Particle colliders market development and evolution models

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Abstract

Main goal of this article—assessment of scientific projects and their economic impact. This assessment includes economic and technological feasibility on the example of elementary physics collider projects. Methodology includes structural integration in other technological fields by means of self-organizing neural maps and anthological retrospective analysis of radical discoveries with their recent impetus for economic development. Self-organizing neural map helps to expose hidden structural similarities of technology spreading and integration with other technologies. This is a new approach exposing the capacity for technology convergence into other industries. Capacity evaluations for integration and emergence of new technologies on the frontiers of elementary particles physics is provided. Explanation of integration problems is explained. Novelty of the study is based on integration of physical attributes into economics enabling new explanations of technology development models. Risk adjusted net present value evaluation is carried out. Comparison of similar projects around the world created in the article shows common frames and model of collider projects development. Risk adjusted model takes into account integration potential of technology under study. Conclusion combining obtained results in neural maps and historical retrospection is made.

Keywords Self-organized neural map · Project evaluation · Economic impact · Collider project · Elementary particle physics

JEL Classification L60 · L6 · C45 · C52

1 Introduction

It is proposed to implement evaluation of collider complexes prospects for elementary particles physics and collider industry in particular case and economics in general. There are two projects in the field of particle physics launched in Russian Federation within the frames of mega Science program—NICA (Moscow) and Tau Fabric (Novosibirsk). This projects are targeted at elaboration of fundamental background in Elementary Particles Physics discipline by means of new approaches—shifting from particles energy to their luminosity to obtain greater results in new discoveries and possible economic applications. These new approaches propose model of

discovering new phenomena and particles with increasingly higher level of luminosity occurring while particles collide at different angles. According to recently created theories such luminosity influence number of emerging particles and events in collider detectors. But Tau Fabric projects raised several urgent issues about its economic and technological viability. There are several works, evaluating collider projects with technological cost models [1] and economic evaluation methods, but they do not take into account critical points and negative outcomes [2] introducing virtual benefits and intangible assets and income by means of manipulating with market class borders uncertainty [3].

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Aside from critical point this work implements self-organized neural map models to analyze integration of collider technologies into other industries. Self-organized neural map models have found their applications in almost all scientific and technological disciplines like biotechnology, microelectronics, engineering, chemistry since 1980's and has been implemented there and have successfully substituted conventional PCA and other methods. Though in economics this method started emerging quite recently. Self-organizing maps have serious advantages in structural dependencies and similarities unveiling between complex objects [4], that makes them popular in many scientific disciplines [5].

2 Methodology

2.1 Structural integration of elementary particle physics in economics at meso-level

In this work info metrics system of technological structural self organization in 24 industries based on patent activity indicators in Russian regions is proposed. According to the main thesis self organization can be a signature of new innovations emergence and growth [6]. But, several assumptions should be made. Basic drawback of such models is distance or similarity between info metric objects that are in this case technological. So angle separation formula applied for measuring similarity [7] is taking into account angular relations or distance between classes of multidimensional objects generated on the base of proper vectors.

$$S_{ij} = \frac{\sum_{k=1}^n x_{ij} \times x_{jk}}{\sum_{k=1}^n x_{ik}^2 \times \sum_{y=1}^n x_{jy}^2} \quad (1)$$

This formula is derived from Euclidean metric system and looks like this:

$$\cos \alpha = \frac{a_1 \times b_1 + \dots + a_n \times b_n}{\sqrt{a_1^2 + \dots + a_n^2} \times \sqrt{b_1^2 + \dots + b_n^2}} \quad (2)$$

For common Euclidean space this formulas are correct but when applied to econometric data they distort real objects substitute composition of this objects with false complexity. They create distorted dependency model and thus can violate rules of space dimensions creation. For example technological vector T consisting of sub vectors $(x_1, \dots, x_n)$ representing dimensions composed from patent class data for particular technology in reality consist of

single "patent" dimension. Most of authors omit this issue and implement angular separation methods for class or object separation and measuring distance [7].

$$\Omega_{UV}^{EA} = \frac{\sum_{e=1}^T J_{ut} J_{vt}}{\sqrt{\sum_{e=1}^T J_{ut}^2 \sum_{e=1}^T J_{vt}^2}} \quad (3)$$

Numerous measures like this are based on angular separation between classes or [7–9] or adjacent class juxtaposition and measures of their overlapping [10–12] or probability distance measures [13] based on hypergeometric distribution of probability. As Jaffe states [9] if there is fundamental measure—it is possible to create proper space and measure in it. But this statement also contains obstacles because measure in technological space can be made between classes only. But patent classes have only one dimension—number of patents, and according to the rules of measuring distance between such groups only distance in one-dimensional space between centroids of such classes is viable. But in this case structural complexity of object is lost. Attempt to create real fundamental parameter for each class like biotechnology or electronics in technological space will be based on technological parameters—mass, size, logical structure, complexity and so on. And this approach will shift study outside economic discipline. In this case compromise variant should be Euclidean measures to expose technological patterns for each objects studied and Decart coordinates to create compatible system for object mapping.

Aside from mentioned problems with multidimensionality there are problems with heteroscedasticity, nonlinearity of data dependencies, their collinearity and non Haussian distribution patterns. This creates obstacles while finding dependency paths between influencing and dependent factors. Well known Kendal or Person correlation coefficients surmise pairwise object dependencies and reactions occurring after certain periods of time and within discrete geometric ranges for particular sets of data. But in real Nature or Economic systems such interactions are very rare and look like this in reality:

$$\sum_{i,j}^{n,m} f(x,y) \leftrightarrow \sum_{j,i}^{m,n} f(x,y) \quad (4)$$

Signature $\leftrightarrow$ means any pairwise all-angle directed and complex [14] between all elements x and y of set f . That means that formulas like (3) and all other coefficients are totally incompatible with this case (4). From the point of view of vector space actions can fill all the space and

Table higher demonstrates comparison main colliders across the world with Tau Fabric. Economic effects and applications with key parameters and discoveries are shown. If we consider integration and applications common patterns can be noticed they are medicine therapy and diagnostics, food processing, isotope and new elements synthesis, irradiation. The closest one to Super Tau Charm Fabric is KEK collider in Japan that became famous for SP super symmetry violation discovery. There are other projects that became generators of dozens of new periodic elements. But all the new ones trans-fermium

As it is seen from the Table 3 colliders are weakly integrated in most significant technological markets despite collider market is included on 100% in mentioned classes.¹ Table down shows co-occurrence of technological direction with each other. Table shows patents co-occurrences of colliders with main patent classes. Such analysis could reveal integration capacity of each technology to form other technologies (Table 2).

As it is evident from the table, colliders show greater integration capacity with technologically compatible industries and technologies. This integration can lead to convergence with laser technologies [17], electronics and particle physics. But while comparing it to other technologies colliders show very low level of patent overlapping

¹ <http://www.freepatentsonline.com/featured/patentclasses.html>.

Table 1 Main markets and their integration

Technological directions (aggregation of patent classes)	GDP	Particles energy ^a	Colliders
Medicine	305 billion USD ^b	0.1–1 eV	5.116 billion USD
Biotechnology	440 billion USD ^c	0.1–0.4 eV	0
Semiconductors	412 billion USD ^d	1 meV	0
Photonics	636 billion USD ^e	1–4 eV	0
Chemistry	5700 billion USD ^f	0.2–20 eV	1 billion USD
Aviation and space	190 billion USD ^g	1 eV	0
Shipbuilding	274 billion USD ^h	1 eV	0
Electronics	1172 billion USD ⁱ	1 eV.	1 billion USD ^j
Nanotechnology	64.2 billion USD ^k	1 eV	0

^ahttp://accelconf.web.cern.ch/accelconf/ipac2013/talks/weib201_talk.pdf^b<https://www.grandviewresearch.com/industry-analysis/home-healthcare-industry>^c<https://www.gminsights.com/industry-analysis/biotechnology-market>^d<https://asia.nikkei.com/Business/Business-trends/Global-semiconductor-market-to-shrink-12-in-2019-trade-group>^e<https://www.mordorintelligence.com/industry-reports/photonics-market-market>^fhttps://www.icca-chem.org/wp-content/uploads/2019/03/ICCA_EconomicAnalysis_Report_030819.pdf^g<https://www.prnewswire.com/news-releases/the-global-commercial-aircraft-market-valued-at-just-over-us191-billion-in-2018-300703315.html>^h<https://es.ndu.edu/Portals/75/Documents/industry-study/reports/2015/es-is-report-shipbuilding-2015.pdf>ⁱ<https://www.globenewswire.com/news-release/2018/06/29/1531798/0/en/Global-Consumer-Electronics-Market-Will-Reach-USD-1-787-Billion-by-2024-Zion-Market-Research.html>^j<https://accelconf.web.cern.ch/accelconf/IPAC2013/papers/weib201.pdf>^k<https://www.asminternational.org/c/portal/pdf/download?articleId=25986127&groupId=10192>

revealing integration capacity. Even though shipbuilding is the only technology with lower frequency of overlapping it is self-reliant technology that is characterized by low number of heavy components with high value added.

But there is significant other application as in already mention fields like high energy lasers. As scientists from Berkeley showed in their experiments lasers are perfect accelerators for electron–positron pairs with energies up to 44 GeV [18] accelerating them with photon–photon and photon–electron interaction [19].

Elementary particle physics is high risk discipline not only as low profit technology but as a generator of a new fundamental results. It happens because nuclear physics per particle energy range and other parameters are much bigger than average among other disciplines. All other technologies integrated with each other because of material and process energy ranges round similar values of 1 eV while particles building all the goods manufactured have unlimited life. Other technological direction have more similar patterns like similar functional behavior—transportation, communication, computation, food preparation and on while colliders main function is colliding particles

and observing their result—that stands apart from most technologies.

Elementary particle physics left the zone of economic indicators and that made it hard task to integrate nuclear physics in other sector of economics.

Recently some attempts to find alternatives for colliders are implemented. Some of them are ambitious or even unproven one's in military sector like creation of anti-nuclear neutrino weapon activating as it is expected nuclear warhead remotely or neutrino sources for detection of warheads [20, 21]. Projects in biotechnology grasp such knowledge field as application of Vavilov–Cherenkov radiation for the development of biological processes monitoring within living cells in real time [22]. Economically beneficial technology seems to be chemical process study in real time by means of x-ray propagation induced with particle collisions or deceleration [22]. Beneficial directions can be predictive chemistry, molecules detection and catalytic process tracing in real time with high energy gamma rays, quantum phenomena studying and some other phenomena hardly processed with conventional methods.

Table 2 Patent compatibility matrix between technologies

	Biotechnology	Laser	Nanotechnology	Photonics	Collider	Medicine	Electronics	Shipbuilding	Aircraft	Textile	Robots	Machine tools	Resource extraction
Biotechnology	0	9044	4246	2125	0	34,958	14,418	0	3	1055	3357	14,439	314
Laser	9044	0	1947	33,420	1900	3048	84,977	1128	2436	1754	9468	13,278	849
Nanotechnology	4246	1947	0	1846	848	2237	9607	25	219	1386	284	1085	43
Photonics	2125	33,420	1846	0	836	596	11,678	3	159	143	289	640	112
Collider	0	1900	848	836	0	0	3779	13	76	84	420	652	186
Medicine	34,958	3048	2237	596	0	0	17,859	0	109	1078	1584	3008	281
Electronics	14,418	84,977	9607	11,678	3779	17,859	0	301	9390	8087	19,741	37,465	8136
Shipbuilding	0	1128	25	3	13	0	301	0	272	72	160	310	11
Aircraft	3	2436	219	159	76	109	9390	272	0	1202	1542	2618	99
Textile	1055	1754	1386	143	84	1078	8087	72	1202	0	733	2619	155
Robots	3357	9468	284	289	420	1584	19,741	160	1542	733	0	14,469	463
Machine tools	14,439	13,278	1085	640	652	3008	37,465	310	2618	2619	14,469	0	2950
Resource extraction	314	849	43	112	186	281	8136	11	99	155	463	2950	0
All	88,294	163,645	23,930	51,970	10,942	73,190	233,597	2295	18,125	19,197	52,541	93,744	13,765

Fig. 3 Neuron weights distribution for 24 technologies in 80 regions of Russian Federation. Matlab Toolbox

Most stable technologies successfully implementing colliders and nuclear physics are pasteurization technologies implementing irradiation to protect food and medical equipment. Besides there are some assumptions that irradiation can be dangerous due to unpredictable chemical reactions massively induced by 10 MeV electron beams.

Already mentioned method to implement neutrino as military project seems to prosperous as several research studies provided by [21] proved theoretical possibility to deploy neutrino sources at 1–200 Tev as military weapon or at least warhead detector. While other scientists proved that neutrino rays [23] lead to drastic increase of isotope decay [24] process thus giving some opportunity for implementation of mentioned technology. But general deceleration of radical innovation in elementary particle Physics can be a sign that even those neutrino ambitious plans will stay just a theory.

3 Results

3.1 Self-organized neural model

Figures down represent neural map weight distribution and heat maps, reflecting similarity or correlation patterns between fields of technology. Figures 3 and 5 reflect weight distribution of analyzed data while Figs. 4 and 6 correspond to the Euclidean metric distance similarities between objects in relevant space of dimensions.

Figure 3 higher reflects neurons distribution in Self organized neural map model created with Matlab Self-Organized Map Toolbox. Asymmetric structure reveals poor distribution and imperfect self-organization, however it showed quite good level of precision with several patterns of similarity between input vectors corresponding to technologies (Fig. 4).

Fig. 4 Input vectors for 24 technologies

Fig. 5 Distribution of weight neurons in Matlab clustering tool

Figure higher demonstrates structural cross industrial dependencies in Matlab Toolbox. There are patterns of significance between aviation and turbines, machine tools and machine building, semiconductors and integrated circuits, integrated circuits and microelectronics.

But, at the same time there are no connection between each of 3 technologies integrated circuits, microelectronics, semiconductors and lithography equipment. That reveals lack of connections in this manufacturing chain or lacks necessary technological level and inner demand between technological chain elements within Russian Federation. Similar isolation can be seen for Elementary Particle Physics (Fig. 4).

Figure higher (Fig. 5) shows distribution of neurons weights for Matlab clustering tool (625 neurons corresponding to 24 input vectors). Despite lower precision of this package in comparison to Matlab Toolbox, distribution is more smooth and heteroscedastic with all neurons self-organized relatively to each other that is reflected in larger number of similar technological patterns between technologies as on the figure down. Closer structural similarities are reflected in closer topologies, while color reflects strength of connection with red as strongest connection yellow—weaker connection and black shows no connection with neural map [25] (Fig. 6).

Fig. 6 Matlab clustering tool input vectors

Matlab clustering tool found more connections. They are machine and machine tools, turbines and aviation, chemistry and petro chemistry, integrated circuits and microelectronics, semiconductors and integrated circuits (very weak), genetics and nanotechnology (very weak), cattle breeding and agriculture. But colliders as major representative of elementary particle physics showed no similarities with other technologies even in this figure.

In this sense neural map creates “relative” similarities between input planes corresponding to input vectors.

3.2 Project evaluation

The only elementary Particles Technology that has applied implementation is particle colliders. There is a plenty of cost models developed for their estimation that are to be considered here.

Besides there are several types of collider project evaluations [26]. There is estimation based on key technological parameters [1]. But more recent estimation was made with the complex rNPV model taking into account aside indirect effects of collider. Model was created for CERN collider complex [2].

$$TPC = \alpha \left(\frac{L}{10 \text{ km}} \right)^{1/2} + \beta \left(\frac{E}{1 \text{ TeV}} \right)^{1/2} + \gamma \left(\frac{P}{100 \text{ MW}} \right)^{1/2} \quad (5)$$

here L —collider tunnel length, E —energy per 1 electron volt/centimeter, P power. Coefficients α , γ are economic parameters, a β coefficient measured for technology. With $\pm 30\%$ fluctuation $\alpha\beta\gamma$ -model corresponds to actual collider costs in the Table 2 with coefficients $c \alpha = \gamma = 2$ billion. USD and coefficient β equal to 1 billion.USD for NC magnets, 2 billion USD for SC magnets, 8 billion USD for NC RF and 10 billion USD for SC RF.²

Super Tau Fabric costs = 2 billion.USD * 0.089 + 2 billion.USD * 0.07 + 2 billion.USD * 0.8944 = 0.178 + 0.14 + 1.7888 = 2.1068 billion.USD. So Russian project Super Tau Charm Fabric is significantly cheaper, especially taking into account the fact that 40 billion rubles (650 million USD—rate 2019 June) will be spent on all the equipment and infrastructure with collider. And even with regard to purchasing power parity comparison that is still cheaper nearly 40% as GDP per capita in USA and Russian federation has ratio 2.19: 1 or (65,112 USD ppp) to (29,642 USD ppp).

² NC, SC, SC RF solenoid magnet types and technology.

From the point of long term prospects CERN project from Switzerland attract attention in many research studies with economic ones among them [27]. This studies provided standt evaluation models. Proposed model for LHC collider includes standard—Bti и Cti parameters that are benefits and costs in period t.R—discount rate at certain period t_i .

$$NPV = \frac{B_{t_i} - C_{t_i}}{(1 + R)^{t_i}}; \quad (6)$$

In order to quantize parameters for CERN model environmental approach [28] was adopted from [29],³ splitting NPV into parts: real income NPV_u and unused income from expected and unused benefits EXV. NPV_u is split into 4 parts of benefits and 4 variable of costs.

First part benefits consist of following variables scientific research articles based on CERN discoveries and their corresponding values, technological advantages for collaborating firms, human capital and cultural effect ($SC_{t_i} + TE_{t_i} + HC_{t_i} + CU_{t_i}$). These variables are “Pro fit from publications”—280 million euro, like induced long term effects [27], “outer favorable factors” TE_{t_i} —5.4 billion euro, “Human Capital” HC_{t_i} —5.5 billion euro, “cultural effects” CU_{t_i} —2.1 billion euro. Outer favorable factors can be effects on collider market sales or applications of nuclear physics in other areas. Cultural effects—payed services provided by CERN, research subcontracting, grants, funding. Expenditures include capital costs, scientists salary and S&T expenditures, working personnel, operational costs $C_{t_i} = (K_{t_i} + LS_{t_i} + LO_{t_i} + O_{t_i}) = 13.5$ bln.euro.

Variable EXV0 describe unused projects prosperous capacity. General model looks following:

$$NPV = \sum_i^t \frac{(SC_{t_i} + TE_{t_i} + HC_{t_i} + CU_{t_i}) - (K_{t_i} + LS_{t_i} + LO_{t_i} + O_{t_i})}{(1 + r)^t} + EXV0; \quad (7)$$

It is quite evident that authors wanted to promote project and installed virtual benefits because of well-known problem of fundamental science weak links to economic sectors. It is evident that authors exaggerated benefits. And this impose limits on application of such models in real project evaluations.

Real benefits can be created by application of adjacent collider markets. Its benefits can be composed of real sector applications and relevant services. There are areas of application in petro-chemistry, automobile industry. Aside from that there is a dozen of positron and electron colliders technologies deployed in diagnostics, medicine, testing, process monitoring. But these are mostly small

Fig. 7 RNPV model evaluation for Tau Fabric

specialized segment having competitor technologies in areas of medicine, chemistry, biotechnology, physics they are applied to. In proposed risk adjusted model rNPV size of market was adjusted according to neural model which excludes alternative market applications on contrast to other research [3] (Fig. 7).

Model obtained following results.

PV of revenue = 74,055,528 usd.

NPV = − 33,657,178 usd.

rNPV = − 26,584,021 usd.

rTC = 739,225,062 usd.

Overall Value of project 74,055,528 dollars but with cost variables it is negative due to the high maintain costs and small market segments. rTC—risk adjusted total cost is equal to Tau Fabric price rTC = 46,571,178,906 roubles while project cost is 40 billion roubles roughly.

4 Discussion

As it was mentioned main disadvantage of Elementary Particle Physics is a big gap between it and other economic system that's why it is very hard to find possible alternative combinations of collider technologies aside from those very specialized. Though some prosperous applications were found while changing basic methods of research in this area. For example Nuclear Magnetic Resonance, that made revolution in diagnostics was discovered apparently from mainstream nuclear physics though it belongs to this research area.

Similar application became positron beam diagnostics implementing annihilation as diagnostic process in real time. Though some studies [30] report that even small doze of gamma rays can result in a heavy damage of cell and DNA structure [31]. Similar hesitation on the safety of products processed with ion beam particles occur in the food irradiation applications. Main idea of irradiation safety was based on relativistic approach that electron—atom collisions can not lead to nuclei radiation emergence due to formation of new isotopes. But 10 MeV electron can

³ Pearce et al. [29].

Fig. 8 Costs and potential comparison for collider projects on CERN example

have thousands and millions of unpredictable collisions with other electrons proving unpredictable combinations of possibly chemically toxic molecule appearance. In addition it was shown that prediction of all this combinations is barely possible even with the most powerful computational systems in chemistry and biotechnology [31].⁴ То есть не возможно предугадать появление опасных токсичных веществ и радикалов.

Figure down aggregates S&T expenditures on collider and particle physics project on the CERN example with global economic output of collider applications. It is evident from the figure that such projects are mainly expendable rather than profitable. Their cost dimensions and variables are large while applications size and path is pretty narrow (Fig. 8).

Colliders market assessment faces same obstacles as high level of cross technological dependence of accelerators and conjugated technologies. Though all general evaluations fluctuate round same value in 3 billion USD.⁵ for colliders sold and 50 billion USD.⁶ for colliders sild with services and subordinate products. Though some authors

make evaluation for goods and services for collider market comparable to all global market similar to those with USA and Japan only [3]. But this can be the result of market frames variations from one study to another as this author include the aggregated cost of irradiated products. In addition it should be stressed that some of the markets like ion beam implantation has quite unique properties creating strong barriers. Ion beam processing of polymers for crosslinking, grafting, solubility increasing and weight reduction has very strong competitive pressure from conventional chemical technologies. So the only proven markets for colliders as well as Super Tau Charm Fabric in Novosibirsk and NICA project in Moscow are food and medical devices irradiation (Fig. 9).

Despite a number of applications collider applications are very specific and narrow. While improving some characteristics they this technology is dependent from vertically and horizontally integrated technologies like machine tools and other equipment. Another disadvantage of such market evaluated with upper level of 5 billion USD. is very rapid saturation due to long life cycle of colliders. Ion beam food processing services are country dependent as they all require various certifications and linked to local production chains.

⁴ Sevilla et al. [31].

⁵ http://accelconf.web.cern.ch/accelconf/ipac2013/talks/weib201_talk.pdf.

⁶ https://www.cockcroft.ac.uk/wp-content/uploads/2016/07/Applications_1.pdf.

Fig. 9 Number of colliders in each collider application segment

5 Conclusion

Recently Elementary Particle Physics with subordinate collider technologies is integrated in economic system but this integration is very specialized and incapacious. Its main part—nuclear physics stemming from discoveries from the first half of twentieth century implemented itself in large number of technological directions though its economic share is not so large as main technologies like photonics or IT. And its part that is already found itself on the market is not expanding due to low number of possible variations and integration with other technologies as neural map showed.

There is a general lack of market size caused by high competition. There are 71 centers providing irradiation services in the world creating strong competition in both research areas and final market products and services. Colliders find their applications though they face serious pressure from competitive technologies and sometimes losing in various properties like penetrative depth,

radiation safety, scale, toxicity but they stay as one of the prosperous frontiers for new horizons in the far future.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix: RNPV model

$$\text{Formula: } rNPV = R_0 \left(P_{npv} - \sum_{i=0}^n \frac{C_{inpv}}{R_{inpv}} \right).$$

Revenue per collider 100,000 usd.

Number of units sold per year = 2000.

Number of employees engaged = 1000.

Duration of project 8 years.

R&D and engineering 5,000,000 usd.

See the Tables 3 and 4.

Table 3 Main discoveries in Elementary Particle Physics and their economic impact

Radical inventions	Year	Effect	Global GDP	Electron volt/life time
Heat waves William Herschel–infrared waves	1800	Heating devices	(\$8.6 billion. (USD) in 2017) ^a	Near infrared light 1 eV/ unlimited lifetime
Jonntan Wilhelm Rittar discovered ultra-violet rays	1801	Medicine, electronics ultraviolet lasers	(1 billion USD) ^b	1 eV/unlimited lifetime
Discovery UV in vacuum	1885	Medicine, electronics, ultraviolet lasers	(\$491.7 ^c mln. + \$369.58 ^d млн. + etc.) 1 bln. USD [%]	1 eV/unlimited lifetime
Discovery of X-rays	1895	Medicine	8.27 billion.USD ^e	0.1–10 MeV/unlimited
Electron discovery (beta particle)	1897	Electron colliders	2.100 billion. USD. ^f	0.1–6 MeV/unlimited
Alfa particles	1899	Medicine, science	506.5 million. USD(2018) ^{g,h}	2–10 MeV/unlimited
Photon discovery (Max Planc)	1900	Photonics	(636 (1%) billion.USD) (2018) ⁱ	2.5 Ev/unlimited
Gamma rays	1900	Medicine	(8.68 billion. USD–11.2 billion USD ^k) (2018) ^l	0–5 MeV ^m /unlimited
Nucleons	1911	Atomic energy	(6 billion. USD) ⁿ %(2018)	1 Mev interaction (1000 Mэb particle)/unlimited lifetime(proton)
Proton discovery	1919	Atomic energy, science, medicine	1.5 + 3.5 billion. dollars ^o	1 Mev interaction (938) Mev/ unlimited life
Deuterium discovery	1931	Thermonuclear	0	10–20 Mev/unlimited life
Neutron discovery	1932	Atomic energy	0.325 billion. dollars. ^p (6.5% of market with 5–5.25 ^q billion USD.)	1 Gev (939 Mev)/unlimited life
Positron discovery	1932	Medicine	0.740 billion dollars ^r	0.1–10 Mev/annihilaton
Strong force	1935	Atomic energy	36.5 billion dollars ^s	1 Mev/unlimited
Muon discovery	1937	Scientific research	0	105 Mev/close to 0
Pion discovery	1937	Scientific research	0	140 Mev/close to 0
Kaon discovery	1947	Scientific research	0	497 Mev/close to 0
Lambda Barion	1950	Scientific research	0	1000–5600 Mev/close to 0
Antiproton	1955	Scientific research	0	938 Mev/close 0
Electron neutrino	1956	Scientific research	0	0.28 eV/unlimited
Muon Neutrino	1962	Scientific research	0	2.7 Mev/unlimited
Ksi Barion	1964	Scientific research	0	1320 Mev/close to 0
Partons (quarks)	1969	Scientific research	0	2.2–1280 Mev/close to 0
J/ψ Meson	1974	Scientific research	0	3000 Mev/close to 0
Tau Lepton	1975	Scientific research	0	1.77 Gev/close to 0
Upsilon Meson	1977	Scientific research	0	9 Gev/close to 0
Gluon	1979	Scientific research	0	1.3 Mev/close to 0
W and Z Bosons	1983	Scientific research	0	80–91 Gev/close to 0
Top quark discovery	1995	Scientific research	0	173 Gev/close to 0
Anti hydrogen	1995	Scientific research	0	1 Gev/close to 0
Tau Neutrino	2000	Scientific research	0	0.28 eV/unlimited

Table 3 (continued)

Radical inventions	Year	Effect	Global GDP	Electron volt/life time
Anti Helium 4 (repeat of Berkley experiment in 1971)	2011	Scientific research	0	4 GeV/close to 0
Higgs Boson	2012	Scientific research	0	125 GeV/close to 0
ahttps://www.wattco.com/2018/03/electric-heating-elements-predicted-growth/ bhttps://www.marketsandmarkets.com/Market-Reports/uv-led-market-143107738.html chttps://www.variantmarketresearch.com/report-categories/semiconductor-electronics/lithography-equipment-market dhttps://www.marketsandmarkets.com/Market-Reports/uv-led-market-143107738.html ehttps://www.grandviewresearch.com/industry-analysis/x-ray-systems-market fhttp://accelconf.web.cern.ch/ACcelConf/ipac2017/talks/tuia2_talk.pdf ghttps://www.mordorintelligence.com/industry-reports/alpha-emitters-market hhttps://www.cockcroft.ac.uk/wp-content/uploads/2016/07/Applications_1.pdf ihttp://sites.fas.harvard.edu/~phys191r/Bench_Notes/B1/NAI_catalog.pdf jhttps://www.mordorintelligence.com/industry-reports/photronics-market-market khttps://www.gminsights.com/industry-analysis/medical-x-ray-market?utm_source=prnewswire.com&utm_medium=referral&utm_campaign=Paid_prnewswire lhttps://www.prnewswire.com/in/news-releases/digital-x-ray-market-growing-at-85-cagr-to-2023-says-x-ray-end-users-and-new-technology-expert-693051421.html mhttp://sites.fas.harvard.edu/~phys191r/Bench_Notes/B1/NAI_catalog.pdf nhttps://www.marketwatch.com/press-release/united-states-proton-therapy-market-size-to-witness-us-7-billion-to-2025-2019-04-05 ohttp://www.acceleratorsamerica.org/files/Report.pdf phttps://indico.cern.ch/event/682411/contributions/2798415/attachments/1594751/2525301/The_Beam_Business_-_Brussels.pdf qhttps://www.prnewswire.com/news-releases/nuclear-medicine-radiopharmaceuticals-market-worth-5-26-billion-by-2023-exclusive-report-by-marketsandmarkets-300831298.html rhttps://www.marketwatch.com/press-release/positron-emission-tomography-pet-market-2019-global-technology-development-trends-and-forecasts-to-2024-2019-04-24 shttps://www.alliedmarketresearch.com/nuclear-power-plant-and-equipment-market				

Table 4 Main collider complexed across the world and their key properties

	Total cost billion of USD (prices 2014)	Size of collider in kilometers	Energy of particles (TeV)/Power of system/luminosity	GDP/applications	Radical discoveries made on this collider
SSC	19–25	87	40 TeV/100 MB/10 ³³ cm ⁻² c ⁻¹	0	No data
FNAL MI	0.4–0.54	3.3	0.12/20 MW/10 ³³ cm ⁻² c ⁻¹	0	1977 Upsilon Meson discovered, 2000 observation of Tau-neutrino
RHIC	0.8–1.2	3.8	0.5/40 MW/10 ²⁷ cm ⁻² c ⁻¹	0	In 1965 anti-Deuterium is synthesized. In 2010 atoms of Anti-Helium 4 are synthesized
TESLA (DESY)	11–14	39	0.5/164 MW/34(43) * 10 ³³ cm ⁻² s ⁻¹ / ^a (plan)	0	No data
VLHC-I	10–18	233	40/60/-	0	No data
NLC (SLAC)	9–15	30	1/152 MW/8.2 * 10 ³³ cm ⁻² s ⁻¹	0	No data
PEP-II (SLAC)	-	-	0.027/-/1.2 * 10 ³⁴ cm ⁻² s ⁻¹	0	No data
NLC/JLC (SLAC-KEK)	9–15	32	1/320 MW/3 * 10 ³⁴ cm ⁻² s ⁻¹	0	No data
ELIC	-	-	0.15/500 MW/7.7 * 10 ³⁴ cm ⁻² s ⁻¹	0	No data
SNS	1.6–1.7	0.4	0.001/20/-	0	No data
LHC (CERN)	7–11	27	14/40/2 * 10 ³⁴ cm ⁻² s ⁻¹ /b	0	In 1995 Antihydrogen is synthesized, in 2013 Higgs Boson observed
CLIC (CERN)	12–18	18	0.5/250 MB/2(5.9) * 10 ³⁴ cm ⁻² s ⁻¹ / ^c (plan)	0	No data
KEK (SuperKEKB)	0.315	-	0.012/80 MB/2 * 10 ³⁴ cm ⁻² c ⁻¹ (8 * 10 ³⁵ cm ⁻² c ⁻¹ (plan))	0	1993 discovery of quark model SP symmetry violation
Project X	1.2–1.8	0.4	0.008/37/-	0	No data
XFEL (DESY)	2.9–4.0	3.4	0.014/10/-	0	No data
NuFactory	7–11	6	0.012/90/-	0	No data
BetaBeam	3.7–5.4	9.5	0.1/30/-	0	No data
SPL (CERN)	2.6–4.6	0.6	0.005/70/-	0	No data
FAIR	1.8–3.0	3	0.008/30/-	0	No data
ILC	13–19	3.4	0.5/230/-	0	No data
ESS	2.5–3.8	0.4	0.0023/37/-	0	No data
GSI (UNILAC)	No data	No data	0.0000011 TeV (11 MeV)	Medical therapy since 1997. Heavy ions are used for irradiation	Barium (1981), Meitnerium (1982), Hassium (1984), Darmstadtium (1994), Roentgenium (1994), Copernicium (1996)
SLAC	No data	No data	0.5 TeV/152 MW/8.2 * 10 ³³ cm ⁻² s ⁻¹	Lasers integrations to acceleration of particles	No data

Table 4 (continued)

	Total cost billion of USD (prices 2014)	Size of collider in kilometers	Energy of particles (TeV)/Power of system/luminosity	GDP/applications	Radical discoveries made on this collider
Berkeley lab (Bevatron)	No data	No data	0.006 TeV/–/–	Lasers integration (BELLA), deployment of technologies enabling integration with medicine and research in genetics	In 1955 synthesis of Antiproton and Antineutron. Synthesised elements—Astatinium, Neptunium, Plutonium, Curium, Americium, Berkelium, Californium, Einsteinium, Fermium, Mendelevium, Nobelium, Lawrencium, Dubnium и Seaborgium
Protvino	No data	No data	No data	No data	B 1970 Antihelium is synthesized-3
NICA (Dubna)	No data	No data	No data	No data	Elements 113, 115, 117, 118 are synthesized
Collider INF (Budker Institute—Novosibirsk)	No data	No data	No data	No data	Anti-Hydrogen is synthesized (1970s)
Super Charm Tau Fabric (Novosibirsk)	0.6	No data	^d 0.005 T38/–/0.5–2 * 10 ³⁵ cm ⁻² c ⁻¹	No data	No data

^a<http://bib-pubdb1.desy.de/record/301932/files/DESY-M-00-05R.pdf>^b<http://bib-pubdb1.desy.de/record/301932/files/DESY-M-00-05R.pdf>^c<http://bib-pubdb1.desy.de/record/301932/files/DESY-M-00-05R.pdf>^dhttps://ctd.inp.nsk.su/wiki/images/f/f3/CDR2_ScTau_ru_vol2.pdf

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