DARK CURRENT MONITOR FOR THE EUROPEAN XFEL

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Abstract

The dark current monitor designed for the European XFEL consists of a resonator, operating with the RF frequency of the accelerator. Prototypes have been produced and successfully tested at the PITZ and FLASH facilities. Since the small charge of the dark current is present in every RF bucket it induces and superimposes a field up to a measurable level. This monitor offers the possibility to measure even small dark currents. In addition to dark current levels down to 40 nA, the monitor allows for charge measurements with sub pC resolution and linear response up to a few nC. The ratio of amplitudes of higher order monopole modes is a function of the bunch length. Measurements at PITZ show the same trend of bunch length compared with a destructive streak camera. Therefore this monitor is also able to measure bunch length in a non-destructive manner. The resonator has been successfully tested at FLASH and the PITZ facility.

INTRODUCTION

Dark current is produced by field emission in the accelerator. It generates a radiation background in the tunnel which damages electronics and activates components. In order to decrease the dark current at the European XFEL different methods including kickers and collimators are planned [1]. To control the dark current level it is necessary to measure and optimize the efficiency of dark current reduction, for which non-destructive monitors are required. Here a new device is described which provides measurements of the dark current, the bunch charge and also bunch length on the ps scale.

SETUP

The device consists of a resonator made from stainless steel with the frequency of the first monopole mode at 1.3 GHz and a bandwidth of 6.7 MHz. Two antennae are used for coupling-out the signals, see Fig. 1 and [2]. The voltage of a monopole mode after a beam passage is given by

$$U = U_0 \sin(\omega t) e^{-\frac{t}{\tau}}, \quad (1)$$

with $\omega = 2\pi f$, the resonance frequency $f = 1299.3 \pm 0.1$ MHz, the decay time $\tau = Q_L/(\pi f)$ and $Q_L = 193 \pm 5$ the resonator loaded quality factor. The amplitude is given by

$$U_0 = qS, \quad (2)$$

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with the sensitivity $S = \pi f \sqrt{\frac{Z}{Q_{ext}} \left(\frac{R}{Q}\right)}$, where q is the beam charge, $Z = 50\,\Omega$ is the line impedance, $Q_{ext} = 252 \pm 4$ is the resonator external quality factor and $(R/Q) = 42.3\,\Omega$ is the simulated normalized shunt impedance. All values (except for (R/Q)) are determined by laboratory measurements and in agreement with the design values (the resonator is produced with high precision without tuners). Using equation (2) the beam charge can

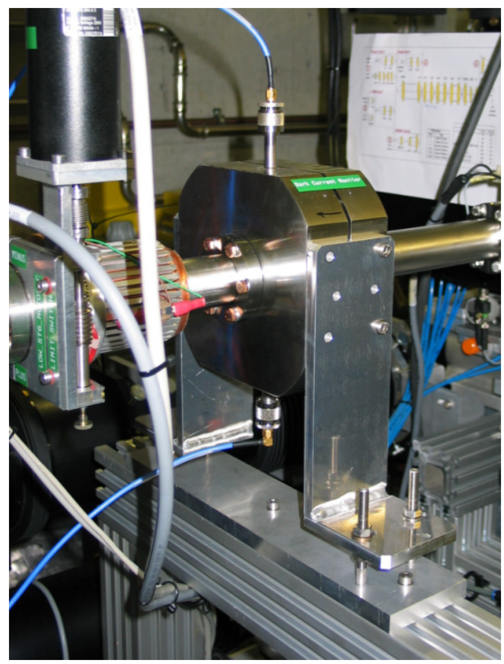

Figure 1: Dark current Monitor at the photo injector test facility.

be calculated by measuring the amplitude. The quality factor of the resonator is designed such that single bunches at the European XFEL with a minimum beam spacing of 222 ns can still be resolved. The signal from each of the two antennae is processed by electronics which consists of circulator, band-pass filter, limiter, down conversion to an intermediate frequency, logarithmic detector and offset and gain control. Due to the logarithmic detector the signal processing range is 70 dB.

MEASUREMENT RESULTS

A prototype of the dark current monitor (DaMon) has been installed at the photo injector test facility at DESY Zeuthen (PITZ). The calibration is done by using the laboratory measurements of the resonator and the response function of the electronics and the attenuation of the cables. The DaMon measurement of the beam charge is compared to those taken with a Faraday Cup (FC), see Fig. 2. A good

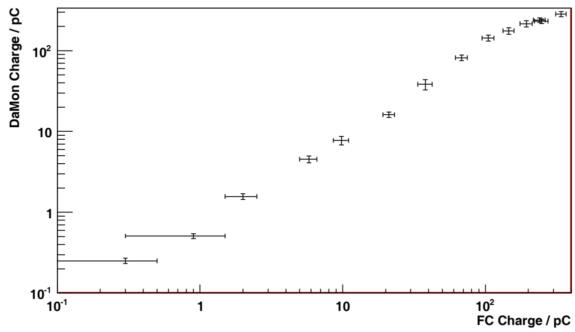

Figure 2: Beam charge taken with the DaMon as a function of results with a Faraday Cup (FC). Error bars are standard deviations of several measurements.

agreement between the DaMon and FC results is visible, the FC shows 2 % lower charges which could be caused by charge loss in the cup. Therefore the laboratory calibration is confirmed with the beam measurement. The noise from the FC readings are larger than that of the DaMon because of a better resolution of the DaMon. The signal from the DaMon is still attenuated by 20 dB, therefore lower charge readings and resolutions down to fC level are possible.

The dark current $I = q/T$ is produced and transfered in the linac with the accelerator frequency of $1/T = f = 1.3$ GHz. Each RF bucket contains a dark current bunch carrying a too low charge q to be detected by a single measurement $U_0 = qS$. But due to the resonant response of the monitor, dark current bunches add fields in the DaMon up to a measurable level, because the decay time is long compared to the dark current spacing T. The resulting envelope amplitude U_{DaMon} is a function of the dark current level as well as the decay time of the signal, determined by the Q_L of the DaMon resonator. Therefore, the dark current can be calculated by

$$I = U_{DaMon} \frac{f}{S} \left(1 - e^{-\pi/Q_L}\right). \tag{3}$$

The DaMon results are compared to those taken with a FC, see Fig. 3. Here the same calibration is used as in the beam charge measurement. The FC results are a factor of about 2.5 higher than the DaMon results, because the FC is 1.56 m nearer to the injector. It was verified that the dark current is reduced by a factor of 2 at a second FC 0.98 m before the DaMon. The remaining difference of dark current is lost due to the aperture of the beamline.

In Fig. 4 the dark current is shown as a function of the injector solenoid current which focus the transverse beam size. The FC could not resolve these low dark current values therefore no comparison was possible. But one can see that dark currents down to 52 nA can be resolved.

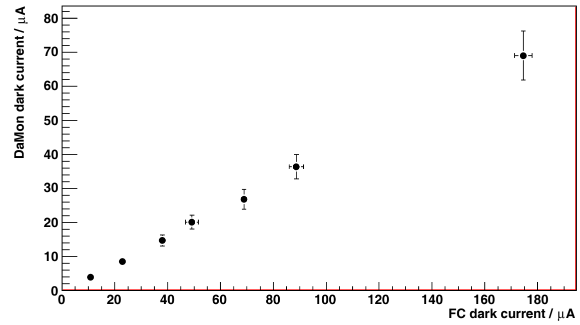

Figure 3: Dark current taken with the DaMon as a function of results with the Faraday Cup.

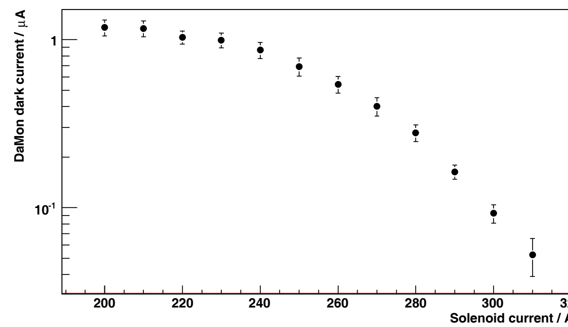

Figure 4: Dark current taken with the DaMon as a function of the injector solenoid current.

The measurements of bunch charge and dark current have been repeated at FLASH. Here the charge measurements are in agreement with the toroids. At FLASH the dark current could not be compared with the FC results because the distance between the devices is too large. The observation limit of the dark current at FLASH is determined to be 40 nA.

Taking into account the beam form factor F the equation (2) has to be modified to

$$U_{0i} = qS_i F(\omega_i, \sigma) \tag{4}$$

for different monopole modes i and the bunch length σ. A Gaussian form factor can be expressed as $F(\omega_i, \sigma) = e^{-\omega_i^2 \sigma^2/2}$ which tends to unity for a bunch length below 1 ps. Taking the ratio of 2 or more monopole mode amplitudes only the bunch length and the resonator properties remain. Especially the ratio of modes with the largest frequency difference end up with the best resolution. Using this method with the DaMon bunch lengths of 1 ps or longer can be detected; this length is expected after the RF gun and before the bunch compression in a SASE machine.

In Fig. 5 the spectrum of the DaMon with beam is visible. The first three monopole modes have the frequencies of 1.299, 3.236 and 5.074 GHz, in between are dipole and quadrupole modes. The third monopole mode is strongly attenuated due to the 25 m long cable between the DaMon

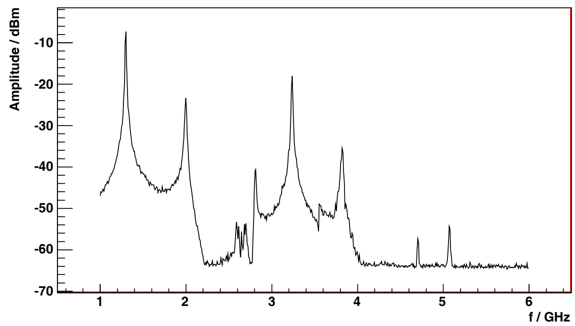

Figure 5: Beam spectrum of the DaMon.

and the spectrum analyzer, but the higher frequency amplitude provides a better bunch length resolution.

The amplitude of the monopole modes has been measured as a function of the injector phase, see Fig. 6. The highest beam energy is reached at phases of zero. For the measurement the spectrum analyzer takes several pulses for each mode. A Gaussian form factor is used. From Fig. 6

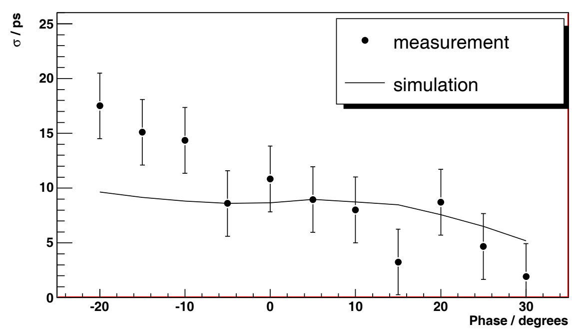

Figure 6: Bunch length measured using the first and third monopole mode from the DaMon signal as a function of injector phase including simulation results.

one can see that the bunch length decreases with increasing phase. This is confirmed by another method using Aerogel as radiator and a streak camera, see Fig. 7. Both show agreement with ASTRA simulations [3] at phases above zero. The variation of the bunch length measurement with the streak camera method is smaller. This could be due to the limited resolution of the spectrum analyzer. At negative phases the simulations do not agree with the measurements taken with DaMon and streak camera; maybe simulation parameters could be better optimized. The streak camera measurements show a better agreement to the simulations at negative phases, here the Aerogel is positioned 4 m downstream compared to the DaMon position.

SUMMARY AND OUTLOOK

A resonator is used to measure non-destructively the dark current down to a lower limit of 40 nA. In addition,

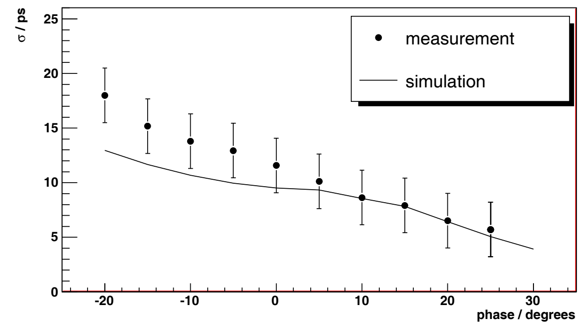

Figure 7: Bunch length measured using Aerogel and a streak camera as a function of injector phase including simulation results. The Aerogel position is 4 m downstream of the DaMon.

the beam charge can be measured with fC resolution. Both beam properties are processed in a prototype electronics and show good agreement with comparable methods. The resolutions are better compared to the values taken with a FC. In addition higher order monopole modes are used to detect the bunch length above 1 ps, which is confirmed by a streak camera method. A dedicated electronics is in development to detect the amplitude of the higher order modes to provide a better resolution of the bunch length measurement.

REFERENCES

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[3] K. Flöttmann, “A Space Charge Tracking Algorithm” (ASTRA), `http://www.desy.de/~mpyflo/Astra_dokumentation/`.