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Time accuracy requirements for fusion experiments: A case study at ASDEX Upgrade

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ABSTRACT

To manage and operate a fusion device and measure meaningful data an accurate and stable time is needed. As a benchmark, we suggest to consider time accuracy as sufficient if it is better than typical data errors or process timescales. This allows to distinguish application domains and chose appropriate time distribution methods. For ASDEX Upgrade a standard NTP method provides Unix time for project and operation management tasks, and a dedicated time system generates and distributes a precise experiment time for physics applications. Applying the benchmark to ASDEX Upgrade shows that physics measurements tagged with experiment time meet the requirements, while correlation of NTP tagged operation data with physics data tagged with experiment time remains problematic. Closer coupling of the two initially free running time systems with daily re-sets was an efficient and satisfactory improvement. For ultimate accuracy and seamless integration, however, continuous adjustment of the experiment time clock frequency to NTP is needed, within frequency variation limits given by the benchmark.

1. Introduction

Fusion experiments are long lasting projects, where design, construction, commissioning, operation, and decommissioning span several decades. During that time people and systems produce an immense number of data, as documents, calculations, system descriptions, operation schedules, operator interventions, measured samples, publications. All these pieces of data are managed over time, i.e. generated, accessed, modified, applied. Vice versa, time is the key to bring all data back into the right sequence, to understand what happened when, in observed physics, technical operation or project management. Although in this paper we will focus onto plasma operation as the most integrated and thus demanding period of the project, the statements hold for the entire project lifetime. In Section 2 we outline which systems and applications need time, in Section 3 we define a benchmark for a good enough time and explain needed time characteristics. In Section 4 we will show what has and will been done to further improve the ASDEX Upgrade (AUG) time system to better match those requirements.

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2. The role of time

Time is significant for many applications and systems:

To manage the project, researchers and engineers define project goals, campaign plans, experiment schedules, they design plant components, or provide system descriptions and prepare publications. These documents or database entries are generated at some time, and eventually modified, and all of these need a time-tag provided by the computer systems when generated or modified.

To operate the plant, there is a supervision level with authorization rules where operators and experimentalists perform interventions, configure systems, chose experiment schedules, access data. Time is needed to know and trace back staff access, applied rules, operation methods and system activities.

Experiment schedules govern the plant systems for plasma control, diagnostics and technical systems. Time and data driven, these systems run control and monitor cycles, sample or output data at specific times or rates, and schedule processes. Knowledge of time is needed to know when actions are to be executed, to time-tag sampled and processed data from plant and physics, to compute time-dependent process data (e.g. time integrals and derivates, duty cycles and protection windows), and manage distributed real-time tasks (process scheduling, process termination, time-out detection; time-tagging of real-time data on the synchronous data bus to detect outdated data, check data traffic and message propagation). Plant systems send I/O and process data as data values plus time-tags to the archive.

All data generated with project management, plant operation and physics measurement are streamed into the central archive. Time information is needed to manage the distributed archive, perform correct version handling, migration of data, and to authorize and document data access.

3. The time needed

How accurate must time be to serve the various applications and systems, and which further requirements do we have to manage time?

As a benchmark we consider a time good enough if we do not have to think about accuracy of time for a specific application, i.e. the time error can be neglected against the data error or typical process timescales (in this paper the term "accuracy" is used for the allowed difference of time between two applications on-site, and not as tolerable difference of time between on-site applications and UTC time). To better understand specific requirements we look into applications and systems needing time (Fig. 1):

Data from project management, engineering design or experiment schedule preparation are results of human thinking and discussion, and as such slow. A second is good enough to know when documents or data were generated or modified.

People involved expect time to be represented as time of day of the local time zone.

The supervision level manages plant system availability and choice of schedules compatible with these, visualizes that information to operators and handles their interventions. The SCADA systems involved run cycles around 1 Hz. A time accuracy of 1 s...100 ms appears then sufficient.

Local operators and (usually local) experimentalists expect time to be represented in time of day.

Plant and plasma control and diagnostics execute experiment schedules. These specify how those systems operate, i.e. when plant systems are switched, when IO, control and monitor cycles are executed, etc. Cycles are equidistant (at variable rate), to satisfy real-time needs and optimize response, matching the controlled processes timescale and the employed actuators' response times. As data errors of typical control tasks are in the order of 10^{-2}, the time accuracy should be better than 10^{-2} of the cycle time:

Plant control is based on industrial PLC technology with control cycles around 10 Hz. Time accuracy then should be around 1 ms. Operators expect time of day representation.

Plasma control operates with up to kHz cycles, needed for stable vertical position control and for precise switching of heating sources at AUG. With ms cycles, time accuracy should be below 10 μs. AUG experimentalists expect time of physics control to be presented in experiment time, as seconds relative to ignition (AUG operates short pulses, where "ignition" is a good reference event; for long pulses with sub-experiments such as for W7-X stellarator [1] this might be extended by further significant physics events). In rare cases to understand complex interdependencies between plant operation and physics, translation between the plant operation's time of day and physics experiment time is needed.

Diagnostics measure sensor data in sample trains with given frequency, either when an event or a time specified in the experiment schedule has come. The sampling frequency matches the observed physics phenomena and the sensors' response times. Sampling frequency ranges from kHz (gas kinetics, tile temperatures) to MHz (magnetics, SXR mode activities,...), in some cases to GHz (e.g. Thomsen scattering,..., which can be neglected, as burst sampling only serves to compute a useful physics meaning with much slower rate). Thus for MHz diagnostics time accuracy should be better than 100 ns, an order of magnitude better than the sampling period, to unambiguously compare physics data from various diagnostics. Furthermore, to avoid errors from wrong sampling frequency, the frequency error should be smaller than the measurement error (which is in the order of 10^{-4} to 10^{-5} for 16 bit sampling). Experimentalists and diagnosticians expect ignition centric experiment time.

The time accuracy needed to manage distributed archives, authentication or access is moderate, around a second accuracy. Software engineers expect local time of day representation.

From discussion of these applications we conclude that in the domain of project and plant management a moderate accuracy of around 1 s is sufficient, for plant operation accuracy should be around 1 ms, and for the domain of physics a high accuracy below 100 ns is needed plus a sampling clock more stable than 10^{-4} to 10^{-5}.

Besides accuracy there are further requirements on handling and management of time:

- The time unit shall be SI second, and time representation shall follow standards (ISO 8061 as [yy-mm-dd zone hh:mm:ss], or short forms), with an exception for physics data, for which as option time should be in seconds relative to a significant physics event (ignition,...).
- Time information shall be provided throughout and span the entire project lifetime, support steady state operation, be real-time accessible, and allow efficient (real-time) processing.
- A minimum number of methods shall be used to define and distribute time information, based on standard solutions; to support technical evolution, time systems shall have an identifier.

4. Improving the time systems of ASDEX Upgrade

By time of decision for ASDEX Upgrade no general criterion for good enough time was available. Particular care was taken to be able to drive data acquisition with MHz samples, and support real-time and steady state applications. This led to the development of a dedicated high performance experiment time system for plasma diagnostics and control. For all other applications the network based NTP time service was a convenient choice (Fig. 1).

NTP [2] provides UTC time, which translates into INT64 Unix time where upper INT32 are seconds since 1970-01-01 UTC 00:00:00 and lower INT32 the second's fraction. UTC and UNIX time are discontinuous because of leap seconds: UTC can have 59 or 61 s during leap minutes, while Unix repeats or skips that second. (During years of AUG operation no problems with leap second adjustment were reported. This may be due to synchronization around midnight, out of AUG operation. However, if NTP should be used for continuous process control and physics measurement, leap seconds must be taken into account.)

Initially, users were free to connect to arbitrary NTP servers (dashed in Fig. 1). This led to time differences between users in the order of seconds, and in some cases even dramatically larger, when badly connected time servers or wrong settings were chosen because of poor knowledge.

Aiming at Section 3's 1 s requirement for project and plant management we now recommend to connect all applications to a dedicated on-site stratum_2 NTP server. This in turn connects to the ptbtime3.ptb.de stratum_1 server plugged to the next available atomic watch (which counts TAI) [3,4]. Typical accuracy is about 10 μs at stratum_1, reduced by WAN communication to around 10 ms at stratum_2. This allows to achieve 1 s accuracy on application layer within the UNIX domain (AUG computing and archive servers and most user and diagnostics workstations operate under Solaris, where as UNIX feature a clock PLL or FLL is implemented

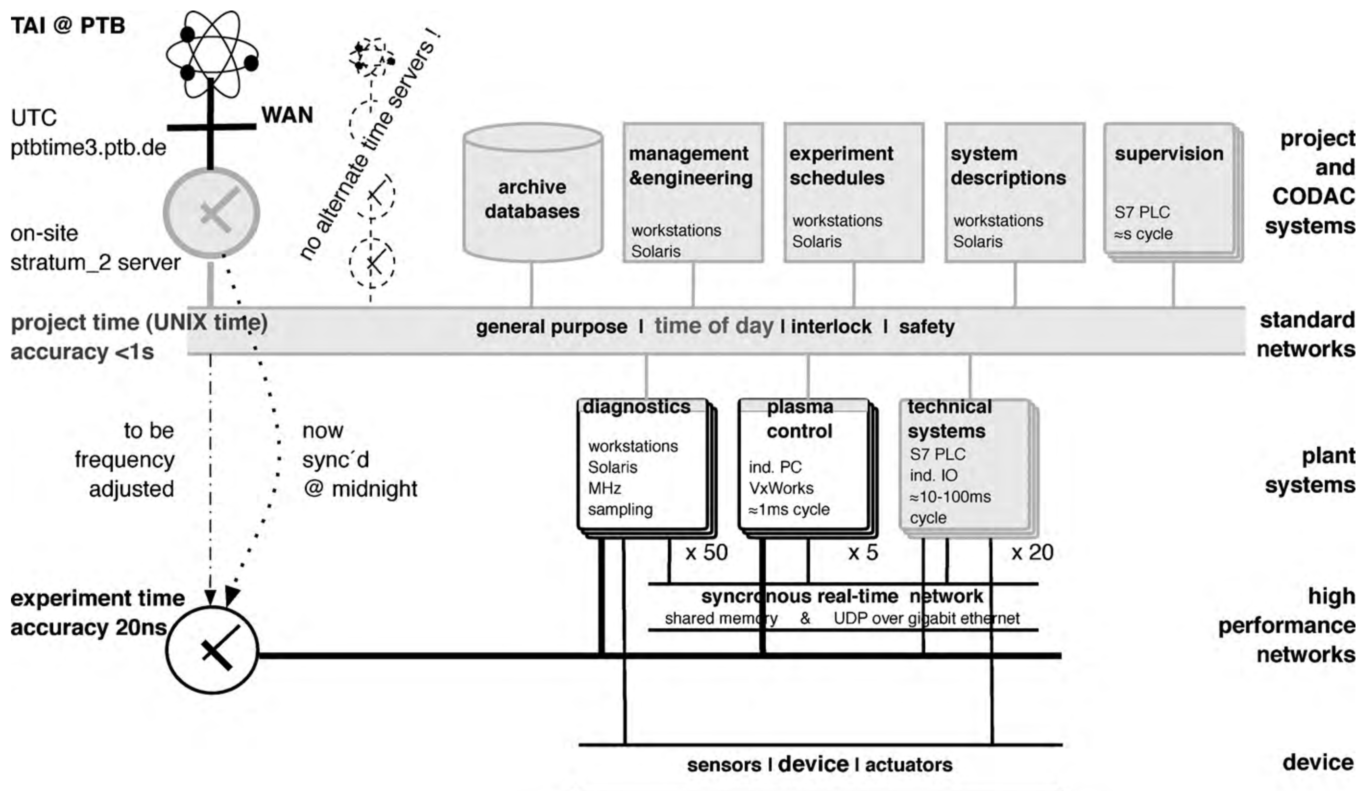

Fig. 1. ASDEX Upgrade systems connected to NTP time (grey) or experiment time (black); dashed are elements eliminated, dotted those added, dash-dotted those to be added.

in kernel space for high time accuracy and clock stability. Standard Windows systems are less accurate, but few such installations exist at AUG, for stand-alone functions. Technical plant systems use S7 PLC with WinCC).

To provide a highly resolved experiment time for the physics domain we use the in-house developed time system [5]: a central time and frequency generator (CTC Central Time Counter) distributes a 20 ns base clock and a phase locked INT64 [ns] experiment time counter via a fiber optics tree network to local receiver boards (UTDC Universal Time-to-Digital Convertor) connected to plant and CODAC systems.

UTDC receiver boards (PCI, cPCI, or embedded FPGA for IO boards [6]) implement time-related services for control and measurement, to read-out the actual experiment time, to generate interrupts at predefined times or schedule real-time processes, to apply programmed trigger sequences to ADCs and IO, and to measure occurrence of time (works like ADC, but measures time values rather than analogue values).

Experiment time computation is trivial, as multiplication of the INT64 [ns] timestamp by 10^{-9} s/ns immediately gives the unique experiment time in [s]. Data sampled or computed by real-time plasma control and diagnostics applications consist of data value plus time value as basic entity [7]. These are streamed into the archive.

AUG uses a discharge oriented shot file to store physics data, with ignition time as time zero. Conversion from absolute experiment time into ignition centric time is automatically done within standard access routines as a simple linear scaling, with the INT64 timestamp of ignition used as offset value, and the value 10^{-9} s/ns as multiplier. (This would also work for continuous operation, where a unique shot independent INT64 timestamp would indicate the defined time zero.)

Operation experience within the experiment time system is excellent. Frequency precision of the CTC quartz is better than 10^{-5} which is sufficient for sampling up to 18 bit, according to the clock stability requirement given in Section 3. The phase locked clock distribution avoids dynamic delays. Static delays in the optical tree distribution from different path lengths (between 20 and 200 m, equivalent to 60–600 ns latency) and cascade depths (1 or 2 fan-out-modules, equivalent to 50 or 100 ns latency) can be path length compensated for each UTDC receiver in 20 ns steps, to stay below Section 3's time accuracy limit of 100 ns. As a result comparing AUG physics data can be done unambiguously even at highest sampling rates.

To compare data sampled with experiment time (e.g. plasma behavior) against those sampled with UTC time (e.g. operator intervention) the conversion between these times is needed. In case the two systems are free running, a (time varying) conversion offset and multiplier must be provided from a continuous measurement of UNIX time vs. experiment time. Or time systems must be coupled to lock within given tolerances, and a fixed conversion can be used.

To avoid that effort we initially decided just to use the same time zero for both systems, i.e. 1970-01-01 00:00:00. However, over time the experiment time drifts against UTC, as a result of the intrinsic statistical deviation of any clocks and CTC's moderate quartz precision of 10^{-5}. The effect is in the order of $86400\,[\mathrm{s/day}] \times 10^{-5} = 0.684\,[\mathrm{s/day}]$, which accumulates to minutes over experiment campaigns. This is far beyond Section 3's 1 s accuracy requirement for plant management, and can even obstruct understanding the failure origin and propagation of complex malfunctions.

To improve the situation to a tolerable level of <1 s we now reset the INT64 experiment time each midnight to CTC equivalent UNIX time (dotted in Fig. 1), at the expense of an eventual discontinuity of experiment time at midnight (this, however, can be tolerated as AUG is short pulse operated without overnight measurement).

For the future, the ideal solution would be to replace the experiment time's free running CTC quartz by a frequency tunable quartz, to continuously readjust experiment time to NTP (dash-dotted in Fig. 1). From Section 3 the upper limit for the permitted clock frequency variation is 10^{-5} (when using up to 18 bit sampling).

5. Summary

For management and operation of a fusion device, various applications need time information. As a benchmark we suggest that a time may be regarded as good enough if we do not have to think about accuracy of time for a specific application, i.e. the time error can be neglected against the data error or typical process timescales. This allows discriminating typical application domains. For human dominated activities such as management or engineering tasks a 1 s time accuracy seems sufficient. For plant supervision and plant operation going down to 1 ms accuracy is needed, while physics control and diagnostics applications require accuracy better than 100 ns, plus sampling clock more stable than 10^{-5}. Further requirements are to present time as time of day or ignition centric, to support real-time functions and steady state and operation over project lifetime, and to use standard solutions and methods, and allow for technical evolution.

The AUG time system combines a standard NTP method providing UNIX time for AUG project and operation management tasks, and a dedicated precise time system establishing a continuous INT64 experiment time with a phase locked 20 ns base clock for all physics applications.

In the physics domain the time accuracy requirements are fully matched by the experiment time system. However, without narrow coupling between experiment time and UNIX time drifts can accumulate beyond limits. Presently, re-setting experiment time daily to UNIX time keeps deviations within margins at cost of discontinuities. In a future, continuous re-adjustment of experiment time to UNIX time via a frequency tunable quartz would permit to achieve all time accuracy requirements if the frequency variation is smaller than 10^{-5}.

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