5th Particle Physics Workshop

National Centre for Physics

Quaid-i-Azam University Campus, Islamabad

PARTICLE BEAMS, TOOLS FOR MODERN SCIENCE

Hans-H. Braun, CERN

- **History and Physics Principles of Particle Accelerators**
  Origins
  From Zyklotron to Synchrotron
  Defocusing + Focusing = Focusing
  Particle Colliders

- **An Overview of Accelerator Applications**
  Synchrotron Radiation, from Nuisance to Bright Light
  Beams for Medicine
  Particle Accelerators for Particle Physics

- **Introduction to Linear e^+/e^- Colliders and CLIC**
  Linear Colliders - Motivation and Concept
  Technical Challenges for Linear Colliders
  CLIC

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1st Lecture

History and Physics Principles of Particle Accelerators

- Origins
- From Zyklotron to Synchrotron
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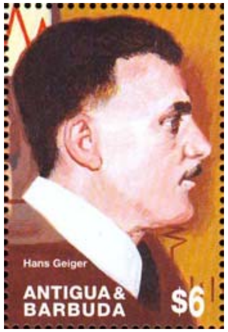
- Particle Colliders

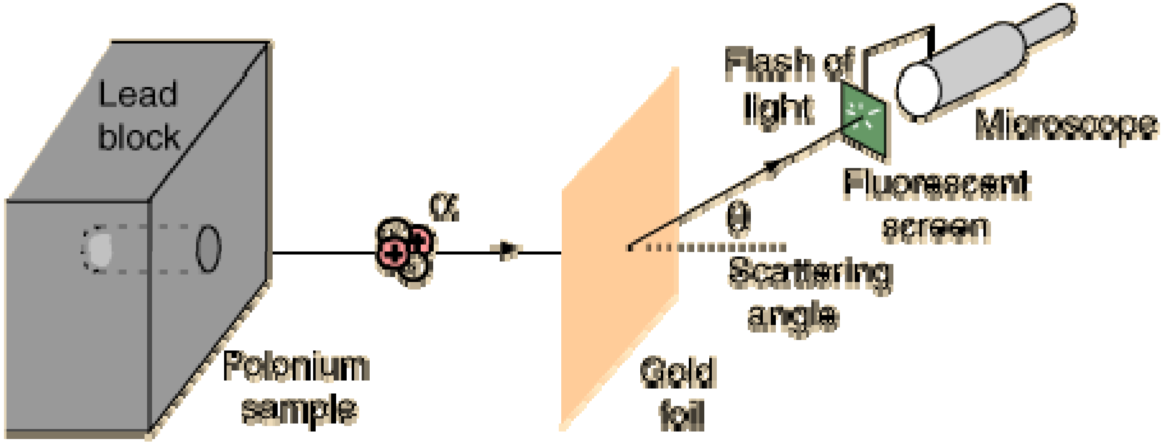
Origins



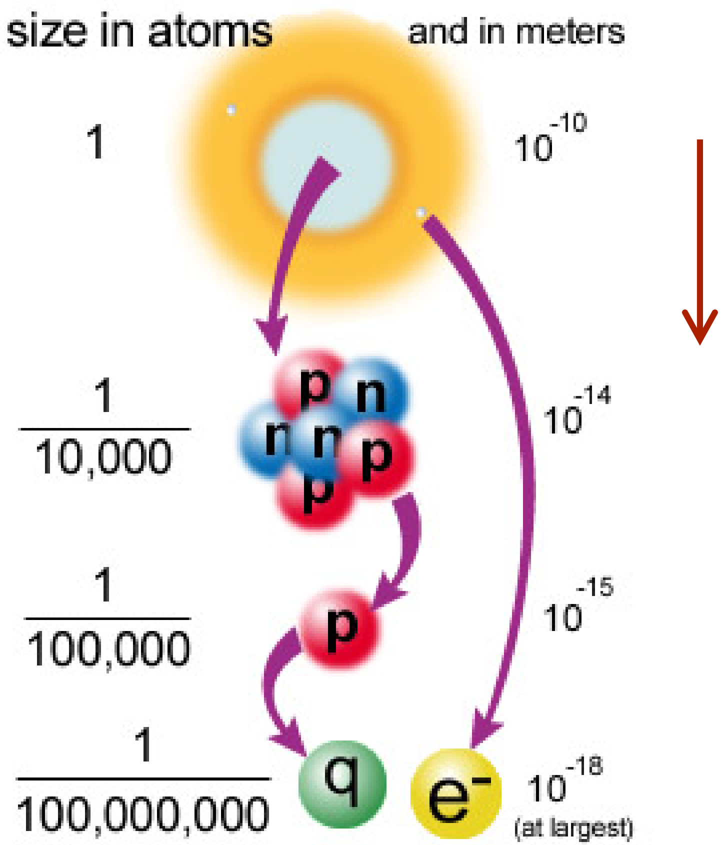
One of the first particle beam set-up's

(Marsden didn't get a stamp)

The Rutherford-Geiger-Marsden Experiment (1906-1913)

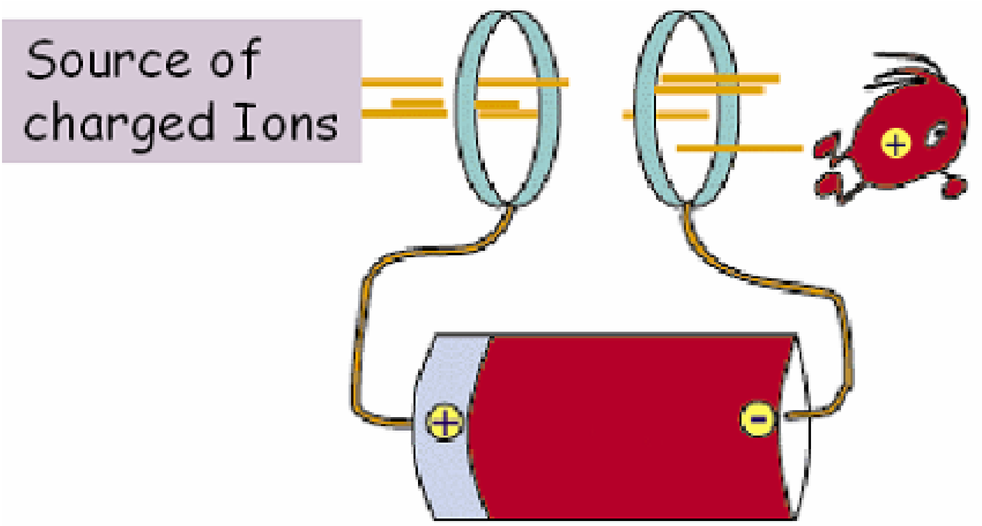


Showed that the Thomson (or Plum Pudding) model of the atom is wrong ! Atoms consists of extremely small nucleus of positive electric charge, carrying almost all the mass of the atoms. The nucleus is surrounded by a diffuse cloud of almost weightless electrons with negative charged.



Rutherford experiment started interest in subatomic length scales

Ernest Rutherford cajoled for years British industry to push development of high voltage sources as replacement for the α-emitters in his experiments.



Why ?

- Higher flux of particles
- Particles of higher velocity ⇔ higher momentum ⇔ higher kinetic energy

Motivations for higher beam energies I

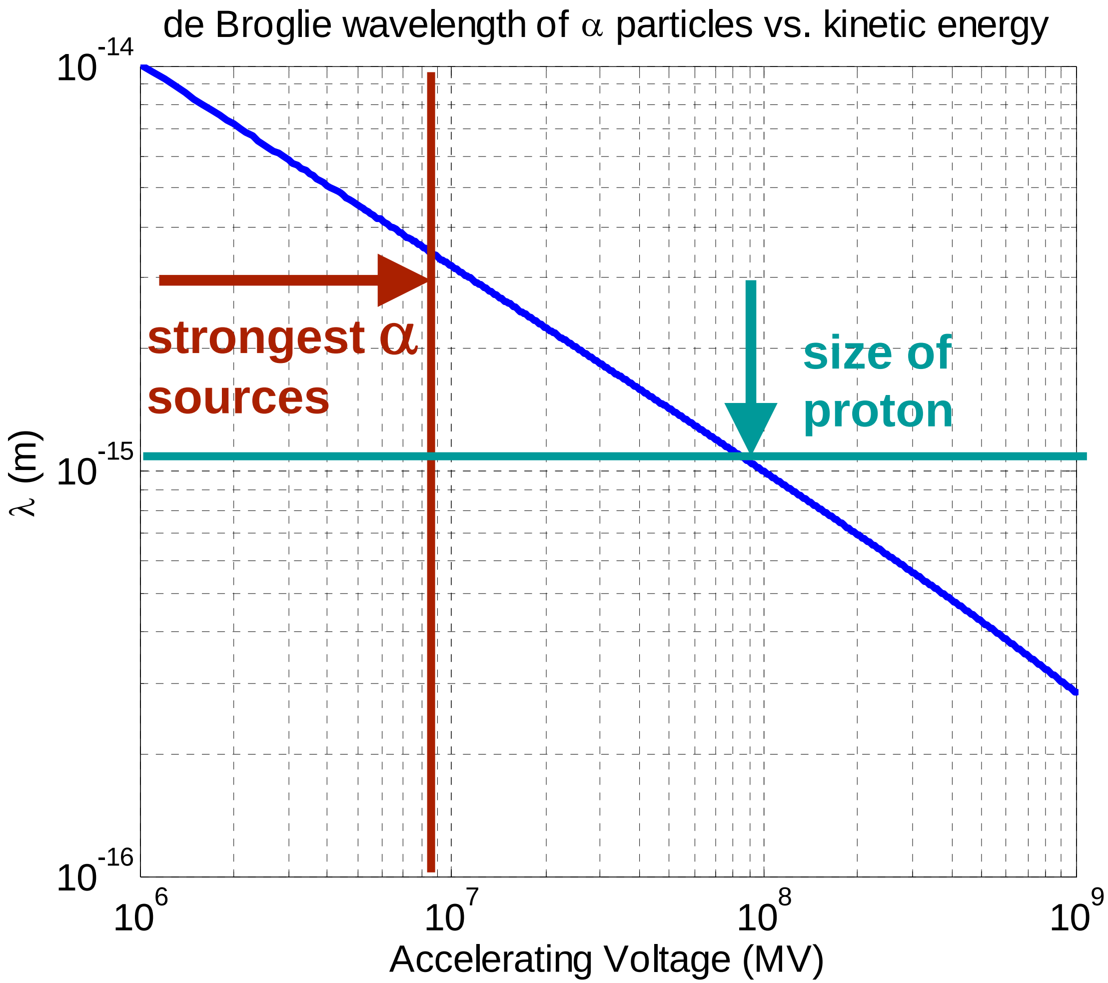
Theory of microscope:

Only objects larger than the wavelength λ of light can be resolved

Louis De Broglie 1923:

Particles have wave properties with wavelength given by

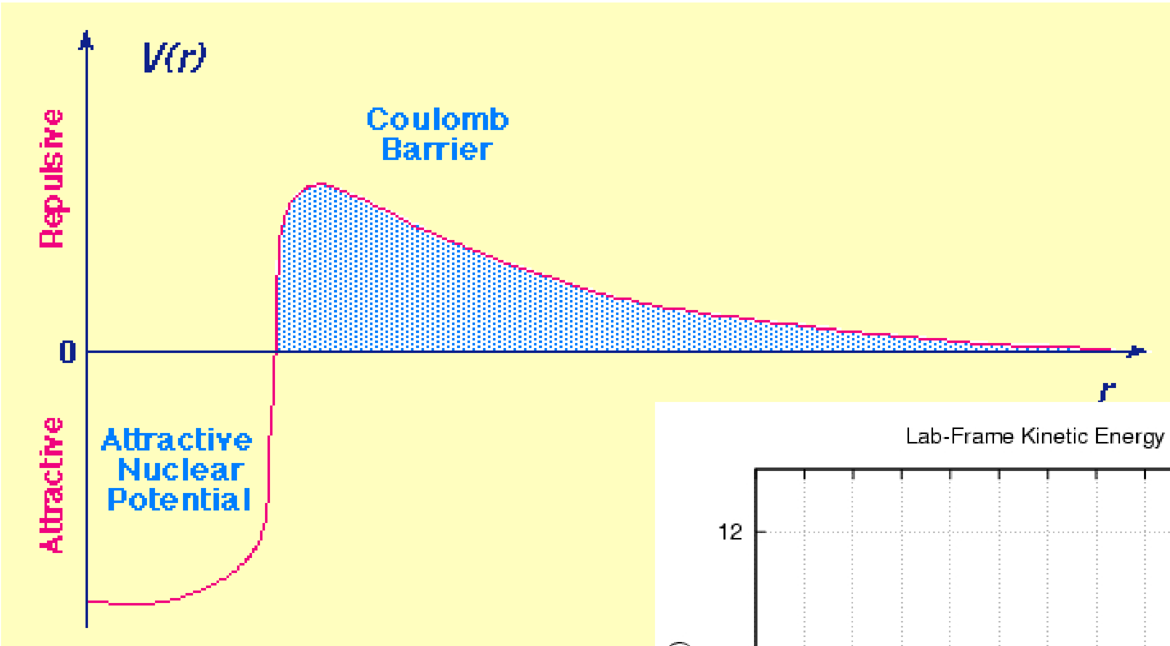
$$\lambda = \frac{h}{P} = \frac{h}{\sqrt{2m\,E_{KIN}}} = \frac{h}{\sqrt{2m\,q\,U}}$$

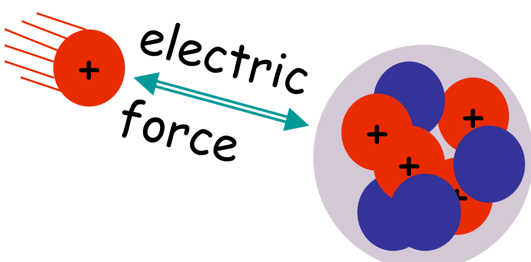


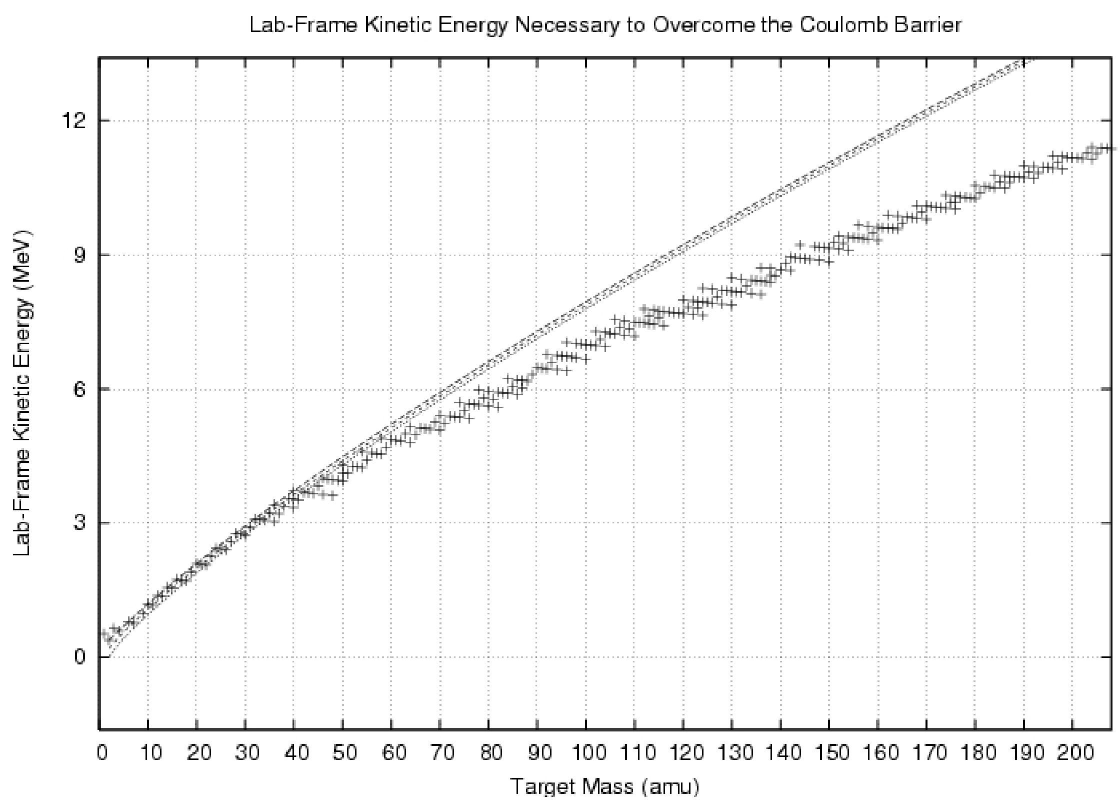
de Broglie wavelength of α particles vs. kinetic energy
λ (m)
10^-14
10^-15
10^-16
10^6
10^7
10^8
10^9
Accelerating Voltage (MV)
strongest α
sources
size of
proton

Motivations for higher beam energies II

Coulomb barrier for charged-particle reactions





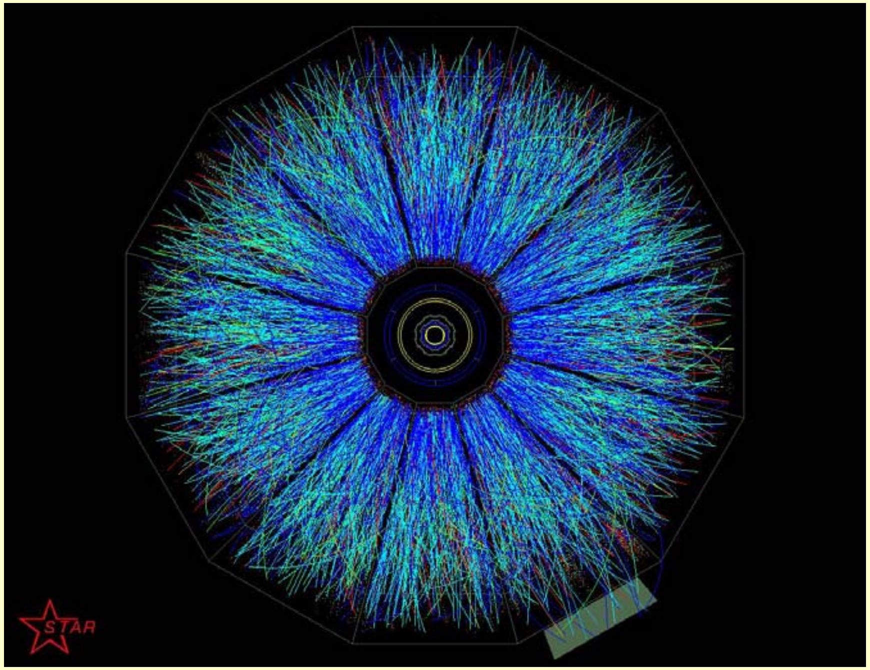


Motivations for higher beam energies III

Einstein* 1905: Energy equivalent to mass

$$E = m\,c^2$$

⇒ Collisions of energetic particles can create new particles, if kinetic energy is sufficient

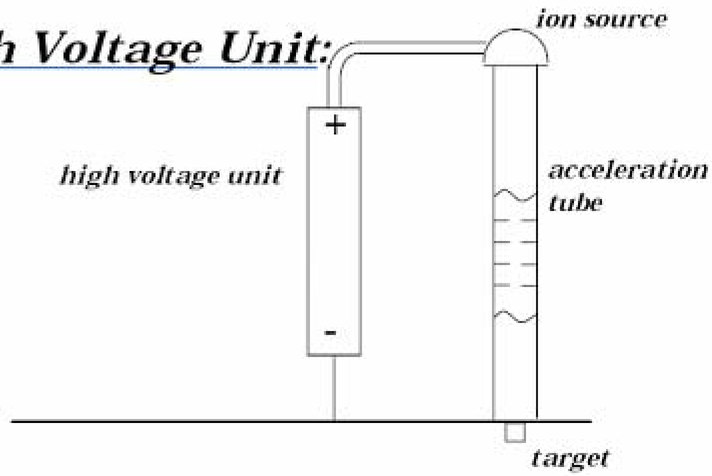


Traces of particles produced in collision of gold atoms at 100 GeV

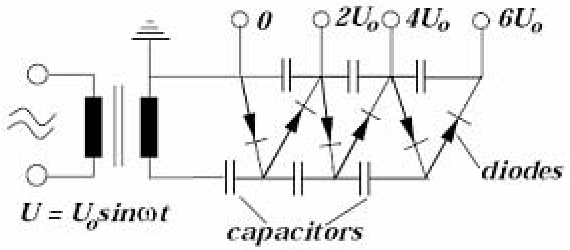
*many stamps

Electrostatic Generators

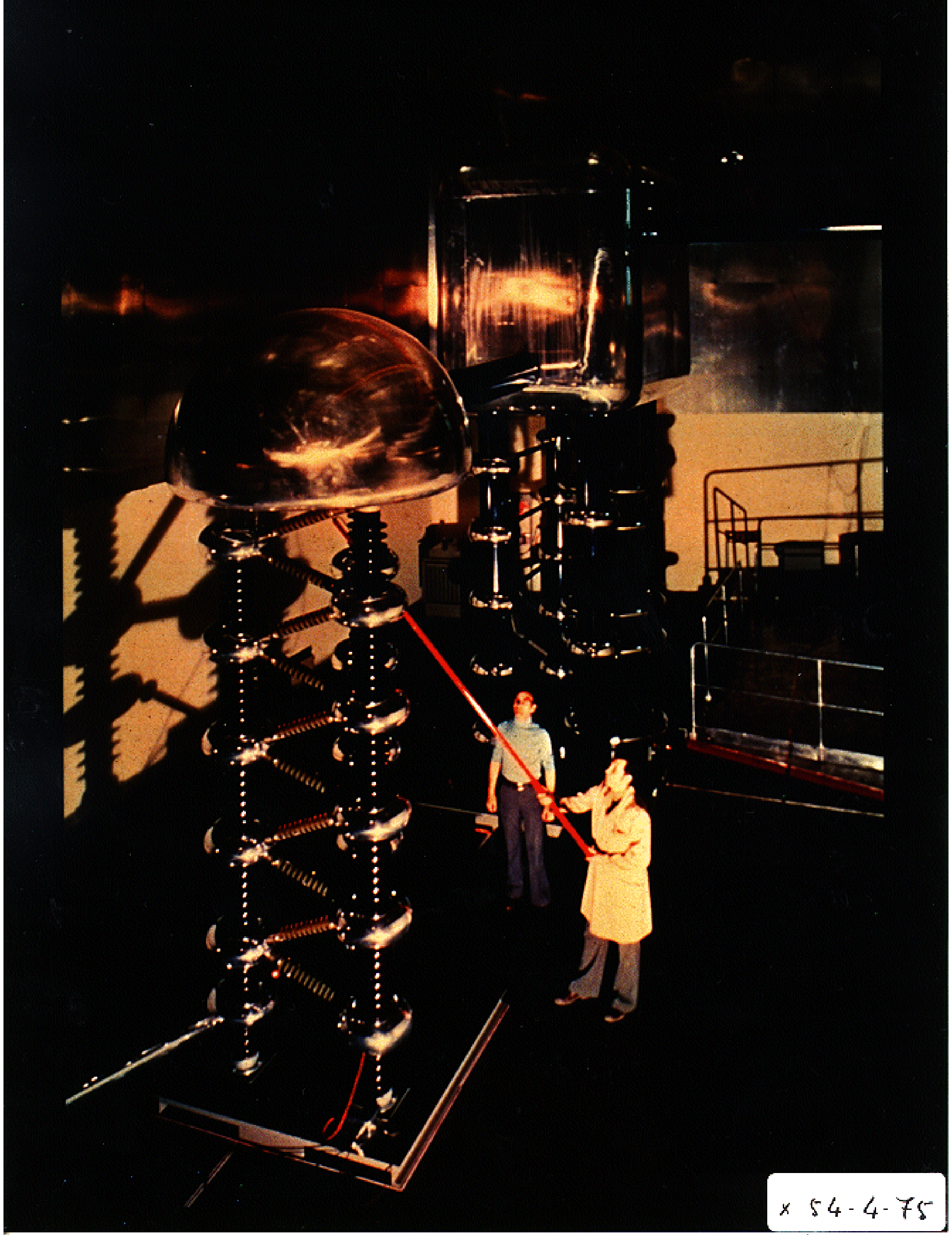
High Voltage Unit:



Cascade Generator:

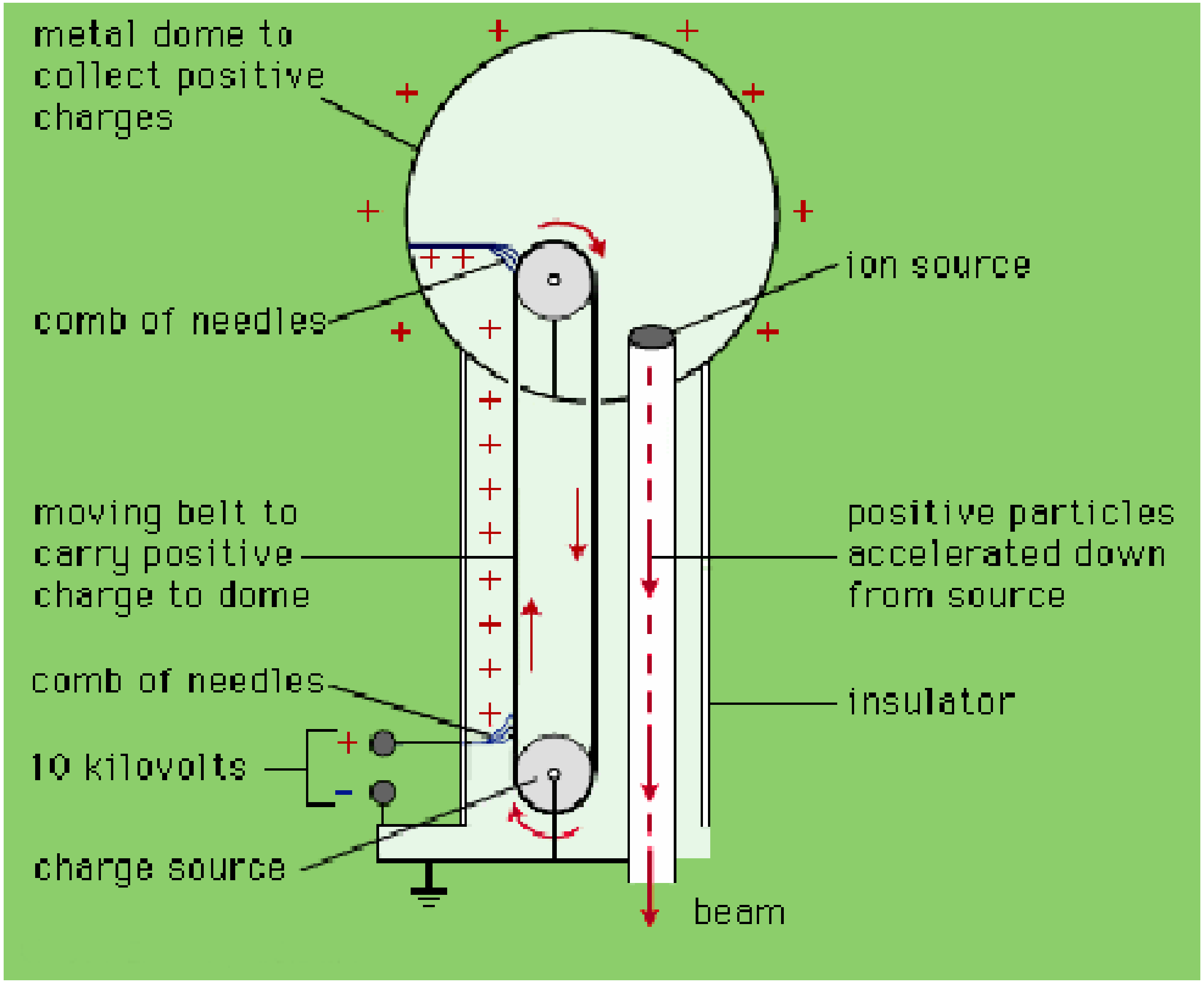


- 1928: Cockroft + Walton 800kV
- 1932: p + Li → 2 He 700kV (p)
  (Nobel Prize 1951)

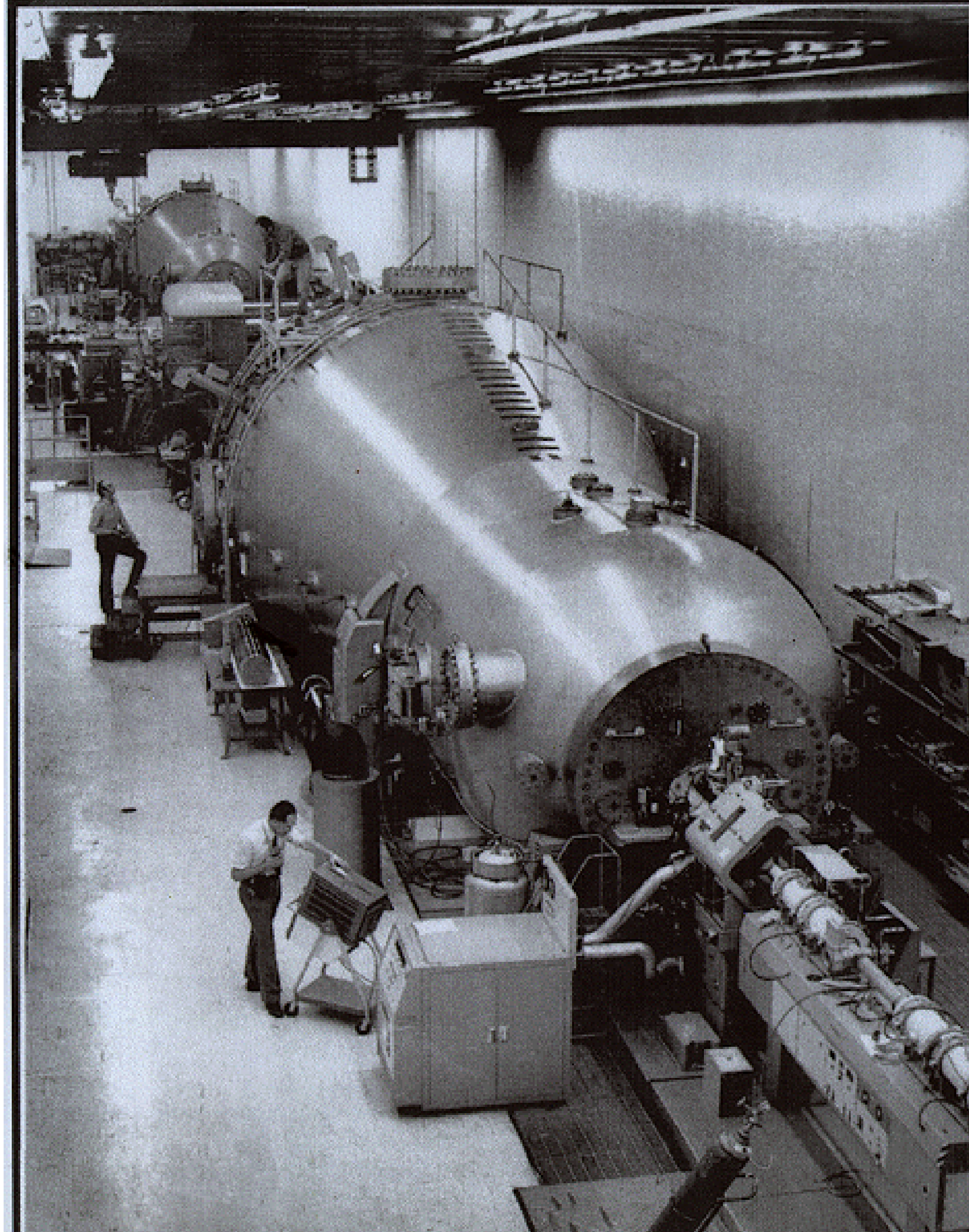


x 54-4-75

Van de Graaff Generator, 1931



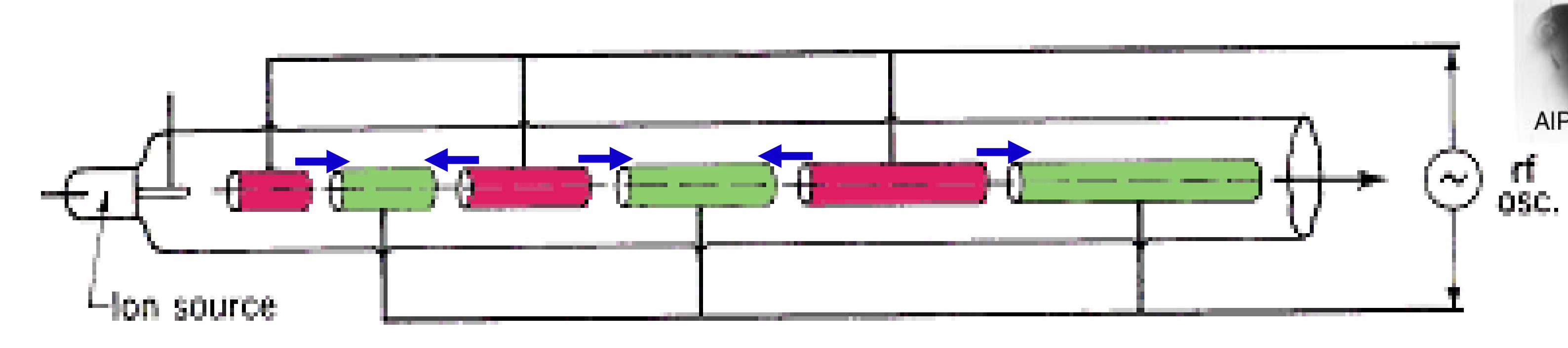
Limited to
≏20MV
by electrical sparking



In Tandem

BNL's Tandem Van de Graaff became operational in 1970 as the world's highest energy Van de Graaff facility and the first with two such accelerators installed back-to-back. Able to accelerate 65 different stable positive and negative ions and a number of radioactive ones, the Tandem has made new isotopes, revealed nuclear interactions and tested the radiation resistance of space-bound electronic devices. This workhorse is now the first link of the chain of accelerators leading to RHIC.

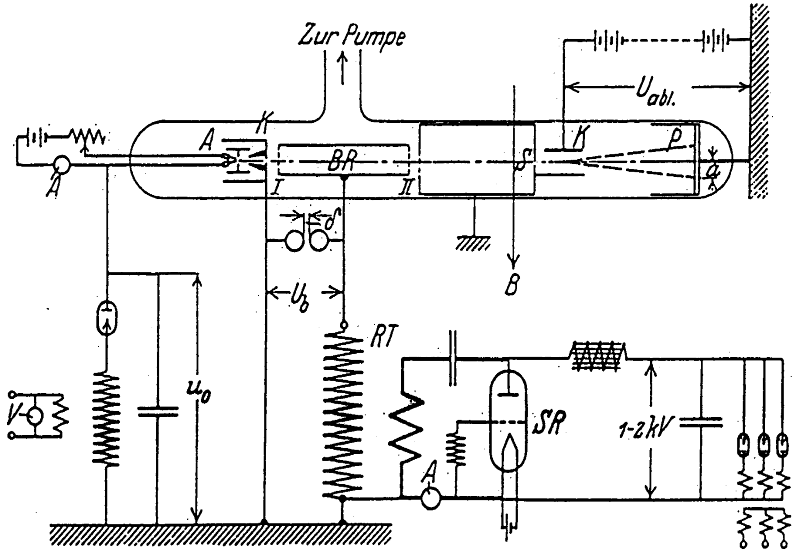
Linear accelerator (Rolf Wideroe 1928)



... and half an RF period later

- Lengths of drift tubes follow increasing velocity $L = \frac{1}{2}\frac{v}{f}$
- Particle gains energy at each gap, total acceleration $N_{GAP} \cdot V_{RF}$

Applied acceleration is *N* times higher than electric voltage !



Wiederoe's first LINAC

In 1928 voltage from RF oscillators was small and the linear accelerator, (or LINAC) not competitive with electrostatic accelerators

RADAR technology boosted the development of RF sources during World War II. This eventually made LINAC's the accelerator of choice for many applications.

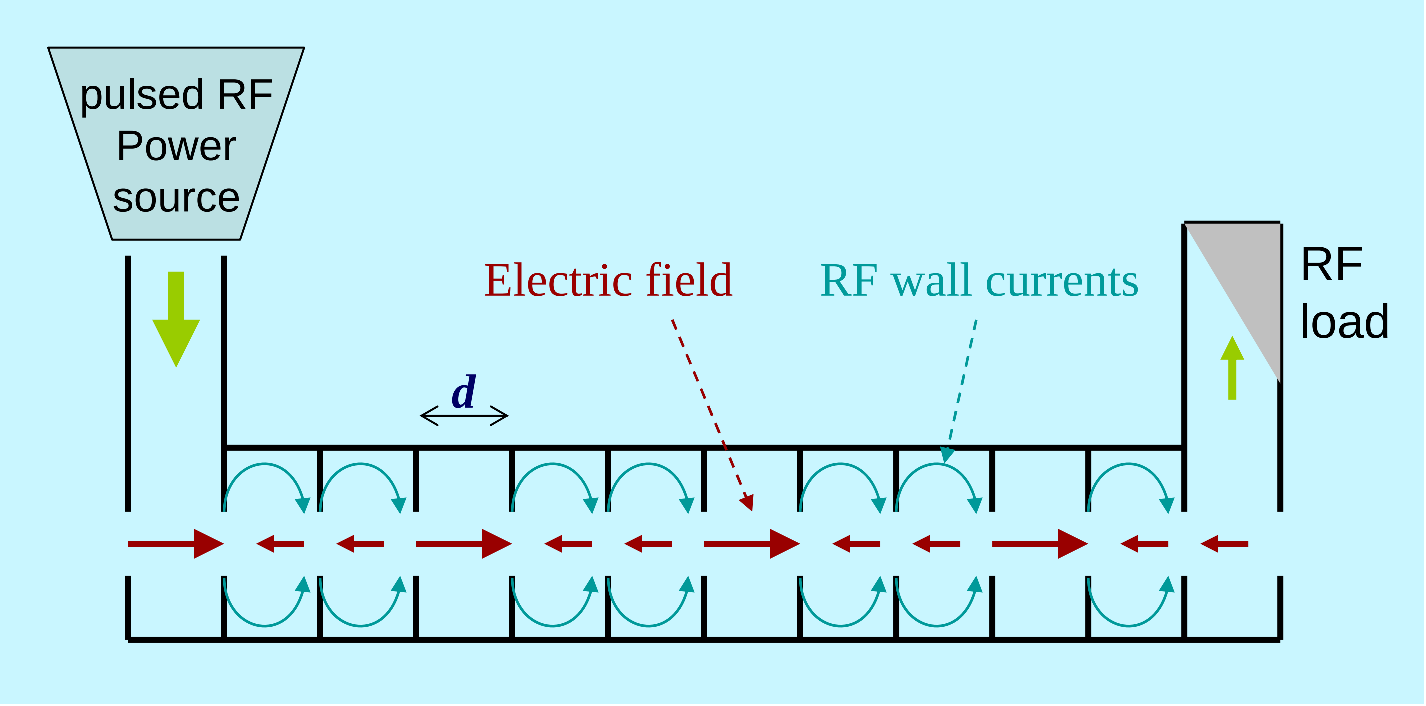
Fermilab proton linac (400MeV)

Inside proton linac

Electron Linacs

Because of higher particle velocity (≈c_0), higher frequency (1.3-30 GHz) and different accelerating structure types.

Most common building block it traveling wave structure.



Electrically coupled TM_{010} resonant cavities

Condition for acceleration $\Delta\varphi = \omega/c \cdot d$,
with $\Delta\varphi$ the phase difference between adjacent cells

TM_{010} "pill box cavity mode"

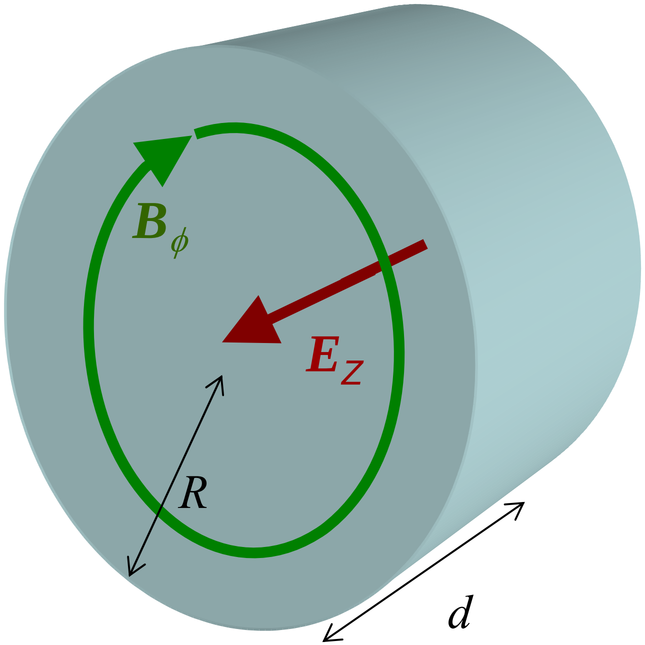
$$E_Z = E_0 J_0(\tfrac{\omega}{c} r)\cos(\omega t)$$

$$B_\phi = -\frac{E_0}{c} J_1(\tfrac{\omega}{c} r)\sin(\omega t)$$

Resonant frequency given by 1st zero

of Bessel function, $\omega = 2.405 \dfrac{c}{R}$

ω independent of d!



Stored Energy

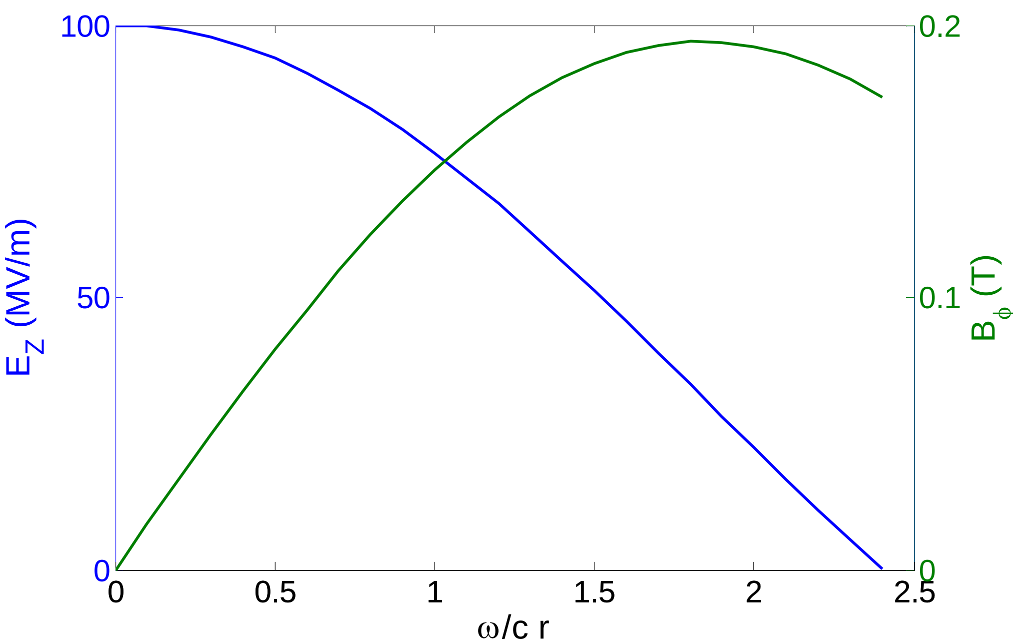
$$W = \int_0^d \int_0^{2\pi} \int_0^R \frac{\varepsilon_0}{2} (E_Z^2 + c^2 B_\phi)\, r\, dr\, d\phi\, dz$$

$$= \frac{\pi}{2} \varepsilon_0\, d\, E_Z^2 R^2 J_1(2.405)^2$$

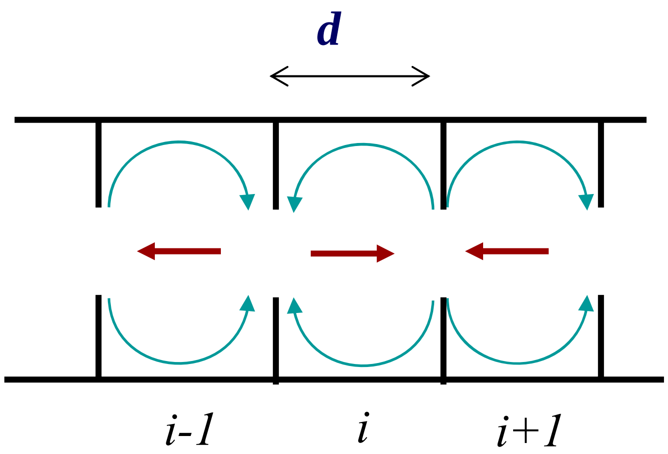
Power loss given by

$$P = -\frac{\omega}{Q} W, \quad Q \approx \frac{7 \cdot 10^8}{\sqrt{f}}$$

(typical Q value for copper accelerating structures)



Coupled chain of resonators



$$E_i'' + \omega_0 E + aE_{i-1}'' + E_{i+1}'' = 0$$

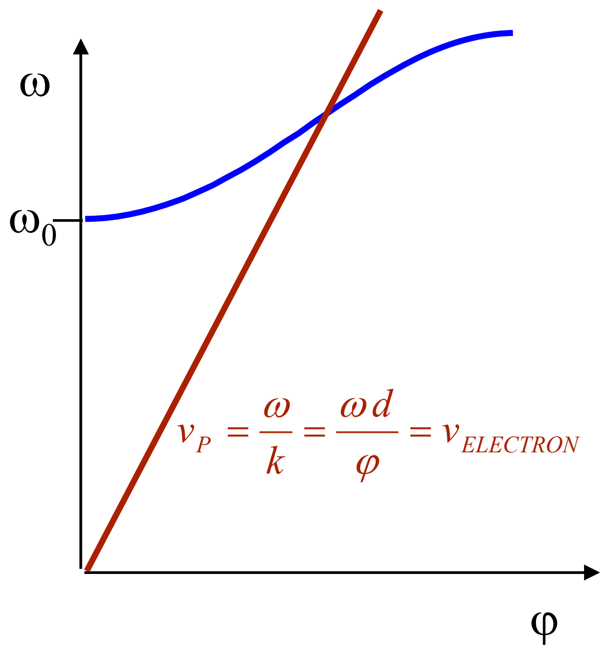
Ansatz

$$E_{i-1} = e^{i(\omega t+\varphi)} \ , \quad E_i = e^{i\omega t} \ , \quad E_{i+1} = e^{i(\omega t-\varphi)};$$

$\Rightarrow$ Dispersion relation $\quad \omega = \dfrac{\omega_0}{\sqrt{1+2\mathrm{a}\cos\varphi}}$

wavenumber $\quad k = \dfrac{\varphi}{d}$

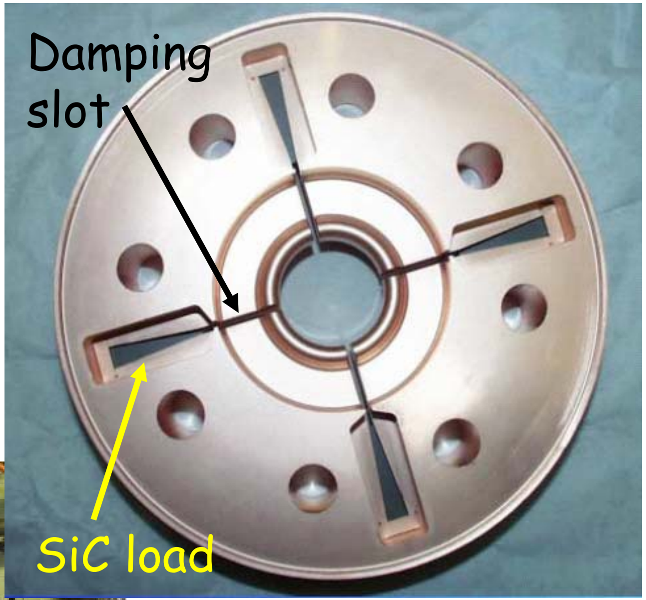
$\Rightarrow$ Group velocity $\quad v_G = \dfrac{d\omega}{dk} = \dfrac{a\, d\, \omega_0 \sin kd}{(1+2a\cos kd)^{\frac{3}{2}}}$

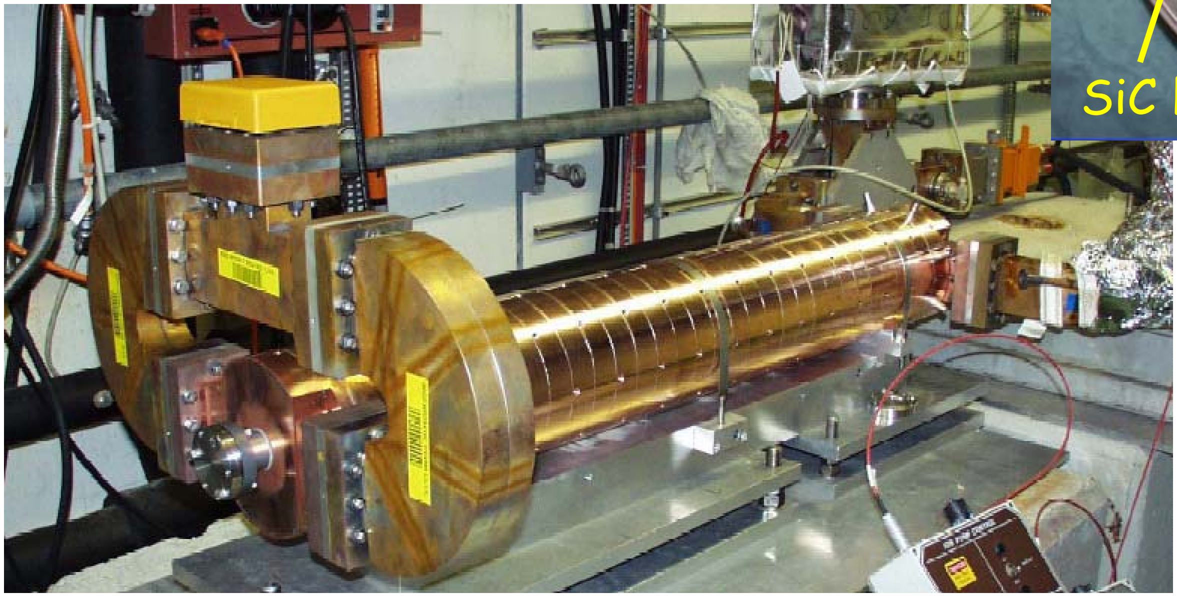


3 GHz accelerating structure of CTF3

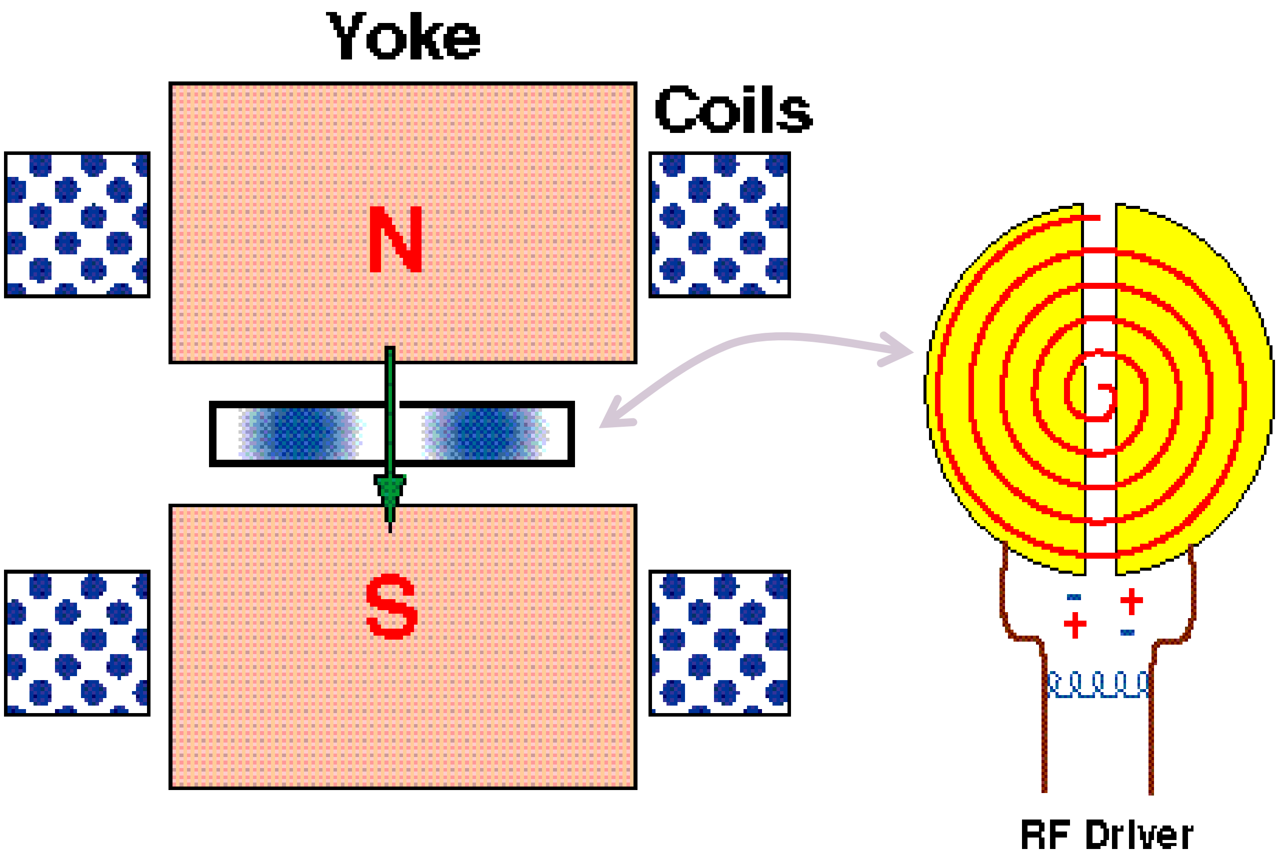
Input power	30 MW
Pulse length	1.5 μs
Length	1 m
Beam current	3.5 A
Acceleration	9 MV
Frequency	2.99855 GHz

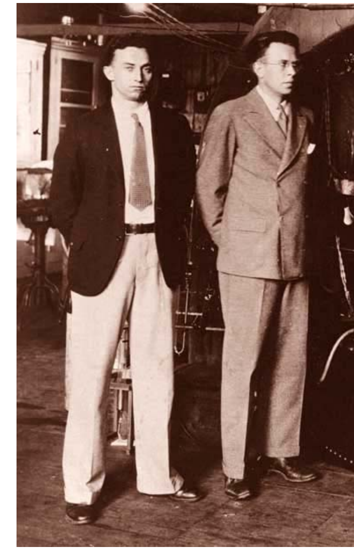
Dipole modes suppressed by slotted iris damping (first dipole's Q factor < 20) and HOM frequency detuning



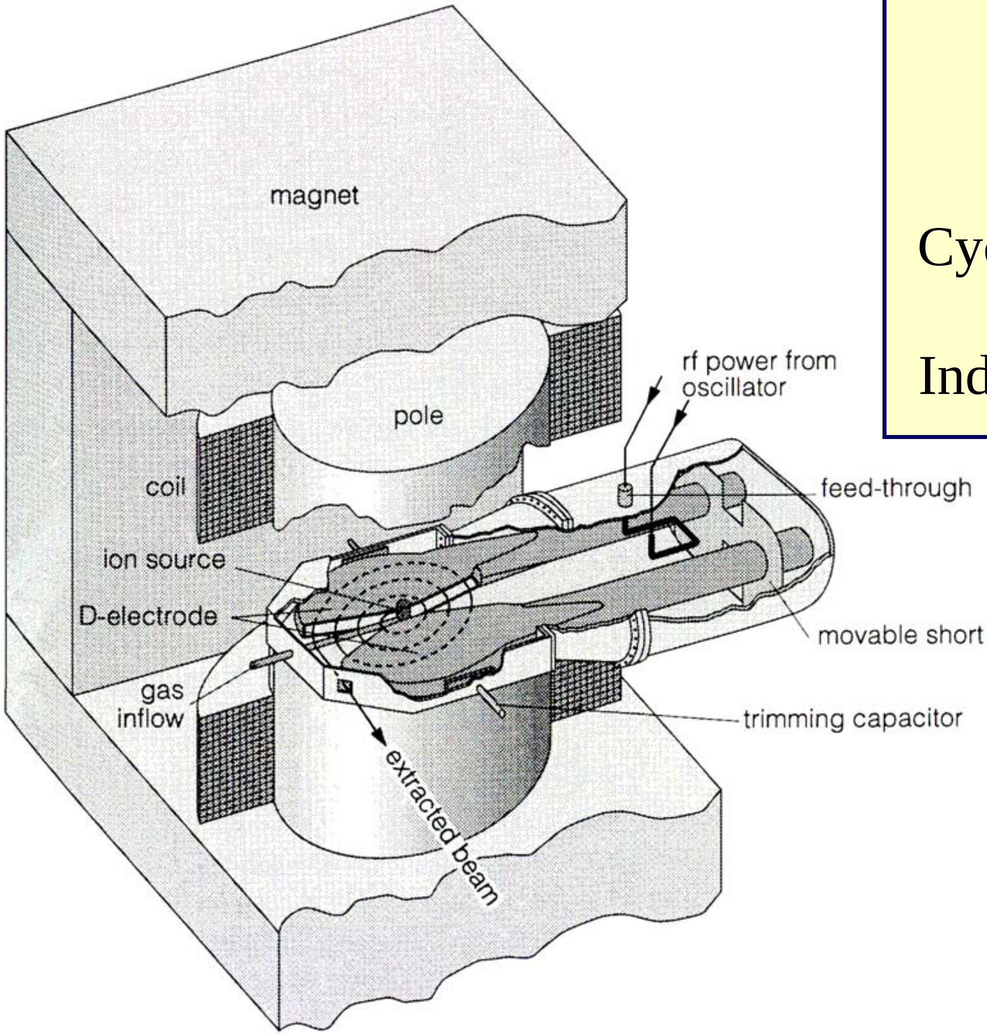


<u>Cyclotron</u> Lawrence & Livingston 1932





The <u>same</u> acceleration gap traversed many times !



Lorentz Force = Centrifugal Force

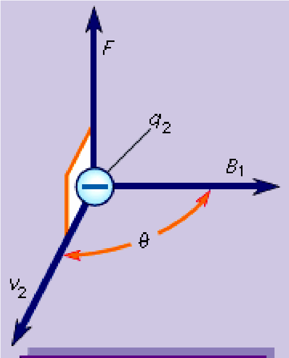
$$evB = \frac{mv^2}{R}$$

Radius of trajectory $R = \frac{mv}{eB}$

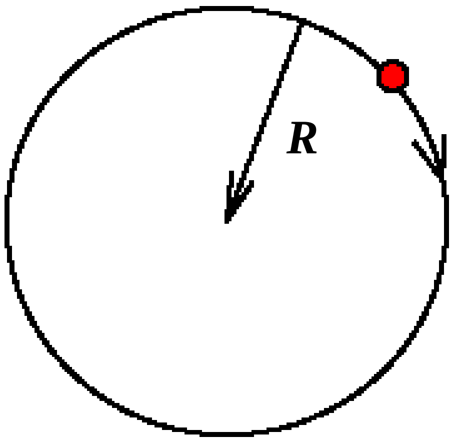
Revolution time $T = \frac{2\pi R}{v} = \frac{2\pi m}{eB}$

Cyclotron frequency $f = \frac{eB}{2\pi m}$

Independent of velocity!



Magnetic force F is perpendicular to the plane of the velocity v_2 of the charge q_2 and the magnetic field B_1



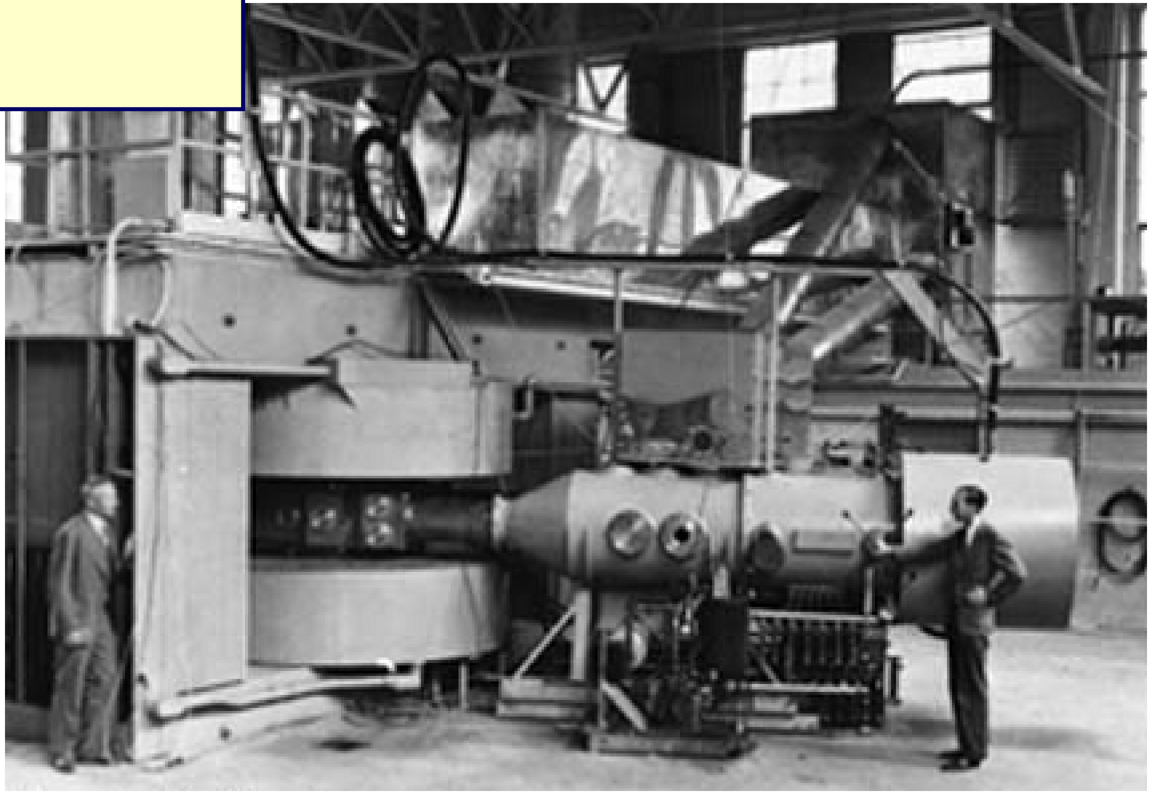
Example: a typical proton Zyklotron

$$B = 1.7\,\mathrm{T}$$

$$R = 0.75\,\mathrm{m}$$

$$f = \frac{e\,B}{2\pi\,m} = 25.92\,\mathrm{MHz}$$

$$E_{KIN} = \frac{(e\,B\,R)^2}{2m_P} = 1.247 \cdot 10^{-11}\,\mathrm{J} = 77.86\,\mathrm{MeV}$$



Theory of relativity

Cyclotron frequency $f = \dfrac{e\,B}{2\pi\, m}$

Independent of velocity?

$$m_{effective} = m_0\left(1 + \frac{E_{KIN}}{m_0 c^2}\right)$$

⇒ Cyclotron principle works only for beam energies

E_{KIN} ⑥ $m_0\, c^2$

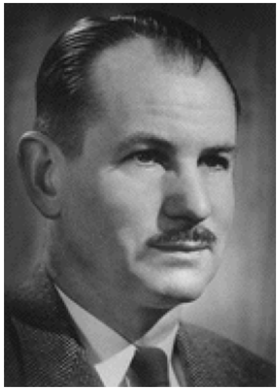
For example for protons

E_{KIN} ⑥ 938 MeV

(with some tricks 🕓600 MeV can be obtained)

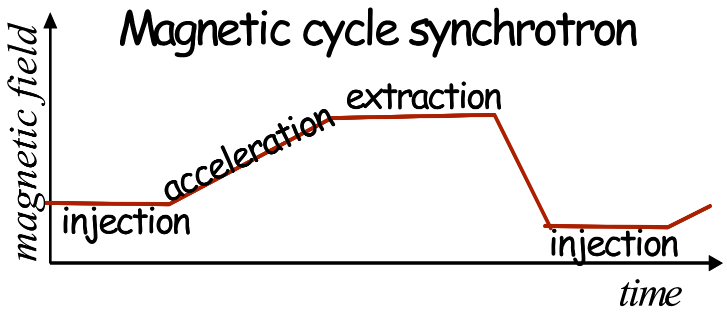
The Synchrotron

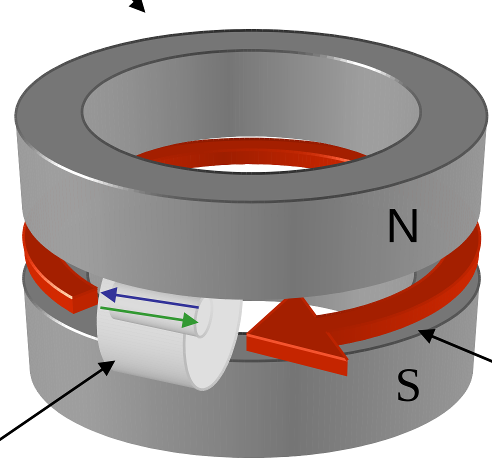
Proposed independently and simultaneously 1945 by McMillan in the USA and Veksler in the USSR

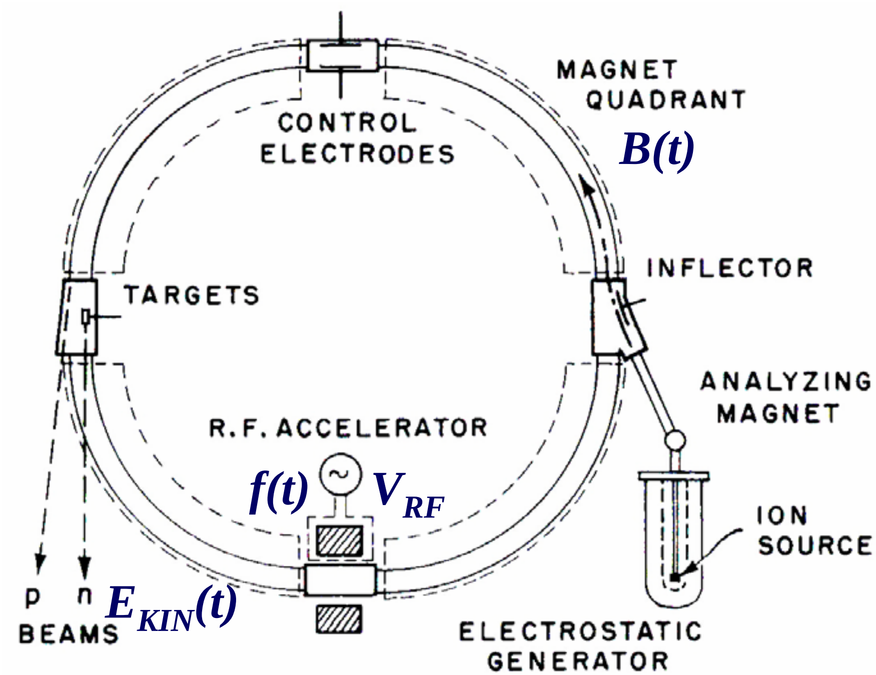


E.M. McMillan

V. Veksler







Layout of an early proton synchrotron

To make synchrotron work
magnetic field, RF frequency and voltage have to be controlled following a system of coupled equations:

$$\frac{dE_{kin}(t)}{dt} = eV_{RF}\, f(t)$$

$$B(t) = \frac{m\,c}{e\,R}\sqrt{\frac{(E_{kin}(t)+m\,c^2)^2}{m^2c^4}-1}$$

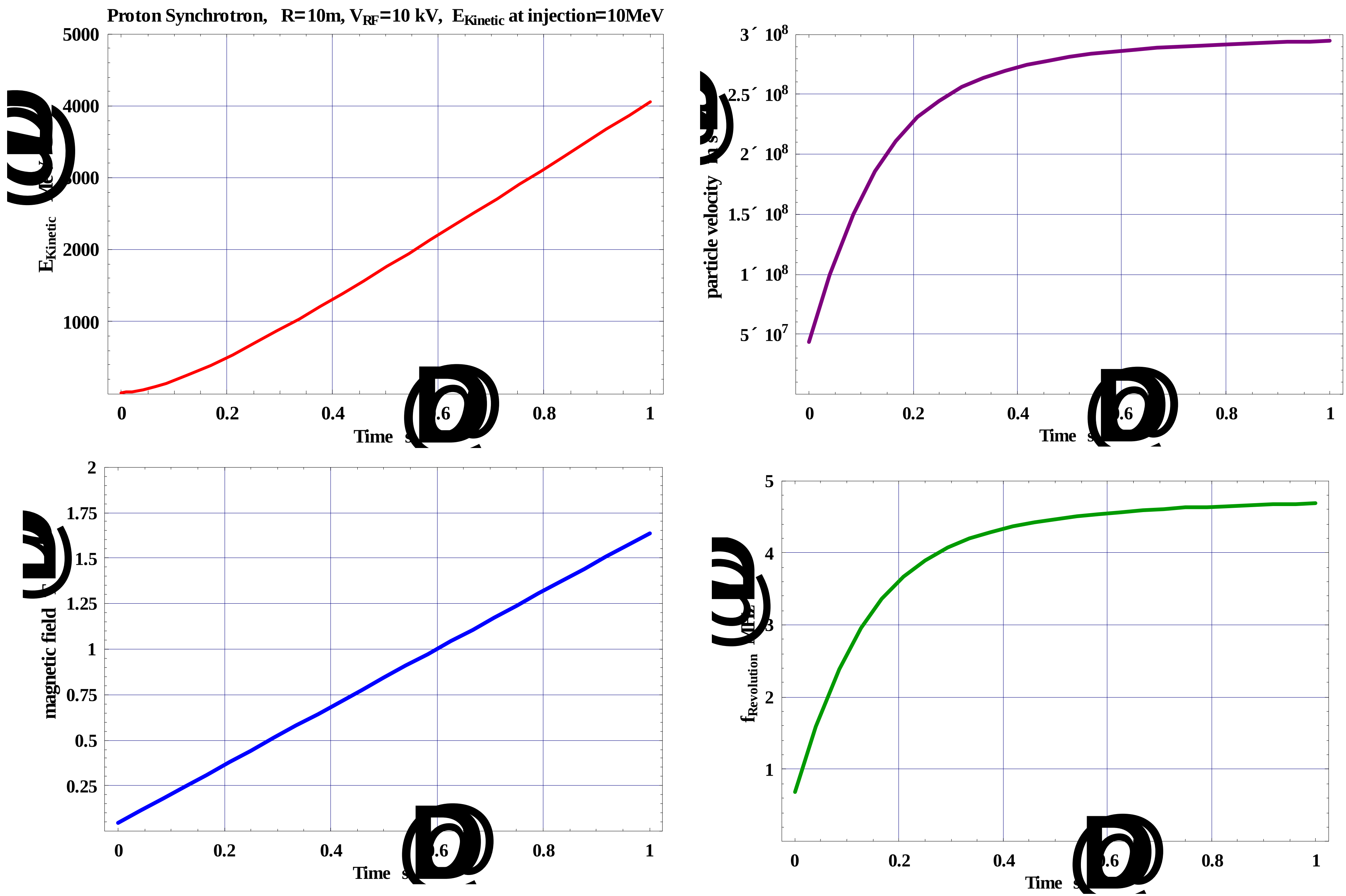
$$f(t) = \frac{v(t)}{2\pi R}$$

$$v(t) = c\sqrt{1-\frac{m^2c^4}{(E_{kin}(t)+m\,c^2)^2}}$$

Taken relativistic mass increase into account !

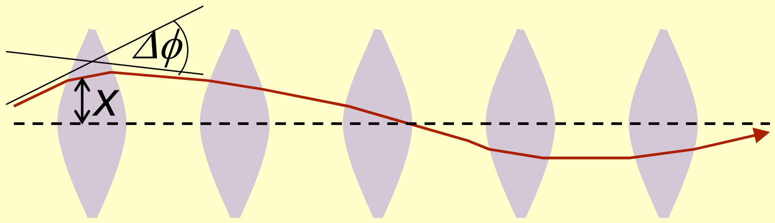
⇒ **Synchrotron can be build for very high energies.**
For proton beams limits are given by achievable magnetic field and size.
Largest synchrotron LHC at CERN (under construction), 27km circumference, B_{MAX}=8.3 T, E_{KIN}=7.000.000 MeV

Variation of parameters with time in a proton synchrotron



How to keep beam particles together ?

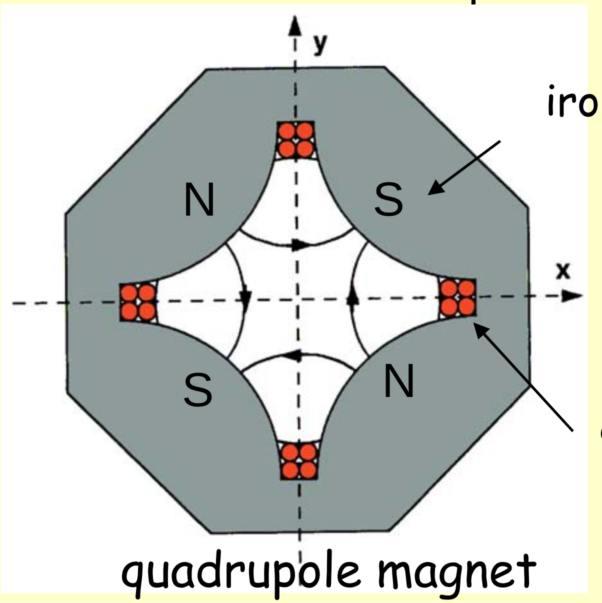
In light optics an array of focusing lenses is used to keep light rays together



The action of each lens can be described as an angle change of the trajectory

$$\Delta\phi = -\frac{x}{f}$$

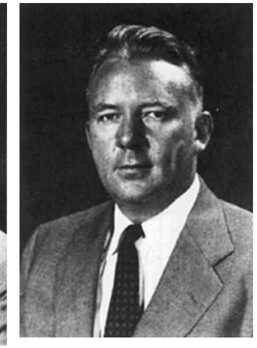
An electromagnet in quadrupole configuration will have a similar effect on a particle beam.



However there is one big difference, considering the direction of Lorentz force you find that it focuses in one plane, but <u>defocuses</u> in the other !

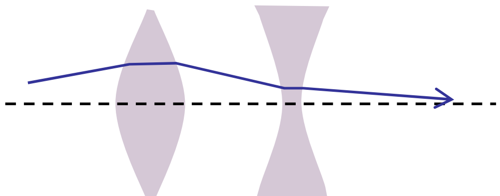
1952 Courant, Snyder and Livingston
propose "alternating gradient focusing"


E. Courant

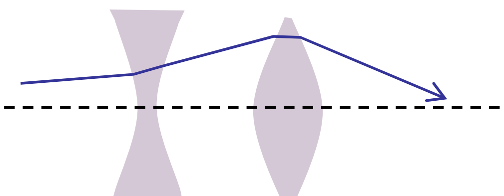

H. Snyder


S. Livingston

focusing + defocusing = focusing



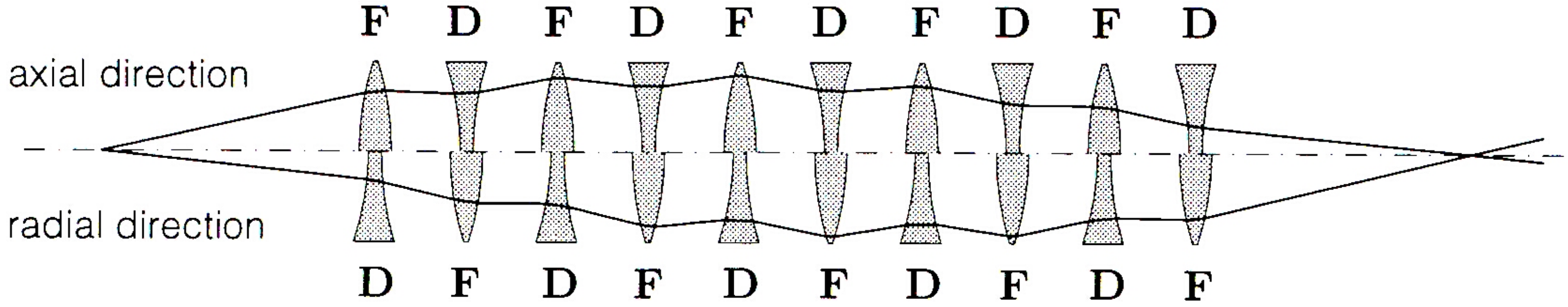
defocusing + focusing = focusing



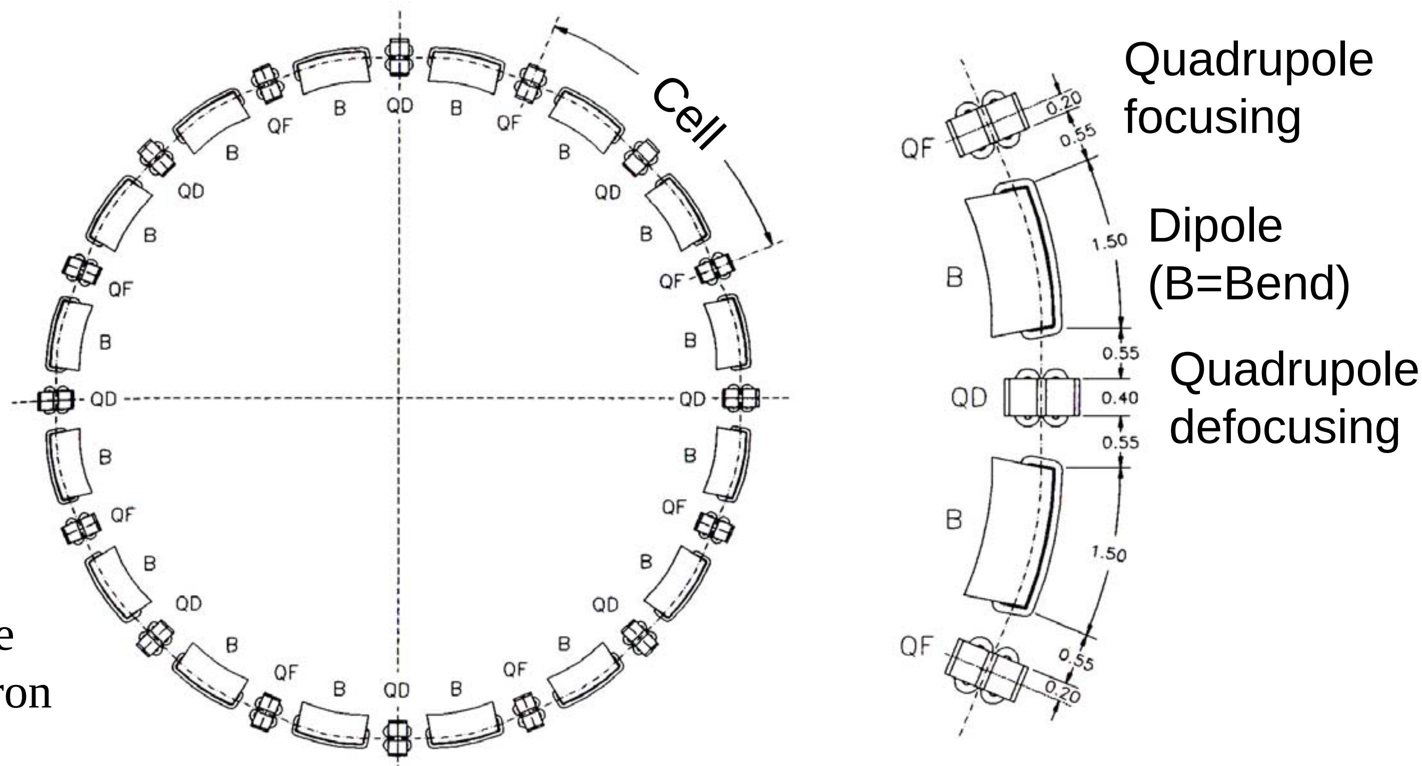
Introduction of AG focusing had tremendous impact
on beam quality and accelerator size and cost !

In turned out that Christofilos from Athens had filed an
U.S. patent on this idea already in 1950, but nobody had noticed !


N. Christofilos



Optical analogy to strong focusing.

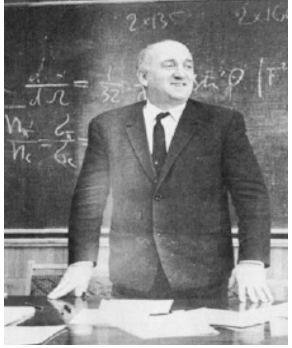


FODO lattice
for synchrotron

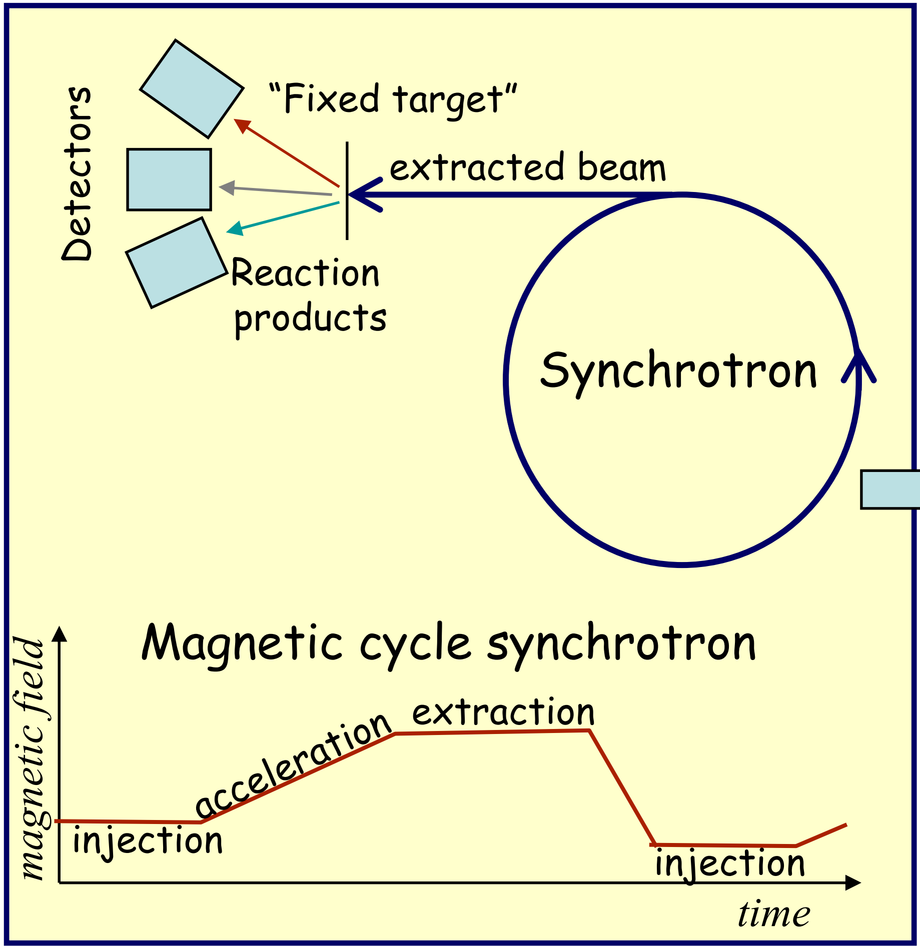
Particle Colliders

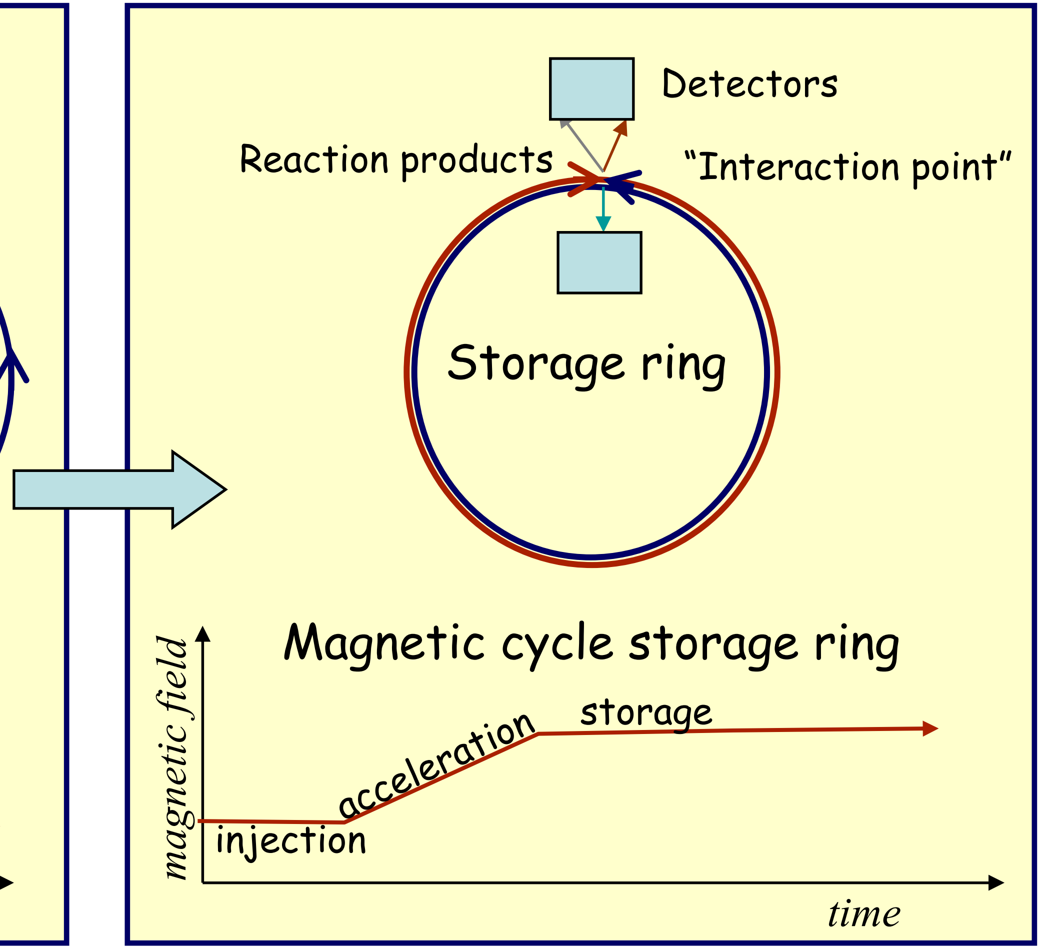
Frascati and Novosibirsk, 1961

B. Touschek*



A. Budker

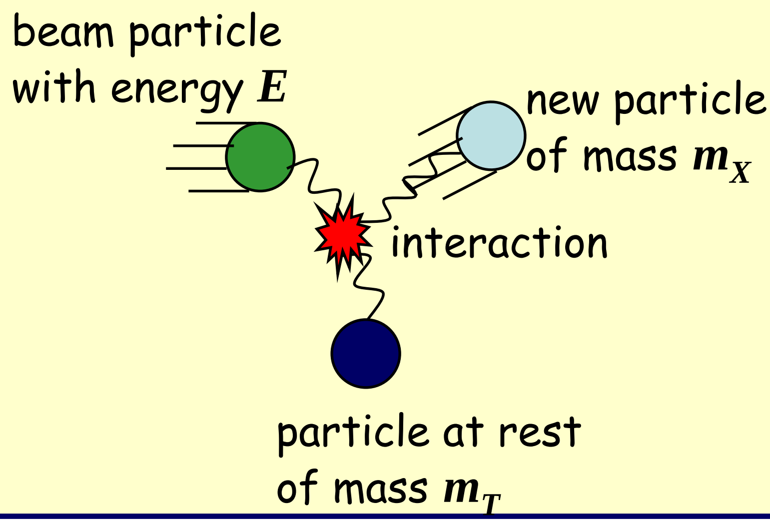




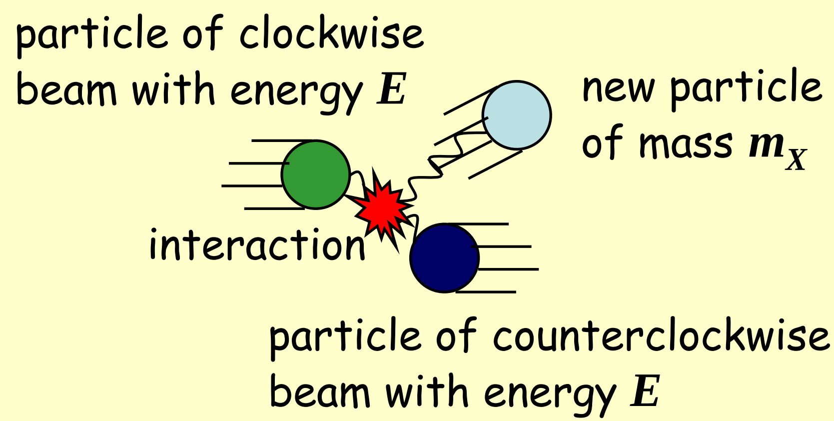
*with Lola

What is the advantage of collider?

Fixed target



Colliding beams

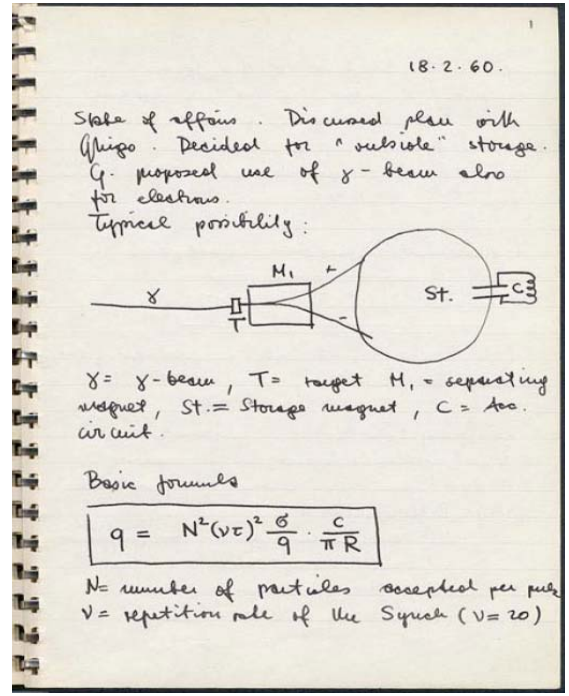


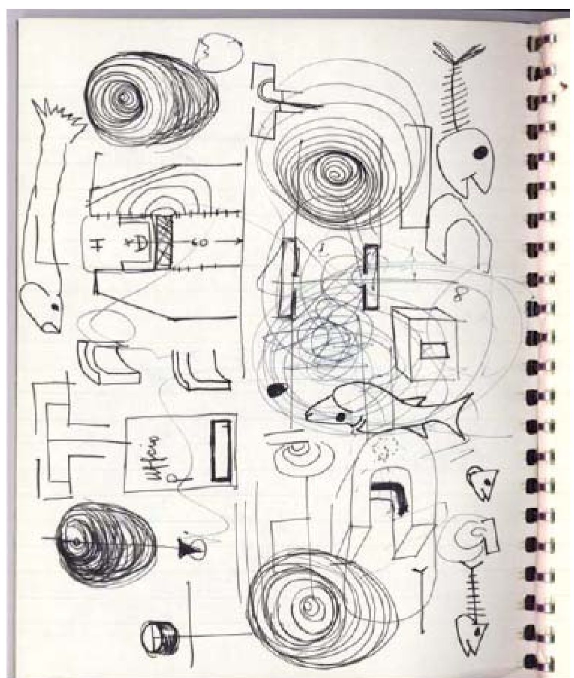
Conservation of energy and momentum

$$E > \frac{m_X^2 c^2}{2 m_T}$$

$$E > \frac{m_X c^2}{2}$$

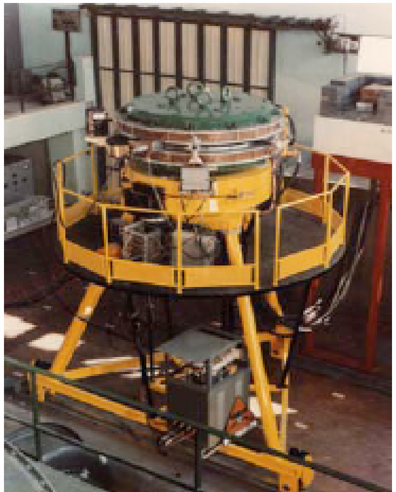
Same pages from Bruno Touscheks 1960 notebook





From AdA to LHC.

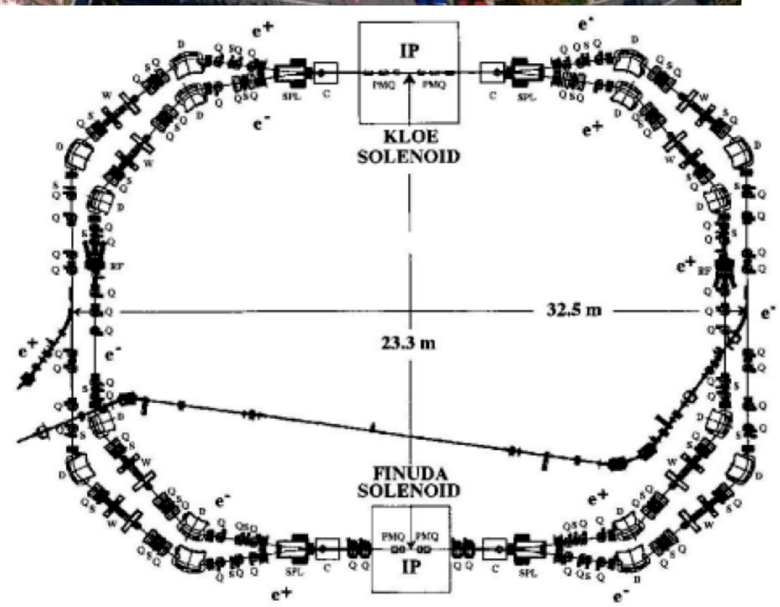
Rings in the world



1961	AdA, Frascati	e^+/e^-
1964	VEPP 2, Novosibirsk, URSS	e^+/e^-
1965	ACO, Orsay, France	e^+/e^-
1969	ADONE, Frascati, Italy	e^+/e^-
1971	CEA, Cambridge, USA	e^+/e^-
1972	SPEAR, Stanford, USA	e^+/e^-
1974	DORIS, Hamburg, Germany	e^+/e^-
1975	VEPP-2M, Novosibirsk, URSS	e^+/e^-
1977	VEPP-3, Novosibirsk, URSS	e^+/e^-
1978	VEPP-4, Novosibirsk, URSS	e^+/e^-
1978	PETRA, Hamburg, Germany	e^+/e^-
1979	CESR, Cornell, USA	e^+/e^-
1980	PEP, Stanford, USA	e^+/e^-
1981	Sp-pbarS, CERN, Switzerland	p/p
1982	Fermilab p-pbar, USA	p/p
1987	TEVATRON, Fermilab, USA	p/p
1989	SLC, Stanford, USA	e^+/e^-
1989	BEPC, Peking, China	e^+/e^-
1989	LEP, CERN, Switzerland	e^+/e^-
1992	HERA, Hamburg, Germany	$e^{+/-}/p$
1994	VEPP-4M, Novosibirsk, Russia	e^+/e^-
1999	DAΦNE, Frascati, Italy	e^+/e^-
1999	KEKB, Tsukuba, Japan	e^+/e^-
1999	PEP-II, Stanford, USA	e^+/e^-
2003	VEPP-2000, Novosibirsk, Russia	e^+/e^-
2007	LHC, CERN, Switzerland	p/p and Pb/Pb
1961	VEP 1, Novosibirsk, USSR	e^-/e^-
1971	ISR, CERN, Switzerland	p/p
2000	RHIC, Brookhaven, USA	ion/ion

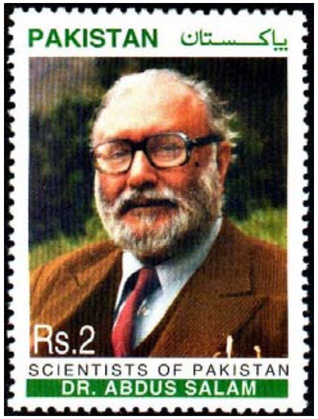
DAΦNE

LNF Frascati
500 MeV e^+/e^- collider



In the tunnel of the CERN $Sp\bar{p}S$ proton antiproton collider
450.000 MeV, 7 km circumference

1967 **Unified Theory of electromagnetic and weak interaction**
Field quanta γ, $W^{\pm}$ and Z^0



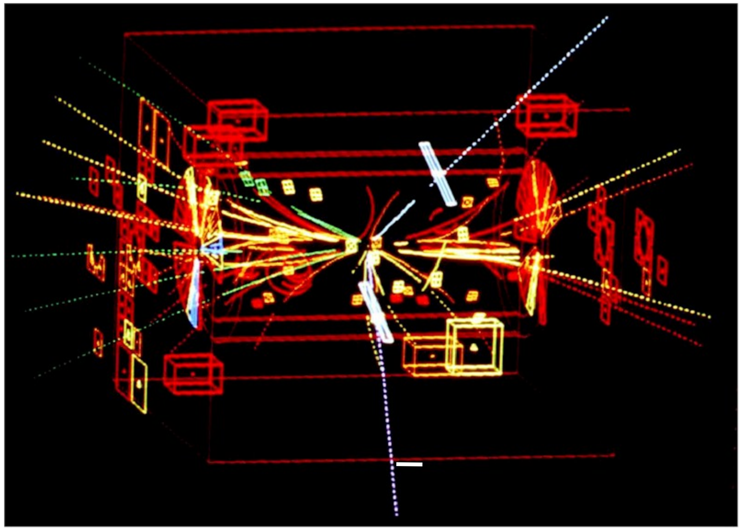
1979 **Nobel price for Glashow, Weinberg, Salam**

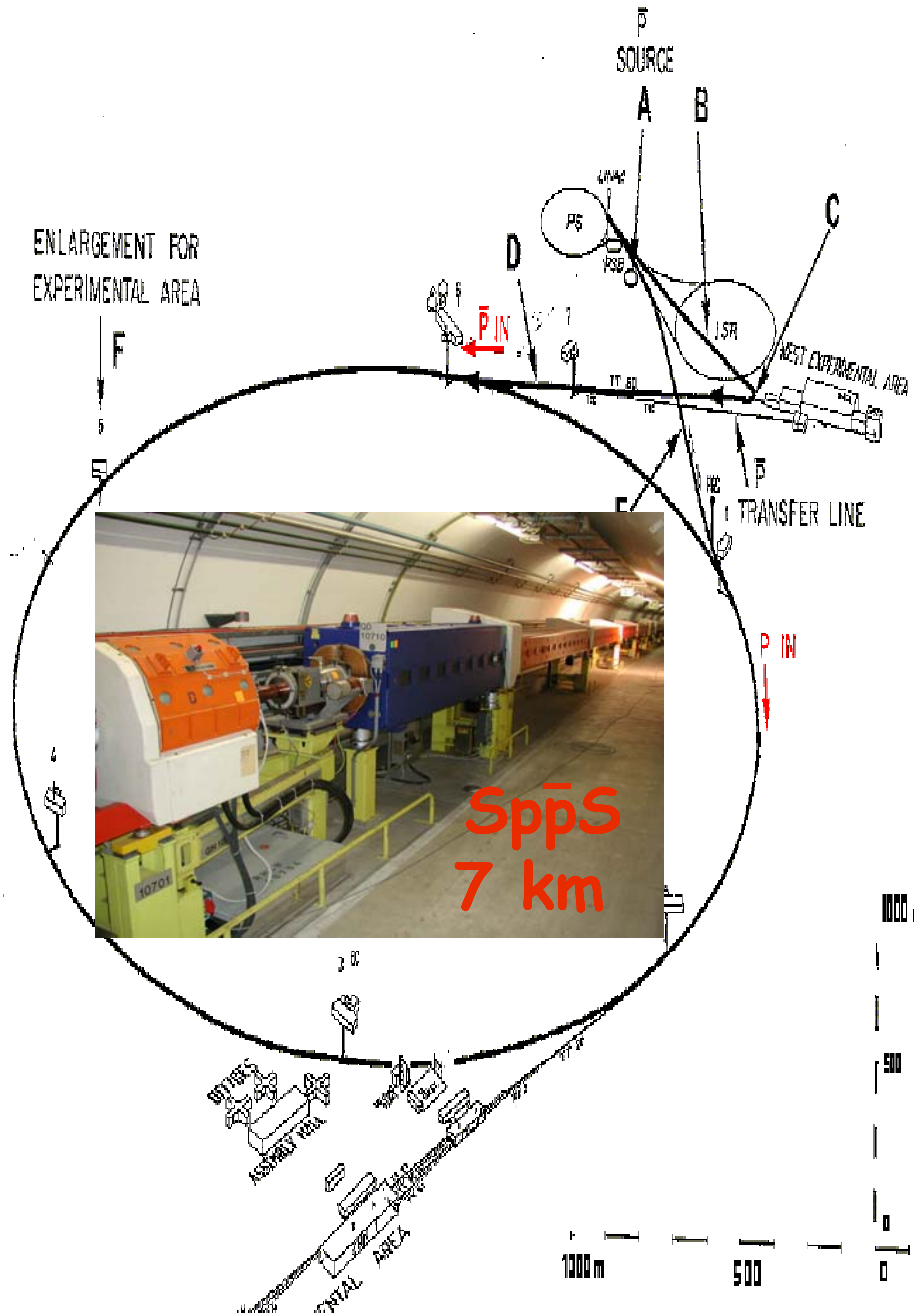
$$M_W^2 = Konst \cdot \frac{1}{\sin^2 \Theta_W}$$

$$M_Z^2 = M_W^2 \cdot \frac{1}{\cos^2 \Theta_W}$$

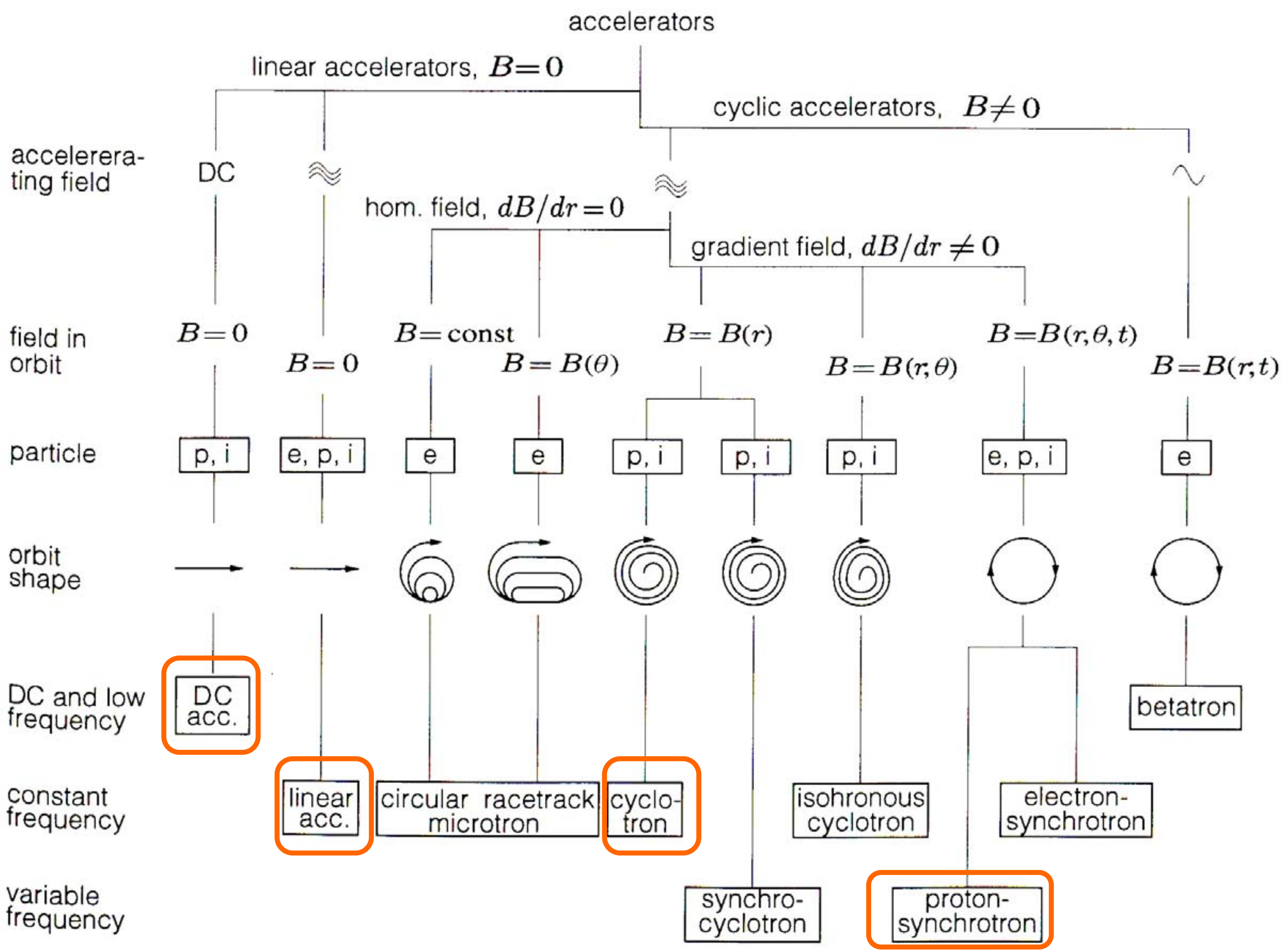
1983 **Discovery of $W^{\pm}$ and Z^0 at Sp$\bar{p}$S /CERN**

1984 **Nobel price for Rubbia and van der Meer**





General Lay-out of the p-p̄ Collider.(From Ref. E)



Working principles of the most common accelerators.

Enabling technologies for accelerators

- Electron, proton and ion sources
- Vacuum systems
- Magnet technology
  - Iron/copper magnets
  - Fast pulsed ferrit magnets
  - Superconducting magnets
  - Permanent magnets
- RF power sources
- Accelerating RF structures
  - Normal conducting
  - Superconducting
- Cryogenic Systems
- Electromagnetic sensors
- High speed electronics
- High precision electronics
- Electric power systems
- Large scale precision alignment
- Large scale computer control systems
- Laser
- Tunnel construction techniques
- . . .

⟺ **Accelerators**

Many technological developments were promoted by accelerator needs

Recommended literature

Accelerator physics general

H. Wiedemann, "Particle Accelerator Physics," (2 volumes), Springer 1993

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Oxford University Press, 2001

S.Y. Lee, "Accelerator Physics," World Scientific, 2004

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World Scientific, 1999

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Springer 2003

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M.J. Smith and G. Phillips, "Power Klystrons Today," John Wiley 1995

M. Sedlacek, "Electron Physics of Vacuum and Gaseous Devices," John Wiley 1996

H. Padamsee, J. Knobloch, T. Hays, "RF Superconductivity for Accelerators,"
Wiley 1998

J. Tanabe, "Iron Dominated Magnets," World Scientific 2005

K. Mess, P. Schmüser, S. Wolff, "Superconducting Accelerator Magnets,"
World Scientific, 1996

For more accelerator book references *http://uspas.fnal.gov/book.html*

PARTICLE BEAMS, TOOLS FOR MODERN SCIENCE

Hans-H. Braun, CERN

2nd Lecture

Examples of Modern Applications and their Technological Challenges

- o Synchrotron Radiation,
  from Nuisance to Bright Light
- o Beams for Medicine
- o Particle Accelerators for Particle Physics