APPLICATION OF EMMA BPMS TO THE ALICE ENERGY RECOVERY LINAC

A. Kalinin[#], D. Angal-Kalinin, F. Jackson, J. K. Jones, P. H. Williams,
ASTeC, STFC Daresbury Laboratory, Warrington, U.K

Abstract

The ALICE Energy Recovery Linac Arc1 button pickups have been recently equipped with EMMA BPM electronics. These EPICS VME BPMs give bunch-by-bunch information about charge and position, allowing investigation of beam dynamics in ALICE in different modes of operation. A Mathematica program is designed to monitor statistically individual bunches (spacing 61.54ns) as well the train as a whole (up to 1625 bunches), allowing the study of jitter and position stability of the beam through the Arc1. The Arc1 has been designed to be isochronous, with the bunch compression achieved through a separate dedicated bunch compressor chicane. The Arc1 incorporates two sextupoles for correcting non-linear longitudinal matrix terms and experimental evidence suggests that the off-centred beam in the sextupoles breaks the linear isochronicity. We present some beam measurement results collected in 2012 using these BPMs.

INTRODUCTION

The ALICE (Accelerators and Lasers In Combined Experiments) facility, shown in Fig.1, is an energy recovery test accelerator operated at Daresbury Laboratory since 2006 [2].

The accelerator consists of: a photoinjector with DC gun (up to 350 keV); buncher and superconducting booster (typically 6.5 MeV beam energy); an energy-recovery loop (typically 26 MeV beam energy) containing a superconducting linac module; a bunch compression chicane; and an FEL undulator.

The main demands on the ALICE beam dynamics and beam quality come from the IR-FEL and the coherent THz emission from the compression chicane used for dedicated experiments. By design the ALICE lattice consists of an isochronous first arc (Arc1), a bunch compressor with R_{56}= –0.28m, and a second arc with R_{56} = +0.28m. The arc design is based on triple bend achromats (TBA) [3], and the R_{56} is tuneable by the strengths of quadrupoles within the arc.

The R_{56} of Arc1 strongly influences the post linac bunch compression. This has been consistently observed in both THz as well as FEL setups. Due to a previous lack of reliable beam diagnostics in Arc1, it has not been possible to investigate beam dynamics in detail, especially through the sextupoles, which are needed to provide second order correction. It has consistently been observed that the two sextupoles steer the beam and modify the transverse optics, making Arc1 non-isochronous and affecting the beam dynamics in the transverse as well as longitudinal planes. FEL lasing was found to be very sensitive to the setting of the first sextupole, whereas the second sextupole has never demonstrated any improvement in either the FEL or THz setups.

In order to understand the beam dynamics in Arc1 and the chicane, the pickups 01 to 06 in Arc1 (see inset of Fig. 1), and an additional pickup in the chicane, have been recently equipped with EMMA BPM electronics. It is possible to connect any five (from seven) pickups to the electronics at a time. These BPMs provide information about misalignments and trajectory errors in Arc1 as well as providing bunch-by-bunch and train-to-train information about charge and position.

Additional information from the time-of-flight (ToF) measurements [4] combined with these observations should be able to provide a better understanding of beam dynamics, and help in explaining the current performance limitations.

We present here the first experimental results obtained using these BPMs, and describe the details of BPM capabilities and the Mathematica processing program used for analysis.

BEAM POSITION MONITORS

One of the ALICE functions is to deliver beam to a NS-FFAG EMMA. EMMA's BPMs [1] are designed for turn-by-turn measurements (turn is 55.2ns). Four of them of the same type are used in the ALICE to EMMA Injection Line to monitor a single bunch train from ALICE. These BPMs were modified to work with ALICE many-bunch trains, which is useful for injection tuning and opens the possibility to apply these BPMs to ALICE as well. The ALICE train bunch rate can be set to (1.3GHz/16)/N, where N=1, 2, ... is an integer. For most of ALICE experiments, N=5 (bunch spacing T=61.54ns). This rate has been used for the BPM measurements below. The train length was up to 1625 bunches (which is typical for IR-FEL operation). The bunch charge was in the range (30 to 60)pC.

The Arc1 and chicane pickups are rectangle pickups with two pairs of horizontal buttons symmetrically spaced from the x, y planes. In the measurements below we calculated the beam offset in the simplest way using a formula $((V11\text{-}V12\mp V21\pm V22))/\Sigma$, and the charge simply as $\Sigma=V11+V12+V21+V22$. The pickups have no fiducials, so the relative positions of the BPM centres to the quadrupole centres, or the beam pipe, are unknown.

Each two-plane BPM (see [1]) comprises two Front-Ends placed near the pickup. Each of them works with two opposite button signals. It first converts them into

#alexander.kalinin@stfc.ac.uk

ISBN 978-3-95450-119-9

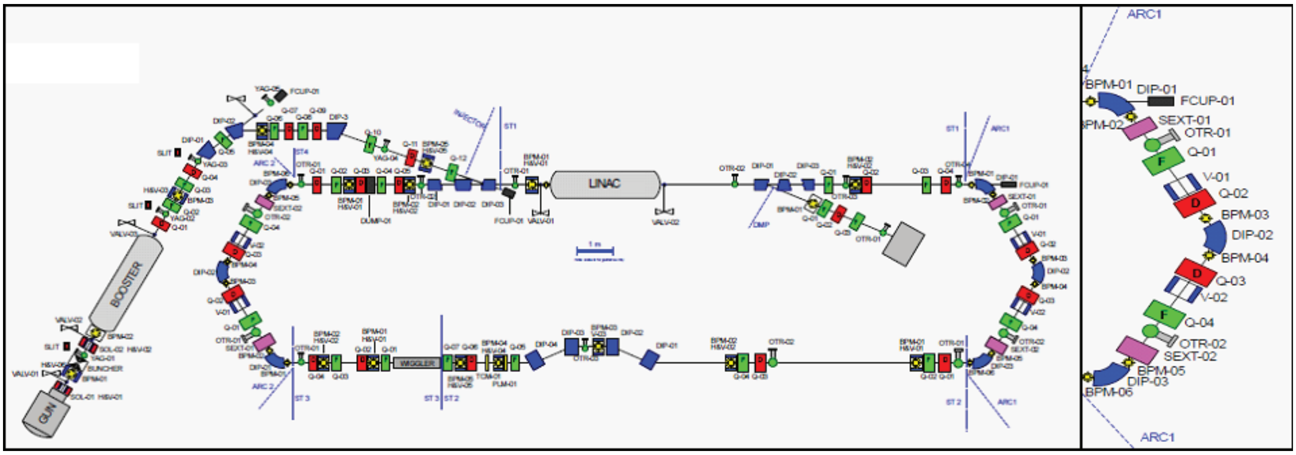

Figure 1: Layout of the ALICE accelerator (magnified Arc1 layout in a box on the right).

compact 700MHz three-period packets and then multiplexes the packets in the time domain into one channel.

The doublets are transmitted through low loss cables to a remote two-channel VME card. In each channel, the bunch-by-bunch doublets are amplified, detected, measured, and then stored in memory. After the last bunch, the card sets the number of detected bunches to be read by EPICS, and then generates a VME interrupt. Next, each memory is read by EPICS in the time between successive injections (max. 10Hz rate).

The Arc1 BPM resolution (on the thermal noise plateau ≥40pC, see [1]) is horizontal 20µm and vertical 10µm.

The BPM output provided by the Mathematica program is given in Fig. 2.

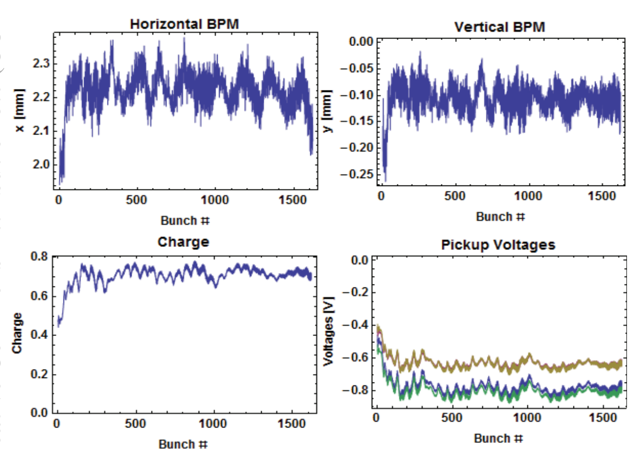

Figure 2: BPM-01 readings (the photo-injector laser is set nominally to 30pC bunch charge). The horizontal axis is the bunch number. The upper plots are transverse bunch offsets. The left lower plot is the bunch charge (arbitrary units), the right one is an auxiliary plot of two pairs of button signals as measured by the ADCs.

MATHEMATICA PROGRAM

Analysis of the BPM signals is performed in the Mathematica programming environment [5]. A windows .NET interface (via ActiveX controls) to the underlying EPICS control system allows the reading of BPM voltages at several Hz, but not at the 10Hz train repetition rate. A much faster native .NET EPICS interface is also available, but does not currently allow passing of the required array data. This is a planned upgrade, and would allow BPM readings to be taken at least as fast as the train repetition rate. Voltage to beam position calculations are performed within Mathematica, so allowances for BPM geometry and scaling can be varied external to the control system. Control of BPM electronics variables, such as delays and channel attenuations, can be done directly from the Mathematica front-end. The Mathematica environment allows for rapid analysis of the beam position data, including FFT analysis, jitter analysis and automated parameter scans. An interface to several optics and tracking codes (MAD, Elegant and GPT), can also allow the simulation of beam dynamics issues, at the same time as experimental data is being taken and analysed. Work has been performed to confirm the feasibility of a feedback system within Mathematica, but is not implemented due to the limited number of BPMs currently available.

BPM READINGS ANALYSIS

The readings presented in Fig. 2 show typical beam behaviour. With imperfectly tuned energy recovery, a global slope appears on BPMs located in the dispersive regions.

All plots show an initial ‘jump’, and ‘ripple’ of various kinds. The first task is to try to identify the sources of each component, whether it comes from the beam or it is a feature of the BPM(s). Next, at least, should be to outline further investigation.

In Fig. 3, DFT spectra of two pairs of pickup voltages given in Fig. 2 are shown, where full frequency range (0 to 8)MHz is divided into low (0 to 350)kHz and high (0.3 to 8)MHz frequency ranges. The DFT resolution is 10kHz. Spectra of other BPMs are similar.

One can see that the ripple of any kind is present in each signal, independently of the button/channel number.

ISBN 978-3-95450-119-9

DFT applied to transverse and charge readings results in spectra that differ from pickup voltage spectra.

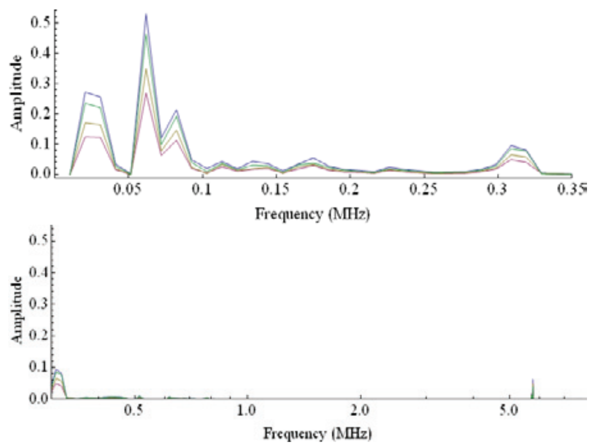

Figure 3: DFT spectra (arbitrary units) of pickup voltages given in Fig. 2. The DC components are subtracted.

Low Frequency Ripple

Consider the low frequency range in Fig. 4. It looks that the minor peaks near 300kHz in all three plots are produced by DC-DC converters of BPM VME cards, that feed analogue electronics. According to the datasheet, the switching frequency of the converters lays near 300kHz. In the charge plot in Fig. 2, this ripple is seen as a faster oscillation (period is about 55 bunches).

In the charge spectrum, the peak (20 to 30) kHz is probably produced by a ripple of the ALICE DC gun high voltage, which is obtained from a switch-mode PS. Its switching frequency is just about 20kHz. [6] This ripple (period is about 800 bunches) is practically not recognizable in Fig. 2. Gun voltage variation causes electron energy variation, and this can cause loss of electrons due to changes in longitudinal (and transverse) dynamics, which in the gun region is highly sensitive to electron velocity, space charge, etc. In addition, the energy modulation should directly manifest itself in the transverse plane in dispersive regions.

The peaks (60 to 80) kHz in the charge spectrum correspond to a slower oscillation in Fig. 2 (period is about 300 bunches). This oscillation that can also be seen in the Faraday Cup signal, and is assumed to be due to the photo-injector laser pulse-to-pulse power variation.

Peaks in the transverse spectra in the range (30 to 200) kHz appear to be produced by a magnetic field ripple of the ALICE dipole and quadrupole magnets (in the horizontal plot of Fig. 2, an oscillation of 170 bunches period corresponds to a most prominent peak at ~100kHz). We have observed that this ripple depends on magnet current settings. The magnets are fed from various types of switch-mode PSs, with switching frequency ranges from 20kHz to 80kHz [6]. One can suppose that stray magnetic field from a magnet in this frequency range can affect the beam through some adjacent thin-wall bellows. One can see that a low frequency ripple in the charge reading does not penetrate into the transverse plane and it can be concluded that the routine intensity normalisation in the BPM does not generate errors in the transverse plane.

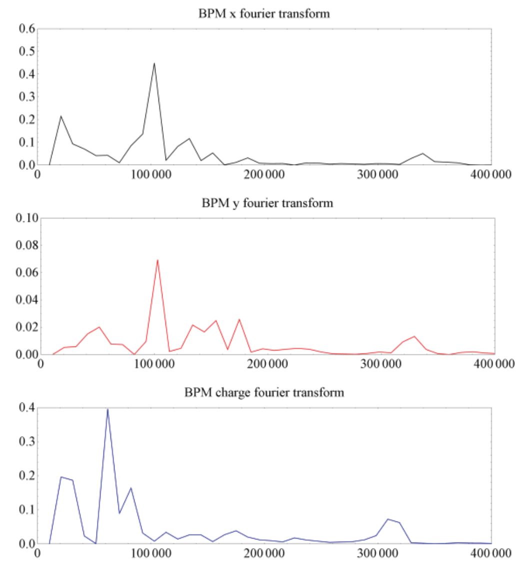

Figure 4: DFT of x, y, and charge BPM-01 readings. A low frequency range is shown. The frequency axis is in Hz.

High Frequency Ripple

In the high frequency range (see Fig. 5), the most prominent peaks in the transverse plane are about 6MHz (in Fig. 2, this three-bunch-period oscillation is seen as some 'hair' but is well recognizable as a fast ripple in the plots of Fig. 6 below). The plots of three BPMs were obtained from three measurements done in different times. Note each peak is accompanied by a smaller side peak separated by 50 kHz.

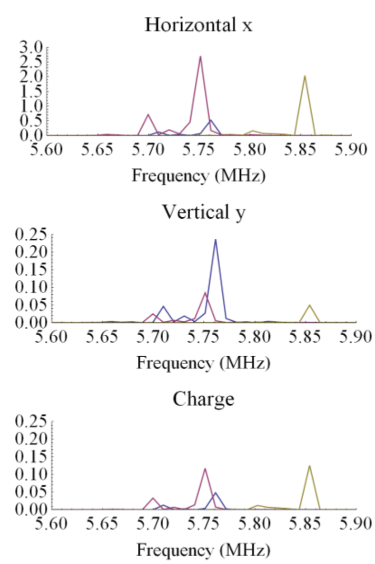

Figure 5: High frequency peaks in three BPMs (BPM01 blue, BPM03 magenta, BPM04 brown).

The origin of this high frequency oscillation, which is mostly prominent in the transverse plane and variable in

ISBN 978-3-95450-119-9

strength for each pickup, is not clear. We noticed that in the beginning of our BPM run on ALICE, this fast oscillation amplitude was considerably lower than that in the data taken presented here. One can carefully suggest that the oscillations might be caused by a dipole TM mode that is excited by off-centre bunches in the buncher/booster/linac RF cavities. In the BPM, this oscillation is under-sampled by the ADC which brings the frequency down. Note such purely transverse oscillation can manifest itself in the charge as well, due to, for instance, imbalance of propagation times in cables, etc.

The ripple of various kinds above exceeds several times the BPM thermal noise position resolution. For some bunch-by-bunch measurements on ALICE this accuracy deterioration is still not decisive. Further investigation using both beam-based models of the accelerator, as well as engineering analysis of the BPMs, is required to obtain a fuller picture of the noise seen.

Charge Transient: Transverse Plane Transients.

All three transients seen in Fig. 2 are shown in detail in Fig. 6. A charge increase over first forty bunches seen in Fig. 6, is a feature of the photo-injector DC gun and has been observed in the Faraday Cup signal as well. Attributing the transients in the transverse plane to BPM intensity normalisation error only does not look correct because, as shown above, the leakage of charge ripple into the transverse plane is low. This conclusion is supported by the fact that for a selected charge transient, the polarity and height of the transverse transients can be somewhat varied depending on the specific ALICE tuning. The transients observed require further investigation.

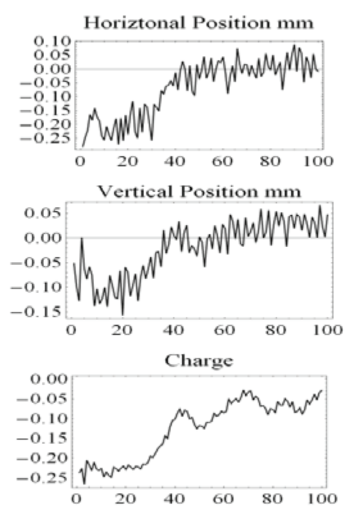

Figure 6: Transients in BPM-01.

JITTER MEASUREMENTS

The BPMs were used for preliminary measurements of the transverse horizontal beam jitter at different locations in the lattice.

Two locations were used at first, BPM-01, at the entrance to Arc1 where the dispersion is small, and BPM-05, at the entrance to the final dipole in Arc1, where the dispersion is large. Measurements of jitter were taken over 100 trains. To remove the effect of initial transients, the first 100 bunches in each train were discarded in the analysis.

The bunch-to-bunch jitter within a train was found as simply as bunch-to-bunch position rms of all bunches in all 100 trains (for each train the centre of mass position is subtracted). The results are shown in Fig.7.

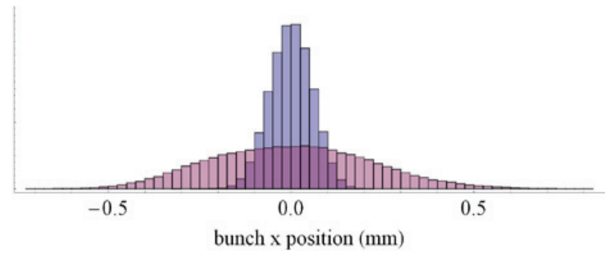

Figure 7: Distribution of bunch-to-bunch position variation in 100 trains of 1500 bunches for BPM-01 (blue) and BPM-05 (magenta).

The bunch-to-bunch jitter rms on BPM-01 (BPM-05) was found to be 60 μm (220μm). At present it is not possible to conclude quantitatively the relative contributions of different beam-sizes and dispersions at the two BPMs to this jitter, since the lattice optics are not well known. In addition, on BPM-05 a significant slope of position was observed over the train (probably due to imperfect energy recovery conditions) which further complicates the analysis.

Thus, jitter measurements need to be carefully examined alongside additional information on lattice optics and beam loading to provide meaningful information. The fast BPMs provide new scope to pursue these studies on ALICE, and which were previously infeasible. In addition, it is envisaged to use these measurements in combination with fast diagnostics on the ALICE IR-FEL radiation to further explore the effects of this beam jitter on the beam dynamics of the FEL.

BEAM ORBIT AND DISPERSION MEASUREMENTS

Beam orbit through the arc was measured by switching on/off the arc quadrupoles. The horizontal beam orbit in the quadrupoles varies from fractions of a mm up to 8 mm. The next stage will be to carry out beam based alignments using these BPMs. This will then allow us to correct for second order terms using the sextupoles, as was originally envisaged.

Dispersion was measured in Arc1 by changing the beam energy using the gradient of the first linac cavity (LC1). For a central beam kinetic energy of 26 MeV, a unit change of LC1 grad set gives a 1.07 % change in beam momentum. LC1 gradient was changed from 33 to 36 (~3% energy variation), with a nominal gradient set at 35.3 for a beam kinetic energy of 26 MeV. The measured dispersion at entry to the arc (BPM01) was found to be ~25mm instead of zero. This is likely to be due to leaking

ISBN 978-3-95450-119-9

of some dispersion from the injection line. The dispersion was measured on BPMs 02-05 with and without switching on the sextupoles. The dispersion measurement results are shown in Fig.8. The setting of SEXT01 to 3A corresponds to an actual FEL setup (where linearisation and compression of the electron bunch is important). SEXT02 does not normally show any improvement in the FEL setup and is also set up at 3A for these measurements to understand its effects.

The linear dispersions are compared against simulations in Table 1. Due to low dispersion at BPM03 and 04 locations, the second order dispersion contribution shows a slight curvature on the data. Since the beam passes off-axis in the sextupoles, as alignment studies in the arc demonstrate, switching on the sextupoles change the linear dispersion (through quadrupole kick) as well as increases the second order dispersion.

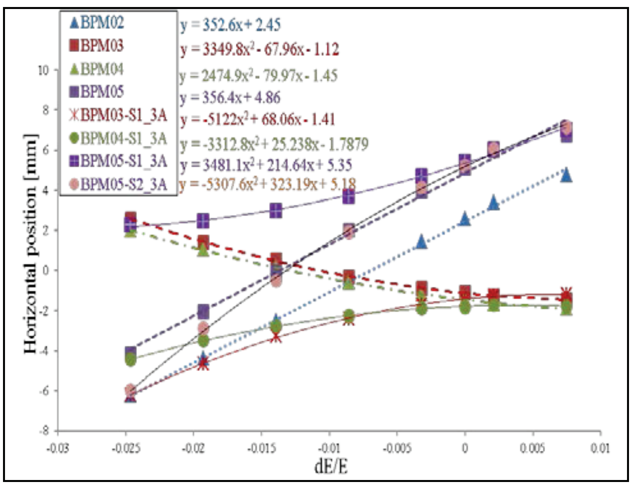

Figure 8: Dispersion Measurements at different BPM locations. S1(2)_3A is for SEXT01(02) at 3A. Fitted equations are shown next to the legend for each case.

Table 1: Linear Dispersion in Arc1

Location	Simulated Dispersion (m)	Experimental Dispersion (m)
BPM01	0.0	0.025
BPM02	0.33	0.352
BPM03	-0.0968	-0.068 +0.068 with S1=3A
BPM04	-0.08521	-0.080 +0.025 with S1=3A
BPM05	0.3424	0.356 0.214 with S1=3A 0.323 with S2=3A

CONCLUSIONS

Several EMMA BPMs have been modified to work with ALICE bunch trains to give bunch-by-bunch and train-to-train information about charge and position. Analysis of BPM signals is done through Mathematica program. In a bunch-by-bunch picture, the BPM readings show an initial jump and ripple of various kinds. Analysis of these peculiar features point us to investigate several ALICE technical systems as well as the BPMs themselves, which we plan to do in future ALICE runs. The BPMs provide us with useful information about bunch-to-bunch and train-to-train jitter, and correlating this information with ALICE IR FEL detector will enhance our understanding of transverse/longitudinal dynamics in ALICE. The experimental data confirms that the beam trajectory in Arc1 is significantly off-centred, explaining the observations of difference in ToF measurements when sextupoles are switched on. We also see significant differences to linear and second order dispersion due to off-centred beam in the sextupoles.

ACKNOWLEDGEMENTS

The authors would like to acknowledge: Graham Cox for creating and supporting the .NET interface to EPICS, as well as general EPICS support; Ian Kirkman has provided much assistance in simulating the electro-magnetic properties of the ALICE BPMS; and Rob Smith for providing technical support for the BPM hardware.

REFERENCES

[1] A. Kalinin et al, “Computing Bunch Charge, Position, and BPM Resolution in Turn-by-Turn EMMA BPMs”, IPAC12.
[2] Y. M. Saveliev, “ALICE: Status, Developments and Scientific Programme”, IPAC12.
[3] H. L. Owen et al, “Choice of Arc Design for the ERL Prototype at Daresbury Laboratory”, EPAC04.
[4] F. Jackson et al, “Electron Beam Dynamics in the ALICE IR-FEL Facility”, FEL12, Kyoto, Japan.
[5] Wolfram Research, Inc., Mathematica, Version 8.0, Champaign, IL (2011).
[6] C. White, R. J. Smith, private communications.

ISBN 978-3-95450-119-9