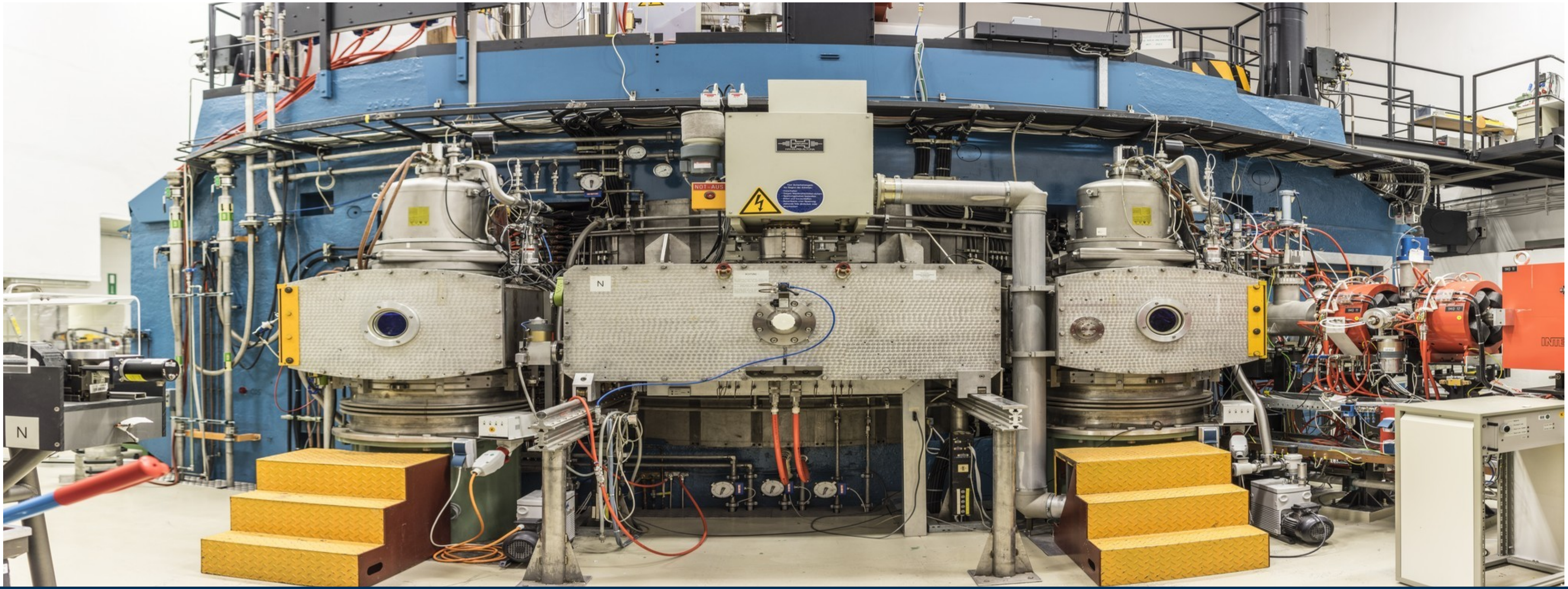


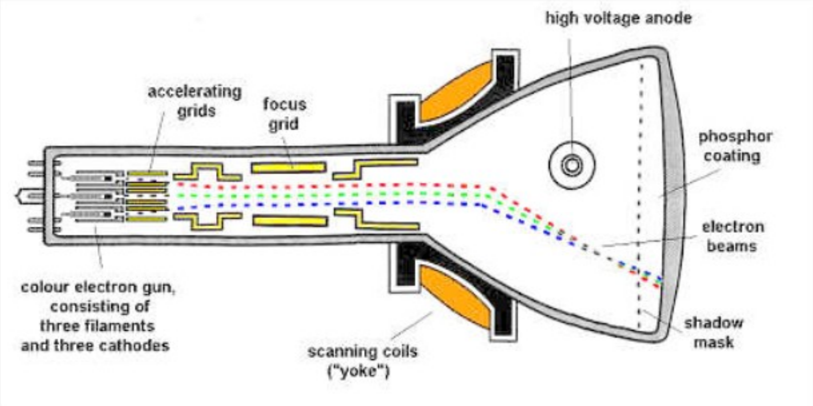
ACCELERATORS

Particle Physics 2020

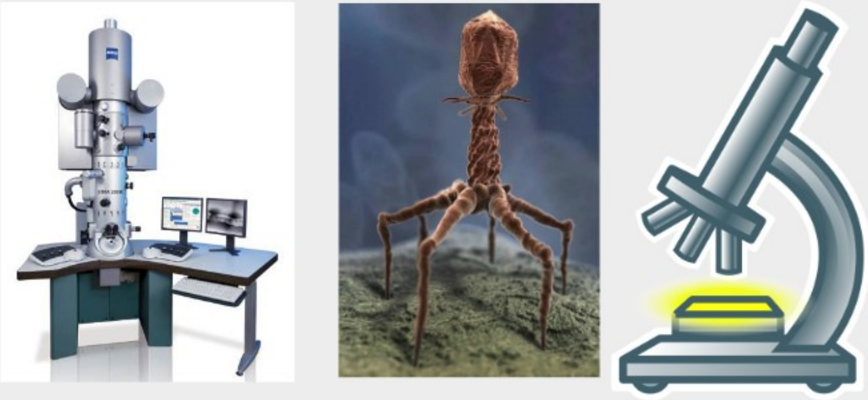
IRAKLI KESHELASHVILI – I.KESHELASHVILI@FZ-JUELICH.DE

Where do we use beams?

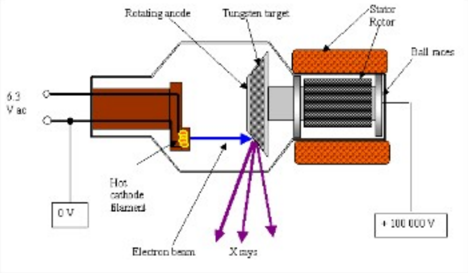
Television Tube



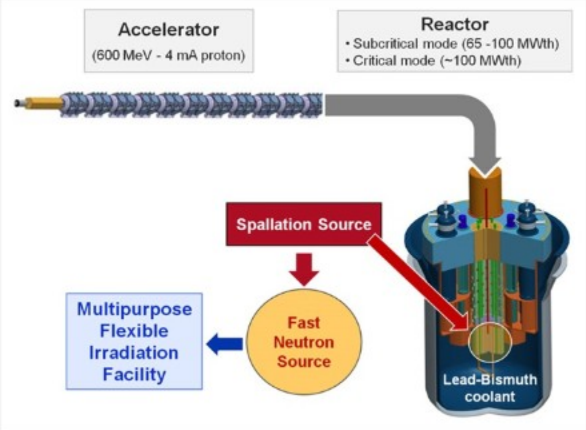
Exploring Micro-cosmos



Medical Applications



Energy Harvesting



Accelerator
(600 MeV - 4 mA proton)

Reactor
- Subcritical mode (65 -100 MWth)
- Critical mode (~100 MWth)

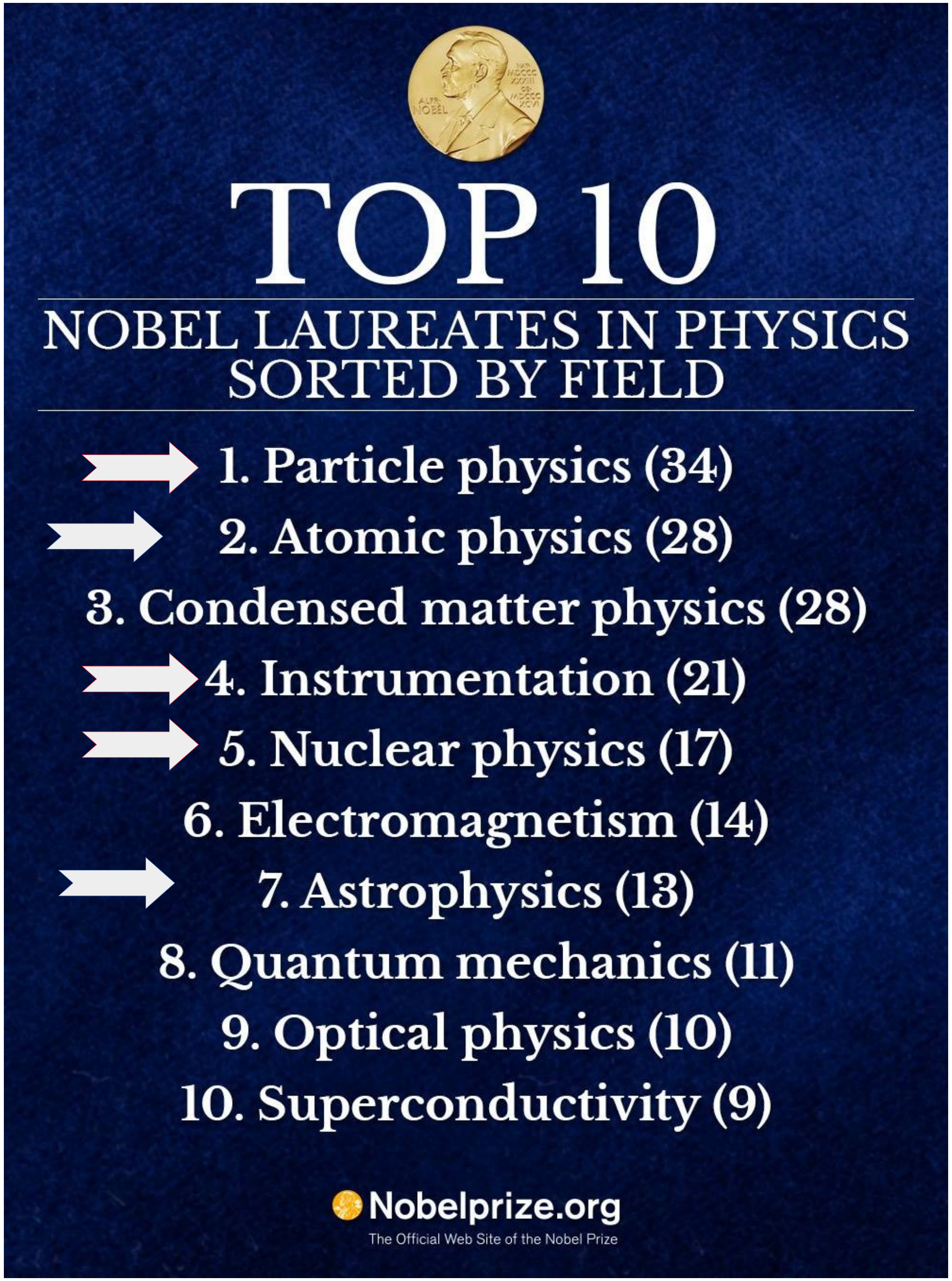
Spallation Source

Fast Neutron Source

Multipurpose Flexible Irradiation Facility

Lead-Bismuth coolant

Importance of scientific instruments



TOP 10

NOBEL LAUREATES IN PHYSICS
SORTED BY FIELD

1. Particle physics (34)
2. Atomic physics (28)
3. Condensed matter physics (28)
4. Instrumentation (21)
5. Nuclear physics (17)
6. Electromagnetism (14)
7. Astrophysics (13)
8. Quantum mechanics (11)
9. Optical physics (10)
10. Superconductivity (9)

Nobelprize.org
The Official Web Site of the Nobel Prize

Worldwide status of 2016

More than **400 B€** of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

> 24'000 particle accelerators have been built globally over the past 60Y.

> 11'000 particle accelerators that have been produced exausively for therapy with electrons, ions, photons.

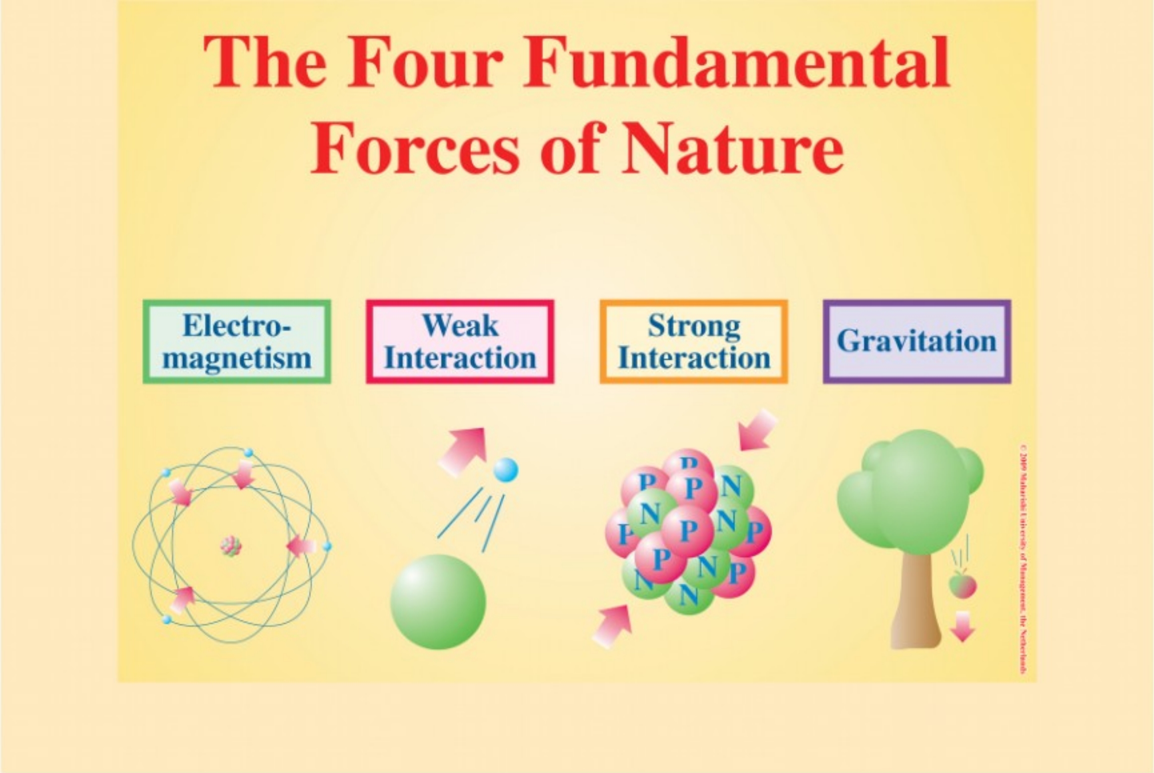
> 24 000 patients have been treated by hadron therapy in EU.

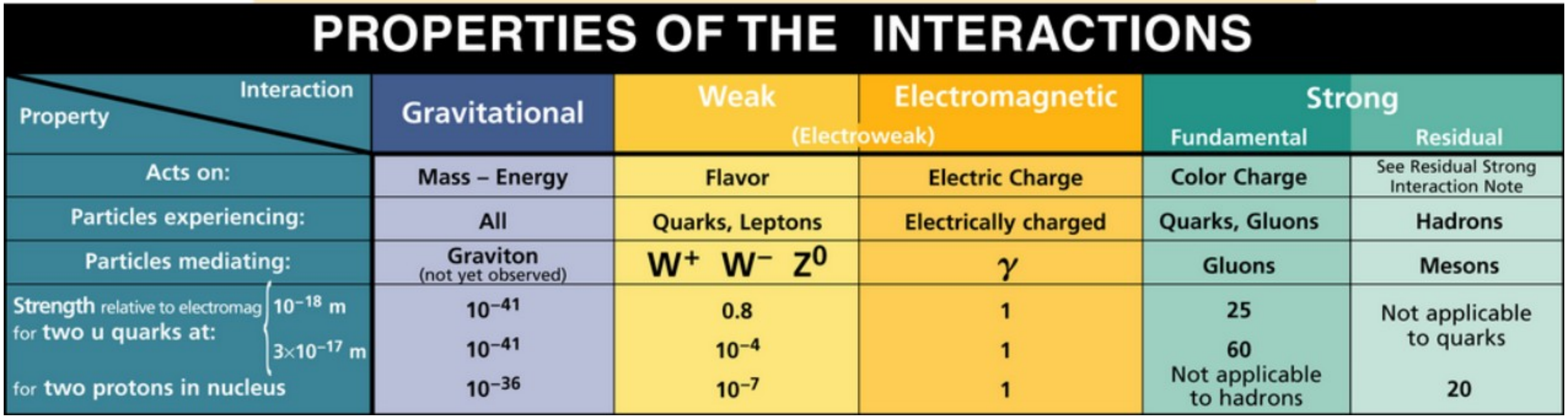
> 75 000 patients worldwide

Around 200 accelerators are used for research worldwide, with an estimated yearly consolidated costs of 1 B€

World's largest particle accelerator
LHC in circumference 27 km and buried 50-175 m.

Which fundamental forces can we use for acceleration?





PROPERTIES OF THE INTERACTIONS

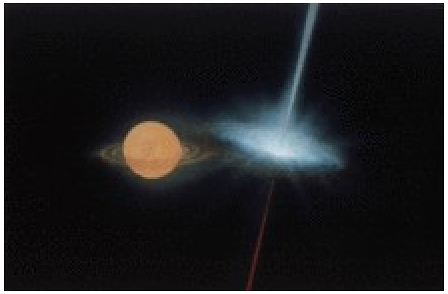
Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

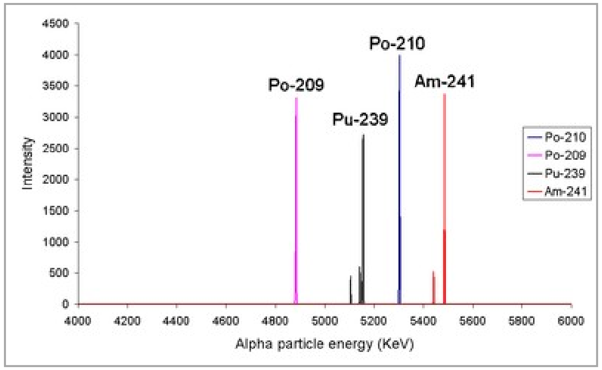
Natural accelerators

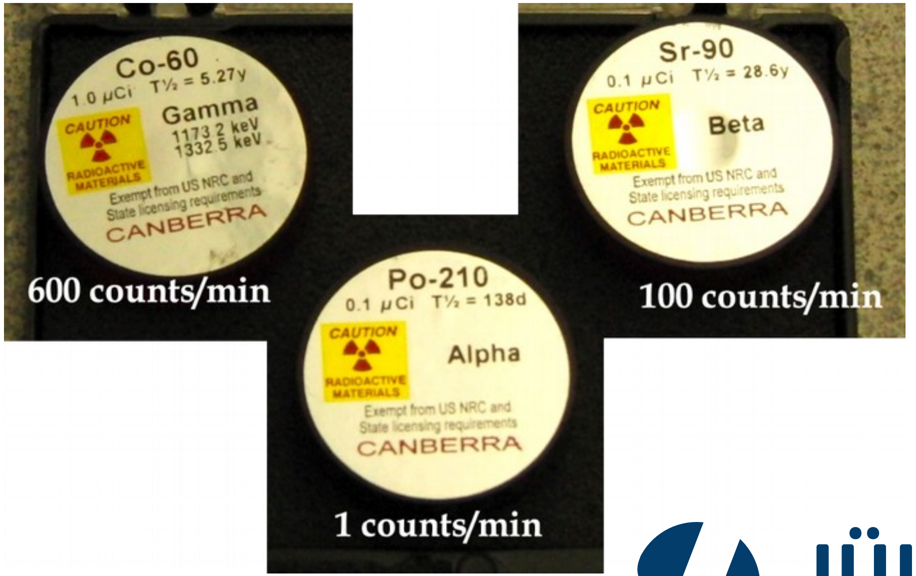
- radioactive decay are in the energy range from a few keV to **~8 MeV**,

corresponding to the typical **energy levels in nuclei** with **reasonably long lifetimes**.

- Very-high-energy gamma rays in the **PeV range** have been observed from sources such as the Cygnus X-3 microquasar.





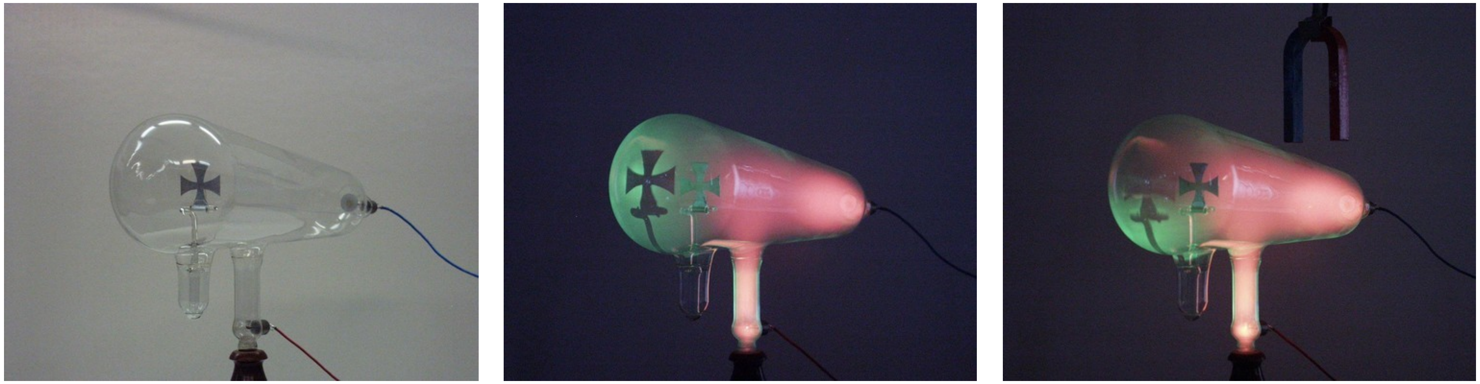


Crookes tube

https://en.wikipedia.org/wiki/Crookes_tube

- **Geissler tube** is an early gas discharge tube used to demonstrate the principles of electrical glow discharge. The tube was invented by the German *physicist and glassblower* **Heinrich Geissler** in 1857.

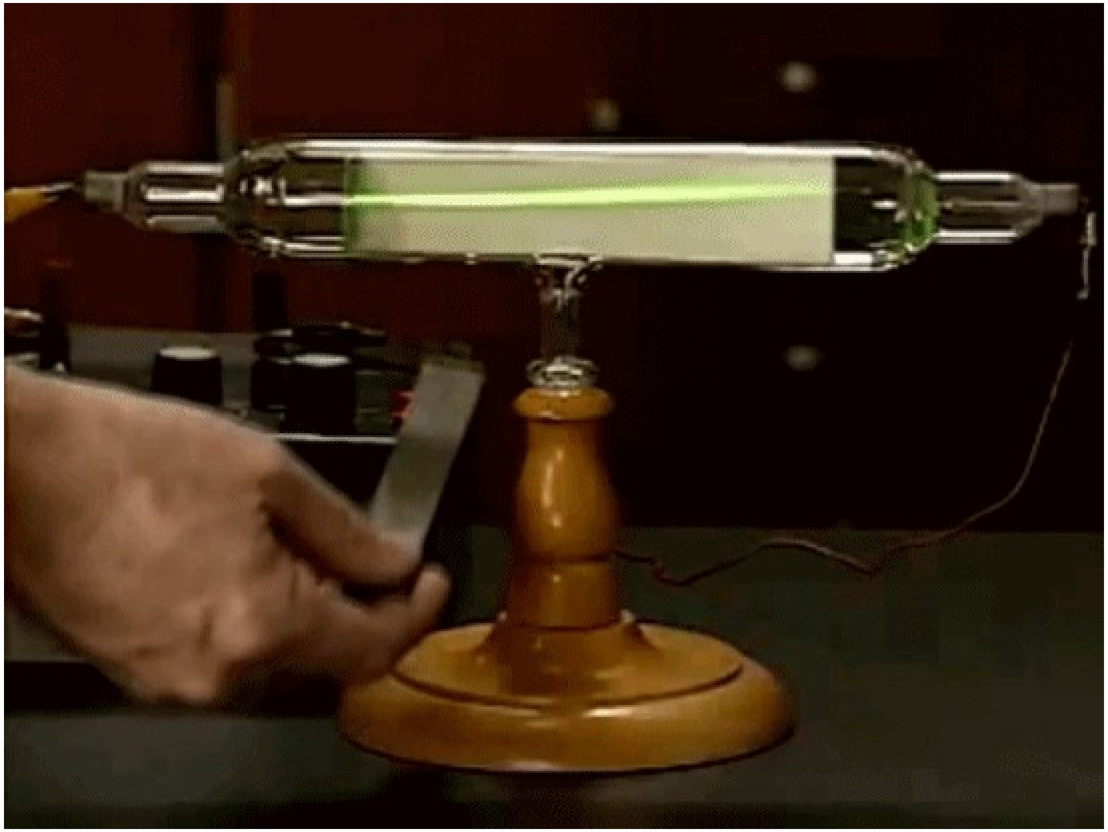
- **Sir William Crookes** was a British chemist and physicist worked on spectroscopy. He was a pioneer of vacuum tubes, inventing the ***Crookes tube*** in 1875. This was a foundational discovery that eventually changed ***chemistry and physics.***
  It was used by Crookes, Johann Hittorf, Julius Plücker, Eugen Goldstein, Heinrich Hertz, Philipp Lenard, Kristian Birkeland and others...
- … Culminating in **J.J. Thomson's 1897** identification of cathode rays as negatively charged particles, which were later named **electrons**.
- **Wilhelm Röntgen** discovered X-rays,Röntgen rays using Crookes tube in 1895, an achievement that earned him the **first** Nobel Prize in Physics in 1901



Crookes tube

Voltage

Vacuum



"electron" or other particle

Rutherford

https://en.wikipedia.org/wiki/Ernest_Rutherford

Ernest Rutherford
(1871-1937)

known as the father of nuclear physics

Nobel Prize in Chemistry he was awarded in 1908

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances",

for which he was the first Canadian and Oceanian laureate.

1927 — Anniversary Address of the President of the Royal Society

Expressed a long-standing "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" available from natural sources so as to

"open up an extraordinarily interesting field of investigation."

History

1900 to 1925 radioactive source experiments. Rutherford -> request for higher energy beams;

1928 to 1932 electrostatic acceleration ->

- Cockcroft & Walton -> voltage multiplication using diodes and oscillating voltage (700 kV);
- Van der Graaf -> voltage charging through mechanical belt (1.2 MV);

1928 resonant acceleration -> Ising establish the concept, Wideroe builds the first linac;

1929 cyclotron -> small prototype by Livingstone (PhD thesis), large scale by Lawrence;

1942 magnetic induction -> Kerst build the betatron;

1944 synchrotron -> MacMillan, Oliphant and Veksel invent the RF phase stability (longitudinal focusing);

1946 proton linac -> Alvarez build an RF structure with drift tubes (progressive wave in 27t mode);

1950 strong focusing -> Christofilos patent the alternate gradient concept (strong transverse focusing);

1951 tandem -> Alvarez upgrade the electrostatic acceleration concept and build a tandem;

1955 AGS -> Courant, Snider and Livingstone build the alternate gradient Cosmotron in Brookhaven;

1956 collider -> Kerst discuss the concept of colliding beams;

1961 eke- collider -> Touschek invent the concept of particle-antiparticle collider;

1967 electron cooling -> Budker proposes the e-cooling to increase the proton beam density;

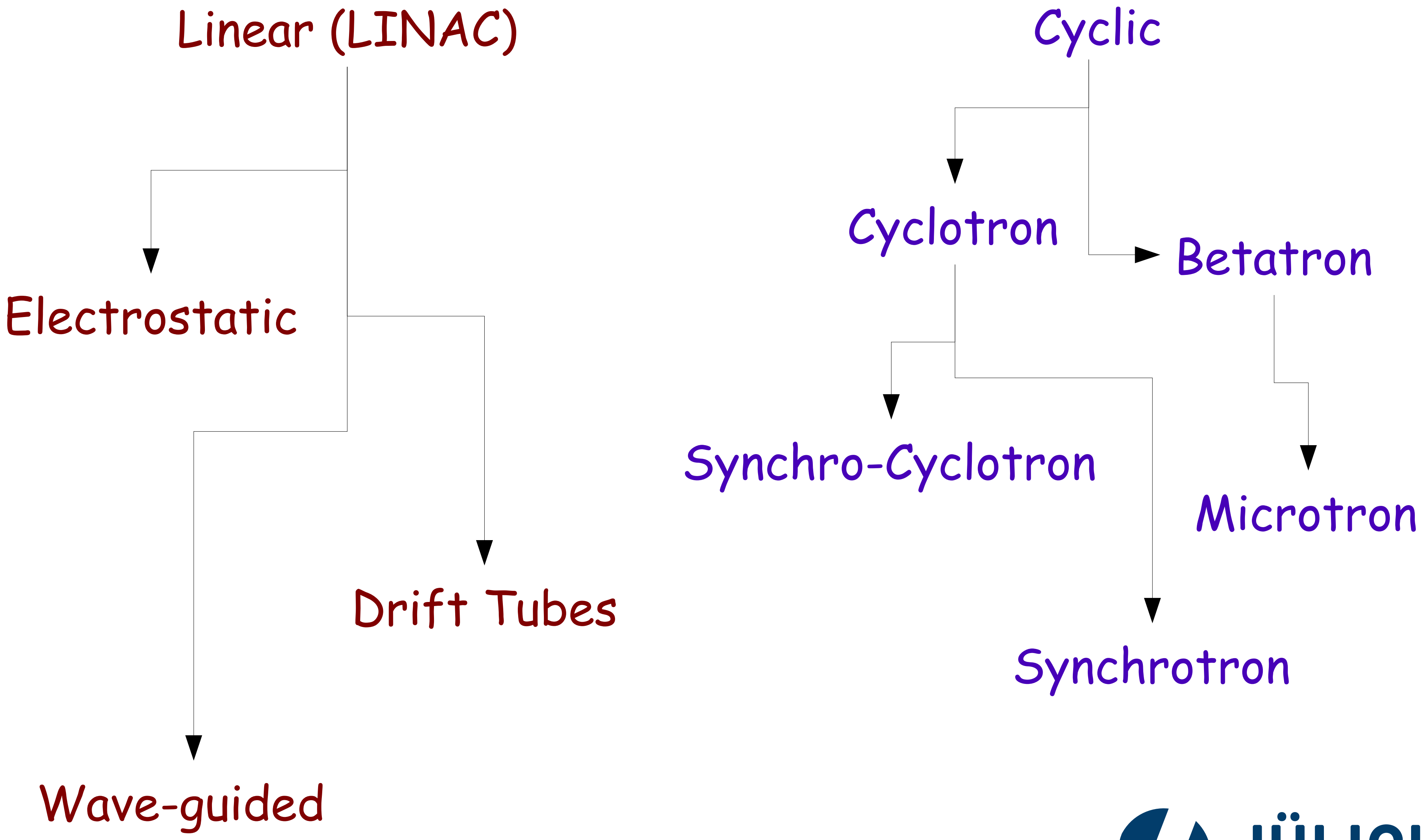
1968 stochastic cooling -> Van der Meer proposes the stochastic cooling to compress the phase space;

1970 RFQ -> Kapchinski & Telyakov build the radio-frequency quadrupole;

1980 to now superconducting magnets -> developed in various laboratories to increase the beam energy;

1980 to now superconducting RF -> developed in various lab to increase the RF gradient.

Classification or types



Types of accelerators:

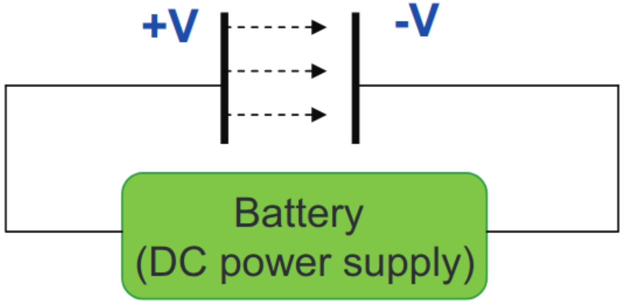
- The electrostatic fields - main disadvantage is that **very large electric fields need** to be generated to accelerate particles to experimentally useful energies.
- The Oscillating Field accelerator, This type of accelerator requires electric fields that periodically change with time.
- Maximum E field can be achieved is ~10 mega Volt !!!
- Maximum B field with iron ~1.6 Tesla and with superconducting magnets ~8 (25) T
- DC voltage acceleration:(DC electric field)
- Magnetic induction acceleration: (Faraday's Law of Induction)

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

- Resonance acceleration: (AC electric field)

$$\Delta V = V_0 \sin(\omega_{rf} t + \phi)$$

$$\Delta W = e\Delta V$$



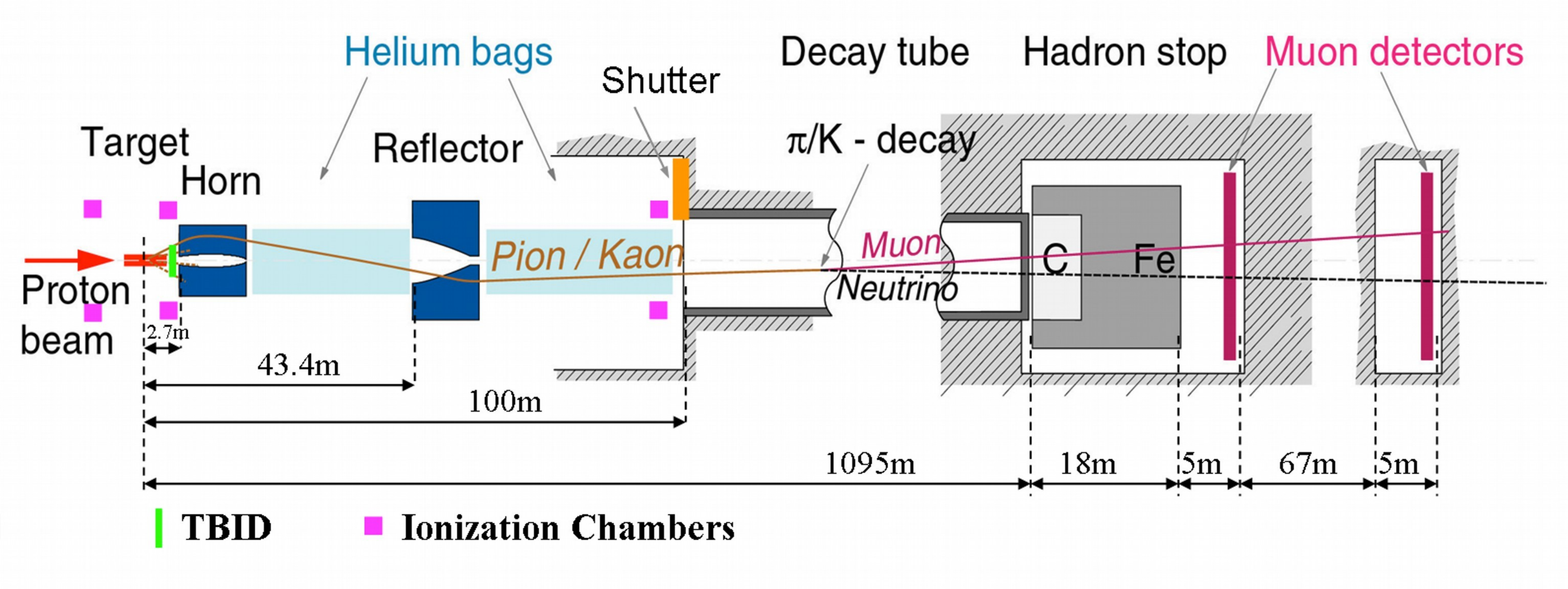
What kind of beams we can accelerate?

Primary beams:

e/e+, protons/antiprotons, heavy ions, (any **charged** particles)...

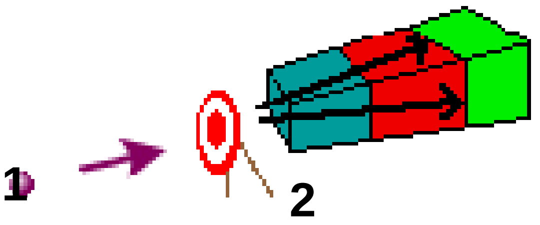
Secondary beams:

muons, π/K, photons, neutrons, neutrinos, ...



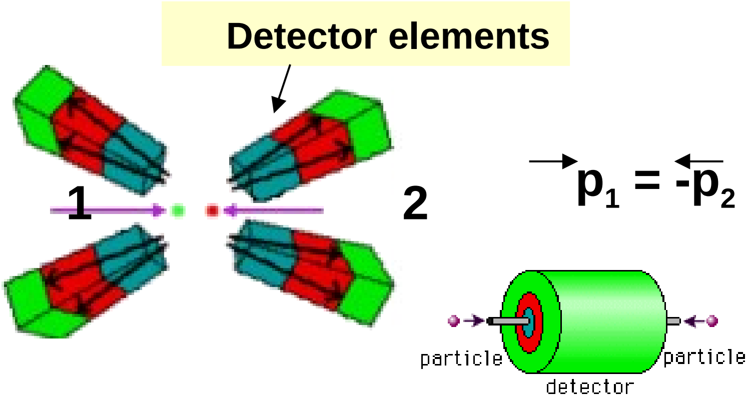
Fix target or collide

Fix target:
- Very hight luminosity (very thick targets)
- low CM energy



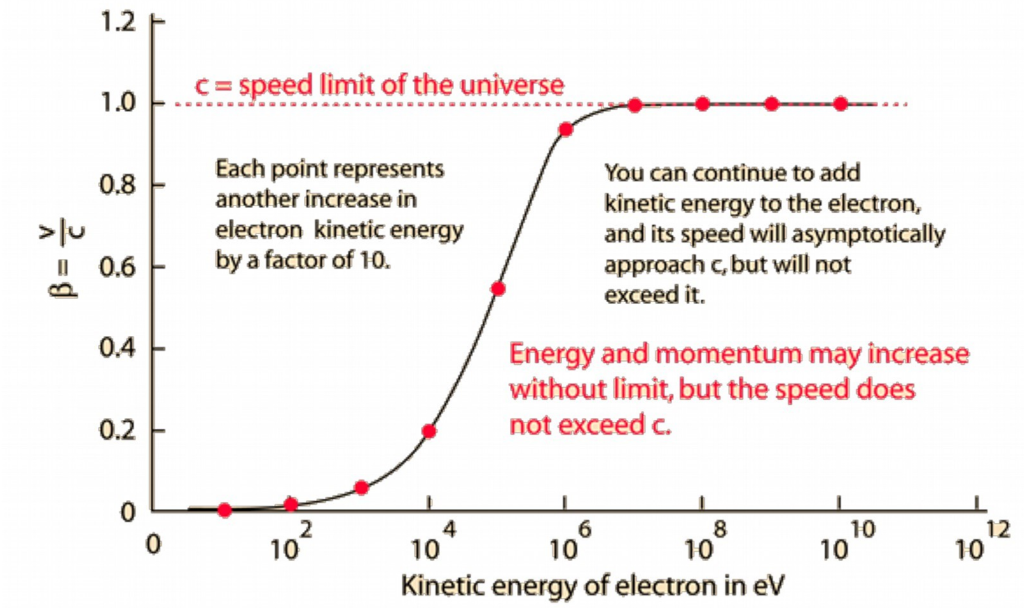
$\vec{p}_2 = 0$

Colliding beams:
- Very hight CM energy
- 4π detectors
- Moderate luminosity



$\vec{p}_1 = -\vec{p}_2$

Relativistic effects

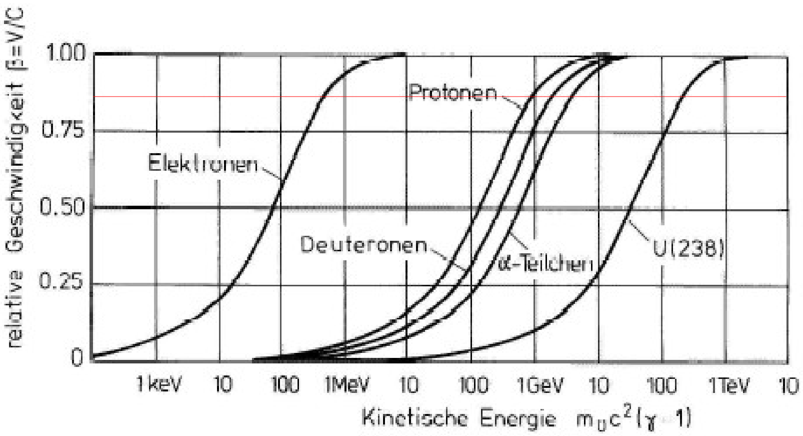


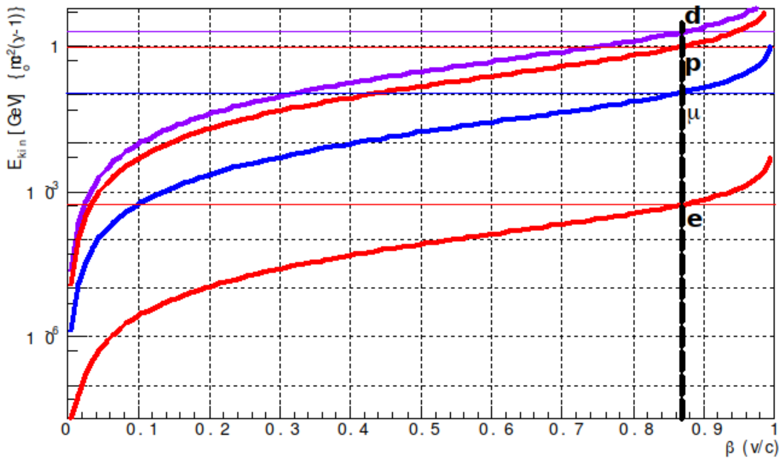
c = speed limit of the universe

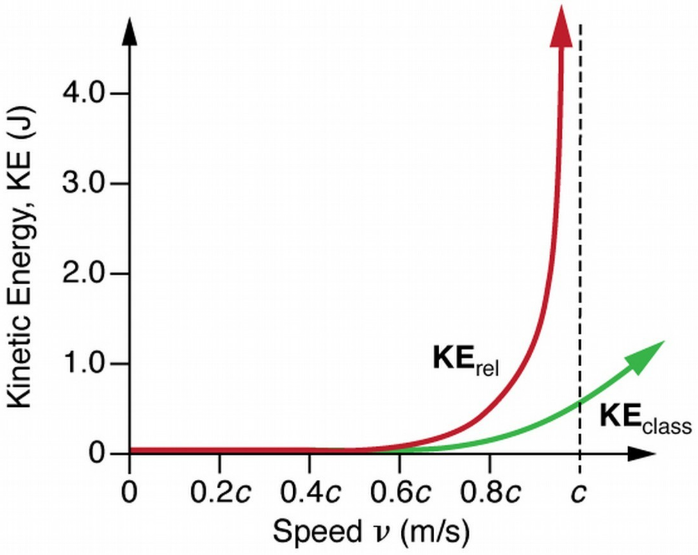
Each point represents another increase in electron kinetic energy by a factor of 10.

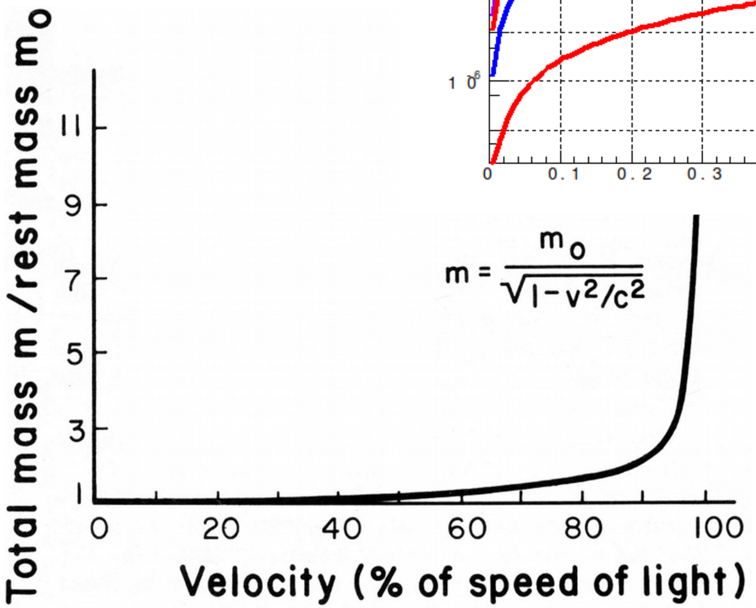
You can continue to add kinetic energy to the electron, and its speed will asymptotically approach c, but will not exceed it.

Energy and momentum may increase without limit, but the speed does not exceed c.







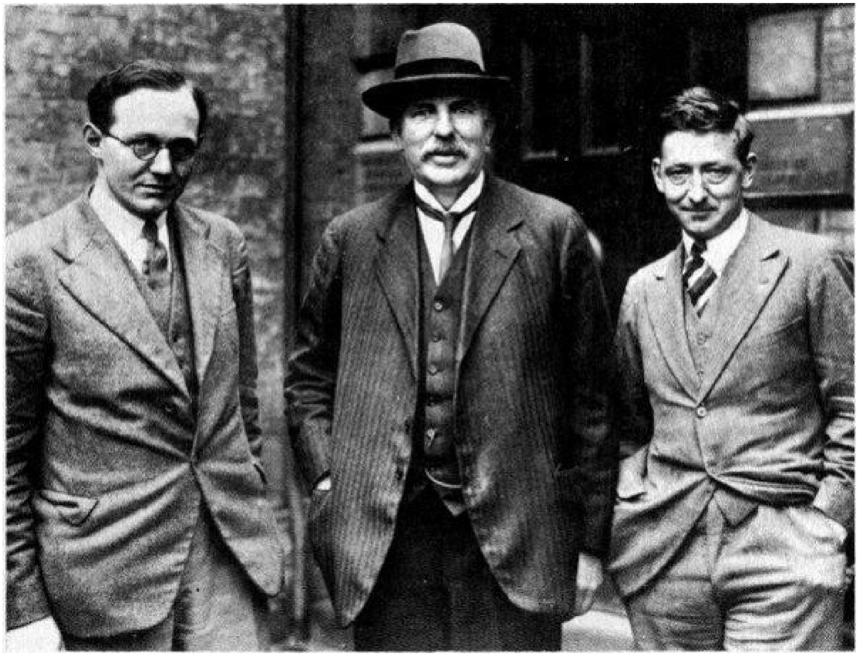


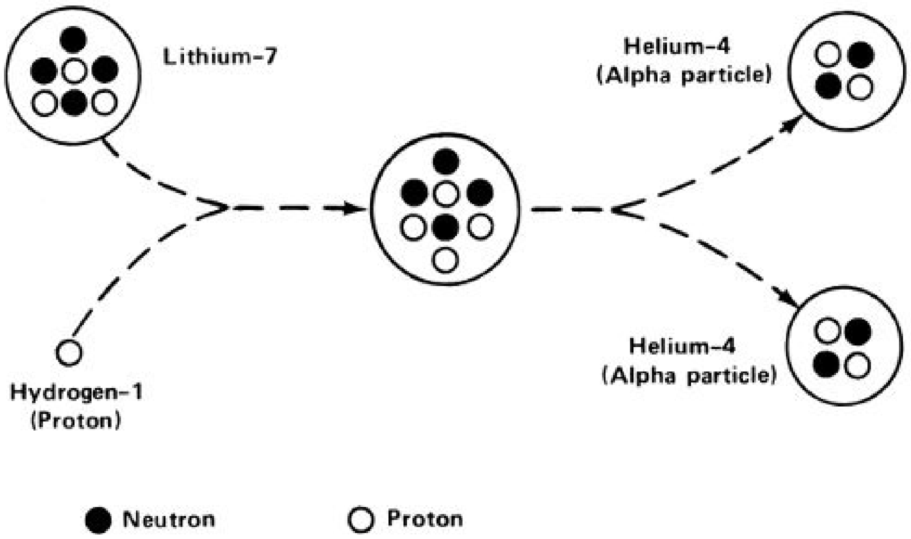
$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

Cockcroft Walton 1932 – Nobel 1951

Cockcroft-Walton electrostatic accelerator

- In 1932, **John Cockcroft and Ernest Walton** became the first scientists to split the atomic nucleus with artificially accelerated particles when they aimed a proton beam from a new type of accelerator at the nuclei of lithium atoms.
- Ernest Rutherford (centre) encouraged Ernest Walton (left) and John Cockcroft (right) to build a high-voltage accelerator to split the atom. Their success marked the beginning of a new field of subatomic research.

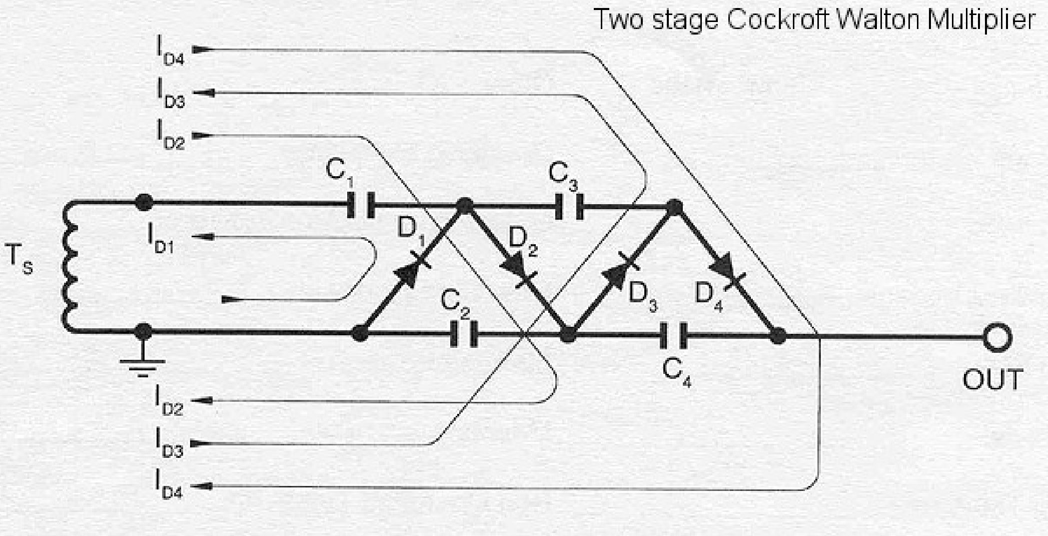




Greinacher multiplier

Less well known is the fact that the circuit was discovered much earlier, in 1919, by **Heinrich Greinacher**, a Swiss physicist. For this reason, this doubler cascade is sometimes also referred to as the *Greinacher multiplier.*

Usage: x-ray machines, television sets, photocopiers and Accelerators...

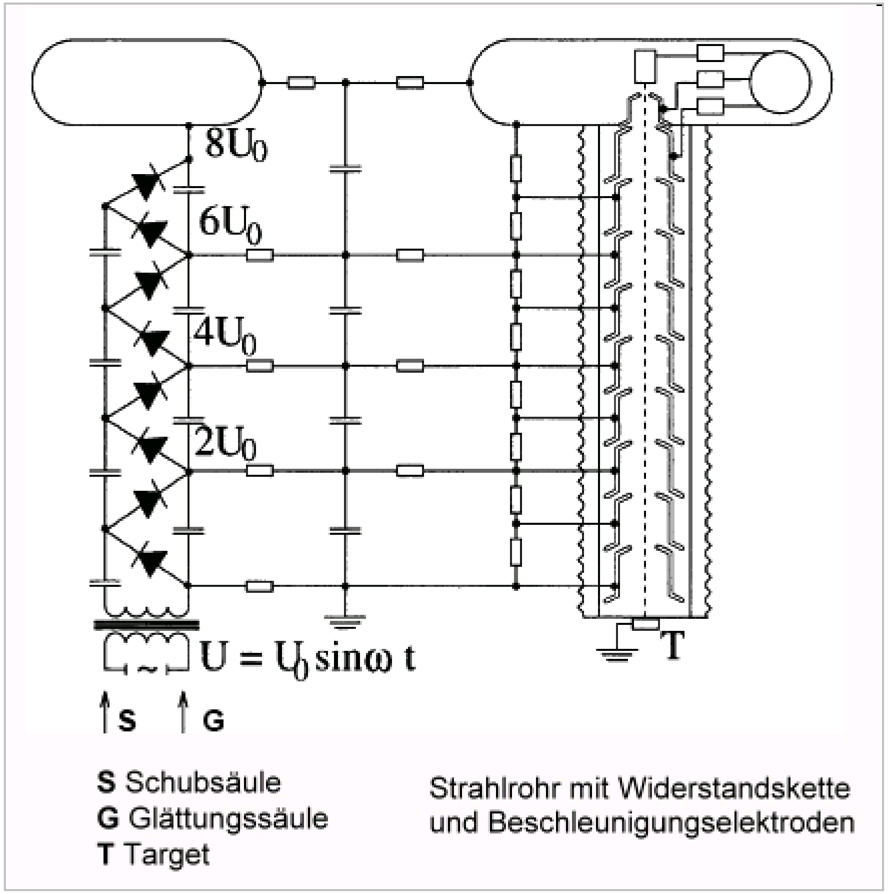


$$V_{out} = 2 \times V_{in}(\text{as RMS}) \times 1.414 \times (\#\text{ of stages})$$

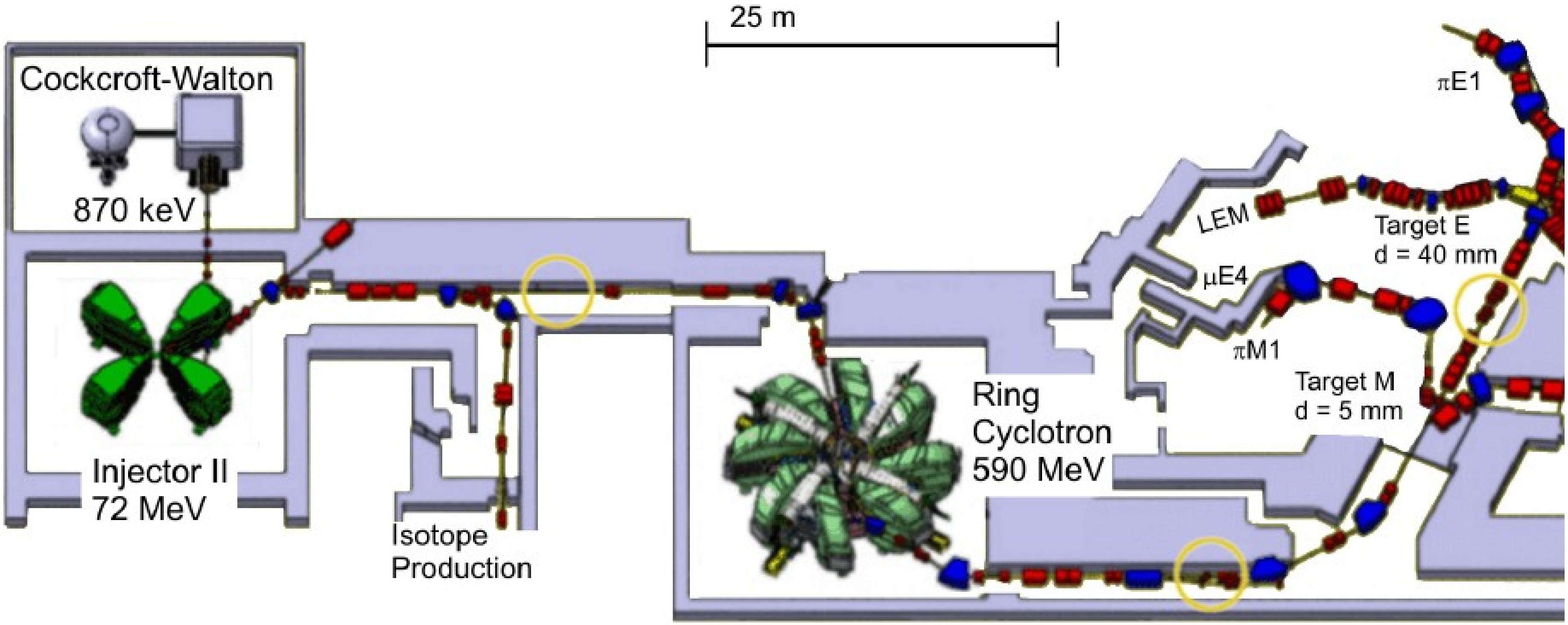
Realization

Physicists still use Cockcroft-Walton accelerators to deliver strong, steady streams of low-energy protons @ PSI (Switzerland).

The machines can turn alternating currents into electrostatic fields corresponding to more than one million volts resulting MeV range beams.



PSI


25 m
Cockcroft-Walton
870 keV
Injector II
72 MeV
Isotope
Production
Ring
Cyclotron
590 MeV
πE1
LEM
Target E
d = 40 mm
μE4
πM1
Target M
d = 5 mm

Van de Graaff

Van de Graaff electrostatic accelerators

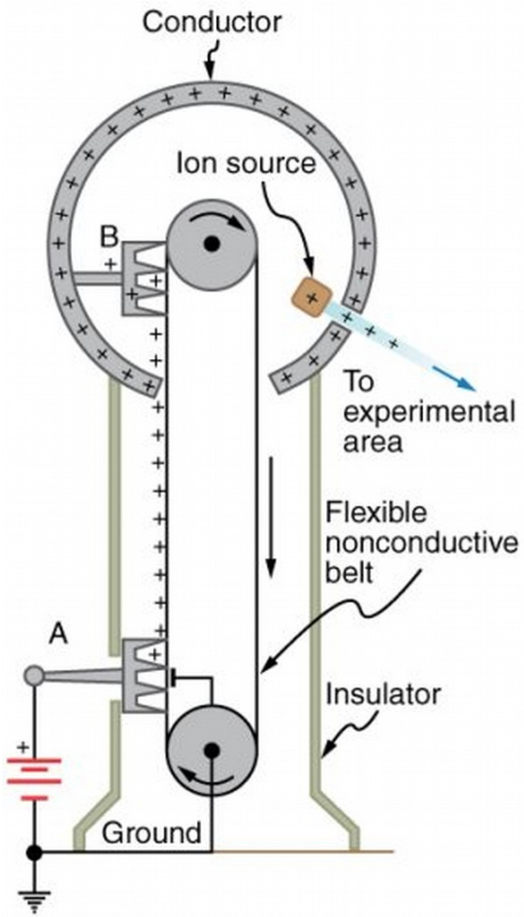
Scientists used this type of accelerator for several decades in physics and biomedical research.

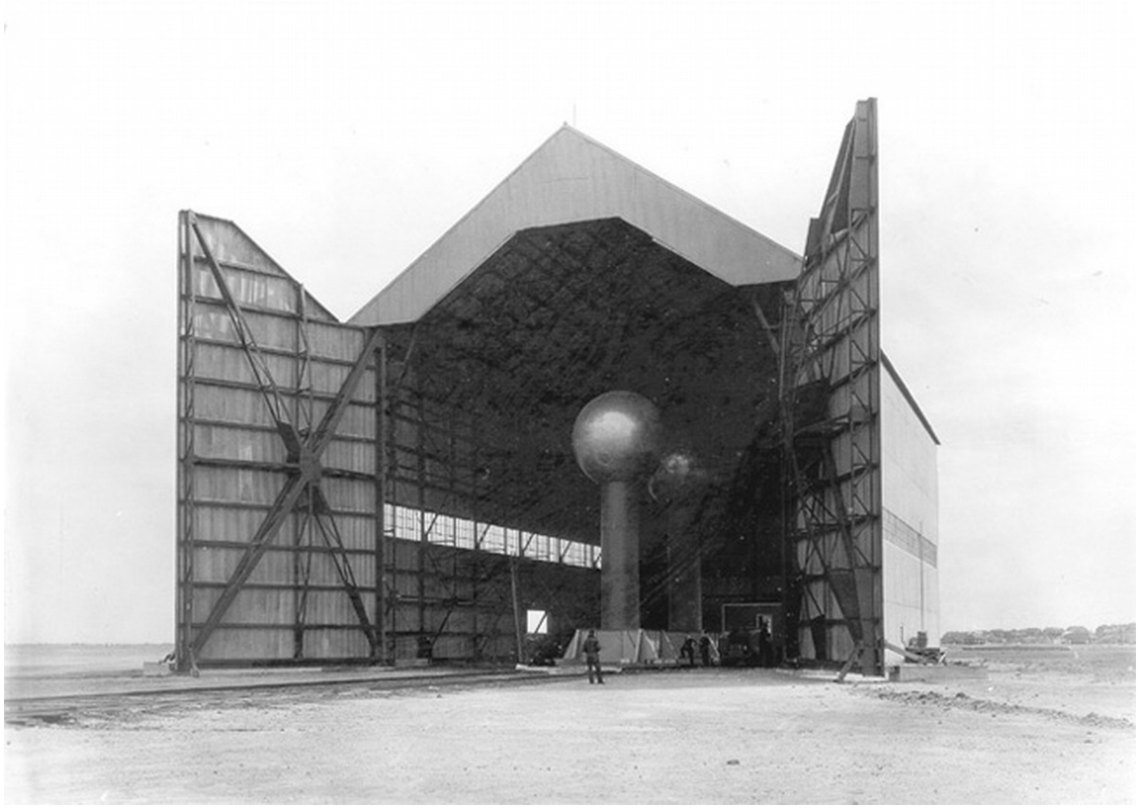
Commercial companies now build modern versions of this machine.

Invented at Princeton University in the 1930s, the accelerator generates a high voltage by charging a large sphere through a moving nonconductive belt.

In the early 1950s, the Massachusetts Institute of Technology (MIT) donated its Van de Graaff machine to the Museum of Science in Boston, where visitors can still see it in action.

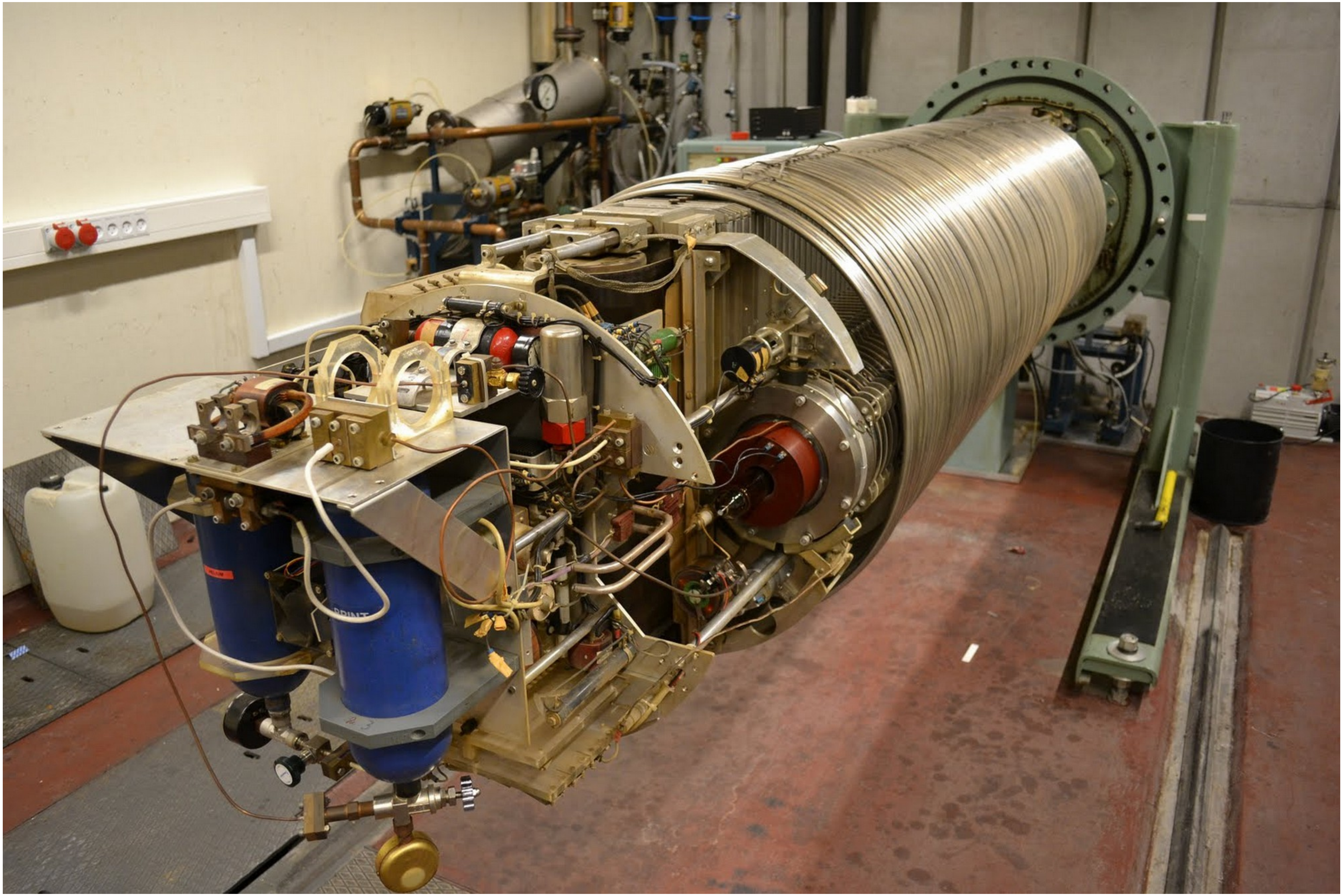
History





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

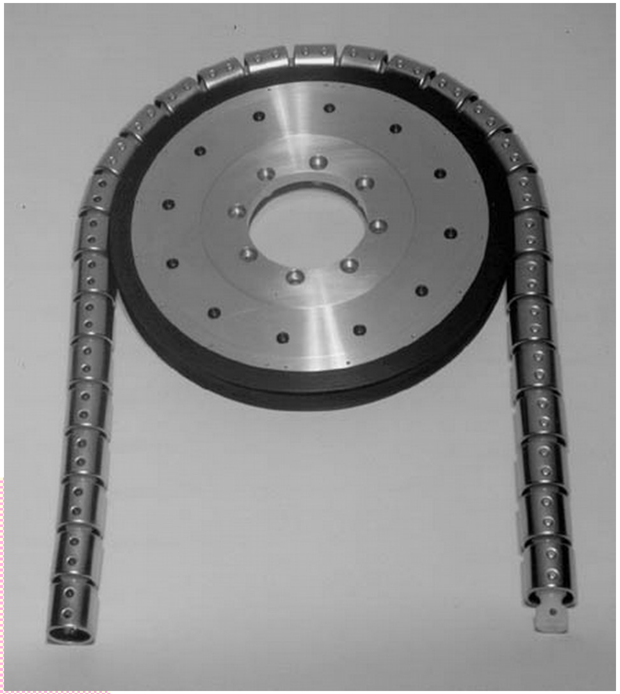
Van de Graaff accelerator

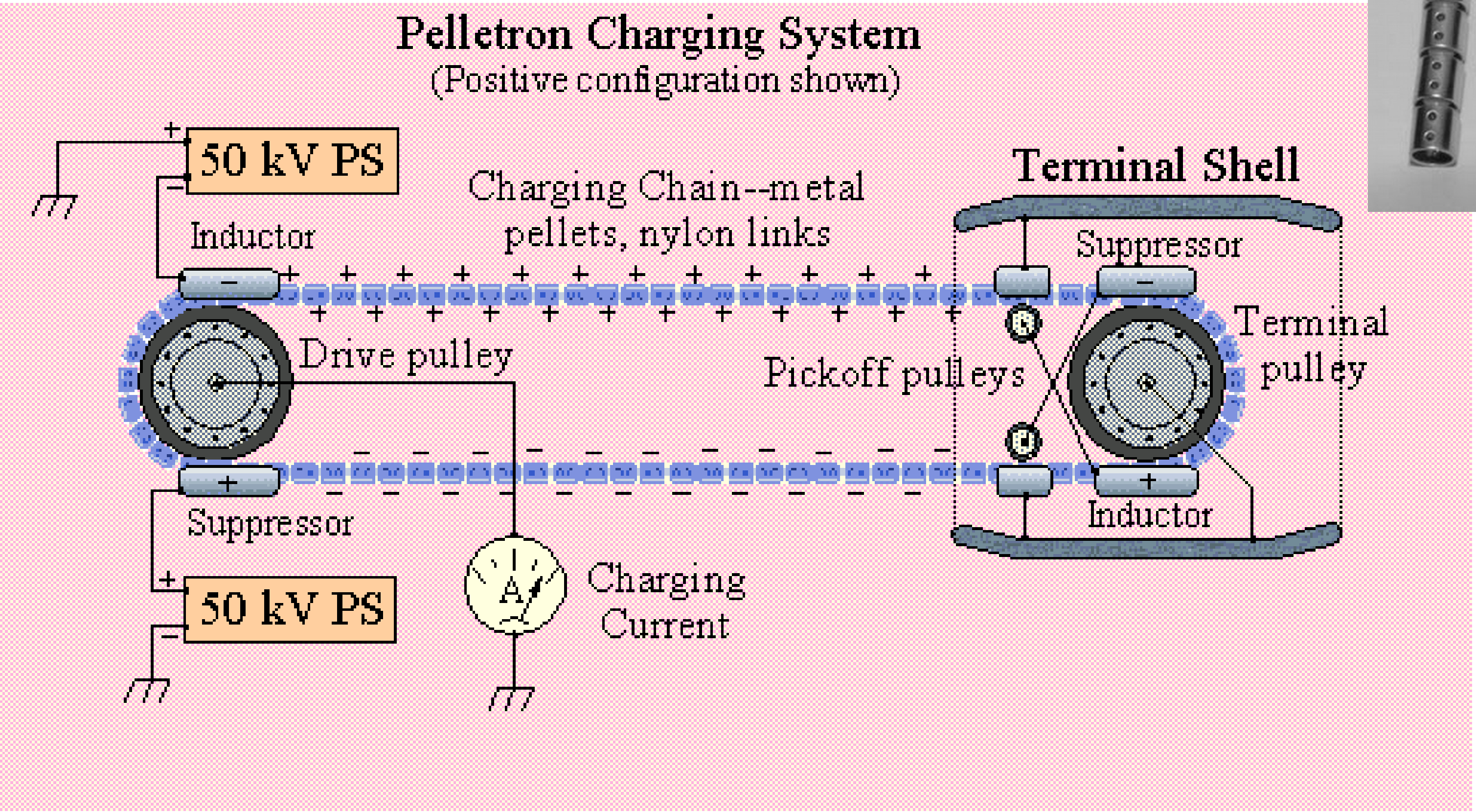


Pelletron

https://en.wikipedia.org/wiki/Pelletron

- Higher stability
- Higher Energy
- Reliability
- Less maintenance required

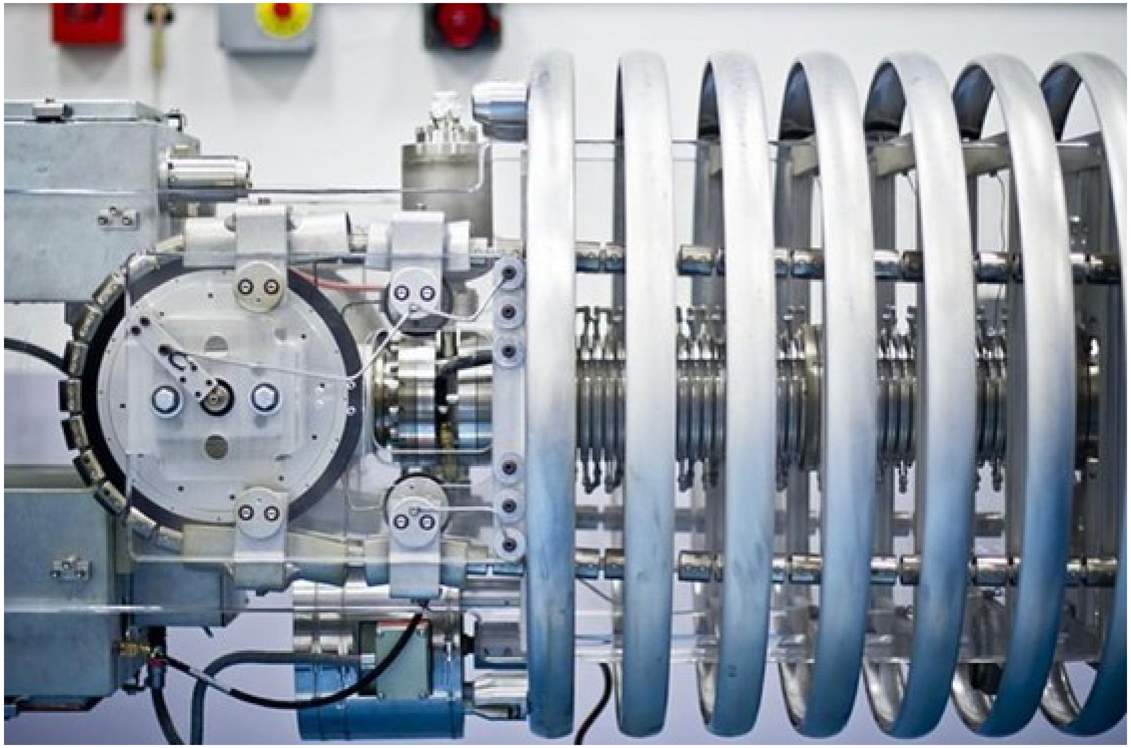


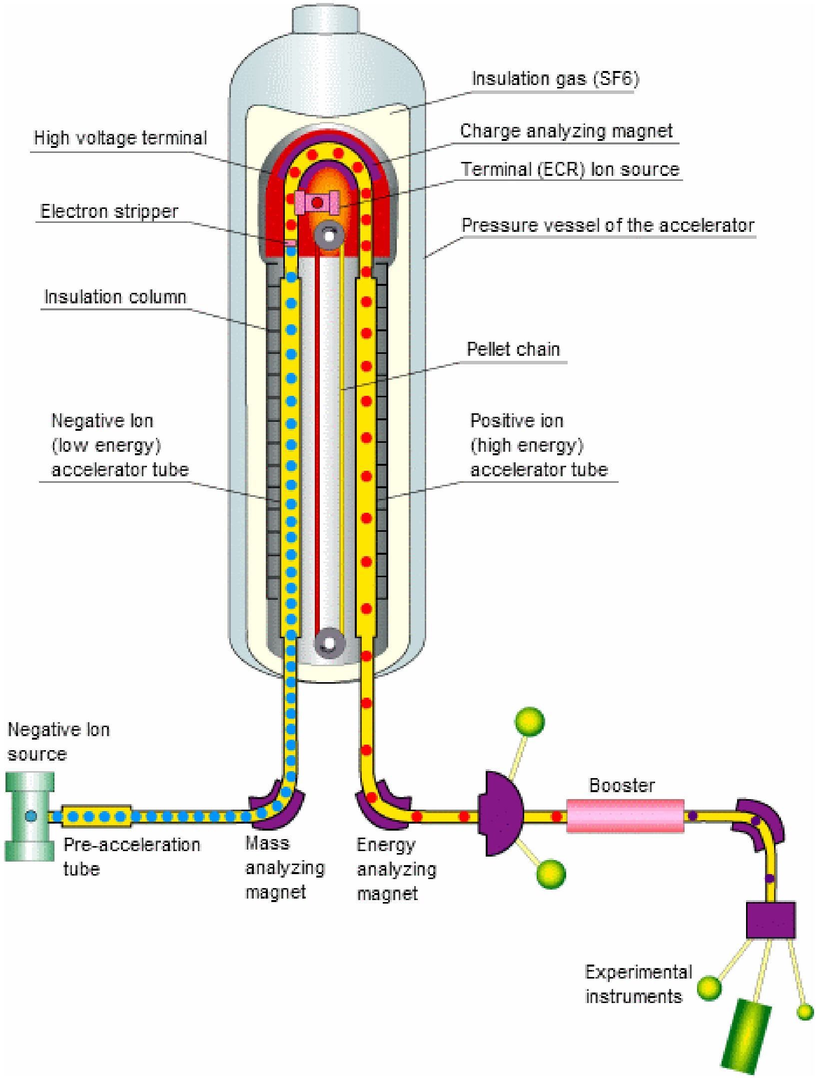


Tandem accelerator

https://en.wikipedia.org/wiki/Electrostatic_nuclear_accelerator#Tandem_accelerators

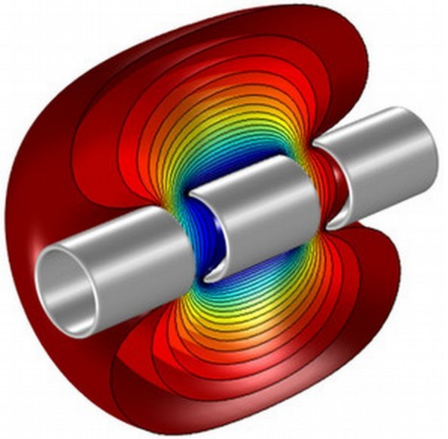
- Doubling the Energy of particles
- Only the (negative) ions can be accelerated



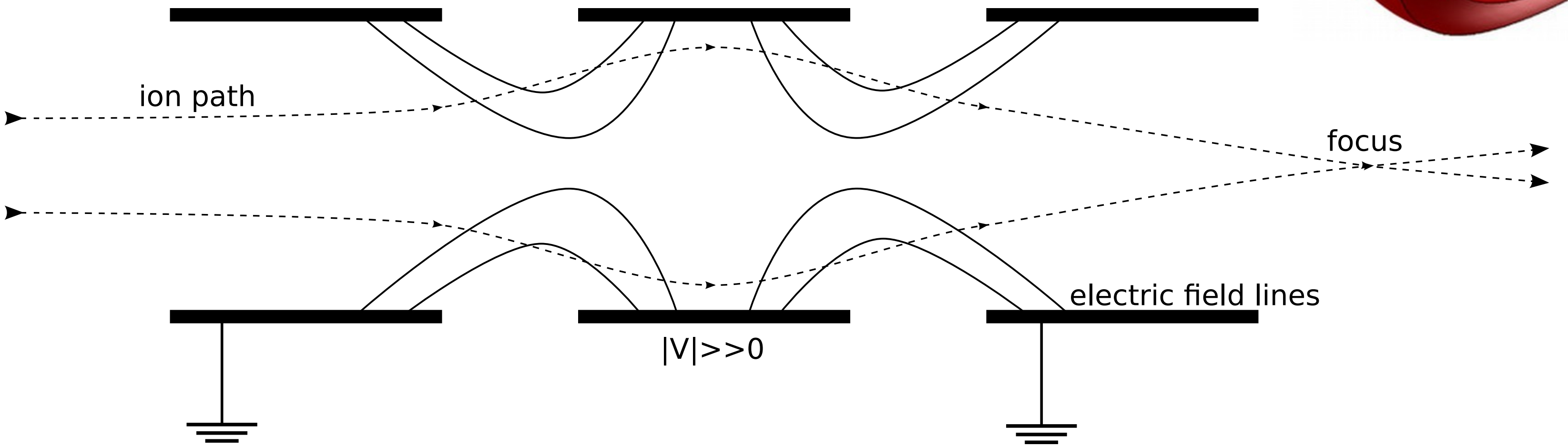


Einzel lens

https://en.wikipedia.org/wiki/Einzel_lens



This slide shows the focusing effect of
a lens arrangement known as an
electrostatic Einzel lens.



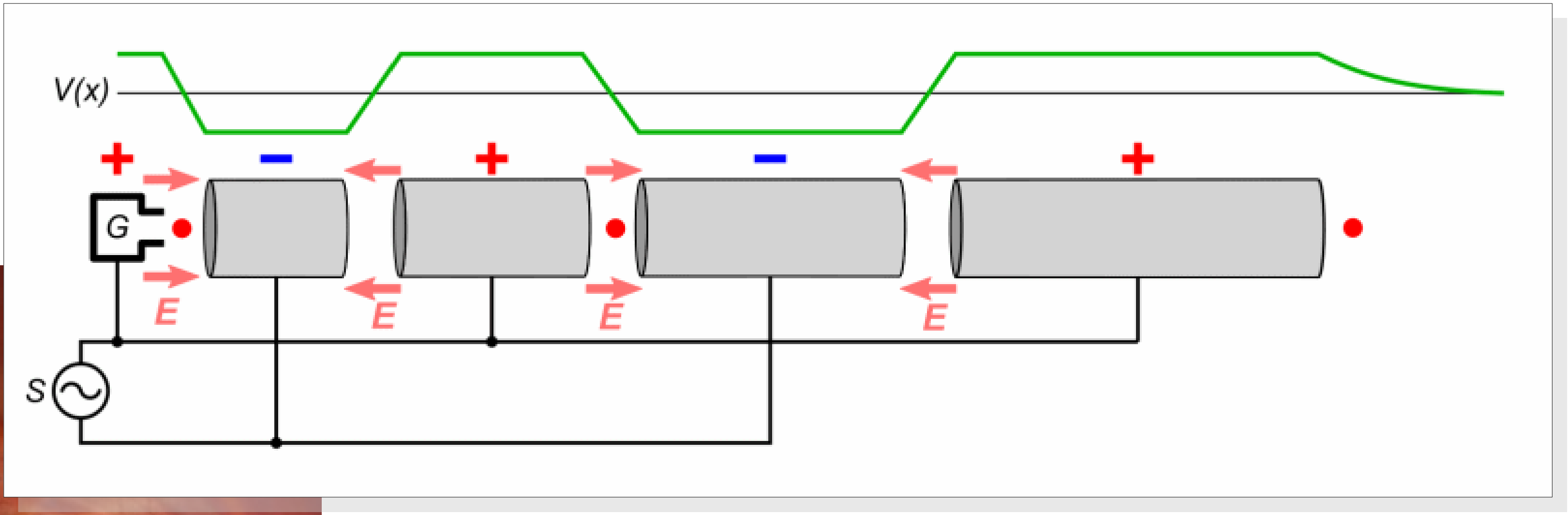
The forces on the charged particle as it enters the gap between the electrodes results in a net focusing, because one gap also decelerates the particle while the other gap accelerates the particle.

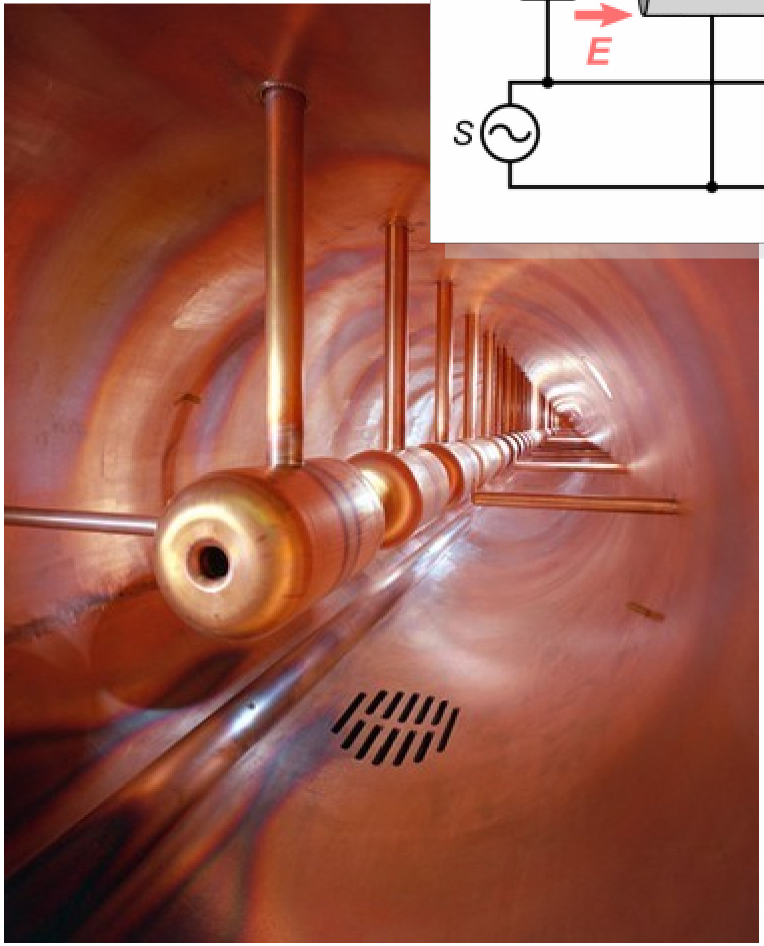
This difference in the amount of time spent traversing the gap is responsible for the net focusing.

Wideröe drift tube accelerator

https://en.wikipedia.org/wiki/Linear_particle_accelerator

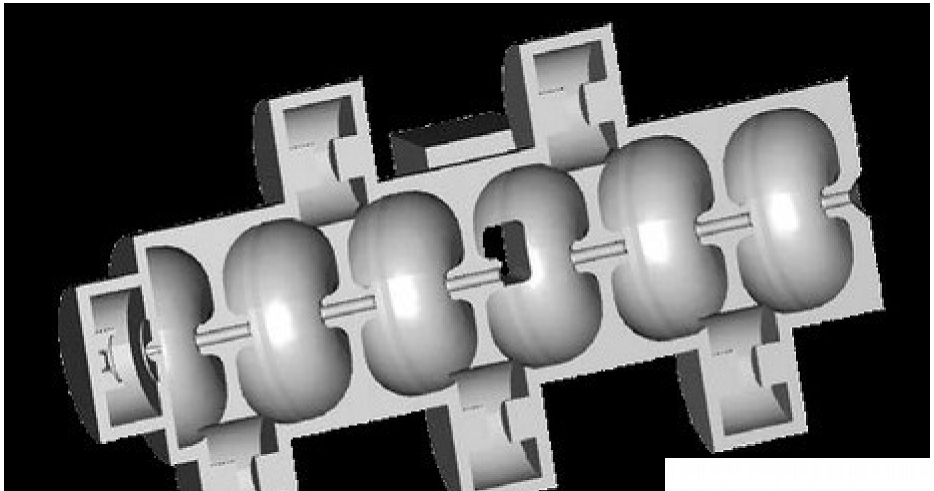
Rolf Widerøe





- Alternating RF field
  - Field between electrodes accelerate
- Large losses due to RF radiation
- Used for low velocity particles

Waveguide cavities



$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

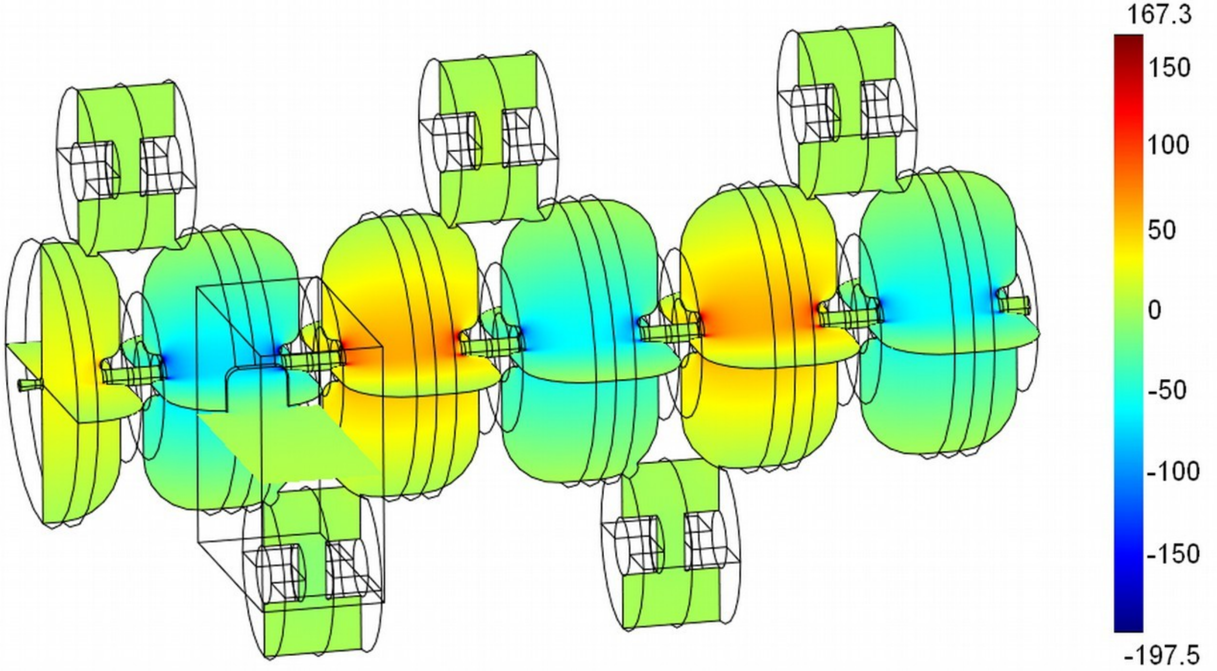
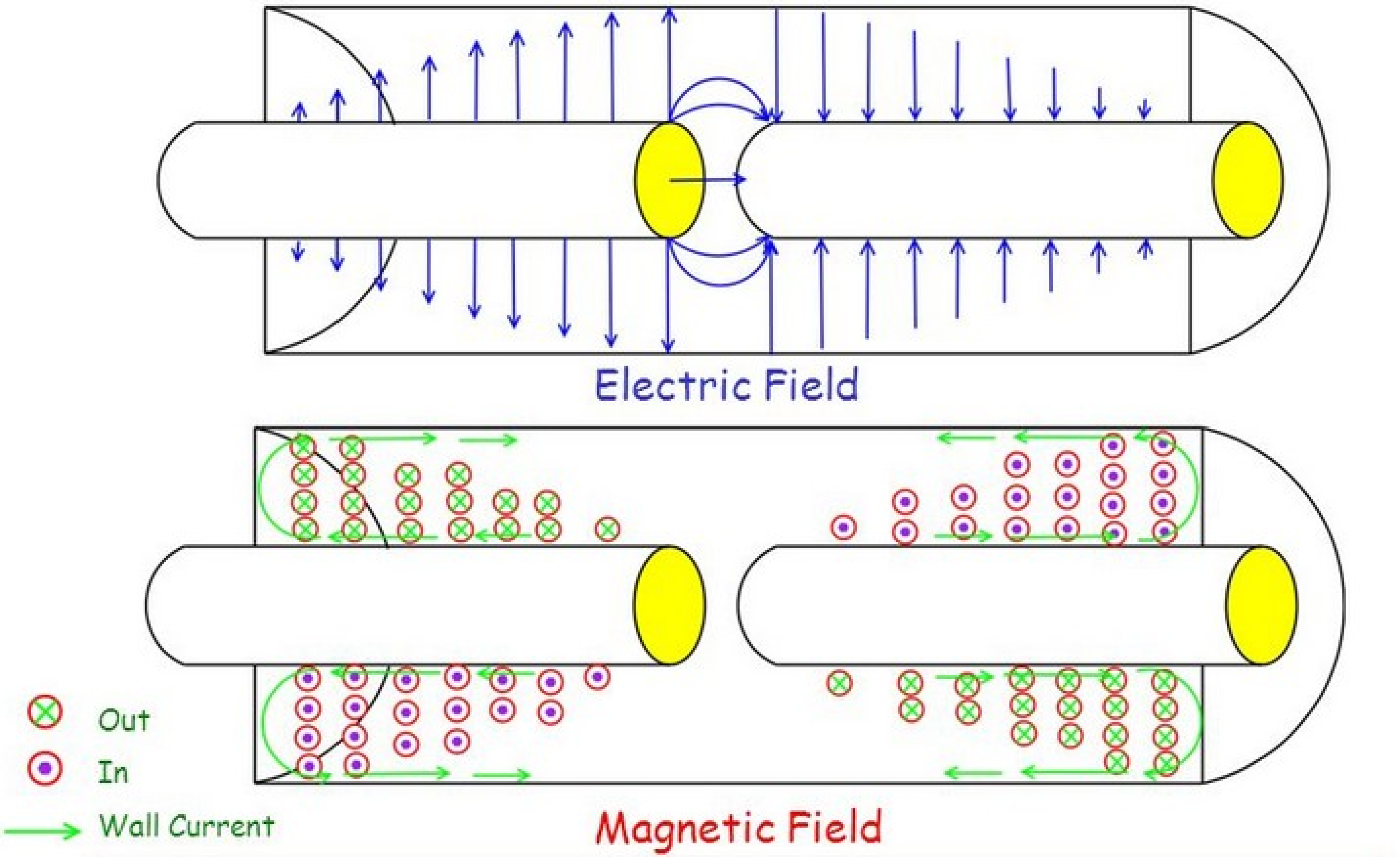


Figure 1: Electric fields (MV/m) within SHELA

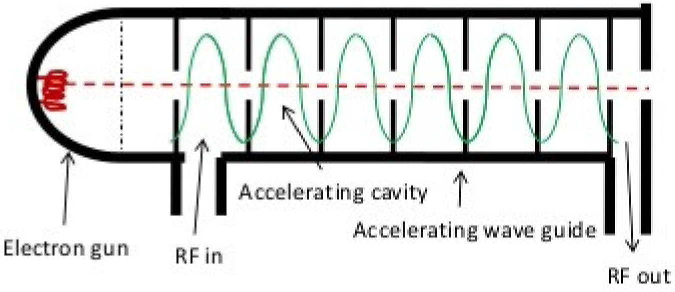
Cavity field pattern

For the fundamental mode at one instant in time.



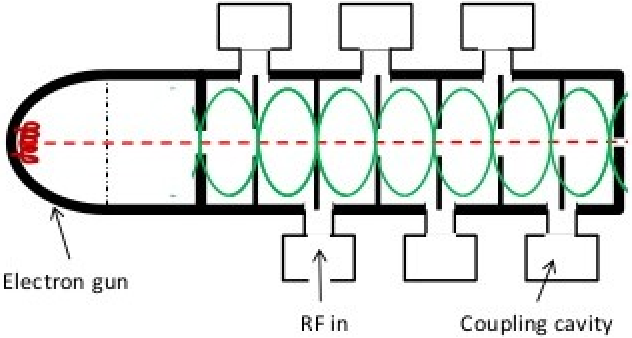
Traveling vs Standing

The wave velocity and the particle velocity have to be equal!
we need a disk loaded structure to slow down the phase velocity of the electric field to achieve synchronism $v_p < c$



Travelling wave structure

In a standing wave structure the electromagnetic field is the sum of two travelling wave structure running in opposite directions.



Standing wave structure

Betatron

https://en.wikipedia.org/wiki/Betatron

Rolf Widerøe

- 2:1 Rule of Betatron

$$\frac{d\phi}{dt}=2[\pi R^2(\frac{dB}{dt})]$$

- Energy of electron at the end of ¼ cycle of alternating magnetic field

$$E=\frac{e c \phi}{2\pi R}$$

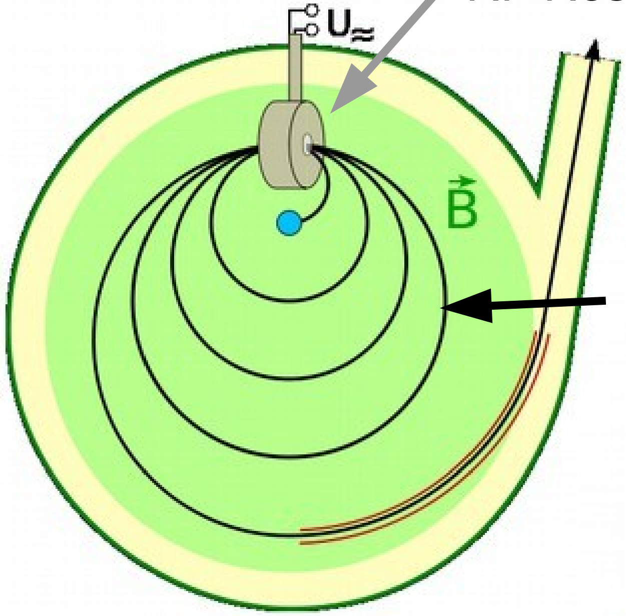
Where:
c – max. velocity of e
e – charge of electron
R – constant radius of orbit
B – magnetic field
Φ – magnetic flux (harmonic)

A German 6 MeV betatron (1942)

Microtron

https://en.wikipedia.org/wiki/Microtron

Vladimir Veksler



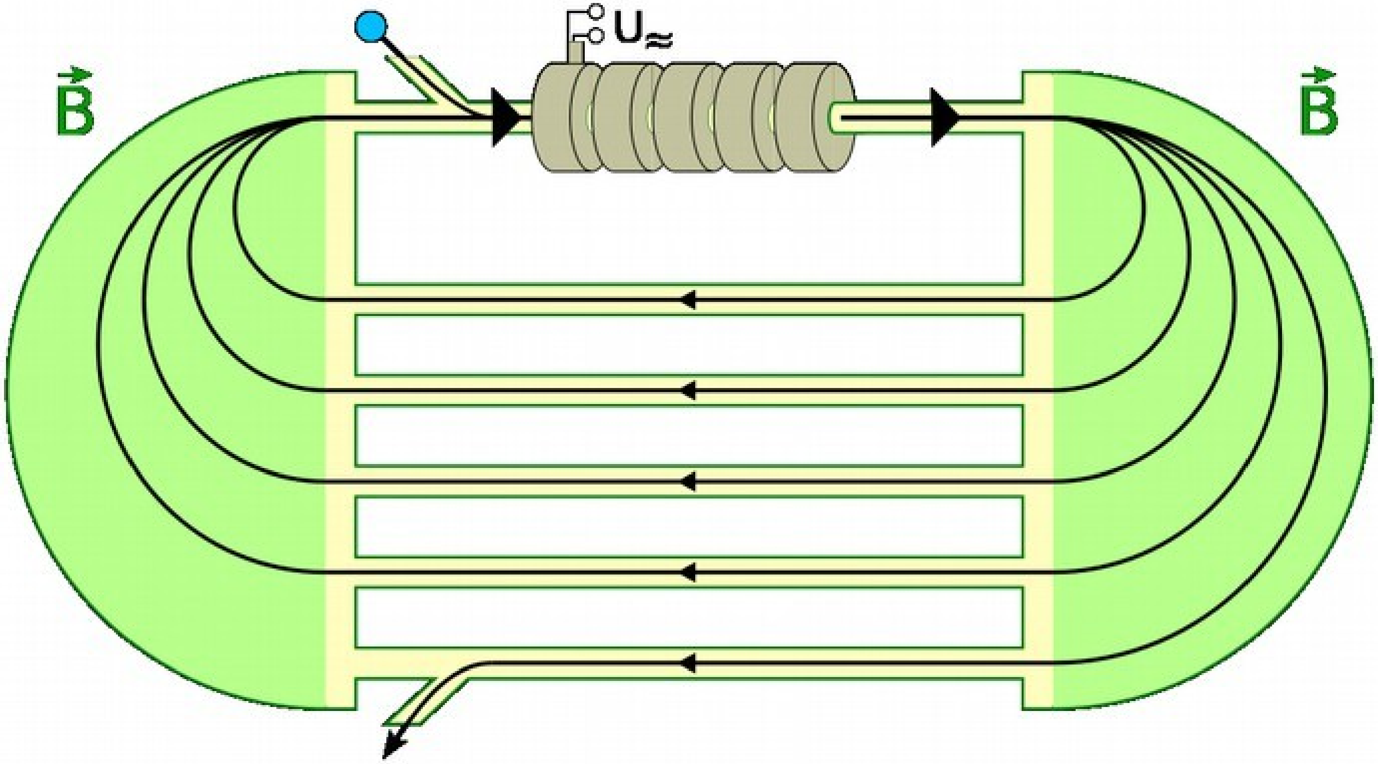
RF Resonator

e orbit

Vacuum Chamber

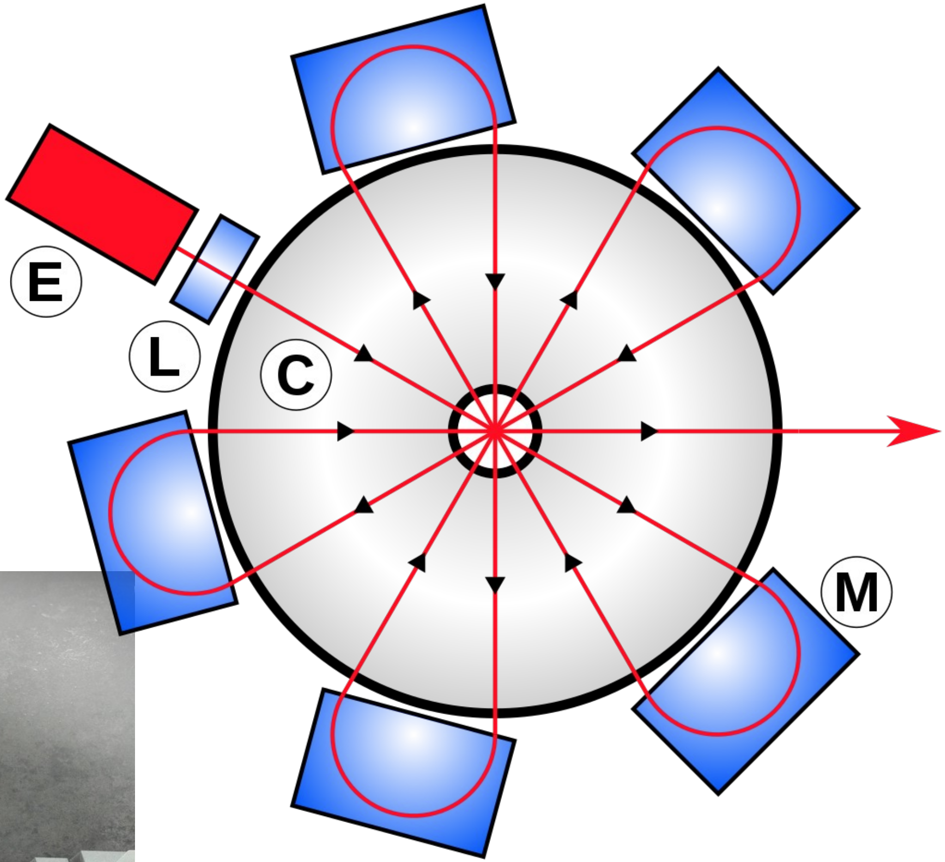
B – constant ; RF – constant

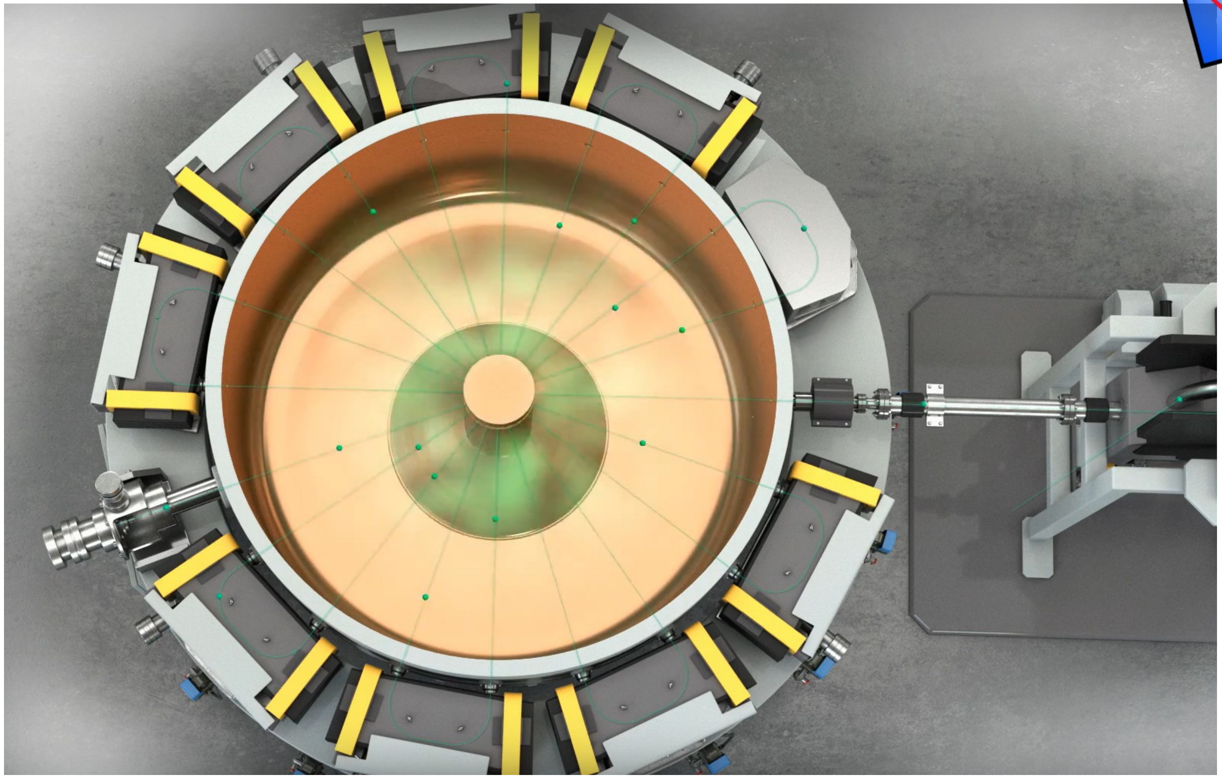
At first circle: Revolution period = RF period
at Nth circle: Revolution period = N x RF periods
N – harmonic number



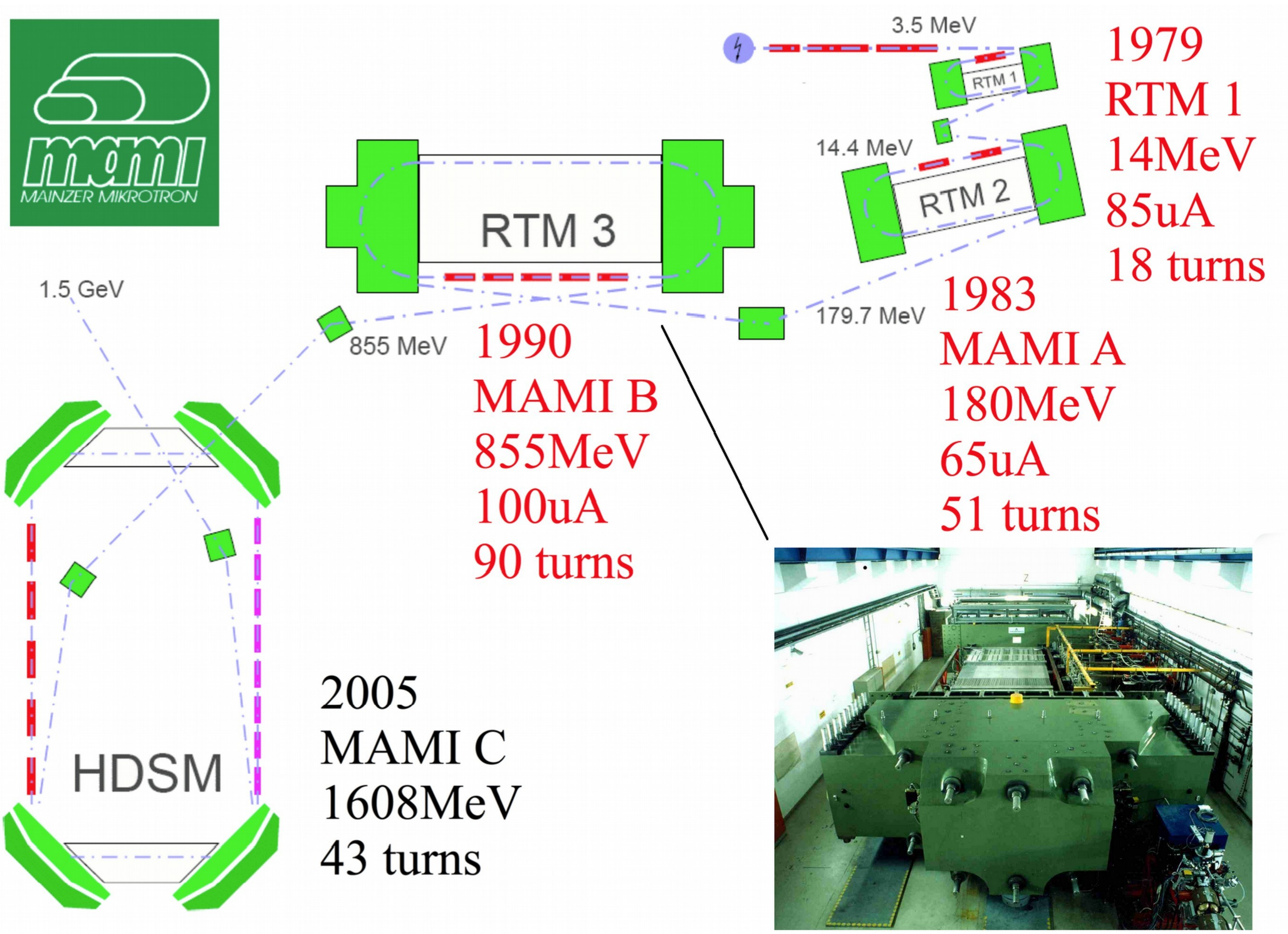
Rhodotron

Also generates continues, high intensity electron beam





MAMI – Mainzer Mikrotron



1979
RTM 1
14MeV
85uA
18 turns

1983
MAMI A
180MeV
65uA
51 turns

1990
MAMI B
855MeV
100uA
90 turns

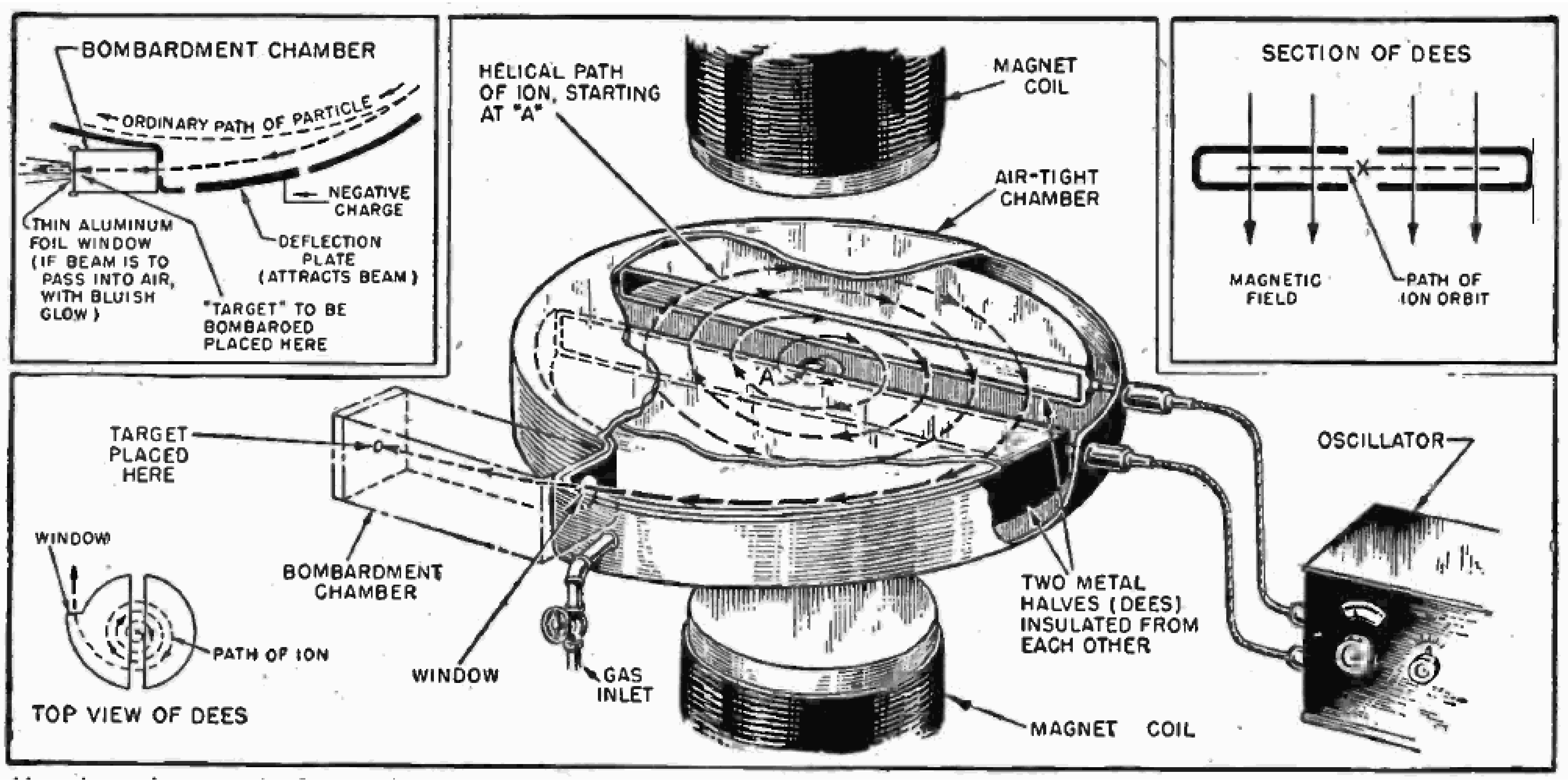
2005
MAMI C
1608MeV
43 turns

https://en.wikipedia.org/wiki/Mainz_Microtron

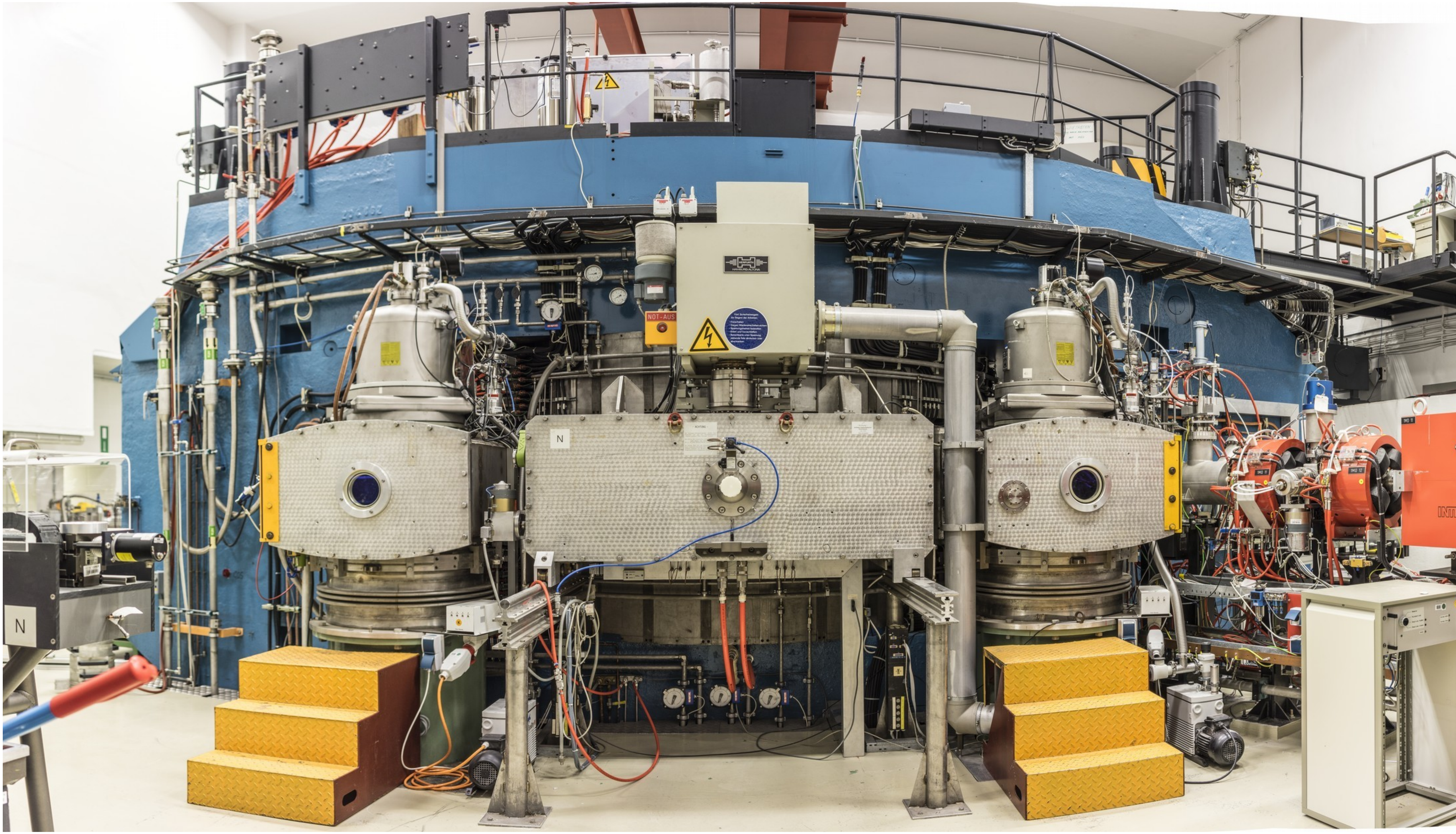
Cyclotron

https://en.wikipedia.org/wiki/Cyclotron

A cyclotron is a type of particle accelerator in which charged particles accelerate outwards from the centre along a spiral path. The particles are held to a spiral trajectory by **a static magnetic** field and accelerated by **a rapidly varying (radio frequency) electric field**.

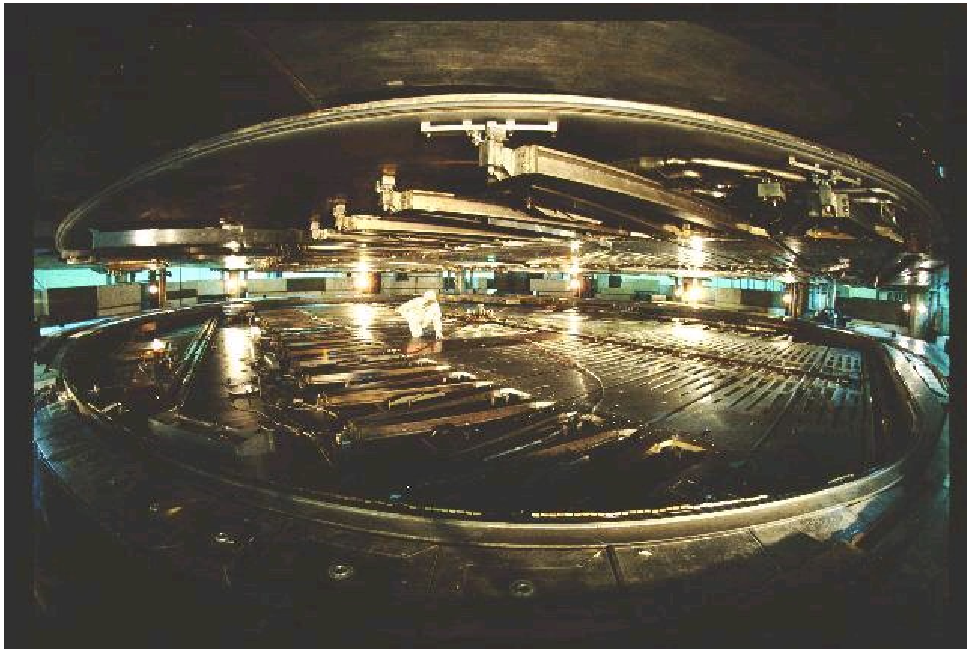


Cyclotron JULIC at FZJ



Cyclotron

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



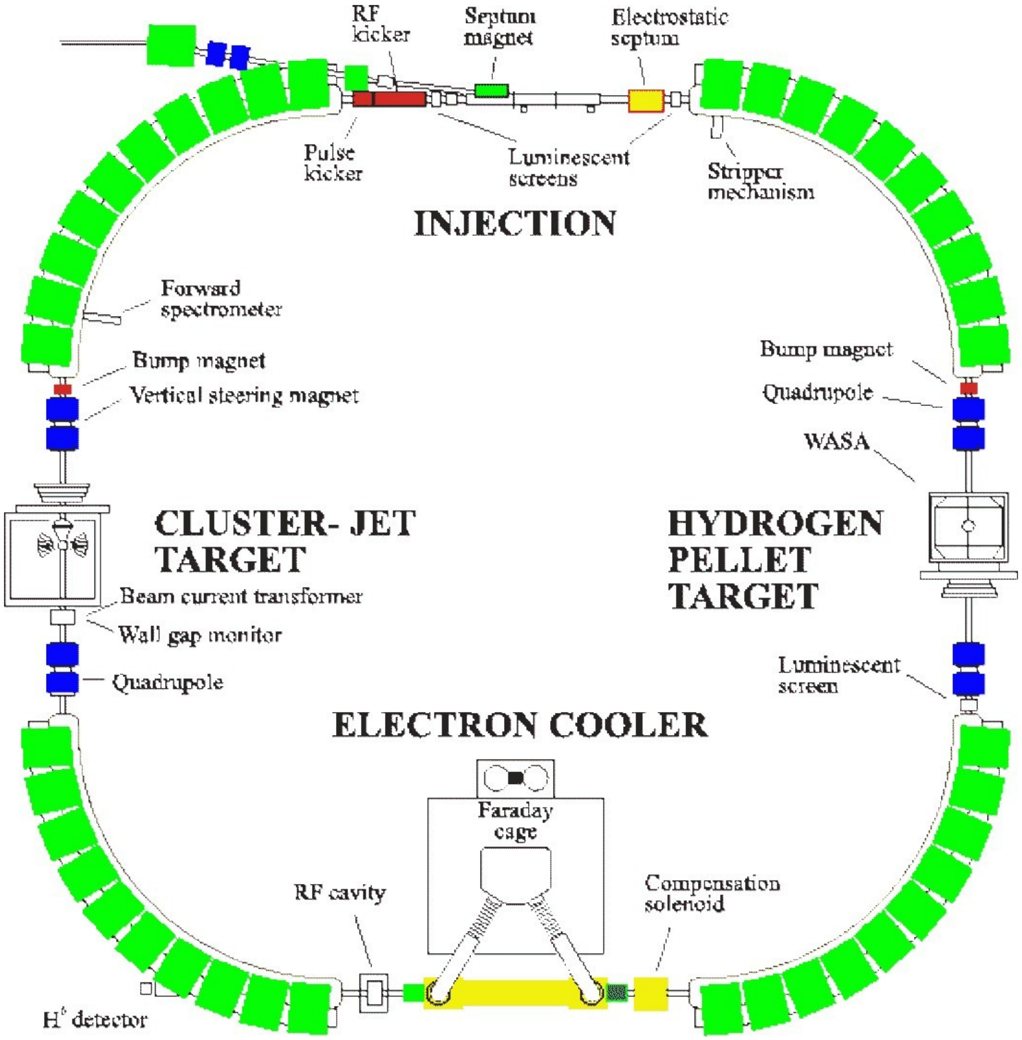
Largest cyclotron
(Triumf, Canada)

Synchrotron

Synchronized variation of accelerating frequency and magnetic field of bending magnets.

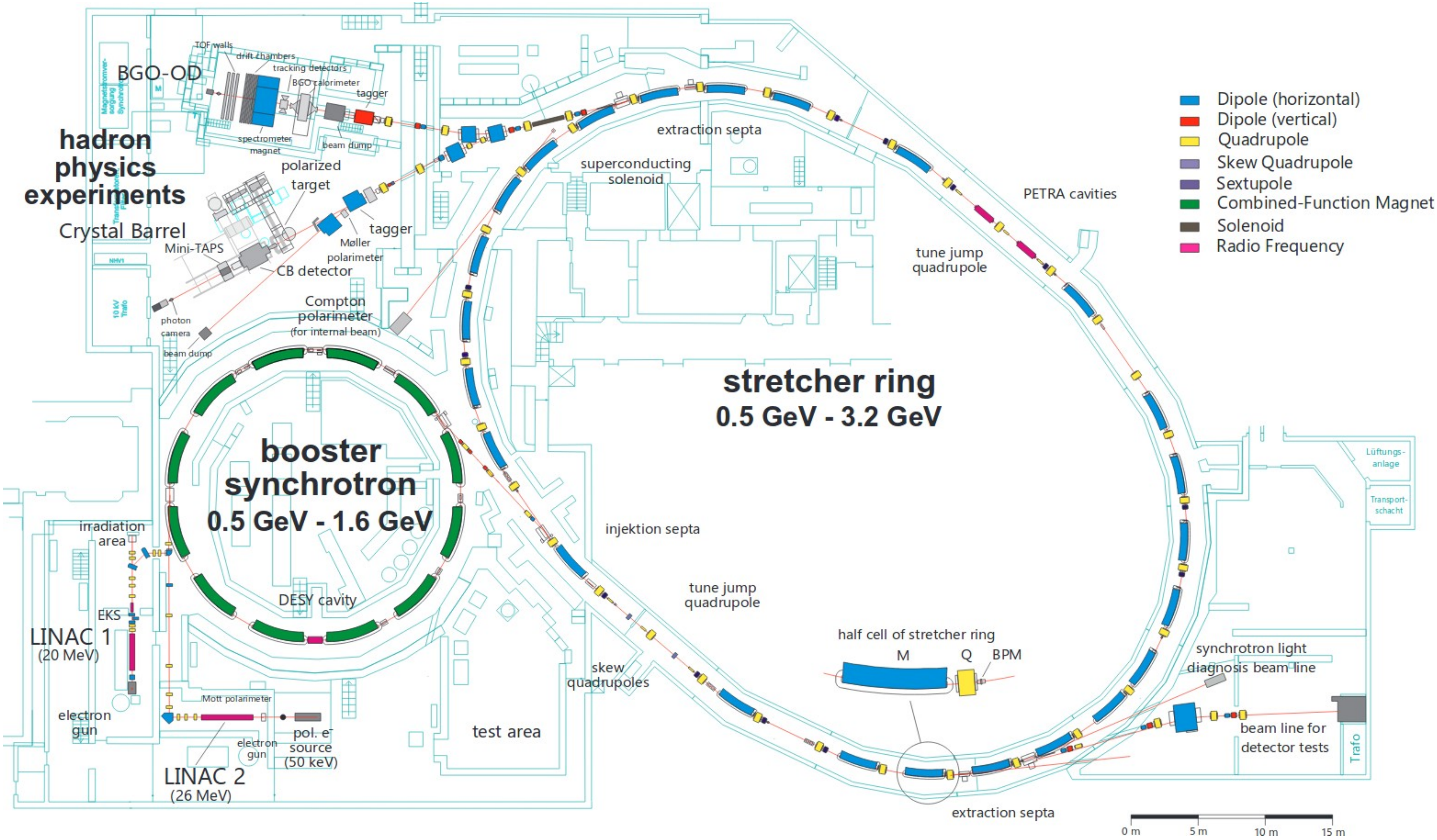
1945 invented simultaneously by

Edwin Mattison McMillan & **Vladimir I. Veksler.**



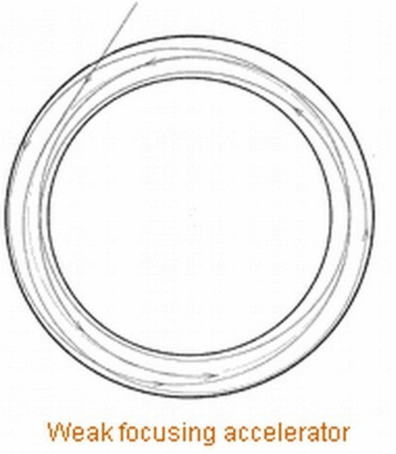
ELSA - Elektronen-Stretcher-Anlage

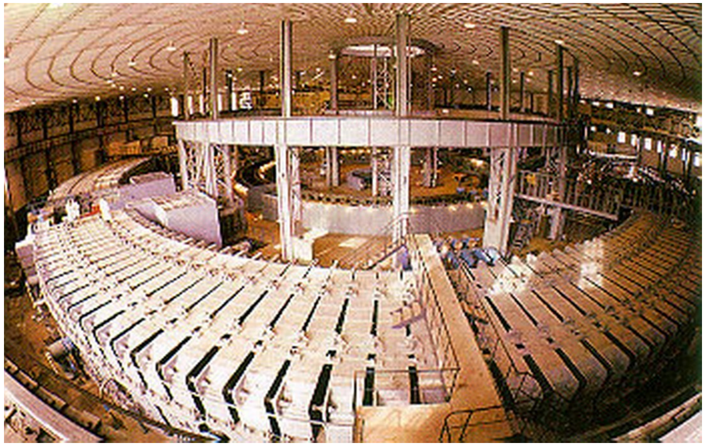
https://www-elsa.physik.uni-bonn.de/elsa_en.html



Weak focusing

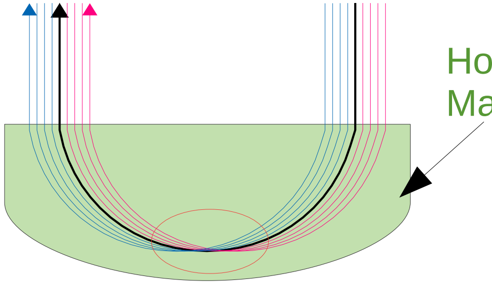
https://en.wikipedia.org/wiki/Weak_focusing





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

“Synchrophasotron“ (JINR)
9 GeV
Magnets: 40.000 t



particles

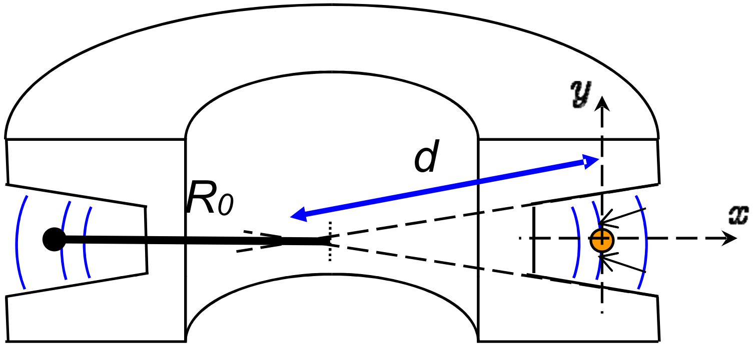
Homogeneous / uniform
Magnetic field

Keeping Focused – Weak Focusing

Without focusing the particles do not experience any restoring force in y-direction, spiral out of control (falling down)

The magnetic field decreases with radius and thus provide restoring Force

Early circular accelerators used weak focusing

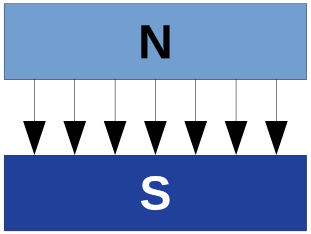


$$n \approx \frac{R_0}{d}$$

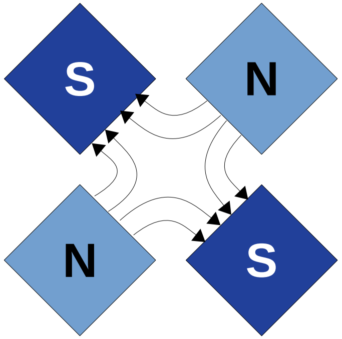
must have
$0 \leq n \leq 1$
for stability

Non Linear Fields

Linear

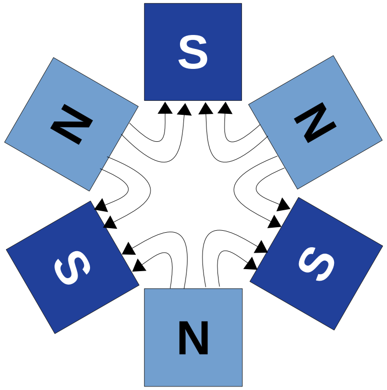


$$B_{x,y} = B_0$$



$$B_x = b_2 \frac{x}{r_0} \qquad B_y = b_2 \frac{y}{r_0}$$

Nonlinear

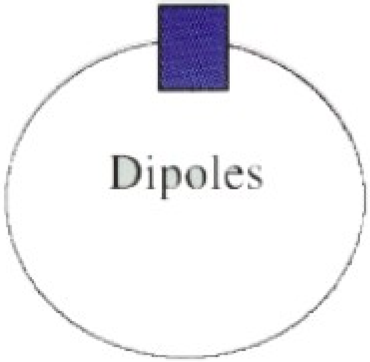


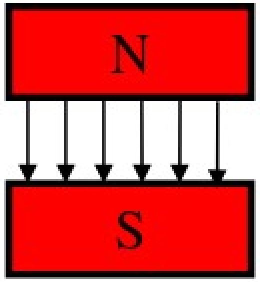
$$B_x = 2\, b_3 \frac{xy}{r_0^2} \qquad B_y = 2\, b_3 \frac{x^2 - y^2}{r_0^2}$$

Note : all elements are in fact ***nonlinear***.

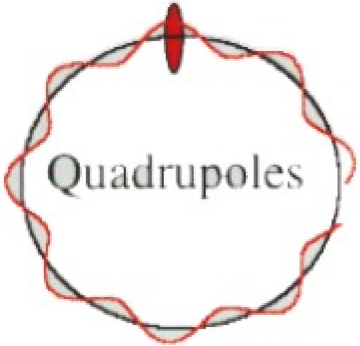
By "**linear**" elements, we refer to those whose principle effects on the beam may be obtained by expanding the Hamiltonian to second order in the dynamical variables. We shall make extensive use of this approximation - usually called the *paraxial approximation*.

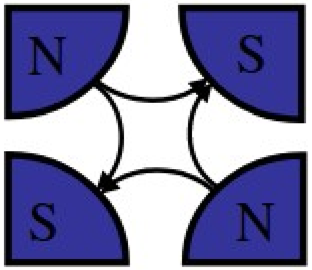
Use of elements



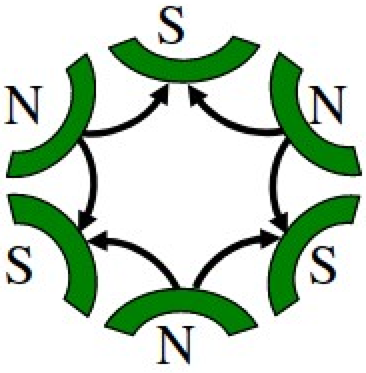


Bending (following reference trajectory)



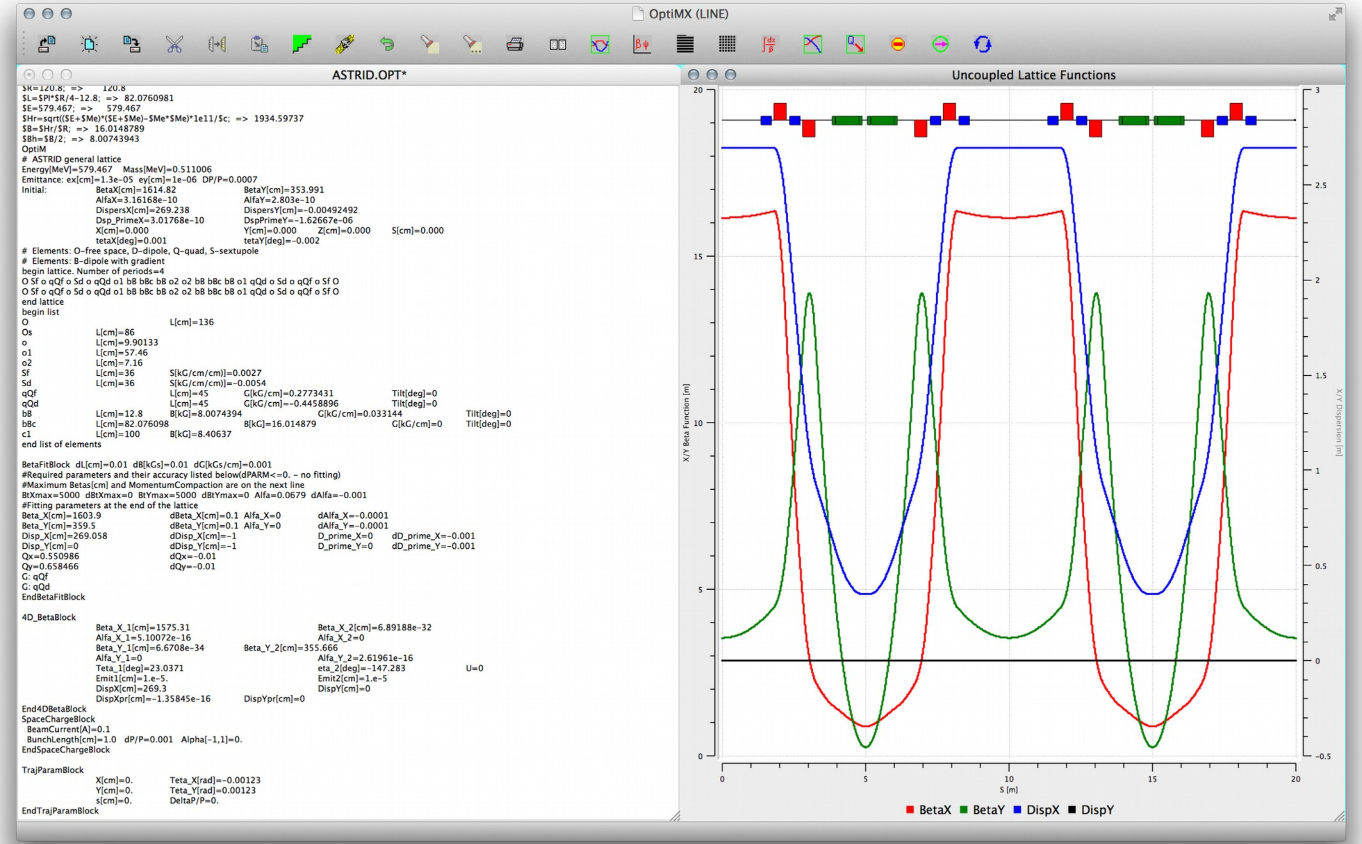


Focusing the beam

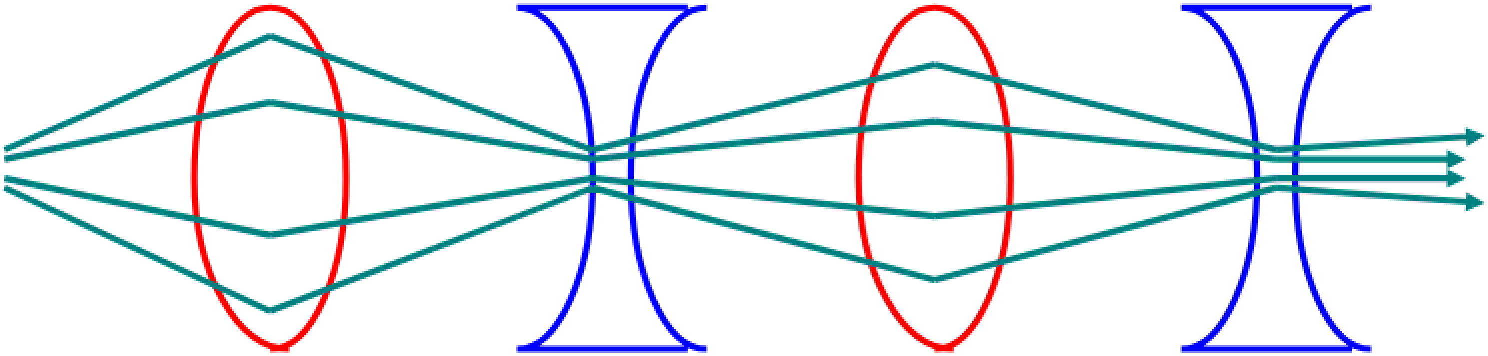


"Chromatic compensation"

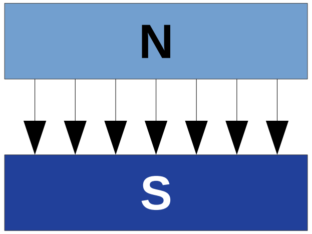
FODO Focusing – Defocusing

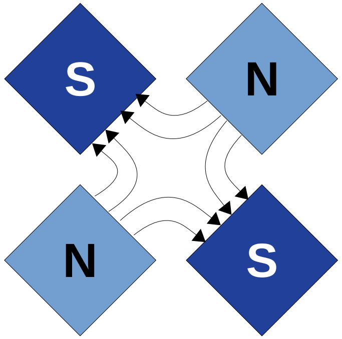


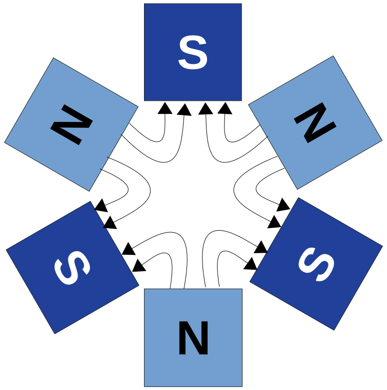
```
$R=120.8;  =>      120.8
$L=$PI*$R/4-12.8;  =>  82.0760981
$E=579.467;  =>     579.467
$Hr=sqrt(($E+$Me)*($E+$Me)-$Me*$Me)*1e11/$c;  =>  1934.59737
$B=$Hr/$R;  =>  16.0148789
$Bh=$B/2;  =>  8.00743943
OptiM
#  ASTRID general lattice
Energy[MeV]=579.467    Mass[MeV]=0.511006
Emittance: ex[cm]=1.3e-05  ey[cm]=1e-06  DP/P=0.0007
Initial:           BetaX[cm]=1614.82              BetaY[cm]=353.991
                   AlfaX=3.16168e-10              AlfaY=2.803e-10
                   DispersX[cm]=269.238           DispersY[cm]=-0.00492492
                   Dsp_PrimeX=3.01768e-10         DspPrimeY=-1.62667e-06
                   X[cm]=0.000                    Y[cm]=0.000       Z[cm]=0.000       S[cm]=0.000
                   tetaX[deg]=0.001               tetaY[deg]=-0.002
#  Elements: O-free space, D-dipole, Q-quad, S-sextupole
#  Elements: B-dipole with gradient
begin lattice. Number of periods=4
O Sf o qQf o Sd o qQd o1 bB bBc bB o2 o2 bB bBc bB o1 qQd o Sd o qQf o Sf O
O Sf o qQf o Sd o qQd o1 bB bBc bB o2 o2 bB bBc bB o1 qQd o Sd o qQf o Sf O
end lattice
begin list
O                            L[cm]=136
Os                 L[cm]=86
o                  L[cm]=9.90133
o1                 L[cm]=57.46
o2                 L[cm]=7.16
Sf                 L[cm]=36      S[kG/cm/cm)]=0.0027
Sd                 L[cm]=36      S[kG/cm/cm)]=-0.0054
qQf                              L[cm]=45      G[kG/cm]=0.2773431          Tilt[deg]=0
qQd                              L[cm]=45      G[kG/cm]=-0.4458896         Tilt[deg]=0
bB                 L[cm]=12.8    B[kG]=8.0074394          G[kG/cm]=0.033144          Tilt[deg]=0
bBc                L[cm]=82.076098             B[kG]=16.014879            G[kG/cm]=0        Tilt[deg]=0
c1                 L[cm]=100     B[kG]=8.40637
end list of elements

BetaFitBlock  dL[cm]=0.01  dB[kGs]=0.01  dG[kGs/cm]=0.001
#Required parameters and their accuracy listed below(dPARM<=0. - no fitting)
#Maximum Betas[cm] and MomentumCompaction are on the next line
BtXmax=5000  dBtXmax=0  BtYmax=5000  dBtYmax=0  Alfa=0.0679  dAlfa=-0.001
#Fitting parameters at the end of the lattice
Beta_X[cm]=1603.9            dBeta_X[cm]=0.1  Alfa_X=0          dAlfa_X=-0.0001
Beta_Y[cm]=359.5             dBeta_Y[cm]=0.1  Alfa_Y=0          dAlfa_Y=-0.0001
Disp_X[cm]=269.058           dDisp_X[cm]=-1                     D_prime_X=0      dD_prime_X=-0.001
Disp_Y[cm]=0                 dDisp_Y[cm]=-1                     D_prime_Y=0      dD_prime_Y=-0.001
Qx=0.550986                  dQx=-0.01
Qy=0.658466                  dQy=-0.01
G: qQf
G: qQd
EndBetaFitBlock

4D_BetaBlock
                   Beta_X_1[cm]=1575.31                         Beta_X_2[cm]=6.89188e-32
                   Alfa_X_1=5.10072e-16                         Alfa_X_2=0
                   Beta_Y_1[cm]=6.6708e-34      Beta_Y_2[cm]=355.666
                   Alfa_Y_1=0                                   Alfa_Y_2=2.61961e-16
                   Teta_1[deg]=23.0371                          eta_2[deg]=-147.283          U=0
                   Emit1[cm]=1.e-5.                             Emit2[cm]=1.e-5
                   DispX[cm]=269.3                              DispY[cm]=0
                   DispXpr[cm]=-1.35845e-16     DispYpr[cm]=0
End4DBetaBlock
SpaceChargeBlock
  BeamCurrent[A]=0.1
  BunchLength[cm]=1.0   dP/P=0.001   Alpha[-1,1]=0.
EndSpaceChargeBlock

TrajParamBlock
                   X[cm]=0.         Teta_X[rad]=-0.00123
                   Y[cm]=0.         Teta_Y[rad]=0.00123
                   s[cm]=0.         DeltaP/P=0.
EndTrajParamBlock
```

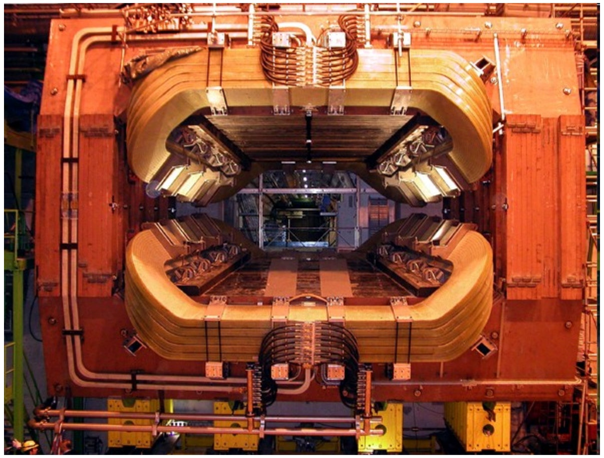


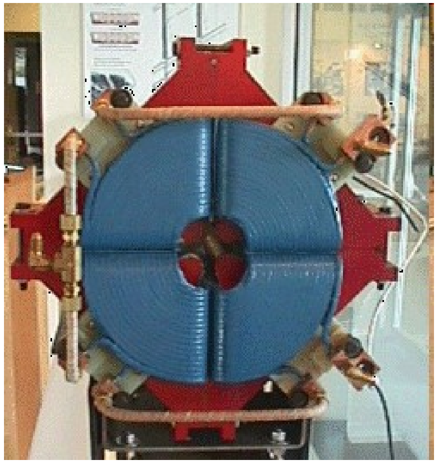
Beam optics


N
S


S
N
N
S


S
N
N
S
S
N





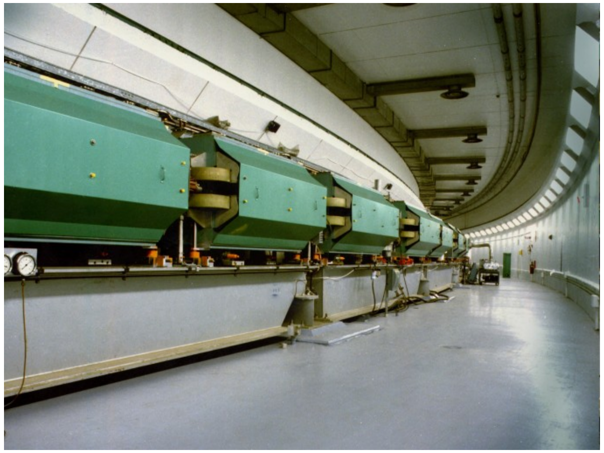

HICAT
Schwerionen-Therapie-Beschleunigeranlage
GSI

Strong focusing

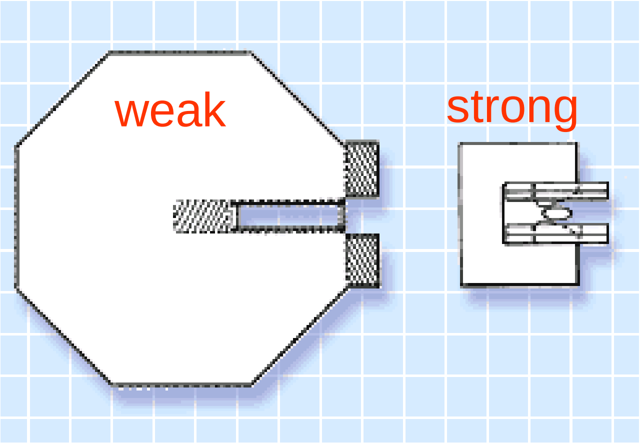
https://en.wikipedia.org/wiki/Strong_focusing

1952: Courant, Livingston, and Snyder: theory of strong focusing with discrete quadrupole magnets for the focusing and dipole magnets for the bending.

Two successive elements, one focusing the other defocusing, can focus in both planes



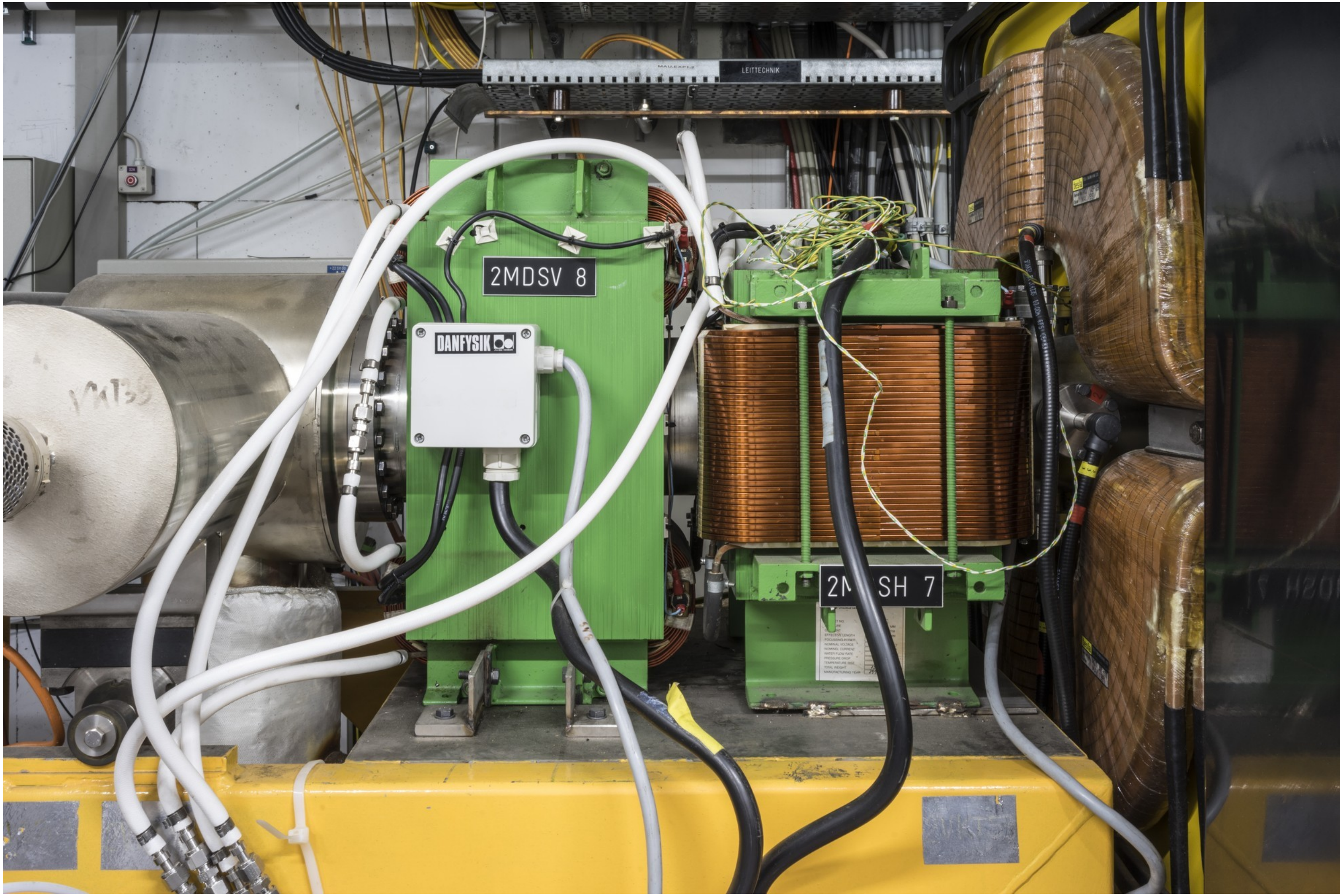
“Alternating Gradient Synchrotron“ (BNL)
30 GeV



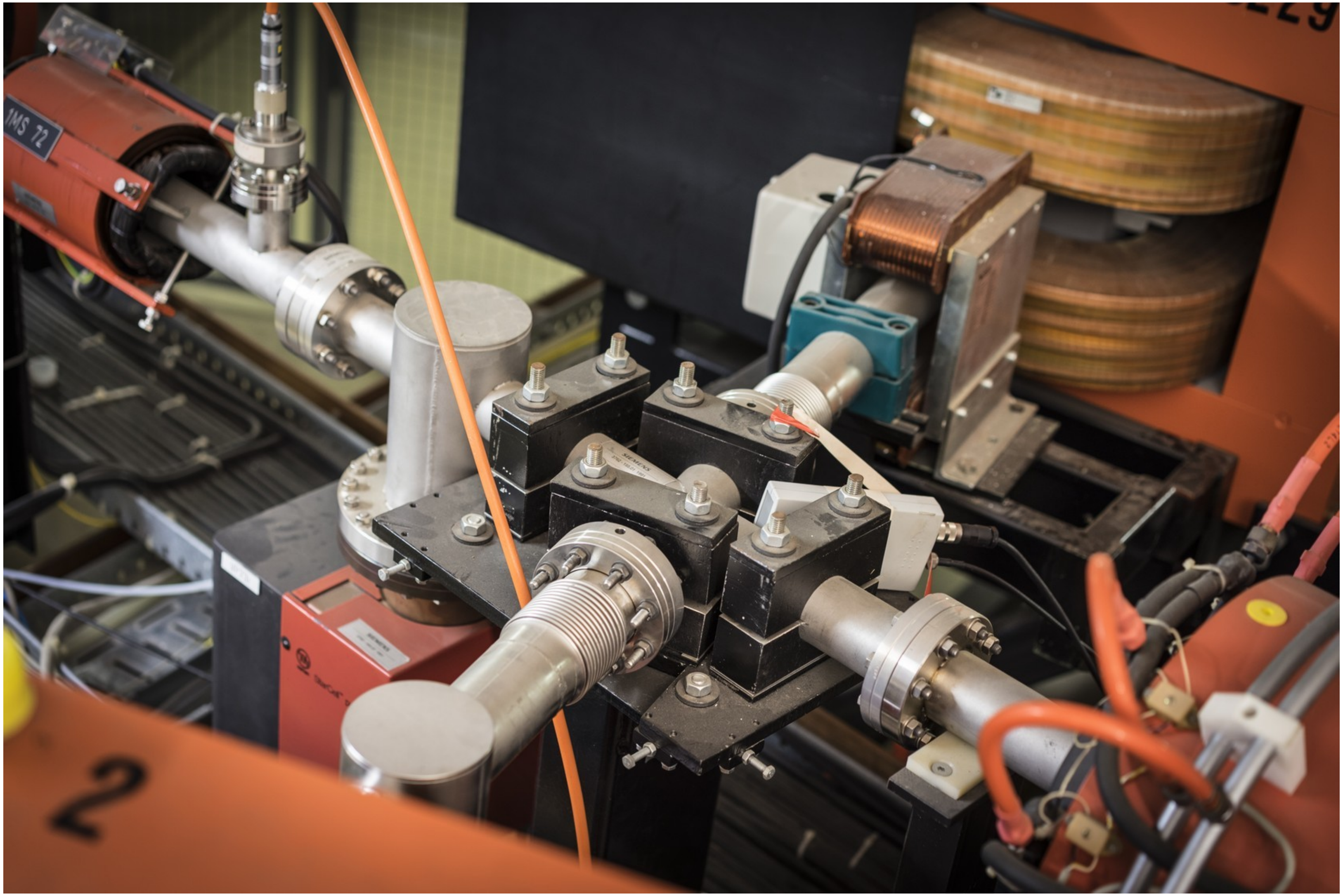
“Super Proton Synchrotron“ (CERN)
400 GeV

Today: ‘only’ strong focusing is used

Steering magnets

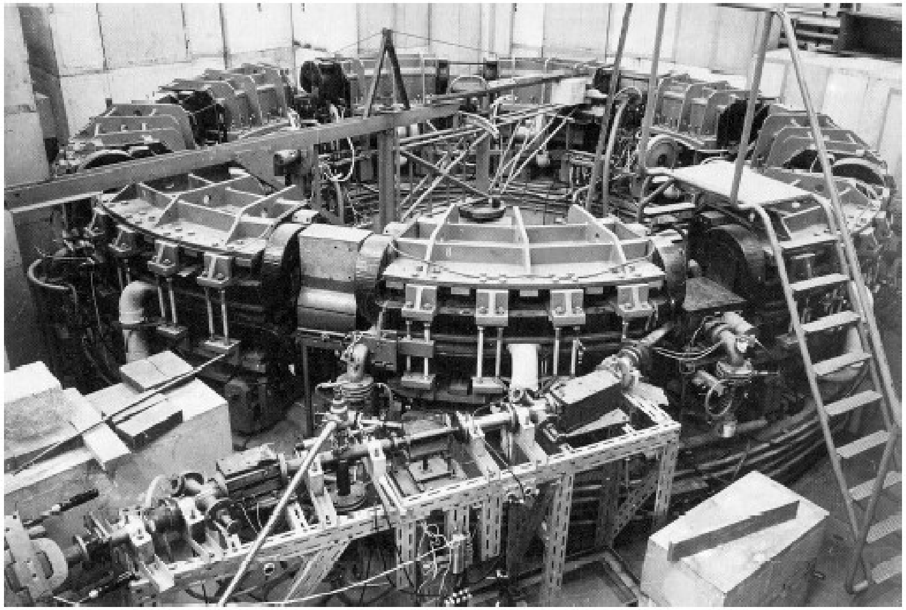


Crossing beams at COSY

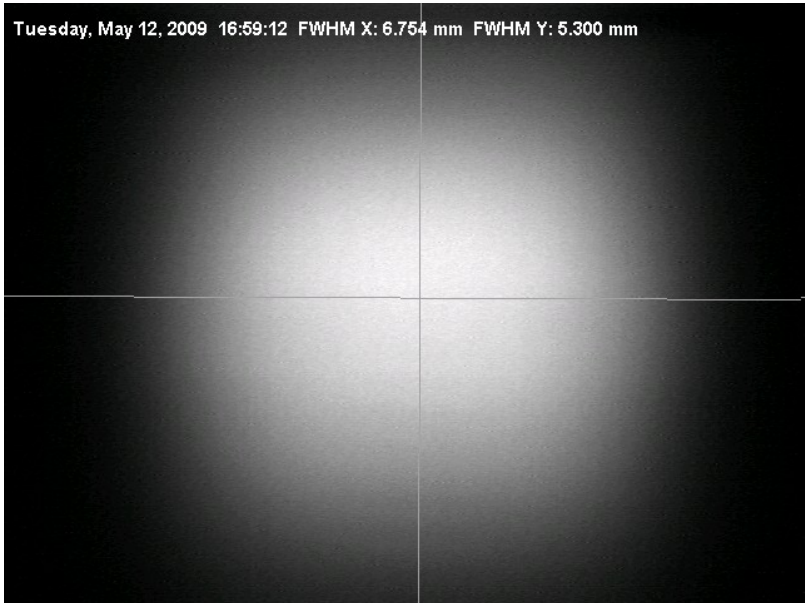


Accelerators – Radiofrequency

Synchrotron:



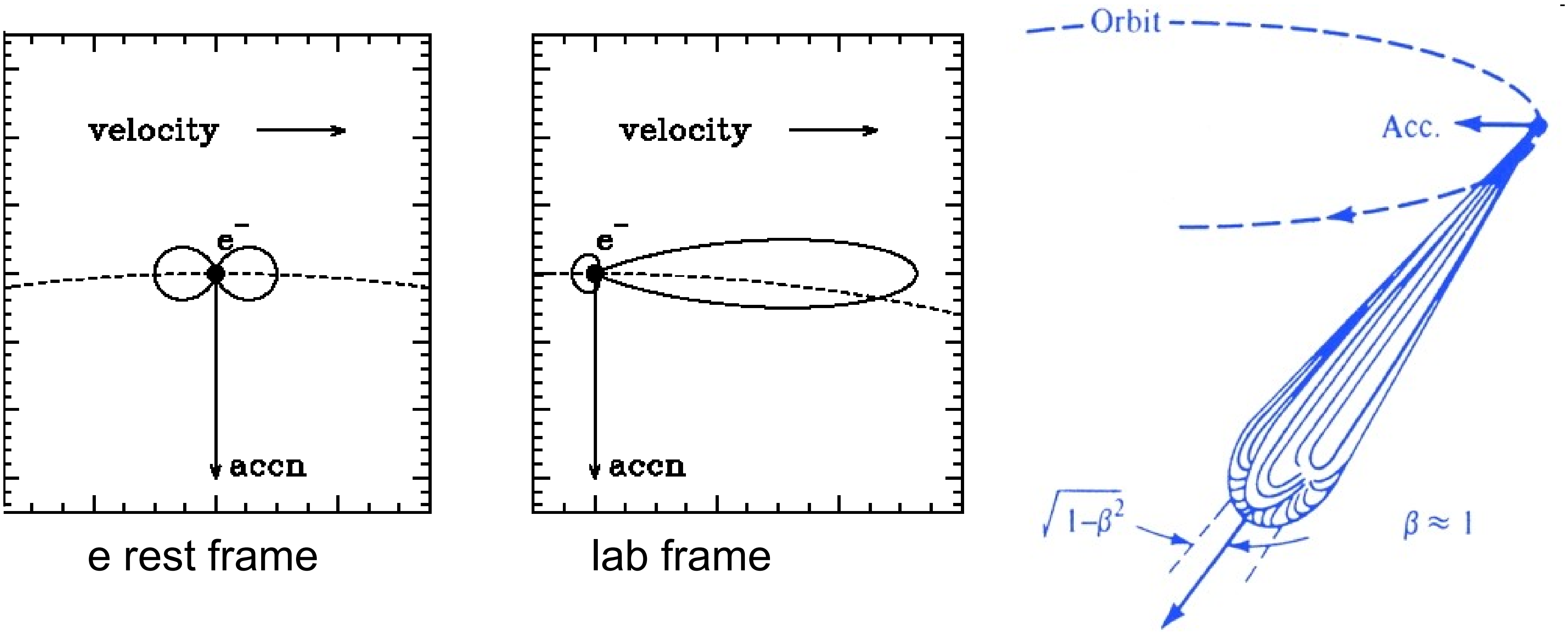
Electron Synchrotron (Bonn)
0.5 GeV



"Synchrotron Radiation"

Accelerators – Radiofrequency

Synchrotron:



e rest frame

lab frame

Synchrotron radiation

Accelerators – Radio-frequency

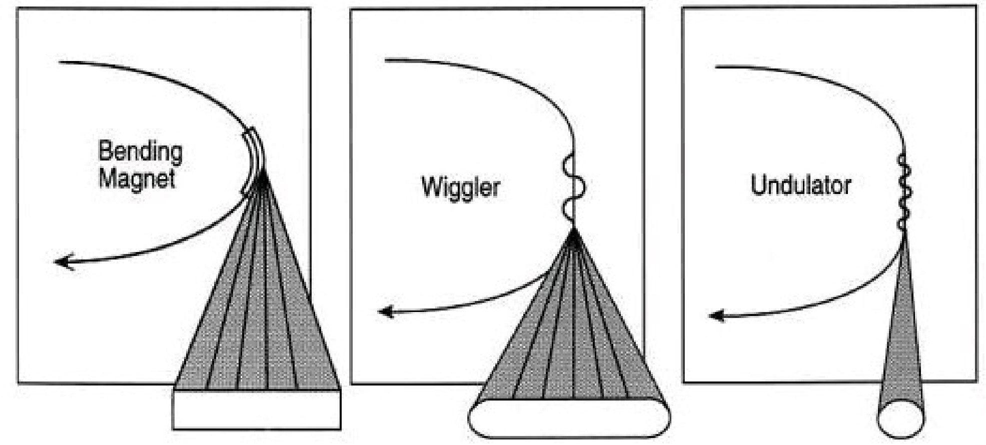
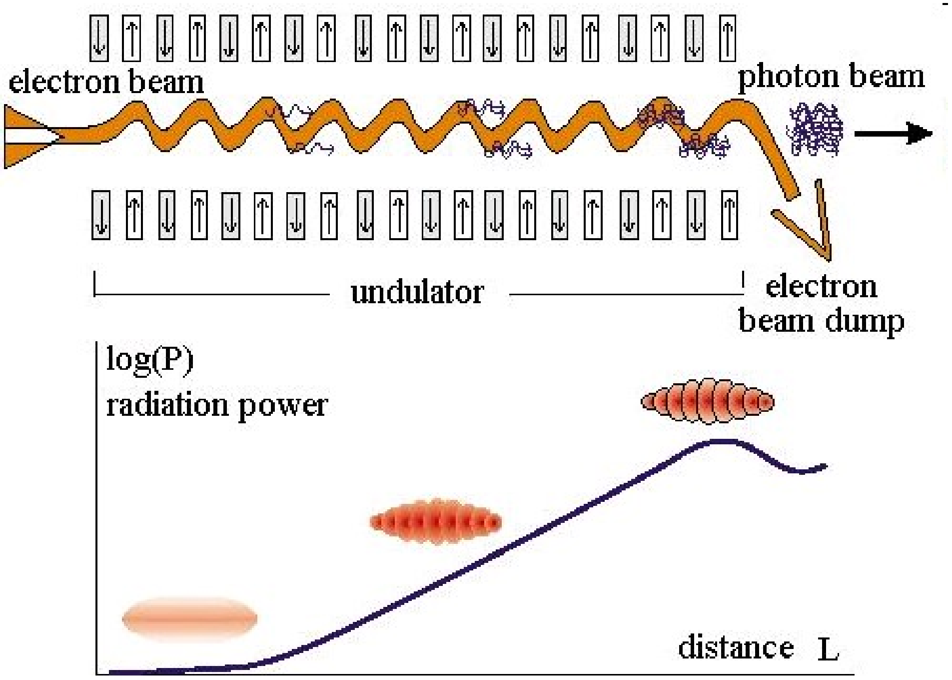


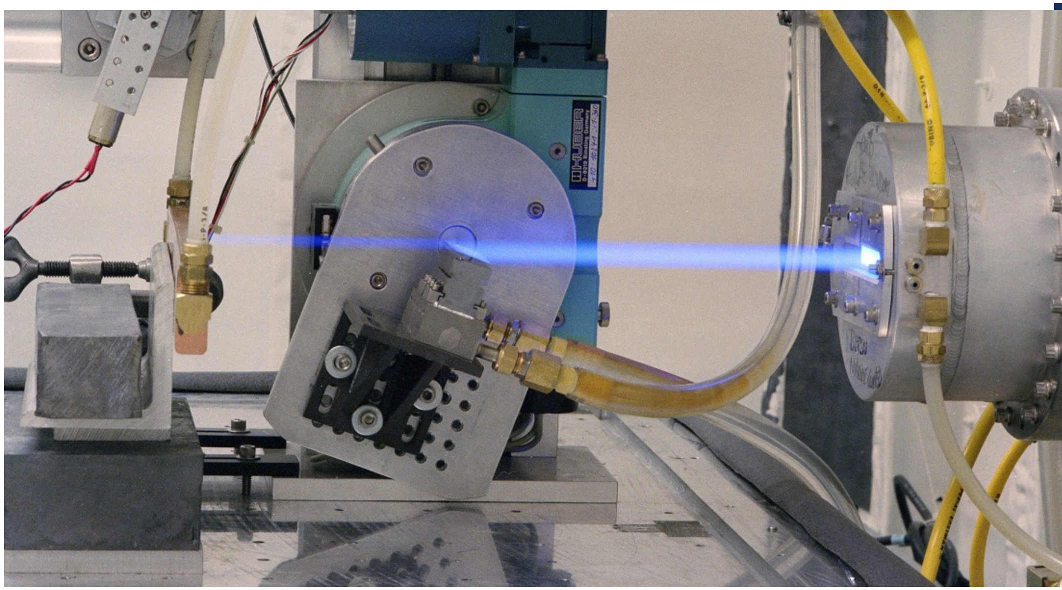
Fig. 1 Schematic of the three approaches used for synchrotron light generation. Bending magnet light is available at all sources. Wigglers or undulators, which are periodic magnet structures installed in straight sections, provide much enhanced flux and brightness. (Figure courtesy of ALS, LBNL)



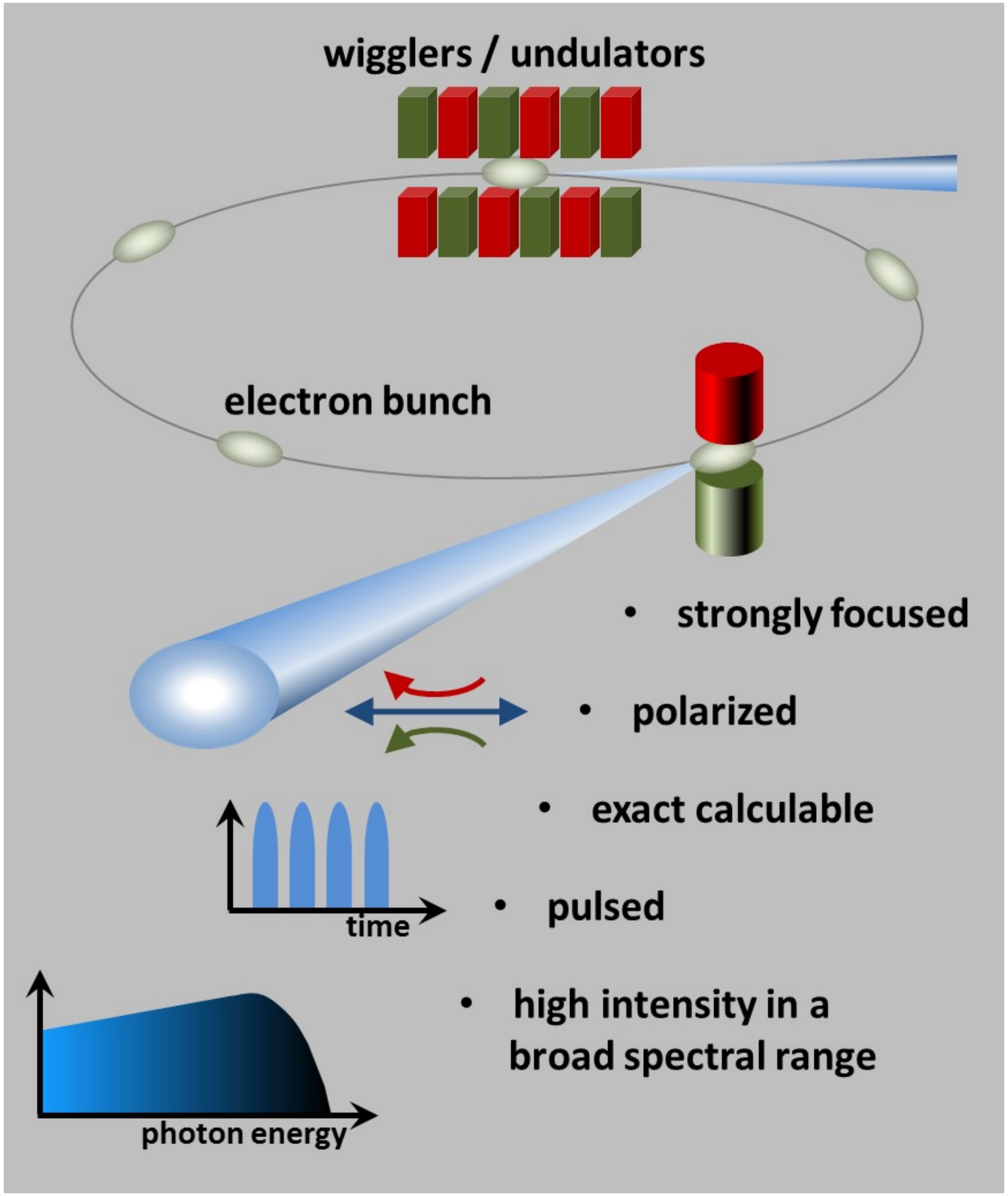
Synchrotron radiation

Accelerators – Radiofrequency

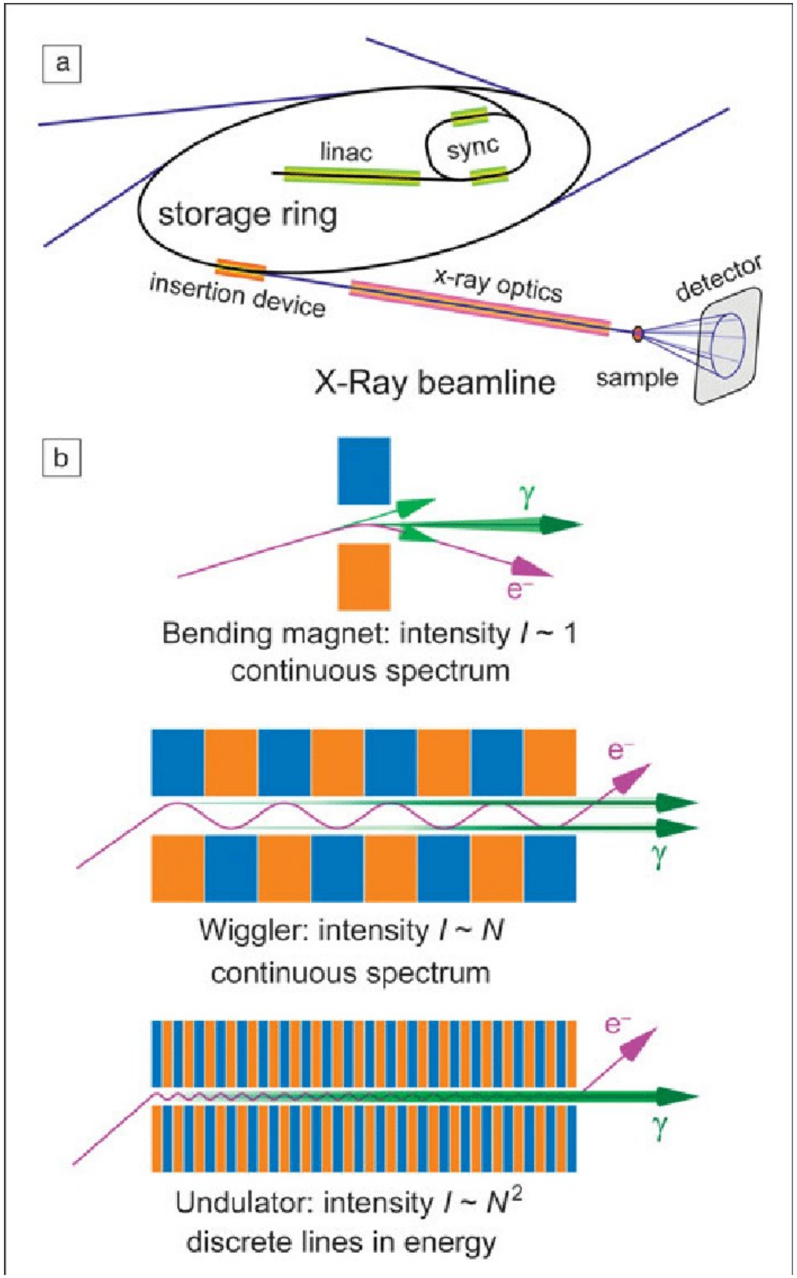
Synchrotron: (Storage of electron beam → „Storage Ring“)



Wigglers and Undulators



- strongly focused
- polarized
- exact calculable
- pulsed
- high intensity in a broad spectral range



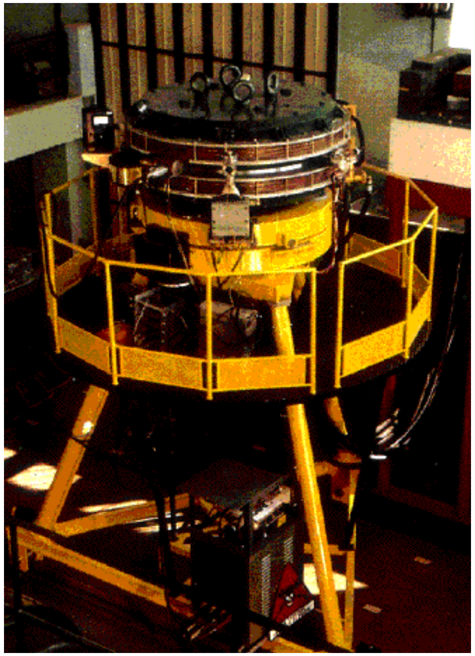
Bending magnet: intensity $I \sim 1$
continuous spectrum

Wiggler: intensity $I \sim N$
continuous spectrum

Undulator: intensity $I \sim N^2$
discrete lines in energy

Particle Colliders

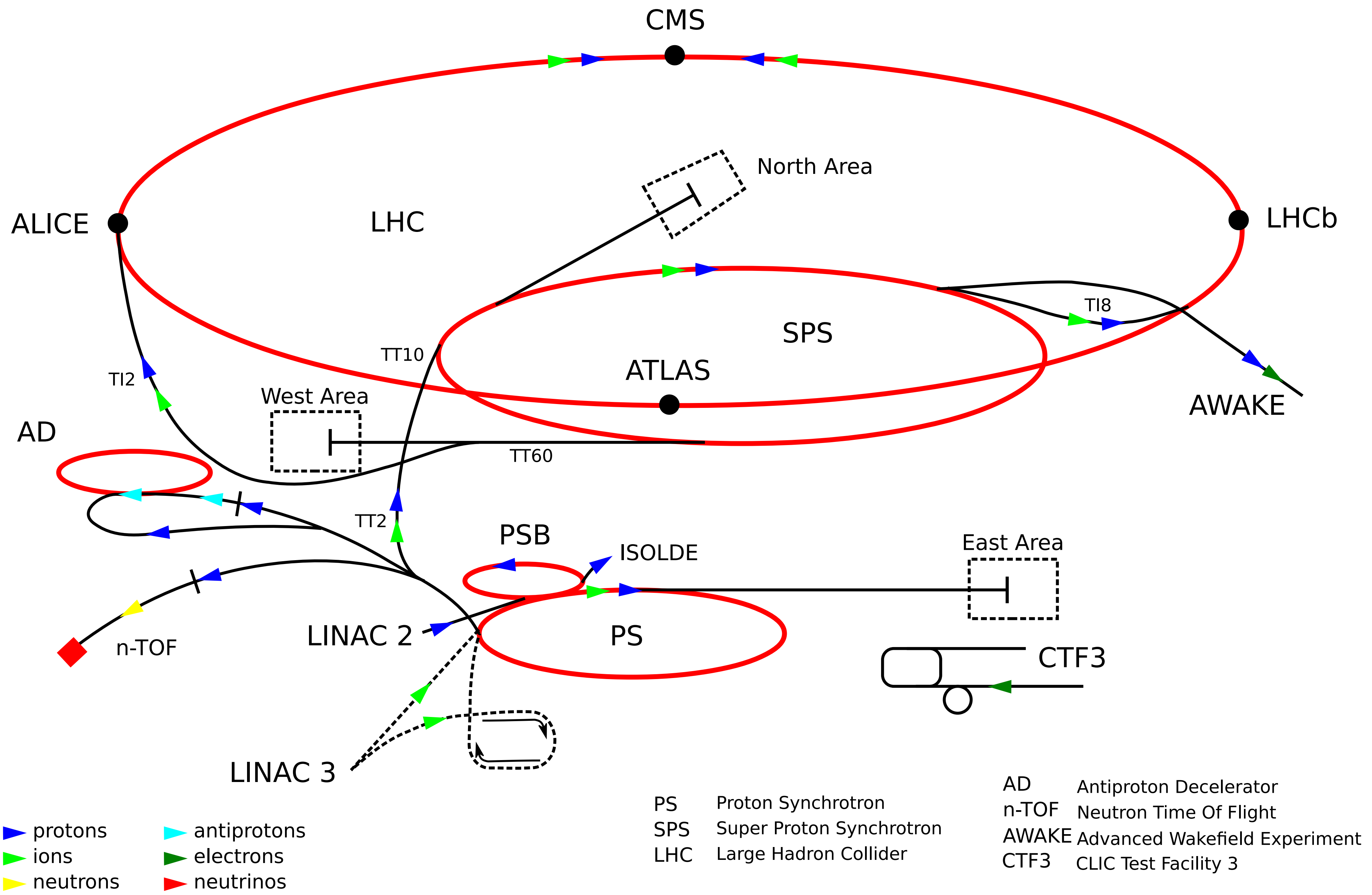
In the 1950's a number of places, MURA, Novosibirsk, CERN,Stanford, Frascati, and Orsay, developed the technology of collidingbeams. Bruno Touschek, Gersh Budker and Don Kerst were thepeople who made this happen.Colliders are now the devices employed to reach the highest energies.



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

LEP/LHC
(CERN)

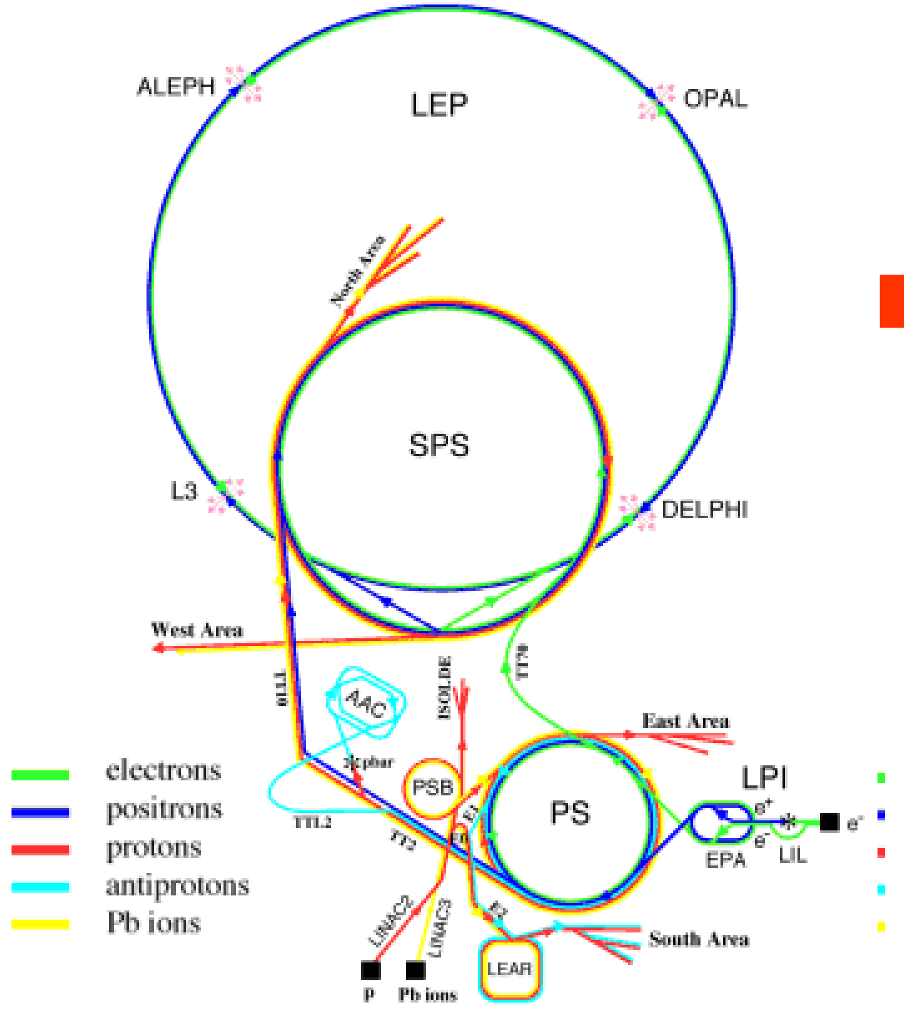
CERN

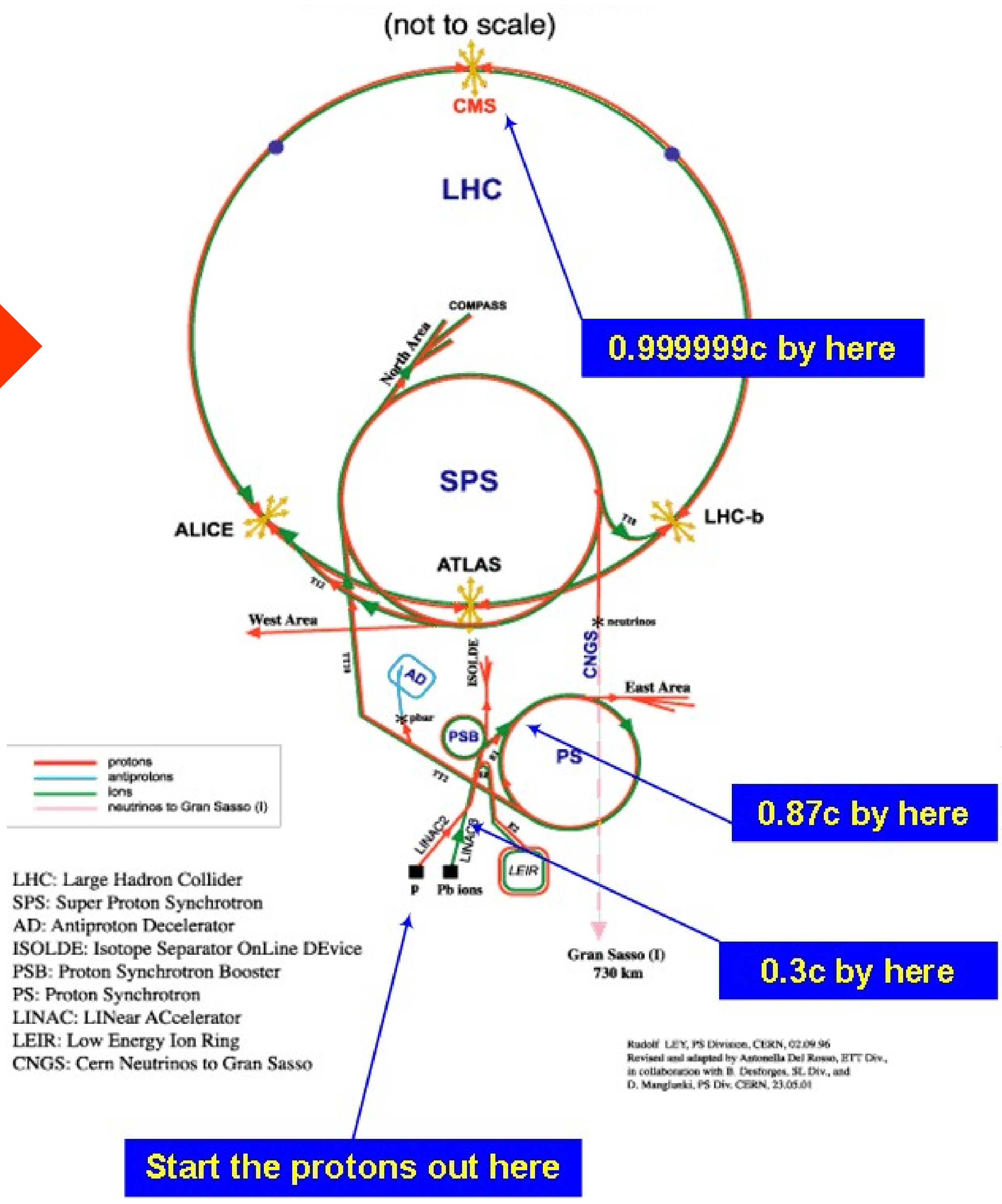


PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider

AD	Antiproton Decelerator
n-TOF	Neutron Time Of Flight
AWAKE	Advanced Wakefield Experiment
CTF3	CLIC Test Facility 3

From LEP to LHC





LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

0.999999c by here

0.87c by here

0.3c by here

Start the protons out here

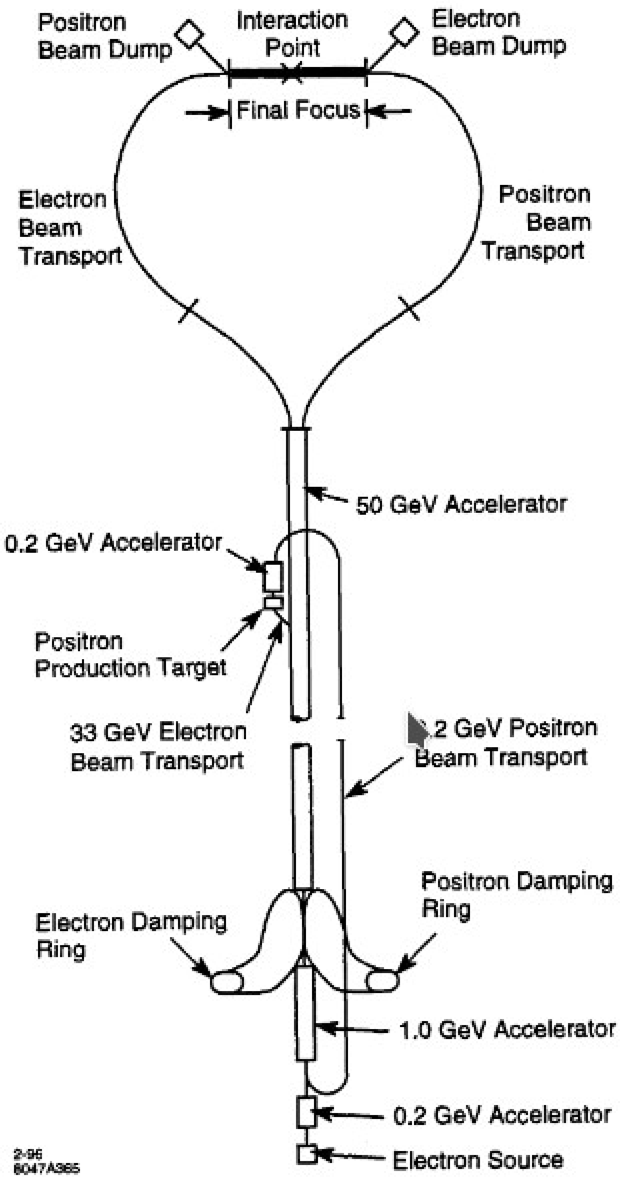
SLAC National Accelerator Laboratory

https://en.wikipedia.org/wiki/SLAC_National_Accelerator_Laboratory

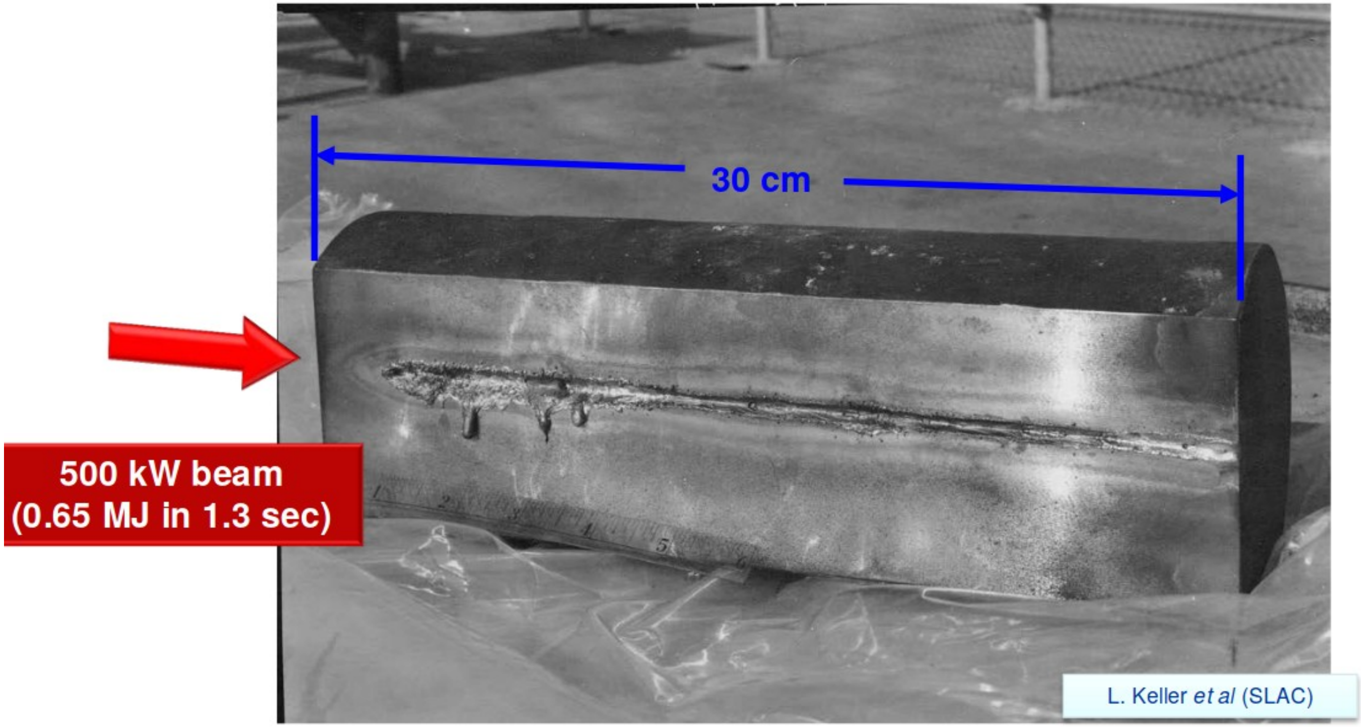
Aerial photo of the Stanford Linear Accelerator Center, showing the 3.2 kilometer building housing the accelerator beam line.

Research at SLAC has produced three Nobel Prizes in Physics:

- 1976: The charm quark—see J/ψ meson
- 1990: Quark structure inside protons and neutrons
- 1995: The tau lepton



Damage test of a 30 cm long Copper Block (SLAC – 1971)



500 kW beam
(0.65 MJ in 1.3 sec)

L. Keller *et al* (SLAC)

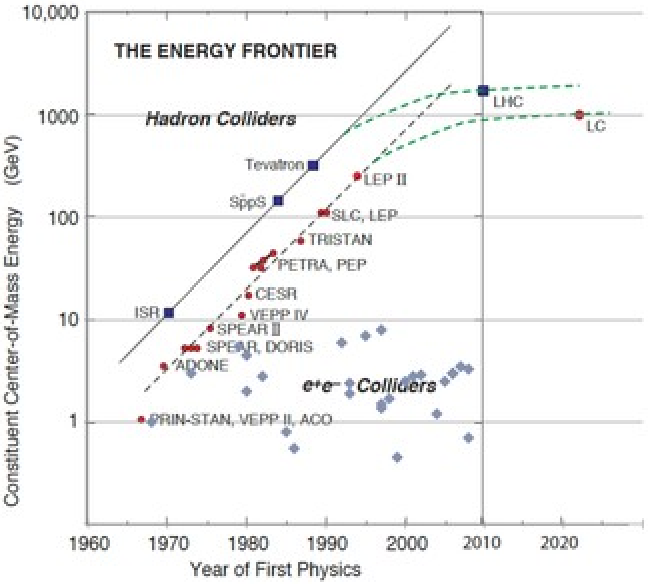
Parameter properties for different acceleration principles

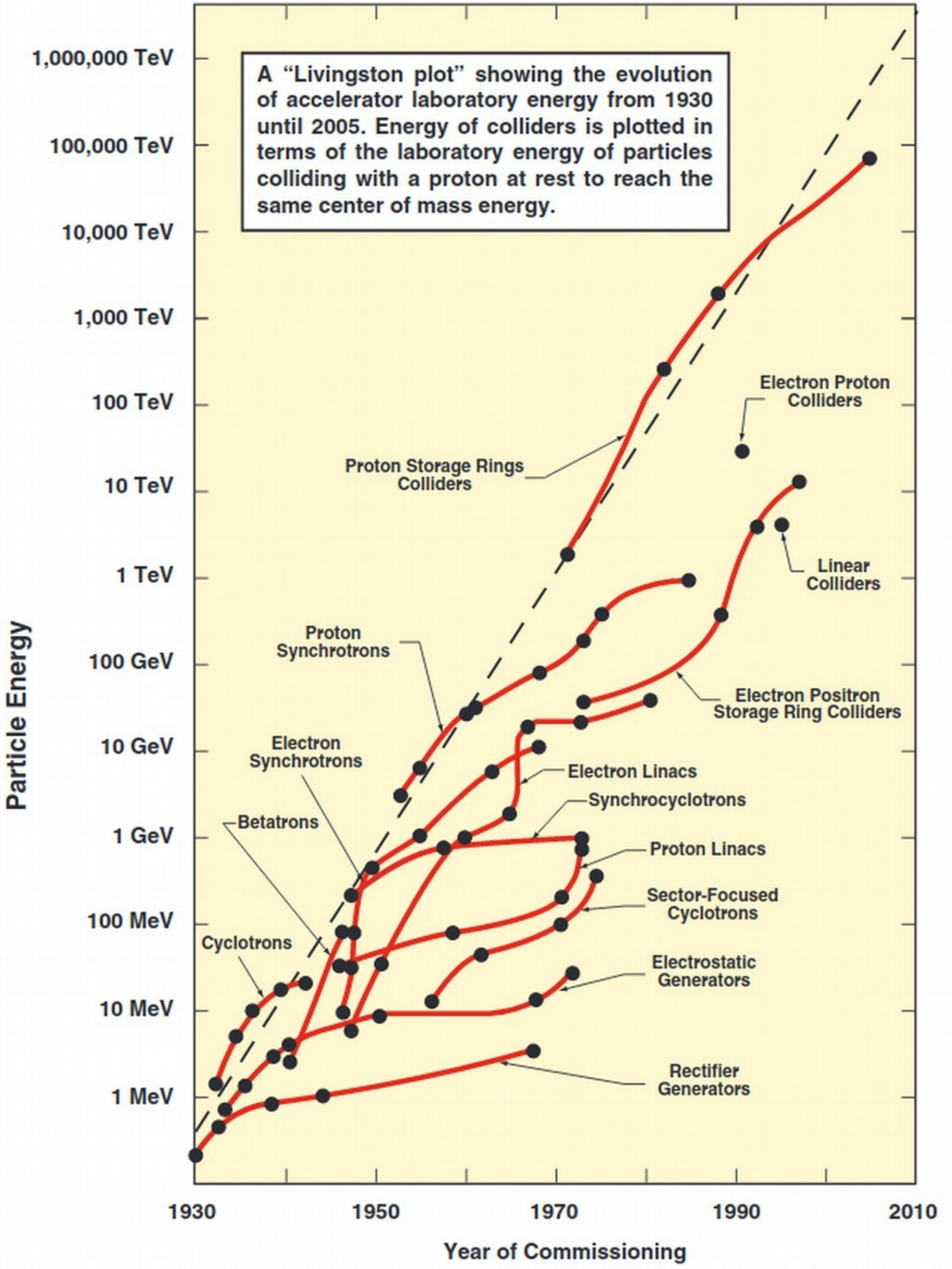
Principle	Energy	Velocity	Orbit	Field	Frequency	Particle flux
	γ	v	ρ	B	f_{rf}	
Microtron	var.	c	~p	const.	const.	const.
Cyclotron	1	var.	~v	const.	const.	const.
Synchrocyclotron	var.	var.	~p	$B(\rho)$	$\sim B(\rho)/\gamma(t)$	pulsed
Isochron cyclotron	var.	var.	$\rho(p)$	$B(\rho,\phi)$	const.	const.
Proton synchrotron	var.	var.	R	~p(t)	~v(t)	pulsed
Electron synchrotron	var.	c	R	~p(t)	const.	pulsed

70 Years of progress

Livingston chart 12 orders of magnitudes over 70 years.

A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.





A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.

International Linear Collider

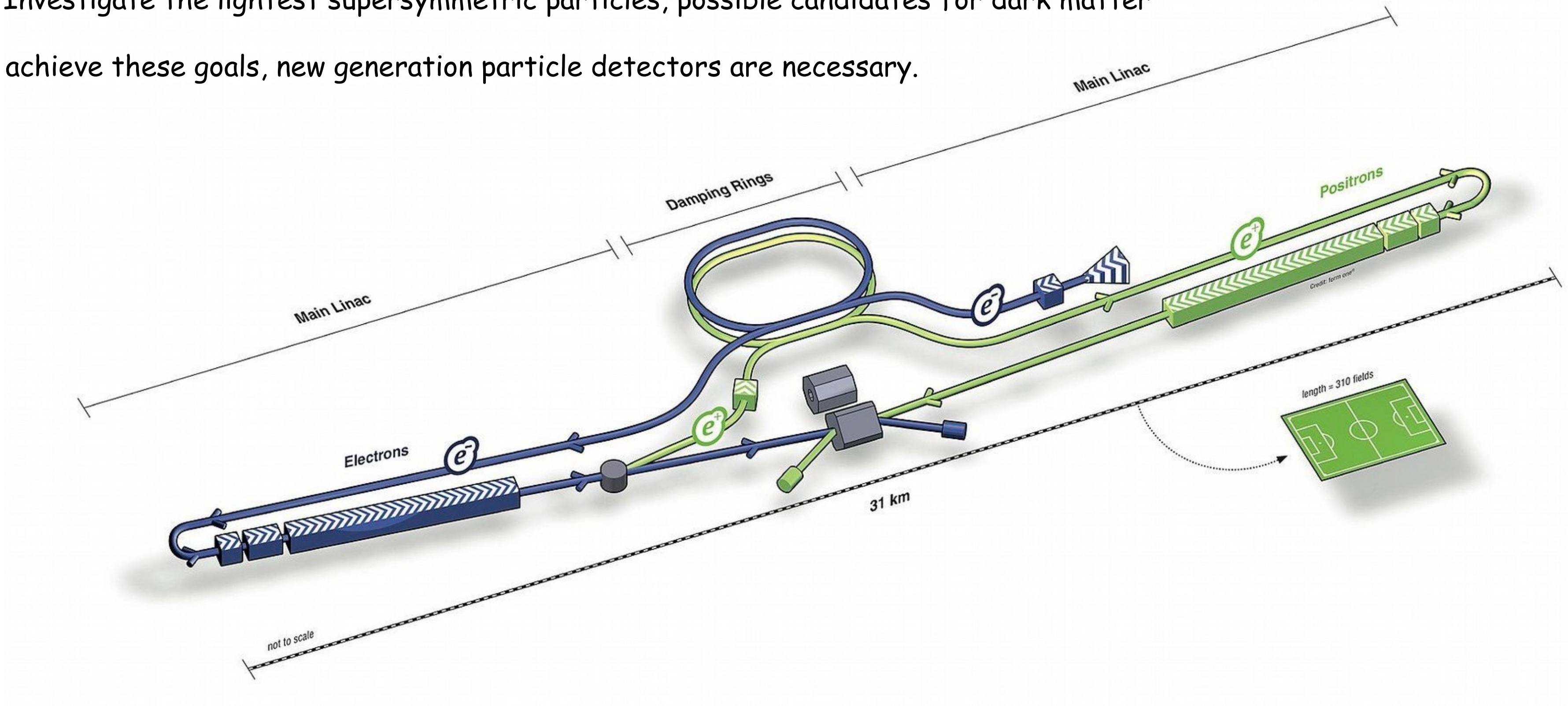
https://en.wikipedia.org/wiki/International_Linear_Collider

It is planned to have a collision energy of **500 GeV** initially, with the possibility for a later upgrade to **1 TeV**

It is widely expected that effects of physics beyond that described in the current Standard Model will be detected by experiments at the proposed ILC. In addition, particles and interactions described by the Standard Model are expected to be discovered and measured. At the ILC physicists hope to be able to:

- Measure the mass, spin, and interaction strengths of the Higgs boson
- If existing, measure the number, size, and shape of any TeV-scale extra dimensions
- Investigate the lightest supersymmetric particles, possible candidates for dark matter

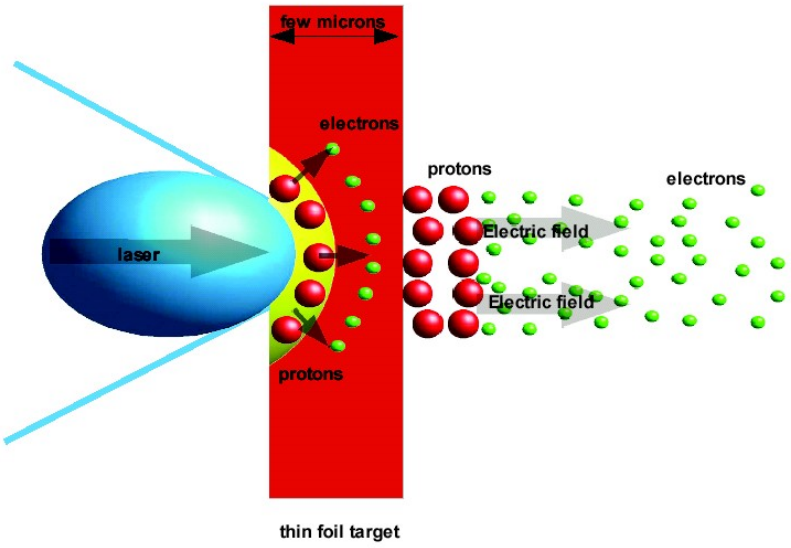
To achieve these goals, new generation particle detectors are necessary.

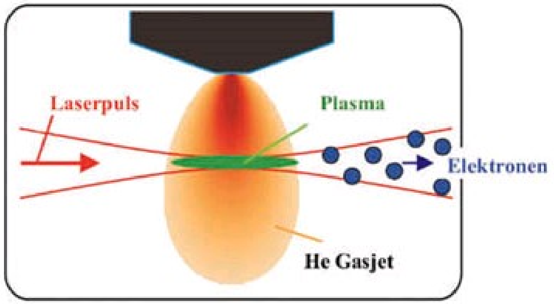


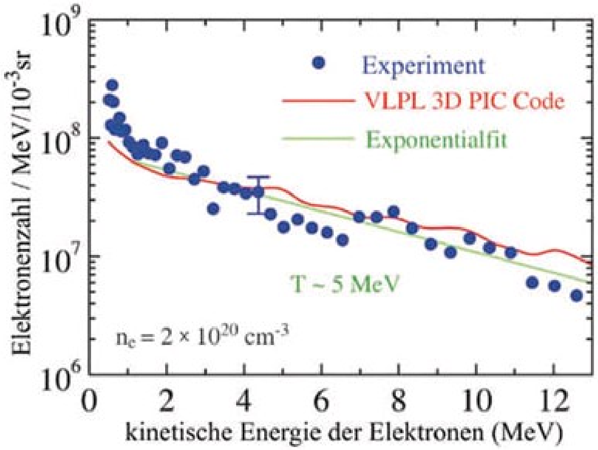
Plasma accelerator

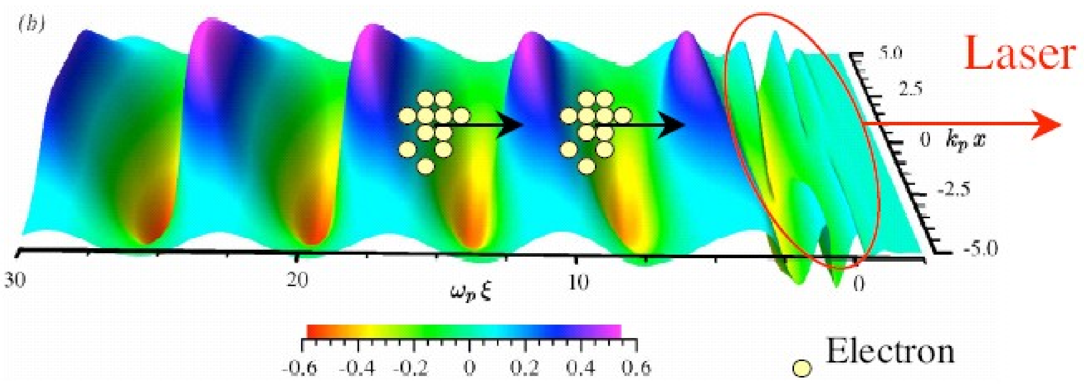
https://en.wikipedia.org/wiki/Plasma_acceleration

The plasma acceleration structures are created either using ultra-short laser pulses or energetic particle beams that are matched to the plasma parameters.

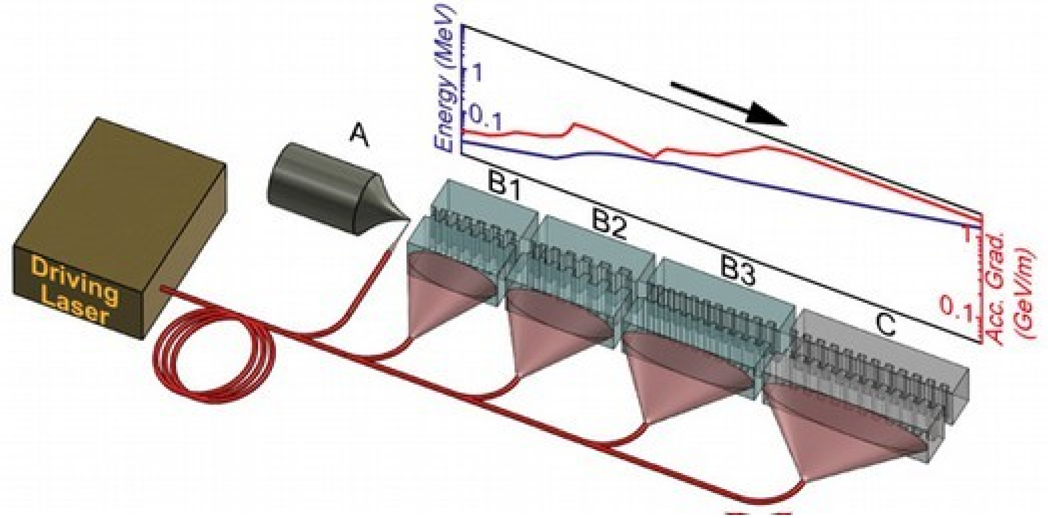


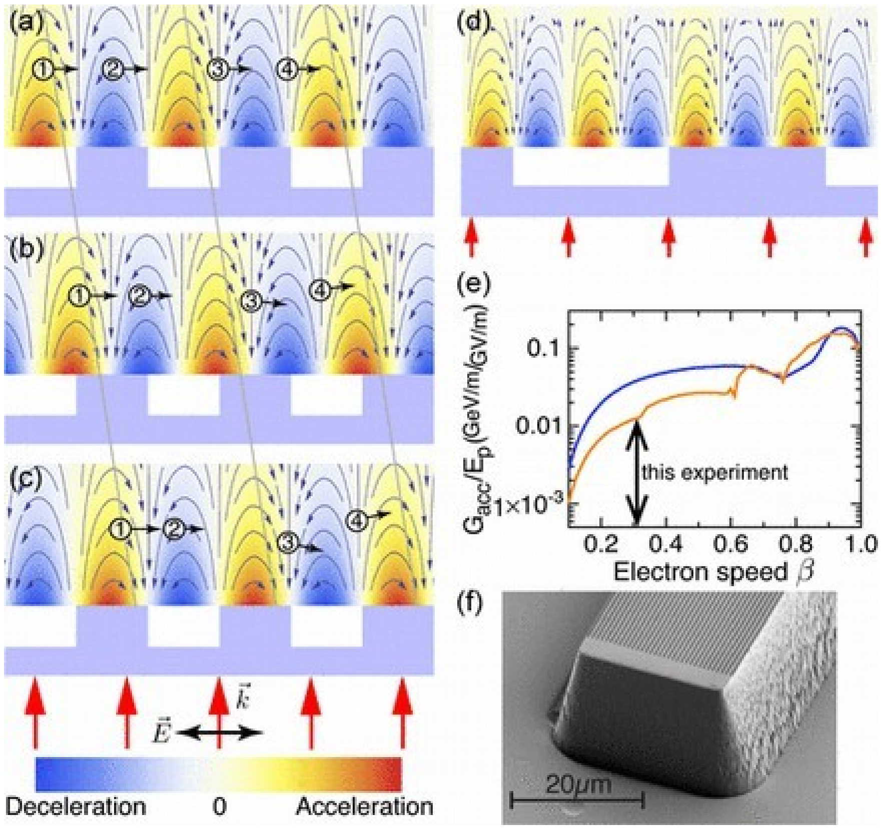






Laser-Based Acceleration





Electrons can be accelerated to the speed of light in several layers and charged with relativistic energies. The electrons from source A initially flow through sections B1 to B3, where they are not relativistically accelerated. In section C, they no longer become faster, but they gain even more energy. For the relativistic acceleration in sections B1 to B3, the gaps between the grooves in the grating must become bigger to facilitate continuous acceleration. A single laser delivers the energy for the acceleration. In the background, the acceleration in gigaelectron volts per meter experienced by the electrons is shown in red. The blue line shows the energy of the particles at the relevant point in the channel. The image is not to scale – the grating structures are smaller than one micrometer

DOI: http://dx.doi.org/10.1103/PhysRevLett.111.134803