STATUS OF ACCELERATORS IN JAPAN

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Abstract

Accelerator-based nuclear physics in Japan began in 1934. The Institute for Nuclear Study(INS) which was a symbol of the "renaissance" age was established as a common use laboratory in 1955. The "modern" age began with construction of a 12GeV proton synchrotron at KEK and an AVF cyclotron at RCNP in 1971. A 20MV tandem accelerator at JAERI, an electron positron collider TRISTAN which is now being converted to KEKB at KEK, ring cyclotrons at RIKEN and at RCNP, heavy ion therapy synchrotron HIMAC at NIRS, synchrotron light sources KEK-PF and Spring-8 are typical examples of modern large accelerators. There are also many small or moderate size accelerators for different fields. For example, about 60% of 1000 accelerators in Japan are electron linacs for medical use. There are also many compact cyclotrons for isotope production, some proton therapy accelerators and compact synchrotron radiation sources. On the other hand TARN II as an electron cooler ring at INS (now KEK-Tanashi) is an excellent example of advanced beam science and technology. A few projects may proceed at RIKEN, KEK and JAERI. But in the next century we will be in the "global" age.

1 INTRODUCTION

Two Cockcroft -Walton accelerators of Japan were completed by Prof. Arakatsu of Taihoku University and a few month later Prof. Kikuchi of Osaka University in 1934. In 1937 Dr. Nishina of RIKEN, a father of Japanese quantum physics completed a small cyclotron and then began to construct a large cyclotron with help of Prof. Lawrence. Prof. Kikuchi and later Prof. Arakatsu who moved from Taihoku University to Kyoto University also began to construct cyclotrons at Osaka and Kyoto, respectively. The Nishina laboratory of RIKEN was a leading one in this " Heroic" age of Japanese accelerator history.

But it was interrupted by the war. Immediately after World War II in 1945 all these cyclotrons were destroyed by the occupation forces and Japanese nuclear physics was stopped. It was the "Dark and Middle" age. In 1951 Prof. Lawrence came to Japan to encourage Japanese nuclear physicists and he recommended to the General Head Quarter of Allied Forces that Japan should re-start fundamental nuclear physics. Then the cyclotrons were re-constructed at RIKEN, Osaka University and ICR, Kyoto University. The "Renaissance" age began.

A leading laboratory of the "renaissance" age was the Institute for Nuclear Study (INS), University of Tokyo which was established as a common use laboratory in 1955. Many physicists came from RIKEN, Osaka University and Kyoto University to INS to construct a variable energy cyclotron and an electron synchrotron. In this age some betatrons, electron linacs and Van de Graaff accelerators were also constructed at different universities.

Table 1. Number of accelerators in Japan (as of March 31, 1997)[1].
Electron accelerators with energy less than 1MeV are omitted.

Accelerators	Total	Hospitals & Clinics	Educational Organizations	Research Institutions	Industrial Firms	Other Organizations
Total	1051	673	55	155	162	6
Cyclotrons	52	17		16	18	1
Synchrotrons	25		2	18	5	
Linear Accelerators	759	624	7	44	81	3
Betatrons	14	10		1	3	
Electrostatic Accelerators	52		15	26	11	
Cockcroft-Waltons	97		27	33	35	2
Transformer-type	23		1	17	5	
Microtrons	29	22	3		4	

In 1971 KEK for high energy physics and RCNP, Osaka University for nuclear physics were established. Both are common use laboratories, and KEK is the first Monbusho (Ministry of Education, Science, Sports and Culture) national accelerator laboratory which is independent of the university. It was the beginning of the "Modern" age. The KEK has become the leading laboratory in this age. Many "modern" accelerators have been built for many purposes up to now.

At present there are more than a thousand accelerators in Japan as listed in table 1 where electron accelerators with energy less than 1 MeV are omitted[1]. We can see that about 60% of Japanese accelerators are electron linacs for radiation therapy at hospitals. Numbers of accelerators for medical and industrial use are growing up while accelerators for fundamental science are concentrated in a few big laboratories.

In the following sections status of major "modern" accelerators in Japan is briefly reviewed[2]. Details are discussed elsewhere in these proceedings.

2 BIG ACCELERATORS

TRISTAN was an electron positron collider at KEK for quark physics. It is now converted to a high-luminosity B-factory, KEKB which consists of an 8GeV electron and a 3.5GeV positron rings. The injector linac is also modified for full-energy injection to the rings. Construction and design study of KEKB are done with international collaborations. It will be operated in this year.

An old 12GeV proton synchrotron at KEK will be supposedly shut down when JHF (Japan Hadron Facility) project will be funded. But at the moment it plays still important roles in the fields of high energy physics, nuclear physics, material science and bio-medical science. A unique project with this synchrotron before the shut-down is a neutrino oscillation experiment in collaboration with Super-KAMIOKANDE which is an underground detector for cosmic neutrino located at Gifu prefecture 250km away from KEK. The synchrotron is being improved for high intensity beam acceleration and fast beam extraction to make this experiment. Fast kicker magnets will be installed in the next year.

SPring-8 (Super Photon ring 8GeV) at the Harima Science Garden City which is the world highest-energy third-generation synchrotron-radiation light source was opened to users in October 1997. This facility has been constructed by a joint group of JAERI (Japan Atomic Energy Research Institute) and RIKEN (Japanese name of IPCR:Institute for Physical and Chemical Research) and operated by the newly-established JASRI (Japan Advanced Synchrotron Radiation Institute). All these Institutes are supported by STA (Science and Technology Agency of the government).

On the other hand KEK-PF which is a 2.5GeV storage ring constructed in 1982 is being modified to another third generation light source. The beam emittance was once improved from 460nm-rad to 130nm-rad in 1986. And the goal of the present improvement of the emittance is 27nm-rad which can be obtained by additional focusing magnets. The brilliance is also improved to 10^{18} photons /sec /mm^2/ mrad^2/ 0.1%b.w..

HIMAC (Heavy Ion Medical Accelerator in Chiba) at NIRS (National Institute for Radiological Science) of STA was completed in 1993 and the clinical trials were started in 1994. The HIMAC which consists of two identical 800MeV/u synchrotron rings and an injector linac accelerates at the moment mainly carbon ions for therapy because of good concentration and biological effect. A unique RF knock-out method is applied for high-quality slow-extraction of the beam synchronized with respiratory motion of a patient. The accelerator is also used for basic research and development at night. One of the unique developments in progress is ^{11}C beam production by projectile fragmentation of carbon beam. The ^{11}C can be used as an RI source for PET. Therefore the high energy ^{11}C beam plays two roles simultaneously of irradiation of the tumor and detection of the irradiated point.

The K=540 RIKEN ring cyclotron also accelerates heavy ions for nuclear physics and other applications. Many exotic nuclei like extremely neutron rich nucleus have been discovered by this cyclotron. Thus the next step is reasonably determined to become the RI beam factory. The first phase of the project which is the construction of two-cascade super-conducting ring-cyclotron system is already funded. The existing ring cyclotron will be used as an injector of the super-conducting cyclotron.

On the other hand the K=400 RCNP ring cyclotron accelerates mainly proton and light ion beams with very high energy resolution. Nuclear physicists can obtain high quality spectra with resolution of 10^4 by using the cyclotron and an excellent spectrograph Grand RAIDEN. A unique temperature regulation method has been developed to stabilize high quality beam. An injector cyclotron constructed early 70's has been also improved for high reliability.

3 TANDEM ACCELERATORS

At JAERI-Tokai a super-conducting linac is working as an energy booster for a 20MV pelletron tandem accelerator. The maximum accelerating energy of the linac is 30MeV/q. High energy nuclear spectroscopy experiments with high resolution are performed by using this system.

Tsukuba University 12MV tandem accelerator has also a small booster linac with energy of 2MeV/q.

Two tandem Van de Graaffs of Kyoto University and University of Tokyo have been replaced by pelletron tandems though the original high pressure vessels are again used in both cases. The terminal voltages have been improved from 5MV to 8MV for Kyoto and from 5MV to 6MV for Tokyo.

The laboratory of Kyushu University 10MV pelletron tandem which is a unique high-gradient field home-made machine works as an accelerator center of Kyushu area.

These modern tandem accelerators have been constructed originally for nuclear physics but recently they are applied for not only nuclear physics but also many other fields such as AMS ^{14}C dating. And many small tandems have been constructed for material science and in particular element analysis, for example, Rutherford backward scattering or PIXE with micro beam.

4 CYCLOTRONS

Besides the RIKEN and RCNP ring cyclotrons there are many cyclotrons in Japan. At JAERI-Takasaki a K=110 AVF cyclotron of TIARA (Takasaki Ion Accelerators for Advanced Radiation Application) works for material science, bio-technology and so on in combination with other small accelerators.

The INS SF-cyclotron is now operated by CNS (Center for Nuclear Study), University of Tokyo, because a few divisions have remained with the cyclotron at the University when INS and KEK (national laboratory for high energy physics) have merged to become the new KEK (high energy accelerator research organization) in 1997. The CNS cyclotron still injects the beam into the electron cooler ring TARN II which belongs now to the new KEK-Tanashi.

The TARN II was originally constructed to study of the design of a heavy ion synchrotron for nuclear physics project NUMATRON. Unfortunately the project was not funded. But the TARN II has been effectively used for design study of HIMAC and is now operated for accelerator and beam physics. One of the excellent experiments of the beam physics with the TARN II is precise observation of dissociative recombination (DR) of the molecular ion $^4HeH^+$ with the ultra cold electron beam whose initial transverse temperature of 100meV is reduced to the order of 1meV by changing the electron guiding field from 3.5T to 35mT with a superconducting magnet as an adiabatic expansion device.

Cyclotrons for isotope production are operated at universities, companies and hospitals. Tohoku University Cyclotron and Radioisotope Center (CYRIC) has operated an AVF cyclotron, which will be replaced by a new larger one. The construction of the new cyclotron begins since this year. But a small cyclotron is enough to produce RI for PET in hospital. Therefore Tohoku University will continue RI production for PET by another compact cyclotron during the construction of the new larger cyclotron because needs for PET RI is very high. In fact there are 31 PET facilities in Japan as of November 1997. On the other hand some cyclotrons produce positron emitters such as ^{27}Si which is used as a positron beam source for material science though some electron linacs are also used for production of high intensity positron beam.

5 LINEAR ACCELERATORS

The first modern linear accelerator for nuclear physics in Japan is the 300MeV Tohoku University electron linac. It has been also used for accelerator physics. For example coherent radiation from the electron beam was discovered by this linac. On the other hand the pulsed beam is not convenient for recent nuclear physics. Therefore a stretcher and booster ring, STB with highest energy of 1.2GeV has been recently attached after a long term experience of a small stretcher ring. The commissioning of STB has been started since November 1997.

There are some other electron linacs for radiation physics, for examples, a 150MeV S-band and a 38MeV L-band linacs at ISIR, Osaka University, a 45MeV linac at Hokkaido University, a 10MeV PNC-OEC quasi-cw linac for transmutation study in collaboration with Nihon University, a 46MeV L-band linac as a neutron source at KURRI, Kyoto University, the 35MeV twin-linac at NERL, University of Tokyo, a 500MeV ETL linac and a 100MeV linac at ICR, Kyoto University. Some other linacs are used as injectors for SR or FEL, which is discussed in the next section. As mentioned above most accelerators in Japan are electron linacs at hospitals. There are also many industrial electron linacs for non-destructive inspection and radiation processing.

On the other hand ion linacs are not so many. At KEK, NIRS and RIKEN there are injector linacs of 40Mev protons, 6MeV/u ions and 3MeV/u ions, respectively. A 30MeV/q super-conducting linac at JAERI is a booster of the tandem as mentioned above. A 7MeV RFQ-DTL of ICR, Kyoto University, A 5MeV RFQ-DTL of KEK and a 2MeV RFQ of JAERI are all proton linacs for accelerator physics or test stand of future projects. At RLNR, Tokyo Institute of Technology a few small ion linacs have been constructed for material science. The maximum energy of the RLNR linacs is 3.4MeV/u. Their accelerating structures are IH (Inter-digital-H) and RFQ. Numbers of linacs for MeV-ion implantation are working at industries.

A linac system composed of a 25.5-MHz split coaxial RFQ (SCRFQ) linac and a 51-MHz IH linac has been completed at INS and is now in operation at the new KEK-Tanashi. This linac has been developed as a prototype of the ISOL post accelerator for E-arena of Japan Hadron Facility (JHF) project. The $^{19}Ne^{2+}$ ion beam whose half life is 17.3sec has been successfully accelerated. The maximum energy of the system is 1.05MeV/u.

6 SR AND FEL

Recently the accelerator-based photon source has been much developed. The first synchrotron radiation (SR) ring in Japan is the SOR ring of ISSP, University of Tokyo which is attached to the INS electron synchrotron and is still in operation though it will be shut down in the near future. The UVSOR of the Monbusho-national Institute for Molecular Science (IMS) is an SR ring at a region of UV light.

A few SR rings have been developed at ETL of MITI (Ministry of International Trade and Industry). They are an 800MeV ring TERAS for SR research, a 600MeV ring NIJI II for SR processing and 500MeV ring dedicated to free electron lasers.

Some SR rings have been constructed for lithography in the semiconductor processing by some companies though they are not so widely used in the actual processing up to now. For example SORTEC was established for the SR processing as a joint venture of several companies encouraged by MITI. But it could not be continued to maintain the operation by the joint venture. Fortunately the main part of the machine has been transferred to Thailand.

On the other hand same size SR rings are in operation in the field of basic research and development at universities or individual industries. Typical examples are the Ritsumeikan University SR which consists of a compact super-conducting solid-pole ring as an accelerator and storage ring and the Hiroshima University SR which is a room temperature race truck ring. In both cases microtrons are used as the injectors. The Sumitomo-Electric NIJI-III ring which was originally constructed to be attached to the ETL linac was transferred to the laboratory at the Harima Science Garden City where a 120MeV linac has been constructed as a new injector. The low energy section of the linac is also operated as an injector for free electron laser (FEL). Sumitomo Heavy Industries, Mitsubishi Electric and NTT are also operating their constructed SRs at their laboratories.

Recently HIT (Himeji Institute of Technology) of Hyogo prefecture is also constructing a storage ring for basic science at the Spring-8 site of the Harima Science Garden City. This 1.5GeV ring, New SUBARU is attached to the injector linac of SPring-8. The unique feature of the lattice structure of this ring is its momentum compaction factor varying from +0.0012 to -0.001.

The first lasing of FEL at the SR ring in Japan was made by TERAS of ETL in 1991. The shortest wavelength of 239nm has been obtained by UVSOR of IMS. On the other hand a few linac-based FELs have become in operation. Two dedicated FEL facilities based-on linacs have been constructed. One is the facility of FELI which has been established as a joint venture laboratory partially funded by MITI. The other is SCARLET of JAERI. The FELI laser is driven by a 165MeV room-temperature S-band electron linac. Since the first lasing in December 1995 FELI has provided excellent photon beams with shortest wavelength of 278nm to users in many fields. However the financial support by MITI to this joint venture project has been finished like SORTEC. It is MITI's policy to initiate the new technology for industries. The cooperating companies of FELI are looking for a successor to continue the operation of FELI. Meanwhile the SCARLET of JAERI which is a laser driven by a 23MeV super-conducting linac with operating frequency of 500MHz has recently realized its stable lasing. Nihon University and Science University of Tokyo are also promoting to construct the compact linac-based FELs.

7 PARTICLE THERAPY

The pioneer work of the particle therapy by cyclotron began at NIRS in 1975. Fast neutrons and protons have been used for cancer treatments. The results for fast neutron therapy was not so excellent and the energy of the proton beam was not enough for treatment of thick tissue. Higher energy proton therapy has been begun at the Tsukuba University with proton beams from the 500MeV booster synchrotron of the 12GeV KEK proton synchrotron. After evaluations for the next dedicated machine Japanese radiologists chose a heavy ion synchrotron as the first priority machine. Thus the HIMAC project started.

But the HIMAC is a very expensive big machine, which is not suitable for a usual hospital. According to the experience of HIMAC, the carbon beam is preferable for therapy. Therefore Hyogo prefectural government has decided to construct a smaller synchrotron which accelerates heavy ions up to carbon for therapy at Harima Science Garden City. The building and the accelerator are under construction. Meanwhile Fukui prefectural government has established the Energy Research Center Wakasa Bay where a 200MeV proton synchrotron with a multi-purpose tandem accelerator as an injector will be applied for proton therapy. The facility will be completed in this year. At Shizuoka prefecture a proton therapy synchrotron is also under construction. These prefectural projects are partially supported by STA. Some other prefectural governments are also thinking to construct particle therapy accelerators.

On the other hand some universities such as Tsukuba University, Kyoto University and Osaka University have planned the construction of dedicated particle therapy accelerators but Monbusho could not fund all projects. Quite recently Tsukuba University has fortunately got Monbusho's financial support to construct a dedicated proton therapy synchrotron. At Kyoto University the ICR accelerator group has studied a combined function compact synchrotron for the medical group in collaboration with a company. A unique multi-feed untuned RF cavity has been developed by this accelerator group. This principle is applied to the Wakasa Bay and Tsukuba University synchrotrons though the Kyoto University project is not yet funded.

Epoch making decision was done by Ministry of Health & Welfare (MHW). The east hospital of National Cancer Center (NCC) of MHW suddenly began construction of proton therapy facility. The 230MeV compact cyclotron has been recently completed. The commissioning of the cyclotron system is in progress. MHW's beginning of the proton therapy will give a great impact to advanced hospitals.

8 ACCELERATOR AND BEAM PHYSICS

In the "Renaissance" age the nuclear experimentalists constructed their accelerators by themselves at many universities. But in the "Modern" age the accelerators for high energy and nuclear physics are concentrated in a few large national laboratories, while the small accelerator comes to be purchasable. Then the accelerator physicists have also gathered to the large national laboratory like KEK, RIKEN, NIRS, JAERI and JASRI. They are mainly involved to their own present or future project. One of the most active accelerator physics groups related to the future project is the KEK-ATF group which has developed the ATF (Accelerator Test Facility) ring for the future linear collider project, JLC.

On the other hand accelerator groups at the universities are diminishing though some accelerator physicists are still working at a few universities. An excellent example is the above mentioned TARN II experimental group at the former INS, University of Tokyo. The beam physics which is not necessarily related to the real large project is important as a fundamental physics at universities for research and education.

Recently some accelerator and beam physicists not only at universities but also at large national laboratories have started to promote fundamental beam physics in Japan. Topics at their symposia are beam halo formation, three dimensional laser cooling, wake field acceleration and so on.

JAERI-Kansai newly established at Kyoto prefecture is promoting photon beam science. A division of the JAERI-Kansai is constructing a test facility for laser-plasma wake-field acceleration. Preliminary experiments have been done by a joint group with KEK and a few universities. This laboratory is one of the hopeful trials if it is well organized in collaboration with universities.

9 IN THE FUTURE

After termination of NUMATRON project the Japanese nuclear physicists have proposed to construct a high intensity proton accelerator as a "future project" of the INS. Thus INS and KEK have merged to become a new KEK in 1997 to realize this project, JHF. The proposed accelerator system of the JHF consists of a 200MeV linac injector, 3GeV rapid cycling booster synchrotron and 50GeV main synchrotron. JAERI is making design study of a 1.5GeV high intensity proton linac as a spallation neutron source. This may be a future up-grade version of N-arena of JHF. There are some other large "future projects" at some laboratories such as the linear collider (JLC) at KEK, electron-ion colliding rings at RCNP, the second phase of RI beam factory MUSES at RIKEN, an accelerator-based hybrid reactor at KURRI (Kyoto University Research Reactor Institute) and so on.

Meanwhile Japanese economics becomes worse. The restructuring of the government has been recently decided by the diet. Monbusho and STA will merge into a new ministry in 2001. Some institutes or some projects will be re-organized. And very large projects like linear collider could not be realized by one country.

Without the economic problem we will make much more worldwide collaborations to promote accelerator science and technology in the 21st century. In the next century we must be in the "post-modern" or "global" age.

10 REFERENCES

[1] 'Statistics on the Use of Radiation in Japan', published by Japan Radioisotope Association, 1997.

[2] Information of Japanese accelerators is also obtained in the articles presented at the Japanese accelerator symposium which is held every two years. The latest one was held in October 1997 and the papers of this symposium are published on the 'Proceedings of the 11th Symposium on Accelerator Science and Technology, Spring-8, Harima Science Garden City, Japan,1997'.