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A Proposal for an Automatic Longitudinal Tomography Demonstration Project in the Proton Synchrotron Booster

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Summary

Longitudinal phase space tomography is a vital tool for beam diagnostics in most of the CERN synchrotrons, it is used to reconstruct the longitudinal phase space, and to measure the longitudinal emittance and energy spread. At present, measurements are taken punctually to confirm that beam parameters meet specifications. However, because measurements are intermittent, any slow variations are difficult to identify, and transient ones may be missed, potentially delaying the identification of faults. This is particularly relevant after Long Shutdown 2, during which significant changes have been made to the LHC injector complex. In the PSB these changes include a new injector linac and injection system, higher injection and extraction energies, as well as new RF systems, amongst many others. This note proposes a demonstration system for automatic tomographic reconstruction in the PSB, and gives an overview of the expected requirements for its implementation, and a proposed solution for meeting them.

Contents

1 Introduction

Longitudinal phase space tomography has been used operationally at CERN for many years in all synchrotrons of the PS complex, and is an invaluable tool for measuring the longitudinal properties of both operational and MD beams. This note discusses why automatic tomography would be beneficial to the complex, the motivation behind a demonstrator project in the PSB, and the requirements for implementing it.

This demonstration would build on experience gained in the PS, in which multi-burst triggering was used to acquire beam profiles sequentially along the ramp in a single cycle [1]. The same principle would be used to acquire profiles from different parts of the PSB ramp, which would then be used for automatic longitudinal tomography.

1.1 Tomographic principle

Tomographic reconstruction is used to reproduce an N-dimensional image from a series of $N-1$-dimensional projections. A 2-dimensional image can be reconstructed from a series of 1-dimensional projections, e.g. imaging with medical CT scans. This principle can also be applied to longitudinal particle distributions in synchrotrons to reconstruct the longitudinal phase space.

Particles in a bunch have some distribution in longitudinal phase space, which will rotate due to synchrotron motion. As the phase space rotates, the distribution is projected onto the longitudinal axis at different angles. Recording the longitudinal profiles on a number of machine turns, suitably spaced to see the projection of the distribution from multiple angles, can then be used to perform tomography and reconstruct the longitudinal phase space. A detailed description of the technique, and the original algorithm used at CERN, can be found in [2].

1.2 Motivation

1.2.1 Automatic Measurement

Beam performance tracking is of significant interest for both LHC-type beams, as well as beams for fixed target experiments, after Long Shutdown 2 [3]. In normal operation, the so-called tomoscope application is used to measure the phase space distribution at specific points in the magnetic cycle to measure beam characteristics. This allows beam parameters to be periodically compared with specifications, but not continuously monitored over extended periods.

The benefit of automatic tomography, is that it will allow more detailed tracking of beam parameters than is presently available. Through tomography both the longitudinal emittance and the energy distribution can be measured and recorded, which is not otherwise possible. Measuring and logging these parameters will then allow long term trends in longitudinal beam performance to be identified, and more effective correlation of longitudinal parameters and other indicators of beam performance. Additionally, by making this data available to operators it will be signficantly easier to identify in which machine the beam parameters start deviating from specifications.

At present the SPS Beam Quality Monitor (BQM) will detect if beams are not meeting specification in the SPS, but it takes time to identify in which machine the problem starts [4]. By giving a continuous measurement of beam parameters, automatic tomography could reduce the time spent debugging, potentially allowing more beam time to be used for physics.

1.2.2 PSB Ring 3 Demonstrator

The PSB is an ideal test bed for automatic tomography. All PSB cycles are injected and accelerated in $h = 1(+2)$, and all but one, the cycle for SPS fixed target experiments, are extracted in $h = 1(+2)$. This gives a uniformity in measurement parameters for most beams, with the SPS fixed target cycle allowing demonstration of changing harmonic number. Additionally, the bunches are typically hundreds of ns long, which will allow hardware with modest sampling rates and bandwidth to be used. Furthermore, by including measurements immediately after injection, it will be possible to monitor the parameters of the beam from Linac4. Ring 3 is proposed for this demonstration, because it is used for all operational cycles, with the exception of nTOF, which uses ring 2.

2 Hardware Requirements

The present signal path for the wall current monitors in the PSB is shown in Fig. 1. For each ring the signal is split into four and digitised; two for tomoscopes, one for the bunch shape monitor and one for the OASIS observation system. The signal paths all have a total attenuation of -18dB.

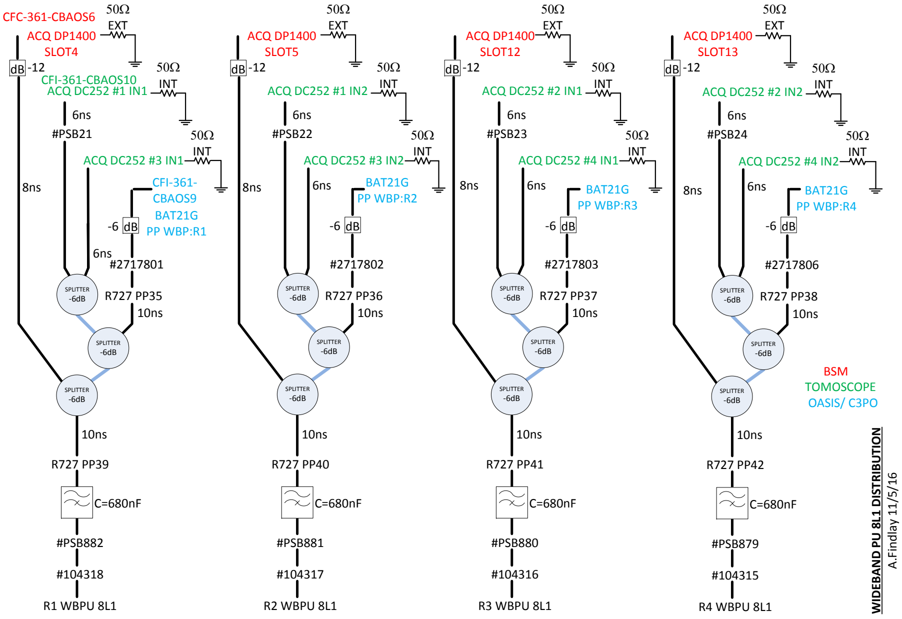
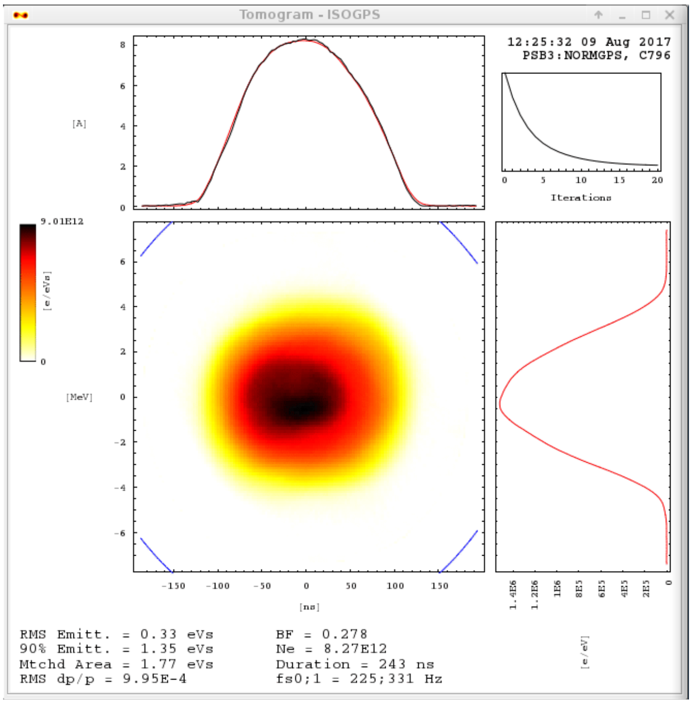


Figure 1: Wide Band Pick Up signal path from all four PSB rings. The digitisers for the tomoscopes are marked in green, the bunch shape monitor in red and OASIS in blue.

The lowest intensity operational beam in the PSB is the low-intensity single bunch beam for the LHC (LHCPROBE before LS2, LHCPILOT after LS2), with intensities as low as 5×10^9 ppb; the highest intensity are the cycles for the ISOLDE facility (NORMGPS and NORMHRS), which currently operate at up to 1×10^{13} ppb. After LS2, the 160 MeV kinetic energy injection and 2 GeV kinetic energy extraction revolution frequencies will be 0.992 MHz and 1.809 MHz respectively. This gives a minimum average beam current of 0.75 mA, and a maximum of 2.6 A. However, at injection the minimum peak current will be the Linac4 average current, which is expected to be 25 mA at start up. Additionally, due to the bunching factor the extraction current can be much higher than the average current, for example Fig. 2 shows the ring 3 extraction reference for the NORMGPS beam to ISOLDE, which has a peak current above 8 A.



```
12:25:32 09 Aug 2017
PSB3:NORMGPS, C796
```

```
RMS Emitt. = 0.33 eVs        BF = 0.278
90% Emitt. = 1.35 eVs        Ne = 8.27E12
Mtchd Area = 1.77 eVs        Duration = 243 ns
RMS dp/p = 9.95E-4           fs0;1 = 225;331 Hz
```

Figure 2: Extraction reference tomogram for ISOLDE ring 3

For the new demonstrator system the proposal would be to add a splitter to ring 3 Bunch Shape Measurement signal path, with a new digitiser and an independent trigger generator. There is a risk that further splitting the signal could cause reflections, however this has not been observed to be a problem for the PSB in the past.

Due to the large current range of cycles in the PSB it will be necessary to either use a digitiser with a large Effective Number of Bits (ENOB), two digitisers with different sensitivities, or to attenuate the signal by different amounts for each cycle. The SPS BQM uses a digital step attenuator from Mini-Circuits [5] to allow attenuation to change between cycles, otherwise known as pulse-to-pulse modulation (PPM). Using the same attenuation solution as the SPS would have the advantage of allowing already existing hardware and software solutions to be duplicated, with very little modification required for the PSB. The proposed signal path for this demonstration, using a PPM attenuator, is shown in Fig. 3.

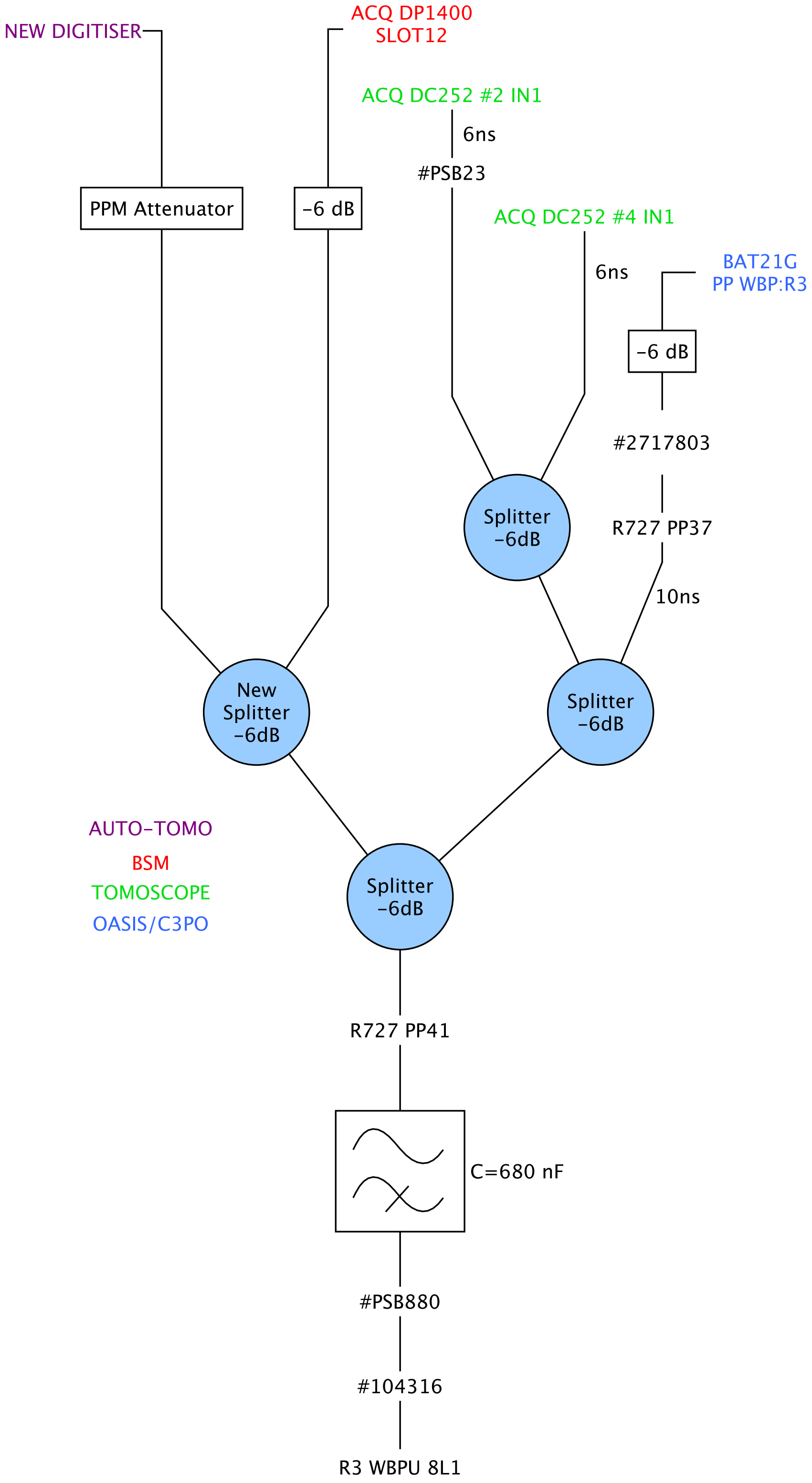


Figure 3: Proposed modified signal path for the ring 3 Wide Band Pick Up

2.1 Digitiser

2.1.1 Signal Range

Assuming a maximum intensity of 1×10^{13} ppb, with a bunching factor of 0.25, gives a peak current of 11.6 A at extraction, and the Linac4 current sets the peak current at injection at a minimum of 25 mA. Therefore, a range of nearly 470, or approximately 54 dB, must be covered. Additionally, it can be assumed that 6 bits are required to adequately sample the lowest peak currents. Three digitiser options may be considered for this demonstration, depending on the constraints:

1. **PPM attenuation, single digitiser**: The attenuator plus digitiser together must cover the 54 dB signal range. The PPM attenuators used for the SPS BQM allow up to 31 dB of attenuation, therefore the digitiser must have 6 bits with an additional 4 bits to cover the remaining 23 dB signal range. A digitiser with an ENOB of 10 or more would be required for this solution.

2. **Fixed attenuation, single digitiser**: To cover 54 dB a single digitiser would require 9 bits in addition to the 6 for the lowest beam currents. Therefore, a digitiser with an ENOB of 16 or more would be required.

3. **Fixed attenuation, two digitisers**: Using two digitisers, with different input attenuation, would allow each to be tuned to a particular intensity range. In this case the first could be used for peak currents from 25 mA to 540 mA and the second from 540 mA to 11.6 A, a factor of 22, or 27 dB, in both cases. For this range an additional 5 bits would be needed, therefore two digitisers, each with an ENOB of 12 or more would be required.

Whilst option 2 would require the minimum amount of hardware and controls, it would require a very high specification digitiser to provide the required ENOB and sampling rate, and is therefore not ideal. Option 3 would require two digitisers with higher specification than the single digitiser required for option 1, which would also make this a high cost solution. Therefore, option 1 is considered to be the most suitable, the requirements for the digitiser are modest and the extra complexity and cost introduced by the attenuator is small.

2.1.2 Sampling Rate and Duration

An additional complication for the PSB comes from the large change in revolution frequency and bunch length during the acceleration cycle. This will make it difficult to sample both the injection and extraction profiles at the ideal rate without changing the same sampling rate and duration. Two possibilities could be considered:

1. Fixed settings, with a high sampling rate and large number of samples, such that the sampling rate at injection gives sufficient samples at extraction. This approach was used for the PS demonstration of multi-burst triggering [1].

2. Variable settings, with sampling rate adapted to the conditions at injection and extraction.

The effect of these options can be seen taking an example based on the LHC25 cycle, for which reasonable parameters are:

- 1.4 eVs at injection, with $V_{h1} = V_{h2} = 4.8$ kV
- 3 eVs at extraction, with $V_{h1} = 8$ kV, $V_{h2} = 0$ kV

This gives bunch lengths of 0.8 μs at injection, and 0.2 μs at extraction. Ideally, the injection would be measured at approximately 0.25 GS/s for 1 μs, and the extraction at approximately 1 GS/s for 0.4 μs. If fixed sampling were required a compromise of 1 GS/s for 1 μs could be used, but this would greatly oversample the injection and lead to a lot of time without beam being sampled at extraction, which would necessitate a small amount of additional pre-processing before tomography could be run.

2.2 Triggering

In 2017 there was a demonstration of multi-burst acquisition in the PS [1], in which two standard timing receiver and generator modules (CTRV) were used to deliver up to 16 bursts of triggers. The experience gained in the PS will be beneficial for deploying this demonstration system in the PSB. A significant difference for the PSB injection/extraction measurements is that only two bursts of triggers would be required. However, a future extension could be considered where additional measurements are taken during the ramp, such as after the injected distribution has filamented and after the longitudinal emittance blow-up.

Figure 4 shows the kinetic energy of the high energy PSB cycle, with four times that would be of interest for automatic tomography identified. These are:

1. 1 ms after injection, to monitor the performance of Linac4.
2. 45 ms after injection, to measure the equilibrium distribution early in the ramp.
3. 105 ms before extraction, to measure the emittance after blow-up and before bunch splitting.
4. 3 ms before extraction, to measure the emittance sent to the PS or ISOLDE facility.

Times 1 and 4 would be chosen for the initial implementation, with 2 and 3 added later if possible.

3 Software Requirements

3.1 Tomography

In 2019 a full translation of the Fortran tomography code to mixed Python/C++ was completed, with extensive benchmarking studies comparing the two versions [6]. By mixing Python and C++ for this development there are benefits gained from both languages. The computationally heavy processes can be run in optimised C++, which gives much shorter execution times. The interfacing and data treatment can be run in Python, which gives very

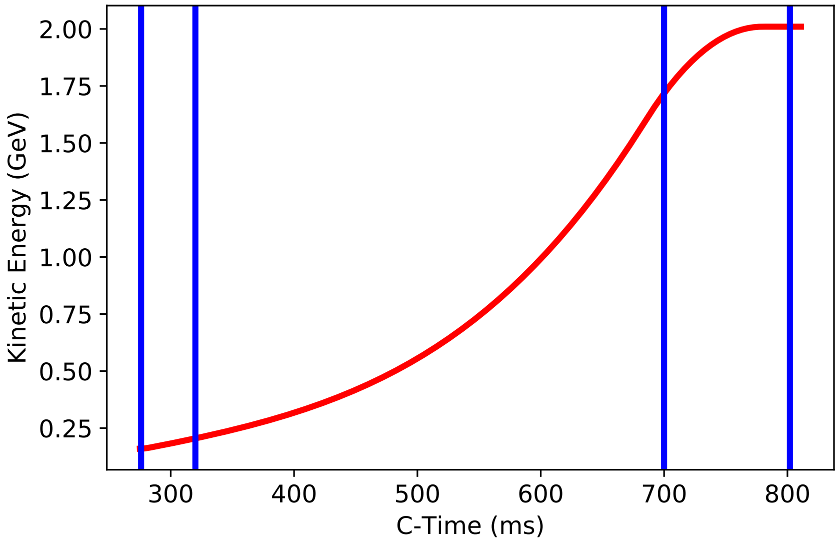


Figure 4: PSB kinetic energy ramp, with possible locations for four separate automatic reconstructions

good flexibility for future developments. The new code is also fully object oriented, which allows flexibility in which parts of the code are used and easy addition of user-specific code.

The new version of the code is fully compatible with operational Tomoscope GUI, for which it is run identically to the legacy Fortran code. For the proposed automatic tomography application this style of use would not be suitable or required. In this case the particle tracking step, which requires a significant fraction of the computation time, can be pre-calculated once and the results stored. Then, for each measurement the stored particle coordinates can be combined with the measured profiles to give a rapid reconstruction. By removing a lot of computational overhead, test cases have achieved equivalent precision to the Fortran with factor of 10 to 20 speed-up in execution time. No signficant additional development is foreseen for the tomography code, however it is expected that some small adaptions and fixes will be required as it becomes used operationally.

3.2 Data Treatment

Processing the measured bunch profiles, running the tomography, and analysing the result will require some development. The test particles must be pre-tracked and their coordinates stored once, then loaded and combined with the corresponding measured profiles. After the reconstruction has been made, some analysis is required and the result must be published in a way that can be sent to the logging service and accessed by higher level applications. Initially a Python development is foreseen for this purpose, this code must be well optimised as the reconstructions and analysis must be completed within the 1.2s basic period, which is the length of the PSB cycle.

An initial set of parameters to be published, and their possible uses is:

- Longitudinal emittance (RMS, 90%): Logged to NXCALS and included in fixed display to monitor longitudinal performance.
- RMS $\frac{dp}{p}$: Logged to NXCALS, available for subscription, e.g. for estimation of dispersive contribution to transverse beam size.
- Energy projection: Available for subscription, e.g. for more accurate transverse emittance measurements through deconvolution.
- Mean energy offset: Logged to NXCALS and included in fixed display to monitor energy of beam from Linac4.
- Phase space distribution: Included in fixed display to allow monitoring of Linac4 and PSB performance.
- Reconstruction discrepancy: Logged to NXCALS and available for subscription to monitor reconstruction precision to ensure machine parameters are not drifting.

This set of parameters would allow sufficient data to be sent to logging to allow analysis of longitudinal performance over long time scales. At the same time additional information would be available for immediate use, either in conjunction with other forms of analysis or for display in the control room.

Two high level applications are also foreseen for this project. First, an operational GUI to control the reconstruction parameters for each beam type, run the tracking, and store the tracked coordinates. Second, a fixed display, which will show the reconstructed phase space at injection and extraction along with significant bunch measurements. With the CO infrastructure officially supporting Python, these are also expected to be Python developments.

3.3 FESA

If the SPS BQM style PPM attenuator is used, there is an existing FESA class (SPSApwlAttenuator) for controlling it. A small amount of additional development likely to be required to adapt the class to the PSB requirements. For control of the digitiser(s) the FESA class used for the SPS bunch length measurement (ABWLM) is likely to be suitable, but is also expected to require some modification for this use case. In both cases, the precise requirements will be known when the hardware has been selected, as this will set the constraints for the functionality of the FESA class.

4 Conclusion

Beam performance tracking is being introduced to the injector complex after LS2, both to track beams from machine to machine and to monitor performance of each machine. Measuring the longitudinal behaviour of the beams is a vital component of that, and automated tomography would enable both the temporal and energy distributions to be measured continuously. This note details a proposal for a demonstration system to be implemented in ring 3 of the PSB. This would allow simultaneous monitoring of the performance of both Linac4 and the PSB.

The PSB in particular is an ideal testbed for this concept. All PSB cycles operate in $h = 1(+2)$, with the exception of SFTPRO, with extracts in $h = 2$. The uniformity of settings greatly reduces the complexity that must be implemented, therefore the effort can be spent on perfecting the data acquisition, analysis and distribution. Upon successful demonstration of automated tomography, the proposal would be to first extend it to all rings of the PSB, and then to gradually higher energy injectors and possibly the anti-proton complex. As additional machines are introduced further complexity will need to be added, such as variable harmonics, large numbers of bunches and compensation for transfer functions of the signal path from wall current monitor to digitiser.

For this demonstration the proposed solution is to use a PPM attenuator, with a 10 bit digitiser and a CTRV delivering at least two bursts of triggers. To interface with the attenuator and digitiser it may be possible to use, with a small amount of modification, existing FESA classes, depending on the hardware selected. The code development for the tomographic reconstruction is complete, and minimal modifications are foreseen, however further developments will be required for pre-processing the raw data, running the tomography, and processing and publishing the result.

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