ADT AND OBSBOX IN LHC RUN 2, PLANS FOR LS2

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Abstract

The primary function of the LHC transverse feedback (ADT), is to damp the injection oscillations and to actively counteract the coupled-bunch instabilities driven by the machine impedance. While the damping function was there since the LHC start-up in 2008, during Run 2 the ADT also became a very important tool to perform active excitation of all kinds and various beam measurements through the whole cycle. High resolution, bunch by bunch, turn by turn beam position data is available within the ADT signal processing, which is made available for real-time, or offline analysis by means of ADTObsBox system. In line with the topic of this Evian LHC performance workshop, the paper documents how both systems evolved during Run 2 and provide an overview of expected upgrades and developments planned for LS2.

ADT IN 2018

After almost 10 years of operation, the ADT is considered to be a mature system. In 2018 only very limited machine down time (<5 hours) was due to the ADT. It is interesting to point out that the nature of the few blocking faults to the machine due to ADT had significantly changed through the Run 2.

The hardware elements are still failing, especially the high voltage equipment and the tetrode power amplifiers require thorough attention. Typical fault duration of this kind lasts from several hours, up to 2.5 days (in 2018 AFT data). But this is expected and thanks to a built-in hardware redundancy, operator training and a sophisticated spare part and maintenance policy these faults are not blocking anymore. The transverse feedback gain is re-distributed on the fly and the faulty power element is replaced at the earliest convenient occasion.

As the transverse damper system becomes increasingly used for all kinds of experiments and sophisticated measurements there is an emerging trend of failures/mishaps leading to a beam dump caused by improper use of the system. To mention two examples, the beam was dumped on beam losses, when during an MD a full strength noise excitation was applied to more than a thousand bunches at flat top. Similarly, an end of fill MD was carried out to investigate the emittance growth with reduced ADT bandwidth. The wrong digital filter coefficient normalization provided excessive gain, pushing the feedback loop beyond the stability limit. The behaviour was later very accurately reproduced by the numeric model [1]. The lesson learned in both cases was, we have a very good understanding of the system and it's interaction with beam, just each experiment needs to be allowed sufficient machine time to properly test and prepare before going large scale.

PRE-LS1 ADT

The ADT was designed and built in the transition era from analogue to fully digital beam control systems (very early 2000's). Therefore the original system design and the expected way to operate it was mainly inspired by the existing, mostly analogue, transverse feedback system already running in the SPS. Shortly after the ADT was fully commissioned for the main function (injection oscillation damping and suppression of the coupled bunch instability) it quickly became apparent that the fully digital architecture offers a potential to do way more than "damping".

The active excitation by a synthesized signal in a form of abort gap cleaning, later the injection gap cleaning was introduced in 2011. This was followed shortly after by a new signal type - white noise. The noise excitation allowed to perform a batch selective transverse emittance blow-up, what completely changed the way the loss maps were performed ever since [2] [3].

The digital signal processing offers a great flexibility in every aspect what allowed for many experimental features introduced and tested just before LS1. A strong transverse feedback is necessary for beam stability. The system measures and damps any measured transverse movement. An unwanted side effect is that the amplitude of the residual natural betatron oscillation is greatly reduced, what makes other vital measurements, e.g. the real time tune measurement challenging. Towards end of Run 1 a feedback gain modulation within the turn was tested introducing the concept of "witness bunches".

The frequency response of the power amplifier and kicker assembly limits the full power ADT bandwidth to about 800 kHz. However, the amplifiers were designed to operate beyond 20 MHz. The full kick strength is needed only to quickly damp the injection oscillations (<100 turns). Later, only a "noise-like" with greatly reduced amplitude, but increased bandwidth is present. The digital signal processing architecture allowed to design pre-distortion filters to compensate for the power system frequency response and make the ADT frequency response flat up to 20 MHz (at a cost of lower kick strength) making it an "ideal", bunch by bunch damper [4]. The availability of this so called "enhanced bandwidth" made the ADT excitation functionality even more attractive, as suddenly it became possible to excite a single bunch within a train of 25ns spaced bunches without touching the neighbour bunches.

ADT is the only system in LHC, where a full rate, bunch by bunch, turn by turn beam position data is available with high resolution and for an unlimited duration. This data is invaluable for beam physicists and the first attempt to make the data available to them were made by transferring obser-

vation buffers of very limited length from the beam position modules (the limit was 1 bunch for 256k turns, 2b/128k, 4b/64k, or 8b/32k turns). Data could only be transferred a few times per minute and the acquisition was not synchronized across the planes and beams.
A simple, single path ADT digital signal processing unit (DSPU) quickly became a limitation to the constantly growing number of new operation modes and required operational flexibility.

ADT EVOLUTION DURING LS1 AND IN RUN 2

A major ADT low-level RF system consolidation was planned for LS1. All originally installed coaxial transmission lines feeding the pickup signals from the tunnel to the surface building SR4 needed to be replaced due to a damage caused by improper installation during LHC construction. This was an occasion to install cabling for an additional set of pickups (Q8, Q10) and replace all 3/8" coaxial cables used for drive and observation signals by a much more suitable 7/8" smoothwall line. A more optimal frequency and phase response of the drive transmission lines allowed to remove the hardwired cable compensating filters and allowed the system impulse response to be shaped entirely in the digital domain, with many advantages and more flexibility.
In order to provide suitable infrastructure for the constantly growing functionality, the original digital signal processing units were replaced by newly designed units featuring a much more powerful FPGA, four independent, dedicated signal chains/feedback paths (main loop, witness loop, cleaning, excitation), digital inputs for four pickups (Q7, Q9, Q8, Q10) and four digital outputs.
Having full rate bunch-by-bunch position data available lead to the birth of the ObsBox system [5]. The ObsBox, in the transverse plane called "ADTObsBox" is a powerful computer system receiving raw position data from optical links (1 Gbps per pickup), storing them in long circular buffers (up to 6 minutes) and making portions of these data available to the users or to perform an online analysis. The data buffers containing data for all bunches of various lengths (typ. 2k, 4k, 32k, 64k turns) are available on demand by the user, or automatically after a given machine event (injection, extraction, beam dump with post mortem).

ADT IN RUN2

The ADT infrastructure was well future-proof consolidated in LS1, allowing the ADT to profit from the two newly introduced ADT components: the ADTObsBox and the sophisticated beam excitation by means of the ADT-AC Dipole. The first application available to the Operation group was the ADT diagnostic panel. Each injection is captured and saved by the ADTObsBox, the injection transient analyzed by the Kotzian algorithm [6] in the machine and results presented as a fixed display in the CCC (Figure 1). The operators can see the bunch by bunch damping time and bunch by bunch betatron tune. Provided the ADT is set to see the beam, the system will measure and the panel will indicate the tune values already after the first 7 turns. This is useful e.g. after long shut down periods, when the beam needs to be threaded through the machine, not making a sufficient number of turns to be measured by the BBQ system.

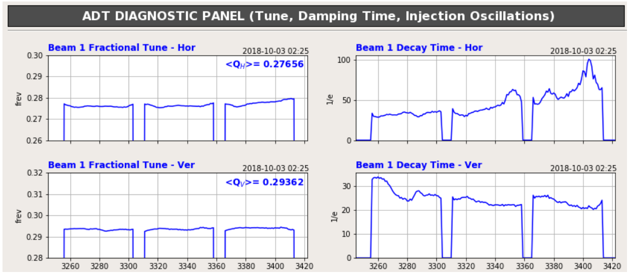

Figure 1: ADT diagnostics panel

The ADTObsBox computing capacity is sufficient to do a real time transverse activity analysis. The stream of position data is analyzed bunch-by-bunch in trenches of 256 turns and the amplitude of the transverse oscillation is calculated. This data is published by means of a FESA class feeding the "Real time transverse activity monitor" fixed display in the CCC. The activity data are also permanently logged in Timber. The following block then analyzes the activity trend and detects an onset of transverse instability [7] [8]. In case a rising trend is detected a trigger is sent to the LHC instability trigger network which allows to freeze all connected instruments and save the data for further analysis. One of the instruments is a 64k turns long buffer in the ADTObsBox, which due to its length, allows to capture most of the developing activity.
A new excitation engine called ADT-AC dipole was introduced during Run 2. It allows to excite selected bunches, even within a 25 ns trains, with programmed amplitude profiles and frequencies for an unlimited amount of time. Together with the ADTObsBox, the instrument is used for a large variety of specialty measurements. A case worth to mention is e.g. MD2091, where the resistive wall tune shift due to different collimator materials was measured with a resolution of 10^{-5} [9]. The results are shown in Figure 2.

A quite complex operational tool for linear coupling measurement and correction was developed in collaboration with the ABP and OP groups [10].

A novel digital signal processing algorithm was developed and tested with beam during the very first dedicated ADT MD in LHC [11]. The currently used approach to the transverse feedback loop employs a two stage signal processing scheme. In the first stage, the closed orbit information is suppressed from the positional data stream by means of a two tap Notch filter. Then the detected oscillation vector is rotated by means of a 7-tap Hilbert phase shifter to apply a momentum kick. Main advantage of this approach is simplicity and a capacity to run with disabled pickups (a degraded mode in case of a pickup failure). The main disadvantage is long group delay, limiting the maximum feedback

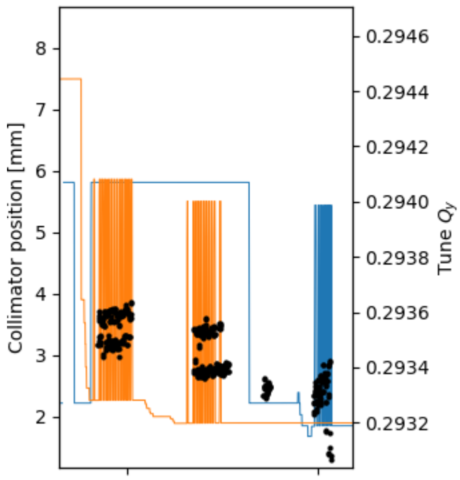

Figure 2: Example of tune shift measurement at 10^{-5} level using ADT infrastructure. Orange trace shows the collimator jaw position, black dots are measured tune values.

loop gain and incompatibility with close to half integer tunes. The newly proposed digital filter was specially designed to use information of last 3 turns only, providing the closed orbit suppression and phase rotation functionality. The new filter architecture was successfully tested with beam during MD4063. The results are very promising. The new filter supports much larger tune spread acceptance, opening various options for the future. Figure 3 shows a comparison of damping times (used as an indicator of ADT performance) for the two architectures as a function of tune deviation from the nominal design operating point.

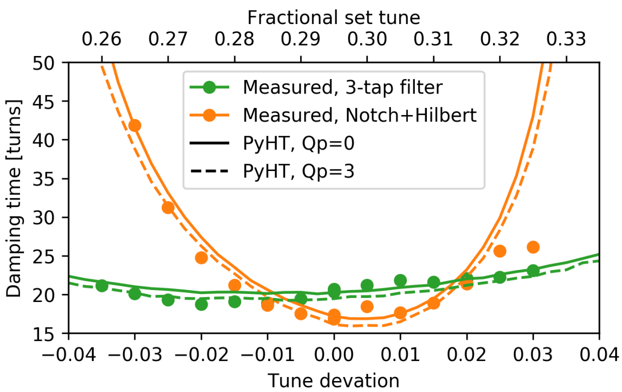

Figure 3: Measured damping times with the currently used filter scheme (Notch+Hilbert) and the 3-tap filter [11].

PARAMETER SPACE FOR RUN III

ADT performance after LS2 is expected to be the similar as in Run 2. The baseline values have been agreed between BE/RF and BE/ABP for Run 3.

The system already runs with ATS optics and it is quite flexible to adapt to a new one, as long as reasonably high β values are available in ADT pickups around IP4 (>120 m). The digital signal processing is compatible with tunes between 0.27 and 0.32. Running close to half integer tune values is possible, but it will require an additional commissioning effort. Tune spread acceptance is estimated as ±0.025 for 50% increase in damping time.

ADT beam position modules are sensitive to per bunch intensity. The total acceptance range is somewhere between $5x10^9$ to $1x10^{12}$. The front end is optimized for a given operating point (e.g. nominal bunch intensity) and then provides optimal performance with a dynamic range of 10 dB. The required damping time of 50 turns, for a single bunch within a train, with both standard and enhanced bandwidth, maintained through the full cycle, is comfortable to achieve. The current beam position measurement noise floor is estimated to be $<0.9\ \mu m_{RMS}$. The ongoing developments aim to improve this figure by a factor of 2-4 for Run 3.

CHANGES IN LS2 AND NEW DEVELOPMENTS FOR RUN 3

Power system

A development program was launched by the BE/RF/PM section to provide an alternative design of the power amplifier anode resistors. The electrical parameters are quite challenging to achieve, as high power (25kW), high frequency (>20MHz), high voltage (15kV), high impedance (900 Ω) and water cooling are not very compatible. The supply of the original resistors is not available anymore, although the manufacturers have proposed a modified version which offers' greater flexibility with regard to repair. CERN has also been developing replacement units which were successfully tested in the machine for the full period of the last run, however upon inspection of these loads during LS2 minor cracks were discovered in the surface of the resin. Development will continue with the CERN loads and it is hoped a series of CERN loads can be produced in-house so that all power amplifiers can be gradually upgraded by end of LS2. The currently used and the new resistors are shown in Figure 4.

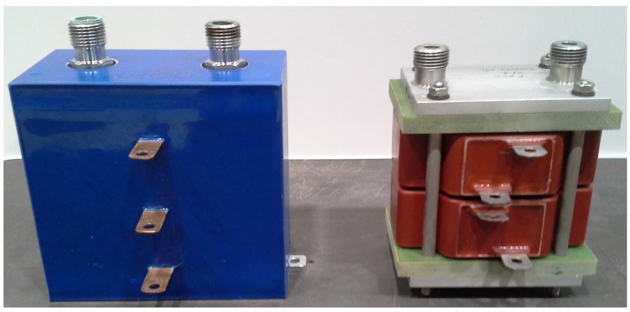

Figure 4: The original model (right) of the anode resistor and the new replacement model (left) produced in-house.

Beam position module upgrade

ADT is a complex system, where a chain of RF, digital and high power analogue subsystems measure the beam oscillation, calculates the correction and applies the kick to the beam. Noise performance of the whole system is currently dominated by the measurement noise of the beam position measurement modules. New receiver, not based on a super-heterodyne principle was tested in 2016. A full engineering prototype was deployed to all Q8 and Q10 pickups in late 2018. The transverse feedback was successfully run through a full machine cycle during the MD4143 "Noise studies with new ADT pickup electronics". The first results look promising, see the comparison of position measurement by the current front-end and the new generation one in Figure 5.

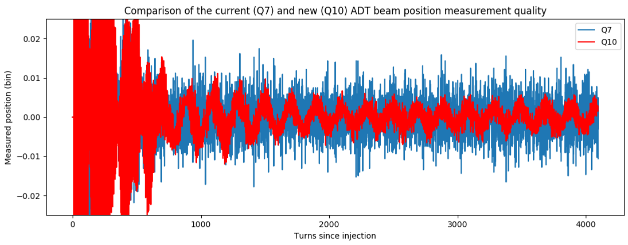

Figure 5: Injection oscillation captured by the current front end (blue) and the new generation front end (red) where a qualitative difference is visible.

High level controls, software consolidation and upgrades

Functionalities of various ADT sub-systems are controlled by means of

- functions for loop gains, phase shifts
- timings for loop start, loop stop, cleaning start, cleaning stop, excitation start, acquisition freeze
- sequences run from the main sequencer
- on demand sequences, or sequences run manually from scripts

The new features were being constantly added to ADT as the needs emerged. As the ADT is one of the vital systems for the LHC operation, it was not always possible to implement a new functionality in an optimal way, as this would require changing already existing interfaces or a lengthy re-commissioning effort which is not possible during the regular machine run. LS2 is as an opportunity to do a major clean-up, removing the "for historical reasons" bits and re-thinking how the ADT should be controlled at the high level. The controls should be moved from "we are in this part of the cycle" approach to "we want the ADT to do this now". New LSA functions will be implemented to control the ADT parameters at the higher abstraction layer and then converted by means of make rules down to the hardware functions.

The ADT consists of a multitude of systems which either controls the ADT subsystems, or acquires data, or for example in the case of the ADTTuneExtraction, a combination of both. These systems depends on one another and modifications to one interface will affect the others subsystems. As mentioned earlier, one of the goals during LS2 is to remove unnecessary legacy features and simplify the overall system as much as possible which will increase the maintainability and make operating the ADT easier. Figure 6 shows the dependencies between the different FESA classes which are associated with the ADT, and how much a change in the interface would impact other modules. The classes with major modifications planned are the ALLAbortGapClean and the ALLADTmDSPU which both belong to the group with the highest impact on submodules since the ADTACDipole is tightly coupled with these classes. The ADTACDipole is also a complex class which was introduced to add a security layer between users and the excitation engine in ADT. It consists of a complex state-machine which goes through multiple stages to verify that the settings which the user is sending to the ADT is safe for the machine. The ADTACDipole is loosely coupled with the LHC coupling correcting server [10] which means that changing the interface would require updating the server, but no changes for the interface are planned for the ADTACDipole except update it to comply with the changes in ALLAbortGapClean and ALLADTmDSPU.

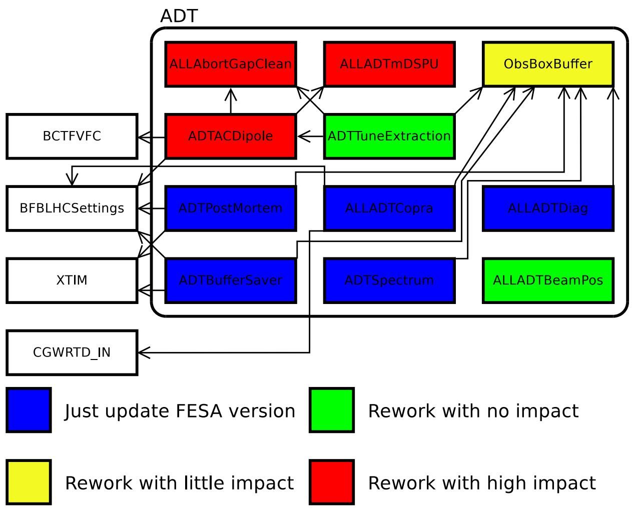

Figure 6: Dependency between FESA classes and impacts of interface changes.

On demand active tune measurement

A prototype of an on-demand tune measurement system has already been developed and tested but to become a fully operational tool it requires further development. For now, only the low precision mode is implemented. Two more advanced modes are foreseen to provide measurements with increasing precision. The algorithms for the higher precision modes must be decided and implemented and after LS2 after an agreement with machine protection to decide safe parameters since the higher precision modes will require either higher amplitude or multiple kick sequences to acquire enough data , some machine time is required to properly verify the functionality and the correctness of the system.

ADTOBSBOX IN RUN 2

As already mentioned, the ADTObsBox was first introduced in 2015 to allow users to download buffers of different lengths with the bunch-by-bunch turn-by-turn positional data from the ADT beam position monitors. Since then the system has provided valuable data for many users around CERN. In late 2017, a storage server was introduced to store the buffers captured by the ADTObsBox and until end of Run 2, it has saved 4.6 TB data of injection, post-mortem and instability events. This data is used for injection quality and drift observations through out of year, post-mortem analysis with 6 second bunch-by-bunch history, instability cause analysis, and various MDs.

The running system is the first proof of principle version and it starts to become obsolete in terms of hardware, but also methods used to transfer the gigabit link positional data to the user. It is prone to problems when trying to cope with the high loads induced from high demands for the data. This combined with the knowledge which has been accumulated during the operations on how the data is being used have led to the decision that a new system must be introduced after LS2. The goal of the new system is to supply many users around CERN with the data from the ADT reliably and support demanding online analysis with low latency.

ADTOBSBOX UPGRADE

The new system will look the same for all normal users but all the underlying technology will be changed, this includes the acquisition cards, firmware, drivers, servers, operating system, and software. Since the interface will be the same, no scripts or FESA classes that currently rely on the ADTObsBox will need to be modified.

Acquisition card

The previous generation used the SPEC cards [12] to acquire the data and this only allowed one data-stream per card to be captured. One of the requirements for the new system is to make all the channels available in one server and to achieve this, an acquisition card that could handle as many channels as possible was required. There where no FPGA cards with a PCIe form factor and many SFP+ slots available on the market so the only possibility was a PCIe FMC carrier with an SFP+ FMC mezzanine card. The carrier that was selected is the TEC0330 [14] from Trenz Electronics and this is paired with the HTG-FMC-X10SFP+ [15] from Hitech Global. This allows for up to 10 channels to be captured by a single card at 1 Gbps. When designing the firmware and the driver, the goal is to create a dynamic card which could be used for different purposes, it is not limited to 1 Gbps but supports 4 different modes which can be seen in Table 1. The reason for it only supporting 7 channels when running in 10 Gbps is the limited bandwidth of the PCIe bus.

Table 1: Bandwidth Specifications

Bandwidth	**Channels**
1 Gbps	10
2.5 Gbps	10
5 Gbps	10
10 Gbps	7

Driver

The previous generation of ADTObsBox used a 6 million long circular buffer which the smaller buffers acquired a part of when they where triggered and by using an offset they could acquire a slice anywhere in the long buffer when triggered. The flexibility of this buffer was never used and in most cases the offset was smaller than the length of the buffer that was being triggered(less than 128k turns). To use less RAM, this buffer will be smaller in size at 2^{18} turns which is twice the size of the largest buffer currently in use to allow for enough data to copy the whole buffer. This if of course flexible and can be increased in the future if the need emerges. The driver will move the long circular buffer from user-space to kernel-space and introduce asynchronous DMA transfers. In the old system the DMA transfer was initiated by a user process and if the system was experiencing a high load this could lead to the process not reading the data fast enough which could crash the driver while the new driver will avoid any perturbation introduced by user-space applications and improve the reliability of the system. Another important factor for moving the buffer to kernel-space is that this allows for many user applications to read the latest data from the buffer with low latency, this introduced the opportunity to have multiple instability detection applications which read from the buffer directly and acquires the latest turn with less than a one turn delay. This would make the ADTObsBox an ideal platform for real low latency instability detection system, the delay which is introduced in the current system is upwards to 400 ms and in the new system, this could be reduced to 100 µs.

Servers

The current servers are obsolete and can not be acquired anymore. The exact replacement type has not been decided yet but the technical specifications are already known. It must be a very powerful server that could run computationally demanding analyses reliably for the whole of run 3. One big change is that the servers are moving away from being pure front-ends and will be configured as normal servers to remove the limitations which are enforced on front-ends by the controls infrastructure at CERN. This allows for a more configurable system which can be fine-tuned for the intended applications and it allows for GPGPU computing and installation of local disk-storage.

Software

A new FESA class called ADTObsBoxBuffer will be introduced which will have the same interface as the current ObsBoxBuffer class but instead of relying on the ObsBox FESA class for the circular buffer it will simply read the buffer from the driver when an acquisition is triggered.

Infrastructure and reliability

COSMOS integration The ADTObsBox is becoming an essential tool for the LHC operations and it is expected to have 100% availability. To achieve this, the system will be integrated with COSMOS(Control Open Source MOnitoring System) [13] to monitor the status of the system and alert the responsible if a fault is detected. There must also be proper follow up of the faults in the future so they can be mitigated.

New data links to the storage server in CCR A dedicated NFS server for the ADTObsBox data was introduced in late 2017 to store injection, post-mortem and instability buffers. Later, it started to be used also for storing data during MDs, where it was discovered that the limited bandwidth of the technical network was a bottleneck and some of the MD data were lost. This will be solved by introducing a dedicated 10 Gbps link between the servers in SR4 and the NFS server in CCR. The fibers are already installed and the only things that are needed is a switch in SR4 and a media convert in the CCR.

Planned features

Introduction of a secondary longer buffer To collect relevant events the system has relied on the instability detection system and the post-mortem event. This means that the system sometimes misses interesting events. The proposed solution to this is to introduce a longer circular buffer which would be based on fast, cheap and reliable hard-drives. One server from Gigabyte that meets the requirements could also hold 12 3.5 inch drives and each drive could store 12 TB which would result in a 31 h uncompressed buffer of both beams, both planes, and all bunches. Streaming compression could be added which would allow for at least 45 h of data which would be enough time for the users to notice the event and download the data from the buffer for further analysis.

Passive bunch by bunch tune measurement There has been a discussion about measuring the bunch by bunch tune passively for a while and the introduction of the new ADTObsBox and the lower noise floor beam position modules with all the 16 pickups being operational makes for perfect opportunity to implement this. The application would collect the data from 4 pickups with a window that must be determined but around 1 s worth of data must be collected to get a resolution of 10^{-3}. The algorithm that extracts the tune must be decided but most likely it will be an FFT or the Kotzian algorithm [6]. This analysis is quite computational heavy, so it would be an ideal project to offload to a GPU-coprocessor.

Framework for online analysis A new framework to allow users to run their own online analysis on the ADTObsBox servers has been tested during 2018 and it has shown great promise. This framework was however developed with a user-space buffer in mind and by changing to kernel-space buffer, this framework is now unnecessary since the clients can interface with the driver directly and access the raw datastreams. However, most users for this are in the ABP group and they mostly use Python so a highly efficient Python interface should be developed. A Python interface to the underlying C++ library was developed which used boost::python and it had troubles receiving data at a rate of 11245 Hz. This could be solved by averaging the data and lowering the data rate or by possible using Cython which seems more efficient.

RE-COMMISSIONING STRATEGY AFTER LS2

During LS2, the ADT will again undergo a major upgrade, update, improvement and consolidation campaign. At restart, the new, never before operated beam position modules will be used, a new high level controls will be in place, new applications and user interfaces will run in the CCC and the control functions will be generated in a different way than before. Without exaggeration, the ADT will be considered "as new" after LS2. A much longer longer commissioning time, than after a regular YETS will be needed to find new settings, fully validate all new functionality, and hand it over to the operations group.

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