

uTCA White Rabbit Timing and Trigger System for Distributed Deterministic Control

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Agenda

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What is a timing system?

02

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03

|
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04

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01 What is a timing system?

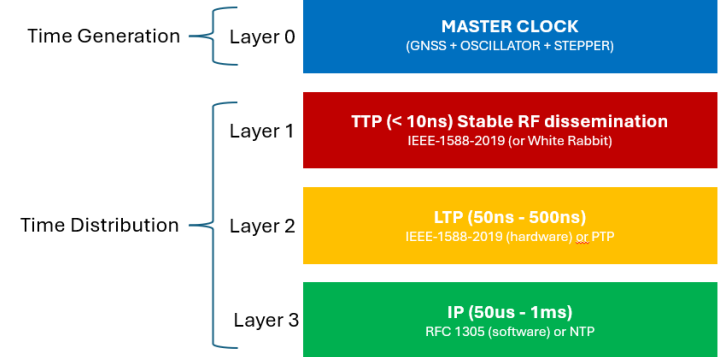
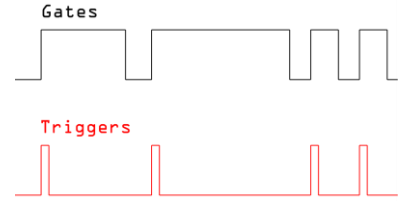
- **Applications: every installation requires timing and synchronization**

- Crucial component used to synchronize and control the operations and events that occur during experiments or beam delivery in a particle accelerator
- Main functions are:
 - **Timing/Synchronization:** ensuring that all the components operate at the correct time relative to each other.
 - **Trigger and gate generation:** generation of deterministic signals to initiate and coordinate subsystem actions, including precise pulses that define the timing of operations such as particle bunch generation.
 - **Deterministic Distribution:** Timing and trigger signals need to be distributed throughout the accelerator facility with minimal delay and jitter (this is especially critical in lasers).
 - **Control and supervision:** configuration and monitoring through the control system.
- Other possible functions:
 - **RF distribution:** allows the reconstruction of the RF signal in the end-nodes (synchrotrons)
 - **Interlocks distribution:** enables the stop of the complete installation in case of failure.

01 Why White Rabbit for facility timing?

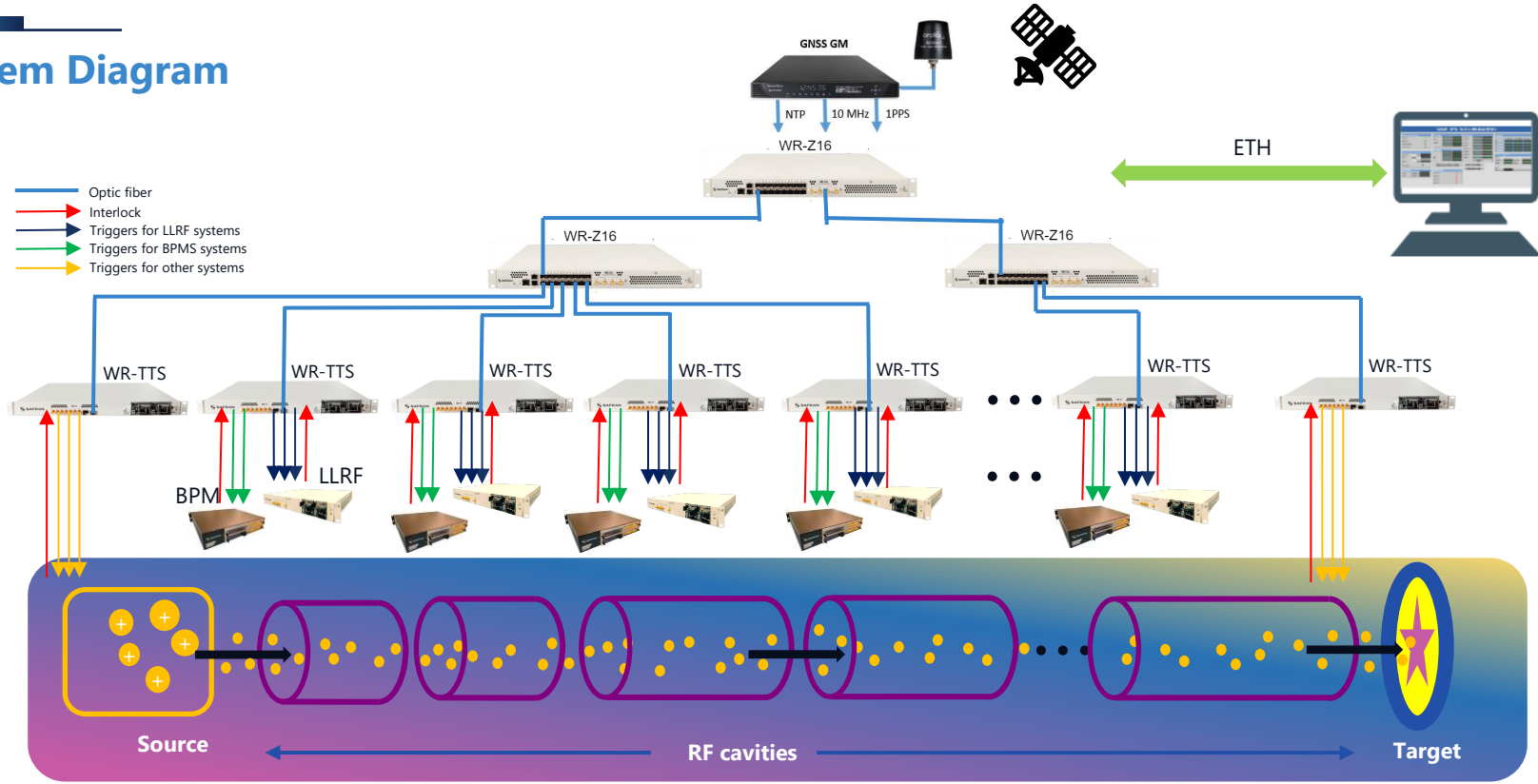
■ Main Advantages

- **Sub-nanosecond synchronization:** provides a common and highly accurate time base across distributed nodes.
- **Deterministic timing over fiber:** enables precise trigger distribution and coherent operation of time-critical subsystems.
- **Scalable and low-maintenance infrastructure:** new nodes can be added easily thanks to plug-and-play optical links and automatic link calibration.
- **Unified timing base:** the same infrastructure supports synchronization, timestamping, and trigger generation for systems such as LLRF, BPM, MPS and diagnostics.



01 Why White Rabbit for facility timing?

System Diagram



02 Safran Solution

WR-TTS: Platform

FIRST VERSION based on

HATI IP
CORE



White Rabbit
Commercial Products

WR-Z16



WR-ZEN TP-32BNC



WR-ZEN TP-FL



WR-SWITCH-LJ



WR-WROX

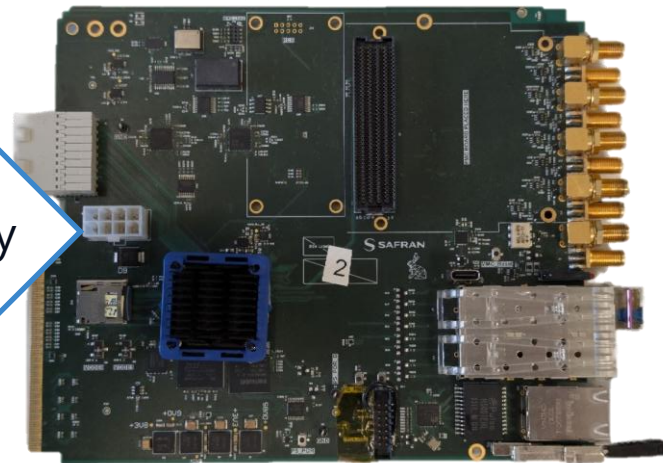


WR-LEN



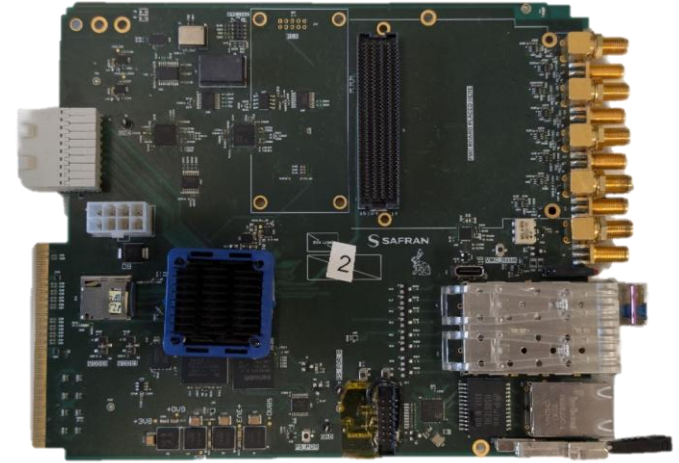
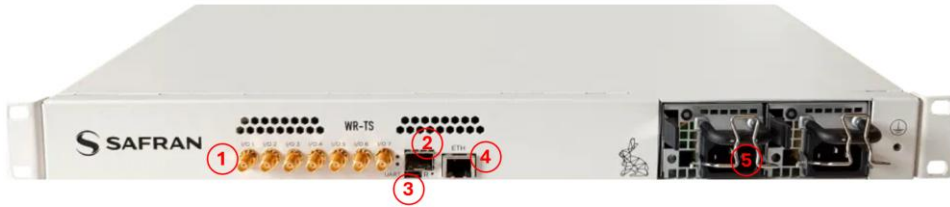
WR circuitry

White Rabbit Timing &
Triggering system



02 Safran Solution

WR-TTS: Platform



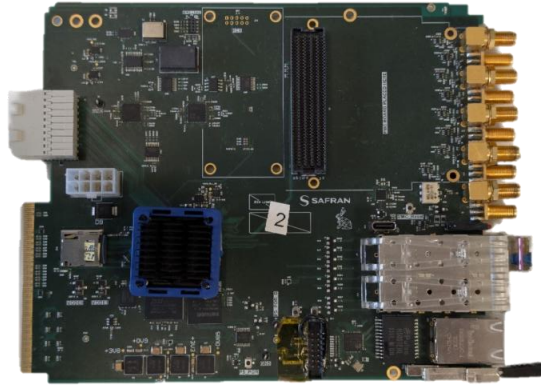
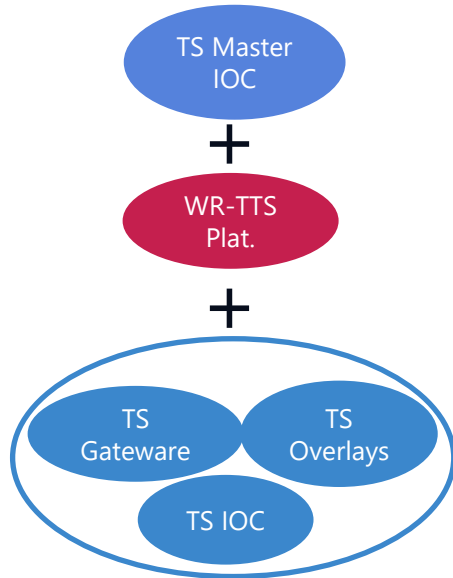
Platform:

- Ultrascale + SoC FPGA-based architecture enabling deterministic real-time processing
- White Rabbit technology
 - Sub-nanosecond time accuracy
 - Very high scalability and large distance links support
 - Nanosecond timestamping
 - **10MHz and PPS outputs**
 - **Master/Slave Mode**
- uTCA form factor.
- Up to 9 configurable in/out ports
- 2 x SFP ports (WR and fast communications)
- 1 x ETH port (control, monitoring and management)
- 1 x USB port (management)
- Event Generation and Detection (nanosecond resolution)
- **FMC and RTM expansion connector for custom I/O and subsystem interfacing**
- EPICS/TANGO Controls integrated

02 Safran Solution

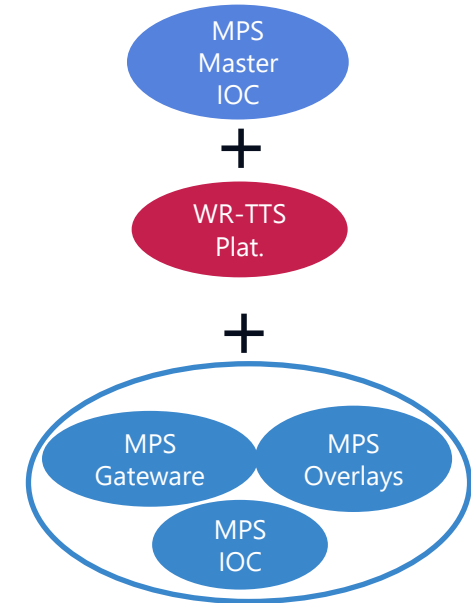
WR-TTS: Same Platform, Different purposes

Timing & Triggering System



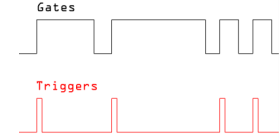
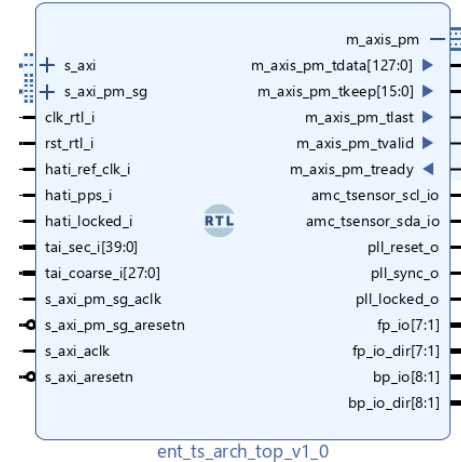
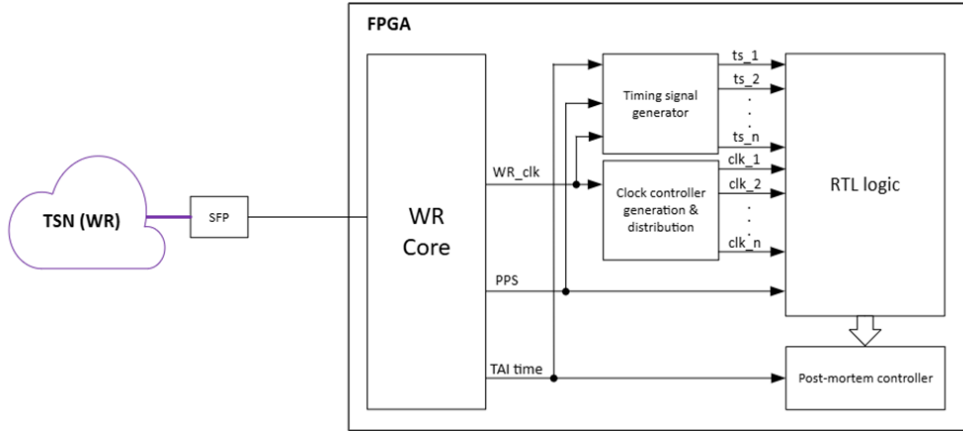
Hybrid Approach??

Machine Protection System



02 Safran Solution

WR-TTS: Timing + Triggering

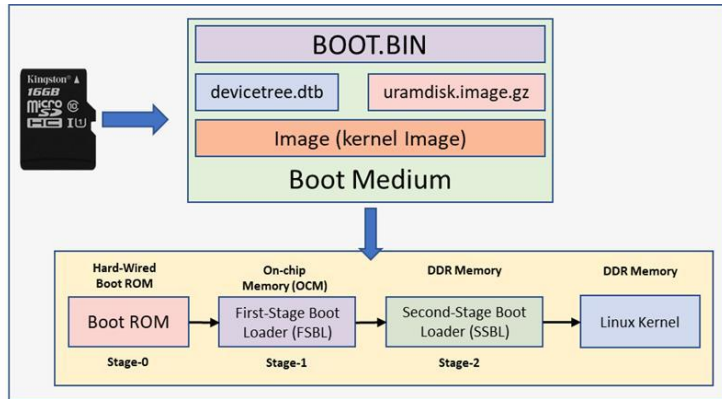


- Sub-nanosecond time accuracy
- Picosecond level precision
- Distance range: over 80 km using fiber
- DWDM compatible
- Dynamic compensation of asymmetries caused by weather conditions

- Programmable single shot or sequence triggers
- Resolution of 4ns.
- Programmable rate, delay and duty cycle.

02 Safran Solution

WR-TTS: Embedded Software

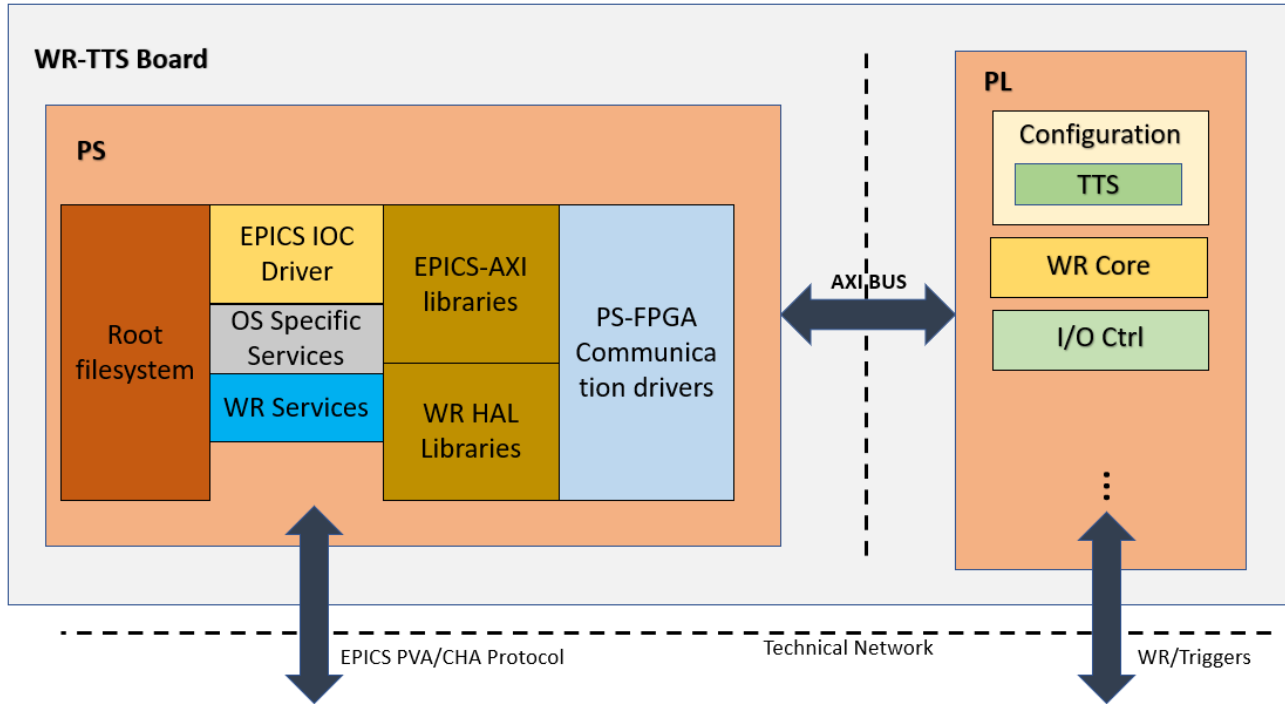


Buildroot-based OS – WR-ZYNQ-OS

- BOOT.bin: FPGA image
- Uboot: instructions to boot the devices
- Devicetree: mapping of devices of the system/hw platform.
- Image: Custom Linux kernel image
- Root filesystem:
 - Linux services for configuring all the components on the platform (PLL, DMA, ADC, I2C devices...)
- Builds a CC Toolchain for:
 - SoC Communication Drivers (AXI)
 - Specific configuration tools (PLL, ADC, DAC, Sensors...)
 - **EPICS base and EPICS components (asyn, seq, autosave..)**
 - **EPICS IOC**

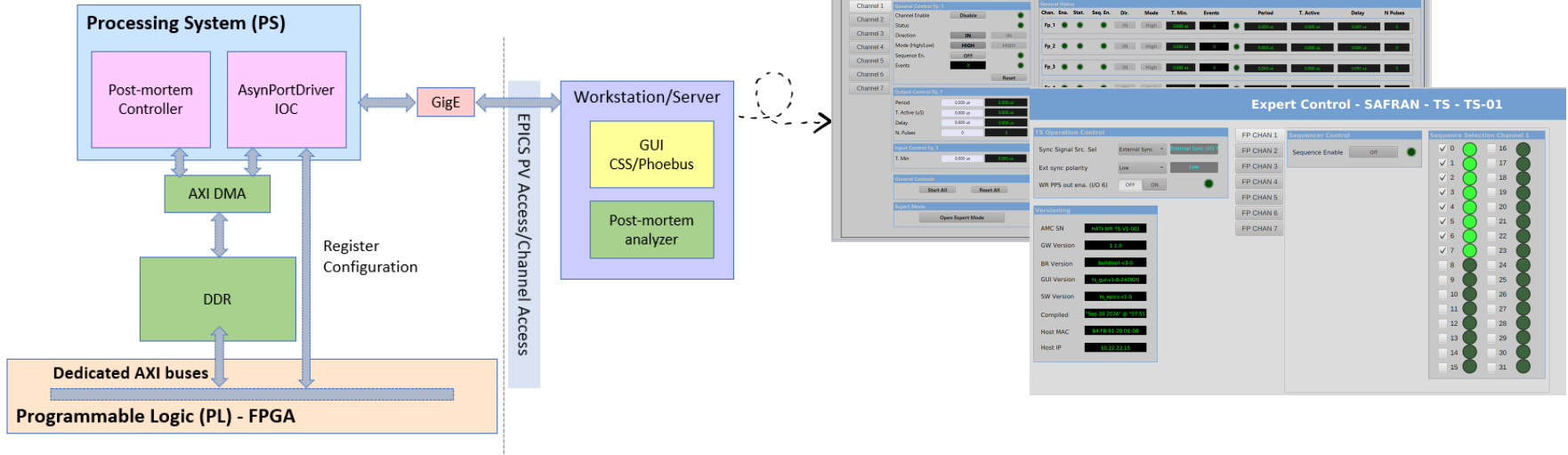
02 Safran Solution

WR-TTS: Embedded Software



02 Safran Solution

WR-TTS: Embedded Software



02 Safran Solution

WR-TTS: Embedded Software

EPICS IOC

- **EPICS 7**
- **Asyn** 4.44-based driver using AXI bus for FPGA-Processor communications
- WBGen to define FPGA addressing and EPICS Asyn connectors
- AXI Register MAP matched with EPICS DB (through asyn)
- Specific functionalities integrated on the EPICS driver (Postmortem, Device components control...)

```
lastreg = new EWBReg( pPrhGen, WB2_REG_ARGS( GEN, PL_FREQ ));
createParam( new EWBFfield( lastreg, WB2_FIELD_ARGS( GEN, PL_FREQ, VAL )));
```



```
##### 'ext_pll_sync' in 'timing_system status & control registers'

record(bo, "$(user):ExtPllSyncCmd")
{
    field(DTYP, "asynInt32")
    field(OUT, "@asyn$(PORT),$(ADDR),$(TIMEOUT))ctl_ext_pll_sync")
    field(DESC, "ext_pll_sync")
}

record(bi, "$(user):ExtPllSyncStat")
{
    field(DTYP, "asynInt32")
    field(INP, "@asyn$(PORT),$(ADDR),$(TIMEOUT))ctl_ext_pll_sync")
    field(SCAN, "I/O Intr")
    field(DESC, "ext_pll_sync")
}

##### PL_Freq

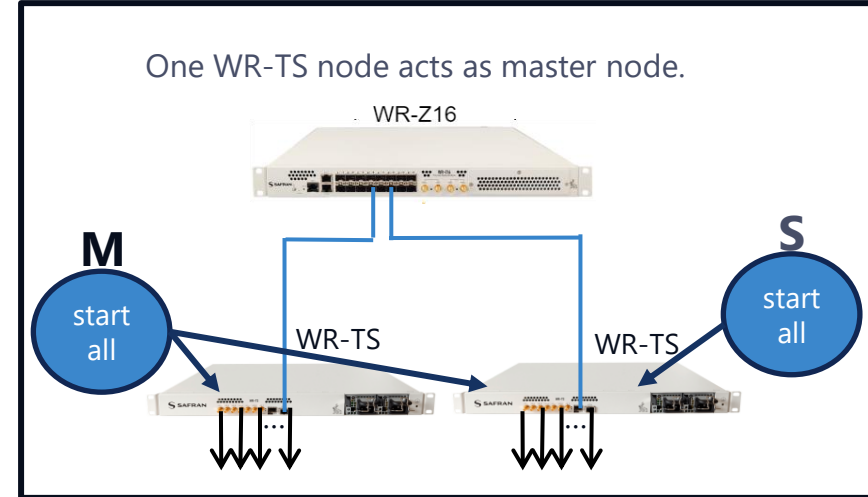
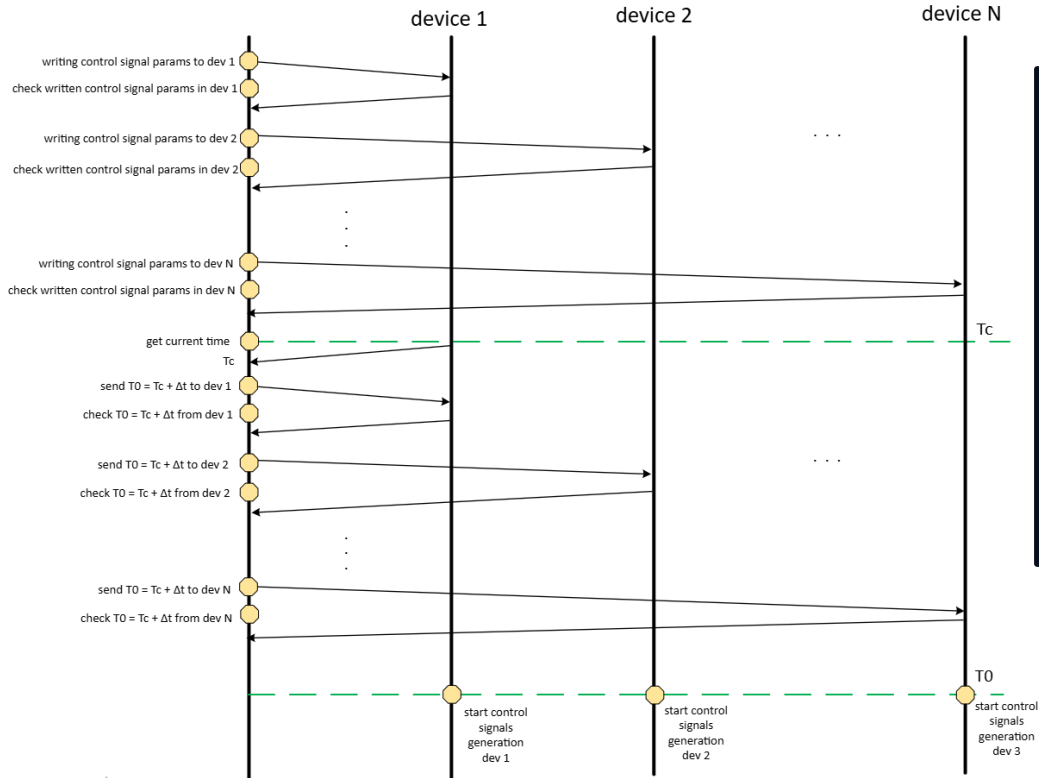
##### 'val' in 'PL_Freq'

record(ao, "$(user):PLFreqValSet")
{
    field(DTYP, "asynInt32")
    field(OUT, "@asyn$(PORT),$(ADDR),$(TIMEOUT))PL_Freq_val")
    field(DESC, "val")
}

record(ai, "$(user):PLFreqValRb")
{
    field(DTYP, "asynInt32")
    field(INP, "@asyn$(PORT),$(ADDR),$(TIMEOUT))PL_Freq_val")
    field(SCAN, "I/O Intr")
    field(DESC, "val")
}
```

02 Safran Solution

WR-TTS: Master-Slave



02 Safran Solution

WR-TS: Graphic User Interface

SAFRAN - Timing System

The screenshot displays the SAFRAN Timing System interface. On the left, there are controls for seven channels (Channel 1 to Channel 7). Channel 1 is selected, showing 'General Control Fp. 1' with options for Channel Enable (Disable), Status (green), Direction (IN), Mode (High/Low) (HIGH), Sequence En. (OFF), and Events (0). Below this are 'Output Control Fp. 1' and 'Input Control Fp. 1' sections with numerical input fields for Period, T. Active, Delay, and N. Pulses. At the bottom left are 'General Controls' (Start All, Reset All) and 'Expert Mode' (Open Expert Mode).

The main area shows a 'General Status' table with the following data:

Chan.	Ena.	Stat.	Seq. En.	Dir.	Mode	T. Min.	Events	Period	T. Active	Delay	N Pulses
Fp.1	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.2	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.3	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.4	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.5	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.6	●	●	●	IN	High	0.000 us	0	0.000 us	0.000 us	0.000 us	0
Fp.7	●	●	●	IN	High	0.000 us	1937	0.000 us	0.000 us	0.000 us	0

At the bottom of the status table, there are indicators for Sync Signal status (green), WR Sync status (green), PLL1 locked (green), and Temperature (41.612 °C).

Input configuration:

- **T.Min:** Minimum time to consider a pulse valid.

Output configuration:

- **Period:** Time between pulses.
- **T. Active:** Time that the signal will be High/Low.
- **Delay:** Time between the starting trigger and the generation of the pulse
- **N. Pulses:** Number of pulses to generate (∞ if 0).

02 Safran Solution

WR-TTS: Sequences of events

- Sequences of events can be defined in .csv files.
- The system loads these sequences in a double buffer in the WR-TS nodes. The WR-TS node executes one sequence of events during the current frame while receiving the sequence data for the following frame.
- /home/epics-user/data/sequencer/

	A	B	C	D
1	period	width	delay	n_pulses
2	20000	10	0	1
3	20000	10	0	1
4	20000	10	0	1
5	20000	10	0	1
6	20000	10	0	1
7	20000	10	0	1
8	20000	10	0	1
9	20000	10	0	1
10	20000	10	0	1
11	20000	10	0	1
12	20000	10	0	1



02 Safran Solution

WR-TS: Graphic User Interface

Expert Control - SAFRAN - TS - TS-01

TS Operation Control

Sync Signal Src. Sel: External Sync (I/O 7)

Ext sync polarity: Low

WR PPS out ena. (I/O 6): OFF ON

Sequencer Control

Sequence Enable: Off

FP CHAN 1
FP CHAN 2
FP CHAN 3
FP CHAN 4
FP CHAN 5
FP CHAN 6
FP CHAN 7

Sequence Selection Channel 1

<input checked="" type="checkbox"/>	0	●	<input type="checkbox"/>	16	●
<input checked="" type="checkbox"/>	1	●	<input type="checkbox"/>	17	●
<input checked="" type="checkbox"/>	2	●	<input type="checkbox"/>	18	●
<input checked="" type="checkbox"/>	3	●	<input type="checkbox"/>	19	●
<input checked="" type="checkbox"/>	4	●	<input type="checkbox"/>	20	●
<input checked="" type="checkbox"/>	5	●	<input type="checkbox"/>	21	●
<input checked="" type="checkbox"/>	6	●	<input type="checkbox"/>	22	●
<input checked="" type="checkbox"/>	7	●	<input type="checkbox"/>	23	●
<input type="checkbox"/>	8	●	<input type="checkbox"/>	24	●
<input type="checkbox"/>	9	●	<input type="checkbox"/>	25	●
<input type="checkbox"/>	10	●	<input type="checkbox"/>	26	●
<input type="checkbox"/>	11	●	<input type="checkbox"/>	27	●
<input type="checkbox"/>	12	●	<input type="checkbox"/>	28	●
<input type="checkbox"/>	13	●	<input type="checkbox"/>	29	●
<input type="checkbox"/>	14	●	<input type="checkbox"/>	30	●
<input type="checkbox"/>	15	●	<input type="checkbox"/>	31	●

Versioning

AMC SN: HATI-WR-TS-V1-001

GW Version: 1.1.0

BR Version: buildroot-v3-0

GUI Version: ts_gui-v1-0-240920

SW Version: ts_epics-v1-0

Compiled: "Sep 20 2024" @ "07:51"

Host MAC: 64-FB-81-20-D1-00

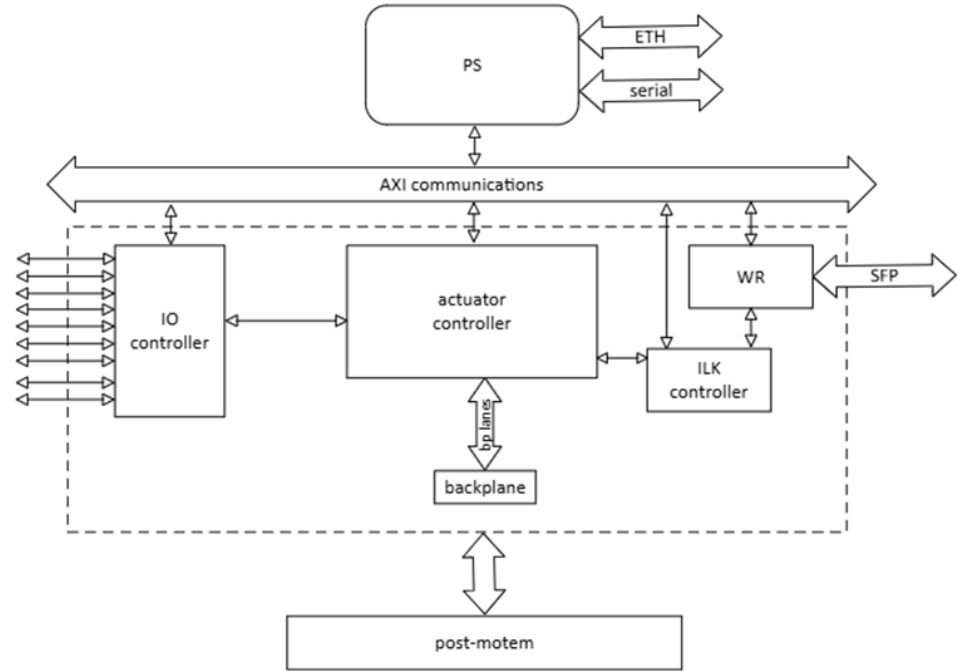
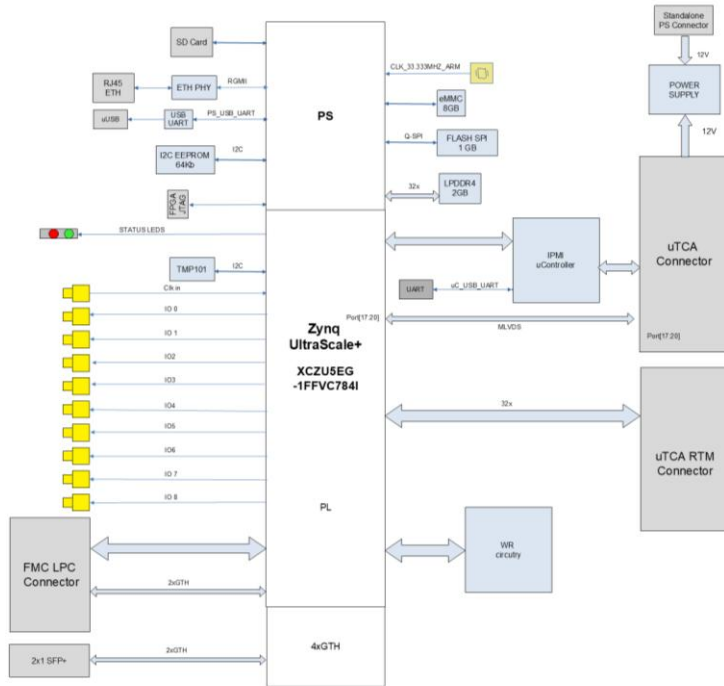
Host IP: 10.22.22.15

Sequences of events mode

- Up to 32 selectable sequences of events.
- Internal PPS or external synchronization signal.

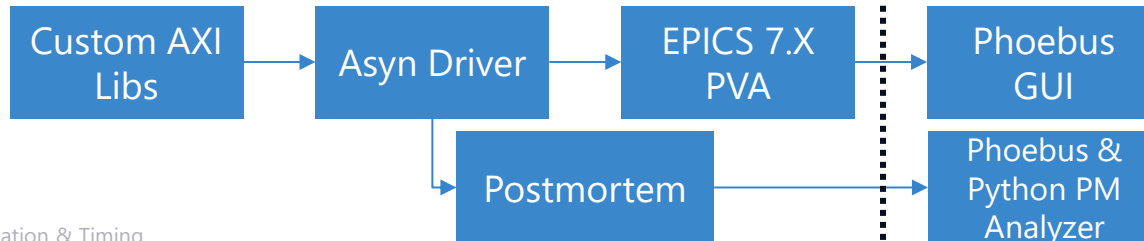
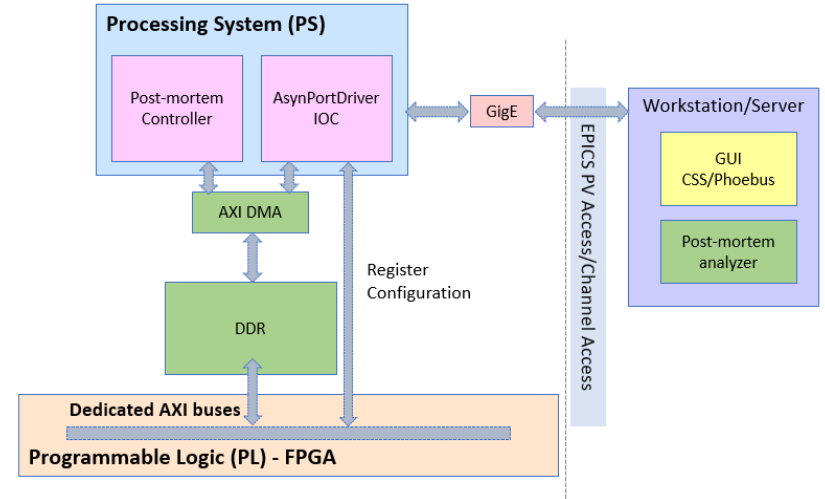
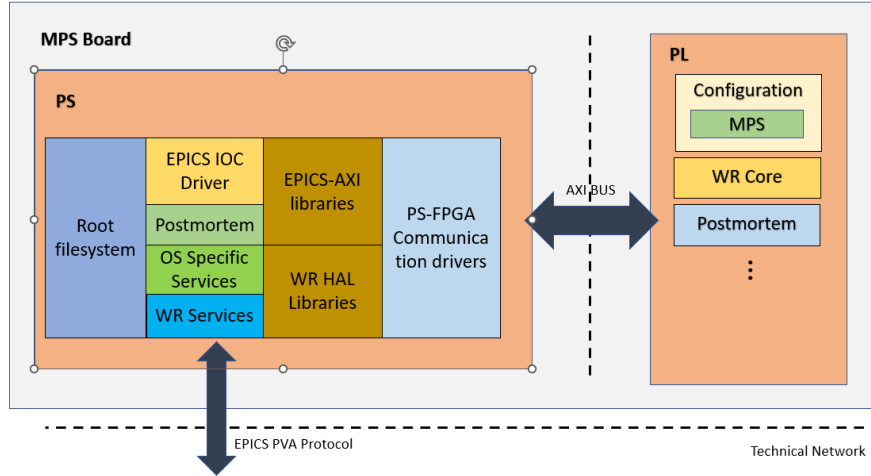
03 Safran Solution

WR-TTS: Machine protection System



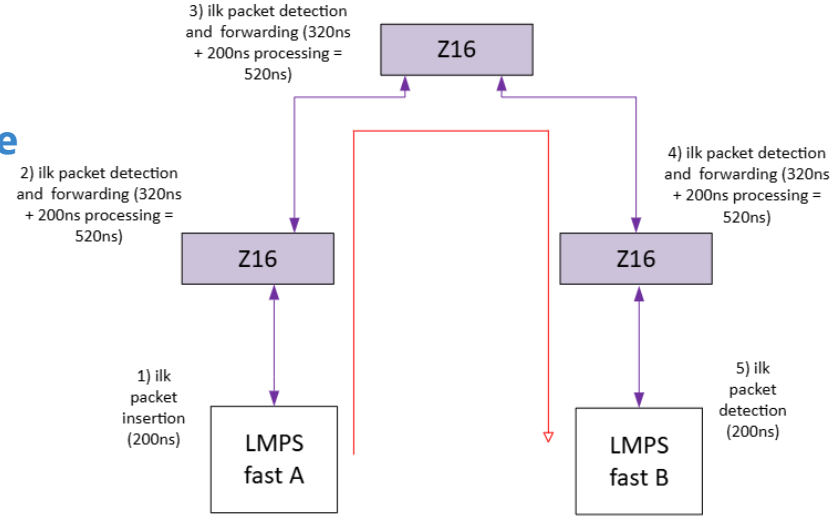
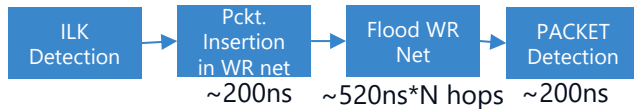
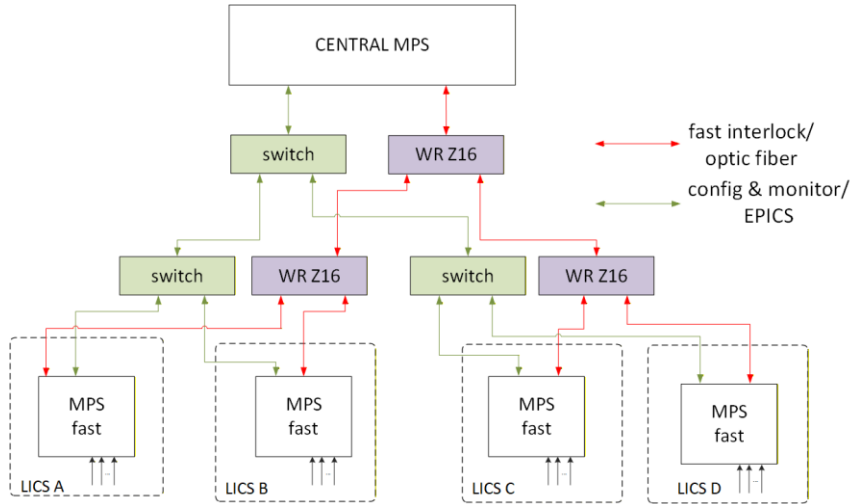
03 Safran Solution

WR-TTS: Embedded Software



03 Safran Solution

WR-TTS: Machine protection System; performance



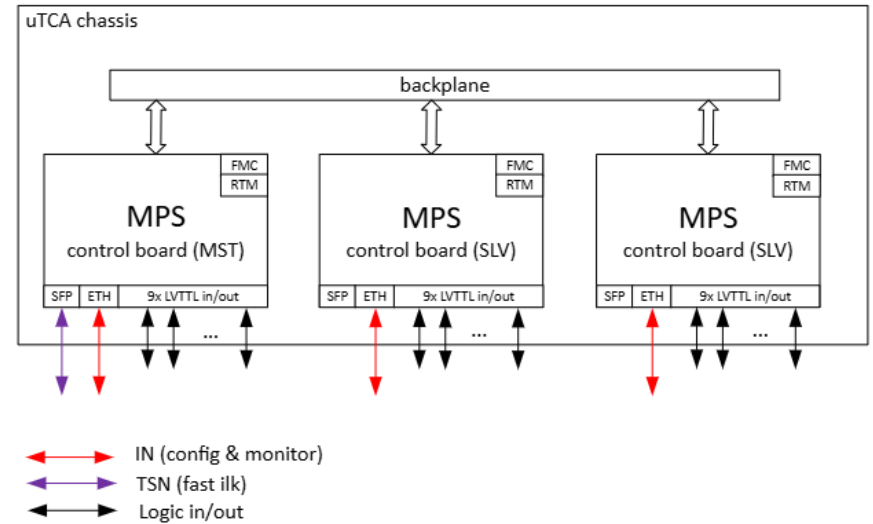
- **Ultra-fast response:** Optical fibers enable near-light-speed signal transmission with nanosecond reaction times (~500ns per hop) (**commas insertion on WR flow**)
- **EMI immunity and galvanic isolation:** Fiber optics are unaffected by electromagnetic interference and ensure complete electrical isolation between systems
- **Long-distance communication:** Signals can travel hundreds of meters with minimal attenuation
- **Scalability and flexibility:** Fiber systems can be easily expanded and reconfigured

03 Safran Solution

WR-TTS: Machine protection System

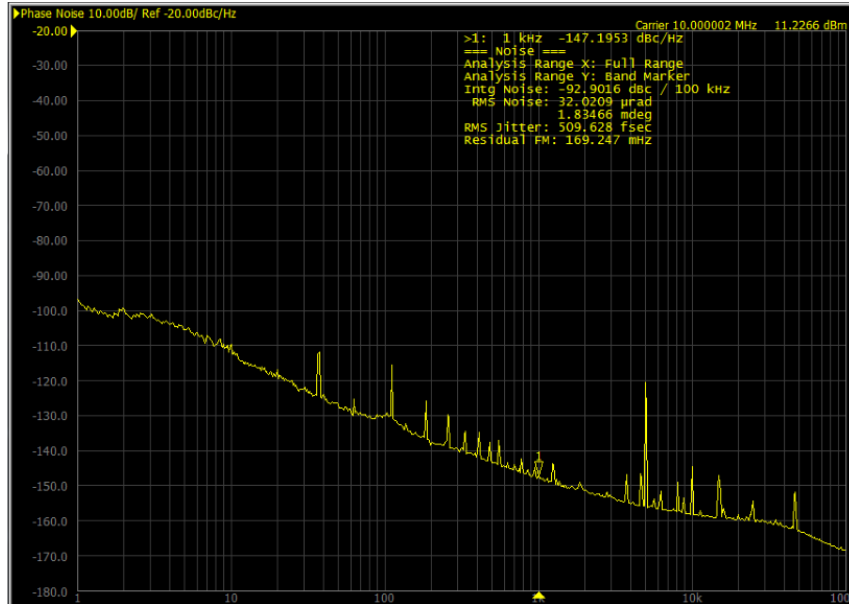


Master-Slave Mode in uTCA Crate



04 Tests & Results

WR-TTS: Jitter Measurements



RMS jitter 10MHz output

~500 fs of RMS jitter
measured at the 10MHz
output

04 Tests & Results

WR-TS: Sequence of events generation

The screenshot displays the SAFRAN - Timing System software interface. The main window shows a 'General Status' table for seven channels (Fp.1 to Fp.7). Each channel has a set of control buttons (Enable, OUT, HIGH, ON) and a 'Reset' button. The 'General Status' table includes columns for Channel, Enable, Status, Sequence Enable, Direction, Mode, Time Minimum, and Events. The 'Events' column shows a sequence of values (133120, 133120, 133120, 133120, 133120, 133120, 213). Below the table, there are status indicators for Sync Signal status, WR Sync status, and PLL1 locked.

Chan.	Ena.	Stat.	Seq. En.	Dir.	Mode	T. Min.	Events
Fp.1	●	●	●	OUT	High	0.000 us	133120
Fp.2	●	●	●	OUT	High	0.000 us	133120
Fp.3	●	●	●	OUT	High	0.000 us	133120
Fp.4	●	●	●	OUT	High	0.000 us	133120
Fp.5	●	●	●	OUT	High	0.000 us	133120
Fp.6	●	●	●	OUT	High	0.000 us	133120
Fp.7	●	●	●	IN	High	0.000 us	213

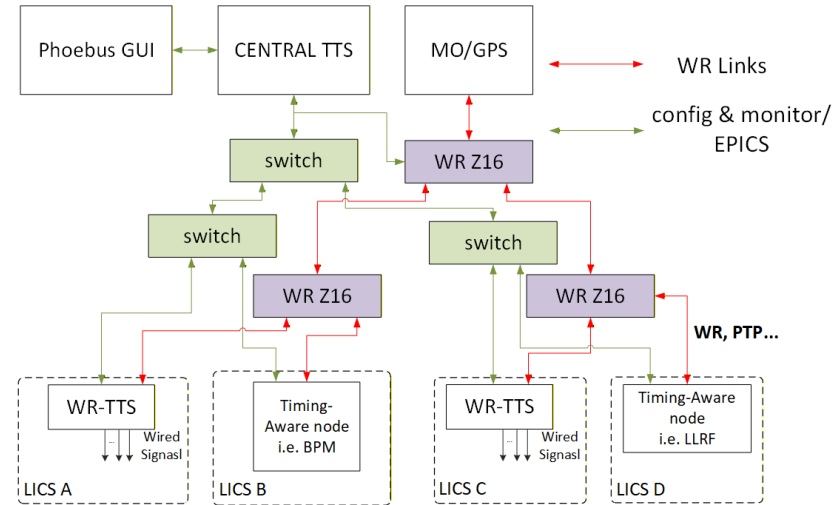
Sync Signal status: ● WR Sync status: ● PLL1 locked: ●

Long term
test

05 Next Steps

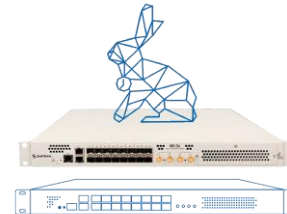
Work in Progress... Phoebus & EPICS-based Central Timing & Synchronization Entity

- **Auto-Discover Timing-aware nodes:** Using EPICS discover tools to get the PVA nodes and their timing-related PVs and **LLDP** for WR nodes.
- **Visual Trigger Programming:** Setup all the gates and triggers and check their shapes and organization in a chart before executing them.
- **Centralized Monitoring:** Monitor the health of the WR-TTS and timing-aware nodes.
- **Alarms Management:** Full TTS ecosystem integrated into the Phoebus Alarm System.
- **MPS Integration:** Fast interlock in case of a timing issue to avoid damages.



Recommendations and advice are Welcome!

Feel free to stop by our booth in the exhibition hall!



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