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Review of different colliders

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Since the first idea of a collider was patented by Rolf Wideröe (1902–1996) in 1943 and the first e^+e^- circular collider, AdA, was successfully principle-proved in LAL, Orsay, France in 1963, different kinds of colliders have been built in the past and planned for the future. In this paper, we will make a rather complete and brief review of the history of different colliders and give a perspective for the future.

Keywords: AdA; ACO; DCI; BEPC; CEPC; SppC; ILC; FCC; LEP; LHC.

PACS numbers: 29.20.−c, 29.20.db

1. Introduction

From 16–17 January 2020, a mini-workshop on Machine-Detector Interfaces (MDI) for colliders was held in IAS HKUST, Hong Kong. I was invited to give a talk on the review of different colliders. I took this as a precious opportunity, both due to the topic being important and my personal connections with whom I have experience in the field of colliders. This review is also my personal looking back and ahead on colliders with a generic nature.

2. The Original Idea of a Collider

On 9 October 2018, I invited J. Haïssinski of LAL, Orsay, France, one of the pioneers of electron–positron colliders, to give an IHEP seminar on "A Historical Account of the First Electron–Positron Circular Collider," and according to J. Haïssinski,[1] it was in 1943, during the second world war, that a Norwegian engineer, Rolf Wideröe, as shown in Fig. 1, who had given some thoughts to the betatron principle while completing his training in Karlsruhe (1923), deposited a secret patent of a nuclear

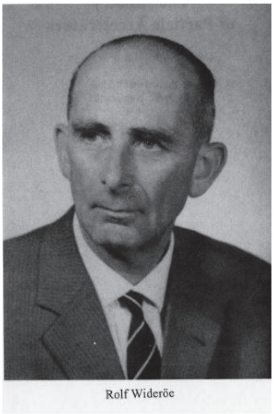

Fig. 1. Rolf Wideröe.

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

Kernreaktionen können dadurch herbeigeführt werden, daß geladene Teilchen von hoher Geschwindigkeit und Energie, in Elektronenvolt gemessen, auf die zu untersuchenden Kerne geschossen werden. Wenn die geladenen Teilchen in einen gewissen Mindestabstand von den Kernen gelangen, werden die Kernreaktionen eingeleitet. Da aber neben den zu untersuchenden Kernen noch die gesamten Elektronen der Atomhülle vorhanden sind und auch der Wirkungsquerschnitt des Kernes sehr klein ist, wird der größte Teil der geladenen Teilchen von den Hüllenelektronen abgebremst, während nur ein sehr kleiner Teil die gewünschten Kernreaktionen herbeiführt.

Erfindungsgemäß wird der Wirkungsgrad der Kernreaktionen dadurch wesentlich erhöht, daß die Reaktion in einem Vakuumgefäß (Reaktionsröhre) durchgeführt wird, in welchem die geladenen Teilchen hoher Geschwindigkeit gegen einen Strahl von den zu untersuchenden und sich entgegengesetzt bewegenden Kernen auf einer sehr langen Strecke laufen müssen. Dies kann in der Weise durchgeführt werden, daß die geladenen Teilchen zum mehrmaligen Umlauf in einer Kreisröhre gezwungen werden, wobei die zu untersuchenden Kerne auf derselben Kreisbahn, aber in entgegengesetzter Richtung umlaufen. Da die geladenen Teilchen dabei nicht von bei der Reaktion unwirksamen Elektronen abgebremst werden und andererseits auf einer sehr langen Wegstrecke gegen die Kerne sich bewegen können, wird die Wahrscheinlichkeit für das Eintreten der Kernreaktionen wesentlich größer und der Wirkungsgrad der Reaktion sehr stark erhöht.

Um die bei der Kreisbewegung entstehenden Zentrifugalkräfte aufzuheben, müssen die umlaufenden Teilchen von nach innen gerichteten Ablenkkräften gesteuert werden, während eine Diffusion der Teile mittels stabilisierender, von allen Seiten auf den Bahnkreis gerichteter Kräfte verhindert wird. Falls die gegen-

Fig. 2. Secret patent of Rolf Wideröe on a particle collider.

"mile," as shown in Fig. 2, which was published openly in 1953. About his circular collider scheme, he wrote: "...and this is when (1943) I had my idea. If it were possible to store the particles in rings for longer periods, and if these "stored" particles

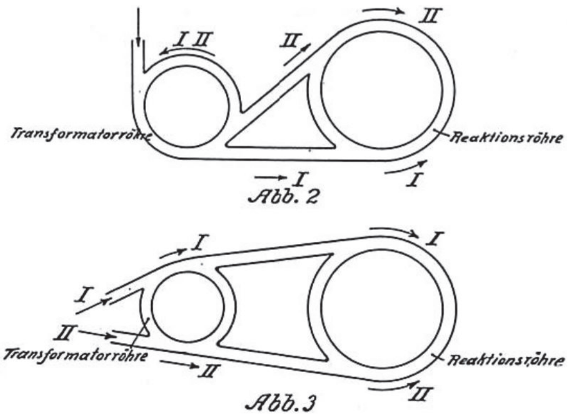

Fig. 3. Schematic drawing of particle colliders.

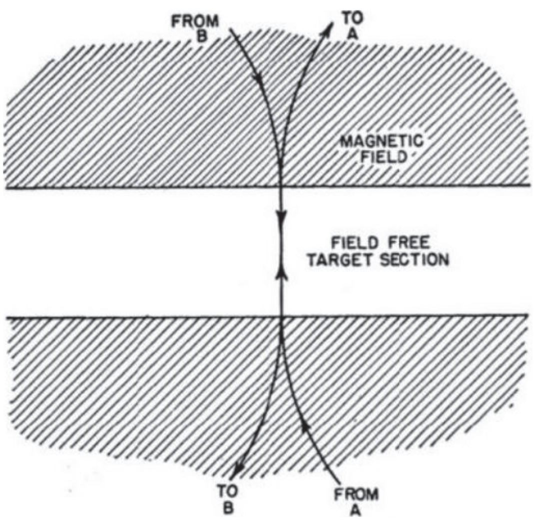

Fig. 4. Schematic drawing of intersecting storage rings (ISR).

were made to run in opposite directions, the result would be one opportunity for collision at each revolution." This is the historically documented original idea of a particle collider as shown in Fig. 3.

3. The Intersecting Colliders

The idea of a collider published in 1953 seems to have induced a burst of proposals and publications.[1] In April 1956, Kerst *et al.* published "Attainment of very high energy by means of intersecting beams of particles,"[2] as shown in Fig. 4, and in June 1956, O'Neill published "Storage-ring synchrotron device for high-energy physics research"[3] as shown in Fig. 5.

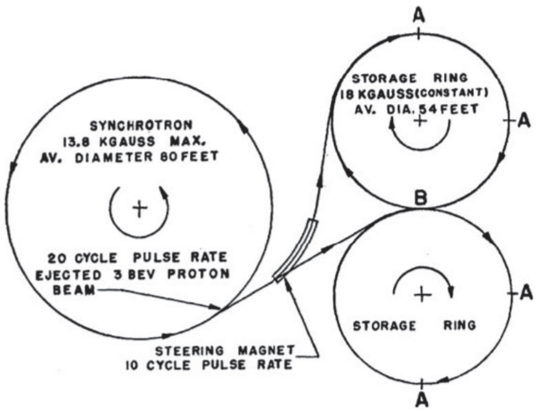

Fig. 5. 3-BeV proton synchrotron layout.

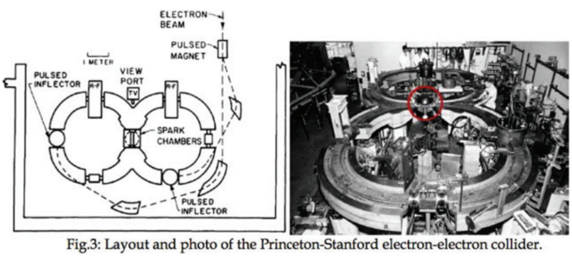

Fig. 6. Princeton-Stanford electron–electron collider layout.

In 1958, Barber *et al.* published a Stanford University Internal HEPL Report, RX-1486, on “A proposed experiment on the limits of quantum electrodynamics,”[4] as shown in Fig. 6.

As for the scientists from the Soviet Union, G. Budker and his group started to work on an e^-e^- storage ring (VEP-1) in autumn 1956 in the Kurchatov Institute (Moscow), and the first injection of electrons in VEP-1 took place in August 1963 in Novosibirsk, which was reported by Budker *et al.*, on p. 274 of Ref. 5, as shown in Fig. 7.

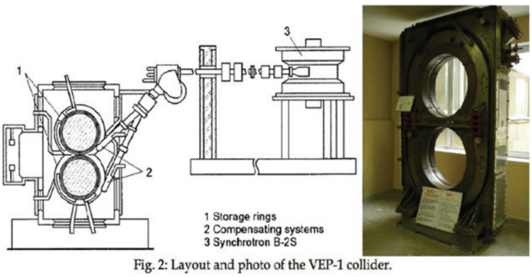

Fig. 7. VEP-1 layout.

Fig. 8. ISR at CERN.

As for first proton–proton collider in the world at CERN, according Lyn Evans' seminar,[6] "at the beginning of the 1960's a debate was raging about the next step for CERN. Opinions were sharply divided between a "large PS," a proton machine of 300 GeV energy or a much more ambitious colliding beam machine, the Intersecting Storage Rings (ISR). In order to try to guide the discussion, in February 1964, 50 physicists from among Europe's best met at CERN. They decided to transform themselves into a European Committee for Future Accelerators (ECFA) under the chairmanship of Eduardo Amaldi. It took nearly 2 years more before the consensus was formed. On 15th December 1965, with the strong support of Amaldi, the CERN Council approved the construction of the Intersecting Storage Rings," as shown in Fig. 8.

In 1968, Simon van der Meer had the first idea of stochastic cooling. In 1972, Schottky signals were observed and interpreted at the ISR, and Van der Meer published a paper on stochastic betatron cooling of transverse emittance; i.e. "Stochastic damping of betatron oscillations in the ISR," CERN/ISR-PO/72-31.[7] In 1972, Schnell made a feasibility study of a stochastic cooling experiment at the ISR. In 1974, the first experimental demonstration of stochastic cooling was obtained, and Rubbia *et al.* proposed a $p\bar{p}$ colliding beam experiment at the SPS, which will be discussed later.

4. Electron–Positron Circular Colliders

According to Pancheri and Bonolis,[8] in September 1959, a conference about the future of high-energy accelerators in physics was held at CERN. Both American and Russian scientists attended it, and electron–positron collisions were also mentioned, but no one knew how to do it. On 27 October 1959, during a seminar in Rome given by Wolfgang K. H. Panofsky, from Stanford University, about the electron–electron rings being built in the USA, the question of using electrons and positrons was raised again, by Bruno Touschek.

Fig. 9. Bruno Touschek.

According to Haïssinski,[1] the official recorded starting point of the launching of the first electron–positron circular collider in the world, the AdA project, was Bruno Touschek's seminar given in Frascati on 7 March 1960, where Touschek (1920–1978), Fig. 9, stressed that electron–positron annihilations would be the pathway to new physics by providing a state of pure energy with well-defined quantum numbers. He also pointed out that CPT invariance would guarantee collisions between electron and positron. A paper by C. Bernadini, G. F. Corazza, G. Ghigo and Touschek on "The Frascati storage ring," in *Il Nuovo Cimento*, Vol. 18, No. 6, was published on 16 December 1960.

As for how the encounter between Wideröe and Touschek took place, one can find detailed information from Pancheri and Bonolis's article, "The path to high-energy electron–positron colliders: from Wideröre's betatron to Touschek's AdA and to LEP."[8] Concerning the history of AdA, it was summarized briefly by Haïssinski[1] with the AdA program initial physics goals:

- Design an injection scheme;
- Measure the beam intensity in real time;
- Check the beam lifetime (RF, gas scattering);
- Measure the bunch size;
- Measure the beam luminosity;
- Observe e^+e^- annihilations into μ and π pairs.

Technical challenges of AdA:

- Design a small enough RF cavity;
- To have enough antimatter in the laboratory and make the e^+ injection efficient enough;
- Achieve and maintain an ultra-vacuum;
- Ensure a reliable magnetic field and RF cavity voltage;

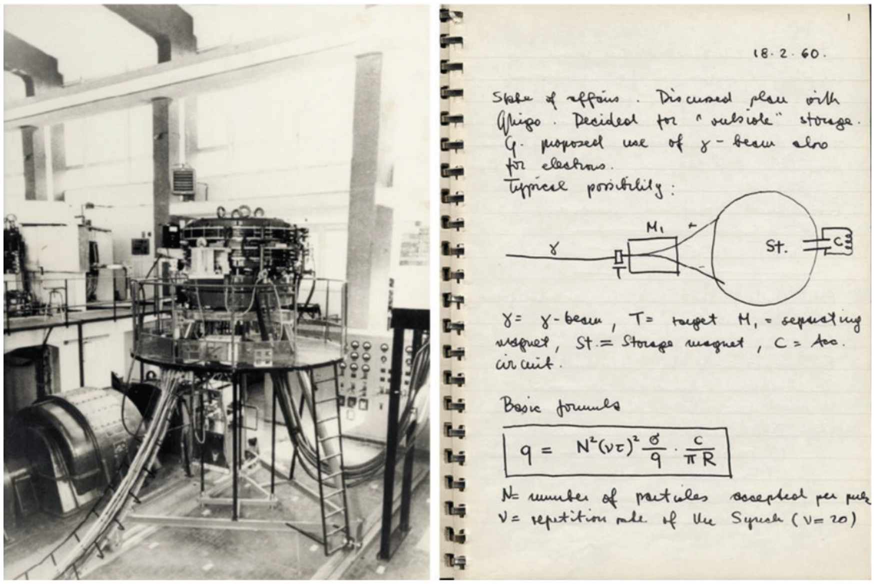

Fig. 10. AdA at INFN, Frascati, Italy.

and a short story timeline of AdA:

- March 1960: Decision to study the possibility of a colliding beam experiment at Frascati;
- May 1961: First electrons stored in AdA, Fig. 10;
- July 1962: AdA is brought to the Laboratoire de l'Accélérateur Linéaire (LAL) at Orsay;
- Spring 1963: Discovery of the Touschek effect;
- Fall 1963 — Spring 1964: First evidence ever for collisions between counter-rotating stored particles.

In 1961, AdA at Frascati faced a vital problem that the electron or positron capture rate achieved in Frascati was lower than anticipated, which was a few 10^2 particles per beam. According to Marin,[9] Fig. 11, during a visit of him and Georges Charpak to INFN, he suggested to Frascati colleagues to use the Linac of LAL, Orsay, France, as injector (Fig. 12) to increase the colliding beam current, that means to increase the beam current to a few 10^7 per beam. In July 1962, AdA was transferred to LAL, Orsay, Figs. 13–15, as described in the book of Matin, Fig. 16, with the AdA collaboration in Orsay created: C. Bernardini, G. Corazza, G. Di Giugno, J. Haïssinski, P. Marin, R. Querzoli and B. Touschek. In fact, when it is decided that AdA will be moved to Orsay, J. Haïssinski was invited back from USA to LAL working on AdA, where he finished his Thesis of State, which was the only diploma obtained in the Frascati–Orsay collaboration on AdA.

Fig. 11. Pierre Marin.

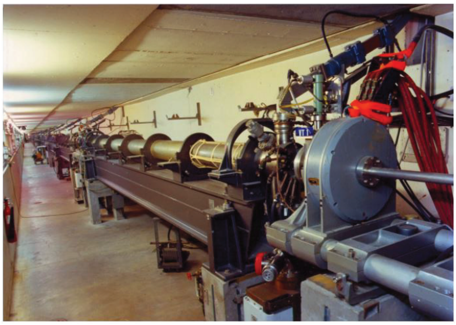

Fig. 12. The Linac of LAL, Orsay, France.

Table 1. AdA parameters.

Parameter	Typical operation value	Units
Energy per beam	200	MeV
Circumference	4	m
Luminosity	$\approx 10^{25}$	$\text{cm}^{-2}\ \text{s}^{-1}$
Beam current, per beam	0.5	mA
Injector (linac) energy	500	MeV
Max field on the orbit	1.45	T
Field index (dB/B)/(dr/R)	0.54	
Vacuum pressure	1	nTorr
RF peak voltage	5.5	kV

In Spring 1964, the first observation ever of electron–positron collisions was finally obtained as shown in Fig. 17, with AdA parameters shown in Table 1 and the luminosity measurement setup shown in Fig. 18.

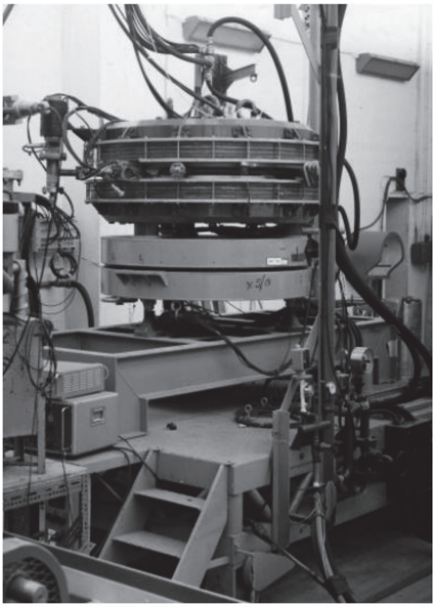

Fig. 13. AdA in LAL, Orsay.

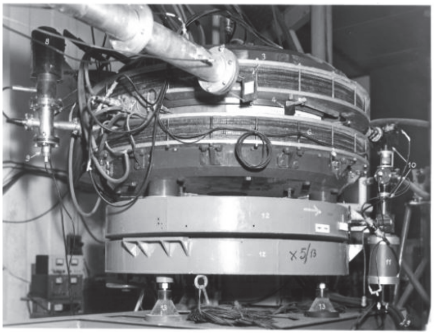

Fig. 14. AdA in LAL, Orsay, with injection beam pipe.

Fig. 15. J. Haïssinski in the control room of AdA.

Fig. 16. The cover of the book by P. Marin.

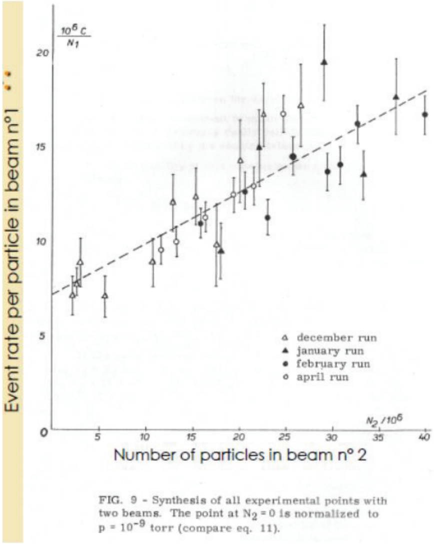

Fig. 17. Event rate versus bunch particle number in AdA.

AdA is important because of its main scientific achievements listed as follows and its impact on future colliders:

- Observation of single stored electrons/positrons.
- Beam lifetime above 5 hours.

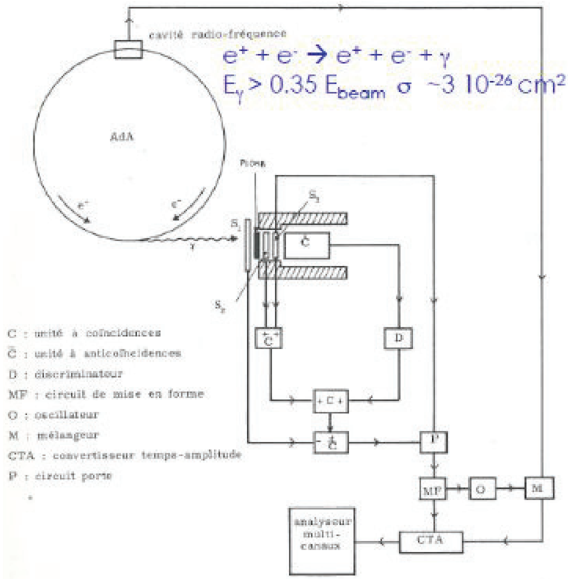

Fig. 18. AdA luminosity measurement scheme.

- Beam scattering by residual gas conform to theory.
- Check of the RF lifetime due to synchrotron radiation quantum fluctuations.
- Discovery and theory of the Touschek effect.
- Identification of the mechanism that determines the stored bunch height (coupling between betatron x and y oscillations).
- First evidence ever of collisions between opposite stored beams.

Pierre Marin (1927–2002), the leader from the French side, wrote a book titled "Un demi-siècle d'accélérateurs de particules," Editions du Dauphin, 2009, where he recalled a quite complete history of the development of electron–positron circular colliders from AdA to LEP. In 2000, at LAL, I asked Pierre whether one day he will write a book on the history of AdA, and he said that he was already working on it. Unfortunately, Pierre Marin passed away in the beginning of 2002. In July 2016, when I attended the PASCOS workshop, XIIth Rencontres du Vietnam, ICISE, Quy Nhon, Vietnam, I met J. Haïssinski, and I asked Jacques about the book of Pierre, and he told me that the book above mentioned in French was completed and published in 2009, after Pierre's passing away, with the help of the association of ACO, and Jacques sent me a volume of this book in 2017. From the book of P. Marin, we know not only about AdA, but more about ACO, DCI and LEP, which we will briefly recall.

Once the principle of an electron–positron collider was proved by AdA, in VEP-II ($E_{\rm cm}$ 1.4 GeV) in BINP (1963), ADONE ($E_{\rm cm}$ 3 GeV) in Frascati (1963) and ACO ($E_{\rm cm}$ 1.0 GeV) in Orsay (1964) were put to construction. According to P. Marin,[9]

Fig. 19. ACO layout.

Fig. 20. J. Le Duff.

H. Bruck from Saclay was nominated as ACO storage ring leader, and the student of H. Bruck, J. Le Duff (Fig. 20), worked on ACO for his Ph.D. thesis.

Among others, ACO should be stressed especially. ACO had the first beam–beam tune shift limitation found in the world; for the first time dipole magnet detector and antisolenoid (Fig. 19); for the first time sextupoles (coils added, but not individual sextupole magnets) used to correct chromaticity (suggested by M. Sands when he visited LAL); for the first time electron and positron polarization observed experimentally; for the first time the bunch lengthening effect observed. Following ACO, LAL decided to build DCI as shown in Fig. 22, which is a two-ring design for electron and positron collisions for the first time in the world, followed by SLAC PEPII, KEK B Factory, BEPC II (after BEPC), Super KEK B Factory, etc. On

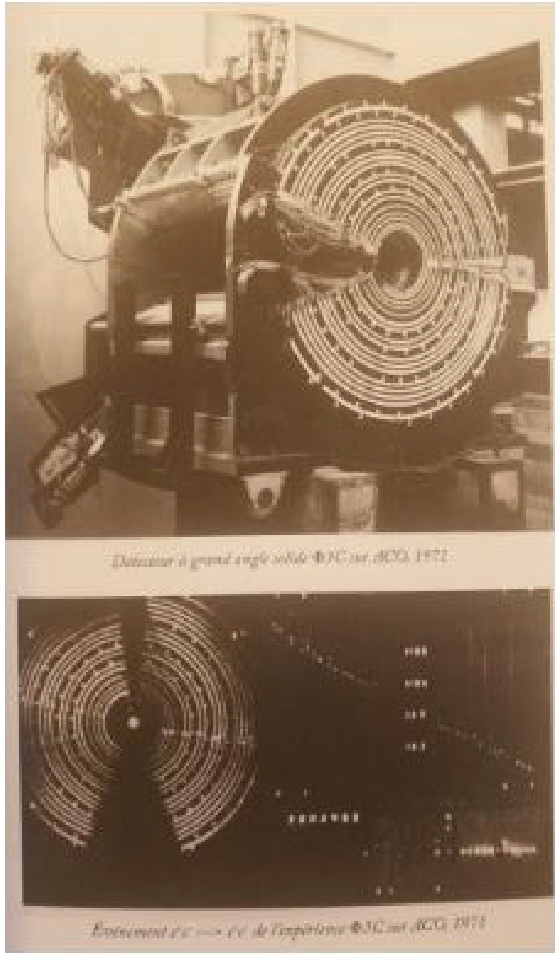

Fig. 21. The ACO detector.

DCI, for the first time, the idea to compensate beam–beam effects by using four beam collision was tested (but not successful) and for the first time the individual sextupoles to correct chromaticity were put to a storage ring.

During my stay in LAL, Orsay for 16 years, where its library and corridors documented the passing histories, the contact with J. Duff, J. Haïssinski, P. Marin, and many others, I have learnt many vivid stories, their pioneering works and scientific visions. J. Le Duff was my Ph.D tutor. J. Haïssinki was committee member of my Habilitation à diriger des recherches, and M. Davier was the director of LAL and was the committee chairman both for my Ph.D. and Habilitation.

As for electron–positron collider development in China, we will refer to an article by Jialin Xie (1920–2016, Fig. 23).[10] Since November 1977, the Chinese high energy accelerator plan was a synchrotron proton machine, on 17 March 1981, in a meeting

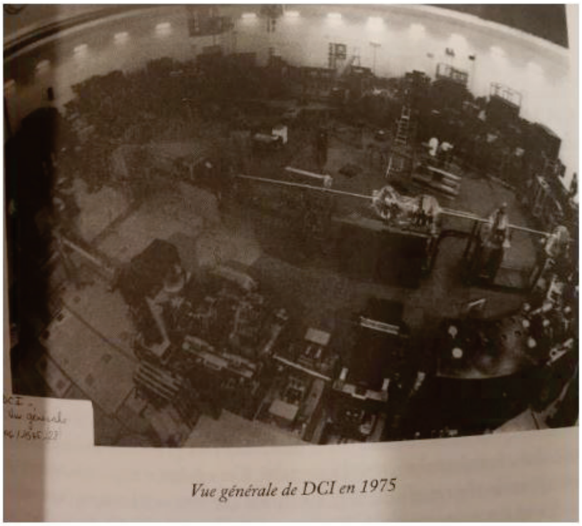

Fig. 22. DCI layout.

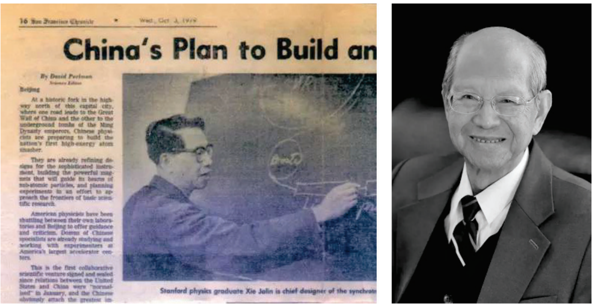

Fig. 23. Jialin Xie.

at the Fermi National Accelerator Laboratory (FNAL) initiated by T. D. Lee between China and the USA on high energy physics collaboration, after J. L. Xie presented the Beijing Proton Synchrotron (BPS), during discussion, Wolfgang K. H. Panofsky from SLAC proposed a 2.2 GeV electron–positron collider (which is later called Beijing Electron–Positron Collider, BEPC). During the following project adjustment, cost checking, etc., many international experts participated, such as B. Richter from SLAC and G. Voss from DESY. On 7 October 1984, the BEPC foundation was laid by Xiao Ping Deng, and the BEPC first collision was realized in October 1988. Since June 1986, as Ph.D. student of Jialin Xie, I am told many histories back late 70s on high energy physics development in China, also recalled in Ref. 10, which are very precious for the future collider development in China. In April 2016, the Asia Committee for Future Accelerators (ACFA) decided to

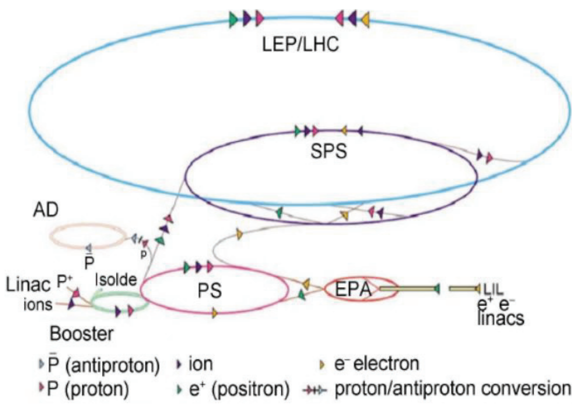

Fig. 24. LEP/LHC layout.

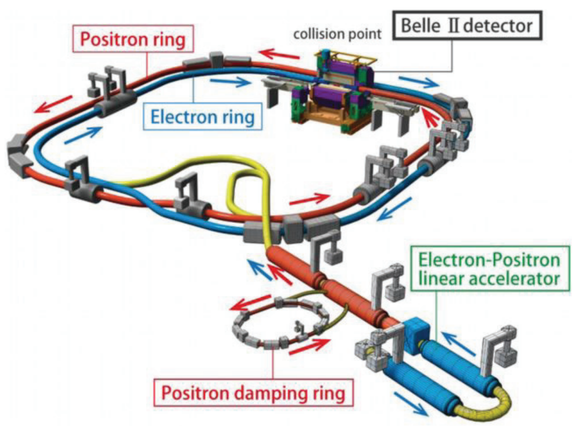

Fig. 25. Super KEK B layout.

establish four named Prizes, with the first Prize named after Jialin Xie, which will be given during IPAC taking place in Asia.

As for CERN, a single ring large electron–positron collider (LEP) with circumference of 27 km, collision center-of-mass energy 91 GeV, was constructed from 1983 to 1989. Between 1990 to 2000, LEP was upgraded in collision energy up to 209 GeV, as shown in Fig. 24. The highest luminosities both for LEP and LEPII were about 10^{32} cm^{-2} s^{-1}.[11]

To increase the luminosity two-ring electron–positron colliders have been built, such as PEPII, KEK B, BEPCII, and Super KEK B as shown in Fig. 25. Super KEK B (electron beam 7 GeV/positron beam 4 GeV) was put into commissioning on 19 March 2018, and luminosity is progressing towards the design goal. The important features of Super KEK B are its sub-millimeter (0.3 mm) β_y at interaction point and its high luminosity goal of 80×10^{34} cm^{-2} s^{-1}.

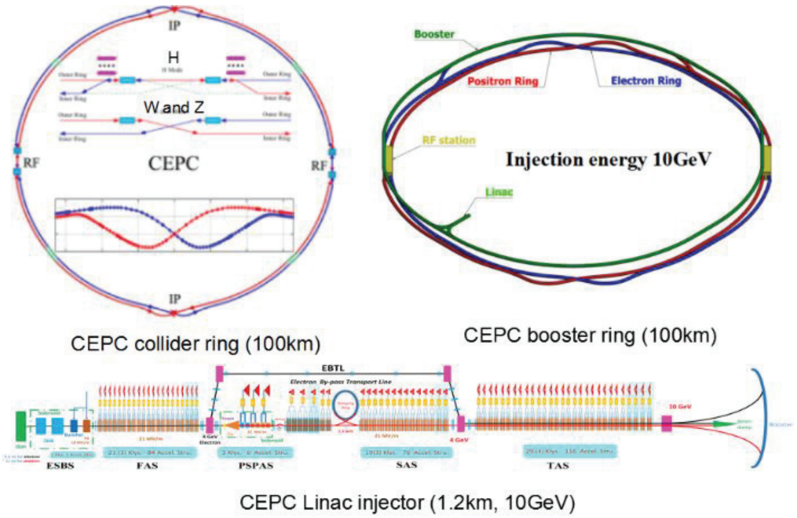

Fig. 26. CEPC layout.

The discovery of the Higgs boson at CERN's Large Hadron Collider in July 2012 raises new opportunities for a large-scale accelerator. Thanks to the low mass of the Higgs boson, it is possible to produce it in the relatively clean environment of a circular electron–positron collider. In September 2012, Chinese scientists proposed a Higgs factory, the so-called Circular Electron–Positron Collider (CEPC),[12–15] as shown in Fig. 26 with luminosity per interaction point at Higgs energy of 5×10^{34} cm^{-2} s^{-1}. In 2013, CERN proposed a Future Circular Collider (FCC).[16] Both CEPC and FCC are of 100 km circumference.

5. Electron–Positron Linear Colliders

On 6 December 2018, I have invited Valery Telnov of BINP, Novosibirsk to give a Linear colliders history talk in IHEP, Beijing.[17] In 1965, M. Tigner published a paper "A possible apparatus for electron clashing-beam experiments,"[18] as shown in Fig. 27. In 1971, G. I. Budker, A. N. Skrinski and their collaborators, in an unpublished note, considered conventional and superconducting linacs as tools for reaching the hundred GeV region. B. Richter recalled that "In 1976, Amaldi in *Physics Letters Journal* independently reinvented Tigner's scheme of superconducting electron linacs with energy recovery. He also considered electron–positron colliders, but could not find a solution that satisfied him for the production of positrons in a sufficiently small phase space to make high luminosity electron–positron colliders a practicality."

In 1978, Balakin *et al.*, gave a talk on "Feasibility of creating a superhigh energy colliding electron–positron beams facility" in the ICFA workshop at FNAL.[19] B. Richter said in "Perspectives of large linear colliders," SLAC-PUB-4482, 1987,[20]

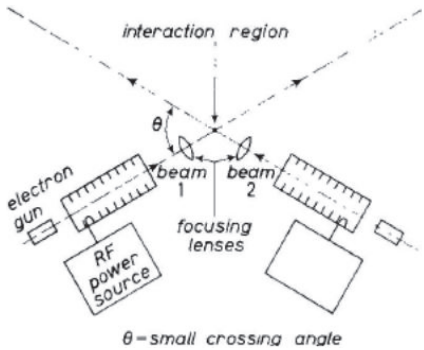

Fig. 27. A linear collider schematic layout.

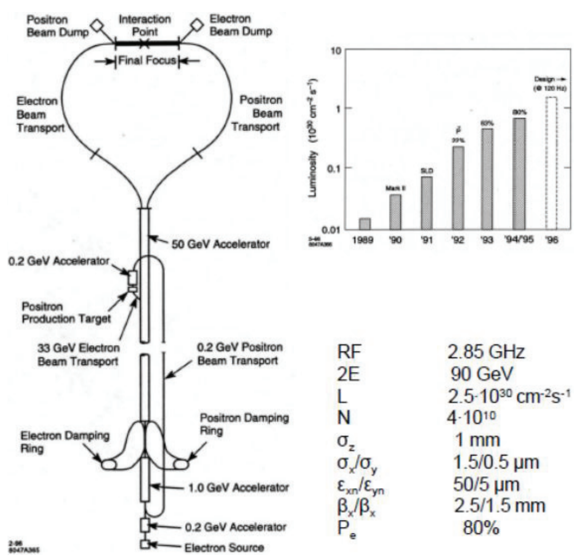

Fig. 28. SLC layout.

that "I believe the seminal event in the birth of the linear collider idea occurred at the ICFA Workshop on "Possibilities and limitations of accelerators and detectors" which was held at Fermilab in October 1978.

SLC was proposed by B. Richter in 1978 and put into operation in 1988, as shown in Fig. 28, which was a principle-proof machine for a linear collider.

According to T. Valery,[17] the key milestones for a LC project on TeV energies are as follows:

- VLEPP (Novosibirsk), 1978: first set of parameters;
- NLC (SLAC) in 1980 as natural step after SLC;
- JLC (KEK) in 1987: recommendations of Japanese HEP committee;

Fig. 29. ILC 250 GeV layout.

- SBLC (DESY) 1990: initiative at DESY (G. Voss);
- CLIC (CERN) 1985: W. Schnell (idea by A. Sessler, 1982);
- TESLA (DESY) 1990: initiative M. Tigner (Cornell) and B. Wiik (DESY);

where the first five projects use warm RF structures and TESLA uses superconducting accelerator technology. The first International workshop on LC was held at SLAC in 1988.

In August 2004, the International Technology Recommendation Panel (ITRP) recommended to ICFA that SC technology be adopted for TeV-scale electron–positron linear collider, with panel members as follows:

- **from Asia:** Gyung-Su Lee, Akira Masaike, Katsunobu Oide, Hirotaka Sugawara;
- **from Europe:** Jean-Eudes Augustin, Giorgio Bellettini, George Kalmus, Volker Soergel;
- **North America:** Jonathan Bagger, Barry Barish (Chair), Paul Grannis Norbert Holtkamp.

In August 2004, ICFA announced the formal name of the future linear collider as International Linear Collider (ILC) at IHEP, Beijing. In 2007, the ILC Reference Design Report and ILC 500 GeV cost were released during the ILC workshop in IHEP, Beijing. In June 2013, the ILC TDR was released formally, and LCC was established by ICFA including CLIC as an option. After the Higgs Boson was discovered in July 2012, in 2017, the Japanese HEP community proposed the ILC 250 GeV as a Higgs factory with luminosity of 1.3×10^{34} cm^{-2} s^{-1}, as shown in Fig. 29, which was endorsed by ICFA. In February 2020, ICFA released a statement on ILC based on the Japanese government input, that ICFA advocates establishment of an international development team hosted by KEK to facilitate transition to the preparatory phase. As for CLIC, it will remain a CERN project.

Chinese scientists have been involved in the ILC collaboration since 2005 working in ILC parameter optimization, linear collider beam dynamics studies, damping ring design, final focus issues on ATF2, 1.3 GHz superconducting technology development, and polarized positron source, as shown in Ref. 23.

6. Hadron–Hadron Colliders

According to L. Evans,[6] in 1974, the first experimental demonstration of stochastic cooling was obtained on ISR at CERN, and Rubbia *et al.* proposed $p\bar{p}$ colliding beam experiment at the SPS, and in 1981, the first collisions in the SPS were

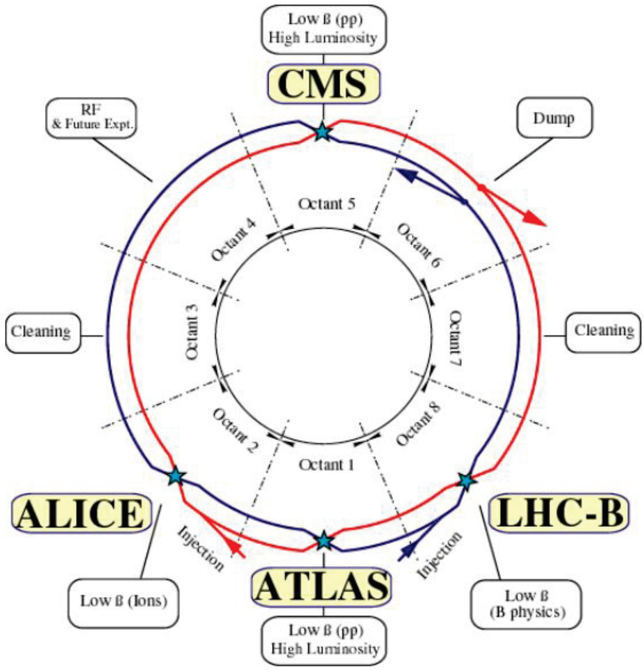

Fig. 30. LHC layout.

realized. The important experiences obtained In term of accelerator physics are: the importance of RF noise; intrabeam scattering; the beam–beam interaction.

After SppbarS at CERN, a bigger $p\bar{p}$ collider, Tevatron, of circumference 6.3 km, was constructed and operated in 1987 at Fermilab, which was the first superconducting collider, with 1.8 TeV center-of-mass collision energy, and remained the highest energy collider until 2009, when it was surpassed by the Large Hadron Collider, LHC, at CERN.

As part of the hadron–hadron collider history, one should not forget the Superconducting Super Collider, SSC, which was started in 1987 and stopped in 1993. The SSC main parameters are as follows:

- 87 km circumference;
- 20 TeV beam energy;
- $L = 10^{33}$ cm^{-2} s^{-1};
- SCC stopped after 14 miles of tunneling were completed and 2 billion US dollars spent.

As a competitor of SSC, a Large Hadron Collider, LHC, was planned, constructed and put into operation as shown in Fig. 30, with the following timeline:[6]

- Preliminary conceptual studies: 1984
- First magnet models: 1988

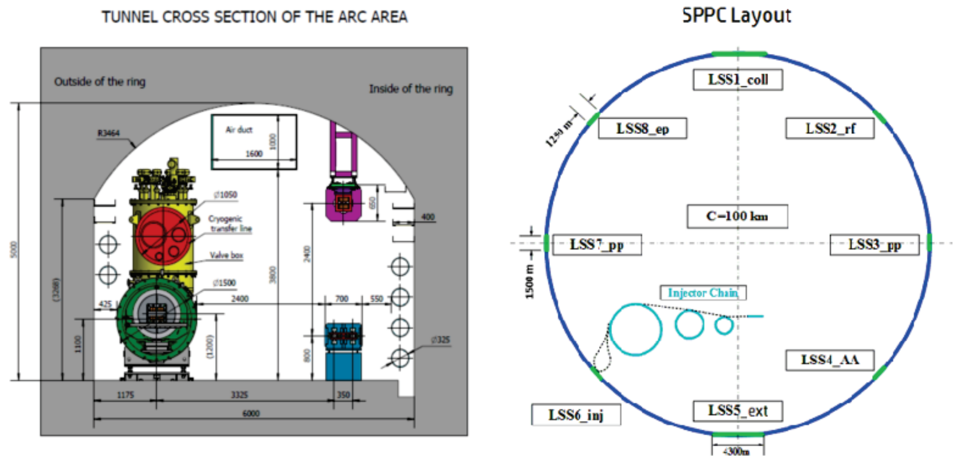

Fig. 31. CEPC and SppC tunnel cross section.

- Start structured R&D program: 1990
- Approval by CERN Council: 1994
- Industrialization of series production: 1996–1999
- DUP & start civil works: 1998
- Adjudication of main procurement contracts: 1998–2001
- Start installation in tunnel: 2003
- Cryomagnet installation in tunnel: 2005–2007
- Functional test of first sector: 2007
- Commissioning with beam: 2008
- Operation for physics: 2010–2035?

The most profound scientific achievement on LHC is the discovery of the Higgs boson, announced on 4 July 2012, which opens the door to the unknown universe, and the era of Higgs arrives.

As future hadron–hadron collider after LHC, SppC[12–15] and FCChh[16] of 100 km circumference, are proposed in IHEP and CERN. As for SppC, as shown in Fig. 31, which will be installed in the same tunnel of CEPC, its baseline design is using 12 T ion-based high temperature superconducting dipole magnets with 2 detectors, 75 TeV center-of-mass of collision energy and luminosity of 10^{35} cm^{-2} s^{-1} per collision.

7. Electron–Proton Colliders

As the first electron–proton collider in the world, HERA, of circumference of 6.3 km, electron beam energy of 30 GeV, proton beam energy of 820 GeV and luminosity per interaction point 1.5×10^{31} cm^{-2} s^{-1}, was put into operation from 1991 till 2007 at DESY, as shown in Fig. 32. It should be noted that it was on HERA that

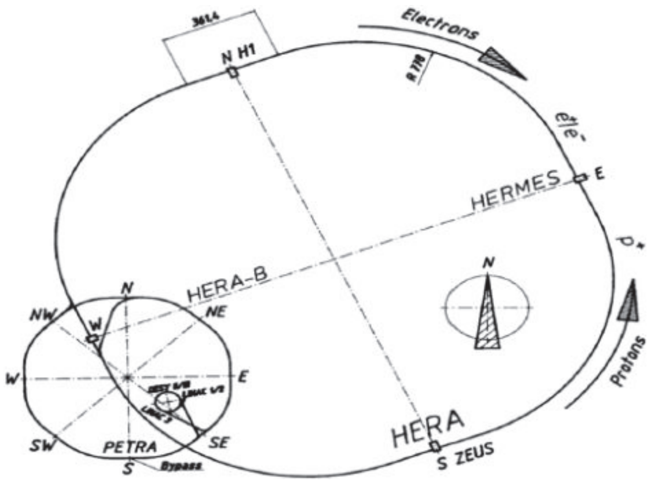

Fig. 32. HERA layout.

electron and positron beams were polarized longitudinally for the first time in a collider. As for the project management, HERA applied international contributions model, so-called "HERA model,"[11] which has important impact to the idea of ILC, and others as well in the future.

8. Electron Ion Colliders

In January 2020, DOE proved eRHIC CD0 at BNL, which is an electron ion collider with electron beam energy of 20 GeV, proton (ion) energy of 325 GeV, and luminosity of 1.4×10^{33} cm^{-2} s^{-1}, as shown in Fig. 33.[11]

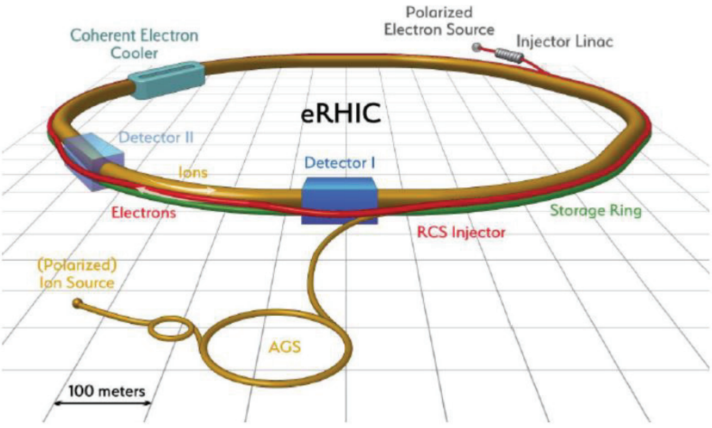

Fig. 33. eRHIC layout.

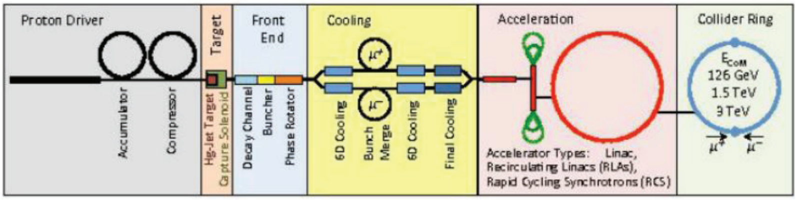

Fig. 34. Muon collider layout.

Table 2. Muon collider parameters.

Parameter	Units	Initial value	Upgrade
Beam energy	GeV	63	63
Average luminosity	$10^{31}/\text{cm}^{-2}/\text{s}$	1.7	8.0
Collision energy spread	MeV	3	4
Circumference	m	300	300
Number of IPs		1	1
$\beta^\star$	cm	3.3	1.7
Number of muons/bunch	10^{12}	2	4
Number of bunches/beam		1	1
Beam energy spread	%	0.003	0.004
Normalized emittance ϵ_N	πmmrad	0.4	0.2
Longitudinal emittance ϵ_N	πmm	1.0	1.5
Bunch length, σ_s	cm	5.6	6.3
Beam size at IP, r.m.s.	mm	0.15	0.075
Beam size at IR quads, r.m.s.	cm	4	4
Beam–beam parameter		0.005	0.02
Repetition rate	Hz	30	15
Proton driver power	MW	4	4

9. Muon Collider

As for lepton Higgs factory, there is another option, which is the so-called muon collider, as shown in Fig. 34.[22,23] The features of a muon collider, compared with a circular or linear electron–positron collider, are that it has a much smaller machine size, and higher upper energy range; i.e. several tens of TeV. However, technically, a muon collider needs more accelerator technology R&D, such as powerful proton superconducting linac technologies, muon production target, and 6D muon bunch cooling, etc. The parameters of a muon collider are shown in Table 2.

10. Ion Collider

NICA is an ion collider project by the Joint Institute of Nuclear Research (JINR) at Dubna,[24] as shown in Fig. 35. The scientific goals of NICA are Relativistic nuclear physics; Spin physics in high and middle energy range of interacting particles; and

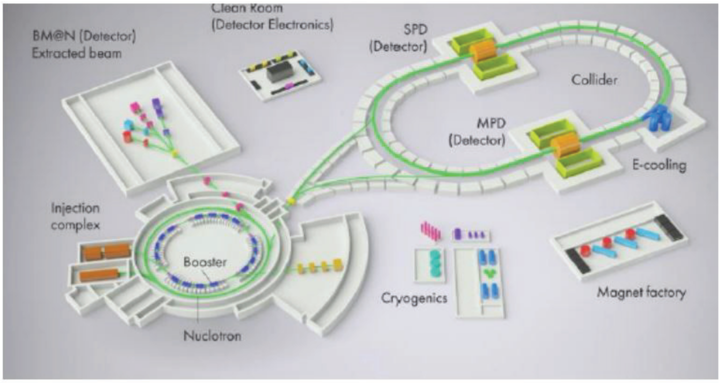

Fig. 35. NICA layout.

Radiobiology. The official start up of the construction was on 25 March 2016 and the full completion will be in 2022.

As for the NICA accelerators,[24] one has a Nuclotron and an ion collider. The main accelerator of the NICA complex is the Nuclotron — superconducting ion synchrotron at magnetic rigidity of about 42 T · m equipped with two injection chains: for heavy and for light ions. The NICA Injection chain for heavy ions consists of: the ion source (KRION-6N), heavy ion linear accelerator (HILac), superconducting booster synchrotron (Booster) and required beam transport lines. The injection chain for light ions includes: Laser ion source (LIS), Source of polarized ions (SPI), Duoplasmatron, RFQ accelerator as a foreinjector, Drift tube linac of Alvarec type

Table 3. NICA parametersc for Au.

Circumference of the ring (m)	503.04		
Structure of the bending arc	FODO, 12 cells		
Number of bunches	22		
R.m.s. bunch length (m)	0.6		
β-function in IP (m)	0.35		
Betatron frequencies, Q_x/Q_y	9.44/9.44		
Chromaticities, Q'_x/Q'_y	−33/−28		
Acceptance (πmmrad)	40		
Momentum acceptance, $\Delta p/p$	±0.010		
Critical energy factor, γ_{tr}	7.088		
Energy of 79 Au, GeV/u	1.0	3.0	4.5
Number of ions per bunch	2.0×10^8	2.4×10^9	2.3×10^9
R.m.s. momentum spread, $\Delta p/p$	0.55×10^{-3}	1.15×10^{-3}	1.5×10^{-3}
R.m.s. emittance, πmmrad	1.1/0.95	1.1/0.85	1.1/0.75
Luminosity, cm^{-2} s^{-1}	0.6×10^{25}	1.0×10^{27}	1.0×10^{27}
IBS growth time, s	160	460	1800

(LU-20) and required beam transport lines. The collider experiments will be provided at two storage rings with two interaction points (IP), with collider parameters shown in Table 3.

11. Summary

The invention of particle colliders has provided human beings efficient tools to explore the fundamental phenomena and rules of the universe of particles. By looking at the histories and the cultures created by pioneers and the scientists nowadays, we believe that more powerful colliders will be continuously built successfully to hunt in the unknown universe.

In this paper we recalled different kinds of colliders, and as for the key accelerator physics issues in electron–positron colliders and proton–proton colliders, they are summarized in another paper.[25]

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