CYCLOTRONS AND FFAGS: FROM NISHINA'S PIONEERING WORK TO RI-BEAM FACTORY*

Michael Craddock, University of British Columbia and TRIUMF, Vancouver, B.C., Canada

Abstract

The first cyclotron to operate outside the USA was built by Yoshio Nishina's group at RIKEN (1935-7). It was quickly followed by three more Japanese machines, establishing a tradition that has produced many important research cyclotrons, culminating in the world's most powerful - the superconducting SRC at the RIKEN RIBF. Moreover, technology transfer has enabled Japanese industry to produce and sell numerous smaller cyclotrons around the world, mostly for isotope production. Japanese scientists have also led the development of Fixed-Field Alternating-Gradient (FFAG) accelerators - from the first suggestion by Ohkawa in 1953 to Mori's construction of the first proton FFAG in 2000. This leadership has continued with the latter's recent pioneering studies of ADSR using a 3-ring FFAG complex to drive the KURRI reactor, and investigations of novel non-scaling FFAGs by ex-members of his team..

INTRODUCTION

First I must thank the organizers of these special lectures for granting me the privilege of speaking about Dr. Nishina's work in pioneering cyclotrons in Japan, and about how those scientists who were inspired by him have not merely continued that tradition but led Japan to a position of accelerator leadership today. Secondly, I must acknowledge my debt to previous writers on the history of Japanese cyclotrons, particularly Dr. Yasuo Hirao, whose invaluable 1986 article [1] I have plagiarized shamelessly. Other useful accounts are those by Kim [2], Low [3] and Heilbron and Seidel [4].

The story of cyclotrons in Japan is an impressive one, beginning with Dr. Nishina's 26-inch cyclotron and culminating, for the moment at least, in the huge superconducting ring cyclotron for RIKEN's RadioIsotope Beam Factory. Nor has this success been confined to the academic sphere: part of RIKEN's mandate was to transfer technology to industry – and indeed Japanese companies have been among the most active in building commercial cyclotrons for industry and medicine.

I have included Fixed-Field Alternating-Gradient (FFAG) accelerators in this talk both because they are members of the cyclotron family of fixed-magnetic-field accelerators (McMillan [5]), and because of their very strong links with Japan. The first suggestion for an FFAG was made in 1953 by Tihiro Ohkawa [6], who had once worked in Nishina's lab. Then 10 years ago, Yoshiharu Mori [7] was the first to build a proton FFAG – and later went on to build the 3-ring FFAG complex at the Kyoto University Research Reactor Institute – currently carrying out tests of Accelerator-Driven Subcritical Reactor operation (ADSR) [8].

CLASSICAL CYCLOTRONS

Cyclotrons, of course, began at Berkeley in 1930. Ernest Lawrence's invention revolutionized nuclear physics at that time, promising the capability of reaching unlimited energies for the study of nuclear structure and reactions - and of doing novel research in biology and medicine with artificially produced isotopes. Figure 1 shows Lawrence and his student Stanley Livingston standing inside the magnet yoke of what was at first a 27-inch-diameter-pole cyclotron, later enlarged to 37 inches. Note the characteristic shape of that magnet because we will come across several more examples later on. Many such magnets had been built for Poulsen Arc radio-wave generators in the days before tubes became available.

Figure 1: Lawrence (right) and Livingston with the 27-inch (later 37-inch) cyclotron.

Anyhow, as we heard in the first talk, Yoshio Nishina had been in Europe for most of the 1920s, working on a variety of topics, mostly as an experimenter, but also in theory, first with Rutherford, and then successively with Born, Bohr and Pauli. When he returned to RIKEN at the end of the decade, fired up with enthusiasm for modern physics, he was given his own laboratory and started an ambitious research programme with groups in quantum theory, cosmic rays, nuclear physics and radiobiology.

By 1935, Nishina had acquired sufficient funding to build a cyclotron of his own. As you can see from the shape (Figure 2), it was again based on a Poulsen Arc magnet. With advice from Lawrence and the experience gained by his assistants, Yasaki and Sagane, whom he had sent to Berkeley, it was brought into operation [9] by April 1937 – the first outside the US - a remarkable achievement considering how well established all the European laboratories were.

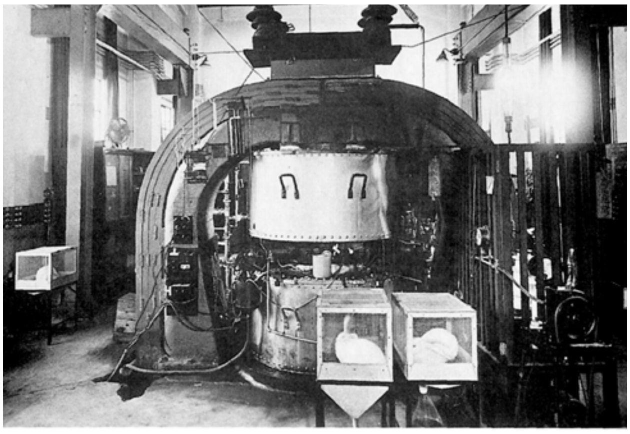

Figure 2: Nishina's 26-inch cyclotron. The two boxes in front contained rabbits for radiobiological experiments.

But hardly was the paint dry on this machine than Nishina was planning a larger one. Indeed, as experiments began he was already ordering parts for a 60-inch cyclotron, just as Lawrence was in Berkeley. Truly a man built in the Lawrence mould! Again, there was close collaboration with Berkeley, with Lawrence ordering two magnets, hoping to make both less costly, and also some other parts that were less expensive to produce in the US. Thus Nishina had a very early start on building this large cyclotron (Figures 3-5).

Figure 3: The 200-ton magnet for the 60-inch cyclotron, with Dr.Nishina (centre) and staff (1938).

This came into operation for the first time in 1939 producing 9-MeV protons, a world record for a brief period, though with very low beam intensity. In fact, some major redesign was needed, and with wartime shortages and the Berkeley link broken, it was only in 1944 that the intensity was raised to 4 μA, and then quickly to 180 μA of protons and 350 μA of deuterons, enabling a full experimental program to begin [10].

But that success was cut short by the end of the Second World War. In November 1945, the US Secretary of War, prompted by General Groves, authorized the destruction of all the cyclotrons in Japan: both cyclotrons were dumped into Tokyo Bay. Subsequent protests by Compton and other US scientists led to the Secretary of War's admission that it was a mistake – cold comfort for RIKEN scientists!

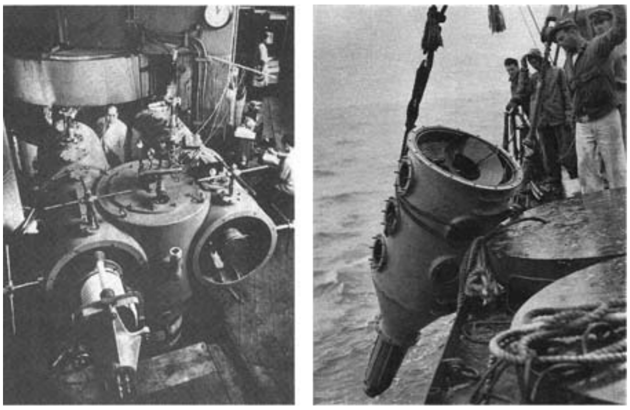

Figure 4: (Left) The 60-inch cyclotron's two dee stems – quarter-wave resonators supporting the dees – with Dr. Nishina standing between them. (Right) One of the dee stems is consigned to Tokyo Bay – a sad day for physics.

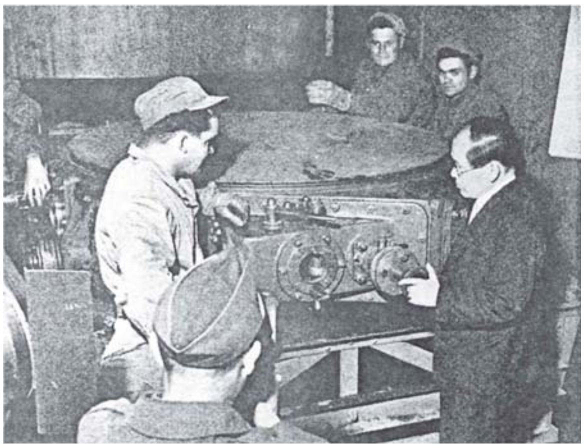

Figure 5: Dr. Nishina pleads with the dismantling team: "This is ten years of my life - it has nothing to do with bombs" [11] - but to no avail.

Besides RIKEN, Osaka and Kyoto Universities had also built cyclotrons. Seishi Kikuchi, originally from RIKEN, had moved to Osaka and also obtained funds for a cyclotron in 1935. Figure 6 (left) shows his 24-inch machine, which in 1938 was producing 20 μA of 5-MeV deuterons. At Kyoto, they were a little later, starting construction of a rather larger 39-inch cyclotron in 1940. But only the magnet (Fig. 6 (right)) was complete by the end of the war. Both cyclotrons were consigned to Osaka Bay.

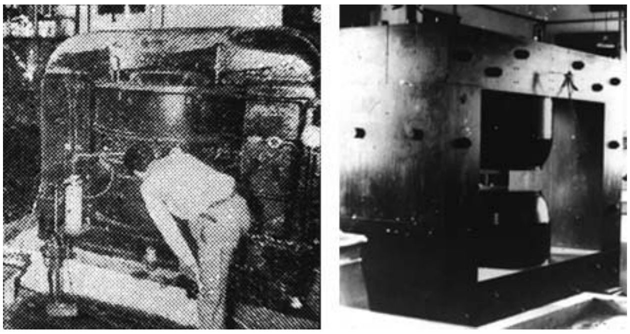

Figure 6: (Left) The Osaka 24-inch cyclotron. (Right) The Kyoto 39-inch magnet.

Although the Japanese machines had been destroyed, the experience gained with them had produced a generation of knowledgeable cyclotron physicists and engineers, ambitious to continue their research. But post-war conditions were economically difficult (Figure 7 (left)) and it was not until the 1950s that the three centres were able to begin construction. Figure 7 (right) shows the most ambitious, Osaka's 44-inch cyclotron, completed in 1954. This machine was notable for having been submerged in a 1961 typhoon, after which it was moved from downtown to a hilltop location.

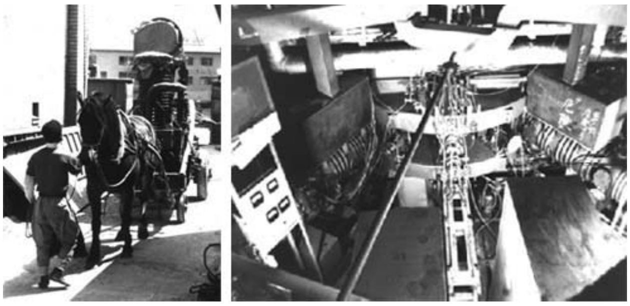

Figure 7: (Left) Diffusion pump transport, Osaka, 1953. (Right) The 44-inch Osaka cyclotron.

Kyoto's Institute of Chemical Research started over with a 41-inch cyclotron (Figure 8). This was completed in 1955, producing strong beams of 7 MeV/u deuterons and alpha particles and operating well into the 1980s. Today it stands outside the ICR, a handsome monument to pioneering days.

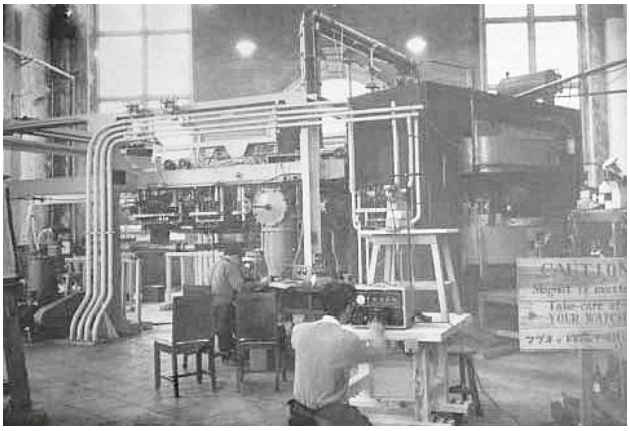

Figure 8: The Kyoto 41-inch cyclotron. The notice warns: "CAUTION – Magnet - Take care of YOUR WATCH!"

RIKEN had been the first (in 1953) to commission a post-war cyclotron, a more modest 26-inch model, having found yet another Poulsen Arc magnet! But they soon began on a much more ambitious project, an 84-inch machine employing a 340-ton magnet, one of the largest-ever classical cyclotrons. This came into operation in 1966, enabling protons to be accelerated to ~20 MeV, and heavier ions (C, N, O) to ~10 MeV/u [12] – presaging the future direction of the lab's research.

Figure 9: The RIKEN 84-inch heavy-ion cyclotron. The red arrow at the top identifies a young employee about whom we will hear more (and who gave the previous talk), Kamitsubo-san.

SYNCHROCYCLOTRON

In the 1950s the Institute of Nuclear Study (INS) was formed at the University of Tokyo. The group there, led by Hiroo Kumagai, built a 280-ton cyclotron with 63-inch poles to a novel design (Figure 10). It could be operated either in fixed frequency (FF) mode to give high-intensity variable-energy proton beams from 7 to 15 MeV (1957), or in frequency-modulated (FM) mode to yield a fixed energy beam of 57 MeV (1958) [13].

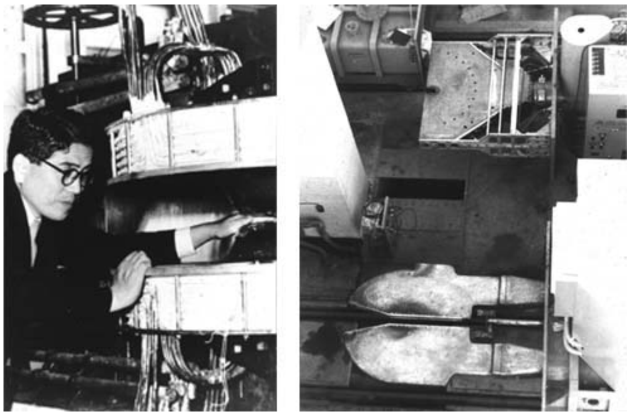

Figure 10: The INS 63-inch cyclotron: (Left) H. Kumagai with the prototype magnet. (Right) Alternative dees for operating in FM mode (above) or FF mode (below). The dees could be moved along rails for insertion into the cyclotron (to the left).

SECTOR-FOCUSED CYCLOTRONS

Then came the age of sector-focused cyclotrons. The first two Japanese designs came into operation in 1974. That at INS, led by Yasuo Hirao, was a three-sector machine [14] with 168-cm poles producing 10-μA beams of 45-MeV protons, and also 17-MeV/u alphas and 6 MeV/u Ne^{6+} (Figure 11).

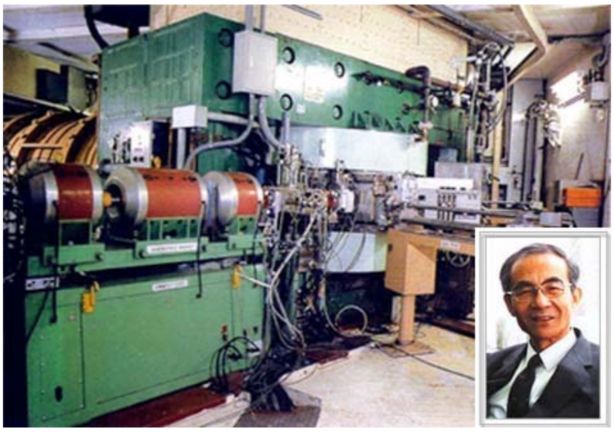

Figure 11: The INS SF cyclotron. Inset: Yasuo Hirao.

A new institute had also been created at Osaka, the Research Center for Nuclear Physics (RCNP). The group there, led by Michiya Kondo, also built a 3-sector machine (Figure 12). This had 230-cm poles, giving 50-μA 85-MeV proton beams, and up to 30-MeV/u alphas [15].

Figure 12: The RCNP Osaka AVF cyclotron; the magnet is almost hidden behind the rf equipment

This machine now acts as injector to a much larger 6-sector 400-MeV spiral-sector ring cyclotron (Figure 13), completed by Iwao Miura's team in 1991 [16]. This is the second-highest-energy proton ring cyclotron after PSI's 590-MeV machine. It also delivers light ion beams of 140 MeV/u for ^{3}He, 100 MeV/u for deuterons and alphas, and 70 MeV/u for slightly heavier ions. Its specialty is producing beams with very high energy resolution.

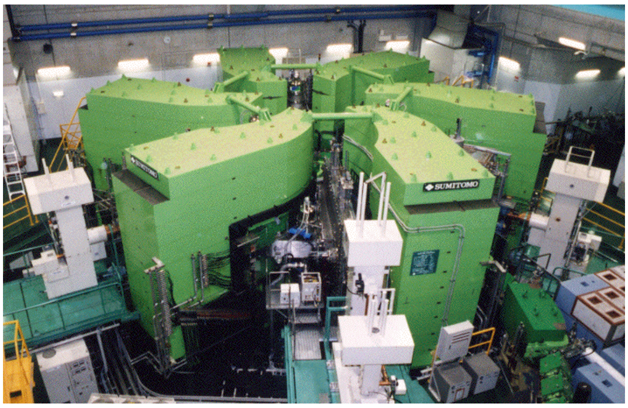

Figure 13: The RCNP 2200-ton 400-MeV ring cyclotron.

Back in 1987, RIKEN, led by Hiromichi Kamitsubo, had produced a similarly massive machine, the 2100-ton K540 RIKEN Ring Cyclotron (RRC) [17]. This has 4 radial sectors and can accelerate heavy ions to an energy of $540(Q/A)^2$ MeV/u (where Q is their charge and A their atomic mass number), or protons to 210 MeV. A K70 compact cyclotron was also built as the injector.

Figure 14: The RIKEN Ring Cyclotron and staff. Inset: Hiromichi Kamitsubo.

But this was only the beginning – the RRC seems to have been a breeder, which under the leadership of Yasushige Yano, has spawned another three ring cyclotrons! These are the K570 fixed-frequency Ring Cyclotron (fRC), the K980 Intermediate Ring Cyclotron (IRC), and the K2600 Superconducting Ring Cyclotron (SRC). Operating in cascade, together with the heavy-ion linac RILAC and the RRC, these form the RadioIsotope Beam Factory (RIBF).

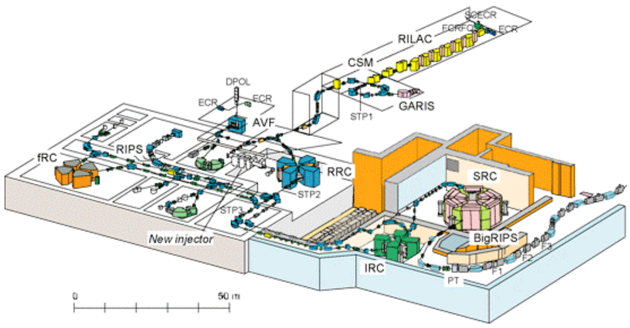

Figure 15: The RIBF cyclotron complex

The most notable of the three is the SRC - the world's most massive (8,300 tons) and most powerful (K2600) cyclotron (Figure 16) – capable of accelerating ions of any mass to 345 MeV/u. Each of its 6 radial magnet sectors is powered by separate superconducting coils – the first cyclotron in which this has been attempted. The 140-ton cold mass was first cooled down at the end of 2005 and the first full-energy beam ($^{27}Al^{10+}$) was extracted in 2006; a full-energy U^{86+} beam followed in 2007 [18]. This pioneering machine is surely a fitting centrepiece for a Nishina Center!

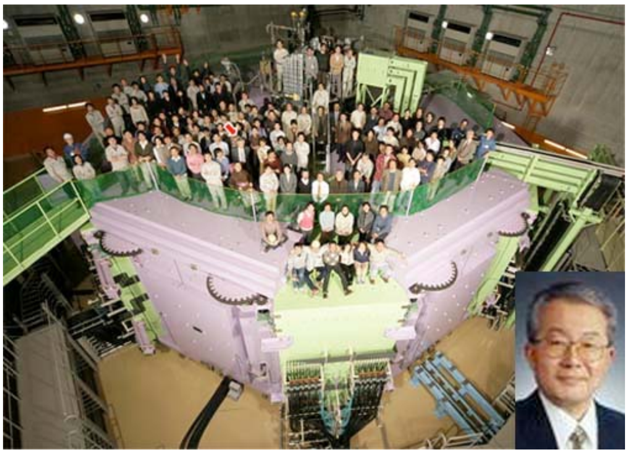

Figure 16: The RIKEN Superconducting Ring Cyclotron and staff. Inset: Yasushige Yano.

Japanese industry played a major role in building the components of these impressive research cyclotrons, and has applied the expertise acquired to becoming a successful international supplier of small cyclotrons for medicine and industry. The Japan Steel Works models include a 17-MeV cyclotron for making PET isotopes. Sumitomo also produces a range of cyclotrons for isotope production, two of which, installed at the National Institute for Radiological Science (NIRS) at Chiba are shown in Figure 17.

Figure 17: The Sumitumo HM-18 (18-MeV H^-) and SHI-930 (89-MeV proton) cyclotrons at NIRS.

FFAG ACCELERATORS

As Figure 18 indicates, FFAGs are the least constrained members of the cyclotron (fixed-magnetic-field accelerator) family, offering a wide variety of operating conditions. Like synchrocyclotrons they are frequency-modulated and run in pulsed mode, but, unlike them, benefit from strong focusing produced by alternating radial field gradients.

The fixed magnetic fields of FFAGs make their orbits spiral outwards, so that they need wider magnets, rf cavities and vacuum chambers than synchrotrons. But their repetition rates can be much faster (up to kilohertz) as there's no need to cycle the magnetic field. Also they have very large horizontal and momentum acceptances. For these two reasons they can deliver much higher beam currents than synchrotrons – a consideration that has fuelled interest in FFAGs for nearly 60 years.

Magnetic field variation B(Θ)	Fixed Frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Isochronous	FFAG

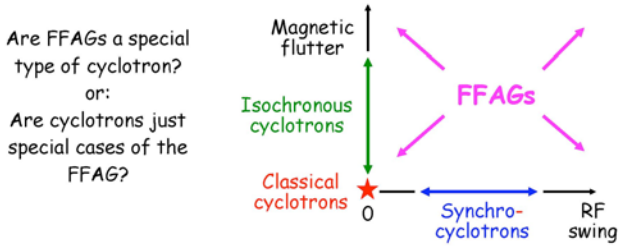

Figure 18: Fixed-field accelerators - the cyclotron family.

They were first proposed independently (presumably by virtue of location and language) by Ohkawa [5] in Japan in 1953, by Kolomensky [19] in Moscow in the same year, and by Symon [20, 21] in the United States in 1954. Donald Kerst [22] added the idea of spiral edge focusing. The most intensive studies of FFAGs were carried out at MURA in Wisconsin in the 1950s and 60s. Several electron models were built and operated, but no proton FFAG until Mori's at KEK in 2000.

Now there is a great deal more interest. Six are in operation for protons, electrons and alpha particles, and two more for electrons are under construction. Also many designs are under study for a variety of particles, including some novel "non-scaling" designs, with diverse applications in view, including cancer therapy, industrial irradiation, driving reactors, providing intense high-energy proton beams and producing neutrinos.

Tihiro Ohkawa

As mentioned above, the first suggestion for FFAGs came from Tihiro Ohkawa (Figure 19), someone who, interestingly enough, though not a direct student of Dr. Nishina, may well have been inspired to take up physics as a career through exposure to him at the age of 16 as a high-school student helping in a RIKEN lab. I contacted Dr. Ohkawa a couple of weeks ago and he explained:

"Incidentally, I met Professor Nishina during war time. Because of the air raid danger, RIKEN was dispersing

Figure 19: L-R: Ernest Courant, Tihiro Ohkawa, David Judd, Nils Vogt-Nilsen, Kent Terwilliger, Felix Adler and Otto Frisch at the 1955 MURA Summer Study.

some of divisions away from Tokyo. The cosmic ray group came to my hometown Kanazawa. Several of the students of the Gymnasium were recruited to help re-establishing the lab. Professor Nishina paid a visit once a month and he would tell us about the time he spent in Bohr's laboratory."

Anyhow, after graduating from Tokyo University, Ohkawa conceived the idea of applying the newly-discovered alternating-gradient focusing to fixed-field accelerators by alternating positive-bending magnets with shorter reverse-bending ones (Figure 20). As the field strength $|B|$ increases outwards in each of the magnets, the gradient dB/dr alternates in sign between the positive– and reverse-bending magnets, providing AG focusing.

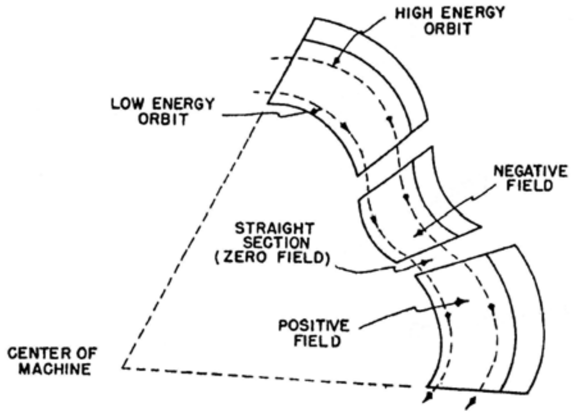

Figure 20: Radial-sector FFAG magnets and orbits.

On alerting Kerst to his earlier work Ohkawa was invited to join the MURA group and spent a couple of years there. Among his most notable contributions was the idea of the two-way FFAG collider [23], where the positive- and reverse-bending magnets are of equal length (Figure 21). The orbits nevertheless close, as the arcs in the positive bends are longer and in stronger field regions than those in the reverse bends. Such a device can therefore support counter-rotating beams of the same charged particle. This was one of the first schemes for a particle collider and formed the basis of the MURA 50-MeV electron model.

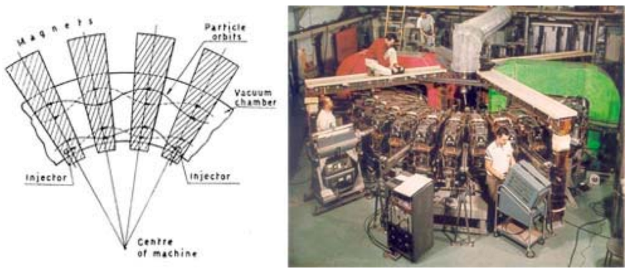

Figure 21: (Left) The two-way collider. (Right) The MURA 50-MeV electron model.

After MURA, Ohkawa moved to CERN and then joined Kerst, who had gone to General Atomics to work on fusion plasmas. There and at UC San Diego he pursued a distinguished career in plasma physics with over 150 publications and over 100 patents. In 1979 he was awarded the Maxwell Prize of the American Physical Society.

Scaling FFAGS

A major concern in the 1950s was to avoid exciting resonances between the transverse betatron oscillations and the magnetic field harmonics, as these could lead to loss of beam quality or intensity. The general resonance condition may be written:

$$\ell \nu_r \pm m \nu_z = n$$

where ν_r, ν_z denote the betatron tunes (the number of transverse oscillations per turn) and ℓ, m and n are integers. To avoid crossing any resonances, FFAGs therefore followed so-called *scaling* designs in which the orbit shape, optics and tunes were kept constant throughout acceleration.

To first order the tunes are given by the same equations as those for imperfectly isochronous cyclotrons:

(radial) $\quad \nu_r^2 \approx 1 + k$

(vertical) $\quad \nu_z^2 \approx -k + F^2(1 + 2\tan^2 \varepsilon)$,

where the field index $\quad k(r) \equiv \dfrac{r}{\langle B_z \rangle} \dfrac{\partial \langle B_z \rangle}{\partial r}$,

the magnetic flutter $\quad F^2 \equiv \left\langle \left[B_z(\theta) - \langle B_z \rangle \right]^2 \right\rangle \Big/ \langle B_z \rangle^2$,

and ε is the spiral angle.

Clearly, achieving <u>constant ν_r</u> requires

$$k = \text{constant},$$

implying magnetic field and momentum profiles of the form:

$$\langle B_z \rangle = B_0 (r/r_0)^k \qquad p = p_0 (r/r_0)^{k+1}.$$

Constant k also means that to achieve <u>constant ν_z</u> we need

$$F^2(1 + 2\tan^2 \varepsilon) = \text{constant}.$$

This quantity must also be given a high value, since usually $k >> 0$ in order to minimize the radial aperture. MURA's recipe was to keep the flutter

$$F^2(r) = \text{constant},$$

by using a constant field profile $B_z(\theta)/\langle B_z \rangle$ and:

- for spiral sectors: choosing <u>constant ε</u>, so the sector axis is a logarithmic spiral:
  $$R = R_0 e^{\theta \cot \varepsilon};$$
- for radial sectors: boosting the flutter F^2 by alternating positive-bending magnets (usually with positive k and so radially focusing (F)) with shorter reverse-bending defocusing (D) magnets, usually with:
  $$B_D = -B_F.$$

Of course, reverse fields increase the mean radius: its ratio to the local radius of curvature, the "circumference factor", is ≥4.45 in the absence of straights [21], but smaller in their presence. The radial-sector design is shown schematically in Figure 20 above.

MURA built several successful electron models, including 400-keV radial-sector, 120-keV spiral-sector, and 50-MeV two-way machines. They also pioneered much of the basic theory of high-energy synchronous accelerators, particularly rf acceleration and beam stacking. But none of the MURA proposals for proton FFAGs of 10, 15, or 20 GeV were funded. It was not until Yoshiharu Mori and his team [7] built the Proof-of-Principle (PoP) 1-MeV radial-sector machine at KEK about 10 years ago that protons were accelerated in an FFAG (Figure 22). They then went on to build a 150-MeV FFAG ring [24] with 12 cells and a small cyclotron as injector.

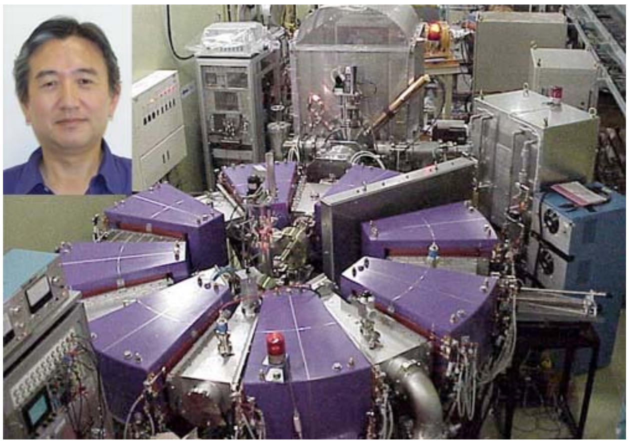

Figure 22: KEK 1-MeV PoP FFAG. Inset: Y. Mori.

Protons pose a greater technical challenge than electrons, because of the need to modulate the radiofrequency rapidly over a wide range. In synchrocyclotrons this had been accomplished using rotary or vibratory capacitors - mechanical devices notorious for their unreliability.

Mori introduced two important innovations. One was Finemet alloy loading of the rf cavities, allowing reliable frequency modulation at up to 250 Hz, and correspondingly high beam pulse repetition rates. Moreover the high permeability of this metallic glass alloy allows quite short cavities to produce high fields, while their low *Q*–value (≈1) permits broadband operation. His second innovation was to build the magnets as combined-function DFD triplets powered as a single unit where the reverse-bend Ds also act as yoke for the central F.

Mori then moved to Kyoto to build a three-ring FFAG complex for ADSR studies (Figure 23): a 2.5-MeV spiral-sector injector, a 20-MeV radial-sector booster, and the 150-MeV 12-cell main ring (similar to that at KEK). This is installed at the Kyoto University Research Reactor Institute (KURRI), and is on the itinerary of one of next Saturday's tours. The world's first experimental demonstration of ADSR was performed here last year [8].

Figure 23: The FFAG complex at KURRI. Note the combined-function DFD triplets built as single entities.

But that's not the only innovative machine at KURRI. Mori has also built the ERIT storage ring (Figure 24) for Boron Neutron Capture Therapy (BNCT), a form of cancer therapy. The ring stores a 70-mA beam of 11-MeV protons, which then produces a very intense neutron beam for patient treatment via a (p,n) reaction on an internal Be target. This enormously intense beam can be maintained over more than 1,000 passages through the target by ionization cooling, using a 250-kV rf cavity, and taking advantage of the huge acceptance of an FFAG [25].

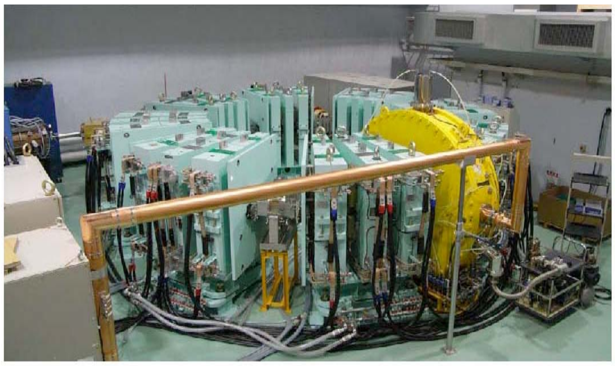

Figure 24: The 8-FDF-cell ERIT storage ring for BNCT.

Another example of an FFAG storage ring is PRISM, a 10-cell ring for muons being built in Osaka for eventual installation at J-PARC. This will collect muon bunches at 68 MeV/c and rotate them in phase space, reducing their momentum spread from ±30% to ±3%. With its large acceptance and high repetition rate, the beam intensity will be high enough to allow ultrasensitive studies of rare muon decays. An initial version using six of the cells has been used to store 0.8-MeV alpha particles (Figure 25) and demonstrate the feasibility of this technique [26].

Figure 25: The 6-cell α-particle test ring for PRISM.

In addition to all these, two commercial companies have been building electron machines for industrial irradiation. NHV in Japan has built and operated a 0.5-MeV FFAG with 6 spiral-sectors, and RadiaBeam in California is building a 12-cell 5-MeV radial-sector FFAG.

There have also been more than a dozen design studies for scaling FFAGs over the last five years or so, most of these in Japan. They cover a wide range of particles (electrons, protons, heavy ions, muons), energies (1 MeV to 20 GeV), diameters (5 cm 400 m), and applications (irradiation, cancer therapy, neutrino production). The smallest of these, Mitsubishi Electric's "Laptop" can be held comfortably in one hand, while the largest, a 10-20 GeV muon ring for a neutrino factory, would spread across the whole J-PARC site (Figure 26). The latter would be the last in a chain of four FFAGs, Mori's most ambitious project [27], feeding muons into a racetrack decay ring, from which neutrinos would be sent off to Super-Kamiokande.

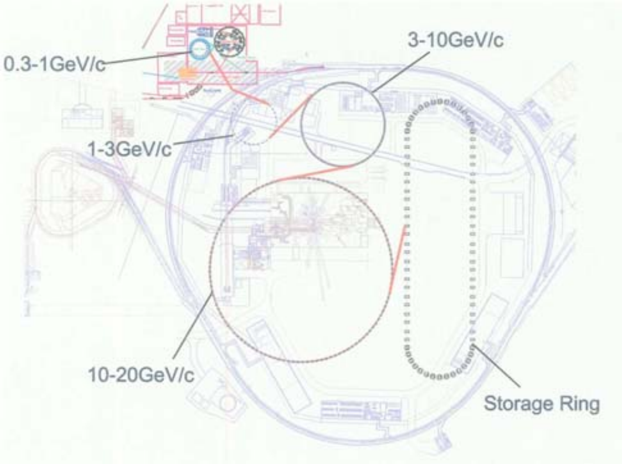

Figure 26: An FFAG-based neutrino factory for J-PARC.

Non-Scaling FFAGs

FFAGs are attractive for accelerating muons because of their very large acceptances. But the muon's 2.2-μs mean lifetime demands very rapid acceleration if it is to survive, and in this case crossing a betatron resonance occurs too rapidly to damage the beam. The rationale for scaling therefore disappears (Mills [28], Johnstone [29]), and less restrictive *non-scaling* designs may be considered in which the tunes are allowed to vary. In particular Johnstone *et al*. [30] proposed using constant-gradient FDF triplets, which would provide greater momentum compaction than comparable scaling FFAGs, allowing fixed-frequency operation, and would be simpler to build than magnets with constant high k.

A demonstration model of such a *linear non-scaling* (LNS) FFAG is currently under construction at Daresbury in the UK, and will come into operation later this year. EMMA is a 42-cell, 2.64-m radius, 10-20 MeV electron model of a 10-20 GeV muon FFAG [31] (Figure 27).

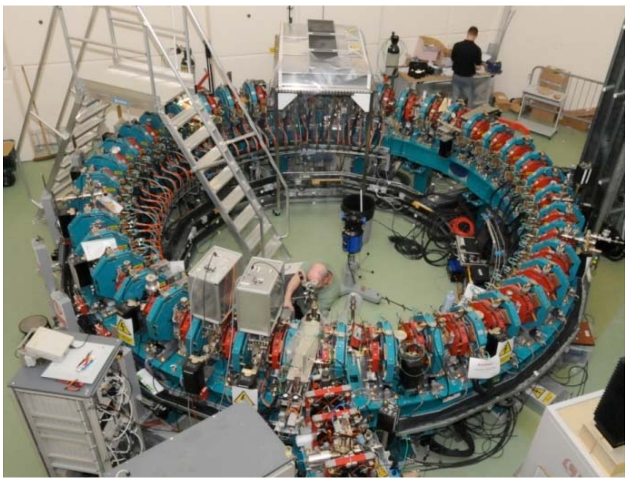

Figure 27: The Linear Non-Scaling FFAG EMMA.

The funding for EMMA also has an allocation for conceptual design of a non-scaling FFAG for cancer therapy. This would require 250-MeV protons or 400-MeV/u carbon ions, and is being studied by a team led by the John Adams Institute in Oxford. The rf equipment required for rapid acceleration would be too expensive for hospitals, especially as the frequency has to be varied over a wide range for these non-relativistic particles. Resonance crossing is therefore again a concern, so designers have searched for non-scaling solutions that nevertheless maintain constant tune. A Fermilab team [32], working on a similar project, has achieved this by angling the magnet edges to provide edge focusing.

The Oxford accelerator design, though, due to two former members of Prof. Mori's group, Shinji Machida and Takeichiro Yokoi, is less radical, but nevertheless quite novel – what might be termed a *quasi-scaling* lattice. They aim to approximate a scaling magnetic field over the narrow orbit region by overlaying 2-, 4-, 6- and 8-pole fields in suitable proportions. To minimize the machine diameter, 4-T superconducting magnets are used, and in these such a superposition is straightforward to implement, with the various multipole coils being wound concentrically on a cylindrical former. The lattice consists of 12 FDF cells, and tracking studies confirm that it provides tunes that vary little with energy, and that it provides good dynamic apertures [33]. Figure 28 shows the overall layout, with the proton ring (radius 6.25 m) and carbon ring (radius 9.2 m) arranged concentrically. The proton injector is a 31-MeV cyclotron, the carbon ion injector an RFQ linac.

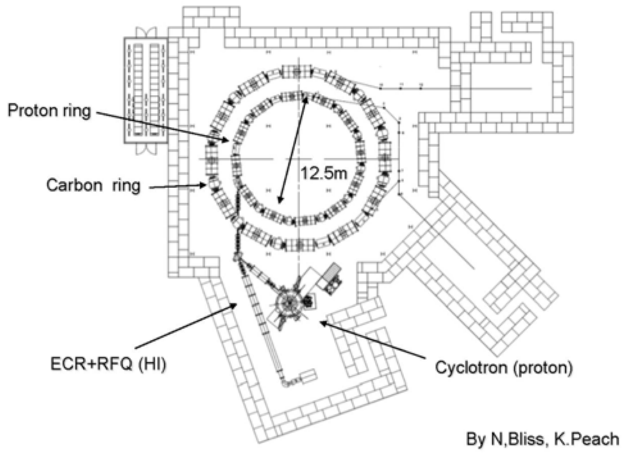

Figure 28: PAMELA layout, showing the proton and carbon ion treatment rooms.

THE NISHINA LEGACY

Dr. Nishina pioneered the construction of accelerators in Japan with instruments whose specifications were as advanced as any in the world at that time. His students and those he inspired have continued to keep Japan in the forefront of cyclotron and FFAG development. He would surely be proud to know that Japanese accelerator physicists are not only renowned for their achievements at home but sought out for their expertise by other countries.

ACKNOWLEDGEMENTS

I would like to express my thanks to all those who made this talk possible by answering my importunate requests for old photographs: Drs. Honma, Kamigaito, Murakami, Noda, Tanabe and Yano, and especially Dr. Hirao. I'm also indebted to the organizers for making available a transcript of the talk.

REFERENCES

[1] Y. Hirao, Proc. 11th Int. Conf. Cyclotrons (Tokyo, 1986) 761.
[2] D.-W. Kim, Hist. Stud. Phys. Biol. Sci. **36**, 243 (2006).
[3] M.F. Low, *ibid*., 275
[4] J. L. Heilbron, R.W. Seidel, *Lawrence and his Laboratory*, (UC Press, Berkeley, 1989).
[5] E.M. McMillan, *Particle accelerators*, in *Experimental Nuclear Physics* ***III*** (Wiley, 1959) 639.
[6] T. Ohkawa, Phys. Soc. Japan Symp. Nucl. Phys. (Tokyo, 1953).
[7] M. Aiba *et al*., Proc. EPAC'00, 581 (2000).
[8] Y. Ishi *et al*., Proc IPAC'10, 1327 (2010).
[9] Y. Nishina *et al*., Sci. Pap. IPSC, **34**, 1658 (1938).
[10] K. Sinma *et al*., Kagaku kenkyujo hokoku, **27**, 156 (1951).
[11] *Life*, **19**:26 (24 Dec 1945) 26-27.
[12] I. Kohno *et al*., Proc. 5th Int. Conf. Cyclotrons (Oxford, 1969), 487.
[13] S. Kikuchi *et al*., J. Phys. Soc. Jpn. **15,** 41 (1960).
[14] Y. Hirao, Proc. 7th Int. Conf. Cyclotrons (Zürich, 1975), 103.
[15] M. Kondo *et al*., *ibid*., 95.
[16] I. Miura *et al*., Proc. 13th Int. Conf. Cyclotrons (Vancouver, 1992), 3.
[17] H. Kamitsubo, Proc. 11th Int. Conf. Cyclotrons (Tokyo, 1986), 17.
[18] Y. Yano, Proc. PAC07 (Albuquerque, 2007), 700.
[19] A.A. Kolomensky, V.A. Petukhov, M. Rabinovich, Lebedev Phys. Inst. Report RF-54 (Moscow, 1953).
[20] K.R. Symon, Phys. Rev. **98**, 1152(A) (1955).
[21] K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett, K.M. Terwilliger, Phys. Rev. **103**, 1837 (1956).
[22] D.W. Kerst, K. M. Terwilliger, K.R. Symon, and L.W. Jones, Phys. Rev. **98**, 1153 (A) (1955).
[23] T. Ohkawa, Rev. Sci. Instr. **29**, 108 (1958).
[24] Y. Yonemura *et al*., Proc. PAC'03, 3452 (2003).
[25] Y. Mori *et al*., Proc. EPAC'08, 3512 (2008).
[26] A. Sato *et al*., *ibid*., 3389.
[27] Y. Mori, Proc. EPAC'02, 278 (2002).
[28] F. Mills, Proc. 4th Int. Conf. Physics Potential and Development of $\mu^+ \mu^-$ Colliders (1997), 693.
[29] C. Johnstone, *ibid*., 696.
[30] C. Johnstone, W. Wan, A. Garren, Proc. PAC'99, 3068 (1999).
[31] R. Edgecock *et al*., Proc. IPAC'10, 4266 (2010).
[32] C. Johnstone *et al*., Proc. PAC'09, TU6PFP080.
[33] K. Peach *et al*., Proc. IPAC'10, 112 (2010).