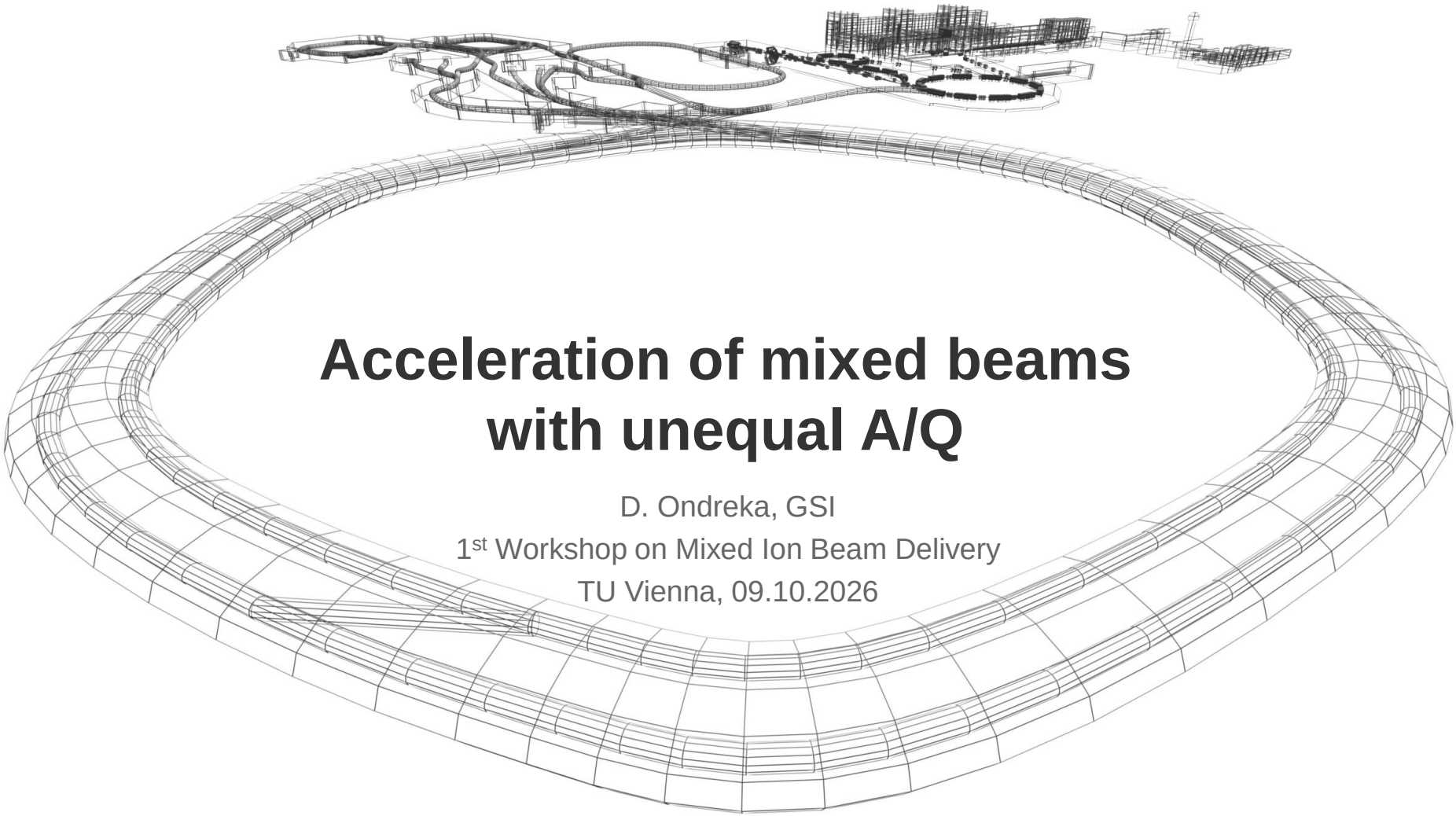


# Acceleration of mixed beams with unequal A/Q

D. Ondreka, GSI

1st Workshop on Mixed Ion Beam Delivery

TU Vienna, 09.10.2026

# Outline

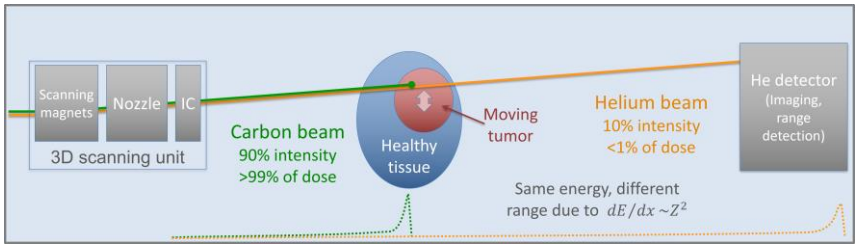
- Motivation
- Overview SIS18 and UNILAC
- Dual-frequency cycle
  - Idea and requirements
  - Implementation
  - Experiment
- Summary and outlook

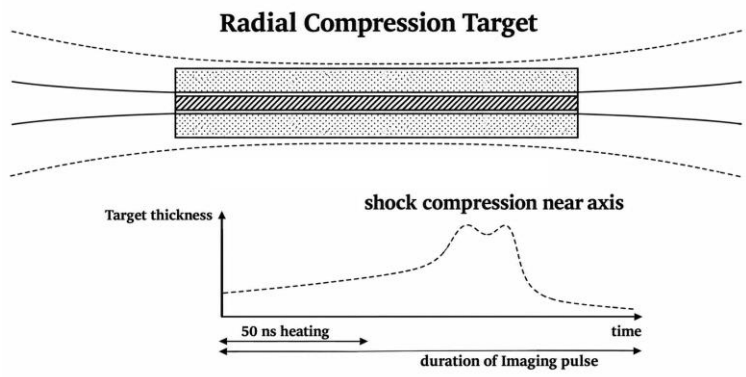
# Motivation

Dual Frequency Acceleration: *"Acceleration and extraction of two ion species with different A/Q in the same synchrotron cycle"*

Why dual frequency acceleration?

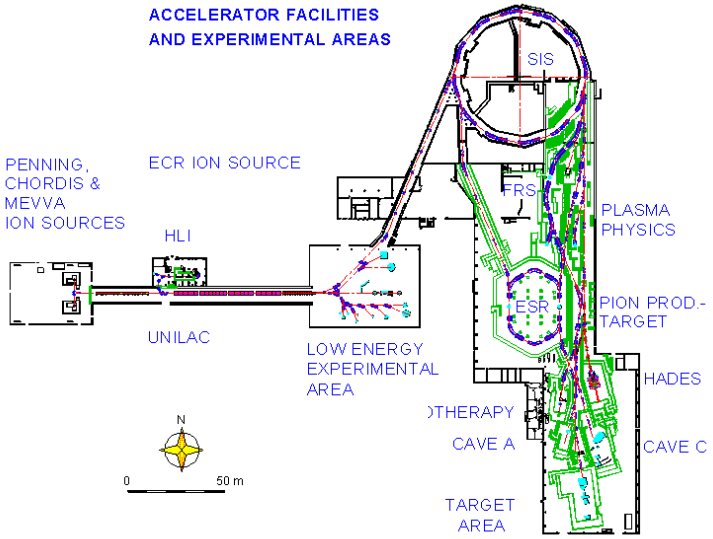
- Mixed beams for range-monitoring in ion therapy
  - Different A/Q allows more ion combinations
  - Applicable even if He used as primary ion (e.g. NIMMS)
- Further possible applications
  - Plasma physics: one ion for heating, one for probing
  - Nuclear physics: 'reference ion' at fragment separator
  - Radiation testing: coincidence experiments
- Interesting accelerator physics challenge

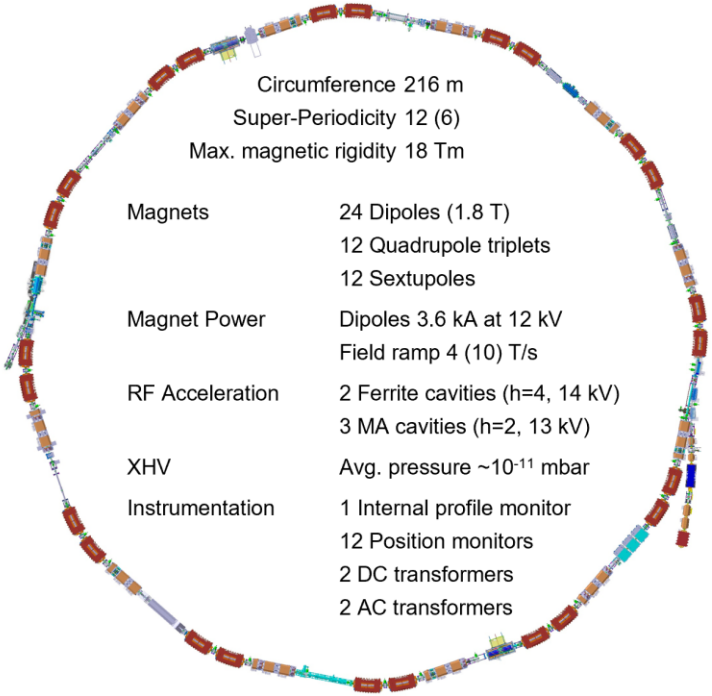



*I. Hofmann, 2000, GSI-2001-4*
*(image processed with ChatGPT)*

# SIS18: Overview



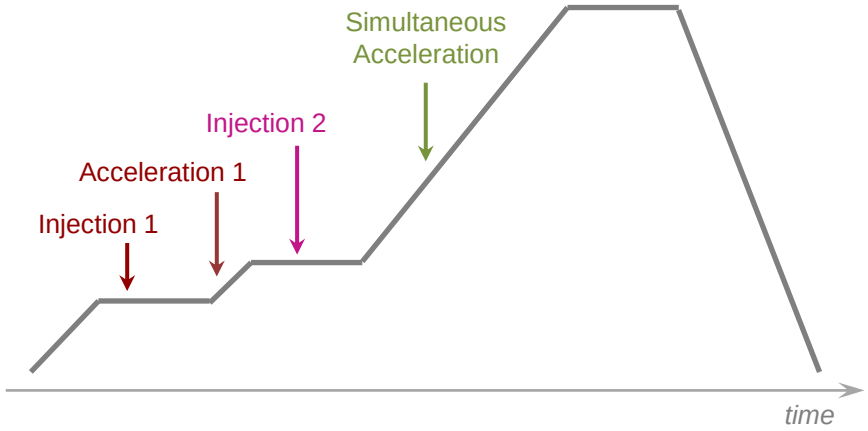




- Synchrotron with NC magnets
- Optics change triplet → doublet during ramp
- Multi-turn injection from UNILAC
  - Up to 3 ion species available at a time
- Flexible RF system with 5 acceleration cavities
  - 3 MA (h=2), 2 Ferrite (h=4)
- Optional electron cooling
- Fast and slow extraction

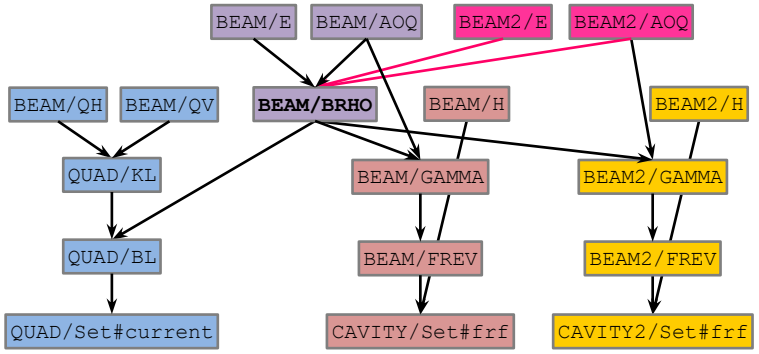
| SIS18 optical parameters | | |
|---|---|---|
| | Injection | Extraction |
| $Q_h$ / $Q_v$ | 4.29 / 3.28 | |
| $Q'_h$ / $Q'_v$ | -4.1 / -5.6 | -6.4 / -4.1 |
| $\alpha_p$ | 0.041 | 0.032 |
| $\gamma_t$ | 4.9 | 5.6 |

# Dual Frequency Cycle: Idea

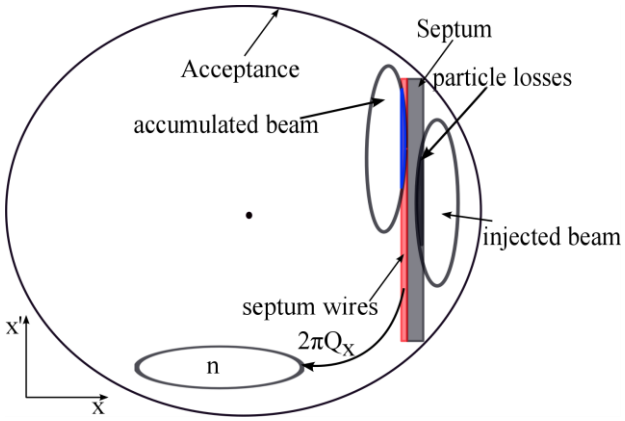
- Different ions can be accelerated in same field
  - Differ only in energy and revolution frequencies
  - Two independent RF programs would in principle suffice
- Basic expectations about mutual influence
  - No net voltage of ‘alien’ RF if harmonics don’t cross
  - Interactions between ions negligible for low intensities
- GSI satisfies all prerequisites
  - UNILAC can provide two ion species at a time
  - SIS18 cavities can run independently without feedback
  - Flexible FAIR control system allowing modifications
- Demonstration experiment in May 2025
  - Available ion species: $^{56}Fe^{25+}$ and $^{209}Bi^{68+}$ ($\chi = 0.73$)

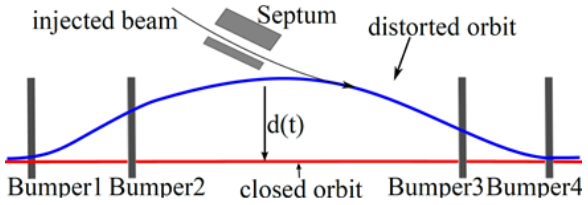


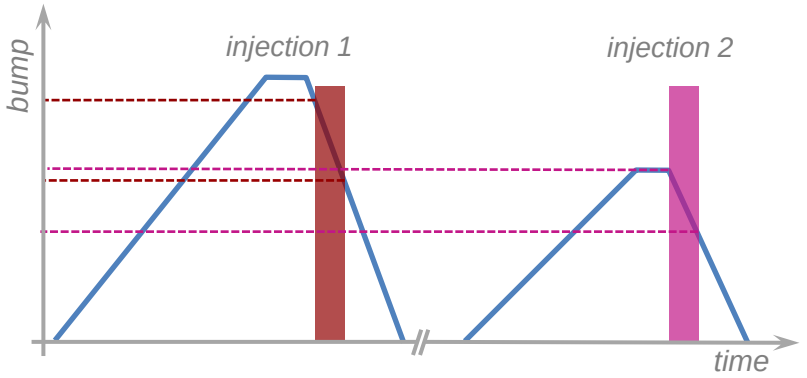

*Extended machine model for dual-frequency acceleration*



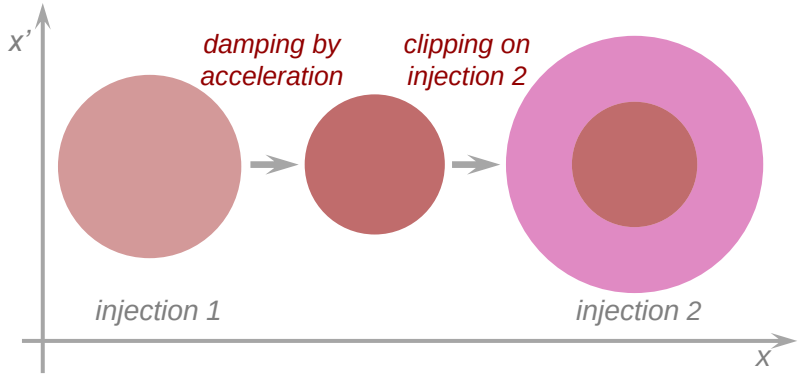
# Sequential MTI




- 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



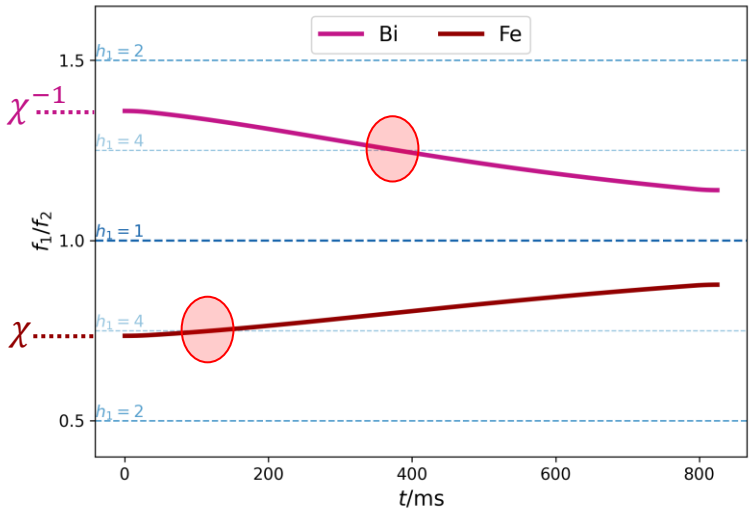
# Dual Frequency Acceleration: Harmonics Constraints

- ‘Alien’ RF must never be RF harmonic

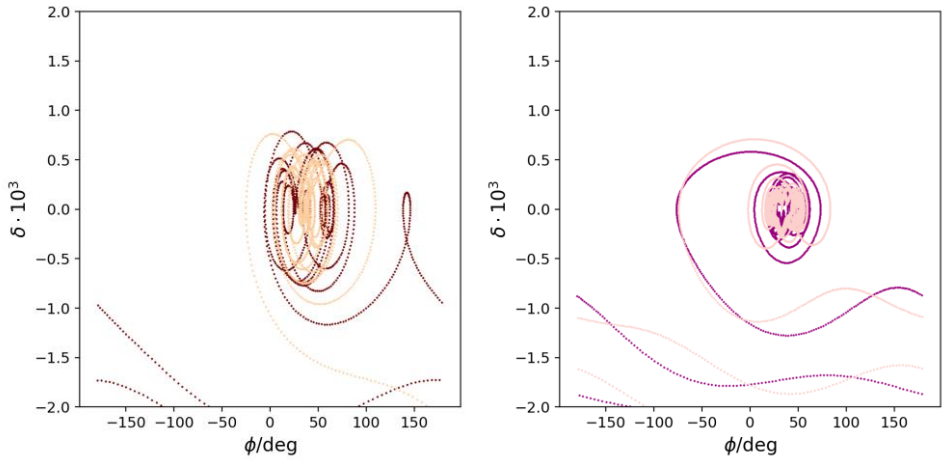
$$\frac{f_1(t)}{f_2(t)} \neq \frac{n}{h_1}$$

- Constraint can be represented graphically
  - Frequency ratio must not cross ‘forbidden lines’
- Strong impact on longitudinal motion if violated
  - High beam loss expected
- Motivated h=2 for demonstration experiment
  - h=4 technically possible, but violates constraint
  - Quantification of effect subject to future studies

*Forbidden lines for Fe/Bi cycle in SIS18*



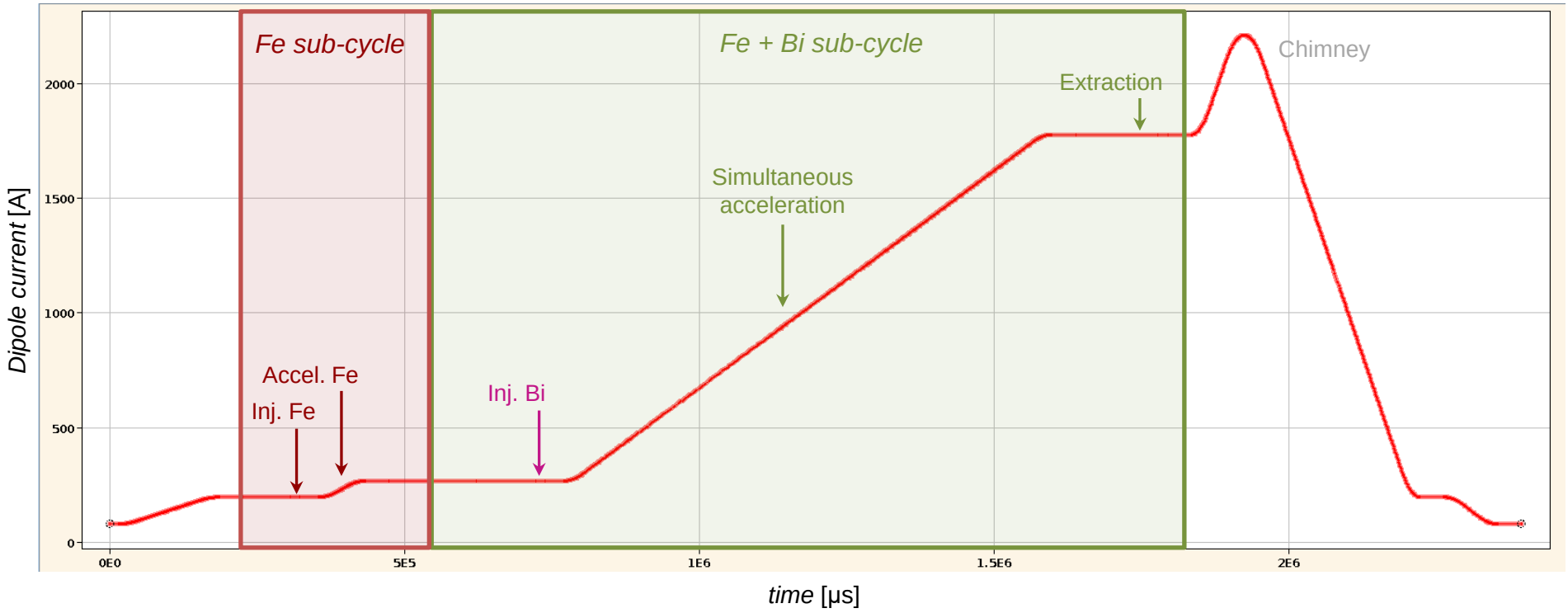

*Influence of ‘alien’ RF at line crossings for h=4 (long. simulation)*



# Cycle: Structure

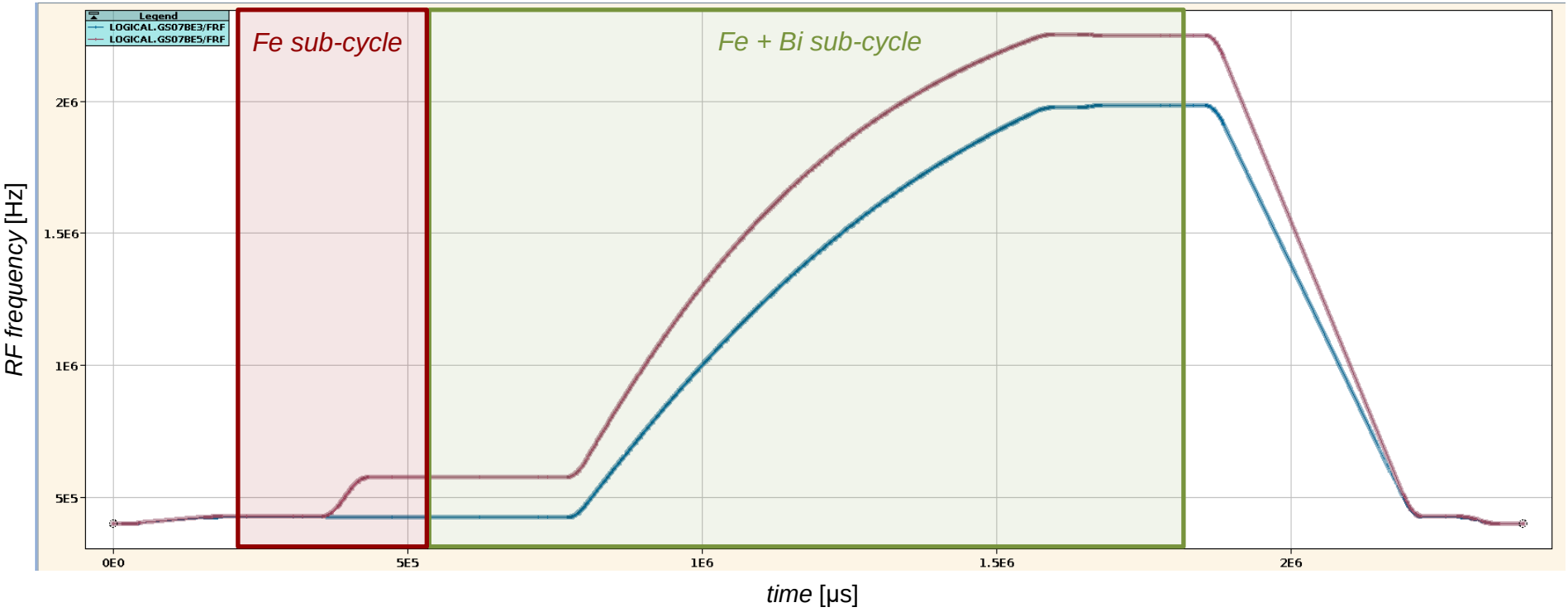
- Technically composed of several sub-cycles
  - Necessary for injections of two ion species

| 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

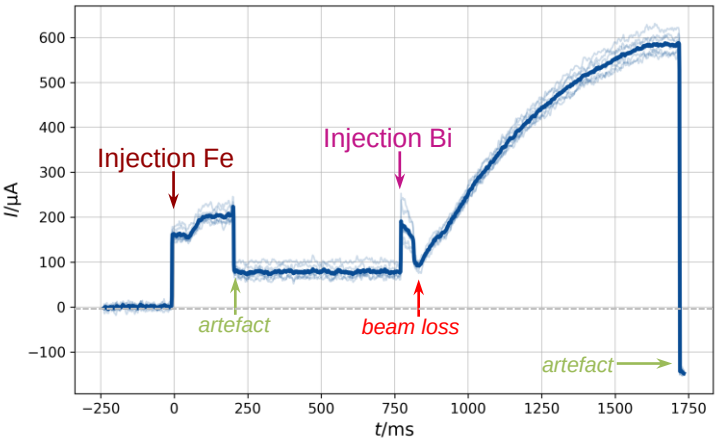
- One MA cavity for each ion species, operated at h=2
- Cavity for first ion operated as usual (synchronized with master DDS)
- Cavity for second ion disconnected from master DDS (unsynchronized)



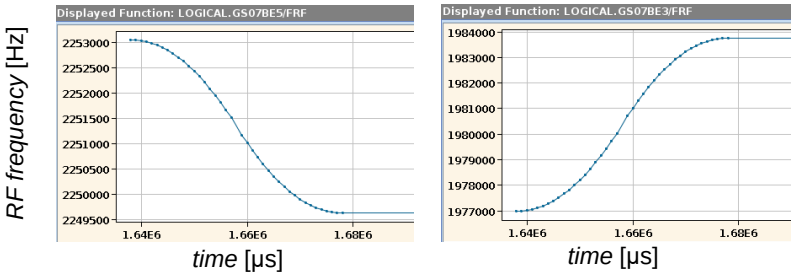
# Experiment: Results

- Simultaneous acceleration successful
  - About $10^8$ Fe and $10^7$ Bi accelerated (determined by offline analysis)
  - High losses for Bi beam with Fe-RF
- Demonstration of two beams
  - Dispersive separation with RF frequency shifts
    - Fe and Bi moved to inner and outer orbit
  - Fast extraction using kicker magnets
  - Observation of two beam spots on screen
- No time for systematic investigations
  - DCT traces and BLM data stored in archiving
  - Record of all parameter changes in database
  - All results based on offline analysis of those data

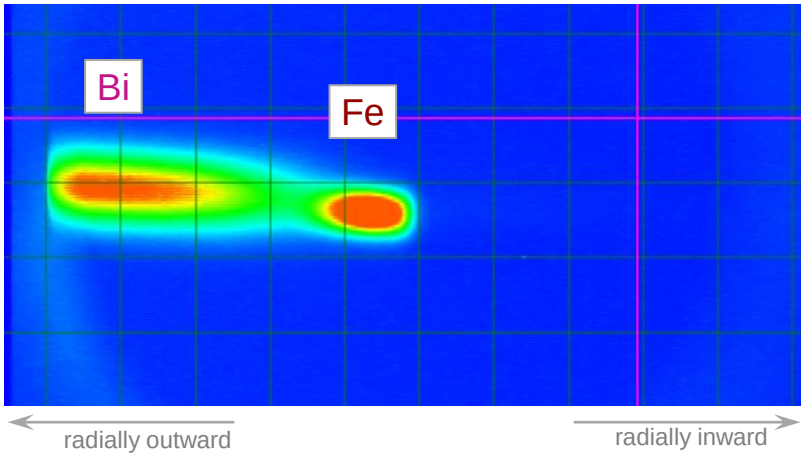
*Current on DCT as seen during experiment*




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




*Beam spots on screen behind magnetic septum*



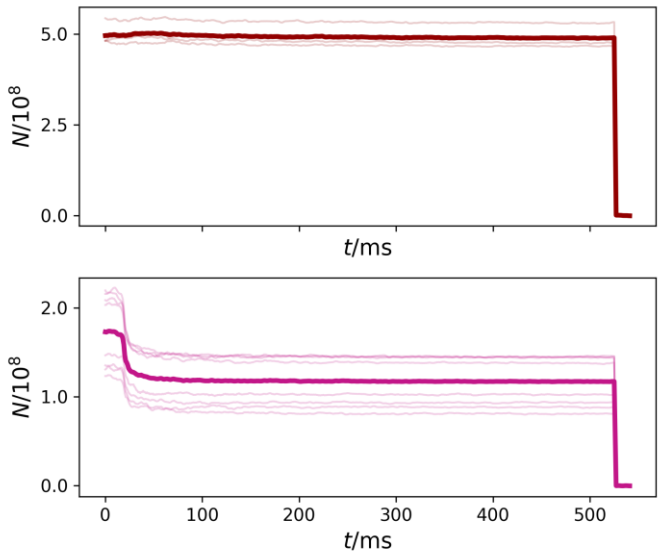
# The Puzzle: Influence of ‘Alien’ RF

- Strong influence of Fe-RF on Bi beam
  - High losses at start of ramp
  - Beam initially lost almost completely
  - Independent of presence of Fe beam
- No visible effect of Bi-RF on Fe beam

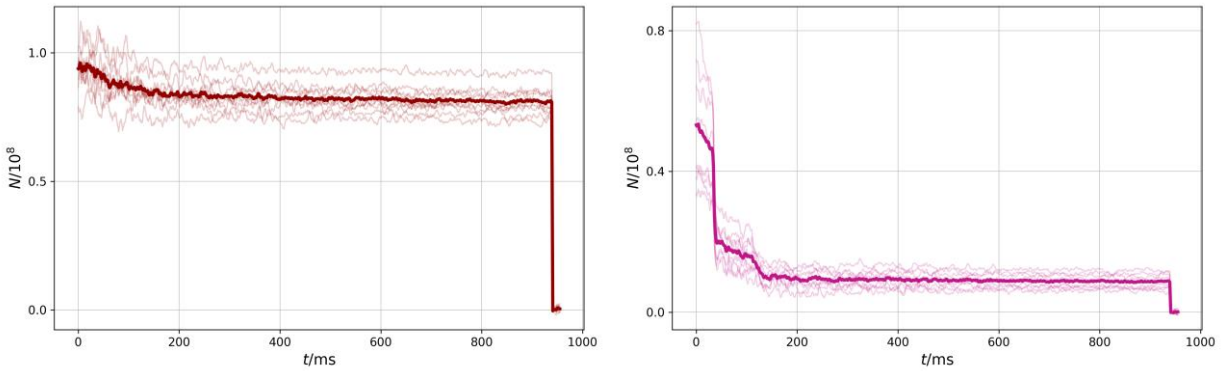
- Mitigation during experiment
  - Reduction of RF voltage (main effect)
    - Reduced ramping speed (2T/s → 1T/s)
    - Reduced bucket area
  - Smaller horizontal beam size
  - Adjustment of horizontal tune

- Obvious questions
  - Why only for Bi beam?
  - Why at start of ramp?

*Intensity trends without ‘alien’ RF*




*Intensity trends with ‘alien’ RF*



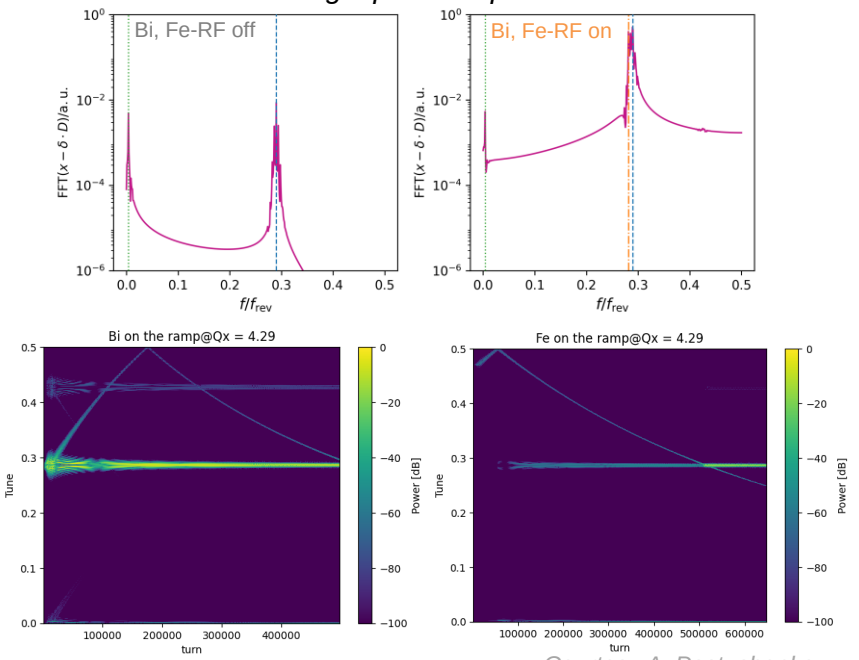
# The Solution: Dispersion at Cavity (1/2)

- Simulations with Xsuite
  - Line set up with energy program for ion 1
  - Acc. cavity: standard configuration (phase zero)
  - ‘Alien’ cavity: phase set to time function $\varphi_2(t)$ defined by integration of frequency $f_2(t)$ of ion 2

- Horizontal spectrum (single particle)
  - Additional line at frequency of ‘alien’ RF
  - Indicates hor. excitation caused by ‘alien’ RF
  - Mediated by non-zero dispersion at cavity
    - ‘Wrong’ orbit after energy change in cavity
    - Leads to change in betatron oscillation amplitude

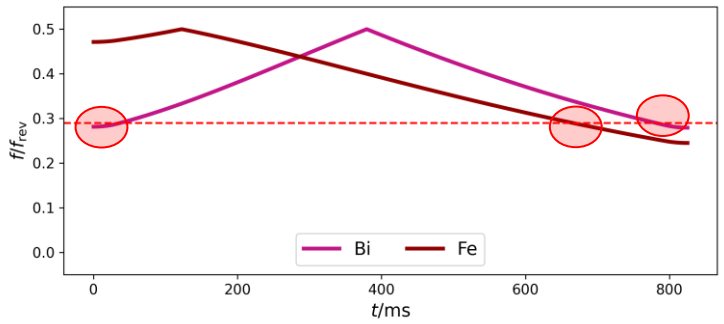
- Resonance condition $\frac{f_a}{f_{\mathrm{rev}}} = N \pm q_x$
  - Strong excitation at betatron side band
  - Provokes horizontal emittance blow-up
  - Losses due to large size of Bi beam at cycle start

*Single particle spectra*



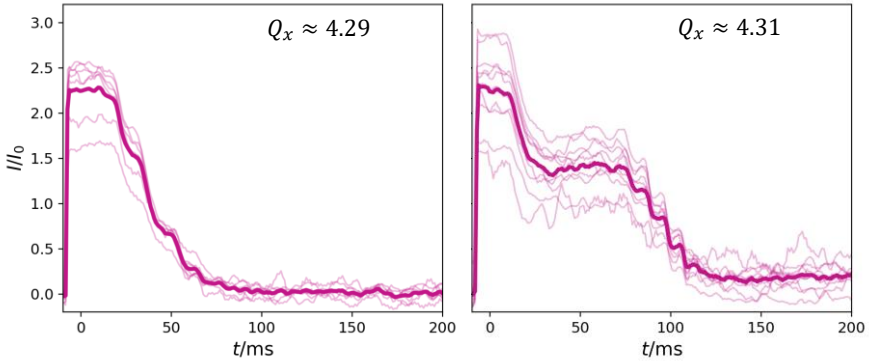

Courtesy A. Pastushenko

*Resonance crossings for Bi and Fe during ramp*

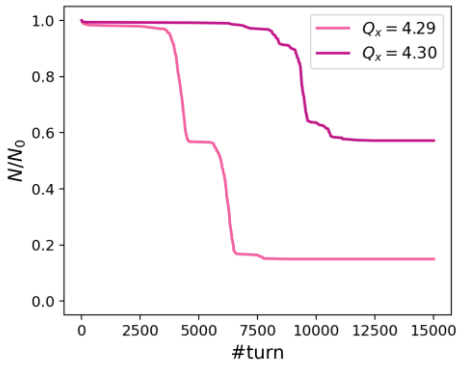


# The Solution: Dispersion at Cavity (2/2)

*Tune dependence of losses in experiment …*

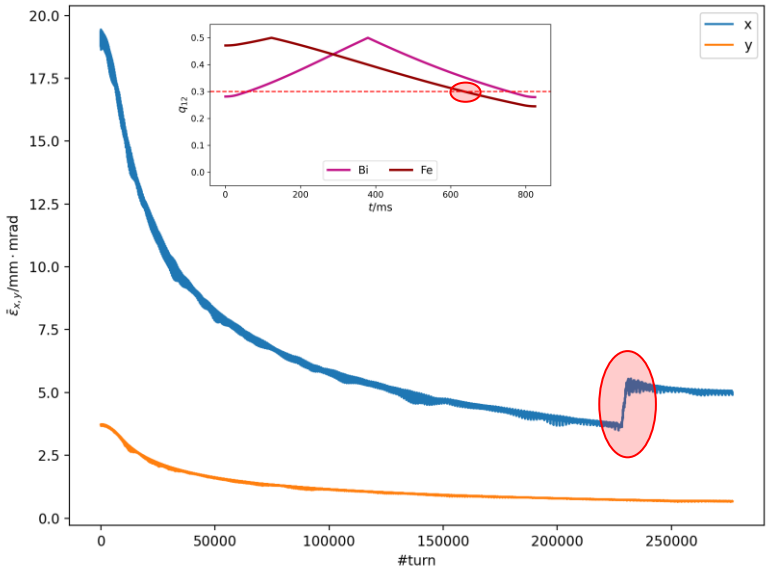



*… and simulation*




- Tune dependence qualitatively understood
  - Losses shift to later times with increasing $Q_x$
- Absence of losses for Fe understood
  - Excitation by Bi-RF crosses tune later in ramp
  - Emittance blow-up seen in simulations
  - Adiabatic damping prevents beam loss
- Systematic studies planned for quantitative evaluation
  - Potential to minimize and measure dispersion at cavity

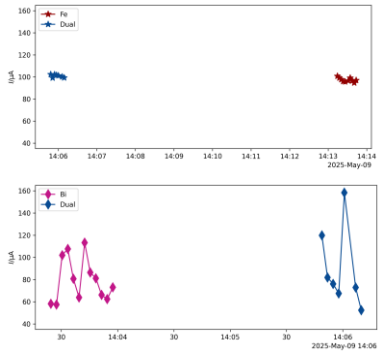
*Hor. emittance blow-up in Fe beam (simulation)*



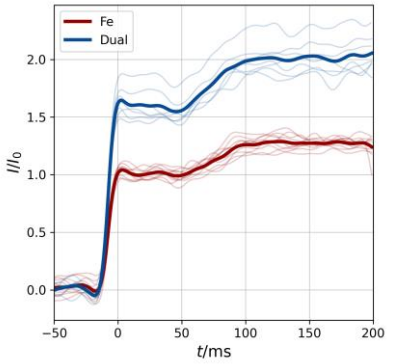
# Beam-beam effects (1/2)

- Goal: search for effects caused by presence of other beam
- Challenging due to unstable beam conditions
  - Bi intensity strongly fluctuating
  - Fe intensity changed despite identical settings
- Strategy
  - Identify reference data sets for single beams with identical settings as for dual beam
  - Try to reconstruct dual beam current by adding scaled contributions from single beams
  - Compare to currents rescaled under assumption of no losses after initial current drops
- Results
  - No scientifically hard statement possible
  - Currents seem to indicate little extra losses
  - Further information from beam loss signals

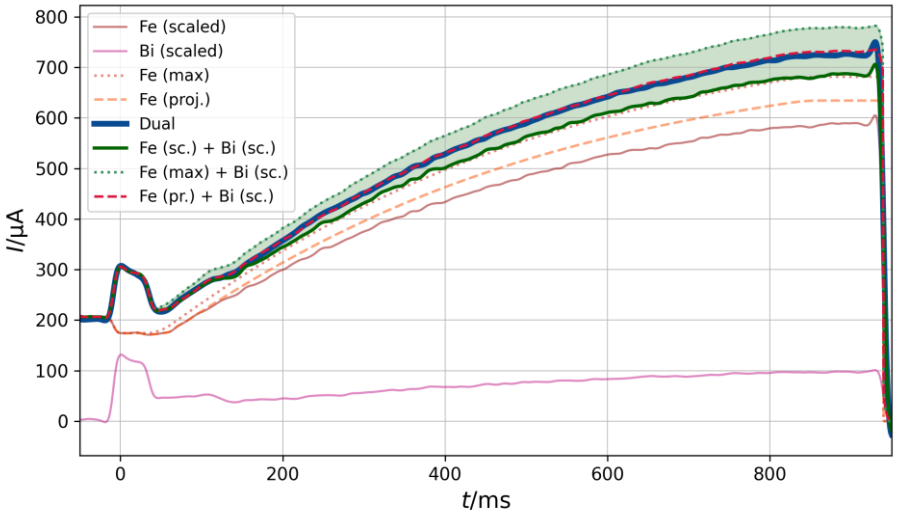
*Stability of injected current*



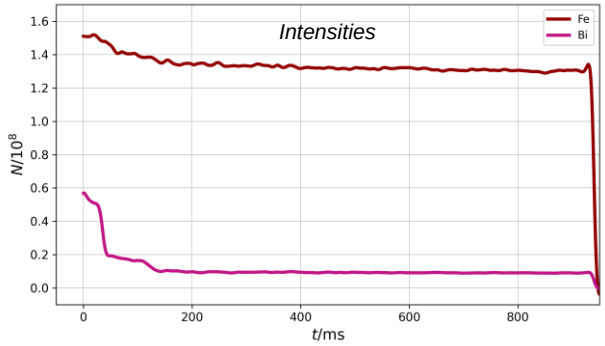

*Fe current in first sub-cycle (settings unchanged)*

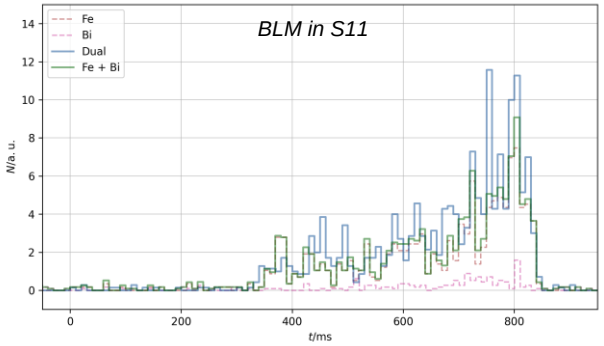


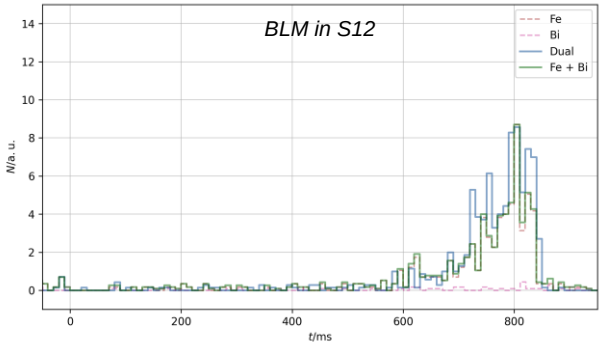

*Current reconstruction in second subcycle*

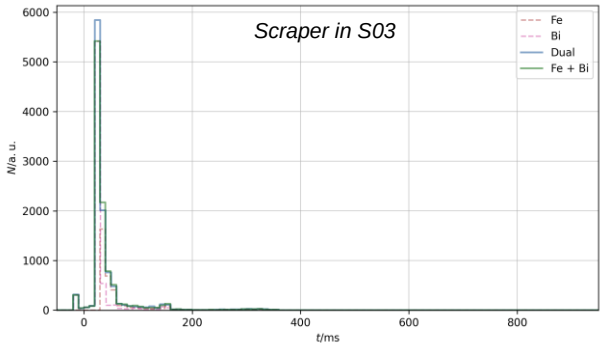


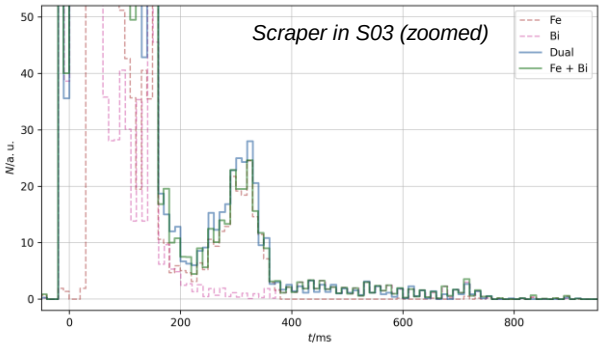
# Beam-beam effects (2/2)

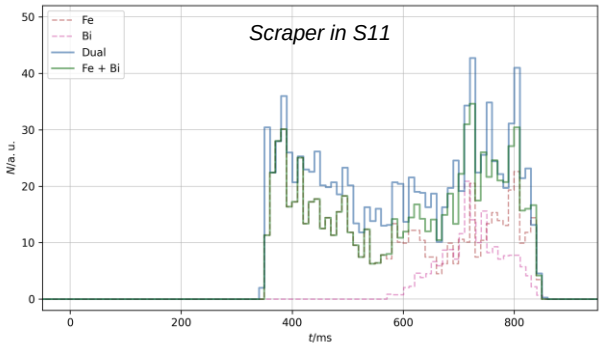


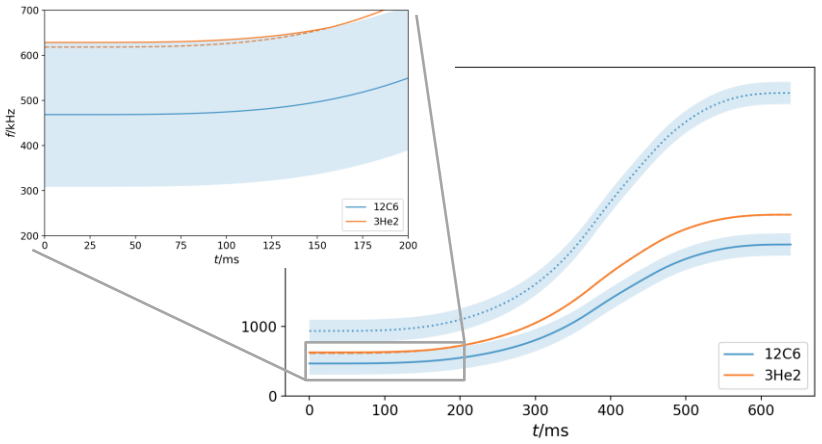

- Beam loss signals for dual beam compared to signals for single beam scaled to reconstructed intensities
  - No significant excess beam loss for dual beam visible
  - Data quality insufficient to judge properly
  - Further systematic investigations necessary to study intensity effects

# Activities at MedAustron

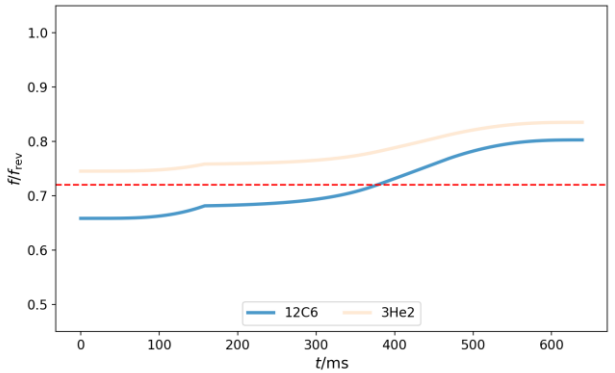
*Elisabeth Renner, Markus Wolf, Katrin Holzfeind, Matthias Kausel*

- Developments for multiple frequencies
  - Intention: addition of higher harmonics
  - Single broad-band cavity (bandwidth <≈ 10 MHz)
    - Compatible with application of multiple frequencies
    - Installed in location with zero dispersion
  - New LLRF based on muTCA-crate
    - Will enable application of multiple frequencies
    - Presently separation of 160 kHz for regulation
- Idea: study influence of ‘alien’ RF at MA
  - Use new LLRF system in feed-forward mode
  - Tune crossing with zero dispersion at cavity
  - Emittance growth as function of dispersion
  - Long-term perspective: mixing C with p or $^{3}$He
- Preparatory test with new LLRF successful
  - Feed-forward acceleration and voltage regulation
  - Brief test adding ‘alien’ RF to verify feasibility
  - No beam loss or significant emittance growth seen
- Promising starting point for further studies

*RF frequency ramps for carbon and ‘alien’ ion ($^{3}He^{2+}$)*



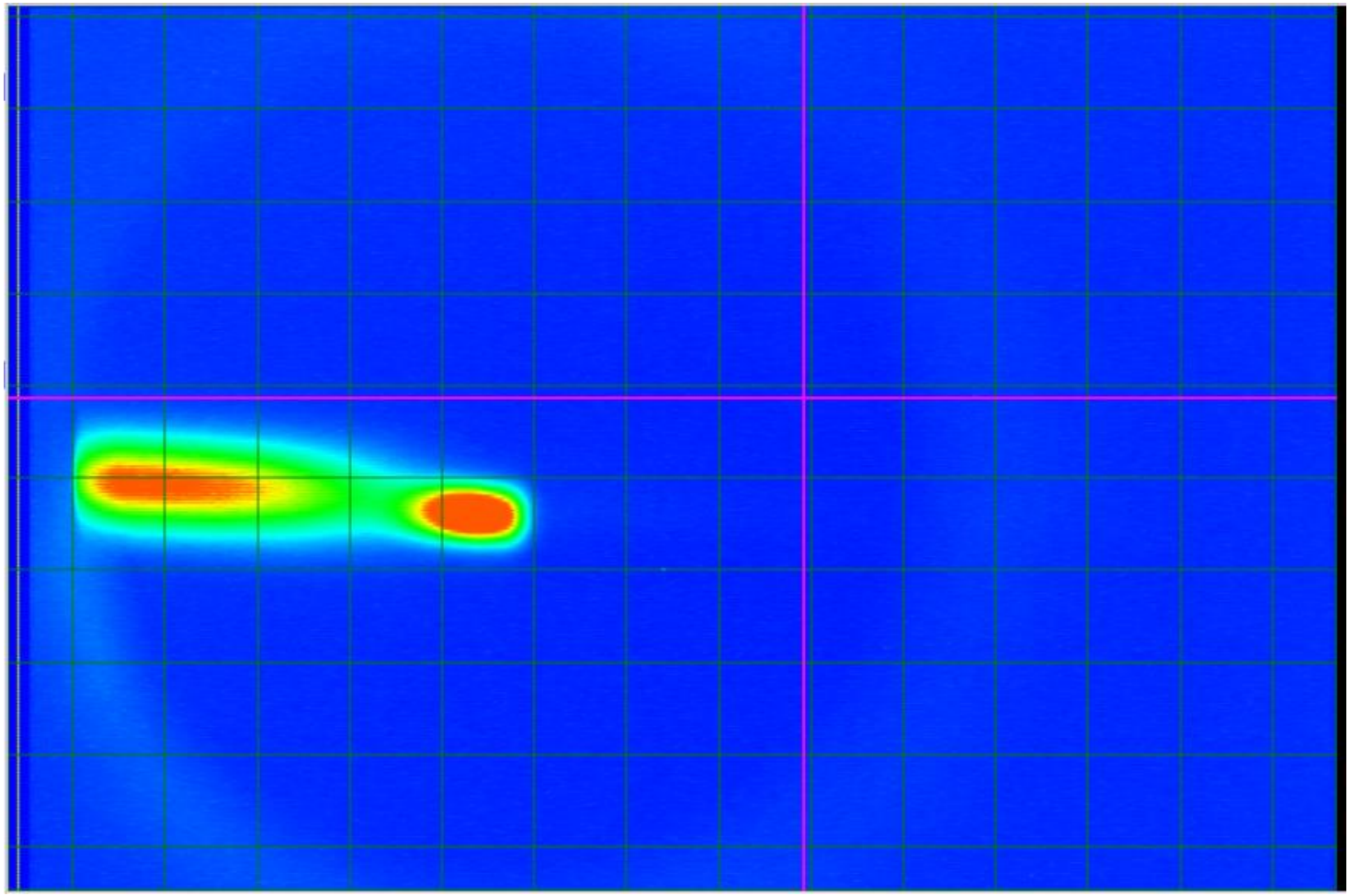

*Hor. excitation by ‘alien’ RF*



# Summary and Outlook

- Dual-frequency acceleration as novel scheme for creating mixed beams
  - Attractive due to larger range of possible combinations of ions
  - Technically requires only two independent RF programs
  - Expected to work for low intensities provided harmonics constraints satisfied
- Successful demonstration with Fe and Bi in SIS18
  - Unexpected high losses observed in Bi beam caused by ‘alien’ RF
- Campaign to reproduce and explain observations
  - Loss mechanism for Bi identified in Xsuite simulations including effect of ‘alien’ RF
  - Excitation of horizontal oscillations mediated by non-zero dispersion at cavity
  - Overlap of excitation frequency with tune causes strong emittance blow-up
  - Effect should be absent in machines with zero dispersion at cavity
- Follow-up studies required to fully exploit potential
  - Quantitative understanding of influence of dispersion at cavity
  - Investigation of beam-beam effects for higher intensities

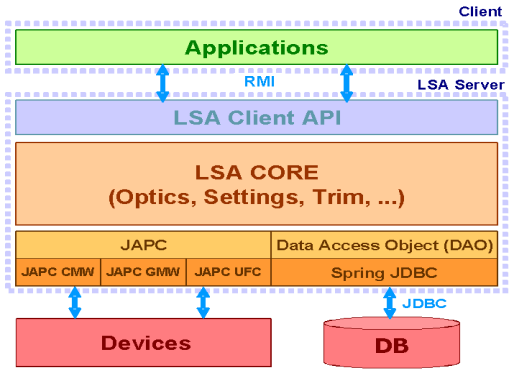
# Thanks for your attention!



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

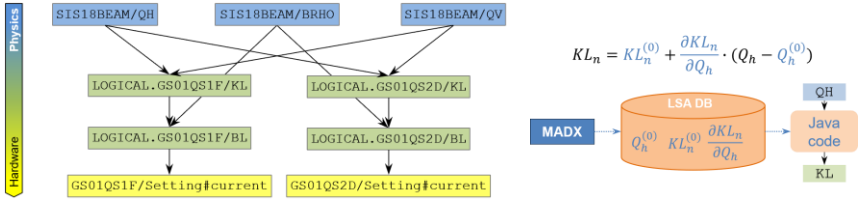
# Set Value Calculation

- 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

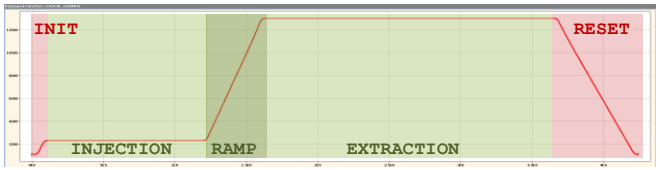



D. Jacquet et al., ICALEPCS2013, THPPC058
H. Hüther et al., PCaPAC2014, WPO005

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

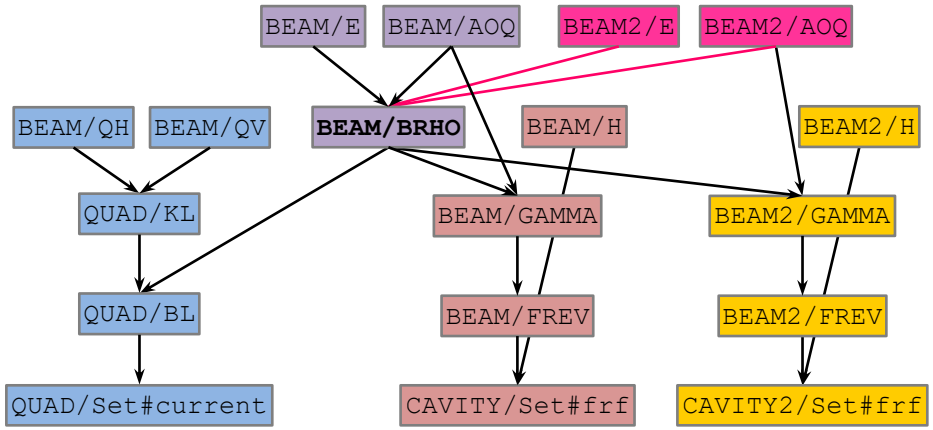



- Powerful **machine model** for GSI/FAIR
  - Designed and maintained by accelerator physicists
  - Generic calculations for all GSI/FAIR accelerators
  - Provides set values and consistent timing
  - Flexible composition of new cycle types



# 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




- SIS18: extension for dual freq. acceleration
  - 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

# Harmonics Constraints

- Constraint equation

$$\frac{f_1(t)}{f_2(t)} \neq \frac{n}{h_1}$$

- Relation between momenta (same rigidity)

$$\beta_2\gamma_2 = \chi \cdot \beta_1\gamma_1$$

$$\chi = \frac{Q_2/M_2}{Q_1/M_1}$$

- Revolution frequency ratio

$$\frac{f_1}{f_2} = \sqrt{\frac{\chi^{-2} + (\beta_1\gamma_1)^2}{1 + (\beta_1\gamma_1)^2}}$$

- Limits

non-relativistic: $\frac{f_1}{f_2} \to \chi^{-1}$

ultra-relativistic: $\frac{f_1}{f_2} \to 1$

*Forbidden lines for Fe/Bi cycle in SIS18*

