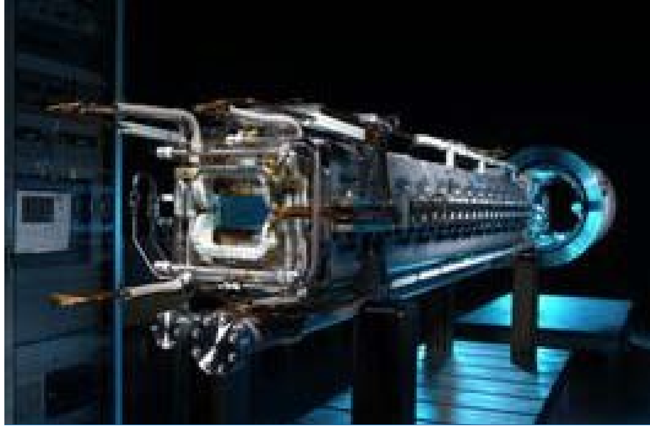
  

FAIR Challenges

Facility for Antiproton and Ion Research

Ralph J. Steinhagen

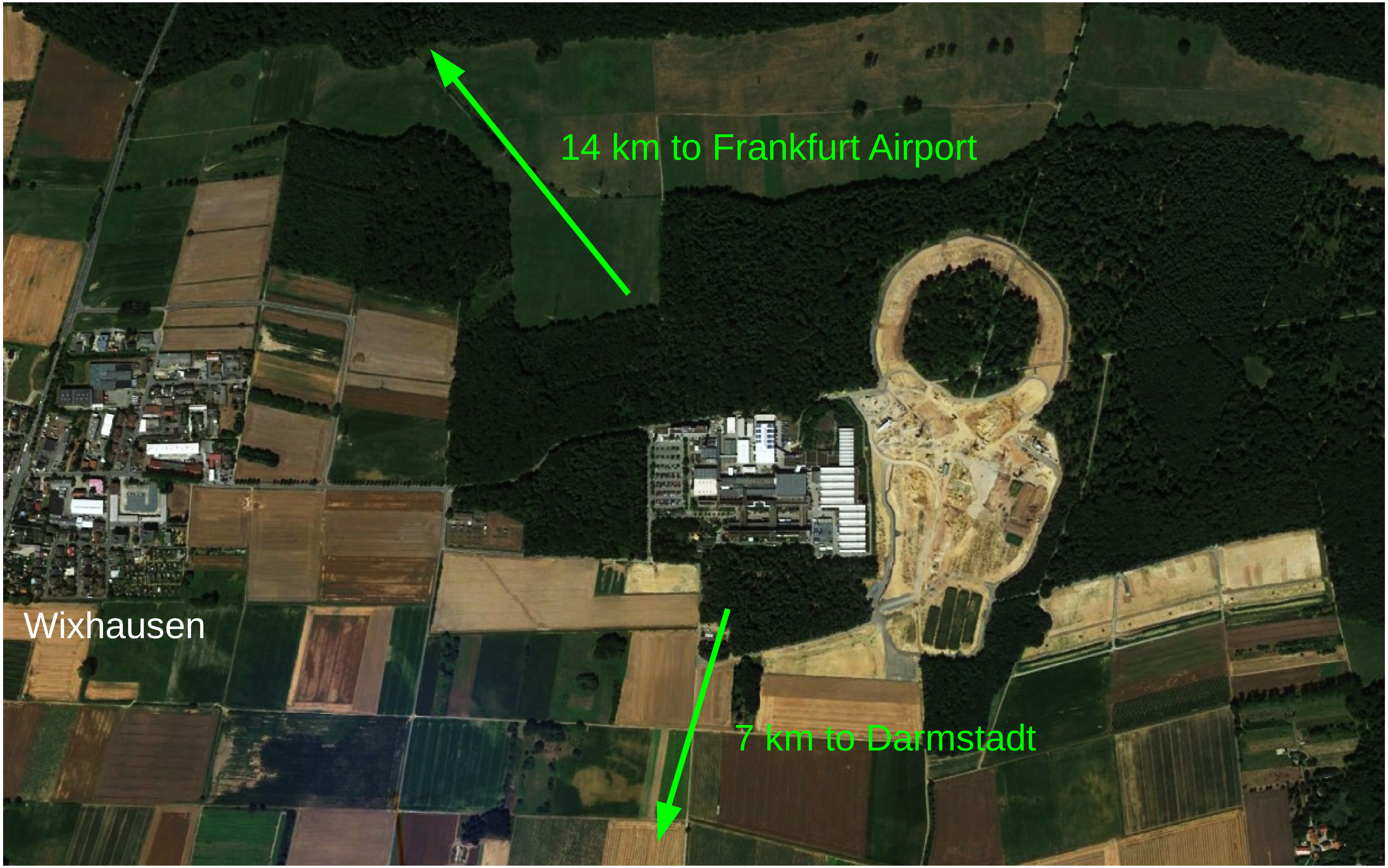
EuCARD^2, Beam Dynamics meets Diagnostics, 4-6 November 2015

Convitto della Calza, Florence, Italy

Finland France Germany India Poland Romania Russia Slovenia Sweden UK

HELMHOLTZ ASSOCIATION

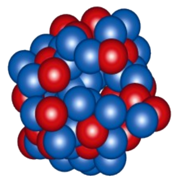
Facility for Anti-proton and Ion Research
Satellite View

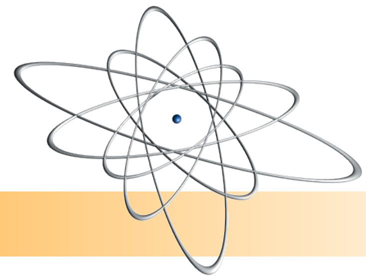


Main Physics Programme

Nuclear Physics & Physics with Hadrons

- Nuclear Reaction from lowest to highest Energies
- Super-heavy Elements
- Compressed Baryonic Matter
- Anti-matter Research
  - new: PANDA (QCD)





Atomic Physics

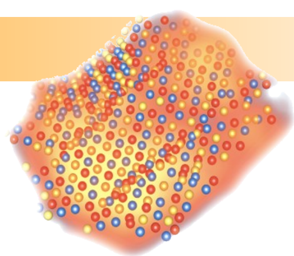
- Atomic Interactions
- Precision Spectroscopy of highly charged Ions

Bio-Physics and Bio-Medical Applications

- Radiobiological effects of ions
- Cancer therapy with ion-beams

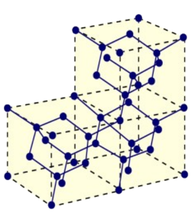
Plasma Physics

- Hot dense Plasmas
- Ion-Plasma Interactions



Material Science

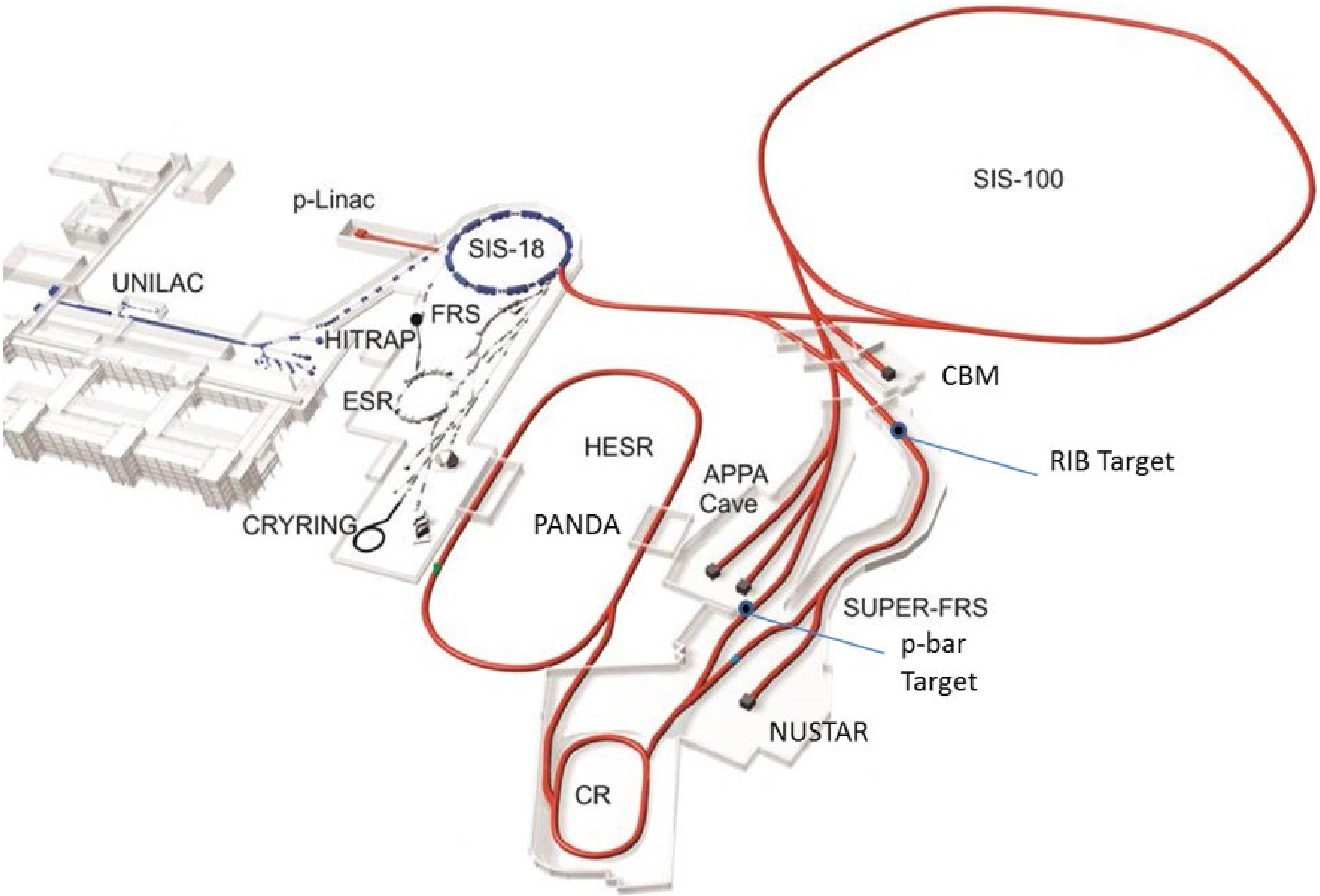
- Ion-Condensed-Matter Interactions
- Nano-structures using ion-beams



Accelerator Technology

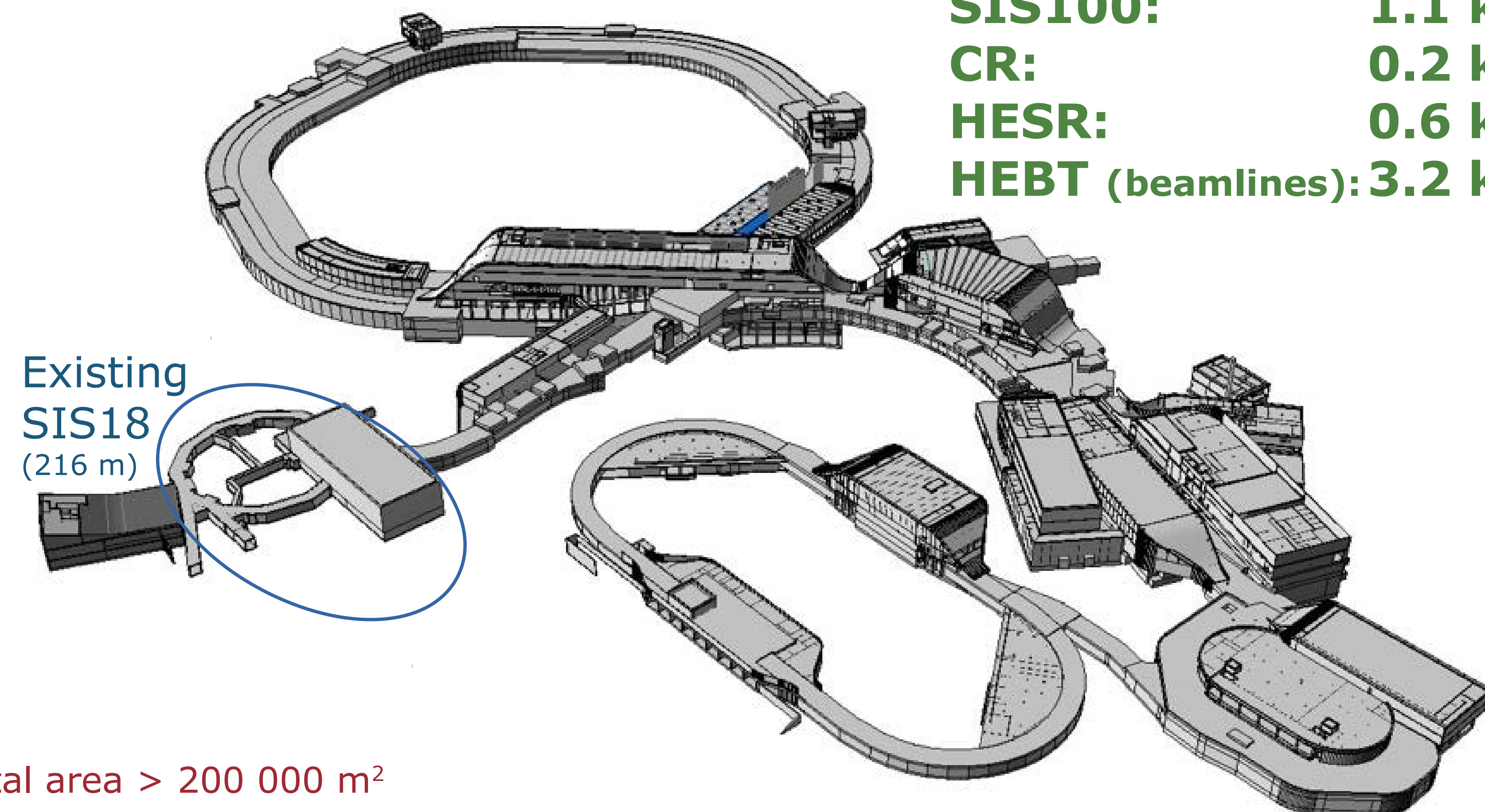
- Linear accelerators
- Synchrotrons and Storage Rings

Modularised Start Version 2020 (MSV0-3)



FAIR Accelerator Complex – Civil Construction

SIS100:	**1.1 km**
CR:	**0.2 km**
HESR:	**0.6 km**
HEBT (beamlines):	**3.2 km**



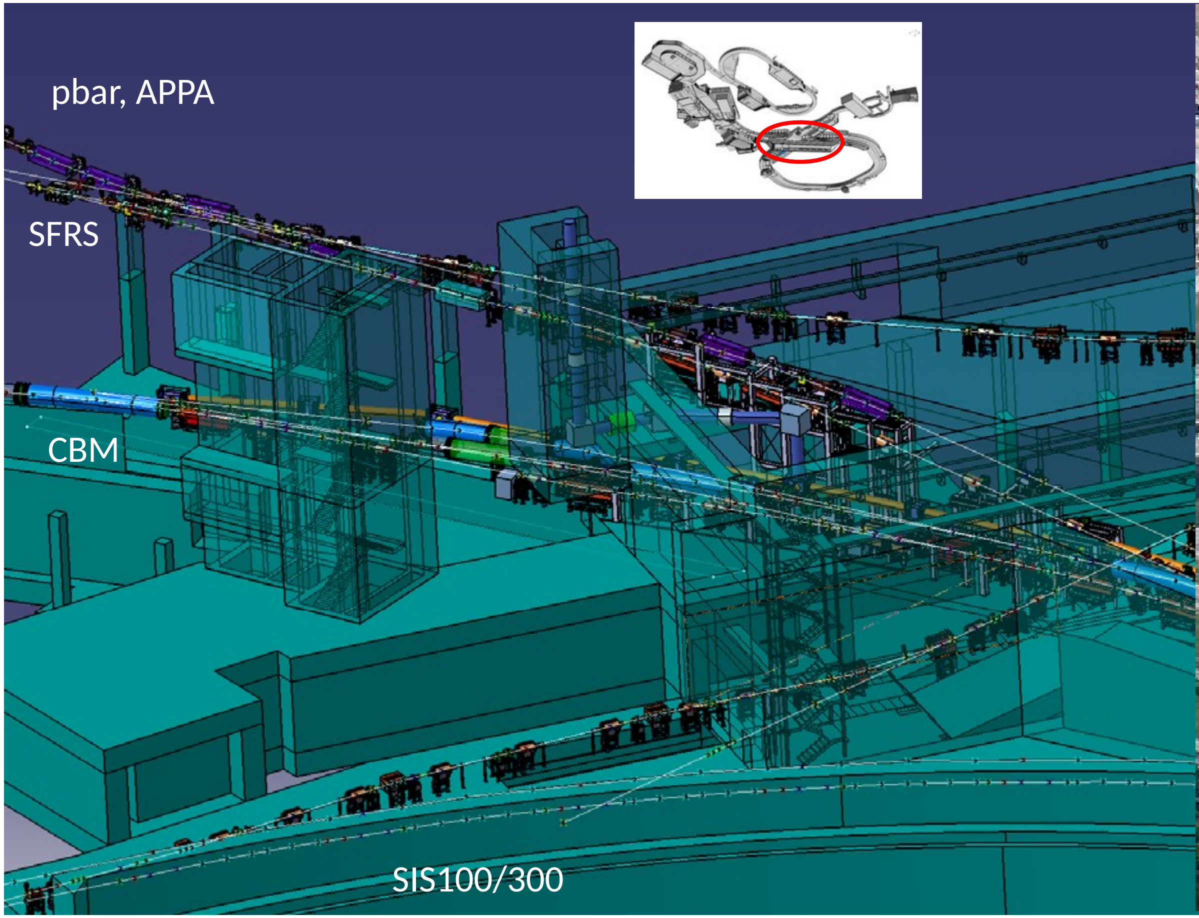
Total area > 200 000 m²

Concrete for FAIR ~ 600 000 m³

(for reference: 3x more than SPS & LHC, ¼ of Hoover Dam)

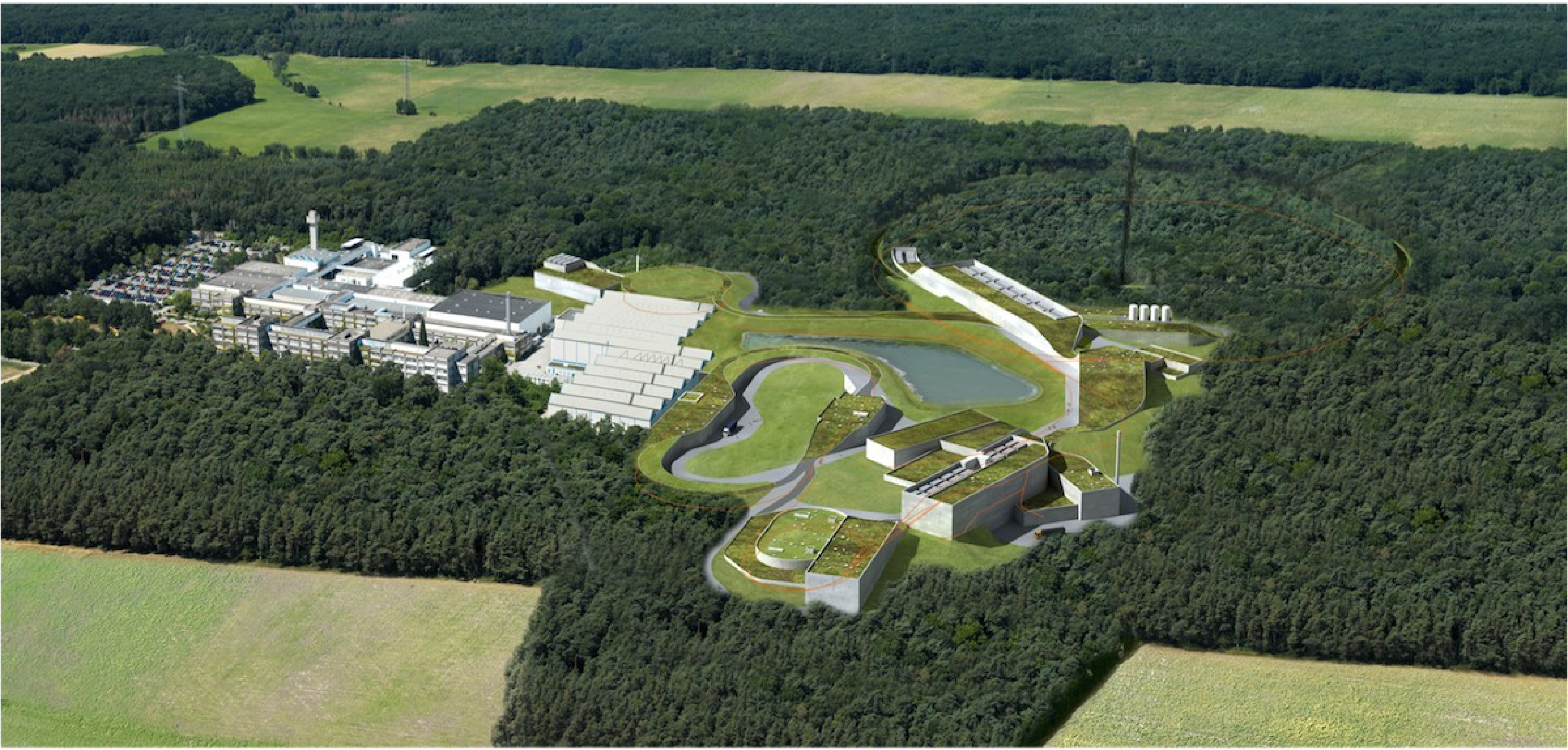
Substructure: 1350 pillars, up to 65 m deep (finished)

High Energy Beam Transfer (HEBT)
– Civil Construction & Integration

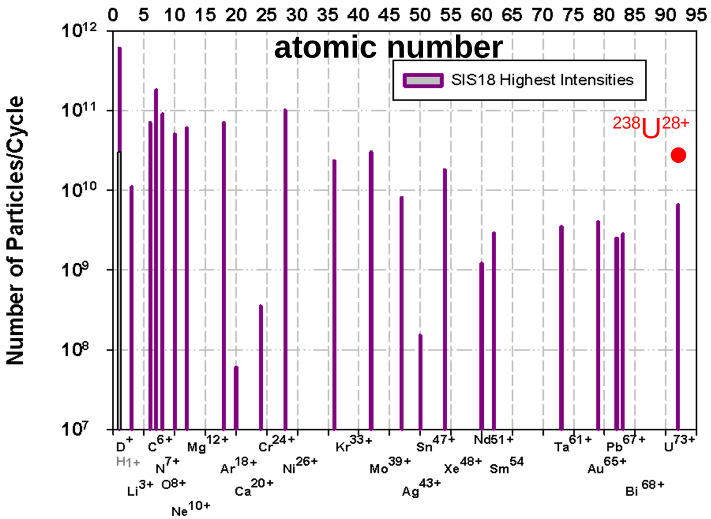


The 'High Five' (Dallas) 2002 → 2005

FAIR – First Stage (MSV0-3)



Primary & Secondary Rare Isotope Beams (RIBs)



SIS18:

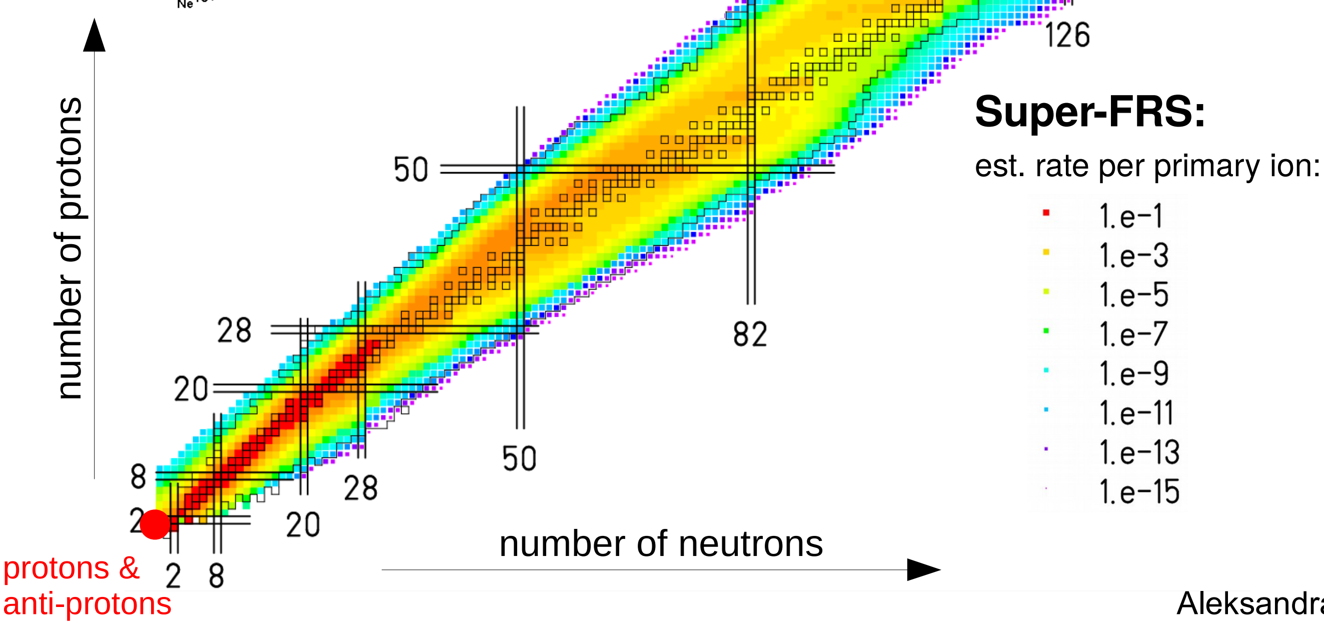
main limitations:

Ion-sources, space-charge, dyn.-vacuum, beam-control

SIS100 ~ 4..8 x SIS18

UNILAC

(nucleo-synthesis)



Super-FRS:

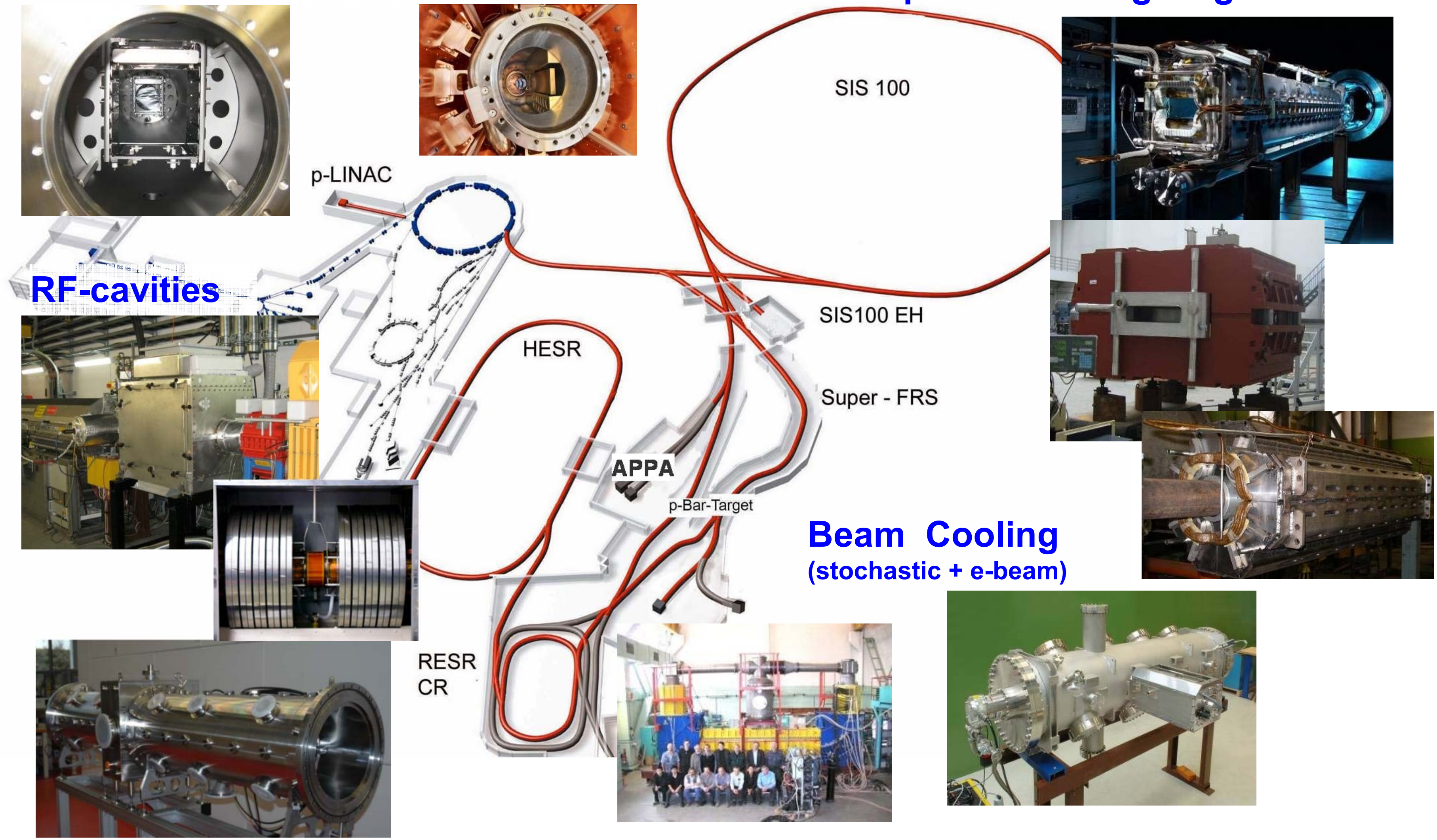
est. rate per primary ion:

Aleksandra Kelic-Heil, Abrabla+EPAX3, July 2015

Accelerator Challenges

Diagnostic and XHV at highest intensities

Superconducting Magnets



RF-cavities

Beam Cooling
(stochastic + e-beam)

FAIR Ring Accelerator Parameters

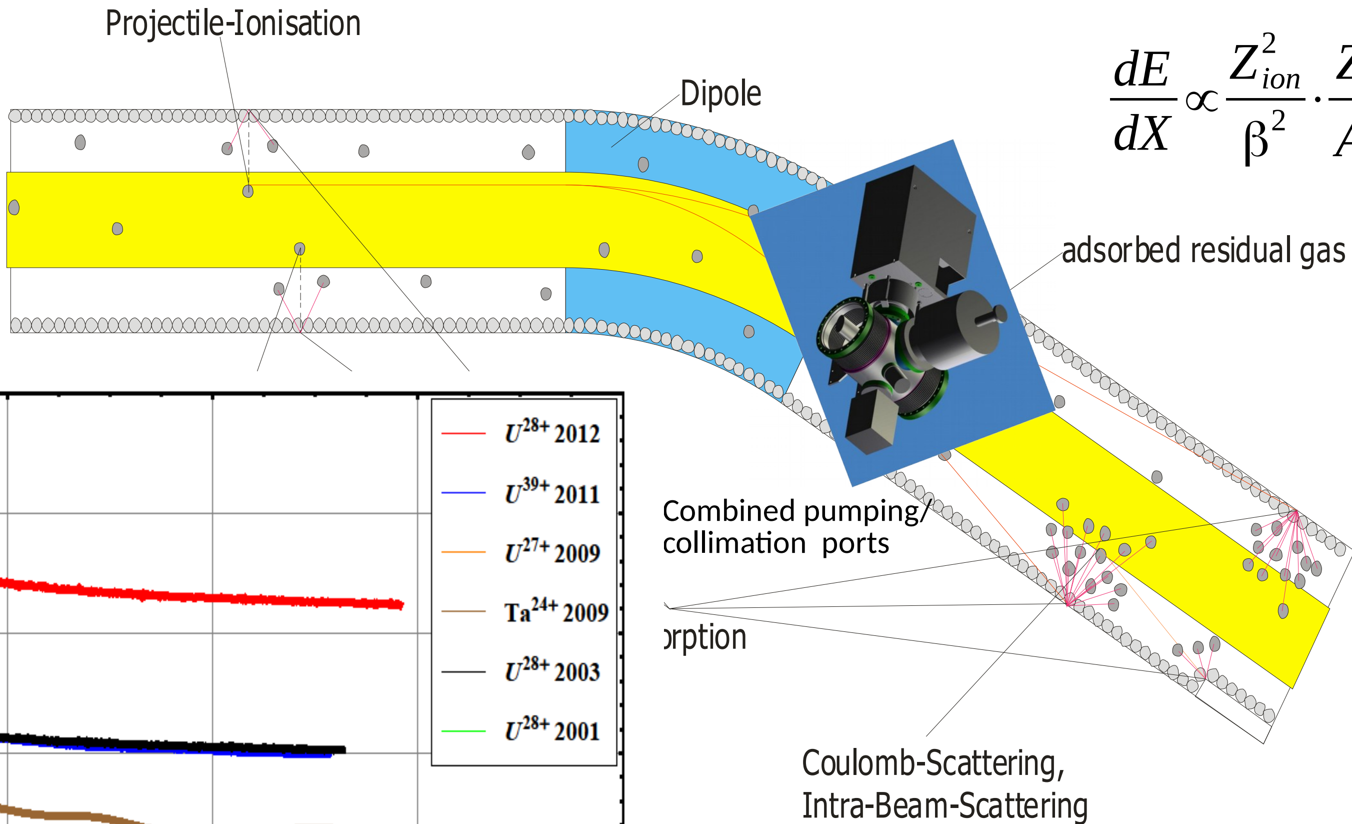
	SIS18	SIS100	CR	HESR
Circumference [m]	216	1083	215	575
Max. beam magnetic rigidity [Tm]	18	100	13	50
Injection energy of protons or anti protons [GeV]	0.07	4	3	3
Final energy of protons or antiprotons [GeV]	4	29	3	14
Injection energy of heavy ions [GeV/u]	0.0114	0.2	0.74	0.74
Final energy of heavy ions U(28+) [GeV/u]	0.2	2.7		
Final energy of heavy ions U(/73+/92+) [GeV/u]	1	11	0.74 (92+)	0.2-4.9 (92+)
Max. beam intensity for protons or antiprotons /cycle	$5*10^{12}$	$2*10^{13}$	10^{8}	10^{10}
Max. beam intensity of ^{238}U-ions /cycle	$1.5*10^{11}$	$5*10^{11}$	10^{8}	10^{8}
Required static vacuum pressure [mbar]	$< 10^{-11}$	$<5*10^{-12}$	$<10^{-9}$	$<10^{-9}$

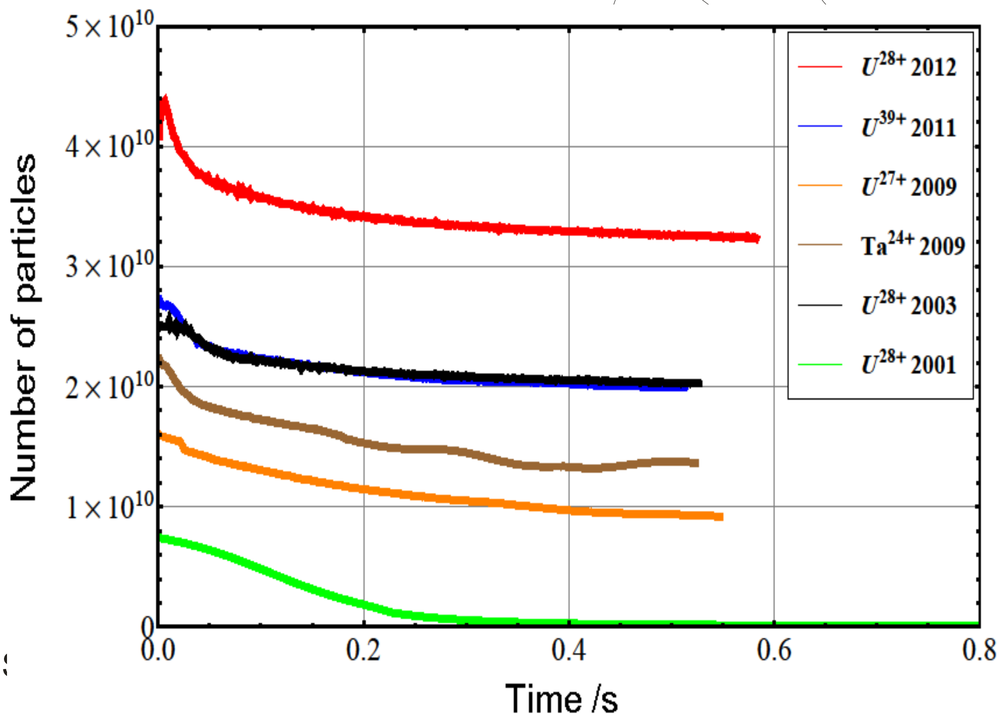
Main FAIR challenges:

- Control of highest proton and (unprecedented) uranium ion intensities
- Excellent XHV vacuum conditions

Challenge: Control of Dynamic Pressure
$U^{28+} + X \rightarrow U^{29+} + X + e$ & Electron-Capture

$$\frac{dE}{dX} \propto \frac{Z_{ion}^2}{\beta^2} \cdot \frac{Z_{gas}^*}{A_{gas}^*}$$





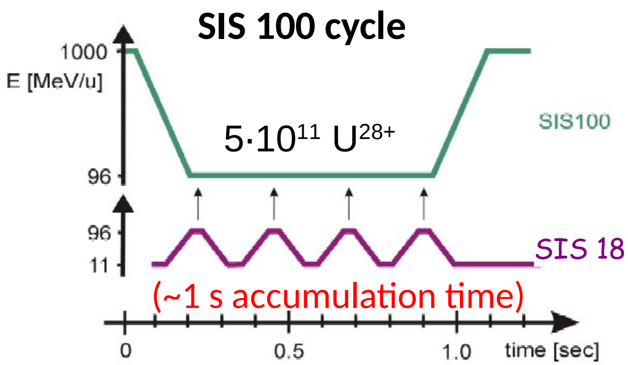
Dynamic pressure:

$$\frac{dP}{dt} = \frac{P - P_0}{\tau_p} + \alpha\, \eta_{loss}\, NP$$

H. Kollmus et al., J. Vac. Sci.(2009)

SIS18 Dynamic Vacuum Control
SIS-18 Hardware Upgrades

- Intense primary heavy-ion beams:
  RIB production (NuSTAR) and plasma physics



	SIS-18 (today/required)	SIS-100
Reference primary ion	U^{28+}	U^{28+}
Reference energy	200 MeV/u	1.5 GeV/u
Ions per cycle	**3E10** / **1.5E11**	**5E11**
cycle rate (Hz)	1 / 2.7	0.5

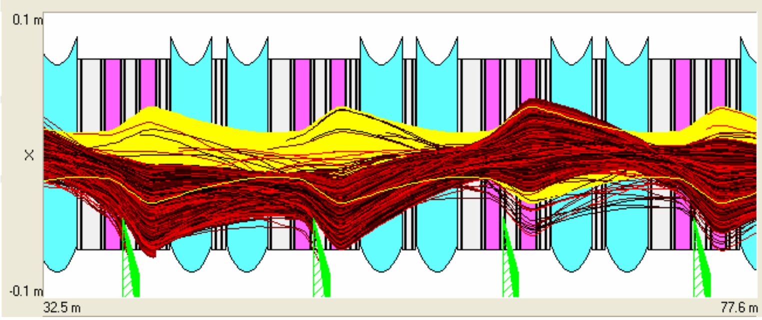
primarily limited by U-ion source

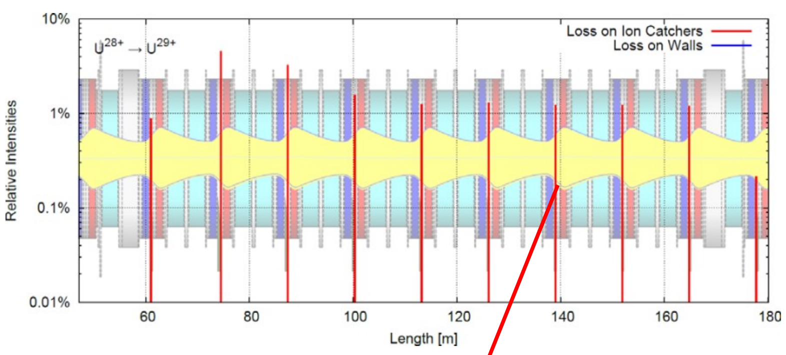
- SIS-18 upgrades for SIS-100 injection:
  - new injection system (larger aperture)
  - NEG coating of vacuum pipe
  - Combined pumping/collimation ports behind dipoles
  - reduction of multi-turn injection loss (ongoing)
  - fast ramping with 10 T/s (ongoing)
  - dual RF system (ongoing)

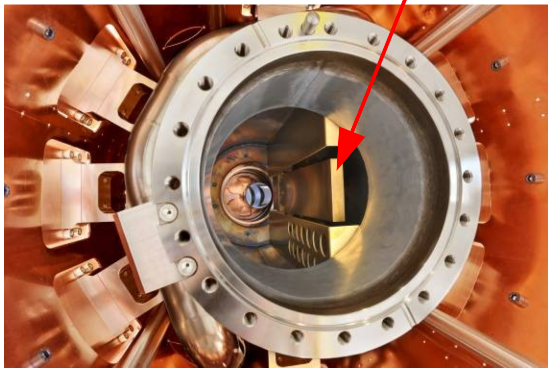
P. Hülsmann, P. Spiller, O. Boine-Frankenheim et al., IPAC 2010

SIS100 Dynamic Vacuum Control
Machine Layout ↔ Lattice Design

- U^{29+} loss positions in SIS100 are peaked (by design) at the cryo-aborbers (collimators)
- **Doublet focusing structure**:
  - **Dipoles act as a charge state separator**
  - 'de-focusing' →'focusing' quadrupole order
  - over-focussing assures beam reaches cryo-absorber
- Dyn. vacuum requires **huge pumping speed:**
  - cryogenic vacuum chambers
    - *N.B. principal reason why SIS100 is cold → super-conducting dipole/quad. Magnets*
  - NEG-coating of most warm vacuum chambers







May have to accept minimal amount of losses
(primary ion-gas interactions, not intercepted by vacuum system or absorbers)
→ need instrumentation to detect, tell-the-difference and to mitigate the other loss-mechanisms

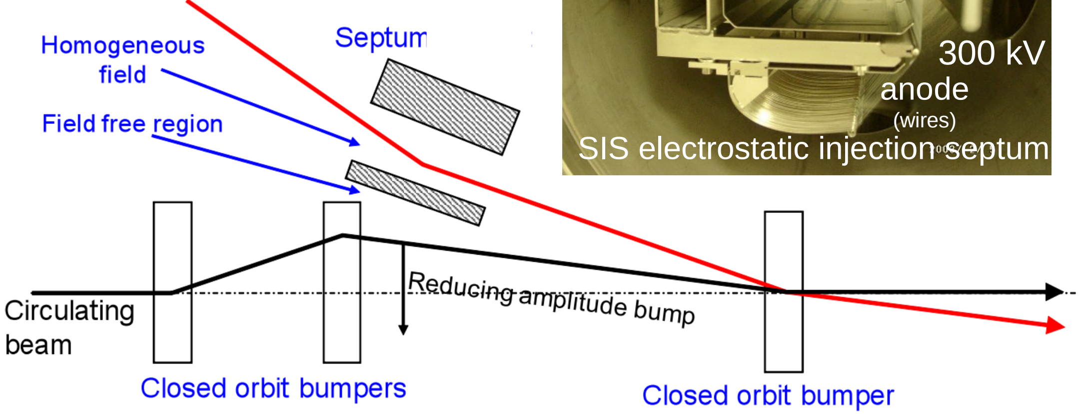
SIS18 Multi-Turn Injection (H-Phase-Space Painting)

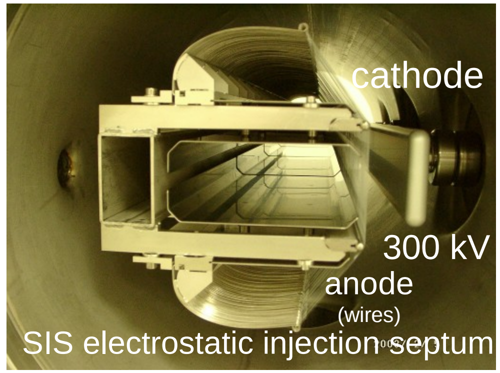
P. Spiller, Y. El-Hayek, U. Blell et al., IPAC'12, 2012

From a linac

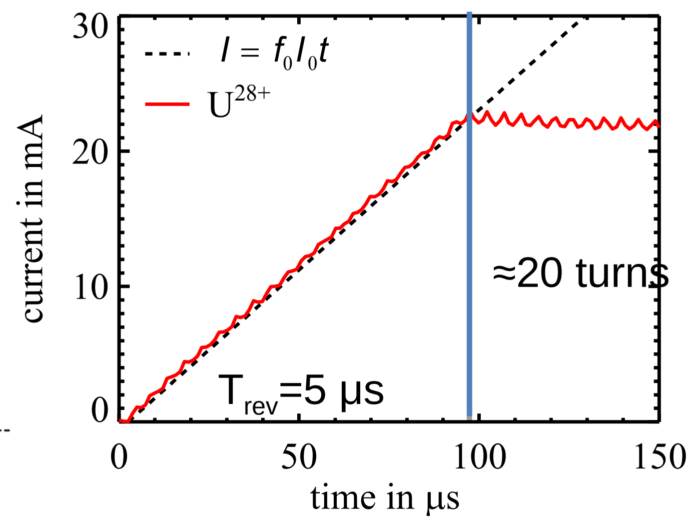
e.g. SIS-18, CERN PSB

courtesy Mike Barnes

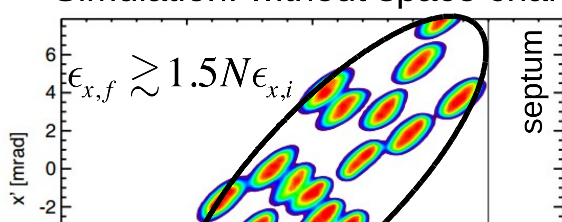




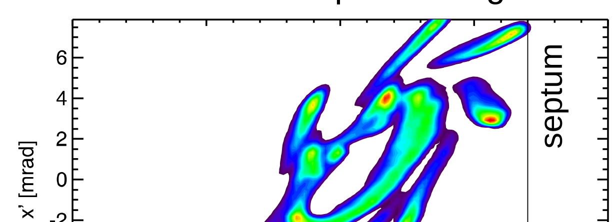
Measured MTI performance in SIS-18



Simulation: without space charge



Simulation: with space charge



Injection losses → dynamic vacuum pressure rise

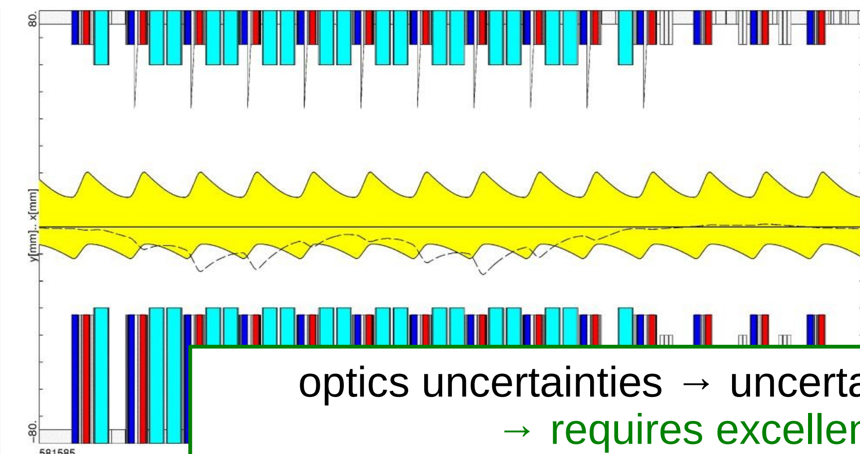
(highly complex: easy to simulate ↔ hard to measure/tune with beam)

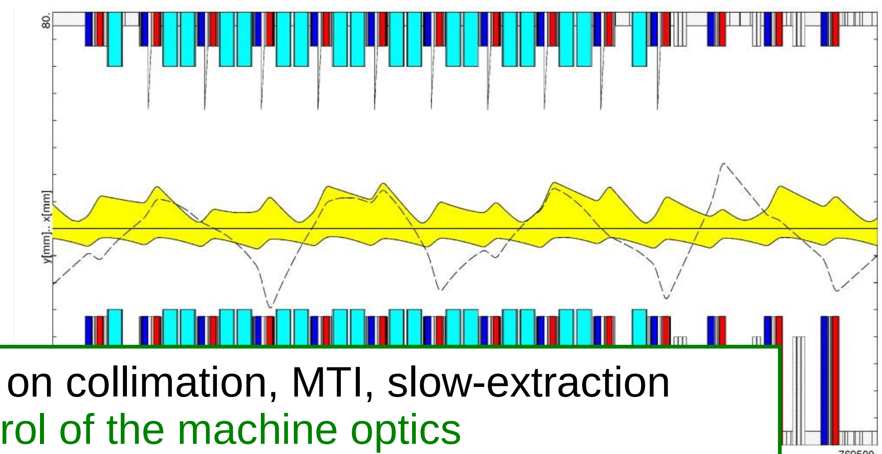
looking forward to: injection steering (BPMs) & turn-by-turn profiles (IPMs)

SIS100 Ion and Proton Lattices

Ion Lattice	
Q_h/Q_v	18.88 / 18.80
γ_t	15.4
D_{max} [m]	1.8
$\varepsilon_h/\varepsilon_v$ [mm mrad]	25 / 10
Energy [GeV/u]	0.4 – 2.7

Proton Lattice	
Q_h/Q_v	21.78 / 17.40
γ_t	**45.5**
D_{max} [m]	3.0
$\varepsilon_h/\varepsilon_v$ [mm mrad]	4 / 2
Energy [GeV/u]	29.0





optics uncertainties → uncertainties on collimation, MTI, slow-extraction
→ requires excellent control of the machine optics
(N.B. gradual proton optics changes from injection → extraction over ~ 200 ms)

- Symmetric doublet lattice (14 x DF)

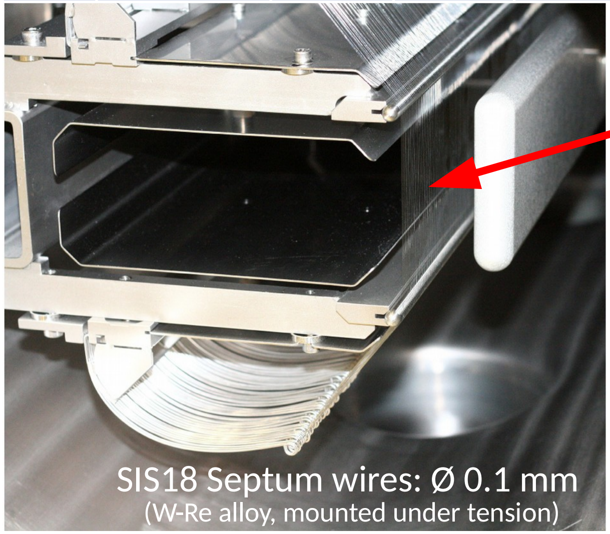
- Symmetry broken to shift γ_t (6 x DF_1, 8 x DF_2)
- Vertical plane only weakly affected

D. Ondreka, S. Sorge, V. Kornilov

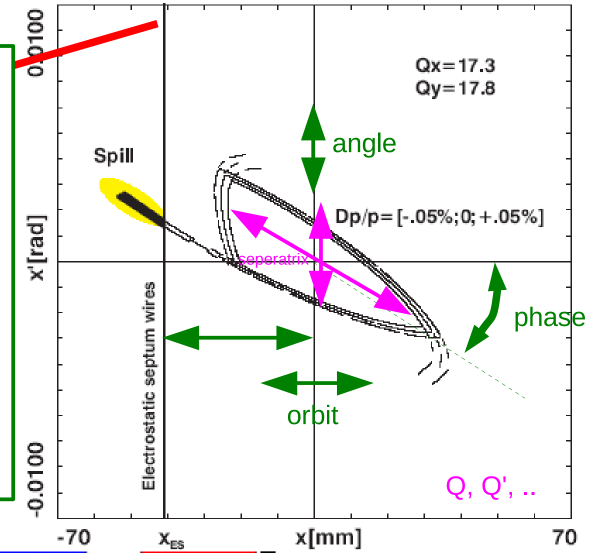
Slow Extraction from SIS-100

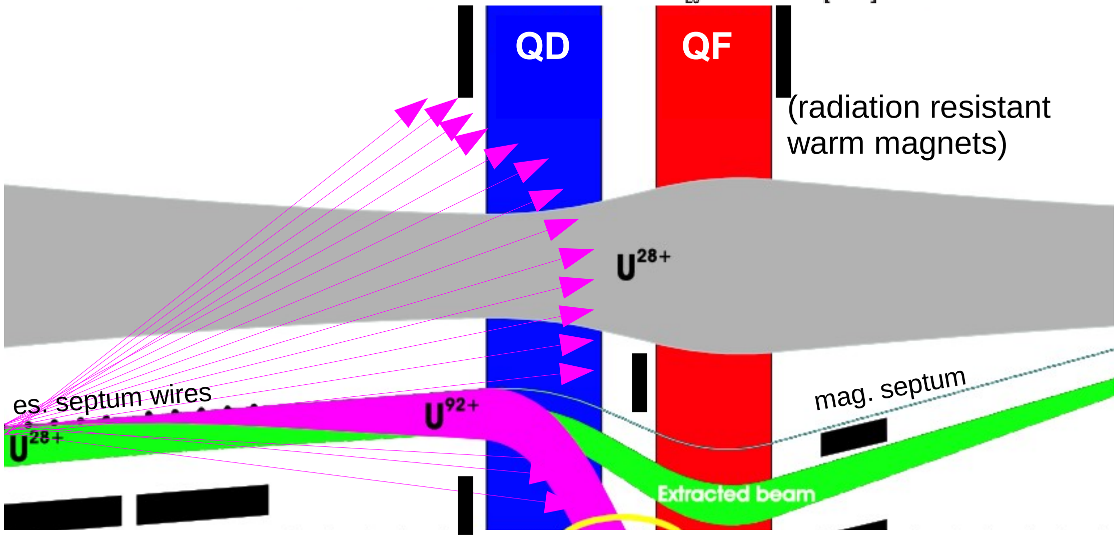
Intense Heavy-Ion Beams for NuSTAR & CBM

Ion	Energy	N/s	spill	Power
U^{28+}	1.5 GeV/u	5E11	> 1 s	10 kW



Optics, Q/Q'(',") drive uncertainties on slow-extraction performance
→ remedy: control of the machine optics, Q/Q', linearisation prior to s.e., …
(highly complex, a lot of work ongoing)



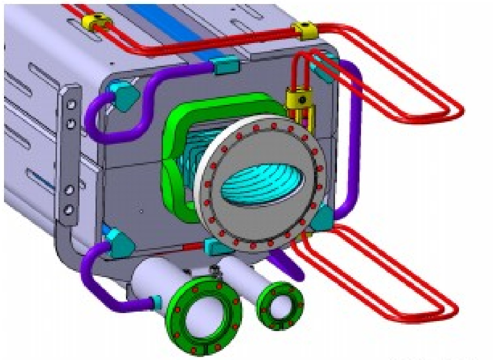


Tracking simulations:
5 % (approx. 500 W) loss in the septum wires
U^{92+} beam loss in warm magnet > 5 W/m

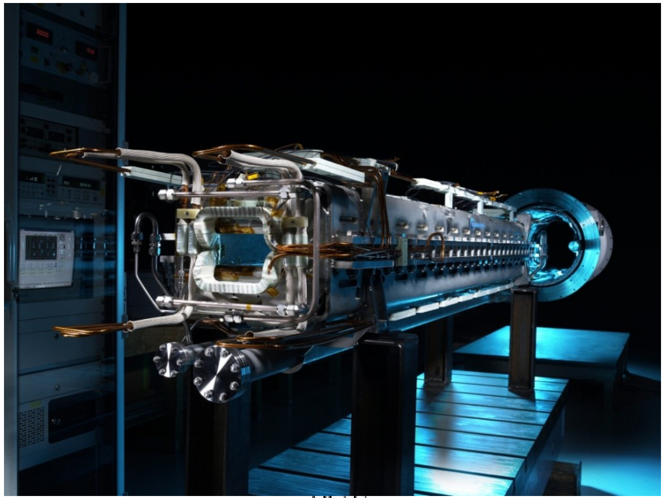
Non-trivial machine protection:
protection of septa wires
down-stream absorbers setup
activation minimisation

SIS-100 Dipole Magnets
Field Quality and Tracking Studies

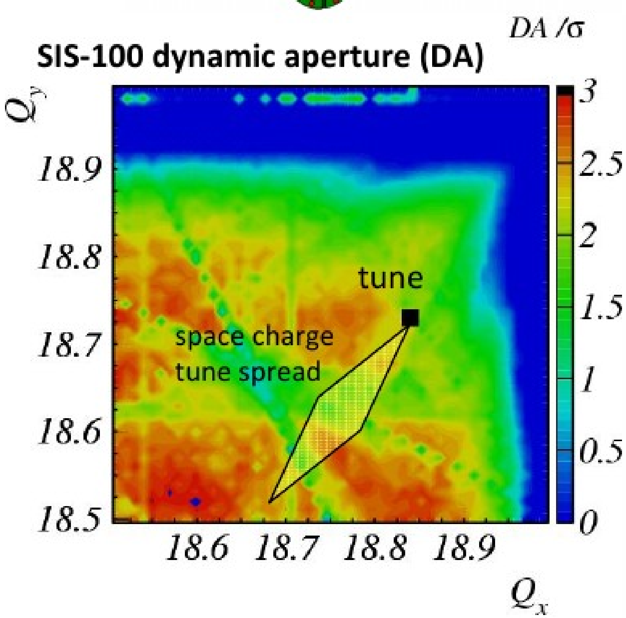
3D model of the SIS-100 dipole with elliptical beam pipe



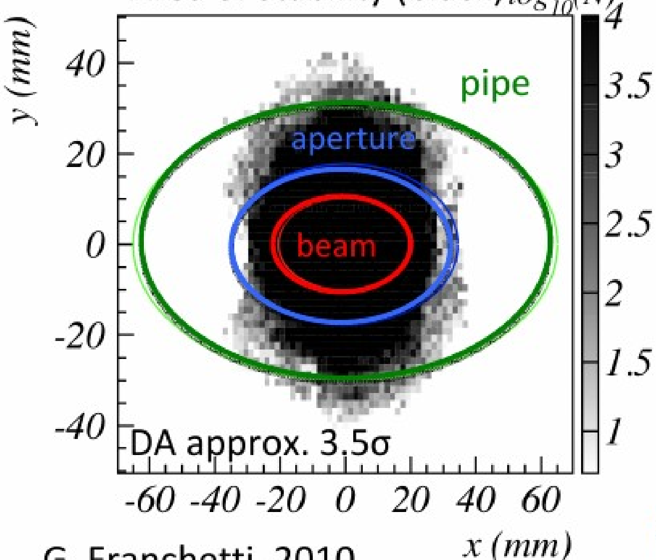
Field errors:
- 2D/3D static calculations
- Measurements
  (prototype magnet)



SIS-100 dynamic aperture (DA)



Area of stability (black)



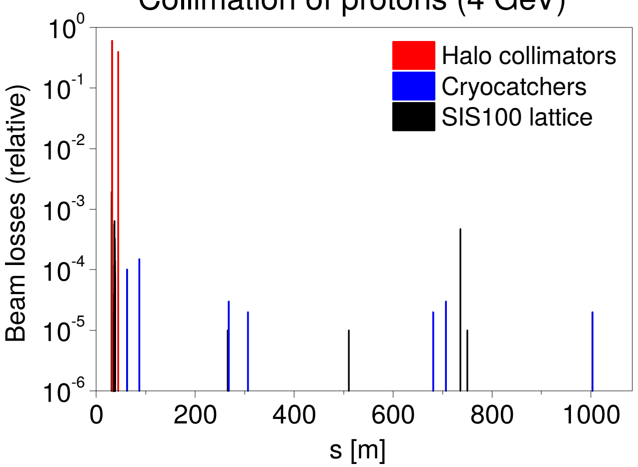
G. Franchetti, 2010

as indicated before:
Optics, Q/Q'(",''') drive uncertainties on collimation, MTI, slow extraction performance
→ remedy: control of the machine optics, Q/Q', control of non-linearities, …
(highly complex, a lot of work ongoing)

'Beam Loss Budget' in SIS100

1. Activation: loss of 'hands-on-maintenance' → '1 W/m criteria'[1]
   - important primarily for localised losses e.g. during slow extraction
2. Ion-induced desorption: increase of vacuum pressure
   - primary reason for SIS100 being a cryogenic machine → beam loss contro/particle stability
   - distributed combined collimation/pumping system for 'stripping' losses in SIS-100
3. Machine Protection: ion-induced damage → ~ 10^{10} of ^{238}U considered to be "safe" (assumes typically beam spot sizes and energies in SIS100/HEBT)
   - energetic ions cause higher damage than protons

Collimation of protons (4 GeV)



*assumes 10s proton cycle & activation limit only

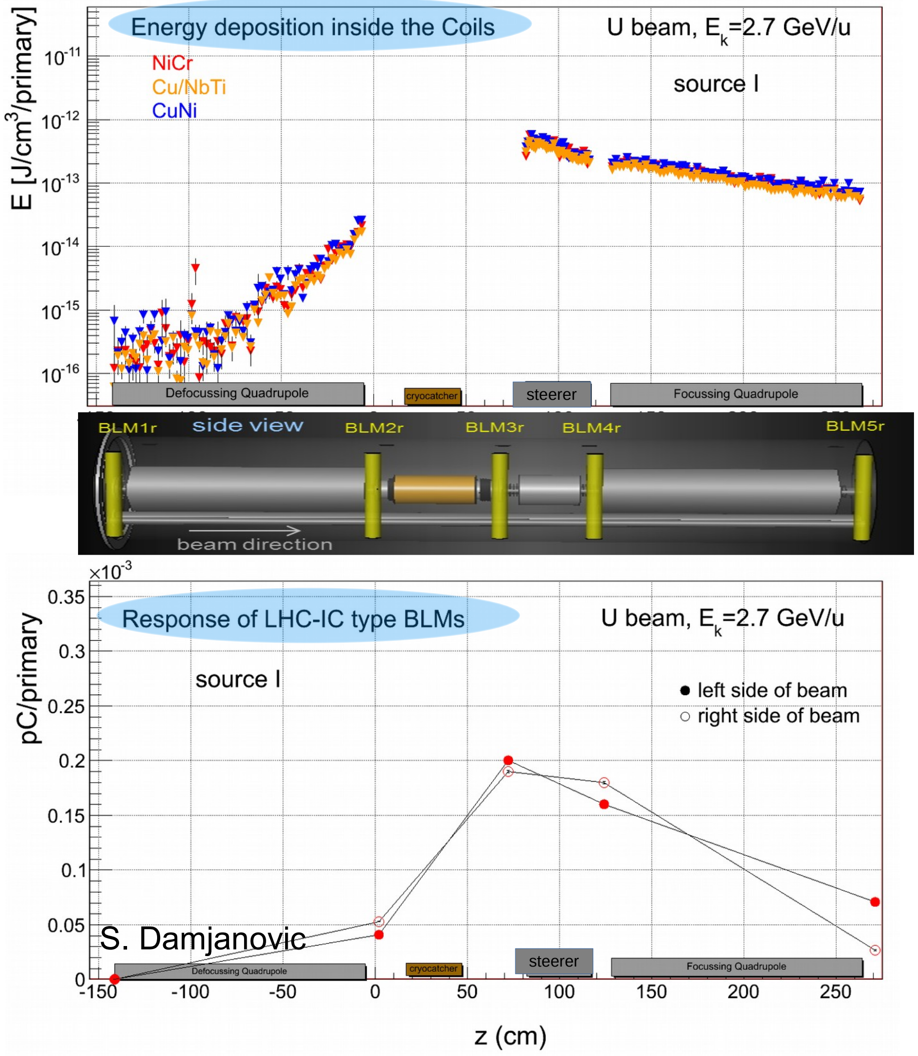
Beam	Loss criteria (injection)	Loss criteria (extraction)	Tolerable losses (injection)	Tolerable losses (extraction)*
Protons	1 W/m	1 W/m	10 %	5 %
$^{40}Ar^{18+}$ ions	2 W/m	1 W/m	30 %	6 %
$^{238}U^{92+}$ ions	4 W/m	2 W/m	20 %	10 %

Caution: '1 W/m' is only indicative!
existing operation, shielding and radiation permit limits instantaneous proton losses to <3% @ 29 GeV and nominal intensities!
→ should aim to be significantly below that limit (ALARA)

*for comparison: CERN-PS: 4-8% losses achieved (data courtesy R. Steerenberg, 19th March 2012)

[1] *N.V. Mokhov and W. Chou, The 7th ICFA Mini-workshop on High Intensity High Brightness Hadron Beams, USA, 1999.*

Sensitivity to Beam Loss
Energy Deposition in Coils vs. IC-type BLM Signals



Quench prevention analysis:
(S. Damjanovic)

- sufficient BLM sensitivity:
  - '$5\cdot10^4$ ions/s' vs. '$5\cdot10^{11}$ ions/cycle'
  - Most-likely loss locations: Primary (Halo-) collimator, secondary collimator, cryo-absorber, warm magnets (extraction)

cannot assume loss-less Ion operation:
primary ion-gas interactions, slow-extraction, …

A) plan to use relative BLM signal to freeze operation around best-case loss reference

B) attempt to define 'acceptable losses'

Beam Transmission Optimisation & ALARA Activation Minimisation

Gretchen Frage: “What are of 'As-Low-As-Reasonably-Achievable' losses”
(in a less precisely known high-intensity ion operation territory)

“when you have excluded the obvious, whatever remains, however improbable, must be the truth.”
→ exhaust reasonable operational practices of controlling parameter known to induce particle loss

Low-intensity beams:

A. Extraction/Injection Matching

- first-turn trajectory steering (BPMs),
- energy matching (B
- coarse collimation (
before propagating
- bunch-length to buc

B. Closed-Orbit Cycle-to-Cycle Feedback (BPMs)

- aperture optimisation (coarse, circulating beam)

C. Tune & Chromaticity Correction (BPMS, BBQ)

- optimises space charge, ΔQ spread, dyn. aperture, beam stability

D. Emittance (blow-up) Monitoring (IPMs, FCTs)

- frequent cause for loss changes

High-intensity beams:

All on the left, with tighter limits, plus

E. Optics Correction

- -up optimisation)
- arises/restores
terms)
- ecks)

F. Detailed Collimation (e.g. 2-stage for protons)

- see Ivan Strasik's talk @ HIC4FAIR'2015

G. Quantitative slow-extraction optimisation

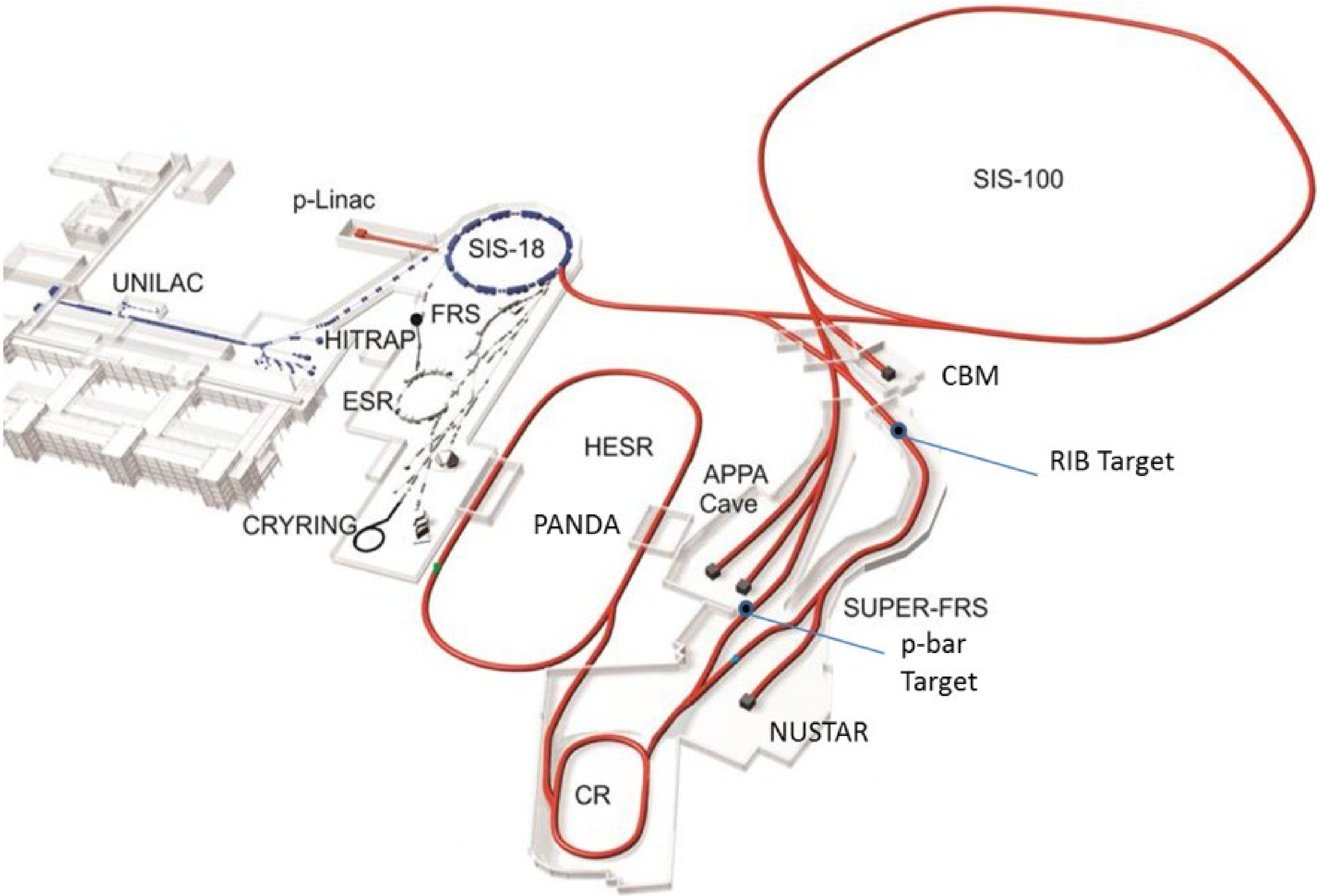
- eval. 'Hardt condition', step-width measurement, …

H. ...

Beam Instrumentation & Diagnostics Tools will be vital for day-to-day FAIR operation!
– not mere 'nice to have' features –

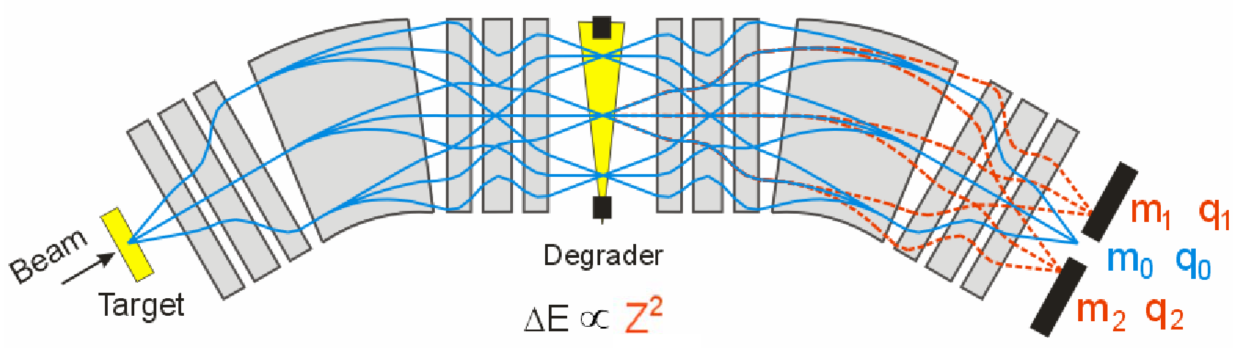
→ 'acceptable losses' := losses remaining after having performed above steps

Modularised Start Version 2020 (MSV0-3)

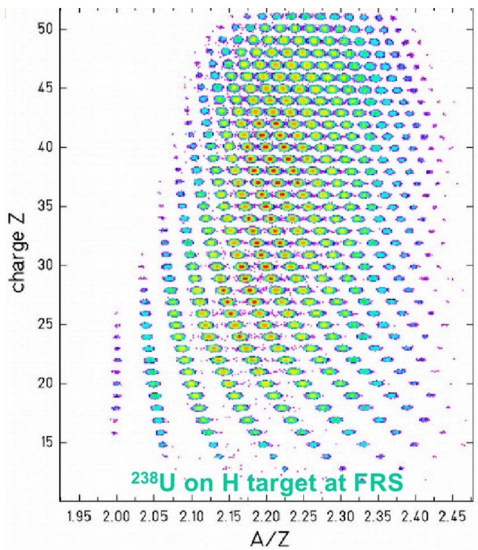


Super-FRS Example: $^{238}U \rightarrow {}^{233}Th$ Degrader
– or how to find a needle in a hay stack

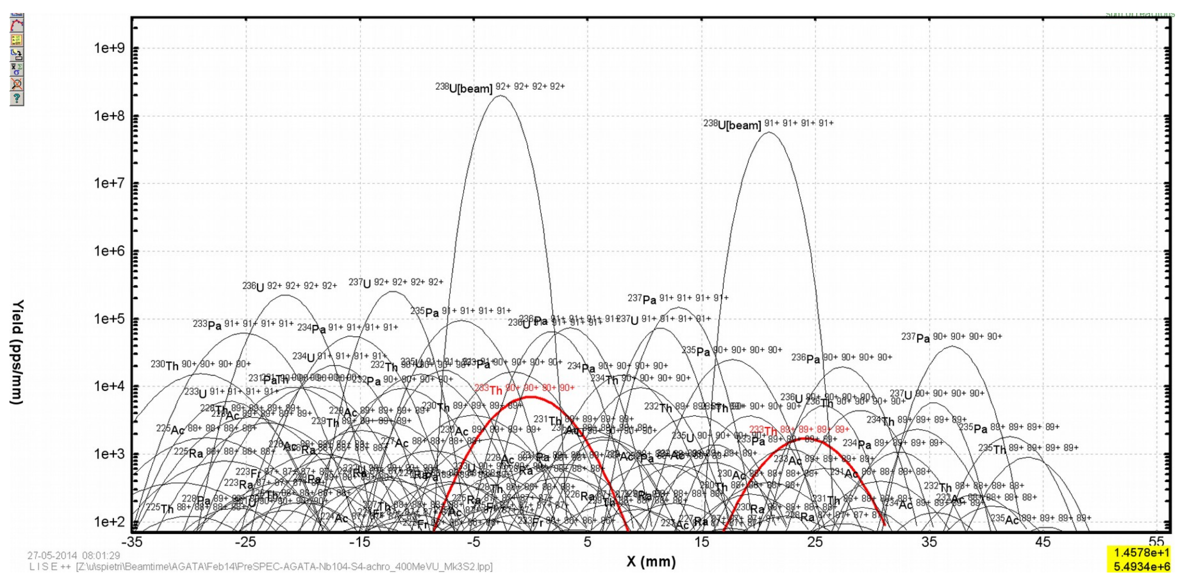
Achromatic in velocity, but dispersive in mass and charge



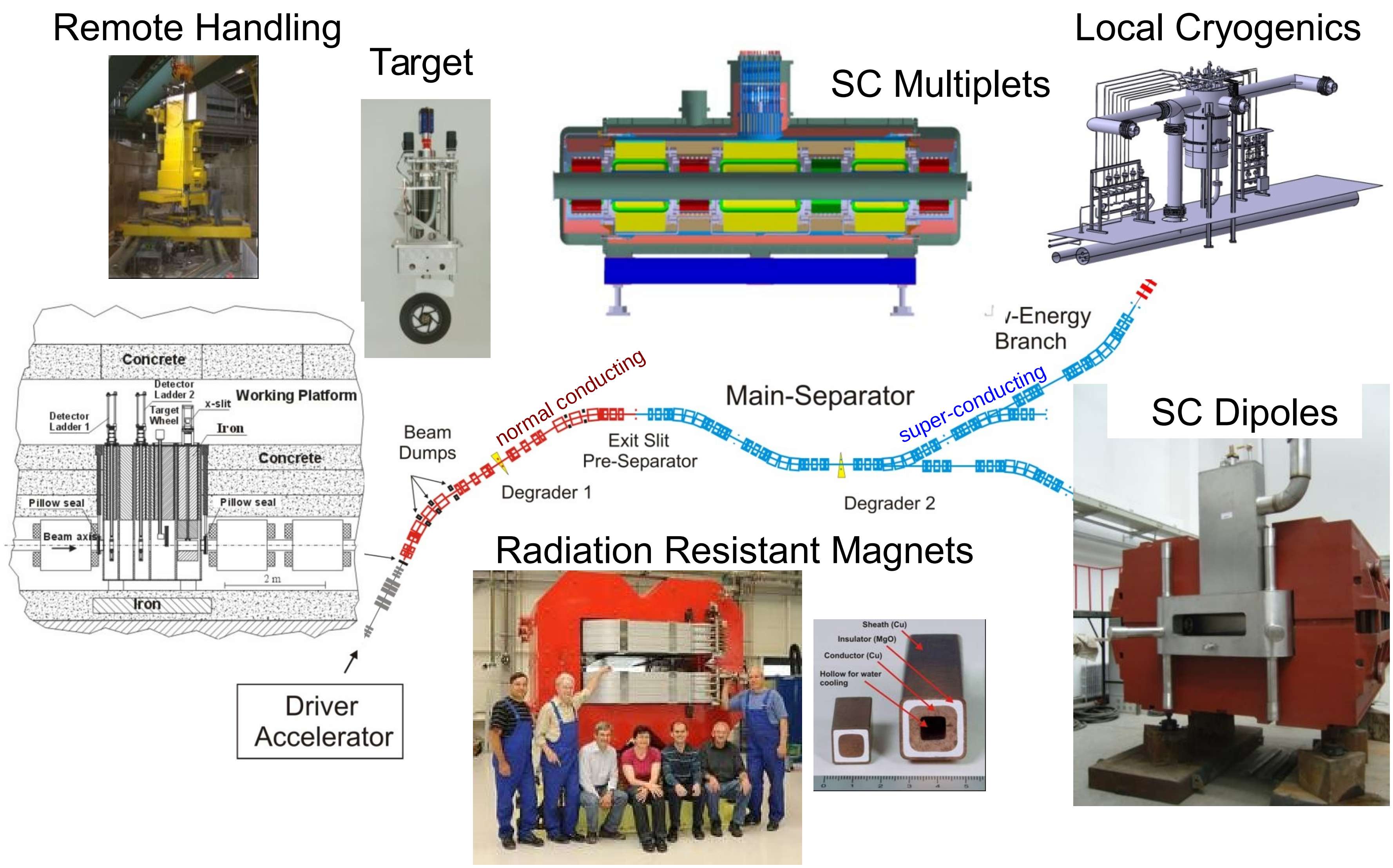
Degrader angle and thickness steers optics for the second spectrometer part



thesis V. Henzl, CTU Prague 2005.

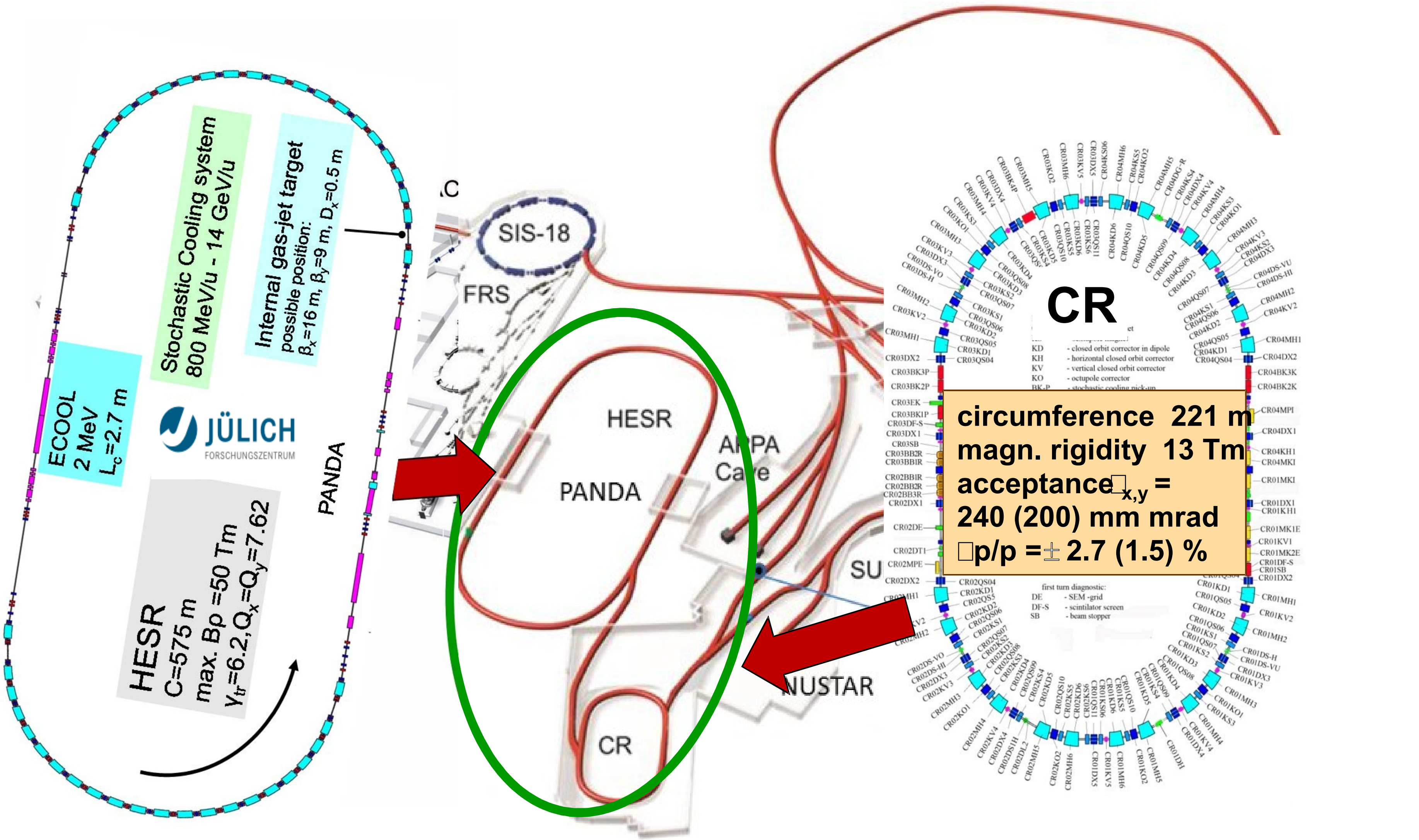


Super-Fragment-Separator (Super-FRS)
Rare Isotope Beam Production (RIB)



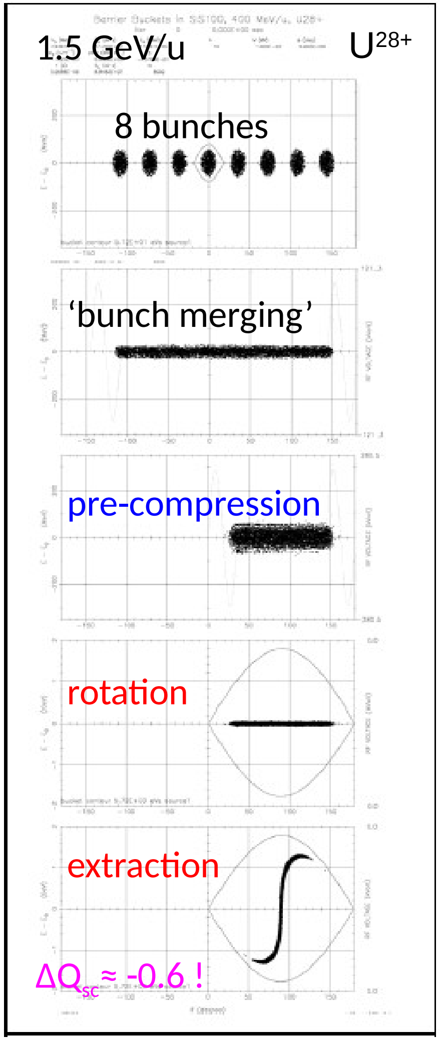
CR, HESR, ESR & Cry Storage Rings

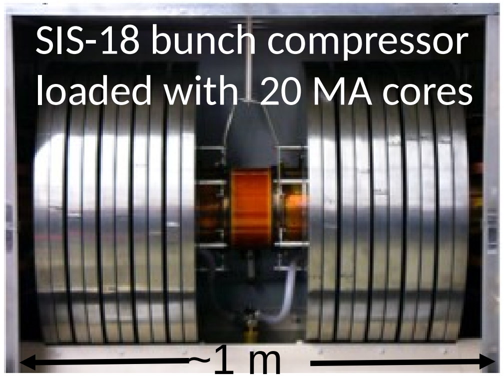
Experiments tightly intertwined with Accelerator Operation

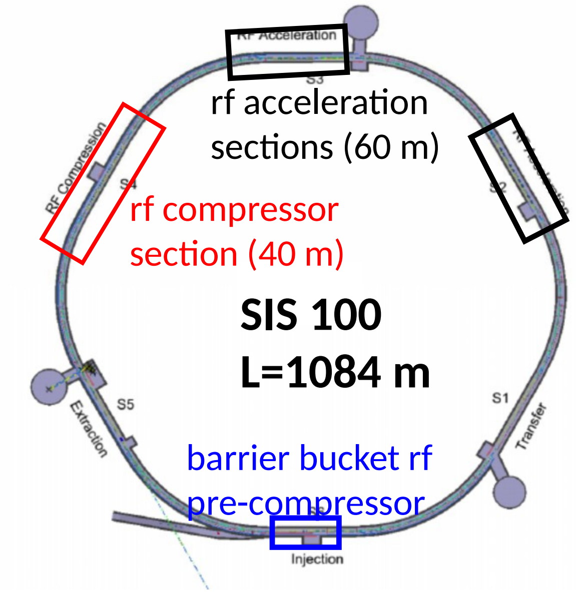


SIS 100 RF: BCMS
Bunch Compression & Merging Scheme

Single bunch formation





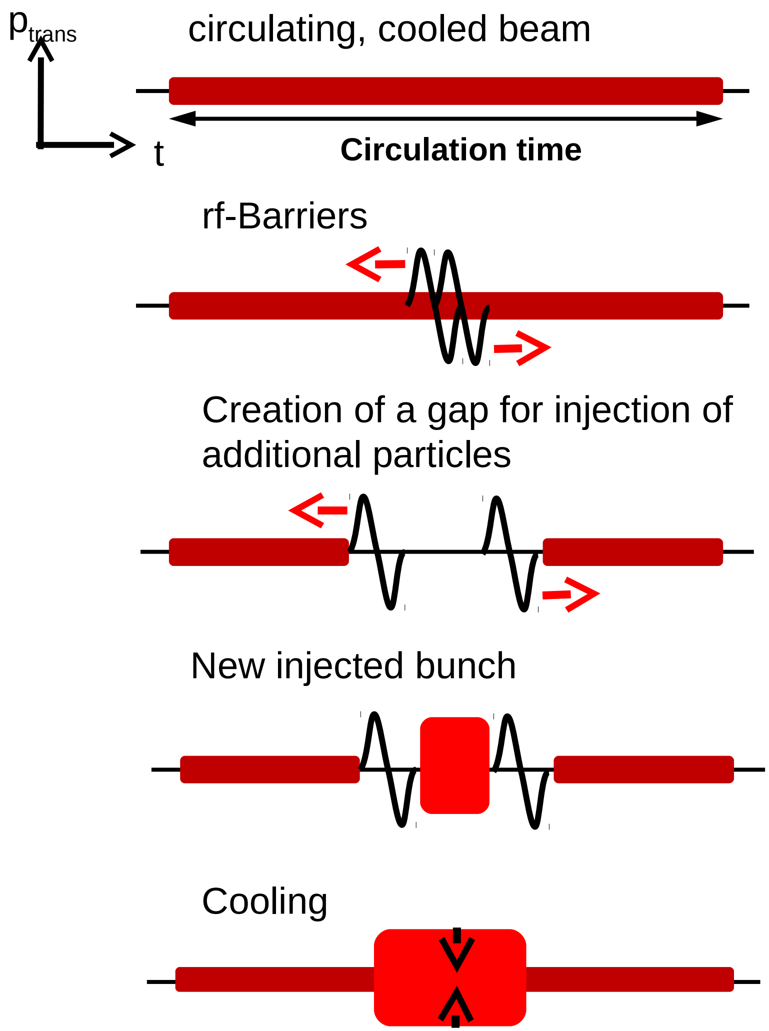


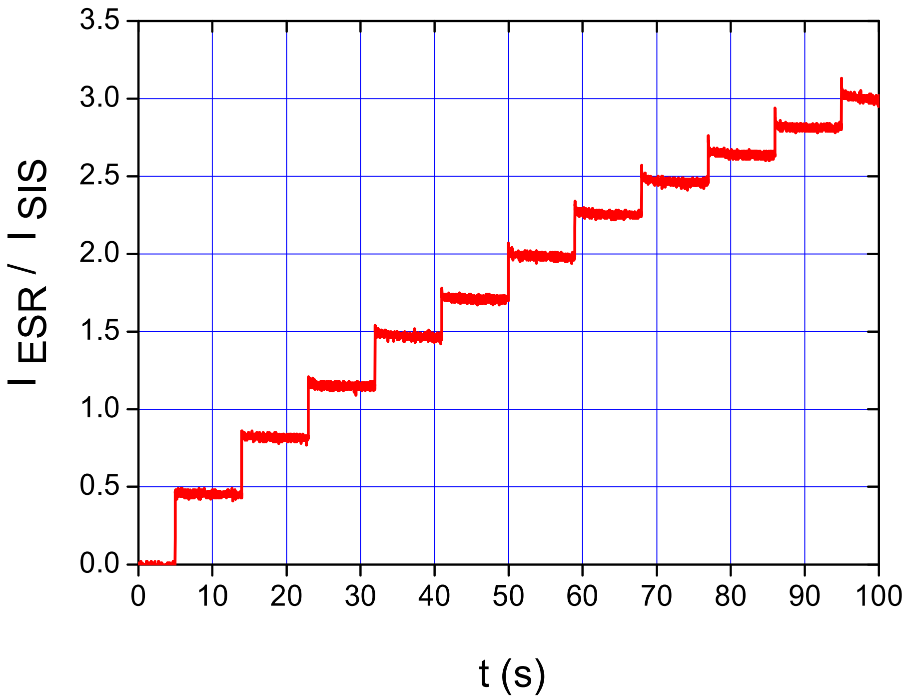
	#cavities	Voltage [kV]	Frequency [MHz]	Concept
Compression	16	600	0.4-0.5 (h=2)	MA (low duty cycle)

Final bunch parameters:

	Particles/bunch	bunch length
1.5 GeV/u U^{28+}	5 x 10^{11}	60 ns
29 GeV protons	2 x 10^{13}	25 ns

Particle-Stacking & Beam Cooling

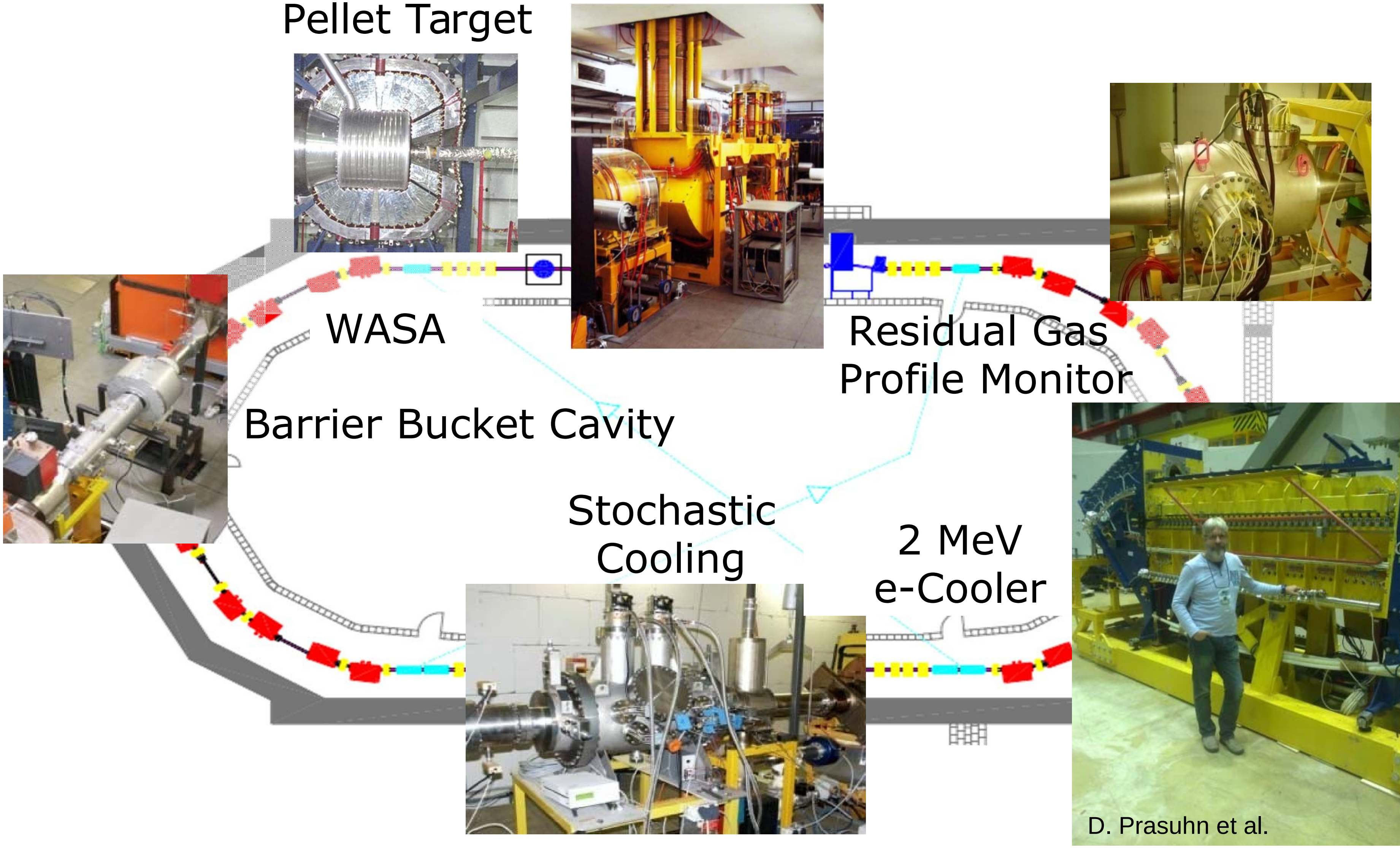




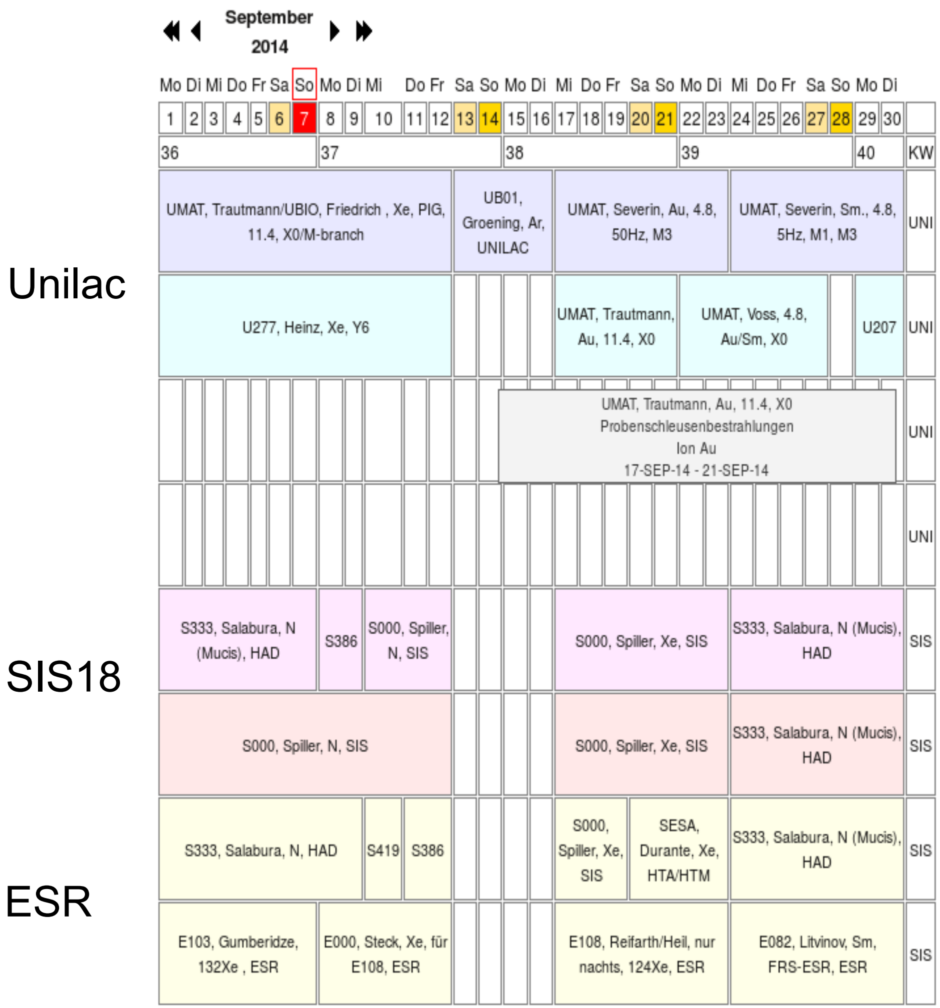
Less beam dynamics and more a technology & machine operation challenge

→ Need good longitudinal diagnostics to tune and orchestrate (SIS100: 20+) RF cavities

HESR Prototyping @ COSY



FAIR Accelerator Operational Challenges
Typical GSI Operation & Beam Time Schedule

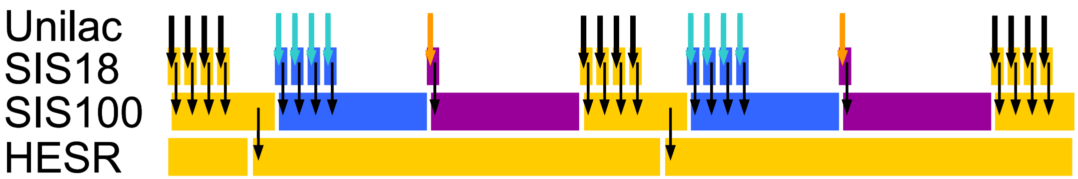


- GSI facility
  - 2 + 1 accelerators (FAIR: 8 → 11++)
  - 20 experimental areas
- Parallel operation
  - UNILAC, SIS18, ESR independent
  - 3 different ion species
  - 5 parallel experiments
- Experiments demand high flexibility
  - Variation of beam parameters (daily)
    - energy, intensity
    - extraction type
    - number of bunches
  - Change of beam sharing (daily)
  - Switching of ion species (weekly)
  - Adjustment of schedule (monthly)

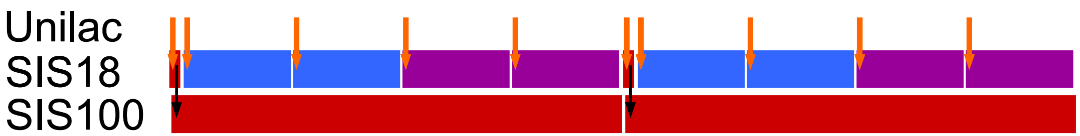
Beam Production Chains

Exemplary Operational Scenarios

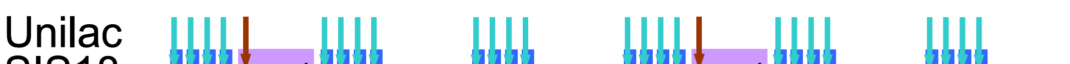
Periodic beam patterns, dominated by one ***main*** experiment – change every two weeks, some run for 2-3 days only:

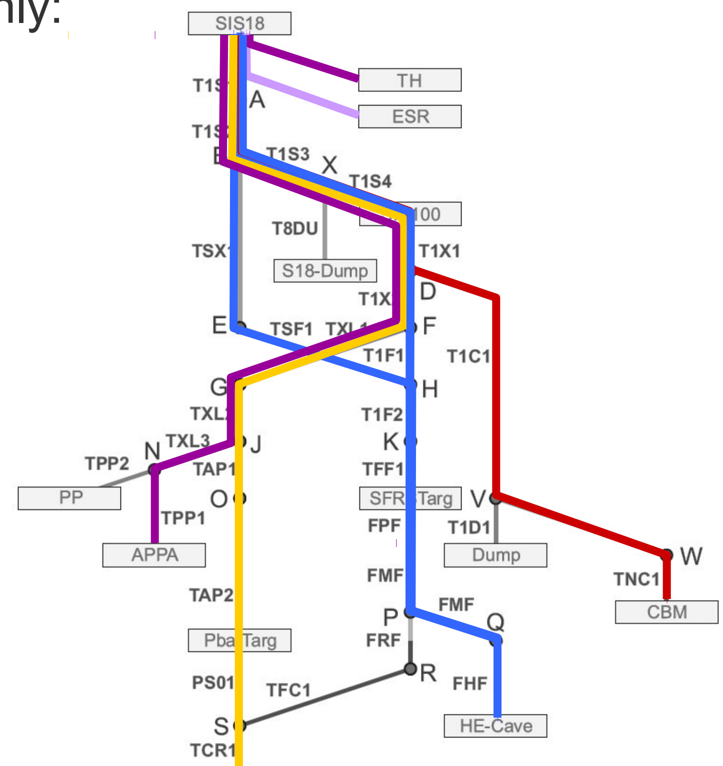


AP + RIB ext. target (U^{28+}) + Biomat



CBM + RIB ext. target (U^{73+}) + AP (LE)





FAIR Operational Challenge:

- presently: 2 shifts for setup of 2 accelerators → FAIR target: 1-2 shift(s) for setting up 5 accelerators + tighter loss control
- Main strategy/recipe to optimise 'beam-on-target':
  - quasi-periodic cycle operation: limit major pattern changes by construction ↔ beam schedule planning (tools)
  - minimise overhead of context switches → smart tools, procedures & semi-automation, e.g. beam-based feedbacks, sequencer, …

Summary
FAIR Challenges vs. Remedies

- SIS18
  - Multi-turn injection optimisation → injection matching (BPMs: x,x',y,y', ..) & turn-by-turn IPMs
  - space-charge limit & dynamic vacuum → passive absorbers, vacuum pumping capacity, beam-loss optimisation
  - control of beam loss and beam parameter quality for high intensities → cycle-to-cylce Orbit-FB & Q/Q' Control
  - factor of 10 for heavy ions → ion source optimisations, multi-turn, beam-stability/space-charge opt. → optics, Q/Q'
- SIS100
  - Slow Extraction → K.O. excitation-based method, faster initial Q/Q' setup
  - Bunch-to-Bucket Injection → extraction/injection steering and fast trans./long. intra-bunch feedbacks
  - Control of beam loss and beam parameter quality for high intensities → cycle-to-cylce Orbit-FB & Q/Q' Control
  - Beam loss budget: activation, dynamic vacuum, machine protection → intensity ramp-up procedures, transmission monitoring & interlocks, BLMs
- CR, HESR, ESR & Cry-Ring
  - accumulation/cooling of primary/secondary beams → BCMS, short bunches → long. diagnostics & online tomography
- FAIR accelerator facility – Operational Challenge
  - fast turn-over → change of experiment about every two weeks, some run for 2-3 days only
  - presently: 2 shifts for setup of 2 accelerators→ FAIR target: 1-2 shift(s) for setting up 5 accelerators + tighter loss control
  - Main strategy/recipe to optimise 'beam-on-target':
    - quasi-periodic cycle operation: limit major pattern changes by construction ↔ beam schedule planning (tools)
    - minimise overhead of context switches → smart tools, procedures & semi-automation, e.g. beam-based feedbacks, sequencer, …
      - N.B. also liberates operators from tedious task to focus on error (pre-)diagnosis and facility optimisations

… can we do it?

Yes, we can!

… backed by beam instrumentation, diagnostics and procedures for tuning FAIR ...