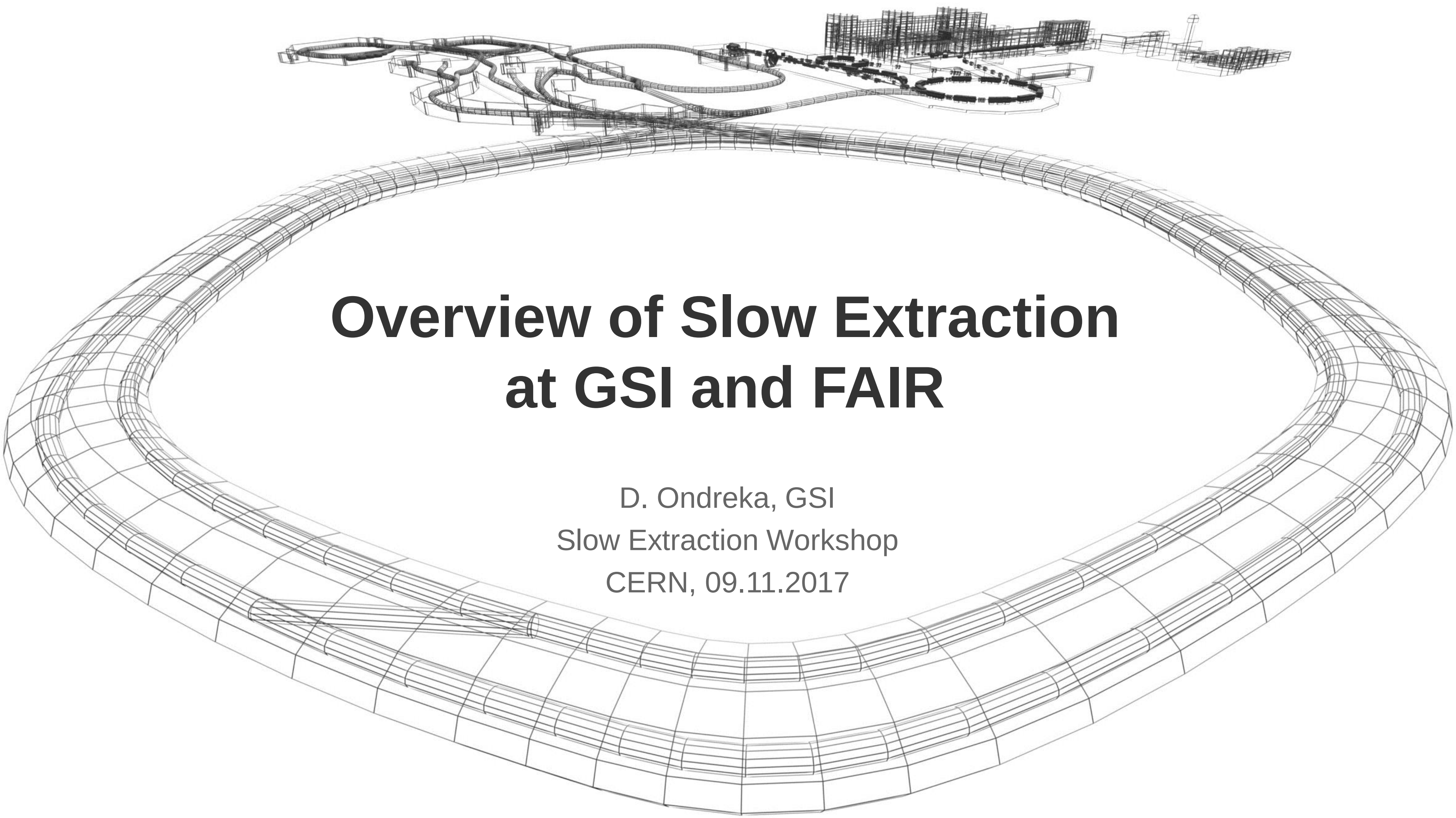


Overview of Slow Extraction at GSI and FAIR

D. Ondreka, GSI

Slow Extraction Workshop

CERN, 09.11.2017

Outline

- Introduction
  - Experiments using SE at GSI and FAIR
  - Overview of GSI and FAIR
- SIS18
  - Upgrade
  - Slow Extraction
- SIS100
  - Lattice Constraints
  - Extraction Geometry
  - Slow Extraction
  - Field Errors
- Summary

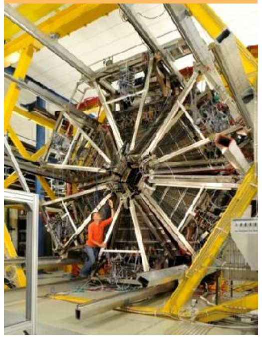
Experiments Requiring
Slow Extraction at GSI and FAIR

- 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

Raster Scanning Installation

HADES Detector



NUSTAR

R3B

LaSpec

MATS

CBM

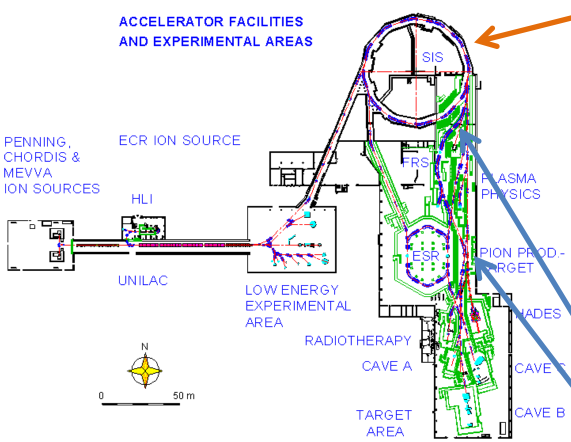
HADES

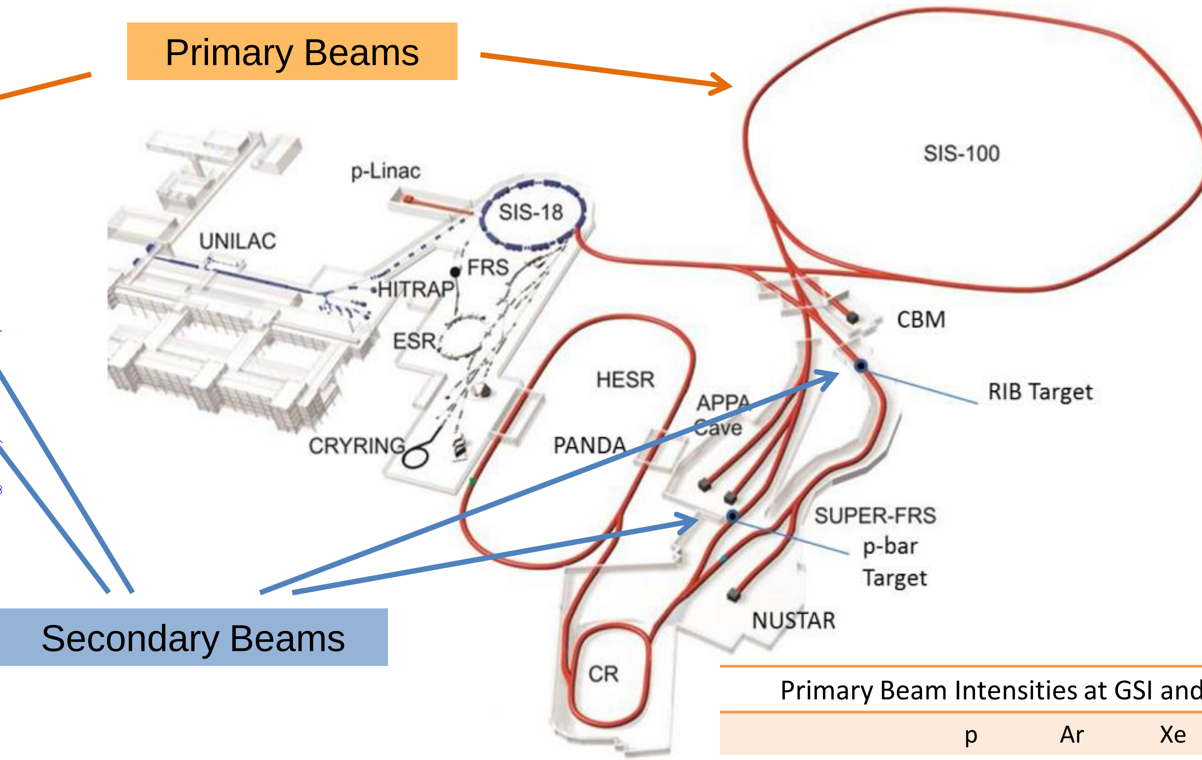
sparc

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
  - Production of Antiprotons
  - High brilliance through cooling

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}	$8 \cdot 10^{10}$	$2 \cdot 10^{10}$	$4 \cdot 10^{9}$
	FAIR	10^{13}	10^{12}	$5 \cdot 10^{11}$	$3 \cdot 10^{11}$

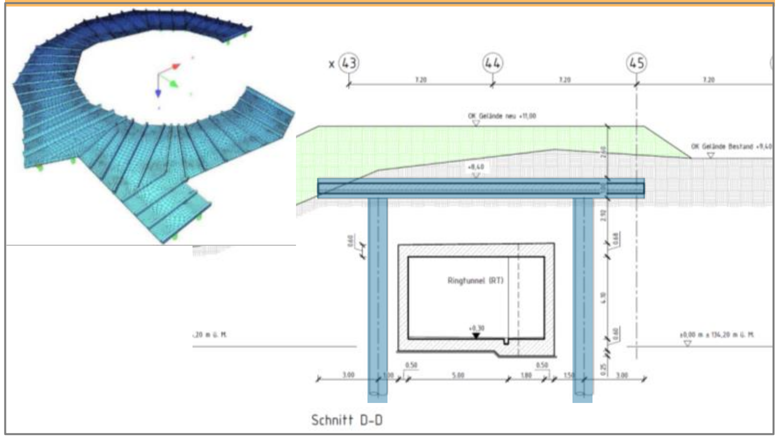
SIS18: Building Upgrade

- Heavy construction work to prepare SIS18 infrastructure for FAIR operation (ongoing)
- Major part concerns improvement of radiation protection for FAIR intensities
  - Additional shielding above existing tunnel
  - Additional shielding in extraction area
  - Under-pressure conditions in tunnel
- New power grid connection for FAIR
  - Enables fast ramping of SIS18
- Completion in spring 2018

Tunnel stub for connection to FAIR

New transformer station (100kV/20kV)

Concrete table construction for increased shielding

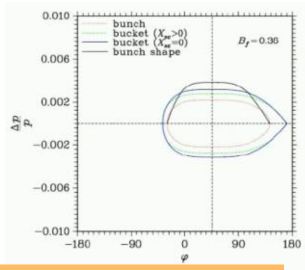


SIS18: Machine Upgrade

- Upgrade of SIS18 to enable injector operation for FAIR (booster mode)
  - Improved dynamic vacuum for operation with low charge state ions (design ion U^{28+})
  - High rep. rate (2.7 Hz) for fast stacking in SIS100
- Higher intensities from SIS18 possible
  - Upgrade of main dipole power converter
    - Ramping speed 10T/s up to nominal field
    - Higher duty cycle due to faster ramps
    - Reduction of SC induced losses at low energies
  - Installation of 3 MA cavities
    - Sufficient RF voltage for fast ramping (50kV)
    - Dual harmonic operation (H=2/4) to decrease space charge induced losses
- Almost completed by now
  - Upgraded power converter commissioning with new power grid connection in spring 2018
  - Commissioning of MA cavities in summer 2018

New filter of dipole PC

New transformers of dipole PC

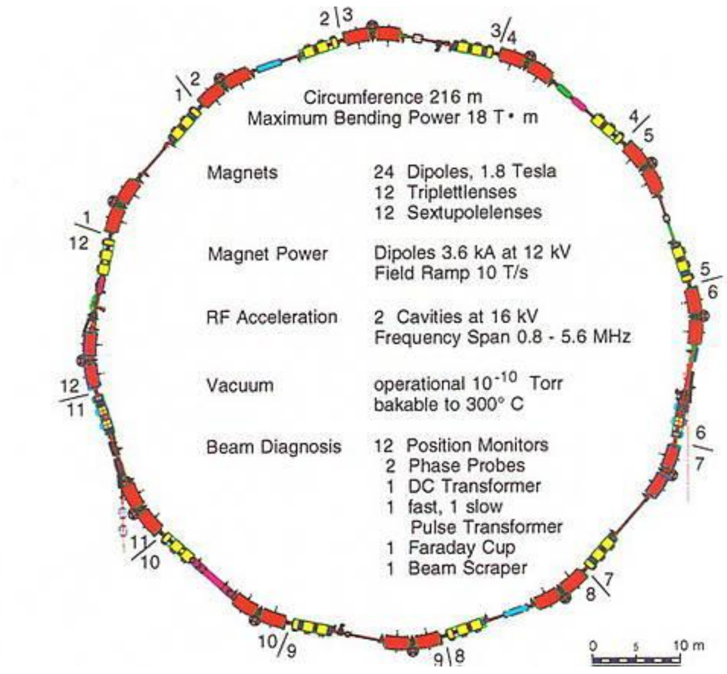


New MA cavities in tunnel

1.8 MW supply unit for MA cavity

SIS18: Overview

- Basic parameters
  - Circumference 216m
  - Max. magn. 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



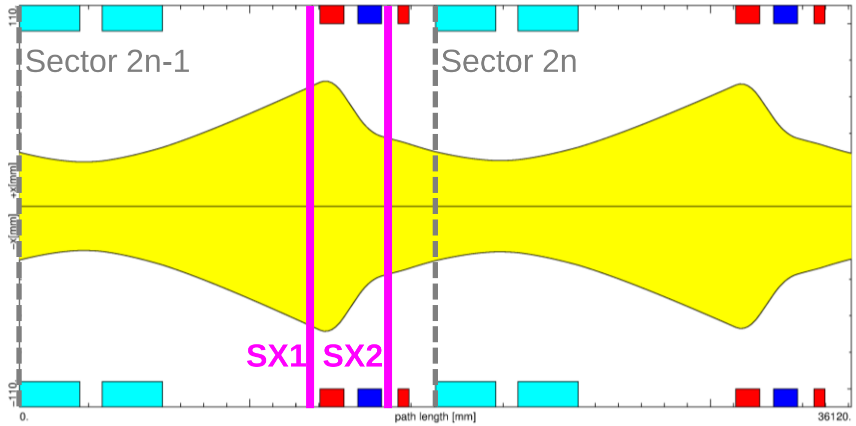
SIS18 optical parameters	
Q_h / Q_v	4.29 / 3.28
Q'_h / Q'_v	-6.4 / -4.1
α_p (inj. / ext.)	0.042 / 0.032
γ_t (inj. / ext.)	4.9 / 5.6

SIS18: Slow Extraction Layout

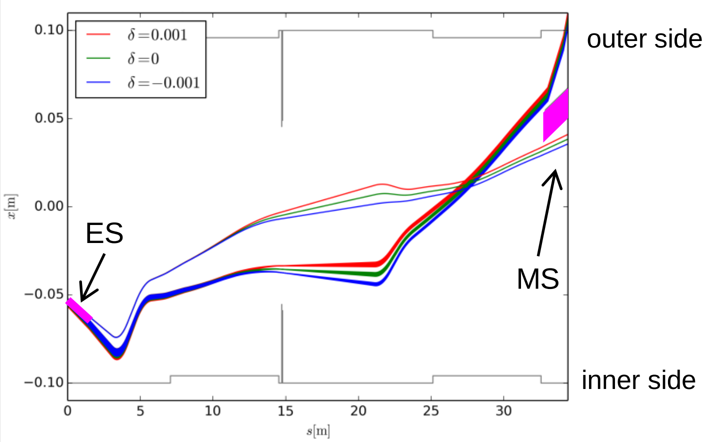
- SIS18 slow extraction scheme
  - Resonance Q_h=13/3 excited by six sextupoles with harmonic distribution (ΔQ'=0)
  - Chromaticity Q'_h normally uncorrected
  - Electrostatic wire septum (ES)
    - 1.5m long, 100µm W/Rh wires
    - max. 160kV @ 18mm gap
  - Magnetic septum (MS)
  - Two local bumps at ES and MS
  - 2 fast quads for quad driven extraction
  - Horizontal exciter for RF KO extraction
- Possible slow extraction modes
  - Quadrupole driven extraction using 2 fast quads
  - RF KO extraction using horizontal exciter
  - Both DC and bunched beams
  - Extraction times about 1s to 10s

More details on slow extraction from SIS18, especially about spill quality, in dedicated talks by P. Schmid, S. Sorge, and P. Forck

SIS18 extraction optic: hor. envelopes



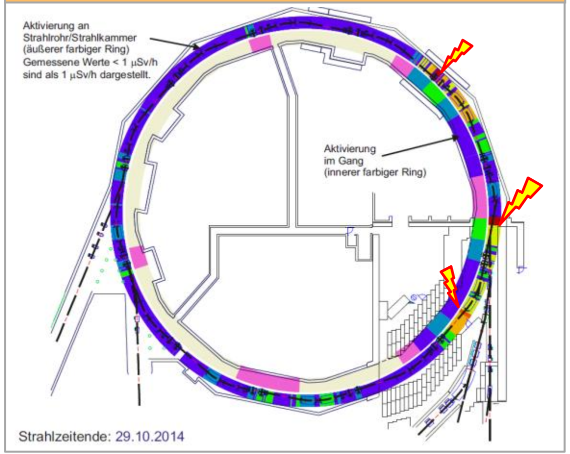
SIS18 extraction geometry



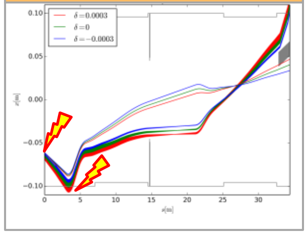
SIS18: SE with Increased Intensities

- Extraction efficiency key issue to profit from higher intensities due to SIS18 upgrade
  - Avoidance of excessive activation
  - Hot spots identified in recent high intensity runs
- Survey and correction of geometry (P. Schmid)
  - Severe misalignment of ES corrected
  - Interfering collimator in S05 retracted
- Significant increase of extraction efficiency observed in beam time 2016
  - Efficiencies up to 90% measured at low energies
  - BUT: Larger deflection from ES necessary
- Installation of new ES foreseen
  - Longer electrodes to increase integral by 50%
  - Very similar to SIS100 ES
  - Waiting for budget approval

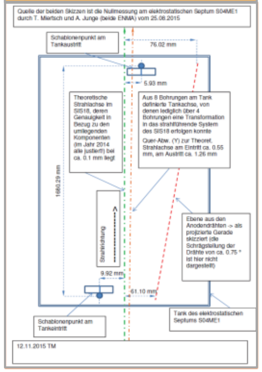
Activation pattern after high intensity SE



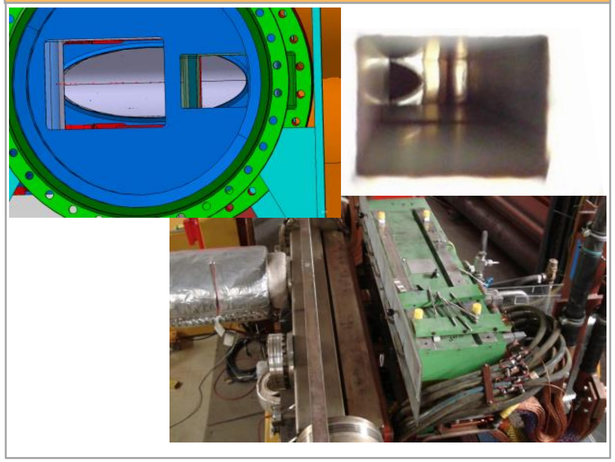
Loss simulation



ES alignment report

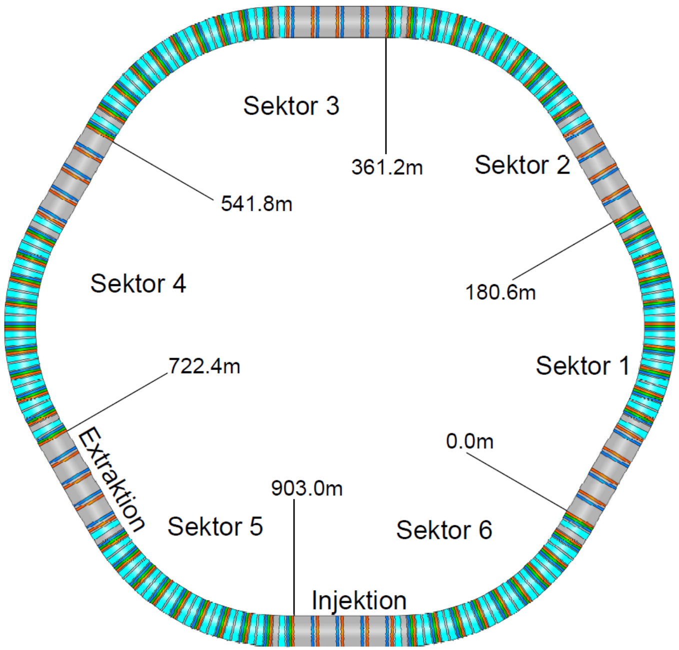


Survey of magnetic septum (MS)



SIS100: Overview

- Basic parameters
  - Circumference 1083 m (= 5 x SIS18)
  - Max. magn. rigidity 100 Tm
  - Max. ramp rate 4T/s
  - 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



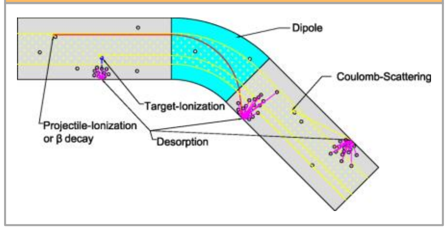
SIS100 optical parameters (SE)	
Q_h / Q_v	17.31 / 17.45
Q'_h / Q'_v	-20.3 / -20.6
α_p	0.005
γ_t	14.2

SIS100: Charge Separator Lattice

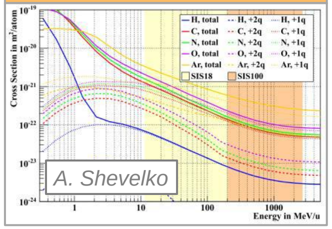
SIS18	GSI	FAIR
Ion	U^{73+}	**U^{28+}**
Max. Energy	1 GeV/u	0.2 GeV/u
Max. Intensity	$4 \cdot 10^{9}$	**$1.5 \cdot 10^{11}$**

- 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+})
- Stable vacuum becomes critical issue
  - High electron loss cross section with residual gas
  - Lost particles create avalanche due to desorption
  - Tighter constraint than SC or current effects
- SIS100 optimized for low charge states
  - DF structure confining losses to well defined spots
  - Low desorption cryo catchers intercepting ions
  - Drawback: High focusing strength required
    - Tunes ~18, nat. chromaticities ~ -20
    - Not ideal for a slow extraction lattice

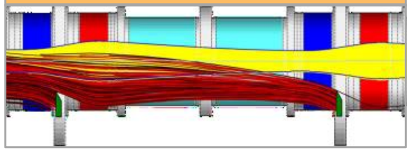
Origin of vacuum instability



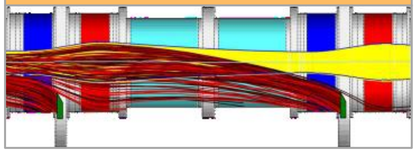
e-loss cross sections



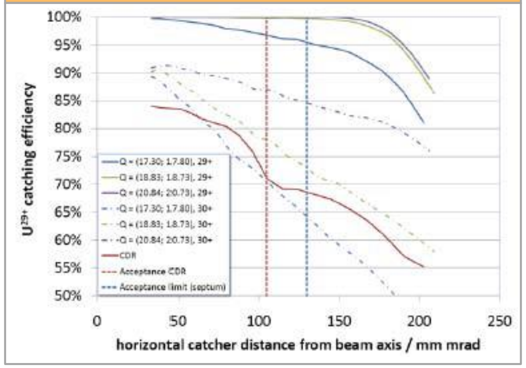
Collimation for U28+ → U29+



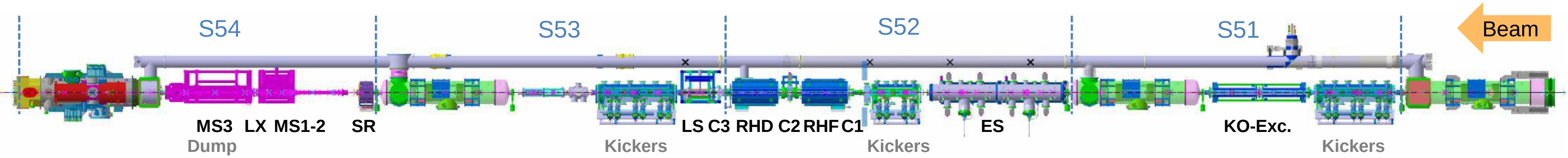
Collimation for U28+ → U30+



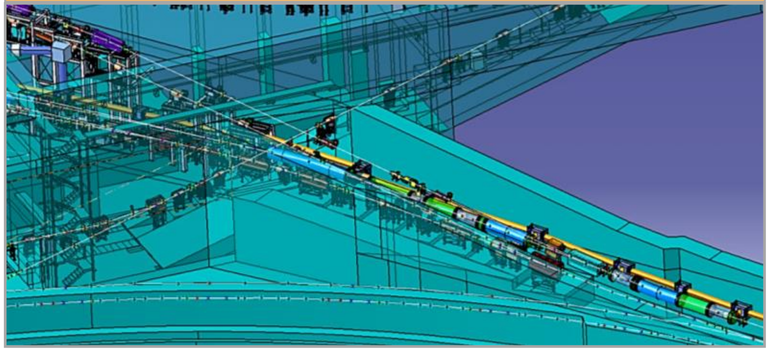
Catching efficiency for different tunes Q_h



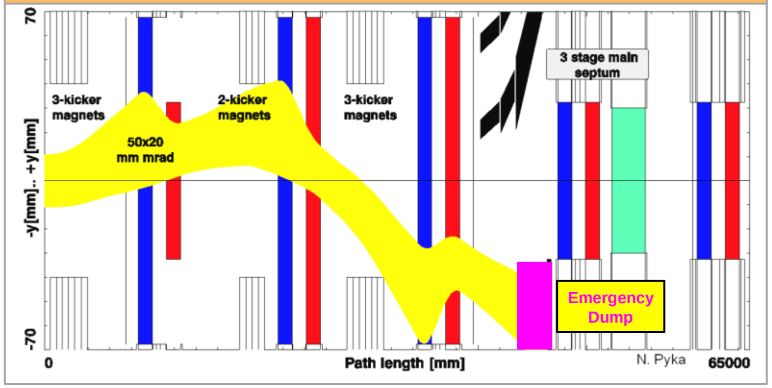
SIS100: Extraction Layout



Extraction lines into FAIR HEBT



Vertical emergency extraction onto integrated dump



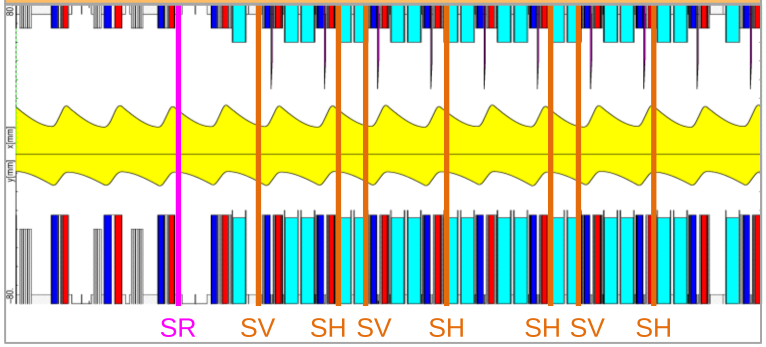
- Tight space requirements
  - Extraction in vertical plane compatible with SIS300 upgrade option
  - One extraction channel for both slow and fast extraction
  - Emergency beam-dump for fast beam-abort integrated into MS3
- Fast and emergency extraction
  - 8 bipolar vertical kickers in 3 cells
  - Straight horizontal path in extraction channel
- Slow extraction
  - Excitation in horizontal plane
  - Lambertson septum for vertical deflection into extraction channel
  - Deflected horizontal path in extraction channel

SIS100: Slow Extraction Layout

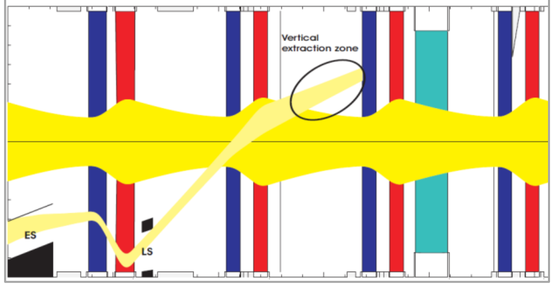
- Devices for slow extraction
  - 6 NC sextupoles for resonance excitation
  - 42 SF sextupoles for chromaticity correction
  - 2 electrostatic wire septa (ES)
    - Each 2.3m long, 100µm W/Rh wires
    - Max. 160kV @ 20mm gap
  - Lambertson septum (LS) for vertical deflection
  - 3 magnetic septa (MS)
  - Lambertson steerer (LX) for hor. correction
  - Hor. exciter for RF KO extraction
  - Quadrupole for quad driven extraction (fallback)
- Base-line slow extraction modes
  - Transverse RF KO extraction
  - DC, bunched or barrier bucket beams
  - Quad driven extraction as fallback
  - Extraction time about 1s to 10s

Choice of KO extraction over quad driven extraction motivated by better positional stability of extracted beam due to fixed optical settings.

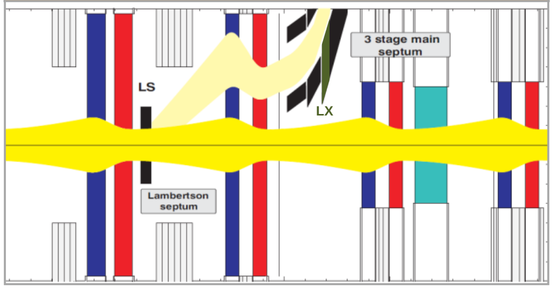
SIS100 slow extraction optic: envelopes



Extraction channel (horizontal plane)



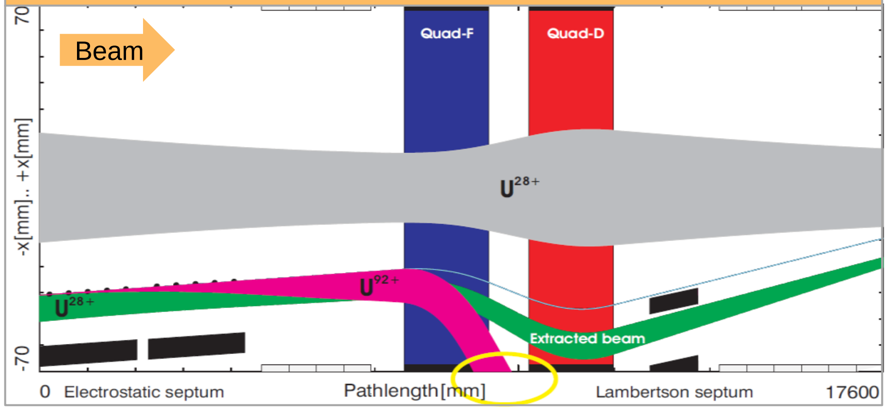
Extraction channel (vertical plane)



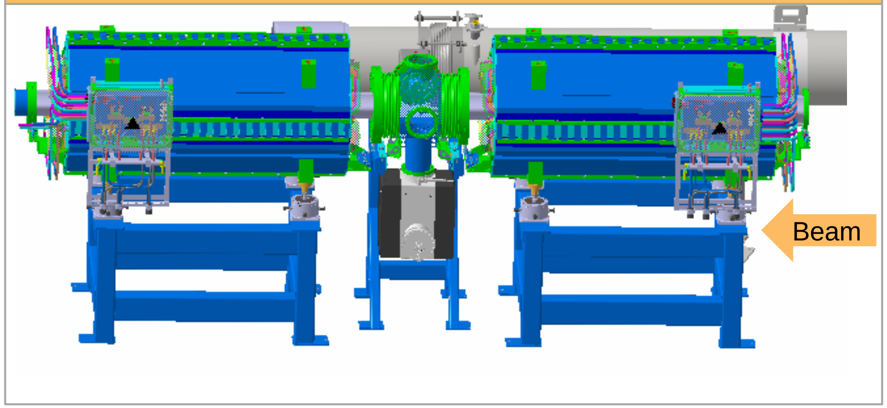
SIS100: Radiation Resistant Quadrupoles

- Challenge: control of losses caused by ions interacting with septum wires
  - Low charge state ions to increase intensities
  - Fully stripped when interacting with wires
  - Change in charge causes large shift in rigidity
  - Lost due to mismatch between fields and rigidity
- Main loss position doublet downstream septa
  - Energy deposition calculated to be prohibitively high for super-ferric quadrupoles
  - Replacement by two separately powered NC normal conducting quadrupoles
  - Radiation resistant coils to cope with high dose
  - Increased aperture for slow and fast extracted beam → star shaped vacuum chamber
- Collimation of losses necessary
  - Control of activation hot spots
  - Avoidance of vacuum degradation

Expected loss position for stripped Uranium in extraction channel



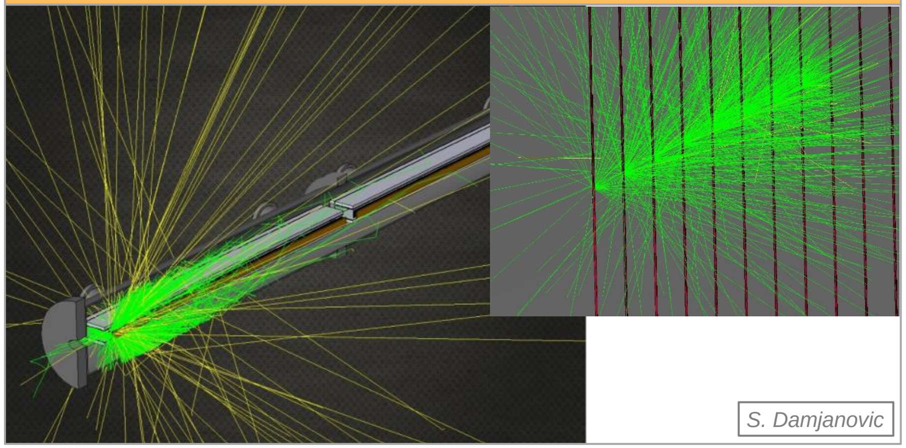
NC radiation resistant quadrupoles in cell S52



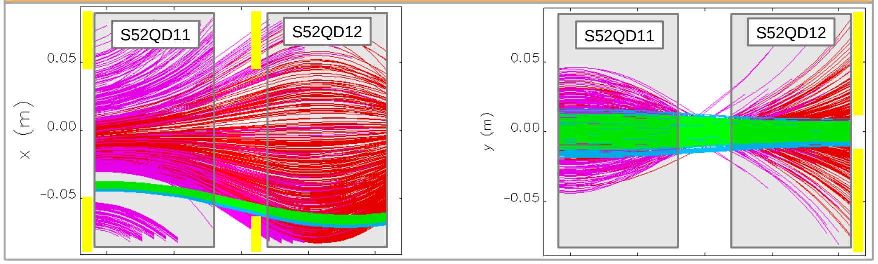
SIS100: Loss Position of Stripped Ions

- Interaction with septum wires
  - Ions colliding with wires fully stripped
  - Species dependent scattering both into extraction path and ring path
  - Transport of scattered ions depends on change in charge Q
- Modeling strategy
  - FLUKA simulation of wire interactions including both septa
  - Ion optical tracking simulation of transport of scattered ion downstream the ES
  - Complex chamber geometries of rad. resistant quadrupoles and Lambertson septum considered
- Determination of loss positions
  - Identification of appropriate positions for collimation of scattered ions
  - Sufficient margin to circulating and extracted beam must be kept

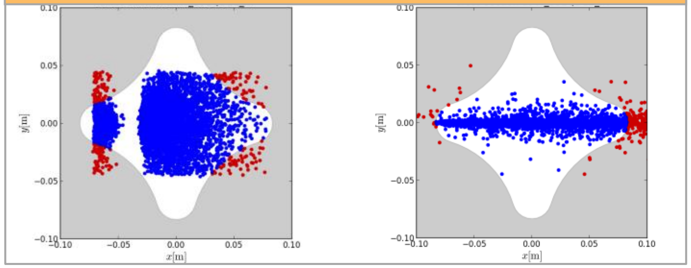
FLUKA simulation of ions interacting with septum wires



Transport of scattered ions through RH quadrupoles



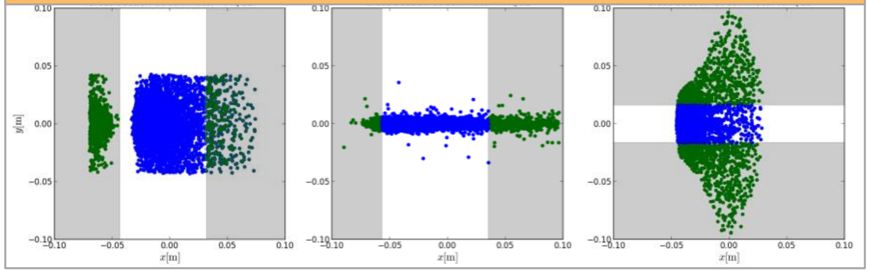
Distribution of scattered ions at entrance to RH quads



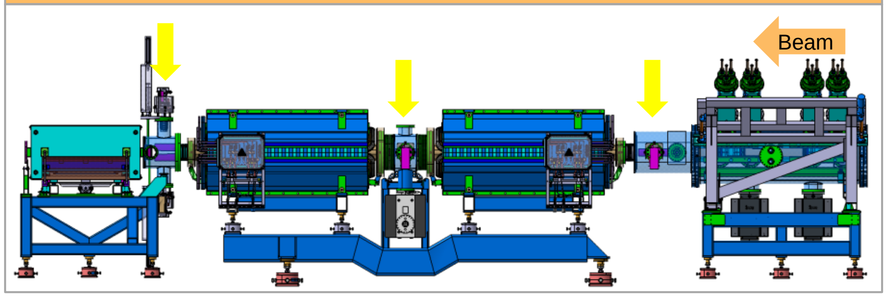
SIS100: Collimation of Stripped Ions

- Three locations for collimators
  - Upstream RRQ-D (horizontally)
  - Between both RRQs (horizontally)
  - Downstream RRQ-F (vertically)
- Collimation efficiency
  - For U^{28+}, up to 75% of stripped particles can be collimated (depending on energy)
  - Unavoidable losses in kickers and quad chambers tolerable
- Collimator design
  - Length about 30cm sufficient to stop primaries
  - Dissipated power up to 500W
  - Preliminary design: water cooled copper blocks
  - More detailed simulations necessary
  - Work in progress

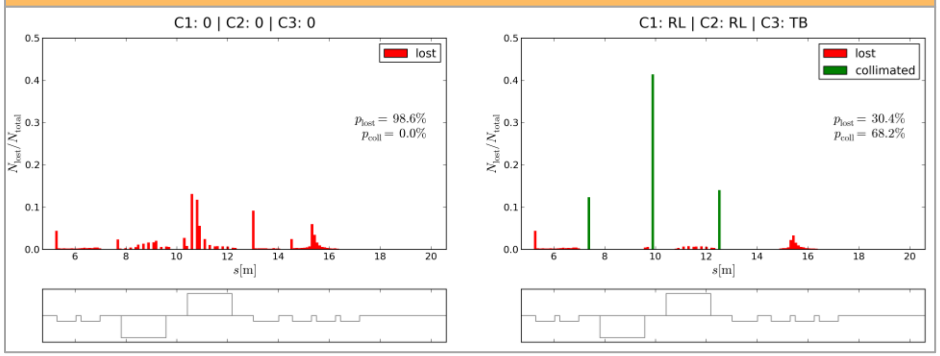
Beam cross section at collimators around radiation resistant quads



Collimator positions around radiation resistant quadrupoles

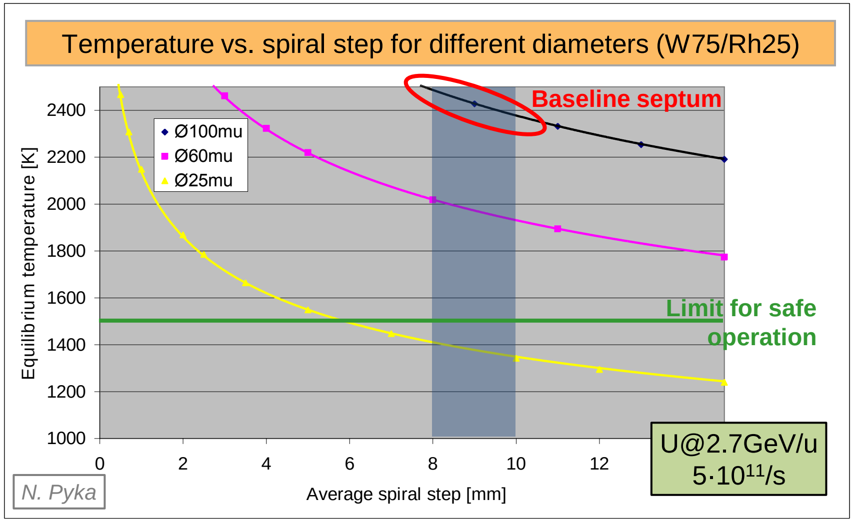


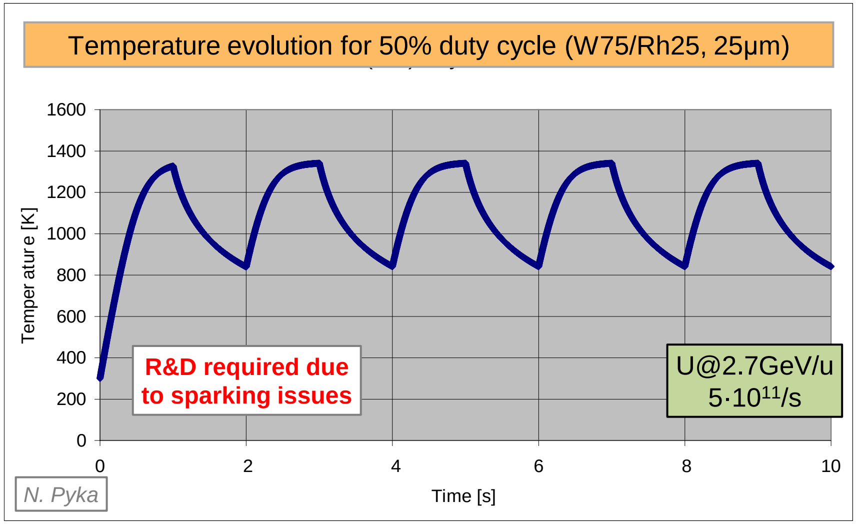
Loss distribution in cells S52 and S53 without and with collimators



SIS100: Septum Wires

- SIS100 SE employs classical wire septum
  - Interactions with septum wires unavoidable
  - Fraction at least diameter over spiral step
  - Energy loss $dE/dx \sim Z^2$ very high for ions like U^{28+}
  - Prohibitively high for SIS18 type wires
- R&D campaign performed
  - Increase of Rh to 25% for better tensile strength
  - Decrease of wire diameter from 100µm to 25µm
  - Thermally stable, tested with beam at SIS18
  - BUT: wires don't withstand sparking discharge
- Baseline septum using 100µm wires
  - Limitation of extraction rate for heaviest ions
  - Tolerable for initial operation of FAIR
- Long-term strategy foresees replacement
  - R&D for sparking problem with W/Rh 25µm
  - Investigation of low-Z wires



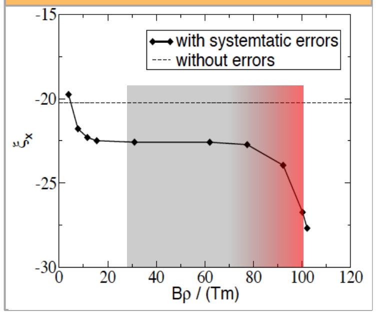


SIS100: Field Errors

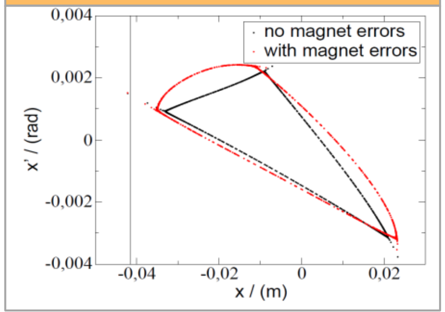
	No err.	64 Tm	100 Tm
k_2l_{sys} [m^{-2}]	0.0	0.03	0.08
k_2l_{chr} [m^{-2}]	-0.47	-0.53	-0.63
k_3l_{cmp} [m^{-3}]	4.9	0.0	0.0
k_2l_{res} [m^{-2}]	0.76	0.76	0.45
Φ_{res} [deg]	153	145	168

- Model for magnet imperfections
  - Model for alignment errors
  - Magnetic measurements of dipoles
  - Model errors for quadrupoles
- Main results (S. Sorge)
  - Settings can be matched to create proper separatrix based on systematic errors
  - Strong dependence on saturation level
  - Little influence of random errors
  - Significant influence of vertical emittance
    - Losses ~5% for nominal emittance
    - Losses ~10% for twice nominal emittance
- Conclusions
  - Expected field errors appear tolerable
  - Emittance dilution must be kept small
  - Good model of systematic errors needed

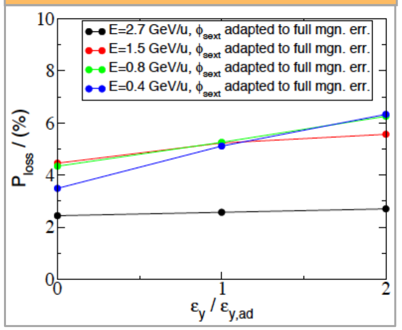
Q'_h with errors



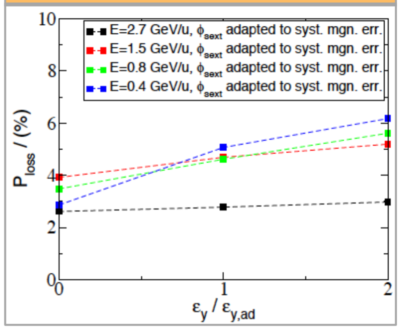
Matched separatrix for 100Tm



Losses with full errors



Losses with syst. errors



All data and plots courtesy of S. Sorge

Summary

- Many GSI and FAIR experiments require slow extraction
  - Production of secondary beams asks for high intensities of primary beam
  - Extraction efficiency is key issue to avoid excessive activation
- SIS18
  - Upgrade for FAIR allows for higher intensities at GSI
  - Extraction efficiency improved by correction of geometry
  - Stronger electrostatic septum required for highest rigidities
- SIS100
  - Lattice structure dominated by operation with intermediate charge state ions
  - Tight space constraints for slow, fast, and emergency extraction in one straight
  - Systematic losses during SE of ions stripped by interaction with wires
  - Replacement of one super-ferric doublet by radiation resistant NC quads
  - Collimation system around radiation resistant quads for loss confinement
  - Baseline septum with 100µm W/Rh wires not sufficient for FAIR design intensities
  - R&D for replacement septum necessary
  - Field errors significant for SE at high excitation, but can be compensated for
  - Dilution of vertical beam emittance must be avoided to keep losses small

Thanks for your attention!

I'd like to thank all colleagues who contributed material for this talk, consciously or unconsciously.
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