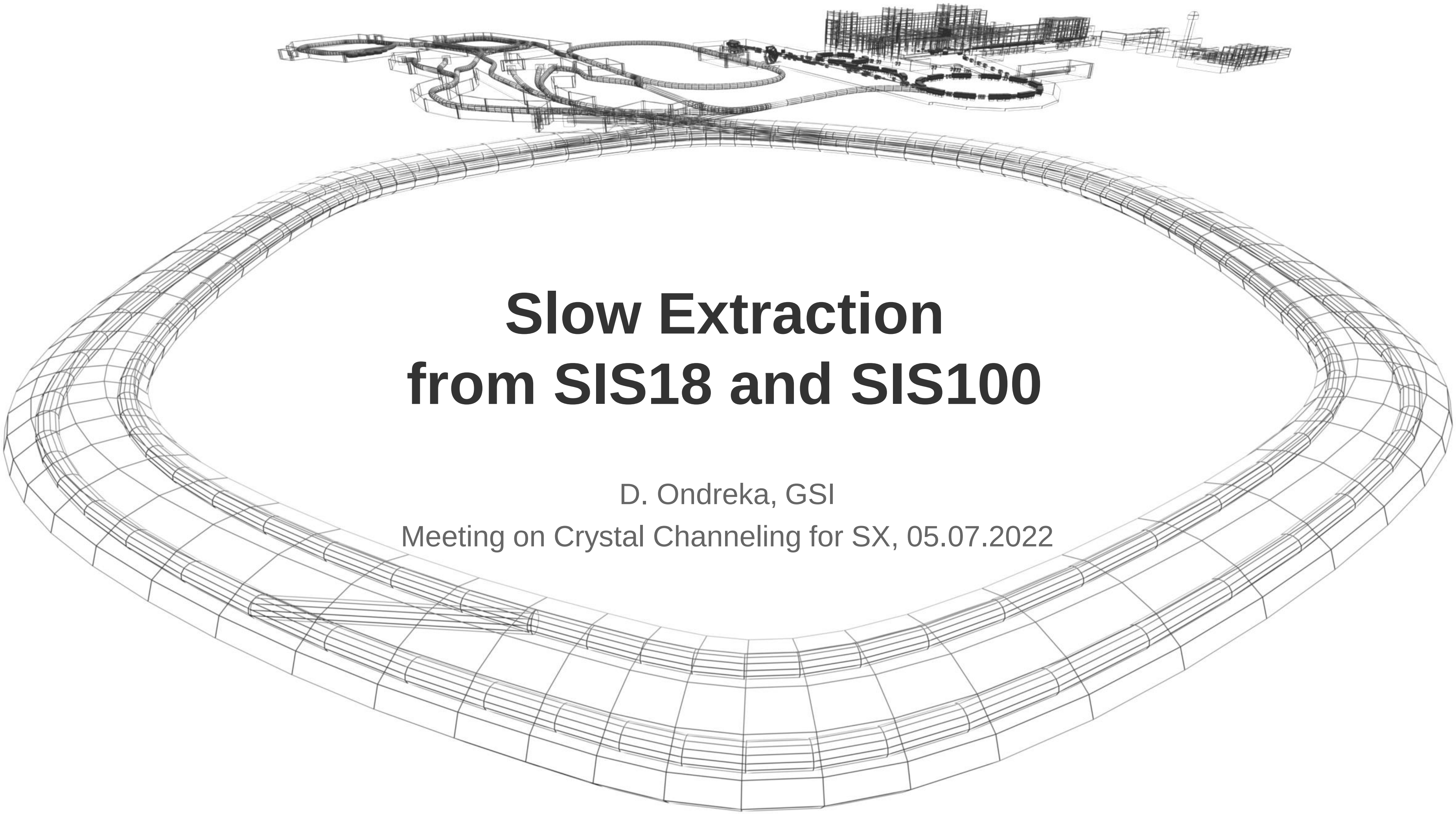


Slow Extraction from SIS18 and SIS100

D. Ondreka, GSI

Meeting on Crystal Channeling for SX, 05.07.2022

Bent Crystals for FAIR?

- Applications of bent crystals in particle accelerators
  - Loss reduction during slow extraction for proton machines
  - Pure crystal extraction in electron machines

- Potential applications to heavy ion machines
  - Machine protection (small fraction of beam hits crystal)
    - Loss reduction during slow extraction
    - Halo collimation (replacement of first-stage scatterer)
  - Pure crystal extraction (full beam hits crystal)

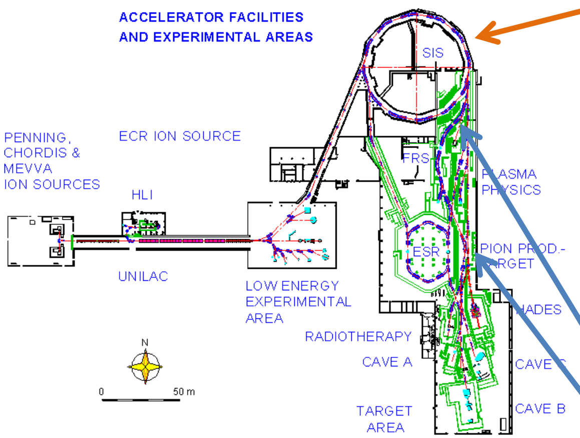
- Main question
  - Under which conditions can heavy ions be channeled?
  - Can these conditions be met in the FAIR machines?
  - What would be the requirements on the crystals?

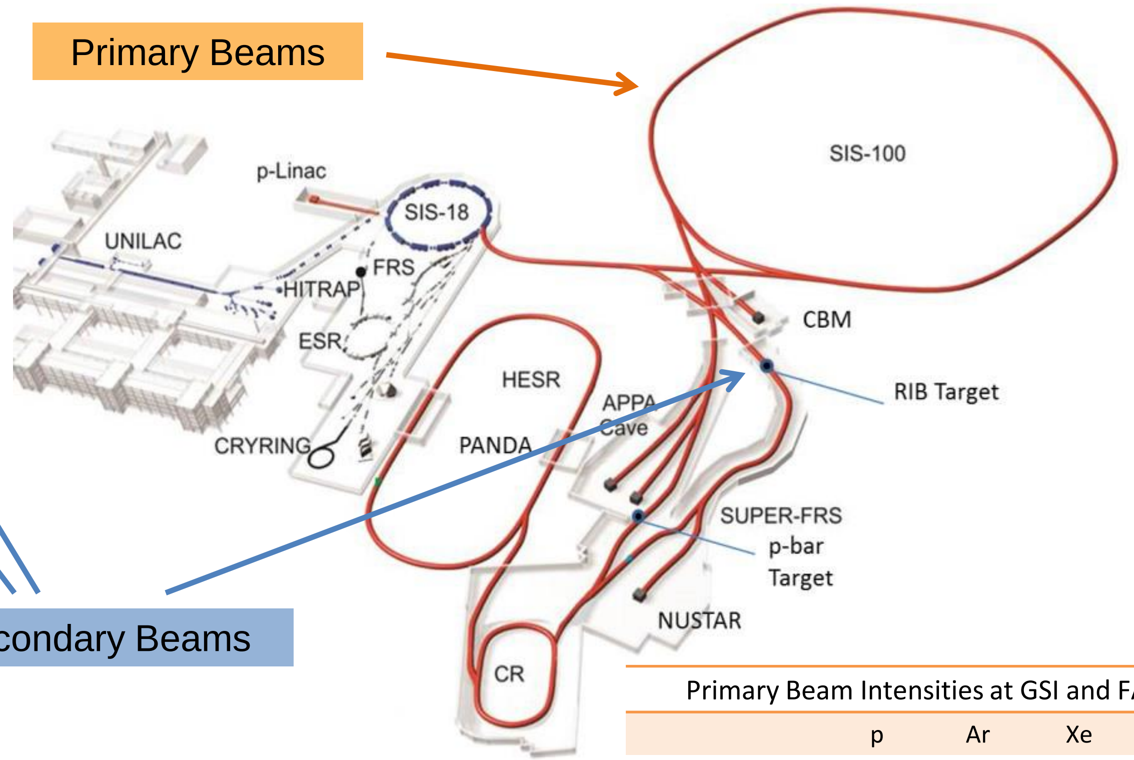
Contents

GSI and FAIR: Overview

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

Primary Beams





Secondary Beams

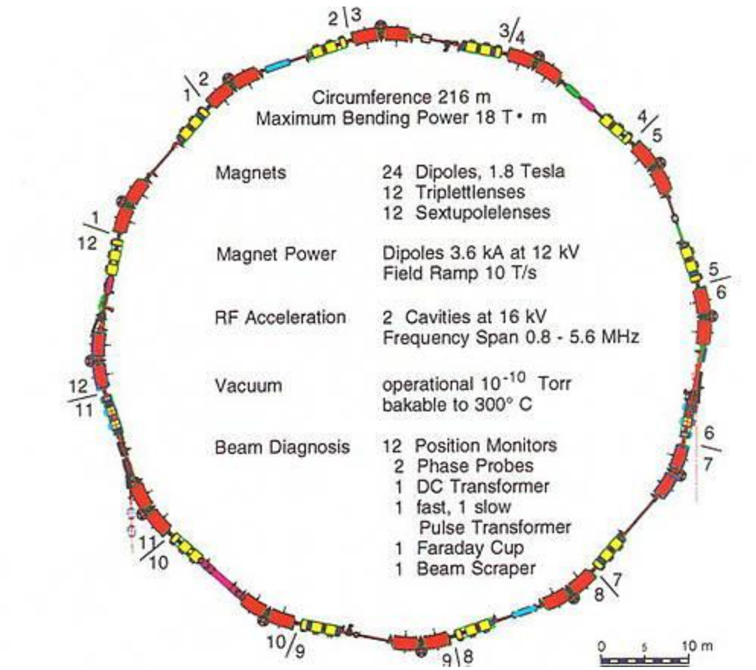
- Breaking the limits of GSI:
  - Primary beam intensities: 100x
  - Secondary beam intensities: 10000x
  - Primary beam energies: 10x
  - Many experiments requiring slow extraction

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

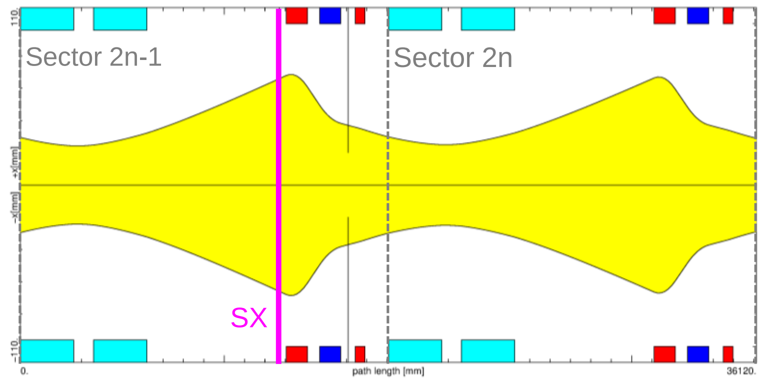
SIS18: Slow Extraction Layout

- Third order resonant extraction
  - Resonance tune Q_r = 13/3
  - Natural hor. chromaticity Q' = -6
  - Two orbit bumps at ES and MS
  - Six sextupoles with harmonic distribution (ΔQ'=0)

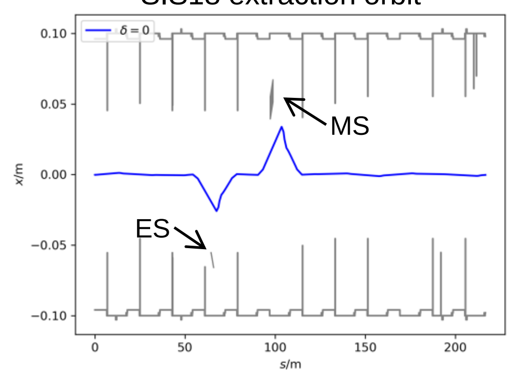
- Devices for slow extraction
  - Electrostatic wire septum (ES)
    - 1.5m long, 100µm W/Rh wires
    - max. 160kV @ 18mm gap
  - Magnetic septum (MS)
  - 2 fast quads for quad driven extr.
  - Hor. exciter for RF KO extr.

- Standard slow extraction modes
  - Quadrupole driven extraction
  - Transverse RF KO extraction
  - Both DC and bunched beams

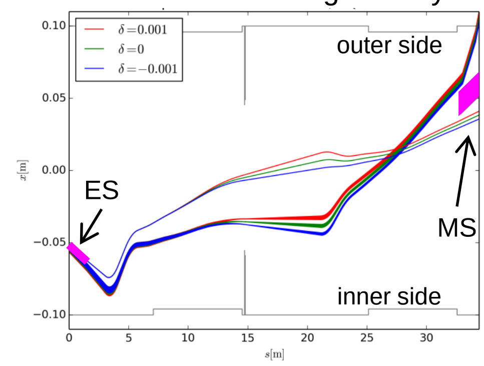
SIS18 extraction optic: hor. envelopes



SIS18 extraction orbit

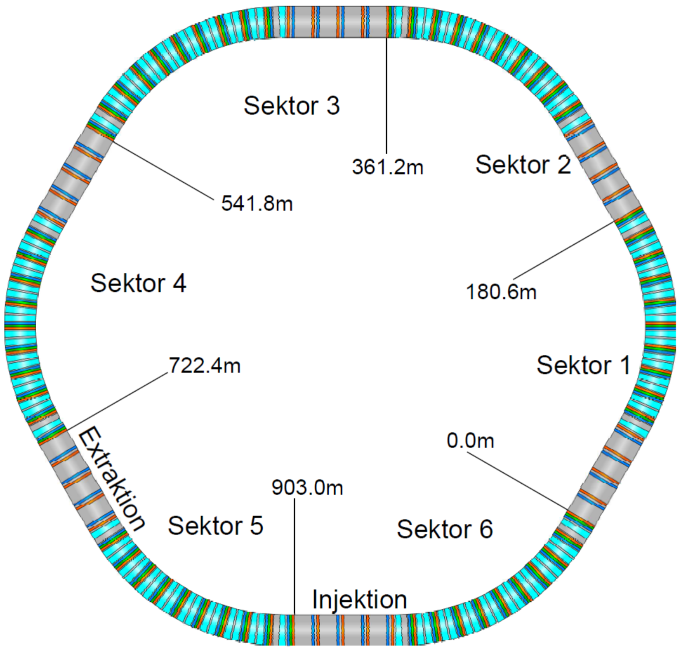


SIS18 extraction geometry



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



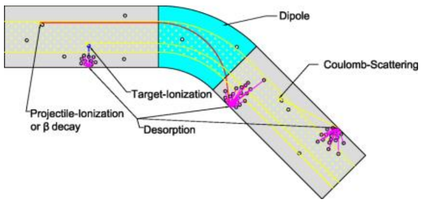
SIS100 optical parameters (SX)	
Q_h / Q_v	17.31 / 17.4
Q'_h / Q'_v	-20.3 / -20.6
α_p	0.005
γ_t	14.2

SIS100: Charge Separator Lattice

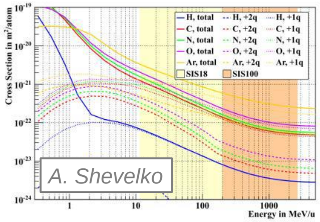
- Increased intensities due to low charge states
  - Higher intensities from linac (no stripping)
  - Increased intensities due to lower space charge
  - FAIR design ion U^{28+} (instead of U^{73+})
  - Emittances like in SIS18 for low charge state ions
- Stable vacuum becomes critical issue
  - High 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

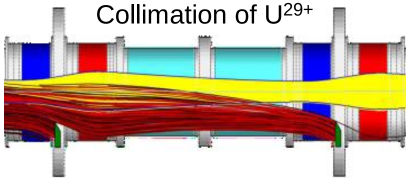
Vacuum instability by desorption



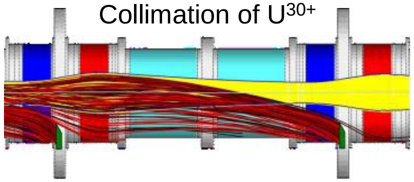
e-loss cross sections



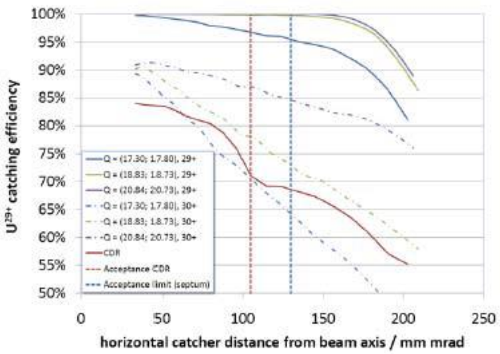
Collimation of U^{29+}



Collimation of U^{30+}



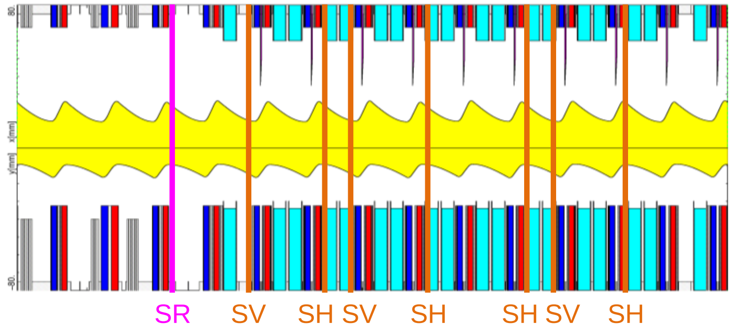
Catching efficiency for different tunes



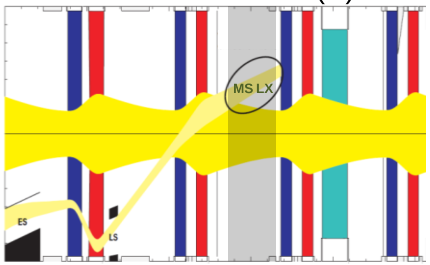
SIS100: Slow Extraction Layout

- 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 100µm 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 mode: KO extraction
  - Forced by small x' acceptance of SX scheme

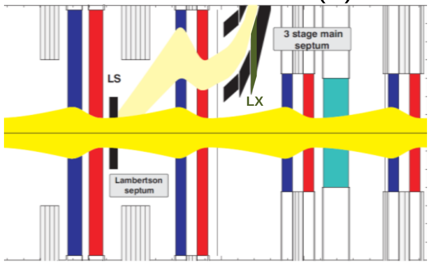
SIS100 slow extraction optic: envelopes



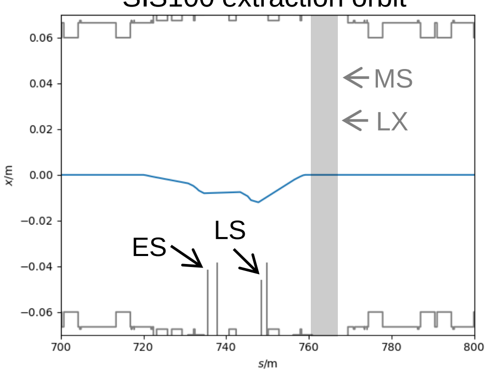
Extraction channel (H)



Extraction channel (V)



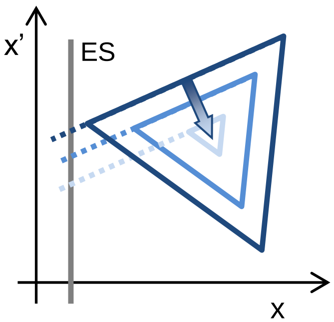
SIS100 extraction orbit



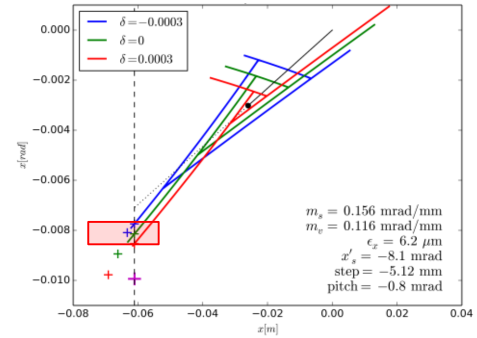
Quad Driven Slow Extraction

- Principle
  - Tune ramp by pair of extraction quads
  - Chromaticity uncorrected ($Q' \approx -6$)
  - Effectively a momentum selection scheme
  - All separatrix sizes contribute to spill
- Features
  - **Large angular spread at ES**
    - Increases (x,x') phase space at ES
    - Prevents dynamic bump scheme
  - Large positional spread at MS
    - Requires higher separation to avoid losses at MS
  - Momentum drift during spill

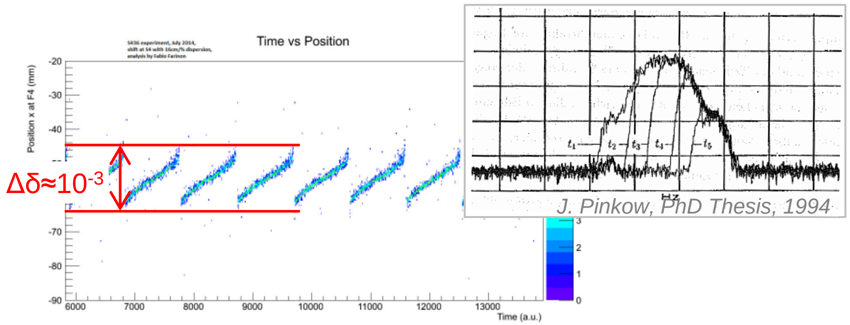
Shrinking separatrices



Angular spread at ES

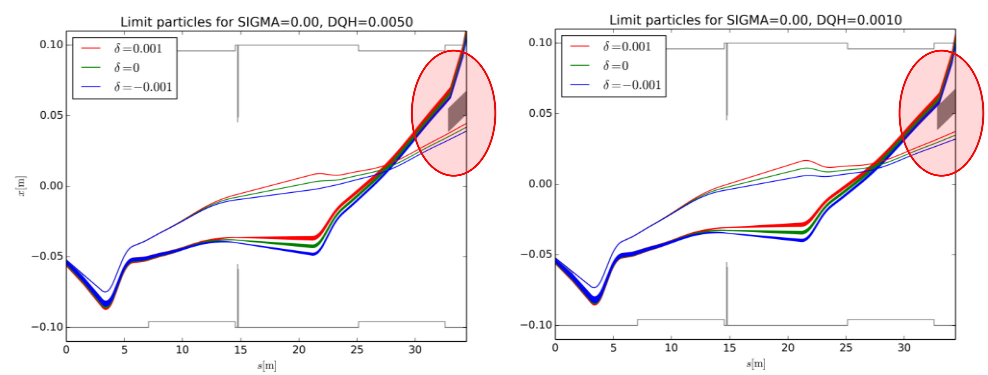


Momentum drift during extraction



Data courtesy H. Weick

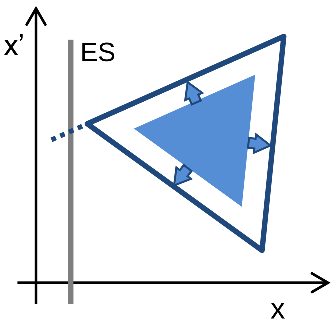
Trajectories at MS for different tune distances



Transverse KO Extraction

- Principle
  - Fixed magnet settings
  - Transverse excitation by band-limited spectrum
  - Excitation makes particles unstable
- Features
  - Requires some degree of chromaticity correction
    - Angular spread at ES would cause high losses
    - Separatrix for far end of momenta may not exist
  - **Small angular spread at ES by design**
- Design extraction scheme for SIS100

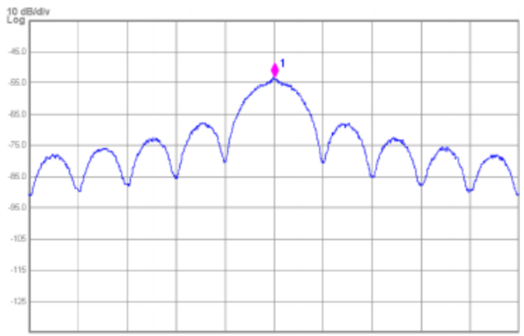
Exciting beam



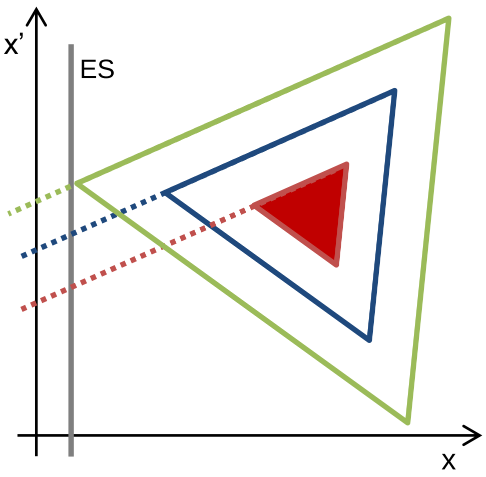
Smallest separatrix must fit horizontal emittance!

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

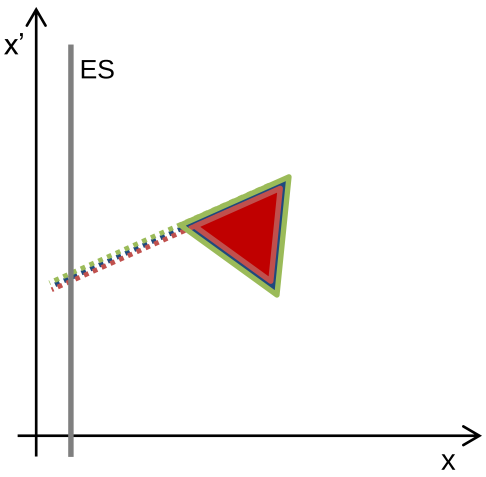
Spectrum of BPSK noise used at SIS18



Chromaticity uncorrected

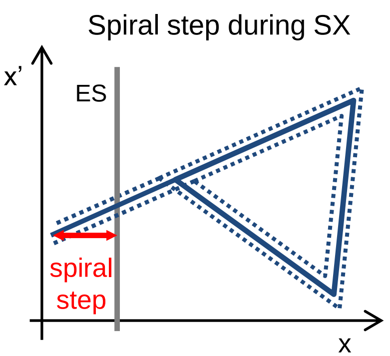


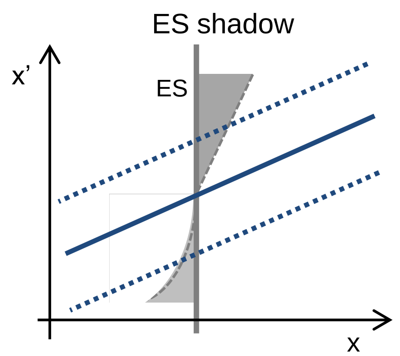
Chromaticity corrected

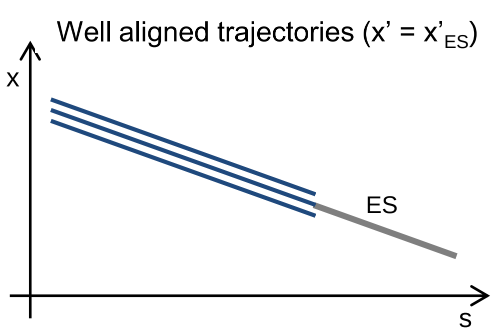


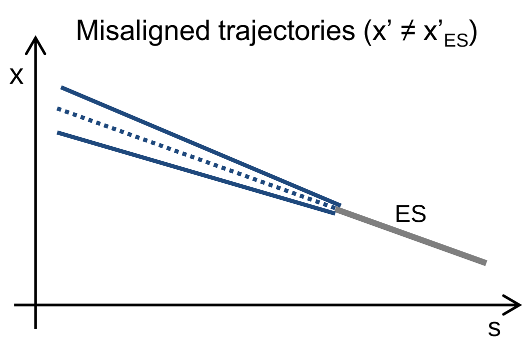
Losses Caused by ES

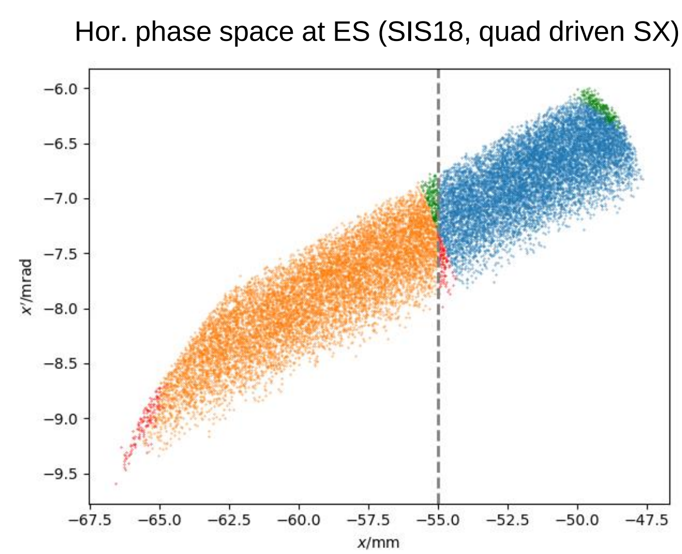
- Geometric wire cross-section
  - Fraction lost: (wire diameter)/(spiral step)
  - Limits: wire properties and beam dynamics
  - Typical values for FAIR: 100µm/[3…10mm]
  - Peak of energy deposition in first wires
- Angular spread at ES
  - Separatrix not infinitely thin in practice
  - Increase of effective thickness
  - Losses more distributed over length of ES







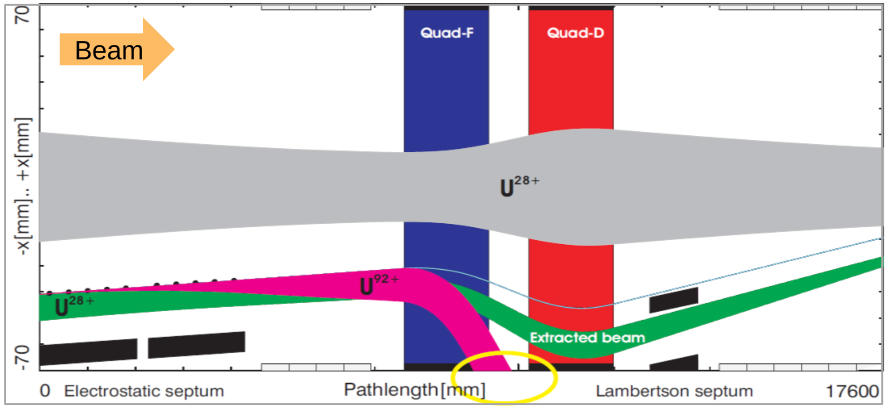




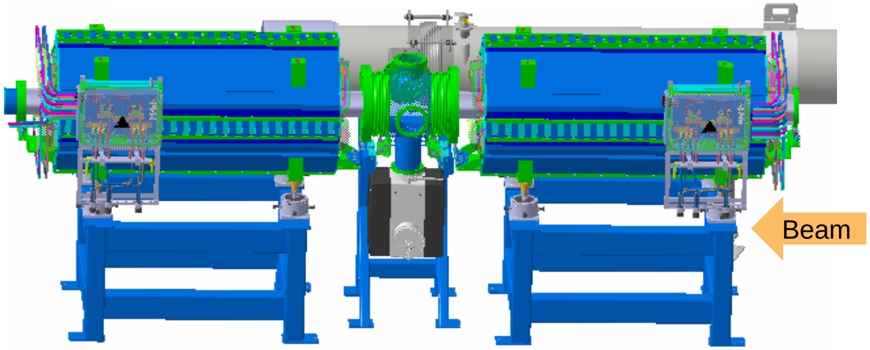
SIS100 SX:
Losses through Septum Wires

- Challenge: control of losses caused by ions interacting with septum wires
  - FAIR intensities require low charge ions (e.g. U^{28+})
  - Fully stripped when interacting with wires
  - Large shift in rigidity causing particles to get lost
- Main loss position: doublet downstream septa
  - Energy deposition prevents use of SC quadrupoles
  - Replacement by two NC 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
- Expectations for losses of U^{28+}
  - Design goal: < 5% losses
  - Collimation systems can digest 10% losses
  - Total beam energy ~30kJ at reference energy

Expected loss position for stripped Uranium in extraction channel



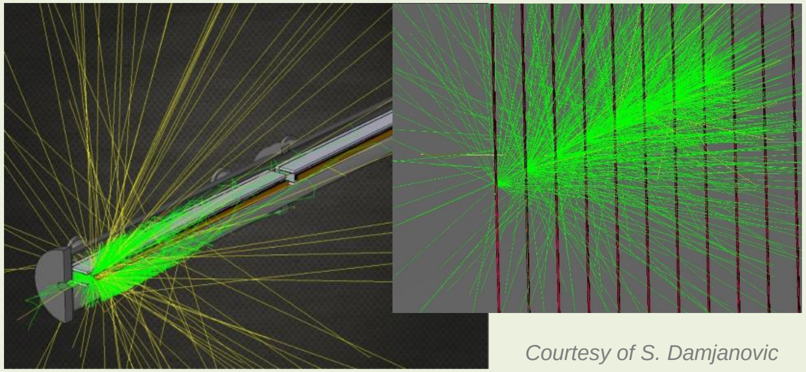
NC radiation resistant quadrupoles in cell S52



SIS100 Stripping Losses: Simulations

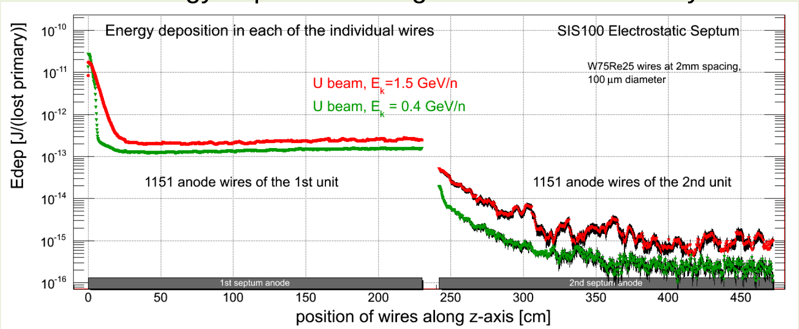
- Interaction with septum wires
  - High energy loss in wires
    - U @ 1.5 GeV/u : dE/E = 6.3 %
    - p @ 10 GeV/u : dE/E = 0.03 %
    - Scattering into ring and extraction path
  - Ions colliding with wires fully stripped
  - Ion dependent scattering and transport
- Simulations
  - FLUKA simulation of wire interactions
  - Ion optical tracking of scattered ions behind ES
  - Real chamber geometries taken into account
- Determination of loss positions
  - Identification of appropriate positions for collimation
  - Sufficient margin to circulating and extracted beam

FLUKA simulation of ions interacting with septum wires

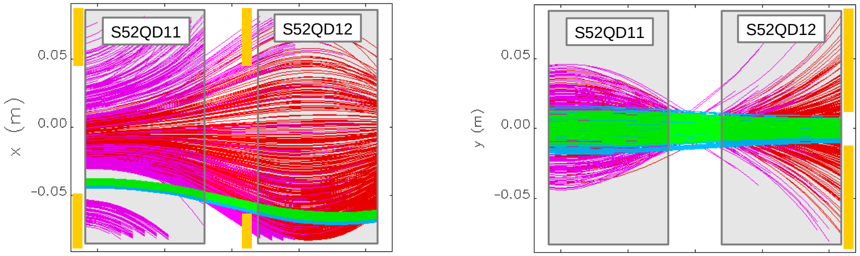


Courtesy of S. Damjanovic

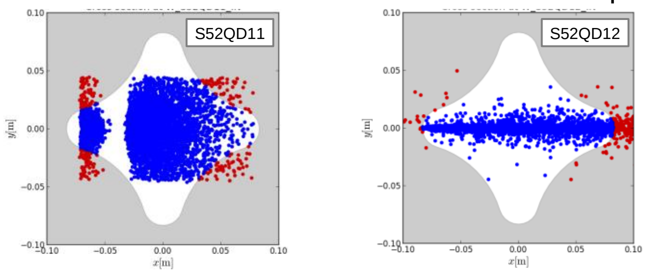
Energy deposition along the two ES wire arrays



Transport of scattered ions through RH quadrupoles



Distribution of scattered ions at entrance to RH quads



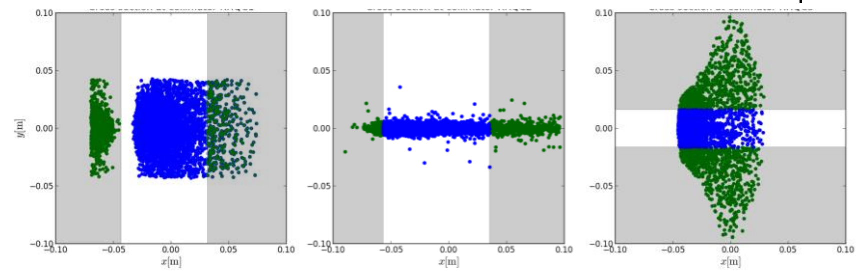
SIS100 Stripping Losses: Collimation

- Three locations for collimators
  - Upstream RRQ-D (horizontally)
  - Between both RRQs (horizontally)
  - Downstream RRQ-F (vertically)

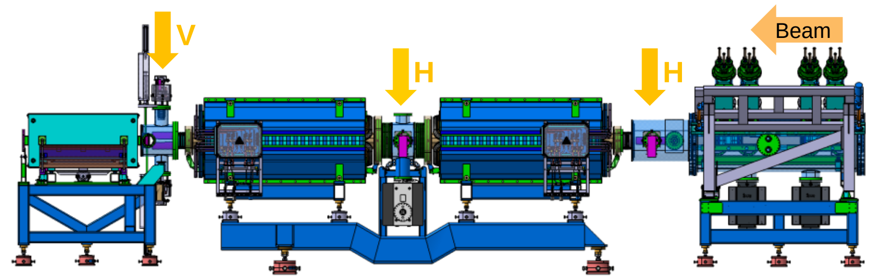
- Collimation efficiency
  - For U^{28+} up to 75% of stripped particles collimated (depending on energy)
  - Unavoidable losses tolerable (kicker magnets, vacuum chambers)

- Collimator design
  - Length about 30cm sufficient to stop primaries
  - **Dissipated power up to 500W per collimator**
  - Water cooled copper blocks

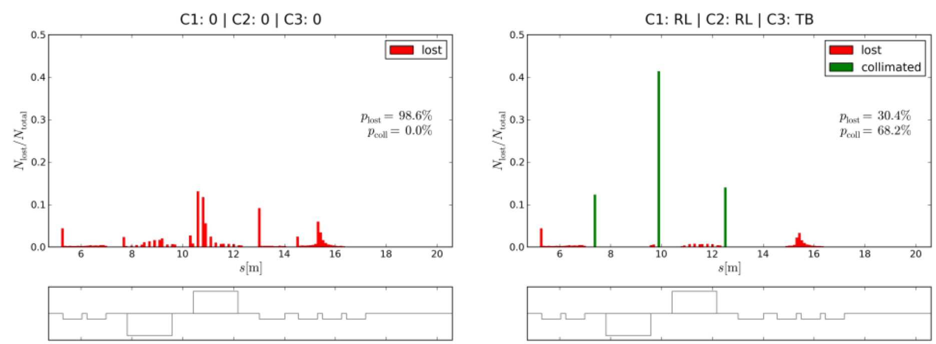
Beam cross section at collimators around radiation resistant quads



Collimator positions around radiation resistant quadrupoles



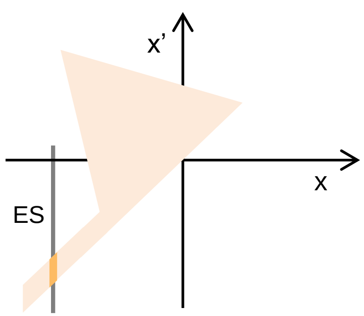
Loss distribution in cells S52 and S53 without and with collimators

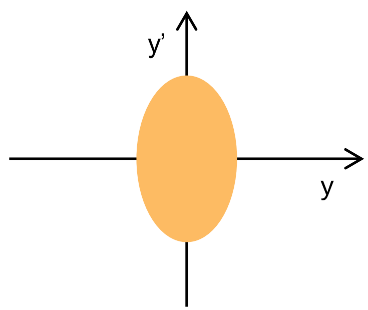


SIS18 Beam Parameters

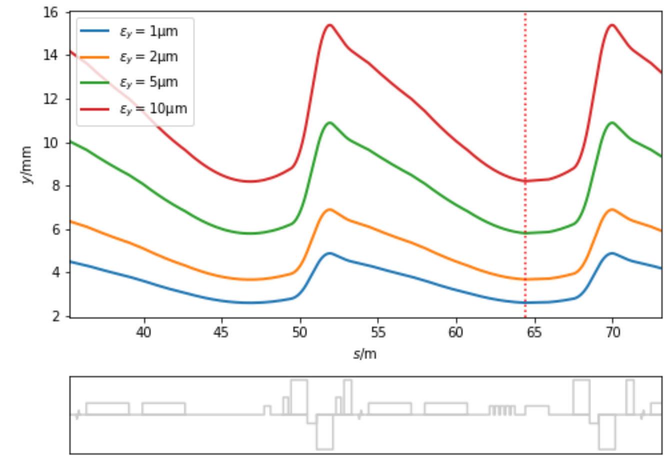
Beam loss	
Beam energy	1 kJ
Max. rep rate	0.5 Hz
Lost fraction	< 20%
Lost power	< 100 W

Transverse beam size	
Hor. radius	~ 0.3 mm
Hor. divergence (KO ex.)	~ 0.1 mrad
Vertical radius	~ 10 mm
Vertical divergence	~ 1 mrad

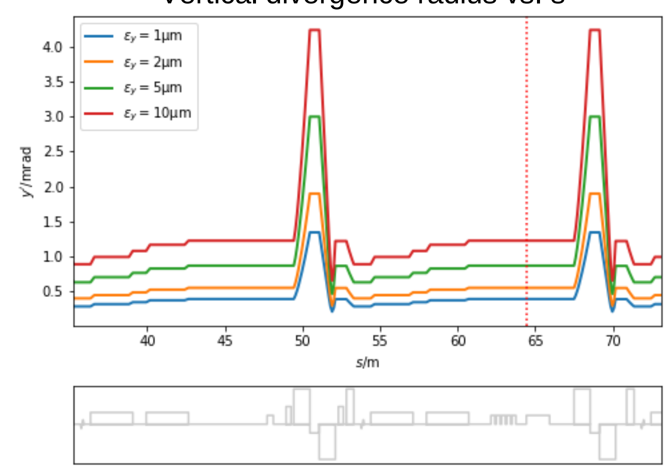




Vertical beam radius vs. s



Vertical divergence radius vs. s

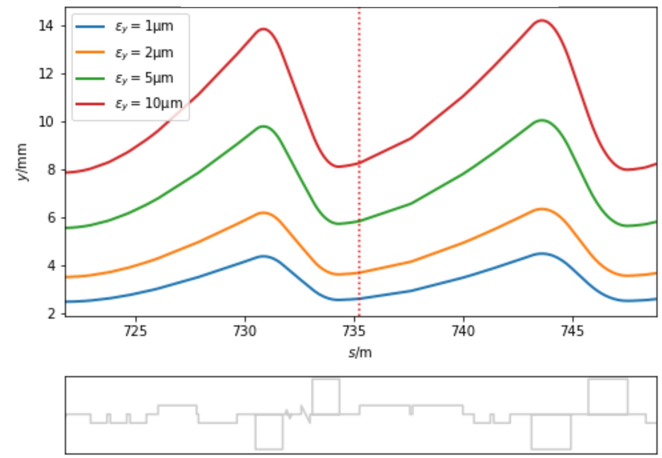


SIS100 Beam Parameters

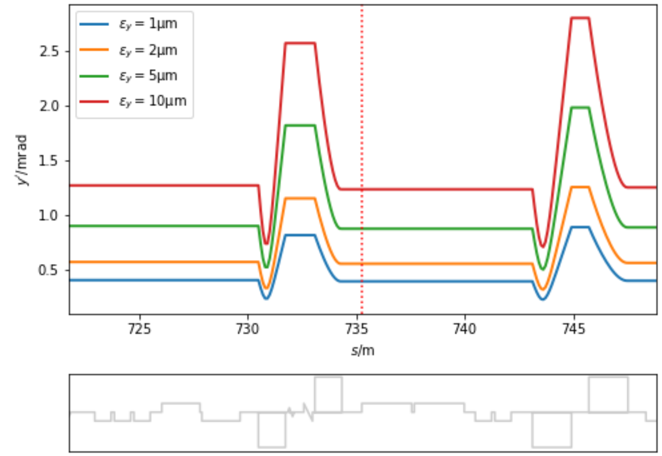
Beam loss	
Beam energy	30 kJ
Max. rep rate	0.33 Hz
Lost fraction	< 5%
Lost power	< 500 W

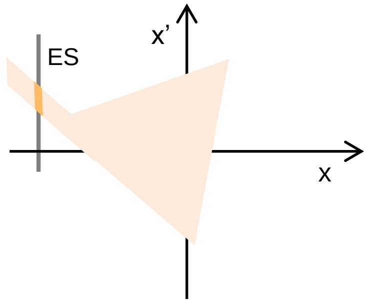
Transverse beam size	
Hor. radius (KO ex.)	~ 5 mm
Hor. divergence (KO ex.)	~ 0.1 mrad
Vertical radius	~ 10 mm
Vertical divergence	~ 1 mrad

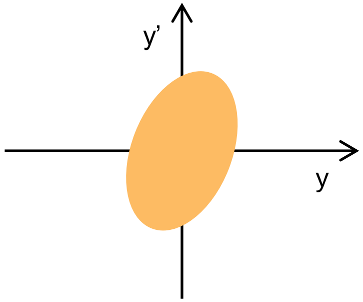
Vertical beam radius vs. s



Vertical divergence radius vs. s







Thanks for your attention!

SIS100 Construction Site 04/2022