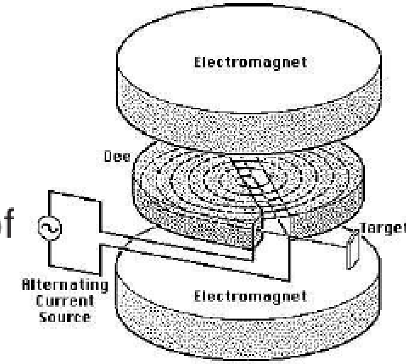
CYCLOTRONS

- A BRIEF HISTORY
- BASIC PRINCIPLES
- CYCLOTRONS NOWADAYS

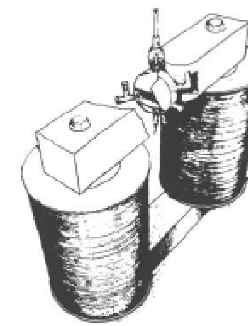
Cyclotron (1/5)



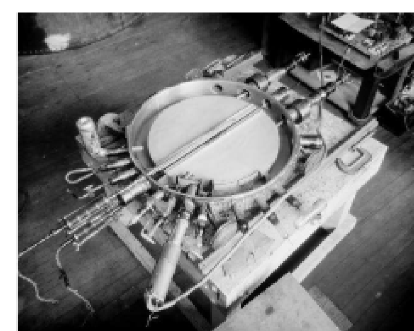
- 1929-1930, Ernest O. Lawrence inspired by Wideroe & Ising ideas invents (the principle of) the cyclotron :

  having read Wideroe's paper, he speculated on the use of a magnetic field to bring the particle back to a *single* accelerating gap next to acceleration.

  - Doing so he found that the revolution frequency in uniform B is constant : the "cyclotron angular frequency", $\boxed{\omega_0 = qB/m}$
  - That allows RF gap voltage at constant frequency, $f_{RF} = qB\,/\,2\pi m$.



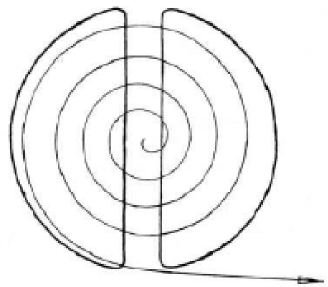
- 1931, Stanley Livingston, Berkeley, demonstration with 5-inch cyclotron by acceleration of hydrogen ions up to 80 KeV (about 40 turns up to $r \approx 4.5$ cm).
- 1932, ϕ30 cm cyclotron built by Lawrence produces protons at 1.25 MeV and breaks atoms *a few weeks after Cockcroft-Walton's Li + p*
- 1934, Berkeley, E.O. Lawrence builds a 27-inch cyclotron, accelerates protons to 3 MeV and D to 5 MeV
- 1939, E. O. Lawrence receives the Nobel Prize "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements".



The device is inserted in the gap of an electromagnet.

- That was just the beginning of a lasting story, yet...

Cyclotron (2/5) - classical



With B constant in time and uniform in space, as particles gain energy from the rf system, they stay in synchronism, but spiral outward in r.

- Non-relativistic cyclotron

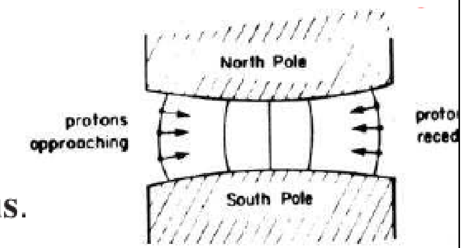
  - orbit : $\boxed{r = v/\omega_0 = mv/qB}$
  - focusing (1) :

    $F_z = qvB_r \approx qv\frac{\partial B_r}{\partial z} \equiv qv\frac{\partial B_z}{\partial r}$

    $\ddot{z} - \frac{qv}{m}\frac{\partial B_z}{\partial r} = 0 \rightarrow \omega_z^2/\omega_0^2 = \nu_z^2 = -\frac{r}{B_z}\frac{\partial B_z}{\partial r} = -k, \quad \boxed{\nu_z = \sqrt{-k}}.$

    hence the field index k needs be negative : **B_z is slowly decreased with radius**.

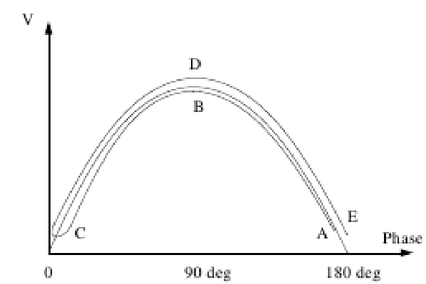
    Similarly, $\boxed{\nu_r = 1 + k}$. This sets the requirement $\boxed{-1 < k < 0}$



  - focusing (2) : is also ensured at lower energy by the electric field.
  - isochronism :

    The condition for vertical focusing, $-1 < k < 0$ (B is not constant), spoils the isochronism.

    As a consequence, the phase is not constant (ABCDE path)



  - bunching : particle beam injected into the cyclotron necessarily gets bunched, at the frequency of the RF (the time interval between two bunches is an RF period)

- The classical limit ($\gamma \approx 1$) is ~25 MeV for protons, 50 MeV for D and α, (about $2-3$% increase in mass), GANIL in Caen accelerates Carbon to about 100 MeV/u...

- That was enough energy to transmute all nuclei... The classical cyclotron allowed discovering oodles of nuclear reactions and isotopes.

  Yet, let's keep in mind : transmutation was not the all story

Cyclotron (3/5) - classical

- Relativistic energies, the bad news :

  - The cyclotron resonance $\omega_0 = qB/\gamma m$, with $r = \beta c/\omega_0$ yields $\boxed{k = \frac{\beta}{\gamma}\frac{\partial\gamma}{\partial\beta} = \beta^2\gamma^2}$

  - so k cannot satisfy $\boxed{-1 < k < 0}$,

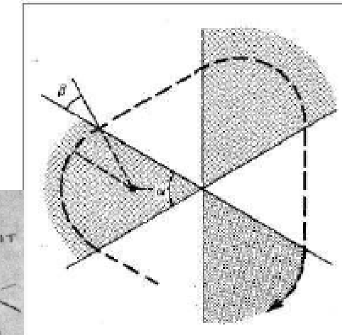
  isochronism requires that $B(r) \propto \gamma$, which yields vertical defocusing...

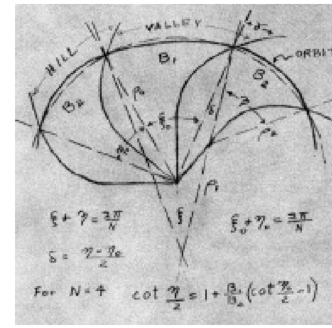
- That was the end of the story, ~ 25 MeV protons, etc... :
  Hans Bethe (1937) :
  "... it seems useless to build cyclotrons of larger proportions than the existing ones... an accelerating chamber of 37 cm radius will suffice to produce deuterons of 11 MeV energy which is the highest possible..."

  Frank Cole : "If you went to graduate school in the 1940s, this inequality ($1 < k < 0$) was the end of the discussion of accelerator theory."

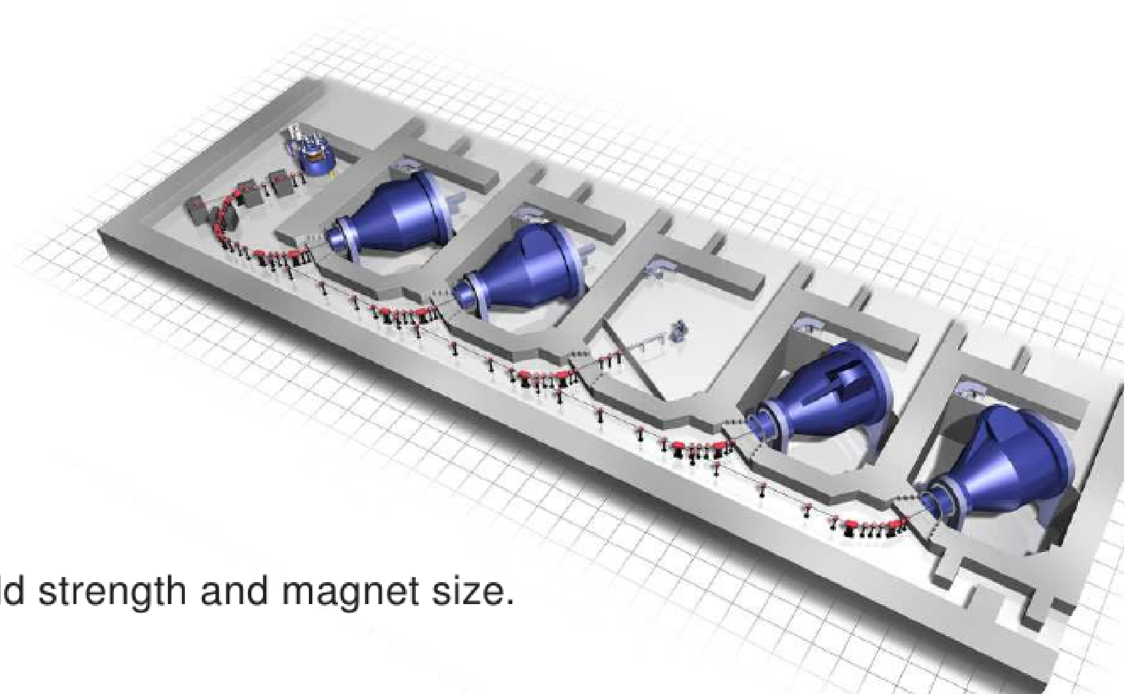
- Until...

Cyclotron (4/5) - Thomas focusing





- 1938, L.H. Thomas, “The Paths of Ions in the Cyclotron”, introduces the “Thomas focusing”, based on separate sector bending, namely, “edge-focusing”,
- 1954, Kerst, spiral edges increase vertical focusing further
  $\boxed{\nu_z = \sqrt{-k + F^2(1 + 2\tan^2\xi)}}$, $\quad F = Flutter = \frac{<B^2>-<B>^2}{<B>^2}$
- That allowed having $B(r)$ increase in proportion to γ, so to ensure constant RF frequency ($\omega_0 = qB/\gamma m$), 8.13 while *preserving vertical focusing*.
- Modern cyclotrons still rely on these principles



- Cyclotron is limited in energy by its field strength and magnet size.

Some famous cyclotrons. Popular applications.

- PSI highest power, ~SNS linac
- TRIUMF
- Proton-therapy
- Radio-isotope production
- Education