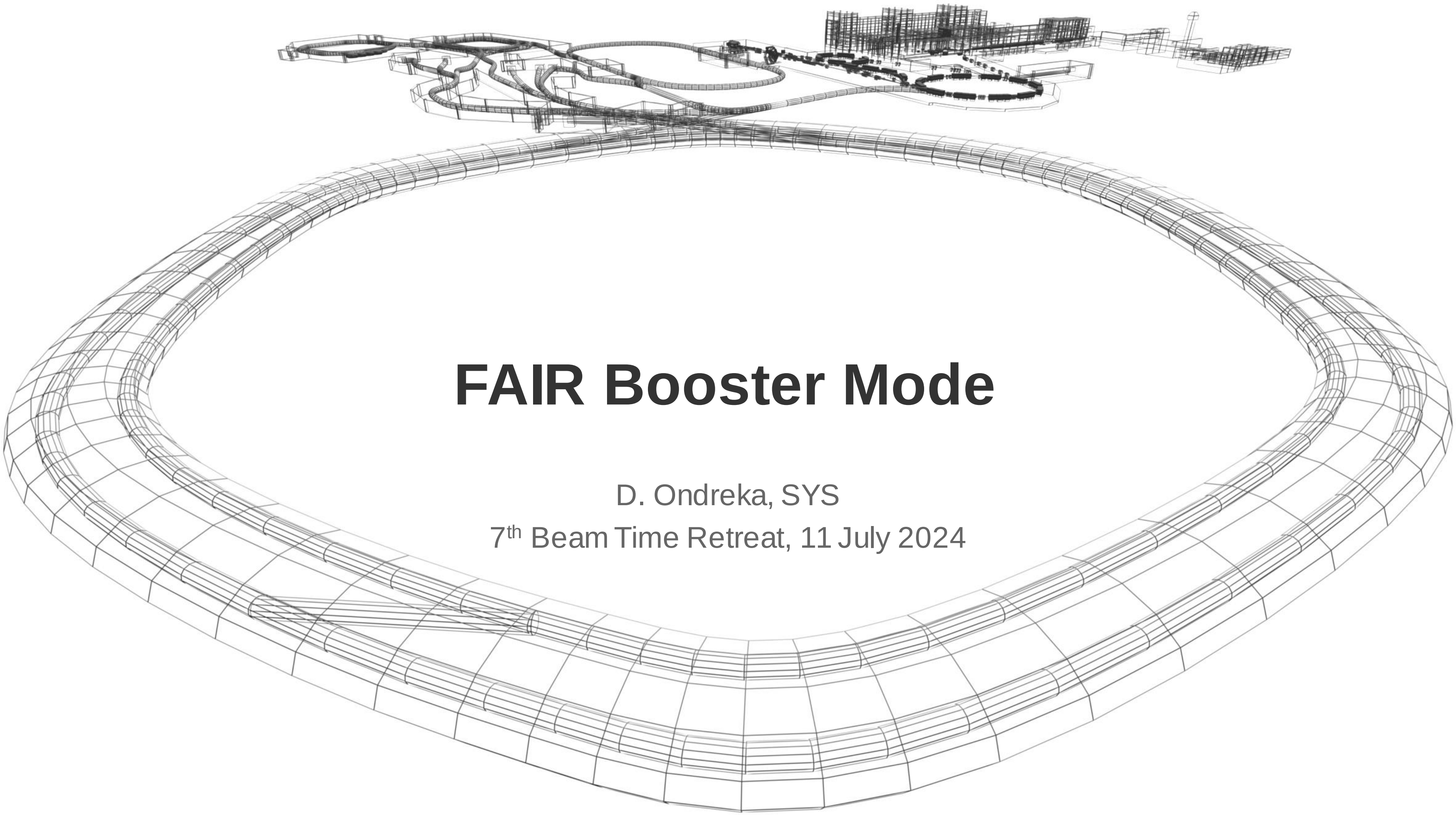

FAIR Booster Mode

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7th Beam Time Retreat, 11 July 2024

Contents

- Booster mode
  - Definition
  - Topics
- Super-cycle development
- Hysteresis effects
- BD applications and booster mode
- Status
- Summary and outlook

Booster Mode

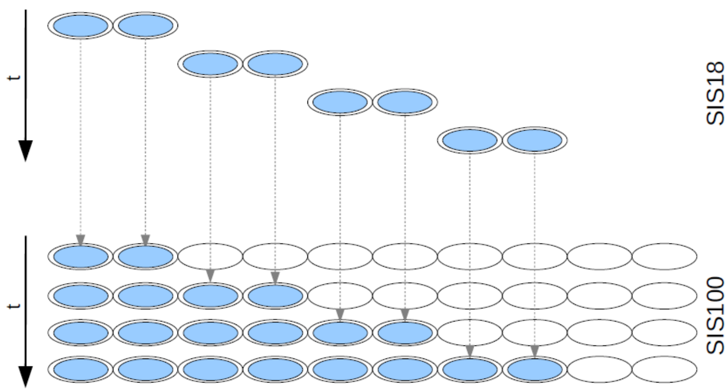
- Goal: reach maximum intensity in SIS100
  - Longitudinal filling by stacking four SIS18 cycles
  - Two empty buckets as beam abort gap
  - Used with **any ion species**

- Fundamental requirements
  - Fastest possible repetition rate
  - Direct ramp-down to injection level
  - Fast extraction only

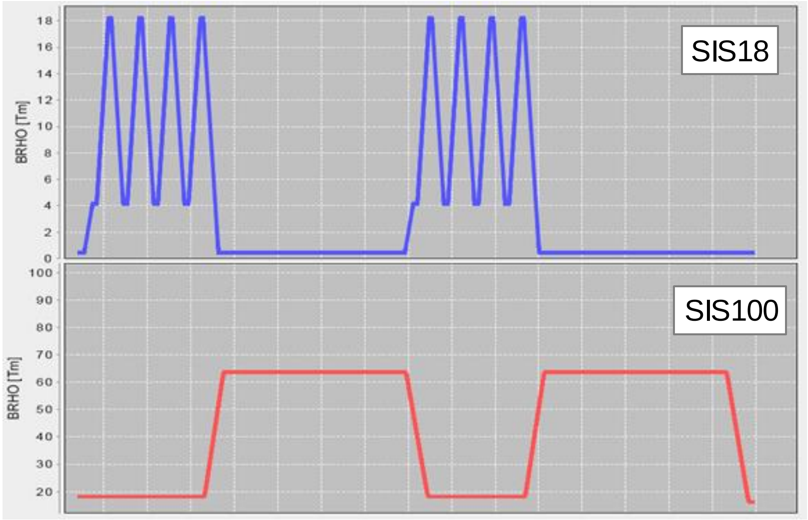
- Repetition rate
  - Original value: 2.7 Hz for U^{28+} (reference)
    - Cycle length 370 ms incompatible with 50 Hz
  - Presently aiming for cycle length 380 ms (2.6 Hz)
  - Cycle time longer for lighter ions to 18 Tm!

- Common misconceptions:
  - booster mode $\nLeftrightarrow$ highest intensities of U^{28+}
  - fastest ramp rate (19 kA/s) $\nRightarrow$ booster mode

Stacking scheme for RIB production



SIS18 and SIS100 cycles for RIB production



Booster Mode: Topics

- Beam physics
  - Acceleration at max. possible ramp rate (19 kA/s)
  - Strong eddy current effects
  - **Hysteresis effects due to special magnetic cycle**

- Hardware
  - AEG power converters
    - Reaching 19 kA/s on down ramp
    - Decrease of rounding time: 32 ms → 24 ms ?
  - MA cavities for H=2
    - Max. voltage, especially for lighter ions

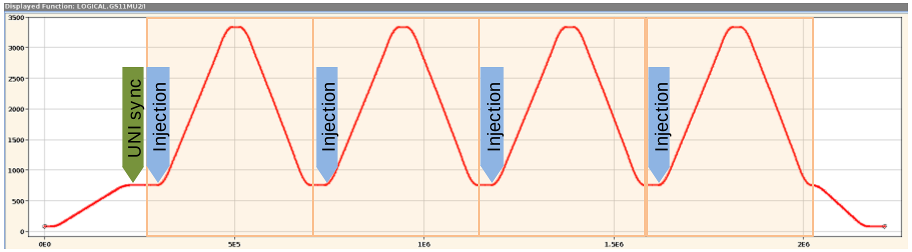
- Machine model
  - **Generation of booster mode cycles**
  - Smallest number of BPs: bunching in INJECTION

- Control system
  - **BD applications handling booster mode properly**
  - Ramped front-ends: smaller min. BP length
  - Coupling with new UNILAC timing system
  - FAIR patterns: repetition of single booster cycle

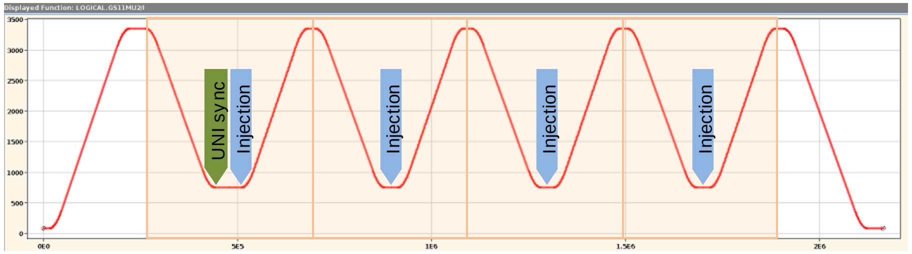
Super-Cycle Development

- Preferred operation:
  n-fold repetition of same cycle
  - May or may not be feasible
- Version 1
  - First successful test with beam (U^{28+}, 2022)
  - Drawback: completely different magnetic hysteresis for first cycle
- Version 2
  - Advantage: same hysteresis for every cycle
  - Drawback: eddy currents different in first cycle due to UNILAC synchronization
  - Successfully used (U^{28+}, 2023; U^{73+}, 2024)
- Version 3
  - Advantage: same hysteresis and eddy currents in every cycle
  - 2 failed test in 2024 (wrong timing graph?)
    - Error analysis ongoing
    - May wait for new UNILAC timing system

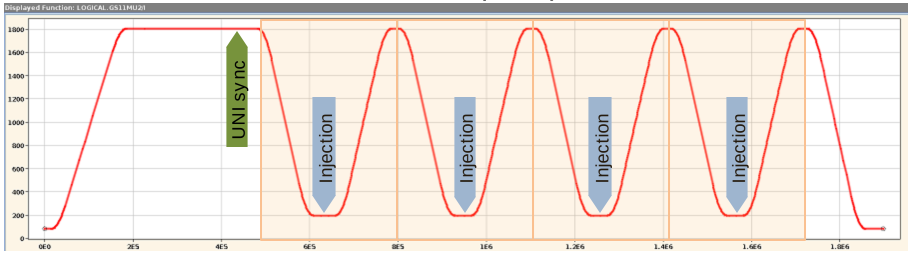
Version 1 (2022)



Version 2 (2023)



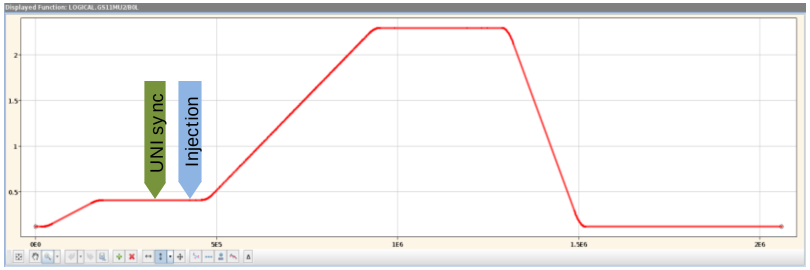
Version 3 (2024)



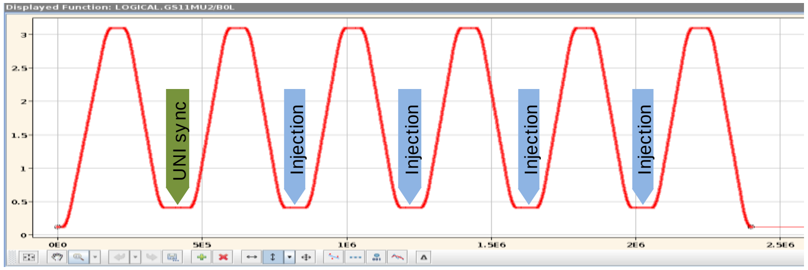
Hysteresis Effects: General

- Different magnetic cycle for booster
  - Direct ramp-down to injection level to save time
  - Hysteresis loop significantly smaller
- Expected general effects
  - Larger remnant field at injection
  - Different shape of excitation curve
- Impact on performance
  - Degradation of injection performance
  - Increased beam loss at start of ramp
  - Measured with special U^{73+} booster cycle U^{73+}
    - Injection into 4/5 repetitions for same eddy currents

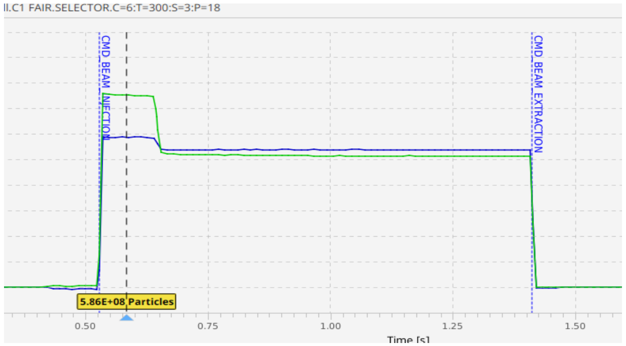
Magnetic field in standard cycle



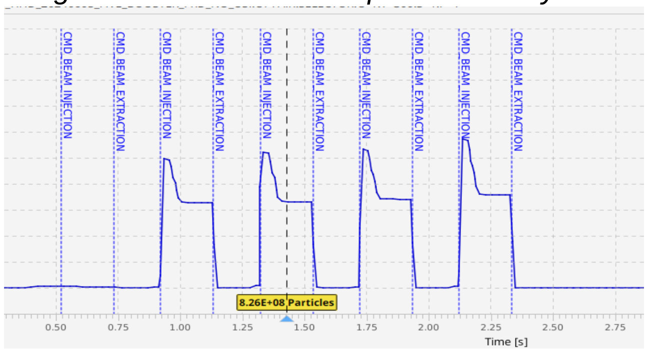
Magnetic field in booster cycle (first injection omitted)



Small losses at start of ramp in standard cycle



High losses at start of ramp in booster cycles



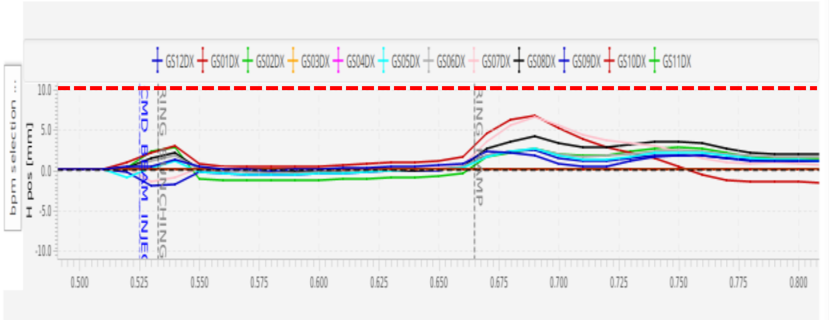
Hysteresis Effects: Dipoles

- Larger remnant field at injection
  - Shift of horizontal orbit towards center
  - Compensation by adjusting B field at injection
- Strong orbit motion at start of ramp
  - Caused by different shape of B(I) curve
  - Good news: cycles appear to behave identical!
- Observation by monitoring orbit
  - Orbit application can display all cycles
  - Data can be exported in binary format
  - Limitations of present software
    - No comparison of different cycles

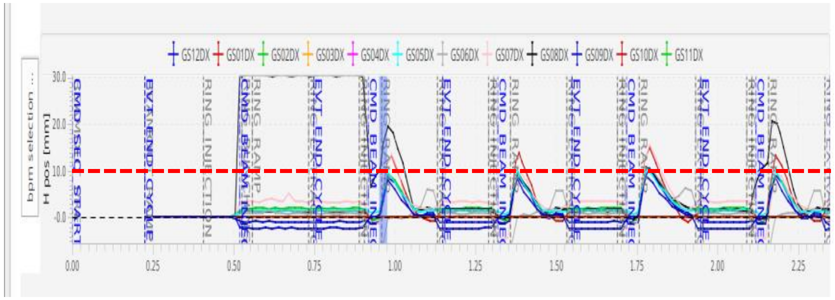
Radial position for same orbit at injection

Cycle	ΔR set value
Booster	8 mm
Standard	-2 mm
Difference	**10 mm**

Horizontal orbit evolution in standard cycle



Horizontal orbit evolution in booster cycles



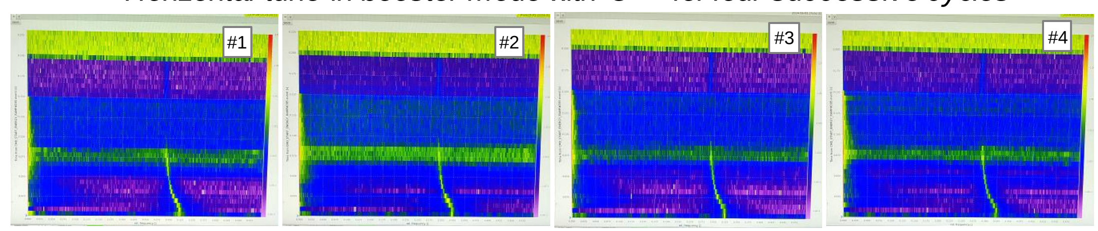
Hysteresis Effects: Quadrupoles

- Larger remnant field at injection
  - Tune shift, esp. large in vertical plane
  - Compensation by adjusting set tunes
- Strong tune motion at start of ramp
  - Caused by different shape of B'(I) curve
  - Good news: cycles appear to behave identical!
- Observation difficult
  - Displayed data: snapshots from video recorded on smart phone
  - Limitations of present software
    - No comparison of different cycles
    - No saving data for different cycles

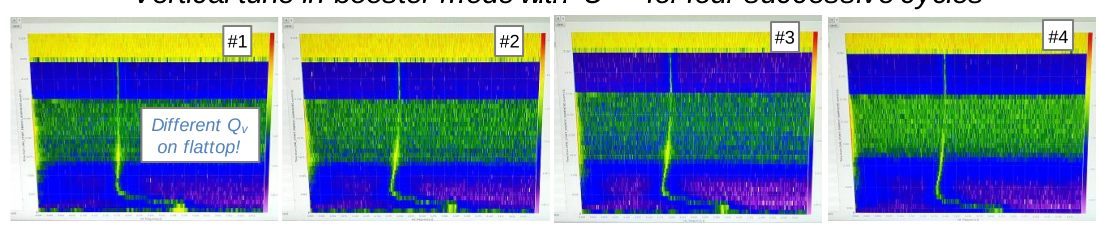
Injection tune set values for U^{73+} for same real tunes

Cycle	Q_h set value	Q_v set value
Booster	4.275	3.21
Standard	4.305	3.315
Difference	-0.03	**-0.105**

Horizontal tune in booster mode with U^{73+} for four successive cycles



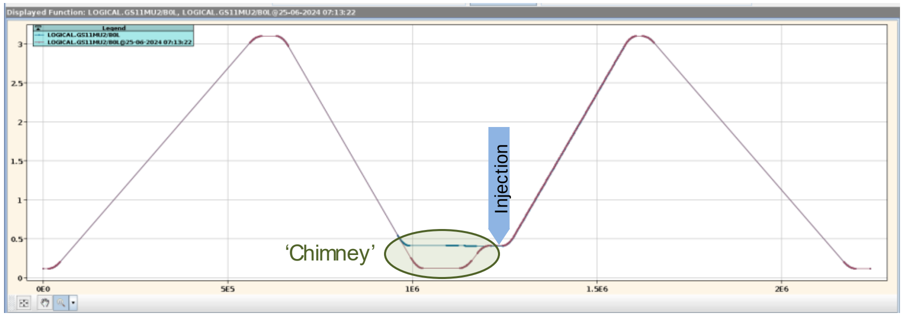
Vertical tune in booster mode with U^{73+} for four successive cycles



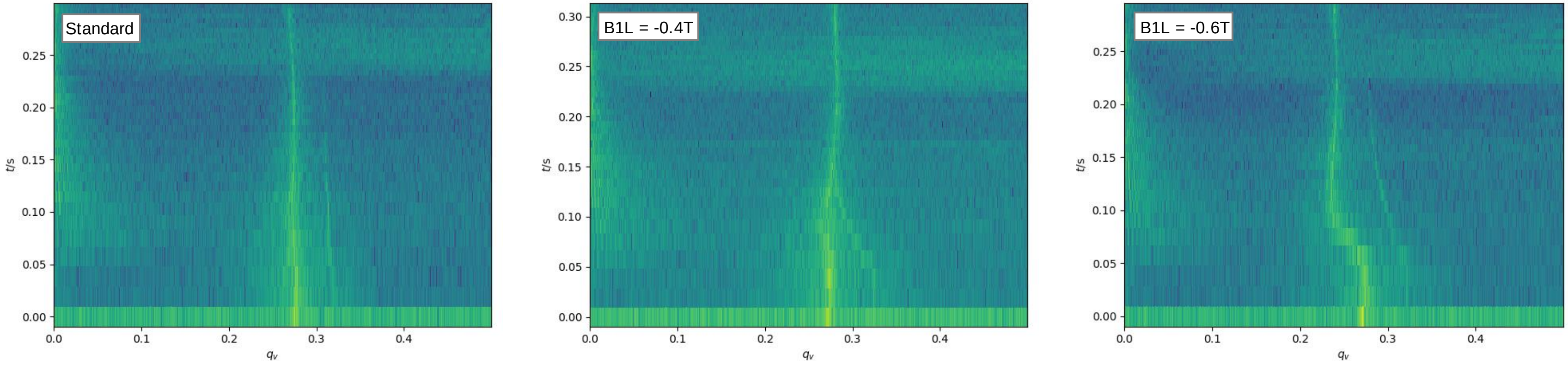
Hysteresis Compensation (I)

- Short test during last week of beam time
  - Made possible due to septum cable failure
  - U^{73+} booster cycle with single injection used
  - Goals: measure and demonstrate compensation
- Measurement of hysteresis
  - 'Chimney' used to change hysteresis loop
  - Injection offsets compensated by set values
  - Separately for dipoles and quadrupoles
  - Data acquired, analysis ongoing

Booster cycle with 'chimney' used for hysteresis measurements

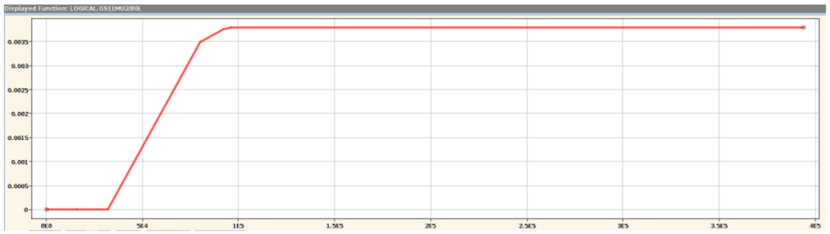


Effect of changing hysteresis loop for D-quadrupoles on vertical tune

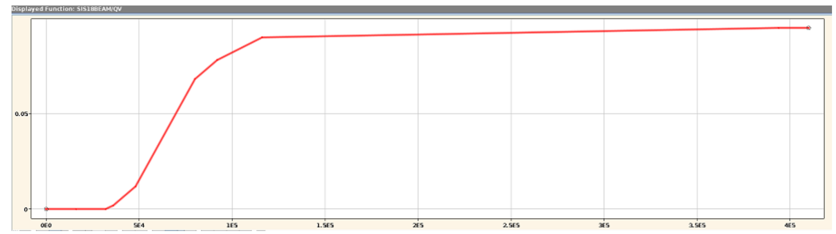


Hysteresis Compensation (II)

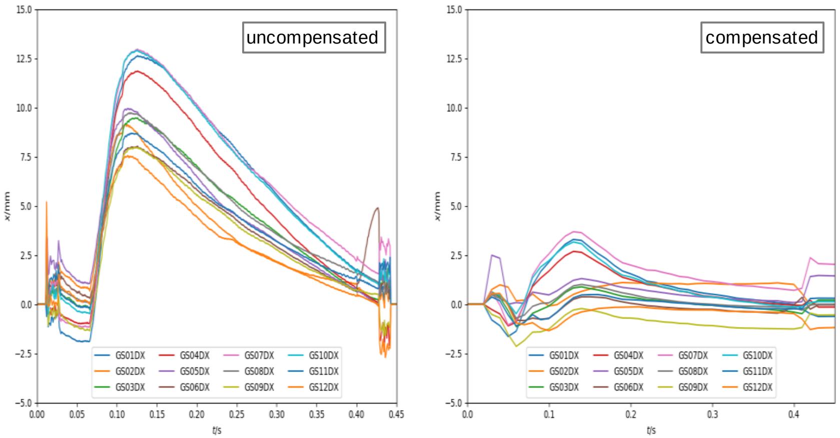
Manual correction trim to integral dipole field



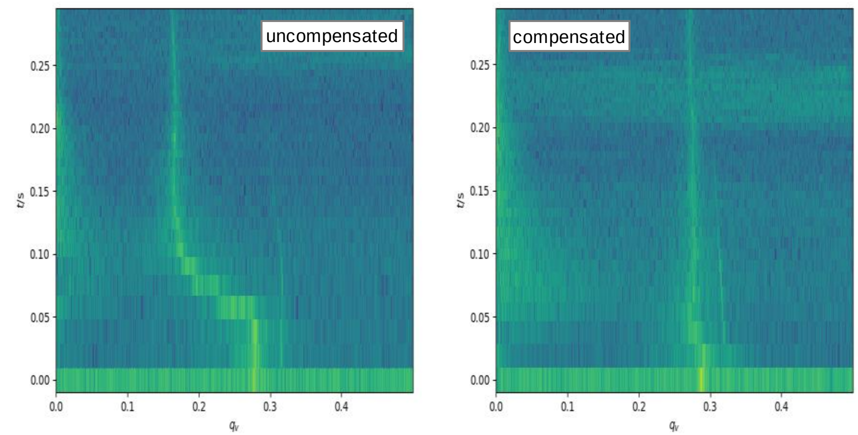
Manual correction trim to vertical tune



Measured horizontal orbit



Measured vertical tune



- Demonstration of dynamic compensation
  - Manual trims during ramp
    - Dipole hysteresis → integral field B0L
    - Quad hysteresis → vertical tune Q_v
- Software tools required for routine operation
  - Orbit correction on ramp
  - Tune correction on ramp

BD applications for booster mode

- Non-uniform behavior of existing applications for displaying beam signals
  - DCT and orbit application
    - All cycles displayed on single time axis at end of super-cycle
  - ACT and tune application
    - Every cycle is displayed when it finishes, erasing the previous one
  - Saving data of individual cycles may or may not be possible

- Goals
  - Allow operators to focus on and diagnose individual cycles
  - Allow operators to compare individual cycles
  - Allow machine physicists to save data of individual cycles

- Considerations for implementation
  - Requirements need to be clarified
  - Present ‘booster mode light’ may not be identical to final solution
  - Final booster mode structure will be part of FAIR pattern concept

Status of Topics

Category	Topic	Demonstration	When	Status
Physics	Ramp rate 19 kA/s with U^{28+}	Reached 18.9 kA/s up, 17.6 kA/s down	12/2023	up: ok down: p.f.i.
Physics	Investigation of eddy current effects			open
Physics	Compensation of hysteresis effects	Manual compensation	06/2024	demo: ok tools: open
HW	Smaller rounding times for AEG			open
HW	Max. voltage for MA cavities to 42 kV			open
Model	Super-cycles with optimal hysteresis	Version 2 successful, version 3 failed	2022+23	p.f.i.
Model	Bunching in injection			open
CS	Adapt BI applications to booster			open
CS	Smaller min. BP length in FG			open
CS	Coupling with new UNILAC timing			open
CS	FAIR patterns: rep. of single cycle			open

p.f.i. = potential for improvement

Comparison to FAIR Requirements

Booster for U^{28+}	FAIR (50 Hz)	Present status
Ramp rate	19 kA/s	18.9 kA/s up, 17.6 kA/s down
Available MA voltage	42 kV	39 kV
Cycle time	**380 ms**	400 ms
Repetition rate	2.63 Hz	2.50 Hz
Stacking time	1.14 s	1.2 s

- Present MA cavity voltage appears sufficient up to ~ $5 \cdot 10^{10}$ particles
- Potential for reducing cycle time to 380 ms
  - Increasing ramp down rate: 10 ms
  - Reducing min. BP length from 16 ms to 12 ms: 4 ms
  - Reducing rounding time from 32 ms to 24 ms: 16 ms
  - Bunching in injection BP: 16 ms

→ *FAIR design parameters for booster with U^{28+} well in reach*

Summary and Outlook

- Booster mode machine development well advanced
  - Demonstrated 2.5 Hz operation with U^{28+} (already in 2023)
  - Hysteresis effects understood and manual compensation demonstrated
  - Apparently four identical cycles possible with suitable super-cycle

- Recommended next steps
  - Activities in SYS
    - Booster mode test with a lighter ion, e.g. Ar^{10+}
    - Investigation of eddy current effects
    - Merging injection and bunching beam process to save time
    - Development of hysteresis compensation tool
  - Light-weight adaptation of BI applications to handle booster mode better