Accelerator-based infrastructures in the fields of particle and nuclear physics

Swedish Research Council

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Foreword

The Council for Research Infrastructures (RFI) within the Swedish Research Council (Vetenskapsrådet) commits a significant part of its annual budget to membership fees for running costs of and investments into accelerator-based infrastructures in particle and nuclear physics. The Swedish activities in these fields are focused on CERN (Geneva, Switzerland) and FAIR (Darmstadt, Germany). In 2019, RFI decided to commission an investigation and landscape analysis of the funded research infrastructures in these fields as input to the Council's work to ensure that this funding is strategically well-spent and of maximum benefit to the research community. The scope of the investigation and landscape analysis is defined by the Terms of Reference issued by RFI, and is reproduced in Annex 1.

During the last year substantial efforts have been made by an external panel of seven Nordic experts, composed of Paula Eerola (University of Helsinki), Steinar Stapnes (Oslo University/CERN), Sunniva Siem (Oslo University), Gabriele Ferretti (Chalmers Technical University), Jens Jørgen Gaardhøje (Copenhagen University), Olga Botner (Uppsala University) and Mattias Marklund (Chair, University of Gothenburg), supported by Niklas Ottosson (Swedish Research Council). The result of their work is presented in the following report, which gives an excellent overview of the field and presents a number of recommendations.

It is now up to RFI and other actors to take the work of the panel into consideration in the future strategic work, aimed to benefit the Swedish research landscape. On behalf of RFI, I would like to thank the panel for its tireless work leading up to the report presented below.

Stockholm, May 2020

Björn Halleröd
General Secretary of RFI, Swedish Research Council

Executive summary

The ultimate goal of particle and nuclear physics research is to understand the basic properties of matter and of the fundamental forces, and to apply this knowledge to improve our understanding of the birth and evolution of the universe. The outstanding questions include e.g. the nature of dark matter, the cause of the prevalence of matter over anti-matter in the universe, the elusive nature of the neutrino, and the emergence of nuclear forces and nuclear masses from the interactions and masses of the constituents of the nucleons, called quarks and gluons. To achieve this goal there is a need for increasingly sophisticated experimental techniques, advanced theoretical understanding and vast computational resources. The experiments are typically performed at state-of-the-art laboratories where accelerated particle beams are used to reproduce conditions similar to those in the universe shortly after the Big Bang, in the interior of neutron stars or in violent cosmic events like supernova explosions. Such endeavours are costly and typically beyond the financial scope of individual nations. That is why Sweden has partnered with other countries to establish and maintain the unique accelerator centres CERN in Switzerland and FAIR in Germany. The participation in these international ventures is primarily prompted by the needs of basic science. However, it is important to stress that the societal benefits of training new generations of highly-skilled professionals in a challenge-rich environment at the cutting edge of technology are significant – as are the applications of transferred technology in industry, medicine and security.

We were given the task to survey and report on the Swedish activities at accelerator-based infrastructures in the areas of particle and nuclear physics, according to the Terms of Reference (Annex 1) as given by the Council for Research Infrastructures (RFI) of the Swedish Research Council (Vetenskapsrådet). In order to do so, the panel sent out questionnaires and conducted hearings within the Swedish research community, to get a detailed overview of the current and future research at the facilities in question.

Sweden is today strongly involved in the CERN and FAIR facilities. CERN has been in operation over a significant time span, since 1954, and is delivering discoveries in particle physics at the Nobel Prize level. Today, the major Swedish activities at CERN focus on the ATLAS and ALICE experiments at the Large Hadron Collider (LHC) and on ISOLDE.

ATLAS (A Toroidal LHC ApparatuS) is a general purpose experiment built to test the predictions of the Standard Model (SM) of particle physics and to push beyond its boundaries with the hope of discoveries that could change our understanding of matter and energy. The project is run by an international collaboration of scientists from over 180 institutions worldwide, currently about 3000 people.

ALICE (A Large Ion Collider Experiment) is the other of the four major LHC experiments with significant Swedish involvement. The aim is to study matter at extreme energy densities and temperatures where nucleons melt, generating a plasma of quarks and gluons. This allows the study of matter at conditions prevalent in the

early Universe, microseconds after the Big Bang. The ALICE collaboration includes about 1800 scientists from over 170 physics institutions around the world.

The ISOLDE (Isotope Separator On-Line DEvice) facility hosted at CERN delivers beams of unstable, radioactive ions for a variety of research programs ranging from nuclear structure and astrophysics to solid state physics and life sciences. It also offers a diversity of isotopes for medical purposes. The ISOLDE project was initiated in the 1960s by Denmark, Norway and Sweden.

While CERN is the “flagship facility” for particle physics, FAIR is often described as the coming “flagship” for nuclear physics. Early science operations are expected to start in 2025/26. Although the accelerator park at FAIR is still under construction, international collaborations of scientists are currently well under way in constructing the components of the four major experimental infrastructures, called the science pillars of FAIR. Swedish researchers make significant contributions to three of these experimental facilities:

NUSTAR (NUclear STructure, Astrophysics, and Reactions) aims to use relativistic ions selected and identified in the coming Super-FRS (Superconducting FRagment Separator) to study the structure and reactions of unstable and exotic nuclei. NUSTAR will also search for and study superheavy elements. The NUSTAR community includes 800 scientists from 39 countries.

PANDA (anti-Proton ANnihilations at Darmstadt) is a general purpose experiment being constructed to take advantage of the planned cooled anti-proton beam. PANDA will perform precision studies of the strong force at distances where quarks form bound states (called hadrons), and study hadronic structure and exotic states. The 400 scientists involved in PANDA represent 18 different countries.

APPA (Atomic physics, Plasma Physics and Applied sciences) is the common name for a number of smaller experiments. In atomic physics the main aim is to study atomic systems under extreme conditions in terms of electric or magnetic field strength. In plasma physics the ion induced pressures and temperatures in materials are tested, and in applied science material modifications and ion therapy are major subjects. Sweden is involved in the SPARC (Stored Particle Atomic Physics Research) collaboration at APPA with prime interest in precise spectroscopy of heavy, highly-charged ions. APPA encompasses about 800 researchers from 30 countries.

Facilities such as CERN and FAIR are central to research in particle and nuclear physics, and are currently difficult to replace when it comes to research on fundamental questions in physics. Overall, the scientific quality at both facilities and of all the experiments is very high. Swedish scientists currently hold or have held leading positions both scientifically and administratively, and have delivered important in-kind contributions to the experimental construction. The international collaborations operating the experiments are well-structured and work in close contact with the facilities themselves.

Participation in facilities like CERN and FAIR, and their associated experiments, are long-term endeavours. The experimental build-up and data-gathering phases cover several different timescales, ranging from 10 to 50 years. If the potential value of these facilities is to be exploited, these long timescales must be reflected in the national strategy for such research.

The Swedish groups working at the facilities, sometimes with overlap between facilities, have different characteristics. While some of the activities are well staffed, others run the risk of becoming under-critical. This may also strongly affect the possibilities to perform in-kind deliveries from Sweden, and to exploit the physics programmes optimally. Therefore, the staffing balance needs to be discussed in the long-term perspective.

In the following text we survey the research fields of particle and nuclear physics and describe the Swedish landscape, including the composition of the contributing university groups. We also give an overview of possible future directions for accelerator-based science, and identify directions that could enhance the diversity of Swedish research in particle and nuclear physics. If Sweden wants to retain the interest of the coming generations in this frontier area of science, it is important to be able to offer researchers and students exciting projects spanning over varying timespans.

Participation in international organisations like CERN or FAIR is regulated by conventions. The membership is open to states only and the membership fees are decided at an intergovernmental level. The different Nordic countries have slightly different strategies with respect to paying the membership fees and financing the experimental projects. It is valuable and important to compare these different working strategies between the Nordic countries – the common feature for Norway, Denmark, and Finland is that the convention-bound fees are budgeted directly by the Ministry instead of the respective research council. The reasoning behind the differing strategies, as compared to Sweden, is to ensure a long-term stability for infrastructure investments as a whole.

Recommendations

Throughout the report we make comments and give recommendations. Our main recommendations to RFI and the Swedish Research Council are given below. These should not be read as necessarily requiring further funding, but as a means for efficient use of investments already made:

1. Bring up to discussion the possibility to transfer the convention-bound membership fees to the Ministry of Education and Research. This would ensure a greater budget stability within the Council for Research Infrastructures, and make it easier to practically handle currency fluctuations and changes in facility costs. As these infrastructure investments are made in an international context, there will inevitably be an interplay between decisions made at the ministry level and decisions made at the RFI level. This would also be in line with how the other Nordic countries deal with convention-bound membership fees. We stress that the scientific evaluation of infrastructure investments should still be done by the Swedish Research Council.
2. For long-term funding and planning, initiate a dialogue between RFI, the Scientific Council for Natural and Engineering Sciences (NT, also a part of the Swedish Research Council), and the Swedish universities involved in the research (e.g. through URFI, the University infrastructure reference group). This would enable a joint coordination of infrastructure spending, in-kind deliveries, and personnel costs, as well as safeguard the staffing balance in the community. The

outcome of such discussions should also be documented and made available to the community. Moreover, a further improvement of the investment return would result from the endowment of each approved experiment with a small budget to support theory activities for closer and more focused collaboration during the lifetime of the experiment.

3. Investments made in terms of membership fees and in-kind deliveries need to be utilised. Today we see a mismatch between investments in research infrastructures and investments in grants for the researchers using them. Therefore, the long-term staffing strategies should be further strengthened by dedicating peer-reviewed project grants within the fields already supported by infrastructure investments from the RFI. This would require a discussion much like the one suggested in recommendation 2 above.

These recommendations are applicable to other types of infrastructures as well, but are especially important here, in view of the large scale, in space, time, money and international reach, of the accelerator infrastructures.

Sammanfattning

Partikel- och kärnfysikforskningen ämnar bidra till en ökad förståelse för de grundläggande egenskaperna hos materien, att beskriva de grundläggande fysikaliska krafterna samt att tillämpa denna kunskap för att förbättra vår förståelse av universums födelse och utveckling. De stora obesvarade frågorna inom dessa fält handlar till exempel om egenskaperna hos mörk materia, orsaken till att materia är vanligare i universum än antimateria, neutrinons svårfångade natur och att förstå ursprunget av kärnkrafter och kärnmassor utifrån interaktionen och massorna av nukleonernas beståndsdelar, så kallade kvarkar och gluoner. För att uppnå dessa mål finns ett behov av alltmer sofistikerade experimentella tekniker, avancerad teoretisk förståelse och omfattande beräkningsresurser. Experimenten utförs vanligtvis på moderna laboratorier där accelererade partikelstrålar används för att återskapa förhållanden som liknar dem i tidiga universum kort efter Big Bang, inuti neutronstjärnor eller i våldsamma kosmiska händelser som supernovaexplosioner. Dessa experiment är resurskrävande och ligger typiskt bortom enskilda nationers finansieringsmöjligheter. Av detta skäl har Sverige gjort gemensam sak tillsammans med andra länder för att etablera och underhålla de unika acceleratorlaboratorierna CERN i Schweiz och FAIR i Tyskland. Deltagandet i dessa internationella anläggningar bestäms främst av de behov som finns inom grundforskningen. Det är emellertid viktigt att inse att det finns betydande samhälleliga fördelar med att utbilda nästa generation av högutbildad personal i en miljö rik på utmaningar och i teknikutvecklingens framkant. Detta gäller även värdet av att överföra och tillämpa tekniken inom industri, medicin och säkerhetssektorn.

Vi har fått i uppdrag att kartlägga och beskriva de svenska verksamheterna vid acceleratorbaserad infrastruktur inom områdena partikel- och kärnfysik. Uppdraget har utförts enlig referensvillkoren (Terms of Reference, Bilaga 1) som uppställts av Rådet för forskningens infrastrukturer (RFI) inom Vetenskapsrådet. För att genomföra uppdraget har panelen skickat ut frågeformulär samt genomfört hearings och intervjuer med det svenska forskarsamhället för att få en detaljerad överblick över den aktuella och framtida forskningen vid de berörda anläggningarna.

Sverige är idag djupt involverat i anläggningarna CERN och FAIR. CERN har varit i drift under en betydande tidsperiod, sedan 1954, och levererar forskningsresultat inom partikelfysik på Nobelprisnivå. Idag fokuseras de stora svenska aktiviteterna på CERN mot ATLAS- och ALICE-experimenten vid Large Hadron Collider (LHC) och på ISOLDE.

ATLAS (A Toroidal LHC ApparatuS) är ett brett experiment som byggts för att testa förutsägelserna av standardmodellen (SM) inom partikelfysik och för att utforska fysik bortom modellens gränser med hopp om upptäckter som kan förändra vår förståelse av materia och energi. Projektet drivs som ett internationellt samarbete av forskare från över 180 institutioner världen över, för närvarande cirka 3000 personer.

ALICE (A Large Ion Collider Experiment) är det andra av de fyra stora LHC-experimenten med betydande svenskt engagemang. Syftet är att studera materia vid så extrema energitätheter och temperaturer att nukleoner smälter, vilket genererar en plasma av kvarkar och gluoner. Detta gör det möjligt att studera materia vid förhållanden som rådde i det tidiga universum, mikrosekunder efter Big Bang. I ALICE-samarbetet ingår cirka 1800 forskare från över 170 fysikinstitutioner runt om i världen.

ISOLDE-anläggningen (Isotope Separator On-Line DEvice) vid CERN levererar strålar av instabila, radioaktiva joner för en mängd olika forskningsprogram; allt från kärnstruktur och astrofysik till fasta tillståndets fysik och livsvetenskaper. Anläggningen erbjuder också en mångfald av isotoper för medicinska ändamål. ISOLDE-projektet inleddes på 1960-talet av Danmark, Norge och Sverige.

Medan CERN är ”flaggskeppsanläggningen” för partikelfysik, beskrivs FAIR ofta som det kommande ”flaggskeppet” för kärnfysik. Tidig vetenskaplig drift förväntas inledas 2025/26. Även om acceleratorinfrastrukturen vid FAIR fortfarande håller på att byggas är internationella forskarkollaborationer på god väg att bygga och leverera komponenterna till de fyra stora experimentella infrastrukturerna som skall nyttja acceleratorn, kallade FAIRs vetenskapliga pelare Forskare från Sverige deltar aktivt vid tre av dessa experimentella pelare:

NUSTAR (NUclear STructure, Astrophysics, and Reactions) syftar till att använda relativistiska joner, separerade och identifierade i den kommande Super-FRS-anläggningen (Superconducting FRagment Separator) för att studera strukturen och reaktioner av instabila och exotiska kärnor. NUSTAR kommer också att söka efter och studera supertunga element. NUSTAR-kollaborationen inkluderar 800 forskare från 39 länder.

PANDA (anti-Proton ANnihilations at Darmstadt) är ett brett experiment som konstrueras för att dra fördel av den planerade kylda anti-protonstrålen. PANDA kommer att utföra precisionsstudier av den starka kraften på avstånd där kvarkar bildar bundna tillstånd (s.k. hadroner) samt studera hadronisk struktur och exotiska tillstånd. De 400 forskarna som idag är involverade i PANDA kommer från 18 olika länder.

APPA (Atomic, Plasma Physics and Applications) är det gemensamma namnet på ett antal mindre experiment. Inom atomfysiken på APPA är huvudmålet att studera atomsystem under extrema förhållanden med avseende på elektriska eller magnetiska fält. Inom plasmafysiken testas det joninducerade trycket och temperaturen i material, och inom den tillämpade vetenskapsdelen är materialmodifieringar och jonterapi huvudämnen. Sverige är involverat i SPARC-samarbetet (Stored Particle Atomic Physics Research) vid APPA med fokus på högupplöst spektroskopi av tunga, högladdade joner. APPA omfattar cirka 800 forskare från 30 länder.

Anläggningar som CERN och FAIR är centrala för forskning inom partikel- och kärnfysik och är för närvarande svåra att ersätta när det gäller forskning om grundläggande fysikfrågor. Sammantaget är den vetenskapliga kvaliteten vid både anläggningar och alla experiment mycket hög. Svenska forskare innehar eller har haft ledande positioner både vetenskapligt och administrativt och har levererat viktiga in-kindbidrag till den experimentella konstruktionen. De internationella kollaborationer som driver experimenten är välstrukturerade och arbetar i nära kontakt med själva anläggningarna.

Medlemskap i anläggningar som CERN och FAIR samt deras tillhörande experiment är långsiktiga åtaganden. De experimentella uppbyggnads- och datainsamlingsfaserna spänner över flera olika tidsskalor, allt från 10 till 50 år. Om det potentiella värdet av dessa anläggningar skall tas till vara måste dessa långa tidsskalor återspeglas i den nationella strategin för sådan forskning.

De svenska forskargrupperna som arbetar vid anläggningarna, ibland med överlapp mellan anläggningarna, har olika sammansättning och förutsättningar. Medan vissa av aktiviteterna är väl bemannade riskerar andra att bli underkritiska. Detta kan starkt påverka möjligheterna att leverera in-kind från Sverige och möjligheten att utnyttja fysikprogrammen optimalt. Därför måste bemanningsbalansen diskuteras i ett långsiktigt perspektiv.

I denna rapport undersöker vi forskningsområdena för partikel- och kärnfysik och beskriver det svenska landskapet, inklusive sammansättningen av de bidragande universitetsgrupperna. Vi ger också en översikt över möjliga framtida riktningar för acceleratorbaserad vetenskap och identifierar riktningar som kan förbättra mångfalden i svensk forskning inom partikel- och kärnfysik. Om Sverige vill att intresset för vetenskapsområdet som ju ligger i den absoluta forskningsfronten bibehålls och förs vidare till kommande generationer är det viktigt att kunna erbjuda forskare och studenter spännande projekt som sträcker sig över olika tidsperioder.

Medlemskap i internationella organisationer som CERN och FAIR regleras av konventioner. Medlemskapet är endast öppet för stater och medlemsavgifterna beslutas på en mellanstatlig nivå. De olika nordiska länderna har något olika sätt att hantera medlemsavgifterna och finansiera experimentprojekten. Det är värdefullt och viktigt att jämföra dessa olika arbetsstrategier mellan de nordiska länderna - det gemensamma för Norge, Danmark och Finland är att de konventionsbundna avgifterna budgeteras för och betalas direkt av ministeriet istället för respektive forskningsråd. Resonemanget bakom de olika strategierna jämfört med Sverige är att säkerställa en långsiktig stabilitet för infrastrukturinvesteringar som helhet.

Rekommendationer

I följande rapport ger vi löpande kommenterar samt rekommendationer. Våra huvudrekommendationer till RFI och Vetenskapsrådet summeras nedan. Dessa bör inte läsas som att de nödvändigtvis kräver ytterligare finansiering. De utgör snarare en grund för att effektivisera användningen av redan gjorda investeringar:

1. Diskutera möjligheten att överföra de konventionsbundna medlemsavgifterna till Utbildningsdepartementet. Detta skulle säkerställa en större budgetstabilitet för RFI och göra det lättare att praktiskt hantera valutafluktuationer och förändringar i kostnader för berörda infrastrukturer. Eftersom dessa infrastrukturinvesteringar görs i en internationell kontext kommer det oundvikligen att krävas ett samspel mellan beslut som fattats på regeringsnivå och beslut på RFI/VR-nivå. Detta skulle vara mer i linje med hur de andra nordiska länderna hanterar konventionsbundna medlemsavgifter. Vi betonar att den vetenskapliga utvärderingen av infrastrukturinvesteringar fortfarande bör göras av Vetenskapsrådet.

2. För att möjliggöra långsiktig finansiering och planering bör en dialog inledas mellan RFI, Ämnesrådet för naturvetenskap och teknikvetenskap (också en del av Vetenskapsrådet) och de svenska universiteten som är involverade i den berörda forskning, till exempel genom Universitetens referensgrupp för forskningsinfrastruktur, URFI. Detta skulle möjliggöra en samordning av infrastrukturutgifterna, in kind-leveranser och personalkostnader samt säkra bemanningsbalansen inom det berörda forskarsamhället. Resultatet av sådana diskussioner bör dokumenteras och göras tillgängliga för forskarsamhället. Dessutom skulle en ytterligare förbättring av investeringsavkastningen kunna åstadkommas genom att varje godkänt experiment kompletteras med en liten budget för att stödja associerade teoriaktiviteter för ett närmare och mer fokuserat samarbete under experimentets livstid.
3. Investeringar gjorda i form av medlemsavgifter och in kind-leveranser måste utnyttjas. Idag ser vi en missmatchning mellan investeringar i forskningsinfrastrukturer och investeringar i bidrag till forskarna som nyttjar dem Därför bör den långsiktiga personalstrategin stärkas ytterligare genom att avsätta projektmedel som fördelas genom peer-review inom de områden som redan stöds av infrastrukturinvesteringar från RFI. Detta kräver en diskussion som liknar den som föreslås i rekommendation 2 ovan.

Dessa rekommendationer går att tillämpa på andra typer av infrastrukturer också, men är särskilt viktiga här med tanke på den stora skalan när det gäller omfattning, tid, pengar och internationell räckvidd för de diskuterade acceleratorinfrastrukturerna för partikel- och kärnfysik.

1. Introduction

The Terms of Reference as delivered by RFI (here given as Annex 1) defined the direction of the work for the report. In order to respond to questions posed, the panel has distributed a written questionnaire among the Swedish groups participating in research at CERN and FAIR, as well as hosted hearings with the same groups. Moreover, a thorough review of the available material on current and future international accelerator efforts, as well as other types of experimental possibilities in the fields of particle & nuclear physics, has been essential in order to properly respond to the questions given by RFI.

From the obtained material, the panel has been able to get an overview of the Swedish research efforts in the field, the Swedish community, and possible future research directions. This has enabled the panel to draw some overall conclusions concerning the RFI investments in the field, and to give some general advice to RFI.

We were also asked to deliver an early short report with recommendations regarding the financial difficulties that the FAIR project has been and is facing. This report was delivered to RFI in May 2019 and is here included as Annex 2.

We would like to thank all the people involved in the Swedish FAIR and CERN programs for providing information and statistics, to Big Science Sweden for providing information concerning industrial and scientific interactions, and Niklas Ottosson for supporting the practical work around this report.

2. Overview of current Swedish activities

2.1 CERN

2.1.1 Overview of CERN

CERN, the European Organization for Nuclear Research, is an accelerator and experimental complex, situated near Geneva. The facility is devoted to probing fundamental questions concerning what our Universe is made of. Currently there are 23 member states, amongst which one is Sweden. The Large Hadron Collider, currently the world's largest and most powerful particle accelerator, constitutes that main accelerator structure at CERN, and has been running since 2008. There are however 10 further accelerators at the CERN facility.

The main experiments, in which Sweden has involvement, are ATLAS, ALICE, and ISOLDE. ATLAS (A Toroidal LHC ApparatuS) is one of the two detectors used to find the Higgs boson, and works with the highest energy scales ever produced in a laboratory. ALICE (A Large Ion Collider Experiment) is a heavy-ion detector, built for studying strongly interacting matter at high energy densities; the quark-gluon plasma. ISOLDE (Isotope mass Separator On-Line facility) is a non-LHC experiment, providing a large variety of low-energy radioactive beams, which can be post accelerated using HIE-ISOLDE to study nuclear processes.

2.1.2 Large Hadron Collider

The Large Hadron Collider (LHC) at CERN provides the worldwide particle physics community with a unique facility and possibility to explore some of the most fundamental questions concerning the composition and evolution of the universe. There is currently no alternative facility for particle physics research at the highest collision energies (14 TeV). The ring hosts four main experiments; ATLAS, CMS, ALICE and LHCb, each governed by their respective international collaboration – the size of which are so considerable that each experiment can be considered a complete infrastructure in its own right. The large amount of data collected from the LHC experiments (~50-70 Petabytes per year) are processed, stored, distributed and analysed via the distributed computing infrastructure WLCG (Worldwide LHC Computing Grid). The collaboration links up national and international grid infrastructures of more than 40 countries and is structured in four levels, or so-called tiers.[1]

Swedish researchers from four universities (Lund University (LU), Stockholm University (SU), Royal Institute of Technology (KTH) and Uppsala University (UU)) participate in the ATLAS experiment. In the ALICE experiment, Swedish participation comes from LU. The Swedish involvement in the common Nordic Tier 1 resource and the national Tier 2 resources is managed by SNIC.

The Swedish LHC community in ATLAS and ALICE is organised in an LHC Consortium (LHCK) which has proved to be a very useful coordination body both

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[1] https://home.cern/science/computing/grid-system-tiers

for the science community and for the Swedish Research Council. LHCK provides national planning and coordination of the Swedish LHC activities, including organisation of common submissions of requests for infrastructure funding.

2.1.3 ATLAS

2.1.3.1 ATLAS science

The Standard Model (SM) of particle physics provides an accurate description of electroweak and strong interactions, but does not account for observed phenomena such as dark matter, neutrino oscillations, non-zero neutrino masses, dark energy and gravity. Many alternative theories on how to extend the SM to incorporate these Beyond the Standard Model (BSM)-phenomena have been proposed and searched for at LHC. The discovery of the Higgs particle in 2012 confirms the mechanism by which elementary fermions and electroweak gauge bosons acquire mass, but raises further questions about the Higgs potential and the Higgs structure.

Examples of physics studies where Swedish researchers have played or play leading roles are:

- Vector Like Quark searches
- Measurements of the properties of the Higgs boson
- Higgs pair production
- Top quark physics
- Search for Supersymmetry, extra dimensions
- Search for Dark matter and new particles
- Search for additional Higgs particles
- Luminosity determination

2.1.3.2 ATLAS timeline

The ATLAS experiment was constructed in the period 1994-2008 and is currently in operation. The operation is interleaved by scheduled shutdowns for maintenance. The on-going long shutdown 2 (LS2) in 2019-2020 is planned to be followed by run 3 during the period 2021-2024. A significant upgrade programme for high-luminosity LHC (HL-LHC) and corresponding upgrades for the experiments is ongoing, with expected installation 2025-2027 and start of operation towards the end of 2027, followed by at least another decade of data-taking.

2.1.3.3 The Swedish ATLAS community

Currently the Swedish ATLAS groups are active in three main areas: physics analysis, operations including computing, and detector upgrades for the HL-LHC.

The community consists of 21 faculty members (12.3 FTE), 10 postdocs/researchers (8.7 FTE), 22 doctoral students and 30 master students.

The Swedish ATLAS community has undergone a significant renewal during the last decade. Today a young generation of well-merited physicists form the core of the community in Sweden, providing a healthy basis for the HL-LHC programme in the forthcoming couple of decades.

The age profile of the ATLAS and ALICE researchers with indefinite contracts is shown in the table below.

Age	25-35	36-40	41-45	46-50	51-55	56-60	60 +
Faculty and researchers	3	2	7	4	4	1	4

2.1.3.4 Leadership positions in ATLAS

Swedish particle physicists have over the years had a large number of leadership and coordinator roles in ATLAS. During the construction phase Swedish physicists have held positions such as deputy spokesperson, collaboration board chair, and project leader. During the operational phase of the LHC, i.e. after the start of the LHC, positions in ATLAS such as run coordinator and data preparation coordinator, which both are members of the ATLAS executive board, have been held by Swedish physicists. A Swedish physicist is the project leader for the LUCID forward detector in ATLAS.

2.1.3.5 ATLAS Construction

Swedish groups took leading roles in the construction of several existing sub-detectors and systems of the ATLAS experiment in the period 1998-2008: the SemiConductor Tracker (UU), the Transition Radiation Tracker (LU), the Tile Calorimeter (SU), the Liquid Argon Calorimeter (KTH), the Luminosity Cherenkov Integrating Detector (LUCID) (LU), and the Trigger and Data Acquisition System (TDAQ) (SU).

The instrumentation funding awarded to LHCK researchers consisted of 93 MSEK from the Swedish Research Council and 36 MSEK from the Wallenberg foundation. The main part of the funding (~80%) was spent on instrumentation for ATLAS and the remaining on ALICE. The funding was spent on both in-kind contributions from the Swedish groups to the experiments, as specified above for ATLAS, and on direct cash contributions to the common fund for the experiments. The common fund is used to cover the cost of the basic infrastructure of the experimental facility such as support structures, cooling and electrical infrastructure.

2.1.3.6 Operation and computing

The LHC collaborations share costs for operations and upgrades based on fractions of registered authorship or each country. In line with the authorship share from Sweden in ATLAS, 1.63% of the total resources for ATLAS operation and upgrades are expected to come from Sweden. All the groups participate in the operational tasks that are required to maintain the quality of information obtained from the ATLAS experiment and its sub-detectors. The operational work amounts to ~25% FTE per author. The salary costs for this operational work are not covered by RFI but only the travel cost to CERN in order to perform the operational tasks.

The work to coordinate and lead operations rotates between groups. Swedish groups have particular expertise regarding the sub-detectors or systems mentioned above in 2.1.2.5 ATLAS Construction, for which Swedish groups participated in the construction.

The operation funding covers travel, housing and per diem for Swedish collaboration members fulfilling compulsory operation tasks at CERN such as shifts and expert operations. Maintenance and Operation (M&O A+B) costs[2] are paid directly by the Swedish Research Council on invoice from ALICE and ATLAS. The cost for computing before 2018 was contributed directly by the Swedish Research Council to SNIC (Swedish National Infrastructure for Computing). Since 2018 the funding for computing resources is applied for directly by LHCK, which they use to pay SNIC for their services. An overview of the resources is given below.

	2014	2015	2016	2017	2018	2019	2020
M&O A+B (kCHF)	429	366	337	368	362	374	381
Computing (kSEK)	*	*	*	*	8450	7846	9905
Operations (kSEK)	3961	4370	4399	4399	4399	5100	5200

Sweden provides Tier-1 and Tier-2 computing resources for the Worldwide LHC Computing Grid (WLCG) in collaboration with the other Nordic countries through the Nordic Data Grid Facility (NDGF). The Swedish groups also have a joint computing project for Tier-3 resources. Sweden has a technical coordination role for the software of the Nordic Tier-1 in the LHC computing. The funding for the computing is included in the grants discussed above.

The Swedish Research Council´s NT funding for salaries – especially for postdocs and PhD students – is an important complement to the funding described above. At the time of the start of the LHC a funding frame of 11 MSEK was allocated by NT for project funding of LHC based research. The table below shows the funding granted for LHC-based projects from 2016 through 2020 (ATLAS and ALICE).

Year	2016	2017	2018	2019	2020
Granted funding (kSEK) from NT	14164	11471	12321	11421	6400

In the table above, 2000 kSEK per year for 2019 and 2020, are granted as a consolidation grant.

[2] M&O category A costs are associated with general shared costs, e.g. consumables such as gas, electricity etc., while category B covers costs associated with maintenance and operations of the specific sub-systems provided by each country.

The reduction by almost a factor 2 for 2020 has severe implications for the possibility to hire and involve PhD students and postdocs in the analysis of the upcoming run 3 data when LHC restarts in 2021. Since these categories of employment are essential for the research outcome, the reduction puts the optimal Swedish utilisation and exploitation of the ATLAS and ALICE infrastructures at significant risk.

2.1.3.7 Upgrade of ATLAS

The ATLAS upgrade for the HL-LHC is planned to be installed and commissioned in a long shut-down 3 (LS3) planned from 2025 to mid-2027. The preparation is in full swing. In preparation for the detector upgrades, the Swedish groups have strongly contributed to the ATLAS scoping document and the technical design reports for the ITK Strip detector, the Tile Calorimeter and the TDAQ but also to the technical proposal for the High Granularity Timing Detector.

In 2012 the Swedish groups received 14.1 MSEK from RFI for the period 2012-2016 for Swedish participation in the upgrade of ATLAS and ALICE experiments.

In 2015, an application from the Swedish groups was granted by RFI amounting to 43.95 MSEK providing the basis for the Swedish ATLAS upgrades deliverables for 2025-27. This funding is to be used for the Swedish share of the CORE cost (mainly based on component costs and excludes cost for development work) but no funding was allocated to any instrumentation activities in Sweden. The CORE value is based mainly on component costs and excludes the labour cost required to produce and test the deliverables.

The main deliverables that Sweden agreed to produce for ATLAS are:

- LU and UU: Silicon hybrids and detector modules for Inner Tracker End-Cap.
- KTH: Electronics boards for luminosity monitoring.
- SU: Read-out electronics boards for TileCal
- UU: Electronics boards for the hardware based tracking for the Trigger system

The Swedish groups have estimated that an additional 19.4 MSEK will be required for non-CORE costs to be able to deliver the above. An application was submitted in early 2019 to RFI and has been granted.

2.1.3.8 Overall impression and outlook

The Swedish ATLAS programme is healthy and well-balanced with young excellent researchers in leading roles. It is well organised across the four groups, the funding is secured for the coming ~ 6 years at least. The student numbers and number of degrees awarded are at a good level, and the international visibility is excellent.

The NT funding for postdocs and PhD students has been reduced during the last years, providing the most glaring concern and risk to the Swedish ATLAS – and ALICE – programmes. The community is nevertheless well prepared for the HL-LHC upgrade projects and will, with continued support from the Swedish Research Council, be able to play an important role in ATLAS and take leading physics analysis and operational roles also after the upgrade. The HL-LHC is expected to be operational until ~2038.

2.1.4 ALICE

2.1.4.1 ALICE Overview

In Ultra Relativistic Heavy Ion Collisions (uRHIC), a state of matter at extreme temperatures (exceeding thousands of billions of degrees Kelvin) characterized by quark and gluon degrees of freedom can be synthesized in the laboratory, the Quark Gluon Plasma, (QGP). This is believed to be the state of the early Universe up to about a millionth of a second after the Big Bang.

After its discovery in experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, the properties of the QGP can now be studied with increasing precision at CERN, using the Large Hadron Collider, that provides collision energies between heavy nuclei (eg. lead, Pb) about 25 times higher than at RHIC, and detectors with much improved capabilities, e.g. the ALICE detector. ALICE is today clearly the leading experiment in the field worldwide. Swedish scientists contribute significantly to this unique experiment.

The field is in rapid development and significant results have been achieved in the first 6 years (run 1 & 2) of LHC operations. These include: 1) the determination of the initial temperature of the QGP through thermal photon measurements, in excess of 3 billion degrees, 2) the determination of the energy loss of heavy quarks (c and b) in the nuclear medium by stimulated gluon emission, an evidence of deconfinement and 3) the determination of salient transport parameters in the QGP medium through the analysis of collective flow phenomena, such as the viscosity.

In spite of rapid and important progress many fundamental questions remain yet to be answered, for example: What are the limits for QGP formation? Is it produced in any collision if the energy (and particle production) is high enough? Can we achieve a unified and coherent ab-initio description of all high-energy collisions? What is the proper description of the initial state of nucleons, is there a gluonic condensate (Color Glass Condensate) with a characteristic saturation density?

2.1.4.2 Sweden's role in ALICE

Sweden (represented by the Lund group) is part of ALICE, which is the dedicated large detector for studies of ultra-relativistic heavy ion collisions and notably of the Quark Gluon Plasma (QGP) at CERN's Large Heavy Ion Collider (LHC).

The ALICE detector has been operating stably and extremely well since 2010. Its unique capabilities include the ability to resolve many thousands of tracks simultaneously in each collision event in the 90 m^3 Time Projection Chamber (TPC) with excellent momentum resolution down to very low transverse momenta. Sweden has contributed significantly to the TPC, notably in the area of electronics, with funds from FRN/RFI and Knut and Alice Wallenberg Foundation (KAW) at the level of approximately 3 M€. The TPC is clearly the most important tracking detector in the ALICE experiment and is supplemented with a number of other detectors, providing, time of flight, multiplicity, near-vertex tracking etc.

The other LHC detectors also now have a heavy-ion program, notably CMS and ATLAS utilizing the particular high-momentum capabilities of those detectors, but ALICE is the only detector that can measure the 'complete event' with good precision, although the many tracks per event, and associated large data size, limit the collision rate that the experiment can sustain. ALICE is clearly the most performant heavy-ion detector in the world and operates at the energy frontier at energies about 25 times higher energy in the center-of-mass than the nearest competitors at RHIC in the USA.

To increase the collision rate that the experiment can sustain and record, a major upgrade of the ALICE detector is currently underway including a new inner tracker detector, major upgrades of the TPC with new readout chambers based on GEM technology and, overall, a major upgrade of all detectors to 'continuous readout'. Currently, the TPC has been removed from the experiment and been transported to a large clean room (house) at the surface where the installation of new chambers and electronics is proceeding very well according to plans. Sweden contributes to the TPC upgrade program with approx. 4 MSEK from RFI. The experiment is expected to start commissioning the new detectors in 2020 and restart data taking in 2021.

There is an approved measurement program until 2029 (LHC runs 3 and 4). Concrete ideas and plans for continued running beyond this timescale (runs 5 & 6) using i.a. lighter beam species, exist and are being developed in more detail. An extended scientific program may require additional upgrades in subsequent long shutdown periods. The ALICE collaboration has submitted a Letter of Intent for the construction of a new Heavy Ion detector based entirely on new super-thin 'stitched' Si technology, which would allow for an almost material-free detector able to measure particles down to almost zero transverse momentum, opening up for entirely new physics studies of, for example, bosonic condensates and chiral symmetry restoration.

Participation in the ALICE experiment requires a membership fee (M&O-category A), as is also the case for ATLAS; and participation in the TPC sub-group operations requires a fee (M&O category B). These amount to approximately 38.5 kCHF and 29.9 kCHF per year, respectively. These running costs are covered by a VR grant to LHCK but are paid directly by VR/RFI, as mentioned above.

2.1.4.3 Computing

The large event size of ALICE events result in computing and storage needs that are similar to those for the ATLAS experiment. As for the other LHC experiments the very large data quantities require special storage and data processing facilities. A special agreement between VR and the WLCG (Worldwide Large Hadron Collider Computing Grid) secures access to grid resources for Swedish ALICE researchers (in partnership with other Nordic colleagues).

2.1.4.4 Comments on group size and structure

The Lund-ALICE group presently numbers 3 senior researchers (1 professor, 1 associate professor and 1 recent associate senior lecturer) and 2 professors emeriti. There are currently 4 PhD students.

The group has, in close cooperation with the world-famous theory group in Lund (author of the PYTHIA model), recently obtained funding for a major research program from the Wallenberg foundation (CLASH project) focusing on the search for QGP in small collision systems. About 58% of the group's operations (about 6.5 MSEK/yr) are covered by external grants with the risk factors that such a funding scenario entails.

Group members have visible leadership and coordination roles in the collaboration and contribute substantially to physics analysis and hardware (notably electronics). Recently, a group member was elected to the ALICE Management Board and the two other group members are physics-working-group conveners for "Flow and correlations" and "Monte Carlo generators and Minimum Bias physics", which also makes them members of the Physics Board of ALICE.

2.1.4.5 Conclusion and future directions

Well defined and approved plans (by the Large Hadron Collider Committee-LHCC and CERN) for data collection and physics analysis with ALICE at LHC exist until at least 2029 within the following overarching scientific research headlines:

4. Characterizing the macroscopic long-wavelength, Quark-Gluon-Plasma (QGP) properties with unprecedented precision (including the flow phenomenon).
5. Accessing the microscopic parton dynamics underlying QGP properties (including understanding jet suppression and stimulated gluon emission in the QGP).
6. Developing a unified picture of particle production from small (pp) to larger (p–A and A–A) systems (including developing integrated models extending e.g. the Lund Model PYTHIA).
7. Probing parton densities in nuclei in a broad (x, Q^2) kinematic range and searching for the possible onset of parton saturation (including the search for a new state of matter, the Color Glass condensate).

On the world scale, the study of relativistic heavy ions collisions is characterized by significant new initiatives at various energy scales. At JINR, SNG, the construction of the NICA facility, which will deliver beams between 4.5 GeV per nucleon for heavy ions (and 12.6 GeV for protons) is progressing well with commissioning this year and next year. At FAIR, Germany, the Compressed Baryonic Matter (CBM) collaboration is developing a detector for extremely high rate data-taking targeted at searching for a critical point in the phase diagram for strongly interaction matter that may be installed at FAIR. In the US, the decision to build the electron-ion collider (EIC) at Brookhaven National Laboratory was recently (February 2020) announced by DOE. A new electron accelerator will be built to collide electrons with protons and ions from the existing Relativistic Heavy Ion Collider (RHIC) in view of mapping out the quark and gluon content of hadrons and cold nuclear matter (in the high-x regime).

CERN remains the unique and world-leading facility for exploring the energy frontier. There are plans to extend the ALICE detector with a forward calorimeter to study the quark and notably gluon content of hadrons and nuclei in the unique so-called low-x regime, already by 2026. In a longer perspective (beyond 2029), it is expected that a physics program will be established for LHC-Run5 and Run6 (i.e. up to 2038). The European Strategy for Particle Physics (not yet released at the time of writing due to CoVID-19 considerations) includes exploitation of the High-Lumi LHC also for Quark-Gluon-Plasma studies. An international proposal also exists to replace the present ALICE experiment and its TPC with an all silicon-sensor based detector exploiting innovative new ultra-thin and flexible Si-technology that has emerged in the last few years.

The Lund group has a long-standing important engagement in relativistic heavy ion physics and contributes importantly to the world leading detector collaboration, ALICE at CERN-LHC, which has concrete approved plans until 2029 and has submitted ideas for new detector developments beyond this time frame. The group has contributed importantly to the ongoing upgrade of the Time Projection Chamber (TPC), the main instrument of ALICE, which will start taking data in 2021 (LHC run3) at collision rates up to 50 kHz.

The Lund group has identified an interesting physics program at the cutting-edge of current research interests in the field and has acquired significant external funding from KAW. Group members have visible important coordinating and leadership roles in the large (>1500 authors) collaboration.

2.1.5 ISOLDE

2.1.5.1 Overview of the ISOLDE experiment

ISOLDE (Isotope mass Separator On-Line facility) is a source of low-energy radioactive beams, i.e. nuclides with an excess or deficit of neutrons that causes them to be unstable. The nuclides are created by the high intensity proton beam from the Proton Synchrotron (PS) Booster at CERN in collision with different types of targets. This yields a variety of fragments that are then mass-separated and delivered to various experiments. While the name ISOLDE has remained unchanged from the start, the experiment has undergone continuous changes, including a physical move from one CERN location to another. ISOLDE should be considered more of an experimental user facility than a single experiment. The current set-up includes the new High Intensity and Energy ISOLDE (HIE-ISOLDE) which accelerates the nuclides to 7.5 MeV/nucleon, with the goal of reaching 10 MeV/nucleon after the shutdown envisioned in a few years' time.

2.1.5.2 ISOLDE science

ISOLDE is CERN's longest running facility that has produced and used about 1300 isotopes of more than 70 elements for studies ranging from fundamental physics (nuclear structure studies, atomic physics, nuclear astrophysics, solid state), to material and life sciences. 113 known isotopes where discovered (first time produced) at ISOLDE. At any given time approximately 450 researchers are working at ISOLDE, with about 50 experiments collecting data every year. Recently a review of ISOLDE's scientific achievements[3] was published and is also described in an invited entry in Scholarpedia.[4] Some of the most interesting scientific highlights of this long experimental program (in addition to extending the chart and precision measurements of nuclear masses) are:

1. The study of beta-delayed multi-particle emission. For very neutron rich or proton rich nuclei, beta dacay can leave the daughter nucleus in a highly exited state allowing for particle emission. Beta-delayed particle emission is of importance

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[3] Journal of Physics G: Nuclear and Particle Physics 0954-3899 (ISSN) Vol. 44 Article nr 044011

[4] http://www.scholarpedia.org/article/The_ISOLDE_facility#Scientific_results

in the description of r-processes, the nuclear reactions responsible in astrophysics for creation of many of the elements heavier than iron, but also for the design of nuclear reactors.

2. The discovery and study of halo structures in nuclei such as ^{11}Be, where one neutron is very loosely bound leading to a spatiality extended structure or even double halos as in ^{11}Li where two such neutrons are present. Such two-neutron halos are particularly interesting in that they display a “Borromean ring” structure. By this it is meant that removing one neutron leaves the remaining system (comprising the other outer neutron and the core) unbound.
3. Nuclear shapes and shape-coexistence were first studied in Hg isotopes using atomic spectroscopy measurements of charge radii. With the REX-ISOLDE post accelerator coulomb excitation reaction became an important tool for these studies and is still an active field today.

More recent highlights are:

- The study of low-energy Coulomb excitations of ^{96}Sr and ^{98}Sr (Phys. Rev. C 94, 054326).
- Very exotic shapes were found for Ra isotopes: Studies of pear-shaped nuclei using accelerated radioactive beams (Nature 497,199-204 (2013)).
- Revised rates for the stellar triple-alpha process from measurement of 12C nuclear resonances: letters to editor. *Nature*, *433*(7022), 136-139.
- The measurement of the electron affinity of radioactive isotopes. For instance in Journal of Physics G: Nuclear and Particle Physics, Volume 44, Number 10, p. 104003, the electron affinity of the radioactive ^{128}I was determined to be 3.059 052(38) eV. Very recently the electro-negativity of an isotope of Astatine (^{211}At, half-life 7.2 hrs) has been measured. Such isotope is used for medical purposes.

2.1.5.3 Swedish involvement in ISOLDE

ISOLDE started operations in 1967 and Sweden has been a member from the beginning. Two major upgrades were performed in 1974 and 1992 and one more (HIE-ISOLDE) is underway.

The direct cost for Swedish participation in ISOLDE is approximately 60 kCHF/year corresponding to 0.2% of the total Swedish contribution to CERN, which amounts to ca. 30 MCHF/year. This makes Swedish participation in ISOLDE cost-effective, since with the additional 0.2% Sweden has access to this radioactive beam CERN facility. The yearly membership fee is paid by an RFI grant. Additional contributions are made by KAW and EU.

The Swedish universities involved are Lund University, Chalmers University of Technology, University of Gothenburg and Uppsala University.

2.1.5.4 Hardware contributions

KAW and the Swedish Research Council have provided funding for the development of the Penning trap-Electron Beam Ion Source (EBIS) and the Resonant Ionization Laser Ion Source (RILIS). The cryomodules for the new superconducting

HIE-ISOLDE post-accelerator have partly been funded through an EU grant to Swedish universities. The total of these Swedish contributions is estimated at 4.9 MCHF which amounts to 8.6% of the total sum contributed by the whole collaboration. This is roughly comparable in percentage to the membership fee that Sweden pays to be part of the collaboration (7%).

2.1.5.5 Outlook

ISOLDE was the first experiment using radioactive beams and this led to a great head-start with respect to the rest of the world. Over the decades, this gap has become smaller, but ISOLDE is still the ISOL facility that can deliver the largest variety radioactive beams and continues to develop new beams. In recent years there has been an significant upgrade of the accelerator, HIE-ISOLDE, increasing the beam energy from 3.5 MeV to 10 MeV per nucleon, which allows going over the Coulomb barrier for many reactions and opens up for new types of experiments.

There is now a move towards higher and higher granularity in detectors to allow for a better kinematic resolution. This leads to a larger number of readout channels and thus to heavier demands on the data acquisition system.

2.1.5.6 Socio-economic returns from ISOLDE

The most directly measurable societal return of ISOLDE is the application to nuclear medicine. There is a continuous demand for isotopes to be used for diagnosis and treatment. ISOLDE provides a place where new production techniques can be developed, as well as an actual production facility.

Radioactive sources also have applications in material science and life science. Amongst them we can highlight the study of radiation damage on materials and the better understanding of heavy-metal toxicity.

Outreach activities have been carried out all throughout the lifetime of the experiments. In the last year, almost 2000 visitors came to ISOLDE in total, mostly from high-schools and universities.

There is also an active and competitive summer internship program, accepting 1-2 Swedish students every year. This does have positive long term consequences and has led to a number of PhD enrolments.

2.2 FAIR

2.2.1 Overview of FAIR

FAIR (Facility for Antiproton and Ion Research) is an accelerator and experimental complex under construction in Darmstadt, adjoining GSI. It is featured as a landmark infrastructure on ESFRI’s 2018 roadmap. The construction is supported by an international agreement from 2010, signed by nine countries besides Germany, among them Sweden and Finland. The central component of FAIR will be a new superconducting synchrotron SIS100 capable of accelerating protons and ions (up to uranium). The primary beams will be delivered to the experiments via a system of storage rings, separators and transfer lines. The current plans for construction envisage a staged approach with Phase 0 operations which started in 2018/2019 and early science operations (Phase 1) in 2025/26 in the so-called Modularised Starting Version (MSV). Technical plans for a further extended version of the facility beyond MSV exist, but no building decision exists today.

The build-up of the facility has been delayed and the cost estimates have dramatically increased. As a consequence of this, RFI specifically asked us for a mid-term reporting on the situation at FAIR which was delivered during May 2019 (Appendix 2).

FAIR will be a multi-faceted research facility allowing for many different and ground-breaking low- and medium-energy nuclear and atomic physics experiments. The FAIR physics program is organised in four “pillars”: APPA, CBM, NUSTAR and PANDA. Its scientific relevance has been evaluated by international panels in 2015 (R. Heuer et al.) and in 2019 (B. Mueller et al.). Swedish interests focus on experiments with relativistic ion beams, specifically the experiments R3B, HISPEC/DESPEC and SHE that are part of NUSTAR, on anti-proton physics with the general-purpose PANDA detector and on studies of matter exposed to extreme electromagnetic fields with APPA/SPARC. Sweden’s role in these projects is commented on below.

The Swedish FAIR community is organised in consortium called S-FAIR. Just like LHCK, S-FAIR has proved to be a very useful coordination body both for the science community and for the Swedish Research Council. In particular, S-FAIR has been essential for the planning and coordination of the various Swedish in-kind contributions to FAIR.

2.2.2 NUSTAR

2.2.2.1 Overview of the NUSTAR experiment

NUSTAR (NUclear STructure, Astrophysics and Reactions) covers a wide range of experimental activities at FAIR gathering a total of roughly 800 scientists with the common scientific goals of furthering our knowledge of atomic nuclei far from stability.

NUSTAR is a crucial experimental endeavour since unstable nuclei comprise the vast majority of the known isotopes and their dynamics plays a crucial role in the formation of stable elements. Recently, this subject has been brought to the fore by the realisation that neutron star mergers are probably the main source of heavy elements such as gold and platinum in r-processes, providing a tight connection between the kind of nuclear physics of interest for NUSTAR and the recent advances in the detection of gravitational waves.

2.2.2.2 NUSTAR science

In testing the limits of nuclear structure, one is led to explore the behaviour of nuclei rich in either protons or neutrons, lying on the edges of the stability region, (the so-called drip-lines) as well as the dynamics of highly excited nuclei. NUSTAR is uniquely suited for these investigations, given the wide range of isotopes produced and the high selectivity of the beam in the planned Super-FRS (Superconducting FRagment Separator). The main advantage of the set-up is that it provides fully stripped ions, allowing for a precise charge determination and thus full isotope identification in both Z and A, where Z is the number of protons in the nuclei and A is the mass number (the number of protons and neutrons in the nuclei). The higher energy of the incoming beam also allows to cover all elements of interest. A further advantage of a higher beam energy is the ability to probe nucleons lying well below the Fermi surface.

The ability to perform the NUSTAR experimental suite is fully dependent on the commissioning of the Super-FRS. Various alternatives have been extensively analysed in the report of April 29, 2019, by an international review board commissioned by the FAIR council. The report strongly suggests to prioritise the completion of the Super-FRS which can already be fed by the (upgraded) heavy ion synchrotron SIS18, without depending on the commissioning of SIS100. This would already allow for a 50-fold increase in the rate of production compared to the current GSI installation, making FAIR the world leading production facility for heavy nuclei. We find this suggestion very appealing since it would allow NUSTAR to start a physics run as early as 2026 without waiting for the completion of the whole FAIR facility.

2.2.2.3 Comparison between NUSTAR and ISOLDE

It is of interest to compare NUSTAR with ISOLDE at CERN (see section 2.1.4.), because of the similarities and possible complementarities in studying radioactive beams.

ISOLDE creates its fragments by colliding protons on heavy targets which can be contrasted with the approach of NUSTAR, which uses heavy nuclei as projectiles at a much higher energy. In a sense, at ISOLDE the fragments arise from the target while at NUSTAR they arise from the projectile. NUSTAR's advantages are a higher energy, a broader variety of nuclides produced and a better mass and charge discrimination, since the fragments are fully stripped. ISOLDE on the other hand has a higher yield, since it uses the intense PS initial proton beam. There is also a complementarity between the two setups when it comes to the kinematics of the final products. NUSTAR nuclides are produced at high speed and this allows to study short-lived isotopes, while ISOLDE´s slower ions are more suitable for certain experiments in atomic physics.

2.2.2.4 Swedish involvement in NUSTAR

The three main experimental activities of the Swedish involvement in NUSTAR are:

- HISPEC/DESPEC (the High-resolution In-flight SPECtroscopy and DEcay SPECtroscopy experiments)
- R3B (the Reactions with Relativistic Radioactive Beams experiment)
- SHE (the SuperHeavy Elements experiment).

Sweden is committed to all three of these experimental activities with participation from Uppsala University (UU), the Royal Institute of Technology (KTH), Lund University (LU) and Chalmers University of Technology (Chalmers). We briefly comment on each.

The number of Swedish scientists participating in NUSTAR is 25 split between seniors (9), assistant professors (1), postdocs (4) and PhD students (9). This corresponds to 17.1 FTE in total. During the period 2016-2018, Sweden held the chair of the NUSTAR council.

2.2.2.5 HISPEC-DESPEC

This experiment, with Swedish involvement from KTH, LU and UU, will study nuclei using energetic radioactive beams and a germanium gamma-ray spectrometer. Ions thus are tagged both as incoming (by the Super-FRS) and outgoing states, allowing studies of spectroscopic aspects of the heavy isotopes (Z >70, A >195). The scientific interest in these isotopes lies mainly in the fact that they are central in the creation of heavy elements in astrophysical r-processes. A future integral part of the HISPEC experiment will be made up of AGATA (Advanced GAmma Tracking Array) which is governed by a separate consortium and not formally a part of the FAIR-project. Swedish participation in AGATA is administered through KTH.

A more detailed breakdown of the current Swedish contribution to HISPEC/DESPEC is as follows: LU: 250 kEUR (of which 150 in-kind), KTH: 650 kEUR (of which 450 in-kind), UU: 60 kEUR. Infrastructure (LU+KTH+UU) 40 kEUR (all figures at the 2005 exchange rate).

2.2.2.6 R3B

R3B, with involvement from Chalmers and LU, is a general purpose, fixed-target experiment, for reactions with relativistic radioactive beams from Super-FRS of energies between 0.3-2 GeV/u. Of the three key instruments involved, Sweden has a large involvement in CALIFA (a gamma-ray and charged particle calorimeter) and NeuLAND (a neutron detector). The Swedish in-kind contributions comprise the CALIFA forward-endcap calorimeter from Chalmers, and the CALIFA Barrel section from LU.

Currently the so-called “Phase-0” of the experiment is underway and expected to last until 2022. This is a positive development since it finally provides the experiment with some beam time, albeit only for roughly 3 months per year and with a limited range of projectile nuclei; no heavy, unstable nuclei have been provided as of the end of 2019 but might be provided by the end of Phase-0, barring unforeseen difficulties. Part of the reason for the limited beam time and composition can be traced to the installation of a new control system for the upstream accelerators UNILAC and SIS18. Still, interesting goals have been identified in spite of the limited conditions, most notably the study of Coulomb dissociation of ^{16}O into ^{12}C + alpha via scattering against a lead target. The reverse process (alpha + ^{12}C to ^{16}O) is of great interest for the formations of oxygen nuclei in stars and R3B has to capability of studying this process in a new kinematic region. The main experimental difficulty is how to properly distinguish the alpha and ^{12}C fragments that have the same mass-over-charge ratio.

The higher beam energy at R3B will allow for a higher rate of production while the experimental setup allows for a complete reconstruction of the kinematic of the events. This will allow a state-of-the-art study of nuclear structure at the edges of the nuclear binding region as well as the in-depth study of (n,γ) reactions (neutron capture, where n stands for neutron and γ for photon), of interest to the above-mentioned astrophysical r-processes.

A more detailed breakdown of the current Swedish contribution to R3B is as follows: LU: 400 kEUR (all in-kind), Chalmers: 850 kEUR (of which 575 kEUR in-kind), Infrastructure, DAQ, electronics (LU+ Chalmers) 550 kEUR (all figures at the 2005 exchange rate).

2.2.2.7 SHE

This experiment, with involvement from LU, is dedicated to the study of (and ideally search for) super-heavy elements. This activity also relies on the completion of Phase-0 and the delivery of the beam from the GSI facility. The organisational and budgetary status of SHE is somewhat unclear, since it lies outside of FAIR cost book per-se, although it seems to be considered part of the Phase-0 operation.

However, given that many people and some institutions involved in SHE are also involved in FAIR, it would be desirable to have a more comprehensive view of the situation, as this would allow a full view of the costs involved and human resources needed. A document to initiate the process to formally include SHE in NUSTAR is expected in 2020.

2.2.2.8 Summary of NUSTAR

All together, the Swedish investment in the NUSTAR facility is estimated to 2.8 MEUR accounting for 6.4% of the total costs. It should be mentioned that the Swedish contributions have been/are being delivered on-time and on-budget and, as far as the NUSTAR activities are concerned, they are among those that can earliest be put into use.

The completion of Super-FRS should be one of the highest priorities of the FAIR activity. Sweden would benefit from starting the experimental programs at NUSTAR in which it is involved, even if Super-FRS will be fed from SIS18 in waiting for the completion of SIS100.

2.2.3 PANDA

2.2.3.1 Overview of the PANDA experiment

PANDA (anti-Proton ANnihilations at DArmstadt) is another one of the four scientific pillars of the FAIR facility in the MSV configuration. PANDA is a hadron physics experiment, which studies the strong force at distances where quarks form bound states, i.e. hadrons. A cooled antiproton beam in the High Energy Storage Ring (HESR) of 1.5 to 15 GeV is delivered to the fixed target made of hydrogen or heavier elements in the centre of the PANDA experiment, which covers a large fraction of the solid angle. The centre-of-mass collision energy will be about 2.3 to 5.5 GeV. HESR will be operated in a high-resolution mode with a momentum spread down to a few times 10^{-5} and beam intensities up to 10^{10} antiprotons, and a high-luminosity mode with beam intensities up to 10^{11} antiprotons in a later stage. The factor 10 increase in luminosity requires the recycling anti-proton ring RESR, which is not included in the MSV. The accurate knowledge of the beam momentum should enable precise excitation function scans and measurement of resonance widths.

2.2.3.2 Comparison to other existing or planned antiproton facilities

At CERN, the antiproton beam is a decelerated beam which operates at a very low energy regime (down to 5.3 MeV at the Antiproton Decelerator AD, and further down to 0.1 MeV with the ELENA ring), with the main goal to investigate the formation and properties of anti-atoms. At J-PARC, an antiproton beam experiment is included in the future planning scenario as part of the extension of the Hadron Experimental Facility (K10 2-10 GeV kaon/pion/antiproton beamline).

2.2.3.3 PANDA science

The main PANDA scientific topics will be:

- Search for exotic hadrons, for example multi-quark states, glueballs, hybrids. These are states that are not required by the particle physics standard model, but are neither forbidden. Studies of these states thus give new information about the parton model and the strong potential.

Comparison to other facilities: Existing electron-positron collider experiments BESIII in China and Belle-II in Japan have excellent possibilities to investigate such exotic hadrons, although they are limited to studies of states that carry the same quantum numbers as the photon. The antiproton beam at PANDA will allow formation of any spin-parity state allowed by the conservation laws. Exotic hadrons are also produced in proton-proton collisions at the LHC, and indeed LHCb has advanced these studies, complemented by ATLAS and CMS. The backgrounds at PANDA are, however, expected to be much lower and since all states with qqbar-like quantum numbers can be produced in formation, i.e. without a recoil, properties such as the mass can be measured with much greater precision.

- High-spin hadrons. PANDA opens up a new window to study high-spin hadrons with its large mass-scale coverage and direct formation of any spin-parity states allowing for large sensitivity to high-spin states.

Comparison to other facilities: The GluEx and CLAS experiment at Jefferson Laboratory utilise electron-nucleon scattering. This production mode is suitable for light hybrid mesons but most other states, e.g. multiquarks and glueballs, are suppressed. The COMPASS experiment at CERN studies hadron structure and hadron spectroscopy with high intensity muon and hadron beams. The experiment will continue in 2021 by studying semi-inclusive deep inelastic scattering off transversely polarised deuterons. At LHCb at CERN, where hadrons are studied in the decay of bottom baryons or bottomium mesons, high-spin states are suppressed. Furthermore, it only gives access to the hadron spectrum within a limited mass range.

- Nucleon structure, which can be parameterised in terms of electromagnetic form factors (EMFF).

Comparison to other facilities: EMFF can be studied at Jefferson Lab in the space-like region and at BESIII in the time-like region. In PANDA, EMFFs can be studied in a high energy time-like region with both electron and muon final states.

- Hyperon studies. Even before the antiproton beam will become available, strange hyperons will be studied with the Phase-0 version of PANDA, which will be launched in 2020. The PANDA Phase 0 setup is based on the HADES experiment, in which ions from the GSI UNILAC linear accelerator and the SIS ring accelerator are brought to a fixed target. The HADES capability to study di-leptons is being combined with calorimeters, particle identification detectors and tracking detectors from PANDA and CBM. The PANDA Phase 0 will offer a possibility to study single strange hyperons with respect to structure spectroscopy and strangeness production in hot and dense matter. PANDA Phase 1 at the MSV will study the production of hyperon – antihyperon pairs for single, double, triple strange and single-charm hyperons. This will be done with unsurpassed statistics for strange hyperons allowing for spin physics, spectroscopy and tests of fundamental symmetries.

It should be noted that the MSV lacks some components, which would enlarge the scientific scope of PANDA. These are the recycling ring for antiprotons, RESR ("Module 5", while the MSV includes Modules 0-3), and the proposed G2H beamline to connect the SIS18 to HESR via ESR. RESR would increase the luminosity by an order of magnitude and facilitate precision physics as well as charm physics. It would also allow for a parallel running of PANDA and NUSTAR. The cost is 23.4 M€. The G2H beamline would make it possible to perform PANDA commissioning at HESR in parallel (parasitic mode) to the NUSTAR program.

2.2.3.4 Swedish involvement in PANDA

The Swedish institutions involved in PANDA are UU, SU, and KTH.

- The PANDA group at UU has in total 10 persons (6.6 FTE/year). The group includes 3 seniors (1.3 FTE/year), no assistant professors, 4 postdocs/researchers (2.6 FTE/year), and 3 doctoral students (2.7 FTE/year).
- The PANDA group at SU has in total 3 persons (2.1 FTE/year). The group includes 1 senior (0.5 FTE/year), no assistant professors, no postdocs/researchers, and 2 doctoral students (1.6 FTE/year).
- The PANDA group at KTH has in total 3 seniors (0.2 FTE/year, i.e. 7% per person). No other personnel.

Only UU has a healthy group structure, with multiple seniors and a good number of junior researchers, providing prospects for future renewal. The groups in SU and especially KTH are under-critical. This is reflected e.g. in the production of PhD and master theses during the past 5 years: 7 MSc and 2 PhD theses from UU, while only 1 PhD thesis from SU and none at KTH. It is stated that the Stockholm group works in close collaboration with the Uppsala group, but the role of the KTH group is not clear from the available documentation, apart from the KTH expertise on high-precision gamma-ray detection and nuclear spectroscopy that is mentioned in connection with the PANDA hypernuclear programme (see below).

The Swedish PANDA community (UU, SU, KTH) is particularly focused on the study of hyperons, i.e. hadrons with one or several light quarks in the nucleon replaced by a strange quark. Hyperons provide an alternative handle on the study of strong interactions, in particular through the hyperon spin. Hyperons may also be formed inside neutron stars and can be used as a tool to investigate their equation-of-state and evolution. The aim of the hypernuclear program of PANDA is to understand the interactions of hyperons with nucleons and other hyperons (SU and KTH). Also, CP violation can be studied in decays of strange hyperons (UU). The UU group is renowned internationally for hyperon studies and has currently also a lot of experimental activities within BESIII that is foreseen to close down in 2025.

The UU group has plans for the PANDA Phase 0 physics analysis. The group will study electromagnetic properties of excited strange hyperons in the low-energy, time-like region, complementary to the high-energy region probed by BESIII and Belle-II.

2.2.3.5 Hardware contributions

The principal Swedish hardware contribution to PANDA constitutes of PWO crystals and development and production of read-out electronics for the electromagnetic calorimeter. PWO characterization for low-energy photons has been done at MAX-lab, Lund, and radiation hardness tests of the electronics have been made at The Svedberg Laboratory (neutrons) and at KVI, Groningen (protons).

The hardware investments into PANDA awarded by the Swedish Research Council amount to 36.8 MSEK for the electromagnetic calorimeter. PWO crystals have been acquired from BTCP, Russia, and CRYTUR, Czechia. CRYTUR is today the only company that can produce PWO crystals of the required quality. 270 k€ (2005 prices) for crystals from BTCP have been accounted for as in-kind contribution. An additional purchase of crystals of 3.1 MSEK from CRYTUR in 2019 will also be accounted as an in-kind contribution. Sampling ADC's for the forward electromagnetic calorimeter have been developed by UU and assembled by SEMICON, Poland. They have been accounted for as an 0.27 M€ (2005 exchange rate) in-kind contribution. UU is presently developing the data concentrators for the experiment.

The Swedish Research Council and UU are currently negotiating an accelerator in-kind contract related to the antiproton production target to a value of 630 k€ (2005 prices). This will involve mechanical construction parts from industry and university mechanical workshops. Carl Trygger's Foundation has contributed 93 k€ to the development of a pellet target tracking system (UU). The UU group is also engaged in developing software for track- and event building for a software filter replacing the hardware triggers.

2.2.3.6 Leadership positions in PANDA

In 2018, Sweden held the management positions of Deputy Spokesperson and Deputy Physics Coordinator within the PANDA collaboration.

2.2.3.7 Conclusions and recommendations

The Swedish scientists active in PANDA have a visible and a well-profiled role in the PANDA physics programme, centred on hyperon studies. The UU group has a healthy composition, while the other Swedish groups active in PANDA are under-critical. It is recommended that the Swedish physicists active in PANDA consolidate their involvement so that they can operate as a single group from the point of view of FAIR. The hardware contributions of Sweden to PANDA are on a solid basis and show a good use of the national resources and facilities. A general issue related to PANDA is the financial problems of FAIR, which may put the timely completion of MSV by 2025 in jeopardy. The 2019 Review of the FAIR facility concluded that “the Super-FRS part of the facility is especially important in scientific terms”. This could mean staging or de-scoping of those parts of the accelerator facility delivering antiprotons to the PANDA experiment.

2.2.4 APPA

The APPA (Atomic, Plasma Physics and Applications) pillar of FAIR consists of three independent collaborations: SPARC for Atomic Physics, HED for Plasma Physics, and BioMat for Applications. SPARC, which is the focus of Sweden´s engagement in APPA, focuses on studying heavy very highly charged ions using storage rings and ion traps. The aim is to study atomic systems under extreme electric and magnetic field conditions, and for almost or fully stripped systems, to determine atomic and nuclear properties to new levels of precision (ppm to ppb). Examples of future measurements include magnetic moments of bound electrons, magnetic moments of nuclei and tests of fundamental quantum electrodynamics (QED) in extremely strong fields.

2.2.4.1 Sweden’s role in APPA

Sweden’s role in APPA is centred around SPARC (Stored Particle Atomic Physics Research Collaboration). The HITRAP facility at SPARC will be world-unique in delivering cold heavy ions of the highest charge states, up to U^{92+}, at intensities sufficient for in-trap spectroscopy. Highly charged ions are accelerated in the heavy-ion synchrotron SIS, stripped in a foil to the desired charge state and injected into the storage ring ESR. In the ESR the ions will be decelerated to an energy of 3 MeV/u. The deceleration stage and the cooling trap of HITRAP has already been commissioned with beam from the ESR as well as with internally produced ions. The Swedish engagement in the HITRAP facility is primarily concerning SPECTRAP, a Penning trap experiment for high-precision optical-spectroscopy of hyperfine-structure transitions in heavy highly-charged ions. The superconducting magnet for SPECTRAP is part of the Swedish in-kind contribution to FAIR.

At the CRYRING@ESR storage ring, delivered as a Swedish in-kind contribution to FAIR, Swedish researchers are involved in the set-up of a COLTRIMS Reaction Microscope (CRY-RIMS). The CRY-RIMS allows measuring the vector momenta of all charged particles (electrons and ions) in coincidence, which are produced in reactions of the highly charged projectile ions with the atoms, molecules or clusters provided by the internal gas target. There is also significant interest in using CRYRING@ESR for studies of dissociative recombination (DR). The combination of the SIS18 and ESR with CRYRING makes this part of FAIR a worldwide unique facility for atomic, nuclear and material science with heavy ions.

The total cost of the APPA experiments is 27.0 M€ (2005 prices). SPARC experiments (as per March 2019) constitute about 13.8 M€.
Sweden contributes in-kind with the following:

- The CRYRING storage ring: 2 M€ and about 2 FTE technical support.
- The Jet target at CRYRING: 149 k€
- Particle detectors at CRYRING: 74 k€
- Laser spectroscopy at HITRAP (SPECTRAP): 277 k€

In addition, Swedish universities contribute (mostly scientist salaries) at about 0.8 FTE/year.

2.2.4.2 Swedish involvement in APPA

The Swedish participation in APPA is centred on the SPARC collaboration. Swedish researchers have leading roles at the management level as well as in the specific experimental sub-collaborations.

Researchers and technicians from Stockholm University are involved in the reconstruction and modifications of the CRYRING storage ring, the gas jet target and the recoil spectrometer. Researchers from Uppsala University have a leading role in the collaboration around the SPECTRAP project.

Presently, three Swedish senior scientists (0.8 FTE) are involved in APPA. Two additional senior scientists will participate once the facilities are in operation.

2.2.4.3 Conclusion and future directions.

Sweden is contributing to the construction of APPA and SPARC with substantial in-kind contributions, notably the CRYRING storage ring and parts of the HITRAP facility. Swedish researchers are engaged in three experimental systems, and there is also involvement on the theoretical side. At the CRYRING storage ring the recombination spectroscopy at the electron cooler is already delivering experimental results. The gas target for CRYRING and HESR is under construction and will be installed in CRYRING later this year for recoil ion momentum spectroscopy. At the HITRAP deceleration and cooling facility a new superconducting magnet for SPECTRAP is in production and is planned to be installed this summer. All internal parts of SPECTRAP are ready and the trap is expected to be operational by the end of 2020.

Regarding personnel the Swedish engagement is on the low side. The current level might be sustainable during the construction phase but, for the operation of the experiments, the possibility to recruit and engage young researchers, including PhD-students, will be crucial. It would also be beneficial for Swedish physicists involved in APPA/SPARC to strengthen their internal collaboration.

3. Future directions for the field of accelerator-based infrastructures

During the fall of 2018, Swedish particle physicists worked out a document summarising the current activities and the future plans of the community, as an input to the European strategy for particle physics. While a majority is involved in the large international collaborations at the ATLAS and ALICE experiments at CERNs Large Hadron Collider, smaller teams are actively investigating the possibilities for experimentation at a lesser scale – at CERN and in other settings. Besides, Swedish scientists are steadily pursuing their long-time participation in (and development of) the international IceCube project, investigating phenomena at the border between particle and astrophysics accessible through exploitation of cosmic or atmospheric neutrino fluxes. The Swedish experimental activities are complemented and enhanced by the work of Swedish theorists within areas like new physics beyond the Standard Model (specifically dark matter), neutrino physics, QCD and in particular through the continuous development of phenomenological Monte Carlo generators.

While the Swedish particle physicists have taken a clear stance in favour of the coming research program at the LHC and HL-LHC, the far future beyond the HL-LHC horison is less certain. One endeavour is considered essential: the construction of a Higgs-factory, an e^+e^- collider that would allow precise determination of the Higgs self-coupling and couplings to other Standard Model particles, in particular the top quark.

On the one hand, the community recognises CERNs importance and leading role in continued development of accelerator technology, and supports the study of long-term options like a high-energy hadron-hadron or hadron-lepton collider. On the other hand, however – and given the current lack of "new physics" discoveries at the LHC – Swedish particle physicists are exploring other venues to address today's outstanding topics, like the make-up of dark matter or the explanation for the baryon-antibaryon asymmetry in the universe.

An example of other Swedish activities is the participation in the underground XENON1T project in Gran Sasso, Italy, searching for dark matter particles through their scattering off Xe nuclei. An upgraded version of the detector, XENONnT, with a total xenon mass of 8 tonnes and designed to reach a sensitivity where neutrinos become a significant background, is presently under construction. The next step will be the proposed DARWIN observatory aiming at a further ten-fold increase in sensitivity. Sweden is involved through a research group at SU.

A small-scale dark matter accelerator-based experiment is the proposed LDMX, designed to search for light dark matter particles in the sub-GeV mass region. This project envisages studying collisions of an electron beam with a fixed target, and could be implemented at the proposed 4-8 GeV beam transfer line at SLAC, the 11 GeV CEBAF beam at Jefferson Laboratory, or a proposed 3.5-16 GeV beam derived from slow SPS extraction at CERN. Swedish scientists at Chalmers, LU and SU are involved.

Researchers from SU and UU participate in the search for hidden particles experiment (SHIP), proposed as a beam-dump facility for the CERN SPS. A specific goal is to search for very weakly interacting long-lived particles, for instance heavy partners of the known active neutrinos, and light supersymmetric particles as proposed in elaborate models of a hidden sector. Such models could provide a new approach to the search for dark matter.

PTOLEMY is a small observatory under development to detect the ubiquitous, cold relic-neutrino background through capture of neutrinos on bound tritium. PTOLEMY could conceivably also be used for detection of sub-GeV dark matter particles. A prototype will be commissioned at Gran Sasso. SU and UU have expressed interest.

Finally, two particle physics projects are proposed for the European Spallation Source (ESS):

A Swedish-led international project aiming to exploit the high neutron flux from the ESS to search for baryon-number violating processes, with a prototype phase called HIBEAM leading to a full-scale NNBAR phase by 2030. Researchers from SU, UU, LU, Chalmers and ESS participate.

A project instigated by Sweden aiming to upgrade the ESS accelerator to generate a very intense neutrino beam directed towards a large water Cherenkov detector in the Garpenberg mine, ~ 500 km away. The goal is to make precision measurements of the CP violation in the neutrino sector. A design study of the accelerator upgrade called ESSnuSB is underway with the participation from UU, LU, LTU, KTH and ESS in collaboration with international partners. A detector study aiming at deployment in the Garpenberg mine needs to be performed. This project is called GRIPnu.

3.1 Comments on some current Swedish initiatives

For this landscape analysis, input to the needs inventory conducted by RFI in 2017 has been provided. Therefore, the projects HIBEAM, GRIPnu and LDMX will be addressed further below.

3.1.1 HIBEAM

HIBEAM (High Intensity Baryon Extraction And Measurement project) is the first stage of an experiment at the ESS to search for baryon-number violating processes. Baryon number (B) and lepton number (L) conservation are characteristics built into the Standard Model via its matter content but do not follow from any fundamental first principles. Indeed, it was pointed out in the 1970s that non-perturbative “instanton” processes might exist, leading to baryon-number non-conservation in electroweak gauge theory. Conserving the combination B-L, these processes would also violate the lepton number L. Baryon-number violation is one of the three necessary so-called Sakharov conditions for the development of matter-antimatter asymmetry in the early universe. With the discovery of neutrino oscillations, ideas emerged coupling B violation to L violation due to out-of-equilibrium decays of heavy states coupling to the neutrino. An example is the popular see-saw mechanism that is compatible with Grand Unified Theories and explains the tiny neutrino masses through couplings of neutrinos to heavy Majorana leptons. Many of the current ideas involve physics at high energy-scales that can be difficult to test. It is therefore needed to look for processes at low energies that can constrain these theories.

Neutron-antineutron oscillation processes are predicted in many theories beyond the Standard Model, including i.a. SO(10) Grand Unified Theories, theories with extra space dimensions and certain supersymmetric theories[5]. The discovery of this process would be of fundamental importance, not only for our understanding of baryon asymmetry in the universe but, in conjunction with other data, possibly also for the understanding of the neutrino sector. The most stringent bounds on neutron conversion are achieved by experiments with cold, free neutrons. The latest results of such experiments, published in 2011, were obtained at the high-flux nuclear reactor at ILL. Neutron-antineutron oscillations can also be searched for in bound systems, albeit with smaller sensitivity due to the large nuclear corrections. Results have been published by Super-Kamiokande (2004) and recently by Sudbury Neutrino Observatory (SNO) in 2018.

The availability of an intense beam of cold neutrons from a very bright source provides an exceptional opportunity to investigate neutron-antineutron oscillations. HIBEAM would operate at a so-called fundamental physics beamline at the ESS and serve as a prototype for a later, fully sensitive detector NNBAR proposed for the large beam port. ESS is supportive of a vibrant fundamental physics program and ESS has expressed a willingness to invest in the development of a dedicated beamline for this and other particle physics experiments.[6] However, HIBEAM also needs a target for interactions of the anti-neutrons and a detector to catch the products and reconstruct the energy. The target and the detector would not be funded by the ESS.

The configuration of HIBEAM would be similar to NNBAR but, owing to the location, the available distance from the beam-port to the target and detector would be much shorter, which would limit the initial sensitivity. On the other hand, deployment of HIBEAM would allow development of the technology and the experimental techniques needed for a zero background events search with the full set-up. The goal for NNBAR is a sensitivity 1000 times larger than that of the ILL neutron-antineutron search.

HIBEAM would also be able to make a competitive search for conversion of neutrons into mirror-particles, hypothetical “dark” neutron twins. Theories of mirror matter postulate the existence of a hidden sector, consisting of particles exactly degenerate in mass with standard particles but with opposite parity. Mirror particles are not subject to standard electroweak or strong forces. They interact gravitationally and might possibly have very weak non-standard interactions with ordinary particles. For this reason, mirror theories are becoming increasingly popular, providing viable dark matter candidates. If mirror-neutrons exist they could only manifest through neutron-mirror neutron oscillations, a baryon-number violating process. HIBEAM foresees an absorber stopping the original neutron beam downstream of the anti-neutron detector, allowing potential mirror-neutrons to coast along and reconvert, to be detected at the end of the beamline. Also for the dark neutron

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5 See for examle arXiv:1809.00246v3

6 However, such an experiment will not be part of the first 15 at the facility and the decisions for instruments number 16-21 is yet to be taken.

searches, an orders-of-magnitude increase in sensitivity with respect to earlier experiments is expected for the final detector set-up.

An NNBAR collaboration was formed in 2014, and an expression of interest was submitted to the ESS in 2015. The interest in Sweden is very high, with almost 30 senior people from LU, UU, SU, Chalmers and ESS listed as collaboration members. Sweden also holds the position of co-spokesperson for HIBEAM/NNBAR.

HIBEAM is a competitive project in subatomic physics uniquely suited to the conditions provided at the ESS. The R&D is foreseen for 2020-22, construction for 2023-24 and start of operations for 2025. The cost for the detector is moderate with the Swedish share of about 30%, i.e. 30 MSEK. NNBAR would only be ready beyond 2028. Competition is scarce – although facilities like DUNE could be used for similar searches in the future.

3.1.2 GRIPnu

Measurement of the value of the leptonic CP violating phase δ_{CP} appearing in the neutrino mixing (PMNS) matrix is one of the “hot topics” in neutrino physics today. A value deviating from zero (or π) might provide a key towards a better understanding of the matter-antimatter asymmetry in the universe. The CP violation in the quark sector of the Standard Model is insufficient to explain this observational fact, yielding a baryon asymmetry that is approximately an order of magnitude too small. The parameter δ_{CP} can be accessed by comparing oscillation properties of neutrinos and anti-neutrinos and is today studied in long baseline neutrino experiments like T2K, using a high intensity neutrino beam from J-PARC, and NOνA in the US, using a neutrino beam from Fermilab. These beams contain mostly muon neutrinos or anti-neutrinos and the process studied is flavour oscillations, leading to the appearance of electron neutrinos (respectively anti-neutrinos) in the beam at a certain distance from the production point. The probability for this process to occur depends on the neutrino mixing angles and on the δ_{CP}. Given the energy of the available beams and the distances to the detectors, the experiments operate close to the first oscillation maximum. However, this may not be optimal for a precision measurement of δ_{CP}. Indeed, given our present knowledge of the neutrino mixing angles, it turns out that with a detector at the second oscillation maximum one could achieve a better sensitivity and be less affected by systematic uncertainties. The second maximum is, however, three times more distant from the neutrino source than the first and so, owing to beam divergence, super-intense neutrino beams are necessary.

Currently ESSnuSB, a Swedish-led consortium involving about 50 scientists from 11 European countries, is conducting an EU-financed study to evaluate the possibility of using the powerful proton beam of the ESS to create a sufficiently intense neutrino beam. The creation of such a beam would necessitate upgrades to the ESS facility. Use of the ESS proton driver for generation of a neutrino beam without reduction in the spallation neutron production-rate requires doubling of the pulse rate. This entails modifications to allow simultaneous acceleration of protons and H^- ions at an average power of 2.5+2.5 MW. Moreover, the proton pulse-length would have to be reduced to avoid overheating problems for the magnetic horn, used to focus pions downstream of the proton target in order to produce a narrow neutrino beam. A way of achieving an order of magnitude reduction of the pulse length is by building an accumulator/compressor ring. The necessary modifications are under study, which should result in a design report by 2021.

The current proposal concerns a design study of the foreseen neutrino detector. The proposed detector is a water Cherenkov detector, monitoring a target volume corresponding to one megaton. The detector would be constructed in an active mine in Garpenberg in Dalarna, about 540 kilometers from the neutrino source and conveniently located at the second oscillation maximum for neutrinos from the ESS. GRIPnu is the name of the proposed neutrino detector-infrastructure. The goal is for the project to appear on the ESFRI Roadmap of large European Infrastructures.

The estimated cost of the facility, including the ESS upgrade and the Garpenberg detector, is of the order 1.3 G€, split approximately 1:1 between the two parts. Data taking could start in 2035 with first competitive results in 2045.

Meanwhile, T2K and NOνA continue taking data. Both have already reported preference for a CP-phase deviating from 0 (and π), albeit at a confidence level of about 95% (2 standard deviations). New facilities at the first oscillation maximum are proposed or under construction:

- T2HK, the successor of T2K, will use the Hyper-Kamiokande detector monitoring a target mass of 0.52 megaton and receiving a neutrino beam from an upgraded 1.3 MW J-PARC facility. The baseline is 295 km. T2HK is listed among the highest priority large-scale infrastructure projects in Japan with construction planned to begin April 2020. The aim is to begin operations in 2026. For the first stage of the experiment only one of the two foreseen water Cherenkov detectors will be in use (implying a mass of 0.26 Mt). After 10 years of running, this configuration would allow discovery of δ_{CP} with a significance > 5σ over 57% of the allowed parameter space. If the CP violation is maximal (i.e. $\delta_{CP} = \pm\pi/2$, as the current results seem to suggest) it will be discovered with a sensitivity of ~ 8σ. A study of the possibility to deploy a far detector at the second oscillation maximum in Korea, is under way.[7]
- DUNE is a detector facility under construction at the Sanford underground laboratory, South Dakota, which will be using a neutrino beamline from the 1.2 (later potentially increased to 2.4) MW Fermilab accelerator complex. The neutrino beam will be optimized for CP-violation sensitivity. The detector is at a distance of 1300 km from the accelerator. The plan is to start data taking in 2026. After 10 years of running the expected performance regarding δ_{CP} would be similar to that of T2HK.[8]
- Anticipating the commissioning of the KM3NeT/ORCA neutrino telescope, presently under construction in the Mediterranean 40 km off-shore from Toulon, the possibility of directing a neutrino beam from the Protvino accelerator facility in Russia is under investigation. The baseline would be 2595 km.

The preliminary numbers for the proposed ESS neutrino facility point to a potential for discovery of δ_{CP} with a significance > 5σ over about 60% of the allowed parameter space, after 10 years of running. The characteristic distinguishing this facility

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[7] Hyper-K design report – arXiv:180504163
[8] DUNE Interim design report – arXiv:1807.10334

from T2HK and DUNE would be the operation at the second oscillation maximum, where the balance between the various sources of systematics is different. This would lead to a more precise measurement.

The ESS neutrino facility project was evaluated positively by the EU and received funding for the machine design study within the Horizon2020 framework. Given that the user interest in Sweden is fairly limited (8 people listed at UU, KTH and LU), it would make sense to seek international funding for the detector design study, as well.

An eventual upgrade of the ESS for neutrino beams and the location of the proposed neutrino facility are questions which lie beyond the scope of this report. Clearly, if a decision to go ahead were taken, major consequences for the financing load on RFI's budget would be expected, especially since the facility would be located in Sweden.

3.1.3 LDMX

Dark matter has been observed so far only through its gravitational effects and is thought to account for 25% of the energy budget of the universe. However, the question whether dark matter consists of fundamental, albeit unknown, particles remains yet unsolved. The Standard Model offers no dark matter particle candidates – as opposed to most Beyond Standard Model theories, including supersymmetry. Weakly interacting massive particles (WIMPs) would have been created at a large rate shortly after the Big Bang and the lightest of them could still exist today contributing to dark matter. Since many years, large effort is being invested in WIMP searches, in particular supersymmetric WIMP candidates. WIMPs are searched for at the LHC where such particles would be directly produced, in underground detectors like XENON looking for recoils of nuclei due to collisions with dark matter particles in the galactic halo. They are also searched for indirectly, in observatories like IceCube, looking for neutrinos from WIMP annihilations in celestial bodies or accumulations in the Milky Way. In spite of steadily improving sensitivity, no sign of WIMPs has yet been seen over a mass range from a few GeV to a TeV and beyond. As a complementary approach, this proposal suggests a search for hidden dark matter candidates with masses close to those of the regular Standard Model matter particles, i.e. in the MeV to GeV range.

Some of the theoretical ideas for extensions of the Standard Model to accommodate dark matter suggest the existence of a hidden "dark sector" consisting of particles that are insensitive to the electroweak and strong forces. Such theories typically assume the existence of "portals", connections between the dark sector and the ordinary Standard Model world provided by mediator particles. The portal believed to be most relevant for models of light dark matter is the vector portal, where the mediator is a "dark photon". Other portals might be important, however, for a general discussion of the dark sector.

LDMX is based on the simple fact that if dark matter has a thermal origin, then it must be possible to also create it in an accelerator-based experiment. In the case of light dark matter, then the most sensitive way to do so, is with an electron beam. In the simplest models, such processes could arise through a mixing interaction between a dark photon and the ordinary photon. The dark photon would be produced in the forward direction, carrying off a large fraction of the electron's energy. The emission would induce a transverse momentum component to the electron's motion, which can be measured. The dark photon is thought to typically decay into non-Standard Model particles. They are invisible in the detector but cause an overall energy/momentum imbalance. In some models, mixed decays into Standard Model and non-Standard Model particles are possible.

The experiment requires a low-current, high repetition rate electron beam with a beam energy in the lower GeV range – and a large integrated luminosity. Implementation would be possible at existing or planned beamlines. The experimental challenge is to ensure that standard bremsstrahlung events can be rejected with exceptionally high efficiency. The signal efficiency and background rejection capabilities of LDMX have been evaluated in a design study[9], indicating a sensitivity reach beyond that of current or planned experiments.

An expression of interest has been submitted to the SPSC at CERN (SPSC-EOI-018) proposing a new linear accelerator, based on the Compact Linear Collider (CLIC) technology for injection of 3.5 GeV electrons into the SPS where they would be accelerated to 16 GeV. The extracted beam would have characteristics optimised for the needs of LDMX.

The cost of the proposed eSPS accelerator facility would presumably be carried by CERN, while the cost of the detector set-up (of the order 10 MCHF) would be shared by the international collaboration. The co-spokesperson for the project, affiliated with LU, was in 2019 granted 26 MSEK from the KAW foundation to ensure progress.

The LDMX project is timely and offers an alternate opportunity for development of the CERN accelerator complex. A discovery of a light dark matter particle would be of fundamental importance. However, the user community in Sweden is small – about 10 people mostly at LU.

3.1.4 Conclusions and recommendations

ESS will be a facility with a uniquely powerful neutron beam providing new opportunities not only for materials physics and life sciences but also for nuclear and particle physics experiments. HIBEAM and the later even more sensitive NNBAR project are designed to take advantage of the ESS beam in searches for baryon-number violating processes. The existence of such processes would have implications on a number of fundamental questions in particle physics and cosmology. Given the large interest among Swedish scientists, support from the Swedish Research Council would leverage the Swedish investments in ESS and be beneficial for the community. GRIPnu requires an upgrade of the ESS to become a neutrino facility. The proposal has been met with interest internationally but the interest in Sweden is limited. The developments worldwide concerning the intended physics goals of GRIPnu should be monitored. Searches for light dark matter is a growing sector within particle physics and in this context the LDMX project offers interesting possibilities. The user community in Sweden is small, however.

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[9] arXiv:1808.05219

3.2 Theory

This report is focused on research infrastructures and their related experimental programs. However, a thriving theory community working closely with the above experimental activities is crucial to reap all the benefits of the combined efforts, so we would like to make some brief remarks on the current situation.

The prime example of theory involvement in the area of interest for this report is the development of the Pythia event generator in Lund which has been, and is, vital for the experimental activities at LHC and elsewhere. The development in this area must continue, motivated by the interest in future colliders, heavy ion physics, neutrino experiments and dark matter.

Apart from the Pythia success story, the connection between theory and experiment in Sweden and the support for encouraging such exchange has been weaker than what one would have hoped for. This is regrettable, since there are many theory groups engaging in research relevant to high-energy, nuclear physics and the search for dark matter.

In high energy physics and dark matter there are groups in all the major universities studying models of particle physics beyond the Standard Model and their potential experimental signatures at ATLAS and elsewhere. Closely related is the research on heavy ion physics, relevant to the ALICE experiment. In hadronic physics, there are groups focusing on hyperon physics, of relevance for e.g. the PANDA experiment. There is also a nuclear theory community developing *ab initio* techniques for computing nuclear properties, of great interest for the experiments at FAIR and ISOLDE, but also in the searches for dark matter. It is important that all these groups fully participate in the ongoing programs.

There are also many theory challenges for the near future that need to be faced. The construction of a "Higgs factory", i.e. a collider which produces a high yield of Higgs particles, will require detailed calculations at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) in the electro-weak sector, as well as theoretical advances and numerical implementations of effective field theories for both the Standard Model and QCD.

At the same time, model building activity should continue, starting with learning from what the lack of discovery of BSM physics at LHC so far has to teach us and moving on to new possible scenarios at future colliders, such as the potential Future Circular Collider (FCC) at CERN.

As compared to the experimental activities, theory research has a totally different set of challenges for the future, costs and flexibility not being the main issues. On the contrary, here the risk lies in missing opportunities of collaboration with the ongoing experiments.

One suggestion to improve the situation in the next 10 years is to endow each approved experiment with a small budget to support one or a few theorists for closer and more focused collaboration during the lifetime of the experiment. This would provide a more sustainable framework for those theorists and experimentalists who want to start working together without the uncertainty of relying entirely on short term funding opportunities.

3.3 Swedish accelerator development activities at CERN

The Swedish accelerator physics activities at CERN are important in view of possible in-kind and/or industrial contributions/contracts to and with CERN, but also as an increasingly important research field on its own. Many fields of science rely on and progress using accelerators as their main instruments, ESS and MAX IV being primary examples in Sweden. Education and research in accelerator physics are important in this perspective.

The last decade the work of Swedish accelerator researchers at CERN has concentrated around the CLIC project where Sweden contributed with the Two-Beam Test Stand (TBTS) at CTF3, the CLIC test facility. The TBTS was instrumental in providing the proof-of-concept for high gradient two-beam acceleration and is now re-used as part of the CLEAR facility, the CERN Linear Electron Accelerator for Research. Sweden is also active in spin-off to use CLIC technology for compact X-ray machines and the future electron linear accelerator as injector to the SPS for dark matter experiments proposed by Swedish scientists (LDMX, see section 3.1.3).

The Swedish accelerator community also contributes to the High Luminosity upgrade of the LHC. Uppsala University operates the FREIA Laboratory test stand for superconducting cavities and magnets that will be used for validating new HL-LHC crab cavities and orbit corrector magnets. A collaboration with industry is developing one of the cryostats for the HL-LHC cold powering system. Another collaboration with industry is working on a new canted-cosine-theta (CCT) type magnet to replace radiation damaged orbit correctors in the LHC during the coming decade.

3.4 Future of accelerator-based physics

All of the experimental activities discussed in this report rely on the existence of high performance accelerators of various types. This reliance extends to many other activities in which Sweden is spearheading, most notably ESS and MAX IV in Lund. Adding to this the increasing role that accelerators are playing in medical research and engineering, it is clear that maintaining an active research program in accelerator-based physics and accelerator development is a crucial strategic interest of Sweden and Europe as a whole.

Here, however, we would like to focus on the future of the accelerator based high-energy frontier, namely the need to develop a new accelerator facility to probe deeper into the structure of the Standard Model of particle physics and its associated Electro-Weak (EW) phase transition, driven by the Higgs mechanism.

In 2012 LHC, and the two main experiments built around it (ATLAS and CMS) discovered the Higgs boson, the last particle predicted by the Standard Model. It has a mass of 125 GeV, and its field provides the necessary ingredient for the spontaneous breaking of the EW symmetry generating the masses of the elementary particles.

The EW transition is one of the most crucial events our universe experienced shortly after its birth and could very well hold the explanation for many currently unanswered questions such as the origin of baryon asymmetry and dark matter. Understanding nature at the EW scale ought to be one of the central focuses of the particle physics community.

At HL-LHC, the expectation is[10] to measure the couplings of the Higgs boson to the heavy vector bosons to 2~3 % accuracy and the couplings to the quarks of the third family with 5~6 % accuracy. A statistically significant deviation from the Standard Model central value would be an unequivocal sign of physics beyond the Standard Model even in the absence of the direct discovery of new particles. However, many models of new physics give rise to very subtle deviations of the Higgs couplings. In order to complement and improve on HL-LHC measurements it is almost universally agreed that the step immediately following the LHC programme must be a precision $e^+ e^-$ collider. Several different designs and locations are being proposed, and a discussion about the pros and cons of each proposal is beyond the scope of this report. The timelines for start of operation for these proposed facilities is in the range 2035-2045, i.e. at the time the HL-LHC draws to a close.

These proposed $e^+ e^-$ colliders aim to operate above the hZ production threshold, pushing the accuracy of the measurements of the above-mentioned Higgs couplings to the per mille level. The full reconstruction of this production mode allows for the absolute determination of the Higgs decay-width and (channel specific) production cross section.

[10] https://arxiv.org/abs/1902.00134

4. Bird's eye view on Sweden´s involvement in accelerator-based infrastructures for particle and nuclear physics

4.1 Staffing and long term strategies from RFI and Universities

Below we list the overall composition of the groups working at the main six different experiments described in the report. The numbers are taken from the survey handed out by the panel during spring 2019 to the Swedish research groups involved at CERN and FAIR. As with all the numbers presented in this report, one has to keep in mind that the CERN activities have been running for an extended period of time, and can be considered very mature, while the FAIR activities are just starting up.

ATLAS	Staff numbers
PhD students	22 (22 FTE)
Postdocs/Researchers	10 (8.7 FTE)
Assistant Professors	1 (0.4 FTE)
Lecturers/Professors	20 (11.9 FTE)

ALICE	Staff numbers
PhD students	4
Postdocs/Researchers	0
Assistant Professors	1
Lecturers/Professors	2

ISOLDE	Staff numbers
PhD students	7
Postdocs/Researchers	6
Assistant Professors	1
Lecturers/Professors	15

APPA	Staff numbers
PhD students	0
Postdocs/Researchers	0
Assistant Professors	0
Lecturers/Professors	3 (0.8 FTE)

PANDA	Staff numbers
PhD students	5 (4.3 FTE)
Postdocs/Researchers	4 (2.6 FTE)
Assistant Professors	0
Lecturers/Professors	7 (2 FTE)

NUSTAR	Staff numbers
PhD students	9 (7.9 FTE)
Postdocs/Researchers	4 (3.7 FTE)
Assistant Professors	1 (0.8 FTE)
Lecturers/Professors	9 (4.7 FTE)

As can be seen from the tabulated staff numbers, the composition of the different groups are heterogeneous, and ATLAS is clearly having the largest total staff number of the six experiments.

The common long (or medium) term strategy of RFI and the universities is to fund the in-kind deliveries to the different experiments. RFI also funds the experiments' maintenance and operations fees. For RFI, a severe long term challenge is the continuous payment of the annual convention bound fees to CERN and FAIR and the long-term membership fees to the respective experiments (i.e. maintenance and operations). These payments are made in foreign currency and fluctuations in the exchange rates result in uncontrollable oscillations of the available remaining RFI budget. For the universities the long term challenges are associated with the recruitment of senior staff members and their respective funding.

Generally, we see a worrying mismatch between investments in research infrastructures and investments in grants for the researchers using them. Therefore, the long-term staffing strategies should be further strengthened by dedicating peer-reviewed project grants within the fields already supported by infrastructure investments from the RFI. For several of the experiments discussed in this report, NT funding for postdocs and PhD students has been reduced during the last years which risks poor returns on the investments made in terms of membership fees and in-kind deliveries.

However, as stressed in the our recommendations given in the conclusions of this report, these efforts are currently not coordinated, and a dialog between RFI, NT, and the different universities would strengthen the long term abilities of Swedish research in this field. Since "long term" in terms of new facilities and new experiments can range from 10 to 50 years in the accelerator community, this requires a national strategy with the aforementioned coordination in order to enable long-term planning and guarantee stability.

4.2 Investment returns

4.2.1 Careers and capacity building

A great societal benefit of constructing and exploiting large-scale infrastructures is training of new generations of students and researchers in an international and innovation-rich high-tech environment. It is almost universally true that there are substantial added values for Sweden to have employees at the facilities, e.g. as fellows at CERN, regardless of the type of experiment. A certain practical know-how can be communicated only by direct interaction between experimenters while on-site. It should not be underestimated that CERN as a whole is a strong trademark and can attract excellent students who will greatly benefit from their time at the facility.

Recently, CERN instigated a study of the career impact of a longer or shorter working experience at the laboratory.[11] Based on more than 2000 answers to a questionnaire, the conclusion stresses that the experience is considered important and positive. Career trajectories are diverse, including both academia, education and private and public enterprises, especially within IT, advanced technologies and finance. Unfortunately, the design and construction times for new accelerator and detector facilities have nowadays often moved way beyond the time horizon of a typical grad student or postdoc. To maintain the benefits, RFI should enable participation in a diversity of large and small-scale projects over different time scales. This requires a stable budget frame for short-term and long-term planning. We recommend an active discussion between RFI, NT, and the universities (e.g. through URFI) in order for this to be made possible.

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[11] arXiv:1910.05116

4.2.2 Technology and instrumentation

To increase technology transfer from the so-called "big science" facilities like CERN, ESO, ESS and others, the organisation Big Science Sweden (BiSS) was created in 2017 to actively promote business contacts between Swedish industry and the "big science" research facilities that Sweden co-finances. The overarching goal is to increase the Swedish industrial return from such facilities, i.e. the ratio between the Swedish percentage share of the value of all supply contracts for a given facility and the Swedish percentage share of its total budget. In addition, collaboration with – and delivery to – researchers and facilities working at the scientific frontier is a means to increase high-tech competence in Sweden and hence increase Swedish competitiveness on the global market.

Big Science Sweden functions as an official Industry Liaison Organization (ILO). It is financed by The Swedish Agency for Economic and Regional Growth (Tillväxtverket) together with the Swedish Agency for Innovation Systems (Vinnova) and the Swedish Research Council. It works pro-actively by initiating contacts with technological enterprises who can potentially deliver equipment to "big science" facilities, by creating a catalogue of potential suppliers of advanced technological solutions and products[12], by arranging relevant courses relating for instance to accelerator technology, artificial intelligence or procurement processes and by arranging networking conferences.

Although it is rather early to judge its success, Big Science Sweden has stated that orders worth about 200 MSEK have already been secured by Swedish companies thanks to their assistance. The orders include deliveries of materials, components and systems to several research facilities, among them CERN. Comments from successful suppliers underscore the value of complex and interesting challenges, of pushing the limits of what can be done in collaboration with researchers, of building up valuable expertise that opens the doors to further high-tech markets and of trademark exposition and promotion.

4.3 Developments of the field in short-, medium-, and long-term

It is fair to say that the whole field of particle and nuclear physics is by now mature. By this we mean a field with a long tradition of successes and the need for a stable long term planning for future activities. It should not be compared every year with the latest (and always different) "hot topic" or expected to deliver new groundbreaking results in rapid succession. The problems that need to be answered today, such as the nature of the electro-weak phase transition, baryogenesis, dark matter, the formation of heavy elements, and the like, require long term planning.

The funding strategies must be adapted to this situation by guaranteeing that the approved projects are brought to completion. The success story of LIGO, the Laser Interferometer Gravitational-Wave Observatory at MIT, is a good example. Since the direct detection of gravitational waves is such a striking and recent event, it is

[12] https://www.bigsciencesweden.se/sv/the-swedish-guide/

easy to forget that it was only the coronation of a long (and at times messy) endeavour that started in the 80's and culminated with the first detection announced in 2016. Let us remember that the first run from 2002 to 2010 was funded even though it was not really expected to detect any signal and served as a groundwork for the next phase of the project. The current situation in particle physics is quite similar.

It is fair to ask however if within the field of particle and nuclear physics one can make some distinction and single out certain areas of interest and/or areas in decline. One possible line of argument is that it is more likely that a major breakthrough in the understanding of the laws of the subatomic word will come from either the high-energy frontier, the high-intensity frontier or the high precision frontier. Experimental facilities such as a new collider, dark matter and neutrino detectors and B-factories (optimised for the production of Bottom quarks) are simply irreplaceable if we want to move forward in this direction.

On the other hand, it is unlikely that new laws of physics will be uncovered by the new nuclear physics facilities that are being built at FAIR. What is at stake there is instead a deeper understanding of the early universe and the important issue of formation of heavy elements inside stars.

In order to stay at the forefront of research in particle and nuclear physics, and to have some flexibility as new discoveries come along, measures ensuring scientific diversity in this field should be stimulated. This would enable the Swedish Research Council, RFI, and universities to support smaller scale projects suggested by groups that have traditionally not been in the field, or to support "outlier" experiments that may be high risk-high gain in character. Such a program could possibly fall under the umbrella of dedicated, peer reviewed project grants in the fields already supported by the RFI (see point 3 in our recommendations, also given in the executive summary).

The long term needs of the Swedish community cannot be separated from those of the international community, given the nature of the field of investigation. The current European strategy for particle physics, adopted in 2013[13] has a strong focus on LHC and upgrades of the LHC and its detectors, now in the process of being implemented. The strategy is currently being updated. The final update report is expected by May 2020.[14] Similarly the NuPECC long-range plan from 2017[15] provides guidance for European priorities in the area of nuclear physics. In both cases the Swedish community actively participates, discusses and plays important roles in shaping the strategies.

4.4 Funding strategies: Comparison with the Nordic Countries

There are possible improvements that could aid the future research possibilities in the field of particle and nuclear physics. Here we give two examples of different funding strategies from the Nordic countries.

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[13] https://cds.cern.ch/record/1551933/files/Strategy_Report_LR.pdf

[14] The current status of the deliberations can be found at: http://europeanstrategyupdate.web.cern.ch.

[15] http://www.esf.org/fileadmin/user_upload/esf/Nupecc-LRP2017.pdf

In Norway the CERN-related activities are organised in one common project with several work-packages, e.g. ATLAS, ALICE, ISOLDE, accelerator studies, technical students, etc. This project is executed by one of the major universities, currently University of Oslo, but covers activities at all involved Norwegian universities. The funding supports: M&O costs, travels, operation, local facilities and post-doc grants. This CERN-related project funding is complemented by another project providing specific infrastructure funding for the Norwegian HL-LHC (ATLAS and ALICE upgrades) and computing contributions. These investments have a size such that they could not be handled by the "ordinary" CERN-related funding. Smaller more specific research projects, either with national or European funding, comes in as additions for shorter time-periods. More importantly, the CERN membership is decoupled from the Research Council of Norway´s regular budget. As a result the currency and GDP changes do not create unforeseeable fluctuations. The board overseeing the activities consists of representatives from the departments and faculties involved in the activities. As a rule, the universities are expected to match the Research Council´s funding and the resources come in the form of e.g. staff allocations, PhD student grants, workshop access and to some extent workshop personnel.

In Finland, the CERN activities are organised through the Helsinki Institute of Physics (HIP). HIP has a national responsibility for CERN-related activities including experimental research, but and also for other related activities such as theory support, technology and knowledge transfer from CERN to applications, organisation of computing, school visits to CERN, and some research projects with synergies with CERN. Since 2010 HIP also coordinates Finnish involvement in FAIR (joint participation with the Swedish Research Council). HIP provides local detector laboratory infrastructure and staff for detector design and construction at both CERN and FAIR.

HIP covers M&O costs of experiments, travel and operational costs of research groups, small-scale R&D, and fixed-term salary support for PhD students and post-docs. The group leaders are given a budget, which they handle as they see fit. There are no permanent research and teaching category staff in HIP, but there is a small permanent staff consisting of lab personnel and a research coordinator. Permanent research staff (faculty: professors, lecturers, university researchers) are employed and paid by the host universities. For investments (detector construction or upgrade) funding is applied from Academy of Finland/Research Infrastructure Committee. HIP is steered by a board, consisting of representatives of the participating universities and an elected member of the HIP personnel. There is a strategic advisory board overseeing and giving advice on the operations.

Thus, we see that Norway and Finland have chosen different routes for associated funding of infrastructure investments, in order to ensure long term stability, as well as other strategies for the convention bound fees. We believe it would be valuable for the Swedish Research Council and RFI to look into these possibilities. Applying a similar approach in the Swedish system could lead to a greater flexibility of future RFI investments in the field, as the funding would not be equally sensitive to e.g. currency fluctuations.

4.5 Possible outcomes of changes in funding structures

Of interest for RFI, as well as the research community, is the question of how to handle budget changes. In particular, the terms of reference (Annex 1) from the RFI stipulated that an overview of strategies and priorities should be investigated, given a budget change of ±10% and of ±25%. We will here go into some detail as to how we have reasoned concerning this.

We will start by considering the question of a budget cut from RFI. More precisely, we have been asked to evaluate the potential impact of a 25% or 10% cut in the Swedish funding for CERN and FAIR, and how the remaining money would best be spent. It was early on realised in the panel discussions that these types of questions are subject to interpretation. We will therefore elaborate on why it is hard to give a well-defined answer, but given these constraints we will still try to give some guidance about how to best think of the matter.

The types of costs that Sweden covers for CERN and FAIR can be broadly divided into three main categories, namely

1. investment costs for build-up of the experiments and facilities,
2. convention-bound running costs paid to the facility and
3. staffing and running costs associated with the national experimental activities at the facilities.

In the first category, large commitments have been made by Sweden both to the build-up to the CERN experiments and both the FAIR experiments and facility through cash and in-kind contributions. In the second category, the annual contribution to CERN is the single largest of all costs considered in this report. For 2019 Sweden paid ~285 MSEK, via the Swedish Research Council. For FAIR the running costs are currently rather modest (the Swedish Research Council paid ~0.5 MSEK during 2019 for the FAIR Phase-0 program) as the facility is still under construction, but will increase steeply in the future when the facility is up and running. Estimates have been made that running costs of at least 45 MSEK/year will be required from Sweden from 2025 and beyond. The final and third category includes the running costs for the specific experiments, e.g. maintenance and operations (M&O) costs for ATLAS and ALICE and the yearly contributions to ISOLDE, as well as the funding allocated to the various Swedish research groups for their activities, given by the national funding agencies (primarily the Swedish Research Council and KAW).

While the investments in category 1) are considerable the money has, from the viewpoint of the funding agencies, already been spent; either through direct payments to the facilities or via grants paid out to Swedish research groups for building the agreed-upon in-kind contribution. Hence these costs cannot be cut by either 10 or 25%.

Furthermore, the yearly tranches in category 2) are calculated via formulas agreed upon by the international partners, including parameters such as the national GDP, and hence cannot easily be changed. The only possible way to cut costs here is therefore to leave a facility (CERN or FAIR) as a whole or to work with other member countries for a general cost reduction.

The only category that remains that can be substantially influenced by national funding policies is 3). However, given how small these costs are in relation to the membership fees it is hard to significantly reduce the total national spending this way without terminating most national research activities. As an example, the yearly contribution from RFI to the LHC-experiments – including the M&O A+B costs for both ALICE and ATLAS, the WLCG computing costs as well as the travel costs and expenses for LHCk to run the national program – is ~25 MSEK. While significant, this is still less than 10% of the yearly CERN membership.

Therefore one should rather think about what research activities can be supported, given a certain infrastructure membership. This leads to the difficult question of possible priorities. There are different routes one may take concerning this. One is to reduce the overall spending to the entire range of experiments. This will however lead to very unfortunate effects on the critical size of many activities. Another option is to single out activities that are deemed sub-critical. The consequence of this action would be that, while saving a small fraction of funding, the investments in in-kind deliveries could possibly be completely lost. There is, as we see it, no simple response to the question of how to efficiently reduce the cost of these activities. However, we believe that the suggested dialogue between RFI, NT, and the universities could give a long term strategy for also handling possible budget cuts concerning accelerator-based infrastructures (primarily CERN and FAIR).

Another question in the terms of reference was what scientific areas/projects should be prioritised if a moderate to significant increase of the total budget would be allocated by the funding bodies. This is of course a much more pleasant question to respond to. Here it is nevertheless also rather tricky to find an optimal response. We believe that an increase in the budget could be best spent in terms of diversity, widening the range of experimental activities at the facilities, making it possible for new users to access CERN, FAIR, or other future facilities in the field. This would also be positive in terms of long term recruitment, staff diversity and balance – all preferable from the perspectives of both the research community, the universities, and the funding bodies.

5. Conclusions and recommendations

Throughout the report we make comments and give recommendations. Our main recommendations to RFI and the Swedish Research Council are given below. These should not be read as necessarily requiring further funding, but as a means for efficient use of investments already made:

1. Bring up to discussion the possibility to transfer the convention-bound membership fees to the Ministry of Education and Research. This would ensure a greater budget stability within the Council for Research Infrastructures, and make it easier to practically handle currency fluctuations and changes in facility costs. As these infrastructure investments are made in an international context, there will inevitably be an interplay between decisions made at the ministry level and decisions made at the RFI level. This would also be in line with how the other Nordic countries deal with convention-bound membership fees. We stress that the scientific evaluation of infrastructure investments should still be done by the Swedish Research Council.
2. For long-term funding and planning, initiate a dialogue between RFI, the Scientific Council for Natural and Engineering Sciences (NT, also a part of the Swedish Research Council), and the Swedish universities involved in the research (e.g. through URFI, the University infrastructure reference group). This would enable a joint coordination of infrastructure spending, in-kind deliveries, and personnel costs, as well as safeguard the staffing balance in the community. The outcome of such discussions should also be documented and made available to the community. Moreover, a further improvement of the investment return would result from the endowment of each approved experiment with a small budget to support theory activities for closer and more focused collaboration during the lifetime of the experiment.
3. Investments made in terms of membership fees and in-kind deliveries need to be utilised. Today we see a mismatch between investments in research infrastructures and investments in grants for the researchers using them. Therefore, the long-term staffing strategies should be further strengthened by dedicating peer-reviewed project grants within the fields already supported by infrastructure investments from the RFI. This would require a discussion much like the one suggested in recommendation 2 above.

These recommendations are applicable to other types of infrastructures as well, but are especially important here, in view of the large scale, in space, time, money and international reach, of the accelerator infrastructures.

Annex 1: Terms of Reference

Background and purpose

The commitments of the Swedish Research Council in the field of accelerator-based infrastructure for particle-/ subatomic-/nuclear physics at facilities such as CERN and FAIR are extensive. The Swedish membership at CERN alone costs ~275 MSEK/year, in addition to which the Research Council supports programs for co-operation of Swedish researchers in several of CERN's experiments such as ATLAS, ALICE and ISOLDE. At the same time, Sweden contributes to the construction of FAIR, for which the Swedish investments currently amounts to ~125 MSEK – a number which will potentially further grow before the completion of the facility. Given the size of these financial commitments, it is important to ensure that the funding is strategically well-spent and of maximum benefit to the research community. Therefore, an investigation and landscape analysis of the funded research infrastructures in the fields of accelerator-based particle-/subatomic-/nuclear physics will be conducted.

Scope, timeline and meetings

The initial task of the group will be to map out Swedish user groups whose research is directly dependent on, or strongly benefits from, the funded infrastructures in the above-mentioned areas. Of particular interest is to understand what overlap exists between user communities at different facilities and how these might develop in the future. In addition, the group should asses the scientific impact of the various Swedish memberships and advice on prioritizations or future initiatives that would provide a better scientific return on investment. Given the ongoing discussions regarding increased costs for the construction of the FAIR facility, the Swedish Research Council would like the group to give special attention to issues regarding FAIR at an early stage in the work so that advice can be given in the early summer of 2019 (see below).

The investigation will be conducted during the calender year of 2019, ending with a presentation of the final report at the first meeting of the Council for Scientific Infrastructures (RFI) in January of 2020. The exact number of physical meetings required will be determined by the group, but a kick-off meeting in late February/early March followed by a follow-up meeting sometime thereafter, as well as a round-up meeting toward the end of the period before writing up the report, is strongly recommended. Further meetings are most likely required but can be conducted via video conferences. Besides this the group is expected to, in dialogue with and with the help of the Swedish Research Council, to inform relevant bodies in the Swedish academic system along the way.

Questions and perspectives

The following list of questions should specifically be addressed by the group and, if possible, be answered in the resulting report:

- Survey of the landscape
  - What are the needs of Swedish particle-/subatomic-/nuclear physics research for large-scale infrastructures, both at present and in the future?

- What is the composition of the user communities at Swedish universities? Are they organized in an optimal way for their common research needs (e.g. in LHCk, S-FAIR etc.)? How is the Swedish user community expected to change in the future, for example as a result of demographic factors (retirement, relocations, etc.) or other structural changes?
- Given the main documents/agreements/contracts that govern the commitments to infrastructures within these fields, possibilities to deliver in-kind, exit clauses, etc. (will be provide by the Swedish Research Council), what are the consequences for Sweden´s possibility to alter its engagements?
- How are outreach activities financed today?

• Analysis

- What is the scientific value of Sweden´s engagement in these infrastructures?
- What are the additional societal and socio-economic returns?
- How is the technology and instrumentation frontiers currently changing in the field and what consequences does this have for the research communities?
- Are new scientific areas emerging while others are in decline? What is the expected development in the short, medium and long term?
- How well are Swedish in-kind supplies handled in the Swedish research system and how would this possibly be managed better? What has the concrete added value, e.g. returns to Swedish industry, been of contributing to the infrastructure through in-kind deliveries?
- Are there substantial added values for Sweden to have employees at the facilities, e.g. as fellows at CERN?
- Have investments in students (teknikstudenter) and summer students given measurable effects?

• Future strategic considerations

- How should the Swedish Research Council act in order for the investments in the fields of particle-/subatomic-/nuclear physics to yield maximum returns for research conducted in Sweden?
- Can Sweden possibly get more scientific and other values out of their memberships of these infrastructures in relation to costs?
- In case of a 25% or 10% cut in the Swedish funding for the infrastructures under considerations, how should the remaining resources best be prioritized? Correspondingly, what areas should be prioritized in case of a 25% or 10% increase in the total budget.

The resulting report should include answers to these questions in relations to all the infrastructures under considerations. However, given the discussion regarding increased costs for the construction of the FAIR facility the group is asked to initially focus their attention on FAIR, so that the Swedish Research Council have the best possible advice in upcoming discussions and negotiations. The group will be asked to as quickly as possible help assess the report from the ongoing project review of FAIR, which is expected to be available in late April 2019.

Annex 2 - Short report on FAIR for RFI

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As part of the Terms of Reference defining our task, the committee evaluating Swedish accelerator based research in particle, subatomic and nuclear physics has been invited to comment on the report of the FAIR Progress and Cost Review Board (from now called the FAIR Report in the text) as delivered by the end of April 2019. The FAIR report will be of great help for decisions to be made concerning FAIR funding – both in Sweden and in the international negotiations within the FAIR council.

We would like to start by pointing out that we, from our recent independent hearing of the Swedish groups participating in FAIR, are impressed by the overall scientific quality of the different pillars of FAIR. We have found that most, if not all, of the scientific directions in which Sweden is involved (NUSTAR, APPA & PANDA) have a highly novel character and hold the promise of significant scientific impact. The Swedish contribution to FAIR is broad, and we expect excellent output from the activities at this facility when up-and-running. Below follows a summary of our discussions regarding the FAIR report.

The FAIR project is indeed in a problematic position, given the significant cost increase (approximately 1.1 billion €, including a 10% contingency) expected until completion 2025. However, the FAIR Report acknowledges that the four scientific pillars APPA, CBM, NUSTAR, and PANDA will be capable of world leading discovery science, which no other facility can match. There is, moreover, no activity singled out as lesser in the above sense and no reasonable de-scoping scenario can be proposed given the far-gone investments in all the activities.

While the FAIR Report is very thorough, we would however have liked to see a more thorough review of what projects would be up-and-running by 2025, as it is likely that not the whole program will be operational at that stage, and this could affect the novelty of the science done at FAIR. Moreover, we would have liked to see a more thorough discussion about cost safeguards, given the significant cost increase already at hand, and that the FAIR management would have made a more specific estimate of the total costs, spending profile and physics capabilities as a function of time given different scenarios. The management seems to have made a significant effort to clarify some issues, such as guaranteeing the scientific quality of the pillars of FAIR, but the uncertain costs for, e.g., civil engineering, leaves us with uncertainty of the total cost estimates until 2025.

The FAIR Report suggests three ways to deal with the economic situation:

1. Fixed annual tranches per shareholder, which gradually change into yearly operation costs. These are estimated to be 160 M€/year. This would, however, bring us to 2027 as the year of completion, not 2025. The consequences of this needs to be clarified. For Sweden the cost would be thus be 1.47% x 2/3 x 160 M€ = 1.6 M€/year for 7 years (and the same amount as operational costs afterwards). For the shareholders this would be a risky option, since without any critical backstop of the construction period there is a great risk of further delays in the start of physics delivery.
2. Germany would to take over the remaining civil construction as in-kind contribution, including the estimated additional personnel and running costs. Since the civil construction is largely carried out by German companies or companies located in the region and thus benefiting the German economy, this option is highly recommended. This would also allow better control and line management of the time-critical resources.
3. All shareholders commit the additionally required funds as cash by mid2019. This option is very unlikely at large.

The second option is recommended, but the remaining funding gap still needs to be brought up for discussion. At this time, it is also unclear what implications – if any – this option might have for the future shared running costs for the facility. The possibility to implement stronger contingency measures, or equivalent, should be discussed in the FAIR council, in order to reduce risks in future investments.

Given FAIR as an example, and the impact such discussions have on international relations, we would strongly advise that future convention bound large scale infrastructure investments are dealt with directly by the relevant Ministry, with RFI only acting as a scientific partner. By doing so, we would guarantee an overall long-term stability for a broad range of infrastructure investments of great importance for Swedish science.

We would also like to point out that since the Swedish participation in FAIR is a joint venture with Finland, a continuous discussion with the Finnish counterparts is essential.

Finally, we like to stress that a possible discontinuation of the Swedish FAIR involvement would (a) render previous (public and private) investments (which the Swedish FAIR has contributed on time, also in-kind) void and (b) cause significant, and most likely irreparable, damage to the Swedish scientific community.

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