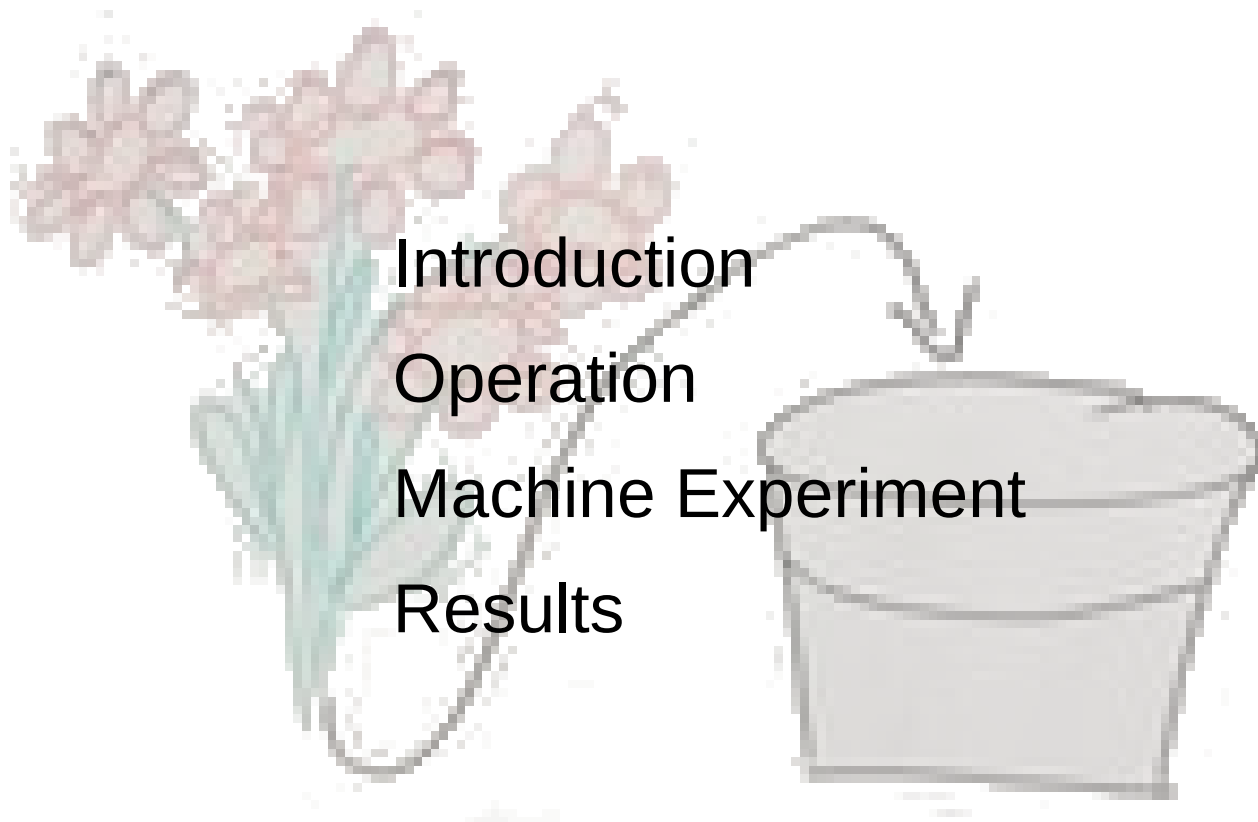


Bunch-to-Bucket (Lite)

Report Machine Experiment 2021

Dietrich Beck, Dieter Lens and many others



Introduction

Operation

Machine Experiment

Results

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

Bunch-to-Bucket (b2b) Transfer System

- new system required for FAIR
- replacement of 'Timing Generator'; **no long cables for analog signals**
- **distributed** system using White Rabbit infrastructure; **mainly digital**
- mode 'bunch 2 bucket'; booster mode SIS18 → SIS100 as prominent use case
- mode 'bunch 2 coasting beam'; so far standard for SIS18 → ESR → CRYRING
- mode 'fast extraction'; extract bunch (to fixed target ...)
synchronization of extracted bunch with plasma physics experiments

- 'Frequency Beating' can be done without hardware development!
- 'Phase Shift' requires development at RRF

Machine Experiment 2021: try bunch 2 bucket with SIS18 → ESR; one shift

B2B Distributed Signals

Example: Fast Extraction

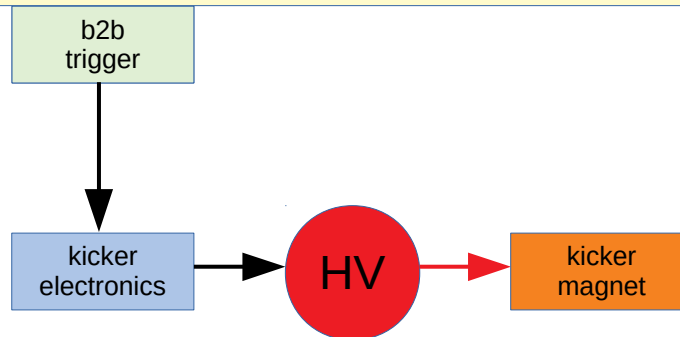


SIS18 RRF
Group DDS

b2b
1 phase meas.

- @flattop: known and fixed DDS frequency (LSA)
- White Rabbit and BuTiS are phase-locked
 - phase measurement of DDS signal
(then, the b2b system can predict the DDS phase at any given time)
 - calculate deadline when the trigger for the kicker shall be generated

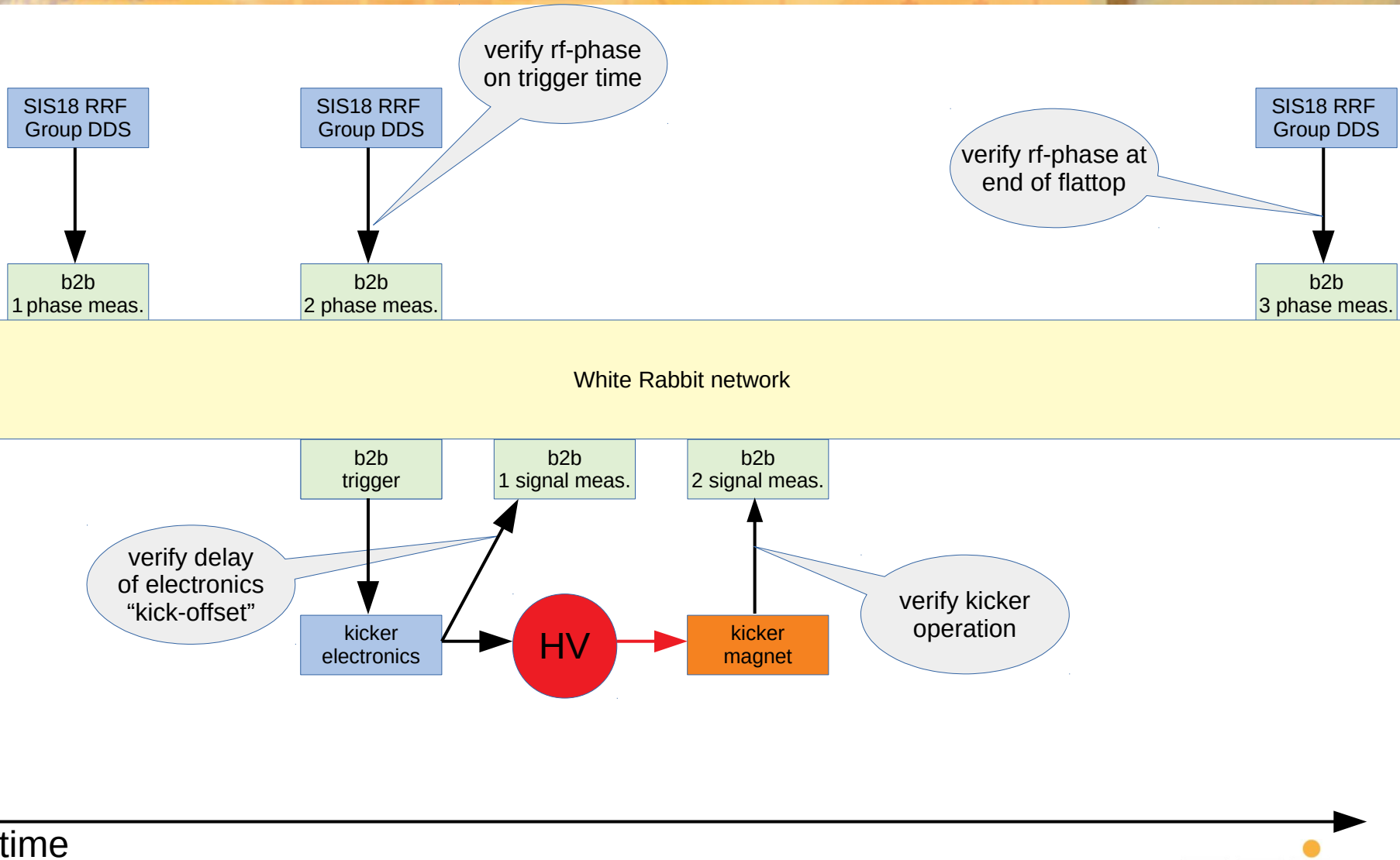
White Rabbit network



time

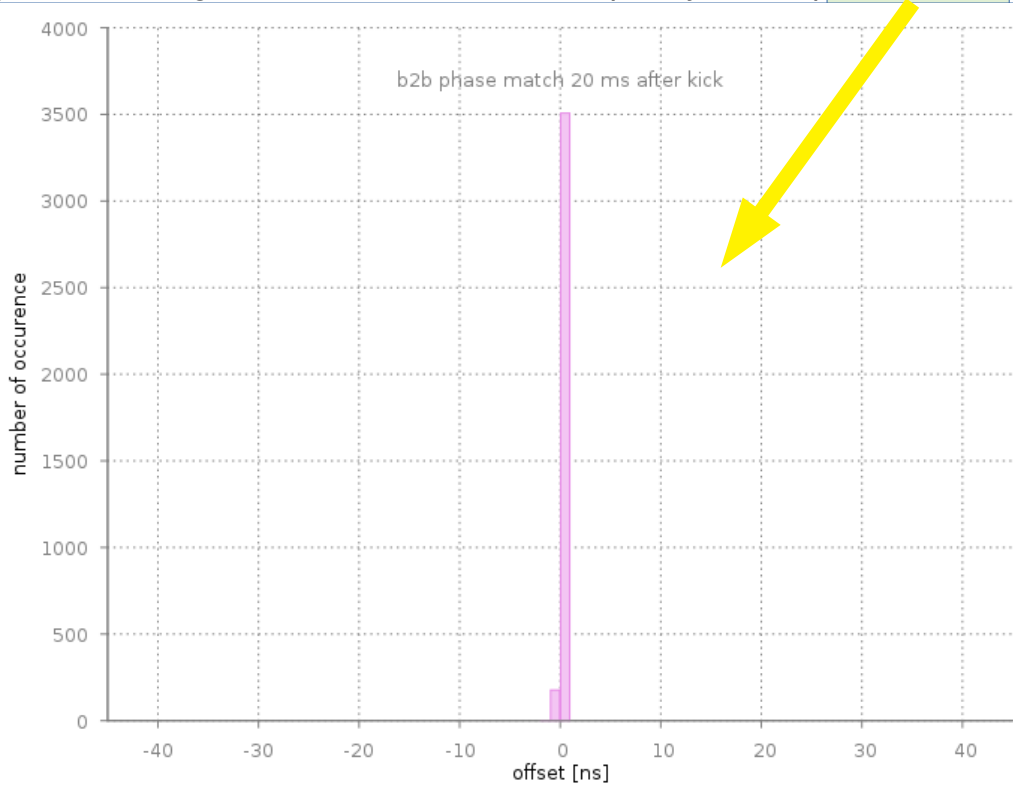
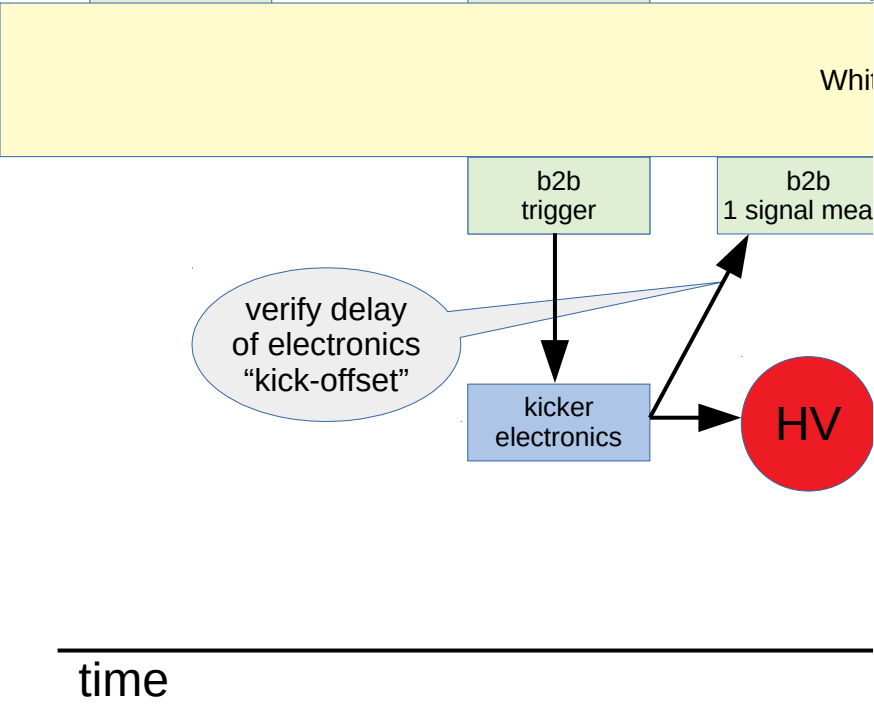
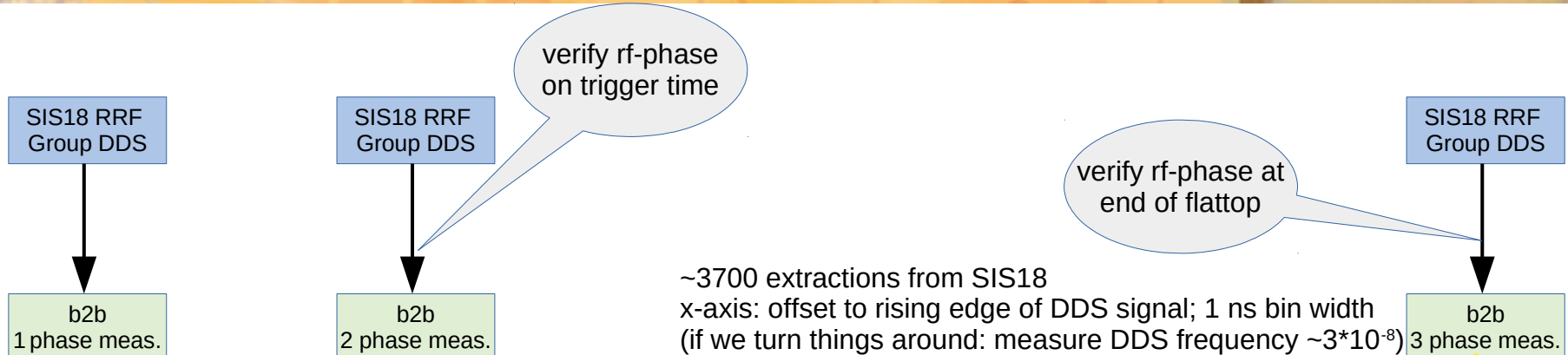
B2B Distributed Signals

Example: Fast Extraction

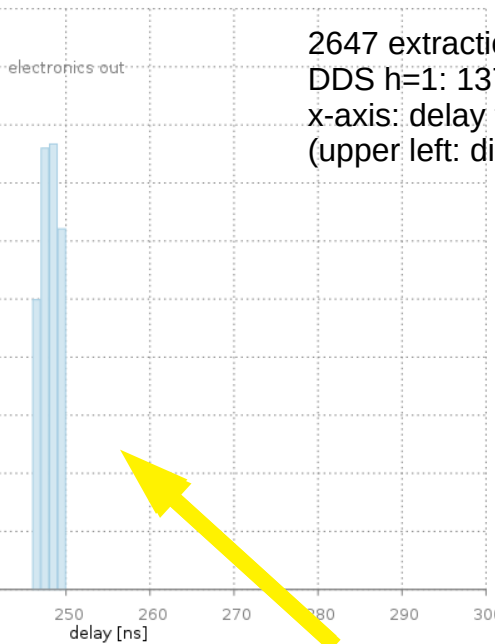
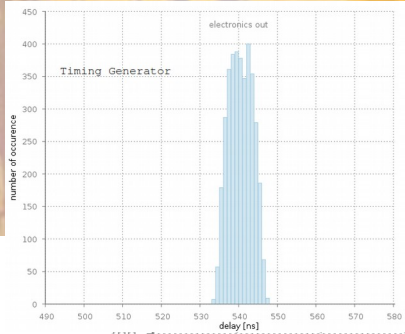


B2B Distributed Signals

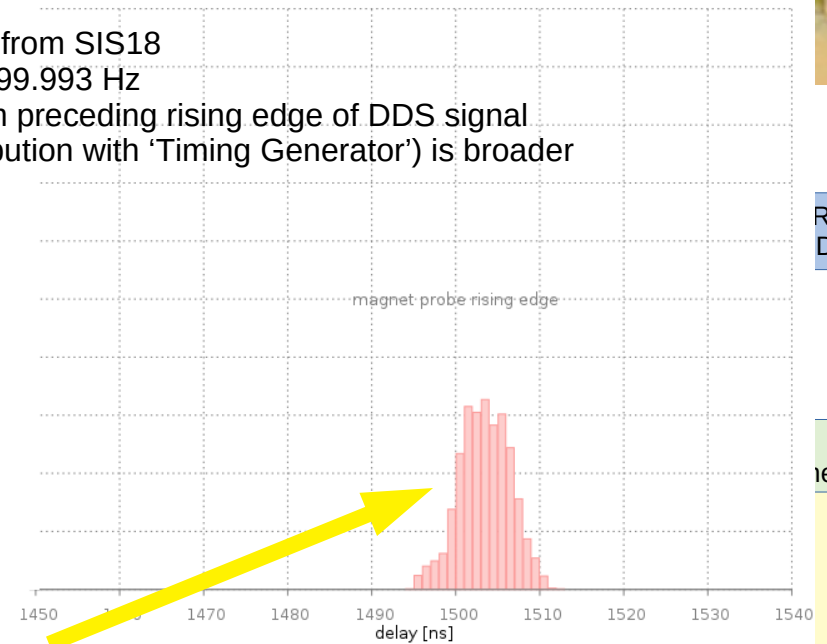
Example: Fast Extraction



B2B Distributed Signals

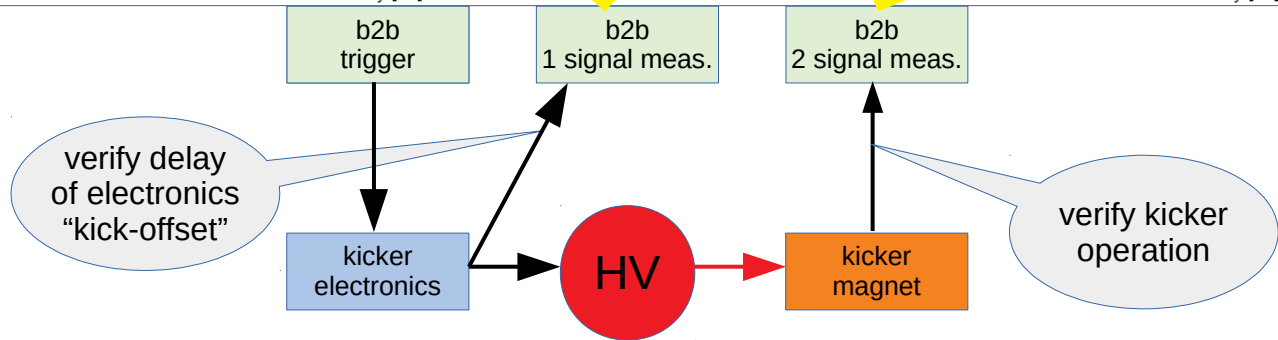


2647 extractions from SIS18
 DDS h=1: 1374999.993 Hz
 x-axis: delay from preceding rising edge of DDS signal
 (upper left: distribution with 'Timing Generator') is broader



RF
DS

meas.



time

Preparation of Beam-Experiment 11 to 18 May 2021: Routine Operation

- the b2b system had been in operation in dry-mode since January 2021
- one shift (8 hours) for a machine experiment scheduled on 17 May 2021

change from 'Timing Generator' to b2b system already on 11 May 2021
one week of routine operation 24/7 with multiplexed beams!

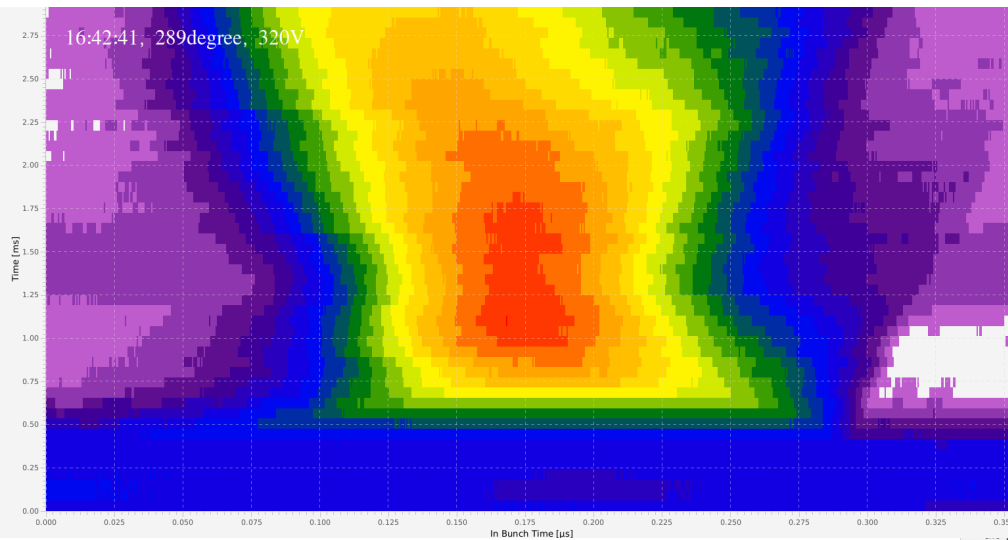
- 11-17 May: 'bunch 2 coasting beam'; krypton beam SIS18 → ESR
- 11-18 May: 'fast extraction'; xenon beam to HHT (PHELIX)

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

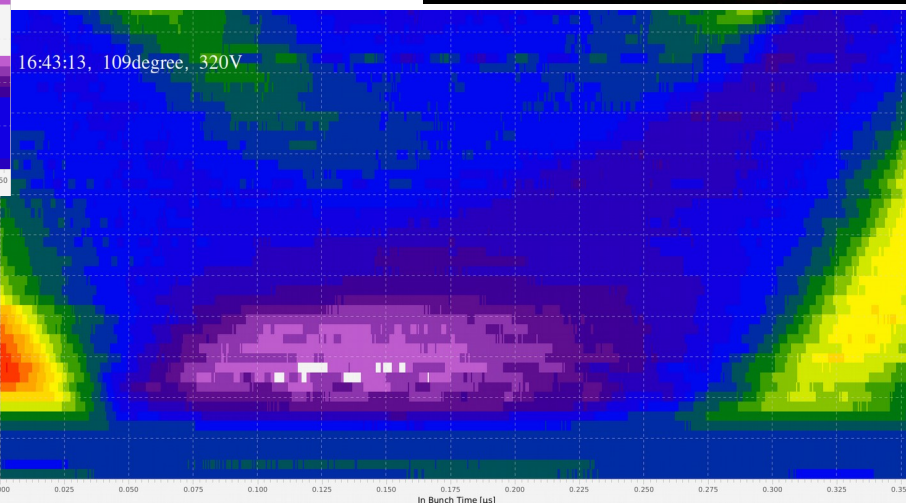
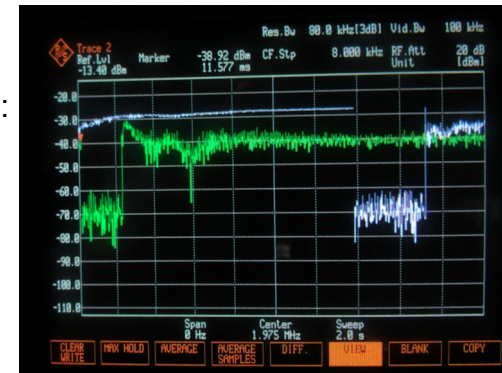
My main worry has been the environment of kicker supply rooms (up to Gigawatts of pulsed electrical power). But there was **not** a single failure after 6 months (broken hardware, loss of White Rabbit lock ...). The colleagues from RHV do an excellent job.

17 May 2021: Bunch-to-Bucket Test SIS18 → ESR

- $^{124}\text{Xe}^{46+}$ @SIS18 → stripper foil → $^{124}\text{Xe}^{54+}$ @ESR
- SIS18: 1979732.979 Hz, ring operated at h=2 (revolution frequency: 989866.490 Hz)
- ESR: 1975118.183 Hz, ring operated at h=1
- beating period 116.6 μs (stripper foil!); only 429(428) RF cycles in SIS18(ESR)
- it took some time to set up everything: excellent job by the ESR team



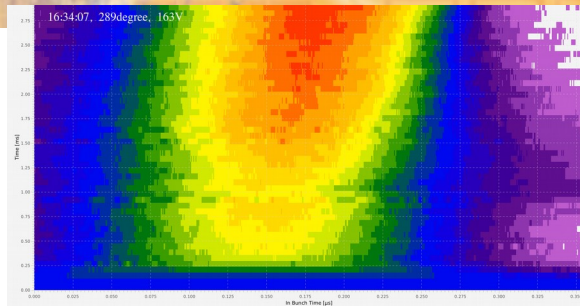
after 1s storage time:
12dB difference



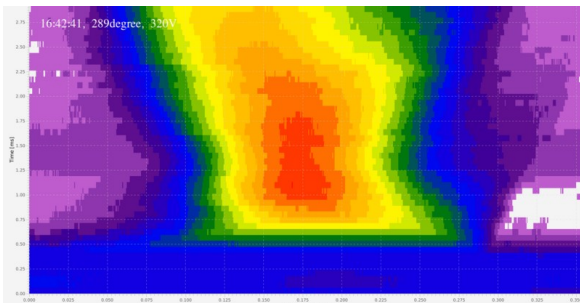
DDS phase difference 289°: proof-of-principle!!!

DDS phase difference 109°: destruction

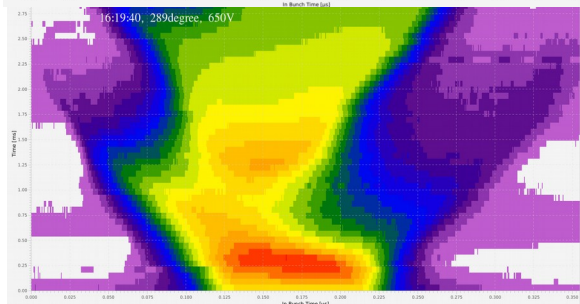
17 May 2021: Bunch-to-Bucket Test SIS18 → ESR



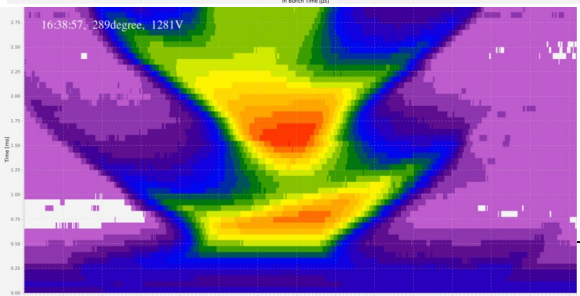
163 V
too little?



320 V
best?



650 V



1281 V
quadrupole oscillations?

tried different ESR cavity gap voltages for a fixed DDS phase difference (289°)

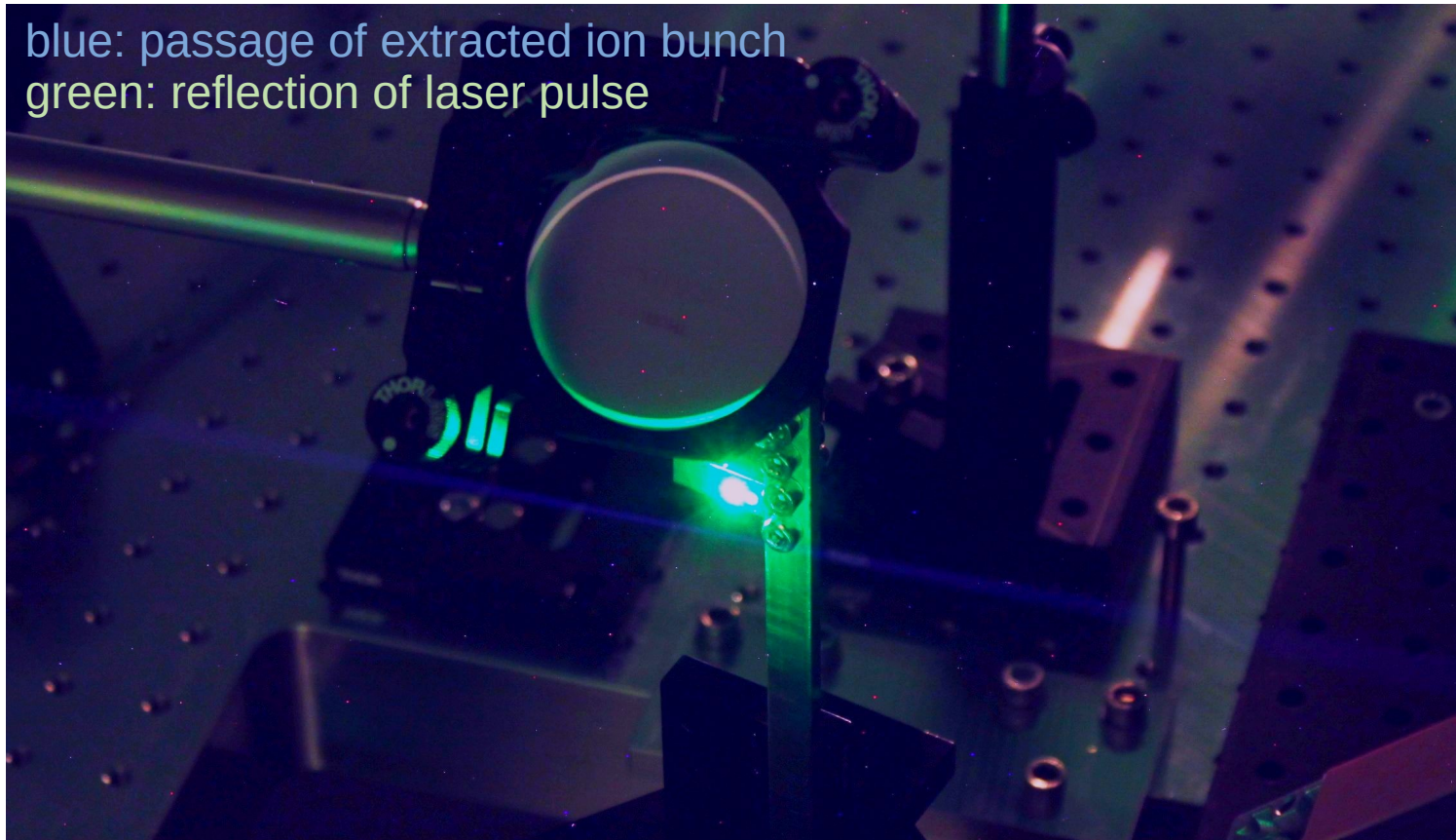
need procedure for matching gap voltages of extraction and injection ring

Bonus: Synchronization of Bunch from SIS18 and Laser Pulse from PHELIX in HHT Cave

- challenge: synchronize PHELIX laser pulse and ion bunch extracted from SIS18
- b2b system: 'fast extraction': trigger SIS18 extraction kicker **and** PHELIX
- GSI-Kurier, CW 41
- synchronization of ions and light better than 10 ns
(10 ns detection limit at HHT during that experiment)



blue: passage of extracted ion bunch
green: reflection of laser pulse



B2B Transfer System in 2021: Summary

- operation in dry-mode since January 2021 + various tests with kickers connected
- one week of routine operation
 - krypton: bunch to coasting beam SIS18 → ESR
 - xenon: fast extraction to HHT
 - reliable operation
- one shift (8 hours) for a machine experiment scheduled on 17 May 2021
 - true bunch-to-bucket demonstrated
 - reproducible and stable matching of bunch and bucket in ESR
 - modified phase difference of SIS18 and ESR h=1 group DDSs
 - modified gap voltage at ESR
- issues
 - b2b system not integrated into control system stack; fixed
 - multitude of parameters: phase difference, gap voltage, what else?
 - little freedom in selecting beating time; employed two tricks for short times ...
 - observation/diagnostic using FCTs requires intense beam (1mA); short observation time
 - triggering MIL devices at beam diagnostics
- beam time 2022
 - go for routine operation ('fast extraction' and 'bunch-to-coasting beam')
 - machine experiments SIS18 → ESR and CRYRING

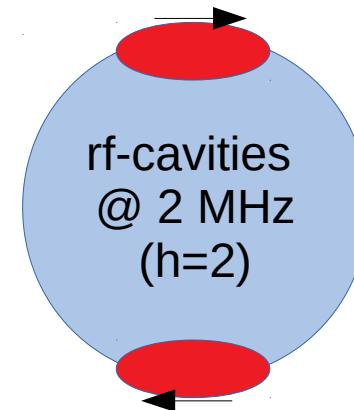
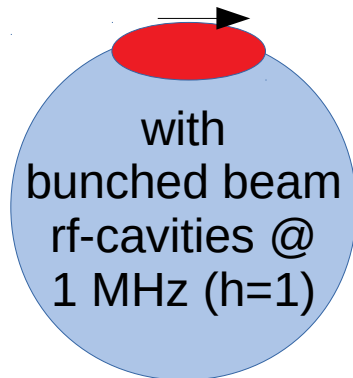
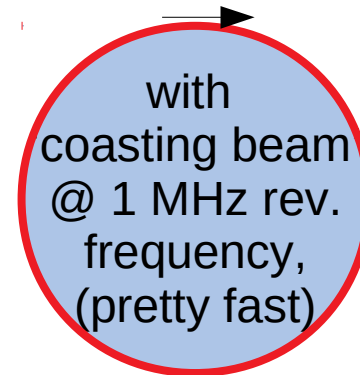
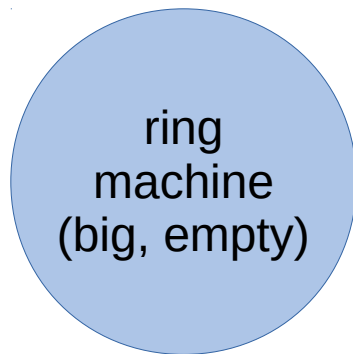
Acknowledgements

- GSI Timing Team: Michael Reese, Alexander Hahn, Enkhbold Ochirsuren, Marcus Zweig, Martin Skorsky, Stefan Rauch (associated), Mathias Kreider
- 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
- ...

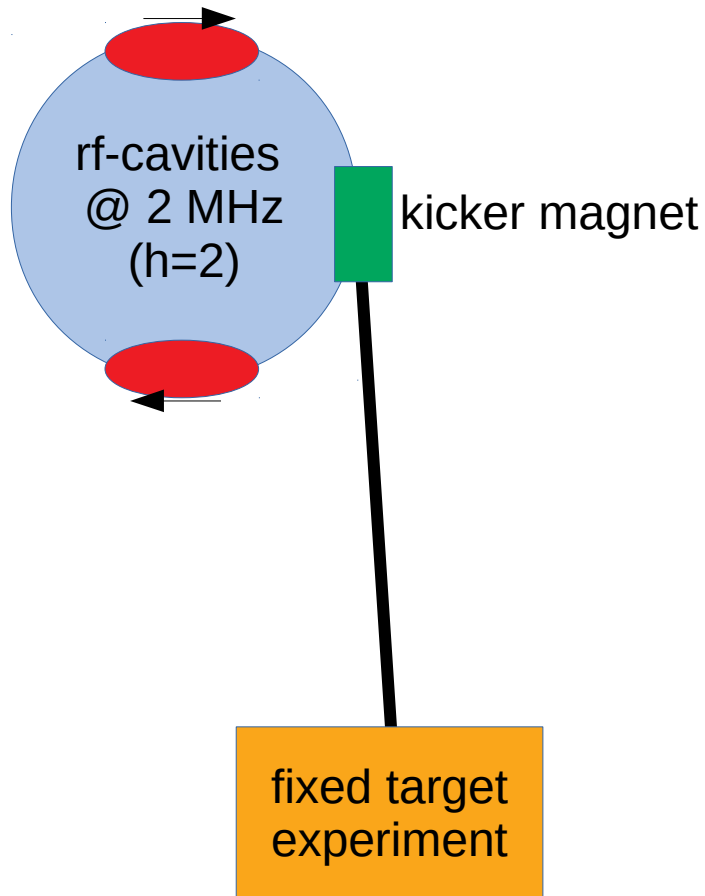
Some figures are pirated from Zsuzsanna Slattery-Major (PHELIX) and Oleksandr Chorniy (Beam Instrumentation)

Backup Slides

B2B Primer



B2B Primer



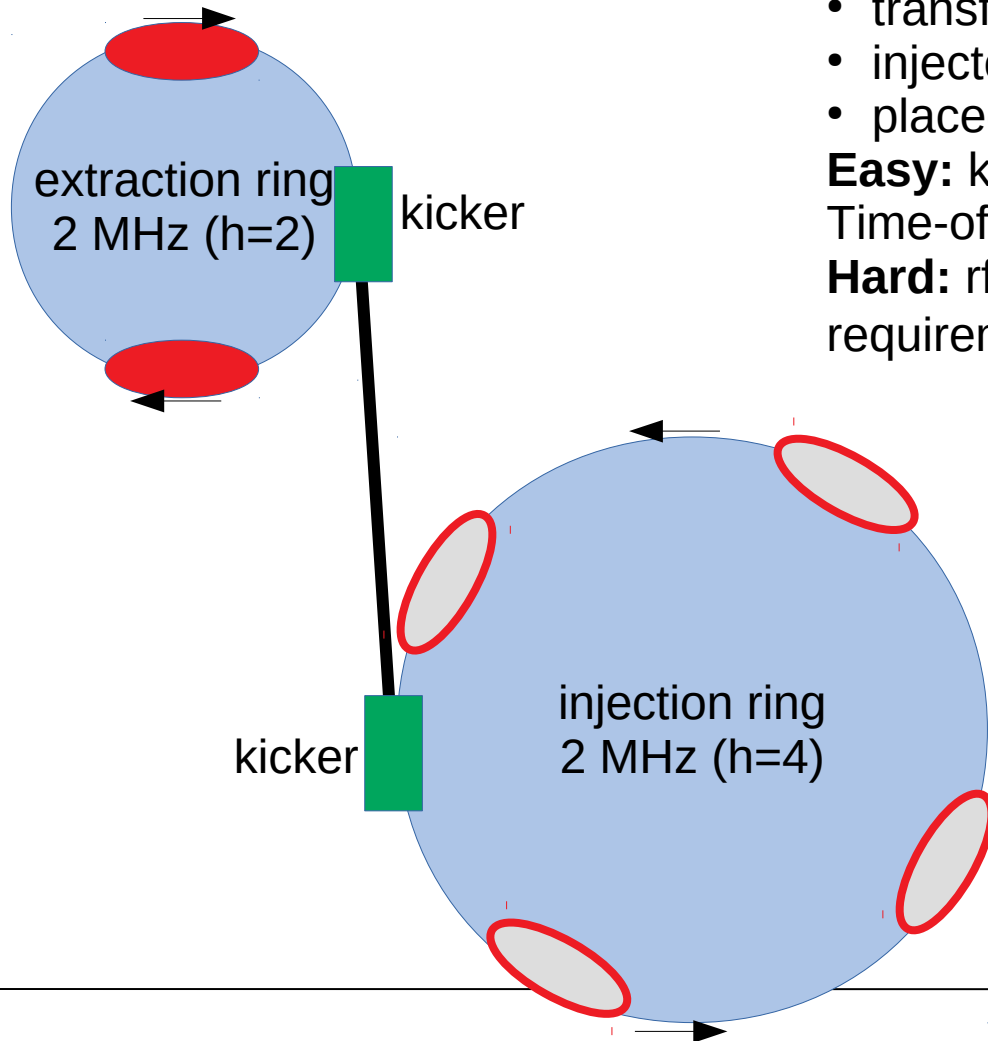
Kicker for SIS18 @ GSI

- fast: rise/fall time \sim ns
- pulse length: $\sim\mu$ s
- 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)

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 ...

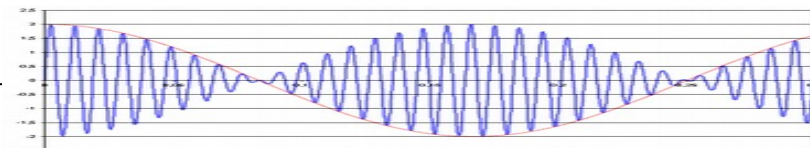
Hard: rf-phase matching of both machines, requirement @GSI/FAIR: $d\phi \approx 0.5$ degree

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 $d\phi \approx 0.5$ degree ~ 1 ns: a GSI White Rabbit Timing Receiver is good enough

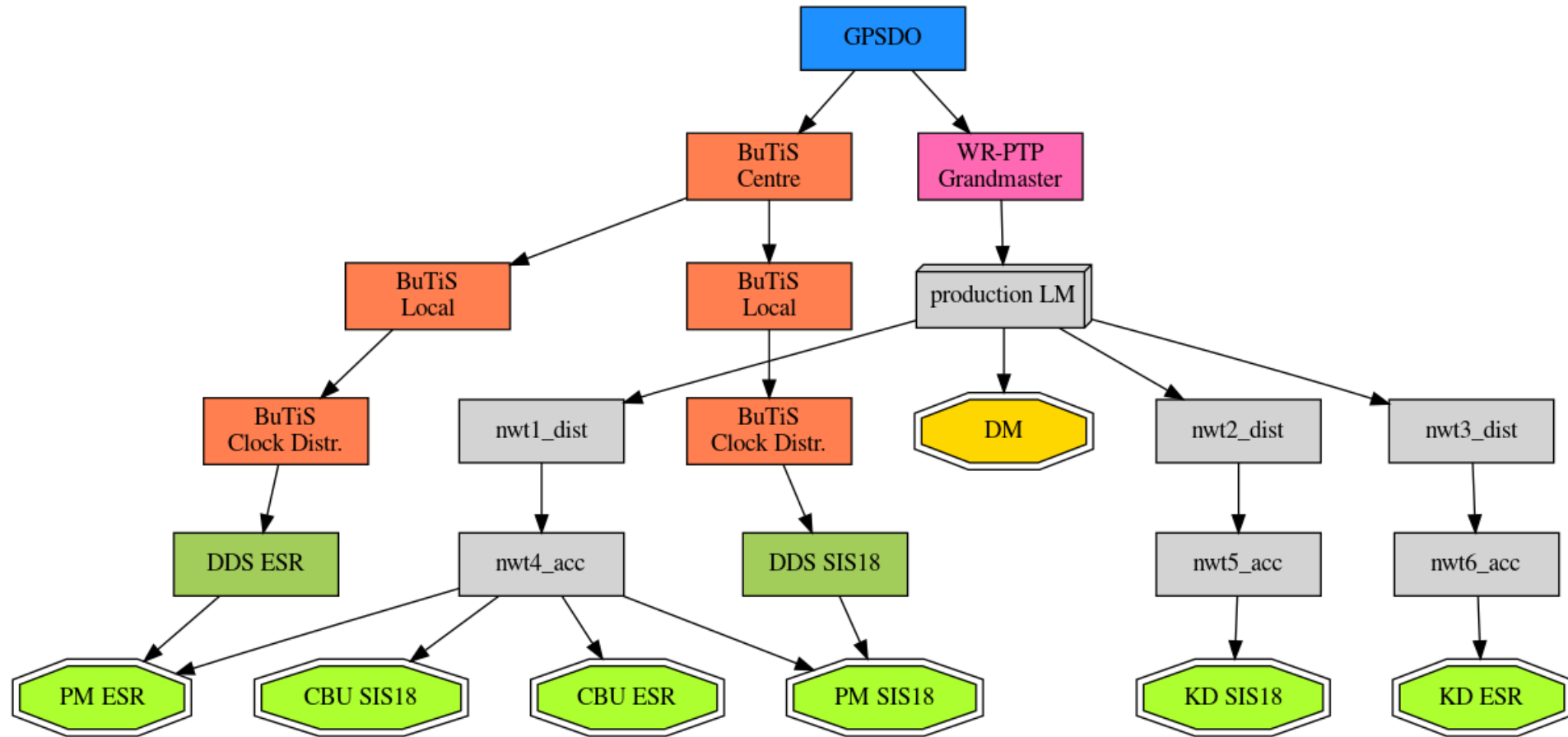
‘Frequency Beating’ can be done without hardware development!

‘Phase Shift’ requires development at RRF

super-simple recipe:

1. measure phase at both rings
2. do some math
3. trigger kickers

Clock Propagation



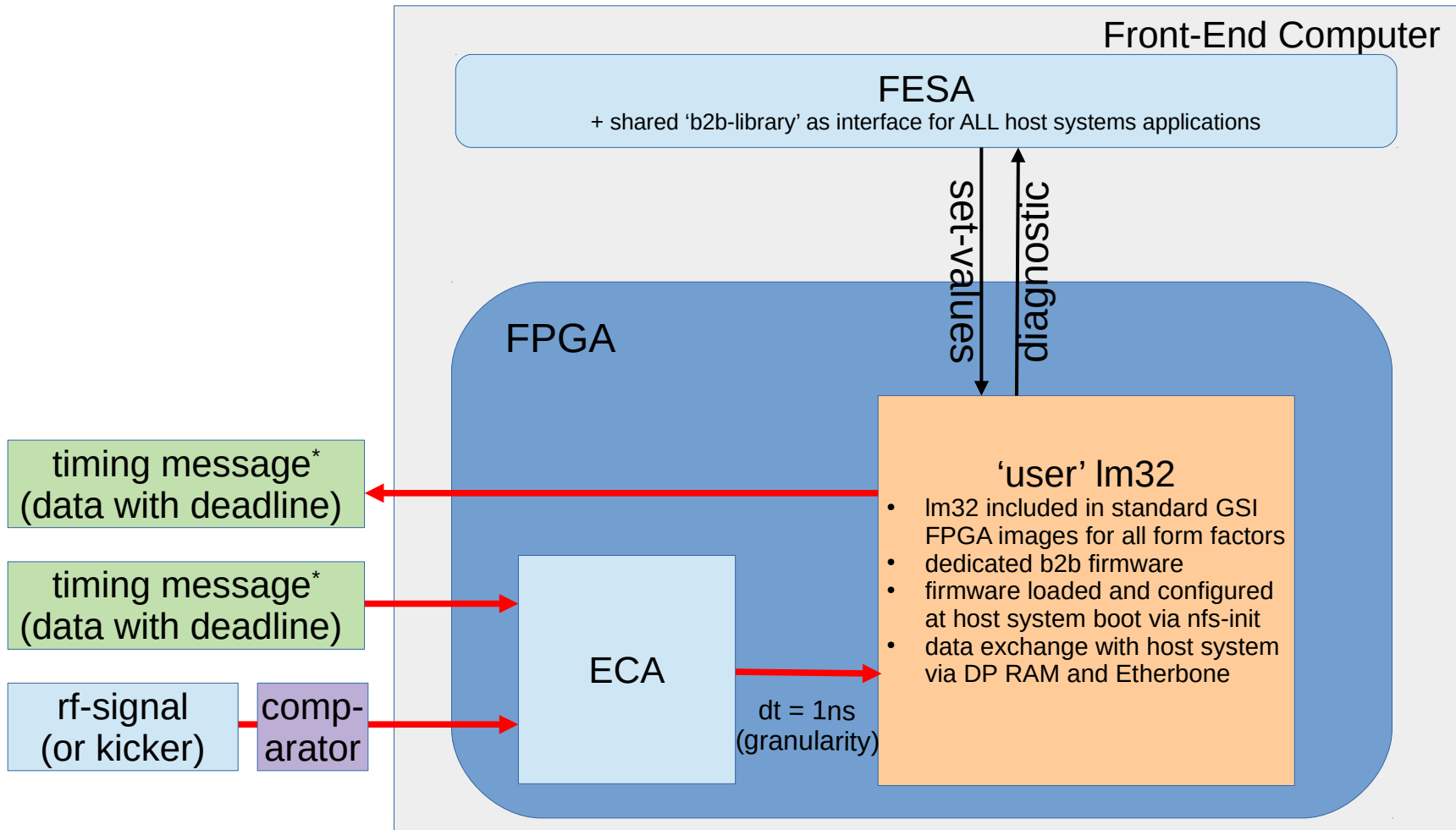
Components: GPSDO (blue), White Rabbit Grandmaster (cyan) and Switches (grey), rf-clock distribution system (BuTiS, brown), rf-group-DDS systems (dark green), nodes of the b2b system (light green) and Data Master of the Machine Timing System (yellow). Nodes with double-lined borders broadcast messages 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 Im32 firmware for hardware, see tr-pmc or tr-amc @ OHWR

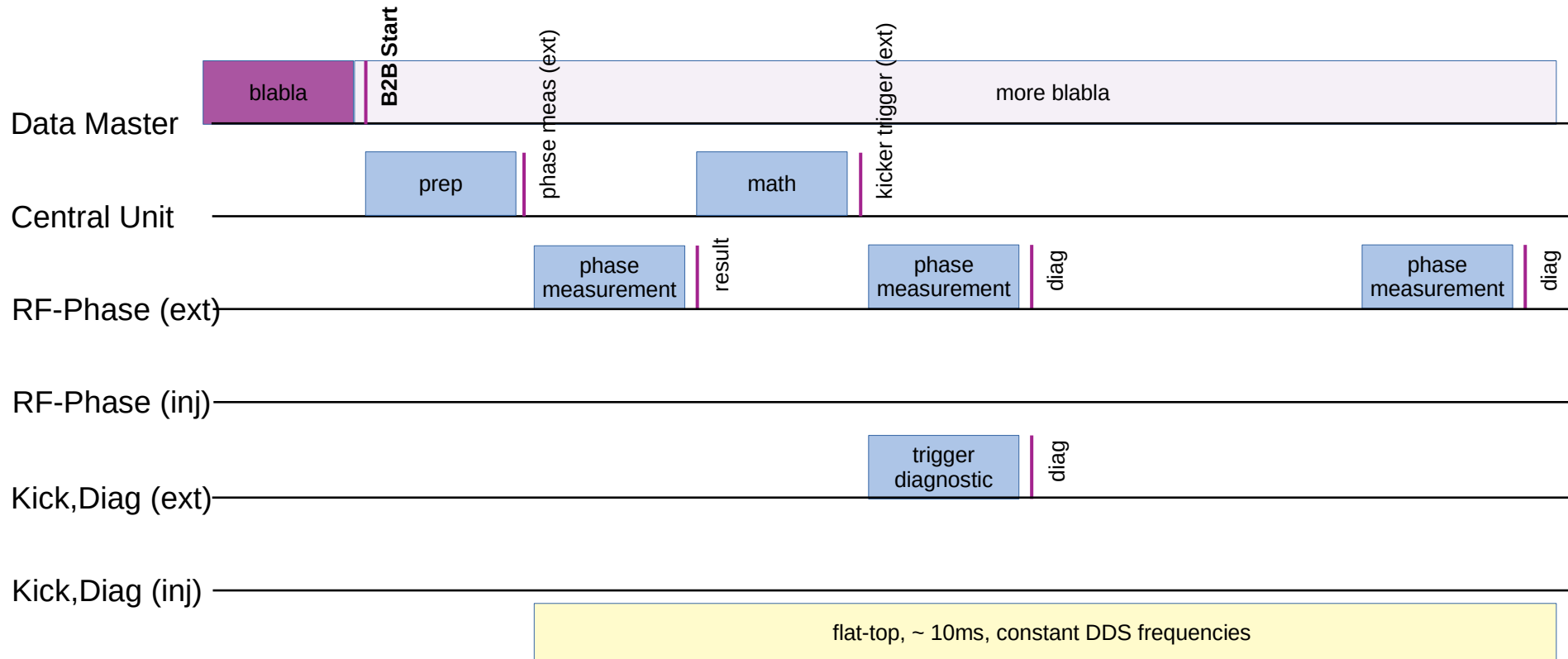


*timing messages are Etherbone broadcast on the White Rabbit network

Procedure: Simple Extraction

(to fixed target or whatever)

- all messages are broadcast and sent $\sim 500 \mu\text{s}$ prior deadline to the WR network
- messages contain 64bit of data (rf-period, phase, measured kick time, ...)
- cyan: message deadline, blue: firmware activity (Im32), 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

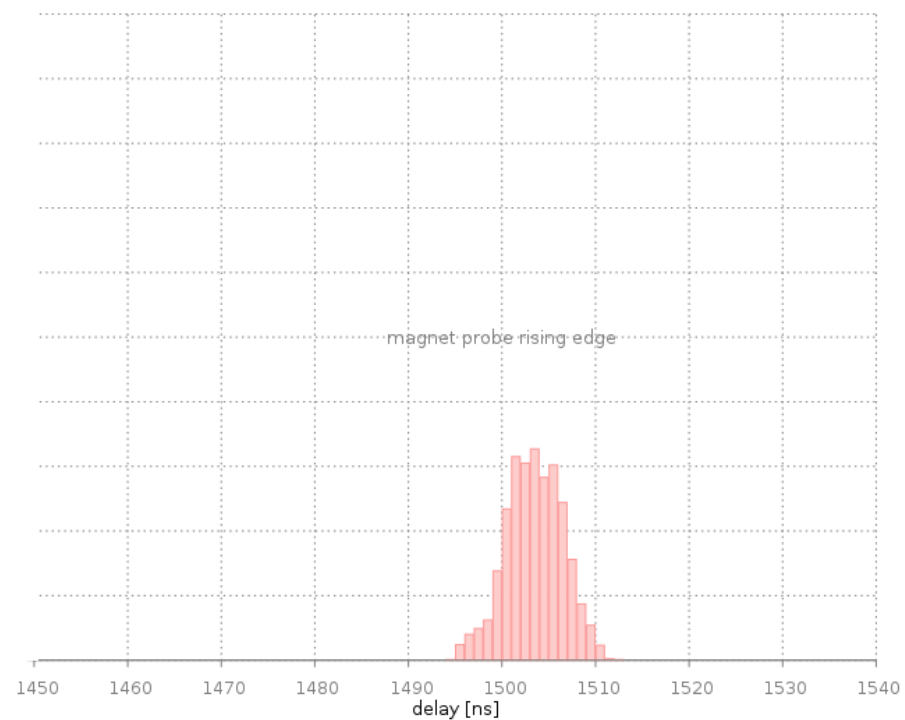
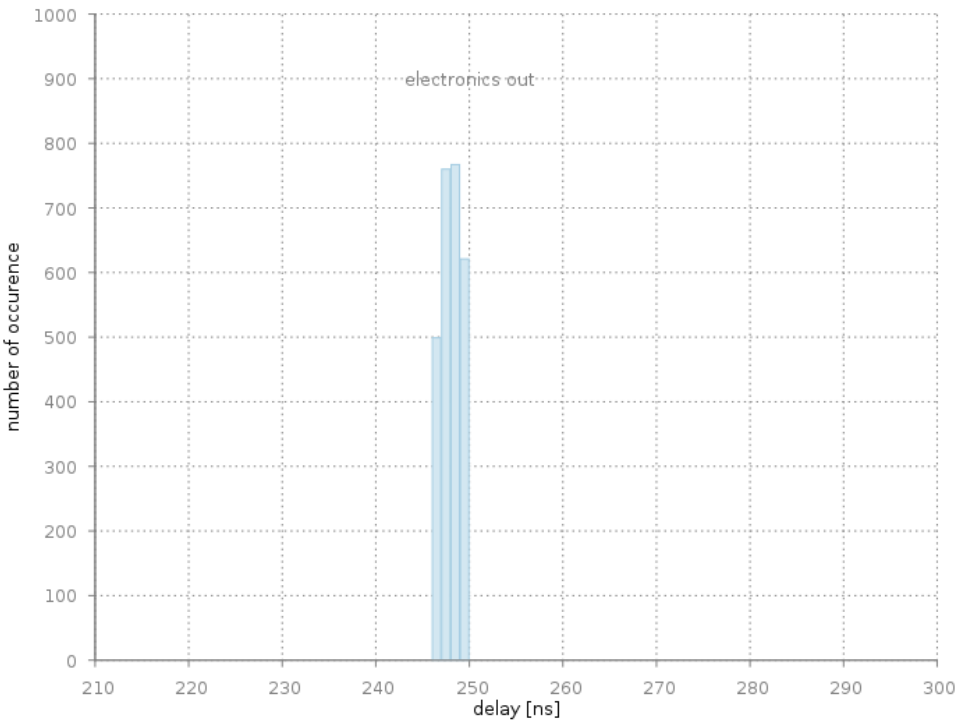
Measure	P1:skew(C1.C3)	P2:skew(C1.C2)	P3:---	P4:---	P5:---	P6:---
value	-703 ps	-828 ps				
mean	-124.7 ps	-253.1 ps				
min	-1.567 ns	-1.253 ns				
max	1.057 ns	937 ps				
sdev	410.3 ps	406.8 ps				
num	605	605				
status						

C1	C2	C3	C4	
DC1M	DC50	DC50	DC50	+
500 mV/div 0 mV offset	1.00 V/div 0 mV offset	1.00 V/div -1.625 V ofst	1.00 V/div 0 mV offset	

Tbase	-300 ps	Trigger	C3 DC
	5.00 ns/div	Norm.	250 mV
500 S	10 GS/s	Edge	Positive

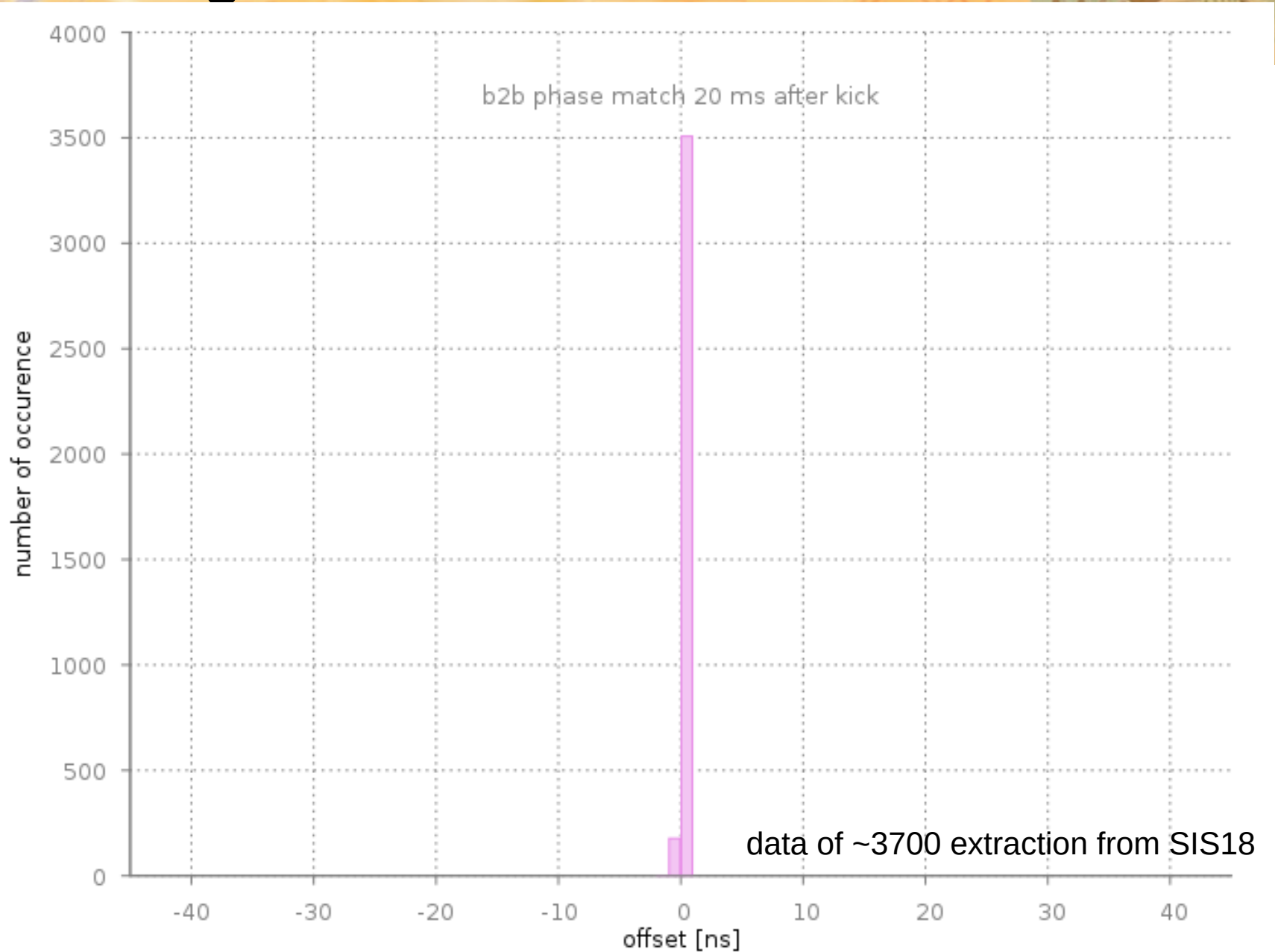
TELEDYNE LECROY

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



Procedure: Bunch-2-Bucket

- all messages are broadcast and sent $\sim 500 \mu\text{s}$ 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

