DEVELOPMENT AND FIRST TESTS OF A HIGH SENSITIVITY CHARGE MONITOR FOR SwissFEL*

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Abstract

The compact X-ray free electron laser SwissFEL, which is presently under development at the Paul Scherrer Institut (PSI) in Villigen, Switzerland, will operate at comparably low charges, allowing the compression of the electron bunches to a few femto-seconds (nominal 200 pC mode) and even towards the atto-second range (short bunch 10 pC mode). A high precision charge measurement turns out to be a challenge, especially in the presence of dark currents, which may occur from high gradient RF gun and accelerating structure operation. In response to this challenge, a higher sensitivity charge transformer and new beam charge monitor electronics were developed in collaboration between Bergoz Instrumentation and PSI. The Turbo-ICT captures sub-pC bunch charge thanks to a new magnetic alloy exhibiting very low core loss. Transmission over a carrier using narrow-band cable television technique preserves the signal integrity from the Turbo-ICT to the BCM-RF. Electro-magnetic and RF interferences are strongly attenuated; the dark current signal is suppressed. First beam test results, which have been performed at the SwissFEL Test Injector Facility (STIF), are presented in this contribution.

SwissFEL AND THE SwissFEL TEST INJECTOR FACILITY

SwissFEL is a compact free electron laser user facility presently under design at the Paul Scherrer Institut in Villigen, Switzerland [1, 2]. The project comprises two FEL beam lines, which will be realized in two phases. The three hard X-ray ARAMIS end stations (phase 1) will provide highly brilliant SASE radiation from 1 to 7 Ångström while the soft X-ray ATHOS beam lines (phase 2) will range from 7 to 70 Ångström [3]. SwissFEL will be operated at 100 Hz repetition rate with two bunches per RF pulse at a bunch distance of 28 ns. Bunch distribution towards the two FEL beam lines will be accomplished at electron energies of 2.1 GeV by fast kickers in a switchyard. The nominal operation at low bunch charges between 10 and 200 pC provides excellent transverse emittances and allows the utilization of compact (in-vacuum) undulators providing full hard X-ray photon flux at comparably low electron energies of 5.8 GeV. Full compression of the low charge electron bunches will lead to ultra-short pulses of < 20 fs (rms at 200 pC) and < 2 fs (rms at 10 pC) in the nominal SwissFEL operation modes and even to towards the atto-second range in a specific short bunch mode of operation. A status of the SwissFEL facility and simulations of its accelerator and FEL performance have recently been summarized in [4].

Most of the design aspects for the SwissFEL accelerator sub-systems as well as the experimental verification of the initial electron beam parameters are presently examined at the 250 MeV SwissFEL Test Injector Facility (STIF) (Fig. 1) [5, 6]. An extensive experimental program is dedicated towards the generation and measurement of the low charge, low emittance electron beam. In this context, prototypes of beam instrumentation specifically designed for the low charge operation modes are being designed and tested – such as cavity beam position monitors [7], transverse profile monitors [8], bunch compressor diagnostics [9] as well as the beam charge monitors presented in this paper.

First operational experience at STIF and preliminary results from (mainly longitudinal) sensitivity studies of electron beam parameters [10] indicate that the tightest tolerances for SwissFEL are driven by the peak current stability, which is mainly related to the longitudinal stability of the RF system (mainly in the injector) and the stability of the bunch charge. In this respect, a reliable and high precision bunch charge measurement with an anticipated resolution of 1% at the low charge (10 pC) operation mode, especially in the presence of dark current from the high brightness RF gun and/or the high gradient accelerating structures, turns out to be an important pre-requisite for stable and reproducible SwissFEL user operation. The design of a prototype bunch charge monitor, the so called Turbo-ICT, and the related BCM-RF electronics as well as first test measurements at the STIF are presented in the following.

TURBO-ICT & BCM-RF PRINCIPLE

The Turbo-ICT sensor and the BCM-RF electronics receiver perform bunch charge measurements with low noise and high accuracy. The Turbo-ICT combines an Integrating Current Transformer [11] of a new kind and front-end electronics in one assembly. The original ICT developed for LEP in 1989 was redesigned to measure bunch charges as low as 10 pC with 1% resolution. Several techniques were used to maximize the signal taken from the beam and minimize the noise from various sources: beam dark current, electronics noise, RF and other electromagnetic interferences.

To maximize the amplitude of signal taken from the beam, the ICT integration time is reduced by a factor of 25 compared to the classical ICT making its amplitude 25

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times higher. The shorter signal requires a processing bandwidth 25 times higher. It causes the bandwidth noise to increase by 25, while the signal noise increases by $\sqrt{25}$ only. The net signal-to-noise ratio is therefore improved by $\sqrt{25}$. The ICT bandwidth increase is made possible thanks to new alloys whose core losses remain below 1% up to 350 MHz.

To further increase the signal multiple cores are used [12]. The available signal is multiplied by the number of cores coupling with the beam. The core windings outputs are combined to optimize the power transmission from cores to front-end amplifier.

The first amplifier stage is located in a front-end electronics box near the sensor. This close proximity is essential to avoid excessive noise pick up. The amplifier noise performance is mainly defined by input impedance and transistor transfer gain. A pHEMT transistor with high transconductance and low input capacitance is used [16]. The front-end modulates a 180 MHz narrow-band carrier similar to cable TV signal transmission improving electromagnetic interference immunity.

In conclusion, the Turbo-ICT and its front-end transform a beam signal whose frequency spectrum extends into the THz region into a narrow-band signal proportional to bunch charge. During this process the dark current signal is rejected by > 40 dB. The setup is shown in Fig. 1.

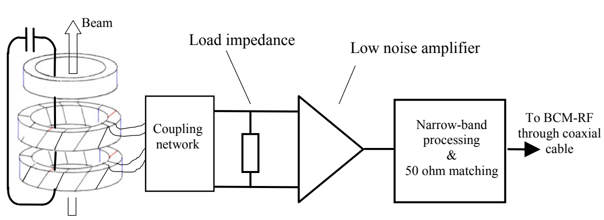

Figure 1: Turbo-ICT with two active cores and front-end.

The Turbo-ICT front-end electronics is powered from the BCM-RF receiver through its output coaxial cable. In the BCM-RF, the modulated carrier is processed through a 500 MHz diplexer removing out-of-band signals. Rejection of 3 GHz dark current signals is about 50 dB. The receiver implements a logarithmic RF amplifier to achieve 90 dB input dynamic range and a 10 MHz output bandwidth. Logarithmic amplifiers are however wide-band devices which demodulate any wide-band noise present on their input. To reduce this noise, a narrow-band filter is located at the input. The filter's centre frequency is adjusted to the RF signal carrier. The log amplifier output signal is proportional to the logarithm of bunch charge. A sample and hold circuit holds the signal magnitude until the next bunch arrives to allow comfortable readout. Fig. 2 shows the BCM-RF input circuit.

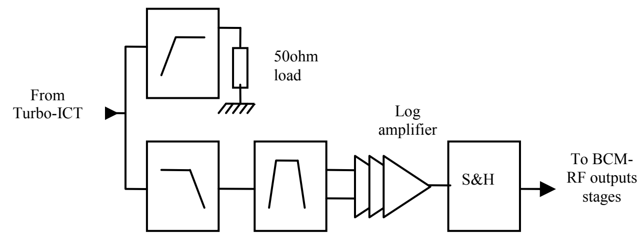

Figure 2: BCM-RF input circuit.

An AD8310 logarithmic amplifier [13] was chosen for its wide input dynamic range and its better sensitivity compared to others models. It is built of six cascaded cells. Each one has a fixed 14 dB gain. The transition from one cell to another produces a periodic log conformance error versus input signal strength of +/- 0.4 dB [13]. BCM-RF circuit features a Microchip PIC microcontroller [14] which can be programmed to correct this systematic error.

TEST SETUP AT STIF

The purpose of the test is to compare measurements from a classical ICT with BCM-IHR electronics to measurements from a Turbo-ICT with BCM-RF electronics. ICT and Turbo-ICT are installed at STIF close to each other. Long cables bring their output signals to their respective electronics. The bunch charge is also measured by a BPM which is calibrated vs. a wall current monitor. Output values from both BCMs are digitalized and processed by LabVIEW.

During the charge scan the bunch charge is decreased by the control room in small steps from a starting value of 200 pC/bunch. For every bunch charge LabVIEW takes 20 measurements, averages them and calculates standard deviation. The standard deviation expresses the measurement noise, since the bunch charge variations are assumed to be minimal. The average value is then processed by a reverse function to get the bunch charge: a linear for the ICT/BCM-IHR and an exponential for the Turbo-ICT/BCM-RF. Figure 3 shows the ICTs/BCMs test setup.

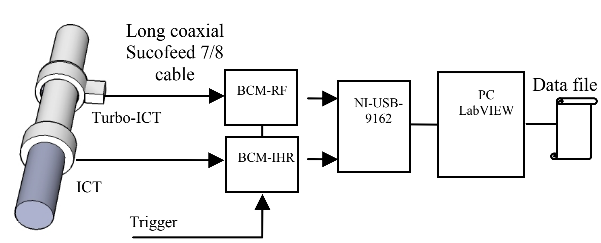

Figure 3: Test setup at STIF.

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MEASUREMENTS & RESULTS

The BCM-IHR was calibrated on site using a 1 nC calibrated source and calibrated attenuators. The linearity error measured during the calibration is less than 1%. The BPM had been calibrated previously by the STIF team using a wall current monitor.

A charge scan from 200 pC to 0.13 pC is performed by control room operators in fourteen steps. Figure 4 shows the ICT/BCM-IHR response and its signal over noise ratio. The signal over noise ratio decreases linearly with beam charge. The ICT/BCM-IHR measures 120 pC with 1% resolution (S/N = 100). In laboratory conditions the BCM-IHR measures 70 pC with 1% resolution, which is almost twice better. One reason may be dark current making the ICT/BCM-IHR signal noisier.

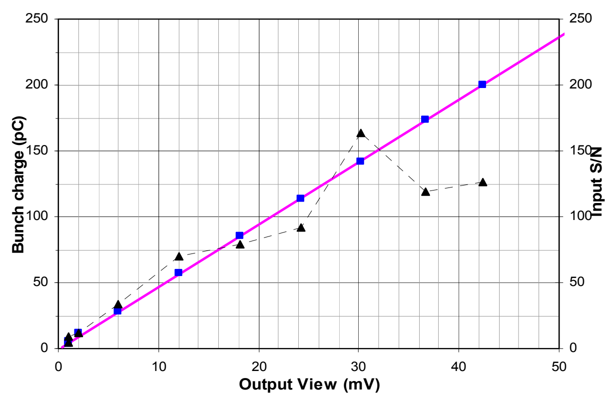

Figure 4: ICT/BCM-IHR response (squares, left axis), signal over noise ratio (triangles, right axis) and reference charge line (left axis).

Figure 5 shows the BPM relative deviation compared to ICT/BCM-IHR from 200 pC to 30 pC. Below this value the ICT/BCM-IHR signal was too noisy to be properly analysed. The relative deviation stays within +/-1%, which confirms the assumption that BPM and ICT/BCM-IHR have a linear response. As a consequence, the ICT/BCM-IHR response was extrapolated to lower charge values using BPM measurements. This extrapolation is the calibration reference for the Turbo-ICT/BCM-RF below 30 pC. At higher charges the BCM-IHR measurements are accurate enough to be directly used as the reference.

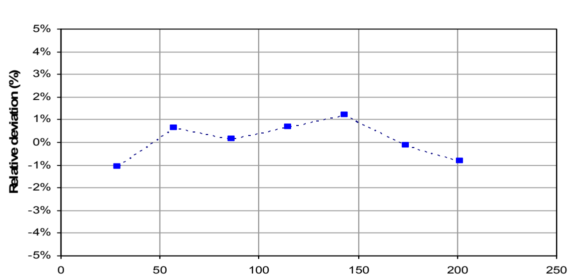

Figure 5: Relative deviation of BPM measurements compared to ICT/BCM-IHR measurements.

Figure 6 shows the Turbo-ICT/BCM-RF response. Even at 5 pC, the signal over noise ratio remains close to 90, i.e. 1.1% resolution, which is slightly better than expected.

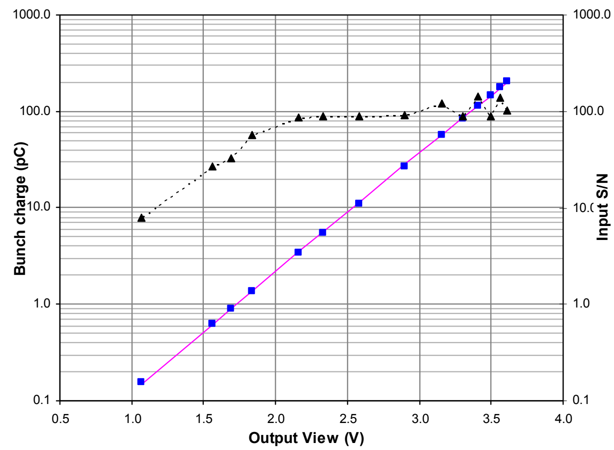

Figure 6: Turbo-ICT/BCM-RF response (squares, left axis), signal over noise ratio (triangles, right axis) and reference charge line (left axis).

The Turbo-ICT/BCM-RF relative deviation is within +/-5%, which is slightly higher than expected (Fig. 7). We have identified three different sources: the log amplifier, the BCM-RF electronics and the BPM. Although the linearity of ICT/BCM-IHR and BPM has been confirmed above 30 pC, linearity of our reference could not be checked for lower charges. It is planned to address this topic in future measurements. Having established better reference will possibly allow recognizing the log amplifier conformance error signature. More points will be taken in order to identify it and try to correct it by using mathematical functions or a predefined correction table.

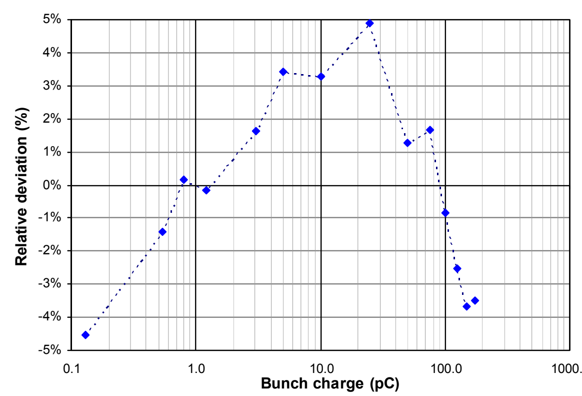

Figure 7: Turbo-ICT/BCM-RF relative deviation compared to BPM charge measurement.

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MOST RECENT RESULTS

Recently measurements were performed by PSI. The results show (Fig. 8) that after setup improvements the BCM-IHR signal is much less noisy. Its measurement is still useful down to 10 pC. This is advantageous for future calibration. Moreover, BCM-RF response on fig. 9 confirms our previous results. Its measurement looks accurate even down to 1 pC. These are preliminary results which required careful analysis.

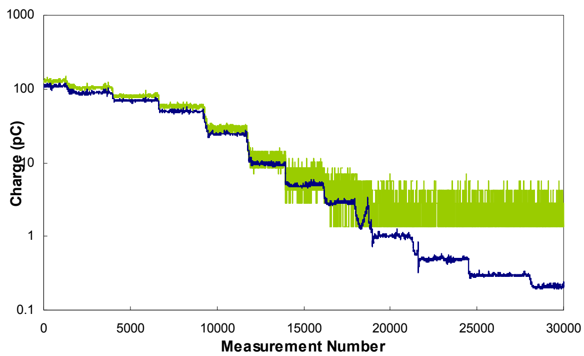

Figure 8: charge measured by ICT/BCM-IHR (green) and BPM (blue).

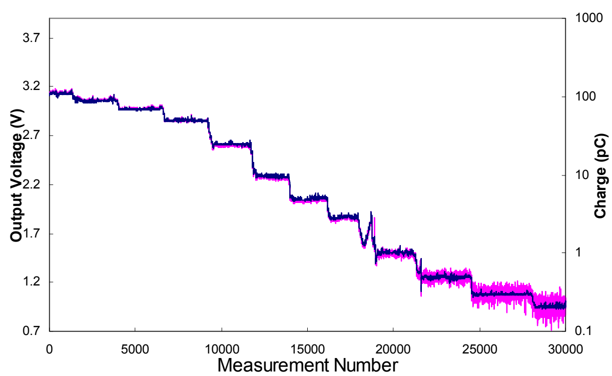

Figure 9: charge measured by Turbo-ICT/BCM-RF (pink) and BPM (blue).

ACKNOWLEDGMENTS

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CONCLUSION

We have described first measurements at STIF using a new non-destructive high sensitivity beam charge monitor. The new instrument was developed by Bergoz Instrumentation with guidance from Paul Scherrer Institut. Measurements were compared and calibrated with a classical ICT associated with BCM-IHR electronics and a BPM. Results show that the new beam charge monitor can measure 10pC single bunch charge with 1% resolution.

We plan to repeat the charge scan with more points in order to establish a better charge reference, to confirm the first measurements, to identify the log conformance error signature and to explore even lower beam charge. The influence of dark current will be studied in depth. Further, charge measurements using the nominal two-bunch beam will be performed.

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