Quality and impact of research in physics in Sweden

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Content

Vetenskapsrådets förord

Vetenskapsrådet har låtit utvärdera forskningsområdet fysik utifrån sin modell för nationella utvärderingar av forskningsämnen. Modellen har utarbetats i samverkan med en rådgivande grupp med representanter från Sveriges universitets- och högskoleförbund och Universitetskanslersämbetet. Utvärderingsmodellen utgår från regeringens instruktion till Vetenskapsrådet, som bland annat innehåller uppdraget att ”utvärdera forskning och bedöma forskningen och dess vetenskapliga kvalitet och betydelse” (§1:6).

Det övergripande syftet med utvärderingen är att bidra till att stärka svensk forskning. Utvärderingen är utformad för bedömning av forskningens kvalitet och betydelse för det omgivande samhället i ett internationellt perspektiv. Genom att lyfta fram såväl styrkor som svagheter kan utvärderingen utgöra underlag för att stärka forskningen; åtgärder kan vidtas av relevanta aktörer, av såväl lärosäten som finansiärer och regering.

Utvärderingen har utförts av en oberoende expertpanel bestående av totalt fjorton experter, varav tolv rekryterats internationellt och två nationellt. Vetenskapsrådet tackar panelen för deras betydelsefulla och mycket väl utförda arbete med att teckna en nationell bild av forskningens kvalitet och betydelse inom fysik i Sverige.

Stockholm, 17 april 2023

Katarina Bjelke

Generaldirektör, Vetenskapsrådet

Vetenskapsrådets sammanfattning av rapporten

Forskningsområdet fysik är en av de största mottagarna av forskningsmedel inom natur- och teknikvetenskap i Sverige. Fysik omfattar grundläggande frågor om hur vi ser på universum idag, men även hur vi närmar oss samhällsutmaningar, som klimatförändringar, eller utvecklar nya tekniska lösningar, exempelvis kommunikationssystem. Många av de vetenskapliga framsteg vi sett under de senaste hundra åren, och som påverkar våra vardagliga liv, har nära koppling till ämnet fysik. De språng vi har tagit i vår förståelse av vår omvärld bygger i hög grad på användningen av avancerade experimentella tekniker. Vissa av dessa tekniker kräver stora investeringar och uppbyggnad av forskningsinfrastruktur. Dessa anläggningar används i stor utsträckning inom forskningsområdet fysik och det har bidragit till betydande vetenskapliga framsteg inom områden som sträcker sig från partikel- och kärnfysik till materialvetenskap.

Mot denna bakgrund har Vetenskapsrådet valt att låta utvärdera forskningsområdet fysik utifrån den modell för nationella utvärderingar av forskningsämnen som myndigheten utvecklat. Modellen har utarbetats i samverkan med en rådgivande grupp med representanter från Sveriges universitets- och högskoleförbund och Universitetskanslersämbetet. Tidigare har ämnet statsvetenskap utvärderats i enlighet med denna modell. Fysik är således det andra ämnet i ordningen och det första inom natur- och teknikvetenskap som utvärderas enligt modellen. Utvärderingsmodellen utgår från regeringens instruktion till Vetenskapsrådet, som bland annat innehåller uppdraget att ”utvärdera forskning och bedöma forskningen och dess vetenskapliga kvalitet och betydelse” (§1:6).

Det övergripande syftet med dessa utvärderingar är att bidra till att stärka svensk forskning. Utvärderingsmodellen är utformad för bedömning av forskningens kvalitet och betydelse för det omgivande samhället i ett internationellt perspektiv. Genom att lyfta fram såväl styrkor som svagheter kan utvärderingarna utgöra underlag för att stärka forskningen; åtgärder kan vidtas av relevanta aktörer, såväl av lärosäten som finansiärer och regering.

Utvärderingen av forskningsämnet fysik har utförts av en oberoende expertpanel bestående av totalt fjorton experter, varav tolv rekryterats internationellt och två nationellt. Underlaget till panelen har bestått av ett urval av publikationer fördelade efter hur stor andel av fysikforskningen i Sverige de berörda lärosätena har. Lärosätena har i form av fallstudier också fått ge exempel där deras forskning i fysik har varit av betydelse för det omgivande samhället. Utöver publikationer och fallstudier har panelen haft tillgång till bibliometrisk analys och deskriptiva data om fysikforskningen i Sverige. Dessutom har panelen fått stöd av 65 internationella granskare, som har läst och bedömt kvaliteten på de inskickade publikationerna, fördelade utifrån respektive granskares expertområde.

Panelen konstaterar på en övergripande nivå att kvaliteten på den vetenskapliga produktionen håller hög kvalitet och framhåller svensk fysikforsknings stora inomvetenskapliga genomslag nationellt och internationellt.

När det gäller forskningens betydelse för det omgivande samhället, framhåller panelen att flera av fallstudierna lyfter fram de svenska lärosätenas starka koppling till industrin, utbildningssystemet och det internationella forskarsamhället. Det finns en bred portfölj av fysikforskning i Sverige, från grundforskning, över innovation och teknikutveckling, till praktiska lösningar för industrin och forskning med bäring på stora samhällsutmaningar (energiförsörjning, klimatkris etc.).

Panelen gör också bedömningen att Sverige är en eftertraktad partner i forskningssamarbeten. I detta sammanhang lyfter de särskilt fram områdena subatomär fysik, fusion, rymd- och plasmafysik, astronomi, astrofysik och kosmologi. Panelens uppfattning är att Sverige har en sund balans när det gäller investeringar i utbildning, teknikutveckling, tillämpad vetenskaplig forskning och grundforskning.

Utöver denna samlade bedömning har panelen även utvärderat fysikområdets olika underdiscipliner var för sig.

Panelen menar att området subatomär fysik är starkt representerat i Sverige och att Sverige har unik infrastruktur för denna forskning. De anser att både den vetenskapliga potentialen av detta forskningsfält och dess samhälleliga påverkan är mycket stor. Panelen framhåller att kvalitén på de svenska bidragen inom den subatomära forskningen är mycket god och att Sverige har mycket goda samarbeten och nätverk inom fältet.

För underdisciplinen atom- och molekylfysik och optik pekar panelen på att Sverige har en lång och stark tradition av forskning inom området och menar att Sverige här har en konkurrenskraftig ställning genom viktig och mycket citerad forskning. Däremot beskrivs det som svårt att uttala sig om samhälleligt genomslag över det korta tidsintervall som underlaget representerar. Panelen ser positivt på att den kunskap som utvecklas i laboratorierna överförs till nystartade företag.

Panelen pekar på att området fusion, plasma och rymdfysik är relativt litet i Sverige, men att det är framgångsrikt genom starkt samarbete och internationellt nätverkande. Panelen bedömer att området kan ha mycket stor samhällspåverkan vad gäller ren energiproduktion, dynamiska rymdprocesser och områden relaterade till exempelvis förmågan att utföra rymdutforskning. De menar vidare att Sverige spelar en aktiv roll i det internationella forskarsamhället och att dess samverkan har gett utdelning. Panelen anser att det är viktigt att upprätthålla och stärka denna utveckling.

Panelen menar att området den kondenserade materiens fysik är starkt representerat i Sverige. De påpekar att detta forskningsfält bidrar starkt till lösningar på samhälleliga utmaningar och driver flera stora tekniktrender. Panelen framhåller särskilt forskningen inom innovativa nya material, energiproduktion och lagringsteknik, där Sverige är väl positionerat för att spela en stor roll. En rekommendation som panelen ger, baserat på vad de sett i ett flertal fallstudier inom området, är att institutionerna bör fortsätta att främja tvärvetenskaplig forskning kopplat till den kondenserade materiens fysik, särskilt i skärningen mellan kemi, ingenjörsvetenskap, biologi och datavetenskap, eftersom panelen bedömer att detta kan ge grogrund för innovationer.

För området astronomi, astrofysik och kosmologi konstaterar panelen att detta är bland de stora fälten inom fysik i Sverige, med högt internationellt anseende och enastående vetenskaplig produktivitet. Panelen pekar på att det svenska deltagandet i European Southern Observatory (ESO) och i European VLBI Network (EVN) utgör en av grunderna för denna framgång. Dess samhälleliga påverkan sträcker sig från skapandet av grundläggande kunskap till utmärkt utbildning och vetenskapsuppsökande program.

När det gäller acceleratorfysik och instrumentering, så lyfter panelen fram att svensk innovation inom acceleratorområdet haft en enorm inverkan på alla större synkrotronbaserade ljuskällor runt om i världen. Utöver MAX IV har Sverige också blivit hemvist för European Spallation Source (ESS). Panelen framhåller även att svenska lärosäten gör viktiga insatser inom instrumenteringsområdena.

För kategorin annan fysik konstaterar panelen att tvärvetenskaplig forskning verkar frodas över hela Sverige och att det inlämnade materialet gett dem en mycket positiv ögonblicksbild av aktiviteten inom området. Baserat på vad de sett i publikationerna och fallstudierna menar panelen att den största potentialen att möta många av de största vetenskapliga och samhälleliga utmaningarna i dag finns inom denna underdisciplin.

Panelen påpekar att vetenskapliga och samhälleliga effekter av många forskningsområden ofta ses först efter ett eller två decennier, men betonar även vikten av grundläggande och nyfikenhetsdriven forskning. Panelen diskuterar också hur forskningens kvalitet och betydelse för det omgivande samhället kan stärkas ytterligare. De pekar på framgångsfaktorer som rör exempelvis internationella samarbeten, forskningsfinansiering och former för kunskapsöverföring till industrin. Med rätt förutsättningar kan fysikforskningen i Sverige fortsatt bidra med kunskap och lösningar på de olika utmaningar som mänskligheten möter.

The Swedish Research Council's summary of the panel's report

The research area of physics is one of the primary recipients of research funding in the natural and engineering sciences in Sweden. Research in physics touches upon fundamental questions about how we view the universe today, but also how we approach societal challenges, such as climate change, or develop new technical solutions, for example communication systems. Much of the scientific progress we have seen over the past century, and which has affected our everyday lives, is closely related to the subject of physics. Advanced experimental techniques play an important role in the leaps taken in our understanding of our physical surroundings. Some of these experimental techniques require significant investments and the building of research infrastructure. These facilities are to a considerable extent used within research in physics, and this has been the means of making significant scientific progress in fields ranging from particle and nuclear physics to materials science.

Against this backdrop, the Swedish Research Council has decided to have the research field of physics evaluated, in accordance with the model for national evaluations of research subjects. The Swedish Research Council developed this model in collaboration with an advisory group including representatives from the Association of Swedish Higher Education Institutions (SUHF) and the Swedish Higher Education Authority (UKÄ). Previously, political science has been evaluated in accordance with this model. Hence, physics is the second subject, and the first within natural and engineering sciences, to be evaluated in accordance with this model. The evaluation model is based on the Government's instruction to the Swedish Research Council, which includes, among other things, the mandate to "evaluate research and assess the research and its scientific quality and significance". The overall purpose of these evaluations is to contribute to strengthening research in Sweden. The evaluation model is designed to assess the quality and impact of research in an international perspective. By highlighting both strengths and weaknesses, the evaluations can form a basis for strengthening research, and relevant actors, universities, as well as funding bodies and the Government, can implement measures.

An independent expert panel with fourteen experts, twelve of whom were recruited internationally and two nationally, carried out the evaluation of the research field of physics. The basis for their evaluation consisted of a selection of publications, selected according to the proportions of physics research in Sweden at the higher education institutions concerned. The higher education institutions were also required to submit case studies describing the societal impact of a selection of their research in physics. In addition to publications and case studies, the panel was provided with bibliometric analysis and descriptive statistics about physics research in Sweden. Furthermore, the panel was supported by 65 international reviewers who have read and assessed the quality of the submitted publications, with the reading assigned based on each reviewer's area of expertise.

The panel concludes that the scientific output is of high quality, and highlights the significant impact of Swedish physics research nationally and internationally.

Regarding societal impact, the panel stresses that several case studies have highlighted the Swedish higher education institutions' strong connection to industry, the education system, and the international research community. Sweden has a broad portfolio of physics research, ranging from fundamental physics via innovation and technology development to applied solutions for industry, with bearings on significant challenges (energy, climate crisis, etc.).

The panel further notes that Sweden is a desirable partner in research collaborations. In this context, the panel particularly highlights the areas of subatomic physics, fusion, space and plasma physics, astronomy, astrophysics, and cosmology. In the panel's assessment, Sweden has a healthy balance in terms of investment in education, technology development, applied scientific research, and basic research.

In addition to these overall assessments, the panel has also separately evaluated the sub-disciplines within physics.

The panel regards the field of subatomic physics as strongly represented in Sweden, and that Sweden has a unique infrastructure for research in this field. They see great potential for both the scientific development and societal impact of this research field. The panel stresses that the quality of the Swedish contributions within subatomic research is excellent, and that Sweden has outstanding collaborations and networks within this field.

For the sub-discipline of atomic and molecular physics and optics, the panel points out that Sweden has a long and robust tradition of research in this field, and believes that Sweden has a competitive advantage here through essential and highly-cited research. On the other hand, it is described as challenging to comment on societal impact over the short time period represented in the data. The panel takes a positive view of the knowledge transfer from laboratories to start-ups.

The panel points out that the area of fusion, plasma, and space physics is relatively small in Sweden, but successful through solid collaborations and international networking. The panel believes this area could have a substantial societal impact related to clean energy production, dynamic space processes, and areas related to the ability to perform space exploration, for example. They further note that Sweden plays a vital role in the international research community, and its collaborations have been fruitful. The panel considers it essential to maintain and strengthen this development.

The panel finds that the field of condensed matter physics has strong representation in Sweden. This research field makes significant contributions to addressing societal challenges, and drives several major technology trends. The panel especially highlights research in innovative new materials, energy production, and storage technology as fields where Sweden is well positioned to play a significant role. A recommendation from the panel, based on what they have seen in several case studies from this field, is for institutions to continue promotion of interdisciplinary research related to condensed matter physics, in particular at the intersections with chemistry, engineering, biology, and computer science, since the panel has found this could provide a breeding ground for innovations.

For the field of astronomy, astrophysics and cosmology, the panel notes that this is a major discipline within physics in Sweden, with a high international reputation and outstanding scientific output. The panel points to the Swedish participation in the European Southern Observatory (ESO), as well as the European VLBI Network (EVN), as the foundations for this success. The societal impact of this field ranges from the creation of basic knowledge to excellent education and science outreach programmes.

In the field of accelerator physics and instrumentation, the panel highlights that Swedish innovations in the area of accelerators has had an enormous impact on all major synchrotron-based light sources globally. In addition to MAX IV, Sweden is also home to the European Spallation Source (ESS), and Swedish universities are making essential contributions in the field of instrumentation.

For the category other physics subjects, the panel concludes that interdisciplinary science is thriving in all parts of Sweden, and that the submitted material gave them a very positive snapshot of the activities in this field. Judging by the publications and case studies, the panel believes that the potential to address many of the significant scientific and societal challenges today exists within this sub-discipline.

The panel points out that, in most research fields, scientific and societal impacts are rarely seen until after one or two decades, but also emphasises the importance of basic, curiosity-driven research. Furthermore, the panel discusses how scientific quality and societal impact may be further improved. They point to success factors related to international collaborations, research funding, and terms of knowledge transfers to the industry, for example. Given the right conditions, physics research in Sweden has every chance of continuously contributing knowledge and potential solutions to the various challenges facing humanity.

1 Introduction by the Swedish Research Council

This introduction, by the Swedish Research Council, gives a national context to the present evaluation, the evaluation model employed, including the selection of research subject, and criteria for the selection HEIs to be included in the evaluation. Supplementary material, such as descriptive statistics, including bibliometrics, and instructions to higher education institutions (HEIs) as well as reviewers, are provided in appendices.

1.1 National quality assurance system

The Government's research policy goal is for Sweden to be among the top research and innovation countries globally, and a leading knowledge nation.[1] Quality assurance of research carried out at HEIs in Sweden is vital to maintain Sweden's position as a successful research nation.

The primary responsibility for quality assurance rests with the HEIs themselves. Consequently, their responsibility is the starting point for the national quality assurance system for which the Swedish Higher Education Authority is responsible. Since 2017, this includes auditing the HEIs' quality assurance of research.[2]

1.2 The Swedish Research Council's evaluation model

The Swedish Research Council has a Government mandate to "evaluate research, and assess its quality and impact" (Förordning (2009:975) med instruktion för Vetenskapsrådet/Ordinance with instructions to the Swedish Research Council, Clause 1:6, (our translation)). In accordance with this mandate, the Swedish Research Council regularly evaluates research in Sweden.

In 2018-2019, the Swedish Research Council developed a model for national evaluations of research subjects and thematic (transdisciplinary) research domains.[3] Formalising the process in a model ensures a predictable format for evaluation. The overall purpose is to contribute to improving the results of Swedish research. This purpose is fulfilled when the Swedish Research Council's evaluations provide input to quality-enhancing measures by the HEIs, the Government, and funding bodies.

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[1] Proposition/Government Bill 2016/17:50 - "Kunskap i samverkan – för samhällets utmaningar och stärkt konkurrenskraft" (PDF). The Swedish Government's website.
[2] Proposition/Government Bill 2020/21:60, - "Forskning, frihet, framtid – kunskap och innovation för Sverige" (PDF), p. 150. The Swedish Government's website.
[3] PM Vetenskapsrådets modell för ämnesvisa och tematiska utvärderingar. Preliminary version 2019-06-19.

Through evaluations conducted in accordance with the model, the Swedish Research Council provides a national picture of Swedish research within a subject area, focusing on the quality and impact of research. This national picture is currently not provided elsewhere in the existing system for national quality assurance of research. The intention is not to use the model to evaluate all research subjects according to a set evaluation cycle. Rather, research subjects are selected based on the Swedish Research Council perceiving a particular interest in conducting an evaluation.[4]

International peer review forms the basis of the evaluation model. The evaluation panels should reflect international experiences of how quality and impact may be improved. The model combines consideration for the HEIs' work input, with the ambition of identifying possible areas for development of the research.

Initially, a preliminary version of the model was developed in collaboration with an advisory group including representatives of HEIs as well as from the Swedish Higher Education Authority. Subsequently, a revised model was tested in a pilot evaluation, on research in political science. The principles for the implementation of the pilot evaluation are to be found in the report ”Quality and impact of research in political science in Sweden”, Swedish Research Council 2021. After this pilot evaluation, lessons learnt and opinions on the model were gathered from several groups: from the panel that wrote the report, from the HEIs included in the pilot, from the original advisory group, and from within the Swedish Research Council. Following this process, the evaluation model was subject to minor revisions on a number of points.[5]

1.3 The present evaluation

The present evaluation is the second evaluation employing the evaluation model. It was launched in 2021, and is dedicated to the research subject of physics. This evaluation has now resulted in the present evaluation report.

The field of physics is one of the major funding recipients within natural and engineering sciences in Sweden. It has impacted both fundamental questions of how we view the universe today, as well as how we approach societal issues, such as climate change, or develop new technological solutions, such as communication systems. Thus, much of the scientific progress we have seen over the last hundred years that has affected our everyday lives is closely connected to physics. The leaps we have taken in our understanding of our surrounding world relies heavily on the use of advanced experimental techniques. Some of these techniques requires large investments and the formation of research infrastructures. The physics community is a strong user of such facilities, and this has been a means to make significant scientific progress,

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[4] PM Process för framtagande av forskningsämnen och teman för utvärdering, Vetenskapsrådet 2020-11-26.

[5] The Swedish Research Council's model for national research evaluations by subject, Reg.nr. 3.2-2018-00113.

in fields ranging from particle and nuclear physics to material science. Based on these premises, the field of physics was chosen for the first national review in the field of natural and engineering sciences.

1.4 The higher education institutions (HEIs)

Twelve HEIs were selected to represent research in physics in Sweden for this evaluation. The selected universities are Lund University (LU), Uppsala University (UU), Stockholm University (SU), Chalmers University of Technology (CTH), KTH Royal Institute of Technology (KTH), Linköping University (LiU), Umeå University (UmU), University of Gothenburg (GU), Karlstad University (KAU), Linnaeus University (LnU), Luleå University of Technology (LTU), and Mid Sweden University (MSU). Together, these twelve HEIs represent 96.8 per cent of all personnel involved in physics and 100 per cent of all PhD students in physics in Sweden. These HEIs also represent 99.3 per cent of all publications between 2016-2020, according to Swepub, and 99.8 per cent of all funded research in physics in Sweden.[6]

1.5 The Evaluation Panel

The Evaluation Panel for the present evaluation consisted of 14 experts from different countries, of which one served as chair and one as vice chair. Eight of the experts were recruited as subject experts with a focus on assessing scientific quality. In addition to these subject experts, the Panel included five experts for the assessment of societal impact, with relevant knowledge of both the international and the national context. The purpose of having a diverse international Panel was to provide a picture of Swedish research from an international perspective. The list of Evaluation Panel members is shown in Table 1 in Appendix 3.1.

The Panel members read and assessed publications and case studies. The assessment of scientific quality was largely based on the reviews done by the external reviewers. The Panel members participated in preparatory meetings, in which the evaluation design was elaborated (together with the Swedish Research Council), and assessment criteria of the scientific quality and the societal impact were discussed.

The Panel members also participated in pre-meetings divided into sub-disciplines within the research subject of physics, and also participated in a three-day meeting with the entire Panel in Stockholm on 28-30 November 2022. During and after the three-day meeting in Stockholm, all members of the Panel participated in the writing of the report, which constitutes Chapter 2 of this report.

The Chair and the Vice Chair participated in planning meetings with the Swedish Research Council, and were responsible for coordinating and

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[6] See Section 3.3 Descriptive statistics in the appendices to this report.

delegation of the work during the preparations and the drafting of the evaluation report. Furthermore, the Chair and Vice Chair were responsible for finalising the evaluation report. The methods used for the assessment are described in Appendix 3.2.

2 The Evaluation Panel's report

2.1 Executive summary

The Panel was charged by the Swedish Research Council to provide an assessment of and knowledge about the scientific quality and societal impact of physics research in Sweden, at national level, from an international perspective. The focus included two components: the scientific output (publications) and the societal impact of research (case studies).

The design of the evaluation was based on a prior model developed by the Swedish Research Council. The material provided to the Panel consisted of (1) a selection of publications reviewed by external referees as well as Panel members, and (2) case studies chosen by the participating HEIs, showing good examples of societal impact. Although the amount of information was substantial, it does of course not encompass the entire physics activities in Sweden. As a result, the opinion of the Panel, as outlined in this document, should be understood within the perspective of the limitations described above.

Regarding the quality of the scientific output (publications), and based on the material we received, our key observations were that these publications are of high quality and demonstrate the high impact of Swedish physics research nationally and internationally. Regarding the societal impact, several of the case studies highlighted the strong connection of the Swedish HEIs to industry, the research and university education system, and the international community. There is a broad portfolio of physics research in Sweden that ranges from fundamental physics to innovation and technology development, to practical solutions for industry and major challenges (energy, climate crisis), while training the next generation of research educators, scientists, and engineers. Particular areas of strength with strong scientific and societal impact identified by the Panel are accelerator development and accelerator-based science facilities (notably MAX IV and ESS, infrastructures located in Sweden with international reach), concepts for advanced materials, energy storage and generation, optical physics, advances in personalised medicine and high-precision healthcare. Sweden is hence well-positioned with its focus on renewable energy sources and renewable innovative, functionalised materials to be a powerhouse in the circular economy.

Swedish HEIs are interconnected on a national scale and in certain areas cooperate closely with major industry partners and/or create spin-off companies. In all sub-disciplines, Sweden is a sought-after and impactful partner, perhaps most notably in subatomic physics (CERN), fusion, space and plasma physics (ITER), astronomy, astrophysics and cosmology (international multi-messenger facilities), where the scale of the required infrastructure is beyond what any single nation can afford. Astronomy and astrophysics are leading fields of physics in Sweden, as demonstrated by the publication impact and international visibility. Scientists of these fields make excellent use of and contribute to international facilities, such as the European Southern Observatory (ESO) and IceCube. Some HEIs also established strong international industrial partnerships by providing know-how and expertise that offer solutions for important immediate and longer-term challenges.

In conclusion, we unanimously recommend the Swedish Research Council to continue its full support for physics research in Sweden to strengthen the global community by gaining knowledge and finding solutions for the various challenges facing humanity.

2.2 Introduction to scientific quality and societal impact of physics

As a backdrop for our assessment of physics research in Sweden, we next provide a succinct description of global challenges that our society faces, as well as a (partial) list of technology trends that are either strongly pursued world-wide or are emerging. Where possible, we then link the publications and case studies provided to these challenges and trends, as a guide for its impact and relevance.

2.2.1 Challenges in society

Modern society faces grand challenges recognised by, e.g., the United Nations, the European Union and specific countries. These are described in terms of climate change, energy shortage, shortage of clean water, rapidly increasing population, increased political polarisation and war, poverty, and uneven distribution of wealth and healthcare. Technology and scientific advances could potentially help to overcome some of the challenges, while others need to be addressed by political means or a combination of these. It is very likely that advances in physics research could, in part, address some of the challenges linked to climate change, energy supply, clean water, medicine, and healthcare, to mention some. Sweden cannot address all challenges alone, but should strike a healthy balance between investments in education, technology development, applied scientific research and basic research.

2.2.2 Technology trends

2.2.2.1 Digital technology trends

For some years, artificial intelligence (AI) has been named as the most transformative technology today, with a great potential to continue transforming society. Several spectacular applications of AI have been published, where super-human performance has been demonstrated in specific use cases, such as image recognition, e.g., AI enabled diagnostics in healthcare. AI in combination with development of robotics process automation (RPA) software has been developed to process, manipulate data and answer text-based intelligent queries as exemplified by the ChatGPT from Open AI (https://openai.com/blog/chatgpt/). The vision of autonomous vehicles has been one driving factor behind the development of computer vision applications to inform decision-making and reasoning. However, many of more impressive examples were initially aimed at demonstrating super-human performance in playing complex strategy games. Application of virtual and augmented reality (VR/AR) has also reached a level of technical readiness that allows for the technology to be applied in many areas, such as remote training, augmented experience in performing arts, and the retail industry. In combination with developments in robotics, advanced remote surgery has become possible. The internet of things (IoT) and 5G technology will allow fast communication and exchange of information between connected devices in our homes or cities.

2.2.2.2 Renewable energy technology trends

The renewable energy technology trends have mainly been driven by the environmental sustainability aspect to find new renewable sources. Large efforts and initiatives within transportation and heating have been made, and the following trends are developing strongly:

- Development of advanced photovoltaics (PV) systems with research in new materials to make solar panels more efficient and environmentally friendly, and devising technologies to concentrate solar power using mirrors and lenses
- Moving away from the traditional lithium-ion batteries toward innovative materials and battery chemistries that offer reduced environmental impact, greater stability, density, and shelf life
- Developing storage solutions that store intermittent renewable energy efficiently and also scale it up to power large geographical areas
- Transitioning from centralised energy storage to a more flexible and portable distributed form of energy storage
- Developing advanced materials, such as 2D materials, to decrease energy consumption in devices
- Use of AI, big data and cloud computing to optimise energy grid performance and utilisation
- Hydro power, from hydroelectrical dams to ocean-based energy harnessed from tides, currents, and waves. Ocean thermal energy conversion.
- Offshore wind turbines
- Alternative source of energy provided by plasma physics

2.2.2.3 Trends in healthcare and medical research

Several trends in health care and medical research have strong connections to the development in physics, where remote healthcare and personalised care are two central trends.

Remote healthcare, where utilisation of AI, robotics, VR/AR and chatbots can contribute to creating the virtual hospital, focuses on deploying machine learning and AI in general to combine data from X-ray, CT and MRI scans with medical records and genomics data to expedite diagnosis. Virtual reality (VR) headsets are used to train doctors and surgeons, allowing them to get intimately acquainted with the workings of the human body without putting patients at risk, or requiring a supply of medical cadavers.

Biomaterials, microfluidics and nanostructures are being developed for monitoring patients, and physiological parameters with wearable devices to assist with personalised health solutions. In addition, it will be critical to provide access to affordable medical diagnostic systems that are mobile and capable of operating in harsh environments for rural areas or areas that lack modern infrastructure and hospitals, as well as affordable medicine.

2.2.2.4 Trends in clean water supply

Clean water as a vital resource for life is under significant threat. The trends in clean water supply with implication on physics focus on new materials and technology used in different parts of the supply chain. To mention some important trends, new efficient purification methods such as nanofiltration membranes are under development, and can be designed to remove specific pollutants while allowing important nutrients to pass through. Reduction in water consumption can be achieved through drip irrigation that could substantially reduce agricultural water demand. Also, older techniques are developed further for improving water availability and safety with small, decentralised distillation units.

2.2.2.5 Fast emerging technologies

Quantum computing: Quantum physics is nowadays reaching technology level and is commonly listed as the next disruptive technology. Big tech companies, start-up companies as well as academic researchers are developing both hardware and software for quantum computing. However, a full breakthrough in terms of a real-world example showing quantum supremacy remains to be seen.

3D printing: 3D printing is already established as a technology for prototyping in many industries. Biomedical applications are an expanding field. 3D printing of functional human tissue and organs is an exciting new field that has the potential to revolutionise discovery and development of new medicines.

Digital access: Even though remote working is not a new technology, the concept evolved rapidly during the COVID-19 pandemic. The unprecedented rapid uptake of digital tools to reduce human interaction during the COVID-19 pandemic has implications that go beyond the office place. It has had implications for higher education, transportation and distribution systems, remote healthcare and many other tasks.

Energy: In the area of solar cells, efficient and stable perovskite cells are becoming mature, and spray-on photo-voltaic materials are being developed. For the latter, thin films are often deposited on plastic substrates to achieve flexibility and conformal mechanical properties, but an innovative wood-based material called nanocellulose is emerging as a promising candidate for a sustainable substrate for organic solar cells. In December 2022, a breakthrough in fusion energy was announced. An experiment at the Lawrence Livermore National Laboratory in California showed that more energy was produced than the energy needed for the laser that created the fusion process. This achievement represents a major step forward for this technology in the long-standing quest for an energy source that has the potential to provide the world with “unlimited” energy. In addition, stellarator-based magnetic fusion systems have demonstrated sustained burns over more than eight minutes, producing GJ-level energy outputs.

2.3 Swedish universities and innovation climate

There are a total of 16 universities in Sweden that are state-owned and have full rights to carry out higher education and research education. In addition, there are two privately owned universities with the same rights as the other universities and twelve state-owned university colleges that have rights to carry out research education in a smaller range of areas.

HEIs in Sweden have the three assignments of 1) carrying out higher education, 2) conducting research and 3) collaborative tasks or science outreach. The third assignment was established by law in 1977. Younger universities and university colleges often do more applied research also in collaboration with industry. Over the past ten years, the universities have been viewed more and more as growth engines in their closest regional environment. Another focus lies on research innovations and the number of spin-off companies founded in the research environment.

Sweden has an overall very good innovative climate, and a habit of creating world brands / global companies such as VOLVO, ABB, Spotify, Ericsson, IKEA and Essity. Sweden also has a very strong start-up scene. Stockholm’s tech start-up scene, for example, is renowned worldwide, ranking third after Switzerland and USA in the Global Innovation Index 2022. The innovative culture comes from several streams, with a high entrepreneurial research tradition as well as attention to trends and a high level of leadership being some of the explanatory factors.

2.4 Overview of publications and case studies

For this evaluation, the included Swedish HEIs submitted, in total, 400 publications for the peer review. The HEIs selected the publications from a list of publications drawn by the Swedish Research Council from the Swedish publication database Swepub. The 400 submitted publications correspond to approximately 2 per cent of all Swedish physics publications from the time period 20162020. At the request of the Panel, the Swedish Research Council matched these publications against data in WoS and produced citation data aggregated by subject code (SCB/Statistics Sweden at five-digit level). For most of these publications, the classification codes supplied by the HEIs have been used. A few codes have been manually changed[7], and when code was missing, a classification has been added.

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[7] Mostly papers classified as ’other physics’ that, after manual review, clearly belong to one of the other categories.

Of the 400 submitted, we are able to match 396 with entries in WoS (in the database at the Swedish Research Council). Of the 400 publications, the same two publications had been submitted by two universities, but here these two publications are only counted once (in total 398 unique publications). A few publications are not classified as article or review, but the same field-normalisation is used for all records, i.e. all publications are normalised as if they were an article or review. Unlike all other statistics, all these are integer counted. This implies that publications with many co-authors and international collaboration will have a much higher weight in the citation statistics (mean citation rate and share of highly-cited publications).

On average, and across areas, the submitted publications show very high citation numbers, which indicates high impact within science. However, 10306 (accelerator physics and instrumentation) only shows modest citation impact, but the number of publications (eleven) is modest. Astronomy, astrophysics and cosmology (10305) shows the highest citation numbers, where 32 per cent of the 53 publications are among the one per cent most cited publications within their field and year. Most publications, 151, are in condensed matter physics (10304), followed by 58 in atomic and molecular physics and optics (10302). 55 publications are in subatomic physics (10301) and 51 in other physics topics (10399). In the area of fusion, plasma and space physics (10303) fifteen publications are found.

Case studies formed the basis for the Panel's assessment of societal impact. These were compiled by the HEIs, and described cases where research within the evaluated area has made a difference to society. Each HEI submitted a number of such case studies, describing how the research conducted at that particular HEI has had an impact on society beyond the research community.

The case studies were discussed by the Panel during five of the remote meetings as well as during the in-person meeting.

Where suitable, the Panel relied on its own expertise and experience in national and international physics communities to provide a calibration of the material provided.

We next present our assessments of the various sub-disciplines that are part of this study, based on the selected publications submitted and external reviews thereof, and the case studies submitted by the HEIs.

2.5 Sub-discipline 10301 subatomic physics

2.5.1 Overall view for sub-discipline 10301 subatomic physics

Sweden is well represented in particle and astroparticle physics, as well as in nuclear physics. Swedish scientists take part in very large collaborations as well as in smaller research groups, and contribute both experimental and theoretical work. Apart from involvement in CERN, the world’s largest particle physics laboratory, and other international endeavors such as the IceCube facility in

Antarctica, the country can also be proud of a number of unique research infrastructures at international and national levels. The high number of publications in the field, and their mean citation rate that is well above average, reflect a productive research environment.

The largest contributions to the sub-discipline come from the Uppsala, Stockholm and Lund Universities. This is also reflected in the number of publications they submitted for this report. Two institutions also contribute in the areas of experimental and theoretical particle physics – the KTH Royal Institute of Technology, and Chalmers University of Technology.

There are a number of large international collaborations in which the institutions above are significantly involved. For example, they participate in activities at CERN, such as in the large experiments ATLAS, ALICE and LHCb at the LHC, or the ISOLDE nuclear physics facility. They also collaborate in non-accelerator experiments across the globe, such as XENON1T or IceCube, in the fields of dark matter and neutrino physics.

Generally speaking, the above-mentioned institutions all contribute to highly relevant and timely research topics, and are well-represented in international collaborations in the field.

The societal impact from Sweden’s involvement in the field can also be judged to be excellent, and ranges from communicating fascinating insights into fundamental physics to spin-offs in industrial and medical applications.

2.5.2 Scientific quality of sub-discipline 10301 subatomic pysics

The five institutions that have submitted publications for review are the Uppsala, Lund, Stockholm, and Chalmers Universities, as well as the KTH Royal Institute of Technology, with the number of publications per institution ranging from 22 to 3. We are aware that these publications may not represent the full spectrum of work performed in these institutions.

Based on the publications and bibliometric information provided, it is clear that, overall, the research work performed is of very high quality, with an average grade of 3.2 (with 4.0 being the highest grade). Of the 55 publications submitted in total, more than a quarter achieved the highest grading of 4.0. About half of them achieved a grading of at least 3.0. This attests that publications with these gradings are internationally excellent in terms of originality, significance and rigour, with some of them even of world-leading quality.

Stockholm University has three publications with the highest grade of 4.0 given by all reviewers, out of nine publications submitted in total. For Uppsala University, this number is five out of 22.

Lund University is another example of an institution where high-quality research with an excellent reach is performed. This is also demonstrated by two publications achieving the highest grade of 4.0, out of a total of 13.

Chalmers and KTH also do very well, even though they submitted a smaller number of publications compared to the three institutions mentioned previously. For Chalmers, one out of the three publications presented obtained the highest grade. KTH, as a member of the ATLAS experiment, presented one publication that received an average grade of 3.5, with a total number of eight publications submitted.

We would like to draw attention to two publications that are excellent examples of outstanding work in different areas of the sub-discipline, and in collaborations of different sizes. The first one is “Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert”, published in Science (361, 147–151 (2018), DOI: 10.1126/science.aat2890). Two Swedish universities, Stockholm and Uppsala, participate with a number of collaborators each in the IceCube experiment, located near the South Pole, which gives them the critical mass to make an important contribution among the more than 300 participating researchers. The publication, at the border between particle physics and astrophysics, marked an important finding regarding the exploration of the origin of cosmic rays, which was also inspirational to the interested general public.

The second publication we would like to highlight is a theoretical work, developed by a small number of physicists (“General Relativity from Scattering Amplitudes”, Phys. Rev. Lett. 121, 171601 (2018), DOI: https://doi.org/10.1103/PhysRevLett.121.171601), including only one Swedish researcher from Uppsala. It is nevertheless a highly original paper that shows that scattering amplitude methods from particle physics can be used to derive classical results in gravity. This has implications for the computation of gravitational waves arising from binary mergers, a problem that is clearly very important, taking into account recent observations of gravitational waves. Many more excellent publications, which appeared in high-impact journals, attest to the very good quality of the Swedish contributions to research in this sub-discipline, as well as to excellent collaboration networks.

Most of the submitted publications contain original scientific work, but there are also a few highly-cited review articles, some of which explicitly reflect the prominent standing and broad overview of their respective authors, and the reputation of their institutions.

2.5.3 Societal impact of sub-discipline 10301 subatomic physics

The societal impact in this discipline was estimated to be consistently in the highest category, with only few exceptions. All the universities inside the discipline provided high-quality case studies with high impact. Work in the domain is collaborative and based on shared research infrastructures that typically require large funding (multi-billion Euro scale for a next generation collider) with long-term (decades) discovery expectations. In addition, the discipline is locally supported by universities in patent processes, getting help in industrial cooperations, and public engagement activities.

The five case studies that were submitted contained a good variety of different ways to create societal impact from proving essential, high-quality scientific work for the global research discipline, publicity surge from the Higgs boson discovery and its beneficial impact for the image and interest of fundamental science in the general public. A good example of a high societal impact case study is from Stockholm University “Explaining the origin of mass by discovering the Higgs boson”. This had a world-wide reach, to all classes of society – global and national reach through the awarding of the Nobel Prize in 2012. Indeed, the discovery of the Higgs boson was of great importance, not only for the scientific community, but also for civil society as a whole, covered by many newspapers and TV stations world-wide. It inspired a new generation of students and even led to changes in physics textbooks from secondary school to university.

Through knowledge sharing from CERN to companies, new business domains have been supported, e.g., in the domain of sustainable energy production with patent creation. It should be noted that CERN is also a Swedish infrastructure, leveraging large and long-term stable funding from all its member states, while contributing to science, technology, and education at multiple levels.

2.6 Sub-discipline 10302 atom and molecular physics and optics

2.6.1 Overall view for 10302 atom and molecular physics and optics

Atomic, molecular and optical physics is described internationally as a discipline that has its central focus in fundamental research into atoms, simple molecules mostly in the gas phase, electrons and light, and their interactions. It was defined in the first half of the 20th century, and the division at the American Physical Society focusing on the topic was founded in 1943. This discipline plays an enabling role underlying many areas of science through the development of methods for the control and manipulation of atoms, molecules, charged particles and light, through precision measurements and calculations of their properties, and through the invention of new ways to generate light with specific properties.

There is a long and strong tradition in the field of atom and molecular physics and optics in Sweden. While this cannot be appreciated directly from the totality of the documents we received (since the universities were limited in the amount of material they could send), the Panel is aware of the dynamism of the field in several of the universities engaged in this review.

The international status of this field in Sweden is certainly competitive, as shown in Section 3.4 (bibliometric statistics for Sweden, by research areas), Figure 1, where the number of publications is in the middle of the scale, but more importantly, the mean citation rate is among the highest of all the relevant fields of physics represented in this figure (the citation rates are for publications between 2016 to 2020).

The Panel received six case studies related to the field of atom and molecular physics and optics (although not all of them could be directly characterised as belonging to such a field). The quality of the case studies in terms of description was very diverse, probably because of a misinterpretation of some of the criteria. For this sub-discipline case, several studies were also incorrectly submitted, further reducing the overall real number of case studies. This precluded us from carrying out an in-depth assessment and comparison across cases.

2.6.2 Scientific quality of 10302 atom and molecular physics and optics

In the field of atom, molecular and optical physics, 79 publications were received. About 15 per cent of the documents were submitted mistakenly to this division, and were moved by the Panel to a more appropriate sub-discipline. After this reassignment, 59 documents were left. All of these publications were reviewed by external reviewers, and upon review by the Panel, only very few of the overall grades provided by the reviewers were altered by us. The average score (on a scale between 1.0 to 4.0) is 3.2, which demonstrates the high quality of the research in general. Of these 59 publications, 24 per cent (14 papers) were ranked to be of the top quality (i.e., 4 stars ranking). These publications covered a very broad range of topics in this field, from very fundamental work all the way to more applied research, demonstrating the high quality of work in Sweden. A total of five Swedish universities were represented in this group of top-quality publications. In addition, 27 publications were ranked as high-quality (grades between 3.0 to 3.7), representing, again, a very broad range of activities. It appears that most of the works in these two categories are published in high-ranked journals over average impact factor around 15, with a broad audience, showing the originality and significance of the research.

We have to underline that the different universities contributed very differently to this sub-discipline, with more than 19 publications from Lund University, and ten publications from Stockholm University. Equal contributions with about five publications each were provided by Linköping University, Uppsala University, KTH Royal Institute of Technology, Umeå University, three for University of Gothenburg and Chalmers University of Technology and one for Mid Sweden University. As no constraints were given to the universities on how to choose the publications, this dissimilar distribution among different institutions only indicates how strong the universities feel they are in the sub-discipline. Namely, that those institutions that contributed most of the publications to this section are – most likely – the strongest institutions in this specific field.

Among the three different areas of this sub-discipline, namely atomic, molecular and optical physics, the last is by far the dominant one. Another interesting feature of the data set provided is the almost total lack of theoretical publications in the sub-discipline. We believe that both these observations are not an authentic representation of reality, but are simply a bias due to the samples provided.

In the following, we present three specific case studies in atomic, molecular and optical physics. These are just examples, based on the personal taste of the reviewers, and the choice of these by no means implies that the other publications were not excellent.

There are only a few examples of traditional atomic physics, but with some abstraction, we can consider the work from Chalmers University of Technology (“Non-exponential decay of a giant artificial atom”, Nat. Phys. 15, 1123–1127 (2019), DOI: 10.1038/s41567-019-0605-6) as part of this sub-field, where the authors could demonstrate that superconducting qubits can be strongly coupled to surface acoustic waves, such that the giant atom regime can be reached with significant internal time delays, giving rise to non-Markovian dynamics. Starting from this work, it is expected that new features of giant atom physics will be discovered in the future. This work was published in Nature Physics.

In the field of molecular physics, we point to the work from Stockholm University (“Rotationally Cold OH- Ions in the Cryogenic Electrostatic Ion-Beam Storage Ring DESIREE”, Phys. Rev. Lett. 119, 073001 (2017), DOI: 10.1103/PhysRevLett.119.073001), where major investments were made in order to build a unique cryogenic storage ring device (DESIREE) that allows for the storage of fast molecular ion beams. Such a device allows for long time observations (minutes to hours!) of internal molecular dynamics. Its specific configuration also allows for study, at the level of a single molecule, of the interaction between molecular and atomic ions/anions. This work was published in Physical Review Letters.

In the field of optical physics, we highlight the work led by Lund University in collaboration with Stockholm University (“Photoionization in the time and frequency domain, Science 17, 358, 893-896 (2017), DOI: 10.1126/science.aao7043”). This work studied the interaction of ultra-short light pulses of attosecond duration in the extreme ultraviolet spectral range to excite atoms. The lack of spectral resolution due to the use of short light pulses has raised issues in the interpretation of the experimental results and the comparison with theoretical calculations. Here, the authors employed an interferometric technique, combining high temporal and spectral resolution, and obtained excellent agreement with theoretical calculations, thereby solving a methodological puzzle.

2.6.3 Societal impact of 10302 atom and molecular physics and optics

Of these six cases, two case studies were deemed of high impact, because they highlighted how new companies and technologies can be created starting from university research. As is usual in scientific research, it is difficult to estimate the actual impact over the short period of time relevant to our evaluation, but it is on the mind of the scientists: When the opportunity arises, the knowledge developed in the laboratories is transferred to start-up companies. In some cases, the application can be quite unexpected, as is usual when the starting point of the research is fundamental.

A good example is the Lund University case study “Advanced laser-based imaging diagnostics using coded light”, related to the information coding in light. This work has some fundamental aspects (as recognised by a series of academic grants, including the very competitive ERC grants), but also includes cooperation with industry, and is already commercialised today. More opportunities are arising, and additional applications are envisaged in fields such as large-scale waste sorting utilising optical technologies.

2.7 Sub-discipline 10303 fusion, plasma and space physics

2.7.1 Overall view for sub-discipline 10303 fusion, plasma and space physics

The discipline of fusion, plasma and space physics is strongly collaborative and international in Sweden. Especially in fusion and plasma physics, equipment and experiments are large and expensive, and thus achievable only by extensive collaboration within a large international consortium. Theoretical research is in many cases related to practical experiments and instrumental development. The overall infrastructure consists of the Swedish Research Unit (SRU), the EUROfusion consortium, the European ITER procurement agency Fusion for Energy (F4E) and the ITER Organisation (IO). The current members of the SRU are KTH Royal Institute of Technology, Uppsala University, Chalmers University of Technology, Lund University and RISE. Space physics is typically related to satellite exploration and measurements on in-situ data, but not so heavily dependent on instrumental techniques as fusion physics, for example.

The research, as shown by the publications and case studies, is highly relevant, as the topic is connected to the domains where the society is searching for solutions, such as clean energy production, dynamic space processes and domains that are related to capabilities of performing space exploration. Sweden plays a vibrant role in the international community in this area. In this sub-discipline, we were able to evaluate 15 publications and three case studies that showed solid quality of research performance, half of them were estimated internationally significant or leading, as judged by international reviews.

The case studies demonstrated significant impact of Swedish research in the area of numerical simulations that model the long-term endurance of fusion reactors operating with plasmas at high temperature plasma. The highlighted contributions included submissions from KTH Royal Institute of Technology and Chalmers University of Technology.
Sweden’s collaborative efforts have paid dividends in this sub-discipline and, given the potential societal impact that fusion and plasma physics have, it is important to sustain and enhance this as we move forward.

2.7.2 Scientific quality of sub-discipline 10303 fusion, plasma and space physics

There are four key institutions in Sweden that carry out research and teaching in this area: Chalmers University of Technology, KTH Royal Institute of Technology, Umeå University and Uppsala University. Most of the publications (11/15) are from Chalmers University of Technology (5), KTH Royal Institute of Technology(6), Umeå University (2) and Uppsala University (2). From the material received in the present evaluation, including the small number of publications (15) and case studies (3), it was not possible to provide a comprehensive analysis. We do note that the work at KTH Royal Institute of Technology (see below) has had a very significant international impact on the magnetic fusion community.

We evaluate the overall scientific quality of this sub-discipline as 3.0 star (average 2.7 of the 15 published publications as evaluated by international reviewers). The research is internationally good/excellent in terms of significance, originality and rigour. Due to the small number of publications and case studies, it is not possible to provide more detailed statistics or evaluation within the topics.

The mean citation rate is lower than of other sub-disciplines in this evaluation, and 13 per cent out of 15 (2/15) publications are among the top 10 per cent cited publications in their field. However, these are in general on a good level, showing the relevance of the research.

We highlight two example publications which received highest-level scores by the reviewers:

The first publication is on "Efficient generation of energetic ions in multi-ion plasmas by radio-frequency heating" (Nat. Phys. 13, 973–978 (2017), DOI: https://doi.org/10.1038/nphys4167). The reviewers commented on this work as follows: "The way of generating energetic ions in plasmas by RF heating of very few minority species is of outstanding novelty and importance not only for fusion but also astrophysical plasmas", and "This experimental work is an important point of reference for MCF, demonstrating efficient plasma heating with multi-ion plasma. The mechanism is also relatively general of plasma and could find applications in astrophysics".

The second publication is on "Analytical expressions for thermophysical properties of solid and liquid tungsten relevant for fusion applications", Nucl. Mater. Energy 13, 42-57 (2017), DOI: https://doi.org/10.1016/j.nme.2017.08.002). Commenting on this work, the reviewers wrote: "Tungsten is the most important wall material in present day fusion experiments. The paper presents an exceptional, significant and important (because useful) data source for its thermophysical properties" and "This article is a review of published data on tungsten and uses this data for empirical analytical expressions of its properties in an area of temperature relevant for MCF research. It is an important point of reference for the field, on which model can be based".

2.7.3 Societal impact of sub-discipline 10303 fusion, plasma and space physics

We perceive a high societal impact from the sub-discipline. As an example, the KTH Royal Institute of Technology case study from 2011 described a significant improvement in the fusion reactor wall material, which led to a proposed change of material from carbon to beryllium or tungsten. The modelling of the wall reactions enabled a selection of wall materials in plasma reactors all over the world. The progress towards a working fusion energy production system was notable, even applaudable.

The modelling effort of this case study resulted in the development of state-of-the-art numerical tools that were fundamental in creating the scientific and societal impact. The validation of the models ensured confidence in the code predictions.

Not only is there an immediate societal impact today, but there is also a tremendous potential for future impact if fusion technology becomes used in energy production, which will affect our entire planet. As discussed in Sections 2.2.1 (climate/energy crisis) and 2.2.2 (emerging technology trends), fusion is seen as a potential solution and has recently seen successes (ignition at LLNL) that merit further attention from the SRC. Equally, space physics research will help to understand the mechanisms and influence of the space plasma and extreme events in the near vicinity of the Earth, and help to improve resiliency against the extreme events on the surface of the Earth.

2.8 Sub-discipline 10304 condensed matter physics

2.8.1 Overall view for sub-discipline 10304 condensed matter physics

According to the material provided by the HEIs, the scientific research in condensed matter physics is on average of very high quality and competitive with international research conducted world-wide. Experimental and applied sciences are dominant in the publications selected by the institutions, and focus on electronic and magnetic phenomena, metallic alloys, organic and inorganic semiconductors, low-dimension materials and nanostructures, which are very relevant areas for innovative technology transfer. The impact on society results in close collaborations between academia and private companies, leading to technology transfer, spin-off companies supported by institutions' incubators.

The overall set of publications sent and assigned to condensed matter physics represents a significant part of all the publications selected by the institutions, indicating that the institutions consider condensed matter physics as a major topic among the sub-disciplines of physics. The assessment of the selected publications reveals that for about 60 per cent of the publications, the quality is internationally excellent in terms originality, significance and rigour, and for about 15 per cent, the quality is that of a world leader.

The impact on society reported in the case studies is dominated by technology transfer through close collaborations with national or international firms. Despite that, the description of the case studies was uneven; about 40 per cent of them were considered to have a high impact on society, either in terms of reach or in terms of significance, but rarely on both aspects.

Certain trends emerge from the review of the top-ranking publications proposed by the universities. It should be noted that physics research at Linköping University is largely dominated by condensed matter and mainly applied to organic and inorganic systems. Chalmers Univeristy of Technology shows very good research in emerging low-dimensional materials, Uppsala University demonstrates strong research potential in correlated electronic systems and magnetism, and KTH Royal Institute of Technology and Lund University have extensive and excellent research expertise in fundamental nanophysics, with semiconductors and metal alloys for various applications. For Stockholm University, the excellence of the publications focuses on theoretical research in condensed matter.

The quality of the case studies in terms of description was very diverse and the criteria were sometimes poorly described and could not be properly assessed. Mid Sweden University was the institution that proposed three case studies, well-described in terms of impact on society and illustrating very well how local ecosystems can be nourished by academic applied research. Chalmers University of Technology proposed a completely different case study, but with a broad global impact on more fundamental research.

2.8.2 Scientific quality of sub-discipline 10304 condensed matter physics

The publications submitted by the institutions are published in high-impact journals (PNAS, Physical Review Letters, ACS Nano, Nano Letters, etc.) and very high-impact journals (Nature, Science), attesting to the overall very good scientific quality of the work achieved. This research is largely dominated by experimental physics. The main topics of the best publications related to fundamental physics concern electronic and magnetic interactions in the solid state, nanostructures, low-dimensional physics, spintronics and more marginally renewable and organic materials (cellulose, lignin). Applied condensed matter physics also makes up an important part of the publications, such as those on sensors, energy production and storage, opto-electronic and electronic devices, and information storage.

Among the outstanding research reported in the publications, two papers on conjugated polymer–polyelectrolyte blends (“Chemical potential–electric double layer coupling in conjugated polymer–polyelectrolyte blends”, Sci. Adv. 3, 12 (2017), DOI: 10.1126/sciadv.aao365), cellulose-based nanogenerators for energy conversion and energy storage (“Cellulose-Based Fully Green Triboelectric Nanogenerators with Output Power Density of 300 W m-2”, Adv. Mater. 32, 2002824 (2020), DOI: 10.1002/adma.202002824) top the list of applied condensed matter physics, attested by comments from reviewers such as: ”Excellent paper combining experimental data and model development” and ” this work is top-level in terms of originality, rigour and significance”.

The discovery of new magnetic phases in quaternary metal alloy or tailored two-dimensional nano-magnetic systems illustrates the excellence of the fundamental research (“Prediction and synthesis of a family of atomic laminate phases with Kagomé-like and in-plane chemical ordering”, Sci. Adv. 3, 7 (2017), DOI: 10.1126/sciadv.1700642), which has promising applications and was commented on very positively by the reviewers: ”Excellent work with broad implication” or ”Experiments at the state-of-the-art”.

Prospective fundamental mechanisms of quantum-dot heat engine pave the way for energy harvesters for quantum technologies (“A quantum-dot heat engine operating close to the thermodynamic efficiency limits”, Nat. Nanotechnol. 13, 920–924 (2018), DOI: https://doi.org/10.1038/s41565-018-0200-5) and received from the reviewers comments such as: ”Impressive experimental realization of a nanoscale heat engine” or ”Remarkable original experimental advance”.

Fundamental research on theoretical predictions in 2D van der Waals heterostructures (“Tunable Phases of Moiré Excitons in van der Waals Heterostructures”, Nano Lett. 20, 12, 8534–8540 (2020), DOI: https://doi.org/10.1021/acs.nanolett. 0c03019) was commented by the reviewers as ”A very useful theoretical paper on a hot topic” and is considered of fundamental importance for the next generation of optoelectronic systems.

An ab initio calculation study revealing the bond strength at the molecular level is able to provide a unique tool for designing systems with targeting electronic and ionic properties (“Distinguishing between chemical bonding and physical binding using electron localization function (ELF)”, J. Phys.: Condens. Matter 32 315502 (2020), DOI: https://doi.org/10.1088/1361-648X/ab7fd8) and has been ”appreciated by the community very much within a short time” as quoted by reviewers.

2.8.3 Societal impact of sub-discipline 10304 condensed matter physics

The impact on society reported by the institutions in the case studies is largely, but not exclusively, dominated by technology transfer from research laboratories to spin-off companies through collaborations with international firms. The presence of international research laboratories of excellence in the field of condensed matter leads to a fertile local ecosystem, conducive to the development of innovative technologies. A very good illustration is the case study reported by Lund University on “Semiconductor nanowires for sustainable energy” with the creation of spin-off companies involving up to a hundred people in R&D, and able to attract international investors.

The significance of the impact on society is well-elaborated in the case studies and relates, for instance, to the challenges facing Sweden and the world in general (see Sections 2.2.1 and 2.2.2) in terms of energy harvesting and storage. Another aspect of the importance of impact concerns training the next generation of researchers and engineers to a high level of competence, which is mentioned in all case studies and is fundamental for Sweden to remain competitive in innovation.

The impact on society in terms of reach is achieved at different levels. Excellent research centres and laboratories support the development of local industry. A good example is the Mid Sweden University institution which combines research on materials development, processing and application, illustrated by three case studies on sensor development, large-scale graphene-based nanomaterials and optical properties of lasers. Such an ecosystem is essential to support the local industrial development in the central region of Sweden.

The impact on society, as shown by the cases, often has a long development period, where research and the development of technology, collaborations, and development of spin-off companies takes up to 20-25 years, as shown in the Linköping University case study on “Novel MAX phase electrical contact materials”. The case study demonstrates both high societal impact and high scientific impact through several publications in high-level journals. The societal impact is created through patents, the creation of a spin-off company Impact Coating AB and the Max-phase contacts favourable in high-temperature contacts, and at the same time lower in price. This has led to a world-wide impact, with an important contribution to increasing the efficiency of high-power electronics used in the production of green energy and, for example, in the designs of electric cars.

A broad impact on society is demonstrated by the study case proposed by Chalmers University of Technology on the graphene flagship (“Graphene and Two-dimensional Materials”), which has generated great scientific impact with a high number of PhD students, publications, citations, an SI standardisation system, and a graduate school. This has facilitated national and international cooperation to develop new applications based on graphene and paved the way for research into low-dimensional materials. At the same time, it has fostered the creation of an ecosystem with innovation projects, involving around 100 national or international enterprises in a wide variety of sectors, such as automotive, battery development, aerospace, and packaging.

The contributing research leading to the impact on society is very diverse, and does not focus on a specific topic or on applied science. Examples include fundamental discoveries and understandings, such as the quantum Hall effect in low-dimensional materials. The exploitation of high-level experimental expertise, such as in electron microscopy; the first-principles computational calculation of defects in stainless steels, or the upscaling development in the growth of materials for large-scale production, illustrate the diversity of the contributing research. The significant impact on society in terms of reach may come from a broad audience or from highly specialised publications. It is worth noting that many of high-ranking publications sent by the institutions are not linked to a case study. Indeed, achieving fundamental research excellence is a prerequisite and an essential building block towards technology transfer, but its exploitation requires time to mature.

In the field of condensed matter physics, the key factors reported in the institutional case studies highlight the importance of cross-disciplines between physics, chemistry and materials engineering, strong connection between industry and academia, consistent IP handling, university incubators, collaborations between universities and/or with large-scale research facilities (CERN, MAX IV).

2.9 Sub-discipline 10305 astronomy, astrophysics and cosmology

2.9.1 Overall view for sub-discipline 10305 astronomy, astrophysics and cosmology

Astronomy and astrophysics are research fields with a very strong heritage in the Swedish physics landscape. Today, astronomy and astrophysics are among the defining fields of physics in Sweden, both in terms of the outstanding quality of observational programmes and theoretical studies and the participation in ground-based and space-based instrumentation and survey programmes. Sweden is an internationally recognised player in the field, as evidenced, for example, by the important role it plays in the European Southern Observatory (ESO), IceCube and other large-scale facilities. The excellent quality of the case studies for societal impact in astronomy and astrophysics are impressively based on this very strong and convincing research profile.

2.9.2 Scientific quality of sub-discipline 10305 astronomy, astrophysics and cosmology

The scientific publications presented appeared in the best journals of the field and with very high impact. The publication record demonstrates that astronomy and astrophysics at Swedish universities produce a large share of outstanding and very good international results. This is strongly supported by a detailed bibliometric analysis. The astronomy and astrophysics research publications are characterised by state-of-the art observations, analysis tools, and numerical and theoretical work.

Examples are the extremely exciting discovery of the shadow of a black hole in the galaxy M 87 with very long baseline interferometry (VLBI) data and the observation of a very early galaxy merger in a z=7.5 galaxy with Atacama Millimetre/Submillimetre (ALMA) observations, indicating the build-up of galaxies in a DM-dominated universe. The image of the black hole shadow and the analysis of this image are seen by a wider science community as breakthrough results in astronomy during the last decade. The consistent participation of the Swedish VLBI group is an important part of this success story. Other highlights are the Gaia data release, with very strong participation by Swedish scientists, and the analysis of magnetic fields of young stars and the direct imaging and characterisation of exoplanets.

The leading astronomy and astrophysics groups in Sweden are located at the universities of Stockholm, Lund, Uppsala, and Chalmers. The research of the Swedish groups is very well-embedded in the international community and makes use of primary international research facilities. Examples are the telescopes and instruments of the ESO, the ALMA Observatory, the VLBI system of telescopes, space missions such as Gaia, and the Ice Cube neutrino experiment. These are all important investments, which pay off by the outstanding science quality of astronomy and astrophysics research in Sweden. In addition, invited review publications in top and very well-cited review journals have been published by Swedish scientists and show the excellent international standing of Sweden in the field of astronomy and astrophysics.

It should be noted that the Swedish research groups have developed a very strong research profile in new and competitive fields: This includes the field of gravitational waves, including multi-messenger astronomy, galaxy and star formation, and exoplanets, just to name a few. The research activities include the development of innovative instrumentation, especially in (sub)millimetre and radio astronomy, optical and infrared astronomy, and transient measurements, and the use of new innovative tools in image analysis and time-dependent data.

2.9.3 Societal impact of sub-discipline 10305 astronomy, astrophysics and cosmology

Astronomy and astrophysics are topics that fill the general public with curiosity and trigger enormous attention. This process includes the general public from children and pupils to adults and their science teachers. The societal impact of this sub-discipline can generally be divided into three areas: public outreach and education activities, the exploitation of cutting-edge instrumentation developments, and the training of excellent master and PhD students, who often enhance the industrial landscape by setting up start-up companies. In this respect, the activities of the Swedish astronomy and astrophysics centres have a high societal impact.

Excellent and high-level illustrations of those three aspects are obtained, which perfectly demonstrate what has been reported on the scientific research in the field. To name only a few: at Chalmers, they excel in science communication and outreach activities based on a comprehensive strategy – including communicating results supported by the Onsala Space Observatory (OSO). This institution also has an impressive technology development programme in radio astronomy, with applications in very varied fields (e.g., quantum technologies), and developed spin-offs from radio astronomy supported by PhD students. Another example is the STIC Code, developed in Stockholm to improve the reliability of space weather forecasts and to increase the lead time for warnings of solar storms that can strongly disturb radio traffic and the electricity grid. Last but not least, Uppsala has a very successful outreach programme, including specific actions on gender equality and participatory science, based on both theory and observations in the fields of stellar and exoplanet physics.

2.10 Sub-discipline 10306 accelerator physics and instrumentation

2.10.1 Overall view for sub-discipline 10306 accelerator physics and instrumentation

Particle accelerators have become indispensable tools in our modern world. They enable scientists to study the nature of matter and energy and resolve very small structures by providing high-energetic particles for collision experiments or for synchrotron radiation generation. These machines, being colliders or synchrotron radiation sources, and their host institutes and universities are drivers for research and development in the rapidly evolving field of accelerator physics.

There is a long and strong tradition in the field of accelerator physics and instrumentation in Sweden, which started as early as the 1960s, with an electron synchrotron for nuclear physics research in Lund, as described in one of the publications available to us ("The saga of MAX IV, the first multi-bend achromat synchrotron light source", Nucl. Instrum. Methods Phys. Res. A 907, 97-104 (2018), DOI: https://doi.org/10.1016/j.nima.2018.03.018).

With the MAX IV facility, the world's first realisation of a fourth-generation light source, and the European Spallation Source (ESS) under construction, Sweden has clearly decided to take a leading position among countries advancing accelerator physics and technology.

It cannot be overstated that the Swedish accelerator community has had tremendous impact on the development of fourth-generation storage ring-based light sources, with the first demonstration of a multi-bend achromat-based magnetic lattice. As already stated above, this breakthrough innovation spurred the upgrade of all synchrotron-based light sources around the world.

Not only is accelerator physics rapidly evolving, but the associated scientific instrumentation is a thriving and rapidly growing field. In fact, instrumentation and accelerators cross-fertilise each other. Based on the publications and case studies we received, we can see that this field is also developing rapidly and aspiring to leading positions in the international scientific community.

Given its importance and impact (scientific and societal) in both the Swedish and international landscape, as well as the quality of the research and training carried out at the Swedish HEIs, we strongly recommend a vigorous continued support of this sub-discipline.

2.10.2 Scientific quality of sub-discipline 10306 accelerator physics and instrumentation

Accelerators are often large and very complex facilities that are very resource-intensive to build and operate. Therefore, many of them are built and operated in a joint effort on national or international level (e.g., ESRF, LHC and EuXFEL). In order to make such large-scale facilities a success, very close collaboration, rapid communication, open exchange, and cooperation at national and international level are required. This has led accelerator physicists to develop their own publication culture, based on the ideal of open sources, with scientific discourse taking place at specific technical conferences and workshops. This fact should be taken into account when evaluating the facilities and their host institutes and universities, especially when it comes to publications related to conventional accelerators that are based on mature concepts and technology.

The research and development of instrumentation, on the other hand, is characterised by extensive and big international collaborations, making it difficult to determine the exact contribution of individual Swedish HEIs. Collaboration reports, roadmaps and review articles are very typical for this field. In general, the big collaborations required to advance the fields are at odds with the competitive publishing style common in other areas of physics.

So far, accelerator physicists have focused their efforts in basically two directions. One direction is the development of the low-emittance and low-energy spread electron guns feeding complex superconducting accelerator structures, which are optimised to maintain excellent injector beam properties (for instance, to feed undulator lines at EuXFEL). The other direction is the development of extremely sophisticated magnet structures for storage rings that manipulate the phase space occupied by the electron beam, thus reducing the emittance in the equilibrium state. The MAX IV storage ring in Lund (Sweden), is an example for such an expertly optimised magnetic structure. Here, we reiterate the groundbreaking development of the multi-bend achromat-based synchrotron, pioneered at MAX IV as an example of the major impact of the accelerator development on the world community: Every synchrotron in Europe, Asia or the USA is either upgraded or being upgraded (multi-billion euro investments).

As a national facility, MAX IV is a joint effort of Swedish universities and research centres. Among the contributing universities, the host Lund University and Uppsala University, with their long experience in accelerator science education and research, are the largest contributors. Unfortunately, we have not received any information (publications or case studies) about accelerator research towards ESS.

The close and long-standing collaboration between Lund and Uppsala Universities in this field paved the way for the success of the MAX IV facility. Swedish accelerator physicists at Lund University have pioneered diffraction-limited storage rings, and are currently actively working to advance accelerator physics by developing new approaches to optimise the radiation properties delivered to users (”Harmonic-cavity stabilization of longitudinal coupled-bunch instabilities with a nonuniform fill”, Phys. Rev. Accel. Beams 23, 074402 (2020), DOI: 10.1103/PhysRevAccelBeams.23.074402). Thus, their research is of great use to all synchrotron radiation users.

Lund University’s extensive and excellent research expertise in accelerator science and technology has ensured its leading role in Sweden. Moreover, it has placed Sweden at the international forefront of accelerator physics and technology. Uppsala University demonstrates strong research in the field of accelerator technology. Stockholm University’s expertise in the field of instrumentation is reflected by its significant role in the ATLAS experiment. For Chalmers University of Technology, the focus of outstanding work is on research in astronomy.

The grading scale and evaluation criteria are the same as in the Research Excellence Framework (REF). The total number of publications in accelerator physics and instrumentation is not high, due to the specific publication culture and large collaborations described above. However, about 25 per cent of the submitted publications were rated four stars, indicating world-leading quality in terms of originality, significance, and rigor. About 42 per cent of the submitted publications were rated three stars, indicating quality that is internationally excellent in originality, significance, and rigor. The average rating for the sub-discipline is three stars, so it can be concluded that the scientific quality of the sub-discipline is quite high.

However, the large number of authors contributing to the collaboration reports and roadmaps makes it difficult to determine the exact contribution of each Swedish HEI. In the field of accelerator physics, there are few publications on ESS, and we look forward to seeing publications in the future, containing details on this important investment as well as scientific discoveries that result from its use.

It is important to note that the Panel recognises that the absence of top 10 per cent (and hence top 1 per cent) in sub-discipline 10306 (see Section 3.4) is not unusual in the area of conventional accelerator physics. Surprisingly, however, neither publications in the field of advanced accelerators, in which several Swedish HEIs are active (most notably Lund University), nor case studies have been provided for this evaluation.

We do note that excellent work is being carried out at Lund University in the area of advanced plasma-based accelerators, but that the Panel did not receive any publications or case studies that relate to this area.

Considering the high quality of the publications we received in the area of instrumentation, even if the total number was not very high, we can conclude that Swedish universities are doing quite well in this area. Along with Lund and Uppsala Universities, Chalmers University of Technology is one of the leading universities in this field.

2.10.3 Societal impact of sub-discipline 10306 accelerator physics and instrumentation

We received a total of five case studies related to accelerator physics and instrumentation to provide examples of the societal impact of this field in Sweden. Accelerator physics is very demanding in terms of instrumentation, requiring specific electronics, vacuum systems, ion-beam optics, radiation protection, and more. It is, in a way, quite a multidisciplinary field that requires knowledge in various sub-fields. Case studies presented by Lund University (”High-Brightness Synchrotron Light Sources”) and UU (”From MAX II to MAX IV”) illustrate nicely the intertwined and mutual influence of the sub-fields. It is often the case that the university laboratories are initially focused on developing very specific instrumentation, such as the case study on neutron detectors reported by Linköping University, that will allow the researchers to develop new experiments, more often to understand the behavior of fundamental aspects of physics. Although it is hard to guess from these initial steps what will be the societal impact, the reports we received demonstrate that the technologies that have been developed have found their way into applications in various fields of technology, such as new techniques for analysing materials, medical devices, specific materials and more. A KTH Royal Institute of Tehnology case study on the development of laboratory X-ray sources, which led to a patent and a spin-off company (“Liquid-metal-jet X-ray sources”), and a Stockholm University case study on the development of a positron emitter irradiation system for radiation therapy and improved treatment delivery verification (“Development of a positron emitter irradiation system for radiotherapy and improved treatment delivery verification”) are examples of this development.

Our impression from the documents we received is that the accelerator/instrumentation community is aware of these opportunities, and we clearly see the reach and significance of this research as far as its impact on society is concerned, even if the specific direction is unclear at the beginning. Of the five case studies we analysed, three were ranked with the best grade A, and two were ranked B.

It is critical to point out that the societal impact of such a field cannot be appreciated only by the documents we received. For example, given the multidisciplinarity of the field, PhD students trained in these topics are very likely to contribute to society (industry) in a large variety of fields.

2.11 Sub-discipline 10399 other physics topics

2.11.1 Overall view for sub-discipline 10399 other physics topics

This sub-discipline “other physics” encompasses topics that are interdisciplinary by nature. In this exercise, this was interpreted by the contributing universities as areas that did not fall easily into one of the other sub-disciplines, and as such led to a highly diverse range of journal paper contributions and case studies. Examples of areas that were included are uses of both experimental and numerical physics-based approaches for health care, medicine discovery and development or advanced biomedicine. Another example from a more fundamental perspective was a range of studies in the area of active matter. The submission comprised 51 publications and 13 case studies for us to consider.

Overall, we were delighted to see a good range of publications in high-impact, respected journals, from both larger and smaller universities. The submission showed a huge diversity in journal type, reflective of the topic of this sub-discipline. In turn, this makes comparison and weighting challenging, but is a marker of the breadth of impact physics has across the sciences. We found ample and compelling evidence of interdisciplinary work at all levels throughout numerous universities, as well as clear indicators of collaborations. As an example, a publication and the related case study submitted by Karlstad University (on “Artificial Intelligence for Sustainable Energy Storage”) was a study involving three universities in Sweden, and one in China. Importantly, we saw that the case studies submitted address societal challenges at the highest level. This included the topics of energy, radiation, nanoscience, and imaging, and the research supported healthcare, life sciences, material sciences, and the environmental sciences; all topics that are discussed in Sections 2.2.1 and 2.2.2 in this document.

2.11.2 Scientific quality of sub-discipline 10399 other physics topics

The health of this discipline was exemplified by the fact that 50 per cent of the submitted journal publications were rated as internationally competitive or leading in terms of significance, rigour and originality. Within this banding of research, we were very pleased to see some exceptional contributions that were very highly cited and acknowledged by external review to be world-leading, “game-changing” results.

We highlight three contributions that received the highest rating from a range of external reviewers as examples, but there were several others of note.

(i) “Fast charge separation in a non-fullerene organic solar cell with a small driving force” (Nat. Energy 1, 16089 (2016), DOI: https://doi.org/10.1038/nenergy.2016.89), submitted by Linköping University. The reviewers noted this to “represent a real breakthrough” with the “solar cell that it presents” opening “an entire field of research”. This “paradigm-changing paper” highlighted the importance of reducing voltage losses in organic photovoltaics by materials design and was deemed “a game-changer”.

(ii) A further example was in the domain of biological imaging using light. The work on “Enhanced photon collection enables four-dimensional fluorescence nanoscopy of living systems” (Nat. Comm. 9, 3281 (2018), DOI: https://doi.org/10.1038/s41467-018-05799-w), submitted by KTH Royal Institute of Technology, provided studies based on reversibly switchable fluorescent proteins. The reviewers commented that ” The study showed the general use of 4D imaging of organelles and fine structures in a range of cell and tissue types”, and that “The paper provides methodology for super-resolution optical microscopy […]. The performance is clearly beyond the state-of-the-art.” The paper shows “outstanding novelty” and “develops outstanding techniques which improves nanoscopic imaging substantially”.

(iii) The work “Over 14% efficiency all-polymer solar cells enabled by a low bandgap polymer acceptor with low energy loss and efficient charge separation” (Energy Environ. Sci. 13, 5017-5027 (2020), DOI: https://doi.org/10.1039/D0EE01828G, also see the case study by Karlstad University on “Artificial Intelligence for Sustainable Energy Storage”), submitted by Karlstad University, describes that over 14 per cent efficiency all-polymer solar cells was enabled by a low bandgap polymer acceptor with low energy loss and efficient charge separation. The reviewers deemed this a “new record efficiency for all polymer solar cells. The novelty is in a new material which is still widely used in the field. The paper was extremely influential”, and the work showed a commendable level of “rigour, originality and significance”.

2.11.3 Societal impact of sub-discipline 10399 other physics topics

Thirteen cases were considered that were distributed across a wide range of topic areas. Particular themes that emerged included medicine discovery/development and healthcare. Interdisciplinary network science leads to understanding and interpretation of complex data sets. We saw the emergence of some common factors for success, including a well-defined problem statement, identification of unmet needs, creation of critical mass in terms of the research team and funding. We saw multidisciplinarity as a key driver, be it with industry, hospitals or researchers in other disciplines (e.g., chemistry, biology).

In one instance, a very successful outcome was achieved by an individual who built a team with a set of skills to address a multitude of problems. The team led to a successful spin-off company with a number of internationally recognised tools for studying complex networks.

We selected three case studies for describing the broader impact of the sub-discipline, but these are taken as examples from the many strong submissions, just to emphasize some points.

(i) An example of synergies through strong collaboration with industry was presented by the case study on “Biophysics” submitted by Chalmers Univeristy of Technology. The FoRmulaEx research centre set out to develop nanophotonic biosensor concepts and surface-based bioanalytical tools in collaboration with researchers from the University of Gothenburg, the Karolinska Institute and AstraZeneca. The strong connection to relevant industry challenges has steered the research in a very productive direction, generating not only high-impact publications but also patents. As a consequence of the IP strategy, several spin-off companies have been established in the AZ BioVentureHub. Furthermore, the centre has strengthened the local ecosystem by a bi-directional flow of students, PhDs, post-docs, lecturers and seminars, both at the academic institutions and in industry.

(ii) A further example of how a well-defined problem led to innovation and scientific advances was presented by Umeå University in the case study of “Brain Biofluid Mechanics”. The group identified a knowledge gap in techniques to assess and analyse the cerebrospinal fluid (CSF) dynamics that could improve the understanding of the pathophysiology of normal pressure hydrocephalus (NPH), a neurological disease that affects elderly persons with symptoms of gait and balance problems, incontinence, and cognitive decline. Further development of the technique and combining with imaging techniques (e.g., MRI) has led to increased understanding of other neurological and eye disorders. The group point out the interdisciplinary collaboration between physics, biomedical engineering, neurology and neurosurgery as a key success factor. The group has trained an impressive amount of PhDs and have attracted ample funding.

(iii) The last example of a case study we would like to describe is also from Umeå University (“Martin Rosvall, interdisciplinary network science and university spin-off Infobaleen”). This case study, in contrast to many other successful cases, revolves around one individual principal investigator and his research group, which has developed algorithms for simplifying and highlighting the important structure in large complex networks of data. The initial research and algorithm development have been highly cited (maps of random walks on complex networks reveal community structure, PNAS 105, 1118 (2008) ~2414 citations and mapping change in large networks, PLoS ONE 5(1): e8694 (2010) ~456 citations). A start-up company, Infobaleen, was spun out from this research. The methods have been further developed and applied to many different business problems. Through interaction with a university incubator and local investors, the company was able to be established, and further growth came through collaborating with people with experience from industry and having time to pitch ideas to potential clients in their networks. Providing all research source code and tools available for anyone to use has also been critical for dissemination in academia and industry, resulting in significant impact.

The studies above, and many of the other contributions, also showed very good evidence of educational links and opportunities for emerging young researchers – including strong industry engagement – which was very good to read for the health of the sub-discipline moving forward.

2.12 Final remarks

As discussed in Section 2.2.1, modern society faces grand challenges recognised by entities such as the United Nations, the European Union and specific countries. Based on the relatively small sampling represented by this study, the Panel deems that Sweden has a healthy balance in terms of investments in education, technology development, applied scientific research and basic research. It has positioned itself well to address challenges linked to climate change, energy supply, clean water, medicine, and health care, while at the same time making important contributions to areas of science, such as particle and astroparticle physics that aim to understand the most fundamental questions surrounding matter and energy, and also the origin of our universe.

The sub-discipline of subatomic physics is strongly represented in Sweden. Unique infrastructure is available to perform the investigations. Fundamental physics questions are addressed at the Swedish institutions, and crucial technology is also developed there. The embedding of the researchers and their activities in large or smaller international collaborations is also beneficial. The scientific potential and the associated societal impact of this sub-discipline are enormous and should continue to be adequately supported. In general, the publications, many of which appeared in high-impact journals, attest to the very good quality of the Swedish contributions to research in this sub-discipline, as well as to excellent and large collaboration networks.

The sub-discipline atom and molecular physics and optics has a long and strong tradition in Sweden. The international status of Swedish research in this field is competitive, as it carries out important and highly-cited research. In fact, the mean citation rate is among the highest of all the relevant fields of physics. The societal impact, evidenced by launching start-up companies, is difficult to estimate over the short time range relevant to our assessment, as the companies are in their early stages. Extremely positive is that when the opportunity arises, the knowledge developed in the laboratories is transferred to start-up companies.

The sub-discipline fusion, plasma and space physics, is relatively small in Sweden, but is impactful by being strongly collaborative and internationally networked. As discussed in Sections 2.2.1 and 2.2.2 as well as in Section 2.7, this sub-discipline can have very high societal impact related to clean energy production, dynamic space processes and domains that are related to capabilities of performing space exploration, for example. Sweden plays a vibrant role in the international community, and its collaborative efforts have paid dividends. The Panel deems it important to sustain and enhance this development.

The sub-discipline condensed matter physics is strongly represented in Sweden. The research topics contribute strongly to societal challenges and are pursuing some of the major technology trends highlighted in Sections 2.2.1 and 2.2.2, respectively. Most notable is the research in innovative new materials, energy production and storage technology, where Sweden is well-positioned to play a major role. Institutions are the natural nodes able to connect disruptive research to societal impact. They are encouraged to keep a high level of excellence in fundamental research to discover new concepts in condensed matter, which is an essential building block in technology transfer, and to foster strong connections between industry and academia. Institutions are also encouraged to expand and promote the training of the next generation of researchers and engineers to a high level of competence, to keep Sweden competitive in innovation. We note that young researchers and PhD applicants are often involved in the societal impacts selected as examples for condensed matter. Because the excellence in condensed matter research reported by the institutions is focused on a selected number of topics, institutions are encouraged to build on their historical leadership in research to maintain a competitive level of excellence at global scale. As highlighted in a number of case studies, institutions are encouraged to foster cross-disciplinary research, in particular at the border with chemistry, engineering, biology, and computer science, which can act as fertile ground for innovations.

For the sub-discipline astronomy, astrophysics and cosmology, the Panel notes that this is among the major topics in physics in Sweden, with high international reputation and outstanding scientific productivity. Swedish participation in the European Southern Observatory (ESO) and in the European VLBI Network (EVN) forms one of the foundations for this impressive success. The universities have established an excellent combination of coherent observational projects, theory, and instrumentation. The societal impact ranges from the creation of fundamental knowledge to excellent education and science outreach programs (such as in Uppsala) and the transfer of development knowledge to industrial applications and the creation of new companies (for example Chalmers).

In the sub-discipline of accelerator physics and instrumentation, Swedish innovation in the area of accelerators has had a tremendous impact on all major synchrotron-based light sources around the world. The first low-emittance multi-bend achromat lattice was implemented at MAX IV. The success of this new concept resulted in the pursuit of diffraction-limited soft and hard X-ray facilities all around the world, with billion-euro investments ensuing. Sweden has also become home to the European Spallation Source (ESS). In addition, Swedish HEIs are making important contributions to the areas of instrumentation. One area that should receive further consideration is the transfer of technology in this sub-discipline towards spin-off companies. The area of plasma-based accelerators, pursued at Lund University could be a prime example for the innovation strategy (surprisingly, no material was submitted on this topic to the Panel).

For the sub-discipline other physics topics, our conclusions are that interdisciplinary science seems to be thriving across Sweden. The submitted material gave us a highly positive, far-ranging snapshot of activity. Indeed, as we reflected on the publications and case studies, we saw that, more broadly, many of the biggest scientific and societal challenges of today lie in this sub-discipline. Interdisciplinary practices are to be commended, and evidence shows that incubators work well and that there are enhancements to both research and teaching practices in these instances. It may be worthwhile for universities to exchange notes and ideas on improving and sharing “best” practices: We do not have information at hand on several aspects of detail, but believe this can only be beneficial to all concerned and could be achieved through focus meetings or exchange visits.

In general, many of the case studies reviewed by the Panel were linked to one or more of the grand challenges, such as climate change, energy supply, clean water, medicine, healthcare, and training the next generation of scientists, albeit in several cases exhibiting a rather weak link. Cases that had strong impact were the consequence of a deliberate and a clear strategy towards innovation and technology transfer by the relevant HEIs, and they are to be commended for it.

As a remark for the Swedish Research Council, the evaluation of the submitted case studies by the Panel was hampered at times by the fact that the interpretation, structure and content of them varied widely amongst the different HEIs and at times seemed disjunct from the purpose of the request. The Panel recognises that alignment of case studies to sub-disciplines and the estimation of their impact carries an implicit degree of bias and, it goes without saying, that some sub-disciplines are more naturally linked to the big challenges that society is facing today (Section 2.2.1).

In science areas such as astronomy, astrophysics, cosmology, and subatomic physics, the impact was shown largely in terms of spin-off results into other technology development and expanding of our understanding of the universe, training of the next generation and triggering interest in science from the general public (with positive consequences for the global science community). For accelerators and physics instrumentation, the main impact is through the development of analytic tools that are used by other science communities (particle physics, photon science, medical applications, inspection tools, etc.). Climate research, materials, condensed matter, energy systems, and biophysics are de facto of great societal benefit, as the know-how and technology can be directly transferred to the general society.

One aspect that was discussed by the Panel is how to further strengthen societal impact and ensuring scientific excellence, and how this relates to the scale of a research centre. Larger centres are typically part of larger national and international consortia with ample funding, and are characterised by having a critical research mass to foster an innovative and scientifically sound environment. Transfer of technological and scientific output to industry occurs through support from university incubators and venture capital, or under direct contract research with industry. Noteworthy is that several of the case studies reported as key factor for success the fact that funding was made available from a combination of the European Union, Swedish research councils and private foundations. Hence, strengthening networks between centres, both national and international strong centres, and collaborations with industry should be considered by decision-makers for further nurturing the Swedish research ecosystem and increasing its global impact.

As a final remark, the scientific and societal impact of many research areas can often be seen within a decade or two, but it should be remembered that our history is filled with many examples where “basic”, curiosity-driven science was recognised as opening up areas with huge technological/societal impact only decades later. The pursuit of knowledge, as well as the research education of next generation scientists and all members of our society, are the core to our human civilisation.

3 Appendices

All the appendices are compiled and written by the evaluation team at the Swedish Research Council and has been used as a basis for the evaluation Panel.

3.1 Evaluation Panel

Table 1. The Evaluation Panel

Name	**Affiliation**	**Country**	**Focus**
Wim Leemans	Deutsches Elektronen-Synchrotron DESY	Germany	Chair
Ursula Hass	RISE	Sweden	Co-chair, Societal impact
Dominique Vernhet	Sorbonne Université	France	Societal impact
Anders Broo	Astra Zeneca	Sweden	Societal impact
Leo Kärkkäinen	Aalto University	Finland	Societal impact
Daniel Zajfman	Weizmann Institute of Science	Israel	Societal impact
Claudia-Elisabeth Wulz	Institute of High Energy Physics, Austrian Academy of Sciences	Austria	Scientific quality 10301 Subatomic Physics
Maria Antonietta Loi	University of Groningen	Netherlands	Scientific quality 10302 Atom and Molecular Physics and Optics

Name	Affiliation	Country	Focus
Markku Poutanen	Finnish Geospatial Research Institute FGI, NLS	Finland	Scientific quality 10303 Fusion, Plasma and Space Physics
Nadine Witkowski	Sorbonne Université	France	Co-chair, Scientific quality 10304 Condensed Matter Physics
Thomas Henning	Max Planck Institute for Astronomy	Germany	Scientific quality 10305 Astronomy, Astrophysics and Cosmology
Atoosa Meseck	Helmholtz-Zentrum Berlin	Germany	Scientific quality 10306 Accelerator Physics and Instrumentation
Catherine Picart	CEA Grenoble	France	Scientific quality 10399 Other Physics Topics (biological physics)
Kishan Dholakia	University of St Andrews	UK	Scientific quality 10399 Other Physics Topics (biophotonics)

3.2 Methods

Assessments of the research carried out at individual HEIs (evaluation units) form the basis for the national picture. The focus is on the results of the research, and more precisely on two components: the scientific output of research production (publications) and the societal impact of research (impact case studies). The scientific quality and the societal impact are assessed as two separate components.

3.2.1 Scientific quality

The Panel was provided with material in the form of publications and cases, and was asked to provide an assessment of these, focusing on what their scientific and societal impact are. The evaluation of publications was based in part on the bibliometric analysis supplied by the Swedish Research Council (see below), the reviews by external referees, and the assessment by the Panel. In general, the bibliometric data (see Section 3.4) indicates the general high quality of publications generated through scientific research in Sweden. All cases were discussed in depth by the Panel and rated for their scientific and societal impact. Specific publications and cases will be highlighted in the subsequent sections where the different sub-disciplines are assessed.

Where suitable, the Panel has relied on its own expertise and experience in national and international physics communities to provide a calibration of the material provided and the standing and impact of physics research in Sweden on the international community.

It is the Swedish Research Council's view that subject experts' reading is necessary to assess the quality of individual publications. Bibliometric indicators cannot replace peer review of the actual research production. Obviously, publications with many citations indicate a large impact in the research community, but citations do not guarantee the most prominent and scientifically important research.

Bibliometrics are therefore only used as a supplement to the reading, to give an overall view of the research production, and to contrast the selected publications with the overall research production in physics in Sweden.

3.2.1.1 Peer review of publications

The HEIs submitted lists of publications to be assessed in the evaluation. The selected publications had to relate to research conducted primarily by researchers active at the HEI in question, and be published during the period in question. The HEIs sent a digital copy of each of these publications.

The number of publications that each HEI was to submit is based on the Swedish Higher Education Authority's (UKÄ) personnel statistics. For details, see Table 5 in Appendix 3.3.

Table 2. Number of publications per HEI

HEI	**Articles**
Lund University (LU)	84
Uppsala University (UU)	72
Stockholm University (SU)	57
Chalmers University of Technology (CTH)	40
KTH Royal Institute of Technology (KTH)	52
Linköping University (LiU)	35
Umeå University (UmU)	16
University of Gothenburg (GU)	12
Karlstad University (KAU)	8
Linneaus University (LnU)	8
Luleå University of Technology (LTU)	8
Mid Sweden University (MSU)	8
Total	400

Along with the list of their most prominent publications, each HEI submitted a text of maximum two pages explaining the selection, to give the Panel an understanding of the selection process. This allowed the HEIs to explain whether their selection of publications is related to any existing strategy for scientific focus or profile, or to national or international collaborations.

Table 3. Distribution of articles on sub-disciplines[8]

Research area	**Number of publications**	**Share of total**
10301 Subatomic Physics	55	14%
10302 Atom and Molecular Physics and Optics	59	15%
10303 Fusion, Plasma and Space Physics	15	4%
10304 Condensed Matter Physics	151	38%
10305 Astronomy, Astrophysics and Cosmology	55	14%
10306 Accelerator Physics and Instrumentation	12	3%
10399 Other Physics Topics	51	13%
Total	**398**	**100%**

The reading was performed by external reviewers, supplemented by members of the Evaluation Panel. Most of the publications were read by 3 reviewers each. The total number of external reviewers was 65 persons and they were all recruited from abroad.

Panel members (scientific quality) read some of the publications to build up an understanding of the material and quality of the publications, and to complement the external reviewers' assessments.

For grading of publications, we adopted the grading scale and assessment criteria on five levels, used in the Research Excellence Framework (REF). Each reviewer gave each publication one overall grade according to the grading scale, see Appendix 3.5.2.

[8] One of the publications in 10302 has been submitted by two different HEIs. This also happened in 10304. We have not counted the duplicates, which makes the total number of unique publications 398, even though there were 400 publications submitted in total.

3.2.1.2 Bibliometrics

The Swedish Research Council uses its publication database (Web of Science/Clarivate Analytics) for bibliometric summaries. The measures used include factors such as production volume, average number of citations, and proportion of highly cited publications. Bibliometrics also shows the primary focus of the research, and collaboration patterns. For bibliometric analysis, see Appendix 3.4.

3.2.2 Societal impact

Case studies form the basis for the Panel's assessment of societal impact. These were compiled by the HEIs, and describe cases where research within the evaluated area has made a difference to society. Each HEI submitted a number of such case studies, describing how the research conducted at that particular HEI has had an impact on society beyond the research community.

Table 4. The distribution of case studies on the different sub-disciplines (The HEIs could relate each case study to up to three sub-diciplines)

Sub-disciplines	Number of case studies related to each sub-discipline
10301 Subatomic Physics	5
10302 Atom and Molecular Physics and Optics	15
10303 Fusion, Plasma and Space Physics	3
10304 Condensed Matter Physics	25
10305 Astronomy, Astrophysics and Cosmology	8
10306 Accelerator Physics and Instrumentation	14
10399 Other Physics Topics	27
Missing = No sub-discipline selected	4

For each case study, three different components were described (under separate headings): (a) Reach and significance – the referred impact on society; (b) Contributing research – the main content of the research that contributed to the impact; and c) Key processes and factors – approaches and conditions that have been crucial to the impact. The instructions given to the higher education institutions can be found in Appendix 3.5.2.

3.3 Descriptive statistics

In this appendix, we present some descriptive statistics for Swedish HEIs conducting research in physics. The statistics are mainly for the twelve HEIs included in the evaluation. The total for the remaining HEIs is presented where applicable.

3.3.1 Physics in Sweden: Staff

For the years 2016–2020, the twelve HEIs included in the evaluation together account for all PhD students and 96.8 per cent of the research and teaching staff in physics. For the breakdown per HEI, see Table 5. The table is sorted in descending order from highest number of research and teaching staff (in full-time equivalents). The same order is used for Table 6 and Table 7.

Table 5. Physics in Sweden: Staffing data. Counts are average number of full-time equivalents (FTEs) for the years 2016–2020. 'Staff' are research and teaching staff with PhD degrees. 'Total' includes PhD students. 'Share all' is share of all HEIs. 'Share included' is share of the HEIs included in the evaluation. Source: Official statistics from the Swedish Higher Education Authority (UKÄ).

HEI	Staff (count)	PhD students (count)	Total (count)	Share all total	Share included total
Lund University	173.0	160.6	333.6	21.6%	22.0%
Uppsala University	165.8	120.6	286.4	18.5%	18.9%
Stockholm University	125.5	102.4	227.8	14.7%	15.0%
Chalmers University of Technology	118.3	40.5	158.9	10.3%	10.5%
KTH Royal Institute of Technology	104.5	104.7	209.2	13.5%	13.8%
Linköping University	54.6	85.4	140.0	9.1%	9.2%
Umeå University	35.6	26.7	62.2	4.0%	4.1%
University of Gothenburg	33.0	13.1	46.1	3.0%	3.0%

HEI	Staff (count)	PhD students (count)	Total (count)	Share all total	Share included total
Karlstad University	13.7	3.9	17.7	1.1%	1.2%
Linnaeus University	10.0	2.7	12.8	0.8%	0.8%
Luleå University of Technology	7.3	9.1	16.4	1.1%	1.1%
Mid Sweden University	7.2		7.2	0.5%	0.5%
Other (total excluded HEIs)	28.0		28.0	1.8%	
Grand total	876.4	669.7	1546.1	1.0	1.0
Total included	848.4		1518.1		

3.3.2 Publications

The number of publications to be assessed, for each HEI included, is decided in proportion to their total count (see Table 5, Column 6), that is, full-time equivalents of research and teaching staff plus full-time PhD students. To avoid a situation where some HEIs would have an unreasonably low number of publications assessed, we adjusted the number so that eight publications is the minimum, while still limiting the total to 400. See Table 6, Columns 2 and 3, for the proportional (rounded to nearest integer) and adjusted number of publications, respectively.

Similarly, the number of case studies for each HEI included to submit is decided based on their relative size. The three largest higher education institutions, in terms of total count in physics that is, are to submit at least nine and no more than eleven case studies. For medium-sized HEIs, the corresponding numbers are six and eight, while the smallest are to submit at least one and no more than three. (See Table 6, last column.) This flexibility is introduced in order to allow the HEIs some margin of manoeuvre in selecting relevant cases, while ensuring there will be a reasonable number of cases both to provide enough material for the Panel to base their conclusions on, and to limit the workload for everyone involved.

Table 6. Number of publications per HEI, in proportion to FTEs and adjusted with a minimum of eight publications per HEI. The adjusted number is used for the evaluation. Number of case studies each HEI should submit. Included HEIs only.

HEI	Proportional	Adjusted	Case studies
Lund University	88	84	9–11
Uppsala University	75	72	9–11
Stockholm University	60	57	9–11
Chalmers University of Technology	42	40	6–8
KTH Royal Institute of Technology	55	52	6–8
Linköping University	37	35	6–8
Umeå University	16	16	1–3
Gothenburg University	12	12	1–3
Karlstad University	5	8	1–3
Linnaeus University	3	8	1–3
Luleå University of Technology	4	8	1–3
Mid Sweden University	2	8	1–3
Total	**400**	**400**	**51–75**

3.3.2.1 R&D funding and costs

The HEIs included together received 98.7 per cent of the grants for research in physics from the Swedish Research Council for the years 2016–2020, and account for 99.8 per cent of the R&D costs (total and average) for the three latest surveys of R&D costs. For the breakdown per HEI, see Table 7. The number of grants and R&D cost are not grounds for inclusion in the evaluation, but confirm the conclusion from Table 5 that the HEIs included carry out the vast majority of the research in physics in Sweden, or at least dominate in terms of resources.

Table 7. Physics in Sweden: R&D funding and costs. 'Grants' are total number of research grants from the Swedish Research Council for the years 2016–2020. 'Costs' are R&D costs in million SEK, total for the three latest surveys. 'Average costs' is the average of R&D costs from the three latest surveys. Sources: Number of research grants from the Swedish Research Council is taken from Prisma, our application handling system. R&D costs are official statistics from Statistics Sweden.

HEIs	Grants	Costs	Average costs
Lund University	59	2244	748
Uppsala University	64	944	315
Stockholm University	71	764	255
Chalmers University of Technology	55	1262	421
KTH Royal Institute of Technology	52	776	259
Linköping University	36	826	275
Umeå University	15	152	51
University of Gothenburg	17	203	68
Karlstad University	1	53	18

HEIs	**Grants**	**Costs**	**Average costs**
Linnaeus University	1	33	11
Luleå University of Technology		44	15
Mid Sweden University		62	21
Other (total excluded HEIs)	5	14	5
Grand total	**376**	**7377**	**2459**

3.4 Bibliometric analysis

This section places Swedish physics in an international context, by comparing the citation of papers by scientists at Swedish institutions to those by scientists in other countries. Citations are used as a measure of the extent to which publications contribute to scholarly work. The assumption is that highly cited work is liable to make a greater contribution to the discipline than less cited work. The metrics, which form the basis for our comparison, are citations as recorded in the Web of Science (WoS). To be more precise, all metrics and statistics are based on the Swedish Research Council's publication database, which is based on data from WoS.[9]

For this analysis, we have used the journal classification schema in WoS and only included the document types Article and Review. There are about 250 research areas in WoS. Of these, fifteen are within physics, according to the 'Nordic' classification.[10] A journal or publication may have up to six different research areas. If a publication has (at least) one research area classified within physics, it is included in this analysis.

Table 8 presents the average citation rate of publications in physics from Sweden compared to those from twelve other countries, for the years 2016 to 2020. The countries are selected based on collaboration (co-authorship) with researchers in Sweden, and are ranked according to the total number of publications counted in WoS.

All citation statistics are 'field- normalised', and counted without self-citations. To perform this normalisation, the number of citations for a publication is divided by the global average number of citations within the same specific subject for the years assessed. By construction, the global average is 1.0. Hence, a field- normalised mean citation score above 1 implies that a country's publications are on average cited more than the world average.

Further, all statistics are based on 'publication fractions'. For example, if a publication has five authors, where one is from a specific country of interest, that country is assigned 0.2 fractions. Publications attributed to a certain country are publications by researchers with an affiliation (address) in that country.

As can be seen from Table 8, the mean citation index for Sweden is 1, implying that publications are cited, on average, at the global average. The top countries in this comparison, USA and Switzerland, reach the citation score 1.4, corresponding to 40 per cent above the world average.

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[9] For general properties of the publication database, how data is prepared and indicators are calculated, see: The bibliometric database at the Swedish Research Council 113-2010-6148 (2017).

[10] The Swedish Research Barometer 2021 ISBN: 978-91-88943-48-4 (2021).

Table 8. Number of publications in physics and citation impact for Sweden and twelve other countries, for the years 2016 – 2020. Data from Web of Science, Clarivate Analytics.

Country	Number of publications	Mean citation rate	Share of top 10 per cent publications
China	297040	1.1	12%
United States	154965	1.4	14%
India	61007	0.7	6%
Germany	55433	1.1	11%
Japan	52136	0.7	6%
Russian Federation	49889	0.4	2%
United Kingdom	39926	1.2	12%
France	37372	0.9	9%
Italy	30716	1	9%
Spain	21678	1	9%
Switzerland	11214	1.4	15%
Netherlands	9816	1.3	13%
Sweden	7793	1	10%
Denmark	4565	1.2	13%
Finland	4173	1	10%

Table 8 also reports the share of articles that are in the top ten per cent of articles cited. This is the proportion of a country's publications that belong to the top ten per cent of most cited publications internationally, for a given subject and year. We note from Table 8 that ten per cent of the total of Swedish publications fall into the top ten per cent share, i.e. at the world average.

3.4.1 Bibliometric statistics for Sweden by publication year

In Table 9, bibliometric statistics for Sweden is shown by publication year. Here we have also included the citation indicator share of top one per cent publications, where the world average by construction is one per cent. From

2017 to 2019 inclusive, the citation impact is stable, with scores above the world average, but for 2020 the citation numbers show a clear decline. However, it is still too early to confirm if this is a trend break; typically, longer time is needed in order to create stable field normalisation values. That is, the figures for a more recent year, such as 2020, are more likely to change over time.

Table 9. Number of publications and citation impact of physics in Sweden by publication year. Data from Web of Science, Clarivate Analytics.

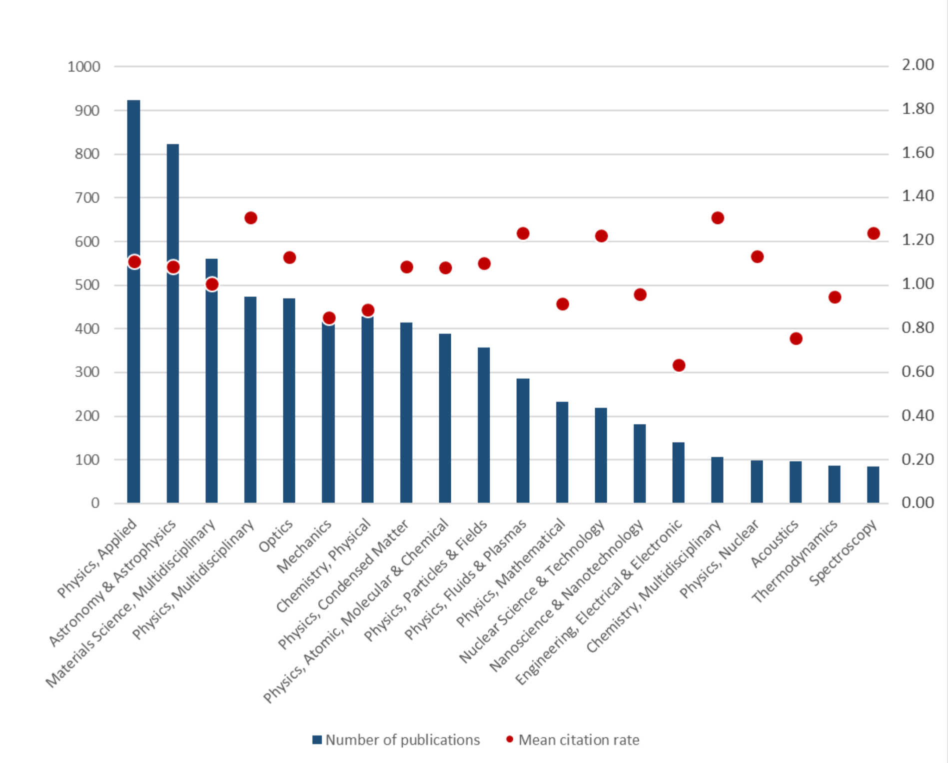
Publication year	Number of publications	Mean citation rate	Share of top 10 per cent publications	Share of top 1 per cent publications
2016	1584	1.0	9%	0.7%
2017	1607	1.1	11%	1.0%
2018	1538	1.1	11%	1.1%
2019	1512	1.1	11%	1.1%
2020	1552	0.9	8%	0.5%
Total	**7793**	**1.0**	**10%**	**0.9%**

3.4.2 Bibliometric statistics for Sweden, by research areas

Figure 1 shows number of publications and mean citation rate for twenty research areas within physics in Sweden. Due to the multi-classification in WoS, these data do not only contain the fifteen (traditional) areas within physics, but also several related subjects. These related subjects are mainly in materials science or chemistry. The two largest areas, in terms of number of publications, are applied physics, and astronomy and astrophysics. Both these areas, as well as most other areas in physics, have a mean citation rate above the world average.

The multidisciplinary topics (physics, chemistry, etc.) include journals with a general or interdisciplinary approach, such as Physical Review Letters and Nature Physics.

Figure 1. Number of publications and mean citation rate by research area. Swedish publications in physics, for publication years 2016 - 2020. Data from Web of Science, Clarivate Analytics.



3.4.3 Bibliometric statistics for Sweden, by organisation

Table 10 shows organisations (author affiliations), countries and number of publications, fractional counting, for organisations with more than 50 publications, and is sorted by number of publications. The statistics are based on publications with at least one author affiliation from Sweden, but the table also includes affiliations/organisations from the other countries. KTH Royal Institute of Technology has the largest number of publications, followed by Uppsala University and Lund University, and Chalmers University of Technology, who all have roughly 1 100 publications (if rounded to nearest hundred). The first non-Swedish organisation, the Max Planck Institute, is found in ninth place in the list.

Table 10. Number of publications by organisation. Includes organisations with a total volume of at least 50 (fractional counting) for the years 2016-2020 (total for all five years). Data from Web of Science, Clarivate Analytics.

Organisation	Country	Number of publications
KTH Royal Institute of Technology	Sweden	1 453
Uppsala University	Sweden	1 138
Lund University	Sweden	1 109
Chalmers University of Technology	Sweden	1 058
Stockholm University	Sweden	719
Linköping University	Sweden	664
University of Gothenburg	Sweden	233
Luleå University of Technology	Sweden	215
Max Planck Institute	Germany	187
Umeå University	Sweden	179
Swedish Institute of Space Physics	Sweden	104
Chinese Academy of Sciences	China	100
University of Copenhagen	Denmark	82
Linnaeus University	Sweden	65
Russian Academy of Sciences	Russian Fed.	63
Univ Paris Saclay	France	59
Aalto University	Finland	57
RISE	Sweden	56
National Institute for Nuclear Physics Italy (INFN)	Italy	56
Technical University of Denmark	Denmark	55
Mid Sweden University	Sweden	55

Organisation	Country	Number of publications
California Institute of Technology (Caltech)	United States	53
Zhejiang University	China	51
University of Oslo	Norway	50

3.4.4 Citation impact for the submitted publications

For this evaluation, the Swedish HEIs included submitted 400 publications in total for the peer review. At the request of the Panel, the Swedish Research Council matched these publications against data in WoS and produced citation data aggregated by subject code (SCB/Statistics Sweden at five-digit level). For most of these publications, the classification code supplied by the universities was used. A few codes have been manually changed[11], and when code was missing a classification has been added.

Of the 400 submitted, we are able to match 396 with entries in WoS (in the database at the Swedish Research Council). Of the 400 publications, the same two publications were submitted by two universities, but here these two publications are only counted once (in total 398 unique publications). A few publications are not classified as article or review, but the same field normalisation was used for all records, i.e. all publications are normalised as if they were an article or review. Unlike all other statistics, all these are counted as integers. This implies that publications with many co-authors and international collaboration will have a much higher weight in the citation statistics (mean citation rate and share of highly-cited publications).

On average, and across areas, the submitted publications show very high citation numbers, which indicates high impact within science. However, 10306 (accelerator physics and instrumentation) only shows modest citation impact, but the number of publications (eleven) is modest. Astronomy, astrophysics and cosmology (10305) shows the highest citation numbers, where 32 per cent of the 53 publications are among the one per cent most cited publications within its field and year. Most publications, 151, are in condensed matter physics (10304), followed by 58 in atomic and molecular physics and optics (10302). 55 publications are in subatomic physics (10301) and 51 in other physics topics (10399). In the area of fusion, plasma and space physics (10303) fifteen publications are found.

[11] Mostly papers classified as ’other physics’, after manual review, clearly belong to one of the other categories.

Table 11. Citation impact of the (394) submitted publications. Note, the statistics is based on integer counts. Data from Web of Science, Clarivate Analytics.

UKÄ/SCB area (5-digit)	Number of publications [Integer counts]	Mean citation rate	Share of top 10 per cent publications	Share of top 1 per cent publications
10301	55	5.8	40%	13%
10302	58	3.5	39%	8%
10303	15	2.1	13%	7%
10304	151	3.9	36%	6%
10305	53	10.3	62%	32%
10306	11	0.9	0%	0%
10399	51	3.7	43%	10%
Total	**394**	**4.8**	**40%**	**11%**

3.5 Instructions regarding reported documents

3.5.1 Instructions regarding reporting of publications to the evaluation

As part of the Swedish Research Council's national evaluation of physics, the participating higher education institutions (HEIs) are asked to select a number of publications to send to the Swedish Research Council. These publications will be peer-reviewed by the evaluation panel and external reviewers according to criteria described in the attached document "Instructions for reviewers". The number of publications that each HEI must submit is shown in the table below. The selection of publications is based on the attached list of publications that the Swedish Research Council has produced from Swepub on 8 April 2022. No other publications may be submitted. The publications must have been published from 2016 through 2020.

The local process for the selection of publications is decided by the respective HEI and must be described in a document to the panel. This description is only intended for understanding the selection process and the selection, and does not constitute a basis for the panel's assessment. In this description, the HEI can relate the selection of publications to e.g. the respective HEI’s possible strategies for scientific focus or profile or to their national and international collaborations.

The publications must be submitted in PDF format via a BOX folder that the contact persons at the HEIs will have access to. One PDF file per publication and named according to a uniform standard including serial number (for example GU_1.pdf, GU_2.pdf ...etc.) Along with the publications, a list of the submitted publications must be submitted (see attached Excel template), as well as the above-mentioned description of the HEI's selection process. The description of the selection process must be in English and include no more than 2 numbered A4 pages in Arial, font size 11, with single line spacing and 2.5 cm margins, references and any images included.

Publications with appendices must be sent to the Swedish Research Council no later than 5 May 2022. For practical questions regarding the submission of publications, please contact: eval_physics@vr.se.

Table 12. Number of publications per HEI

HEI	Articles
Lund University (LU)	84
Uppsala University (UU)	72
Stockholm University (SU)	57
Chalmers University of Technology (CTH)	40
KTH Royal Institute of Technology (KTH)	52
Linköping University (LiU)	35
Umeå University (UmU)	16
University of Gothenburg (GU)	12
Karlstad University (KAU)	8
Linneaus University(LnU)	8
Luleå University of Technology (LTU)	8
Mid Sweden University (MSU)	8
Total	400

3.5.2 Instructions about the societal impact case studies

The higher education institutions were given the following instructions with regard to each of the three components, and were asked to limit the length of each case study to at most three pages (excluding references).

- Reach and significance – the referred impact on society

Describe the referred impact on society, to which the research at the submitting higher education institution (HEI) has contributed distinctly and substantially, and how the society has benefitted specifically. It is mainly this component of the case study that will be assessed and graded by the evaluation panel, and hence it is vital with a clear description of what the impact was, who or what was affected, and how.

The impact described must have occurred within the past five years. The contributing research must have been published within the last 20 years and have been conducted either by researchers employed at the submitting HEI at the time of publishing or by the current HEI's research staff (also in previous positions). (Please find further instructions for your description of contributing research under b) below.)

The impact of research on society may manifest itself in a variety of ways. The Swedish Research Council hence welcomes a diversity of case studies, indicating the impact research has had on separate as well as a multitude of areas of society, such as the economy, civil society, cultural activities, politics, public administration, corporations, public health, the environment, or quality of life. The impact may involve individuals as well as organisations or groups, and may refer to shifts or changes in activities, attitudes, understanding, behaviours, competences, possibilities, policies, approaches, or processes. Further, the impact may manifest itself locally, or at a national or international level.

The impact on society may affect a large number of individuals/organisations, etc. (broad reach) or be of vital importance for a smaller number of individuals/organisations, etc. (great significance). For the panel's assessment, it is important that you describe the reach as well as the significance of the referred impact. Please highlight also possible ethical aspects of your research including dual-use or unintended consequences from the deployment of the technology or the research methods at large.

Please give references to verify the impact, i.e., to verify that this change to society has occurred and that research at the submitting HEI made a distinct and substantial contribution. References may consist of references to relevant documents, or contact information to persons with relevant knowledge.

- Contributing research – the main content of the research that contributed to the impact

Describe briefly the content of the HEI's research outputs that distinctly and substantially have contributed to the impact described under (a) above. Explain how this content has been essential. Please also choose up to three of the six sub-disciplines of physics that best capture this research content.

The described research outputs must be published within the last 20 years, and the referred impact on society must, as stated above, have occurred within the last five years. The research contributing to the impact may build on work carried out over several years or be the result of an individual project; and it may be carried out by an individual researcher, a group of researchers, or in collaboration with researchers at other HEIs.

Enclose in an appendix a list of up to ten key publications. The contributing research must have been published within the last 20 years and have been conducted either by researchers employed at the submitting HEI at the time of publishing or by the current HEI's research staff (also in previous positions). On this list of publications, all authors must be specified (with the order of authors corresponding to that of the published works and authors from the submitting HEI marked with bold font), title, and publication type, as well as year.

- Key processes and factors – approaches and conditions crucial to the impact

If applicable, describe how your processes to promote the impact of your research have contributed to the particular impact described under (a). You may also include contextual factors (characteristics of the context where the impact occurred) that you judge as essential for this case. Closely elaborating on how these processes and contextual factors have been essential to the described impact is central for making your case studies valuable to decision makers in government and at HEIs.

You may consider the following pathways for the impact:

- External or internal use for supporting society through providing access to infrastructures and measurements facilities built for research purposes.
- Talent creation – e.g. thesis /PhD papers done with industry that create technology transfer, or even job fairs for intern positions; assessment of the impact graduates have made after completion of their degree.
- Dissemination of state-of-the-art research results for the benefit of society, in technology transfers, project works, consulting services, participation in expert bodies for the government and organised conferences with industry participation.
- Direct research impact through patents, or technology transfers from research results applications.

The following are a few examples from earlier evaluations/studies of approaches and conditions that in various contexts have been brought forward as important for the societal impact of research: research profile and strategy; extent and type of as well as conditions for research funding; framework for incentives for funding and staffing; the composition, recruitment, career paths and mobility of research staff; gender equality; publication strategies; collaborations within as well as outside academia, nationally as well as internationally; governance, management and basic values.

We would like to stress that you are free to bring up any processes you deem essential to your work.

Refer to relevant written evidence verifying your description, e.g. documents or persons (including contact information), who can confirm that the procedures and conditions you put forward have indeed contributed to the impact described under (a).

The societal impact of the research – template for impact case studies

The case studies below relate to research in physics.
Name of the HEI and departments/equivalents that have contributed to the belowcase studies:
Name of the contact person for this evaluation:
Briefly justify (maximum ¼ A4 page) the choice of case studies:

CASE STUDY 1

(Maximum 3 pages, excluding references. Please number the pages.)

Title of this case study:

Please choose the (maximum) three of the following six sub-disciplines of physics that best capture the research underpinning this case study:

☐ 10301 Subatomic Physics
☐ 10302 Atom and Molecular Physics and Optics
☐ 10303 Fusion, Plasma and Space Physics
☐ 10304 Condensed Matter Physics
☐ 10305 Astronomy, Astrophysics and Cosmology
☐ 10306 Accelerator Physics and Instrumentation
☐ 10399 Other Physics Topics, please indicate what:

a) Reach and significance – the impact on society referred to:
b) Contributing research – the main content of the research that contributed to the impact:
c) Key processes and factors – approaches and conditions that have been crucial to the impact:

CASE STUDY 2

(Maximum 3 pages, excluding references, format according to case study 1 above.)

Please add further case studies up to the maximum number of case studies for your HEI.

3.5.3 Instructions for reviewers

First, we would like to thank you for agreeing to act as a reviewer in this evaluation of Swedish research in physics. Your participation, as a distinguished subject matter expert in the field of physics, forms the foundation for both the quality and legitimacy of the evaluation.

This document provides you with instructions on how to carry out your task as a reviewer.

3.5.3.1 Conflict of interest

If you consider that you have a conflict of interest in relation to any of the articles that are selected for you, you must not make any assessment of that specific article and you must to inform us about this. Examples of potential conflicts could be close collaboration in a professional context with any of the authors, obvious friendship or enmity, family ties, relationships of economic dependency, superior/subordinate relationship, or if you are involved in the matter in a way that may give rise to doubts about your ability to make an impartial judgment.

3.5.3.2 Access to the publications

You will have access to the publications through a link to a file sharing service (Box) sent to you separately. The link gives you access to a folder where the publications we have assigned to you are available for you to read.

3.5.3.3 Template for assessment

We will ask you give your assessment of each publication using an Excel template. The template will be pre-populated with the list of the publications that you have been assigned. In the template, you should grade each publication using the scale presented below. For each grade, we also ask you to provide a short explanatory comment (one or two sentences).

Please submit the completed Excel sheet to eval_physics@vr.se no later than October 15, 2022.

3.5.3.4 Assessment criteria

Since this concerns assessment of the outputs from the higher education institutions (HEIs), we have chosen to adopt the grading scale and assessment criteria used in the Research Excellence Framework (REF). Hence, we ask you to give one overall grade on the scientific quality of each publication according to the scale displayed in the table below. The grade should be indicated in the Excel assessment template along with a short explanatory comment (one or two sentences).

Table 13 Criteria and definitions of starred levels.

Four star	Quality that is world-leading in terms of originality, significance and rigour.
Three star	Quality that is internationally excellent in terms of originality, significance and rigour, but which falls short of the highest standards of excellence.
Two star	Quality that is recognised internationally in terms of originality, significance and rigour.
One star	Quality that is recognised nationally in terms of originality, significance and rigour.
Unclassified	Quality that falls below the standard of nationally recognised work, or work which does not meet the published definition of research for the purposes of this assessment.

Scientific quality should be assessed in terms of originality, significance and rigour, defined as:

Originality will be understood as the extent to which the output makes an important and innovative contribution to understanding and knowledge in the field. Research outputs that demonstrate originality may do one or more of the following: produce and interpret new empirical findings or new material; engage with new and/or complex problems; develop innovative research methods, methodologies and analytical techniques; show imaginative and creative scope; provide new arguments and/or new forms of expression, formal innovations, interpretations and/or insights; collect and engage with novel types of data; and/or advance theory or the analysis of doctrine, policy or practice, and new forms of expression.

Significance will be understood as the extent to which the work has influenced, or has the capacity to influence, knowledge and scholarly thought, or the development and understanding of policy and/or practice. Significance includes but should not be limited to the visibility and reputation of the journal where the work is published and the number of citations the work has amassed. Work may be highly significant even with few citations if, for instance, it has influenced a narrow but consequential stream of research or if it has important implications for public policy.

Rigour will be understood as the extent to which the work demonstrates intellectual coherence and integrity, and adopts robust and appropriate concepts, analyses, sources, theories and/or methodologies.

Supplementary criteria – level definitions

In assessing outputs, the reviewers will look for evidence of originality, significance and rigour, and apply the generic definitions of the starred quality levels as follows:

In assessing work as being four-star, reviewers will expect to see some of the following characteristics:

- outstanding novelty in developing concepts, paradigms, techniques or outcomes
- a primary or essential point of reference
- a formative influence on the intellectual agenda
- application of exceptionally rigorous research design and techniques of investigation and analysis
- generation of an exceptionally significant data set or research resource.

In assessing work as being three-star, reviewers will expect to see some of the following characteristics:

- novelty in developing concepts, paradigms, techniques or outcomes
- an important point of reference
- contributing very important knowledge, ideas and techniques which are likely to have a lasting influence on the intellectual agenda
- application of robust and appropriate research design and techniques of investigation and analysis
- generation of a substantial data set or research resource.

In assessing work as being two-star, reviewers will expect to see some of the following characteristics:

- providing useful knowledge and the application of such knowledge
- contributing to incremental and cumulative advances in knowledge
- a thorough and professional application of appropriate research design and techniques of investigation and analysis.

In assessing work as being one star, reviewers will expect to see some of the following characteristics:

- providing useful knowledge, but unlikely to have more than a minor influence
- an identifiable contribution to understanding, but largely framed by existing paradigms or traditions of enquiry
- competent application of appropriate research design and techniques of investigation and analysis.

Research will be graded as ‘unclassified’ if it falls below the quality levels described above.