Investigation and Realization for FAIR Bunch-to-Bucket Transfer System

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Doctoral candidate: *Jiaoni Bai*

Professor: *Prof. Dr. Oliver Kester*
Supervisors: *Dr. David Ondreka*
Dr. Dietrich Beck

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Outline

- Synchronization from the Viewpoint of Beam Dynamics
- Accuracy of the Synchronization Window
- Characterization of the WR Network
- Test Setup
- Application of the System
- Open issues and improvement

Synchronization from the Viewpoint of Beam Dynamics

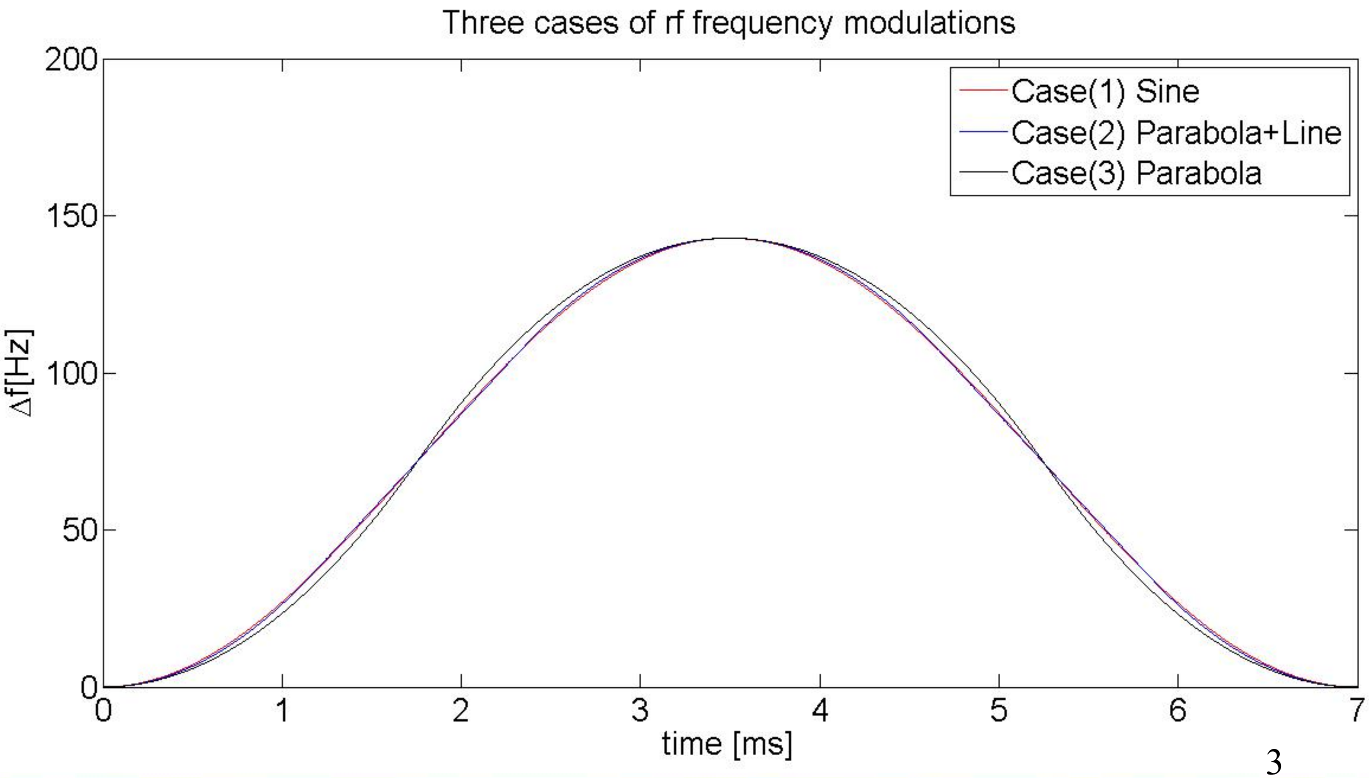
Phase shift method

The obtained phase shift $\Delta\phi$ is determined by the rf frequency modulation Δf_{rf} and the duration of the frequency modulation T

$$\Delta\phi = 2\pi \int_{t_0}^{t_0+T} \Delta f_{rf}(t)dt$$

Requirements:

- Max Δf_{rf}
- continuous and small enough $\frac{d\Delta f_{rf}}{dt}$
- $\frac{d^2\Delta f_{rf}}{dt^2}$ small enough



Synchronization from the Viewpoint of Beam Dynamics

Tab. 1: The parameters accompanying with the rf frequency modulation of the SIS18 for U^{28+} from SIS18 to SIS100

		Longitudinal dynamics					Transverse dynamics
		Average radial excursion	Relative moment shift	Synchronous phase	Bucket size	Adiabaticity	Chromaticity tune shift
	Requirement[1]	$\pm 2.4 \cdot 10^{-4}$	±0.008	±6.5°	>80.0%		$< \pm 10^{-2}$
√√	Case (1)	$<4.18\cdot 10^{-6}$	$<1.40\cdot 10^{-4}$	<±4.5°	>86.0%	$<5.3\cdot 10^{-5}$	$\Delta Qx = -9.1 \cdot 10^{-4}$ $\Delta Qy = -5.74 \cdot 10^{-4}$
√	Case (2)	$<4.18\cdot 10^{-6}$	$<1.40\cdot 10^{-4}$	< ±4.2°	>86.5%	$<5.9\cdot 10^{-5}$	
√	Case (3)	$<4.18\cdot 10^{-6}$	$<1.40\cdot 10^{-4}$	< ±6.0°	>82.5%	$<6.3\cdot 10^{-5}$	

Matlab test result:

- Sinusoidal modulation is better for the beam adiabaticity compared with the parabola modulation.
- Triangular and rectangle modification are not applicable at all.

[1] The requirements are from the PBSP department.

Synchronization from the Viewpoint of Beam Dynamics

Tab. 2: The parameters accompanying with the rf frequency modulation of the SIS18 for H^+ from SIS18 to SIS100

		Longitudinal dynamics					Transverse dynamics
	4 Gev/u H^+	Average radial excursion	Relative moment shift	Synchronous phase	Bucket size	Adiabaticity	Chromaticity tune shift
	Requirement[1]	$\pm 0.8 \cdot 10^{-4}$	±0.008	±6.5°	>80%		$< \pm 10^{-2}$
×	Case (1) 7ms	$< 4.09 \cdot 10^{-5}$	<0.0041	<±34.7°	>27%	<0.04	
√	Case (2) 20ms	$< 3.9 \cdot 10^{-6}$	$< 3.9 \cdot 10^{-4}$	<±4.2°	>86%	$< 1.9 \cdot 10^{-4}$	$\Delta Qx = -2.925 \cdot 10^{-3}$ $\Delta Qy = -1.716 \cdot 10^{-3}$

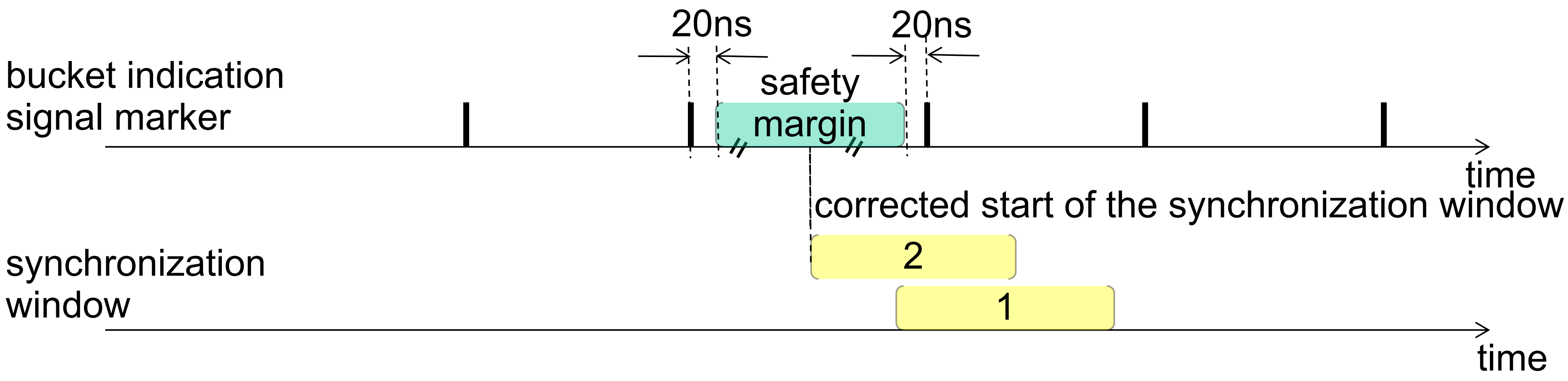
Matlab test result:

- Parameters accompanying with the 7 ms sinusoidal modulation are far beyond the acceptable range.
- A 20 ms sinusoidal modulation is used to guarantee these requirement.

[1] The requirements are from the PBSP department.

Accuracy of the Synchronization Window

The synchronization window is used to select the **same rising edge** of the bucket indication signal marker at the source and target synchrotrons.



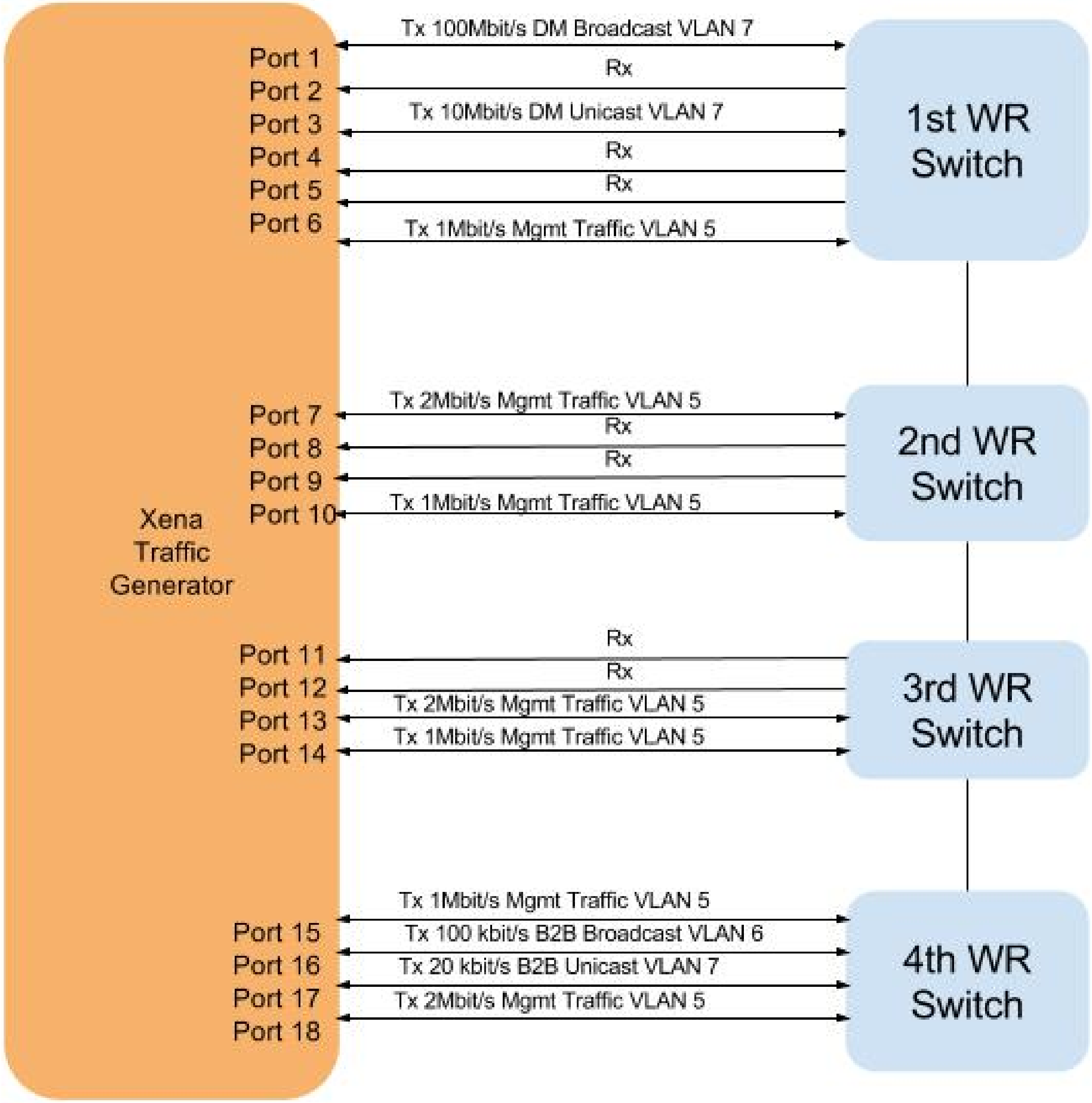
Calculation is based on

- PAP module: uncertainty 0.1°
- BuTiS uncertainty: 100 ps
- SCU: the timestamp of the BuTiS clock uncertainty: 1 ns

Result:

- Uncertainty of the corrected start of the synchronization window is < 3ns
- Accuracy requirement of the start of the synchronization window is 450ns

Characterization of WR network



Test setup

- DM traffic
  Broadcast 100Mbit/s
  Unicast 10Mbit/s
  DM VLAN with priority 7

- Management traffic Broadcast 100Mbit/s
  Management VLAN with priority 5

- B2B traffic
  Broadcast 100kbit/s
  B2B VLAN with priority 6
  Unicast 20kbit/s
  DM VLAN with priority 7

Tx: Transmitter
Rx: Receiver

The figure and test result are from the reference [1]

[1] C. Prados and J. Bai. Testing the WR Network of the FAIR General Machine Timing System, 2016.

Characterization of WR network

Tab. 3: The 45 days test result of the WR network for the B2B transfer

	lost frame	FER	misordered frame	maximum frame transfer latency
B2B Broadcast	$8/45\_days$	$7.1 \cdot 10^{-8}/45\_days$	$0/45\_days$	30 µs/switch
B2B Unicast	$0/45\_days$	$0/45\_days$	$0/45\_days$	23 µs/4_switches

FER (no forward error correction)

The frame error rate (FER) caused by the bit error rate (BER)[2] of the fiber connection.

$FER = (BER - m \cdot 10^{-12}) \cdot 880 = (n - m) \cdot 10^{-12} \cdot 880$

where n is the total fiber connections, m is the number of the fiber connections to the frame receive FECs.

In the test setup,

B2B Unicast: n=5, m=1 => FER = $0.35 \cdot 10^{-8}$?

B2B Broadcast: n=21, m=17 => FER = $0.35 \cdot 10^{-8} < 7.1 \cdot 10^{-8}$ ×

No conclusion, a long term test should be done for the verification.

Not meet the requirement. The firmware of the WR switch is still under development by CERN.

[2] C. Prados and M. Lipinski. White Rabbit and Robustness, 2011.

Characterization of WR network

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Latency

Upper bound latency between any two B2B related SCUs < 500 µs

100 µs is used for the SCU coding and decoding time

The latency of a 2 km optical fiber is about 10 µs

Maximum number of switches between B2B related SCUs and DM

$$(500-100-10)/23 \bullet 4 = 67$$

Maximum number of switches between two B2B related SCUs

$$(500-100-10)/30 = 13$$

Characterization of WR network

Latency

Maximum layer for B2B Unicast frame

$$(500-100-10)/23 \bullet 4 = 67$$

bit error →

Maximum layer for B2B Broadcast frame

$$(500-100-10)/30 = 13$$

bit error →

FER (no forward error correction)

$0.58 \cdot 10^{-7}$
one lost frame every 3 days

$1.14 \cdot 10^{-8}$

one lost frame every 12 days

The tolerable layers of WR switch depends not only on the upper bound transfer latency, but also the tolerable FER of the B2B transfer system.

- no forward error correction mechanism => the layers is mainly decided by the tolerable FER

e.g. one lost frame is acceptable per month, maximum 18 and 4 layers for the B2B Unicast and Broadcast.
e.g. one lost frame is acceptable per year, maximum 1 and 0 layers for the B2B Unicast and Broadcast.

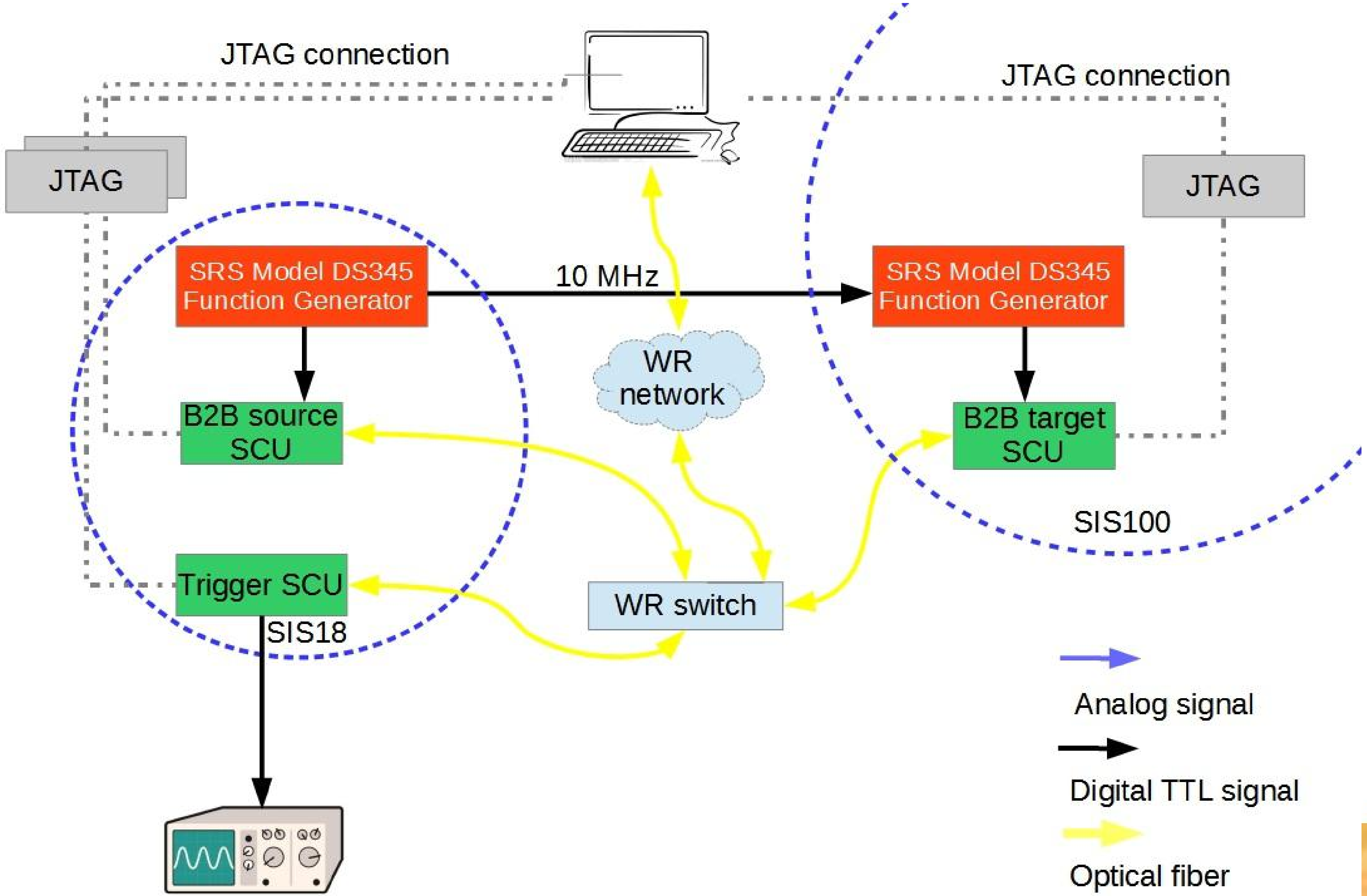
- specific forward error correction mechanisms are used and the FER is 10^{-15} [2] => the layers of WR switch is mainly decided by the tolerable transfer latency

Maximum 67 and 13 layers for the B2B Unicast and Broadcast

[2] C. Prados and M. Lipinski. White Rabbit and Robustness, 2011.

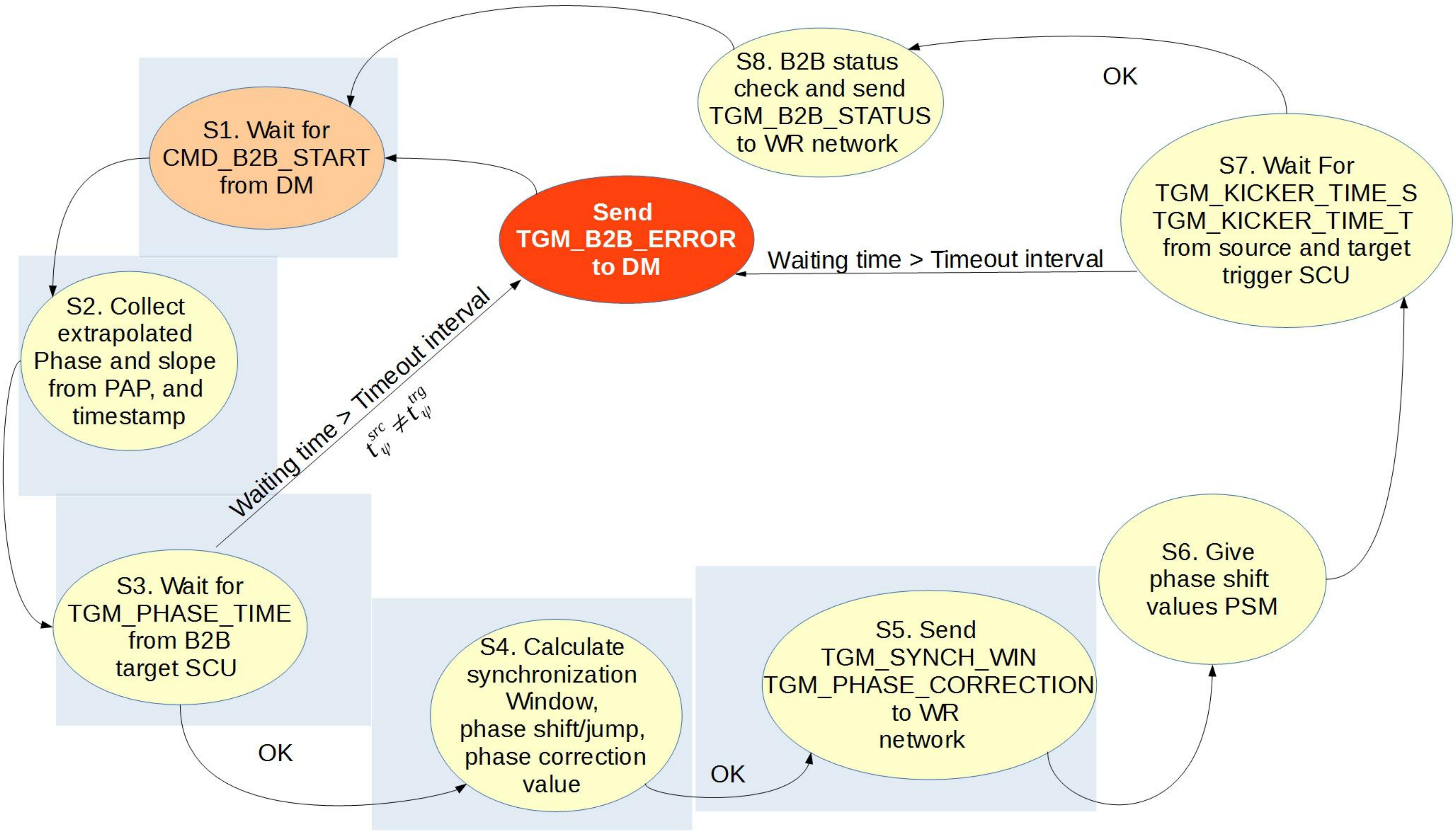
Test setup

The test setup realizes the phase collection, the calculation of the synchronization window and the redistribution of the synchronization window => verify that the firmware of the B2B related SCUs running on the soft CPU, LM32, meets the time constraints of the B2B transfer system.



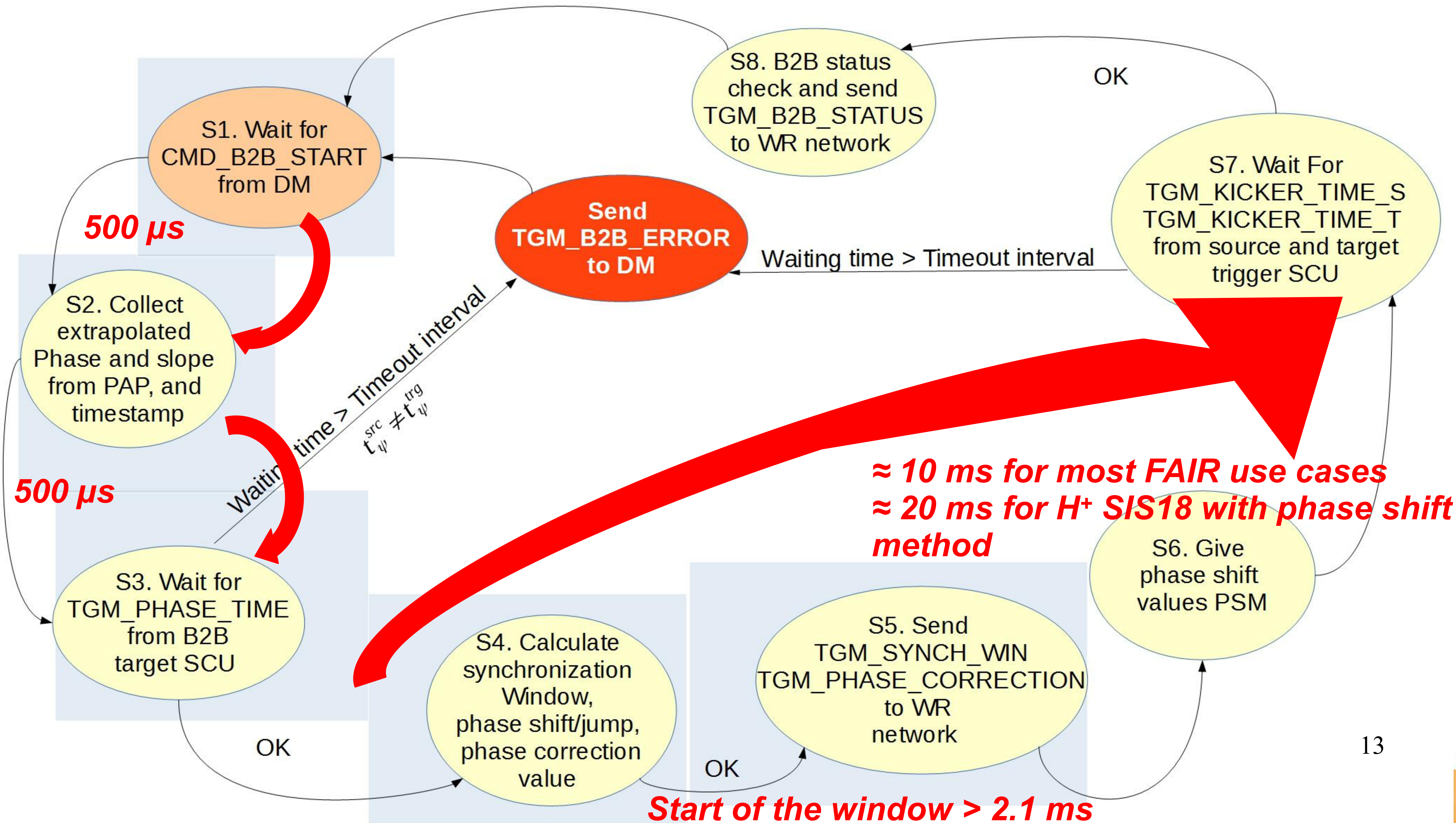
Test setup

Flow chart of the firmware of the B2B source SCU



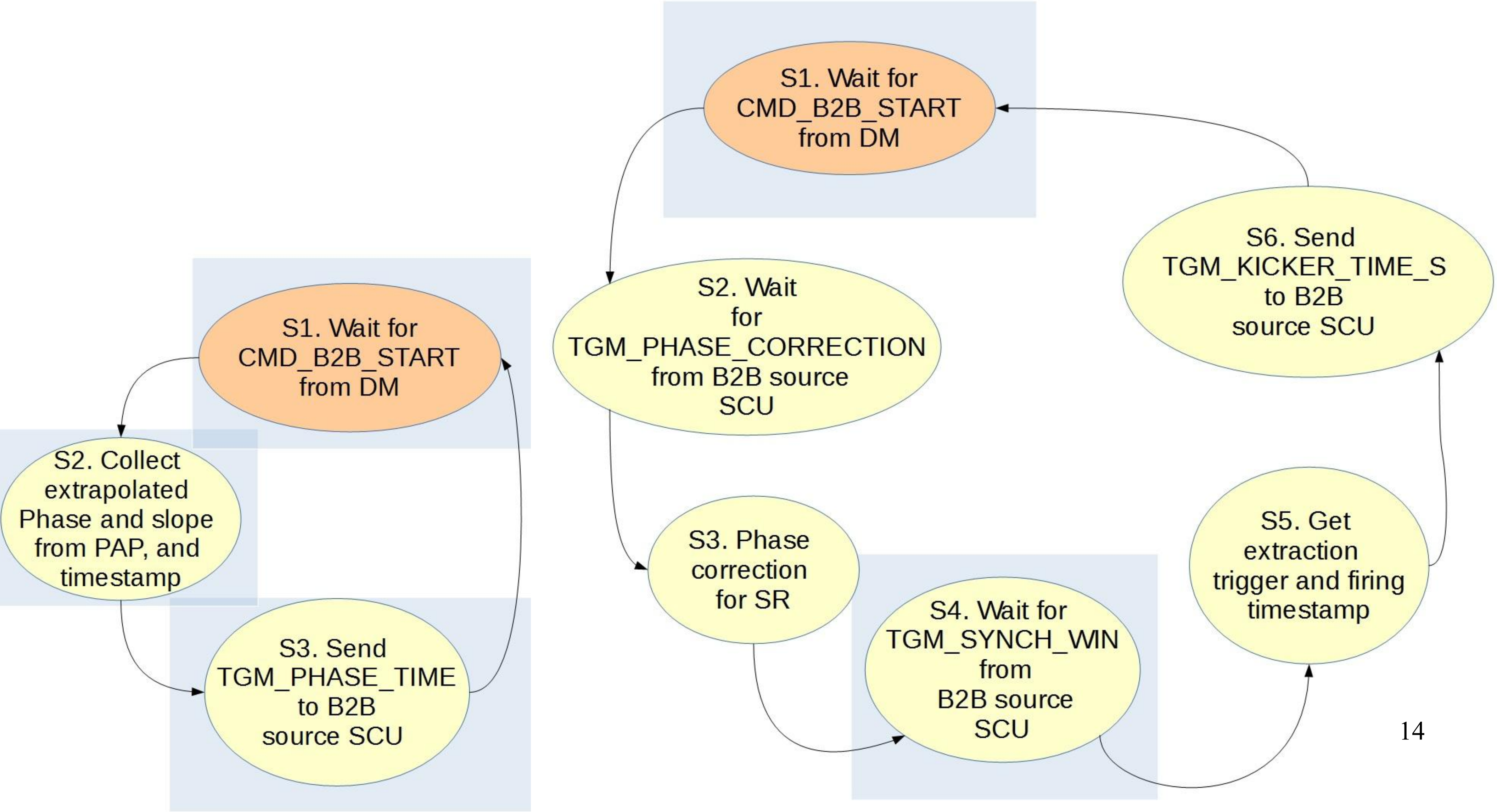
Test setup

Main time constraints of the B2B transfer system



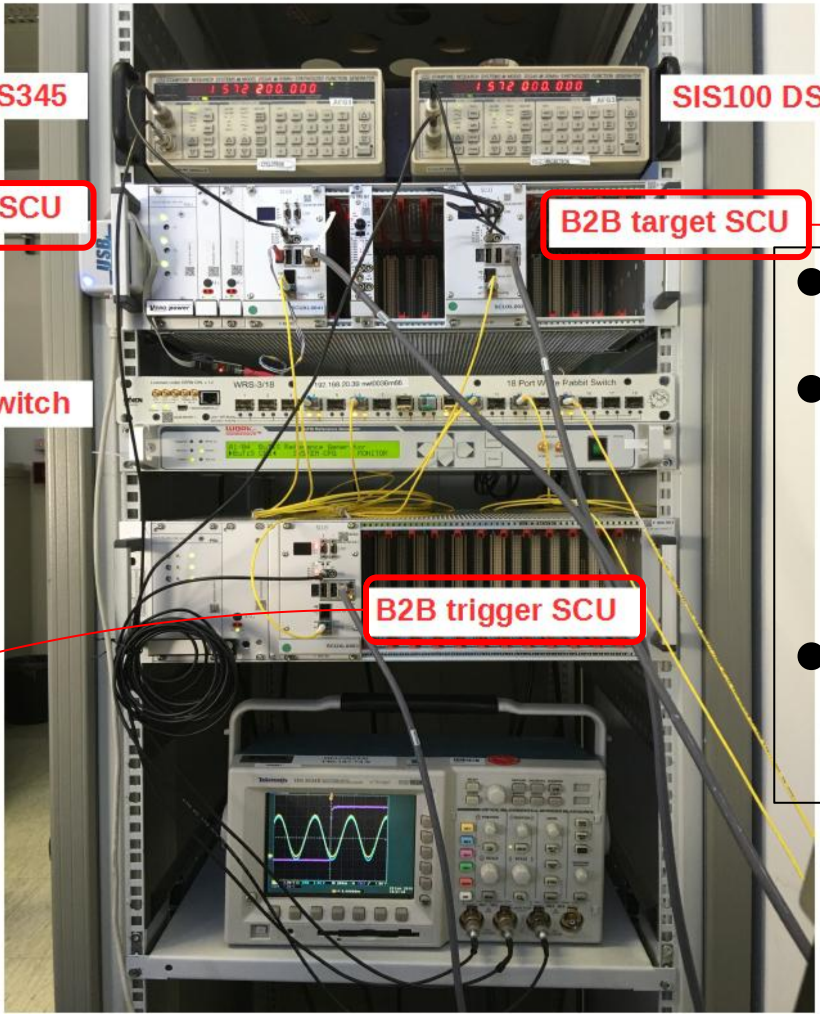
Test setup

Flow chart of the firmware of the B2B target SCU and trigger SCU



Result

- Waiting for the timing event from DM.
- Measure the timestamp of the positive zero-crossing of the signal from the DS345.
- Waiting for the timing event from the B2B target SCU.
- Calculate the synchronization window.
- Send the start of the synchronization window to the WR network.



- Waiting for the timing event from DM.
- Measure the timestamp of the positive zero-crossing of the signal from the DS345.
- Send the timing event to the B2B source SCU.

- Waiting for the timing event from DM.
- Waiting for the start of the synchronization window from the WR network.

Application of the system

Tab. 4: The application of the FAIR B2B transfer system for FAIR use cases

No	Application of FAIR B2B transfer system to FAIR accelerators	B2B injection center mismatch
1	U^{28+} bunches from SIS18 to SIS100	±0.4°
2	H^{+} bunch from SIS18 to SIS100	±0.4°
3	Four bunches from SIS18 to ESR	±0.5°
4	One bunch from SIS18 to ESR	±0.5°
5	from ESR to CRYRING	±0.5°
6	H^{+} from SIS100 to CR via the Pbar target e.g. 28.8 Gev/u → 3 Gev/u	±41.5°
7	Rare isotope beams from SIS100 to CR via the Super FRS e.g. 1.5 Gev/u → 740 Mev/u	±2.1°
8	from CR to HESR	±1.2°
9	from SIS18 to ESR via the FRS e.g. 550 Mev/u → 440 Mev/u	±31.2°

For application 6 and 9, the B2B transfer system may work for the barrier bucket or the unstable fixed point beam accumulation.

Open issue & improvement

Open issues:

- The synchronization of the magnetic hole after the Pbar with the antiproton beam
- The synchronization of the bunch compressor with the beam

Improvement:

- In order to reduce the synchronization time, the synchronization process can be started during the acceleration.

Thank you!

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