	9
30	0.868	10
40	0.854	8

of coherence was computed using the known intensity imbalance, similar beam sizes were extracted from the data, however there were some inconsistencies across the range of slit separations measured.

Table 2: Summary of ATF2 Imbalanced Interferometer Measurements

slit separation (mm)	$\mathcal{V}$	$\lvert\gamma\rvert$	σ_y (µm)
20	0.693	0.930	11
30	0.640	0.858	10
40	0.592	0.794	10

The inconsistencies may be due to fitting errors or shot to shot variations in the beam but it is worth noting the intensity imbalance measurements are more consistent. When plotted against the slit separation 6 the complex degree of coherence for the imbalance measurement is consistent with the 10 µm beam size profile, while the balanced measurement has a larger spread, perhaps due to the problems of measuring high visibilities.

In an attempt to reduce the shot to shot variations introduced by the damping ring injection cycle, measurements were performed using a similar setup at the Australian Synchrotron storage ring.

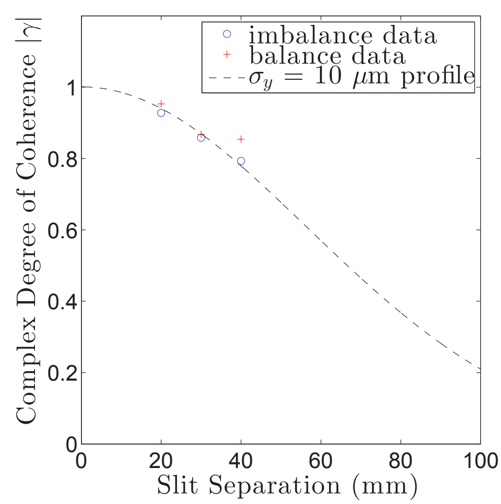

Figure 6: The complex degree of coherence for various slit separations for the imbalance interferometer.

ASLS MEASUREMENTS

The optical diagnostic beamline on the AS storage ring has a stable beam, unfortunately the pick-off mirror configuration is not optimal for interferometry. At ATF2 the visible light pick-off mirror captures the light symmetrically above and below the optical axis. However, Fig. 7 shows how the narrow opening angle of the ASLS optical diagnostic beamline and the pick-off mirror that only samples the top half of the beam introduces an imbalance in the intensity of the two beams in the interferometer. The imbalance ratio is ≈ 0.6 which means it needs to be corrected for in the analysis of the interferogram in order to achieve an accurate measurement; we cannot use the assumption that $I_1 = I_2$. This was done by measuring individually the

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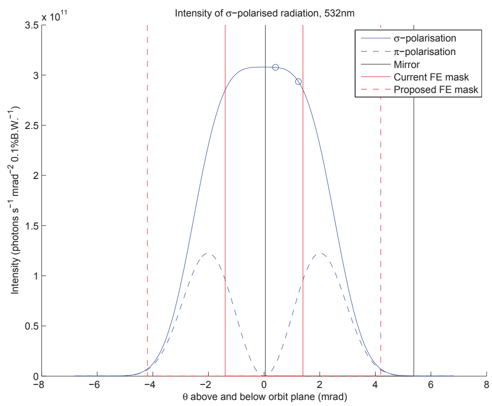

Figure 7: The ASLS optical diagnostic beamline visible radiation fan. The blue circles indicade the angular position the interferometer slits sample the beam.

top and bottom beam intensity by blanking them off in turn and capturing an image. This measured intensity data is then used to unfold the complex degree of coherence from the interference pattern.

Another disadvantage of the AS storage ring is that the nominal beam size at the optical diagnostic beamline is not very small to begin with; a nominal beam height of $\sigma_y = 58\,\mu\text{m}$ for a 1% emittance coupling ratio. An attempt was made to reduce the coupling by turning off the skew quadrupoles (which are set during user beam to increase the coupling in order to increase the beam lifetime).

Measurements were taken using a slightly different configuration than at ATF2 and the AS setup is shown in Fig 8.

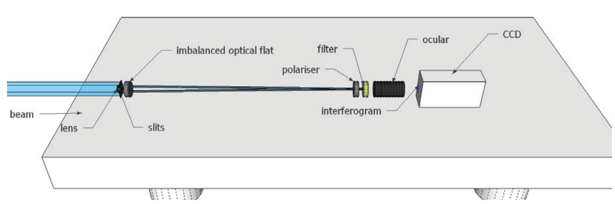

Figure 8: The refractive optics setup of the intensity imbalance interferometer on the optical diagnostic beamline at the Australian Synchrotron.

Two beam configurations were created; one at nominal 1% emittance coupling for a large beam size; and one with the skew quadrupoles off. For each beam configuration the beam size was measured with the interferometer and with the intensity imbalanced interferometer. The results are summarised in Table 3. The intensity of the two beams were measured for each interferogram that was taken since we cannot use the $I_1 = I_2$ assumption. The interference pattern was fit to obtain $\mathcal{V}$, then $|\gamma|$ was computed and finally the beam size determined.

The measurements are in reasonable agreement but due to the small opening angle of the beamline the slit separation is limited to up to 10 mm. At 10 mm separation the visibility changes very little with beam size so the analysis is very sensitive to fitting errors. This highlighted a problem with the ASLS data that the CCD has an internal threshold for removing background which results in an unphysical absolute zero background. As a result a DC shift is introduced to the data that will give the wrong value for the visibility. This can be see in Fig. 9 and Fig. 10 where the minima of the sinc envelope has a series of data points at exactly zero.

Table 3: Summary of ASLS Balance and Imbalanced Interferometer Measurements

beam mode	$\mathcal{V}$	$\|\gamma\|$	σ_y (μm)
Balance skew zero	0.795	0.804	58
Imbalance skew zero	0.546	0.790	61
Balance skew user	0.707	0.734	69
Imbalance skew user	0.484	0.704	74

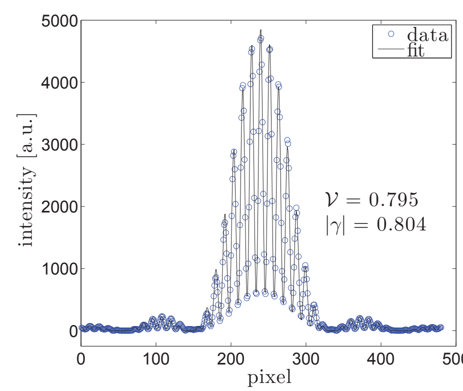

Figure 9: Interferogram with the skew quadrupoles off.

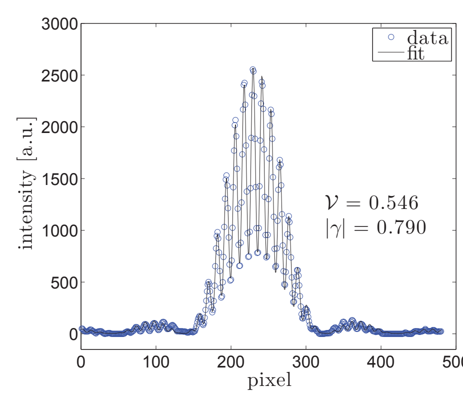

Figure 10: Interferogram taken with the intensity imbalance interferometer with the skew quadrupoles turned off.

This problem was not observed at ATF2 at KEK where the CCD used gave the raw counts in the pixels including the dark counts due to noise.

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VIRTUAL BEAM MEASUREMENT

The vertical beam size at the ASLS optical diagnostic beamline is more than an order or magnitude larger than for future damping ring and light source storage ring designs. Very small beam sizes producing visibilities close to unity are required to properly test the intensity imbalance interferometer, so a 24 time demagnified virtual source was created at the ASLS optical diagnostic beamline by placing a concave lens directly in front of the slits. The nominal beam size at the optical diagnostic beamline source point is 58 μm (for a calibrated lattice and 1% coupling), so the virtual source was $\approx$ 2.4 μm. The beam size was measured with the intensity imbalance interferometer to be 2.6 μm, demonstrating the true advantage of the technique.

CONCLUSION

The intensity imbalance interferometer achieved the aim of reducing the visibility in a controlled way and still measuring the correct beam size. This technique improves the sensitivity of the Mitsuhashi apparatus and can measure very small beam sizes with less than 1 μm accuracy. Two experimental setups were tested with the imbalance method, however neither had the ideal conditions of a very small beam size and stable beam to demonstrate the full potential of the apparatus. It remains one of the best direct measurements of beam sizes in accelerators and further work will attempt to improve the optical beamline at the Australian Synchrotron to take advantage of the interferometer.

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[3] Hamamatsu CCD model number C5985.

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