# CHARACTERISATION OF THE MAX-II ELECTRON BEAM: BEAM SIZE MEASUREMENTS

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### *Abstract*

Over the last year investigations of the MAX-II electron beam characteristics have been made. Examples of investigated parameters include the beam size, bunch length, vacuum and Touschek lifetimes, and the machine functions. Several upgrades of the MAX II ring have been performed since the commissioning 1995 like a new 100 MHz RF system with a 500 MHz Landau cavity, exchanged injector, and a variety of insertion devices. There is hence a need to systematically characterize the present machine. This systematic characterisation is now underway and this article describes details of the beam size measurements.

## INTRODUCTION

A systematic and detailed characterisation of the MAX II ring is now underway. This characterisation includes measurements of the Twiss functions, dynamic apertures, energy acceptance, beam emittance and energy spread, beam lifetimes, beam stability to mention a few examples. As part of this work, measurements of the transverse size of the electron bunches has been done using a synchrotron radiation (SR) profile monitor at the D111 diagnostic beamline. The utilised approach has been to measure the synchrotron radiation profile in the visible wavelength region with a standard CCD camera and make use of digital image processing to account for diffraction effects on the SR wavefront. Vertical beam sizes down to 30 µm, corresponding to an emittance on the order of 100 pm rad, could be measured using visible light. In order to avoid deforming heat loads on the optics the profile measurements were carried out at close to zero-current.

## MEASUREMENT SETUP

The setup at the D111 beamline is shown schematically in Fig. 1. It is in large parts identical to the one used by [1], as the SiC mirror, the baffles and the lens are placed inside the ring vacuum and have not been replaced since the first beam size measurements [2] took place.

Two different spectral filters were used; a dichroic filter and a laser line interference filter. The former transmitted between 505±15 to 575±15 nm while the latter had a transmission window at 488±0.6 nm with a Full Width Half Maximum (FWHM) of 3±0.6 nm.

The CCD camera used as a detector utilises a 1/3" Sony Progressive Scan CCD with 1032 x 778 pixels, a pixel size of 4.65x4.65 µm and a bit depth of 8. Sensor efficiency is at its peak for wavelengths 500-515 nm.

## METHOD

An estimate of the D111 beamline Point-Spread Function (PSF) was computed using retarded potentials to calculate the synchrotron radiation wavefront due to a single electron passing through the D111 bending magnet. Using Fourier optics calculations the wavefront could then be propagated through a set of optical elements to obtain the resulting image at the CCD sensor array. These computations were made using the Synchrotron Radiation Workshop (SRW) software [3].

After taking an image of the SR distribution with the described setup, the transverse electron density distribution could be obtained using the Lucy-Richardson algorithm [4][5] to deconvolve the image with the estimated PSF. By fitting normal distributions to the

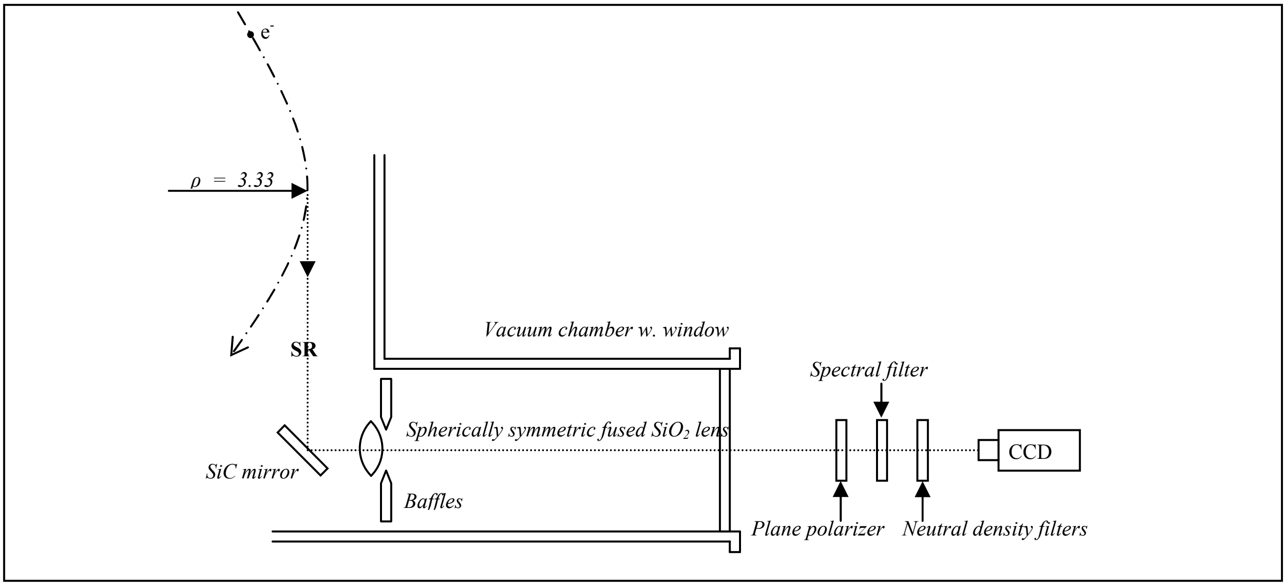

Figure 1: The MAX-II D111 beamline setup for electron beam profile measurements.

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beam, the beam sizes could be determined.

### *Point-Spread Function*

The PSF is the inverse Fourier transform of the Optical Transfer Function (OTF), which defines the properties of the measurement system.

$$\Im(PSF) = OTF = MTF \cdot e^{iPTF} \tag{1}$$

The amplitude component of the OTF is called the Modulation Transfer Function (MTF) and is commonly used when specifying optical systems. Modulation Transfer Function curves at 488 nm for the D111 beamline can be seen in Fig. 2 and Fig. 3.

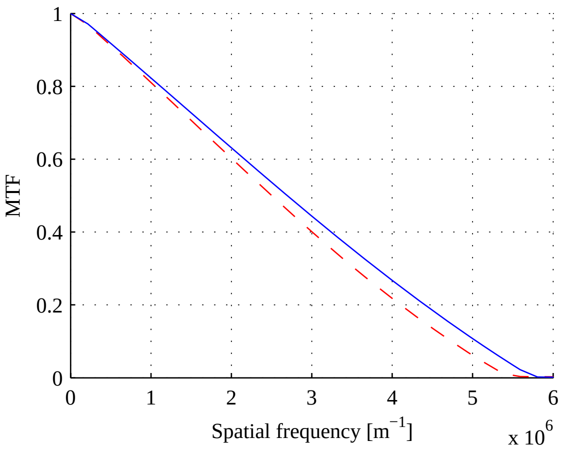

Figure 2: MTF curve in the horizontal plane for the D111 beamline, using σ- (solid) and π-polarised SR (dashed).

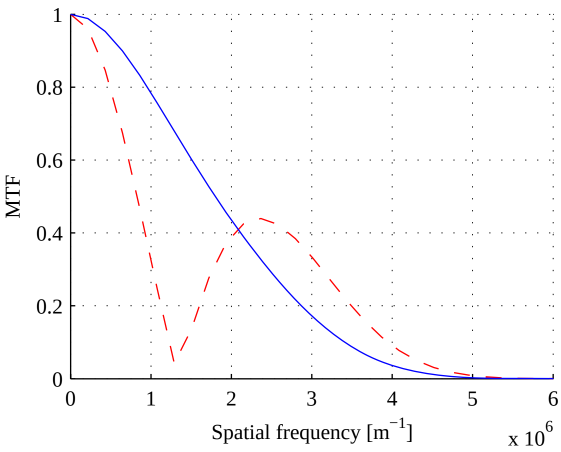

Figure 3: MTF curve in the vertical plane for the D111 beamline, using σ- (solid) and π-polarised SR (dashed).

## RESULTS

Dichroic filter measurements during June to September 2005 were made at close to zero-current, with minimum induced coupling by the skew quadrupole. Obtained beam dimensions were $\sigma_x$ = 91 μm and $\sigma_y$ = 30 μm without insertion devices. With insertion devices beam dimensions were $\sigma_x$ = 79 μm and $\sigma_y$ = 31 μm. A comparison between measured and calculated SR distribution is shown in Fig. 4.

Later measurements during December 2005 at 30 mA current using the 488 nm interference filter yielded $\sigma_x$ = 101 μm and $\sigma_y$ = 35 μm, with no insertion devices and minimum induced coupling by the skew quadrupole. A comparison between measured and calculated SR distribution is shown in Fig. 5.

The signal to noise ratio in the acquired images was consistently within 19-24 dB.

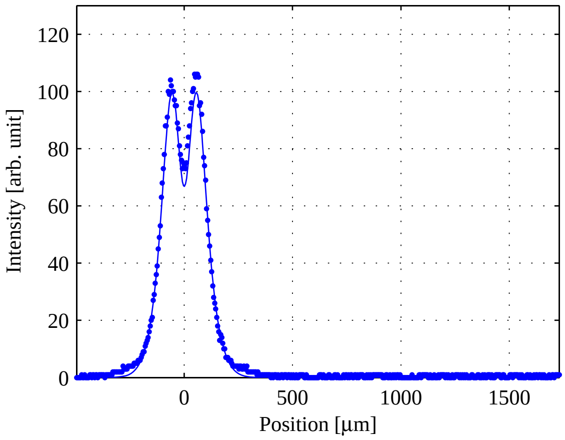

Figure 4: Vertical cross-section of calculated and measured SR distribution. I = 7.5 mA, λ = 540 nm, 70 nm FWHM. No insertion devices.

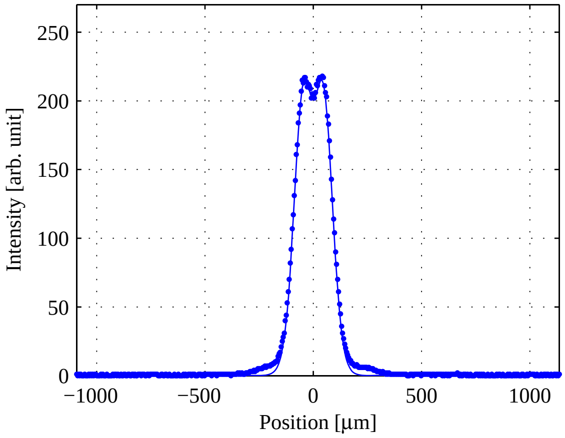

Figure 5: Vertical cross-section of calculated and measured SR distribution. I = 30 mA, λ = 488 nm, 3 nm FWHM. No insertion devices.

## DISCUSSION

### *Optical Transfer Function Errors*

It should be noted that the quality of the estimated PSF is difficult to judge. The main uncertainty in the PSF arises from the quality of the D111 optics. Time and machine access constraints prevented a measurement of the optics PSF.

Mirror deformation due to SR heating was observed, as a rapid beam size increase with increasing current was observed over 80 mA. This observation was in agreement with previous observations by [1]. As no change in the beam lifetime could be observed the cause of the apparent beam size increase could be concluded to be due to changing optics.

The spectral width of the SR reaching the CCD introduces uncertainties into the PSF calculation, due to chromatic effects in the D111 optics, primarily the lens. This effect was significant for the dichroic filter, where it had to be compensated for when calculating the PSF. For the interference filter, there was no significant change in the result depending on whether the 3 nm width was compensated for or not. The assumption of monochromatic SR was thus considered a viable approximation in the case of the interference filter.

### *Measurement Error Sources*

As can be seen in Fig. 4 and Fig. 5, there is good agreement between the calculated and measured SR intensity distribution, especially so where the interference filter has been used. However, there is a discrepancy in the distribution tails for the vertical direction. The likely cause is a background present in the measured images. Possible background sources include diffuse reflections on the mirror chamber walls, diffuse reflections inside the $e^-$ beam dipole chamber, mirror carbon deposits and scattering in optical elements. The latter two should result in a broadening of the obtained electron density distribution, while the first will result in a homogenous background level in the measured SR image. The result of diffuse reflections inside the dipole chamber is more difficult to predict and hence to compensate for.

### *Result Validity*

As the expected electron density distribution is a bivariate normal distribution, the degree to which this is the case can be used to test the result. In both the dichroic and the interference filter measurements, a $\chi^2$ test of the hypothesis that the acquired $E(x,y)$ is a bivariate normal distribution yields that the hypothesis cannot be discarded for a significance level of 0.95.

A second test consists of computing the theoretical SR distribution from a bivariate normal distribution with the obtained beam dimensions and testing against the measured SR distribution. The hypothesis that the theoretical and measured SR distributions are identical cannot be discarded for a significance level of 0.95, using a $\chi^2$ test.

### *Resolving Power*

As shown in Fig. 2 and Fig. 3, studying the vertically polarised synchrotron radiation component ($\pi$-component) is advantageous only when studying small details in the vertical direction. This advantage appears at 0.5 µm and 0.8 µm, for the interference filter and dichroic filter respectively. Otherwise, the horizontally polarised component ($\sigma$-component) can be used with less demand on sensor contrast sensitivity. It should be noted that the "dip" for the $\pi$-component results in a "blind" region as image vertical spatial frequencies here will be filtered. Thus vertical details around 0.77 µm for the interference filter and 1.3 µm for the dichroic filter will not be registered as such.

The maximum attainable resolution for measurements at the D111 beamline depends on the contrast sensitivity and pixel size of the utilised sensor. Neglecting the limit imposed by the CCD pixel size and imposing contrast requirements equivalent to the Rayleigh criterion for the diffraction limit in the far-field the theoretical resolution limit of the D111 beamline optics is 0.22 µm horizontally and 0.27 µm vertically. As the CCD pixel size is 4.65 µm however, the measurement resolution limit is 9.3 µm. Thus, the main limit to the resolution is the CCD, rather than the beamline optics. This is a positive result as the camera is not located in vacuum and can be switched.

In contrast, using classic far-field diffraction theory, the theoretical resolution limit is 35 µm vertically. Thus without digital image enhancement, the D111 optics would have been the limiting factor.

## CONCLUSIONS

Beam size measurements at the MAX-II D111 diagnostic beamline were successfully carried out using visible synchrotron radiation at 540 nm central wavelength, 70 nm FWHM and 488 nm central wavelength, 3 nm FWHM. The latter range gave better agreement between measured and computed synchrotron radiation distributions.

Utilising a theoretical estimate of the measurement setup Point-Spread-Function, the Lucy-Richardson deconvolution algorithm could be used to obtain a 9.3 µm resolution. The resolution limit was set by the pixel size of the utilised CCD camera. Theoretical resolution limits for the D111 beamline optics at 488 nm are 0.22 µm horizontally and 0.27 µm vertically using the $\pi$-polarised SR component.

## REFERENCES

[1] Å. Andersson, ”Electron beam profile measurements and emittance manipulation at the MAX-laboratory”, PhD thesis, Lund University 1997, p.58-60.

[2] Å. Andersson, M. Eriksson, O. Chubar, ”Beam profile measurements with visible synchrotron light on MAX-II”, proceedings of the European Particle Accelerator Conference, EPAC 1996, Barcelona, Spain, 10-14 June 1996.

[3] O. Chubar, P. Elleaume, "Accurate And Efficient Computation Of Synchrotron Radiation In The Near Field Region", proceedings of the European Particle Accelerator Conference, EPAC 1998, Stockholm, Sweden, 22-26 June 1998, p.1177-1179.

[4] L. B. Lucy, "An iterative technique for the rectification of observed distributions", Astronomical Journal Vol. 79 #6, June 1974, p. 745-754.

[5] W. H. Richardson, "Bayesian-based iterative method of image restoration", Journal of the Optical Society of America A 62, 1972, p. 55-59.