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An *ex post* impact study of MAX-lab

Short version | October 2017

OLOF HALLONSTEN AND OSKAR CHRISTENSSON
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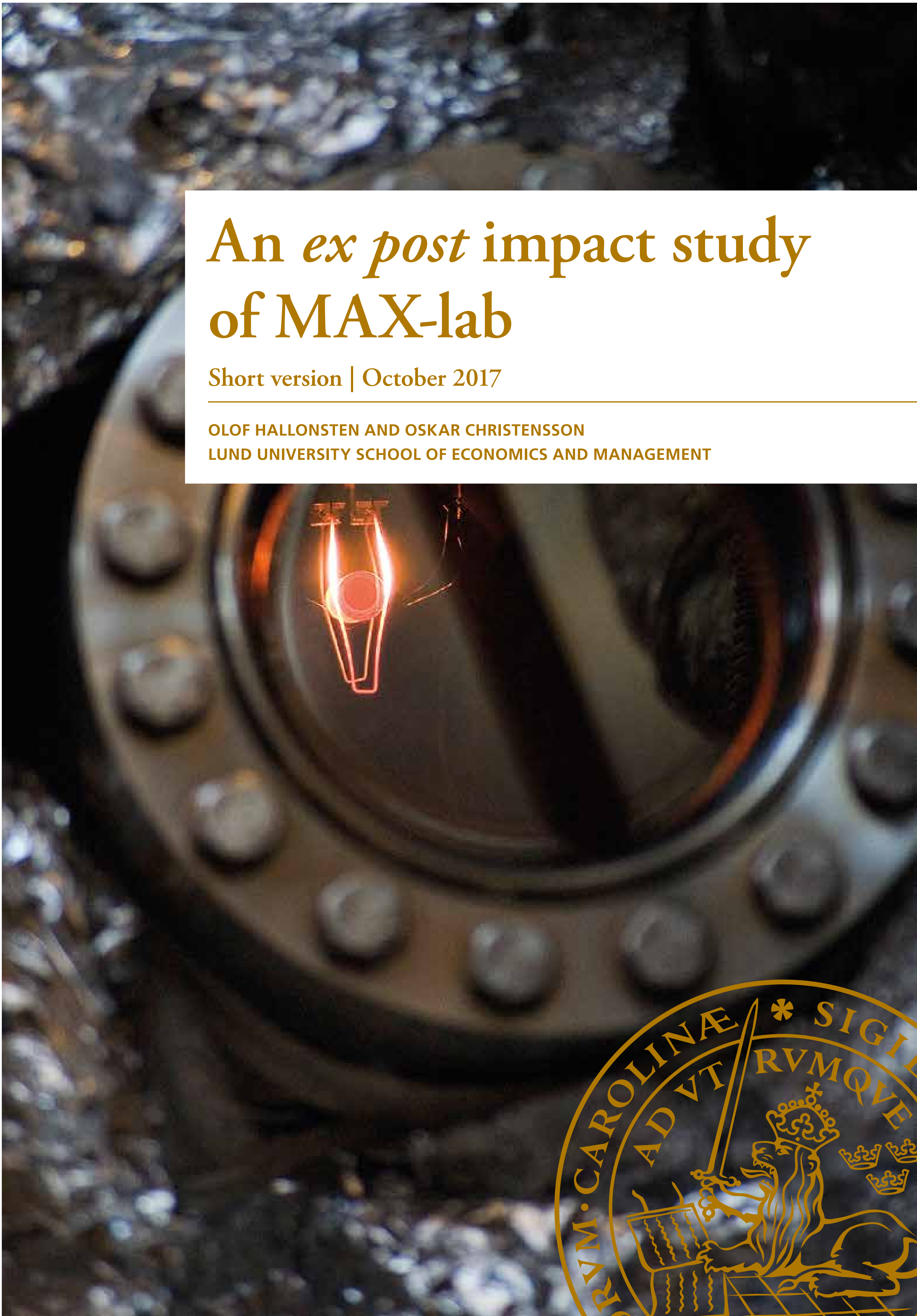

“Is there a reasonable alternative to MAX-lab for Swedish science and technology? Not really: without it, the Swedish users could still access ESRF and other national facilities – but the experience of other countries shows that without a strong national facility the quality and quantity of synchrotron activities would degrade, confining Sweden to a second-rank role.”

Report from the review of the MAX laboratory, Lund, May 2009,
Swedish Research Council report 5:2010, p 24.

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Preface

This is the short version of the report of a study undertaken in 2016-2017 on charge by the Office of the Vice-chancellor of Lund University, and the Swedish Research Council, who also jointly funded the study. The full version of the report will be published separately. In this short version, sources are only given in connection with direct quotes and factual statements. A selected list of literature and other sources used is found at the end.

The following people have read and commented on earlier versions of this report, and contributed significantly to its quality: Ralf Nyholm, Yngve Cerenius, Ingolf Lindau, Thomas Ursby, Bent Schrøder, Derek Logan, Bengt EY Svensson, Svante Svensson, Örjan Skeppstedt, Mats Benner, and Stacey Sörensen.

In addition to those mentioned, we would like to thank Frank Lehner, Stephan Haid, Thomas Kaiserfeld, Jesper Andersen, Johan Holmberg, Anette Styrberg, Julia Lindkvist, Ildikó Toth, Helena Ullman, Jonas Palm Annika Nyberg, Stefan Urniaz and all the interviewees (see list at the end) who were generous with time and information.

Introduction

The MAX laboratory, abbreviated and commonly known as MAX-lab, was a Swedish national research facility located at the Northern campus of Lund University in Southern Sweden. It was originally a small-scale university project in nuclear physics and grew over the years to a Swedish and international user facility for experimental research with synchrotron radiation, which is the use of extremely intense electromagnetic radiation (infrared, visible, ultraviolet and x-rays) for various studies of materials, and with vibrant and highly productive research programs in accelerator physics and nuclear physics. MAX-lab started operation for scientific use in 1986 and closed its facilities 29 years later, in December 2015, ahead of the opening of the successor facility MAX IV (located on a remote site) in June 2016.

MAX-lab had a remarkable history: The first MAX machine (MAX I) was a home-made accelerator, built by a group of enthusiasts with funding from a series of small grants, and mostly an internal university affair. It was originally designed for use in nuclear physics, and adjusted to produce synchrotron radiation in the course of its construction process. When in 1995 the purpose-built synchrotron radiation source MAX II was inaugurated, it brought a significant expansion of the user community and only two years later, the lab had some 400 annual user visits by scientists from 20 countries and within scientific fields as disparate as surface physics and structural biology. By then, MAX-lab had become a national research facility, funded and overseen by the Swedish Natural Sciences Research Council (Naturvetenskapliga Forskningsrådet, NFR). It had attracted investments by several public and private funders and strong support from local and regional authorities, and it had established itself as a vital resource for many fields of research in Sweden, which had made crucial advances with high international scientific standard in symbiosis with the experimental facilities at MAX-lab. The achievements of the lab, and of its users, had become known internationally and its innovative approach to accelerator and instrument development lauded by leading international experts. Another ten years later, MAX-lab was in the midst of a highly advanced and ambitious development project and campaign to replace its existing laboratory resources with a world-leading synchrotron radiation facility under the name MAX IV. When the activities at MAX-lab were discontinued in late 2015, this ambition had been fulfilled and the MAX-lab teams, Lund University, the Swedish scientific communities, and the various patrons of MAX-lab could proud themselves with an achievement that had put Lund University and Sweden on the map internationally, as a natural center of gravity in Northern Europe for infrastructure and instrument development, and scientific use, of synchrotron radiation, a true area of strength on the current global scientific scene.

As a synchrotron radiation facility, providing experimental resources for studies of materials (including biomaterials) to scientific users, MAX-lab has since the beginning of user operation in 1986 been an *open* and *user-oriented* laboratory. As such, it takes place in a group of roughly 40 synchrotron radiation user facilities worldwide (beginning of the 2010s) that serve tens of thousands of scientists in a wide range of sciences. The user-orientation means that MAX-lab, like all synchrotron radiation facilities, functioned as a dynamic and generic resource for scientific communities to make use of, as part of their ordinary research activities. This means that the scientific output of MAX-lab (as any synchrotron radiation lab) is, for the most part, the work of the external users. This presents a challenge to any evaluation of the performance and impact of such labs, including this one. Acknowledging that MAX-lab most of all was a *provider of opportunities* – many times absolutely vital opportunities – for research activities in universities, institutes, and industrial firms, means that proper attention can be paid to the role that MAX-lab had in Swedish (and Nordic, and global) science. Important in this context is the realization that for MAX-lab to be productive and make a scientific impact, it had to actively *cultivate a user community*, and the ability to do so proved crucial for the long-term survival and success of the lab.

MAX-lab remained part of Lund University for its whole history, and this academic connection meant both constraints and opportunities. Integration into the education and research activities of the university enabled contact with vibrant academic communities, but the most important feature of the lab-university alliance was MAX-lab's *essentially academic mode of organization*, which is unusual for synchrotron radiation labs internationally but which secured a close relationship with the user communities and fostered a scientific and academic approach also to the development of infrastructure and instrumentation.

This ex post impact study of MAX-lab takes these essentially qualitative acknowledgements of key features of the lab as a point of departure, which means that the study itself is a deep and qualitative investigation of effects that do not let themselves be captured by simple quantitative indicators but require comprehensive contextual analyses and well-informed discussion. There are several methodological challenges to fulfilling this task, but these have been remedied by the adoption of an open and eclectic approach to the subject, to method, and not least to the definition of impact, which is seen as variable, dynamic, and many times indirect, rather than simply quantifiable and direct. This short version, unavoidably, leaves many of the important nuances out and provides very condensed summaries of the findings. The interested reader should preferably look to the full-length version of the study report for comprehensive and detailed analyses.

Method and material

This is an *ex post* study, which is convenient in terms of delimitations but which creates other method-related challenges such as lack of availability of some material, and incomplete reminiscences of informants.

The study is based on four types of sources. First, as background, some secondary sources were used, most of all personal memoirs of people involved in the buildup and development of the lab, but also scholarly work. Second, printed material, among which the MAX-lab activity reports stand out as tremendously rich in information, has been used for facts and detailed information. Third, MAX-lab employees have been generous enough to provide statistics and detailed compilations of data. And fourth, we have conducted a number of interviews (see list at the end).

Background

To the extent that MAX-lab is Big Science, it is probably "transformed Big Science" or "new Big Science" or at least a latter-day variety of Big Science where large and complex infrastructure is operated not for giant centrally planned and organized experiments (like the work in particle physics at e.g. CERN) but for a variety of projects that each rather qualify as 'little' or 'ordinary' science (Hallonsten 2016a: 43ff). Synchrotron radiation was originally an unwanted byproduct of accelerators built for particle physics experiments, and in the first few decades of exploitation of synchrotron radiation, the activities grew in the shadows of the large particle physics programs, using their machines "parasitically" (Hallonsten 2015; Hallonsten and Heinze 2015). The development of synchrotron radiation "from esoteric endeavor to mainstream activity" (Birgeneau and Shen 1997) was a gradual process that expanded the use of this very advanced experimental resource beyond the physics disciplines and deep into the ranks of chemistry, biology, and medicine. This growth of importance of synchrotron radiation was connected to a broader process in the sciences, whereby new cross-disciplinary constellations emerged and established themselves, eventually taking the fore as the most promising and prestigious sciences of the early 21st century. Materials science (including nanotechnology) and the life sciences did not form as disciplines in a traditional sense, through specialization within existing fields, but rather by the gathering of scientists from a variety of disciplines around new problems and the use of new types of instruments and methods, where synchrotron radiation played a key role, and supported by new funding initiatives from public and private actors with the agenda of supporting research with long-term strategic importance for society and the economy. The 29-year history of MAX-lab, and its growth into an important role for Swedish and Nordic science, coincided with this process and enabled much of its progress in Sweden and Scandinavia.

Connected to this historical process is the growth of importance of *research infrastructures* in research and innovation policy, on European level as well as in most industrialized nations. This testifies to the tremendous importance of technological resources with multidisciplinary and generic character, which synchrotron radiation laboratories like MAX-lab are key examples of.

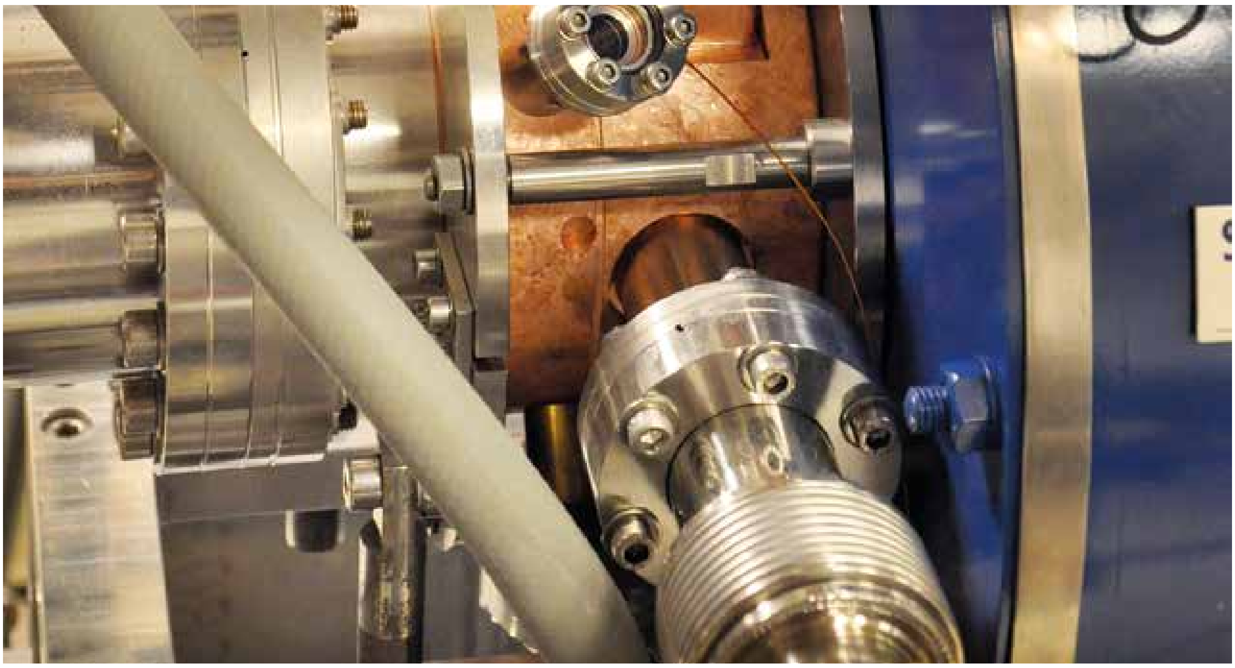
The development of synchrotron radiation as an experimental technique, between the mid-1960s when it first was exploited and until today, was astonishing. On the technical side, radiation quality improved by one order of magnitude roughly every 24 months (Frahm and Williams 2007). On the scientific side, a user community of tens of thousands of users annually in the world was built up. The broadening of the disciplinary base was remarkable, with the expansion to applications in biology perhaps the most profound development. In 1997, the first Nobel Prize was awarded for a discovery that built strongly on work done with the help of synchrotron radiation, and between 2003 and 2012, another four Nobel Prizes in chemistry was awarded for achievements with a similarly strong connection to synchrotron radiation (Hallonsten and Heinze 2015: 846).

Very simplified, synchrotron radiation can be used for spectroscopy, crystallography, and imaging. In the early days, synchrotron radiation was predominantly used for spectroscopic studies of the electronic structure of materials, and the broadening of the user base to biology and larger parts of chemistry was predominantly achieved by an improvement of the conditions for crystallography, which is a method for determining the structures of molecules. Imaging, in turn, is the use of synchrotron radiation for purposes similar to hospital or airport x-ray machines, only with dramatically higher resolution. All three techniques exist in many varieties and are enormously important for the sciences that form the base of today's industrial use of advanced materials and biomaterials (including drug design).

A brief history of MAX-lab

MAX-lab folded itself rather neatly into the very strong Swedish tradition in spectroscopy, which had flourished at the universities in Uppsala and Linköping, at Chalmers University of Technology in Göteborg, and the KTH Royal Institute of Technology in Stockholm, since the early 20th century. At both MAX I and MAX II, instruments were built in close collaboration with groups from these universities, which brought their expertise and skill to the lab and formed the backbone of the user community. When MAX-lab expanded its scientific program to chemistry and life science in the 1990s, similar alliances with prominent user groups in Denmark and locally in Lund, formed a key axis for development. This means that MAX-lab became an integral part of a renewal of Swedish science in the 1980s and on, with internationalization and focus on some particular areas of strength that are very visible today (materials science, life science).

The MAX project was proposed in the mid-1970s by a group of nuclear physicists in Lund, and towards the end of the decade, synchrotron radiation enthusiasts who had spent time abroad and brought back valuable experience suggested that the machine be modified to also produce synchrotron radiation. By then, the nuclear physicists had employed Mikael Eriksson as chief designer and constructor of MAX, and he was appointed professor of accelerator



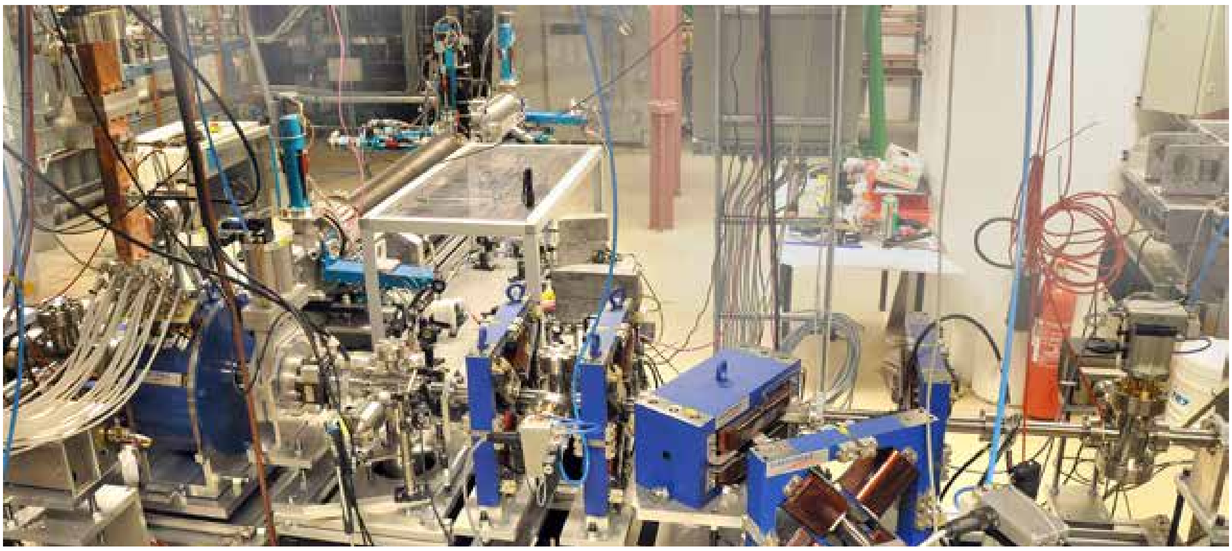
physics at Lund University in 1984, by a move by university leadership to secure the future of MAX. Under his leadership, the MAX machine was built by a group of creative and inventive people, and the project attracted several likewise creative and inventive users and instrument builders from all over Sweden, who equipped the machine with instrumentation that enabled quite some scientific success to be achieved in the first years of operation, in the end of the 1980s. Also the nuclear physics program thrived. The successes of the synchrotron radiation activities prompted plans for a major upgrade, the MAX II, which was granted funding in 1991 and inaugurated four years later. Beamlines were built mainly in collaboration with user groups from several Swedish universities. With the opening of MAX II, and the subsequent start of operation of several more beamlines, also with applications in biology, the MAX-lab user community grew dramatically (a tripling between 1991 and 2002), and the output (in publications, see below) also soared. The third MAX ring was built in the first years of the 2000s. A persisting funding shortage, identified by several evaluations (see list in appendix), was only resolved when in 2009 the MAX IV project was approved and the MAX-lab organization expanded and renewed to facilitate the construction of this major facility project. In the shadow of this major task, MAX-lab continued to serve a growing user community until the three rings were closed in late 2015 (MAX I had been taken out of synchrotron radiation operation in 2012 and was only used for nuclear physics in the last years).

All three MAX machines were very cheap in international comparison, also if making a gross approximation of all the time and effort put into instrument design, development and maintenance by external user groups. The most important funders, over the years, were the National Council for Planning and Coordination of Research (Forskningsrådsnämnden, FRN), the Natural Sciences Research Council (Naturvetenskapliga Forskningsrådet, NFR), and the private Knut and Alice Wallenberg Foundation (KAW).

Scientific and technological impact

Synchrotron radiation is a *generic* experimental technique that serves users in a wide range of sciences, and synchrotron radiation laboratories like MAX-lab therefore exist largely in response to a demand in scientific communities. On the most rudimentary level, therefore, the fact that the total number of users that did experimental work at MAX-lab over its 29-year history – approximately 15,000 – is in itself testimony to great scientific impact of the lab on Swedish, Nordic, and international science.

Figure 1 shows the annual number of users that visited MAX-lab over the years. The share of foreign users has beein in constant growth, and remained over 50% from 2007 and on. MAX-lab was, hence, both a national and international user facility: Eight Swedish universities and colleges were represented among the users already in 1987-88; in 2005-06 they were fifteen; and the number of countries represented rose from 9 in 1987-88 to 36 in 2012, remaining above 30 until the lab closed in 2015.[1]



[1] All numbers (in figure 1 and 2) were extracted from the MAX-lab activity reports and from complementary data received via email from Ralf Nyholm, 2 November 2015. The data for the years 1987 to 2006 denote years from August to June; whereas from 2007 and on they denote calendar years. Data on users and output include both synchrotron radiation and nuclear physics use.

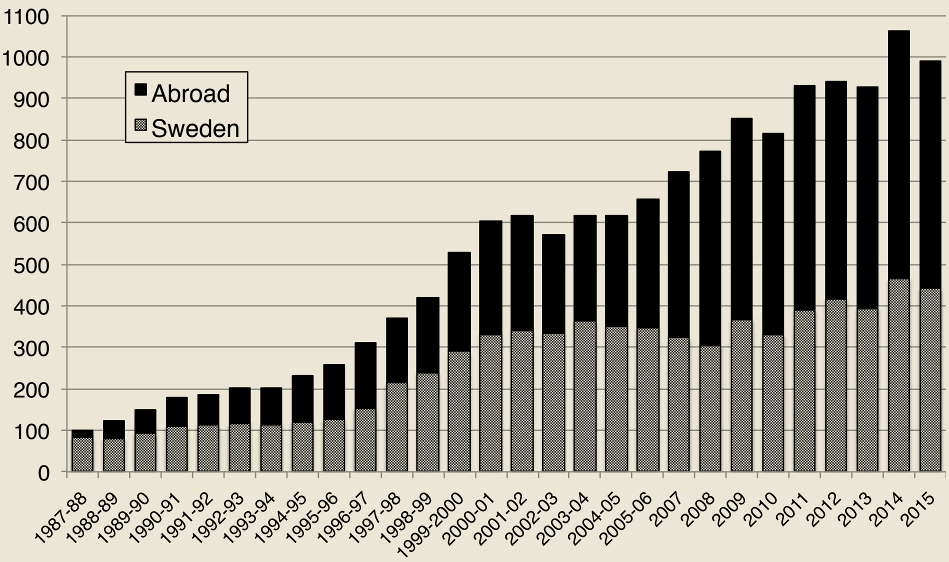


Figure 1: Total number of MAX-lab users (individuals), 1987-2015

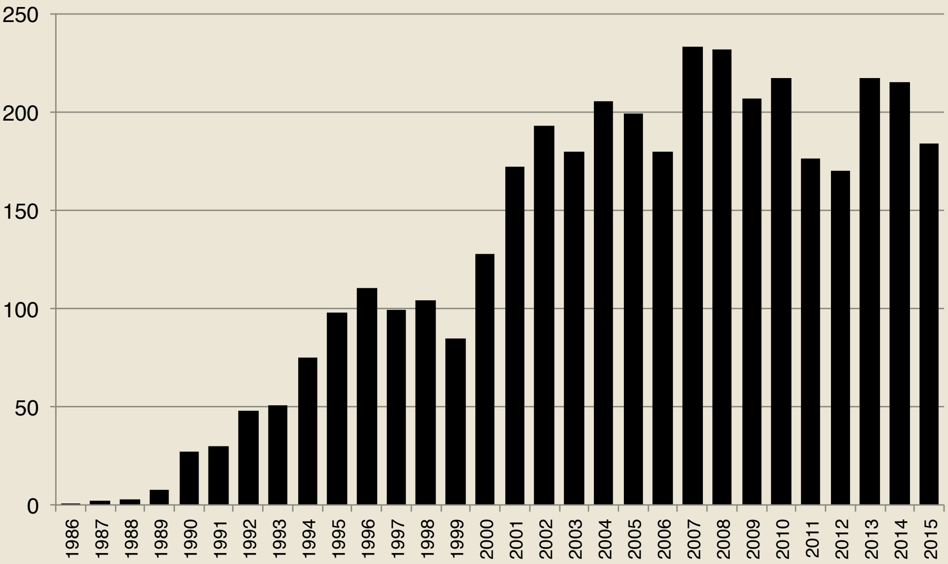


Figure 2: Number of journal articles based on work done at MAX-lab, 1986-2015

Moving on to output, a total of 3,849 journal articles were recorded by MAX-lab as having been published on basis of work done at MAX-lab in 1986-2015, in 588 different journals. The latter figure is in itself testimony to the disciplinary breadth of the scientific program of MAX-lab.

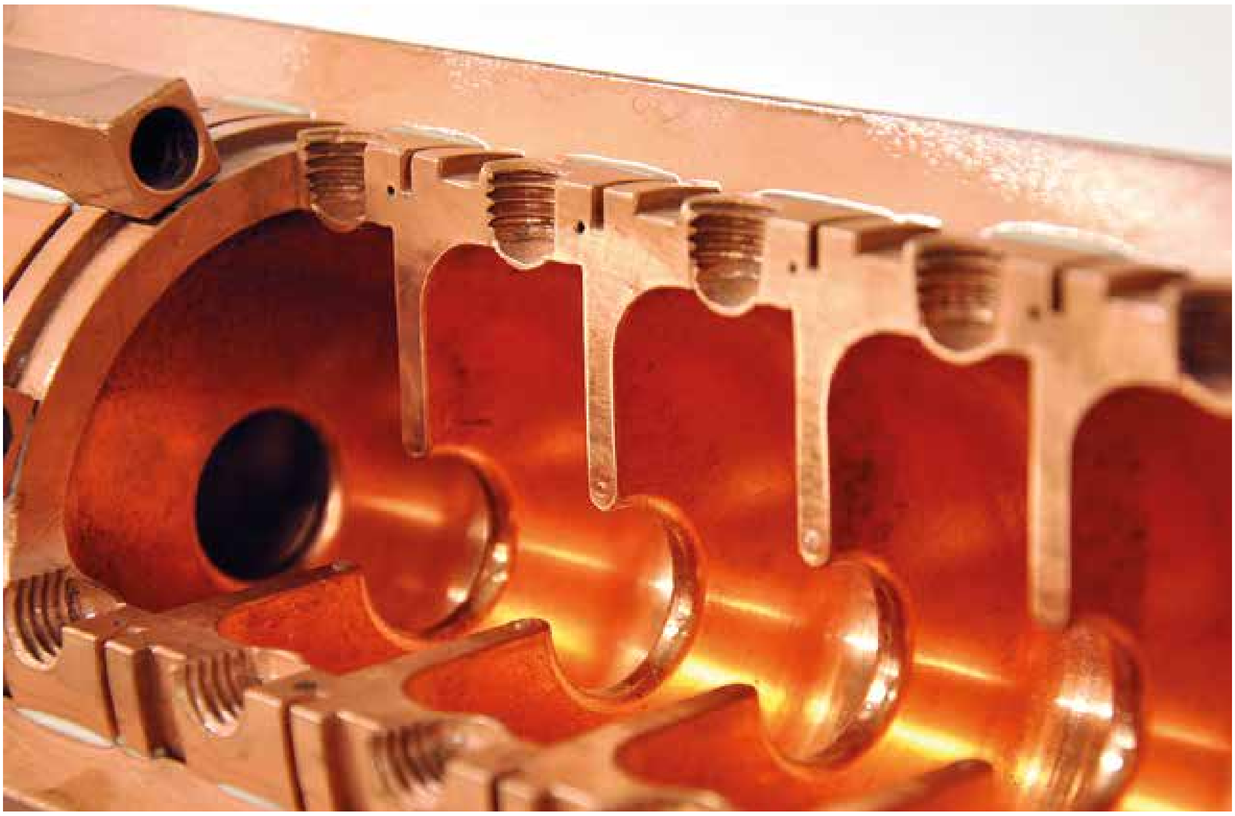
It would be tempting to conduct a citation analysis of the publications with the help of e.g. the Web of Science (WoS) database, but the built-in methodological flaws – not least time frames (1987 and 2015 articles would be assessed side by side although the former on basis of thirty years and the latter only on basis of two, and so on) – are serious enough to avoid it. Another type of bibliometrics-inspired analysis, building on the work within the recent "facilitymetrics" literature strand (Heidler and Hallonsten 2015; Hallonsten 2016b), shows that 180 of the 3,849 journal articles (or 4.7%) that build on work done at MAX-lab appeared in one of nine identified high profile journals, whose impact factor (in WoS) is high but whose informal reputation in the scientific communities is especially high, namely *Nature, Science, Cell, Physical Review Letters, Advanced Materials, Nano Letters,* the *Journal of the American Chemical Society (JACS), Proceedings of the National Academy of Sciences (PNAS)*, and the *Journal of Applied Crystallography.* In this measure, MAX-lab compares rather well with leading facilities abroad.

Doctoral theses represent not only scientific results but also a deeper contribution to the scientific community, namely a contribution to the professional education of scientists. 618 doctoral theses are listed as building on work done at MAX lab (1986-2015), published and defended at 83 different universities and institutes in 26 countries, and 259 of them (41.9%) outside Sweden. Most common among universities are Uppsala University (103 theses), Lund

University (95), Copenhagen University (37), KTH Royal Institute of Technology in Stockholm (36), Oulu University in Finland (35), Karolinska Institute in Stockholm (22), Chalmers University of Technology in Gothenburg (20 + 5 jointly with Gothenburg University), Linköping University (20), the Swedish University of Agricultural Sciences in Uppsala (19), and Aarhus University in Denmark (17). While the prospects of tracing the careers of these doctoral students are grim, and thus a thorough assessment of the contribution of MAX-lab to science and society through the training of doctors is not possible, the figures nonetheless yield that over 600 people have visited MAX-lab as part of their doctoral training, and possibly or likely earned skills that are hard to replace, that they have brought back to the rest of Sweden and the rest of the world. A similar argument can of course be made regarding the many postdocs and visiting scientists that have spent longer time than the typical user in the lab, and who also are highly likely to have gained very valuable experiences and knowledge that they have brough with them to coming positions and assignments in their careers.

Concerning specifically *accelerator physics,* the repeated evaluations of MAX-lab (see list in appendix) have commented that the accelerator physics research activities and the inventions and new solutions that they have produced have had a key role in the success of the laboratory. Accelerator physics has been one of the three main activities of the lab from the start, and the group has had an important output of its own, including some fifteen doctorates. The group's excellent performance has earned it a worldwide reputation matched by few. The comprehensive evaluation research at Lund University in 2008 consequently mentioned the accelerator physics activities specifically when naming (some parts of) physics in Lund "one of the crown jewels" of the university, noting that this is "a unique asset for Lund University and is recognized internationally as such", and that the group has developed "pioneering concepts" that are "copied and implemented in other facilities around the world" (Lund University 2008: 21, 351, 368). Its first major impact was the MAX II ring, given the possibilities this opened for the synchrotron radiation user community. Later achievements, internationally lauded, include many solutions implemented in the MAX II and III rings, and of course the path-breaking magnet design for MAX IV. The width of the international network of the accelerator physics group testifies to a high standing in the global community.

On the side of *instrumentation*, as noted, the developments at MAX-lab from the mid-1980s and on connect to a long tradition of instrumentation development at Swedish universities, foremost in Uppsala, Stockholm, Linköping and at Chalmers in Gothenburg. This was a continuation and augmentation of the Nobel Prize-winning work of Manne Siegbahn (1924) and Kai Siegbahn (1981) in x-ray spectroscopy, and efforts that contributed greatly to the renewal of materials science in Sweden and its growth to preeminence and a national scientific area of strength (Gribbe 2016). Users from these and other universities became involved in instrument development at MAX-lab early on, and a symbiosis between the lab and its user community developed that had great positive consequences for both, and impact on Swedish science as a whole. On MAX I, spectroscopy and imaging dominated, but as soon as MAX II was taken into operation, the life science applications were systematically explored and a new user community of biologists and chemists mobilized and made contributions to instrument development. Also



pharmaceutical industry got involved (see below).

The greatest importance of MAX-lab for Swedish science probably lies in the area of *materials science*, where the pioneering work with electron spectroscopy at MAX I in the late 1980s contributed greatly to renewal and internationalization of the field. A number of groups in Uppsala, Linköping, Stockholm and Gothenburg were users of synchrotron radiation internationally in the 1980s and made up a backbone of the MAX-lab user community that secured early scientific productivity and a solid ground for the continued developments to build on. Surface science was a cornerstone from the start, and remained so. The user community expanded within Sweden (to e.g. Karlstad, Lund) and internationally (most notably to Finland and Estonia). The 2004 international evaluation of Swedish research in condensed matter physics noted that MAX-lab, from the point of view of this scientific area, "has been, and continues to be, an extremely successful and highly competitive facility," which has "shaped a significant fraction of high-quality condensed matter physics research in Sweden" and "placed several […] groups in a world-leading position" (VR 2005: 27-28).

The physics departments of *Uppsala University* and *Linköping University* have been mentioned already; these had large groups of users throughout the whole history of MAX-lab and engaged in instrument development as well as lab governance and committee work. Uppsala physicists have been directly involved in the design and construction of as many as eight beamlines at MAX-lab, and earned a significant competitive advantage from their investment of money, time and effort in building these instruments, and their share of the total annual number of users of MAX-lab between 1989 and 2010 was never below 10%. A deeper analysis of the user lists reveals both a core group of loyal returning users (a fourth of them are listed as users in five activity reports or more) and a large number of temporary users (more than a third are only listed once). These figures are matched by unequivocal statements by interviewees: For some parts of the physics research in Uppsala, synchrotron radiation and MAX-lab have been absolutely vital. The 2006-07 comprehensive evaluation of all research at Uppsala University confirms the view. The physicists in Linköping exhibit a similar pattern, forming a natural part of the national community of users that developed around MAX-lab early on and a similar mix of loyal returners and users only visiting once or twice. In the early years (1987-89), physicists from Linköping made up as much as 13% of the total number of users of MAX-lab. Their contributions to instrument development were likewise very strong.

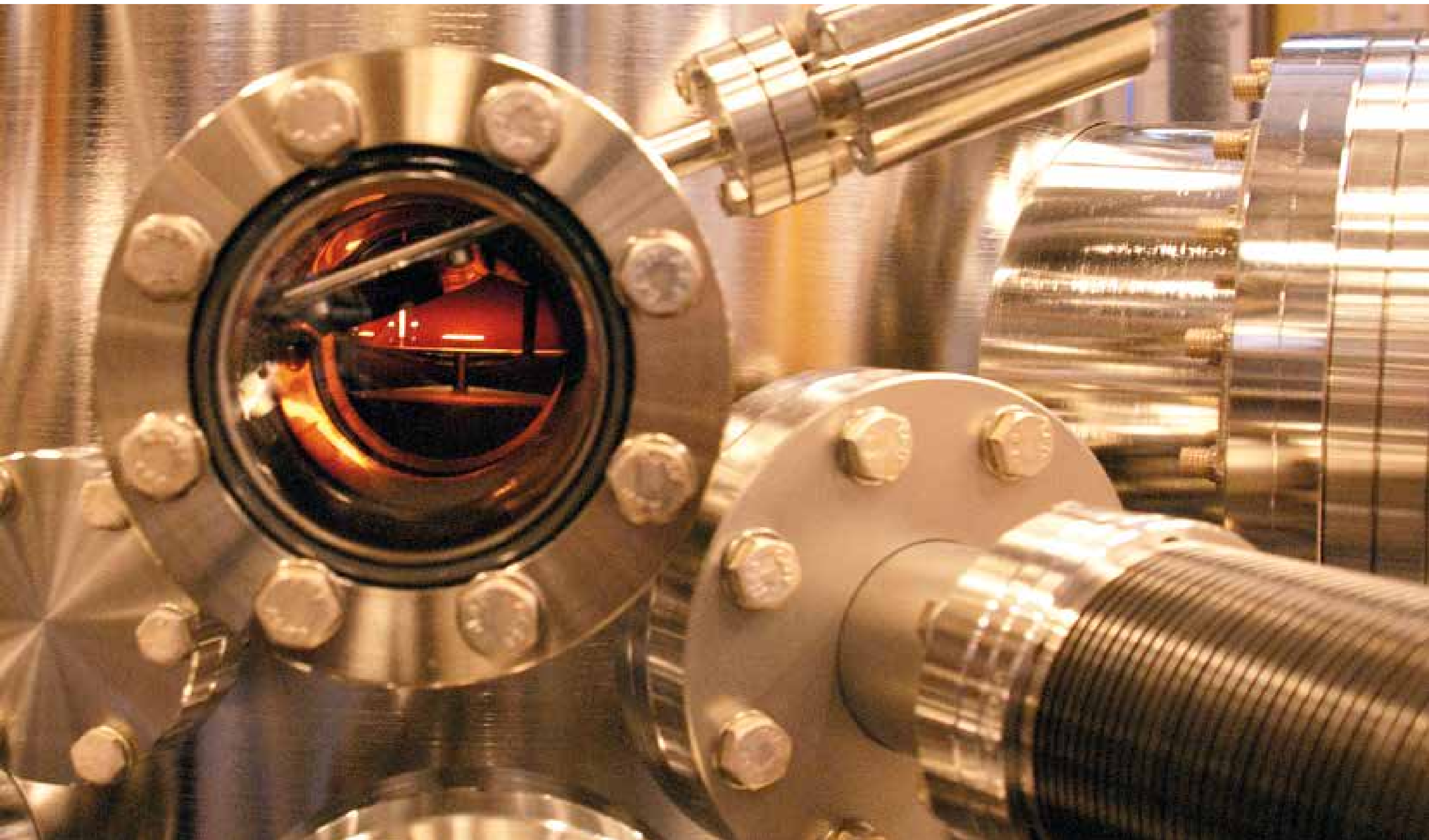
It has been claimed that the most deep and profound impact of synchrotron radiation on the sciences has been in the *life sciences,* where applications for biology and medicine, including pharmaceutical industry (structure-guided drug design), have been greatly exploited since the mid-1990s. At MAX-lab, the first life science beamline started operation in 1997, and some years later, a second beamline with several experimental stations specialized for crystallography, was taken into operation. Both were developed, built and operated with great involvement from chemists and biologists at Lund University and Copenhagen University, and with financial involvement from the firms AstraZeneca and NovoNordisk. The opening of these experimental opportunities at MAX-lab meant a significant broadening of the user base, numerically and disciplinarily but also geographically. For the groups that benefited from this buildup at MAX-lab, in Sweden and the other Nordic countries where not least structural biology had long been an aera of strength, the

impact was huge, as also noted in the 1999 evaluation of Swedish research in structural biology by the Swedish Natural Sciences Research Council (see appendix).

A specific feature of the experimental opportunities for life science research at MAX-lab, which is unusual in international comparison, is what can be called the mode of *"low throughput"* – by using the contrast to the dominating ideal of *high throughput* in synchrotron radiation-based structural biology studies. The somewhat lower technical performance of MAX-lab's life science beamlines was thus turned into an advantage, and helped developing and cultivating both the user community and the lab's internal capacity in the area. Partly due to under-use by the pharmaceutical companies that had invested in the beamline, and partly due to lower demand for beamtime than international competitors, MAX-lab was able to institutionalize a certain flexibility in the scheduling of beamtime and thus give groups in the close vicinity (on both sides of Øresund) swifter and more direct access, which created a niche for MAX-lab in the structural biology community, as a lab where a local user community could train students and explore method and new solutions. The somewhat lower beam quality increased the time for data taking which gave users room to modify samples and experiment during beamtime, to an extent that also is not typically possible at other labs, where all preparation must be done in advance to allow maximum utilization of the short beamtime slot one has managed to get.

The *nuclear physics* activities at MAX-lab built on a long tradition in Lund, and was the initial motivation for the buildup of the lab. Scientifically, the activities were separate from the synchrotron radiation program, and much smaller, comparable to the volume of research of a beamline on MAX I. The MAX I ring was also the only of the three MAX storage rings that was used for nuclear physics activities; for the better part of the history of MAX-lab on 25% of its total time of operation. Already from the start, the nuclear physics group had an extensive international network of collaborators that visited MAX-lab frequently, which compensated somewhat for its lack of a national user base of the kind that the synchrotron radiation activities of MAX-lab had from the start. Overall, the nuclear physics activities at MAX-lab remained productive and kept its niche throughout the whole of the history of the lab.

MAX-lab played an important role as a *motor for the renewal* of Swedish science in some specific fields. Materials science and the life sciences have been mentioned above and both these fields benefited greatly from MAX-lab in terms of the new experimental opportunities offered, and that the user communities also took great part in developing, but also because MAX-lab became a gateway of sorts to the international communities of the respective fields. As a resource for skilled and driven researchers obtaining access in open competition, MAX-lab enhanced experiments and pushed developments to an international standard, that would not have been possible otherwise. First, this was a matter of access – in the 1980s and 1990s, access to synchrotron radiation was restricted on the international scene, and MAX-lab became an important resource for the Swedish and Nordic communities. In the long run, the lab became a resource for these groups and for the scientific communities beyond the availability of experimental resources, as a key node in networks and, in the long run, functioning as a vehicle for internationalization of Swedish science. MAX-lab connected Swedish and Nordic scientists to pioneers of synchrotron radiation abroad, and remained a reliable partner in the international accelerator development and synchrotron



radiation community, to the benefit of Swedish and Nordic science.

The *user association* played an important role in this, functioning as a natural partner for lab leadership and a natural forum for the gathering of the user communities around important issues. The annual MAX-lab user meetings/annual meetings of the user association became a forum, early on, for the exchange of all kinds of knowledge and experience among MAX-lab users, and thus in the long run as a recurrent event that fortified and developed the user community, on international level. It is no surprise that the association became a role model for similar groups abroad. Other *workshops and conferences*, organized by MAX-lab and/or at and around MAX-lab, had similar functions of gathering events and platforms for network building and maintenance among users.

Economic impact

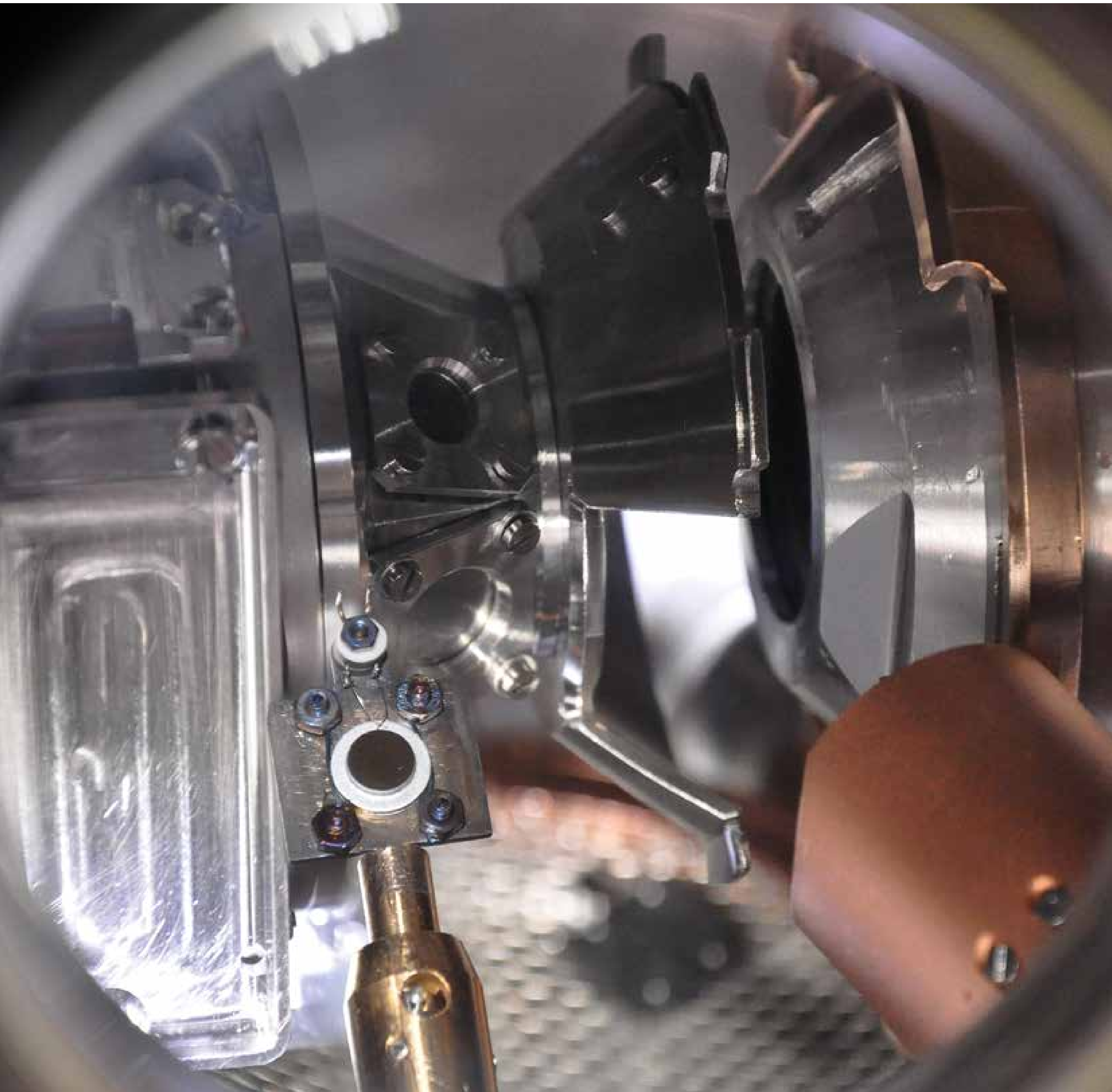
Today, hardly any scientific activity escapes the attempts of evaluating its (positive) impact on the economy, and the dominant view of science is that it is most of all an engine for innovation. Also research infrastructures are evaluated in terms of their societal and economic "footprint" and the technology and knowledge transfer they accomplish, and investments in new research facilities are often motivated by expected economic payoffs (see e.g. the campaign to locate the ESS in Lund). While research facilities like MAX-lab have the capability of creating economic impact in a number of quite different ways, most of them are difficult to measure. Luckily, pure logic conveys the unlikeliness that investments in advanced technology, the employment of high-skill labor, the continuous inflow of likewise high-skill users making temporary visits, and the ongoing use of the facilities for rather advanced experimental scientific research, *would not* render any economic output. A typical classification of the economic impacts of research facilities is (1) procurement, (2) technology/knowledge transfer (including "spinoffs"), and (3) industrial use (see Hallonsten 2016a: 200; Meusel 1990: 365-366).

In all three, it is necessary to maintain a *holistic view* on impact and look beyond the easily distinguishable, to other impacts later on, at other places, and in other contexts. There is nothing to suggest that scientific work or technological development done at MAX-lab, say, in the 1990s, could not appear in refined form in some innovation put together by a business and marketing genius somewhere in the world several decades from now. This concerns not only technology/knowledge transfer and industrial use, but also procurement, which involves mutual learning by the lab and the supplier firm.

With respect to *procurement*, the rather mundane economic effects that stem from investments in conventional facilities (buildings, office supplies, and so on) are no different from any construction project. Here, MAX-lab injected several hundred million SEK into the local, regional and national economy. But in the category of *high tech* procurement, the potential for long and unpredictable *sequences of impact*, involving technology and knowledge transfer and further innovation down the road, are most likely to occur. Such secondary effects are likely to appear, since suppliers of goods and services on the high tech side tend to undergo significant learning as part of the procurement processes, enhancing their in-house knowledge (Autio et al 2004; Schmied 1982). Similarly, the employees of a lab like MAX-lab gain significant specialized skills and know-how that they bring with them when migrating to other parts of the economy.

Three specific cases can be used to demonstrate how MAX-lab has pushed the boundaries of technology in its development of new instrumentation, and thus helped firms innovate. In both cases, the long-term buildup of trust and personal relationships proved absolutely crucial. The three-party collaboration between MAX-lab, a group of Uppsala physicists, and the instrument developer Scienta in the 1980s produced the legendary *Scienta SES-200 analyzer* which is widespread at synchrotron radiation facilities worldwide. The development was made largely by the Uppsala physicists, on basis of technologies owned by Scienta, with the specific purpose of equipping one of the MAX I beamlines with a new analyzer, and Scienta manufactured and marketed the instrument commercially. The symbiotic relationship between MAX-lab and the Uppsala physics department (see above) was decisive for the success of the SES-200, and for Scienta as a whole. Intriguingly, the analyzer was never patented but marketed by the results it helped producing at MAX-lab, and while competitors have built their own varieties of the device, this is seen as beneficial for the whole industry, and the global synchrotron radiation community, in wider perspective. The accelerator components manufacturer *Scanditronix* developed a similarly symbiotic relationship with MAX-lab early on, which gave the firm access to the competence of the MAX-lab accelerator physics group and built a trustful relationship that made the procurement of magnets for the MAX II ring better and cheaper. Interestingly, patents were absent – the buildup of knowhow and competence among key people was what secured the continued technological development. The third example is *Erik Olssons Mekaniska*, a local mechanical engineering manufacturer in the small village of Tollarp, some 50 km north-east of Lund, which got to deliver the tripods for the MAX II magnets because it could demonstrate a precision of the equipment for mechanical engineering that the MAX-lab accelerator constructors had a hard time finding elsewhere. Technically, the choice to go with Olssons was unconventional, but successful and not least very cost efficient. Once the design and construction proved to work, when MAX II was successfully taken into operation, Erik Olssons Mekaniska got several new customers around the world, in the accelerator construction business and elsewhere. The exchange of competence and knowledge between MAX-lab and the three firms exemplified here is evident and has led to a long-term competitive advantages that the firms have exploited in several other customer relations.

The direct *industrial use* of MAX-lab has been comparably minor. Speculation holds that direct industrial use of synchrotron radiation facilities is increasing on global level, due to determined strategies of many (or most) labs to achieve such a development, but it is also quite clear that it remains on rather low levels, i.e. a few per cent or in the best cases ten to fifteen per cent of the total use. MAX-lab is no exception – direct industrial use never exceeded five per cent. However, it is likely that a certain amount of unrecorded use by commercial firms, as part of collaborations with non-commercial users from e.g. academia and research institutes, has occurred. The most significant examples of direct industrial use are the firms AstraZeneca and NovoNordisk who purchased recurring slots of beamtime in the early 2000s. Also the mediator companies SARomics biostructures and Collodial Resources, who undertook analyses at the beamlines at MAX-lab as a service sold to clients in industry, stand out as regular users in the 2000s.



Educational and public impact

Science and technology capture people's imagination and has important roles in public debate and popular culture. Research infrastructures such as MAX-lab, with their delicate and complex assemblages of high tech instrumentation, often become the focus of attention for those with a fascination and interest in scientific progress, as symbols for this progress and for the extreme technical and intellectual sophistication of later day scientific achievements. Therefore, although it did not have a traditional visitor's center, MAX-lab partly functioned as a science center where school classes and the interested general public could get a glimpse into the exciting world of materials science and life science and its use of synchrotron radiation. The lab and its activities connect to a broad range of features of the everyday life of people, that also involve very specialized scientific and technological advancement, such as drug development and the development of new materials that enhance the performance of gadgets and gears like batteries, digital storage media, and transport vehicles.

MAX-lab has taken this role seriously though the years, providing a range of services to the general public and to students of different levels in order to help in the raising of their awareness about science and the stimulation of their interest, through for example the Open House Days, Teacher's Days, and visits by school classes. Overall, MAX-lab's press coverage has been sparse but positive.

Specifically on the side of *education*, MAX-lab's integration with Lund University has meant that its potential for rasing awareness and provoking the interest of students has been quite extensively utilized. Key personnel have remained part of the faculty of Lund University and retained duties in teaching and supervision throughout their tenures at MAX-lab. Several courses and programs have been taught over the years at MAX-lab, and by MAX-lab employees, and some remain today. Several undergraduate programs in a variety of fields at other Swedish universities have also used MAX-lab for visits and thematic lectures and course modules on synchrotron radiation and its use in various disciplines.

An activity with particularly strong impact is the *Summer School in synchrotron radiation research*, organized every year from 1985 and until 2014. The role of the summer school in cultivating a user community on long term has been significant, given its broad focus on different uses of synchrotron radiation, and very practical hands-on elements, but also involving basic accelerator technology which increased the awareness and devotion in the user community. The extensive international network of people around MAX-lab was often used to invite distinguished scientists as lecturers on the school, which maintained a high quality over the years. A unique feature of the school was the direct access to MAX-lab. As the user community expanded disciplinarily (see above), more and more fields were represented among the students, but the school retained its inclusive and holistic grip on synchrotron radiation, involving teaching on all fields of application as well as instrument development and maintenance.

MAX-lab and Lund University

The relationship between MAX-lab and Lund University is probably most accurately described as a *symbiosis*, or a win-win relationship where world class instruments are developed and made available to university researchers (benefiting not least from the geographical proximity to the lab) and the univeristy's broader capacity and talent pool, not least students, is made available to the lab. The continuous throughput of students and the intellectual renewal that it secures in the academic setting is at the core of the role of universities in society, and universities are therefore unique loci for scientific progress. Research infrastructures, with the potential of providing unique opportunities for experimental work in a wide range of sciences, fills a different role on basis of which symbiotic relationships with academic environments can be established and developed.

The annual number of users of MAX-lab affiliated with Lund University grew dramatically over the years, and while some of this increase stems from the growth in number of MAX-lab staff (who also undertook research at the lab and counted as users), it is also clear that the lab became more an more of a resource for the whole university as time passed. The number of Lund University departments represented in the local user community doubled, from 10 to 21, between 1988 and 2010.

The nuclear physics activities at MAX-lab was a continuation of one branch of nuclear physics at the Department of Physics at Lund University, that started the MAX construction project in the 1970s and remained users until 2015. For this group, the existence of MAX-lab was absolutely decisive. The accelerator physics group (and later department) was always part of MAX-lab and inseparable from the construction and operation of the MAX machines, and it was originally born out of the nuclear physics activities. The creation of a professorship in accelerator physics in 1984 secured the future of the lab but also established the foundations for an excellent research and teaching environment in accelerator physics at Lund University. In the late 1980s, the university created a professorship in synchrotron radiation physics, and the division that was built up around it today counts 45 staff members. In chemistry, it is clear that especially the groups involved in macromolecular crystallography were swift in identifying the potential of having a synchrotron radiation facility as neighbor, and have reaped great benefits.

Generally, MAX-lab seems to have fertilized the local university environment by its constantly developing international orientation and participation at the forefront of several of the technologies and sciences of synchrotron radiation. MAX-lab has been identified as an early example of a cross-disciplinary "meeting point" at the university, that also served as inspiration for future similar inter-faculty projects (Melander 2006: 205).

Concluding discussion

The gradual, evolutionary buildup of MAX-lab was highlighted already in the introduction to this study, and has been returned to repeatedly. From small-scale university project in the 1970s and 80s, over a great expansion of scientific breadth and size and scope of the user community, and to an internationally renowned user facility in the 2000s that closed in 2015 in order to move into the large, and in many respects world-leading, MAX IV in 2016, the history of MAX-lab is a truly remarkable slice of late modern history of science.

There are at least two complementary ways of viewing this history from the perspective of assessing *impact:* One is characterized by fascination and astonishement that this was at all possible, and the other is characterized by an itching feeling that suboptimality and inefficiency has plagued the lab and prevented many remarkable achievements. Most of the previous evaluations of MAX-lab (see appendix) convey a balance of these two messages.

An analysis of the history of MAX-lab from a science policy perspective has concluded that while MAX-lab was unique in Sweden, it embodied some core features of the Swedish science policy system, namely decentralization, indecision, and a notorious lack of ability to make strategic priorities (Hallonsten 2011). The argument is that exactly because MAX-lab was the result of its champions' clever manuevering through a science policy system that was not directly hostile but also not very favorable to initiatives of the kind, rather than a result of deliberate and coherent policy-making and planning, successes were achieved at MAX-lab that lack counterparts abroad. On basis thereof, it is tempting to suggest not only that the pursued path of MAX-lab was the only way in which it could have been built at all, and that once it was built, it paved the way for another regime of science policy and funding, where pooling of resources around strategically important projects and areas is more accepted and a common ingredient. Some things suggest that this is exactly what happened: While Sweden had some large projects also before MAX-lab, and certainly participated in most international scientific collaborations, the situation is quite different today. Not only have both MAX IV and ESS come into being in Lund; the Science for Life Laboratory (SciLifeLab) in Stockholm/Uppsala is another major venture that builds on strategic priorities and resource mobilization, and the focus of the last decade's governmental research policy has clearly been on purposeful mobilization of resources in some strategically important areas.

This study's focus was clear from the beginning; it is the MAX-lab that closed in December 2015, that has been analyzed. Given this starting point, MAX IV should be viewed as form of impact of MAX-lab, and quite a spectacular one: Beyond doubt, MAX IV would not have existed if it wouldn't have been for the more than three decades of buildup of MAX-lab that preceded it, and beyond doubt, MAX IV is a world leading synchrotron radiation facility in some key aspects.

Concluding this shortened version of the report of the *ex post* impact study of MAX-lab, some things deserve to be reiterated. The academic culture at MAX-lab, noted in the introduction, has meant that the lab has developed in an *evolutionary* mode, perfecting the key *technical adaptability* and *organizational responsiveness* that is built into synchrotron radiation laboratories. During its 29-year history, the lab was almost in constant change. Some new instrument was always under construction. During times, a new accelerator was being built and commissioned, or upgraded. A constant curiosity and interest in trying new things, improving existing instrumentation, and breaking boundaries – the essence of classic academic science – characterized the lab through its whole 29-year history. The *crucial alliance* between a synchrotron radiation facility and its user community was near-perfected at MAX-lab, with the main result that the lab and its users drove the development *in reciprocity*, to mutual benefit. The *broadening of the user base*, from solid state physics to chemistry and biology, from local/national and to Nordic/global, from a smaller group of Swedish physicists to a broader set of academic environments throughout Sweden, is itself a testimony to great (and increasing) scientific impact: MAX-lab became a vital resource for a wide range of excellent Swedish and Nordic research activities.

MAX-lab put Lund and Sweden *on the map* in the global synchrotron radiation community, and in wider circles, and functioned as a *vehicle for the internationalization* of research activities in parts of physics, chemistry and biology at Lund University and Sweden/Scandinavia as a whole. This is especially true for surface physics and structural biology. MAX-lab plucked into, and catalyzed, some core developments in Swedish science at the end of the 20th century and contributed to the *renewal* of several fields in materials science and life science, which among other things is seen in the Linnaeus Grants, strategic research areas, and similar excellence centers. MAX-lab *paved the way* for strategic mobilization around areas of strength in the 2000s, by showing what collaborative efforts between Swedish (and Nordic) universities and research policy and funding agencies can achieve.

MAX-lab was most of all an *enabler*, and in this role it had a system-bearing function, both as a platform for research of various kinds (first in nuclear physics, accelerator physics and materials physics, then in biology, and also in several other fields along the way) and as a vehicle for renewal and internationalization of Swedish science in the concerned fields. MAX-lab's impact on Swedish and Nordic science, on local and regional society, on Lund University, and so on, was enormously complex and multifarious. The report has managed to convey some broad brushstrokes and the details of some specific forms of impact, but surely missed out on some. There are several secondary, tertiary (and further down the road) effects that cannot be assessed today but are very likely to happen.

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Appendix

CHRONOLOGICAL LIST OF PREVIOUS EVALUATIONS OF MAX-LAB, AND EVALUATIONS THAT PARTLY CONCERN MAX-LAB

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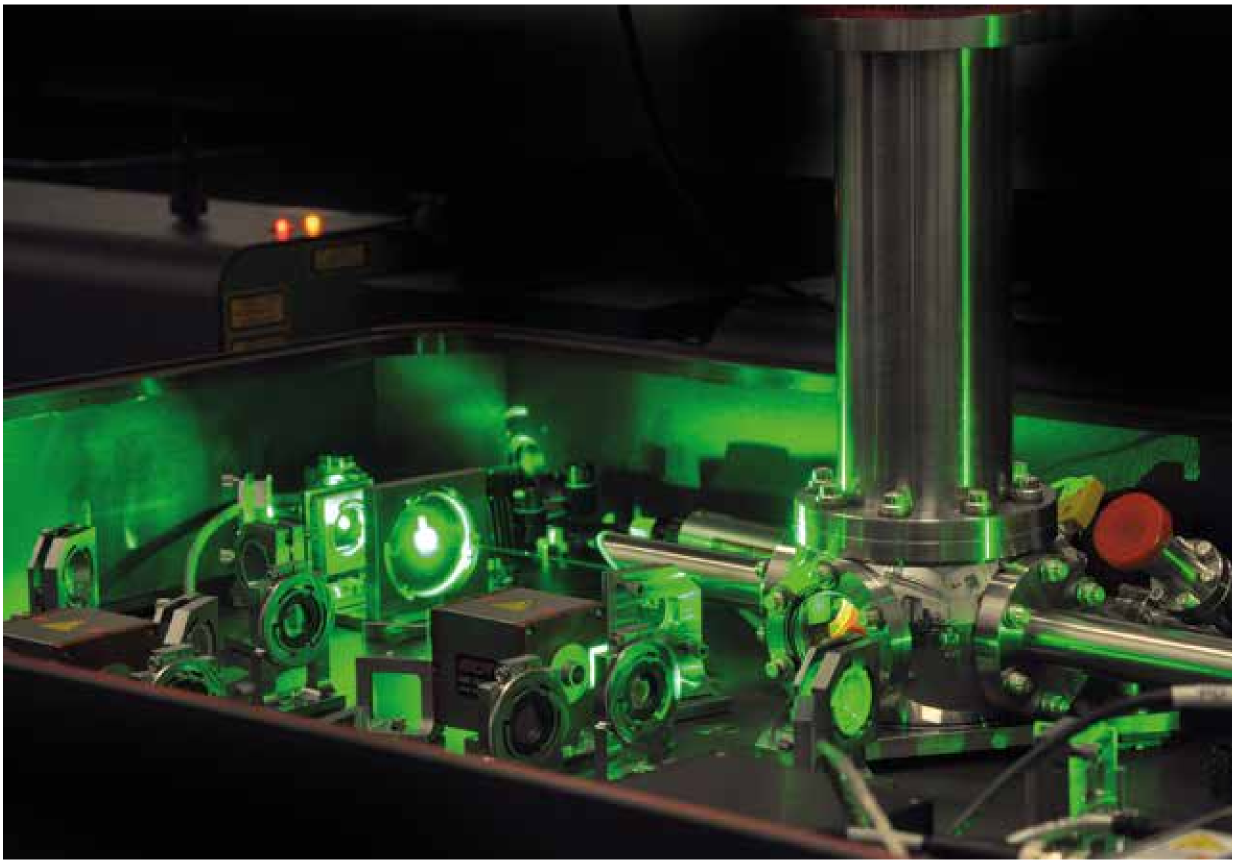

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An *ex post* impact study of MAX-lab

MAX-lab was a Swedish national research facility for synchrotron radiation, nuclear physics, and accelerator physics, in operation between 1986 and 2015 and located on the northern campus of Lund University. This report is the result of a comprehensive analysis of the impact of MAX-lab on science, economy, and society, and on local, national and international level. The report is based on official documentation, statistics, interviews, and previous studies of the history of MAX-lab. Its analysis and conclusions contribute to a broader and deeper understanding of the role of research infrastructures in science and society.

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