Acknowledgements

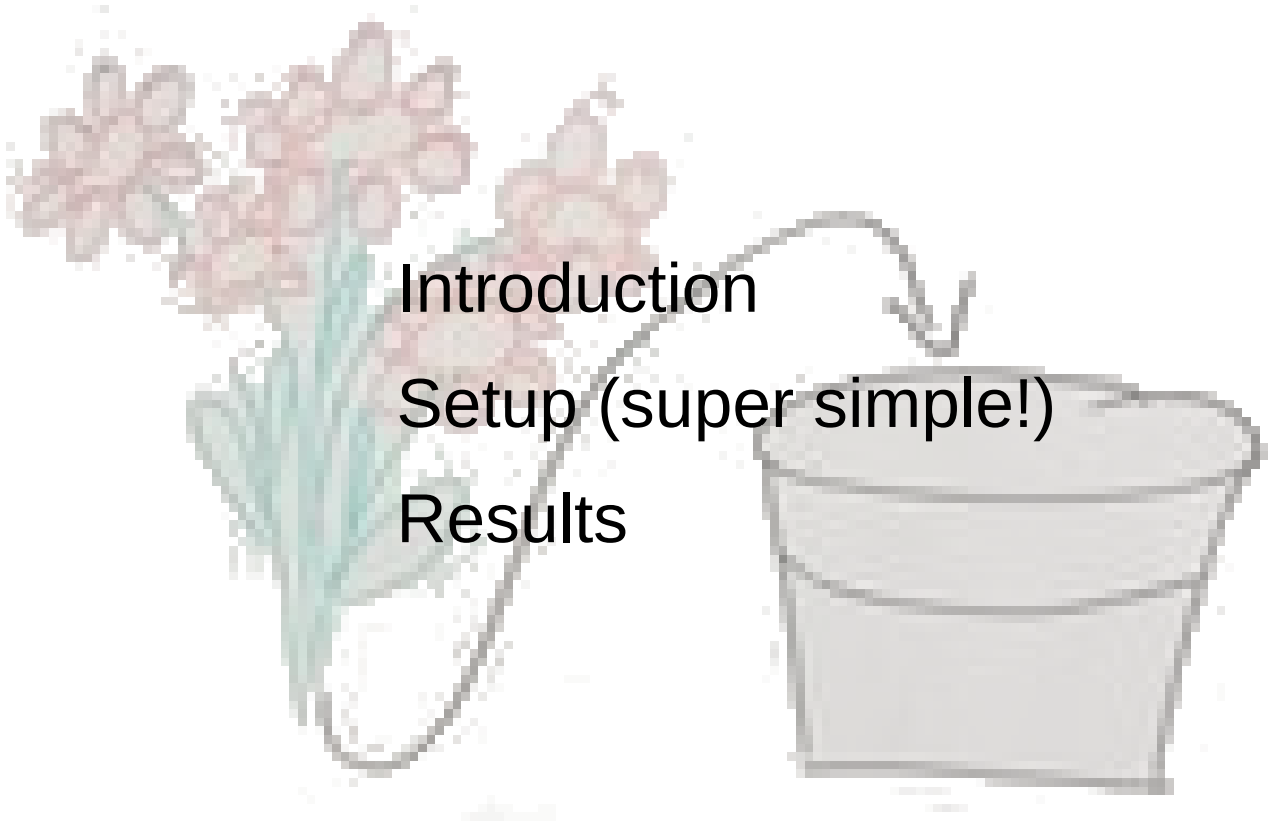
- GSI Timing Team: Michael Reese, Jiaoni Bai, Alexander Hahn, Enkhbold Ochirsuren, Marcus Zweig, Martin Skorsky, Stefan Rauch (associated), Mathias Kreider, Cesar Prados, Anjan Suresh, Wesley Terpstra
- GSI Bunch-to-Bucket: Dieter Lens, Dietrich Beck, David Ondreka, Harald Klingbeil, Ralph Bär, Bernhard Zipfel, Jiaoni Bai, Thibault Ferrand, Dominic Day, Karsten Koch, Jürgen Florenkowski, Markus Steck …
- GSI groups: Ring-RF, Ring HV, Accelerator Control System, Experiment Electronics, Beam Instrumentation, PHELIX Crew, the ESR Team ...
- White Rabbits from CERN and elsewhere
- ...

Some figures are pirated from Jürgen Florenkowski (Ring HV - Kicker), Zsuzsanna Slattery-Major (PHELIX), Oleksandr Chorniy (Beam Instrumentation) and the GSI web site.

Bunch to Bucket (Lite)

… and first operation

Dietrich Beck, Dieter Lens and many others - GSI



Introduction

Setup (super simple!)

Results

https://www-acc.gsi.de/wiki/BunchBucket

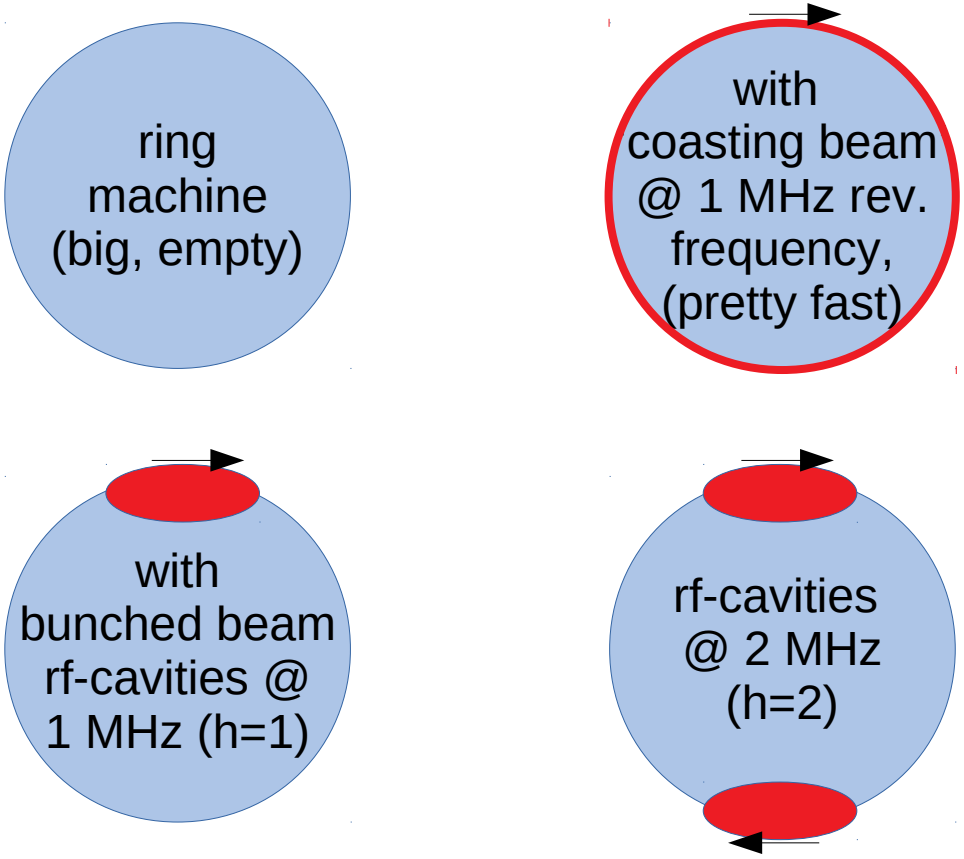
Outlook: Facility for Antiproton and Ion Research

Photo 2014-05-25: Jan Schäfer for FAIR

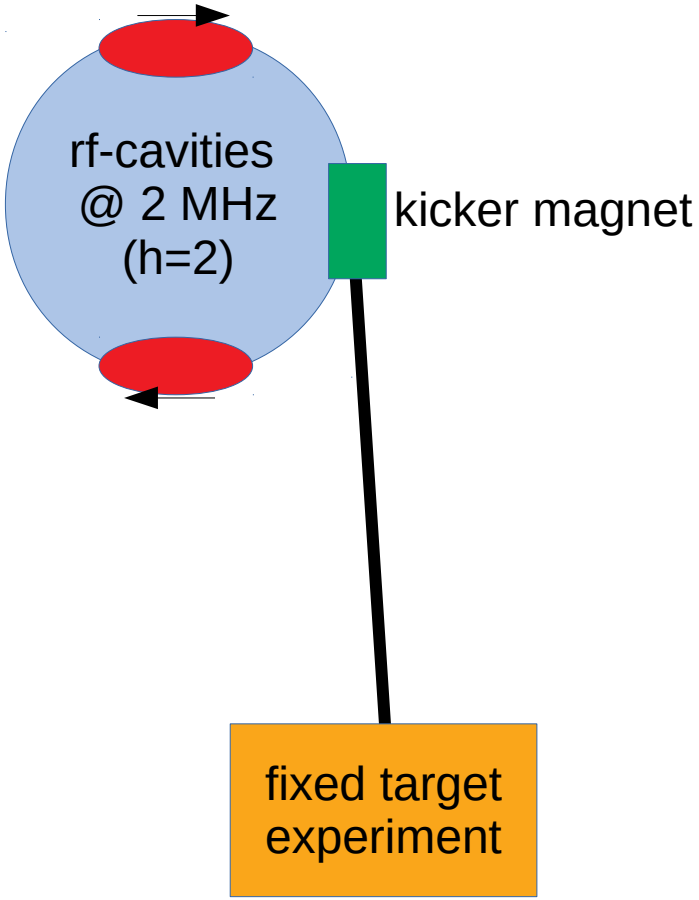
Outlook: Facility for Antiproton and Ion Research

Photo 2021-September: GSI

B2B Primer


ring
machine
(big, empty)
with
coasting beam
@ 1 MHz rev.
frequency,
(pretty fast)
with
bunched beam
rf-cavities @
1 MHz (h=1)
rf-cavities
@ 2 MHz
(h=2)

B2B Primer



Kicker for SIS18 @ GSI

- fast: rise/fall time ~ns
- pulse length: ~µs
- pulse has up to 2.5 GW power

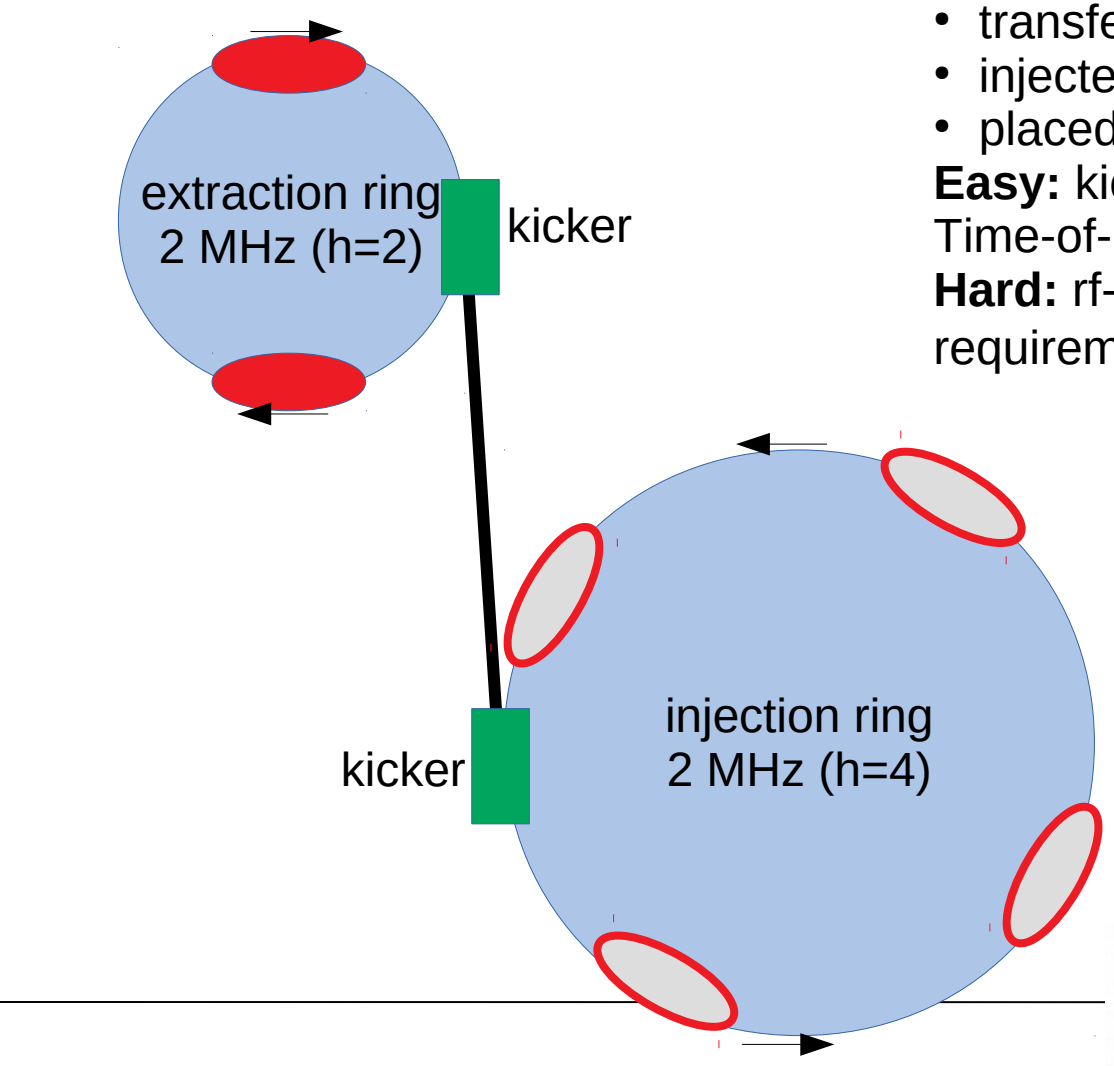
timing of kicker trigger

- bunch position determined by rf-phase
- rf-phase measurement
- just generate a trigger signal at a fixed phase
- (the operators have a ‘phase knob’ to tune the phase to the best value)

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

B2B Primer



Bunch-to-Bucket Transfer

- bunches are extracted ...
- transferred ...
- injected …
- placed into the center of an empty rf-bucket

Easy: kicker timing, just consider Time-of-Flight, delays …

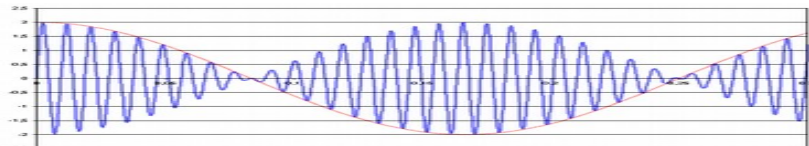
Hard: rf-phase matching of both machines, requirement @GSI/FAIR: $d\varphi \approx 0.5$ degree

Phase Matching

- either phase shift method, or
- frequency beating method

Frequency Beating

- ratio of ring circumferences are integer numbers
- slight detuning of frequencies



FAIR: New Bunch-2-Bucket Transfer System

Here: Bunch-2-Bucket-Lite

- with control loops off, DDS frequencies match known values from settings management
- no frequency measurement required

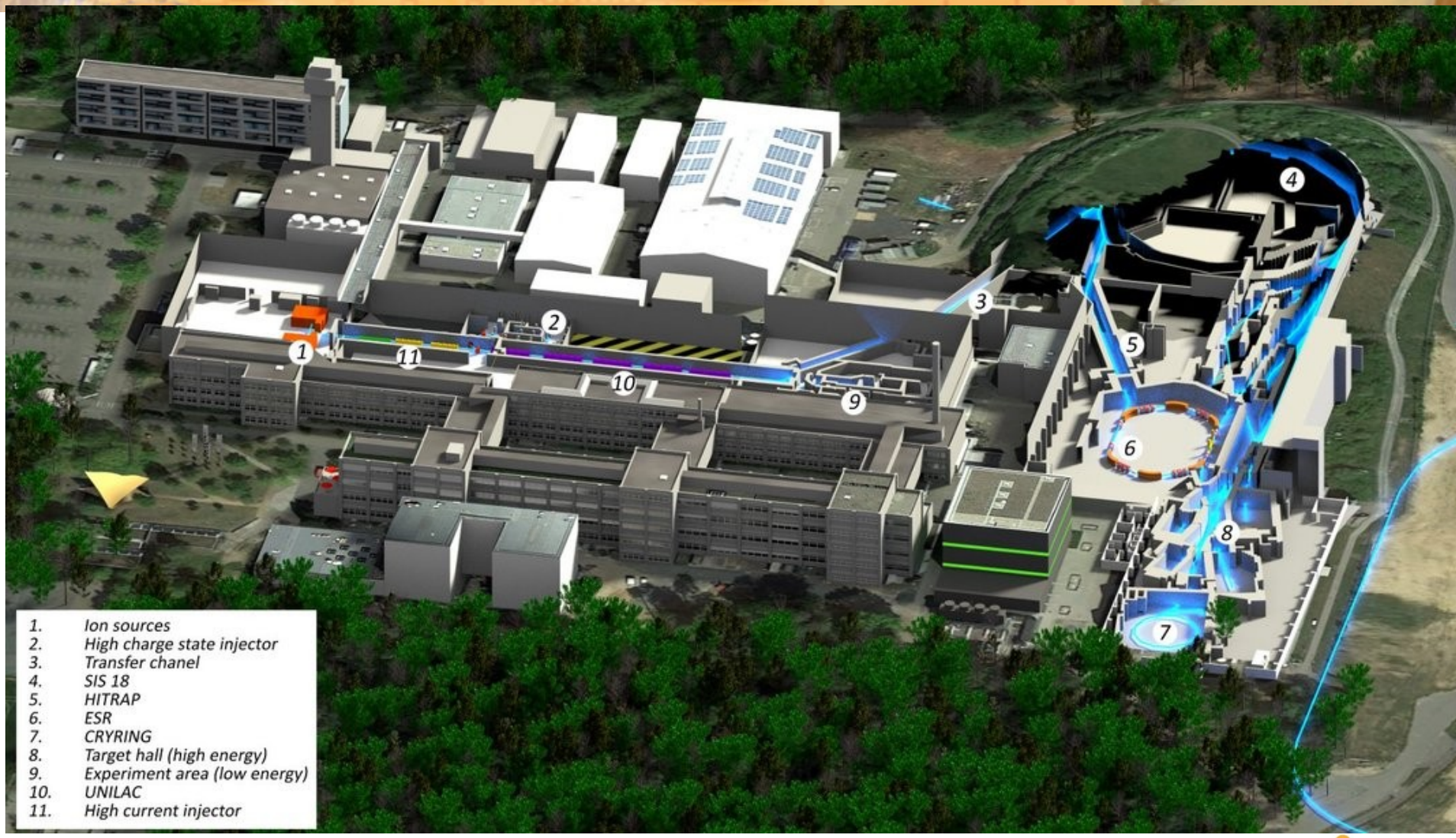
- White Rabbit and rf-clock-system BuTiS share the same reference clock
- identical propagation of time
- it does not matter where and how we measure/reproduce signals[1]

requirement dφ ≈ 0.5 degree ~1 ns: a GSI White Rabbit Timing Receiver is good enough

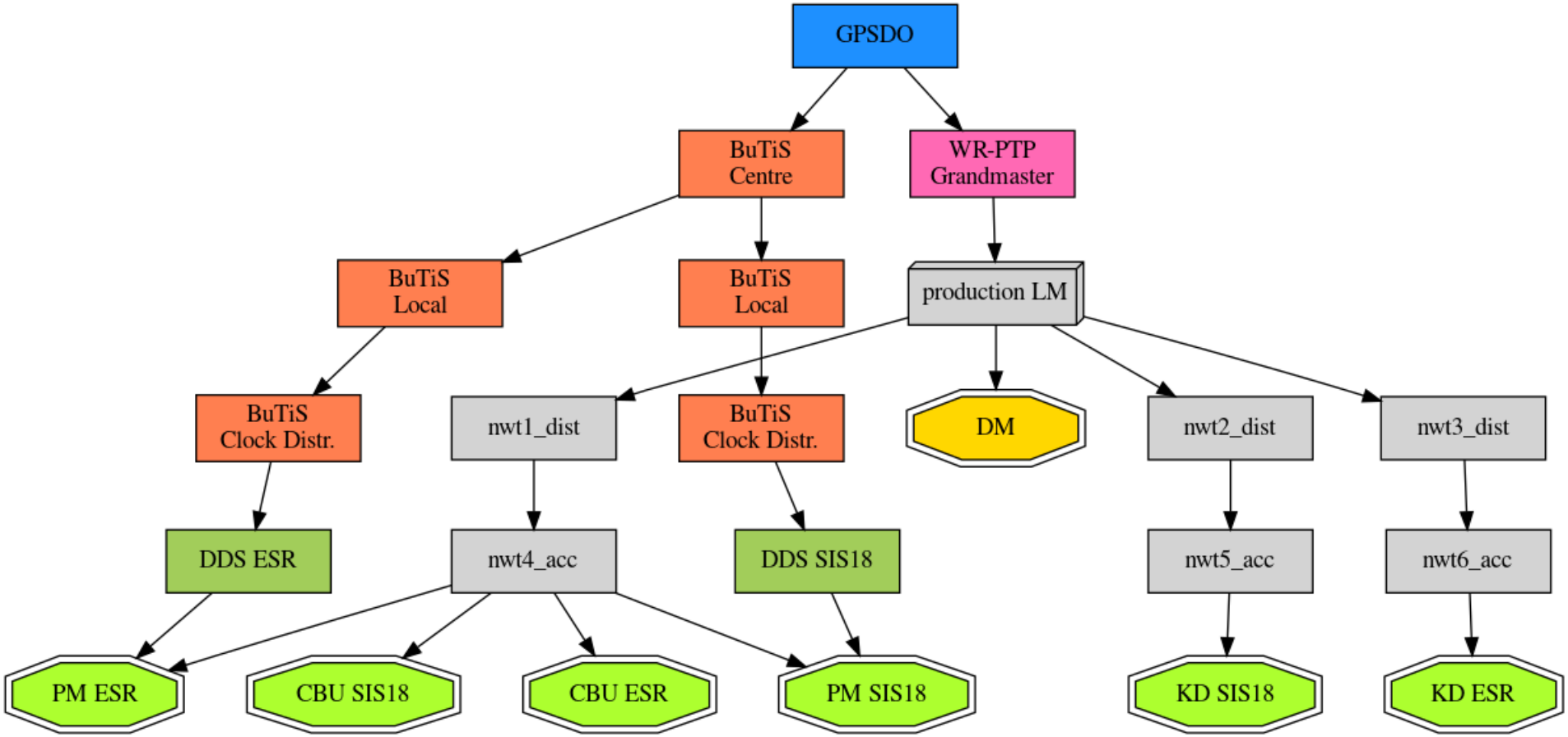
‘Frequency Beating’ can be done without hardware development!
‘Phase Shift’ requires development at RRF

super-simple recipe:
1. measure phase at both rings
2. do some math
3. trigger kickers

Test New Development at GSI



Clock Propagation

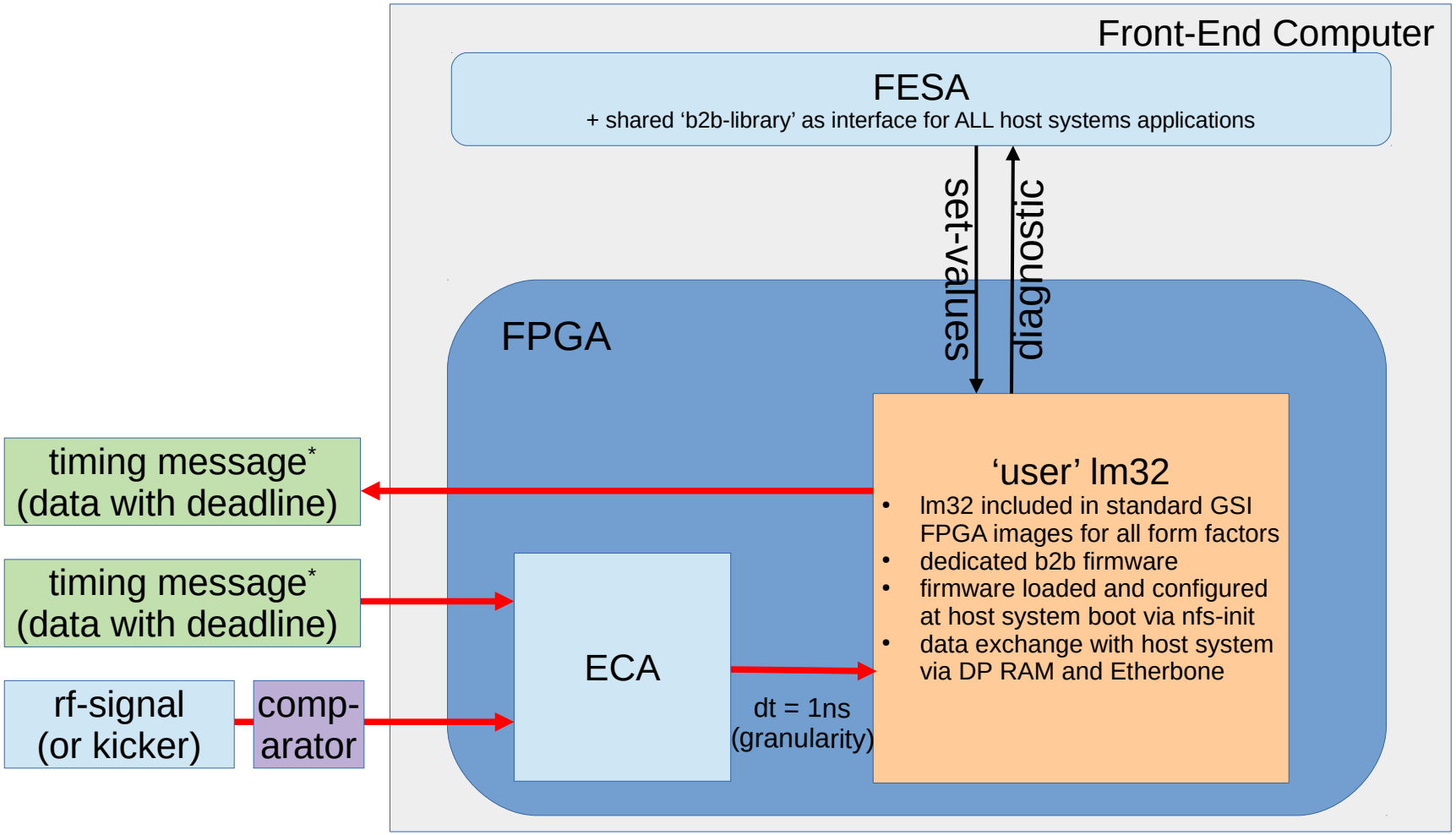


Components: GPSDO (blue), White Rabbit Grandmaster (cyan) and Switches (grey), rf-clock distribution system (BuTiS, brown), rf-group-DDS systems (dark green), nodes of the b2b system (light green) and Data Master of the Machine Timing System (yellow). Nodes with double-lined borders broadcast messages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

B2B Node

hardware+gateware: 'GSI-Off-The-Shelf' (GOTS) except lm32 firmware
for hardware, see tr-pmc or tr-amc @ OHWR

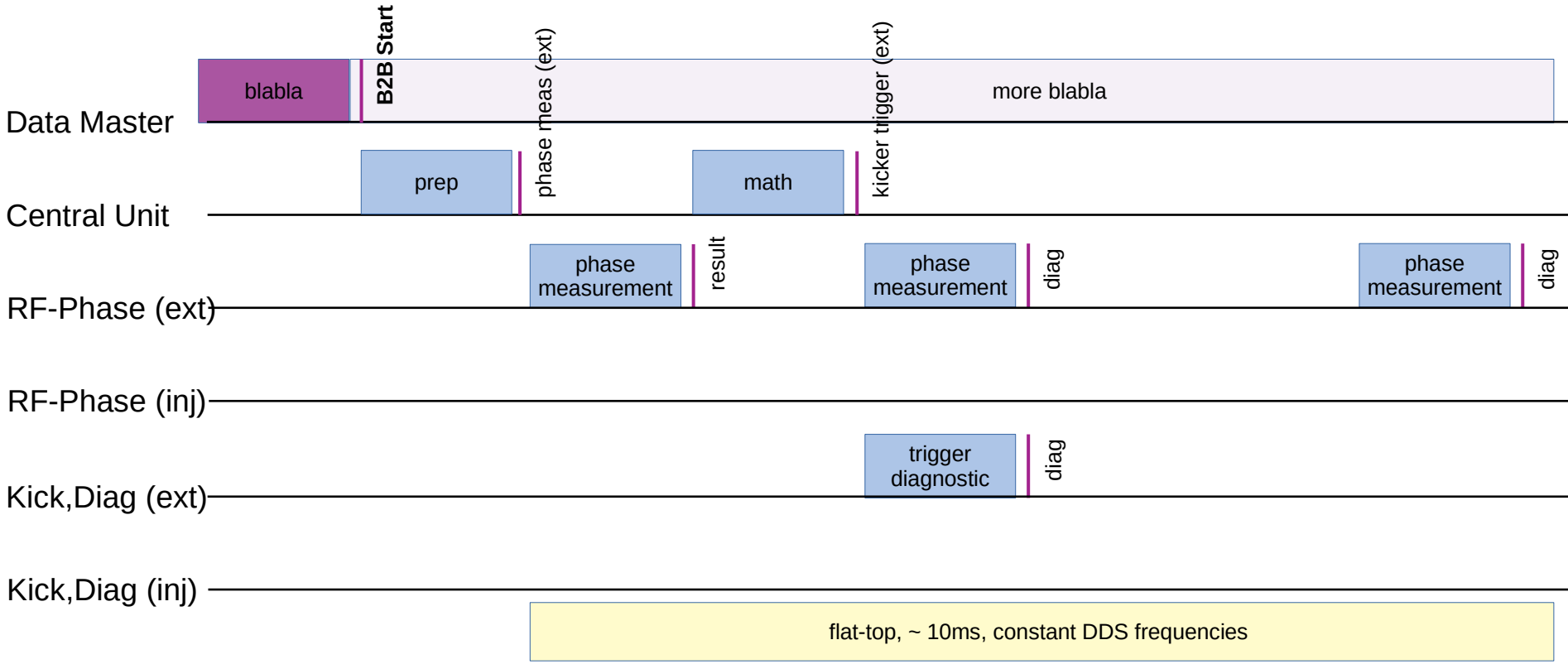


*timing messages are Etherbone broadcast on the White Rabbit network

Procedure: Simple Extraction

(to fixed target or whatever)

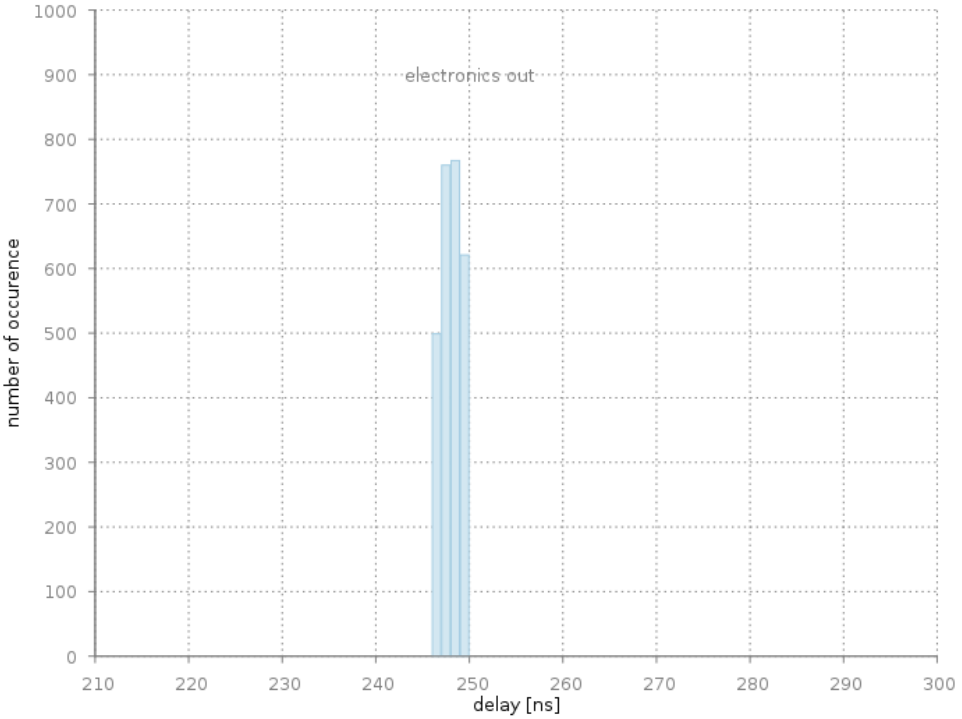
- all messages are broadcast and sent ~500 µs prior deadline to the WR network
- messages contain 64bit of data (rf-period, phase, measured kick time, ...)
- cyan: message deadline, blue: firmware activity (lm32), yellow: ring @ extraction level
- two additional phase measurements serve for cross checks (clock propagation, DDS frequency)
- figure not to scale

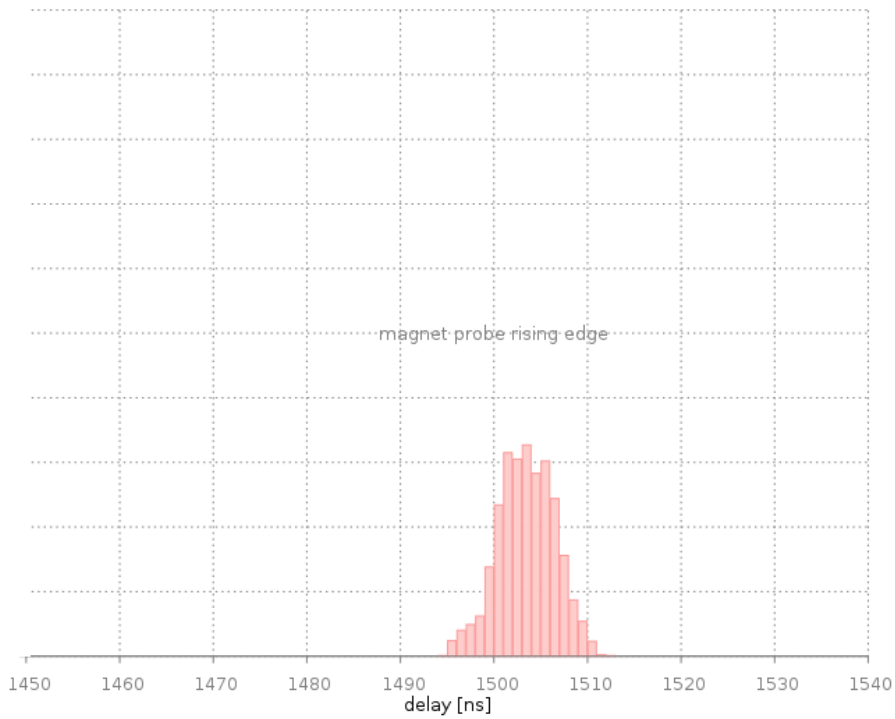


Proof-of-Principle: 1st Dry-Run

- yellow: rf-signal from SIS18 Group-DDS
- blue/cyan: timing messages by the B2B system
  here: trigger signals generated by a Timing Receiver

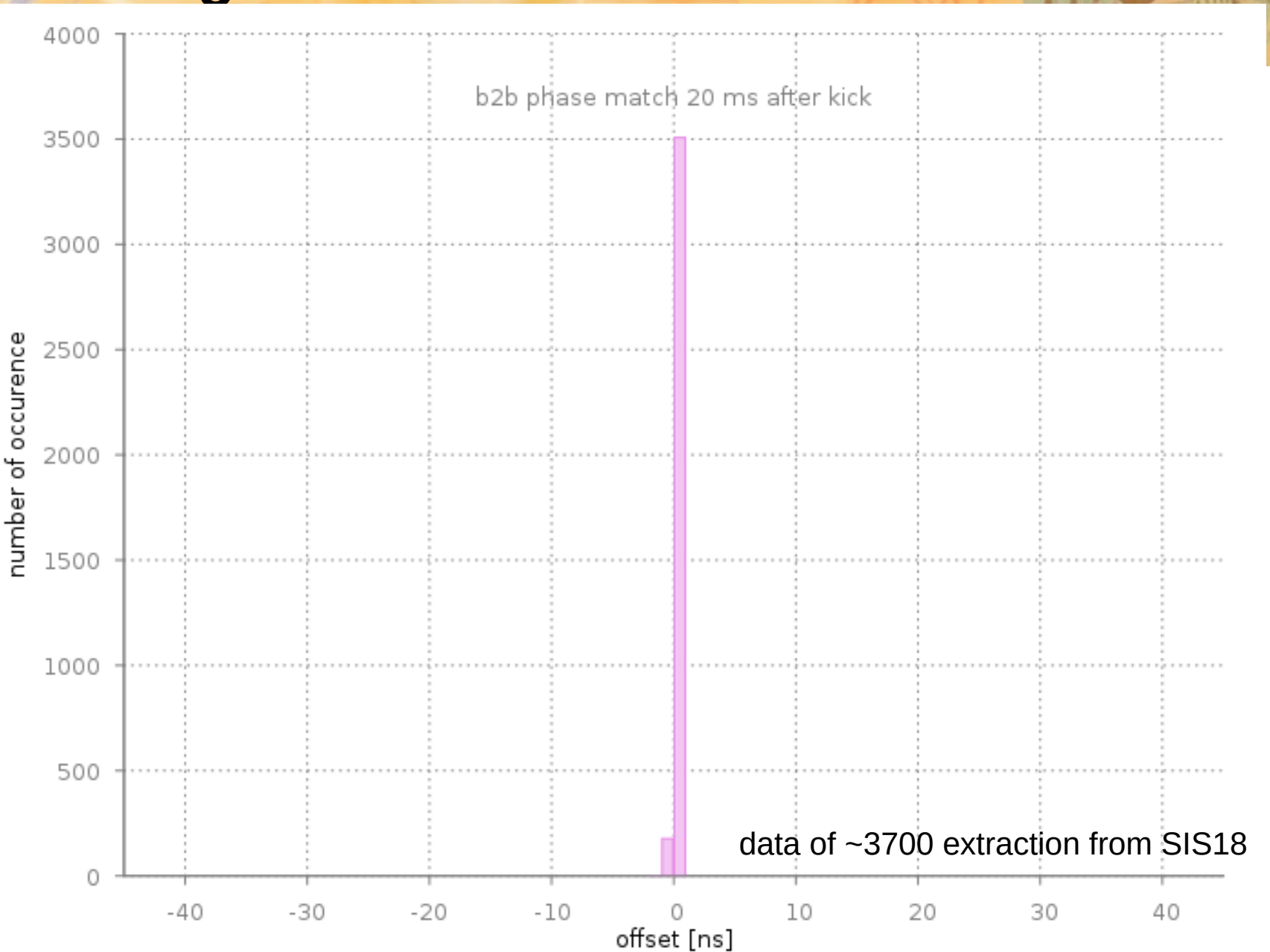
Diagnostic: Kicker Signals





- histograms: time distribution of electronic signals (rising edge)
- here: data of 2647 extractions from SIS18
- left: output of kicker control electronics (~ kicker internal signal to high power unit)
- right: kicker magnet probe (proof kicker has actually fired)
- data of each of extraction must be delivered to customers via the WR network within 1ms after the kick

Diagnostic: Remeasure DDS Phase



11 to 18 May 2021: Routine Operation

- the b2b system had been in operation in dry-mode since January 2021
- we just had asked for one shift (8 hours) for a machine experiment with the system

But... we had the chance using the system for full 8 days with ‘real’ routine operation

- no fancy stuff like true bunch-to-bucket
- challenge 1: stable 24/7 operation without failures
- challenge 2: multiplexed beams (serving multiple experiments in parallel)

Luckily, this has been an almost boring exercise. Everything worked as expected. 😎

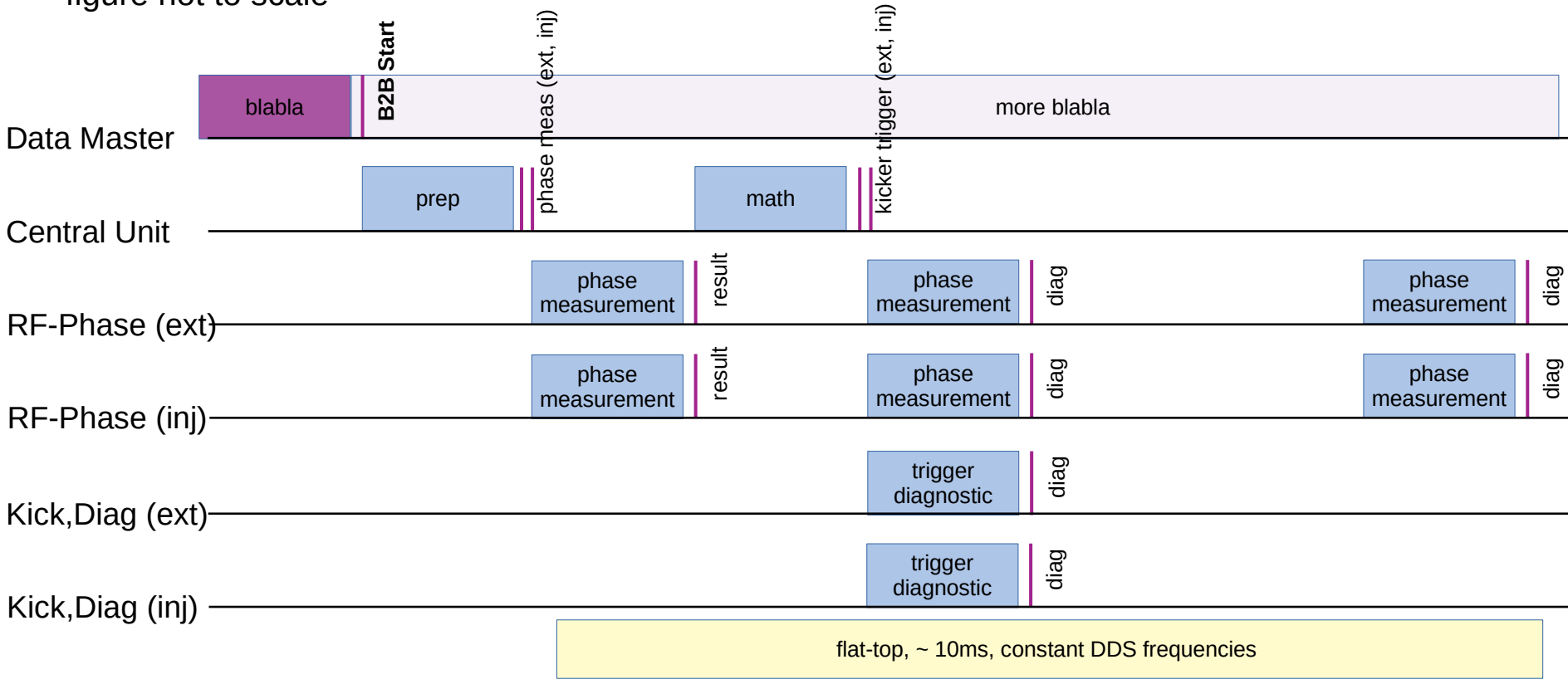
But it was a huge success to see the system actually works as part of an accelerator!

Actually, the users were pleased with the performance and reliability.

My main worry has been the environment of kicker supply rooms (up to Gigawatts of pulsed electrical power). But there was **not** a single failure after 6 months (broken hardware, loss of White Rabbit lock …). The ‘kicker colleagues’ do an excellent job.

Procedure: Bunch-2-Bucket

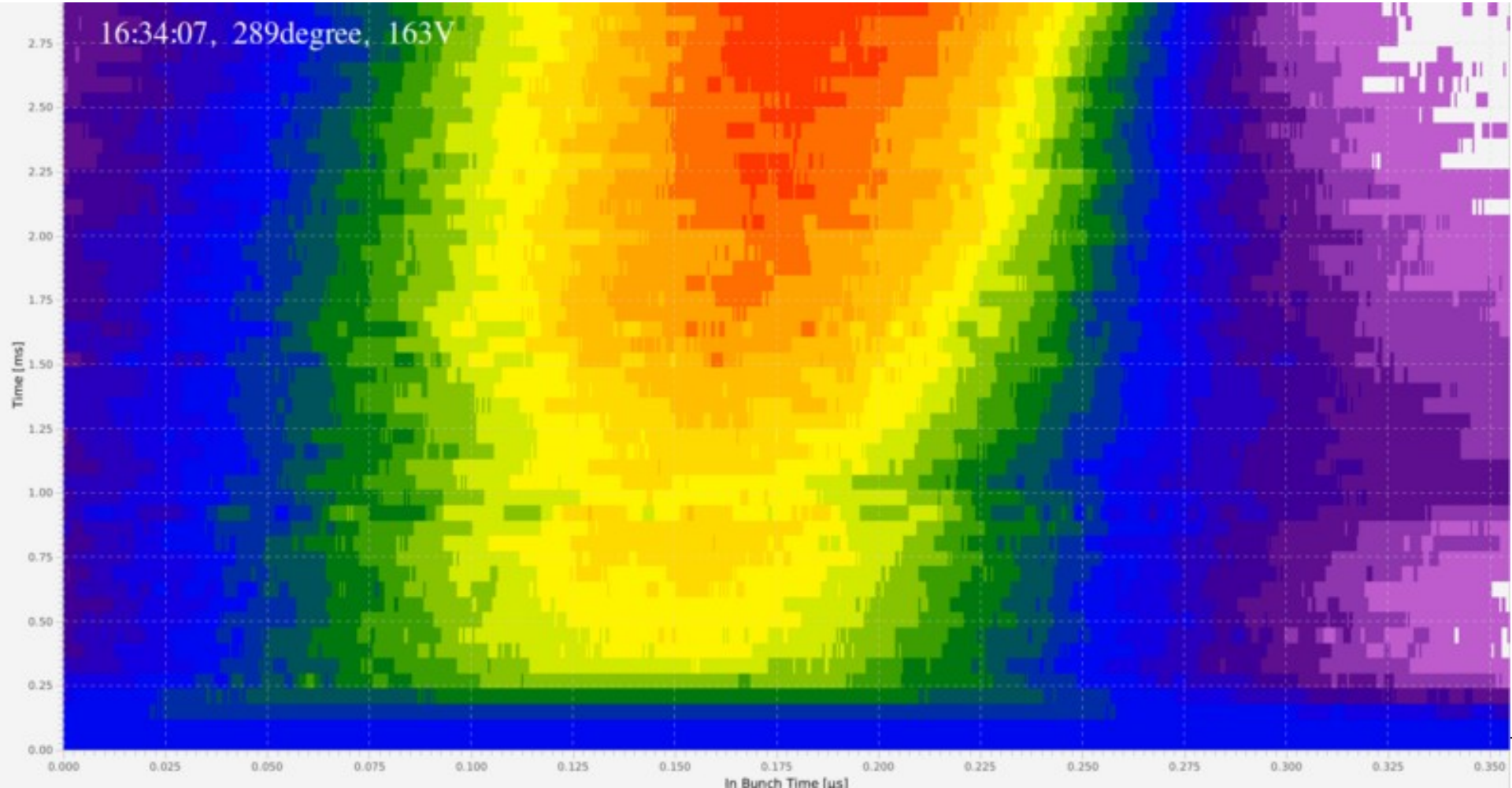
- all messages are broadcast and sent ~500 µs prior deadline to the WR network
- messages contain 64bit of data (rf-period, measured phase, kick time, diag data, ...)
- cyan: message deadline, blue: firmware activity (lm32), yellow: ring @ extraction level
- two additional phase measurements serve for cross checks (clock propagation, DDS frequency)
- figure not to scale



17 May 2021: 1st B2B Transfer SIS18 → ERS

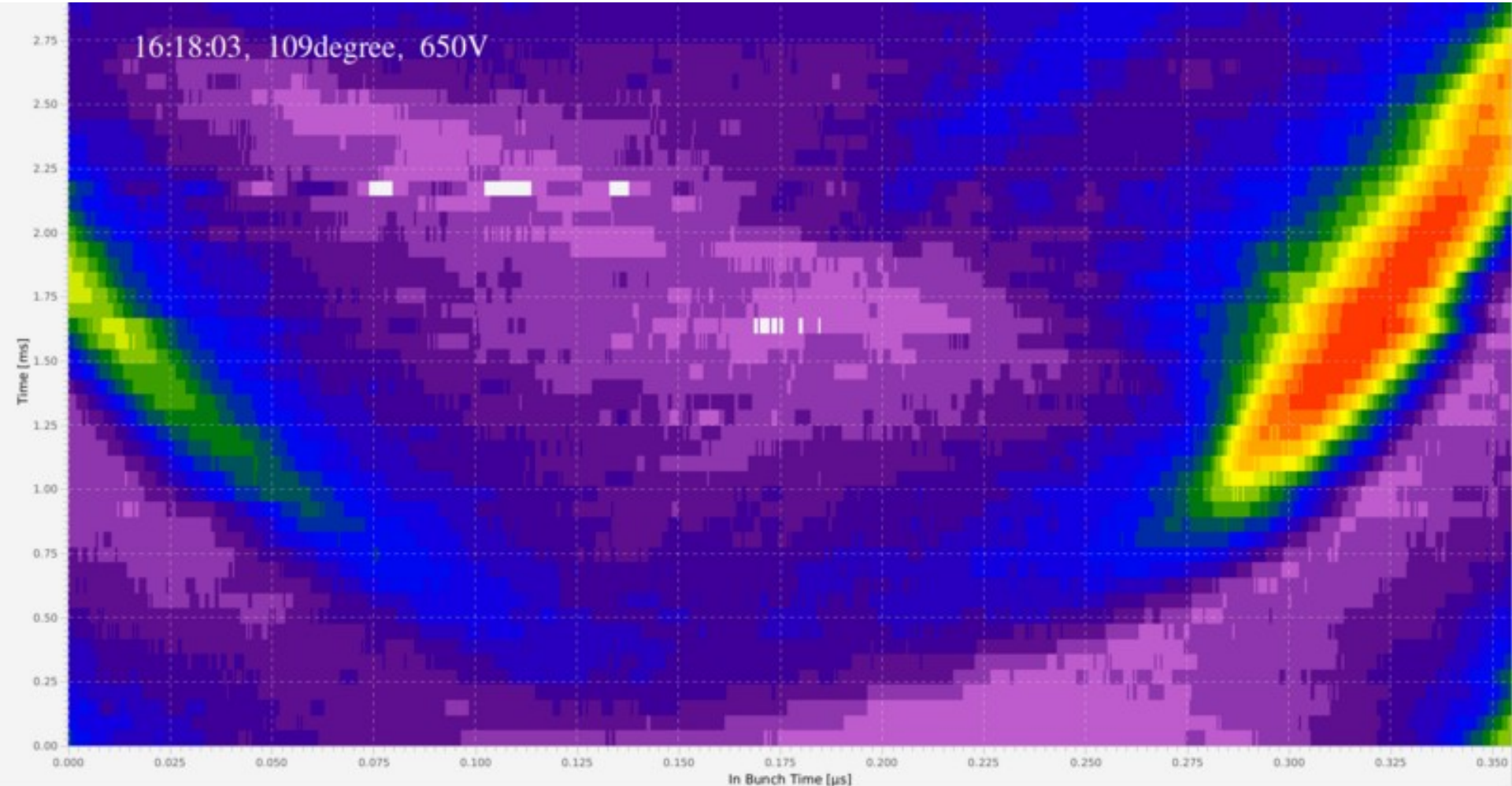
- proof-of-principle: dedicated machine experiment (one shift)
- as usual: success at 30 minutes prior end of shift :-)

below: evolution of a bunch trapped in a rf-bucket at correct phase difference



17 May 2021: 1st B2B Transfer SIS18 → ERS

below: destruction of a bunch at correct phase difference **+ 180 degree**



Important Aspect: Plasma Physics @ GSI/FAIR
‘Bonus Program for B2B Tests’

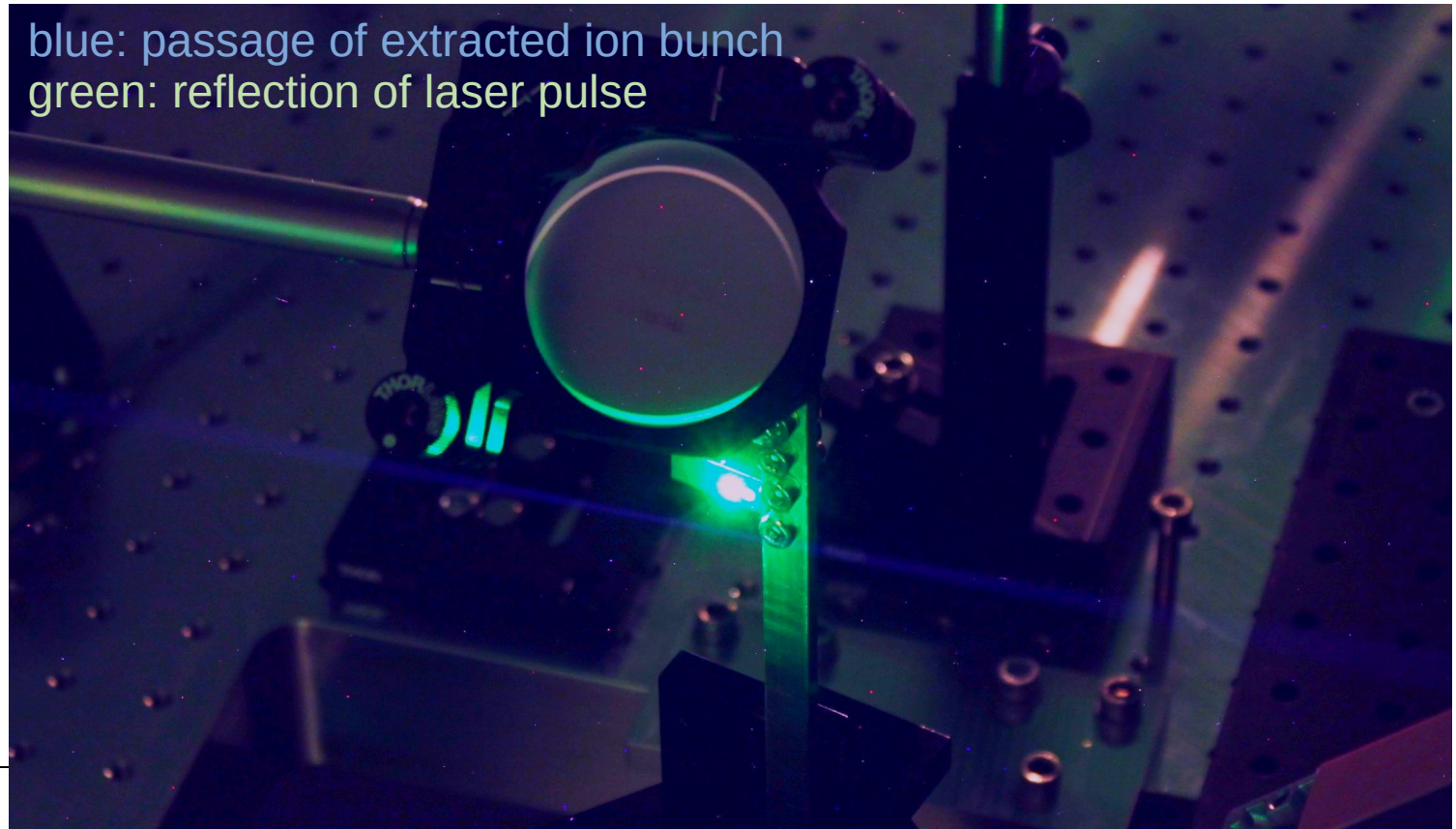
here: PHELIX facility – a high energy, high intensity pulsed laser

- up to 200 J
- up to 500 TW
- up to ~10^{16} W/cm^2 focused intensity

May 2021: test experiment in cave HHT

challenge: synchronize PHELIX laser pulse and ion bunch extracted from SIS18

b2b system: rf-phase measurement, then trigger SIS18 extraction kicker **and** PHELIX



Routine Operation for Beam-Time 2022

Plan: Full replacement of the old GSI beam transfer and synchronization system for the entire beam-time 2022.

- ‘fast’ extraction from main synchrontron SIS18 (demonstrated 2021)
- beam transfer to storage ring ESR (demonstrated 2021)
- ‘fast’ extraction from ESR (demonstrated 2021 with ‘dry beam’)
- beam transfer from ESR to storage ring CYRING
- ‘fast’ extraction from CRYRING

Todo:

- get all equipment (ordered, but …)
- survive unexpected power-cuts
- find s.o. to pull cables from A to B …
- full integration into the accelerator control system (machine model, LSA, FESA)

Next years: three more rings for FAIR + surprises