SINGLE PULSE SUB-PICOCOULOMB CHARGE MEASURED BY A TURBO-ICT IN A LASER PLASMA ACCELERATOR

F. Stulle*, J. Bergoz, Bergoz Instrumentation, Saint-Genis-Pouilly, France
W.P. Leemans, K. Nakamura, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract
Experiments at the Berkeley Lab Laser Accelerator (BELLA) verified that the Turbo-ICT allows high resolution charge measurements even in the presence of strong background signals. For comparison, a Turbo-ICT and a conventional ICT were installed on the BELLA petawatt beamline, both sharing the same vacuum flanges. We report on measurements performed using a gas-jet and a capillary-discharge based laser plasma accelerator. In both setups the Turbo-ICT was able to resolve sub-picocoulomb charges.

INTRODUCTION

Imaging plates and scintillating screens are widely used in laser plasma accelerators (LPAs) for beam diagnostics [1-3]. They allow accurate measurements of the transverse profiles and the bunch charges even in the presence of strong background signals, which often accompany the beam signal due to the LPA working principle. For example, the laser – plasma interaction creates a strong electromagnetic pulse. However, plates and screens are obstacles for the particle beam, degrading beam quality or even capturing particles. And they are susceptible to X-rays. Complementing them by non-destructive charge diagnostics would be highly desirable.

One possibility would be to use integrating current transformers (ICTs) [4]. Previous studies comparing an ICT to a scintillating screen at a gas-jet based LPA [5] have shown that an ICT can provide accurate charge information for this type of accelerators [6]. However, the measurement setup needed to be carefully arranged to reduce the detrimental influence of electromagnetic pulses and other background signals. Capillary-discharge based LPAs [7-10] create even stronger background signals. Consequently, the beam diagnostic must be even less sensitive to such influences.

Examples of ICT signals recorded at a gas-jet based LPA and a capillary-discharge based LPA are shown in Fig. 1 and 2. Note that the background signals were highly variable.

At the gas-jet based LPA the background is a mostly constant offset. For the deduction of the charge a constant background is irrelevant. At the capillary-discharge based LPA the background contributes higher frequency components to the measured signal. This background signal has an important impact on the deduction of the charge.

*stulle@bergoz.com

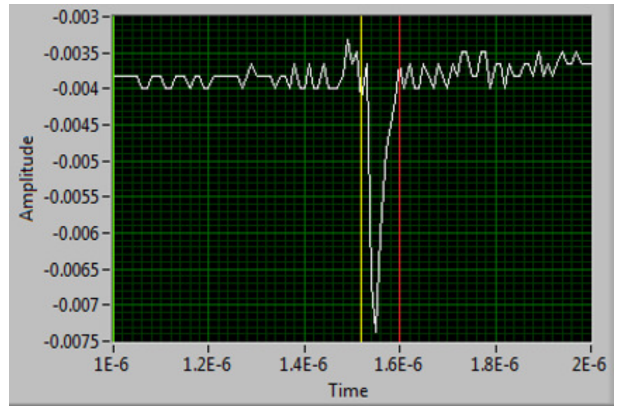

Figure 1: ICT signal recorded in a gas-jet based LPA. The peak between the yellow and red lines is the signal induced by a 10 pC bunch. The constant offset is irrelevant for the deduction of the charge.

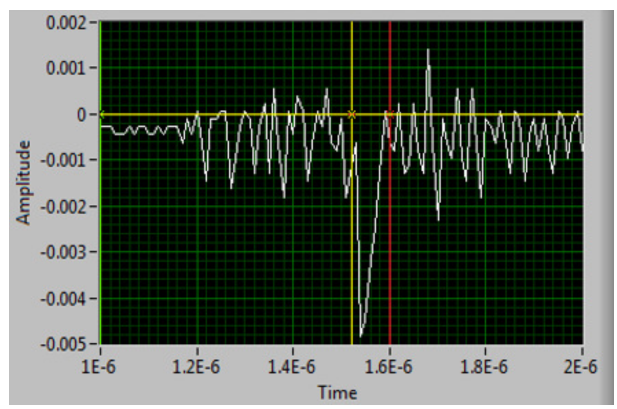

Figure 2: ICT signal recorded in a capillary-discharge based LPA. The peak between the yellow and red lines is the signal induced by a 18 pC bunch.

The Turbo-ICT current transformer and the corresponding BCM-RF electronics have been developed to address the requirements of X-ray free-electron lasers (X-FELs) and LPAs. Thanks to narrow band-pass filtering at a high center frequency, typically 180 MHz, they show little susceptibility to background signals, including electromagnetic pulses, dark current and long particle bunch tails.

To demonstrate the Turbo-ICT advantages for LPAs, a Turbo-ICT was installed in the Berkeley Lab Laser Accelerator (BELLA) petawatt beamline at the Lawrence Berkeley National Laboratory [10]. For comparison, a normal ICT was included in the same vacuum flanges as the Turbo-ICT.

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In this paper we compare experimental results obtained by the Turbo-ICT and the ICT. Measurements were performed using a gas-jet target and a capillary-discharge based target. A comparison including measurements by a scintillating screen was reported in [11].

EXPERIMENTAL SETUP

The BELLA petawatt beamline could be operated using a gas-jet target or a capillary-discharge target. In these targets the plasma was created and the interaction with the laser took place. Since the particle beam created at the laser – plasma interaction point could contain particles of high angular divergence, the beam was collimated before reaching the diagnostics instruments. After passing a spectrometer, the beam was dumped.

A simplified sketch of the experimental setup is shown in Figure 3. More details about the experiments and the BELLA petawatt beamline can be found in [11] and [12].

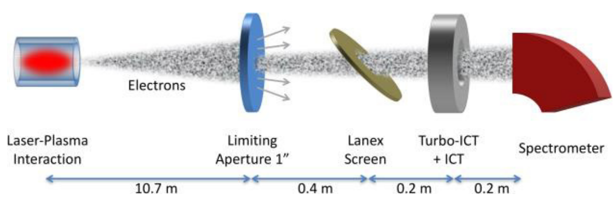

Figure 3: Schematic of the measurement setup

Using two kinds of laser targets allowed to compare the charge diagnostics under considerably different noise conditions. The background signals not only differed in amplitude but also in spectrum. The capillary-discharge based LPA produced a stronger background reaching to higher frequencies.

The ICT was sensitive to the low frequency part of the beam spectrum ranging from about a kHz to above 10 MHz. Its output pulse had a FWHM of about 30 ns. Integrating this pulse over a short time interval resulted a value proportional to the input pulse charge. Unfortunately, in LPAs the frequency range covered by the ICT has been found to be prone to strong noise contributions [2, 6].

The Turbo-ICT was sensitive to higher frequencies of the beam spectrum. Its response was centered around 180 MHz with a bandwidth of 15 MHz. By using such a frequency band its output signal was not a pulse but a resonance. The apex of this resonance was proportional to the input pulse charge.

Figure 4 shows the expected output resonance of the Turbo-ICT installed at BELLA. This signal was reconstructed from vector network analyzer measurements performed in the laboratory prior to installation. To be comparable to the oscilloscope measurements (Tektronix DSO3054, 500 MHz bandwidth, 2.5 GS/s) performed during the experiments, the influence of cable losses and oscilloscope bandwidth was estimated and taken into account for the calculation of the signal shown.

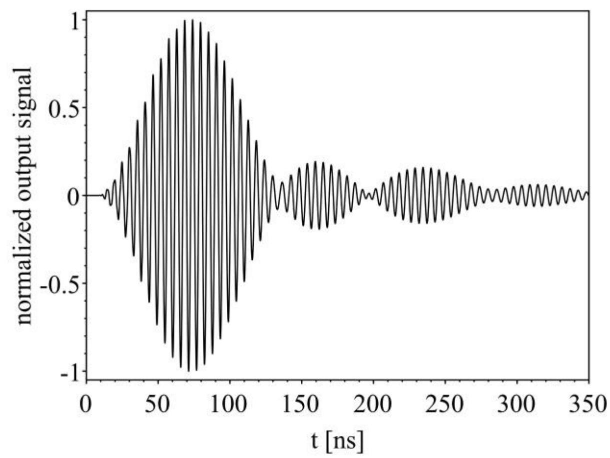

Figure 4: Normalized Turbo-ICT output signal as deduced from laboratory measurements and taking into account the influence of the experimental setup.

The Turbo-ICT bandwidth was similar to the ICT bandwidth. But working at higher frequencies had the advantage of avoiding many sources of random noise or systematic background signals.

If the spectra of the background signals are known prior to Turbo-ICT production, its center frequency can be shifted to a quiet band. A detailed description of Turbo-ICT and BCM-RF is given in [13].

During the experiments, the signal of the ICT was recorded by a 100 MS/s digitizer (National Instruments NI-USB 5133). Digitizing its output waveform allowed to compensate for the influence of low frequency background signals. The resulting waveform was integrated. Cable attenuation was not relevant for these measurements.

The Turbo-ICT signal was detected using the BCM-RF electronics, which created a DC voltage logarithmically proportional to input charge. This DC voltage was also recorded by above-mentioned digitizer. Turbo-ICT and BCM-RF were connected by 90 ft of LMR-200 coax cable. The cable attenuation at the Turbo-ICT resonance frequency was estimated to be 4.3 dB, which was taken into account for the deduction of the charge.

ICT, Turbo-ICT and BCM-RF were calibrated prior to installation using their respective calibration procedures. Thanks to sharing the same vacuum flanges, ICT and Turbo-ICT simultaneously measured exactly the same electron beam. That means, in average they should result the same charge readings. Only their respective noise should differ.

RESULTS USING A GAS-JET TARGET

For the gas-jet based LPA, Figure 5 shows the charge measured by the ICT versus the charge measured by Turbo-ICT. The plot reveals a very good linear correlation between the two diagnostics systems. Fitting a line to the data results:

$$Q_{\mathrm{fit}} = 0.88\, Q_{\mathrm{Turbo-ICT}} + 0.13\ \mathrm{pC}\,.$$

The major contribution to the data scatter around the fit line can be addressed to the noise present in the ICT measurements. This fact can be deduced from the distribution of the data points. After removing the linear correlation, the standard deviation of the data points is:

$$\sigma_{\text{ICT}} = 1.3\ \text{pC}\,.$$

The standard deviation varies from 1.0 pC at low charge to 2.4 pC at high charge. The noise of the Turbo-ICT measurements is too small to have a relevant impact. It must be well below 1 pC.

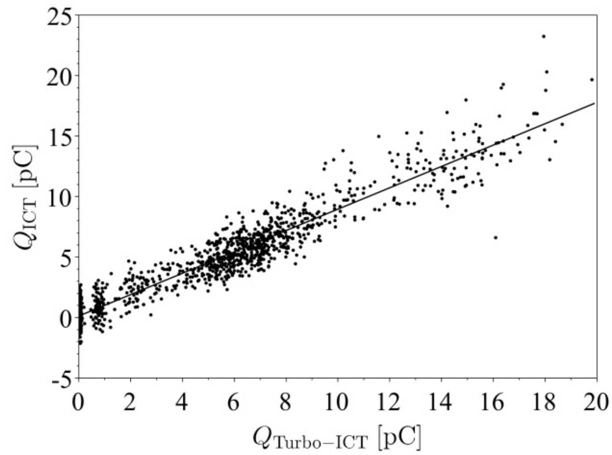

Figure 5: For the gas-jet based LPA, charge measured by the ICT versus charge measured by the Turbo-ICT. The line is a linear fit to the data.

That the fit slope does not equal unity means a small systematic error must have been present during the measurements. Possible causes are errors in the experimental setup, e.g. insufficiently compensated cable attenuation, errors in the data analysis, e.g. the calculation of charge from the digitized ICT signal, or the influence of a systematic background signal proportional to charge.

The small fit offset of 0.13 pC is not relevant, because it is well below the ICT noise level. Such a small offset could have been induced by many effects. It does not even have a high statistical significance.

Turbo-ICT Output Signal

The noise immunity of the Turbo-ICT was further examined by measuring the Turbo-ICT output signal directly on an oscilloscope, i.e. without using the BCM-RF (Figure 6).

The measured response agrees very well with the expected Turbo-ICT output signal deduced from vector network analyzer data and assuming an infinitely short input pulse (compare Figure 4).

Minor differences are visible. But the contribution of noise remains irrelevant, i.e. at the level of the oscilloscope accuracy and noise. Note that only the signal around the resonance apex is relevant for the determination of the input charge.

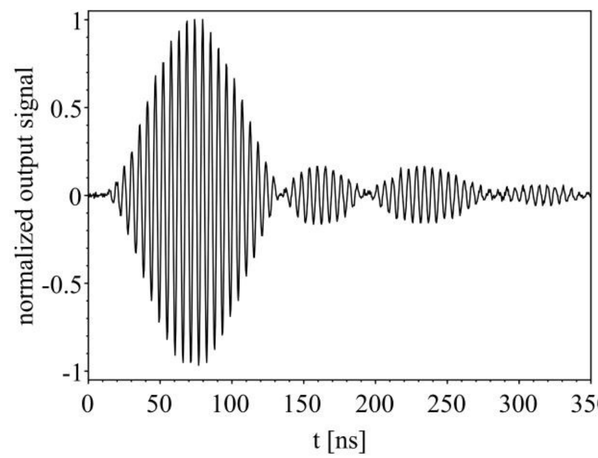

Figure 6: Normalized Turbo-ICT output signal measured on an oscilloscope.

RESULTS USING A CAPILLARY-DISCHARGE TARGET

For the capillary-discharge based LPA, Figure 7 shows the charge measured by the ICT versus the charge measured by Turbo-ICT. The data still exhibits a linear correlation. But the data scatter is considerably stronger. Furthermore, the data consists of two parallel bands of similar properties with an offset of about 30 pC. Linear fits to these two bands result:

$$Q_{\text{fit1}} = 0.83\ Q_{\text{Turbo-ICT}} + 26.6\ \text{pC}$$
$$Q_{\text{fit2}} = 0.82\ Q_{\text{Turbo-ICT}} - 3.75\ \text{pC}\,.$$

Their respective standard deviations are:

$$\sigma_1 = 8.5\ \text{pC}$$
$$\sigma_2 = 8.2\ \text{pC}\,.$$

Since the banding was only recognized during data analysis, its cause could not be investigated in detail. In the experimental data at hand no clear correlation to other measured quantities was found. A possible explanation could be timing jitter between the beam and a short background signal sometimes falling within the ICT integration window and sometimes not.

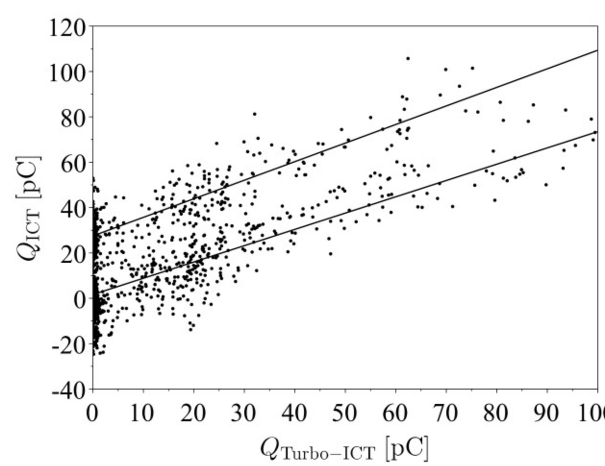

Figure 7: For the capillary-discharge based LPA, charge measured by the ICT versus charge measured by the Turbo-ICT. The data splits into two parallel bands. The lines are linear fits to these bands.

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As for the gas-jet measurements, the noise captured by the ICT contributed most to the data scatter. Without banding the standard deviation of the ICT measurements would be:

$$\sigma_{\mathrm{ICT}} = 8.4\ \mathrm{pC}\,.$$

Calculating the standard deviation over the full data set, i.e. including banding, results in:

$$\sigma_{\mathrm{ICT}} = 16.9\ \mathrm{pC}\,.$$

The quality of the data is only sufficient to deduce an upper limit for the Turbo-ICT noise of a few pC.

The fit slopes of 0.83 and 0.82, respectively, are very similar to the fit slope of 0.88 obtained with the gas-jet target. This fact signifies that most likely errors in the experimental setup or data analysis caused the slope deviating from unity. The experimental setup and data analysis remained unchanged except for the laser target. But the background signals changed considerably. Hence, the fit slopes should have differed more between gas-jet measurements and capillary-discharge measurements if background signals would have had a major influence.

On the other hand, the strong offsets of the two bands of 26.6 pC and -3.75 pC, respectively, must have been caused by background signals impacting the ICT measurements.

CONCLUSION

Experiments have been carried out at the BELLA petawatt beamline to examine the suitability of a Turbo-ICT current transformer and the corresponding BCM-RF electronics for accurate charge measurements at LPAs.

For comparison, a Turbo-ICT and a conventional ICT were installed inside the same vacuum flanges, ensuring that they measure the same particle beams. To test the charge diagnostics under different noise conditions, the LPA was operated using a gas-jet target and a capillary-discharge target.

For both LPA targets, Turbo-ICT and ICT measurements correlated linearly. But the ICT measurements contained a considerable amount of noise, reaching $\sigma_{\mathrm{ICT}} = 1.3$ pC for the gas-jet target and $\sigma_{\mathrm{ICT}} = 8.4$ pC for the capillary-discharge target. On the other hand, the noise of the Turbo-ICT measurements was at such small levels that its contribution remained invisible in the data.

Consequently, the ICT and the Turbo-ICT proved to be useful charge diagnostics for gas-jet based LPAs. But only the Turbo-ICT allows to resolve sub-picocoulomb charges.

For capillary-discharge based LPAs, the ICT provides useful information only after careful setup and if the beam charge is at least of the order of a few 10 pC, while the Turbo-ICT still resolves at least picocoulomb pulses.

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