Lawrence's **Cyclotron Accelerator** and Its Developments

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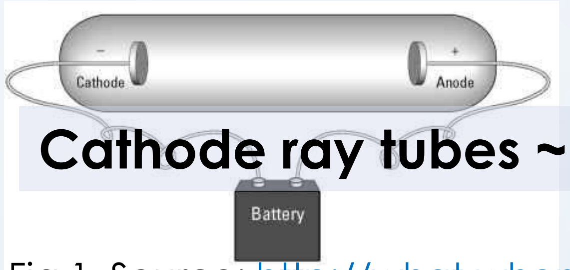
Outline

- Introduction
- Timeline of Inventions
- Classical Cyclotron
- Relativistic considerations
- Development of cyclotron devices
- Notable Examples
- Conclusion
- References

Introduction

Earlier accelerators were electrostatic field based



Cathode ray tubes ~ late 1800s

Fig 1. Source: http://what-when-how.com

Cockroft and Walton ~ 1920

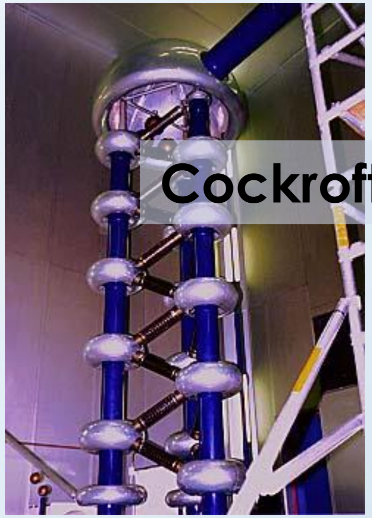


Fig 3. Source: http://blazelabs.com/e-exp15.asp

Van de Graff ~ 1930

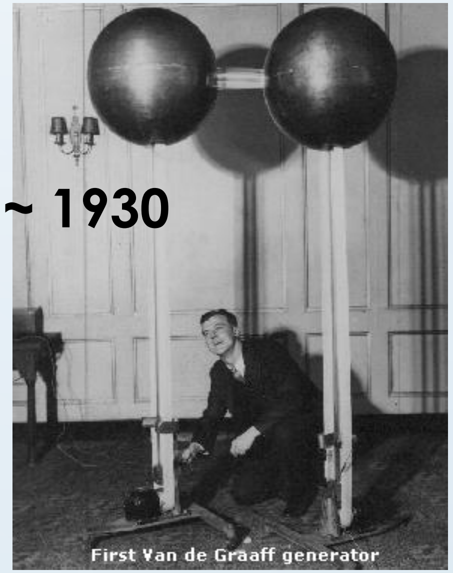


Fig 2. Source: http://cst.mos.org/sln/toe/history.html

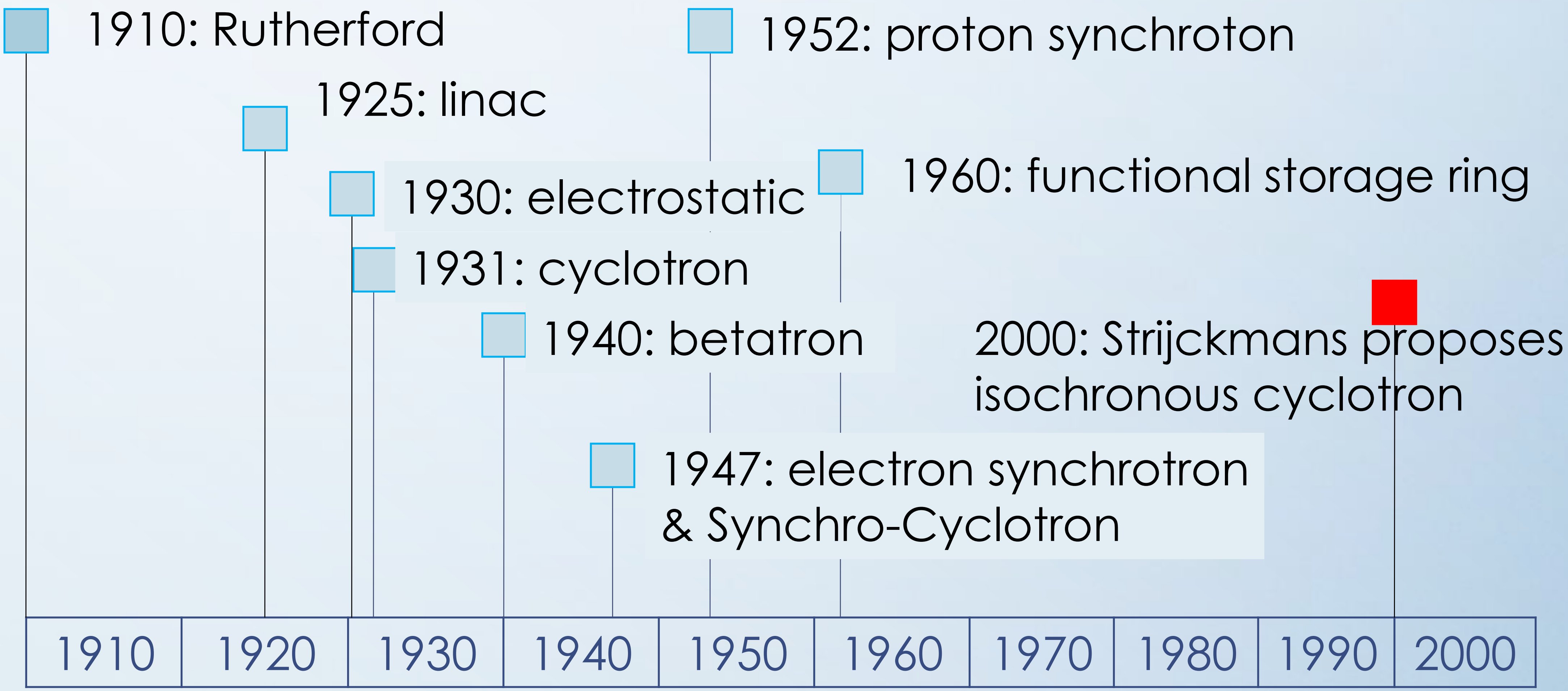
Practical limitations using high voltage: problem with **corona**, **insulation** and **design** of vacuum tubes were difficult

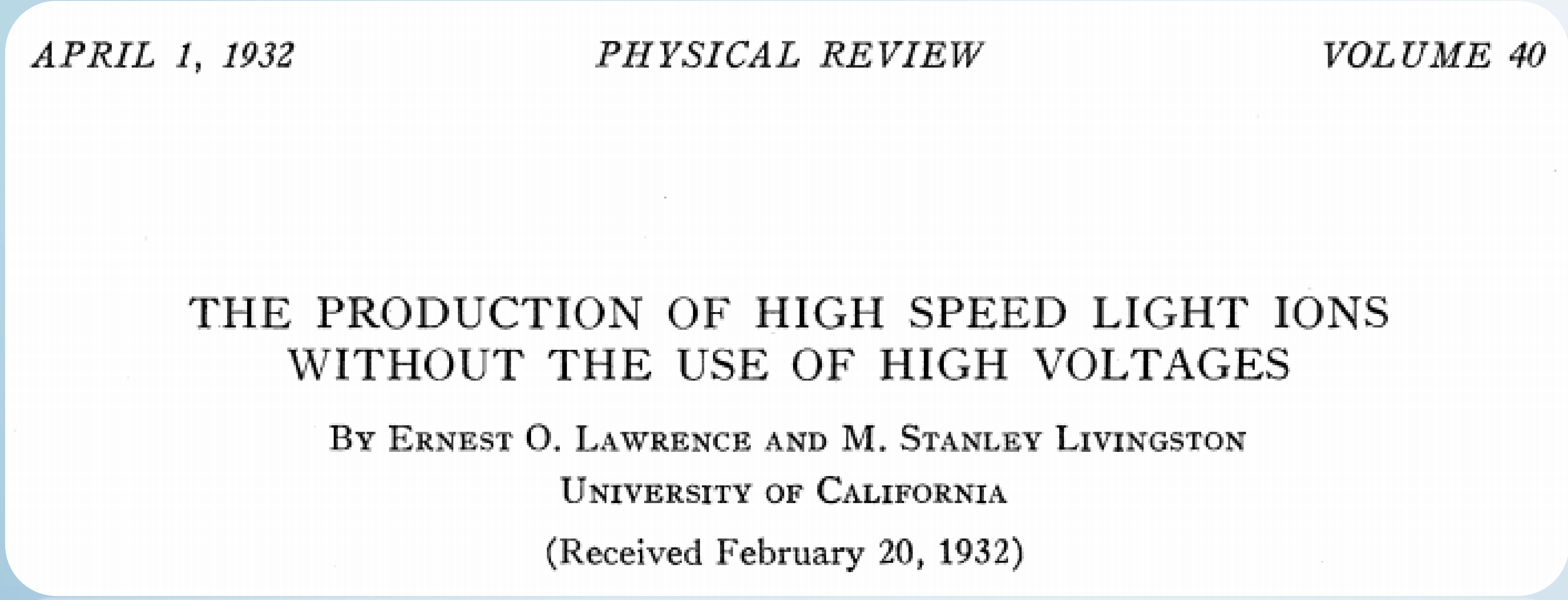
Introduction (cont)

"It is required **a vacuum tube many meters long** to accelerate lighter projectiles (such as **alpha particles**). Therefore, bending those particles into **a circular path** to send them through the same electrode repeatedly was better."

Timeline of Inventions

Timeline of Inventions




APRIL 1, 1932 PHYSICAL REVIEW VOLUME 40

THE PRODUCTION OF HIGH SPEED LIGHT IONS WITHOUT THE USE OF HIGH VOLTAGES

By Ernest O. Lawrence and M. Stanley Livingston
University of California

(Received February 20, 1932)

The Classical Cyclotron Accelerator

The Experimental Method

Fields provide focusing effect!

Connected to high frequency oscillator

Peak value 4000 V

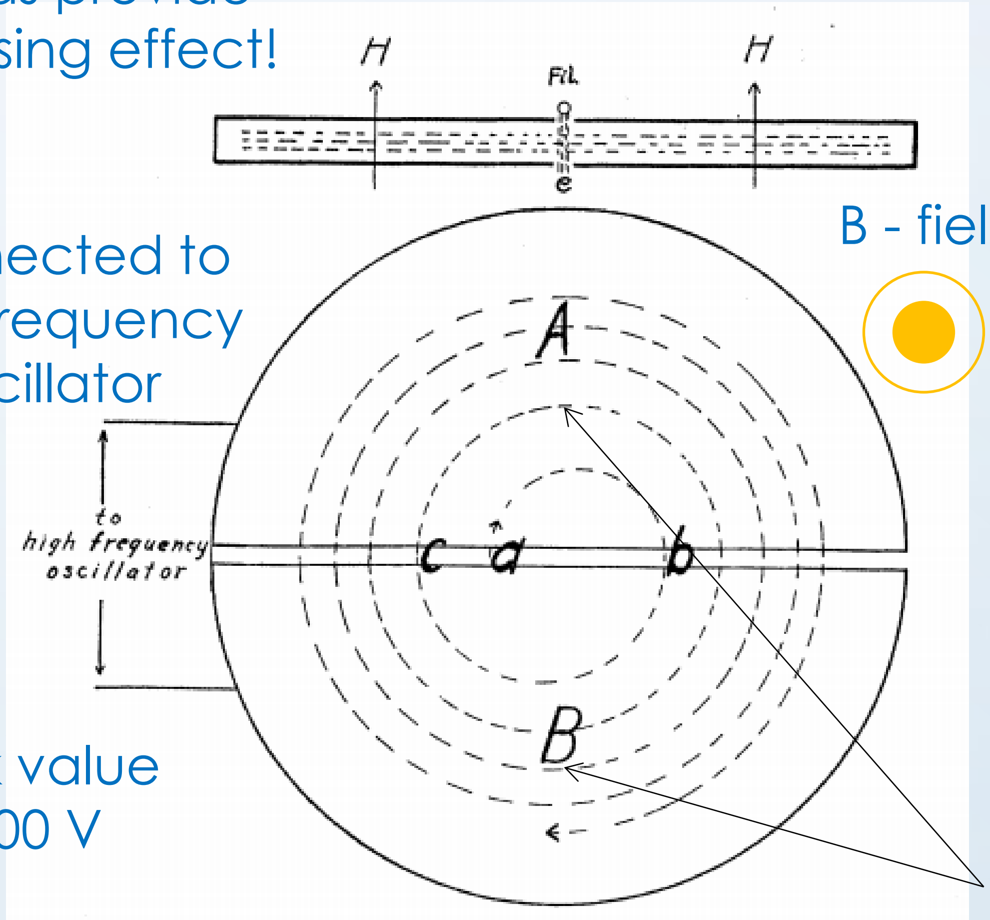


Fig.4 Diagram of experimental method for multiple acceleration of ions [Phys. Rev. 40, 19]

B - field

Electrodes
(Semi circular hollow plates)

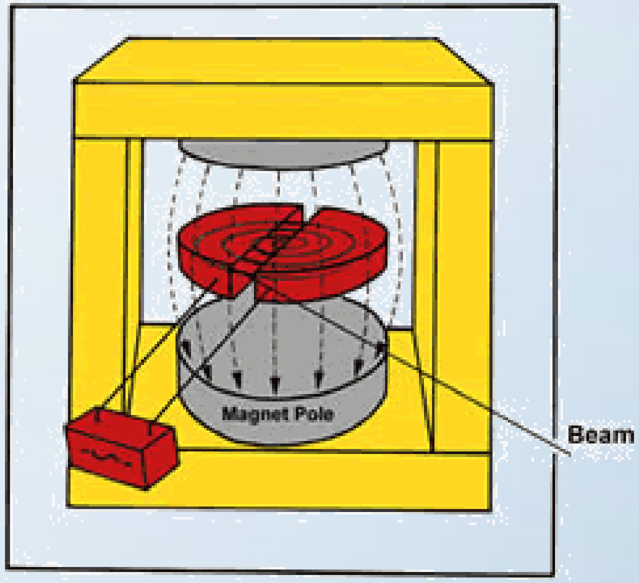


Fig.5 The dees, driven by an RF oscillator, lie between the poles of a magnet excited by direct current.

http://www.nobelprize.org/nobel_prizes/themes/physics/kullander/

Experimental Arrangement

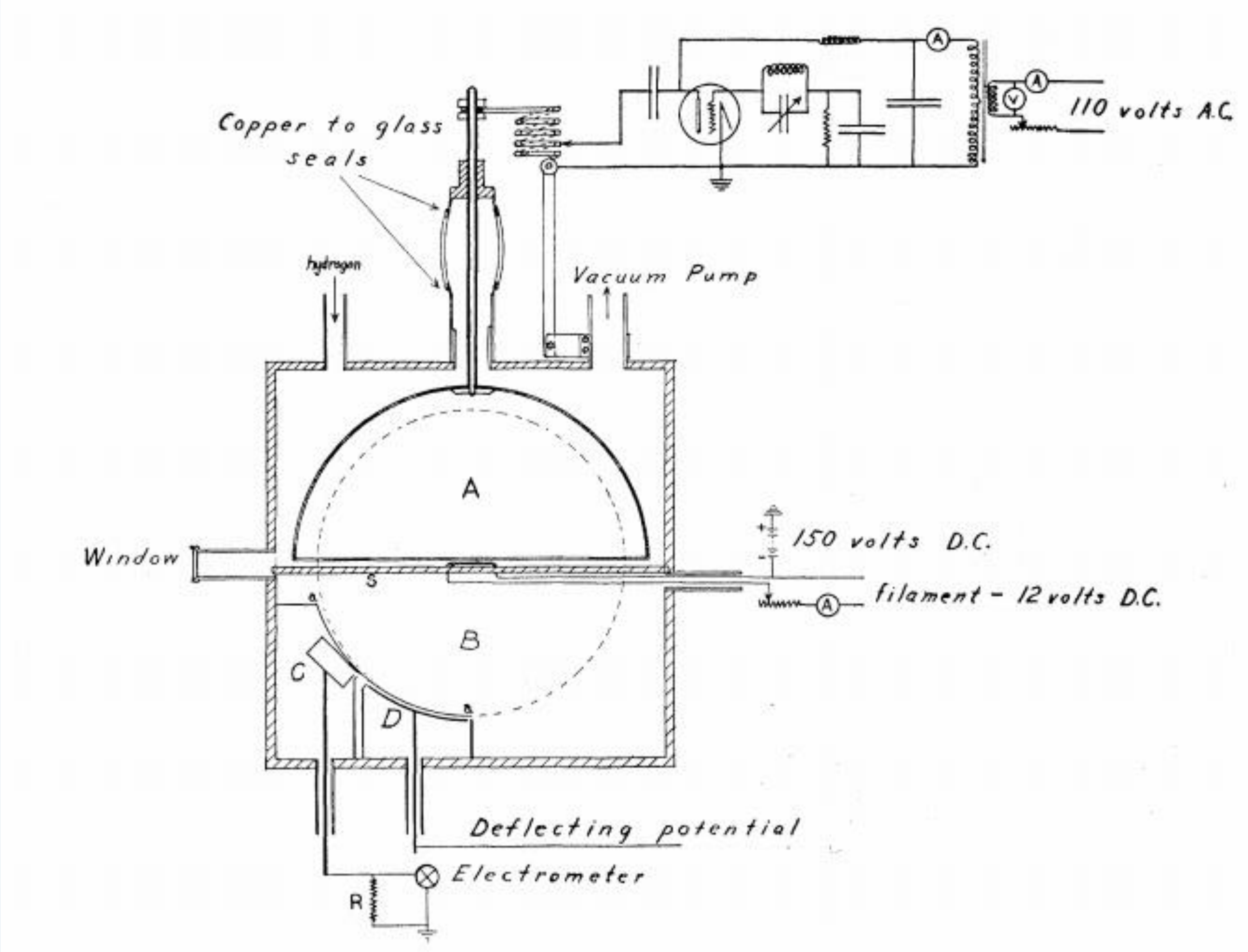


Fig.6 Diagram of apparatus for the multiple acceleration of ions[Phys. Rev. 40, 19]

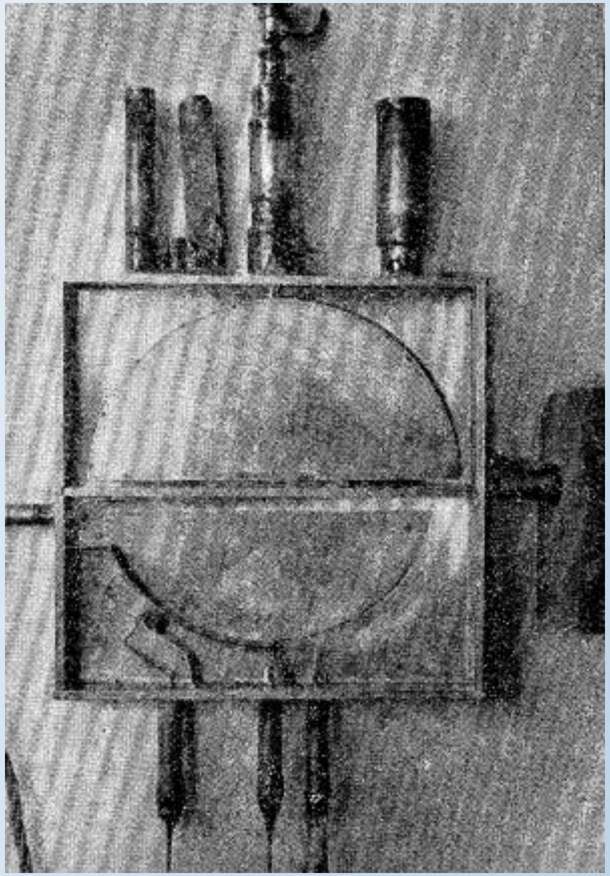
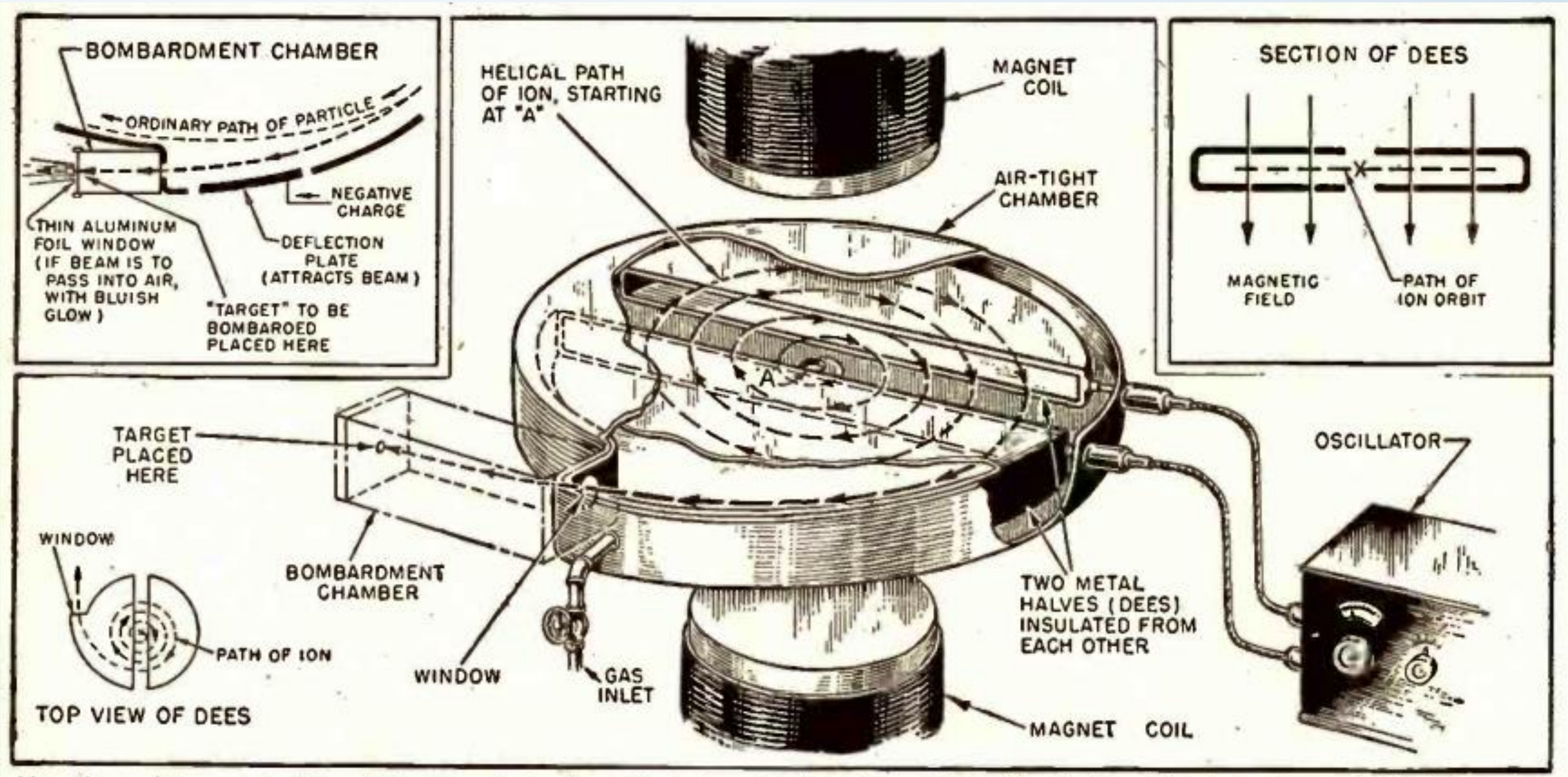


Fig.7 Tube for the multiple acceleration of light ions – with cover removed [Phys. Rev. 40, 19]

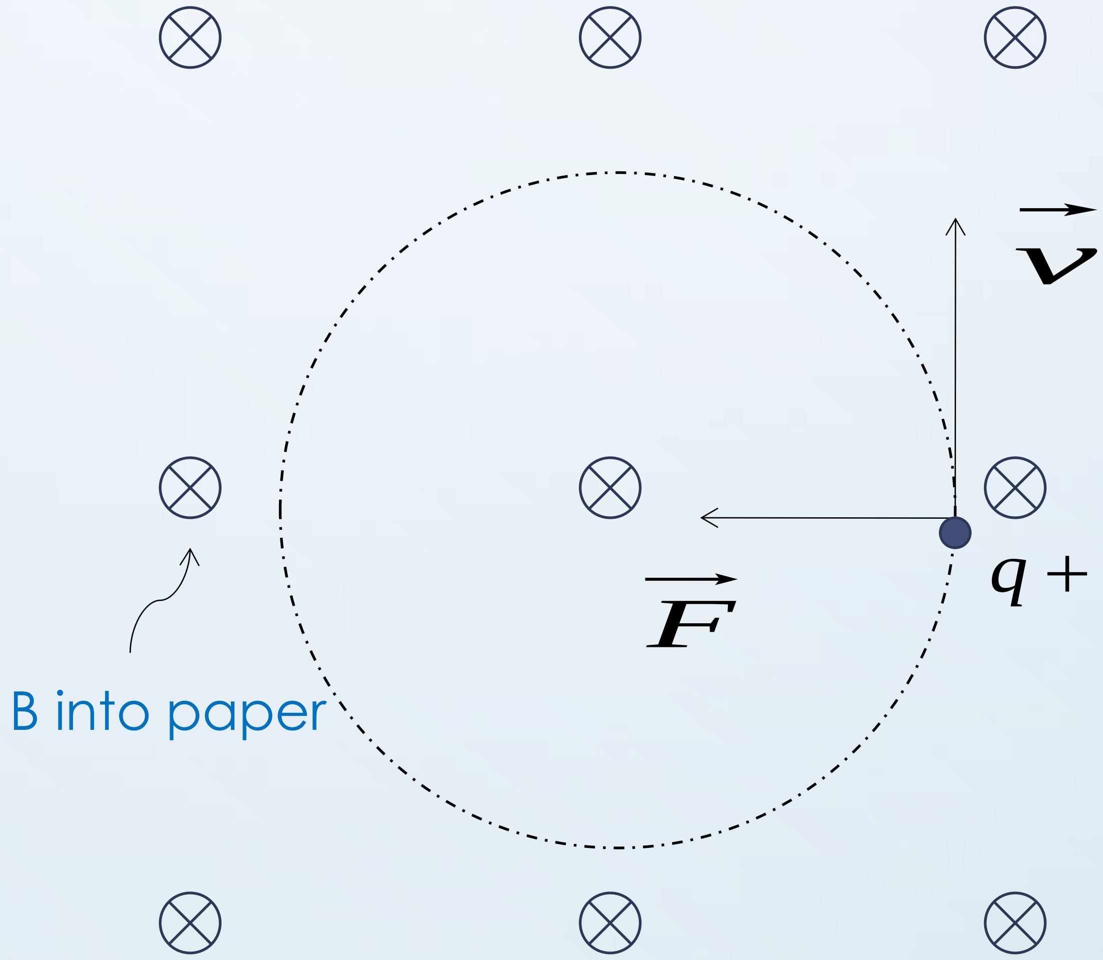
Principle of Operation



How the cyclotron works. Size of the magnets has been kept down to show dees path of the electron. See photo above for their true size.

Fig.8 How the cyclotron works. Source: http://www.americanradiohistory.com/Archive-Radio-Craft/1940s/Radio-Craft-1947-Jun.pdf

Governing Relation in Cyclotrons



A positive particle q sees a centripetal force at right angles to the direction of motion:

$$\frac{mv^2}{r}\hat{r} = q\vec{v} \times \vec{B}$$

$$r = \frac{mv}{qB}$$

The angular frequency of rotation

$$\omega = qB/m$$

Gyrofrequency

Relativistic Considerations

Relativistic Considerations

The relativistic mass can be rewritten as

$$m = \frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0$$

Lorentz factor

The angular frequency of rotation

$$\omega' = \frac{qB}{\gamma m} = \frac{qB}{m_0}\sqrt{1-\left(\frac{v}{c}\right)^2}$$

This modification has the following effect on the gyrofrequency

$$\frac{v}{c} = 50\% \Rightarrow \gamma = 1.155 \Rightarrow \omega' = 0{,}86\omega$$

$$\frac{v}{c} = 99\% \Rightarrow \gamma = 7.1 \Rightarrow \omega' = 0{,}14\omega$$

For example:

Proton Energy	**% Frequency decrease**
10 MeV	~1%
250 MeV	~21%
1.0 GeV	~52%

How to manage the relativistic change in mass?

Development of cyclotron devices

Development of cyclotron devices

- **There are at least 3 kinds of cyclotrons:**

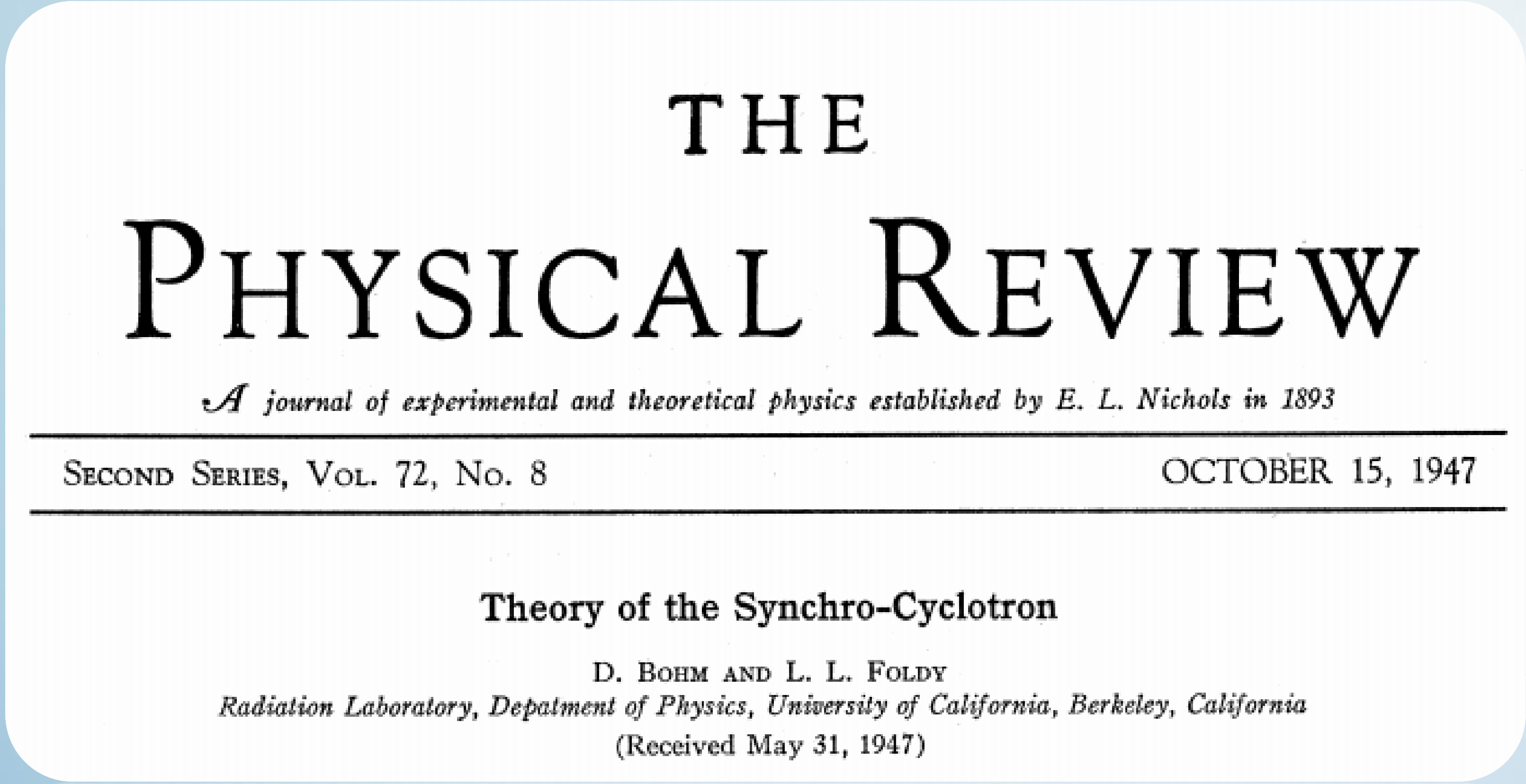
CLASSICAL CYCLOTRON

SYNCHRO – CYCLOTRON

ISOCHRONOUS – CYCLOTRON

Classical (Review)

- **CLASSICAL**: (original)
  - Operate at fixed frequency ($\omega = qB/m$) and ignore the mass increase
  - Works to about 25 MeV for protons ($\Upsilon = 1.03$)
  - Uses slowly decreasing magnetic field 'weak focusing'



THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 72, NO. 8 OCTOBER 15, 1947

Theory of the Synchro-Cyclotron

D. BOHM AND L. L. FOLDY
Radiation Laboratory, Depatment of Physics, University of California, Berkeley, California

(Received May 31, 1947)

Synchro – Cyclotron

Synchro – Cyclotron

- **SYNCHRO – CYCLOTRON**: let the RF frequency ω decreases as the energy increases
  - $\omega = \omega_0 / \Upsilon$ to match the increase in mass ($m = \Upsilon m_0$)
  - Uses same decreasing field with radius as classical cyclotron

PERGAMON

Computerized Medical Imaging and Graphics 25 (2001) 69–78

Computerized Medical Imaging and Graphics

www.elsevier.com/locate/compmedimag

The isochronous cyclotron: principles and recent developments ☆

K. Strijckmans*

Institute for Nuclear Sciences, Ghent University, INW-RUG, Proeftuinstraat 86, B-9000, Gent, Belgium

Received 20 April 2000

ISOCHRONOUS-CYCLOTRON

Isochronous – Cyclotron

- **ISOCHRONOUS**: raise the magnetic field with radius such that the relativistic mass increase is just cancelled
  - Pick $B = \gamma B_0$ {this also means tat B increases with radius}
  - Then $\omega = qB/m = qB_0/m_0$ is constant
  - Field increases with radius – magnet structure must be different!

Magnet Structure

Orbit stability is related to the magnetic induction as a function of the radius:

$$B(r) = \frac{1}{r^n}$$

Field index n!

This is used for Isochronous

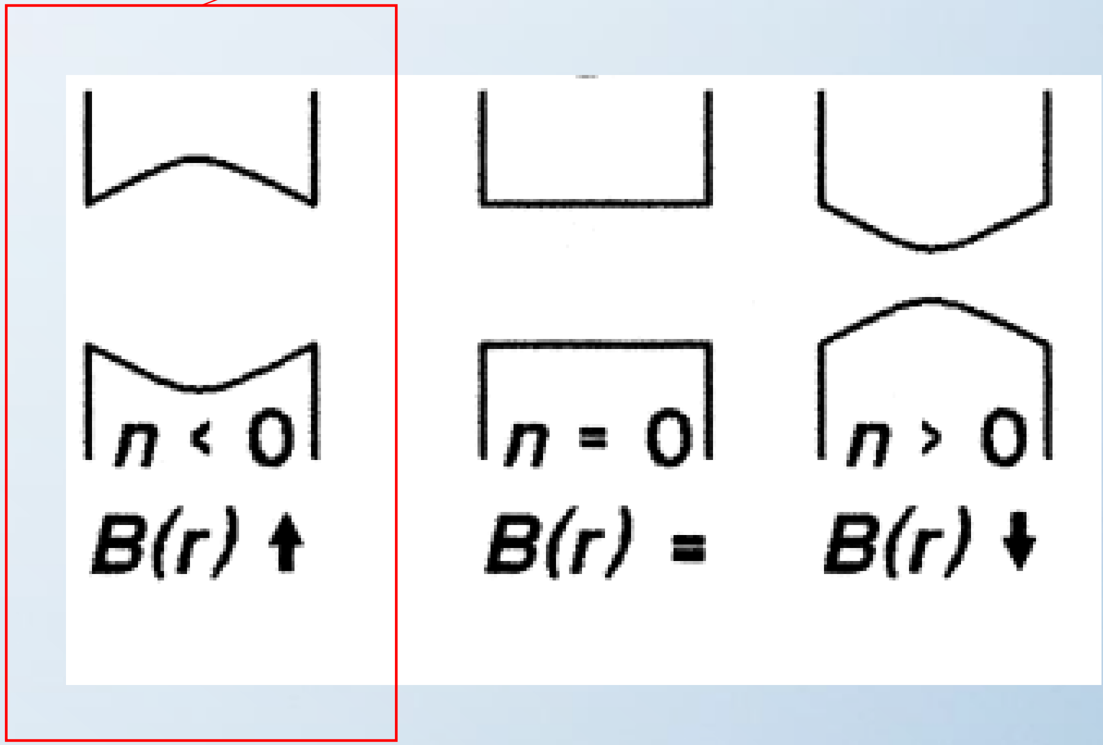
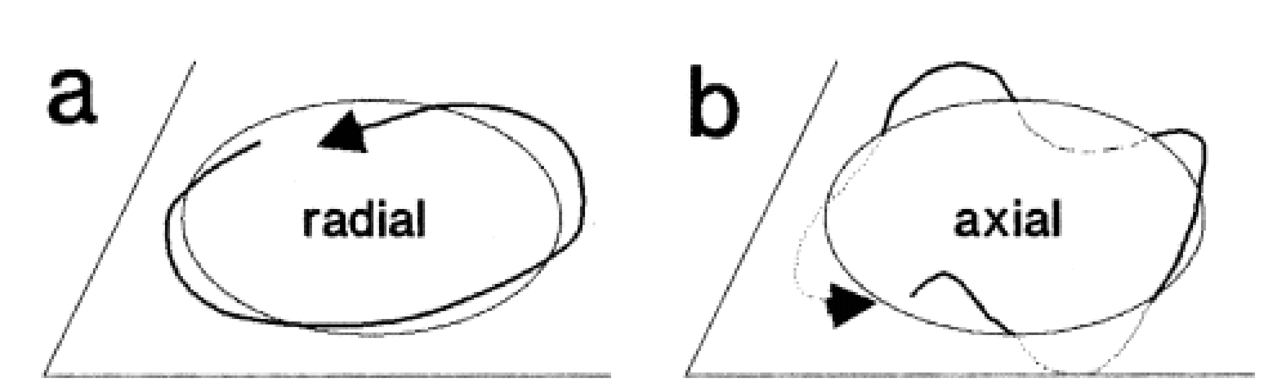


Fig.9 field index n determines magnet structure

Orbit Stability



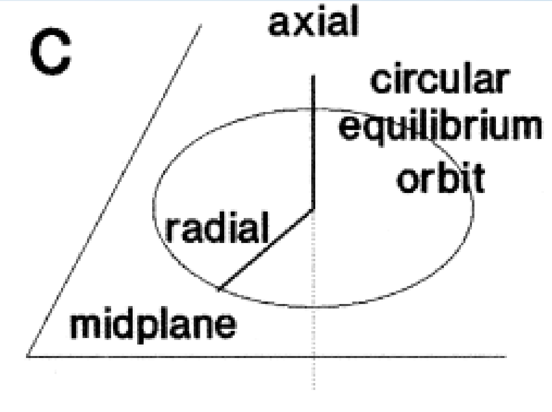


Fig 10. Radial (a) and axial (b) oscillations about a circular equilibrium orbit (c).

Orbit Stability (cont)

An alpha particle, which has **a positive electric charge**, experiences Lorentz forces

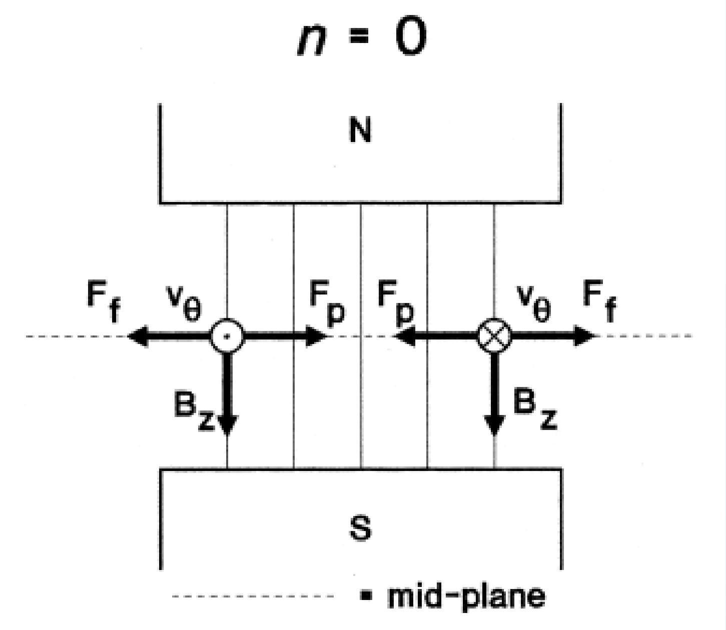


Fig 11. Radial forces for a zero field index; also valid in the mid-plane of for any field index

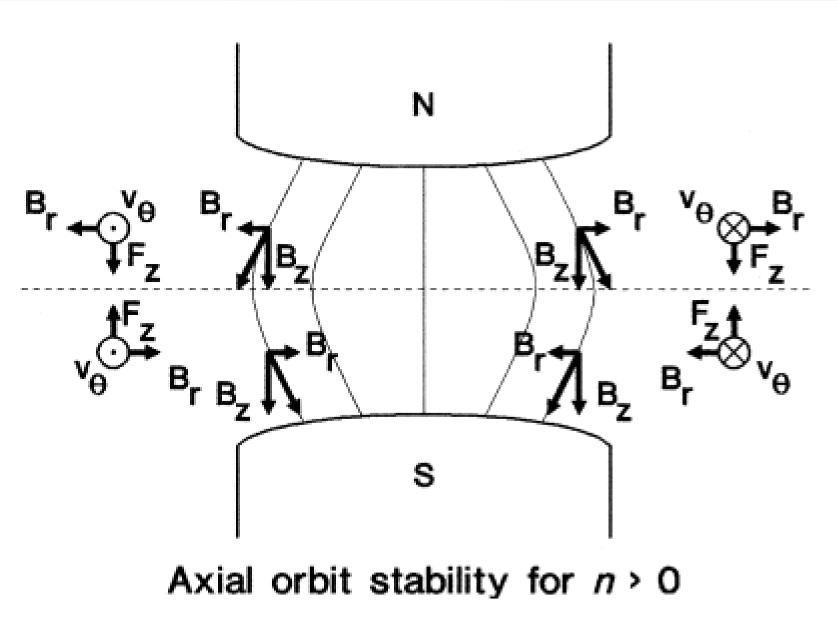


Fig 12. Axially focuussing forces Fz for a positive field index

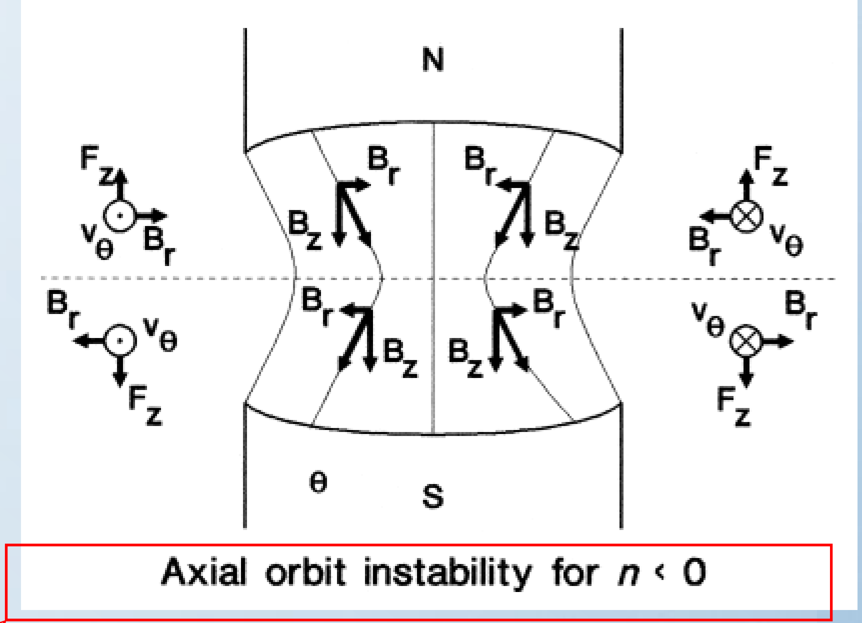


Fig 13. Axially defocusing forces Fz for a negative field index

How to prevent an axial orbit instability for n<0?

The principle of **Thomas focusing** to solve the axial orbit instability

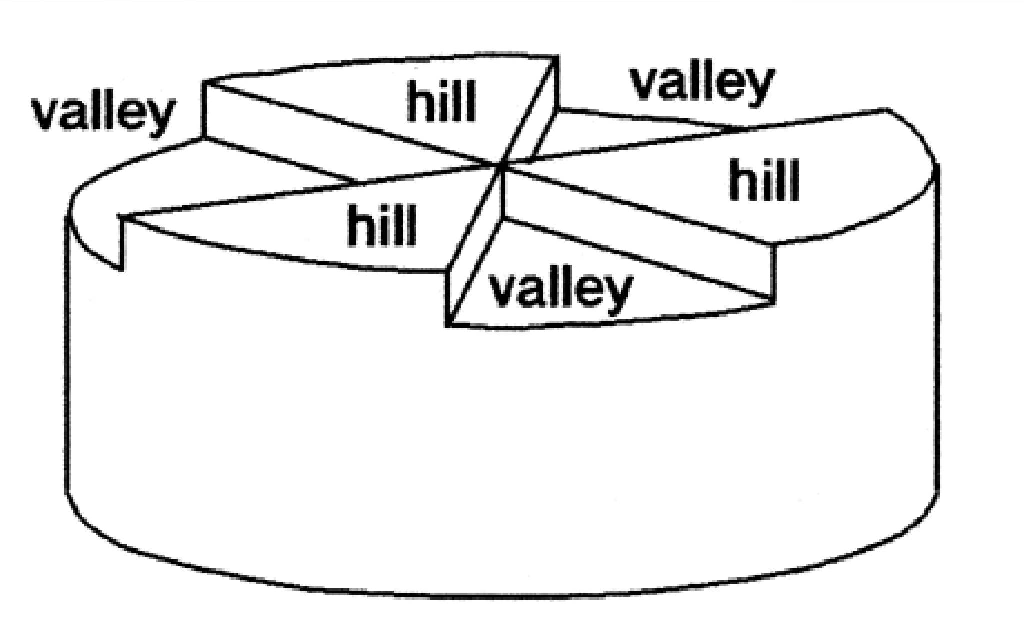


Fig 13. Magnet pole of an isochronous cyclotron, i.e. A sector focussed or AVF (azimuthally varying field) cyclotron plane (reproduced with permission of Jhon Wiley & Sons. Ltd from Strijckmans K. Charged particle accelerators. In; Z.B. Afassi, editor. Chemical analysis by nuclear methods. Chichester (UK), 1994)

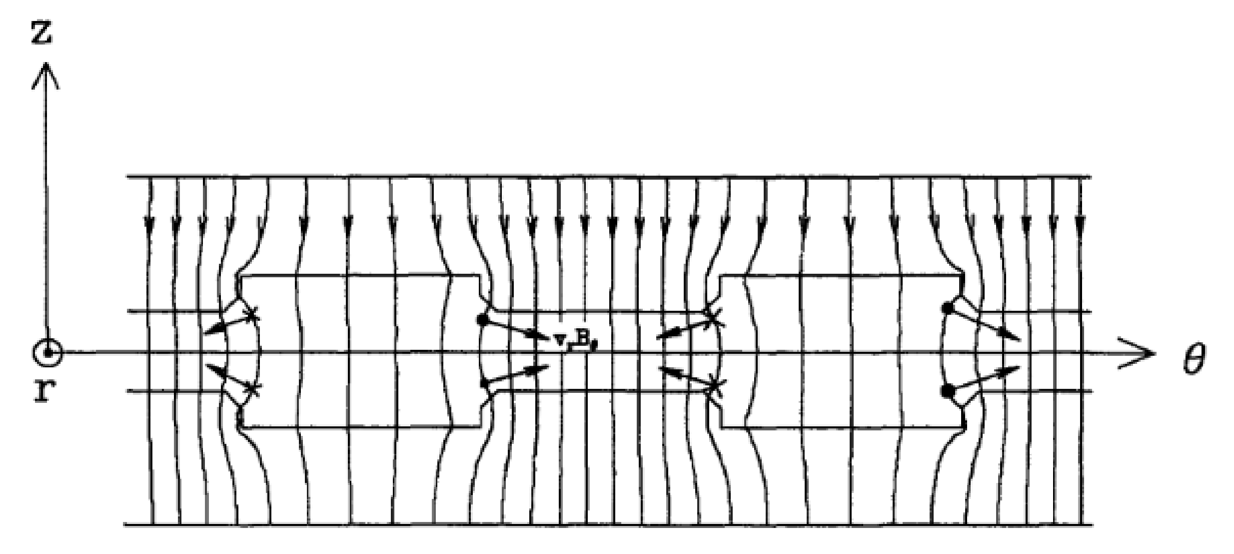


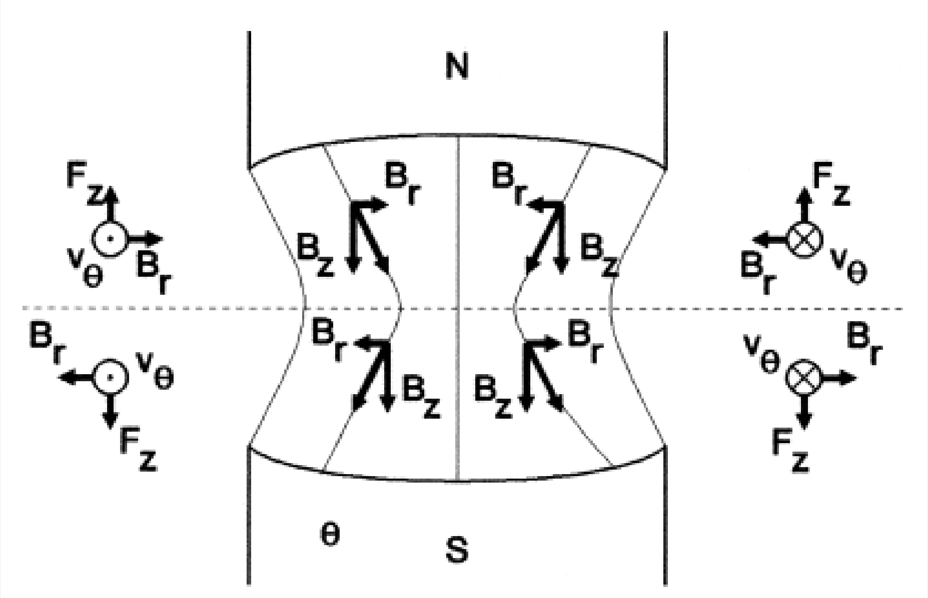
Fig 14. Thomas force acts always towards the median plane. The dot means that the particle has a velocity component from the paper and the cross that the particle has a velocity component towards the paper. (Heikkinen, Pauli, 1994)

Positive and Negative ions

Actually, the cyclotron can be used to accelerate not only **the positive** but **also negative ions**

For the positive ions

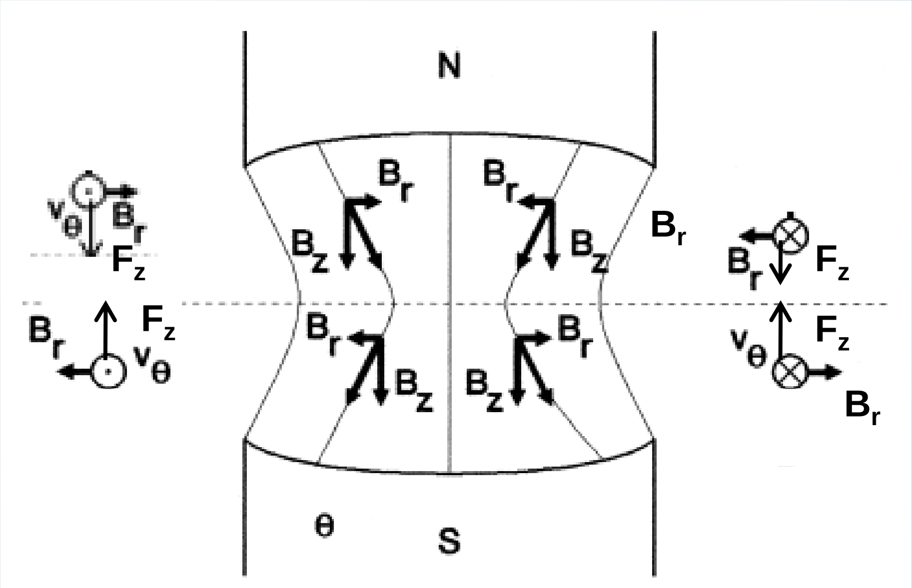
(a)



Axial orbit instability for n < 0 with the positive ions

For the negative ions

(b)



Axial orbit stability for n < 0 with the negative ions

Fig 15. Whether the "magnetic structure for n < 0" causes the axial ion orbit instability or not, it depends on the charge on the ion (positive or negative). **"The magnetic structure for n < 0" doesn't cause the axial orbit instability for the negative ions.**

Notable Examples

Notable Examples

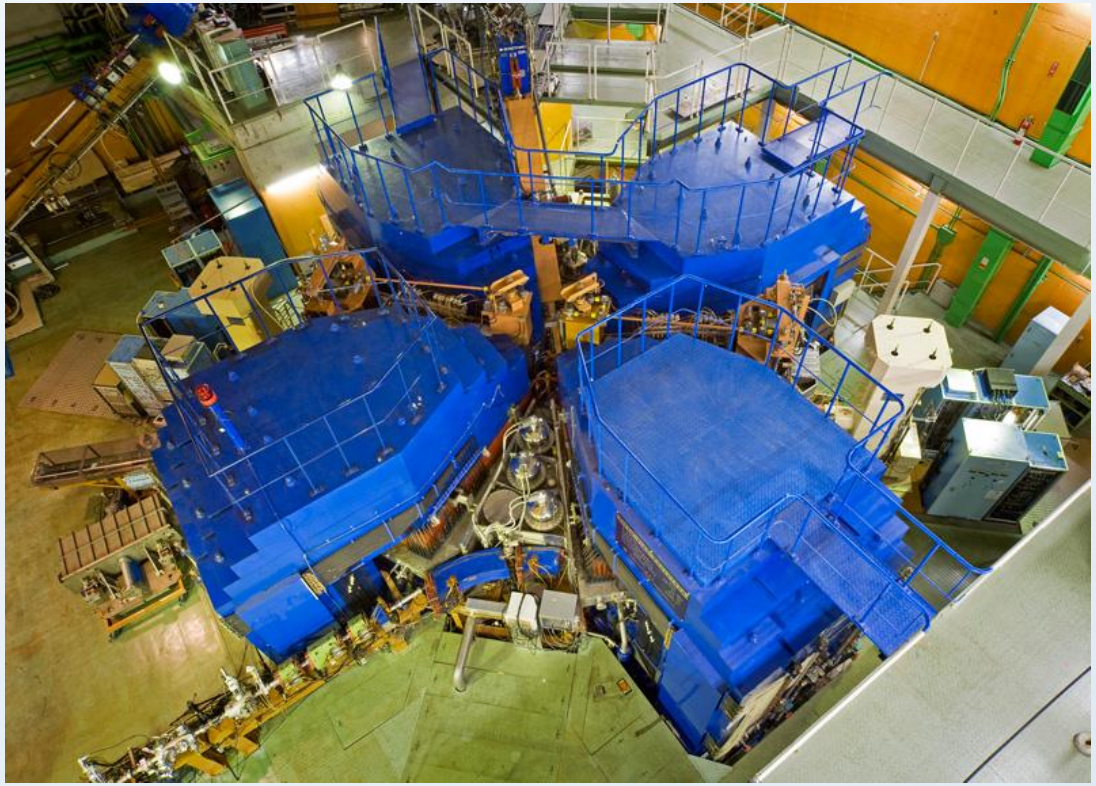


Fig 15. SRC Cyclotron at RIKEN laboratory in Japan.
Source: http://www.nishina.riken.jp/facility/RRC_e.html

Fig 16. One of the TRIUMF's Cyclotrons.
Source: http://www.triumf.ca/headlines/current-events/new-milestone-for-tc-99m-production

CONCLUSION

- E. O. Lawrence invented cyclotron which operate at fixed frequency ($\omega = qB/m$) and ignore the relativistic change in mass
- The relativistic change in mass was solved by:
  - ❖ Bohm and Foldy
    - o By raising the magnetic field with radius such that the relativistic mass increase is just cancelled
  - ❖ Strijckmans
    - o By decreasing RF frequency ω as the energy increases
- Initiated a big science, a new way of doing science
  - – Tevatron, LHC, etc

References

- **Lawrence, E. O., Livingston, M. S. *Production of high speed light ions witout the use of high voltages.* Physical Review 40, 19- 35, Apr. 1, 1932.**
- **D. Bohm, L. Foldy. *Theory of the synchro – cyclotron.* Physical Review 72, 649, 1947.**
- **Strijckmans K. *The isochronous cyclotron: principles and recent developments*. Comput Med Imaging Graph 2001; 25: 69 – 78.**
- **Heikkinen, Pauli. *CYCLOTRONS*. University of Jyvàskylâ, Accelerator Laboratory, Jyvàskylâ, Finland (1994)**

References (cont)

- **Pictures:**
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