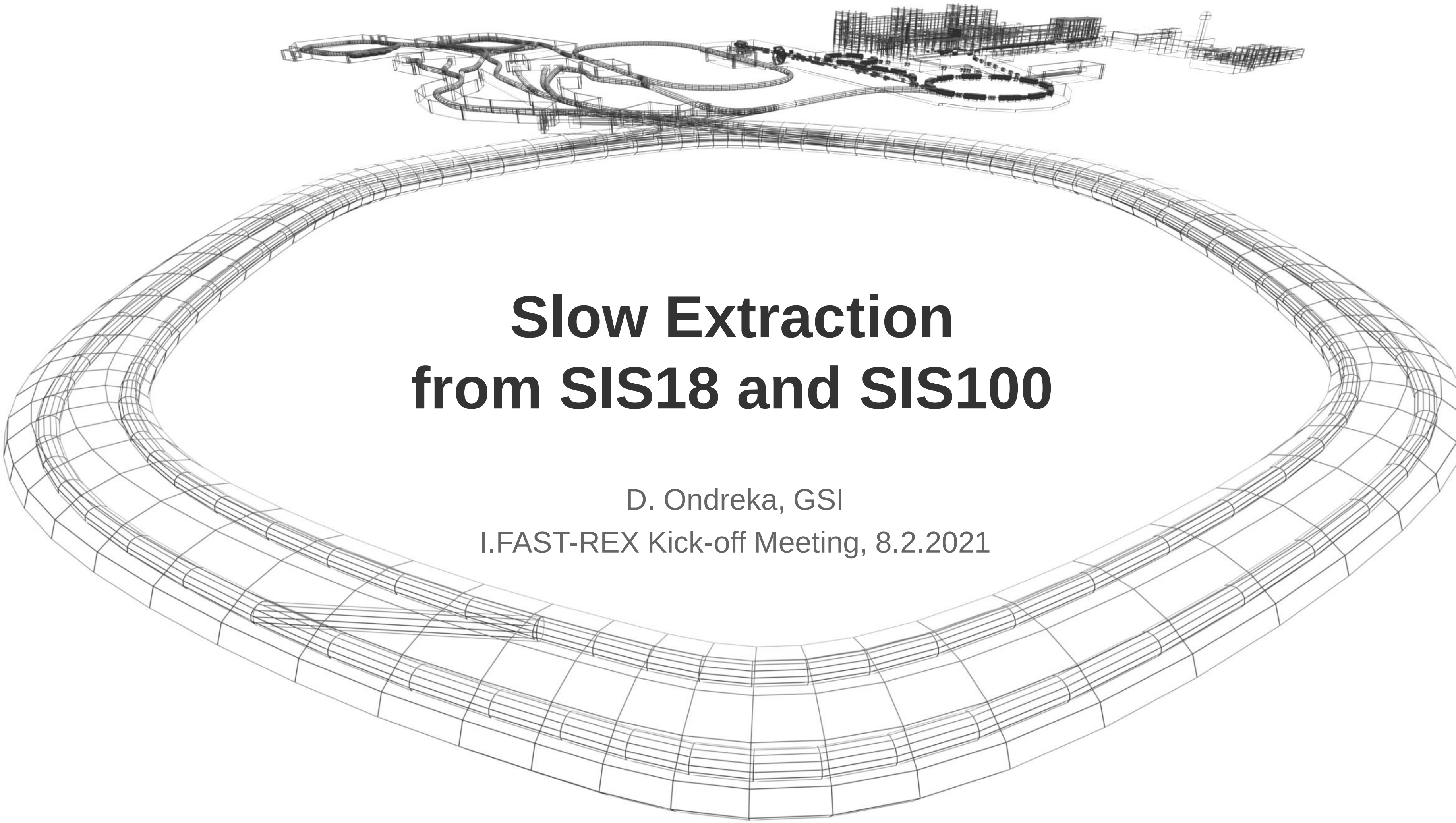


Slow Extraction from SIS18 and SIS100

D. Ondreka, GSI

I.FAST-REX Kick-off Meeting, 8.2.2021

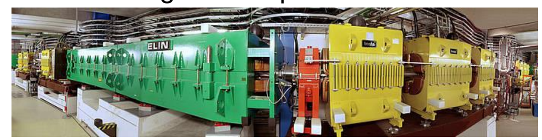
Contents

- Overview of FAIR
- Slow Extraction from SIS18
- Slow Extraction from SIS100
- Developments for FAIR
- Summary

Experiments Requiring
Slow Extraction at GSI and FAIR

- Experiments from a wide range of fields
  - Nuclear and astro-physics
  - Atomic physics and material sciences
  - Hadron physics and strong interactions
- Fixed target experiments
  - Irradiation of targets with slow extracted beams
  - Primary beams from protons to Uranium
  - Typically rate limited by detection systems
  - Typically extraction times of a few seconds
- Secondary beam production
  - Standard for FRS and Super-FRS
  - Also applied for HADES
  - Requires **highest intensities** of primary beams
  - Motivation for low charge state operation at FAIR
- High intensity slow extraction
  - Experiments at GSI profit from SIS18 upgrade
  - Major challenge for SE from SIS100 for FAIR

Fragment Separator FRS



HADES Detector

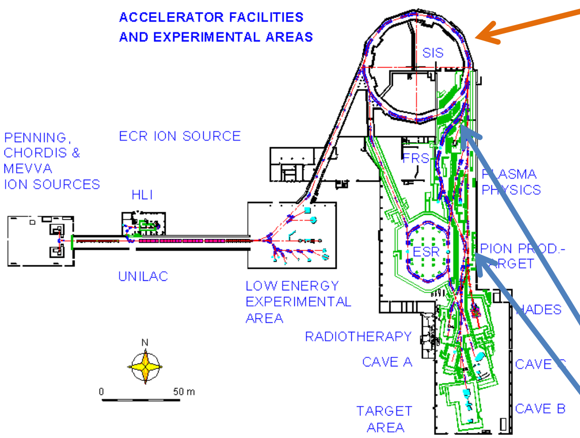
Raster Scanning Installation

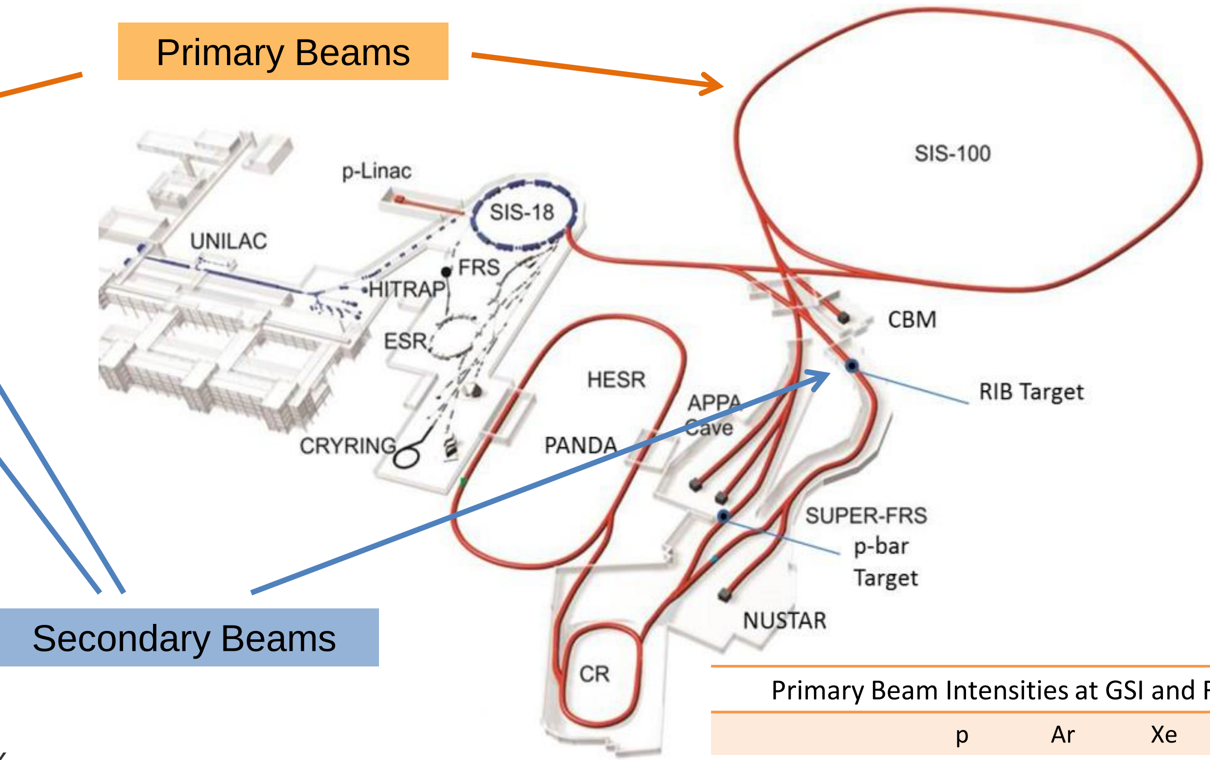
CBM HADES

sparc BIOMAT

GSI and FAIR: Overview

FAIR is GSI’s big brother: overall topology and operation principles are identical





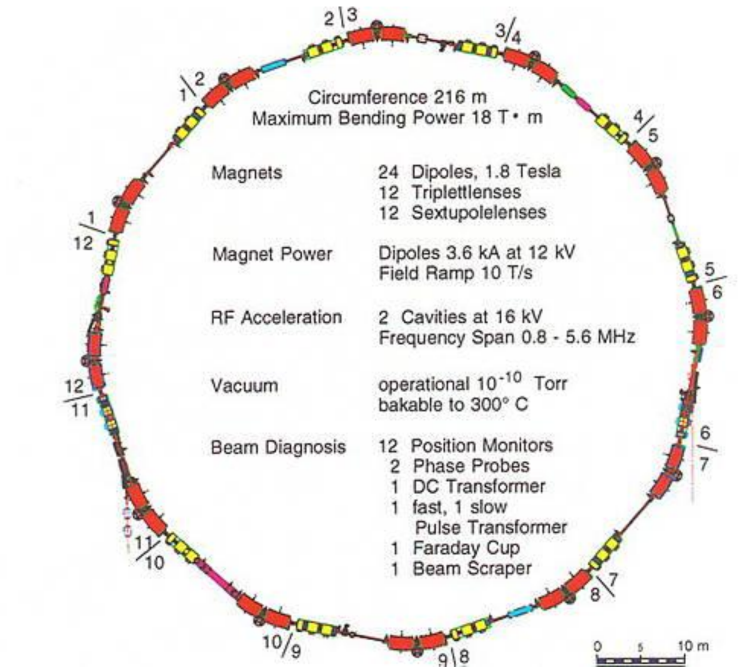
- Breaking the limits of GSI:
  - Primary beam intensities: 100x
  - Secondary beam intensities: 10000x
  - Primary beam energies: 10x
  - Many experiments requiring slow extraction

Primary Beam Intensities at GSI and FAIR

		p	Ar	Xe	U
Charge number	GSI	1	18	48	73
	FAIR	1	10	21	28
Energy [GeV/u]	GSI	4.7	1.7	1.3	1.0
	FAIR	28.8	6.6	4.0	2.7
Intensity [Ions/s]	GSI	10^{11}	$8\cdot10^{10}$	$2\cdot10^{10}$	$4\cdot10^{9}$
	FAIR	10^{13}	10^{12}	$5\cdot10^{11}$	$3\cdot10^{11}$

SIS18: Overview

- Basic parameters
  - Circumference 216m
  - Max. magnetic rigidity 18Tm
  - Max. ramp rate 4T/s (10T/s)
- Ion optical layout
  - Super-periodicity 12 (6)
  - Triplet focusing at injection
  - Doublet focusing at extraction
  - Transition during ramp
- Working modes
  - Multi-turn injection (painting)
  - Slow extraction to fixed targets
  - Fast extraction to targets and storage ring ESR
  - Optional electron cooling at injection

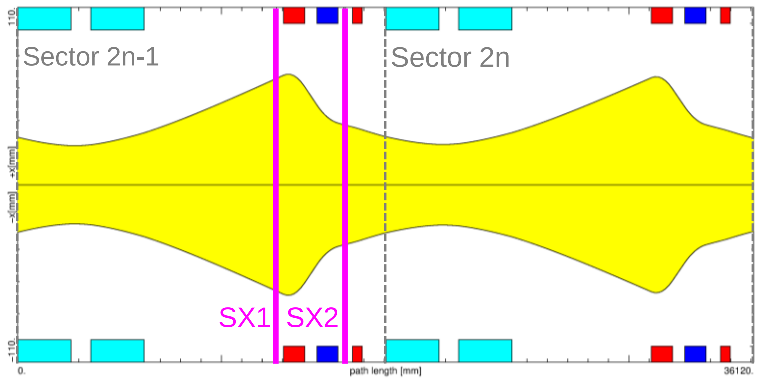


SIS18 optical parameters	
Q_h / Q_v	4.29 / 3.28
Q'_h / Q'_v	-6.4 / -4.1
α_p (inj. / ext.)	0.042 / 0.032
γ_t (inj. / ext.)	4.9 / 5.6

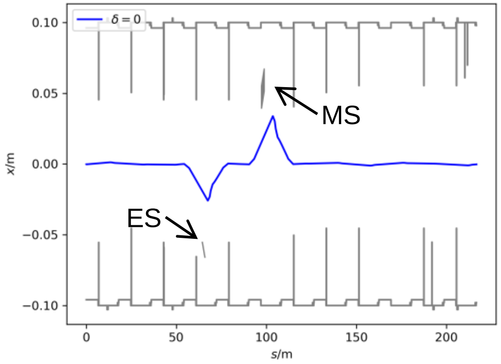
SIS18: Slow Extraction Layout

- Third order resonant extraction
  - Resonance tune Q_r = 13/3
  - Natural hor. chromaticity Q' = -6
  - Two orbit bumps at ES and MS
  - Excitation by six sextupoles with harmonic distribution (ΔQ'=0)
  - Six additional chromaticity sextupoles
- Devices for slow extraction
  - Electrostatic wire septum (ES)
    - 1.5m long, 100µm W/Rh wires
    - max. 160kV @ 18mm gap
  - Magnetic septum (MS)
  - 2 fast quads for quad driven extr.
  - Hor. exciter for RF KO extr.
- Standard slow extraction modes
  - Quadrupole driven extraction
  - Transverse RF KO extraction
  - Both DC and bunched beams

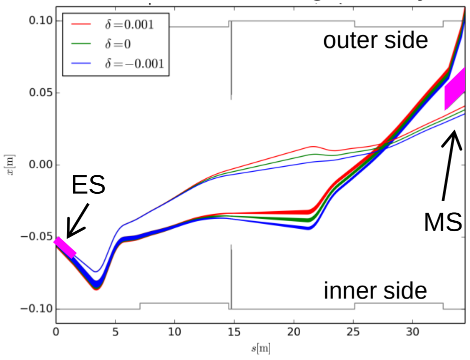
SIS18 extraction optic: hor. envelopes



SIS18 extraction orbit

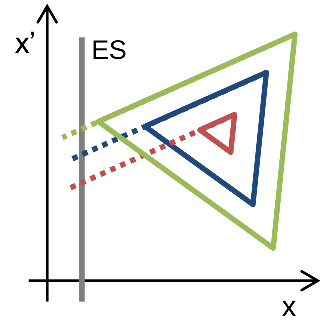


SIS18 extraction geometry



Quad Driven SlowEx: Advantages for Spill Quality

- Quad driven extraction at SIS18
  - Tune ramp by pair of extraction quads
  - Chromaticity uncorrected ($Q' \approx -6$)
  - Effectively a momentum selection scheme
  - All separatrix sizes contribute to spill



$$\Delta Q(\delta) = Q + Q'\delta - Q_r$$

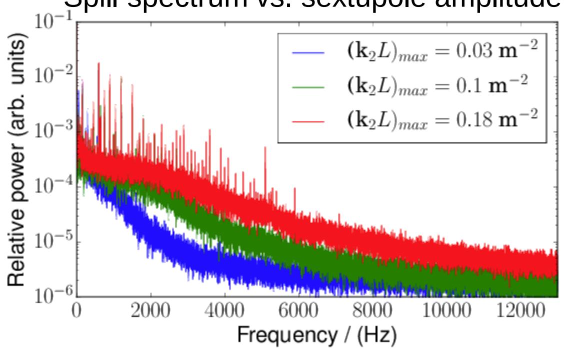
$$\Delta Q_{tr} \sim \sqrt{\varepsilon_x} \cdot S$$

$$\Delta T_{tr} \sim \frac{1}{\Delta Q_{tr}} \sim \frac{1}{S}$$

- Intrinsic spill smoothing by transit time spread
  - Explored in SIS18 by R. Singh, S. Sorge, et al.
  - Spread ΔT_{tr} created by different $\Delta Q(\delta)$
  - Frequency cutoff at about $1/\Delta T_{tr}$
  - Smears out spikes from ripples above cutoff
  - Optimal for small sextupole strength and emittance
    - Limit on decreasing strength by spiral step $\Delta x \sim S$
    - Limit on decreasing emittance by intensity

See R. Singh's talk

Spill spectrum vs. sextupole amplitude



R. Singh, 2018

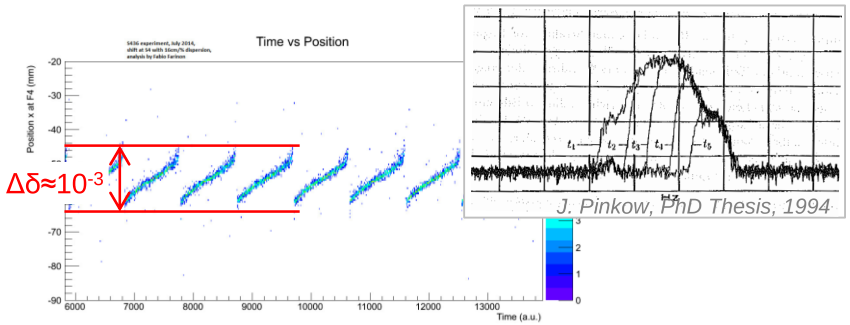
- Allows further smoothing by tune modulation

- Good spill quality comes at a price
  - Scheme has some disadvantages (next slide)
  - Tradeoff depends on experiment

Quad Driven SlowEx: Drawbacks

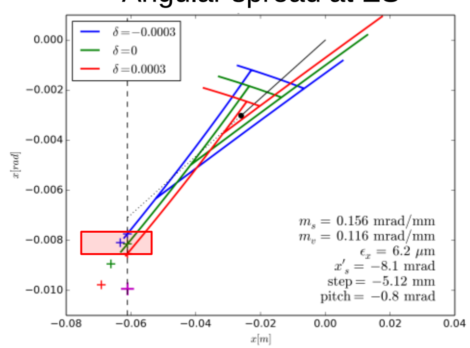
- Momentum drift during spill
  - May create position drift at target
  - For some experiments it’s a feature…
- Large angular spread at ES
  - Increased losses at ES, esp. for large emittance
  - Prevents dynamic bump scheme
- Large positional spread at MS
  - Requires higher separation to avoid losses at MS
  - May create position drift at target
  - Response about 10mm/mrad in SIS18

Momentum drift during extraction

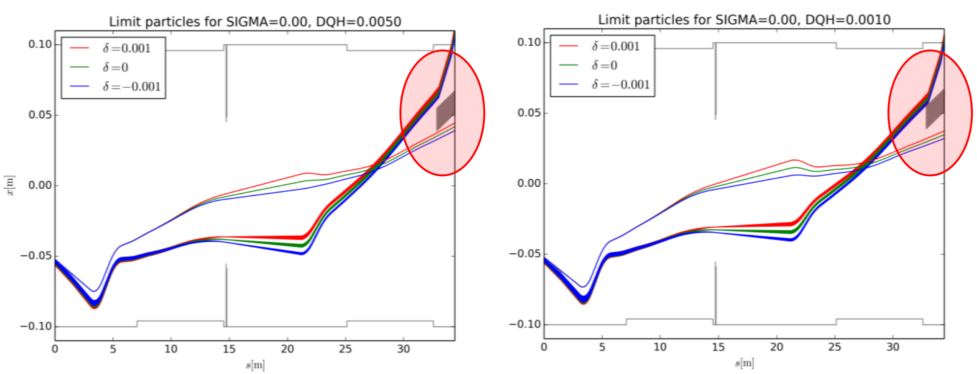


Data courtesy H. Weick

Angular spread at ES

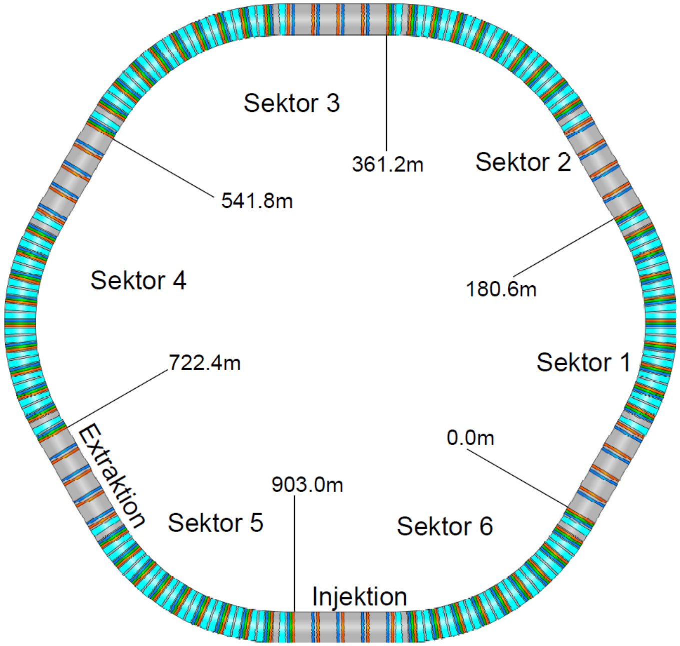


Trajectories at MS for different tune distances



SIS100: Overview

- Basic parameters
  - Circumference 1083m (= 5 x SIS18)
  - Max. magnetic rigidity 100Tm
  - Max. ramp rate 4T/s
  - Mostly super-ferric magnets
- Ion optical layout
  - Super-periodicity 6, 14 cells per period
  - DF focusing structure (charge separator lattice)
  - Optimized for operation with intermediate charge state ions
- Working modes
  - Batch injection from SIS18
  - Slow extraction to fixed targets
  - Fast extraction of compressed single bunches to fixed targets or storage rings



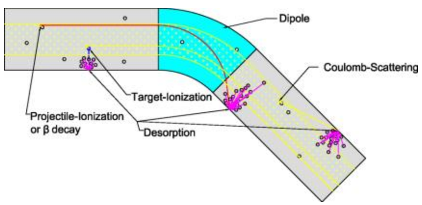
SIS100 optical parameters (SE)	
Q_h / Q_v	17.31 / 17.4
Q'_h / Q'_v	-20.3 / -20.6
α_p	0.005
γ_t	14.2

SIS100: Charge Separator Lattice

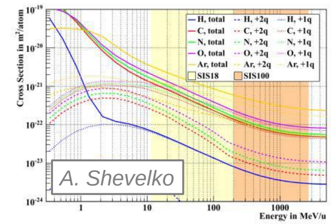
- Increased intensities due to low charge states
  - Higher intensities from linac (no stripping)
  - Increased intensities due to lower space charge
  - FAIR design ion U^{28+} (instead of U^{73+})
  - Emittances like in SIS18 for low charge state ions
- Stable vacuum becomes critical issue
  - High electron loss cross section with residual gas
  - Lost particles create avalanche due to desorption
  - Tighter constraint than space charge
- SIS100 optimized for low charge states
  - DF doublet confining losses to well defined spots
  - Low desorption cryo catchers intercepting ions
  - High focusing strength for best performance
    - Tunes ~18, nat. chromaticities ~ -20
  - Not ideal for slow extraction

FAIR	SIS18	SIS100
Ion	U^{73+}	U^{28+}
Max. Energy	1 GeV/u	2.7 GeV/u
Max. Intensity	10^{10}/s	10^{11}/s

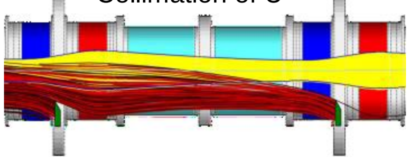
Vacuum instability by desorption



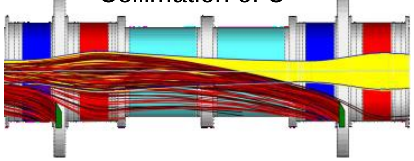
e-loss cross sections



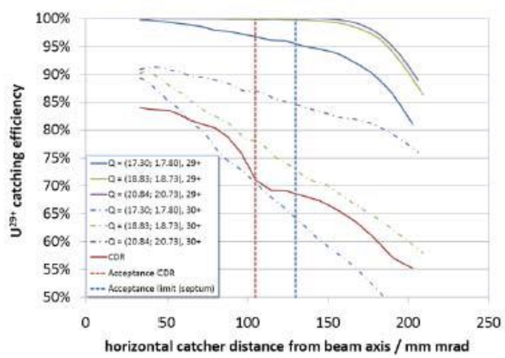
Collimation of U^{29+}



Collimation of U^{30+}



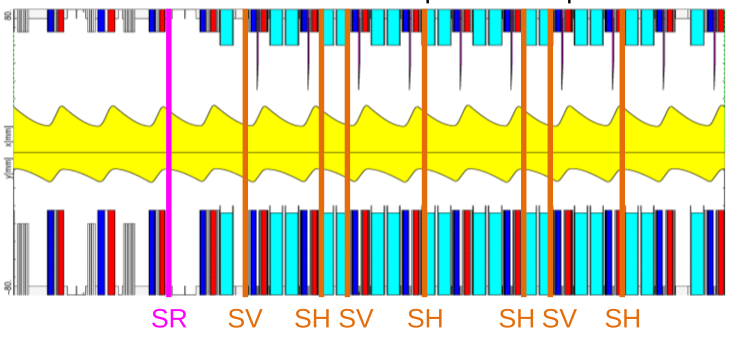
Catching efficiency for different tunes



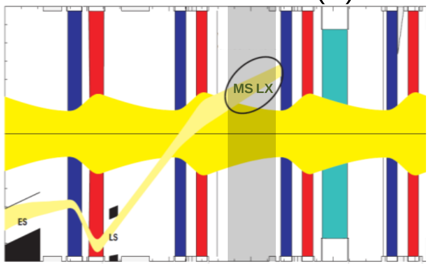
SIS100: Slow Extraction Layout

- Third order resonant extraction
  - Resonance tune $Q_r = 52/3$
  - Excited by six sextupoles with harmonic distribution
  - 42 additional chromaticity sextupoles
  - Large natural hor. chromaticity Q' = -20
  - Vertical extraction through Lambertson septum (LS)
  - Single orbit bump at ES/LS
- Devices for slow extraction
  - 2 electrostatic wire septa (ES)
  - Lambertson septum (LS) for vertical deflection
  - 3 magnetic septa (MS)
  - Lambertson steerer (LX) for hor. correction
  - Hor. exciter for RF KO extraction
- Design slow extraction modes
  - Transverse RF KO extraction
  - DC, bunched or barrier bucket beams
  - Quad driven extraction as fallback

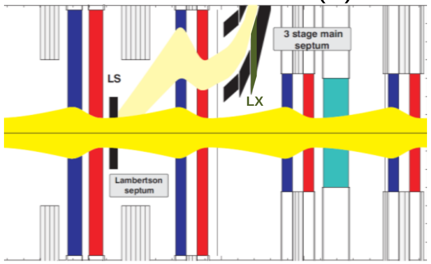
SIS100 slow extraction optic: envelopes



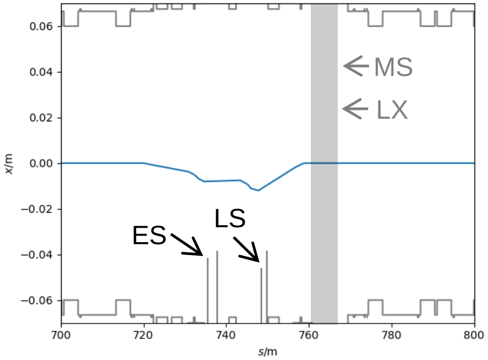
Extraction channel (H)



Extraction channel (V)



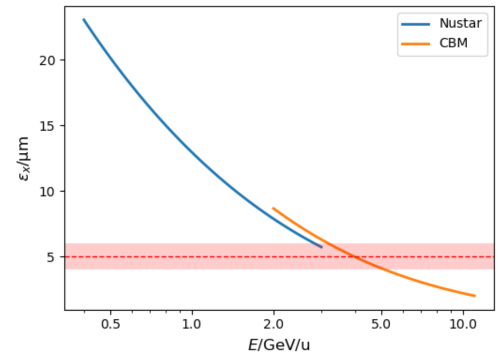
SIS100 extraction orbit



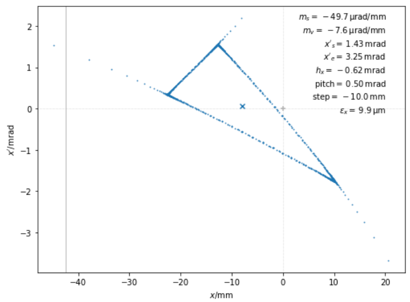
Challenges for SIS100

- Stronger geometric constraints
  - Separation of beam from LS only ±3mm
  - Large response of 15mm/mrad from angular mismatch at ES to position change at LS
  - No independent orbit bump at LS
  - Precludes quad driven extraction with large chromaticity for emittances greater than 4 um
  - Main reason for KO extraction as design mode
- Quad driven extraction
  - Angular spread at ES must be kept small
  - Requires sufficiently small chromaticity
  - Angle at ES must be dynamically adjusted
    - Angle bump at ES
    - Change of phase of sextupole distribution
  - Intrinsic smoothing less effective
- Large horizontal tune Q_h~18
  - More sensitive for same relative PC ripple dI/I
  - Main quad PC specified for dI/I < 10^{-6} on flattop
  - Measurement for acceptance test challenging

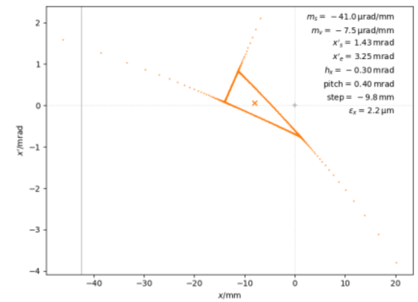
Extraction emittances in FAIR



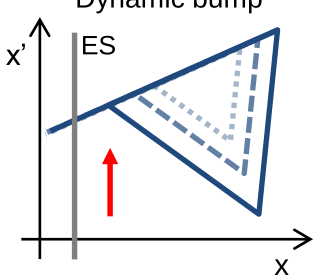
Separatrix for Nustar ref. beam



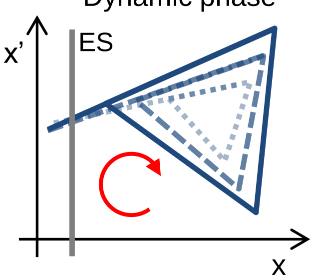
Separatrix for CBM ref. beam



Dynamic bump

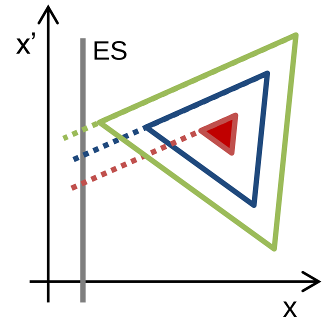


Dynamic phase



Transverse KO Extraction

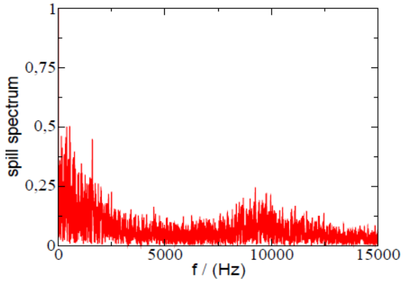
- KO extraction at SIS18
  - Fixed magnet settings
  - Transverse excitation by bandlimited spectrum
  - Presently BPSK pseudo-random noise
- Boundary conditions
  - Requires some degree of chromaticity correction
    - Angular spread at ES would cause high losses
  - Sextupole strength no longer a free parameter
    - Losses constrain ratio of Q' and S, favoring larger S
- Impact on spill quality
  - Sensitivity to ripples high for low chromaticity
  - Smaller transit time spread due to missing contributions from very small ΔQ
  - Worse spill quality than for quad driven extraction seen in simulations and experiment
- Important topic due to relevance for SIS100
  - Strong interest in improvements for KO
  - Investigation of better excitation signals
  - Studying influence of VHF cavity



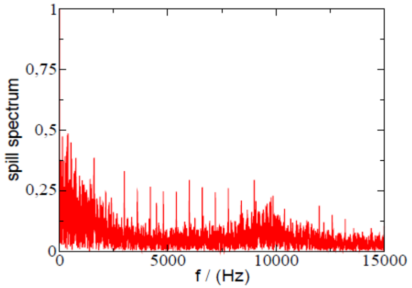
Smallest separatrix must fit horizontal emittance!

$$\Delta x' \sim \sqrt{A_{\max}} - \sqrt{A_{\min}} \sim \frac{Q'\delta_{\max}}{S}$$

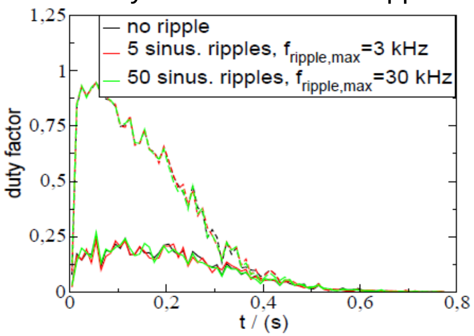
KO spill spectrum (/wo ripple)



KO spill spectrum (/w ripple)



Duty factor /w and /wo ripple



Diagrams courtesy S. Sorge

Developments for FAIR: Tune Modulation

- Spill quality improvement by tune modulation
  - Discovered in SIS18 by R. Singh et al.
  - Artificial ripple in main or extraction quad tested
  - Modulation frequency related to transit time spread
  - Optimal results require changing frequency

See R. Singh's talk

Spill smoothing by tune modulation

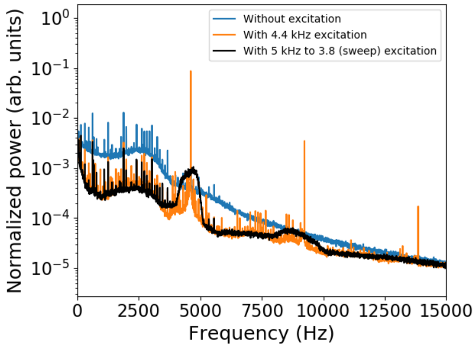
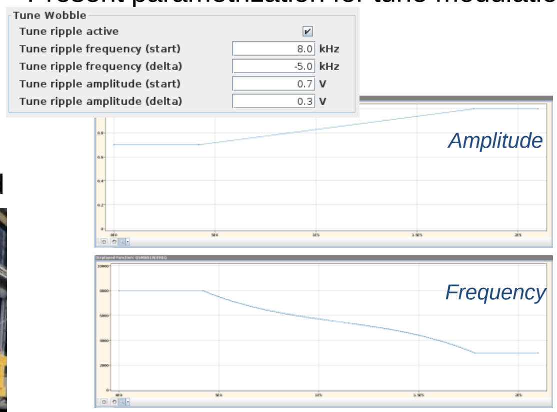


Diagram courtesy R. Singh

- Next steps for SIS18
  - Gain more experience during operation
  - Integration into standard operation ongoing
    - Simple parametrization available
  - Setting up frequency ramp biggest challenge
    - Recipe exists, but only experts can do it
    - Software required integrating instrumentation and settings generation

Present parametrization for tune modulation



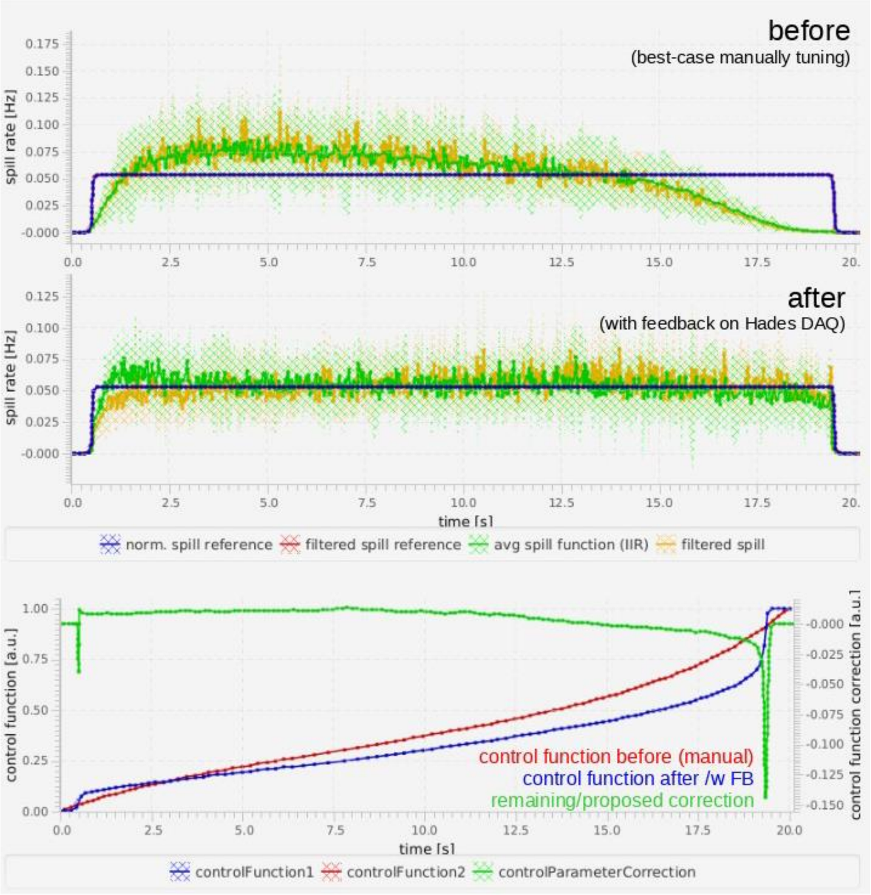
- Next steps for SIS100
  - Efficiency for SIS100 conditions under study
  - PC for modulation on extraction quad foreseen
  - Measurements on extraction quad planned
    - Magnet transfer function
    - Vacuum chamber effect

SIS100 extraction quad

Developments for FAIR: Cycle-to-Cycle Feedbacks

- General strategy
  - Relying on reproducibility of machine
  - Can't compensate cycle-to-cycle fluctuations
  - Advantages
    - No limitation on processing time
    - Averaging over many cycles possible
    - Group delay is not an issue
    - Software solution providing high flexibility
    - Fast development cycle
  - Service architecture under development

- C2C feedbacks for slow extraction
  - Macro-spill feedback
    - Creation of flat spill to optimize detector usage
    - Successfully tested for HADES beam at SIS18
  - Future developments
    - Mains power harmonics reduction
    - Control of beam parameters at injection



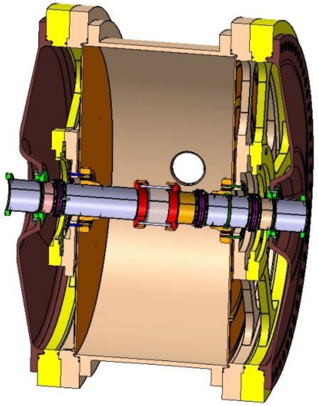
Diagrams courtesy R. Steinhagen

Developments for FAIR: VHF Spill Cavity

- Spill quality improved by bunching
  - Smoothing effect of synchrotron oscillations
  - Successfully used for medical physics at SIS18
  - Imprinted few-MHz RF structure detrimental for experiments at HADES and FRS
  - Frequencies above 40 MHz acceptable
- Development of demonstrator VHF cavity
  - Refurbished Unilac resonator with added pipe
  - Expected frequency around 75 MHz
  - Not suitable for high intensity beams
  - Completion delayed due to problems with beam pipe and ceramic gap
  - Installation expected Q3/2021
- Simulation results for SIS18 (S. Sorge)
  - Moderate bunching improves spill quality
  - Small residual RF structure
  - For higher voltages macro structures due to synchro-betatron coupling appear

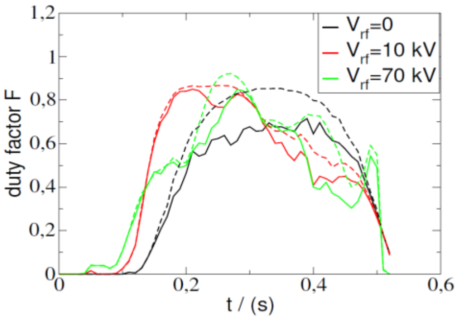
Original resonator

Resonator with beam pipe

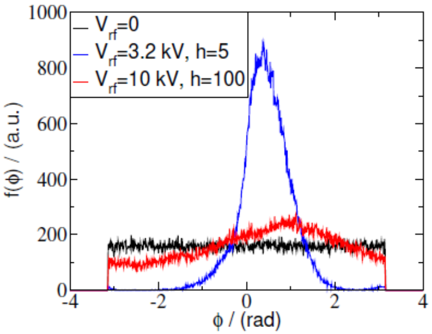


Images courtesy P. Huelsmann

Duty factor vs. VHF cavity voltage



Residual RF structure vs. harmonic number

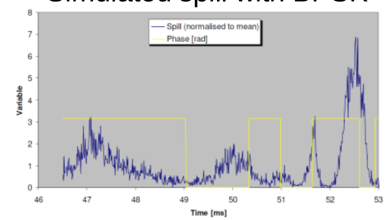


Diagrams courtesy S. Sorge

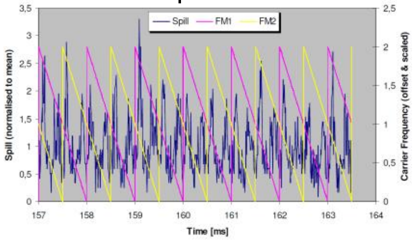
Developments for FAIR: KO Extraction

- Excitation signal
  - BPSK signal used at SIS18 not ideal
    - Piecewise coherent excitation causes rough spill
    - Especially pronounced for low chromaticity
  - Dual-FM investigated
    - Simulations show better spill quality
    - Tests in SIS18 inconclusive so far
    - Requires higher voltage than BPSK

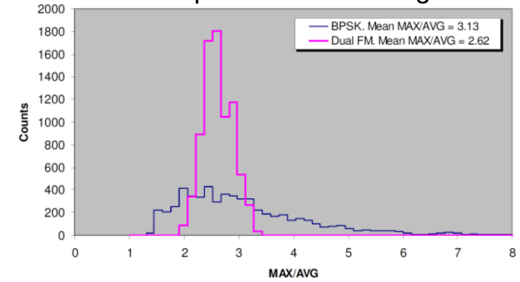
Simulated spill with BPSK



Simulated spill with Dual-FM



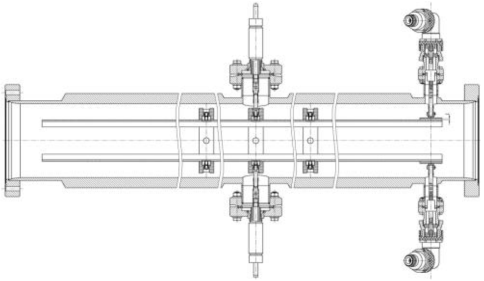
Comparison of max/avg



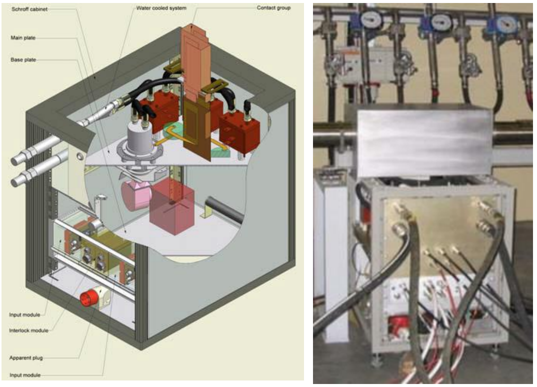
Diagrams courtesy M. Kirk

- Exciter
  - Peak-to-Peak voltages of 10 to 15 kV for SIS100
  - Difficult to realize with strip line exciter
  - Considering to use electrostatic kicker instead
    - Plates driven by tetrode amplifier
    - Radiation hard solution similar to RF cavities
    - Easily scalable in power/bandwidth
    - Synergies with TFS kicker possible
    - Requirements very similar to LHC ADT
      - Could be used as a template
      - Minimization of development effort

LHC ADT Kicker



LHC ADT tetrode amplifier



Images courtesy W. Höfle (CERN)

Summary:
Priorities for FAIR

- Main focus on spill quality in SIS100
  - Exclusive source for CBM (and HADES)
  - Source for Super-FRS at highest intensities
  - Constraints from SIS100 lattice
    - Low chromaticity (independent of extraction mode)
    - Design mode KO extraction (simple)
    - Quad driven as fallback, but only with dynamic bump or sextupole phase change (complex)

- Most important topics
  - Spill smoothing for low chromaticity schemes
  - Spill smoothing for KO extraction
    - Dependence on excitation signal
    - Creation of optimal excitation signal

- Central role of SIS18
  - Continued user operation even in FAIR
    - Justifies further work on quad driven scheme
    - Integration of developments into routine operation
  - Testbed for SIS100 developments

Thanks for your attention!

Thanks to all who have contributed and continue to contribute to the development of slow extraction for FAIR.