Development of the Timing System for the Bunch-to-Bucket Transfer between the FAIR Accelerators

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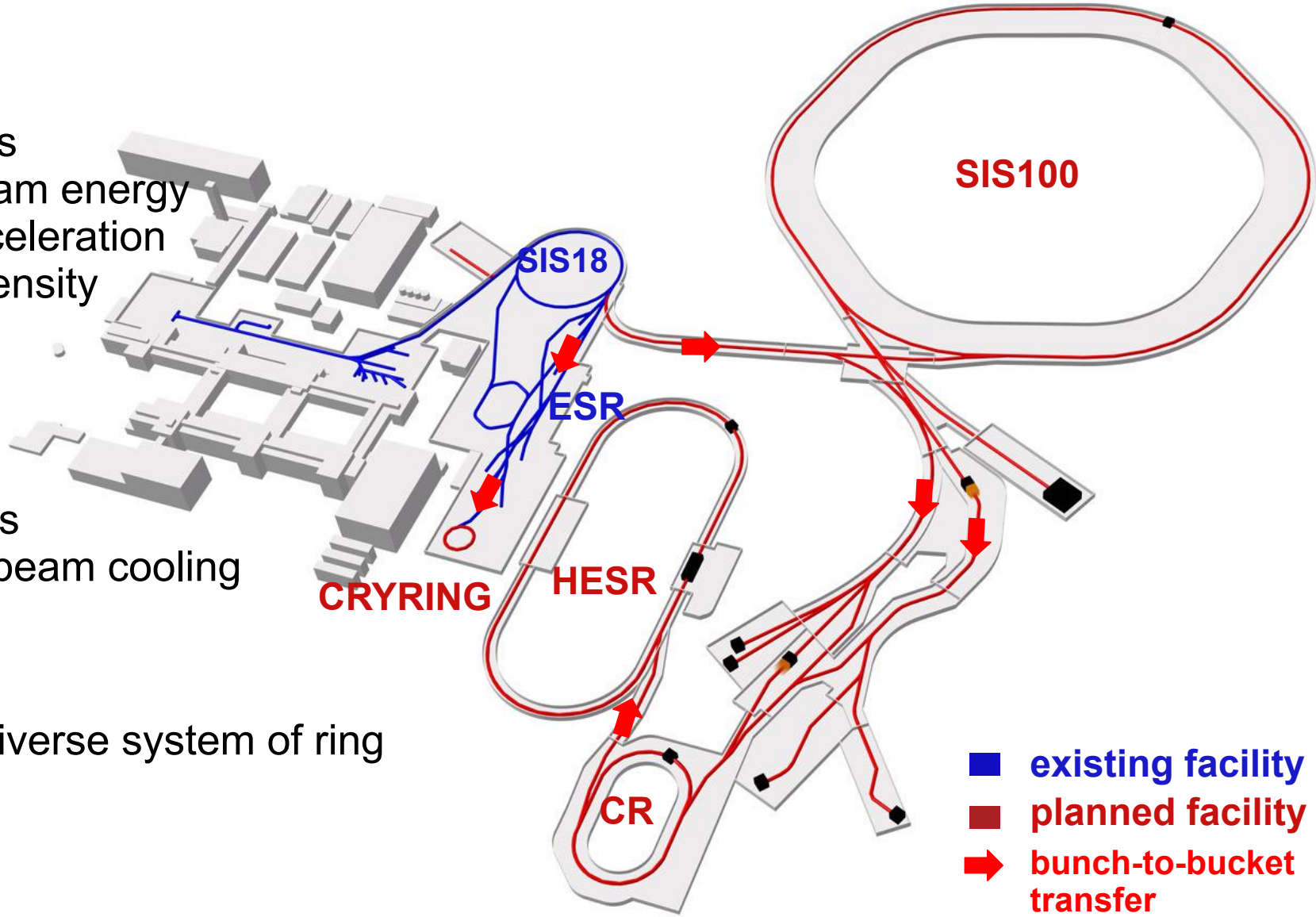
Outline

- GSI & FAIR Overview
- Concept & Motivation
- Theoretical Background
- Implementation
- Experimental Work for Implementation
- Application - FAIR Use Cases
- Outlook & Summary

GSI & FAIR Overview

- Synchrotrons
  - High beam energy
  - Fast acceleration
  - High intensity
- Storage rings
  - Unique beam cooling

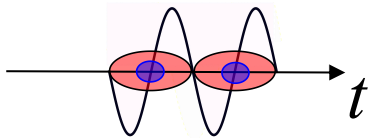


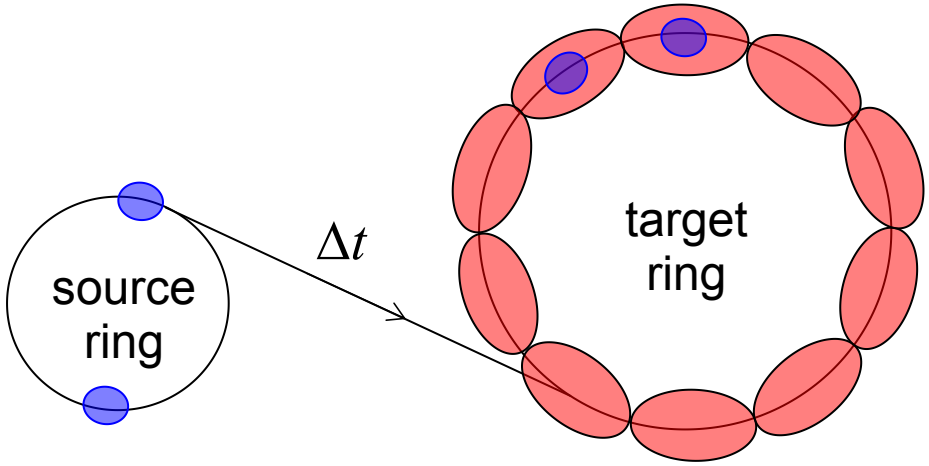
- FAIR has a diverse system of ring accelerators

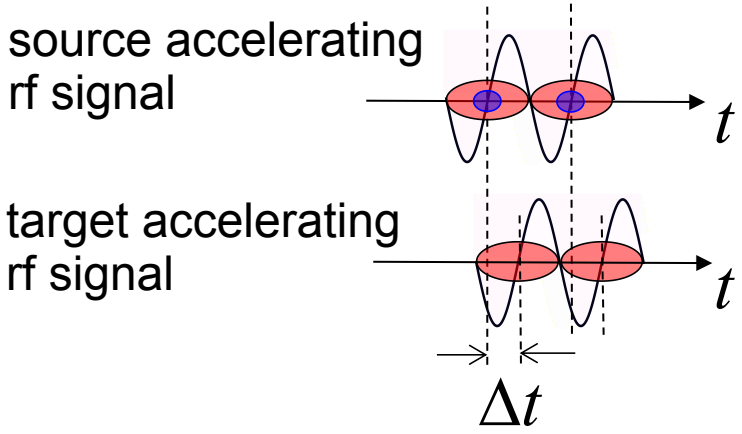
Concept

Bucket: stable phase space area where beam can be captured and accelerated [1] => stationary bucket

Bunch: a group of particles captured in a bucket [1]



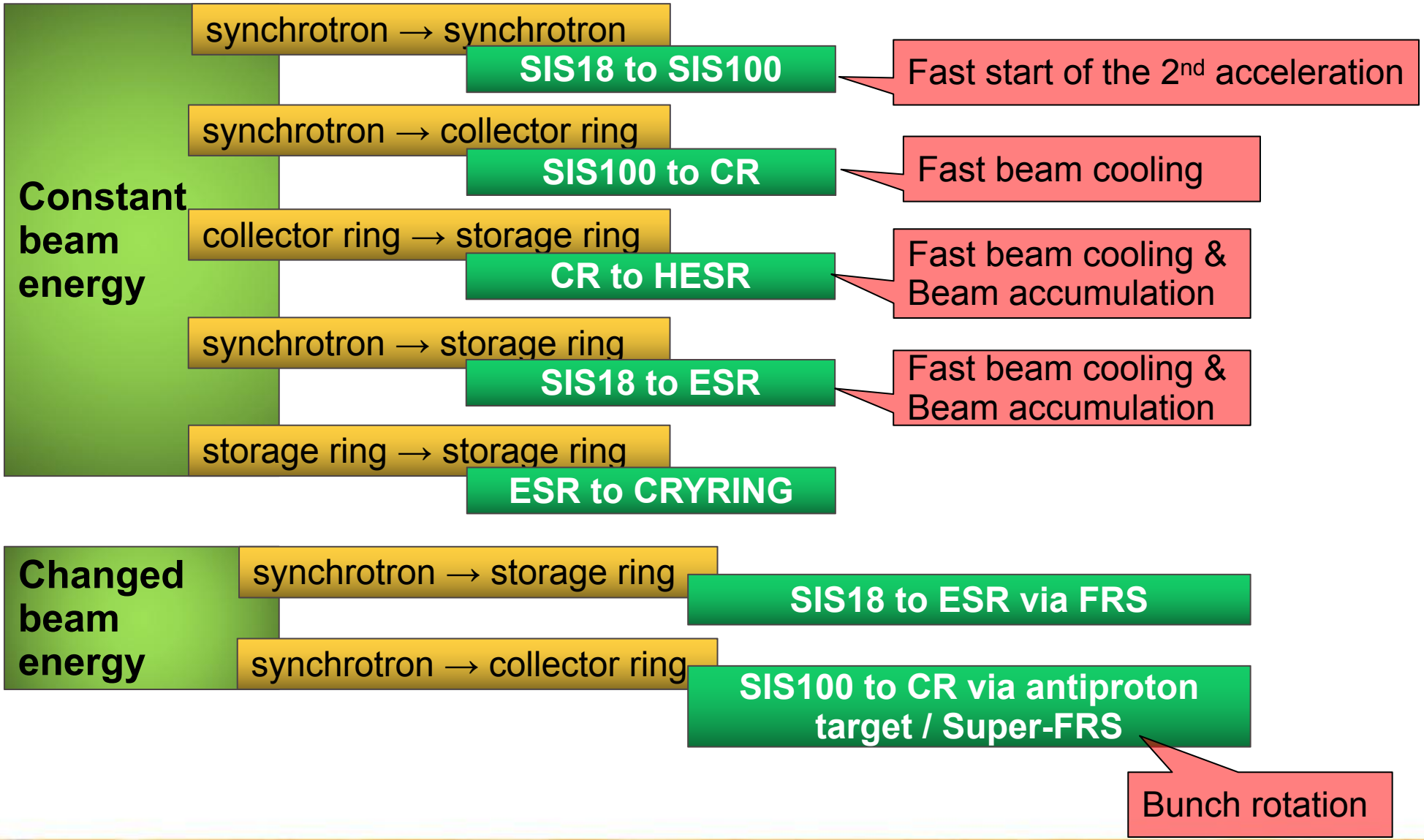




Bunch-to-Bucket transfer: bunches, circulating inside the source ring, are transferred into the center of buckets of the target ring.

[1] Fermilab, Accelerator Glossary of Terms

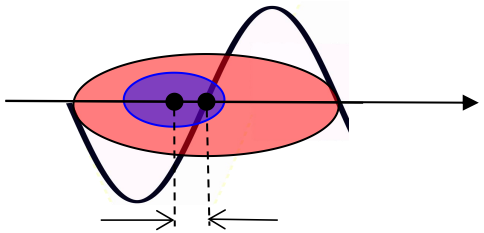
Challenges of B2B Transfer



Requirements

FAIR B2B transfer system:

- Applicable for transfers between rings with an arbitrary circumference ratio
- Beam transfers with constant and changed energy
- Tolerable B2B injection center mismatch and upper bound time requirement
  (For most FAIR use cases $\pm 1^\circ$ and 10 ms)



$\Delta\theta$ B2B injection center mismatch

- Parallel operation (e.g. simultaneous SIS18→SIS100 & ESR→CRYRING)
- Input from the Machine Protection System (SIS100 emergency dump)
- Indication for beam diagnostics

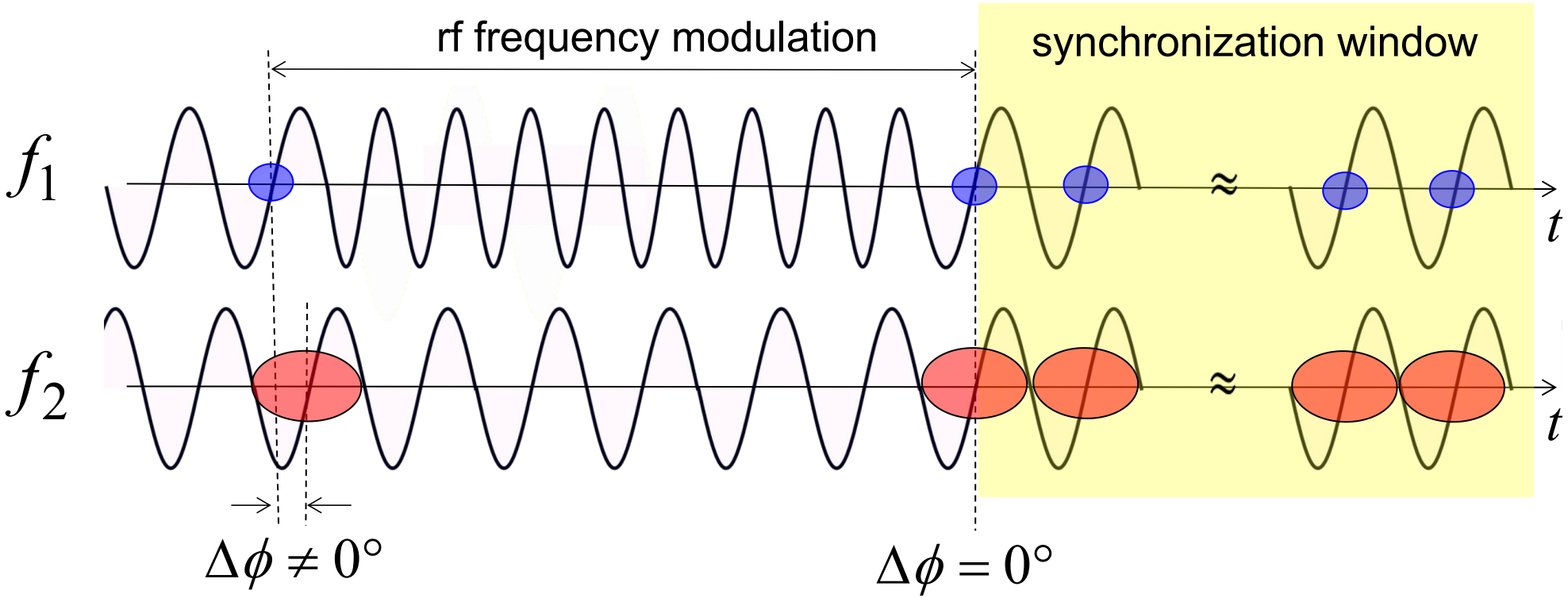
Synchronization Method 1

Phase shift method

Precondition: $m \bullet C_1 = C_2$

m: integer
C: circumference

$f_1 = f_2$

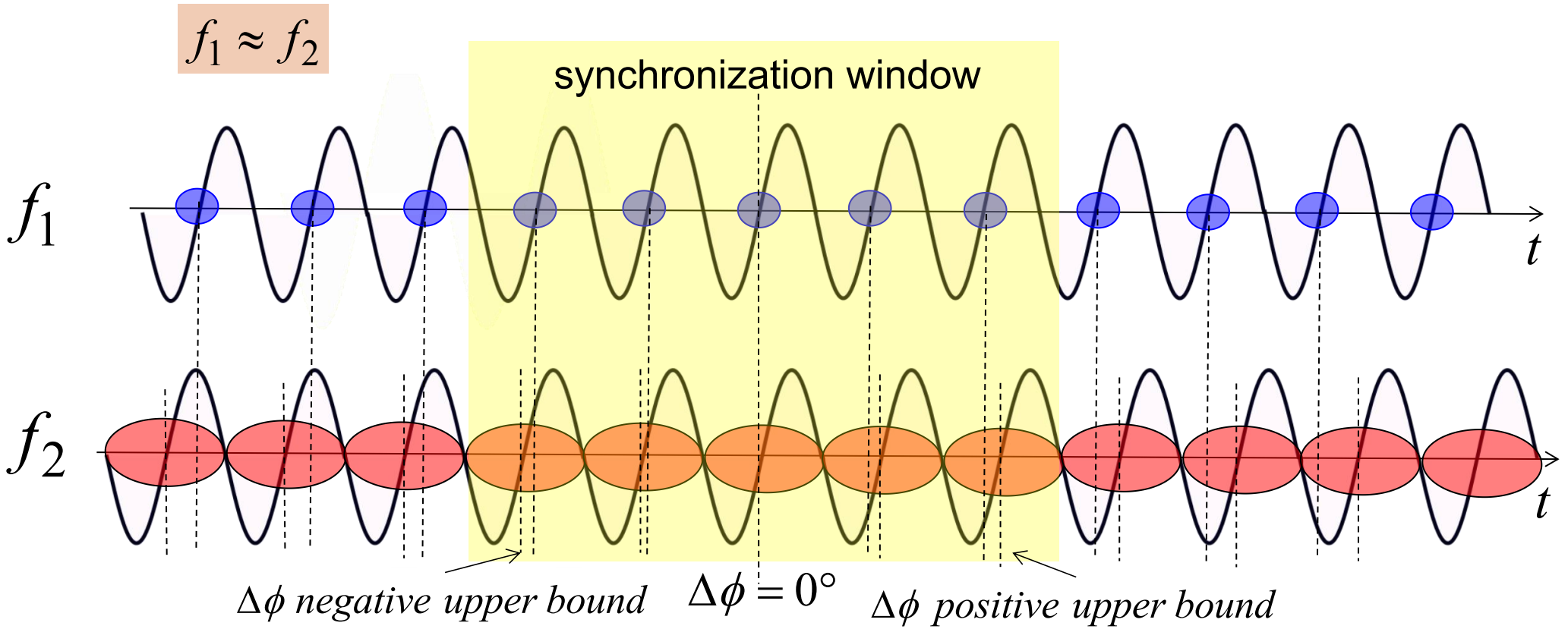


Synchronization Method 2

Frequency beating method

Precondition: $m \bullet C_1 \cong n \bullet C_2$

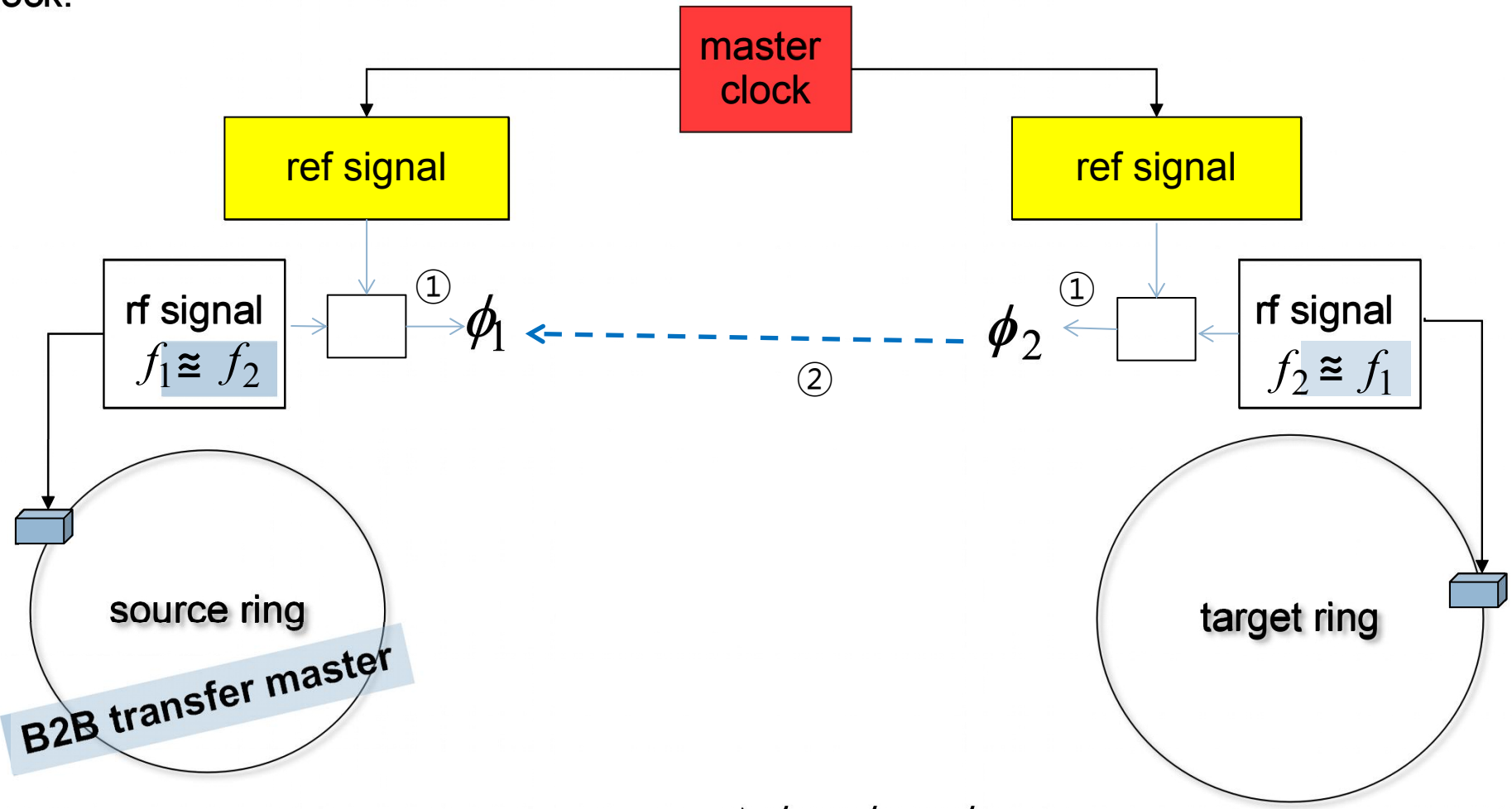
m, n: integer
C: circumference



For FAIR, both methods will be used.

Implementation

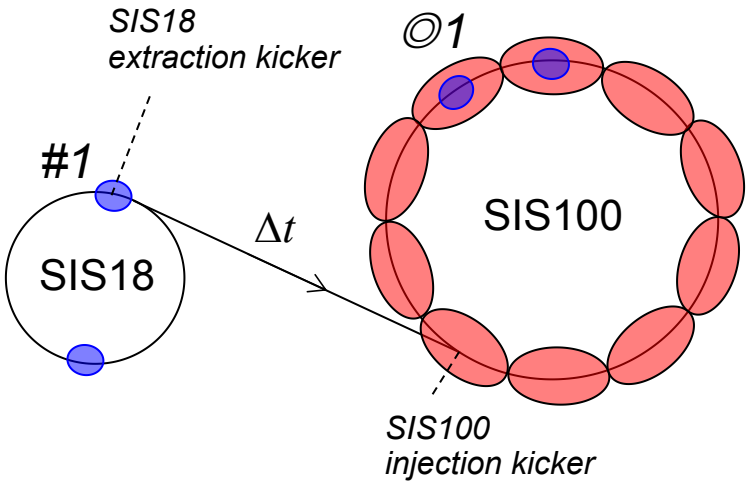
· **FAIR B2B transfer system** is based on reference signals derived from a master clock.



③ phase difference between two rf systems $\Delta\phi = \phi_1 - \phi_2$

Implementation

- **Coarse synchronization –** *synchronization window*
- **Fine synchronization**
  bucket indication signal + delay compensation
  e.g. buckets ◎1 and ◎2 are filled



Indication for SIS18 extraction kicker

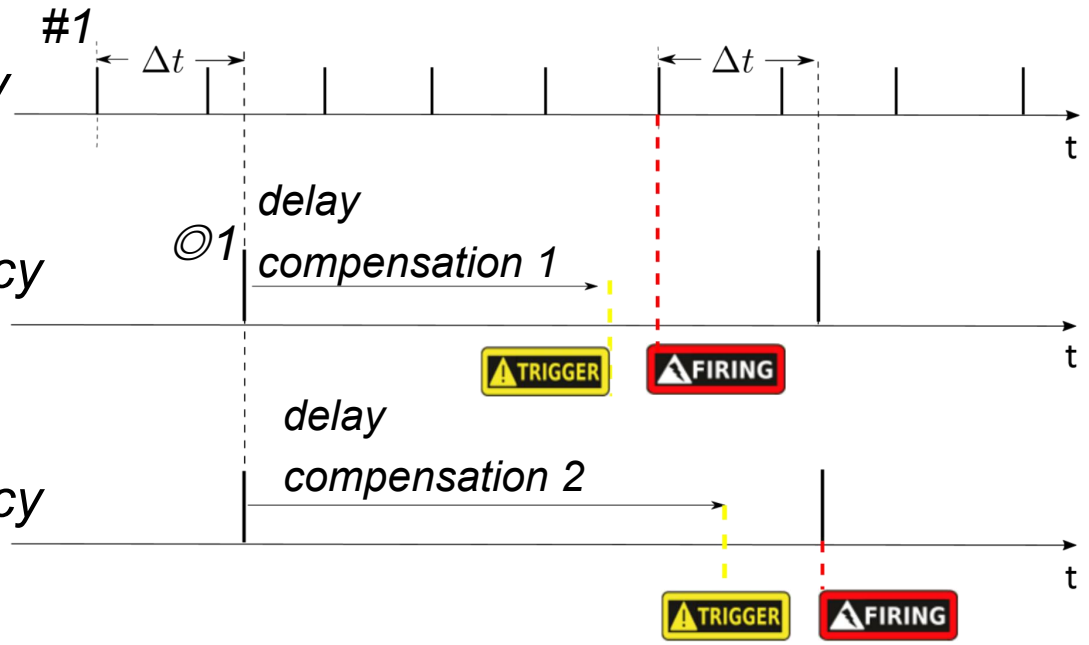
SIS18 revolution frequency marker @ SIS18

SIS100 revolution frequency marker @ SIS18

bucket indication signal

SIS100 revolution frequency marker @ SIS100

Indication for SIS100 injection kicker



Characterization of WR Network for B2B Transfer

Data transfer via the white rabbit (WR) network

- **G**eneral **M**achine **T**iming (GMT) system = Timing Master + WR network + Front End Controller **D**ata **M**aster (DM) **S**calable **C**ontrol **U**nit (SCU)

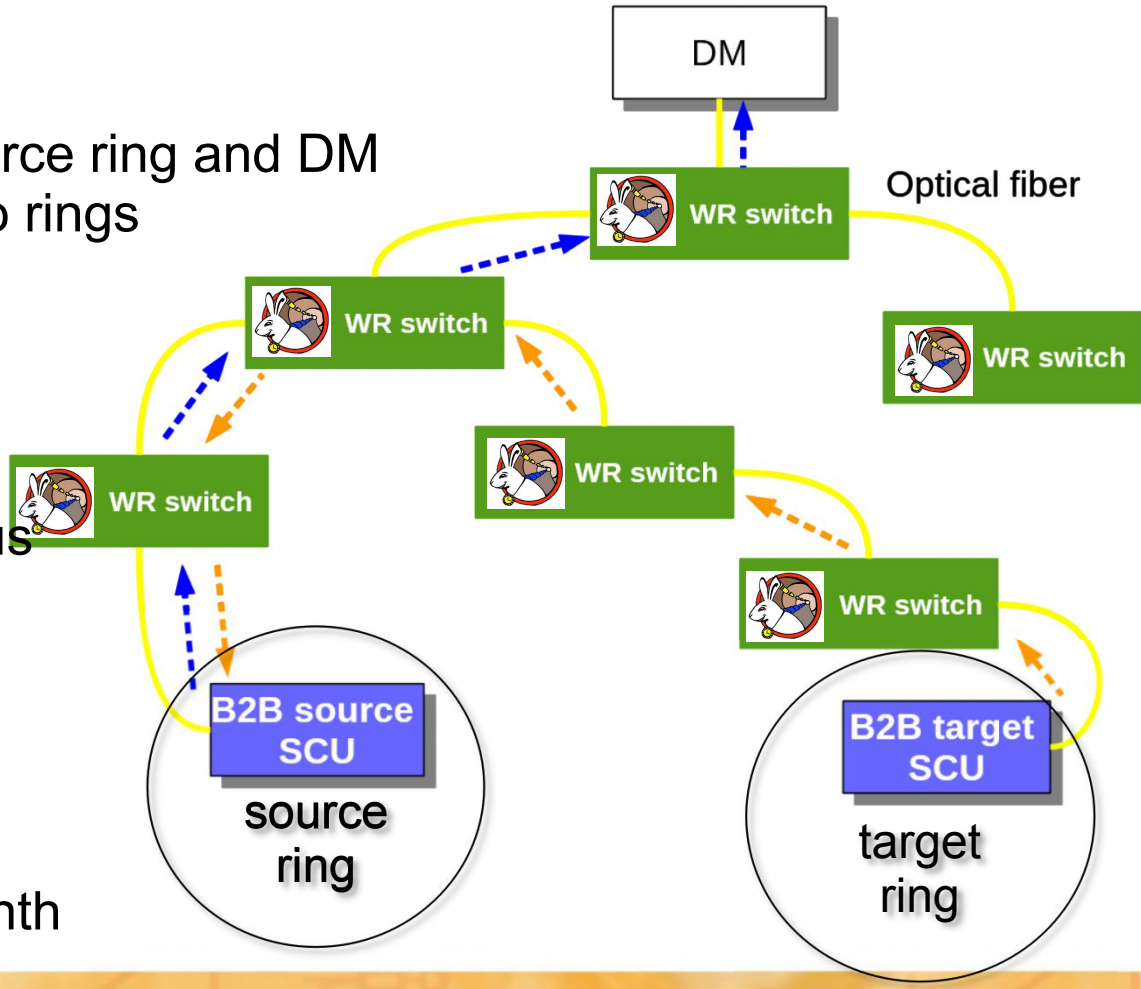
Two type B2B messages

- 1st type B2B message between source ring and DM
- 2nd type B2B message between two rings

Requirements:

- No misordered frame
- Transfer latency on network ≤ 400 μs
- Tolerable frame loss rate
  - 1st type 0.22×10^{-7}
  - 2nd type 0.43×10^{-8}

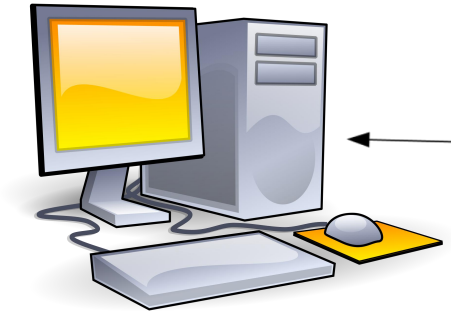
  One B2B transfer failure every month

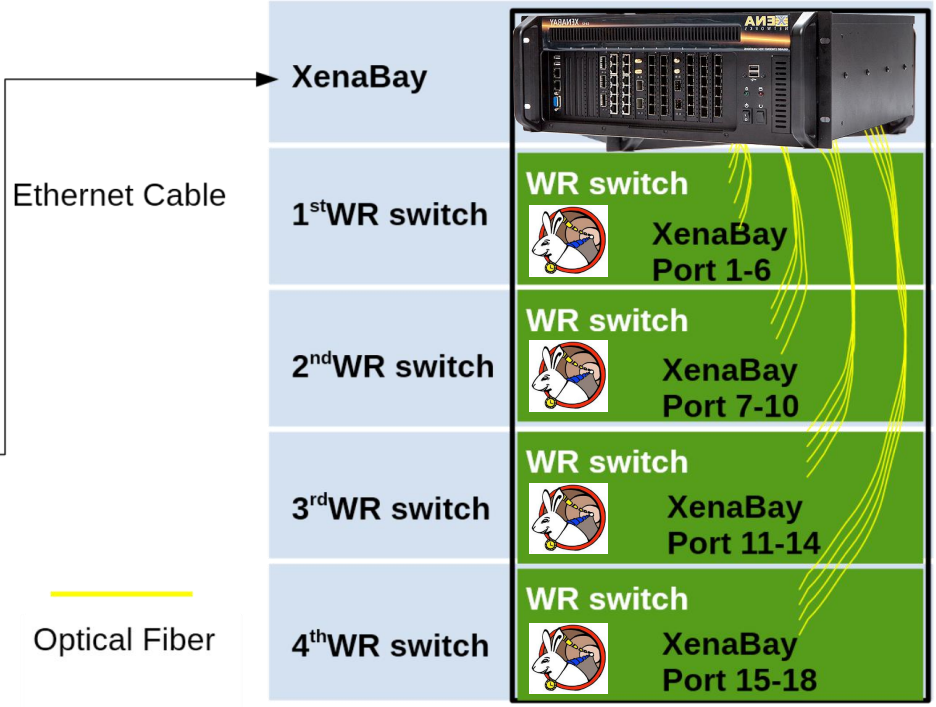


Characterization of WR Network for B2B Transfer

Test setup

Simulate actual FAIR WR network traffic





Results of 45 days test for the B2B transfer [3]:

- Misordered frame → Requirement met
- Transfer latency → Requirement met
- Lost frame → Requirement not met

Firmware update of the WR switch is triggered by this result

In case all requirements are met:

- Up to 38 WR switch layers can be used between DM and source ring
- Up to 8 WR switch layers can be used between two rings

Fit FAIR WR network architecture

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

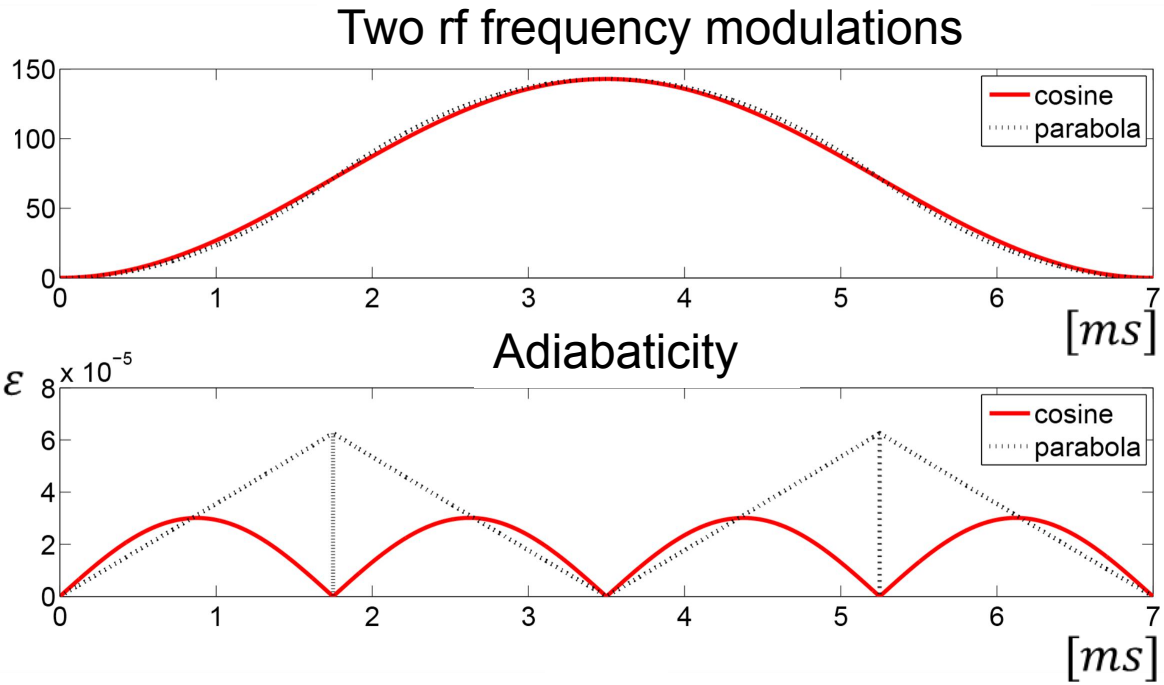
Requirements for Phase Shift Method

Phase shift $\Delta\varphi_{shift} = 2\pi \int_{t_0}^{t_0+T} \Delta f \, dt$

$$\varepsilon \sim \frac{d\Delta f}{dt} \cdot \frac{d^2\Delta f}{dt^2}$$

- **Requirements:**
  - Max Δf ← beam pipe aperture
  - $d\Delta f/dt$ continuous ← continuous synchronous phase
  - $d\Delta f/dt$ small ← bucket size
  - $d^2\Delta f/dt^2$ small ← adiabaticity

Adiabaticity

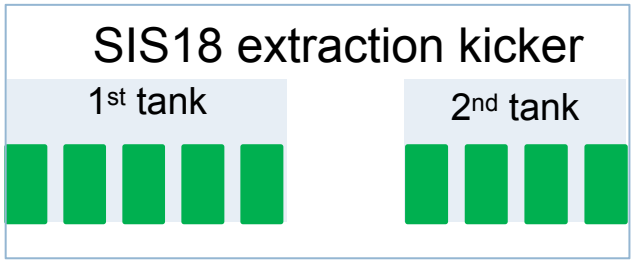


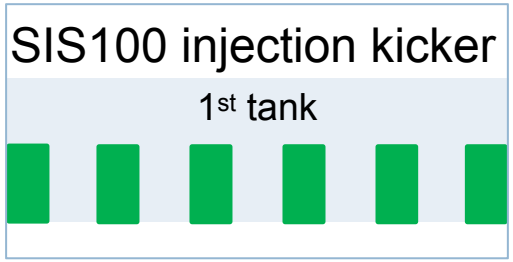
- **I checked the beam dynamics for rf frequency modulations by Matlab:**
- **Assumption:** adiabaticity ≤ **10^{-4}**
  - Cosine modulation is better for the beam adiabaticity than the parabola modulation
  - SIS18 U^{28+} beam: 7 ms cosine modulation for the phase shift of π √
  - SIS18 H^+ beam: 50 ms cosine modulation for the phase shift of π

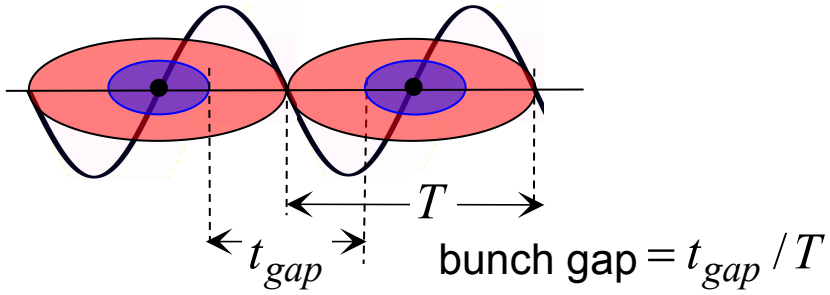
Frequency beating method

Requirements for Kicker Trigger

SIS18 extraction and SIS100 injection kicker trigger scenarios







Required bunch gap for two trigger scenarios of lightest and heaviest ions

	Energy MeV/u	All kicker units in a SIS18 tank are triggered at same time (bunch gap)	All kicker units in a SIS18 tank are triggered individually (bunch gap)	All kicker units in a SIS100 tank are triggered at same time (bunch gap)	All kicker units in a SIS100 tank are triggered individually (bunch gap)
H^{+}	4000	13%	12%	20%	18%
U^{28+}	200	16%	14%	24%	21%
U^{73+}	970	**25%**	22%	**35%**	31%

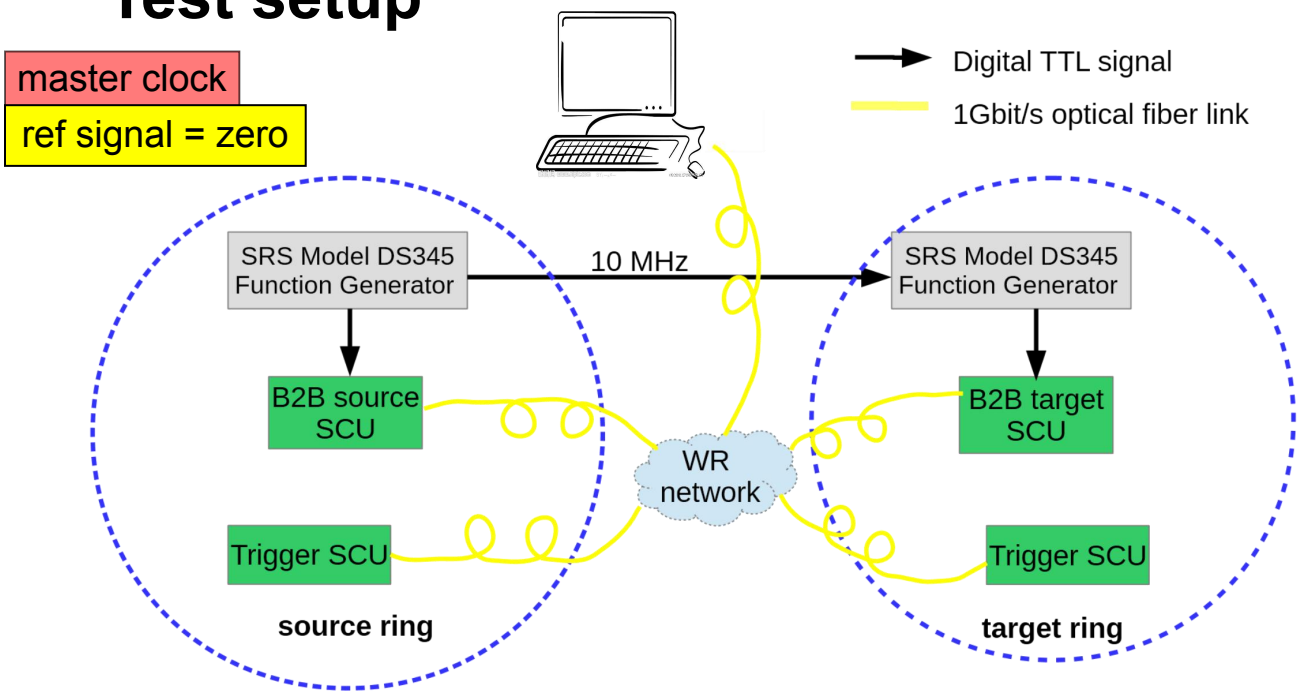
I calculated the technical constraints for the transfer of lightest & heaviest ion beams:

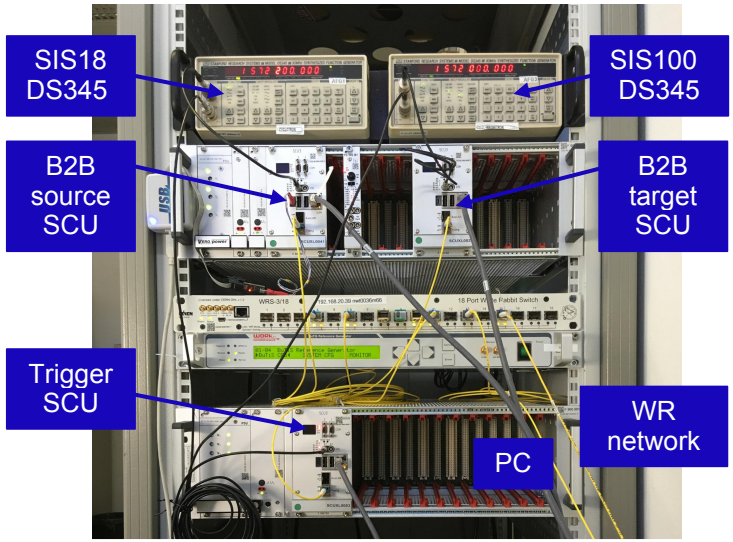
- When bunch gap ≥ 25% (U^{73+}), all kicker units in a SIS18 tank can be triggered at same time as today for all ion beams
- When bunch gap ≥ 35% (U^{73+}), all kicker units in the SIS100 tank can be triggered at same time for all ion beams

➢ Individual trigger of kicker units in one tank allows for a smaller bunch gap

Test Setup in Timing Aspect

Test setup





Task running on Latticemico 32	Processing time	Requirement
Read phase value	450 ns	< 10 µs
Send phase to WR network	3.2 µs	< 10 µs
Read phase from WR network	3.0 µs	< 10 µs
Calculate synchronization window	12.6 µs	< 100 µs

- I developed the B2B firmware running on LatticeMico32 (LM32) of different SCUs.
- I measured the processing time of the firmware → B2B transfer requirements are met

Comparison of Two Synchronization Methods

Frequency beating method:

- Frequency beating method is a general solution – only choice for many FAIR use cases
- Frequency beating method is faster ≤ 10 ms

Phase shift method:

- Phase jump – special phase shift – is efficient for FAIR use cases
  - Target ring is empty
  - Constant energy beam transfer
  - Changed energy beam transfer

Application - FAIR Use Cases

My investigation of the B2B transfer system for FAIR use cases

Whether frequency beating method **must** / **can** / **can not** be used

No	FAIR use cases	Required	B2B injection center mismatch
1	Two U^{28+} bunches from SIS18 to SIS100	can	±0.4°
2	One H^+ bunch from SIS18 to SIS100	can	±0.4°
3	Two bunches from SIS18 to ESR	must	±0.5°
4	One bunch from SIS18 to ESR	must	±0.5°
5	One bunch from ESR to CRYRING	must	±0.5°
6	One bunch from CR to HESR	must	±1.2°
7	One RIB bunch from SIS100 to CR via the Super-FRS. e.g. 1.5 GeV/u → 740 MeV/u	can	±2.1°
8	H^+ from SIS100 to CR via the antiproton target. e.g. 28.8 GeV/u → 3 GeV/u	can not	±41.5°
9	One RIB bunch from SIS18 to ESR via the FRS e.g. 550 MeV/u → 440 MeV/u	must	±31.2°

Successful due to constant beam energy

$$m \bullet C_1 \cong n \bullet C_2$$

Acceptable only for this case with changed beam energy

Not acceptable due to changed beam energy $E^{secondary}/E^{primary}$ = arbitrary

Phase jump

Summary & Outlook

Summary

- Investigation of the WR network for the B2B transfer
- Investigation of two synchronization methods from the beam dynamics perspective
- Investigation of the technical constraints for different trigger scenarios of the SIS18 extraction and SIS100 injection kickers
- Analysis of the application of the B2B transfer for all FAIR use cases
- Build of the test setup in the timing aspect

· **FAIR B2B transfer system** is applicable for the FAIR transfers of

✓ constant energy beams with an arbitrary circumference ratio.
changed energy beams together with some beam accumulation methods.

Outlook

Solution for the FAIR use case of the B2B transfer from SIS18 to ESR via the FRS, e.g. the barrier bucket beam accumulation.

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Thank you for your attention!