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AUTOMATIC ADJUSTMENT AND MEASUREMENT OF THE ELECTRON BEAM CURRENT AT THE METROLOGY LIGHT SOURCE (MLS)

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Abstract

The electron storage ring MLS (Metrology Light Source) is used by the Physikalisch-Technische Bundesanstalt (PTB), the German metrology institute, as a primary source standard of calculable synchrotron radiation in the ultraviolet and vacuum ultraviolet spectral range. For this, all storage ring parameters have to be appropriately set and measured with low uncertainty. E.g., the electron beam current can be varied by more than 11 orders. This adjustment of the electron beam current, and thus the spectral radiant intensity of the synchrotron radiation, for the specific calibration task is conveniently performed fully automatic by a computer program.

INTRODUCTION

The PTB, the German metrology institute, utilizes the electron storage ring Metrology Light Source (MLS) [1] in Berlin - Adlershof for the realization of the radiometric units in the near infrared, visible, ultraviolet and vacuum ultraviolet spectral range. For this purpose, the MLS is operated as a primary source standard, i.e., the spectral radiant intensity of the synchrotron radiation (SR) is calculated by means of the Schwinger equation [2]. Adapting this to electron storage rings, where the electron revolves, the Schwinger equation has to be multiplied with the revolution frequency n, 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

$$I = N \, \mathrm{e} \, \mathrm{n}, \tag{1}$$

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. 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, but this is not the focus of this paper.

In this paper we focus on the variation of the electron beam current over more than 11 decades. The adjustment of the electron beam current is widely used for the calibration of wavelength-dispersive spectrographs or for the calibration of counting detectors, with very low electron beam currents, even single photon detectors can be calibrated. To facilitate these calibrations, a fully automated program was developed for the adjustment of the electron beam current to the desired value and its accurate measurement.

INSTRUMENTATION

At the MLS, the stored electron beam current can be varied by more than 11 decades, that means 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, 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.

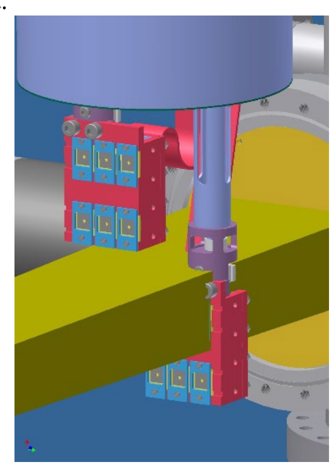

Figure 1: Schematics of the photo diodes assembly (red) as illuminated by the synchrotron radiation (green).

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Currents in the upper range, i.e., above some mA, are measured with two commercially available DC parametric current transformers (PCT) [4], which are traceably calibrated on a regular basis. For an absolute determination of the electron beam current, the offset signal of these monitors have 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] and also seems to slightly depend on the stored current itself, most probably due to some thermal effects. 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.

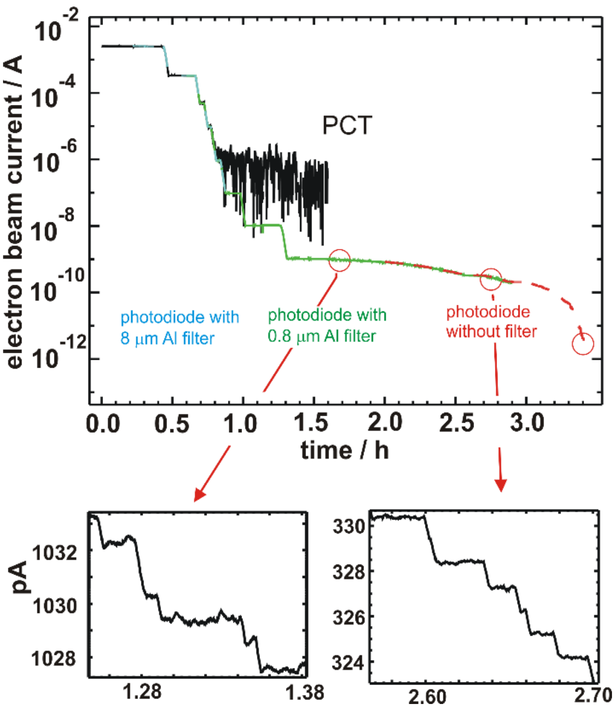

Figure 2: Illustration of the electron beam measurement over more than 11 decades.

For the measurement of electron beam current below approximately 1 mA, LN_2-cooled windowless Si photodiodes [5] 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 from above. Two individual blocks each with 6 photo diodes are in usage right now, as is illustrated in Fig. 1. On one block, the photo diodes in the lower row are covered with Al filters with 8 µm in thickness (thick filtered diodes), photo diodes in the upper row are unfiltered. The second block differs from the first only in the fact, that the lower photo diodes are covered with 0.8 µm thick Al filters (thin filtered diodes). The filtered photodiodes are connected by long low-noise cables to electrometers [6] that are placed outside of the storage ring housing. The unfiltered photo diodes are connected to I/U transformers [7] that are mounted close by in the storage ring housing and the voltage signal is measured by DVM that are located outside the ring. Normally only one photo diode of each kind is used.

For the reduction of the electron beam current a vertical scraper is used, that is placed close to the stored beam and thus greatly reduces the beam lifetime.

BASIC MEASUREMENT PROCEDURE

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

$$I_{MLS} = k_{D1} \cdot I_{D1} \quad (2)$$

is determined for the thick filtered photodiode by comparison with the electron beam current measured by the PCTs first. This is done for electron beam currents in the range from 10 mA to 0.1 mA. This so calibrated photodiode is than used for the beam current measurement down to the µA region. In the µA region the thin filtered diodes are inserted and the measured photo current is compared to the one from the thick filtered diode, giving the calibration factor k_{D2} This photo diode is then used for the beam current measurement down to the nA region.

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%.

It should be mentioned that the calibration factors depend on the electron energy. For 630 MeV electron beam energy, the calibration factors are roughly 34 mA/mA for the 8 µm Al filtered photo diode and 2.8 mA/mA for the 0.8 µm Al filtered diode, respectively.

Electron currents in the range of some nA, are determined by counting the number of stored electrons, first developed at the Tantalus electron storage ring [8] and also utilized at the SURF electron storage ring [9]. To do this, 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 $1 \cdot 10^{-7}$.

Figure 2 illustrates the measurement of the electron beam current over the entire range. Because the measurement is rather time consuming, a computer program based on the python language was developed to do this task fully automated as is described in the next section.

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AUTOMATED PROGRAM

Basically, the program performs the measurement sequence as described above: It controls the position of the feed-throughs with the photo diodes and the position of the scraper used to reduce the electron beam current. It automatically determines the calibration factors for the photo diodes. In the range below some nA, the program also performs the electron counting. To give an impression, the top panel of the program is shown in Fig. 3.

Figure 3: Top panel of electron beam current control program.

Once a target beam current value is given, the program automatically sets the electron beam current to this value. The program records all tasks, so that also later an offline check or re-evaluation of the recorded data can be performed. First, the program determines the calibration factor that relates the photo current of the thick filtered photo diode to the PCT -measured electron beam current. Therefore, the program, by successive placement of the scraper close to the electron beam, reduces the current to approx. 10 mA first, thereafter to 1 mA and 0.1 mA. At these values the electron beam current measurement are performed for some 100 s by the PCT and the photo diode. Figure 4 shows as example such a calibration measurement. Then, a linear fit is performed for the three measurement points at 10 mA, 1 mA and 0.1 mA, yielding the calibration factor and the PCT offset value, see Fig 5 for an example. Thereafter, the program sets the electron beam current to the preselected value by repeated placement of the scraper close to the beam.

Since it was observed that the measured photo current slightly depends on the measurement range of the electrometer, the program can be optionally used in a special mode which controls the measurement range of the electrometer and corrects possible deviation. For this, the photo current is measured for about 100 s in the respective upper measurement range of the electrometer. Then the electrometer is switch to the next lower range by the program and the photo current is measured in this range for another 100 s. A possible deviation is than corrected by an additional factor. Moreover, for each measurement range offset values, that have to be determined separately before, can be subtracted before matching the measurement in the two adjacent measurement ranges. These offset values can result from poorly balanced input amplifiers of the electrometer and can be in the range of several tens of µA. Figure 6 shows an example of this feature.

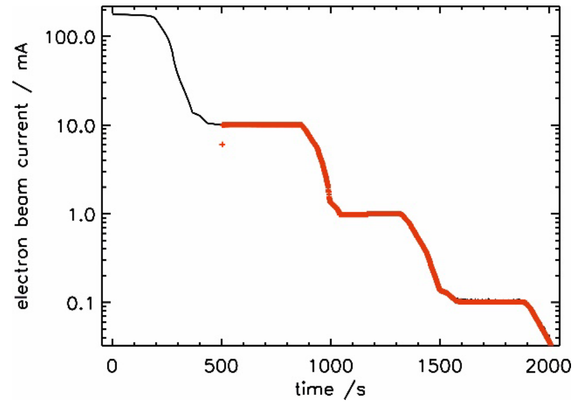

Figure 4: Black: measured electron beam current with the PCT; Red: Measured photo current of the 8 µm filtered photo diode multiplied with the calibration factor.

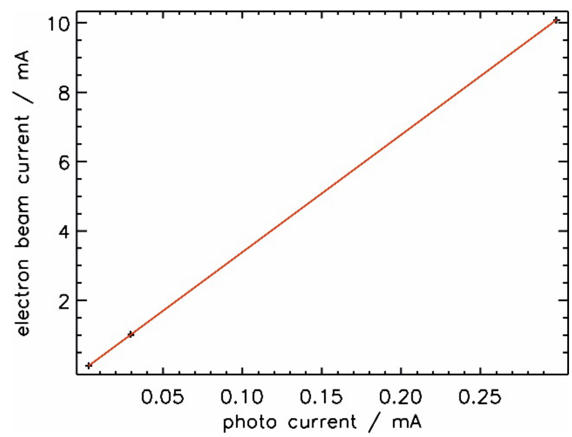

Figure 5: Example of the determination of the calibration factor for the 8 µm filtered photo diode.

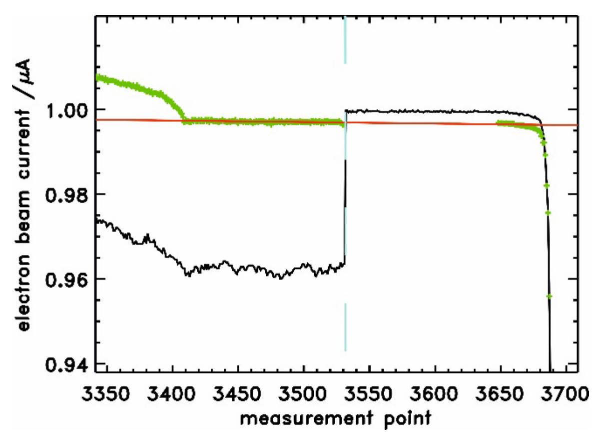

Figure 6: Example for the adjustment at a range switch of the electrometer: black: beam current measurement with the thick filtered diode; vertical dashed line indicates the range switch, green curve: calculated electron beam current keeping track of the previous range switches, red line: fit to the plateau values.

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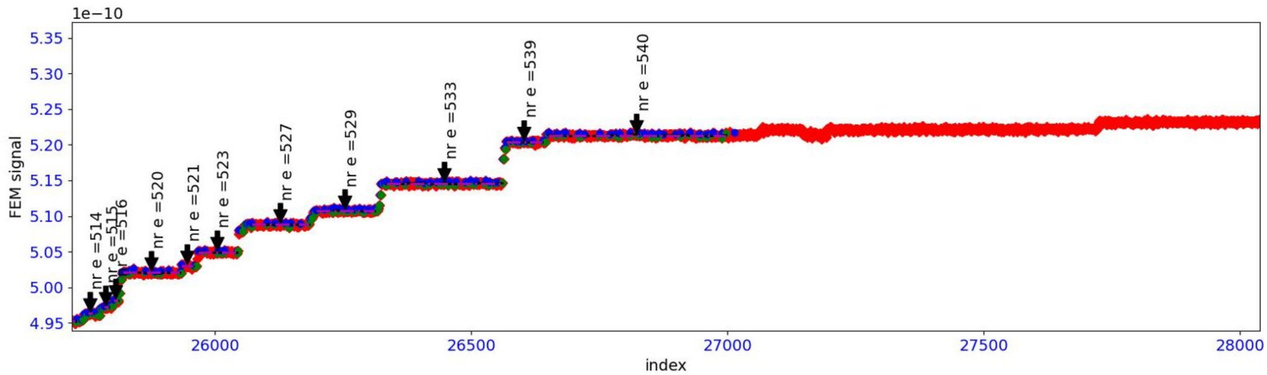

Figure 7: Example of electron counting in the range of 500 electrons (500 pA).

Electron currents below approx. 1 nA can be measured by counting the electrons when they are kicked out by the scraper. One electron is equivalent to an electron beam current of 1 pA. Figures 7 and 8 show examples from the electron counting by the program.

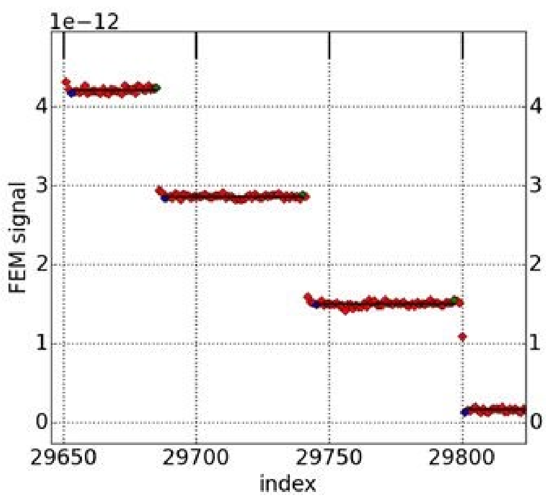

Figure 8: Example for counting of last three electrons.

The program adjusts and measures the target value normally in the range of several µA or nA. The special calibration tasks are then performed with this selected stored electron beam current, e.g. the calibration of an energy dispersive detector. After the calibration has been performed, the program can thereafter be used to reduce the beam current further into the counting rang.

Doing this allows for a stringent test of the measured beam current in the nA range: The values given by the photo current measurement, that ultimately relates to the PCT current measurement, and the beam current value obtained by counting the electron can be compared. From the degree of agreement, an uncertainty of the beam current measurement in the intermediate range, i.e., the beam current rage between the PCT measurement and electron counting range can be estimated.

This has up to now only been performed once: The electron counting resulted in a value of 541 pA, which is regarded as the true value. The current measured with the thick filtered diode was 539 pA, that of the thin filtered diode 536 pA. This is very promising but, has to be confirmed by further measurements. Using the option to control the measurement range of the electrometer resulted in a slightly worse result of 527 pA, showing that most probably the offset values for the measurement ranges are not predefined correctly.

SUMMARY

An automated program to control and measure the electron beam current at the MLS over a range of more than 11 decades has been developed. This program will highly facilitate the setting of the appropriate beam current needed for a calibration task. The program basically works as planned. A first comparison of the measurement of the mean current by photo diodes calibrated with the PCT current measurement to that resulting from electron counting is very promising but, has to be proven by further measurements.

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