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Analysis of Scientific and Technological Performance and Impact of Synchrotron Radiation Light Source Based on Beamlines: A Case Study of Advanced Photon Source

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Abstract: Synchrotron radiation light source has brought about new discoveries in a wide range from basic scientific research, technical innovation to industry fields, which is offering extreme experimental means and conditions as a kind of typically large scientific user facility, like a giant microscope. Meanwhile, several major challenges, such as high technical complexity, long construction period and cost risk, request more caution of management practices. Monitoring and evaluating the scientific and technological performance are effective solutions to optimize the operation and use of synchrotron radiation light source.

This paper assessed the scientific and technological performance and impact of Advanced Photon Source (APS) in USA as an example, especially from the perspective of 68 simultaneously beamlines/endstations, which are the key components of research infrastructure and the frontier of scientific service. The main dataset was constructed based on the academic paper records allocated from the official website, including the output using APS and by the staffs of APS focusing on the establishment, development and upgrade of APS during 1985 to 2019. Each beamline was analyzed under the framework of "facilitymetrics", and the quantitative performance measures included overall trend and activity level, discipline distribution, requirements in various countries, academic impact, hot themes and main experimental approaches.

Furthermore, several issues about the sustainability of large facility were discussed briefly: (1) the necessary of upgrade; (2) the challenge and alternativity from new disruptive experimental instruments and technology; (3) supporting trans-disciplines scientific research effectively; (4) international cooperation and different access demands in various countries user.

Keywords: Research infrastructure; Advanced Photon Source; Beamlines; Performance Evaluation; Bibliometric analysis

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Introduction

Synchrotron radiation is the electromagnetic radiation emitted by charged particles at a speed close to that of light when they travel along an arc-shaped orbit in a magnetic field. With excellent performance such as high brightness, wide band, narrow pulse, high collimation, high polarization, high purity and accurate prediction, synchrotron radiation has become an irreplaceable giant research tool. Synchrotron radiation has evolved from the first generation, also called parasitic facility, because the accelerators rely on the storage ring accelerator; to the second generation, an independent platform facility; and to the third generation with enhanced core performance, such as higher brightness and reduced emittance; then to the fourth-generation, diffraction-limited storage rings and the fifth-generation light source represented by free electron laser. There are more than 50 light sources in the world, including operational or under construction. They are mainly the third and fourth generations, which are the largest number of platform-based major technology infrastructures.

Generally, construction and operation of synchrotron radiation light source need large investments and long construction periods. Decision maker have pay more attention to how to make better use of them to accelerate the scientific, social and economic development and ensure their sustainable operation. Monitoring and evaluating the scientific and technological performance is an effective solution to optimize the operation and use of large research infrastructure. And bibliometric measures could show contributions to science made by research infrastructures. In 2013, Olof Hallonsten proposed the concept of “facilitymetrics” which focused on the technical reliability, competition for access and publication records primarily, and pointed out the increasing demand for quantitative assessment at the facility level[1]. Then, he and his research team explored a series of issues. Like is it effectively that using simple publication counts in performance assessment of large research infrastructure[2-3], which metrics could assessing productivity of research infrastructure[4], etc. Recently, they explored the levels of genericity of different instruments, or beamlines, at a synchrotron radiation facility, which reflected by disciplinary diversity and Herfindahl-based index[5].

This topic also caused some discussion in economic management and strategic research fields. Chiara provided a preliminary analysis of the returns to R&D investment in large research infrastructures in Europe, and pointed out that using both a cost effectiveness ratio and a bibliometric citation count as metrics to evaluate the return to R&D investment in these research infrastructures[6]. Thiago showed the result of an exhaustive survey conducted by *Instituto de Pesquisa Econômica Aplicada* and two econometric models, logit and probit, were used to “measure” the modernity of the research infrastructure in Brazil[7]. Knudsen provided insights into the process of mapping and gave a hitherto largely unknown landscape of global Energy research infrastructures[8] Beatrice [et] al. identified four typical research collaboration patterns, and explored interrelation between the individual and organisational drivers of collaboration based on research infrastructure and key instrument[9].

We realized that key instruments and beamlines become new insight perspective, because of their accessibility and offering special, even unique, experimental techniques in the world. These distinct techniques attract world-class scientists, user groups and scientific research communities. In order to make full use of instrument and techniques resources, European and American light sources have built kinds of research infrastructure alliance network, coordinating technology strategy and machine time[10].In November 2017, Europe established the League of European Accelerator- based Photon Sources (LEAPS)[11], and then issued *LEAPS Strategy 2030*[12], coordinating the development routes of nearly 20 synchrotron radiation light sources in Europe, and proposing upgrades and joint development plans covering the whole technology chain and core components such as photon sources, X-ray optics and diagnosis, sample environment and positioning, and detectors. In a series of strategic documents involving the materials science and new energy batteries, and the prevention and control of COVID-19[13-15], techniques relating to synchrotron radiation light sources, such as nanoscale 3D/4D/in-situ imaging, high-throughput, femtosecond time-resolved imaging, UV-fluorescence imaging, atomic probe tomography, have attracted particular attention. They provide strong support for frontier scientific breakthroughs, strategic industrial development and people's well-being. Meanwhile, emphasis on developing the base synergy and complementary capabilities of the light source with other research infrastructures and instruments such as neutron sources, free-electron laser, cryo-electron microscopes, etc[16], jointly supporting the European Horizon Framework task and serving the national/regional strategic scientific and technological plans[17-18].

In this paper, Advanced Photon Source (APS) affiliated to USA Department of Energy Argonne National Laboratory was selected as an example. We make attempt to reveal the changing of scientific and technological output performance and impact of synchrotron radiation source (SRS) from the perspective of beamlines and experimental technologies, and analyze the role of experimental technology in the development of SRS, aiming to highlight the key role of advanced experimental technology in facilitating the development of synchrotron radiation source and attracting first-class scientific researchers.

Methodology

The beamlines of Advanced Photon Source

APS is a national user facility under the US Department of Energy, which is operated and managed by Argonne National Laboratory. The facility was put into operation in 1996, with an electron beam energy of 7GeV, which can provide users with hard X-rays, a maximum brightness of over 20keV. It is currently the highest energy synchrotron radiation source in America. At present, APS has 68 simultaneously operating X-ray beamlines (see the Fig.1, separated by dots). A large number of beamlines provide a unique combination of capabilities, with main considerations such as energy range and tunability, special sample environment, time structures and beam size[19].

These beamlines can be divided into two categories: 47 insertion devices and 21 bending magnet beamlines. Among them, 43 beamlines are controlled by the APS X-ray Science Department (XSD). Beamline 35-ID is funded by the National Nuclear Security Administration of the U.S. Department of Energy and jointly operated by Dynamic Compression Sector (DCS) of Washington State University, APS, National Nuclear Safety Administration, Army Research Laboratory and University of Rochester[20]. Beamline 26-ID is operated jointly by APS and the Center for Nanoscale Materials (CNM) of Argonne National Laboratory[21]. The other 23 beamlines are operated entirely by collaborative teams[22].

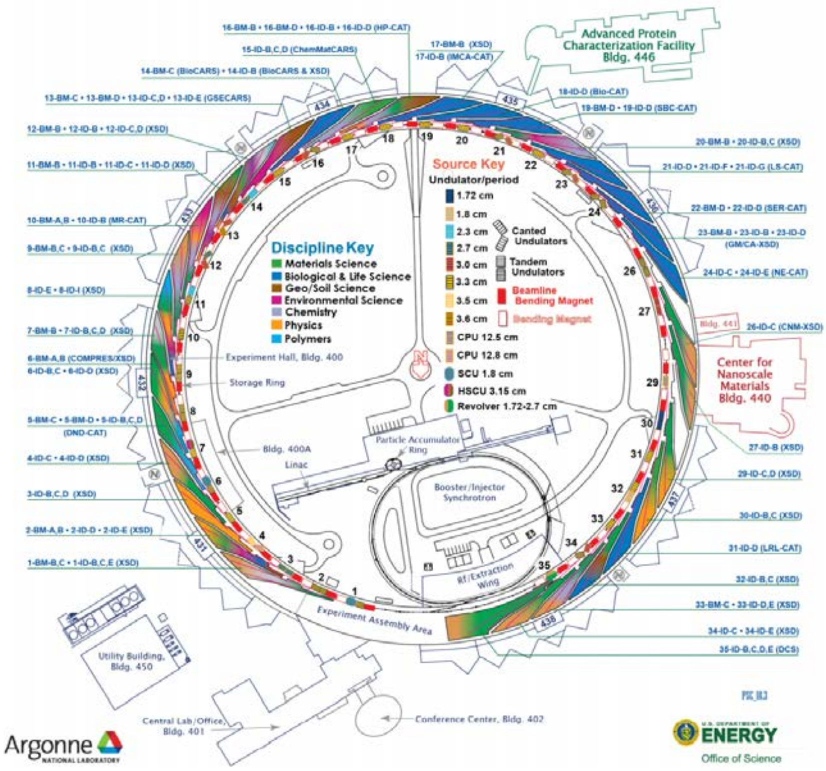


Fig. 1 Distribution of APS Beamlines

Dataset

The main data record was obtained from the database of the official website (https://beam.aps.anl.gov/pls/apsweb/pub_v2_0006.review_start_page) of APS. 27,579 records with info of beamlines and experiment techniques were downloaded (in October 2020). With unique identification DOI published by APS's official database, 22,617 papers were retrieved from the Web of Science database, and each beamline performance parameter was associated with the papers.

The Framework of Analysis

In this study, several qualitative and quantitative analysis methods were adopted, like measurement analysis, trends analysis, contrast analysis, visualization tools. And interpretations were based on data and investigation of some expertise and engineers (Fig.2). The quantitative performance measures included overall trend and activity level, discipline distribution, requirements in various countries, academic impact, hot themes and main experimental approaches.

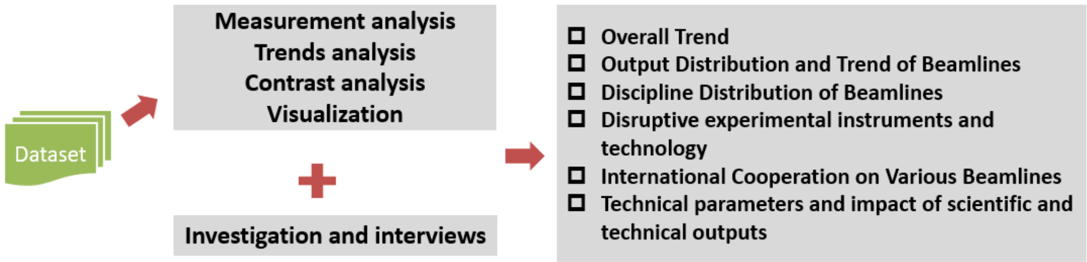


Fig. 2 Analysis Methods and Framework

Overall Trend Analysis

The overall trend (see the Fig.3) suggested that APS had scientific outputs since its conceptual design and construction phase. Cho, et al from Argonne National Laboratory published the first paper focusing on the conceptual design of APS. APS launched the first light in 1995 and was officially in operation at 1996. The scientific output increased year by year, from 79 articles in 1996 to 983 articles in 2005 during ten years. Then occurred a four-year plateau from 2005 to 2009, during which APS carried out a series of optimization and upgrade of infrastructure resources and performance, the sample environment and so on. For example, added 3 new beamlines that can be used for structural biology research[23]; the beamlines operated by Life Sciences Collaborative Access Team (LS-CAT) launched the first light[24]. The medium resolution inelastic X-ray scattering spectrometer MERIX of the 30-zone beamline[25] and the high-resolution inelastic X-ray spectrometer HERIX were put into service. After 2009, scientific output entered a new stage of rapid growth, with the annual number of papers exceeding 2000 in 2016 and reaching a peak of 2,191 in 2018. The compound growth rate from 1996 to 2019 was 15.09%. The number of projects carried out on APS in fiscal year 1998 showed a continuous and significant upward trend, and the number of projects exceeded 6,000 in 2016.

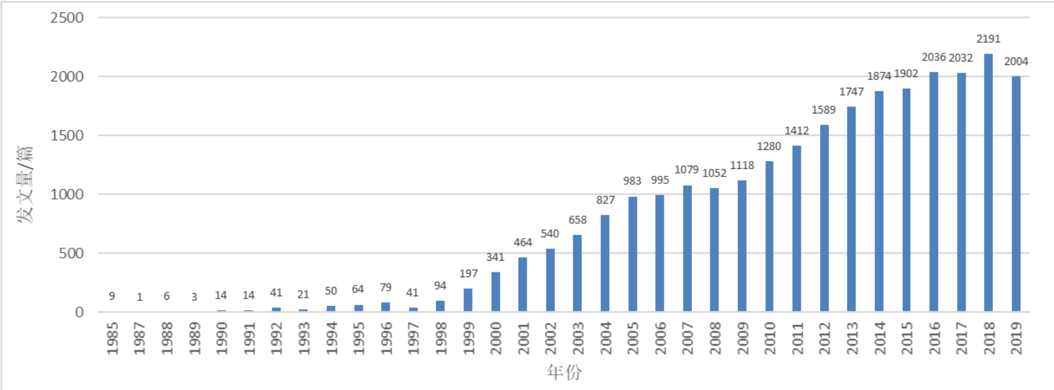


Fig. 3 Trend of Paper Records

Output Distribution and Trend of Beamlines

Productive beamlines

The distribution of paper of each beamline was shown in the following tab. 1. In terms of counts, the top three beamlines were 24-ID (1829), 11-ID (1591) and 23-ID (1558). 24-ID has two experimental end-stations, C and E, which mainly offering micro-diffraction, single crystal diffraction, multi-wavelength anomalous dispersion, single-wavelength anomalous dispersion, microbeam and other techniques to study the crystallography of biological macromolecules at subatomic resolution (<0.85Å). 11-ID has three experimental end-stations, B, C and D, which offering high-energy X-ray diffraction, X-ray diffraction, distribution function, time-resolved X-ray absorption fine structure (XAFS), time-resolved X-ray diffraction and other methods to study ultrafast processes such as crystalline and amorphous material measurement, material structure, phase transition, energy conversion and storage. 23-ID has two experimental end-stations, B and D, which adopt techniques such as macromolecular crystallography, Microdiffraction, Single-wavelength anomalous dispersion, Single-crystal diffraction, Microbeam, Multi-wavelength anomalous dispersion at subatomic (<0.85 Å) resolution.

Active beamlines

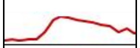
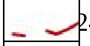
The proportion of published papers in recent three years, which was calculated by dividing the number of papers published in the last three years by the total number of papers published, was an index measuring recent output. The proportion of papers published of each beamline reveals that the top four 29-ID (84.21%), 35-ID (75.76%), 06-BM (71.79%) and 27-ID (50.00%) did not publish papers until 2014-2016. 29-ID had two experimental end-stations, C and D, which focused on condensed matter system by means of resonant soft X-ray scattering (RSXS) and angle-resolved photoemission spectroscopy (ARPES). 35-ID had four experimental end-stations, B, C, D and E, which adopt techniques such as time-resolved X-ray scattering, phase contrast imaging, radiation imaging to carry out material and earth science research, with wide measurement range, stress and long duration. 06-BM had two experimental end-stations, A and B, which are dedicated to white light energy dispersive diffraction, and can be used for measurement of large-volume and high-pressure materials. 27-ID, which provided medium-resolution momentum-resolved resonant inelastic X-ray scattering, is mainly used in physical, material and chemical research.

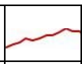
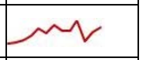
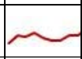
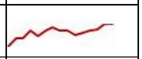
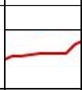
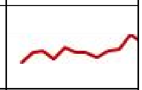
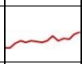
Output trend of beamlines

It was worth noting that the outputs of 09-BM (45.45%), 17-BM (39.69%), 09-ID (37.67%) and 10-BM (36.86%), which were four long-term running beamlines, shows an obvious upward trend. 09-BM was mainly used in materials and chemistry research, providing focused and adjustable X-ray beam for XAFS and XANES experiments, with the ability of fast XAFS and in-situ observation of low-energy and high-energy X-rays. Designed for rapid acquisition powder diffraction using area detectors, 17-BM provides a variety of sample observation environments, making it ideal for parametric/in-situ/operational XRD and PDF measurements. 09-ID supported nano-fluorescence imaging, coherent diffraction imaging (09-ID-B end-station) and ultra-small-angle X-ray scattering experiment (09-ID-C end-station). 10-BM was dedicated to X-ray absorption spectroscopy, providing in-situ time-resolved (4-minute extended X-ray absorption fine structure) experiments, low-resolution fluorescence spectrum, etc. It was mainly used for catalysis, materials science and environmental research, and observation of radioactive materials. In terms of technical features of these beamlines, time resolution ultrafast optics, in-situ observation, multi-sample environment and adjustable experimental conditions were favored by users.

However, 14-BM (1.26%), 01-BM (10.8%), 19-BM (11.08%) and 22-BM (11.96%) showed a downward trend. 14-BM, 19-BM and 22-BM were beamlines for mainly structural biology, and the decline of their research output was related to the breakthrough and application of cryo-electron microscope. One of the key steps of protein structure analysis based on synchrotron radiation source was to obtain a single crystal for X-ray diffraction, crystal growth of purified biological samples was needed, but many complex macromolecular substances were difficult to crystallize. Cryo-electron microscope could achieve atomic high-resolution imaging without making macromolecular samples into crystals. Cryo-electron microscope won the Nobel Prize in Chemistry in 2017, which attracted wide attention in the field of biology and alleviated certain demand. It suggested that the disruptive experimental instruments and technology challenges for research infrastructure sustainability. And we could find that more and more light sources install Cryo-EM to response, actually they established the more integrated experimental environment for researchers.01-BM was mainly used for optical and detector testing, supporting the development of new techniques, and evaluation or calibration of optical detectors produced by other laboratories and industries.

Tab.1 Output Distribution and Trend of APS Beamlines

Beamline	Number of Publication/Paper	Proportion of Total Publications/%	Proportion of Published Papers in the Last Three Years/%	Change Trend	Beamline	Number of Publication/Papers	Proportion of Total Publications/%	Proportion of Published Papers in the Last Three Years/%	Change Trend
01-BM	176	0.78%	10.80%		15-ID	789	3.49%	18.00%	
01-ID	455	2.01%	18.02%		16-BM	461	2.04%	24.95%	
02-BM	275	1.22%	25.45%		16-ID	777	3.44%	17.76%	
02-ID	434	1.92%	14.52%		17-BM	383	1.69%	39.69%	
03-ID	274	1.21%	18.61%		17-ID	734	3.25%	13.35%	
04-ID	450	1.99%	20.22%		18-ID	433	1.91%	16.86%	
05-BM	251	1.11%	27.49%		19-BM	406	1.80%	11.08%	
05-ID	556	2.46%	17.09%		19-ID	1264	5.59%	14.72%	
06-BM	39	0.17%	71.79%		20-BM	660	2.92%	29.09%	
06-ID	541	2.39%	18.67%		20-ID	312	1.38%	21.79%	
07-BM	61	0.27%	29.51%		21-ID	1509	6.67%	20.01%	
07-ID	176	0.78%	23.30%		22-BM	552	2.44%	11.96%	
08-BM	109	0.48%	3.26%		22-ID	1415	6.26%	15.27%	
08-ID	594	2.63%	24.07%		23-ID	1558	6.89%	15.21%	
09-BM	264	1.17%	45.45%		24-ID	1829	8.09%	22.80%	
09-ID	300	1.33%	37.67%		26-ID	108	0.48%	31.48%	
10-BM	334	1.48%	36.83%		27-ID	34	0.15%	50.00%	

10-ID	445	1.97%	14.83%		29-ID	19	0.08%	34.21%	
11-BM	1016	4.49%	27.66%		30-ID	128	0.57%	23.44%	
11-ID	1591	7.03%	26.65%		31-ID	233	1.03%	15.88%	
12-BM	443	1.96%	28.67%		32-ID	390	1.72%	22.82%	
12-ID	915	4.05%	26.01%		33-BM	219	0.97%	17.35%	
13-BM	505	2.23%	28.32%		33-ID	192	0.85%	18.23%	
13-ID	810	3.58%	25.80%		34-ID	302	1.34%	17.88%	
14-BM	398	1.76%	1.26%		35-ID	33	0.15%	75.76%	
14-ID	186	0.82%	11.29%						

Discipline Distribution of Beamlines

At the beginning of design, APS defined the service fields for each beamline, which were Life Science, Material Science, Chemistry, Physics, Environment Science, GeoScience, Polymer Science and Atomic Physics. From the perspective of the discipline distribution of beamlines, 70.59% of the beamline stations could provide support for research in the field of materials science; 23 beamlines that could provide support for studies in chemistry and physics, accounting for 45.10%. It was also found that 74.51% of the beamlines provided support for two or more disciplines, and only 13 beamlines support one discipline. Compared with the designed target disciplines, these beamlines accomplished the strategic missions successfully, their service capabilities also extend to the disciplines intersect with the target.

Tab. 2. Discipline Layout of Beamline

Discipline	**Number of Beamlines**	**Outputs Proportion(%)**
Materials science	36	70.59
Chemistry	23	45.10
Physics	23	45.10
Life sciences	22	43.14
Environmental science	14	27.45
Geoscience	11	21.57
Polymer science	5	9.80
Atomic physics	1	1.96

Tab. 3. Target disciplines and outputs disciplines of beamlines

Beam lines	**Target Disciplines**	**Life Science**		**Material Science**		**Chemistry**		**Physics**		**Environment Science**		**GeoScience**		**Polymer Science**		**Atom Physics**	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
01-BM	Material Science; Physics	14	7.95	176	**100**	41	23.30	176	**100**	24	13.64	13	7.39	13	7.39	1	0.57
01-ID	Material Science; Physics; Chemistry; Life Science	455	**100**	455	**100**	455	**100**	455	**100**	39	8.57	21	4.62	3	0.66	0	0.00
02-BM	Physics; Life Science; GeoScience; Material Science	275	**100**	275	**100**	17	6.18	275	**100**	14	5.09	275	**100**	3	1.09	2	0.73
02-ID	Life Science; Material Science; Environment Science	434	**100**	434	**100**	60	13.82	35	8.06	434	**100**	22	5.07	7	1.61	2	0.46
03-ID	Physics; GeoScience; Life Science; Chemistry; Material Science	274	**100**	274	**100**	274	**100**	274	**100**	48	17.52	274	**100**	2	0.73	0	0.00
04-ID	Physics; Material Science	13	2.89	450	**100**	82	18.22	450	**100**	45	10.00	30	6.67	12	2.67	1	0.22
05-BM	Material Science; Polymer Science; Chemistry; Environment Science	9	3.59	251	**100**	251	**100**	32	12.75	251	**100**	5	1.99	251	**100**	0	0.00
05-ID	Material Science; Polymer Science; Chemistry; Life Science	556	**100**	556	**100**	556	**100**	61	10.97	17	3.06	6	1.08	556	**100**	0	0.00
06-BM	Material Science; GeoScience	2	5.13	39	**100**	4	10.26	6	15.38	3	7.69	39	**100**	0	0.00	0	0.00
06-ID	Physics; Material Science	30	5.55	541	**100**	102	18.85	541	**100**	60	11.09	12	2.22	10	1.85	0	0.00
07-BM	Physics	12	19.67	14	22.95	6	9.84	61	**100**	1	1.64	8	13.11	1	1.64	1	1.64
07-ID	Material Science; Atom Physics; Chemistry	15	8.52	174	**98.86**	174	**98.86**	18	10.23	13	7.39	15	8.52	3	1.70	174	**98.86**
08-	Chemistry; Life	10	**10**	109	**100**	10	**10**	7	6.4	109	**100**	1	0.9	6	5.5	0	0.0

Beam lines	**Target Disciplines**	**Life Science**		**Material Science**		**Chemistry**		**Physics**		**Environment Science**		**GeoScience**		**Polymer Science**		**Atom Physics**	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
BM	Science; Environment Science; Material Science	9	**0**			9	**0**		2				2		0		0
08-ID	Material Science; Polymer Science; Physics	31	5.22	594	**100**	48	8.08	594	**100**	14	2.36	4	0.67	594	**100**	1	0.17
09-BM	Material Science; Chemistry; Environment Science	5	1.89	264	**100**	264	**100**	44	16.67	264	**100**	3	1.14	16	6.06	0	0.00
09-ID	Chemistry; Material Science; Life Science	300	**100**	300	**100**	300	**100**	53	17.67	20	6.67	23	7.67	18	6.00	0	0.00
10-BM	Material Science; Chemistry; Environment Science; Physics	3	0.90	334	**100**	334	**100**	334	**100**	334	**100**	3	0.90	20	5.99	0	0.00
10-ID	Material Science; Environment Science; Chemistry	17	3.82	445	**100**	445	**100**	106	23.82	445	**100**	7	1.57	16	3.60	1	0.22
11-BM	Chemistry; Material Science; Physics	30	2.95	1016	**100**	1016	**100**	1016	**100**	112	11.02	25	2.46	22	2.17	0	0.00
11-ID	Chemistry; Environment Science; Material Science; Physics	94	5.91	1591	**100**	1591	**100**	1591	**100**	1591	**100**	34	2.14	94	5.91	5	0.31
12-BM	Material Science; Polymer Science; Chemistry; Physics; Environment Science	54	12.19	443	**100**	443	**100**	443	**100**	443	**100**	3	0.68	443	**100**	2	0.45
12-ID	Chemistry; Material Science; Life Science; Polymer Science; Physics	915	**100**	915	**100**	915	**100**	915	**100**	116	12.68	11	1.20	915	**100**	0	0.00
13-BM	GeoScience; Environment Science	36	7.13	106	20.99	98	19.41	93	18.42	505	**100**	505	**100**	6	1.19	0	0.00

Beam lines	**Target Disciplines**	**Life Science**		**Material Science**		**Chemistry**		**Physics**		**Environment Science**		**GeoScience**		**Polymer Science**		**Atom Physics**	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
13-ID	GeoScience; Environment Science	54	6.67	210	25.93	193	23.83	171	21.11	810	**100**	810	**100**	8	0.99	1	0.12
14-BM	Life Science	398	**100**	17	4.27	16	4.02	3	0.75	7	1.76	2	0.50	8	2.01	0	0.00
14-ID	Life Science	164	**88.17**	11	5.91	9	4.84	5	2.69	4	2.15	2	1.08	3	1.61	0	0.00
15-ID	Material Science; Chemistry	75	9.51	788	**99.87**	788	**99.87**	44	5.58	34	4.31	46	5.83	21	2.66	0	0.00
16-BM	Material Science; GeoScience; Chemistry; Physics	24	5.21	461	**100**	461	**100**	461	**100**	71	15.40	461	**100**	0	0.00	0	0.00
16-ID	Material Science; GeoScience; Chemistry; Physics	47	6.05	777	**100**	777	**100**	777	**100**	157	20.21	777	**100**	1	0.13	0	0.00
17-BM	Chemistry; Material Science	2	0.52	301	**78.59**	301	**78.59**	59	15.40	63	16.45	0	0.00	11	2.87	0	0.00
17-ID	Life Science	690	**94.01**	10	1.36	8	1.09	1	0.14	1	0.14	3	0.41	7	0.95	0	0.00
18-ID	Life Science	433	**100**	63	14.55	58	13.39	16	3.70	30	6.93	1	0.23	31	7.16	0	0.00
19-BM	Life Science	405	**99.75**	5	1.23	3	0.74	1	0.25	2	0.49	2	0.49	1	0.25	0	0.00
19-ID	Life Science	1264	**100**	24	1.90	17	1.34	7	0.55	7	0.55	8	0.63	10	0.79	0	0.00
20-BM	Material Science; Environment Science; Chemistry	15	2.27	660	**100**	660	**100**	124	18.79	660	**100**	28	4.24	29	4.39	1	0.15
20-ID	Material Science; Environment Science; Chemistry	18	5.77	312	**100**	312	**100**	34	10.90	312	**100**	21	6.73	8	2.56	1	0.32
21-ID	Life Science	1508	**99.93**	37	2.45	26	1.72	3	0.20	9	0.60	4	0.27	21	1.39	0	0.00
22-BM	Life Science	550	**99.64**	3	0.54	3	0.54	2	0.36	0	0.00	0	0.00	3	0.54	0	0.00
22-ID	Life Science	1412	**99.79**	19	1.34	18	1.27	8	0.57	4	0.28	2	0.14	14	0.99	0	0.00

Beam lines	**Target Disciplines**	**Life Science**		**Material Science**		**Chemistry**		**Physics**		**Environment Science**		**GeoScience**		**Polymer Science**		**Atom Physics**	
		Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
23-ID	Life Science	1557	**99.94**	13	0.83	10	0.64	5	0.32	2	0.13	3	0.19	8	0.51	1	0.06
24-ID	Life Science	1829	**100**	17	0.93	17	0.93	5	0.27	10	0.55	0	0.00	7	0.38	0	0.00
26-ID	Physics; Material Science	18	16.67	108	**100**	9	8.33	108	**100**	18	16.67	6	5.56	1	0.93	0	0.00
27-ID	Physics; Material Science; Chemistry	10	**29.41**	34	**100**	34	**100**	34	**100**	1	2.94	10	**29.41**	1	2.94	0	0.00
29-ID	Physics; Material Science	0	0.00	19	**100**	4	21.05	19	**100**	4	21.05	0	0.00	0	0.00	0	0.00
30-ID	Physics; Material Science; GeoScience; Life Science	128	**100**	128	**100**	47	**36.72**	128	**100**	7	5.47	128	**100**	1	0.78	2	1.56
31-ID	Life Science	233	**100**	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
32-ID	Material Science; Life Science; GeoScience	390	**100**	390	**100**	70	17.95	61	15.64	24	6.15	390	**100**	6	1.54	9	2.31
33-BM	Material Science; Physics; Chemistry	13	5.94	219	**100**	219	**100**	219	**100**	35	15.98	12	5.48	16	7.31	3	1.37
33-ID	Material Science; Physics; Chemistry; Environment Science	32	16.67	192	**100**	192	**100**	192	**100**	192	**100**	20	10.42	23	11.98	3	1.56
34-ID	Material Science; Physics; Environment Science; GeoScience	18	5.96	302	**100**	36	11.92	302	**100**	302	**100**	302	**100**	4	1.32	2	0.66
35-ID	Physics; Material Science; GeoScience	6	18.18	33	**100**	5	15.15	33	**100**	3	9.09	33	**100**	0	0.00	1	3.03

International Cooperation

International Cooperation on Various Beamlines

Besides the United States, China is the country with the largest number of APS publications, 2,557, accounting for 11.31% of the total, far exceeded second-ranking Canada. This indicated that China and the United States have enjoyed a solid foundation of cooperation in the APS. Germany and Britain have published more than 1,000 papers.

The proportion of international cooperation on papers reflected the accessibility of beamlines. High-level cooperation beamlines were 27-ID (85.29%), 20-ID (84.80%) and 20-BM (82.31%). 27-ID focused on the following themes: the spin-orbit coupling, magnetic excitation and regulation laws of transition metal oxide Sr2IrO4, Mott insulator Sr3Ir2O7 and double perovskite Sr2FeOsO6 in condensed matter physics research. South Korea, Canada and Germany were its key partners. 20-ID mainly involved the distribution of arsenic, mercury, bromine, lead and other elements in the environment (veins, rivers or underground sediments, soil pollution, etc.) and cultural relics (fossils, hairs). 20-BM mainly involved electro-catalytic process, electrode materials of lithium, sodium ion batteries and fuel cells, and the distribution of arsenic, chromium, mercury and other elements. Canada played an important role in their cooperation networks, then China and Germany.

However, 35-ID (9.09%), 05-ID (18.41%) and 06-BM (25.64%) have a lower proportion of cooperative output. 35-ID is the initiation research of Exploding Metal Foils carried out by the United States, Britain, Poland and Russia, while the research in the United States mainly focuses on the ultrafast dynamic properties, dynamic behavior and defects of materials under impact compression. 05-ID mainly involved the crystal structure and phase-behavior of polymers, biological macromolecules, nanomaterials, etc. However, there is no significant difference between the research topics of the United States and other countries in terms of keyword frequency. The cooperative research of 06-BM was the in-situ stress observation of bismuth ferrite, zinc oxide, olivine, magnesite and other elements carried out by the United States, Britain, the Netherlands, Spain, China, while the research in the United States mainly focuses on the in-situ measurement of lithium ion batteries and aluminum alloys, and the observation of the strain of battery lattice under pressure and temperature.

Tab.4 International Cooperation on Beamlines

Beamline	Number of Publication/ Paper	US Output/%	International Cooperation	
			Proportion/ %	TOP5 Countries (Number of Publications/Paper)
01-BM	176	90.91	46.88	Australia (22); China (11); France (9); Germany (7); Britain (7)
01-ID	455	92.31	49.76	China (55); Canada (36); Germany (33); Denmark (30); Australia (21)

Beamline	Number of Publication/ Paper	US Output/%	International Cooperation	
			Proportion/ %	TOP5 Countries (Number of Publications/Paper)
02-BM	275	95.27	49.24	China (40); Australia (26); Germany (22); Britain (20); Switzerland (13)
02-ID	434	95.85	52.40	Australia (94); Germany (44); China (30); France (17); Britain (16)
03-ID	274	98.91	52.03	Germany (58); China (31); France (27); Japan (20); Canada (8)
04-ID	450	98.67	54.95	China (57); Germany (41); Britain (37); Canada (35); Japan (35)
05-BM	251	97.61	27.35	China (19); France (9); Germany (7); Canada (5); Britain (5); Switzerland (5)
05-ID	556	99.64	18.41	Canada (14); France (14); China (11); Britain (10); Japan (10)
06-BM	39	100.00	25.64	United States (39); Britain (4); Spain (2); Netherlands (2); China (1); Germany (1); Switzerland (1); Turkey (1)
06-ID	541	96.12	49.81	Germany (70); France (54); China (34); Britain (34); Japan (33); South Korea (33)
07-BM	61	100.00	27.87	Australia (11); Spain (5); Britain (4); China (1); Germany (1); France (1); South Korea (1); Switzerland (1); Italy (1)
07-ID	176	97.73	47.67	Germany (21); Japan (17); China (13); Britain (10); South Korea (10); Denmark (10)
08-BM	109	94.50	33.01	China (7); Canada (7); Australia (4); Italy (4); Germany (3); France (3); Switzerland (3)
08-ID	594	96.46	41.54	China (70); South Korea (39); Canada (30); Britain (18); Japan (17)
09-BM	264	93.56	57.89	China (65); Canada (36); Saudi Arabia (15); Britain (11); Germany (9)
09-ID	300	96.67	40.00	Canada (31); China (20); Japan (18); Germany (17); France (14)
10-BM	334	99.40	36.14	China (40); Australia (17); South Korea (12); Germany (11); Canada (10)
10-ID	445	97.75	35.17	China (43); Australia (17); Britain (15); India (14); Canada (13)
11-BM	1016	85.14	58.15	France (130); China (103); Germany (78); Britain (70); Canada (59)
11-ID	1591	88.94	69.40	China (521); France (112); Britain (111); Germany (103); Australia (80)
12-BM	443	95.26	39.81	China (68); France (23); Australia (18); South Korea (14); Germany (13)

Beamline	Number of Publication/ Paper	US Output/%	International Cooperation	
			Proportion/ %	TOP5 Countries (Number of Publications/Paper)
12-ID	915	96.94	36.19	China (95); Germany (43); South Korea (37); Canada (31); Britain (30)
13-BM	505	92.67	57.48	China (84); Germany (45); Canada (40); France (38); Australia (26)
13-ID	810	94.81	57.29	China (142); Germany (138); France (85); Britain (60); Russia (55)
14-BM	398	83.42	39.76	Australia (47); Canada (38); Japan (13); Germany (9); France (9)
14-ID	186	83.87	49.36	South Korea (17); Australia (13); France (11); Canada (10); Germany (10)
15-ID	789	87.07	55.17	Australia (115); China (56); Germany (50); Denmark (30); France (28)
16-BM	461	90.02	69.16	China (193); Germany (39); Japan (38); Canada (19); Britain (14); France (14)
16-ID	777	94.08	59.78	China (209); Germany (54); Japan (51); Canada (35); Britain (35)
17-BM	383	97.13	40.59	China (49); Britain (15); Spain (15); Saudi Arabia (12); Germany (11); France (11); Australia (11)
17-ID	734	94.96	31.13	Canada (59); Britain (41); China (32); Germany (19); Australia (19)
18-ID	433	95.61	30.43	Britain (19); China (17); Germany (17); France (16); Canada (15)
19-BM	406	92.61	37.77	Canada (46); Britain (21); Germany (15); China (14); Poland (12)
19-ID	1264	91.06	45.35	Canada (177); China (98); Britain (72); Germany (47); France (44)
20-BM	660	76.21	82.31	Canada (215); China (122); Germany (46); Britain (29); South Korea (22)
20-ID	312	80.13	84.80	Canada (113); China (44); Germany (27); Britain (19); Australia (18)
21-ID	1509	97.95	31.33	China (139); Canada (69); Britain (57); Germany (40); France (31)
22-BM	552	99.46	30.60	China (30); Japan (30); Britain (24); Germany (15); Canada (12)
22-ID	1415	98.37	28.45	China (74); Britain (50); Japan (50); Germany (37); Canada (31)
23-ID	1558	92.43	37.78	Canada (139); China (95); Britain (71); Australia (57); Germany (54)
24-ID	1829	97.48	29.78	Canada (109); China (100); Germany (72); Britain (70); France (39)

Beamline	Number of Publication/ Paper	US Output/%	International Cooperation	
			Proportion/ %	TOP5 Countries (Number of Publications/Paper)
26-ID	108	100.00	41.67	France (8); South Korea (8); Germany (6); Britain (6); Australia (5); Switzerland (5); China (4); Colombia (4)
27-ID	34	100.00	85.29	South Korea (10); Canada (9); Germany (8); China (6); France (5)
29-ID	19	100.00	68.42	Germany (6); Britain (6); China (2); Switzerland (2); Canada (1); France (1); Korea (1); Spain (1); Italy (1)
30-ID	128	99.22	69.29	Germany (37); China (18); Canada (17); France (14); Japan (12)
31-ID	233	92.70	30.56	Canada (26); Spain (13); Britain (7); New Zealand (7); China (6); Germany (6); Singapore (6)
32-ID	390	97.18	40.90	China (55); South Korea (25); Switzerland (21); France (20); Britain (17)
33-BM	219	100.00	35.16	China (19); Germany (13); Britain (10); France (10); Czech Republic (6)
33-ID	192	96.88	36.02	China (18); Germany (13); Israel (10); Canada (6); France (5); Korea (5)
34-ID	302	96.03	64.48	Britain (91); China (41); Germany (40); Australia (18); South Korea (15)
35-ID	33	100.00	9.09	Britain (2); Russia (1); Poland (1)

Various demands of different countries

The analysis of the output of different countries on each beamline suggested that the demands for beamlines varies greatly from country to country. Canada had a strong demand for 19-ID, 23-ID and 24-ID in life science and 20-BM and 20-ID in chemical materials research, while Germany payed more attention to 11-ID, 11-BM and 06-ID for chemical materials and physics research. The studies carried out on 11-ID mainly involved the crystal structure, mechanical properties and deformation behavior of martensitic transformation, metallic glasses, lithium-ion battery, titanium alloys by means of high-energy X-ray diffraction and in-situ observation. There are two main reasons for this phenomenon. The first is the availability of local research infrastructure that can provide similar functions and capability, the second is the scientific excellence of proposal tested by peer review because of the scarcity of beamlines working time.

Tab.5. Demands of different counties

NO.	Countries	Paper count	%	TOP10 beamlines
1	US	21096	93.28	24-ID(1783); 21-ID(1478); 23-ID(1440); 11-ID(1415); 22-ID(1392); 19-ID(1151); 12-ID(887); 11-BM(865); 13-ID(768); 16-ID(731)
2	CN	2557	11.31	11-ID(521); 16-ID(209); 16-BM(193); 13-ID(142); 21-ID(139); 20-BM(122); 11-BM(103); 24-ID(100); 19-ID(98); 12-ID(95)
3	CA	1452	6.42	20-BM(215); 19-ID(177); 23-ID(139); 20-ID(113); 24-ID(109); 21-ID(69); 11-BM(59); 17-ID(59); 13-ID(48); 19-BM(46)
4	DE	1312	5.80	13-ID(138); 11-ID(103); 11-BM(78); 24-ID(72); 06-ID(70); 03-ID(58); 16-ID(54); 23-ID(54); 15-ID(50); 19-ID(47)
5	UK	1099	4.86	11-ID(111); 34-ID(91); 19-ID(72); 23-ID(71); 11-BM(70); 24-ID(70); 13-ID(60); 21-ID(57); 22-ID(50); 17-ID(41)
6	FR	964	4.26	11-BM(130); 11-ID(112); 13-ID(85); 06-ID(54); 19-ID(44); 24-ID(39); 13-BM(38); 23-ID(38); 16-ID(32); 21-ID(31)
7	AU	770	3.40	15-ID(115); 02-ID(94); 11-ID(80); 23-ID(57); 14-BM(47); 13-ID(36); 02-BM(26); 13-BM(26); 01-BM(22); 01-ID(21)
8	JP	700	3.10	11-ID(57); 13-ID(51); 16-ID(51); 22-ID(50); 23-ID(45); 16-BM(38); 04-ID(35); 06-ID(33); 22-BM(30); 19-ID(27)
9	KR	506	2.24	08-ID(39); 12-ID(37); 06-ID(33); 11-ID(30); 24-ID(29); 04-ID(27); 32-ID(25); 21-ID(23); 20-BM(22); 11-BM(20)
10	CH	340	1.50	11-ID(38); 19-ID(27); 32-ID(21); 23-ID(20); 11-BM(18); 24-ID(18); 17-ID(14); 21-ID(14); 02-BM(13); 12-ID(12)

Energy parameters and impact of scientific and technical outputs

Tab. 6 showed the impact and core technical parameters (including energy and core experimental techniques) of the papers produced by each beamline, and analyses the relationship between the maximum energy and the average citations per article as an indicator of the impact of the papers (Fig. 4). It seems that there is no significant correlation between the maximum energy and the average number of citations per article, i.e. the higher the energy, the higher the impact of the output paper. Outputs with high average citation frequency are concentrated in the beamlines of life science research such as structural biology and macromolecular crystallography. Their highest energies are in the range of 13.5-20 KeV, which is low in the APS energy spectrum.

Experimental techniques, the most widely laid out, were macromolecular crystallography (10), micro-fluorescence (hard X-rays) (10), high-pressure diamond-to-top anvils (8), X-ray absorption fine structures (8), and single-wavelength anomalous scattering (8), indicating a high demand for these techniques in scientific activity.

Analysis of the five more influential beamlines 23-ID, 19-ID, 24-ID, 12-BM and 14-BM shows that they all mainly serve research related to structural biology, macromolecular crystallography and other life science fields. The experimental technical capabilities of 23-ID, 19-ID, 24-ID, 14-BM and 19-BM involve subatomic resolution (<0.85 Å), large unit cell crystallography, single-wavelength anomalous scattering, multi-wavelength anomalous scattering, microbeam technology, in addition to the 14-BM which offers fiber diffraction to biosafety level 2/3.

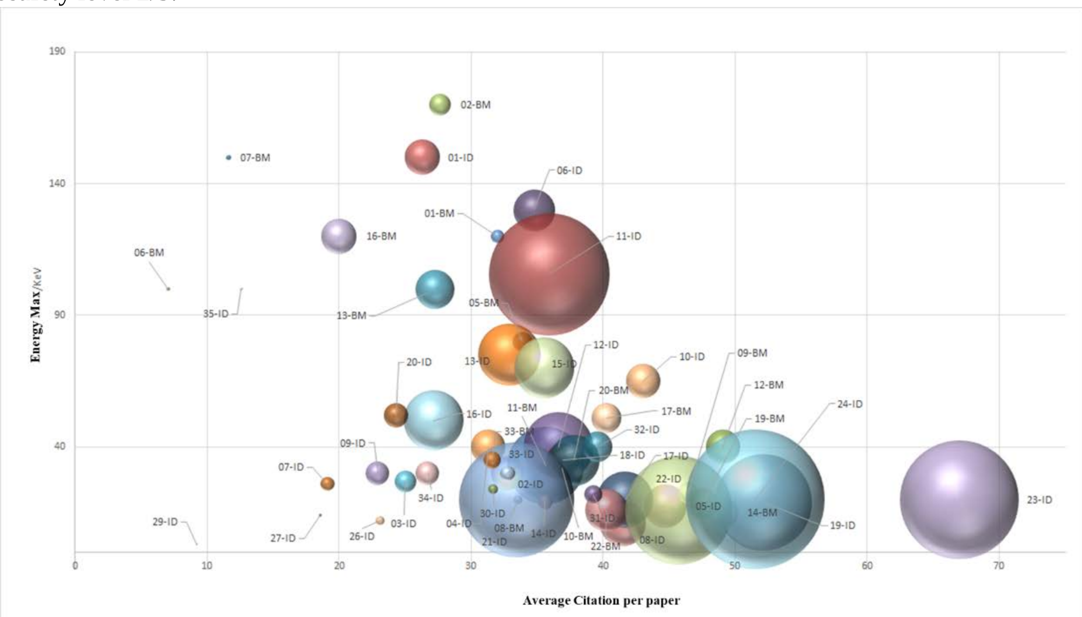


Fig. 4. Scatter of max energy of beamlines and impact of S&T outputs

Tab.6. Energy parameters and impact of S&T outputs (partly)

Beamlines	**Citation**	**Citation per paper**			**Energy range /keV**	**Experimental technology**
		Count	Relative count	Rank		
01-BM	5632	32.00	0.81	32	50-120keV;6-30keV	Optics testing; Detector testing; Topography; Energy dispersive X-ray diffraction; White Laue Single Crystal Diffraction
01-ID	11961	26.29	0.67	40	50-150keV;41-136keV;46-116keV	High-energy X-ray diffraction; Tomography; Small-angle X-ray scattering; Fluorescence spectroscopy; Pair distribution function; Phase contrast imaging
02-BM	7600	27.64	0.70	36	11-35keV;10-170keV	Tomography; Phase contrast imaging; Micropositioning system
05-BM	8506	33.89	0.86	26	10-42keV;4.5-25keV;4.5-80keV	Powder diffraction; Tomography; Wide-angle X-ray scattering; X-ray absorption fine structure; High-energy X-ray diffraction; General diffraction
05-ID	24872	44.73	1.13	9	6-17.5keV	High-resolution powder diffraction; X-ray standing wave measurements; SAXS/MAXS/WAXS
…	…	…	…	…	…	…

Conclusion

Large research infrastructures are characterized by huge investment, long construction period and high complex technical difficulty. Upgrade facility performance and service capacity could ensure the sustainable development of SRS. Given increasing interdisciplinary and accelerated iteration of experimental technology, it is necessary to keep a close eye on emerging experimental technologies and related disciplines while meeting the needs of scientific research frontier.

The development of APS showed that the number of papers hit a plateau after ten years of operation. Yet the opening of new beamlines, the use of new spectrometers and experimental techniques, and the improvement of sample environment have injected new vitality into APS, ushering in the second wave of scientific output growth.

APS beamlines mainly serve eight disciplines: life science, materials science, chemistry, physics, environmental science, geoscience, polymer science and atomic physics, and provide users with a variety of tools and capability combinations. Macromolecular crystallography, hard X-ray fluorescence, high pressure diamond anvil, X-ray absorption fine structure and single-wavelength anomalous dispersion were widely used experimental techniques.

A large number of international collaborative research have been carried out on APS, which played an important role as a platform, the scientific output of different countries varied greatly in terms of research topic and quantity. For example, Canada produced more scientific output in the fields of life science and chemical materials, while Germany produced more in chemical materials and physics. The research in China mainly focuses on the crystal structure, mechanical properties, deformation behavior, phase transformation response and pressure induction mechanism of metallic glass, lithium ion battery and high entropy alloy by means of high-energy X-ray diffraction, in-situ observation and high pressure. On the one hand, these differences reflect the inability of current experimental facilities to meet current demand, and the competitive scientific level and value of the proposals. On the other hand, they also give a clue to the cooperation tendency of APS in proposal review.

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