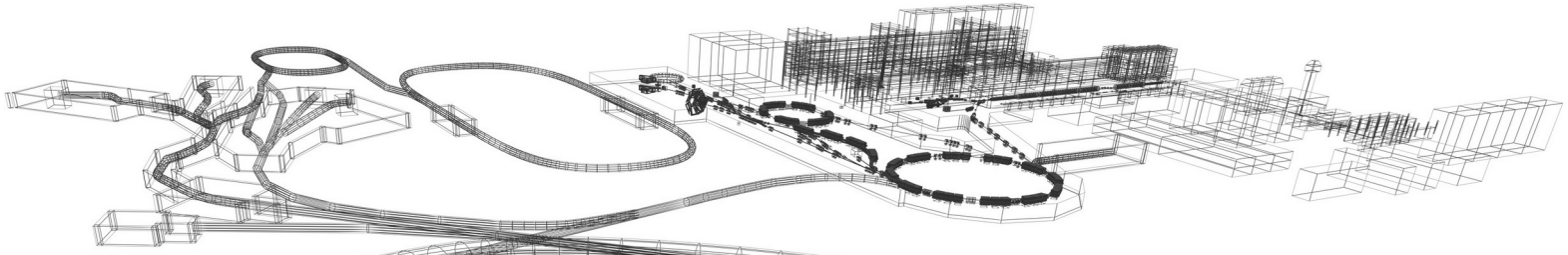
Acknowledgements

- GSI Timing Team: Enkhbold Ochirsuren, Marcus Zweig, Stefan Rauch, Mathias Kreider, Martin Skorsky, Frederic Ameil, Alexander Hahn, Michael Reese
- GSI ACC-IT Team: Peter Pfister, Christoph Handel, Rosemarie Vincelli …
- CERN Team: Greg Daniluk, Maciej Lipinski …
- External: Alessandro Rubini, Adam Wujek …
- ...

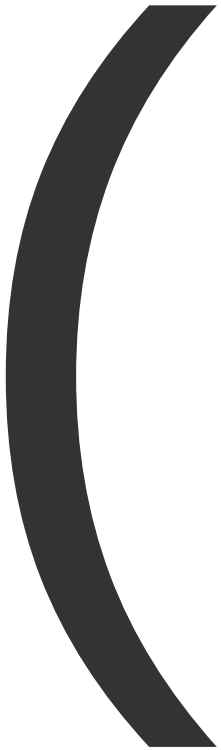


The White Rabbit based Timing System for GSI and FAIR

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

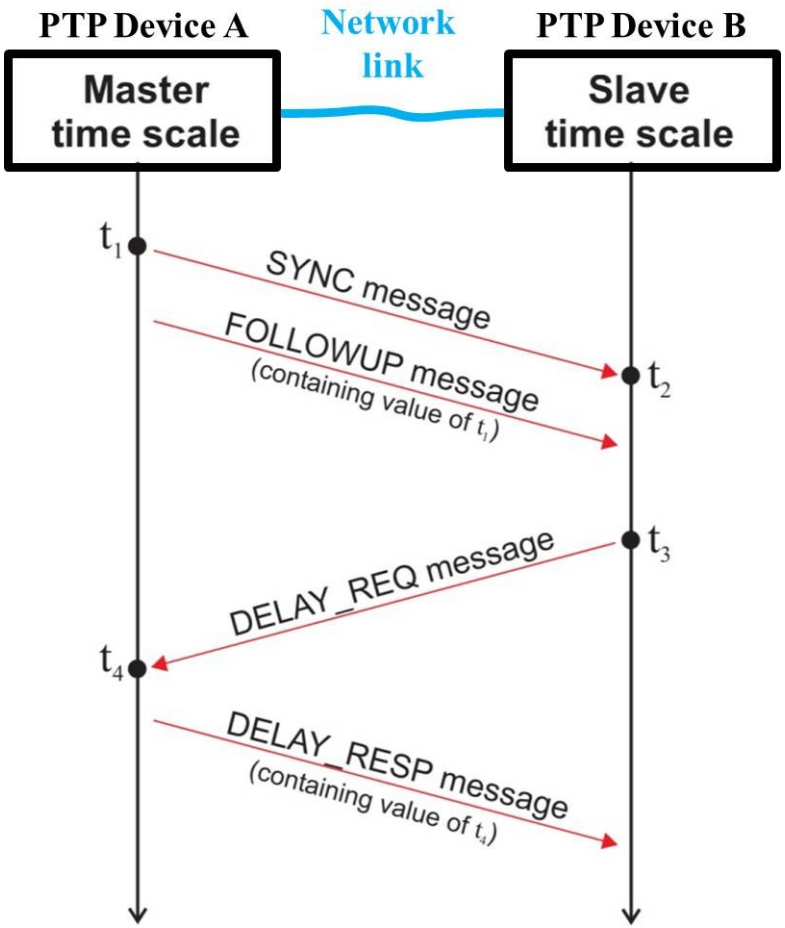
Dietrich Beck, TOS, GSI, d.beck@gsi.de

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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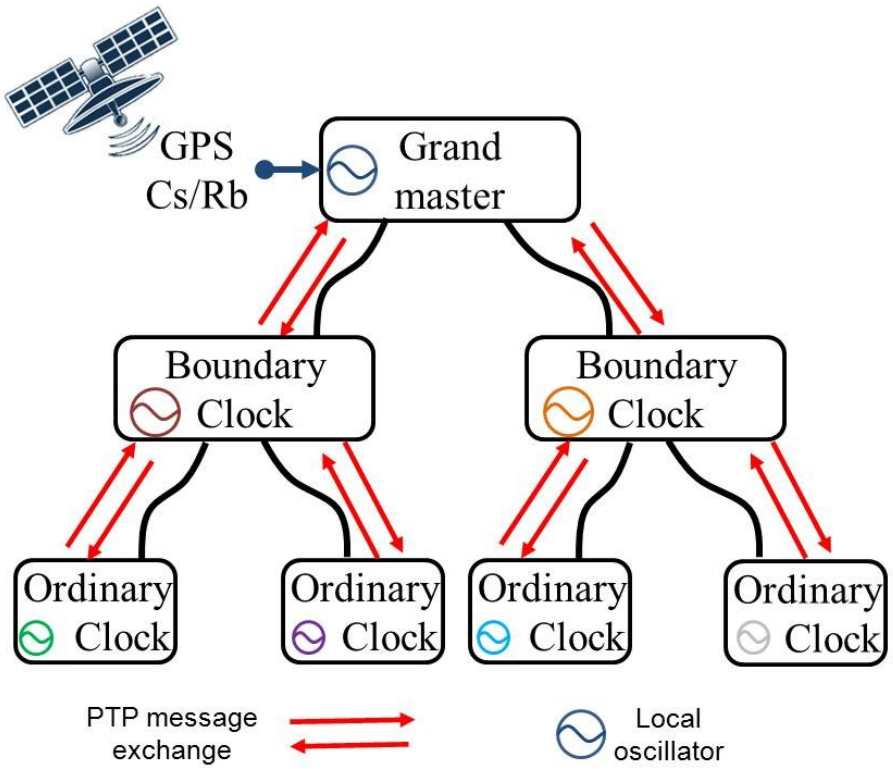

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- Hierarchical network
- Shortcomings of traditional PTP:
  - devices have free-running oscillators
  - frequency drift
  - ...

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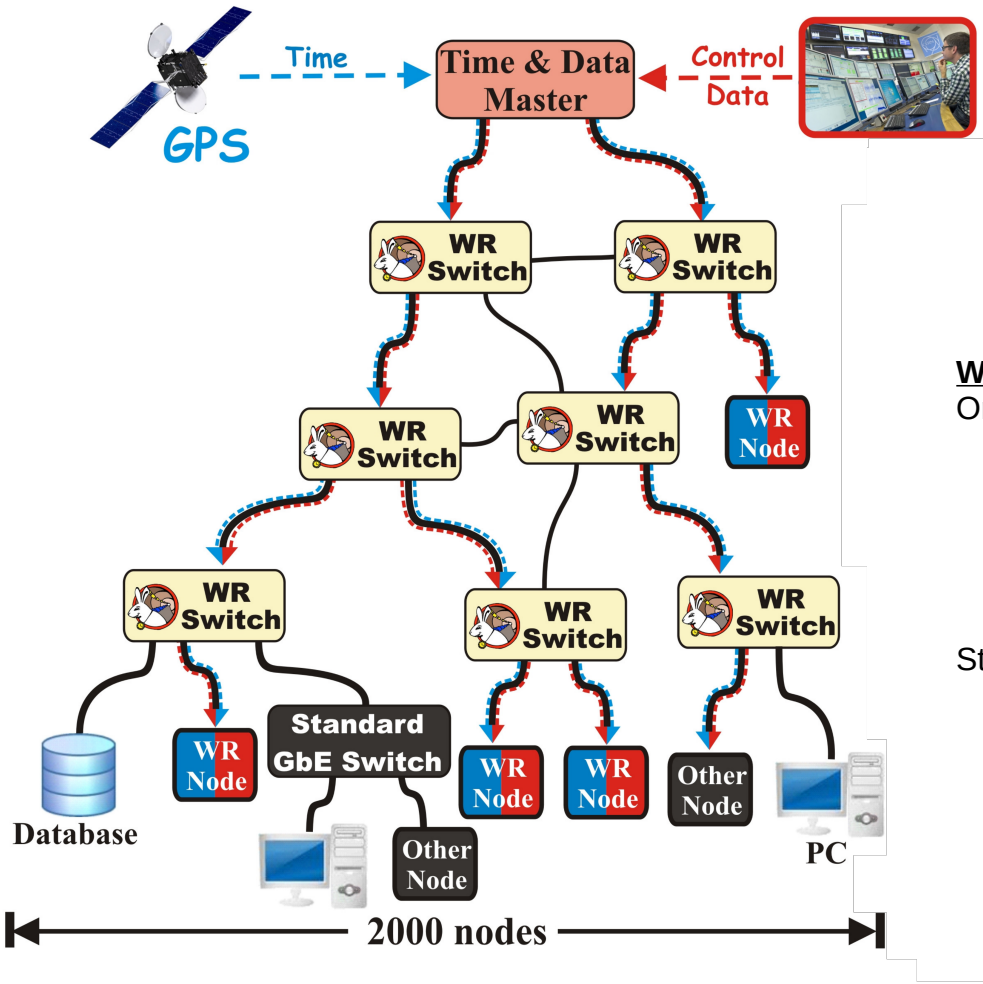

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  - ...

White Rabbit

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 and Plans

- **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)

WR Switch

Seven Sol, Spain
Creotech, Poland

OPNT, Netherlands
SyncTechnology, China

Simple VME FMC carrier (SVEC)

Janz Tec AG, Germany

Simple PCIe FMC carrier (SPEC)

Creotech, Poland
INCAA, Netherlands
Seven Solutions, Spain
ISD S.A., Greece

Compact Universal Timing Endpoint (Cute-WR-DP)

SyncTech, China

Digitizers

Struck, Germany
SP Devices, Sweden

GPS Disciplined Oscillator

Seven Solutions, Spain

ZEN TP-32 BNC

Seven Solutions, Spain

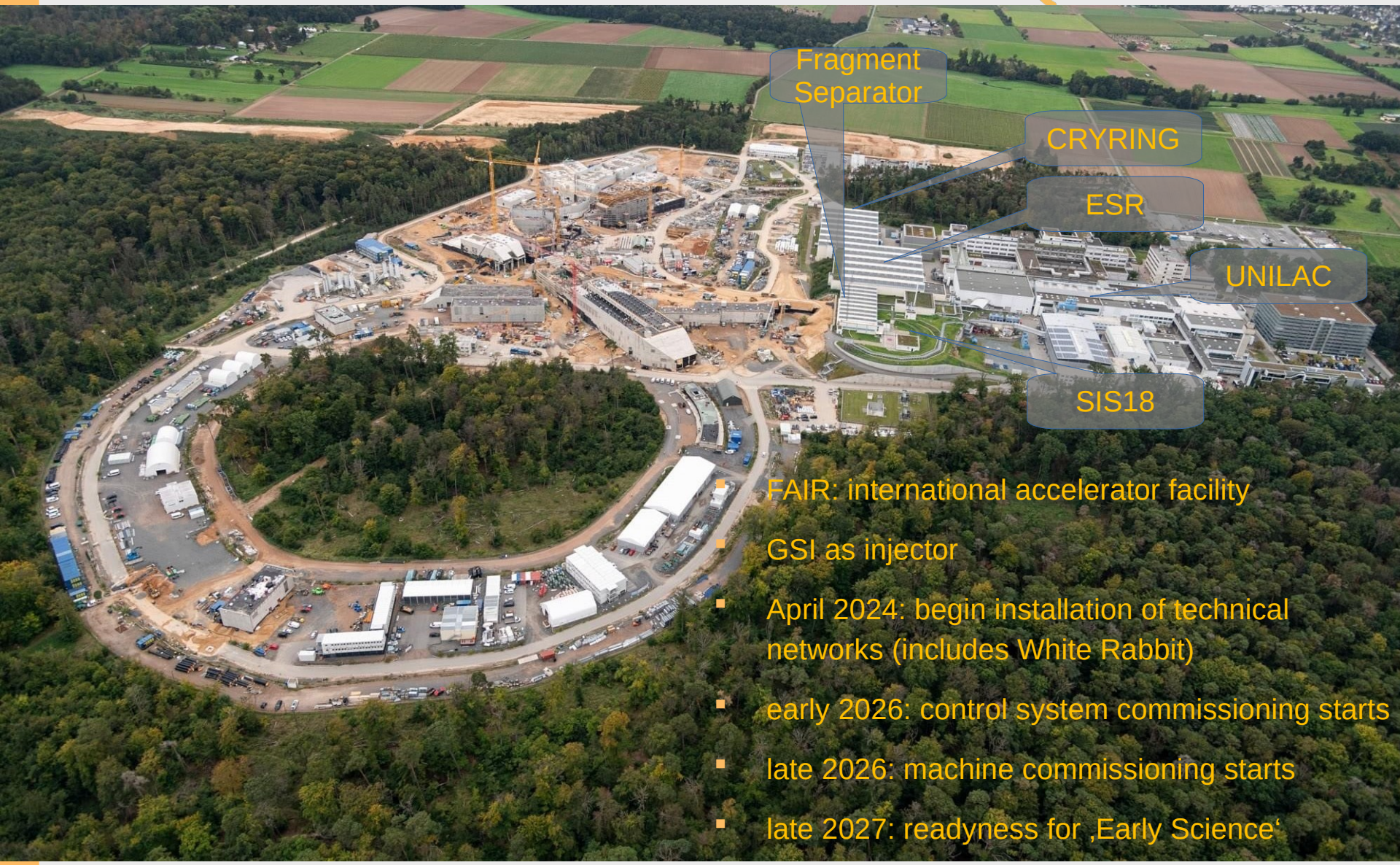
PXI module

Sundance, UK

Companies selling White Rabbit

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

FAIR from the Control System Perspective



- FAIR: international accelerator facility
- GSI as injector
- April 2024: begin installation of technical networks (includes White Rabbit)
- early 2026: control system commissioning starts
- late 2026: machine commissioning starts
- late 2027: readyness for ‚Early Science‘

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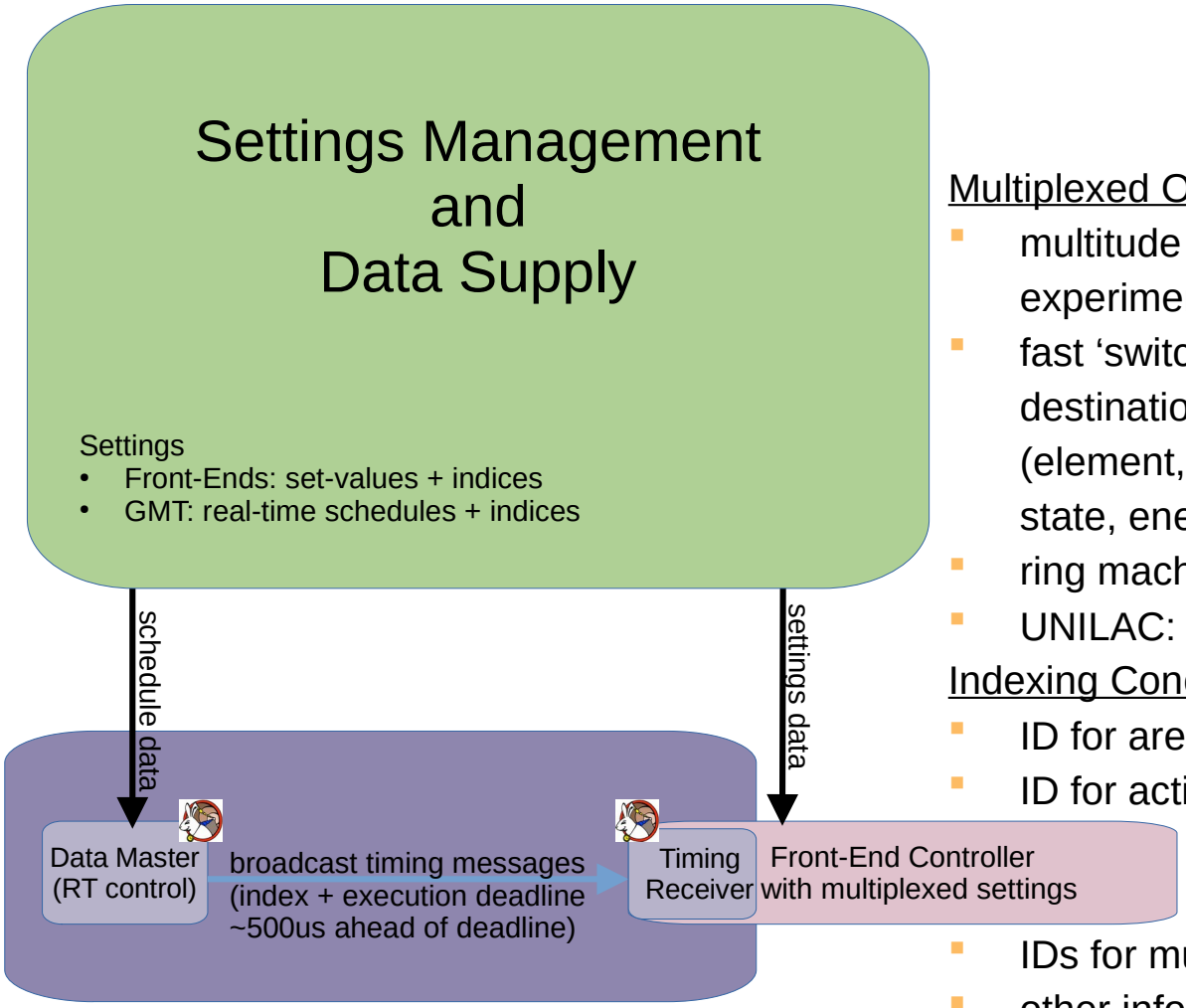
Multiplexed Operation, Control System Stack and GMT



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

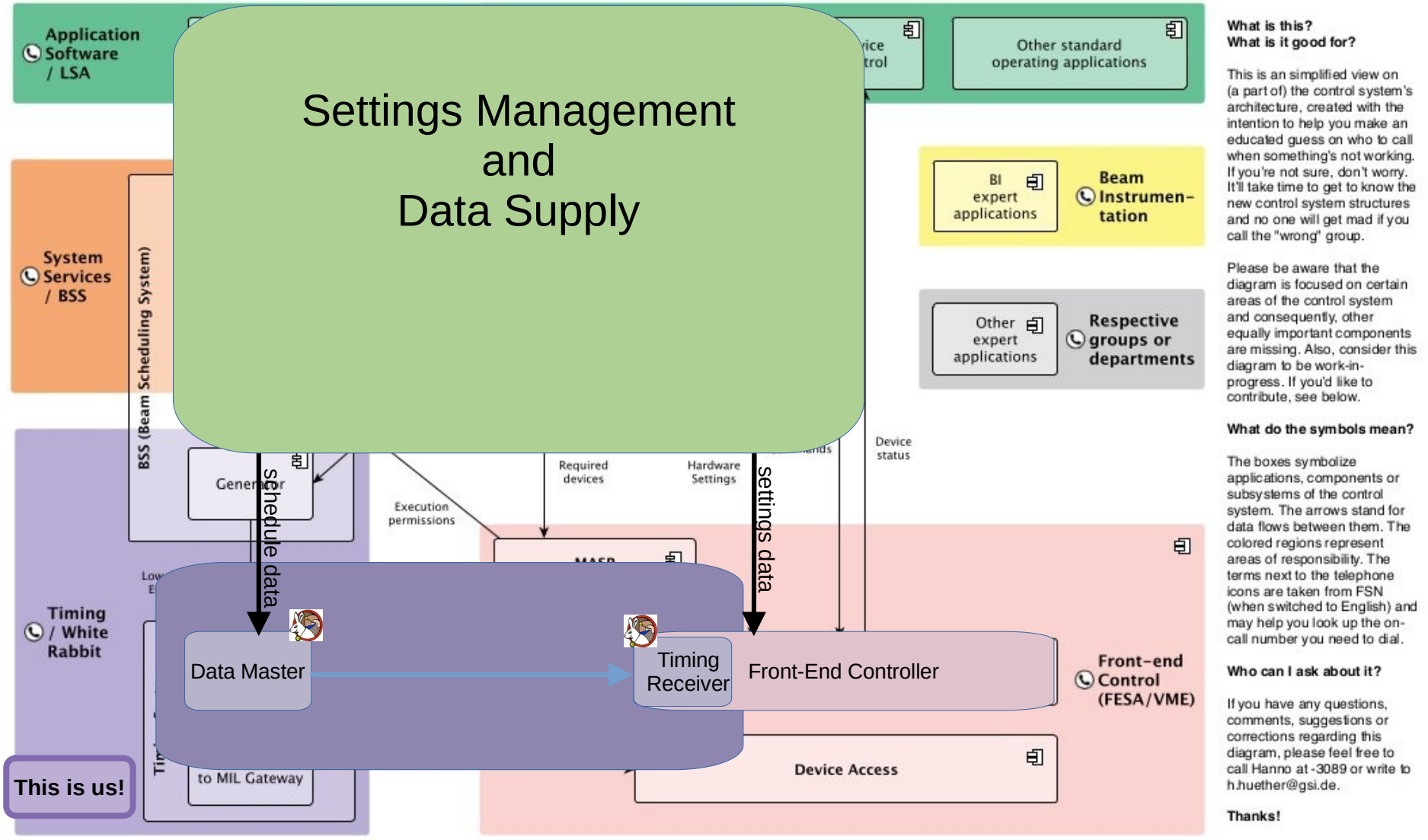
Indexing Concept

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

Control System Stack – Involvement of Seven Distinct Teams

Who you gonna call?

GSI



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!

Control System Stack – Involvement of Seven Distinct Teams

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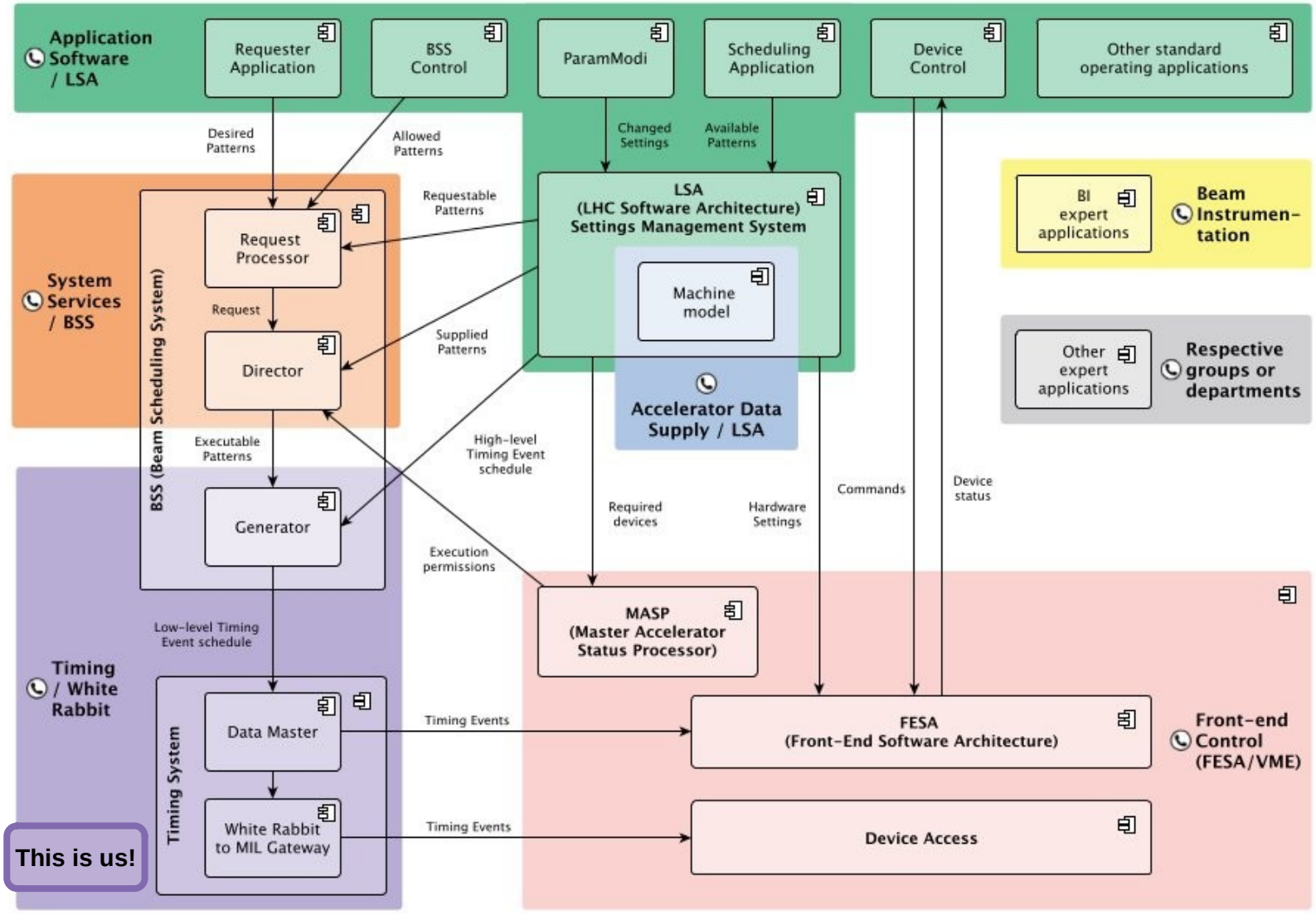

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Thanks!

(FAIR) from the Control System Perspective
Control System Productive @ GSI

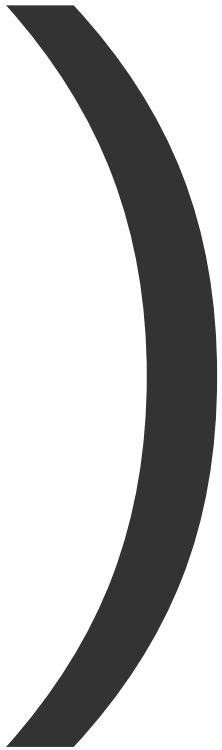
'FAIR Control System' @ GSI campus

Control System, GMT, White Rabbit operation

- since 2016: CRYRING (ring, ions-sources, Linac)
- since 2018: SIS18, ESR, all beamlines
- since 2022: synchronization of transfers between all ring machines
- iterative development with each beam-time
- 2025/2026: UNILAC

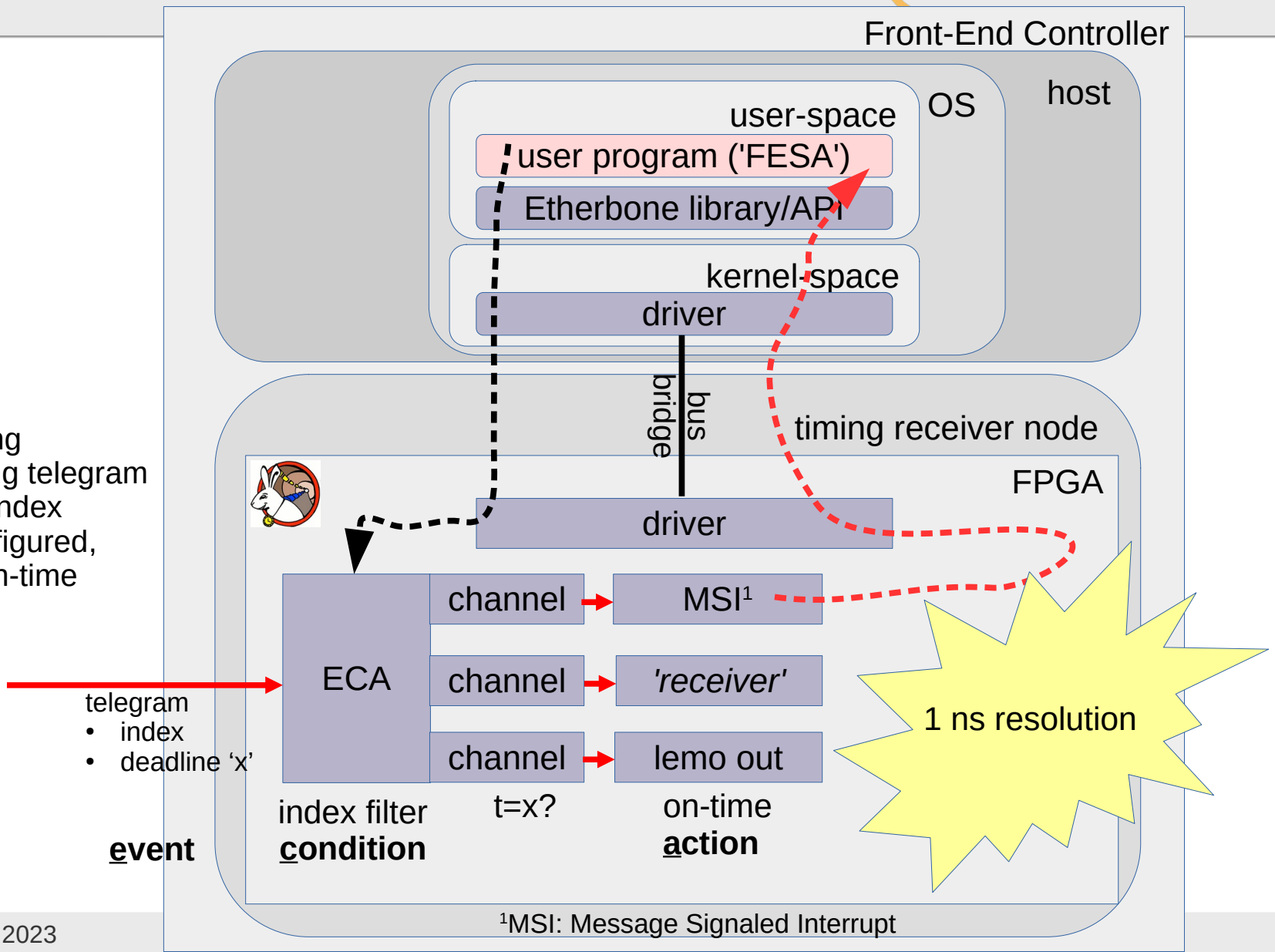
FAIR Campus including 'First Science+'

- 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

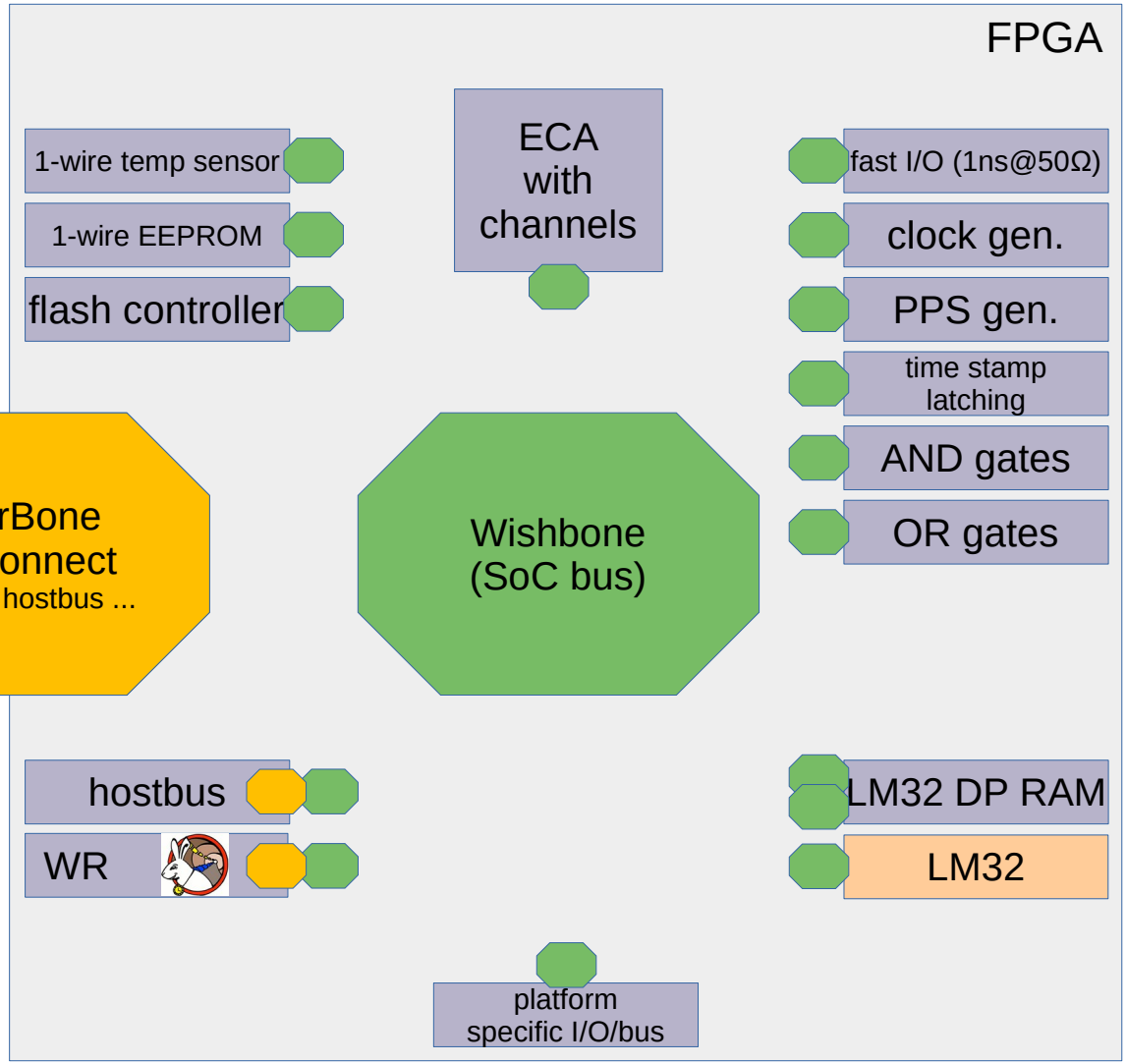
- configuration of IP cores
- LM32 softcore:

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

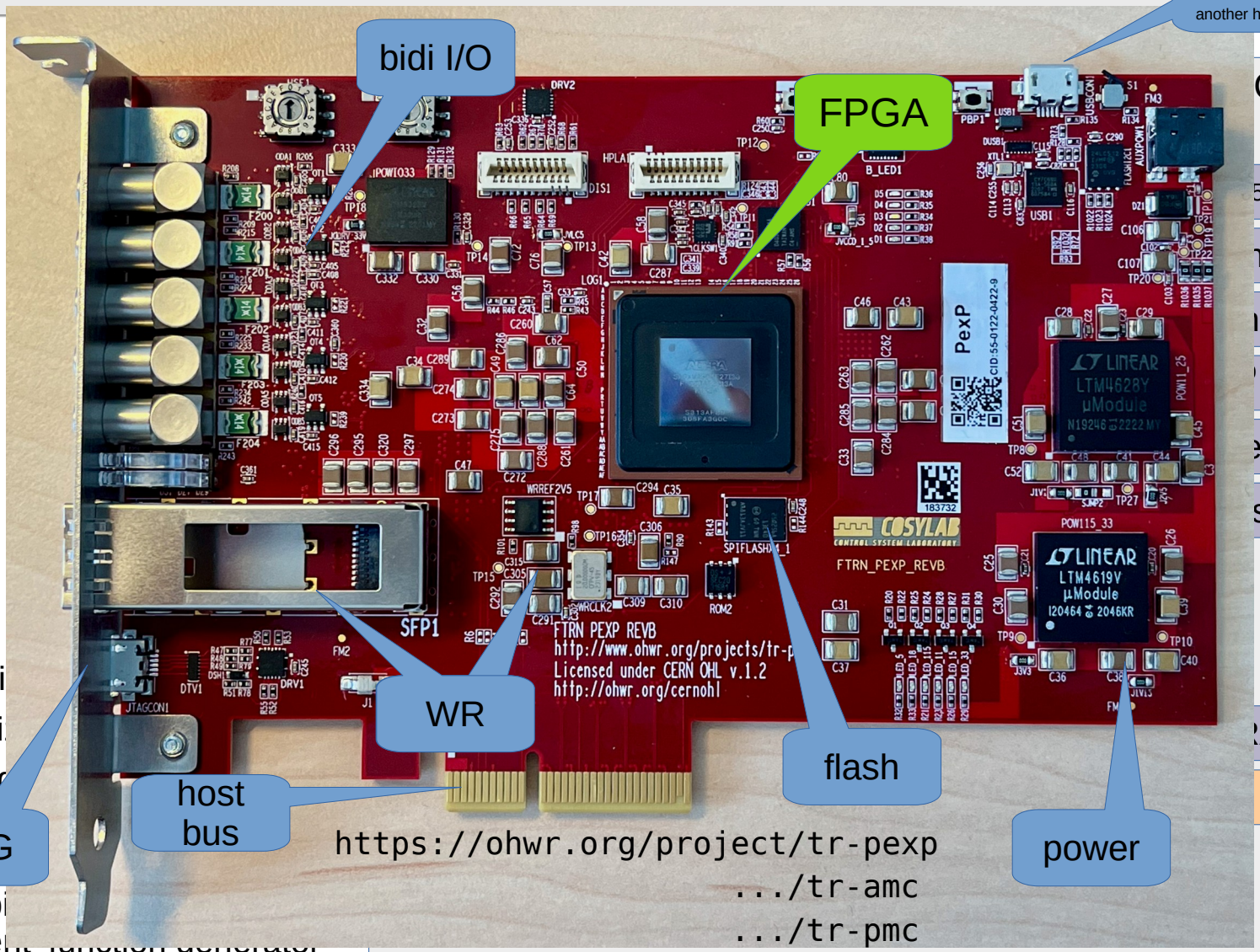
  example: ramping up dipole magnet current or rf-cavity frequency

  hard real-time

  synchronosly at many nodes



Common Features for Nodes …



no appli

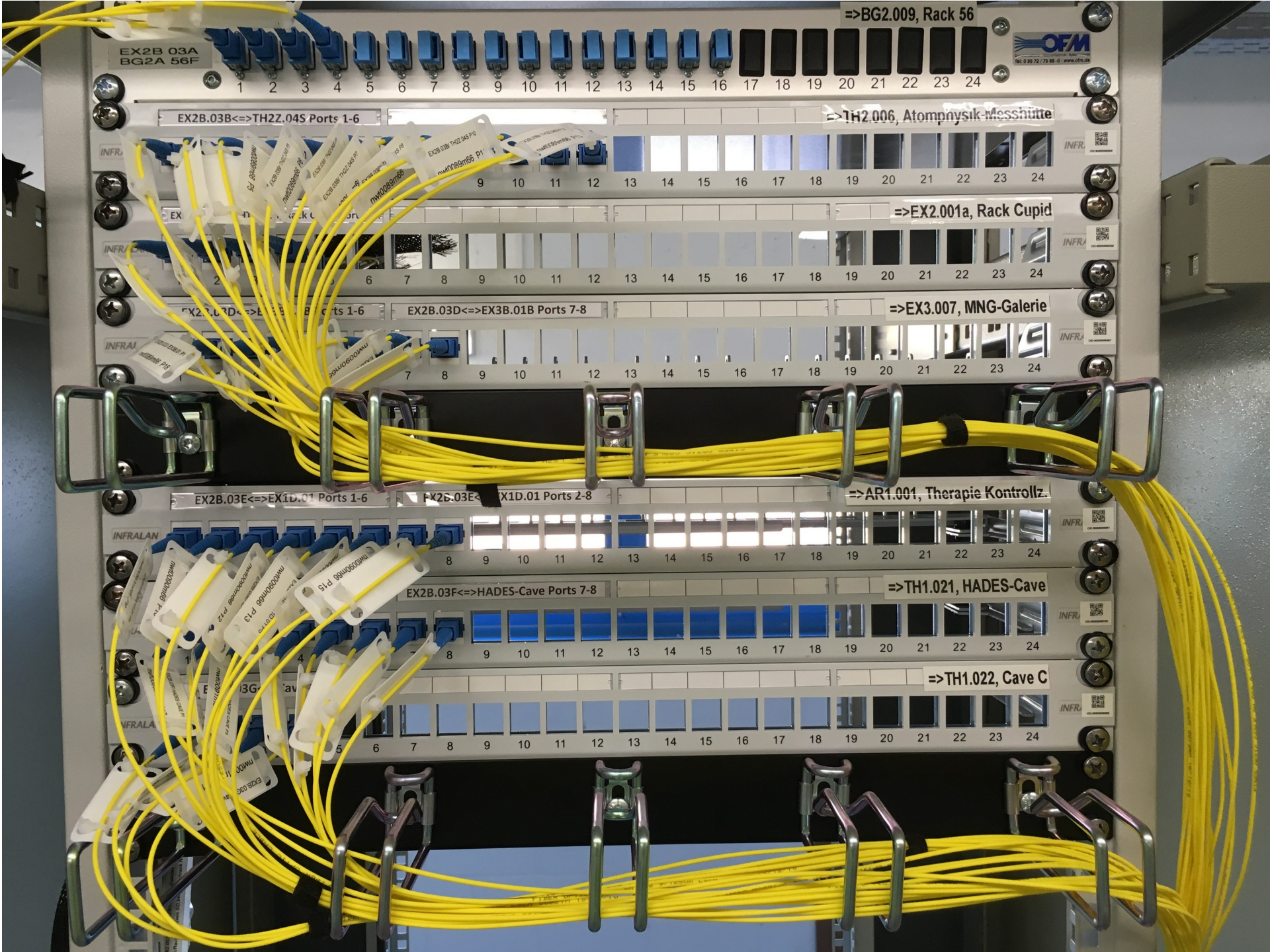
customi

- confi

ramp

curre


PS20
PS21
YR03KV6G
YR03KV7K
YR03KD1D
YR03KH1
10V=50A
10V=160A
YR02KD
10A =5V
Ua=10V
A
B
C
D


=>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
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

Integration into IT Environment
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 more like regular IT switches (modifications merged with ohwr.org, of course ...)
  - integrate White Rabbit network into ACC-IT infrastructure
- contribution/help by Alessandro Rubini, Adam Wujek and Christoph Handel

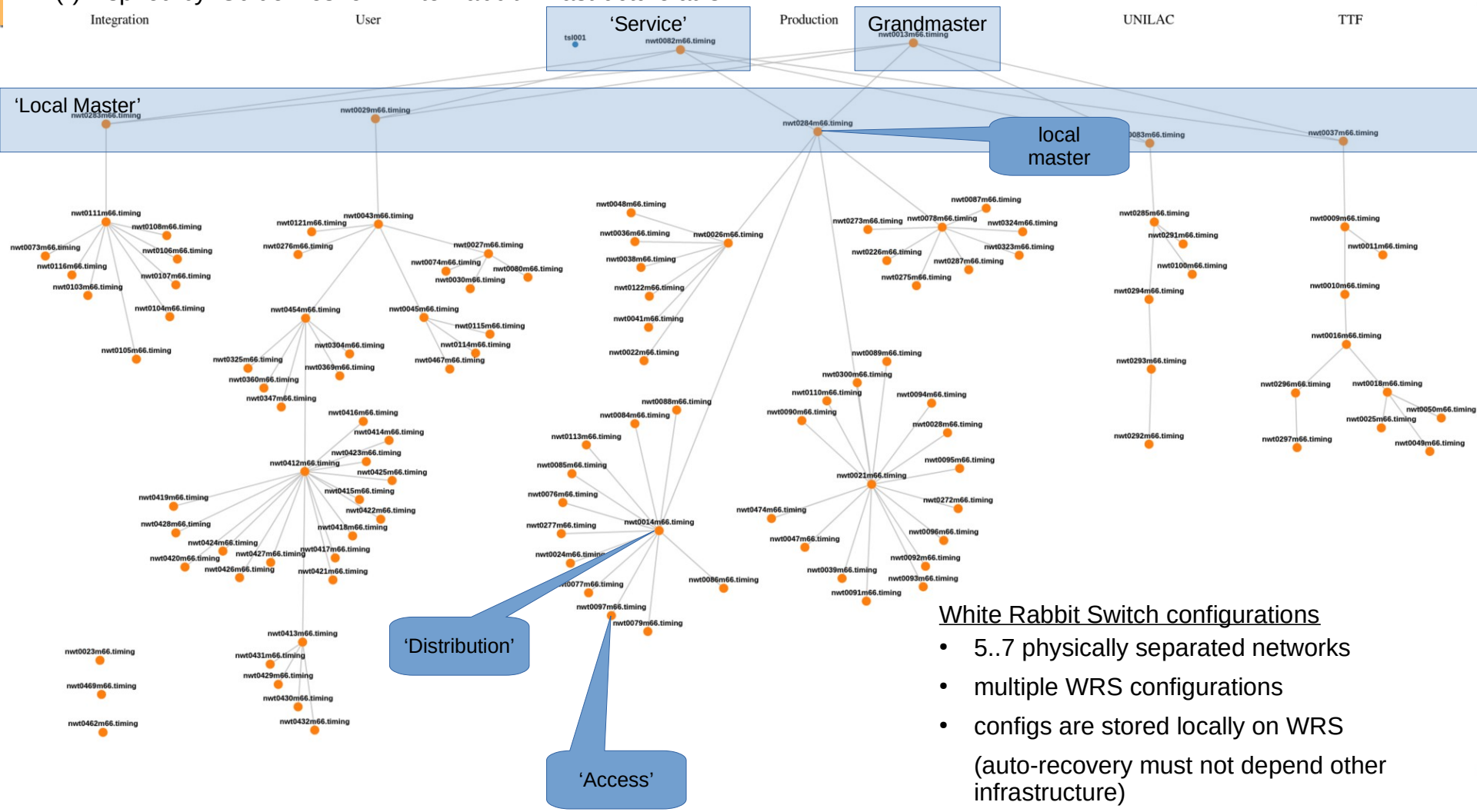
Integration into IT Environment
Accelerator IT and Central IT

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

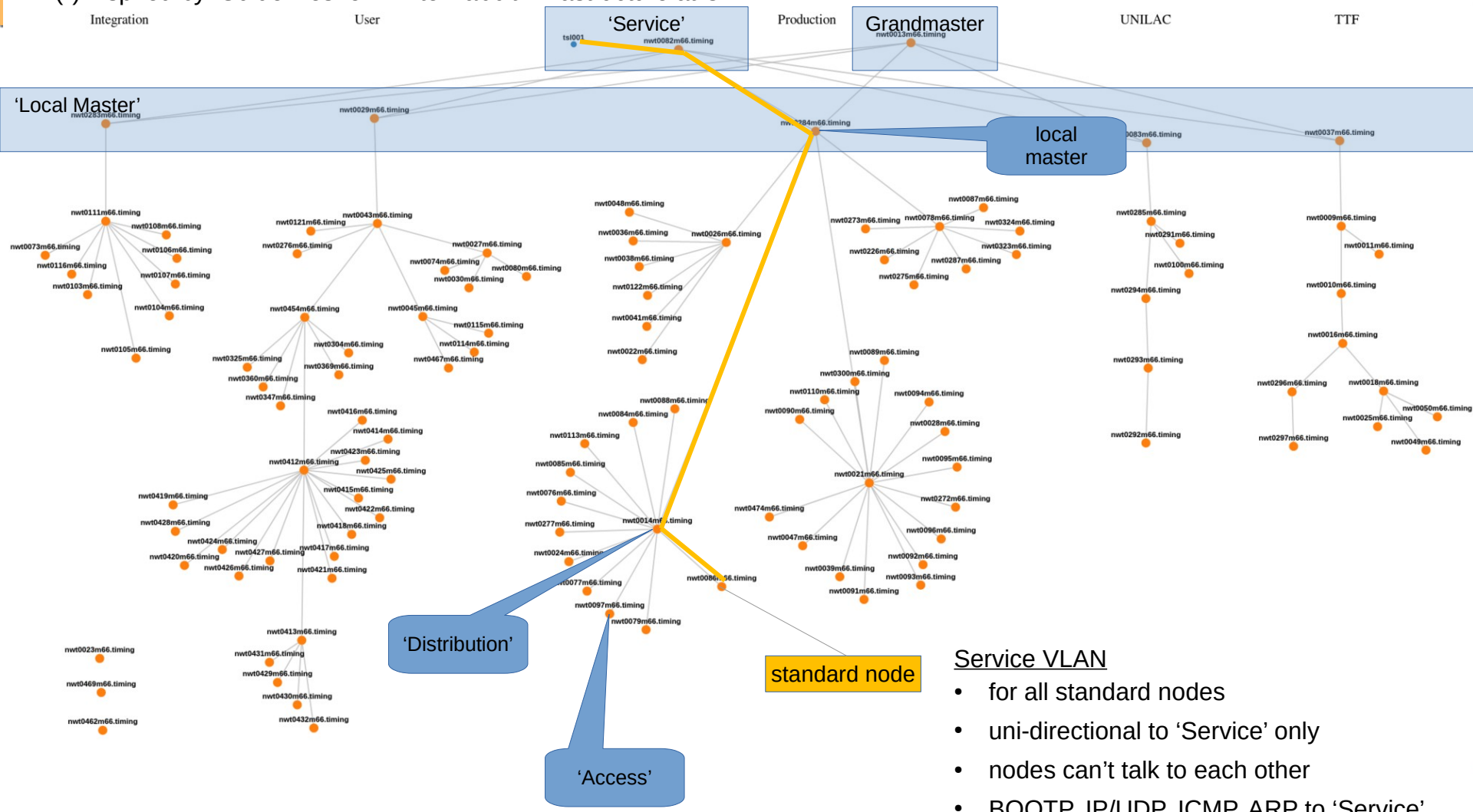
- 5..7 physically separated networks
- multiple WRS configurations
- configs are stored locally on WRS

  (auto-recovery must not depend other infrastructure)

figure from ‘netdisco’ (2022)

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

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

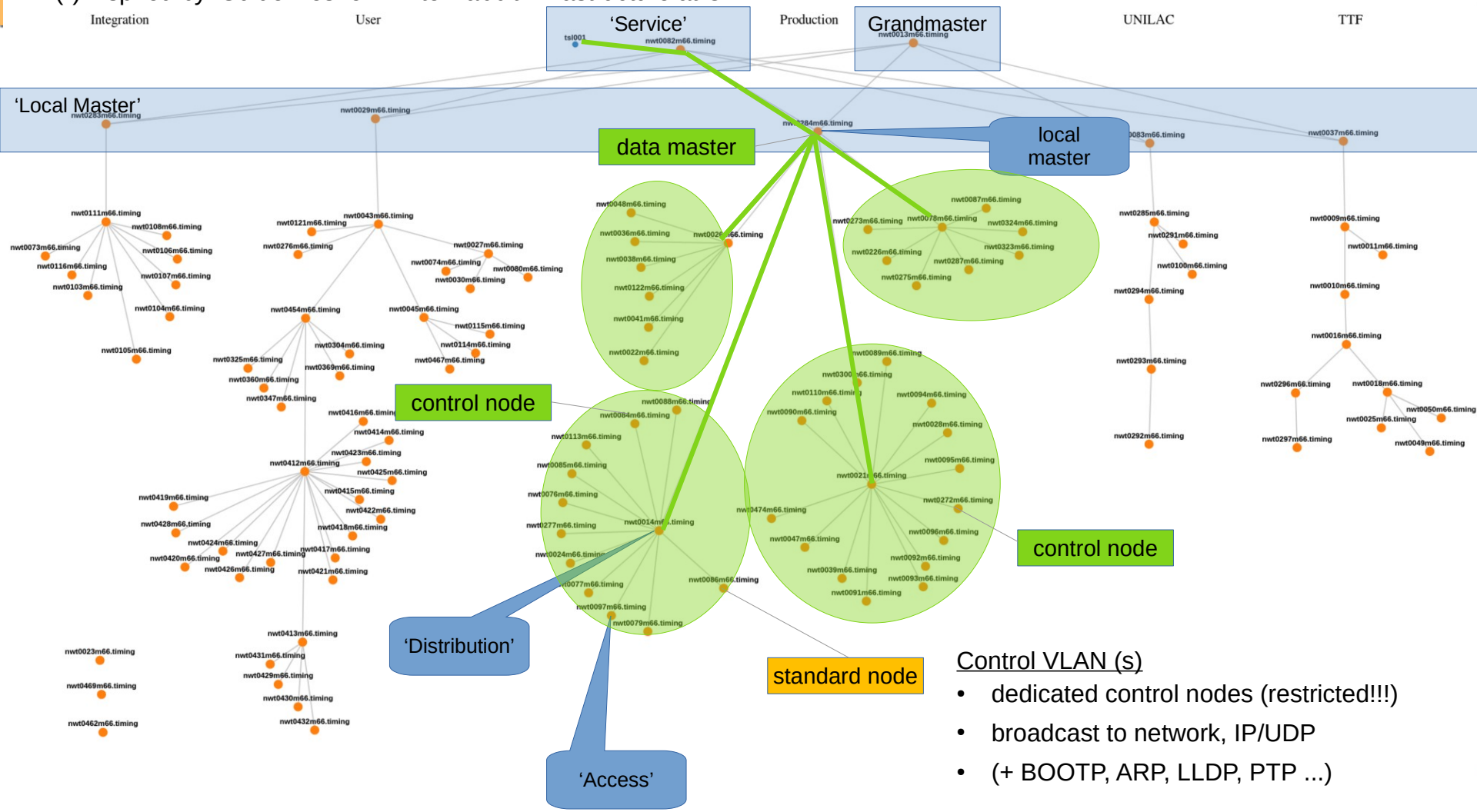


Service VLAN

- 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’

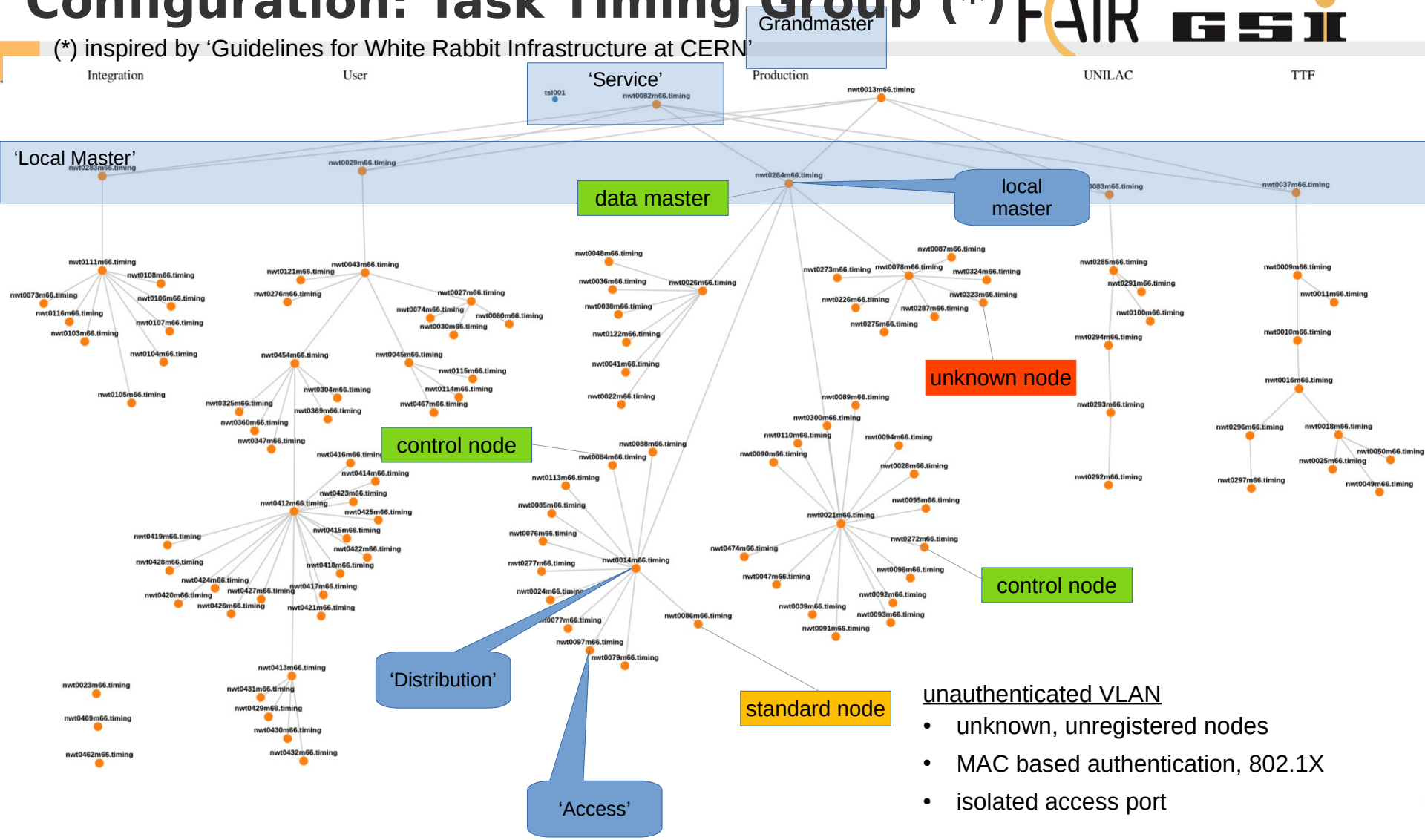


Control VLAN (s)

- 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

2022: Experience from Operation

- preparation ahead of beam time
  - start – 6 months: **feature freeze and release** WRS, data master and nodes
  - start – 4 months: **‘integration tests’** with all control system layers
  - start – 2 months: **‚dry-runs‘** for severe testing of acceleator facility at full scale
- 24/7 operation
  - ~**6 months of beam operation, including on-call service (rarely requested)**
  - shutdown operation, rare (!) maintenance windows

<u>good (White Rabbit), no issues with</u>

- 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 …)
- ...

<u>bad (White Rabbit)</u>

- WRS: 12 units with broken fans; not hot-swappable – survived by passive cooling :-/
- WRS: power supply neither redundant, nor (hot-)swappable
- (looking forward to WRS v4)
- ...

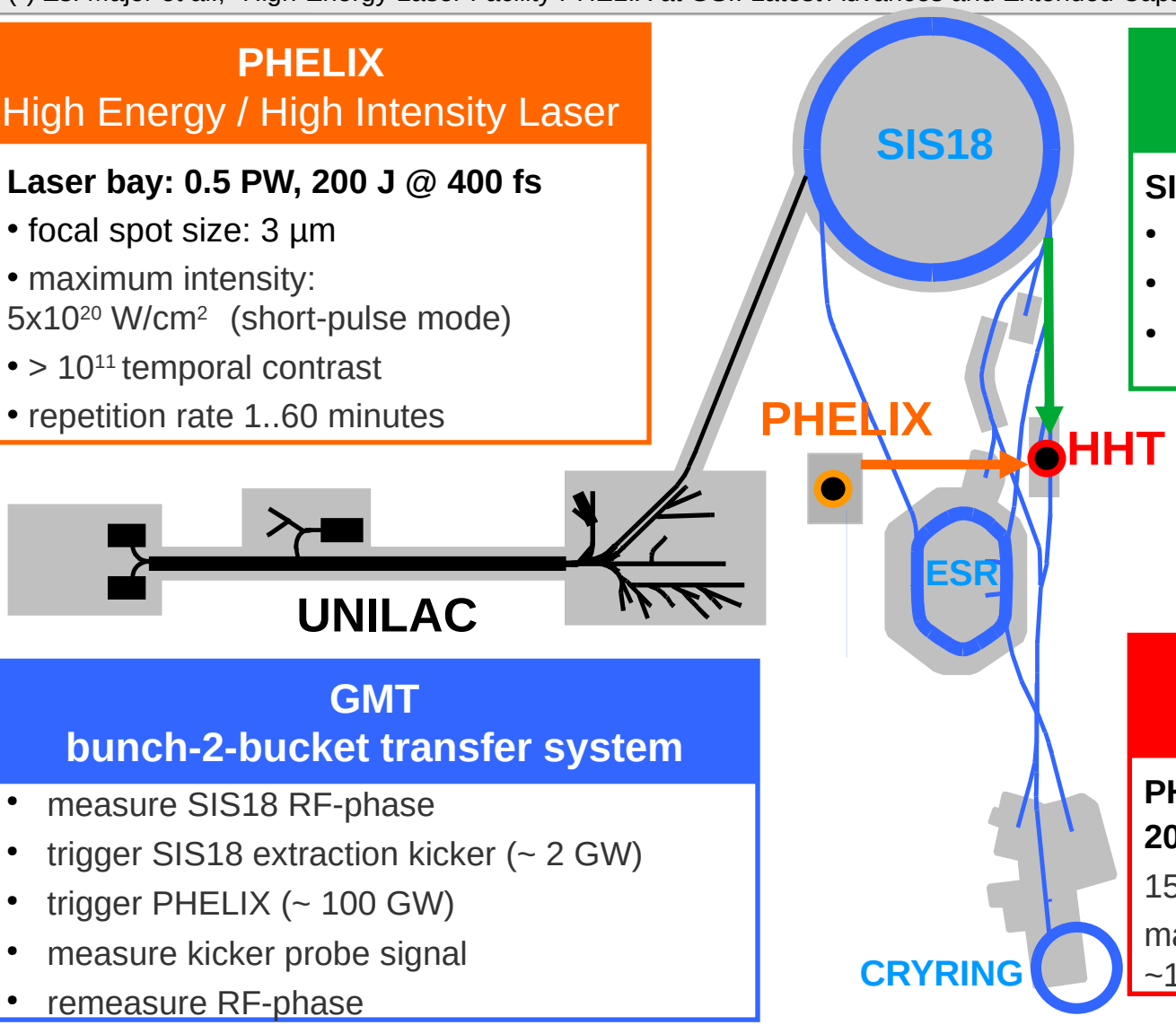
GMT Precision (Accelerator Control)
Sync PHELIX Pulse and Ion Bunch (*)

(*) 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: 5×10^{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

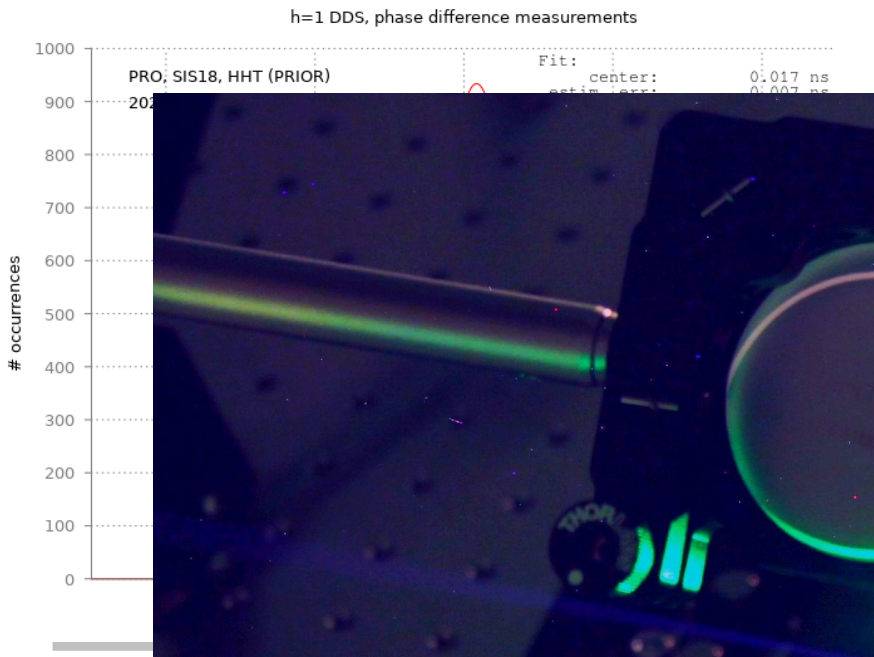
- measure SIS18 RF-phase
- trigger SIS18 extraction kicker (~ 2 GW)
- trigger PHELIX (~ 100 GW)
- measure kicker probe signal
- remeasure RF-phase

HHT

PHELIX:
200 J @ 1 – 10 ns, 2ω
15 cm beam diameter
maximum focussed intensity:
~10^{16} W/cm^2

GMT Precision (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)



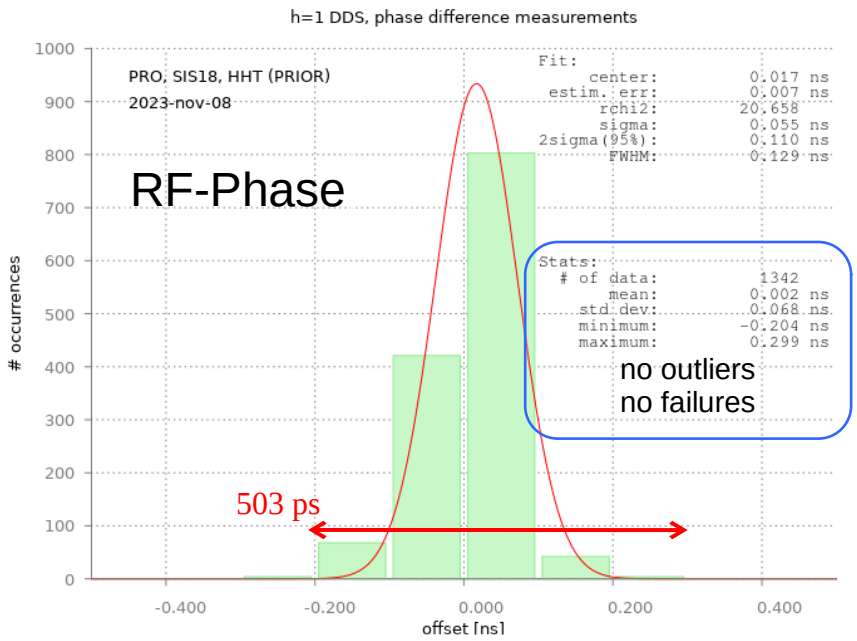
SIS18

coincidence within 10ns (uncertainty of measurement)

- measure kicker probe signal
- remeasure RF-phase

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)



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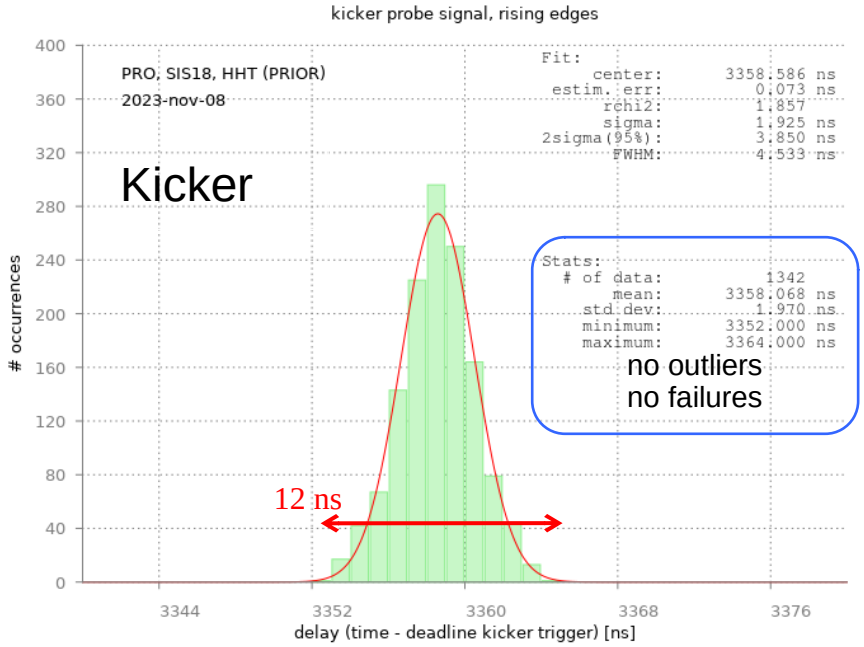


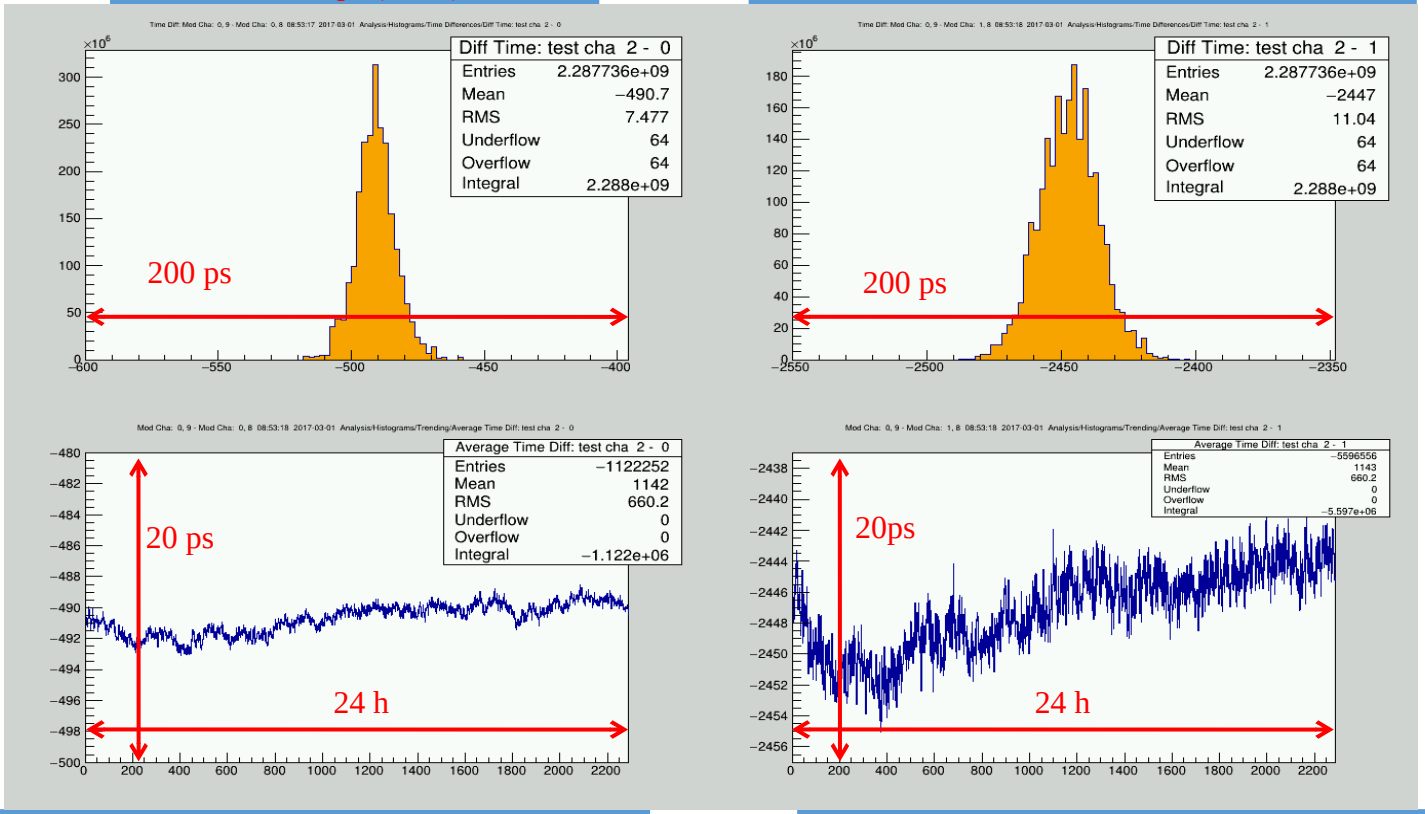
GMT Precision (Experiments, DAQ)
Time-of-Flight Measurements (*)

(*) 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

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 precision at planned deadline
  - routine operation for all rings and transfer lines since 2018
  - beam times 2018..2022: very reliable operation; almost invisible in failure statistics
- 2023, 2024: ~62 (+60) WR switches and ~350 (+600) nodes in productive (other) use
- FAIR
  - spring 2024: begin installation
  - add ~95 WRS and ~850 nodes for ‚Early Science‘
- UNILAC Upgrade
  - installation already started
  - add ~30 WRS and ~300 nodes
  - challenges: 50 Hz cycle rate, > 30 kHz timing message rate

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 ...)

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)

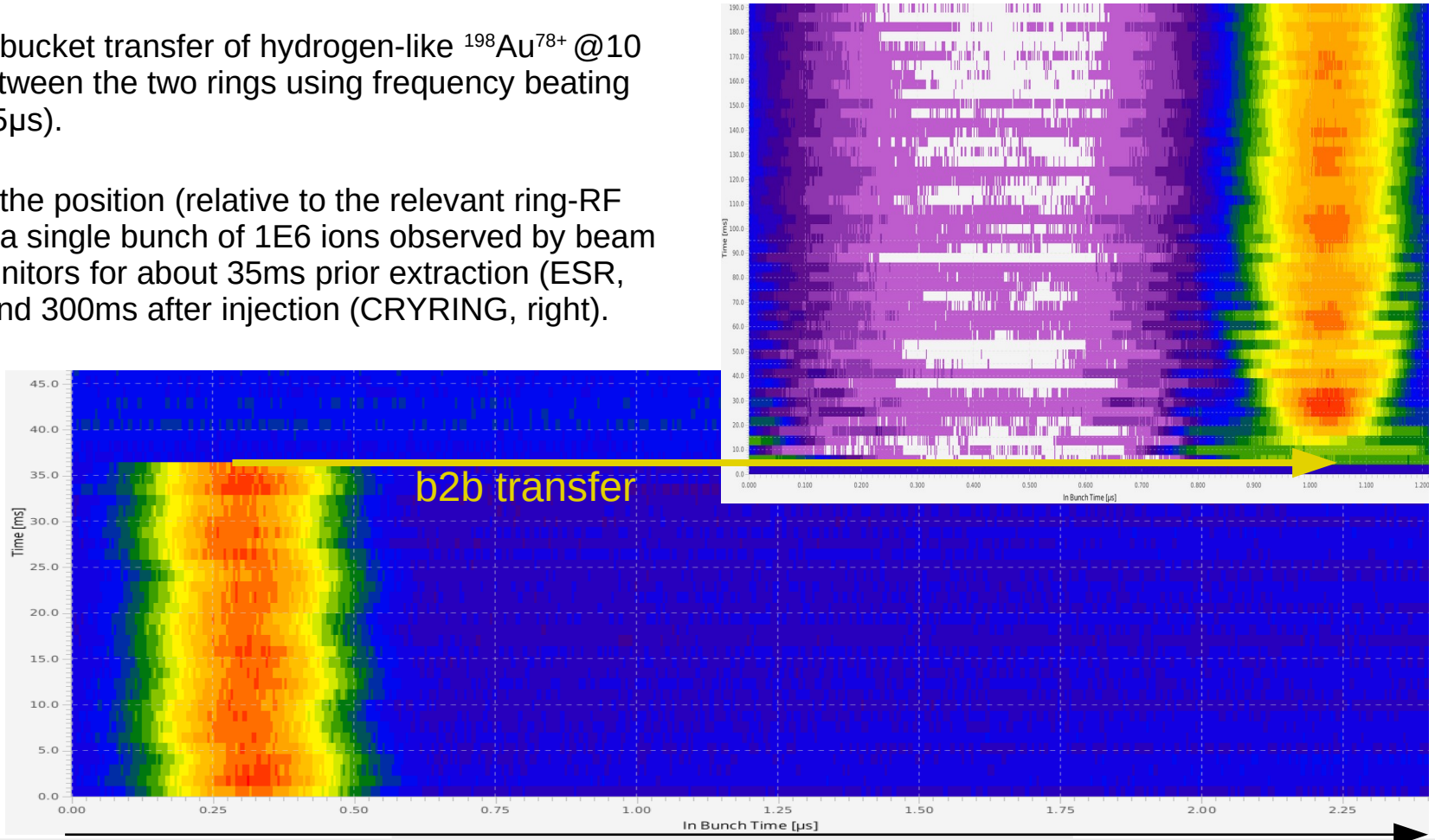
in-kind contribution SI
Arria V based
~220 units
www.ohwr.org

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).

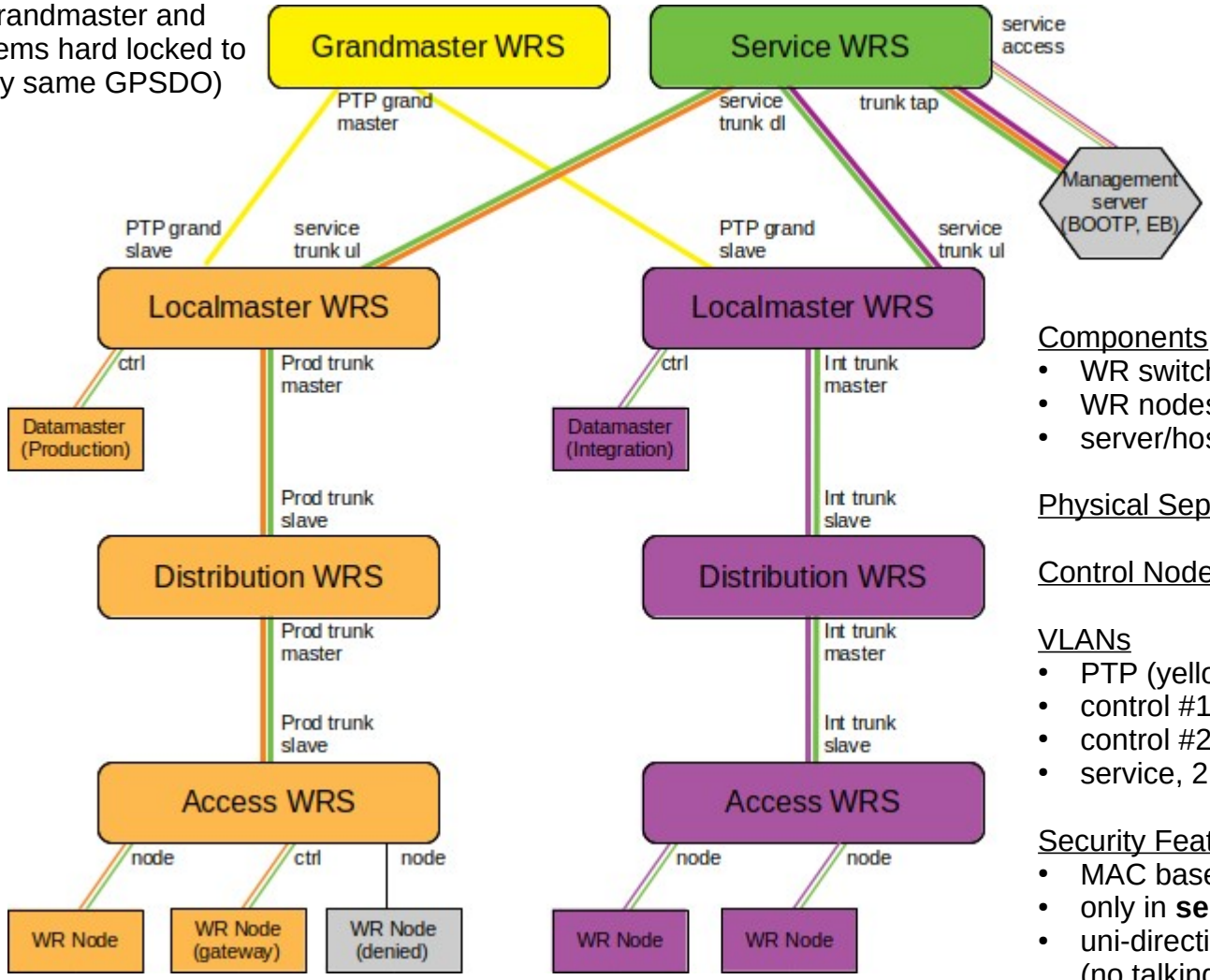
Shown is the position (relative to the relevant ring-RF signal) of a single bunch of 1E6 ions observed by beam profile monitors for about 35ms prior extraction (ESR, bottom) and 300ms after injection (CRYRING, right).



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)

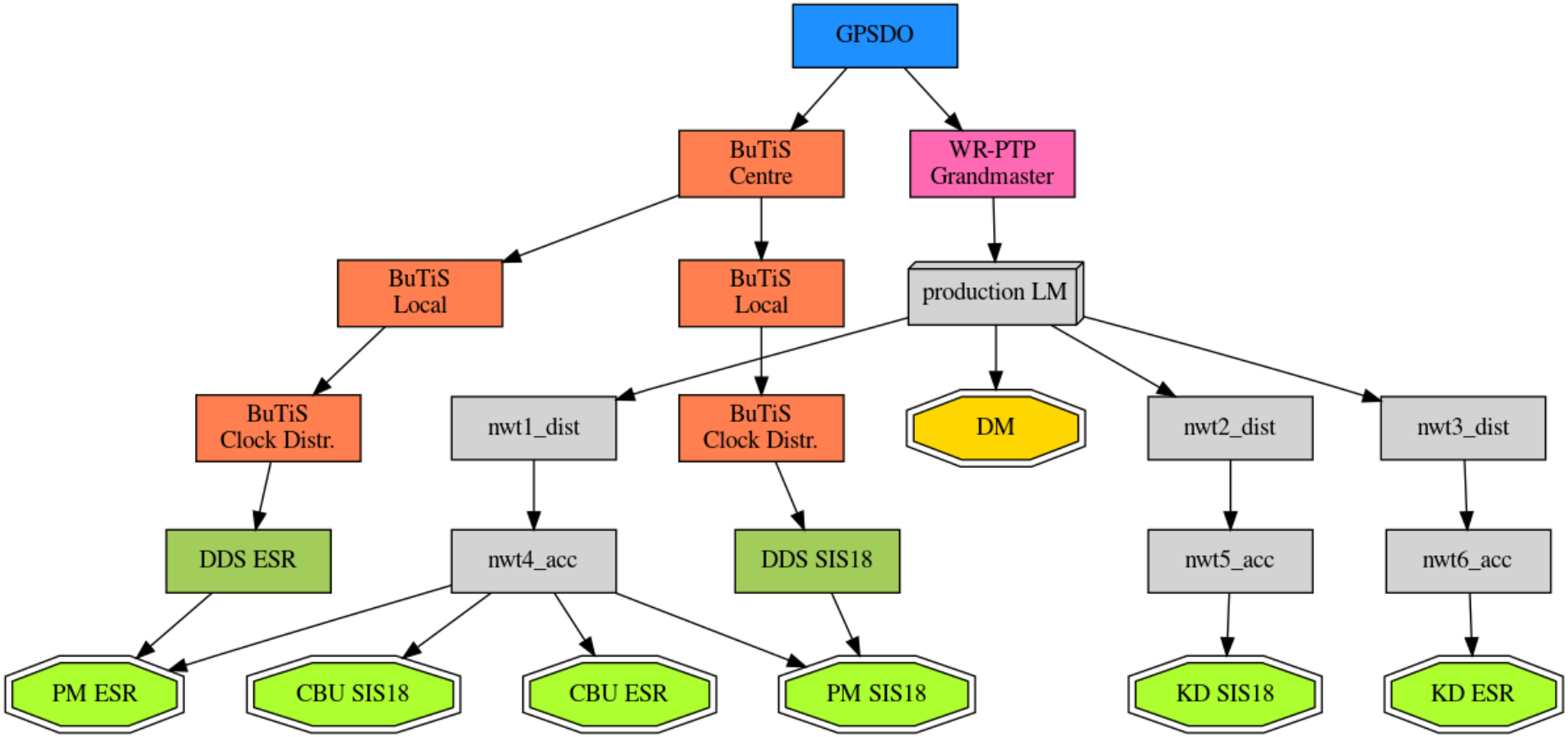
Physical Separation of Networks

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 (no talking to other nodes)

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)

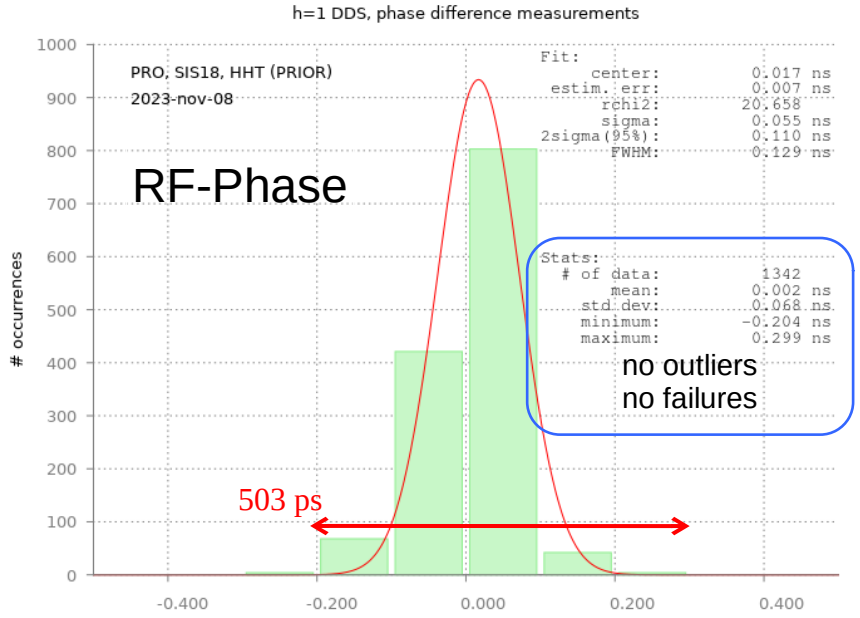
Integration into IT Environment Accelerator IT and Central IT

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)
- all integrated into accelerator IT infrastructure: user roles, accounts, security, **maintenance**
- …

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

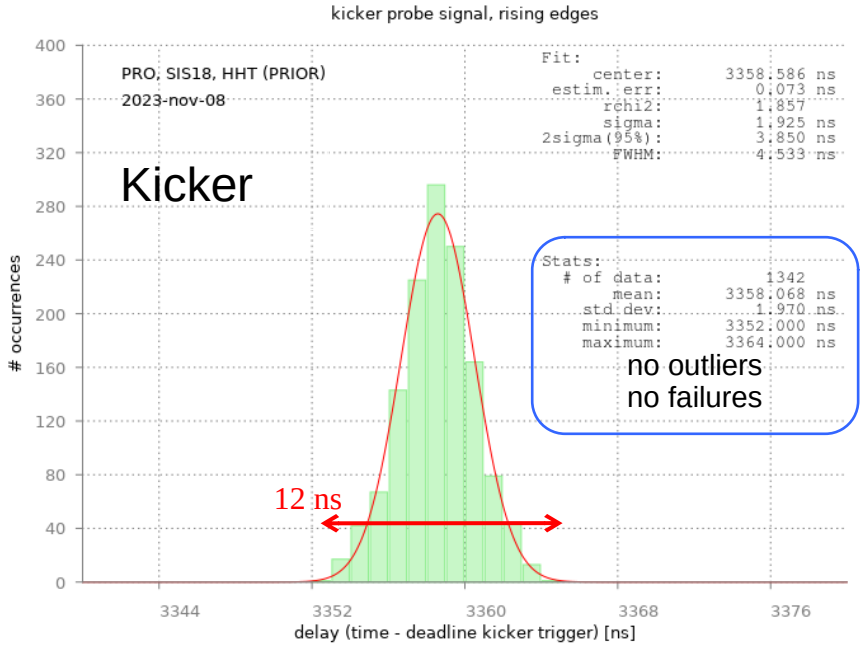
(*) Zs. Major et al., "High-Energy Laser Facility PHELIX at GSI: Latest Advances and Extended Capabilities", in preparation (2023)



SIS18

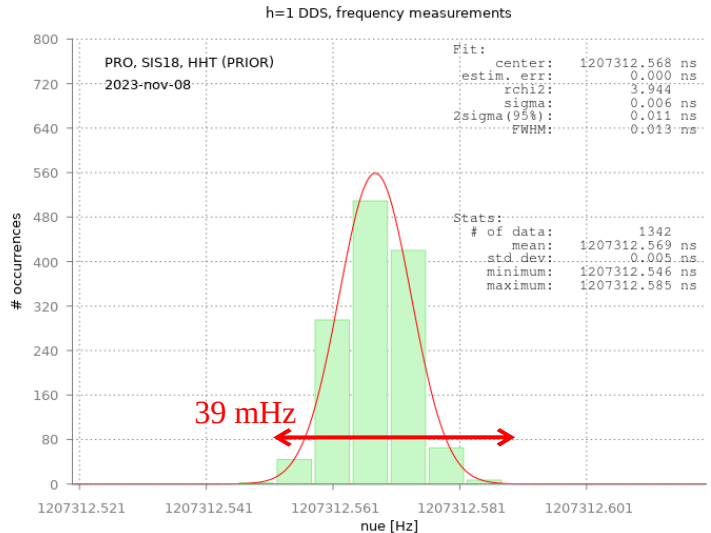
SIS18, here:

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



bu

- mea
- trigg
- trigg
- mea
- rem



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