SENSITIVITY OPTIMIZATION OF THE STANDARD BEAM CURRENT MONITORS FOR XFEL AND FLASH II

M. Werner, R. Neumann, J. Lund-Nielsen, N. Wentowski, DESY, Hamburg, Germany

Abstract

There is a tendency to operate 4th generation SASE driven light sources at very low charge in order to further shorten the pulse length. Therefore the operation range of XFEL and FLASH II was extended to a charge range of as low as 20 pC to 1 nC. For a reliable charge measurement down to 20 pC, a low noise design of the signal chain from the monitor head to the digitizing ADC is necessary. This paper describes the steps taken in order to increase the sensitivity and dynamic range of the monitors currently used in the FLASH accelerator, and the basic theoretical background will be explained. Finally, first results are presented.

INTRODUCTION

The linear accelerators FLASH II and XFEL will operate with up to 30 macropulses per second, each macropulse consisting of up to 3600 (FLASH II) or 2700 (XFEL) bunches. The bunch repetition rate is 4.5 MHz maximum. The standard current monitors currently used in the FLASH accelerator offer a resolution between 2 and 3 pC RMS. The goal was to improve the resolution below 1 pC RMS.

TOROID SETUP

The monitors to be used for FLASH and XFEL include 4 pickup coils and 2 test coils, each consisting of a single winding (Fig. 1). The 4 pickup signals are combined with a simple signal combiner for minimal beam position dependence; the test coils are used for calibration and continuous self test.

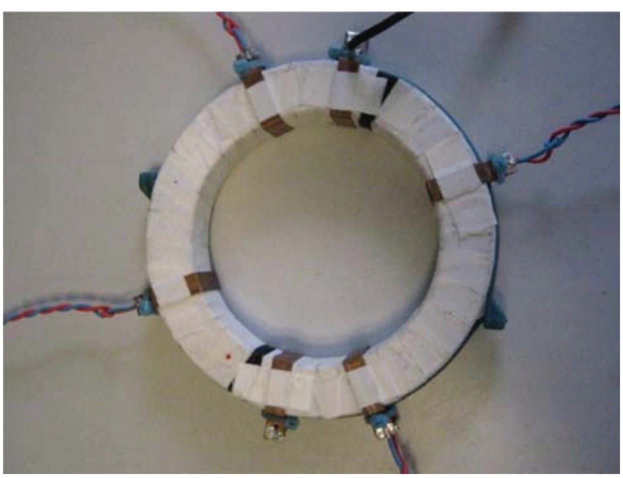

Figure 1: Photo of standard toroid with its 4 pickup coils and 2 test coils (1 winding each).

IMPEDANCE MATCHING

For optimum power transfer at a certain frequency *f*, the load resistor R_L has to be matched to the output impedance Z_{out} of the toroid coils and the signal combiner at this frequency:

$$R_L \approx Z_{out}(f) \approx \mu_0 \cdot \mu_r(f) \cdot f \cdot n^2 \cdot \frac{A}{r}$$

where n = number of windings, A = ferrite cross section, r = effective toroid radius, $\mu_r(f)$ = relative permeability of the ferrite core at frequency *f*.

This expression depends on the frequency directly by the factor *f* and indirectly by the frequency dependent factor $\mu_r(f)$.

Frequency Dependence of the μ_r

Fig. 2 shows the result of a rough μ_r measurement: for low frequencies, the μ_r is almost constant, whereas for high frequencies, the μ_r drops and $\mu_r \cdot$f is almost constant.

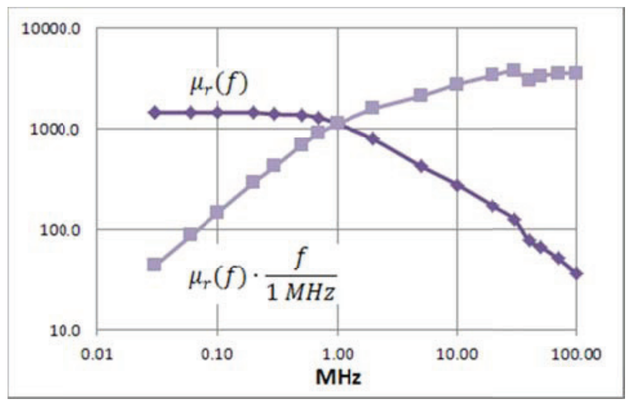

Figure 2: Rough frequency dependence of μ_r and $\mu_r \cdot$f for the ferrite core (material: Vitrovac 6030F).

Two Possibilities of Impedance Matching

Some applications require a flat amplitude response for a certain frequency range. In this case the load resistor for the pickup coil must be matched to the source impedance of the coil for the low edge frequency. Then the system works as a current transformer for all frequencies above this edge frequency. The disadvantage of this operation mode is a low power transfer ratio for the higher frequencies.

For applications requiring maximum sensitivity, the impedance matching has to be done for the upper edge frequency, sacrificing the flat frequency response. See Fig. 3 for a comparison of both operation modes.

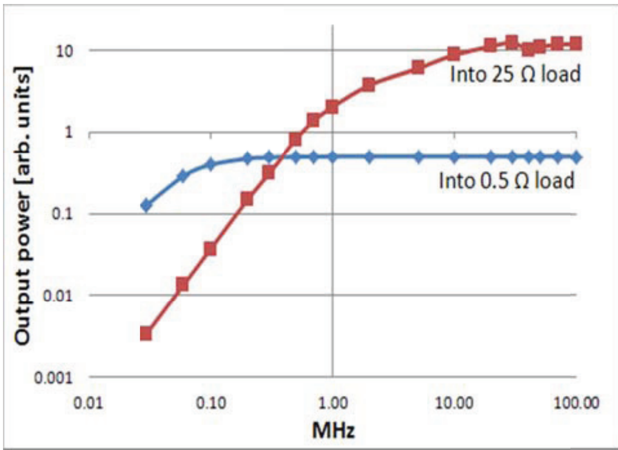

Figure 3: Simulation of output power for two impedance matching modes: flat frequency response ("into 0.5Ω load") and maximum output power ("into 25Ω load").

IMPROVEMENTS

Amplifier

The input circuit of the amplifier currently used for FLASH was adapted to the actual operation requirements (upper frequency limit 20 MHz instead of 100 MHz, lower requirements regarding wideband input impedance matching, noise reduction by additional input impedance matching transformer), so we gained an SNR improvement of 9 dB. Under certain conditions a further improvement by 4-5 dB is possible using a commercial low noise amplifier [6].

Signal Combiner

We replaced coaxial technique with differential twisted pair technique, and we changed from an impedance matched arrangement of dual-input signal combiner elements with 3 dB loss each to a simple four-input low-loss combiner with just parallel connections, which was possible due to our limited frequency range. So we could reduce the signal loss by approx. 6 dB.

Change of the Coil Impedance Matching

In the original design, the impedance was matched for flat frequency response by transformers (n1 : n2 = 1 : 15) directly at the pickup coils. By removing these transformers, we got close to matching at high frequencies and increased the amplitude by more than 20 dB. We did not aim for optimal matching in order to keep the design simple.

THEORETICAL RESOLUTION LIMIT

The possible resolution q_{res} of the bunch charge (for equality between signal and thermal noise of the amplifier) was calculated (detailed deduction see [8]). The result of the calculation was:

$$q_{res} \approx C_1 \cdot \sqrt{\frac{8 \cdot k \cdot T}{\mu_0 \cdot \pi^2} \cdot \frac{1}{(\mu_r(f_{HI}) \cdot f_{HI}) \cdot f_{HI}} \cdot \frac{r}{A} \cdot 10^{\frac{F_{dB}}{10}}}$$

where C1 = correction factor (between ≈1 and ≈3),
$k = 1.38 \cdot 10^{-23}$ J/K, T = 290 K,
$\mu_r(f)$ = frequency dependent relative permeability,
f_{HI} = upper system frequency limit, r = toroid radius,
A = toroid cross sectional area,
F_{dB} = noise figure of amplifier.

For our non-optimized test setup (described later in this paper), the factor C_1 was 2.7; for optimized loss free impedance matching to the load resistor at the upper system frequency and optimized loss free filters, C_1 is expected to be clearly lower.

FIRST EXPERIMENTAL RESULTS

The improved current monitors were tested in the lab (test setup see Fig. 4) and in the FLASH accelerator.

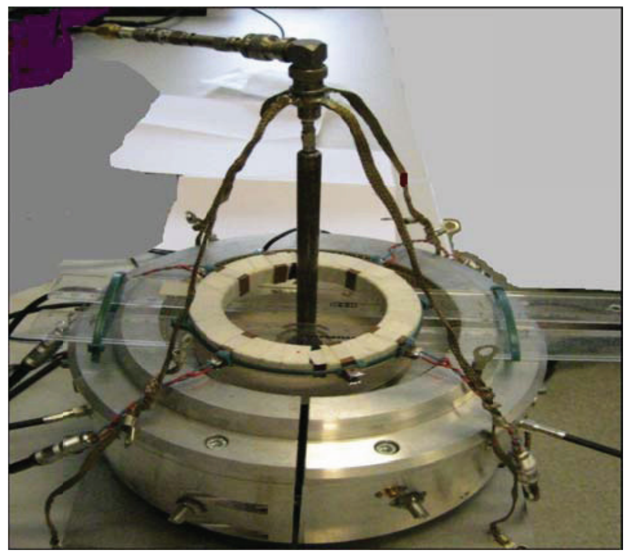

Figure 4: Photo of test setup.

Lab Results for 1 pC Pulse Charge

Even with a test charge as low as 1 pC, we got a clear signal, see Fig. 5.

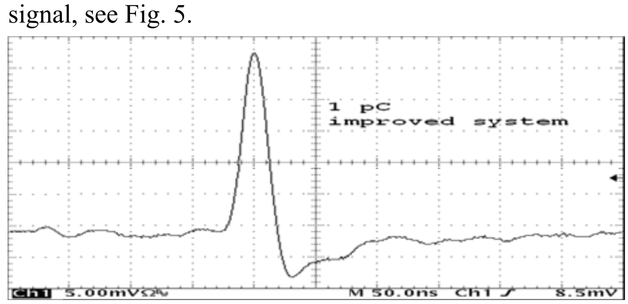

Figure 5: Lab test with the new system: even a pulse of 1 pC is far above the noise level (BW = 20 MHz, non-averaged). Noise level ≈ 0.018 pC RMS corresponding to $1.2 \cdot 10^5$ electrons RMS.

Comparison between Old and New System for 10 pC Pulse Charge in the Lab

Fig. 6 shows a lab measurement of the output signal of an old large size monitor type currently used in the dump area of FLASH. In contrast, Fig. 7 shows a lab measurement for an improved standard size device. In both cases the input signal was a pulse with a charge of 10 pC ($6.2 \cdot 10^7$ particles). The improvement of the system is evident.

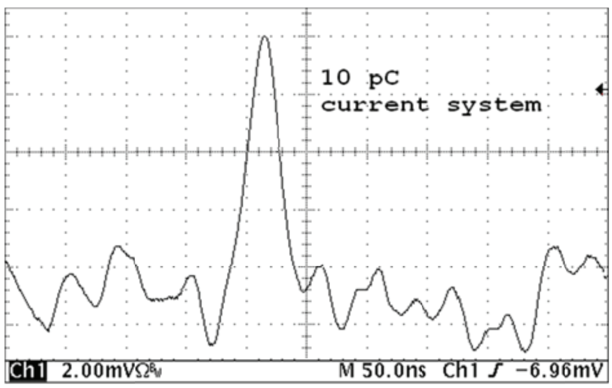

Figure 6: Lab test with 10 pC pulse from current (old) system: noise level ≈ 1.7 pC RMS corresponding to $1.1 \cdot 10^7$ electrons RMS (BW=20MHz, non-averaged). Note that a large size toroid was used – for old standard size systems the result would be about 2 times better.

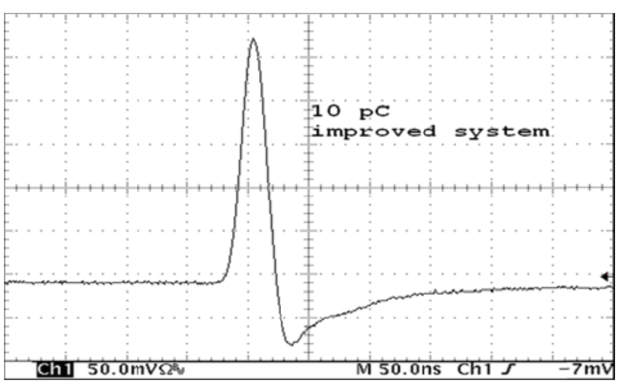

Figure 7: Lab test with 10 pC pulse from new system (BW = 20 MHz, non-averaged).

Lab Test with Special Amplifier

In a test setup with a special commercial low noise amplifier [6] we achieved a resolution of ≈ 0.008 pC RMS.

Results from the FLASH Accelerator for 8 pC

Tests in the accelerator with a bunch charge of 8 pC showed a good improvement over the current "old" systems (Fig. 8). But a comparison between the track "new toroid with amp * 100" of Fig. 8 and the smooth track in Fig. 7 shows that the resolution in FLASH is degraded by more than an order of magnitude compared to the lab measurements. This degradation is obviously the result of electromagnetic interference (EMI) in the proximity of the monitor.

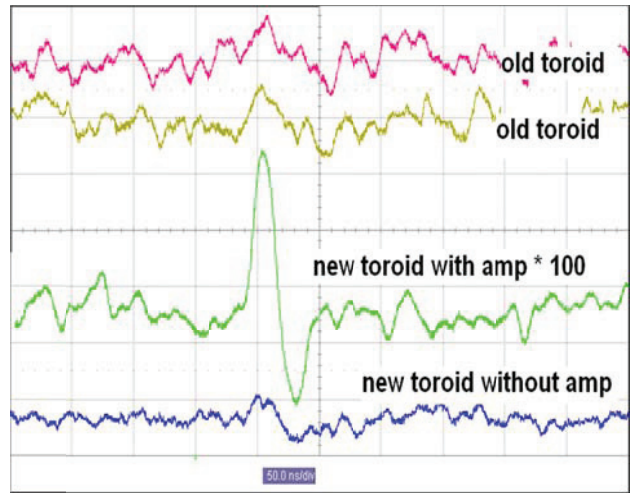

Figure 8: Operation in FLASH with 8 pC bunches. Estimated noise level for the new toroid with amplifier: 0.6 pC RMS (BW=20MHz, non-averaged). The old toroids are always operated with amplifiers (amplitude amplification of 70) because of their low output signal.

CONCLUSIONS AND OUTLOOK

With the improvement of our current monitors, we could increase the signal to noise ratio (SNR) by more than 30 dB in the lab; we could show a resolution of better than 0.01 pC. In the real accelerator, the resolution was limited by electromagnetic interference (EMI), but the improvement was already enough to fulfil the actual requirements of FLASH II and XFEL. For a further improvement, EMI investigations would be necessary.

For special applications, a further improvement of the resolution should be possible by optimizing the geometry of the ferrite core and the signal processing chain.

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