Cyclotrons: Old but Still New

The history of accelerators is a history of inventions

William A. Barletta

Director, US Particle Accelerator School

Dept. of Physics, MIT

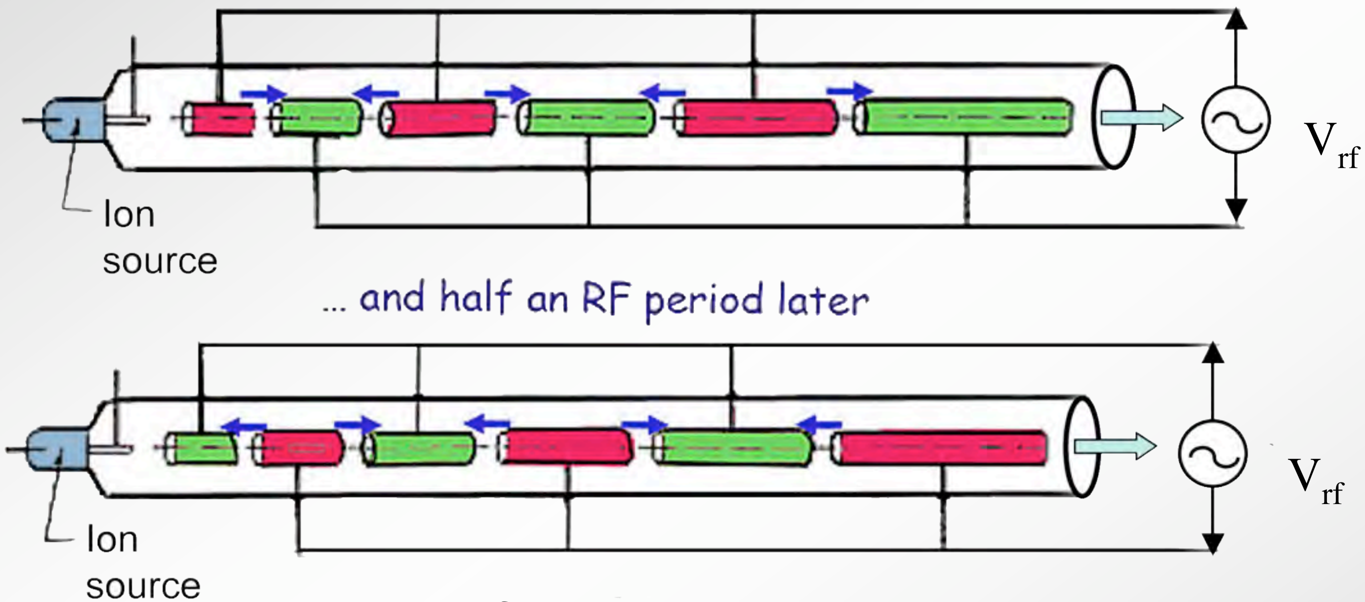
Economics Faculty, University of Ljubljana

~ 650 cyclotrons operating round the world

- Radioisotope production
  - >$600M annually
- Proton beam radiation therapy
  - ~30 machines
- Nuclear physics research
  - Nuclear structure, unstable isotopes,etc
- High-energy physics research?
  - DAEδALUS

Cyclotrons are big business

Cyclotrons start with the ion linac (Wiederoe)



Phase shift between tubes is 180°

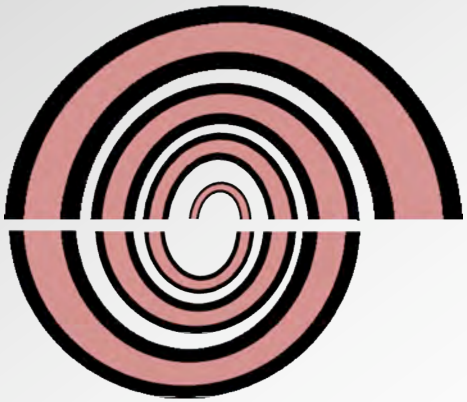
As the ions increase their velocity, drift tubes must get longer

$$L_{drift} = \frac{1}{2}\frac{v}{f_{rf}} = \frac{1}{2}\frac{\beta c}{f_{rf}} = \frac{1}{2}\beta\lambda_{rf}$$

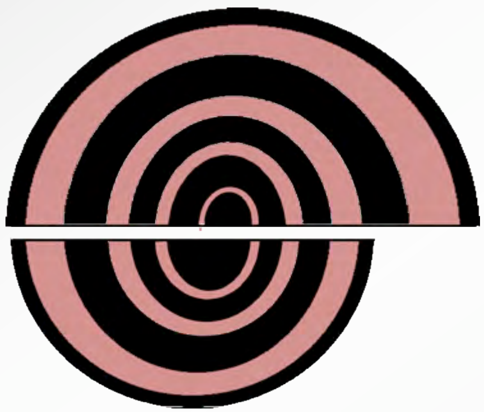
$E_{tot} = N_{gap} \bullet V_{rf}$ ==> ***High energy implies large size***

To make it smaller,
Let's curl up the Wiederoe linac…

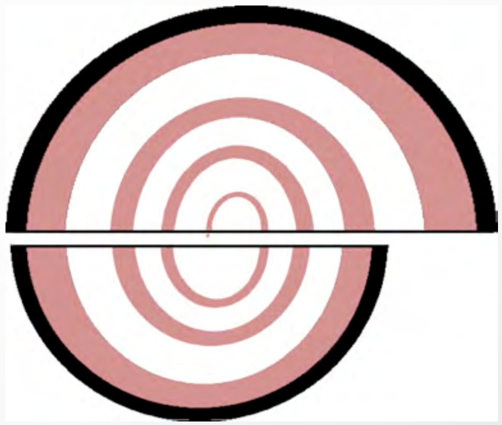
Bend the drift tubes



Connect equipotentials



Eliminate excess Cu

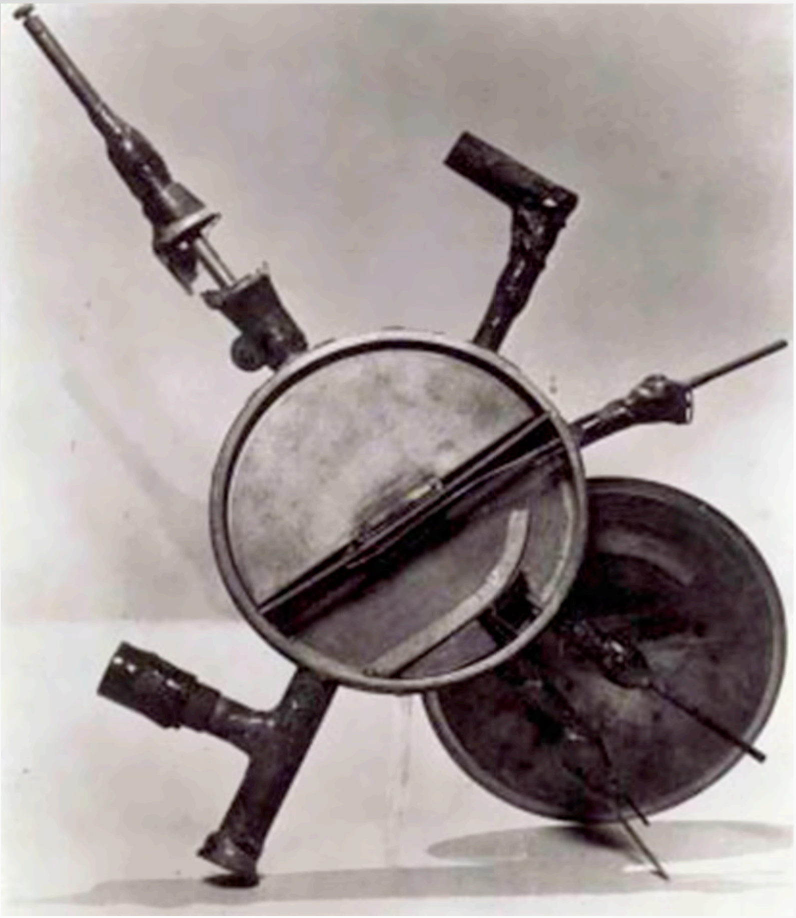


Supply magnetic field to bend beam

$$\tau_{rev} = \frac{1}{f_{rf}} = \frac{2\pi\, mc}{eZ_{ion}} \frac{\gamma}{B} \approx \frac{2\pi\, mc}{eZ_{ion} B} = const.$$

Orbits are isochronous, independent of energy

… and we have Lawrence's* cyclotron



The electrodes are excited at a fixed frequency (rf-voltage source)

Particles remain in resonance throughout acceleration

A new bunch can be accelerated on every rf-voltage peak:

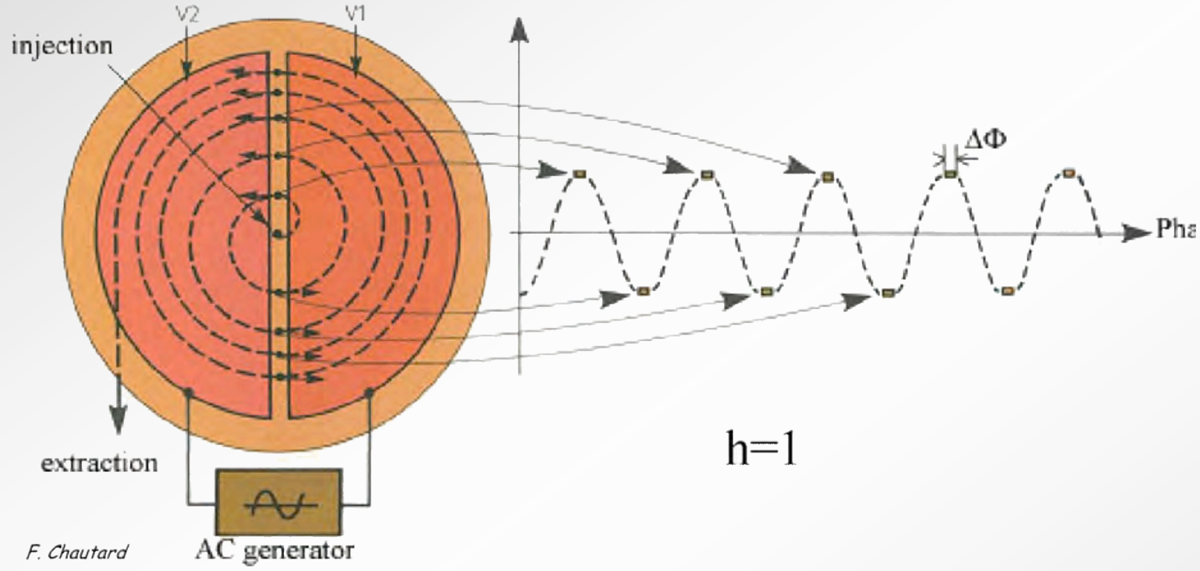
===>
"continuous-wave (cw) operation"

Lawrence, E.O. and Sloan, D.: Proc. Nat. Ac. Sc., 17, 64 (1931)

Lawrence, E.O. & Livingstone M.S.: Phys. Rev 37, 1707 (1931).

* The first cyclotron patent (German) was filed in 1929 by Leó Szilard but never published in a journal

Synchronism only requires that $\tau_{rev} = N/f_{rf}$



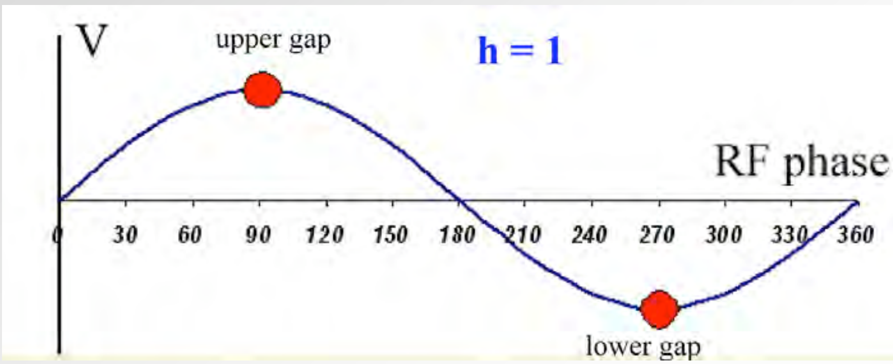
"Isochronous" particles take the same revolution time for each turn.

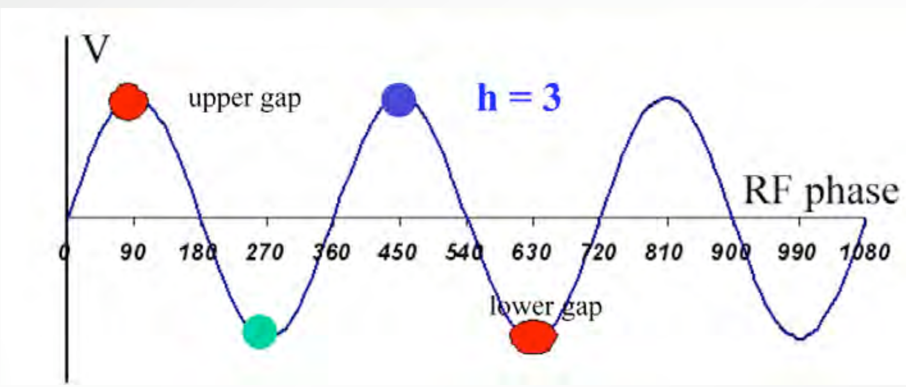
If $\omega_{rf} = h\ \omega_{rev}$, where h ("harmonic number") is an integer, the particle is in resonance with the RF wave.

For gaps 180° apart, any odd integer will work (h = 1, 3, 5,……).

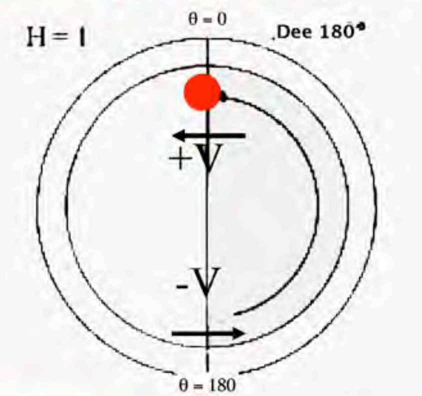
Source: F. Chautard

Harmonic motion allows more bunches in the cyclotron ==> increased beam current

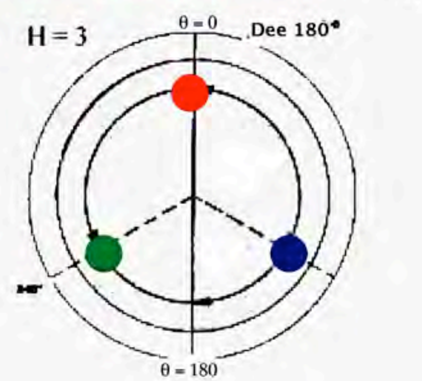




1 bunch per turn $\omega_{rf} = \omega_{rev}$



3 bunches per turn $\omega_{rf} = 3\omega_{rev}$



For the same rf frequency the beam goes 3 times slower

Source: F. Chautard

Harmonics are useful for heavy ions

- Let Charge = Qe & Mass =Am_a, where m_a = 1 a.m.u.
- The cyclotron equation becomes

$$\boxed{\omega_{rf} = h\omega = h\left(\frac{Q}{A}\right)\left(\frac{e}{m_a}\right)B}$$

- RF systems have a limited bandwidth.
  - If Q/A < 1, one can go to h > 1
- Maximum kinetic energy T (non-relativistic) is $T = \frac{m}{2}\omega^2 r_{\max}^2 = \frac{Am_a}{2}\left(\frac{Q}{A}\frac{eB}{m_a}\right)^2 r_{\max}^2$

$$\boxed{\frac{T}{A} = \frac{(eBr_{\max})^2}{2m_a}\left(\frac{Q}{A}\right)^2 = K\left(\frac{Q}{A}\right)^2}$$

- The "K-factor" characterizes the bending power of the magnet

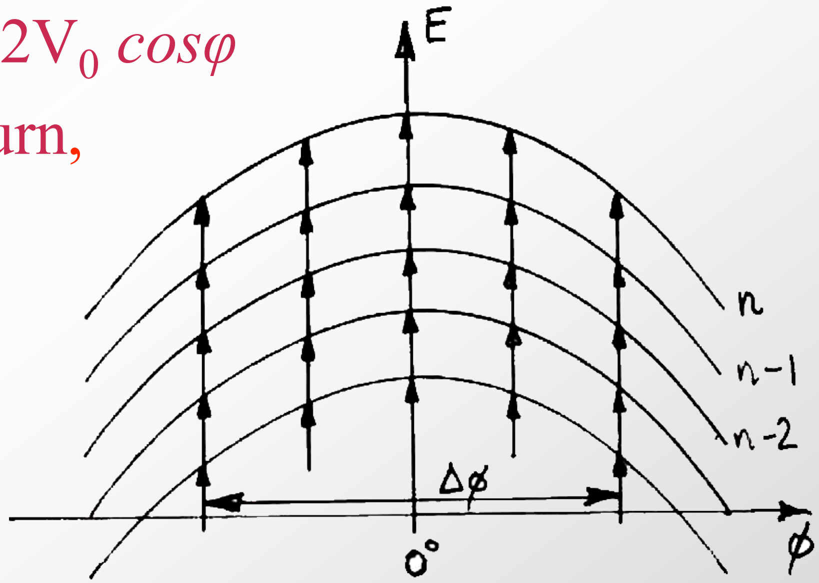
Longitudinal motion in cyclotrons

- **Isochronism** ==> all ions have equal orbit time independent of energy.

  ∴ ions arrive at the gap at the same rf phase φ on every turn

- If the voltage across the gap is $2V_0 \cos\varphi$ & if there are 2 crossings per turn, then after n turns

$$\boxed{E_n = 4nqV_0 \cos\varphi}$$



- In ideal cyclotrons, there is
  - no phase wander
  - no phase focusing ===>

Energy spread in the beam

Source: M. Craddock

Control of energy spread

- In principle, all phases $-\pi/2 < \varphi < \pi/2$ can be accelerated
  - Larger $|\varphi|$ requires larger n for a given energy, leading to:
    - greater exposure to field imperfections
    - lower beam quality & greater losses
- In practice, phase spread in beams $\Delta\varphi \leq 40°$
  - good beam quality
  - low losses
  - better turn separation
- Select $\Delta\varphi$ in the central region:
  - artificially by slits
  - naturally by obstacles
  - naturally by electric focusing

Source: M. Craddock

Why doesn't the beam fall out of the machine?
Transverse focusing keeps the beam together

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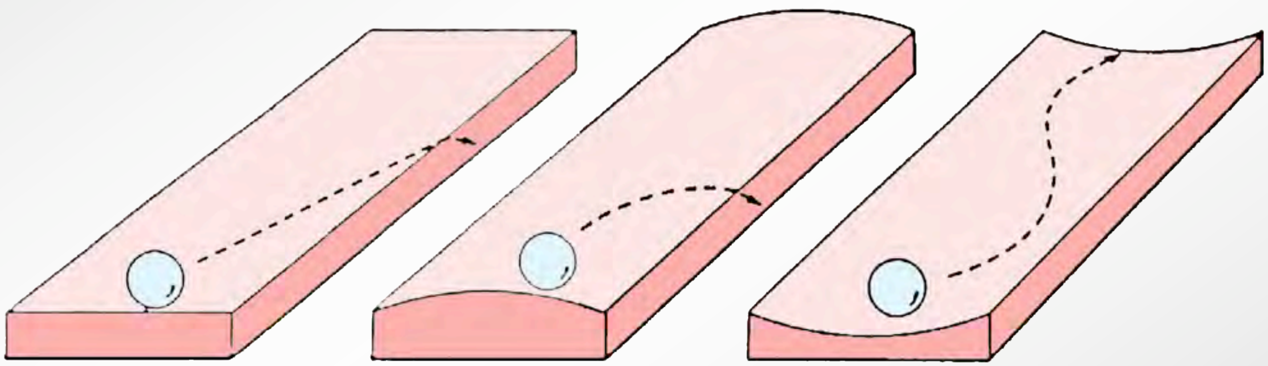
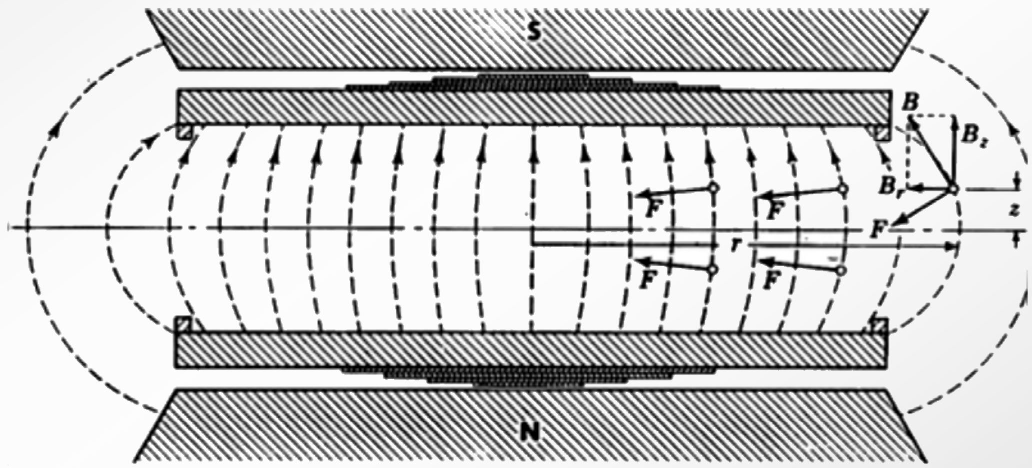
- E or B fields provide restoring forces to stabilize particle orbits
- Similarly, "defocusing" refers to situations with unstable orbits.



Bowling alley analogy of systems of forces which produce neutral, unstable, and stable orbits

What does focusing have to do with beam intensity?

- Early cyclotron builders found that the beam kept hitting the upper & lower pole pieces with a uniform field
- They added vertical focusing of the circulating particles by sloping magnetic fields, from inwards to outwards radii



- At any time, $\langle B_{vertical} \rangle$ sensed during a particle revolution is larger for smaller radii of curvature than for larger ones

Orbit stability via weak focusing

- Focusing in the vertical plane is provided at the expense of weakening horizontal focusing
- Suppose along the mid-plane varies as

$$B_y = B_o/r^n$$

- $n = 0$ ==> a uniform field with no vertical focusing
- For $n > 1$, B_y cannot provide enough centripital force to keep the particles in a circular orbit.

Cross section of weak focusing circular accelerator

For stability of the particle orbits we want $0 < n < 1$

This approach works well
until we violate the synchronism condition

- Recall that

Synchronism condition: $\Delta\tau_{rev} = N/f_{rf}$

and

$$\tau_{rev,o} = \frac{2\pi\, mc}{e}\frac{\gamma}{B} \approx \frac{2\pi\, mc}{eB}$$

- What do we mean by violate?
  - Any generator has a bandwidth Δf_{rf}

- Therefore, synchronism fails when

$$\tau_{rev,n} - \tau_{rev,o} = \frac{2\pi\, mc}{e}\frac{(\gamma_n - 1)}{B} \approx \Delta f_{rf}$$

The Lawrence cyclotron has a maximum energy

An obvious invention fixes this problem:
Change f_{rf} ==> the synchro-cyclotron

- For B = constant, to maintain synchronism

$$f_{rf} \sim 1/\gamma(t)$$

- The energy for an ion of charge Z follows from $\frac{1}{r} = \frac{ZeB}{cp}$

But this requires pulsed rather than CW operation
(one bunch in the machine at a time)

==> Average current is reduced by the number of turns to full energy (~1000x) to ~ 0.1 μA

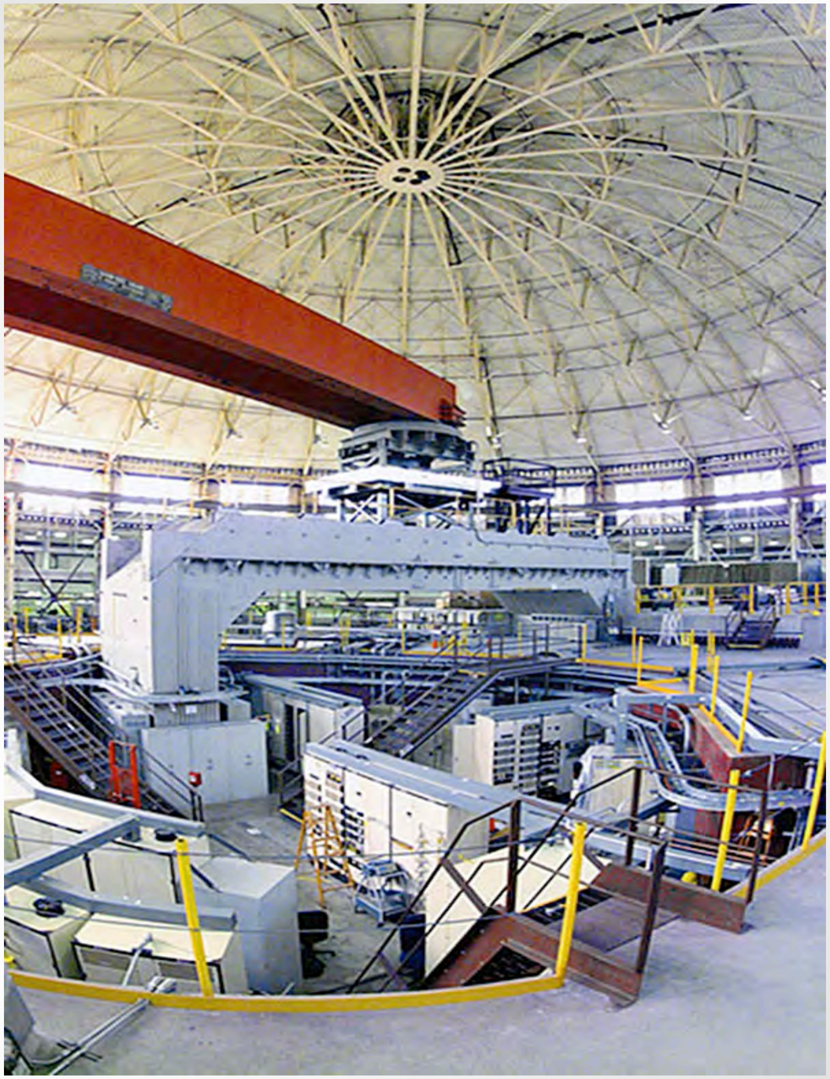
Ex: Lawrence's 184-in cyclotron

R_{max} = 2.337 m

B = 1.5 T

M_{yoke} ≈ 4300 tons !!

Just how large is a 4300 ton yoke?

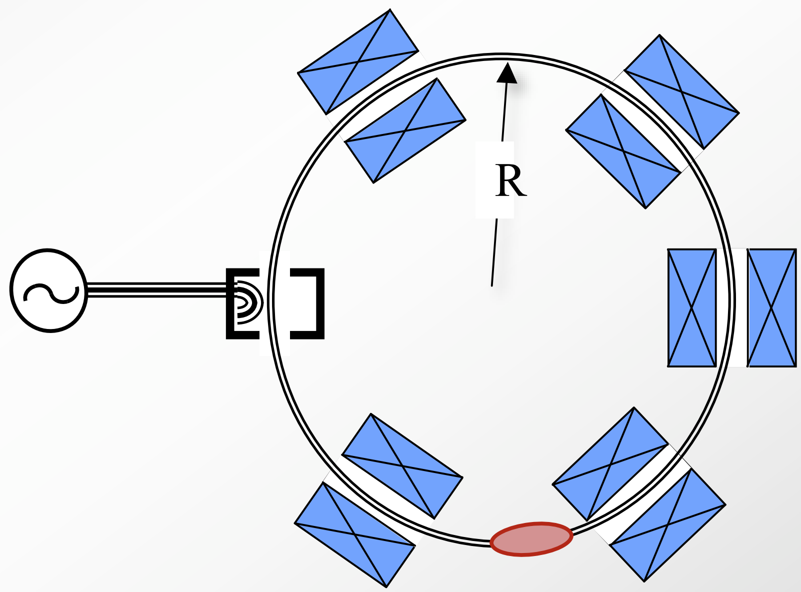


The synchrotron introduce two new ideas: Change B_{dipole} & Change ω_{rf}

- For low energy ions, f_{rev} increases as E_{ion} increases
- ==> Increase ω_{rf} to maintain synchronism
- For any E_{ion}, circumference must be an integral number of rf wavelengths

$$C = h\,\lambda_{rf}$$

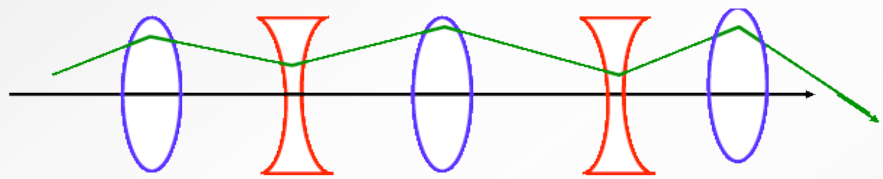
- h is the harmonic number



$$C = 2\pi R$$

$$f_{rev} = 1/\tau = v/C$$

Add another great invention to synchrotrons: separate the focusing magnets from bending



The magnets get much smaller, but…

Like the synchrocyclotron only one $E_{particle}$ is in the machine at any given time

==> Reduced average intensity persists

BUT when relativity becomes important…

- Isochronism in the classical cyclotron & the Lorentz factor

$$\gamma = E_{tot}/m_o$$

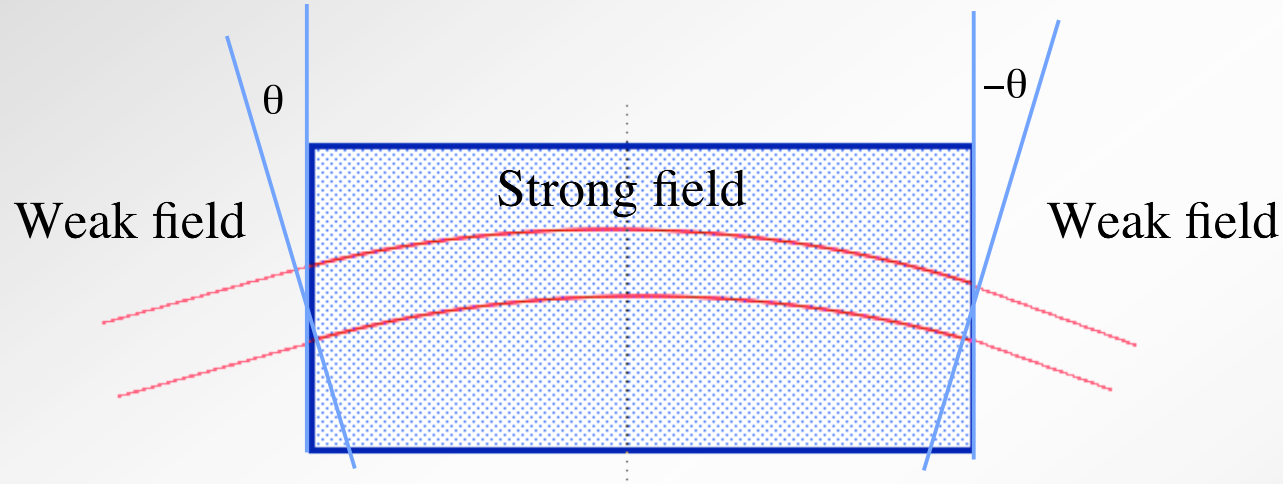
- Then

$$\boxed{\omega_{rev} = \frac{Q\,B(r)}{m_o \gamma(r)}}$$

- Therefore, ω_{rev} = constant ==> $B(r) = \gamma(r)\, B_o$ (i.e., $\mathbf{n < 0}$)

Not compatible with a decreasing field for vertical focusing

High intensity beams need non-time-varying focusing
Dipole fields can focus beams



If the transition from a weak field to a strong field

is not orthogonal to trajectory the beam can be focused

"Edge focusing"

Relativistic, fixed field accelerators
enable higher average currents via edge focusing

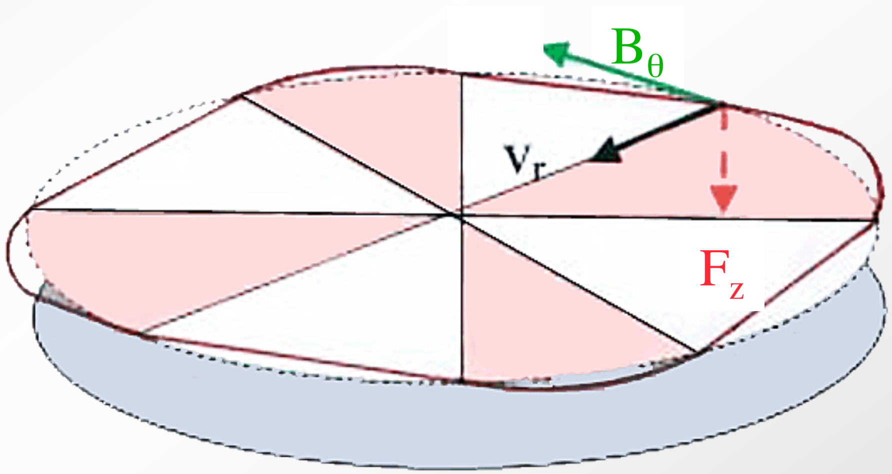
Adding extra vertical edge focusing yields

- Sector-focusing or ISOCHRONOUS cyclotrons
  - An azimuthally varying magnetic field => edge focusing
    - counters the vertical defocusing of isochronous positive dB/dr
    - proposed by Thomas (1938)
    - demonstrated by Richardson et al. (1950)
    - CW operation, high beam intensity

Source: M. Craddock

Vertical (Thomas) focusing (1938)

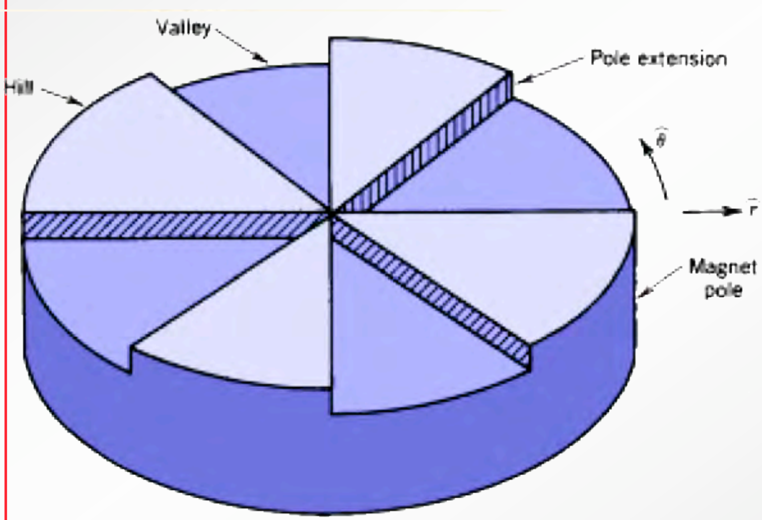
- We need to find a way to increase the vertical focusing
- One can obtain $\mathbf{F_z}$ with $\mathbf{v_r}$, $\mathbf{B_\theta}$
- ==> find an azimuthal component $\mathbf{B_\theta}$ & a radial velocity component $\mathbf{v_r}$
- ==> a non-circular trajectory

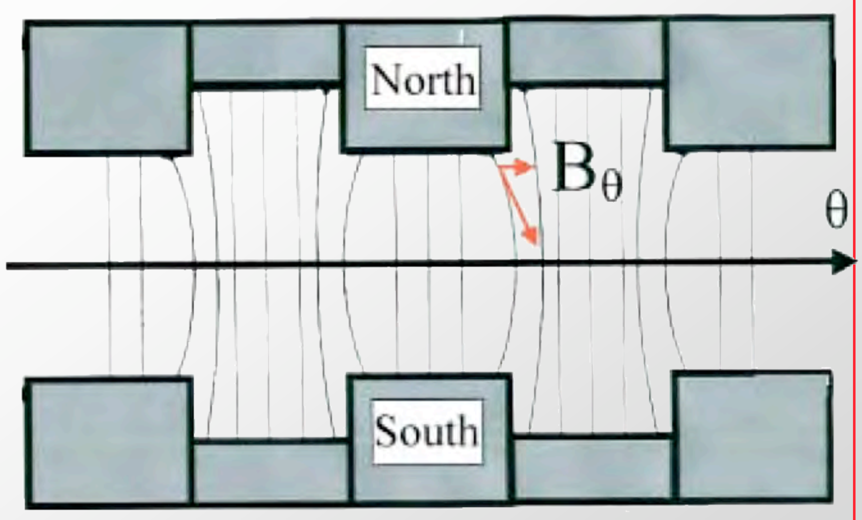


===> Sectors

Azimuthally varying fields ==> B_θ

- B_θ created with :
  - Succession of high field and low field regions
  - B_θ appears around the median plane
- Valley : large gap, weak field
- Hill : small gap, strong field

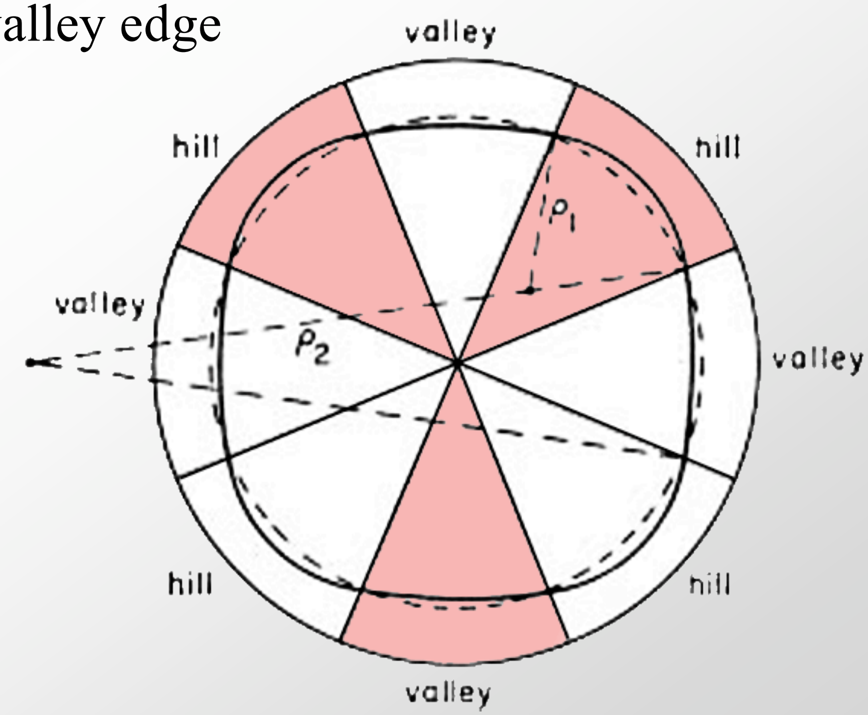




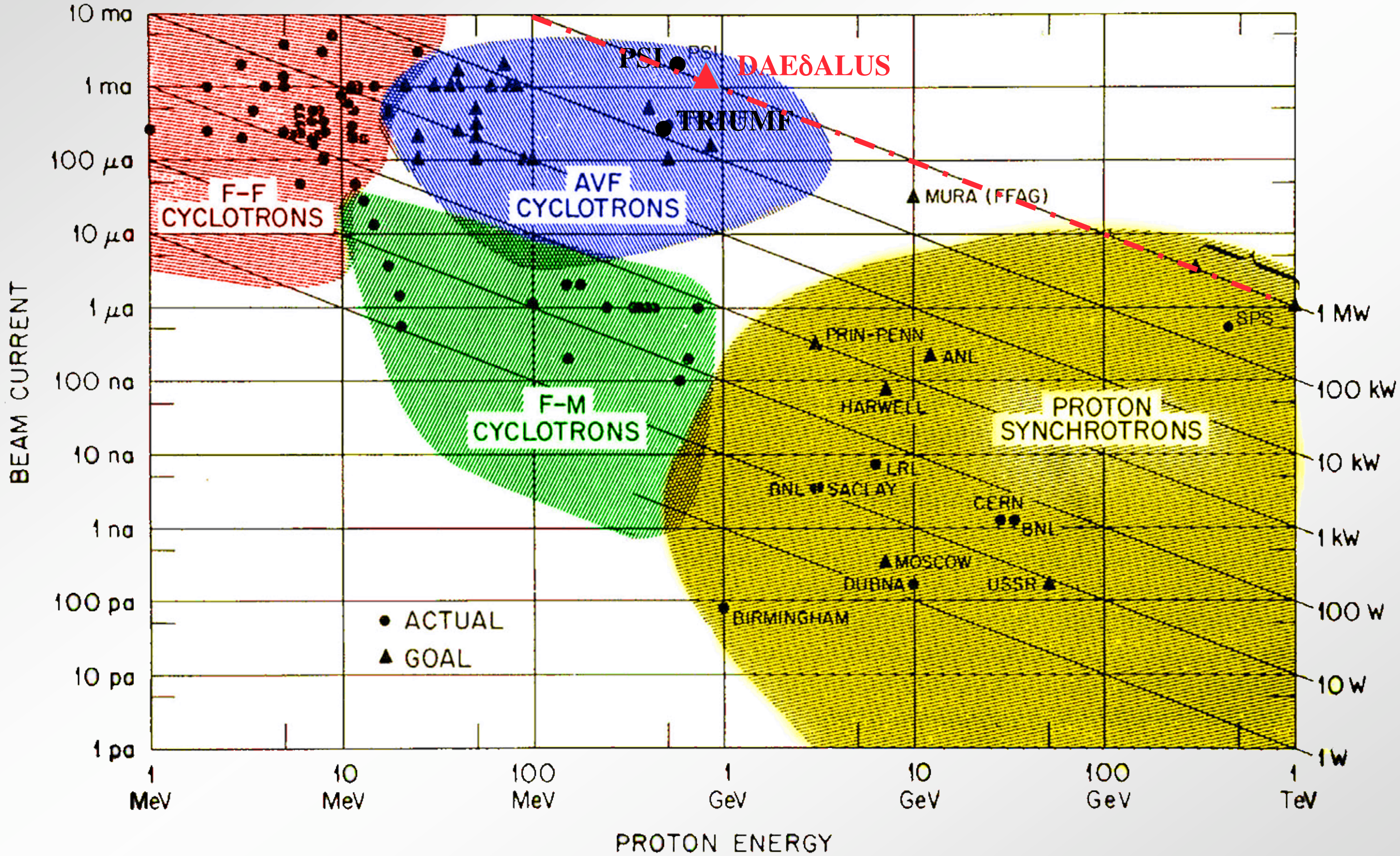
Creation of radial velocity component: v_r

- Valley : weak field, large trajectory curvature
- Hill : strong field, small trajectory curvature ==>
  - Trajectory is not a circle
  - Orbit not perpendicular to hill-valley edge
- ==> Vertical focusing:

$$F_z \sim v_r \times B_\theta$$



Average current vs. beam energy
for circular accelerators



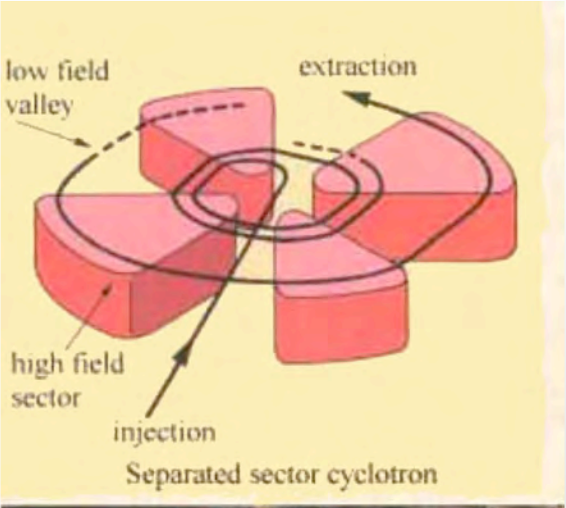
CW cyclotrons provide ~1000x higher beam currents than pulsed ones

Source: M. Craddock

In the extreme let B in the valley go to zero: Separated-sector cyclotron

- First proposed by Hans Willax (1962) for the Swiss meson factory - a 590-MeV proton ring cyclotron
- In separate-sector cyclotrons:
  - sectors have individual yokes & coils
  - valleys are magnetic field-free
    - available for rf, injection, extraction & diagnostics
- Small pole gaps need fewer amp-turns
  - give hard-edge fields
    - the flutter, $F^2 = H^{-1} - 1$ can reach ~1

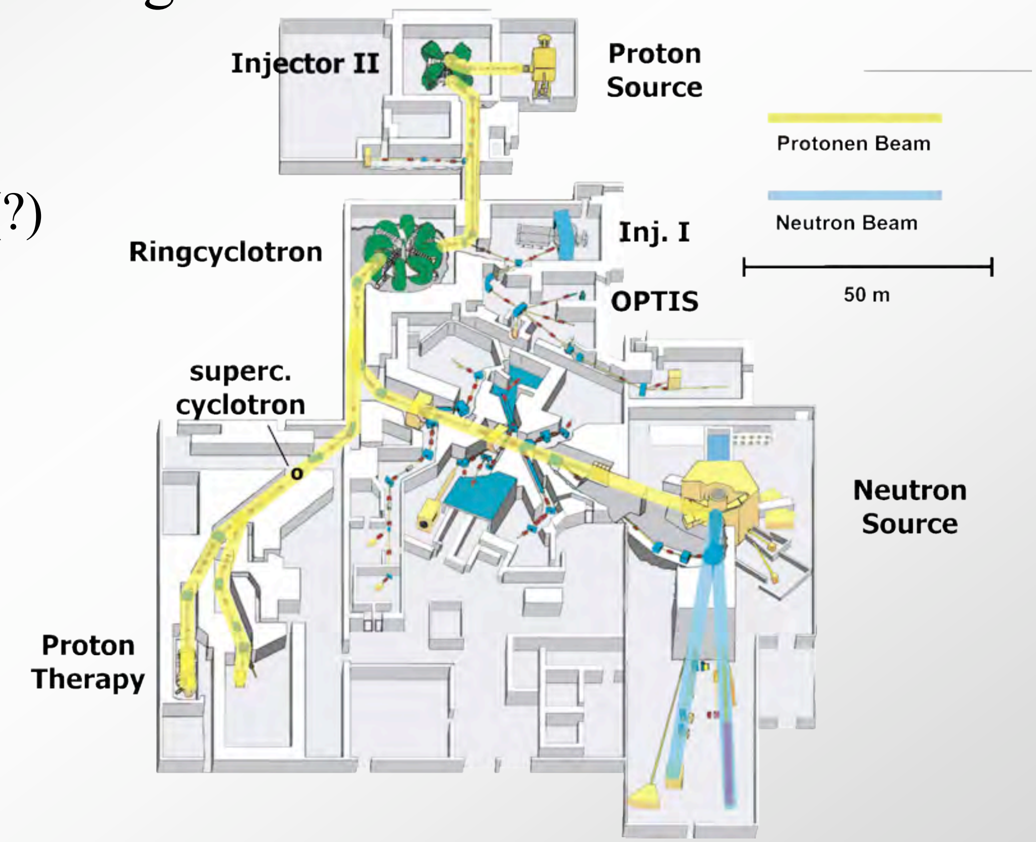
    (where H = hill fraction),
  - Makes possible *βγ ~1* (~400 MeV /u) with radial sectors).
- Needs a medium-energy injector



Source: M. Craddock

PSI cyclotron provides 1.3 MW of protons

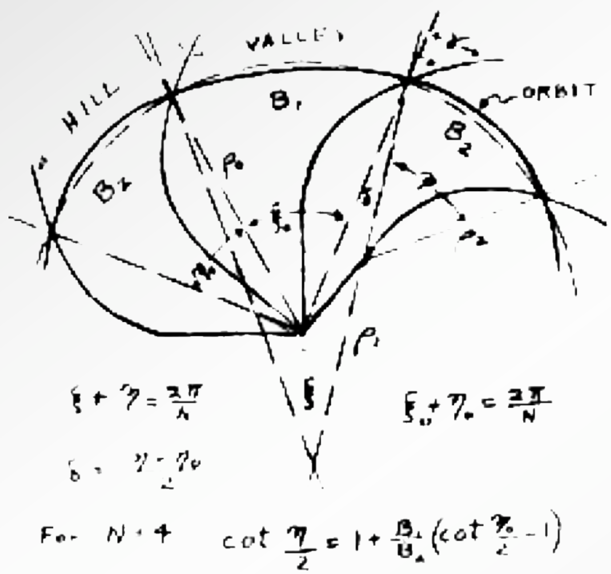
- Characteristics of the PSI design
  - Large
  - 580 MeV, 1.8 mA
  - ~300 - 500 M$ per copy (?)
  - High efficiency (~40%)
  - Very low losses (0.01%)
  - Complex for flexibility
- Primary uses
  - Spallation neutron source
  - Medical therapy

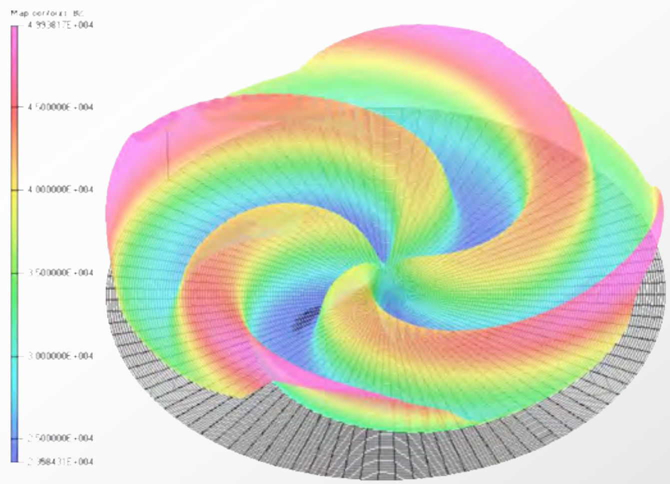


Are there other cyclotron approaches at the 1 MW level?

Sectors need not be symmetric
(D. Kerst, 1954)

- Tilting the edges (θ angle)
  - Valley-hill transition becomes more focusing
  - Hill-valley transition is less focusing





By the strong focusing principle (larger betatron amplitude in focusing, smaller in defocusing)

Net effect of spiraled sectors is focusing

TRIUMF - 520 MeV proton cyclotron
(lower half of main magnet)

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The diameter of the machine is about 18 m

PSI design of spiral-arm ring cyclotron for Accelerator Driven Sub-critical Reactor

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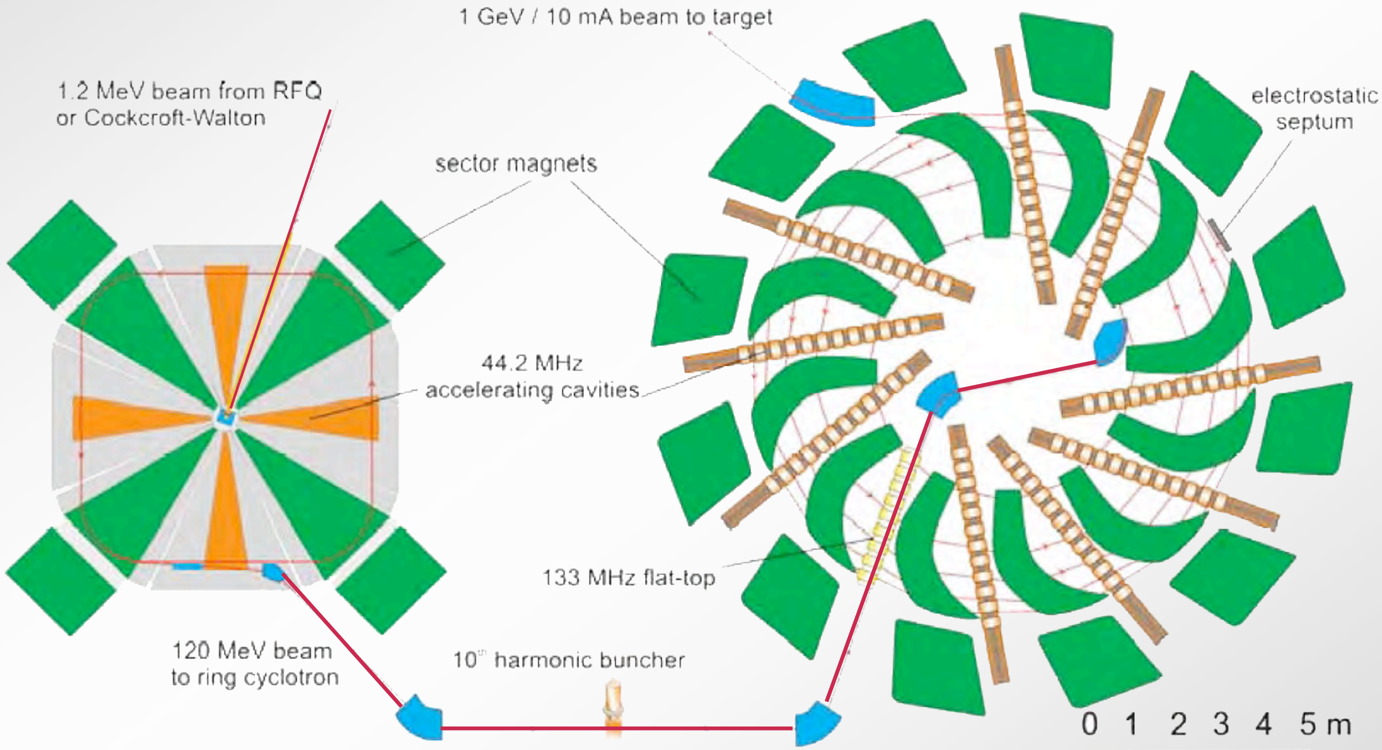
- Scaled-up PSI 70-MeV injector & 590-MeV ring cyclotron to produce 10-mA 1-GeV proton beam for ADSR



Indian designs for thorium-based reactor (k_{eff} ~0.98) require 1 - 2 MW for 750 MW_{th} reactor

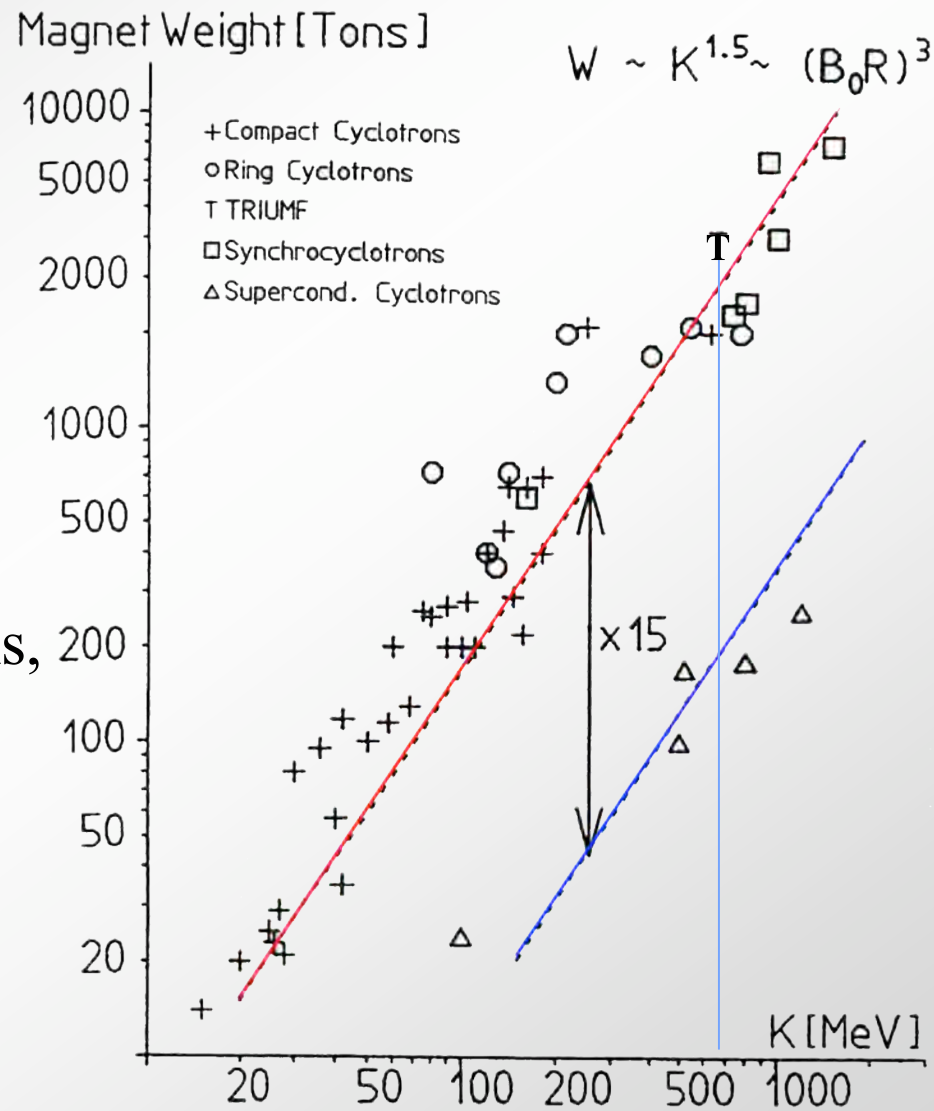
Basic functions of ADS sub-systems
Accelerator coupled to Reactor

- ❖ Proton accelerator
  - ➢ MW-class beam of ~ 1 GeV protons
- ❖ Spallation Target
  - ➢ Molten high-Z material
  - ➢ Neutrons emitted in nuclear reaction induced by high-energy protons
  - ➢ Materials resistant to neutron irradiation & liquid metal corrosion at high-temperature
- ❖ Sub-critical reactor
  - ➢ Operates through continuation of self-terminating fission chains,
    - each triggered by spallation neutron or its derivative neutrons
- ❖ Attributes:
  - ➢ Inherently safe
  - ➢ No restriction on fuel type
    - less dependence on delayed neutrons
  - ➢ Well suited for long-lived minor actinide incineration

Source: Banerjee

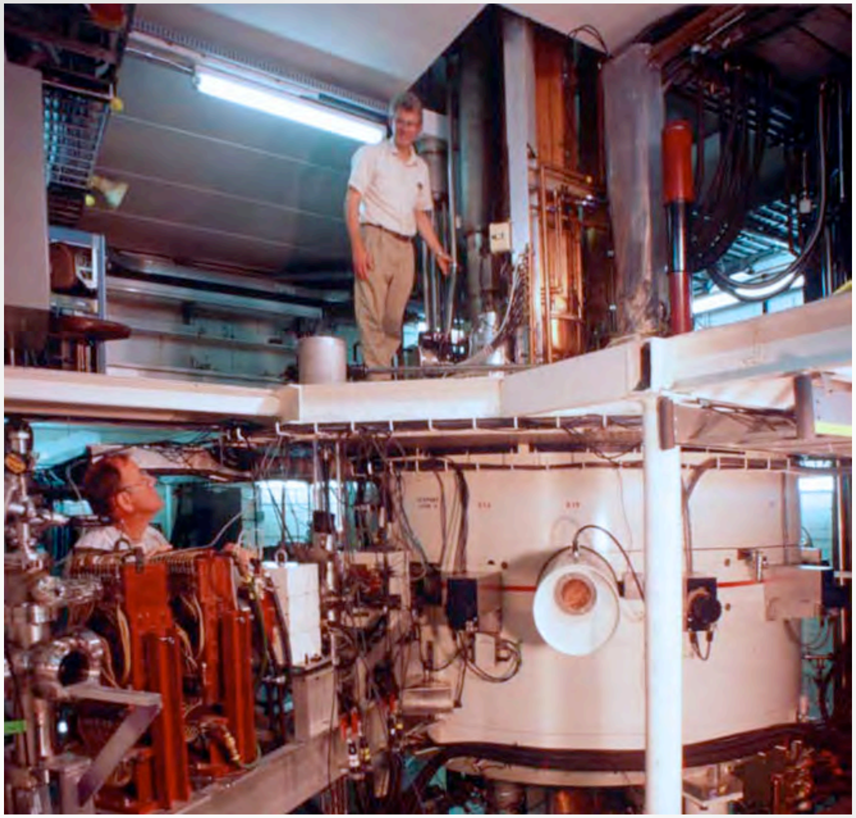
But these machine are huge
Why superconducting cyclotrons?

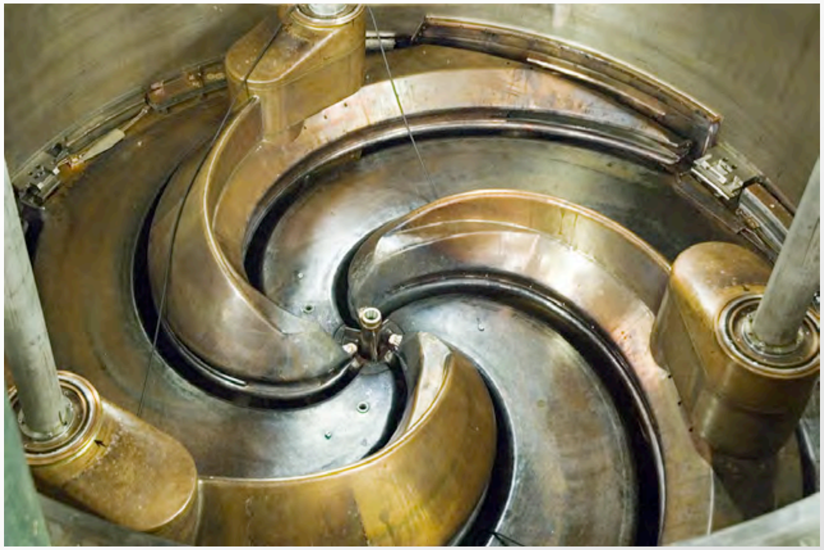
- Superconducting coils allow:
  - increased magnetic field strength & reduced size
  - reduced electrical power hence
  - **==> Reduced cost**
- Plot shows the weight of steel in various cyclotrons, roughly ∝ (radius)^3
- For given energy, SC magnets weigh ~ 1/15 of resistive-coil magnets



K500 Superconducting cyclotron at MSU

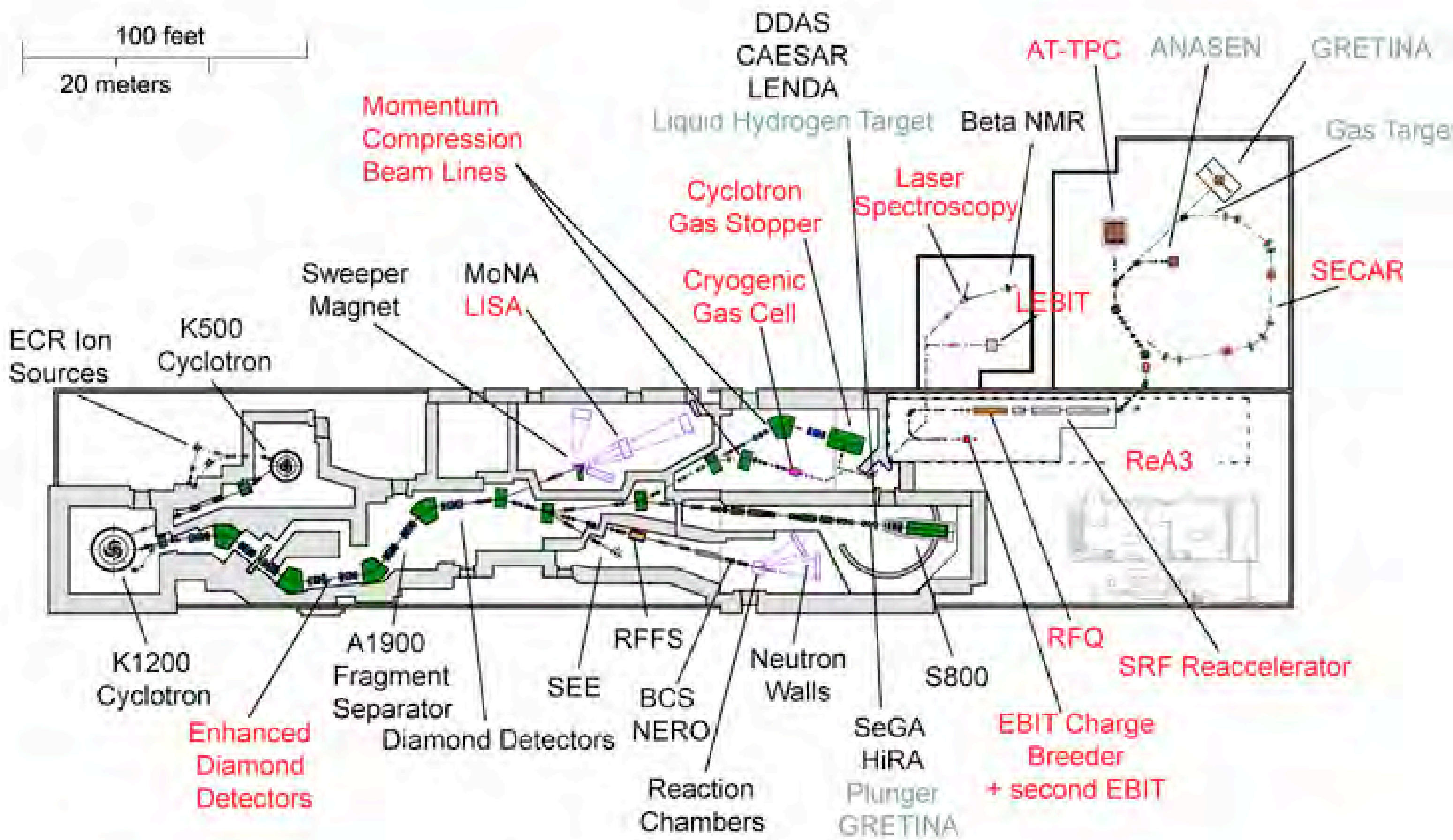
- The first operating cyclotron with SC coils (Blosser 1982)
  - Accelerates heavy ions (atomic number Z, mass A) to $500(Z/A)^2$ MeV/u.



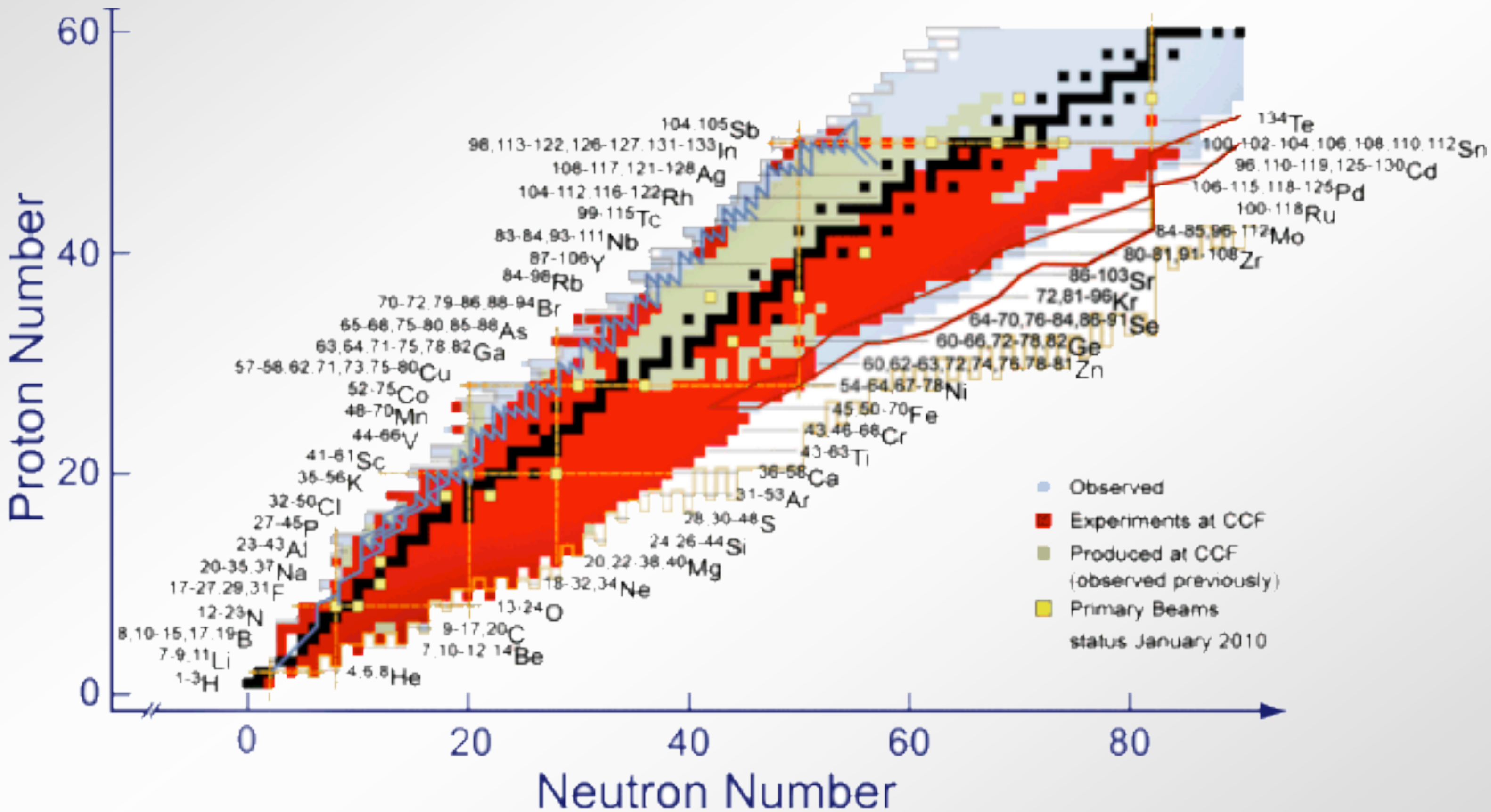


5 T dipole field

NSCL: K500 injects the K1200 cyclotron which sends ions to fragmentation target



Beams produced at MSU's NSCL

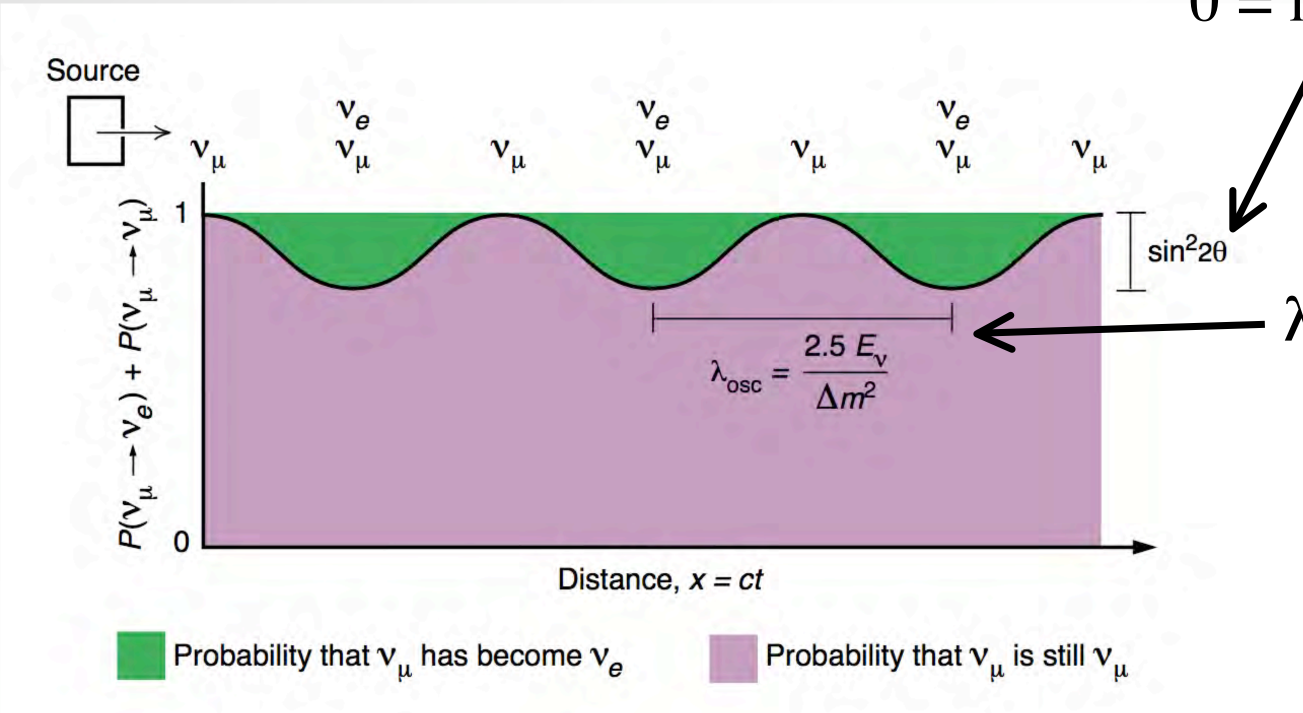


Neutrino oscillations can reveal CP violation

- Example: Muon neutrinos change to electron neutrinos as they propagate through space

- CP Violation ⇒

θ = mixing angle



λ = oscillation frequency

NOTE: $\lambda/E \sim 1/\Delta m^2$

Measuring CP violation needs powerful neutrino sources

- CP Violation $\Rightarrow$ $\boxed{\text{Prob}(\nu_\mu \rightarrow \nu_e) \neq \text{Prob}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$

- Two next generation experiments
  - Long Baseline Neutrino/antineutrino Experiment (LBNE) – Conventional Approach
    - Send high-energy beam from Fermilab to DUSEL (South Dakota)
    - LBNE has *one beam* with a near (1 km) and a far detector (1300 km)
    - Far detector is a very large (300 kton water Cerenkov detector with phototubes)
  - Daedalus – A New Powerful Approach
    - One detector & multiple low-energy antineutrino sources at different distances

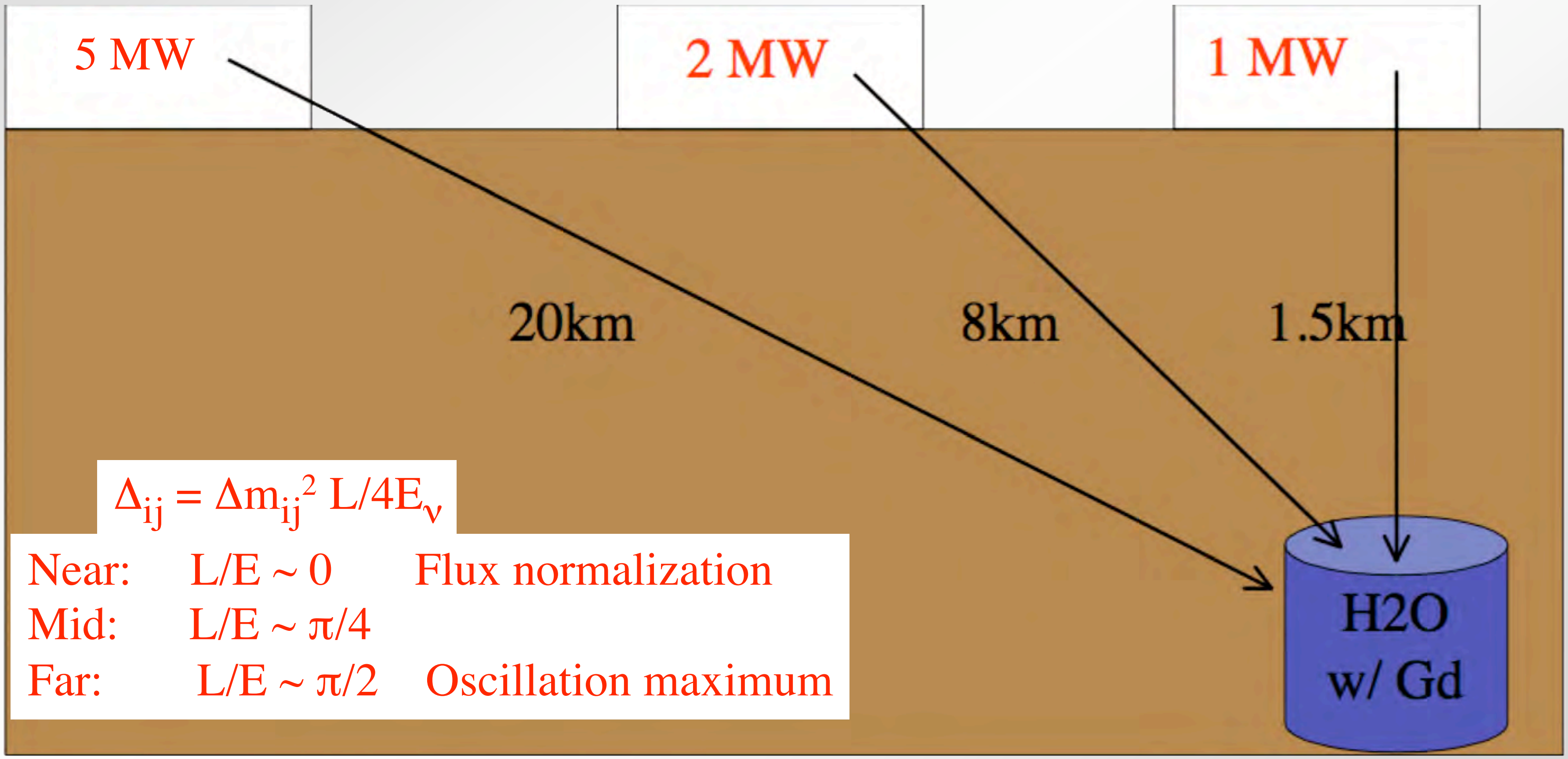
      (1.5 km, 8 km, 20 km)
    - Use same large water detector as LBNE

Both approaches can operate simultaneously

Source: M. Shaevitz

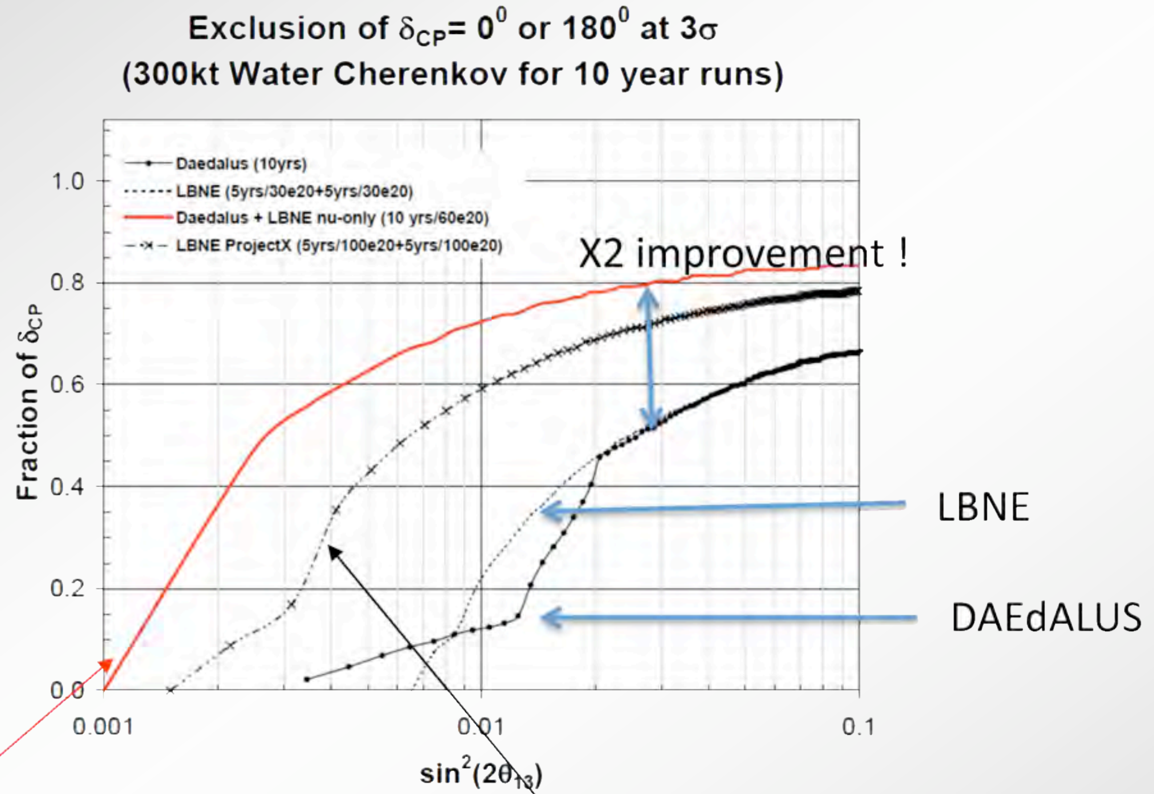
Megawatt Cyclotrons for Neutrino Physics: DAEδALUS

Decay-At -Rest antineutrino source to measure CP-violation in the neutrino sector



Source: J. Conrad

Why we are excited about DAEδALUS

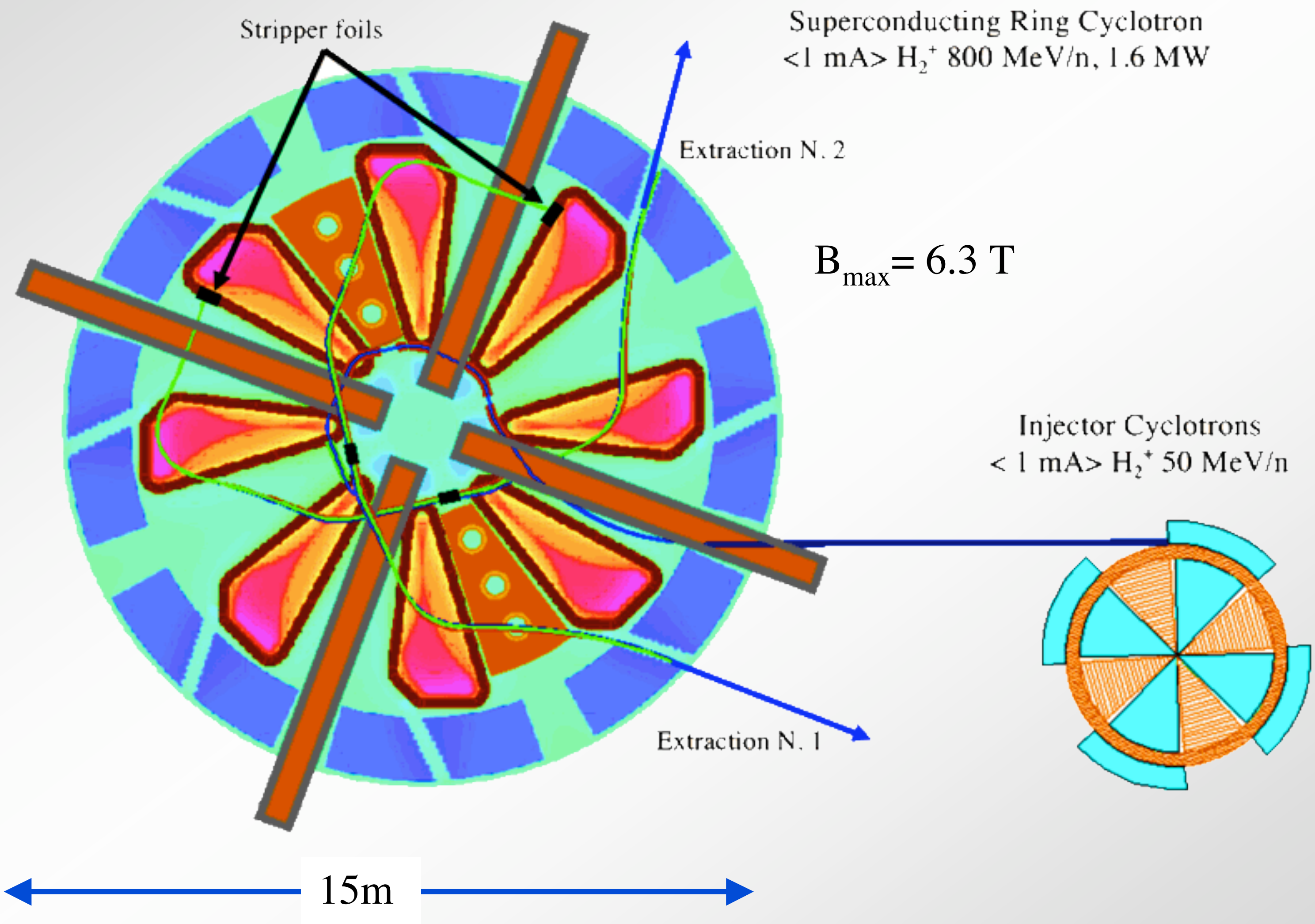


Combined is better than a Project X (“superbeam”) experiment!

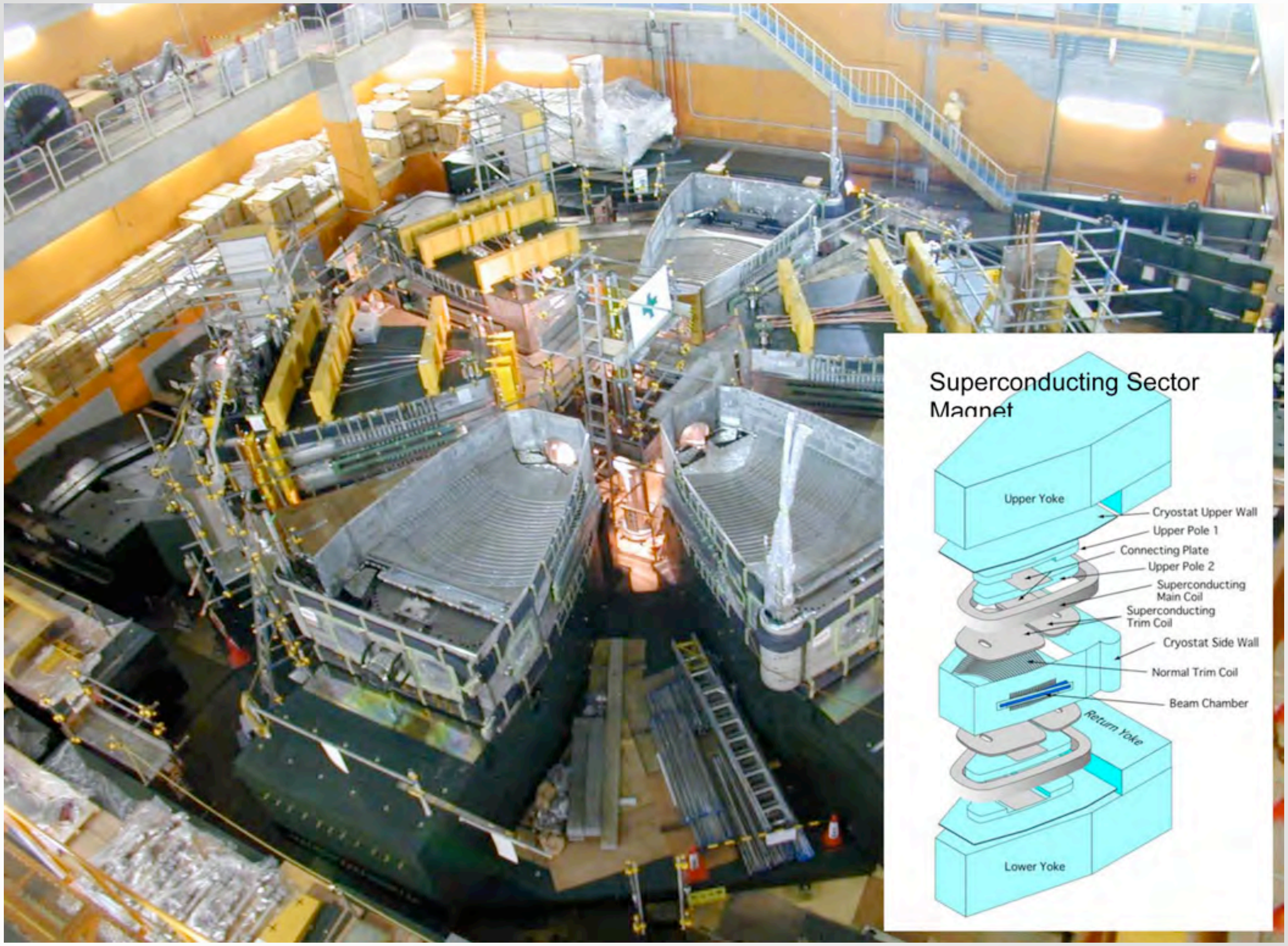
DAEdALUS cyclotrons would a hybrid of PSI ADSR & RIKEN

Source: J. Conrad

Superconducting Ring Cyclotron



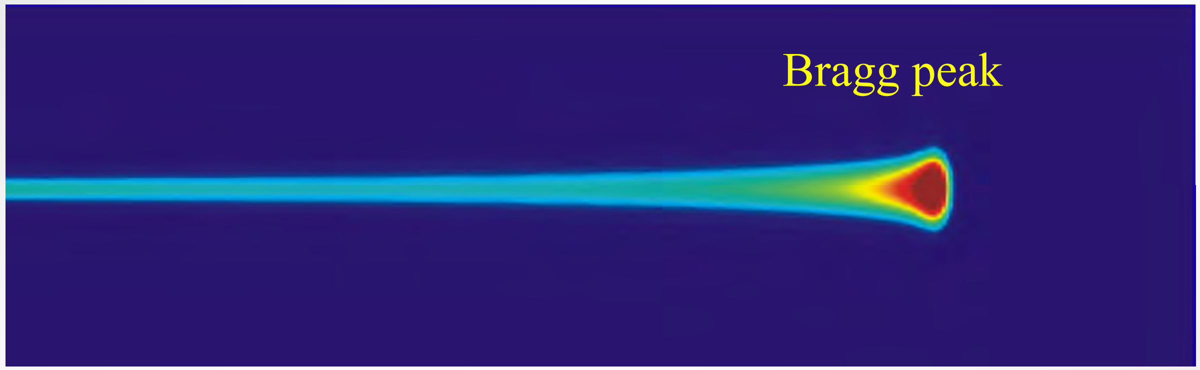
Sector cyclotron for more intense rare isotope beams: with 3.5 T superconducting magnets: RIKEN

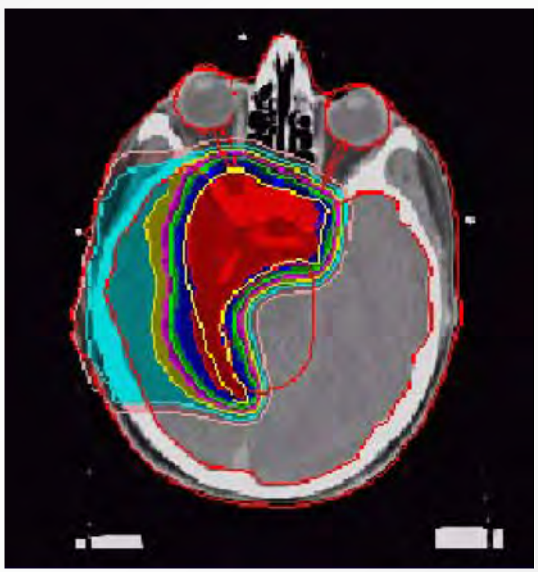


Completed November 2005 – the 140-ton cold mass cooled to 4.5K

A medical application for cyclotrons: Tumor control with hadron beams

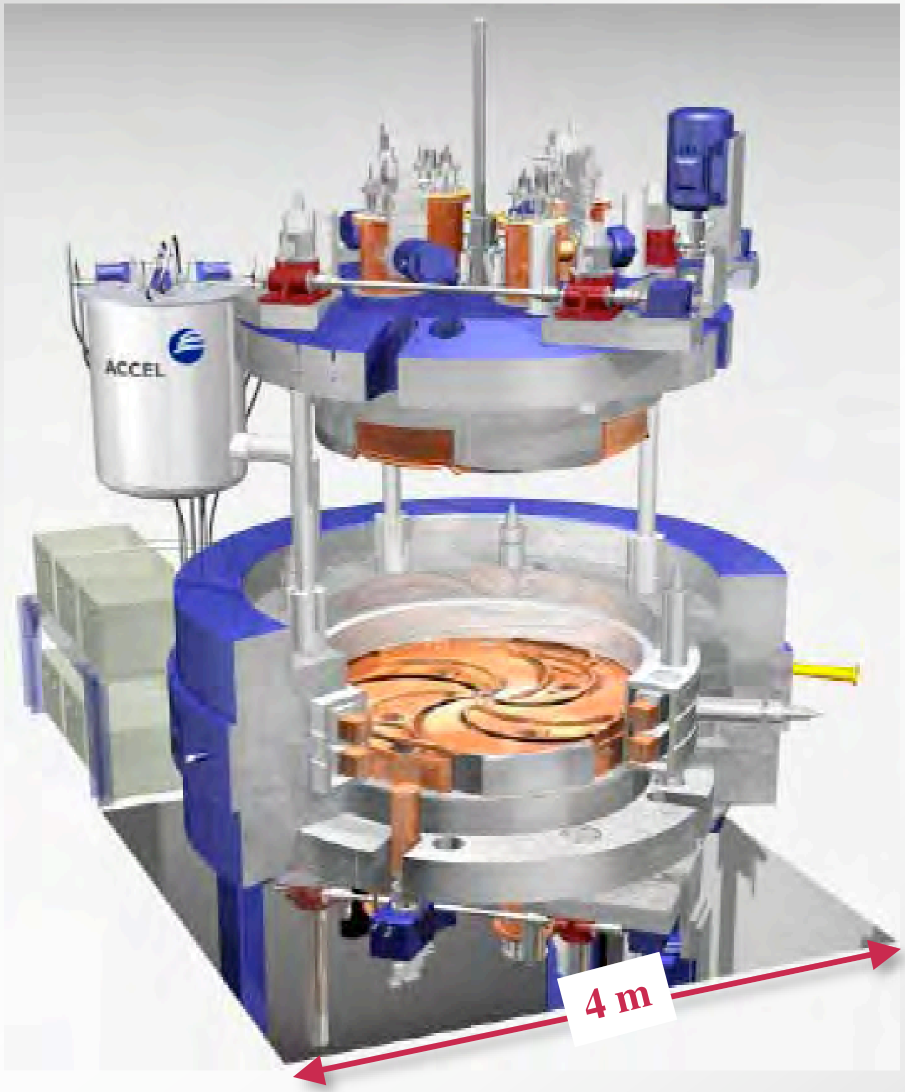
Proton beam





Hadron therapy allows for the best treatment of deep tumors with minimized dose to healthy tissue

Spiraled cyclotrons for proton therapy



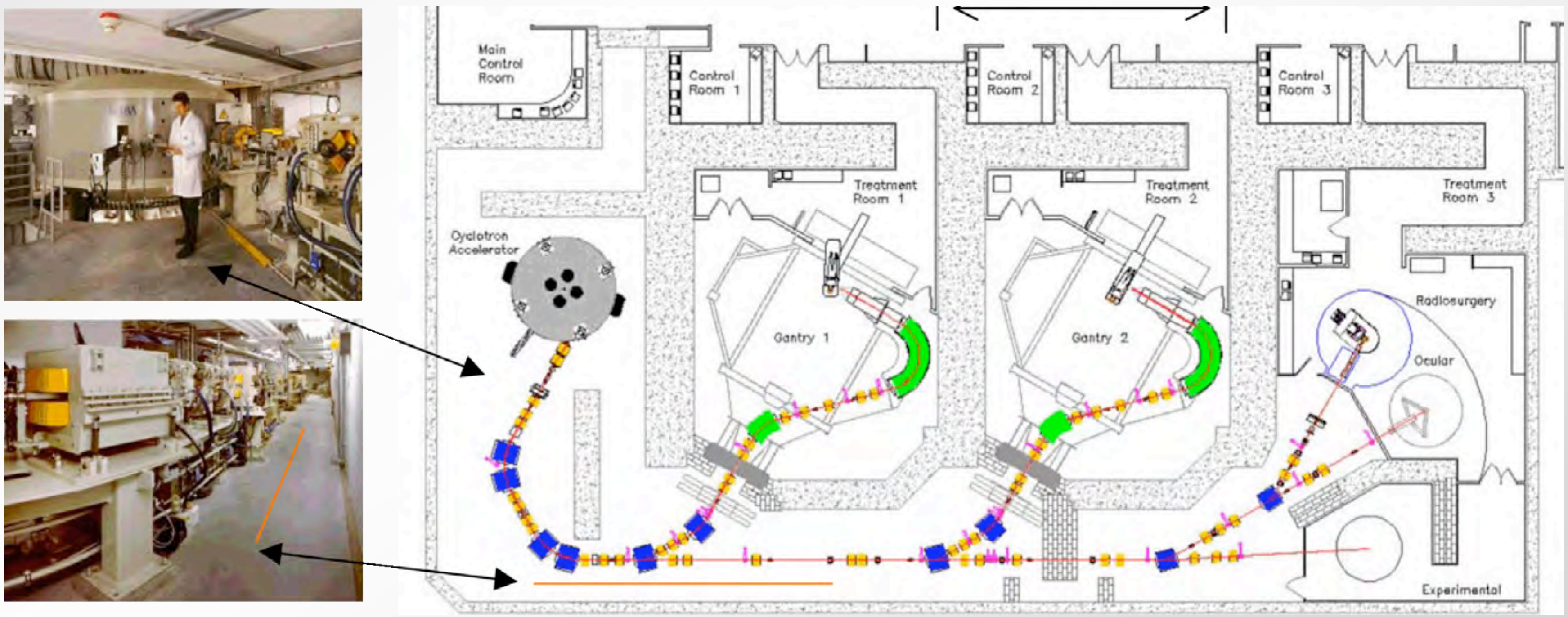
Energy range: ~100 - 230 MeV

Current: 5 nA - 500 nA

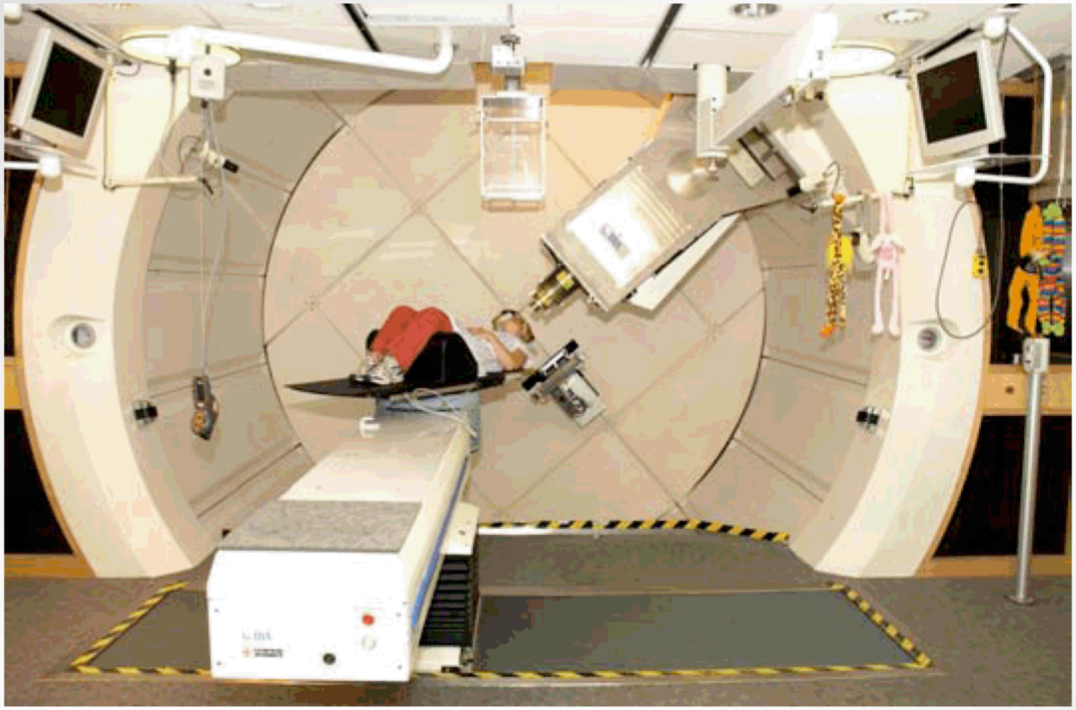
~ 240 tonnes

Layout of NPTC treatment level at MGH

- Radiation delivery system includes a cyclotron & an array of over 50 magnets, each weighing 1,000 to 5,000 lbs (in orange, blue and green)
- Protons can be delivered sequentially to any of the 3 treatment rooms by bending the beam using the magnets.
- Radiation is isolated to individual treatment rooms with 5 feet thick concrete walls.



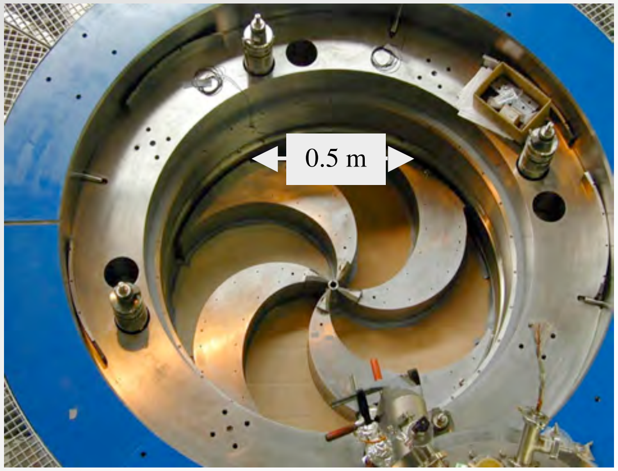
Patient's view of a proton therapy center

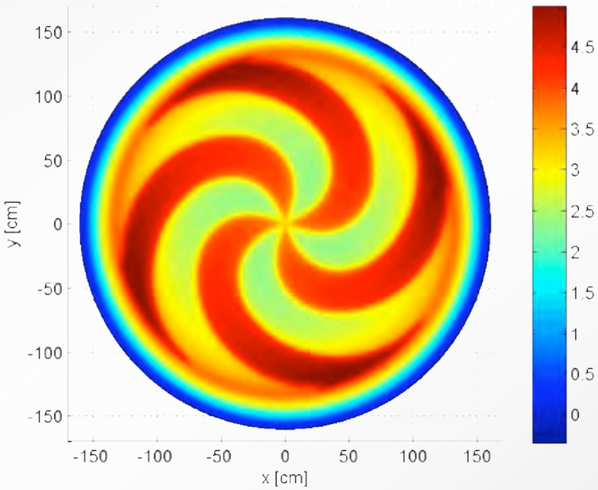


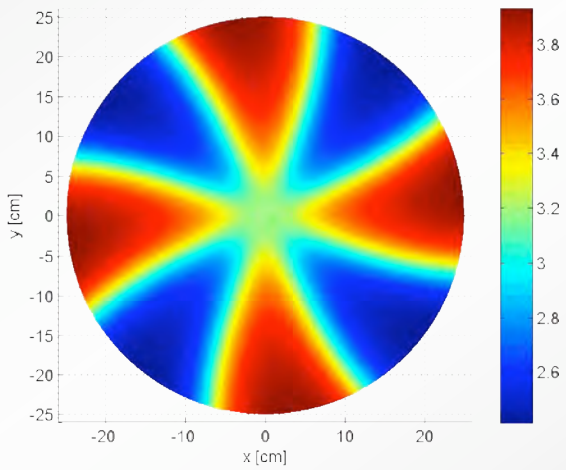
Doubling the B field in the cyclotron ==> a different model

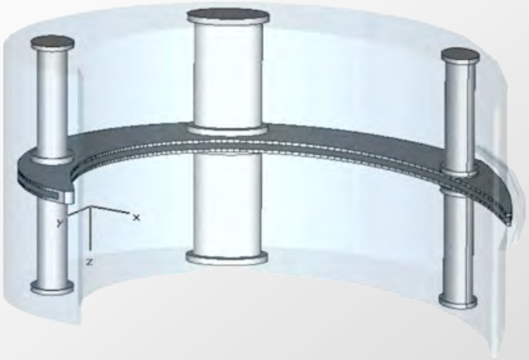
Let's look inside a 250 MeV Proton Machine

- The spiral structure is responsible for vertical beam focusing



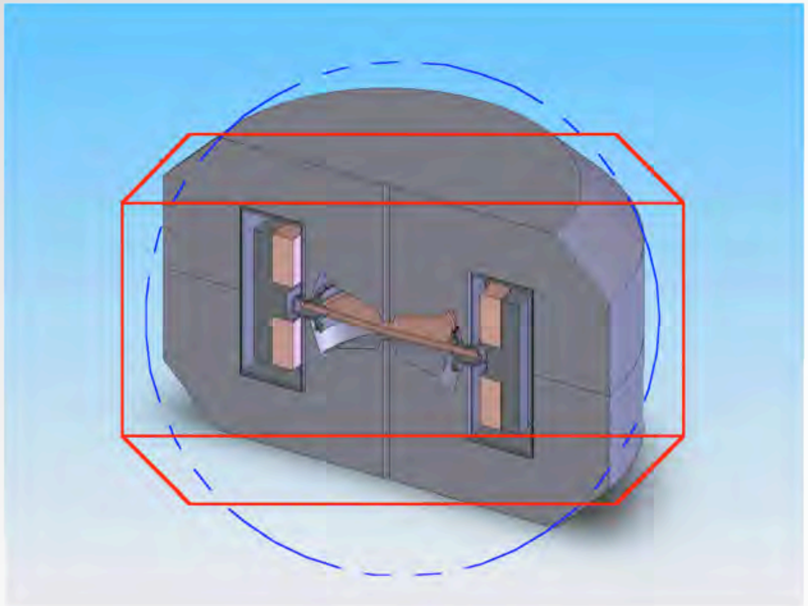






Cyclotrons can be made very compact by going to high magnetic fields:

- $E_{final} \approx K \cdot r^2 B^2$

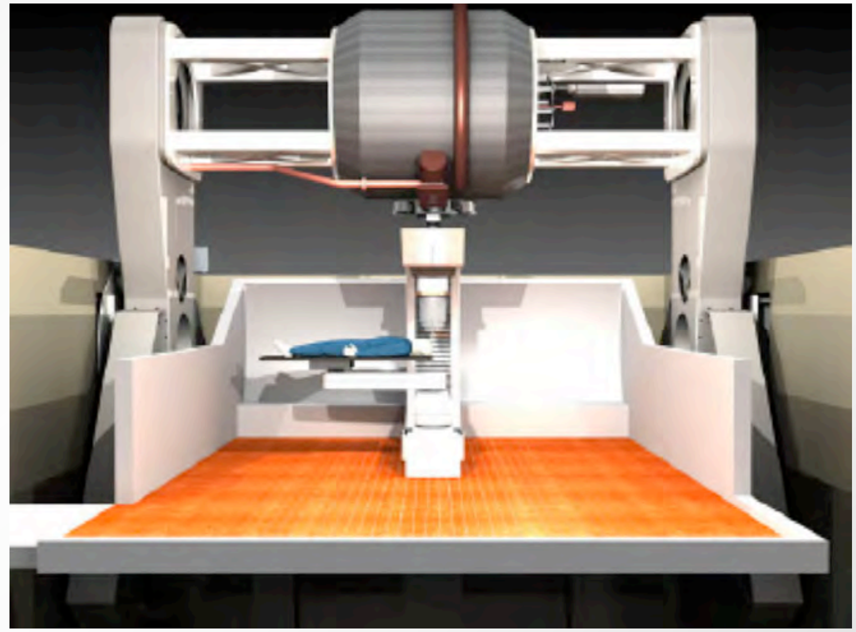


An efficient cyclotron electromagnetic structure is almost spherical- the size then scales inversely and cubically with increasing field for a given ion and final energy.

B (T)	Final Radius (m)	Size Decreases by:
1	2.28	1
3	0.76	1/27
5	0.46	1/125
7	0.33	1/343
9	0.25	1/729

Source: T. Antaya

9 T cyclotron for proton radiotherapy (PBRT)
Even further size reduction



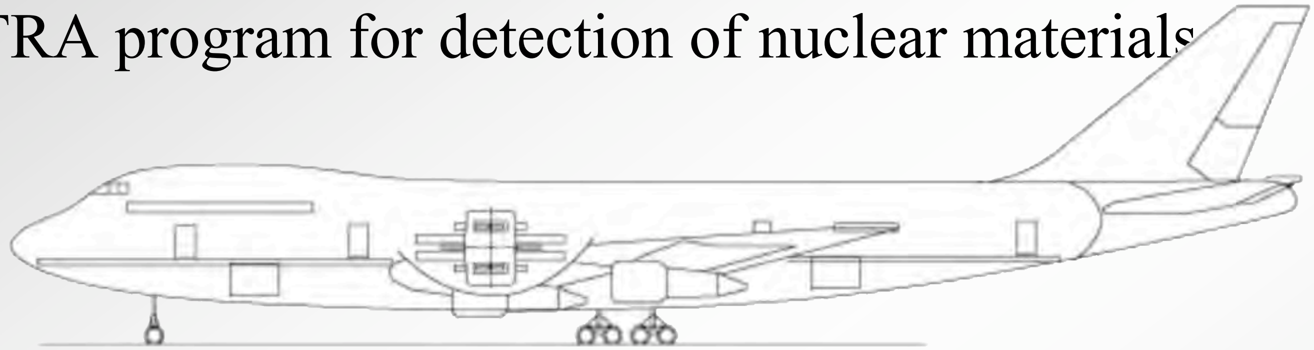
Reduces the cost of PBRT by an order of magnitude ($150M to $20M)

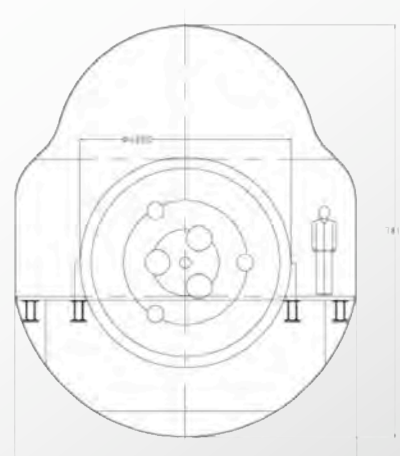
Weight = 90 T

Mevion Monarch 250 MeV

1 GeV Protons at 6T: Transportable Compact SC Cyclotron?

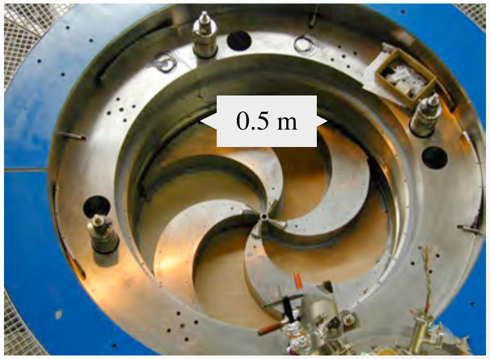
- DTRA program for detection of nuclear materials





Source: T. Antaya

Compact SC Cyclotrons:
Challenges at high intensity

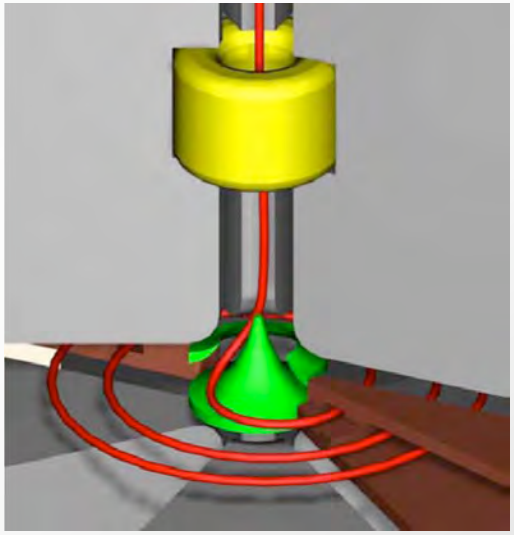


- At injection:
  - Large space charge in small central region
    - How to get the beam into the cyclotron
- At extraction:
  - Highly efficient extraction at high energy is unproven
    - How to get the beam out of the cyclotron
- During acceleration:
  - Limited space for rf to support large energy gain per turn
    - $I_{peak} \sim V_{rf}^3$
  - Limited vacuum pumping access for potentially large beam-induced gas load

To bring this approach to high intensity requires much work

How does the beam get in?

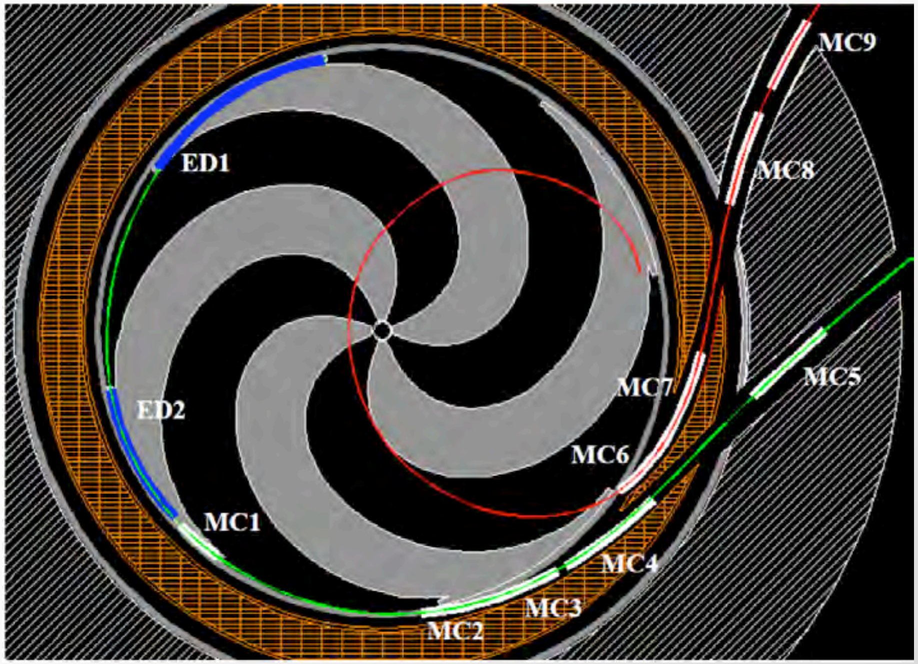
- Originally, ion sources were placed at the center of the cyclotron,
  - But - space & power are limited
  - Gas incompatible with good vacuum
  - Access difficult



- External sources are now common
  - Axial injection requires a 90° vertical bend
    - good at low energies
- Radial injection is typical at higher energies (2nd stage cyclotrons)
  - Requires extra horizontal bending at entry
- Sector cyclotrons made such schemes much easier
  - Valleys provide space for equipment & low or zero magnetic field.

Extracting the beam;
We need an off-ramp

- We need large turn spacing
  - Favors large rf voltage
- We want the beam to exit on a well specified path
- Basic approach is to perturb the beam orbit into a magnetically shielded septum
- Example: Electrostatic deflector
- For some ions a stripping foil could be used to change the orbit



New cyclotrons are coming…

After 80 years cyclotron technology delivers

- Strong commercial opportunities
- Pharmaceuticals for functional medical imaging
- Cost-effective radiation therapy
- Forefront nuclear physics
- Spallation neutrons for materials research
- Challenging accelerator physics and engineering
- And we hope, the answer to CP violation in the neutrino sector

[redacted]