Introduction to Accelerator Physics

Yuri A. Litvinov
y.litvinov@gsi.de

Heidelberg WS 2022/23
Physikalisches Institut der Universität Heidelberg

Introduction to Acclerator Physics

Goal of this lecture course
Introduction to accelerator physics

-1- Experimental aspects:

Accelerator components;
Beam properties;
Beam handling.

-2- Theory:

Beam optics;
Beam dynamics;
Simulations (exercises).

Organisation

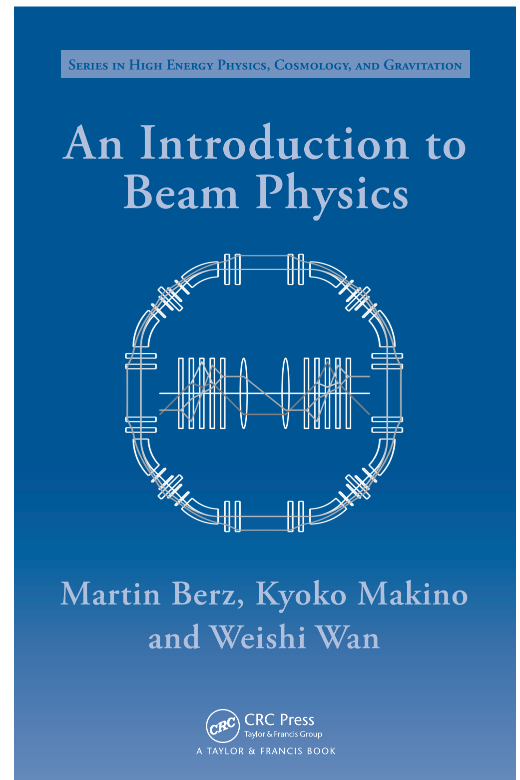
- Prerequisites:
  Knowledge: Electrodynamics, Special Relativity, Quantum Mechanics
  Lectures: Experimental Physics I-V
- Addressing: Master Students (Bachelor Students)
- Accompanying Tutorials:
  Wednesdays 16:15-18:00 (Tutor: Tamasi Rameshchandra Kar)
- "hands on" computer exercises (Python)
  First date: 19th of October (**today**!)
- More Information on the Web:
  https://uebungen.physik.uni-heidelberg.de/vorlesung/20222/1611

Literature

No dedicated script! Content depends also on your wishes!

M. Berz, K. Makino and W. S. Wan

An Introduction to Beam Physics



Frank Hinterberger

Physik der Teilchenbeschleuniger und Ionenoptik

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

More Literature

Klaus Wille: *Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen. Eine Einführung* (Broschiert) Teubner Verlag 2001, also in English, Oxford University Press; book is difficult to get!

E. Wilson: *An Introduction to Particle Accelerators*, Oxford University Press 2001

Helmut Wiedemann: *Particle Accelerator Physics*, 3. Auflage, Springer 2007, ISBN 3540490434

CERN Yellow Reports:
CERN Accelerator School Proceedings
CERN Document Server

Lecture Dates

https://uebungen.physik.uni-heidelberg.de/vorlesung/20222/1611/lecture

Date	Topic
19.10.2022	Introduction and basic definitions
26.10.2022	Accelerating structures
02.11.2022	Accelerator Components
09.11.2022	Optics with magnets (1)
16.11.2022	Optics with magnets (2)
23.11.2022	Equations of motion
30.11.2022	Phase ellipses and magneto-optical system / Transverse beam dynamics
07.12.2022	Transverse beam dynamics, beam stability / Longitudinal beam dynamics
14.12.2023	Phase space and beam cooling (Invitation)
11.01.2023	Space charge and beam-beam dynamics
18.01.2023	Physics at Storage Rings
25.01.2023	Physics at Colliders
01.02.2023	New accelerator technologies
08.02.2023	Student seminar
15.02.2023	reserve
22.02.2023	reserve

Wednesdays, 14:15-16:00

„Leistungskontrolle“

Tutorials

Tamasi Rameshchandra Kar

(Kai Schweda)

Introduction and details

Today at 16:15 in this lecture room

successful accomplishment → certificate (Master)
- number of credit points = 4
- no grades given (only “pass”)
- lecture qualifies for master examination (MVMOD)

sign up here:

https://uebungen.physik.uni-heidelberg.de/vorlesung/20222/1611

Excursions (!) (?)

We can organise excursions to

GSI Helmholtz Center in Darmstadt

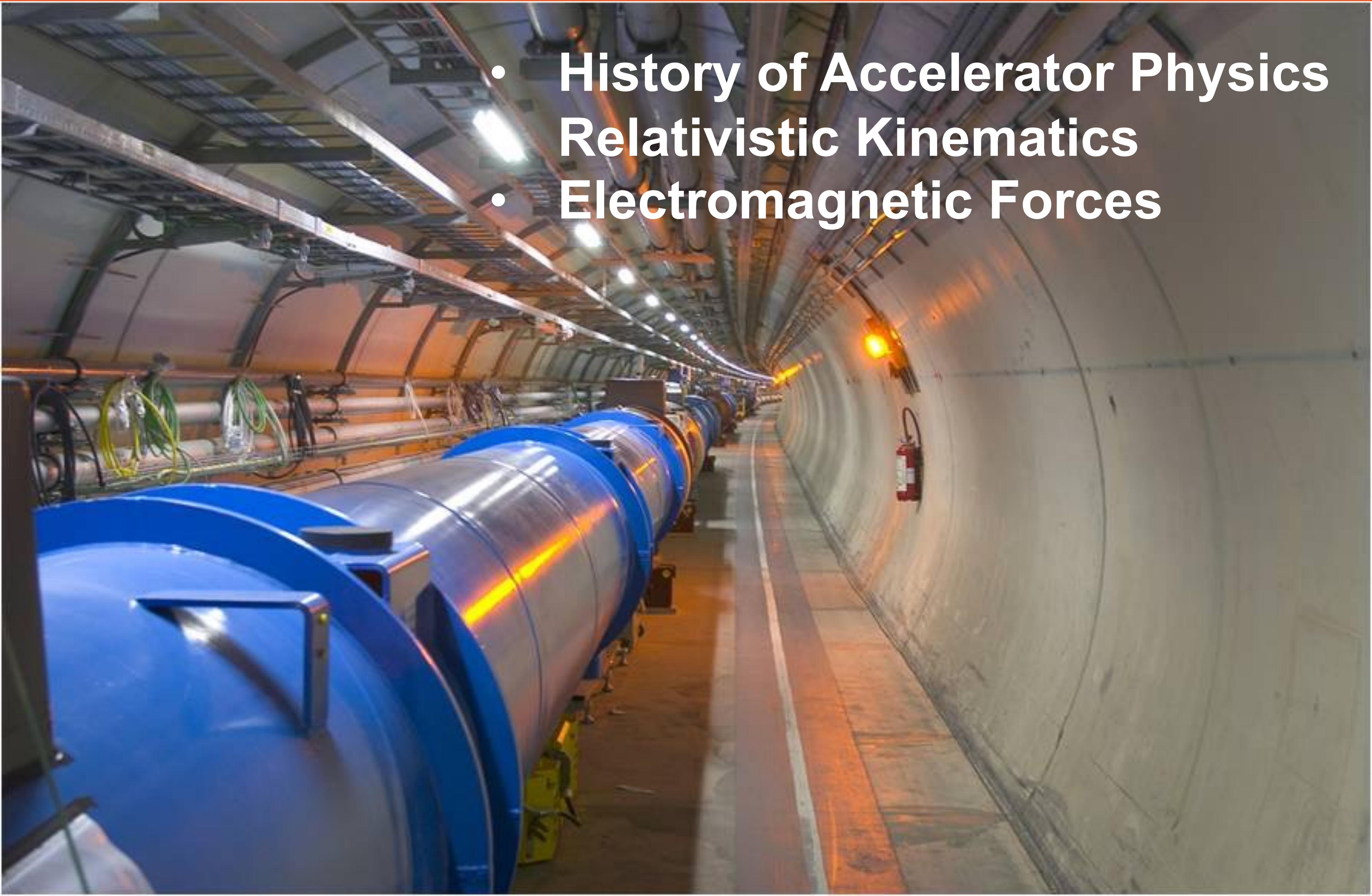
MPI-Kernphysik, Heidelberg

Depends on your interest!!!

QUESTIONS?

1. INTRODUCTION

- History of Accelerator Physics
  Relativistic Kinematics
- Electromagnetic Forces



History of Particle Accelerators (1)

1862 Theory of Electromagnetism

$$1\ \mathrm{Mx} \equiv 10\ \mathrm{nWb} = 10^{-8}\frac{\mathrm{kg\ m^2}}{\mathrm{A\ s^2}}$$

1887 Electromagnetic Waves

James Clerk Maxwell
(1831-1879)

$$1\ \mathrm{Hz} = 1\frac{1}{\mathrm{s}}$$

Christian-Albrechts-Universität zu Kiel

Heinrich Rudolf Hertz
(1857-1894)

1886 Anode rays

Beam of positively-charged particles

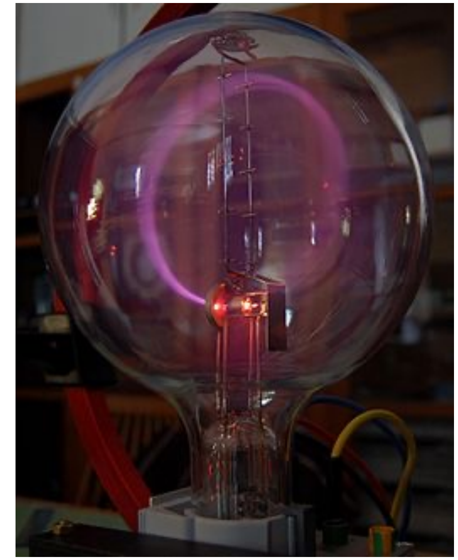
Gotthilf-Eugen Goldstein
(1850-1930)

Figures: Wikipedia

History of Particle Accelerators (2)

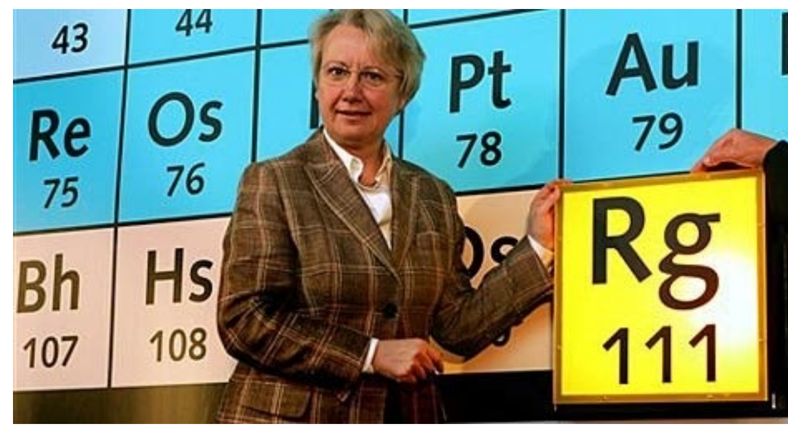
1894 First Electron Beam

Cathode rays



Philipp Lenard
(1862-1947)

1895 X-rays

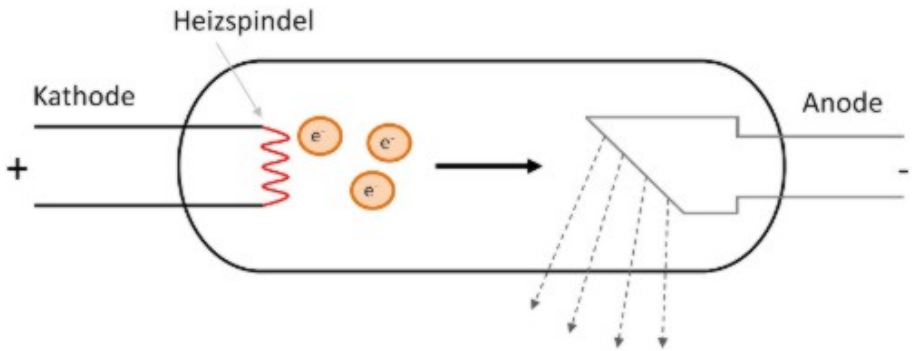


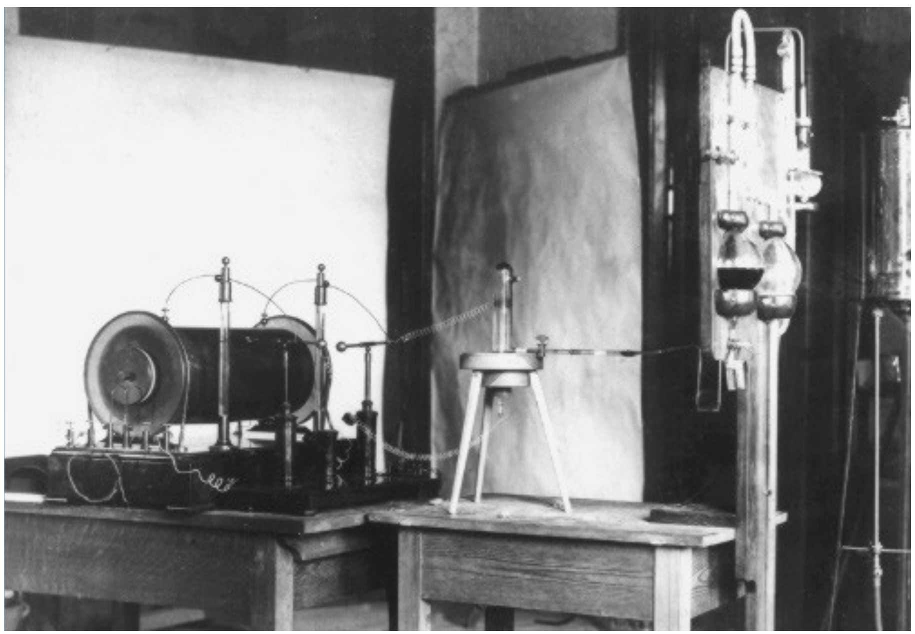
Wilhelm Conrad Röntgen
(1845-1923)

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Figures: Wikipedia

First Electron Accelerator

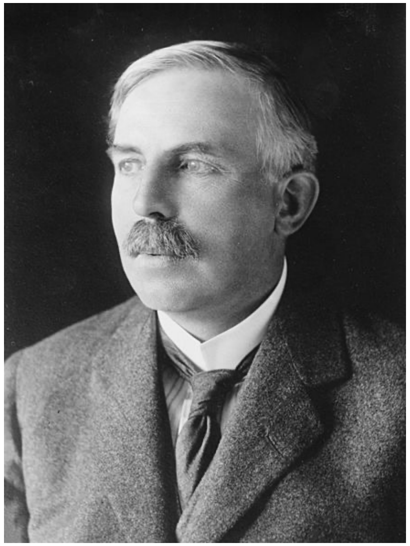




1895 Wilhelm Conrad Röntgen

Units

History of Particle Accelerators (3)



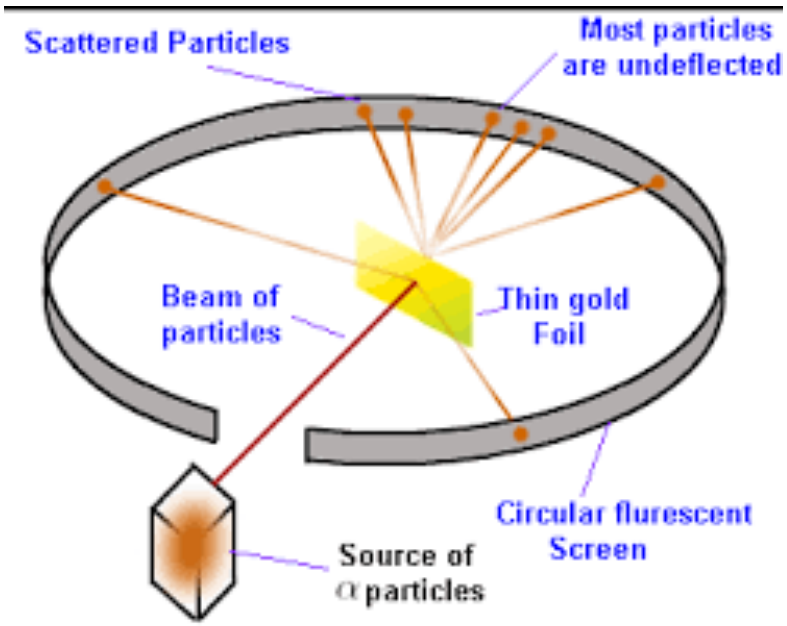
Ernest Rutherford
(1871-1937)

Radioactivity

1911 First Reaction

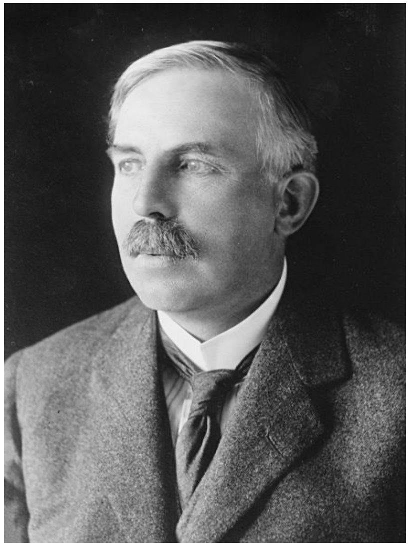
$\alpha_{7,7}$ from Radium-C
(^{214}Po decay)

^{197}Au(α,α)^{197}Au



Relativistic Kinematics (1)

History of Particle Accelerators (3)



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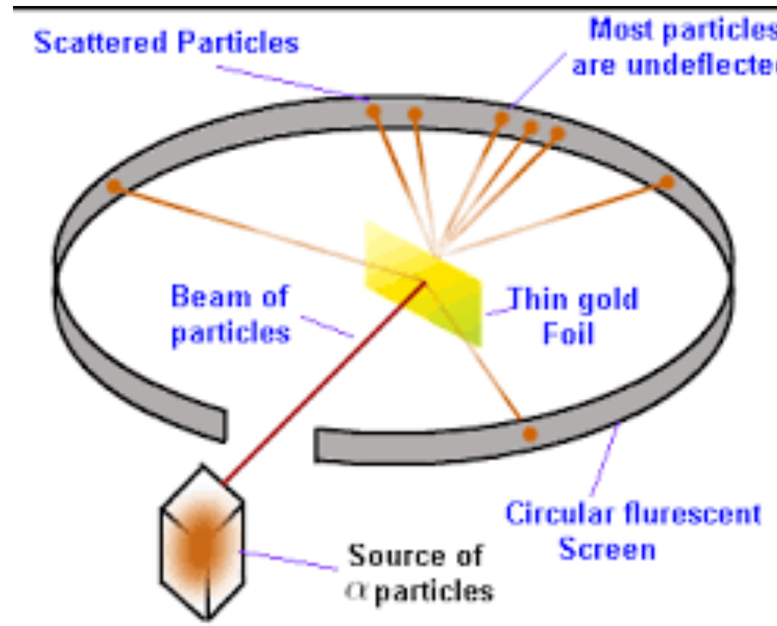


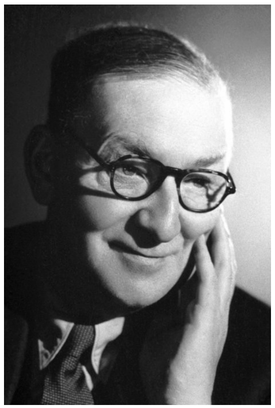
1919 First Nuclear Reaction

^{14}N(α,p)^{17}O

1928-1932 Linear, Circular, Electrostatic Accelerators

History of Particle Accelerators (4)

1932 Cockroft and Walton Accelerator



Sir John Douglas Cockcroft
(1897-1967)

Ernest Thomas Sinton Walton
(1903-1995)

Particle acceleration

Protons @ 400 keV

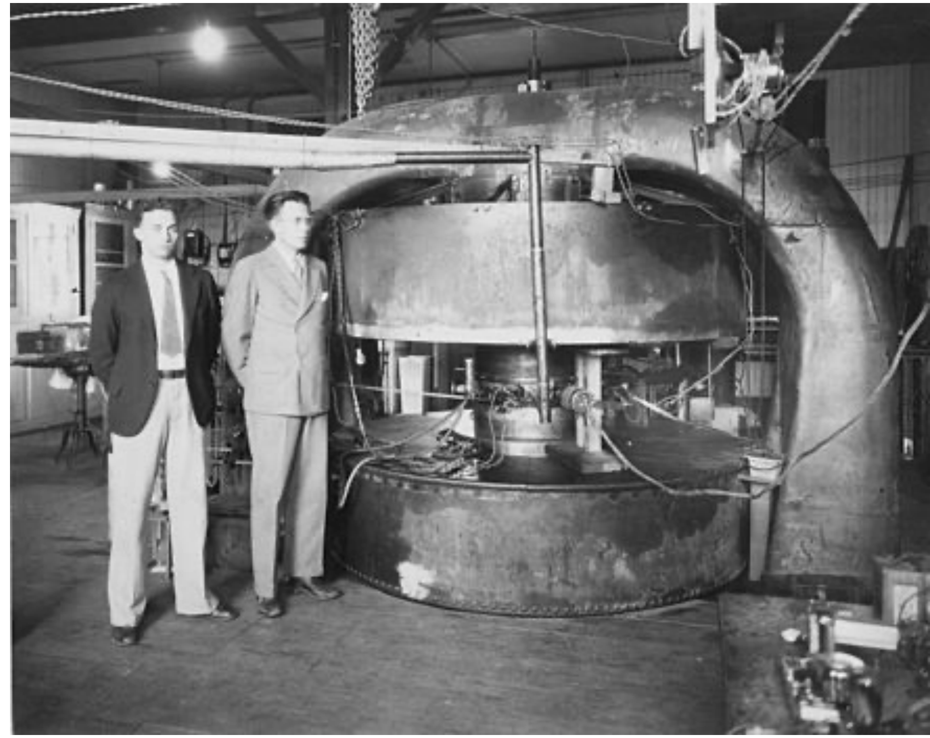
$$p + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$
$$\rightarrow {}^{7}\mathrm{Be} + n$$

Figures: Wikipedia

History of Particle Accelerators (5)

1932 Livingston Cyclotron

Milton Stanley Livingston
(1905-1986)



Protons @ 1.2 MeV after 150 revolutions

Ernest Orlando Lawrence
(1901-1958)

Cyclotron

Figures: Wikipedia

History of Particle Accelerators (6)

>>> 1939 Various-Size Cyclotrons ***Lawrence***

Protons @ 9 MeV
Deuterons @ 20 MeV
Helium-Nuclei @ 40 MeV

>>> >>> >>> >>>

Relativistic Kinematics (2)

History of Particle Accelerators (6)

>>> 1939 Various-Size Cyclotrons ***Lawrence***

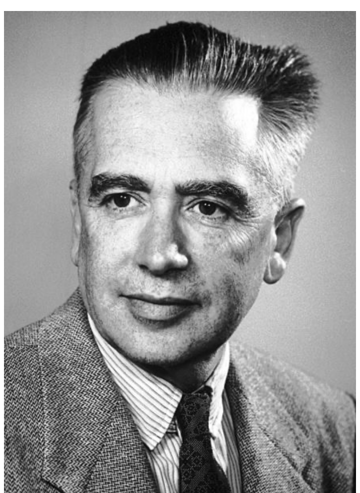
Protons @ 9 MeV
Deuterons @ 20 MeV
Helium-Nuclei @ 40 MeV

>>> >>> >>> >>>

>>> 1950s Bevatron

(1st synchroton)

p @ 6.3 GeV + Cu target
1955 discovery of antiproton



Emilio Gino Segrè
(1905-1989)

Owen Chamberlain
(1920-2006)

1956 discovery of antineutron
Bruce Cork et al.

Figures: Wikipedia

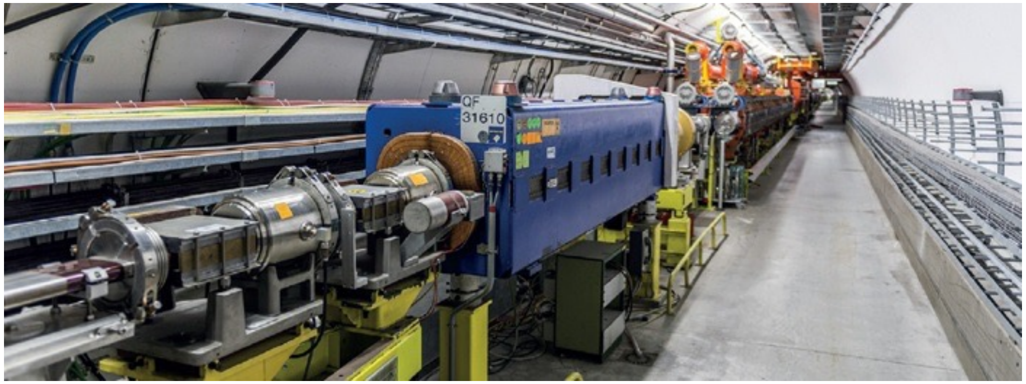
History of Particle Accelerators (7)

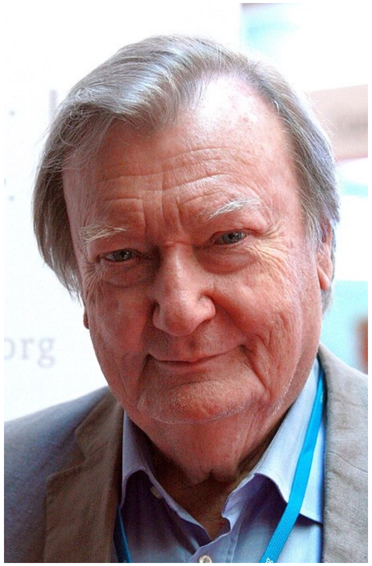
>>>   >>>   >>>   >>>

>>> 1980s Super Proton Synchrotron

p @ 100-1000 GeV
1983 discovery of Z and W bosons

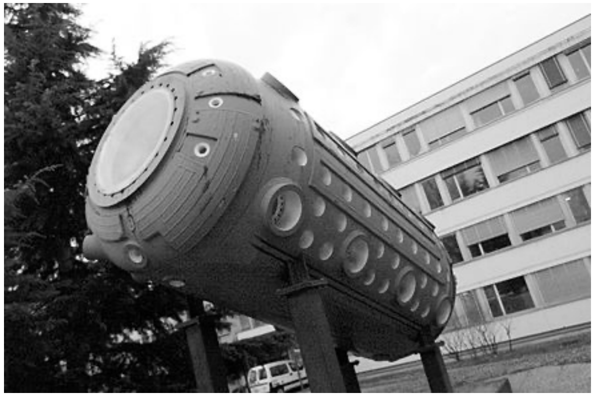
W^{+}-W^{-} pair ~ 160.7 GeV
Z^{0} ~ 90 GeV





Carlo Rubbia
(1934-)

Simon van der Meer
(1925-2011)



Bubble chamber

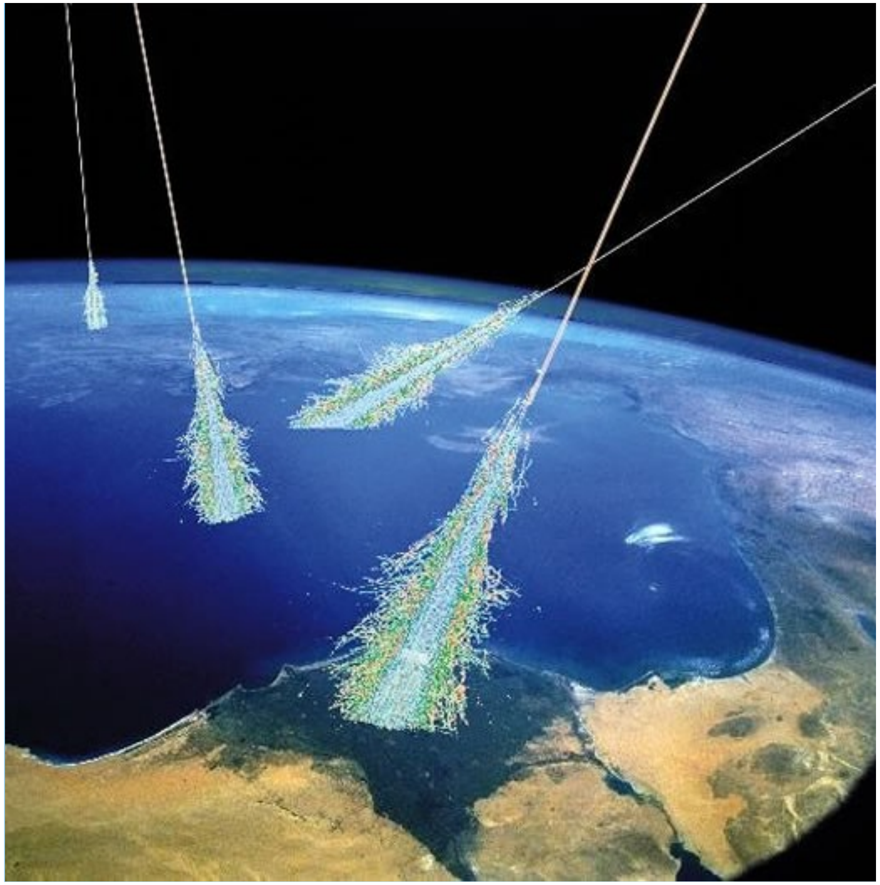
Figures: CERN, Wikipedia

History of Particle Accelerators (8)

1920 *first cascade generator* (H.Greinacker)
1922 *patent for betatron idea* (J.Slepian)
1924 *linear accelerator invented* (G.Ising)
1928 *first linear accelerator in Aachen* (R.Wideröe)
1929 *cyclotron main principle* (E.Lawrence, N. Edlefsen)
1931 *first Van-de-Graaf Generator* (van des Graaf)
1931 *first cyclotron* (E.O.Lawrence, M.S Livingston)
1932 *Cockcroft-Walton-Generator, first nulcear reaction* (J.Cockcroft, E Walton)
1939 *invention of klystron* (W.W. Hansen, K.Varian, S.Varian)
1941 *first Betatron* (D.W.Kerst, R.Serber)
1943 *principle of storage ring patented* (R.Wideröe)
1944 *principle of microtron* (V.I.Veksler)
1945 *principle of synchrotron* (E.M. Mc Millan, V.I.Veksler)
1946 *first electron synchrotron* (F.K.Goward, D.E.Barnes)
1947 *first electron linear accelerator* (E.L. Ginzton et al.)
1947 *study about proton linear accelerator* (L.Alvarez, W.K.H.Panofsky)
1947 *study about proton synchrotron* (M.L.Oliphant)
1949 *320-MeV electron synchrotron in Berkeley* (E.M.McMillan)
1950 *“Strong focussing” principle* (N.Christophilos)
1952 *first proton synchrotron in Brookhaven* (G.K.Green et al.)
1961 *first electron positron storage ring AdA in Frascati* (B.Touschek)
...
2006 *1GeV electrons with Laser-Plasma acceleration* (W.Leemans)

Particle Acceleration in Universe

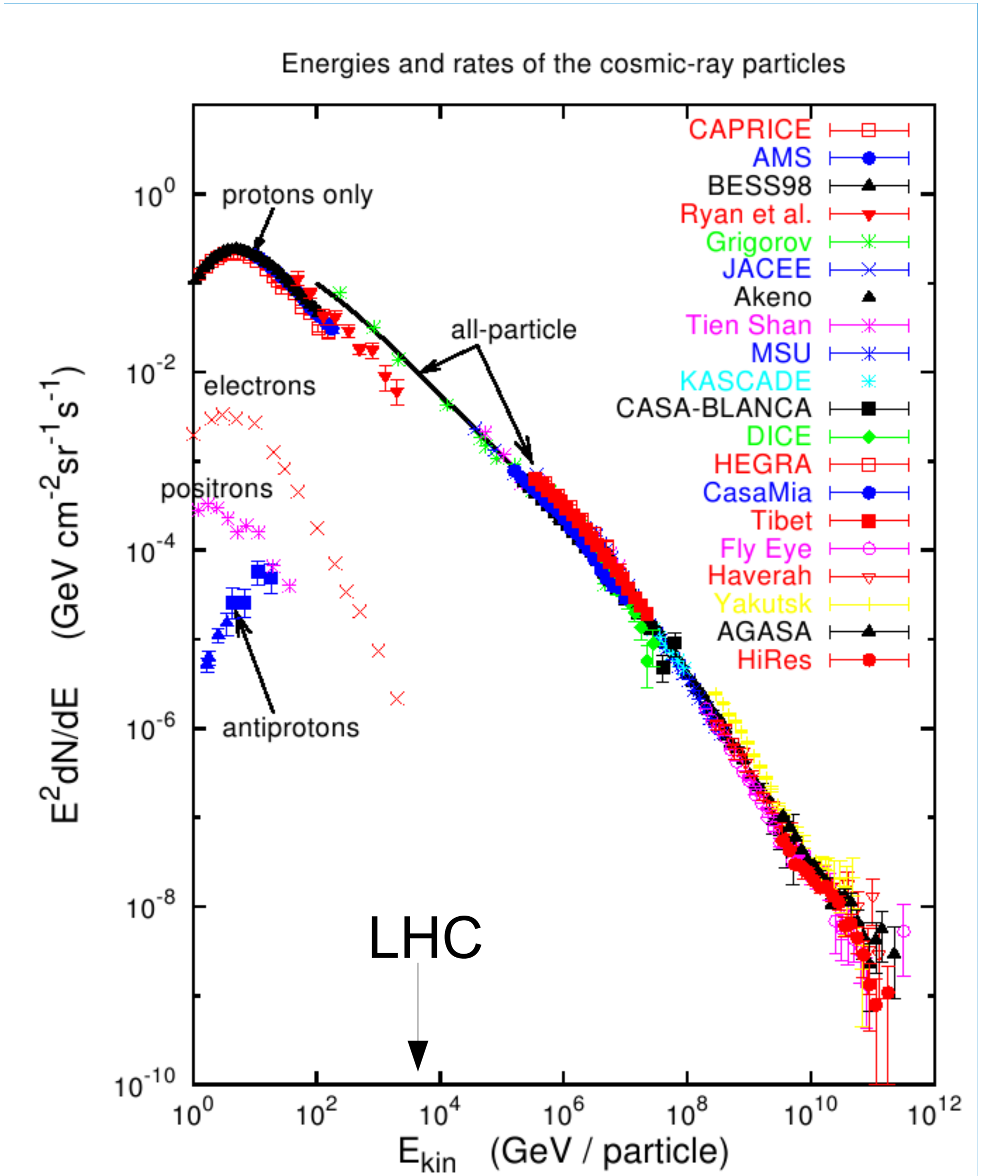
1912 Cosmic rays



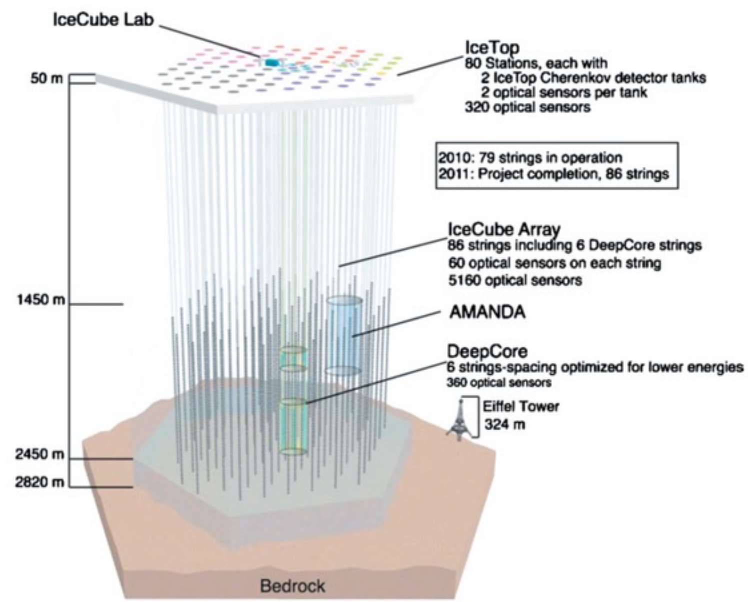
Victor Franz Hess
(1883-1964)

Figures: Wikipedia

Particle Acceleration in Universe

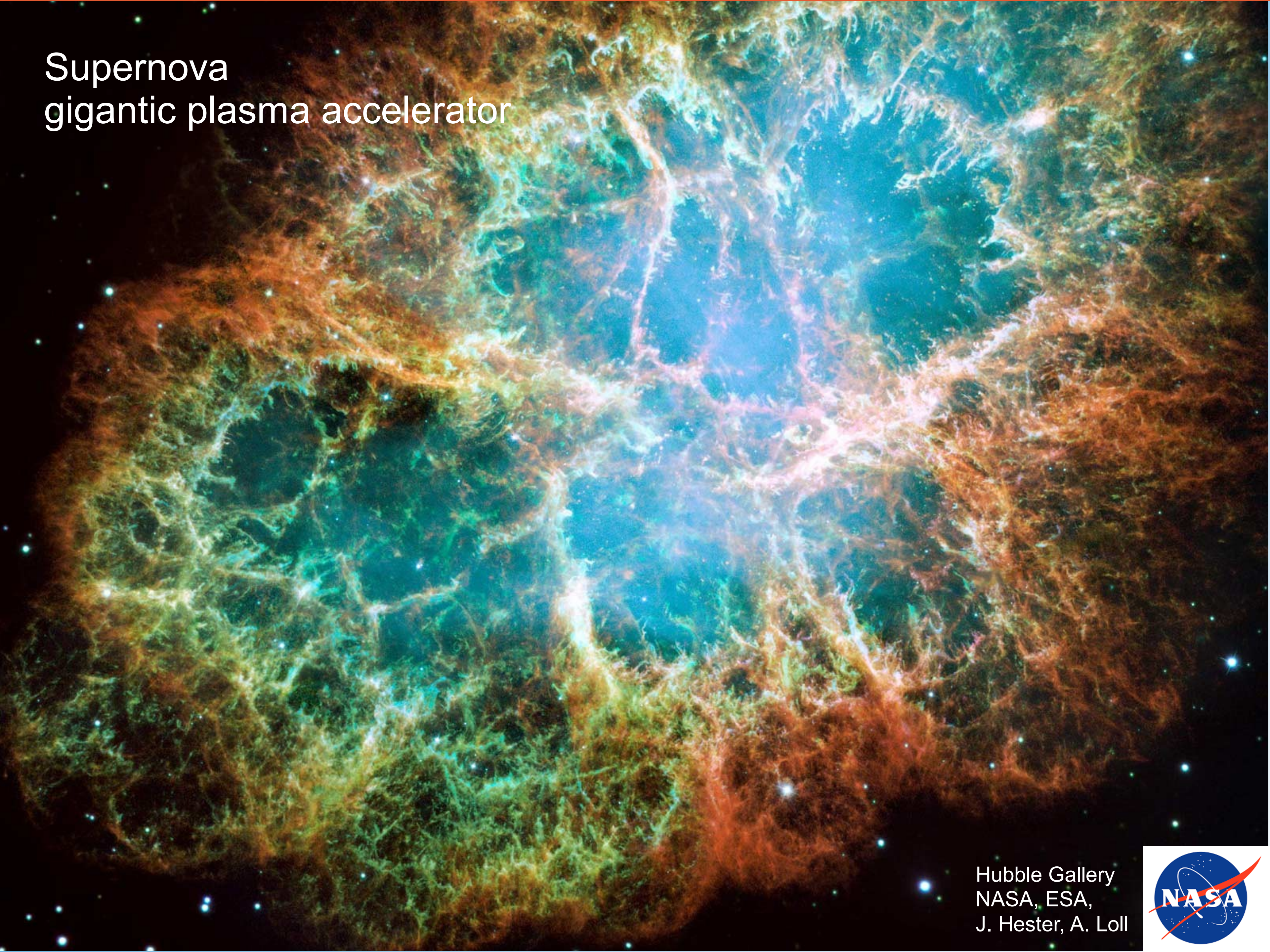


H.E.S.S. in Namibia



Ice Cube in Antarctica

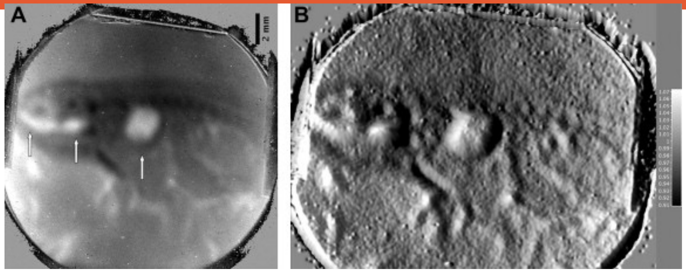
Supernova
gigantic plasma accelerator

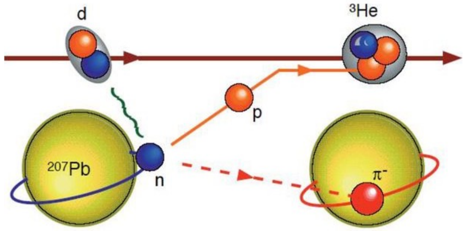


Hubble Gallery
NASA, ESA,
J. Hester, A. Loll

Applications of Accelerators

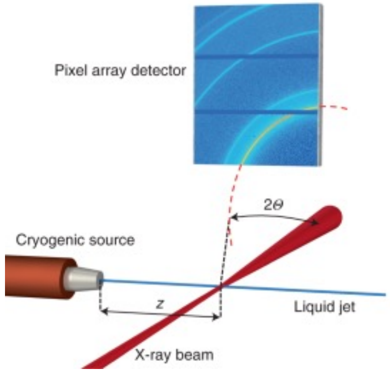
Investigation of small structures (scattering experiments, microscopy)





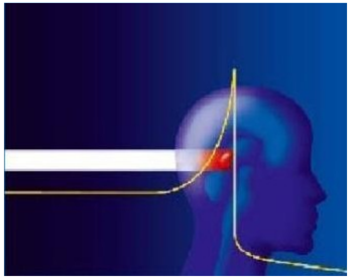
Excitatios of molecules, atoms, nuclei, baryons .. (spectroscopy)

Production of new particles (Higgs, SHE,…)



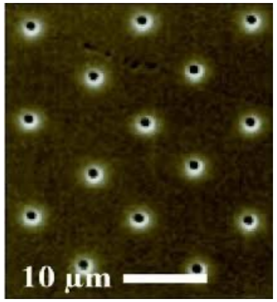
Exotic states of matter (quark-gluon plasma, neutron matter, …)

Synchrotron radiation (diffraction, spectroscopy, microscopy, lithography, metrology, …)



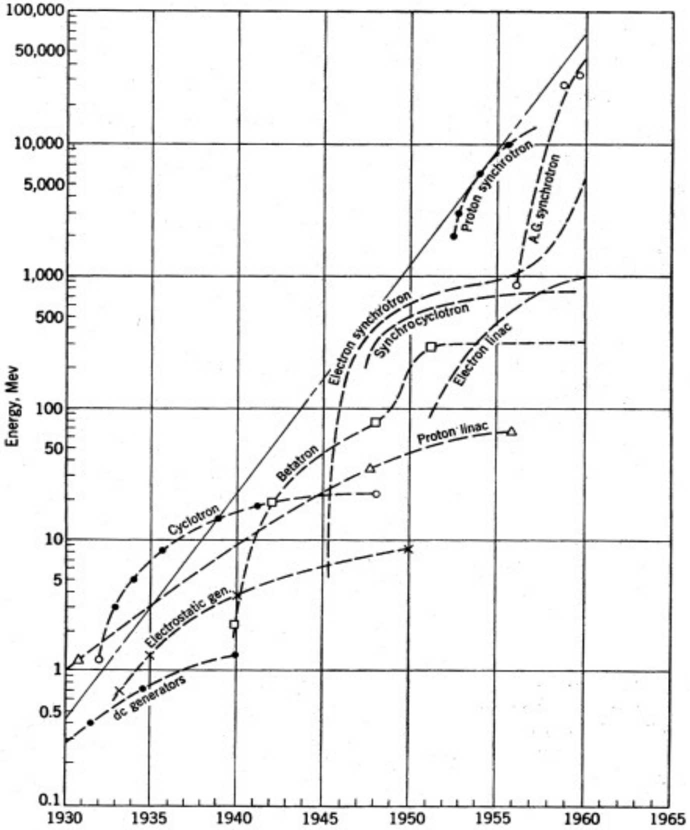
Radiation therapy (gammas, protons, heavy-ions…)

Production of isotopes for medicine ….

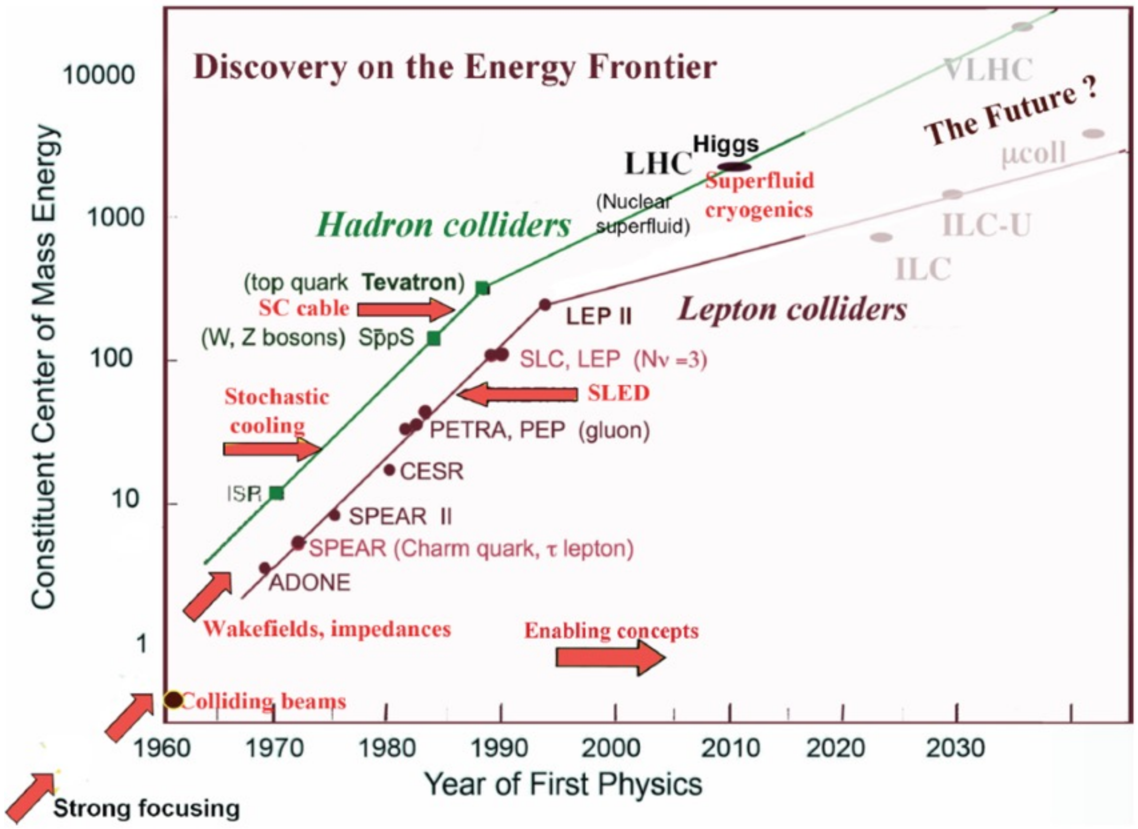


Space travel, radiation resistant materials, new materials, energy research …

Livingston Plot



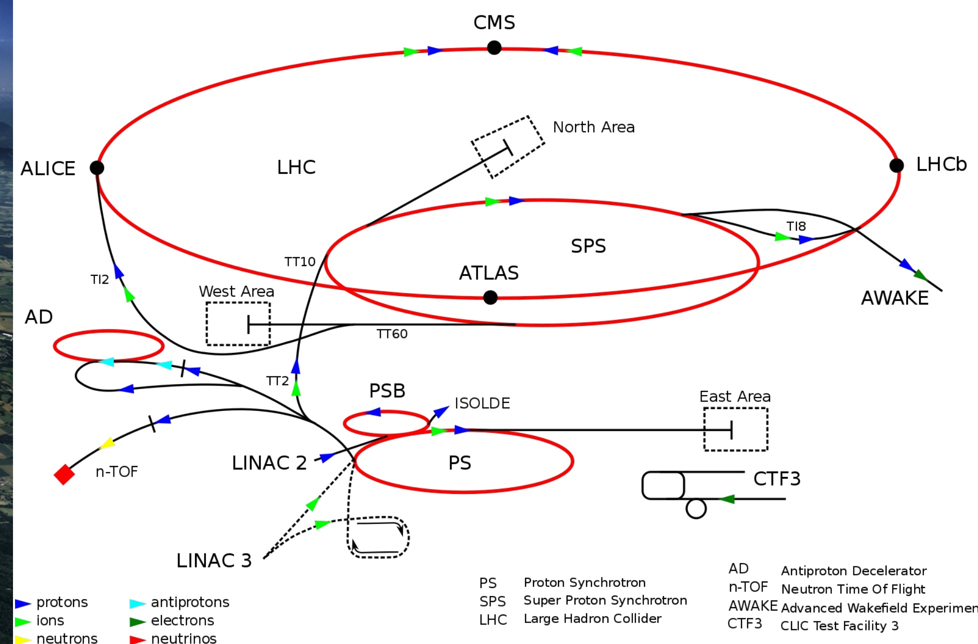
Up to 1960s



From 1960s

SNOWMASS 2013

The Large Hadron Collider at CERN



Started operation in 2009

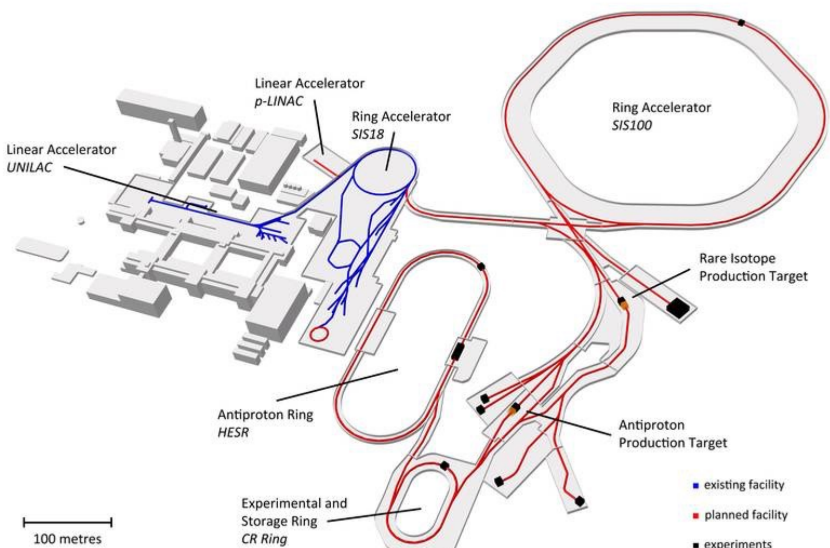
Circumference 26.7 km

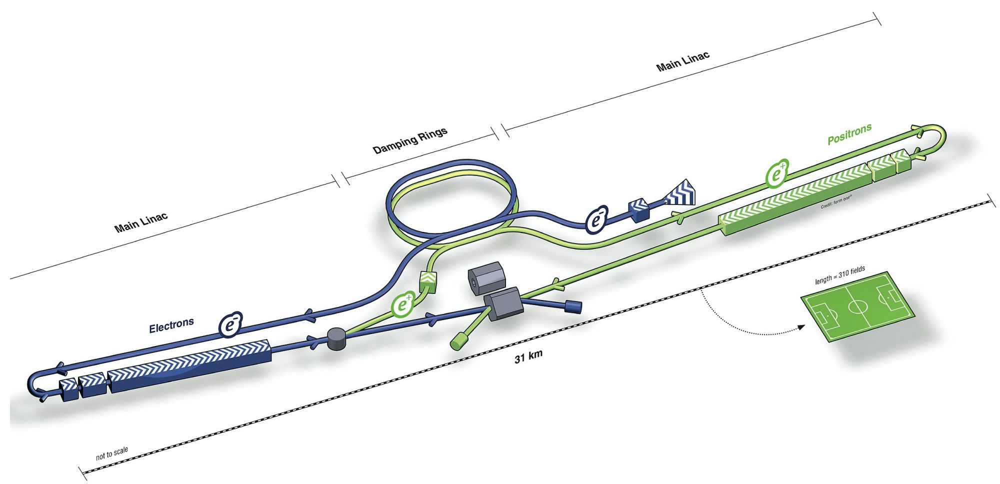
Proton-proton collisions at center-of-mass energy 14 TeV (13 TeV achieved)

Lead-lead collisiions. Energy of each beam is 2.76 TeV/A.
Center-of-mass energy is 1148 TeV.

Figures: CERN

Post-LHC Future Accelerators





Resolution

The wavelength of a probe should be comparable with the size of the object

$$\frac{\lambda}{2\pi} = \frac{\hbar c}{pc} = \frac{197.3}{pc} \quad [\mathrm{MeV\ fm}]$$

If you like to study the structure of a nucleon

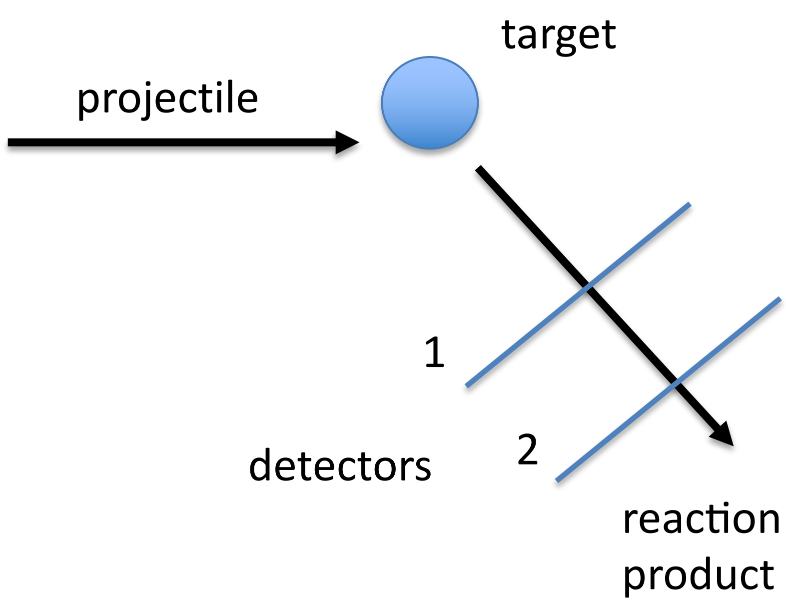
$$0.1\ \mathrm{fm} \ \rightarrow p \Rightarrow 10\ \frac{\mathrm{GeV}}{c} \Rightarrow E > 10\ \mathrm{GeV}$$

Quality of a Beam

Momentum spread $$\frac{\Delta p}{p}$$

Energy spread $$\frac{\Delta E}{E}$$

Geometrical size $$\Delta x,\ \Delta y$$



Important Parameters

Beam Intensity - number of particles per time unit

Luminosity

Target thickness	$\rho = 10^{10}$ particles/cm^2
Intensity	$I = 10^{10}$ particles/s
Luminosity	$L=\rho I=10^{20}\ cm^{-2}s^{-1}$

Particle type p …… U

Electrons, positrons, muons, neutrinos, pions, kaons …

Radionuclides

….. Chicken

Polarisation

$$P = \frac{(N_+ - N_-)}{(N_+ + N_-)}$$

Electrons, protons, ^3He

Secondary beams

Synchrotron radiation

Production of Radionuclides

WordPress.com

Acceleration of electrically charged particles in electromagnetic fields (1)

- **Lorentz force**

$$\underbrace{\vec{F} = q}_{\text{charge}}(\overbrace{\vec{E}}^{\text{electric field strength}} + \underbrace{\vec{v}}_{\text{velocity}} \times \overbrace{\vec{B}}^{\text{magnetic field strength}})$$

$$\vec{E} = \vec{E}(\vec{r}, t)$$
$$\vec{B} = \vec{B}(\vec{r}, t)$$

- **Time and position dependent fields**

$q = \pm 1e$ - **For most of elementary particles**

$q = \pm Ne$ - **For highly-charged ions**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acceleration of electrically charged particles in electromagnetic fields (2)

- **Acceleration (longitudinal)**

Only $E_{||}$ counts in the acceleration process

Change of momentum $$\Delta\vec{p} = \int_{t_1}^{t_2} \vec{F} dt = \vec{p}(t_2) - \vec{p}(t_1)$$

Change of energy $$\Delta E = \int_{r_1}^{r_2} q(E + v \times B) dr = \int_{r1}^{r_2} qE dr$$

(since $d\vec{r} \perp \vec{v} \times \vec{B}$ **)**

$E_{\perp}$ **acts (** $\vec{v} \times \vec{B}$ **as well) to change the direction**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acceleration of electrically charged particles in electromagnetic fields (3)

- **Useful relations**

$$q\vec{E}_{||} = \frac{d\vec{p}_{||}}{dt} = \underbrace{\frac{d\gamma}{dt}m\vec{v}}_{①} + \gamma m\frac{d\vec{v}_{||}}{dt} \;(=)$$

① $$\frac{d\gamma}{dt} = \frac{d}{dt}\left(\frac{1}{\sqrt{1-\beta^2}}\right) = \frac{\beta}{(1-\beta^2)^{3/2}}\frac{d\beta}{dt} = \gamma^3\beta\frac{d|\vec{v}|}{dt}\frac{1}{c}$$

$$(=)\; q\vec{E}_{||} = \gamma m\left(\frac{d\vec{v}_{||}}{dt} + \frac{\vec{v}_{||}}{c}\gamma^2\beta\frac{d|\vec{v}|}{dt}\right) = \gamma m\left(1 + \frac{v}{c}\gamma^2\beta\right)\frac{d\vec{v}_{||}}{dt}$$

If $v_{||} \approx v$ **then** $\vec{v}_{||}\frac{dv}{dt} \approx v\frac{d\vec{v}_{||}}{dt}$

Acceleration of electrically charged particles in electromagnetic fields (4)

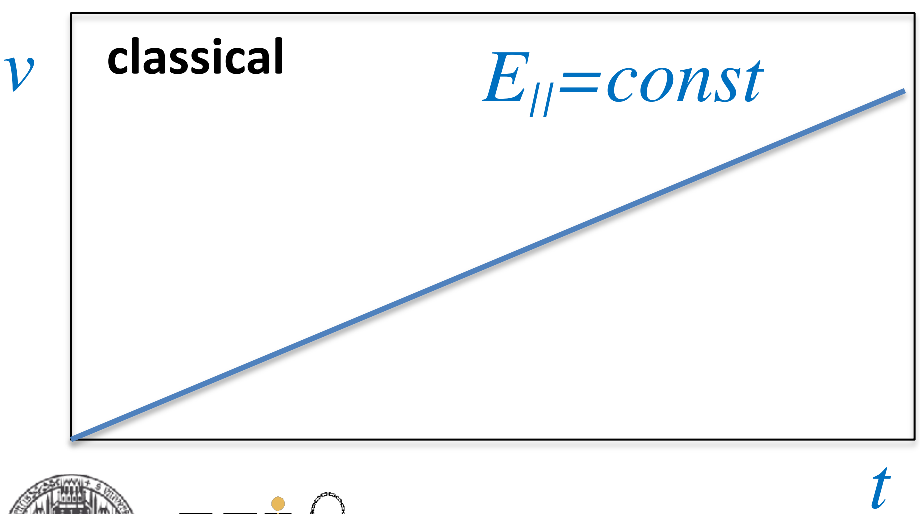
- continue

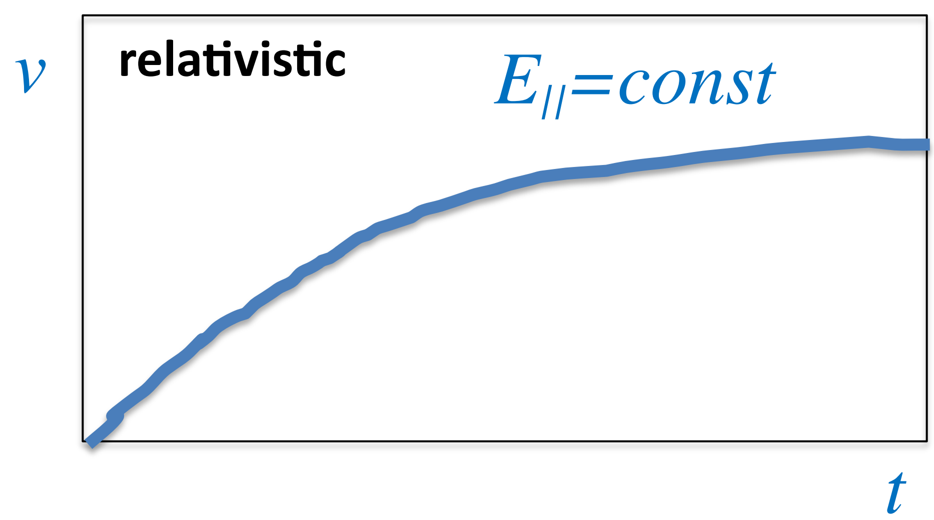
$$q\vec{E}_{||} = \gamma^3 m \frac{d\vec{v}_{||}}{dt}$$

$$\Downarrow$$

$$\frac{d\vec{v}_{||}}{dt} = \frac{q\vec{E}_{||}}{\gamma^3 m}$$

$$1 + \beta^2\gamma^2 = \gamma^2$$





HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acceleration of electrically charged particles in electromagnetic fields (5)

- **Orthogonal acceleration**

Centripedal acceleration

$$q(\vec{E_\perp} + \vec{v} \times \vec{B}) = \frac{d\vec{p_\perp}}{dt} = \gamma m \frac{d\vec{\gamma_\perp}}{dt}$$

$$\left| \frac{d\vec{v_\perp}}{dt} \right| = \frac{v^2}{\underbrace{\rho}_{\text{Bending radius}}}$$

Acceleration of electrically charged particles in electromagnetic fields (6)

- continue

$\Rightarrow$ **If electric field**

$$\gamma m \frac{v^2}{\rho} = q\vec{E}_\perp$$

$$pv = qE_\perp \rho$$

Electric rigidity

Electric rigidity

$$E_\perp \rho = \frac{pv}{q}$$

$$[1\ \frac{\mathrm{V}}{\mathrm{m}} \cdot 1\ \mathrm{m} = 1\ \mathrm{V}]$$

Acceleration of electrically charged particles in electromagnetic fields (7)

- continue

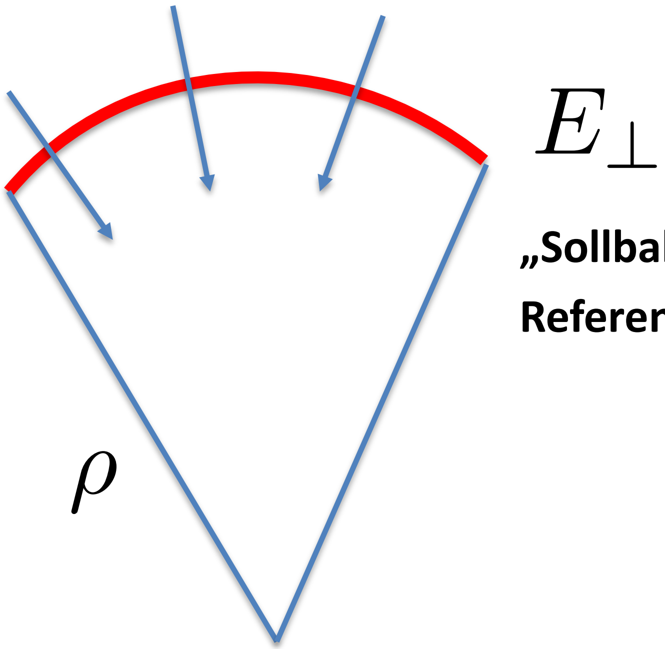
$\Rightarrow$ **If magnetic field** $\gamma m \frac{v^2}{\rho} = qvB_{\perp}$

Magnetic rigidity $\boxed{B\rho = \frac{p}{q}}$ $\boxed{[1\ \mathrm{T} \cdot 1\ \mathrm{m} = 1\ \mathrm{Tm}]}$

If *q=1* then [1 Tm e = 0.29979 GeV/c]

Acceleration of electrically charged particles in electromagnetic fields (8)

- **continue**



„Sollbahn“

Reference orbit