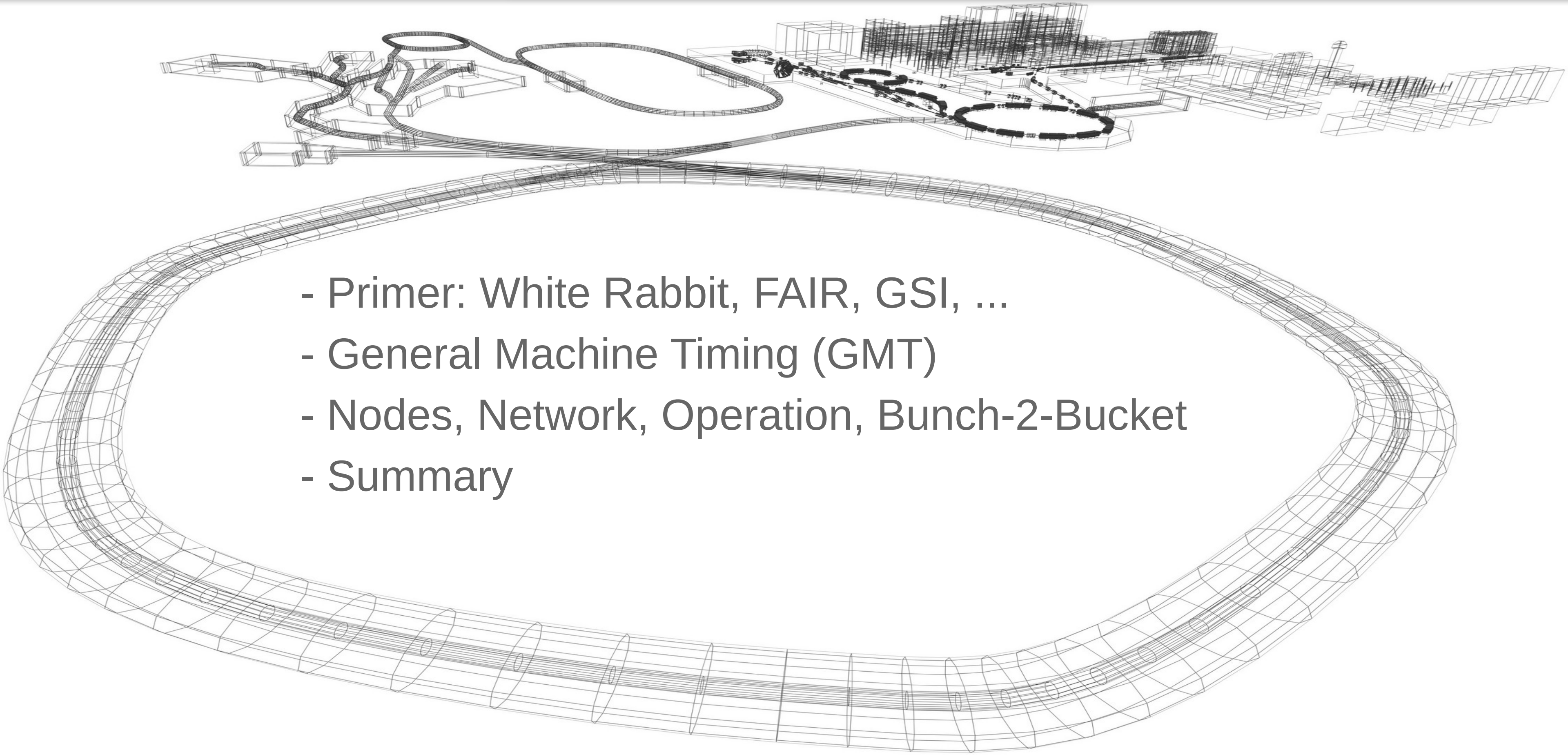
# Acknowledgements


- GSI Timing Team: Enkhbold Ochirsuren, Marcus Zweig, Stefan Rauch, Mathias Kreider, Martin Skorsky, Marco Dennstädt, Michael Reese, Anna Ranz, Alexander Hahn, Frederic Ameil
- GSI ACC-IT Team: Peter Pfister, Christoph Handel, Rosemarie Vincelli …
- GSI Ring-RF Team: Dieter Lens, Bernhard Zipfel, Stefan Schäfer, Martin Hardieck …
- GSI Ring-HV Team: Isfried Petzenhäuser, Jürgen Florenkowski ...
- CERN Team: Greg Daniluk, Maciej Lipinski, Adam Wujek …
- ...

# The White Rabbit based Timing System for GSI and FAIR



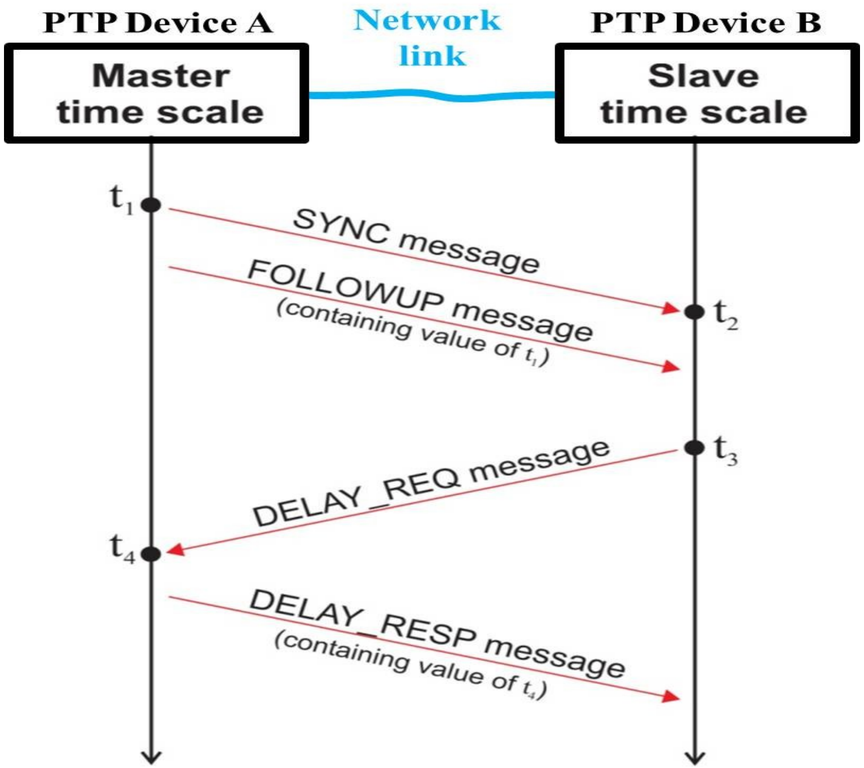
- Primer: White Rabbit, FAIR, GSI, ...
- General Machine Timing (GMT)
- Nodes, Network, Operation, Bunch-2-Bucket
- Summary

# General Machine Timing: GMT (Some Background)

(

# White Rabbit (Seen by a User)

**(borrowed from `https://ohwr.org/project/white-rabbit/tree/master/figures`)**




**Precision Time Protocol (IEEE 1588)**

- Frame-based synchronisation protocol
- Simple calculations:
  - link delay: $\delta ms = ((t4 - t1) - (t3 - t2)) / 2$
  - offset from master: $OFM = t2 - (t1 + \delta ms)$

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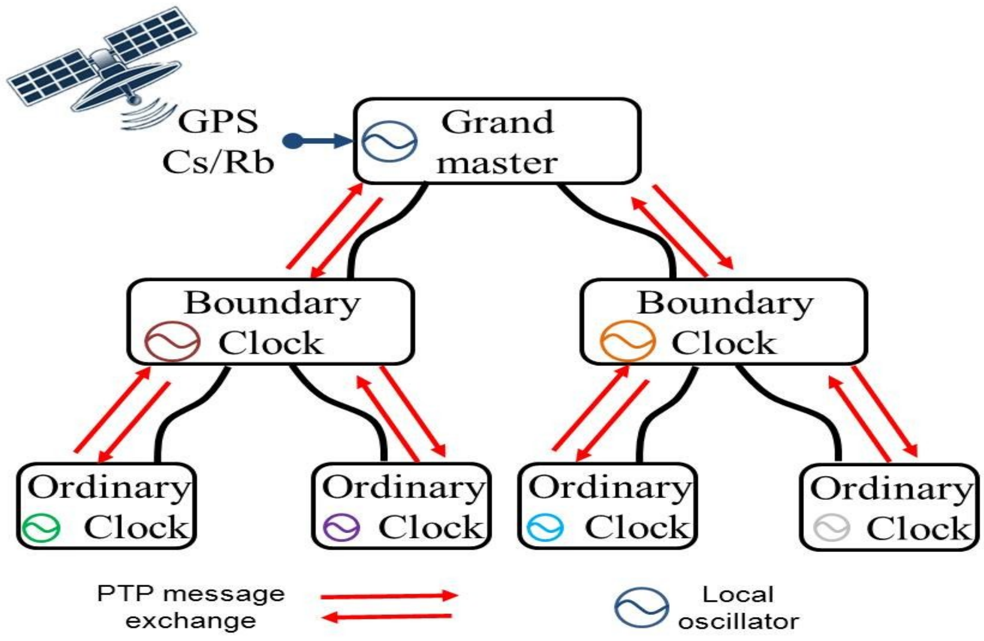


**Precision Time Protocol (IEEE 1588)**

- Frame-based synchronisation protocol
- Simple calculations:
  - link delay: δms = ((t4 −t1 )−(t3 −t2 )) / 2
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- Hierarchical network
- Shortcomings of traditional PTP:
  - devices have free-running oscillators
  - frequency drift
  - ...

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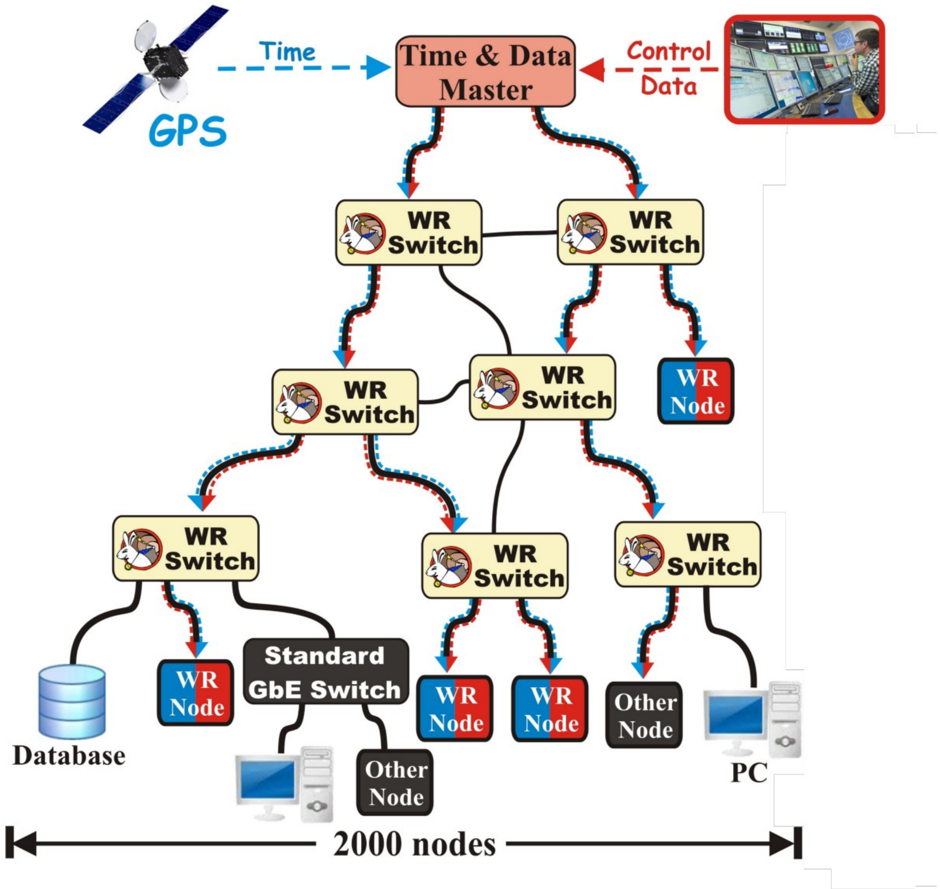


**<u>Precision Time Protocol (IEEE 1588)</u>**

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- Hierarchical network
- Shortcomings of traditional PTP:
  - devices have free-running oscillators
  - frequency drift
  - ...

**<u>White Rabbit</u>**

Originally

- *Extension* of IEEE 1588 Precision Time Protocol
- **Sub-ns synchronisation @ physical hardware layer**
  - requires dedicated network switches (~ SyncE, DDMTD, Link delay model)
- **Deterministic data transfer**

Status

- **WR concepts now part of IEEE Std 1588-2019**
- WR redefined to mean an open-source *implementation* of the **High-Accuracy profile** guaranteeing 1 ns accuracy and the friendly community around this development

# White Rabbit: Open and Commercially Available Off-the-shelf

(borrowed from `https://ohwr.org/project/white-rabbit/tree/master/figures`)

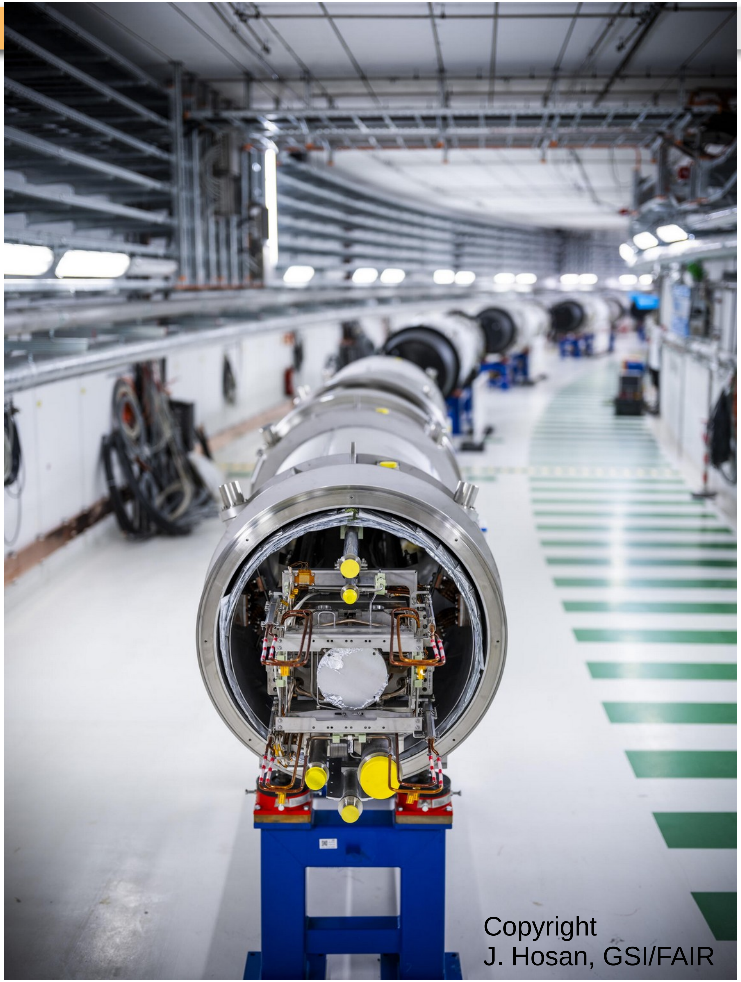

<u>Companies selling White Rabbit</u>

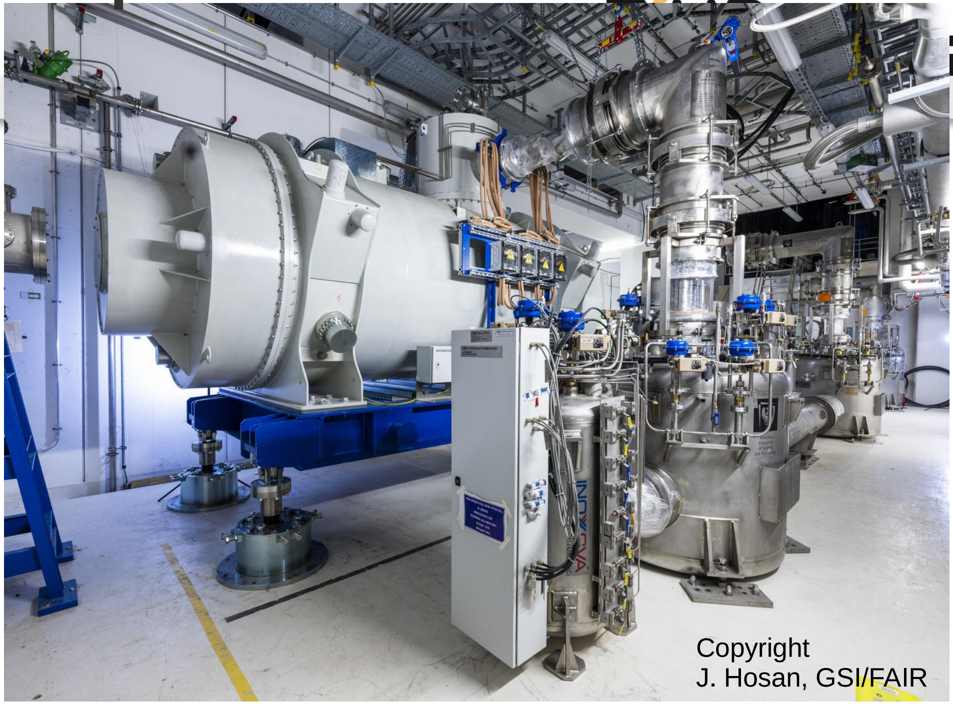
`https://ohwr.org/projects/white-rabbit/wiki/wrcompanies`

# FAIR from the Control System Perspective


- FAIR: international accelerator facility
- GSI as injector (UNILAC → SIS18 → FAIR)
- installation of technical networks started
- spring 2026: commissioning starts
- late 2027: readyness for ‚Early Science‘

# FAIR from the Control System Perspective

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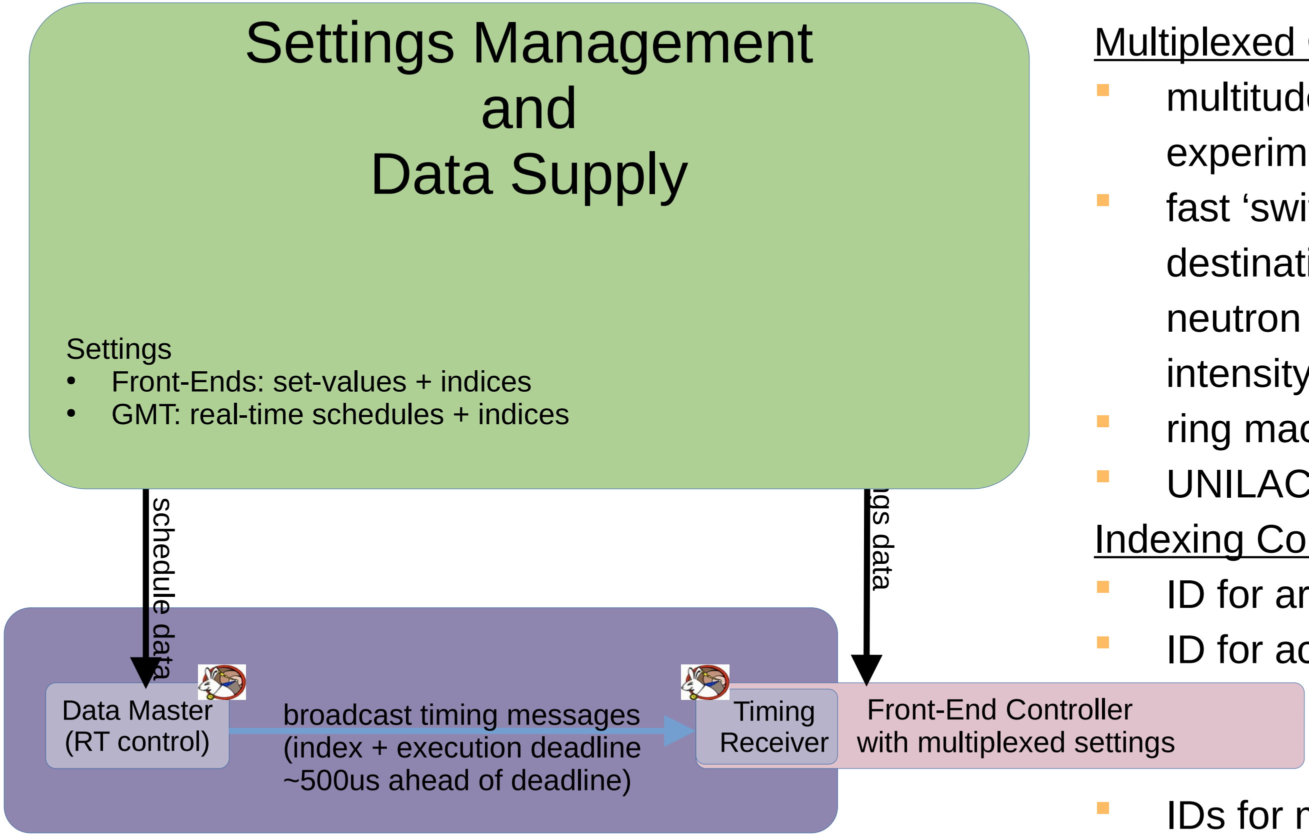
# Multiplexed Operation, Control System Stack and GMT




General Machine Timing System:
trigger Front-Ends with multiplexing index on-time

Multiplexed Operation

- multitude of beams for many experiments simultaneously
- fast 'switching' between beam destinations and properties (element, neutron number, charge state, energy, intensity, focus …)
- ring machines: 1Hz switching
- UNILAC: 50 Hz switching

Indexing Concept

- ID for area, location (‚where')
- ID for action (‚what to do')
- IDs for multiplexing context (‚which')
- other information

# FAIR from the Control System Perspective


'FAIR Control System' @ GSI campus

Control System, GMT+ White Rabbit operation

- since 2016: CRYRING (ring, ions-sources, Linac)
- since 2018: SIS18, ESR, FRS, all beamlines
- since 2022: synchronization of transfers between all ring machines
- iterative development with each beam-time

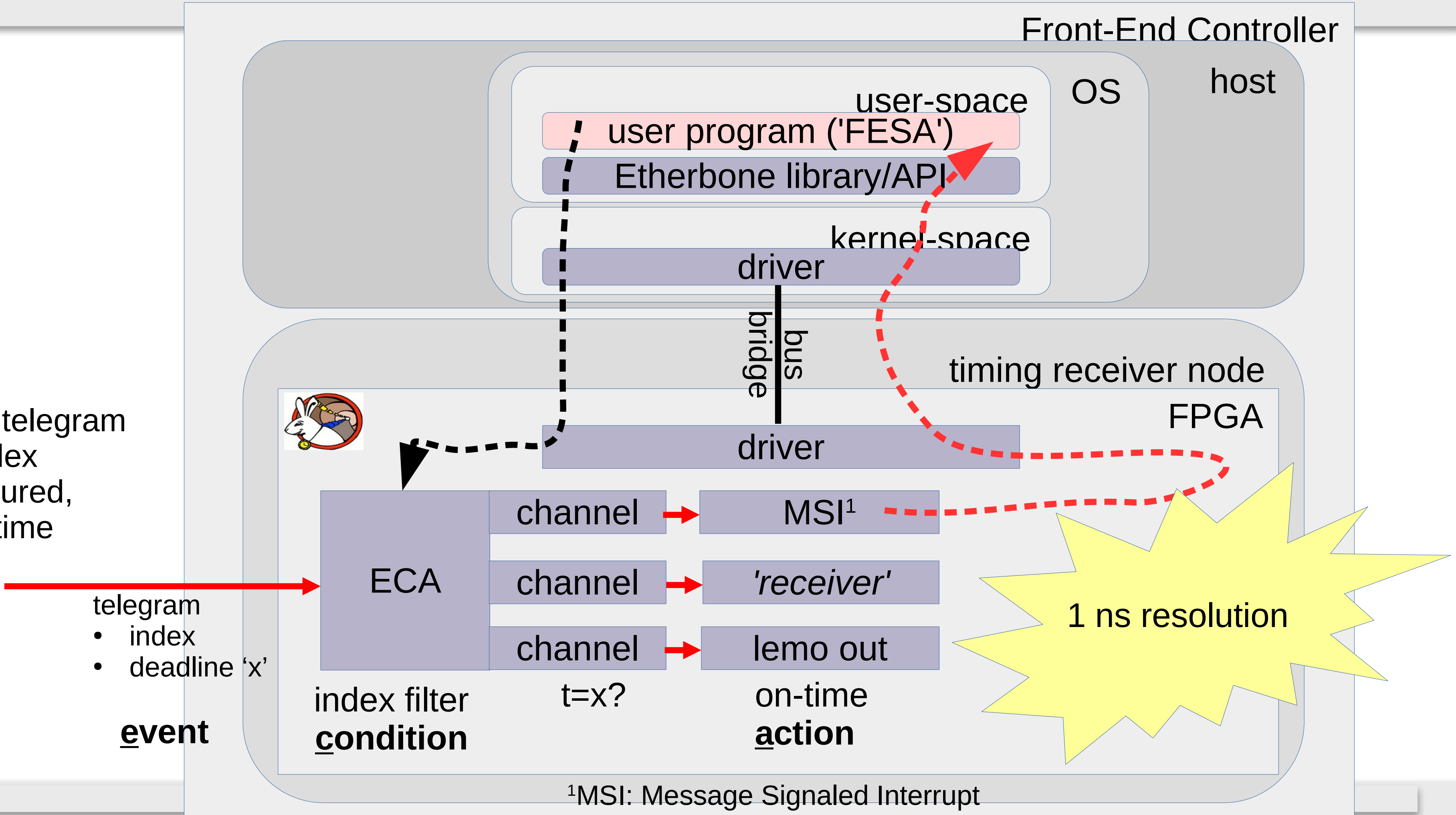
FAIR Campus including 'First Science+'

- SIS100
- Super Fragment Separator
- more beamlines, new things

)

# General Machine Timing

Machine Timing
- Event: timing telegram
- Condition: index
- Action: configured, executed on-time




[1]MSI: Message Signaled Interrupt

# Common Features for Nodes
# ’Everything Happens in the FPGA’

no application specific VHDL!

instead: customization via

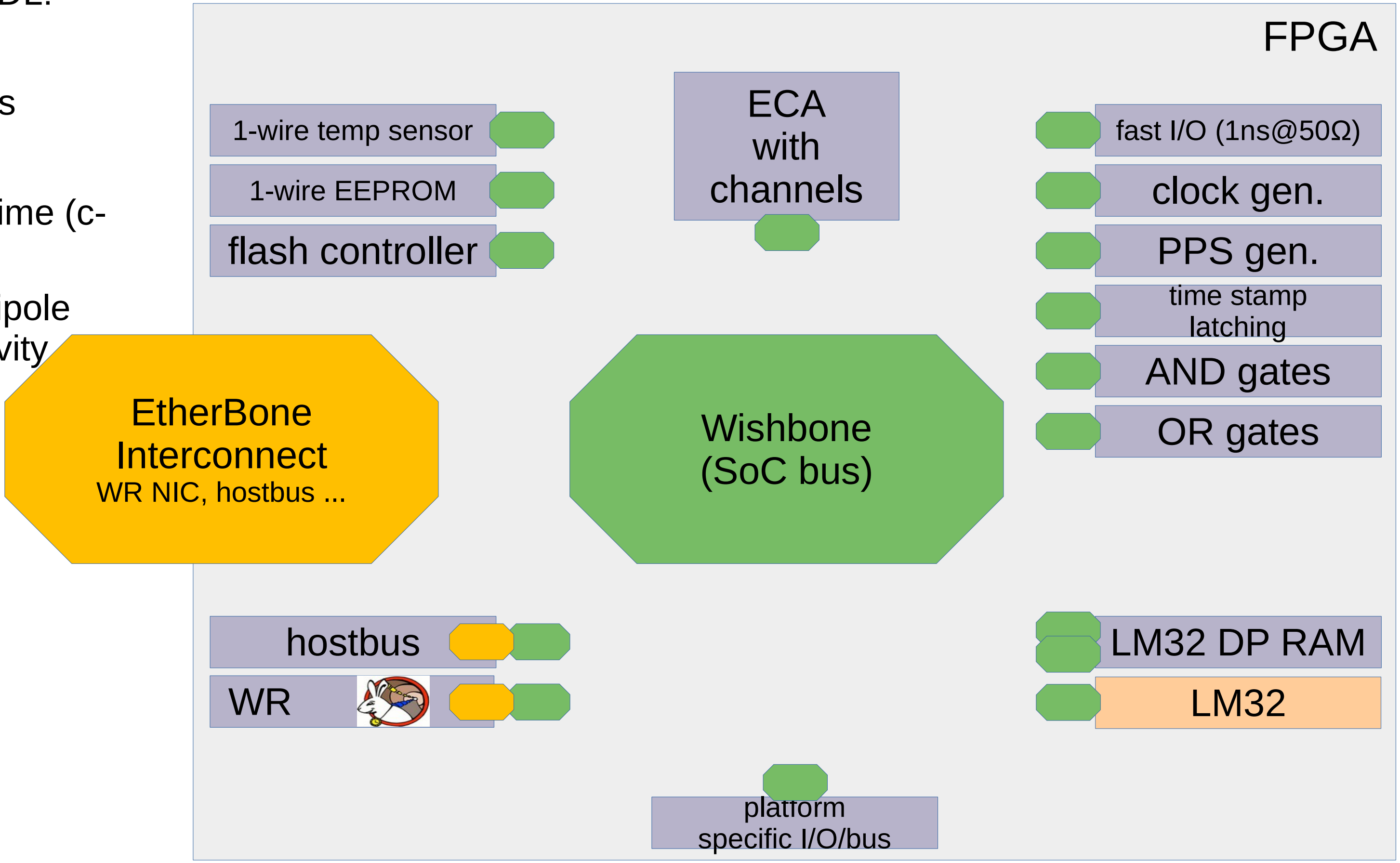
- configuration of IP cores
- LM32 softcore:

  upload binaries at run-time (c-code, OS-less)

  example: ramping up dipole magnet current or rf-cavity frequency

  hard real-time

  synchronosly at many nodes



# Common Features for Nodes ...

no applica
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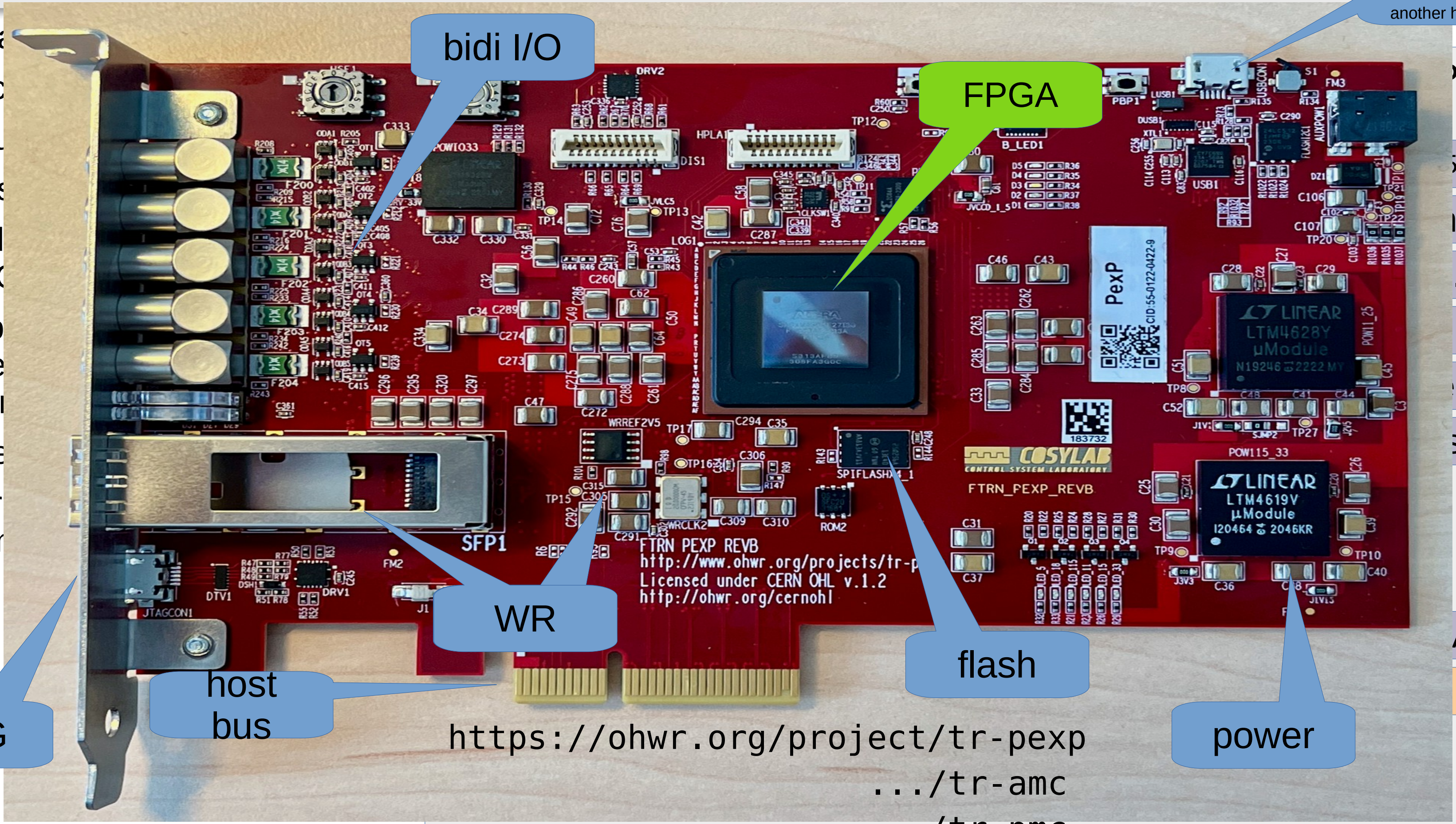


https://ohwr.org/project/tr-pexp
.../tr-amc
.../tr-pmc

PGA
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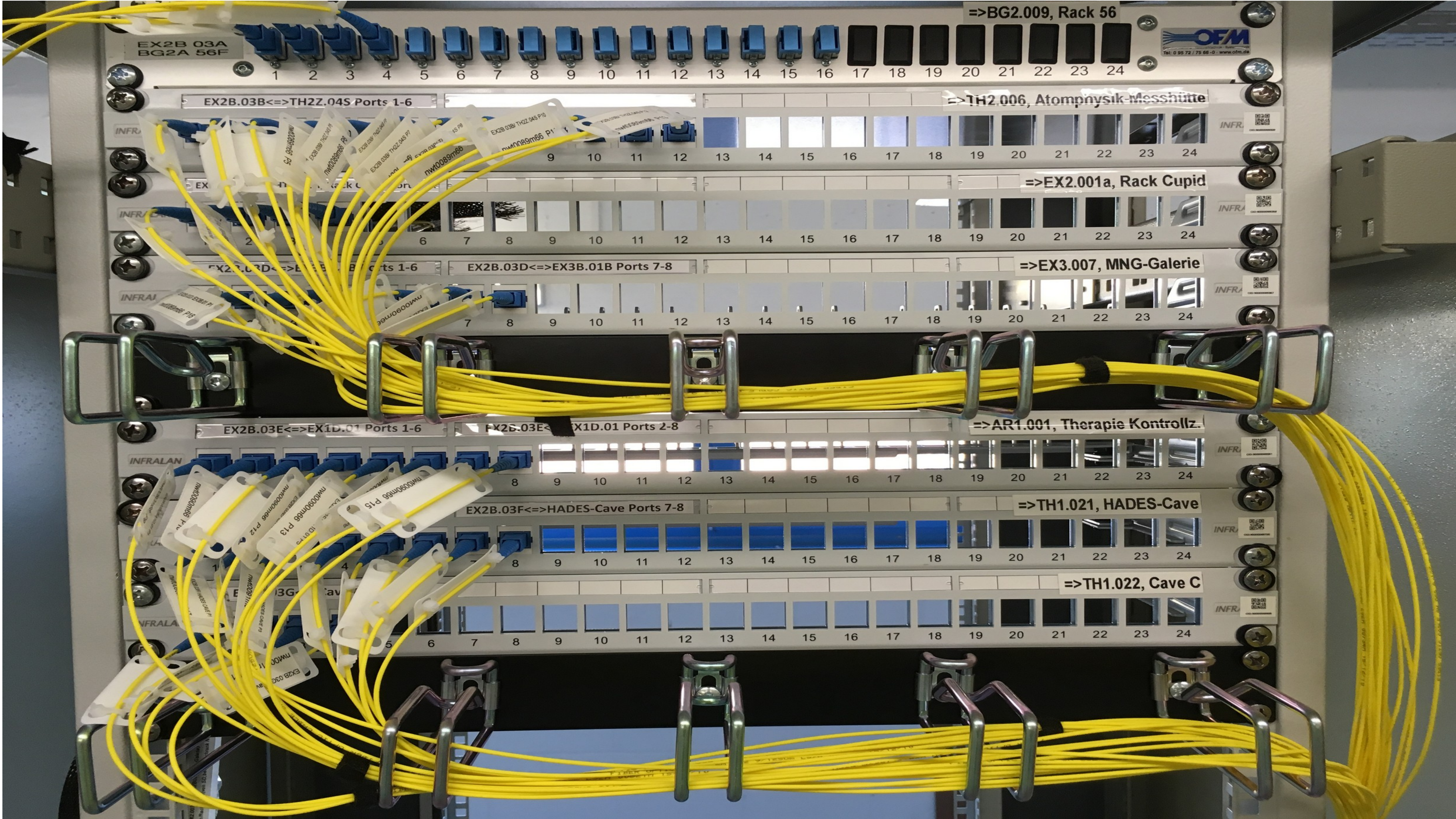

=>BG2.009, Rack 56
EX2B 03A
BG2A 56F
EX2B.03B<=>TH2Z.04S Ports 1-6
=>TH2.006, Atomphysik-Messhütte
=>EX2.001a, Rack Cupid
EX2B.03D<=>EX3B.01B Ports 7-8
=>EX3.007, MNG-Galerie
=>AR1.001, Therapie Kontrollz.
EX2B.03E<=>EX1D.01 Ports 1-6
EX2B.03F<=>HADES-Cave Ports 7-8
=>TH1.021, HADES-Cave
=>TH1.022, Cave C
INFRALAN


GTS3QT32

# Integration into IT Environment
# Lesson Learnt: No Need to Reinvent the Wheel

TL;DR: This worked out extremely well.

Detailed version:

- we thought: we are able to run our own IT infrastructure ...
- we discovered: we are unable to run our own IT infrastructure efficiently
- 'reboot' with the help of IT people
- approach
  - modify firmware of White Rabbit Switch to behave like regular IT switches
    (of course: modifications merged with ohwr.org ...)
  - integrate White Rabbit network into ACC-IT infrastructure
- contributions/help by Alessandro Rubini, Adam Wujek and Christoph Handel

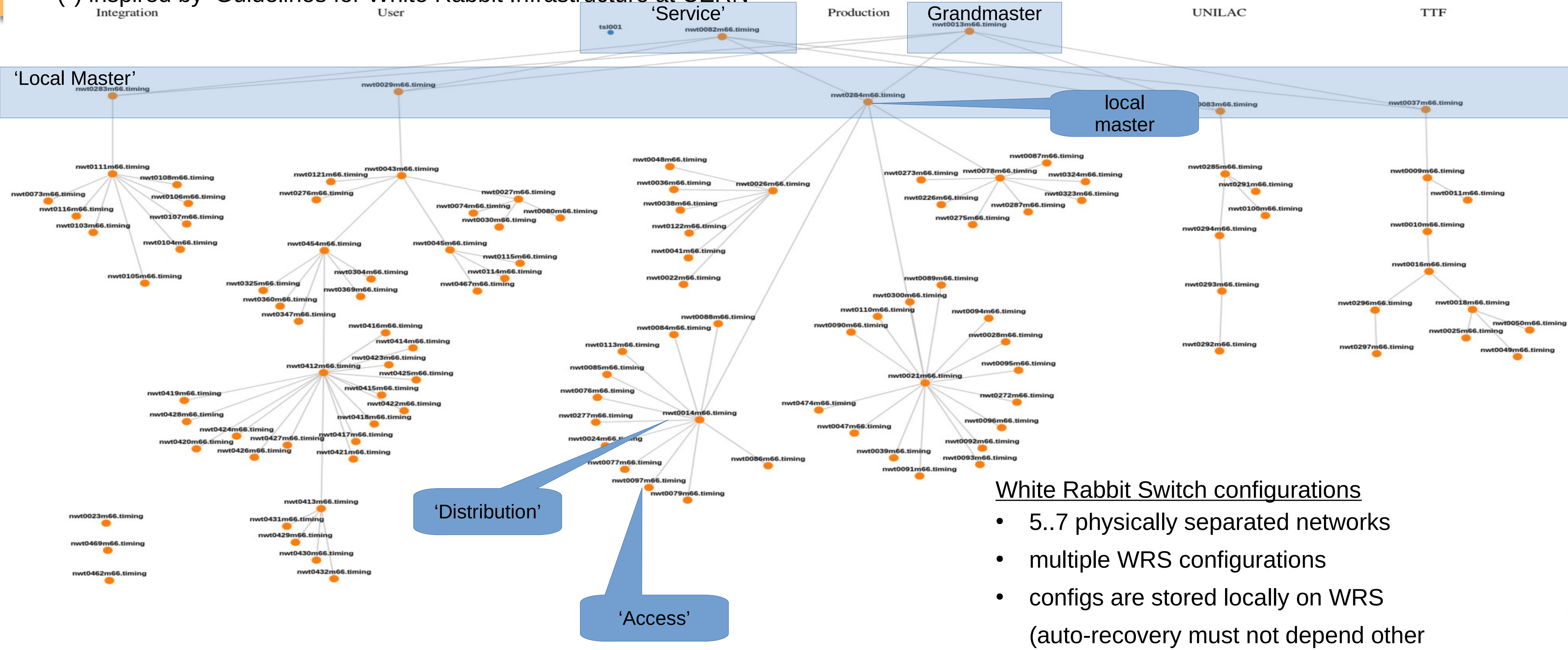
# Integration into IT Environment
# Accelerator IT and Central IT

they provide ...

- IP backend, dedicated subnets and VLANs, unique on the GSI campus
- redundant DHCP/BOOTP servers for all WRS and nodes
- redundant name servers for all WRS and nodes
- redundant Radius servers (VLANs, 802.1X)
- protected White Rabbit switch management network (‚plug-and-play')
- ...
- Icinga: WRS monitoring (health)
- Grafana: monitoring of key parameters
- Netdisco: auto-discovery of switches and nodes (really cool!)
- ...
- user roles, accounts, security, …
- **maintenance**
- …

# Integration into IT Environment, Configuration: Task Timing Group (*)

(*) inspired by ‘Guidelines for White Rabbit Infrastructure at CERN’




White Rabbit Switch configurations

- 5..7 physically separated networks
- multiple WRS configurations
- configs are stored locally on WRS

  (auto-recovery must not depend other infrastructure)

figure from ‘netdisco’ (2022)

# 2025: Experience from Operation

- preparation ahead of beam time (months!)
  - **feature freeze and release** WRS, data master and nodes
  - **‘integration tests’** with all control system layers
  - **dry-run(s)‘** for severe testing of accelerator facility at full scale
- 24/7 operation
  - ~**6 months/y of beam operation, including on-call service (rarely requested)**
  - **‘shutdown operation’** (‘beam operation but without on-call service’),
  - **rare (!) maintenance windows**

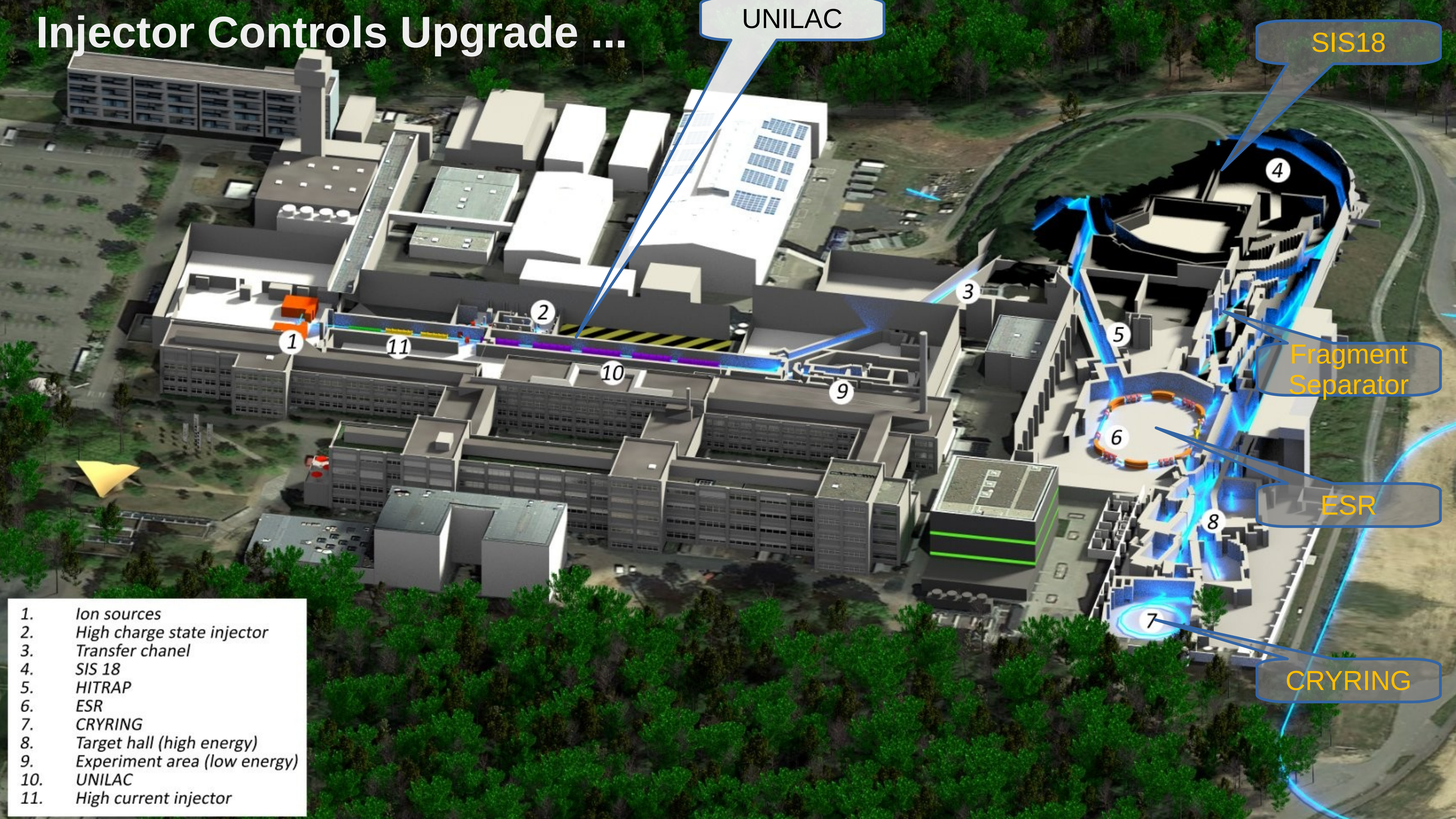
good (White Rabbit), **no issues** with

- nodes: monitor uptime, (dis)continuites of PTP time, loss of track-phase
- network: monitor switches and fibre links
- flawless recovery after a major power-cut (~1 hour, UPS dead …)
- ...

bad (White Rabbit)

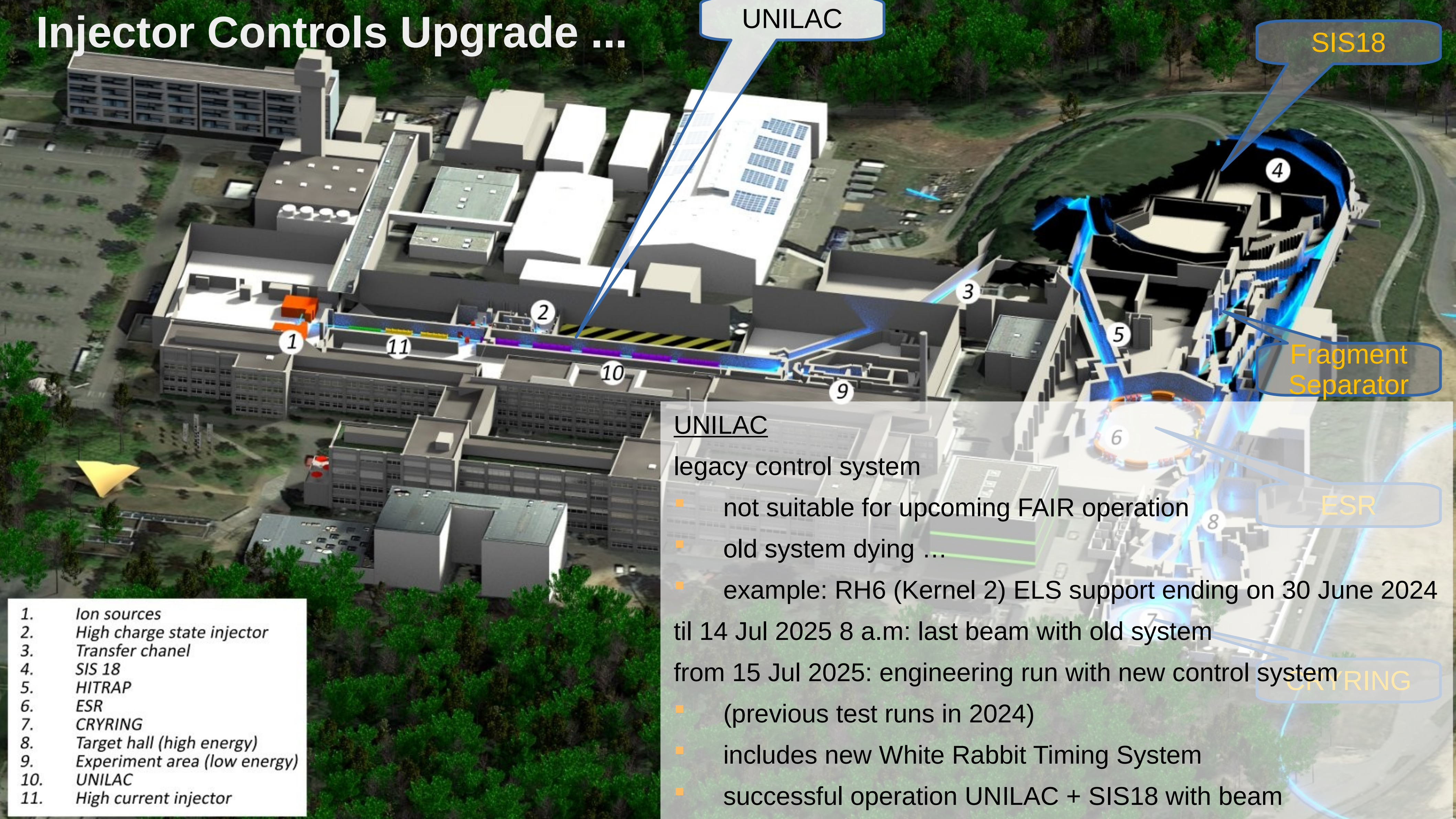
- WRS: 21 units with broken fans since 2016 (no hot-swap); 2nd fan keeps WRS alive; always replace both fans
- WRS: power supply neither redundant, nor easily swappable (lucky: so far reliable without issues)

# Injector Controls Upgrade ...




1. Ion sources
2. High charge state injector
3. Transfer chanel
4. SIS 18
5. HITRAP
6. ESR
7. CRYRING
8. Target hall (high energy)
9. Experiment area (low energy)
10. UNILAC
11. High current injector

# Injector Controls Upgrade ...




<u>UNILAC</u>

legacy control system

- not suitable for upcoming FAIR operation
- old system dying ...
- example: RH6 (Kernel 2) ELS support ending on 30 June 2024

til 14 Jul 2025 8 a.m: last beam with old system

from 15 Jul 2025: engineering run with new control system

- (previous test runs in 2024)
- includes new White Rabbit Timing System
- successful operation UNILAC + SIS18 with beam

UNILAC

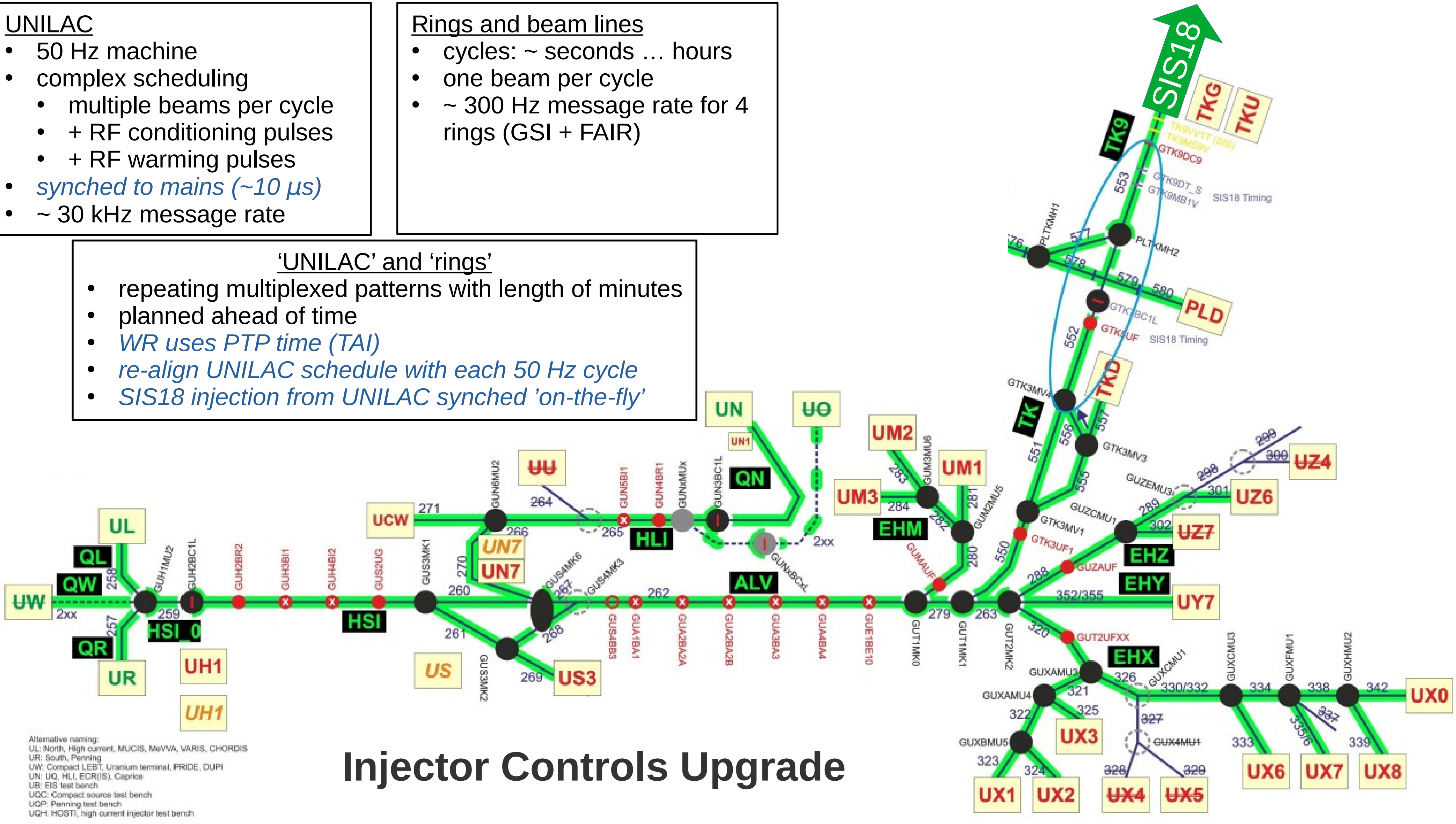
- 50 Hz machine
- complex scheduling
  - multiple beams per cycle
  - + RF conditioning pulses
  - + RF warming pulses
- *synched to mains (~10 µs)*
- ~ 30 kHz message rate

Rings and beam lines

- cycles: ~ seconds … hours
- one beam per cycle
- ~ 300 Hz message rate for 4 rings (GSI + FAIR)

‘UNILAC’ and ‘rings’

- repeating multiplexed patterns with length of minutes
- planned ahead of time
- *WR uses PTP time (TAI)*
- *re-align UNILAC schedule with each 50 Hz cycle*
- *SIS18 injection from UNILAC synched ’on-the-fly’*

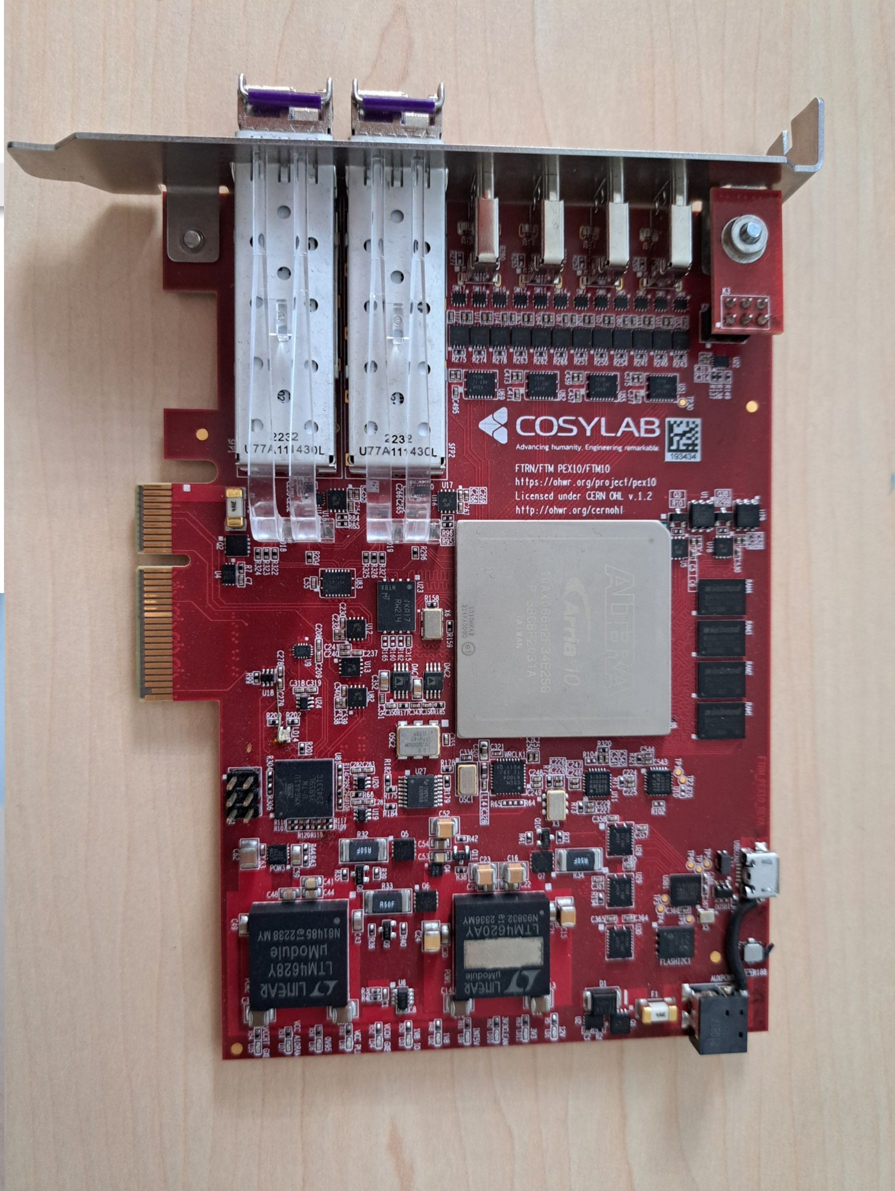



# Injector Controls Upgrade

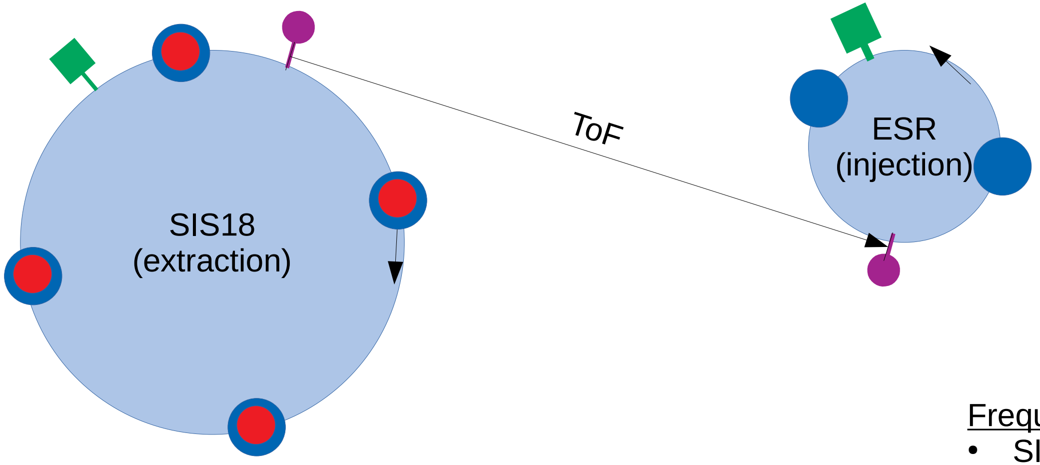
# Injector Controls Upgrade

- 2 distinct production networks: ‘unilac’ and ‘rings’
- 2 Data Masters
- tight synchronization in hard real-time (White Rabbit network)
- upcoming: new Data Master HW with 2 WR ports
  (presently using old 1 port version + ugly VLAN tricks)

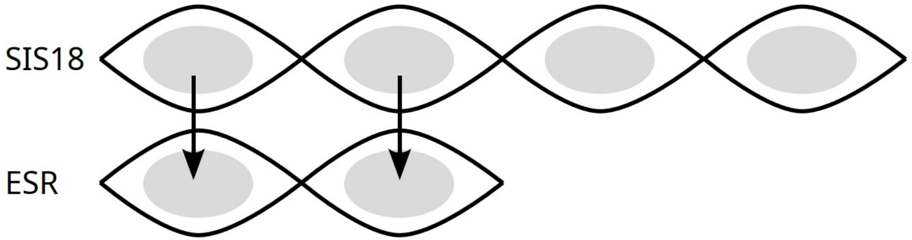
BTW: all new GSI WR formfactors done with Arria 10 GX FPGAs
(previously Arria II or V GX)

# 2025: Bunch-to-Bucket Transfer between Ring Machines
# Here: Frequency Beating








- ions circulate in a ring machine
- acceleratation using RF-cavities ⇒ stable regions, 'buckets'
- formation of ion bunches
- transfer bunches: from buckets (SIS18) to buckets (ESR)
- phase matching to better than 1 degree required

<u>Frequency Beating</u>, integer ratio of ring circumferences

- SIS18(216m)→ESR(108m)→CRYRING(54m)
- f_rev (SIS18) ~ 1.3 MHz; f_rev (ESR) ~ 2.6 MHz
- H=4 (SIS18) ~5.2 MHz; H=2 (ESR) ~5.2 MHZ

⇒ frequency beating

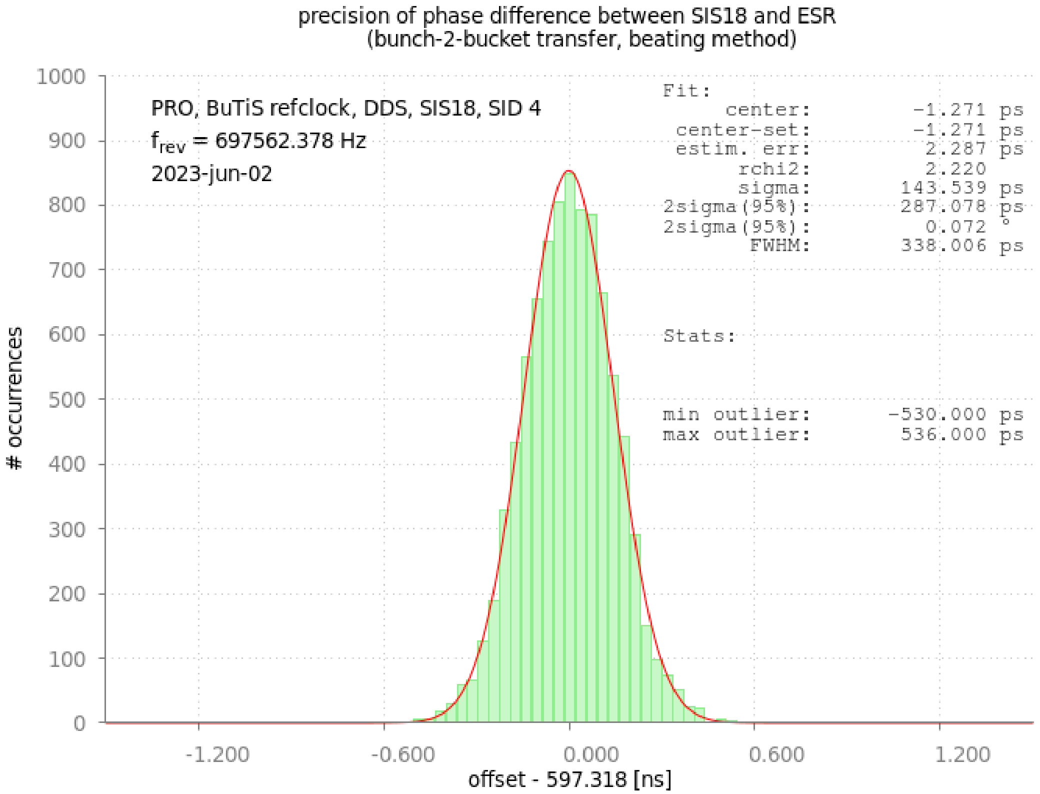
- 'just wait until the phase of both rings matches'

**White Rabbit @ GSI**

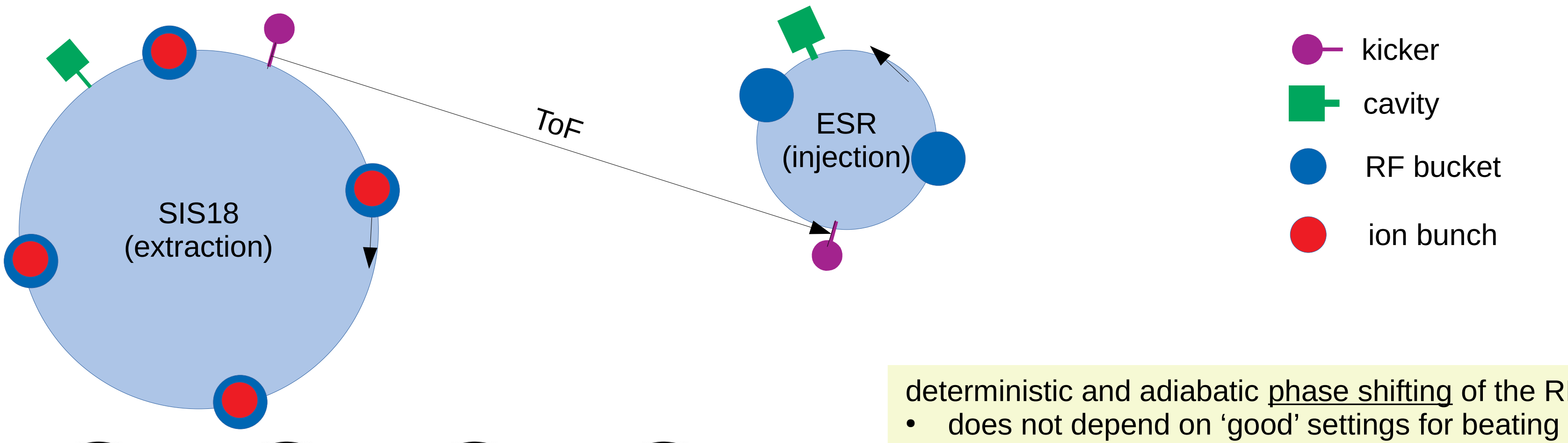
- precise phase measurements
- triggering of kickers
- distributed FPGA with embedded LM32 soft-core
- FPGAs communicate via the White Rabbit network

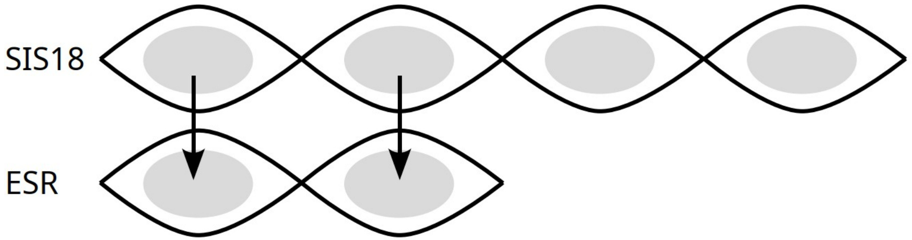
# 2025: Bunch-to-Bucket Transfer between Ring Machines (Frequency Beating)

- 2020/q4: demonstrated at SIS18, ESR
- 2022/q1: routine operation at SIS18, ESR, CRYRING
- routine operation frequency beating between SIS18 → ESR → CRYRING
- ‚phase measurement' of h=1 group DDS systems with White Rabbit time
  - until 2022: operation with 1 ns precision
  - since 2023: operation with sub-ns precision



# 2025: Bunch-to-Bucket Transfer between Ring Machines
# Here: RF Phase Shifting




deterministic and adiabatic phase shifting of the RF
- does not depend on ‘good’ settings for beating
- requires additional effort at RF systems

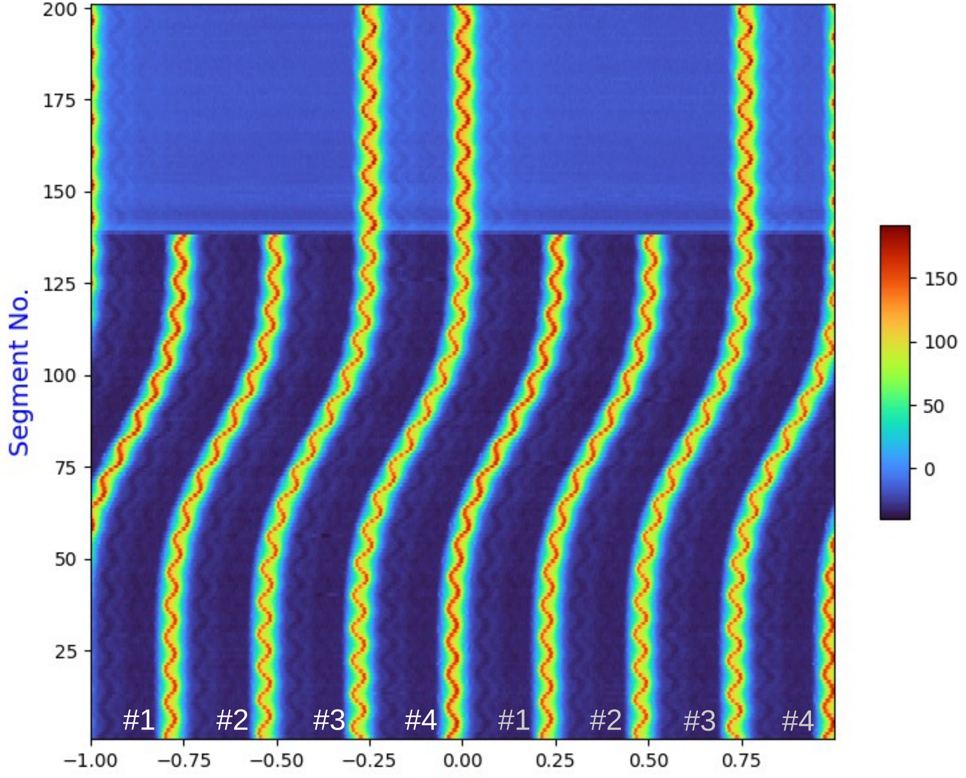
**White Rabbit @ GSI**
precise phase measurements
triggering of kickers
distributed FPGA with embedded lm32
FPGAs communicate via the White Rabbit network

- ions circulate in a ring machine
- acceleratation using RF-cavities ⇒ stable regions, ‘buckets’
- formation of ion bunches
- transfer bunches: from buckets (SIS18) to buckets (ESR)
- phase matching to better than 1 degree required

# May 2025: Phase Shifting in SIS18 (12 ms, #069)

SIS18 (FCT)

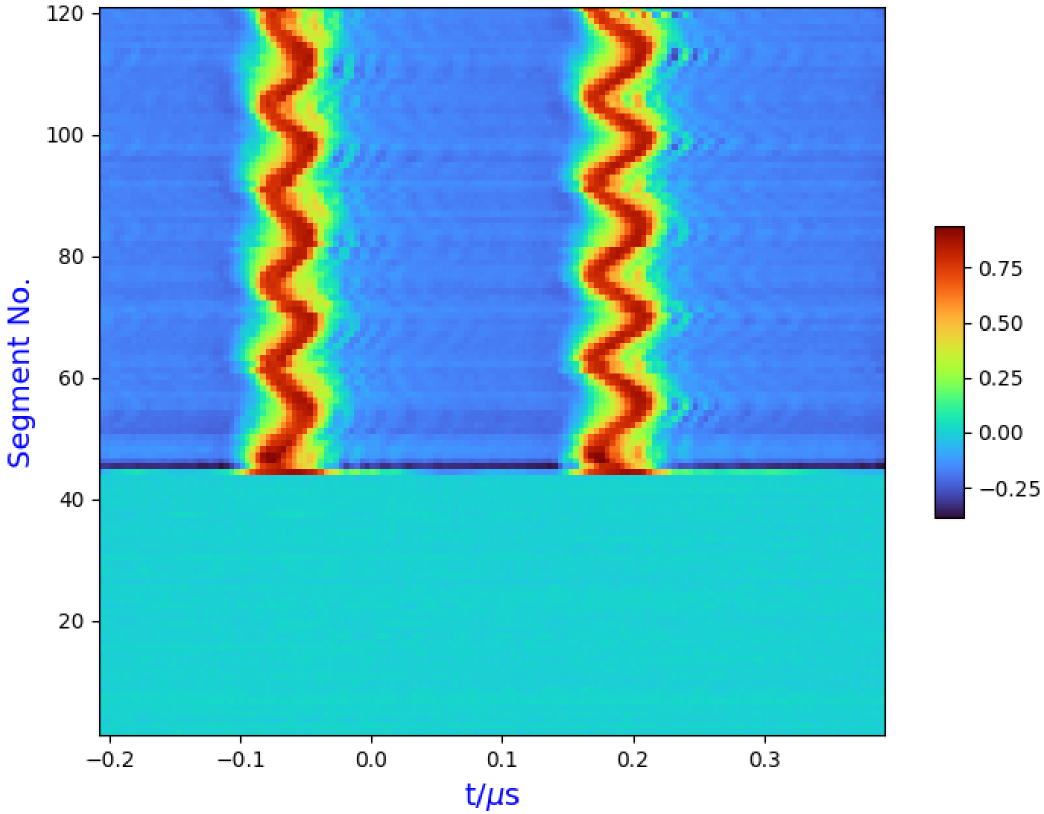
$T_{rev}$ ~ 1 µs; $T_{sync}$ ~ 1.2 ms




1 segment = 100µs

ESR (FCT)

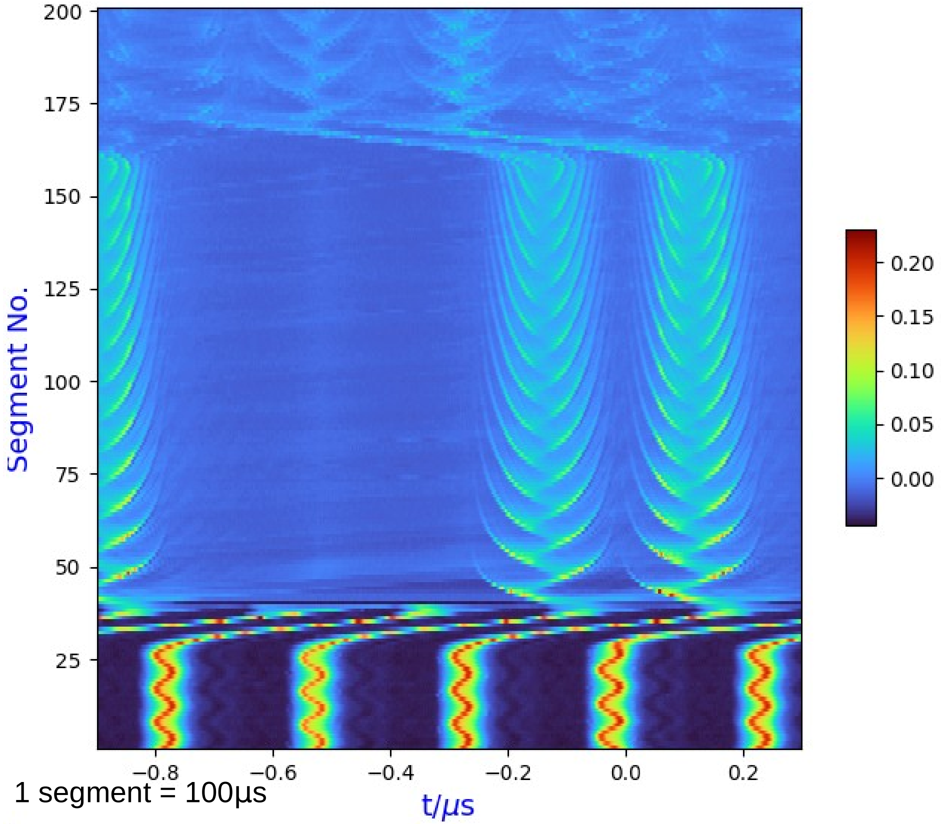
$T_{rev}$ ~ 0.5 µs; $T_{sync}$ ~ 1.6 ms



# Phase Shifting in SIS18 (1.5 ms, #087)

SIS18 (FCT)

$T_{rev}$ ~ 1 µs; $T_{sync}$ ~ 1.2 ms

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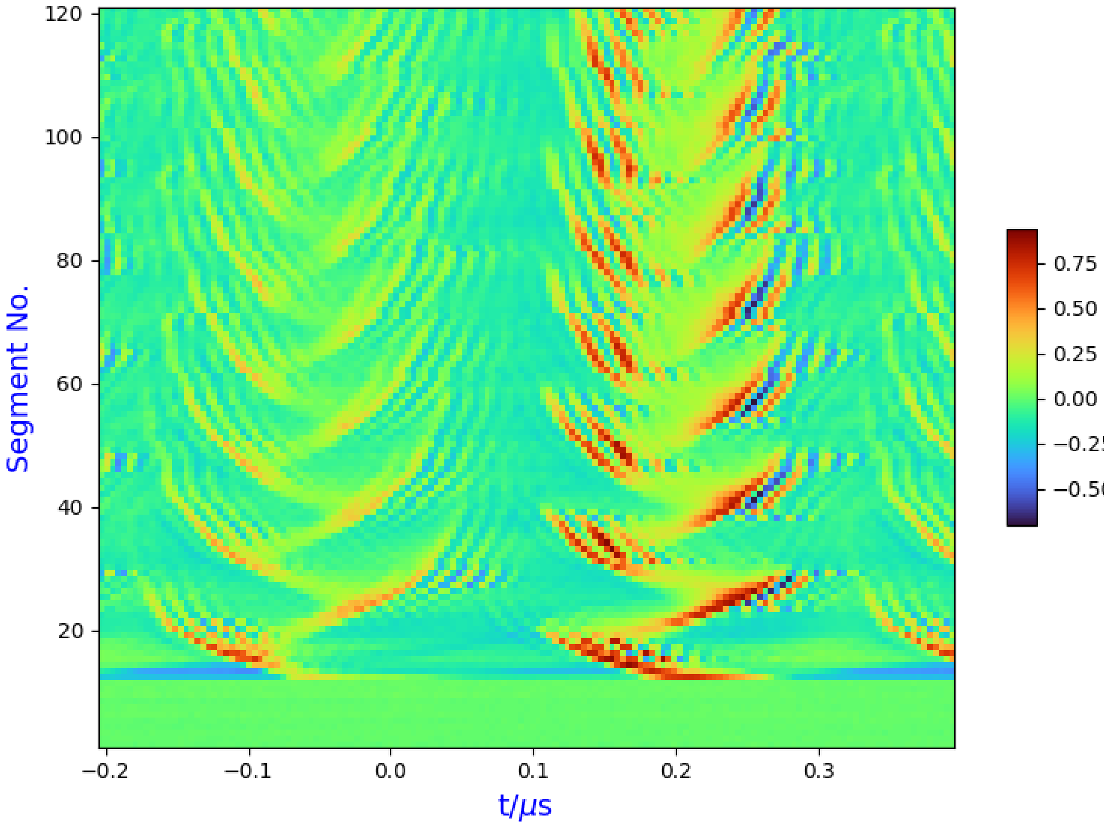


# Summary and Outlook

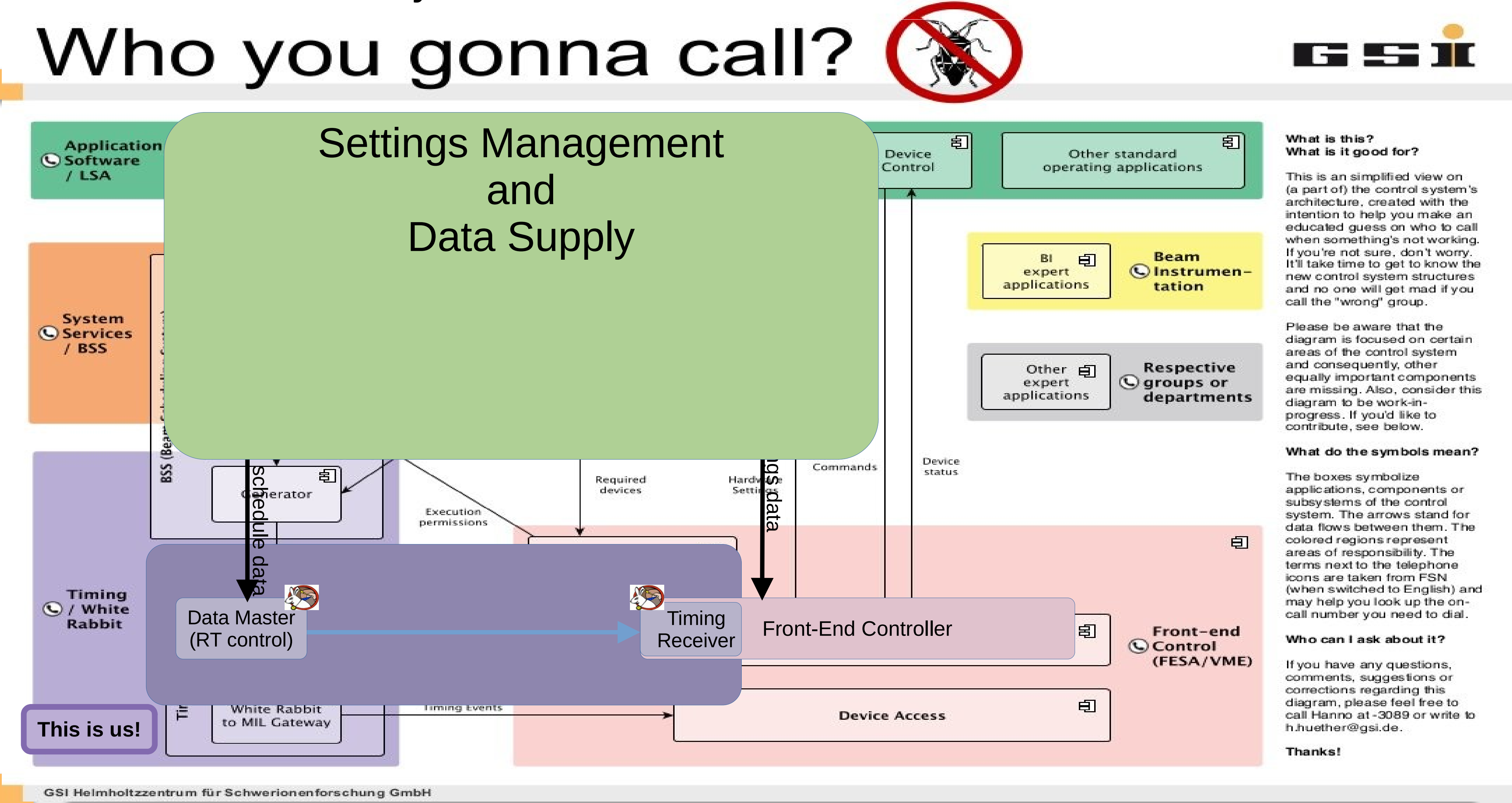
- ‘FAIR’ General Machine Timing (GMT) system installed at GSI, since 2016
  - based on White Rabbit
  - common notion of time, 1ns granularity, 10-100 ps precision
  - broadcast of ‘timing messages’ with upper bound latency
  - execution of tasks with 1ns resolution at planned deadline
  - routine operation for all rings and transfer lines since 2018
  - beam times 2018..2025: very reliable operation (almost invisible in failure statistics)
- 2025: ~76 WR switches and ~533 nodes in productive use
- 2025: Injector Controls Upgrade, **all** GSI machines use White Rabbit based timing
- FAIR
  - spring 2026: begin commissioing
  - add ~95 WRS and ~850 nodes for ‚Early Science‘

# Thank You For Your Attention

```
https://ohwr.org/project/tr-pexp .../tr-amc  .../tr-pmc - hardware
https://github.com/GSI-CS-CO/bel_projects - gateware, firmware, software
https://www-acc.gsi.de/wiki/Timing - some docs
```

## (Backup Slides ...)

# Control System Stack – Involvement of Seven Distinct Teams



# Control System Stack – Involvement of Seven Distinct Teams


**What is this?**
**What is it good for?**

This is an simplified view on (a part of) the control system's architecture, created with the intention to help you make an educated guess on who to call when something's not working. If you're not sure, don't worry. It'll take time to get to know the new control system structures and no one will get mad if you call the "wrong" group.

Please be aware that the diagram is focused on certain areas of the control system and consequently, other equally important components are missing. Also, consider this diagram to be work-in-progress. If you'd like to contribute, see below.

**What do the symbols mean?**

The boxes symbolize applications, components or subsystems of the control system. The arrows stand for data flows between them. The colored regions represent areas of responsibility. The terms next to the telephone icons are taken from FSN (when switched to English) and may help you look up the on-call number you need to dial.

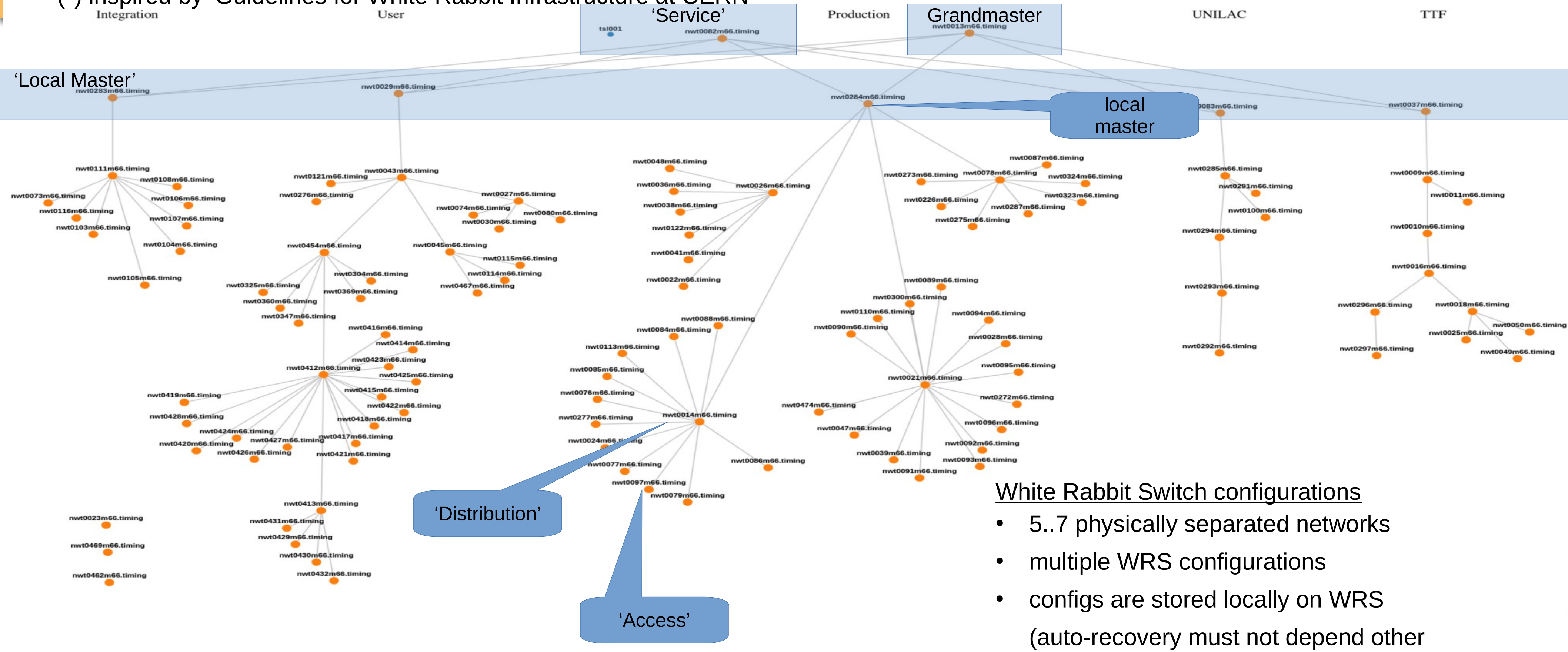
**Who can I ask about it?**

If you have any questions, comments, suggestions or corrections regarding this diagram, please feel free to call Hanno at -3089 or write to h.huether@gsi.de.

**Thanks!**

# Integration into IT Environment, Configuration: Task Timing Group (*)

(*) inspired by ‘Guidelines for White Rabbit Infrastructure at CERN’




## White Rabbit Switch configurations

- 5..7 physically separated networks
- multiple WRS configurations
- configs are stored locally on WRS

  (auto-recovery must not depend other infrastructure)

figure from ‘netdisco’ (2022)

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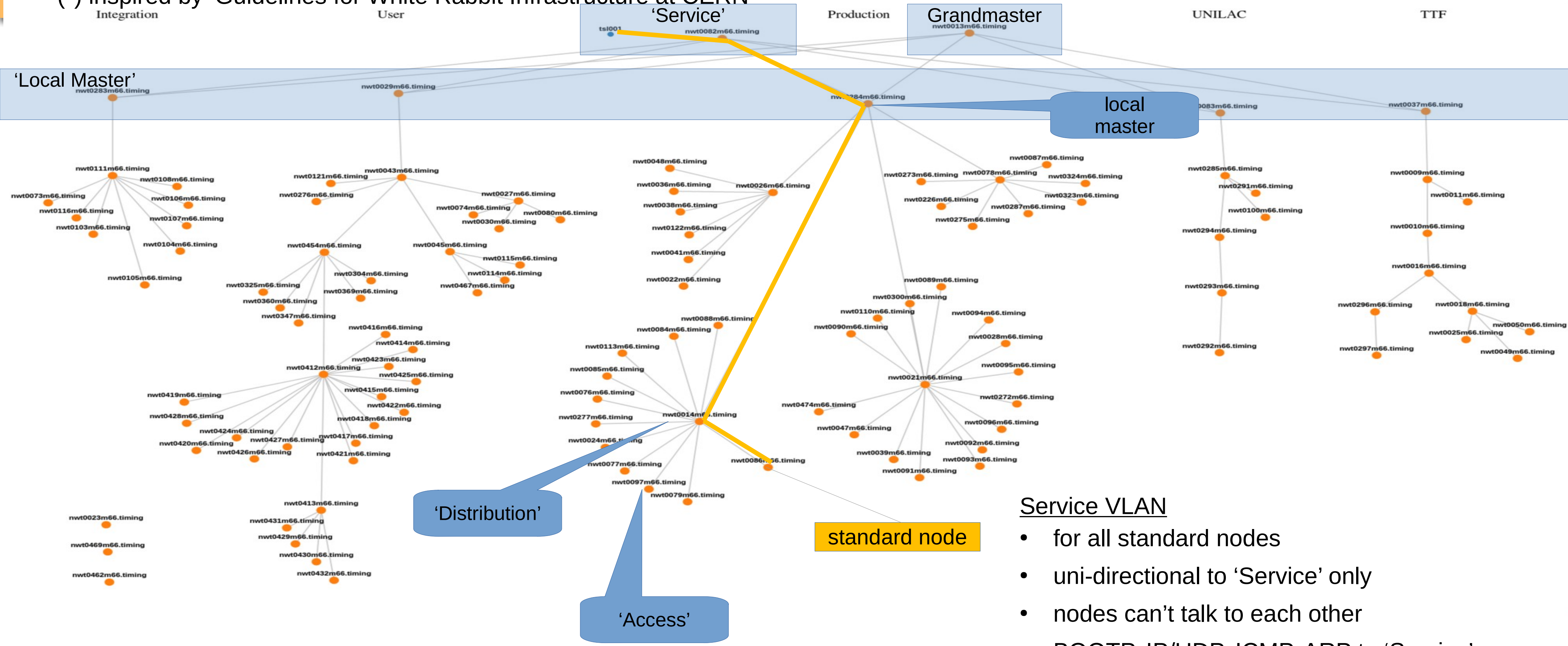
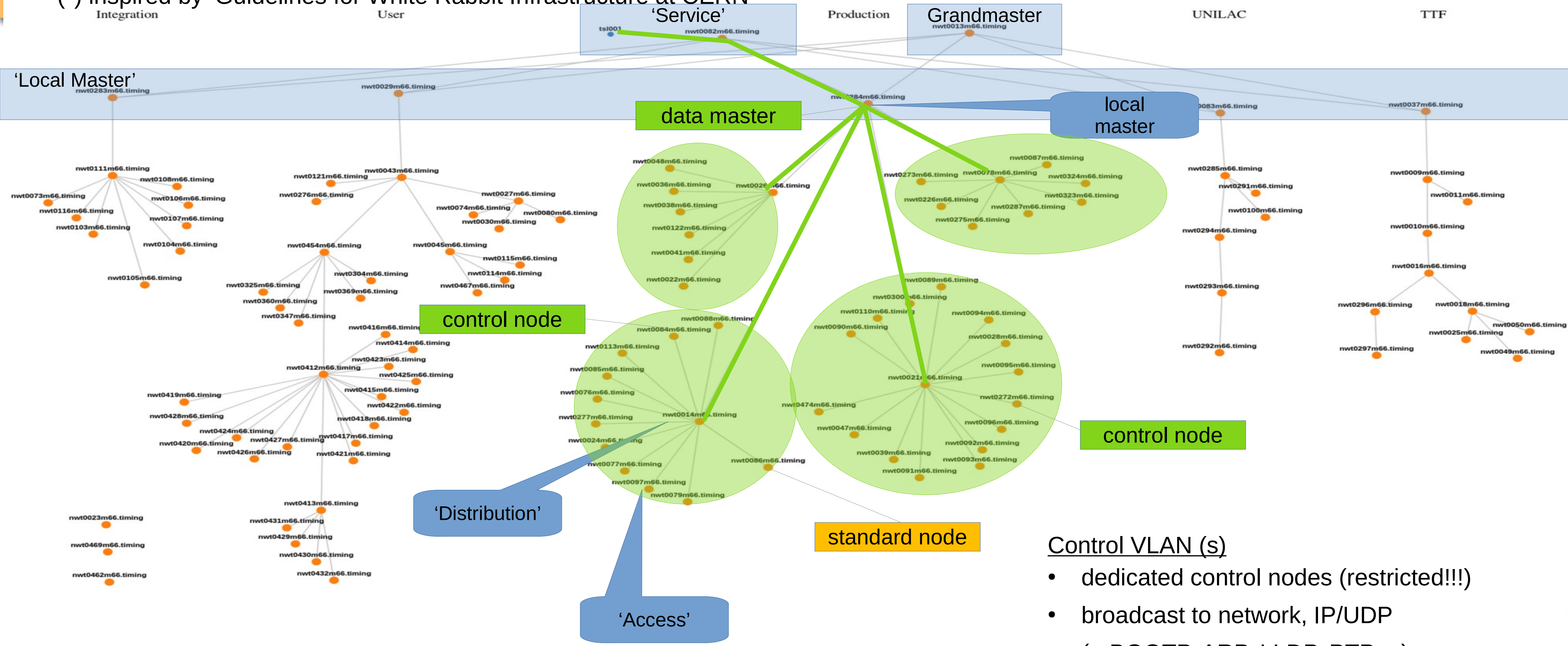



## Service VLAN

- for all standard nodes
- uni-directional to ‘Service’ only
- nodes can’t talk to each other
- BOOTP, IP/UDP, ICMP, ARP to ‘Service’
- PTP, LLDP to ‘Access’

# Integration into IT Environment, Configuration: Task Timing Group (*)

(*) inspired by ‘Guidelines for White Rabbit Infrastructure at CERN’

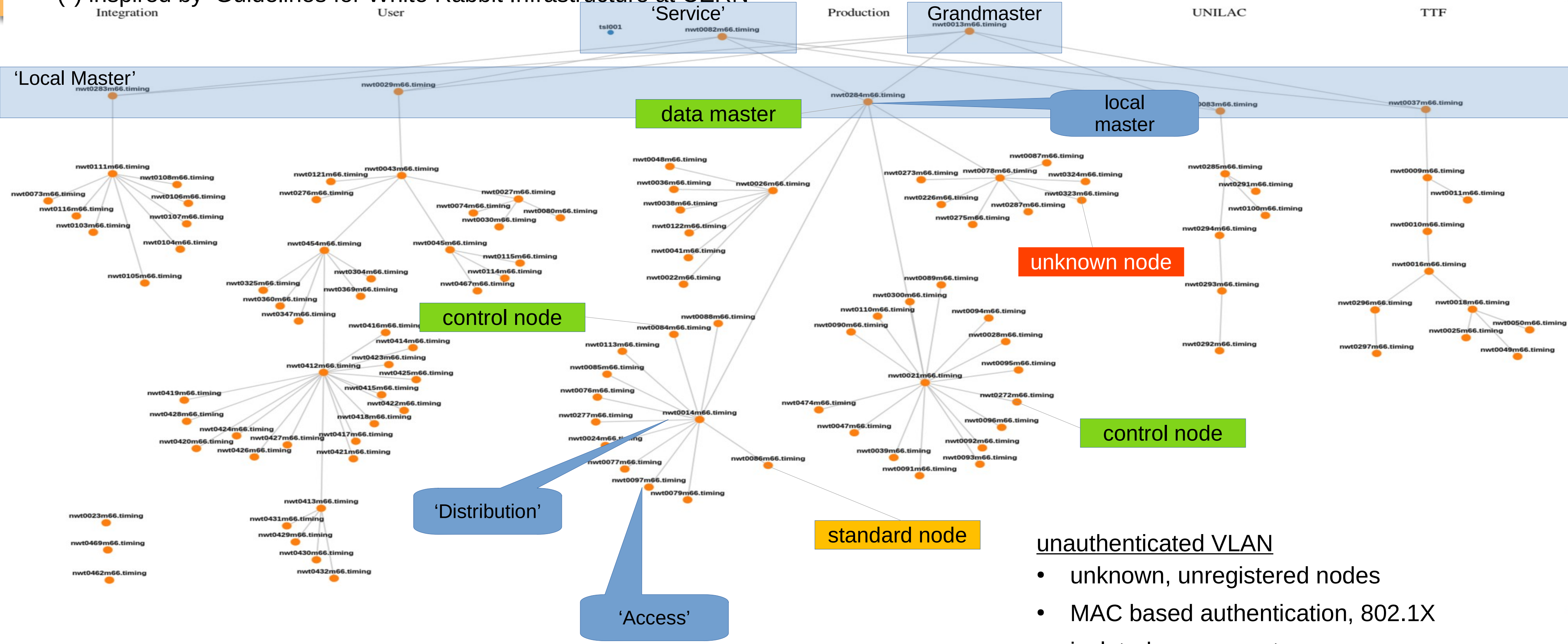



<u>Control VLAN (s)</u>

- dedicated control nodes (restricted!!!)
- broadcast to network, IP/UDP
- (+ BOOTP, ARP, LLDP, PTP ...)

# Integration into IT Environment, Configuration: Task Timing Group (*)

(*) inspired by ‘Guidelines for White Rabbit Infrastructure at CERN’




<u>unauthenticated VLAN</u>

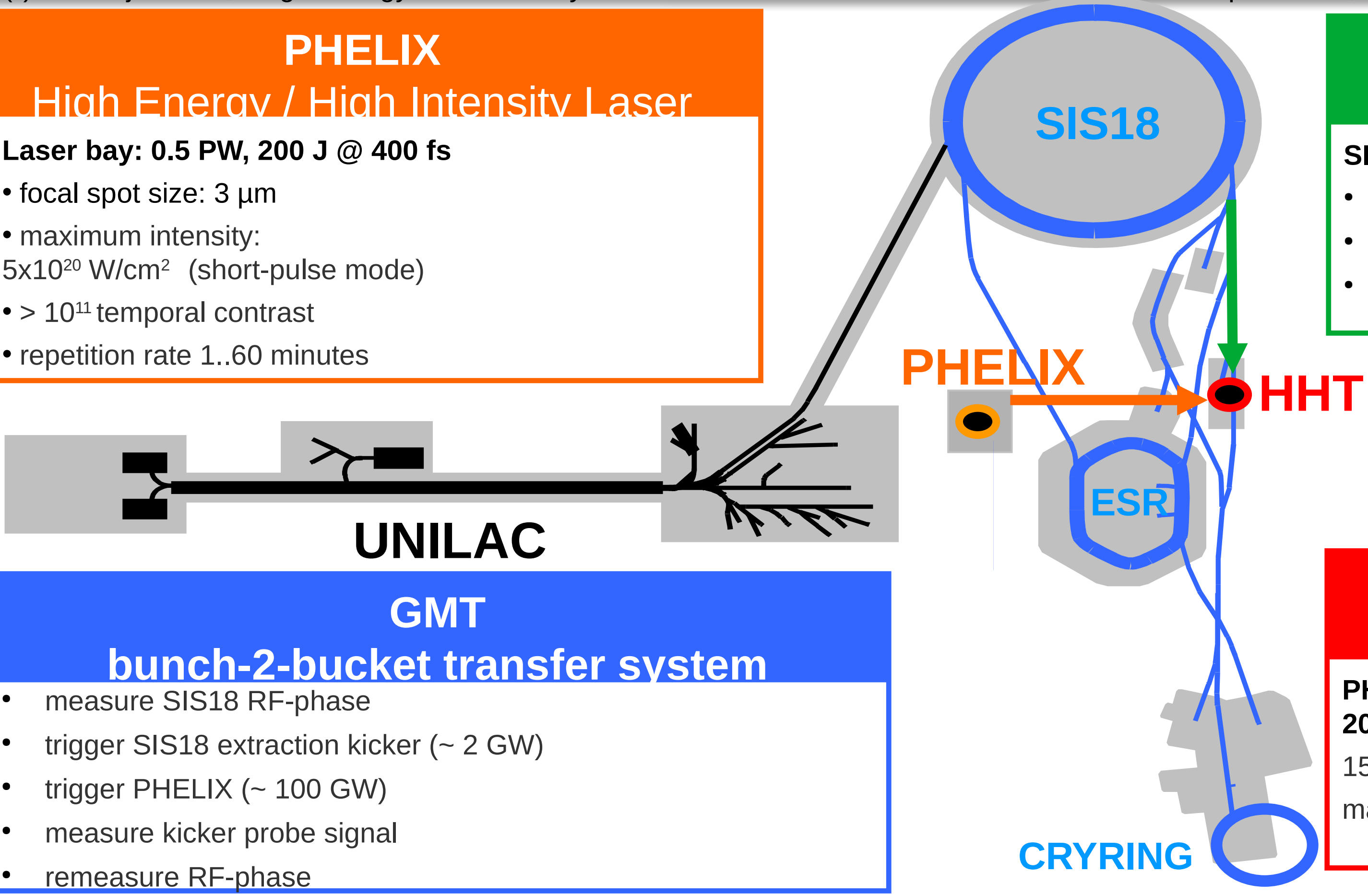
- unknown, unregistered nodes
- MAC based authentication, 802.1X
- isolated access port

# GMT Precision (Accelerator Control)
# Sync PHELIX Pulse and Ion Bunch (*)

(*) Zs. Major et al., "High-Energy Laser Facility PHELIX at GSI: Latest Advances and Extended Capabilities", in preparation (2023)

## PHELIX
## High Energy / High Intensity Laser

**Laser bay: 0.5 PW, 200 J @ 400 fs**
- focal spot size: 3 µm
- maximum intensity: 5x10[20] W/cm[2] (short-pulse mode)
- > 10[11] temporal contrast
- repetition rate 1..60 minutes




## SIS18

**SIS18, here:**
- **extracted bunch**
- length ~100ns
- v/c ~ 0.9

## GMT
## bunch-2-bucket transfer system

- measure SIS18 RF-phase
- trigger SIS18 extraction kicker (~ 2 GW)
- trigger PHELIX (~ 100 GW)
- measure kicker probe signal
- remeasure RF-phase

## HHT

**PHELIX:**
**200 J @ 1 – 10 ns**, 2ω
15 cm beam diameter
maximum focussed intensity: ~10[16] W/cm[2]

# GMT Precision (Accelerator Control)
# Sync PHELIX Pulse and Ion Bunch (*)

(*) Zs. Major et al., "High-Energy Laser Facility PHELIX at GSI: Latest Advances and Extended Capabilities", in preparation (2023)

**PHELIX**

High

**Laser ba**

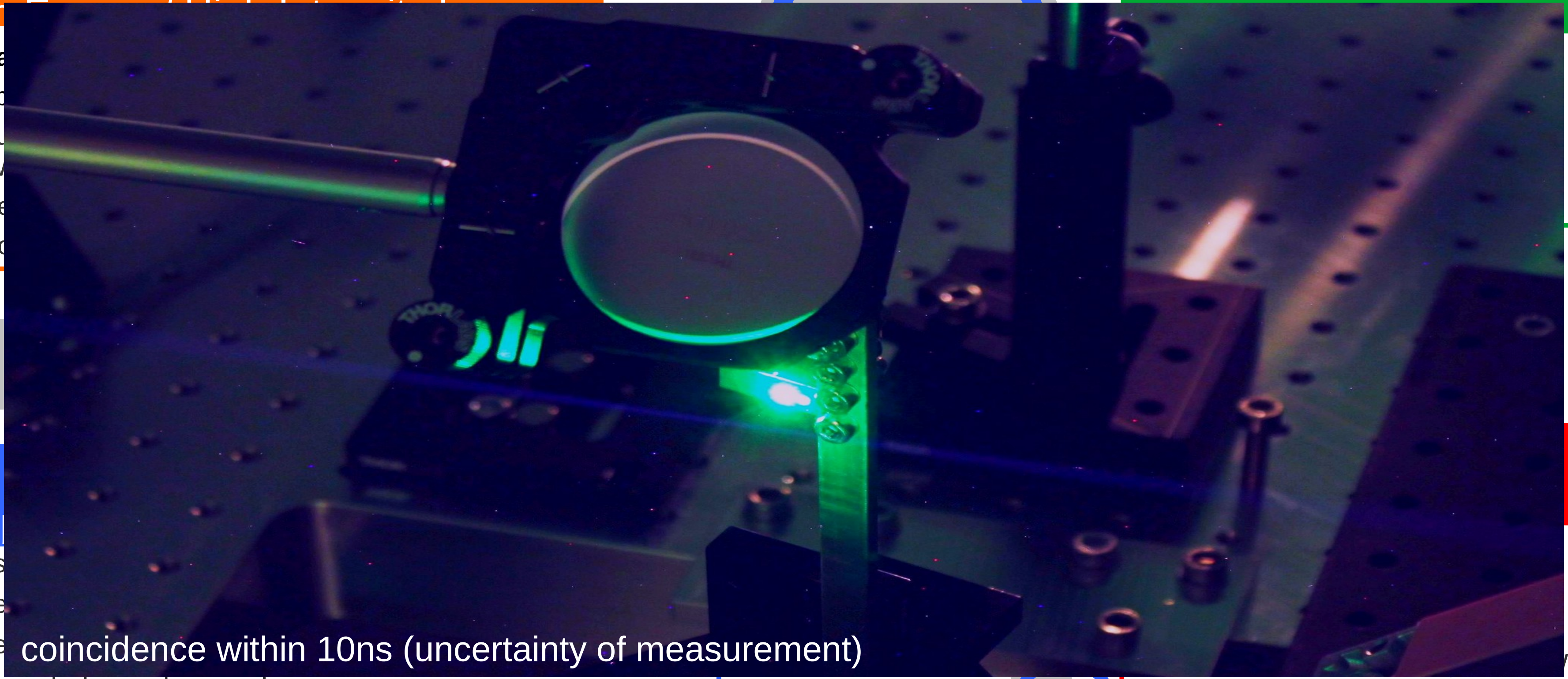
- focal sp
- maximu
5x10[20] W
- > 10[11] te
- repetitic

**SIS18**

- meas
- trigge
- trigge
- measure kicker probe signal
- remeasure RF-phase

/cm²

CRYRING



# GMT Precision (Control)
# Sync PHELIX Pulse and Ion Bunch (*)

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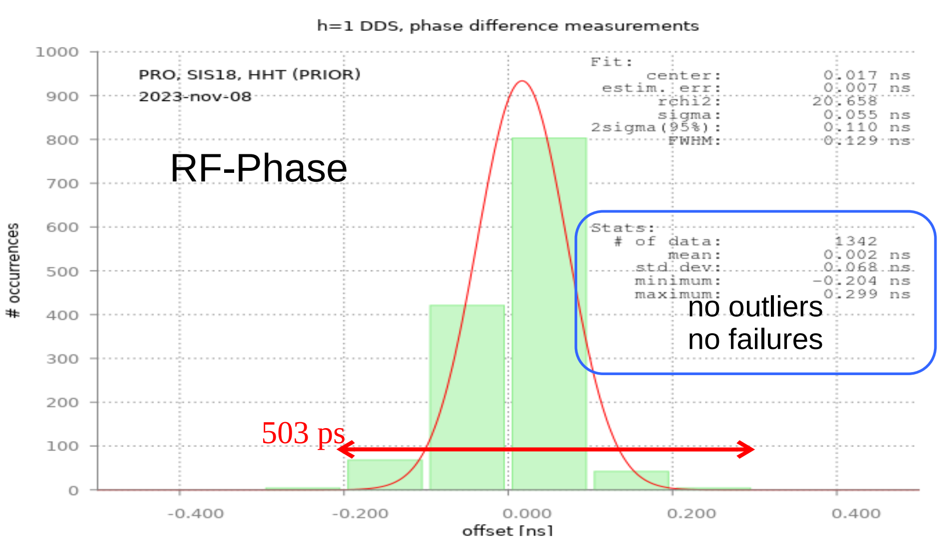


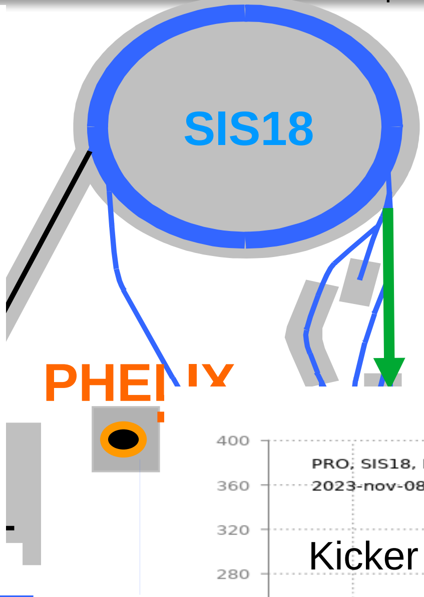


## SIS18

**SIS18, here:**

- **extracted bunch**
- length ~100ns
- v/c ~ 0.9

## GMT
## bunch-2-bucket transfer system

- measure SIS18 RF-phase
- trigger SIS18 extraction kicker (~ 2 GW)
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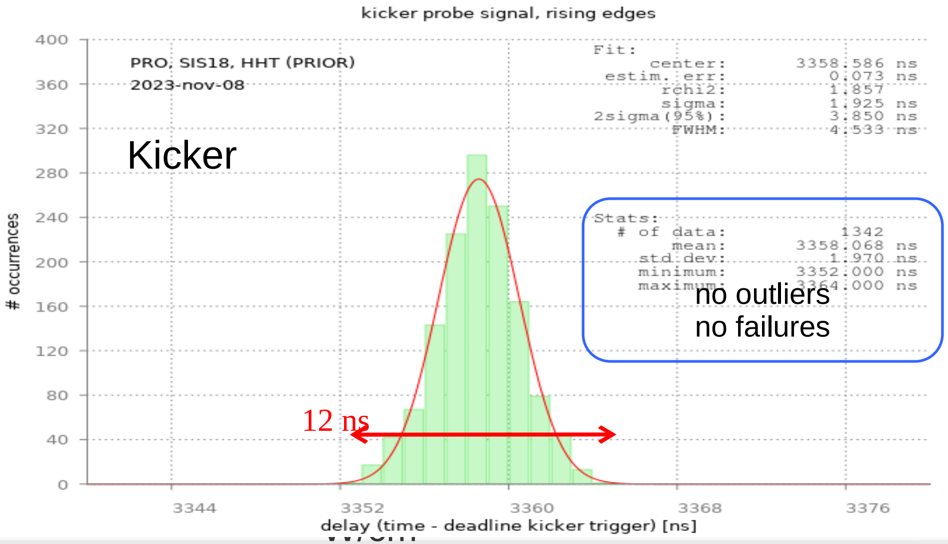


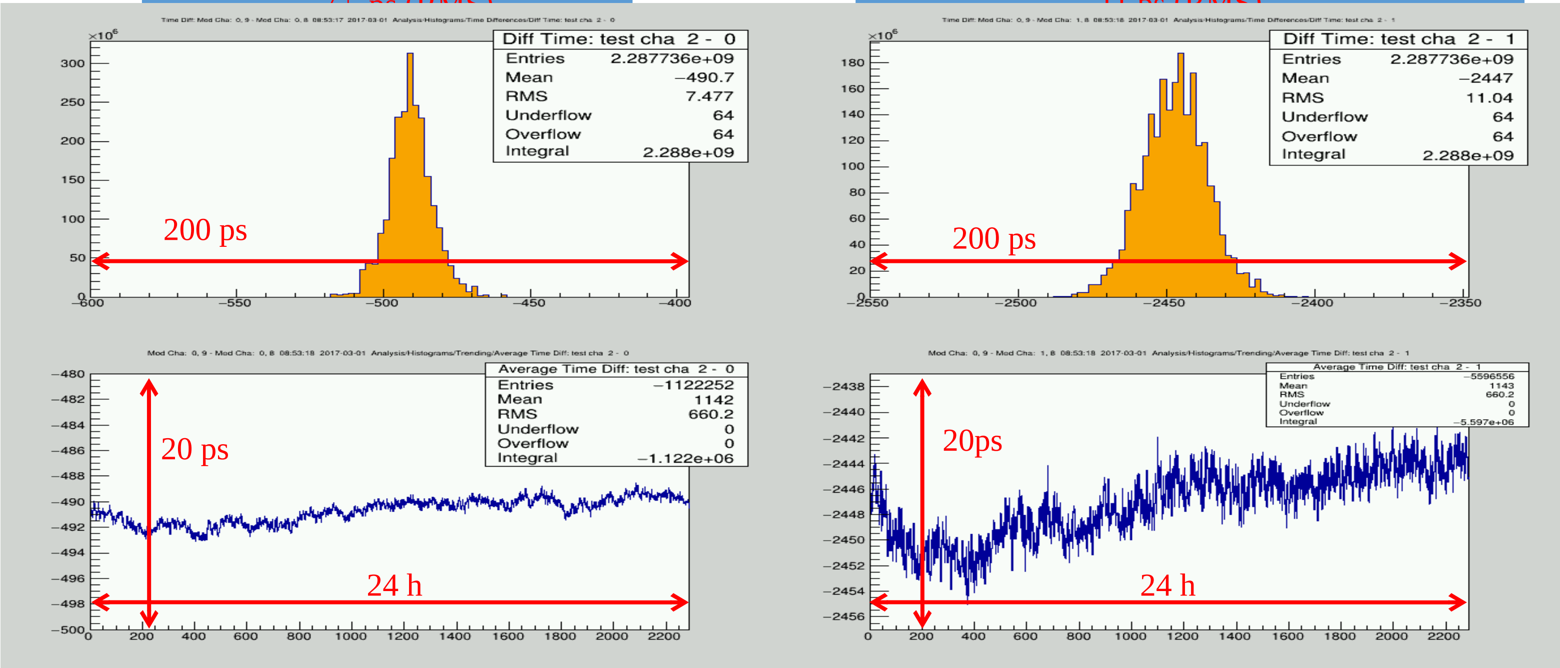
# GMT Precision (Experiments, DAQ)
# Time-of-Flight Measurements (*)

(*) N. Kurz et al., “White Rabbit 200 MHz Clock Effects on TOF Measured with High Resolution VME TDC VFTX” (2023)

time difference between 2 channels
fed in **identical** VFTX:
7.5 ps (RMS)

time difference between 2 channels
fed in **different** VFTX, synched by White Rabbit
11 ps (RMS)

→ jitter GMT, WR
~8 ps (RMS)




trending of average time differences
between 2 channels fed in **identical** VFTX
(each entry is average of 1000000 TOF measurements

trending of average time differences
between 2 channels fed in **different** VFTX
(each entry is average of 1000000 TOF measurements

# 2023: Experience from Operation II

good

- flawless recovery after a long (~ one hour, UPS down) power-cut during shutdown
- no issues with fiber links:

  SFP[1]s with DOM[2]: monitor voltage, current, temperature, TX/RX laser power ...
- ...

bad

- broken fans at about 12 White Rabbit Switches, detected by temperature monitoring

  no ‚tacho-signal’, not ‚hot-swappable‘; life expectancy better than 8 yrs, but ...

  in case you know a source for ‘IT quality’ (cisco type) fans, please let us know

  good: switches may survive some time with passive cooling (no interruption of operation)
- WRS power supply not redundant, not hot swappable‘; good: no issues so far
- ...

[1]SFP: Small Form-factor Pluggable
[2]DOM: Digital Optical Monitoring

# White Rabbit @ GSI: Switches Off-the-shelf, Nodes Based on Arria GX

## WR Switch

Seven Sol, Spain
Creotech, Poland


~99 units in use

## Scalable Control Unit (SCU3)

in-house development
Arria II based
~580 units

## PEXARIA V (PCIe ArriaV)

in-house development
Arria V based
~370 units

## Scalable Control Unit (SCU4)

in-house development
Arria X based
under development

## TR for PCIe (TR-PEXP)

in-kind contribution SI
Arria V based
~630 units
www.ohwr.org

## TR for AMC (TR-AMC)

in-kind contribution SI
Arria V based
~280 units
www.ohwr.org

## TR for PMC (TR-PMC)

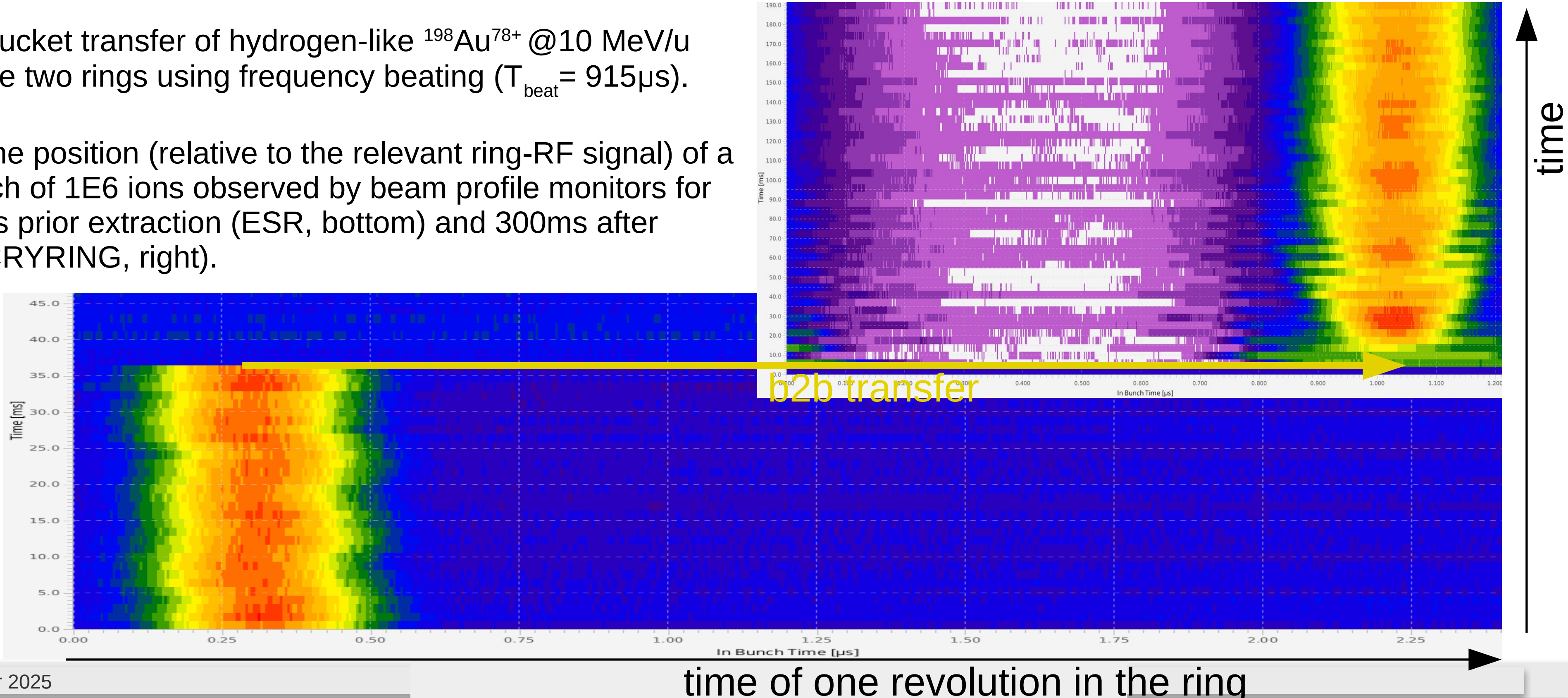
in-kind contribution SI
Arria V based
~220 units
www.ohwr.org

# 2022: Experience from Operation II

BTW: Since 2022 we have White Rabbit based synchronization **of transfers** between all ring machines, the so-called ‚bunch-to-bucket transfer system‘ is used in routine operation!

Bunch-to-bucket transfer of hydrogen-like $^{198}Au^{78+}$ @10 MeV/u between the two rings using frequency beating ($T_{beat}$= 915µs).

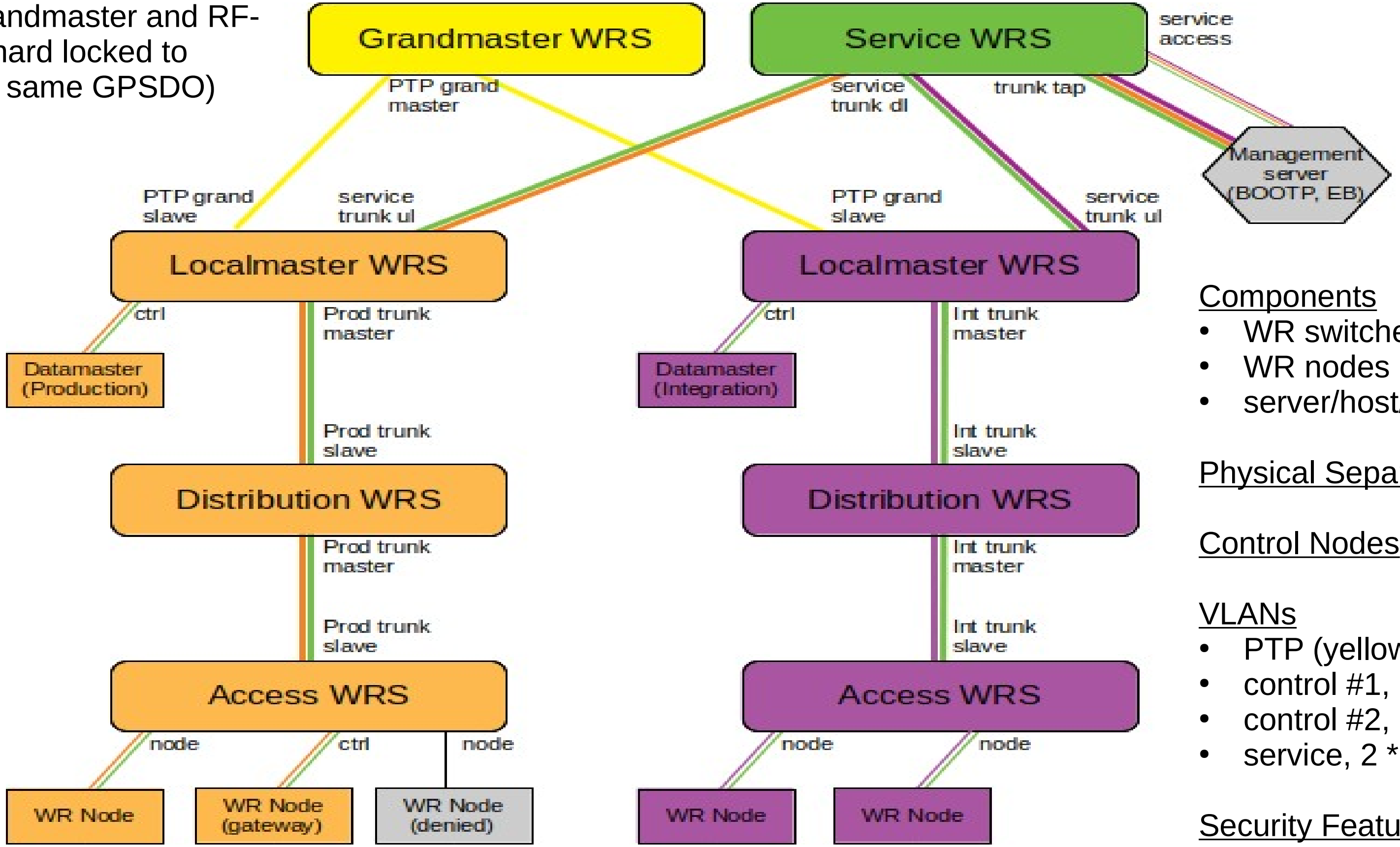
Shown is the position (relative to the relevant ring-RF signal) of a single bunch of 1E6 ions observed by beam profile monitors for about 35ms prior extraction (ESR, bottom) and 300ms after injection (CRYRING, right).



# Integration into IT Environment, Configuration: Task Timing Group (*)

(*) inspired by ‘Guidelines for White Rabbit Infrastructure at CERN’

(WRS Grandmaster and RF-Systems hard locked to physically same GPSDO)




Components
- WR switches (boxes)
- WR nodes (rectangles)
- server/host/IT (hexagon)

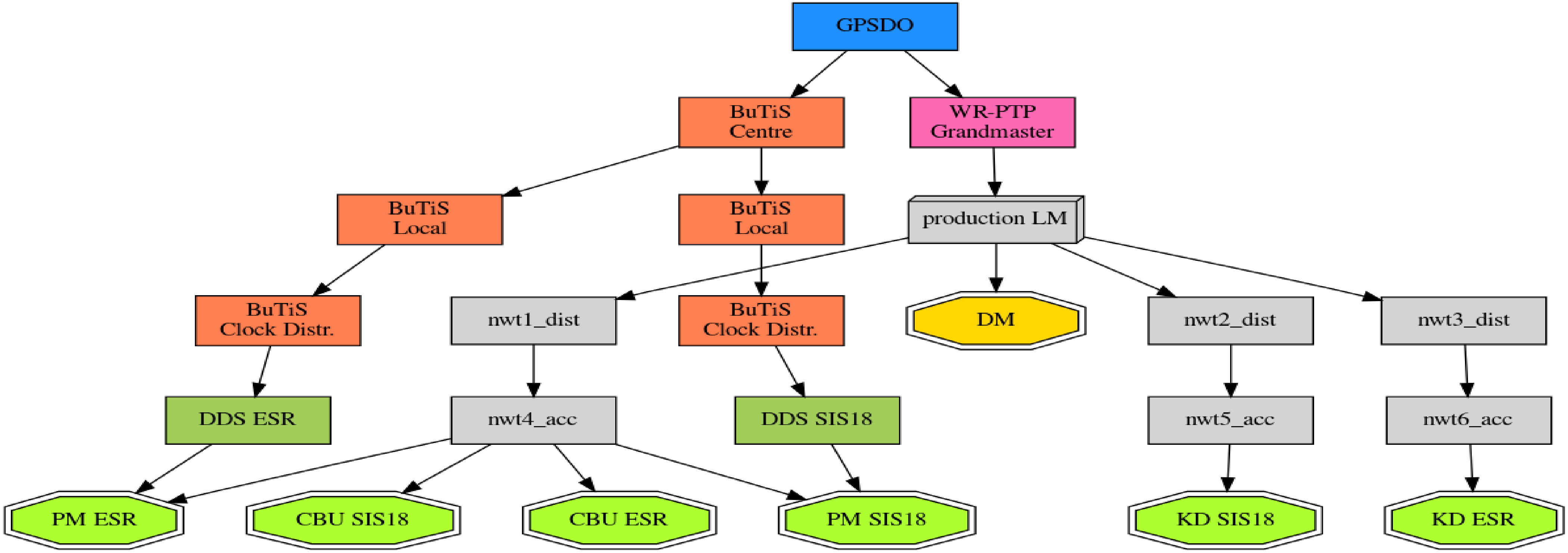
Physical Separation of Networks

Control Nodes: broadcast of ‘telegrams’

VLANs
- PTP (yellow)
- control #1, production (orange)
- control #2, integration (magenta)
- service, 2 * uni-directional (lime)

Security Features for Regular Nodes
- MAC based authentication (802.1X)
- only in **service VLAN**
- uni-directional to management master only

# Clock Propagation




Components: GPSDO (blue), White Rabbit Grandmaster (cyan) and Switches (grey), rf-clock distribution system (BuTiS, brown), rf-group-DDS systems (dark green), nodes of the b2b system (light green) and Data Master of the Machine Timing System (yellow). Nodes with double-lined borders broadcast messages to the White Rabbit network.
Black arrows indicate clock propagation.

Roles of WRS: LM (local master), dist (distribution switch), acc (access switch)
Roles of b2b: CBU (Central Bunch-2-bucket Unit), PM (Phase Measurement), KD (Kicker and Diagnostic)

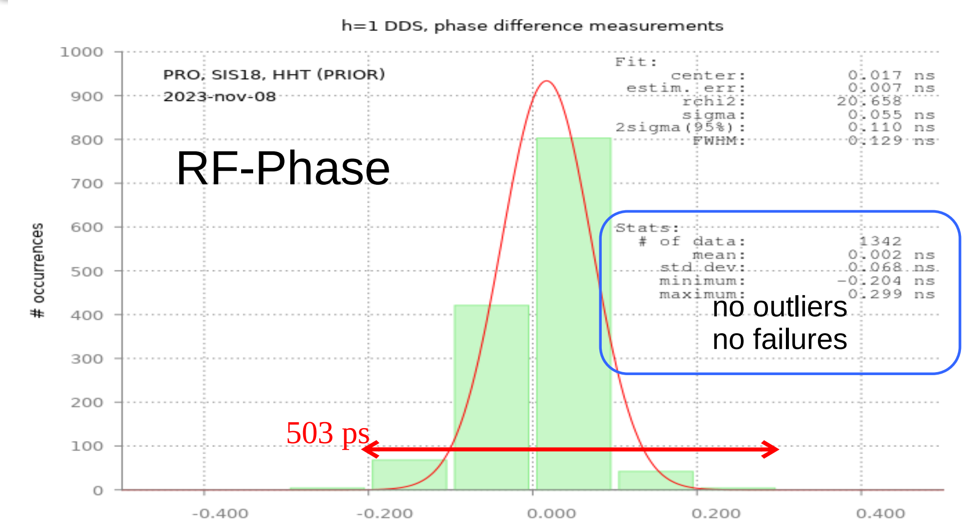
# Integration into IT Environment
# Accelerator IT and Central IT

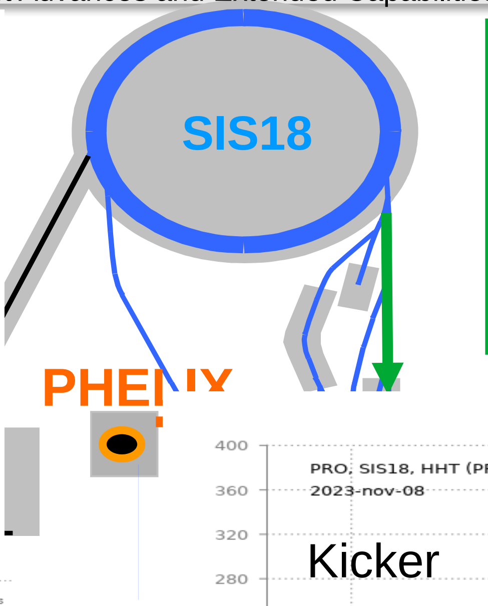
they provide ...

- IP backend, dedicated subnets and VLANs, unique on the GSI campus
- redundant DHCP/BOOTP servers for all WRS and nodes
- redundant name servers for all WRS and nodes
- redundant Radius servers (VLANs, 802.1X)
- protected White Rabbit switch management network (‚plug-and-play‘)
- (central firewall management)
- management server for all White Rabbit networks
- FNT-command: tool for documenting installations
- Icinga: WRS monitoring (health)
- Grafana: monitoring of key parameters
- Netdisco: auto-discovery of switches and nodes (really cool!)
- web server: remote management (dedicated tools)

# GMT Precision (Control)
# Sync PHELIX Pulse and Ion Bunch (*)

(*) Zs. Major et al., "High-Energy Laser Facility PHELIX at GSI: Latest Advances and Extended Capabilities", in preparation (2023)



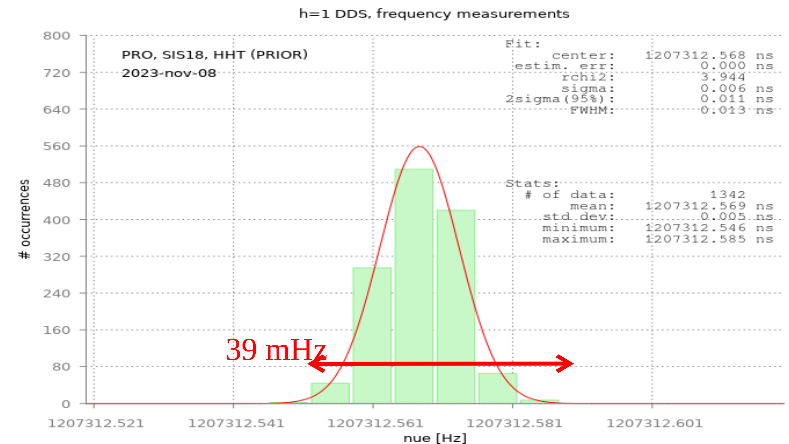

## SIS18

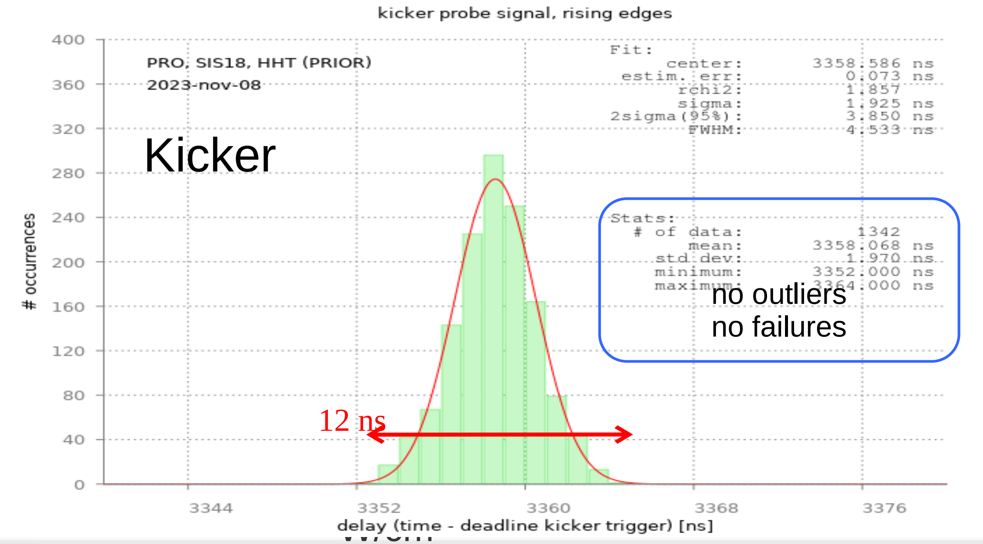
**SIS18, here:**

- **extracted bunch**
- length ~100ns
- v/c ~ 0.9

b

- meas
- trigge
- trigge
- meas
- reme



# Kicker Power Supply ...

1. pre-fire (~1 µs): discharge capacitors → 'transformer+electron tubes' → high voltage → charge cables
2. fire: ~ 1µs later, discharge cables via electron tubes, up to 200 MW per tube (pulse length < 1µs)