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# Formation and expansion of a new organizational field in experimental science

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This paper examines the formation and expansion of a new organizational field in experimental science: synchrotron radiation laboratories. These labs were once peripheral servants of some specialisms of solid-state physics, but over the 40 years studied they have grown into a worldwide generic resource for tens of thousands of users in a broad spectrum of disciplines. The paper uses insights primarily from historical institutionalism, but also neo-institutional theory, to analyze the formation and expansion of the organizational field of synchrotron radiation laboratories, and thus contributes to the analysis of the rather dramatic growth of this tool for experimental science from a small-scale lab curiosity to a generic research technology. But the key contribution of the paper is to provide insights into multi-level and multi-dimensional change in science systems by analyzing the emergence and expansion of a new organizational field in experimental science, which has implications not least for science policy.

*Keywords: synchrotron radiation laboratories; organizational fields; generic research technologies.*

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## 1. Introduction

Synchrotron radiation is one of the world's fastest-growing laboratory resources for experimental work in the natural sciences and has undergone dramatic and diversifying technical improvements in the past few decades, expanding its area of use into several branches of physics, chemistry, biology, and materials science. Using extremely intense electromagnetic radiation (light and X-rays) produced by polygonal particle accelerators, synchrotron radiation has become institutionalized as a critical lab resource for tens of thousands of scientists worldwide and a tool for the advancement of the forefront in many science areas. Originally an unwanted waste product in accelerators for particle physics collisions (e.g. Fermilab and CERN), synchrotron radiation was long a marginal phenomenon championed by only a few devotees. But the vast technical improvement and dramatic growth in its scientific usefulness has expanded the user base so that nowadays synchrotron radiation labs are purpose-built service facilities used primarily by research groups from universities and other public research organizations, but also by industrial firms, who visit synchrotron radiation labs occasionally to conduct experiments as part of their regular projects.

Several historical studies have analyzed parts of the history of synchrotron radiation by chronicling particular labs, both those where synchrotron radiation has been a complementary activity (e.g. to particle physics) and those that have been purpose-built (Crease 2008, 2009; Doing 2009; Hallonsten 2011, 2015; Heinze et al. 2015a; 2015b; Lohrmann and Söding 2013; Westfall 2008b, 2012). The sociological analysis of the history of these labs is, however, only in its infancy, despite their promising characteristics as complex yet distinct cases of multi-level continuity and change. Synchrotron radiation facilities operate large-scale scientific instrumentation (Big Science) for a disciplinarily varied set of ordinary small-scale research projects (Little Science), thus taking part in cutting-edge developments on instrumentation and scientific method in alliances with various scientific communities, research funders, policy actors, and other organizations. This makes the several-decades-long history of synchrotron radiation laboratories a particularly suitable case for the study of the gradual formation and expansion of organizational fields in science, from which insights for the sociological analysis of research organizations, and for science policy and management studies, can be gained.

This paper follows and complements previous research that analyses Big Science at the national system level (Crow and Bozeman 1998; Hallonsten and Heinze 2012; Ritter 1992; Westwick 2003) and on the level of individual labs and their transformations (Doing 2009; Hallonsten and Heinze 2013; Westfall 2012). It takes the *field* perspective and pays considerable attention to the *content of the activities* of these labs. Thus, it adds to the knowledge of how science systems transform through organizational and institutional change, but also through the complex interaction of scientific and technical development in disciplinary communities. It also considers the sustaining and promotion of these developments in cross-disciplinary organizations and sectors, and the role of policy and management at various levels in the science system as a whole. The analysis makes use of two key theoretical concepts: first, historical institutionalism and its conceptual tools for explaining *gradual but cumulative institutional change* (Mahoney and Thelen 2010; Mahoney 2000; Streeck 2009; Streeck and Thelen 2005; Thelen 2003). Second, it uses the concept of *experimental systems* and their role in science and society (Joerges and Shinn 2001; Rheinberger 1997; Shinn and Joerges 2002). In addition, apt references are made to the theoretical school where the concept of *organizational fields* originated and has been given the most attention, namely neo-institutional organization theory (DiMaggio and Powell 1983; Mizruchi and Fein 1999; Wooten and Hoffman 2008).

The paper applies the two key theoretical concepts selectively and in combination, to analyze the formation and expansion of a new organizational field in experimental science, following and complementing previous studies of the early formation and diffusion of organizational models for universities and other research organizations (Geiger 1986; Cole 2010; Westwick 2003). It also considers recent contributions to the understanding of how new types of organizations in science emerge and form maturing fields by the proliferation and institutionalization of common practices and organizational patterns, inside and outside pre-existing structures and systems (Mody 2011; Choi and Mody 2012; Powell et al. 1996, Powell et al 2005). These fine contributions notwithstanding, there is a remarkable lack of studies about the emergence and growth of organizational fields in science, and this paper contributes to the advancement of this important topic, empirically as well as theoretically.

An organizational field typically includes a range of entities. While the present analysis acknowledges the role of organizations such as funding bodies, policy-makers, scientific communities, other research labs, and universities, the focus remains clearly on the labs themselves, in order to reduce the complexity of the analysis, which would otherwise extend beyond the scope of a single journal paper. For conceptual and methodological reasons, the analysis is also limited to Europe and the USA. Asia and the former Soviet Union, where some significant contributions to the development of synchrotron radiation have doubtless been made, have been excluded because they have science policy systems with some radically different characteristics, which place them beyond the scope of what one paper can convey. With these limitations, the number of organizations in the field remains at a manageable level (the total number of synchrotron radiation labs taken into operation in Europe and the USA remains below 30 (see Table 1)) which permits a level of detail that does the topic justice while still not distorting the bird's-eye view that is instrumental for the field-level perspective. The field-level perspective also prevents too much attention being paid to the otherwise very important 'micro-foundations' of institutional organizational analysis (Powell and Colyvas 2008). This has been covered in other publications which focus on the micro-levels (Hallonsten 2011, 2015; Heinze et al. 2015a; 2015b). The present focus on the field is also complementary to our previous work conveyed in publications in this journal, where we have compared the national systems of national laboratories in Germany and the USA (Hallonsten and Heinze 2012), two individual labs in these two systems that both had key roles in the emergence and growth of synchrotron radiation as an experimental technique in their respective countries as well as on the world stage (Hallonsten and Heinze 2013).

This paper uses a detailed historical narrative on the emergence and growth of synchrotron radiation as an experimental resource and on the concurrent growth of the number of labs. It applies the theoretical concepts mentioned to show the following points. First, in accordance with the predictions of neo-institutional theory, the majority of the synchrotron radiation labs were established within pre-existing research organizations such as universities and national research institutes. Second, the formation of the organizational field gained momentum particularly once dedicated single-mission synchrotron radiation labs started to emerge outside pre-existing research organizations. Third, field expansion occurred primarily because of the eventual consolidation of a highly reliable and customary experimental system used in many disciplinary contexts and applications. Fourth, and confirming predictions from historical institutionalism, several gradual, but cumulative, institutional processes were at work in the whole process, operating both on the level of single organizations and on the level of the organizational field. Fifth, as the organizational field entered a period of expansion and consolidation, isomorphic change began to show as labs started to imitate each other technologically and organizationally.

Section 2 contains a history of synchrotron radiation and synchrotron radiation labs. Section 3 outlines the

**Table 1.** List of synchrotron radiation laboratories, in chronological order

| Opened | Name | GeV | Location | Type | Closed |
|---|---|---|---|---|---|
| 1968 | Tantalus | 0.24 | WI | (1st gen) exception | 1981 |
| 1974 | DORIS | 3.5 | GER | 1st gen parasite | 1982 |
| 1974 | SPEAR | 4.5 | CA | 1st gen parasite | 2002 |
| 1980 | CHESS | 5.5 | NY | 1st gen parasite | |
| 1981 | BESSY | 0.8 | GER | 2nd gen (UV/soft X-rays) | 1998 |
| 1981 | SRS | 2.0 | UK | 2nd gen (UV/soft X-rays) | 2007 |
| 1981 | Aladdin | 1.0 | WI | 2nd gen (UV/soft X-rays) | |
| 1982 | DORIS II | 5.0 | GER | Upgraded 1st gen parasite | 2012 |
| 1982 | NSLS | 0.75 | NY | 2nd gen (UV/soft X-rays) | |
| 1984 | NSLS | 2.8 | NY | 2nd gen (hard X-rays) | |
| 1987 | MAX I | 0.55 | SWE | 2nd gen (UV/soft X-rays) | |
| 1990 | ASTRID | 0.58 | DK | 2nd gen (UV/soft X-rays) | |
| 1993 | ELETTRA | 2.0 | ITA | 3rd gen (UV/soft X-rays) | |
| 1993 | ALS | 1.9 | CA | 3rd gen (UV/soft X-rays) | |
| 1994 | ESRF | 6.0 | EUR | 3rd gen (hard X-rays) | |
| 1995 | DELTA | 1.5 | GER | 3rd gen (UV/soft X-rays) | |
| 1996 | APS | 7.0 | IL | 3rd gen (hard X-rays) | |
| 1997 | MAX II | 1.5 | SWE | 3rd gen (UV/soft X-rays) | |
| 1998 | BESSY II | 1.7 | GER | 3rd gen (UV/soft X-rays) | |
| 2001 | SLS | 2.4 | CH | 3rd gen intermediary | |
| 2003 | ANKA | 2.5 | GER | 3rd gen intermediary | |
| 2003 | SPEAR3 | 3.0 | CA | 3rd gen intermediary | |
| 2005 | FLASH | – | GER | 4th gen (UV/soft X-rays) | |
| 2006 | SOLEIL | 2.75 | FRA | 3rd gen intermediary | |
| 2007 | DIAMOND | 3.0 | UK | 3rd gen intermediary | |
| 2007 | MAX III | 0.7 | SWE | Exception (UV/soft X-rays) | |
| 2009 | PETRA III | 6.0 | GER | Exception (hard X-rays) | |
| 2009 | LCLS | – | CA | 4th gen (hard X-rays) | |
| 2010 | ALBA | 3.0 | SPA | 3rd gen intermediary | |
| 2012 | ASTRID 2 | 0.58 | DK | Exception (UV/soft X-rays) | |
| *2015?* | *NSLS-II* | *3.0* | *NY* | *3rd gen intermediary* | |
| *2015?* | *MAX IV* | | *SWE* | *3rd gen intermediary* | |
| *2015?* | *SOLARIS* | | *PL* | *3rd gen intermediary* | |
| *2015?* | *XFEL* | – | *EUR* | *4th gen (hard X-rays)* | |

Fourth-generation sources are not comparable to first-, second-, and third-generation sources in terms of technical implications of electron energy as expressed in GeV. Tto avoid confusion, their electron energies are not noted in this table

theoretical concepts, and Section 4 analyzes the history with the aid of these concepts and their adaptation to the empirical material. Section 5 summarizes our main points and highlights some key implications, including policy relevance.

## 2. History of synchrotron radiation and synchrotron radiation laboratories

The origins of synchrotron radiation research date back to the heyday of particle physics in the late 1950s and early 1960s, when small-scale projects and programs started exploratory utilization of the radiation at particle physics labs in Europe and the USA.

Particle physics (or high-energy physics, as the terms are used interchangeably) had a privileged position in the Cold War era due to its connection with nuclear energy and warfare and the superpower competition. The search for smaller and smaller particles and forces by the construction of increasingly larger particle accelerator complexes became a regular and expected feature of public science, enjoying generous funding and political support in the USA, Western Europe, Japan, and the former Soviet Union (Greenberg 1999: 218–9 (first edn 1967)). Its progress (i.e. the continuous discovery of new particles), required particle collisions of continuously higher energy, which typically meant larger and costlier machines, and therefore accelerators rapidly became outdated and were abandoned in favor of new ones. A fundamental law of physics is that particles charged with high energies, whose trajectories are bent (e.g. in a round-shaped accelerator), inevitably lose energy that is emitted as synchrotron radiation, which is very intense electromagnetic radiation in the infrared, visible, ultraviolet (UV), and X-ray ranges.[1] This energy loss was a nuisance to particle physicists and made them meticulously diagnose the characteristics of synchrotron radiation, which was theoretically shown to have great potential for experimental use in spectroscopic and crystallographic studies within physics, chemistry, and the biosciences. In practice, such use would require a rather demanding exercise of extracting the radiation from the accelerators, focusing and tuning it, and handling its transport to instruments and samples without hazards or damaging equipment (Haensel 2007: 16–7; Winick and Bienenstock 1978: 41). In the early- to mid-1960s, DESY (Deutsches Elektronen-Synchrotron) in Hamburg and the National Bureau of Standards in Washington, DC undertook some pioneering work with radiation from comparably unstable synchrotron accelerators. This work proved the usefulness, but accentuated the need for significantly more reliable sources and related technical solutions (Codling 1997; Heinze et al. 2015a; Lohrmann and Söding 2013).

The first step towards the real practical utility of synchrotron radiation was the advent of the *storage ring* accelerator design concept, a machine that keeps bunches, or beams, of electrons (or, in later cases, protons) in constant circulation (i.e. stores them). Although entirely driven by particle physics, the development of the storage ring also brought a leap in the quality of the synchrotron radiation because storage rings emit continuous beams of light whereas synchrotrons only deliver short (millisecond) flashes. But this was merely a first step. Experimental work using synchrotron radiation had to be conducted entirely on the basis of the generosity of particle physicists whose interest in minimizing energy loss ran counter to the prospects of optimizing the emission of synchrotron radiation. Also, for practical reasons, researchers with insight into the potential of synchrotron radiation, and active in fields most likely to benefit greatly from its use, seriously questioned the worth of the efforts (Kunz 2007: 14).

Two pioneering efforts, at DESY and Stanford University, respectively, paved the way for a breakthrough of sorts in the 1970s. DESY and the Stanford Linear Accelerator Center (SLAC) both built storage rings for particle collisions in the early 1970s, and already at their opening, small-scale projects began using the continuous beam radiation produced, which ranged across a spectrum stretching into X-rays. The projects started regular 'parasitic'[2] use of the machines DORIS (at DESY) and SPEAR (at SLAC) in 1974 (Hallonsten and Heinze 2013: 594, 596), and their work in spectroscopy, scattering, microscopy, and imaging in the mid-1970s confirmed and exceeded many expectations,[3] but also incentivized practitioners to innovate to safely handle the very intense X-rays and not least, given the parasitic operation, improve radiation quality while not obstructing the particle physics programs. A major innovation was the so-called *insertion devices* that consist of arrays of magnets in the straight sections of storage rings that make the electron beam turn several times and thus emit synchrotron radiation in a significantly more focused beam (Hallonsten 2015; Munro 1996: 141). Insertion device technology has since been optimized and nowadays dominates the production of synchrotron radiation. All synchrotron radiation sources built since the early 1990s are technically optimized for using insertion devices, which can accurately be considered to be a key piece in the very complex technological systems of synchrotron radiation laboratories.

Nevertheless, in the late 1970s the mode of operations was still parasitic, and despite many astonishing results, synchrotron radiation was still considered to be an esoteric and peripheral experimental tool. The unreliable, parasitic status at prestigious particle physics labs, and the generally insufficient stability of their operation, meant that larger potential user groups remained doubtful. Nonetheless, in the mid- to late-1970s, governmental funding bodies in Europe and the USA started to support some plans in the scientific communities for the design and construction of dedicated, non-parasitic facilities. In the USA, the Tantalus machine at the University of Wisconsin (funded by the National Science Foundation) was replaced by the purpose-built Aladdin, and Brookhaven National Laboratory, in need of a new big project for focusing its capacity, was given the task of constructing the first dedicated synchrotron radiation facility within the national labs system, the National Synchrotron Light Source (NSLS) (Crease 2008; Lynch 1997). In Europe, the monopolization of national particle physics budgets by CERN, the pan-European collaborative project, (Hallonsten 2014: 36) led to the unemployment of accelerator constructors and capital alike, and a few dedicated synchrotron radiation sources were established to make use of the abandoned competence, including the Synchrotron Radiation Source (SRS) in Daresbury, UK, opened in 1981, and the MAX laboratory in Lund, Sweden, opened in 1986 (Hallonsten 2011).

A common and convenient way of retrospectively classifying synchrotron radiation facilities is by naming them first-, second-, and third-generation sources. The first labs of the 1960s and early 1970s, using radiation parasitically and as described above, are the first generation. The storage rings-based facilities purpose-built for synchrotron radiation, planned and built beginning in the late 1970s, are the second generation. Although the designs of these facilities did not include insertion device technology, they were built with many straight sections that allowed the eventual implementation of insertion devices. The synchrotron radiation facilities with storage rings, beamlines, and experimental stations all optimally designed for the use of insertion devices, the first of which were turned on in the early 1990s, are the third-generation (Shenoy 2003: 3–4; Winick 1994: 7). Characteristically, the second generation had a rather primitive design (from today's perspective) but they were purpose-built and dedicated to synchrotron radiation. Thus, importantly, they were organized not as parasitic projects depending on the goodwill of particle physicists (and the governmental agencies responsible for them) but as labs in their own right, with quite heavy demands on the organizational capacities to run their experimental systems at an acceptable level of performance (including accelerator, vacuum systems, experimental stations, data collection facilities, and safety). They were intended to accommodate a growing and diverse user community with varying expectations and demands (at that time primarily representing solid-state physics, chemistry, materials science, and some life sciences).

The real breakthrough for synchrotron radiation came in the late 1980s and the 1990s. Opportunities created by the concentration of particle physics into fewer labs, and the awakened interest of larger scientific communities, led to the planning of several synchrotron radiation projects in Europe and the USA in the early- to mid-1980s. In particular, the mission crisis of some US national labs (Westfall 2008a; 2008b; 2012) opened a window of opportunity, and in Europe, a healthy political climate for new scientific mobilization enabled both national and collaborative initiatives to take shape (Hallonsten 2014). Already in the mid- to late-1970s, major public research sponsors, including the German Federal Research Ministry, the European Science Foundation, and the National Academy of Sciences, had commissioned reports to evaluate the demand for synchrotron radiation sources and possible locations (Cardona 1977; European Science Foundation 1977; National Academy of Sciences 1976). These reports both catalyzed the ongoing construction of second-generation sources and broadened the political interest in further projects, and what would eventually become the third generation. Insertion devices, invented and tried at parasitic labs (first at SPEAR/SLAC), enabled a leap in performance, but most of all in operations reliability and stability. They became the key technological innovation that eventually enabled the construction of optimized synchrotron radiation sources which were stable enough for routine operation (Hallonsten 2015; Westfall 2008b: 575).

However, it was the eventual optimization of many other components of the labs' experimental systems for insertion device-produced radiation that constituted the real breakthrough in performance and reliability. The promises of synchrotron radiation in the so-called hard X-ray spectrum (wavelengths of 1 Ångström or shorter) and the optimization of instruments and technical solutions in the soft X-ray and UV spectra (wavelengths of 1 Ångström and longer) led to the default separation of the insertion device-based third-generation synchrotron radiation sources in hard X-rays and UV/soft X-rays. The former category required very large accelerator rings (several hundred meters in circumference), which warranted a European collaborative effort and in 1994, the European Synchrotron Radiation Facility (ESRF) opened to users in Grenoble, France. It is run by 12 European countries and had total construction costs of approximately US$800 million (in 2012 prices) (Hallonsten 2013: 502). The USA decided to build its own, similar machine. In 1996, the Advanced Photon Source (APS) opened to users at the Argonne National Laboratory in Illinois, after nine years of construction and approximately US$1 billion spent (Westfall 2012). These two machines are still the largest synchrotron radiation facilities in Europe and the USA, serving several thousand users annually. The other group of third-generation labs was made up of smaller facilities built to deliver UV radiation and soft X-rays, thus complementing the big ones. Comparably low-cost (often less than a tenth of the ESRF and APS), these labs were also affordable for smaller countries. The first to open was the Advanced Light Source (ALS) at Lawrence Berkeley National Lab, in 1993, followed by the ELETTRA in Trieste, Italy, the same year and then the DELTA in Dortmund, Germany (1995), the MAX II in Lund, Sweden (1997), and the BESSY II in Berlin (1998) (see Table 1) (Hallonsten 2011: 199).

Simultaneously, both the first- and second-generation sources thrived and provided alternatives to the third-generation labs within specific scientific niches. In the USA, the NSLS served several hundred users annually at its two rings for UV and X-rays synchrotron radiation, respectively (Crease 2009). In the UK, the SRS in Daresbury had been in operation since 1979, and the existing programs at DESY and SLAC did not cease to grow in importance and ambition but gained strength by gradually taking over larger and larger shares of the operation of the SPEAR and DORIS storage rings (Hallonsten and Heinze 2013). All these developments were driven by a growing interest in synchrotron radiation in various scientific disciplines and an associated demand for access to the labs. The opening of new labs also enabled an expansion of areas of use and facilitated the growing interest.

In the first decades, experimental use of synchrotron radiation was dominated by various studies within materials sciences. In particular, nanotechnology has benefited greatly from the technical improvements of experimental techniques brought by high-quality synchrotron radiation. But it is the vast growth in life science users at synchrotron radiation labs worldwide that has probably brought the highest visibility and most direct impact of the results. When the third-generation sources for hard X-rays (ESRF and APS) opened in the mid-1990s, they were large-scale organizations built to accommodate thousands of users annually, optimizing the experimentation and data taking at their several dozens of parallel-run beamlines. This setup enabled another level of mainstream operation, where users could count on the high reliability of the instruments and hence expect a high throughput of experimental results, something especially important for life science users whose reluctance about using big machines was often significant, especially in comparison with those from physics disciplines. Cutting-edge results as well as broadening of the user base ensued. In 1997 the Nobel

Prize was awarded for the first time for a discovery that relied heavily on analysis work done with synchrotron radiation (John Walker, chemistry). Beginning in 2003, the chemistry prize has been awarded for synchrotron radiation-related work every three years: Roderick MacKinnon (2003), Roger Kornberg (2006), Ada Yonath (2009), and Robert Lefkowitz and Brian Kobilka (2012). The formidable explosion of synchrotron radiation use across a wide spectrum of the natural sciences in the 1990s is reflected in the manifold increase of users worldwide. For example, the ESRF achieved a five-fold increase of its number of users in only five years, from a little over 1,000 in 1995 to over 5,000 in the year 2000 (Hallonsten 2013: 505).

Simultaneously, technological innovation on nearly all parts of the experimental systems enabled vast improvements in the performance parameters and a significant lowering of costs. The most important long-term effect of these developments was the emergence, in the late 1990s, of a new type of third-generation source that would combine the performance of the large hard X-ray sources (ESRF and APS) with the soft X-ray/UV sources into what can be called intermediary energy sources, the first of which was built at the Paul Scherrer Institute (PSI) in Villigen, Switzerland, in the late 1990s. Opening for users in 2001, the Swiss Light Source (SLS) was the first of a whole new family of medium-sized and comparably low-cost sources that sufficiently matched the big ones in performance but required lower investments which also made them viable for smaller countries with increasing demands for synchrotron radiation from domestic scientific communities. In the first decade of the new millennium, several such sources opened in countries like France, Spain, and the UK. Accordingly, SLAC rebuilt its old SPEAR machine, and several other sources are currently being built or are being planned in Scandinavia and Central Europe (see Table 1). As the number of labs grew and communities became organized and structured, several 'best practices' emerged and spread for accelerator and instrument operation, scientific user support, user access (including peer review of proposals for experiments), sample preparation and handling, data management, parallel accommodation of vastly different scientific and technical requests from users, and the continuous development and refinement of technologies as well as organizations.

Table 1 shows that while new synchrotron radiation labs have been built at a constant pace since the beginning of the 1980s, few older labs have been closed. Synchrotron radiation is therefore still in an expansion phase, and there are four current trends that are especially worthy of attention. First, the emergence of what could be called fourth-generation light sources, which are not synchrotron radiation sources in a strict sense but rather a kind of radical refinement of some extreme performance parameters by the use of linear accelerators (instead of polygonal storage rings) and very long insertion devices to produce what is called *free electron laser* for use in some exceptionally performance-intensive experiments. Second, there was the ambitious modernization and upgrades of the two 'big ones' (APS and the ESRF), for the purpose of remaining competitive, despite rivalry from various new sources. Third, the desertion of the last particle physics machines in favor of a concentrated global effort in particle physics at CERN in Geneva, which has produced a new type of synchrotron radiation source that makes use of segments of very large rings (originally built for particle physics) and delivers at the edge of the theoretically possible in terms of radiation quality. Finally, it appears that the proliferation of a best practice for the design of whole facilities, to save time and money in their construction, has reached a state where the same blueprints are used for more than one lab. Whereas previously, the pace of technological refinements of storage ring technology and other components warranted unique designs for all new labs (including magnets and vacuum) to provide exceptional capabilities in some niche area, it now seems that the technical development is reaching some kind of limit. An example of such a 'copycat' facility is the SOLARIS facility being built in Poland on the basis of an exact copy of the (renowned) storage ring design of MAX IV in Lund, Sweden.

## 3. Theoretical framework

As noted in Section 1, there is a remarkable lack of studies on the emergence and growth of organizational fields in science. Only very few studies explicitly apply the fields perspective to organizations in basic experimental science (Mody 2011; Powell et al. 1996, 2005). Most of the contributions to the study of emergence and growth of institutionalized practices that form new organizational fields in science rely on detailed historical accounts but have limited theoretical anchoring. Therefore, this work is exploratory not only in its empirical ambitions but also in applying theory.

Two different but complementary approaches are used. First, we connect to the sociology of science and technology by using the concepts *generic instruments* (Joerges and Shinn 2001; Shinn and Joerges 2002), and *experimental systems* (Rheinberger 1997) as tools to describe how synchrotron radiation transformed from a peripheral and exploratory technique used in a narrow class of experiments (primarily in solid-state physics) into a resource for a broad range of disciplines. This occurred by technological advancements in tandem with progress in the scientific disciplines concerned, and was facilitated by various processes of organizational adaptation, expansion, and diversification. The two concepts of generic instruments and experimental systems were originally introduced to explain how inventions in science or engineering can be made available and useable for a wider range of purposes, gradually occupying independent positions in a so-called interstitial arena between science, state, and industry (Shinn and Joerges 2002). But these concepts are also useful for understanding how large-scale laboratory techniques, with an intrinsic potential to serve many purposes, can be gradually refined and adjusted to new audiences through technical improvements and scientific proof-of-concept. Importantly, as will be shown, it is when viewing whole synchrotron radiation laboratories as experimental systems that the quality of these labs as generic instruments makes sense. The labs have been refined and adjusted to multidisciplinary, and partly open-ended, use by purposeful work to integrate all the technical components and organizational elements in comprehensive efforts to lower the barriers to new utilizations.

The second theoretical tool is the conceptualizations of gradual but cumulative institutional change within historical institutionalism, and the several gradual change processes that produce institutional renewal, including *layering*, *conversion*, and *displacement*. These processes have been shown to be forceful tools for understanding change that is not caused by exogenous shocks and that contributes to long-term, macro-level institutional persistence through adaptation and renewal (Mahoney 2000; Streeck 2009; Streeck and Thelen 2005; Thelen 2003). With the aid of insights from this literature, field formation and expansion can be explained in terms of a balanced mix of change within organizations and at field level. We have previously shown that processes of layering, conversion and displacement can operate simultaneously at the infrastructure, organization, and science levels, and on different time scales (Hallonsten and Heinze 2013). This typology of processes can be rewardingly used to understand the long-term renewal of large research organizations through a series of smaller steps that interact and aggregate to broader changes. Here, a similar multi-dimensional application of these tools is used, but with the field and its constituent organizations as the primary focus, contrasting processes of change on various levels to analyze the long-term development of the organizational field.[4] *Layering* is then taken to mean a process by which new arrangements are added on top of pre-existing structures, thus enabling the accommodation of new elements without excessively compromising the logic of the pre-existing laboratory, for example the opening of a new experimental facility at an already existing lab, which primarily adds new capacities in the pre-existing organization and thus constitutes *intra-organizational layering*. But layering can also happen on field level (i.e. by the creation of an entirely new lab with a fully fledged experimental infrastructure on a greenfield site), which is foremost an event outside the framework of a pre-existing organization and thus constitutes *field-level layering*. However, both intra-organizational and field-level layerings have a potential influence on field and organization level, because they alter the balances between supply and demand of certain experimental opportunities. *Conversion*, for its part, means that capacities for one set of goals are redirected to other ends, in a process that neither adds new capacities nor terminates the existing capacities. This is of particular interest for the discussion of the adaptation and change of individual labs as well as organizational fields in science, because it gives existing structures new purposes or orients them to new goals and missions. In the context of this paper, the typical example is that an existing scientific machine is upgraded or rebuilt to be used for synchrotron radiation instead of particle physics, or a synchrotron radiation facility is upgraded to better meet the demands of the community. *Displacement* is similar but refers to the succession of instruments or facilities for the same purpose: the dismantling of an old lab and the construction of a new one, either within the same organization or within the same national science system or disciplinary research community, or the lab-level process (e.g. discontinuing one set of instruments dedicated to one set of purposes and replacing them with another set of instruments built for slightly different purposes).

This capacity of the conceptual tools from historical institutionalism to facilitate multi-level and multi-dimensional analyses of gradual change is instrumental for our purposes, because this paper constitutes a change of analytical level from national systems (Hallonsten and Heinze 2012) and, individual labs (Hallonsten and Heinze 2013) to the level of the *organizational field* of synchrotron radiation laboratories. The field-level perspective is crucial for understanding, not least from a policy perspective (see Section 5), how synchrotron radiation grew from a lab curiosity to a mainstream experimental resource, and the analysis facilitated by the concepts from historical institutionalism is crucial for making sense of the field-level transformations described in Section 2. For example, the construction of a new piece of scientific infrastructure will affect the science dynamics at the lab and, by extension, the sciences as a whole because new scientific activities will gradually start incorporating it, gain from it, and develop in (partial) symbiosis with it. With some time lag, it will also lead to the creation of new organizational units to host the experimental system that the infrastructure and its instruments make up, and its scientific community. Obviously, research infrastructure has a much broader technological and physical extension than a single lab and must therefore also be examined as a property of the organizational field of labs. Likewise, the scientific utilization of infrastructure runs across the field, and organizational structures also become field properties by the proliferation of best practices.

The focus on the organizational field anchors the conceptual approach in yet another theoretical tradition, namely neo-institutional theory which is where the concept of organizational fields originated and belongs. Therefore, in this analysis, some references are also made to core postulations of neo-institutional theory so that the proper connection to this tradition is secured. But neo-institutional theory is not used *per se* as a tool in the analysis, which has mainly to do with the fact that its proponents and practitioners have, for the most part, studied established fields and internal changes in such fields rather than the emergence, formation and expansion of fields.

## 4. Synchrotron radiation labs as an organizational field

The result of the analysis in this section is shown schematically in Fig. 1. The *initiation period* of the organizational field of synchrotron radiation is identified as occurring during the mid- to late-1970s. Although some parasitic use of particle physics machines had already occurred in the 1960s, it was the activities from the early 1970s and on, foremost at the SPEAR, DORIS, and CHESS machines (at SLAC, DESY, and Cornell University, respectively), that proved that labs could be run to serve different user groups from different scientific communities and produce results remarkable enough to motivate the rather large investments that were necessary (Doing 2009; Hallonsten 2015). The results displayed the potential of synchrotron radiation, but these initial efforts remained peripheral to the mainstream of those scientific disciplines that would later benefit considerably from the accomplishments at synchrotron radiation labs. The most important reason that these scientific breakthroughs did not drive a swift growth in the use of synchrotron radiation across a broader spectrum of the natural sciences was that the infrastructures were still run parasitically. The storage rings emitting synchrotron radiation were under the control of particle physicists, who allowed synchrotron radiation practitioners onto their sites out of generosity, and who essentially controlled such use by deciding the fundamental performance parameters of the machines and regulating access. Hence, these initial efforts to establish synchrotron radiation facilities constituted *intra-organizational layering* because new technical equipment and scientific/technical staff were added to existing particle physics infrastructure, within existing labs. The initiation of the organizational field is therefore interpreted as having occurred by the creation of three parasitic first-generation labs (see Fig. 1, first column). It should be noted that in the field perspective these constraints, that forced the pioneers of synchrotron radiation experimentation to remain in parasitic mode, were largely created and sustained by the extraordinary contemporary status of particle physics in national (and international) science and science policy systems, and its connection to national security (the 'military–industrial complex'), which inhibited the exploration of new uses of large-scale instruments. This wider contextualization also helps to explain several subsequent events.

On the technological side, the parasitic situation spurred efforts that had a profound long-term effect. The unreliable performance of the experimental activities of these parasitic ventures and the often suboptimal quality of the radiation led synchrotron radiation practitioners to develop and implement insertion device technology. Thus, not only did they instantaneously yield much higher quality radiation, but after many years of technical testing and improvement, they also became the backbone of the third-generation labs, including the giants (ESRF and APS). This means that crucial field-level elements of what allowed the formation and expansion of an organizational field in the 1980s and 1990s had already been initiated at this early parasitic stage.

Despite the rather impressive scientific results that emerged from parasitic synchrotron radiation activities in the mid-1970s, the broader scientific communities did not immediately take up the new opportunities. Rather, it took a number of years until the demand for synchrotron radiation in the scientific communities was judged significant enough to warrant the launch of dedicated labs. When research funders on both sides of the Atlantic published their aforementioned reports on the long-term supply and demand of high-quality synchrotron radiation and the future sources that would provide it, they relied on strong support from the scientific communities. This support convinced the sponsors that they would have to

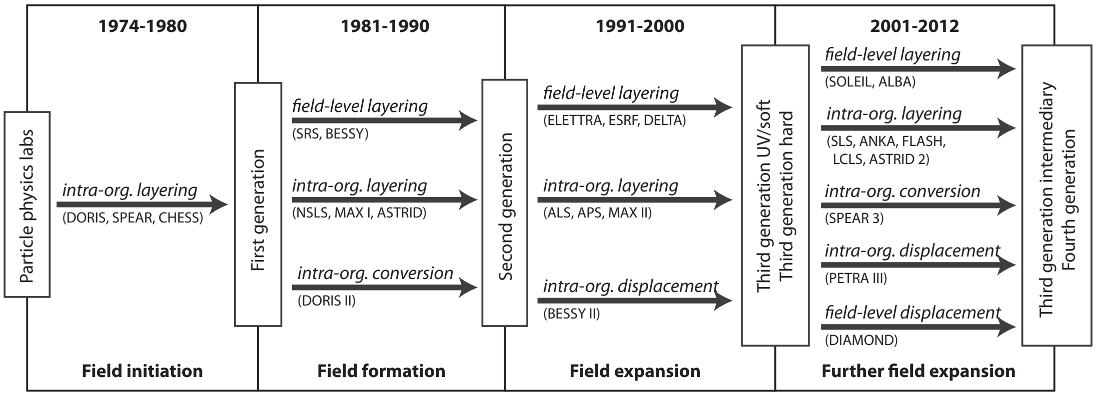

**Figure 1.** Institutional Processes and Field Formation and Expansion, 1974–2012.

move ahead to ensure that their countries would obtain a good position in the international competition for synchrotron radiation that was soon to unfold.[5] The role of scientific communities providing support in these developments shows that the growth of an organizational field obviously requires the forging of alliances with actors in established, adjacent sectors.

Most interestingly, the considerable investments in second-generation labs in the early 1980s and onwards were channeled predominantly into existing labs and universities, first via *intra-organizational layering* (NSLS at Brookhaven, MAX I at Lund University, and ASTRID at Aarhus University), second via *intra-organizational conversion* (DORIS upgraded to DORIS II at DESY), and third via *intra-organizational displacement* (Aladdin substituting Tantalus at the SRC). These developments are consistent with the predictions of neo-institutional organization theory that organizational fields emerge from pre-existing organizations (DiMaggio and Powell 1983).

A sizeable share of funding, however, also went into building entirely new research organizations (SRS in Daresbury, UK, and BESSY in West Berlin). These second-generation labs, dedicated to synchrotron radiation and with storage rings independent from particle physics, added further momentum to the formation of the organizational field, as did the NSLS which was founded as an entirely new lab, but within the established formal organizational boundaries of Brookhaven National Laboratory. They were clearly important in the process of liberating the synchrotron radiation community from its Babylonian exile in particle physics labs. SRS and BESSY show that the formation of the organizational field included not only intra-organizational changes and adaptations, but also the foundation of new and dedicated labs, and thus *field-level layering* (see Fig. 1, second column).

The second-generation facilities did not incorporate insertion devices as a central component, because when these facilities were designed in the late 1970s, the prospects for the technology were still uncertain. This can be interpreted as *ambiguity* on the technical side: a new and promising design existed but it was considered too uncertain as a basis on which to build an entire experimental system for a lab that was supposed to contribute swiftly to satisfying a growing demand in the scientific communities. Fortunately for these second-generation labs, however, their designs included straight sections that were sufficiently long to host insertion devices, and most of them also implemented this technology in the late 1980s and 1990s, with considerable success. This meant that they also actively contributed to the development of synchrotron radiation sources as generic instrumentation.

With the field in formation and the generic capabilities of synchrotron radiation proven, the real wave of expansion of the field was not far away. The proof-of-concept of the insertion device technology had occurred almost simultaneously with the opening of the second-generation sources in the early 1980s, which meant that a consolidated technical design concept for full-fledged synchrotron radiation laboratory experimental systems emerged in parallel with the realization of the potential of synchrotron radiation among policy-makers, funders and not least, broader scientific communities. The proliferation of best practices and consensus around the technical design helped to convince policy-makers, on the basis of credible scientific results, that sponsorship should be scaled up, and the gradual strengthening of this support from the policy and funding side was, of course, also instrumental in the further development of the field.

The step from formation to expansion of the field, from ambiguous to consolidated infrastructure concepts, and from a merely generic to indeed customary scientific resource occurred through considerable capital investments, in the early- to mid-1990s. These investments established third-generation labs of two distinct types (hard X-rays and UV/soft X-rays) and were channeled into both existing labs via *intra-organizational layering* (ALS at Berkeley, APS at Argonne, and MAX II in Lund), *intra-organizational displacement* (BESSY II replacing BESSY I), and *field-level layering* (ELETTRA, DELTA, and most importantly, the ESRF). Funded and operated by 17 European countries in collaboration, the ESRF constituted a major step in the initial expansion of the field, as it showed determination on the part of policy-makers. It also established a large lab with potential to serve thousands of users annually, on a greenfield site. The ESRF was not the first lab with insertion devices at the core of its experimental system (ELETTRA, DELTA and ALS came first), but it was arguably most influential in the institutionalization of best practices at the field level by its purposeful optimization of technologies, its almost industry-like organization of operations and user support, and its ambitions and eventual success in providing its experimental resources to scientists across Europe on a customary basis. Similar to the process of field formation (above), the field's early expansion occurred through a mix of intra-organizational layering, intra-organizational displacement, and field-level layering (see Fig. 1, third column).

The field expansion of the 1990s continued well into the 2000s with the same pattern of gradual institutional change processes (see Fig. 1, fourth column). Several new sources, both of the third and fourth generations, were established in existing labs, such as SLS (at PSI), ANKA (at Forschungszentrum Karlsruhe), ASTRID 2 (at Aarhus University), FLASH (at DESY), and LCLS (at SLAC), thus highlighting the continued importance of *intra-organizational layering*. At the same time, there are examples of sources substituting older ones, such as PETRA III gradually replacing DORIS II (at DESY), exemplifying the role of *intra-organizational displacement* in the overall development of the field. Still other facilities underwent *intra-organizational conversion* (e.g. SPEAR, which was upgraded to SPEAR 3 (at SLAC)). In addition, at the field level, SOLEIL and ALBA were established as new and dedicated, single-mission labs and thus represent *field-level layering*, while DIAMOND, a new lab, replaced SRS in Daresbury in 2007 by *field-level displacement*.

As outlined above, the expansion of the organizational field of synchrotron radiation labs is strongly related to the improved and sophisticated insertion device technology. During the 1970s, when the insertion device technology was first developed, synchrotron radiation activities were still peripheral and parasitic. Indeed, the development of insertion device technology was sparked by discontent with the low quality of the radiation available for the parasitic activities (Hallonsten 2015). The generic character of the experimental systems of synchrotron radiation labs was perhaps discernible but not so clearly accentuated. The situation from the mid-1990s and onwards stands in stark contrast to this. The insertion device technology was the essential technical centerpiece of the third-generation labs, but organizationally, these labs were characterized by their distinctive focus on an efficient accommodation of a large and diverse group of external users, particularly including researchers from the life sciences, and also with the ambition of facilitating the continuous expansion of the user community into new areas. The insertion device technology facilitated this user orientation, which is the ultimate proof of the role of the experimental systems of synchrotron radiation labs as generic technology.

Fig. 2 illustrates the degree of diversity within the entire organizational field, both in the years of opening of the labs and in one fundamental technical aspect: the electron energy, measured in giga electron volts (GeV).[6] The first generation (parasites) are diverse in both time and energy level because they were designed, built, and taken into operation on the basis of a whole other set of ambitions and demands, formulated by the scientific needs of particle physicists. As can be seen in Fig. 2, the energy level preferred by particle physicists at the time never became a preferred energy level for synchrotron radiation. No purpose-built synchrotron radiation labs ever settled on this level but remained higher (APS and ESRF) or lower (most labs). The second-generation sources show (see Fig. 2) the ambiguous status of the infrastructure in the phase of their commissioning—their diversification in energy signal uncertainty in the field with regard to the design of the experimental systems and their core technical components. The third generation manifests the settlement on insertion device technology as the core element of the experimental systems. This is especially evident for the five UV/soft X-ray third-generation sources, which are close in electron energy and were opened during a time span of only six years (ELETTRA, ALS, DELTA, MAX II, and BESSY II). The hard X-ray sources, although there are

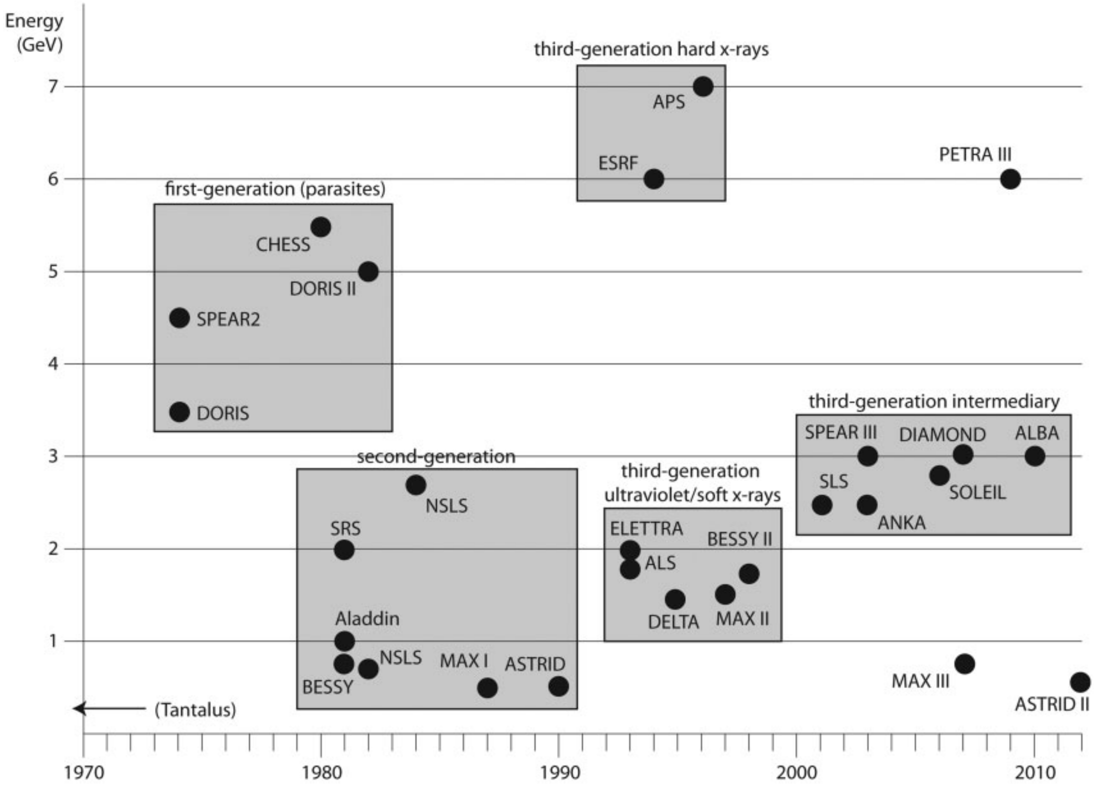

**Figure 2.** The organizational field of synchrotron radiation laboratories, 1974–2012.

only two of them (ESRF and APS), are also convergent in technical terms, although it seems the competitive advantage of a higher energy of 1 GeV was perceived to be sufficiently great to cause a partial redesign when the APS was being constructed (see above). For the intermediary third-generation sources, it is even more obvious that infrastructure had entered a consolidated phase: all are in the small interval of 2.5–3 GeV. The MAX III, ASTRID II, and PETRA III are exceptions. MAX III and ASTRID II complemented and partly replaced MAX I and ASTRID as servants of very specialized Nordic spectroscopy communities requiring optimized radiation at very low energy ranges (Hallonsten 2011). PETRA III is a rebuilt segment (1/9) of the very large PETRA ring for particle physics at DESY in Hamburg, and its electron energy is therefore a particle physics heritage rather than the product of a deliberate choice by synchrotron radiation users (Lohrmann and Söding 2013).

Fig. 2 deserves a note of its own. This graphical illustration of the evolution of the field by the cross-tabulation of electron energy and year of start of operation of the labs manages to quite forcefully convey several important points. Although the electron energy variable is slightly misguided for characterizing the technical and scientific performance of the labs, it still gives a rough indication of their basic performance parameters and the orientation of their activities. As noted above, the first generation (parasites) had an electron energy that was determined by the needs of particle physics at the time of their opening. The diversity of electron energy levels in the second generation hints at some (quite expectable) ambiguity regarding appropriate technical designs in the field-formation phase. The concentration of the two types (hard X-ray and UV/soft X-ray) of third-generation facilities at two energy levels testifies to their functional specialization. The narrow range of energy levels in the group of intermediary third-generation labs opened in the 2000s shows a maturing field that has settled on a dominant design and a best practice. It should be noted that there is a lack of deviation in the figure.

## 5. Conclusions

The analysis in Section 4 showed that the combined application of concepts from historical institutionalism and science and technology studies in new empirical areas have great potential for contributing valuable perspectives and insights to the sociology and history of science, and science policy and management studies, by broadening their conceptual and empirical reach. In addition, the above analysis places the spotlight on the remarkable development of synchrotron radiation from a peripheral lab curiosity to a mainstream and crucial resource for cutting-edge experimental work in a wide range of sciences. This history also deserves to be analyzed from the perspective of how new research areas grow to prominence. But the focus here, and the most important contribution made, is to chronicle, conceptualize and analyze the formation and expansion of a new organizational field in experimental science. This field-level perspective and long historical reach is instrumental for the understanding of how contemporary publicly funded science is organized and how it renews itself on the basis of scientific advance and technological innovation, in tandem with the broader shifts in society and the economy with regard to what areas and applications are judged strategic and worthy of priority. The analysis of the formation and expansion of the organizational field of synchrotron radiation labs yields a number of interrelated conclusions that concern this specific empirical material but that can probably be generalized into guiding assumptions to be applied and adapted in studies of other organizational fields in science.

First, the organizational field of synchrotron radiation labs was born from the parasitic use of a byproduct of particle physics labs. This shows that something that is initially considered to be a waste product can later be proven sufficiently useful to give rise to a whole new class of experimentation and purpose-built labs to host it. Furthermore, and more specifically, it was the limitations of parasitic use that sparked the technological innovation that later became the infrastructural backbone of the entire organizational field of synchrotron radiation labs, namely insertion device technology. This means that the initiation of the field occurred due to the provision of good ideas, some seed funding for adding technical infrastructure to existing particle physics facilities, and the dedication of some scientific staff operating their instrumentation in parasitic mode. The emergence of the new organizational field started though small-scale, yet eventually influential, internal organizational modifications (intra-organizational layering), in this case universities and national research labs, consistent with the postulates of neo-institutional theory.

But the formation of the organizational field was not confined to these pre-existing universities and national research labs. Rather, it gained momentum particularly once dedicated single-mission synchrotron radiation labs were established on greenfield sites. It should be noted that, although the initial group of such independent labs (i.e. those referred to as second-generation) did not use the eventual consolidated design based on insertion device technology, their contribution to the development of the field was immense because their launch marked the end of the parasitic era, and thus the early phase of field emergence.

Fundamentally, the field expansion was enabled by the consolidation of the insertion device-based storage ring technology. Although its development originated in the parasitic era when its scientific relevance was still peripheral, insertion device technology enabled the development of reliable experimental systems operated by streamlined organizations and used as customary research infrastructures in many disciplinary contexts. This generic experimental system, built around insertion devices, is the key to the proliferation of the use of synchrotron radiation as a recognized tool for organized experimental science.

Confirming predictions from historical institutionalism, several gradual but cumulative processes of institutional change are identifiable in various phases of the development, both on the level of single organizations and on the field level. Perhaps most important among the processes is *intra-organizational layering* (i.e. the adding of major new experimental facilities within pre-existing research organizations). It occurs over the whole period and it therefore contributes to the initiation, formation, and expansion of the field. Many of the labs launched by this process are prominent members of the field (e.g. NSLS, ALS, APS, and LCLS). After the initiation phase, *field-level layering* appears to be the single most important process (i.e. the launch of new, purpose-built synchrotron radiation facilities on greenfield sites). In the years 1981–2012 seven entirely new, single-mission and dedicated synchrotron radiation labs were established outside pre-existing organizations, including pioneers such as SRS, BESSY, ELETTRA, and perhaps most importantly, ESRF.

Some signs of consolidation are also visible in the later phase of expansion, not least the isomorphic change tendencies of labs imitating each other both technologically and organizationally.[7] Perhaps the most important are the intermediary energy third-generation labs that are very much alike in size and basic function and whose organization also are reminiscent of each other, with institutionalized best practices for user support, peer review-based handling of applications for access, auxiliary facilities (e.g. for sample preparation and data processing), and short- and long-term technical and scientific development of the labs. For future research, it would be interesting to further the use of neo-institutional theory and explore how the concepts of isomorphism (including the tripartite classification in coercion, normative pressure, and mimesis) (DiMaggio and Powell 1983) and ‘rationalized myths’ (Meyer and Rowan 1977) can be used to explain the seeming convergence of practices and standards in the field in later stages of expansion.

These conclusions are instrumental for the understanding of the particular case of the emergence and growth of synchrotron radiation as a generic resource for experimental science, and the formation and expansion of the new organizational field. Obviously, the historical narrative in Section 2 is abridged and thus simplified, but there are several extensive chronicles of individual cases in the history of science that can provide complementary information, especially on the micro-level to supplement the field perspective of this paper. Importantly, the combination of such detailed historical cases studies and the sociologically oriented analysis of whole fields improves our understanding how science as a social system undergoes change and renewal. The prospects for further similar analyses of the rich body of historical accounts of science in the transformative second half of the 20th century (and beyond) appear promising. In particular, the application of the concepts from historical institutionalism on other cases appears promising because this theoretical approach provides particularly robust tools for analysis of multi-level and multi-dimensional change in science systems, organizational fields in science, and within research organizations. Change is essential to science, and the analysis of change is essential to history and sociology alike and highly relevant to science policy studies. Not only will it add new perspectives and angles to a truly intriguing topic, it will also provide crucial field-level overviews concerning the long-term growth and proliferation of new techniques, new experimental tools, and new ways of organizing the utilization of these tools in cutting-edge experimental science.

Of particular use for science policy-makers, faced with the double challenge of supporting new research infrastructures and, at the same time, reconfiguring or even downsizing existing capacities, are the theory-informed insights about change. First, the analysis shows that layering (at both field and organizational levels) is the dominant process of gradual, cumulative change. This is no coincidence, because layering allows investments in new research capacities without direct loss for the pre-existing, dominant capacities (here particle physics), given that sufficient resources are available. Especially in cases where the scientific establishment is strong and has veto power, layering is the most likely and recommendable renewal strategy, because it engenders comparatively little conflict, particularly in comparison to dismantling or displacement. Since it is often found at the beginning of more thorough processes of renewal, from a science policy point of view, layering appears as a key strategy for research sponsors as change agents. Second, the analysis provides yet another piece of evidence for the prominent role of serendipity in the development of science (Merton and Barber 2004). It shows that the support of sponsors and research managers for the marginal and esoteric efforts to launch synchrotron radiation research at particle physics labs provided the growth environment in which synchrotron radiation research could eventually blossom. The lesson in policy terms is clear: seemingly peripheral activities that challenge dominant structures also deserve attention and should be considered for generous support, should they prove promising. Third, and related, it is clear that in the stages of field formation and expansion, the liberation of synchrotron radiation research from its organizational and infrastructural exile in particle physics facilities was instrumental, which means that a growth environment alone does not suffice. It needs to be complemented by opportunities for organizational independence, that are granted in a timely fashion.

## Acknowledgements

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## Notes

1. The wavelength of the radiation emitted depends fundamentally on the accelerator design but can also be altered with the aid of auxiliary equipment. Synchrotron radiation was in fact predicted theoretically 1864 by James Clerk Maxwell in his famous equations. The name had its origin with the first detection of the radiation at a synchrotron in 1947 (Blewett 1988), but strictly speaking, the name is erroneous because synchrotrons have rarely been used for experimental work with radiation (with some exceptions in the late 1950s and early 1960s). The preferred accelerator type is instead the storage ring (see below in Section 2), but the name 'synchrotron radiation' has nonetheless been canonized.
2. This was the colloquial term used at the time for the utilization of synchrotron radiation produced by accelerators designed for particle physics (Hallonsten 2015).
3. For example, an early crystallographic measurement at the Stanford Synchrotron Radiation Laboratory showed 'a factor of at least 60 greater' intensity, which meant 'unique advantages (. . .) in X-ray diffraction studies of protein crystals' (Phillips et al. 1976: 128). Another experiment, using the extended X-ray absorption fine structure (EXAFS) spectroscopic technique, showed a performance improvement compared to state-of-the-art home laboratory X-ray sources (rotating anode sources) of an astonishing factor of 100,000 (Hallonsten 2015).
4. The concept of 'coproduction' of scientific lab settings and experimental opportunities (Jasanoff 2004) could be a useful addition to the tools used in the analysis. We encourage such cross-fertilization of conceptual tools but remain here with historical institutionalism in order to keep our focus.
5. The strategic orientation of the public sponsors in this regard can be illustrated by the fact that the ESRF, as the first hard X-ray third-generation source, was technically geared towards an energy level of 6 GeV, which enticed the planners of its North American counterpart (APS), built only two years later, to go for 7 GeV and thus a somewhat higher general level of performance (Westfall 2012: 447). Similar competition between facilities is seen in the mid-1990s when the UV/soft X-ray sources (ALS, ELETTRA, DELTA, MAX II, and BESSY II) competed to come online first (see also Fig. 1) (Hallonsten 2011: 198–200).
6. Although this parameter is by no means the only determining factor for the performance of a synchrotron radiation source, it indicated (up until the early 2000s and the advent of the intermediary third-generation sources) the scientific ambition of labs because those labs of higher energy (typically above approximately 4.5 GeV) were capable of delivering hard X-rays, whereas those of lower energy focused on the UV and soft X-ray region. It should be noted that the energy level for fourth-generation sources, as expressed in GeV, is not comparable to conventional synchrotron radiation sources (i.e. those of generations one to three), because their basic technical design is essentially different.
7. The recent complete imitation of the MAX IV technical design by the constructors of the Polish synchrotron radiation facility SOLARIS is thus far unique and should be treated as an exceptional case of technical mimesis.

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