The Spectrum of Particle Accelerators

JAI Accelerator Physics Course
Lecture 1

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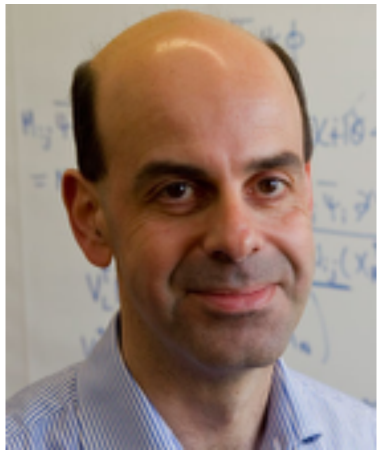
www.suziesheehy.co.uk

I’ll put the slides up there (under ‘teaching’)

as well as the JAI indico page

https://indico.cern.ch/event/668489/page/11598-home

Some of your other lecturers (Michaelmas):



Prof. Emmanuel Tsesmelis, CERN

Dr. Stuart Mangles,
Imperial College

Prof. Riccardo Bartolini,
Oxford/JAI and Diamond

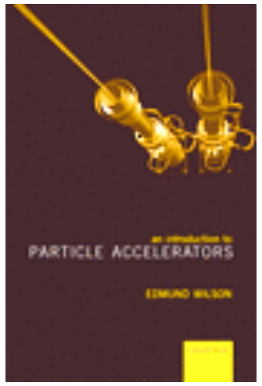
Dr. Aakash Sahai,
Imperial College

Dr. Ryan Bodenstein,
Oxford/JAI

Accelerator physics course

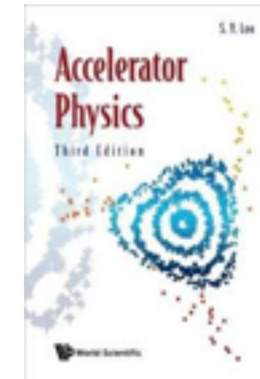
- Runs over Michaelmas & Hilary terms
- Lectures and tutorials - videoconference facility available for RHUL/IC students.
- If you want to arrange accommodation overnight Weds-Thurs please contact Sue Geddes sue.geddes@physics.ox.ac.uk and she may be able to line up a room in a college.
- In Hilary term: design study project (for JAI students from Oxford, RHUL and ICL)

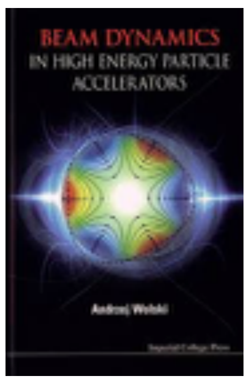
Useful textbooks:



"An Introduction to Particle Accelerators", E. Wilson
http://www.oup.com/uk/catalogue/?ci=9780198508298

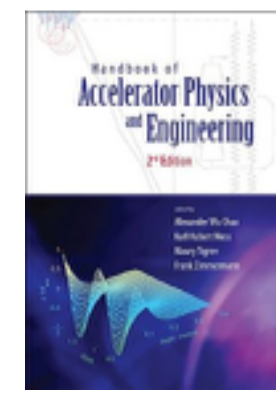
Accelerator Physics, S. Y. Lee



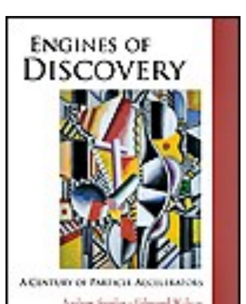


Beam Dynamics in High Energy Particle Accelerators, A. Wolski

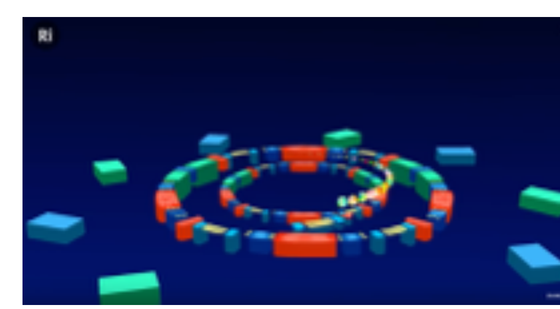
Handbook of Accelerator Physics & Engineering, (3rd edition now), A. Chao & M. Tigner



Interest/outreach:



"Engines of Discovery", A. Sessler, E. Wilson
http://www.worldscientific.com/worldscibooks/10.1142/8552

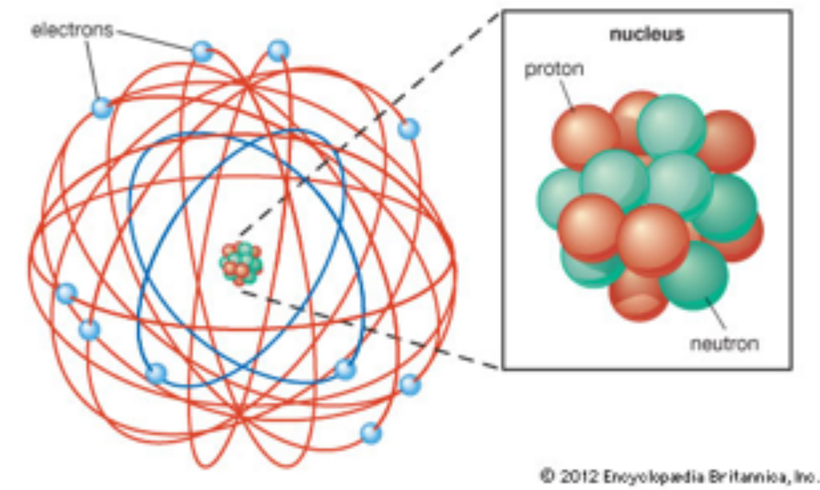


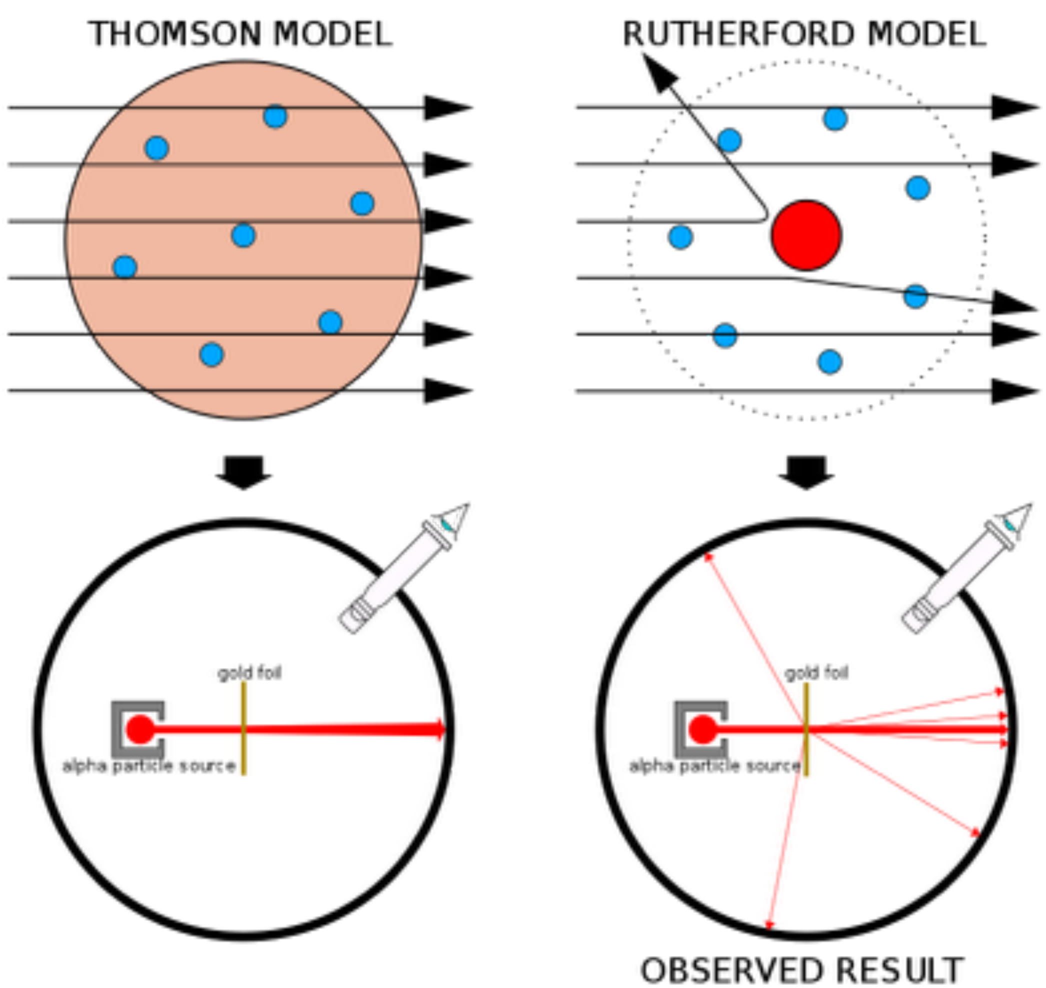
"Accelerators for Humanity" video series, Royal Institution
http://richannel.org/collections/2016/particle-accelerators-for-humanity

Outline

- Intro to particle accelerators in general
- Different types of accelerators
  - Electrostatic
  - Linac
  - Cyclotron
  - Betatron, microtron, rhodotron
  - Synchrotron
  - FFAG

The early 1900's…





E=4.78 MeV

Rutherford gold foil experiment, 1911

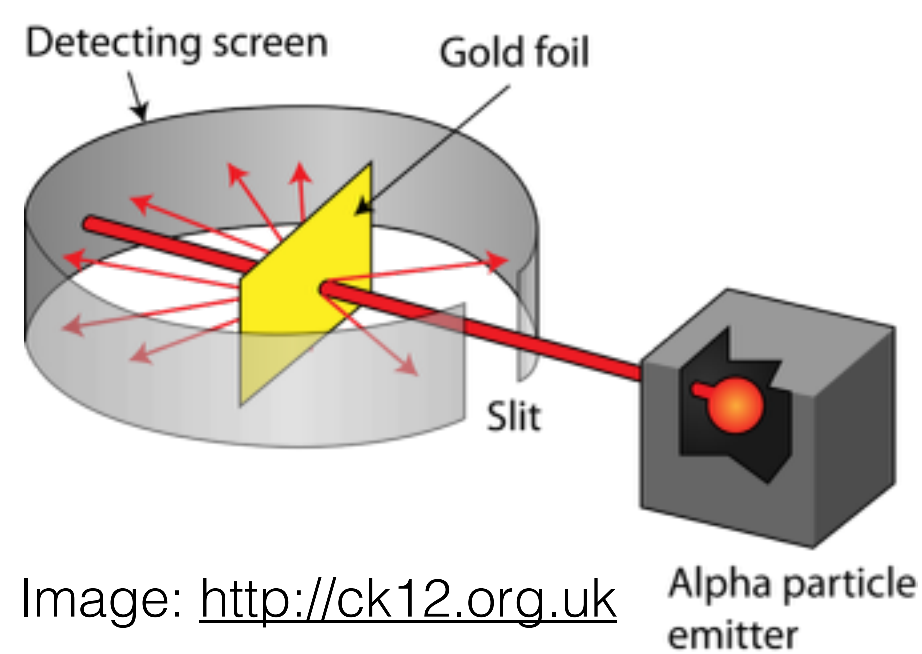


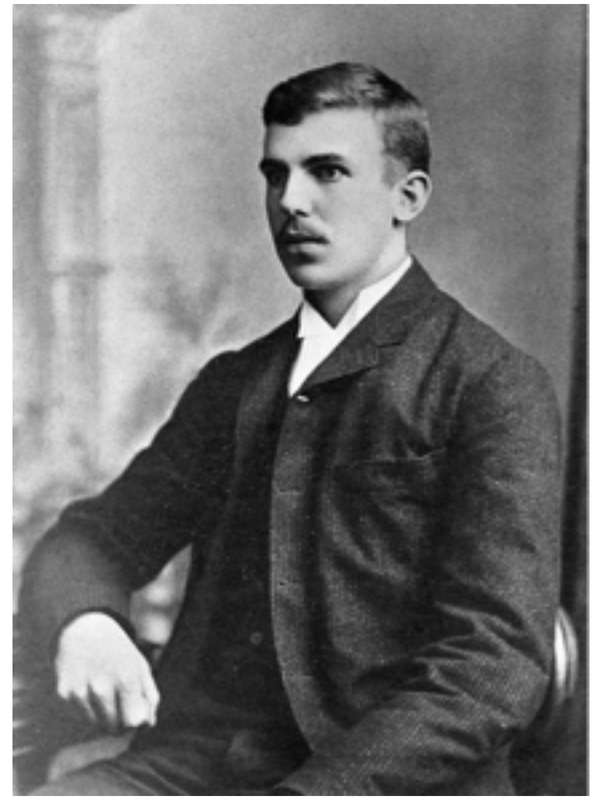
Image: http://ck12.org.uk

The 1920's


High or Low
The Dirt Must Go
HOOVER
PHONE
84
HOOVER


ELECTRIC STYLE SHOW
Electrical Expo
ON DISPLAY DAILY
OTTER TAIL POWER CO.
FEATURING
RUNNING WATER
HOT WATER
COOKING
APPLIANCES
REFRIGERATION
CLEANERS
WASHERS

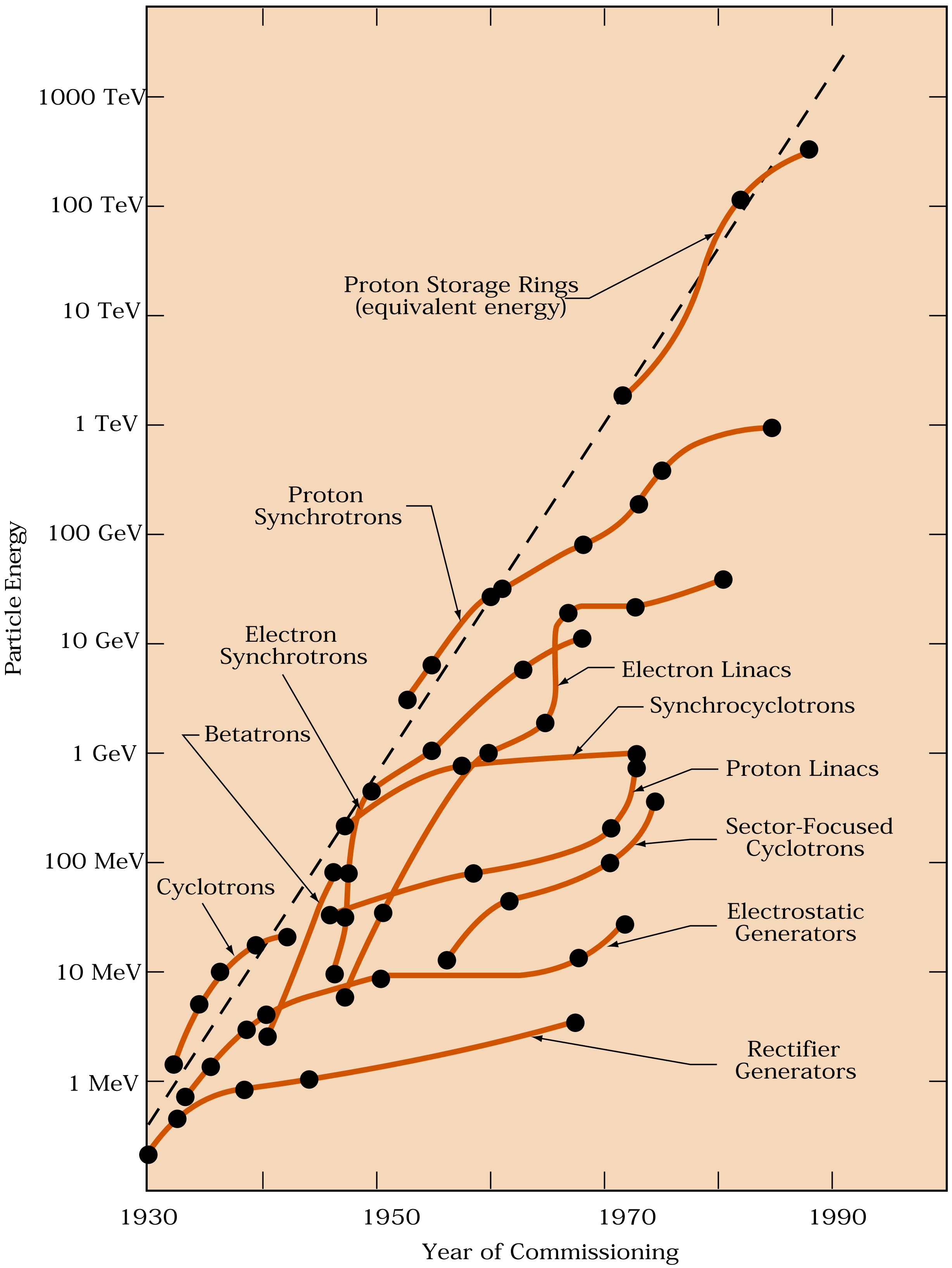
Earlier, when Rutherford was 21…



"*it has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the alpha- and beta-particles from radioactive bodies*"

Ernest Rutherford
Address to the Royal Society, 1927

‘Livingston plot’

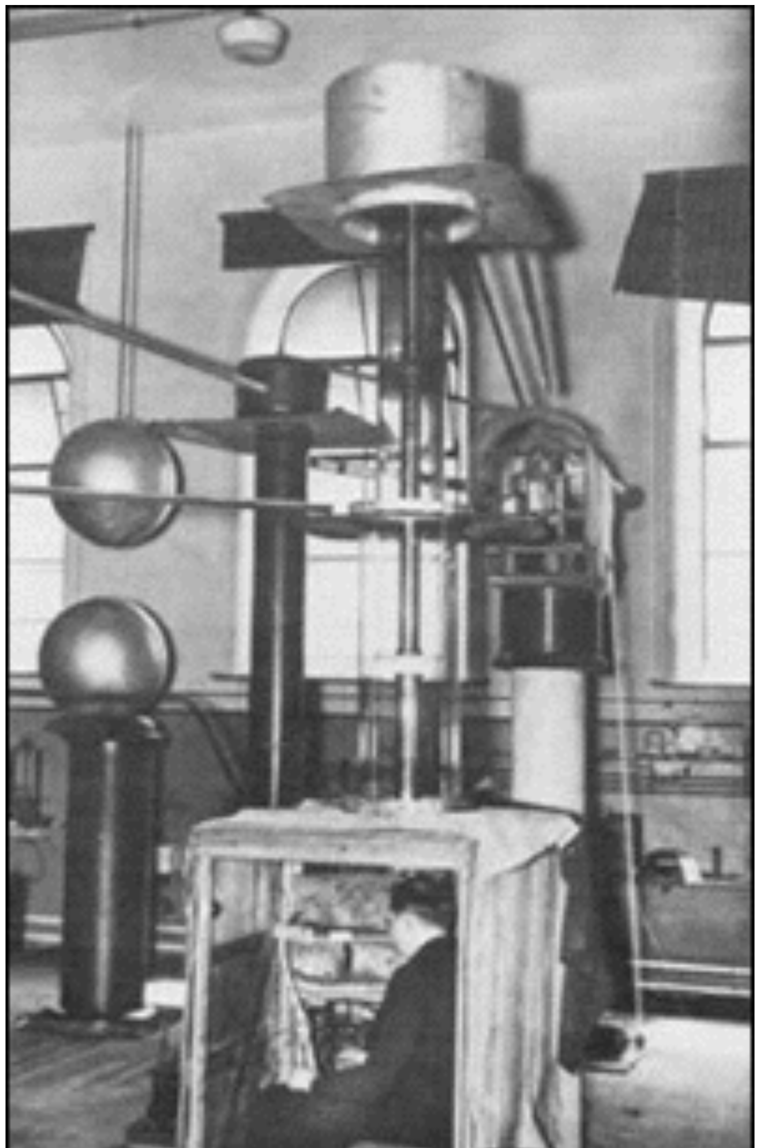


M. Stanley Livingston first noted that advances in accelerator technology increase the energy records achieved by new machines by a factor of 10 every six years.

Image: http://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf

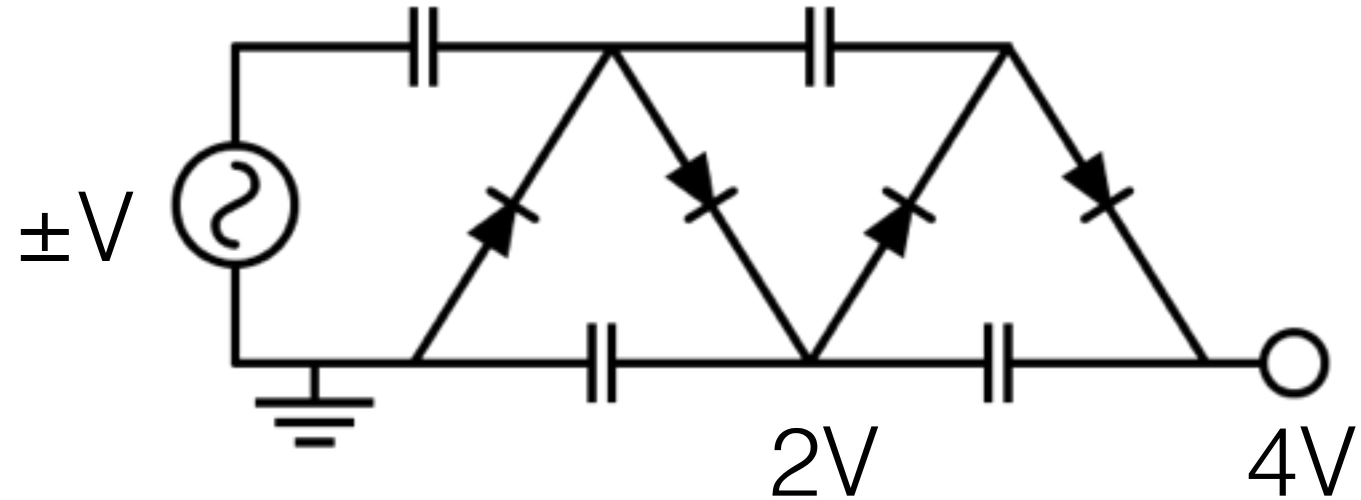
Electrostatic Accelerators (1/2)

Cockcroft Walton accelerator



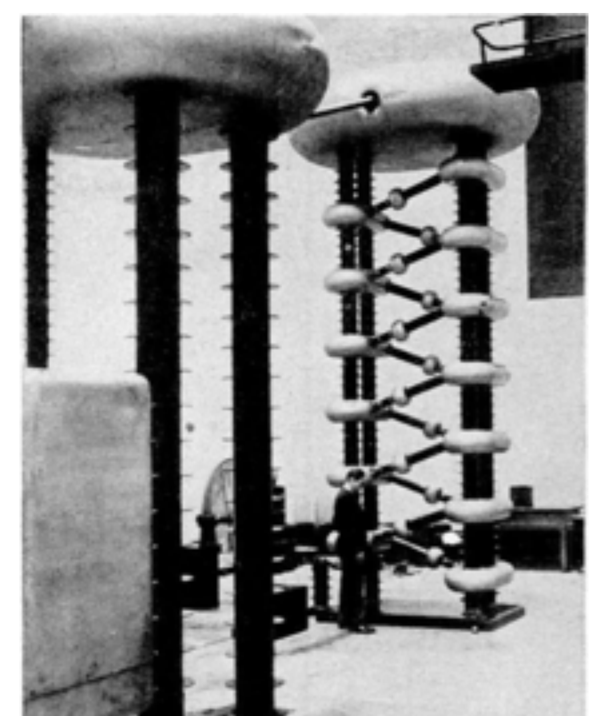
Walton and the machine used to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

https://www.youtube.com/watch?v=ep3D_LC2UzU

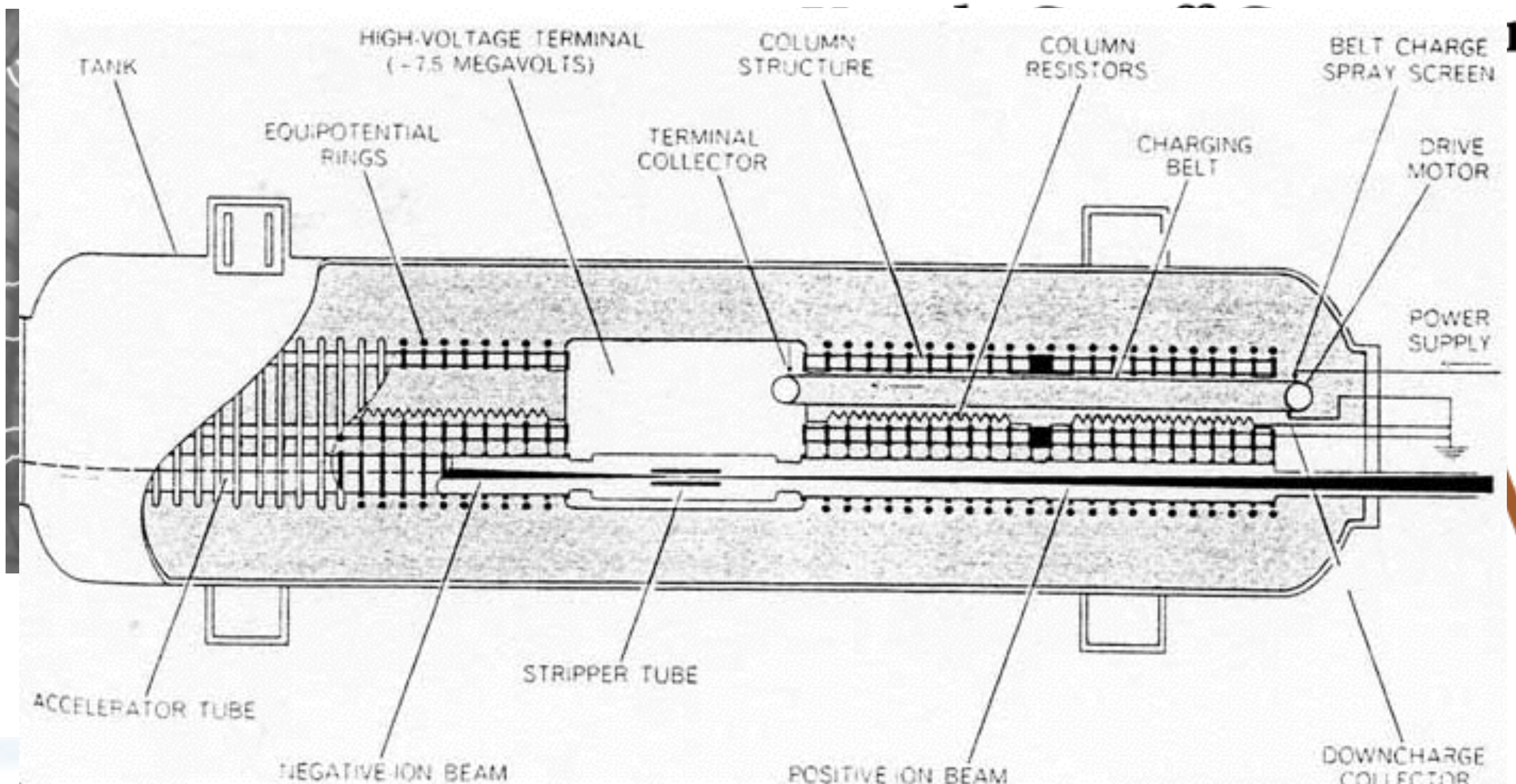


1.2 MV 6 stage Cockcroft-Walton accelerator at Clarendon Lab, Oxford University in 1948.

Electrostatic Accelerators (2/2)

Van de Graaff accelerator

Robert Van de Graaff



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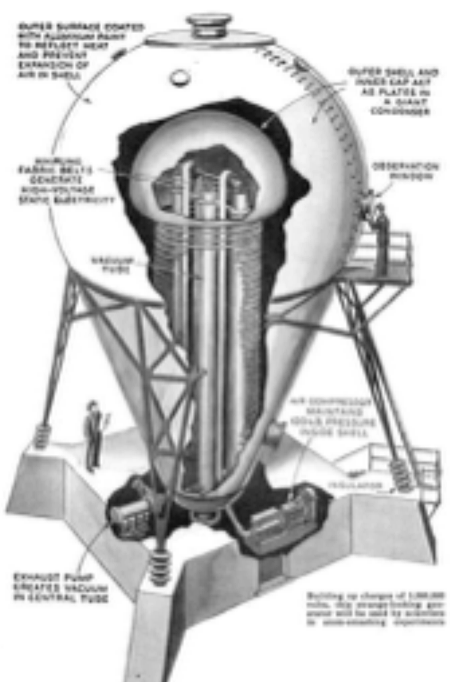
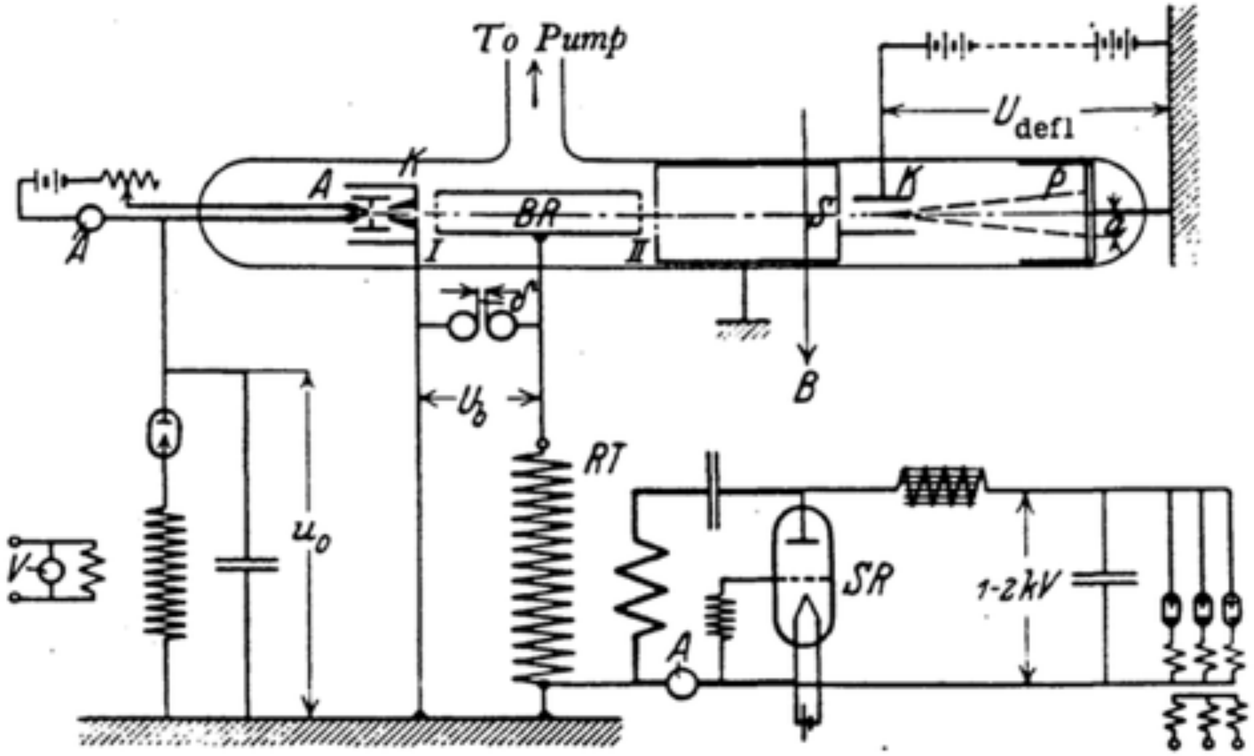
1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference of potentials



The Westinghouse atom smasher, 1937

Linear Accelerators (1/3)

- Rolf Widerøe, 1924
- His PhD thesis was to realise a single drift tube with 2 gaps. 25kV, 1MHz AC voltage produced a 50keV kinetic energy beam.
- First resonant accelerator (patented)

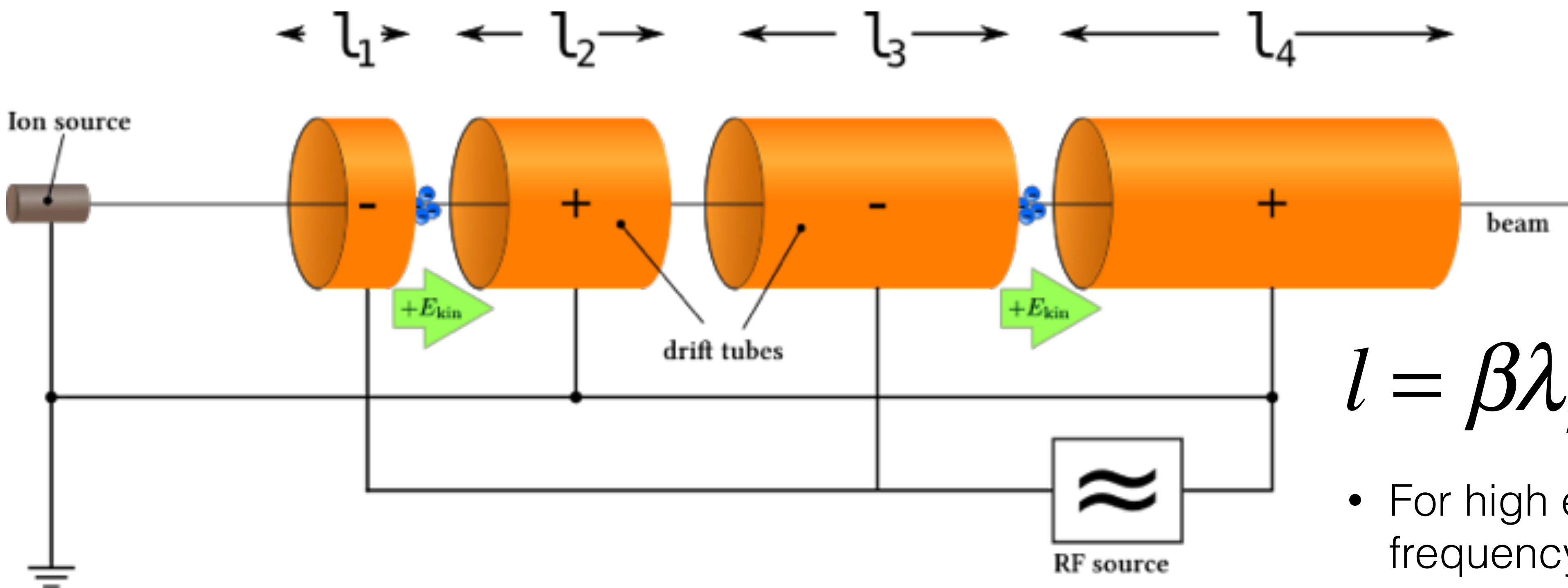


The linear accelerator & it's AC powering circuit

Historical note: He was influenced by Gustav Ising's work, which was never realised in practise as he didn't use an AC source.
Ising, Gustav. *Arkiv Fuer Matematik, Astronomi Och Fysik* **18** (4), 1928

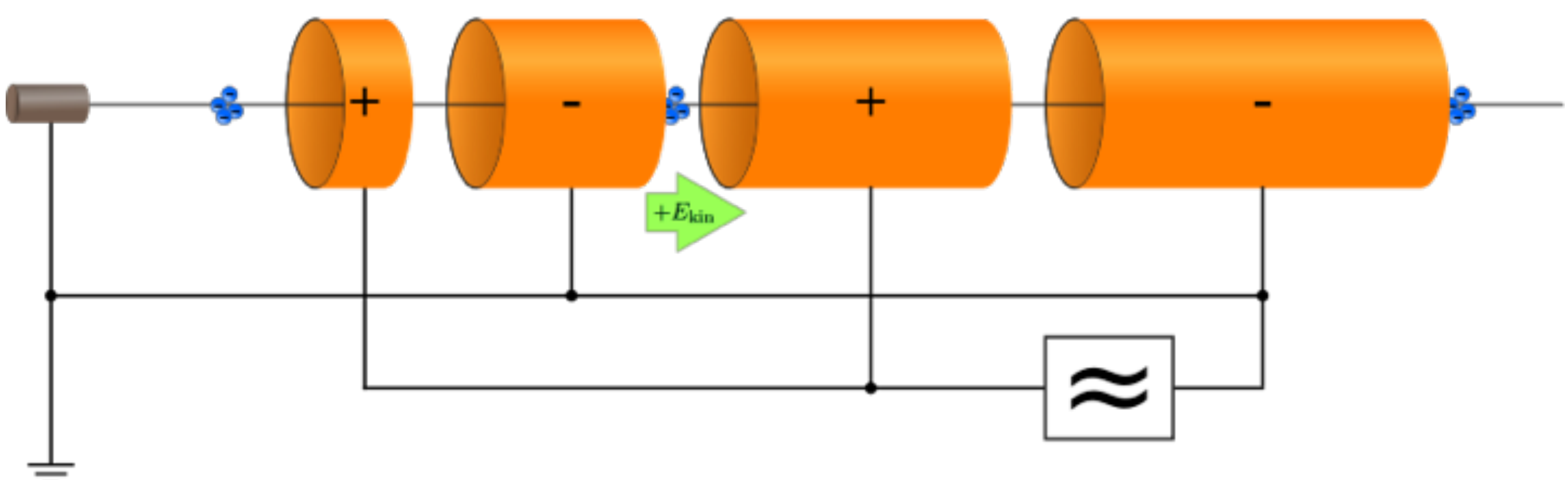
Linear Accelerators (2/3)

- Remember: there is no field inside a conductor



$$l = \beta\lambda_{rf} / 2 = v / 2 f_{rf}$$

- For high energy, need high frequency RF sources
- Weren't available until after WWII



But Wideroe's idea was not quite an RF cavity, Alvarez introduced that…

Linear Accelerators (3/3)

Advantages:

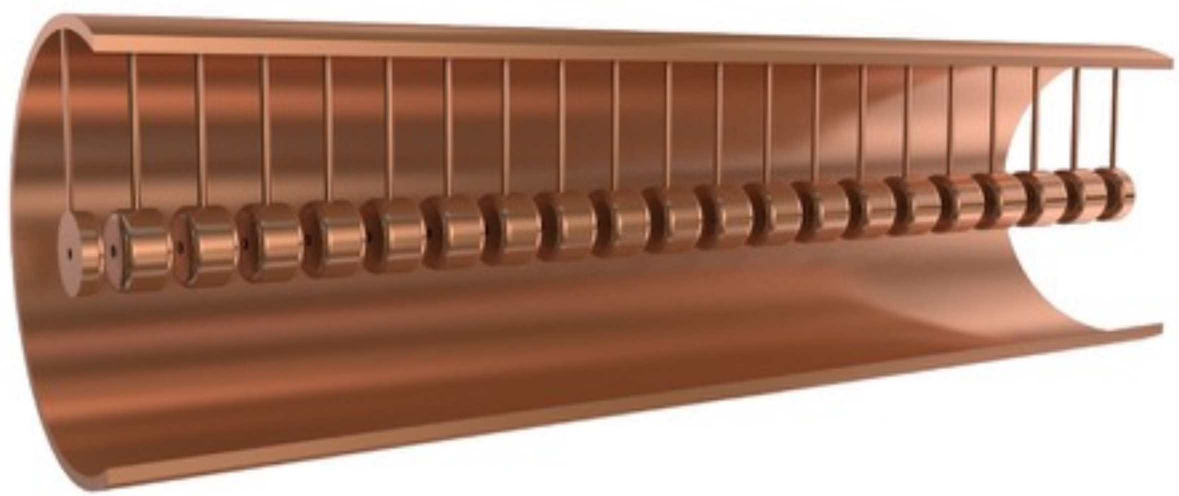
- Can accelerate ions to unlimited energies in principle
- Good for high energy electrons, no synchrotron radiation
- Good beam quality & small spot size

Disadvantages:

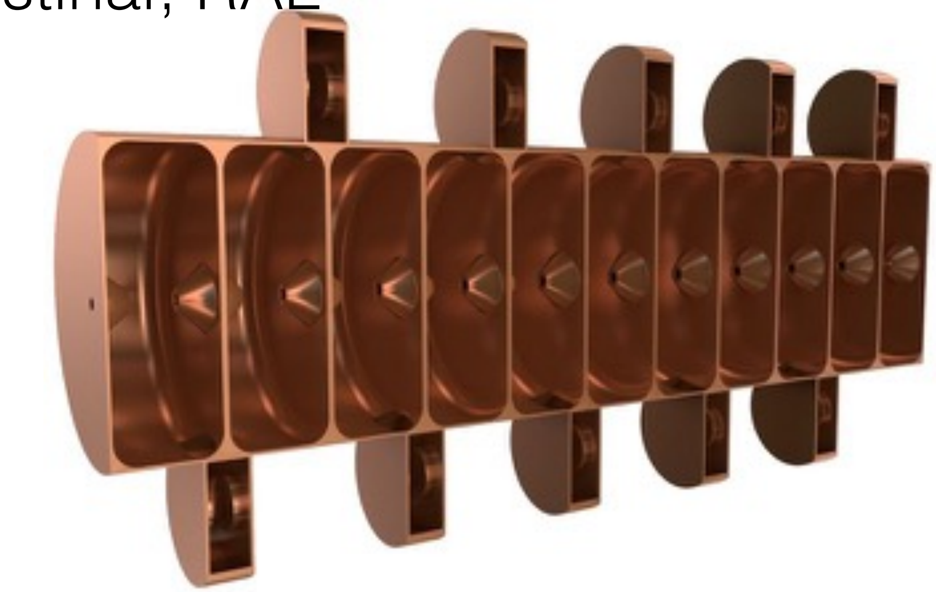
- Can be very long (and thus expensive)
- Each gap is only used once

Linac Structures

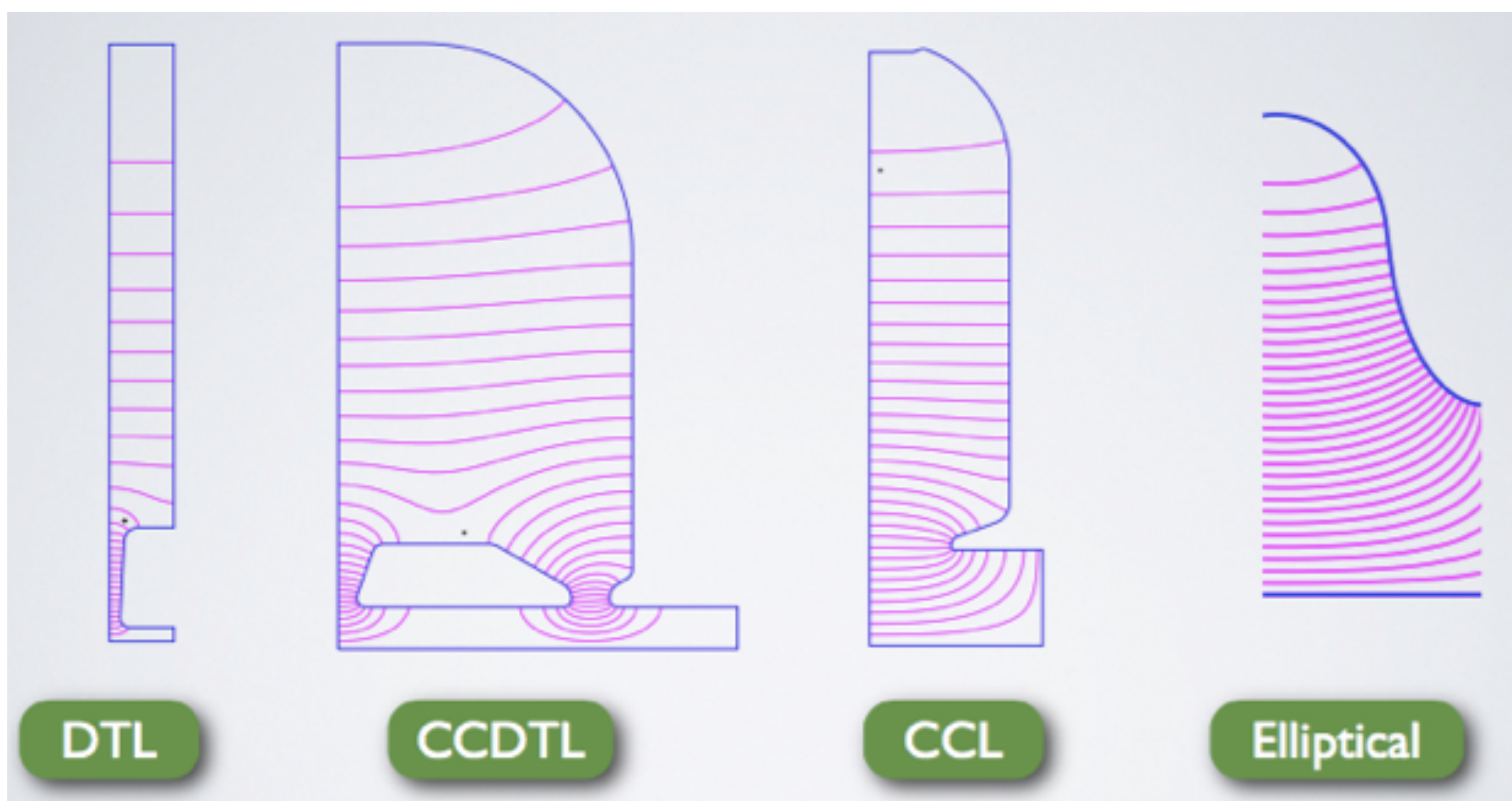
Images thanks to Ciprian Plostinar, RAL



DTL: Drift Tube Linac



CCL: Coupled Cavity Linac



F. Gerigk, CERN

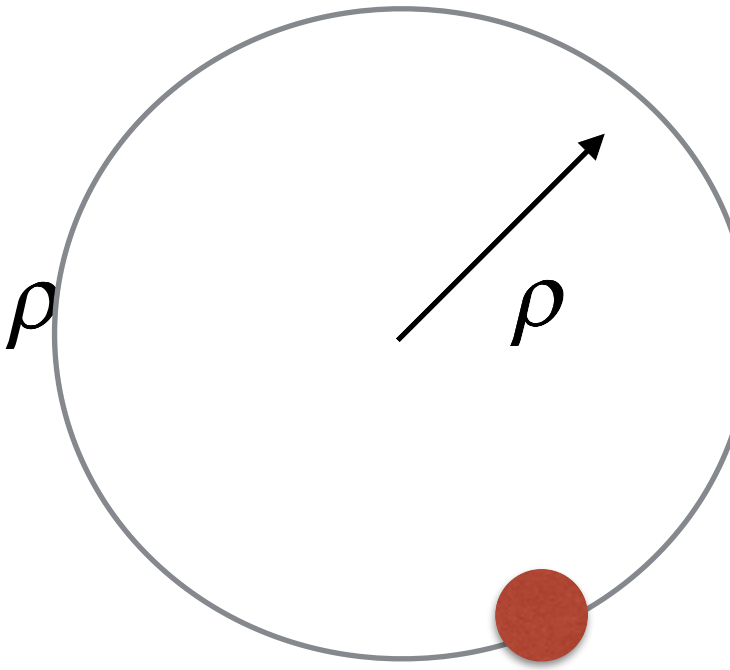
Cyclotrons (1)

Centrifugal force = magnetic force

$$\frac{mv_\theta^2}{\rho} = qv_\theta B_z$$

Ernest Lawrence

Revolution frequency $\omega_0 = v_\theta / \rho$



Lawrence: "R cancels R!"

Cancelling out rho gives:

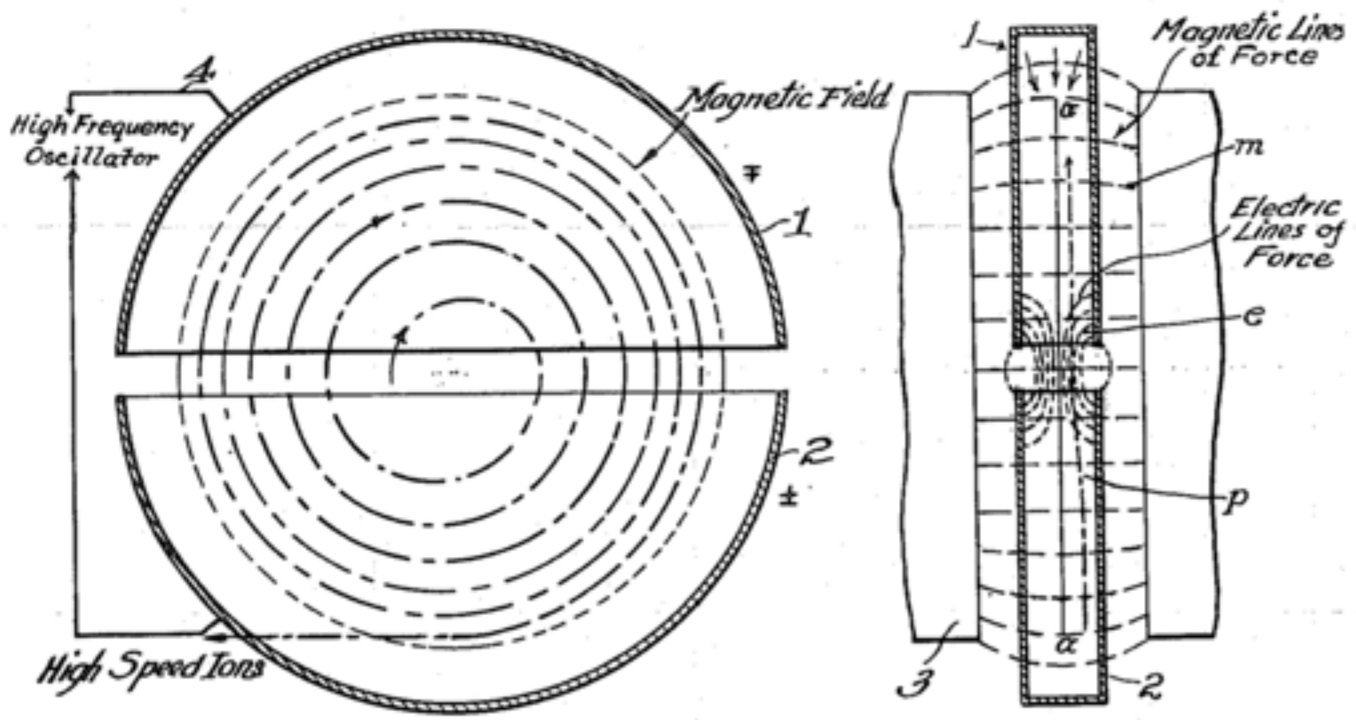
$$\omega_0 = qB_z / m$$

$$\rho = mv / qB_z$$

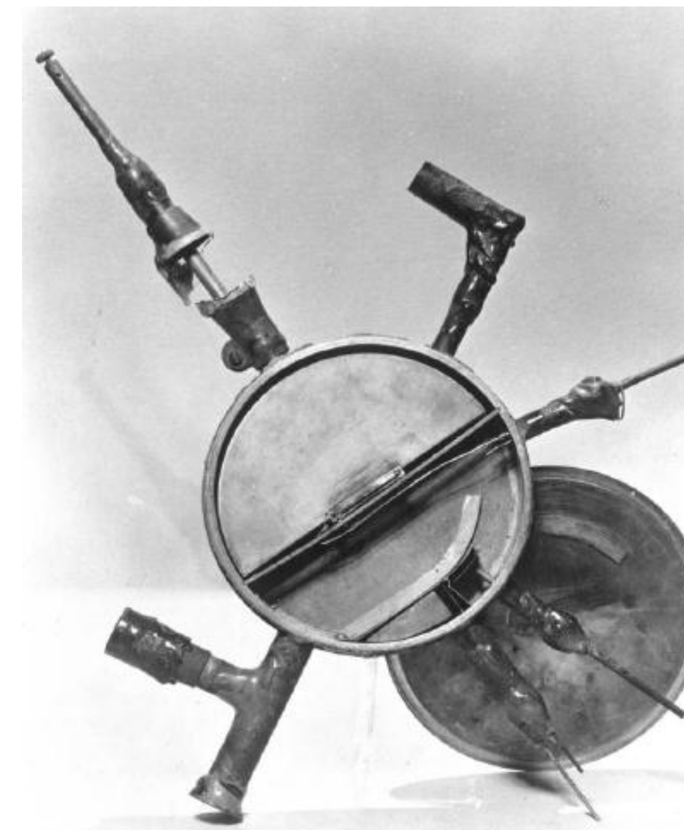
ie. for constant charge q and mass m, and a uniform magnetic field B, the angular frequency is constant. ie. the rf frequency can be constant. The orbit radius is proportional to speed, v.

Q. What is the issue with this statement?

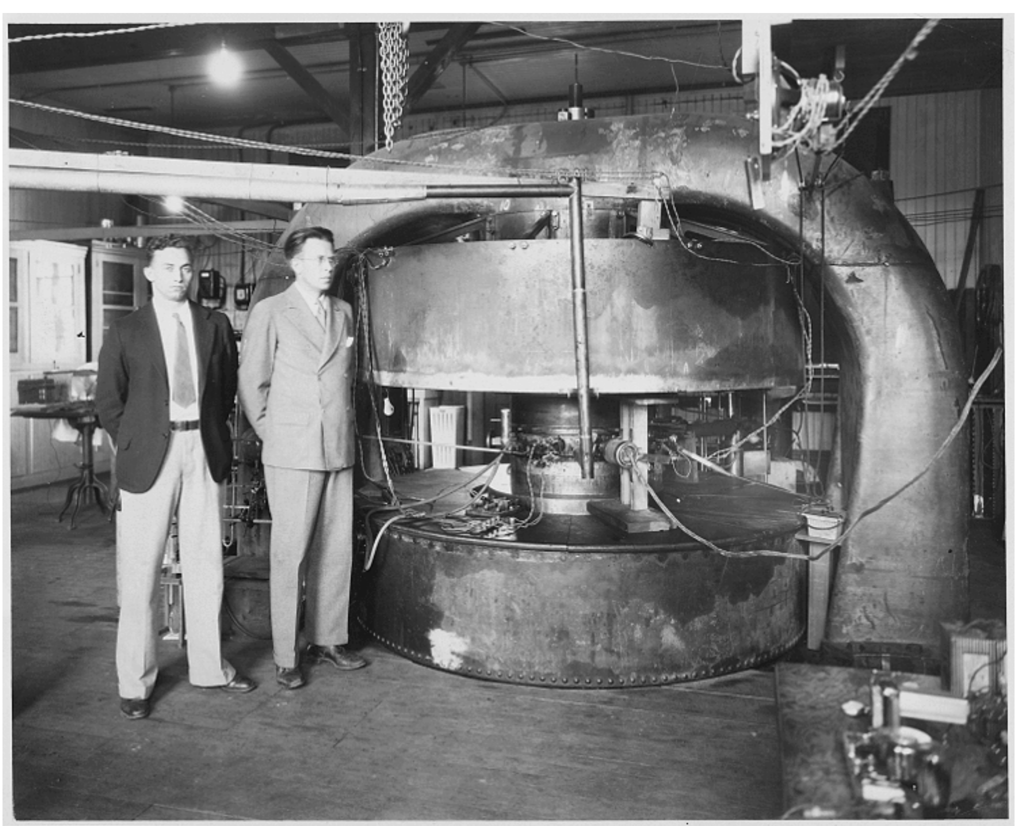
Cyclotrons (2)



The Cyclotron, from E. Lawrence's 1934 patent



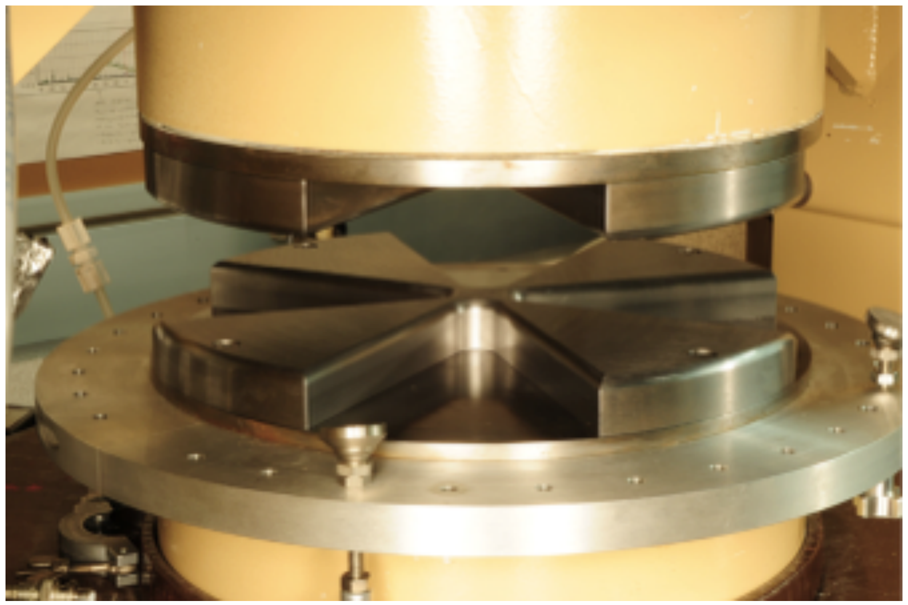
The first cyclotron



We will discuss cyclotron focusing in Transverse Dynamics I

E. Lawrence & M. Stanley Livingston

AVF cyclotrons (3)

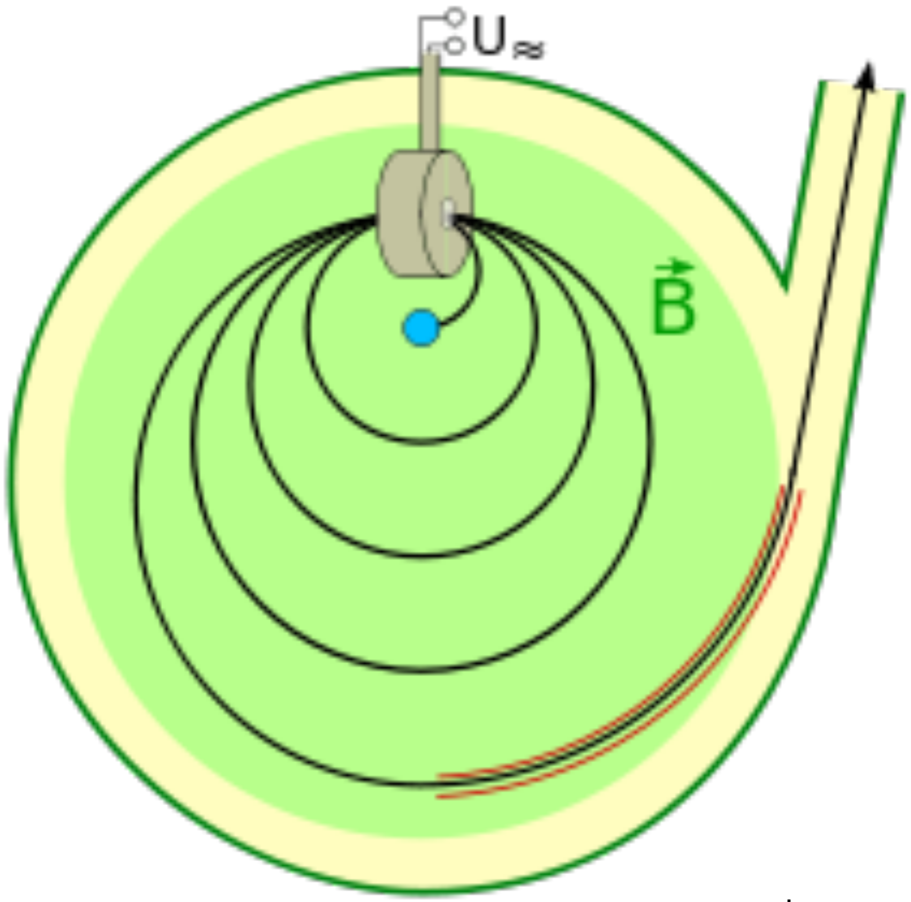


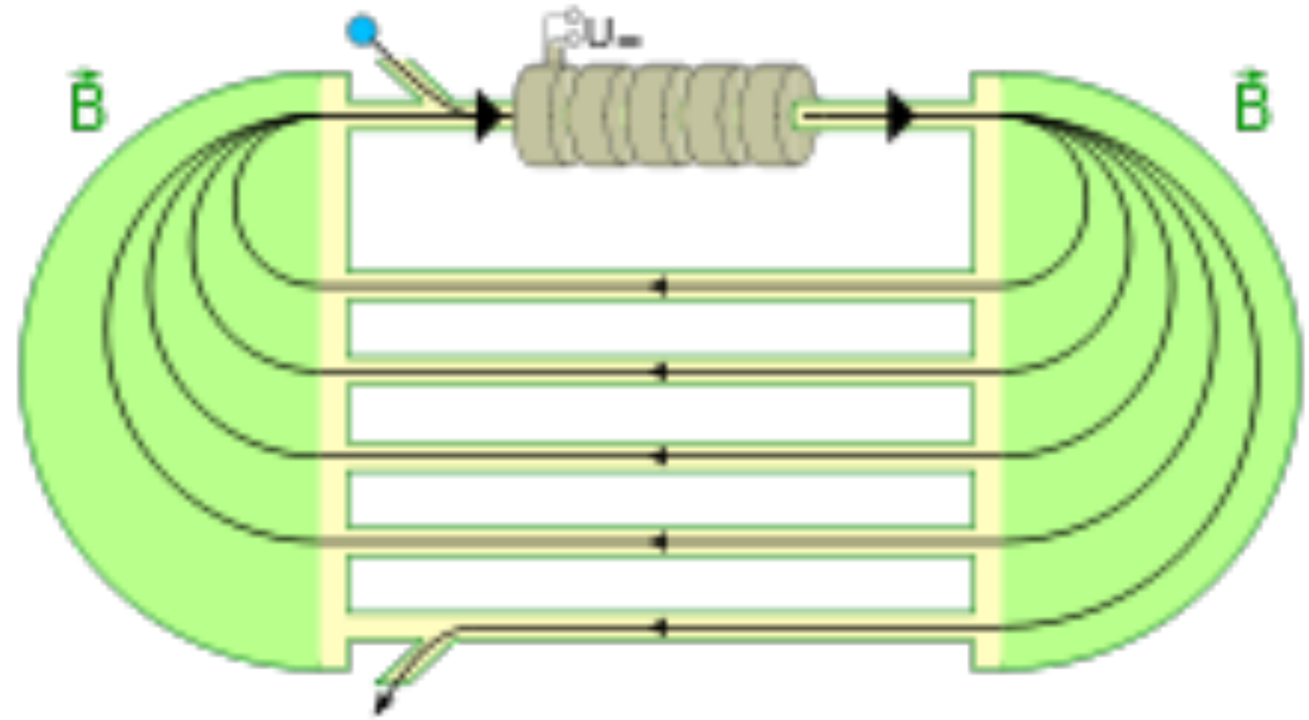
Introduce hills/valleys which increases focusing
(they don't have to be symmetric)

Can have a spiral angle which increases focusing
as in the PSI 590MeV cyclotron.

For more, see M. Seidel, CAS lecture notes, Grenada

Microtron





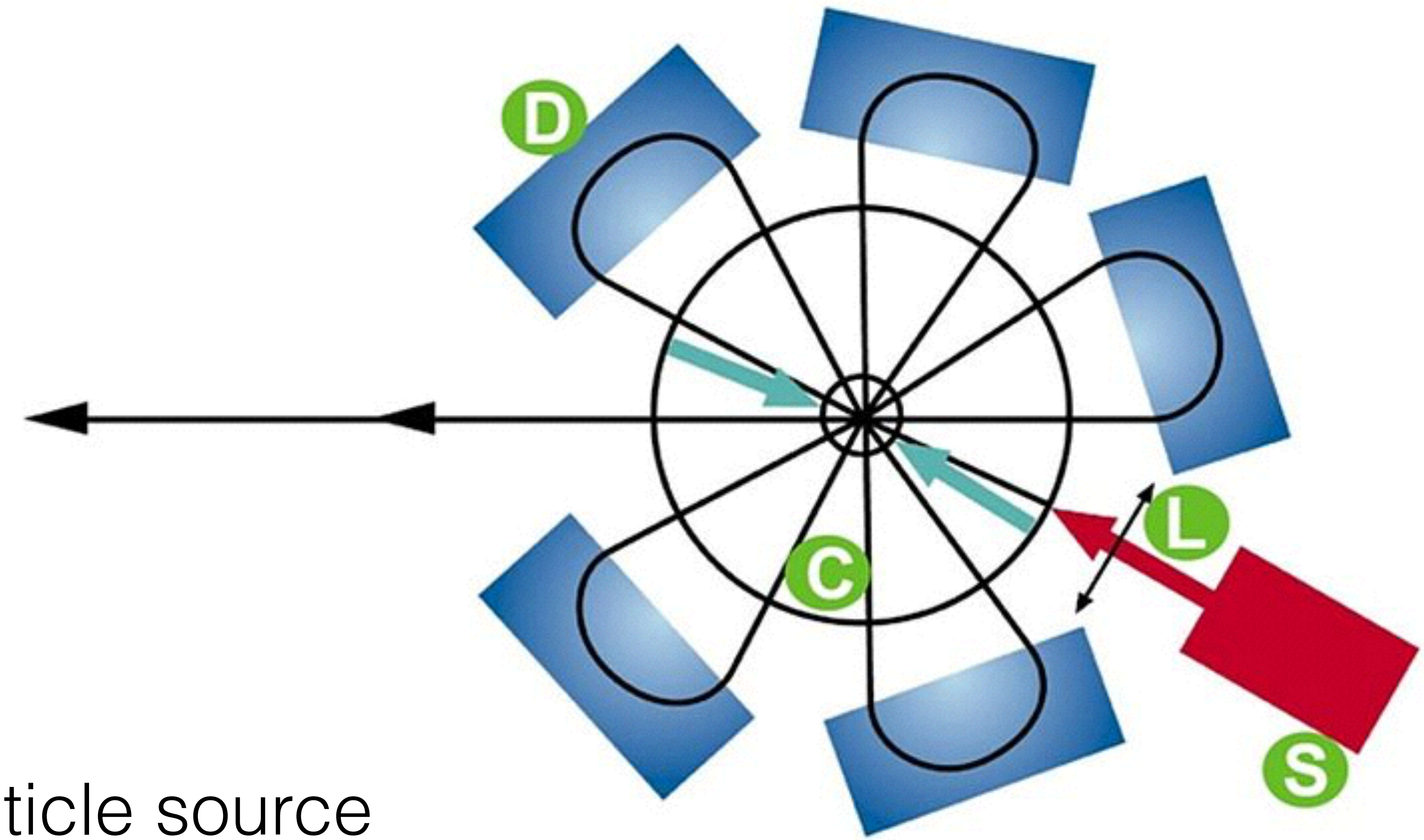
Images: wikimedia commons

- Uses a linear accelerator structure instead of the dee electrodes of the cyclotron
- Mostly used for electrons as assumes constant frequency RF & B field in the ultra relativistic limit.

Veksler, I. V. (1944). "A New Method of the Acceleration of Relativistic Particles". *Doklady Akad. Nauk SSSR* (in Russian) **43**: 346.

Rhodotron

Invented 1989



S: particle source
C: coaxial cavity
D: bending magnets
L: focusing lens

Energy gain ~ 1 MeV per crossing

Betatron

D.W. Kerst, Phys. Rev. 58, 841 (1940)

- Like a transformer with the beam as a secondary coil
- Usually used for relativistic electrons (so different from a cyclotron).
- Max energy achieved 300 MeV
- Accelerating field produced by a changing magnetic field that also serves to maintains electrons in a circular orbit of fixed radius as they are accelerated

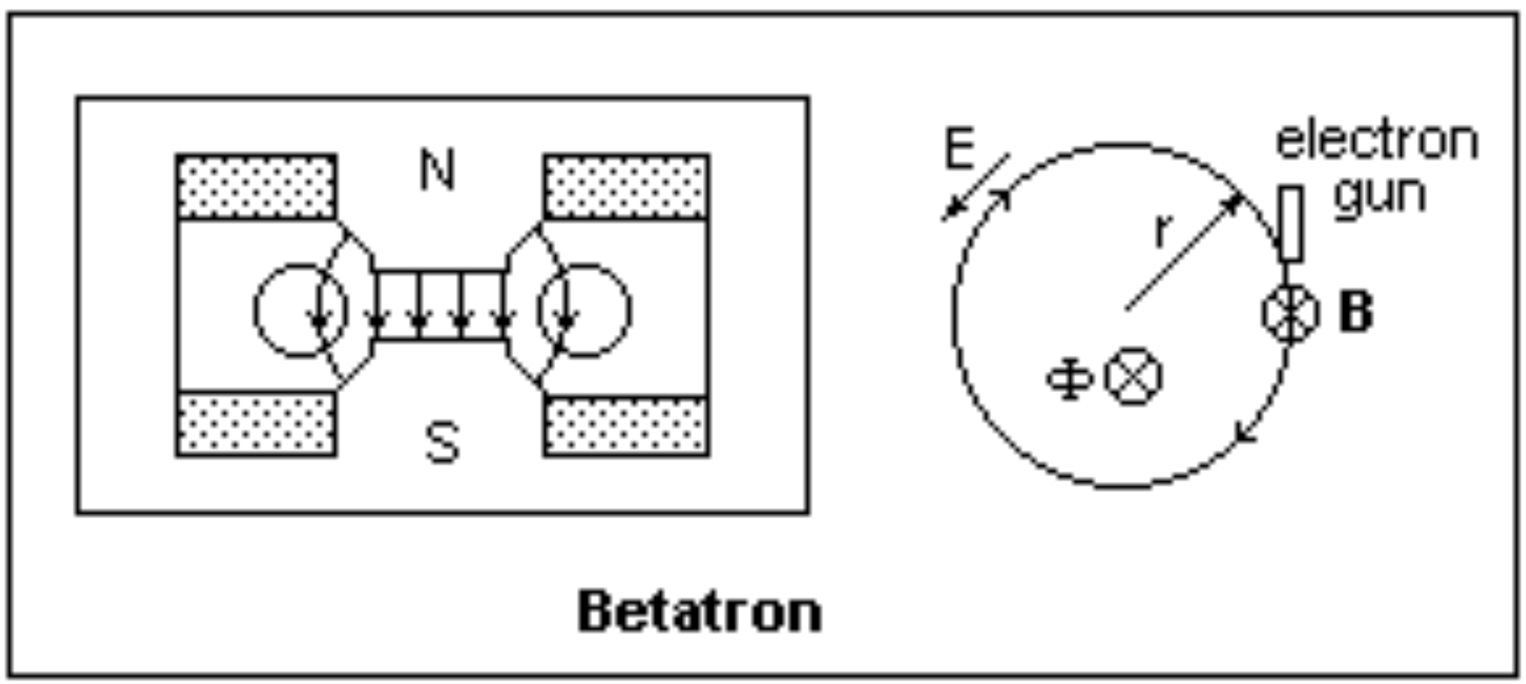


Image: http://mysite.du.edu/~jcalvert/phys/partelec.htm#Tron

$$B_{orbit} = \frac{\bar{B}}{2}$$

Lorentz force law gives…

$$\frac{mv^2}{r} = qvB_{orbit}$$

So max. momentum is

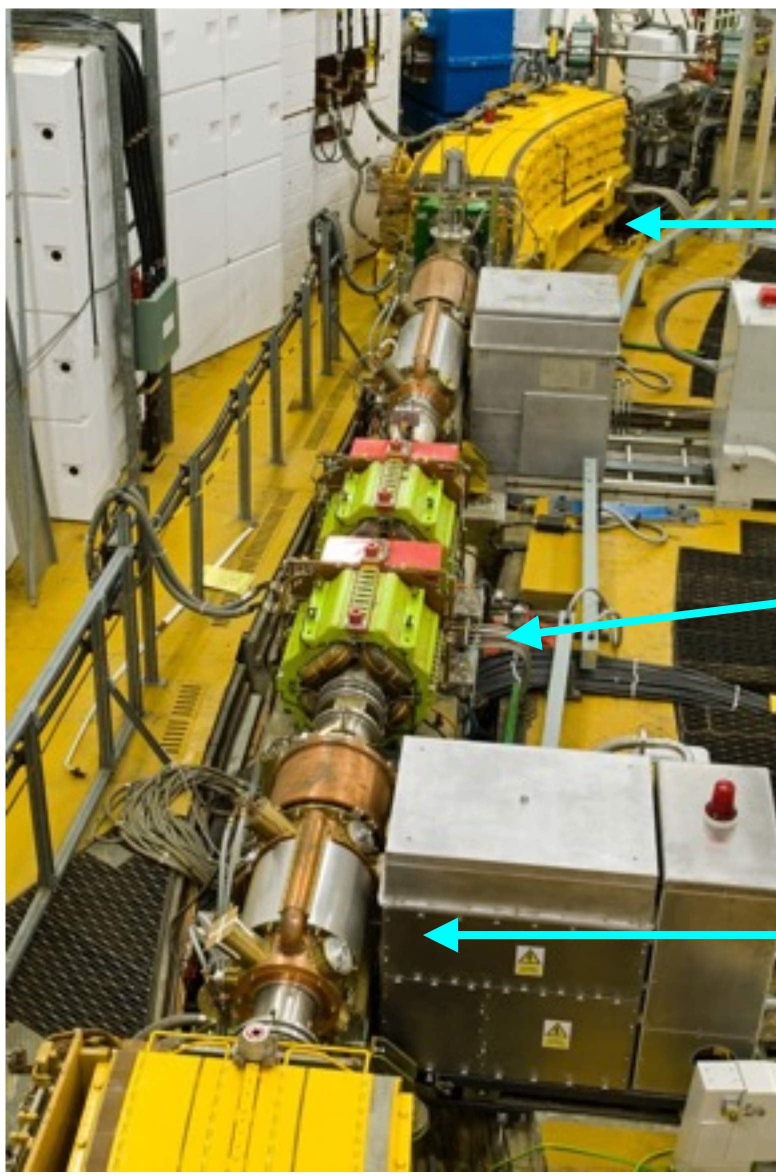
$$p = rqB_{orbit}$$

Exercise: Find the same result using Faraday's law of induction

(solution: http://teachers.web.cern.ch/teachers/archiv/hst2001/accelerators/teachers%20notes/betatron.htm)

Synchrotrons (1)

"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field … which would be varied in such a way that the radius of curvature remains constant as the particles gain energy through successive accelerations" - Marcus Oliphant, 1943



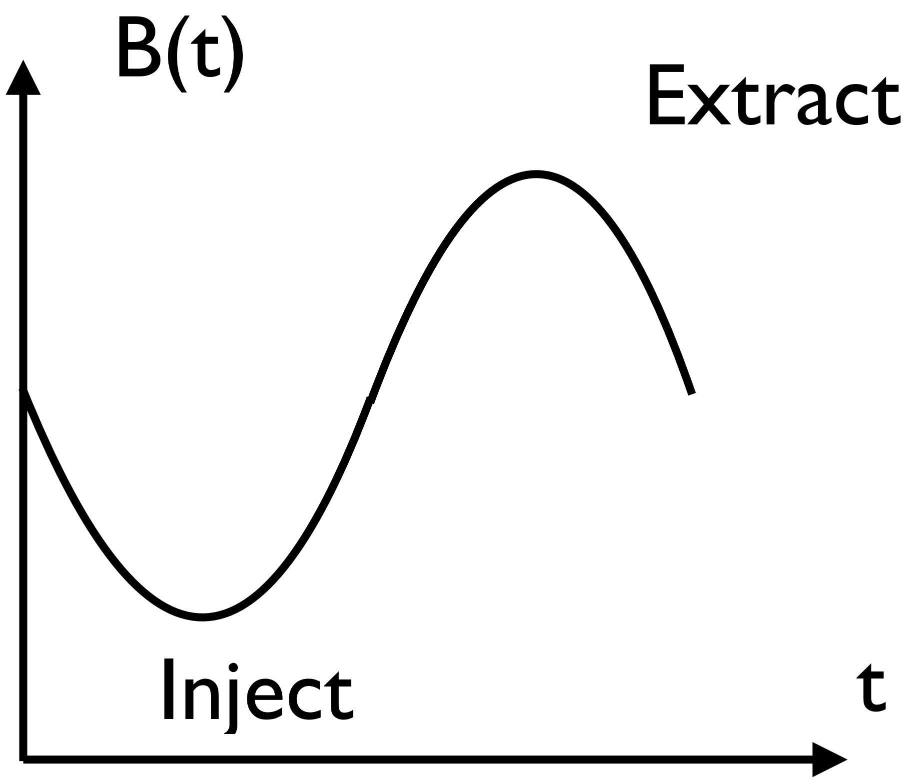
dipole magnets

quadrupole magnets

rf cavity

Image courtesy of ISIS, STFC

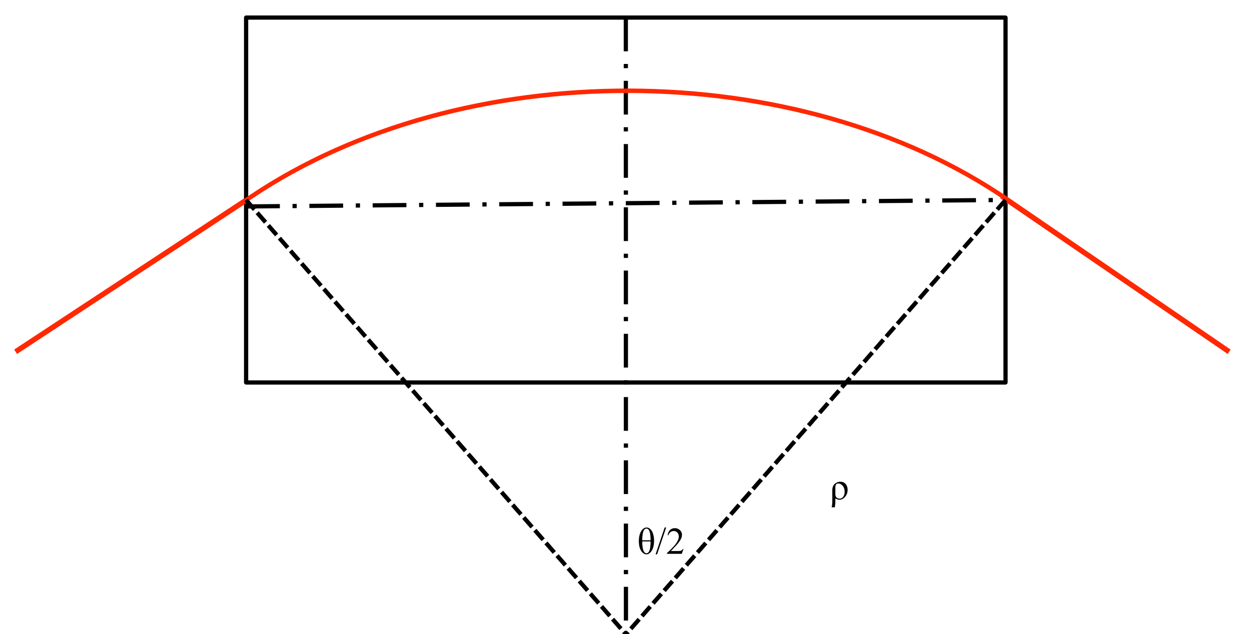
Synchrotrons (2)



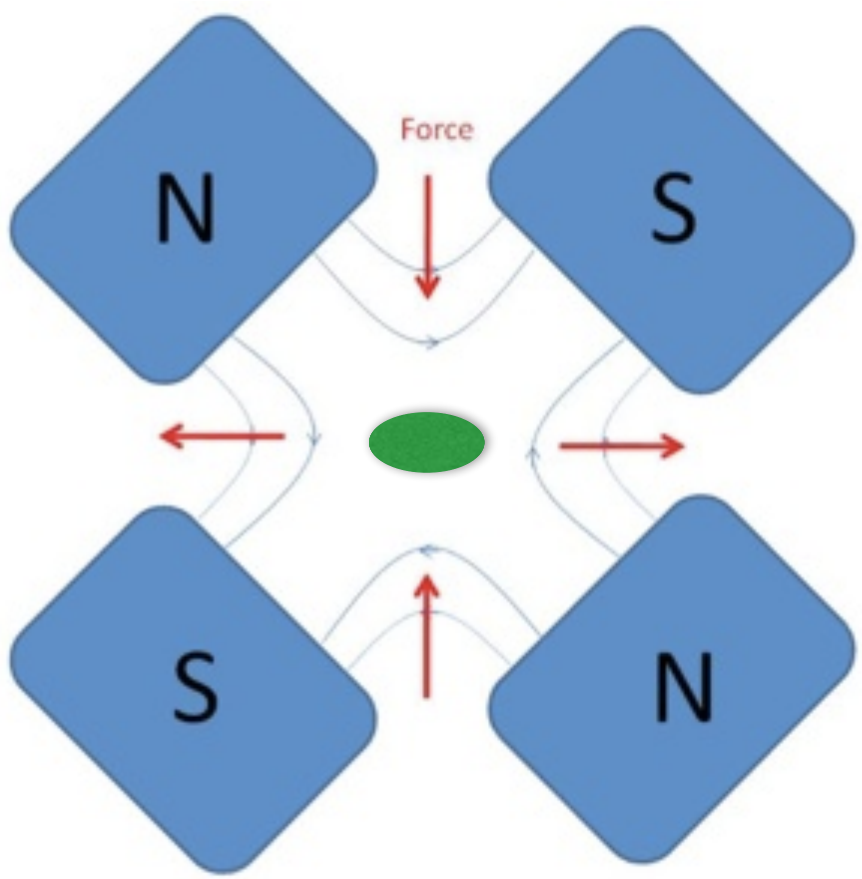
Typical synchrotron magnet cycle

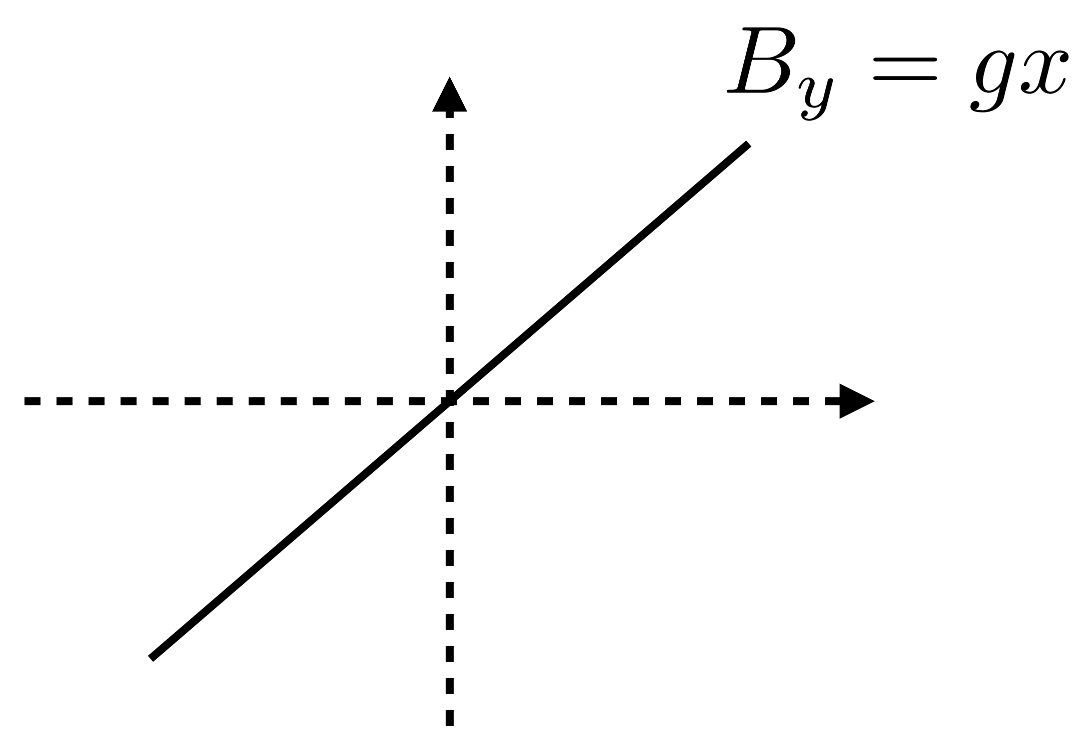
Bending angle in dipole magnet

$$\sin(\theta/2) = \frac{B(t)L}{2(B(t)\rho)} \qquad \theta \approx \frac{B(t)L}{p(t)/q}$$



Synchrotrons





$$k = \frac{g}{p/q}$$

$$\frac{1}{f} = \frac{L(dB(t)/dx)}{p(t)/q}$$

'normalised gradient' of quad

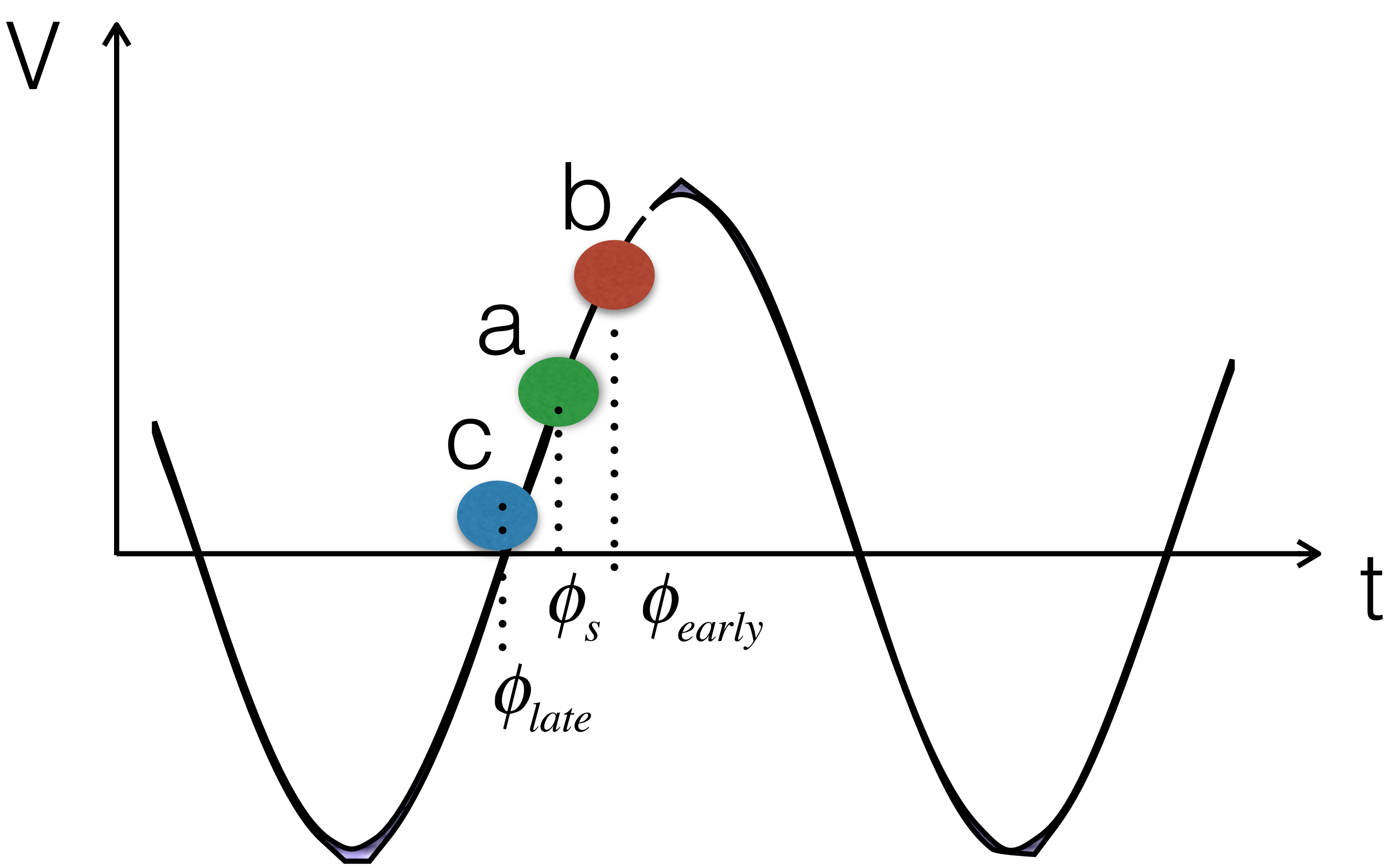
Synchrotrons - Phase stability

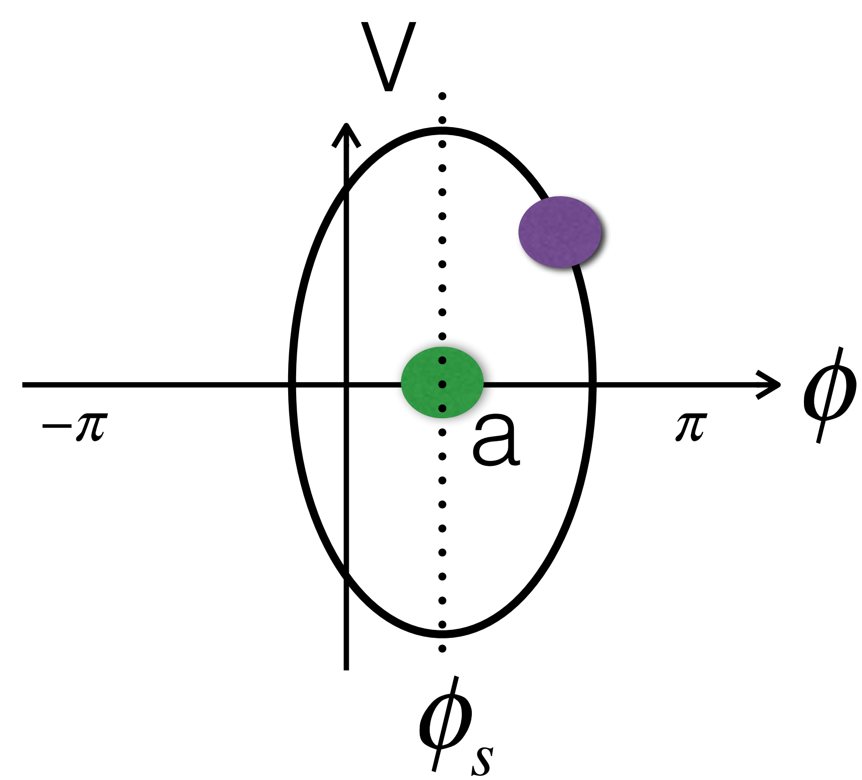
a - synchronous

b - arrives early, sees higher voltage, goes to larger orbit -> arrives later next time

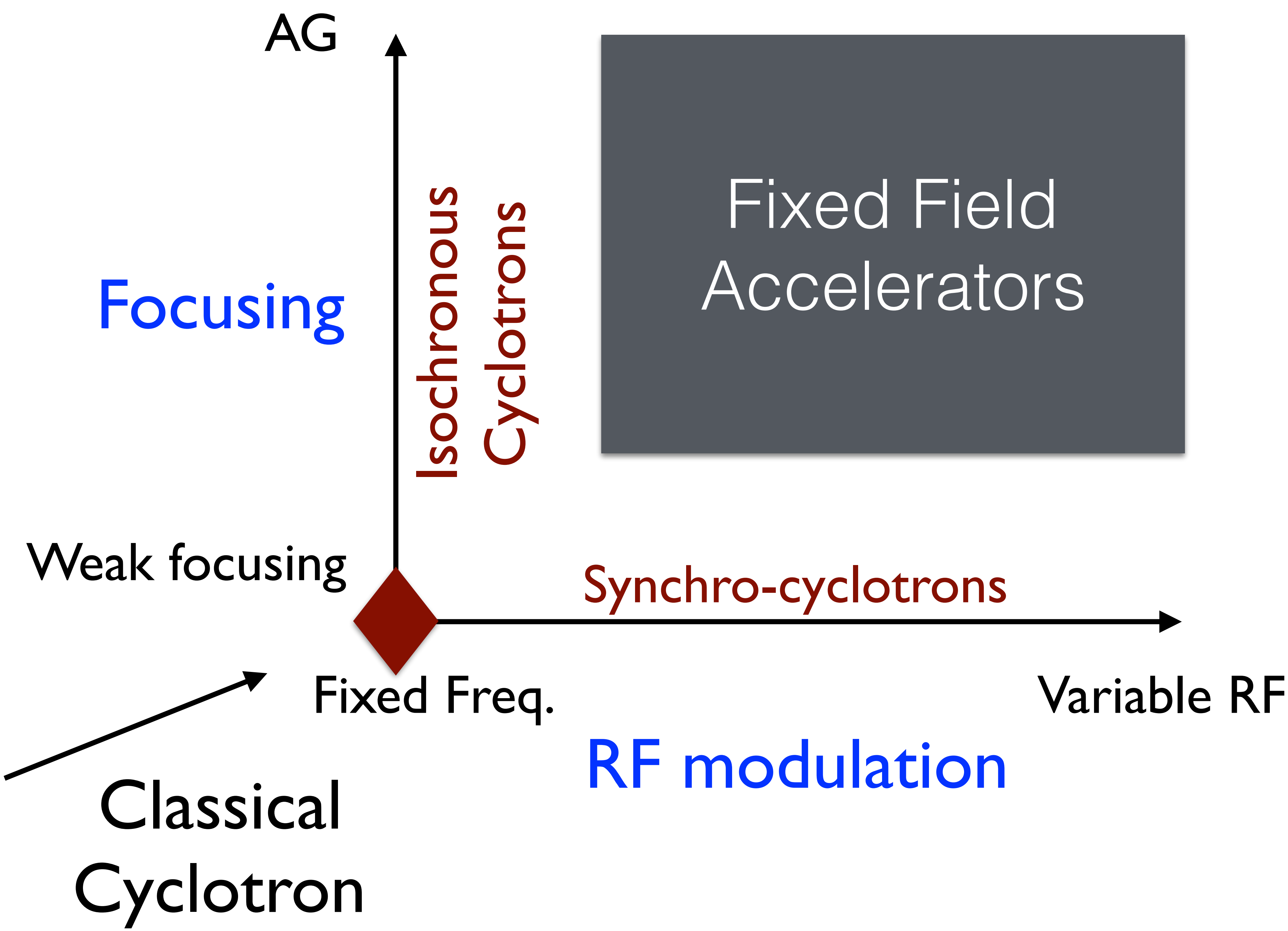
c - arrives late, sees lower voltage, goes to smaller orbit -> arrives earlier next time

$$V = V_0 \sin(2\pi f_a + \phi_s)$$





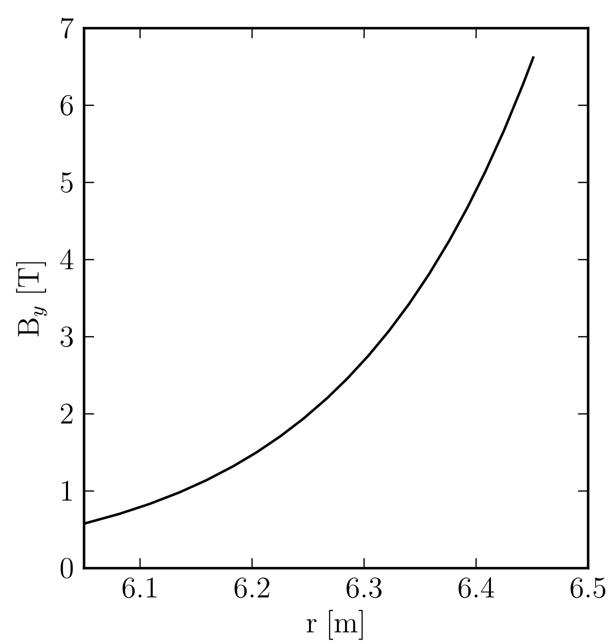
The circular fixed-field accelerator family

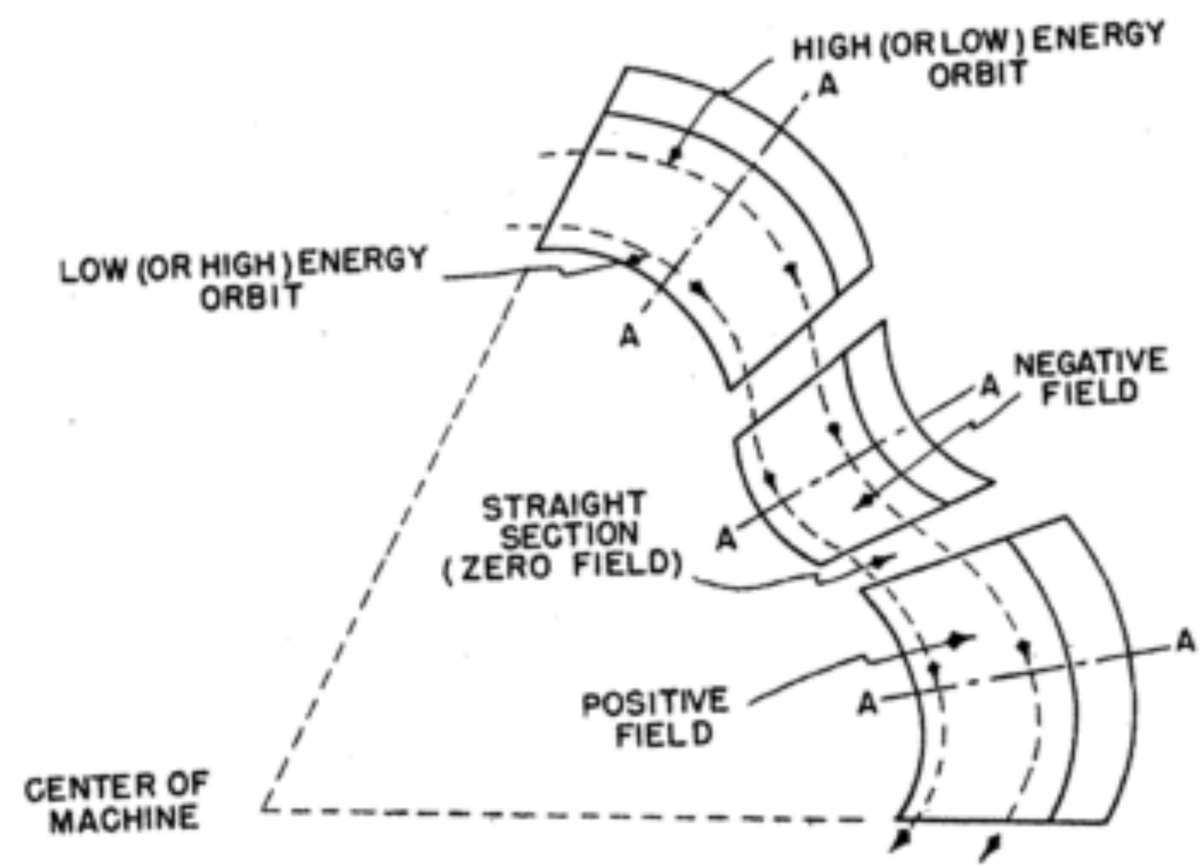


FFA(G)s

- If the field profile is of a particular form, we call this type of FFA a ‘scaling’ type.
- Alternating magnets have opposite bending fields
- Beam moves radially with energy

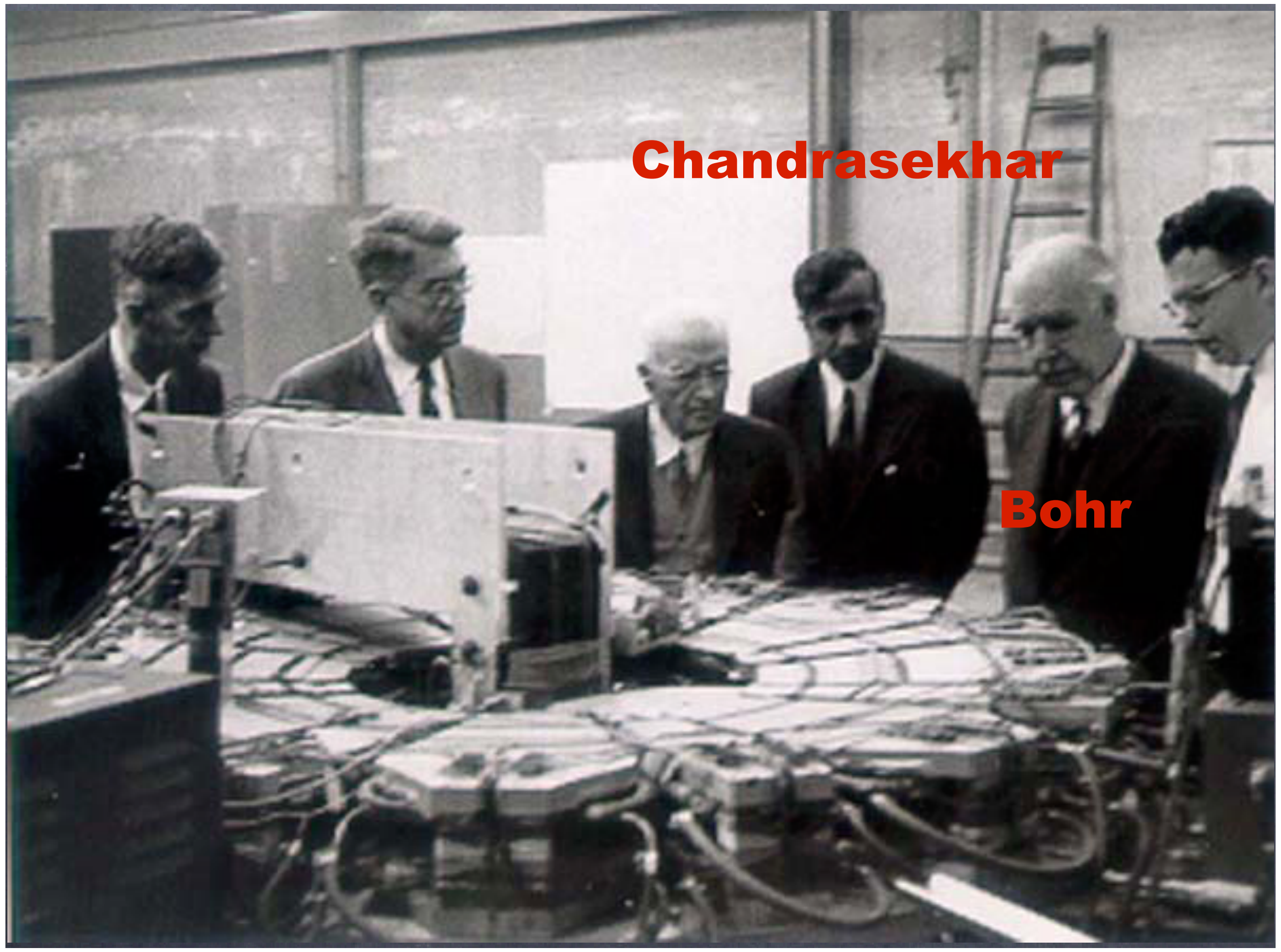
$$B_y = B_0 \left(\frac{r}{r_0} \right)^k F(\theta)$$

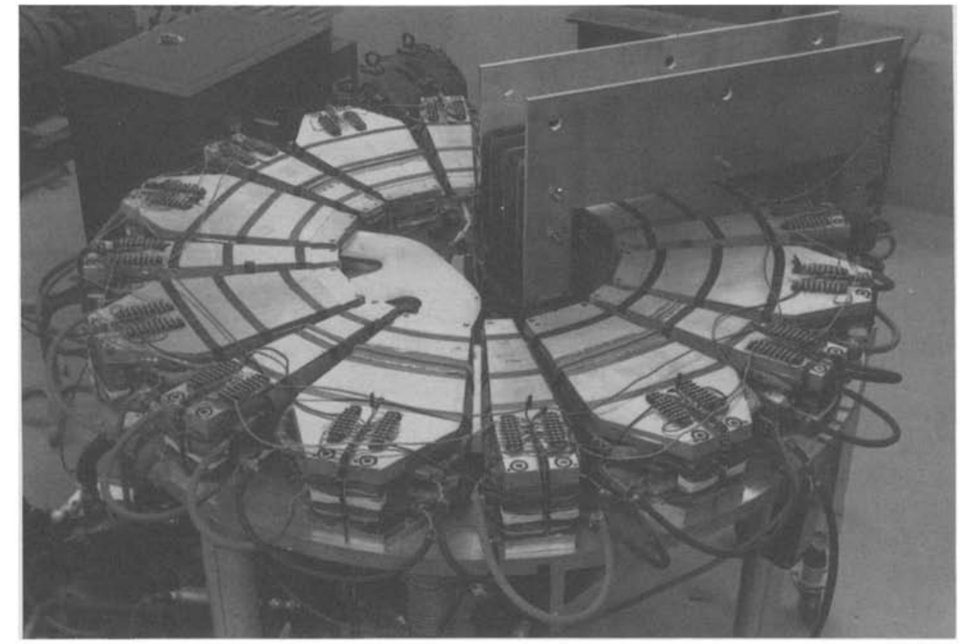


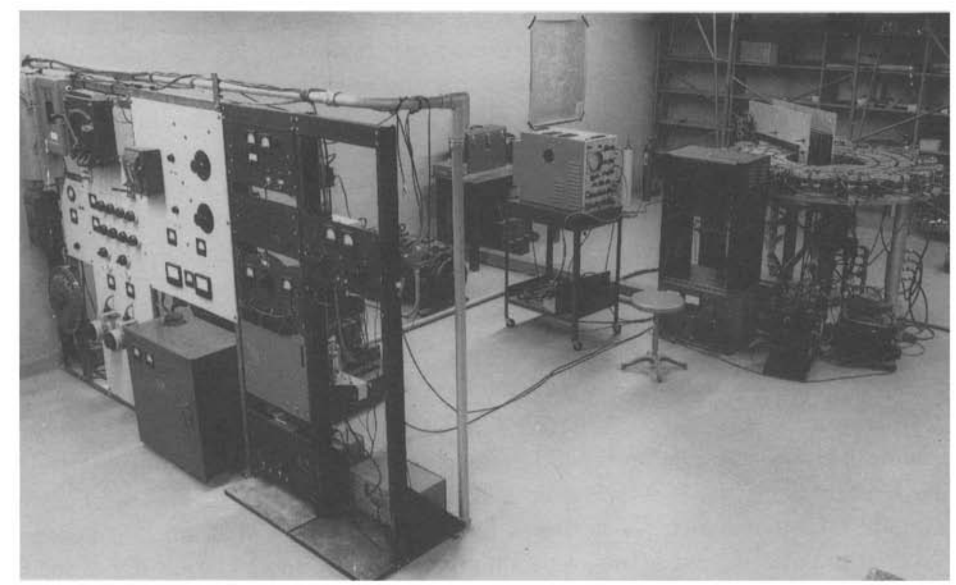


Note that this field profile does NOT satisfy isochronicity

$$\omega = \frac{eB}{m\gamma} \neq const.$$







1956

- L. W. Jones, AIP Conference Proceedings, 237, 1 (1991)

Interesting Reading: K. R. Symon, 'The Mura Days'
https://accelconf.web.cern.ch/accelconf/p03/PAPERS/WOPA003.PDF

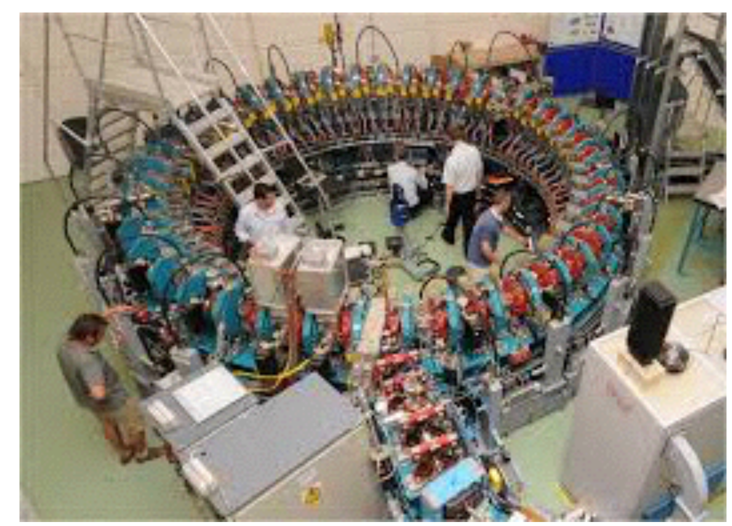
FFAs

- In the late 90's and in 2000's, the FFA idea was re-awakened in Japan,
- Particular focus on hadron FFAs of scaling type
- Recently non-scaling type driven by UK collaboration

Scaling (zero-chromatic)

Proof of Principle machine built in 1999 at KEK, demonstrated 1kHz rep. rate

Non-Scaling (chromatic)



EMMA, Daresbury Lab, UK

We've covered:

- Different types of accelerators
  - Electrostatic
  - Linac
  - Cyclotron
  - Betatron, microtron, rhodotron
  - Synchrotron
  - FFA

But we have not covered many other types!
Including laser-plasma accelerators, dielectric wall accelerators and more.

Next Lecture

- Will be a live cross to the LHC Control Centre at CERN
- Prof. Emmanuel Tsesmelis will present a lecture from there.
- See you at 2:15pm

Additional references

- More information on betatrons: http://web.mit.edu/course/22/22.09/ClassHandouts/Charged%20Particle%20Accel/CHAP11.PDF