Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status of the FAIR Project April 2019

29 April 2019

I. Executive Summary

The FAIR Project is based on the scientific pillars APPA, CBM, NUSTAR and PANDA. Their programmes will enable unique and world leading discovery science. **The breadth and reach of these programmes will remain unsurpassed at the planned start of FAIR operation in 2025 and for many decades beyond.**

With foresight and adequate planning of resources, the different parts of the Project can be brought on sequentially, beginning to produce world-leading science before the end of 2025. However, it will be very challenging to finish the whole Project by the end of 2025 with the available resources, even if the additionally required funds will be available.

The Committee recommends the highest priority be given to completing all civil construction and installing the Super-FRS first, using the SIS18 – Super-FRS beam line for commissioning and early operation. All other accelerator components are then to be commissioned subsequently following availability and installation.

The new management is now working very well. Within the limits of legal constraints, FAIR and GSI are closely integrated to the point that the technical managing director of FAIR is now responsible also for GSI accelerator infrastructure. The new management team has really got the Project moving again, evidenced by the good progress in civil construction and procurement. As a consequence of a lack of cost culture in the past, they have found many areas where inadequate cost estimates were made or many missing items simply not identified at that time, which results in a substantial cost increase.

The extra cost is distributed over three items, machine components (215 M€, actual price), personnel and running cost (85 M€, actual price) and civil construction and infrastructure (550 M€, actual price). The relatively large increase in the third item can be explained by necessary replanning by the new management and overheated market conditions in civil construction.

The numerous in-kind contributions represent a risk with respect to project execution since the performance of the provider and / or shareholder is out of the hands of the management. A common management tool for these cases is the use of peer pressure exerted on the shareholders by regular short progress reports at Council meetings.

Within the present funding cap, the only feasible plan would be to complete SIS100 and the CBM experimental hall. In that case, an investment in up-to-date scientific infrastructure of an amount between 400 M€ and 600 M€ (actual price) would have been spent in vain. The scientific potential of the facility would be reduced to less than one quarter of the MSV. In view of the Committee this would form an extreme waste of public funds and leave major scientific capabilities untapped.

Delaying or reducing part of the MSV's scope is not recommended, for scientific and also cost reasons. Interrupting and later resuming a part of civil construction would lead to very considerable additional cost and considerable obstruction of the use of the already working parts of the facility. In particular in the southern area, where the civil construction is not yet contracted, more than 90% of the accelerator components are either delivered or under construction. In the northern area, civil construction is contracted and will be completed soon. This will allow for ample time of installing, testing and commissioning the SIS100 in parallel with the early science programme using SIS18 and the Super-FRS.

A decision whether additional spare parts which are needed for commissioning (additional ca. 30 M€, actual price level) are to be procured from the construction budget or a future operation budget is required by end 2019.

Commitments by the partners for bridging the funding gap would be highly desirable in order to avoid interruption of the ongoing construction process. Any further delay of the Project will increase the price by at least 50 M€ per year. The funding structure of the Project should be such as to allow the management to handle funding uncertainties in a flexible way. Provisions for more flexible multi-annual loans should be foreseen in the financial rules to allow efficient cash management.

In summary, the FAIR Modularized Start Version (MSV) is to be constructed and completed in full as soon as possible. All else would be an extreme loss of science and waste of resources.

II. Table of Contents

III. Establishment and Charge of the Committee

Following the FAIR Council Decision XVII.6.1(5), a detailed review of the progress and financial status of the FAIR Project is to be carried out not later than 2019. This detailed review shall **explicitly not deal with any question of scope of the FAIR facility**. The FAIR Council stipulated the request for the 2019 review in the context of other strategic resolutions, in particular to continue with the construction of the FAIR Modularized Start Version (MSV) and to share the additional funding needed for its completion.
At the 24th meeting of the FAIR Council on 4th/5th July 2018 and with some decisions in writing immediately after this meeting, the Council agreed on Terms of Reference and the composition of the FAIR Progress and Cost Review Board, termed "Committee" in the following. Council Decision XVII.6.1(1)[1] was recalled and forms also part of the Terms of Reference. The Terms of Reference and the Composition of the Committee are attached as Appendices 1 and 2.

IV. Meetings of the Committee

During the period November 2018 till April 2019, the Committee held a number of meetings, some of them dedicated to special issues:

- 21st November 2018: Kick-off meeting (full Committee), with address by the Council Chair
- 10th January 2019: Meeting on civil construction (civil construction experts, plus other attendees from the Committee on own discretion)
- 5th February 2019: Science meeting (scientific experts, plus Committee attendees on own discretion)
- 21st/22nd February 2019: Full Committee meeting, including presentations from the Chair of the Joint Scientific Council of FAIR and GSI and the Chair of the "Cost-Book working group" (see below).
- 12th March 2019: Meeting on funding issues (financial experts, plus Committee attendees on own discretion)
- 4th/5th April 2019: Full Committee meeting, final meeting.

During all meetings, video connection was provided for Committee members who were unable to attend in person. The Chair of the Committee participated in all meetings.

In addition to the meetings above, the Committee also took into consideration the results and the report of the Cost-Book working group of the FAIR Administrative and Finance Committee, as it was provided to the FAIR Council[2] for their 25th meeting on 5th/6th December 2018. Three Committee members (including the Chair of the Committee) serve also as members of the Cost-Book working group.

The Committee was presented with the following documents:

- The regular report on the general state of the FAIR company, as it was provided for

[1] *The Council confirms the stepwise approach to the realization of the FAIR project outlined in the Convention, Article 5 (6), starting with the Modularized Start Version (MSV), according to Article 5 (2) of the Convention.*
[2] *The FAIR Council unanimously considers the Report of the AFC Cost Book Working Group as viable input to the FAIR Review Process (Decision XXV.15.3).*

the 25th Council meeting

- The regular Project report, as it was provided for the 25th Council meeting
- The regular FAIR risk report, as it was provided for the 25th Council meeting
- The regular FAIR experiments report, as it was provided for the 25th Council meeting
- The regular report to the Council on accelerator contributions, as it was provided for the 25th Council meeting
- The report by the Cost-Book Working Group, as it had been provided for the 25th Council meeting, with the clear indication that this document is to be treated confidentially also by the Committee members and not to be spread further, because of the enclosed detailed Cost Book 8.0.
- The “FAIR executive status and progress summary for the shareholders for initial discussions with the governmental organisations” document as agreed on in the 24th Council meeting, in its form after the 25th Council meeting, as it was provided also to the Council
- A short document, summarizing the scientific opportunities at FAIR, also for non-scientists, as it was provided also to the Council after its 25th meeting
- An extensive document on the science possible with FAIR, accepted for publication in Physica Scripta (this was provided also to the Council after its 25th meeting)
- A document on the operation modes of FAIR, with some additional explanations by the authors, was also provided. Because of its rather technical nature, it was never brought to the attention of the Council.

Apart from the kick-off meeting, the slides of the oral presentations held at the various meetings are available at indico (`http://indico.gsi.de/e/fair-review-board`, password `L_Committee`) as supporting material.

The Committee found the support by the management during the review exemplary. Material was provided and questions were answered without unnecessary delay. The figures presented seem consistent to the Committee.

V. Findings

V.1 Scientific relevance of the FAIR experimental programme

The FAIR experimental programme is based on four pillars, in alphabetical order: APPA, CBM, NUSTAR and PANDA. The scientific members of the Review Committee, with Professor Berndt Mueller as convener, met with representatives of each of the pillars, where their different scientific objectives were critically examined. Professor Mueller then gave a summary of conclusions, endorsed by the other scientific members, in a presentation to the full Committee. A written report is also attached as an appendix. In addition, a report was given by the chair of the Joint Scientific Council of FAIR and GSI, Professor Sibaji Raha which concurred with that of the scientific members of the Committee.

Their conclusion is that the science programs of the four FAIR pillars will enable unique, and in many aspects, world leading discovery science. The breadth and reach of these programs will remain unsurpassed at the planned start of FAIR operation in 2025 and for many years beyond.

The Committee sees here an affirmation of its recommendation that the full MSV is to be completed expediently.

V.2 Management of GSI/FAIR

A 2015 Review found that the FAIR Project suffered greatly from conflicts between GSI and FAIR. It recommended radical change in the structure of the management with strong leadership qualities and much more cohesion between GSI and FAIR. As a consequence, a restructuring took place in 2015 with a new team of three managing directors working closely together for the common good and strategic objectives of both GSI and FAIR.

The Review Committee found that this new structure is now working very well. Within the limits of legal constraints, FAIR and GSI are closely integrated to the point that the technical managing director of FAIR is now responsible also for GSI accelerator infrastructure. The new team has really got the Project moving again, evidenced by the good progress in civil construction and procurement. As a consequence of a lack of cost culture in the past, they have found many areas where inadequate cost estimates were made or many missing items simply not identified at that time.

The Review Committee was presented with the new procedures and tools needed to manage the Project. The Committee is convinced that the quality of these tools is now adequate to manage this Project in an efficient and modern way.

In a complex one-of-a-kind project like FAIR with a high level of in-kind contribution, the FAIR management can never be expected to be in complete control. It requires the partners to honour their obligations in delivering equipment in a timely manner in order not to affect the Project progress. Inability to do this can put other areas of the Project in jeopardy. Unfortunately, there is evidence of that already happening which, if not corrected, will have an adverse effect on the Project schedule and cost.

In the following sections V.3. to V.10, the specific questions asked in the Terms of Reference formulated by Council in July 2018 are addressed.

V.3 Is the milestone end of the year 2025 for the full MSV still realistically achievable from a technical perspective?

It will be very challenging to finish the whole Project by the end of 2025 with the available resources, even if the additionally required funds are made available. However, with foresight and adequate planning of human and financial resources, the different parts of the Project can be brought on sequentially, beginning to produce world-leading science before the end of 2025.

V.4 In case of partial achievement, which parts of the Project could be realized by when?

The Committee addresses this question below (V.8./V.9). High priority should be given to commissioning the Superconducting Fragment Separator (Super-FRS) and starting up a world class physics programme by the end of 2025 with SIS18 as its injector. SIS100, the High Energy Storage Ring (HESR) and the Collector Ring (CR) will then be commissioned sequentially as resources become available. Civil Construction is to be completed for the whole Project with highest priority, in order not to hinder installation and the early science programme.

V.5 Which parts of the MSV could be realized within the given Cost Cap?

Within the present cost cap of 1,262 M€ (2005 prices, see Terms of Reference), it is not possible to place a contract for the construction of the southern area which houses theSuper-FRS, the CR, and the HESR. Therefore, the FAIR would then be limited to SIS100 feeding just one of the pillars (CBM). All the equipment already constructed for the other accelerators would have to be put into storage. This would automatically lose the major fraction of the scientific programme of FAIR. In this case, an amount of at least 400 M€ (actual price) spent on buildings and scientific installations would have been spent in vain, probably more. As components contributed in kind often are a factor 1.5 – 2.5 more expensive than their escalated cost-book value, the actual total sum of wasted components could well amount to up to 600 M€ (actual price).
The Project might thus even face reclaims of up to 400 M€ (actual price).

V.6 For which part of the MSV is an additional budget required?

The Cost Book Working Group has identified cost overruns across the whole complex, not in any single area. This relates also to the civil construction area and personnel cost.

V.7 What is the additional budget needed to realize the full MSV?

The cost increase can be assigned to 3 areas, Machine Components, FAIR Site and Buildings (FSB), and Personnel. The Review Committee used the following methodology to examine each of these.

Machine components

The Cost Book Working Group (CBWG) examined in detail missing components or cost increase during five two-day meetings with the people responsible for each technical system of FAIR. A detailed report has been written and presented to AFC and Council (*Report of the Administrative and Finance Committee Cost Book Working Group, dated 28 November 2018*). The total cost increase presented to the Review Committee by the chairman of the CBWG is **215 M€** (actual price) **not including contingency.** For contingency, the CBWG recommended to assume 10% of the total value of the accelerator.

FAIR Site and Buildings

A subgroup of the Review Committee specialized in civil construction examined the extra cost projections of FSB. This consists of two large areas:

For the ongoing contract for the north part of the site, the contractual price is known but as in any large civil construction contracts there are potential extra costs due to claims for unforeseen conditions and extra work to be expected. As usual in such large civil contracts civil works are based on re-measurement, fixed unit prices and final cost based on materials actually used.

For the work on the south part of the site, the tendering for civil construction and technical building installation is in progress but the contracts have not yet been negotiated. There is therefore much more uncertainty with market forces playing a strong role.

The present best estimate of the potential cost increase including also the technical buildings installation (here contracts will be placed jointly for north and south) is about **550 M€** (actual price) **not including contingency.**

It is to be stated that the specified estimated value exceeds the one according to German standard procedure for civil construction estimates in the public sector by about 230 M€. That previous estimate was carried out for the Project end of 2016. Meanwhile, more detailled planning was possible and carried out by the new management. Also, the German market for civil construction is rather tight and busy at the moment if not even overheated. Both factors contribute to the increase in construction cost.
At this stage of the Project, an additional contingency of the order of 10% of the total civil construction cost would be wise.

In general, the committee found that the Project is very well managed with respect to civil construction, compared to many other publicly funded projects of similar and also smaller scales within Germany.

Personnel

A presentation of extra personnel requirements was made by the administrative managing director of GSI/FAIR. The new management was obliged to do a complete re-planning of personnel requirements in 2016. In addition, following the necessary restructuring of the Project, it was deemed essential to have control over civil construction by the Project itself. This is fully supported by the Committee. As a result of this, it was found that the previous estimate was totally inadequate to complete the MSV. The extra requirement for personnel and running costs integrated over the construction period is approximately **85 M€** (actual prices), **not including contingency.** The uncertainty of this figure is specified as 10% by the management.

Summary

The sum of the additional funding needs amounts to 850 **M€** (actual price), **not including contingency.**

In addition, the Cost-Book working group identified a number of spare parts that will be required at the time of commissioning and which have to be procured soon. Some of them will be contributed by the in-kind partners through existing contracts. An additional number of spares with a value of about 30 M€ (actual price) will have to be purchased starting end of 2019, and a decision will be required soon whether to add these costs of additional 30 M€ (actual price) on top of the construction budget (not contained in the figures of the previous paragraph), or whether to have early access to operation funds for procuring them.

As for contingency, the Committee recommends to assume at least 10% of the total construction cost (accelerator, civil construction, personnel).

V.8 Which alternatives could be identified for the realization of the FAIR Project?
V.9 What is the impact of these alternatives on the planned scientific programme?
(These two separate questions from the Terms of Reference are considered jointly)

There is no scientifically meaningful and cost-effective alternative to completing the MSV. For the sequence of realization, the Committee was presented with two options allowing the start of an early scientific programme.

(1) The first of these is to build a new beamline (additional funding required[3] of about 20 M€ - 25 M€, actual price, not contained in the MSV budget) from the already operating machine SIS18 to the HESR. This would allow for operating the HESR by beginning of 2024. Indispensable for this option is contracting and realization of the whole civil construction in the southern area without delay.

(2) The second proposal requires priority to be given to the Super-FRS. It is already foreseen that the Super-FRS can be fed from both SIS18 as well as from SIS100. If proper resources are allocated, it can be finished by end 2024, commissioned, and begin performing world-leading science with beams from SIS18 with no extra cost to the Project[3]. In order to allow early access to the scientific potential of the Super-FRS, also this would require contracting and realization of the complete civil construction in the southern area without delay.

The Committee is not in favour of the first version for a number of reasons:
It will dilute the scope of the Project and cost an additional 20 M€ - 25 M€ (actual price). Also, some resources will have to be moved away from the main objective of finishing the

[3] Besides the extra funds already specified in V.7.

MSV. Instead of putting resources into an additional beam line, the direct beam line from the SIS18 to the CR and the installation of the CR could be envisaged being prioritized as they are part of the MSV and the CR being already contracted to about 90%.

The second proposal is much more attractive to the Review Committee. It requires priority to be given to the Super-FRS, which is a “jewel” of the FAIR Project, in the very heart of the facility. It is already foreseen that the Super-FRS can be fed from both SIS18 as well as from SIS100. If proper resources are allocated, it can be finished by end 2024, commissioned and performing an active scientific programme with beams from SIS18 by the end of 2025. This will already give a 50-fold increase in the rate of production of rare nuclei compared with the present GSI installation and thus be the world-leading instrument for producing heavy rare nuclei. It also decouples from the commissioning of SIS100, which is a complex machine that may need more time for installation and commissioning than foreseen. When SIS100 is finished, it will give another big boost in performance.

After commissioning the Super-FRS and depending on the progress with the SIS100, it would then be possible to continue commissioning the two storage rings CR and HESR, which have been contracted to 90% and 100%, respectively, later allowing SIS100 to provide an operating facility with beam.

The installation sequence for the preferred option allows for NUSTAR getting to world-leading science soon, APPA-SPARC using the storage rings as soon as they are installed, PANDA commissioning their experiment with protons also at that moment, APPA-Plasma and APPA-Biomat using the APPA hall initially with beam from SIS18.

Parallel to this, the presently to 2/3 contracted SIS100 (with its already fully contracted tunnel) can then be installed and commissioned while FAIR is already delivering science. This would be a huge advantage´and allow for timely team formation and operation experience. Once SIS100 is in operation, CBM will also be served, as well as the Super-FRS with a 1000-fold increase of production rate of heavy rare nuclei as compared to the present installations. SIS100 can then also be used to provide HESR with antiprotons.

It is to be pointed out that this scenario relies on not delaying the civil construction in the southern area, to have it ready for installation according to the accelerator time schedule.

The Committee stresses that it will not be meaningful from a scientific and Project point of view to even further postpone any procurement now, as this would lead to a cost increase out of scale. SIS100 is contracted to 2/3 and will probably anyhow take longer to complete than assumed. In the southern area, both storage rings are nearly fully contracted and will need a housing soon. In addition, the technical installations of the southern area were designed in a cost effective way such that any partial completion of the buildings would require another serious re-planning for supplies also for the Super-FRS.

Therefore, the Committee does not see any scientifically and economically meaningful way of saving by postponing any component of the MSV.

V.10 Which actions would be indispensable for the success of the FAIR Project?

- The progress of civil construction must not be interrupted, as resuming it at a later stage would be much more costly. The funds necessary for continuing construction (the additional funds for civil construction and personnel) should be found urgently.
- At present, the Project is suffering from a cost increase and a lack of commitments due to insufficient funding. Previous experience has shown that overcoming the lack of commitments takes enormous effort and a lot of time. Thus, besides finding the necessary means of continuing civil construction without delay, a scheme has to be implemented to prevent a similar lack of funding in the future, the more so as all specified cost increases are without any contingency.
- The Accelerator part of the Project to a large extent is composed of contributions in kind. As much as an in-kind contribution is attractive to the Project (fixed cost, collaboration with an often known partner) and to the shareholder (support of own laboratories or industry), in its execution a number of specific problems can arise which require immediate action. Thus it would be desirable to have a direct command line from the Project management to the in-kind provider. The Committee is aware that such a procedure might face opposition by the shareholders but still recommends it as desirable. At the very least, at every Council meeting there ought to be a standard agenda item where each shareholder gives a brief summary of the status of their in-kind contributions. Experience from other laboratories show that this kind of peer pressure might be a suitable instrument for preventing in-kind contributions from falling behind schedule.
- A particular time critical item for the FAIR Project is the local cryogenics for SIS100 and also for Super-FRS, which is even more critical in view of the strong recommendation to give it high priority. However, manufacturing of these essential components has not yet been started. As these cryogenic components are on the critical path of the Project, the Committee recommends that the shareholder in charge of these contributions presents an execution plan for the delivery of all components with manufacturing schedule, capacity planning, production sites, etc., at the latest for the summer Council meeting in July 2019.
- A decision of how to fund spare parts required for commissioning, of a value of about 30 M€ (actual price), will be required by end 2019, whether from the construction budget or from an operation budget which is not yet existing.

V.11 Finance issues

A funding gap like the one encountered at FAIR is not desirable. However, it is not uncommon and, given the scope and complexity of the Project and after a change of the management, not even surprising, taking into account the total investment planned. In the opinion of the Committee, the funding structure of the Project should be such that it allows the management to deal with funding uncertainties in a more flexible way. Providing a fixed construction cost figure leads to a considerable inflexibility in handling such a gap, in particular if provisions for contingency are not made as in the present case. A subgroup of the Committee considered this at a special meeting and sees the following possibilities:

<u>Option 1</u>
One possibility to put financing on a more easily managed basis would be to consider fixed annual tranches per shareholder. Gradually, these annual contributions could be used also

for commissioning and operation, depending on the progress of the Project. [Experience so far has shown that a cost increase of the Project often coincides with a delay in completion of construction so that this might not be completely unreasonable.] Temporary additional financial needs, e.g., for spending peaks or unforeseen short-term needs could be covered by loans or advances of shareholders [pay more now, less later], in case they disapprove loans to be covered by their later contributions[4]. This would also avoid losing time while waiting for making provisions for additional funding by the shareholders. For the shareholders, this would be considered as a sound, reliable and projectable approach. An earlier FAIR working group had projected annual operation costs of 192 M€ (actual price)[5] for the whole facility (including GSI accelerators)[6]. Extracting the GSI machines from this figure and sharing the rest according to shareholding, an amount of about 160 M€ (actual price) would have to be annually shared.

Option 2

In case the shareholders need substantially more time to consider this proposal, and taking into account the shareholding ratio, the fact that civil construction is anyhow carried out by German companies or companies located close to Germany, and the current situation of the construction market in Germany (high cost increase rates and incalculable market situation in complex large-scale projects), the Committee proposes as second and maybe more feasible way out: Germany would take over the remaining civil construction as in-kind contribution, including also the estimated additional personnel and running costs (dominated by civil construction) of the order of 84 M€. This could be done sufficiently quickly in order not to again delay civil construction. The other shareholders then have to provide cash for purchasing the remaining accelerator components, or they have to provide them in kind. It would then be at the disposal of the non-German shareholders as to whether the accelerator installation would happen according to plan or undergo further delay. The Committee is of the opinion that details of such an approach could be well worked out ahead of the decisive Council meeting in summer 2019, where decision about funding would be required. Alternatively, in order to ensure project progress without interruption, Germany could temporarily take over the remaining civil construction, providing additional time for all shareholders to agree on the details of a funding model described above as Option 1.

Option 3

A third option is that all shareholders are ready to commit the additionally required funds as cash by mid 2019. In this case the Committee still advises to set up a scheme like the one mentioned first, in order to also buffer possible additional risks. It is stressed again that **the Project does not have any contingency budget.**

Spare parts:

The Committee recommends having the necessary spare parts ready at commissioning. The required extra 30 M€ (actual price) could be easily included in option-1 model and simply

[4] At the European Synchrotron Radiation Facility exists a funding model allowing to take loans related to contributions of some of the shareholders, whereas others advance their funds instead and shall contribute less later.

[5] The operation costs were estimated for the year 2020 and thus can be considered "actual" at present.

[6] Without funds for a research division which was additionally considered when analysing the FAIR operation cost.

added to the construction cost in an option-2 or option-3 model. Whether to consider these costs as part of an early operation cost is left to a Council decision.

Consideration about financial decisions:
In many international research facilities, representatives of funding bodies are participating in meetings of the Council and of the Finance Committee. At FAIR, many of the delegates to the Council have a scientific background. This helps in making scientific decisions but complicates decision making processes on financial issues. The Committee is of the opinion that in addition to the delegates, representatives of the funding bodies of each partner should participate at least in those meetings of the Council where important financial decisions are to be made.

Consideration about late decision making:
If a decision on how to fund the additional costs will come later than mid 2019, the following is to be considered: A delay of the Project will cost additionally 50 – 60 M€ p.a. [personnel and running cost, price increase, delayed contracts, etc.]. This would have to be put on top of the already listed excess cost. This may be compared to 10 M€ p.a., which would be the interest to be paid for a 300 M€ loan at 3% interest rate. Delaying a funding decision beyond mid 2019 without provision for a bridge loan would thus not only be the most costly path forward, but also lead to an additional delay of the science program with risk of losing discovery potential.

VI. Recommendations

(1) Conforming to Council decisions and the scientific case, the MSV is to be completed in the most expedient way possible.

(2) The civil construction and conventional infrastructure are to be contracted and constructed in full according to the present execution plan without any delay. All else would lead to significant additional costs and delays.

(3) In-kind contributions have to be more carefully monitored at the level of Council. In particular it is recommended to have a direct command line from the Project management to the in-kind provider. At the very least, at every Council meeting there ought to be a standard agenda item where each shareholder gives a brief summary of the status of their in-kind contributions.

(4) The particular case of local cryogenics is to be resolved with high priority and, if necessary, with re-assignment of the components to another contributor or procurement by FAIR.

(5) The first machine to be commissioned should be the Super-FRS. In the case of resource conflicts, priority is to be given to the Super-FRS.

(6) The availability of the necessary spare parts at time of commissioning has to be ensured.

(7) The funding structure of the Project should be such as to allow the management to handle funding uncertainties in a more flexible way.

(8) Provisions for more flexible multi-annual loans should be foreseen in the financial rules to allow efficient cash management.

(9) It would be wise to foresee a contingency of at least 10% for the total construction cost.

(10) Any further delay of the Project is to be avoided, as any delay will increase the price by at least 50 M€ per year.

(11) In addition to the delegates, representatives of the funding bodies of each partner should participate in Council meetings where important financial decisions are to be made.

VII. Concluding Remarks

The FAIR Project has gained a tremendous momentum and is in full swing of execution in all aspects. The motivation and engagement of all people is great. It is essential for the Project success to keep this momentum and motivation by ensuring full continuation of completing the MSV without any interruption. This will be the fastest and most economical way to achieve operation and science of FAIR.

VIII. Appendices

Appendix 1	Terms of Reference
Appendix 2	Members of the Committee
Appendix 3	Evaluation of the FAIR science case

Appendix 1

to the

Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status

of the FAIR Project

April 2019

Terms of Reference

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Preparation of a detailed review of progress and financial status of the FAIR project in 2019

(after the 24th Council Meeting, 04/05 July 2018 – Version 30 July 2018)

Rationale and Scope of the FAIR Progress and Cost Review

A detailed progress and cost review was requested by the FAIR Council for 2019, based on Council Decision XVII.6.1(5), taken at the 17th Meeting of the FAIR Council at GSI/FAIR Darmstadt on 29 September 2015:

> (5) The Council asks the Management to prepare for a detailed review of the progress and financial status of the FAIR project not later than 2019.

In the respective Council Minutes, the scope of the review is specified as follows: "The detailed review of the progress and financial status of the FAIR project, to be prepared by the Management not later than 2019, shall explicitly not deal with any question of scope of the FAIR facility."

The FAIR Council stipulated the request for the 2019 review of the project progress and financial status in the context of other strategic resolutions, in particular to continue with the construction of the FAIR Modularized Start Version (MSV) and to share the additional funding needed for its completion. The full text of the according Council Decision XVII.6.1 is attached as Appendix A.

FAIR Progress and Cost Review Board – Draft Terms of Reference

Mission

The FAIR Progress and Cost Review Board will examine the progress and the cost development observed in the FAIR project as compared to the time schedule and cost plans provided by the Management.

Background

FAIR, the Facility of Antiproton and Ion Research, is to be established in Darmstadt, adjacent to the GSI Helmholtzzentrum für Schwerionenforschung GmbH. FAIR will be a world-class new accelerator facility with a core 1100 meters circular accelerator with additional storage rings and experimental stations. FAIR shall allow for a large variety of unprecedented fore-front research in physics and applied science. The FAIR Project is established in collaboration with national and international partners. With about 70% of the shares, GSI GmbH in Darmstadt is the largest shareholder of the international FAIR GmbH.

In response to delays in civil construction and a cost increase in the overall project, an international project review was carried out in February 2015. The FAIR Council, in its 17th meeting in September 2015, decided to preserve the scientific-technical scope of the FAIR project (the FAIR Modularized Start Version (MSV)), and to adapt the earlier cost cap for its completion accordingly. The Council agreed on a value of 1,262 M€ (2005 prices) as the new cost cap for the FAIR MSV, not including the exceptional additional site-related costs of 95 M€ (2005 prices), already borne by Germany. The FAIR Council also stated that the FAIR facility should be realized in a staged approach until 2025.

To examine the further progress and cost development of the project, the FAIR Council requested the Management to prepare for a detailed review of the progress and financial status of the FAIR project not later than 2019.

Tasks of the FAIR Progress and Cost Review Board

The FAIR Progress and Cost Review Board is requested to examine the progress of the project, its financial status and the prospects of its completion according to the time scales provided by the Management.

It will also consider the cost projections presented by the Management and make its own assessment on the overall prospects of the project given the time scales for completion.

In particular, the Review Board shall make an assessment on the following specific questions:

Time schedule

- Based on the assessment of the project progress does the Review Board consider the milestone end of the year 2025 for the realization of the full MSV still realistically achievable from a technical perspective?
- In case of partial achievement which parts of the project could be realized by when?

Budget vs. Costs

- Which parts of the MSV could be realized within the given Cost Cap?
- For which parts of the MSV is an additional budget required?
- What is the additional budget needed to realize the full MSV?

Alternatives for further proceeding and their impact on the science case

- Taking into account the answers to the questions above: Which alternatives could be identified for the realization of the FAIR project?
- What is the impact of these alternatives on the planned scientific program?
- Which actions would be indispensable for the success of the FAIR project?

The Review Board should also address any other questions they find relevant within the framework of their given tasks.

Charge to the FAIR Management

In order to support the Review Board in fulfilling its tasks the Management will provide detailed progress reports on the realization of the civil construction works, the accelerator construction and the experiment realization.

Moreover, it will provide a detailed accounting of the expenses already incurred or committed, of the in-kind contributions contracted or attributed, and the current risk report.

It will also provide projections of the actions and costs until completion of the MSV as much as possible based on available tendering documents and on the outcome of the latest Cost Book Review and further documents deemed necessary and requested by the Review Board.

Depending on the project status vs. schedule and the cost situation vs. available funding, the Management will also develop alternative scenarios for the continuation of the construction and outline the respective consequences.

Membership

The FAIR Progress and Cost Review Board shall comprise up to 13 external experts (no employees of either FAIR GmbH or GSI GmbH), one of whom shall be the Chairperson of the Board. Its members need to have suitable complementary expertise in finance, civil construction, accelerator technology and large scale experiments as well as in project management and administration of big science projects, in particular the construction and operation of large research infrastructures.

Travel expenses and other costs related to the activities of the FAIR Progress and Cost Review Board will be covered by FAIR. In addition, the members will be remunerated with an attendance fee of 200 EUR per meeting day (according to Council Decision XXI.9.11)

Planned Procedure of the Review

The Review Board will be provided with the project related documents prepared by the Management in a timely manner, in order to enable the Board to formulate its final assessment in April 2019. After appointment of the Review Board, a kick-off meeting for an introduction to the FAIR project will be arranged in consultation with the Chair. This kick-off meeting is intended for Q4 2018 preferably in October 2018. Part of the kick-off meeting will be to agree with the Review Board the process for the review and related documents / presentations. Intermediate communication and meetings shall happen after the kick-off meeting and until the final meeting as requested by the Board.

Presentation of Results

(according to Council Decision XXIV.7.1 (4))

The results from the project review in terms of assessment, recommendations and conclusions shall be delivered to the AFC and the Council in April 2019 allowing for discussion in the AFC in May 2019 and for decisions in the Council meeting in summer 2019.

Appendix A – Related Council Decision XVII.6.1

(1) The Council confirms the stepwise approach to the realization of the FAIR project outlined in the Convention, Article 5 (6), starting with the Modularized Start Version (MSV), according to Article 5 (2) of the Convention.

(2) The Council states that the target completion date for the Modularized Start Version should be not later than 2025.

(3) The Council asks the FAIR Management to provide for approval by the Council a suitable document summarizing the reasons for the delay in realization of FAIR and the respective cost increases as well as a reasoned proposal of the MSV construction time scale and financing schedule, in a manner which is communicable to decision makers in all partner countries.

(4) Taking into account the prolonged time schedule for the realization of the FAIR Modularized Start Version and the concomitant cost increases, a staged approach is agreed upon for speeding up the start of experiments.

(5) The Council asks the Management to prepare for a detailed review of the progress and financial status of the FAIR project not later than 2019.

(6) The Council defines the value of 1,262 M€ (2005 prices) as cost cap for the FAIR Modularized Start Version, not including the exceptional additional site- related costs of 95 M€ (2005 prices), already borne by Germany.

(7) In order to enable the Management to expedite contracting of design works, civil construction, and accelerator and detector component construction for all four FAIR experimental areas in the framework of the MSV, the Council asks the Shareholders and the Associated Partner to assure the necessary additional funding as soon as possible (cf. Table 1). Commitments to cover additional 158 M€ (2005 prices) have to be made at the latest by the end of the first half of 2016; commitments to cover another 90 M€ (2005 prices) will have to be made by 2019. This additional funding will be required from 2019 onwards for the completion of the MSV, and is to be provided in principle as cash contribution.

(8) The Council asks the Management to continuously look for any cost saving measures.

(9) The Council asks the Management to continue its effort to attract additional Shareholders to the project who will be able to bring in additional intellectual and financial resources for the project.

(10) The Council takes note that with this approach, a re-definition of the already planned in-kind contributions will not be necessary.

(11) The Council understands the necessity that all parties involved do their utmost to continue to provide all experimental groups of the MSV experiments with adequate funding for R&D and detector construction to avoid negative consequences for the experiments due to the delays and the construction staging.

Table 1: Additional contributions needed for the completion of the MSV

	M€ @2005, commitments required		
	Total	***by first half 2016***	***by 2019***
Finland	*1.2*	*0.8*	*0.4*
France	*6.5*	*4.1*	*2.4*
Germany	*173.*	*110.6*	*62.7*
India	*8.7*	*5.5*	*3.2*
Poland	*5.8*	*3.7*	*2.1*
Romania	*2.9*	*1.8*	*1.1*
Russia	*43.*	*27.5*	*15.6*
Slovenia	*2.9*	*1.8*	*1.1*
Sweden	*2.4*	*1.5*	*0.9*
UK	*1.2*	*0.8*	*0.4*
Subtotal	***248.***	***158.1***	***89.9***

In favour: DE, FI+SE, FR, IN, PL, RO, RU, SI

Against: none

Appendix 2

to the

Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status

of the FAIR Project

April 2019

Members of the Committee

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Members of the Review Committee

Name	Affiliation
Lyndon Evans - CHAIR	CERN
Abhijit Sen	Institute for Plasma Research (IPR), India
Agneta Nestenborg	European Spallation Source (ESS), Sweden
Barbara Jacak	Department of Physics, University of California, USA
Bernard Dormy	Former Chair of TREF CERN and AFC ESS
Berndt Mueller	Brookhaven National Laboratory, USA and Duke University, USA
Catherine Césarsky	CEA, former ESO DG, Chair of SKA Board
Dmitriy Sinyushin	JSC State Specialized Design Institute (SSDI), Russian Federation
Juha Äystö	University of Jyväskylä, Finland
Matthias Vollmer	Federal Ministry of the Interior, Building, and Community (BMI), Germany
Norbert Holtkamp	SLAC Stanford, USA
Thomas Klinger	Wendelstein 7-X, Max-Planck-Institut für Plasmaphysik, Germany
Yifang Wang	Institute of High Energy Physics (IHEP), China

Appendix 3

to the

Report

of the

FAIR Progress and Cost Review Board:

Detailed Review of Progress and Financial Status

of the FAIR Project

April 2019

Evaluation of the

FAIR science case

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Evaluation of the FAIR Science Case

Juha Äystö, Barbara Jacak, Berndt Mueller, Abhijit Sen, and Yifang Wang

20 February 2019

FAIR Experiments for DAY-1 and Beyond

The 2017 NuPECC Long Range Plan describes FAIR as a European flagship facility for the coming decades and states that all four scientific pillars will provide unprecedented means to forefront research in physics and applied sciences on both a microscopic and a cosmic scale. In conjunction with the comprehensive FAIR Project Review 2019 we were asked to evaluate the planned FAIR science program with respect to its uniqueness and world leading nature in the context of an anticipated start of FAIR Phase 1 operations in 2025.

In preparation for this evaluation, a pre-meeting with presentations from all 4 FAIR science pillars was held on February 5, 2019. Subsequently, all 4 collaborations were asked to submit outlines highlighting the unique capabilities and expected results of their programs within the first 5 years of data taking. The evaluation by our committee is based on the material received in the course of this process, as well as on publicly available documents that describe the goals and expected scientific impact of the 4 components of the FAIR program.

In the following we provide evaluations of the planned science programs of the four pillars in alphabetical order: APPA, CBM, NUSTAR, and PANDA. <u>Our summary conclusion is that the science programs of the four FAIR pillars will enable unique and in many aspects world leading discovery science. The breadth and reach of these programs will remain unsurpassed at the planned start of FAIR operations in 2025.</u>

We re-iterate that the recently initiated FAIR Phase-0 physics program constitutes a critical foundation assuring a vigorous Phase-1 science program "right out of the gates" in 2025. The NUSTAR program, in particular, would benefit from an "early start" with beams from the SIS-18 for commissioning and first experiments with 50-fold beam intensity even before beams from the SIS-100 become available.

Atomic Physics, Plasma Physics, and Applied Sciences (APPA):

The APPA research pillar encompassing Atomic Physics, Plasma Physics, Biophysics and Material Science has an impressive scientific program that is interdisciplinary in nature and that addresses many exciting and frontline science questions. The program is well aligned with the present start-up plan of FAIR, namely, the Modularized Start Version (MSV), and can therefore be expected to fulfill its scientific goals in a timely manner. The APPA program has many unique features that give it a distinct edge over similar competing programs worldwide and that greatly enhances its potential for making high impact scientific contributions. These features arise from a combination of the unique capabilities of the proposed FAIR facility and the concomitant access to novel parametric regimes.

SPARC: The research program in Atomic Physics consisting of a large number of diverse small experiments is to be particularly commended for its choice of scientific goals that aim to test the validity of present quantum field theory in the limit of extreme Coulomb fields and to also carry out precision measurements of fundamental constants in such a regime. The experiments hope to fully exploit the unique features of the FAIR facilities for storage and trapping of heavy ions and the wide range of available beam energies. These features, that include the availability of heavy ions from rest (in HITRAP) to cooled relativistic ions at high-Z (HESR; up to γ=6) and advanced instrumentation (e.g. internal targets, cryogenic detectors, and novel XUV laser systems), provide a distinct competitive edge to the SPARC experiments over other worldwide installations pursuing similar scientific goals.

Plasma Physics: The HED@FAIR program of plasma physics aims to study high energy density physics by using energetic heavy ion beams to compress matter to extremely high densities/temperatures under a variety of conditions. Such states of matter can provide valuable insights into the behavior of strongly coupled plasmas and are also relevant for planetary science. The competitive edge that the FAIR experiments will have in this area are that the intense, high energy, heavy ion beams at FAIR will be able to uniformly heat large-volume samples to quasi-steady-state conditions creating high-entropy and high-energy-density states of matter. This is in contrast to intense laser matter interaction experiments that are restricted to extremely small volumes and very short time scales that do not permit access to the kind of quasi-steady-state conditions that FAIR will explore. The HED@FAIR experiments will also be able to utilize the unique diagnostic abilities of the proton microscope (PRIOR) to obtain novel insights into HED physics.

Biophysics and Materials Science: The **biophysics** program of FAIR plans to build upon and extend the existing programs at GSI to investigate radiation protection for manned space travel and the use of ion therapy in oncology. The proposed program will benefit from the unique FAIR facility to accelerate heavy ions up to 10 GeV/n thus allowing a full simulation of the cosmic ray spectrum, and to increase the speed of the cancer treatments. The **materials science** program aims to explore novel material phases by irradiating samples enclosed in diamond anvil cells at extreme pressures/temperatures with relativistic heavy ions and characterizing accessible non-equilibrium phase space. The FAIR accelerator complex will make available a large variety of heavy ion beams with high intensities (> 5 10^9 ions/s) and energies high enough to fully penetrate the pressure cells. The high-pressure materials science experiments are ready to go on DAY-1 of the planned FAIR experiments and will have a strong competitive edge over other worldwide experiments that lack such beam energies/intensities or the use of heavy ions.

General comments: While the global competitive matrix looks highly favorable for the APPA program at the present time, the comparative assessment rests on FAIR adhering to the current planned schedule for its Day 1 commencement and the absence of any unexpected long delays in starting operations. Any such long delay can bring in competition from some of the other major facilities that are currently under development. It is recommended that due consideration be given to planning corrective measures for the research program by keeping in mind the risk factors in the construction schedule of the project.

Some of the high-power laser programs worldwide and also powerful Z pinch experiments are capable of reaching the same HED targets that APPA plans to explore. APPA needs to exploit its unique capability of producing high volume warm dense matter coupled with better diagnostics to retain a competitive edge in such experiments and thereby provide a complementary perspective. It is recommended that efforts be made to establish strong collaborative links with the high-power laser physics community for joint research in the HED area.

Among the three major research areas of APPA, the BIO-MAT program is likely to face the most severe competition from other international facilities. FAIR will thus need to closely monitor worldwide progress in these areas and be flexible and innovative in its own scientific program to remain at the cutting edge.

Compressed Baryonic Matter Experiment (CBM):

The CBM Collaboration has identified key measurements that are very important for gaining a full understanding of the QCD phase diagram. These measurements include:

- The excitation function of multi-strange hadrons, including the anti-Ω^+. CBM will search for non-monotonic behavior as a function of beam energy, which could indicate the onset of a phase transition to quark gluon plasma, locating the critical temperature. CBM will also study multi-strange hadron correlations with other particles. Through these studies, one will be able to better constrain the equation of state of QCD matter at densities relevant for neutron stars and their mergers.
- A search for exotic bound states of hadrons with one or more strange quarks. A search will also be made for strange di-baryons. Lifetime measurements of single and double Λ hypernuclei will be possible. CBM will dominate the world data for such searches already after the first year of running.
- High precision measurements of di-lepton production in both the di-electron and di-muon channels will be the first in this energy range. Excitation functions of both the low and intermediate mass regions are needed to elucidate the thermal evolution of the system. The CBM measurements could provide evidence for the onset of chiral symmetry restoration at the higher temperatures.

The collaboration has wisely focused on those observables which require a large statistical sample but have small cross sections, resulting in a planned program that is well matched to the impressive beam intensity capabilities of FAIR. The planned rate capability of CBM is very high and will make optimal use of the FAIR heavy ion beams for study of QCD matter at high net baryon density and high temperature.

The rate capability resulting from the high-intensity, high-rate measurements with CBM allow the collaboration to measure rare processes, such as multi-strange hadron production at modest beam energy, and also those with low signal to background ratios. The planned di-lepton measurements are both very important and very difficult because the signal to background ratio is in the range of 1:100. These results from CBM will be unique in the world. While there is overlap in collision energy with the Beam Energy Scan at RHIC, RHIC's collision rate will be orders of magnitude smaller. Consequently, RHIC will not be able to perform the multi-strange hadron, exotic QCD bound state, or high precision di-lepton measurements proposed by CBM in Phase 1.

It should be noted that the Phase-0 activities of CBM, namely installing and utilizing prototype detectors into the STAR Experiment at RHIC, are of utmost importance. This work will not only allow GSI scientists to have the first look at physics in the FAIR energy range, but will also train the students and postdocs who will carry out the FAIR physics. Furthermore, utilizing the novel detector technologies developed for CBM in the lower rate environment at STAR offers a crucial development step. The most successful new detector technologies were developed in such a fashion, building upon experience with prototype detectors under "battle" conditions. Proceeding with the Phase-0 effort at STAR will help ensure flawless performance of CBM with the high rate FAIR beams.

Nuclear Structure, Astrophysics, and Reactions (NUSTAR):

The science of the NUSTAR Collaboration will be driven by the Super-FRS, which will be the world's most powerful in-flight separator for fully stripped exotic nuclei up to relativistic energies. The program has an extraordinarily high discovery potential and impact on its scientific domains. The nearest competitors to NUSTAR are the RIBF at RIKEN and the FRIB facility under construction at MSU. Their profiles at lower energies, e.g. between 200 and 350 MeV/u, form a partly overlapping but mostly complementary program as compared to the FAIR NUSTAR.

The Super-FRS is a large acceptance superconducting fragment separator with three branches serving different experimental areas including a low-energy, a high-energy and a ring branch. Rare isotopes of all elements up to uranium can be produced via projectile fragmentation and fission of primary beams with 1.5 – 2.0 GeV/u, which are spatially separated as secondary beams within some hundreds of nanoseconds. Very short-lived rare nuclei, isomers, unbound states and resonances with non-nucleonic degrees of freedom can be studied efficiently. Competitiveness of the proposed NUSTAR DAY-1 science is based on highly luminosity and highest purity in particular for heavy isotopes (Z>60), new excitation modes accessible and a high-resolution spectrometer mode of the Super-FRS (at 20 Tm). Storage and cooler ring experiments with a world-wide unique energy range from keV to GeV rely on unrivalled past experience of GSI.

The DAY-1 program of NUSTAR will have world-wide unique and leading capabilities for the study of exotic nuclei that will provide important insights into the structure and dynamics of nuclei. The experiments will probe the limits of nuclear stability with respect to protons and neutrons and allow for search and precision studies of unbound nuclei up to and beyond the proton and neutron drip-lines as well as search for new decay modes. It is expected that of the order of a thousand new nuclei will be measured for their fundamental properties, providing crucial new information on exotic nuclei and of nuclear matter, also of interest for exploring the properties of neutron star matter, core collapse supernovae and neutron star mergers.

Understanding the heavy element synthesis in the rapid neutron capture process and in particular the 3rd r-process peak is a common goal for all NUSTAR experiments at DAY-1. This is reached by means of comprehensive measurements of lifetimes, masses, neutron branching ratios, neutron capture rates, dipole strengths, and the level structures of neutron-rich nuclei along and beyond the $N = 82$ and $N = 126$ isotones. These short-lived neutron-rich isotopes create waiting points within the r-process and determine the mass-flow towards the heaviest elements which, by fission, also create intermediate mass nuclei including those at the second r-process peak around mass numbers $A = 130$.

Recent discoveries of a neutron star merger by gravitational waves and related direct multi-messenger signals have for the first time shown direct ongoing synthesis of heavy nuclei in the region of the 3rd r-process peak. This is opening a timely, exciting and challenging field for nuclear physics combined with astronomy and astrophysics. In relation to neutron stars and their merger properties the Equation of State (EoS) of asymmetric nuclear matter will be investigated by the R3B setup by measuring the dipole polarizability and total neutron-removal cross sections closely related to neutron-skin thicknesses of heavy neutron-rich nuclei, such as neutron-rich Sn and Pb isotopes beyond N=82 and 126, respectively. FAIR beams together with the highly efficient detection set-ups are unique for these measurements since they require the highest energy neutron-rich beams to reach the highest accuracy for constraining the symmetry energy.

A unique high-energy capability of the Super-FRS can be utilized to search for and study exotic resonances such as p- and n-rich Lambda as well as Sigma hypernuclei as well as those with nucleon excitations by using the last two sections of the FRS or later Super-FRS. The experiments will result in key information on the production and π-mesonic decays of hypernuclei by measuring their binding energies, lifetimes as well as the branching ratios of different mesonic decays. By the success of these experiments, precise information on the hadronic interactions with strangeness and their dependence on the isospin in the nuclear matter will be revealed.

Within NUSTAR physics questions are addressed by several sub-collaborations. Starting with the DAY-1 configuration, with the increasing experience and with rising luminosity the strategy is evolutionary going towards more and more exotic nuclei, from more inclusive measurements to more exclusive studies. It is expected that the production rates of rare nuclei will increase by a factor of 50 from the phase-0 experiments to the DAY-1 configuration SIS-100 + Super-FRS and a factor of about 1000 when the full intensity primary beams become available at SIS-100.

The DAY-1 experiments will rely on the detection instrumentation provided by all NUSTAR sub collaborations, including the Super-FRS itself in a spectrometer mode, the R3B setup for kinematical complete reaction studies, gamma-ray and particle spectroscopy setups of HISPEC and DESPEC, a cryogenic stopping cell for low-energy beams and MATS/LaSpec for precision measurements of ground state properties, masses and charge radii. The ILIMA storage ring experiment will probe large scale scans of masses.

NUSTAR early start with beams from the SIS-18?

Given the readiness of the detector setups planned for the DAY-1 program it would be clearly advantageous to be able to start Super-FRS operation as early as possible with SIS-18 beams. Commissioning of the Super-FRS and, in particular, its beam diagnostics and ion tracking detector system is also of direct interest for the experimental collaborations and an excellent mode for them to contribute to the success of the NUSTAR program.

Antiproton Annihilation at Darmstadt Experiment (PANDA):

PANDA is a general purpose 4π detector using proton-antiproton collisions to study detailed properties of QCD and to test its predictions. In addition to PANDA, there are a number of other experiments in operation or in planning for similar physics, including BES-III, BELLE-II, LHCb, GlueX, etc. Comparing to others, PANDA has a number of unique features:

1) All possible states with exotic quantum numbers or higher spins can be produced and studied, while BES-III and BELLE-II are limited to the vector production channel from e^+e^- collisions or the following decays.
2) Production cross sections for most states to be studied are higher than those in e^+e^- collisions.
3) Backgrounds are much lower than those from fixed-target experiments, such as LHCb and GlueX.
4) The cooled antiproton beams provided by the HESR enable excitation function scans with unprecedented energy resolution and the measurement of resonance widths below 1 MeV.

Although the strong interaction between quarks is well described by QCD, the masses and spins of hadrons, which are made of quarks, remain inadequately understood. New types of hadrons predicted by QCD, such as glueballs, still remain to be discovered. A number of hybrid and multi-quark states candidates have been found but have not yet been confirmed and/or understood. Therefore, a systematic search for exotic hadrons and a detailed of study of QCD and hadron structure, are needed.

PANDA is an promising experiment which can deliver the following breakthrough results in its first 5 years operation:

Glueballs: There are quite a few scalar candidates which are sometimes hard to distinguish from normal hadrons, in particular when there are mixings. Pseudoscalar and tensor glueballs may decay to “golden” channels such as $\phi\phi$, $\omega\omega$, $\rho\rho$, $\eta\eta$, KK etc. PANDA can obtain more than 1 million events in each channel, giving a definite answer to the existence of glueballs. BES-III and BELLE-II cannot get such a high statistics, while LHCb suffers from larger backgrounds.

Hybrids containing charm quarks: A number new particles known as X, Y, Z particles, some of which could be heavy-flavor hybrids, have been discovered, recently but their exact constituents are not clear. Thanks to the high cross sections and democratic couplings, all of them could be produced in p-pbar collisions and studied with little background. In particular, X(3872) with a $J^{PC}=1^{++}$ and negligible couplings to e^+e^- initial states can be readily produced at PANDA. Other new particles with similar spin-parity could also be abundantly produced.

Hyperons: PANDA will have the advantage of producing hyperon pairs in reactions with relatively large cross sections (micro-barns), enabling a rich physics program comprising hyperon production, hyperon spectroscopy and hyperon decays. One example is hyperon Dalitz decays, *i.e.* $Y^* \to Ye^+e^-$, which give access to hyperon electromagnetic structure in the low-q^2 region that is complementary to the hyperon structure studies by BES-III at high-q^2 values in $e^+e^- \to Y\bar{Y}$.

Proton structure: The structure of hadrons can be probed with PANDA via its coupling to virtual photons in the time-like regime, complementary to those in the space-like regime. The electric and magnetic form factors of the proton, $|G_E|$ and $|G_M|$, and their ratios, R, can be measured in a large range of q^2 via $\bar{p}p \leftrightarrow e^+e^-$. The PANDA measurements can extend the form factor measurements of BES-III in terms of q^2 range and accuracy, and offer the unique possibility to probe the time-like form factor in $\bar{p}p \to \mu^+\mu^-$. PANDA will also have the ability to study the proton form factors in the unphysical domain by exploiting a final state with an additional pion $\bar{p}p \to \pi^0 e^+e^-$ that brings the (anti)proton off-shell.