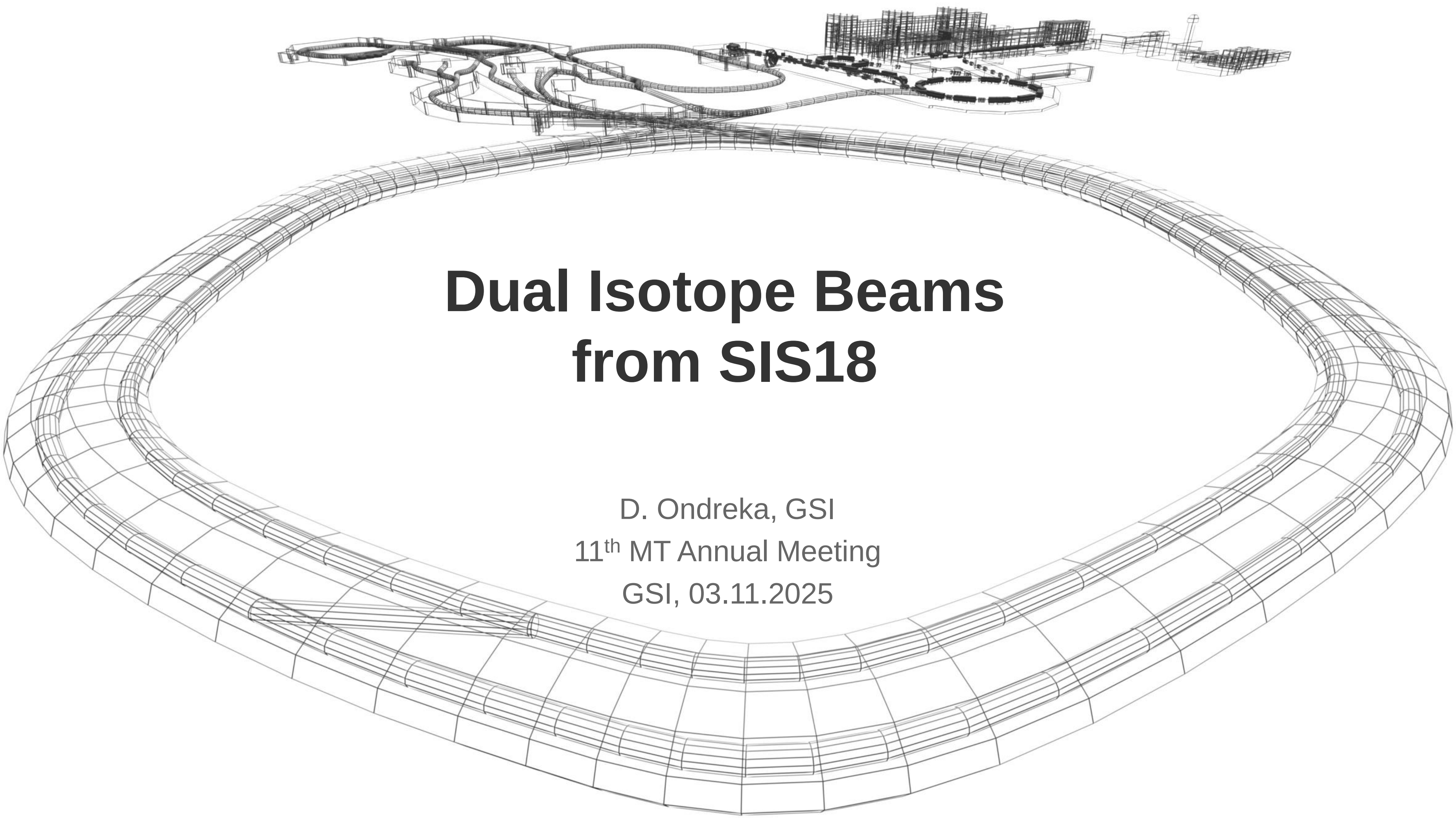
Dual Isotope Beams from SIS18



D. Ondreka, GSI

11th MT Annual Meeting

GSI, 03.11.2025

Outline

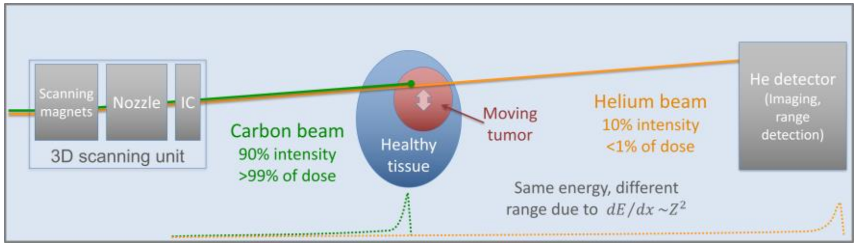
- Motivation
- Overview SIS18 and UNILAC
- Dual isotope cycle
  - Idea and requirements
  - Implementation
  - Experiment
- Summary and outlook

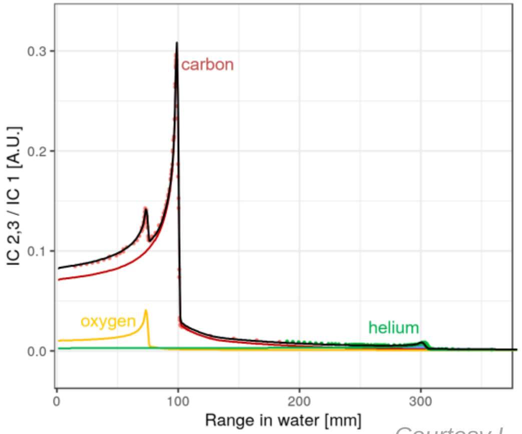
Motivation

Dual Isotope Beam: *“Acceleration and extraction of two ion species with different A/Q in the same synchrotron cycle”*

Why dual isotope beams?

- Mixed beams for range-monitoring in ion therapy
  - Carbon for treatment, helium for range detection
  - $C^{6+}/^{3}He^{2+}$ one way to provide contamination free beam
- Further possible applications
  - Plasma physics: heating and probing with two species
  - Fragment separator: small fraction of ‘reference ion’
  - Precise energy calibration of primary beam
- Interesting accelerator physics challenge

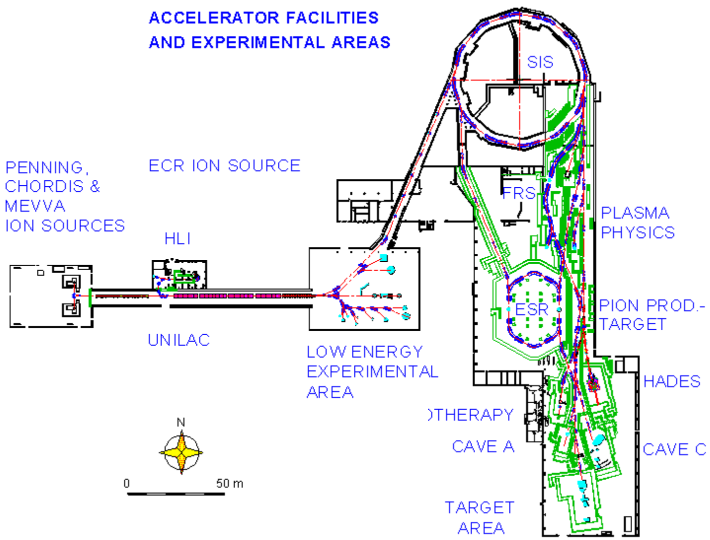


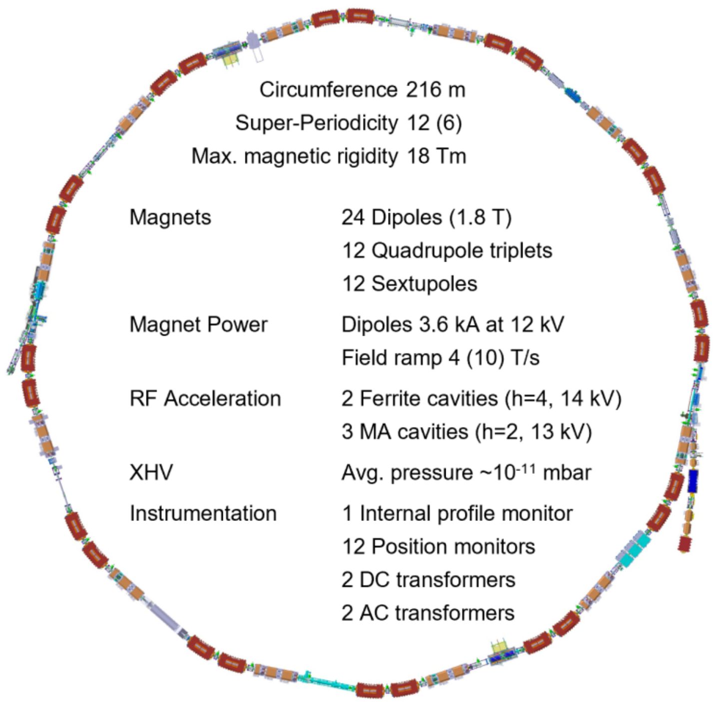


Courtesy L. Volz

MATTER AND TECHNOLOGIES

SIS18: Overview





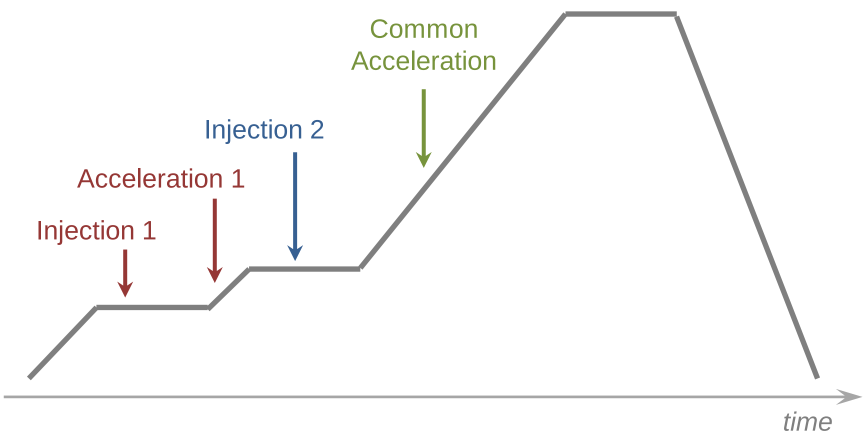
- Synchrotron with NC magnets
  - Fast ramping up to 10 T/s
  - Optics change triplet → doublet during ramp
- Multi-turn injection (painting) from UNILAC
  - Up to 3 ion species available at a time
  - Optional electron cooling (usable for stacking)
- Flexible RF system with 5 acceleration cavities
- Fast and slow extraction

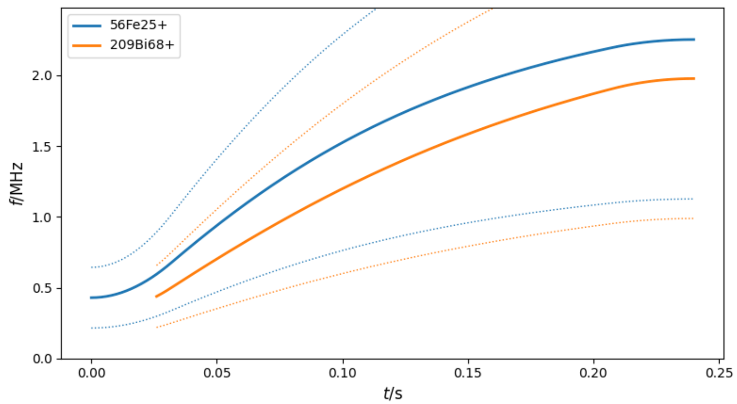
SIS18 optical parameters

	Injection	Extraction
Q_h / Q_v	4.29 / 3.28	
Q'_h / Q'_v	-4.1 / -5.6	-6.4 / -4.1
α_p	0.041	0.032
γ_t	4.9	5.6

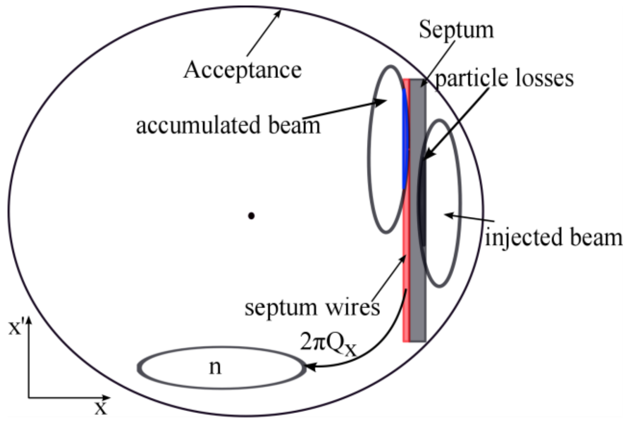
Dual Isotope Cycle: Idea

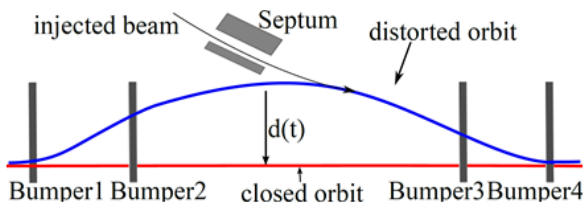
- Different ions can be accelerated in same field
  - Differ only in energy and revolution frequencies
  - Two independent cavities would in principle suffice
- Basic expectations about mutual influence
  - No net voltage of 'foreign' RF if harmonics don't cross
  - Interactions between ions negligible for low intensities
- Facility satisfies all prerequisites
  - UNILAC can provide two ion species at a time
  - SIS18 cavities can run independently without feedback
  - Just need to program the correct set values!
- Challenges for the control system
  - **Cycle with two injections of two different ions**
  - **RF set values for two ion species in single cycle**

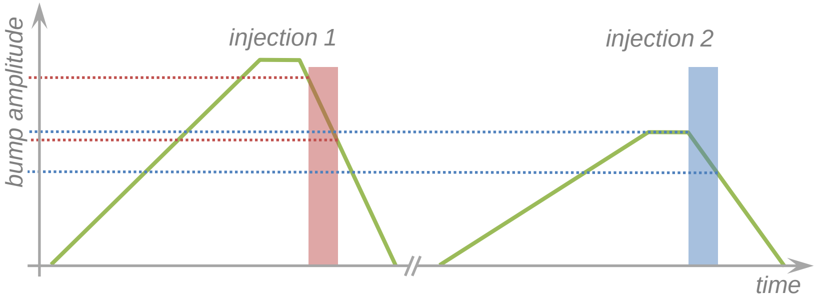




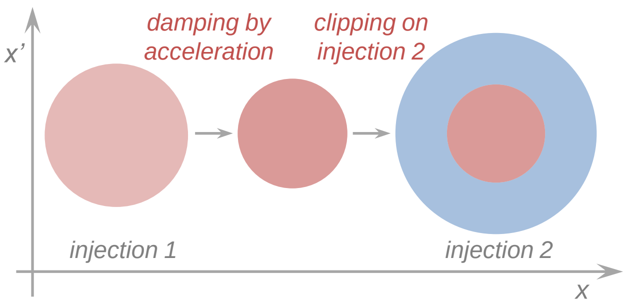
Double MTI





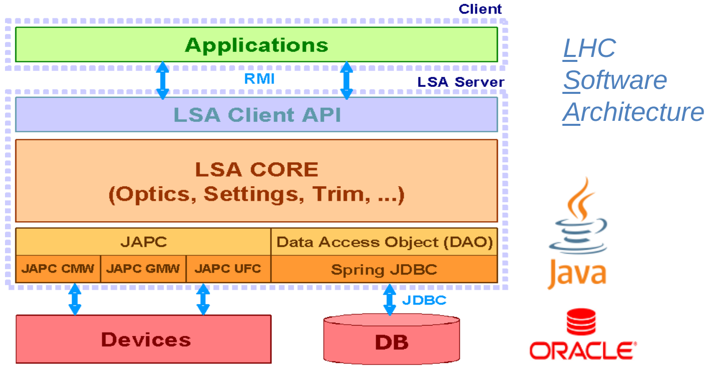


- Multi-turn injection (MTI) from UNILAC
  - Accumulation of beam in hor. phase space
  - Four bumpers affecting dynamic bump
- Two beams nested in phase space
  - **Smaller bump for second injection needed**
- Further optimizations possible
  - Dispersive separation: inner and outer orbit
  - Electron cooling to merge beams in phase space



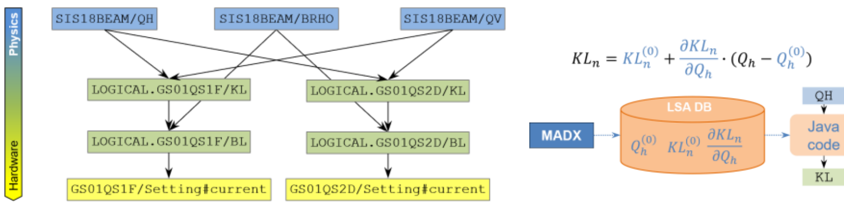
Set Value Calculation

- Set value calculation based on LSA framework
  - Invented by CERN, co-developed by CERN/GSI
  - Object model for description of accelerators
  - Interface for definition of physics algorithms

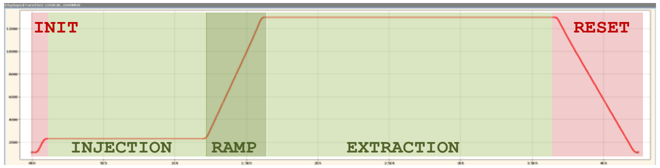


D. Jacquet et al., ICALEPCS2013, THPPC058
H. Hüther et al., PCaPAC2014, WPO005

- Core features
  - Accelerator quantities represented by **parameters**
  - Dependencies expressed in **hierarchy**
    - **Rules** implemented as Java code by physics experts
  - Cycles segmented into **beam processes**

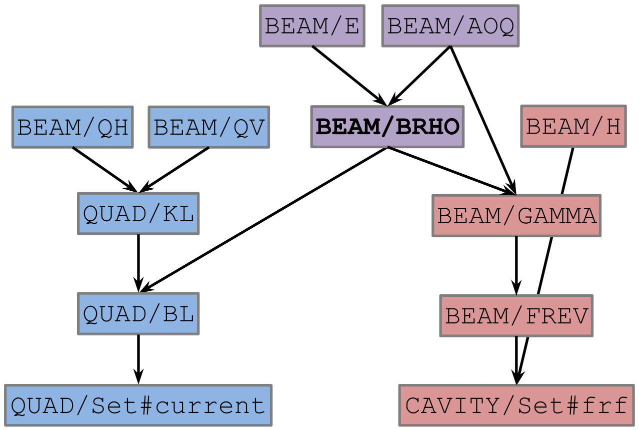


- Powerful **machine model** for GSI/FAIR
  - Designed and maintained by accelerator physicists
  - Generic calculations for all GSI/FAIR accelerators
  - Provides set values and consistent timing
  - Flexible composition of new cycle types



Extension of RF Model

- Generic hierarchy for circular accelerators
  - Central role of magnetic rigidity BRHO
    - Derived from beam and cycle parameters
  - Hierarchy separated into magnet and RF parts
    - Magnets depend on BRHO and tune, chroma, …
    - RF depends on BRHO and bucket size, harmonic, …
  - No interdependencies below BRHO



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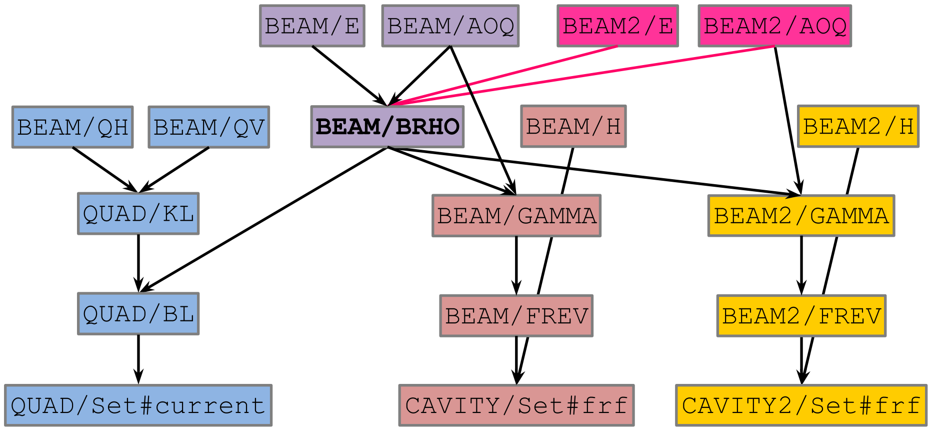
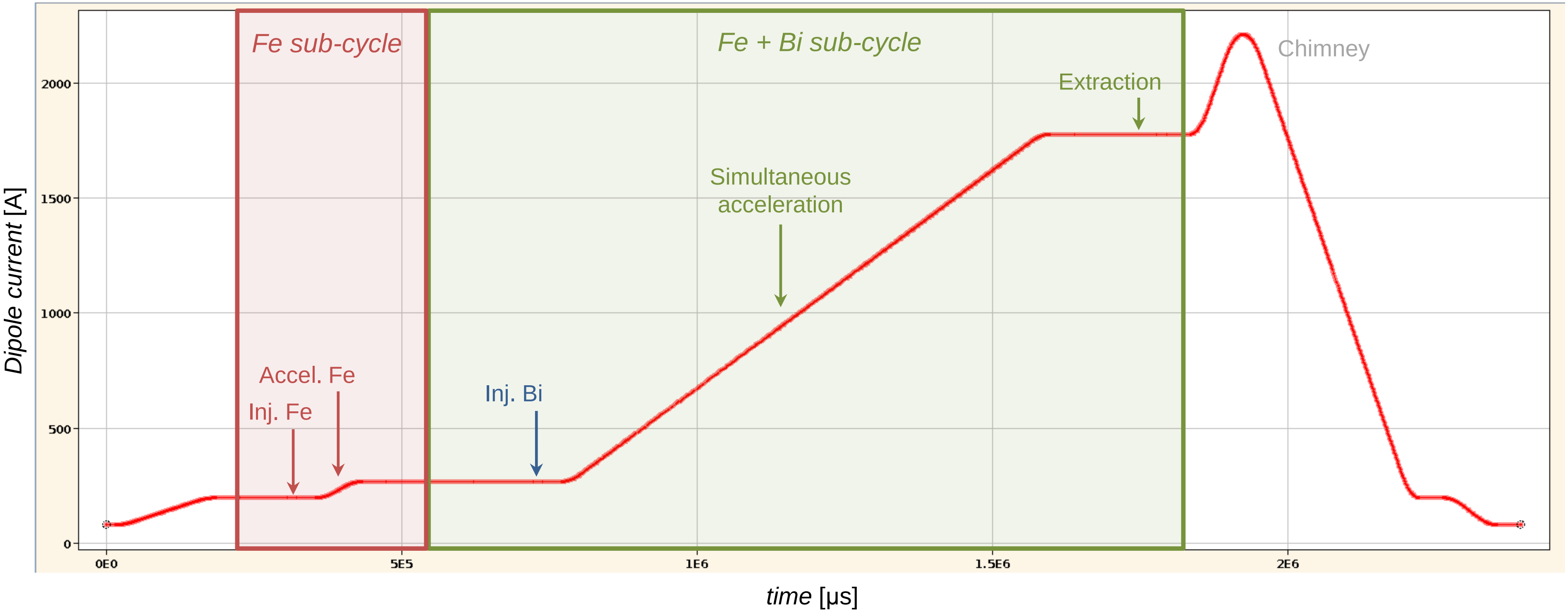


- SIS18: extension for dual isotope beams
  - Add input parameters for second ion
    - Modify BRHO calculation for second injection
    - Use first ion as reference for BRHO
  - Add copy of RF hierarchy for second ion
    - Calculate RF parameters once for each ion
    - Sent cavity set values to selected cavity per ion
- Extension almost transparent
  - Need only switch of RF synchronization manually

Cycle: Structure

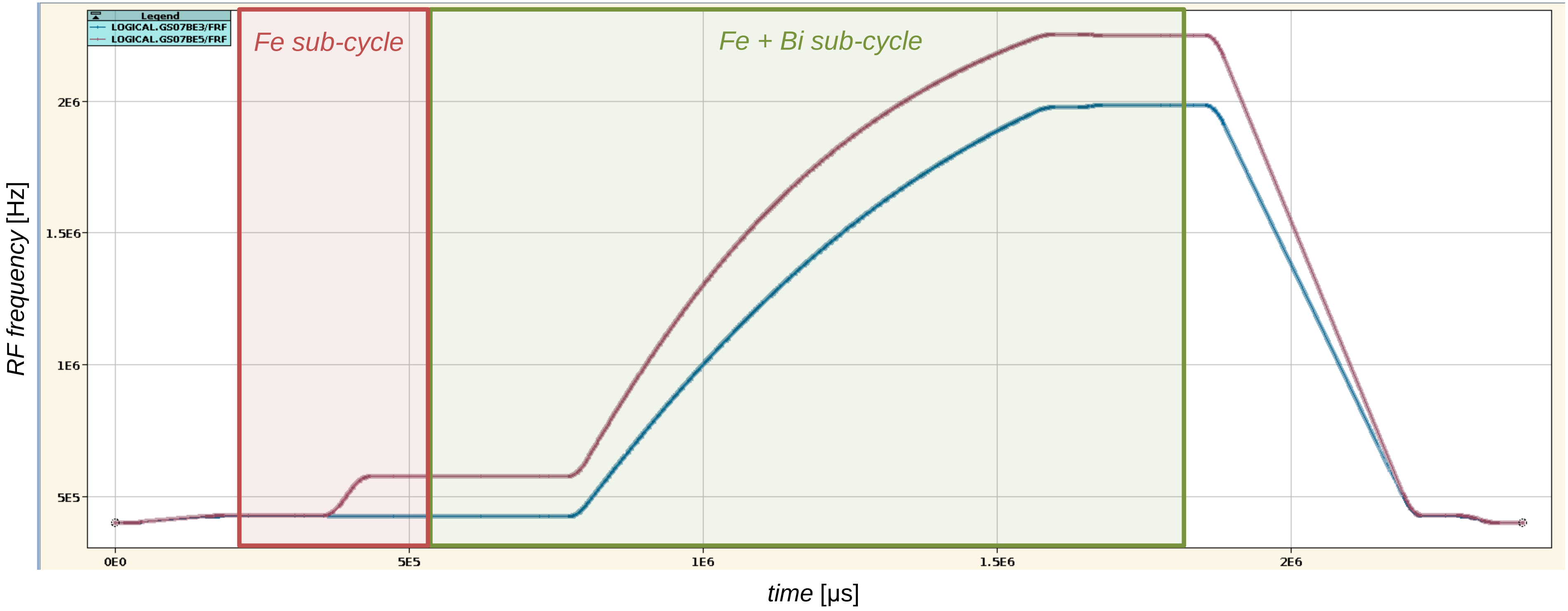
- Technically composed of several sub-cycles
  - Necessary for injections of two ion species
  - Causes artifacts in current measurements

Beam Parameters		
Ion	$^{56}Fe^{25+}$	$^{209}Bi^{68+}$
E (Inj. 1) [Mev/u]	11.36	–
E (Inj. 2) [Mev/u]	20.90	11.14
E (Extr.) [Mev/u]	673.4	400.0



Cycle: RF

- One MA cavity for each ion species, operated at h=2
- Cavity for first ion operated as usual (synchronized with master DDS)
- Cavity for second ion disconnected from master DDS (unsynchronized)

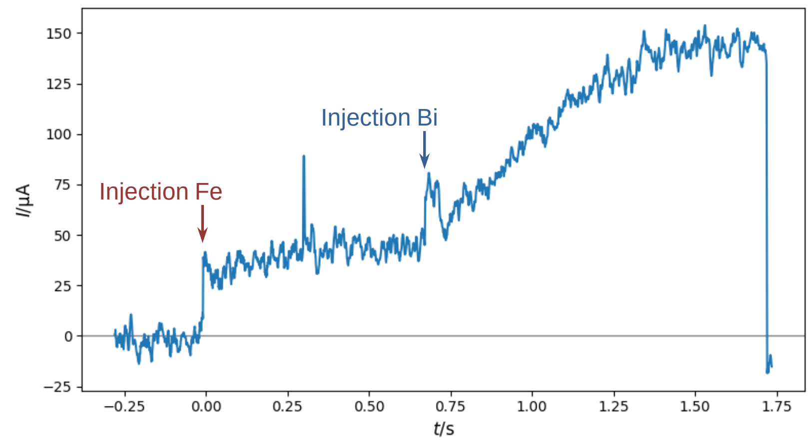


Experiment: Results

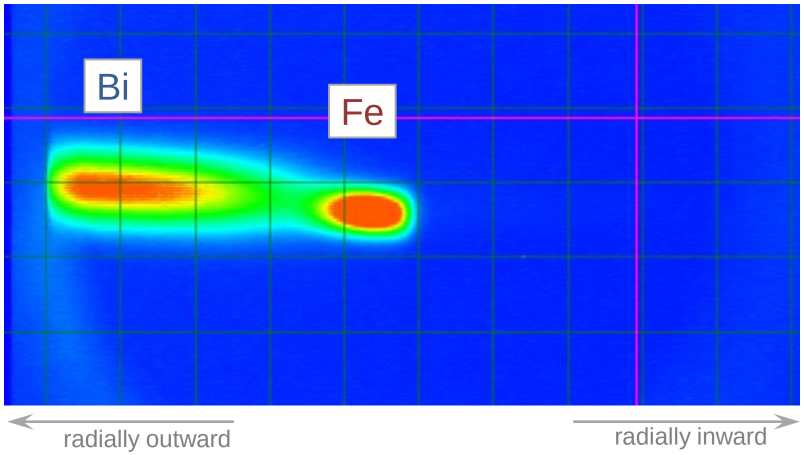
- Simultaneous acceleration successful
  - About 1 – 2·10^7 particles per species
  - Transmission estimated to around 70%

- How to demonstrate there are two beams?
  - Dispersive separation with RF frequency shifts
  - Fe and Bi moved to inner and outer orbit
  - Fast extraction using kicker magnets
  - Observation of beam spots on screen

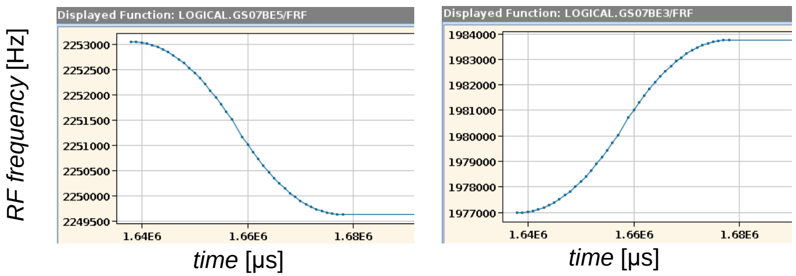
Current on DCT during cycle



Beam spots on screen at magnetic septum



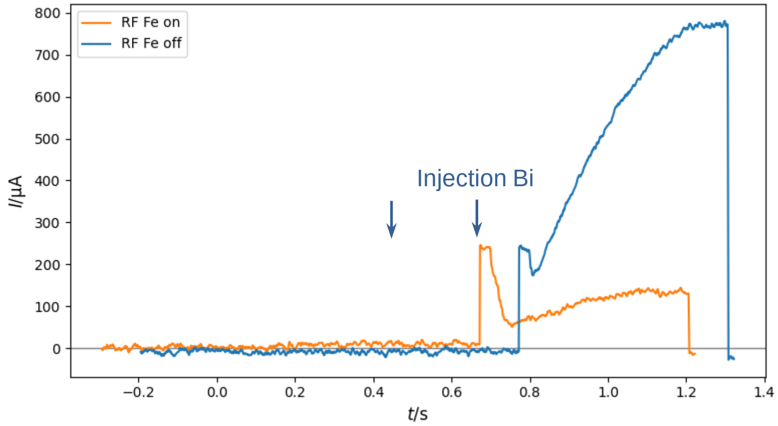
Frequency offsets for Fe (left) and Bi (right)



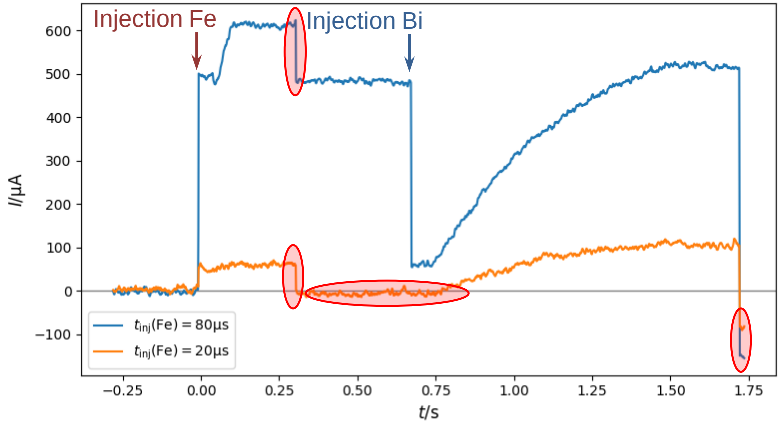
Experiment: Challenges

- Strong influence of second RF observed
  - Initially larges losses
- Mitigation measures
  - Reduced ramping speed
  - Smaller horizontal beam size
    - Short injection pulses (Fe: 20µs, Bi: 5µs)
    - Leads to small intensities
- Performance difficult to quantify
  - Measurements with DCT have artifacts
    - Spurious current drop and zero line offset
    - Caused by sub-cycle structure
  - Need to repeat measurements

Effect of RF for Fe on Bi (no Fe injected)



Artifacts in current measurement

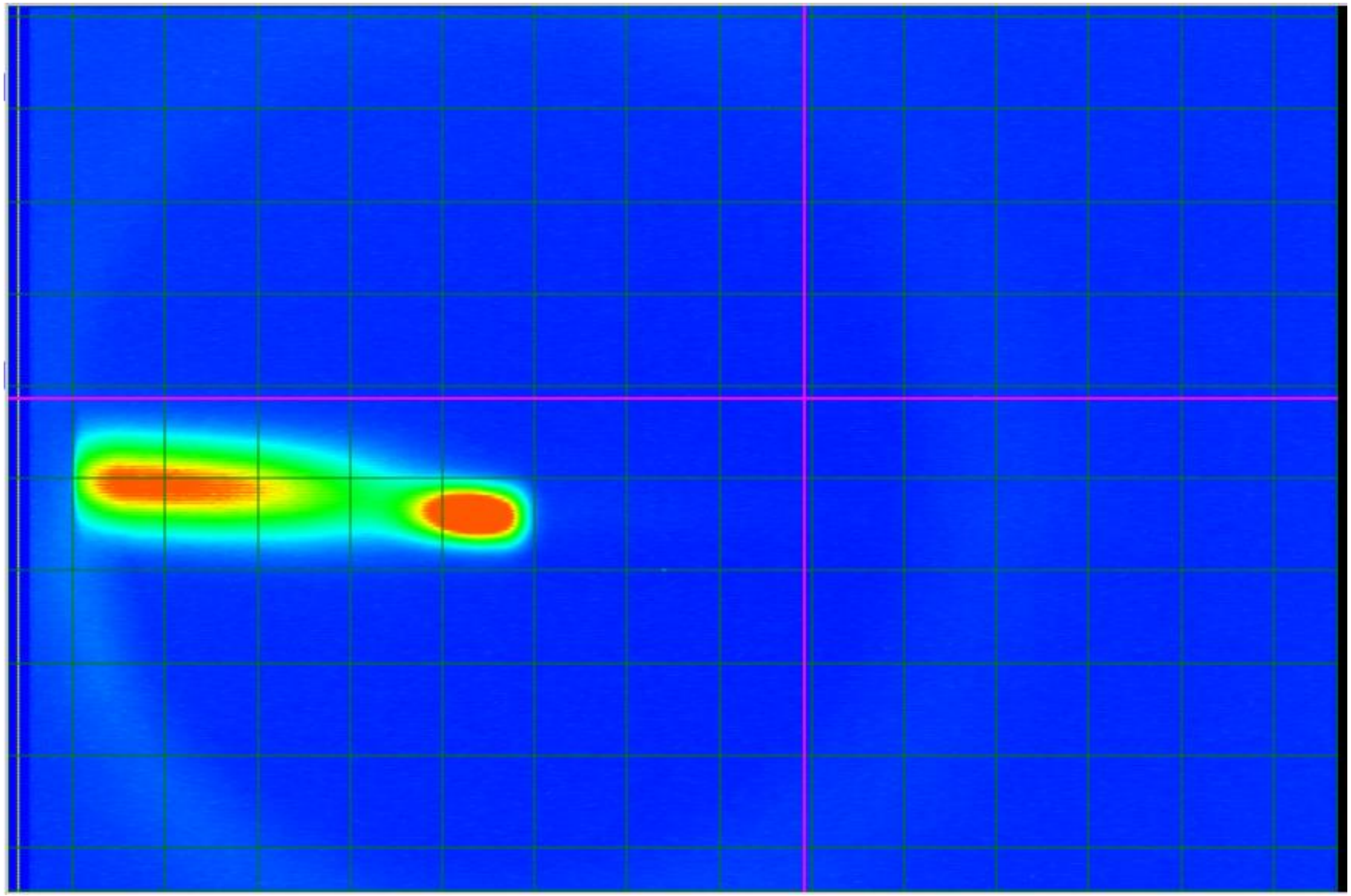


Summary and Outlook

- Simultaneous acceleration of Fe and Bi in SIS18 demonstrated
  - Manageable effort due to flexibility in RF system and machine model
  - Significant influence of ‘foreign’ RF observed
  - Mitigated by decreasing horizontal emittance at expense of intensity

- Next steps
  - Repetition of experiment with improved instrumentation
    - Systematic measurements for clarifying and quantifying loss mechanisms
    - Elimination of DCT artifacts, frequency selective measurements
    - Application of electron cooling to minimize emittance
  - Simulation of process and benchmarking with experiment
    - Influence of ‘foreign’ cavity and loss mechanisms
    - Non-trivial, because standard tools not adapted to this use-case

Thanks for your attention!



Special thanks go to Holger Liebermann, who implemented the RF model extensions, and the ring RF group for their support!