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PRECISE MEASUREMENT OF SMALL CURRENTS AT THE MLS

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Abstract

The Physikalisch-Technische Bundesanstalt (PTB), the National Metrology Institute of Germany, utilizes an electron storage ring – the Metrology Light Source (MLS), located in Berlin, as a radiation source standard in the VIS, UV and VUV spectral range. In order to be able to calculate the absolute intensity of the radiation, the electron beam current has to be measured with low uncertainty. In this paper we focus on the measurement of the beam current in a range of several nA to 1 pA (one electron) by means of Si photodiodes, detecting synchrotron radiation from the beam. Electrons are gradually scraped out of the ring and the diode signal is analyzed afterwards. The exact number of stored electrons then can be derived from the signal. The measurement is carried out automatically with an in-house developed software.

INTRODUCTION

The Metrology Light Source (the MLS) is the electron storage ring owned by the Physikalisch-Technische Bundesanstalt located in Berlin and dedicated to metrology and technological developments in the spectral ranges from far IR to extreme UV [1]. The main parameters of the MLS are presented in Tab. 1.

Table 1: Main Parameters of the MLS

Parameter	Value
Circumference	48 m
Injection energy	105 MeV
Operation Energy	50 to 629 MeV
Revolution frequency	6.25 MHz
Beam Current	1 pA (1 electron) to 200 mA

The MLS is utilized as a primary source standard and, therefore, PTB has installed and is operating all the equipment required for the measurement of the storage ring parameters required for calculation of the spectral photon flux with high accuracy [2]. The spectral intensity of the synchrotron radiation can be calculated by means of the Schwinger equation [3]. One of the contributors into the spectral power accuracy is the value of the electron beam current, therefore it has to be measured and controlled with a lowest possible uncertainty.

At the MLS the beam current can be varied in the range from 200 mA to 1 pA (a current of a single electron). The current is controlled over the whole range with a good accuracy (typical relative uncertainty < 10^{-2} to 10^{-4}). In this paper the main point of interest is the lower range of the electron beam current (a few nA and less). In this range the accuracy of the current measurement can be significantly improved by counting the exact number of the electrons circulating in the storage ring. Since the revolution frequency of the ring can be measured with high precision (better than 10^{-8}), the electron beam current is also known to this accuracy.

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MEASUREMENT OF THE ELECTRON BEAM CURRENT

In the upper range (from 1 mA and more), the current is measured by two commercially available DC parametric current transformers (PCTs, made by Bergoz Instrumentation, France) [4]. The PCTs have a relative uncertainty of about 10^{-4} in this current range.

In the lower ranges the beam current is measured by 4 sets of Si photodiodes (AXUV100 and SXUV100 diodes with 10 mm x 10 mm area, made by Opto Diode Corp.). In each set there are 3 diodes (see Fig. 1) with a different attenuation of synchrotron radiation. The attenuation is made using two different Aluminum filters (3 diodes (D1) with a thick filter (8 µm) cover the range of 20 mA and less, and 3 diodes (D2) with a thin filter (0.8 µm) are used for the range below 0.01 mA. The third type is the unfiltered diode (D3 and D4) which covers the range of low currents (10 nA and less).

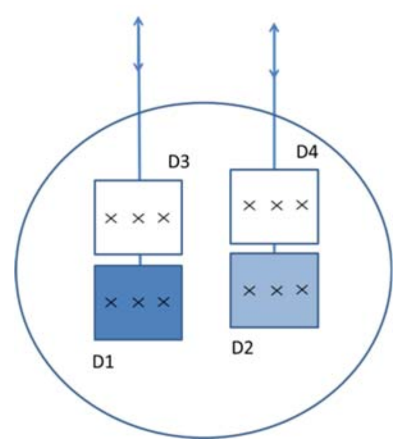

Figure 1: Photodiodes set-up at the MLS.

When the synchrotron light is hitting the diode, it produces a photocurrent which can be amplified, transferred into a voltage and then measured via a volt meter. All filtered diodes and two unfiltered diodes (1 on each set D3 and D4) are connected to Keithley 617 electrometers [5]. The rest of the diodes – 4 unfiltered diodes – are connected to the FEMTO current-voltage converters (I/U) [6] (FEMTO diode) followed by Agilent 34401A [7] a digital voltmeter (DVM), which have better signal to noise ratio than the Keithleys. The diodes connection scheme is presented in Fig. 2.

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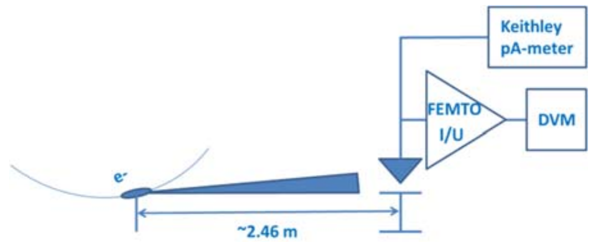

Figure 2: Diode connection scheme at the MLS.

EXPERIMENTS AT THE MLS

At the MLS different experiments on the different current ranges are performed. Often it is required to reduce the beam current to a certain value. This is usually done by using a mechanical scraper, which is a tungsten plate, which can be moved close to the beam and the beam particles can be lost on it by hitting it. The scraper is manipulated by servomotor which can be moved with an accuracy of a few micrometers. The beam current is controlled over the whole range down to the required value. First by the PCTs, and when the thick filtered diode is inserted, the current value from the diode is matched with a value of PCT. If the required current is in the range of a thin filtered diode, the value of the thin filtered diode will be matched with the value of the thick filtered.

In some of the experiments at the low electron beam currents (1-2 nA and less) it is required to find out the exact value of the beam current. In this case the beam current is scraped down until the required value and then it is measured all the time during experiment by means of unfiltered diodes. After the experiment the exact number of electrons during experiment can be found. This can be done by gradual scraping of the electrons from the ring. So one can move the scraper closer to the beam until it loses a few electrons (the loss should not be too big, because it can introduce a counting error) then move it out to register the signal. Repeating this procedure until the beam will have 0 electrons and analyzing the signal afterwards, it is possible to define the exact number of electrons in the ring before the scraping and the number of remaining electrons during the scraping. Software written in Python has been developed for scraping and electron counting.

Change of the Vertical Beam Size

At the beginning of this work it was supposed that bigger beam sizes are leading to easier scrapping, therefore, it was assumed that the beam size should be increased during the scraping. Usually the vertical scraper is used. At the MLS it is possible to increase the vertical beam size by driving a stripline kicker with a “white noise” generator (WN). Dependence of the vertical beam size at 10 μA beam current on the WN voltage is presented in Fig. 3. The beam size is measured by the source point imaging system [2]. Around 0.25 V and more the beam size is becoming WN defined. All data in this chapter were taken at the beam energy of 629 MeV.

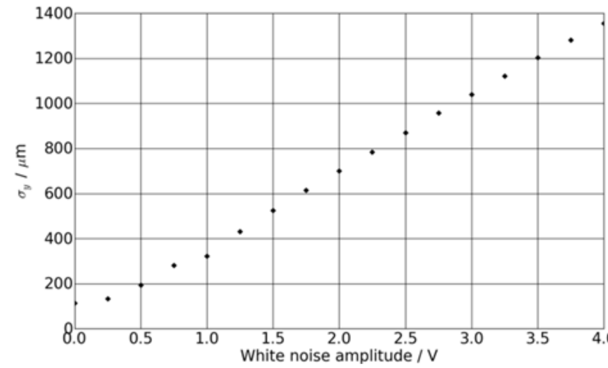

Figure 3: Dependence of the vertical beam size on the WN voltage (at 10 µA electron beam current).

The diode signal depends on the white noise amplitude (or the beam size), see Fig.4. This can be explained by the fact that not all of the emitted photons are hitting the diode in the vertical direction.

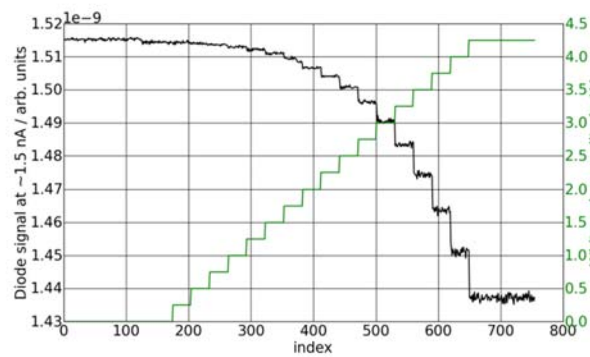

Figure 4: Dependence of the diode signal connected to FEMTO on the WN voltage (at ~1.5 nA electron beam current).

In Fig. 4 one can see the loss of one electron at the index (each index point corresponds to 1 s) of about 125. Using this step one can roughly estimate the equivalent number of electrons from which the emitted light is not hitting the diode (see Fig. 5). So all in all at 4.25 V of WN the diode signal weakens for about 70 steps of a single electron.

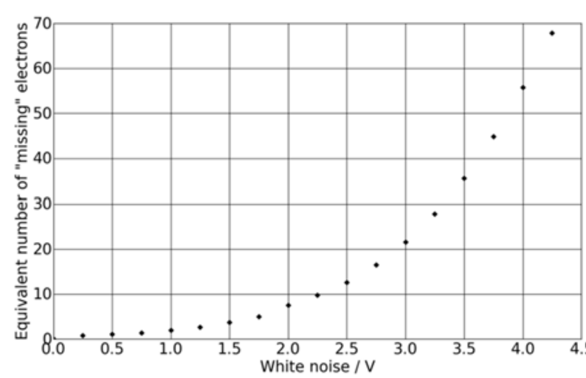

Figure 5: Number of “missing electrons” (equivalent of electrons from which the emitted light is not hitting the diode) depending on the WN voltage (at ~1.5 nA electron beam current).

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The synchrotron light of a single electron is radiated in the forward direction and most of the radiation is emitted within an angle of $\pm 1/\gamma \approx 0.81$ mrad, where γ is Lorentz factor ~ 1231 for the MLS at 629 MeV. Additional angular spread of the radiation is caused by the angular spread of the electrons in the beam, which is defined by the vertical beam emittance and Twiss parameter gamma. This angle can be written as $\sigma_{y'} = \sqrt{\varepsilon_y \gamma_{twiss}}$. Using the data from Fig. 3 and Twiss beta function = 11.5 m at the position of the size measurement system, the emittance change vs WN voltage can be found. Using this dependence and taking $\gamma_{twiss} = 0.77$ 1/m, the dependence $\sigma_{y'}$ vs WN voltage can be found (see Fig. 6). The source point measurement system is located in the same beamline as the diodes.

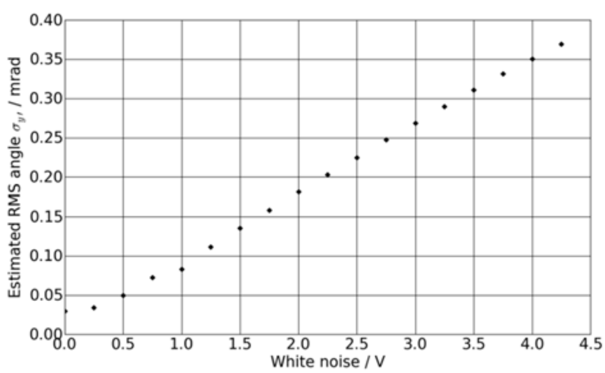

Figure 6: Estimated RMS angle depending on the WN voltage (at ~1.5 nA electron beam current).

From Fig. 6 one can see that $1/\gamma$ term is dominating for the MLS. This means that even without applying the WN voltage the diode is not detecting about 1% of radiated photons. This can be estimated assuming Gaussian beam as:

$$\left(1 - \mathrm{erf}\left(\frac{0.5d}{L \cdot \frac{1}{\gamma} \cdot \sqrt{2}}\right)\right) \cdot N \sim 18,$$

where $d = 5\cdot10^{-3}$ m half of the diode size, $L = 2.458$ m is the distance from the source point to the diode, $N \sim 1487$ is the number of electrons in the ring and the error function:

$$\mathrm{erf}(x) = \frac{1}{\sqrt{\pi}} \int_{-x}^{x} e^{-t^2} dt.$$

For more precise estimation of this effect one could use the Schwinger equation and find the exact amount of radiation, which is not hitting the diode, but this is ongoing work and not covered in this this paper yet.

The signal itself also becomes noisier when the WN is applied. The dependence of the noise of a FEMTO diode signal on the WN voltage at two different beam currents (rough estimations: 4.7 nA and 1.5 nA) is presented in Fig. 7. It was calculated in the following way. First, a part of the signal with constant white noise amplitude and without electron loss was normalized to its mean value, then the standard deviation of this signal was found. This procedure was applied to each amplitude value of the white noise. For comparison, the standard deviations of the signal at 1.5 nA were additionally rescaled on the factor of 4.7/1.5. A rough estimation of a change of the signal, which corresponds to a loss of one electron, is presented in Fig. 7. This step is called further a single electron step. For the electron counting to be possible, the noise level should be less than half of the single step. The counting is much easier when the noise level is less than a quarter of the single step. So one can see that counting of 1.5 nA is possible but it becomes impossible at 4.7 nA using a signal from only one diode. It is not recommended to apply the WN voltage of more than 2 V, because after 2 V the noise level increases.

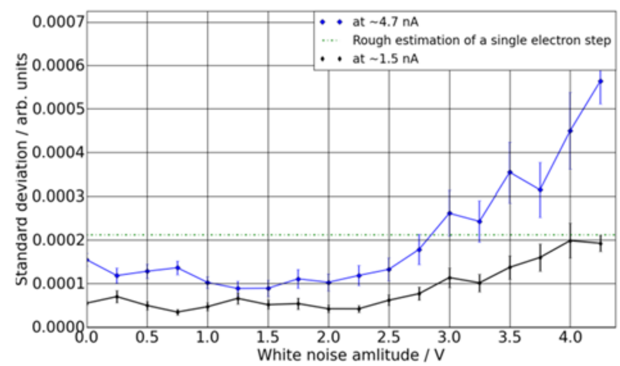

Figure 7: Dependence of the noise of the photodiode signal on the WN voltage (at ~4.7 nA (blue) and ~1.5 nA (black) electron beam current).

Sum of Signals from Different Diodes

There are 6 unfiltered diodes installed at the MLS. Two of them are connected to Keithley pA meters and using them it is possible to count up to 1 nA. Then the noise level becomes too high. But one can use the 4 other diodes connected to the I/U converters (FEMTO) and their sum to decrease the noise level. One can assume that all diode signals are uncorrelated because they are all connected independently of each other. Nevertheless it was found that they become correlated after a certain value of applied WN voltage. The Pearson's correlation coefficients [8] of 3 FEMTO signals vs applied WN voltage are presented in Fig. 8.

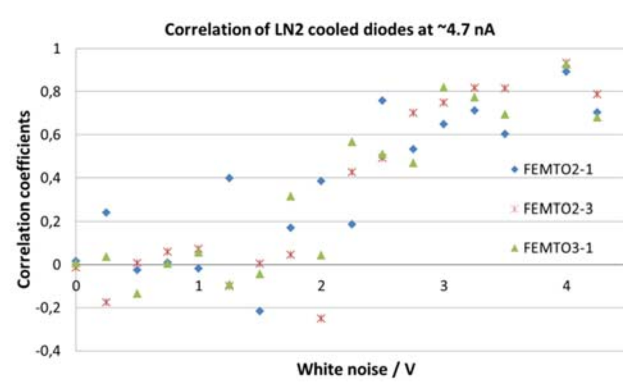

Figure 8: Correlation of 3 FEMTO diodes depending on the WN voltage (at ~4.7 nA electron beam current).

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The signals become correlated for the WN voltage of more than 2 Volt. This can be explained by the fact that photons emitted by a part of the electron beam with large angular deviation do not reach diodes and this happens for all diodes simultaneously.

In the standard user optic at the MLS the WN voltage is 0.75 V at low currents. At this voltage the diode signals are not correlated and therefore they can be summed in order to reduce the noise. In order to compare the noises of different signals depending on the beam current, the beam was scraped with big steps (1 nA to 0.25 nA) from about 5.8 nA down to 0. On each step the scraper was moved out and then long (more than 100 points) signals without electron loss were recorded, let's call such parts of the signals as plateau. One FEMTO diode at the day of measurement was out of order, so only 5 signals were measured.

The sum of the signals can be calculated as the weighted arithmetic mean in the following way:

- First all signals should be shifted to 0 at 0 electrons in the ring;
- At higher currents > 2 nA the plateaus are linearly drifting with time due to the thermal effects. Therefore the signal should be fitted with a linear function and then one should remove the fitted slope from each plateau;
- Then each plateau of each signal should be normalized to the mean value of the plateau calculated for the highest value of the beam current (5.8 nA in this case) of the corresponding signal;
- Then one can find the standard deviation of the plateau signal, this is the noise level of the plateau. Doing this for each plateau and each signal one can find the noise levels depending on the beam current $\sigma_{k,j}$, where k is the number of diode signal and j is the number of plateau. That is what is plotted in Fig. 9.
- With the last step one should find the weighted mean of every signal, the weights are calculated as: $w_{k,j} = \sigma_{k,j}/\sigma_{i,j}$, where i is one fixed diode number, so the weight for $k = i$ is equal 1. The sum of n signals can be found as: $S_{\Sigma,j}(t) = \frac{\sum_{k=1}^{n} S_{k,j}(t)\cdot w_{k,j}}{\sum_{k=1}^{n} w_{k,j}}$ for each plateau j and each measured point t. Now one can find the noise level of the sum signal.

The horizontal line plotted in Fig. 9 marks estimated half of the single electron step. As it was already noticed above, the electron counting is reliable, when the noise level is around a quarter of a single step. This means less than 1500 electrons. Then with higher noise levels it is also possible to count but one needs more time to record longer plateaus in order to decrease the statistical error, and analyse the sum of the signals. So the possible number of counted electrons at the MLS is less than 3000, which corresponds to 3 nA of a beam current.

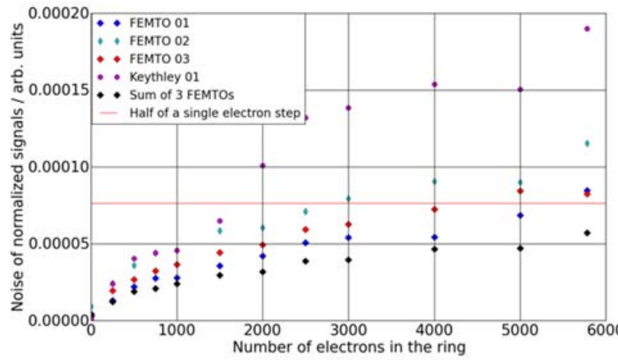

Figure 9: Noises of signals from different diodes depending on the number of electrons in the ring in standard user optic at the MLS.

CONCLUSION

PTB uses the MLS as a radiation source standard, which is dedicated to metrology and technological developments in the spectral ranges from far IR to extreme UV. For the experiments at the MLS with the lower current (less than 3 nA) the exact amount of circulating electrons needs to be found after and during the experiment. This can be done with an in-house developed software. The number of electrons corresponding to currents up to 1.5 nA can be counted using only one signal. At the range of 1.5 nA to 3 nA counting is also possible but is not absolutely confident. Long scraping time and the use of the sum of the signals from different diodes is necessary.

It is not recommended to use the white noise voltage of more than 2 V, because the signals from different diodes become correlated and noisier. The sum of them will not improve the statistical error or the noise level of the signal. The signals should be summated as the weighted arithmetic mean.

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