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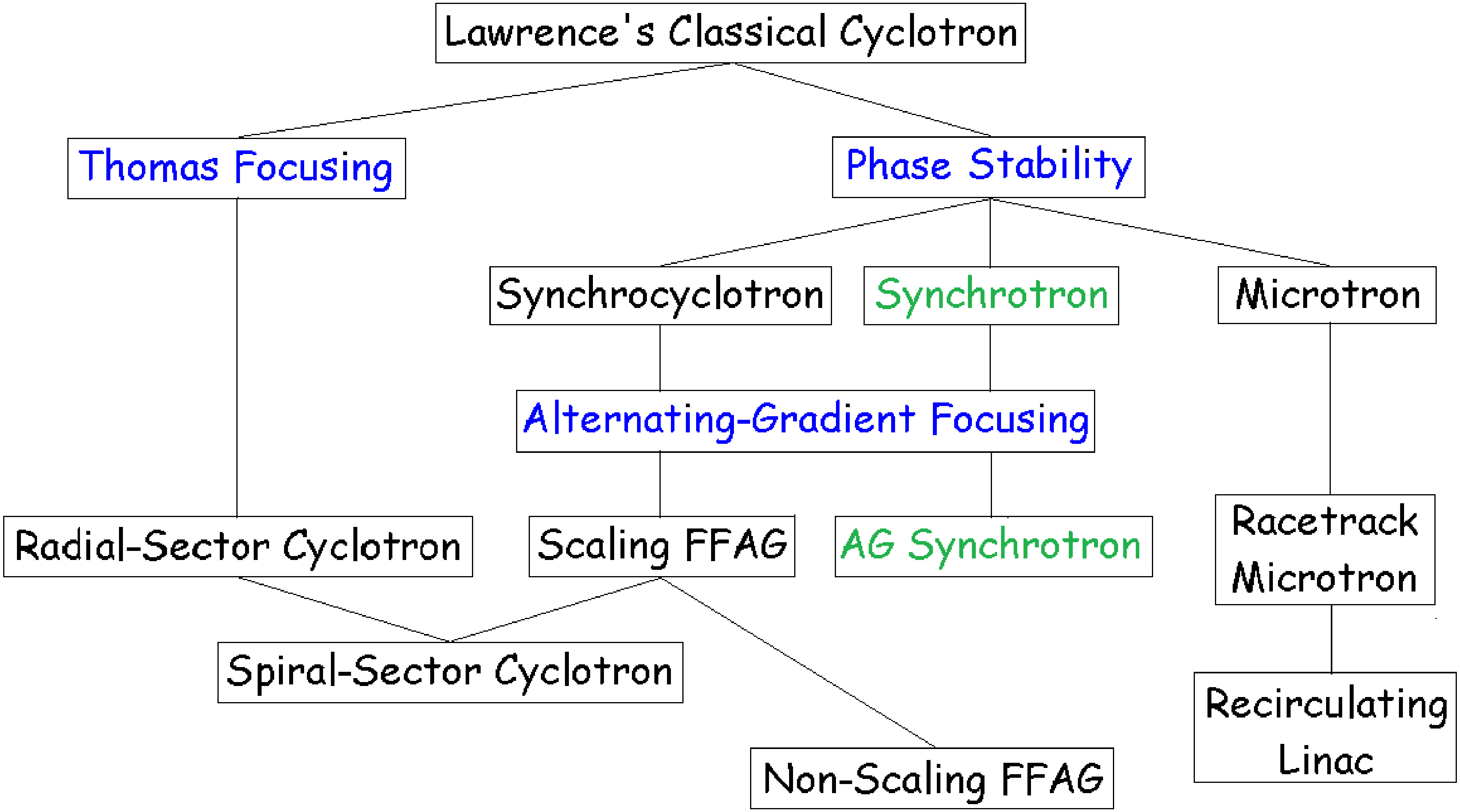
CYCLOTRONS:
FROM SCIENCE TO HUMAN HEALTH

M.K.Craddock

Department of Physics and Astronomy,
University of British Columbia,
and
TRIUMF

E-mail: craddock at triumf.ca

THE CYCLOTRON – ANCESTOR OF ALL "CIRCULAR" RF ACCELERATORS


Lawrence's Classical Cyclotron

Thomas Focusing

Phase Stability

Synchrocyclotron

Synchrotron

Microtron

Alternating-Gradient Focusing

Radial-Sector Cyclotron

Scaling FFAG

AG Synchrotron

Racetrack Microtron

Spiral-Sector Cyclotron

Non-Scaling FFAG

Recirculating Linac

Fixed magnetic-field accelerators (cyclotron family) in black

Varying magnetic-field accelerators (synchrotron family) in green

WHY CELEBRATE CYCLOTRONS NOW?

It's their 80th anniversary:

September 1930: Ernest Lawrence reports initial experiments in "Science".
December 1930: Sharp magnetic resonance peaks & 6-keV H_2^+ ions.
January 1931: A larger magnet: 80-keV H_2^+ ions.
April 1931: Livingston awarded Ph.D.

And where better than in California!

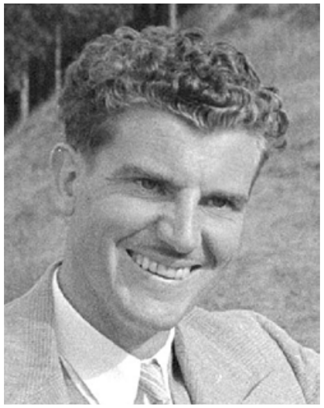
…where Lawrence built the early machines, culminating in the 184" synchrocyclotron (740-MeV protons) and 6-GeV Bevatron, developed ion linacs,

- and founded the UC Berkeley Rad Lab, now LBNL.

...and where Reg Richardson, his ex-student, first demonstrated:

- synchrocyclotron operation & phase stability
- a Thomas sectored cyclotron
- (at UCLA) a >25-MeV isochronous cyclotron

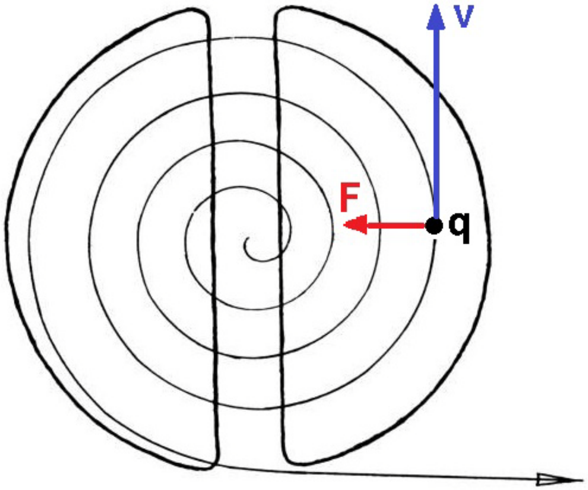
and proposed an H^- cyclotron meson factory (later built at TRIUMF).



THE CYCLOTRON PRINCIPLE

When the 27-year-old Lawrence worked out the particle dynamics for his scheme of immersing Widerøe's drift tubes in a magnetic field, he found an unexpectedly favourable result:

For an ion with mass m, charge q, moving with velocity $\underline{v}$ normal to uniform induction $\underline{B}$, the Lorentz Force $\underline{F} = q\,\underline{v} \times \underline{B}$ produces a circular orbit, and



$$q\,\cancel{R}\omega\,B = m\,\cancel{R}\omega^2 = m\,\omega.$$

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

∴ "Cyclotron Frequency" $\boxed{\omega=\frac{qB}{m}}$ is independent of $\underline{v}$

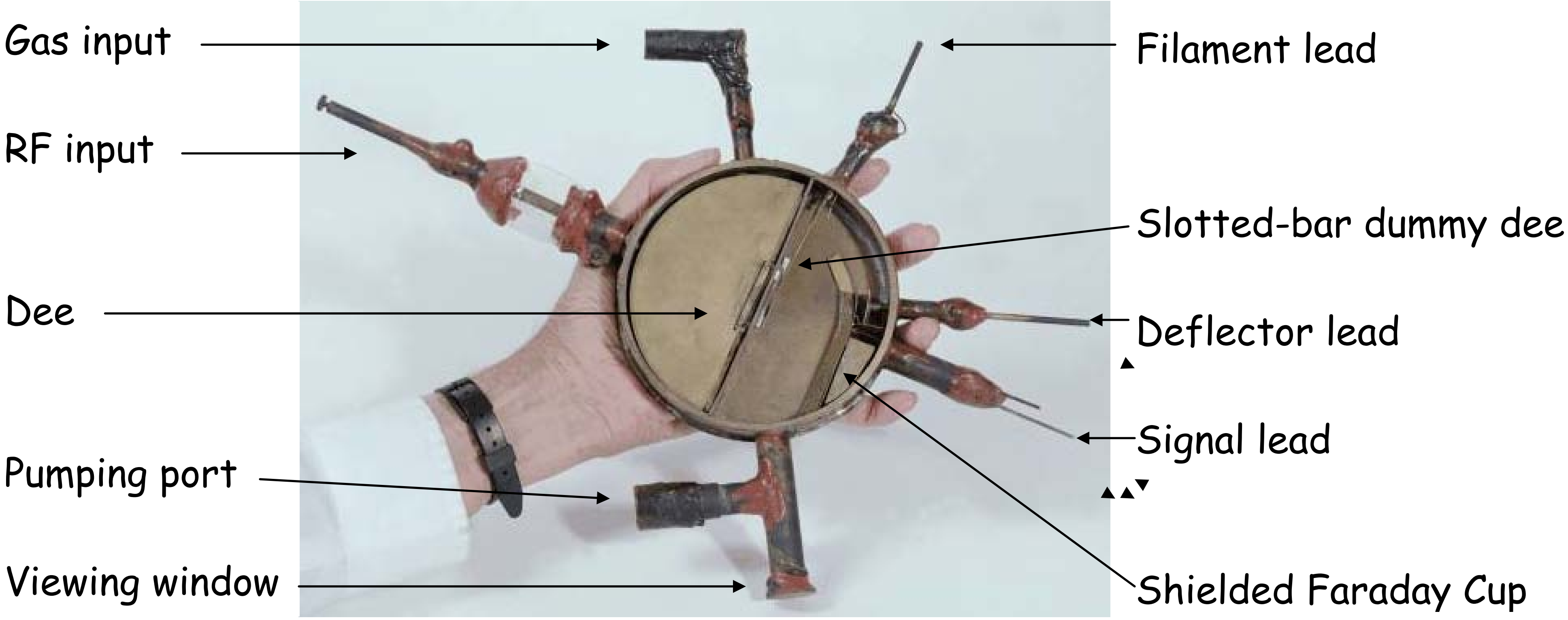
- and the orbits are "isochronous".

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"

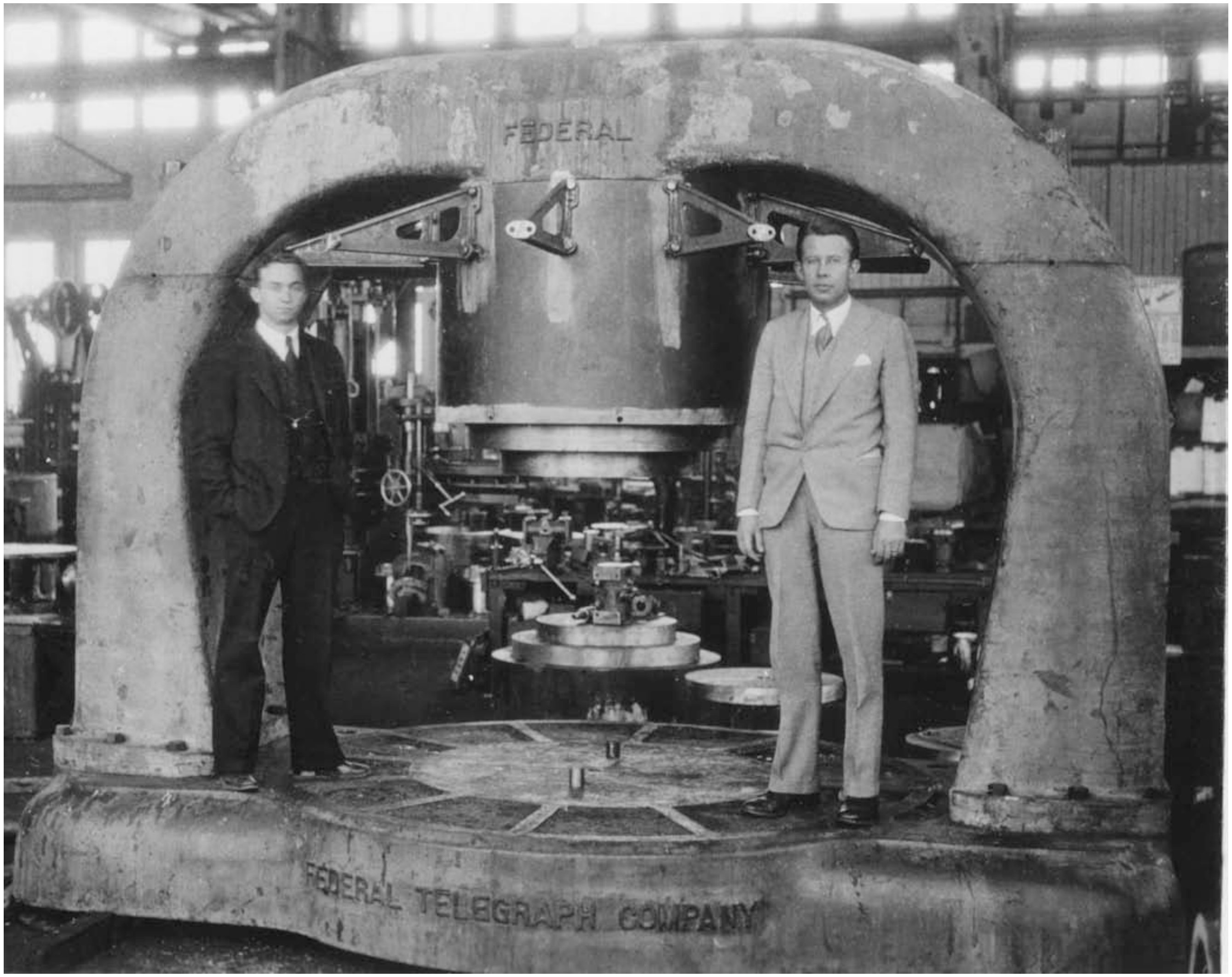
FIRST CYCLOTRON MODELS – Fall 1930



A new student, Stanley Livingston, then took over, building a "4-inch" 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.

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.

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

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 :

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

and with the 60-inch:

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

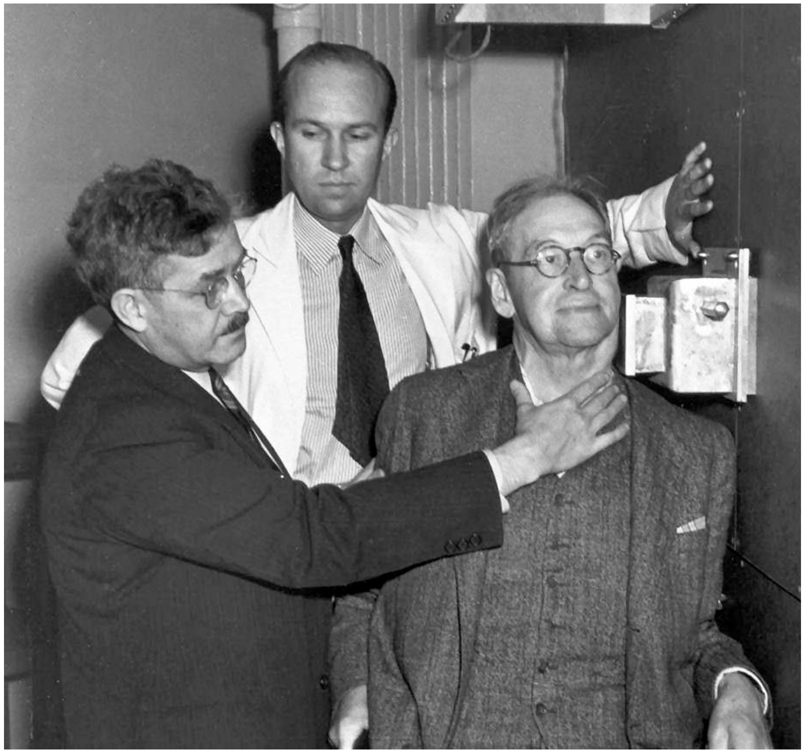
APPLICATIONS

Radioisotopes were quickly adopted as tracers for:

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

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

- ^{32}P for polycythemia & leukemia
- ^{131}I 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.

RELATIVISTIC LIMIT

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

As a particle's energy E is raised, Einstein's formula $E = mc^2$ tells us that its inertial 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 8-MeV limit 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+} & N^{4+}
- with $V_{rf} = 200$ kV.

SYNCHROCYCLOTRONS

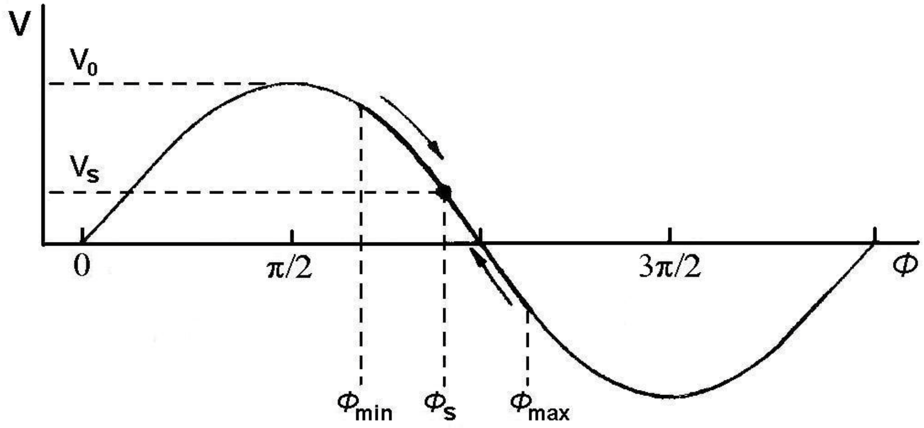
The first attempts to reach $E > 20$ MeV involved giving up isochronism

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

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

- the magnetic field $B \approx$ constant,
- the ion frequency $\omega \propto 1/m \propto 1/E$ - decreases with E,
- the radius $r \propto v/\omega \propto v\,E$ - increases with E → spiral orbit.

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



THE 37-INCH SYNCHROCYCLOTRON

The first demonstration of synchrocyclotron operation 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 first experimental demonstration of phase stability.

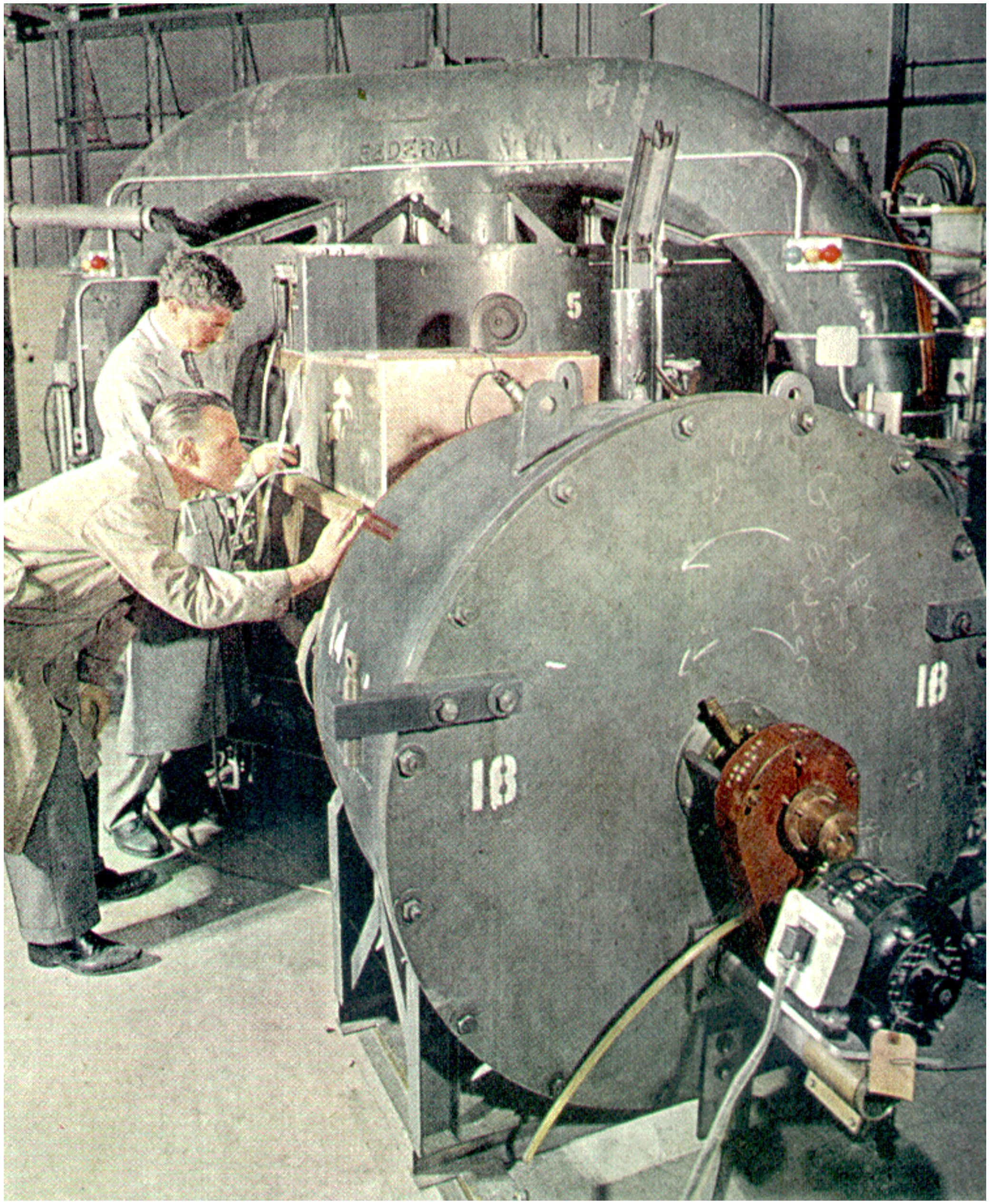


Photo by Ralph Crane

Lawrence and Reg Richardson (rear) pose by the converted 37-inch.
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 $V_{rf} = 1$ 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 (m))	Magnet wt. (t)	Proton energy (MeV)	Date first 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

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 ion beam therapy. 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:

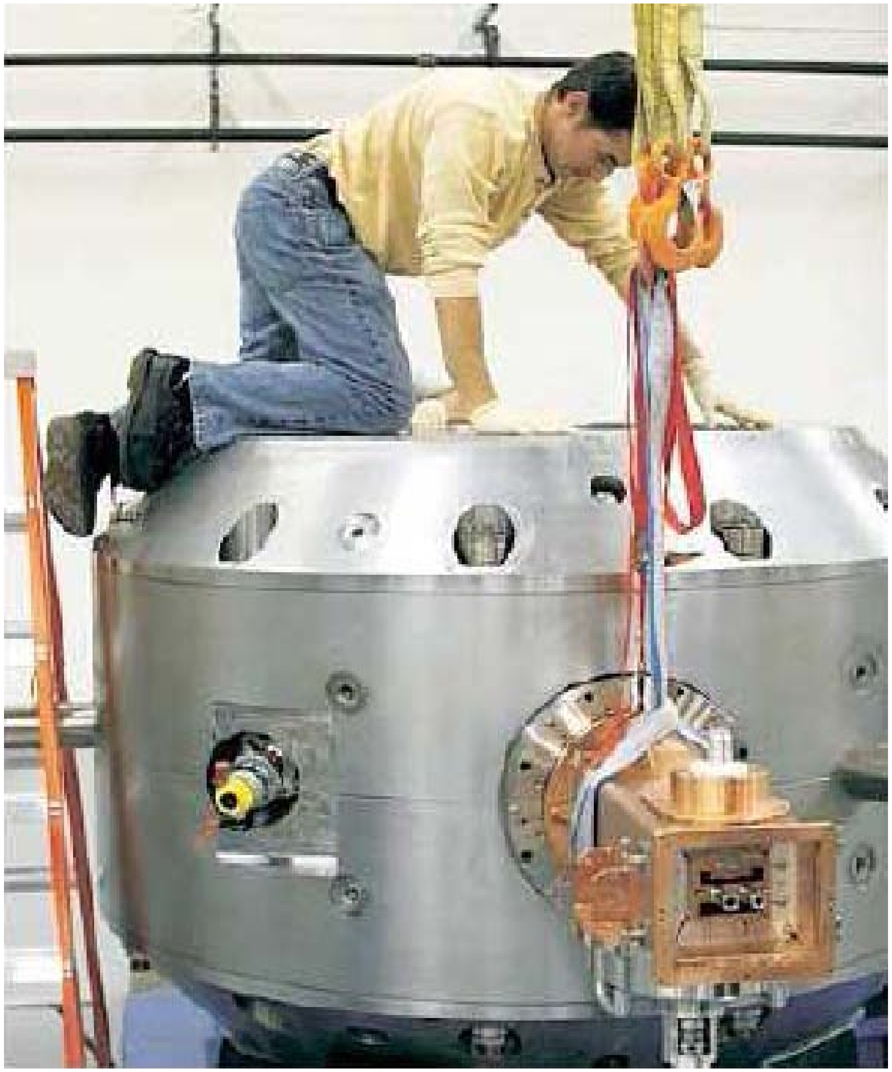
- trials began at the Berkeley 184" in 1952, at Uppsala S-C in 1956
- a joint MGH/Harvard S-C program (1961-2002) treated 9115 patients
- other programs with S-Cs in France, Japan and the USSR.

SUPERCONDUCTING SYNCHROCYCLOTRONS

A recent growth of interest in proton therapy – and desire to cut costs - has led to proposals for superconducting synchrocyclotrons:

- higher magnetic fields → smaller radii r → lighter magnets $\propto r^3$.

Tim Antaya (MIT) has designed a cryogen-free 9-T magnet for the Still River Systems Monarch-250 synchrocyclotron, to be mounted on a rotating gantry.



Compactness makes this challenging! The turn separation at 250 MeV is only 6 μm – so beam extraction relies on amplifying this to 1 cm by a local field perturbation.

First extracted beam: April 2010.

Currently being installed in Barnes Jewish Hospital, St.Louis.

THE THOMAS CYCLOTRON

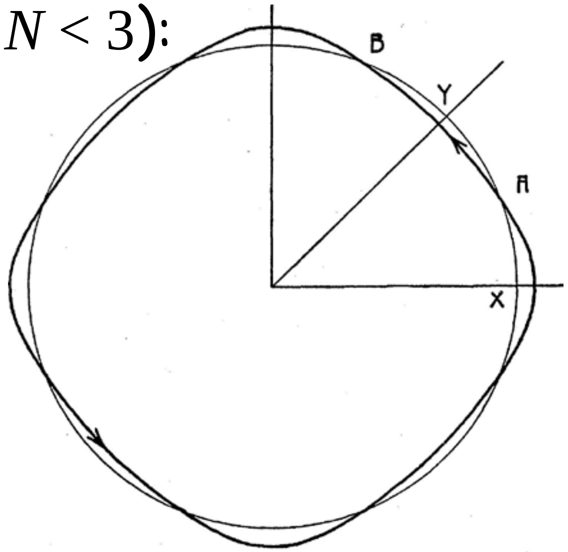
Back in 1938 Llewellyn Thomas (in reaction to Bethe's predicted energy limit) had pointed out a way to allow cyclotrons to be run isochronously (and thus with intense cw beams) at relativistic energies: the vertical defocusing associated with rising field $B=\gamma B_0$ may be countered by an azimuthally 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 $N < 3$):

$$\boxed{\nu_z^2 = -\beta^2\gamma^2 + \tfrac{1}{2} f^2}$$

- a simple result from some intimidating maths.

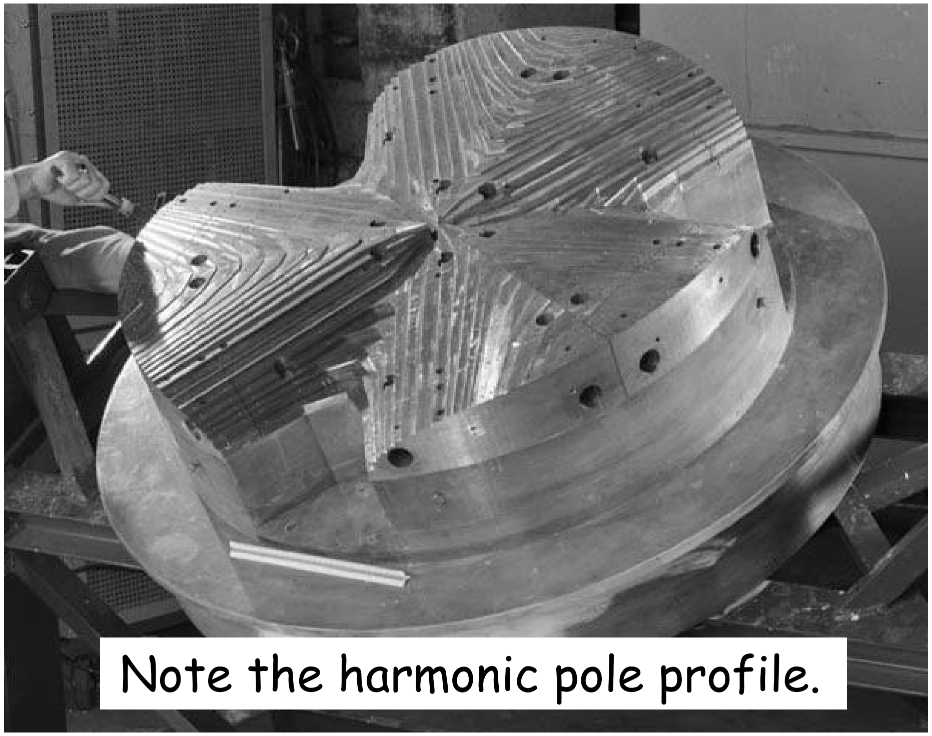


(Thomas was a Welsh-born, Cambridge-educated US immigrant, probably better known for
- **Thomas precession**
- **Thomas-Fermi statistical model of the atom.)**

THE FIRST SECTOR-FOCUSING CYCLOTRON

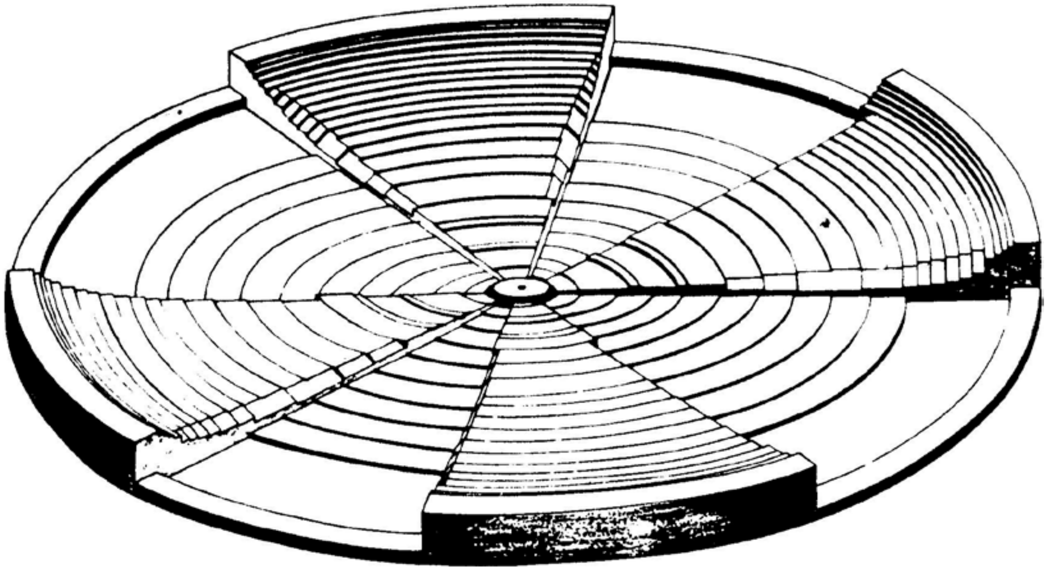
In 1950 an apparent lack of uranium reserves led the US to authorize the Livermore Materials Test Accelerator - a 350-MeV, 500-mA cw deuteron linac, estimated to cost $300M - to breed fissile isotopes by neutron irradiation. A 10-MeV 1st stage was built - 18 m in diameter!

Reg Richardson argued that a 300-MeV Thomas cyclotron could be built for a lot less than $300M, and with Kelly, Pyle, Thornton and Wright, built two 3-sector electron models. Like classical cyclotrons they required very precise shaping of the magnetic field, but 54 circular trim coils made this a lot simpler than using steel shims. Electrons were successfully accelerated to $\beta = 0.5$ (as for 300-MeV deuterons) and extracted with 90% efficiency – but the work, performed in 1950, remained classified till 1956!



Note the harmonic pole profile.

EARLY RADIAL-SECTOR CYCLOTRONS



The first isochronous sector-focused cyclotron for ions was built by Heyn & Khoe at Delft in 1958. It had 4 sectors, pole diameter 86 cm, and 12.7 MeV top proton energy. The pole-pieces were carefully shaped.

Half a dozen others quickly followed, but only one (Milan, 45-MeV H^-) had a top energy >25 MeV/u, the maximum for classical cyclotrons. That's because it's difficult to achieve high magnetic "flutter" F^2 in a single compact magnet. Here $F^2 \equiv \left\langle (B-\overline{B})^2 \right\rangle / \overline{B}^2$ - the normalized mean square deviation of **B** - replaces Thomas's $\frac{1}{2}f^2$ for non-harmonic poles – i.e. $\boxed{\nu_z^2 = -\beta^2\gamma^2 + F^2.}$

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

COMMERCIAL RADIAL-SECTOR CYCLOTRONS

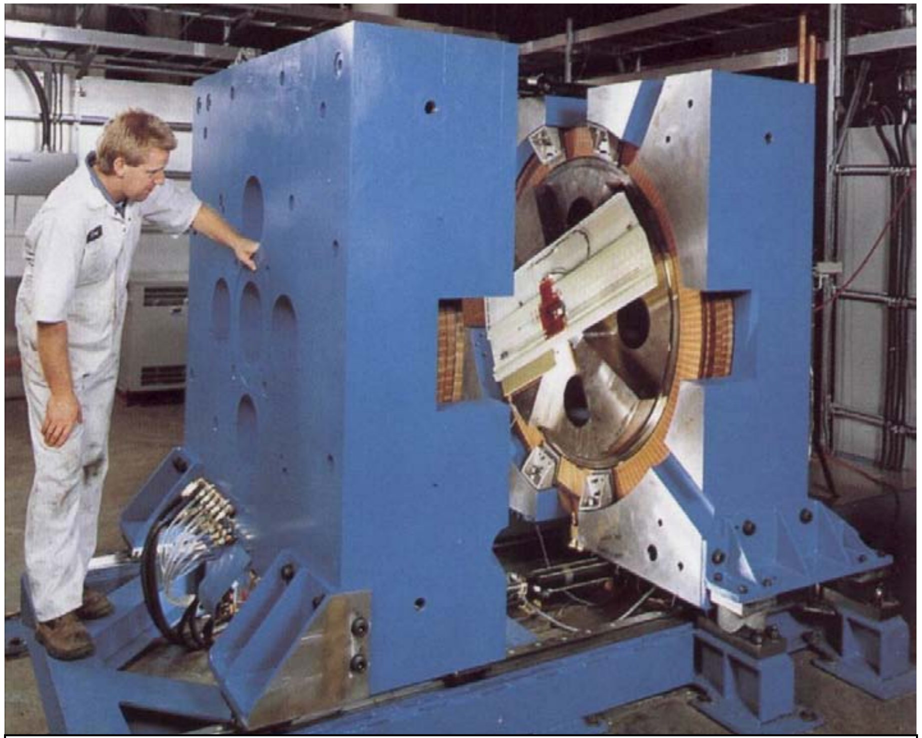
Nowadays there are >800 small radial-sector cyclotrons

- with maximum energies 3.5 MeV to 70 MeV
- supplying beams of H^+, H^-, D^+, D^-, ^{3}He and ^{4}He
- at beam intensities up to 2 mA
- mostly used for producing radioisotopes for medicine & industry
- currently supplied by 11 commercial manufacturers in 32 models
    - Advanced Cyclotron Systems (formerly EbCo) – Canada
    - Advanced Biomarkers Technologies - USA
    - Best Cyclotron Systems – Canada
    - China Institute of Atomic Energy
    - Efremov Institute (NIIEFA) - Russia
    - Euro MeV – France (previously supplied by Oxford Instruments)
    - General Electric Healthcare - USA
    - Ion Beam Applications – Belgium
    - KIRAMS – South Korea
    - Siemens – Germany
    - Sumitumo Heavy Industries – Japan

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

TWO ISOTOPE-PRODUCTION CYCLOTRONS

ACSI TR14/19



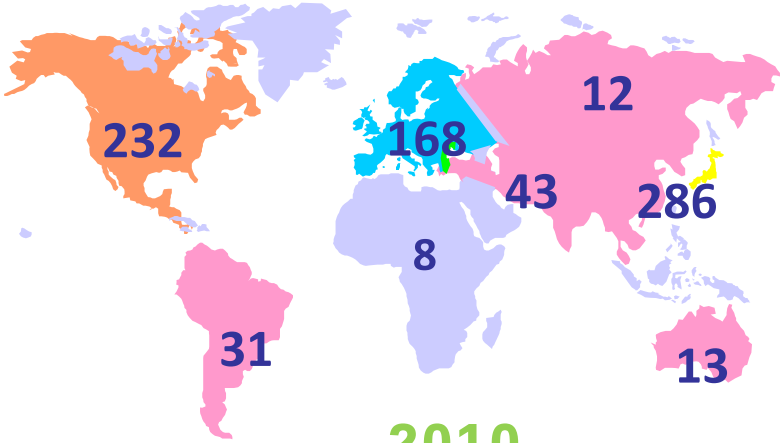
Delivers 300 μA H^- at 14-19 MeV or D^- to 7-9.5 MeV - sufficient to produce short-lived isotopes for PET scans, such as ^{11}C ($\tau_{1/2} \approx$ 20 m), ^{13}N (10 m), ^{15}O (2 m) and ^{18}F (110 m).

IBA CYCLONE-30

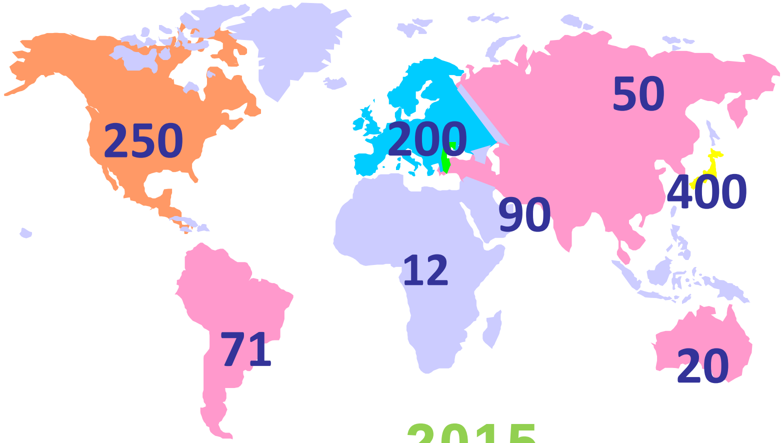
Delivers ≤1500 μA H^- at 15-30 MeV - sufficient to produce a wider variety of isotopes for use in both PET and SPECT scans, including ^{67}Cu, ^{67}Ga, ^{111}In, ^{123}I, and ^{201}Tl.

PET Market growth 2010 - 2015

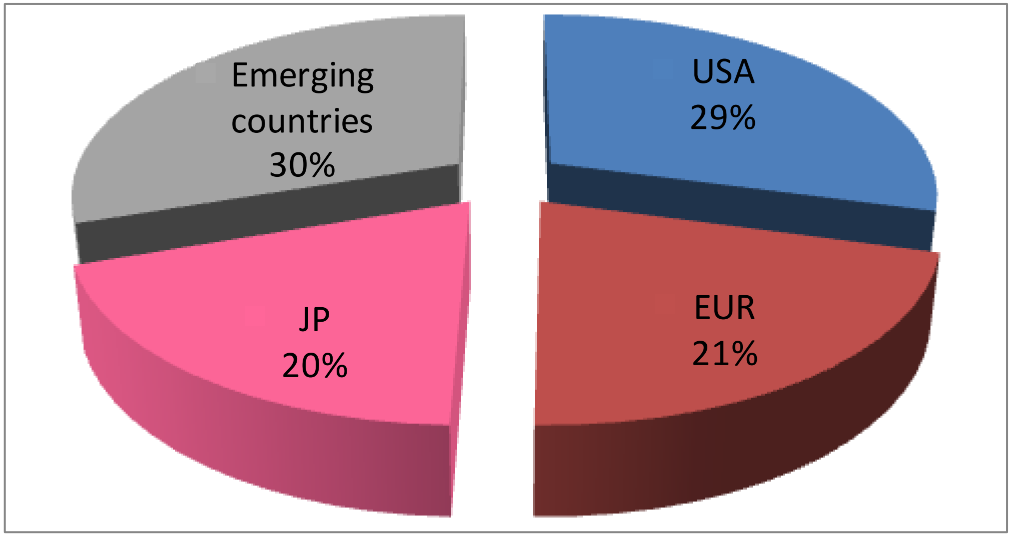
PET Cyclotron installed base



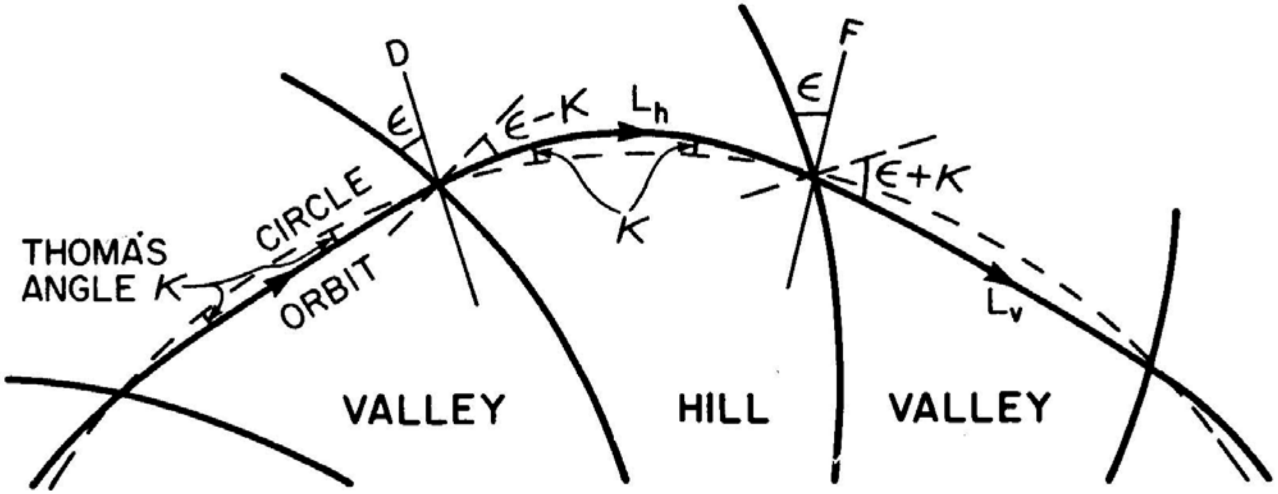
2010
793 cyclotrons



2015
1093 cyclotrons



ALTERNATING LENSES IN SPIRAL-SECTOR CYCLOTRONS



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

Spiral angle ε >> κ → edge-crossing angles κ + ε (a strong F lens)

or κ - ε (a less strong D lens)

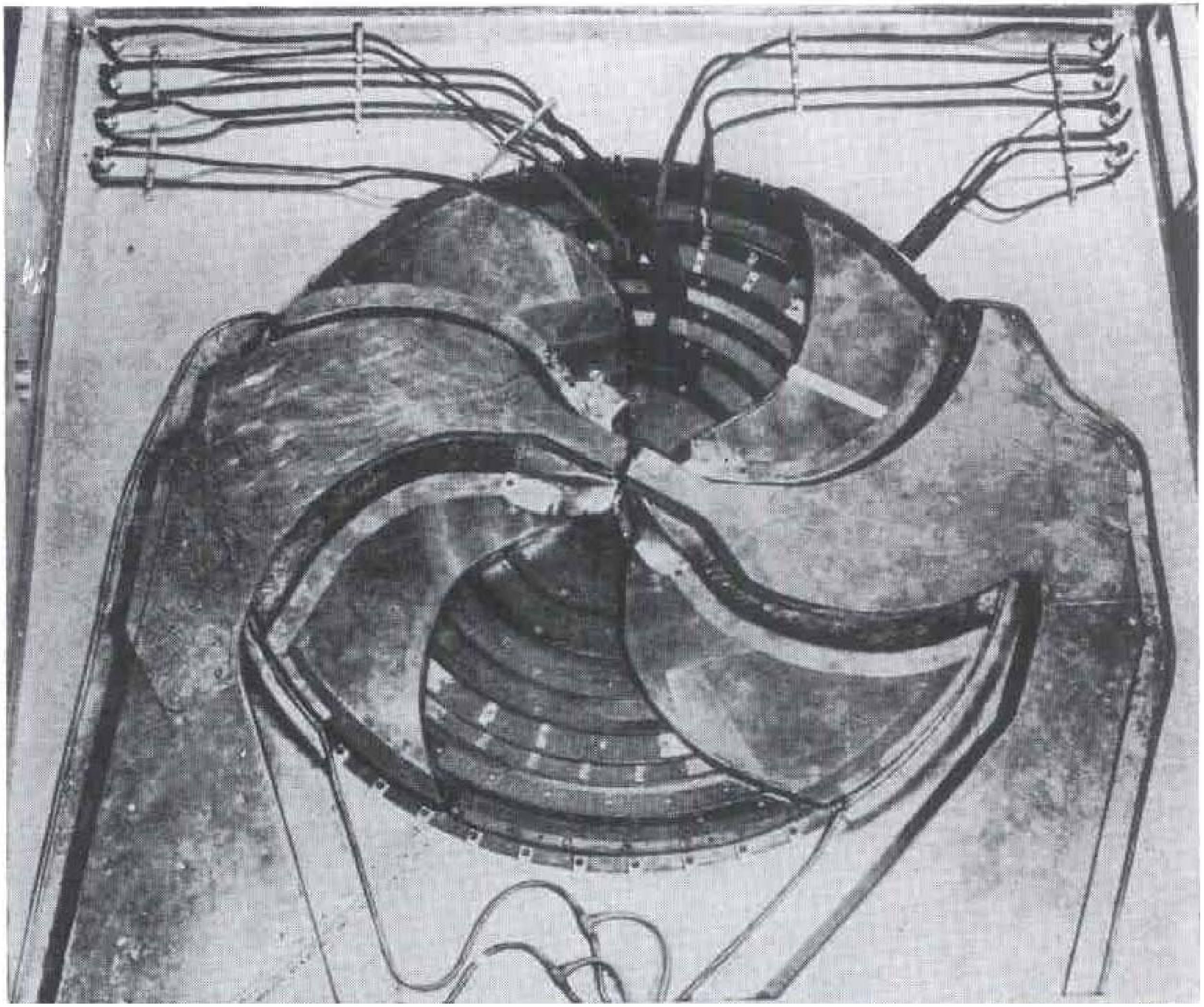
Overall we have

$$\boxed{\nu_z^2 = -\beta^2\gamma^2 + \frac{N^2}{N^2-1} F^2\left(1 + 2\tan^2\varepsilon\right)}$$

The powerful $2\tan^2\varepsilon$ term enhances the flutter focusing x3 for $\varepsilon = 45°$.

Spiralling was quickly adopted for isochronous cyclotrons, is now used for most proton machines >40 MeV, and has allowed designs ≤12 GeV.

UCLA 50-MeV p/H⁻ CYCLOTRON (1960)



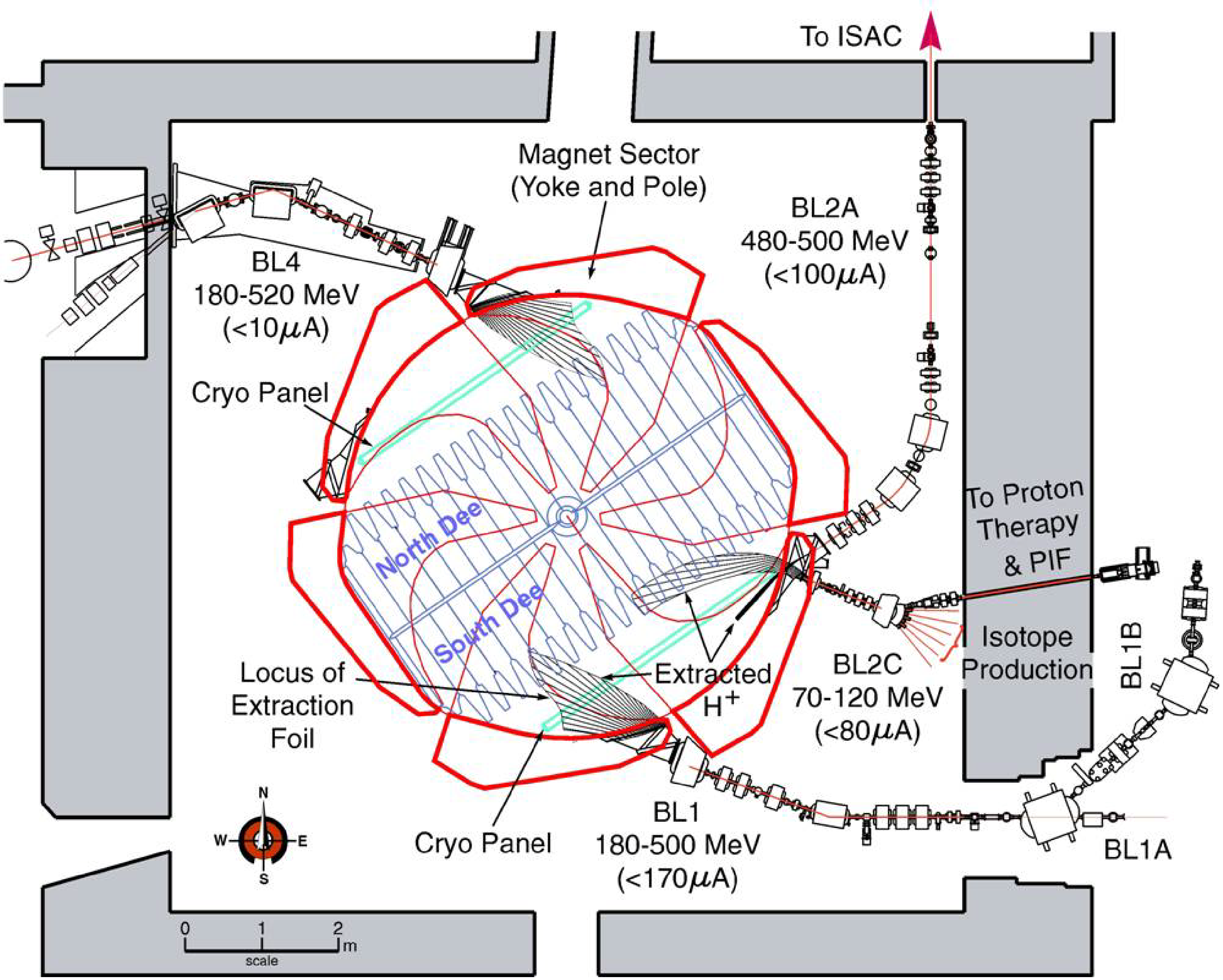
- 49-inch diameter poles – very compact for 50 MeV
- RF electrodes are not D-shaped – "in-valley" spiral cavities
- Followed Colorado's lead by using H^- ions – easy beam extraction

IBA C235 PROTON THERAPY CYCLOTRON (1998)

- A very compact 230-MeV proton cyclotron
- Now operating in 12 hospitals worldwide – another 13 sold (including 3 Sumitumo HI clones)

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



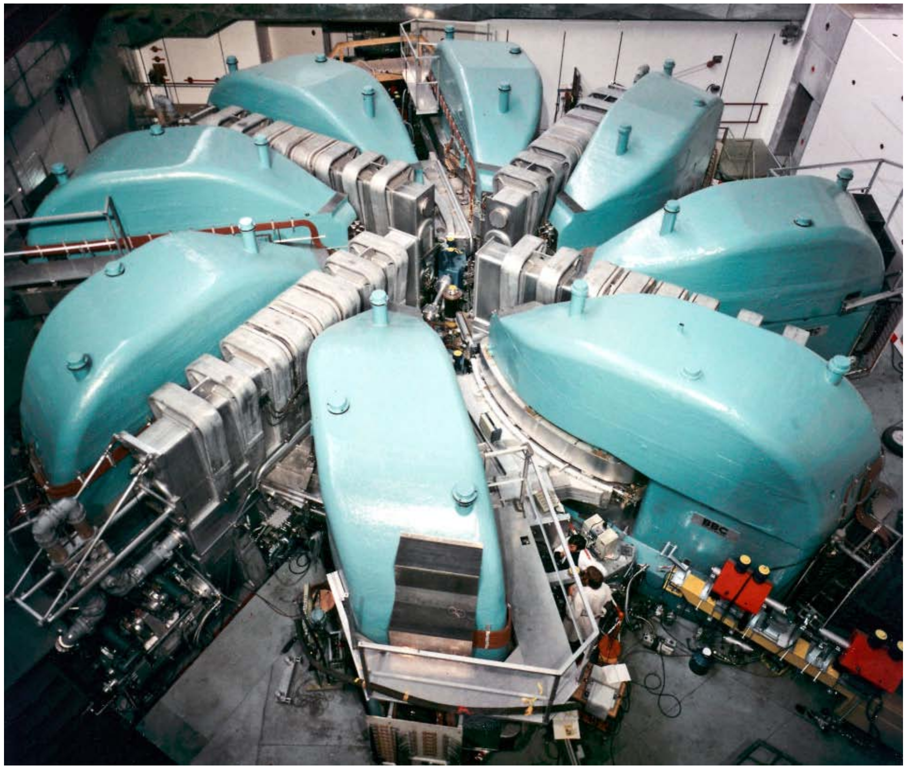
By using a variety of foil shapes for partial extraction at lower energies, TRIUMF currently extracts 3 beams of variable energy and intensity simultaneously – and proposes to add a 4th.

SEPARATE-SECTOR (RING) CYCLOTRONS

First proposed by Hans Willax (1962) for the Swiss meson factory - a 70-590 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 $\beta\gamma \approx 1$ (≈400MeV/u) with radial sectors).
- medium-energy injector is needed.

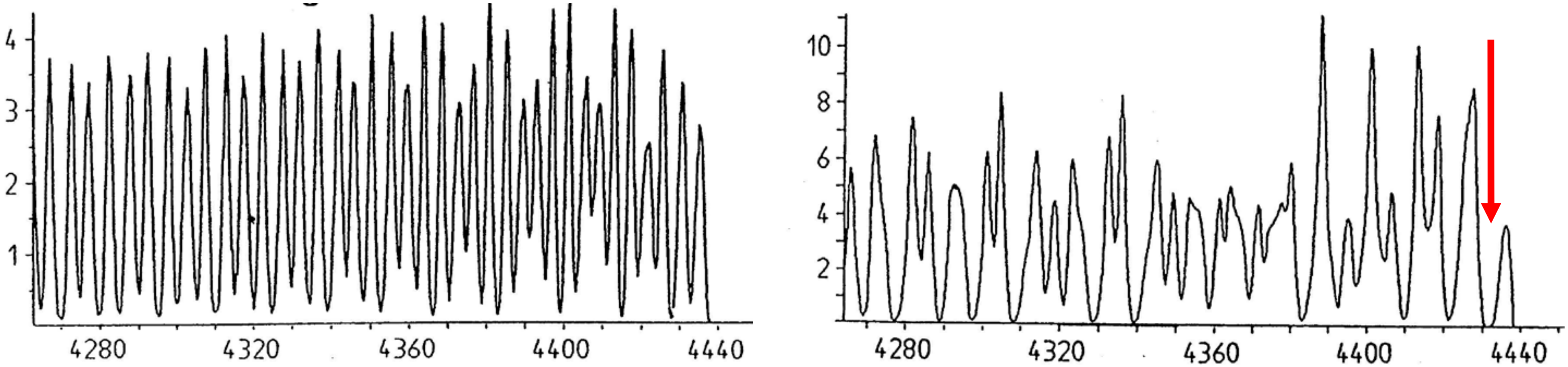


The PSI 590-MeV 2.2-mA separated-sector ring cyclotron, showing the 8 spiral magnets and four 1-MV rf cavities.

PSI 590-MeV RING CYCLOTRON

High energy gain → high turn separation → efficient extraction.

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



Beam intensity v. radius (mm): (left) well-centred; (right) off-centred.

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 $\nu_r \approx 1.5$ at extraction, and very short bunches (to restrict energy spread $\propto \cos\phi$). With 99.97% extraction efficiency, 2.2-mA external beams are routine, and 3-mA beams are planned.

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

LARGE SEPARATE-SECTOR CYCLOTRONS

	Pole dia. (m)	Magnet wt. (t)	Sectors (Spiral)	Proton / Ion Energy (MeV)	First beam
PSI Villigen	9.30	1990	8 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	6 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

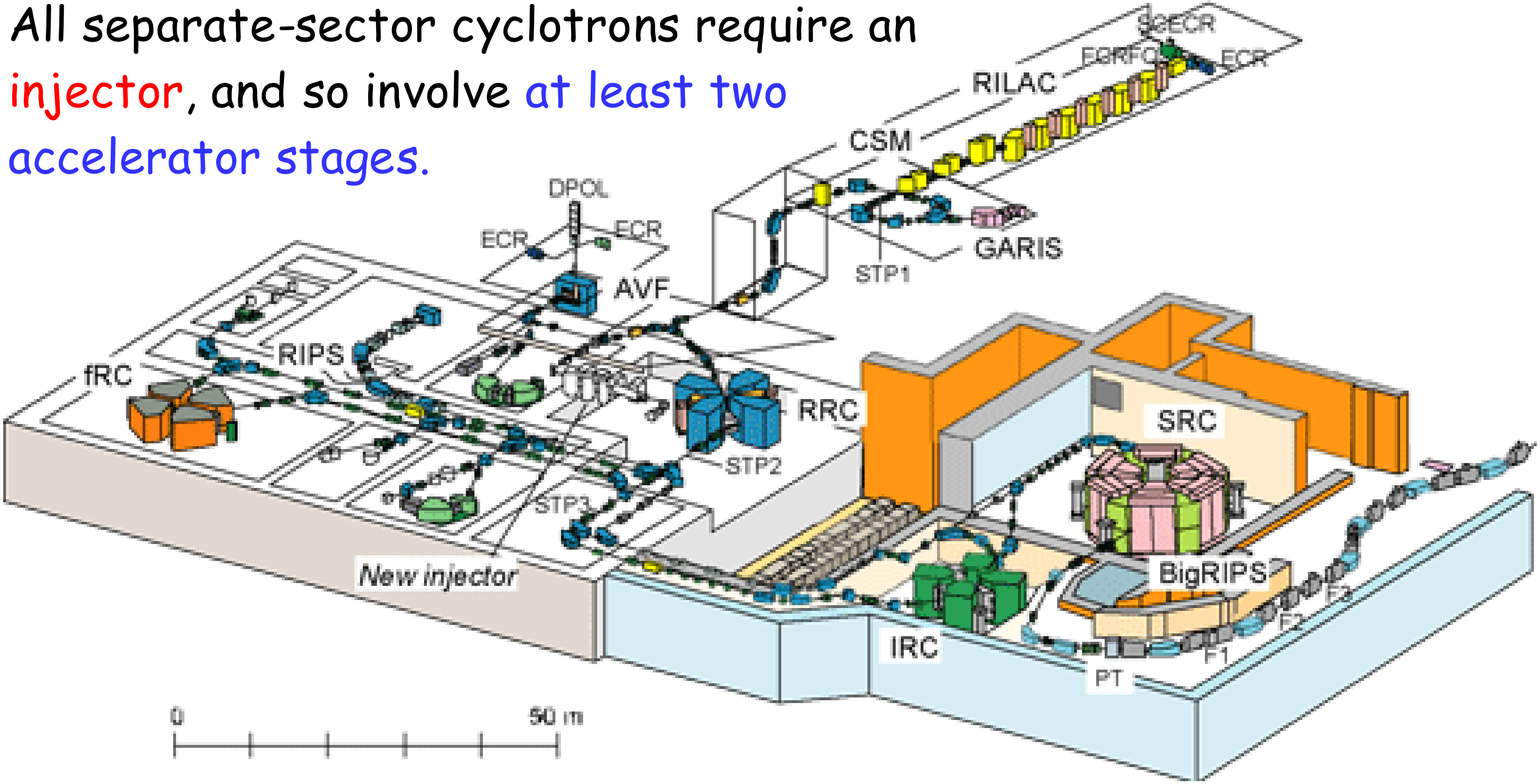
* Extraction orbit diameter

Note that all but two of these are radial-sector cyclotrons
- mainly designed for heavy ions (where $\beta\gamma < 1$).

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

MULTISTAGE CYCLOTRON SYSTEMS

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

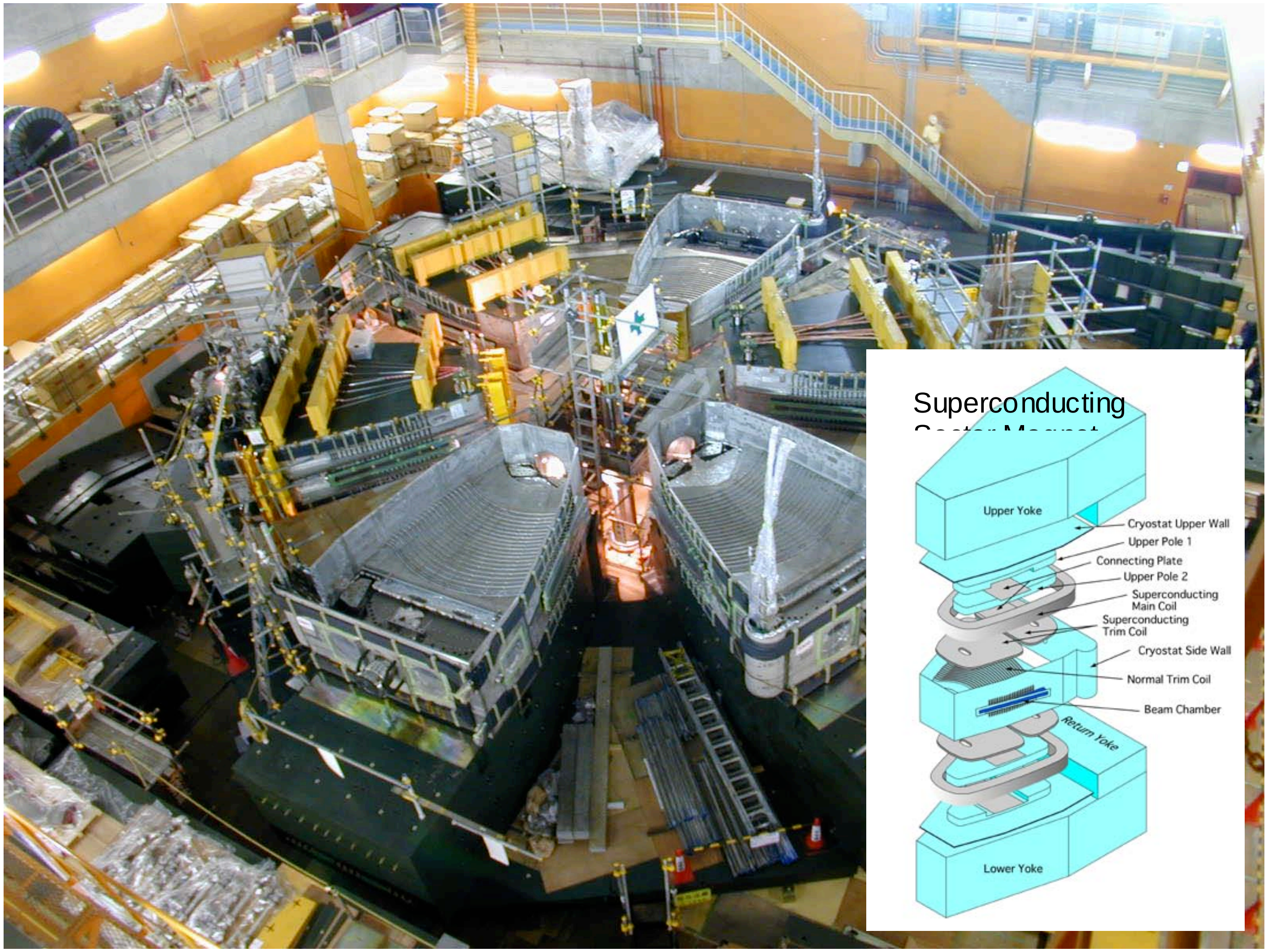


The RIBF involves a chain of one linac and 5 cyclotrons. It can deliver 345-MeV/u beams over the mass range A = 50 – 92.

Of the 3 new ring cyclotrons, the most novel and challenging – and the world’s most massive – and most powerful - is the 8300-ton SRC.

RIKEN K2600 SUPERCONDUCTING RING CYCLOTRON

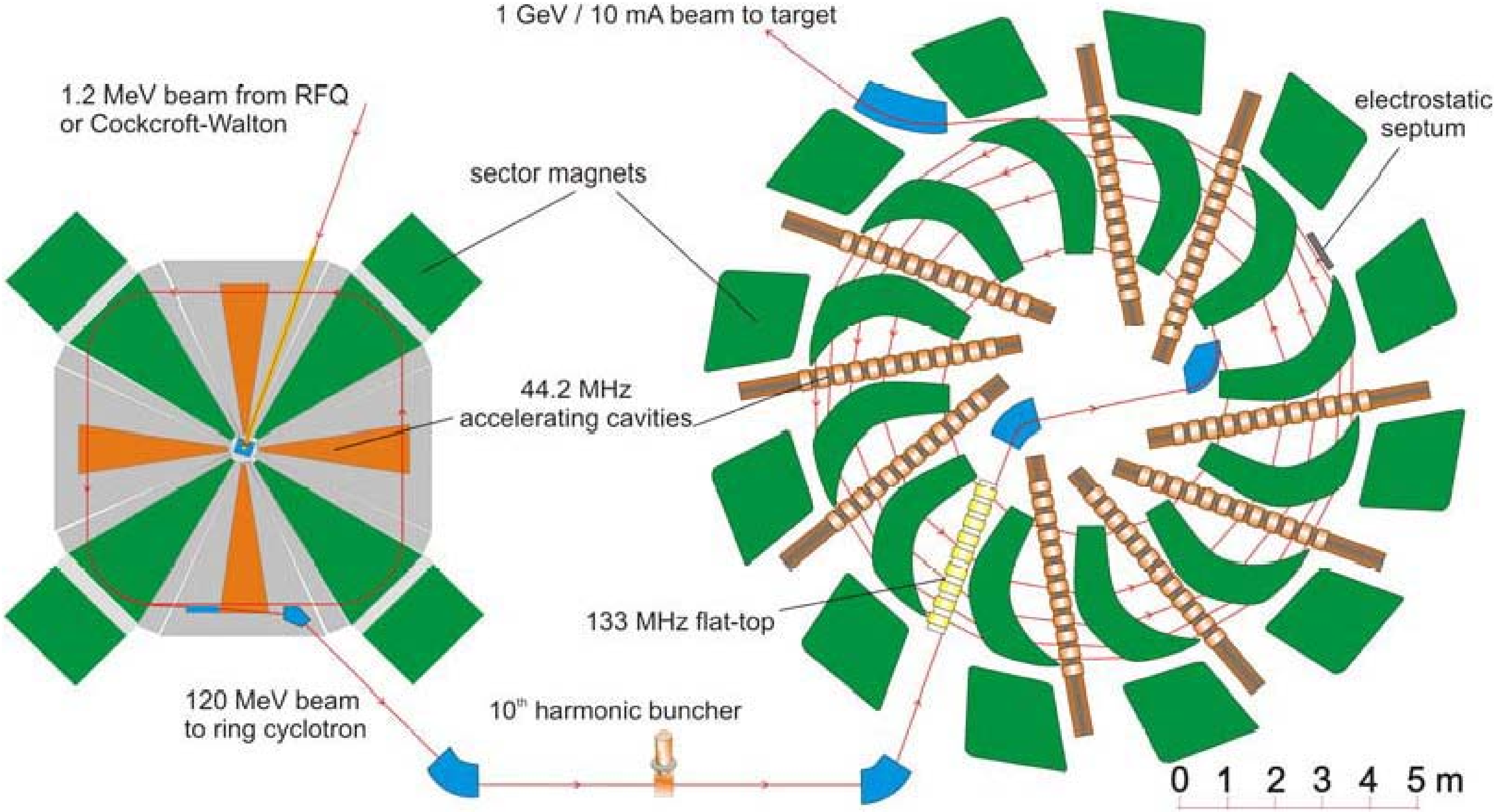
Yasushige
Yano



Completed November 2005 – the 140-ton cold mass cooled to 4.5K.
A 345 MeV/u beam of $^{27}Al^{10+}$ was extracted in December 2006,
followed by U^{86+} in March 2007.

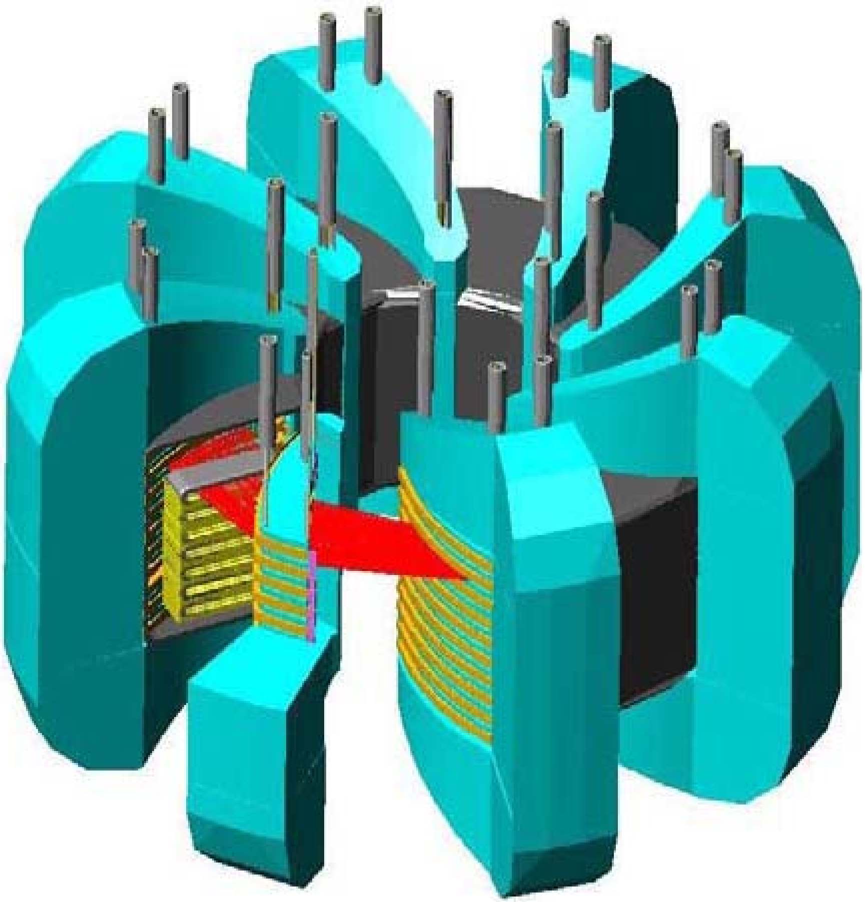
HIGH-ENERGY RING CYCLOTRONS (1)

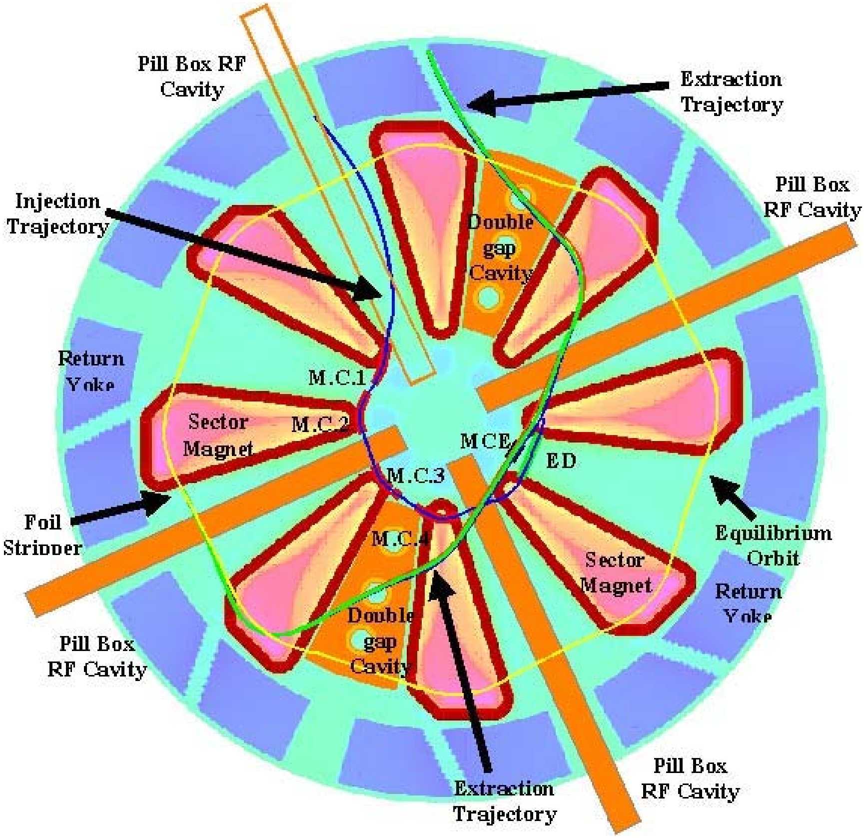
Several designs have been proposed for accelerating high-intensity cw beams to GeV energies.



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.

HIGH-ENERGY RING CYCLOTRONS (2)





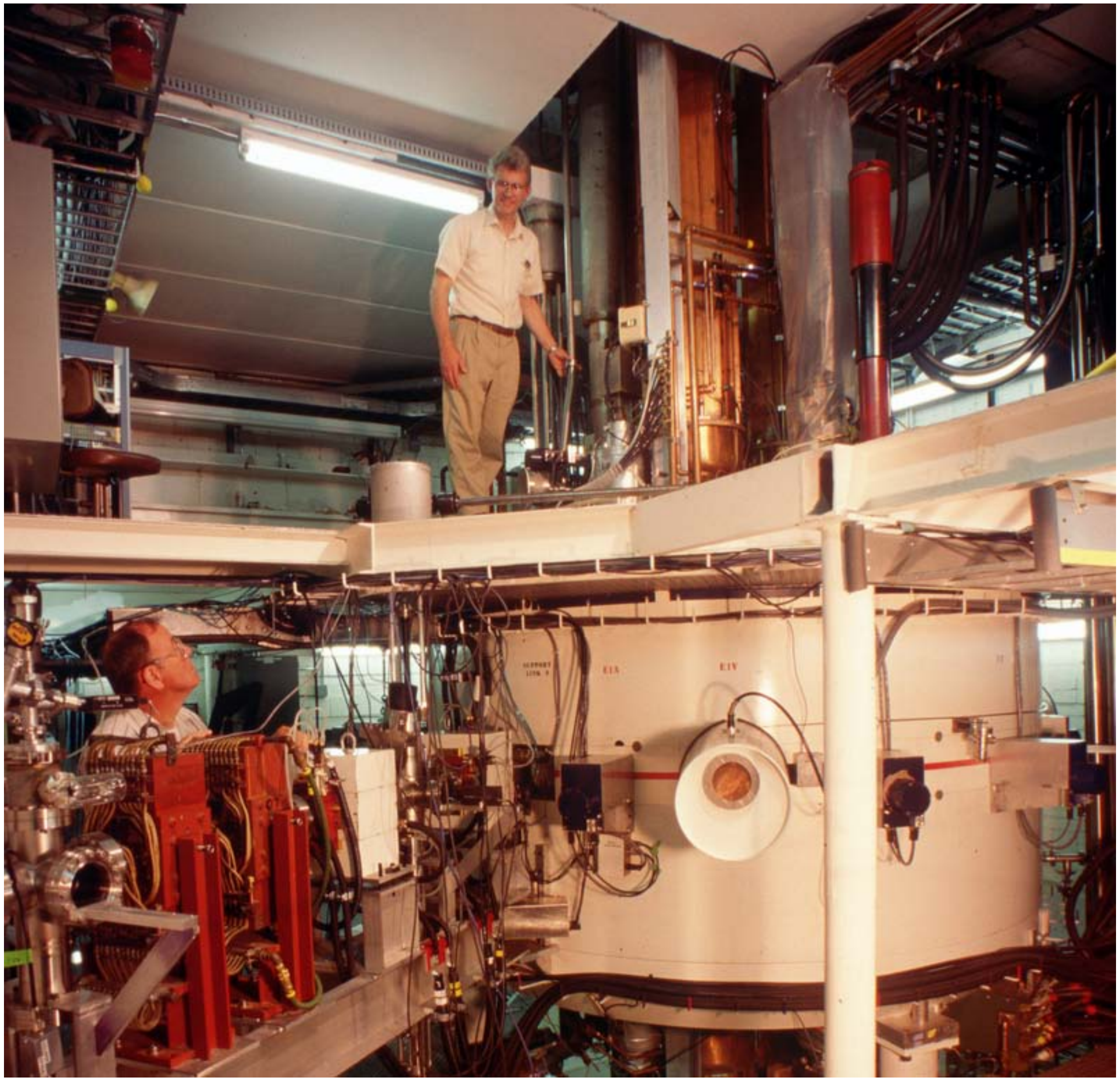
7-stack 800-MeV cyclotron to deliver 7 x 2-MW = 14-MW proton beams for ADSR.
(P. McIntyre et al., Texas A&M, Brookhaven NL & Idaho NL).

Superconducting 800-MeV/u cyclotron to deliver 5-MW peak (2-MW avg.) H_2^+ beams for ν production for DAEδALUS.
(Calabretta et al., LNS Catania)

COMPACT SUPERCONDUCTING CYCLOTRONS

The first superconducting cyclotron design was the K520 at AECL Chalk River (Bigham, 1979) – but slow government funding let to Henry Blosser's K500 at MSU being the first to operate (1982).

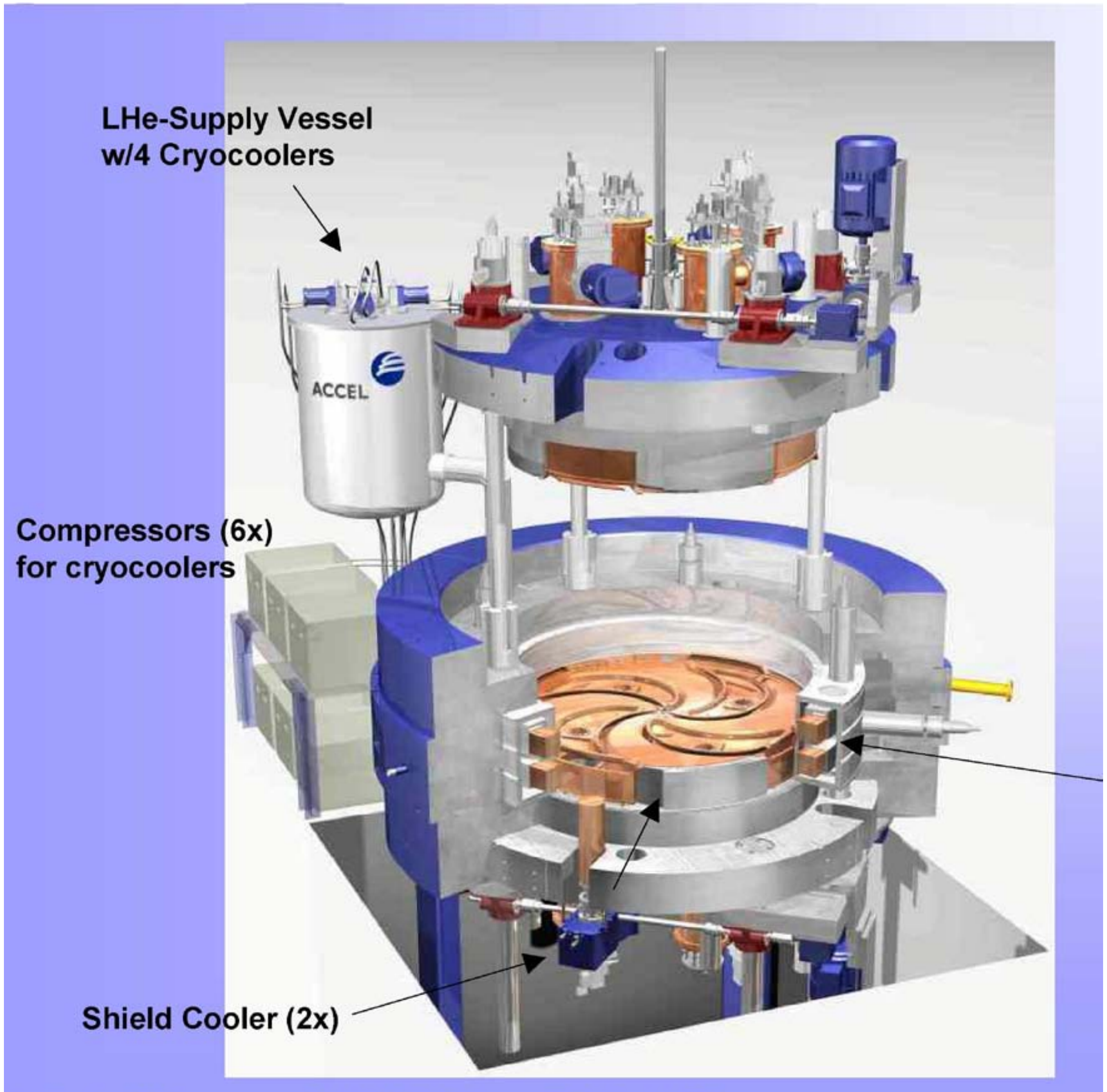
The K500 can accelerate heavy ions to $500(Z/A)^2$ MeV/u. Many similar compact heavy-ion cyclotrons have been built, ranging up to K1200.



ACCEL/VARIAN PROTON THERAPY CYCLOTRON

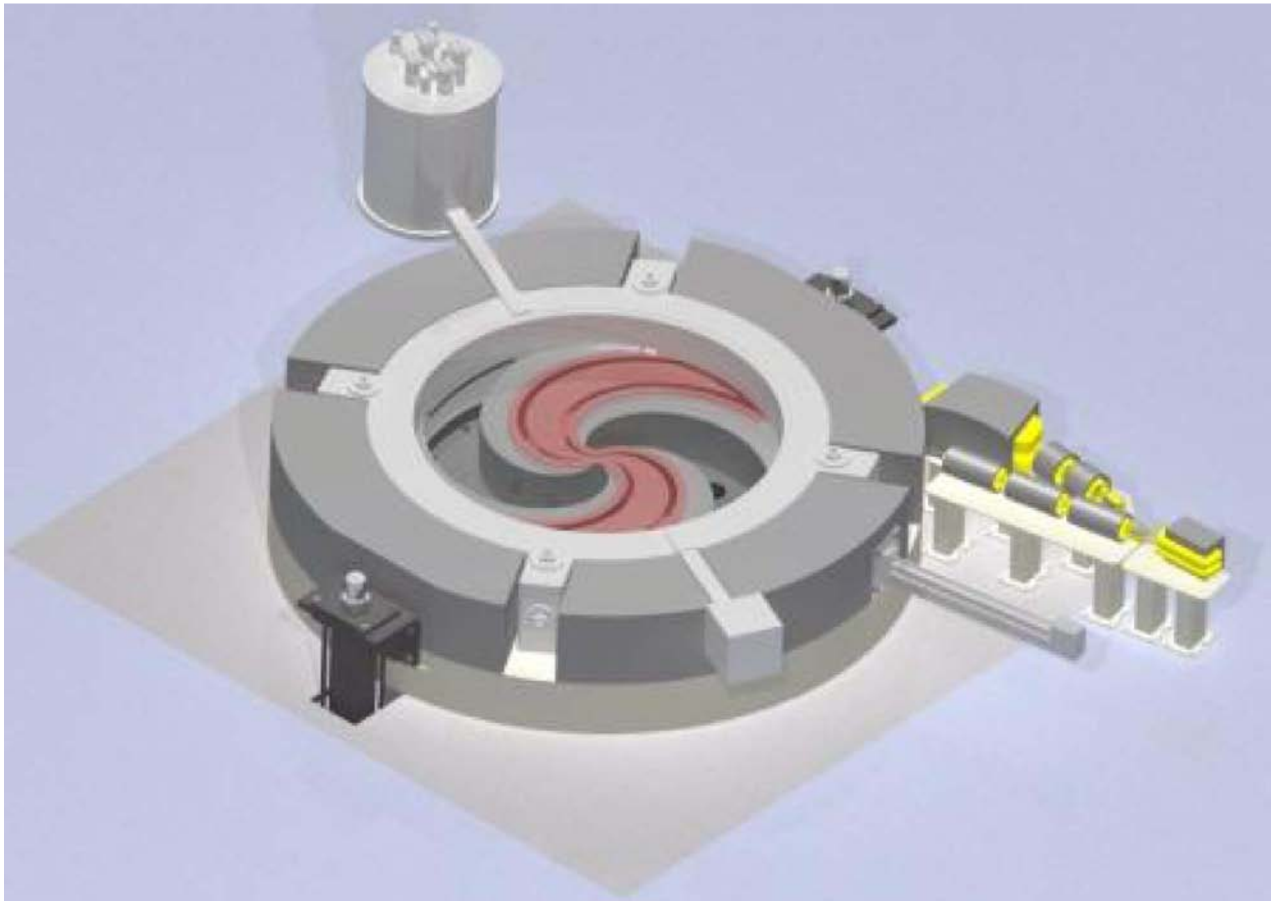
This superconducting cyclotron (based on a design by Blosser et al.) delivers a 250-MeV beam for proton therapy. The 90-ton magnet yoke is 3.1 m in diameter.

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.



A. Geisler, ACCEL Instruments GmbH, 18A3, Cyclotrons 2004, October 2004

IBA-JINR C400 CARBON/PROTON THERAPY CYCLOTRON



This joint IBA-Dubna design will provide a range of ions for therapy:

- 400-MeV/u $^{4}He^{2+}$, ($^{6}Li^{3+}$), ($^{10}Be^{5+}$), $^{12}C^{6+}$
- 265-MeV protons by stripping H^{2+}.

The outer diameter is 6.6 m, the magnet weight 700 tons.

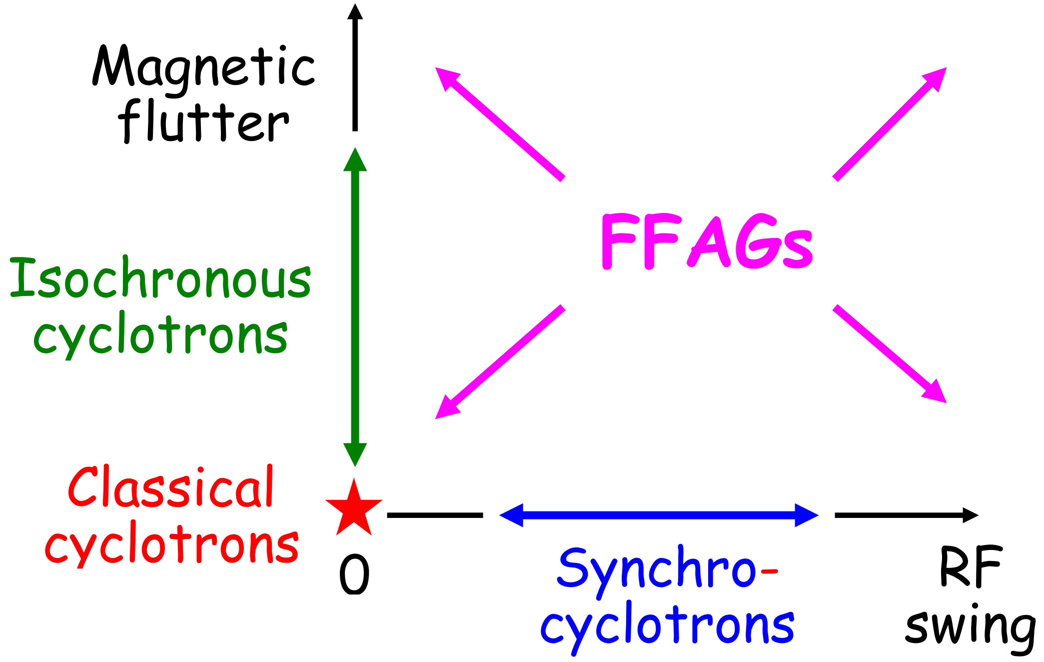
Construction will begin soon on the first C400, to be installed in Caen.

FFAGs - Fixed Field Alternating Gradient accelerators

Fixed Magnetic Field - members of the **CYCLOTRON** family[1]

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

But FFAG enthusiasts sometimes express an alternative view:
- cyclotrons are just special cases of the FFAG!



Magnetic flutter

Isochronous cyclotrons

Classical cyclotrons

0

Synchro-cyclotrons

RF swing

FFAGs

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[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, emittances and beam currents than in synchrotrons, at the expense of wider magnets, rf cavities and vacuum chambers)
- 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.

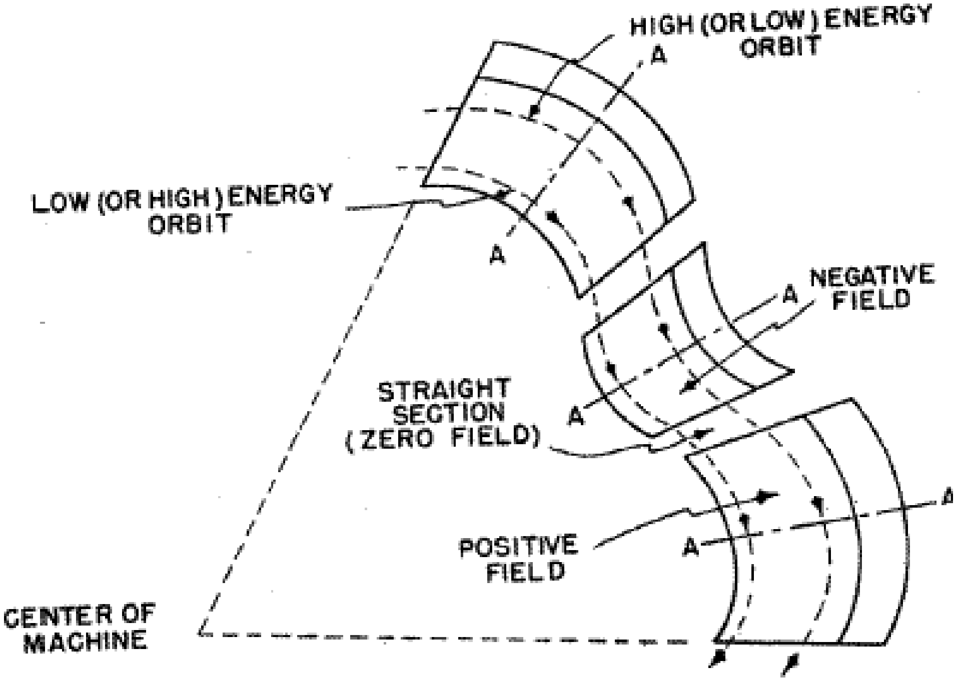


FIG. 2. Plan view of radial-sector magnets.

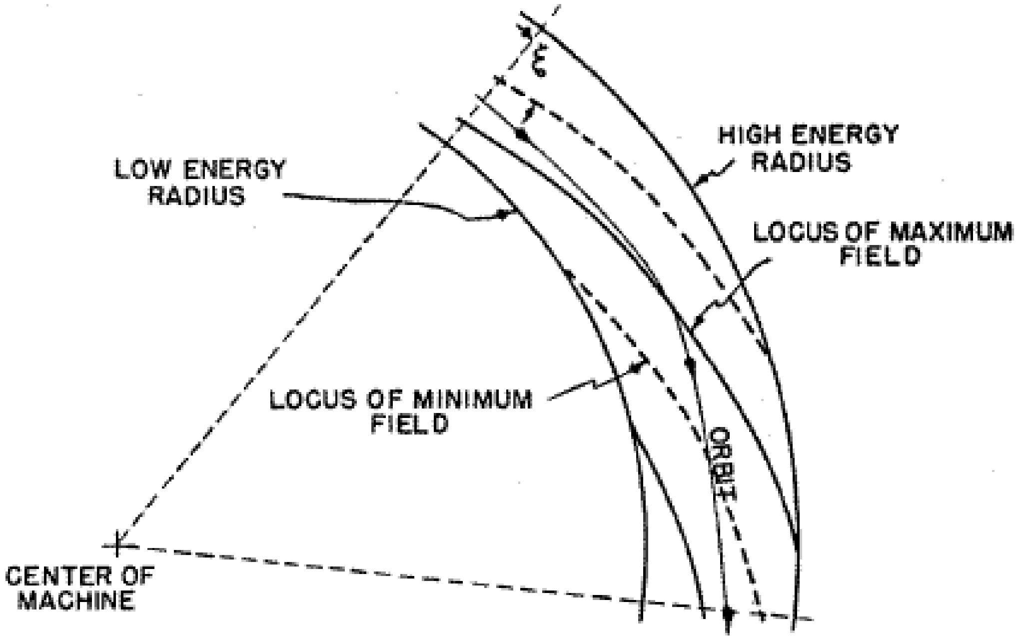


FIG. 3. Spiral-sector configuration.

In the 1950s, to avoid crossing betatron resonances, the MURA team adopted the "Scaling" principle – where orbit shape, optics, and tunes were kept constant.

RECENT SCALING FFAGs

MURA built several successful electron models, but the first proton FFAG was Mori's 1-MeV "POP" at KEK (2000), followed by a 150-MeV ring in 2003. Another 6 are now operating (for p, e, α) and 3 more (e) being built, including:

Mori's FFAG Complex at Kyoto University Research Reactor Institute.
The World's first test of Accelerator-Driven Sub-critical Reactor (ADSR) operation was performed at KURRI in March 2009.

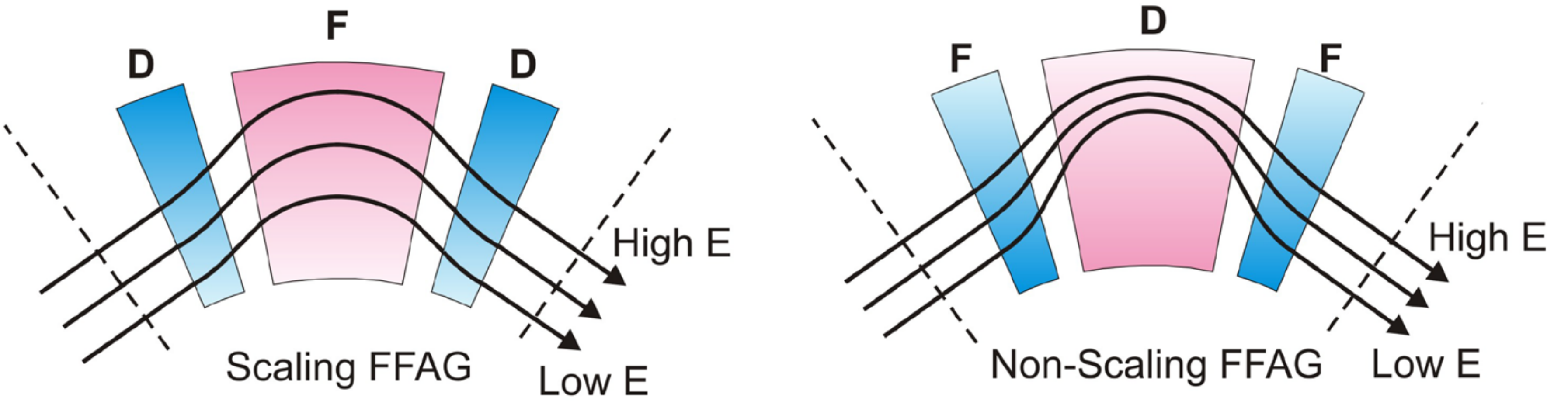
LINEAR NON-SCALING (LNS) FFAGs

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) → resonance crossing ignorable (Mills '97)
- Less expensive than recirculating linacs.

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

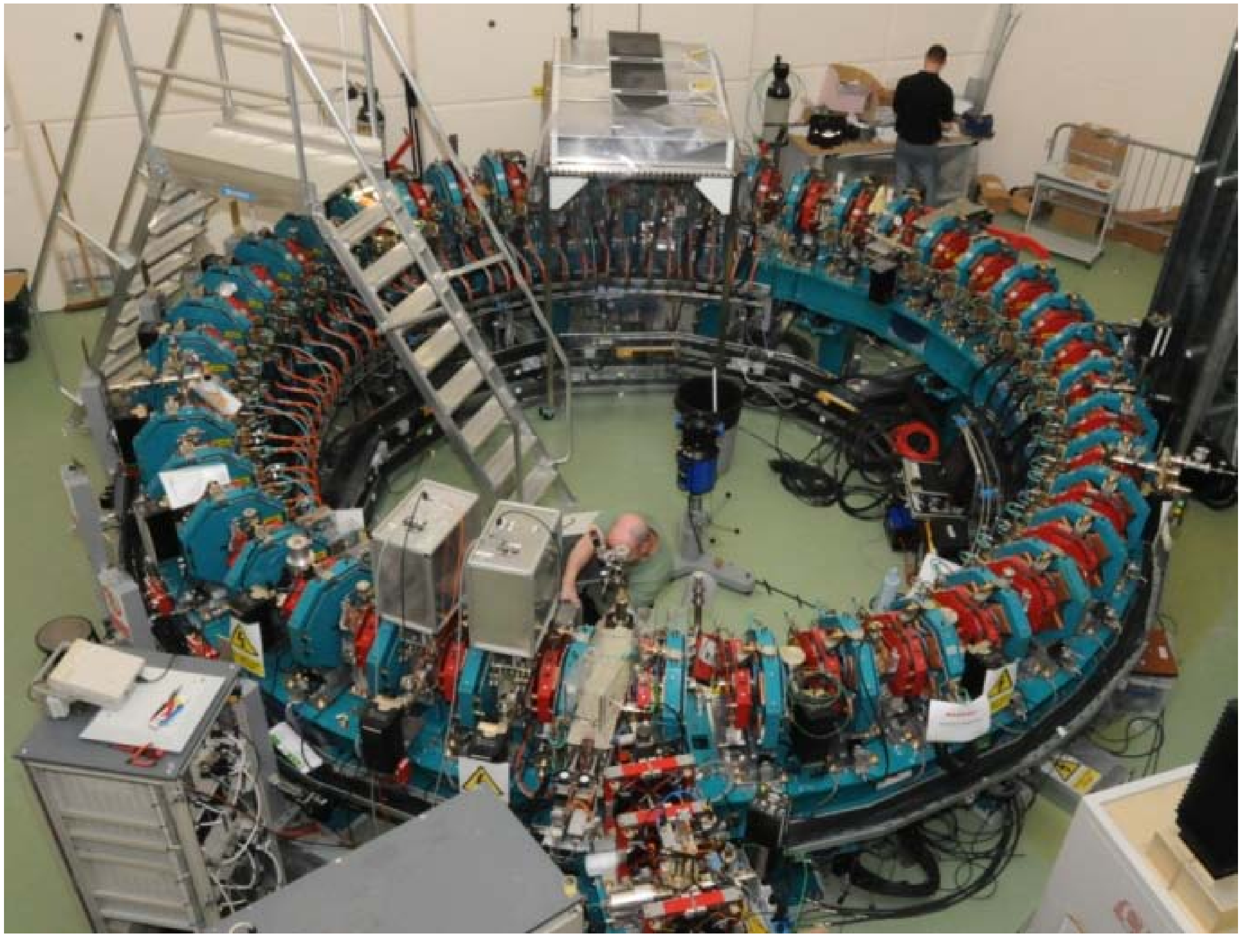
- "**LINEAR**" magnets with <u>constant</u> <u>negative</u> field gradients (i.e. quadrupoles)



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

LNS-FFAGs chosen for 12.5-25 & 25-50-GeV μ stages in ν-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.
First accelerated beam (with 19 distributed rf cavities!) March 2011.

FROM SCIENCE TO HUMAN HEALTH

Cyclotrons continue to support front-line scientific research:

- Nuclear Physics with radioactive isotopes
- Particle Physics with pions, muons and nuclear SM tests
- Condensed Matter and Materials Science via spallation neutrons, μSR and β-NMR
- Chemistry with muonium
- Zoology and Botany via radioactive tracers

Even more cyclotrons are used for medical research & treatment:

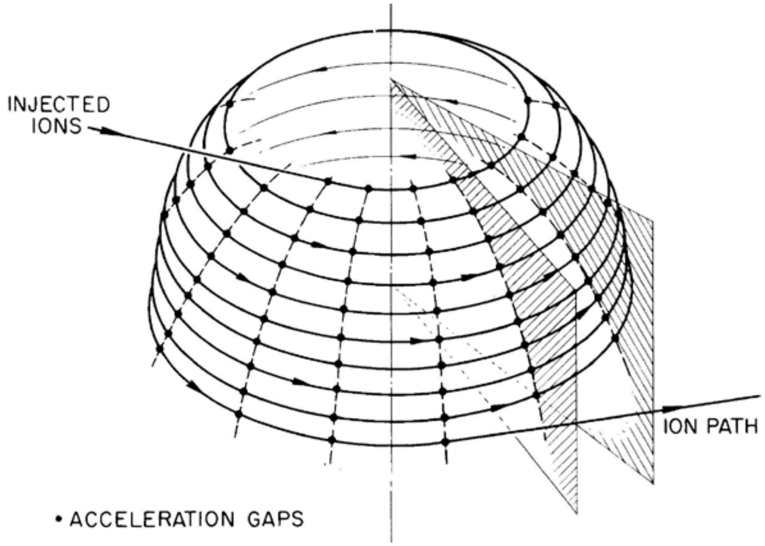
- Pathology using radioactive tracers
- Diagnosis using radioactive isotopes via Scintigraphy or SPECT or PET tomography
- Cancer therapy via implanted radioisotopes
- Cancer therapy using proton or ion beams.

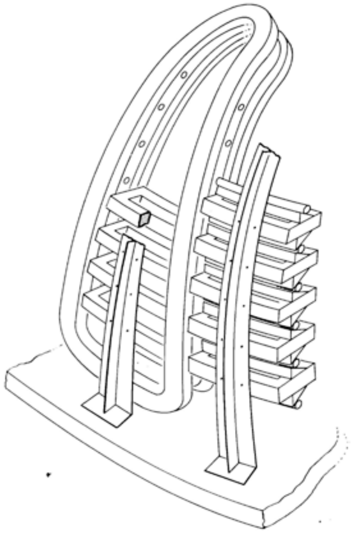
The slides are at: http://trshare.triumf.ca/~craddock/APS11/

EXTRA

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.



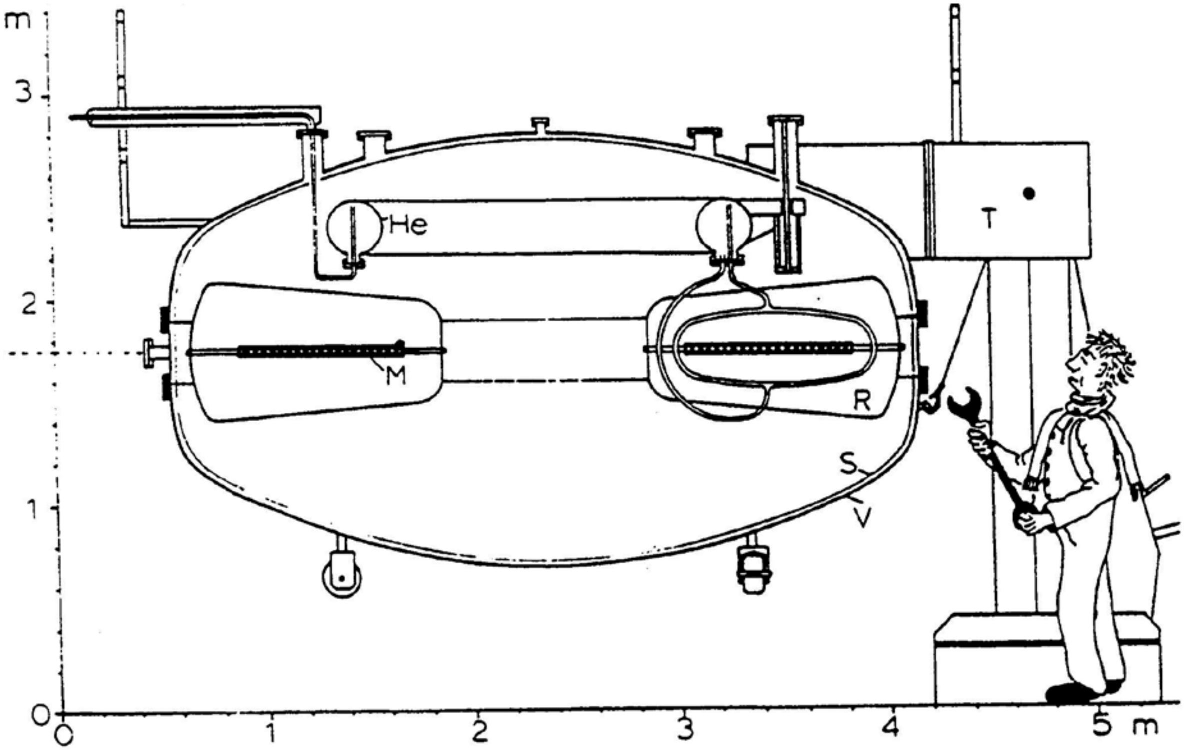


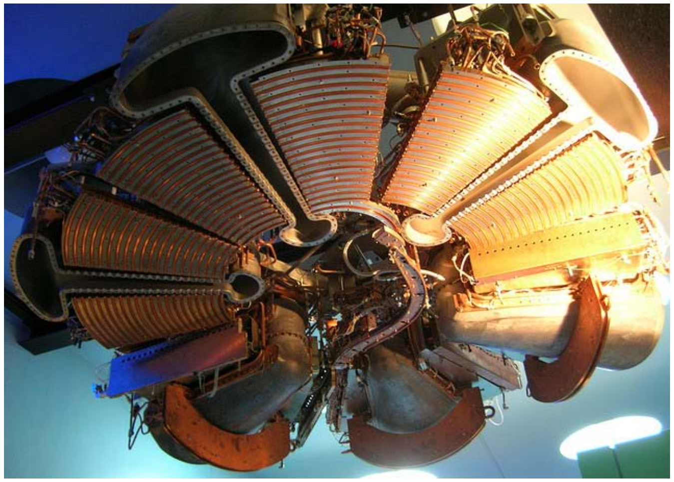
To achieve a 65-mA beam at 1 GeV for Chalk River's Intense Neutron Generator (ING) project, 60 turns were proposed, and 100 rf cavities.

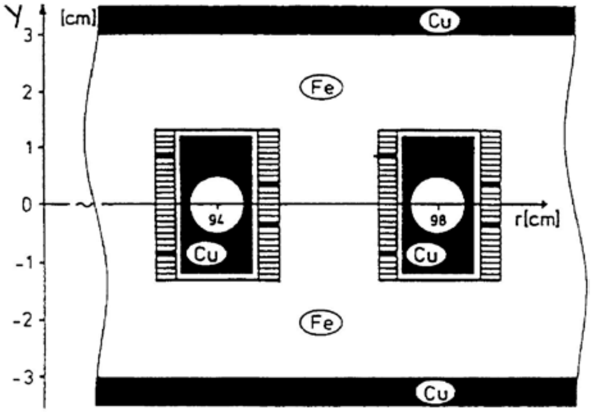
For energies <800 MeV, a flat spiral was found to be acceptable.

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 S^{14+} beam from a tandem was accelerated through 6 turns to 72 MeV.

REFERENCES AND ACKNOWLEDGEMENTS

I have found the following resources very helpful, and recommend them for further reading:

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2. M.S. Livingston, *The Development of High-Energy Accelerators* (Dover, 1966).
3. M.S. Livingston, *The History of the Cyclotron* , Proc. 1975 Cyclotron Conf. (Birkhaser Verlag, 1975)
4. J.R. Richardson, *A short Anecdotal History of the Cyclotron,* Proc. 1984 Cyclotron Conf., 617 (IEEE Press, 1984).
5. F. T. Cole, *Oh Camelot! A Memoir of the MURA Years* ; http://accelconf.web.cern.ch/accelconf/c01/cyc2001/extra/Cole.pdf
6. L. Jones, F.E. Mills, A.M. Sessler, K.R. Symon, D.Young, *Innovation Was Not Enough* (World Scientific, 2009).

See also: M.K. Craddock, K.R. Symon, *Cyclotrons and FFAGs,* Rev. Acc. Sci. Tech. **1**, 65 (2008).