ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-TUA2WD01

FAIR COMMISSIONING – CONCEPTS AND STRATEGIES IN VIEW OF HIGH-INTENSITY OPERATION

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Abstract

The Facility for Anti-Proton and Ion Research (FAIR) presently under construction, extends and supersedes GSI's existing infrastructure. Its core challenges include the precise control of highest proton and uranium ion beam intensities, the required extreme high vacuum conditions, machine protection and activation issues while providing a high degree of multi-user mode of operation with facility reconfiguration on time-scales of a few times per week. Being based on best-practices at other laboratories, this contribution outlines the applicable hardware and beam commissioning strategies, as well as concepts, beam-based and other accelerator systems that are being tested at the existing facility in view of the prospective FAIR operation.

INTRODUCTION

Civil construction of the initial modularised start version of FAIR has started. Accelerator-related hardware commissioning (HWC) is targeted to commence in 2022, followed by commissioning with beam (BC), and physics user operation by 2025. A schematic overview of the existing and new facility is shown in Figure 1.

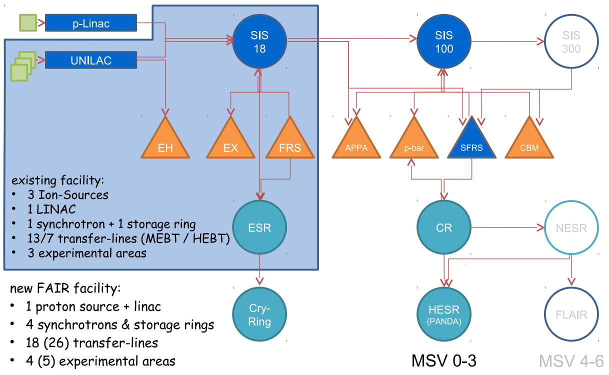

Figure 1: Schematic overview of the existing and new FAIR accelerator facility. The operational complexity increases from presently $O(n^2)$ (GSI) to $O(n^2$ (FAIR) due to the longer accelerator chains.

In addition to the existing UNILAC [2], SIS18 [3], and ESR [4], the FAIR accelerator complex will extend the existing GSI infrastructure by a dedicated anti-proton production target, the Super Fragment Separator (Super-FRS) for the production of rare isotope beams (RIBs) and five new accelerators [5, 6]: a dedicated high-intensity proton linac [7], the SIS100 synchrotron [8], as well as the experimental CRYRING, CR and HESR storage rings [9, 10].

Some of the noteworthy features of FAIR include:

- the control of a wide range of proton, anti-proton, primary and RIBs, with targeted design intensities ranging from $3 \cdot 10^{13}$ ppp (particles-per-pulse) for protons at 29 GeV/u up to $5 \cdot 10^{11}$ ppp for $^{238}U^{28+}$ at 2.7 GeV/u – a factor 100 higher than similar existing facilities at those energies,
- the flexibility to reconfigure the facility for up to 7 experiments in parallel, with many of these experiments lasting only 5 to 6 days, as well as
- the resulting complexity increase (presently: $O(n^2)$, FAIR: $O(n^5)$) due to the larger facility, longer accelerator chains, and especially more precise beam and machine parameter control that is required at the targeted intensities and energies:
  - excellent XHV vacuum conditions (e.g. SIS100: vacuum $< 10^{-12}$ mbar) and the precise control of dynamic-vacuum or other beam loss mechanism,
  - emittance preservation, control of space-charge, transverse and longitudinal beam dynamics starting in the primary beam pre-injectors, as well as
  - acceptable machine protection and minimisation of machine activation (ALARA-principle: 'As Low As Reasonably Achievable').

OPERATIONAL AVAILABILITY, EFFICIENCY & CHALLENGES

While FAIR will provide highest primary beam intensities and highest selectivity for the rarest of RIBs, an implicit assumption and requirement is that the facilities' flexibility of serving a similar number of parallel-running experiments and similar beam-on-target efficiency (machine availability) will be maintained. Figures 2(a) and 2(b) provide a historic overview of the achieved beam-on-target (BoT) merit figure and typical experiment duration per ion species. Over the past ten years – which is more representative for the targeted FAIR physics programme – GSI could achieve a BoT efficiency figure of about 75 % with respect to the scheduled beam-time while the vast majority of experiments last typically less than 5 days, with with the exception of a few long running experiments integrating their data over up to a month for a given species.

With the expected number of parallel experiments, it is expected that the facility and associated beam-production-chains (BPCs, [11]) need to be reconfigured or re-setup about once per day. In addition, the operational complexity increases significantly due to the inherently longer BPCs

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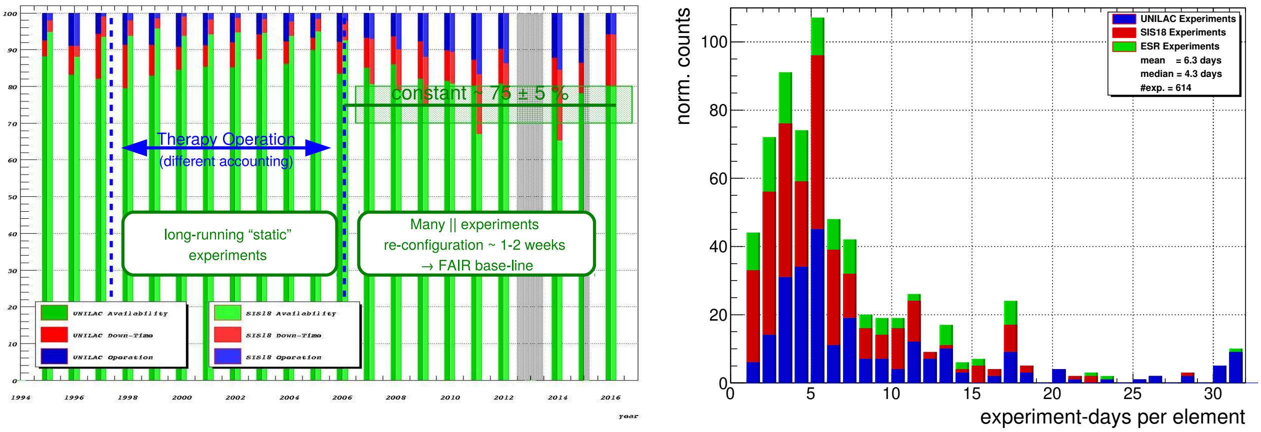

(a) beam-on-target efficiency between 1992 and 2016

(b) average experiment duration per ion species

Figure 2: Beam-on-Target efficiency and average experiment duration per ion-species. Ion source exchanges are factored out from UNILAC and SIS18 data (constant overhead). The availability includes time used for experiments, detector tests, machine development, as well as beam to down-stream accelerators Down-time: unscheduled down-time and standby; Operation: accelerator setup and re-tuning [12].

(linked to the larger number of sequential accelerators), the ALARA principle of minimising activation especially at high energies, as well as accelerator-physics challenges related to high-intensity operation (ie. space-charge, collective effects, etc.). For example, while operating with highest beam intensities, changes to the beam intensities for experiments in or directly after SIS100 need to back propagated through the accelerator chain to either the ion sources, the linac's RF chopper, or the SIS18 where these intensity changes and losses can be safely accommodated while minimising the activation or other collateral effects (e.g. dynamic vacuum). Since many of the experiments last only two to three days, any of these type of changes or BPC setup need to be executed in a most efficient, safe, and therefore often semi-automated fashion in order to maintain an overall high BoT figure of merit of the specific experiment and facility.

FUNDAMENTAL STRATEGY & PRINCIPLES

The 'FAIR Commissioning & Control (Sub-) Project' has been launched in 2015 in order to coordinate the various activities related to:

- the above mentioned operational challenges,
- the development of concepts and efficient strategies for the pending Hardware- (HWC) and Beam Commissioning (BC) of FAIR, as well as
- the integration of the related accelerator equipment into the controls system and machine operation paradigms.

These activities have been sub-divided into two working groups (WGs): the 'FAIR Commissioning & Control WG' (FC2WG [1]) which focuses on the accelerator-related system integration, commissioning and operation aspects, and the 'FAIR Control Centre WG' (FCC-WG [13]) which focuses on the control room ergonomy (acoustics, console layout, lighting, etc.), functional relationships between the main control room (MCR) and secondary infrastructure, and civil construction interfaces related to the FAIR Control Centre (FCC [13]).

Both working groups are open to all who can participate and are willing to contribute to these subjects. They follow a long-term strategy and 'lean principles' that apply (where applicable) best engineering practices common in the manufacturing industry to the 'manufacturing of particle beams' inside the FAIR accelerator facility. These processes are being complemented by best-practices at GSI, CERN and other similar existing large hadron accelerator facilities as well as operational experiences within the high-intensity and high-brightness accelerator community at large. Thus, many of the FC2WG concept and strategies may – by design – appear familiar with those found at other facilities, either because they were assimilated where possible or adapted to the specific needs of FAIR where applicable in order to minimise potential regression with respect to established best-practices operation standards and to avoid 'reinventing the wheel'[1].

Continuous Improvement

One of the important underlying FC2WG concepts is the 'continuous improvement'[2] paradigm that aims at exploiting opportunities for streamlining the setup of new BPCs and to minimise 'wastes', sources of errors, or unnecessary intermediate steps. This improvement is driven by a continuous process of identifying opportunities or minimising short-comings, evaluation and planning of possible remedies. Their execution and review of the achieved results are

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[1] "Imitation is the sincerest form of flattery", Charles Caleb Colton

[2] also: *jap. 'Kaizen'*

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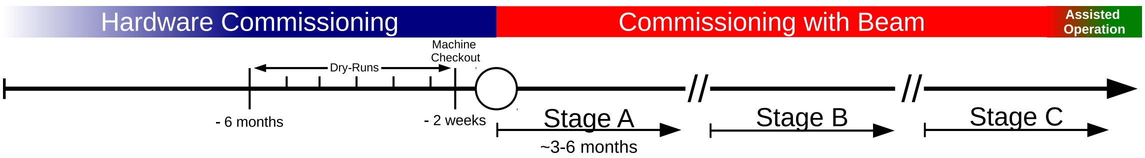

Figure 3: Schematic structure of the targeted hardware- (HWC) and beam commissioning (BC) sequence. SIS100 is expected the first accelerator to start its HWC in 2022, followed by Super-FRS and then the rest of the FAIR facility once Stage-A has been completed for each sub-accelerator along the BPC.

done according to the set optimisation criteria. Two of the common examples are the development of commissioning procedures and 'poka yoke' inspired and design-based minimisation of error sources.

Commissioning Procedures The FAIR HWC as well as BC will be driven by *commissioning procedures* as an evolving operation standards (or 'recipe') that formalise and document the best-practice of how to boot-strap and operate an accelerator efficiently [14, 15]. These procedures are developed, updated and maintained jointly by the various stake-holders (beam physics/machine/system experts etc.) and are kept initially on a light-weight Wiki-based system to facilitate easy editing and once they are more established are being transferred to an approval-based specification document. These procedures define when, where and how the individual accelerator sub-systems and interfaces fit in the overall commissioning and operation concept. These procedures are also the basis for further controls integration steps into semi-automated sequences that shall assist the operator on a day-to-day basis. A schematic view on planned commissioning structure is shown in Figure 3.

The commissioning of FAIR is subdivided into two parts which are executed in overlapping sequence for the given sub-accelerator in the chain once it becomes available:

HWC: focusing on site-acceptance-tests that verify the individual equipment's conformity with contractual design targets. These are typically performed during the initial commissioning, after major upgrades or modifications, or in case the systems' as-good-as-new performance need to be re-validated. Most of these individual systems and commissioning tasks are done in parallel for efficiency reasons and are supported by semi-automated testing tools such as the sequencer [16, 17]. The HWC is coordinated by the machine's sub-project leaders and executed by the equipment group experts responsible for the specific equipment.

Dry-Runs: are rehearsals starting typically three to six month before the actual BC, and tests the conformity of system's controls integration and readiness in view of BC. For this purposes the accelerator is put into a state assuming that beam could be injected into the accelerator sub-sector. Systems that are unavailable at this stage are initially ignored, noted down, and followed-up at a defined later stage until all system become available.

The last dry-run referred to also as 'machine checkout' is an intense accelerator performance tests (e.g. machine patrols, magnet/PC heat runs, etc.) that starts typically two weeks before the targeted BC.

BC: focusing on the commissioning of beam-dependent equipment and on tracking of the beam progress through the BPC. It is further divided and grouped into the following three stages:

Stage-A: using 'pilot beams' or "easily available" ions (e.g. Ar) to perform the most basic checks such as threading, injection, capture, beam cooling, RIB conversion, acceleration (or deceleration in case of storage rings), stripping and extraction. These tests are always done with 'safe' ie. low-intensity and low-brightness beam. Initially low-intensity ions are preferred due to the simpler optics and beam dynamics, and then protons in order to asses high-intensity effects and transition crossing. Prior to moving to the subsequent BC stages, the target is to complete this stage for each FAIR accelerator by 2025.

Stage B: performing the intensity ramp-up and commissioning of special systems. The main aim of this stage is to achieve and maintain the required nominal beam parameters, nominal transmission and beam loss targets, as well as the commissioning and validation of the machine protection and interlock systems. Possibly unsafe operations during this and following stages are always preceded by checks with safe (ie. low-intensity) beams.

Stage C: which focuses on the establishing of routine operation with nominal intensities and the transition to faster semi-automated setup and switching procedures between different BPC or beam parameter sets. N.B. the first time this stage is considered as 'commissioning' or 'assisted operation', but subsequently passes over to 'regular operation' done rather by operators on a 24h/7 shift rota than by system or accelerator experts.

Error Minimisation & Poka-Yoke As schematically illustrated in Figure 4, *'poka yoke'*[3] is the prevention of

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[3] A *poka-yoke* is any mechanism in a process that helps an equipment operator to avoid (*yokeru*) inadvertent mistakes (*poka*).

ISBN: 978-3-95450-202-8 doi:10.18429/JACoW-HB2018-TUA2WD01

inefficiencies, inconsistencies and wastes by design or 'error proofing' principle – a culture of stopping and fixing problems early, when and where they occur. Its main aim is to minimise error-propagation and to avoid the proliferation of costs of mitigating problems at a late project stage where the possibility of influencing the mitigation is very limited. A common example is, for example, fixing potential sources of problems with high-intensity beams already at the source or while operating with low-intensity rather than with high-intensity beams, or addressing first basic parameters and single-particle effects before moving towards more complex higher-order effects: e.g. first fix injection processes, trajectory, orbit, Q/Q' before addressing space-charge or slow-extraction-related problems. This lead to the introduction and enforcing of a a 'pilot-beam' and 'intensity ramp-up' concept, that prescribes to always verify the basic machine function and machine safety with low-intensities prior to increasing and moving on with high-intensity beams.

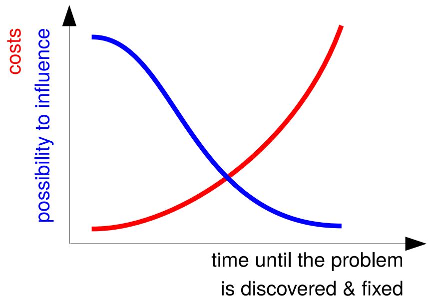

Figure 4: Schematic cost vs. time since a failure has been detected and fixed.

Respect for People

Another important FC2WG aspect is the development, training, and sufficient support of the personnel. The operators have to perform complex tasks over prolonged periods requiring concentration and their undivided attention. Thus it is important to provide an environment that positively impacts personnel performance and in turn the FAIR performance by minimising disturbing elements (ie. acoustics, lighting, lines of communication, etc.) and activities/tasks that put unnecessary strain on employees. This influenced the design, ergonomy and functional requirements on the FAIR Control Centre [13, 18], as well as the development of smart tools and procedures, such as beam-based feedback and monitoring systems (e.g. [19–21]) or sequencer framework for the semi-automated execution of commissioning procedures [16, 17] in order to automate routine task in order that operator talents are utilised and focused on more important tasks that cannot be automated (e.g. performance improvement, handling or errors and exceptions etc.).

These requirements are particularly important in view of increase of number of accelerators that roughly increase by a factor 4 for FAIR compared to the existing GSI facility and the fact that operators and system experts are expected to likely remain a scarce resource. Various possible operation paradigms are under evaluation. The extremities are covered by:

- One operator per machine: this scheme focuses on optimising the accelerator individually and is similar to present operation at GSI. The advantages are better skilled operators, causing less operational errors and faster beam set-up for a specific accelerator (only). The disadvantages cover [but are not limited to] reduced interface efficiencies of transferring beams across accelerators domains, limited possibility of setting up multiple experiments in parallel, and limited flexibility of shift planning (an operator can only be replaced by another with the same expertise). This scheme requires a much larger pool of operators (59 compared to presently 23 persons, excluding cryo-operators), increasing the annual operation costs of FAIR, and cannot avoid potentially idle resources when not all accelerators or experiments are being operated.
- One operator per BPC/experiment: this scheme focuses on the optimisation of the beam production chain across accelerators to the experiments and is the proposed control and operation strategy for FAIR. The advantages of this scheme are a more efficient set-up and interface across accelerators and to the experiments, reduced number of required personnel (30-37 compared to presently 23 persons, excluding cryo-operators), the operator being an expert and more highly motivated to deliver the required beam parameter ("my experiment"), and more redundancy thus flexibility with respect to shift planning. Some of the disadvantages to be addressed are better and continuing training requirements for operators, requirement of more common tools and automation of standard processes across accelerators, and adapted console scheme.

Hybrid options between these two extremities are possible and are being evaluated: e.g. that the more experienced shift-leaders/operators that can cover a broader range of accelerator domains are paired with operators that are machine-type specialists (e.g. linacs, ring accelerators).

SEMI-AUTOMATION & BEAM-BASED CONTROL STRATEGY

To optimise turn-around times, to establish a safe and reliable machine operation, and to improve the beam parameter qualities, a shift from a presently predominantly manual 'analog' to an automated 'fully digital' control and operation paradigm is in progress. The aim is to automate routine tasks to minimise inadvertent errors (i.e. 'poka yoke' principle), to aid the frequent machine (re-) set up, to control beam-parameters to a higher precision, and to minimise unnecessary strain on operating crews in order that their talents are optimally utilised and focused on more important tasks that cannot be automated.

Thus a comprehensive suite of semi-automated measurement applications, as well as fully-automated beam-based feedbacks (FBs) is being prepared, and will be deployed as generic tools across all FAIR accelerators. These cover a wide range of beam parameters ranging from beam transmission [21], trajectory, orbit [19], tune and chromaticity [22, 23], machine optics, emittance preservation and manipulations, fast turn-by-turn feedbacks, as well as specialised machine-specific feedbacks, for example, for the optimisation of multi-turn-injection process, slow resonant extraction [20], as well as diagnostics to aid the set up of injection energy, stochastic and electron cooling methods.

As a proof-of-concept, a selected limited set of automated beam parameter measurement and feedback systems have been tested as early prototypes at the SIS18 during the machine development studies in 2016. These are now being deployed operationally during the recommissioning in 2018: a new beam transmission monitoring system, an automated beam parameter scanning application, and a cycle-to-cycle orbit- as well as a macro-spill feedback.

In addition to beam-based FBs, a multitude of additional technical controls services and tools are being developed in view of semi-automation of repetitive tasks that are common during commissioning and operation, e.g.:

- Sequencer [16, 17]: automatising routine tasks, commissioning procedures, as well as automatic ‘as-good-as-new’ system validation tests that drive preventative maintenance and provide an early warning of potentially compromised machine function,
- Digitizer [24]: which provide comprehensive, generic monitoring of all analog signals to track and quickly isolate faults, to monitor equipment performance, and which is a crucial prerequisite for migrating to the new all-digital FAIR Control Centre,
- Accelerator & Beam Modes [25]: the concept has formalised the existing communication of intended accelerator operation to the experiments, FAIR and wider community of what to expect and when, in order to condition the control sub-system responses accordingly. These modes follow the actual different operation mode of the machine ie. ’NO BEAM’, ’PILOT BEAM’, ’INTENSITY RAMP-UP’, ’ADJUST’, and ’STABLE BEAMS’.
- Archiving System [26]: which collects and stores all accelerator data centrally that are pertinent for the analysis of the accelerator performance as well as its proper function.
- Beam Transmission Monitoring System [21]: implementing a beam-based interlock that prevents poor transmission performance across the BPCs, to minimise machine activation, and to avoids scenarios that might cause/or otherwise complicate machine protection incidents.

FAIR CONTROL CENTRE (FCC)

The present GSI main control room is too small for an efficient operation of the substantially larger FAIR accelerator facility, and cannot be easily upgraded to suit the requirements of FAIR, without compromising beam operation of the existing GSI accelerator facility. Thus a new control centre will be constructed on site to be completed by 2023, in time for the HWC of SIS100 [13, 18] with the primary goals being:

- provide sufficient room for the operation of the existing and enlarged accelerator facility,
- provide a public representation that is adapted and that relates to the high-quality level of the research that is performed at FAIR (management of visitors),
- provide an environment that positively impacts personnel performance and in turn the FAIR performance by minimising disturbing elements (ie. strong focus on ergonomics), and
- provide a credible ’vision statement’ that facilitates solving issues and facility optimisations by offering an efficient communication platform for operation, accelerator or equipment experts, and experiments.

CONCLUSION

FAIR roughly quadruples in size and has an significantly increased operational complexity in comparison to the existing accelerator facility at GSI. Hardware commission is expected to start with SIS100 in 2022, followed by the (re-)commissioning of 4 accelerator and Super-FRS in quick succession to be ready to provide beam for physics by 2025. Planning and testing of possible commissioning and operation strategies, controls system integration, and semi-automated tools has been started already now with the existing GSI facility as a test-bed.

The underlying core design principles for these activities are coordinated by two WGs open to all who can participate and are willing to contribute to these subjects, and follow lean management principles of *continuous improvement*, *respect for people*, and *poka yoke* (ie. stop-and-fixing errors at the source and when they occur leading to the ’pilot-beam’ and ’intensity ramp-up’ concepts).

ACKNOWLEDGEMENTS

The presented concepts and strategies are based on existing experience and best-practises at GSI, CERN and other large hadron accelerator facilities. The valuable contributions, advice and recommendations in particular regarding the ergonomics, control room design, and operation from our CERN colleagues R. Giachino, M. Lamont, D. Manglunki, R. Steerenberg, J. Wenninger and others are greatly acknowledged.

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