System Design
Studies and Modifications

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4th SIS100 Workshop, Kloster Eberbach

22 September 2025

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- Slow extraction with field errors
- Xsuite studies of KO extraction
- Emergency beam dump
- Halo collimation
- Kicker cable issues

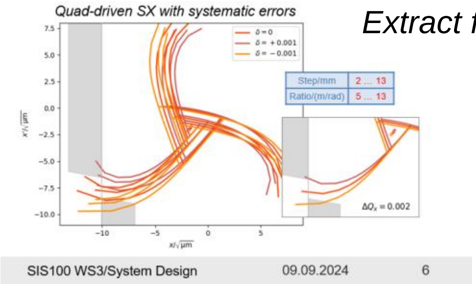
- Summary

Slow Extraction with Field Errors

B. Galnander

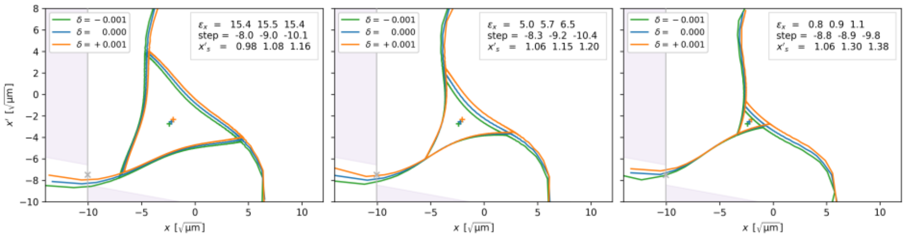
- Slow extraction design affected by errors
  - Main challenge: b_5 (dip) and b_6 (quad)
  - Reported during last SIS100 WS
  - Requires changes to SX design

- Adapted SX design defined
  - Working schemes with baseline lattice
    - KO extraction
    - COSE
  - Schemes requiring b_5 corrector
    - Quadrupole-driven SX
  - High extraction efficiency in ideal machine
  - Designed with margin for field errors

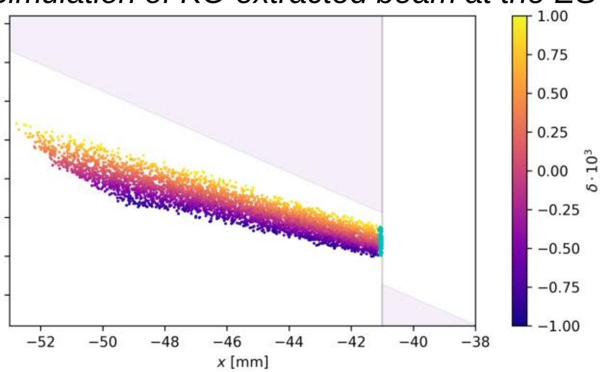


Extract from WS3

Working quad-driven SX with b5 compensation



Simulation of KO extracted beam at the ES



SX performance of adapted design

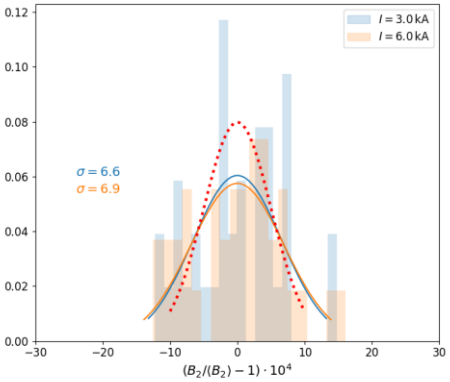
SX Scenario	b5-Corr	Losses
KO, 8 um	No	1.8%
KO, 28 um	No	2.2%
COSE, 10 um	No	2.1%
COSE, 28 um	No	3.5%
Quad-scan, 10 um	Yes	3.2%
Quad-scan, 15 um	Yes	3.9%

SX with Field Errors: Random Error Studies

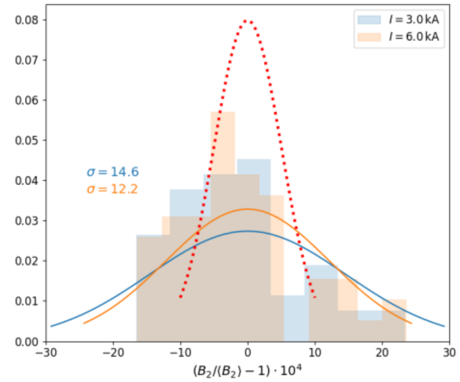
S. Sorge (APH)

- Magnet errors taken into account
  - Alignment errors (±2mm)
  - Variation of integral field
  - Random multipole errors
- Simulation procedure per scenario
  - 10 random error seeds
  - Optimizer to match separatrix (size, step, angle)
  - Tracking with MAD-X: 1000 particles, 25000 turns
- Preliminary result: adapted design robust
- Remaining issues
  - Possible underestimation of quad field variation
  - Missing quadrupole roll
  - Difficulties with matching for COSE
  - To be solved before publishing of report

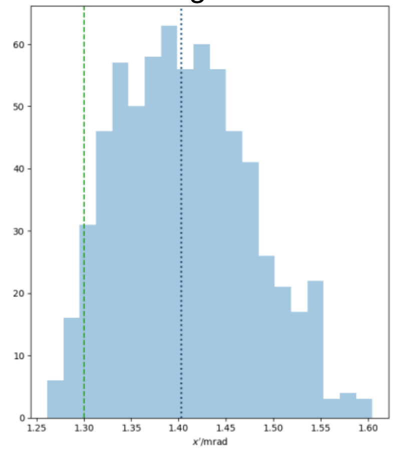
$\Delta B_2/B_2$: magnetometer 2



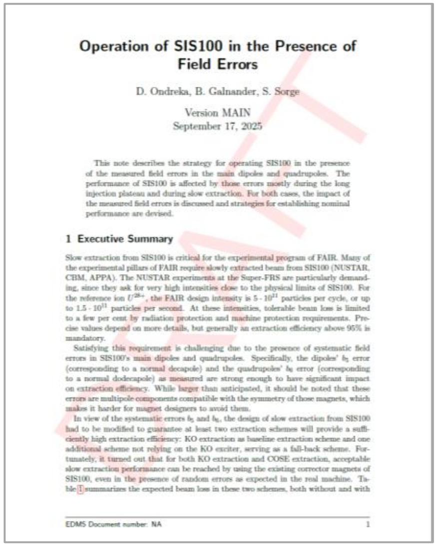
$\Delta B_2/B_2$: all magnetometers



COSE: angle mismatch



Report available (draft)



Operation of SIS100 in the Presence of Field Errors

D. Ondreka, B. Galnander, S. Sorge

Version MAIN
September 17, 2025

This note describes the strategy for operating SIS100 in the presence of the measured field errors in the main dipoles and quadrupoles. The performance of SIS100 is affected by those errors mostly during the long injection plateau and during slow extraction. For both cases, the impact of the measured field errors is discussed and strategies for establishing nominal performance are devised.

1 Executive Summary

Slow extraction from SIS100 is critical for the experimental program of FAIR. Many of the experimental pillars of FAIR require slowly extracted beam from SIS100 (NUSTAR, CBM, APPA). The NUSTAR experiments at the Super-FRS are particularly demanding, since they ask for very high intensities close to the physical limits of SIS100. For the reference ion U^{28+}, the FAIR design intensity is $5\cdot10^{11}$ particles per cycle, or up to $1.5\cdot10^{11}$ particles per second. At these intensities, tolerable beam loss is limited to a few per cent by radiation protection and machine protection requirements. Precise values depend on more details, but generally an extraction efficiency above 95% is mandatory.

Satisfying this requirement is challenging due to the presence of systematic field errors in SIS100's main dipoles and quadrupoles. Specifically, the dipoles' b_5 error (corresponding to a normal decapole) and the quadrupoles' b_6 error (corresponding to a normal dodecapole) as measured are strong enough to have significant impact on extraction efficiency. While larger than anticipated, it should be noted that these errors are multipole components compatible with the symmetry of those magnets, which makes it harder for magnet designers to avoid them.

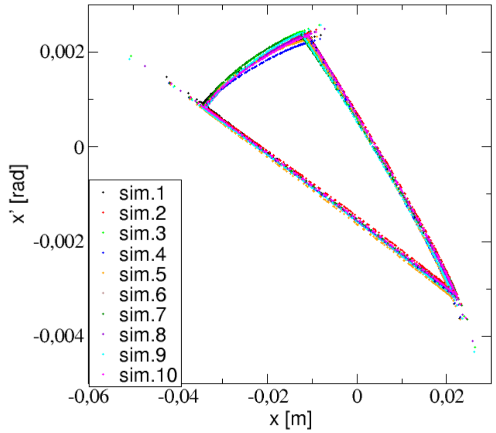
In view of the systematic errors b_5 and b_6, the design of slow extraction from SIS100 had to be modified to guarantee at least two extraction schemes will provide a sufficiently high extraction efficiency: KO extraction as baseline extraction scheme and one additional scheme not relying on the KO exciter, serving as a fall-back scheme. Fortunately, it turned out that for both KO extraction and COSE extraction, acceptable slow extraction performance can be reached by using the existing corrector magnets of SIS100, even in the presence of random errors as expected in the real machine. Table 1 summarizes the expected beam loss in these two schemes, both without and with

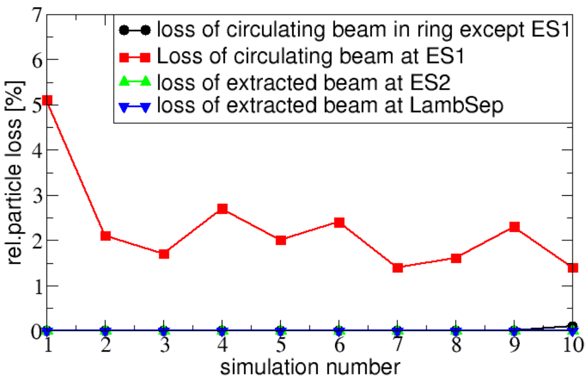
EDMS Document number: NA 1

SX with Field Errors: Random Error Studies

S. Sorge (APH)

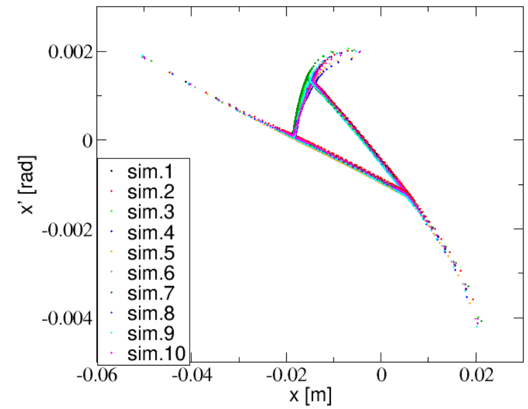
KO extraction, 28 mm*mrad (U28+, 400 MeV/u)

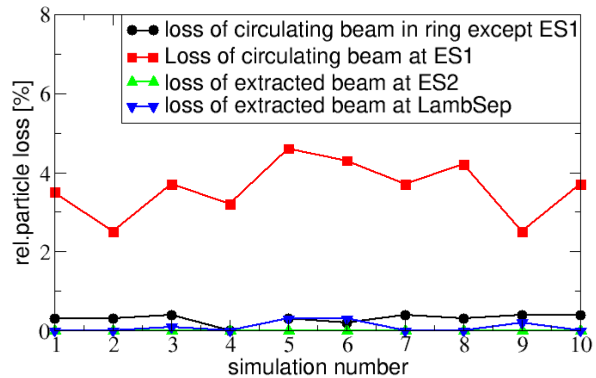




Losses (ideal)	2.2%
Avg. losses (errors)	2.3%

COSE, 10 mm*mrad (U28+, 1.5 GeV/u)





Losses (ideal)	2.1%
Avg. losses (errors)	3.9%

probably artefact from angle mismatch

KO Extraction:
Excitation and Spill Quality

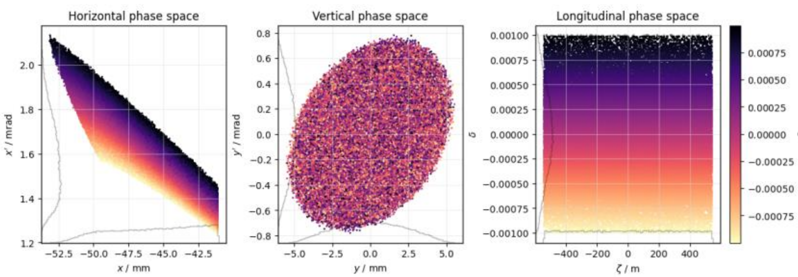
Ph. Niedermayer (ACC)

- Simulation toolbox for SIS100 established
  - Xsuite on HPC (0.1Mpart * 0.6Mturns in few hours)
  - First runs (U28+, 1.5 GeV/u) by Ph. Niedermayer
  - Successfully benchmarked with Elegant
  - Training of SYS members ongoing

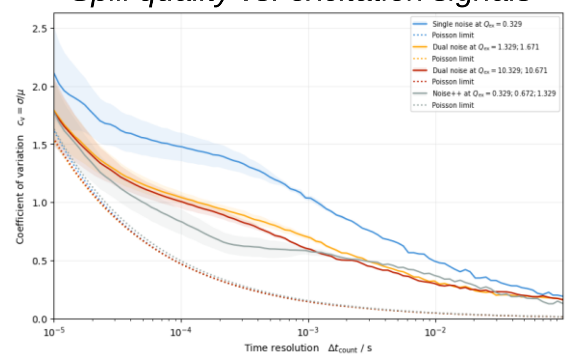
- Preliminary results
  - 95% extracted within 2 s with $\Delta U_{RMS} \leq 500$ V
  - Much better spill quality for multi-freq signals
  - Most signals within present KO exciter spec

- Work to be continued within SYS
  - Systematic study to validate exciter requirements

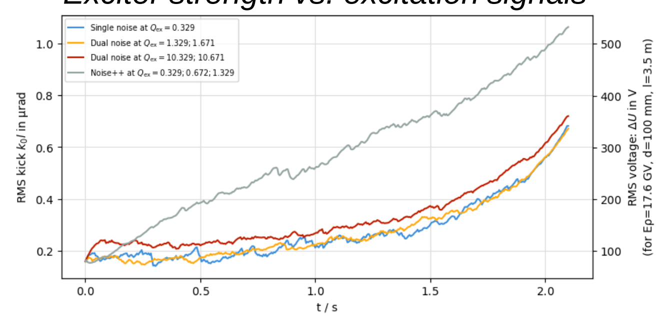
Phase space plots from Xsuite



Spill quality vs. excitation signals



Exciter strength vs. excitation signals

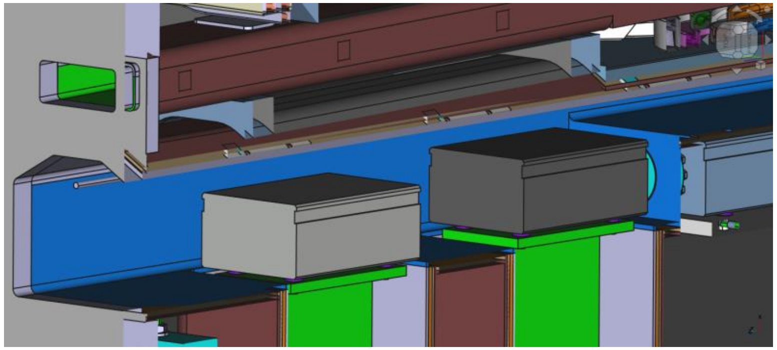


Beam Dump: Missing Pieces

R. Martin

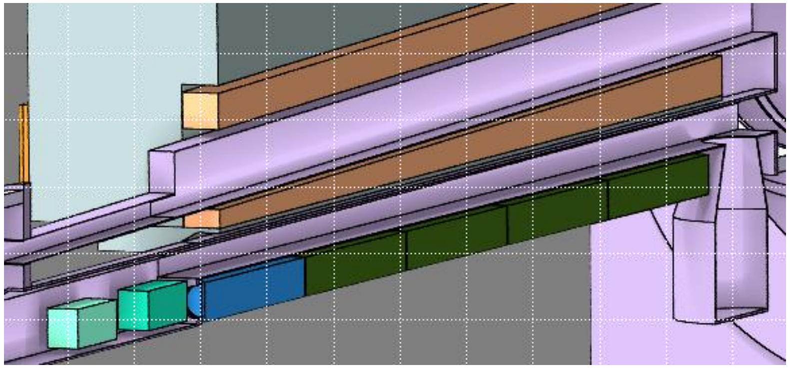
- Internal carbon absorbers
  - Supplier only delivers pedestal (I-beam)
  - Carbon absorber including holder must be designed and procured
    - Sandwiched structure of CFC material
    - Test of sample by vacuum group pending (handling for installation)

Present status of carbon holder design (Elytt)



- Material for external absorbers decided
  - First block made from Ti6Al4V
    - Required to avoid damage from proton dumps
  - 5 Densimet blocks to be delivered by Elytt
  - Ti6Al4V block needs to be procured

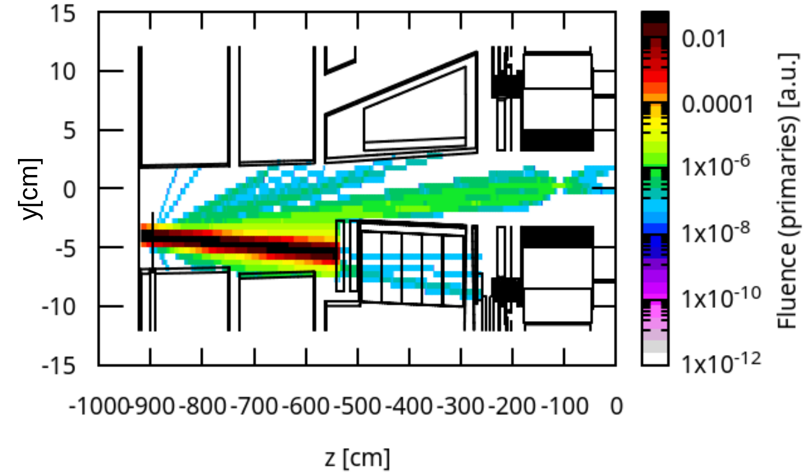
Internal and external absorbers



Beam Dump: Quenching for U28+

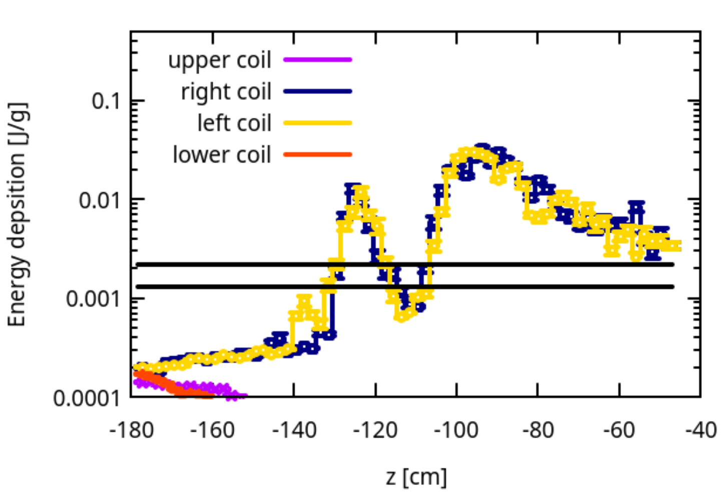
R. Martin

- FLUKA simulations for $5 \cdot 10^{11}$ U28+ at 1.5 GeV/u
- Quench limit exceeded by more than factor 10
- Root cause: secondaries created in diffusor
- Strong defocusing in first quad behind dump
- Mitigation by tungsten wedge will be investigated

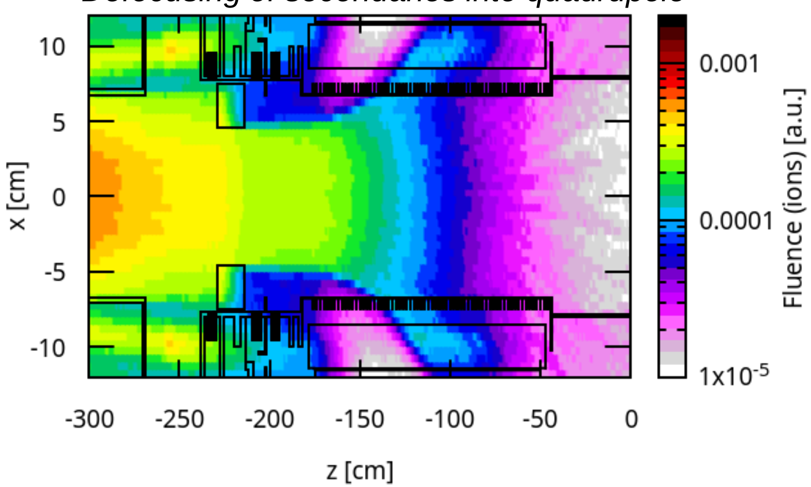


Trajectories through beam pipe

U28+ beam, tighter absorber, larger offset, quads on



Defocusing of secondaries into quadrupole

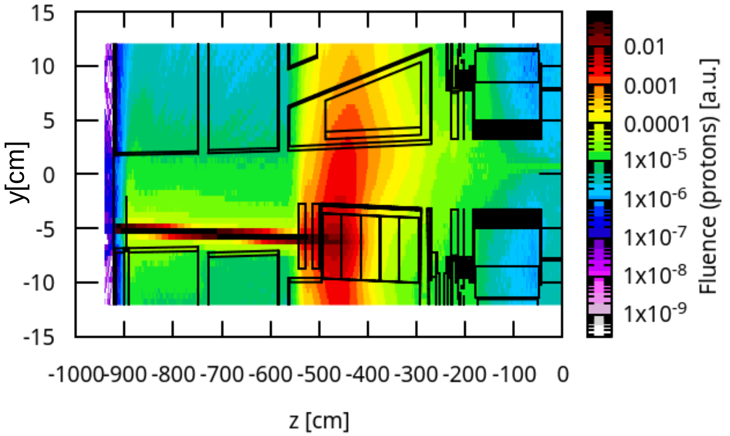


Beam Dump:
Quenching for Protons

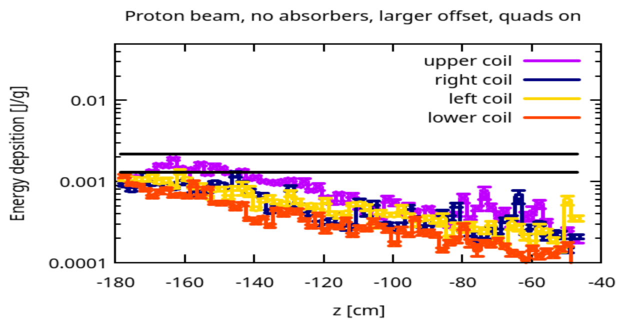
R. Martin

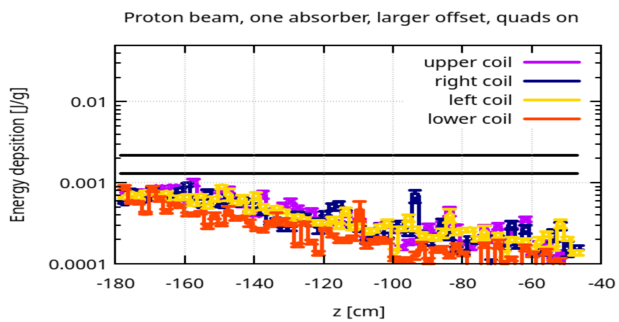
- FLUKA simulations for $2.5 \cdot 10^{13}$ p at 29 GeV/u
- Lower quench limit exceeded
- Root cause: shower created in external dump
- Mitigation through tungsten absorber proposed
- Challenging integration between valve and cryostat

Fluence of protons

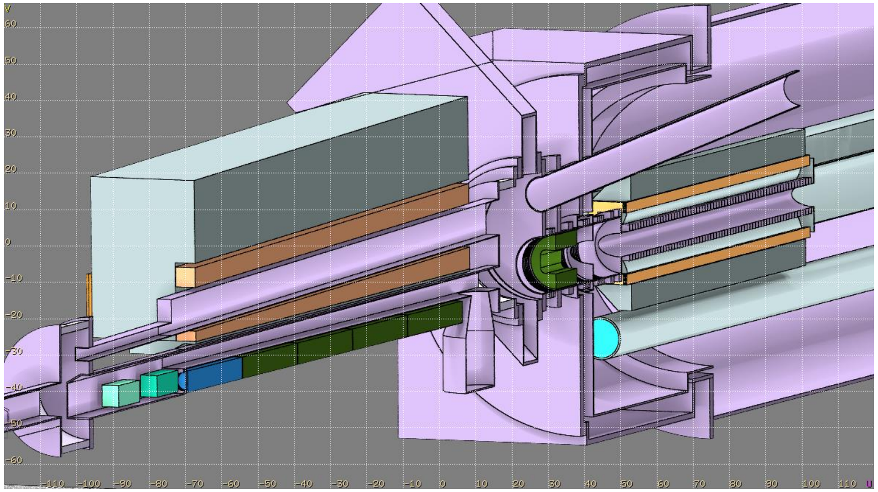


Energy deposition w/ and w/o absorber



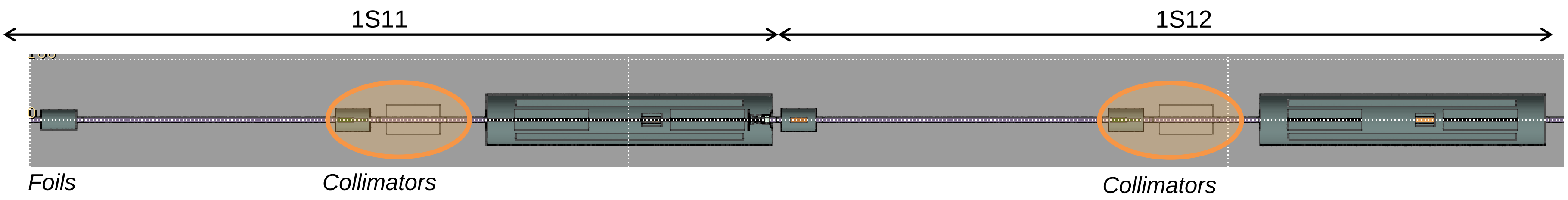


Tungsten absorber within beam pipe

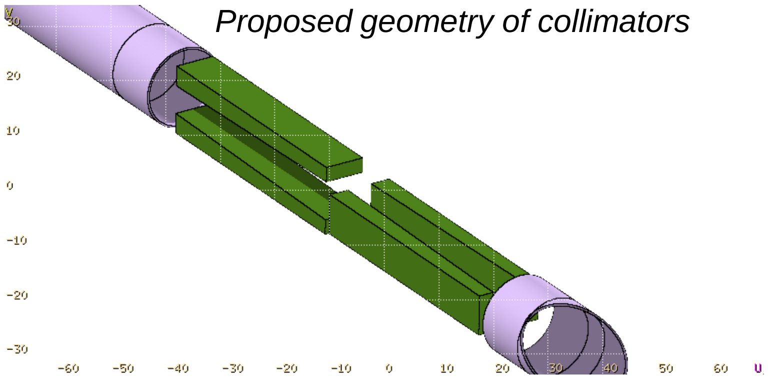


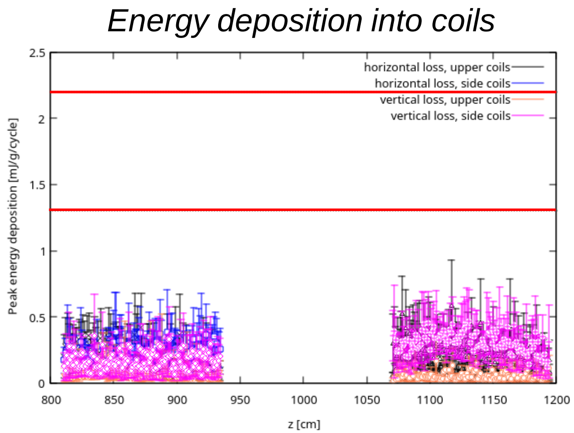
Halo Collimation:
Protons and Fully Stripped Ions

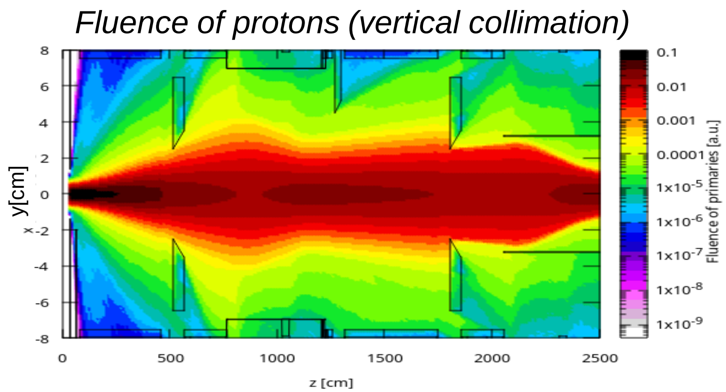
R. Martin, L. Bozyk (SIS)



- Geometry of collimator blocks decided
  - Separate collimators for H and V
  - Much simpler manufacturing and handling
- Quadrupoles will not quench
- Verification of multi-pass performance ongoing



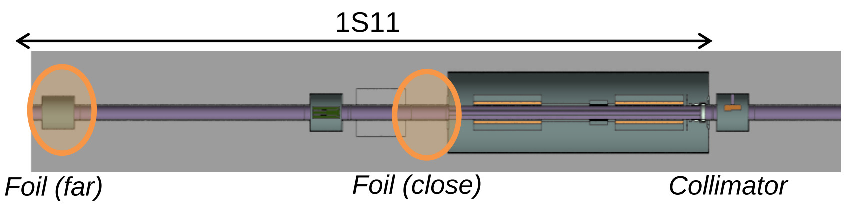




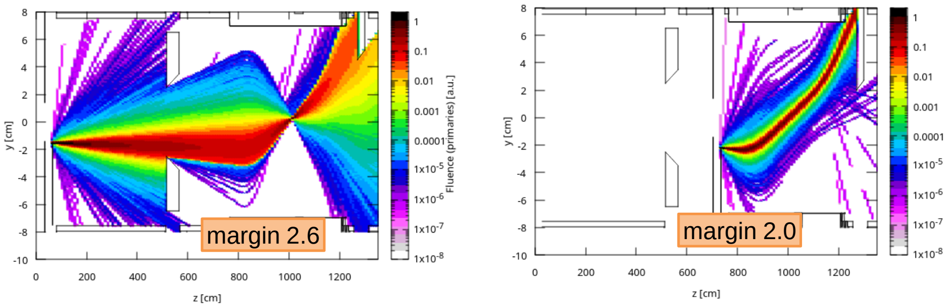
Halo Collimation:
Partially Stripped Ions (Vertical)

R. Martin

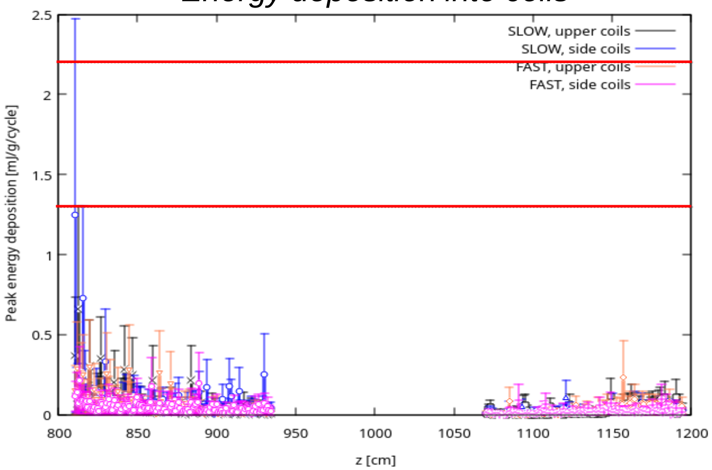
- High energy deposition in chamber
  - U28+, design intensity: 10 to 30 W for 5% loss
  - Additional losses in CWT
- Position of stripping foil to be decided
  - Close position: 15 W loss but only margin 2.0
  - Far position: 30 W loss but full margin (2.6)
  - Alternative: install two stripping foils
- Quadrupoles will not quench
- Radiation damage seems acceptable



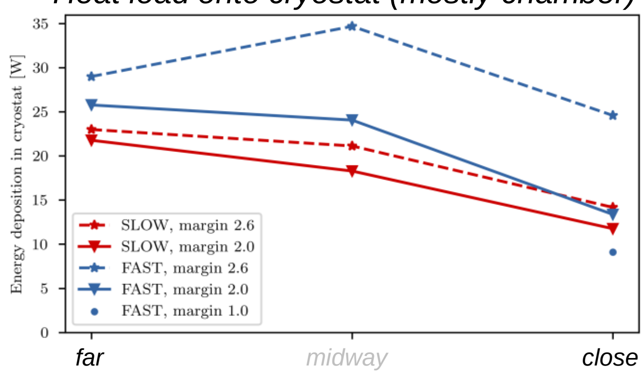
Stripped particles for far and close foil position (margin 2.6)



Energy deposition into coils



Heat load onto cryostat (mostly chamber)

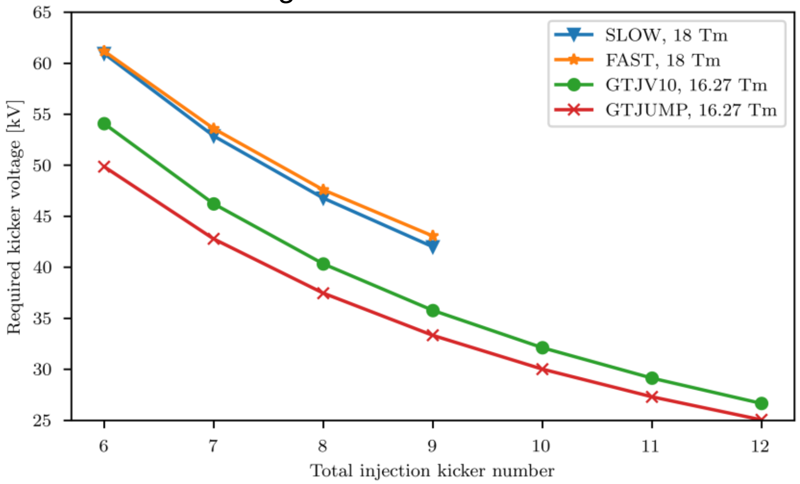


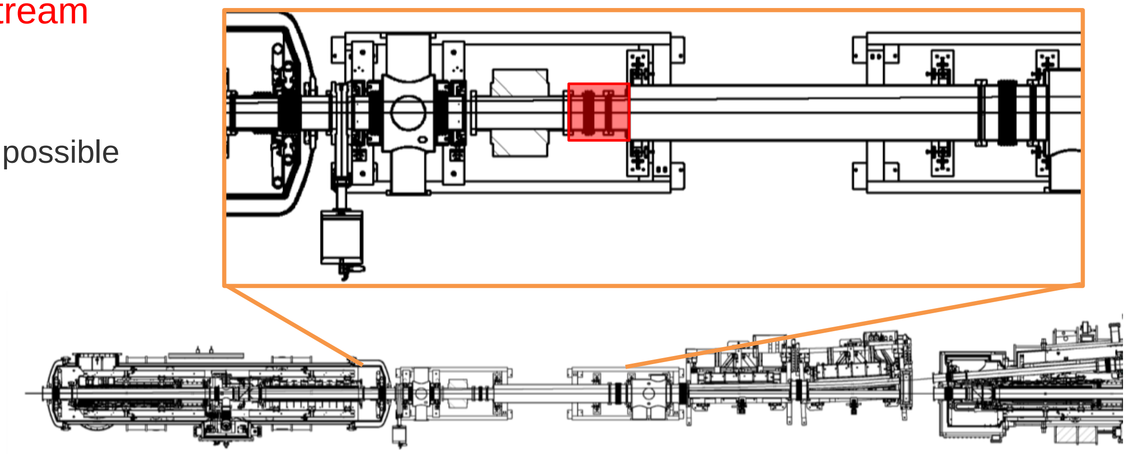
Kicker Cables: Injection

R. Martin

- Installation of two additional kicker units
  - Second module downstream of first
  - Relaxes requirements on max. voltage
- Extensive studies of scenarios
  - Example: SLOW optic
    - Design injection at 18 Tm
      - 6 units: 61 kV
      - 8 units: 48 kV
    - Limit of max. 40 kV voltage, injection with ‘tricks’
      - 6 units: injection at 13 Tm possible
      - 8 units: injection close to 18 Tm possible
- Aperture transition to be moved downstream
  - Reasons: more units and margin for ‘tricks’
  - Larger aperture for at least 20 cm more
  - Shift BI components as far downstream as possible

Kicker voltage vs. number of kicker units





Kicker Cables: Extraction

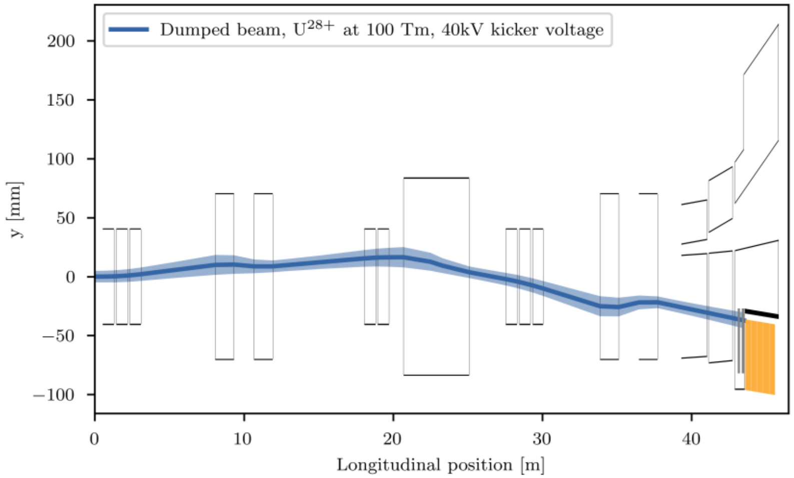
R. Martin

Consequences of 40 kV max. voltage

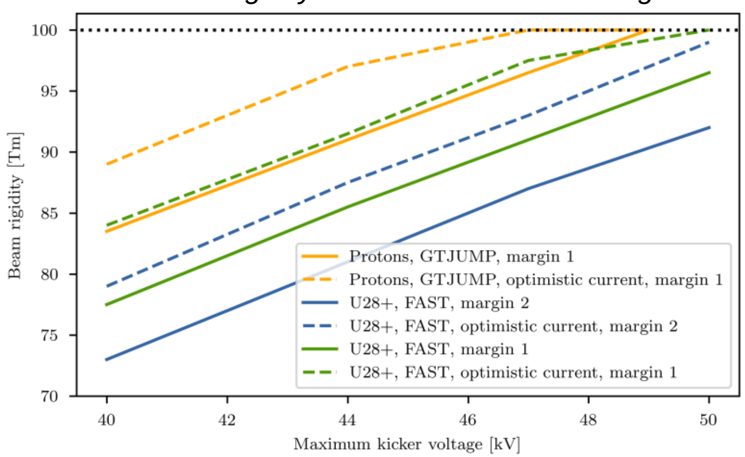
- Slow extraction (optic SLOW)
  - Safe emergency dumping up to 69 Tm
  - Sufficient for NUSTAR U28+ reference beam
  - No experiments with high intensities above 69 Tm
    - Dumping of 10^{10} above 69 Tm is acceptable (and better than uncontrolled loss!)
- Protons for pbar (optic GTJV10, $Q_v = 10.3$)
  - Extraction up to 100 Tm possible with jump optic
  - Polarity change from cycle to cycle required!

- Limitations for other modes
  - Fast extraction (optic FAST)
    - Extraction and dumping up to 85 Tm
  - Protons (optic GTJUMP with $Q_v = 18.3$)
    - Extraction and dumping up to 73 Tm

Dumping in SLOW optic with 40 kV at 100 Tm



Max. rigidity vs. available kicker voltage



List of Open Topics

Category	Topic
SX with errors	Eliminate remaining issues and finalize report
KO extraction	Systematic study to validate exciter requirements
Beam dump	Design and procurement of carbon absorber including holder
Beam dump	Switching of first external absorber from W to Ti
Beam dump	Study on preventing quenches from U28+ dumps
Beam dump	Decision on W absorber to prevent quenches from proton dumps
Halo coll. (p + fsi)	Verification of multi-pass collimation efficiency
Halo coll. (psi, v)	Decision on foil layout (number of foils, position)
Injection system	Shift of aperture transition in cell 1S61

Summary

- Robust design for SX in presence of b_5 and b_6 developed
  - KO extraction and COSE work without b_5 corrector
  - Draft version of report ready, finalization after resolution of issues
- KO extraction simulation with Xsuite support present KO exciter design
- Few beam dump topics require decisions and actions
- Foil configuration for vertical halo collimation must be decided
- Consequences of reduced kicker voltage determined
  - Injection: essentially no more issue due to 2 additional units
  - Extraction/Dumping: no issues for First Science++, even protons work

Thanks for your attention!

Special thanks go to those who did most of the work presented here:
L. Bozyk (SIS); B. Galnander, R. Martin (SYS); Ph. Niedermayer (ACC); S. Sorge (APH)