PARTICLE ACCELERATORS - THE ULTIMATE MICROSCOPES

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& TRIUMF

TRIUMF Student Seminar

http://trshare.triumf.ca/~craddock/PartAccel.pdf

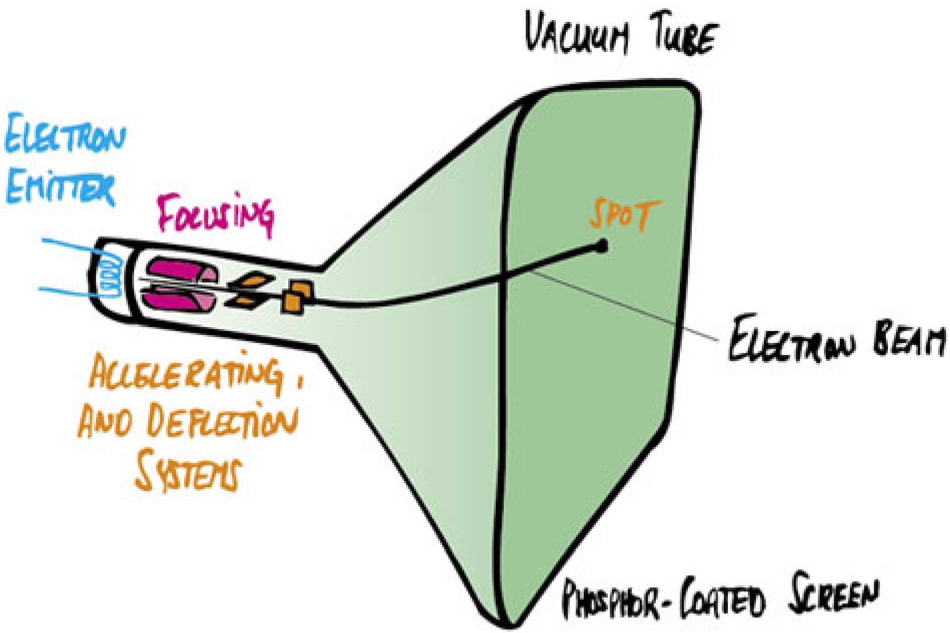
PART 1

1. Introduction and Classification
2. Electrostatic Accelerators
3. Radiofrequency (RF) Linear Accelerators
4. Classical Cyclotrons
5. Particle Beams & Weak Magnetic Focusing
6. The Relativity Challenge
7. Synchronous Acceleration
   - Synchrocyclotrons
   - Synchrotrons

THE ESSENTIALS

- Particle source (electrons, protons, ions)
- Vacuum
- Electric field for acceleration
- Magnetic and/or electric fields for focusing and steering
- Controls

A familiar particle accelerator:



CERN, Geneva – The LHC and SPS tunnels and the Swiss-French border

PARTICLE ACCELERATORS AS MICROSCOPES

Conventional microscopes can't resolve objects smaller than the wavelength of light ($\lambda \approx 0.6\,\mu m$).

But the discovery of the wave nature of particles, with

$$E = h\nu \qquad \text{and} \qquad p = h/\lambda$$

showed that high enough momentum p could give any desired resolution!

The optical limit of $\approx 0.6\,\mu m$ corresponds to $p \approx 2$ eV/c.

For higher momenta, particles are easier to produce & control than photons:

Electrons of 10 keV → p = 100 keV/c (x 50,000) → $\lambda = 10^{-11}$ m (0.1 Å)

- so electron microscopes can resolve individual atoms.

Electrons of 20 GeV→ p = 20 GeV/c (x 10^{10}) → $\lambda = 6 \times 10^{-17}$ m (0.06 nucleon)

- enabling Taylor *et al.* to observe quarks in protons at SLAC.

SCIENTIFIC APPLICATIONS OF ACCELERATORS

Discipline		Tools
Particle Physics		$e^\pm$, $p^\pm$; γ, ν, μ, π, K, n
Nuclear Physics		e, p, ions; γ, n, π
Atomic Physics	)	e; γ, n, β, μ
Molecular Physics	)	via
Chemistry	)	electron microscopes
Condensed-Matter Physics	)	X-ray tubes
Materials Science	)	synchrotron rad'n sources
Surface Science	)	spallation neutron sources
Geology	)	β-NMR
Biology	)	μSR
Archaeology	)	mass spectrometry

MEDICAL AND INDUSTRIAL APPLICATIONS

Medical Diagnosis using X-rays, radioisotopes, PET scans	)
Cancer Therapy using X-rays, γ-rays, protons, C^+ ions	) ~5,200
Electron beam welding	)
Polymerization of plastics	)
Semiconductor circuit processing	)
Ion implantation	) ~8,500
Sterilization of food and waste	)
Borehole diagnostics	)
Dangerous material detectors	)

Plasma heating for fusion reactors

Inertial fusion reactors

Nuclear waste transmutation

Electronuclear breeding

Accelerator-Driven Subcritical Reactors

ENERGY RANGES OF DIFFERENT ACCELERATORS

?
|_____e__|_________|_________|$\mu\pi$__K__N|___Jψ__Υ|_____WZ|_H_______|_________|

ENERGY (eV) 100k 1M 10M 100M 1G 10G 100G 1T 10T

↑ LINEAR ↓

DC

Cock'rft-W-->

van de Graaff --> Tandem-->

RF

---Ion & Proton Linacs-------------------SNS-->

--Electron Linacs--------------------------------SLAC-> - - -ILC->

Induction

Pulsed

--Induction Linacs->

--Betatrons------------------>

↑ RECIRCULATING ↓

Fixed-Field

CW

--Microtrons-> Racetrack M'ns--> Recirc.Linacs->

--Cyclotrons--->

--Isochronous Cyc'ns-----PSI-> - - - - - - - - - - >

Pulsed

--Synchrocyclotrons-----Gatchina->

--FFAGs------------KEK-> - - - - - - - - - - - - - - - - ->

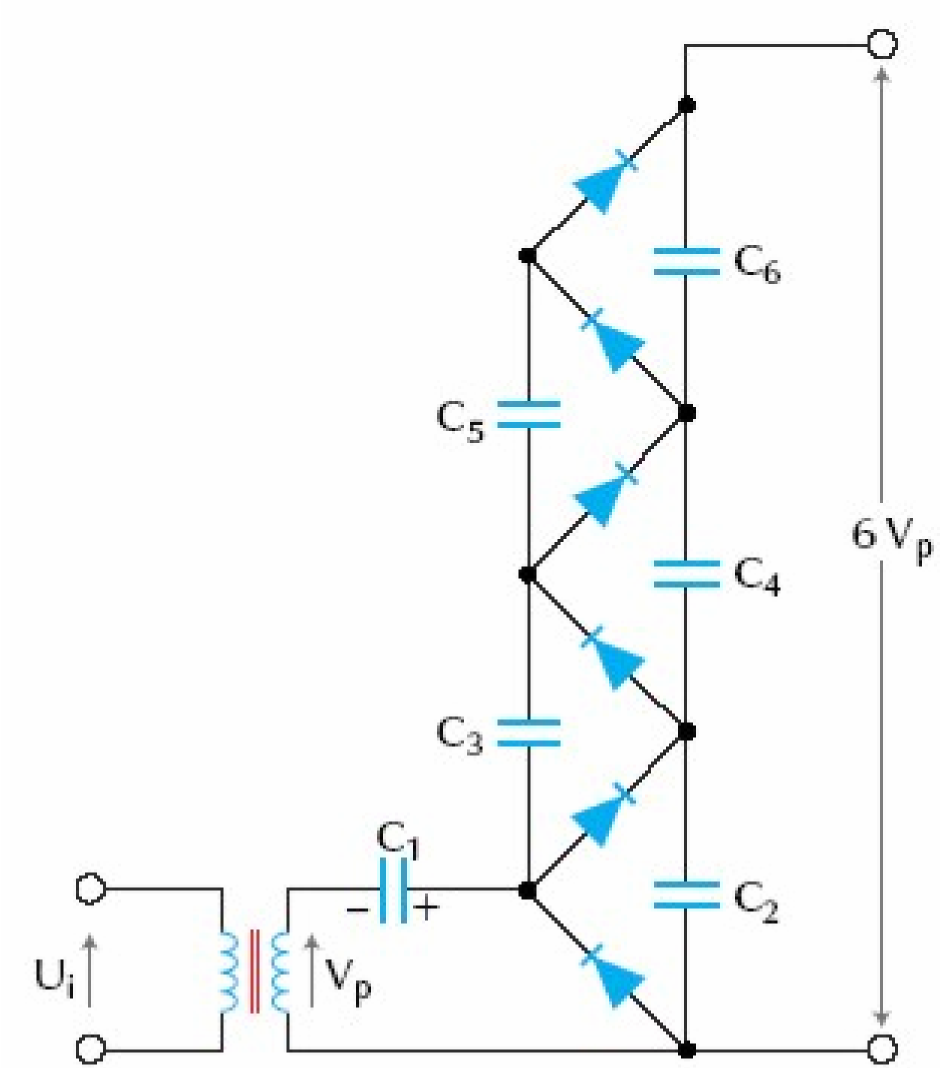
Cycling

Pulsed

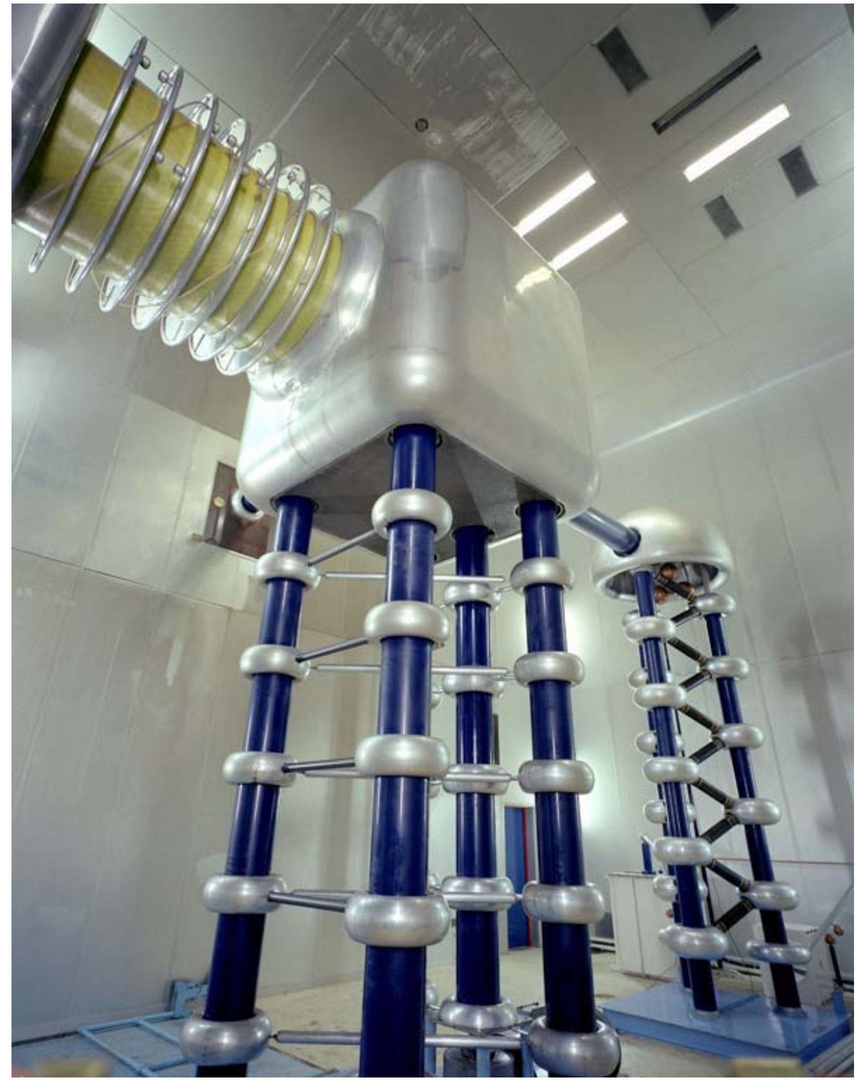
--Electron Synchrotrons-LEP->

---Proton Synchrotrons---------Tev^{n}--LHC->

DC HIGH-VOLTAGE ACCELERATORS – COCKCROFT-WALTON GENERATORS

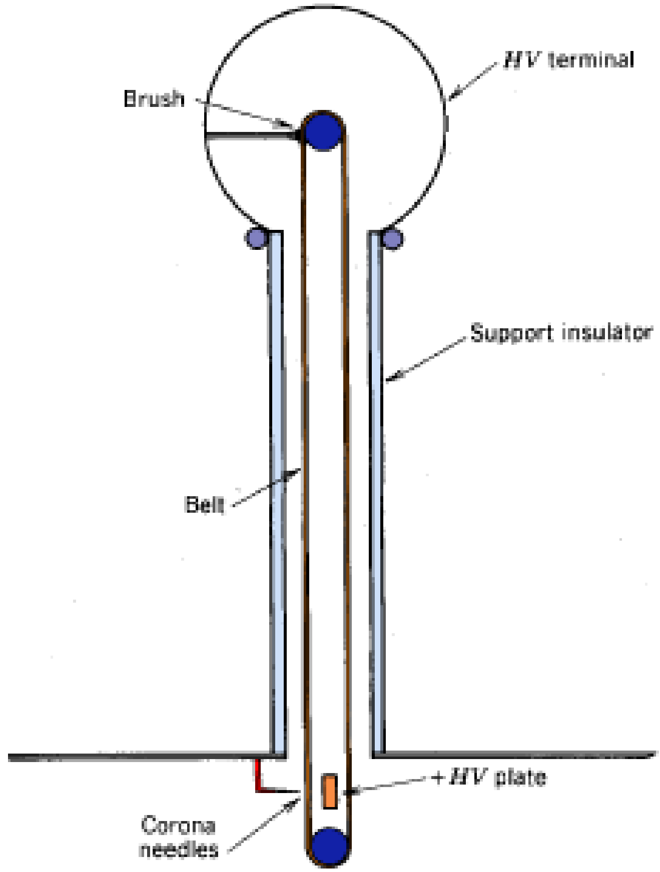


Cockcroft & Walton's cascade-rectifier voltage-multiplication circuit.

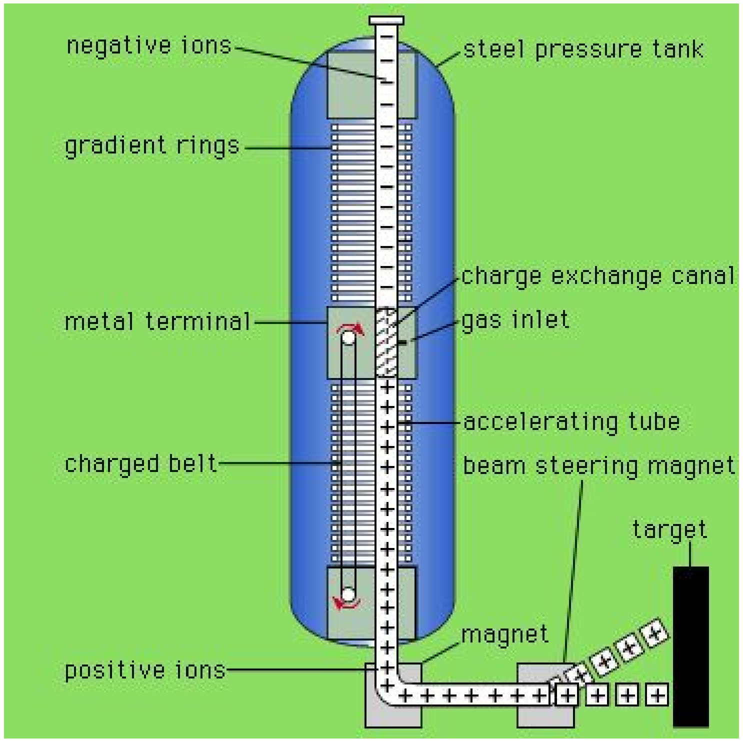


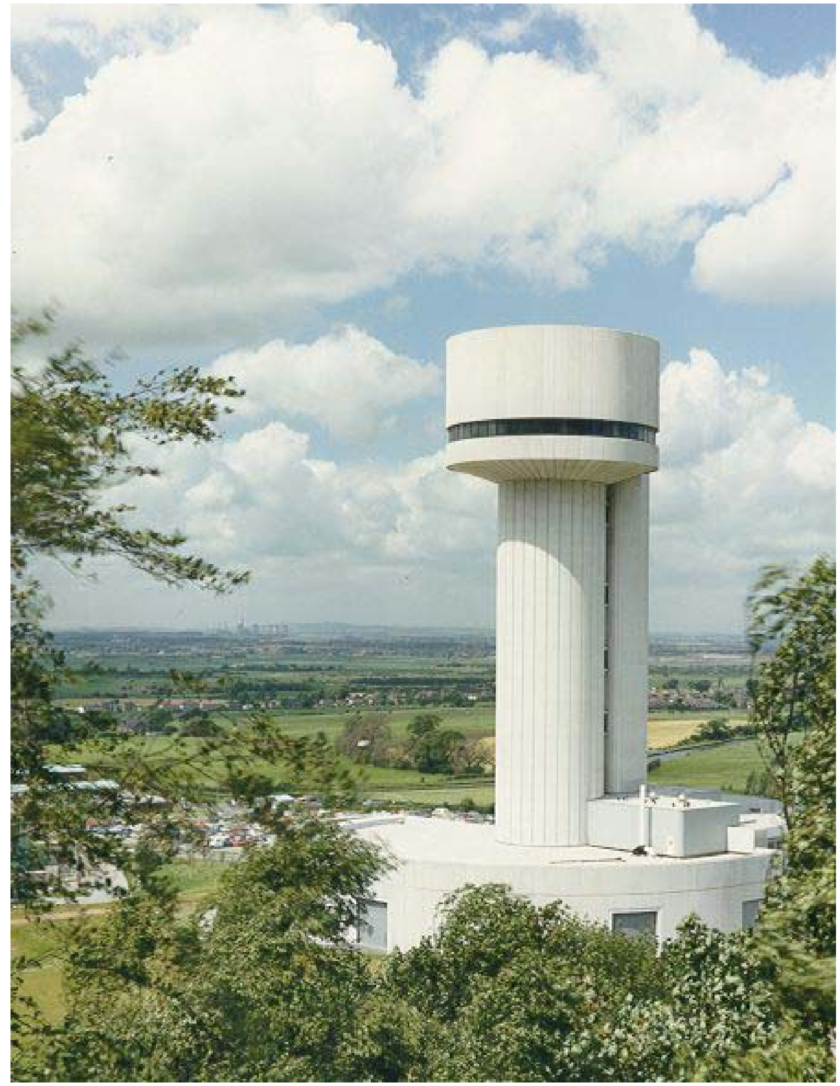
Fermilab 750-keV Cockcroft-Walton generator (R) & ion-source stand (L).

DC HIGH-VOLTAGE ACCELERATORS – VAN DE GRAAFF GENERATORS



DC HIGH-VOLTAGE ACCELERATORS – TANDEM VAN DE GRAAFFS



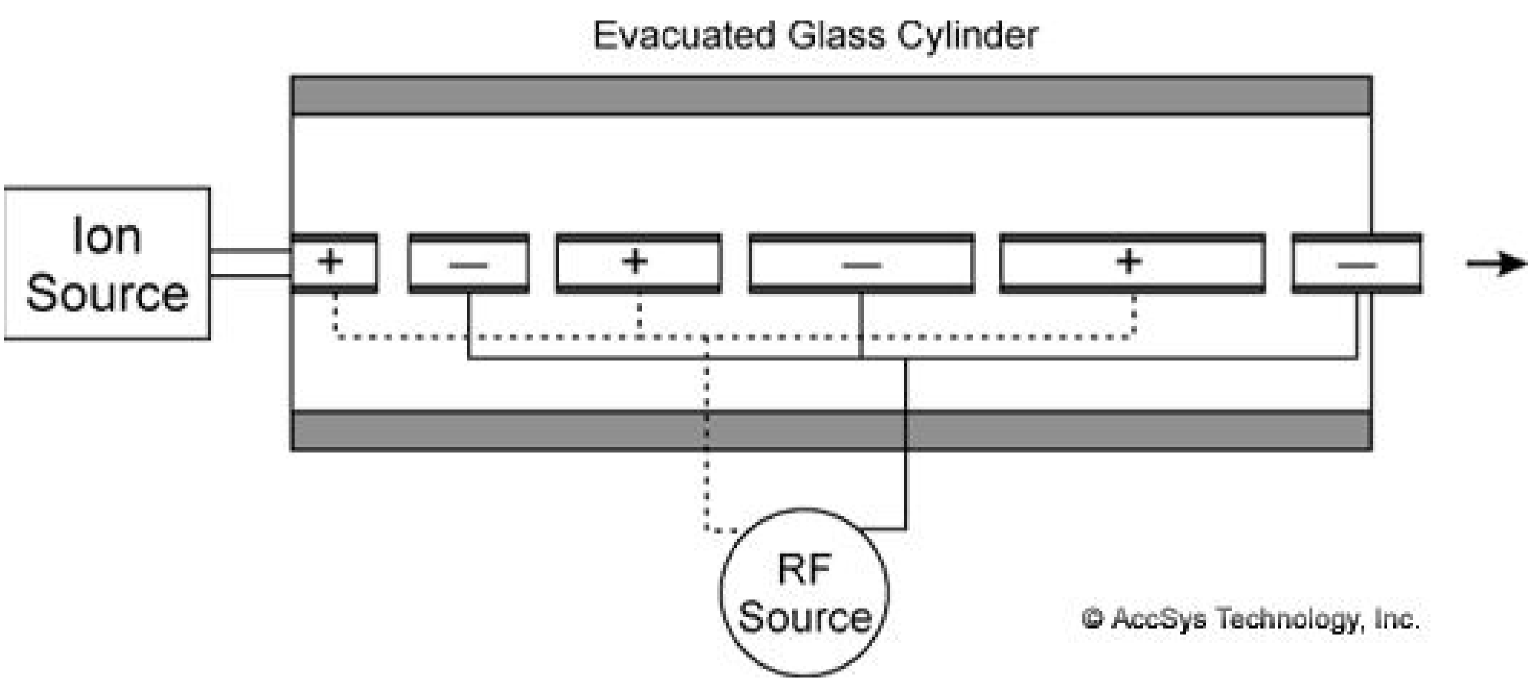


Above: Daresbury folded tandem
(20 MV in a 230-ft tower).
Left: Yale 22-MV tandem.

LOW-VOLTAGE AC (RF) LINEAR ACCELERATORS (LINACS)

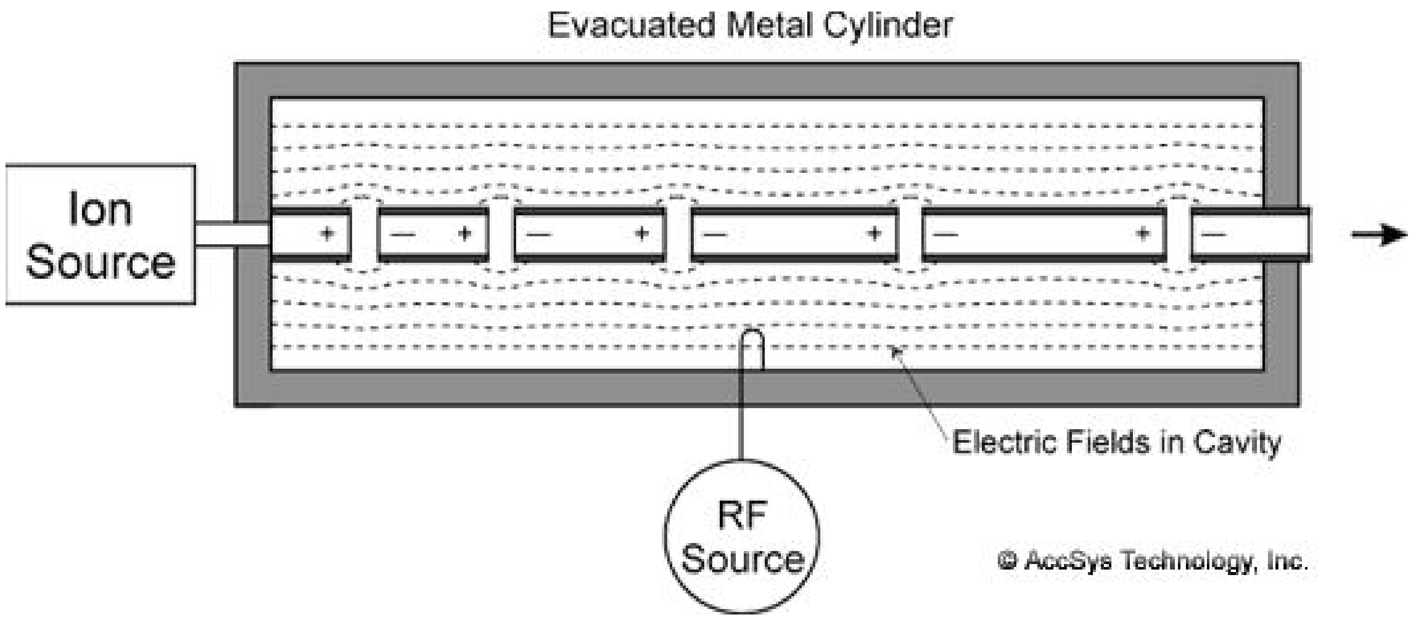
- First suggested by Ising in 1924 (a travelling-wave proposal).
- Wideröe (1928) achieved 28-keV alkali ions, in a fixed-field version.
- Lawrence & Sloan accelerated Hg ions to 1-2 MeV (1930), 2.85 MeV (1934)

- The crucial innovation was the field-free drift tubes, shielding the ions from the electric field whenever it reversed direction.
- Note that the beam is non-continuous - a stream of short pulses – separated by the rf period τ .
- Also, the drift-tube lengths ℓ_n must increase with ion velocity: $\ell_n = v_n\tau/2$

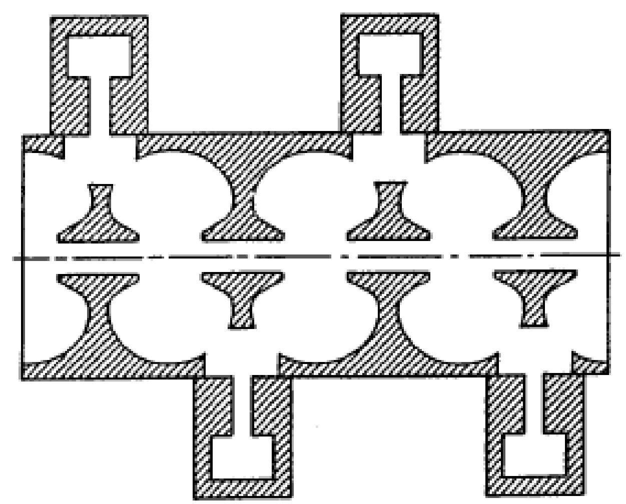


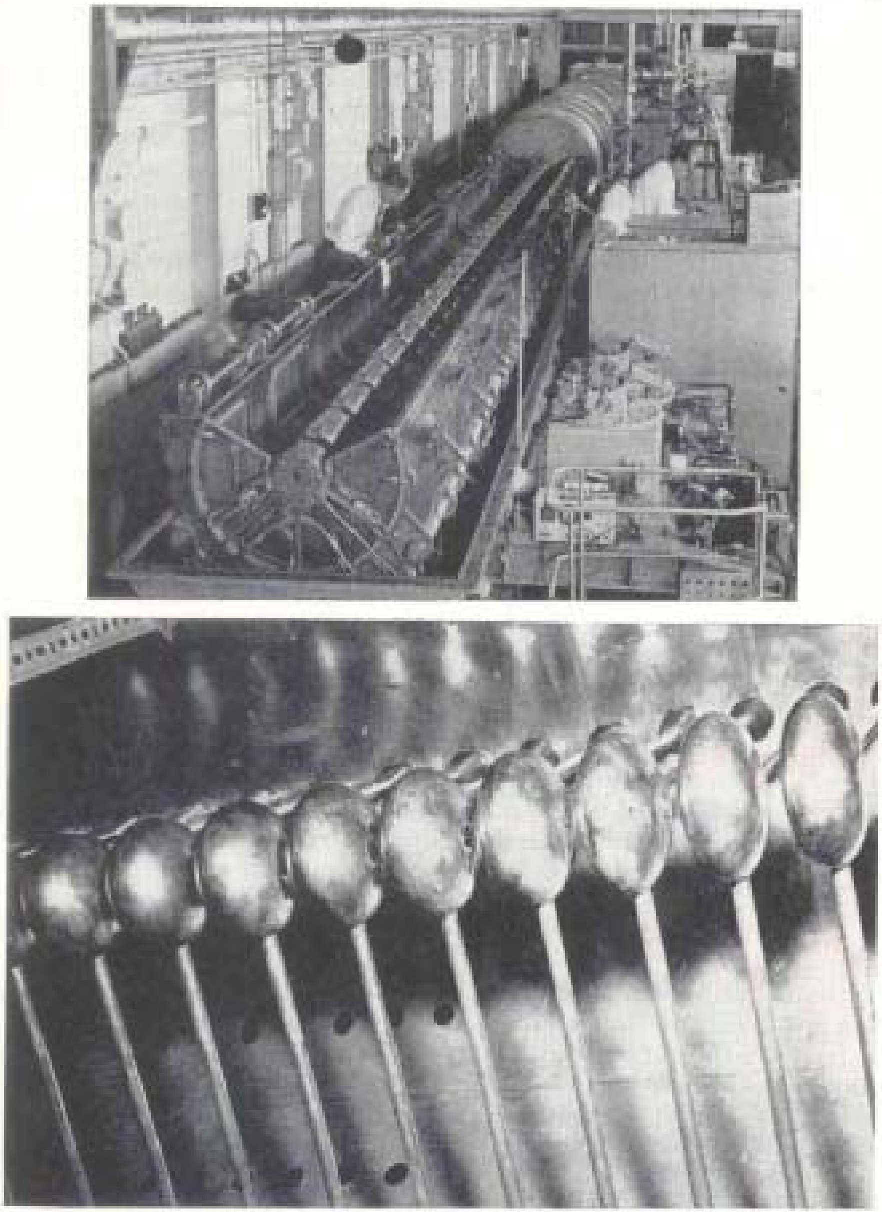
MODERN PROTON AND ION LINACS

Following Alvarez (1946), modern practice is to immerse the drift tubes in an electromagnetic cavity:



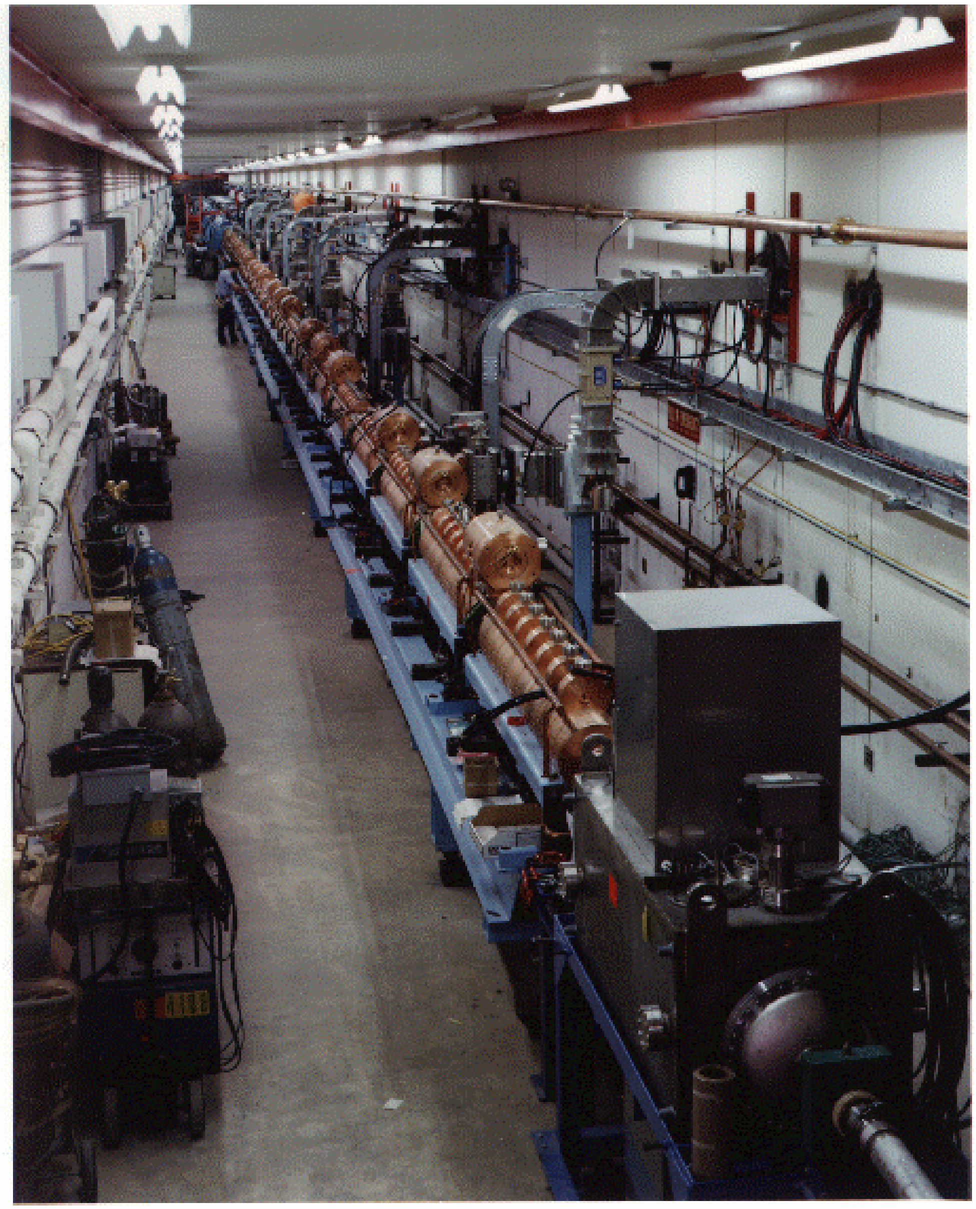
For protons above 100 MeV, the drift tubes are incorporated in a "coupled-cavity" design - introduced at Los Alamos in the 1960s.



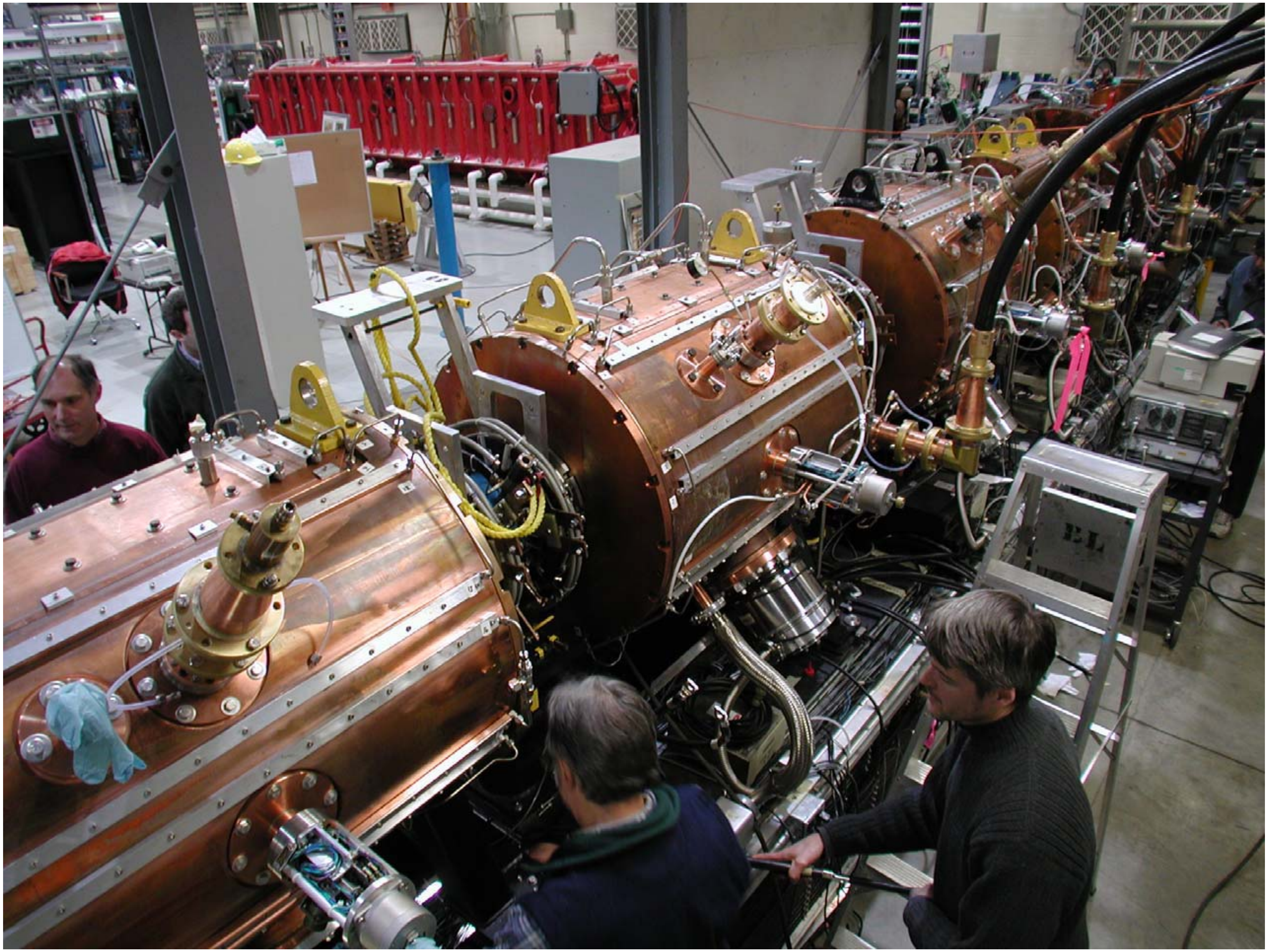


Courtesy of United Kingdom Atomic Energy Authority

Rutherford Lab proton linac drift tubes:
Top: at 50 MeV; Bottom: at 0.5 MeV.



Fermilab 400-MeV proton linac,
using side-coupled cavities



ISAC 1.5 MeV/u Drift-Tube Linac

The ISAC 150-keV/u RFQ linac

RFQ LINACS

Radio-frequency quadrupole linacs:

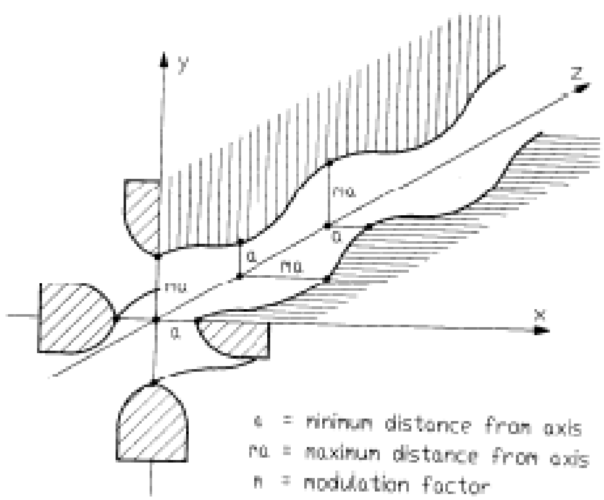
- were proposed by Kapchinsky and Teplyakov (1970)
- were demonstrated at Los Alamos (1980).
- have largely replaced DC accelerators as injectors of protons & ions.

The RFQ operates at low energy:

- accepting a continuous beam at a few keV
- bunching it with nearly 100% efficiency
- focusing and accelerating it to a few MeV.

Think of it as an electric quadrupole

- whose rf oscillations provide AG (Alternating Gradient) focusing
- whose pole-tip radius modulation provides E_z for acceleration.



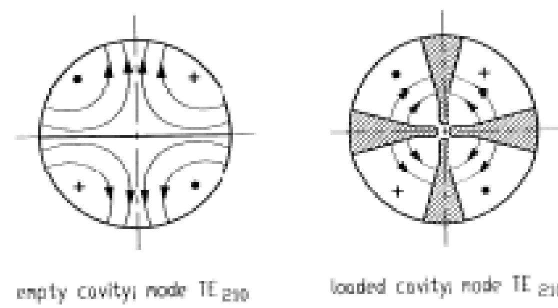
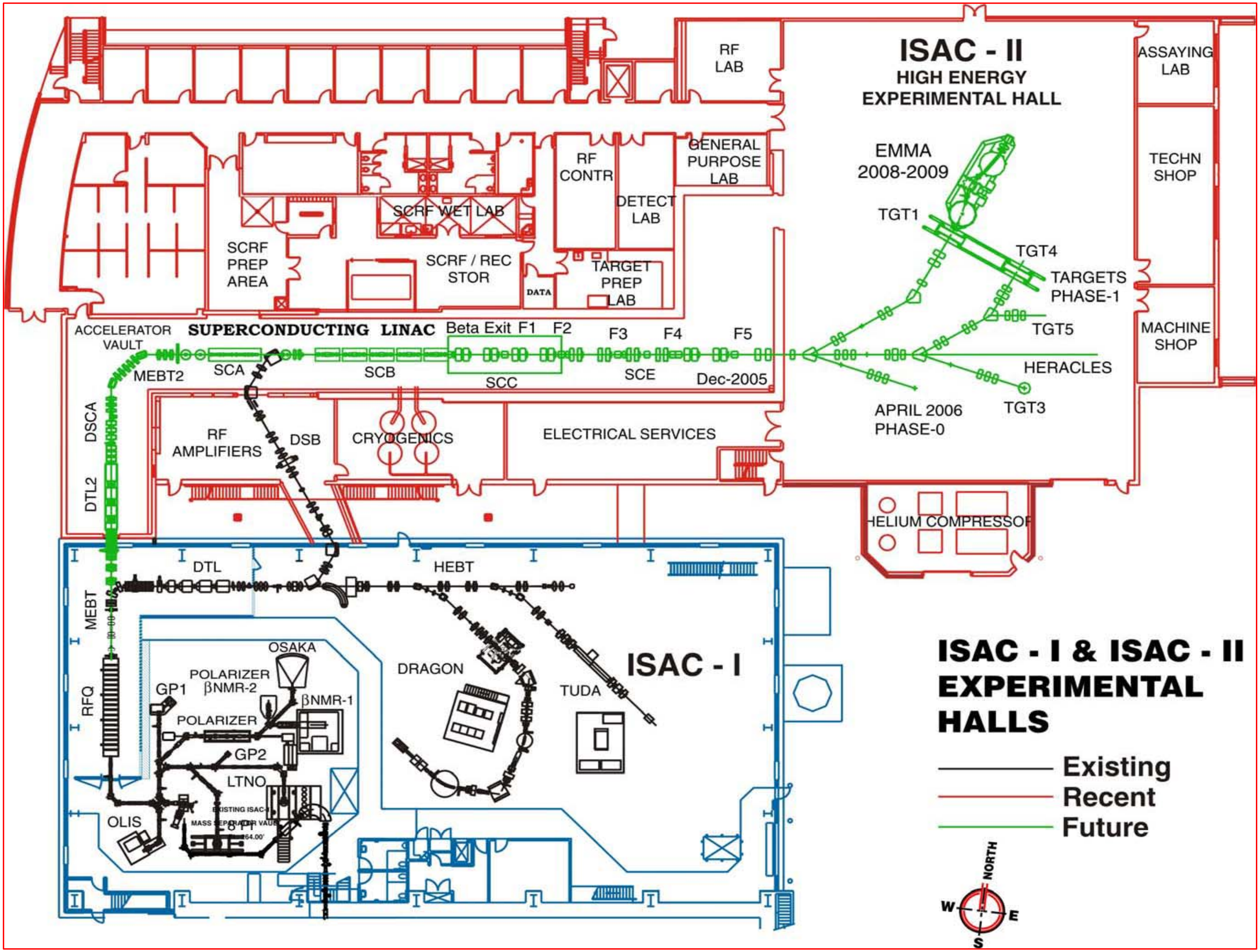


Fig. 17 TE_{210} field pattern in empty and loaded cavities


ISAC - II
HIGH ENERGY
EXPERIMENTAL HALL
RF LAB
ASSAYING LAB
TECHN SHOP
MACHINE SHOP
EMMA 2008-2009
TGT1
TGT4
TARGETS PHASE-1
TGT5
HERACLES
TGT3
APRIL 2006 PHASE-0
GENERAL PURPOSE LAB
RF CONTR
DETECT LAB
TARGET PREP LAB
DATA
SCRF WET LAB
SCRF / REC STOR
SCRF PREP AREA
ACCELERATOR VAULT
SUPERCONDUCTING LINAC
Beta Exit
F1
F2
F3
F4
F5
MEBT2
SCA
SCB
SCC
SCE
Dec-2005
DSCA
DTL2
RF AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
HELIUM COMPRESSOR
DTL
HEBT
MEBT
RFQ
OSAKA
POLARIZER
βNMR-2
βNMR-1
GP1
POLARIZER
GP2
LTNO
OLIS
EXISTING ISAC-I
MASS SEPARATOR VAULT
DRAGON
TUDA
ISAC - I
ISAC - I & ISAC - II
EXPERIMENTAL
HALLS
Existing
Recent
Future
NORTH
W
E
S

SUPERCONDUCTING LINACS

Linacs need a separate EM field for each accelerating gap -
so to reach high energies with normal-conducting rf cavities requires:

- very high power and ∴ usually pulsed operation;
- very long machines, as field strength is limited.

Thus LANSCE (800 MeV x 1 mA = 0.8 MW protons), operating on a 12% duty cycle, needs 65 MW rf power (150 MW mains?). Located in a remote part of New Mexico, it can afford to run only 3 mo/y.

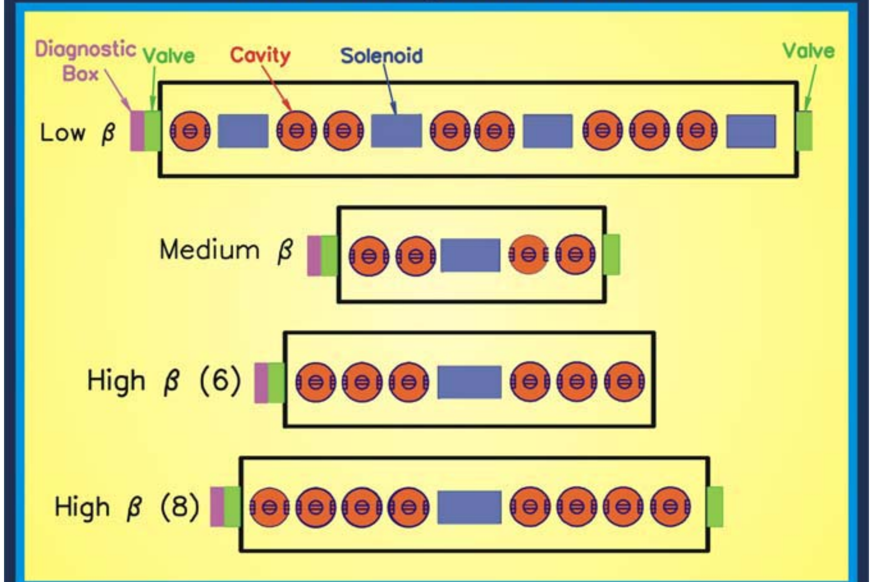
Superconducting cavities have therefore been pursued since ~1960 in the hope of reducing the power dissipation in the walls to zero.

Success came in the 70s and 80s using niobium:
- first heavy ions (range of v, few cavities - ATLAS….now ISAC-II)
- then electrons (v=c, many cavities same size - Cornell, CEBAF, LEP)
- now protons (wide range of v, many cavities - 1-GeV SNS).

Furthermore, much higher fields can be produced – up to 30 MV/m.

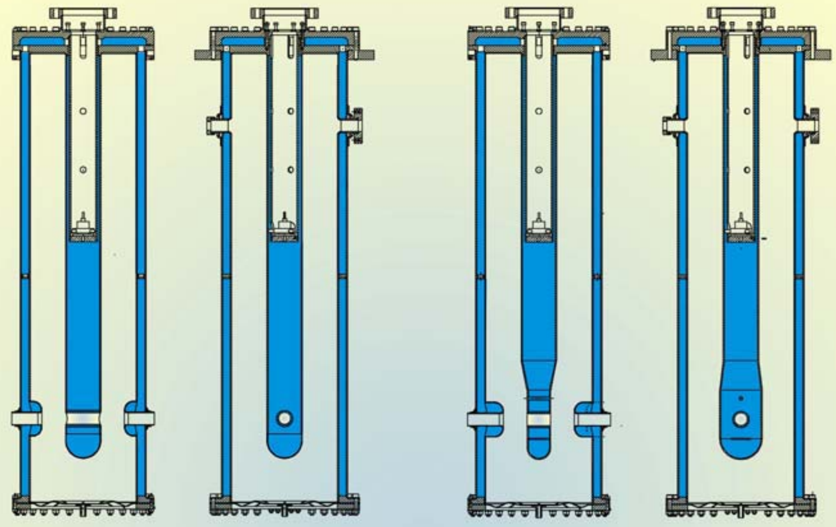
ISAC Superconducting RF Cavities

ISAC-II Cryomodules



Prototype Cavity

Medium Beta Cavities



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

freq=106.08MHz

$E_p/E_a \simeq 5$

$H_p/E_a \simeq 100 \ G/(MV/m)$

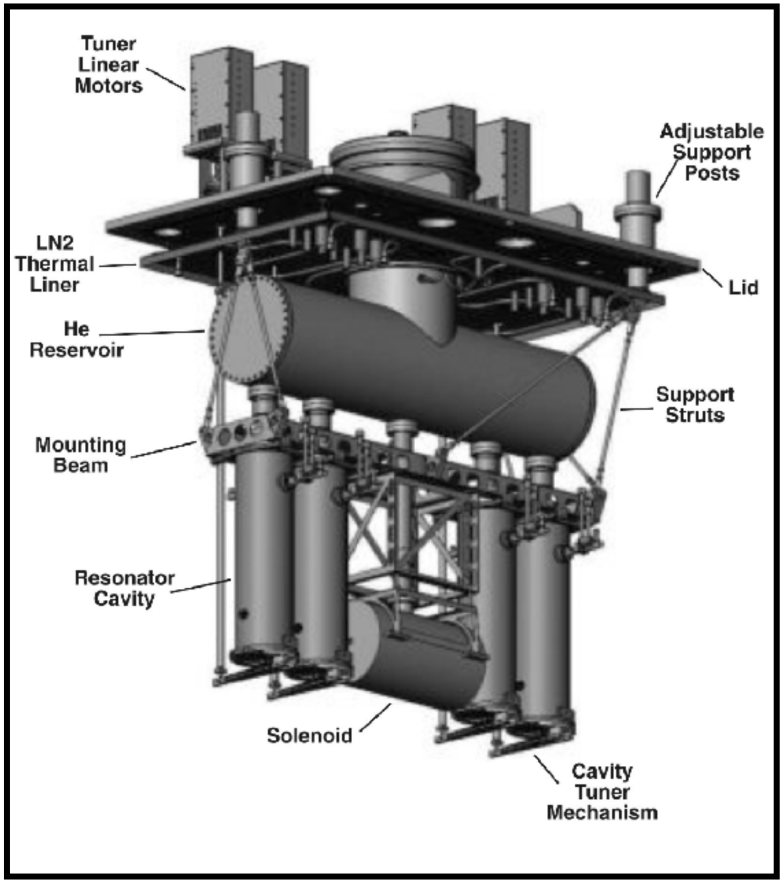
$U/E_a \simeq 0.09 J/(MV/m)^2$

$\Gamma \simeq 19\Omega$

Medium Beta Cryomodule

- 2x2x1m stainless steel box vacuum vessel
- LN2 cooled copper sheet used as thermal shield
- Mu metal between vacuum tank and LN2 shield
- Cold mass suspended from lid on three adjustable support pillars

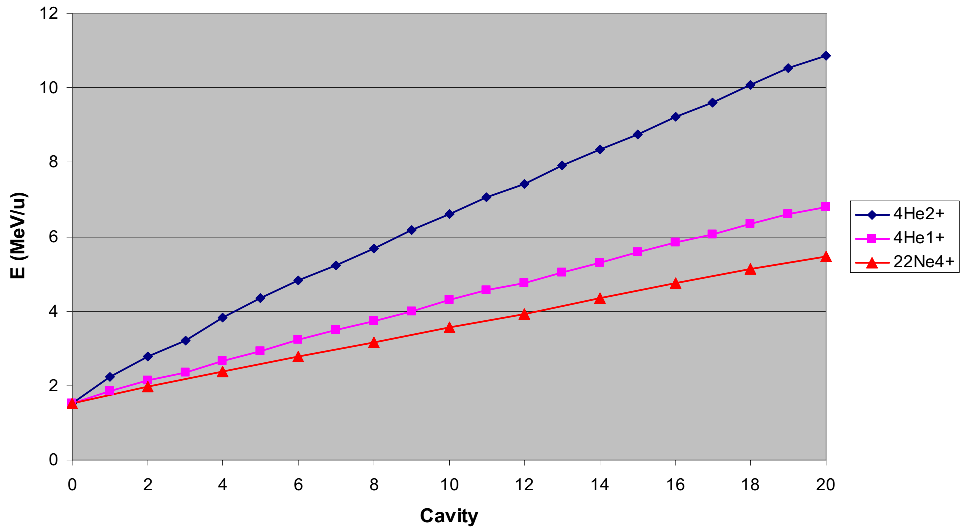
- Four cavities Ep=30MV/m
- One SC solenoid @ 9T
- V_{eff}=4.3MV
- Single vacuum for thermal insulation and rf



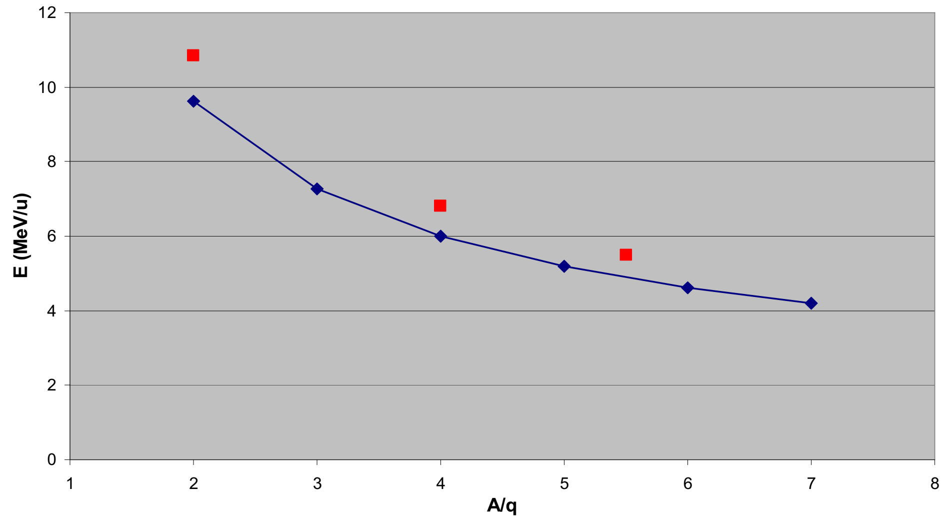
Lid Assembly in Assembly Frame

THE ISAC-II SUPERCONDUCTING LINAC

The last of the 8 cryomodules, containing 40 superconducting niobium cavities, was installed in March 2010. Radioactive ion beams can now be accelerated up to 6.5 MeV/u ($Q/A = 1/6$) or 16.5 MeV/u ($Q/A = \frac{1}{2}$).



Energy history during acceleration.



Expected E_{final} for 6MV/m and actual E_{final}

Commissioning beams

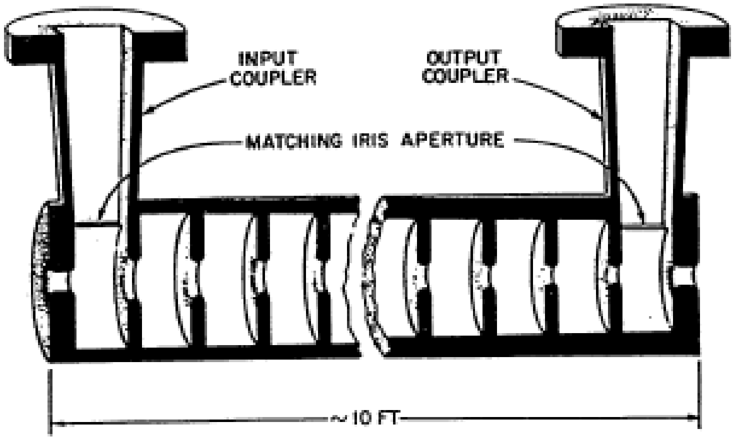
- A/q=5.5 (22Ne4+)
- A/q=4 (40Ca10+, 20Ne5+, 12C3+, 4He1+)
- A/q=2 (4He2+)

Performance

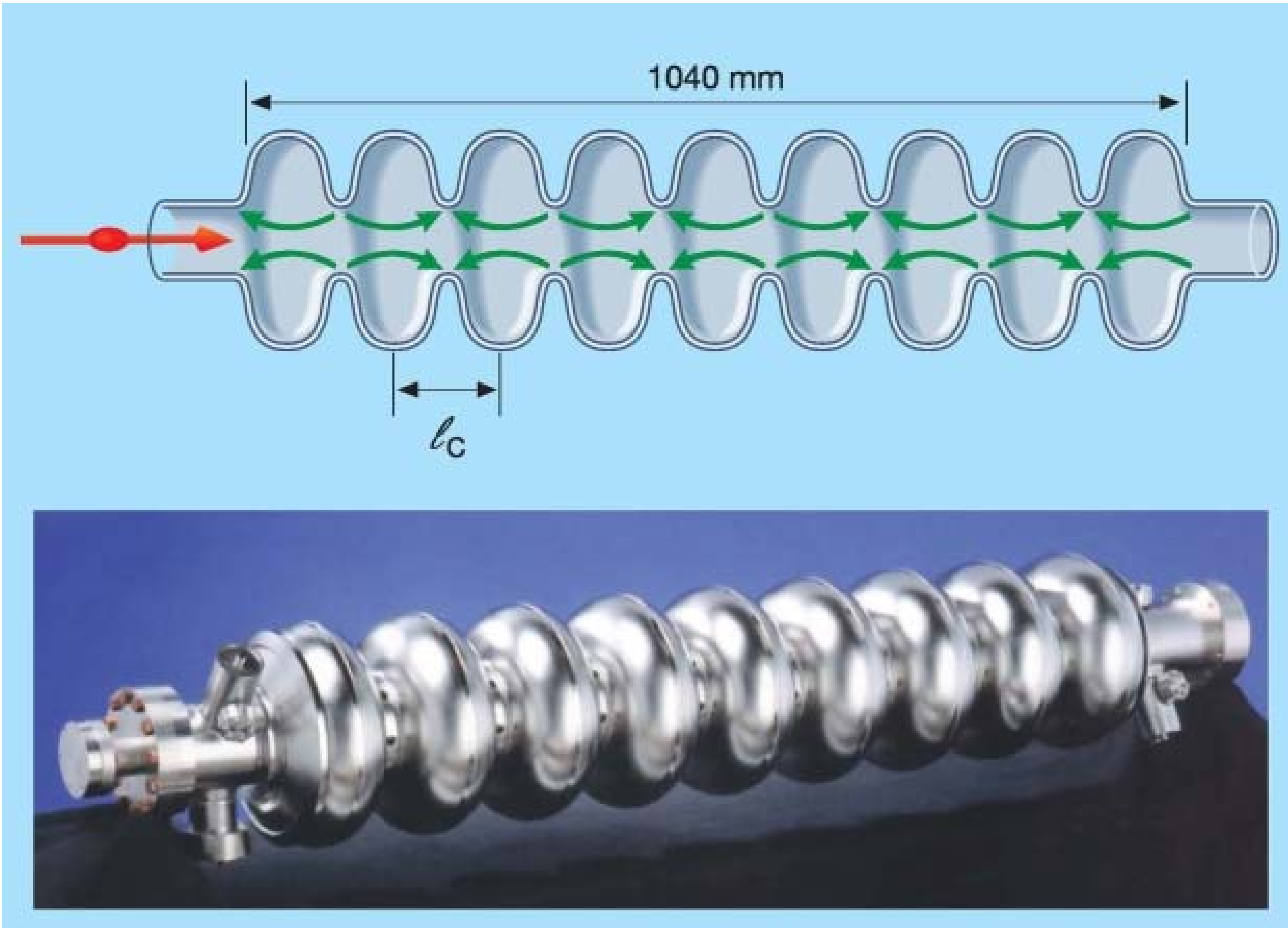
- Power @ 7W/cavity
- Design gradient is 6MV/m
- Average gradient is 7.2MV/m
- Final energy is 10.8, 6.8 and 5.5MeV/u for A/q=2, 4, 5.5 respectively
- Transmission >90%

ELECTRON LINACS

Electrons are usually accelerated by travelling EM waves in disc-loaded waveguides, whose dimensions determine the wave's speed.
As an electron's speed $v \rightarrow c$, the speed of light, at relatively low energies (~500 keV), the waveguide dimensions can be kept constant for the higher energies, and those parts of the linac built from identical sections (as for the 50-GeV SLAC linac, below).



SUPERCONDUCTING CAVITIES FOR H.E. ELECTRONS



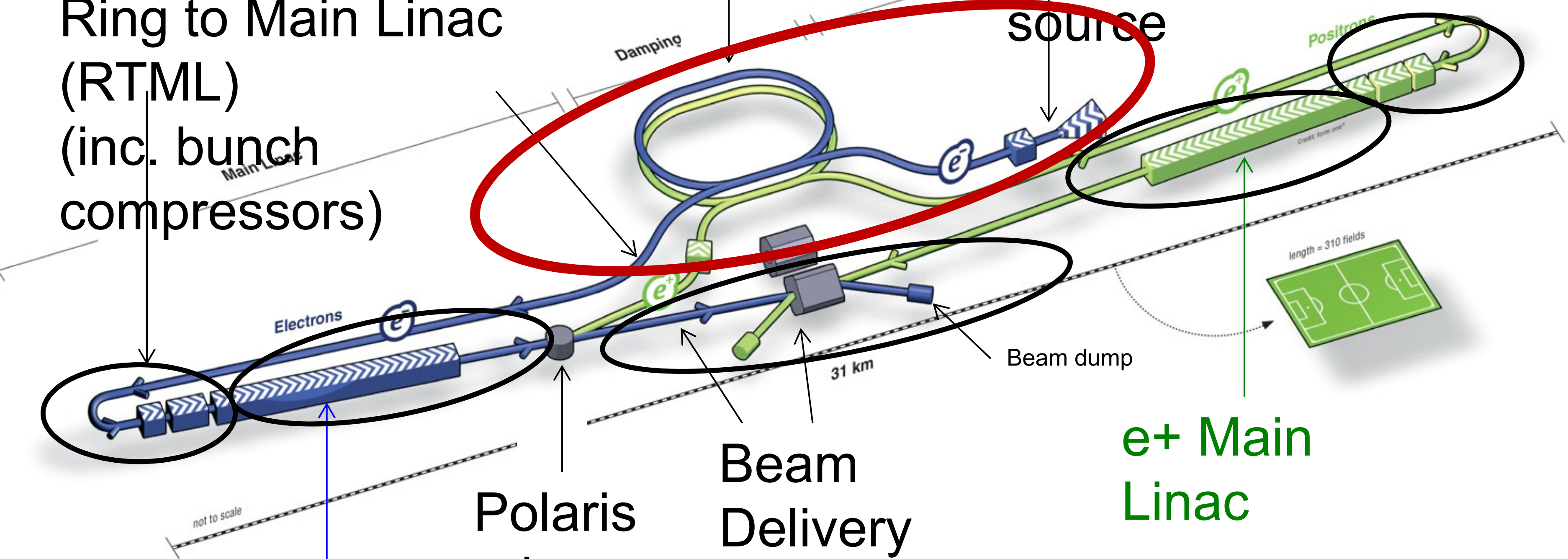
9-cell niobium cavity for the FLASH free electron laser linac at DESY

ILC in a Nutshell

Damping Rings

Polarised electron source

Ring to Main Linac (RTML)
(inc. bunch compressors)



e- Main Linac

Polarised positron source

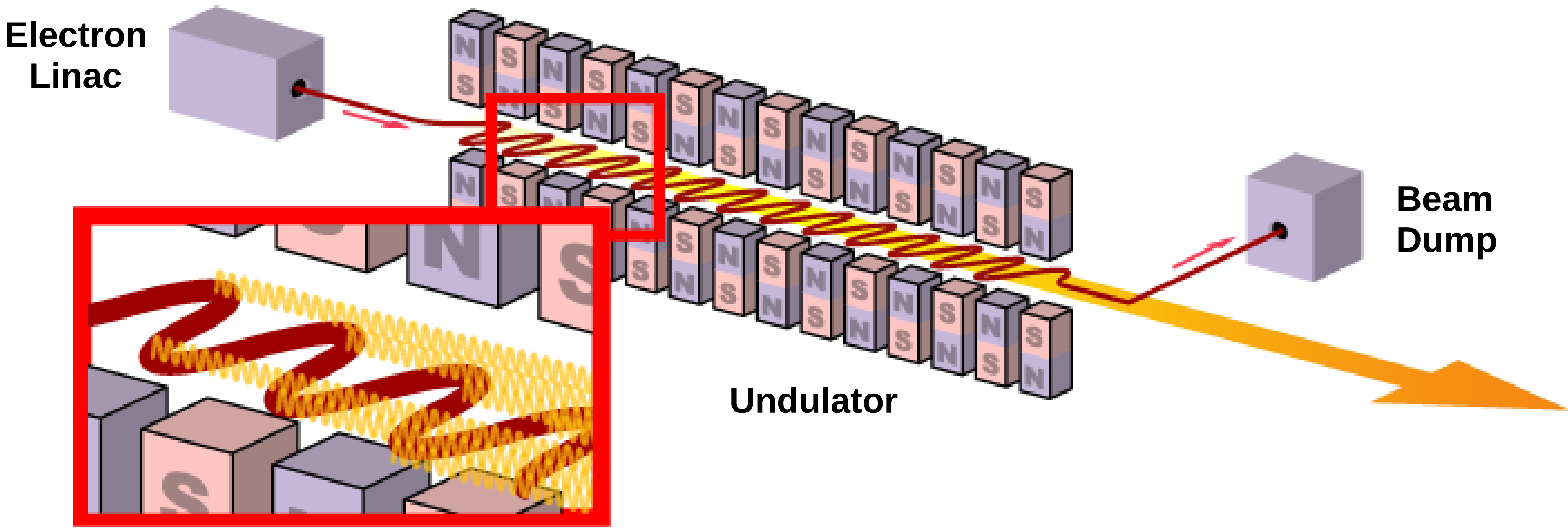
Beam Delivery System (BDS) & physics detectors

e+ Main Linac

not too scale

ILC Scheme | © www.form-one.de

FREE ELECTRON LASER



Electron oscillations in the magnetic undulator produce e-m radiation, leading to further stimulated emission downstream.

If $eB\lambda_u << 2\pi\beta m_e c$, where λ_u is the undulator wavelength, the radiation will form a narrow coherent beam.

Adding a mirror at each end forms an optical cavity → laser action.

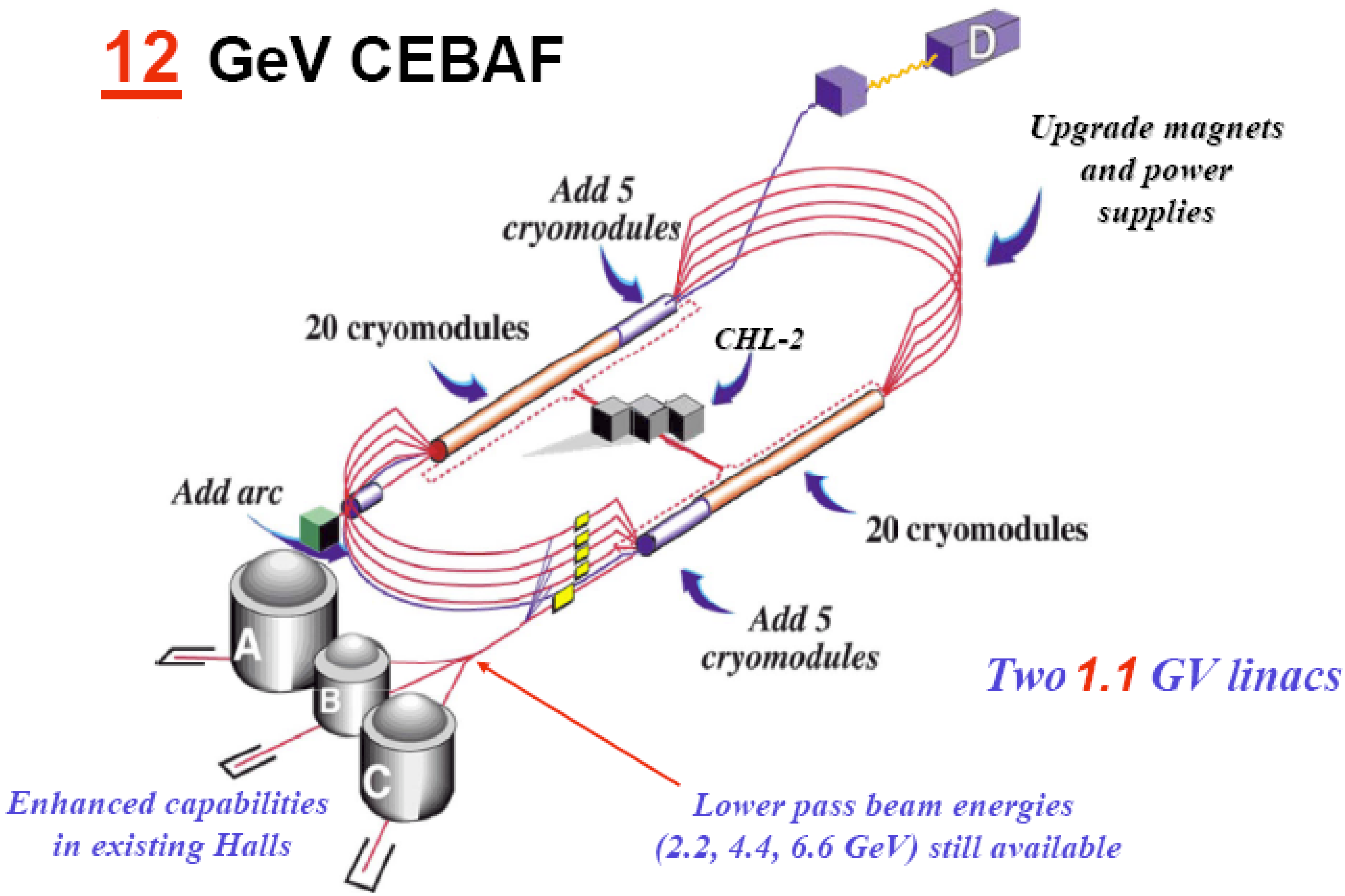
Expensive, but: - huge spectral range – microwaves to X-rays (x 10^7)

- tunable ~ $\pm$10%

RECIRCULATING LINACS

The first and best-known is CEBAF (Continuous Electron Beam Accelerator Facility) at Jefferson Lab (Virginia).

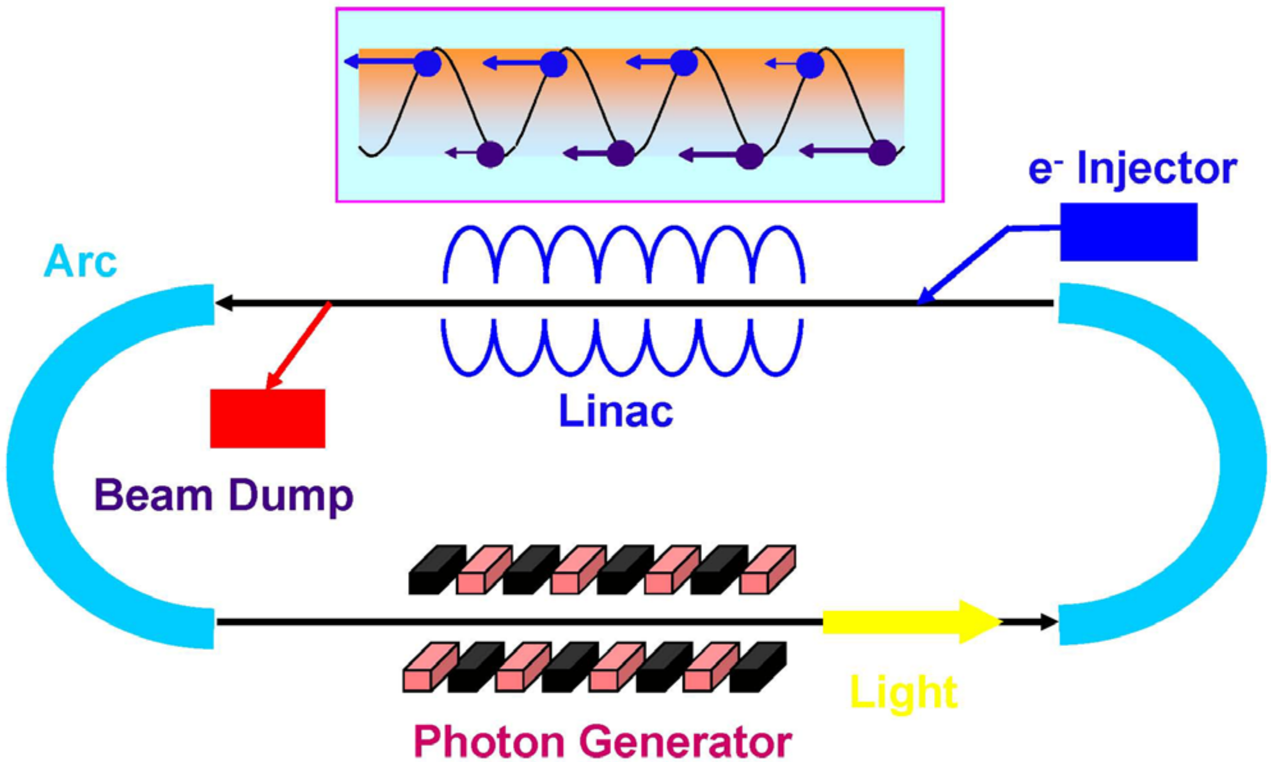
- currently 6 GeV x 200 μA (two 0.6-GeV linacs x 5 separated orbits)
- upgrade to 12 GeV recently approved (add more superconducting rf)



ENERGY RECOVERY LINAC (ERL)

2 passes through linac
- 1st accelerates
- 2nd decelerates
- energy returned to
  rf cavity.

This makes possible
high beam currents
with modest rf power.



The beam emittance is determined purely by the electron gun
- can be very small compared to circulating beams in synchrotrons, whose emittance is enlarged by random emission of radiation photons.

High current & small emittance → very bright radiation source.

Also low energy dump →low waste heat & low radioactivity.

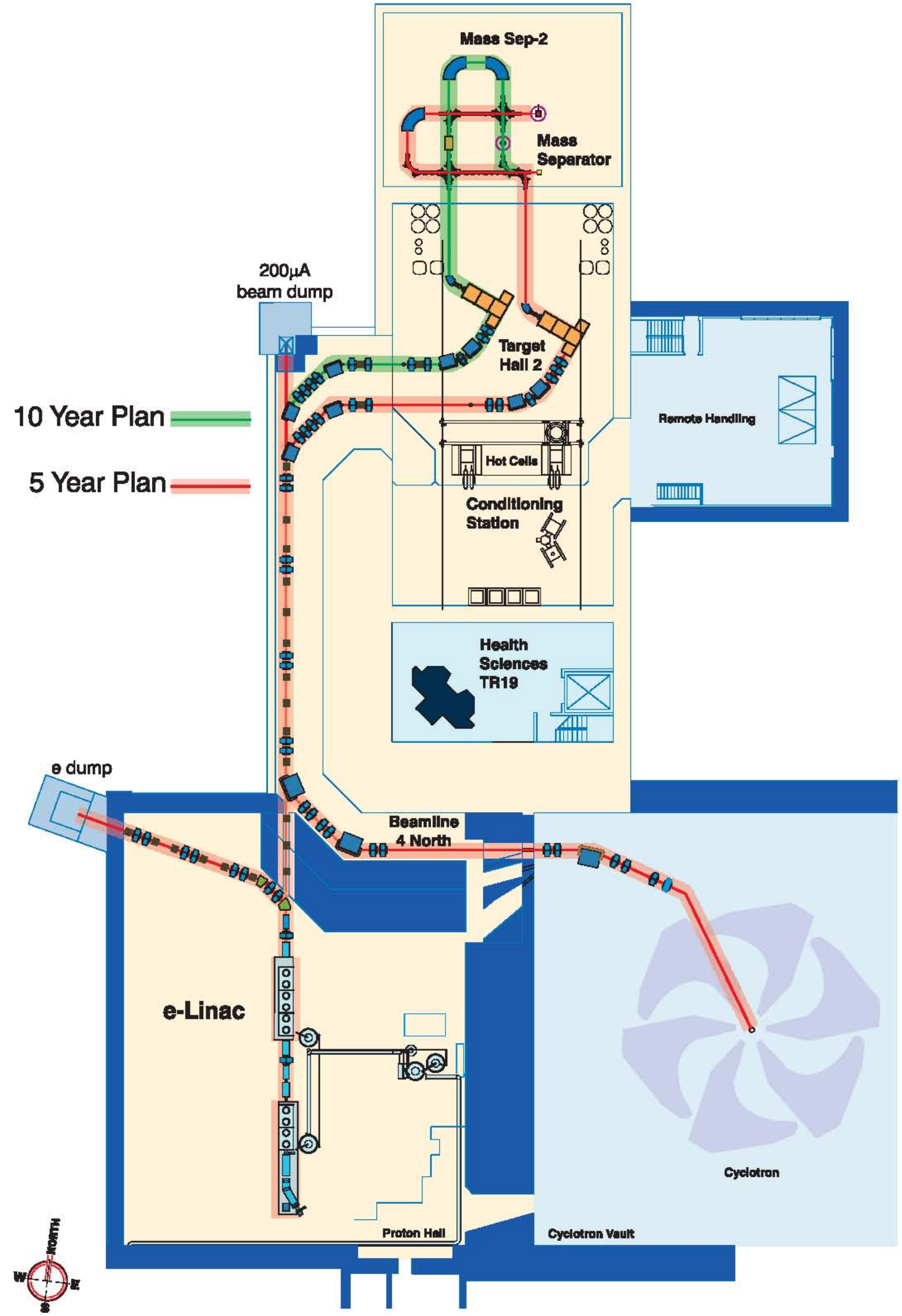
THE ARIEL PROJECT

To provide 3 independent radioactive-ion beams for experiments, TRIUMF plans to add 2 new production targets, fed by:

- ≤200 μA of ~450-MeV protons (from the cyclotron via BL4N)
- 10 mA of 50-MeV electrons from a superconducting linac (via the photofission process)

$$e \longrightarrow \boxed{W} \xrightarrow{\ \gamma\ } \boxed{U} \rightrightarrows \text{fission isotopes}$$

- yielding a range of isotopes not available from proton reactions.



E-Linac Baseline Layout

Injector linac

(acceleration & additional bunching)

10 MV/m, Q=10^{10}

10 mA, 5-10 MeV gain

$\leq$ 100 kW beam pwr

NC buncher

Main linac

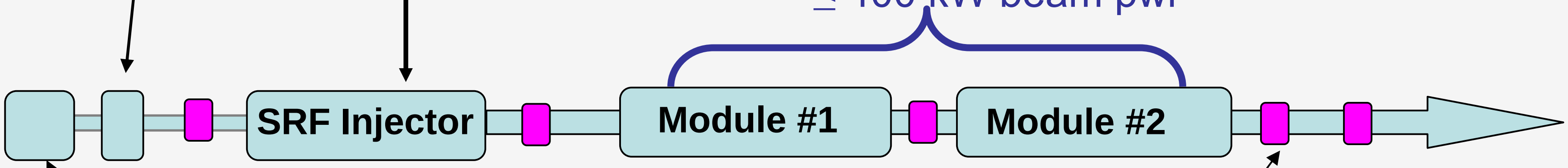
Two cryomodules

Two 9-cell cavities/module,

10 MV/m, Q=10^{10}

10 mA, 40 MeV gain

$\leq$ 400 kW beam pwr



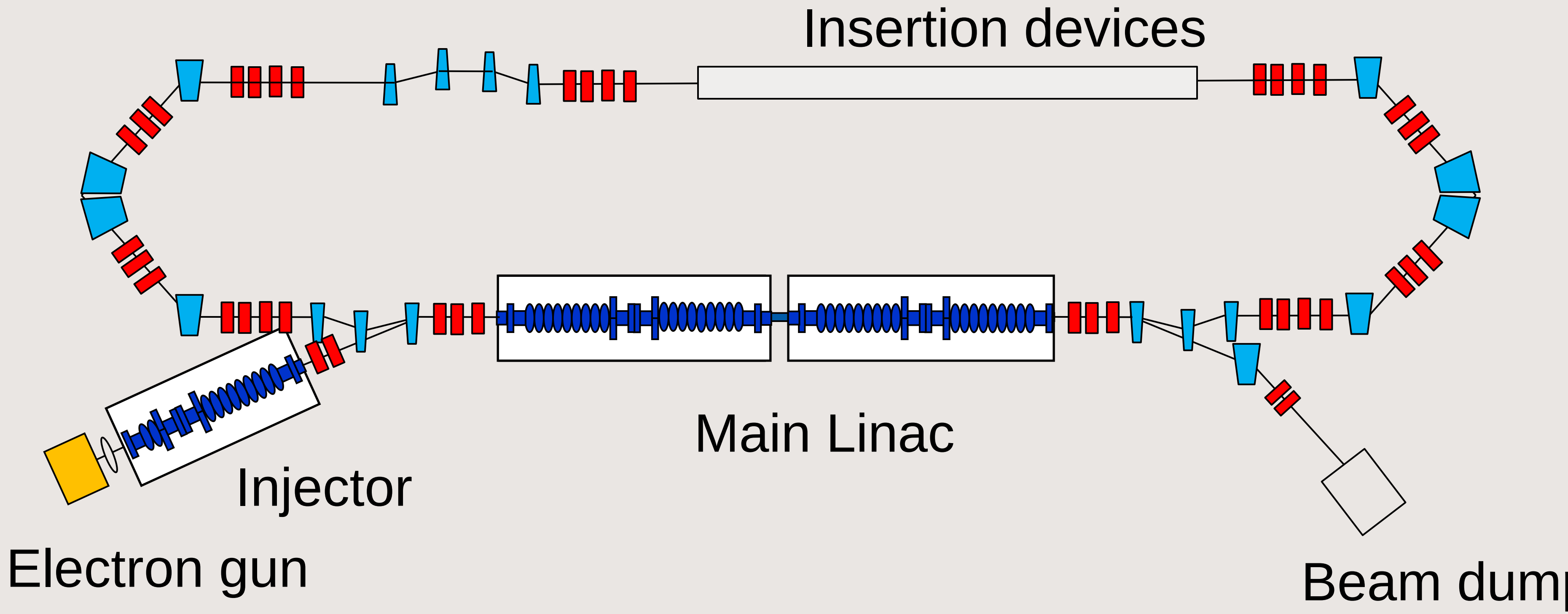
Thermionic gun: triode; 100 keV; 650 MHz

Focusing & diagnostic packages

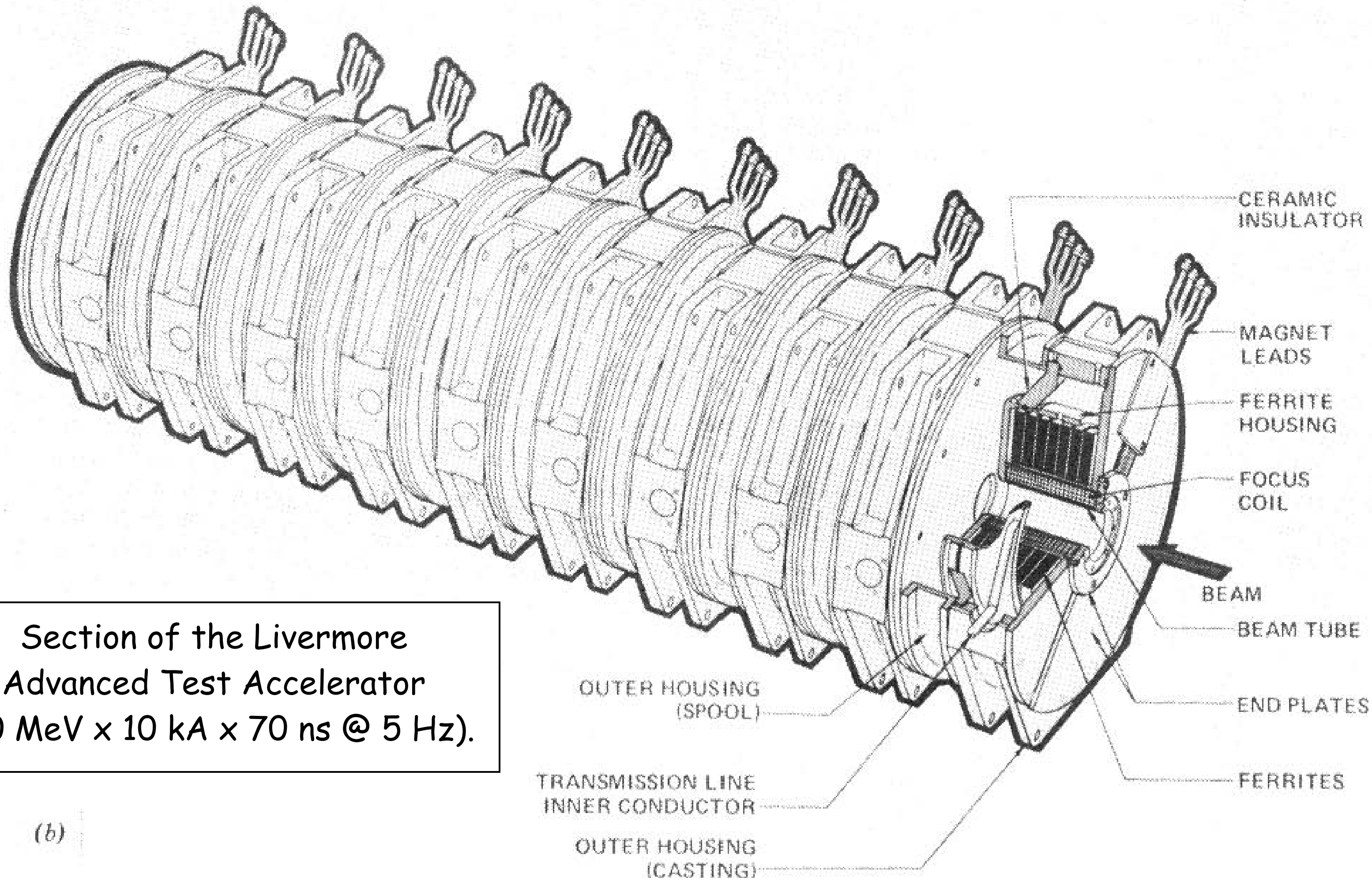
Division into injector & main linacs allows:

- Possible expansion path to test-bed for
  - Energy Recovery Linac (ERL) – e.g. 10 mA, 80 MeV
  - Recirculating Linear Accelerator (RLA) – e.g. 2 mA, 160 MeV

ERL Extension of the E-Linac



INDUCTION LINACS



Section of the Livermore Advanced Test Accelerator (50 MeV x 10 kA x 70 ns @ 5 Hz).

Pulsed toroidal magnetic fields in a series of modules induce an accelerating electric field along the axis.

- Good for very high peak current (>10 kA) pulsed beams;
- Astron injector 3.7 MeV x 350 A in 300 ns pulses @ 1 kHz.

MAGNETIC RESONANCE - THE CYCLOTRON

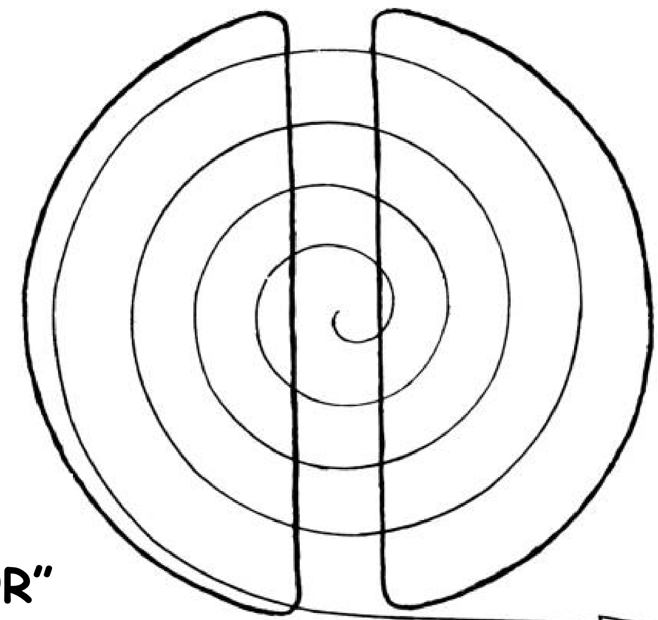
At Berkeley, the 27-year-old Ernest Lawrence saw Widerøe's linac article and set a grad student, Dave Sloan, to repeat and improve on his work. By 1930 they had achieved 1-2 MeV Hg ions.

Widerøe's paper had also reported an unsuccessful attempt to build a "beam transformer" - a betatron, where particles circulating in a rising magnetic field would be accelerated by the induced electric field.

Perhaps it was this that led Lawrence to consider a circular version of the drift-tube linac, using a uniform and constant magnetic field to return the particles repeatedly to the same accelerating gaps between two D-shaped electrodes.

Animation

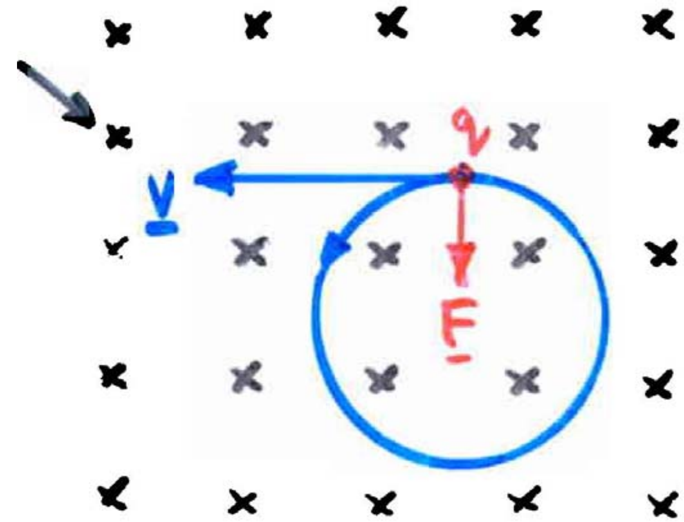
Courtesy of ATOMKI Cyclotron Laboratory, Hungary



"THE CYCLOTRON AS SEEN BY THE INVENTOR"

THE CYCLOTRON PRINCIPLE

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



Suppose uniform magnetic induction B is applied perpendicular to the velocity v of a particle with mass m, charge q:

The Lorentz Force $\underline{F} = q\,\underline{v} \times \underline{B}$ produces a circular track, and

$$q\,v\,B = m\,v^2/r = m\,\omega$$

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

- and the orbits are "isochronous".

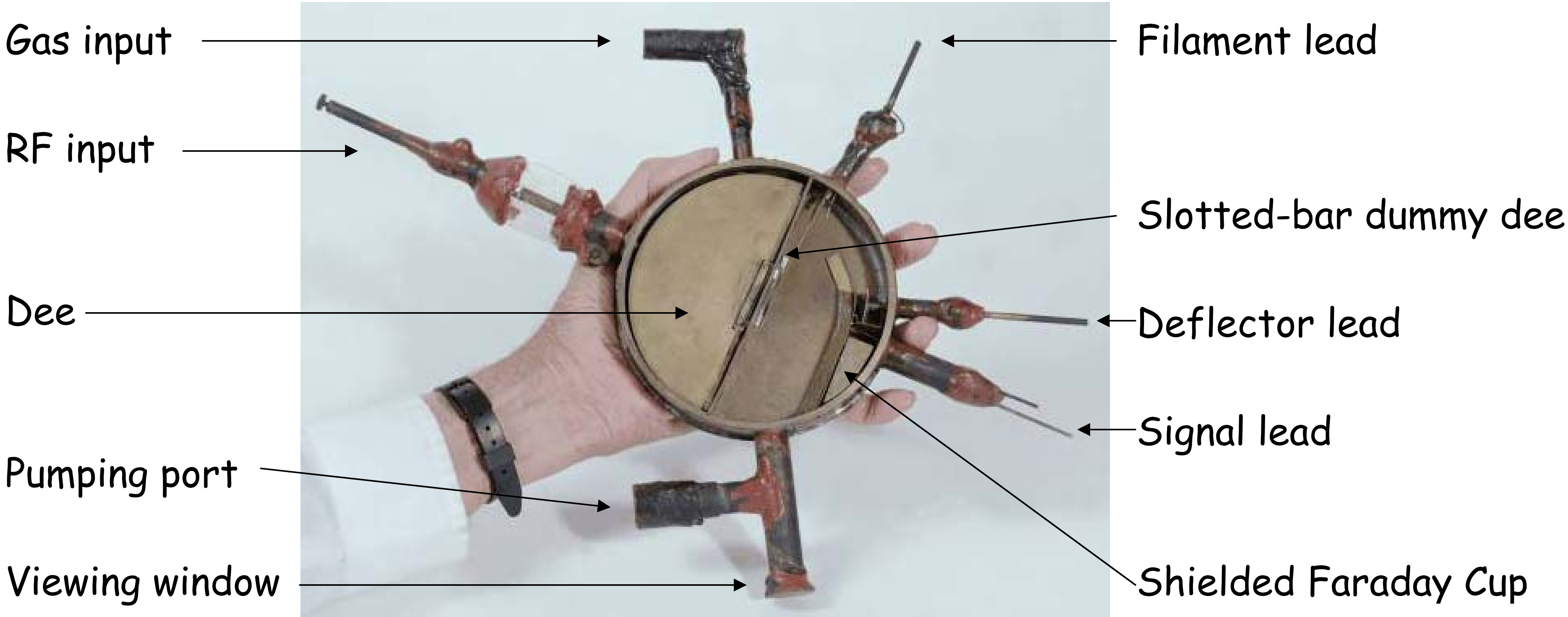
So:- the electrodes can be excited at a fixed rf frequency,

- the particles will remain in resonance throughout acceleration,
- and a new bunch can be accelerated on every rf voltage peak:

- "continuous-wave (cw) operation"

Note also that: $\boxed{r = \frac{mv}{qB}}$ radius $\propto$ velocity v.

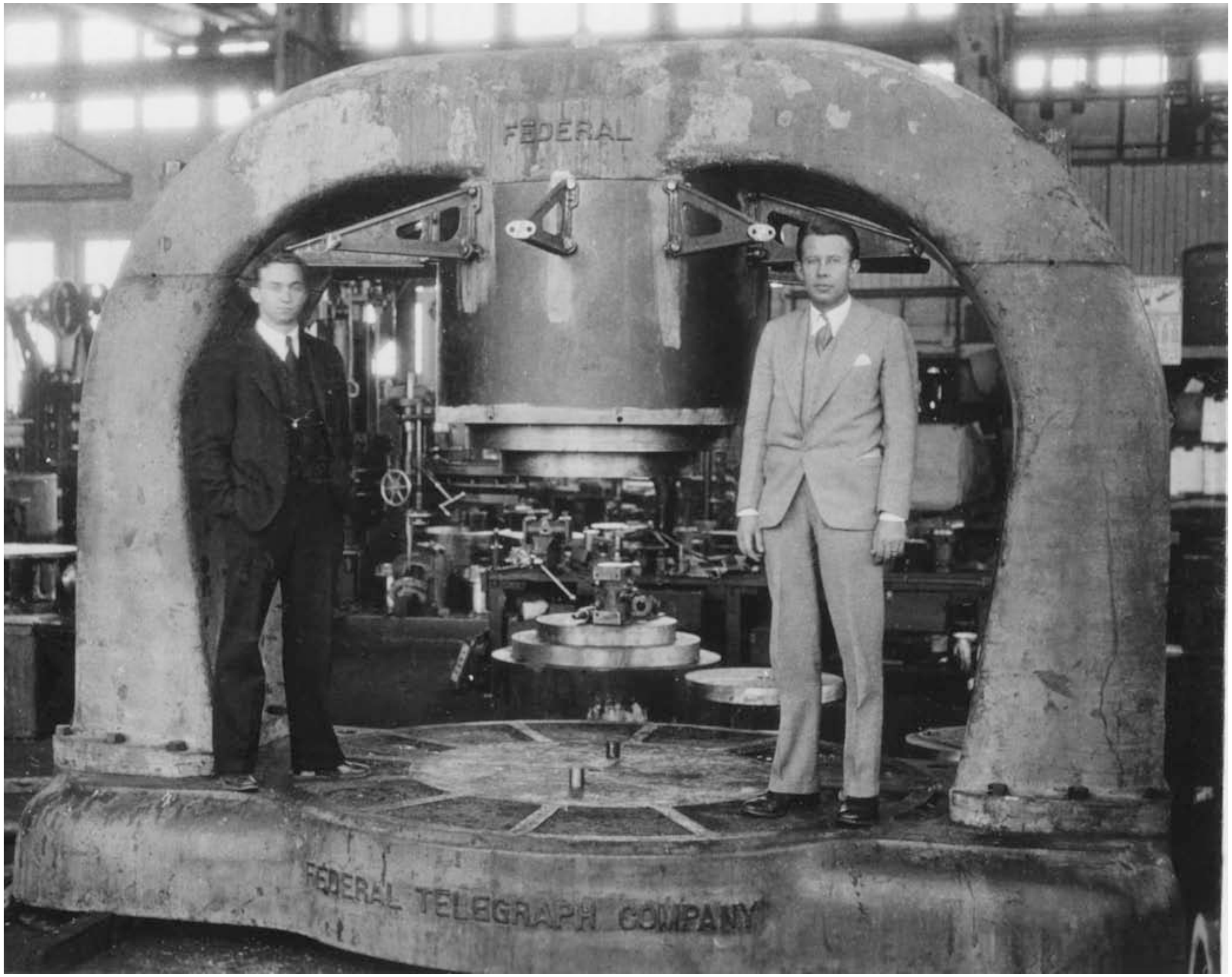
FIRST WORKING CYCLOTRON – Fall 1930



In late 1930, Lawrence's student, Stanley Livingston, built 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.

TRANSVERSE FOCUSING

In accelerators and beam transport systems, "focusing":

- does not generally refer to creation of a point focus;
- it means keeping a beam of neighbouring particles together by an E and/or M field distribution that provides restoring forces, leading to stable orbits.

Similarly, "defocusing" refers to situations with unstable orbits.

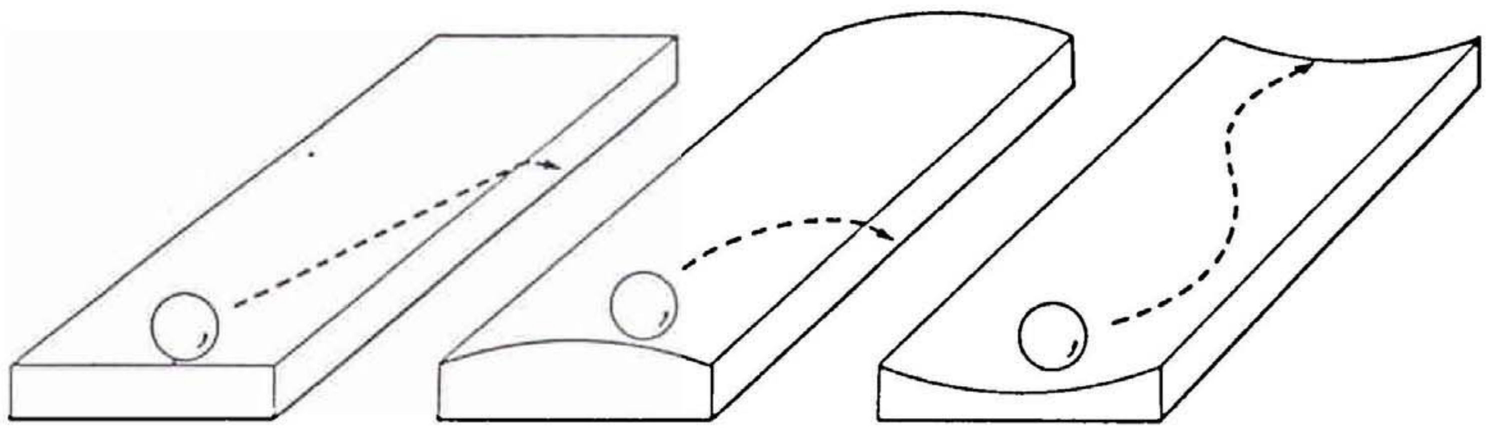
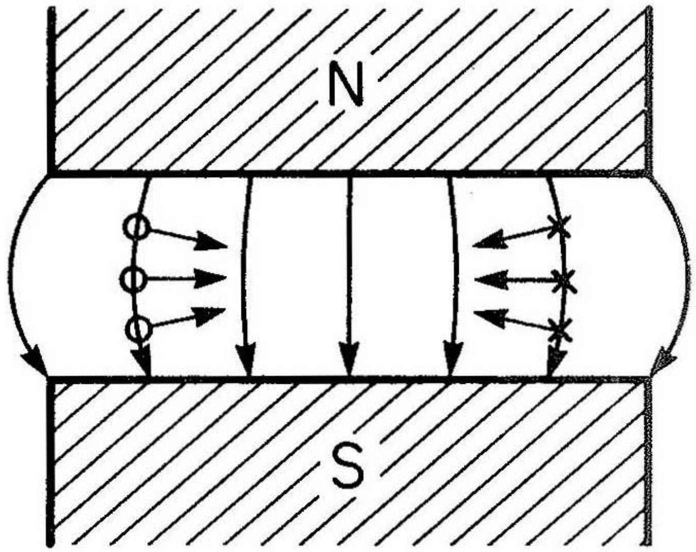


Fig. 2-1. Bowling alley analogy of systems of forces which produce neutral, unstable, or stable orbits.

WEAK (UNIFORM-GRADIENT) FOCUSING



Cyclotron

Synchrotron

An outwardly-decreasing (negative-gradient) field $\Rightarrow$ vertical focusing.

MAGNETIC GRADIENT FOCUSING - AXIAL

Taking (r, θ, z) coordinates about the mid plane,

the axial (usually vertical) force $\quad F_z = e\, v\, B_r$

& by Taylor expansion $\quad = e\, v\, (\partial B_r/\partial z)\, z$

& since curl B = 0 $\quad = e\, v\, (\partial B_z/\partial r)\, z$.

Since F_z is linear in z we expect SHM – "betatron oscillations"

and identify $\quad - m\, \omega_z^2 = e\, v\, (\partial B_z/\partial r)$

The focusing strength is described by the "tune" ν_z [Q_z in Europe]

– *i.e.* the number of oscillations per turn:

$$\boxed{\nu_Z = \frac{\omega_Z}{\omega} = \sqrt{\frac{-e}{m\omega}\frac{v}{\omega}\frac{\partial B_Z}{\partial r}} = \sqrt{\frac{-r}{B_Z}\frac{\partial B_Z}{\partial r}} \equiv \sqrt{-k}}$$

where the logarithmic field gradient k is called the "field index".

Note that:- locally $B_z \sim r^k$

- many authors use $n \equiv -k$
- positive axial focusing requires $k < 0$ (B decreasing with r)
    - provided naturally by B fall-off towards pole edge.

For cyclotrons there are conflicting requirements:

- axial focusing requires $k < 0$, i.e. B_z falling with r;
- fixed frequency $\omega = qB_z/m$ requires $B_z \propto m \propto E$, so rising with r!

If we choose isochronism, then $r \propto v \equiv \beta c$, $B_z \propto m = \gamma m_0$, resulting in axial defocusing:

$$\boxed{\nu_z^2 = -k = -\frac{\beta}{\gamma}\frac{d\gamma}{d\beta} = -\beta^2\gamma^2.}$$

MAGNETIC GRADIENT FOCUSING - RADIAL

For radial motion (usually horizontal) we find:

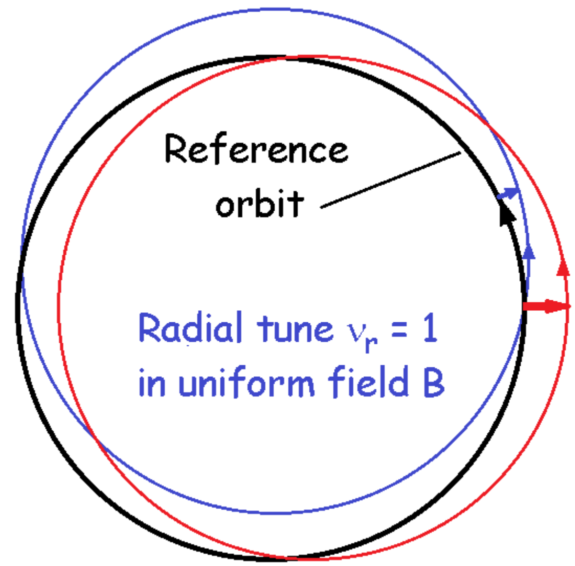
$$\boxed{\nu_r = \sqrt{1+k}} \qquad \text{cf. } \nu_z = \sqrt{-k}$$

[curl**B** = 0 --> complementary r & z focusing]

$\therefore$ For stability in both planes:

$-1 < k < 0$

- negative as expected,
  but only allowing "weak focusing": $\boxed{0 < \nu < 1}$
  - <1 oscillation/turn !



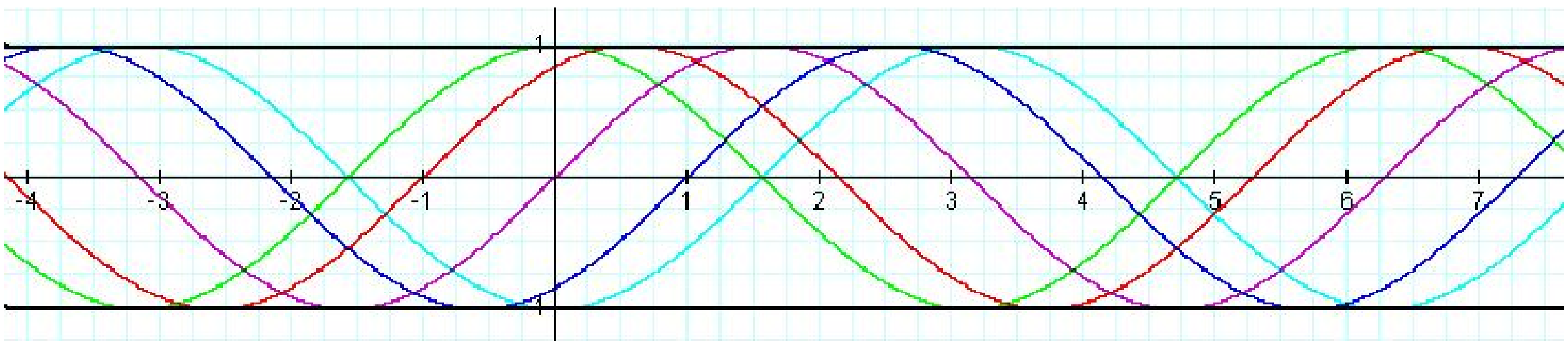
Displaced orbits
show origin of ν_r = 1

BETATRON OSCILLATIONS & EMITTANCE

With uniform focusing, charged particles will follow sinusoidal paths with amplitude A_u and phase δ (where u stands for transverse x or z):

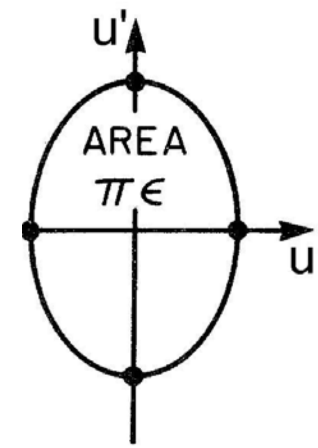
$$\boxed{u = A_u \cos(\nu_u \theta + \delta)}$$

An aperture of half-height A can therefore accommodate a beam of particles with any phase δ and all amplitudes $A_u \leq A$, oscillating within a uniform envelope. [N.B. only $A_u = A$ orbits are shown in the sketch.]



Note that the divergence $u' = \dfrac{du}{r d\theta} = \dfrac{-\nu_u A_u}{r} \sin(\nu_u \theta + \delta)$.

So in u-u′ phase space, particles move in elliptical paths with $A_u \leq A$, whose overall area – a useful measure of (range of displacement) x (range of divergence) - is known as the beam's "emittance" $\boxed{E = \pi\varepsilon = \pi \nu_u A^2 / r}$.



RELATIVISTIC PROBLEMS

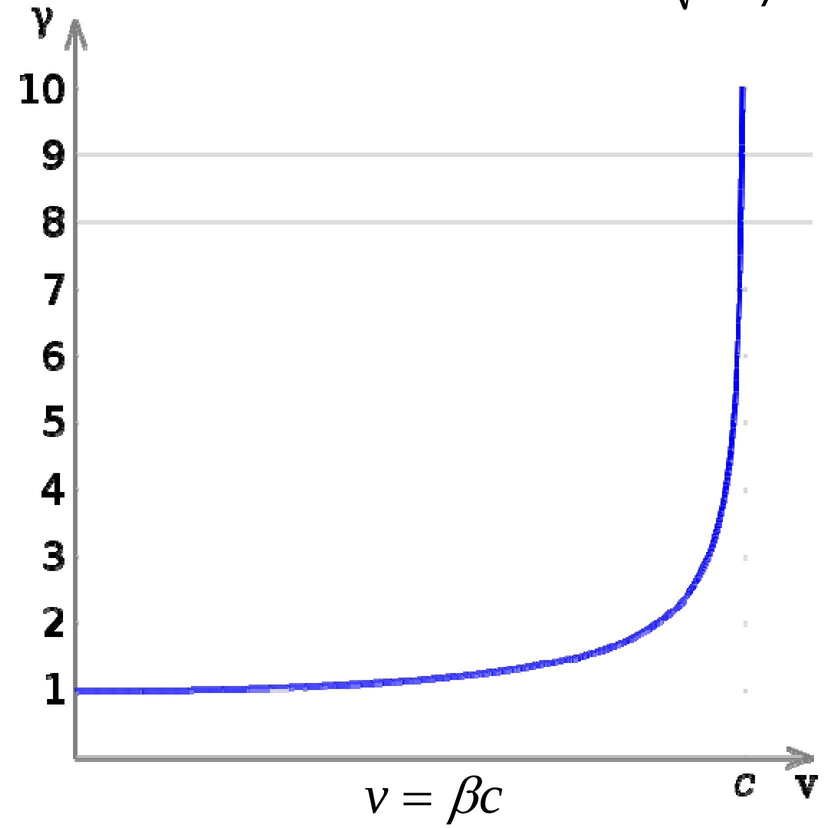
Lawrence's group built a series of cyclotrons of increasing size in the 1930s, culminating in the 60-inch "Crocker" (10-MeV p, 20-MeV d, 40-MeV α) - and were imitated in labs all over the world.

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

Special relativity tells us that $E = mc^2$ - so increasing E increases m, and in uniform B the angular frequency qB/m falls. Bethe & Rose (1937) predicted an 8-MeV limit for D^+ with $V_{rf} = 50$ kV.

[Isochronism might be recovered by making $B(r) \propto m(r)$
but a positive field gradient dB/dr
--> unacceptable vertical defocusing.]

$$\gamma = \frac{E}{E_0} = 1 + \frac{T}{E_0} = \frac{m}{m_0} = \frac{B}{B_0} = \frac{1}{\sqrt{1-\beta^2}}$$



SYNCHRONOUS ACCELERATION

Earliest options for higher E involved abandoning isochronism and

- Allowing 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

Discovery of the Phase Stability Principle (Veksler '44, McMillan '45) gave confidence that particles would remain in phase with the rf.

Two approaches:

- constant B, changing r → synchrocyclotron
- constant r, changing B → synchrotron

SYNCHROCYCLOTRONS

Keep $B \approx$ constant

$\therefore \quad \omega \propto 1/m \propto 1/E$ - frequency decreases with E;

and $\quad r \propto v/\omega \propto v\,E$ - radius increases with E.

Demo by Richardson et al. (1946) on 37" cyclotron at Berkeley;

First full size was Berkeley 184" (190 MeV d^+, 1946; later 700 MeV p)

Biggest : Gatchina : 1000 MeV, 7800 tons, 6.85 m pole diameter.

SYNCHROTRONS

Radius r = constant (small diameter beam pipe

$\therefore \quad \omega = v/r$ increases to c/r (ring of magnets

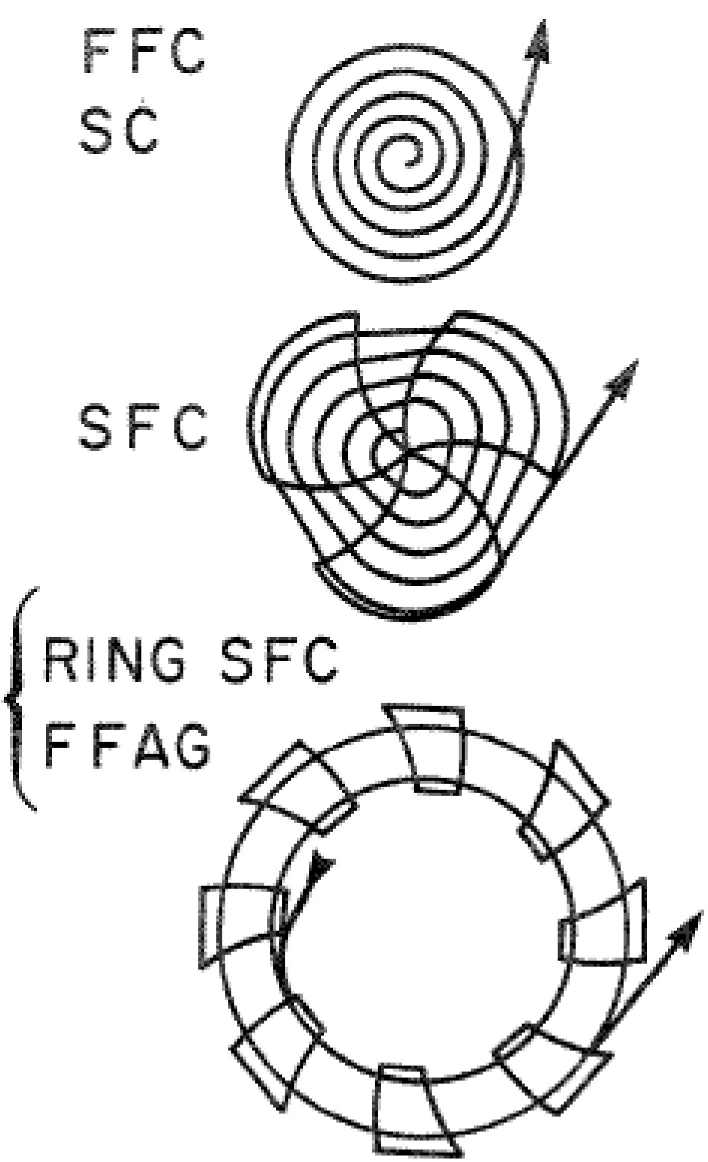
$B \propto m\,\omega \propto E\,v$ increases (ramping B is slow

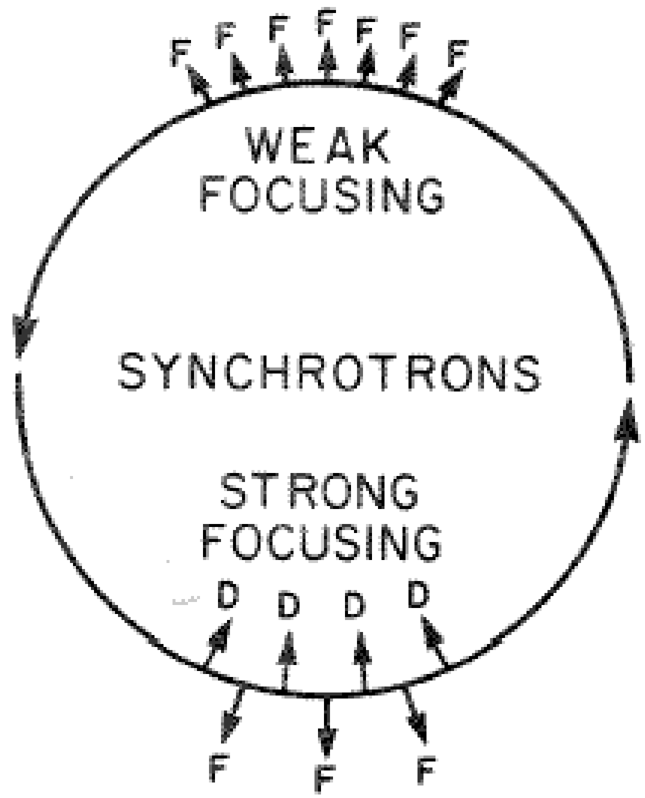
First for e^- : Berkeley 300 MeV (1949)

First for p : Brookhaven 3 GeV Cosmotron (1952)

Biggest weak focusing synchrotron : Dubna, 10 GeV, 36000 tons

THE CYCLOTRON AND SYNCHROTRON FAMILIES





FFC = fixed frequency cyclotron
SC = synchrocyclotron
SFC = sector-focused cyclotron
FFAG = fixed field alternating gradient

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).

SUPERCONDUCTING SYNCHROCYCLOTRONS (1)

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

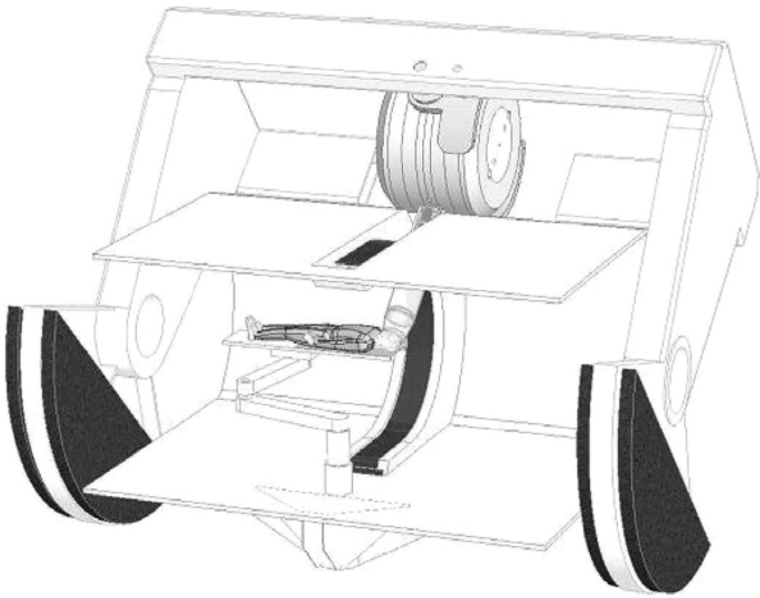
→ lighter magnets $\propto r^3$.

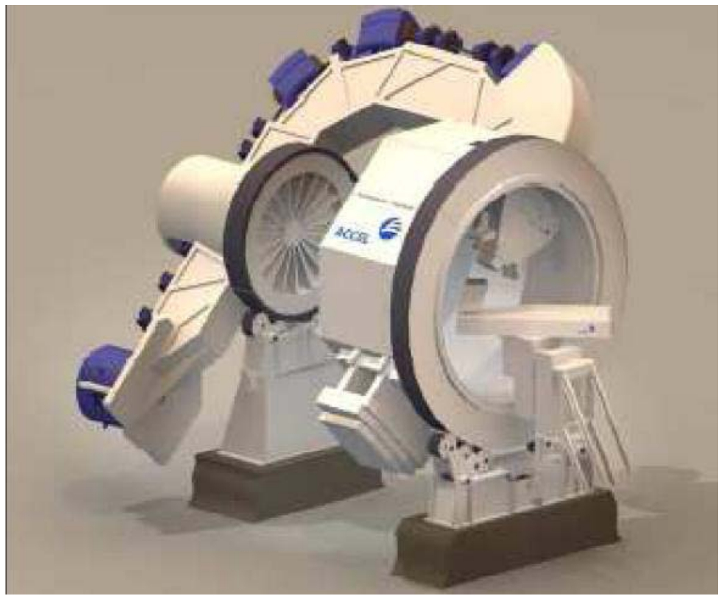
Using Nb_3Sn coils, Tim Antaya (MIT) has built a cryogen-free 9-T magnet for the Mevion (formerly Still River) S250 synchrocyclotron – light enough to mount on a rotating gantry!

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! One is in operation (St. Louis), another delivered (NJ).

SUPERCONDUCTING SYNCHROCYCLOTRONS (2)

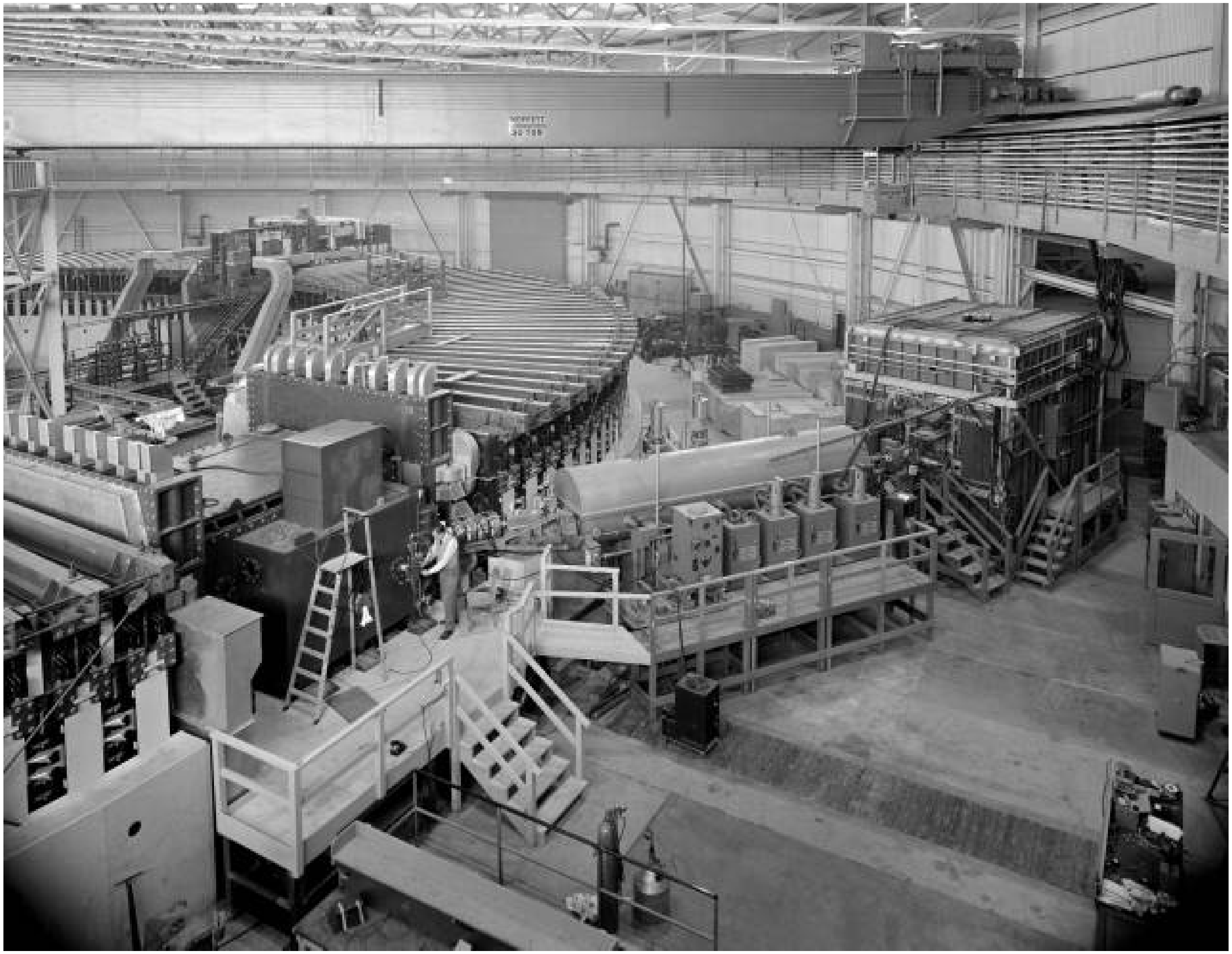
The Mevion SC is light enough to mount on a rotating gantry, and the whole system fits in a single room - but there are concerns about patients' exposure to stray radiation.





An alternative scheme adopted by Varian-Accel and IBA would place the S-C in a separate room, with beam delivery via a rotating gantry. The IBA design, with standard NbTi coils, achieves 5.6-T fields, and so is larger than Mevion's. Beam commissioning is under way.
A superconducting SC is also planned for the Italian CycLinac project.

WEAK-FOCUSING SYNCHROTRONS – THE 6-GeV BERKELEY BEVATRON



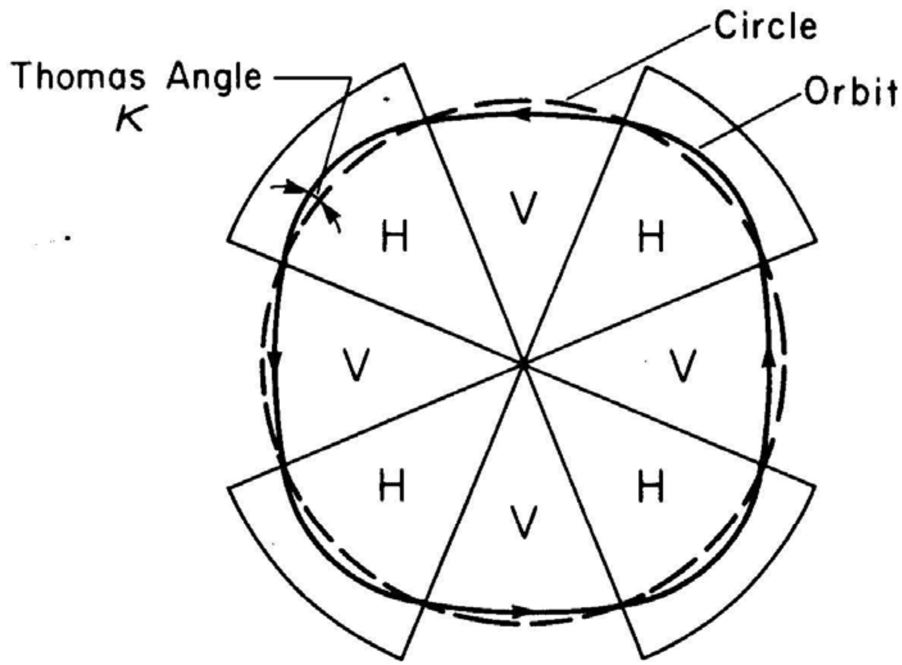
Orbit radius = 19 m Magnet weight = 9,700 tons Pulse interval = 5 s
Note the 10-MeV linac injector, fed by a Cockcroft-Walton HT set.

PART 2

1. Sector Focusing – Radial-Sector Cyclotrons
2. Strong (i.e. Alternating) Focusing
3. Alternating-Gradient Synchrotrons
4. Spiral-Sector Cyclotrons
5. Fixed-Field Alternating-Gradient Accelerators
   - Scaling FFAGs
   - Non-Scaling FFAGs

SECTOR-FOCUSED CYCLOTRONS - I

Radial-sector pole pieces are used to give an azimuthal variation in field (AVF) strength -B_h-B_v-B_h-B_v-- and so a "scalloped" orbit, where ions cross the sector edges at a small "Thomas angle" κ

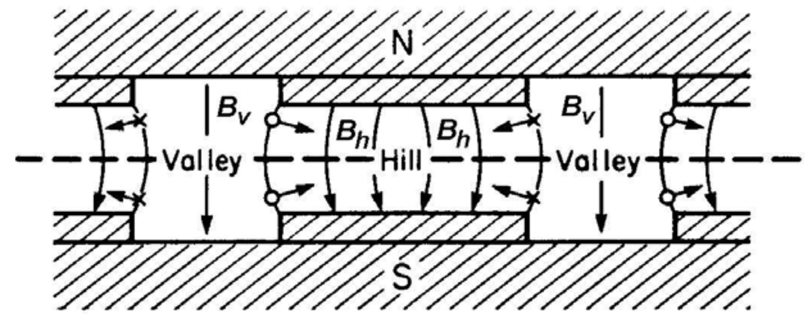


$$\boxed{\kappa = \frac{\pi}{N}\frac{(B_h - \overline{B})(\overline{B} - B_v)}{(B_h - B_v)\overline{B}},}$$

each time experiencing axial edge focusing – always positive.

Defining the magnetic "flutter" by

$$\boxed{F^2 \equiv \left\langle \frac{(B - \overline{B})^2}{\overline{B}^2} \right\rangle = \frac{(B_h - \overline{B})(\overline{B} - B_v)}{\overline{B}^2},}$$



and averaging the small impulses over the orbit, we find a contribution to the axial tune: $\boxed{\Delta \nu_z^2 = F^2.}$

Overall, for an isochronous magnetic field: $\boxed{\nu_z^2 = -\beta^2\gamma^2 + F^2,}$

so that $\nu_z^2 > 0$ provided $F^2 > \beta^2\gamma^2$.

SECTOR-FOCUSED CYCLOTRONS – II

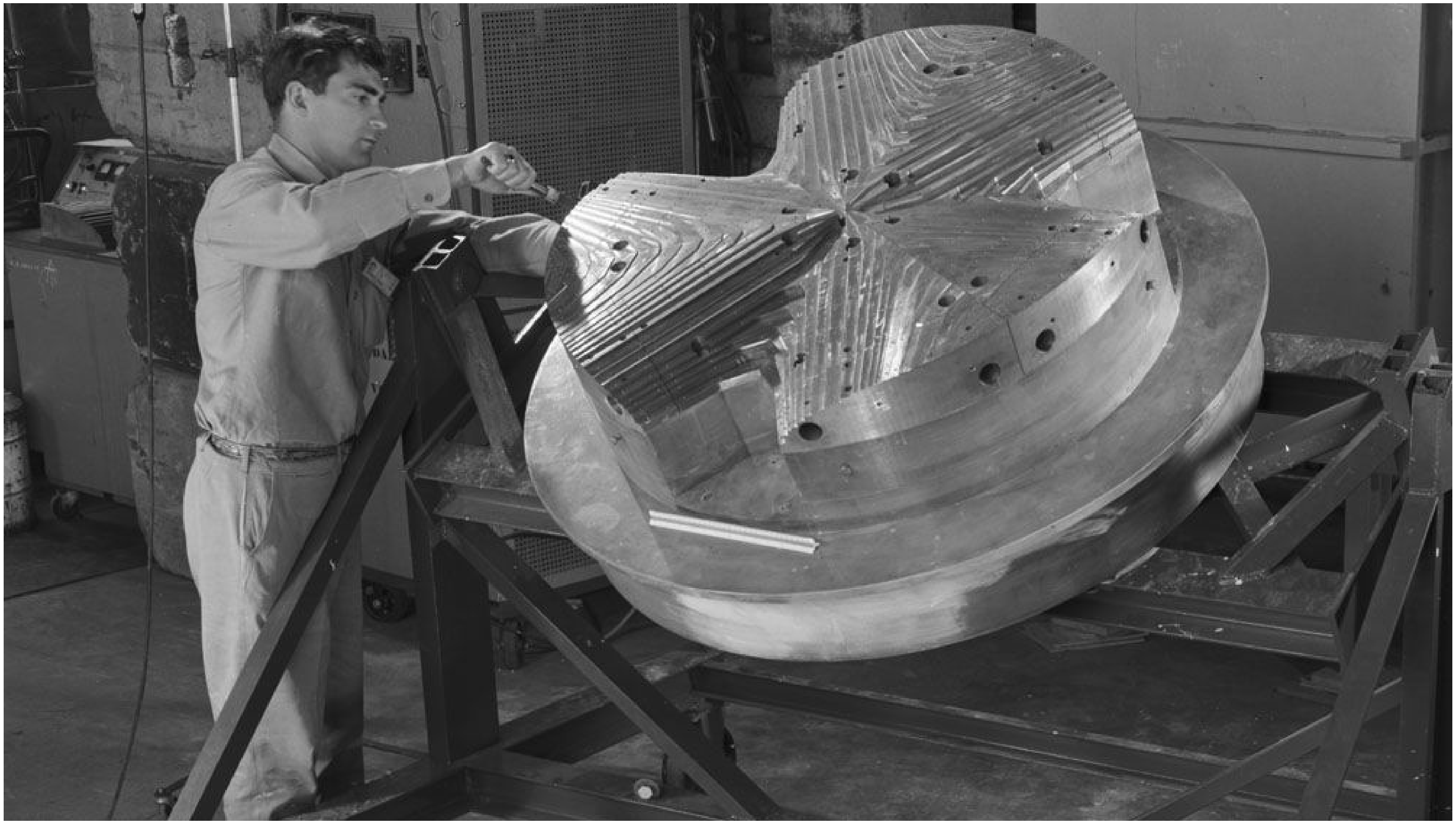
L.H. Thomas in 1938 was the first to show that AV Fields could be used to counter isochronous defocus-ing - proposing a $\cos N\theta$ variation with N=3 or 4.
(A Welsh-born American, probably better known for

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

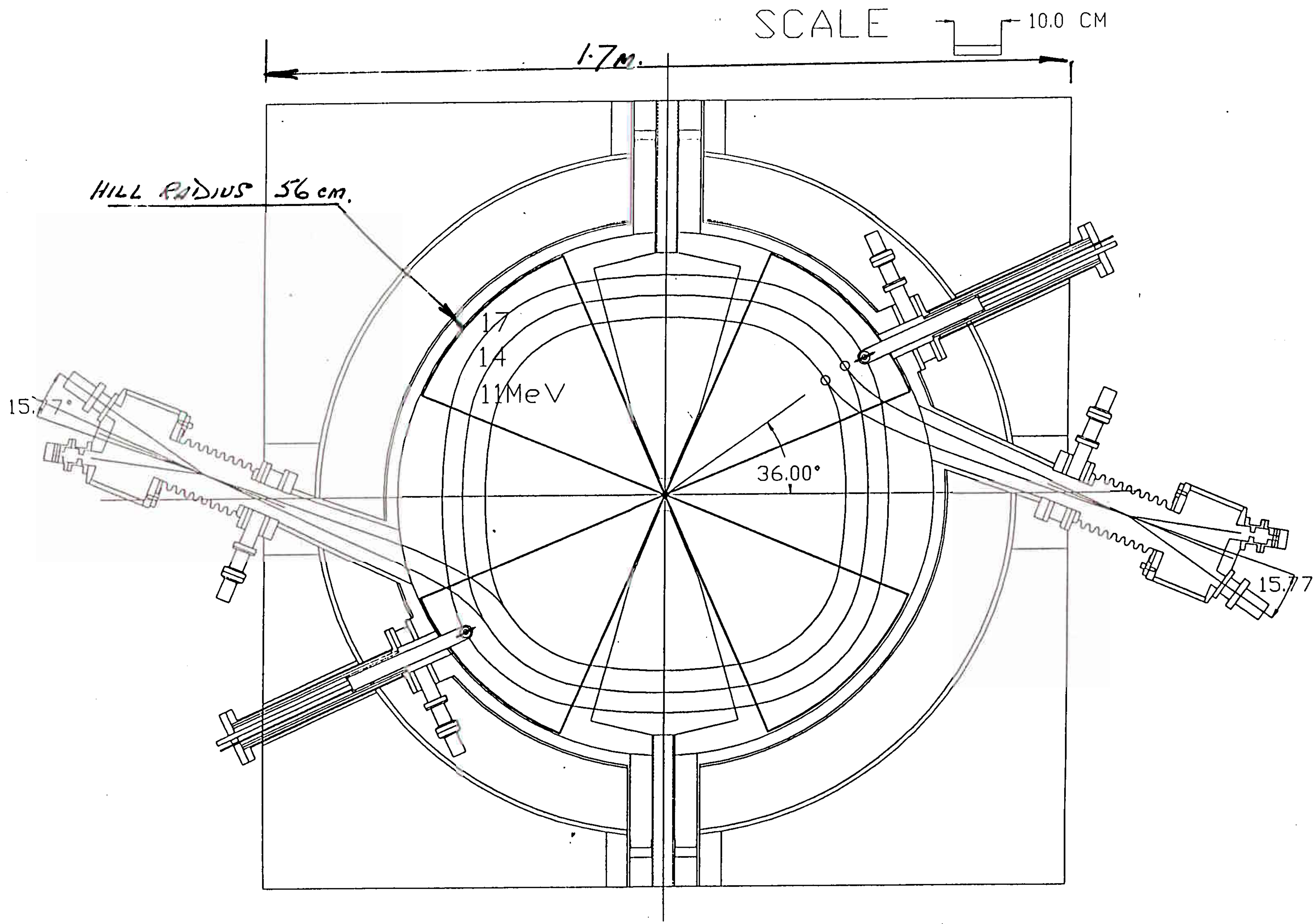
His idea was neglected until Reg Richardson's team at Berkeley built two 3-sector electron models in 1950, reaching β = 0.5. Not declassified till 1956!
(Born in Edmonton, schooled in Vancouver & L.A.,

- first demonstration of phase stability
- first synchrocyclotron
- UCLA 50-MeV sector-focused cyclotron
- TRIUMF 500-MeV cyclotron meson factory.)

THE FIRST SECTOR-FOCUSING CYCLOTRON

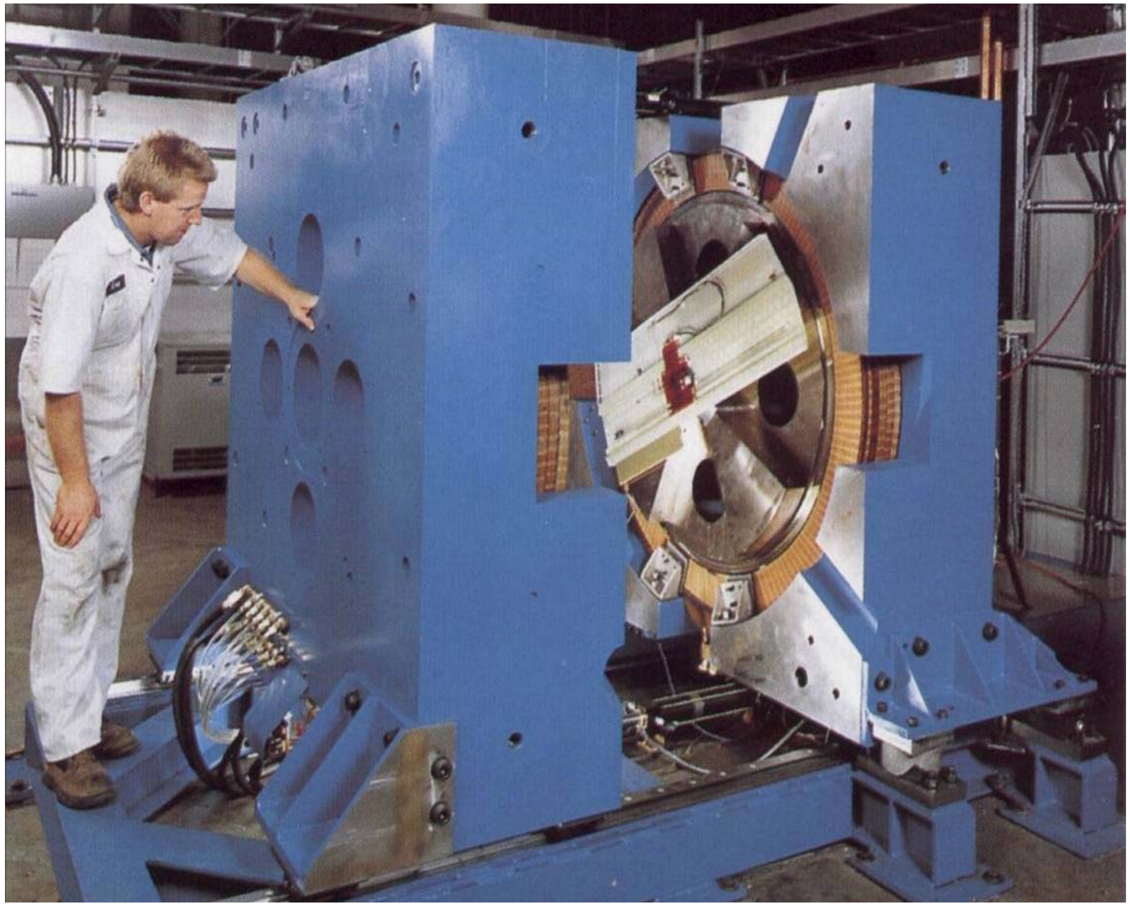


- One pole of a model built by J.R. Richardson et al. at Berkeley in 1950
- Electrons were accelerated to $\beta = 0.5$ (simulating 300-MeV deuterons)
- Based on L.H. Thomas's 1938 proposal
- Note the harmonic pole profile (à la Thomas)



TR13 General Layout

TR14/19 CYCLOTRON



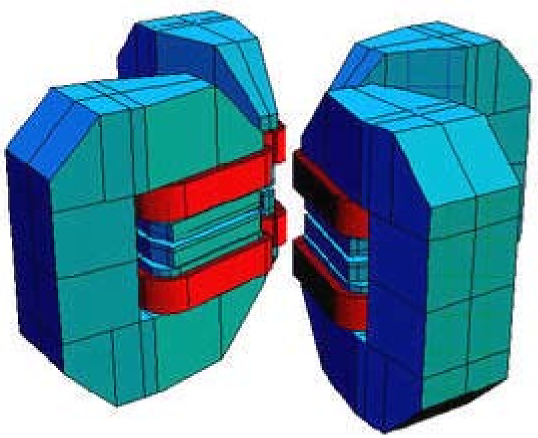
The TR14/19 (originally TR13) accelerates 300 μA H^- to 14-19 MeV or D^- to 7-9.5 MeV. [Note the field-measuring apparatus.]

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

RADIAL-SECTOR CYCLOTRONS

- There are ~800 small radial-sector cyclotrons (≲50 MeV)
- Mostly used for producing radioisotopes
- Hard to achieve $F^2 > 0.3$ with single poles and coils.

In separate-sector cyclotrons:

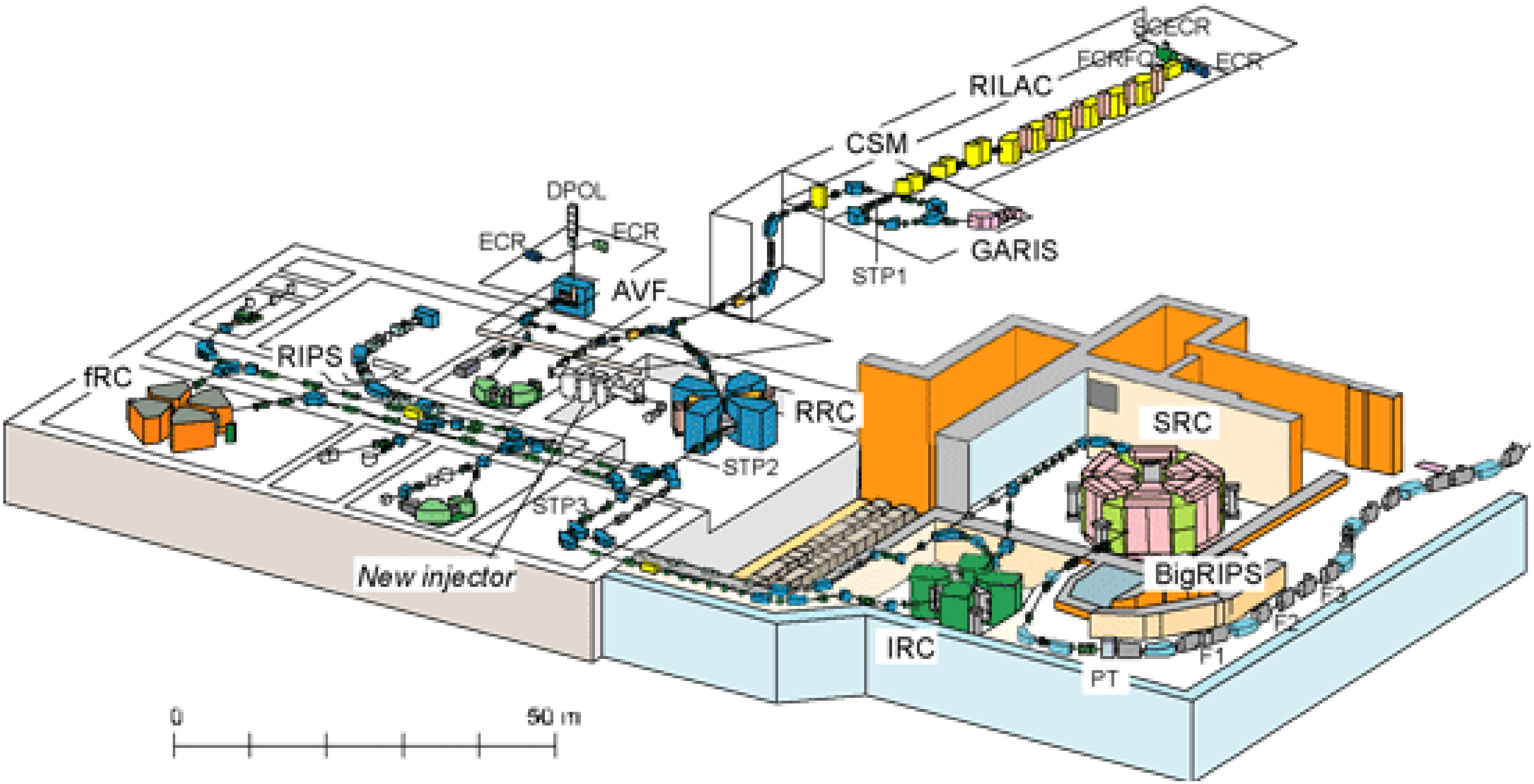


- the sectors have individual yokes and coils
- the valleys are: - magnetic field-free
  - available for rf, injection, extraction & diagnostics
- the flutter $F^2 = H^{-1} - 1$ can reach ≈1 (where H = hill fraction), making it possible to reach $\beta\gamma \approx 1$ (≈400 MeV/u).

There are ~12 large separate-radial-sector cyclotrons:

- mainly designed for heavy ions (where high β is not desired)
- with energy capability up to K = 2600 (345 MeV/u U^{86+}),
  - where $\boxed{K = \frac{(eB\rho)^2}{2m_u}}$ and $\boxed{\frac{T_{\max}}{A} = K\left(\frac{Q}{A}\right)^2}$.

The RIKEN RadioIsotope Beam Factory (RIBF)

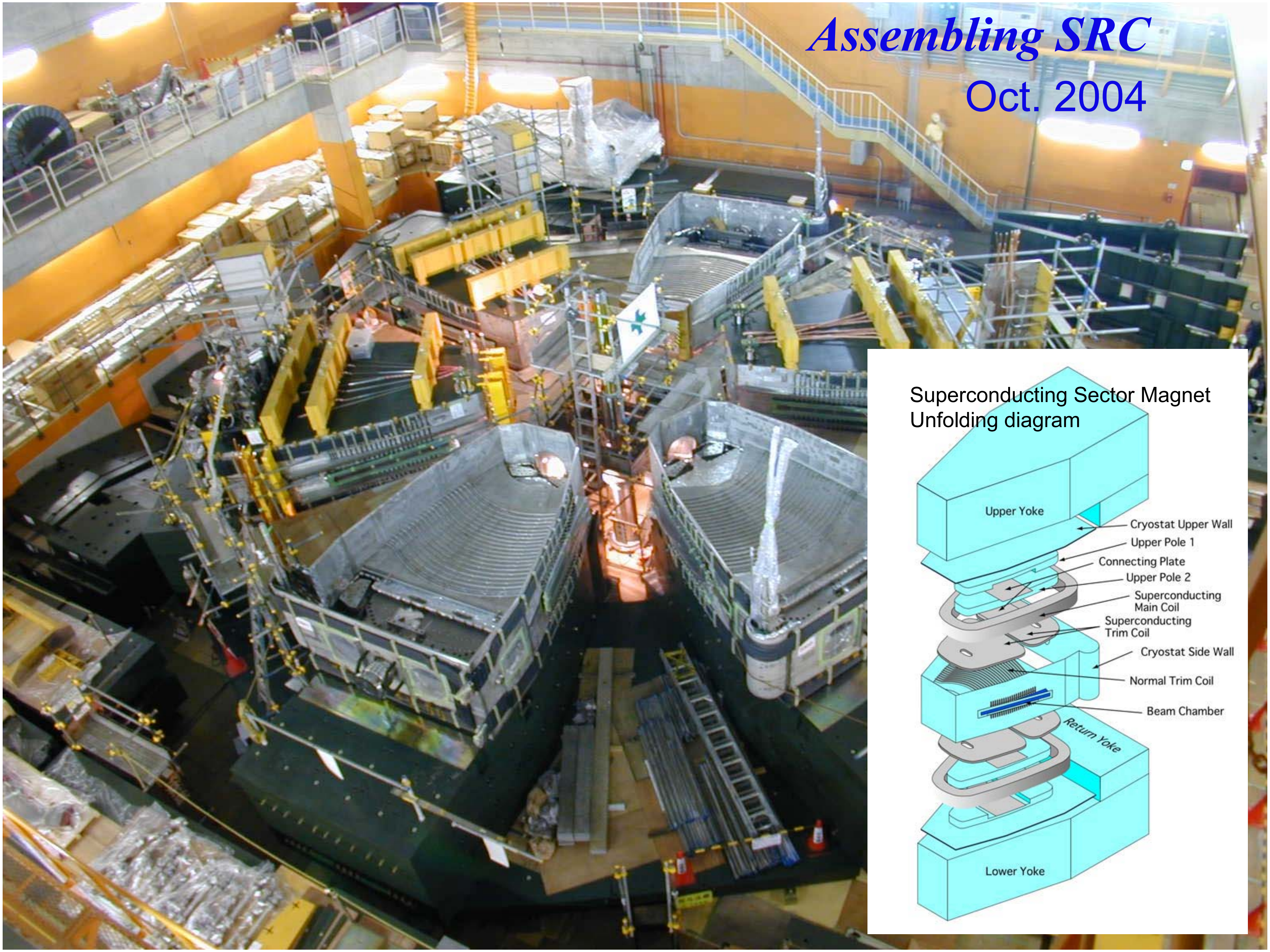


The RIBF involves a chain of one linac and 5 cyclotrons. It can deliver 345-MeV/u beams over the mass range A = 50 – 92.

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.

Assembling SRC

Oct. 2004




K2600-MeV SRC
On Nov. 7 2005 full excitation of sector magnets achieved.
A 140-ton cold mass cooled down to 4.5 K for 3 weeks.

"STRONG" FOCUSING FROM ALTERNATING LENSES

With the first Weak-Focusing Synchrotrons came a potential problem: the maximum vertical betatron oscillation amplitude is set by the magnet aperture A: $z = A\cos(\nu_z\theta + \psi)$.

$\therefore$ the maximum divergence $\hat{z}' = \dfrac{1}{r}\dfrac{\widehat{dz}}{d\theta} = \dfrac{\nu_z A}{r}$

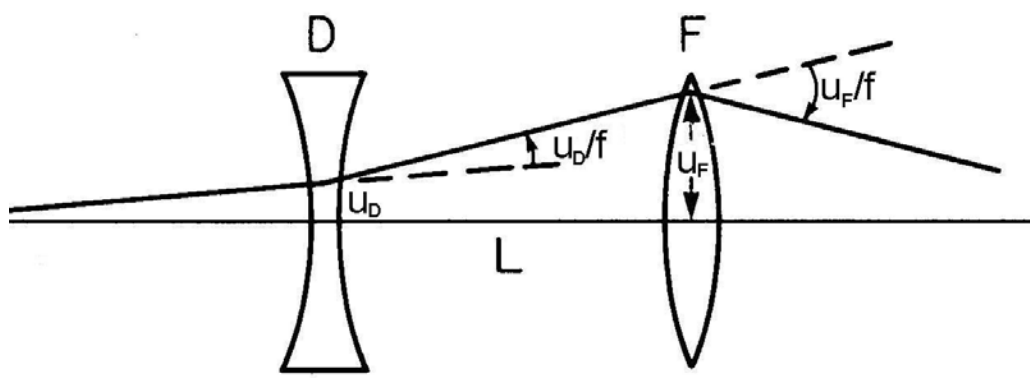
and the beam current accepted $\propto$ beam emittance $\boxed{\pi A\hat{z}' = \dfrac{\pi\nu_z A^2}{r}.}$

So, as WFS (with $\nu_z \leq 1$) get larger, beam current decreases $\propto 1/r$.

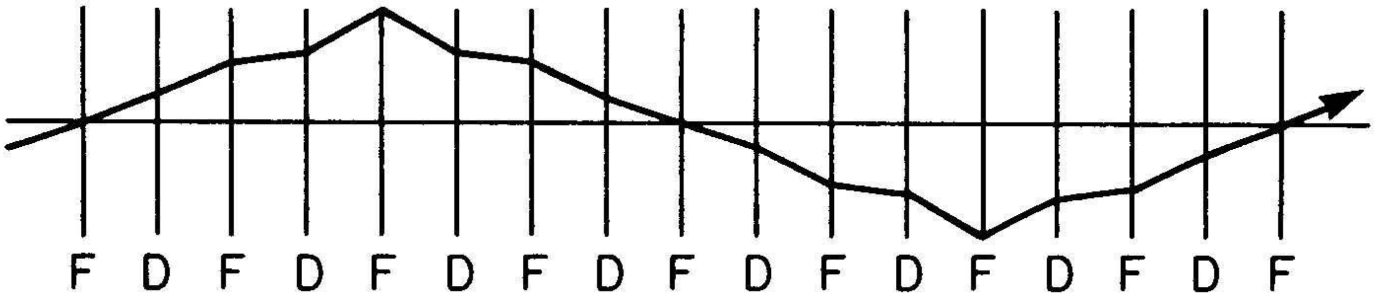
Solution is Alternating Gradient (AG) focusing:

Discovered by Christofilos (1950) & Courant, Livingston & Snyder ('52).

- alternating F and D lenses are overall focusing
- the deflexion ($\propto$ u) is always greater at F than D.
- an old principle in optics.



ALTERNATING FOCUSING (continued)



N.B. – Net effect is focusing in both directions;

– it works for a chain of alternating F & D lenses;

– a vertically F gradient lens is horizontally D;

- and vice-versa – so it's focusing in both planes.

- no upper limit to lens strength → $\nu_u > 1$

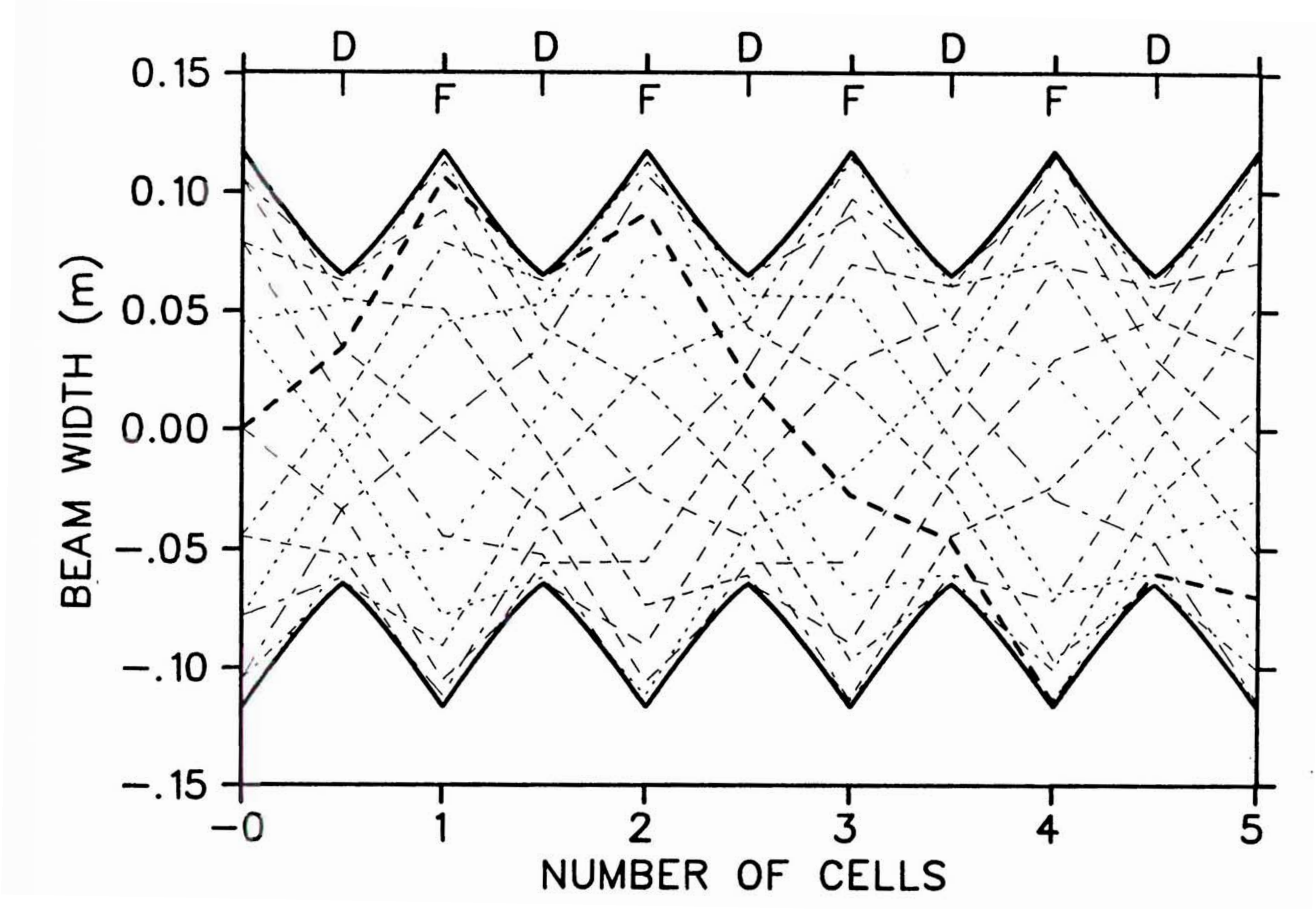
First used in "combined function" AG (bending and focusing) dipoles.

Now usually provided by "separated function" quadrupole magnets.

All high energy circular accelerators are now based on AG focusing.

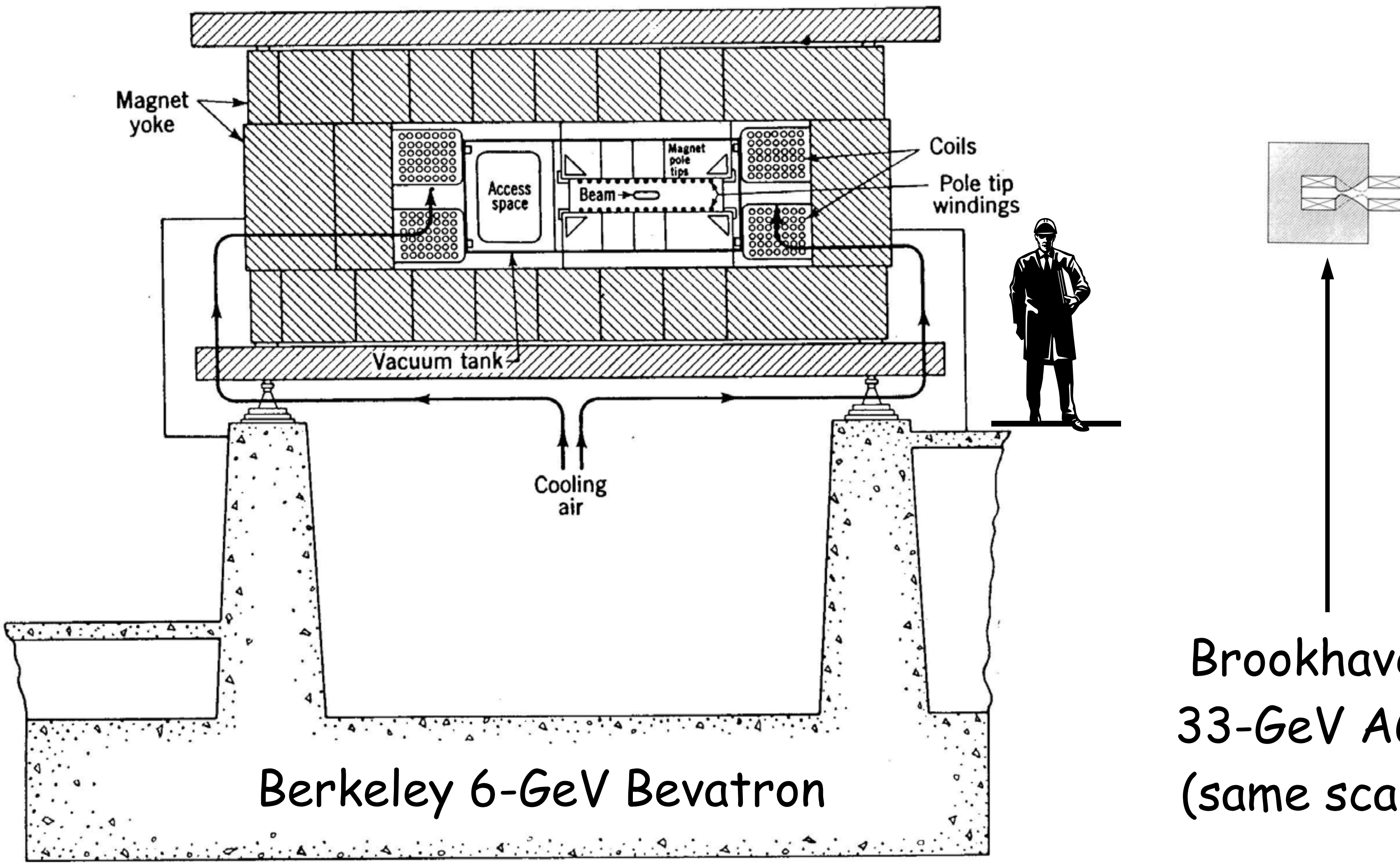
Note that transverse gradients are not essential

– it works for edge lenses too – as in spiral-sector cyclotrons.



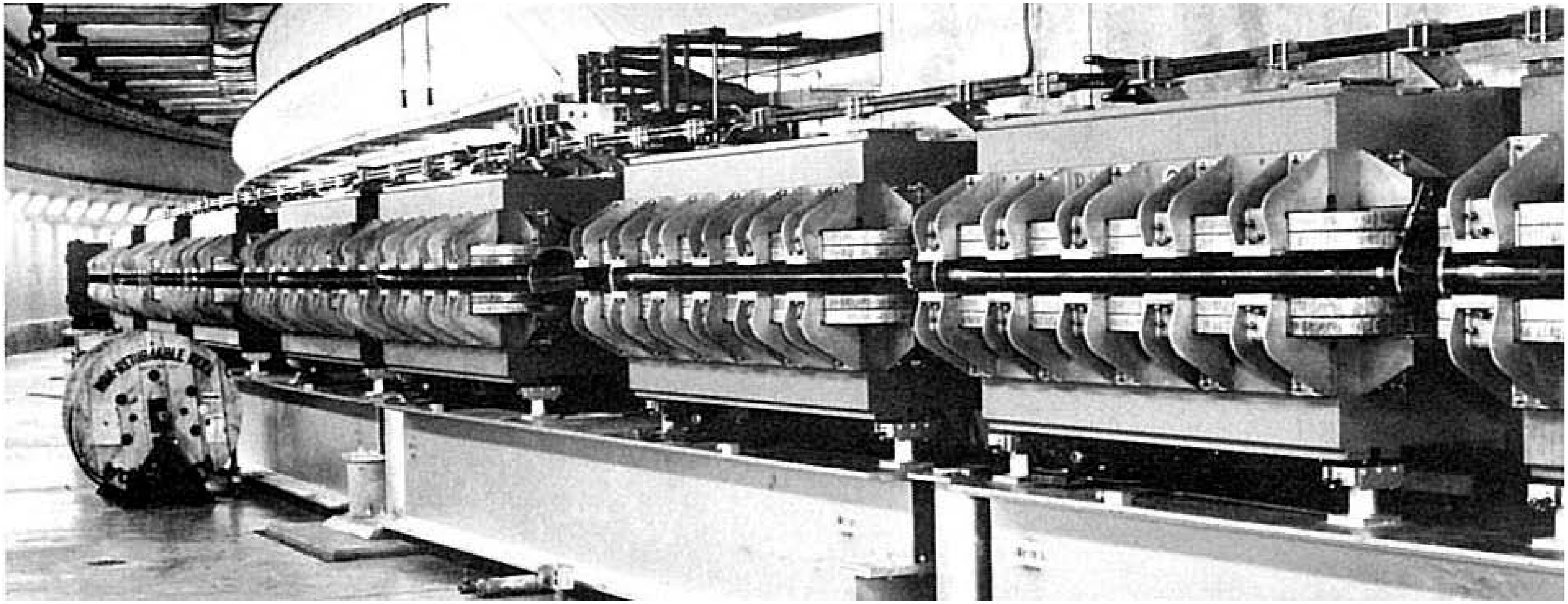
Alternating focusing in a FODO lattice, showing long wavelength betatron oscillations of various phases (but the same amplitude) within an overall envelope exhibiting the lattice periodicity.

WEAK & STRONG FOCUSING SYNCHROTRONS

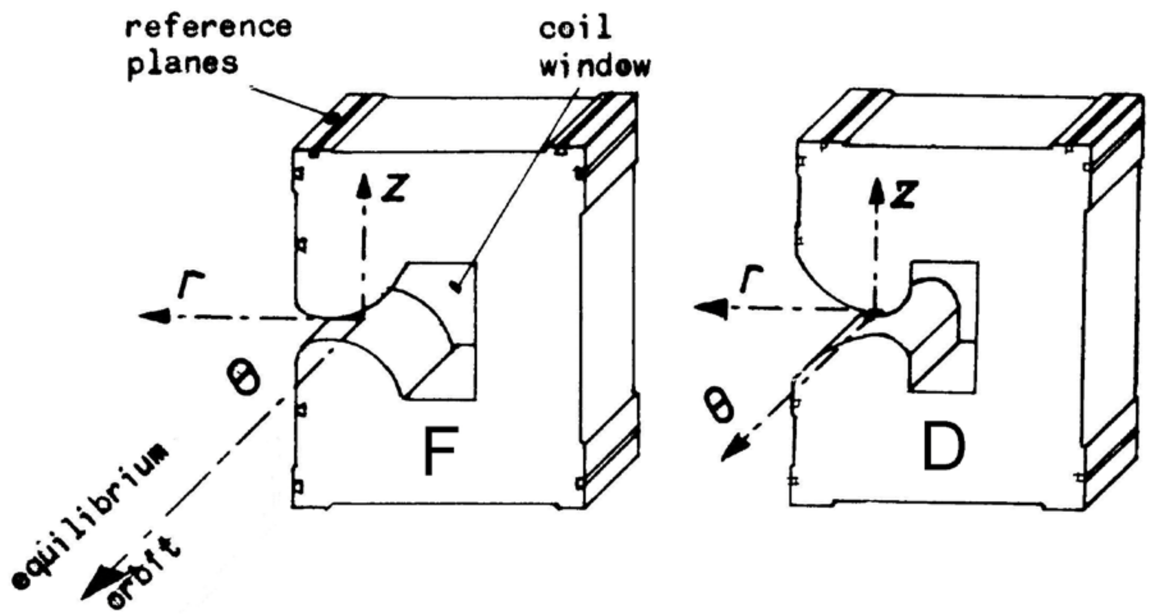


The tight focusing provided by high-gradient AG magnets enabled vacuum chambers and magnet cross-sections to be greatly reduced.

33-GeV BROOKHAVEN AG SYNCHROTRON



In the BNL AGS the horizontally focusing (F) and defocusing (D) magnets are arranged in pairs: –FF-DD-FF-DD-....



COMBINED FUNCTION - SEPARATED FUNCTION

The first AG synchrotrons used "combined-function" magnets:

- each magnet both bends and focuses the beam;
- wedge-shaped pole gap limits central field strength;
- fixed focusing - no tuning flexibility;
- lengthy magnets weaken alternating focusing effect.

Nowadays it's more usual to separate those functions:

- using dipole bending magnets with parallel polefaces - no focusing;
- and quadrupole focusing magnets - no bending;
- independent powering of quadrupoles allows changes in tune;
- space for extra components provided by stronger dipole fields;
- localized quadrupoles strengthen alternating focusing effect.

QUADRUPOLE MAGNET

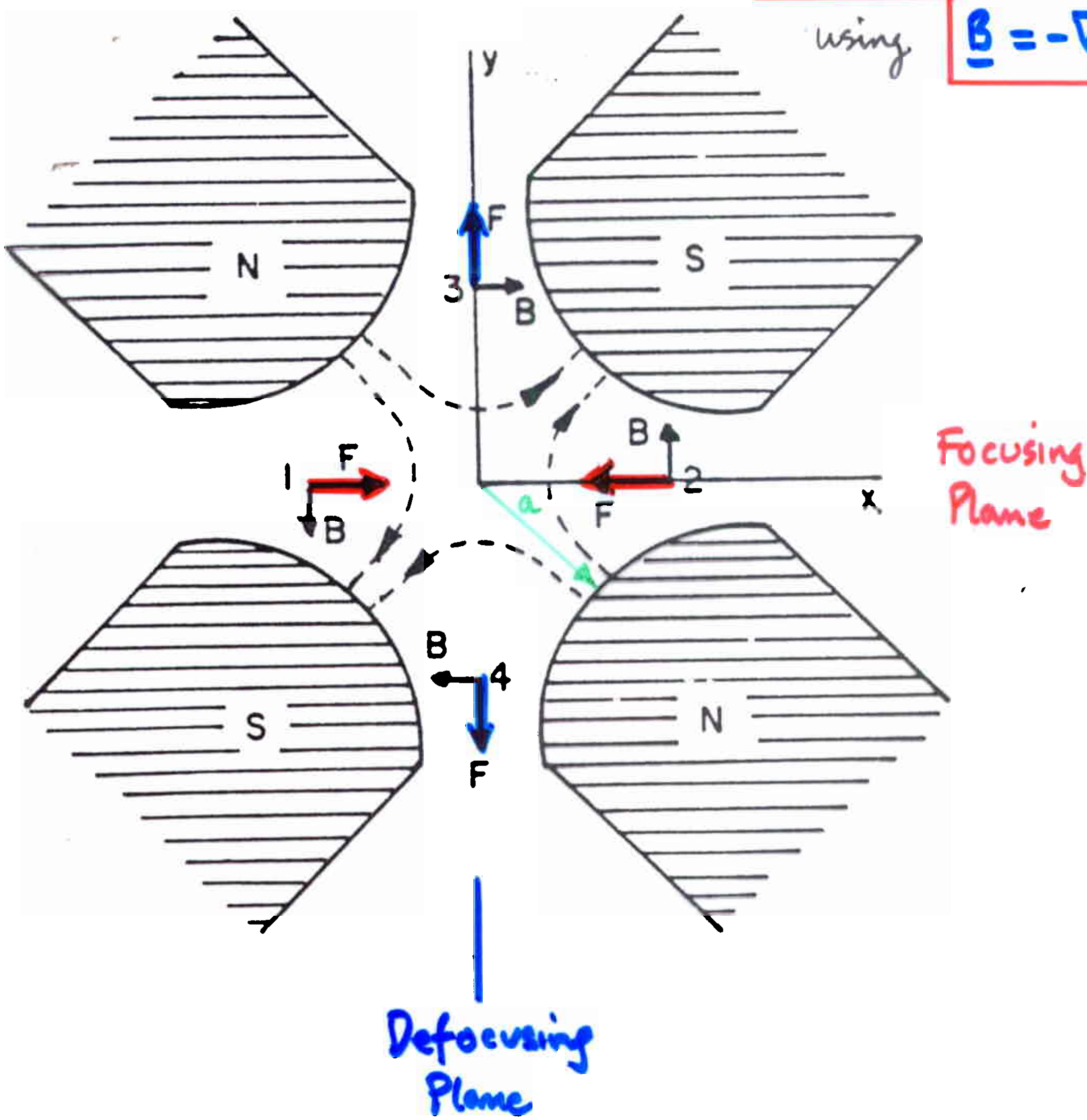
$$B_x = g\,y \qquad B_y = g\,x \qquad \boxed{|B| = g\,r}$$

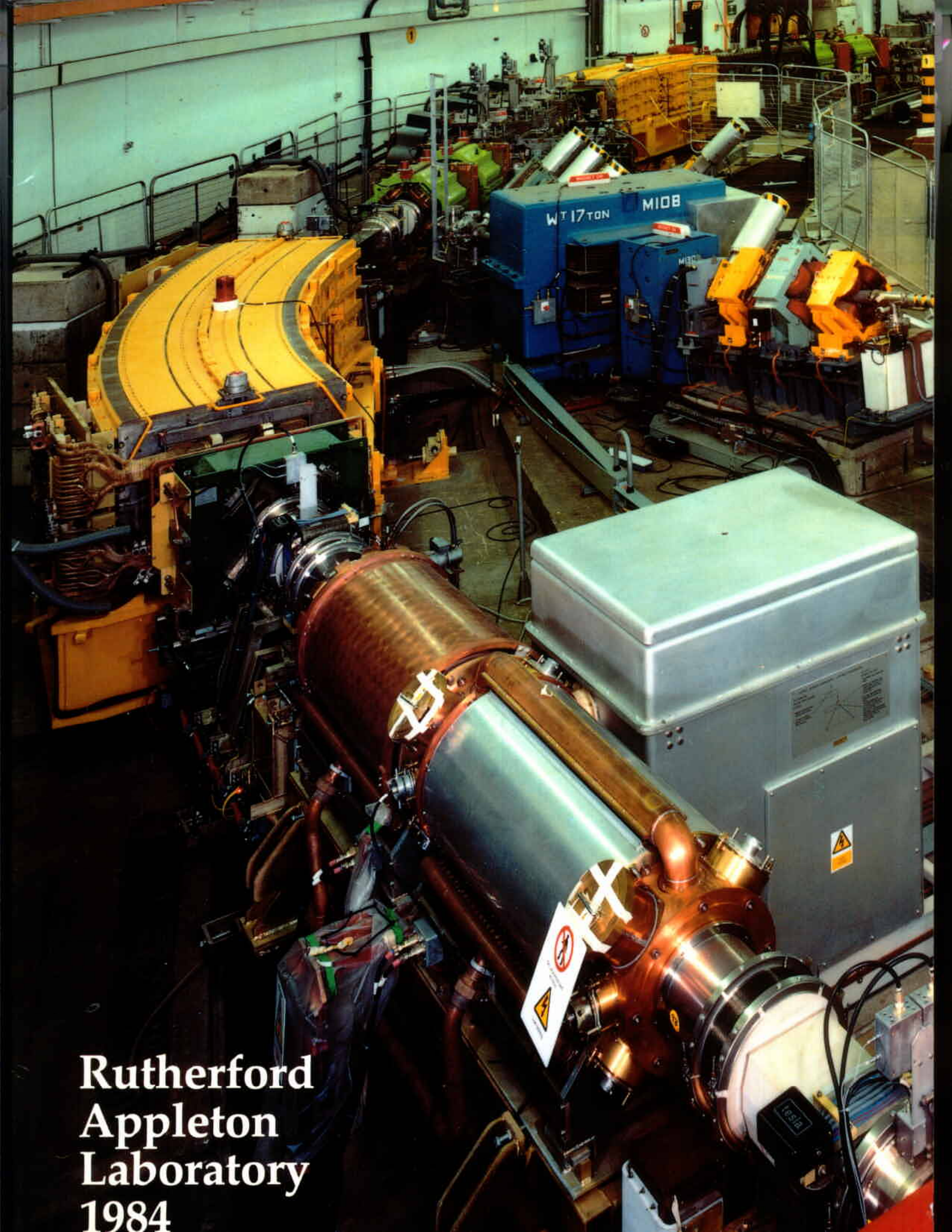
$$= B_o \ @\ r = a$$

$$\frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x} = \boxed{\frac{\partial |B|}{\partial r} = g = \frac{B_o}{a}}$$

– derivable from hyperbolic magnetic potential $\boxed{\phi = -g\,x\,y}$

using $\boxed{\underline{B} = -\nabla\phi}$





Rutherford Appleton Laboratory 1984

Fermilab – 450-GeV Main Ring (above) and 1-TeV Tevatron (below)

CERN, Geneva – The LHC and SPS tunnels and the Swiss-French border

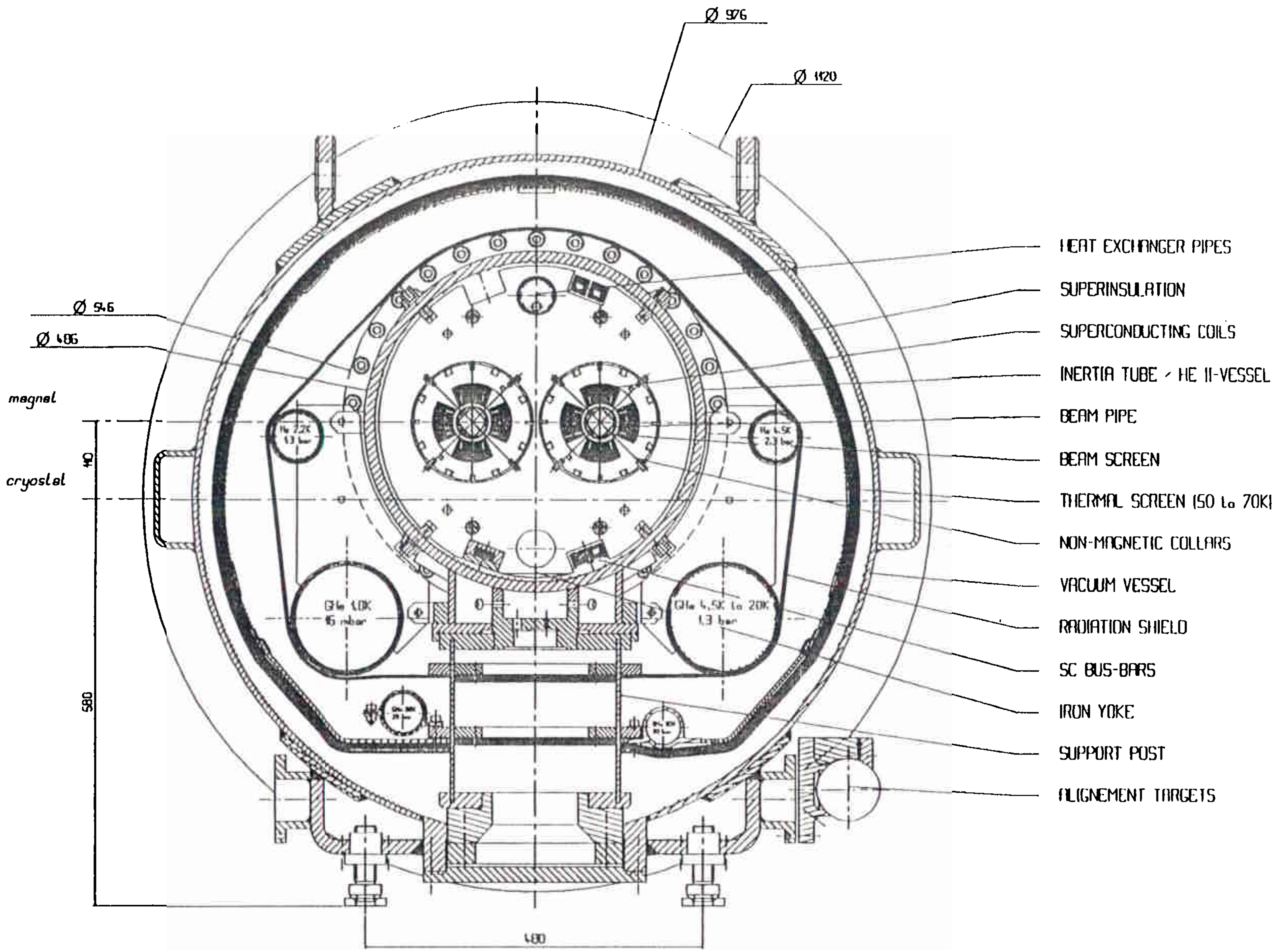
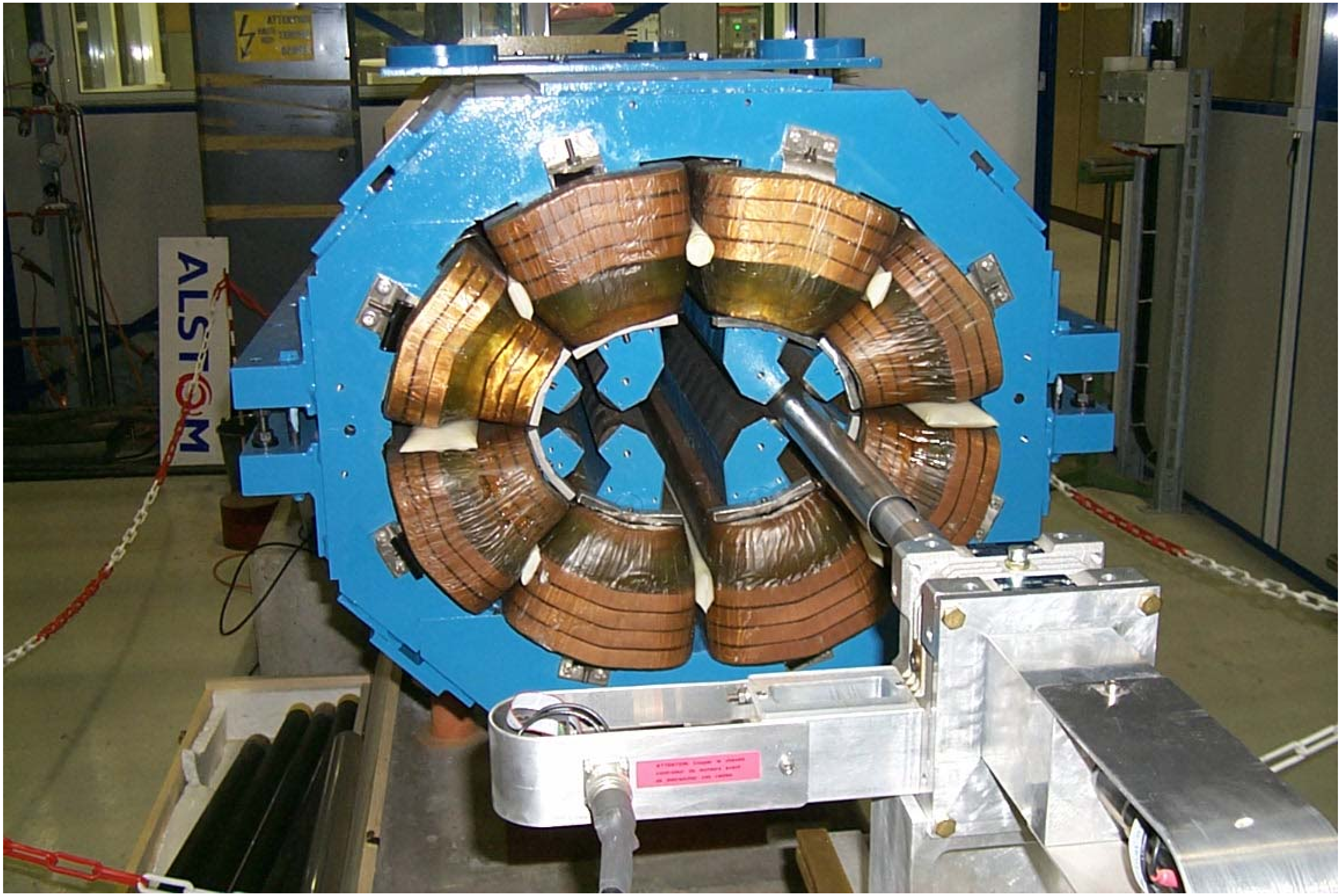
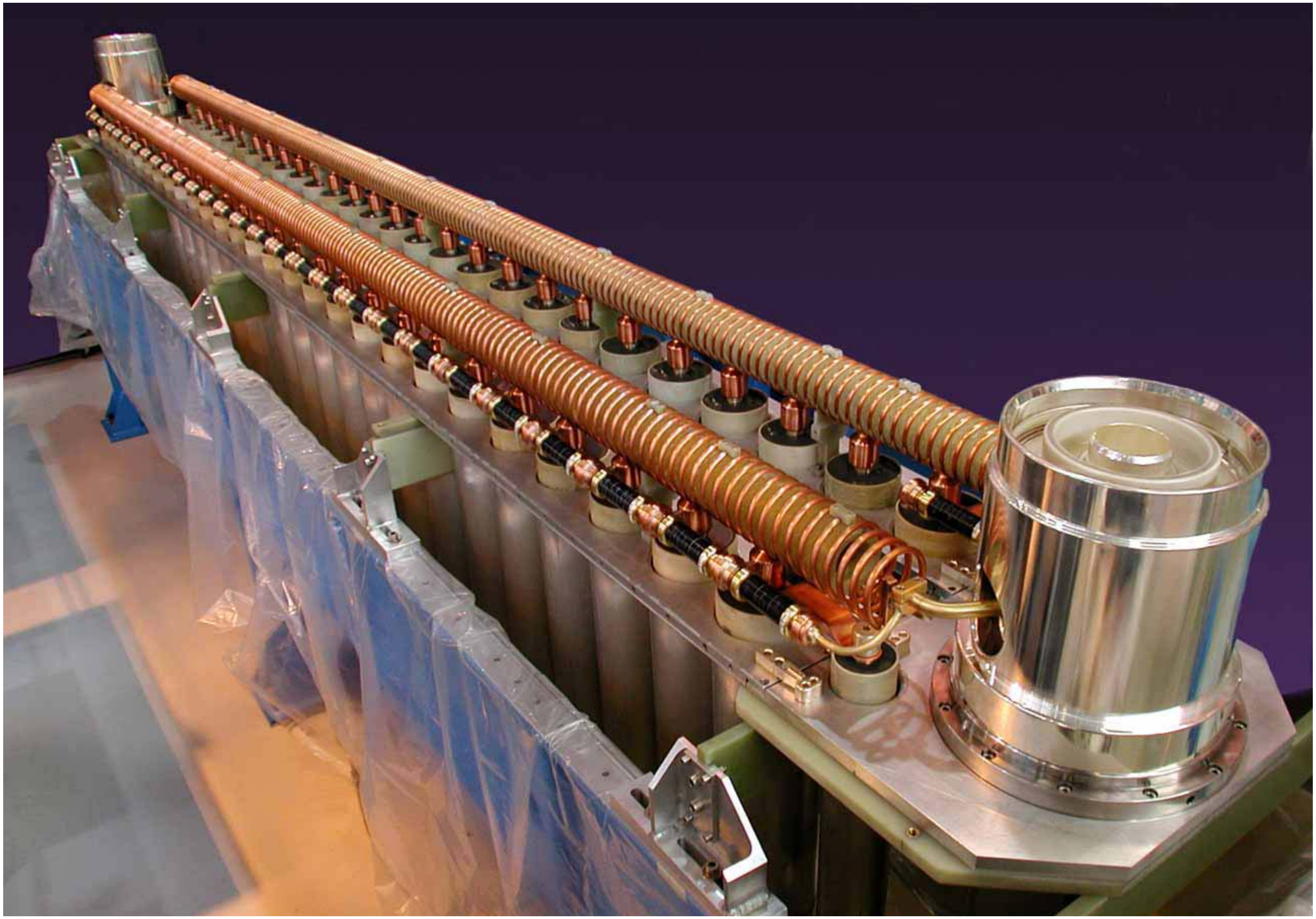


Figure 11: Schematic cross-section of the quadrupole



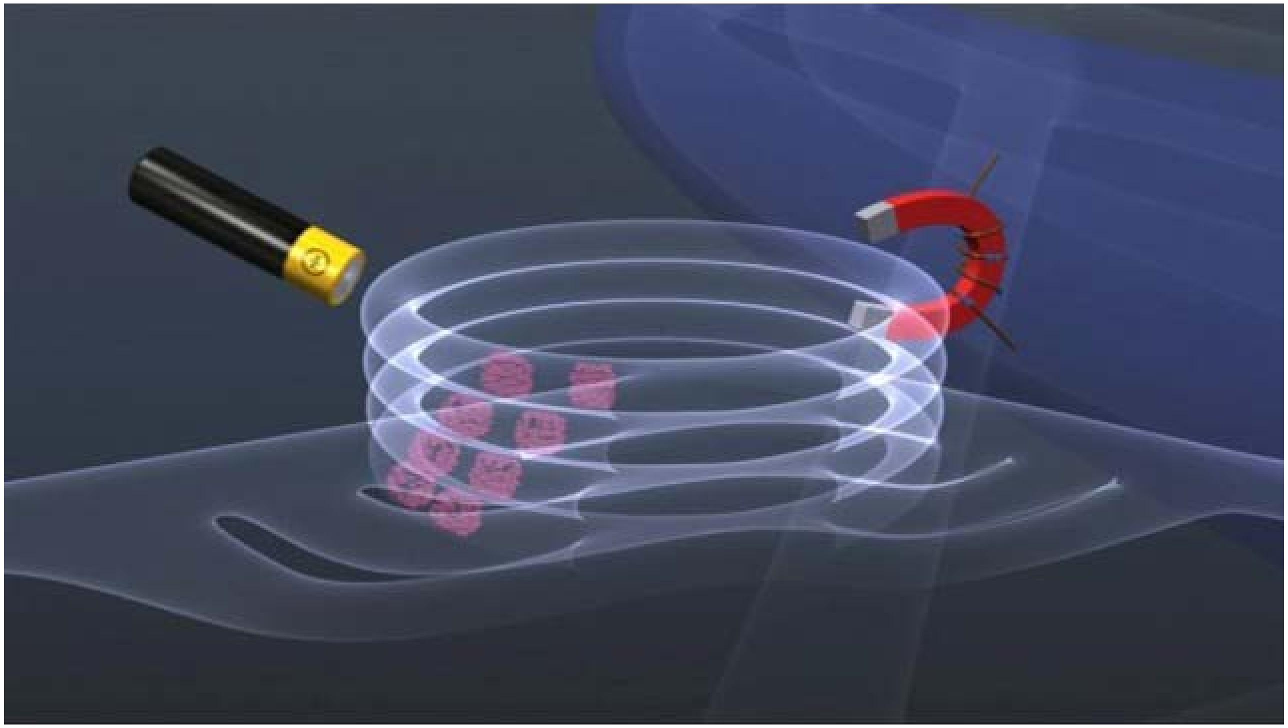
TRIUMF-CERN Collaboration – Twin-aperture warm quadrupole for the LHC

LHC KICKERS

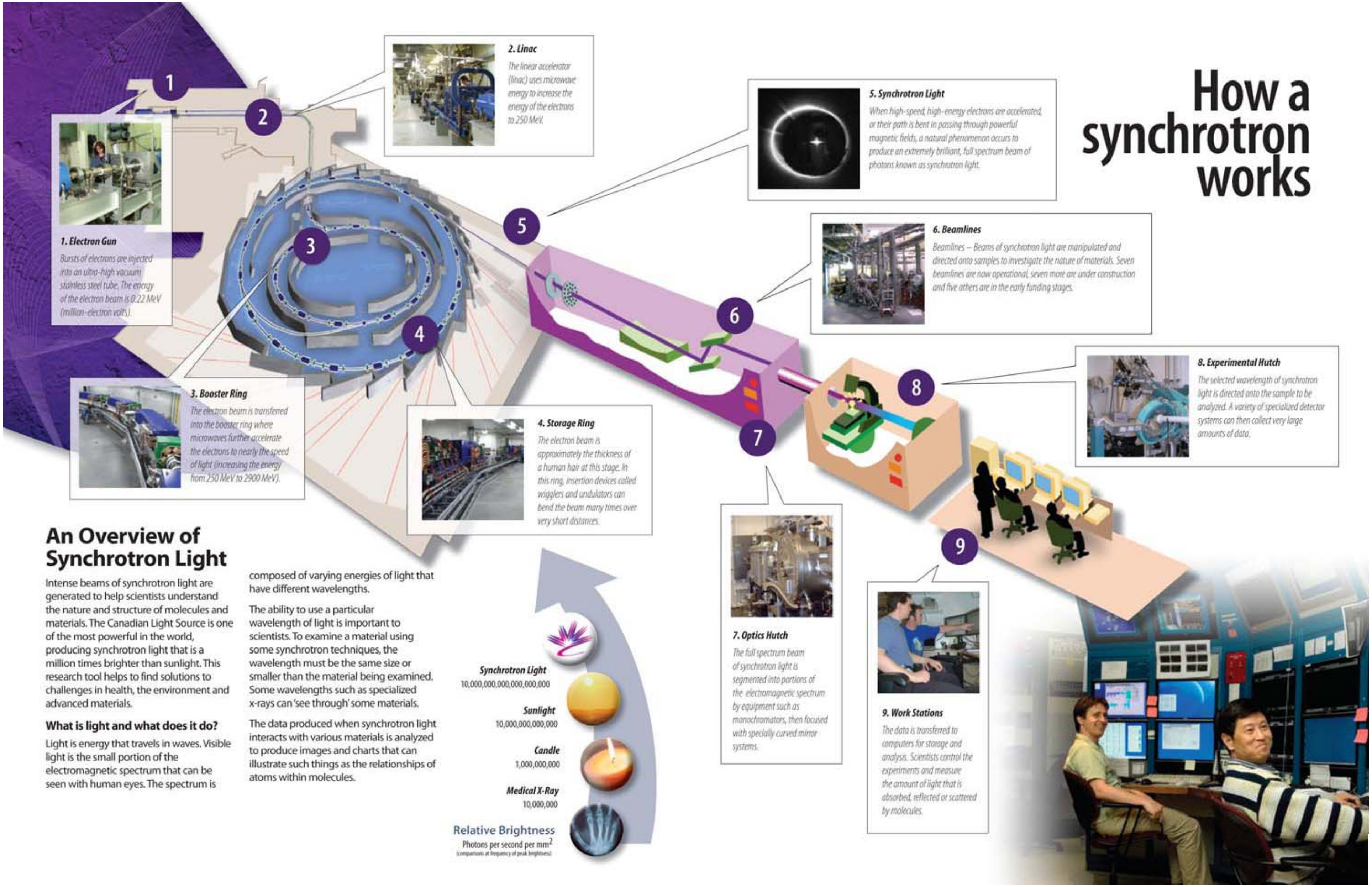


One of nine pulse forming networks built by TRIUMF for the LHC injection kickers

BOTTLE TO BANG

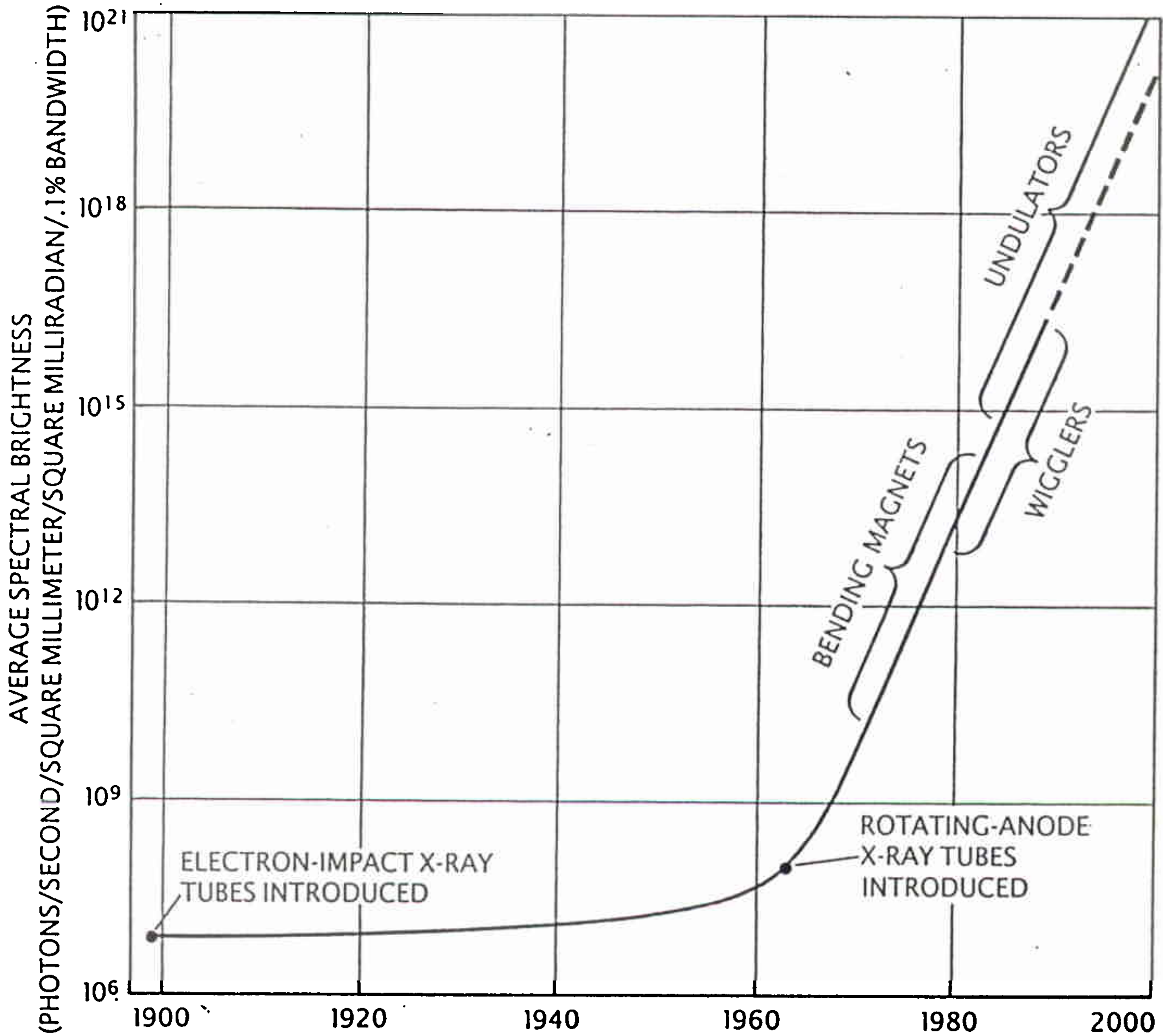


http://cdsweb.cern.ch/record/1125472

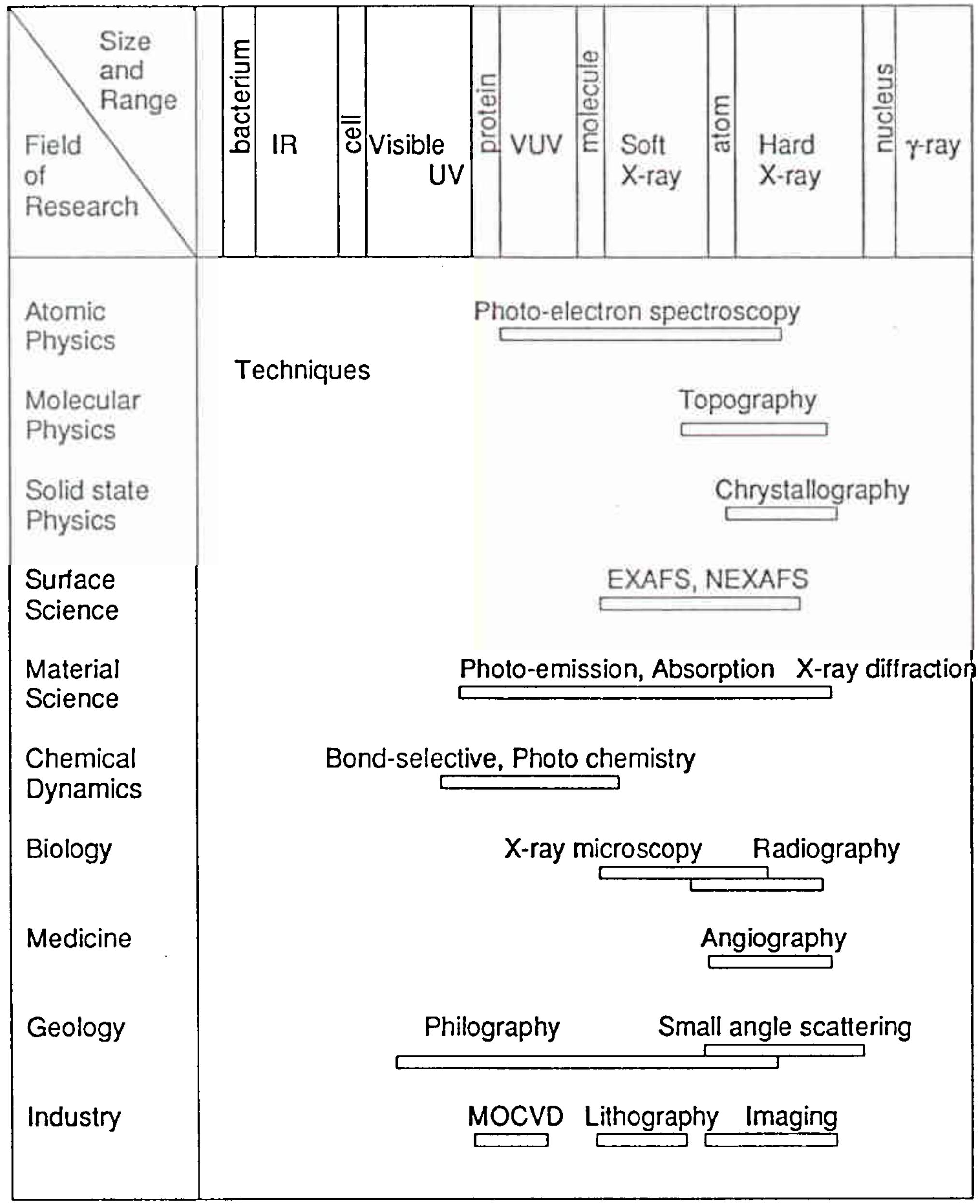


THE CANADIAN LIGHT SOURCE IN SASKATOON

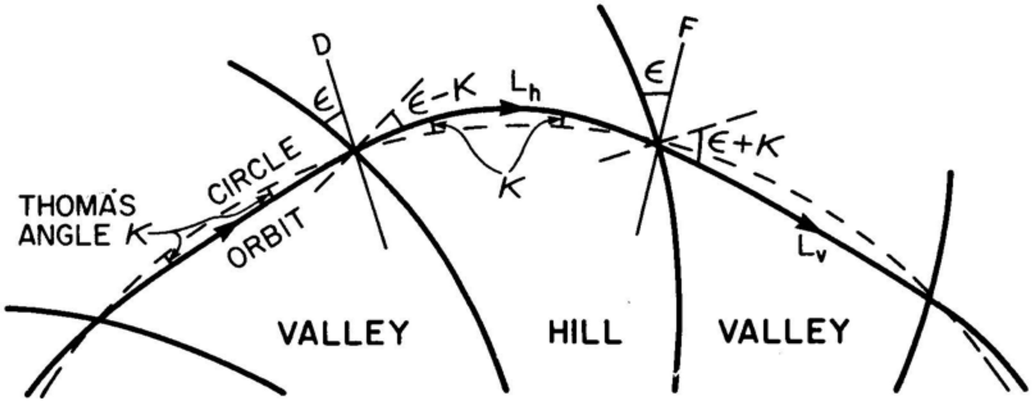
250-MeV electron linac + 2.9-GeV booster synchrotron + storage ring



BRIGHTNESS OF X RAYS has increased by many orders of magnitude since the advent of synchrotron-radiation sources. Undulators in storage rings are the brightest source.


Size and Range
Field of Research
bacterium
IR
cell
Visible UV
protein
VUV
molecule
Soft X-ray
atom
Hard X-ray
nucleus
γ-ray
Atomic Physics
Molecular Physics
Solid state Physics
Surface Science
Material Science
Chemical Dynamics
Biology
Medicine
Geology
Industry
Techniques
Photo-electron spectroscopy
Topography
Chrystallography
EXAFS, NEXAFS
Photo-emission, Absorption
X-ray diffraction
Bond-selective, Photo chemistry
X-ray microscopy
Radiography
Angiography
Philography
Small angle scattering
MOCVD
Lithography
Imaging

ALTERNATING FOCUSING FOR CYCLOTRONS - SPIRAL SECTORS



Kerst (1956) suggested using spiral sectors to increase the axial focusing.

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

or κ - ε i.e. a less strong D lens.

The focal powers become
$$\frac{1}{f_z} = \pm \frac{e\left(B_h - B_v\right)}{mv} \tan\left(\varepsilon \pm \kappa\right)$$

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

Spiralling is now used for most isochronous cyclotrons over 40 MeV.

The powerful $2\tan^2\varepsilon$ term has enormously increased the energies attainable:

- TRIUMF: 70 – 520 MeV H^-, 250 μA (→ 450 μA); $\varepsilon \lesssim 70°$
- PSI: 590 MeV p, 2 mA (→ 3 mA); $\varepsilon \lesssim 35°$
- providing 1000× more intense beams for π, μ, n & RI production;
- designs exist up to 12 GeV!

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

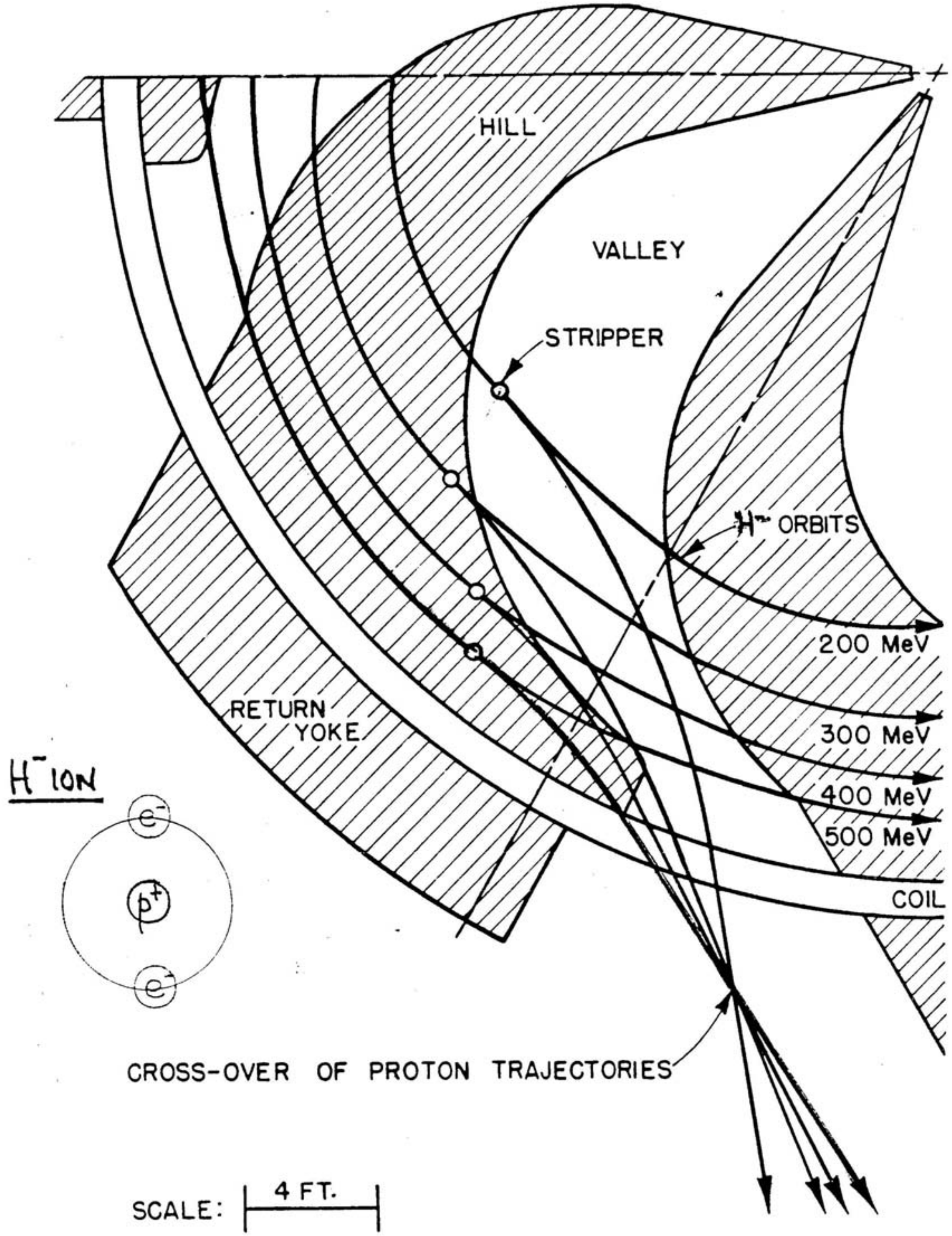
- Note iron-free valleys to maximize flutter
- Spiral angle increases with radius and energy from 0° to 70°
- H^- ions allow 4 separate extracted beams, but restrict hill field to 0.6 T

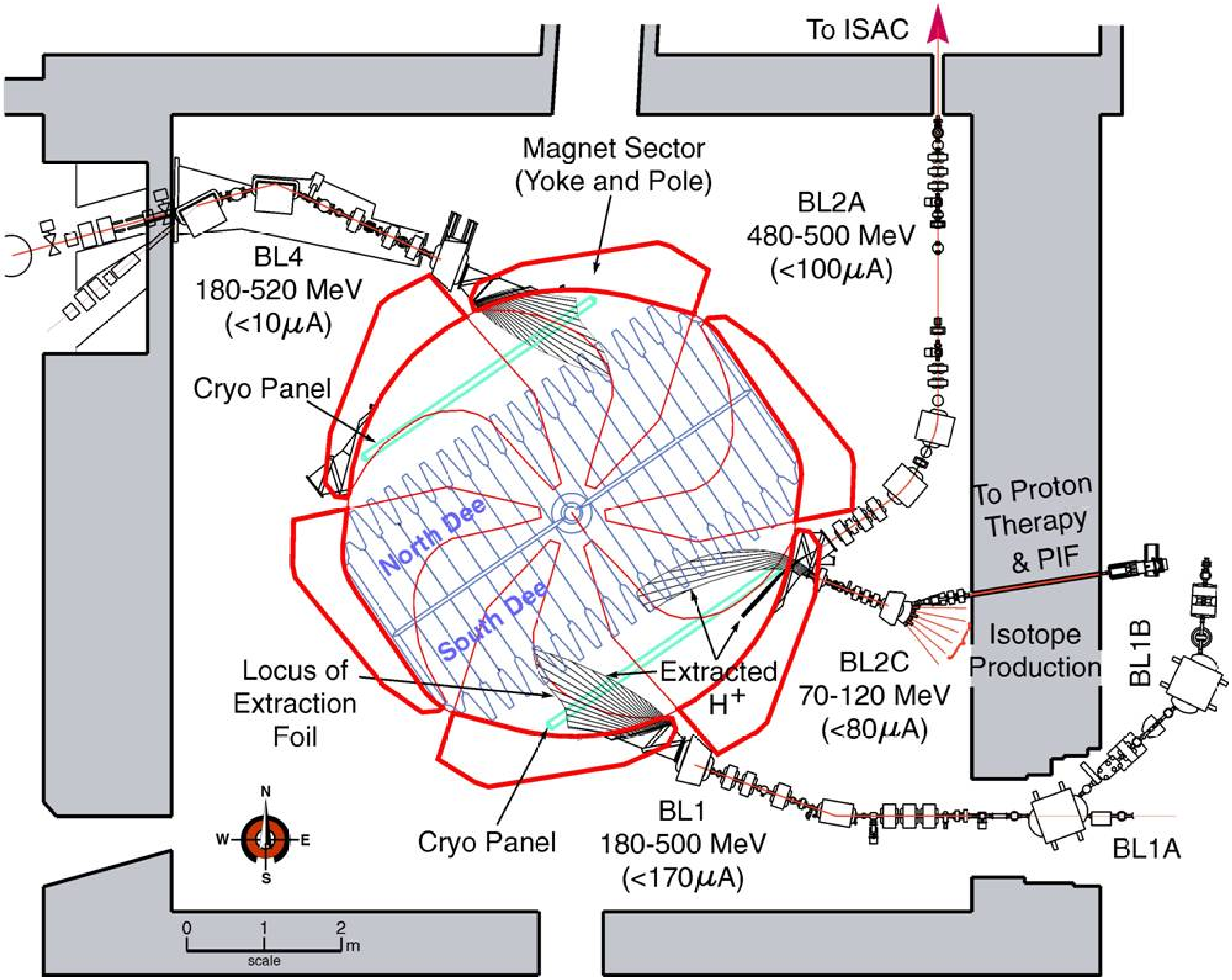
VARIABLE-ENERGY EXTRACTION BY H⁻ STRIPPING

When a high-energy H⁻ ion impinges on a thin foil, the two electrons are stripped off, leaving the positively charged proton bending in the opposite sense.

The foils are typically made of 25-µm pyrolytic graphite.

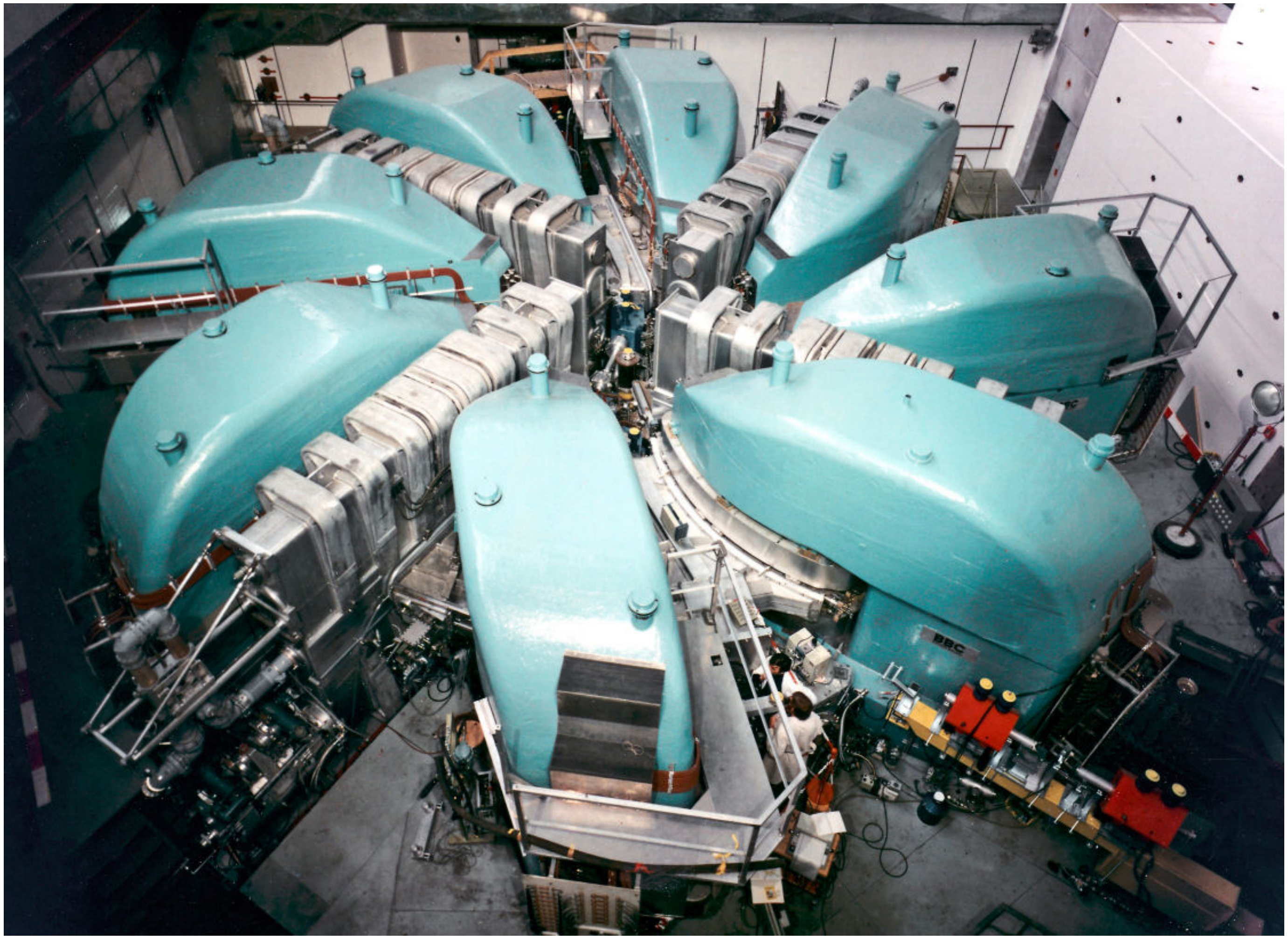
The foil azimuth for each radius is chosen so that the proton trajectories cross in a "combination magnet" that steers all into one beam line.



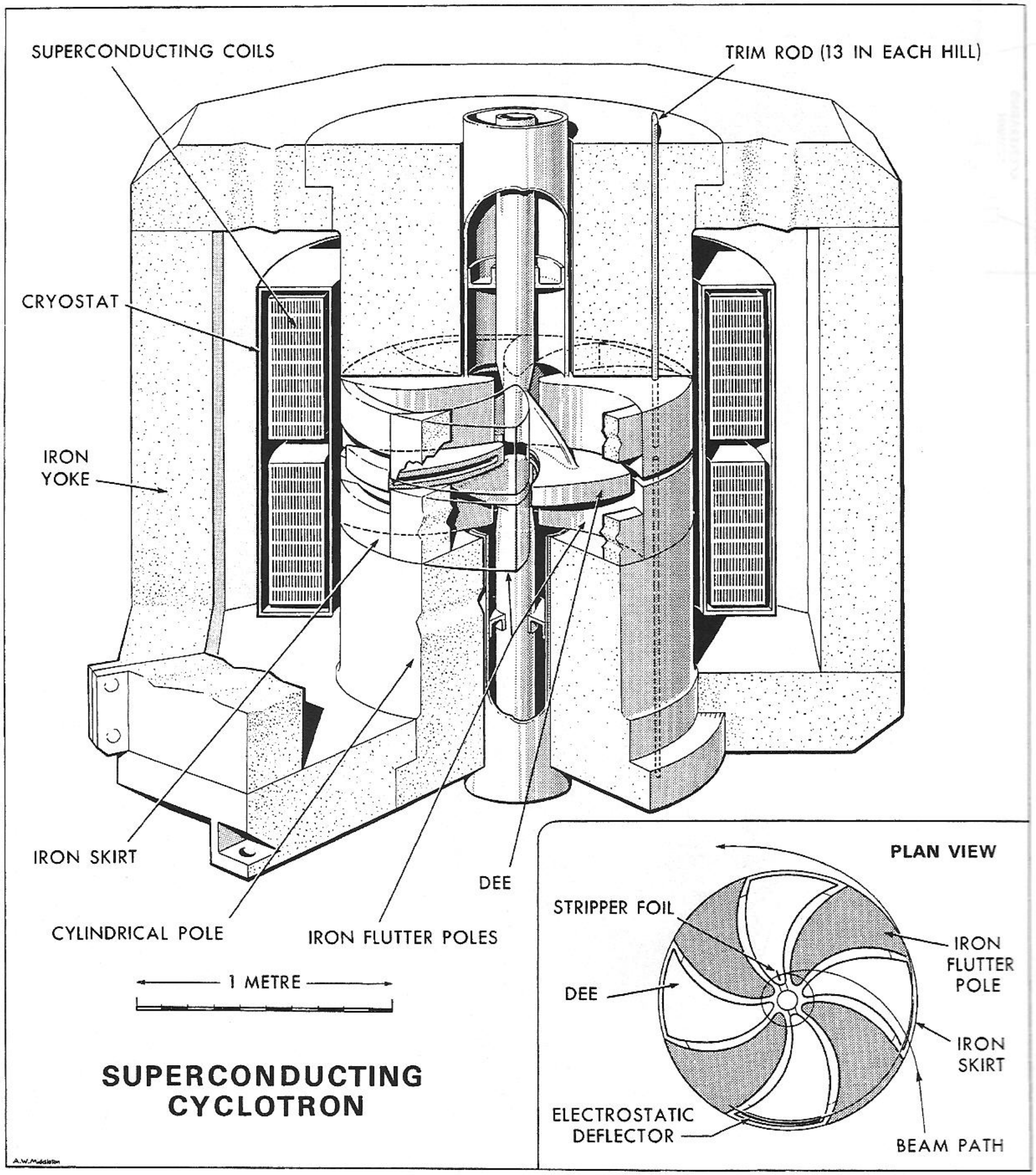


By using a variety of foil shapes for partial extraction at lower energies, TRIUMF currently extracts 3 beams of variable energy and intensity simultaneously – and proposes to add a 4th.

PSI 590-MeV RING CYCLOTRON

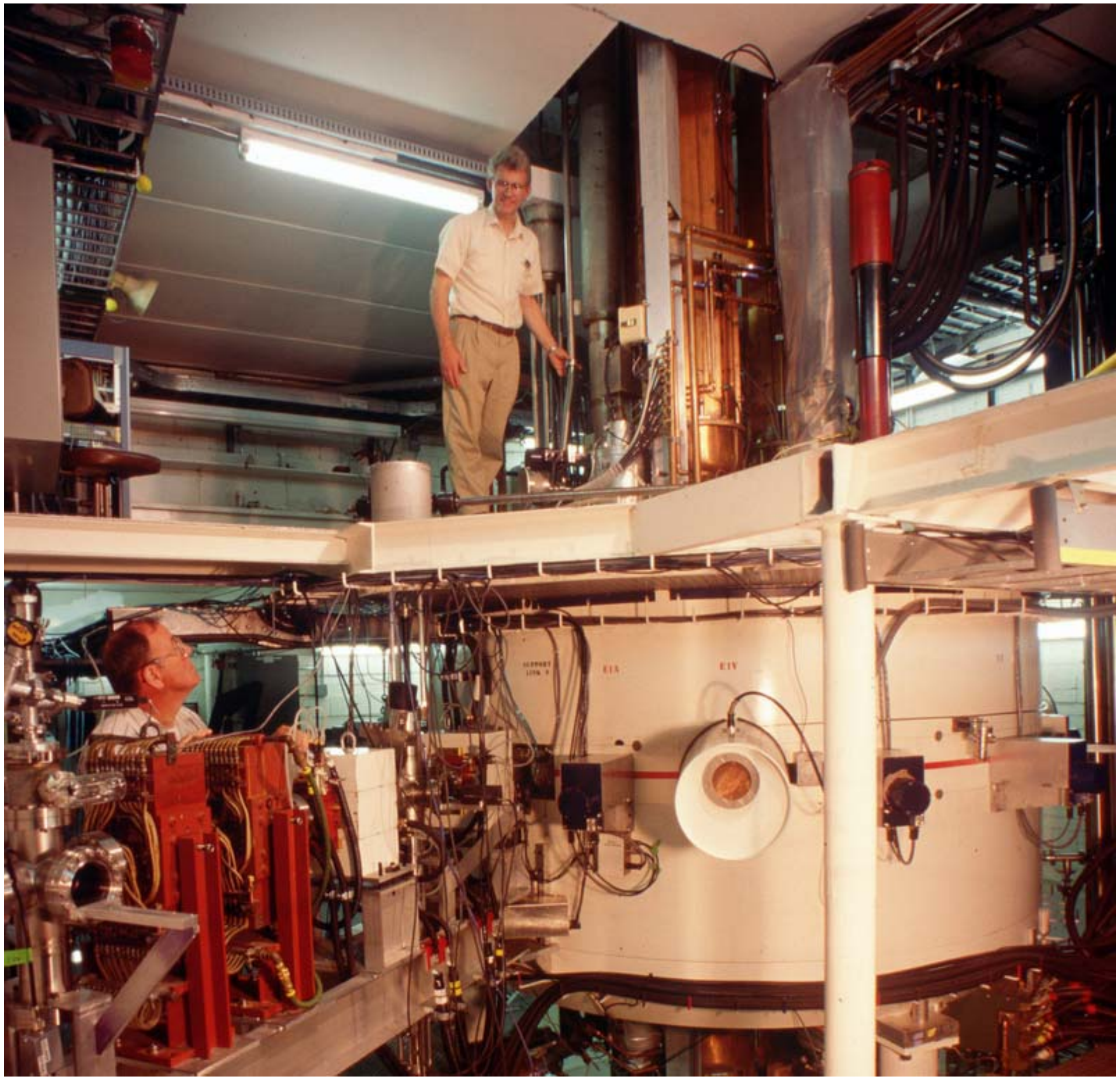


This separated-sector ring cyclotron, with 8 spiral magnets and four 1-MV rf cavities, delivers a 2.2-mA proton beam – the world's highest power particle beam (1.3 MW).



The first superconducting cyclotron design – the K520 at AECL Chalk River

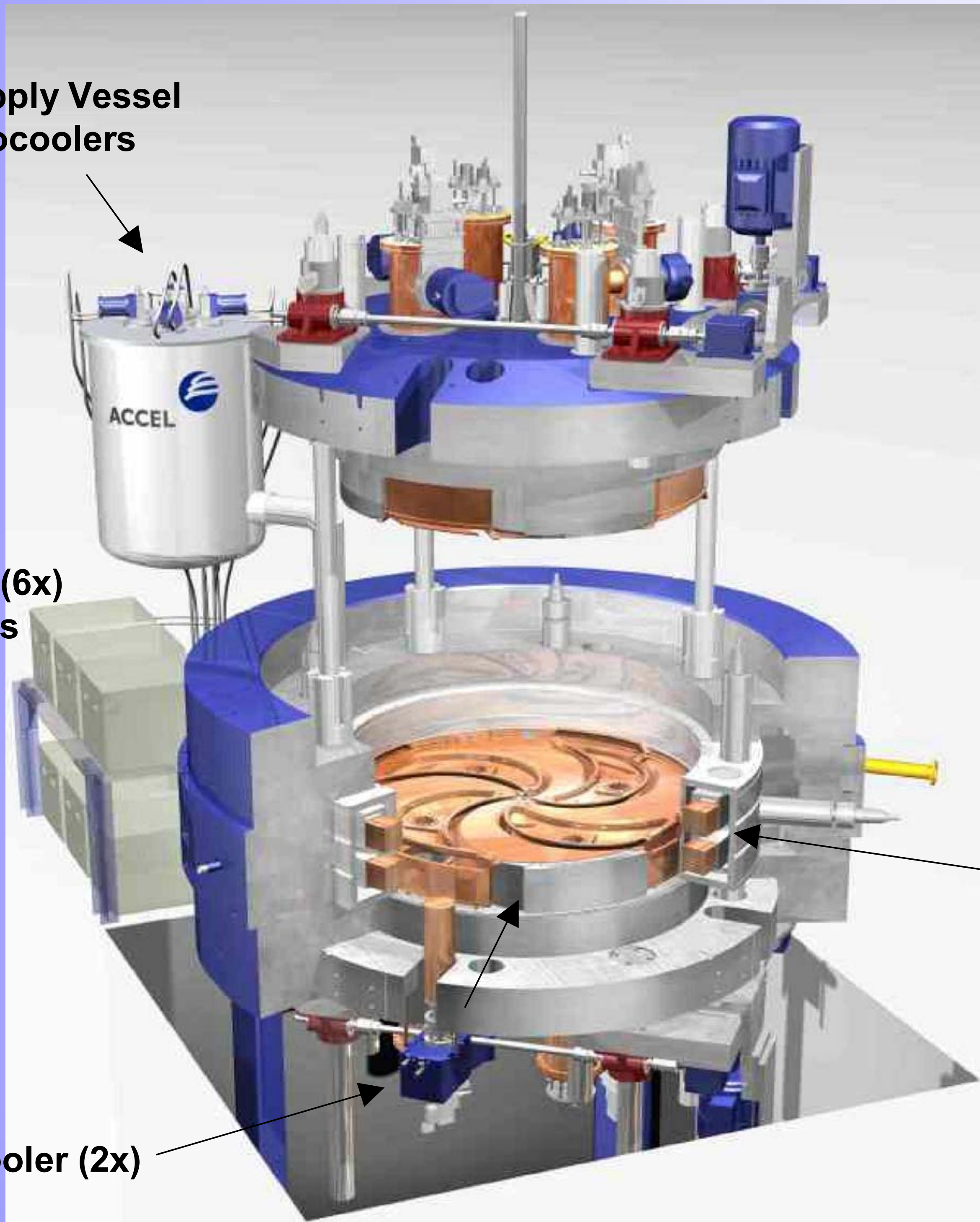
K500 SUPERCONDUCTING CYCLOTRON AT MSU

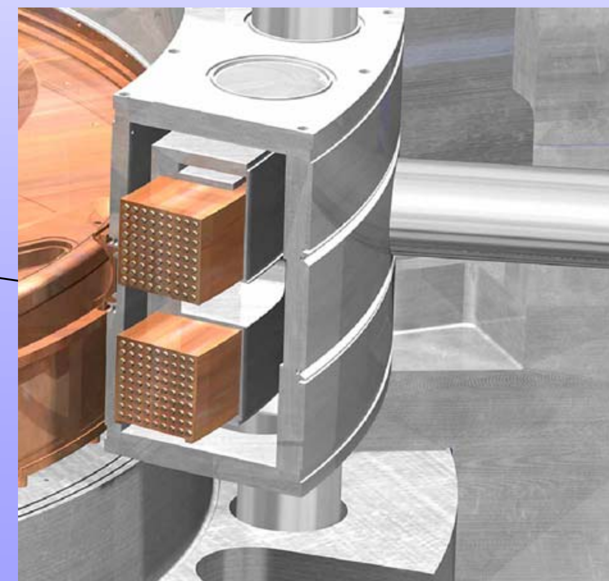


- The first cyclotron with superconducting coils to operate (Blosser 1982)
- can accelerate heavy ions (atomic number Z, mass A) to $500(Z/A)^2$ MeV/u.

ACCEL

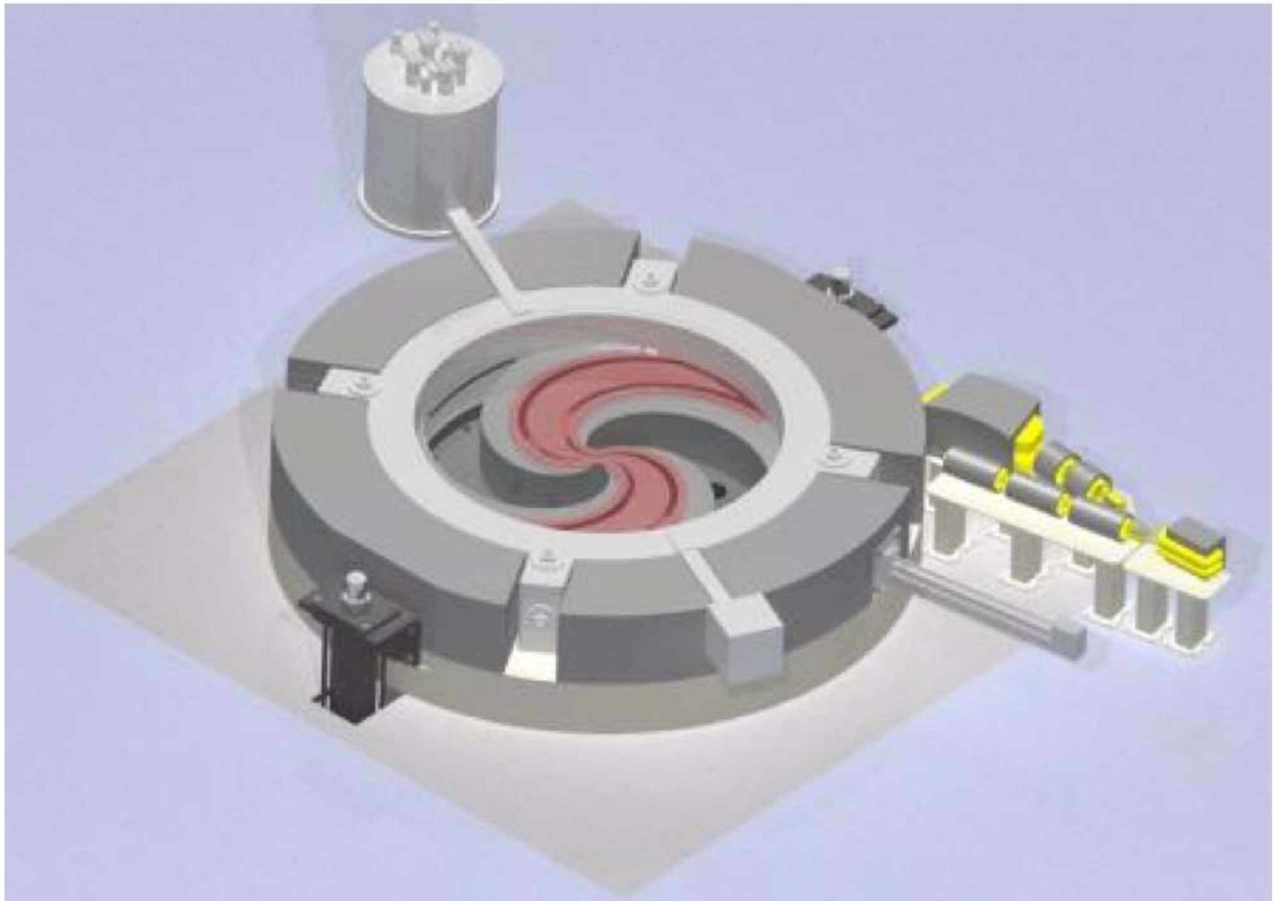
250 MeV Superconducting Proton Cyclotron





Superconducting Coil

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.

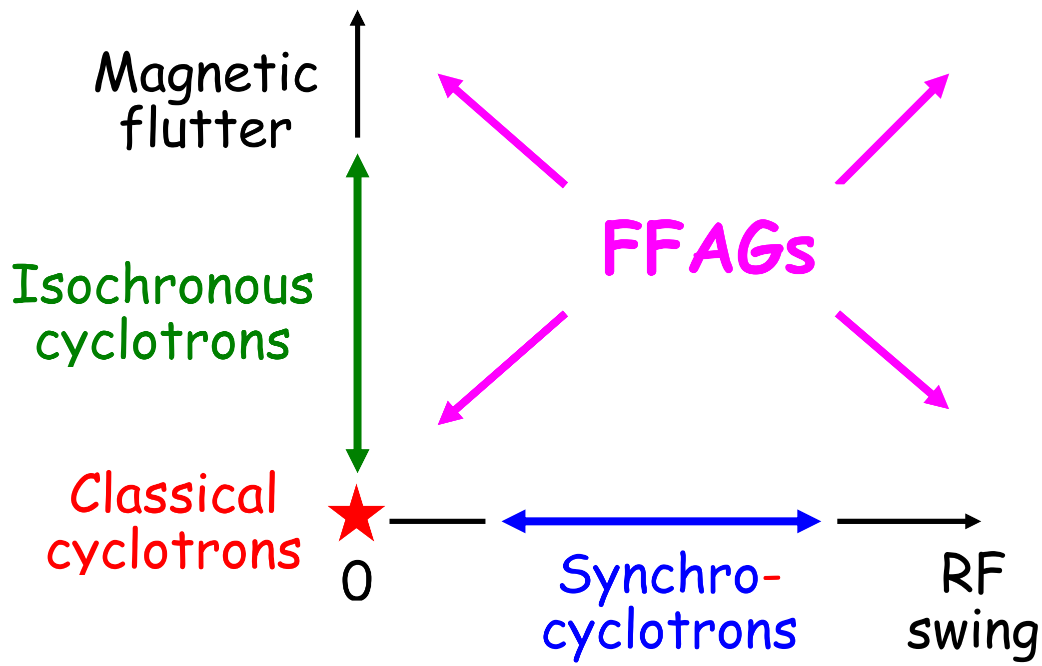
Construction will begin soon on the first C400, to be installed in Caen.

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!



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.

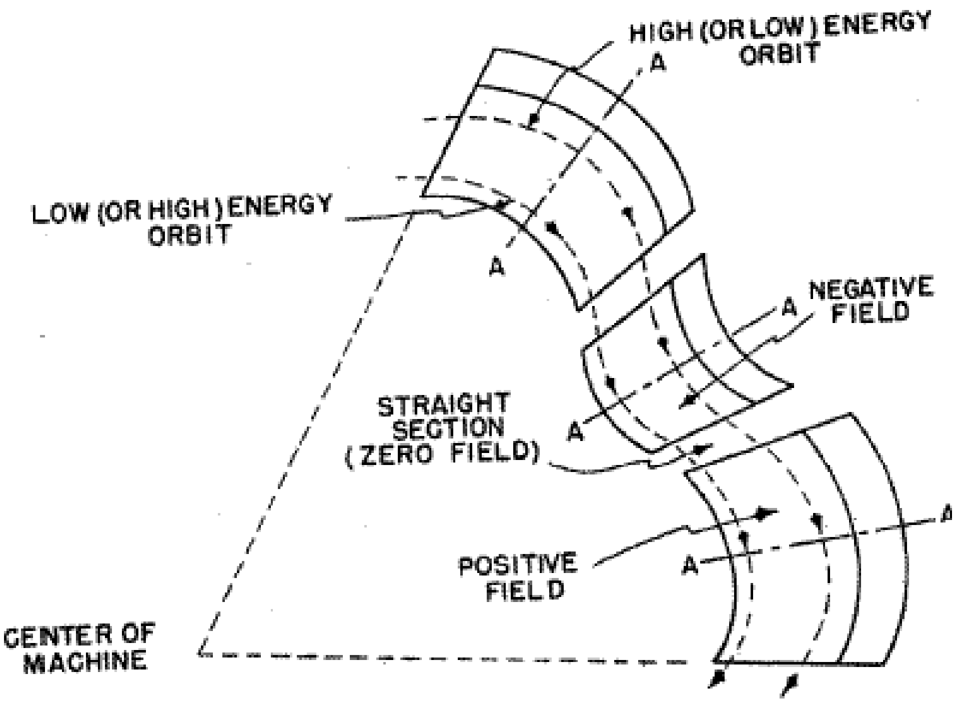


FIG. 2. Plan view of radial-sector magnets.

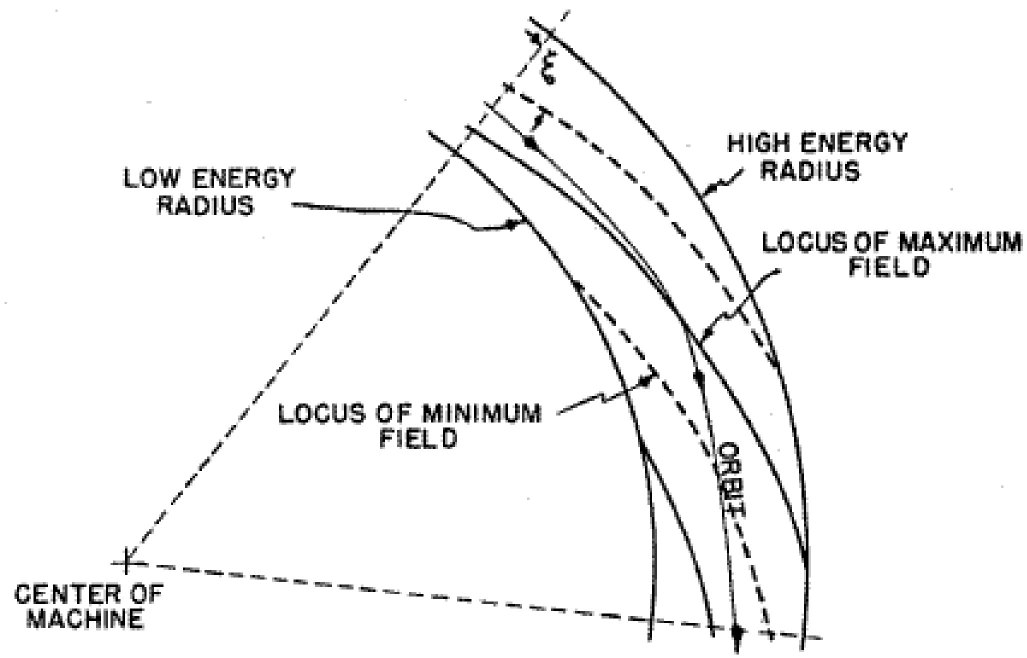


FIG. 3. Spiral-sector configuration.

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 - HORIZONTAL TUNE ν_r

Resonances were a worry in the 1950s, because of slow acceleration: if, at some energy, the betatron oscillation wavelength matches that of a harmonic component of the magnetic field, the ions may be driven into resonance, leading to loss of beam quality or intensity.

The general condition is $\boxed{\ell \nu_x \pm m \nu_y = n}$ where ℓ, m, n are integers.

So "**Scaling**" designs were used, with:

- the same orbit shape at all energies
- the same optics " " " " "
- the **same tunes** " " " " " $\Rightarrow$ no crossing of resonances!

To 1st order, the (radial tune)^2 $\nu_r^2 \approx 1 + k$ (even with sector magnets)

where the average field index $k(r) \equiv \dfrac{r}{B_{av}} \dfrac{dB_{av}}{dr}$ and $B_{av} = \langle B(\Theta) \rangle$

So large constant ν_r requires k = constant ≥ 0

$$\Rightarrow \quad B_{av} = B_0 (r/r_0)^k \quad \text{and} \quad p = p_0 (r/r_0)^{(k+1)}$$

SCALING FFAGs - VERTICAL TUNE ν_z

In the vertical plane, with sector magnets and to 1st order,

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

where the 2nd term describes the Thomas and spiral edge focusing effects.

Note $k > 0 \Rightarrow$ vertical defocusing

$\therefore$ large constant, real ν_z requires large, constant $F^2(1 + 2\tan^2\varepsilon)$

MURA kept (1) magnetic flutter $F^2 \equiv \left\langle \left(\frac{B(\theta) - B_{av}}{B_{av}} \right)^2 \right\rangle$ = constant

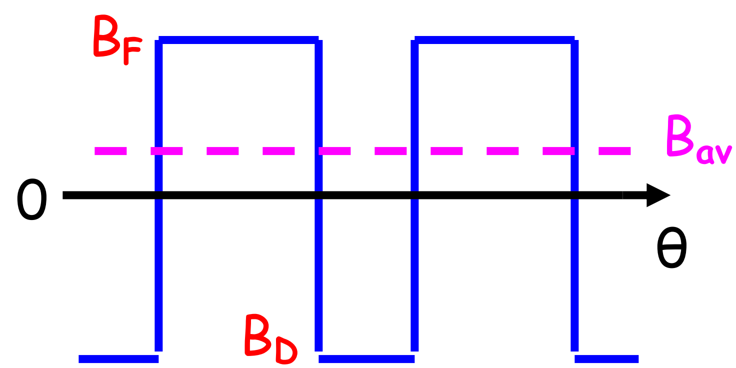
(most simply achieved by using constant profile $B(\Theta)/B_{av}$)

(2a) for spiral sectors,

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

(2b) for radial sectors,

$B_D = -B_F$ to boost F^2.



Note - reverse fields increase average radius:

$\Rightarrow$ >4.5x larger (Kerst & Symon '56 - no straights)

[Not so bad with straights: KEK 150-MeV FFAG has "circumference factor" 1.8]

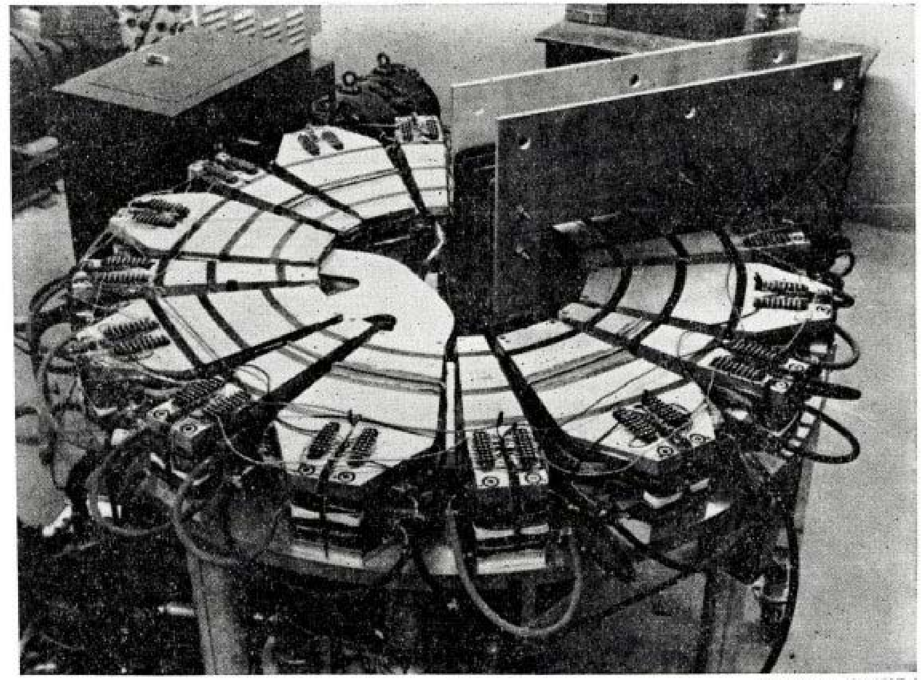
MURA Electron FFAGs

400keV radial sector

50 MeV radial sector

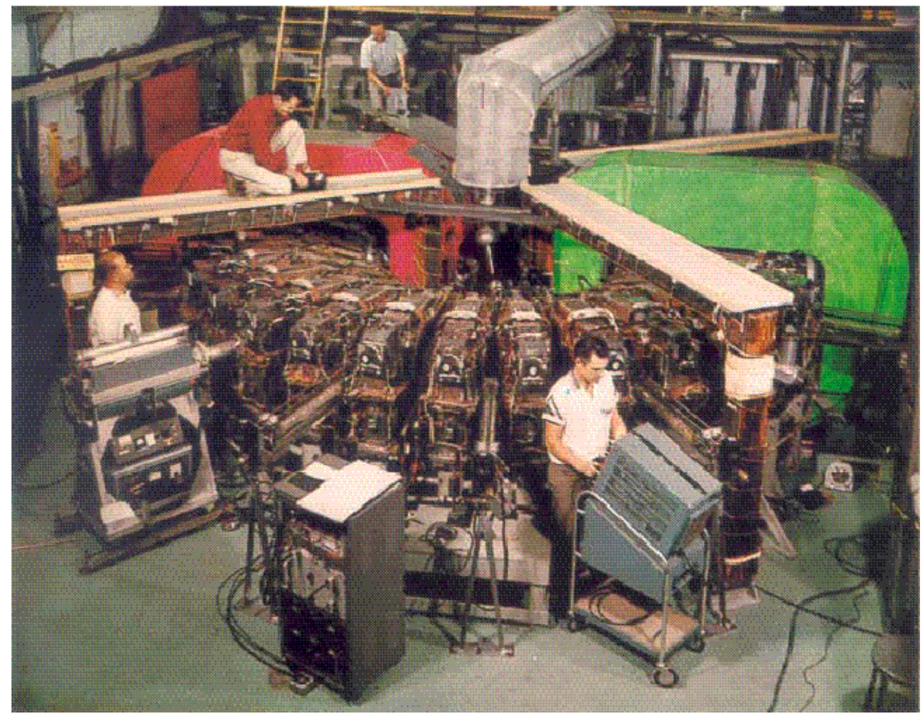
120 keV spiral sector

Courtesy of MURA



Courtesy of MURA

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



THE FFAG REVIVAL

In spite of their promise of much higher beam intensity than AG synchrotrons at GeV energies through their:

- higher repetition rates, and
- larger radial and momentum acceptance,

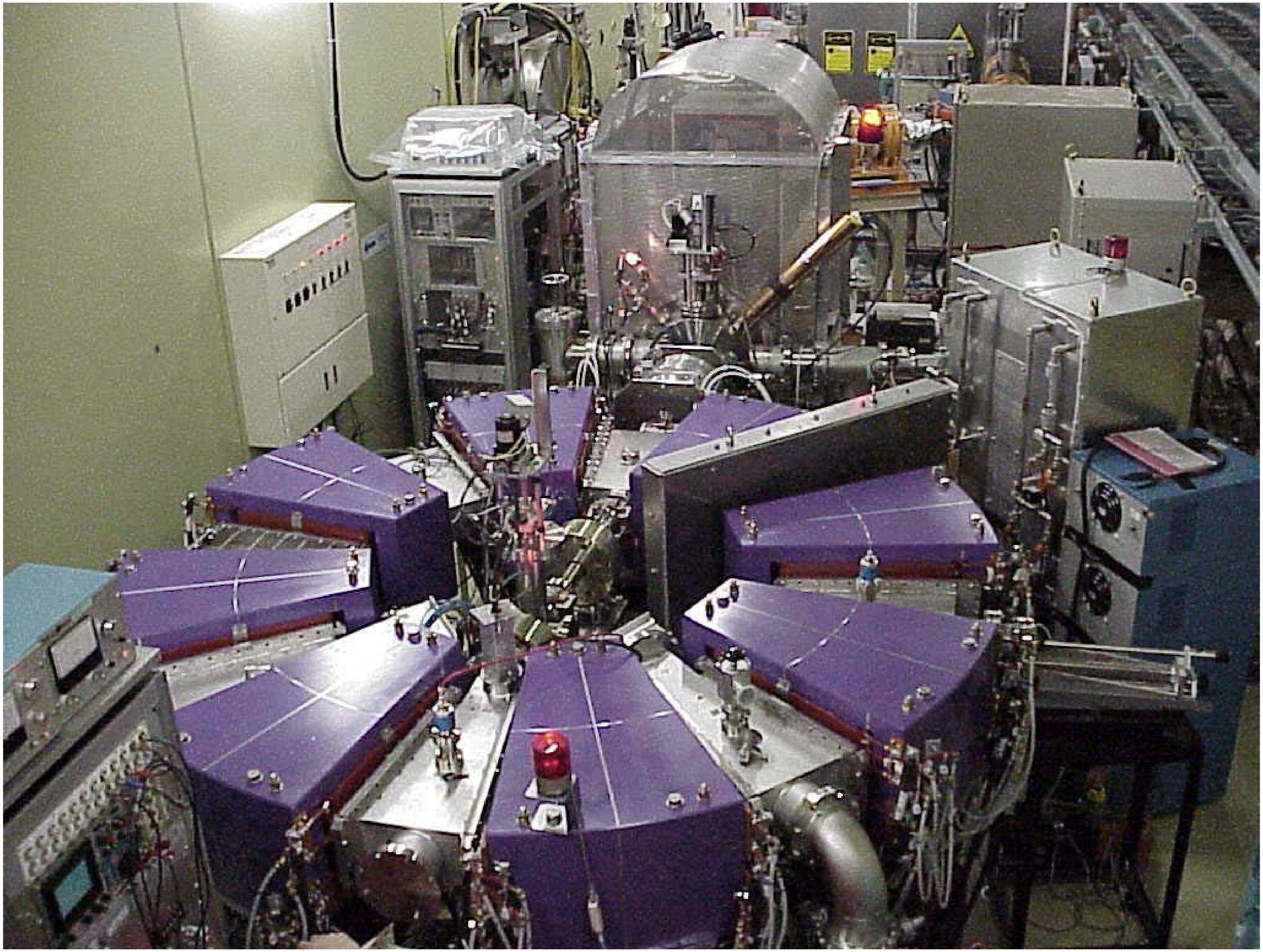
two major factors deterred construction of proton FFAGs until recently:

- their complicated magnet shapes (difficult to design and expensive to build)
- the unreliability of the mechanical tuners required for rapid frequency modulation for all particles heavier than electrons.

But in the late 1990s two independent new approaches were taken:

- Mills & Johnstone (Fermilab, 1997) proposed a non-scaling lattice for a muon accelerator
- Mori (KEK, 1999 – also with muons in view) started building a 1-MeV proton scaling FFAG - with solutions to the technical problems.

KEK Proof-of-Principle 1 MeV proton FFAG



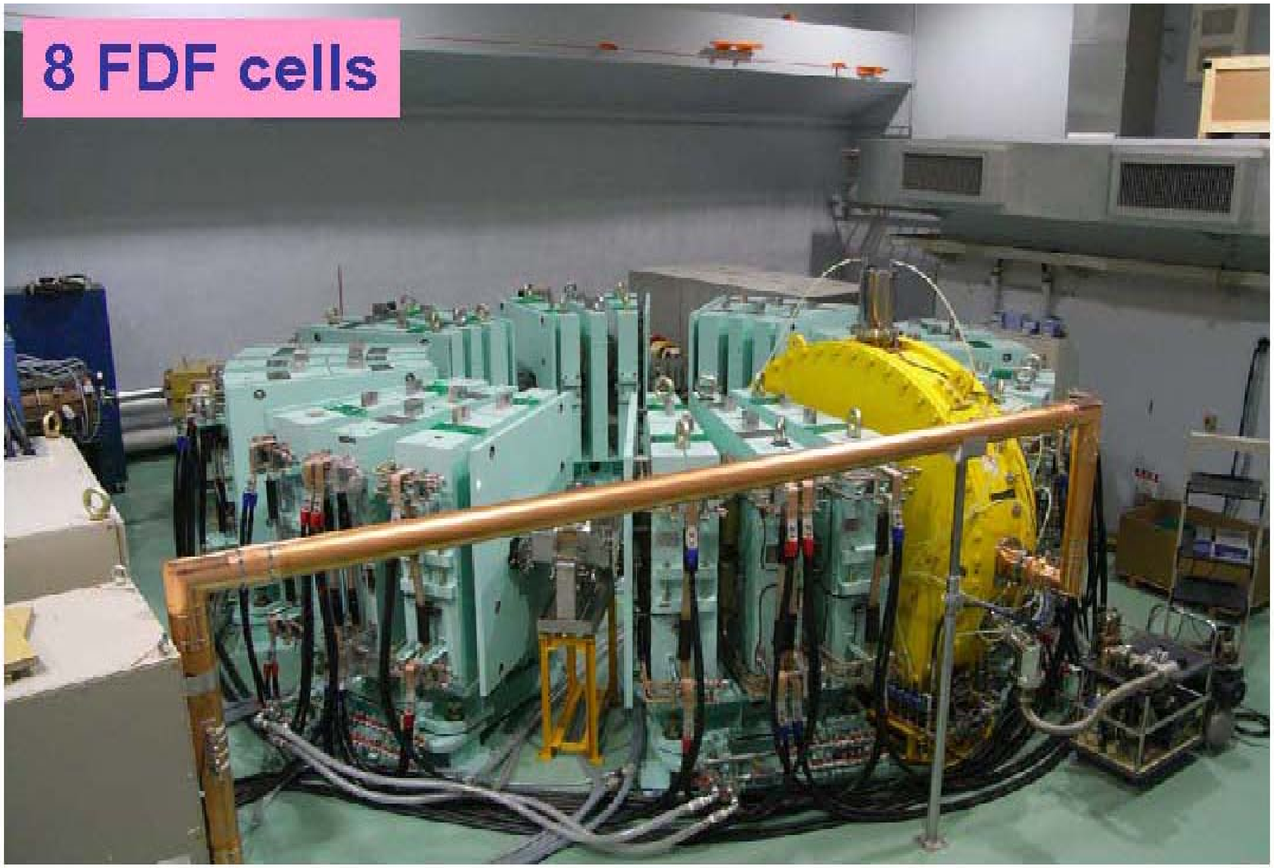
KEK 150-MeV 12-Sector Proton FFAG

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.

KURRI ERIT STORAGE RING FOR BNCT

(ERIT = Energy/Emittance Recovery Internal Target)



70-mA of circulating 11-MeV protons produce an intense neutron beam (>10^9/cm^2/s at the patient) via the Be(p,n) reaction.

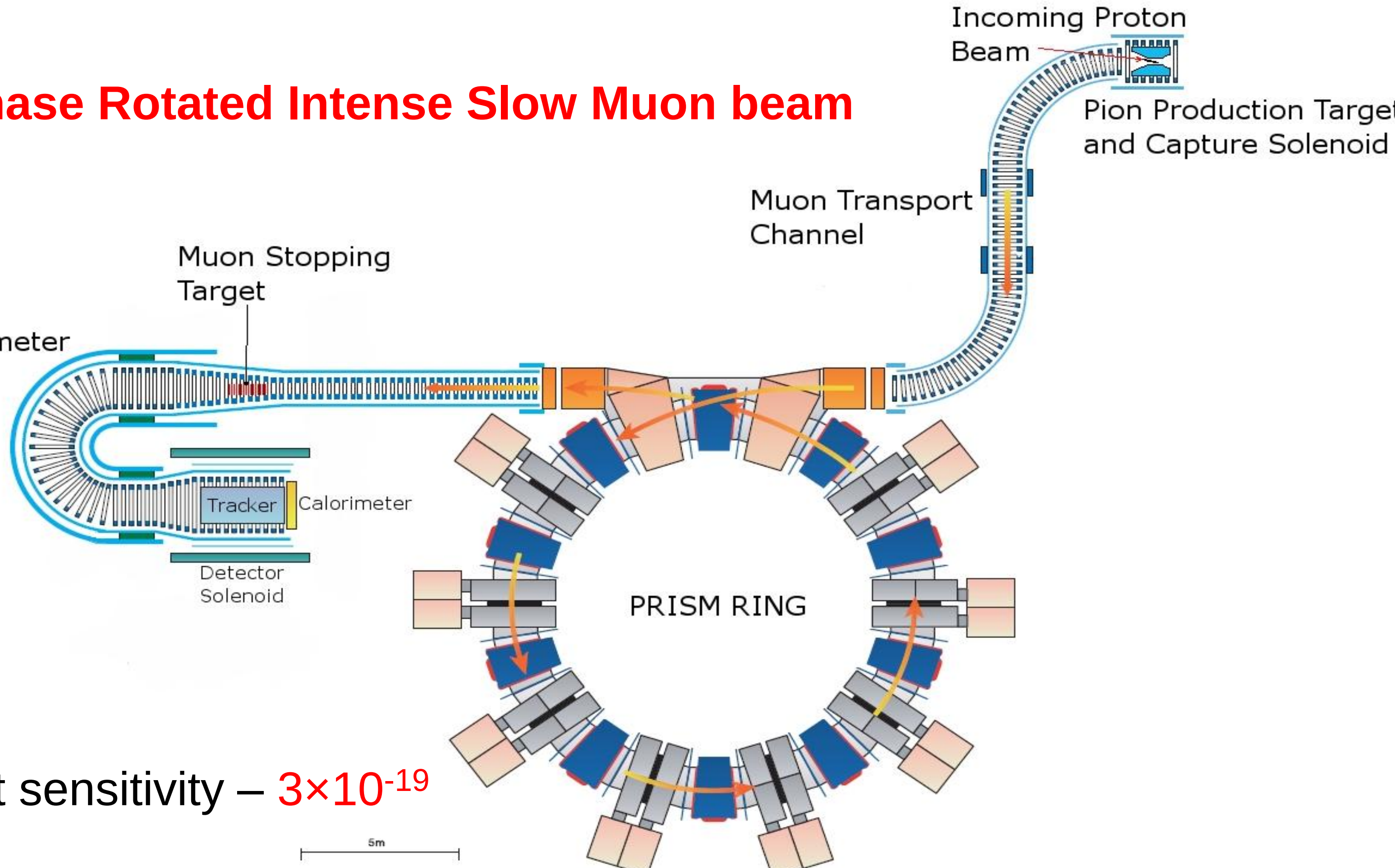
V_{rf} = 250 kV plus large FFAG acceptances (>3000 mm-mrad, ±5% $\delta p/p$) allow ionization cooling to maintain stable beam over 1000 turns.

α–PARTICLE TEST RING FOR PRISM AT RCNP OSAKA

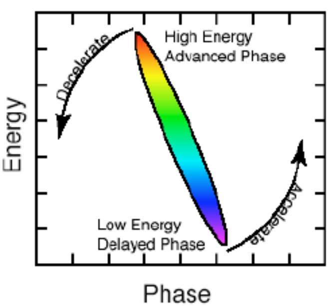
Using 6 of the PRISM muon storage ring's 10 sectors
to demonstrate bunch rotation in phase space

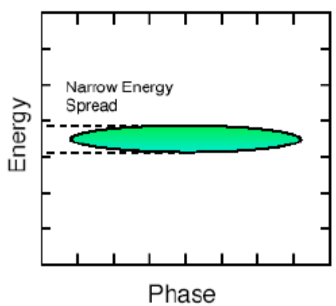
Layout of the PRISM/PRIME

PRISM - Phase Rotated Intense Slow Muon beam



Single event sensitivity – 3×10^{-19}





The PRISM/PRIME experiment based on FFAG ring was proposed (Y. Kuno, Y. Mori) for a next generation cLFV searches in order to:

- reduce the muon beam energy spread by phase rotation,
- purify the muon beam in the storage ring.

J. Pasternak

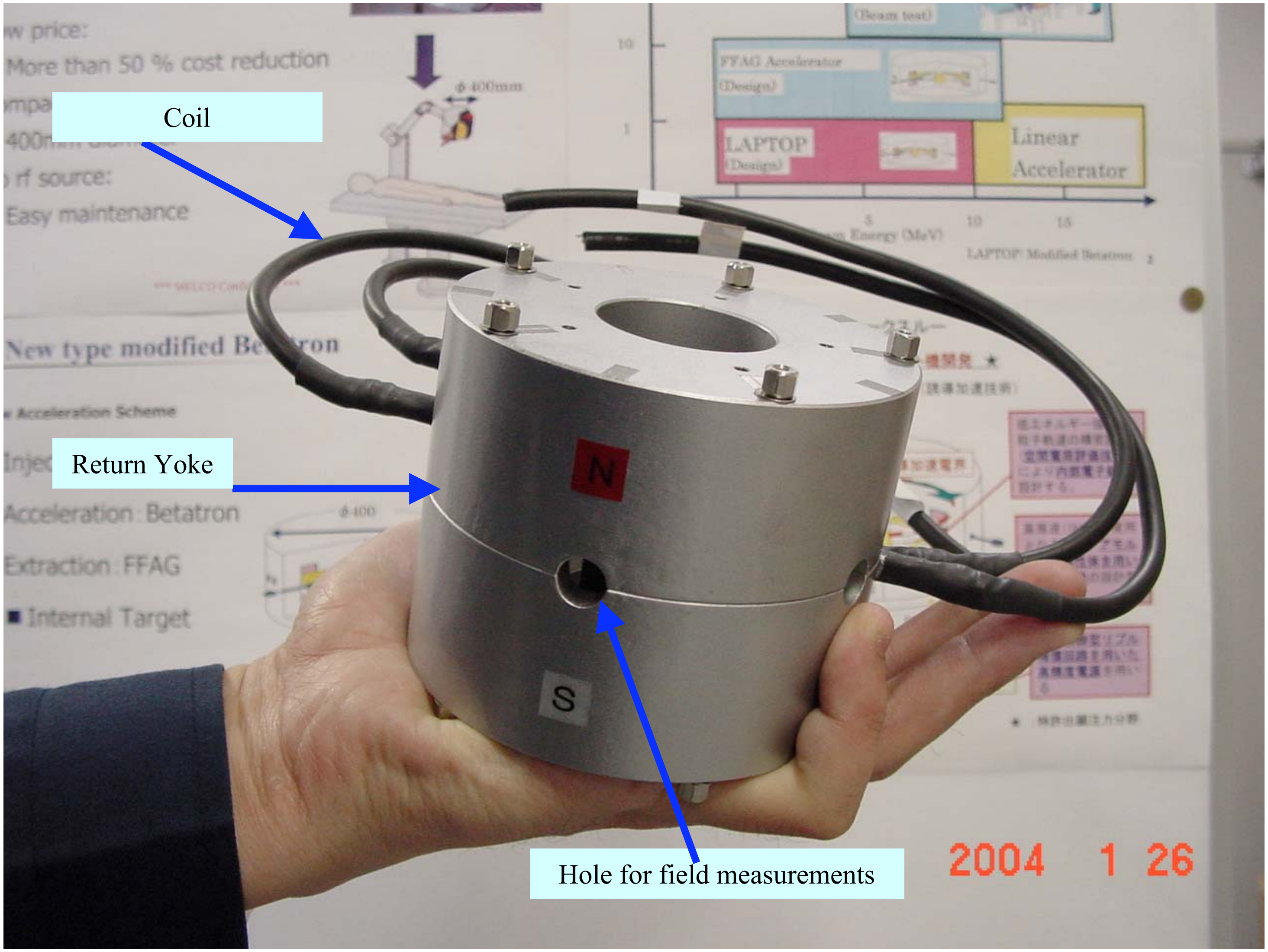
SCALING FFAGs - DESIGN STUDIES

	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
MElCo - Laptop	1	e	5	35°	.023 -.028	1,000	Hybrid - Magnet built
eFFAG	10	e	8	47°	0.26 - 1.0	5,000	20-100 mA
LPSC RACCAM	180	p	10	54°	3.2 - 3.9	>20	Magnet sector 2008
Ibaraki Med.Acc.	230	p	8	50°	2.2 - 4.1	20	0.1 μA
MElCo - p Therapy	230	p	3	0°-60°	0 - 0.7	2,000	SC, Quasi-isochronous
MElCo - Ion Therapy	400	C^{6+}	16	64°	7.0 - 7.5	0.5	Hybrid (FFAG/synch^n)
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35 - 1.8	0.5	" " " "
NIRS Chiba	400	C^{6+}	12	0°	10.1 - 10.8	200	Compact
- Hadron	100	"	12	0°	5.9 - 6.7	"	radial
Therapy	7	C^{4+}	10	0°	2.1 - 2.9	"	sectors
Mu Cooling Ring	160	μ	12	0°	0.95 ± 0.08		Gas-filled
J-PARC	20,000	μ	120	0°	200		Δr = 0.5 m, ~10 turns.
Neutrino	10,000	"	64	0°	90		
Factory	3,000	"	32	0°	30		Q≈1 rf cavities allow
Accelerators	1,000	"	16	0°	10		broadband operation

MITSUBISHI ELECTRIC

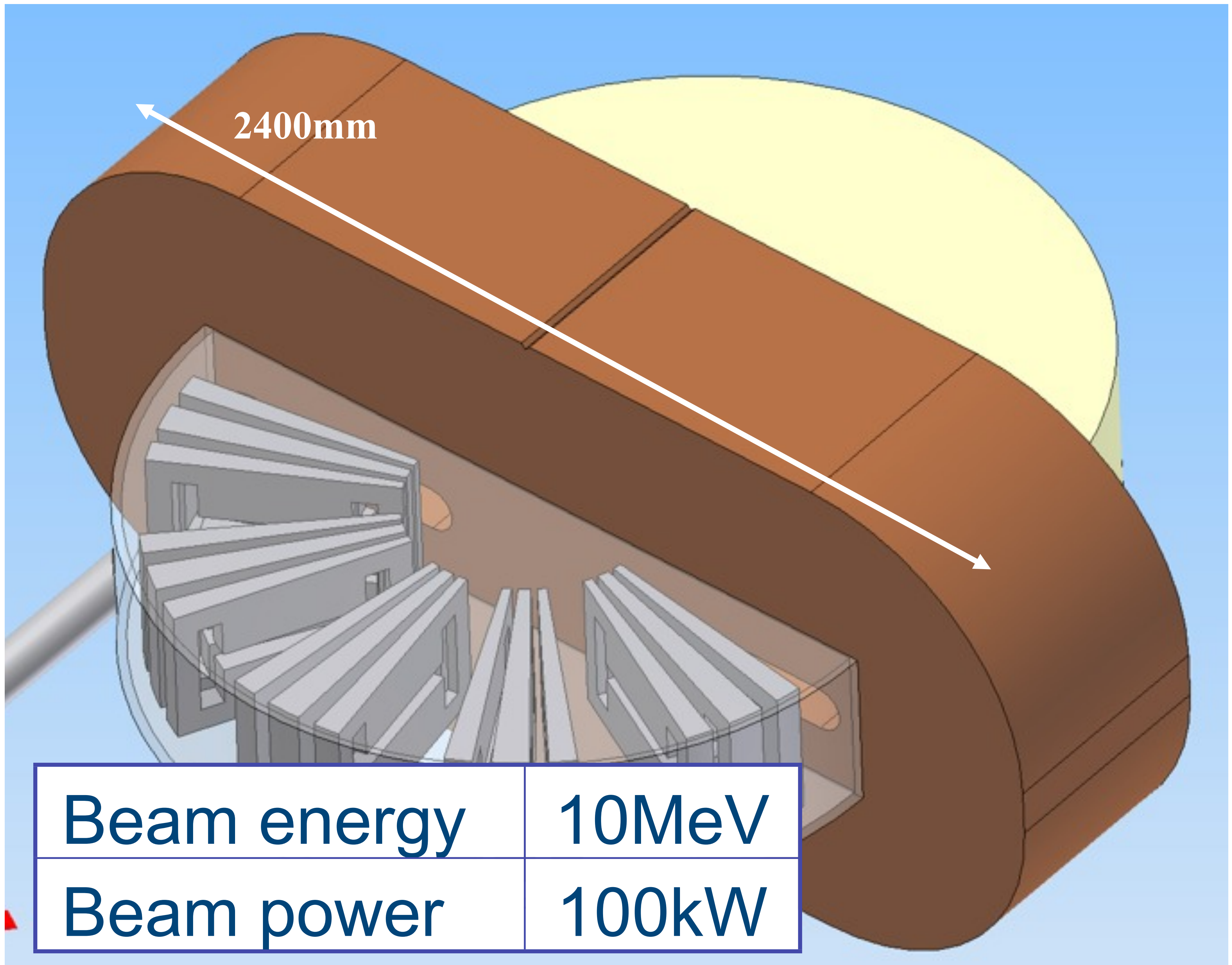
Spiral Magnet

Changes for the Better



The present study is partially supported by the REIMEI Research Resources of Japan Atomic Energy Research Institute.

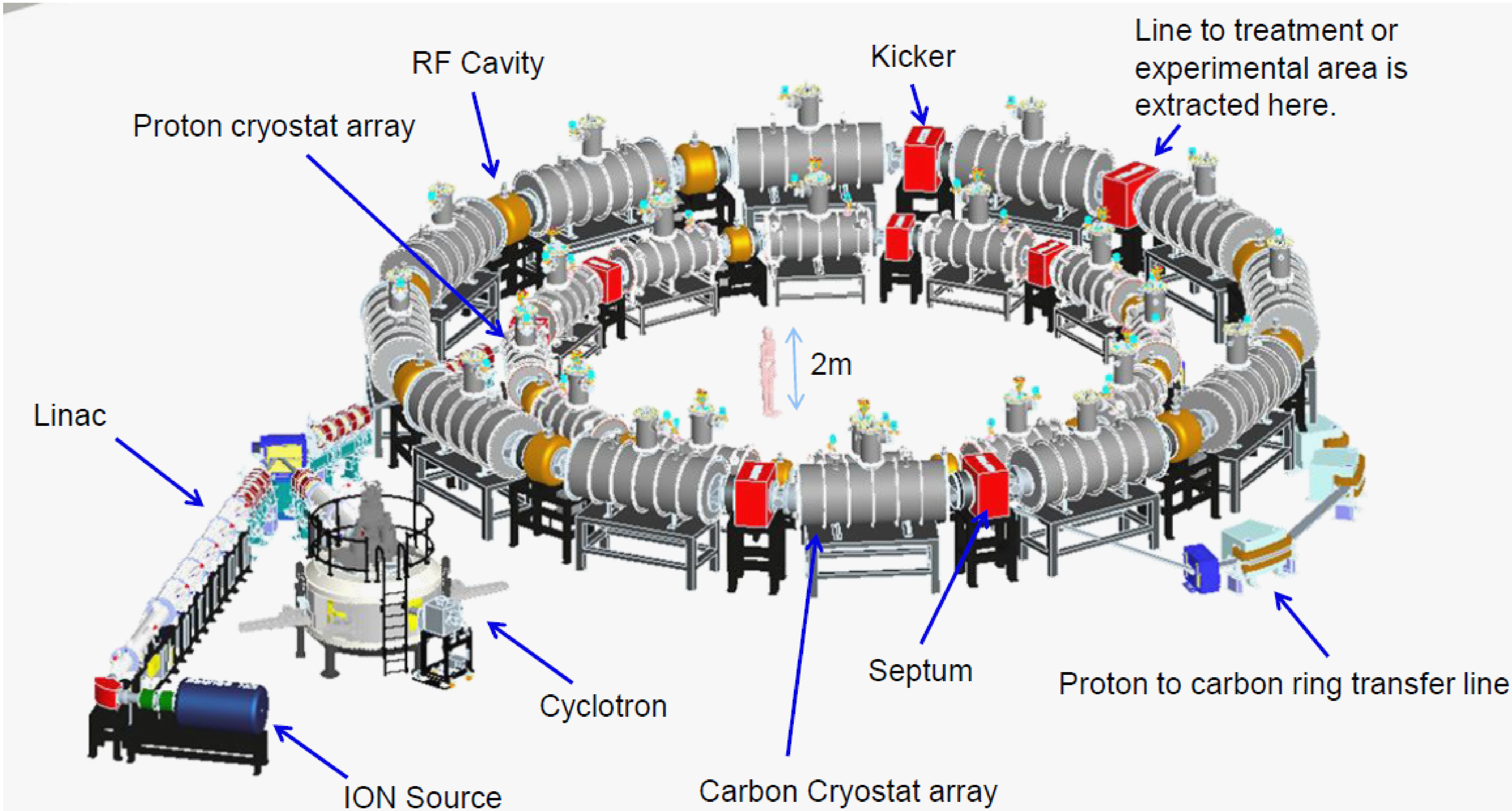
10MeV Electron Accelerator



Beam energy	10MeV
Beam power	100kW

NHV Corporation

PAMELA CANCER THERAPY FFAGs (Adams Inst. Oxford)

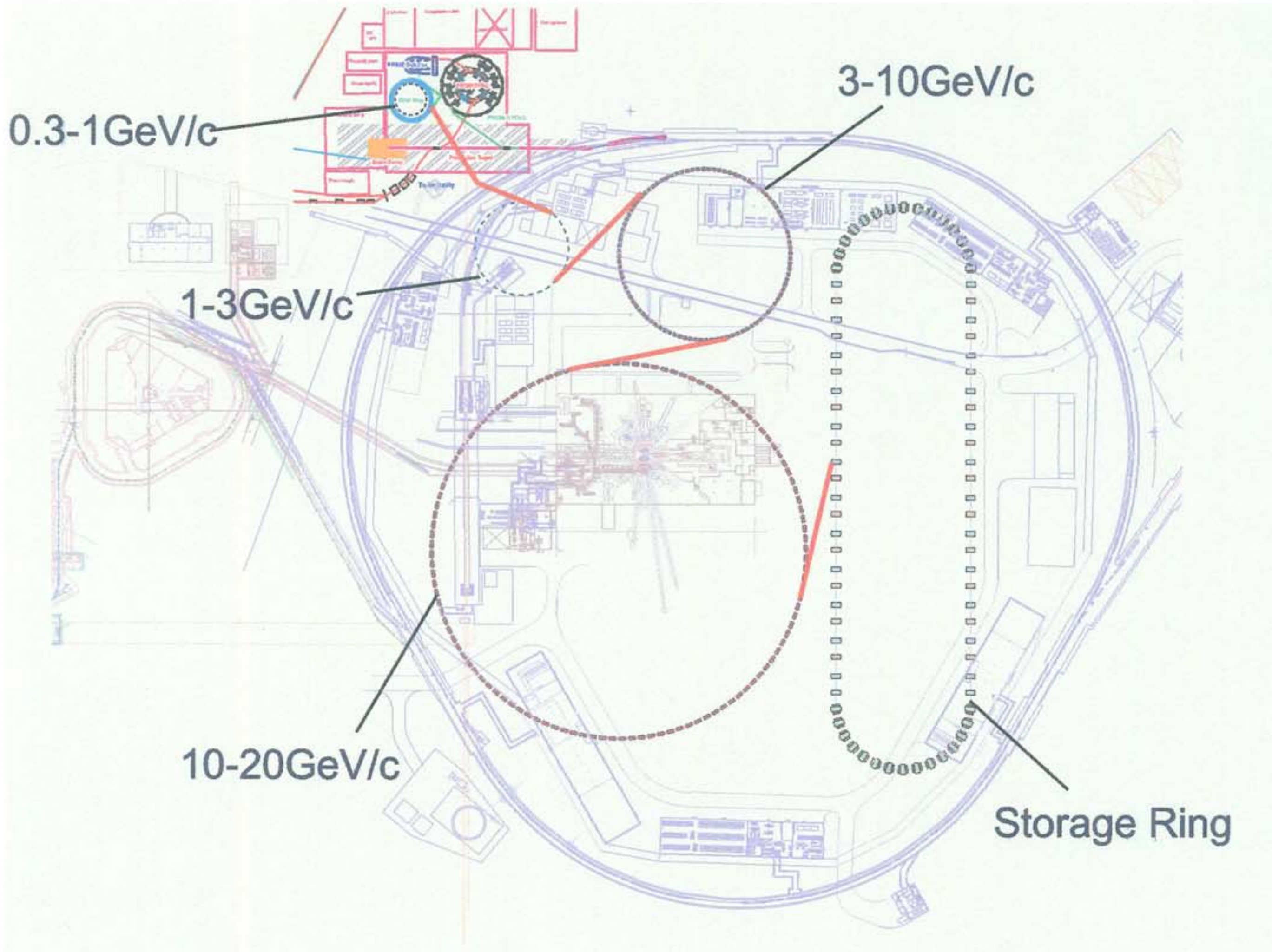


The small ring delivers 31-250 MeV protons

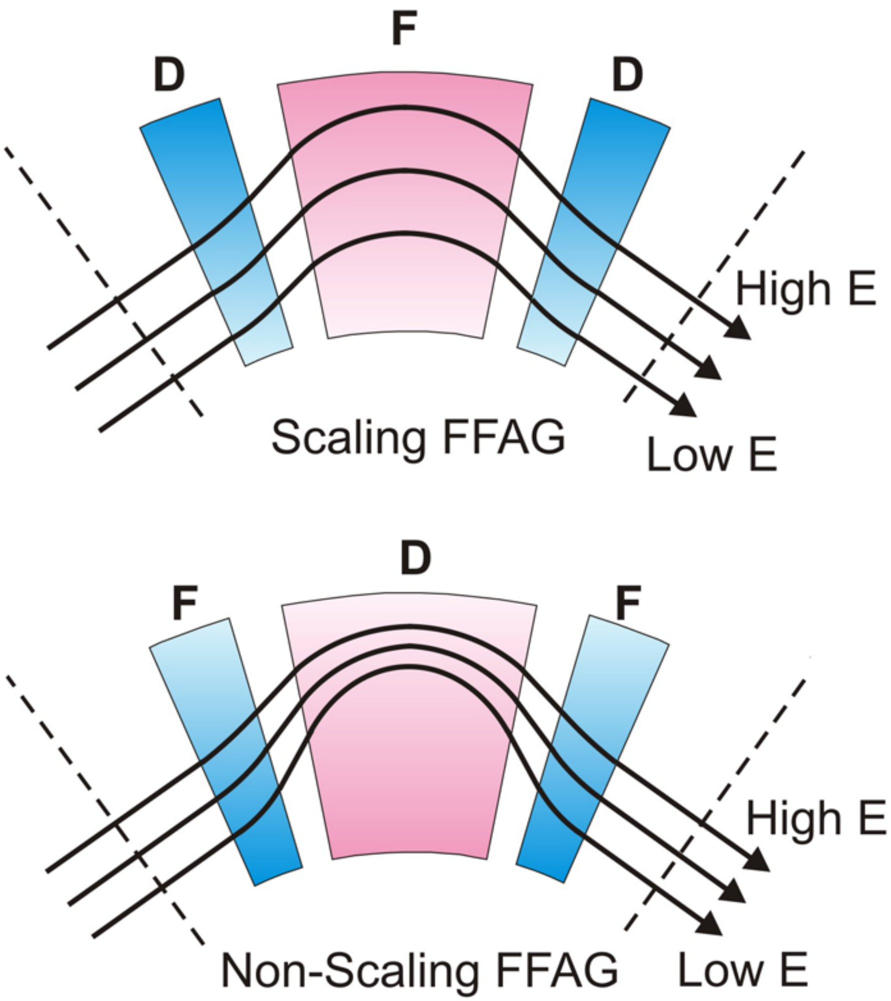
The large ring delivers 68-400 MeV/u C^{6+} ions

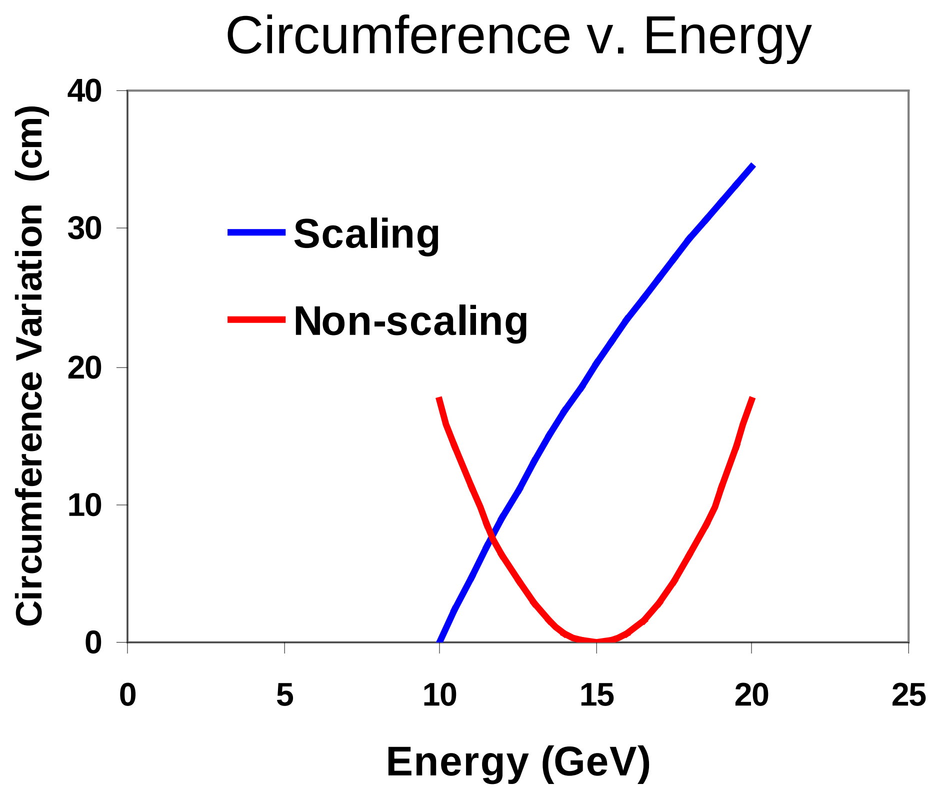
Superconducting 2-, 4-, 6- & 8-pole magnets keep the tunes constant.

Neutrino Factory : FFAG based



SCALING v. LINEAR NON-SCALING FFAGs





$$C(p) = C(p_m) + \frac{12\pi^2}{e^2 q^2 N L_{FD}} (p - p_m)^2$$

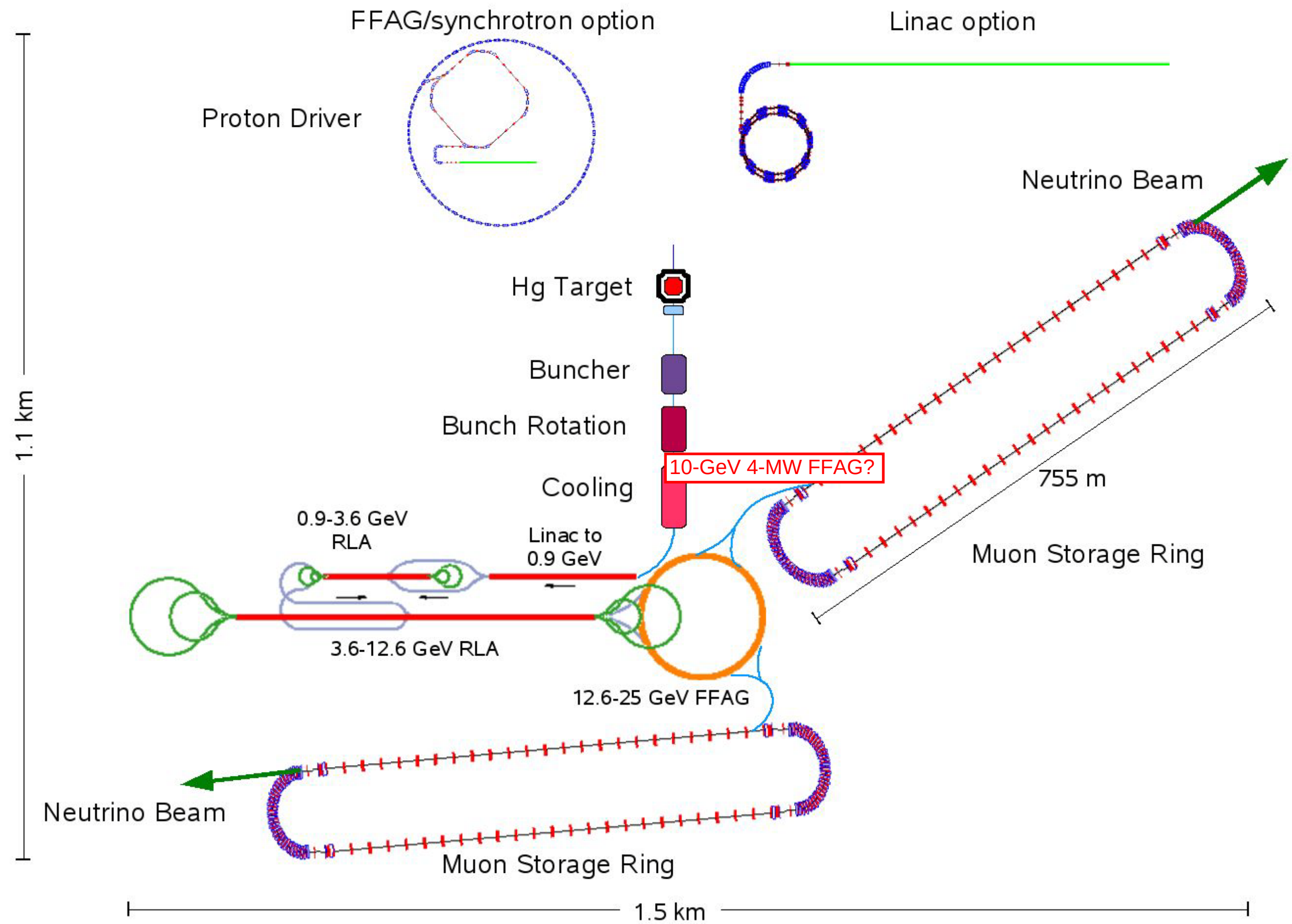
Non-scaling FFAGs using linear (i.e. constant-gradient) magnets offer :

- Greater momentum compaction (& hence narrower radial apertures);
- No high-order multipole field components to drive betatron resonances;
- Simpler construction.

NEUTRINO FACTORY – INTERNATIONAL DESIGN STUDY

Until March 2012 the IDS design included two non-scaling FFAGs:

- a high-intensity 10-GeV proton "driver"
- a 12.6-25 GeV muon accelerator



But then the Daya Bay reactors discovered a large ν mixing angle θ_{13}, lowering the optimum μ energy for ν production to 10 GeV – so for the final stage there's now a choice: 5-10 GeV FFAG, or 3-10 GeV RLA.

But for a few-TeV muon collider, NS-FFAGs are the only feasible option.

ELECTRON MODEL FFAG "EMMA"

A Proof of Principle machine for linear-B non-scaling FFAGs
to demonstrate their two novel features:

- Safe passage through many low-order structural resonances
- Acceleration outside buckets.

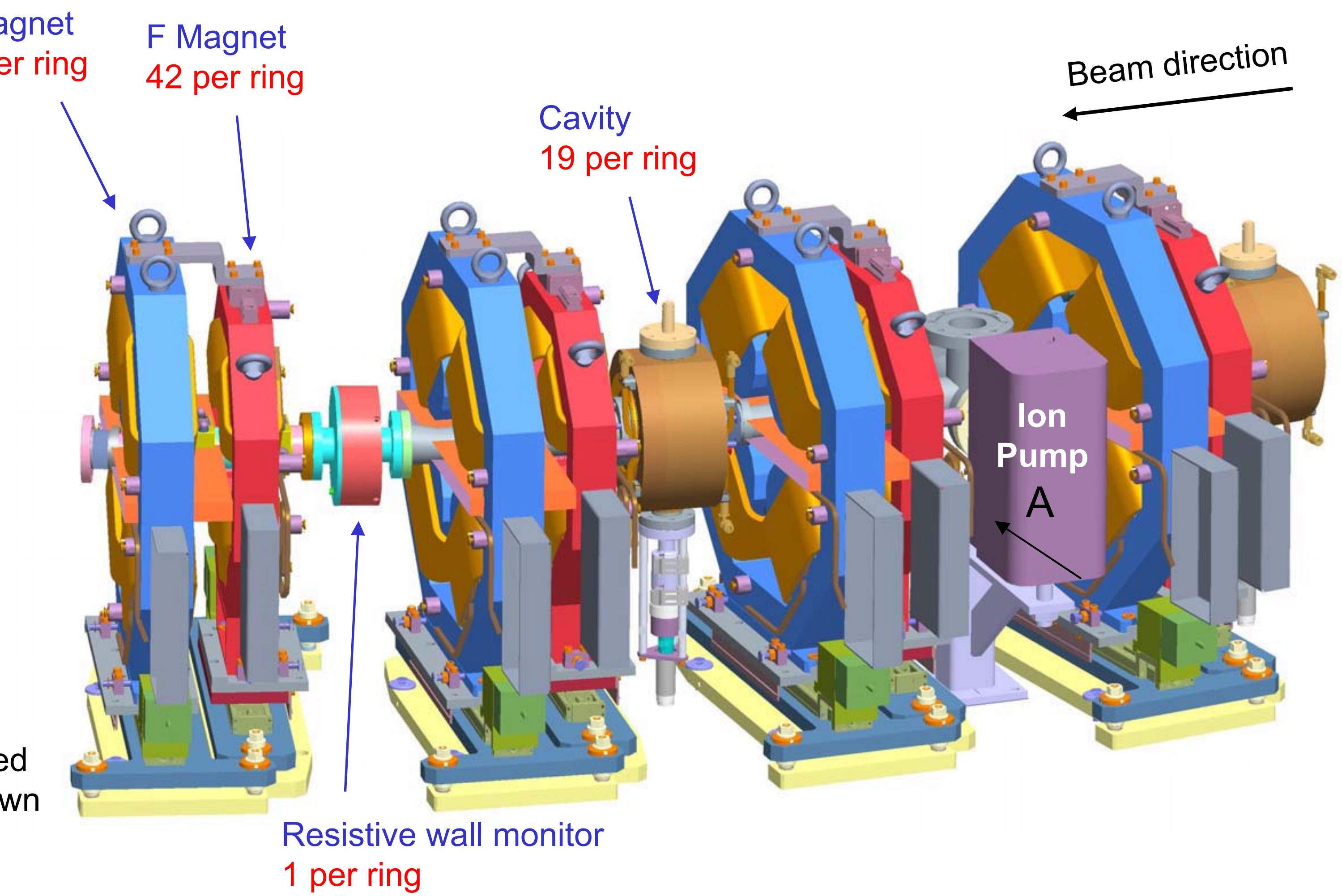
Studies have focused on an electron FFAG - with relativistic parameters similar to one for 10-20 GeV muons:

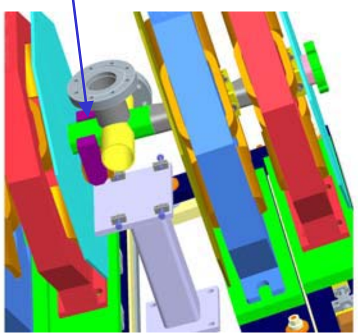
Energy	10-20 MeV
Circumference	15.9 m
Cells	42
B_{max}	0.2 T
F quad length	6.0 cm
D quad length	6.8 cm
RF frequency	1.3 GHz
Volts/cavity	19 kV

Daresbury Lab (UK) has offered lab space and a 7-35 MeV injector.
UK funding ($16M) started April 2007.
NSERC grant awarded to Canadian collaborators.

4 CELLS

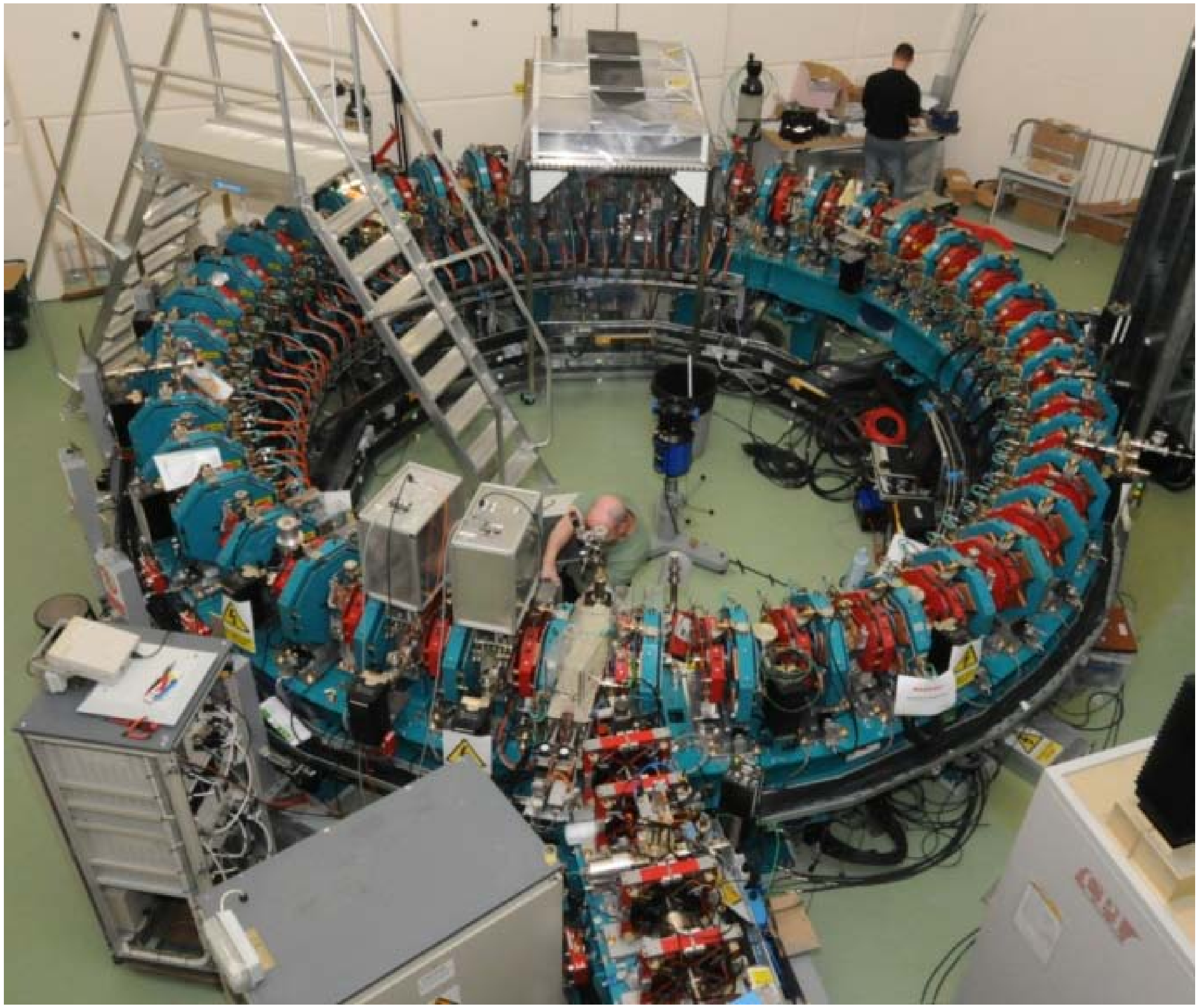
Without field clamp plates shown





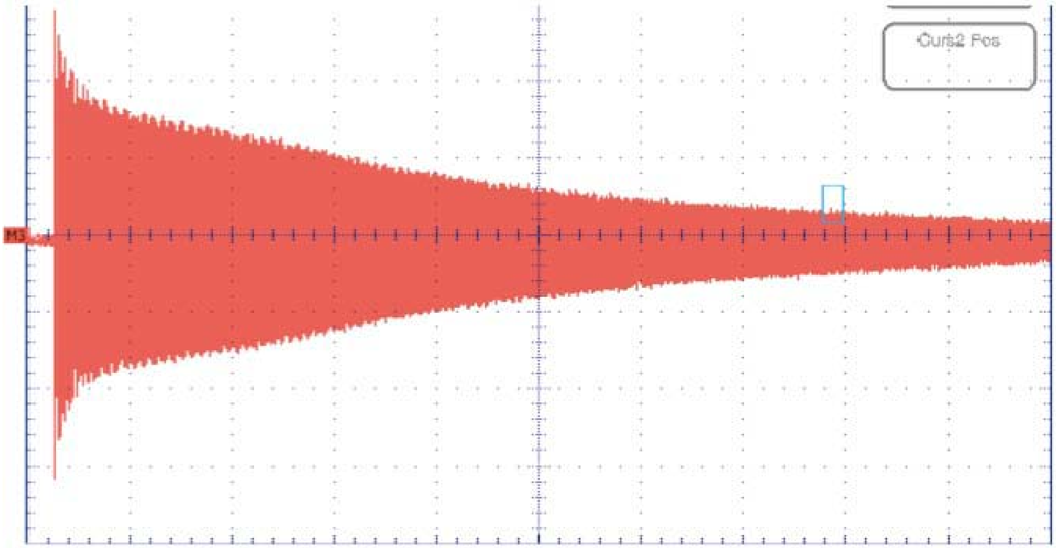
View on A
with Ion Pump removed
Field clamp plates shown

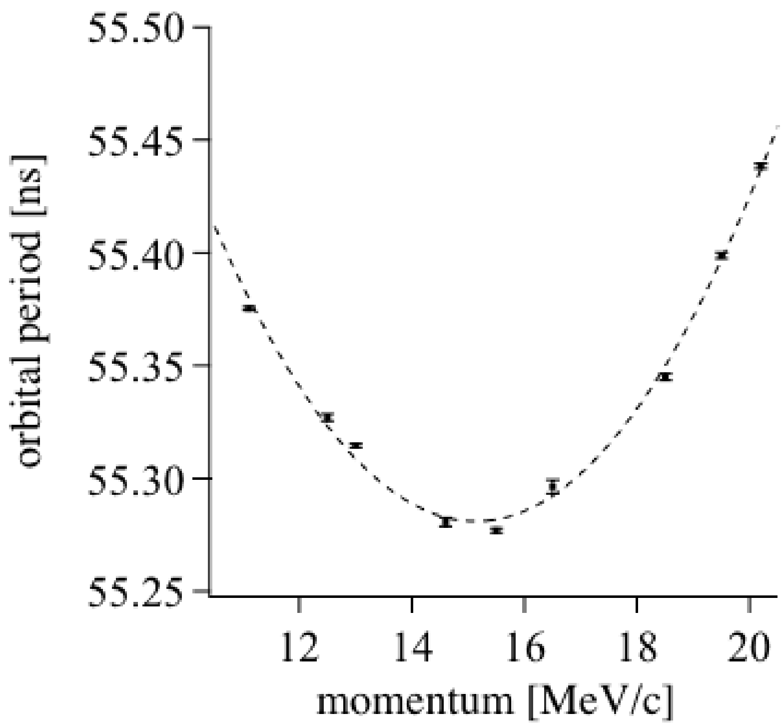
EMMA – THE FIRST NON-SCALING FFAG



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.

EMMA COMMISSIONING - 1

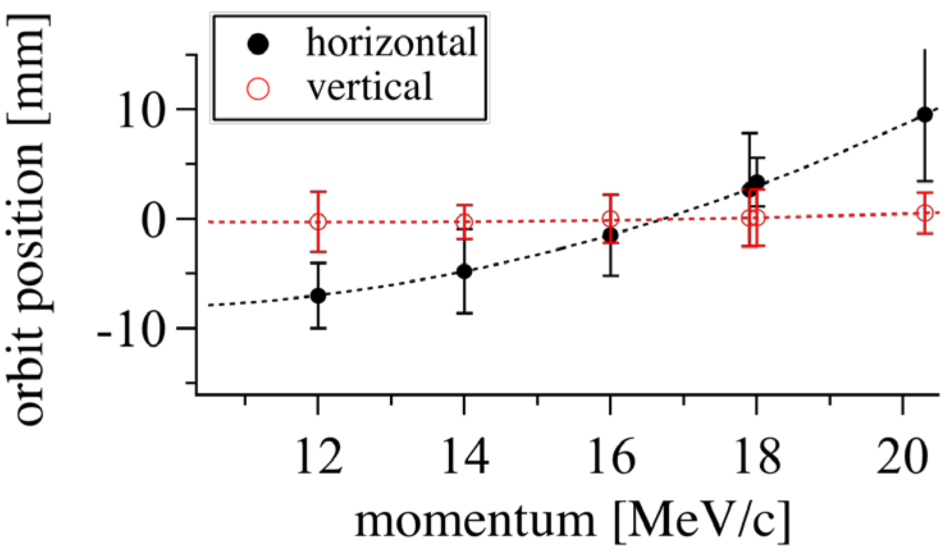


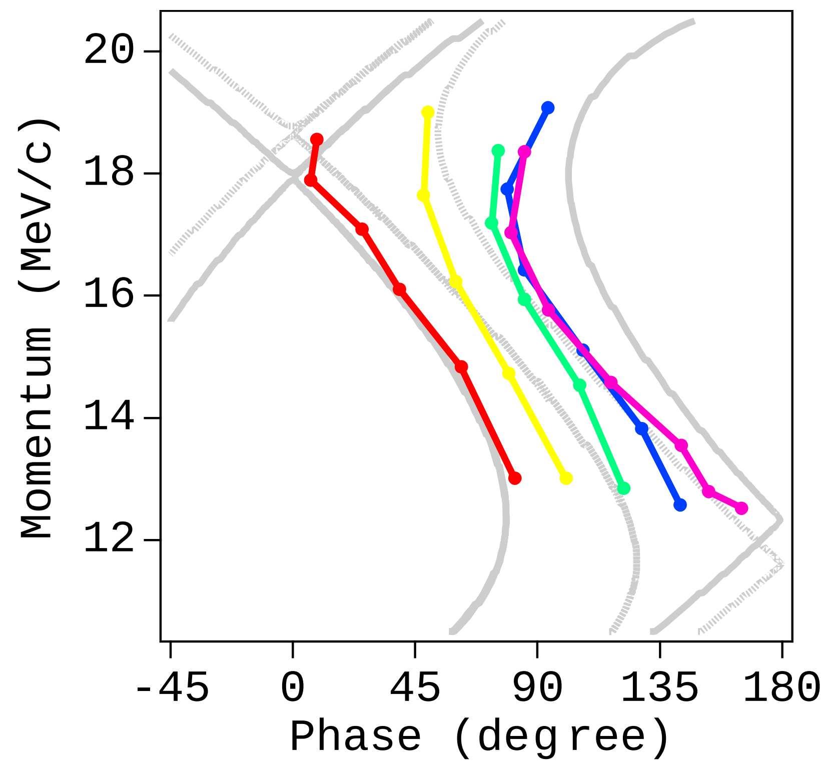


Left: Beam current v. time at fixed momentum (first observations of circulating beam show survival for > 1000 turns – August 2010).

Right: Orbital period v. momentum, showing the expected parabolic dependence.

EMMA COMMISSIONING - 2

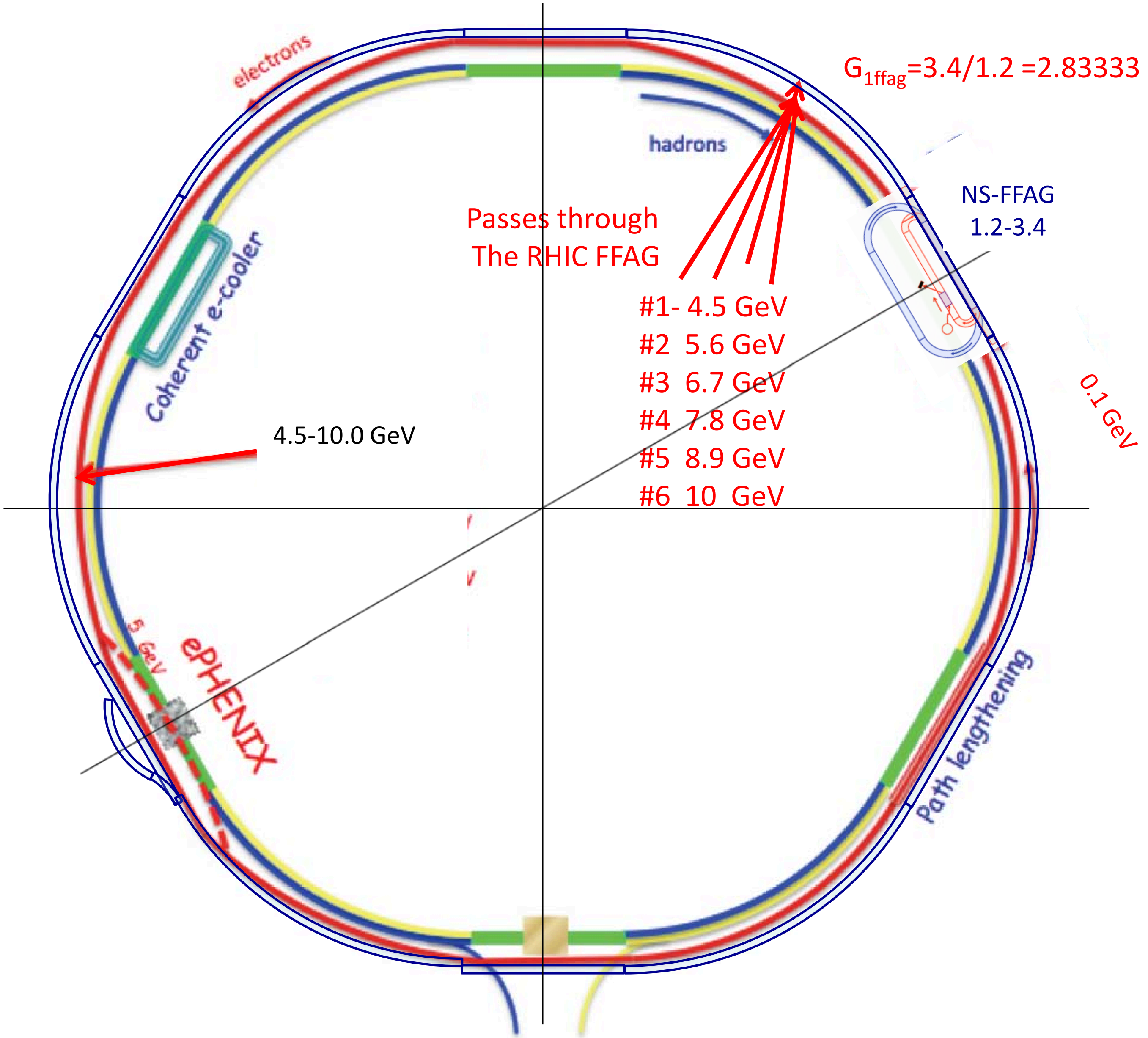




Left: Orbit position vs momentum

Right: Momentum versus rf phase, for 5 different initial phases (colour), compared to theoretical limits (grey).

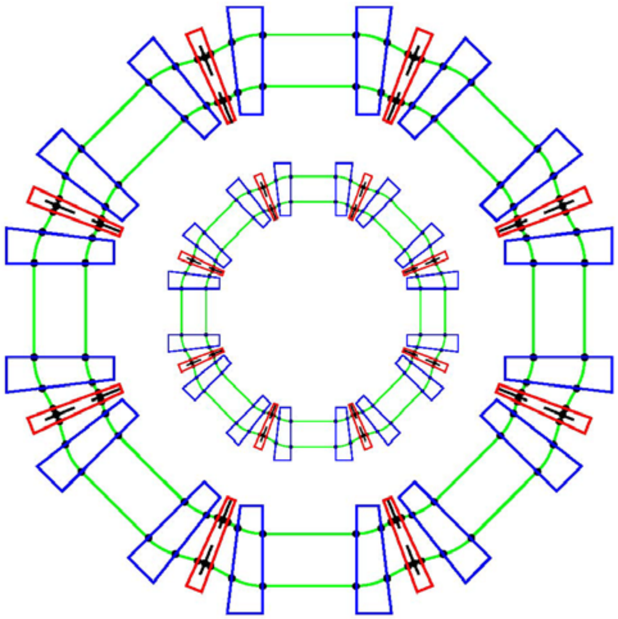
NS – FFAG's: 1.2→3.4 & 4.5→10 GeV



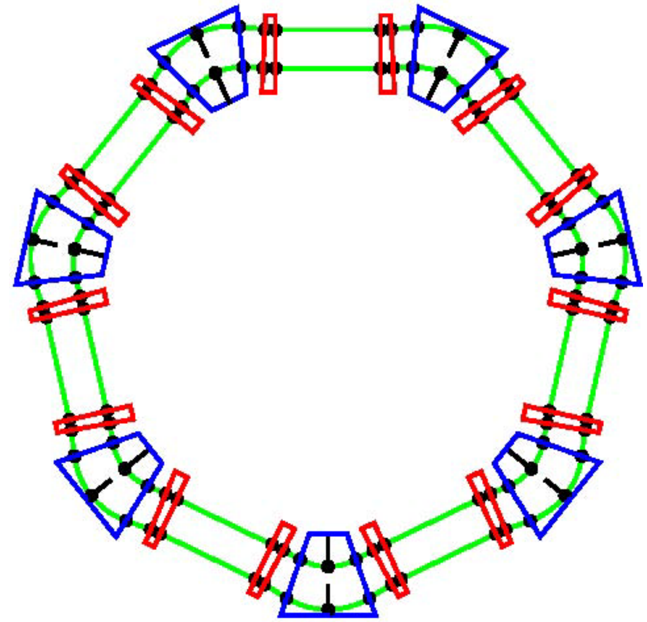
#2 FFAG	in li
11.1 GeV	→
12.2 GeV	→
13.3 GeV	→
14.4 GeV	→
15.6 GeV	→
16.7 GeV	→
17.8 GeV	→
18.9 GeV	→
20.0 GeV	→
21.1 Gev	→
22.2 GeV	→
23.3 GeV	→
24.4 GeV	→
25.5 GeV	→

NON-LINEAR NON-SCALING FFAGs

By using radial-sector magnets with non-linear fields, Rees (2004) and Johnstone (below, 2008-12) have been able to devise NS-FFAGs for GeV muons and ions that have constant tunes and are also isochronous.

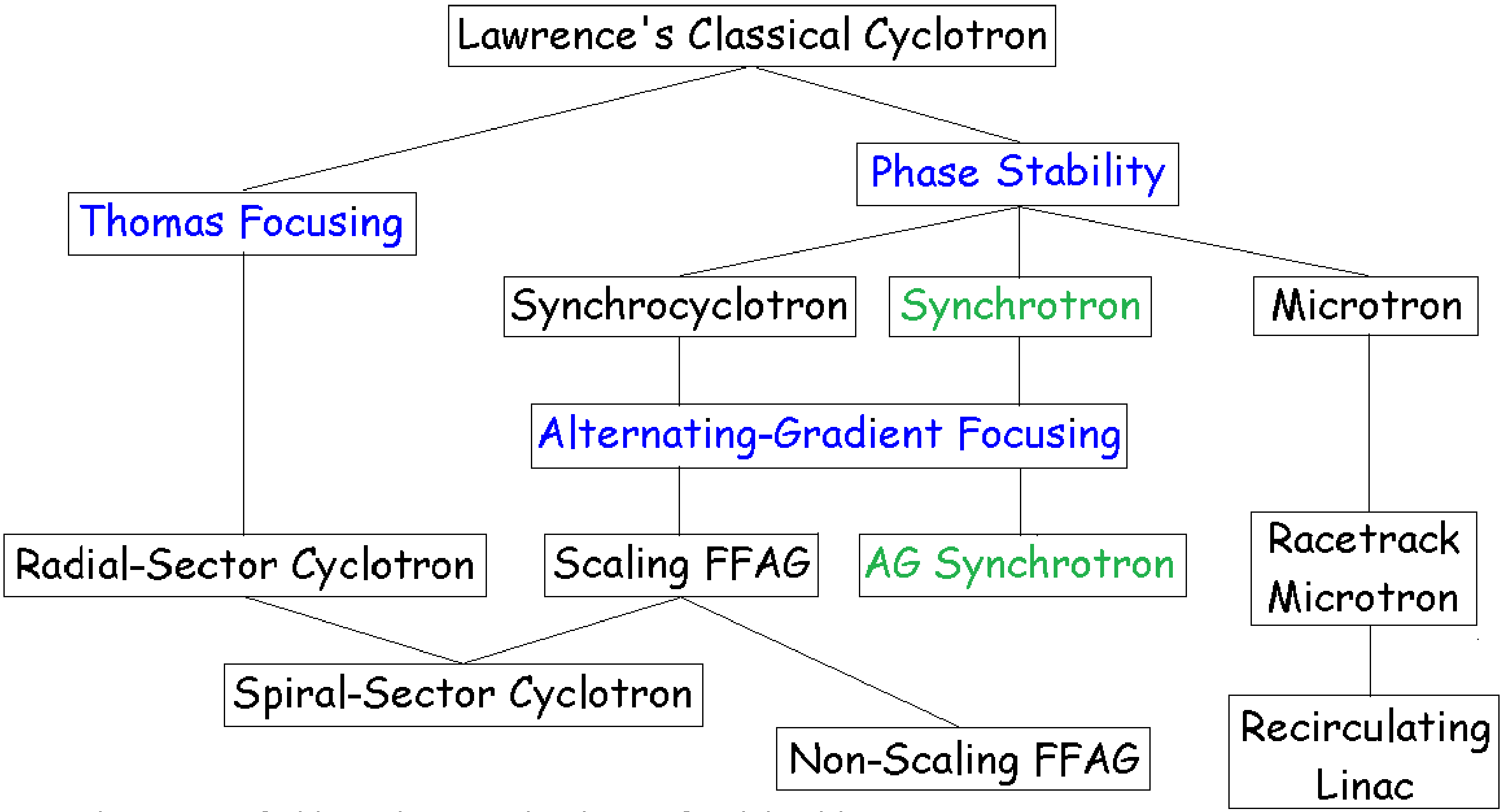


A pair of 8-cell-FDF rings form a multi-ion cancer treatment facility. The inner ring (orbit radii 2.75-3.39 m) takes protons from 30-250 MeV, and acts as injector to the outer ring (5.5-6.9 m) for carbon ions (68-400 MeV/u).



A 7-cell DFD ring for Accelerator-Driven Subcritical-Reactor (ADSR) operation. A high-intensity proton beam is accelerated from 0.33-1.0 GeV and from an injection radius of 4.35 m to an extraction radius of 5.13 m.

THE FAMILY TREE OF "CIRCULAR" RF ACCELERATORS



Fixed magnetic-field accelerators (cyclotron family) in black

Varying magnetic-field accelerators (synchrotron family) in green

http://trshare.triumf.ca/~craddock/PartAccel.pdf