An Introduction to cyclotrons

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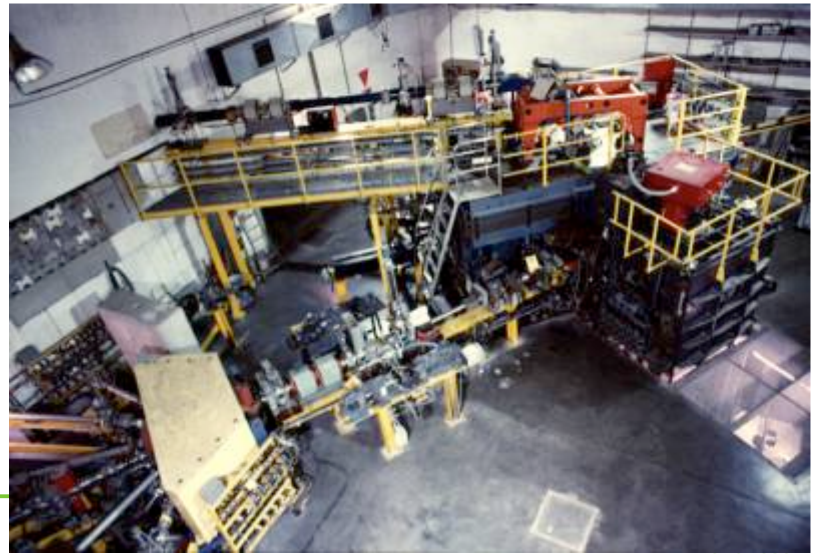
Yves Jongen, Founder & CRO
IBA sa

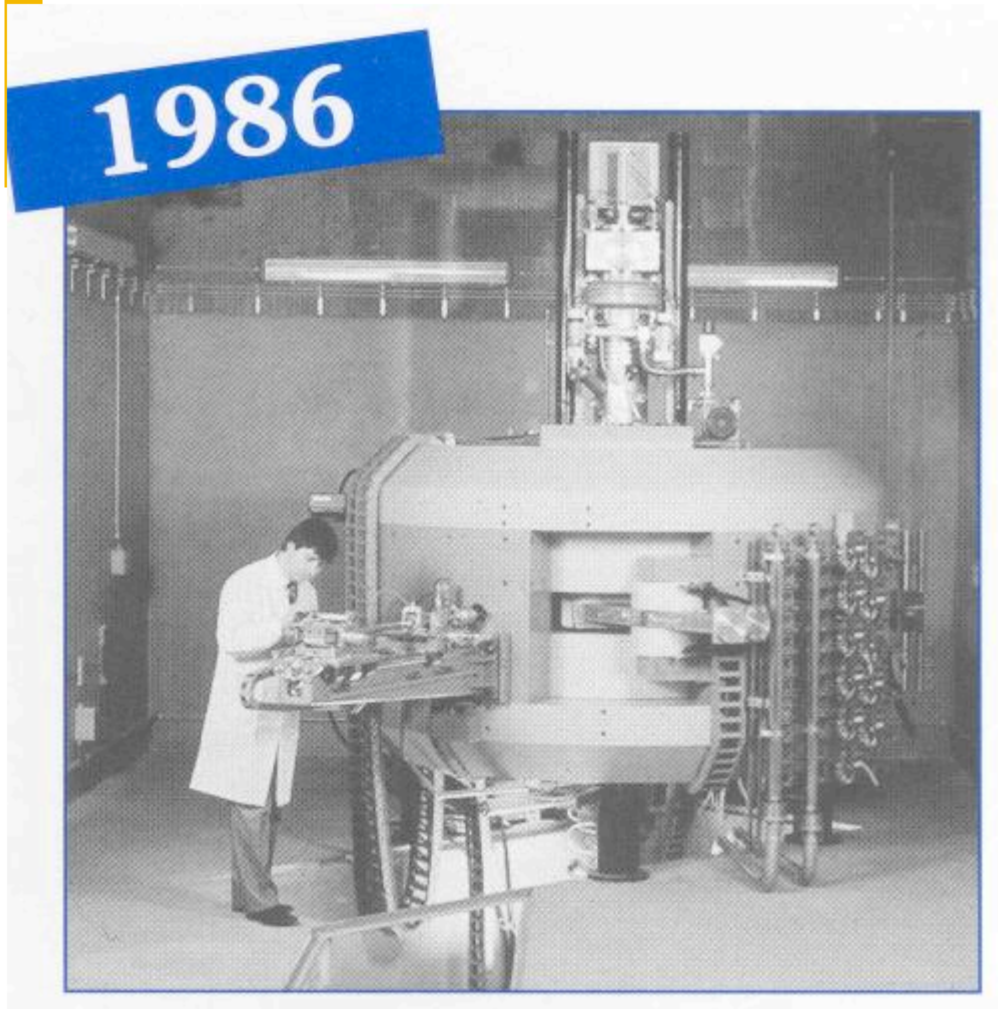
… a Belgian classic insult !

Cyclotrons: an old tradition in Belgium

- Belgium is one of the first European country to install a cyclotron in 1947
- UCL cyclotron Centre at LLN in 1970



Once upon a time…



- A university researcher had imagined to produce a cyclotron…
- Producing 5x more output and consuming 3x Less energy than any existing cyclotrons…
- A new story (and a new company) was starting

Course outline

- First principles
- Stability and focusing
- The synchrocyclotron
- The isochronous cyclotron
- Building a cyclotron
- Isochronous cyclotrons in proton therapy


First principles

Force exerted by an electric field on a proton

$$\vec{F}_{elec} = q\,\vec{E}$$

The electric field along the trajectory supplies energy

Accelerating gaps of RF cavity

The electric field orthogonal to the velocity does NOT supply energy (but does cause an acceleration)

Field of the electrostatic deflector

Force exerted by an magnetic field on a proton

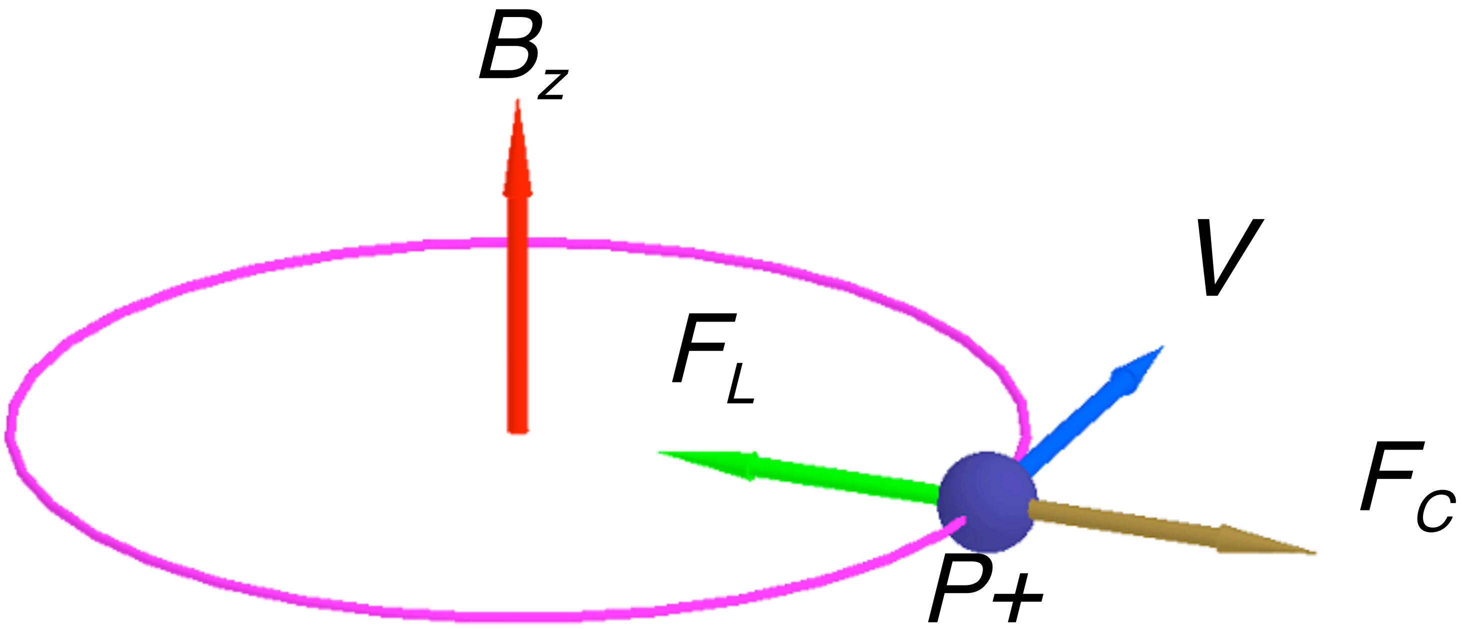
$$\vec{F}_{\text{magn}} = q\,(\vec{v} \times \vec{B})$$

The magnetic force is orthogonal to the magnetic field and to the velocity

The magnetic field does NOT supply energy (but does cause an acceleration)

The result is a change in the direction of the velocity (centripetal acceleration)

Orbit in a uniform magnetic field (2)



The proton in a uniform magnetic field

The motion in the magnetic field is defined by the balance between the magnetic force and the centrifugal force

$$q\,v\,B = m\,\frac{v^2}{r}$$

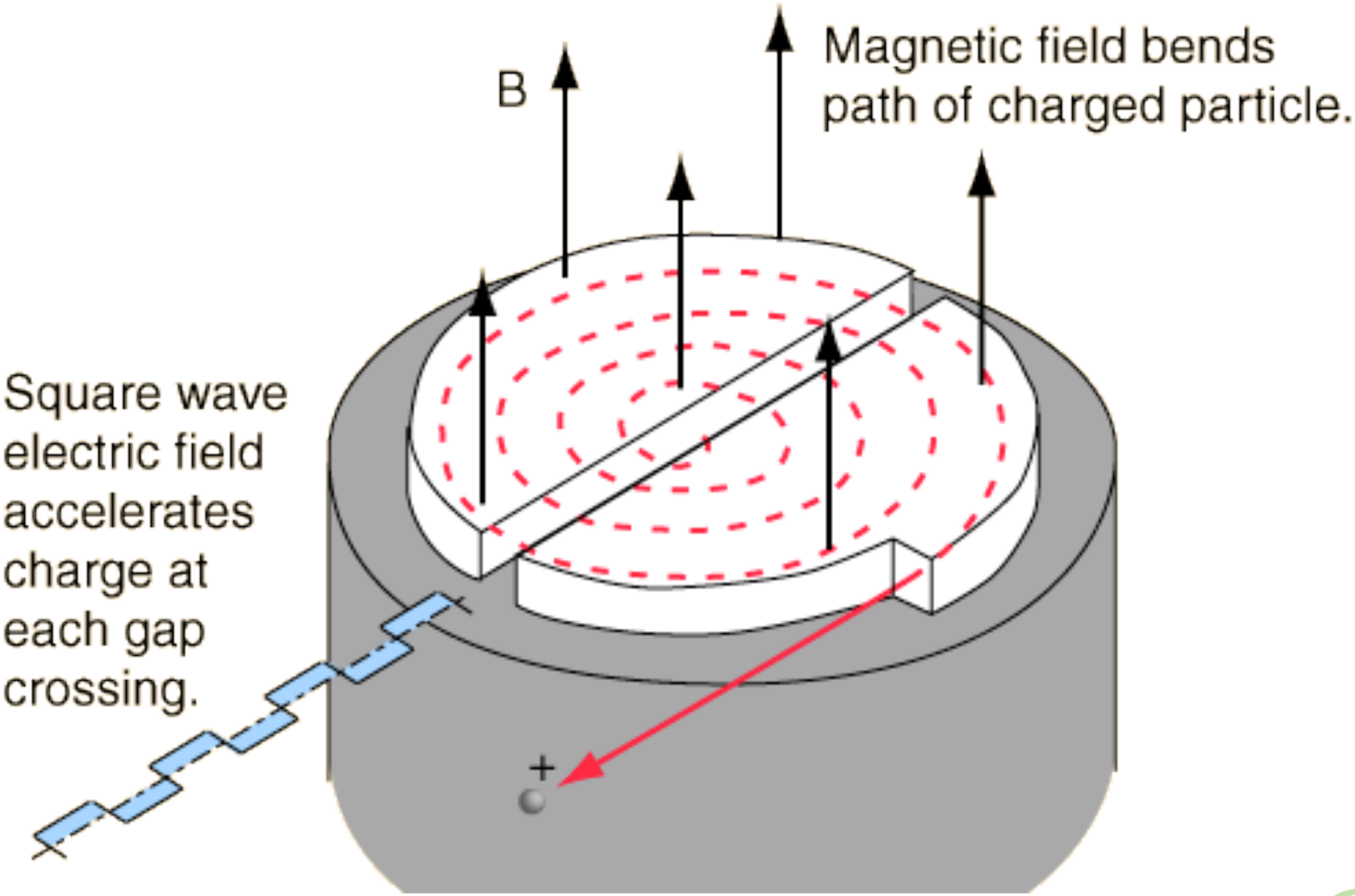
$$q\,\omega\,r\,B = m\,\omega?r$$

This can also be written

$$\boxed{\grave{u} = \frac{qB}{m}}$$ (in radians/s)

Thus defining the **cyclotron frequency**

The base of all cyclotrons



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Relativity

- Einstein's famous equation tells us that energy and mass can be converted to each other. A body of mass m_0 represents an amount of energy $E_0=m_0c^2$
- If this body receives some kinetic energy T, its total energy will be: $E_{tot} = E_0+T$
- The additional kinetic energy will result not only in an increase of velocity, but also in an increase of mass: $m > m_0$
- We have: $\gamma = m/m_0 = E_{tot}/E_0 = (E_0+T)/E_0$
- We define similarly: $\beta = v/c$

Relativistic effects on 230 MeV protons

For 230 MeV protons

- Beta is 0.596 (the protons are traveling at 59.6% of the speed of light, or 179,000 km/sec)
- Gamma is 1.245 (the mass of the proton has increased 24.5% over the mass at rest)

The relativity and the cyclotron

$$\boxed{\grave{u} = \frac{qB}{m}}$$

- If protons are accelerated in a uniform magnetic field, the relativistic mass increase will result in a decrease of the orbital frequency as the protons are accelerated
- To keep the protons rotating at the same frequency, it is necessary to increase the magnetic field with radius, in a way that matches exactly the relativistic mass increase
- But this creates a big problem!


Stability and focusing

Why do we need focusing forces

- The unrolled trajectory in a PT cyclotron is about 4 km long
- You need to reach a target that is less than 1mm in size at the degrader
- Can you reach this by proper aiming?

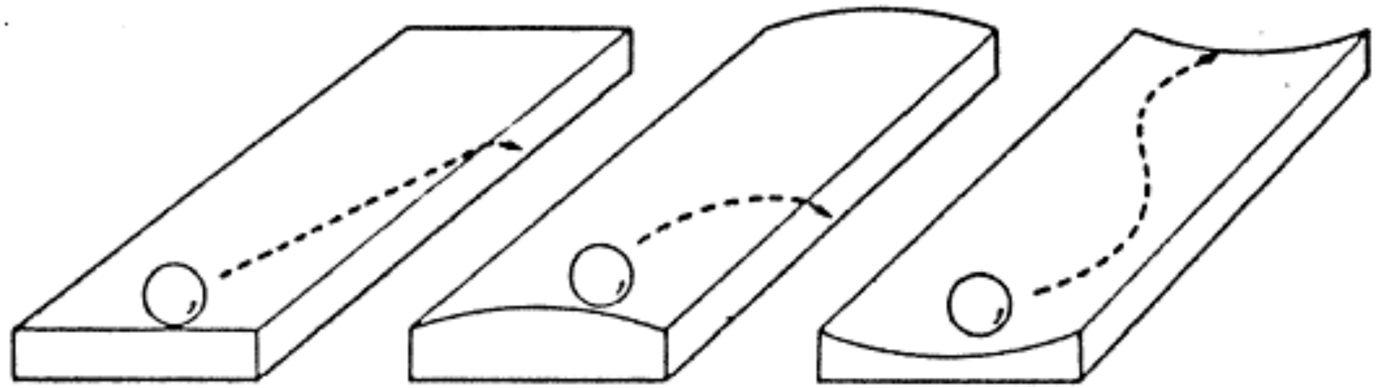
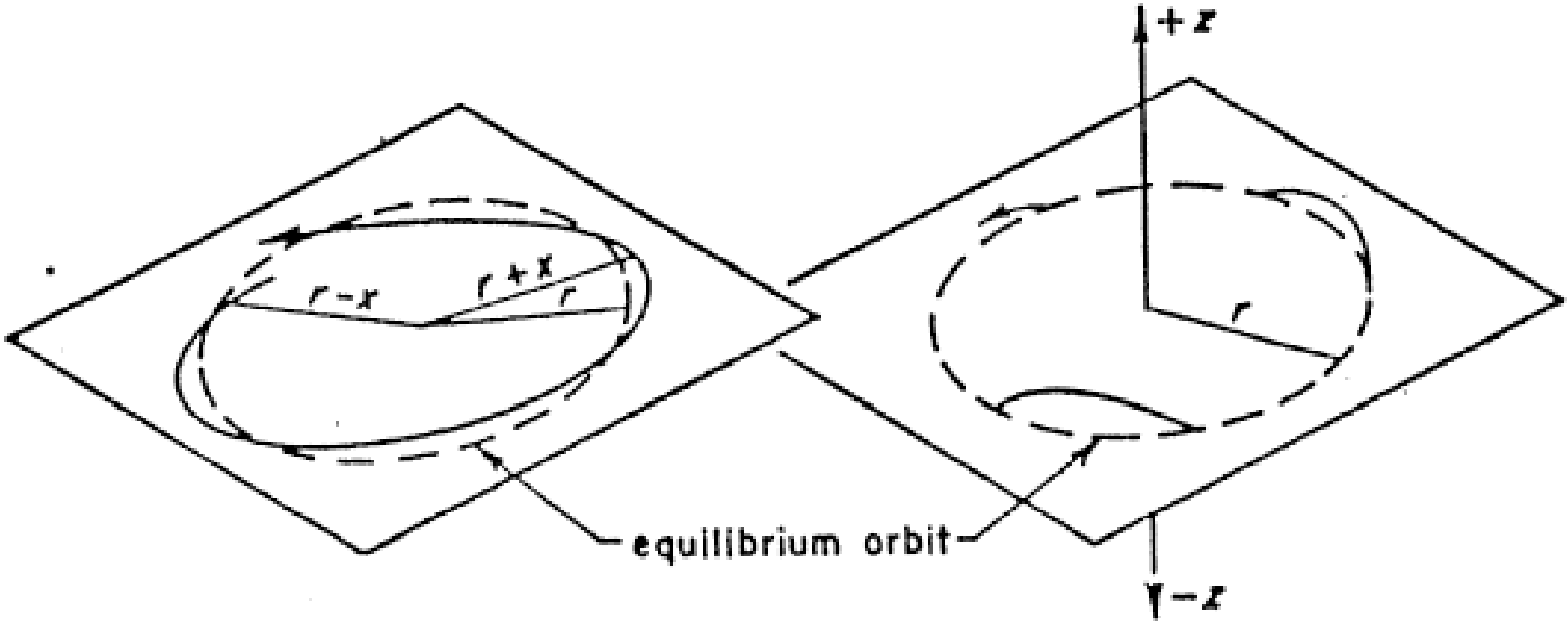


Fig. 2-1. Bowling alley analogy of systems of forces which produce neutral, unstable, or stable orbits.

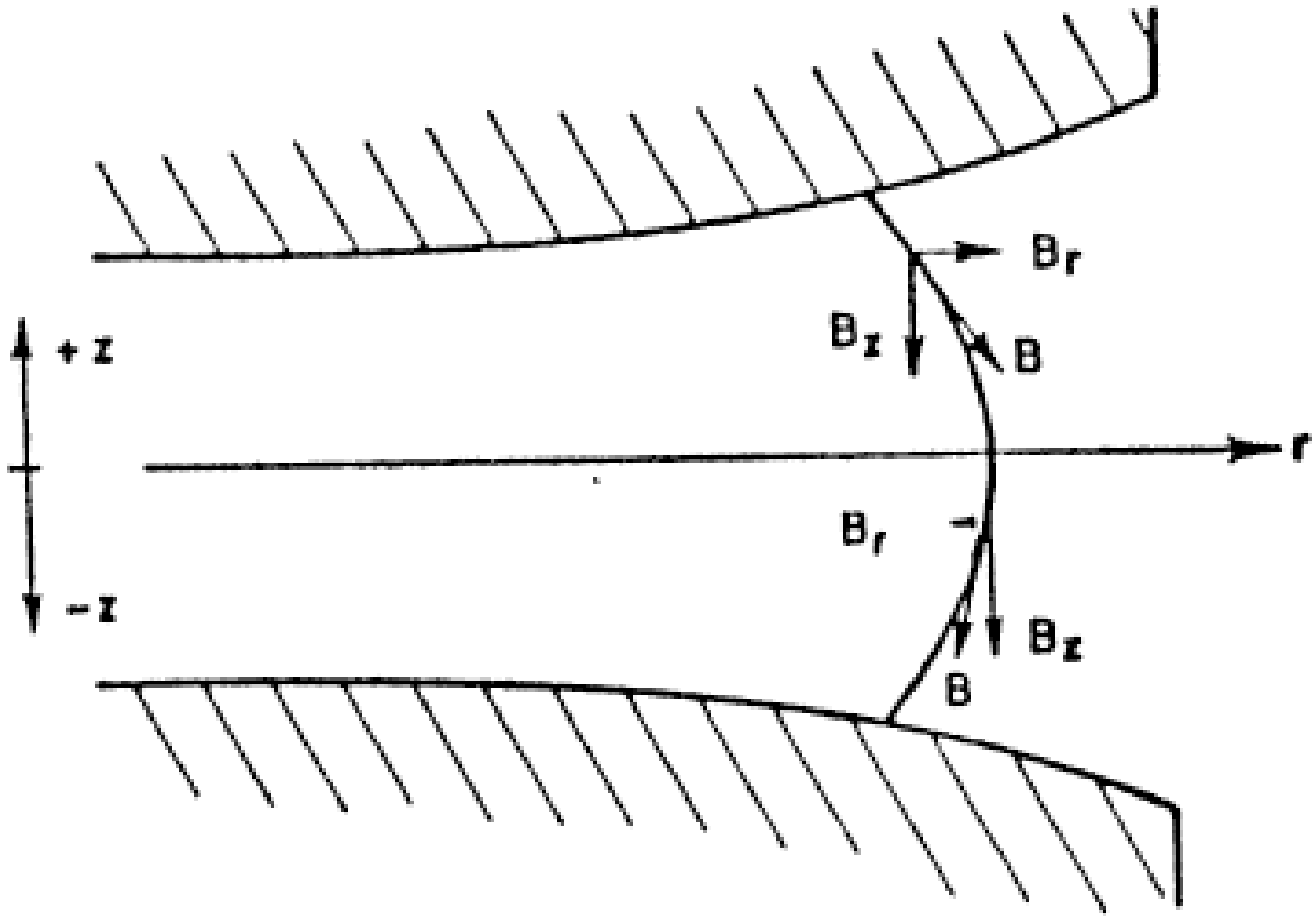
Radial and axial oscillations around the equilibrium orbit



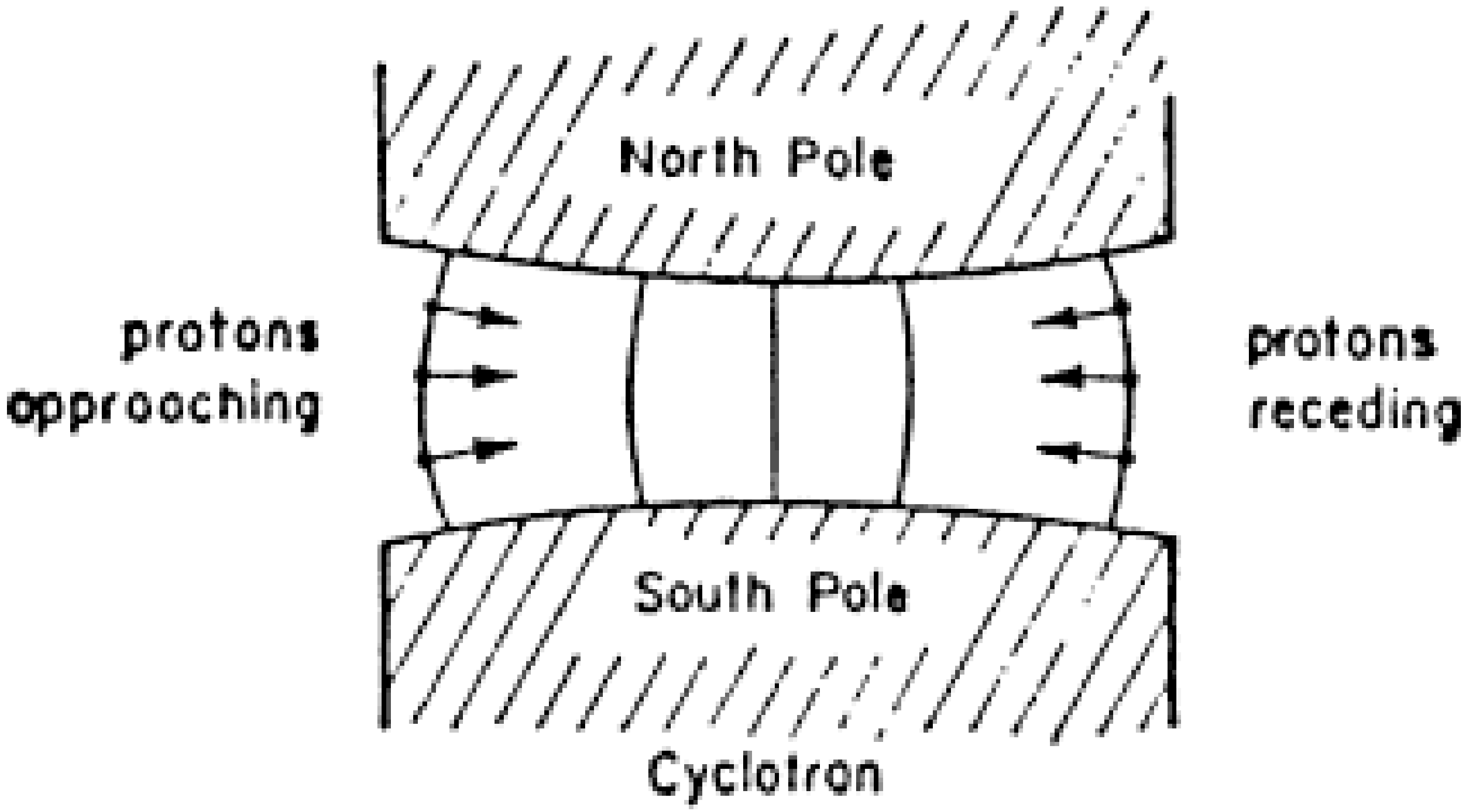
Vertical focusing

- Let's assume for the moment a magnet with rotational symmetry
- If a proton is too high (too low), a restoring force must bring it back in the median plane (MP)
- This force must be provided by the magnetic field
- The force is orthogonal to the field and the velocity
- If the force must be vertical, the velocity is azimuthal, then the magnetic field must be radial, increasing in one direction above the MP, and in the opposite direction below MP
- The magnetic field line must be curved

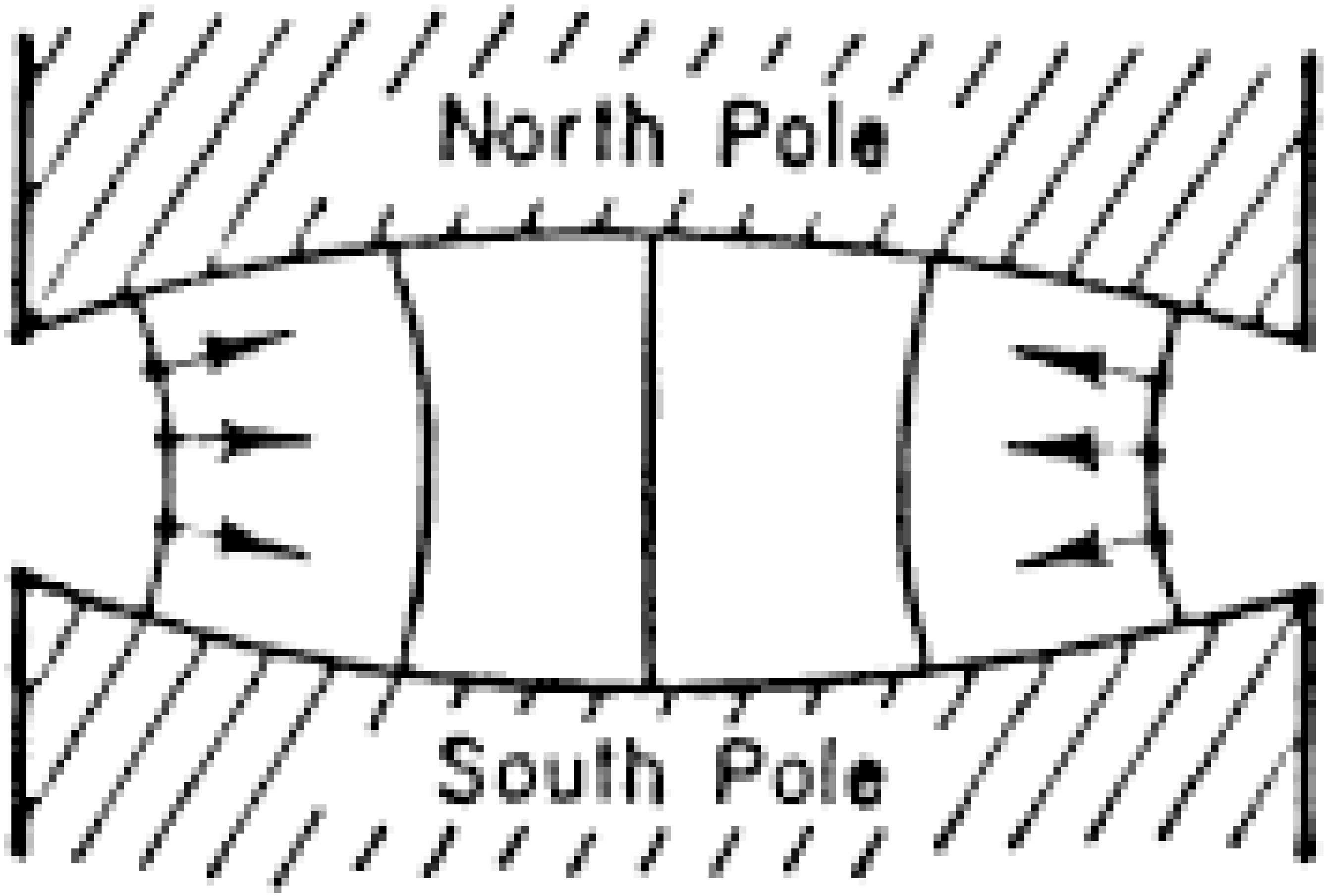
Bent field lines provide axial focusing



Cyclotron magnet providing axial focusing



Impractical cyclotron!



The field index

- Let's define the "field index" N as:

$$N = - (dB/B) / (dR/R)$$

- In simple words: how many percents does the magnetic field decrease when the radius is increased by 1%?

Betatron frequencies (tunes)

ν_R is the number of radial oscillations per turn

ν_z is the number of axial oscillations per turn

$$\nu_z^2 = N$$

$$\nu_r^2 = 1-N$$

Therefore, for stability, 0 < N < 1

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Consequence for cyclotron design

- In a magnet with rotational symmetry, the axial stability requires a field decreasing with radius, with $0 < N < 1$
- The rotation frequency of the ions will decrease for two reasons: the relativistic mass increase, and the radial field decrease
- If a fixed acceleration frequency is used, the beam will be 90° out of phase with the accelerating field after 20…40 turns
- This is the energy limit of “classical” cyclotrons

Synchrocyclotrons

The synchro-cyclotron

- If the rotation frequency of the ions decreases during acceleration, let's make a cyclotron where the RF is modulated in frequency to follow the frequency decrease of the protons
- The frequency of the main RF resonator is modulated at 200….600 Hz by a rotating variable capacitor
- Actually, it's the converse: thanks to the phase stability, the protons rotation frequency is locked to the RF frequency
- Slow acceleration: very low dee voltages are used
- The accelerator is not CW anymore, but produces a pulsed current

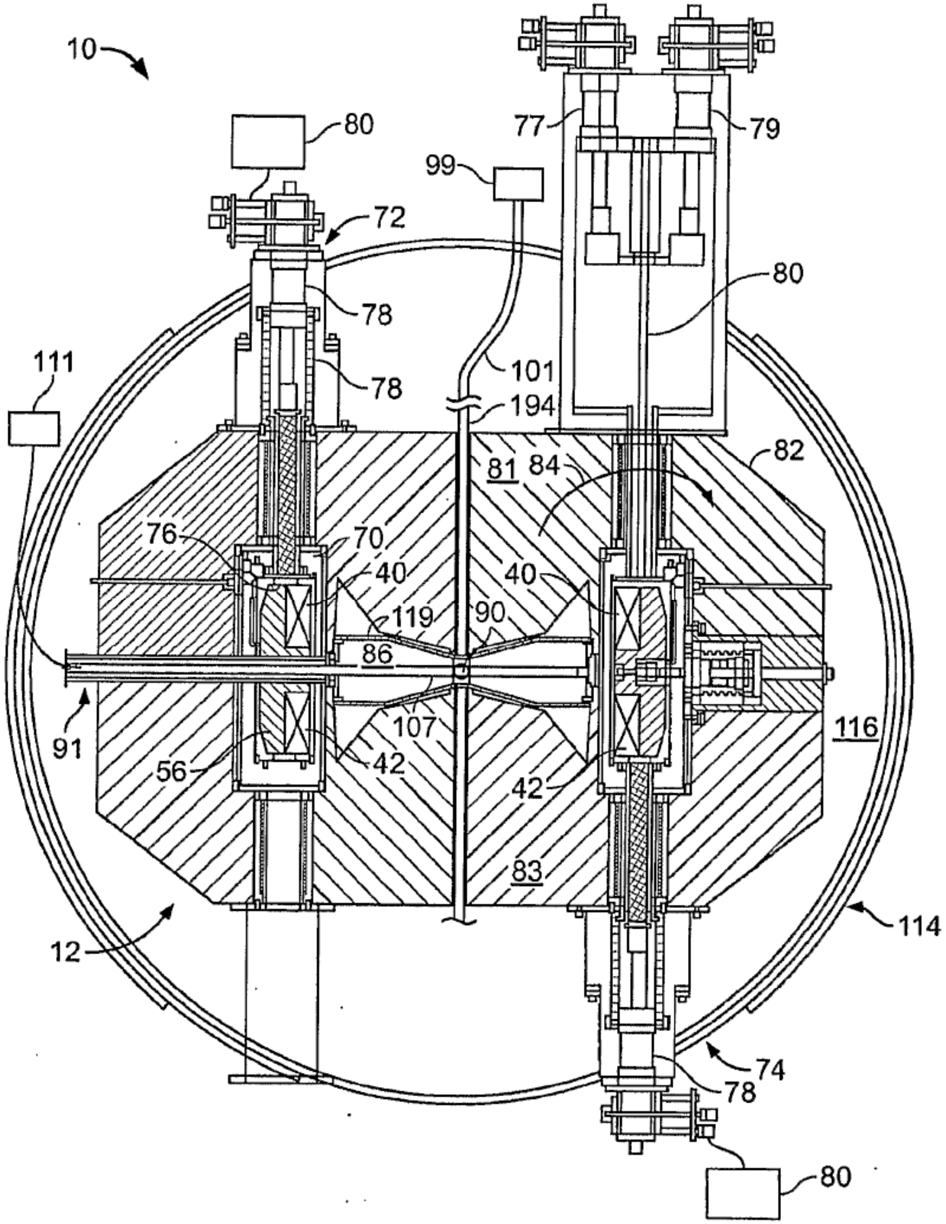
A glimpse to phase stability in SC

- In a SC, protons are accelerating on the decreasing part of the RF sine wave, past the maximum: later phases get less accelerating voltage
- A proton entering the accelerating gap earlier than the reference particle will get more energy, resulting in a larger Br
- The more energetic particle will have a slower rotation frequency, and lose its phase advance
- Conversely, a particle coming late to the gap will gain time
- Protons will oscillate in phase and energy around the reference particle
- A complete phase oscillation takes many turns

SC in proton therapy

- Synchro-cyclotrons have had an important role in PT
- Most of the initial experience in PT was developed on the old SC of Harvard who treated xx patients until 2002
- In Orsay, the 200 MeV SC has very good extraction efficiency and has treated many patients
- Still Rivers is developing a 250 MeV very high field SC
- But SC have a pulsed beam, which can be a disadvantage for pencil beam scanning, or voxel scanning

The high field synchro-cyclotron of Still Rivers

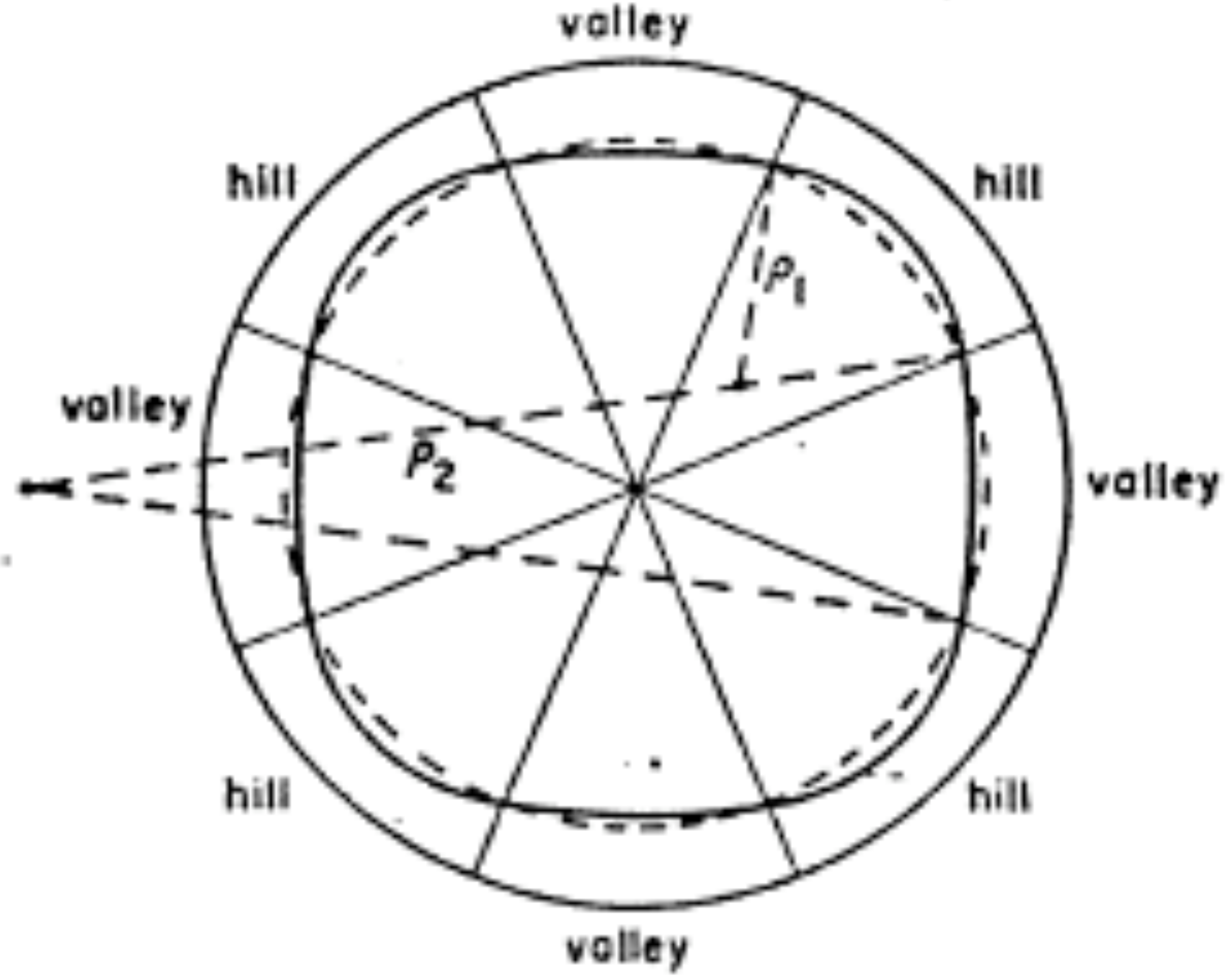


Isochronous cyclotrons

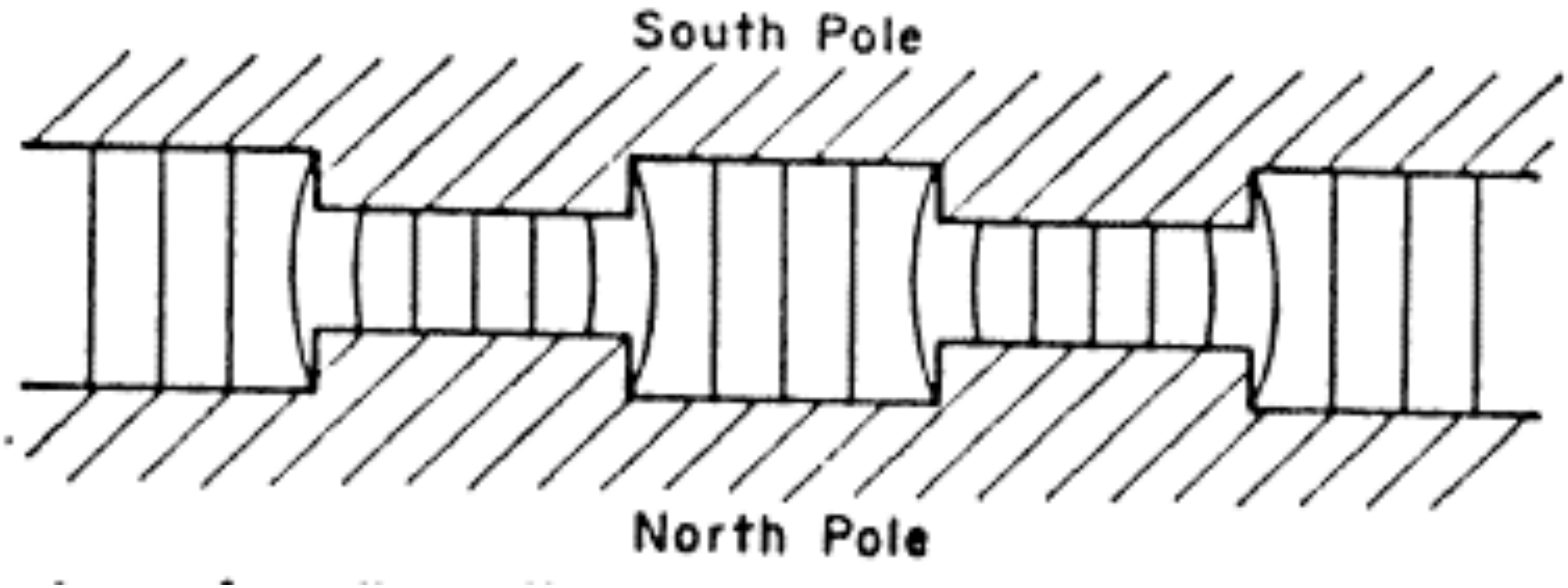
How could we make an isochronous cyclotron?

- Isochronism requires a field increasing with radius to compensate the relativistic mass increase
- But such a field is axially defocusing: can we provide another focusing force exceeding the axial defocusing of the radially increasing field?
- If we want to provide an axial restoring force, the only choice left is the combination of radial velocity component, and azimuthal magnetic field components
- This means that the field looses the symmetry of revolution. And orbits are not anymore circular

The sector focused cyclotron



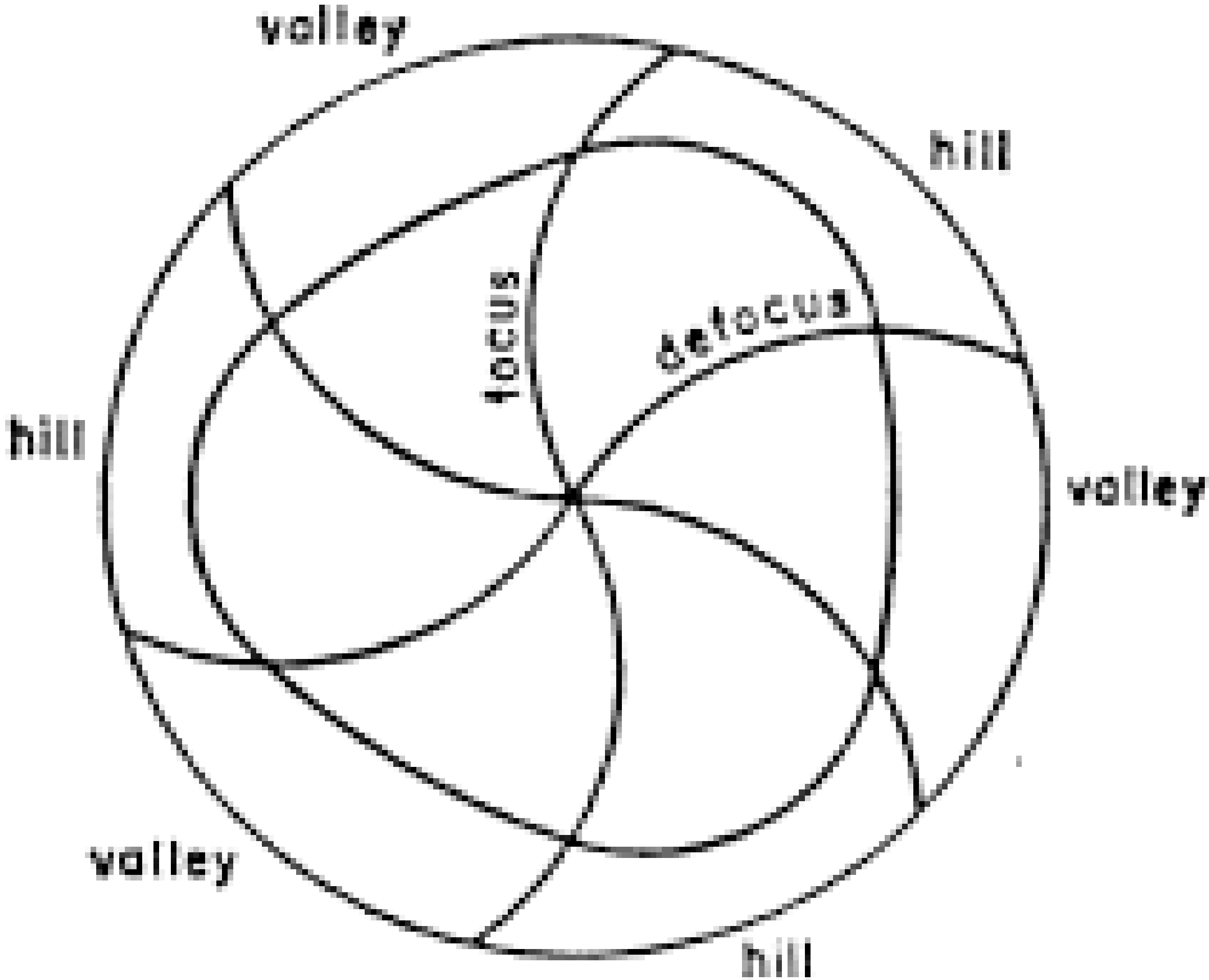
Field lines along an unrolled trajectory



Alternate gradient focusing, and spiral

- We know that a succession of alternating focusing and defocusing lenses of equal strength is globally focusing (yes, this is counterintuitive; it is due to the fact that the beam is always larger in the focusing lens than in the defocusing lens)
- Giving a spiral shape to the sectors provide alternate gradients, globally focusing

Adding spiralisation increases focusing



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Axial focusing in a spiral sector cyclotron

$$\text{í}_z^2 = N + \left(1 + 2 \cdot \mathrm{tg}^2 \text{æ}\right) \cdot F$$

$$F = \frac{\langle B^2 \rangle - \langle B \rangle^2}{\langle B \rangle^2}$$

Increasing <B> decreases the flutter

<B>	B_h	B_v	F
2.1	3.1	1.1	22.7%
3.5	4.5	2.5	8.2%
7	8	6	2.0%

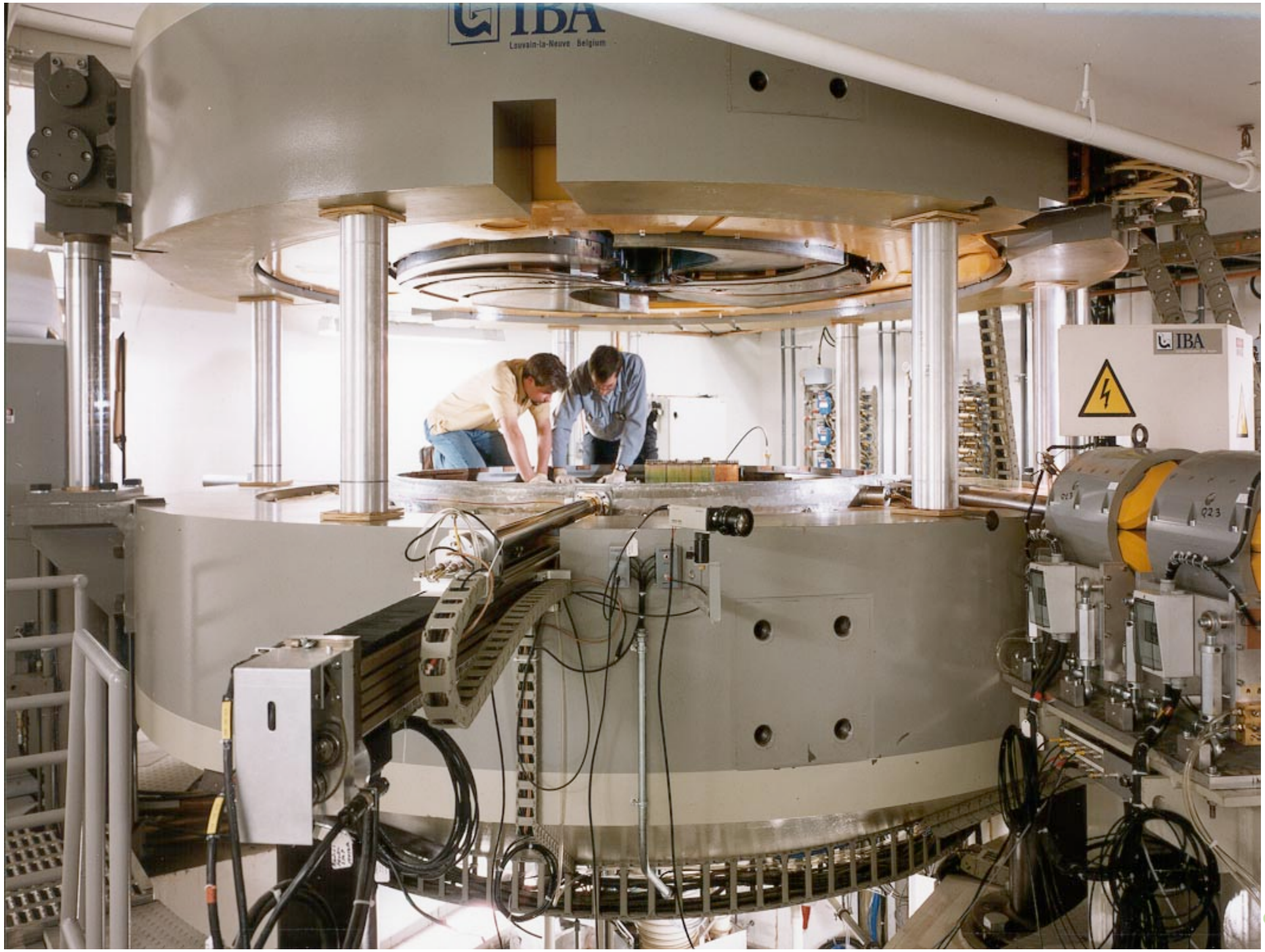
- If you want to do a very small cyclotron, like Still Rivers, you need a very high average magnetic field
- With a very high average magnetic field, the flutter becomes too low, and a SC is the only possible solution


Building a
cyclotron

Pole Casting

Machining of an IBA cyclotron magnet

The magnet opens at MP: accessibility!



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PT cyclotron: two RF cavities in opposite valleys

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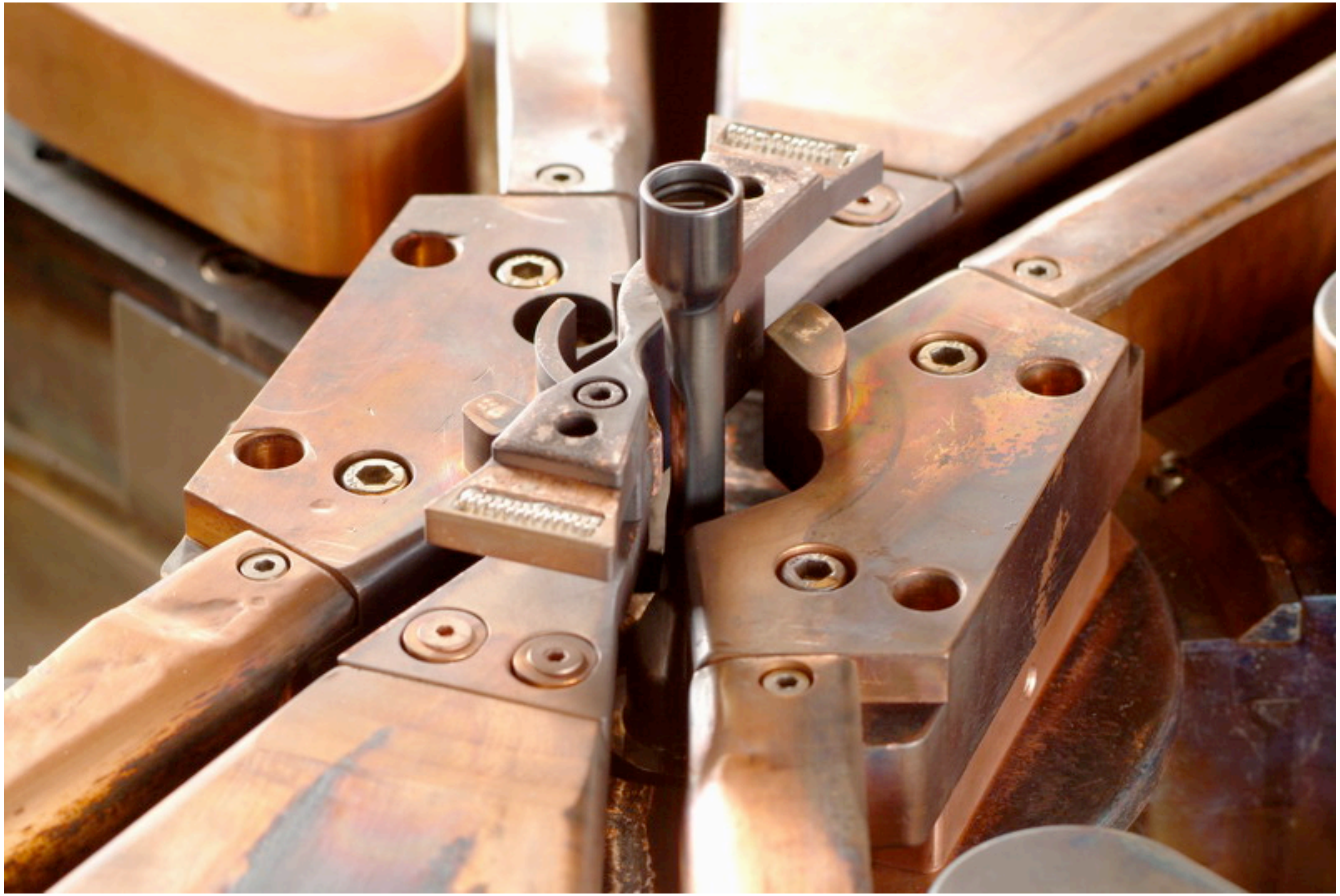
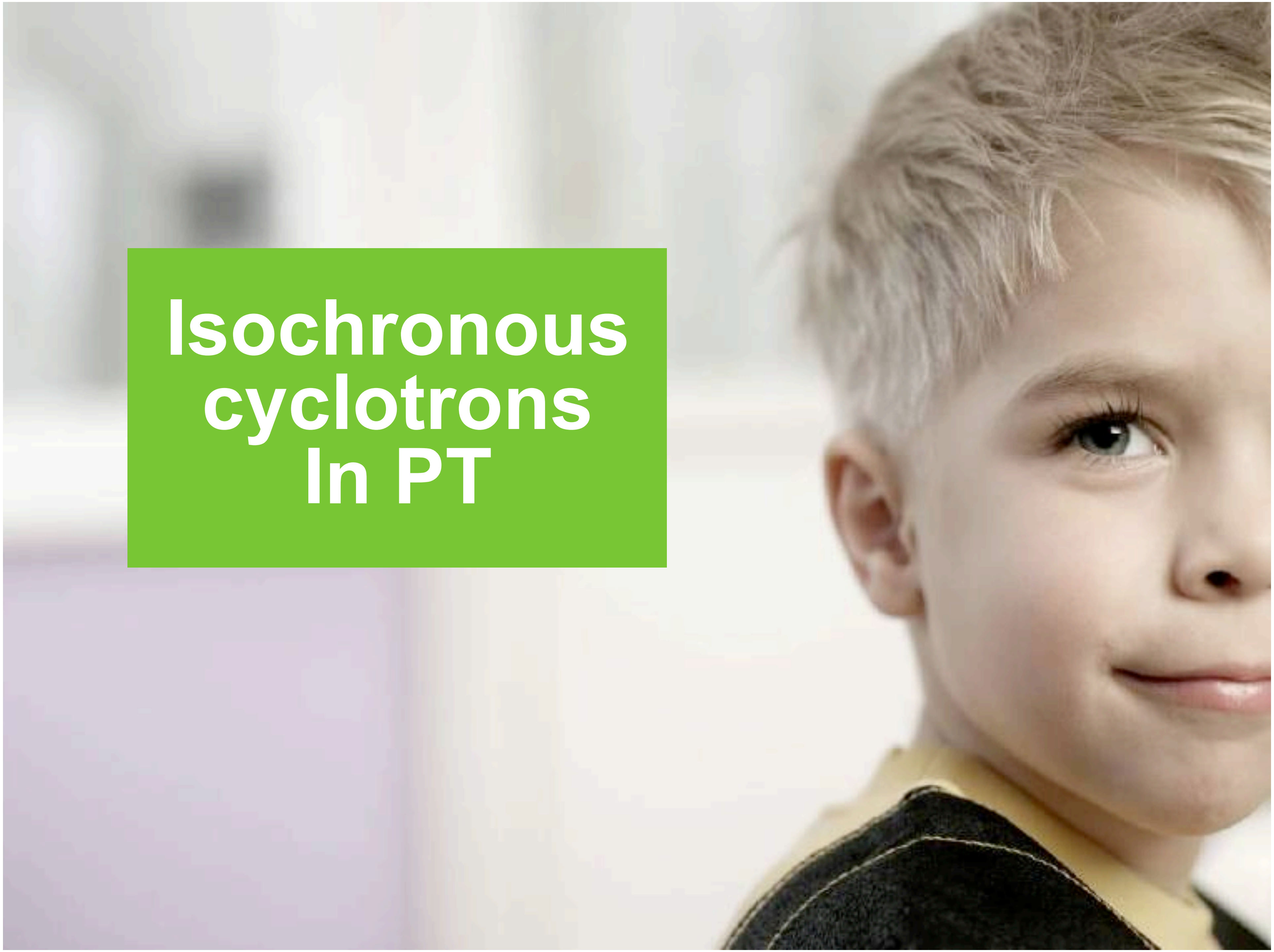
Ion source and central region



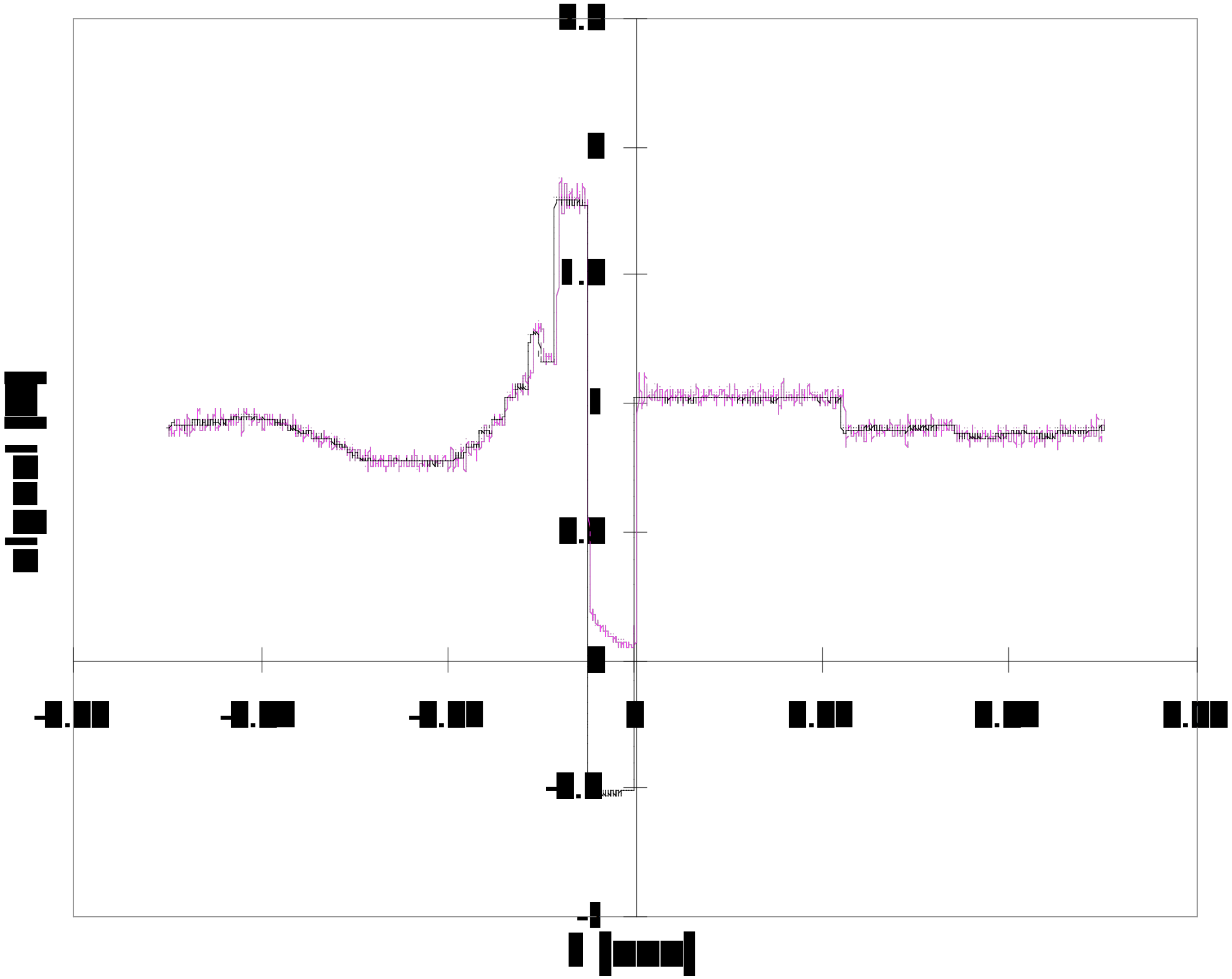
Electrostatic deflector


Isochronous
cyclotrons
In PT

Cyclotrons for Proton therapy?

- In 1991, when IBA entered in PT, the consensus was that the best accelerator for PT was a synchrotron
- IBA introduced a very effective cyclotron design, and today the majority of PT centers use the cyclotron technology
- Over these 15 years, users came to appreciate the advantages of cyclotrons:
  - Simplicity
  - Reliability
  - Lower cost and size
  - But, most importantly, the ability to modulate rapidly and accurately the proton beam current

Proton beam current regulation



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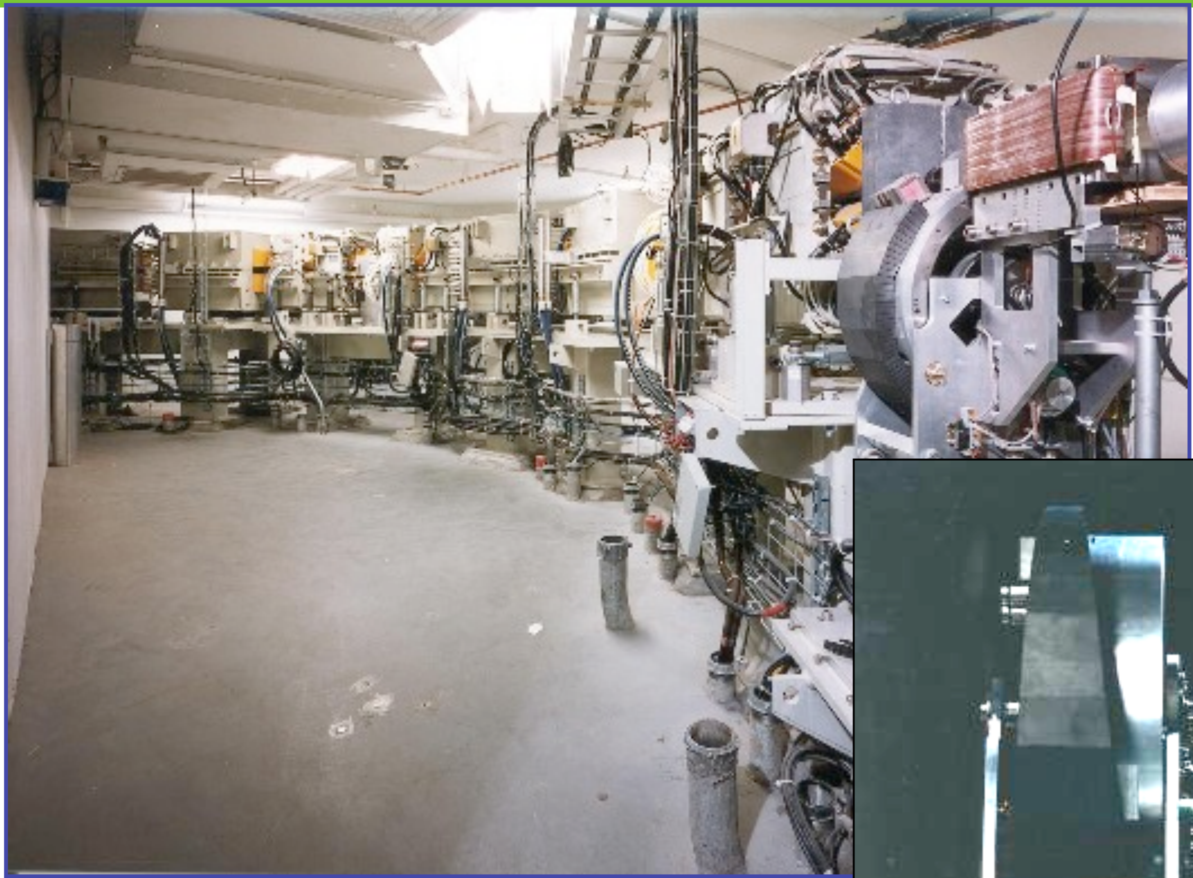
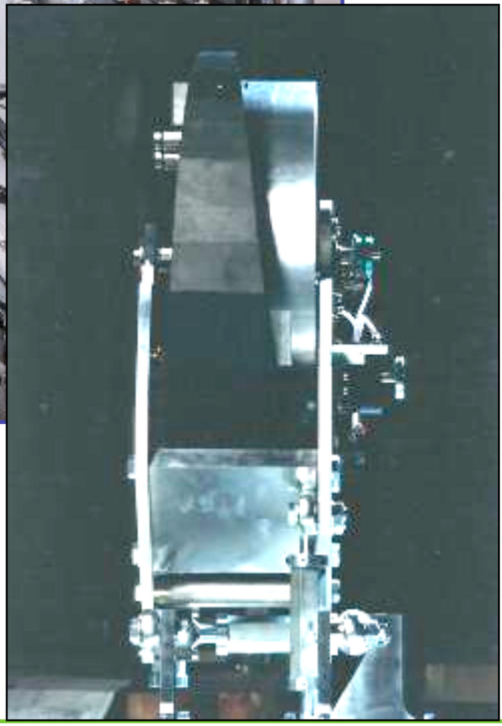
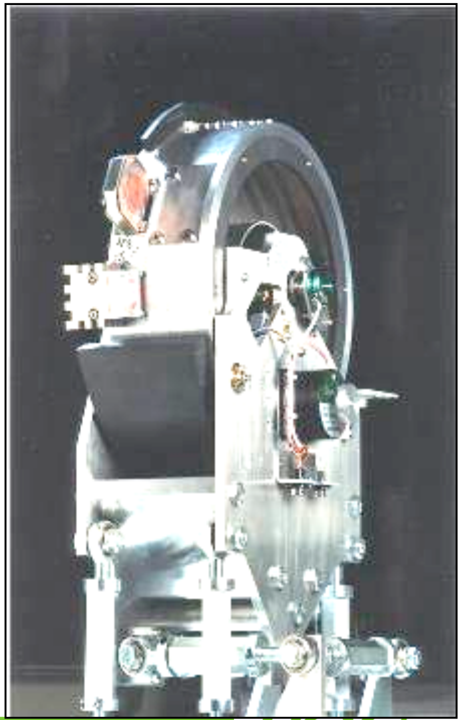
Change of energy?

- Cyclotrons are simpler at fixed energy
- Energy change by graphite degrader at waist after cyclotron exit, followed by divergence slits and energy analyzer
- This very effectively decouples the accelerator from the patient
- With carbon beams, fragmentation products are effectively eliminated in slits and ESS
- Yes, neutrons are produced, but ESS is well shielded and the average beam current in PT or CT is very low > little activation
- How fast? 5 mm step in energy in 100 msec at PSI (vs. 2 sec for synchro). But respiration cycle is 2…4 seconds, so 100 msec is fine

The degrader and ESS







Thank you…