Swedish Needs in X-ray Science 2025

Report from the Swedish Synchrotron and Free-electron laser user organisation (SSUO) to the Swedish Research Council

Vetenskapsrådet
Swedish Research Council

2025

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Dnr 2024-05979
ISBN 978-91-89845-41-1

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List of abbreviations

ARPES	Angle-resolved Photoemission Spectroscopy
BESSY	Berlin Electron Storage Ring Society for Synchrotron Radiation
Balder	Beamline at MAX IV for hard X-ray spectroscopy
BioMAX	Beamline at MAX IV for macromolecular crystallography
Bloch	Beamline at MAX IV for photoelectron spectroscopy
CDR	Conceptual Design Report
CERN	European Organization for Nuclear Research
CeXS	Center for X-rays in Swedish Materials Science
CoSAXS	Beamline at MAX IV for coherent small-angle X-ray scattering
DESY	Deutsches Elektronen-Synchrotron
DanMAX	Beamline at MAX IV
Diamond	UK national synchrotron facility
EBS	Extremely Brilliant Source (ESRF upgrade)
EM	Electron microscopy
EPN	European Photon and Neutron (science campus)
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EuXFEL	European X-ray Free-Electron Laser
FEL	Free-electron laser
FemtoMAX	Ultrafast beamline at MAX IV
FinEstBeAMS	Finnish-Estonian Beamline for Materials Science
FlexPES	Beamline at MAX IV for flexible photoelectron spectroscopy
ForMAX	Beamline at MAX IV for forest-based materials
FragMAX	Fragment screening platform at MAX IV
GeV	Giga-electron volt
HAXPES	Hard X-ray Photoelectron Spectroscopy
HERCULES	Higher European Research Course for Users of Large Experimental Systems
HiPPIE	Beamline at MAX IV
ILL	Institut Laue-Langevin
LINXS	LINXS Institute for X-ray and Neutron Science
MAX 4U	Upgrade initiative for MAX IV
MAX IV	Swedish synchrotron facility in Lund
MAX-I	First storage ring at MAX-lab in Lund
MAX-II	Second storage ring at MAX-lab
MAX-III	Third storage ring at MAX-lab
MAX-lab	Predecessor laboratory to MAX IV in Lund
MAXPEEM	Beamline at MAX IV for photoelectron spectroscopy/microscopy
MBA	Multi-bend achromat
MX	Macromolecular crystallography
MedMAX	Proposed bio/medical imaging beamline at MAX IV
MicroMAX	Beamline at MAX IV for microfocus crystallography

MyFab	Swedish research infrastructure for micro- and nanofabrication
NanoMAX	Beamline at MAX IV for nano-focused X-rays
NextBioForm	Vinnova-funded network for biologics formulation
P21	Swedish Materials Science Beamline at PETRA III
PETRA III	Synchrotron facility at DESY, Hamburg
PETRA IV	Proposed upgrade of PETRA III
PSI	Paul Scherrer Institute
RIXS	Resonant inelastic X-ray scattering
SAXS	Small-angle X-ray scattering
SLS	Swiss Light Source
SOLARIS	Polish national synchrotron facility
SOLEIL	French national synchrotron facility
SPF	Short-pulse facility at MAX IV
SSUO	Swedish Synchrotron and FEL User Organisation
SXL	Proposed soft X-ray Laser project at MAX IV
Species	Soft X-ray beamline at MAX IV
SpectroWISE	Planned spectroscopy beamline project at MAX IV
TDR	Technical Design Report
TomoWISE	Proposed advanced imaging beamline at MAX IV
UHV	Ultra-high vacuum
URG	MAX IV University Reference Group
WISE	Wallenberg Initiative Materials Science for Sustainability
XAS	X-ray absorption spectroscopy
XES	X-ray emission spectroscopy
XFEL	X-ray Free-Electron Laser
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

Vetenskapsrådets inledning

Denna rapport, författad av styrelsen i Swedish Synchrotron and Free-Electron Laser User Organisation (SSUO), ger en översikt av överväganden kring storskaliga infrastrukturer för produktion av röntgenljus ur perspektivet av svenska användare. Rapporten beställdes av Rådet för forskningens infrastrukturer (RFI) under 2024 som en uppföljning till den kartläggning av svenska forskningsbehov inom området som senast genomfördes 2018–2019. Rapporten har författats av SSUO:s styrelse och färdigställdes under 2025.

Rapporten belyser hur svenska forskningsbehov och resursanvändning inom området har utvecklats mellan 2018 och 2024, samt diskuterar frågor som rör framtida instrumentering, kompetensförsörjning, internationell utveckling och samordning av användargrupper. Den bygger vidare på *Utredning av synkrotronljus och frielektronlaserlandskapet utifrån den svenska forskningens behov* från 2019, skriven av Per Ahlberg, Gisela Brändén, Marianne Sommarin och Anders Nilsson (som i föreliggande rapport refereras till som "the 2019 report").

Rapporten är en fristående expertanalys och speglar författarnas egna bedömningar och slutsatser. Rapporten utgör nu ett av flera underlag i Vetenskapsrådets fortsatta strategiska arbete med att utveckla infrastrukturer för svensk röntgenvetenskap och maximera forskningsnyttan av investeringar i anläggningar som MAX IV och andra relevanta ljuskällor.

Vetenskapsrådet tackar SSUO:s styrelse för det betydande arbete som lagts ned och för de insiktsfulla analyser och förslag som presenteras.

Stockholm, november 2025

Lisbeth Olsson

Huvudsekreterare, Rådet för forskningens infrastrukturer, Vetenskapsrådet

Authors' preface

This report, commissioned by the Swedish Research Council and authored by the executive board of the Swedish Synchrotron and Free Electron User Organisation (SSUO), provides a strategic overview of X-ray science in Sweden from the perspective of Swedish users. It focuses mainly on synchrotron radiation (SR) and free-electron laser (FEL) research as it stands in 2025. It is intended as an update to a report from 2019 by Ahlberg, Brändén, Nilsson and Sommarin (D.nr. 2018-00061), herein referred to as "the 2019 report".

As part of the process of writing this report the SSUO board initiated a survey that was distributed to the Swedish user community through the MAX IV user office to all users on their mailing list. Furthermore, SSUO board members distributed the link to their contact networks. The list of questions in the survey can be found in Appendix 1. Secondly, the SSUO board interviewed key representatives of the user and facility communities, who are listed in Appendix 2. The interviews were structured around questions from the Terms of Reference for this report supplied by the Swedish Research Council (Appendix 3). Thirdly, the authors commissioned a bibliographic study from LINXS and the Lund University Collaboration Office. This study was based on the LINXS-Lund University data set version 3.2. The data on the total participations and authors participating in light source-related publications was downloaded from www.scival.com on 2nd December 2024 with some additional data downloaded on 25th January 2025. The analysis was performed and provided with permission by Martin Stankovski-Clark, Farhad Khotbehsara & Franz Hennies in 2025. These data are presented in Figures 1, 2, 5 and 6.

Sammanfattning

Rapporten belyser vikten av synkrotronljus för Sveriges vetenskapliga produktion och visar att svenska forskare är djupt engagerade i det globala vetenskapliga synkrotronljus- och frielektronlasersamhället, med omfattande användning av storskaliga forskningsanläggningar, t.ex. den svenska anläggningen MAX IV, och PETRA III, ESRF och EuXFEL m. fl. MAX IV är en världsledande synkrotronljuskälla som servar både nationella och internationella forskare och används för forskning inom flera discipliner, t.ex. materialvetenskap, biologi, kemi och fysik.

En central styrka inom Sveriges röntgenvetenskapliga forskning är dess metodologiska mångfald och tvärvetenskapliga ansats, som omfattar både grundläggande och tillämpad forskning. De strategiska investeringarna i MAX IV, tillsammans med tillgången till andra högenergetiska synkrotroner och frielektronlaseranläggningar, möjliggör för svenska forskare att genomföra banbrytande studier inom exempelvis katalys, energilagring, funktionella material, livsvetenskaper och läkemedelsutveckling, både inom akademin och i allt högre grad inom industrin.

Rapporten tar även upp framväxande utmaningar och rekommendationer för framtida infrastrukturutveckling. Vi diskuterar MAX 4U-uppgraderingen, som har föreslagits för att upprätthålla MAX IV:s konkurrenskraft inom synkrotronljusbaserad forskning. Behovet av förbättrade detektorteknologier och databehandlingskapacitet lyfts fram, med förslag på riktade program för att stärka svensk expertis inom datadriven fotonvetenskap.

En viktig del av Sveriges synkrotronstrategi, som diskuteras i rapporten, är att främja samarbeten mellan MAX IV och andra nationella och internationella anläggningar, särskilt den närliggande European Spallation Source (ESS). Integration av röntgen- och neutronmetoder öppnar nya möjligheter för materialkarakterisering och strukturbiologiska tillämpningar.

Rapporten förespråkar riktade investeringar i infrastruktur, användarstöd och utbildningsprogram för att maximera forskningsresultat och säkerställa fortsatt excellens inom röntgenvetenskap. Även initiativ som nationellt diskuteras men som av författarna bedöms mindre prioriterade är belysta.

Sammanfattningsvis drar rapporten slutsatsen att svenska investeringar i synkrotron- och frielektronlaserforskning är väl avvägda med avseende på både globala och nationella trender, men att fortsatta insatser krävs från många aktörer för att hantera tekniska och ekonomiska utmaningar. Strategisk styrning, förbättrad tillgång till stråltid och internationella partnerskap kommer att vara betydelsefulla för att bevara Sveriges framstående roll inom röntgenvetenskap och bibehålla dess roll i att driva framsteg inom fotonbaserad forskning.

Summary

This report highlights the importance of synchrotron radiation (SR) for Sweden's scientific output, demonstrating that Swedish researchers are highly engaged in the global photon science community, with significant usage of a number of large-scale research facilities like the Swedish facility MAX IV, as well as the international facilities PETRA III, ESRF, EuXFEL and others. MAX IV is a world-leading SR source serving both national and international scientific communities, fostering research across multiple disciplines, including materials science, biology, chemistry, and physics.

A core strength of Sweden's X-ray science community lies in its methodological diversity and interdisciplinary approach, spanning fundamental and applied research. The strategic investments in MAX IV, combined with access to other high-energy synchrotrons and free electron (FEL) facilities, enable Swedish researchers to perform cutting-edge studies in e.g. catalysis, energy storage, functional materials, life sciences, and drug development, both in academia and, increasingly, in industry.

The report also emphasises emerging challenges and recommendations for future infrastructure development. We discuss the MAX-4U upgrade that has been proposed as a step to maintain MAX IV's competitive edge in synchrotron research. The necessity of enhanced detector technologies and data-handling capabilities is shown, with calls for dedicated programs to strengthen Swedish expertise in data-driven photon science.

An important aspect of Sweden's synchrotron strategy involves fostering collaboration between MAX IV and other national and international facilities, particularly the nearby European Spallation Source (ESS). The integration of X-ray and neutron methodologies presents new opportunities for comprehensive material characterization and structural biology applications.

The report advocates for targeted investments in infrastructure, user support, and training programs to maximize research output and ensure sustained excellence in X-ray science in close collaboration with Swedish universities.

Overall, the report concludes that Swedish investments in synchrotron and FEL research are well-aligned with global and national trends, yet continued efforts are needed to address technical and financial challenges. Strategic governance, enhanced access to beamtime, and international partnerships will be crucial in securing Sweden's leadership in X-ray science and maintaining its role in pioneering advancements in photon-based research.

1 Significance of photon science for Sweden

X-ray science represents a key area of expertise within Swedish research, and Swedish X-ray scientists are internationally recognized for their pioneering contributions to the field. This scientific tradition dates back to the development of X-ray emission spectroscopy (XES) by Manne Siegbahn in the 1920s and the advancement of X-ray photoelectron spectroscopy (XPS) by his son Kai Siegbahn in the 1980s (both awarded Nobel Prizes in physics for their discoveries). Additionally, the successful development of a Swedish synchrotron by Mikael Eriksson and colleagues at the former MAX-lab in Lund from the 1970s onwards further contributed to Sweden's leadership in X-ray research. It culminated with MAX IV, the world's first synchrotron based on multi-bend achromat (MBA) technology, which has subsequently been adopted by all major synchrotrons world-wide as part of their upgrades.

A bibliographic survey commissioned from LINXS Institute for X-ray and Neutron Science (LINXS) and the Lund University Collaboration Office as part of this report[1] revealed that Sweden lies in seventh place in Europe in terms of total author participations[2] in light source publications from 2014 to 2023. The 5 130 participations recorded represent 1.1 % of the total scientific research output in Sweden (464 151 participations) under that period (Figure 1a). This is a greater proportion than all other countries in Europe with the exception of France (1.4 %), Switzerland (1.3 %) and Germany (1.2 %). Looked at in another way, in terms of the number of unique authors active in light source publications as a proportion of the total number of unique authors of science papers, Sweden lies in third place in Europe (2.9 %), after Switzerland and France (3.0 %) (Figure 1b). Approximately 8 % of Sweden's scientific publication from light sources during 2014–2023 originated from free electron lasers (410 participations).

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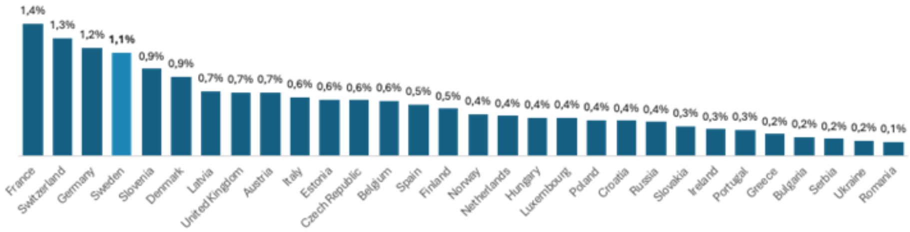
[1] Swedish participation in light source publications globally 2014-2023 – Internal report for the Swedish Synchrotron and Free Electron Laser Users Organisation (SSUO); Stankovski Clark, M., Abbas Pour Khotbehsara, F., and Hennies, F., LINXS Institute for Advanced Neutron and X-ray Science and the Cooperation Office, Lund University, (Feb 2025), © Some rights reserved.

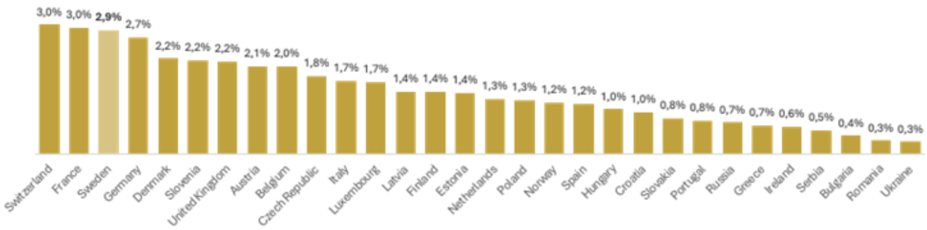
[2] A participation is defined as a unique author contribution to a research article. A single article may thus result in several participations.

Figure 1a. Europe Top 30 – percent of participations related to light source science vs all science in each country in the period 2014 to 2023



Proportion of participations in light source publications in each country vs. all participations in all science for that country, as indexed in the Scopus database.

Figure 1b. Europe Top 30 – percent of authors engaged in light source science in all science in each country in the period 2014 to 2023



The corresponding proportions of authors participating on those light source publications vs. all authors participating in all science in the country, as indexed in the Scopus database. The histograms are restricted to the 30 top countries in Europe by absolute volume of participation in light source publications.

Figure 2 shows the trend in participation of researchers from different Swedish universities in light source publications from 1996 to 2023. The main centres of light source research in Sweden are Lund University and Uppsala University, whose researchers contributed 32 % and 28 % respectively of total participations under 2014–2023. These are followed by KTH at 17 % and Stockholm University at 15 %. A cluster of six other universities lies around 4–8 %[3]. Apart from a general upward trend, no significant variation can be seen in the output of any individual university. The visible decline in overall output in 2023 overall, as well as for all the top contributing universities, may be a delayed effect of the COVID-19 pandemic in 2020–2022.

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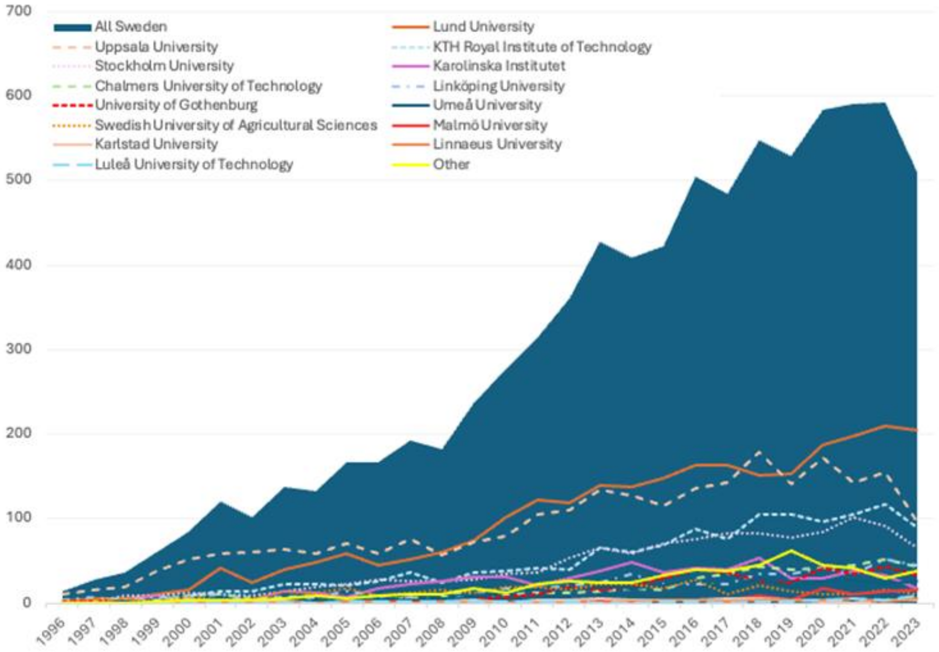
[3] The percentages add up to more than 100 % due to participations of multiple universities in the same publication - see legend to Figure 2.

Figure 2. Participation of MAX IV URG member universities in light source publications over time



Analysis of the participation of Swedish universities in light source publications from 1996 to 2023. The filled dark blue area diagram in the back shows the total number of participations in light source publications with at least one Swedish affiliation per year. The overlaid line diagrams show the number of participations with at least one affiliation from the universities that are members of the MAX IV University Reference Group (URG), with any other organisations collected in the category "Other". Each line diagram shows the proportion of the total set in the area diagram in which the corresponding entity participates. Several Swedish organisations can participate in a single publication, so the line diagrams do not sum up to the level of the area diagram.

We would like to highlight that the Swedish research community that uses light sources is very diverse. This community covers a wide range of topics, ranging for example from macromolecular crystallography (MX) to fundamental atom and molecular physics to applied research on functional devices. In this way, it encompasses researchers from many different areas (e.g. from fields within biology, medicine, chemistry, physics, engineering). At one extreme, some experiments are very standardised, for example MX, where the hardware and software are quite similar across Europe and the world, meaning that samples can essentially be shipped to almost any synchrotron and experiments performed remotely within a few hours. For this kind of research, synchrotron light sources and free-electron lasers are often only one of multiple research tools used by research groups to solve a given scientific problem. At the other extreme are experiments where the sample environments, data collection protocols and data processing software are unique to either the beamline or the research groups themselves. This type of experiment often involves lengthy stays at the light source involving several group members. For researchers working in this way, developing X-ray methods at large scale facilities is often a main research goal in itself.

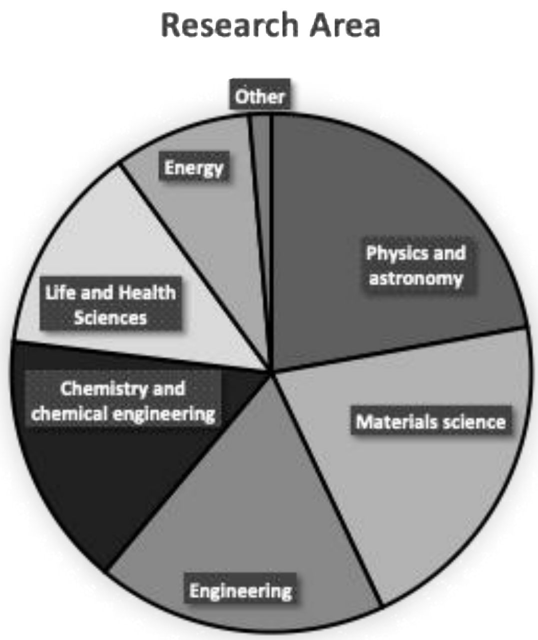
This diversity in the use of synchrotrons and free-electron lasers is one of the core strengths in the nature of such facilities: they cater to a very broad audience of researchers in academia and industry, but that also makes general statements about their usage challenging. With this in mind, it is important to understand that both the attitude and needs of researchers using such facilities will vary widely. In this report, we will therefore give an overview of the needs of the Swedish X-ray community but given its highly diverse nature we cannot cover everything, and we are also aware that needs within the research community might at times be conflicting (at least within the framework of limited resources). When describing the user community, we will therefore aim to showcase examples that can highlight its variety rather than aiming to be all-encompassing.

2 Swedish research needs

2.1 Research at large-scale facilities funded and co-funded by Sweden

Modern X-ray science is performed at large-scale accelerator-based facilities with very diverse applications cutting across many fields of science. As noted above, due to this breadth of scientific fields, research questions, methods and approaches, the interests and needs of the Swedish community are also diverse (see Figure 3). A few selected examples representing different fields are given below. The aim of these examples is to highlight the diversity of the field and to give some insights into current method developments and requirements, but the sample is inevitably incomplete.

Figure 3. Distribution of SSUO members in various research areas



The chart shows the distribution of research areas that members of SSUO connect themselves to. On average, one researcher connects to nearly 2.4 areas. Source: SSUO user survey autumn 2024.

Swedish funding goes to a variety of synchrotron and free-electron laser facilities, reflecting the breadth of research. Naturally, the main share of the budget is allocated to MAX IV in Lund which functions as the Swedish national node for X-ray science. MAX IV has storage rings with lower electron energies (1.5 and 3 GeV) than some other facilities in Europe and thus caters more towards the production of soft X-rays and lower hard X-ray beams. Additional funding is devoted to complement MAX IV research opportunities with access to the higher energy storage rings ESRF in Grenoble, France and PETRA III in

Hamburg, Germany. At PETRA III, Swedish funding results in privileged access to beamtime.

Storage rings have limitations when it comes to temporal resolution and ultimate photon density. They are complemented nowadays by X-ray free-electron lasers, with eight facilities in user operation worldwide (four of which are located in Europe) that produce intense and ultrashort X-ray pulses. Swedish funding is also given to the European XFEL facility (EuXFEL), which allows for experiments at a rather high repetition rate. This results in unique research opportunities that cannot be satisfied elsewhere in the world at the moment. Swedish usage of the EuXFEL facility is high (5.5%, see section 3.1 below).

All in all, Sweden focuses its funding on a powerful and complementary set of facilities. Acknowledging the diversity of Swedish research performed at large-scale X-ray facilities, the funding allocation to facilities appears well-distributed and matches well with the expectations of the community.

2.2 Examples of important scientific developments

2.2.1 Catalysis *in operando*

X-rays allow us to probe and understand the chemical configuration of molecules adsorbed on surfaces. During catalytic processes, the interaction of molecules with the surface is the fundamental step that often determines the energy need of the process as well as the outcome. This applies to virtually all processes that are necessary for a transformation of energy production for a sustainable future like the production of solar fuels, conversion of CO_2, or alternatives to using natural gas as chemical feedstock.

Usually, probing these processes requires ultra-high vacuum conditions and is limited to steady-state conditions of the reactions without information on the fundamental reaction steps. Swedish researchers have pioneered the field by overcoming both limitations, albeit in separate experiments so far: using a free-electron laser, reaction steps could be dissected on the femtosecond timescale in vacuum. A Swedish-owned instrument at PETRA III now allows recording spectra at pressures up to 1 bar, which is about 100 times more than any other instrument allows. The potential upgrade to PETRA IV would shrink the beam size and enable the instrument to reach even higher pressures, potentially up to 3 bar, even closer to industrial reaction conditions. It is proposed to build a similar instrument in Sweden at MAX IV within the SpectroWISE beamline project. Swedish researchers are furthermore working on merging both concepts into a single instrument to combine spectroscopy, up to 1 bar pressure, with FEL-enabled femtosecond time-resolution within the Wallenberg initiative for materials science of the Knut and Alice Wallenberg foundation. The project is led by Martin Beye at Stockholm University.

2.2.2 Energy conversion and storage

Hot topics in X-ray science with a large potential impact on society are energy conversion (e.g. solar cells, thermoelectricity and water splitting) and storage (e.g. batteries and supercapacitors), and Swedish researchers are very active in this field. X-rays can give a unique understanding in such devices across length scales, from the atomic characterisation of materials and interfaces to the understanding of the function of a whole device towards a long-term analysis of device stability and important degradation processes. For these purposes, scattering as well as spectroscopy techniques are commonly used by Swedish researchers, often at multiple synchrotrons around the world.

Future developments in this Swedish line of research are aligned with scientific developments around the world and focus on increasing access to device characterisation during operation (*in operando*), real time investigations of materials and their interfaces (*in situ*) as well as accompanying the X-ray characterization with additional, complementary probes simultaneously (multimodal). The latter especially requires the upgrade of instrumentation at synchrotrons beyond the core methods normally available but promises large benefits for a better understanding of materials, interfaces and devices.

2.2.3 Advanced functional materials

Research on functional materials is a cornerstone in the portfolio of Swedish X-ray science with successful collaborations between academia and industry. The range of materials studied with synchrotron radiation and free-electron lasers is very broad, from exploratory studies of materials with potential for future magnetic and non-magnetic data storage and processing, to novel materials for sensing applications, porous or monolayer materials for electrodes, thermoelectrics, hard coatings for cutting tools, radioactive materials and materials for application in functional devices.

Success in this field of synchrotron radiation X-ray science hinges on the availability of a large set of spectroscopic and diffraction techniques (sometimes with nanometre resolution) in various sample environments, including cryogenically cooled or heated environments, as well as the availability of external electric and magnetic fields. Successful materials science research is coupled to programs to grow and pre-characterize the materials before beamtime. While in special cases the sample growth needs to occur in close vicinity to the experiment, or even in-situ at the beamline due to challenges in transporting for example air-sensitive samples in vacuum suitcases, often the materials are produced and pre-characterized in the researcher’s home labs before specific research questions are proposed and answered at synchrotron radiation facilities. Especially the handling of radioactive materials here poses organizational challenges that also concern the organization of future combined MAX IV–ESS samples (see section 8 below).

A concerted effort is needed for a successful project using synchrotron radiation, from sample production and characterization through to the beamtime and subsequent data analysis. The required project budget has therefore outgrown typical grant sizes in the past years and successful future projects within this research area are thus endangered. At the current stage, ad-hoc solutions are used, such as cross-financing between projects, use of old samples or old characterization data, or international collaborations with partners that have access to larger budgets. For sustainable success in Swedish synchrotron radiation and free-electron laser research, larger project grants are required.

2.2.4 Cutting edge life sciences research

Synchrotron radiation-based life science research is carried out at all major Swedish universities and utilizes several beamlines at MAX IV, including BioMAX, MicroMAX, CoSAXS, NanoMAX and ForMAX. Examples from BioMAX include the development of both small molecule and protein-based therapeutics targeting multiple diseases. Examples from NanoMAX include 2D fluorescence mapping of fibrotic lung tissue samples. At the ForMAX beamline, even if it is primarily oriented towards investigating forestry related samples, the X-ray energy is also optimal for scanning both life science and food science related samples. Experiments carried out range from in-situ 4D tomography of freeze-dried probiotics to SAXS imaging of brain tissue and tomography of tendons.

Though not in itself a photon-based method, cryo-electron microscopy is increasingly becoming integrated into the portfolio of methods offered by synchrotrons around the world. In Europe, powerful cryo-electron microscopes are available at Diamond Light Source, the ESRF, the DESY campus, SOLEIL and SOLARIS. Such an electron microscope (externally funded) has just been installed at MAX IV, and co-localization with beamlines such as BioMAX, MicroMAX, CoSAXS and ForMAX promotes synergies between electron- and photon-based structural biology techniques. Cryo-EM can be used to study large, challenging macromolecular complexes but is a relatively expensive and low-throughput technique compared to X-ray crystallography, so the latter will remain the method of choice for smaller proteins and complexes that can be crystallized. Also, X-ray crystallography is uniquely suited for high-throughput screening of protein-ligand complexes that are critical to both the academic and pharmaceutical sector, as well as fragment screening (see next section), and finally time-resolved studies such as those possible at MicroMAX. Thus, continued support to X-ray crystallography beamlines is justified.

2.2.5 Drug development

Atomic resolution structures of biological macromolecules provide crucial insights into their function and are essential for understanding biomolecules and developing therapeutics. Structure based drug development is currently used by both academic and industry users at MAX IV for the development of novel drugs targeting for example cancer, inflammation and viral infections such as COVID-19. Swedish researchers working with drug development are also frequent users of Diamond Light Source, DESY and to some extent the ESRF, especially since remote data collection eliminates the need for travel.

BioMAX was one of the first operational beamlines at MAX IV and has been highly productive for several years, providing the life science community with a state-of-the-art and highly dependable beamline. In recent years, automated data collections and remote access have been well established and are now routine, leading to a very high and efficient output for all users.

Crystallographic fragment screening has become an established drug development strategy: to date, it has led to the discovery of six novel drugs, and more than 40 additional molecules are currently in clinical trials. Fragment screening technology is implemented at Diamond Light Source and the ESRF. FragMAX at MAX IV, which was funded through the Swedish Research Council 2018 call for grants promoting accessibility to infrastructure, has made structure-based fragment screening available and feasible for academic users. This opens a range of exciting possibilities for academic users to access fragment screening to address both basic science questions and to use it for the development of novel drugs.

2.2.6 Soft matter

There is significant interest in soft matter research in Sweden, encompassing a wide range of application areas. At the CoSAXS beamline of MAX IV, small-angle X-ray scattering (SAXS) has been used to study supramolecular hydrogels, with applications in biomimetic materials and optoelectronics, as well as to study the structure of quick clays, the collapse of which is often responsible for landslides. SAXS is also used extensively to study the physicochemical properties of drug formulations, both small molecules and, especially, biological drugs such as antibodies and biosimilars. The latter was the subject of a concerted community action through the NextBioForm network funded by Vinnova. LINXS also recently funded a successful theme called “Northern Lights on Food”, which aimed to better understand the complex structures of foodstuffs and how they change during processing, as well as the structure of food packaging. This theme, which brought together academia and industry, had a significant soft matter perspective, utilising a variety of X-ray and neutron scattering techniques. The ForMAX beamline, funded by the Knut and Alice Wallenberg Foundation and the Swedish forestry industry through the Treesearch network, has a special focus on the development of novel fibrous materials from forest resources, but can also be used for e.g. food science and biomedical research.

2.3 Results of the user survey

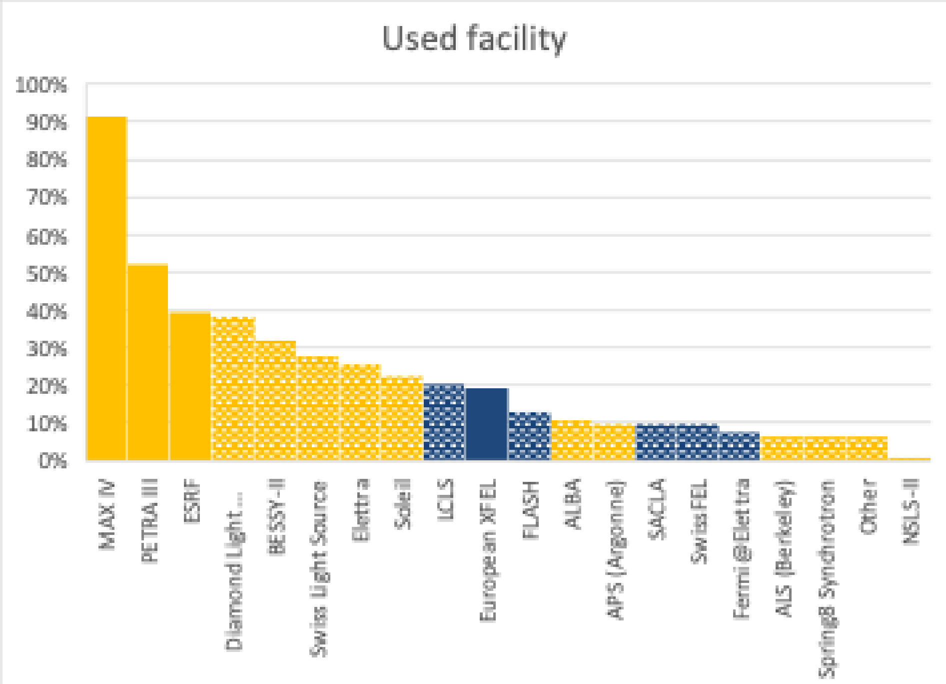
The user survey was distributed as described above, and the questions can be found in Appendix 2. With 119 respondents, the survey reflects a significant part of the Swedish community that uses synchrotrons and free electron lasers but does not represent the full breadth of the field. We believe that the community is much larger and thus the survey results may be biased, for example towards MAX IV users (since the user mailing list was one of the means to distribute the survey) or towards researchers that are critical towards the facilities and used the survey as a means to voice their criticism.

It is hard to get a good estimate of the actual size of the SR user community in Sweden. However, we can attempt an estimate based on usage of MAX IV. In 2024, MAX IV registered about 800 Swedish users and nearly 190 projects lead by Swedish affiliates. We might speculate that a majority of the 119 respondents to our anonymous survey are project leaders with a long-term interest in Swedish SR science. Given the potential bias of responses towards active MAX IV users, we may have received replies from more than half of the Swedish community of SR PIs. Unfortunately, we cannot quantify the number of SR users that have not been active in 2024 at MAX IV.

Naturally, the national synchrotron facility MAX IV received a large part of the user comments (see section 3 below for details). In contrast to the 2019 report, responses reflect that several past areas of criticism of MAX IV have developed very positively and the current activities and future plans of MAX IV promise to develop it in exactly the direction that caters best to the needs of the community. Nevertheless, answers from the user survey still pointed to some deficiencies which have been forwarded to the MAX IV management as input for future developments. Details will be discussed later in this report. In general, the connection between the research community at Swedish universities and MAX IV should be stimulated and ensured by different means that will be discussed in the recommendations.

Notably, Swedish researchers who have signed up as members of SSUO report experience from 14 different synchrotron or free-electron laser facilities around the world. Nearly everyone claims experience from MAX IV, and 90 % have experience from more than one facility. More than half the Swedish researchers use four or more different facilities, and a quarter actually use six or more. The Swedish community is thus not only very diverse but also uses many different facilities that are not funded by the Council for Research Infrastructures (and also not paid for by the researchers; see Figure 4).

Figure 4. Facilities used by SSUO members



On average 4.5 different facilities have been used by each member. The facilities co-funded by the Council for Research Infrastructures are solid coloured, not funded are dotted, synchrotrons are yellow and free-electron laser facilities are blue. Source: SSUO user survey autumn 2024.

Besides MAX IV, Swedish funding goes to synchrotron sources that operate at a higher electron energy to produce X-ray beams with complementary properties to those of MAX IV and thus open other opportunities. About three quarters of the Swedish researchers in SSUO claim experience from one of the three non-Swedish, but co-funded by the Council for Research Infrastructures, facilities (ESRF, PETRA III and/or EuXFEL).

Beyond that, usage of other facilities, not co-funded by the Council for Research Infrastructures, is justified by Swedish researchers mostly due to the availability of special equipment or methods (about 50 % of the replies). About a quarter replied that it is easier to get beamtime elsewhere, while another reason was the lower level of user support at MAX IV as compared to other facilities.

2.4 Industrial usage of synchrotron radiation in Sweden

Synchrotron radiation has become an indispensable tool for advanced materials characterization and innovation, for industry as well as academia. Swedish companies have increasingly recognized the value of synchrotron radiation for solving complex industrial challenges. In 2024, MAX IV allocated 850 hours of proprietary beamtime, of which 52 % was to Swedish companies.

For example, SECO Tools and Husqvarna stand out for their research on hard coatings for cutting tools. Cutting tools endure extreme conditions during use, such as high temperatures and mechanical stress during turning and cutting. Synchrotron techniques such as X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS), allow these companies to investigate the microstructure, phase composition, and thermal stability of coatings at unprecedented resolution.

Gränges, a global leader in aluminium engineering, uses synchrotron radiation to advance flux-free brazing technology for heat exchangers. Heat exchangers must exhibit excellent thermal conductivity, corrosion resistance, and mechanical strength. By employing synchrotron techniques such as XPS and XAS, Gränges studied the interaction of aluminium surfaces at the atomic level, optimizing processes and materials to achieve superior performance without relying on flux-based brazing methods. Similarly, AlfaLaval has studied heat exchangers made of stainless steel.

Access to synchrotron radiation is also of key importance for the Swedish pharmaceutical and food industry, directly by big pharma companies such as AstraZeneca, small-to-medium enterprises such as Sprint Bioscience and Camurus, as well as contract research organisations such as SARomics Biostructures. In the pharma sector, rapid access, remote access, automation and high throughput are critical to the success of drug design projects.

Despite its transformative potential, many industrial users without prior knowledge of synchrotron facilities face significant barriers, particularly in advanced data analysis. An analysis of current bottlenecks was recently published by the Swedish Research Council[4]. To address the problem, Swedish academia must play a pivotal role in bridging the gap. Universities and research institutes often partner with industry to provide expertise in experiment design, data collection, and analysis. Collaborative projects not only facilitate access to synchrotron facilities but also train industry personnel in interpreting complex datasets.

For instance, collaborations between MAX IV and academic institutions enable research programs tailored for industry. Examples are a number of Vinnova-financed programs in their calls “Industrial pilot projects for utilisation of large-scale infrastructures for neutron and photon-based techniques” in several calls between 2018 and 2023 which involved companies, universities or public research institutions like RISE, and MAX IV. These programs typically involve developing tailored experimental setups and are enabled by the expertise of synchrotron scientists. As a result, industrial partners can overcome knowledge barriers and unlock the full potential of synchrotron radiation for their R&D efforts.

While the benefits of synchrotron radiation are clear, broader industrial adoption faces challenges such as high costs, limited in-house expertise, and the need for long-term commitment. To mitigate these issues, Vinnova and the Swedish Research Council have invested in initiatives that promoted industrial usage of

[4] Bottlenecks that delay the benefits of large-scale research infrastructures (pdf)

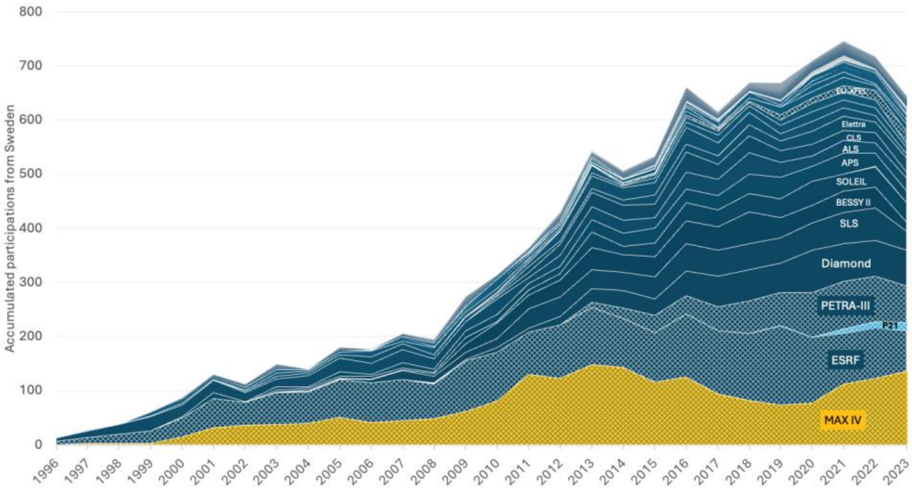
synchrotron radiation facilities, including subsidized access programs, training workshops, and public-private partnerships aimed at fostering innovation.

3 Facilities co-funded by the Swedish Research Council

3.1 Overview

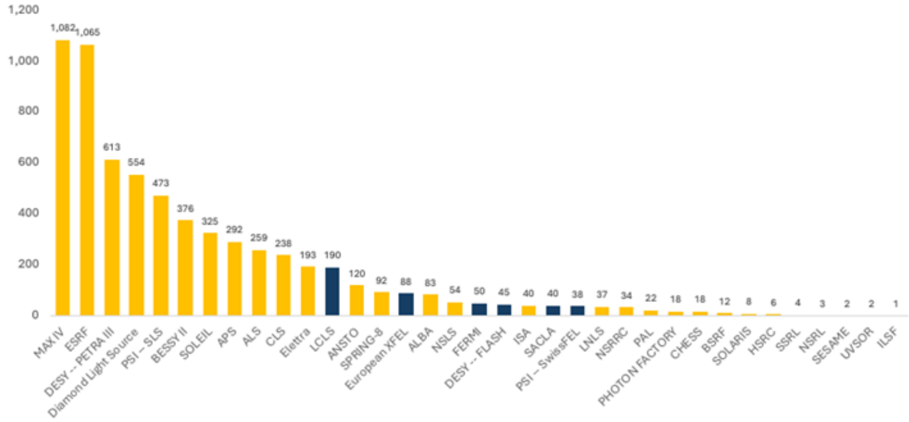
The Swedish Research Council currently funds MAX IV with 390 million SEK annually (2024 numbers), as well as Swedish participation in PETRA III (particularly the materials science beamline P21; 15.6 million SEK), the European XFEL (83.2 million SEK), and the ESRF, Europe's largest SR facility (23.2 million SEK). Statistics from MAX IV and the Swedish Research Council point to 41 % Swedish usage of MAX IV in 2023 as well as 5.5 % of the European XFEL, 2.2 % of the ESRF and 7.4 % of PETRA III in 2024.

Figure 5a. Swedish participation in light source publications per facility and year



Graph of accumulated participations in light source publications by Swedish researchers per year from 1996–2023. The MAX IV statistics (yellow) include the old MAX-lab facility. Publications from the Swedish beamline P21 at PETRA III are counted separately (light blue). Facilities funded by the Swedish research council have hatched backgrounds, the others solid.

Figure 5b. Light sources listing publications with participations from Sweden 2014–2023



Histogram of total Swedish participations 2014–2023 by light source. Synchrotrons are coloured yellow, free-electron lasers blue.

Figure 5a shows the accumulated number of author participations in light source publications by Swedish researchers, per facility, from 1996 to 2023. Accumulated data from 2014 to 2023 are also shown as a histogram in Figure 5b. A steady increase in participations in publications from MAX IV between 2020 and 2023 can be observed (from 77 to 136 participations per year), as well as a decline in output from the ESRF under the same period (from 121 participations per year to 75). Though the ESRF is historically the second most productive light source for Swedish users (Figure 5a, it has been replaced by PETRA III in recent years (83 participations in 2023), with the P21 beamline representing a significant part of that output (15 participations in 2023). Diamond Light Source, which is not funded by the Swedish Research Council, lies in fourth place historically but in third place in 2023 (65 participations). Figure 4 confirms the central importance of MAX IV for Swedish photon science and also justifies the use of additional funds for complementary light sources.

Nevertheless, the budget distribution is not aligned with the direct research output from two significant facilities: on one hand, MAX IV takes a larger share of the budget than is reflected in the publication output, but for this Swedish centre for synchrotron radiation research, the national investment is necessary. It is also part of an international tacit deal of exchanging international users between nationally funded facilities. In fact, one can say that the integration of a successful MAX IV into the international research community is the foundation for Swedish researchers to also be successful at international facilities. On the other hand, the budget share of the EuXFEL is also larger than the share in publications. This is justified by the need of certain research questions for intense, pulsed X-ray radiation that is not fulfilled by any other facility, and that the operation of an appropriate facility is much more expensive. A further discussion can be found in section 3.2 below.

3.2 Update on MAX IV and its beamlines

MAX IV is Sweden's national synchrotron radiation facility, building on decades of technical expertise developed at the previous MAX-lab, including its MAX-I, MAX-II and MAX-III storage rings. MAX IV was the world's first fourth-generation synchrotron, inaugurated in 2016. It was the first to implement multi-bend achromat (MBA) technology that offered a huge reduction in emittance. A testament to the significance of this idea is that other synchrotrons around the world have adopted the MBA technology, either in new constructions or in upgrades of existing facilities. MAX IV consists of two storage rings operating at 1.5 GeV and 3 GeV respectively. At the time of writing of the 2019 report, MAX IV was in a very early stage of operation. Of the 16 funded beamlines, only three were open for users (BioMAX, HIPPIE and NanoMAX) and six were in the commissioning phase (FinEstBEAMS, Bloch, Balder, MAXPEEM, Veritas and FemtoMAX). A further seven were at different stages of development (Species, FlexPES, SoftiMAX, CoSAXS, DanMAX, ForMAX and MicroMAX). None of the beamlines accepting users had yet reached maturity.

One can safely say that the situation is radically different today. Sixteen beamlines are now operational (five on the 1.5 GeV ring, ten on the GeV ring and the ultrafast beamline FemtoMAX), all of which are accepting general user proposals. For details of the current beamlines, see the MAX IV annual report for 2024[5]. In 2024 MAX IV hosted 1 732 users from 280 institutions in 34 countries[6]. Many of the deficiencies pinpointed in the 2019 report have been addressed. For example, automation of sample changing at the BioMAX beamline is now highly streamlined and fully unattended data collection is possible from large numbers of samples, just as at other world-leading beamlines of the same type. The total number of users has increased by 80 % compared to the highest number at the former facility MAX-lab, including a 70 % increase in the number of Swedish users[7]. More than half of the users in 2023 had not used MAX IV before. The current proportion of Swedish users is around 40 %, only slightly lower than it was at MAX-lab in its last year of operation. The more rapid increase in the non-Swedish user community can be partially attributed to the world-leading status of some of the new beamlines. The fraction of submitted proposals with a Swedish principal investigator has decreased slightly from 47 % in 2022 to 40 % in 2024; in contrast, the acceptance rate for Swedish proposals increased from 46 % to 55 % between 2022 and 2023. However, the proportion of Swedish usage varies strongly by beamline, from 81 % in 2023 at ForMAX to only 10 % at Bloch. This can be explained in part by the financing models for some of the beamlines (e.g. FinEstBeAMS, DanMAX, ForMAX) but also by the international competitiveness of some other beamlines, e.g. Bloch

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[5] MAX IV Annual Report 2024 (pdf)

[6] Source: Presentation by director Olof Karis at MAX IV user meeting, January 2025

[7] Source: Report to the Swedish Research Council by Franz Hennies

where the angle-resolved photoemission spectroscopy (ARPES) community at Swedish universities has declined.

MAX IV publications are steadily increasing and are set to hit 300 per year in the near future.

3.3 Comments on EuXFEL

The European X-ray free electron laser (EuXFEL) recently changed the funding model for their operations budget to better reflect actual usage. Since Swedish scientists are very active at EuXFEL, the membership fee paid by the Swedish Research Council increased strongly. Before we discuss some opinions from the synchrotron and free-electron laser user community, we will describe the environment and motivations in more detail.

Swedish research at EuXFEL is very successful. Swedish researchers are involved in building instrumentation there, enabled by close collaborations between Swedish research groups and EuXFEL, as well as common PhD students. EuXFEL provides uniquely many free-electron laser pulses per second, and alternative free-electron lasers are in general not on par with its capabilities. Sweden as a stakeholder can use its strategic influence to promote facility developments best aligned with the needs of Swedish researchers - an opportunity that does not exist at any other free-electron laser.

In our user survey, Swedish free-electron laser users mainly criticised the pulse time structure of EuXFEL and seem to prefer a constant repetition rate with temporally equally spaced pulses, potentially even with more pulses per second, like the LCLS-II in Stanford, USA is starting to provide. Strategic influence should be used to promote such an upgrade to the EuXFEL. In the meantime, a dedicated support program to aid Swedish researchers to access the LCLS-II (e.g. through travel support) could be envisioned to enable best science opportunities for Swedish free-electron laser researchers that specifically need high-repetition rate with evenly spaced X-ray pulses. This would ensure Swedish readiness for the complex experiments for the potential upgrade of the EuXFEL.

Additional comments in the survey also addressed missing instrumentation for particular experiments without a common agreement on which instrument is most urgently missing to many researchers.

It is generally obvious that there is a disconnect between free-electron laser users and synchrotron users. While free-electron laser users nearly all also use synchrotron radiation facilities for complementary studies, it is not the case that the general synchrotron radiation user also uses free-electron lasers. This is clear just from the size of the communities, reflecting that synchrotrons serve many experiments at the same time, on the order of 20–30 per synchrotron with about ~40 synchrotrons in user operation worldwide, with strong user communities that have grown since the discovery of synchrotron radiation 75 years ago, while typical free electron lasers can only run a single experiment. EuXFEL can run up to three experiments simultaneously. There are only about eight free-electron lasers in user operation worldwide and the first X-ray free-electron lasers have now been in user operation for less than 20 years. This limitation in the parallel number of experiments as well as in the maturity of the community naturally also limits the research output from free-electron lasers compared to synchrotrons.

Nevertheless, free-electron laser radiation allows for femtosecond time-resolved and non-linear X-ray experiments that can address very different research questions than experiments at synchrotrons. Although the methods used are often similar, the obtained information content is not. These connected research lines are important in the Swedish research landscape.

A direct comparison between budget requests to the Council for Research Infrastructures and publication output numbers is very difficult due to the different parameters that the research addresses. The relative importance of the free-electron laser and synchrotron communities cannot and should not be decided by the communities themselves, but a higher-level strategic analysis needs to be conducted. In preparing this report, it became obvious that opinions within the user community about the relative importance of infrastructure support for synchrotrons versus free-electron lasers diverge widely. This report can thus not supply direct guidance on the question of how to balance the relative budget requests to the Council for Research Infrastructures between free-electron lasers and synchrotrons.

Discussions with the user community point to challenges in mitigation of the increasing EuXFEL cost. The only way to limit the required EuXFEL budget seems to be to limit Swedish access to EuXFEL. Besides the certain impact on Swedish research output, this might also lead to distorted incentives: on one hand, if access to EuXFEL is limited, Swedish free-electron laser researchers will need to go to other free-electron laser facilities for experiments. This will increase travel costs, renders earlier investments less meaningful and brings Swedish users to facilities where no strategic influence can be exerted. Furthermore, the only option to implement limited access is at the stage of granting proposed beamtime. However, this might lead to an awkward situation where either Swedish researchers are left out of projects, in order not to challenge granting of beamtime, or that they actually put other investigators forward on their own research projects for the same reasons. A solution to this problem is complex and can only be found in discussions between all shareholders of EuXFEL, EuXFEL management, the Council for Research Infrastructures representatives and the user community.

3.4 Swedish materials science beamline P21 at PETRA III

The Swedish Materials Science Beamline P21 at PETRA III in Hamburg has been purpose-designed to complement MAX IV and the ESS in advancing materials science, in particular to provide capabilities for studying materials under real-world conditions i.e. *in situ* or *in operando*. Funded by the Swedish Research Council, the beamline is operated by DESY and governed by the

Center for X-rays in Swedish Materials Science (CeXS), run by KTH, Linköping and Uppsala Universities.

The beamline operates at significantly higher photon energies than available at MAX IV, ranging from 40 to 150 keV. This enables deep penetration into bulk materials, which is essential for non-destructive studies of internal structures and properties. Key applications of the beamline are found in the fields of characterizing structural materials (superalloys, ceramics) and energy materials (batteries, fuel cells), catalytic studies and time-resolved studies, for example to follow crack propagation.

By enabling such experiments complementary to what MAX IV can offer, the P21 beamline is an important addition to Sweden's synchrotron research infrastructure.

3.5 Swedish usage of the ESRF

The European Synchrotron Radiation Facility (ESRF) provides high-energy X-ray beams to researchers from around the globe. Sweden, as one of the founding member countries of the ESRF, has played a significant role in both its development and utilization. As a member state, Sweden contributes financially to the ESRF through the NordSync consortium[8] via the Swedish Research Council. Swedish researchers utilize the ESRF's capabilities for the full breadth of synchrotron applications.

The ESRF was often an important nexus for collaboration between Swedish universities, research institutes, and industrial partners. The ESRF-EBS upgrade was completed in 2020 and increased the beam brilliance, similar to what is proposed in MAX 4U (see below). However, during the relatively long upgrade of the ESRF (2 years "dark time"), Swedish research groups moved their engagements from the ESRF to beamlines at other facilities such as Diamond, BESSY and SOLEIL. SLS will also be an alternative for these research groups when its own upgrade is finished. The long dark time has apparently affected the Swedish user community negatively, as engagement in the ESRF by many former user groups has not recovered after the upgrade, as reflected in the decline in participation in ESRF publications (Figure 5a). This trend has been driven in particular by structural biology. Still, some researchers heavily rely on special experimental capabilities at the ESRF, long-standing collaborations, or established protocols and instruments that are missing at alternative facilities.

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[8] Evaluation of NORDSYNC and Nordic Membership of the ESRF (pdf)

4 Use of facilities not funded by the Council of Research Infrastructures

According to the results of the user survey, about 25 % of synchrotron- or free-electron laser-based experiments are carried out at facilities not funded by the Council for Research Infrastructures. On the other hand, more than 50 % of publications with synchrotron or free-electron laser use by Swedish scientists in the past 10 years include other facilities than the ones funded by the Council for Research Infrastructures (Figure 5). This could be partially due to the use of or publications emerging from MAX IV being low between 2017 and 2020, with publications increasing since.

From the user survey and interviews with user representatives, two main reasons are apparent for the use of facilities not funded by the Council for Research Infrastructures:

1. Method or experiment only available at another facility
2. Users apply to several (many) facilities and go where they are granted beamtime. Our membership statistics show that many regular synchrotron users have beamtimes at several different facilities.

A further reason for choosing other facilities (over MAX IV in particular) could be that travel support is provided by the facility (e.g. at Diamond Light Source travel and accommodation are paid for 3–4 users per beamtime). For remote access experiments, even transport costs for the samples are covered. An additional reason given is collaborations, which could be either on-going ones with beamline scientists or collaborations with international researchers for whom a different synchrotron is more feasible.

Overall, we note that an increasing fraction of experiments is being carried out at facilities funded by the Council for Research Infrastructures and the Swedish investment in infrastructure is justified. Such investments improve the accessibility for Swedish researchers (in the case of PETRA-III through preferential access regulations, at ESRF through the amount of access adapted to national investments and travel support). They also enable Swedish influence in strategic decisions when developing the infrastructures further. Other international facilities provide an important complement, when a technique is not available. It is therefore both justified that Swedish users use facilities not funded by the Council for Research Infrastructures, and that non-Swedish users have access to MAX IV.

Diamond Light Source is set to shut down from December 2027 until January 2030 for a major upgrade. This may result in both Swedish and international users turning to MAX IV as an alternative. The MAX IV leadership say that they are prepared for this and welcome it, but it is important that the Diamond Light

Source shutdown does not result in a significant reduction in the proportion of beamtime allocated to Swedish users at MAX IV.

5 Prospects for developments at MAX IV

5.1 The MAX IV soft X-ray laser

In the past, there was a project to convert the short-pulse facility (SPF) injector at MAX IV into a soft X-ray laser, called SXL. The project seems to have lost steam for various reasons, such as the general delay in MAX IV generating research output, the past underperformance of the low-frequency FemtoMAX beamline at MAX IV[9] and the growing competition from more operational free-electron laser user facilities worldwide with higher repetition rates in the MHz regime. The SXL project no longer appears to be aligned with the most pressing needs of the community, while at the same time the required budget for building and operation staff grew and the potential additional research opportunities shrank. Due to this mismatch, we propose that the SXL project is not pursued further.

In order to fulfil near- and long-term needs of the Swedish user community, an upgrade of the existing MAX IV seems more promising. Future long-term alternative developments towards a new facility could also fill a gap in the international landscape: a facility that provides femtosecond pulsed hard X-rays at repetition rates up to the MHz regime with substantially lower pulse intensities than from free-electron lasers would open new opportunities in line with Swedish expertise and research needs, e.g. time-resolved experiments on batteries, energy conversion and catalysis. Such a facility, discussed by some members of the user community, can be rather small, might require investments on the order of tens of millions of SEK and is currently missing on the international landscape of X-ray facilities. To date, conceptual designs have been put forward within the Wallenberg initiative for materials science led by Hermann Dürr at Uppsala University and a demonstrator is proposed such that in five to ten years from now, the concept might be ready to decide upon the installation of such a facility. While a community is still forming around this idea, a need has been recognized that could potentially be addressed by a Swedish facility in the future.

5.2 The MAX 4U upgrade

Sweden has world-leading competence in accelerator physics, as proven by the pioneering design of the 3 GeV electron storage ring at MAX IV. MAX IV is the world’s first fourth-generation synchrotron facility utilizing the multi-bend achromat (MBA) concept. It is a revolutionary advance in electron storage rings with its miniaturisation and combination of several magnetic functions into the same magnetic blocks, invented and tested at the former MAX III electron

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[9] This beamline can be considered a development step towards the SXL but has not yet produced encouraging scientific output. In fact, it made the connected operational challenges of such a facility visible.

storage ring. The MBA concept is now being adopted in upgrades of other synchrotron radiation facilities around the world and significantly reduces the emittance while enhancing the brightness and coherence of the synchrotron light.

Presently, the MAX IV Laboratory is at the conceptual stage of an ambitious upgrade initiative known as MAX 4U, which aims to ensure that MAX IV stays competitive for Swedish research with X-rays for the coming decades. Central to MAX 4U, described as an ingenious and cost-effective surgical intervention by insertion of inverse bends into the magnetic lattice, is the reduction of the synchrotron's emittance to 50-100 pmrad, which would result in significantly enhanced X-ray coherence and brilliance, with smaller beam spots on the samples. The improved coherence would empower coherent X-ray diffraction and imaging, X-ray microscopy, and resonant inelastic X-ray scattering (RIXS) experiments with micron or even sub-micron beam spots on samples. However, to take full advantage of the lower emittance in the 3 GeV ring, the beamline optics also need to be upgraded to enhance energy and spatial resolutions. These advancements would make *in-operando* and *in-situ* studies more accessible, which is particularly relevant for tackling complex scientific and technological challenges such as energy conversion, chemical and biochemical reactions. Furthermore, the higher spatial resolution as a result of the upgrade would support advancements in X-ray microscopy and imaging, allowing for detailed visualizations of structures at the nanoscale.

A key goal of MAX 4U is to achieve the upgrade within the minimum possible dark period of less than a year, and with minimal disruption to ongoing research activities, aiming for completion by 2030. Notably, the 1.5 GeV ring would remain in normal operation throughout the upgrade of the 3 GeV ring. By delivering improved coherence, increased brilliance, and enhanced experimental capabilities with smaller beam spots, this upgrade would ensure that MAX IV remains at the forefront of innovation and discovery well into the next decade and beyond.

Presently, the final total cost of the MAX 4U project is not known. It will necessarily include both the accelerator upgrade itself and upgrading of the optics of at least some of the existing beamlines to take advantage of the smaller emittance of the 3 GeV ring. Therefore, MAX IV is currently carrying out a "Beamline Preparedness Review" to estimate the total cost, which should be weighed against alternative uses of funding towards building new beamlines and improving user support at the existing facility. The true benefit for the different beamlines also needs to be clearly communicated, as several beamlines will, from the user perspective, not benefit as much as others. The wishes of the user community should be clearly taken into account.

5.3 New beamlines at MAX IV

As part of new beamline development at MAX IV, the Wallenberg Initiative Materials Science for Sustainability (WISE) funded conceptual design reports (CDRs) for three beamlines, which were written during autumn 2023 with input from the user community through workshops with more than 100 scientists. Of these, two were selected to continue with technical design reports (TDRs): SpectroWISE and TomoWISE.

If funded and built, SpectroWISE will be a HArd X-ray PhotoElectron Spectroscopy (HAXPES) beamline with a photon energy range of 2.1 – 15 keV. It will offer both ultra-high vacuum (UHV) and ambient pressure endstations. As such the beamline is intended to complement the Species and HiPPIE beamlines, which offer ambient pressure photoelectron spectroscopy at a lower photon energy range (and are both highly oversubscribed). By using higher photon energies, probing deeper into samples is possible, which enables studying functional interfaces and carrying out *in operando* measurements.

The HAXPES technique is available at several other European synchrotrons, however ambient pressure capabilities are not regularly available, and these measurements can only be done at a large facility (i.e. not using equipment in a university laboratory). MAX IV enables these measurements at higher pressures due to the low emittance of the X-ray beam. The user community for HAXPES is large in Sweden (about 100 scientists attended a workshop to discuss the beamline in 2023) and HAXPES was mentioned most often as the technique missing at MAX IV in our user survey. The beamline, if funded, is therefore likely to fulfil a strong need from the Swedish user community.

If funded and built, the new imaging beamline TomoWISE will focus on advanced X-ray imaging techniques tailored to address grand challenges in sustainability, materials science, and life sciences. This aligns with Sweden's vision for addressing sustainability challenges. Its focus on materials science, energy solutions, and life sciences underscores the importance of state-of-the-art imaging in tackling pressing global issues.

Another proposed and highly prioritised beamline is MedMAX, a bio/medical imaging beamline for tomography of soft materials. Tomography is possible at other MAX IV beamlines such as DanMAX, ForMAX and NanoMAX, but there is no beamline dedicated to the method at present. MedMAX would allow visualisation of complex structures and processes in life sciences and soft matter down to sub-µm resolution using hard X-ray tomographic microscopy. Experiments at MedMAX could contribute to understanding of poorly understood physiological and pathogenic processes by enabling µm resolution functional anatomy and pathoanatomy of tissues and even small animals. The beamline is proposed to operate in three modes: µm resolution *in vivo* and *ex vivo* tomography, medium resolution (10-30 µm) fast *in vivo* tomography and nano holo-tomography, with basic spectroscopic capabilities. If funded and built, MedMAX will be one of the most expensive beamlines built at MAX IV, partly due to its length, which is necessary to maximise coherent information and the field of view. Support for a TDR for MedMAX is currently provided by Lund University, but obtaining funding for construction and operation of MedMAX looks likely to be a major challenge.

6 Connections between MAX IV and the Swedish research community

Many countries around the world operate national synchrotrons that cater to an academic user community at many tens of national universities, for example in Germany, France, Italy, the UK, and the USA. In contrast, the number of Swedish universities with SR activities is substantially smaller, and they centralize the basic scientific research community in Sweden and in some cases foster collaboration with industry. This makes it imperative for both the universities and MAX IV, as the Swedish centre for X-ray science, to interact closely and stimulate common developments. The 2019 report described in detail the variety of different activities and initiatives to further X-ray science and use of large-scale facilities by Swedish researchers, which has included strategic recruitments and collaborations through targeted centres around X-ray science, which still exist today. We therefore refer to the 2019 report for a description of some of the initiatives which increase knowledge around synchrotron and free-electron laser facilities and enable new user groups. In addition to these, we would like to highlight some initiatives by MAX IV, where targeted workshops are held together with universities, to inform about the possibilities at MAX IV and to invite new users. Furthermore, since the 2019 report, the fast access program at MAX IV proposed therein has been established, which allows new users to test new ideas or experiments during a shorter beamtime and use the results to apply for full beamtime.

The connection between MAX IV and the Swedish universities is further ensured through the University Reference Group (URG). The URG consists of representatives for all Swedish Universities with research related to synchrotron radiation or free-electron laser facilities. The URG have recurring meetings with MAX IV management and constitute an important link between MAX IV and the user community. A common view among users is that the recent separation of the URG into a “science URG” and a “management URG” is not beneficial. It is likely that this will lead to less interest from “management” in the science and also less interest and understanding in the “science URG” for the problems associated with securing and prioritizing the funding needed to facilitate the research.

LINXS Institute for Advanced Neutron and X-ray Science (LINXS) was established in 2017. LINXS funds networking activities in scientific “themes” within the three core areas of soft matter, hard matter and life science. Current and past themes include integrative pharmacology, food science, cultural heritage, quantum materials, advanced imaging and image analysis, environment and climate. LINXS connects researchers in Lund using MAX IV and the ESS (see below) with an international community. Similar initiatives should be stimulated at other universities in Sweden, or (preferably) the remit of LINXS expanded to cover the whole of Sweden. The LINXS webinar series aiming to get users “ready for beamtime” is a very good initiative that should also be advertised and promoted by MAX IV to the whole of the Swedish community.

Several suggestions for further strengthening the connection between universities and MAX IV have come up in the preparation of this report. For example, the instrument of strategic recruitments should be used between MAX IV and universities to the benefit of both, since MAX IV could commit to provide research opportunities (experimental floor space and beamtime) while the university commits with the recruitment to grow the Swedish synchrotron radiation user community. The Swedish Research Council could stimulate or even support such initiatives through dedicated funding instruments, for example through start-up packages given under very specific conditions. We propose to introduce a specific funding scheme at the Swedish Research Council that allows university groups to suggest and install instrumentation at MAX IV in close collaboration with MAX IV. Such a funding scheme could replace direct MAX IV investments in instrumentation.

Engagement of the user community and growth towards new users should be fostered by targeted workshops, ideally organised from within the user community in close collaboration with MAX IV. Workshops should also specifically cater to young scientists to attract new users. MAX IV could react by for example easing access for new incoming junior group leaders, either formally or by making this an evaluation criterion in the proposal review (as is done for example at the LCLS). Here, the instrument scientists could take a proactive role to encourage new users and give support in writing competitive applications.

A very good example that specifically supports the connection between X-ray facilities and universities is the WISE initiative for sustainable materials science by the Wallenberg foundation. Here, many of the mentioned instruments to stimulate the community are applied, like strategic recruitments, dedicated community building workshops (connecting industry and academia), as well as installing specific funding programs to build strategically appropriate instruments at MAX IV are being used very successfully. Potentially organisations like SciLifeLab and MyFab could benefit from similar integrated concepts and the Swedish Research Council could support such developments.

7 Detectors and data

While synchrotron radiation sources have continuously improved, culminating in the successful user operation of free-electron lasers and storage rings based on MBAs (pioneered by MAX IV), optimal usage requires a fully optimized pipeline leading to research output, including beamlines, instruments, detectors, data acquisition and analysis software and hardware. While Swedish researchers have historically excelled in building excellent beamlines and developing novel instruments (though potentially this has declined in the recent past), larger gaps can be found in Sweden today in the development of detectors and data handling.

The development of optimal X-ray detectors is now a matter of highly specialized expertise, experience and large investments in chip fabrication. Two international development strands can be identified, with the Paul Scherrer Institute (PSI) in Switzerland and their spin-off company DECTRIS dominating one strand, while other developments are pursued in large international collaborations (e.g. AGIPD at EuXFEL and the Timepix/Medipix collaboration headed by CERN). Due to their years-long experience, competing with PSI/DECTRIS is not advised; furthermore, Swedish detector specialists play a role in collaborations with them. Investing in detector development does not seem appropriate and the necessary detectors should be bought or acquired through collaborations.

In any case, it is important to further develop detector operation and the hardware and software pipelines from the detector to the analysed data in a more streamlined way. Here, the Swedish community needs to invest more and further develop appropriate expertise in order to allow for continued high-level research output. Other synchrotron radiation facilities speak of the “data deluge” from modern detectors and investments into appropriate algorithmic developments, computing facilities for storage and analysis (high-performance computing) are taking ever larger shares of the operation cost of facilities. Our user survey reveals a perception by the user community, especially that of MAX IV, that the allocated resources at MAX IV and in Sweden for personnel, hardware and the developed expertise lag behind other countries and facilities. Since expertise in handling and processing of large data is not only important for synchrotron radiation science, but also for modern society in general, it is proposed that efforts are undertaken to develop specific programs between universities and MAX IV in this direction, benefitting the optimal use of MAX IV as well as providing high-valued education for Swedish experts.

Finally, to address the increasing complexity of instruments and experimental setups for the best use of MAX IV or similar facilities, we propose to create a (potentially virtual) “Swedish centre for X-ray instrumentation and data handling” that coordinates efforts between different universities for the best use of MAX IV, potentially under the guidance of MAX IV. A first step could be the organisation of workshops, e.g. in collaboration with SSUO.

8 Connections between MAX IV and ESS

Sweden and Denmark are hosts to the European Spallation Source (ESS) located in Lund, which aims to be one of the world's most advanced neutron sources, with the ambition of starting a user program in 2027. This puts Sweden in the almost unique position of having world-leading X-ray and neutron sources only a few hundred metres from each other. Although the neutron community is smaller than the X-ray community, and has a different topical distribution, connecting Swedish synchrotron radiation and free-electron radiation users with the neutron scattering users is desirable. Most neutron users already use X-rays or are open for X-ray use, while the reverse is perhaps not as true. Nevertheless, the scientific ecosystems are similar, and transfer of methodology is relatively easy. The synergies are especially strong in materials science, soft matter and structural biology. All three fields benefit from complementary information provided by synchrotron radiation, free-electron lasers, and neutron scattering for a deeper understanding of complex systems.

Combining X-ray and neutron scattering, diffraction and imaging techniques in materials science can provide a more comprehensive understanding of a material's structure and properties such as magnetic anisotropy, phase transitions, strain, defects, cracks and mechanical properties, hydration as well as molecular interactions in materials and tracking lithium-ion movement in batteries. The combination of X-ray and neutron investigations allow to visualize both heavy and light elements within the same material. A more complete understanding of material behaviour can be achieved, e.g. of complex magnetism in nanoparticles and of high-temperature superconductivity.

In structural biology, neutron crystallography can be used to find hydrogen atom positions in proteins, DNA etc., which is extremely difficult with X-rays. In the soft matter area, a combination of small angle X-ray and neutron scattering analyses can provide valuable insights into formulation of biological drugs.

Experience at other facilities such as the ESRF and ILL highlights the necessity for smooth administrative procedures for the transfer of samples from one facility to another as samples irradiated by neutrons can become radioactivated. It should also be possible to make common applications for beamtime at the two facilities in an easy manner. The proximity of ESS and MAX IV also presents possibilities for common training activities such as PhD courses similar to the HERCULES training course in Grenoble, as the theoretical and practical aspects of the complementary methods often overlap. The proximity also opens the possibility for common lab-based hubs as sample preparation nodes. Establishment of a strong shared instrument infrastructure, e.g. at Science Village Scandinavia, would create a powerful common environment for sample preparation.

Other activities that should be encouraged are direct scientific exchanges between ESS and MAX IV scientists. At present the two facilities have an informal exchange programme called “Over T/here” where small groups of scientists visit the other facility a few times per year. Each visit has a different theme, and they are an opportunity for facility staff to meet those of the other facility and exchange knowledge.

As mentioned above, the efforts of LINXS in Lund to bring together X-ray and neutron scientists could serve as inspiration at a national level.

9 Comments on specific questions

Before we conclude this document by summarising our main recommendations, we specifically answer some questions from the Terms of Reference (Appendix 3).

How should the Council for Research Infrastructures/The Swedish Research Council act to ensure that the investment in MAX IV will provide maximum return for research conducted in Sweden?

From the user perspective, the best conditions for Swedish synchrotron research will be achieved if MAX IV keeps running reliably with good user support. It should provide access to a variety of experiments, which cover a large fraction of the broad range of user needs. With this in mind, it is important that the Council for Research Infrastructures/the Swedish Research Council investment ensures stable, long-term financing of the running of the facility that covers periods of rapidly fluctuating costs, and that the management can focus its attention on strategic developments of the facility and the associated research environment. A reduction in the number of parties that MAX IV has to negotiate with around financing and a clarification of their respective roles would be positive in this respect.

For the development of the research environment, we propose that MAX IV uses its role as the national centre for synchrotron radiation research to:

- lead efforts to promote its attractiveness to academia and industry in Sweden to attract and support university groups to come as new users
- support Swedish users specifically with dedicated travel grants and long-term access programs
- stimulate strategic hires at universities by offering additional benefits like floor space and access to beamtime.

The last point could also be efficiently supported by targeted grants from the Swedish Research Council to support the common development of experimental infrastructure between universities and MAX IV.

What is being done abroad today that should already or in the future be done on MAX IV (within the currently available beamline setup)?

Other facilities are more advanced than MAX IV in terms of available support during experiments, most specifically in detector development and data analysis facilities, tools and procedures. While the development of new detectors is a costly and risky task where Sweden is already most likely too late to make an impact, dealing with and processing large amounts of data and storage is an important task that needs to be and can be solved in a more efficient way at MAX IV. The MAX IV leadership is aware of this problem. To enable broadening and growth of new user communities of non-X-ray scientists and industry, there is a need for more specialized, directed support and access modes of users to treat synchrotron radiation data. This has been envisioned at PETRA III. Here, opportunities open to strengthen the collaboration between MAX IV and Swedish universities, since MAX IV needs to address the data deluge, while universities need to educate students to deal with large amounts of data. The Swedish Research Council could help here by stimulating and supporting strategic recruitments and with dedicated funding programs to strengthen data handling and storage.

Does a Swedish utilization of MAX IV require a specific focus in terms of future instrumentation at the facility?

No, the consensus among Swedish users appears to be that a national facility for a “small” country like Sweden should provide broad opportunities. The Swedish community does not always need the most sophisticated instrumentation, but rather easy access to well-functioning setups (this is particularly important for education). While a good mixture of simpler and internationally highly competitive instruments is necessary, MAX IV could focus more on providing good access to “simple”, “bread and butter” experiments. Many users feel that the focus on new developments has sometimes been too strong at MAX IV. MAX IV could play a leading role in educating students in synchrotron science and could thus make use of the strong Swedish expertise in the field. This again aims at strengthening the connection between MAX IV and universities, which is considered one of the unique aspects of the specifics of the Swedish environment, where one facility caters to a “small” number of universities.

What can/will be done at MAX IV that would be unique but that is not currently invested enough in? If these areas are invested in, can Swedish users make use of them in a satisfactory way? Are there areas at MAX IV today, where the interest from the Swedish research community is weak?

The strong international exchange between synchrotron and XFEL facilities makes it hard to identify experiments that are scientifically valuable, but also not in focus at other places. The uniqueness of MAX IV is rather found in the close connection of the facility with a “small” number of universities, that should be leveraged in a better and more strategic way, as mentioned above.

Focusing on specific research opportunities instead, there are certainly instruments where Swedish usage is larger than at others, but the community is ever-changing, interests are changing and can in turn also be stimulated and supported. No general statement can be made, other than to propose to connect MAX IV even closer to the Swedish community and stay in close exchange to rectify upcoming issues. The Swedish Research Council should support this with dedicated grant opportunities that strengthen the connection between MAX IV and Swedish universities.

How can the Swedish user community in the synchrotron radiation and free-electron laser area best be coordinated or stimulated so that the Council for Research Infrastructures'/the Swedish Research Council's investments provide maximum research returns?

Swedish X-ray science has historically been very successful, but very unorganised. The mentioned and proposed initiatives in strengthening the connection between MAX IV and user groups and universities are already the foundation stone for the development of a more coherent community. With the reinvigorated SSUO, we hope to contribute also to an improved development of the community, stimulated by workshops and exchanges and hope for funding support by the Swedish Research Council for this endeavour.

10 Recommendations

While we already motivated and formulated the main recommendations in the preceding text, we repeat here the three most important ones from this report.

Funding

- The general funding distribution of the Council for Research Infrastructures towards the different complementary facilities is (very) good and should be maintained.
- Funding should be secured in the long term and responsibilities of the funders clarified, specifically giving a long-term perspective for the MAX IV operation budget.
- The increase in budget for EuXFEL needs to be carefully monitored, but solutions should not impair the excellent Swedish free-electron laser research. An adequate solution requires further discussions with international partners and the community. A strategic decision cannot be prepared by community representatives alone.
- A decline in ESRF usage could be reflected in the future budget distribution.

Development of MAX IV

- We recommend developing MAX IV from “just a synchrotron” to the national centre for synchrotron radiation research in close collaboration with all interested Swedish universities.
- Such a development should be reinforced by targeted calls, funded by the Swedish Research Council, for projects that connect MAX IV and university groups, directly in the scientific fields that use MAX IV, but also for instrumentation for MAX IV, and especially for data handling and processing. In order to strengthen this connection, investments in the areas of instrumentation for MAX IV and around data at MAX IV should be made collaboratively between MAX IV and university groups.

User support funding

- The Swedish Research Council project grants should increase in budget in order to allow for internationally competitive research with synchrotrons and free-electron lasers (naturally at the expense of the number of grants).
- Alternatively, competitiveness of projects with synchrotrons and free-electron lasers could be supported by the Swedish Research Council through other means, like travel support or support in accessing preparation and characterization facilities.

11 Appendix 1: Details of the SSUO user survey

The anonymous SSUO user survey was made available through the MAX IV Indico site along with the possibility to sign up for SSUO membership. There were 124 respondents of whom 100 signed up for membership.

Questions asked were:

1. Please give the percentage of your experiments that use MAX IV. (123 answers)
2. Please give the percentage of your experiments that use other Swedish funded facilities (ESRF, PETRA, EuXFEL). (106 answers)
3. Please give the percentage of your experiments that use facilities without Swedish funding support. (105 answers)
4. If you use facilities without Swedish funding, what is your main reason for doing so? (124 answers)
   a. Method/experiment only available at another facility: 72 (58.1 %)
   b. Difficulty in getting beamtime at Swedish facilities: 37 (29.8 %)
   c. Other facility provides support for travel: 18 (14.5 %)
   d. Other: 22 (17.7 %)
5. If you answered "Other" above, please state your personal reason here. (22 answers)
6. What techniques/instruments (if any), which would be of great importance for your research, are missing from Swedish-financed facilities?

12 Appendix 2: List of interviewees

Olle Björneholm (Uppsala University), chairman, MAX IV University Reference Group

Olof Karis (Uppsala University), director, MAX IV

Andreas Lindblad (Uppsala University), spokesperson, SpectroWISE

Felix Roosen-Runge (Lund University), vice-chair of SNSS (Swedish Neutron Scattering Society)

Jonas Weissenreider (KTH), chairman, FASM (MAX IV user organisation)

Philippe Wernet (Uppsala University), chairman, EuXFEL Scientific Advisory Committee

13 Appendix 3: Terms of reference

Translated from the original Swedish.

Activities at MAX IV started in 2016 and in 2018 an initial investigation was conducted with the aim of mapping the needs of Swedish research in the synchrotron radiation and free-electron laser area and to investigate the extent to which the distribution of resources met these needs. The purpose of the current follow-up is to investigate how needs and resources have developed from 2018 to 2023.

The funding of synchrotrons (SR) and free electron lasers (FEL) for the production of X-ray light occupies a large part of the Council for Research Infrastructures' available budget, and by far the largest investment in the area consists of the operating support for MAX IV, where the Swedish Research Council is the main financier.

Issues to be highlighted:

- What research needs exist in Sweden that utilize X-rays from synchrotron and free electron sources?
  - Which of these needs are covered by the instruments at the facilities that the Council for Research Infrastructures currently finances? What investments are being made and is the impact of the Swedish research that comes out of each facility on par with the investments?
  - Overview of the synchrotron radiation and free-electron laser sources and their beamlines, so that one can relate to the whole of the range. Which, if any, technology/instrumentation areas are missing or weak relative to the needs?
  - How large is the use of sources other than those the Council for Research Infrastructures funds and how important is this use for Swedish research? Does the Council for Research Infrastructures invest in sources in its funding that are relevant to the Swedish research community?
  - Are relevant efforts being made today to increase knowledge in Sweden about the methods used at synchrotron radiation and free-electron laser facilities so that new user groups can come in? What needs to be done to further raise awareness of these resources?
- Which areas within the synchrotron radiation and free-electron laser field are undergoing strong change?
  - How is the front line of engineering/instrumentation changing and what are the consequences?

  - How is the Swedish user landscape changing, e.g. as a result of demographic changes (retirements, relocations, etc.) or other structural changes? Are new areas on the rise while others are on the decline?
- How should the Council for Research Infrastructures/the Swedish Research Council act to ensure that the investment in MAX IV will provide maximum return for research conducted in Sweden?
  - What is being done abroad today that should already or in the future be done on MAX IV (within the currently available beamline setup)?
  - Does a Swedish utilization of MAX IV require a specific focus in terms of future instrumentation at the facility?
  - What can/will be done at MAX IV that would be unique but that is not currently invested enough in? If these areas are invested in, can Swedish users make use of them in a satisfactory way? Are there areas at MAX IV today, where the interest from the Swedish research community is weak?
- How can the Swedish user community in the synchrotron radiation and free-electron laser area best be coordinated/stimulated so that the Council for Research Infrastructures'/the Swedish Research Council's investments provide maximum research returns?
  - Is it practically possible, and if so, desirable, to more actively coordinate the Swedish synchrotron radiation and free-electron laser users with the neutron scattering users (in light of ESS)?
  - Should MAX IV be given a special responsibility for building long-term Swedish competence in the synchrotron radiation and free-electron laser area?
  - How can the transfer of knowledge to Swedish users from the foreign experts active at MAX IV be stimulated?
- When considering the above issues, consideration should be given to several perspectives:
  - A large Swedish future use of MAX IV is desirable.
  - How should the Council for Research Infrastructures/the Swedish Research Council and MAX IV relate to the closure of Diamond Light Source from December 2027 until January 2030?