HISTORY OF ACCELERATOR DEVELOPMENTS IN JAPAN

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Abstract

History of accelerators in Japan is extending for about seventy years from its genetic period in the 1930s. In the very early stage, our pioneers aimed at the cutting edge of nuclear physics and stood already a competitive stage. These advantages to be kept further were unfortunately destroyed completely by the World War II. On the other hand, various developments of accelerators themselves and related technologies had proceeded evolutionary in USA during that interruption. Since then, pursuing efforts have been continued for many years so far. In recent years, the level of accelerator technologies in Japan reached to an international level or some of them came to the front.

In this paper, some historical stories of accelerator developments in Japan are described, in author's personal prejudice, and all the names are cited without titles.

1 GENERAL BACKGROUND

In 1917, the RIKEN was established in Tokyo as a private institute for physical and chemical research. Fifteen years later, the Osaka University was established by collecting together many young and excellent scientists grown up at the RIKEN and other universities in 1932. The first president was H. Nagaoka who proposed the Saturn model of atom in 1904.

In the meantime, the big earthquake around Tokyo in 1923, the world's financial panic in 1929, the Manchurian Incident in 1931, etc. were the typical social events.

Concerning nuclear physics, discovery of deuterium by Urey, concept of neutron by Chadwick, proton-neutron configuration of nucleus by Heisenberg, discovery of positron by Anderson, truly artificial nuclear disintegration by Cockcroft and Walton, invention of cyclotron by Lawrence, all of these scientific events were presented in 1932, so called "Wunderliches Jahr". People thought with enthusiasm "the era of nuclear physics has come !" and thus both RIKEN and Osaka university became the two centers in Japan in early days of accelerators and nuclear physics.

2 BEFORE THE WAR II

2.1 RIKEN

In 1932, Y. Nishina constructed a Van de Graaff generator and obtained 600 kV. It was, however, too weak for Japanese humidity to be utilized for nuclear physics. In 1933, he constructed a Cockcroft-Walton generator and observed positron spectrum from artificial radioactivities by cloud chamber, and then started researches by D-D neutrons with R. Sagane et al.

In 1935, Nishina and Nishikawa groups were assembled as a laboratory of nuclear physics supported by several private companies and construction of the small cyclotron was started immediately, whose magnet was converted from a Poulsen arc magnet, similar to the case of the second cyclotron by E. Lawrence and M. Livingston, and had a diameter of 26 inches and a weight of 23 tons. The first beam of 3 MeV deuterons was obtained in April 1937, when the War of Aggression into China occurred.

This small cyclotron was actively used not only in nuclear physics but also in biomedical applications. Studies on beta-spectra of radioactivities with cloud chamber, radioactivities of thorium irradiated by neutrons for searching transuranic elements, fission products of thorium and uranium irradiated by neutrons, these were typical works in nuclear physics. At the same time, early biomedical studies were also carried out such as assimilation of sodium-24 by plants, genetic studies of irradiation of silkworm nits, leucopenia by irradiation and effect of pentose nucleic-acid, photosynthesis by using radioactive carbon.

In 1937, just after the completion of the small cyclotron, Nishina started the construction of a larger one. At that time, Lawrence was going to construct the 60 inch cyclotron, and he made another same magnet yoke of 200 tons for Nishina with his courtesy. After arriving at Japan, its pole face was machined at Ishikawazima Shipyard, and was installed at RIKEN in June 1938. The rf-system was still a lumped impedance type simply enlarged from that of the small one. This cyclotron was to accelerate 9 MeV protons. It was, however, not able to accelerate enough number of ions. The reasons of such performance were as follows: n-value at large radius was too high to accelerate, corresponding minimum dee voltage was much higher than of achieved, evacuation speed was too low to maintain vacuum pressure during acceleration, etc. Although the intensity was quite faint and unstable, its energy was even the world's highest one at that time. Notwithstanding the eagerness of many nuclear physicists to use its highest energy beam, Nishina did not agree and was going to improve its performance. T. Yazaki and others visited to LRL to learn how to improve, and were surprised at the completely different structure of rf-resonator and evacuation system. They got all of the blueprints with the courtesy of Lawrence and Cooksey. Soon, the Pacific War began in December, 1941. The rf- and vacuum- systems were newly made following to the design at LRL and then the proton beam of 9 MeV, 4μA was obtained in February, 1944. It was the last period of the War II. Any research in nuclear physics was not able to be done.

Radioisotope production for radioluminous paint, application of radioisotope to metallurgy, and then measurement of enrichment of uranium isotope and accumulation of basic data for utilizing atomic energy such as cross sections of neutron absorption and fission were barely performed till the end of the War II.

2.2 Osaka University

In 1933, S. Kikuchi moved to the newly established Osaka University from Nishikawa group at RIKEN as a fresh associate professor in order to open up the new field of nuclear physics. He built the advanced Cockcroft-Walton generator and competed with the group of E. Fermi in the researches with D-D neutrons. He and his group, H. Aoki and K. Husimi, carried out the measurement of gamma-ray energies and intensities on the inelastic scattering of fast neutrons with various kinds of nuclei, and also the similar measurements on the slow neutron capture. These experiments showed the earliest evidence indicating the "nuclear magic number" and were the excellent pioneering works of nuclear spectroscopy. At that time, they had only Geiger counter for observing gamma-ray energy.

In 1935, he made a plan of cyclotron construction and obtained a fund from a private science foundation. The construction was finished in 1938. This cyclotron had a diameter of 24 inches and a weight of 25 tons, and was able to accelerate deuterons of 5 MeV, 20μA. Researches were concentrated on the observation of radioactive products with a 180° focusing beta-spectrometer. Kikuchi and his co-workers, Y. Watase, J. Itoh, E. Takeda, and S. Yamaguchi, showed that the positron spectrum of nitrogen-13 agreed well with Fermi distribution, instead of Konopinski-Uhlenbeck theory. They also carried out the world's first experiment of the gamma-gamma angular correlation.

In 1940, besides, he began to construct a Van de Graaff generator enclosed in a pressurized tank, with Husimi and T. Wakatsuki, in order to make more precise experiment of neutron-nucleus interaction. This work was, however, interrupted by the War. This work was succeeded by K. Sugimoto later and produced successful results in a new field of nuclear solid-state physics.

2.3 Kyoto University

The third group was B. Arakatsu and his co-workers, K. Kimura and Y. Uemura. They had begun nuclear physics using a Cockcroft-Walton generator at Taiwan, in 1934. After moving to Kyoto University, they built the same machine again, in 1936, and carried out the studies on nuclear photo-disintegrations of various nuclei using high energy gamma-rays produced by lithium-proton and fluorine-proton reactions. Neutron breeding by fission of uranium and biomedical effects of neutrons were also studied.

In 1940, five years later than of RIKEN and Osaka University, they also started the construction of cyclotron. The magnet had a diameter of 39 inches and a weight of 80 tons. It was designed to accelerate deuterons up to 10 MeV. The social situation was, however, already very serious and Japan was going to rush headlong into the War. Progress of the construction became slower and slower. At the end of 1944, only the magnet was barely completed. It was almost the final stage of the War. The coil had never been installed.

3 AFTER THE WAR II

In August 1945, the War II finished and Japan was governed by the General Head Quarter of the occupation forces. In November of that year, the occupation forces destroyed the two cyclotrons at RIKEN and threw them away into the Tokyo Bay. It took more than five days to remove the bigger one. In December, the other two cyclotrons at Osaka and Kyoto universities were also sunk under the Osaka Bay. Thus all of experimental nuclear sciences including applications in Japan were forbidden.

Outside of Japan, on the other hand, various kinds of developments related to accelerators were carried out, such as discovery of the phase stability principle and successful constructions of synchrocyclotrons and synchrotrons, developments of proton and electron linear accelerators etc.

It is worthwhile to point out that J. Itoh and D. Kobayashi at Osaka University discovered the principle of electron microtron independently from the other authors in 1947.

3.1 Small Cyclotrons at RIKEN, Osaka Univ. and Kyoto Univ.

In 1951, Lawrence came to Japan suddenly. He visited RIKEN and inspected the remaining facilities including existence of another Poulsen arc magnet. In the meeting at the Science Council of Japan (JSC), he suggested strongly the reconstruction of cyclotron in a moderate size.

After many discussions among S. Kaya, S. Tomonaga, K. Husimi et al, both constructions of a small cyclotron (26 inches, 23 tons) by using another Poulsen arc magnet at RIKEN by a support of the Ministry of International Trade and Industry (MITI), and of another small one (44 inches, 45 tons) by using the remaining power supplies for magnet and rf-system at Osaka University by a support of the Ministry of Education, Science and Culture (MESC) were decided. At the same time, Kyoto University planned further to construct a small cyclotron (41 inches, 80 tons) by supports of private companies. These three small cyclotrons were completed during 1953 ~ 1955, through various kinds of severe difficulties in the ruin after the War.

The first one at RIKEN (by E. Tajima et al) was used not to nuclear physics but to produce short-life isotopes for medicine and to study radiation effect for highly polymerized compounds. The other two cyclotrons (Osaka cyclo. by Wakatsuki, Yamaguchi et al, Kyoto cyclo. by Kimura, Uemura et al) were used actively for various researches of nuclear structures and nuclear reactions for many years.

3.2 Establishment of INS

Following to the constructions of three small cyclotrons, nuclear physicists mainly around Tokyo were eager to have more advanced facility in Tokyo area which can produce mesons. After long and hot discussions in the related societies for more than two years, establishment of the new institute, which has internationally competitive big accelerators and is opened for the whole country, was finally proposed to the government by the JSC. Thus the new institute was established, being named the Institute for Nuclear Study (INS), University of Tokyo, in 1955. Kikuchi moved to INS as the first director. The first accelerator was decided as a 60 inch class cyclotron, according to the opinion of Kikuchi, and the second one was expected to aim at a class of meson production.

Concerning the design of the cyclotron, there were two kinds of the choice, classical- and synchro- cyclotron, and hot discussions were continued between Tokyo and Osaka groups. Final decision was the unique two-mode cyclotron, frequency-fixed (FF) and frequency-modulated (FM), with one magnet of 63 inches in diameter and 280 tons in weight. Careful design and model test of the magnet were carried out in order to prove the feasibility of widely variable field by H. Kumagai (described as Aoki at Osaka University previously), J. Sanada, K. Matsuda, S. Suwa et al. The FF was completed in 1957 and showed the new importance of variable-energy beams in nuclear physics. The FM was then completed in 1958 and opened up the new field of direct reaction. The new extraction mode at n=1 with an additional C-electrode realized high-duty beam and the world's highest extraction efficiency of synchrocyclotron for many years.

After starting the construction of 63 inch cyclotron, the high-energy physics division was assembled to start construction of the second accelerator above mentioned and Kumagai moved to the new division and S. Yamaguchi also moved to this division from Osaka University. Discussion was concentrated on the choice of proton or electron. Strong-focusing principle was already discovered. Final decision was the new strong-focusing electron synchrotron in order to build up high-energy accelerator technology but not to utilize in high-energy physics, and therefore it was not planned any experimental hall at that stage. Construction of this machine (ES) was completed in 1962 as the third strong-focusing electron synchrotron and accelerated energy was 750 MeV at that stagy. In 1966, this machine was upgraded to 1.3 GeV.

In 1963, very early stage of the researches by use of synchrotron radiation (SR) from the ES was initiated. Later in 1975, the dedicated SR-ring (400 MeV) was installed as the world's first one. These ES and SR-ring were well utilized for many years even after establishment of the National Laboratory of High Energy Physics (KEK) in 1971. On the other hand, T. Tomimasu constructed several SR-rings (TERAS, NIJIs) at the Electro-Technical Laboratory (ETL), independently from the nuclear physics society. These machines developed Free Electron Laser (FEL) oscillation successfully.

3.3 Developments of Tandem Van de Graaff

As was mentioned above, the researches with INS cyclotron showed the importance of variable energy beams, and particularly implied the existence of isobaric analog resonances. For such the nuclear spectroscopy, Tandem Van de Graaff has an advantage of precise change of its energy. In the 1960s, both Tokyo and Kyoto Universities installed Tandem Van de Graaffs. Performances of these machines were, however, not so sufficient. Sometime, A. Isoya found an insulator belt set up with many big staples when he had been to the laboratory of H. Herb at Wisconsin University from INS. He imagined immediately a pellet-chain for previously used insulator belt. After various kinds of trials, he installed his developed pellet-chain and accelerating tube into the working machine at Kyusyu University, which was also built by himself, as the world's first case. His contributions to Van de Graaff technology are highly appreciated so far.

Tandem machine has also another advantage in heavy-ion acceleration. Because of beam quality and capability of heavy-ion acceleration, tandem machine had not made over the principal role not only in nuclear physics but also in application to cyclotron for many years.

3.4 At Tohoku University

As was mentioned above, the strong-focusing principle was discovered in 1952. Only a few weeks later, T. Kitagaki from Tohoku University, who constructed the smallest betatron (r=3.2cm, 1.5MeV) at Osaka University in 1950 and electron synchrotron (40MeV) at Tohoku University in 1954, proposed to separate the function of focusing and bending in a synchrotron orbit by using alternating quadrupole lenses in straight sections between dipole bending magnets (Separated Function type), and gave the parameters for a 100 GeV proton synchrotron. He also proposed the advantage of cascade-stage synchrotrons comparing with single stage to accelerate to higher energy. These ideas were realized firstly at the FNAL 500 GeV synchrotron in 1972, indeed. The second one is the KEK-PS (12 GeV), in 1976. The design of separated function in synchrotron or storage ring is now quite common, and the previous combined function is rather special.

In the 1960s, M. Kimura and Y. Torizuka constructed an electron linac (300 MeV) for nuclear physics at the Laboratory of Nuclear Science, Tohoku University. Although nuclear physics society did not agree to the process to get the fund of construction, unfortunately, that machine contributed to produce very interesting results in photo-nuclear reaction for many years.

3.5 AVF (SF) Cyclotron at INS and RCNP

All of the cyclotrons above mentioned were so-called classical ones, although many sector-focusing ones had already been constructed successfully in the world. The first one in Japan was the INS-SF cyclotron (K=68), started the construction from 1969. One year later, Osaka University was approved to establish the Research Center for Nuclear Physics (RCNP) and to construct bigger AVF cyclotron (K=120). Constructions of these two AVF cyclotrons were completed at almost same time in 1973 as the two central facilities for nuclear physics researches in Japan for many years. Capabilities of the latter machine by M. Kondo, I. Miura et al and the related high-resolution experimental systems by H. Ikegami have been particularly highly appreciated in the world.

3.6 Ring Cyclotron at RIKEN and RCNP

Kumagai and K. Matsuda moved to the new RIKEN at Wako-shi, and in 1966, construction of the similar as of INS but much improved machine of only the FF mode (84 inches, 340 tons) was completed which was able to accelerate not only light ions but also heavy ions to extend the researches to many other fields including various applications. This machine initiated the field of "heavy ion science".

Based on the experiences of the variable frequency cyclotron above mentioned, M. Odera constructed the unique heavy ion linac (RILAC) at RIKEN, in 1975, which has similar rf-resonator of wide frequency range as of the cyclotron but, of course, without bending magnet. After completion of RILAC, the large ring cyclotron of radial-sector type for heavy ion (RRC, K=540) was constructed by H. Kamitsubo in 1986 which was injected heavy ions from RILAC. Later, another injector of AVF cyclotron with ion source of axial injection type was added.

A few years later than RRC at RIKEN, I. Miura also constructed the spiral-sector ring cyclotron (K=450) at RCNP which is injected from the previous AVF cyclotron, in order to upgrade capability in light ion nuclear physics.

3.7 Establishment of KEK

After construction of the ES at INS, the related societies had discussed continuously the third high-energy hadron accelerator of 50 GeV class from 1962 to 1970, and the study group for proton synchrotron was assembled at INS in 1964. On the other hand, among JSC, MESC and related societies, various kinds of serious discussions about necessity, scale and organization etc. of the future project had been continued. On the final stage, Hushimi proposed the compromise plan of 1/4 reduction of budget. After tedious discussion for one year, the new institute KEK was finally established to construct 12 GeV PS, in 1971. The first director general and director of accelerator division were S. Suwa and T. Nishikawa, respectively. This National Laboratory has grown up the biggest center of accelerator developments in Japan.

3.8 Developments at the Last Stage of INS

After establishing RCNP and KEK, INS itself planned the high-energy heavy-ion synchrotron (NUMATRON) project in 1977. At that time, there were several important items to be proved the feasibilities such as of heavy-ion injector linac, multiturn-injection, wide-range rf-system, low-intensity online beam monitor, ultra-high vacuum etc. Various kinds of R&D for these items were carried out such as ECR ion-source, RFQ linac (LITL, TALL), IH linac, heavy-ion storage ring (TARN), heavy-ion cooler synchrotron (TARN II) etc. Successful results of low-energy ion cooling, stochastic- in TARN and electron beam- in TARN II, stimulated a world's trend of cooler ring constructions. The latter TARN II achieved not only successful result of R&D, but also the interesting results of molecular physics to open up a new field. Although the project itself did not be realized, most of the results in these R&D are successfully utilized in the medical heavy-ion synchrotron (HIMAC) at the National Institute of Radiological Sciences (NIRS) and many other future projects such as of RIKEN.

4 NOWADAYS

After construction of KEK-PS, many large accelerator projects were carried out or are going on, such as Photon Factory, TRISTAN and KEKB at KEK, Ring Cyclotron at RCNP, RRC, ISR, SRC and MUSES at RIKEN, SPring-8 at Harima Science City, HIMAC at NIRS, High-Intensity Proton Accelerator for Neutron Science at JAERI combined with JHF project at KEK etc. Related to these projects, various kinds of technology developments were evolutionally performed.

In contrary with such the large projects, strong needs of small facilities in various fields of applications are growing up, particularly in medical applications. For this purpose, several developments are going to start. One of such the R&D is being progressed by Y. Mori at KEK, which is an FFAG (Fix Field Alternating Gradient) synchrocyclotron to accelerate protons in a small size. The FFAG was formerly proposed by C. Ohkawa at University of Tokyo in 1953, at almost the same time as of the strong focusing. These ideas stimulated the revival of the Thomas theory of cyclotron in 1938 and then many AVF and ring cyclotrons have been constructed. However, the FFAG machine itself has never been realized except small electron model so far. But, most of these developments are ongoing items and are not a kind of history to be described in this paper.