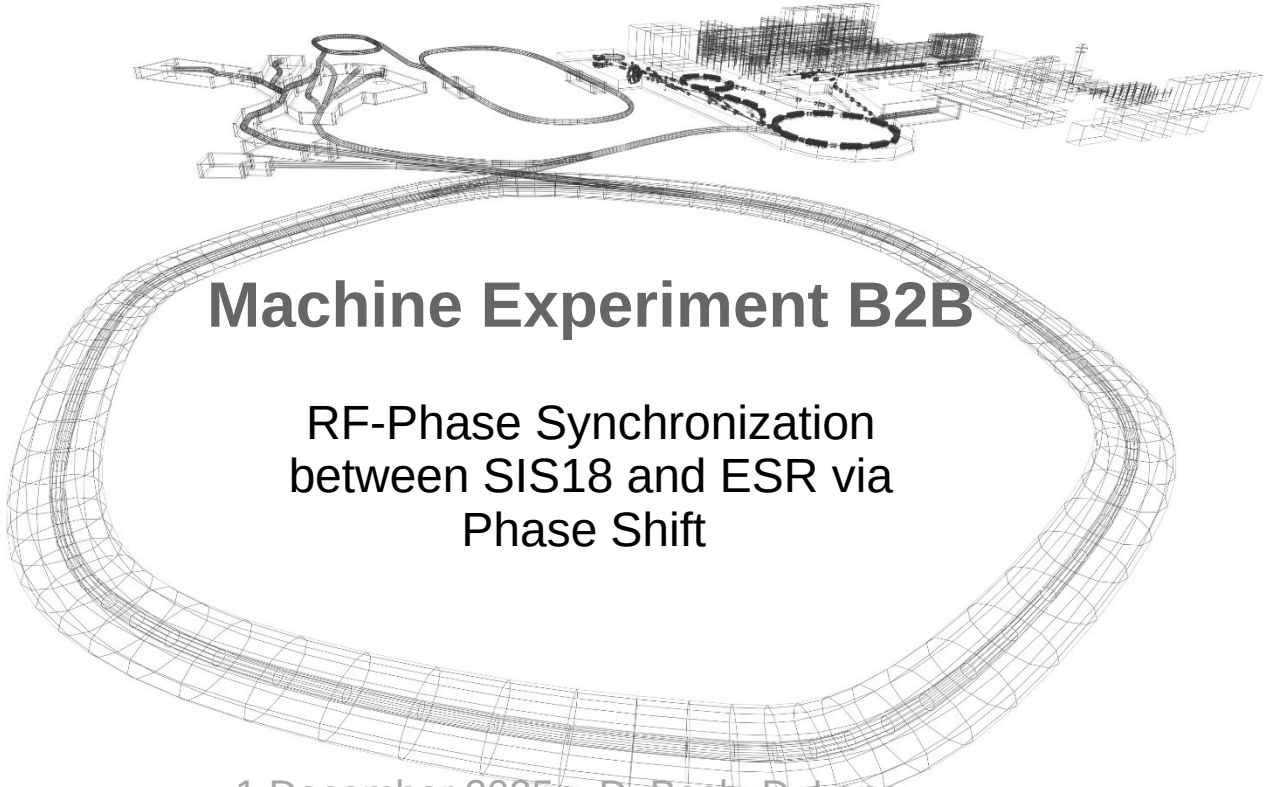


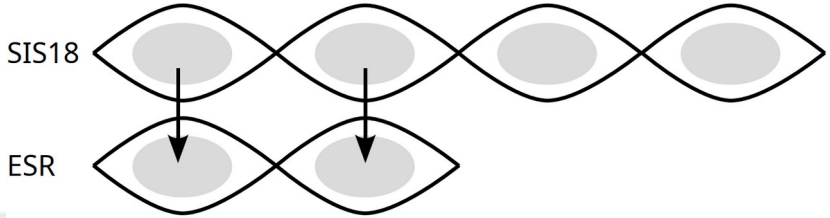
Machine Experiment B2B

RF-Phase Synchronization
between SIS18 and ESR via
Phase Shift

1 December 2025 – D. Beck, D. Lens

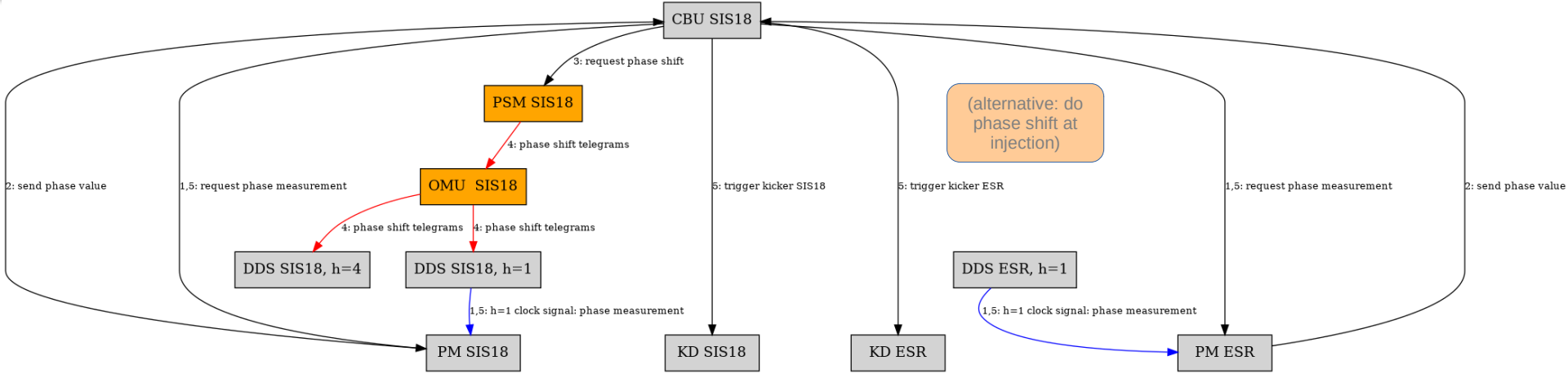
2025: Bunch-2-Bucket Transfer with Phase Shift Method

- transfer ion beams from one ring to another at GSI and FAIR
- phase matching between bunch and bucket to better than 1 degree
- joint work of ACO and RRF
- original plan
  - SIS18 → ESR → YR; SIS18 → SIS100: frequency beating (integer circumference ratio)
  - SIS100 → CR → HESR; phase shift (‚fractional' circumference ratio)
- why invest time in phase shift now?
  - frequency beating requires appropriate beat period
  - SIS18 → ESR lessons learned: sometimes b2b system is faced with inappropriate beat period
  - First Science, SIS18 → SIS100: plan B, just in case ...
- 2025-may-26: machine experiment SIS18 (h=4) → ESR (h=2); $^{12}C^{6+}$ @ 400 MeV/u
  - new: deterministic and adiabatic phase shifting of the RF in the ring



2025: Phase Shift and Frequency Beating Methods

(distributed FPGAs - digital system)



CBU: **C**entral **B**2B **U**nit @ extraction ring

PM: **P**hase **M**easurement, @ RRF supply rooms

DDS: **D**irect **D**igital **S**ynthesis (signal generator), @RRF supply rooms

KD: **K**icker Trigger and **D**iagnostics, @kicker rooms

PSM: **P**hase **S**hift **M**odule prototype; added for phase-shifting

OMU: **O**ptical **M**ixer **U**nit prototype; added for phase-shifting (phase shift multiplier)

black arrows: b2b real-time messages via White Rabbit network

blue arrows: ~1m copper cable

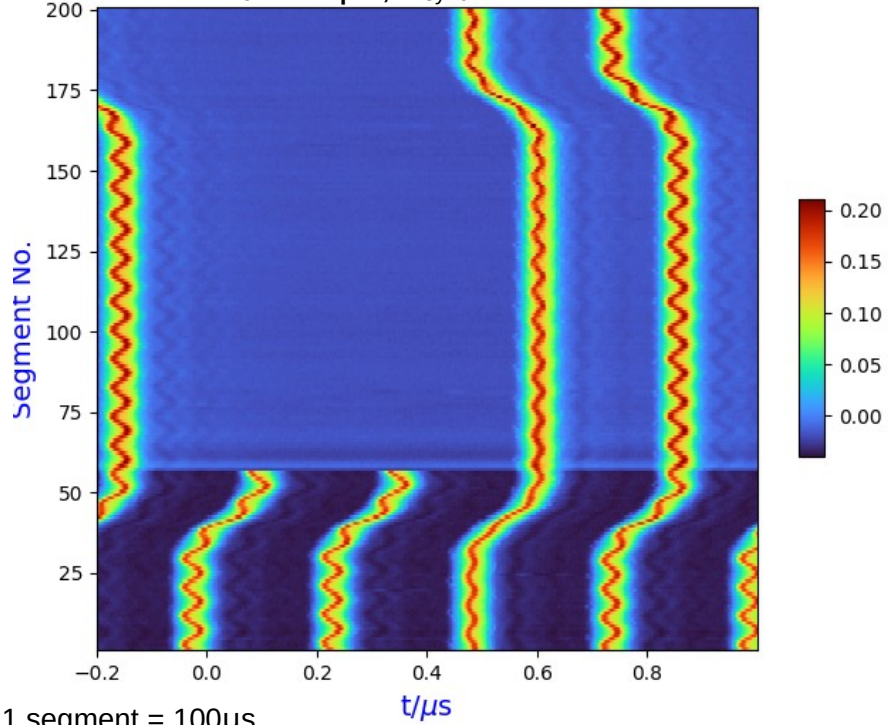
red arrows: local multi-mode fibre links

1. request 1st phase measurement(s)
2. collect measured phase values
   - frequency beating: CBU calculates time for phase match
   - phase shift: CBU calculates phase shift at time of transfer
3. request phase shift (here: extraction ring)
4. perform phase shift
5. trigger kickers and 2nd phase measurement

Phase Shifting in SIS18 (4 ms, #037)

SIS18 (FCT)

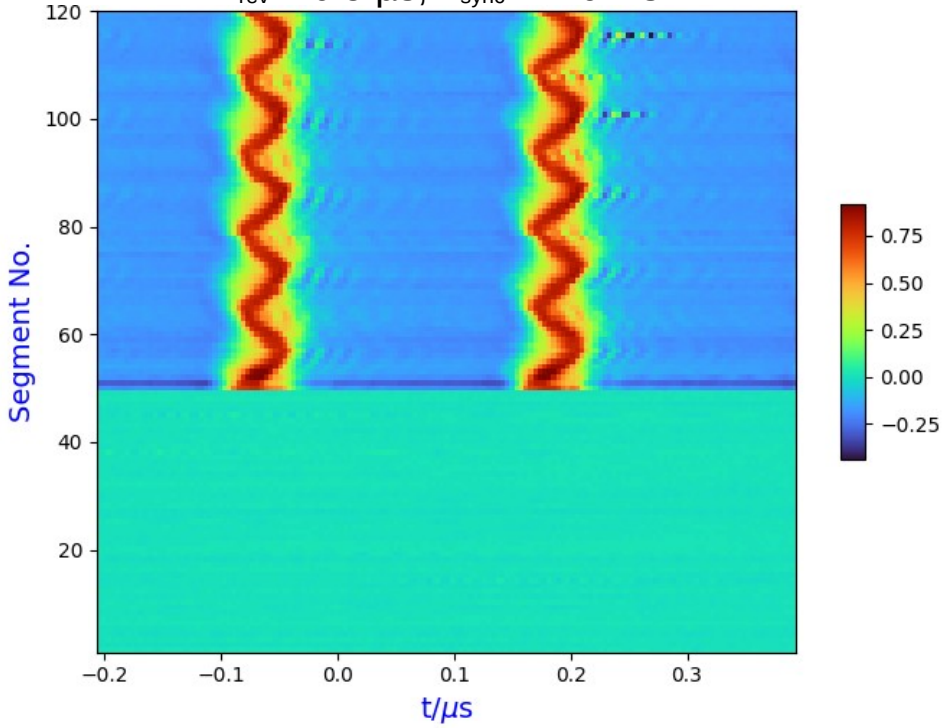
T_{rev} ~ 1 µs; T_{sync} ~ 1.2 ms



1 segment = 100µs

ESR (FCT)

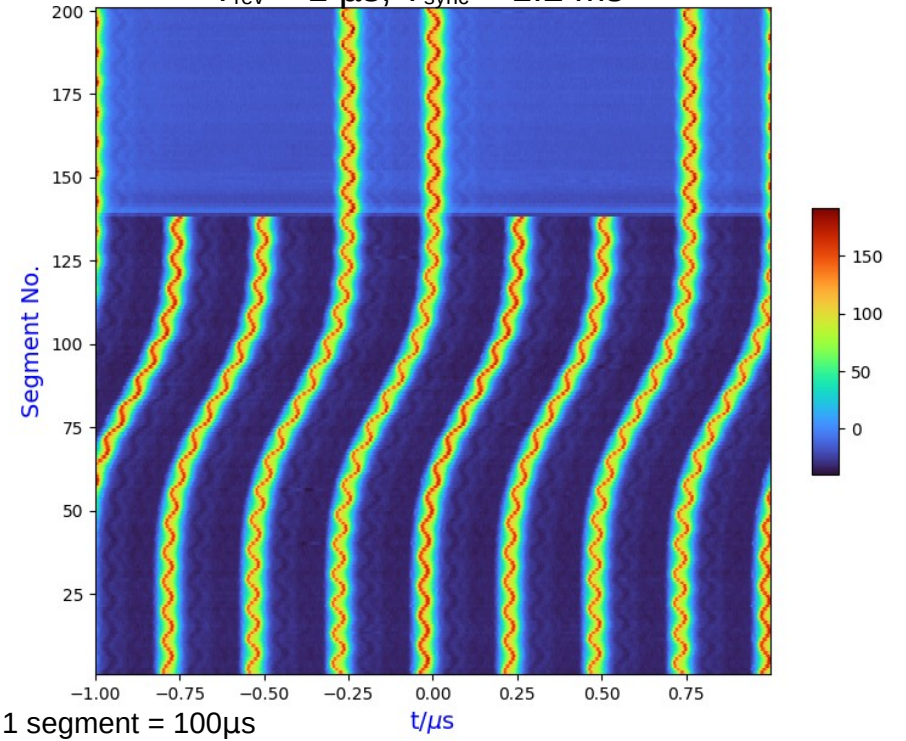
T_{rev} ~ 0.5 µs; T_{sync} ~ 1.6 ms



Phase Shifting in SIS18 (14 ms, #069)

SIS18 (FCT)

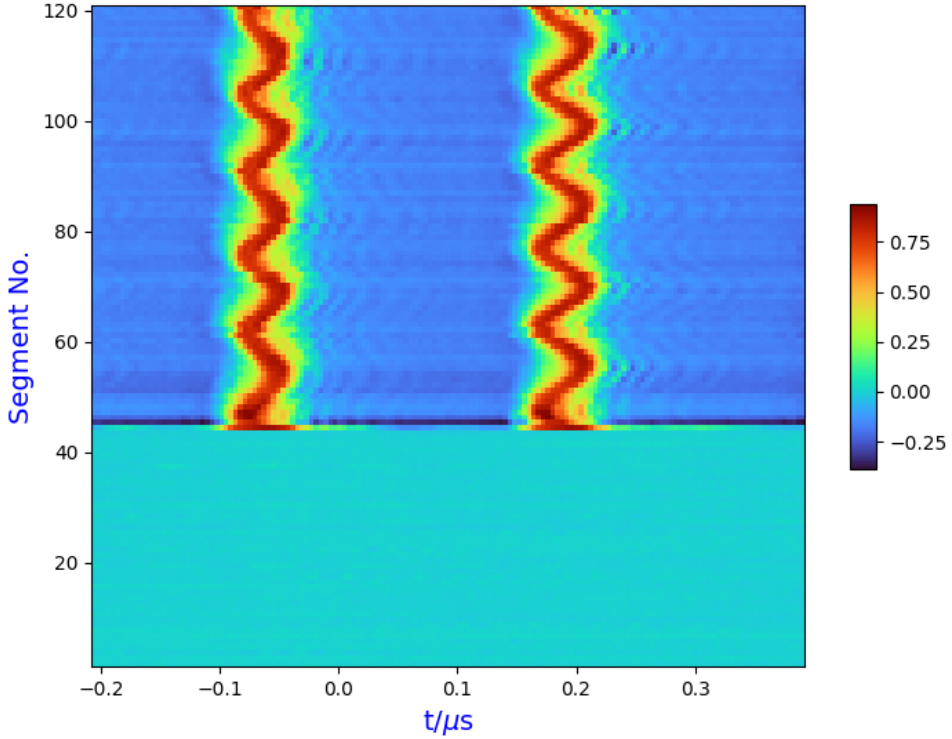
T_{rev} ~ 1 µs; T_{sync} ~ 1.2 ms



1 segment = 100µs

ESR (FCT)

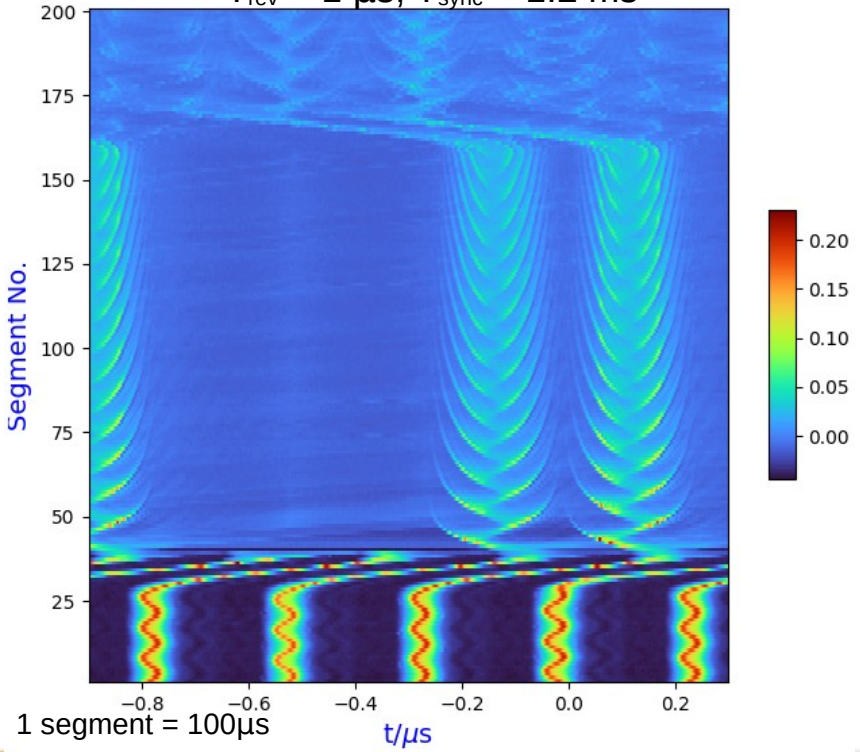
T_{rev} ~ 0.5 µs; T_{sync} ~ 1.6 ms



Phase Shifting in SIS18 (2.5 ms, #087)

SIS18 (FCT)

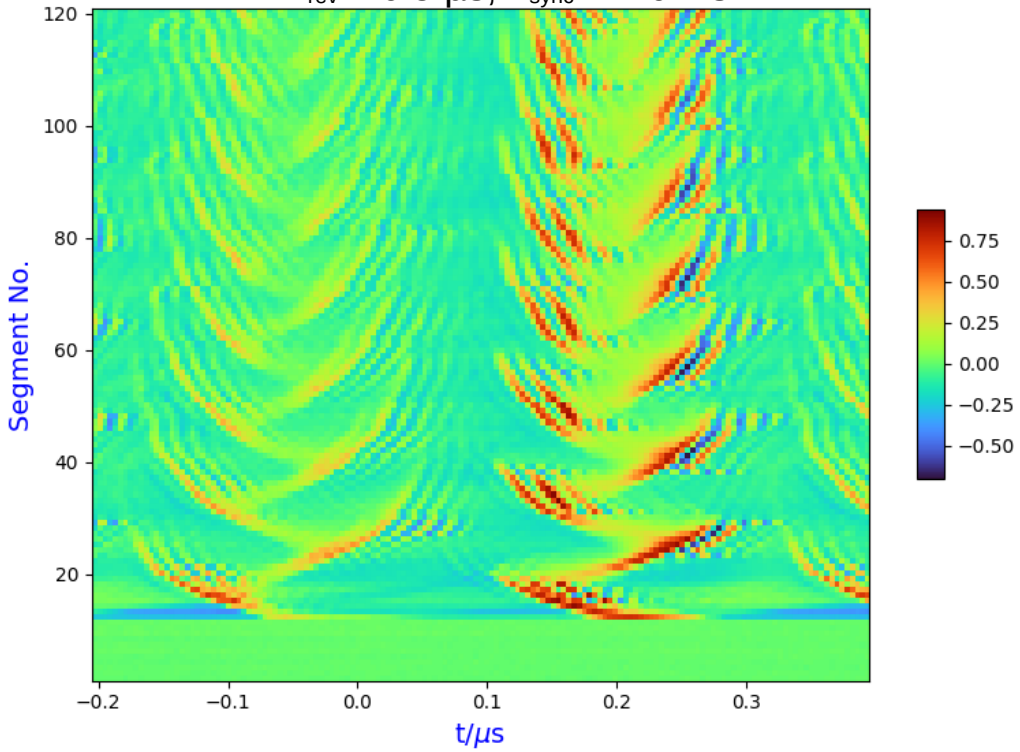
T_{rev} ~ 1 µs; T_{sync} ~ 1.2 ms



1 segment = 100µs

ESR (FCT)

T_{rev} ~ 0.5 µs; T_{sync} ~ 1.6 ms



Summary

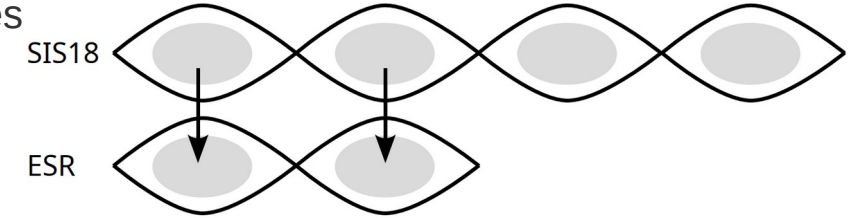
- Achieved
  - bunch-2-bucket transfer with phase-shifting with SIS18 **or** ESR ferrite cavities
  - new PSM (S. Schäfer) and OMU (D. Ziegelmann, M. Hardieck) prototypes: only single harmonic with two fixed (pre-defined) harmonic numbers supported (currently h=4, h=2, h=1)
  - (first test of B2B with beam phase control switched on)
- Lessons Learned
  - caveat ESR injection septum: usable only til ~8 ms after start of beam process ‘extraction fast’
  - synchronization of cavity DDS should (shall ?) be monitored
  - found a few issues with back-shifting of phase after flat-top
- Next
  - resolve issues
  - next B2B-MDE: verify ±1° precision at phase matching
  - integration into control system stack: phase shift time, OMU harmonic numbers ...
  - hardware and firmware upgrade of OMU required
  - extend system from 3 to 4 rings, SIS100: first ring with larger circumference

Backup Slides

- …

Bunch-2-Bucket System I

- transfer ion beams over the whole range of isotopes from one ring to another at GSI and FAIR
- phase matching between bunch and bucket to better than 1 degree
- joint work of ACO and RHF
- lots of support from RHV, EEL, ESR, SYS, BEA ...
- distributed, digital system
  - RHF: BuTiS (clock distribution)
  - ACO: White Rabbit (clock, time and event distribution)
  - BuTiS and White Rabbit are phase locked → determinism, no drifts
  - fibre optics, no copper
  - time based
    - ‚observed signal at time T_1‘
    - ‚request action at time T_2’
  - signals, triggers are measured or generated locally (not distributed via long cables)



Bunch-2-Bucket System II

- action:
  - trigger kicker
    - transfer between rings
    - all ‚fast extractions' of all rings
    - 2020/q4: demonstrated at SIS18, ESR
    - 2022/q1: routine operation at SIS18, ESR, CRYRING
  - synchronization of low-level-RF between rings (h=1)
    - 2021/q2: demonstrated frequency beating SIS18 → ESR
    - 2022/q1: routine operation frequency beating; SIS18 → ESR → CRYRING; stacking in ESR
    - 2025/q2: demonstrated phase shift method SIS18 → ESR (prototype)
- detection and monitoring
  - ‚phase measurement' of h=1 group DDS systems
    - until 2022: routine operation with 1 ns precision
    - since 2023: routine operation with sub-ns precision

Bunch-2-Bucket System II

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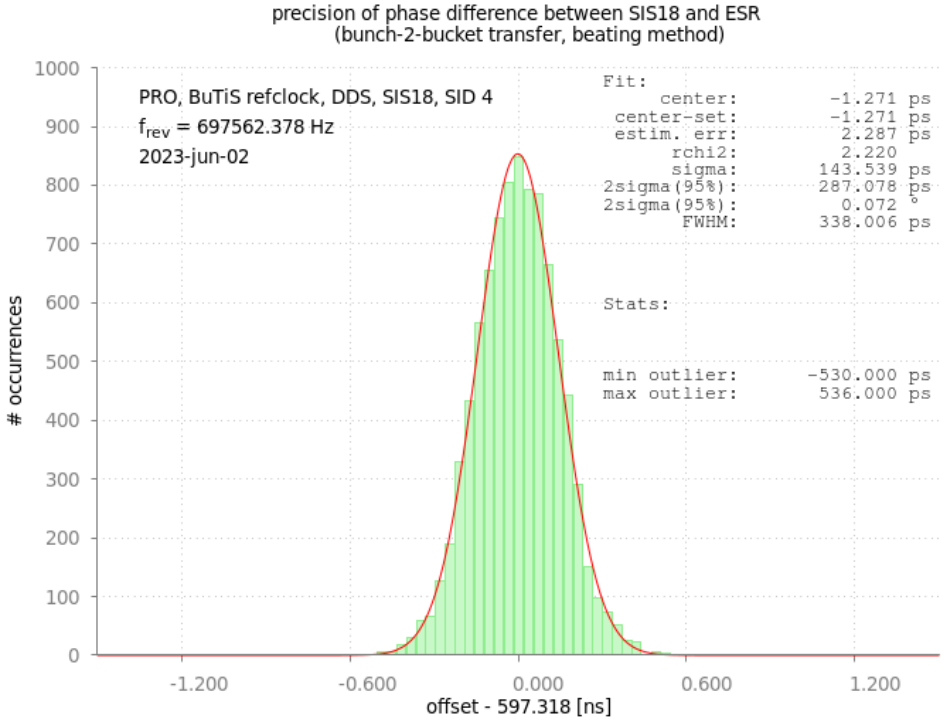

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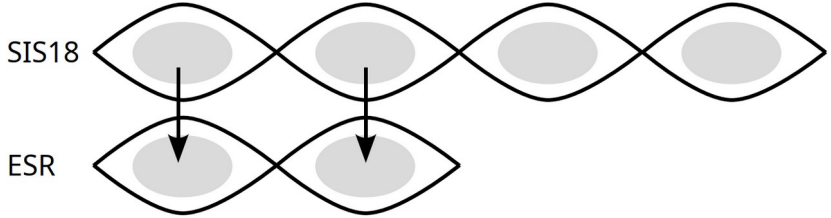
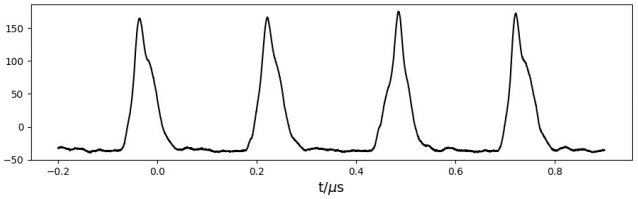
- detection and monitoring
  - ‚phase measurement' of h=1 group DDS systems
    - until 2022: routine operation with 1 ns precision
    - since 2023: routine operation with sub-ns precision
  - kicker magnet probe: time of rising edge (all rings) and flat-top length (SIS18, ESR) using a simple comparator; data delivered to customers 1 ms after kick via timing message

Phase Shifting in SIS18 (4 ms, #037)

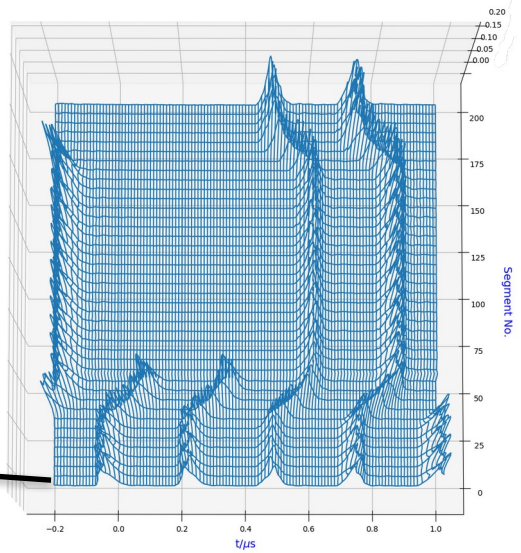
- SIS18 settings:
  - $^{12}C^{6+}$ from 11.4 to 400 MeV/u, h=4
  - cooler on during injection
  - 2 out of 4 SIS bunches transferred to ESR
  - Typical intensities:
    - 5.0E9 particles in SIS18
    - 2.5E9 particles extracted (2/4)
    - 6.0E8 particles stored into ESR



- no optimization of SIS settings to minimize dipole oscillations or to optimize bunch shape



segment #1



SIS18: phase shifting + beam phase control