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HEINRICH HEINE
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JÜLICH
FORSCHUNGSZENTRUM

Autumn Lectures / Tbilisi / 2013

Particle Accelerators

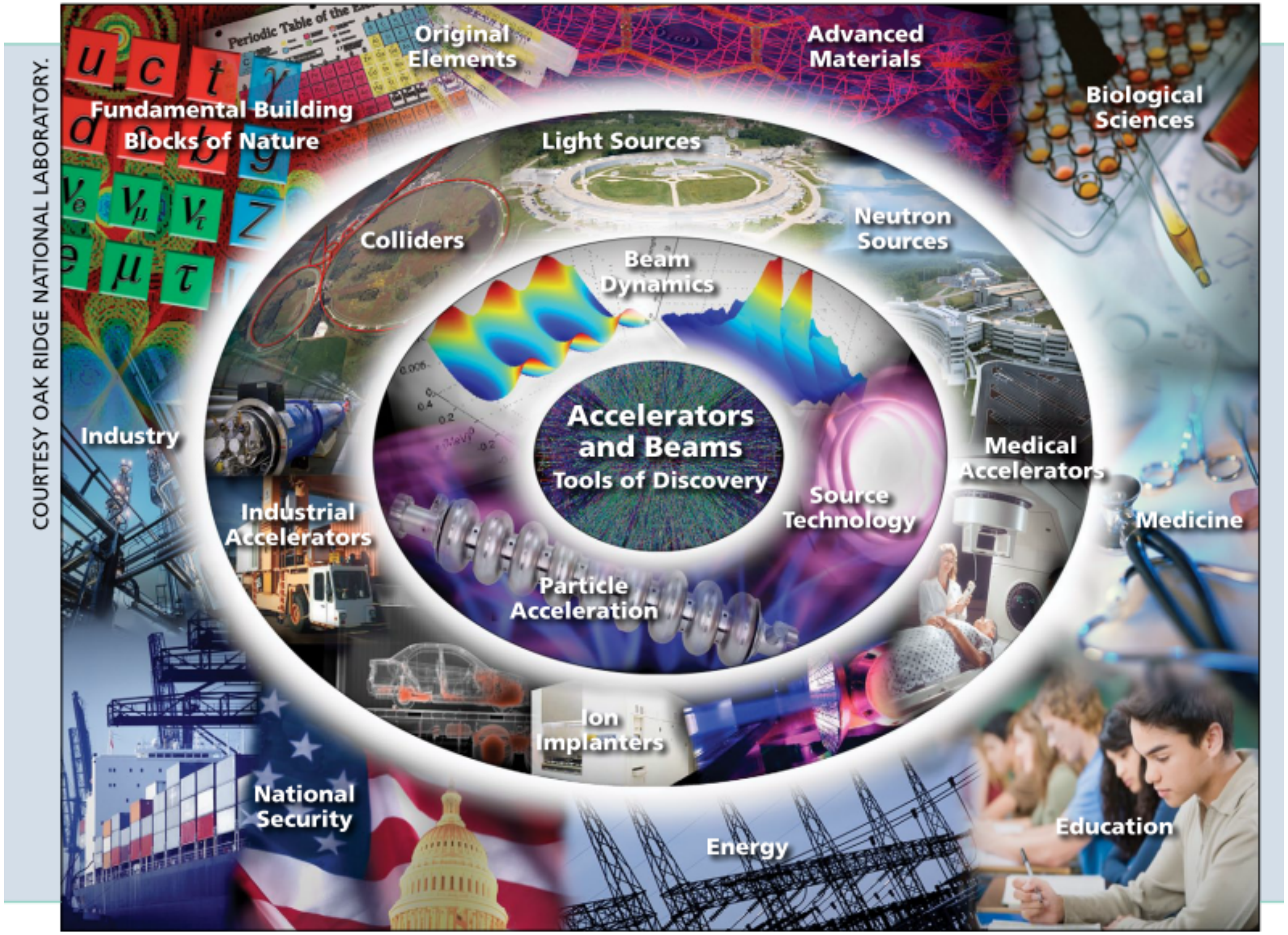
21 October 2013 | Markus Büscher

Heinrich Heine (1797 – 1856)

HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF

Denk ich an Deutschland in der Nacht,
Dann bin ich um den Schlaf gebracht,
Ich kann nicht mehr die Augen schließen,
Und meine heißen Thränen fließen.

Accelerators – Prelude



Accelerators – Prelude

Particle accelerators are devices that produce energetic beams of particles which are used for

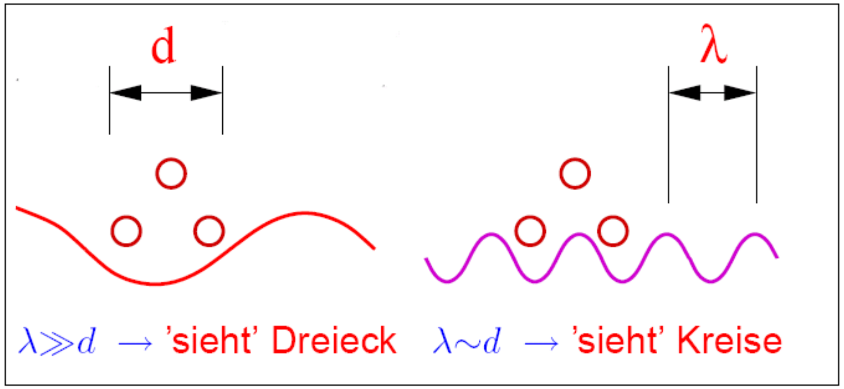
- Understanding the fundamental building blocks of nature and the forces that act upon them (nuclear and particle physics)
- Understanding the structure and dynamics of materials and their properties (physics, chemistry, biology, medicine)
- Medical treatment of tumors and cancers
- Production of medical isotopes
- Sterilization
- Ion Implantation to modify the surfaces of materials
- National Security: cargo inspection, …

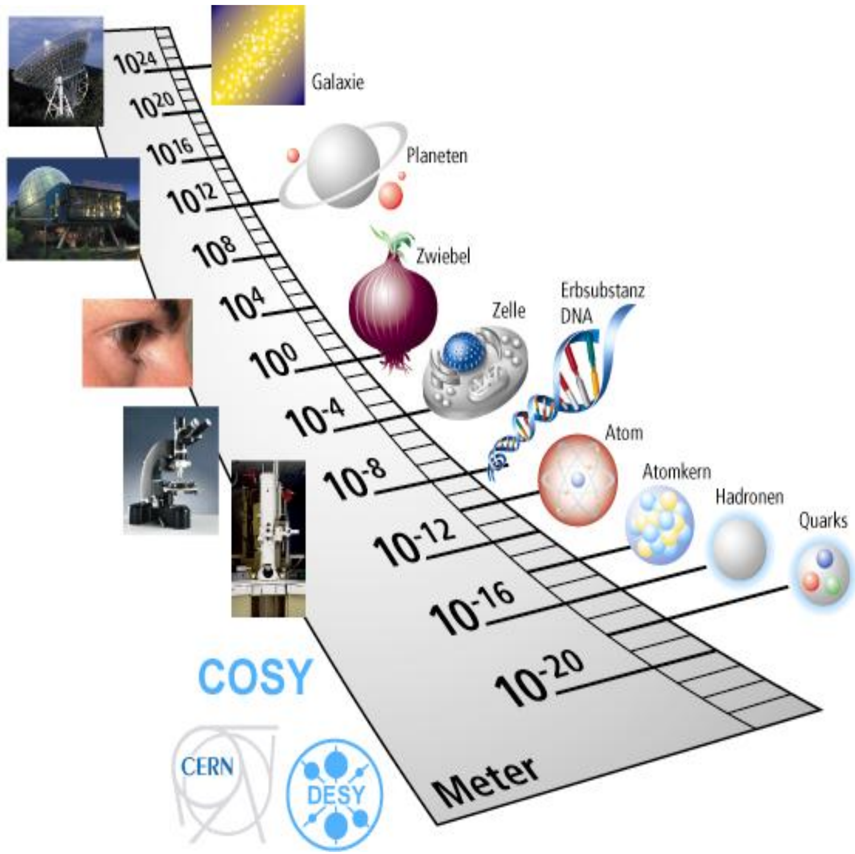
There is active, ongoing work to utilize particle accelerators for

- Transmutation of nuclear waste
- Generating power more safely in sub-critical nuclear reactors

Accelerators – Introduction

Why do we need accelerators ?



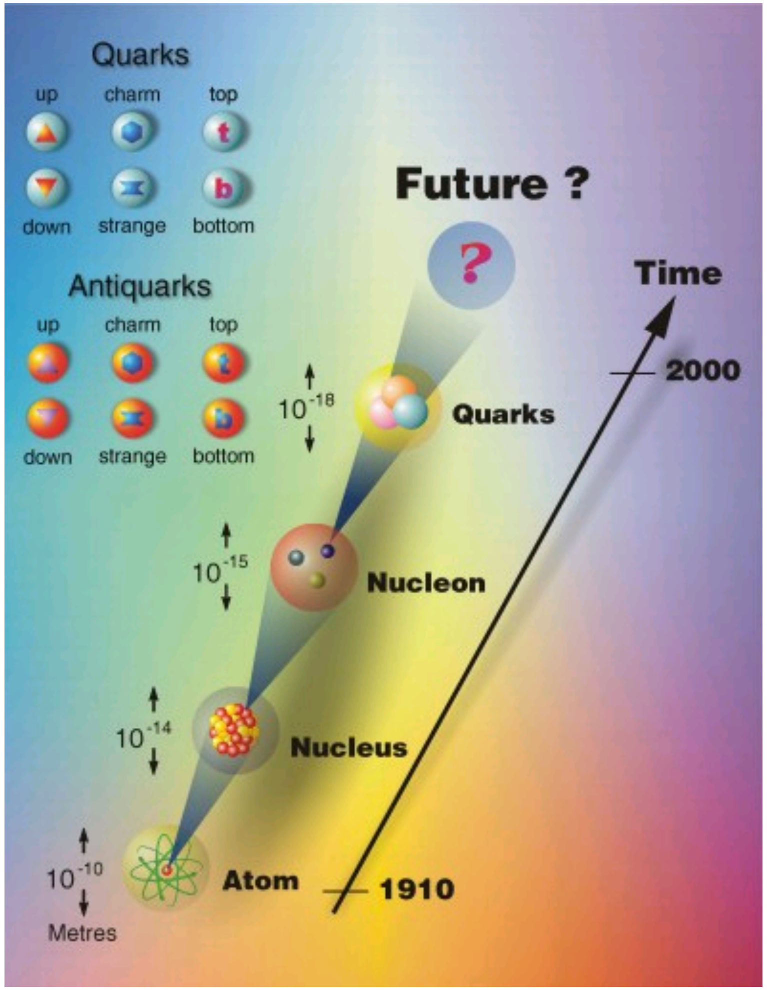


Accelerators – Introduction

Why do we need accelerators ?

Investigation of ever smaller spacial dimensions - requires better resolution, i.e. higher energies („energy frontier“).

Also:
Investigation of ever rarer processes („intensity frontier“) and more subtle effects („precision frontier“)



Accelerators – Introduction

There are a few 10.000 accelerators in use around the world:

Nowadays the majority of accelerators are used in different types of applications

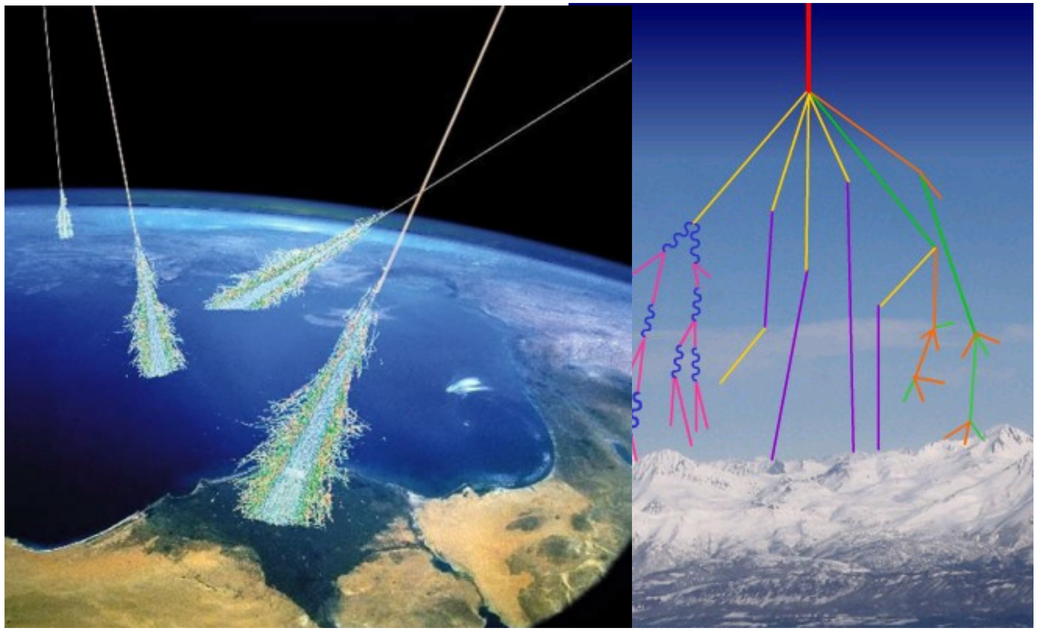
World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)

Category	Number
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

In this lecture, I will go through their use as a tool for exploring the interior of matter

Accelerators – Natural

Radioactive sources
(e.g. pitchblende (UO_2))

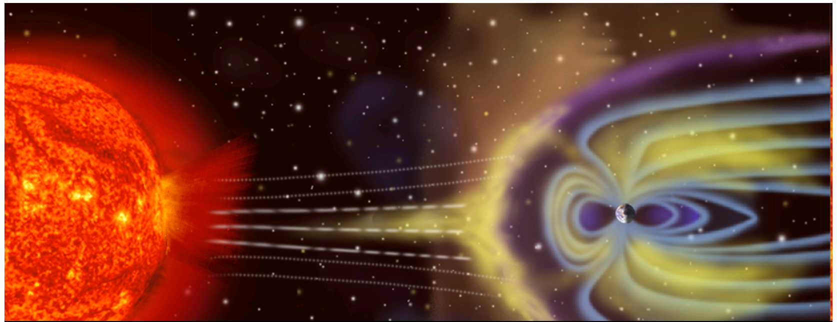


Cosmic rays

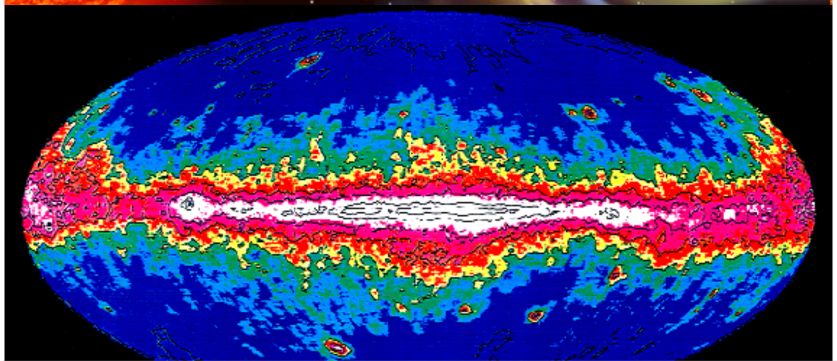
Accelerators – Natural

Cosmic Rays

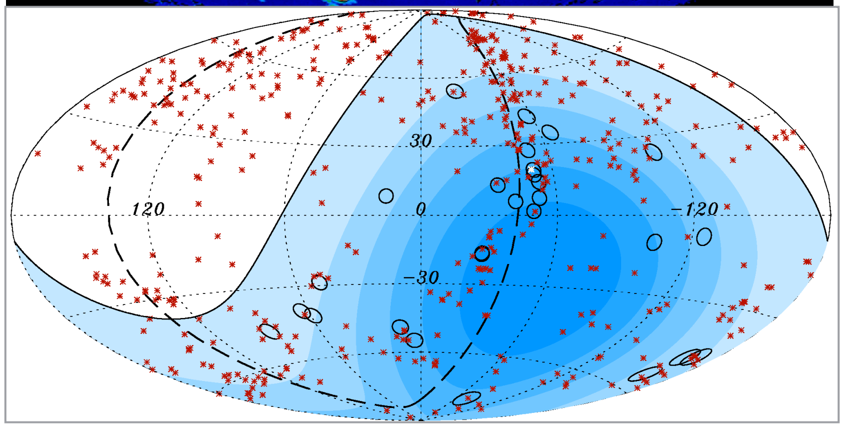
… from the sun



… from the galaxy

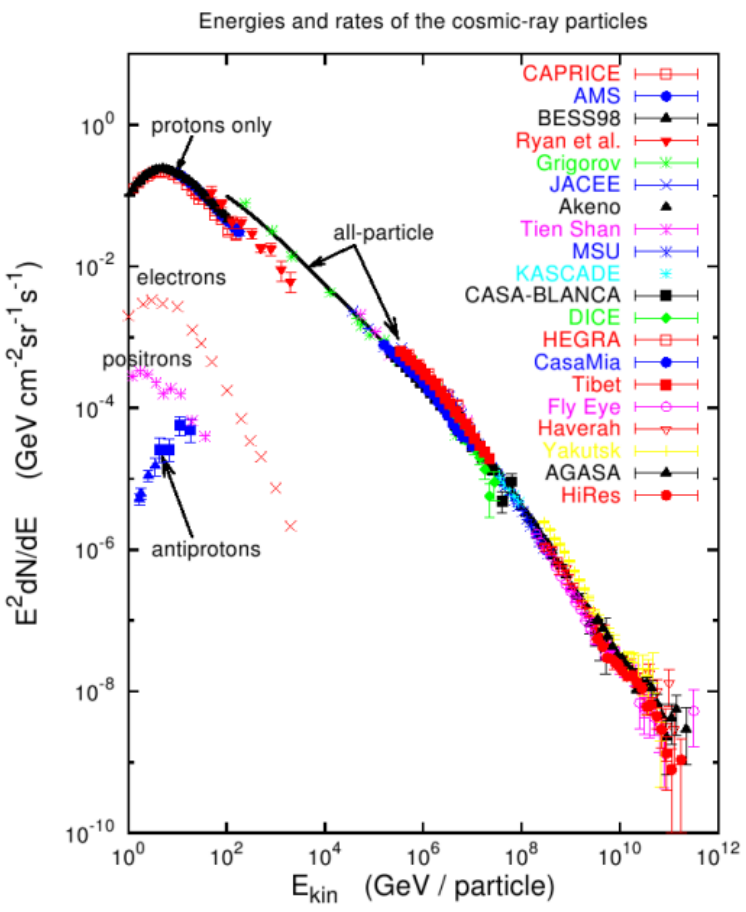


… from AGN (Black Holes)



Accelerators – Natural

Cosmic Rays: flux on earth



The spectrum extends to much higher energy than available at accelerators, but the flux at these high energies is way-to-small to be useful for nuclear and particle physics reactions.

What are the acceleration mechanisms ?

(AMS on last space shuttle)

Accelerators – Natural

Radioactive sources

α- and β-emitters:

have limited energy range

E. Rutherford already in 1927 wanted to have α-particles with energies larger than those provided by radioactive sources …

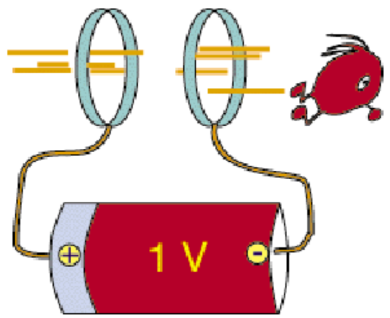
Accelerators – Basics

- production of energetic particles for nuclear reactions:
  use Lorentz force $F = q(E + v \times B)$ to accelerate charged particles

- magnetic force $q(\mathbf{v} \times \mathbf{B})$ perpendicular to velocity
  - does not contribute to acceleration
  - can be used for focussing and guiding
  - $B_\perp$ determines curvature of trajectory $$B_\perp \rho = \frac{\gamma m v}{q}$$ $$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

- electric force $q\mathbf{E}$
  - component parallel to velocity: acceleration
  - component perpendicular to velocity: focussing and guiding
  - $E_\perp$ determines curvature of trajectory $$E_\perp \rho = \frac{\gamma m v^2}{q}$$

Electrostatic Accelerators



"electron-Volt" (eV)

$1\ \mathrm{eV} = 1.602 \times 10^{-19}\ \mathrm{J}$

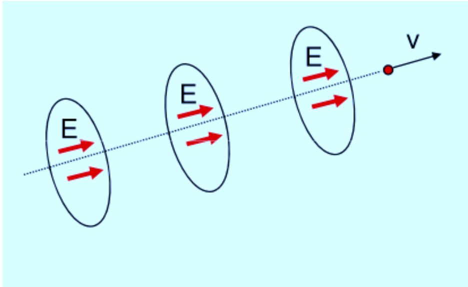
Accelerators – Basics

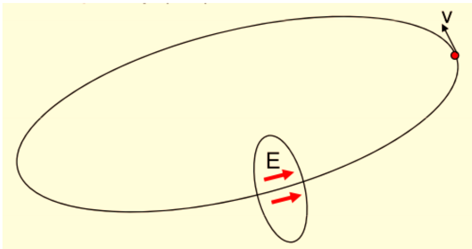
Principle: "Device that accelerates a beam of fast-moving, electrically charged ions or subatomic particles in electric fields."

Types:

(I) Linear accelerator ("Linac")
- DC (electrostatic)
- AC (radiofrequency, RF)

Circular (cyclic) accelerator
- Cyclotron
- Synchrotron
- Betatron → Microtron
- Storage rings

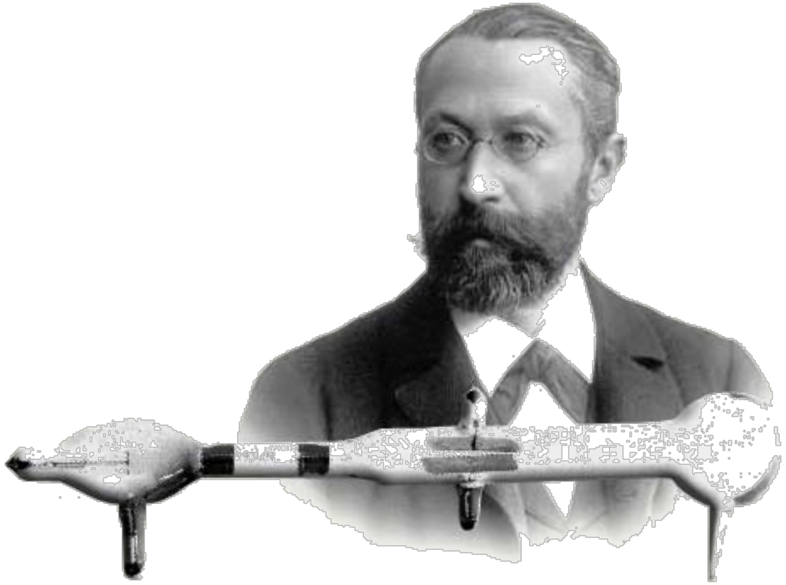




(II) Fixed-target accelerators (linear, circular)
Colliders (linear, circular collider)

(III) Secondary Beam machines
Light sources (synchrotron radiation)

Accelerators – Man made

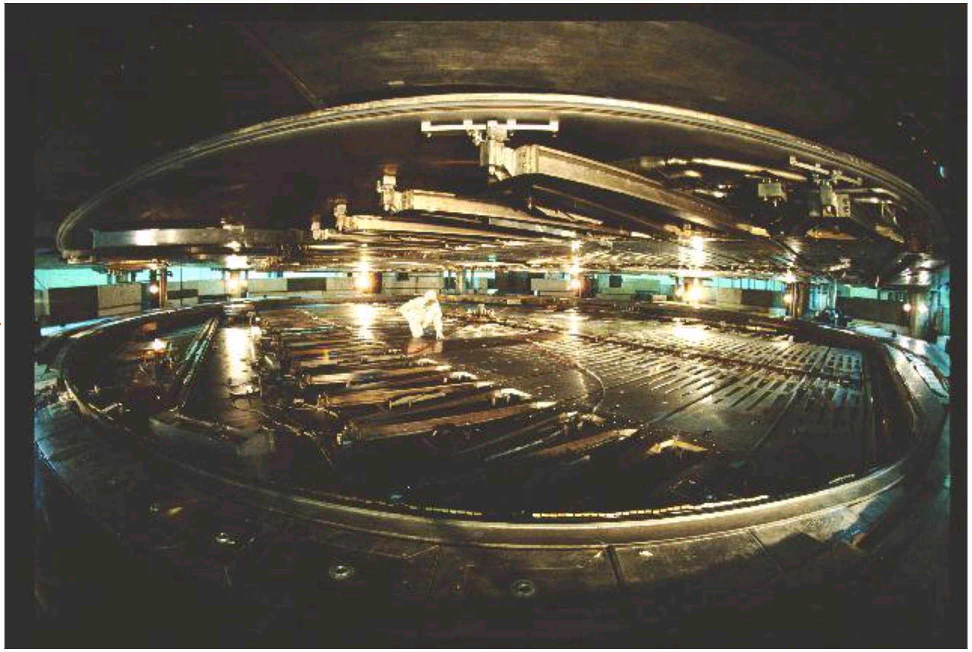


Cathode rays
Linear electron acceleration (~1897)
(K.F. Braun)

SLAC
(Stanford, USA)

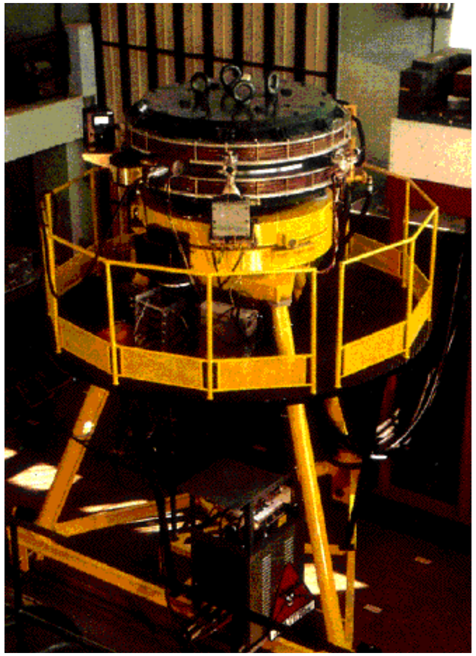
Accelerators – Man made

First cyclotron (~1930)
(E.O. Lawrence)



Largest cyclotron
(Triumf, Canada)

Accelerators – Man made

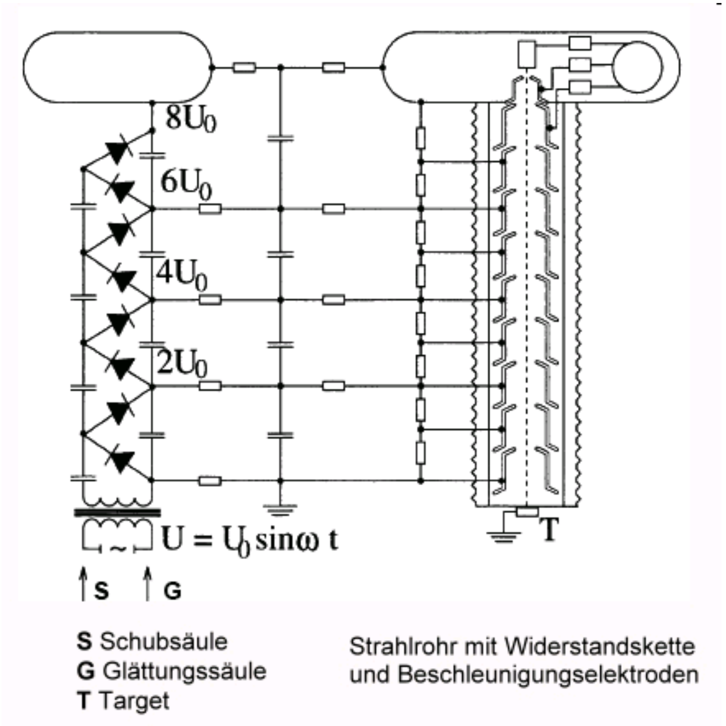


First e+e- collider (~1958)
(AdA, Frascati)

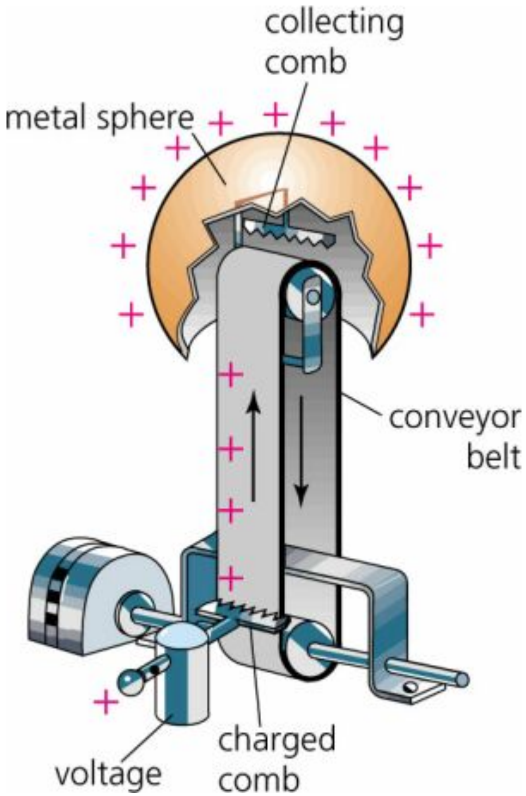
LEP/LHC
(CERN)

Accelerators – Electrostatic

Voltage generators:



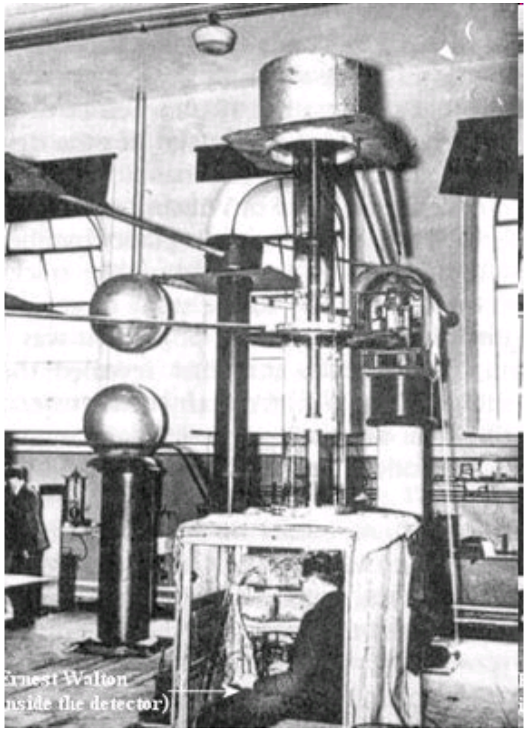
Cockroft-Walton
HV Multiplier

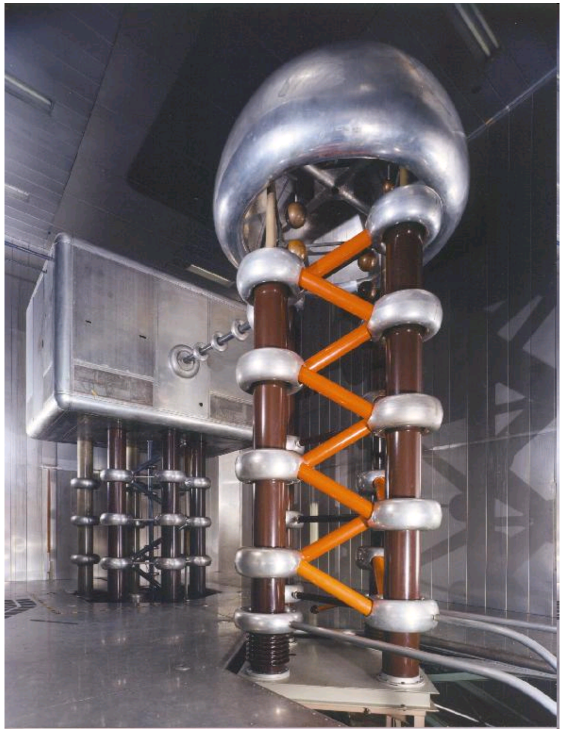


Van de Graaff

Accelerators – Electrostatic

Cockroft Walton accelerator:

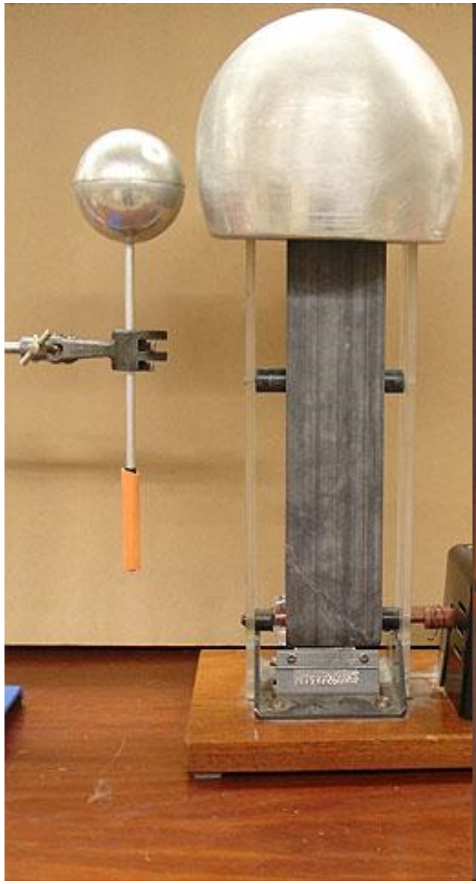




One of the cheapest and popular ways of generating high voltages at relatively low currents is the classic multistage diode/capacitor voltage multiplier, known as Cockcroft Walton multiplier, named after James Cockcroft and Ernest Walton.
The circuit was first discovered in 1919 by H. Greinacher.
For this reason, this doubler cascade is sometimes also referred to as the Greinacher multiplier.

Accelerators – Electrostatic

Van de Graaff (generator):



Accelerators – Electrostatic

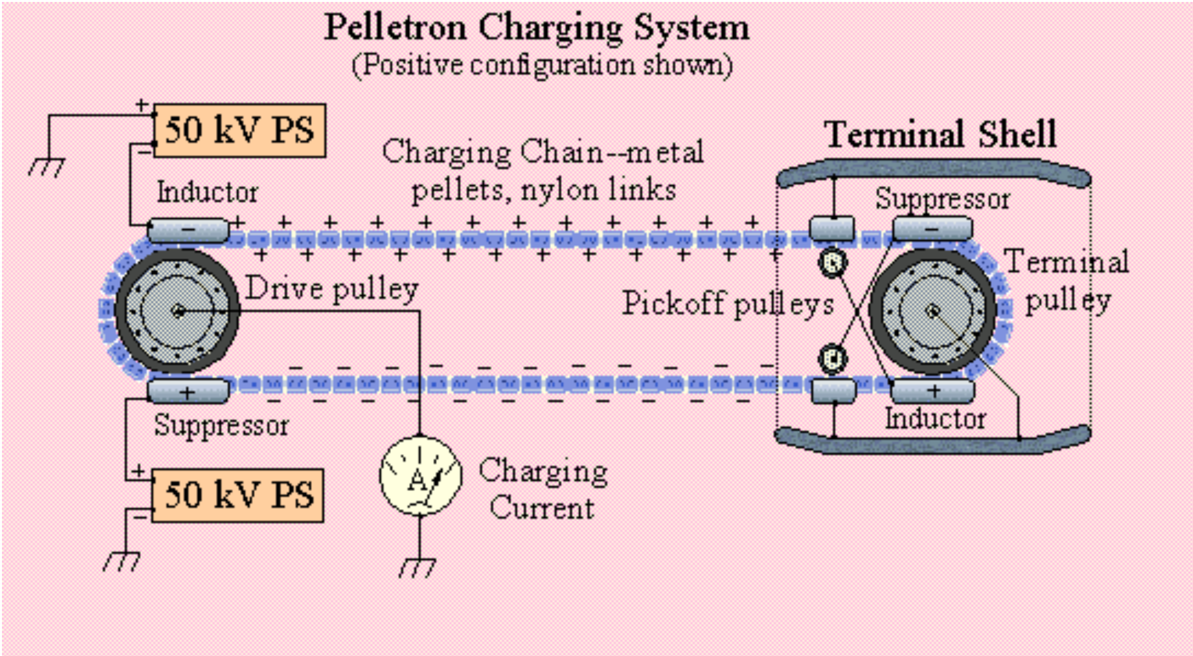
Van de Graaff accelerator:

FIG. 11. The giant Van de Graaff high-voltage generator in its airship-dock laboratory near New Bedford, Massachusetts. (Courtesy of Professor Van de Graaff.)

The accelerating voltage achievable by a C-W accelerator is limited by the capacitors and diodes.
To obtain higher accelerating voltages a **Van de Graaff accelerator** is used. The Van de Graaff machine was designed by R. Van de Graaff (1901-1967).
Here a continually moving belt of insulating material runs between two pulleys, which are separated by an insulated column, to transport charge.

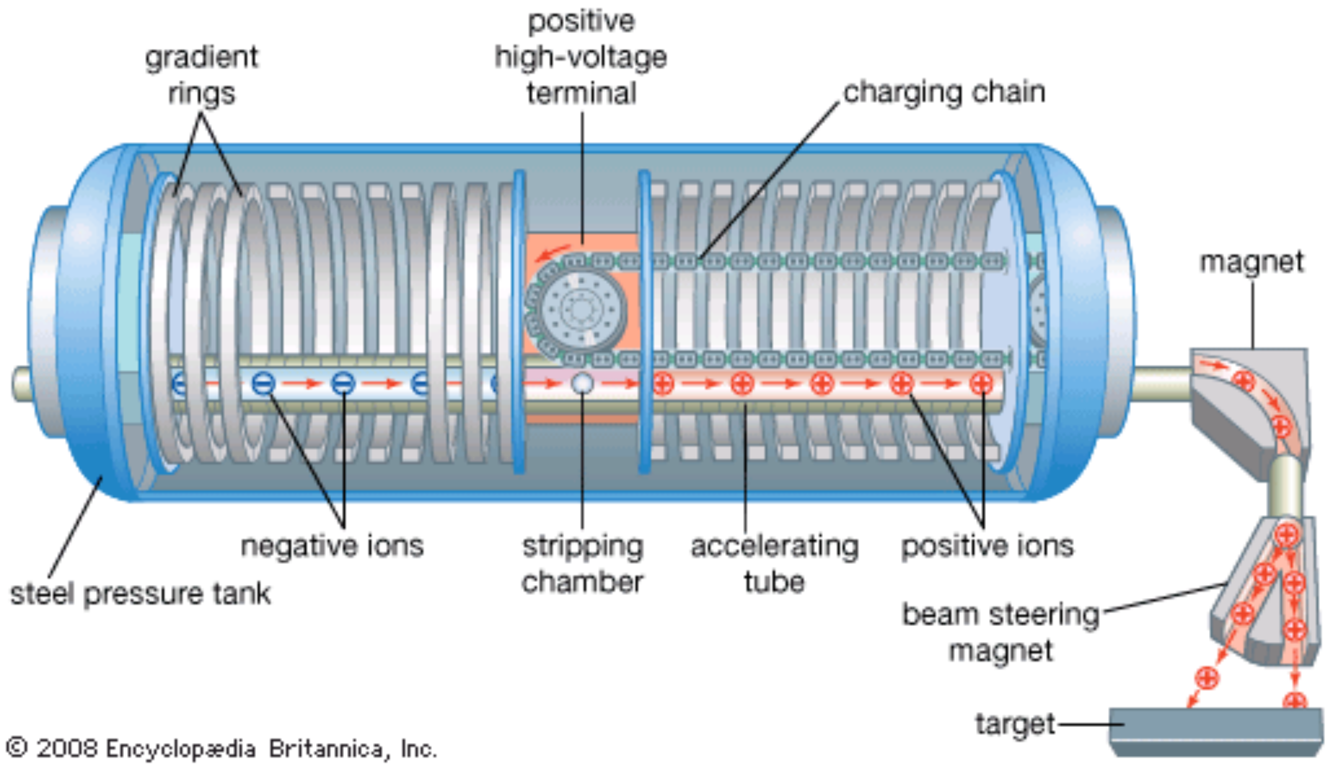
Accelerators – Electrostatic

Pelletron accelerator:



Accelerators – Electrostatic

Tandem accelerator:



Accelerators – Electrostatic

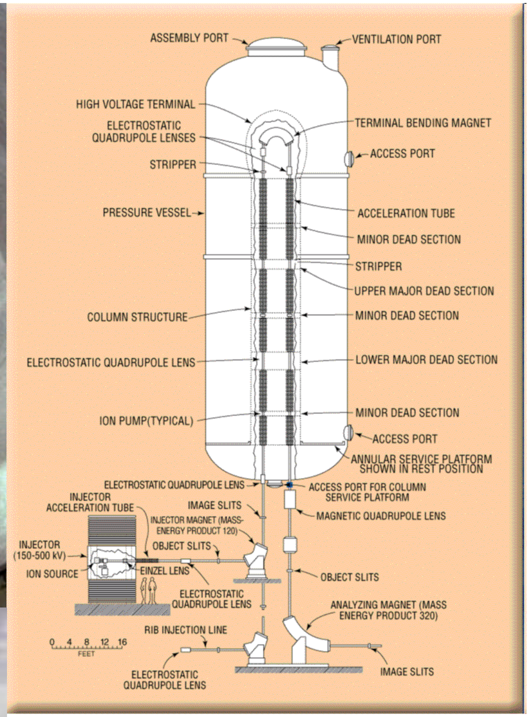
Tandem accelerator:

Munich

Cologne

Accelerators – Electrostatic

Tandem accelerator:



Vertical assembly

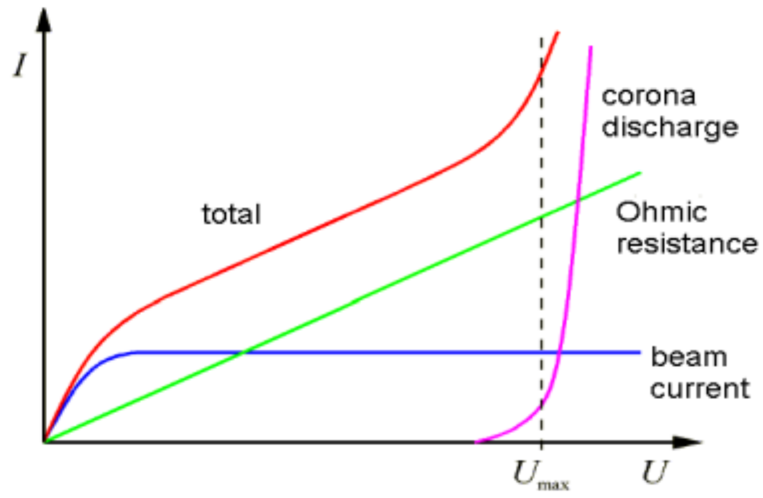
A variation of the VdG accelerator is the **tandem accelerator**, which can produce accelerating potentials twice as high. *Negative ions* are produced which are then accelerated to an electrode which froms part of a VdG. The ions are then stripped of 2 of their electrons and emerge as *positive* ions, accelerating away from the central electrode towards the target. The ions thus gain kinetic energy *twice*, once as negative ions and then as positive ions.

Accelerators – Electrostatic

Limitations:

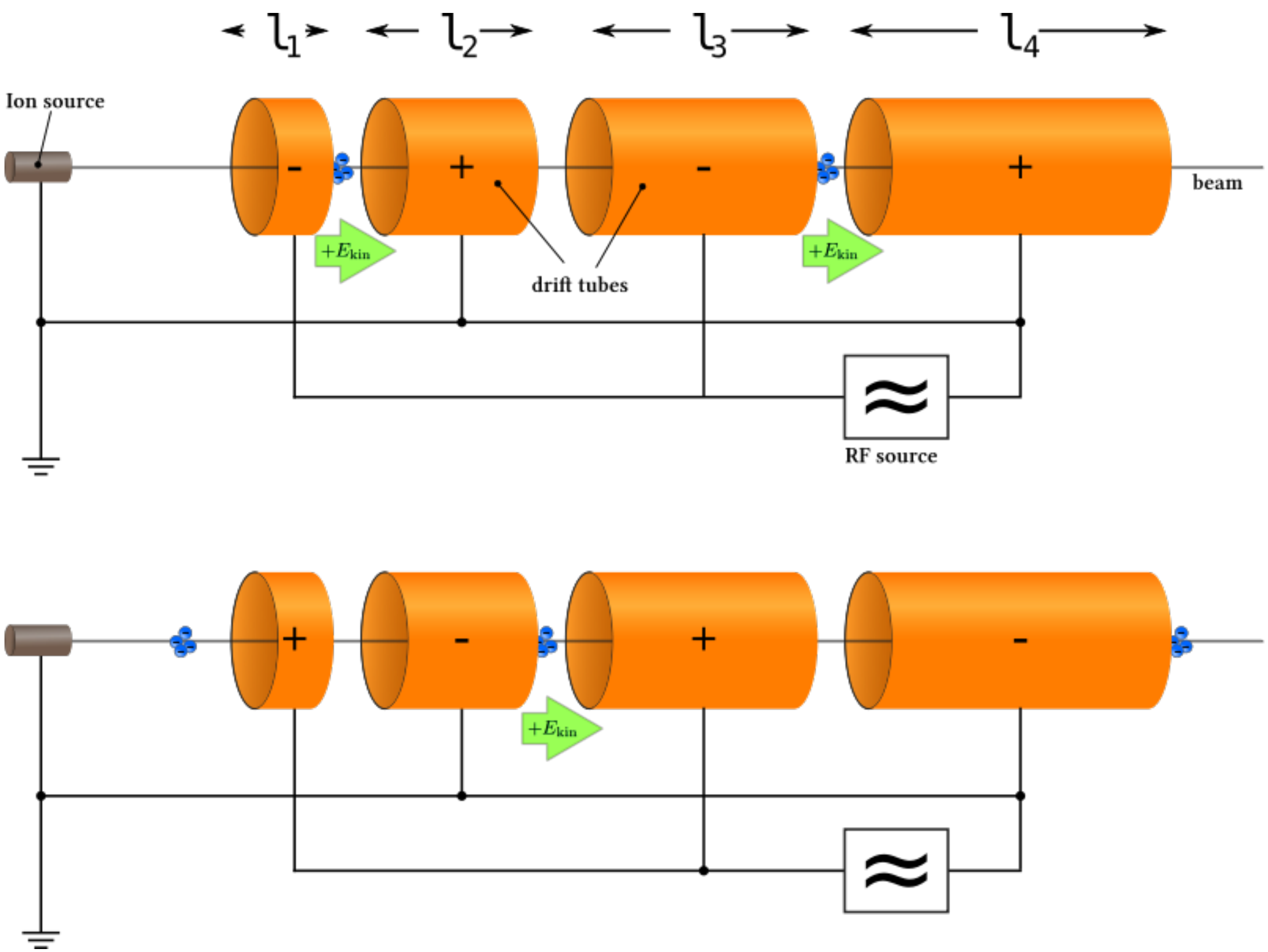
- corona discharge
  - is also used to stabilize voltage
- surface currents on insulators of acceleration column
- discharge in insulation gas
- discharge on surfaces (surface roughness)

- air insulation : 2 MV
- high pressure N_2 and SF_6: up to 25 MV

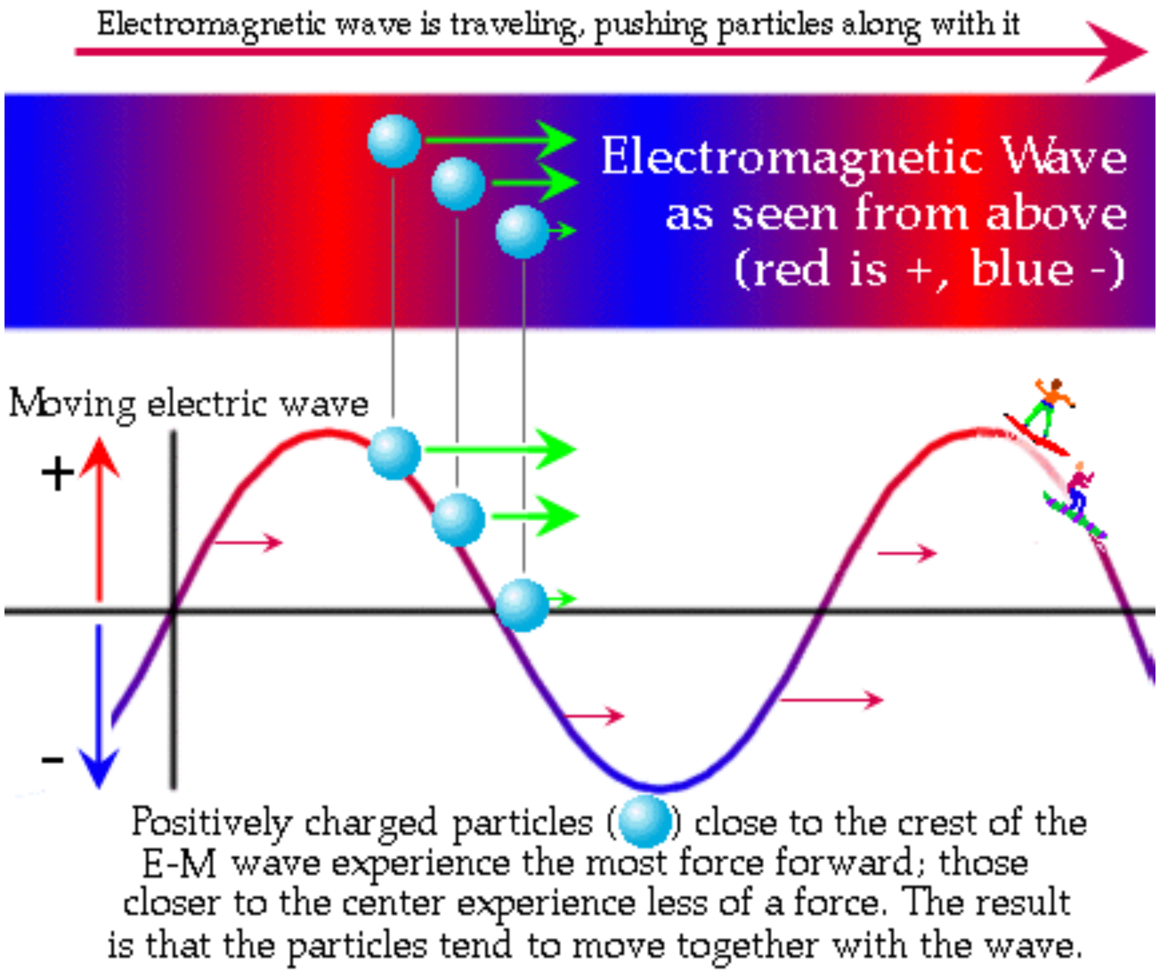


Accelerators – Linear

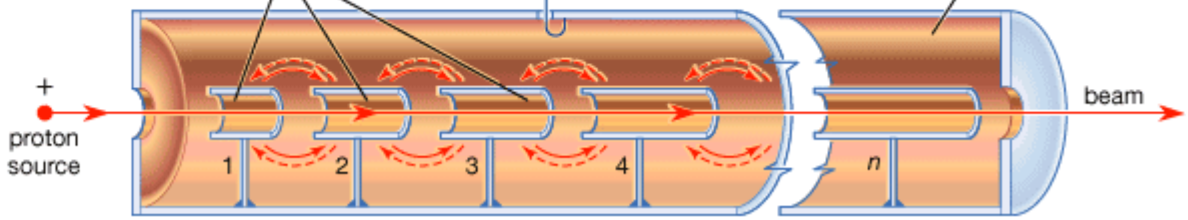
Drift tubes:



Accelerators – Linear



Accelerators – Linear



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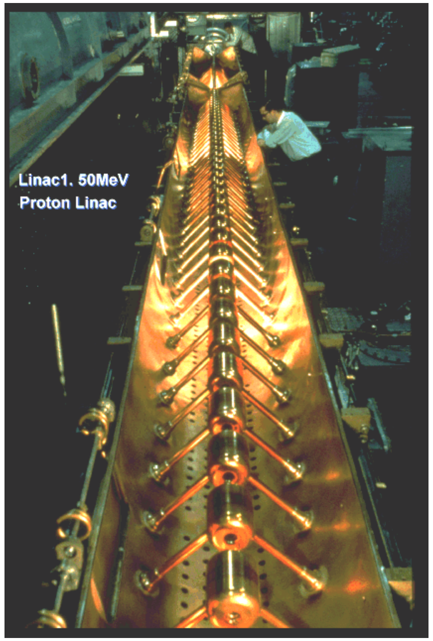
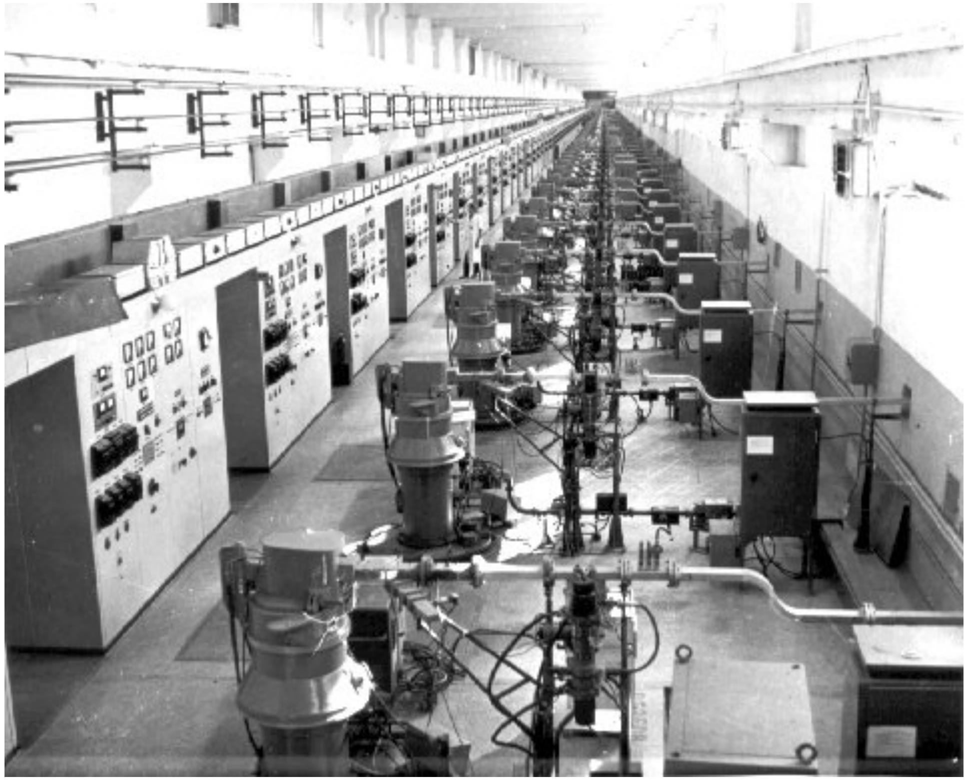


Accelerators – Linear

RF linacs:



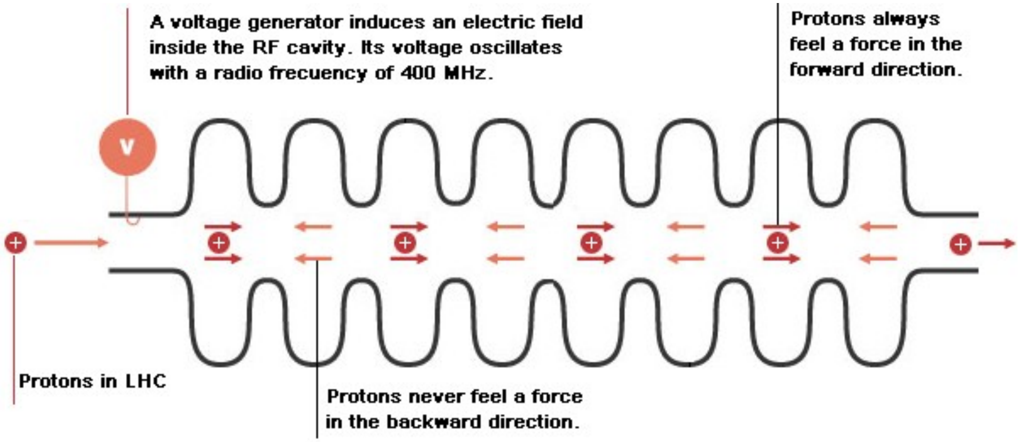
Accelerators – Linear

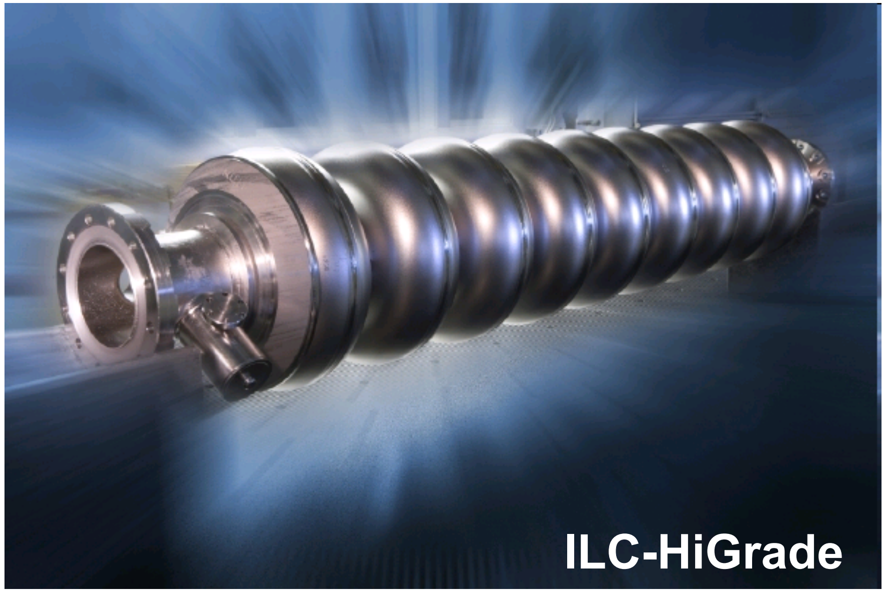
RF linacs: Stanford Linear Accelerator Center

Length: 3.2 km, max. e^+/e^- energy 50 GeV

Accelerators – Linear

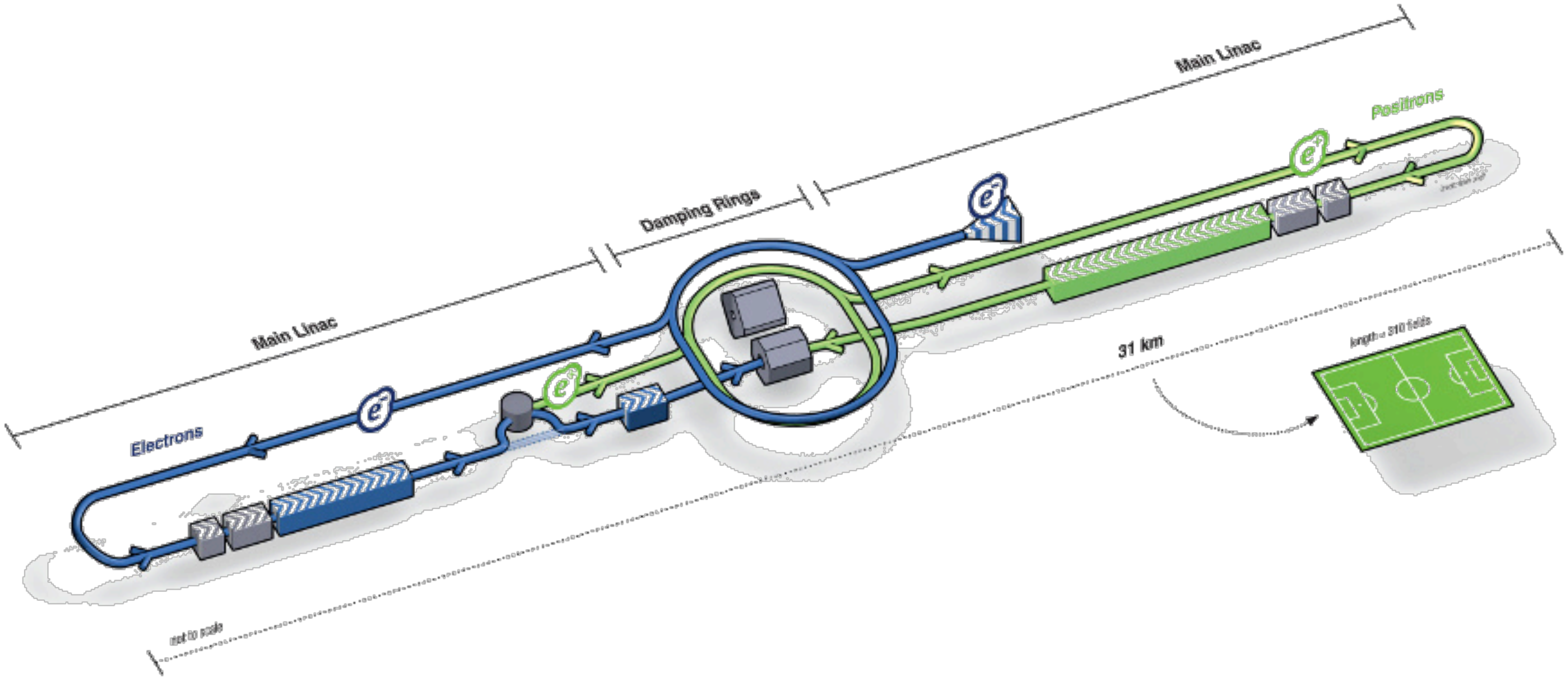
RF cavities (superconducting):





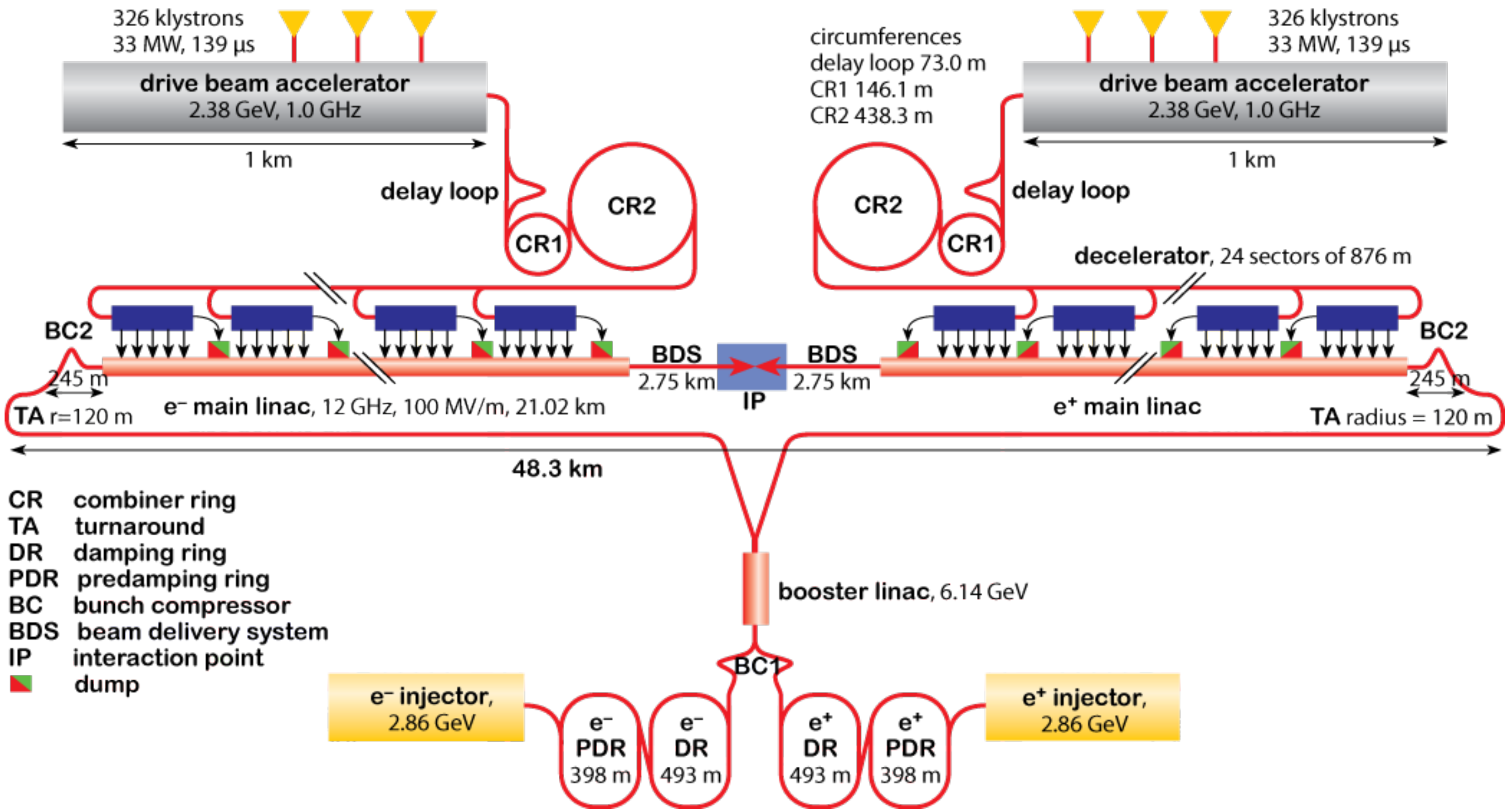
Accelerators – Linear

Future plans: ILC



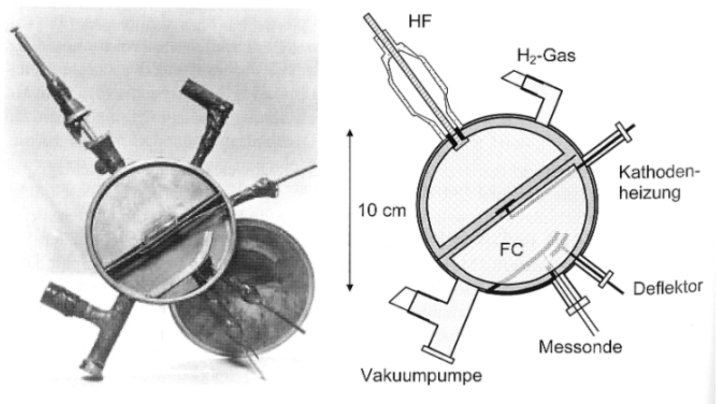
Accelerators – Linear

Future plans: CLIC



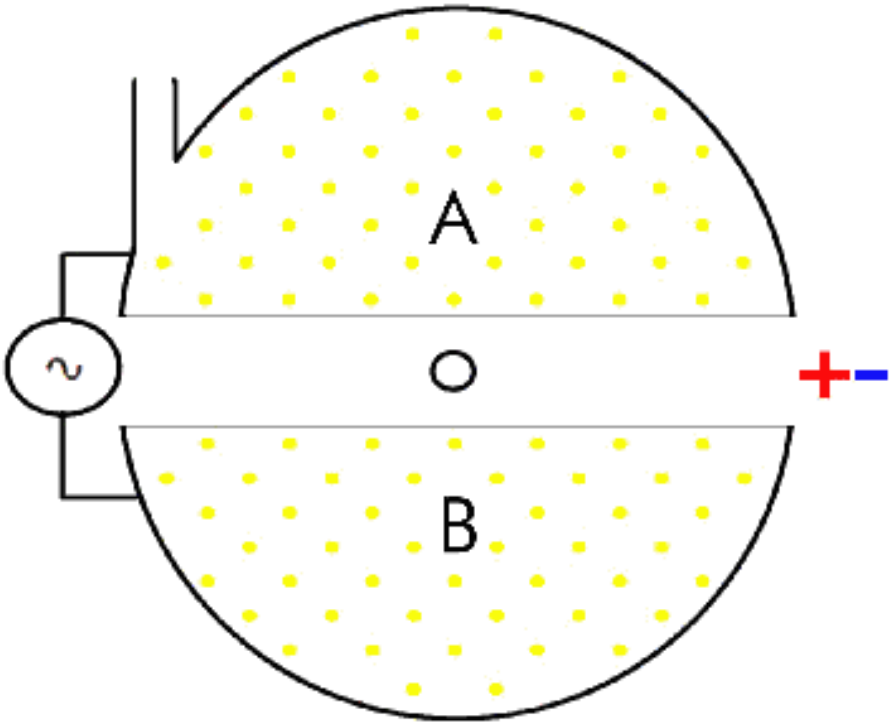
Accelerators – Circular

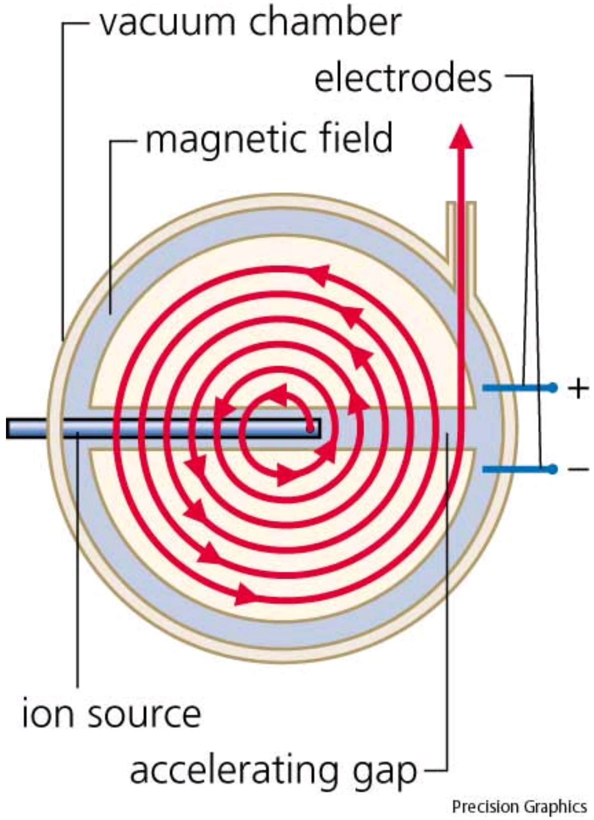
1924 Ising	Proposal to use time-varying fields across drift tubes for „resonant acceleration“
1928 Wideröe	Demonstration of Ising´s principle with a 1MHz, 25 kV oscillator (making 50 keV potassium ions)
1929 Lawrence	Conceives cyclotron
1931 Livingston	Demonstration of cyclotron, acceleration of p to 80 keV
1932 Lawrence	Cyclotron produces 1.25 MeV p; splitting of atoms Nobel Prize in 1939



Accelerators – Circular

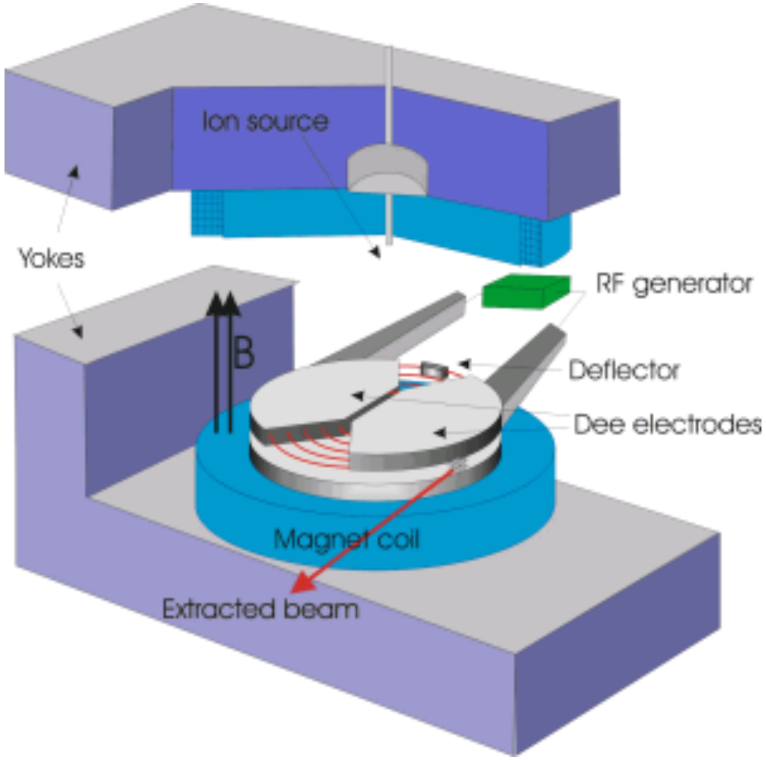
Cyclotron:





Accelerators – Circular

Cyclotron:

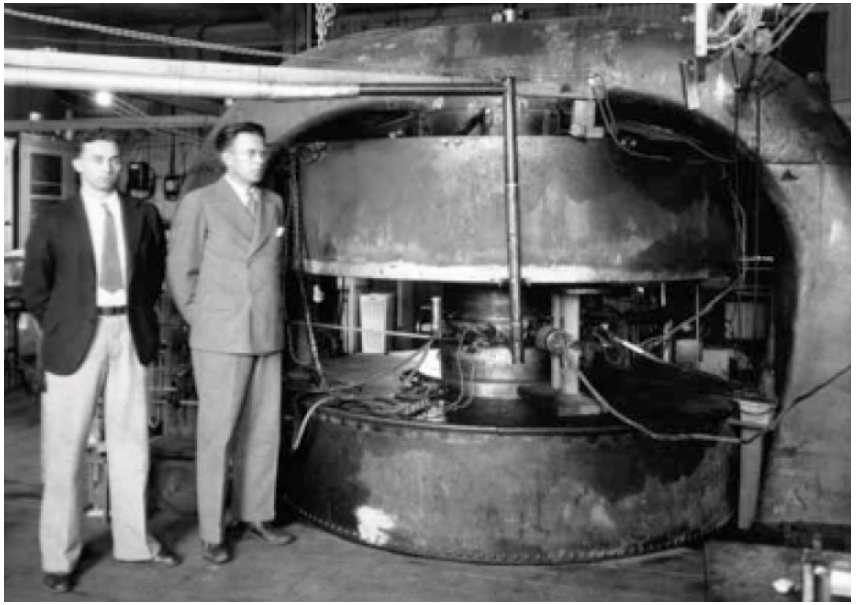


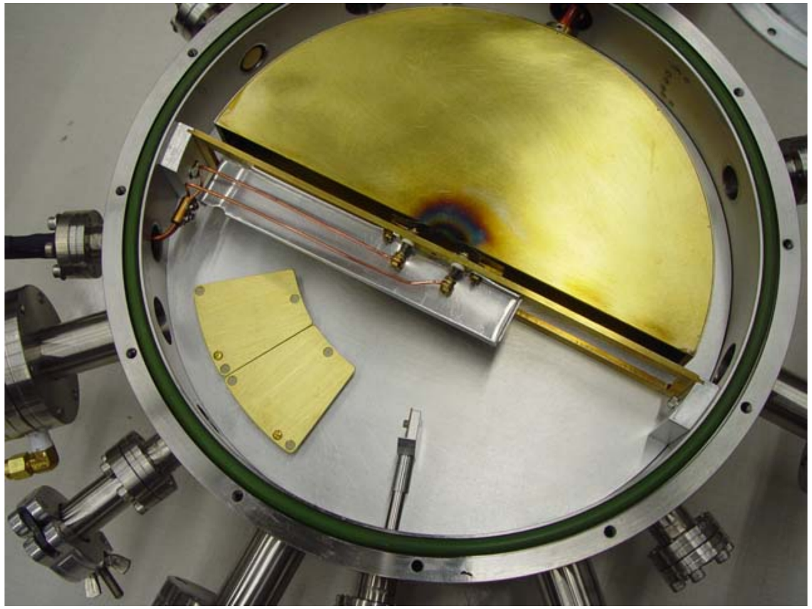
Cyclotron frequency

$$\omega = \frac{|q| \cdot B}{m}$$

Accelerators – Circular

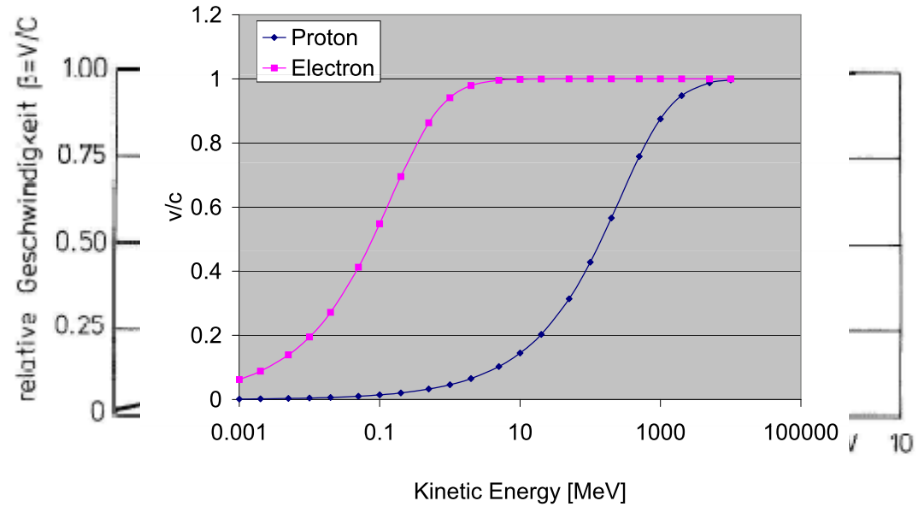
Cyclotron:





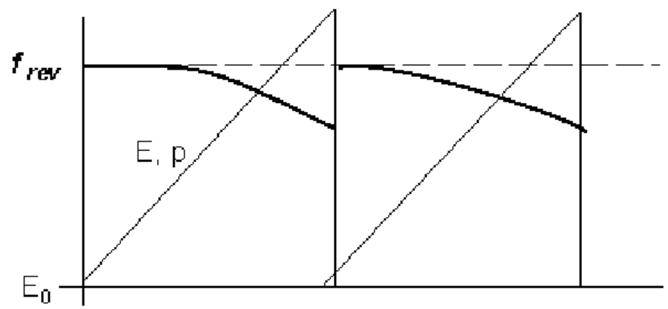
Accelerators – Circular

Cyclotron:



Synchro-Cyclotron: → pulsed operation

$$\omega_z = \frac{e B_z}{\gamma m_0}$$



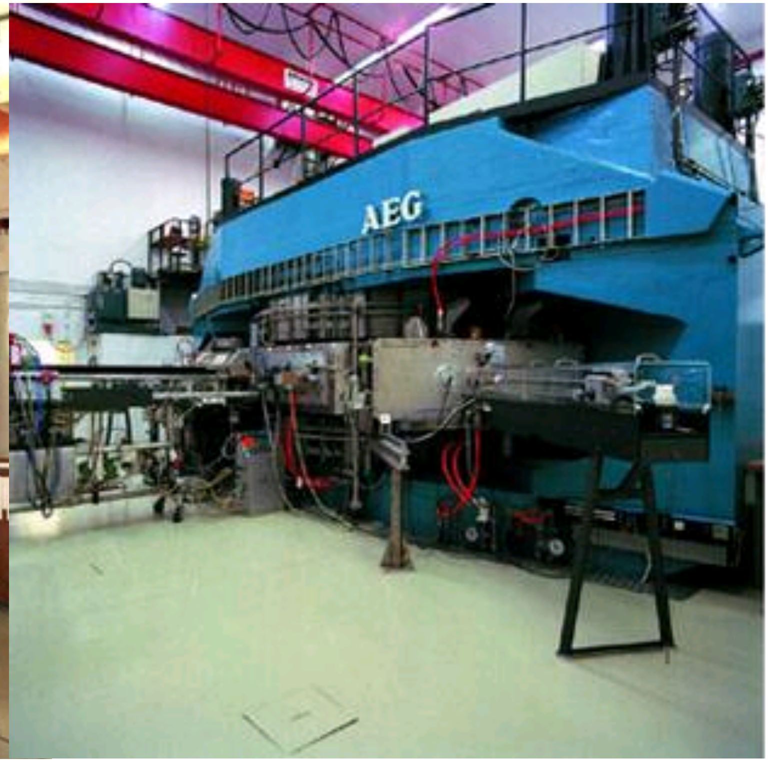
Isochronous-Cyclotron:

$$\omega_z = \frac{e B_z(r)}{\gamma m_0} = \text{const.}$$

Accelerators – Circular

Cyclotron:

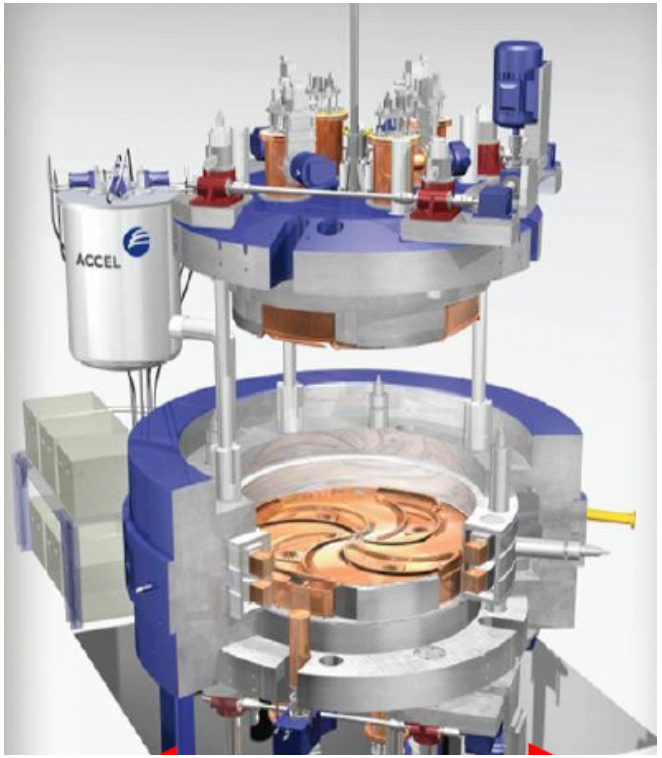
Bonn



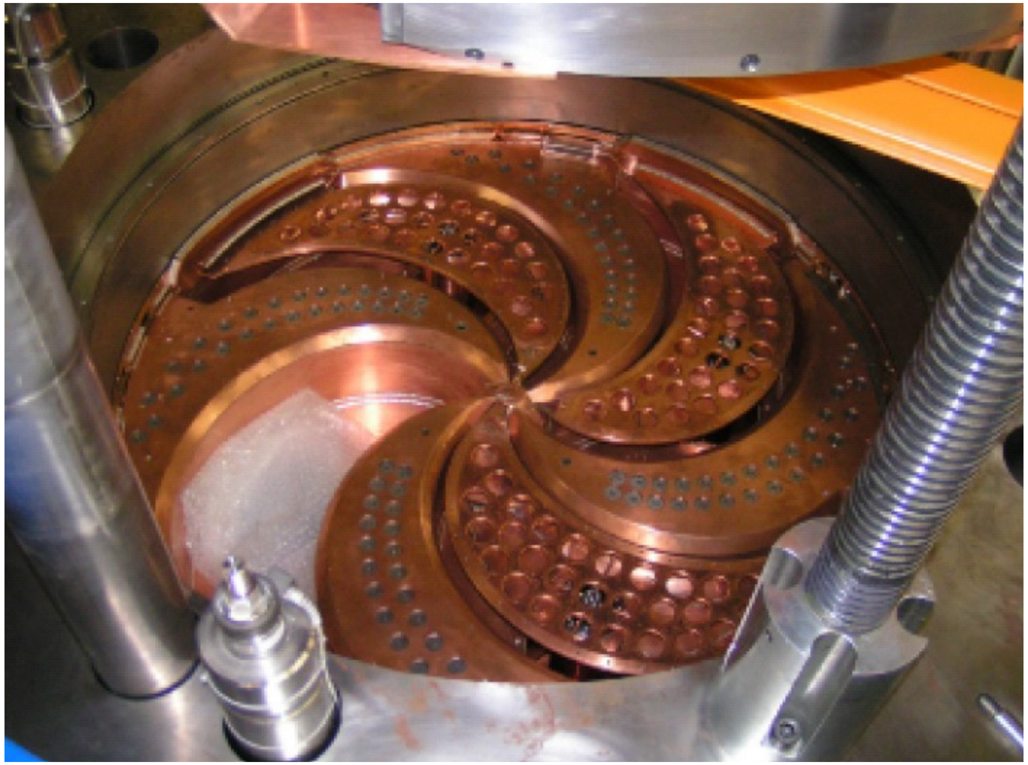
Jülich („JULIC“)
Injector for COSY

Accelerators – Circular

Cyclotron:



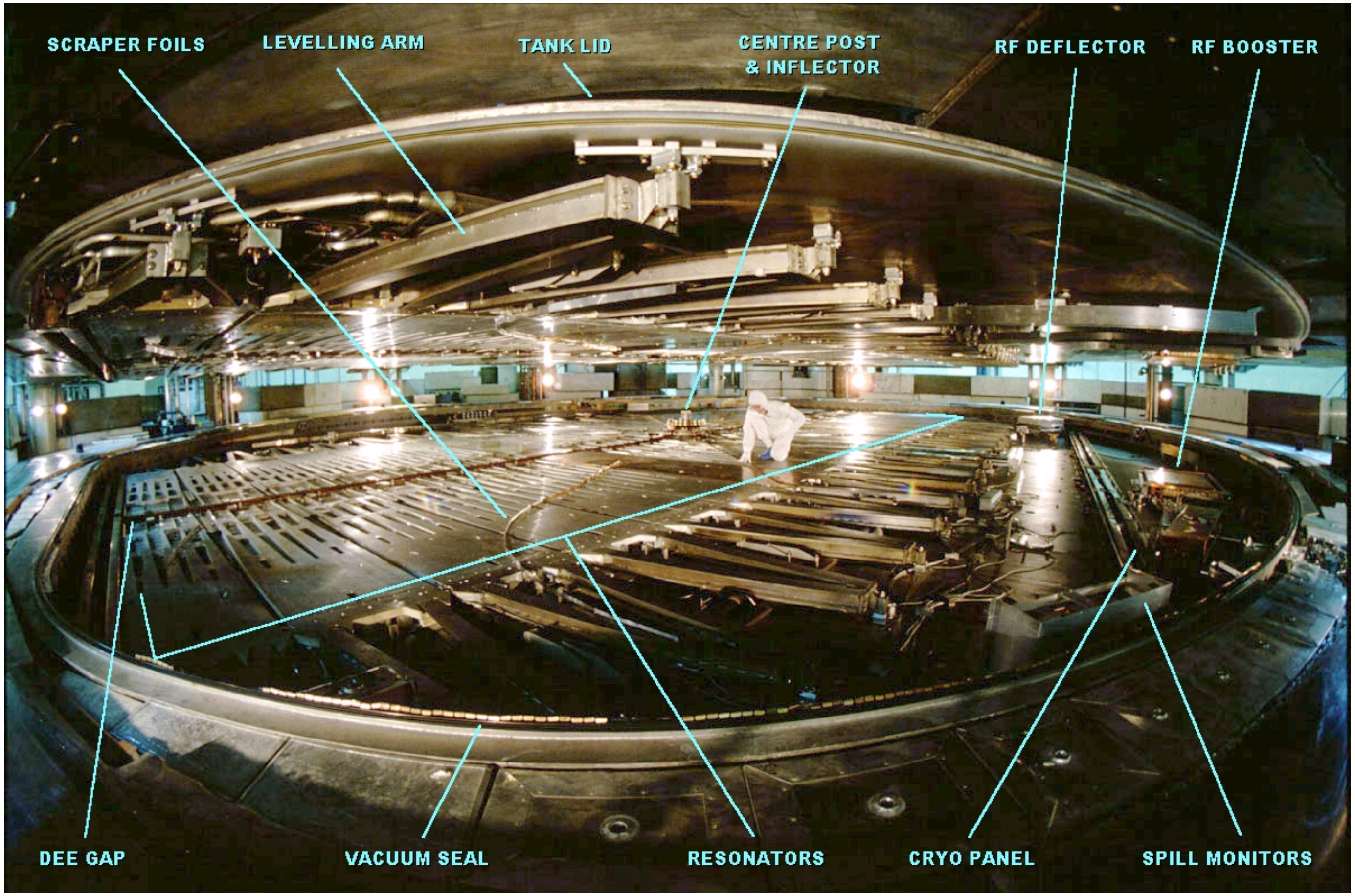
SC



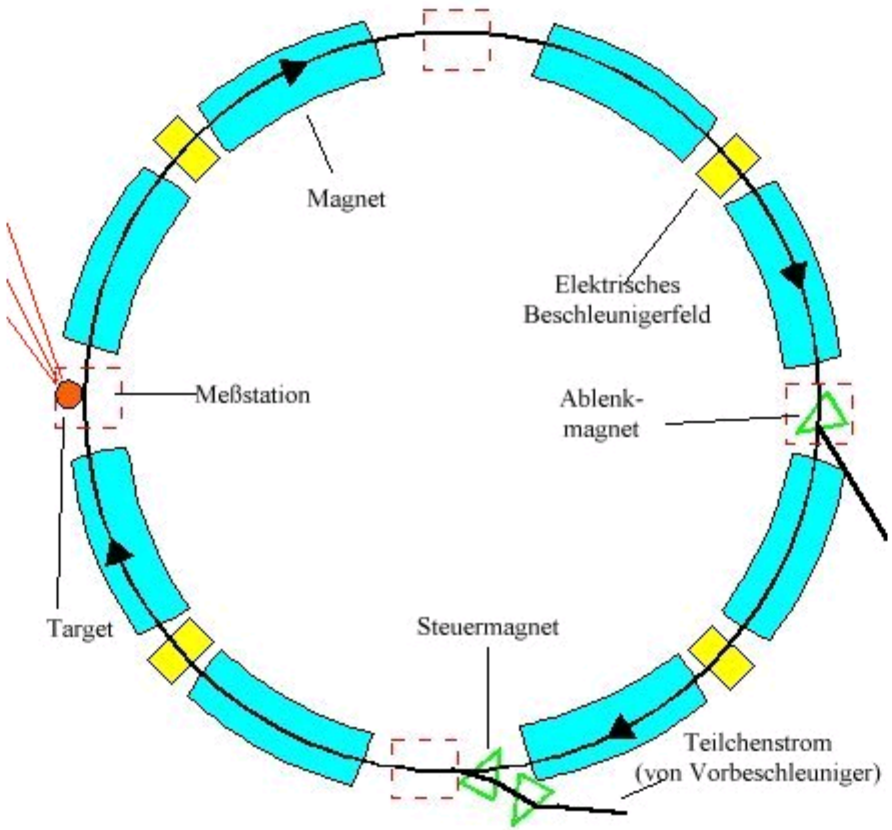
Compact cyclotron IBA
(radiation therapy)

Accelerators – Circular

Cyclotron:

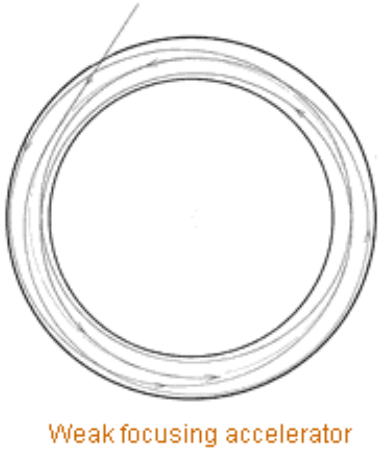


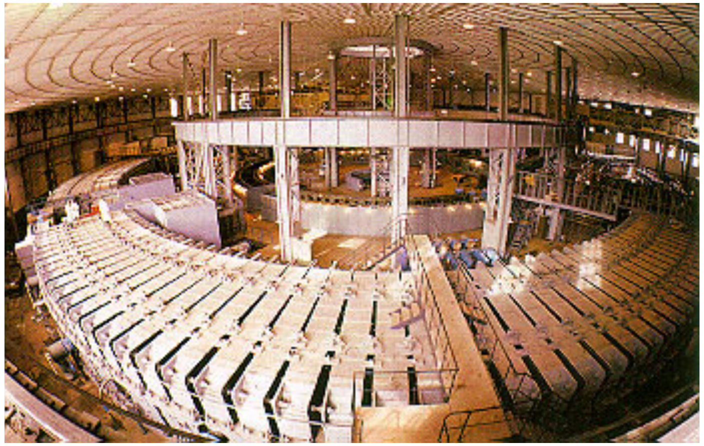
Accelerators – Synchrotron



Synchronized variation of accelerating frequency and magnetic field of bending magnets. 1945 invented simultaneously by **Edwin Mattison McMillan** and **Vladimir I. Veksler.**

Accelerators – Synchrotron





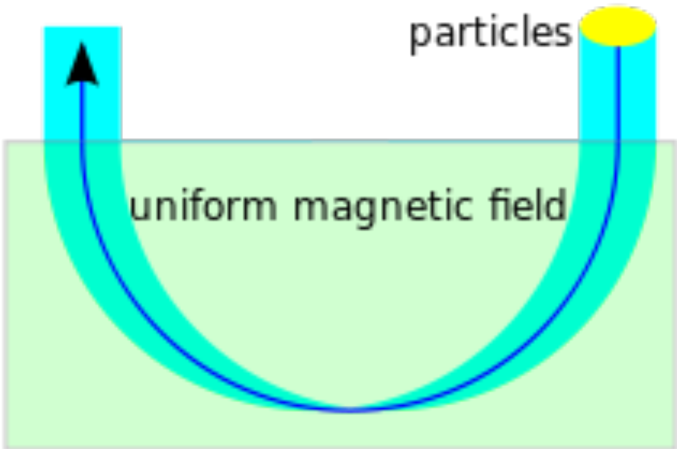
Weak focusing

"Cosmotron" (BNL)
3.3 GeV
Magnets: 2.000 t

"Synchrophasotron" (JINR)
10 GeV
Magnets: 36.000 t

Accelerators – Synchrotron

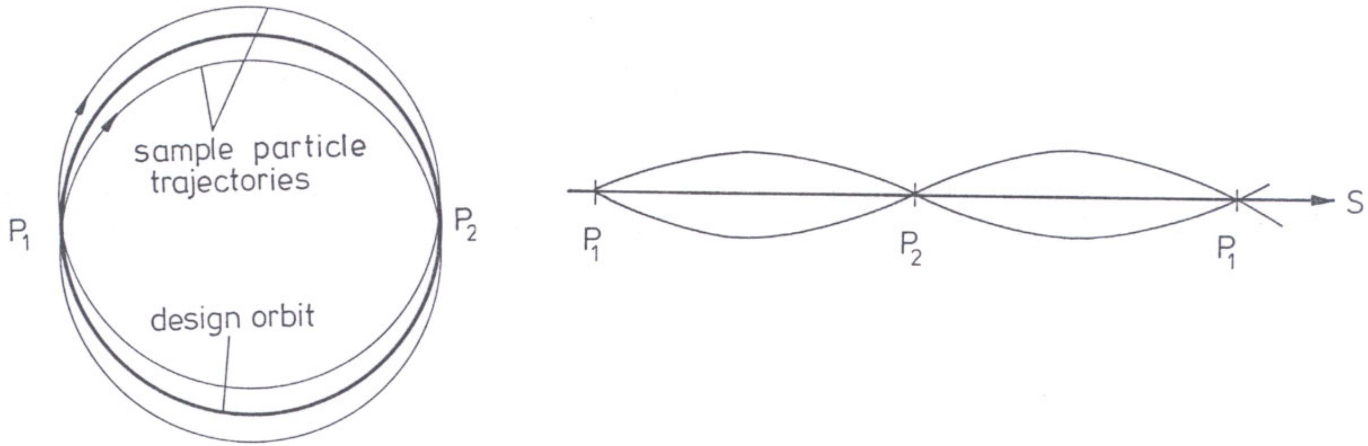
Weak focusing



A particle bunch with position variance gets focused in a magnetic field. In reality, the beam will not get focused to a point, but keeps a finite spot size due to divergence.

Accelerators – Synchrotron

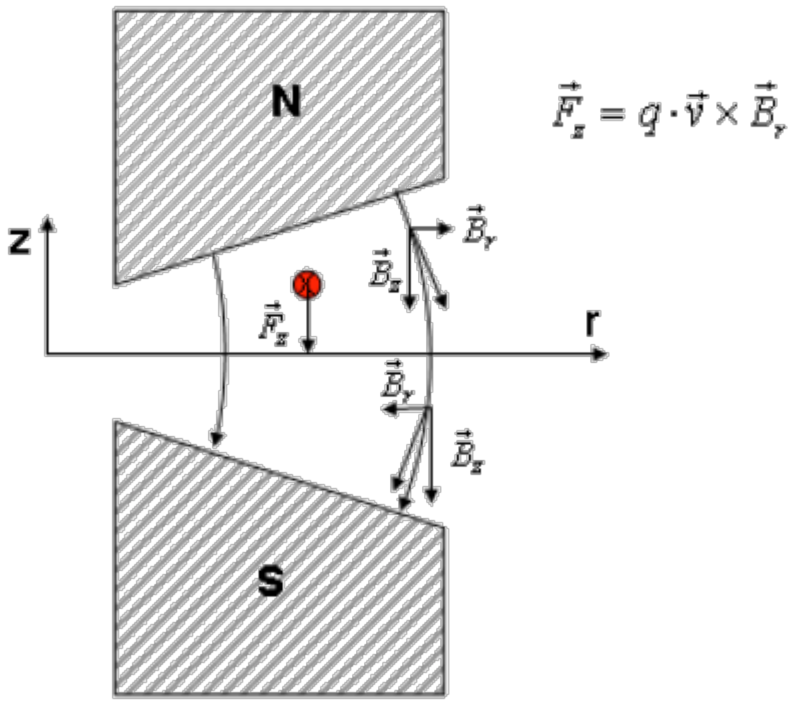
Weak focusing ("geometric focusing")



"Betatron oscillations"

Accelerators – Synchrotron

Field gradients: vertical focusing

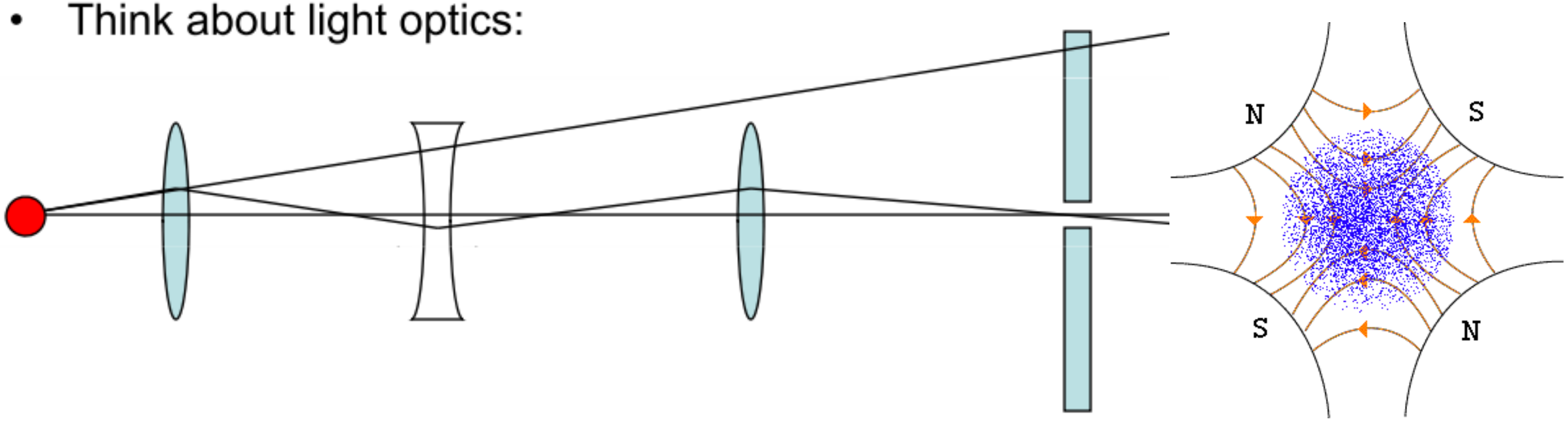


In the presence of a "barrel-shaped" magnetic field, the magnetic force acting on a particle displaced from the equilibrium orbit has a vertically focusing component F_z

Accelerators – Synchrotron

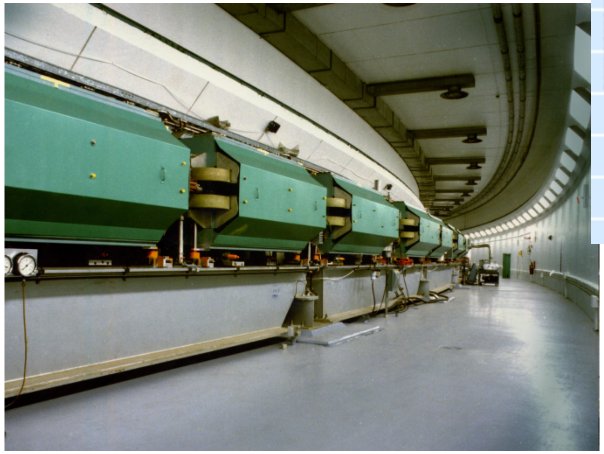
Strong focusing:

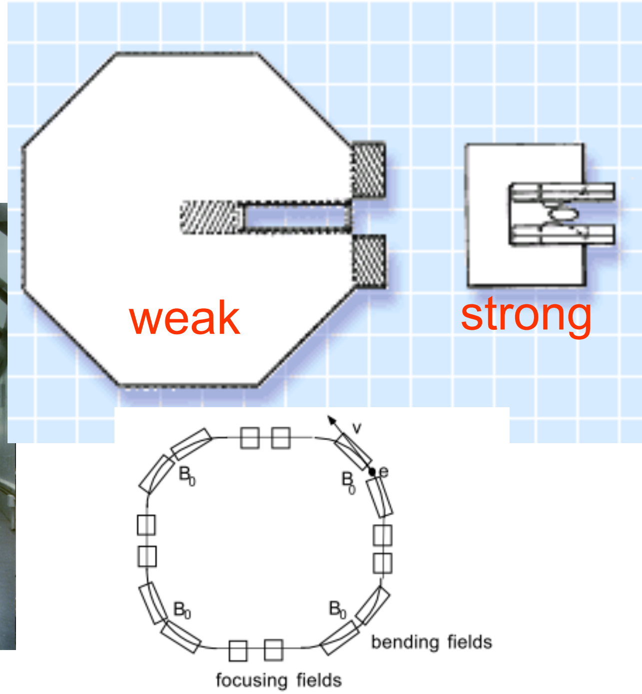
- Suppose two particles start the acceleration process. One has exactly the correct energy, position and angle, so that it is properly accelerated. The accompanying particle has slightly different starting parameters. We need some way of ensuring that non-perfect particles are also accelerated.
- Think about light optics:



- This concept was first applied to particle accelerators by Courant, Livingston, and Snyder.
- It is known as “Strong Focusing” or “Alternating Gradient Focusing”.

Accelerators – Synchrotron



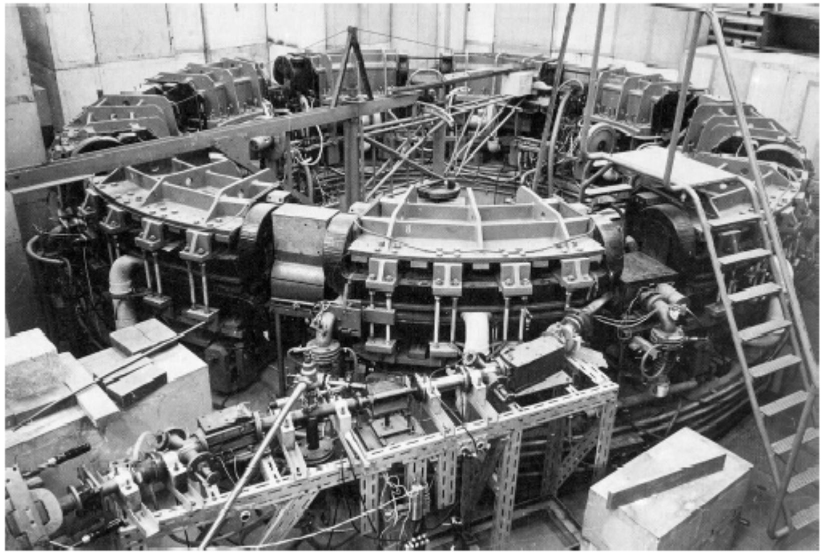


Strong focusing

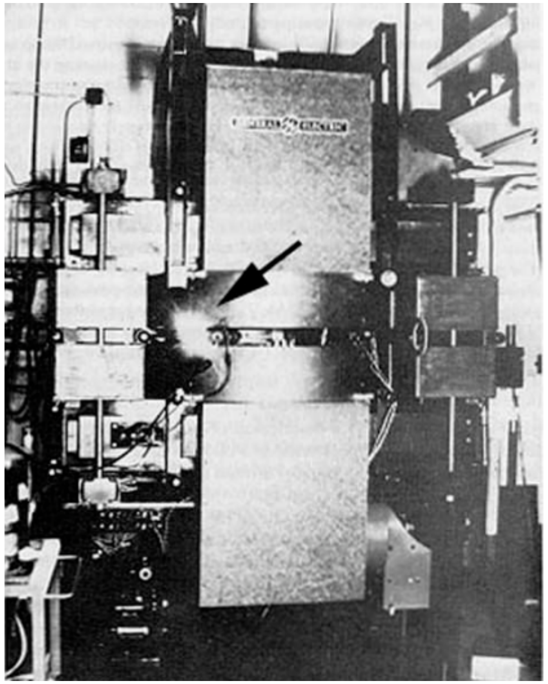
“Alternating Gradient Synchrotron“ (BNL)
30 GeV

“Super Proton Synchrotron“ (CERN)
400 GeV

Accelerators – Synchrotron

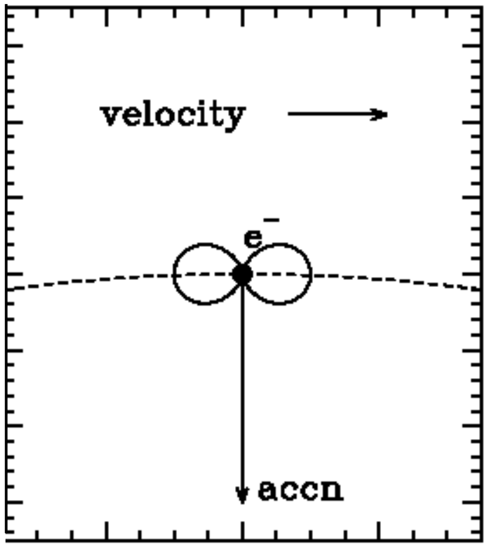


Electron Synchrotron (Bonn)
0.5 GeV

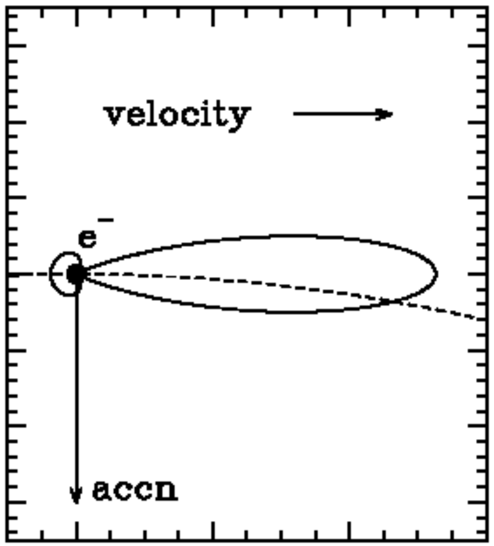


“Synchrotron Radiation“
(1946)

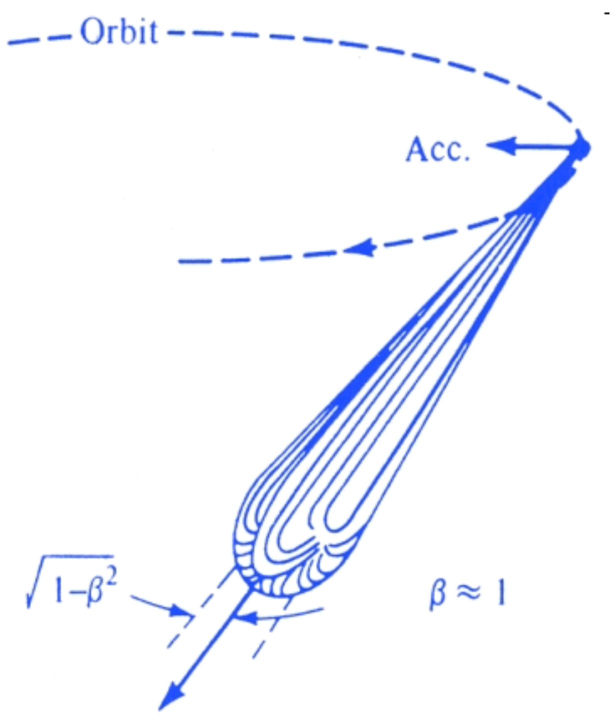
Accelerators – Synchrotron



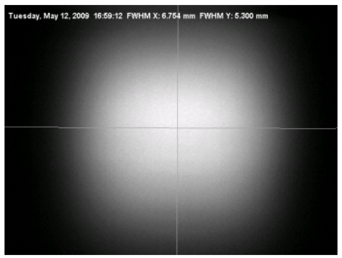
e rest frame



lab frame



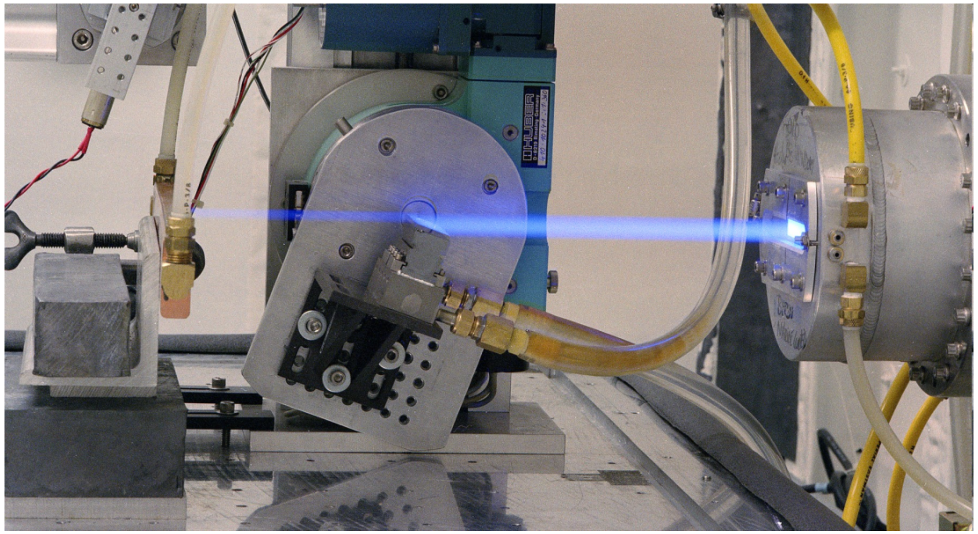
Synchrotron light



Accelerators – Synchrotron

Synchrotron light:

In 1956 the first experiments were carried out using synchrotron light at Cornell in the USA. Over the years the number of experiments increased, all using machines built for high energy particle physics. This changed in 1980 when the UK built the world's first synchrotron dedicated to producing synchrotron light for experiments. Now there are around 70 synchrotron light sources around the world, carrying out a huge range of experiments with applications in engineering, biology, materials science, cultural heritage, chemistry, environment science and many more.



Accelerators – Synchrotron

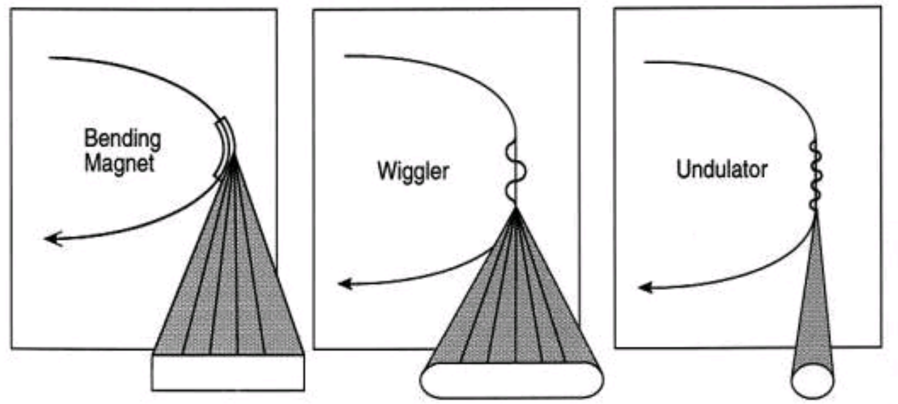
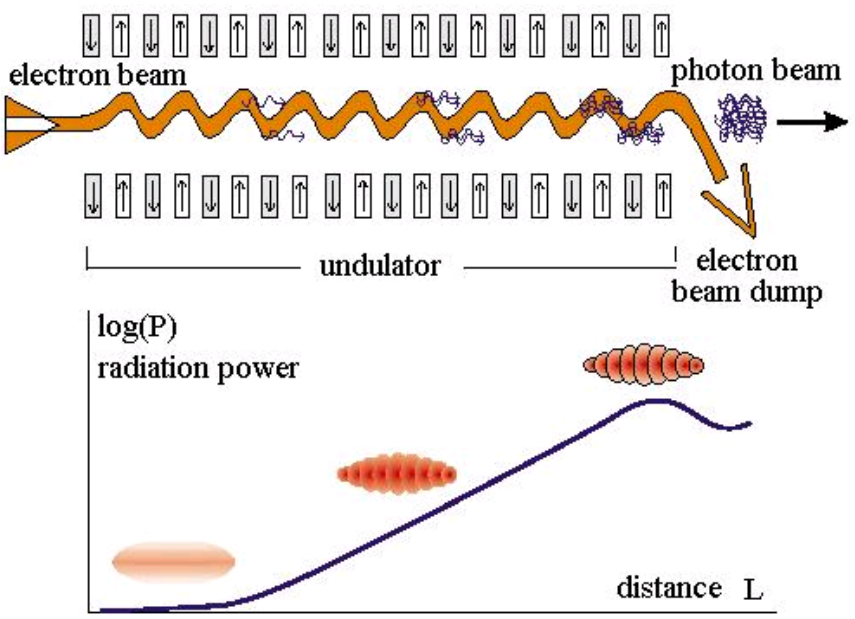


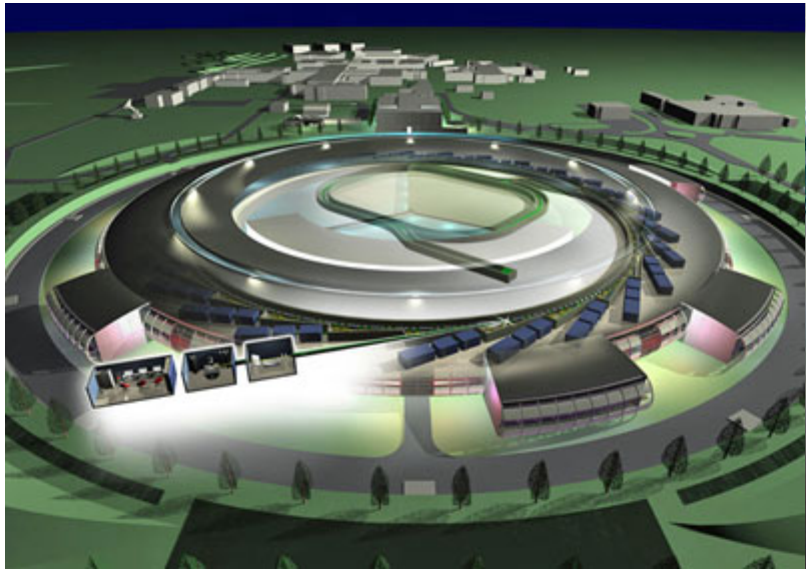
Fig. 1 Schematic of the three approaches used for synchrotron light generation. Bending magnet light is available at all sources. Wigglers or undulators, which are periodic magnet structures installed in straight sections, provide much enhanced flux and brightness. (Figure courtesy of ALS, LBNL)

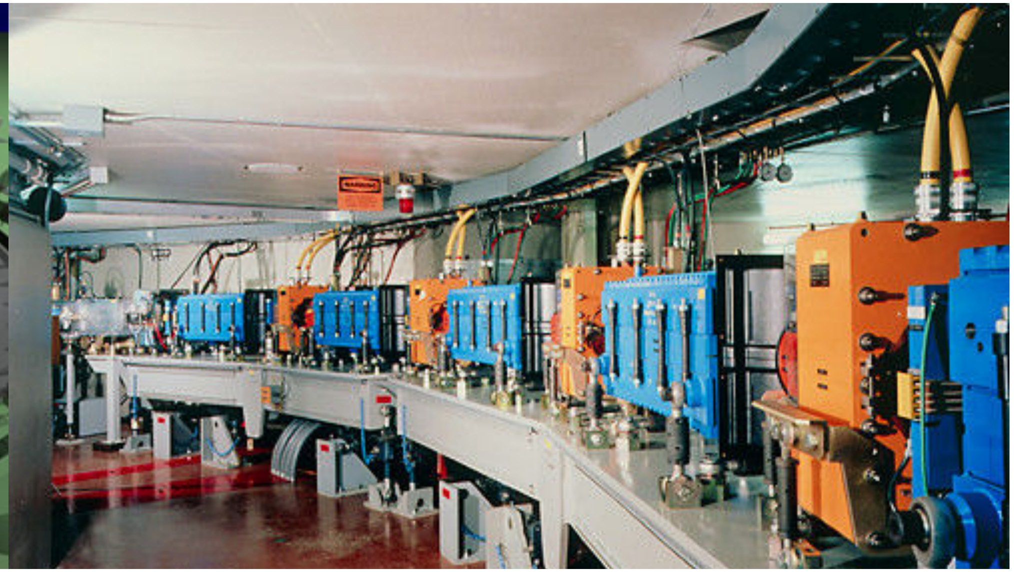


Synchrotron light

Accelerators – Synchrotron

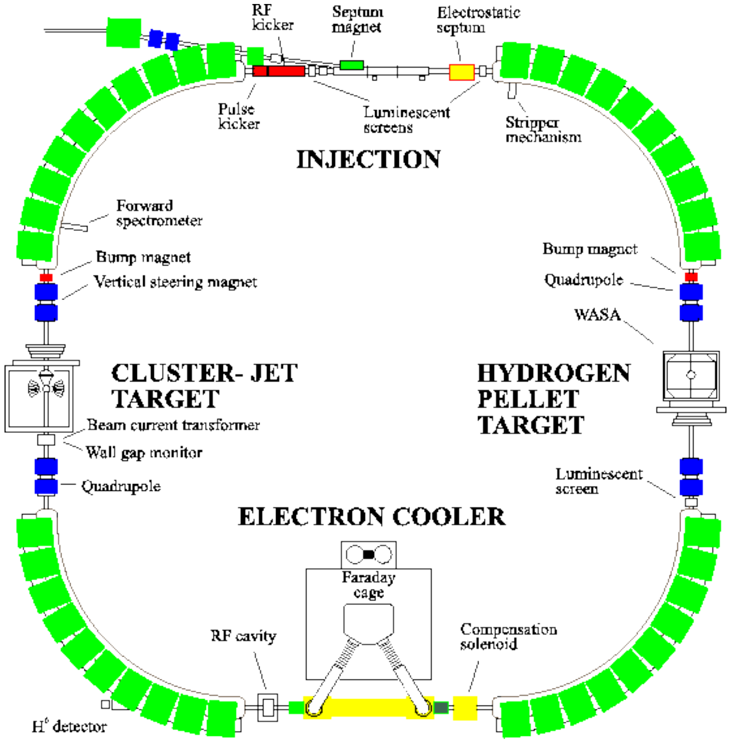
Storage of electron beam → „Storage Ring“





Accelerators – Synchrotron

Storage Ring: Proton, Deuteron, …



CELSIUS (Uppsala)

COSY (Jülich)

Accelerators – Circular

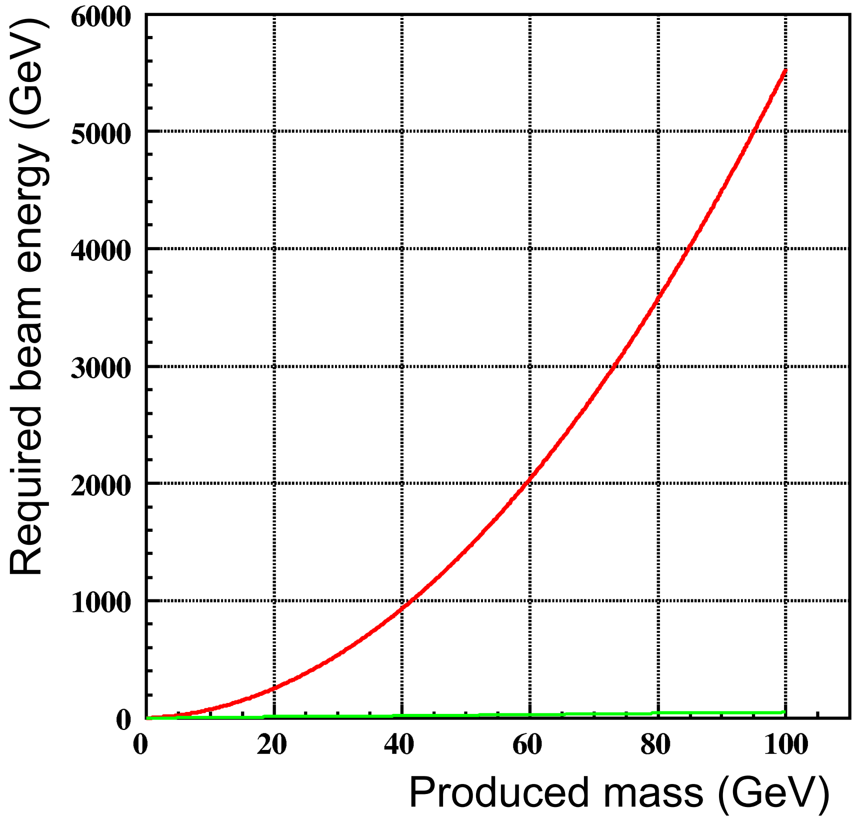
Accelerator	Frequency	B-field	Orbit
Cyclotron	Fixed	Fixed	Variable
Synchrocyclotron	Variable	Fixed	Variable
Synchrotron	Variable	Variable	Fixed

Übersicht der Kreisbeschleuniger:

Prinzip	Energie γ	Geschwindigkeit v	Orbit r	Feld B	Frequenz f_{RF}	Teilchen-fluss
Zyklotron	1	variabel	$\propto v$	const.	const.	const. [a]
Synchro-Zyklotron	var.	var.	$\propto p$	$B(r)$	$\propto \frac{B(r)}{\gamma(t)}$	gepulst
Isochron-Zyklotron	var.	var.	$r = f(p)$	$B(r, \varphi)$	const.	const. [a]
Proton/Ion-Synchrotron	var.	var.	R	$\propto p(t)$	$\propto v(t)$	gepulst
Elektron-Synchrotron	var.	var.	R	$\propto p(t)$	const.	gepulst

[a] kontinuierlicher Strahl, jedoch HF moduliert

Accelerators – Collider



For fixed-target experiments:

$$T_p = \frac{(2m_p + m_M)^2 - (2m_p)^2}{2m_p}$$

... the required beam energy grows strongly!!

Reason:
→ Mass of projectile grows as γm
→ Huge momentum of cm system
→ Less energy available for particle production

Solution:
→ Collider rings
→ Lab. system ≡ cms
→ Momentum of cms = 0
→ Available energy = 2 x beam energy

Accelerators – Collider

The storage ring collider idea was invented by R. Wiederoe in 1943

- Collaboration with B. Touschek
- Patent disclosure 1949


Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
11. MAI 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

№ 876 279

KLASSE 21g GRUPPE 36

W 687 VIIIc / 21g

Dr.-Ing. Rolf Wideröe, Oslo
ist als Erfinder genannt worden

Aktiengesellschaft Brown, Boveri & Cie, Baden (Schweiz)

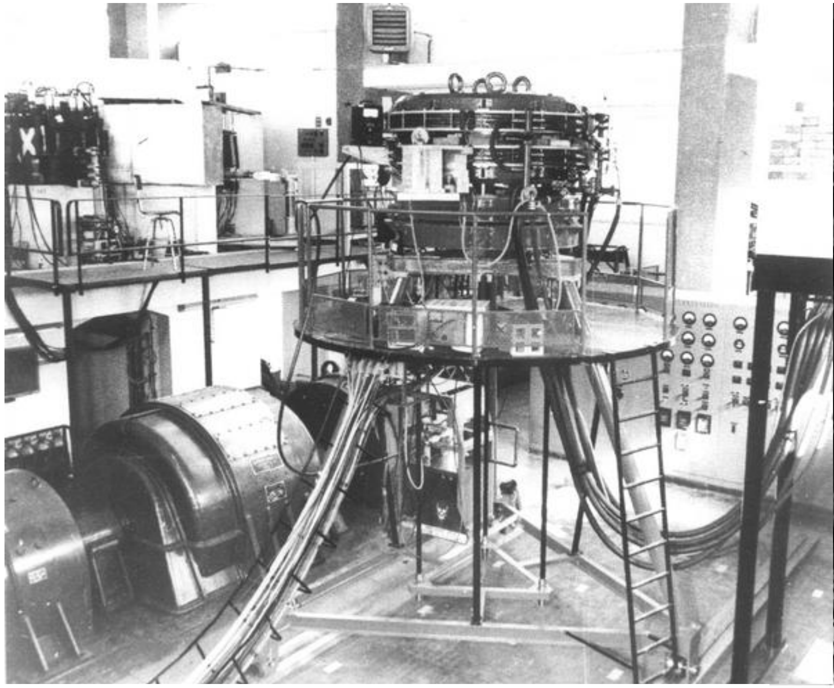
Anordnung zur Herbeiführung von Kernreaktionen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 8. September 1943 an
Patentanmeldung bekanntgemacht am 18. September 1952
Patenterteilung bekanntgemacht am 26. März 1953

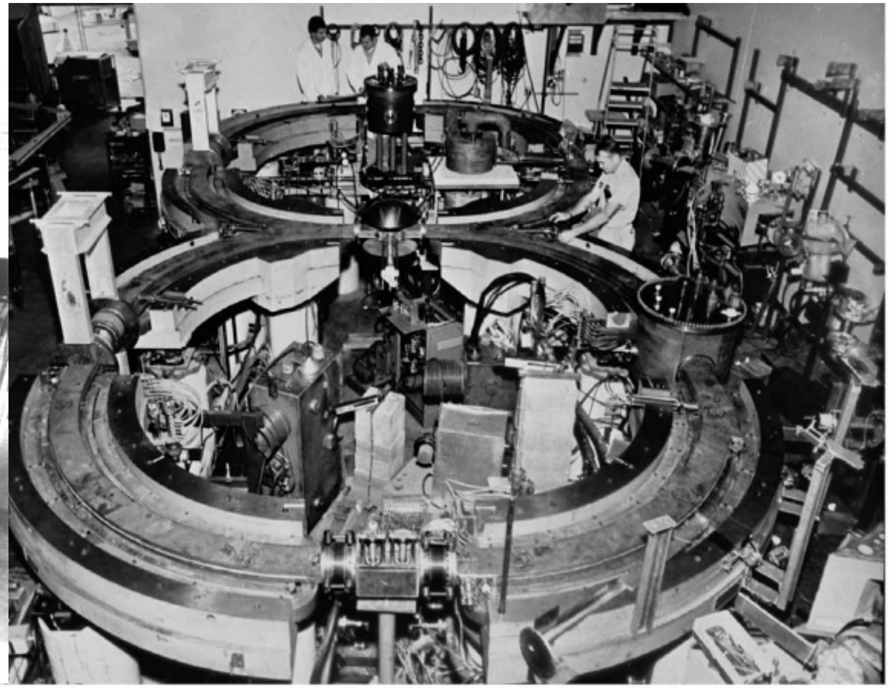
Apparatus
to produce
nuclear reactions

Accelerators – Collider

Early Designs



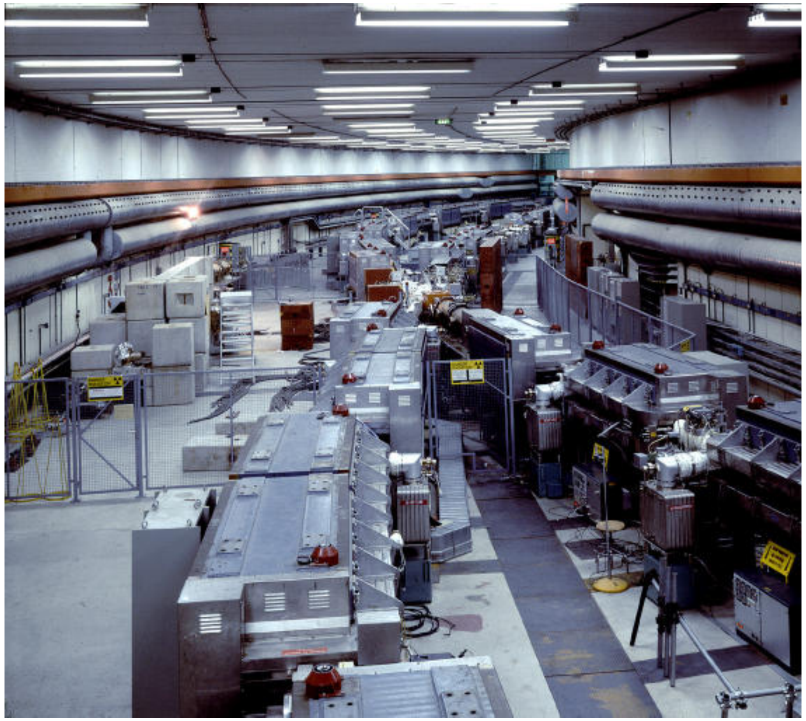
AdA (Frascati), e^+e^- (1961-64)



Princeton-Stanford colliding beam storage rings - 1960

Accelerators – Collider

Separate Rings

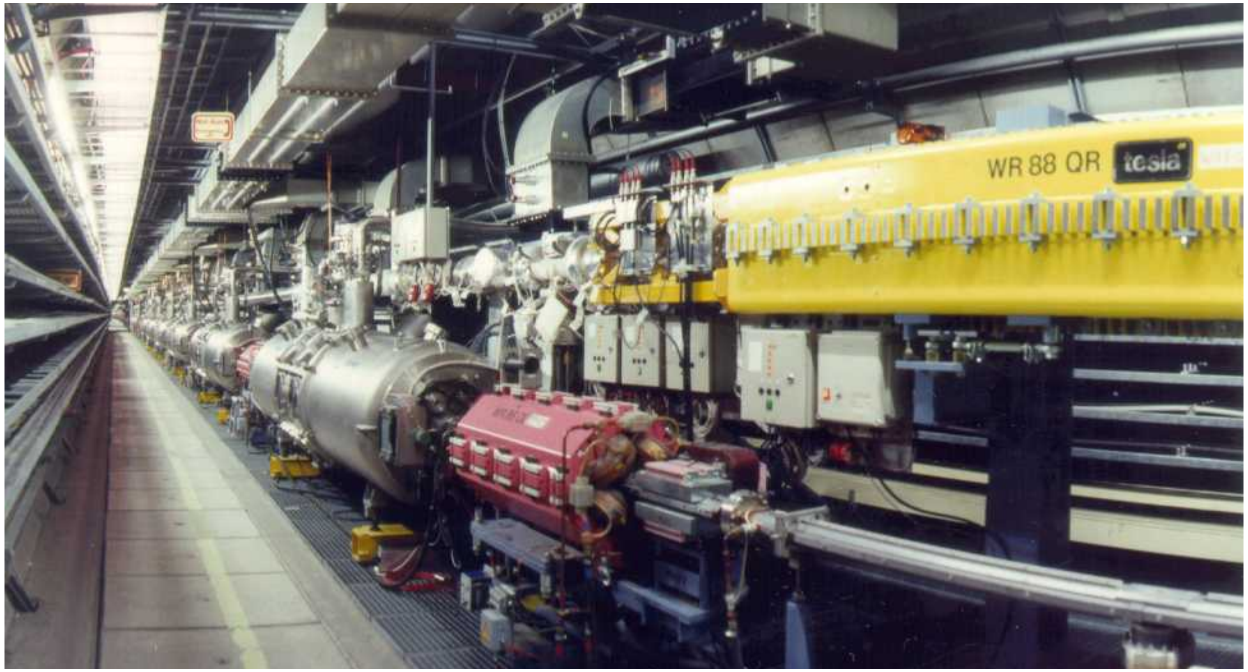


ISR (CERN)
Proton-Proton

RHIC (BNL)
pp, Ion-Ion

Accelerators – Collider

Separate Rings

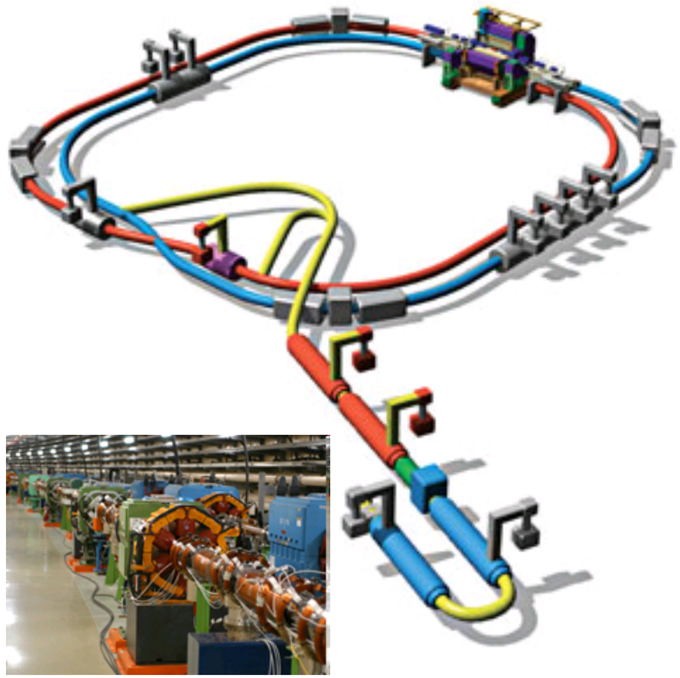


HERA (DESY)
e-p

Accelerators – Collider

Separate Rings

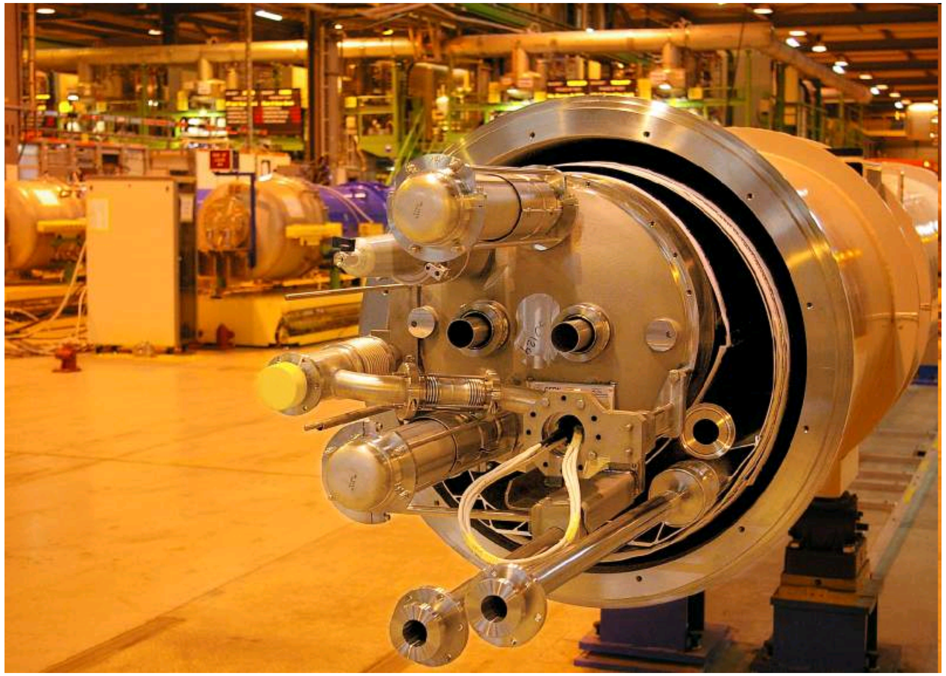
DAFNE (Frascati)
electron-positron

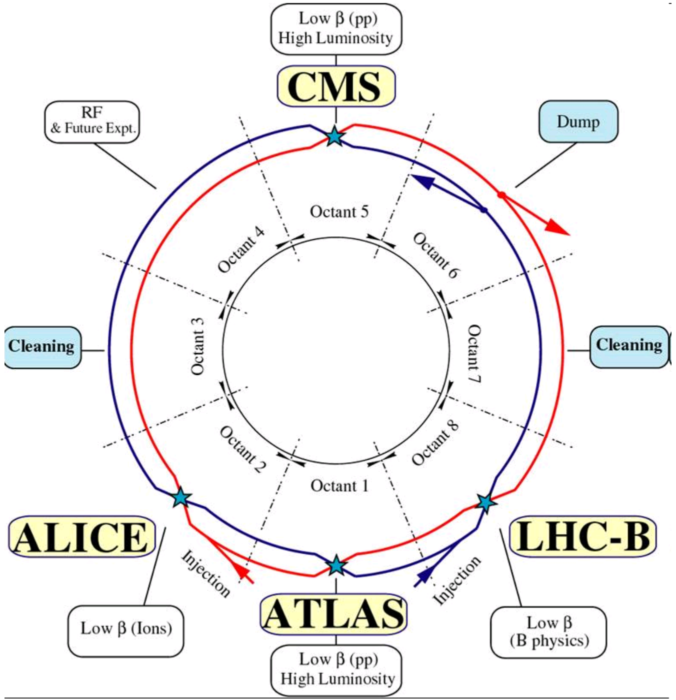


KEKB (Japan)
electron-positron
asymmetric collider

Accelerators – Collider

Separate Rings

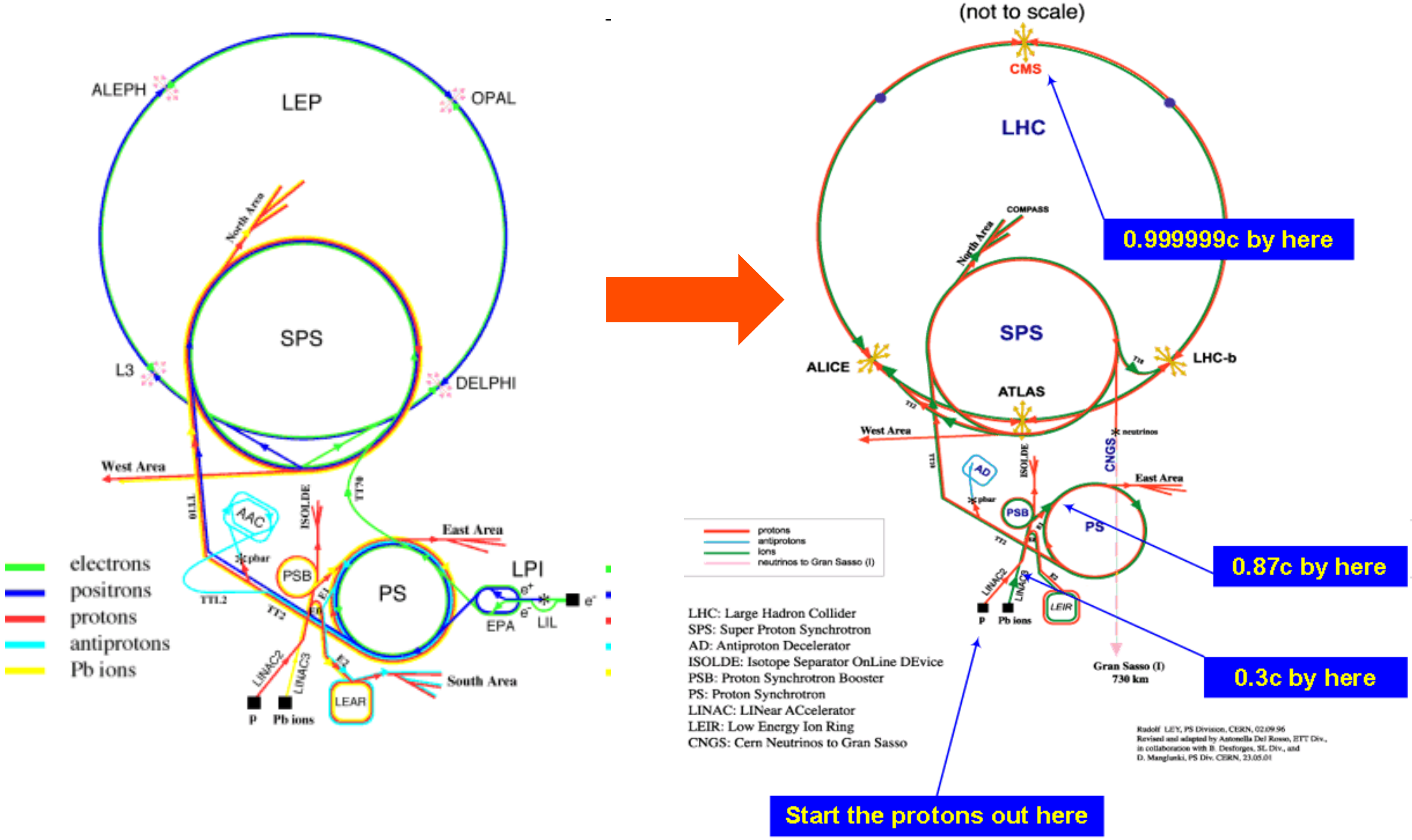




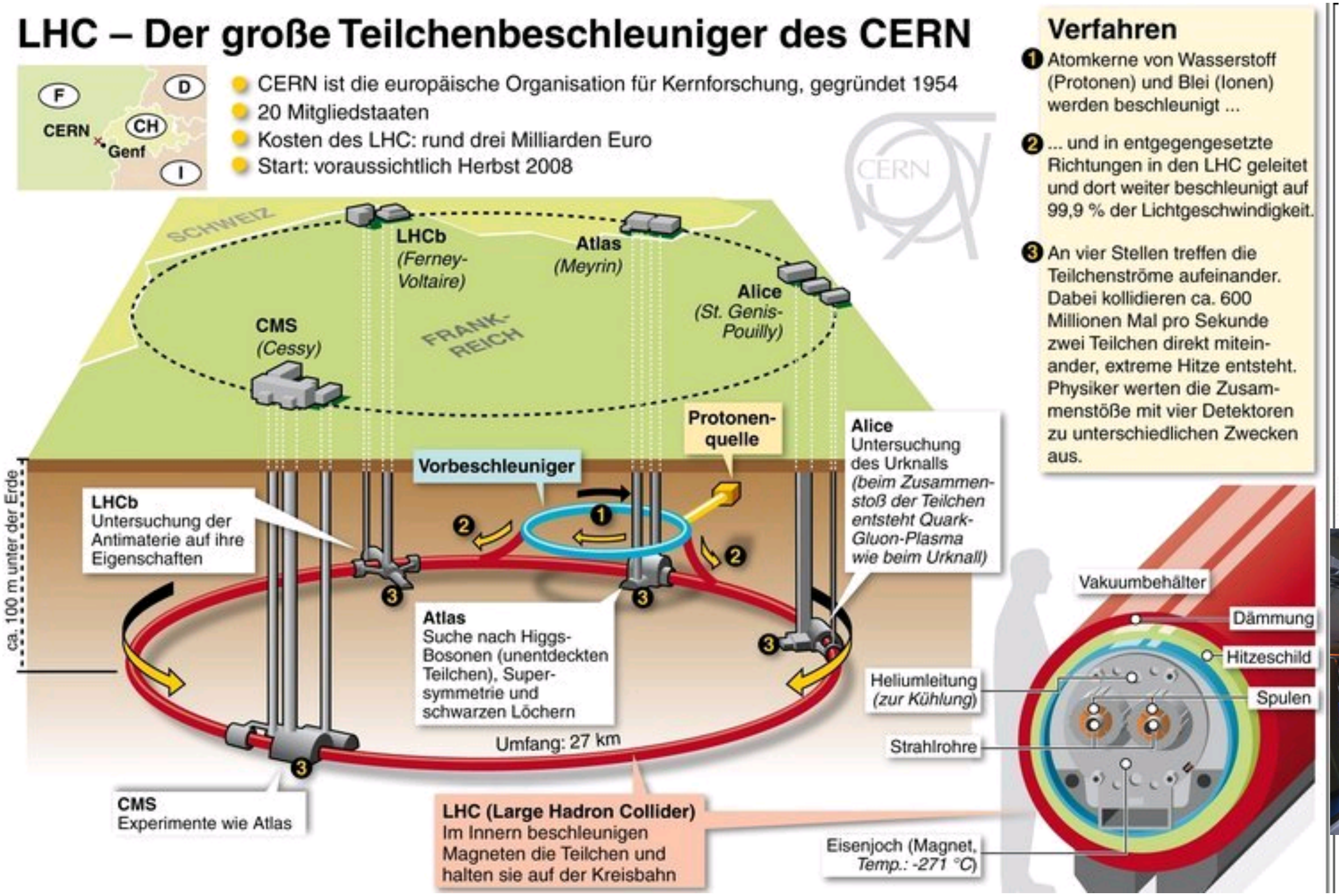
LHC (CERN)
proton-proton, ion-ion

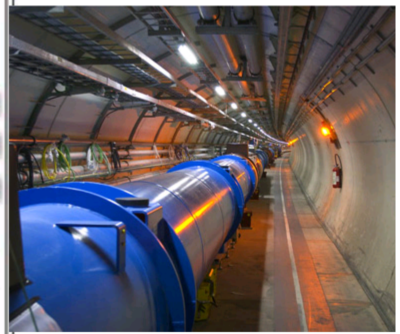
Accelerators – Facilities

CERN:



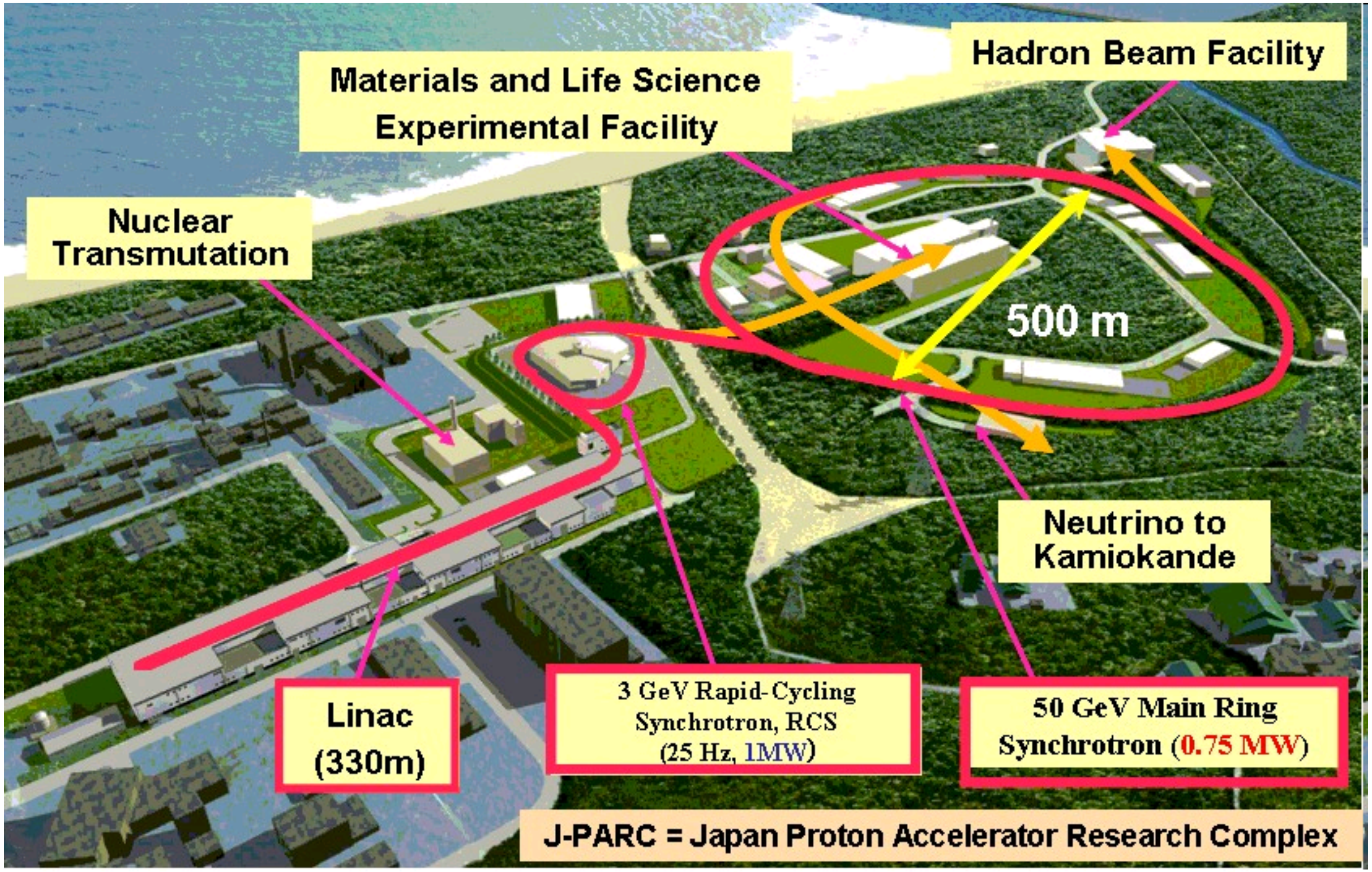
Accelerators – Facilities





Accelerators – Facilities

J-PARC:



Accelerators – Facilities

FAIR at GSI:

Accelerators – Summary

Today particle accelerators are a (the) major tool for basic research

- **Not just the physical sciences, but also biological and other sciences**

Today particle accelerators serve the nation and society in many ways

- **They are utilized in medical, security and industrial applications**
- **Some have said their impact ranks among the highest of modern technology**

Exercises

Exercise (Isocyclotron)

Find the radial dependence of the magnetic field $B_z(r)$ in an isocyclotron with angular frequency ω_z.

Exercise (LEP at CERN)

The main dipole magnets of the Large Electron Positron (LEP) collider had a bending radius of 3096 m.

(a) How strong was their magnetic field when LEP accelerated electrons to 105 GeV?

(b) This field strength is relatively small, why was the field not increased to increase the energy?

(c) The LEP tunnel was about 26.6km long. What fraction of it was used for bending the beam?