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Deliverable:

Report on performance optimization of installed high resolution beam position and size instrumentation.

Executive summary:

The ATF2 collaboration has in the past years developed several position and size sensitive instruments for high resolution measurements of the ATF2 beam. This report is focussed on important improvements to two of the main devices installed at ATF2, the C-band Beam Position Monitors (CBPM) and Interaction Point Beam Size Monitor (IP-BSM), recently implemented by the RHUL, KEK and UoT teams as part of the E-JADE programme.

Both the CBPMs and IP-BSM were successfully upgraded to enable separately measuring subsequent bunches extracted from the ATF damping ring with separations of 180-200 ns.

These improvements are significant as they allow feedback techniques to be applied to reduce the beam position jitter at the interaction point (Task 2.6). They are also important in the context of Tasks 2.1 (Beam Size Minimisation) and 2.5 (Beam Instrumentation and control).

1. INTRODUCTION

High resolution instrumentation is essential at ATF2 to measure the nanometre size beams which are produced. The corresponding R&D is also of utmost relevance for future linear colliders (ILC or CLIC), due to the extremely small beams which will need to be controlled. The main devices used at ATF2 and currently under development as part of WP2 are:

- Cavity Beam Position Monitors operating in C-band, fixed at every quadrupole magnet along the beam line (CBPM) [1] and near the Interaction Point (IP-BPM).
- A dedicated Beam Size Monitor at the Interaction Point (IP-BSM), based on measuring the rate of Compton scattered photons as the beam is scanned across a fringe pattern generated by two interfering laser beams [2].

The CBPMs and IP-BSM were recently successfully upgraded to enable separately measuring subsequent bunches extracted from the ATF damping ring with separations of 180-200 ns. This report focuses on these two major improvements of the beam instrumentation at ATF2.

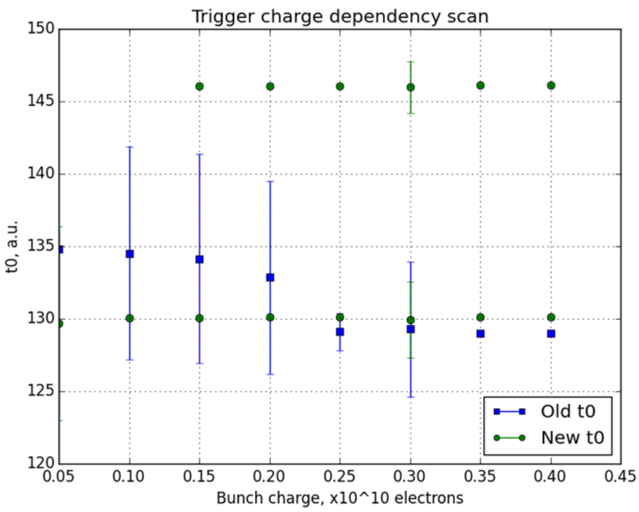

Fig. 1: Old (blue) and new (green, 2 bunches) arrival time detection schemes.

2. CAVITY BEAM POSITION MONITORS

Cavity Beam Position Monitors (CBPMs) are resonant microwave cavities that are used to sense the position of an electron beam with a high resolution reaching below 100 nm. An inherent problem using resonant devices is the ring-down of the signals produced by the beam: in case the decay time of the signal is comparable with the distance between bunches, the signals overlap, and so the signal generated by the previous bunch is added to or subtracted from the one generated by the following bunch of particles. At the same time, longer ring-down times provide longer signals for sampling and analysis and thus are helpful in achieving higher resolution and relaxing the requirements on the data acquisition system and digital processing. In the case of ATF2, bunches are separated by typically 200 ns, while the decay time of the CBPM signals is around 300 ns. Clearly, some overlap of the signals is to be expected. For running feedback systems and achieving stable operation, ATF2 diagnostics have to provide bunch-by-bunch measurements. A dedicated effort to enable measuring subsequent bunch positions was hence made as an upgrade of the current system.

To enable measuring the position of several subsequent bunches, their arrival must first be detected with high precision for propagation of the signals to the correct time. A special version of the so called “reference” signal – from a position-independent mode in an additional smaller, same frequency cavity, processed by a fast diode rectifier, is used for the arrival detection. The upgrade effort started with work on the arrival time detection. The new algorithm is already able to detect multiple bunches, while also reducing systematic effects and improving the precision compared to the previously deployed version. A comparison of the performance of the two algorithms for different bunch charges is shown in Figure 1.

Different possibilities exist for the signal subtraction. The method which was tried is bunch-to-bunch propagation and subtraction of complex signal phasors. The advantage is that it preserves the phase information, which can then be used for detecting the sign of the offset with respect to the symmetry axis of the cavity. With this method, single bunch calibrations could be applied to process multiple bunches. In practice, however, it was found that because an extrapolation onto subsequent bunches is required, a number of measured parameters of the system, such as the frequencies of the position and reference cavities, or the arrival times of both bunches, degrade the precision of extrapolation, making it unacceptably lo. It is much more efficient to calibrate the CBPMs with multiple bunches. The calibration can then be used for different values of the bunch spacing with significantly less degradation in performance than if single bunch calibrations were used, as long as the differences in bunch spacing remain moderate.

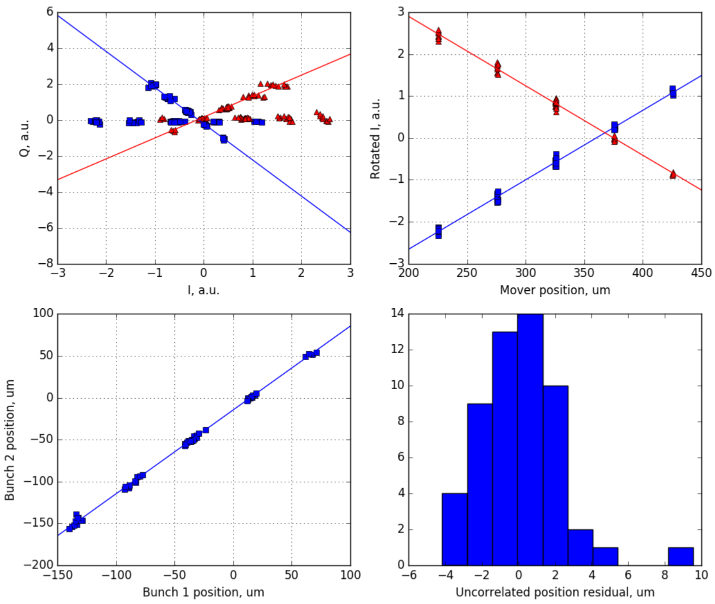

Fig. 2: CBPM position calibration measured for 2 bunches at 200 ns separation: quadrature (Q) vs in-phase (I) signal before and after rotation, bunch 1 in blue, bunch 2 in red (top left), position calibration of the rotated I-signals, bunch 1 in blue, bunch 2 in red (top right), bunch 2 vs bunch 1 position correlation (bottom left), uncorrelated residual between bunch 1 and bunch 2 position (bottom right).

3. BEAM SIZE MONITOR AT THE INTERACTION POINT

The Beam Size Monitor (IP-BSM) is used to measure beam sizes as small as about 45 nm at the interaction point of ATF2 [3]. As it is a scanner that averages data over multiple accelerator pulses, the results can be affected by beam position jitter. This is one of the limitations to reduce the beam size below its present level. The jitter can in principle be measured using a set of dedicated C-band beam position monitors installed near the IP (IP-BPM) [4] and later subtracted from the beam size measurement. However, the resolution of these dedicated devices is too poor for the bunch population of N = 10^9 electrons presently used to obtain the smallest beam sizes at ATF2.

As the ATF ring can be operated with multiple bunches per extraction, and as it was shown that the beam position jitter of the 2^{nd} bunch is sufficiently correlated with that of the 1^{st} bunch to enable efficient reduction by FONT feedback [5], the IP-BSM was upgraded to separately measure subsequent bunches, by adjusting the laser timing and detector gate, and using a fast Cherenkov detector as photon counter instead of the previously used NaI scintillator. Figure 3 shows the detected photon signal and gate timing when the 1^{st} (left panel) and 2^{nd} (right panel) bunches are measured. The blue lines show the beam signals detected by the electrode of one of the strip-line Beam Position Monitors (BPM) in the beam line. The two bunches are extracted with 180 ns separation. The photon signals and detector gate are shown in pink and yellow, respectively, when the laser timing is adjusted for either the 1^{st} or the 2^{nd} bunch.

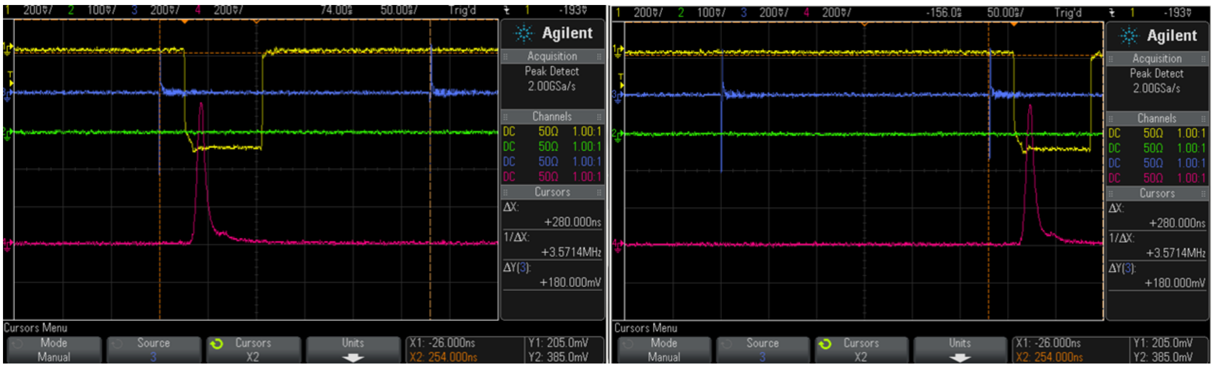

Fig. 3: IP-BSM photon detector signals for the 1^{st} bunch (left) and 2^{nd} bunch (right). The detector gate, beam and photon signals are shown in yellow, blue and pink, respectively.

The beam position stabilization through FONT feedback is limited by the resolution of the strip-line BPMs used as input, which depends on the beam intensity. Figure 4 shows the beam position fluctuations with the feedback ON and OFF for the present operational bunch population of N=10^9 electrons. The beam jitter was enhanced using random jitter sources at the entrance of the ATF2 beam extraction line, and the jitter amplitude A can be controlled by changing the amplitude of these jitter sources. As can be seen, the beam position jitter is reduced when the feedback is ON. The residual beam position fluctuation is limited by the resolution of the BPMs used for the feedback. The level of the residual beam jitter corresponds to that from the random jitter source when the amplitude is set to about A = 0.1.

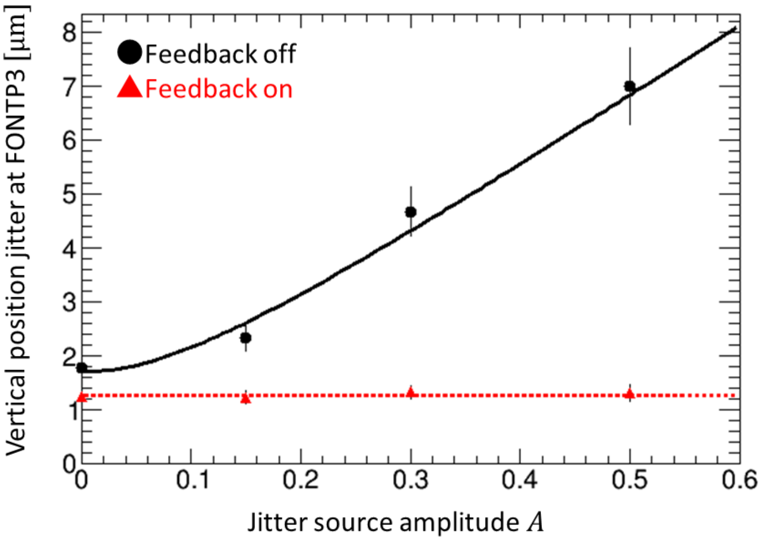

Fig. 4: The beam position fluctuation with feedback ON and OFF at the operational bunch population of N=10^9 electrons.

The IP-BSM evaluates the beam size at the IP by comparing it to the laser fringe pitch [2,3]. A small beam size results in a large modulation of the photon signal. Figures 5 and 6 show the IP-BSM photon signals for the 2nd bunch without and with feedback, respectively. A summary of measured modulations with FONT feedback ON and OFF is presented in Figure 7 as a function of the amplitude of the random jitter source. As can be seen, the modulation was reduced for large jitter amplitudes when the feedback was OFF, while on the other hand, with the feedback turned ON, the modulation remained large even for large beam position jitter. The dependence of the modulation reduction on generated beam jitter implies a beam size growth of about 131 nm per unit of jitter amplitude A without feedback. Since the residual position fluctuations with feedback ON correspond to generated jitter with an amplitude A = 0.1 for an operational bunch population of N=109 (see Figure 4), one can estimate that the contribution to effective beam size growth from beam jitter was reduced by the feedback down to 13 nm.

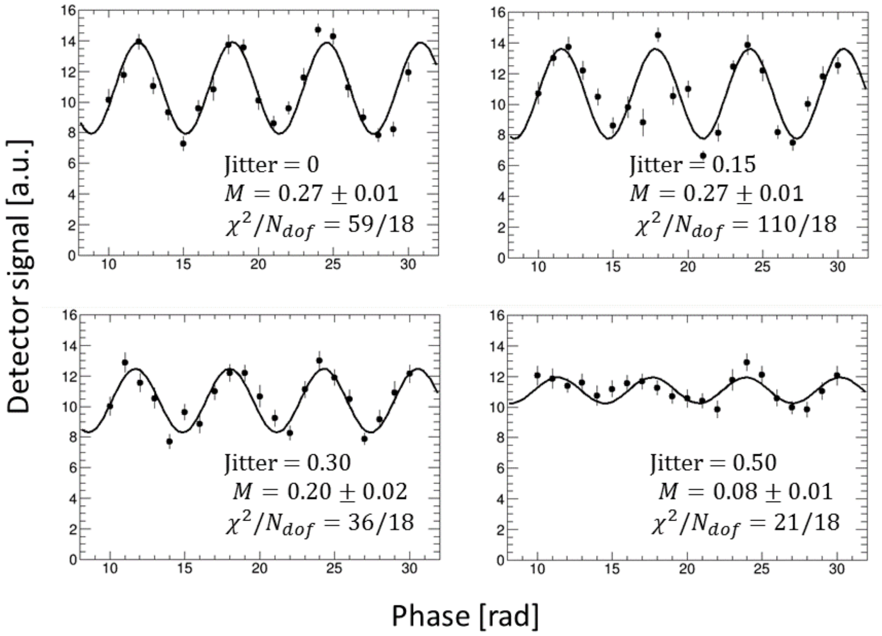

Fig. 5: The IP-BSM modulation for FONT feedback OFF.

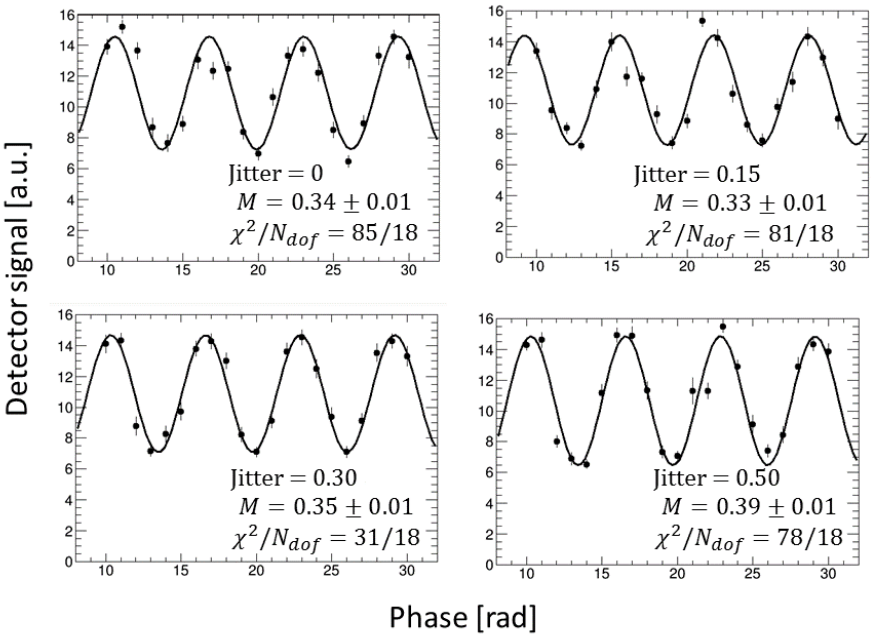

Fig. 6: The IP-BSM modulation for FONT feedback ON.

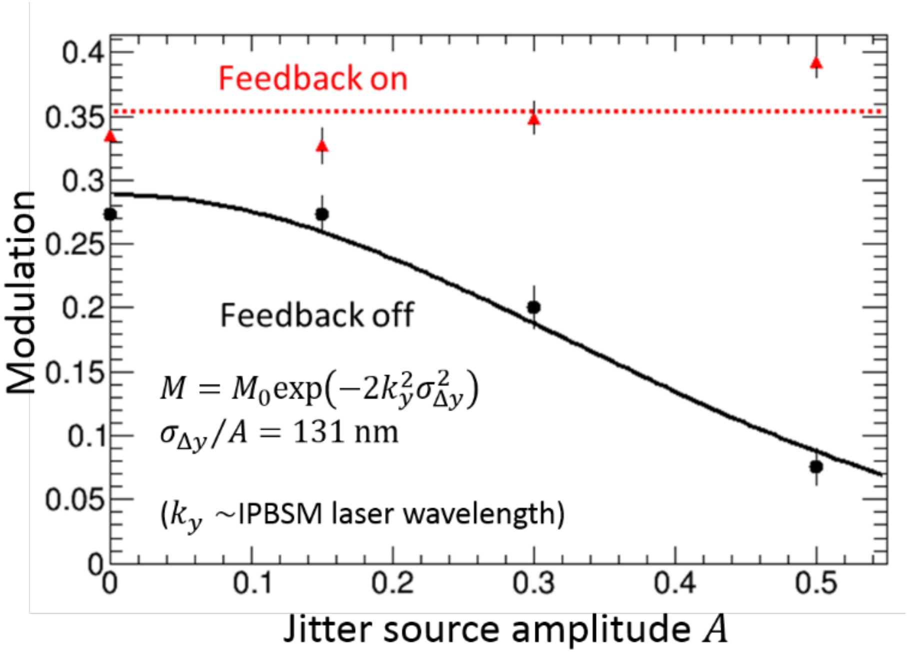

Fig. 7: Summary of the IP-BSM modulation for FONT feedback ON/OFF.

4. FUTURE PROSPECTS

Further studies are required to evaluate and optimise the performance of the CBPM system in multi-bunch measurements. Ultimately, the performance is limited by the finite number of samples available for analysis between the bunch arrivals. At ATF2, it is not expected that single bunch resolutions [1] can be achieved with multiple bunches, although one can still aim for the order of a micron.

The new capability of the IP-BSM to measure the beam size of the second bunch will in the near future enable studies of effects from using bunches with more than $N=10^9$ electrons. It is expected that beam position jitter plays an important role in the beam size increase observed at the interaction point for larger bunch charges. By using feedback to reduce the jitter of the second bunch, the small beam sizes presently routinely measured with bunch populations of $N=10^9$ electrons will hopefully be also be achieved with higher bunch charges.

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