ALICE ERL INTRA-TRAIN VARIATION INVESTIGATION USING BUNCH-BY-BUNCH BPMS

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Abstract

The ALICE ERL is a test facility at Daresbury Laboratory. We present investigations of charge variations and transverse variations in the ALICE trains (up to 1625 bunches, spacing 61.54ns, bunch charge up to 60pC), using EMMA BPMs for bunch-by-bunch measurements [1]. In addition to the BPMs, we used Faraday Cup, photo-detectors of several kinds and bunch arrival time monitors. The developed technique allowed us to find that the source of charge variations was solely the photoinjector laser. As for transverse variations, a preliminary conclusion is that they are due to transverse jitter of the laser beam spot on the gun cathode. We measured also IR FEL sensitivity to charge and transverse variations. The technique can be used at single bunch photoinjector machines and is planned to be applied to a new facility VELA now under commissioning at Daresbury Laboratory.

INTRODUCTION

The ALICE facility is an energy recovery test accelerator that operates at Daresbury Laboratory. [2]

The accelerator consists of (following the beam): a Photoinjector with DC Gun (up to 350 keV); a 1.3GHz Buncher; 1.3GHz SC Booster (typically 6.5 MeV) and Linac (total up to 26 MeV); Arc1; a bunch compression chicane; an IR FEL undulator; Arc2; the Linac again; and a dump. (See facility layout in [1]).

The beam can be set as a single bunch, or a train. The bunch rate can be set to $((1.3\text{GHz}/16))/N$ where $N = 1,2, \ldots$ For most of ALICE experiments $N = 5$ (bunch spacing $T = 61.54$ns, train length up to 1625 bunches). The bunch charge is up to 60pC. The ALICE beam diagnostics means have been screens and Faraday Cups (FCs).

With application of EMMA BPMs to ALICE in early 2012, investigation of misalignments of quadrupoles and sextupoles in Arc1 as well as measurement of dispersion through the arc became possible. The results presented in [1] were obtained for train centre of mass.

The bunch-by-bunch ability of these BPMs provided us with important information about intra-train variations. [1] In order to investigate the origin of these variations, several experiments were undertaken since [1] till December 2012, when ALICE operation was stopped for installation of a new linac. In this paper, we present results obtained during this period, that allowed us to identify sources of intra-train variations and interpret the results presented in [1]. We describe synchronous monitoring of the electron beam and photoinjector laser beam that was essential part of the investigation technique. We also present some results of investigation of effects of intra-train variations on IR FEL power.

The variation investigation technique developed can also be used as an effective tool for single bunch photoinjector machines to monitor bunch jitter. We are now making some investments into its application to a new facility VELA (former EBTF, [3]) at Daresbury Laboratory.

REVIEW OF THE INVESTIGATION

A bunch-by-bunch BPM and its software were described in [1]. For investigation of variations, observed initially in Arc1, we later replaced one BPM into ALICE injection part (Gun – Buncher – Booster).

Bunch-by-bunch horizontal and vertical position and bunch charge pictures, obtained with the BPMs (see Fig. 1) show typically some transient at the start, variations of various kinds, and some end transient. Charge variations were total up to 10%. Biggest transverse variations were about ten times the BPM thermal noise (BPM resolution was 20µm/10µm in horizontal/vertical plane for bunch charge 40pC). The transverse transients and variations depended on tuning of the machine.

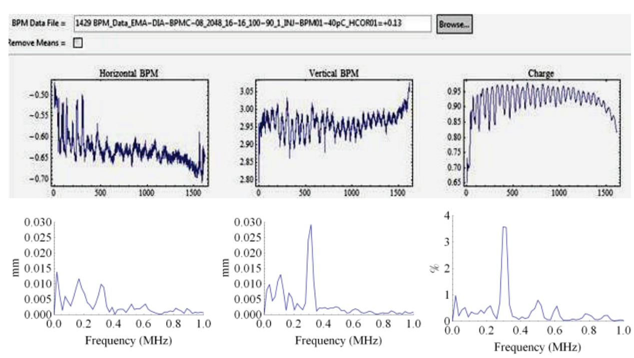

Figure 1: Typical bunch-by-bunch pictures of horizontal and vertical positions (mm), and bunch charge (V) as delivered by a BPM. The spectra are shown in the lower row.

Leaving transients for separate analysis, we applied DFT to regular part of trains (later we used whole train of 1625 bunches, and Hann window). Full frequency range was 8.12MHz (bunch spacing $T = 61.54$ns), the DFT bin was 10kHz, the (-6)dB resolution with Hann window was two bins.

The spectra (Fig. 1) have sets of peaks. Some of them are common for both charge and position. Prominent peaks lay in the region (0 to 0.8)MHz.

In [1], for some peaks in the charge spectra we had noticed that these variations were also seen in the FC

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signal, and assumed that they come from photoinjector (PI) laser. For other peaks, we speculated other possible sources. None of those assumptions have survived. As we discovered later, the source was merely the PI laser. Finally, we found that the charge spectra of the BPM, FC, and a photodiode that was used to directly measure the laser power, were all in good agreement.

We tried to use same approach to transverse spectra. A quadrant position detector was used to measure the PI laser spot jitter on the virtual cathode. We observed some similarity in the detector pictures (including the transients) and spectra to BPM pictures and spectra obtained earlier, but had no possibility to go further and investigate in details due to break for linac installation.

VARIATIONS SOURCE IDENTIFICATION

For bunch-by-bunch charge variation investigation we compared readings of three instruments: a BPM (in the injection part), a FC (after the booster), and a photodiode (PD). The PD (DET210 of Thorlabs) that was routinely used for PI laser pulse train power monitoring, is installed after a splitter the other output of which (through an attenuator) is directed to the gun cathode. The attenuator is used to set bunch charge. The FC and PD signals were digitised using an oscilloscope and read through ALICE network. To provide synchronous reading of the oscilloscope data and EPICS BPM data, we slowed ALICE repetition rate from nominal 10Hz to 1Hz.

A recorded shot of the FC and PD signals as captured on the scope is shown in Fig. 2. The FC signal has some droop (due to a blocking capacitor in its electronics) which is seen on the right. With a long lossy cable, a FC response to individual bunch is a pulse whose exponential tail overlaps the following bunches, so the step response needs about ten bunches to come to plateau. Individual bunches can be seen as a ripple about 20%. The bandwidth is of several MHz. A PD signal is a train of 1ns bell-shape pulses that come to the cable end as individual exponential pulses.

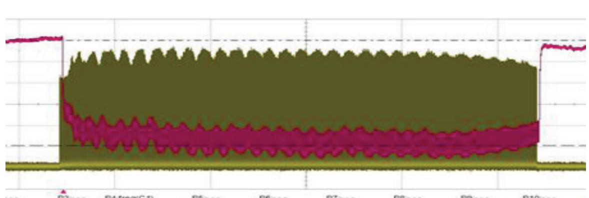

Figure 2: The FC (red) and PD (green) signals.

After some pre-processing of FC and PD data, the spectra were taken. For two extreme bunch charges 15pC and 60pC the spectra of the three instruments are shown in Fig. 3. Note the PD signal stays constant for any bunch charge, so any difference in the PD spectra in Fig. 3 is due to noise.

A good agreement of three spectra allows us to make a conclusion that a source of the intra-train charge variations is the PI laser (IC-532-5000 from High Q Laser Production). One more conclusion is that that in charge measurements, one can trust in either beam instrument: the FC and the BPM.

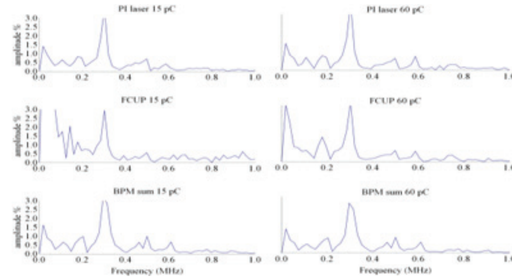

Figure 3: DFT of PD, FC, and BPM signals for bunch charges 15pC and 60pC.

To advance in identification of transverse variations sources, we contemplated to apply the same approach as above. We planned to compare the BPM readings with readings of a quadrant position detector (QPD) installed at the virtual cathode. A QPD (PDQ80A from Thorlabs) was installed and tested with PI laser beam but no direct comparison to BPM was possible as no electron beam was available since December 2012.

The QPD has four quadrants of the diameter about 8mm. For a light spot of a few mm size, its position is calculated as $M \cdot (A \pm B \mp C + D)/(A + B + C + D)$ (same expression as in the BPM). For a square spot, the QPD is linear, and the scale coefficient M comes to 1/4 of the spot size.

The QPD signal from the PI laser was digitized with an oscilloscope. The spot was round, its size estimated by eye was 4mm. The 'bunch-to-bunch' spot position pictures for $M = 1$, and corresponding spectra are shown in Fig. 4. With QPD bandwidth 150kHz, the 300kHz peaks are really twice higher.

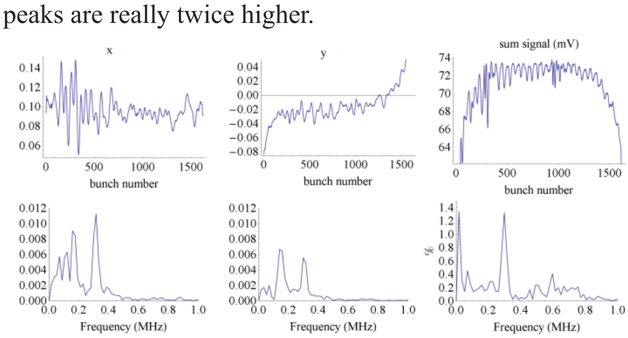

Figure 4: The 'bunch-to-bunch' PI laser spot position and intensity as produced by the QPD. The spectra are shown in the lower row.

One can compare the QPD data to BPM data measured earlier. For comparison we should take a BPM that was closest to the cathode. Between the cathode and the BPM, there were two only elements: a Gun solenoid, and a pair of correctors. Fig. 1 presents this BPM, for a nominal solenoid current and a horizontal corrector current +0.13A. This shot was selected as it matches best Fig. 4. Note other shots with differing envelopes still have spectra similar to the spectra shown in Fig. 4.

The similarity of Fig. 4 and Fig. 1 allows us to suggest that both the electron beam position transients and

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prominent intra-train variations observed with the BPMs were due to position transients and jitter of the PI laser spot on the cathode.

FEL SENSITIVITY TO BUNCH OFFSET

With transverse position variations taking place at ALICE, the question arises as per their effect on the performance of the ALICE IR FEL. [4] To investigate this, an experiment was performed to record simultaneous readings of a bunch-by-bunch FEL radiation detector (PEM, PEM-10.6-1x1 from VIGO System S. A.), a bunch arrival time monitor (BAM [5]) in the Arc2 end, and a BPM after the Arc2 first dipole magnet (dispersion 0.3m). The PEM pulses that were similar in shape to the PD pulses above were in same way digitised by oscilloscope.

The FEL damping time was about 6μs (cavity modulation bandwidth of 25kHz). For significantly faster transverse variation the cavity stored field can be considered as undisturbed.

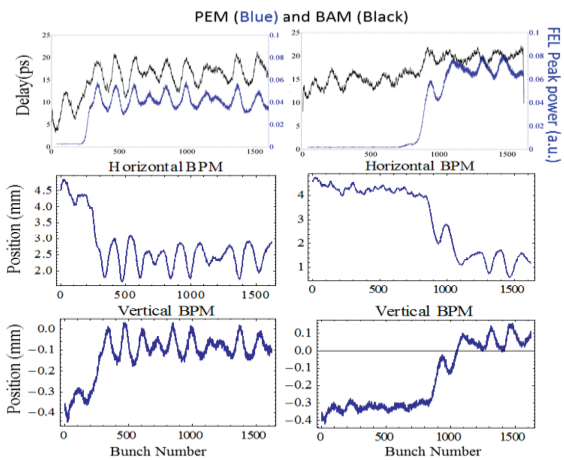

Figure 5: The readings of PEM, BAM, and BPM for two IR FEL power levels.

Figure 5 shows PEM and BAM signal envelopes, and horizontal and vertical BPM readings for two different levels of averaged-over-variation radiation power. The cavity lengths were set such as to start the lasing after 1/10 and 1/2 of the train length respectively (the cases '1/10' (left) and '1/2' (right)).

Some spectra of Fig. 5 are shown in Fig. 6. First, compare a spectrum of the radiation power envelope (top left, the case '1/10') to a spectrum of the corresponding position variation measured by a BPM at a downstream dispersive region (bottom left). The spectra are similar as they should be. They have two dominant peaks of about 100kHz and 130kHz. Beating of these variations is clearly seen in Fig. 5 (left).

Then, compare a spectrum of a horizontal variation taken before lasing (Fig. 6 bottom right, the case '1/2') to a spectrum of same variation taken after the lasing starts (bottom left, the case '1/10'). They are also similar, with the difference that the FEL 'amplifies' the variation. A before-lasing variation spectrum can be translated to the FEL through a factor $b = sqrt\,(\beta_{FEL}/\beta_{BPM}) = 0.7$.

Now we can conclude that the train centre of mass has an offset as regards to the maximum of the FEL power-vs.-offset curve, which is greater than total magnitude of the variations at the FEL. With the offset close to or lower than the magnitude, the second harmonics of the dominant peaks would appear at the spectra Fig. 6 (left).

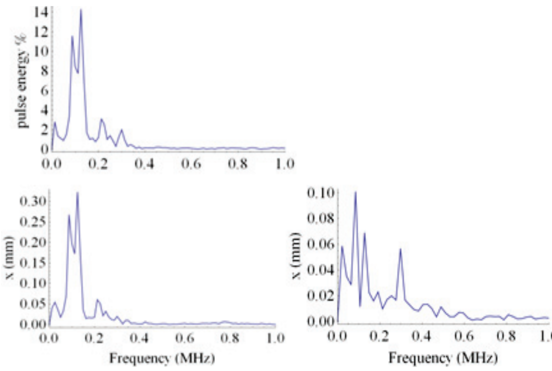

Figure 6: The IR FEL power envelope spectrum (top left), and the horizontal variation spectrum (bottom left). At bottom right is the variation spectrum of the train part before lasing.

At this curve point, one can estimate the FEL sensitivity to offset: 26% of total power per $b \cdot 0.17\text{mm} = 0.12\text{mm}$ of total magnitude both as taken from Fig. 6 (top left and bottom right). Compare this to a result of 12% of a Genesis simulation that was carried out for the centre-of-mass offset as 0.2mm, and a 0.2mm sinusoidal variation of a 100-bunch period (i.e. 160kHz). One can assume that the centre-of-mass offset is larger roughly three times than the offset used in the simulations (for parabolic curve approximation).

BAM readings analysis can be found elsewhere [5].

SUMMARY

The bunch-by-bunch EMMA BPMs have proved to be effective in application to ALICE ERL trains. Same BPMs will be used on a new facility VELA. For VELA as injector of CLARA [6] it looks vital to have been equipped as well with an advanced intensity/position diagnostics of the PI laser beam at the virtual cathode.

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