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EIGHTY YEARS OF CYCLOTRONS

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80 YEARS OF CYCLOTRONS (1930)

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64 YEARS OF SYNCHROCYCLOTRONS (1946) 60 YEARS OF ISOCHRONOUS CYCLOTRONS (1950) 54 YEARS OF FFAG ACCELERATORS (1956) 10 YEARS OF PROTON FFAGS (2000) (measured from the first experimental demonstration)

Unfortunately, lack of time obliges me to omit any discussion of:

- electron cyclotrons (microtrons)
- almost all developments after 1970.

RESONANCE ACCELERATION

Ernest Lawrence moved from Yale to Berkeley in 1928, hoping to advance from research on the photoelectric effect to nuclear physics

- an exciting new field promised by Rutherford's 1919 Manchester discovery that MeV particles could induce nuclear reactions
- especially exciting if intense beams could be accelerated artificially!

In the 1920s DC voltages >200 kV were hard to produce and control - but perhaps energy could be added in a series of low-voltage steps, pulsed or AC, synchronized to the particle's arrival: "resonance acceleration"?

First to suggest a practical scheme was Gustav Ising in a 1924 Swedish journal, using drift tubes. Seeing this, a Norwegian grad student in Germany,

Rolf Widerøe, built a two-gap linac powered by a 1-MHz 25-kV oscillator, accelerating Na⁺ and K⁺ ions to ~50 keV (1928).





MAGNETIC RESONANCE - THE CYCLOTRON

At Berkeley, the 27-year-old Ernest Lawrence saw Widerøe's article in 1929.

[In Fall 1930 he set a grad student, Dave Sloan, to repeat and improve on this work. By December 1930 they had achieved 200-keV Hg ions with 11-kV rf, and in 1931 1.26-MeV Hg with 25-kV rf.]

Widerøe's paper had also reported an unsuccessful attempt to build a "beam transformer" - i.e. a betatron, where particles circulating in a magnetic field would be accelerated by raising the field - attributing his failure to inadequate "stabilization" - i.e. focusing - by the field.

Lawrence, seeing Widerøe's diagrams, was perhaps led to consider combining the drift tubes with the magnetic field, using the latter to return the particles repeatedly to the same accelerating gaps - but not understanding German, luckily missed the focusing warning!



THE CYCLOTRON AS SEEN BY THE INVENTOR

THE CYCLOTRON PRINCIPLE

When Lawrence worked out the particle dynamics, he found an unexpectedly favourable result:

For a particle with mass m, charge q, moving with velocity v normal to uniform magnetic induction <u>B</u>, the Lorentz Force $F = q v \times B$ produces a circular orbit, and

$$q R \omega B = m R \omega^2 = m \omega$$
.



"R cancels R", as Lawrence announced triumphantly to his students!

.: "Cyclotron Frequency"

 $\omega = \frac{qB}{m}$ is independent of \underline{v}

- and the orbits are "isochronous".

So:- the electrodes can be excited at a fixed rf frequency,

- the particles will remain in resonance throughout acceleration,
- and a new bunch can be accelerated on every rf voltage peak: - "continuous-wave (cw) operation"

 $R = \frac{mv}{aB}$ Note also that: radius ∞ velocity v.

FIRST CYCLOTRON MODELS - Summer 1930

One of Lawrence's students, Nels Edlefsen, had completed his Ph.D. and was waiting to take up a job in September. He built these two "crude models":

- the first (right) from a flattened glass flask, silvered on the inside,
- the second (left) from "two copper duants waxed together on a glass plate".

The latter "gave slight evidence of working" – enough for them to send an optimistic letter to "Science" in September 1930.



FIRST CYCLOTRON MODELS - Fall 1930



A new student, Stanley Livingston, then took over, building a "<u>4-inch</u>" version in brass. Clear evidence of magnetic field resonance was found in November, and in January 1931 they measured 80-keV protons.

Ions were produced from the residual gas by a heated filament at the centre. Note the liberally applied red sealing wax for vacuum tightness - and Glenn Seaborg's left hand.

MAGNETIC AND ELECTRIC FOCUSING

Not only were all the components of later cyclotrons present in the 4-inch, but Lawrence and Livingston's first paper (1932) shows that they clearly understood the importance of the axial focusing provided by the magnetic and electric fields (as emphasized in these drawings from Lawrence's 1934 patent application).



WAS LAWRENCE REALLY THE INVENTOR?

Several people had considered the cyclotron idea before Lawrence:

- Gabor (1924, unpublished)
- Flegler (1926, unpublished
 - discouraged by Widerøe's pessimism about orbit stability)
- Steenbeck (1927, unpublished)
- Szilard (patent filed, January 1929).

The only person who attempted to build one was Jean Thibaud in Paris, beginning in November 1930, after Lawrence's first paper. He improved on Lawrence by placing the ion source outside the vacuum chamber, but his papers do not claim successful acceleration.

The credit for an invention does not lie just in having an idea - but in going on to demonstrate that it works! On that basis, Lawrence's claim is secure - an important one, as the cyclotron principle is the basis of all circular accelerators except the betatron.

EARLY CYCLOTRONS AT BERKELEY

Pole Diameter	Year	Energy & Particle
	1930	13-keV p
4-inch	1931	80-keV p
11-inch	1932	1.22-MeV p
	1933	5-MeV H_2^+ , 1.5-MeV $lpha$
27-inch	1934	5-MeV d (0.3 µA)
	1936	6.3-MeV d (20 μA)
37-inch	1938	8.5-MeV d (100 μA)
	1939	16-MeV d (100 μA)
ou-inch "Crocker"	1940	16-MeV d (200 μ A), 40-MeV α

Note that the larger machines concentrated on H_2^+ , d & α (Q/A = $\frac{1}{2}$). Operating with maximum magnetic field (~1.8 T) then needed only 14-MHz rf, rather than the challenging 28 MHz required for protons.

THE 11-INCH CYCLOTRON



THE 27-INCH (LATER 37-INCH) CYCLOTRON



Livingston (left) is said to have grumbled: "Lawrence got the Nobel Prize and I got my Ph.D." - but it was awarded after just 8 months' research! Most of Berkeley's 1930s nuclear physics was performed with this machine.

WHY WAS THE MAGNET YOKE SO LARGE?



It had been designed for the Federal Telegraph Company's "Poulsen Arc" Generator for radio transmission in pre-tube days. The Berkeley magnet was built for the U.S. Navy in WWI, and was war-surplus.

THE 60-INCH "CROCKER" CYCLOTRON



Mr. Crocker financed the cyclotron and an associated medical lab. Note the quarter-wave coaxial transmission-line dee stem & rf feeds. Standing, from left: Cooksey, Lawrence, Thornton, Backus, Salisbury. Above: Alvarez, McMillan. (Nobel laureates in red.)

BEYOND BERKELEY

Over 20 cyclotrons were built in the U.S. between 1934 and 1940, stimulated by the diaspora of Lawrence's Ph.D. students and the return of postdoctoral visitors (and another 11 overseas from 1937).

The first departure was Stan Livingston, who built cyclotrons at:

- Cornell (16-inch, 2-MeV protons, 1935)
- MIT (42-inch, 11-MeV deuterons, 1940).

CYCLOTRONS IN 1940

	Baby	Small	Medium	Large
Pole diameter (in.)	13-16	20-27	35-42	60
Energy (MeV)	1-2	3-7	8-12	16
U.S.A.	3	5	14	2
Europe			6	
USSR		1	1	
Japan		1	1	1

ELECTRIC & MAGNETIC FOCUSING

Theoretical treatments of:

- electric focusing in the dee gaps, and
- weak magnetic focusing



were first provided - independently and nearly simultaneously - by

- Morris Rose (Cornell, 20 December 1937) and
- Robert R. Wilson (Berkeley, 27 December 1937).

For a magnetic field H(r), both showed that the vertical tune (as it was later named) is given by:

$$v_{z} = \sqrt{-\frac{r}{H}\frac{\partial H}{\partial r}}.$$

Neither analysed the radial motion – presumably because it was not expected to cause any beam loss. If they had, maybe today we'd speak of "cyclotron oscillations", rather than "betatron oscillations" (in honour of Kerst & Serber's 1941 analysis for that machine).

RELATIVISTIC LIMIT

But the classical cyclotron quickly became a victim of its own success.

As a particle's energy E is raised, Einstein's famous formula $E = mc^2$ tells us that its mass m will increase too,

- so in uniform B the angular frequency qB/m will fall
- and the particle will drift out of phase with constant-frequency rf.

Bethe & Rose (1937) predicted an <u>8-MeV limit</u> for D⁺ with V_{rf} = 50 kV (with $\sqrt{V_{rf}}$ dependence).

Classical cyclotrons reached their zenith with the:

- Stockholm 225-cm (1952) and
- Oak Ridge 86-inch (1954),

both providing 22-MeV p, 24-MeV d, C^{3+} & N⁴⁺

- with $V_{rf} = 200 \text{ kV}$.

WHAT BECAME OF THE CLASSICAL CYCLOTRONS?

The smaller ones suffered various fates:

- conversion to synchro- or isochronous cyclotrons
- bending magnets for particle experiments
- museum exhibits
- dismantled
- forgotten! (Columbia 1965-2007)



The 37-inch back at Berkeley after service as a synchrocyclotron at UCLA



A dee stem from the RIKEN 60" is dumped in Tokyo Bay, 1946.

SYNCHROCYCLOTRONS

The first attempts to reach E > 20 MeV involved giving up isochronism

- allowing an ion's frequency $\omega = q B/m$ (and ω_{rf}) to vary
- at the price of <u>pulsed</u>, rather than continuous operation
- and hence beam currents reduced x 1/1000 to ~ 0.1 μ A

In the synchro- (or frequency-modulated "FM") cyclotron option:

- the <u>magnetic field B ≈ constant</u>,
- the ion frequency $\omega \propto$ 1/m \propto 1/E decreases with E,
- the <u>radius</u> $r \propto v/\omega \propto v E$ increases with $E \rightarrow$ spiral orbit.

Discovery of the <u>Principle of Phase</u> <u>Stability (Veksler '44, McMillan '45)</u> gave confidence that the ions would stay in phase with the rf, oscillating around a "synchronous phase" ϕ_s .



THE 37-INCH SYNCHROCYCLOTRON

The <u>first demonstration of</u> <u>synchrocyclotron operation</u> was by Richardson, Mackenzie, Lofgren & Wright (1946), who shimmed the 37" magnet to simulate the frequency drop expected for deuterons being accelerated to 200 MeV, and installed FM rf.

This was also the <u>first experi-</u> <u>mental demonstration of phase</u> <u>stability</u>.

Lawrence and Reg Richardson (rear) pose by the 37-inch for Life magazine. Note the huge rotating capacitor for frequency modulation (foreground).



THE 184-INCH SYNCHROCYCLOTRON



The Berkeley 184" was begun in 1939 as a classical cyclotron, to be operated with $V_{rf} = 1 \text{ MV}$, but WWII interrupted rf installation and it was used to test mass spectrographic separation of uranium isotopes. FM rf was installed in 1946, yielding 190 MeV d⁺ (700 MeV p in 1959).

LARGE SYNCHROCYCLOTRONS

	Pole diameter	Magnet wt.	Proton energy	Date first
	(m))	(†)	(MeV)	operated
UCRL Berkeley	4.70	4300	350	1946
			740	1957
U. Rochester	3.30	1000	240	1948
Harvard U.	2.41	715	160	1949
AERE Harwell	2.80	660	160	1949
Columbia U.*	4.32	2487	380/560*	1950
McGill U.	2.29	216	100	1950
U. Chicago	4.32	2200	450	1951
GWI Uppsala*	2.30	650	187	1951
Carnegie I.T.	3.61	1500	450	1952
U. Liverpool	3.96	1640	400	1954
LNP Dubna*	6.00	7200	680	1954†
CERN Geneva	5.00	2560	600	1958
NASA SREL	5.00	2765	590	1965
PNPI Gatchina	6.85	7874	1000	1967†
IPN Orsay	3.20	927	200	1977†

* Later modified with spiral sectors.

† Still in operation

THE LARGEST SYNCHROCYCLOTRON



The Petersburg NPI synchrocyclotron at Gatchina, with a pole diameter 45% larger than the Berkeley 184" and a magnet weighing 7874 tons, delivers 1- μ A beams of 1000-MeV protons.

THE THOMAS CYCLOTRON

Back in 1938 Llewellyn Thomas (in reaction to Bethe's predicted energy limit) had pointed out a way to allow cyclotrons to be run isochronously (and thus with intense cw beams) at relativistic energies: the vertical defocusing associated with rising field $B = \gamma B_0$ may be countered by an azimuthally varying field (AVF) $B(\theta) = \overline{B}(1 + f \cos N\theta).$



This produces a non-circular 'scalloped' orbit, and a qv_rB_θ component of F_z - everywhere a restoring force, to counter the defocusing $qv_\theta B_r$ (tho' unstable for N < 3):

 $v_z^2 = -\beta^2 \gamma^2 + \frac{1}{2} f^2$

- a simple result from some intimidating maths.

(Thomas was a Welsh-born, Cambridge-educated US immigrant, probably better known for

- Thomas precession
- Thomas-Fermi statistical model of the atom.)



THE MATERIALS TEST ACCELERATOR (MTA)

Thomas's idea was neglected for 12 years, possible reasons being:

- the perceived difficulty of creating pure $\cos N\theta$ fields;
- the onset of World War II;
- synchrocyclotrons' success in vastly extending the energy range.

But in 1950 an apparent lack of uranium reserves led to a crash US program to breed fissile isotopes by neutron irradiation. The Livermore Materials Test Accelerator was a 350-MeV, 500-mA cw deuteron linac (estimated to cost \$300M).

Since 12 MHz was the highest frequency for which cw rf tubes were available, the vacuum tank diameter was 18 m. Alvarez built Mark I, the first 18-m long section (the biggest vacuum tank ever?), achieving 50 mA at 10 MeV in 1953, with 18 MW rf.



THE FIRST SECTOR-FOCUSING CYCLOTRON

Back at Berkeley, Reg Richardson argued that a 300-MeV Thomas cyclotron could be built for a lot less than \$300M. In 1950, with Kelly, Pyle, Thornton and Wright, he built two 3-sector electron models. Like classical cyclotrons they required very precise shaping of the magnetic field, but 54 circular trim coils enabled this to be done more

efficiently than with clumsy steel shims.

Electrons were successfully accelerated to $\beta = 0.5$ (the same as 300-MeV deuterons) and extracted with 90% efficiency - but the work was not declassified till 1956!



Note the harmonic pole profile.



EARLY RADIAL-SECTOR CYCLOTRONS I

Several classical cyclotrons were modified with radial sectors in the 1950s to provide stronger axial focusing and higher beam intensity (Los Alamos, MIT,.....) - but were not made isochronous.

The first sector-focused ion cyclotron was completed by Heyn & Khoe at Delft in 1958. It had 4 sectors, a pole diameter of 86 cm and a top proton energy of 12.7 MeV. The hill pole-tips were carefully shaped.



Fig. 21. Shims on pole tips of the Delft cyclotron

EARLY RADIAL-SECTOR CYCLOTRONS II

Others quickly followed.

	Pole diameter (m)	Sectors	Energy (MeV/u)	1 st beam
Delft	0.86	4	12.7 (p)	1958
Birmingham	1.02	3	5.5 (d)	1961
Moscow	1.50	3	16 (d)	1961
Karlsruhe	2.25	3	25 (d)	1962
Orsay	1.20	3	17 (α)	1965
Milan	1.66	3	45 (H [_])	1965

Notice that only the last machine has a top energy >25 MeV/u, the maximum for classical cyclotrons. That's because it's difficult to achieve high flutter F^2 in a single compact magnet.

To achieve stronger focusing, and to reach higher energies, many cyclotron designers turned to the strong focusing of spiral sectors.

COMMERCIAL RADIAL-SECTOR CYCLOTRONS

Nowadays there are ~300 small radial-sector cyclotrons

- with maximum energies 3.5 MeV to 50 MeV
- supplying beams of H^+ , H^- , D^+ , D^- , ³He and ⁴He
- at beam intensities up to 2 mA
- mostly used for producing radioisotopes for medicine & industry
- in at least 34 models
- supplied by at least 8 commercial manufacturers:
 - Advanced Cyclotron Systems (formerly EbCo) Canada
 - General Electric USA
 - Japan Steel Works Japan
 - Ion Beam Applications Belgium
 - Scanditronix Wellhofer Sweden
 - Siemens Germany
 - Sumitumo Heavy Industries Japan
 - The Cyclotron Corporation USA

Note that 3 cyclotrons operated by TRIUMF for MDS Nordion supply isotopes sufficient for 2,500,000 medical tests/treatments per year.

ALTERNATING LENSES IN SPIRAL-SECTOR CYCLOTRONS



Kerst (1955) suggested using spiral sectors to provide "strong" alternating focusing in FFAG accelerators.

Spiral angle $\epsilon \gg \kappa \rightarrow edge$ -crossing angles $\kappa + \epsilon$ (a strong F lens) or $\kappa - \epsilon$ (a less strong D lens)

Overall we have
$$v_z^2 = -\beta^2 \gamma^2 + \frac{N^2}{N^2 - 1} F^2 \left(1 + 2\tan^2 \varepsilon\right)$$

The powerful $2\tan^2 \varepsilon$ term enhances the flutter focusing ×3 for ε = 45°. Spiralling was quickly adopted for isochronous cyclotrons, is now used for most proton machines >40 MeV, and has allowed designs ≤12 GeV.

EARLY SPIRAL-SECTOR CYCLOTRONS

Spiral pole tips were added to low-energy cyclotrons at U. Illinois ('58) and Dubna ('59), but new cyclotrons quickly showed that spiral sectors made relativistic energies readily achievable.

	Diameter of	Sactora	Maximum	Energy	Date first
	pole (m)	Sectors	spiral	(MeV)	operated
UCLA	1.25	4	47 °	<mark>50</mark> р/Н	1960
UCRL Berkeley	2.24	3	56 °	<mark>60</mark> p	1961
U. Colorado	1.32	4	45°	30 H	1962
Oak Ridge NL	1.93	3	30 °	75 p	N
U. Michigan	2.11	3	43 °	37 p	1963
Philips Eindhoven	1.30	3	35 °	30 p	N
U. Manitoba	1.17	4	48°	50 H	1964
Philips Duphar	1.40	3	45°	28 p	N
V.U. Amsterdam	1.40	3	37 °	33 p	1965
AERE Harwell	1.78	3	45°	<mark>53</mark> p	N
Michigan S.U.	1.63	3	10 °	<mark>56</mark> p	• • •
Washington U.	1.37	3	low	29 p	N

UCLA 50-MeV p/H⁻ CYCLOTRON (1960)



- 49-inch diameter poles very compact for 50 MeV
- RF electrodes are not D-shaped "in-valley" spiral cavities
- Followed Colorado's lead by using H⁻ ions easy beam extraction

OAK RIDGE ANALOGUE-II ELECTRON MODEL (1962)



- Beam extracted at β = 0.86 (record for any sector-focused device)
- Specially-shaped pole-tip coils produce isochronous AV field
- Elegantly preserved as two coffee tables.

LARGER SPIRAL-SECTOR CYCLOTRONS

	Pole dia.	Sactora	Max ^{m.}	Proton / Ion	First
	(m)	Sectors	spiral	energy (MeV)	beam
U. Maryland	2.67	4	52°	100 / K180	1970
CGR-MeV 930	2.16	4	53°	95 / K115	1972
RCNP Osaka	2.30	3	52°	85 / K140	1974
TRIUMF Vancouver	17.17	6	70 °	70- <mark>520</mark> / —	1974
INP Kiev	2.40	3	45°	80 / K140	1976
Dubna U400M	4.00	4	40 °	— / K540	1991
IBA/SHI C235	2.24	4	60°	232 / —	1998
PNPI Gatchina	2.05	4	60°	45-80 / —	

Notice that the number N of sectors chosen rises with top energy. This reflects the behaviour of the radial tune:

$$v_r \approx \sqrt{1+k} = \gamma$$

and a desire to avoid approaching the dangerous intrinsic resonances $v_r = N/n$ where *n* is a low integer. The general rule is to keep

$$N \ge 4\hat{\gamma}.$$

AXIAL INJECTION

Axial injection makes it possible to inject beams into a cyclotron at low energy from the large or complex sources needed to produce negative, polarized or heavy ions.

Two types of 90° electrostatic deflector were developed:





8-kV mirror inflector for 10 keV d (Powell & Reece, Birmingham) 15-kV spiral inflector for 50-kV p (Belmont & Pabot, Grenoble)



By using a variety of foil shapes for partial extraction at lower energies, TRIUMF currently extracts 3 beams of variable energy and intensity simultaneously – and proposes to add a 4th.

SEPARATE-SECTOR (RING) CYCLOTRONS

First proposed by Hans Willax (1962) for the Swiss meson factory - a 590-MeV proton ring cyclotron.

In separate-sector cyclotrons:

- sectors have individual yokes & coils
- the valleys are:
 - magnetic field-free
 - available for rf, injection, extraction & diagnostics
- Small pole gaps need less amp-turns and give hard-edge fields
- the flutter $F^2 = H^{-1} 1$ can reach ≈ 1 (where H = hill fraction), making it possible to reach $\beta\gamma \approx 1$ ($\approx 400 \text{ MeV/u}$) with radial sectors).
- a medium-energy injector is needed.



PSI 590-MeV RING CYCLOTRON (2)

High energy gain \rightarrow high turn separation \rightarrow efficient extraction.

The original hope was to achieve an extraction efficiency >90%, allowing acceleration of $100-\mu A$ proton beams.



In practice it was found possible to achieve complete turn separation on the final orbit with the help of off-centring at injection, radial tune $v_r \approx 1.5$ at extraction, and very short bunches (to restrict energy spread $\propto \cos \phi$). With 99.97% extraction efficiency, 2-mA external beams are routine, and 3-mA beams are planned.

PSI's 1.3 MW beam remains the world's most powerful.

LARGE SEPARATE-SECTOR CYCLOTRONS

	Pole dia.	Magnet	Sectors	Proton / Ion	First
	(m)	wt. (t)	(Spiral)	Energy (MeV)	beam
PSI Villigen	9.30	1990	<mark>8</mark> 35°	590	1974
Indiana UCF	6.92	2000	4 —	208 / K210	1975
HMI Berlin	3.80	360	4 —	72 / K130	1977
ISN Grenoble	4.50	400	4 —	K160	1981
GANIL CSS1 & 2	6.90	1700	4 —	K380	1982
NAC Stellenbosch	9.09	1400	4 —	220 / K220	1985
RIKEN RRC	7.12*	2100	4 —	210 / K540	1986
IMP Lanzhou	7.17	2000	4 —	K450	1988
RCNP Osaka	8.00*	2200	<mark>6</mark> 30°	400 / K400	1991
RIKEN fRC	6.60*	1320	4 —	K570	2006
RIKEN IRC	8.30*	2720	4 –	K980	2006
RIKEN SRC	10.72*	8300	6 —	K2600	2006

* Extraction orbit diameter

Note that all but two of these are radial-sector cyclotrons

- mainly designed for heavy ions (where $\beta\gamma < 1$).

$$\frac{T_{\max}}{A} = K \left(\frac{Q}{A}\right)^2$$

HIRFL K450 SEPARATE SECTOR CYCLOTRON



Energy: 10-100 MeV/u, 10¹⁰~10¹¹ pps (C-Bi)

COMPACT SUPERCONDUCTING CYCLOTRONS

The first superconducting cyclotron design - the K520 at AECL Chalk River (Bigham, 1979).

The drawing shows the upper and lower coils in their annular cryostat, within a complete cylindrical steel yoke that also provides magnetic shielding.

Access for rf, vacuum, ion source, etc., is from top and bottom.

Slow government funding led to completion after:-



K500 SUPERCONDUCTING CYCLOTRON AT NSCL/MSU





- The first cyclotron with superconducting coils to operate (Blosser 1982) - can accelerate heavy ions (atomic number Z, mass A) to $500(Z/A)^2$ MeV/u.

COMPACT SUPERCONDUCTING CYCLOTRONS

	Pole dia.	Magnet	Sactore	Proton / Ion	First
	(m)	weight (t)	Sectors	Energy (MeV)	beam
NSCL MSU	1.42	90	3	K520	1982
AECL Chalk River	1.39	170	4	K520	1985
NSCL MSU	2.20	265	3	K1200	1988
Harper Hospital	0.64	22	3	<mark>50</mark> (d)	1988
Texas A&M U	1.42	90	3	K520	1988
Oxford Instruments	0.50	1.5	3	12 (H)	1990
LNS Catania	1.80	176	3	K800	1994
KVI Groningen	1.88	320	3	200 / K600	1994
ACCEL (PSI)	≈1.6	90	4	250 / —	2006
ACCEL (RPTC Munich)	≈1.6	90	4	250 / —	2008
Kolkata	1.42	90	3	K520	2009
IBA/JINR C400	3.74	660	4	260 / <mark>K1600</mark>	
LNS Catania	≈2.7	350	4	260 / <mark>K1200</mark>	

SEPARATED-ORBIT CYCLOTRONS

SOCs were conceived (Russell, 1963) as extremely intense GeV proton drivers for spallation neutron sources more powerful than a reactor. The turns are completely separated, each having its own beam pipe and magnet, avoiding any betatron resonances and giving 100% extraction.



To achieve a 65-mA beam at 1 GeV for Chalk River's Intense Neutron Generator (ING) project, 60 turns were proposed, and 100 rf cavities. For energies <800 MeV, a flat spiral was found to be acceptable. At Oak Ridge a 200-800 MeV SOC and an 11-turn 10-50 MeV prototype were designed. One of the 12 magnet sectors was built (right).

THE TRITRON SUPERCONDUCTING SOC



The Munich K85 TRITRON was the only SOC

ever built (Trinks, 1998). It had 12 tiny magnet



sectors, each 6 cm high with 20 2-cm square channels containing the coils, copper shielding and 1-cm beam aperture. With cryogenic vacuum and 6 superconducting rf cavities, a 40-MeV S¹⁴⁺ beam from a tandem was accelerated through 6 turns to 72 MeV.

FFAGs - Fixed Field Alternating Gradient accelerators

Fixed Magnetic Field - members of the CYCLOTRON family¹

Magnetic field	Fixed Frequency	Frequency-modulated
variation B(0)	(CW beam)	(Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Isochronous	FFAG



1. E.M. McMillan, Particle Accelerators, in Experimental Nuclear Physics, III, 639-786 (1959)

THE FFAG IDEA

- was to introduce alternating "strong" focusing to fixed-field accelerators (enabling higher rep rates and beam currents than in synchrotrons)
- either by alternating +ve and -ve bending magnets with radial edges, creating Alternating Gradient focusing (Ohkawa, Kolomensky, Symon, 1953-4)
- or by using spiral sector magnets (Kerst 1955) as later used in cyclotrons.







K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett and K.M. Terwilliger, *Phys. Rev.* 103, 1837 (1956)

BASIC CHARACTERISTICS OF FFAGs

are determined by their FIXED MAGNETIC FIELD

- Spiral orbits
 - needing wider magnets, rf cavities and vacuum chambers (compared to AG synchrotrons)
- Faster rep rates (up to kHz?) limited only by rf capabilities

 not by magnet power supplies
- Large acceptances
- High beam current

The last 3 factors have fuelled the interest in FFAGs over 50 years!

The most intensive studies were carried out by Symon, Kerst, et al. at the Mid-west Universities Research Association (MURA) in the 1950s and 60s – who adopted the "scaling" principle

- and built several successful electron models.

SCALING DESIGNS

Betatron resonances were a big worry in early days, because of low $\Delta E/turn$:

So "Scaling" designs were used, with:

- the same orbit shape at all energies
- the same optics
- the <u>same tunes</u> """"" \Rightarrow no crossing of resonances!

To 1st order, the tunes are given by

$$v_r^2 \approx 1 + k$$
 $v_z^2 \approx -k + F^2(1 + 2\tan^2 \varepsilon)$

So constant high tune values require:

• constant average field index $k(r) \equiv \frac{r}{B_{av}} \frac{dB_{av}}{dr} >> 0$ where $B_{av} \equiv \langle B(\Theta) \rangle$

(and hence $B_{av} = B_0 (r/r_0)^k$ and $p = p_0 (r/r_0)^{(k+1)}$)

• constant magnetic flutter F^2 (i.e. constant profile $B(\Theta)/B_{av}$) B_F (maximized for radial sectors by choosing $B_D = -B_F$ $_0$

• constant spiral angle ε (sector axis follows $R = R_0 e^{\Theta \cot \varepsilon}$)



MURA Electron FFAGs

400 keV radial sector \longrightarrow

50 MeV radial sector

120 keV spiral sector



Courtesy of MURA



K.R. Symon, Proc PAC03, 452 (2003)



Courtesy of MURA

SUBSEQUENT HISTORY

In spite of the success of the electron models, none of MURA's proposals for **proton FFAGs** (0.5, 10, 15, and 20 GeV) were funded. Nor were proposals for 1.5-GeV × 4-mA spallation neutron sources by Argonne and Jülich in the 1980s. The first **proton FFAGs** were Mori's at KEK (1 MeV 2000, 150 MeV 2003).

Since 2000 an explosion of interest!

- 6 more now operating (for p, e, α) and 3 more (e) being built
- ~15 designs under study:
 - for protons, heavy ions, electrons and muons
 - many of novel "non-scaling" design
- with diverse applications:
 - cancer therapy
 - industrial irradiation
 - driving subcritical reactors
 - intense many-GeV proton beams
 - producing neutrinos.



KEK Proof-of-Principle 1-MeV proton FFAG

FFAG Complex at Kyoto University Research Reactor Inst.



The World's first test of Accelerator-Driven Sub-critical Reactor (ADSR) operation was performed in March 2009.

LINEAR NON-SCALING (LNS) FFAGs

FFAGs look attractive for accelerating muons in μ Colliders or ν Factories

- Large acceptance (in r & p) eliminates cooling & phase rotation stages
- Rapid acceleration (<20 turns) \rightarrow resonance crossing ignorable (Mills '97)
- Less expensive than recirculating linacs.

NON-SCALING approach first tried by Carol Johnstone (arc 1997, ring '99)

• "LINEAR" magnets with <u>constant</u> <u>negative</u> field gradients (i.e. quadrupoles)



- Greater momentum compaction (& hence narrower radial apertures);
- Less orbit-time variation \rightarrow fixed rf frequency & cw operation;
- No multipole field components to drive betatron resonances >1st order;
- Simpler construction ($B \propto r$ rather than r^k).

LNS-FFAGs chosen for 12.5-25 & 25-50-GeV μ stages in v-Factory I D Study

EMMA - THE FIRST NON-SCALING FFAG



EMMA is a 10-20 MeV electron LNS-FFAG model for a 10-20 GeV muon accelerator for a neutrino factory - currently undergoing beam commissioning at Daresbury, UK.

REES'S ISOCHRONOUS IFFAG

G.H. Rees^{1,5} has designed several FFAGs using novel 5-magnet "pumplet" cells, in which variations in field gradient and sign enable each magnet's function to vary with radius - providing great flexibility.



- The example shown is an isochronous design (IFFAG) for accelerating muons from 8-20 GeV in 16 turns.
- This is remarkable in achieving both isochronism and vertical focusing at highly relativistic energies (77 $\leq \gamma \leq$ 190) without invoking spiral magnet edge focusing [recall isochronous $\Delta v_z^2 = -(r/B_{av})(dB_{av}/dr) = -\beta^2 \gamma^2$].
- The highest energy spiral-sector isochronous cyclotron design had $\gamma \leq 15$.
- 3 magnet types per cell (instead of 2) provide extra degrees of freedom, so that the vertical focusing term is no longer restricted to $F^2(1 + 2\tan^2 \epsilon)$.

FINAL THOUGHTS

- Lawrence's magnetic resonance principle underlies all recirculating accelerators
- Lawrence's classical cyclotron has proved a potent source of more advanced fixed-field accelerators:
 - Synchrocyclotrons
 - Isochronous cyclotrons
 - FFAGs
- Cyclotrons have proved remarkably adaptable to new technologies and techniques:
 - Injection from external ion sources
 - Injection and extraction by stripping
 - Separate-sector ring layouts
 - Superconducting magnets

Let's wish them another productive 80 years!

REFERENCES AND ACKNOWLEDGEMENTS

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DISCOVERIES WITH CLASSICAL CYCLOTRONS

Though cyclotrons' energy stability was poorer, their energy range overtook that of dc accelerators during the 1930s, enabling broader studies of:

- nuclear reactions
- neutron production and interactions
- induced radioactivity.

"More new isotopes have been made artificially than there are stable ones in nature" (Kurie, 1938)

With the Berkeley 27/37-inch these included :

- ¹⁴C, ²⁶Na, ³²P, ⁵⁹Fe, ¹³¹I
- Technetium (first artificial element),

and with the 60-inch:

- Astatine, Neptunium, Plutonium (all in 1940)
- Curium, Berkelium, Californium, Mendeleevium (post-war).

APPLICATIONS

Radioisotopes were quickly adopted as tracers for:

- chemical reactions
- biological processes in plants and animals
- medical studies.

Medical <u>treatments</u> were developed, under the leadership of Ernest's brother, John Lawrence "the father of nuclear medicine":

- ³²P for polycythemia & leukemia
- ¹³¹I for thyroid conditions
- neutron cancer therapy.

About 200 patients were treated with neutrons, though the doses were later judged to have been too high.

The photo shows the first patient, Robert Penney (November 1939) with Robert Stone (left) and John Lawrence.



IMPACT OF SYNCHROCYCLOTRONS

In 1946 synchrocyclotrons provided a dramatic advance in energy:

- for deuterons from 16 MeV to 190 MeV
- (and a little later) for protons from ~20 MeV to 350 MeV.

S-Cs were the energy frontier machines from 1946-53 (11 big ones were built then), opening up the new field of particle physics by:

- making possible controlled experiments with pions and muons;
- enabling measurement of their production, properties, decay modes and interactions.

S-Cs also pioneered <u>ion beam therapy</u>. In 1946 Robert Wilson, Lawrence's one-time student, pointed out that ions might be more effective than X-rays in treating deep-seated tumours because of their finite range and Bragg peak. S-Cs gave the right energy beams:

- trials began at the Berkeley 184" in 1952, at Uppsala S-C in 1956
- a joint MGH/Harvard S-C program (1961-2002) treated 9115 patients
- other programs with S-Cs in France, Japan and the USSR.

SYNCHROCYCLOTRON OPERATION

Synchrocyclotrons proved much easier to commission and operate than classical cyclotrons:

- The magnetic field tolerances were much more relaxed;
- Beams would remain in resonance over thousands of turns;
- Low rf voltages (~20 kV) were adequate for reaching nOO MeV.

On the other hand:

- Pulsed operation (60-2000 Hz) lowered beam currents to <1- μ A;
- Pulse stretching was needed to permit coincidence measurements;
- The mechanical systems used for rapid rf frequency modulation were unreliable.

From 1967 to 2007 only one new synchrocyclotron was built, but, led by T. Antaya, there is now a growing interest in <u>superconducting</u> <u>synchrocyclotrons</u> using high-field magnets for <u>applications</u> where <1- μ A beams suffice. Thus Still River Systems is building, and Varian and IBA are considering, 250-MeV proton cancer therapy machines.

A PET CYCLOTRON - THE ACSI TR14/19



The TR14/19 (originally TR13) accelerates 300 μ A H⁻ to 14-19 MeV or D⁻ to 7-9.5 MeV. [Note the field-measuring apparatus.]

These energies are sufficient to produce the short-lived tracer isotopes needed for PET scans, such as ¹¹C ($\tau_{1/2} \approx 20$ m), ¹³N (10 m), ¹⁵O (2 m) and ¹⁸F (110 m), elements common in biological molecules.

IBA C230 PROTON THERAPY CYCLOTRON (1998)



- A very compact 230-MeV proton cyclotron
- Now installed at 14 hospitals worldwide

TRIUMF 70-520 MeV H⁻ CYCLOTRON (in 1972)



- Note iron-free valleys to maximize flutter
- Spiral angle increases with radius and energy from 0° to 70°
- H⁻ ions allow 4 separate extracted beams, but restrict hill field to 0.6 T

PSI 590-MeV RING CYCLOTRON (1)



The PSI 590-MeV 2-mA separated-sector ring cyclotron, showing the 8 spiral magnets and 4 1-MV rf cavities

MULTISTAGE CYCLOTRON SYSTEMS

All separate-sector cyclotrons require an injector, and so involve at least two accelerator stages.



The RIKEN RadioIsotope Beam Factory (RIBF), in its "Fixed-Energy Mode" shown here, involves 1 linac and 4 cyclotron stages and delivers 345-MeV/u beams for the mass range A = 50 - 92. (H refers to the rf harmonic: H = ω_{rf}/ω_{ion} .)

RIKEN K2600 SUPERCONDUCTING RING CYCLOTRON



Completed November 2005 – the 140-ton cold mass cooled to 4.5K. A 345 MeV/u beam of ²⁷Al¹⁰⁺ was extracted in December 2006, followed by U⁸⁶⁺ in March 2007.

HIGH-ENERGY RING CYCLOTRONS

Several designs have been proposed for accelerating high-intensity cw beams to GeV energies.



This recent one is a scaled-up version of the PSI 70-MeV injector and 590-MeV ring cyclotron, designed to produce a 10-mA 1-GeV proton beam for Accelerator-Driven Subcritical Reactor (ADSR) operation.

HARPER HOSPITAL SUPERCONDUCTING CYCLOTRON

The first superconducting cyclotron built for medical purposes was the 50-MeV _____ deuteron machine used for neutron therapy at the Harper Hospital, Detroit (Blosser, 1988).

This machine is small and light enough (22 t) to be mounted on gantry rings (diameter 4.6m)² and rotated ±90° around the patient.



ACCEL/VARIAN PROTON THERAPY CYCLOTRON

This superconducting cyclotron (based on a design by Blosser et al.) delivers a 250-MeV beam for proton therapy. The 90-ton magnet yoke is 3.1 m in diameter.

Two machines are in operation - one at PSI, Villigen, and the other at Rinecker Proton Therapy Center, Munich. Beam is delivered by a beam line mounted on a conventional rotating gantry.

