CYCLOTRONS AND FFAGs IN 2004

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Abstract

This paper attempts to summarize the highlights of the work presented at the 17th International Conference on Cyclotrons and Their Applications - at least as perceived by the author. Advances in the design of both isochronous cyclotrons and FFAG accelerators are discussed.

INTRODUCTION

This year we celebrate a major anniversary: it was 75 years ago that Ernest Lawrence discovered the magnetic resonance principle and first conceived of the cyclotron. His graduate student J.J. Brady [1] later recalled his 27-year-old supervisor's excitement following this eureka moment in early 1929:

"He came bursting into the lab....., his eyes glowing with enthusiasm, and pulled me over to the blackboard. He drew the equations of motion in a magnetic field [$MR\omega = eRH$]. 'Notice that R appears on both sides,' he said. 'Cancels out. R cancels R. Do you see what that means? The resonance condition is not dependent on the radius.... *Any* acceleration!' .... 'R cancels R,' he said again. "Do you see?' ...... He left in a rush, I suppose to tell other people that R cancelled R."

Three-quarters of a century later, Lawrence's excitement seems fully justified. Magnetic resonance is the basis for all circular accelerators, and his original constant-field fixed-frequency concept has proved remarkably adaptable, allowing many powerful variations:

- rf frequency modulation to counter the relativistic increase in mass at higher energies (at the expense of pulsed operation and low beam intensity);
- magnetic field ramping to keep the accelerating beam at a fixed radius;
- sector focusing to regain cw operation and high beam intensity at moderate energies;
- radial profiling of the magnetic field, either for isochronism or AG focusing.

These variations, introduced more than 50 years ago, have led to the designs we now refer to as synchrocyclotrons, synchrotrons, isochronous cyclotrons and FFAGs (fixed-field alternating-gradient accelerators). The three varieties with fixed magnetic field and spiralling orbits can all be regarded as members of the cyclotron family, as indicated in Table I. (Note, though, that some FFAG workers take a different perspective, claiming that cyclotrons are just special cases of the FFAG!)

Table I: The cyclotron family

Magnetic field gradient	Fixed frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Sector-focused	FFAG

Over the last 40 years, virtually all attention has been focused on one variety, the sector-focused isochronous cyclotron. Hundreds of these have been built for a wide variety of applications, and dramatic improvements in performance have been achieved through various technical innovations, such as:

- the use of powerful ion sources, mounted externally;
- beam extraction by resonance or stripping;
- accurate computation of fields and orbits;
- superconducting magnets;
- multistage designs using ring cyclotrons.

Over the last few years, however, there has been a resurgence of interest in FFAGs for applications requiring large acceptance and very high repetition rate (>50 Hz). Moreover, it has become apparent that FFAG designs need not be restricted to the ‘scaling’ approach explored in the 1950s. Dropping this restriction has revealed a range of interesting new design possibilities - some too recent to have been included in the conference program. So I hope I may be forgiven for devoting a larger portion of this review to FFAGs than their one session might seem to justify.

TRAITS AND TRENDS

The task of summarizing this conference is an intimidating one. There is no way I can do justice to all the 155 papers presented, so I apologize in advance to the many authors whose good work will not receive the attention it deserves. With the limited space available it seems best to concentrate on the highlights, hoping that the choice of these will not be too biased by my special interests. I will begin by listing what seem to me the most notable trends since our last conference in 2001. This is a mixture of good and bad news - fortunately with the former predominating:

- Very few major machines have begun operation:
    - IBA 230 MeV cyclotron in Zibo, China
    - 150 MeV FFAG at KEK.
- Many new cyclotrons are under construction or proposed.
- Except for RIKEN, VECC (Kolkata) and CIAE (Beijing), all new cyclotrons are being built primarily for applications other than nuclear research.
- A few more cyclotrons are shifting their emphasis from nuclear towards materials research or therapy (Berkeley 88" in 2004, Uppsala in 2005).
- Many technical innovations and improvements in performance are being made at existing cyclotrons.
- 3D field computations are now considered accurate, detailed and fast enough to replace models, *e.g*:
    - magnetic fields for the RIKEN SRC
    - EM fields for the PSI 590-MeV and ACCEL 250-MeV cavities.

- There continues to be a strong market for small commercial cyclotrons, with continued improvements in performance (*e.g.* the new TR30 at MDS Nordion, routinely delivering >1 mA).
- There has been an explosion of interest in FFAGs.

NEW CYCLOTRONS

Under construction

RIKEN-RIBF: The three new cyclotrons being built at RIKEN, together with the existing K540, constitute the most ambitious cyclotron project anywhere. When complete, the complex will provide 400-MeV/u light ions (A<40) and 350-MeV/u heavy ions (A≤238). The impressive photographs and statistics still leave a visitor unprepared for the reality of these gigantic instruments.

The *SRC* (K2500) is now more than half assembled. Even with superconducting coils the magnet (8,300 t) will take the prize for heaviest cyclotron from the longtime holder PNPI Gatchina (7,800 t). The overall diameter (18.4 m) is only slightly less than that of the TRIUMF cyclotron (21.0 m).

The *IRC* (K980, 2,720 t) is now fully assembled in place. The *fRC* (K570, 1,320 t) magnet is almost complete at the factory, and the whole cyclotron will be installed at RIKEN in 2005.

The *Kolkata K500* cryostat has been installed in the magnet; cooldown and power tests are about to start.

ACCEL reported that their prototype 250-MeV superconducting cyclotron for proton therapy (based on an MSU design) is now fully installed at PSI. Tests of the 90-t magnet have been satisfactory and rf commissioning is under way. A clone in Munich is also progressing well. First beam is expected in both early in 2005.

IBA announced the successful operation of their third *C230* proton therapy cyclotron in Zibo, and the sale of three more (Beijing, Seoul, Jacksonville).

Construction of the *VINCY* cyclotron (K134) has been resumed at the Vinča INS in Belgrade, and the first phase, allowing production of ^{18}F, should be completed in 2006. Subsequent phases will yield 65-MeV p, 7-MeV/u α and 3-MeV/u Ar^{6+} for biomedical and materials research, isotope production and proton therapy.

The *Flerov LNR* in Dubna is building a *DC-72* cyclotron for installation in Slovakia and a *DC-60* for Kazakhstan, both multipurpose machines. The DC-72 will accelerate ions with *A/Z* from 1 (H^-) to 7.167 (Xe^{18+}), the former to 72 MeV, the latter to 2.7 MeV/u. The DC-60 is designed to allow smooth energy variation from 0.4 to 1.66 MeV/u for ions with $6 \leq A/Z \leq 12$.

Table II: New medium and large cyclotrons

Cyclotron	K#/Energy	Ions	Coils	Purpose
Under construction				
RIKEN - SRC	K2500	HI	SC	Nucl. Ph.
- IRC	K980	HI	RT	" "
- fRC	K570	HI		" "
VECC Kolkata	K500	HI	SC	Nucl. Ph.
ACCEL (×2)	250 MeV	p	SC	Therapy
IBA (×3)	230 MeV	p	RT	Therapy
VINS VINCY	K134, 65MeV	HI, H^-	RT	Multiple
JINR-FLNR				
- DC72 [Bratislava]	K137, 72MeV	HI, H^-	RT	Multiple
- DC60 [Astana]	K61	HI	RT	Multiple
Proposed				
IBA	300 MeV/u	C, H_2	SC	Therapy
LNS - SCENT	250 MeV/u	C, H_2	SC	Therapy
JAERI	K900, 300MeV	HI, p	SC	Materials
ENEA	120/140 MeV	H-	RT	ADSR
IBA	110 MeV	H-	RT	ADSR
CIAE [Approved]	100 MeV	H-	RT	RI beams

Proposals

IBA have developed a 300-MeV/u cyclotron to accelerate H_2^+ and light ions with $A/Z = 2$ for ion therapy. It is based on the C230 design but uses superconducting coils in a 656-t magnet. Rapid switchover between species is planned.

The *LNS SCENT* superconducting cyclotron would accelerate H_2^+ and light ions to 250 MeV/u for ion therapy and radioisotope production. Light ions would be extracted conventionally but protons by foil stripping.

JAERI (Takasaki) are proposing a K900 superconducting cyclotron to produce 150-MeV/u heavy ions and 300-MeV protons for biotech and materials research. Four spiral sectors are used, as in all the therapy machines described above.

ENEA is considering 120/140-MeV 2-mA H^- cyclotron designs for the TRADE ADSR (accelerator-driven subcritical reactor) experiment at the TRIGA reactor. *IBA* described a 110-MeV 2-mA H^- cyclotron for this application, from which protons could be extracted by stripping, or H^- ions by self-extraction (for injection into a synchrotron). An interesting feature is a magnetic inflector.

CIAE (Beijing) propose a 75-100-MeV 200-500-μA H^- cyclotron as driver for their BRIF radioactive ion beam project. The 433-t magnet has 4 radial sectors. The project has received government approval.

SECONDARY BEAM FACILITIES

RIKEN: Good progress is being made in the installation of the 70-m-long *BigRIPS* spectrometer, whose two stages will first separate and then tag the RI beams produced either by fragmentation or by in-flight fission. To achieve the desired large acceptance (10 mrad, 6% $\delta p/p$), superconducting quadrupoles with a bore of 24 cm are used; field gradients of 14 T/m have been achieved.

In a later phase, two major facilities will be added: the *Rare RI Ring* for precision mass measurement, and the

SCRIT Self-Confining RI Ion Target, in which radioactive ions will be trapped in an electron storage ring for electron scattering measurements.

GANIL: *SPIRAL* is now in full operation, with the CIME cyclotron accelerating RI beams produced by an ISOL target bombarded by heavy ions from the GANIL cyclotrons. The *SPIRAL-2* project would allow CIME to accelerate fission products formed by irradiation of a UC_2 target with the neutrons produced from a 5-mA deuteron beam accelerated in a 40-MeV/u superconducting linac. A funding decision is expected soon.

HIRFL: The *CSRm* accumulator/synchrotron (2.8-GeV p, 1.1-GeV/u C^{6+}) is complete and beams are now being commissioned. The extracted beam line and fragment separator have also been installed. The *CSRe* ring (500-MeV/u U^{92+}) for internal experiments with stable or radioactive ion beams is partially assembled.

JINR-FlerovLNR: the *DRIBS* project, in which an ISOL source driven by the U400M cyclotron produces $^6He^+$ and $^8He^+$ beams for acceleration in the U400, has been completed and initial beam measurements made.

LNS: The *EXCYT* project will use the 15-MV tandem to accelerate radioactive ions produced in an ISOL source driven by heavy ion beams from the K800 cyclotron. The target and ion source have been successfully tested at GANIL, and the charge-exchange cell at ORNL. First beams are expected early in 2005.

TRIUMF: ISAC-II installation has begun with the magnets for the dog-leg beam-line from ISAC-I. The first medium-β cryomodule has been successfully tested and an α-particle test beam accelerated. For 2005-10 it is proposed to install a second 100-μA proton beam line and target system for RI beam development.

TECHNICAL INNOVATIONS

Ion sources

ECR sources continue to be popular for a variety of applications. Higher magnetic fields (2-4 T) using superconducting magnets, together with higher-frequency rf (28 GHz), now allow the production of 10-50 mA (total) beams of highly charged ions. For top performance, careful design of the extraction optics and of the central dip in the solenoid field is essential. Interesting new features include the location of the solenoid inside the sextupole in the compact HIRFL source SECRAL, and the use of HTSC (high-temperature superconducting) cable in the Pantechnik source PKDELIS. (HTSC cable has also been successfully applied to a SQUID beam monitor at RIKEN.)

RF systems

Solid-state devices are increasingly being used in high-power rf amplifiers (≤40 kW at higher frequencies) and in HV power supplies (≤100 kW), though inductive output tubes (IOTs) are finding favour in some situations.

For cavity design, the capacity and speed of modern computers make it possible to calculate not only the electric and magnetic fields with great accuracy, but also the parasitics throughout the cyclotron, the beam-cavity interaction, the temperature distribution and the mechanical deformation.

The feasibility of dispensing with full-scale models seems to be confirmed by the successful operation of the first replacement cavity for PSI's 590-MeV cyclotron and of the ACCEL cyclotron cavities. (For magnets also, designers are increasingly bypassing model measurements, notably in the case of the RIKEN SRC.)

Beam dynamics

Here too, greater computer power is having an important impact. 3D simulations of high-current beams in the PSI cyclotrons show that it is possible to obtain reasonably accurate results that take into account magnetic, rf and self-consistent space-charge fields (including the effects of neighbouring bunches), beam-cavity interactions and collimation.

On the experimental side, the first results were presented from the 20-keV SIR Small Isochronous Ring at NSCL in which beams of H_2^+ or D^+ can be stored for ≈200 turns for the study of space-charge effects. For a beam intensity corresponding to ≈4 mA in the PSI cyclotrons, a coasting beam was found to break up quickly (≈5 turns) into ≈20 bunches, which then coalesced into about half that number - in agreement with computer simulations.

FFAGs

Scaling FFAGs

Resonance crossing was a big worry in the early days of AG focusing, because of the low energy gain/turn. The *scaling* principle was therefore adopted, whereby the orbit shape, optics and tunes are kept the same at all energies. This requires sector magnets with:

- constant field index over the aperture
- equal and opposite F and D fields (radial sectors)
- constant spiral angle (spiral sectors).

Several electron models were built and operated successfully at MURA, but no proton FFAG until Mori's recent 1-MeV PoP (Proof of Principle) and 150-MeV machines at KEK [2]. An important technical innovation in these (remember the rotary capacitors on synchro-cyclotrons?) is the use of FINEMET metallic alloy tuners, which offer:

- rf modulation at 250 Hz or more, and so high beam-pulse rep rates;
- high permeability, and so short cavities with high effective fields;
- low Q (≈1), allowing broadband operation without any need for active tuning.

Four more FFAGs are now under construction in Japan: a 3-ring complex at Kyoto University Research Reactor for an ADSR experiment; and the PRISM phase rotator for muon cooling at J-PARC. Some parameters of these machines are given in Table III.

Table III: Scaling FFAGs built or being built

	E (MeV)	Ion	Cells	Spiral angle	Radius (m)	Comments/ 1st beam
KEK-PoP	1	p	8	0°	0.8-1.1	2000
KEK	150	p	12	0°	4.5-5.2	2003
KURRI	150	p	12	0°	4.5-5.1	120 Hz, 1 μA
-ADSR	20	p	8	0°	1.3-1.9	in 2005
	2.5	p	8	40°	0.6-1.0	[1kHz, 100μA, 200MeV later]
PRISM	20	μ	10	0°	6.5	Phase rotator

In addition, more than a dozen different scaling FFAG designs from Japan (Table IV) were described at the recent FFAG'04 Workshop [3]. These range from a fist-sized 1-MeV prototype for electron irradiation, to medium-sized sources for proton and ion therapy, to the 240-m diameter 10-20 GeV superconducting muon ring proposed for a J-PARC neutrino factory. All the Japanese radial-sector FFAGs use DFD triplet cells.

Non-scaling FFAGs

FFAGs were originally proposed for accelerating muons in μ colliders or ν factories because their large acceptance (in *r* and *p*) removes the need for cooling and phase rotation stages. But Johnstone [4] realized that the rapid acceleration (<20 turns) needed to avoid excessive decay would render resonance crossing harmless, and proposed a *non-scaling* approach in which the optics and tune were allowed to vary. In particular, she proposed using FDF cells, with constant-gradient "*linear*" superconducting magnets, making the orbit circumference *C(E)* pass through a minimum instead of rising monotonically (Figure 1). The variation in orbit period is thereby reduced, allowing the use of high-*Q* fixed-frequency rf, in

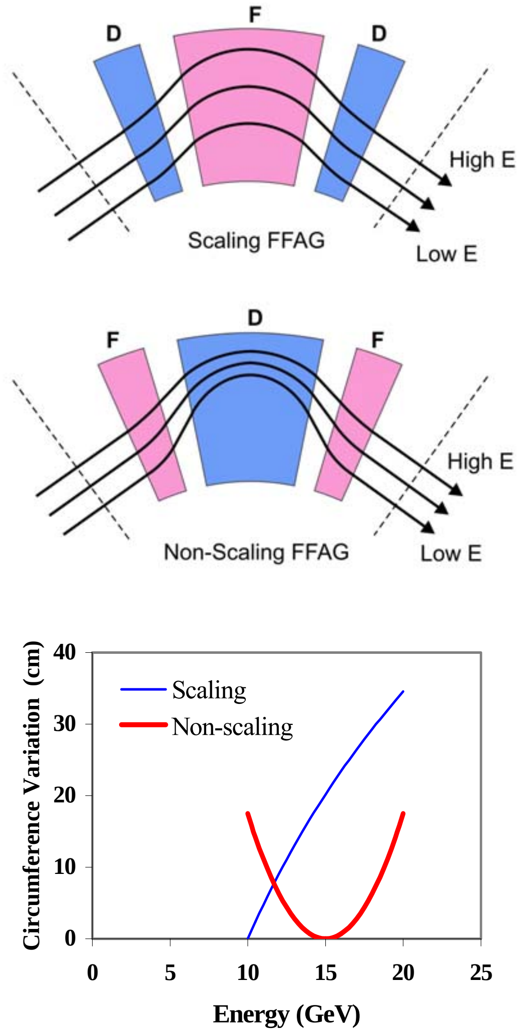

Figure 1: Scaling and non-scaling FFAG orbit patterns (above), and circumference variation with energy (below).

Table IV: Scaling FFAGs - design studies

Accelerator	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
Ibaraki Medical Acc.	230	p	8	50°	2.2-4.1	20	0.1 μA
eFFAG	10	e	8	47°	0.26-1.0	5,000	20-100 mA
MElCo - Laptop	1	e	5	35°	0.023-0.028	1,000	Hybrid, Magnet built
MElCo - Ion Therapy	400	C^{6+}	16	64°	7.0-7.5	0.5	Hybrids =
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35-1.8	0.5	FFAG/synchrotrons
MElCo - p Therapy	230	p	3	0°	0-0.7	2,000	SC, quasi-isochronous
NIRS Chiba	400	C^{6+}	12	0°	10.1-10.8	200	Compact
- Ion Therapy	100	"	12	0°	5.9-6.7	"	radial-sector
Accelerators	7	C^{4+}	10	0°	2.1-2.9	"	designs
J-PARC	20,000	μ	120	0°	120		Δr = 0.5 m, ≈10 turns
Neutrino	10,000	"		0°	55		Superconducting
Factory	3,000	"		0°	30		magnets
Accelerators	1,000	"		0°	10		Broadband rf operation

which the muons oscillate in phase across the rf voltage peak (3 crossings), just as in an imperfectly isochronous cyclotron.

Various FDF lattice designs have been developed by Johnstone, Berg, Trbojevic, Keil and their collaborators [3]. Some parameters for Berg's latest cost-optimized lattices are given in Table V. Above 5 GeV their costs are significantly lower than those of recirculating linacs.

Table V: Cost-optimized lattices for muon FFAGs

Energy	Circumference	Cells	Turns	Decay
2.5-5 GeV	246 m	64	6	6%
5-10 GeV	322 m	77	10	7%
10-20 GeV	426 m	91	17	8%

Efforts are currently focused on design of a 10-20 MeV electron model to confirm the viability of the non-scaling magnet design and fixed-frequency acceleration.

Non-linear non-scaling FFAGs for muons

By using non-linear field profiles and a slightly more complicated dFDFd cell structure, Rees [3] has been able to design a 123-cell, 1255-m circumference, muon ring that is exactly isochronous at 20 discrete energies from 8 to 20 GeV - a muon cyclotron! Although isochronous cyclotron designs in this energy range have been reported before [5], they have relied on spiral-edge focusing. What is remarkable here is that there is no spiral - the focusing stems purely from flutter and alternating gradients.

An alternative 10-20 GeV scheme by Schönauer [3] uses 66 BFDbDFB cells with only 4 non-linear magnets per cell, so that the total of these is only 264, compared to 615 for Rees. This ring is not as closely isochronous, but has roughly constant ν_r and ν_z.

Non-linear non-scaling FFAGs for hadrons

Another interesting avenue has been opened by Ruggiero [3], who has used non-linear magnets in non-scaling FDF cells to design a number of medium-energy proton FFAGs:

- 1.5 GeV replacement for the AGS Booster (R = 128 m, N = 136, 2.5 Hz, 40 μA)
- 1 GeV 10 MW proton driver (R = 32 m, N = 40, 1000 Hz, 10 mA)
- 250 MeV proton therapy FFAG.

As only modest rf voltages are assumed, no resonance crossings are allowed, but he is able to keep the tunes sufficiently constant by using fields that are non-linear in both r (a lot) and θ (a little), so that the changes in radial gradient balance those in flutter.

The exploration of non-scaling lattices has only just begun; there seems plenty of scope for more variations.

APPLICATIONS

As indicated by the construction of new cyclotrons and conversion of old ones, the familiar applications - radioisotope production, ion therapy, ion implantation, and materials research and analysis - continue to grow in popularity. Two less familiar but notable applications have been developed at RIKEN.

The multitracer technique uses a cocktail of radioisotopes produced by irradiating heavy-metal targets with 135-MeV/u N, C or O ions. Over 50 elements have been studied, with 20 or more being traced simultaneously in applications ranging from chemistry, biology and medicine to engineering and environmental science. This powerful technique not only allows many elements to be measured at the same time, but makes possible direct comparisons of their behaviour.

Plant breeding has also benefited from N-ion irradiation, which has been found highly effective in inducing mutagenesis in seed embryos at a particular stage during fertilization. These mutations turn out to be more stable and more varied than those induced by low-LET radiation. Particular success has been achieved with garden flowers, where improved varieties of dahlia, rose and verbena have been developed commercially and marketed in the hundreds of thousands.

ACKNOWLEDGEMENTS

First, on behalf of all the attendees, I would like to express our grateful thanks to the local organizers and staff for the excellent organization of the conference and the magnificent hospitality. The receptions, with musical accompaniment, and the city and lab tours, were all memorable and enjoyable events. Arranging for the delegates to experience a typhoon was perhaps not too difficult, but ensuring that it passed overhead 12 hours before the dinner cruise on Tokyo Bay, just in time for the sky to clear and the waves to subside, showed impressive lines of communication to the powers above. The cruise, with its commemoration of the two cyclotrons lying in the deep below, will not easily be forgotten.

We are also indebted to the authors, speakers and Program Committee for presenting and organizing the exciting new material that made the conference worth attending. In particular, I would like to thank the many speakers whose slides I borrowed for my talk.

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