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TOPICAL REVIEW

Analysis of the Research Progress of Electromagnetic Railgun Based on CiteSpace

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ABSTRACT An electromagnetic railgun is a new type of weapon with ultrahigh speed based on electromagnetic thrust. It is used in important military domains, such as long-range strikes, strategic air defense, and ballistic interception. It is also used in aerospace fields, such as space debris cleanup, microsatellite launch, and space station relay launch, so its future prospects are excellent. We analyzed 1324 publications on electromagnetic railgun using CiteSpace and identified information including authors, institutions, journals, and popular research topics and trends. Our analysis found that the University of Texas is the research institution that has published the most documents on electromagnetic railgun, and French researcher Markus Schneider has published the most documents. The journals of IEEE Transactions on Magnetics and IEEE Transactions on Plasma Science have played an important role in promoting the development of electromagnetic railgun. The research direction of electromagnetic railgun has a distinct multidisciplinary characteristic because it touches on physics, engineering science, mathematics, materials science, energy and fuel, communication technology, instrumentation, and computer science. The development process of electromagnetic railgun can be grouped into three stages: basic theoretical research, engineering research, and system optimization research. The major research topics include electromagnetic force, armature design, rail materials, pulsed power supply, armature–rail contact surface characteristics, and coupling analysis of multiple physical fields. Future electromagnetic railgun will be scalable in terms of armature–rail contact characteristics and life span, energy storage density of power supply, current-carrying capability and thermal management of launcher materials, optimization design of armature structure, and complex data processing of control systems.

INDEX TERMS Electromagnetic railgun, CiteSpace, knowledge map, visualization.

I. INTRODUCTION

Today, all major military powers in the world are vigorously developing new subversive weapons, striving to win the first opportunity and gain advantages in military competition. As the main new weapon, electromagnetic railgun has been studied for a long time. In the early 20th century, with the advent of the electrical age, Prof. Kristian Birkeland [1] is a representative who has applied for many invention patents in electromagnetic railgun. Especially into the 1970s and 1980s, the research on electromagnetic railgun became an academic hotspot after Dr. Marshall's team at the Australian National University [2] accelerated a 3g polycarbonate projectile to 5.9km/s on a 5m-long electromagnetic rail launcher using a 550MJ monopole generator as well as a plasma armature. Although the theory of electromagnetic railgun is not complicated, it has not been truly engineered due to limitations in materials, power supply, multi-physics coupling and other technologies. After entering the 21st century, the United States took the lead in launching an upsurge in engineering

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research on electromagnetic railgun [3], [4], followed by China and other countries. Various research prototypes of electromagnetic railguns have sprung up, especially after 2010, a large number of Chinese scholars have devoted themselves to the research on electromagnetic railgun, and there is a strong tendency to catch up from behind [5], [6], [7].

At present, there are a large number of documents related to electromagnetic railgun, and there are some problems in organizing and analyzing the documents based on traditional methods of reading and conclusion, such as heavy workload and strong subjectivity. Since the knowledge map played a role in scientometric analysis, it has been widely used for its remarkable macro-research advantages of objectivity and quantification [8]. Based on the related documents of electromagnetic railgun downloaded from the database of Web of Science (WoS), the scientific literature analysis software CiteSpace is used to count and sort out the development trend of the field from the aspects of publication volume, keywords, authors and published journals. And the corresponding knowledge map drawn by the software is used to explore evolution process of the research frontiers and hotspots in the field, providing reference for future research [9], [10], [11], [12].

The remainder of this study is organized as follows. The next section presents the data collection and research methods. Section III presents the results of the bibliometric analysis of the data. The research hotspots and trend analysis are shown in Section IV. Section V concludes the contributions, implications and development directions for further research.

II. DATA COLLECTION AND RESEARCH METHODS

A. DATA COLLECTION

This article uses the Web of Science (WoS) database as the data source, and the search deadline is October 31, 2023. The WoS database search selects ''Web of Science Core Collection,'' and inputs in the search formula: TS = ('railgun' OR 'railguns'), document type (select review and paper), 1395 research documents related to ''railgun'' were obtained. With the help of CiteSpace data deduplication function, 1324 documents were finally obtained. Since the document on electromagnetic railgun in the database was first published in 1991, therefore, we systematically review the documents from 1991 to 2023 and study the research trend of electromagnetic railgun in the past 33 years.

B. RESEARCH METHOD

The analysis tool used in this paper are the WoS database's own analysis tools and the visual analysis software CiteSpace. CiteSpace is a bibliometric tool developed by Dr. Chaomei Chen at Drexell University (USA) based on JAVA. It can analyze relevant information in a large number of documents, such as the number of documents, cooperation of authors and institutions, co-occurrence and clustering of keywords, cooperation of countries, co-occurrence analysis of research topics, and display the information in the form of visual map. By analyzing the maps, effective information can be found, and the research development vein, hotspots and trends in the research field can be analyzed intuitively.

III. BIBLIOMETRIC ANALYSIS

The aim of this paper is to demonstrate visually the intellectual structures and developments in raigun research for the period 1991–2023, and in particular its intellectual turning points and emerging trends from the following perspectives: subject categories, major journals and highly cited authors, as well as keywords analysis.

A. ANALYSIS OF THE VOLUME OF PUBLICATIONS

The annual number of documents can directly reflect the development process of the research field and is of great significance in predicting its future development trends. Draw a line graph for the 1,324 documents counted according to the annual publication volume by CiteSpace, as shown in Figure 1.

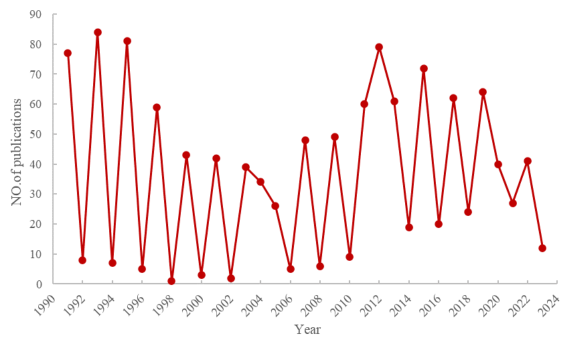

FIGURE 1. The annual number of documents related to railgun from 1991 to 2023.

As can be seen from Figure 1, the annual publication volume in the field generally shows a fluctuating trend, and the trend of publications can be roughly divided into the following two stages.

1) 1991-2010 (FLUCTUATION PERIOD)

The numbers of annual published documents fluctuate greatly during this period, especially the numbers of documents in adjacent years varied greatly. The reason may be that the electromagnetic railgun research team is relatively stable, and various academic institutions have periodicity in the publication of documents. According to WoS literature statistics, from 1991 to 2003, electromagnetic launch technology forums were held in odd years, and papers were published during next year,so the output cycle of most research achievements related to electromagnetic railgun coincided with the publication cycle of documents, that is about two years. As a result, the number of documents published in odd years was generally high, while the number of documents published in even years was generally low. It can be seen that academic forums played an important role in the research progress of electromagnetic railgun.

2) 2011-2023 (STEADY GROWTH STAGE)

During this period, the number of published documents showed an obvious upward trend, with the number of documents published each year reaching more than 70, and the number of published documents in adjacent years did not change much. The reason may be that the world's major military powers and well-known research institutions have invested sufficient human and financial resources in the research of electromagnetic railgun in order to achieve technological breakthroughs in the field. During this period, the research on electromagnetic railgun was diversified, such as electromagnetic railgun launch devices, plasma armature characteristics, solid armature geometric design, transition ablation of rails, and measures to prevent transition ablation of armature-rail contact surfaces, and optimization of pulse forming network trigger time sequence, etc. In the past four years, although the number of published documents has fluctuated slightly, the overall number of published documents has remained at a high level, with the annual number of documents published being around 40. Especially in recent years, with the rapid development of high and new technologies represented by artificial intelligence, some important breakthroughs have been made in the engineering of electromagnetic railgun, and the experimental demonstration stage of electromagnetic railgun in some military powers may have been completed and accelerated into the engineering application stage. In a word, the current research on electromagnetic railgun tends to be stable and mature, and the weaponization of electromagnetic railgun is getting closer and closer.

B. ANALYSIS OF DOCUMENT FUNDING AGENCIES

An analysis of the funding status of 1,324 documents shown that 530 documents were funded by 185 national or local funding organizations, accounting for 40.03% of the total number of publications. Among them, 145 were supported by National Natural Science Foundation of China, it can be seen that documents from China receive more national-level funding, indicating that China pays more attention to the field of electromagnetic railgun. As a weapon that may change the mode of naval warfare in the future, the United States, as the number one military power, has also invested a lot of financial resources in the R&D and engineering realization of railgun, and its funding agencies are mainly defense departments, including the Office of Naval Research (23: number of funded documents), Department of Defense (16), Department of Energy (11), Army Research Laboratory (7), Air Force Office of Scientific Research (6) and Naval Research Laboratory (5). Russia, as a traditional military power, its funding agencies mainly consist of the Russian Foundation for Basic Research (14), Russian Academy of Sciences (6) and Ministry of Education and Science of the Russian Federation (3). Other funding agencies in the research field of electromagnetic railgun are Spanish government (16), German Ministry of Defense (9), etc. Table 1 provides the top 10 funding agencies with the most funded publications.

TABLE 1. Statistics of the top 10 funding agencies with the most funded publications.

Ranking	Funding Agency	Number of Documents
1	National Natural Science Foundation of China	145
2	Office of Naval Research	23
3	United States Department of Energy	16
4	Spanish Government	16
5	Russian Foundation for Basic Research	14
6	United States Department of Energy	11
7	German Ministry of Defense	9
8	Fundamental Research Funds for The Central Universities (China)	9
9	Specialized Research Fund for The Doctoral Program of Higher Education (China)	9
10	National Basic Research Program of China	8

C. ANALYSIS OF NATIONAL COOPERATION NETWORK

The top 10 countries with the most publications in the field of electromagnetic railgun were summarized by bibliometrics, as shown in Table 2.

TABLE 2. Top 10 countries with the number of publications.

Sequence Number	County or region	Number of documents	Centrality
1	USA	543	0.76
2	PEOPLES R CHINA	339	0.4
3	RUSSIA	117	0.37
4	FRANCE	113	0.22
5	English	41	0.44
6	Japan	39	0.0
7	Italy	34	0.03
8	Germany	26	0.03
9	JAPAN	25	0.1
10	India	23	0.0

A total of 1324 documents from 29 countries and regions were included in the WoS database, of which 543 documents from the United States topped the list, followed by 339 documents from China, 117 documents from Russia, 113 documents from France, 41 documents from Britain, 39 documents from Japan, 34 documents from Italy, 26 documents from Germany, 25 documents from Iran and 23 documents from India. Countries with more than 10 documents also include Lithuania with 22 documents, South Korea with 19 documents, and Turkey with 11 documents.

The mapping of national and regional cooperation networks denotes the cooperation and connection between different countries and regions in the research field, which provides a new perspective for evaluating the academic influence and scientific research capacity of countries and regions. CiteSpace software was utilized to map national cooperation networks, which is shown in Figure 2. The size of the nodes in the graph represents the number of documents issued by

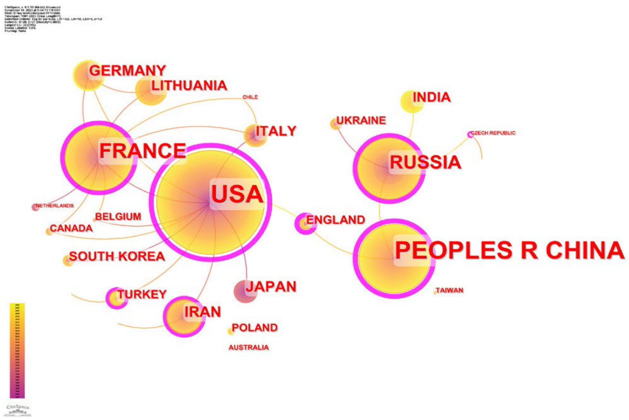

FIGURE 2. National cooperation network.

countries and regions, the connecting lines reflect the strength of the cooperative relationship among them, the color of the outer contour line of the nodes reflects the centralities of countries and regions.

The United States and China are the two largest nodes in the cooperation network map, indicating that the United States and China have more documents in this field than other countries. The purple outer rings in the map represent high betweenness centrality and a sudden increase in the number of published documents. The United States has the largest betweenness centrality of 0.76, which shows that the United States is in a central position in the field of railgun and has cooperative relationships with 10 countries. In the past ten years, the number of documents belonging to Chinese scholars has increased significantly, and the number of publications has jumped to second place. Its betweenness centrality is 0.4, ranking third. This shows that the participation of Chinese scholars in international cooperation has increased significantly, but there is still a big gap with the United States, which needs to be further improved. In addition, the centrality of the United Kingdom is 0.44 and Russia is 0.37, indicating that these two countries have more opportunities to cooperate with other countries in the research of EM railgun.

D. ANALYSIS OF JOURNALS WITH PUBLICATIONS IN TERMS OF EM RAILGUN

The analysis of journals is helpful to understand the core journals and main research directions in the research field and to provide guidance for scholars to choose publishing platforms. A journal statistical analysis was performed on 1324 documents, it is founded that documents in the field of electromagnetic railgun were published in 183 journals, and the top 10 journals were shown in Table 3. There are 575 documents published in IEEE Transactions on Magnetics, accounting for 43.36% of the total number of documents, including the documents from 1982 to 2009, and providing an important platform for researchers to understand the research content and technical characteristics of electromagnetic railgun in this period. The second largest journal is IEEE Transactions on Plasma Science, which includes 413 documents accounting for 31.15% of the total number of publications in the field since 2011, although the impact factor of which is only 1.5, it is currently recognized as the authoritative journal related to electromagnetic railgun and has the most important influence in the industry in recent years. Most of the latest research results on electromagnetic railgun were published in this journal, which has become a powerful tool for researchers to understand the progress of electromagnetic railgun research [15]. The top 10 journals in terms of number of publications are provided in Table 3. In summary, the journals organized by the IEEE Association include most of the documents in the research field of electromagnetic railgun. In particular, the journals of IEEE Transactions on Magnetics and IEEE Transactions on Plasma Science play a pivotal role in promoting the development of electromagnetic railgun.

TABLE 3. Statistics of top 10 journals.

Ranking	Periodical	Frequency	Percentage of total	Journal impactor
1	IEEE Transactions on Magnetics	575	43.36%	2.1
2	IEEE Transactions on Plasma Science	413	31.15%	1.5
3	High Temperature	20	1.51%	1.0
4	Defence Technology	14	1.06%	5.1
5	International Journal of Applied Electromagnetics and Mechanics	14	1.06%	0.6
6	Review of Scientific Instruments	14	1.06%	1.6
7	Technical Physics Letters	12	0.90%	0.6
8	International Journal of Impact Engineering	9	0.68%	5.1
9	Journal of Applied Physics	9	0.68%	3.2
10	Technical Physics	8	0.60%	0.7

E. ANALYSIS OF RESEARCH DIRECTION

The WoS database is assigned to one or more subject categories, according to the journal in which it was published. Using the journal subject classification system, all documents were assigned to one or more subject categories as shown in Figure 3. The graph shows the top 10 research directions. The research on electromagnetic railgun is primarily concentrated in physics (1247: number of documents), engineering science (933), mathematics (368), materials science (365), energy and fuel (261), communication technology (240), instrumentation (91) and computer science (74). On the one hand, some researchers devote themselves to applying new technologies to the theoretical research of electromagnetic railgun, so many research directions are closely related to

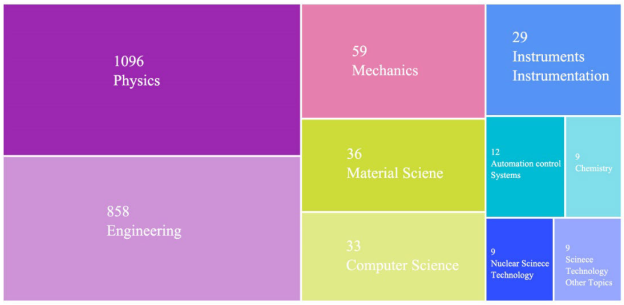

FIGURE 3. The top10 research directions related to railgun.

TABLE 4. Top 10 prolific institutions related to railgun.

Ranking	Institutions	Number of Documents
1	Univ Texas	191
2	US Department of Defense	118
3	French-German Research Institute of Saint-Louis	93
4	Russian Academy of Sciences	75
5	Huazhong Univ Sci & Technol	66
6	Nanjing Univ Sci & Technol	64
7	US Navy	58
8	US Army	52
9	Beijing Institute of Special Electromechanical Technology	43
10	Chinese Academy of Sciences	36

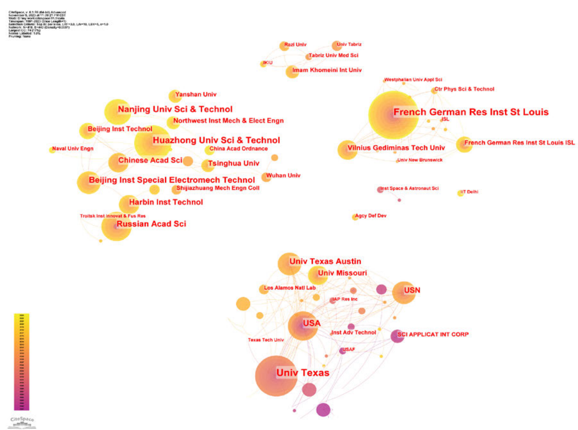

FIGURE 5. Visualization of the prolific institutions related to electromagnetic railgun.

basic theories, such as physics. On the other hand, there are many practical problems in the engineering application of electromagnetic railgun, and many documents often focus on a specific engineering problem, such as applied science. It can be seen from Figure 4 that the research on electromagnetic railgun involves many fields and has a high demand for basic scientific research, showing obvious multi-disciplinary characteristics.

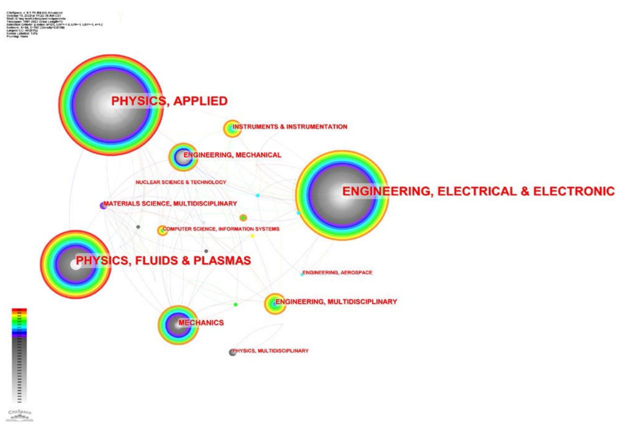

FIGURE 4. Subject co-occurrence network.

F. ANALYSIS OF RESEARCH NSTITUTIONS

The analysis of research institutions is helpful to understand the key research institutions and to provide guidance for scholars to choose cooperation and exchange institutions. At the same time, the number of documents published by research institutions also reflects the influence of the institution in the field [16]. The statistics of the top 10 institutions related to electromagnetic railgun in the WoS database are shown in Table 4. There are two institutions with more than 100 documents: the University of Texas and the U.S. Department of Defense. Other organizations with more than 50 documents include the U.S. Navy. The visualization of the prolific institutions related to electromagnetic railgun is shown in Fig. 5.

It can be seen from Table 4 that the organization with the largest number of documents is the University of Texas (14.43% of the total documents), which began to undertake the research on 9MJ experimental guns weaponization program in 1985 [17]. The U.S. military has shown great interest in the war potential of electromagnetic railgun, with the U.S. Army Research Laboratory (3.93%) conducting theoretical research programs on railguns since the 1980s. In 1990, the US Army established the Institute of Advanced Technology in cooperation with the University of Texas at Austin, focusing on the research of solid and hybrid armatures, armature-rail interface characteristics and electromagnetic emitter materials [18], [19], [20], [21], [22], [23]. In 1991, the US Department of Defense (8.91%) established the Joint Committee on electromagnetic railgun to coordinate the research work of the Army, the Department of Energy, the Defense Atomic Energy Agency and the Strategic Defense Initiative Agencies, focusing on the research of high-power technology, launcher technology, hypervelocity missile technology and ship suitability technology of electromagnetic railgun. The U.S. Agency Collaboration Network is shown in Fig.6.

The French-German Institute of St. Louis (7.02%) is a military high-tech research institute established by the French Armed Forces and German Federal Ministry of Defense, which is currently a leader in the field of electromagnetic launch in Europe, and its research covers a number of

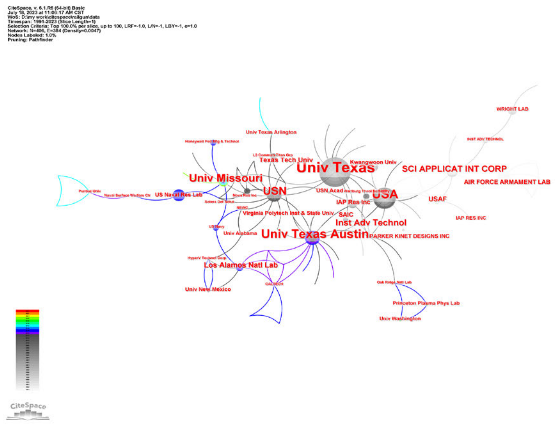

FIGURE 6. Map of research institutions cooperation networks of USA.

key technologies, such as railgun launchers with different calibers, armatures, pulse power supplies, superconductors, ultra-fast switches and so on. In 1997, the Institute developed the ''PEGASUS'' full-scale railgun prototype, which can accelerate 500g projectiles to 2.3km/s, and after continuous optimization, it can now accelerate the kilogram projectiles to more than 2.5km/s [29], [30]. In 2018, the institute developed the large-caliber electromagnetic railgun NGL-60 [31] and was committed to research on energy storage, launch devices and mechanical properties. The French-German Agency Collaboration Network is shown in Fig.7.

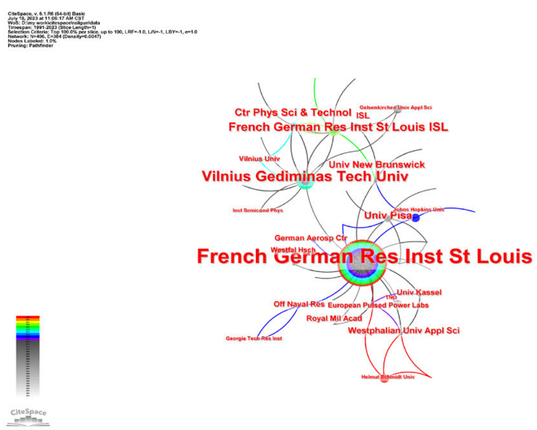

FIGURE 7. Map of research institutions cooperation networks of french-german.

In 2016, the Russian Academy of Sciences (5.66%) realized the acceleration of gram-class projectiles to 11km/s by its affiliated High Temperature Joint Research Institute. In 2017, 100g plastic projectiles were accelerated to 3.2 km/s by using a high-power (over 2GW peak power) magnetohydrodynamic pulse generator developed by the Institute of Fluid Dynamics of the Siberian Branch. Therefore, it has deep theoretical research on plasma armature launching mechanism, armature-rail contact mechanism, material optimization, dynamic modeling and simulation [32], [33], [34]. The Huazhong University of Science and Technology (5.66%) has been published documents on electromagnetic railgun since 1999, primarily focusing on the sliding electrical contact characteristics, armature technology and pulse power supply technology [35], [36], [37], [38]. The Nanjing University of Science and Technology (4.83%) has published documents on electromagnetic railgun almost every year since 2008, mainly studying on the multi-field coupling characteristics of launchers, armature and rail ablation, pulse power supply technology, interior ballistic technology and reliability analysis of propellant [5], [39]. The Beijing Institute of Special Electromechanical Technology (3.25%) has been engaged in the research of electromagnetic launching technology since 2003, which mainly researches on the electric energy conversion efficiency and the life span of railgun [40], [41], [42].The Institute of Electrical Engineering of the Chinese Academy of Sciences (2.72%) conducted research on hybrid energy storagetechnology using armatures with different structures in 2013, and designed a two-turn planar enhanced electromagnetic railgun in 2017 to study its export kinetic energy and electrical energy conversion efficiency [43], [44]. The China-Russia Agency Collaboration Network is shown in Fig.8.

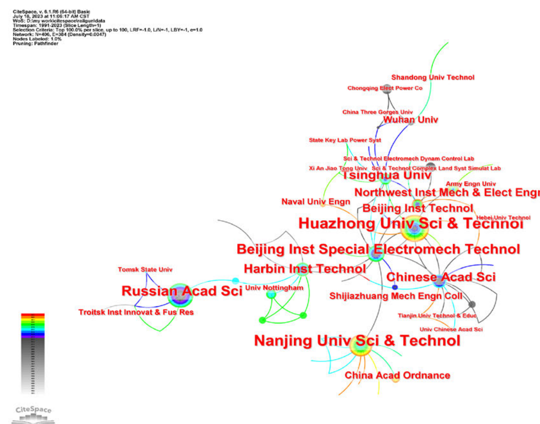

FIGURE 8. Map of research institutions cooperation networks of china-russia.

Generally speaking, the research institutions in the field of electromagnetic railgun are primarily research institutes, and the contribution of colleges and universities is also obvious.

G. ANALYSIS OF RESEARCH NSTITUTIONS

In bibliometric analysis, it is usually necessary to find core authors to discover the backbone of the research field. Statistical analysis is performed based on the Price formula $M = 0.749N_{max}^{1/2}$, where M is the number of documents issued by the core author, N_{max} is the number of documents issued by the author with the most documents in the statistical period, and when the number of publications is greater than or equal to M, the author is named core author. Statistical analysis of the literature was performed, N_{max} =56, M=5.61. The results showed that those with 6 or more documents are the core

TABLE 5. Top 20 authors with the number of publications.

Ranking	Author	Country	Number of Papers
1	Schneider, Markus	France	56
2	Li, Jun	China	43
3	Xia, Shengguo	China	34
4	Li, Baoming	China	34
5	Mcnab, Ian R	USA	33
6	Stefani, F	USA	33
7	Chen, Lixue	China	33
8	He, Junjia	China	31
9	Yan, Ping	China	28
10	Zhukov, B G	Russia	27
11	Hundertmark, Stephan	France	23
12	Kurakin, R O	Russia	25
13	Engel, Thomas G	USA	21
14	Bauer, DP	USA	20
15	Hsieh, KT	USA	20
16	Persad, C	USA	20
17	Zielinski, AE	USA	20
18	Cui, Shumei	China	19
19	Shvetsov, GA	Russia	19
20	Parker, JV	USA	18

TABLE 6. Top 5 co-cited documents in EM railgun.

Ranking	Frequency	Strength	Centrality	Author	Journal Name
1	71	17.38	0.28	PARKER JV	IEEE T MAGN
2	70	3.72	0.11	Barber JP	IEEE T MAGN
3	50	8.55	0.07	Stefani F	IEEE T MAGN
4	32	7.11	0.13	RASHLEIGH SC	J APPL PHYS
5	30	5.77	0.09	Fair HD	IEEE T MAGN

authors, with a total of 150 authors. Table 6 provides the top 20 authors by publication volume.

Based on the author co-occurrence analysis function of CiteSpace software, we can obtain relevant author information and cooperation network in the electromagnetic railgun field. Figure 9 shows the author's cooperation network of WOS. Table 6 provides the information of the top 20 authors. It can be founded that Markus Schneider has the most documents of 56.

In the CiteSpace visualization diagram, nodes are presented in the form of annual rings. The size of the node reflects the number of documents published by the author. The connection between the nodes reflects the cooperative relationship between authors. The appearance of red annual

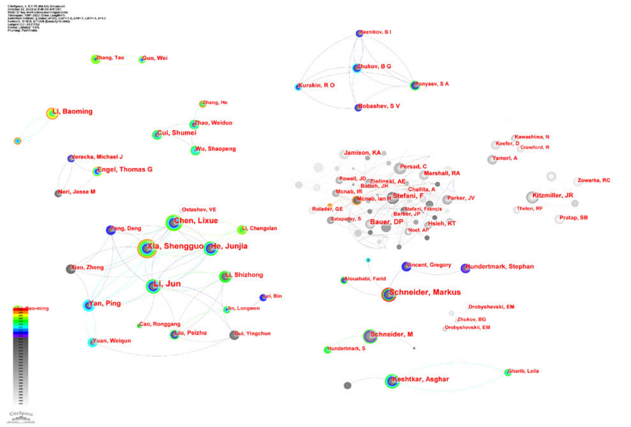

FIGURE 9. Author cooperation network map.

rings in the node indicates that the number of documents published in a certain period has increased rapidly.

Among the author collaboration networks in the field, the largest network includes StefaniF (33: number of documents belonging to the author), McnabIanR (33), BauerDP (20), HsiehKT (20), ZielinskiAE (20), and PersadC (20), ParkerJV (18), JamisonKA (13), BarerJP (11) and many other well-known American core authors. The close cooperation among them is mainly due to the establishment of the Joint Committee on electromagnetic Railgun by the U.S. Department of Defense and the investment of a large amount of funds. The Committee operates effectively in a collective mode by getting together outstanding talents, which makes the United States always in an international leading position in the field of electromagnetic railgun research. There are many links between nodes in the author cooperation network map, and the outermost ring color of nodes is red, which indicates that they still have high publication volume in recent years, reflecting that Chinese scholars not only cooperate closely with each other, but also devote themselves to the study of the hotspot direction in the field of the electromagnetic railgun.

It is worth noting that another important author cooperation network mainly includes four core authors including Russian scholars ZhukovBG (27), KurakinRO (25), BobashevSV (10), and PonyaevSA (8). They formed a stable and cooperative research team, and the outermost color of the nodes in the Citespace visualization map is also relatively bright. By reading and analyzing the literature, it was found that the research direction of the team in recent years has mainly focused on armature technology, launch performance, and the applications of electromagnetic railgun launch.

Other prominent networks include Engel et al. [55], University of Missouri, USA, with 3 authors publishing 21 documents, and Cui et al. [56], [57], Harbin Institute of Technology, China, with 4 authors publishing 19 documents.

H. ANALYSIS OF CO-CITATION OF JOURNAL AND DOCUMENT

The analysis of co-cited journals and documents is helpful for scholars to select important journals, and also provides valuable references for scholars to select target journals for submission [11].

1) DOCUMENT CO-CITATIONS

The citation frequency of the document reflects the attention of people to the corresponding hotspot and the importance of the document in the field. The map of document co-citation network in electromagnetic railgun from 1991-2023 is shown in Fig. 10. Table 6 provides the top 5 co-cited documents. It can be seen that the highest frequency of co-cited document is the article of ''Why plasma armature railguns don't work (and what can be done about it)'' published by PARKER JV in the journal of IEEE Transactions on Magnetics in 1989 [58]. It is pointed out that the Launching velocity of plasma armature is limited by arc strike, and the technology combined with advanced ceramics is proposed to reduce the armature heat and suppress the arc strike. Secondly, Barber and McNab [59] found that magnetic blow-off forces are important and may be the final step in a series of events that ultimately leads to transition in 2003, and developed models that can predict the conditions under which blow-off will occur. Thirdly, Stefani and Parker [60] developed an experimental technique to measure the damage of aluminum armature and discussed the experimental results.

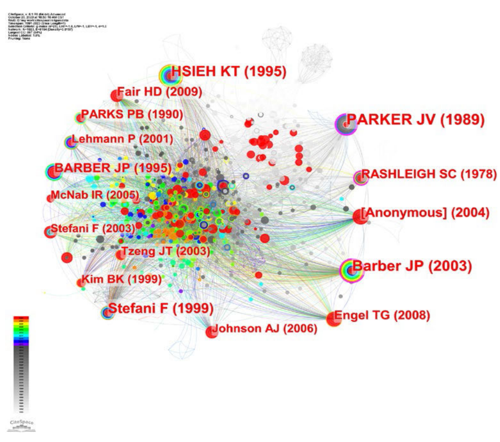

FIGURE 10. Document co-citation network.

Overall, among the top five cited documents, the journal of IEEE Transactions on Magnetics contains the most documents (4), accounting for 80%, indicating that this journal plays an important role in the development of electromagnetic railgun. In addition, high-centrality document plays an important role in linking and mediating the keyword network map. The higher the centrality, the stronger the role of control and guidance in the whole network. It can be seen from Table 6 that PARKER JV and RASHLEIGH SC is in the top 2 in terms of document centrality.

2) JOURNAL CO-CITATIONS

The top 5 co-cited journals related to electromagnetic railgun are provided in Table 7. From the perspective of co-citation frequency, the journal of IEEE Transactions on Magnetics has the highest frequency of co-citation in the field of electromagnetic railgun from 1991 to 2023, accounting for 54.54% of the top 5 journals.

TABLE 7. Top 5 co-cited journals in EM railgun.

Ranking	Cited Journals	Category	Impact Factor	Frequency	Centrality
1	IEEE T MAGN	ELECTRICAL AND ELECTRONIC ENGINEERING	2.1	937	0.68
2	IEEE T PLASMA SCI	PHYSICS, FLUIDS & PLASMAS	1.5	472	0.16
3	J APPL PHYS	PHYSICS, APPLIED	3.2	191	0.34
4	INT J IMPACT ENG	ENGINEERING, MECHANICAL	5.1	62	0.13
5	REV SCI INSTRUM	PHYSICS, APPLIED	1.6	56	0.09

In the perspective of journal influence, the International Journal of Impact Engineering has the highest impact factor among the cited journals, indicating that the journal is among the top authoritative journals in the field of machinery research related to electromagnetic railgun. It is beneficial for us to have a better understand of the cutting edge of research on rail material structure of electromagnetic railgun by paying attention to the journal.

On the whole, among the top 5 cited journals, the journals on electronics and electricity are the most important, followed by fluids and plasma, which shows that the research of electromagnetic railgun is not only a mechanical issue, but also a plasma science issue. Furthermore, the centrality of journals in electronics and electricity is very high, for example, the centrality of the journal of IEEE Transactions on Magnetics is as high as 0.68, indicating that the journal has a strong guidance for the research of electromagnetic railgun.

IV. ANALYSIS OF POPULAR RESEARCH TOPICS AND TREND

This article uses keyword analysis to examine popular research topics in the field of electromagnetic railgun research.

A. ABBREVIATIONS AND ACRONYMS

Keywords are a highly concentrated summary of the research content of a paper. Statistical analysis of the frequency and centrality of keywords can reveal the most popular research topics and their development trend. CiteSpace is used to draw a keyword cooccurrence map in the field of electromagnetic railgun research: the higher the keyword occurrence frequency on the map, the greater the node radius. The font size of the node reflects its centrality, and the connections between nodes represent the relevance of related topics. Cluster analysis of keywords can help to identify popular research topics related to electromagnetic railgun.

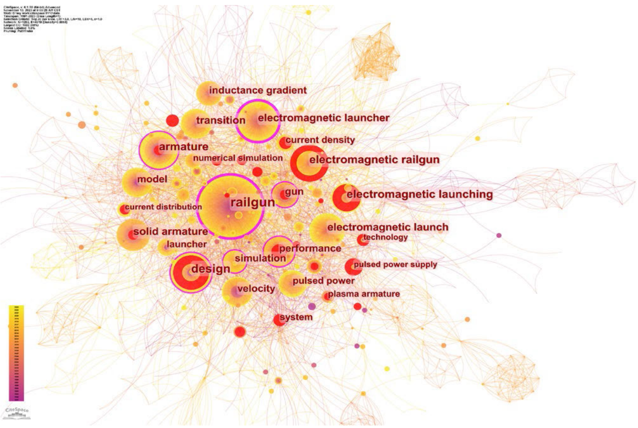

FIGURE 11. Keyword co-occurrence network.

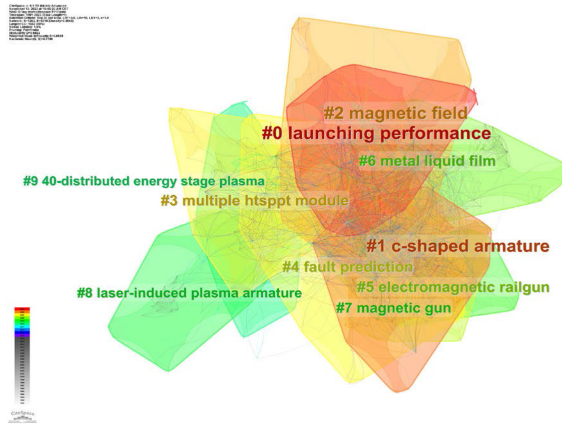

FIGURE 12. Clustering map of keywords.

We applied the logarithmic likelihood ratio (LLR) algorithm to the cluster analysis of keywords; the results are shown in Figure 11. The cluster numbers are 0 through 9—the smaller the cluster number, the greater the scale of literature research under this cluster. This literature can be divided into an analysis of the armature–rail electrical contact mechanism of the electromagnetic railgun and research on the launch characteristics. This analysis shows that the current electromagnetic railgun technology focuses primarily on armature ablation, armature-rail structure optimization design, power supply system, system simulation, and mathematical model construction.

We drew the keyword distribution map shown in Figure 11 based on WoS documents. The keyword with the highest frequency is railgun. After excluding self-directed keywords, the high-frequency keyword is electromagnetic launcher, armature, design, system and so on. Based on the keywords, we found two different research routes in the field of electromagnetic railgun. The first route is basic theoretical research on electromagnetic railguns, including keywords such as design, system, transition, etc. The second route is engineering application research on electromagnetic railgun, including keywords such as electromagnetic launcher, armature, pulsed power, performance, velocity and so on.

B. KEYWORD CLUSTER ANALYSIS

Using CiteSpace for keyword clustering analysis, the keyword clustering diagram is shown in Figure 12. Using the LLR clustering algorithm, the clustering module value Q and the average contour value S will appear after clustering. It is generally believed that clusters with Q greater than 0.3 have a significant structure, while clusters with S greater than 0.5 are reasonable. The 10 clusters with the highest frequency are retained, and the statistical results are shown in Table 8.

As shown in Table 8, current research on electromagnetic railgun is focused on 10 main fields, including launching performance, C-shaped armature, magnetic field and so on. After excluding self-directed clusters from the WoS database, the largest cluster is launching performance. This result indicates that launch performance is the most popular research topic for electromagnetic railgun, followed by C-shaped armature and magnetic field.

TABLE 8. Top 10 clustering map of keywords.

Ranking	Clustering map of keywords
1	Launching Performance
2	C-shaped Armature
3	Magnetic Field
4	Multiple HTSPPT Module
5	Fault Prediction
6	Electromagnetic Railgun
7	Metal Liquid Film
8	Magnetic gun
9	Laser-induced Plasma Armature
10	40-Distributed Energy Stage Plasma
Q	0.6922
S	0.8895

C. KEYWORD EVOLUTION ANALYSIS

Keyword evolution analysis can be used to reveal the development process of related research as well as the main research content at each stage. We used CiteSpace to draw a diagram of keyword evolution. The results are shown in Figures 13 and 14. In the figures, the position of the keywords reflects the year it first appeared. The meaning of the node radius, font size, and connections between nodes are consistent with those in the keyword distribution map. These figures also show that research on electromagnetic railgun can be traced back to the end of the last century. Based on a combination of the evolution map and WoS documents, the research in electromagnetic railgun can be grouped into three stages. Table 10 provides detailed statistics for the top 15 keywords.

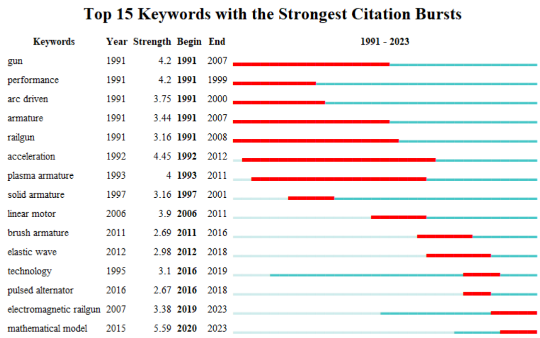

FIGURE 13. Top 15 keywords with citation bursts.

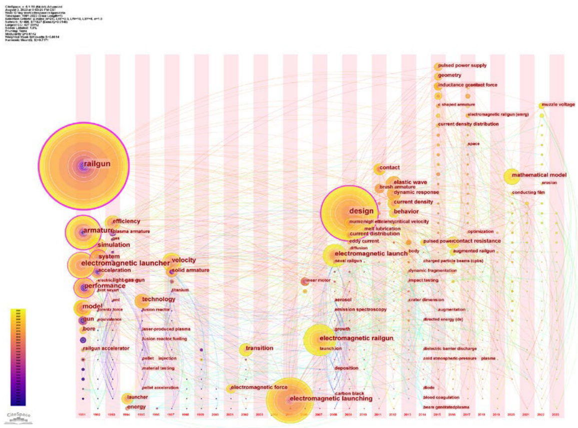

FIGURE 14. Keyword co-occurrence evolution.

1) BASIC THEORETICAL RESEARCH STAGE

The basic theoretical research stage was from 1991 to 2004. From the 1990s onward, major military powers in the world, notably industrially developed countries represented by the United States, Russia, and Europe, continued to strengthen their research on electromagnetic railgun. Along with the development of new technology, the quality, power supply, and output kinetic energy of the experimental armatures and projectiles have continued to increase. Researchers have focused on the basic launch theories of electromagnetic railgun, including electromagnetic force, acceleration, launch speed, plasma armature, arc and so on. In 1991, Usuba et al. [61] applied fusible separation of electrodes to railgun armature current distribution management. In 1993, Lehmann et al. [62] made the current evenly distributed on the entire armature by properly designing the armature shape and selecting the correct materials. And Peterson [18] applied the hydraulic assembly of a customized railgun to the plasma seal of the armature. In 1995, Hsieh [63] applied Lagrangian expression to study the mechanical and temperature diffusion processes of moving conductors, which was then used to couple with the electromagnetic fields. And Barber and Dreizin [64] proposed a contact impedance model to explain the transition ablation phenomenon at the armature–rail contact surface. In 1997, McNab [65] proposed the use of a pulsed magnetohydrodynamic generator as the pulse power supply for the railgun, and Hsieh and Kim [66] established a three-dimensional model of the sliding electrical contact of the railgun armature–rail contact surface for numerical simulation research. In 1999, Kim and Hsieh [67] used three geometric parameters to analyze the influence of the geometric shape of the track and armature on the current density distribution and inductance gradient. And Stefani and Parker [60] experimentally measured the damage of the aluminum armature and discussed the damage mechanism. In 2001, McNab et al. [46] evaluated the parameters of the pulse power supply, launcher, and projectile required for the electromagnetic railgun used by the navy. In 2003, Barber et al. [68] reviewed the formation mechanism of armature transition ablation and concluded that this phenomenon was the result of the combined action of multiple mechanisms.

2) ENGINEERING RESEARCH STAGE

The engineering research stage was from 2005 to 2017. Three main categories of keywords emerged on the evolution chart during this period. The first category is vocabulary related to electromagnetic railgun launch, such as efficiency; the second category is vocabulary related to the efficiency of railgun power supply; and the third category is vocabulary related to the armature–rail electrical contact. In terms of basic theoretical research, the continuous breakthroughs in key technologies made since 2005 have brought about significant progress in the engineering of electromagnetic railgun.

In 2005, Fair [69] summarized a number of advanced technologies that have contributed to the engineering development of electromagnetic railgun. And McNab et al. [70] studied the railgun pulse power supply system to meet the requirements of firing rate and ship-specific interface. In 2007, Sitzman et al. [71] successfully designed, built, and tested an inductive pulse power supply to power a small electromagnetic railgun. And Daneshjoo et al. [72] studied the dynamic response of the structure of an electromagnetic railgun rail and the critical speed of armature through modeling. In 2009, Schneider et al. [73] measured the magnetic diffusion of a railgun using a giant magnetoresistance sensor. And Engel et al. [55] studied the maximum theoretical launching efficiency of an electromagnetic launcher with a constant inductance gradient using a spiral launcher. In 2011, Dedié et al. [74] efficiently controlled a 20-stage toroidal XRAM generator using a countercurrent thyristor. In 2012, Motes et al. [75] discovered that Joule heat was the main source of heat in the armature of high-energy railguns in their simulation calculation. In 2013, Liebfried and Brommer [76] supplied power to a small-caliber railgun using a semiconductor switch-controlled four-stage XRAM generator as an inductive pulse power supply. In 2014, Watt et al. [20] studied the planning mechanism of an aluminum armature on a non-flat copper rail using a semiconductor switch-controlled four-stage XRAM generator. In 2015, Jin et al. [77] analyzed the electromechanical characteristics of rails with different cross-sectional shapes by simulating the coupling between the electromagnetic and structural fields. In 2017, Liebfried [78] reviewed the structural composition and performance of different types of inductive pulse generators.

3) SYSTEM OPTIMIZATION STAGE

Keywords in the field of electromagnetic railgun research from 2018 to the present include resistance among others. With continuous advancements in electromagnetic railgun engineering, mathematical modeling of railgun systems and integrated circuit modeling followed a trend toward overall system research. Moreover, keywords such as muzzle indicated that studies on the armature–rail contact performance of electromagnetic railgun became more detailed and in-depth.

In 2018, Li and Lin [79] provided a systematic discussion of the launch mechanism and dynamic measurement methods. In 2019, Yin et al. [80] analyzed the distribution characteristics of the ballistic magnetic field in C-type armature railguns based on the diffusion equation of a magnetic field. In that same year, Dai et al. [81] analyzed the local convergence characteristics of current and heat during the electromagnetic propulsion process based on the dynamic multifield coupling model. In addition, Li et al. [82] used finite element software simulation to analyze the current distribution characteristics of a non-flat armature–rail contact surface of the electromagnetic railgun. In 2020, Zhu and Li [83] analyzed the sliding electrical contact characteristics of an enhanced railgun based on contact impedance and a sliding friction coefficient. Also in 2020, Gao et al. [84] analyzed the muzzle-arc plasma flow field of aluminum vapor and air-mixed gas based on a multicomponent plasma migration model. Furthermore, Lin and Li [85] numerically simulated the deformation characteristics of the railgun solid armature using an explicit finite element method, and Li et al. [86] calculated the effects of armature motion speed on the magnetic field and current density distribution on the rail based on finite element model of the railgun. In 2021, Xie et al. [87] summarized the material composition, preparation, metallographic structure, and characteristics of advanced rail materials and clarified the future direction of track material development. Zhou and Li [88] performed finite element thermodynamic temperature field simulation analysis of the thermal radiation performance to facilitate thermal management of rails. Li et al. [89] obtained high-precision motion speed of armature in the railgun bore by training the magnetic probe array data with improved two-way long-short-term memory network.

Several important studies were published in 2022. Zhou et al. [90] automatically detected damages on railgun bore using deep learning and computer vision detection algorithms. Wei et al. [91] measured the temporal-spatial distribution of rail transient temperatures for different launch speeds using an instantaneous temperature measurement system. Tang et al. [92] effectively suppressed the muzzle arc of enhanced railgun by optimizing the algorithm of the passive muzzle-arc control device. Özer and Öztürk, [93] quickly determined the optimal trigger sequence of the pulse power supply of a multistage railgun system by changing the basic parameters of the genetic algorithm. Liu and Li [94] established a lightweight design model of the busbar and reduced the busbar area to 59.2% of the original value using constrained topological optimization and hierarchical optimization of the global stress. Furthermore, they established a topological optimization model for the busbar under the constraint of limited capacity [95]. Based on a multi-physical field-coupling effect simulation, Ren et al. [96] analyzed the damage of the armature in the rail and found that the degree of armature ablation could be reduced by improving the lubrication between the armature and the rail. Praneeth and Singh [97] simulated and compared several different rail models and found that a wedge-shaped rail could increase the armature launch speed by 7%. Zhang et al. [98] studied the coupling effect of multi-physical fields based on an instantaneous multifield-coupling mathematical model and found that multifield coupling effect enhanced the armature flux density, reduced the temperature of the high-temperature zone, increased the temperature of the low-temperature zone, and made the temperature distribution in the armature more uniform. Then they studied the multi-physical field-coupling model of the thin lubricating film between the armature and the rail and found that a thin film of liquid at the armature–rail interface substantially reduced the armature temperature [99].

Continued research in the field was published in 2023, Song et al. [100] used cold-sprayed CuCrZre-W as a dispersion-strengthened copper coating to improve the arc ablation resistance, reduce the arc ablation area and depth, and limit the adhesion of molten aluminum to the rail. Tang and Wang [101] connected the arms of armatures to the form of a ring and increased the overall mechanical strength of the armature while keeping the torque constant. Hao et al. [102] achieved greater projectile launch speed and efficiency with improved simulation methods based on the rail and coil structure and coupling magnetic field. Liao et al. [103] studied the armature–rail interface characteristics at high electric current density and high transient temperature based on magnetothermal hydrodynamic lubrication theory. Ge et al. [104] designed a muzzle-arc suppressor based on the principle of gap-arc discharge and effectively suppressed the muzzle arc and improved the launch performance by directing the current into the arc suppressor. Beemer and McNab [105] proposed the use of electromagnetic railgun based on a lunar electromagnetic mass accelerator to perform space exploration missions in the future and to transport materials to and from the lunar south pole and NASA's Gateway Space Station.

After extensive subject classification and keyword analysis of a large volume of documents related to electromagnetic railgun, we identified the following research trends for future development of electromagnetic railgun:

1. Theoretical investigation on cutting-edge issues, such as armature–rail contact characteristics and life span of large-diameter electromagnetic railgun.

2. Engineering studies of such issues as energy storage density of power supply for high-energy launch devices, current carrying capability, and thermal management of rail and armature materials.

3. Research on armature structure optimization design technology of ultra-high-speed integrated launch components under the action of multi-physical field coupling.

4. System control and testing technology for electromagnetic railguns must solve such problems as large system scale, high real-time requirements, high system energy, requirements for fault prediction, diagnosis and protection, complex test objects, and complex data processing caused by multiple test types.

V. CONCLUSION

Statistical analysis results of documents on electromagnetic railgun have led to the following conclusions:

1. From 1991 to 2023, the United States occupied a larger share (41.01%) of the field of electromagnetic railgun research, followed by China (25.60%). In terms of major research institutions, The top three institutes are located in the United States and Europe: The University of Texas, the U.S. Department of Defense, and the French-German Institute of St. Louis.

2. In the field of electromagnetic railgun research, U.S. scholars and Chinese scholars are the most prominent, but there is little cooperation or exchange between them. Markus Schneider has published the most among researchers. The journals of IEEE Transactions on Magnetics and IEEE Transactions on Plasma Science play a pivotal role in promoting the development of electromagnetic railgun.

3. The development process of electromagnetic railgun can be grouped according to three stages: basic theoretical research, engineering research, and System optimization research. Before 2004, the focus was on theoretical research related to the launch of electromagnetic railgun. From 2005 to 2017, the focus was on the engineering application of electromagnetic railgun. Since 2018, the focus has been on numerous specific issues following the engineering stage of electromagnetic railgun. In the future, electromagnetic railgun research has growth potential in armature–rail contact characteristics and service life, energy storage density of power supply, current carrying capacity and thermal management of rail and armature materials, design optimization of armature structure, and complex data processing of control systems.

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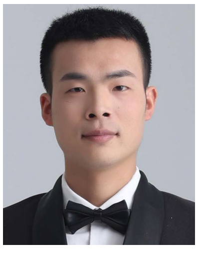

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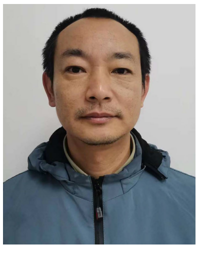

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