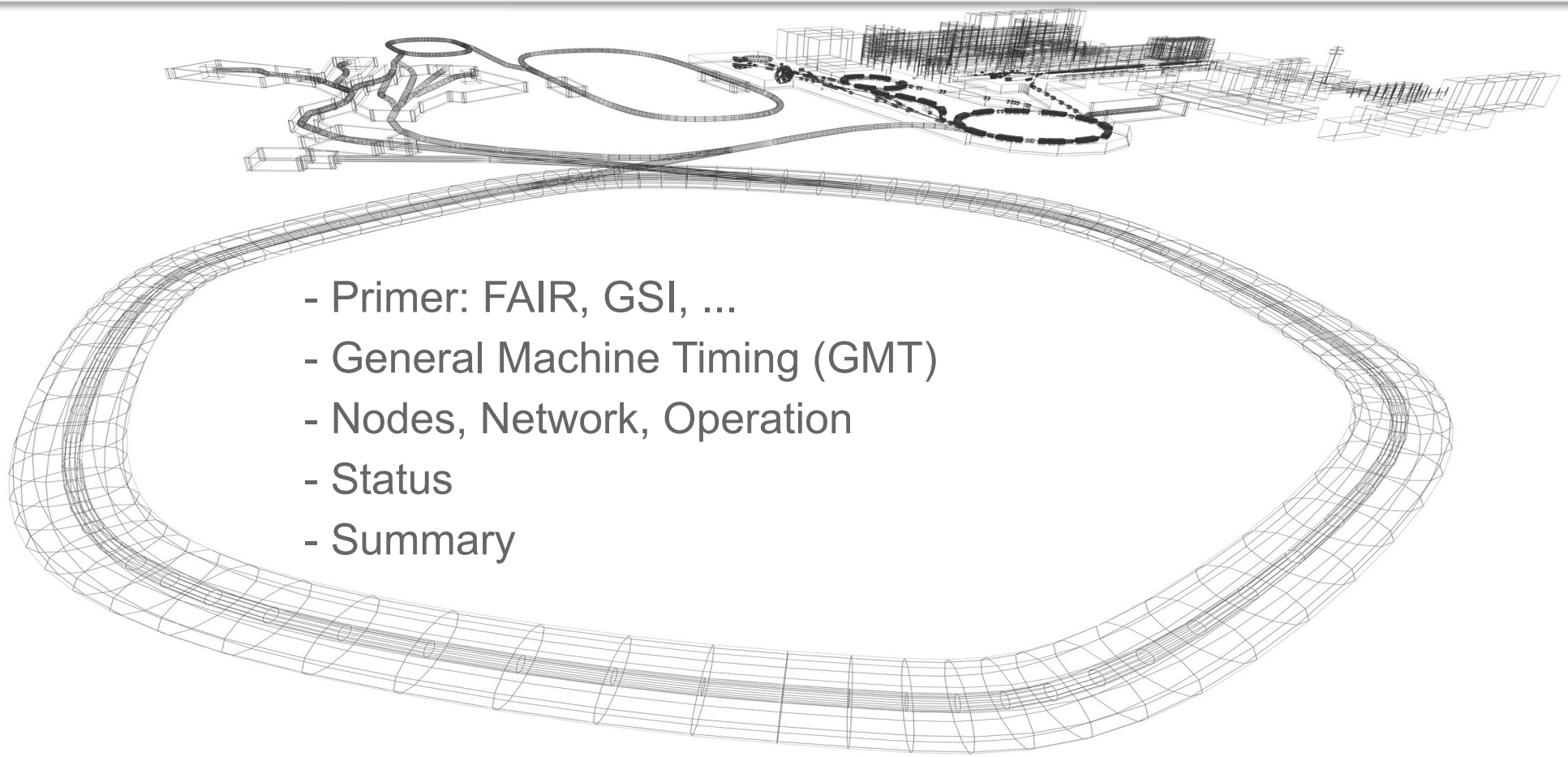
Acknowledgments

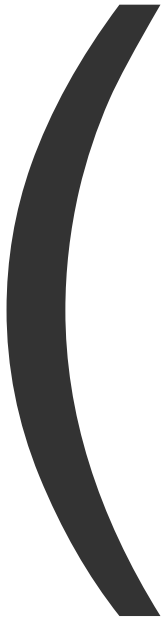
- GSI Timing Team: Enkhbold Ochirsuren, Marcus Zweig, Stefan Rauch, Mathias Kreider, Martin Skorsky, Marco Dennstädt, Michael Reese, Anna Ranz, Alexander Hahn, Frederic Ameil
- GSI ACC-IT Team: Peter Pfister, Christoph Handel, Rosemarie Vincelli …
- GSI Ring-RF Team: Dieter Lens, Bernhard Zipfel …
-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

WR at GSI and FAIR: Status Report



- Primer: FAIR, GSI, ...
- General Machine Timing (GMT)
- Nodes, Network, Operation
- Status
- Summary

General Machine Timing: GMT (Some Background)



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: readiness for ‚Early Science‘

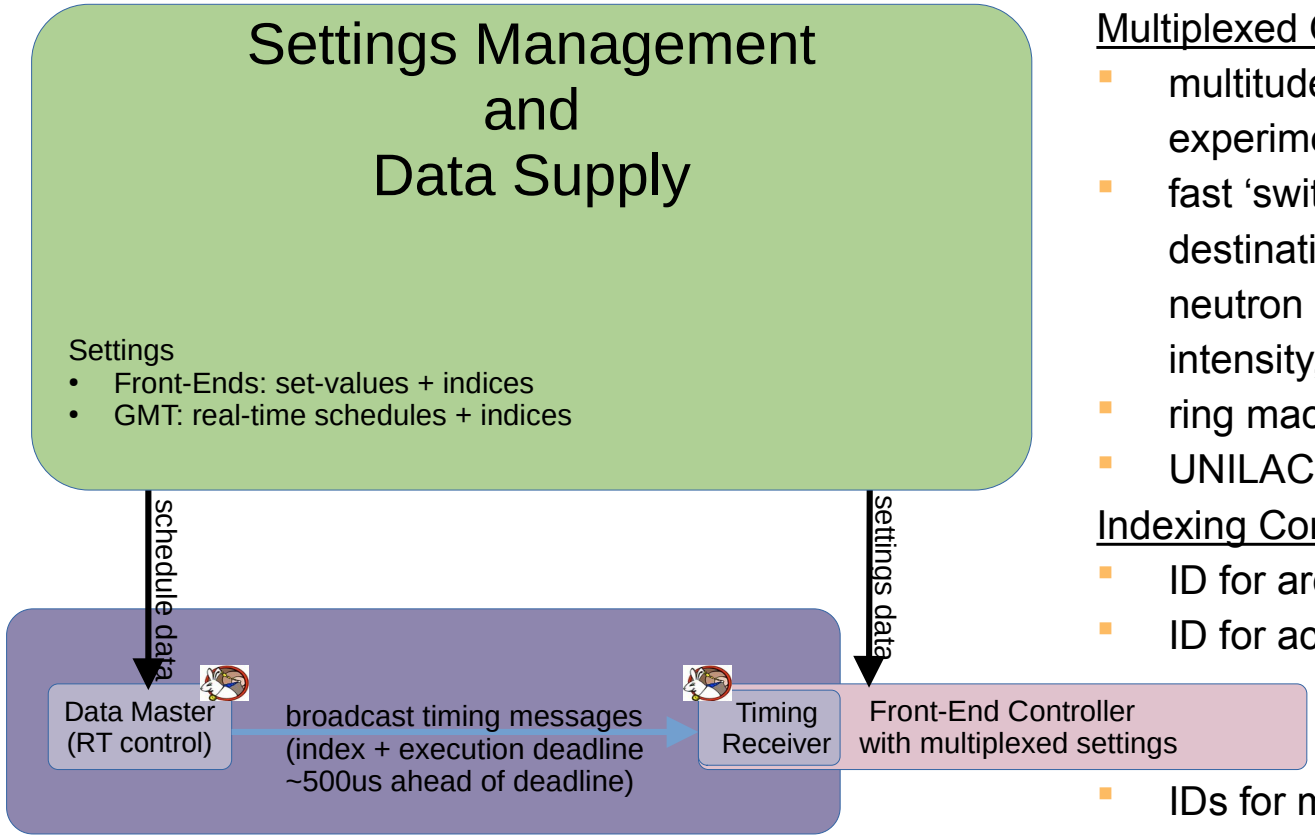
FAIR from the Control System Perspective

SIS100 ring tunnel

transfer line from GSI to FAIR

- FAIR: international accelerator facility
- GSI as injector
- installation of technical networks started
- spring 2026: commissioning starts
- late 2027: readiness for ‚Early Science‘

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 setting‘)
- other information

FAIR from the Control System Perspective

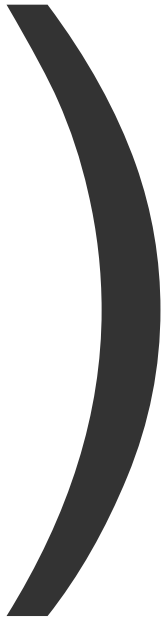
'FAIR Control System' @ GSI campus

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

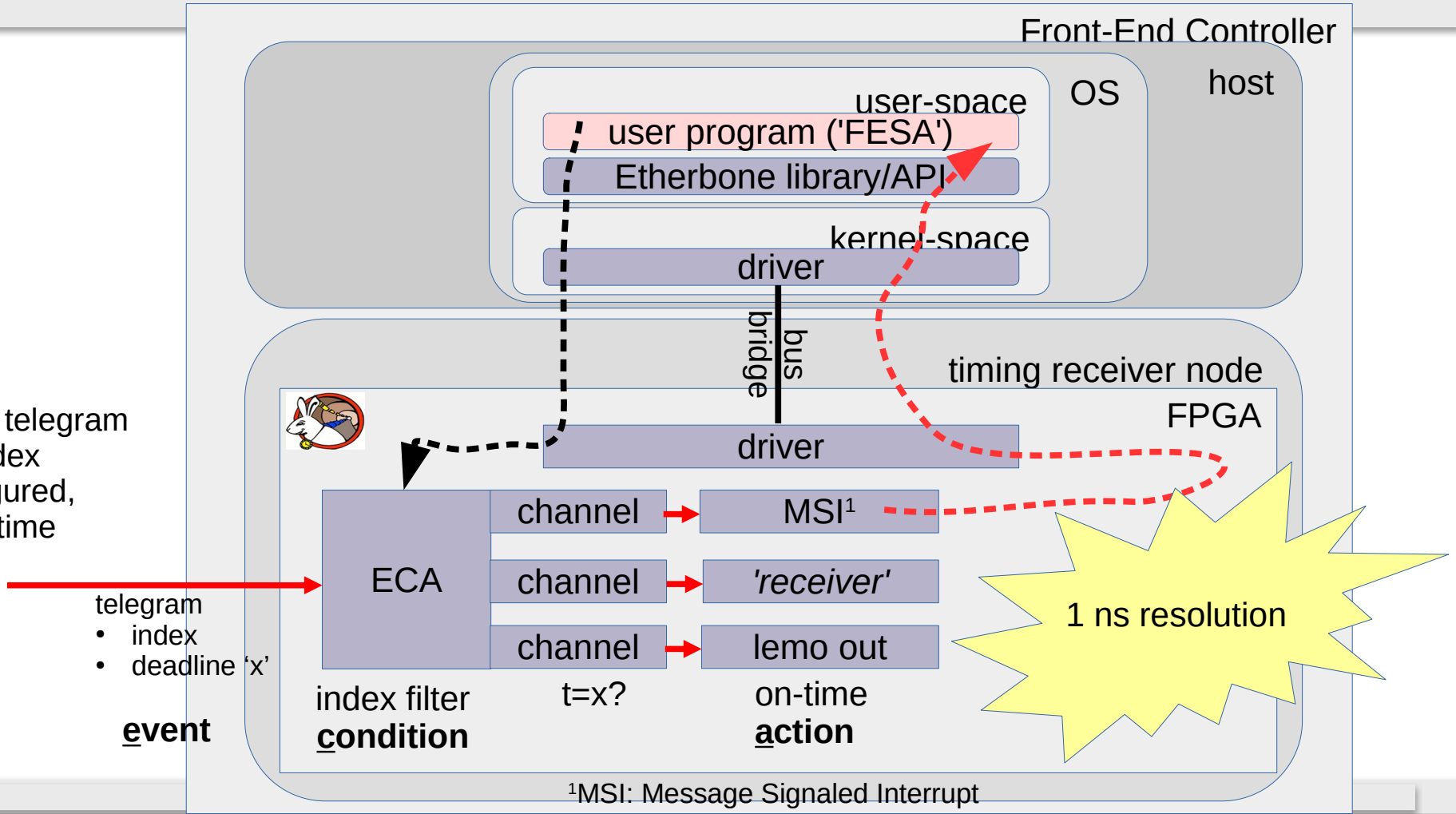
FAIR Campus including 'First Science+'

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



General Machine Timing

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



Common Features for Nodes
'Everything Happens in the FPGA'

no application specific VHDL!

instead: customization via

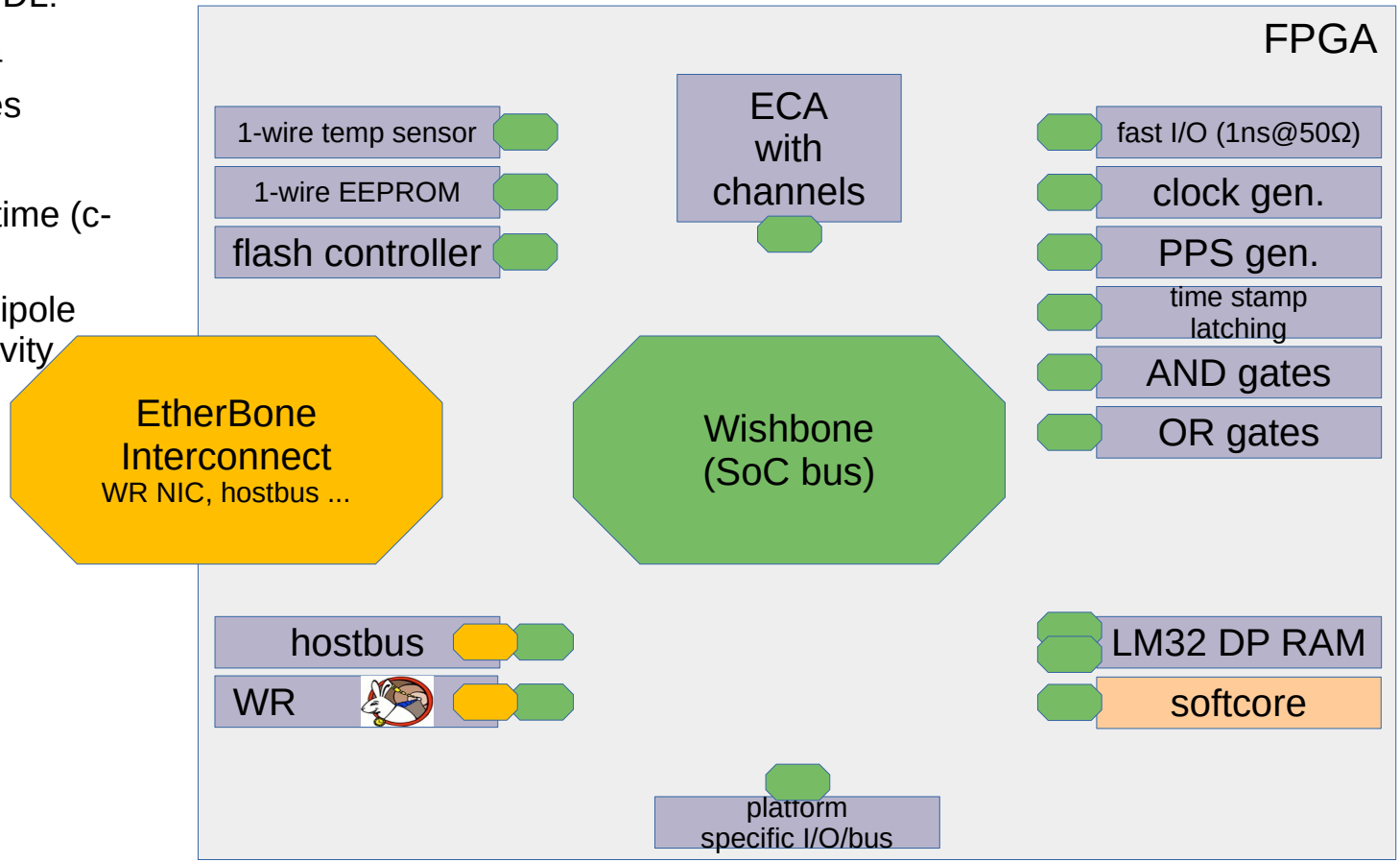
- configuration of IP cores
- (LM32) softcore:

  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

instead: c

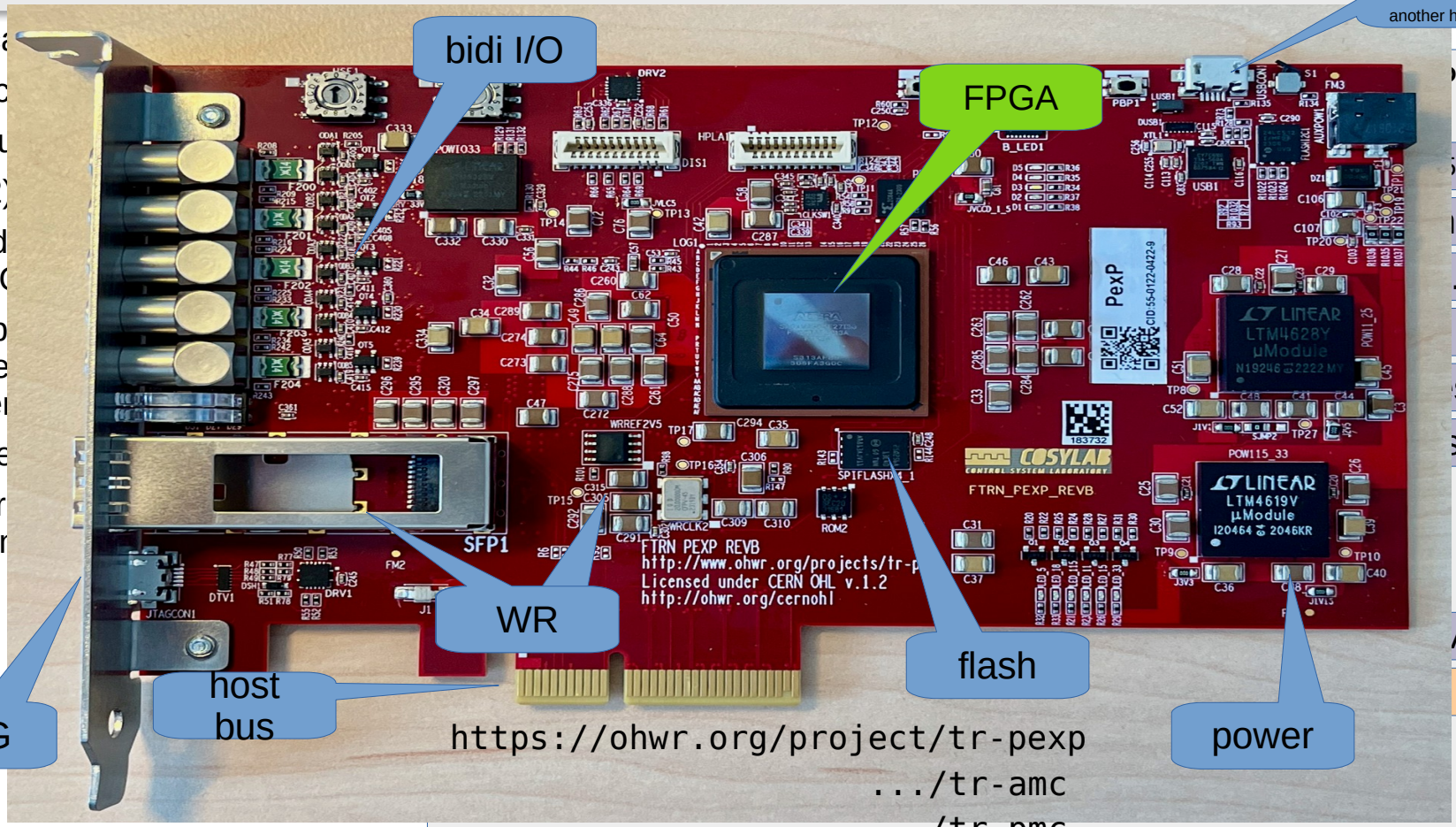
- configu
- (LM32)

  upload
  code, C

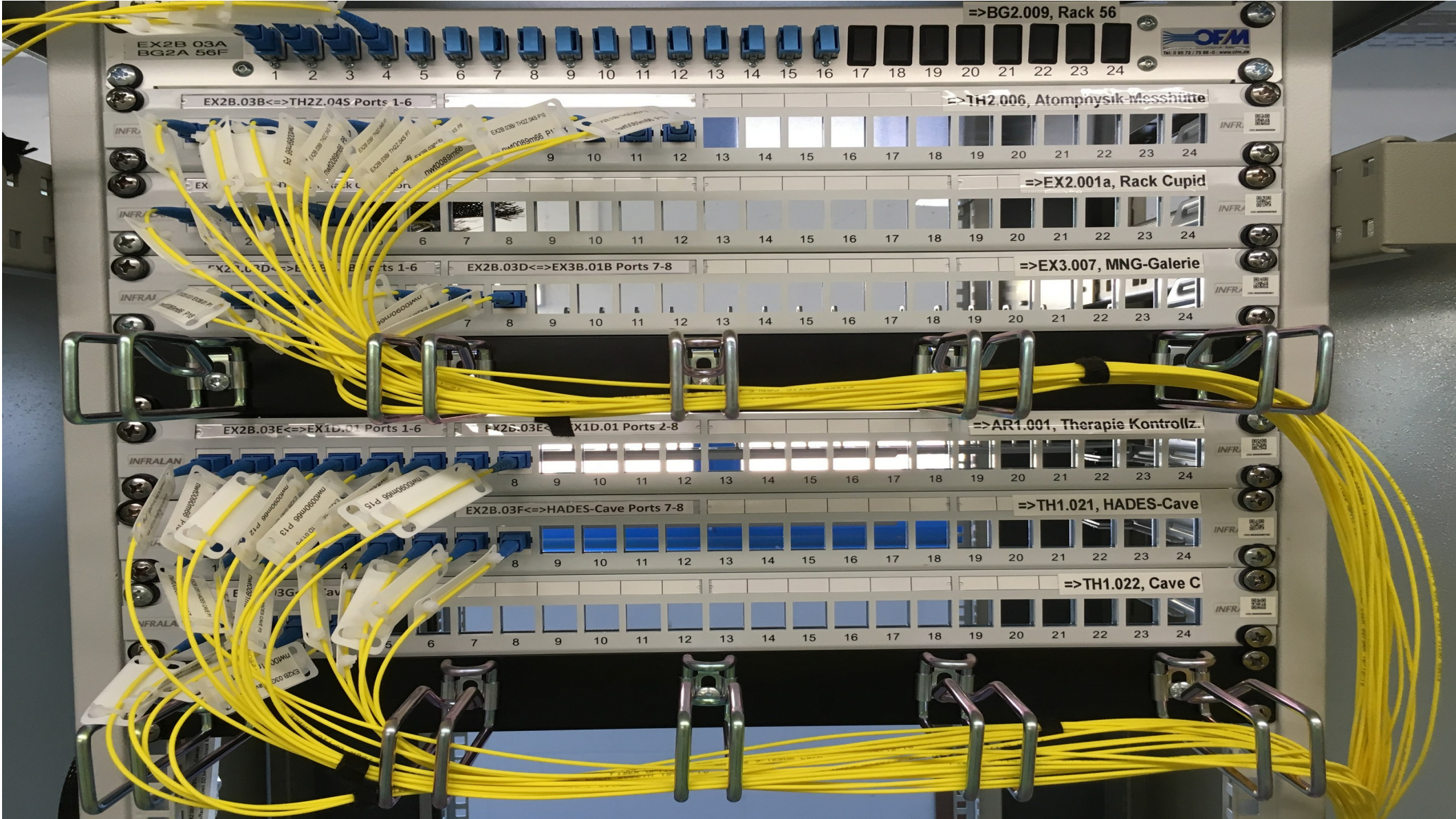
  examp
  magne
  freque

  hard re

  synchr
  many r



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


EX2B 03A
BG2A 56F
=>BG2.009, Rack 56
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
EX2B.03E<=>EX1D.01 Ports 1-6
=>AR1.001, Therapie Kontrollz.
EX2B.03F<=>HADES-Cave Ports 7-8
=>TH1.021, HADES-Cave
=>TH1.022, Cave C


GTS3QT32

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the years: modified firmware of White Rabbit Switch to behave more like regular IT switches; MIBs, 802.1X …
thanks to C. Handel, A. Rubini, A. Wujek; merged into OHWR)

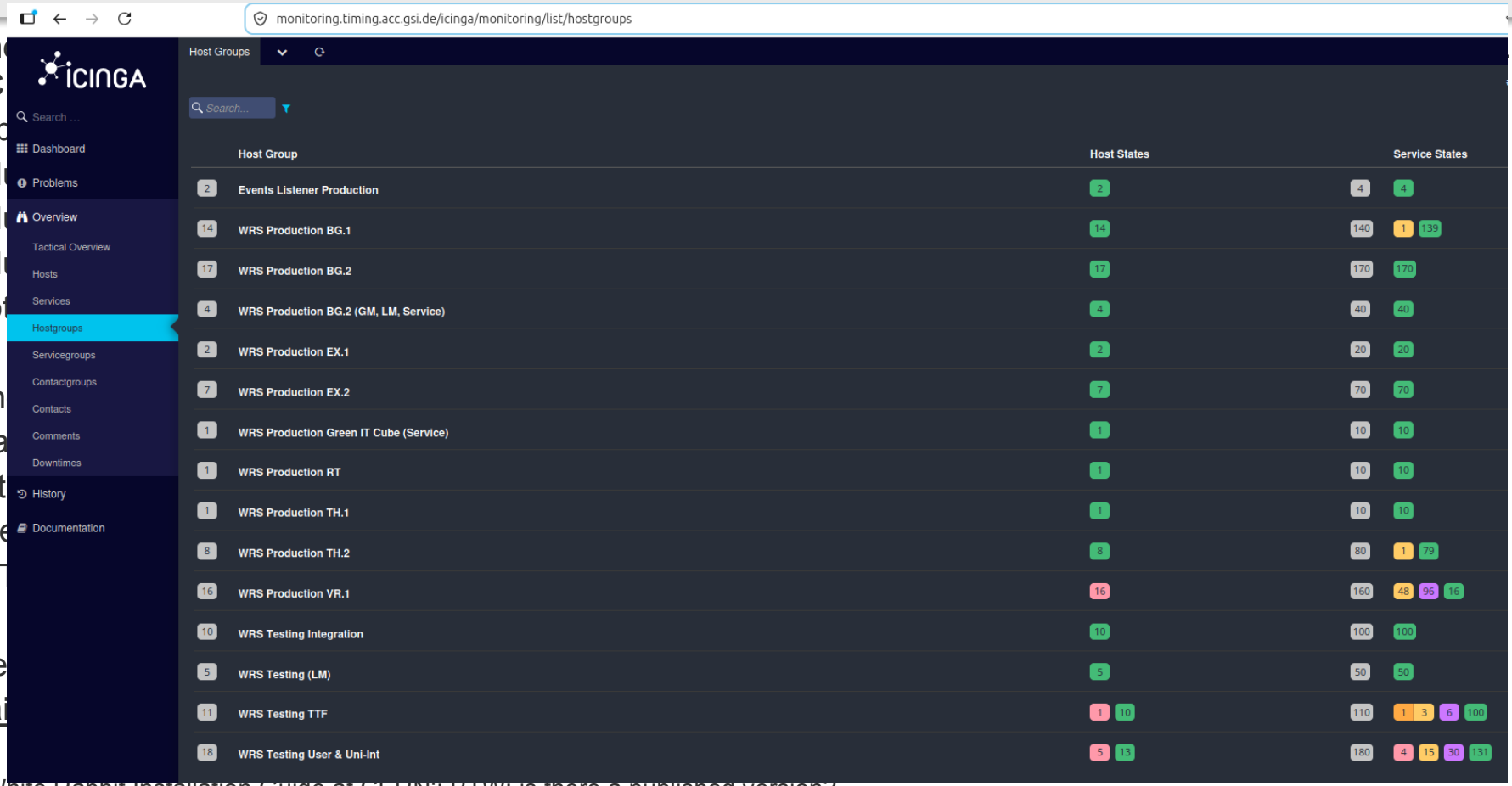
- IP backend, dedicated subnets and VLANs, unique on the GSI and FAIR campus
- redundant DHCP/BOOTP servers for all WRS and nodes
- redundant name servers for all WRS and nodes
- redundant Radius servers (VLANs, 802.1X)
- protected White Rabbit switch management network (‚plug-and-play')
- ...
- Icinga: WRS monitoring (health)
- Grafana: monitoring of key parameters (WRS packet rates, temperatures, fan set-values ...)
- Netdisco: auto-discovery of switches and nodes and how they are connected (really cool!)
- OpenSearch: Logging (all WRS log messages go here ...)
- FNT Command: documentation (very useful)
- ...
- user roles, accounts, security, …
- **maintenance**

[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over th
thx to C

- IP b
- redu
- redu
- redu
- prof
- ...
- Icin
- Gra
- Net
- Ope
- FNT
- ...
- use
- **mai**



[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the years: modified firmware of White Rabbit Switch to behave more like regular IT switches; MIBs, 802.1X …
thx to C. Handel, A. Rubini, A. Wujek; merged into OHWR)

- IP backend, dedicated subnets and VLANs, unique on the GSI and FAIR 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 (WRS packet rates, temperatures, fan set-values ...)
- Netdisco: auto-discovery of switches and nodes and how they are connected (really cool!)
- OpenSearch: Logging (all WRS log messages go here ...)
- FNT Command: documentation (very useful)
- ...
- user roles, accounts, security, …
- **maintenance**

[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the years: modified firmware of White Rabbit Switch to behave more like regular IT switches; MIBs, 802.1X …
thx to C. Handel, A. Rubini, A. Wujek; merged into OHWR)

- IP backend, dedicated subnets and VLANs, unique on the GSI and FAIR campus
- [redacted]

- Grafana: monitoring of key parameters (WRS packet rates, temperatures, fan set-values ...)
- Netdisco: auto-discovery of switches and nodes and how they are connected (really cool!)
- OpenSearch: Logging (all WRS log messages go here ...)
- FNT Command: documentation (very useful)
- ...
- user roles, accounts, security, …
- **maintenance**

[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the years: modified firmware of White Rabbit Switch to behave more like regular IT switches; MIBs, 802.1X …
thx to C. Handel, A. Rubini, A. Wujek; merged into OHWR)

- IP backend, dedicated subnets and VLANs, unique on the GSI and FAIR 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 (WRS packet rates, temperatures, fan set-values ...)
- Netdisco: auto-discovery of switches and nodes and how they are connected (really cool!)
- OpenSearch: Logging (all WRS log messages go here ...)
- FNT Command: documentation (very useful)
- ...
- user roles, accounts, security, …
- **maintenance**

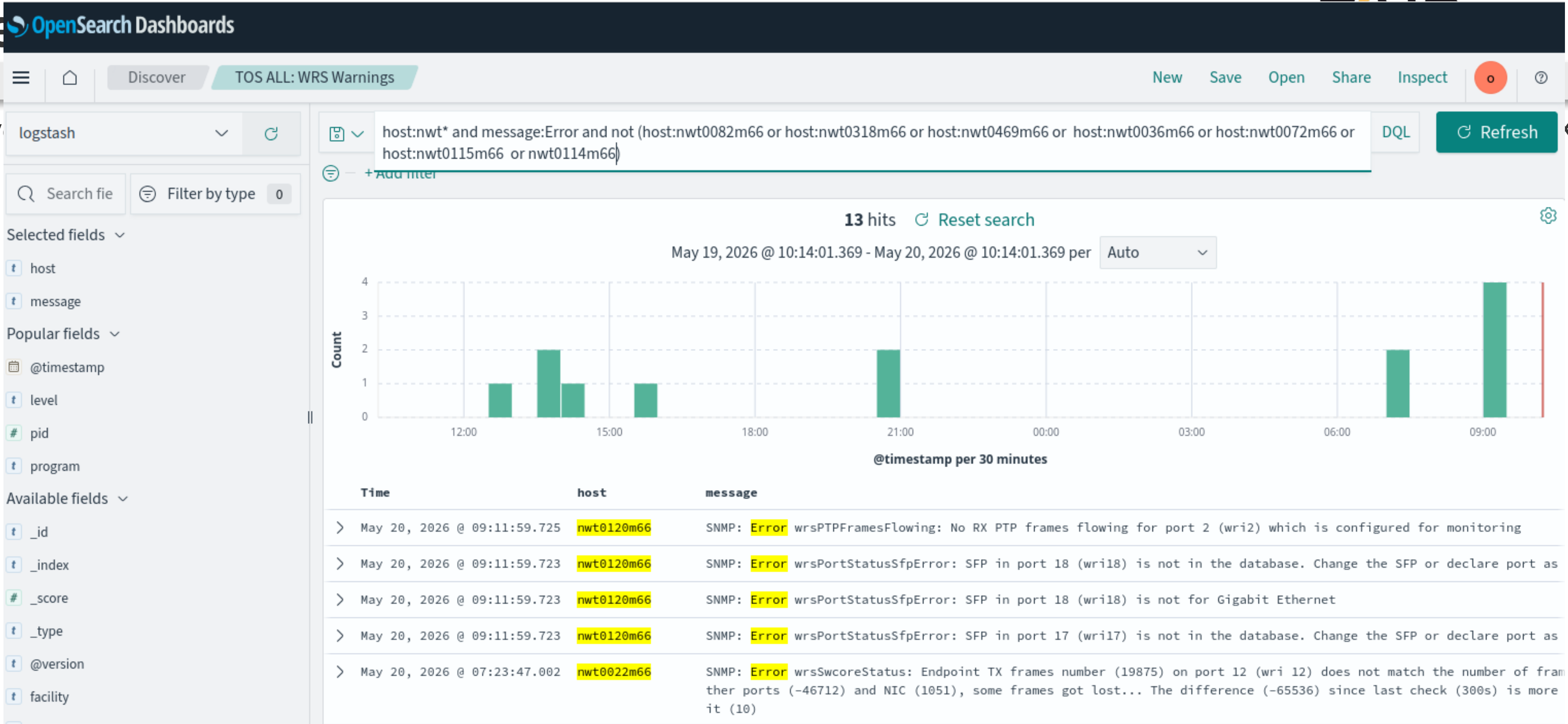
[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment

Le

(ov … (…

thx



- …
- user roles, accounts, security, …
- <u>**maintenance**</u>

[1] see ‚White Rabbit Installation Guide at CERN‘; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the years: modified firmware of White Rabbit Switch to behave more like regular IT switches; MIBs, 802.1X …
thx to C. Handel, A. Rubini, A. Wujek; merged into OHWR)

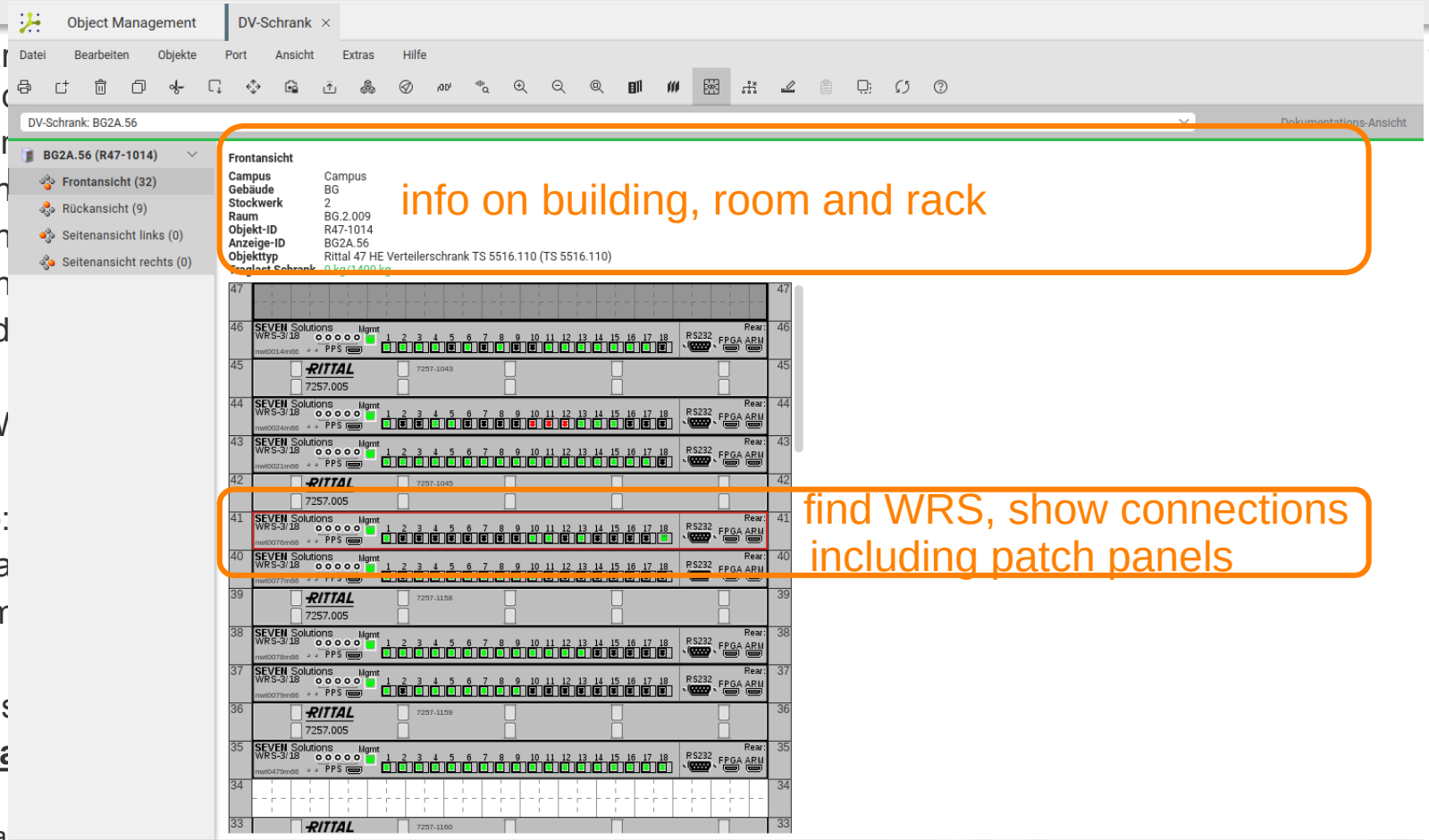
- IP backend, dedicated subnets and VLANs, unique on the GSI and FAIR campus
- redundant DHCP/BOOTP servers for all WRS and nodes
- redundant name servers for all WRS and nodes
- redundant Radius servers (VLANs, 802.1X)
- protected White Rabbit switch management network (‚plug-and-play')
- ...
- Icinga: WRS monitoring (health)
- Grafana: monitoring of key parameters (WRS packet rates, temperatures, fan set-values ...)
- Netdisco: auto-discovery of switches and nodes and how they are connected (really cool!)
- OpenSearch: Logging (all WRS log messages go here ...)
- FNT Command: documentation (very useful)
- ...
- user roles, accounts, security, …
- **maintenance**

[1] see ‚White Rabbit Installation Guide at CERN'; BTW: is there a published version?

Integration into IT Environment
Lesson Learnt: Let IT People do the IT Stuff

(over the year … 1X …
thx to C. Han

- IP backer
- redundan
- redundan
- redundan
- protected
- ...
- Icinga: W
- Grafana:
- Netdisco:
- OpenSea
- FNT Com
- ...
- user roles
- **maintena**



[1] see ‚White Ra… Installation Guide at CERN‘, BTW: Is there a published version?

Integration into IT Environment
GSI White Rabbit Team

- planning of installation
- installation of WR switches
- patching
- configuration; WRS configured via local dot-config (auto-recovery must not depend on other infrastructure)
- operation
  - monitoring
  - on-call service
- documentation
- …

2026: Experience from Operation

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

- nodes: monitor uptime, (dis)continuites of PTP time, loss of track-phase
- network: monitor switches and laser power of fiber links
- flawless recovery after a major power-cut (> 1 hour, UPS without power …)
- support from White Rabbit Collaboration; WRS firmware → v7.0 → v8.0 → v8.0x (get PWM set-value via SNMP)

bad (White Rabbit)

- WRS: power supply so far reliable without issues; but not easily swappable (just in case)
- WRS: NAND flash may become corrupt if WRS is not powered for a long time (years)
- WRS: fans (next slide)

WRS Fans :-(

30 switches with broken fans since 2016

- no monitoring of fan speed
- very often, a failure of one fan can not be detected by temperature monitoring
- need to visit all WRS in the facility regularly
- we learned how-to replace fans quickly; caveat: not allowed during operation
- always replace both fans

In general: Try to keep WRS ‘FPGA temperature’ below 60 degree, but the environment is often not ideal

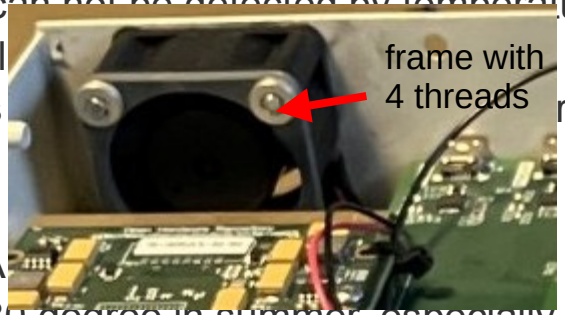
- room/rack temperatures up to 30 degree in summer, especially during operation
- misbehaving equipment in the same rack (warm air pushed out at the front, not at the back)
  → try to find cooler places for WRS; basically move WRS to the lower part of a rack
- in some locations: (sticky?) dust gets trapped at ‘fingers’ of FPGA heat sink: air flow reduced
  → compressed air spray through SMB plugs on front panel as most effective emergency measure
- maybe fans could be more powerful (just comparing to the fan noise of of regular IT switches)

Fans of standard 1U IT switches never have these problems → we tried to find an alternative but without success
Help from WRC to find a another source for fans will be highly appreciated!

WRS Fans :-(

30 switches with broken fans since 2016

- no monitoring of fan speed
- very often, a failure of one fan can not be detected by temperature monitoring
- need to visit all WRS in the facil
- we learned how-to replace fans ring operation
- always replace both fans



In general: Try to keep WRS 'FPGA but the environment is often not ideal

- room/rack temperatures up to 30 degree in summer, especially during operation
- misbehaving equipment in the same rack (warm air pushed out at the front, not at the back)
  → try to find cooler places for WRS; basically move WRS to the lower part of a rack
- in some locations: (sticky?) dust gets trapped at 'fingers' of FPGA heat sink: air flow reduced
  → compressed air spray through SMB plugs on front panel as most effective emergency measure
- maybe fans could be more powerful (just comparing to the fan noise of of regular IT switches)

Fans of standard 1U IT switches never have these problems → we tried to find an alternative but without success
Help from WRC to find a another source for fans will be highly appreciated!

WRS Fans :-(

30 switches with broken fans since 2016

- no monitoring of fan speed
- very often, a failure of one fan can not be detected by temperature monitoring
- need to visit all WRS in the facility regularly
- we learned how-to replace fans quickly; caveat: not allowed during operation
- always replace both fans

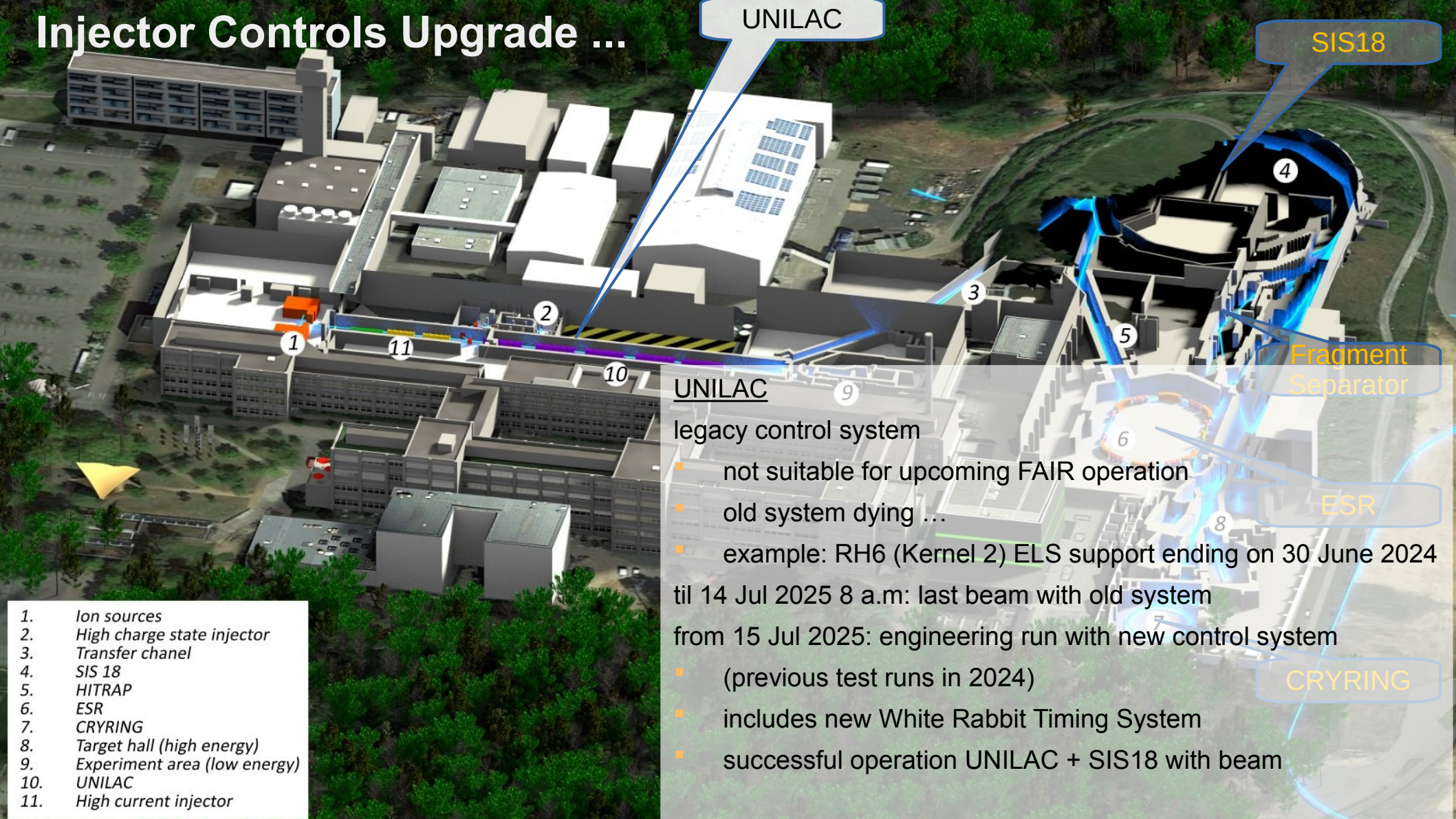
In general: Try to keep WRS ‘FPGA temperature’ below 60 degree, but the environment is often not ideal

- room/rack temperatures up to 30 degree in summer, especially during operation
- misbehaving equipment in the same rack (warm air pushed out at the front, not at the back)
  → try to find cooler places for WRS; basically move WRS to the lower part of a rack
- in some locations: (sticky?) dust gets trapped at ‘fingers’ of FPGA heat sink: air flow reduced
  → compressed air spray through SMB plugs on front panel as most effective emergency measure
- maybe fans could be more powerful (just comparing to the fan noise of of regular IT switches)

Fans of standard 1U IT switches never have these problems

We have ~400 v3 WRS: Any suggestions for upgrading our v3 WRS to a better fan type?

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

UNILAC

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

Injector Controls Upgrade

- 2 distinct production networks: ‘injector’ 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 form factors done with Arria 10 GX FPGAs
(previously Arria II or V GX)

Starting up FAIR - The Plan ...

FAIR @ GSI, 2026

- installation of technical networks started
- spring 2026: commissioning starts
- end 2026: 1st beam to FAIR site
- 2027: readiness for ‚Early Science‘

5 February 2026

UNILAC

- technical defect → fire incident, ~200 firefighters
- good: fire protection measures in previous years ...
- … fire remained localized to one building
- inside that building: substantial damage to technical infrastructure!

5 February 2026

WR Installation one building level below the fire

- soot, firefighting water, condensation ...
- lost all active electronics – 18 WRS, nodes ...
- passive installation must be redone too … 😭

- UNILAC machine itself without major damage ...
- … but bringing it back to operation will take some time

Starting up FAIR – New Plan (Tentative - to be Confirmed)

@FAIR, Building G0407A.E20

FAIR @ GSI, 2026

- installation of technical networks started
- spring 2026: commissioning ~~starts~~ started
- summer 2026: install ~90 WRS in H0719A, SFRS
- autumn 2027: commissioning beamlines + SFRS - *Early Science* - using the PARTIH* injector
- spring 2028: *Early Science* operation using the InterLAC* injector
- autumn 2028: *First Science* = *Early Science*+SIS100 commissioning

* tentative names

Summary and Outlook

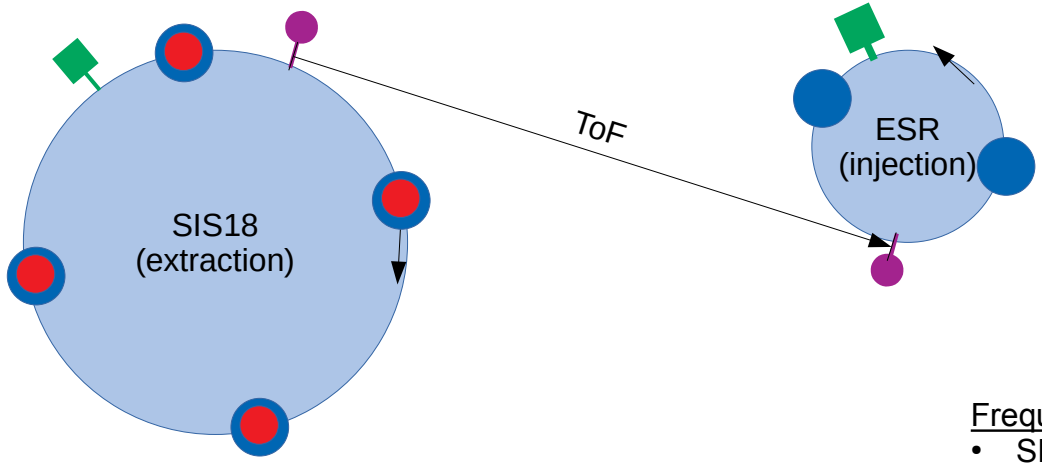
- ‘FAIR’ General Machine Timing (GMT) system installed at GSI, since 2016
  - based on White Rabbit
  - common notion of time, 1ns granularity, 10-100 ps precision
  - broadcast of ‘timing messages’ with upper bound latency
  - execution of tasks with 1ns resolution at planned deadline
  - routine operation 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
- 2026: fire incident: lost all WR equipment at Injector (18 WRS, nodes ...)
- FAIR going on at full speed, installation and commissioning started, first beam to the FAIR site planned for next year (2027)

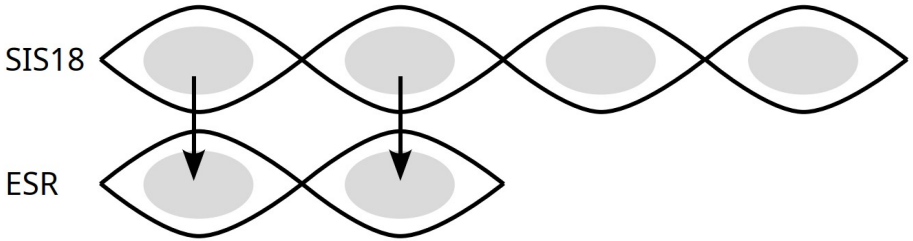
Thank You for Your Attention

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

(Backup Slides ...)

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





- ions circulate in a ring machine
- acceleration 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

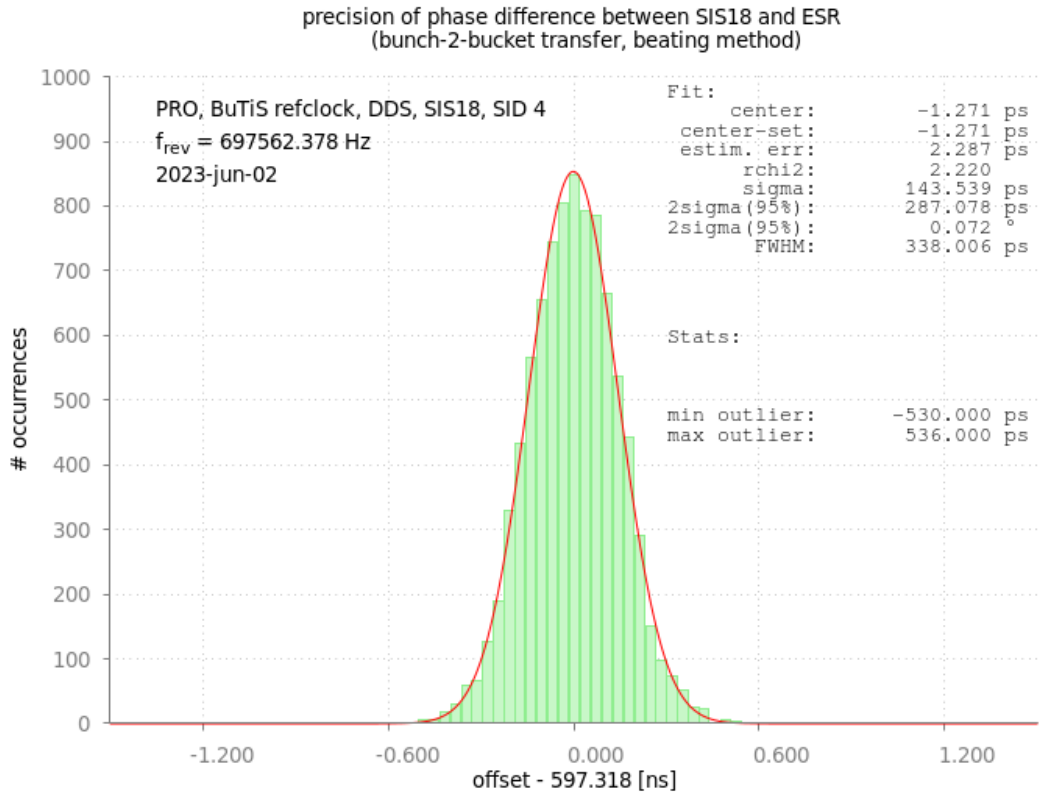
Frequency Beating, integer ratio of ring circumferences
- SIS18(216m)→ESR(108m)→CRYRING(54m)
- f_rev (SIS18) ~ 1.3 MHz; f_rev (ESR) ~ 2.6 MHz
- H=4 (SIS18) ~5.2 MHz; H=2 (ESR) ~5.2 MHZ

⇒ frequency beating
- 'just wait until the phase of both rings matches'

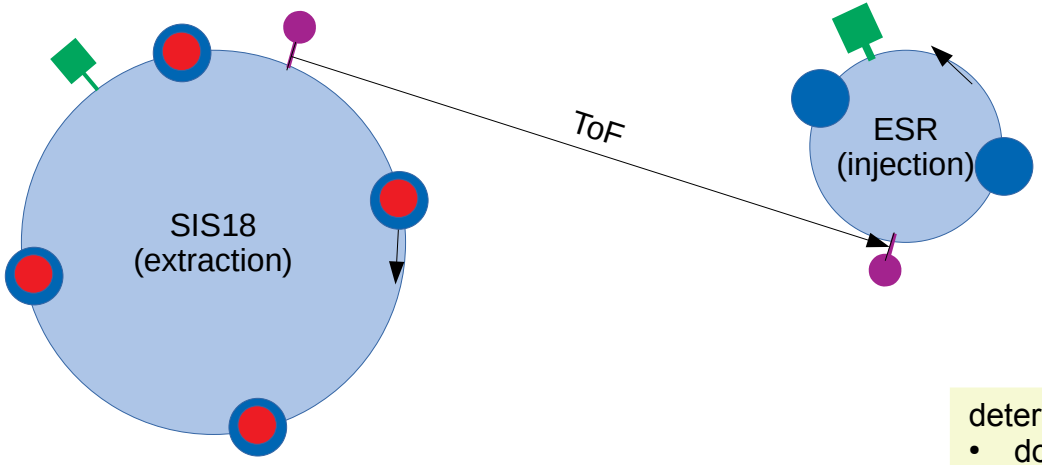
White Rabbit @ GSI
- precise phase measurements
- triggering of kickers
- distributed FPGA with embedded LM32 soft-core
- FPGAs communicate via the White Rabbit network

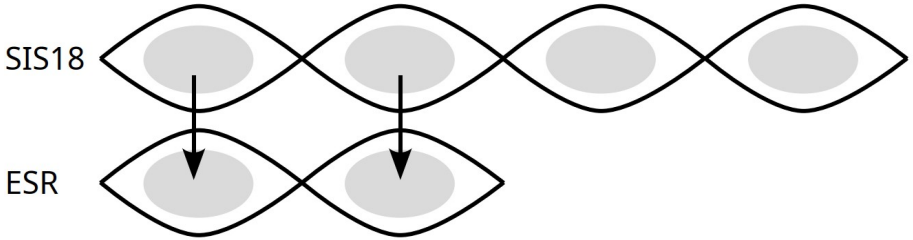
2025: Bunch-to-Bucket Transfer between Ring Machines (Frequency Beating)

- 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





- ions circulate in a ring machine
- acceleration 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

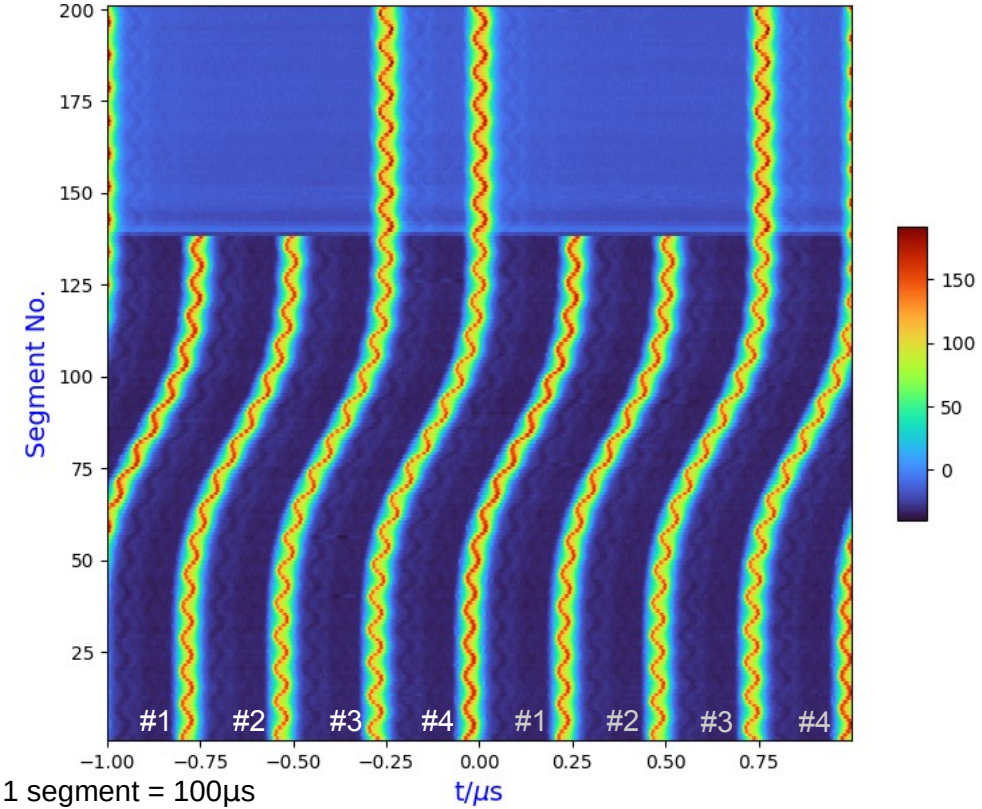
deterministic and adiabatic phase shifting of the RF
- does not depend on ‘good’ settings for beating
- requires additional effort at RF systems

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

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

SIS18 (FCT)

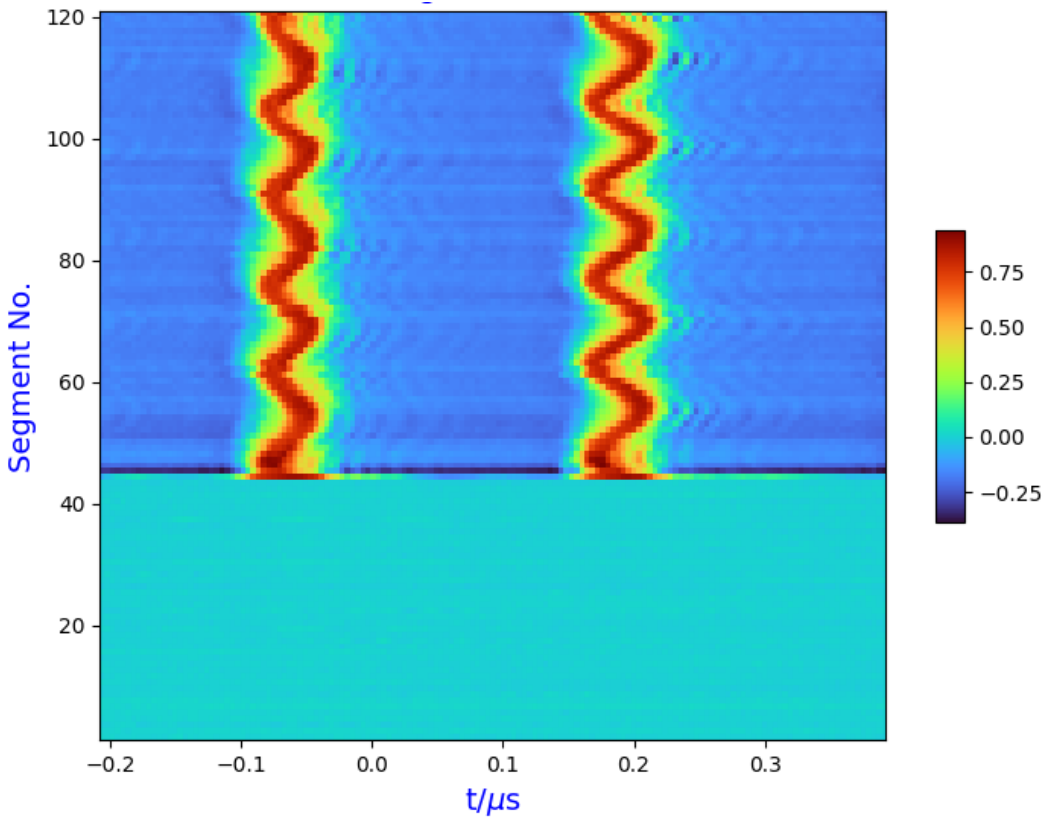
T_{rev} ~ 1 µs; T_{sync} ~ 1.2 ms



1 segment = 100µs

ESR (FCT)

T_{rev} ~ 0.5 µs; T_{sync} ~ 1.6 ms



Dietrich Beck, TOS, GSI, d.beck@gsi.de