

ACCURATE MEASUREMENT OF SMALL ELECTRON BEAM CURRENTS AT THE MLS ELECTRON STORAGE RING

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Abstract

The PTB, the German metrology institute, utilizes the electron storage ring Metrology Light Source (MLS) in Berlin - Adlershof for the realization of the radiometric units in the ultraviolet and vacuum ultraviolet spectral range. For this purpose the MLS can be operated as a primary source standard of calculable synchrotron radiation, by means of the Schwinger equation, with very flexible parameters, especially in terms of electron beam energy and electron beam current. We report on improvements in the measurement of the electron beam current in the nA and pA range. In this range the electron beam current can be very accurately measured by counting the number of stored electrons.

INTRODUCTION

The MLS is used by the Physikalisch-Technische Bundesanstalt (PTB) as a primary source standard of calculable synchrotron radiation [1] in the UV and VUV spectral range. Therefore, special equipment has been installed to measure all parameters entering the calculation with small uncertainty. In this paper we focus on the equipment for measuring the electron beam current, the measurement of the remaining parameters is described in [1]. The Schwinger equation [2] used for the calculation, originally describes the spectral energy irradiated per solid angle by one electron moving on a circular arc, i.e. moving in a homogenous magnetic field. Adapting this to electron storage rings, where the electron revolves, the Schwinger equation has to be multiplied with the revolution frequency ν , yielding the spectral radiant intensity for one stored electron. If N electrons are stored, which is equivalent to a stored electron beam current I of

$$I = N e \nu, \quad (1)$$

then the spectral radiant intensity of synchrotron radiation from electron storage rings is directly proportional to the stored electron beam current, i.e. the number of stored electrons [3]. With the necessary equipment installed to measure and control the electron beam current over a wide dynamic range, the radiant intensity of the synchrotron radiation can be adjusted accordingly without changing the spectrum. It should be mentioned that the stated direct proportionality between N and the spectral radiant power is only valid for wavelengths that are shorter than the length of the stored electron bunches, typically being in the mm range, and therefore no coherence effects are present in the near IR, VIS, VUV and soft X-ray spectral range.

The variation of the electron beam current does not change the spectral characteristics of the synchrotron radiation. The spectral characteristics, on the other hand, can be changed by adjustment of the electron energy. At the MLS, e.g., the electron beam energy can be chosen to be between 105 MeV and 630 MeV, which changes the characteristic wavelength between 735 nm and 3.4 nm, respectively. This allows creating a tailor-made spectral shape for specific applications and avoiding unwanted high-energy parts of the spectrum, which could lead to instabilities due to thermal load, optics degradation, higher diffraction orders or increased stray light.

MEASUREMENT OF THE ELECTRON BEAM CURRENT AT THE MLS

At the MLS, the stored electron beam current can be varied by more than 11 decades from a maximum current of approx. 200 mA down to a single stored electron (1 pA). As a matter of course, the equipment for a controlled adjustment of the electron beam current must be installed at the storage ring in order to utilize this potential. This is implemented only at a few other facilities worldwide [4], since most electron storage rings are operated as large-scale synchrotron radiation user facilities, which do not have the flexibility of changing the operational parameters such as electron beam current or electron beam energy. At the MLS, equipment is also installed to monitor the beam size over the whole possible range of electron beam current [5].

Upper Electron Beam Current Range

Currents in the upper range, i.e. above some mA, are measured with two commercially available DC parametric current transformers (PCT) [6]. For an absolute determination of the electron beam current, the offset signal of these monitors has to be carefully measured and taken into account; this offset signal is dependent on the electron energy, i.e. the magnetic induction of the surrounding bending magnets [3]. The relative uncertainty of the electron beam current measurement by the PCT is given by the uncertainty in the calibration factor and the non-linearity. The relative uncertainty of each of these contributions is $1 \cdot 10^{-4}$. A further uncertainty is given by the oscillating drift of the offset current, which is typically some μA .

Intermediate Electron Beam Current Range

For the measurement of electron beam current below approximately 1 mA LN₂-cooled windowless Si photodiodes [7] with linear response are used that are

irradiated by the direct synchrotron radiation covering the full spectral range from the vacuum UV to the IR. In a special UHV front end section inside the storage ring housing these photodiodes can be moved into the orbital plane of the synchrotron radiation by means of computer controlled stepper motors. Two individual pairs of photodiodes with different filters in front are in usage right now, as is illustrated in fig. 1 and described in table 1. The photodiodes are connected by long low-noise cables to electrometers that are placed outside of the storage ring housing. Photodiode D1 and D3 are - by means of a scanner [8] - alternatively connected to an electrometer [9], as are D2 and D4, respectively. So always the photocurrent from two photodiodes, one on each feed through, can be measured in parallel.

The calibration factor k_{D1} , which relate the photocurrent I_{D1} to the electron beam current I_{MLS} by

$$I_{MLS} = k_{D1} \cdot I_{D1}$$

is determined for photodiode D1 by comparison with the electron beam current measured at the upper end of the range by the PCTs. The photocurrent of photodiode D2 is then compared to that of photodiode D1 at currents in the μA range and the relating calibration factor k_{D2} is determined. In the nA range the D3 or D4 photocurrents can then be calibrated by comparison to the D2 photocurrent. The relative uncertainty in this intermediate electron beam current range is dominated by the non-linearity of the photodiodes and drifts and is estimated to be well below 2 % (see below for an example).

part of the figure shows the number of electrons during a calibration task, e.g. the calibration of an energy-dispersive detector. Occasionally an electron is lost due to collision with the residual gas, resulting in a beam lifetime of more than 30 h for these electron beam currents. For the down-counting of the electrons after the calibration task (right part of Fig. 3), the lifetime of the electron beam is artificially reduced by means of the scraper.

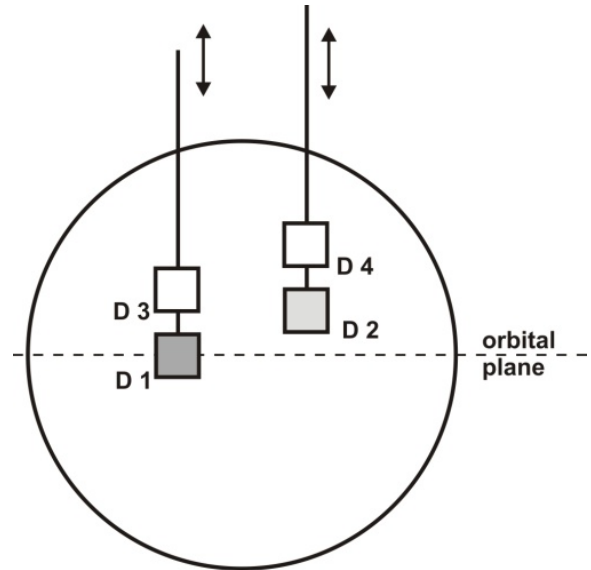


Figure 1: Scheme of the photodiode set-up.

Lower Electron Beam Current Range

Electron currents in the lower range, i.e. below 1 nA, are determined by counting the number of stored electrons, first developed at the Tantalus electron storage ring [10] and also utilized at the SURF electron storage ring [4]. To do this, after the actual calibration task has been completed, the electrons are gradually kicked out of the storage ring by a mechanical scraper that can be placed closely to the electron beam, while measuring the step-like drop of the synchrotron radiation power by the cooled, unfiltered photodiodes. The electron beam current is then given by the product of electron number, electron charge and revolution frequency (eq. 1). Once the number of stored electrons has unambiguously been determined, the relative uncertainty in the electron beam current measurement is dominated by the relative uncertainty in the measurement of the revolution frequency, which is about $1 \cdot 10^{-7}$.

Example

Figure 2 illustrates the reduction of the electron beam current by means of a scraper over the whole range with the overlapping measurement range of the PCTs (black curve) and photodiodes (coloured curves). For electron beam currents below 1 nA a step-like decrease of the electron beam current becomes visible and is clearly seen around 300 pA. Fig. 3 shows the measurement of the electron beam current for a few stored electrons. The left

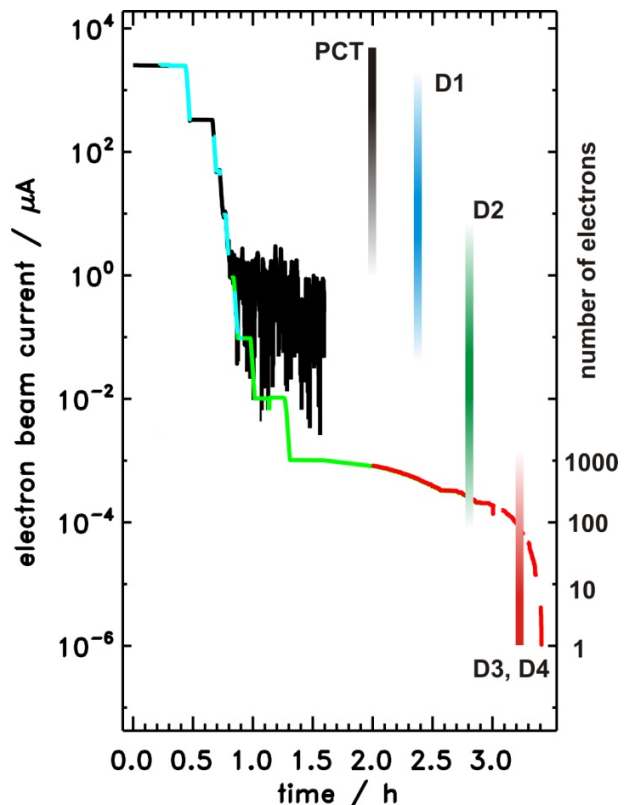


Figure 2: Example of a current measurement over 11 decades.

Table 1: Diodes used for Measurement of Small and Intermediate Currents

Diode	Filter	Approx. calib. factors k_{Di} A/A
D1	8 μm Al	34
D2	0.8 μm Al	2.8
D3, D4	none	1

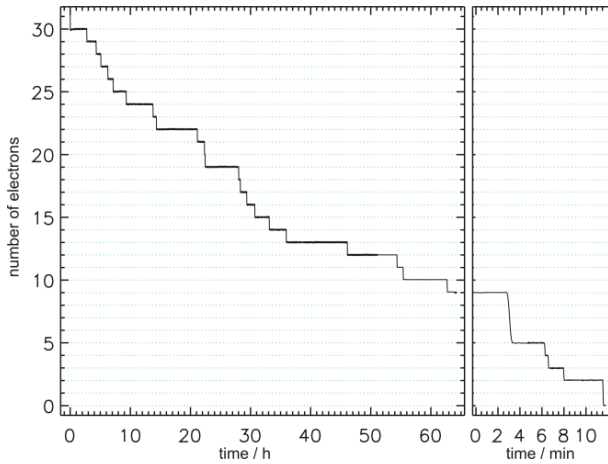


Figure 3: Electron counting in the lower current range.

Limitations, Possible Improvements

The current measurement over 11 decades as described above works reliable. Nevertheless, there are some topics that can be improved. A little bit cumbersome is, e.g., the effect, that there a small changes ($< 10^{-3}$ relative) in the measured photocurrent when the measurement range of the electrometer changes. Especially, care has to be taken in the electron counting regime that not both measurement channels (for D3 and D4) are range-switched simultaneously since the step in the current measurement due to the shift in the measurement range could be taken as a change in the electron number.

Figure 4 shows the electron beam current in the range of 220 electrons for D3 (black) and D4 (red). Especially the D3 signal shows a significant part of noise. This electronic noise, inherent at the electron storage ring, is most likely captured due to the long cables leading the photodiode signal outside of the storage ring housing to the scanner-electrometer unit.

Figure 5b shows a comparison of the electron beam current measurement at the switching point from D2 to D4 at approx. 56 nA. The calibration of D2 (blue curve) is traceable to the PCT current measurement at around 10 mA, the calibration of D4 (red curve) is traceable to the electron counting at approximately 440 electrons. At time $t = 0$ s the current measurement is switched from diode D2 to D4, the dashed curve shows the extrapolated value that would have been measured by D2 after the switching. The photocurrent of D4 first increases with time, when the photodiode is initially irradiated by the

synchrotron radiation. This drift is most likely due to a change in the spectral responsivity due to charging of the SiO_2 top-layer of the photodiode or surface decontamination, e.g. the desorption of an ice layer, of the photodiode surface. At time $t \approx 300$ s the electron beam current has been further reduced into the sub-nA range. It is known from experience that in this pA current regime the drift in spectral responsivity is greatly reduced and even reversed. So, e.g., at 75 pA (electrons), the spectral responsivity decreases relatively with a rate of $1 \cdot 10^{-4}$ /min. Thus taking the value of the current measurement of D4 before the reduction of the electron beam current and comparing it to the value measured with D2 at the same time, both measurements agree within a relative accuracy of better than $2 \cdot 10^{-3}$. Nevertheless, this drift in spectral responsivity, even if it is very small in the pA range, prevents the calibration factors from being extrapolated over a wide range of stored electrons.

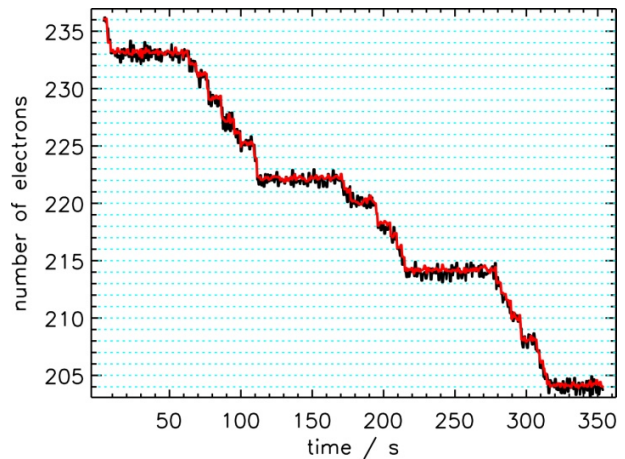


Figure 4: Noisy photocurrent from photodiodes D3 (black) and D4 (red).

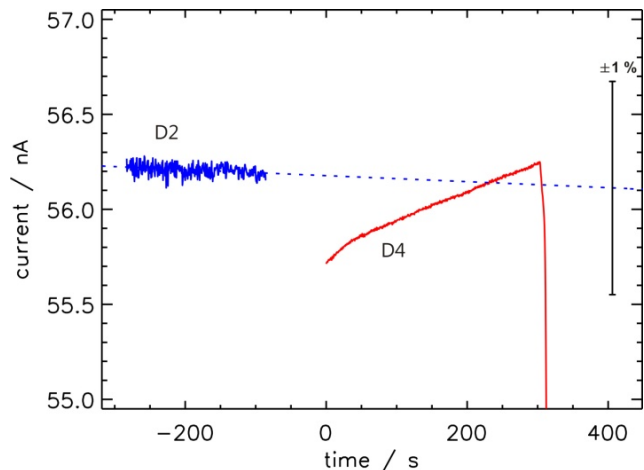


Figure 5: Test of photodiode calibration at the transfer point from photodiode D2 to D4 at 56 nA.

IMPROVEMENTS IN THE LOW ELECTRON BEAM CURRENT MEASUREMENT

In a first step, different equipment for the measurement of the photodiode current has been tested. The small photodiode currents are converted by means of commercially available current-voltage (I/U)-converters [11] before the signal is guided by the long low-noise cable out of the storage ring housing, where the signal is then measured by means of a digital voltmeter (DVM). The I/U-converter covers a range of 10 decades. The range switching has been done manually for this testing but is planned to be performed computer controlled after the testing of the equipment has ended. This set-up has significantly reduced the noise level and allows the counting of several thousands of electrons, as, e.g., can be seen in Fig. 6. The signal in this graph shows a significant improvement to the situation shown in Fig. 4, which was measured with the old set-up at a much lower electron number.

Even at an electron beam current in the range of 5800 pA (electrons) indications for the step-like decrease of the electron beam current can be seen, Fig. 7. The next aim is to reduce the small ripple of 50 Hz line frequency still present at the photodiode current and to investigate the source for the drift in sensitivity.

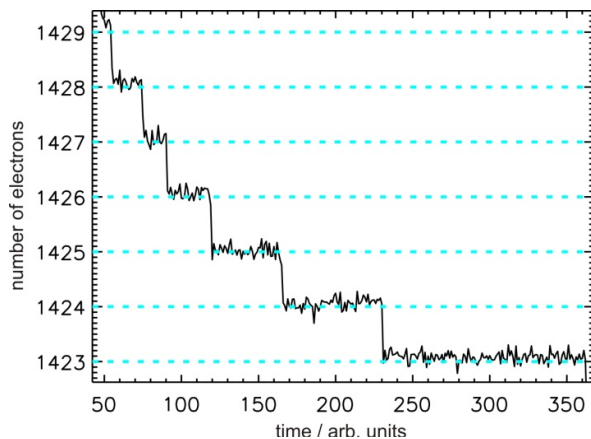


Figure 6: Improved photocurrent measurement.

SUMMARY

The instrumentation for electron counting at the MLS electron storage ring has been greatly improved. More than 1000 electrons can be unambiguously counted now and with further adaptation of the equipment even the counting of much higher numbers seem feasible. This improvement in the measurement of very low electron beam current will reduce the uncertainty in the calculated photon flux of the synchrotron radiation which is used for calibration tasks, e.g. the calibration of photon counting detectors.

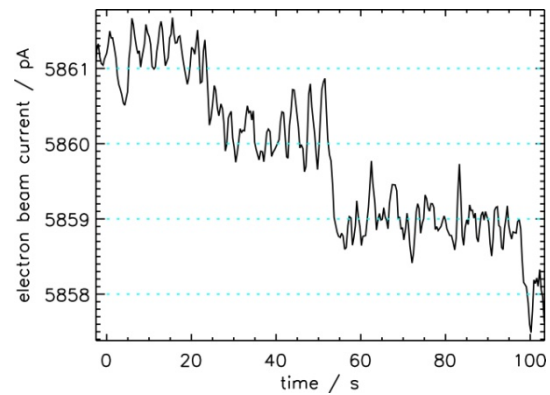


Figure 7: Measured photodiode signal in the 5800 pA range. Indications for a step-like decrease of the electron beam current can be seen.

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