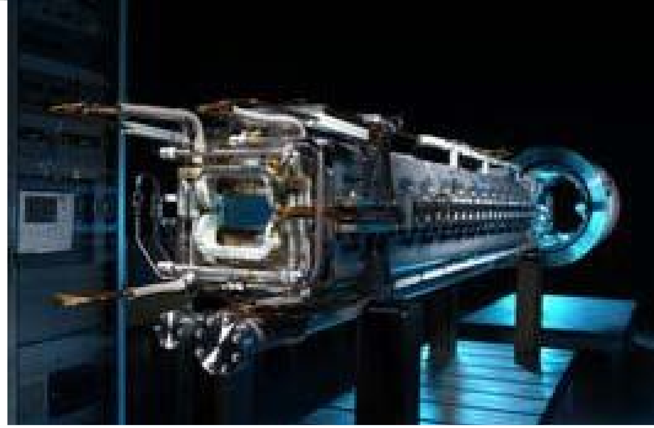


FAIR Commissioning Concepts & Strategies in View of High-Intensity Operation

Ralph J. Steinhagen

for the FAIR Commissioning & Control Sub-Project

HB2018

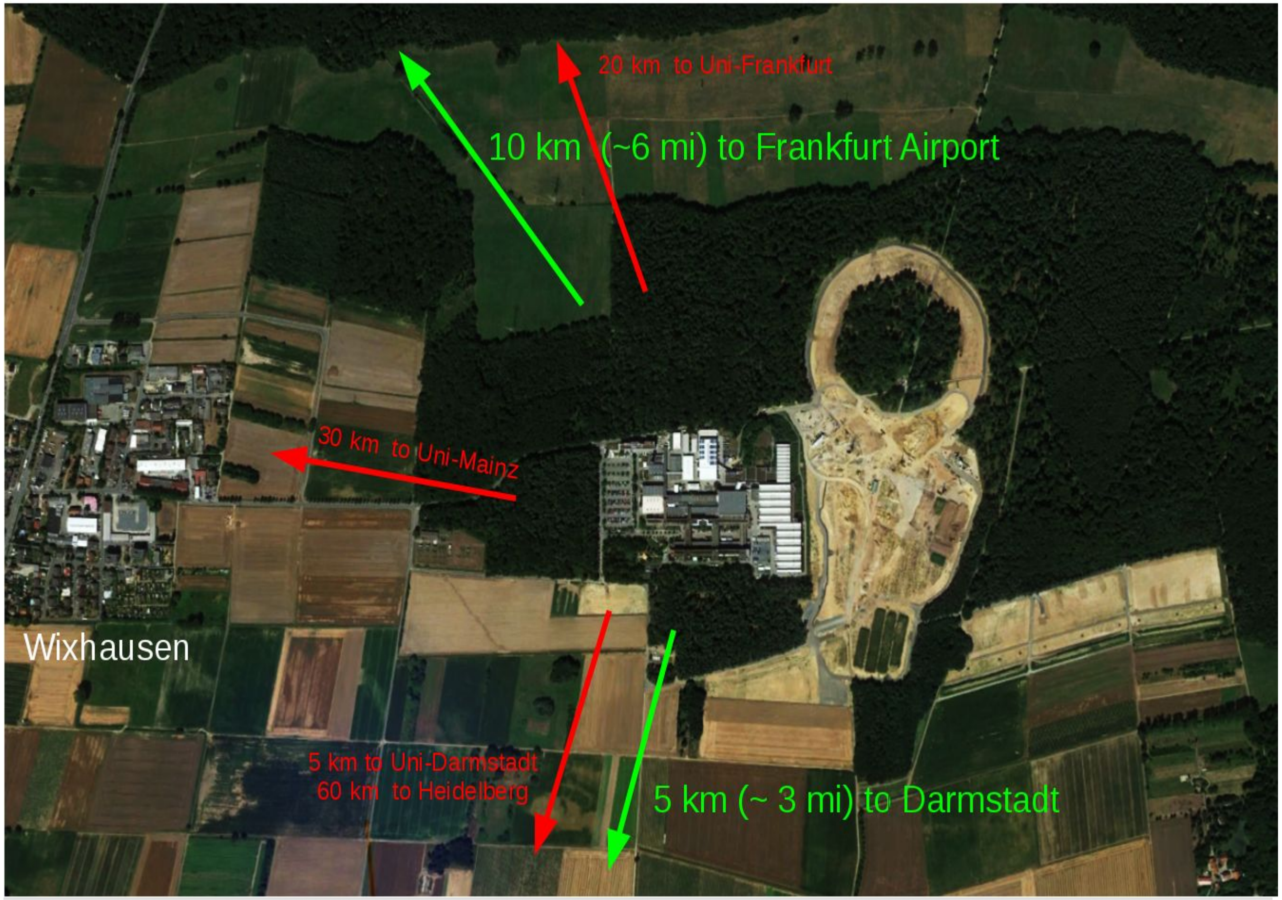
61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

Daejeon, Korea, 17-22 June, 2018

Finland France Germany India Poland Romania Russia Slovenia Sweden UK

GSI HELMHOLTZ ASSOCIATION FAIR

Facility for Anti-proton and Ion Research
„The universe in the laboratory"

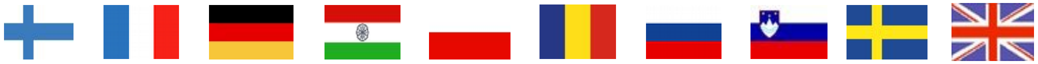


Facts & figures:

- 10 primary shareholders
- ~ 3000 scientists from 50+ countries
- 1.4 billion EUR construction costs (2005 figures)
- HW/Beam Commissioning: 2022 → 2025

- GSI (est. 1969):
  - ~ 1400 staff
  - 350 PhD candidates
  - 113 MEUR budget

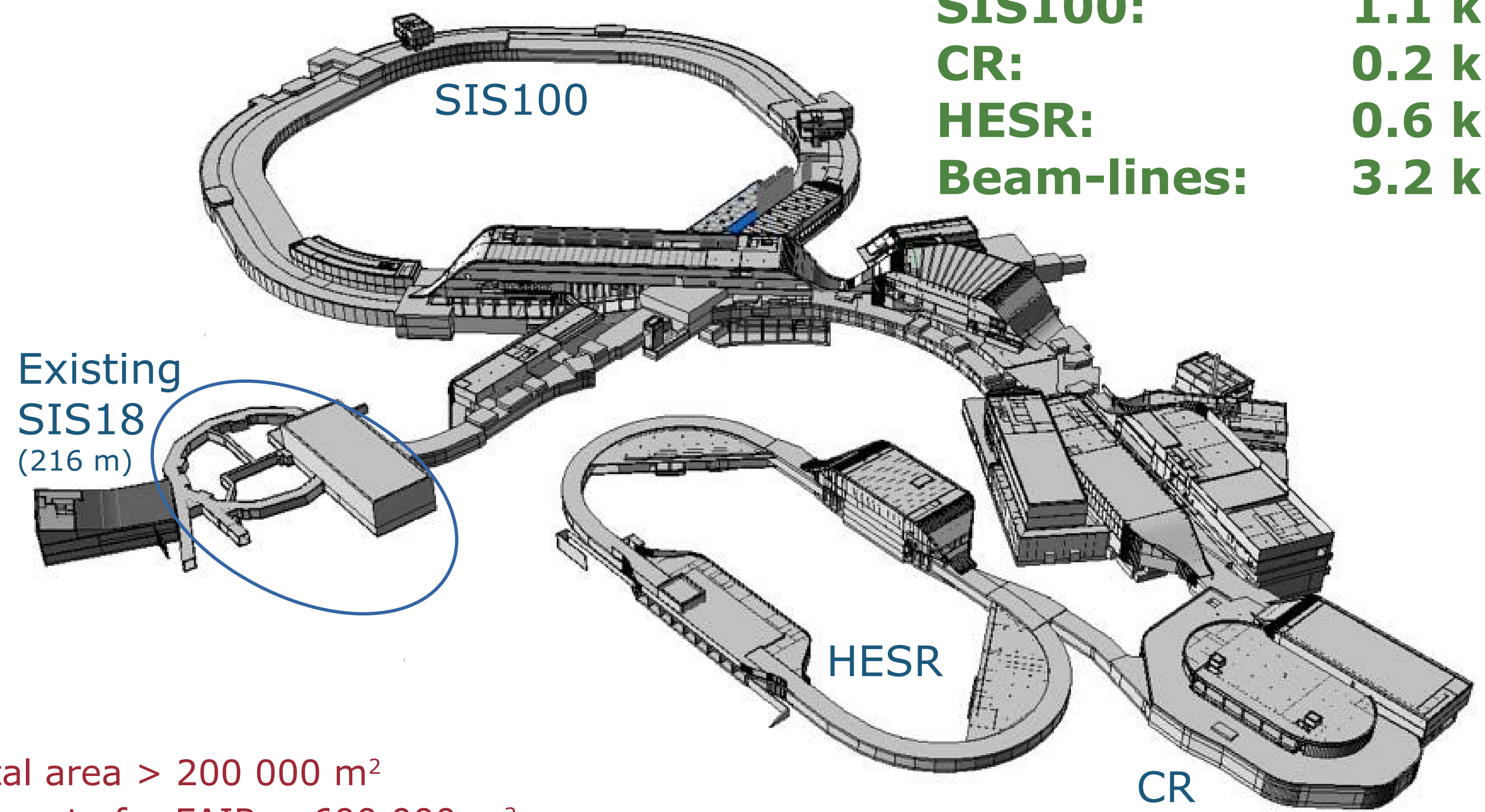
primary shareholders:



Video about FAIR: link to YouTube
(mostly upcoming Civil Construction)

FAIR Accelerator Complex – Civil Construction

SIS100: 1.1 km
CR: 0.2 km
HESR: 0.6 km
Beam-lines: 3.2 km

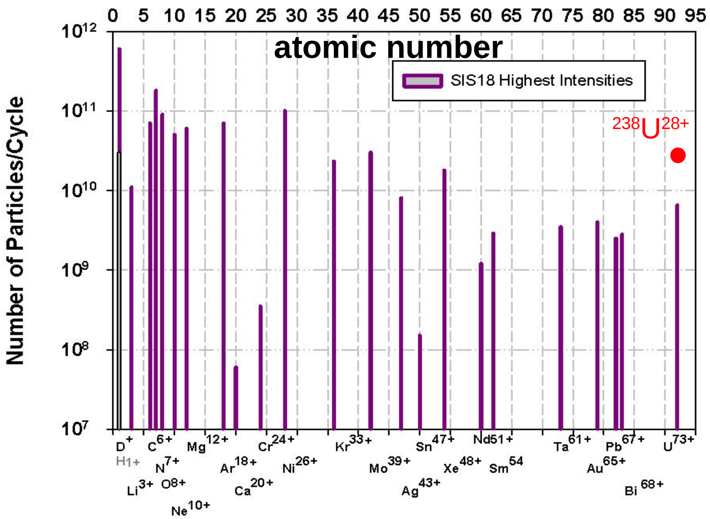


Total area > 200 000 m^2
Concrete for FAIR ~ 600 000 m^3
(for reference: 3x more than SPS & LHC, ¼ of Hoover Dam)
Substructure: 1350 pillars, up to 65 m deep (finished)

SIS18 Preparation for High-Intensity Operation (Top Shielding) and Connection to SIS100

SIS100 Tunnel Cut-and-Cover Excavation

Primary & Secondary Rare Isotope Beams (RIBs)

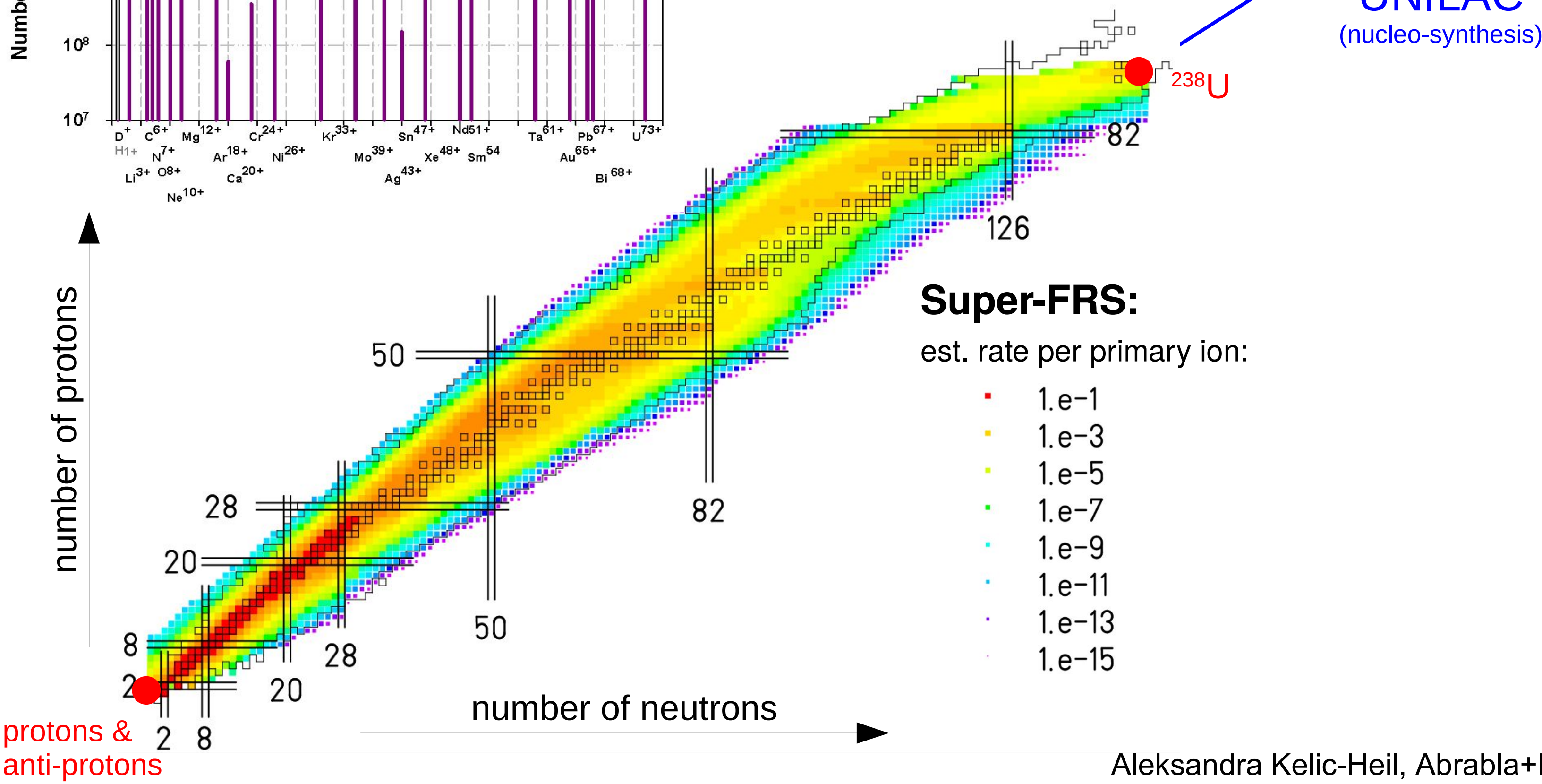


SIS18:

main limitations:

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

SIS100 ~ 4...8 x SIS18



Super-FRS:

est. rate per primary ion:

- 1.e−1
- 1.e−3
- 1.e−5
- 1.e−7
- 1.e−9
- 1.e−11
- 1.e−13
- 1.e−15

Aleksandra Kelic-Heil, Abrabla+EPAX3, July 2015

Modularised Start Version

GSI → FAIR Transition in 2018, 2022 → 2025 (SIS100)

experiments' requirements → **consequences for the accelerator facility**

SIS18 → SIS100 'booster-mode'

(3 Hz accumulation, minimise time at low E)

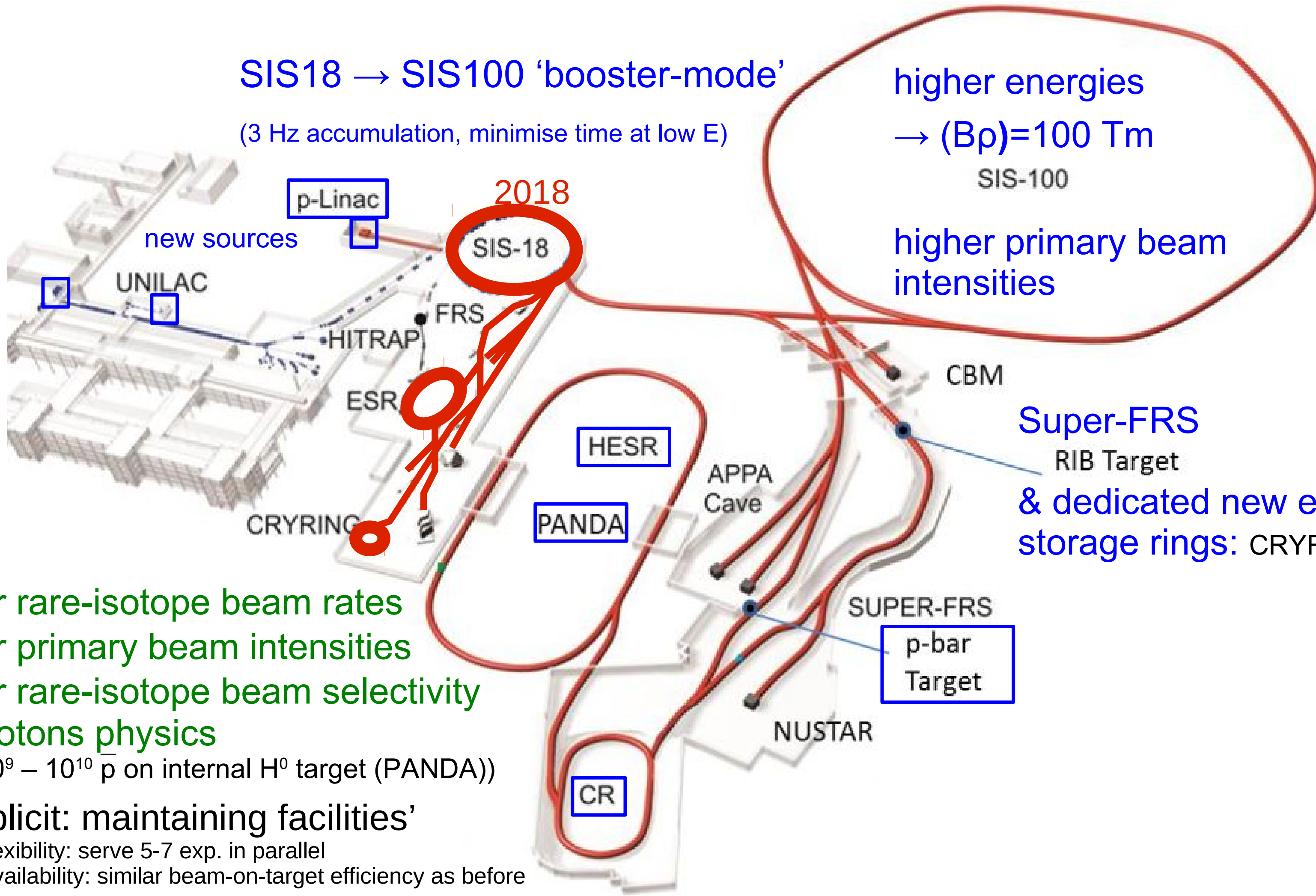
higher energies

→ (Bρ)=100 Tm

higher primary beam intensities

Super-FRS

& dedicated new experimental storage rings: CRYRING, CR, HESR



higher rare-isotope beam rates
higher primary beam intensities
higher rare-isotope beam selectivity
antiprotons physics
(N.B. 10^9 – 10^{10} $\bar{p}$ on internal H^0 target (PANDA))

… implicit: maintaining facilities'

- flexibility: serve 5-7 exp. in parallel
- availability: similar beam-on-target efficiency as before

FAIR Ring Accelerator Parameters

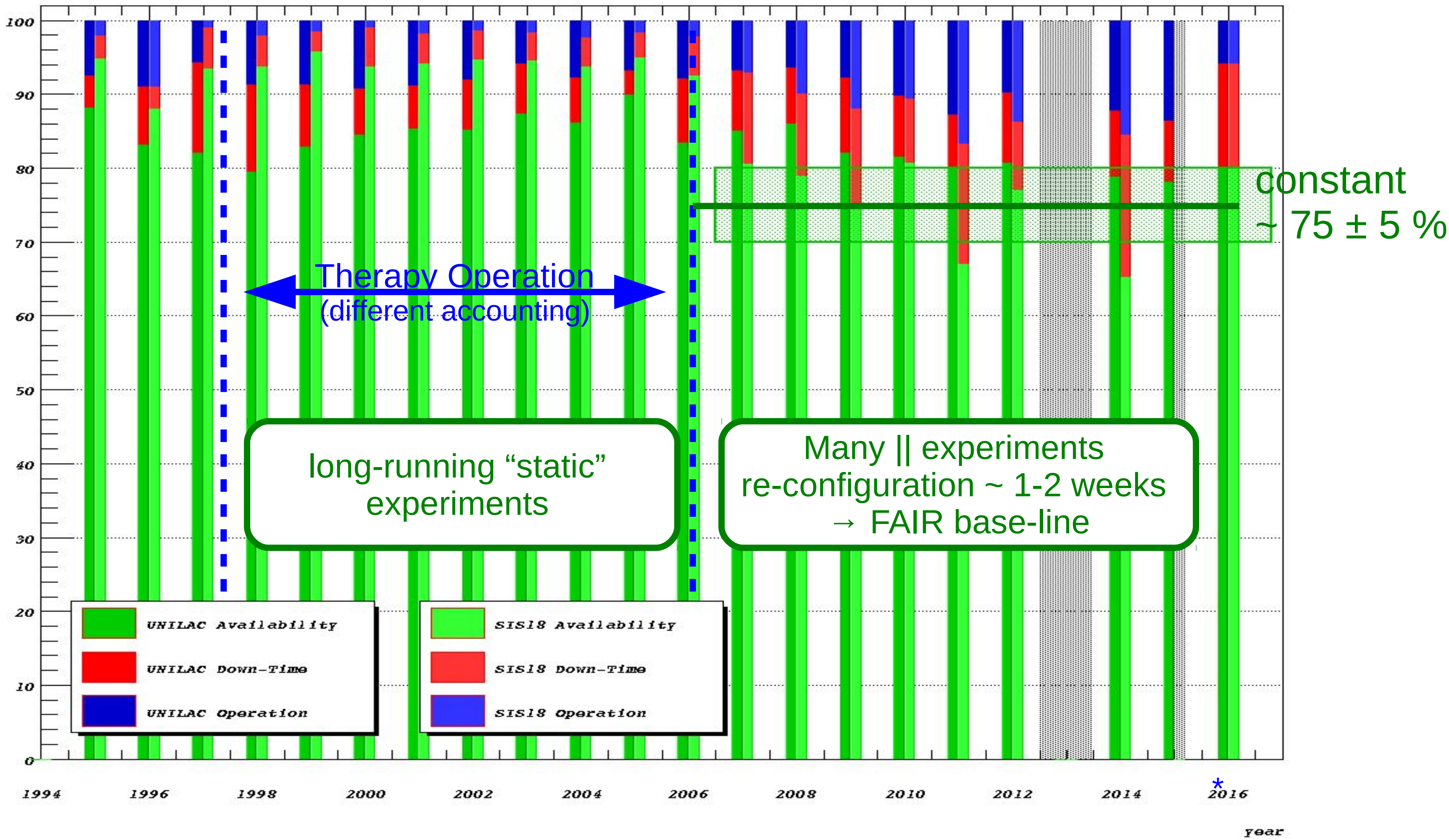
	SIS18	SIS100	CR	HESR
Circumference [m]	216	1083	215	575
Max. beam magnetic rigidity [Tm]	18	100	13	50
Injection energy of protons or anti protons [GeV]	0.07	4	3	3
Final energy of protons or antiprotons [GeV]	4	29	3	14
Injection energy of heavy ions [GeV/u]	0.0114	0.2	0.74	0.74
Final energy of heavy ions 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) high ion intensities**
  - machine protection & machine activation
  - XHV vacuum ↔ min. partially-charged ion charge state changes

→ **facility operational & overall complexity**

Accelerator Experience & Efficiency
1995-2016: U. Scheeler, S. Reimann, P. Schütt et al.

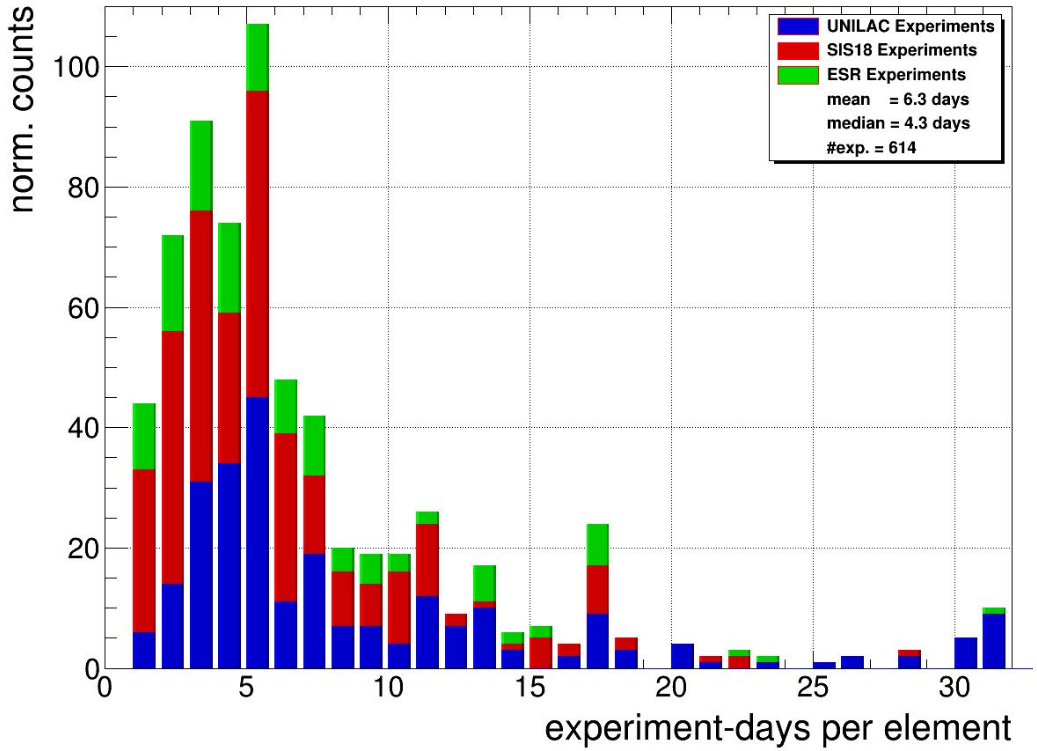


Based on: U. Scheeler, S. Reimann, P. Schütt et al., "Accelerator Operation Report", GSI Annual Scientific Reports 1992 – 2015 + 2016 (D. Severin)
https://www.gsi.de/en/work/research/library_documentation/gsi_scientific_reports.htm
N.B. ion source exchanges are factored out from UNILAC & SIS18 data (~ constant overhead)
Availability: *experiments + detector tests + machine development + beam to down-stream accelerators;*
Down-time: *unscheduled down-time + standby;* Operation: *accelerator setup + re-tuning*

* 2018 operation limitations:
- only ½ UNILAC (w/o A3 & A4)
- only 1 element in SIS18

Accelerator Experience & Efficiency

or: .. how to move/transform accelerator operation from 3 (GSI) → 9 (FAIR) machines



bottom line (1st order):

A) an 'average' GSI/FAIR experiment lasts about 5 days

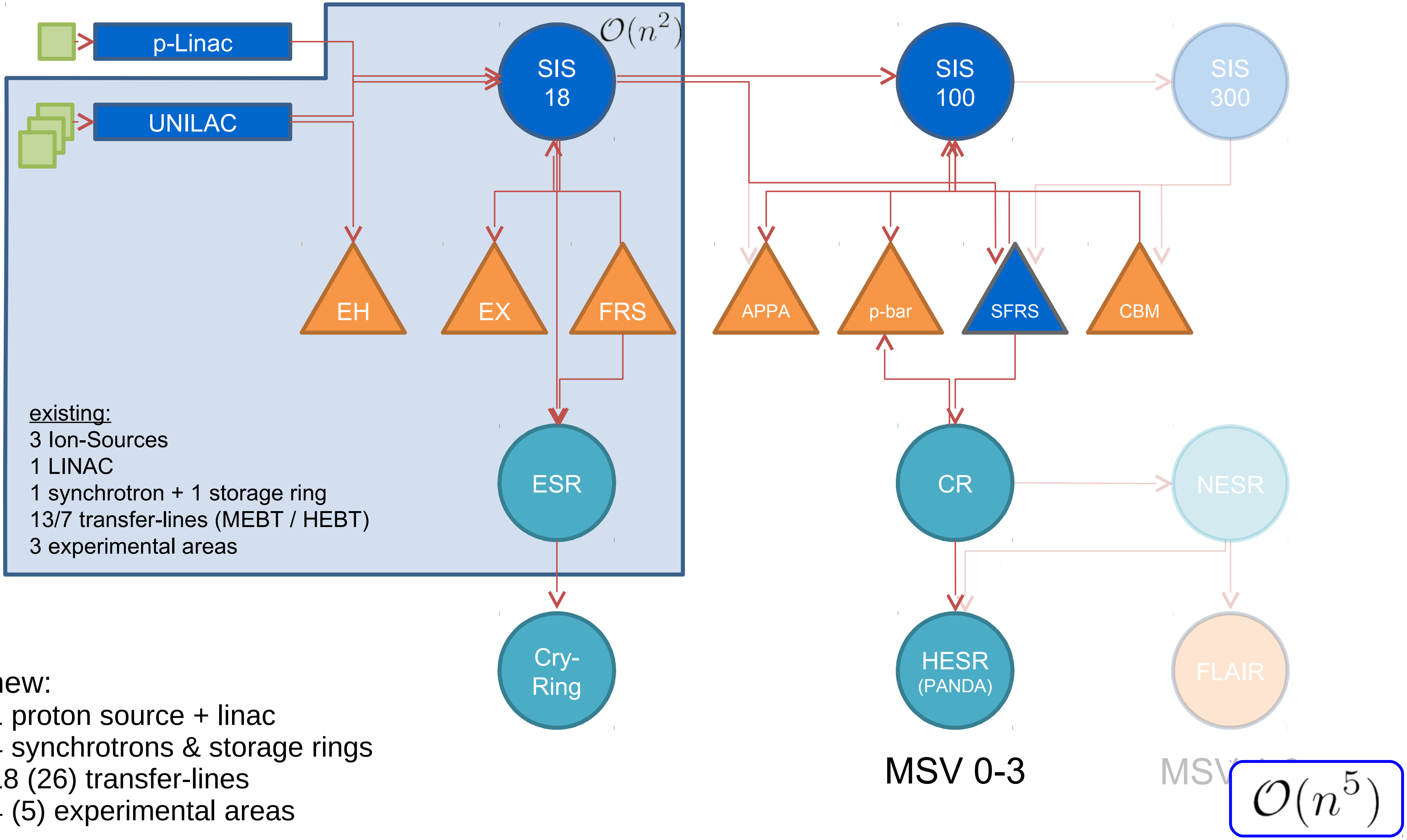
B) FAIR will accommodate about 5-6 parallel experiments

→ expect:

- setup of new beam-production-chain (BPC) about once per day
- longer BPCs (↔ number of sequential acc.) → larger complexity

GSI to FAIR Transition

GSI 3 → FAIR 8½ (11+) accelerator(-like) machines

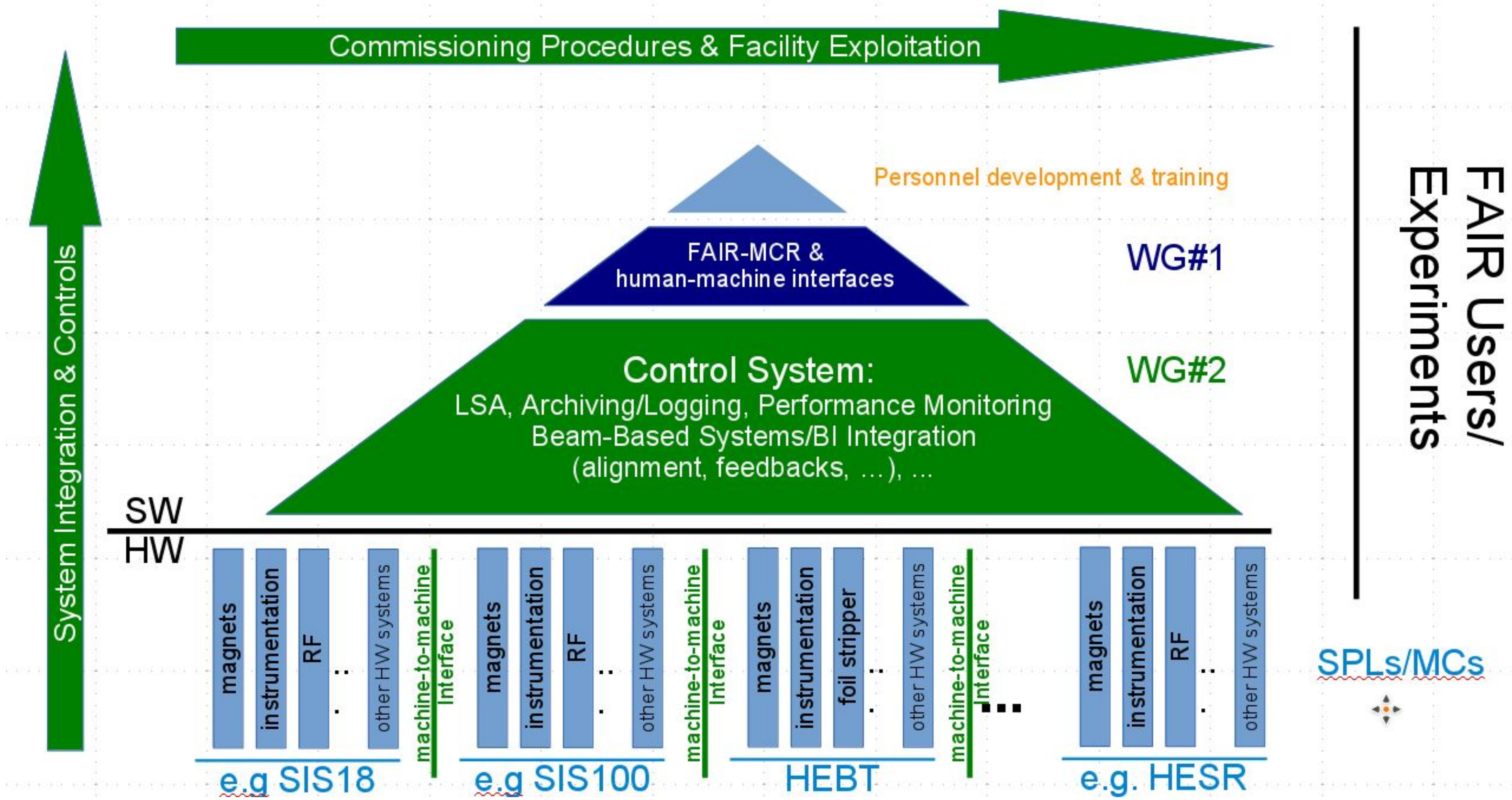


new:
1 proton source + linac
4 synchrotrons & storage rings
18 (26) transfer-lines
4 (5) experimental areas

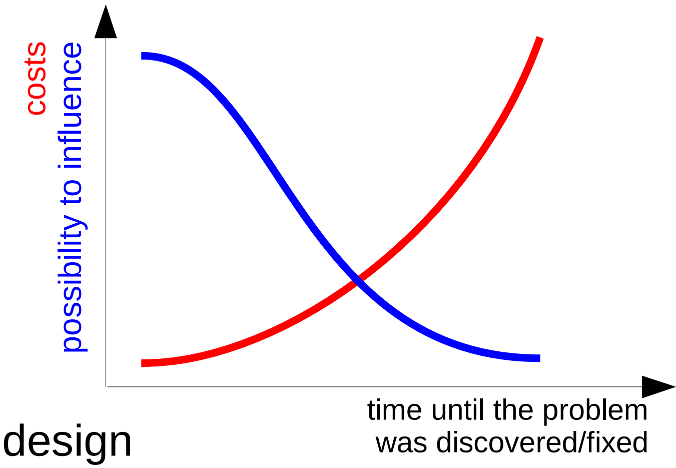
FAIR Commissioning & Control Project

more details: http://fair-wiki.gsi.de/FC2WG/

An accelerator is more than the sum of its parts:



- FAIR Commissioning & Control- & FAIR Control Centre (MCR/Building aspects)
  - platform to identify, coordinate, and work-out FAIR commissioning and operation
  - open to all who can participate and are willing to contribute to these subjects!



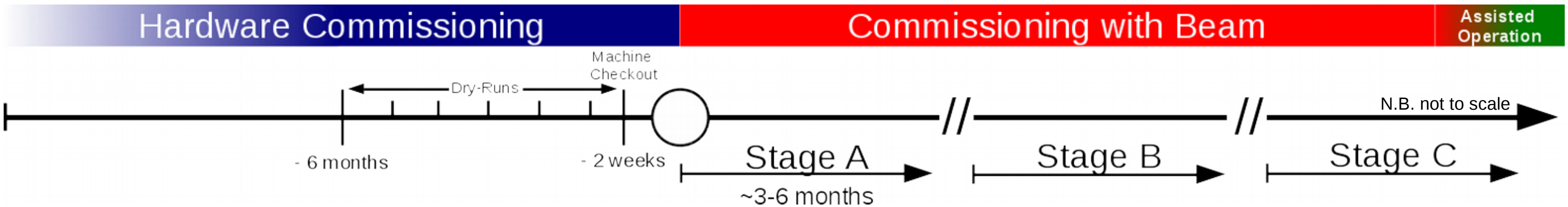
Both WGs follow a long-term strategy and 'lean principles':

- Continuous improvement:
  - Right processes:
    - produce right results & getting it right the first time
      - *commissioning procedures as evolving operation standard*
      - system integration: determine of what, how and when is needed
  - Prevention of inefficiencies, inconsistencies & wastes by design
    - 'poka-yoke' or 'error proofing' principle – culture of stopping and fixing
      1. early, when and where they occur (at the source)
      2. with low-intensity beam rather than with high-intensity beam
      3. addressing first basic parameters before complex higher-order effects
    - Examples:
      - first fix injection, trajectory, orbit, Q/Q' before addressing space-charge or slow-extraction problems
      - important losses for low-intensity beam have larger impact for high-intensity beam (↔ activation)
        - pilot-beam concept: <u>always</u> verify machine safety with low-intensities before moving on to high-intensity beams

- Respect for people – “develop people, then [/and] build products [/accelerators]”
  - optimise operation ↔ smart tools & procedures, e.g. beam-based feedbacks, sequencer, …
    - automate routine task so that operator talents are utilised and focused on more important tasks
  - training, investment in and development of people – minimise overburden/strain of personnel

Commissioning without & with Beam

https://fair-wiki.gsi.de/FC2WG/HardwareCommissioning/
https://fair-wiki.gsi.de/FC2WG/BeamCommissioning

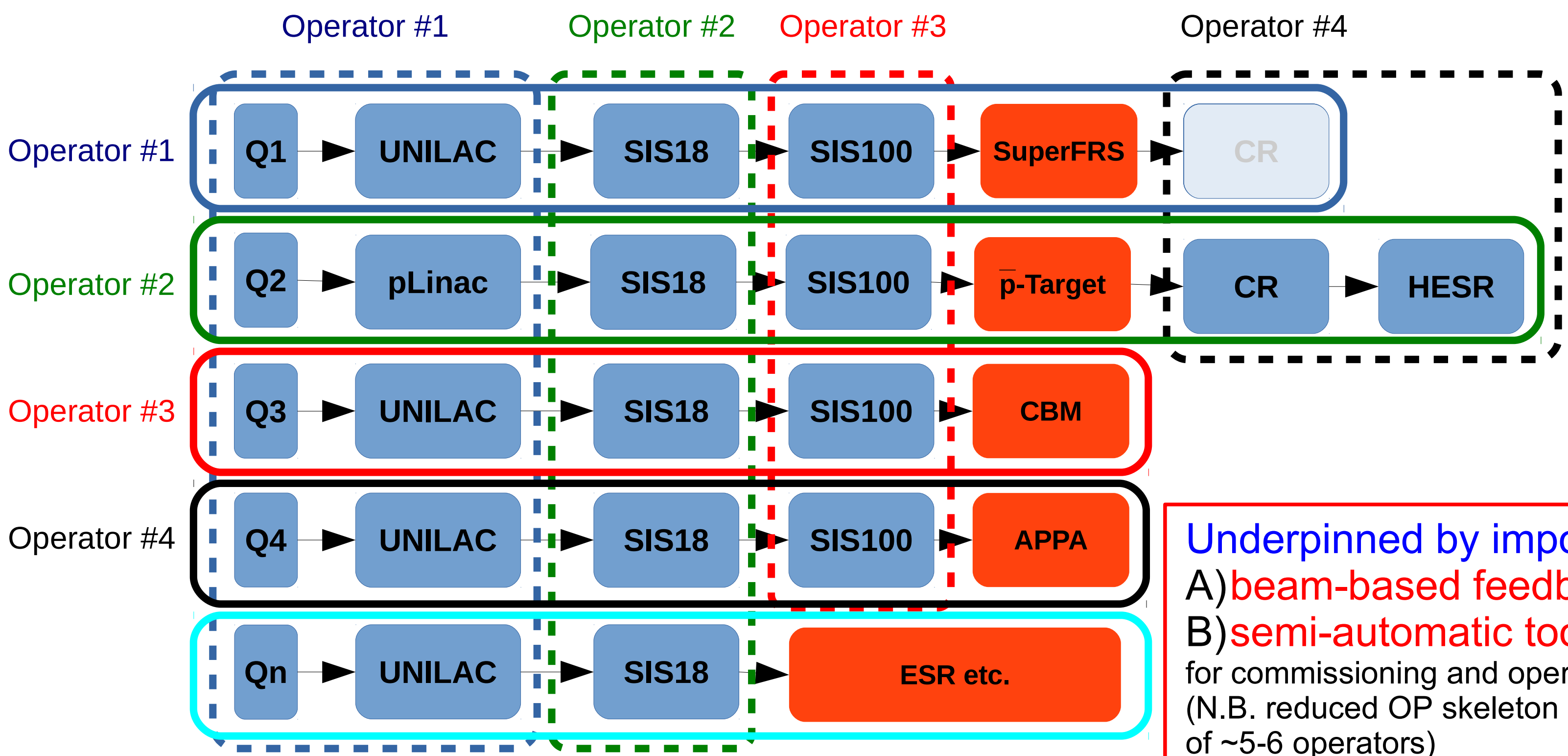


A) Hardware Commissioning (HWC) – conformity checks of the physical with contractual design targets,
  - || commissioning of individual systems & tasks ↔ SPLs/equipment group responsibility

B) Commissioning with Beam (BC) – commissioning of beam-dependent equipment
  - Focus on tracking beam progress through the the beam production chain (BPC)
    - threading, injection, capture, acceleration and extraction
  - + 'Dry-Runs': checks conformity of system's controls integration and readiness for Commissioning with Beam
  - Staged-Approach:
    - Stage-A: Pilot beams/”easily available” ions (e.g. Ar)
      - basic checks: threading, injection, capture, cool, convert, acceleration/decelerate, stripping & extraction
      - always done with 'safe' ie. low-intensity/brightness beam (Ions: simpler optics, beam dynamics → Protons: transition crossing)
    - Stage B: Intensity ramp-up & special systems
      - achieving and maintaining of nominal transmission and beam losses, commissioning and validation of machine protection & interlock systems
      - Possibly unsafe operations always preceded by checks with safe beam
    - Stage C:Production operation with nominal intensities
      (N.B. first time counted as 'commissioning' or 'assisted operation' → later: 'regular operation')
      - push physics and beam parameter performance (emittance, momentum spread, ...)
      - identify and improve upon bottlenecks impacting FAIR's 'figure-of-merit
      - <u>make fast setup and switch-over between different beam production chains routine</u>

Operation/Control Paradigm

- Some important OP boundary conditions:
  A) Compared to GSI, FAIR facility size and complexity increases roughly by a factor 4
  B) Expect some improvement but 'Operator' & 'System Expert' will likely remain a scarce resource
- One strategy item: 'One Operator per Accelerator Domain' vs. 'One Operator per Experiment':

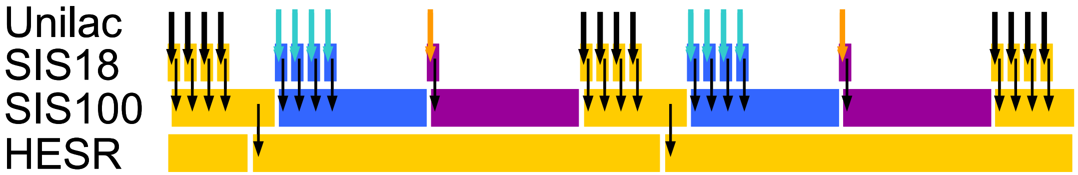


Underpinned by importance of:
A) beam-based feedbacks
B) semi-automatic tools
for commissioning and operation of FAIR (N.B. reduced OP skeleton crew (nights) of ~5-6 operators)

Beam Production Chains

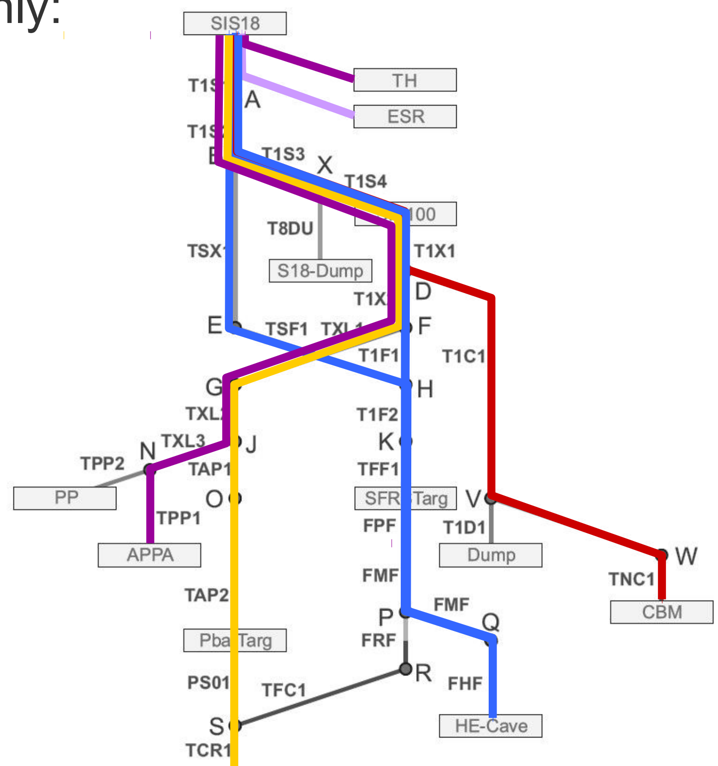
Exemplary Operational Scenarios

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, …

Beam-based Cycle-to-Cycle feedbacks

Generic Beam Control (focus on use-case)

1. Transmission Monitoring System
2. Orbit Control
3. Trajectory Control (threading, inj./extr., targets)
4. Q/Q'(') Diagnostics & Control
5. TL&Ring Optics Measurement + Control
(LOCO, AC-dipole techniques etc.,)
6. RF Capture and (later) RF gymnastics
7. Longitudinal Emittance Measurement
8. Transverse emittance measurement
9. Transverse and longitudinal feedbacks

Bread-and-Butter systems for OP ~ ideally for SIS18 restart

Machine-specific Beam-Based Systems:

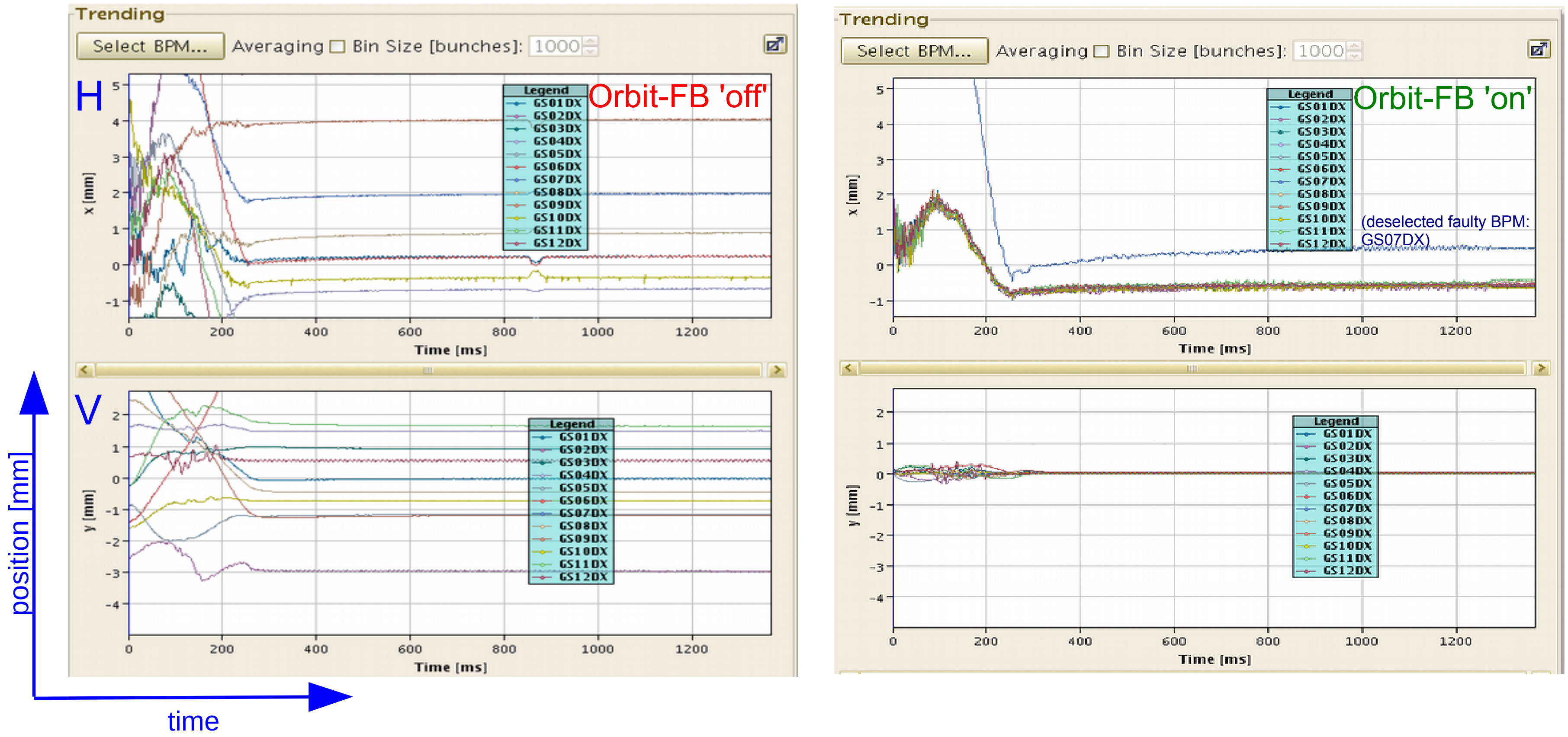
- SIS18: multi-turn-Injection (N.B. highly non-trivial, complex subject), Slow-Extraction (K.O. exciter, spill-structure, …)
- SIS100: Slow-Extraction (K.O. exciter, spill-structure, …), RF Bunch Merging and Compression
- ESR, HESR & CR: Stochastic cooling, Schottky diagnostics, …, tbd.

Generic:

- Remote DAQ of Analog Signals
(strong impact on HKR migration/operation!)
- Facility-wide fixed-displays, facility & Machine Status ("Page One")
- context-based monitoring of controls and accelerator Infrastructure,

Cycle-to-Cycle Orbit-FB Proof-of-Concept

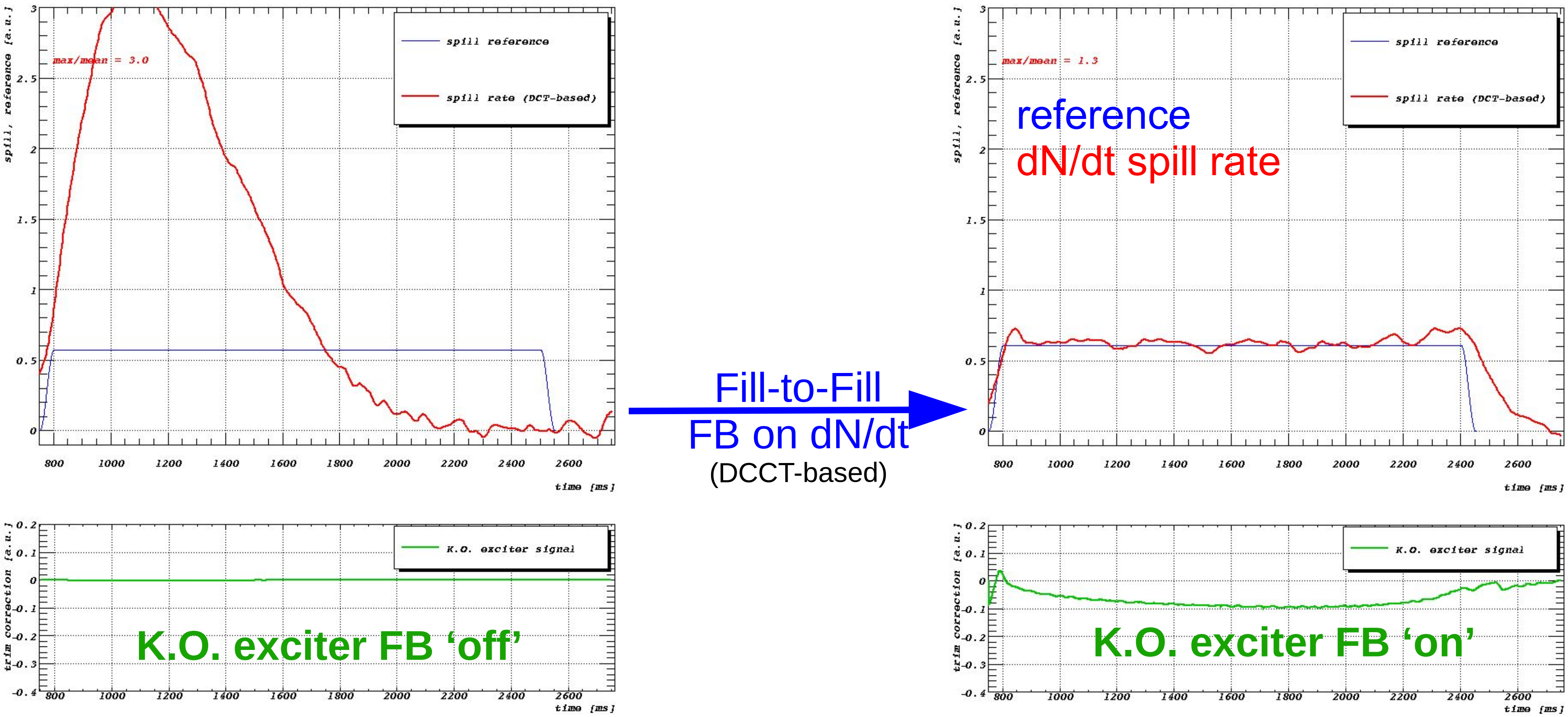
B. Schlei, H. Liebermann, R. Steinhagen



- some workarounds needed, but overall success and results look promising
  - need to follow-up: reliability, performance issues related to CO & BI + detailed integration before being put into regular operation (→ routine operation for >2018 looks feasible)
  - N.B. remaining horizontal oscillation due to uncorrected Δp/p mismatch → radial-loop/Energy-FB

Cycle-to-Cycle Macro-Spill-FB Proof-of-Concept

R. Steinhagen, H. Liebermann → presented at IPAC’17



- some workarounds needed, but overall success and results look promising
  - need to follow-up: K.O. exciter power-limitation handling
    - alternative: FB using fast extraction quadrupole or main-quads
  - Desirable: direct FB signal from experimental detectors

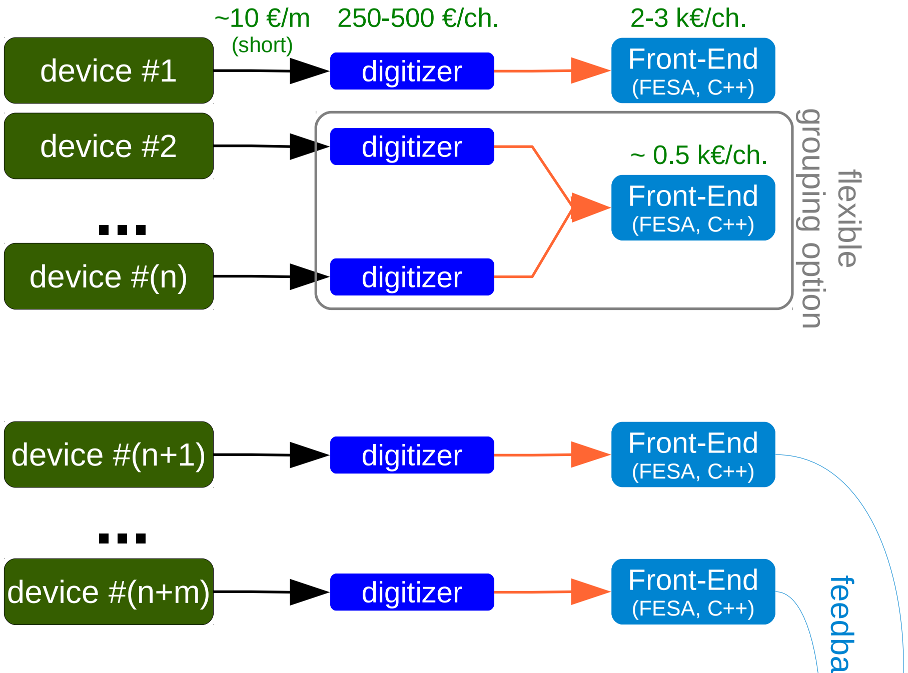
Additional Technical Controls Facilities in view of Commissioning & Operation

- **Sequencer** (N.B. based on previous work at CERN)
  - automatisation of routine tasks and system validation tests (HWC, BC & Operation)
  - automatic 'as-good-as-new' tests ↔ preventative maintenance/early warnings
- **Digitization and continuous monitoring of analog signals**
  ↔ fully digital control room
  - tracking/isolation of faults (↔ post-mortem)
  - less-biased performance indicator
- **Accelerator & Beam Modes**
  - communication of intended accelerator operation to experiments, FAIR and wider community
  - what to expect and when, beam time performance tracking & analysis
- **Archiving System**
  - *… collect and store all pertinent accelerator data centrally to facilitate the analysis and tracking of the accelerator performance as well as its proper function.*
- **Beam Transmission Monitoring System**
  - beam interlock that prevents poor performance, minimises machine activation (ALARA), or avoids scenarios that might cause/or otherwise complicate machine protection incidents

- many more ...

Digitization of Analog Signals at FAIR
https://edms.cern.ch/document/1823376/

- targeted concept
  (underlying assumption: scopes/digitizers are cheap, RF switches are expensive)



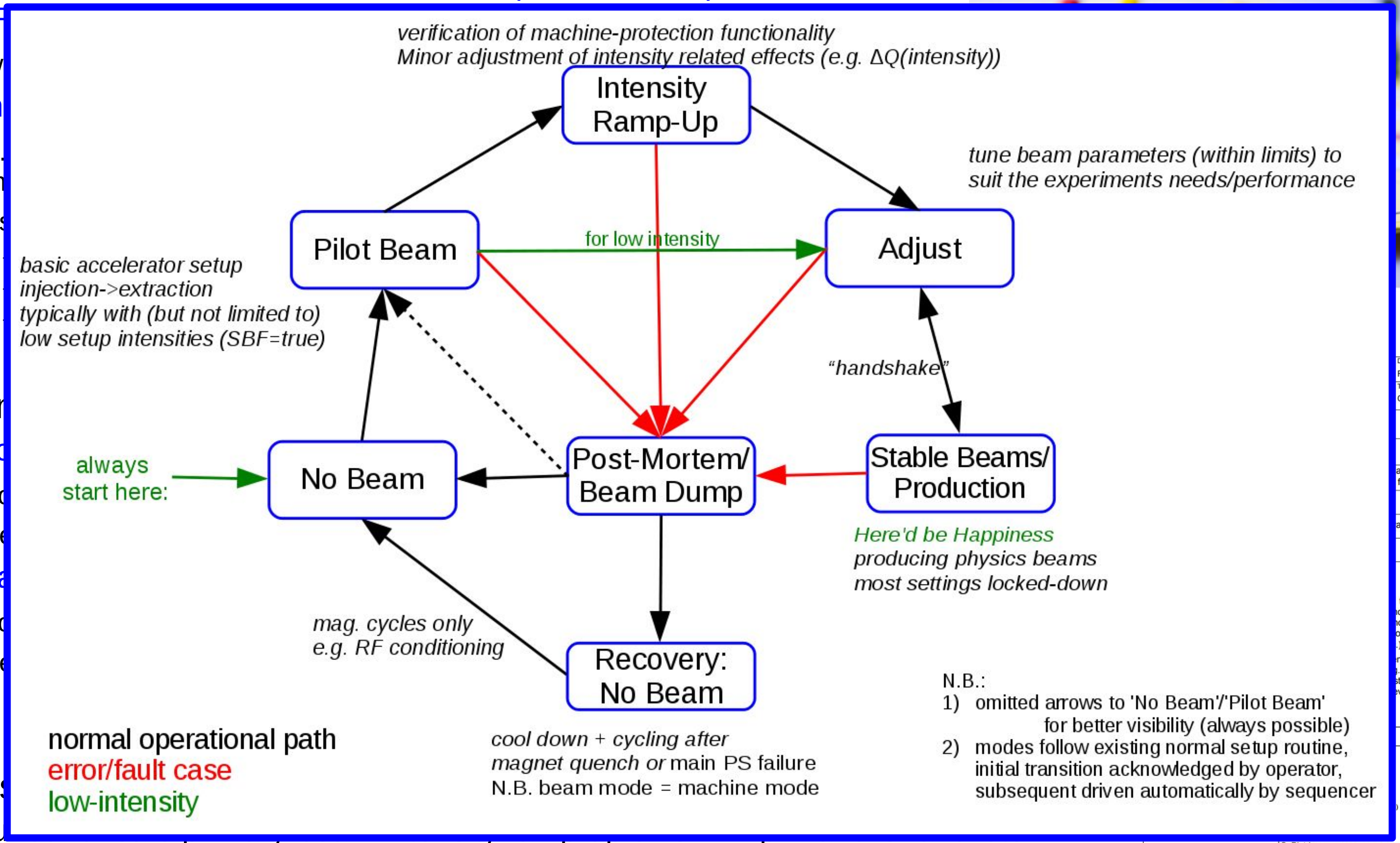
start deployment ≥2018 (SIS18), crucial for:
- migration to new FAIR Control Centre (FCC),
- optimisation of commissioning & operation
- tracking/isolation of faults (↔ post-mortem)
- less-biased performance indicator

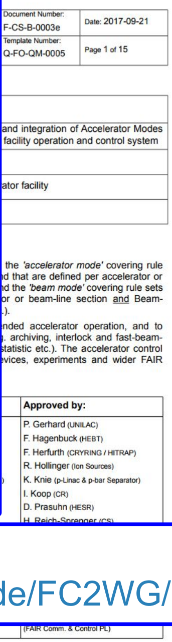
link: more details

Accelerator & Beam Modes

https://edms.cern.ch/document/1823352/

- Purpose:
  - Communication of intended accelerator operation to experiments, FAIF
    - w
  - Con
    - e. m
    - as
- Main r
  1) Acc
     - co
     - de
  2) Bea
     - co
     - de
- propos
  - requ
  - more fine-grained options for facility availability, performance tracking & analysis





copy on:
https://fair-wiki.gsi.de/FC2WG/

FAIR Archiving System
https://edms.cern.ch/document/1176039/

- *… collect and store all pertinent accelerator data centrally to facilitate the analysis and tracking of the accelerator performance as well as its proper function.*

- Combined Archiving and Post-Mortem storage concepts
- Aim at storing maximum reasonable amount of data
  - facilitates data mining (performance trends, rare failures, …)
  - key to understanding and improving accelerator performance

Quality Management	Document Type:	Document Number: F-DS-C-11e	Date: 2016-07-18
FAIR	Detailed Specification	Template Number: Q-FO-QM-0005	Page 1 of 24

Document Title:	**Detailed Specification of the FAIR Accelerator Control System Component "Archiving System"**
Description:	This document is the Detailed Specification of the accelerator control system component 'Archiving System'. Its task is to collect and store all pertinent accelerator data centrally to facilitate the analysis and tracking of the accelerator performance as well as its proper function.
Division/Organization:	CSCO
Field of application:	FAIR Project, existing GSI accelerator facility
Version	V 4.5

Prepared by:	Checked by:	Approved by:
V. Rapp L. Hechler R. Steinhagen	**FAIR-C2WG-ALL** A. Reiter (BI) M. Schwickert (BI) J. Fitzek (CO) S. Reimann (OP) P. Schütt (OP) C. Omet (SIS-100 MP) D. Ondreka (System Planning) I. Lehmann (Machine-Exp.) D. Severin (Machine-Exp.) **MPLs & MCs***	R. Bär (Controls) R. Steinhagen (FAIR Comm. & Control)

Archiving

Post-Mortem

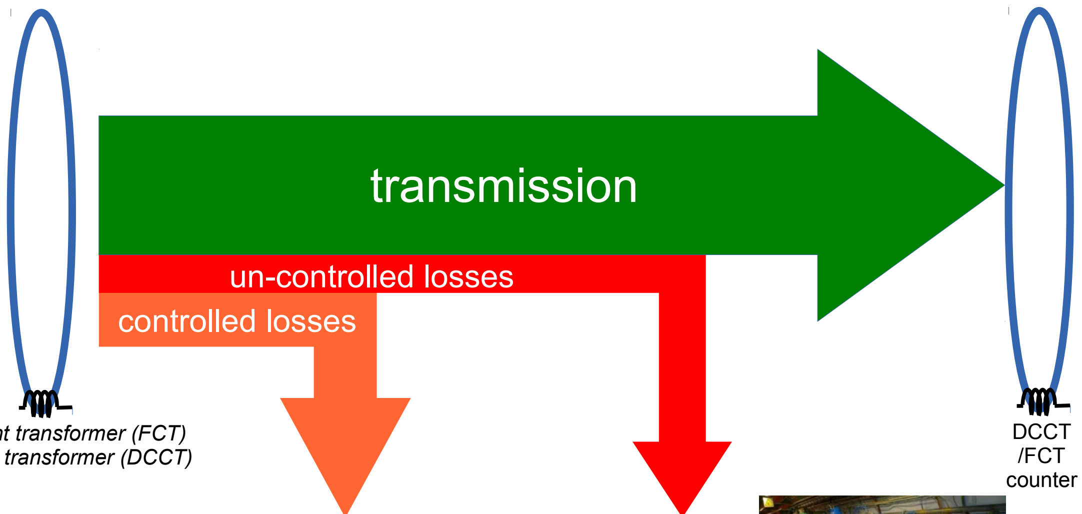
N.B. importance: quantitative accelerator performance and bug/fault-tracking indicators

Beam Transmission Monitoring (BTM)

https://edms.cern.ch/document/1823362/

Ion-Source

$$I_{source}(t) = \frac{dN_{source}(t)}{dt}$$



Fast current transformer (FCT)
DC current transformer (DCCT)

DCCT
/FCT
counter

Experiment

primary (secondary)
ions-on-target/s

$$I_{target}(t) = \frac{dN_{target}(t)}{dt}$$

$$\frac{dN_{collimator}(t)}{dt}$$

dynamic vacuum, ε-blow-up/tails, slow-extraction, ...
→
cryo- & beam-halo collimators, rad-hard magnets, extra shielding, ...

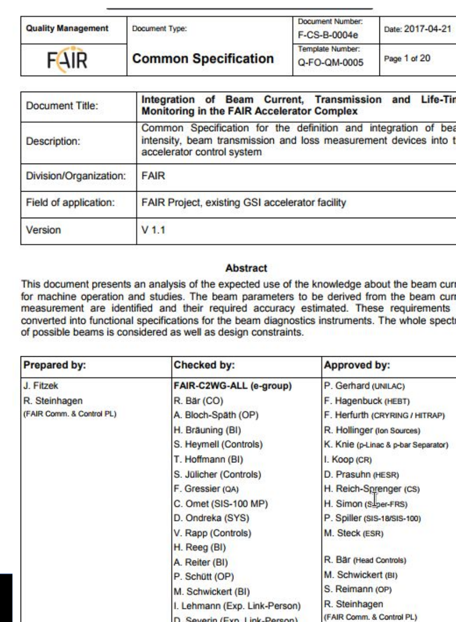
less-avoidable losses
(may need to accept a given amount)

$$\frac{dN_{loss}(t)}{dt}$$

beam instabilities, aperture constraints, slow beam drifts across e-septa
→
activation & machine protection

avoidable losses
(ALARA: should minimise before MP & Activation limits kick in)

online dosimetry (abs. reference)



Quality Management	Document Type:	Document Number: F-CS-B-0004e	Date: 2017-04-21
FAIR	Common Specification	Template Number: Q-FO-QM-0005	Page 1 of 20

Document Title:	**Integration of Beam Current, Transmission and Life-Time Monitoring in the FAIR Accelerator Complex**
Description:	Common Specification for the definition and integration of beam intensity, beam transmission and loss measurement devices into the accelerator control system
Division/Organization:	FAIR
Field of application:	FAIR Project, existing GSI accelerator facility
Version	V 1.1

Abstract

This document presents an analysis of the expected use of the knowledge about the beam current for machine operation and studies. The beam parameters to be derived from the beam current measurement are identified and their required accuracy estimated. These requirements are converted into functional specifications for the beam diagnostics instruments. The whole spectrum of possible beams is considered as well as design constraints.

Prepared by:	Checked by:	Approved by:
J. Fitzek R. Steinhagen (FAIR Comm. & Control PL)	**FAIR-C2WG-ALL (e-group)** R. Bär (CO) A. Bloch-Späth (OP) H. Bräuning (BI) S. Heymell (Controls) T. Hoffmann (BI) S. Jülicher (Controls) F. Gressier (QA) C. Omet (SIS-100 MP) D. Ondreka (SYS) V. Rapp (Controls) H. Reeg (BI) A. Reiter (BI) P. Schütt (OP) M. Schwickert (BI) I. Lehmann (Exp. Link-Person) D. Severin (Exp. Link-Person)	P. Gerhard (UNILAC) F. Hagenbuck (HEBT) F. Herfurth (CRYRING / HITRAP) R. Hollinger (Ion Sources) K. Knie (p-Linac & p-bar Separator) I. Koop (CR) D. Prasuhn (HESR) H. Reich-Sprenger (CS) H. Simon (Super-FRS) P. Spiller (SIS-18/SIS-100) M. Steck (ESR) R. Bär (Head Controls) M. Schwickert (BI) S. Reimann (OP) R. Steinhagen (FAIR Comm. & Control PL)

§§ Radiation Permit – limits on total dose per year (facility & external)

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 (I
  before propagating t
- 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

- Inj./extr. mismatch (Δβ, Δμ) correction (ε-blow-up optimisation)
- arises/restores
  terms)
- ecks)

e 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

FAIR Control Centre (FCC)

https://edms.cern.ch/document/1821654/

Requirements & Conceptual Design – primary goals:

- provide sufficient room for the operation of the existing and enlarged GSI/FAIR facility
- ergonomics: Main Control Room should not “get in the way of it’s primary function”
  - establish functional relationships between MCR & ancillary rooms
  - validate/check w.r.t. FAIR Commissioning & Control concept
  - validate/check whether input for building planner is feasible and consistent with DIN/ISO norms

N.B. surface numbers are approximate and may change due to civil construction constraints
outer hull measurements, colour, design, etc. may change

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FAIR	**Common Specification**	Template Number: Q-FO-QM-0005	Page 1 of 25

Document Title:	**Common Specification for the FAIR Control Centre in view of Commissioning, Operation, and operational Exploitation of the FAIR Accelerator Facility**
Description:	Functional requirements, ergonomics, and design of the FAIR Control Centre (FCC) covering: FCC Main Control Room (MCR), MCR-related meeting and conference rooms, visitor’s gallery, and ancillary infrastructure.
Division/Organization:	FAIR/GSI
Field of application:	FAIR Project, existing GSI accelerator facility
Version	V 1.1

Abstract

This document describes the user-level functional requirements, ergonomics considerations, and derived design of the FAIR Control Centre (FCC) from an accelerator commissioning, operation, and operational exploitation point of view, including experiments that are tightly intertwined with accelerator operation. This specification builds upon best practises and operational experiences with similar, existing accelerator infrastructures at GSI, CERN and other large international laboratories, and summarises the present user-community understanding, discussions and ergonomics in view of the future operation of FAIR. This document extends, combines, and supersedes previous FAIR specifications F-DS-C-21e and F-DS-C-22e.

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N.B. FCC “ready” for HWC starting 2022 (+ backup option)

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