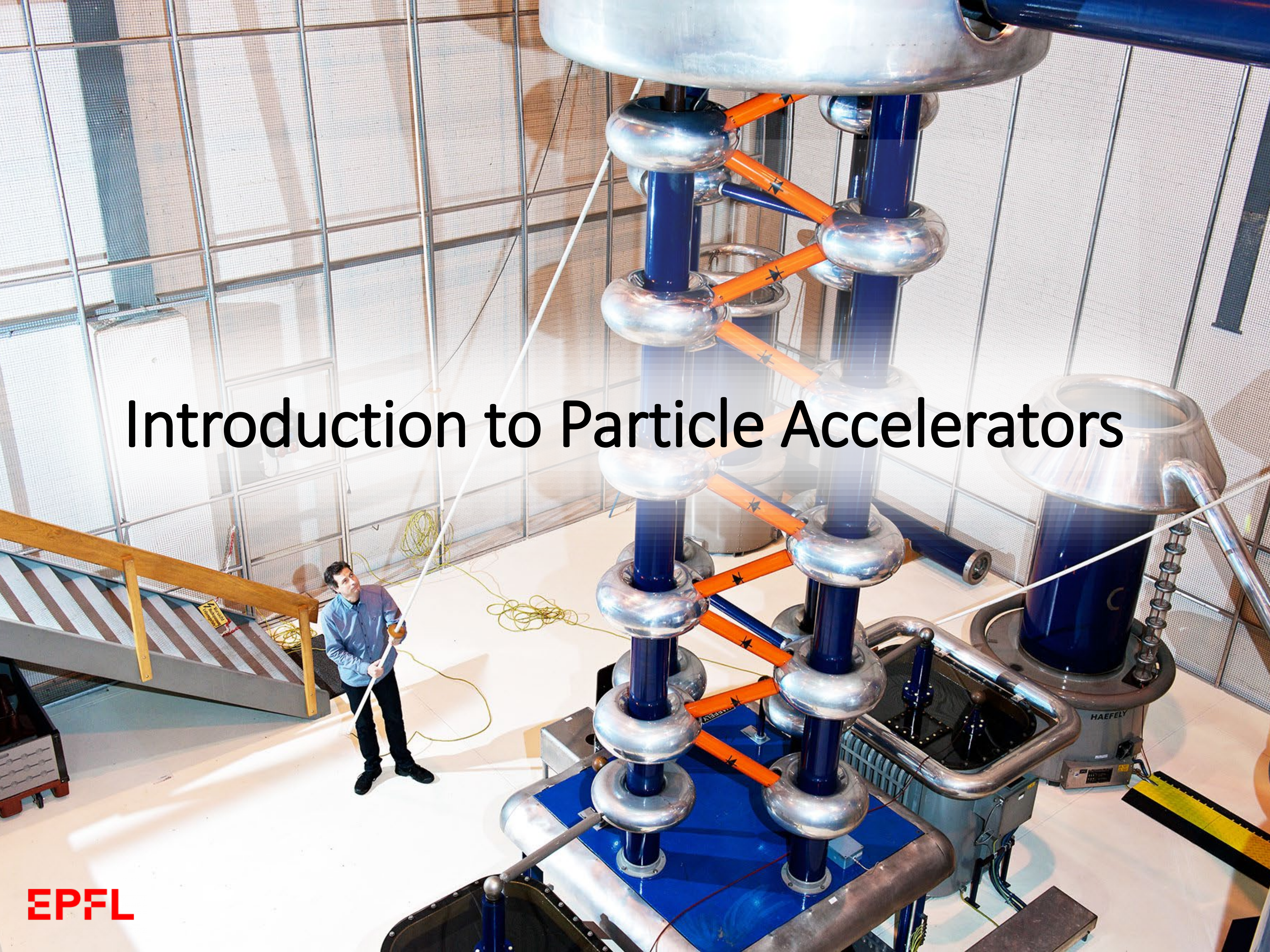
Introduction to Particle Accelerators



EPFL

LPAP
Laboratory for Particle Accelerator Physics

LPAP Team:

Christophe Lannoy, EPFL/CERN	christophe.lannoy@epfl.ch
Yi Wu, EPFL/CERN	yi.wu@epfl.ch
Raziyeh Dadashi, EPFL/PSI	raziyeh.dadashimotlagh@epfl.ch
Leon van Riesen-Haupt, EPFL	leon.vanriesen-haupt@epfl.ch
Werner Herr, CERN/EPFL	werner.herr@epfl.ch
Tatiana Pieloni, EPFL	tatiana.pieloni@epfl.ch
Mike Seidel, EPFL / PSI	mike.seidel@epfl.ch

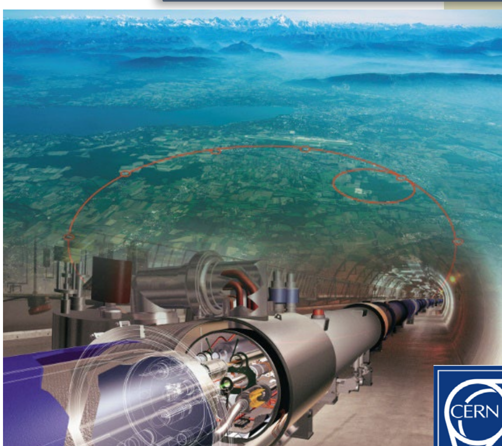
Accelerators connect CERN, PSI and EPFL

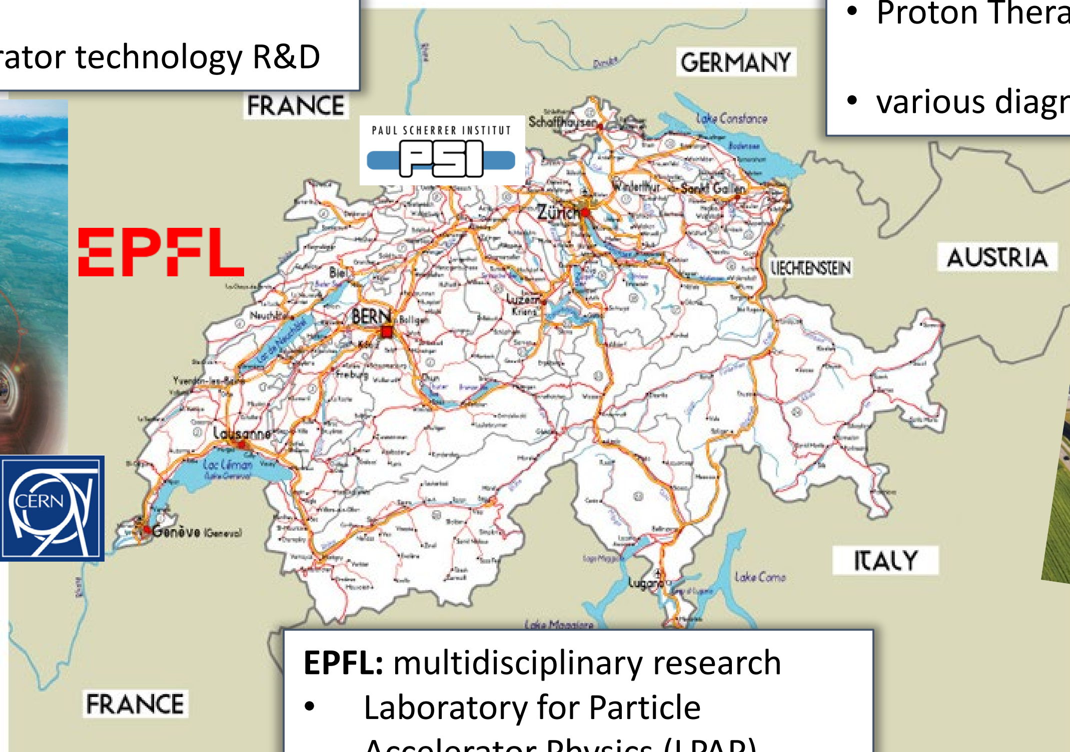
CERN
- Large Hadron Collider + upgrade
- FCC studies (hh, ee, eh)
- CLIC linear collider study

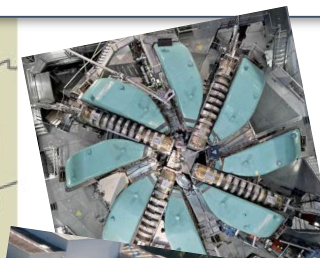
- various accelerator technology R&D

PSI
- Synchrotron Light Source
- Free Electron Laser
- High Intensity Proton Accelerator
- Proton Therapy

- various diagnostic methods at RIs







EPFL: multidisciplinary research
- Laboratory for Particle Accelerator Physics (LPAP)
- Swiss Plasma Center
- advanced manufacturing
- computer science

Accelerator Concepts, their History and their Applications

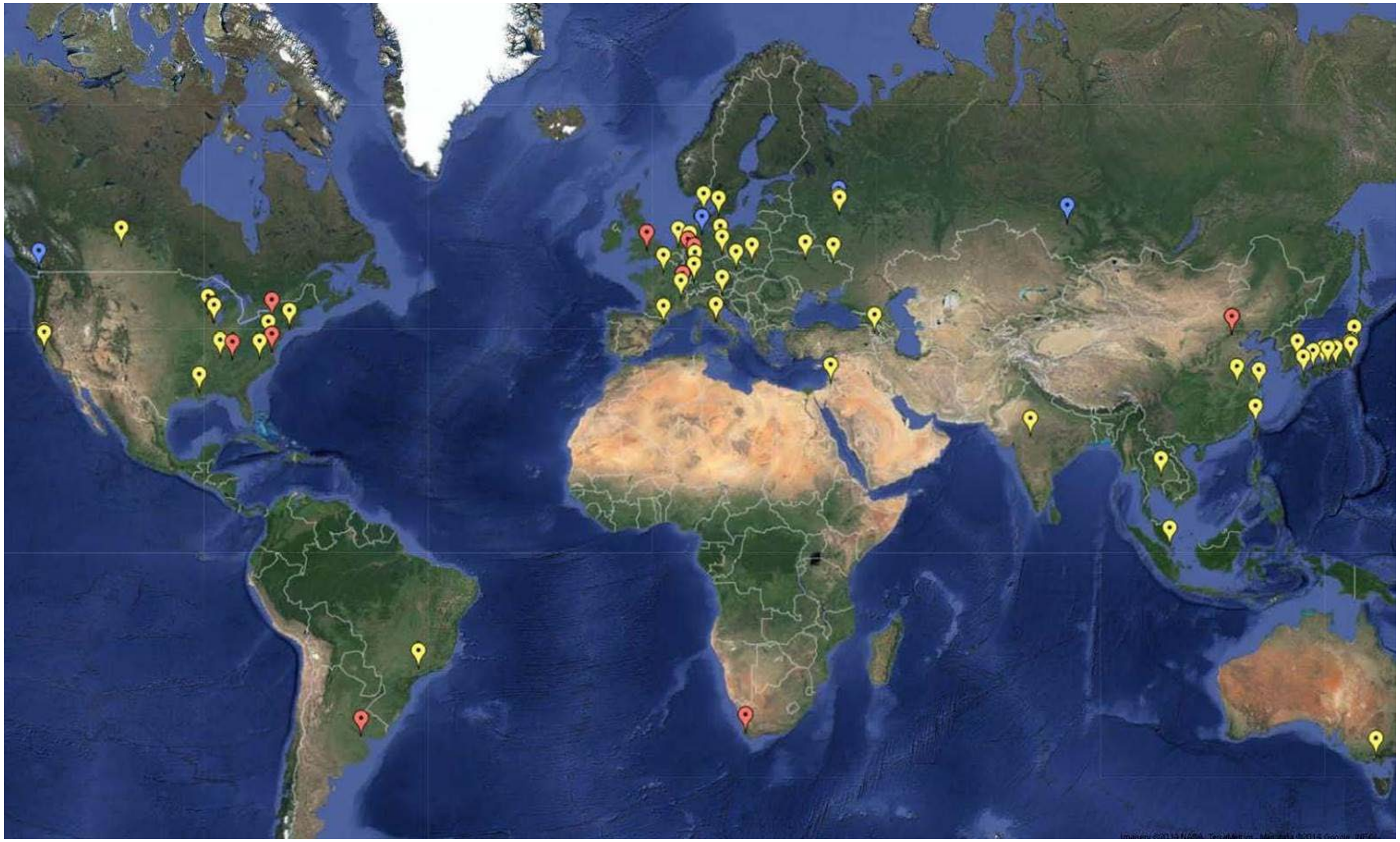
Laboratory for Particle Accelerator Physics, EPFL

EPFL

World Accelerators:
instruments for science and industry

>30'000 accelerators

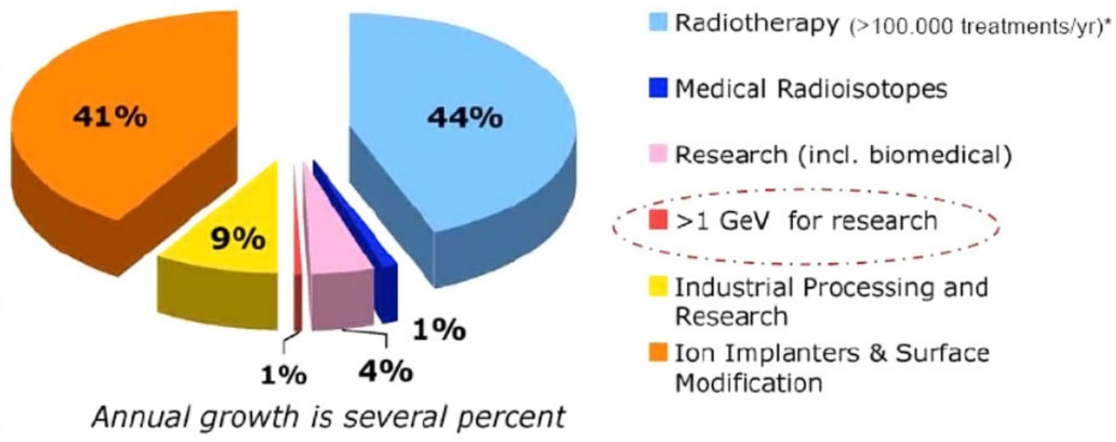
- 2 G$ market
- 500 G$ of goods produced with accelerators



Accelerators: Applications

>30.000 accelerators worldwide
Figure: distribution by the number

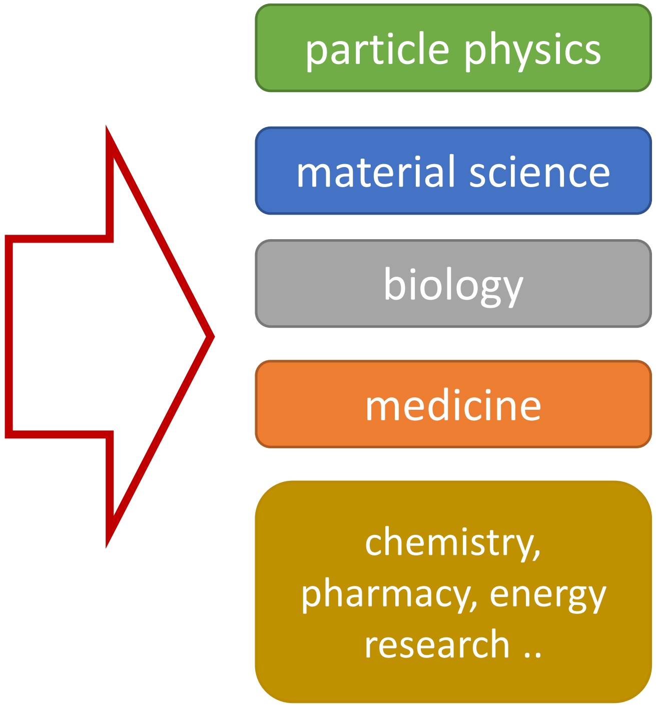
large research infrastructures (LHC, E-XFEL, FAIR, ESS, HERA) can cost Billions …



[Ph.LeBrun, JUAS]

Accelerators for Research: Motivation to build and develop them …

- particle colliders
- synchrotron light sources (brightness)
- free electron lasers (time resolution)
- neutron sources
- other particle sources (neutrinos, muons ..)
- cancer therapy accelerators (γ, p, C)



→ in most applications the accelerator is needed to generate secondary radiation: exotic particles, X-rays, neutrons …

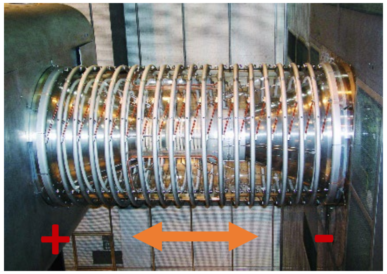
Acceleration of Particles?

	Mass	Acceleration	Velocity
Motorcycle	300 kg	1 g	0.085 km/s
Bullet	0.004 kg	10^5 g	1 km/s
Proton	$1{,}7\times10^{-27}$ kg	10^{13} g	12.000 km/s (4.1 % × c)
Electron	$9{,}1\times10^{-31}$ kg	2×10^{16} g	275.000 km/s (92 % × c)

factor 2000 (proton vs. electron mass)

810 kV (proton and electron)

example: acceleration of particles in Cockcroft Walton at PSI

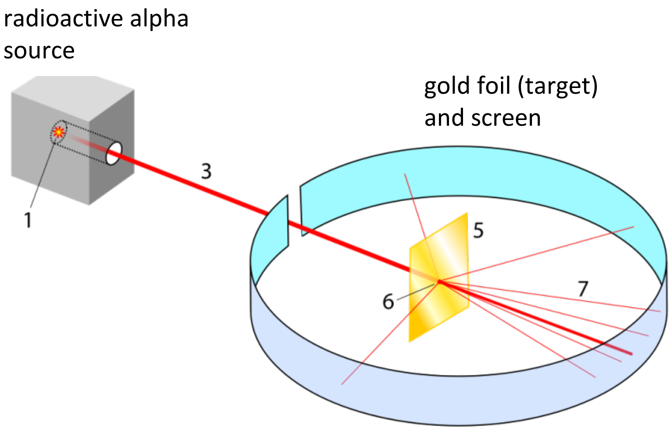


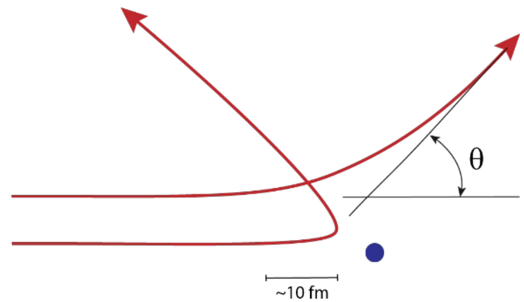
0.8 m, 810 kV

→ particles are quickly «relativistic»

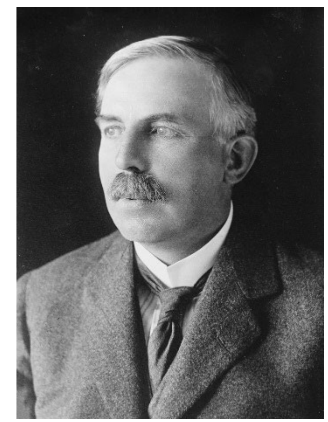
→ electrons and protons behave quite differently

Rutherford scattering
- a model for accelerator applications





$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin^4(\theta/2)}$$



[Ernest Rutherford, Nobel Prize 1908]

… results showed that around 1 in 8000 alpha particles were deflected by very large angles (over 90°) … [Wikipedia]

Lord Rutherford (1927 @ Royal Society):

“I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances”.

→ today a main application for accelerators is to generate tailored radiation for scattering experiments

examples for probing matter at different energies

	Energy	equivalent wavelength
alpha from rad.decay	**4.9 MeV**	**6.4 fm**
thermal neutrons	**0.025 eV**	**1.8 Å**
photons, SR	**12.4 keV**	**1 Å**
high energy electrons	**100 GeV**	**10^{-17} m**
LHC protons	**7 TeV**	**2×10^{-19} m**

Rutherford

(1Å = 10^{-10}m, 1fm = 10^{-15}m)

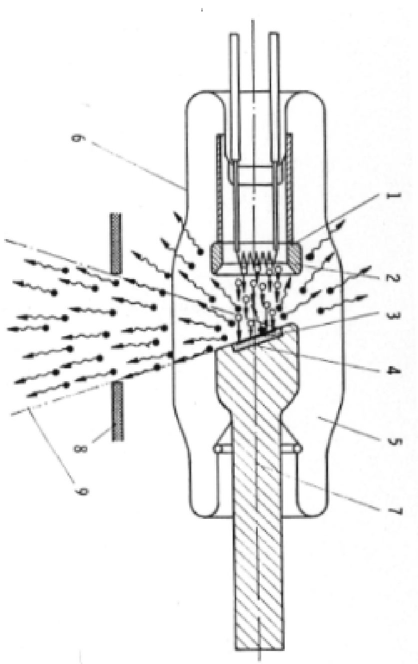
the **de Broglie wavelength** sets the length scale for objects under study using scattering

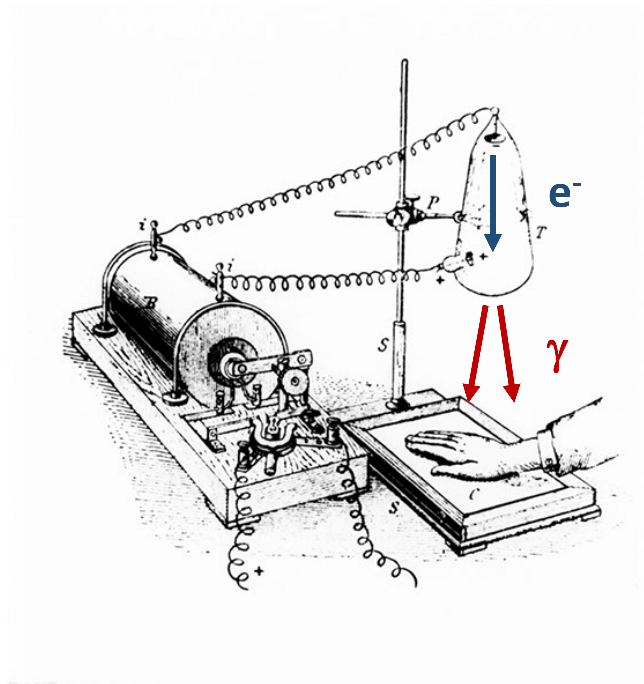
$$\lambda = \frac{h}{p} = \begin{cases} \frac{hc}{E_k} & \text{for } v \approx c, \\ \frac{hc}{\sqrt{2m_0c^2E_k}} & \text{for } v \ll c. \end{cases}$$

$$hc = 1.24 \text{ GeVfm}$$

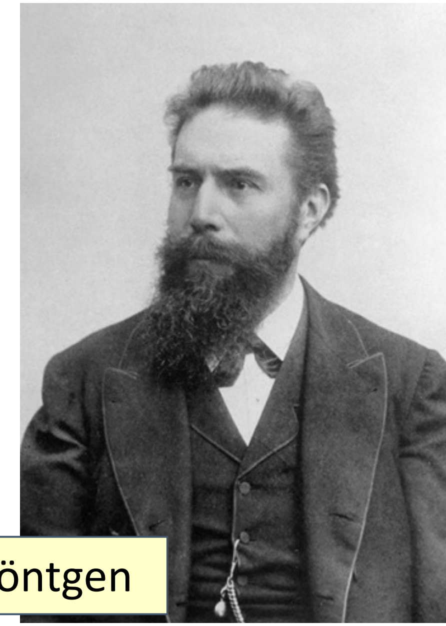
$$hc = 12.4 \text{ keV}\mathring{A}$$

Roentgen Image (1896)



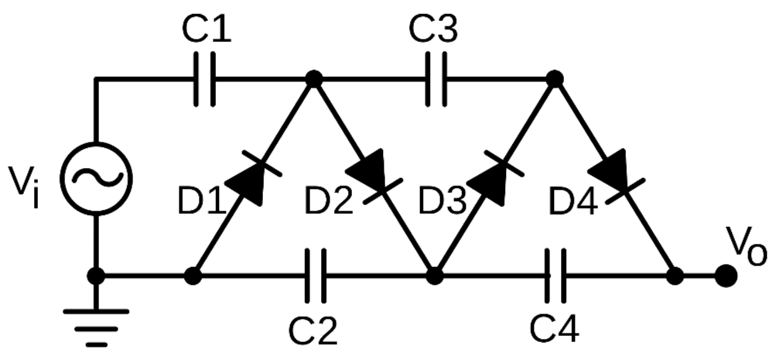


X-rays: secondary radiation generated by an „accelerator“

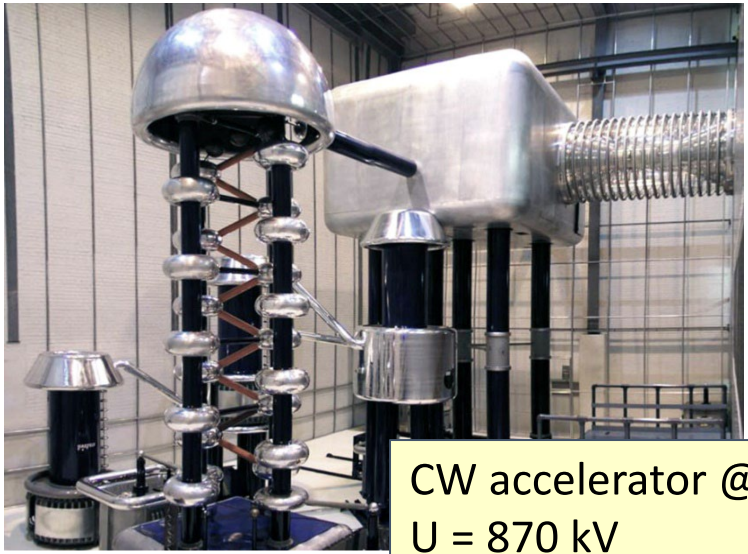


W.C.Röntgen

Cockcroft Walton (DC) Accelerator



cascade circuit to generate high voltages



CW accelerator @ PSI
U = 870 kV

In 1932 Cockcroft and Walton used this circuit design to power their particle accelerator, performing the first artificial nuclear disintegration.

The Nobel Prize in Physics 1951

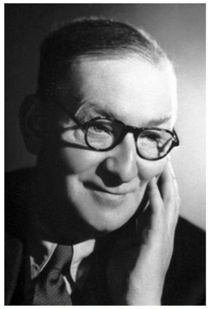


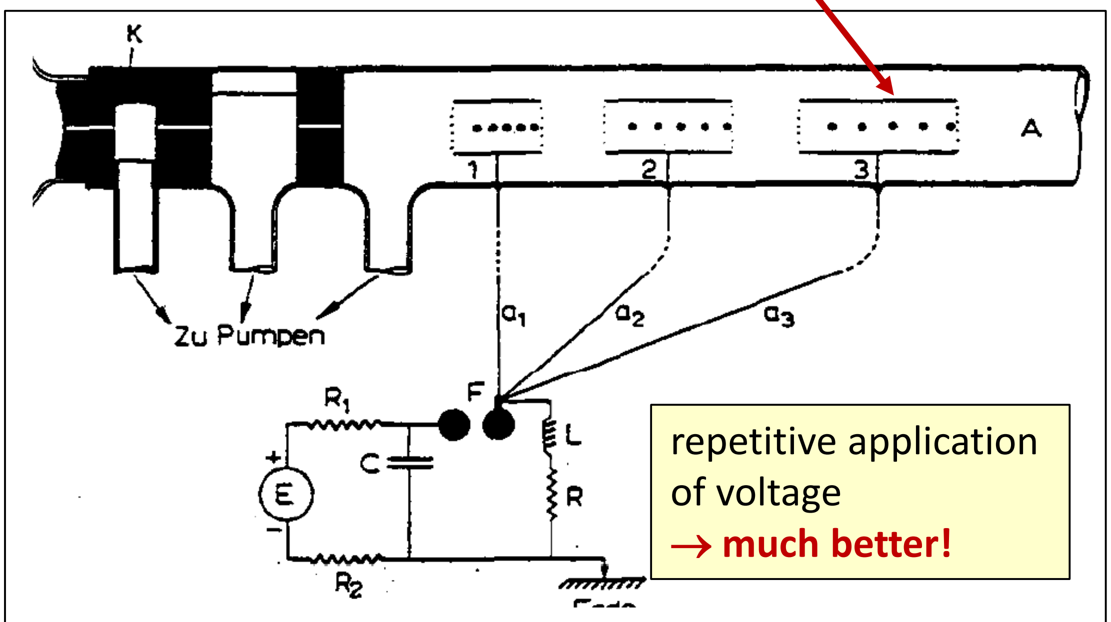
Photo from the Nobel Foundation archive.
Sir John Douglas Cockcroft

Photo from the Nobel Foundation archive.
Ernest Thomas Sinton Walton

First proposal for a linear accelerator

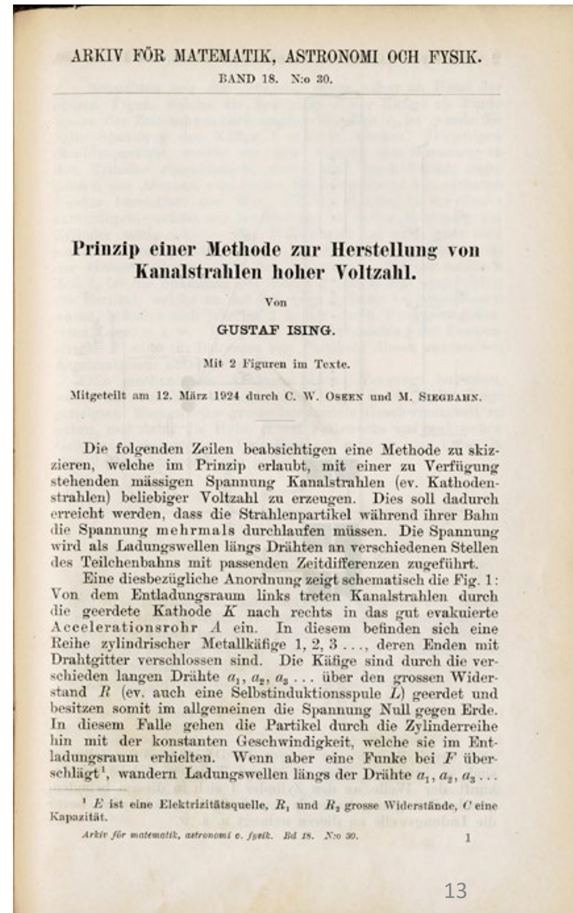
1924: Gustav Ising, Prof. at the technical university Stockholm

$L \propto v$



repetitive application of voltage

→ **much better!**



ARKIV FÖR MATEMATIK, ASTRONOMI OCH FYSIK.
BAND 18. N:o 30.

Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

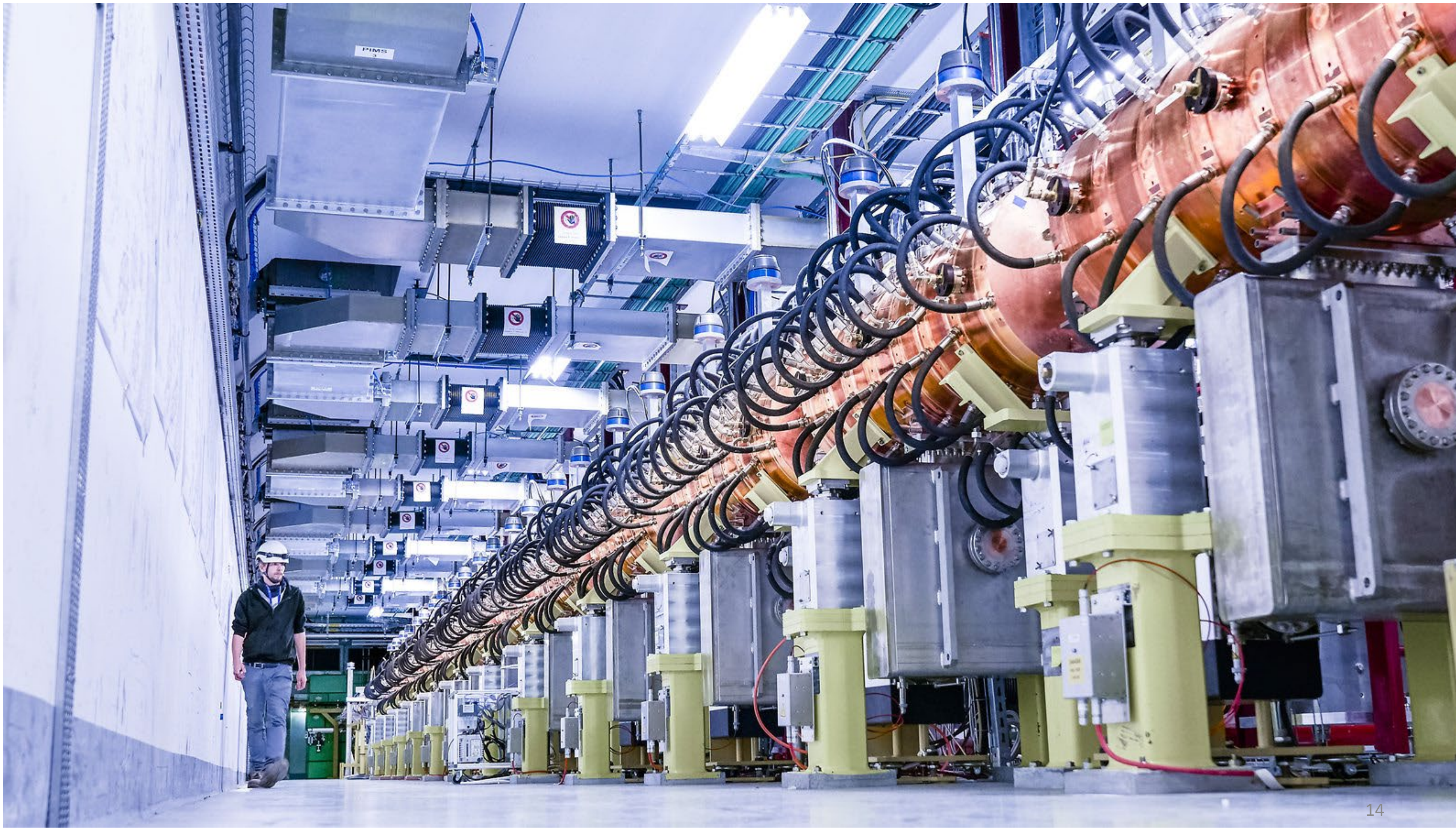
Mitgeteilt am 12. März 1924 durch C. W. OSEEN und M. SIEGBAHN.

Die folgenden Zeilen beabsichtigen eine Methode zu skizzieren, welche im Prinzip erlaubt, mit einer zu Verfügung stehenden mässigen Spannung Kanalstrahlen (ev. Kathodenstrahlen) beliebiger Voltzahl zu erzeugen. Dies soll dadurch erreicht werden, dass die Strahlenpartikel während ihrer Bahn die Spannung mehrmals durchlaufen müssen. Die Spannung wird als Ladungswellen längs Drähten an verschiedenen Stellen des Teilchenbahns mit passenden Zeitdifferenzen zugeführt.

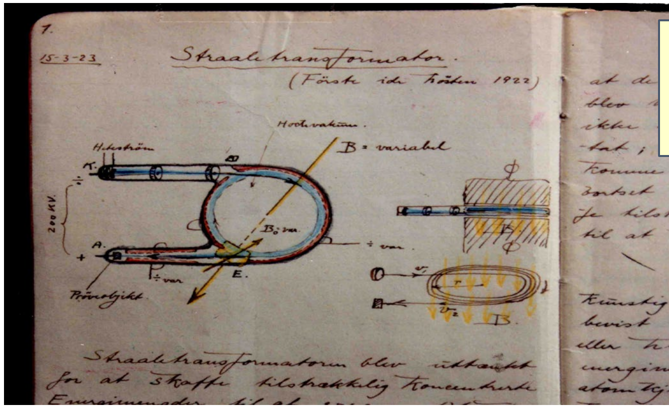
Eine diesbezügliche Anordnung zeigt schematisch die Fig. 1: Von dem Entladungsraum links treten Kanalstrahlen durch die geerdete Kathode K nach rechts in das gut evakuierte Accelerationsrohr A ein. In diesem befinden sich eine Reihe zylindrischer Metallkäfige 1, 2, 3 . . ., deren Enden mit Drahtgitter verschlossen sind. Die Käfige sind durch die verschieden langen Drähte $a_1, a_2, a_3 \ldots$ über den grossen Widerstand R (ev. auch eine Selbstinduktionsspule L) geerdet und besitzen somit im allgemeinen die Spannung Null gegen Erde. In diesem Falle gehen die Partikel durch die Zylinderreihe hin mit der konstanten Geschwindigkeit, welche sie im Entladungsraum erhielten. Wenn aber eine Funke bei F überschlägt[1], wandern Ladungswellen längs der Drähte $a_1, a_2, a_3 \ldots$

[1] E ist eine Elektrizitätsquelle, R_1 und R_2 grosse Widerstände, C eine Kapazität.

CERN LINAC 4 160 MeV (90 meter linac)



Rolf Wideröe: Betatron (1927)



Wideröes Notebook

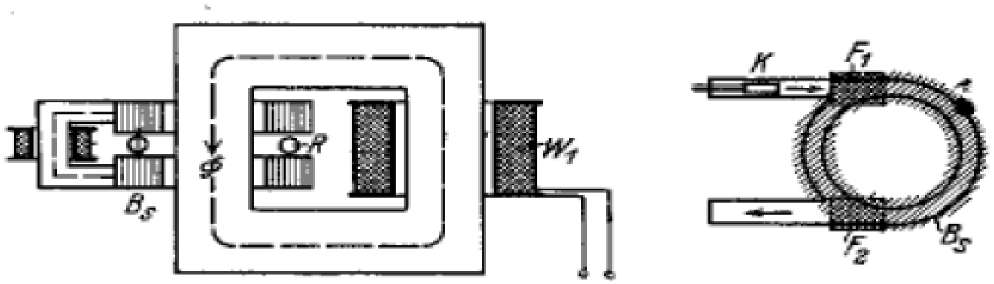
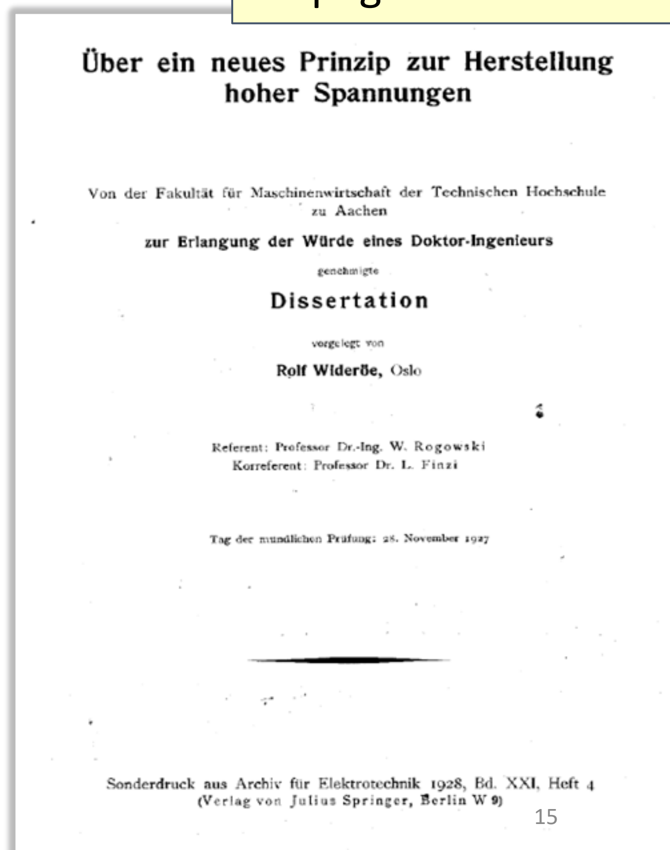


Bild 11. Wirkungsweise des Strahlentransformators.

Wideröe calls the idea Beams-Transformer, meaning the beam replaces the secondary winding in a transformer

$$\dot{\vec{B}} = -\nabla \times \vec{E}$$

Dissertation Aachen, 27 pages!



Über ein neues Prinzip zur Herstellung hoher Spannungen

Von der Fakultät für Maschinenwirtschaft der Technischen Hochschule zu Aachen

zur Erlangung der Würde eines Doktor-Ingenieurs

genehmigte

Dissertation

vorgelegt von

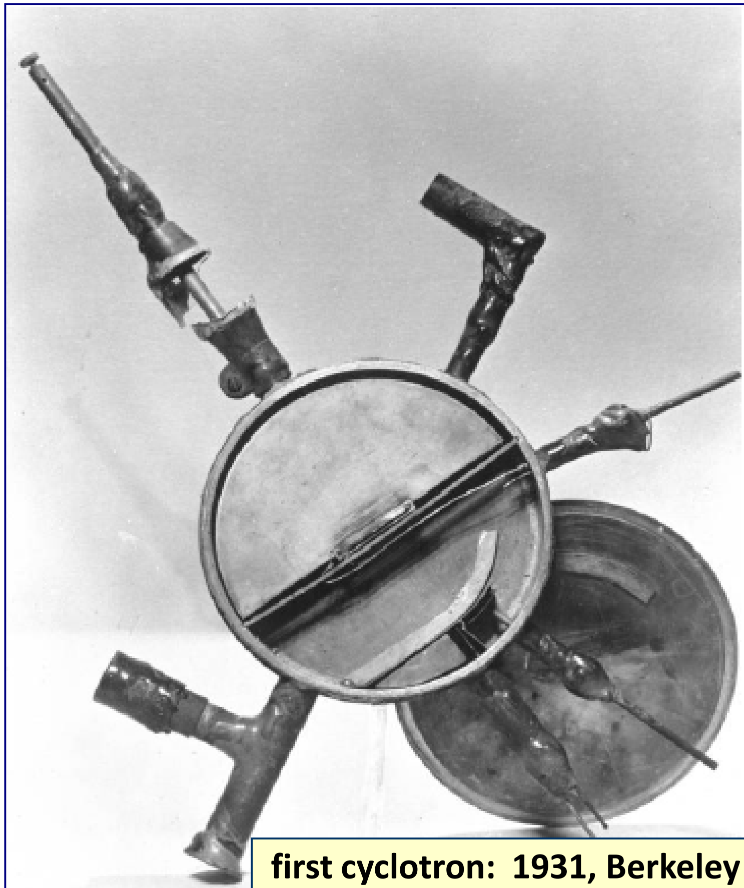
Rolf Wideröe, Oslo

Referent: Professor Dr.-Ing. W. Rogowski
Korreferent: Professor Dr. L. Finzi

Tag der mündlichen Prüfung: 28. November 1927

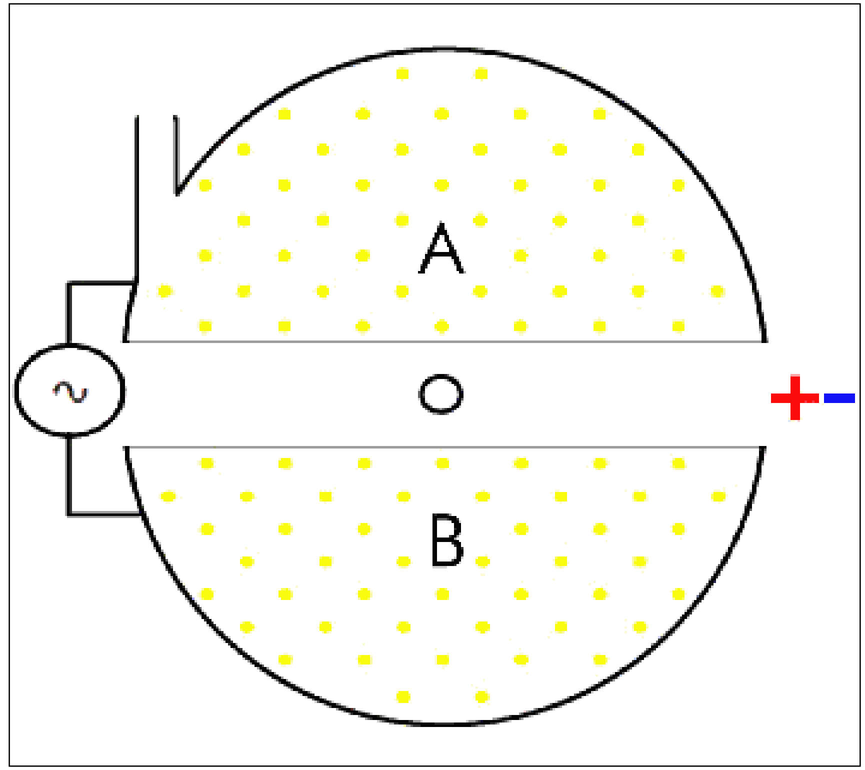
Sonderdruck aus Archiv für Elektrotechnik 1928, Bd. XXI, Heft 4
(Verlag von Julius Springer, Berlin W 9)

Resonant Acceleration: Cyclotron



first cyclotron: 1931, Berkeley

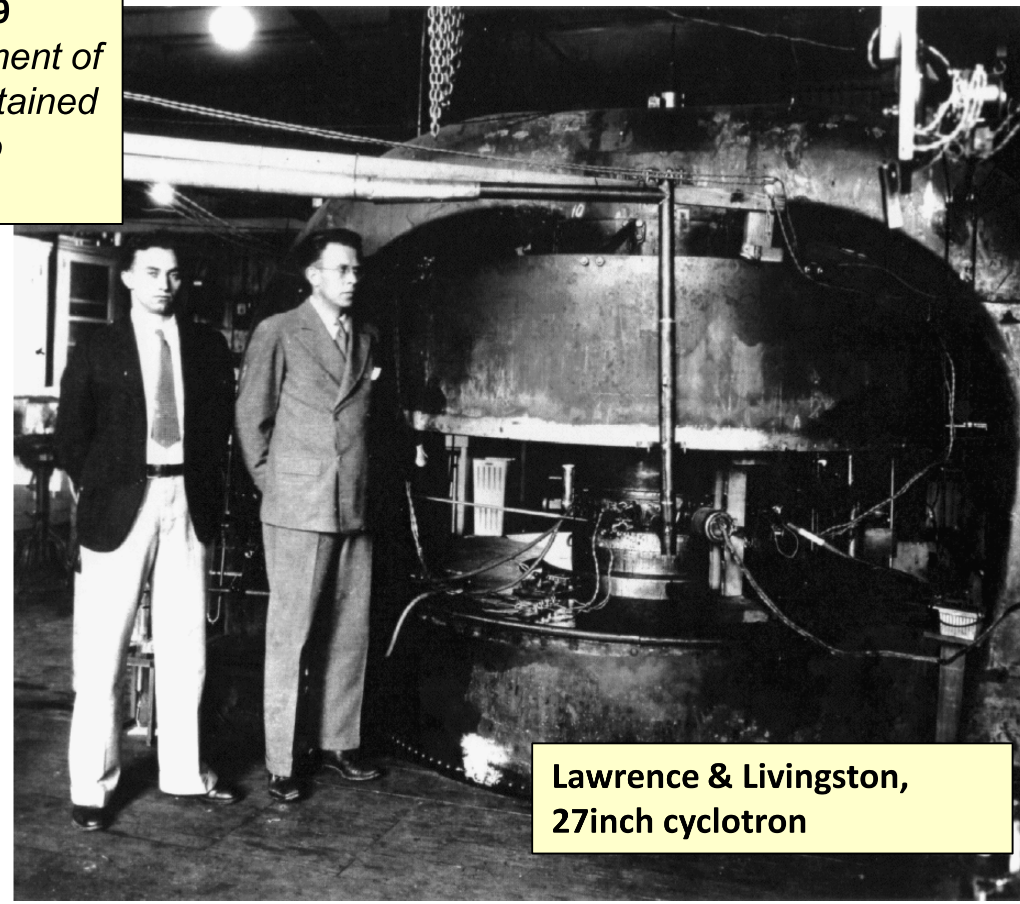
1kV gap voltage, 80keV Protons



Principle: alternating RF voltage
multiple acceleration steps

History of the Cyclotron

Ernest Lawrence, Nobelpreis 1939
"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"



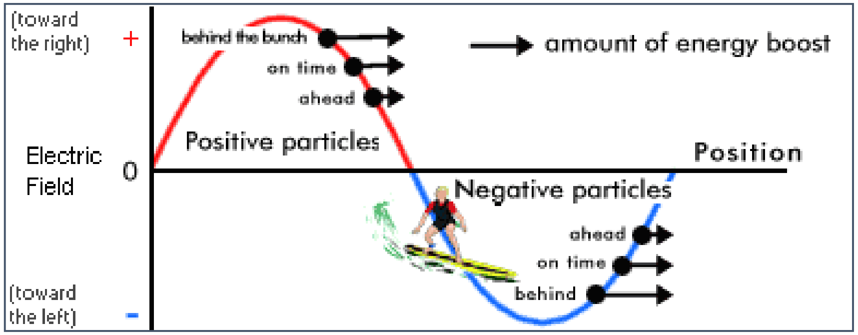
Lawrence & Livingston, 27inch cyclotron

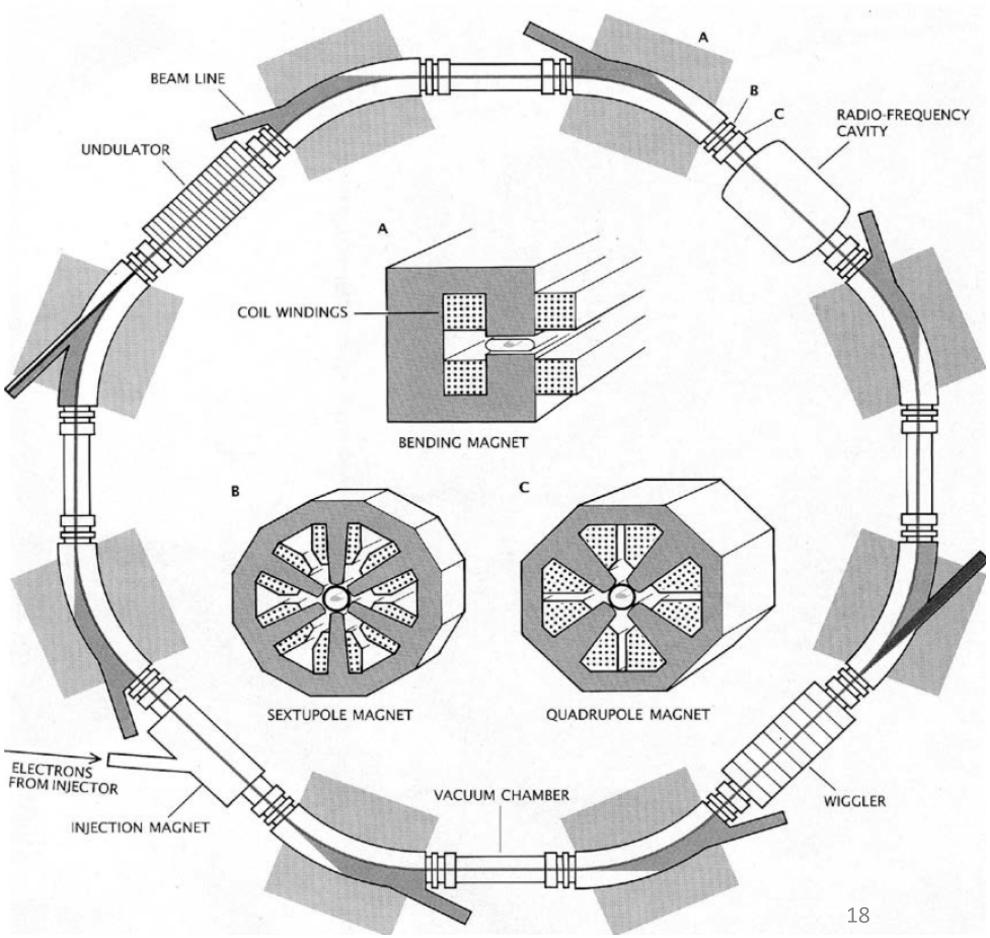
John Lawrence (center), 1940'ies
first medical application: treatment of cancer with neutrons using the 60inch Zyklotron

Synchrotron

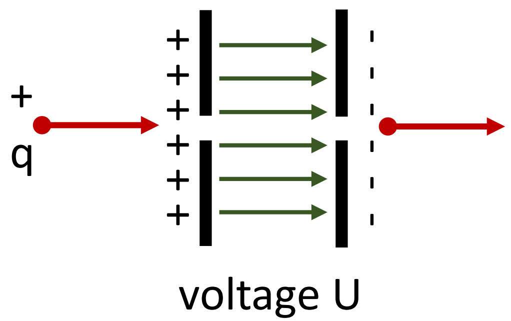
- McMillan (USA) and Veksler (UdSSR) independently in 1945
- concepts of phase stability (longitudinal focusing) and alternating gradient focusing

phase stability:
"surfing on the RF-wave"





Energy and Current



kinetic energy gain:

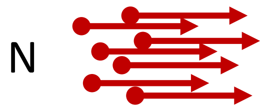
$$\Delta E_k = qU$$

units:

1eV = 1.602×10^{-19} Joule

1MeV = 10^6eV

1GeV = 10^9eV



current =
charge × #particles / time

$$I = qN/\tau$$

units:

1A = 1 C/s = 6.2×10^{18} particles/s

10nA = 10^{-8}A = 6.2×10^{10} particles/s
(e.g. cancer therapy)

basic relativistic relations


A.Einstein
1879-1955

relativistic energy-momentum relation:

$$E = \sqrt{m_0^2 c^4 + c^2 p^2}$$

$$E = m_0 c^2 + E_k$$

$$v = c\sqrt{1 - m_0^2 c^4 / E^2}$$

$$= \beta c$$

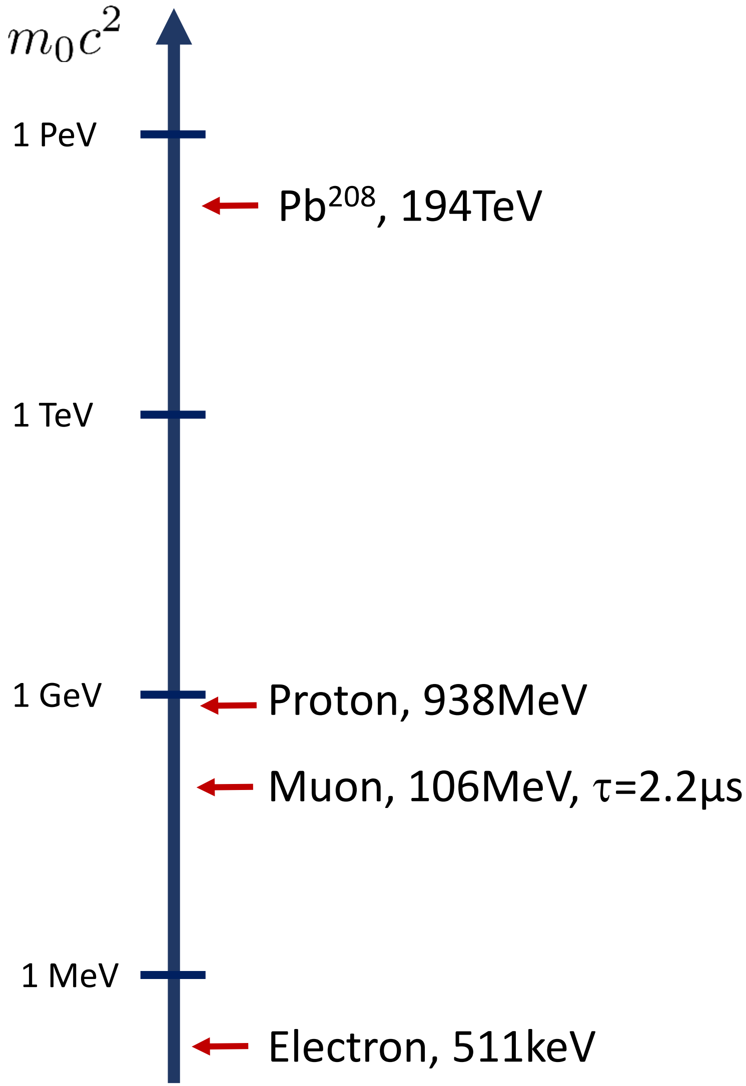
$$p = \beta c \cdot \gamma m_0$$

in the limit $E \rightarrow \infty$: $v \rightarrow c, \; m_{\text{eff}} \rightarrow \infty$

$$\gamma = \frac{E}{m_0 c^2} = 1 + \frac{E_k}{m_0 c^2}$$

$$\beta = \sqrt{1 - 1/\gamma^2}$$

Particles to Accelerate



Wide range of rest masses from electron to heavy ions

The accelerators differ vastly, e.g.

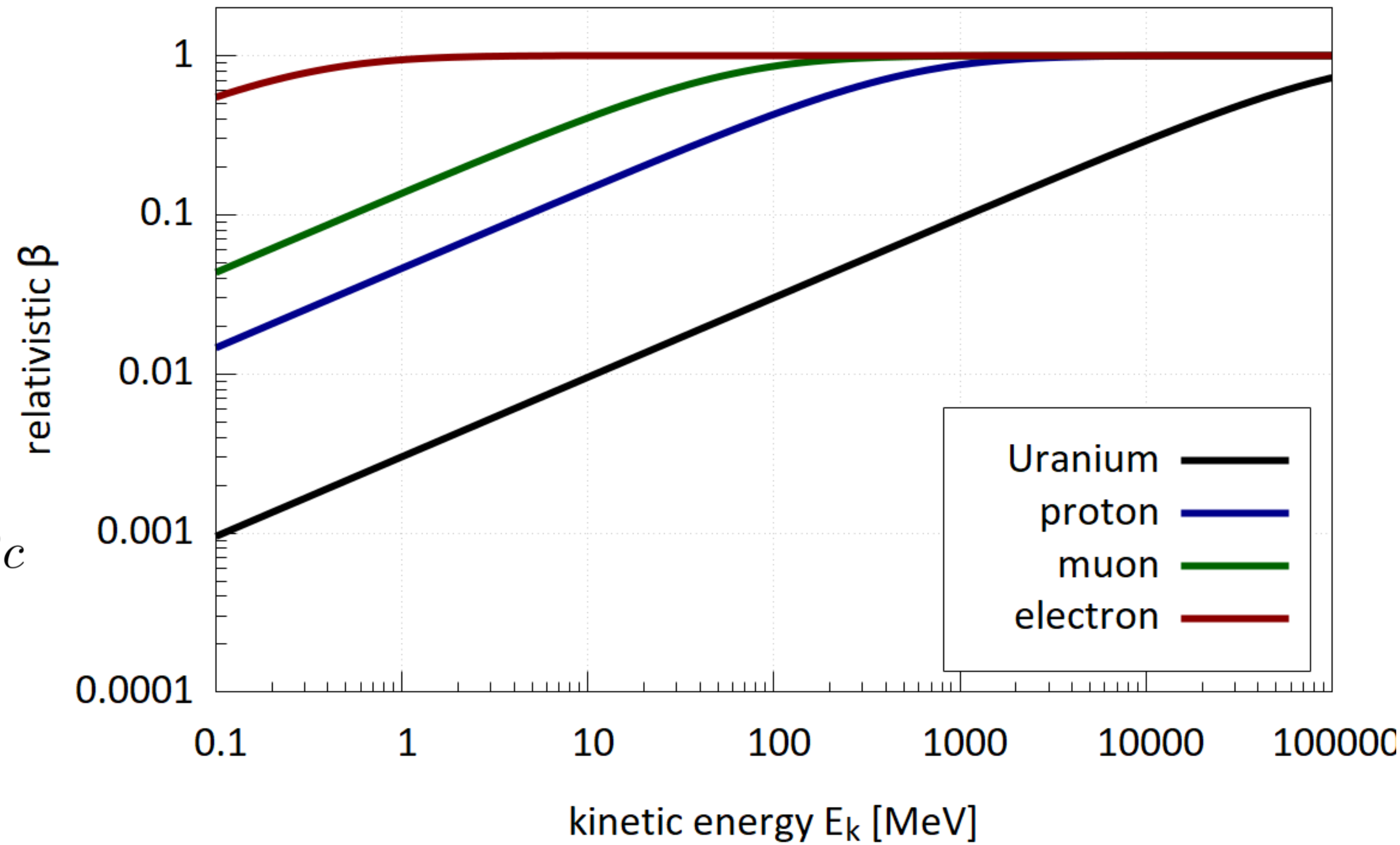
- particle speed in cavities
- synchrotron radiation power
- activation by losses
- requirements for vacuum

The muon as a heavy lepton is interesting for particle physics

$1\text{eV} = 1.602 \times 10^{-19}$ Joule

$1\text{eV} \cong 1.783 \times 10^{-36}$ kg

Speed of different particles vs energy

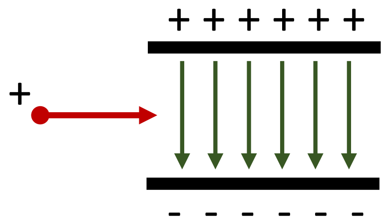


$$v = \beta c$$

Charged Particles in EM Fields?

call: **responseware.eu**, session ID: **accel21**

electric field

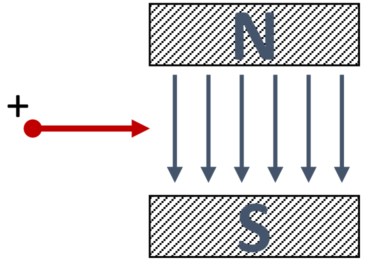


A. particle moves straight

B. path is bent, energy unchanged

C. path is bent, energy increased

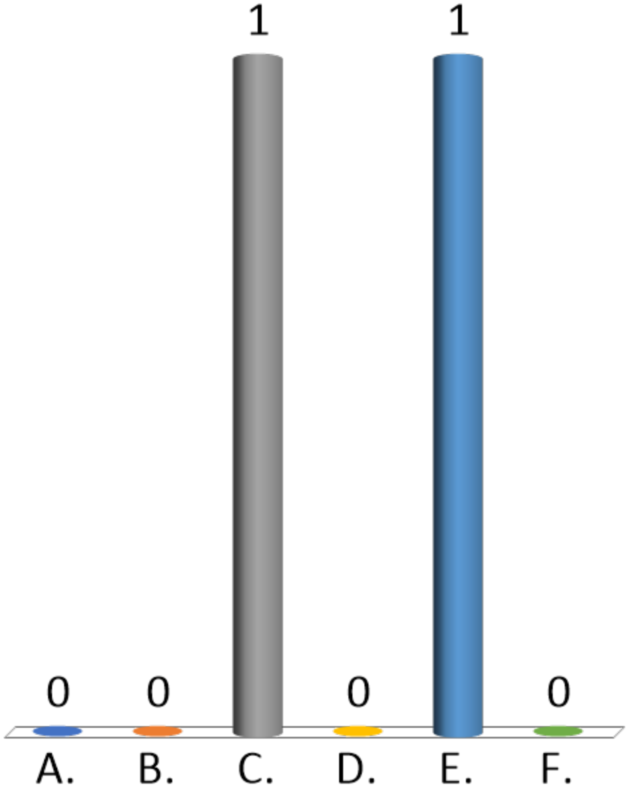
magnetic field



D. particle moves straight

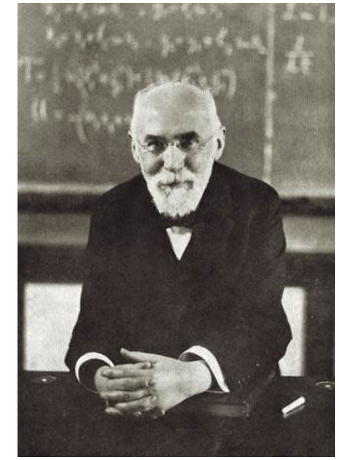
E. path is bend, energy unchanged

F. path is bent, energy increased



Lorentz Force

$$\vec{F} = e\vec{E} + e\vec{v} \times \vec{B}$$ (charge = e)



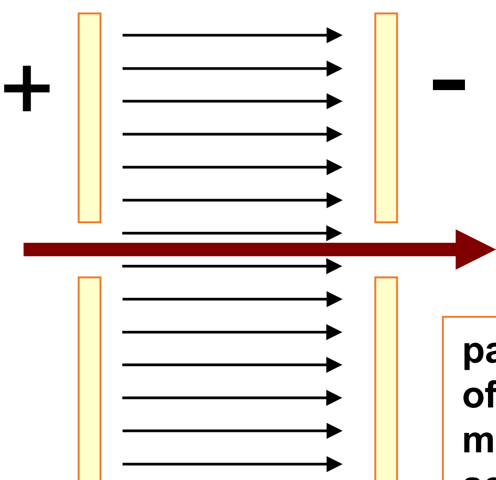
H.A.Lorentz
1853-1928

electric field

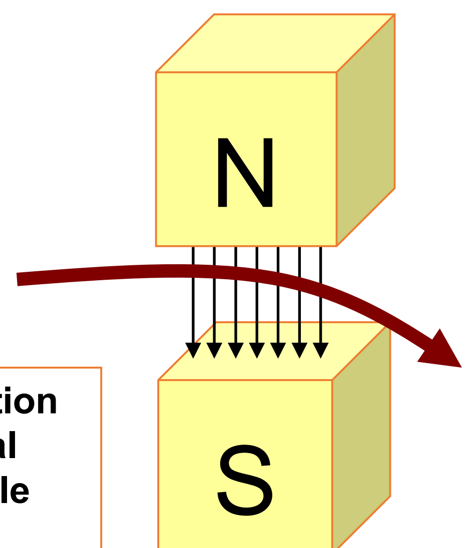
energy gain: $\Delta E_k = eU$

magnetic field

bending: $B\rho = p/e, \ \Delta E_k = 0$



path bending and acceleration of particles are fundamental mechanisms of each particle accelerator



in practical units:

$$B\rho = 3.3356\, p$$

$[\mathrm{Tm}]$ $[\mathrm{GeV/c}]$

[see appendix]

Next: Medical and Industrial Applications

- Overview on industrial applications
- Particle Therapy
- Isotopes

Accelerators: Essential Tools in Industry

Ion Implantation

- Accelerators can precisely deposit ions modifying materials and electrical properties (boron, phosphorus)

Semi Conductors

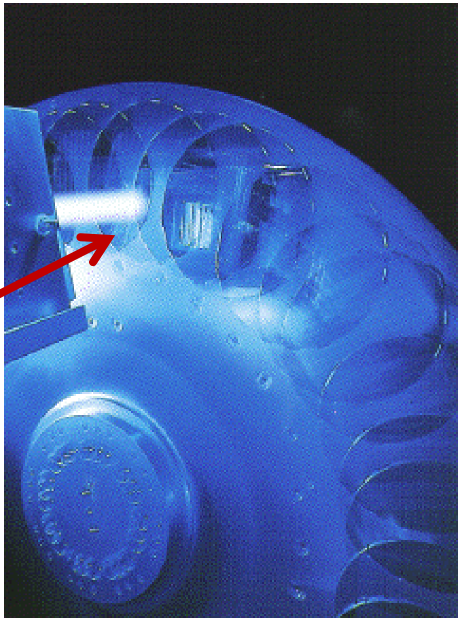
- CMOS transistor fabrication of essentially all IC's
- CCD & CMOS imagers for digital cameras
- Cleaving silicon for photovoltaic solar cells
- Typical IC may have 25 implant steps

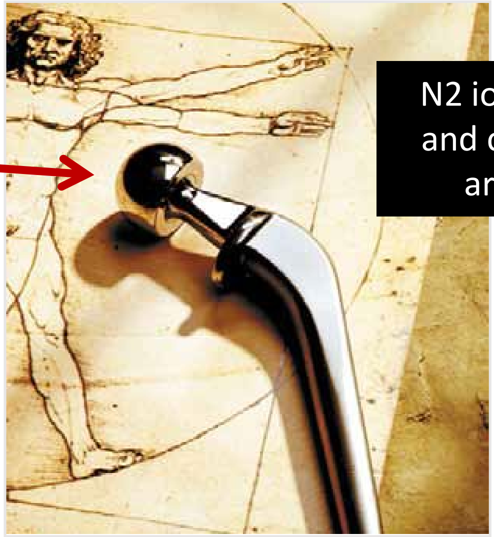
Metals

- Harden cutting tools
- Reducing friction
- Biomaterials for implants

Ceramics and Glasses

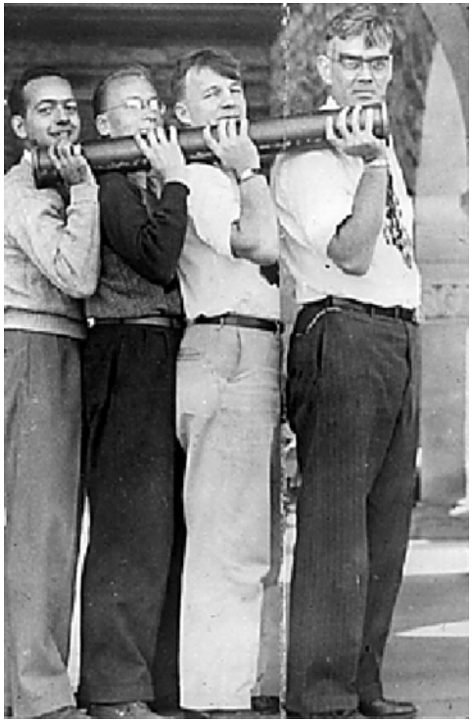
- Harden surfaces
- Modify optics
- Color in Gem stones!





X-Ray radiotherapy: using electron beams to produce X-Rays

Varian brothers started at Stanford



1947, 2 MeV/m
One meter long

50,000,000

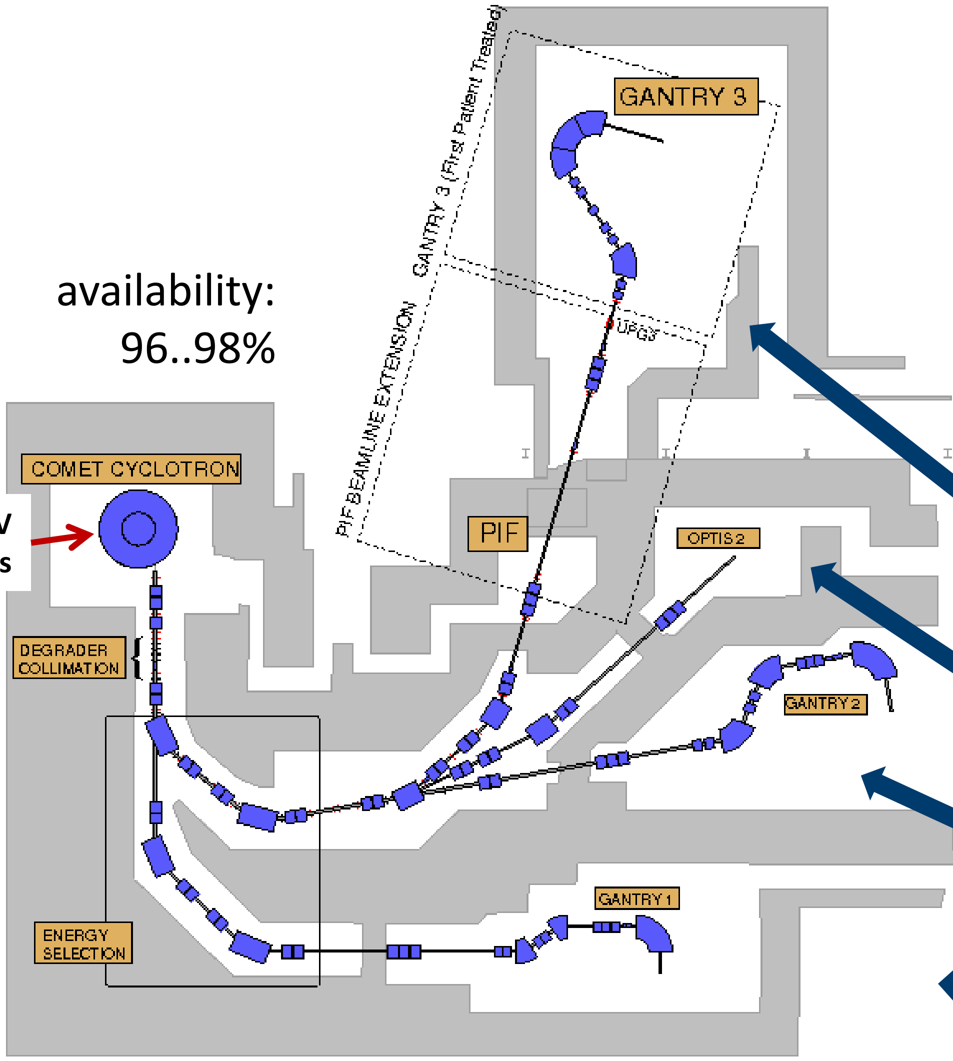
patients treated with photons

[VARIAN]

PSI Proton Therapy Facility PROSCAN

availability:
96..98%

250 MeV
protons



Gantry 3
(up to 12 Patienten pro Tag)

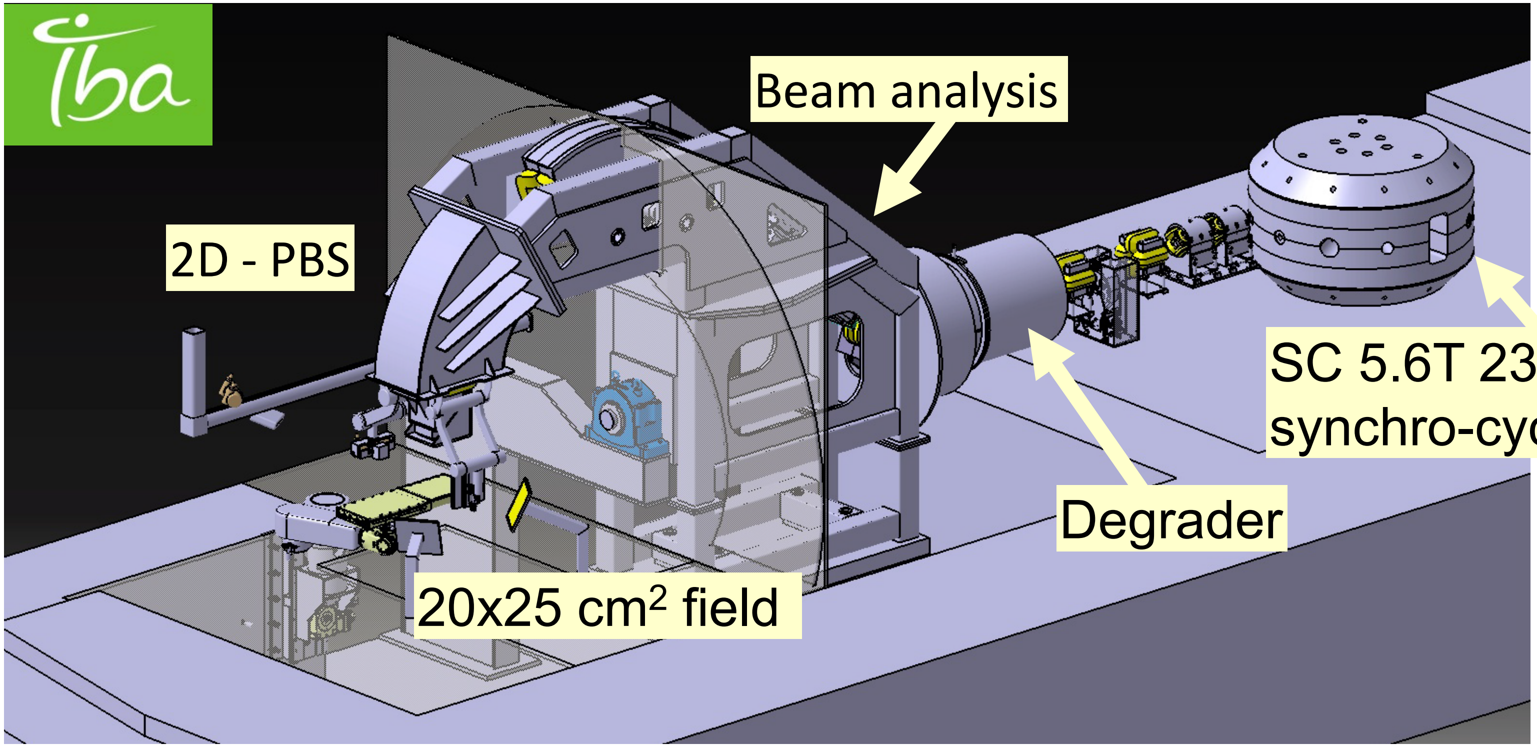
OPTIS
(eye melanoma treatment)

Gantry 2

Gantry 1

July 2018, first patient on Gantry 3 [PSI/CPT]

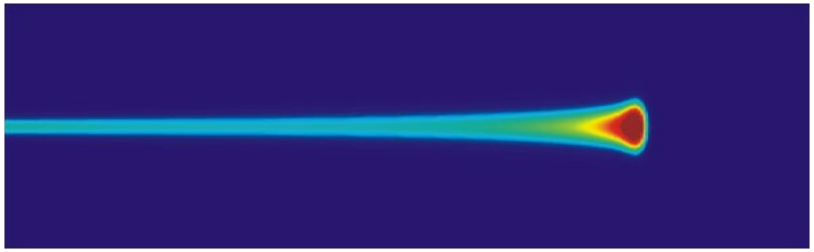
IBA: compact treatment facility using high field synchro-cyclotron

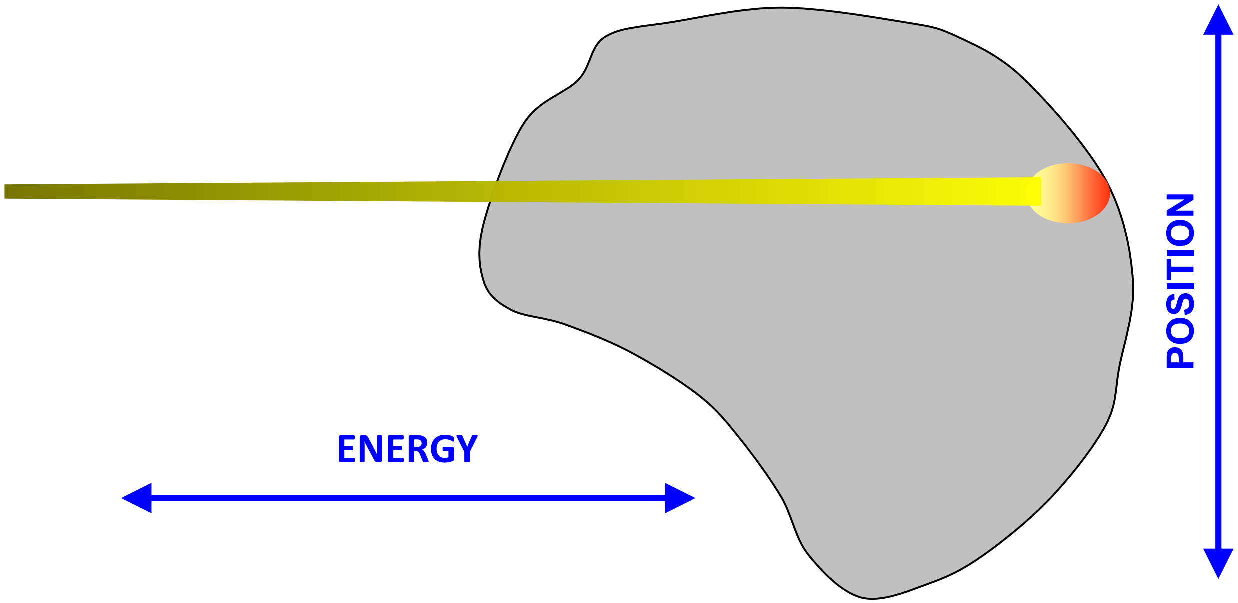


- required area: $24 \times 13.5 m^2$ (indeed small)
- 2-dim pencil beam scanning

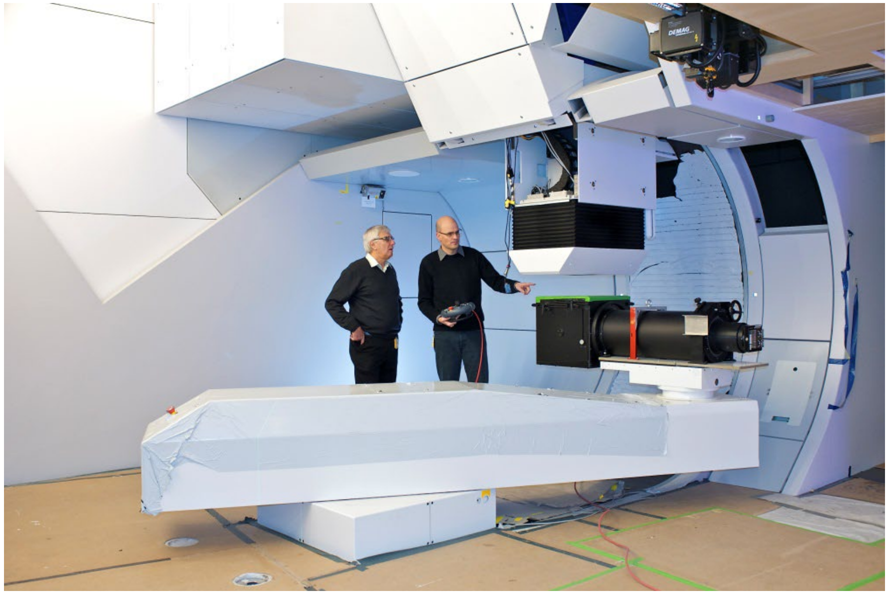
Particle Therapy with Protons / Ions

Treatment of deep seated tumors with best protection of the surrounding





Beam Delivery example: PSI Gantry II



Gantry 2 during commissioning (2010)

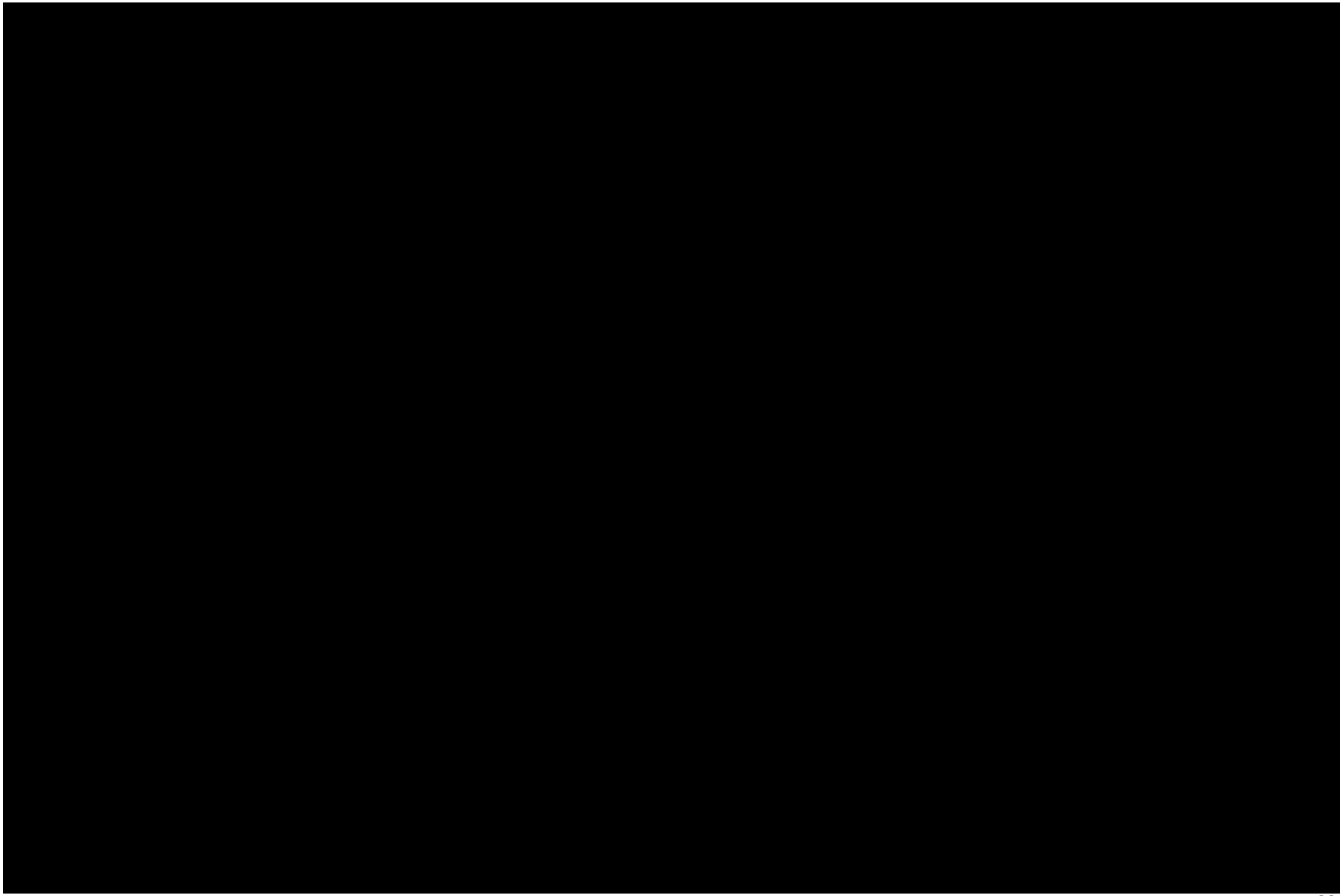
Gantry 2 during installation (2008)

- radius 4 m, weight 180 t, magnet 40t
- precision 2D scanning, **δ≈1mm**
- fast energy change, 100 ms/step
- modern in-situ imaging (CT, X-ray)

accelerator physics challenges for gantries:

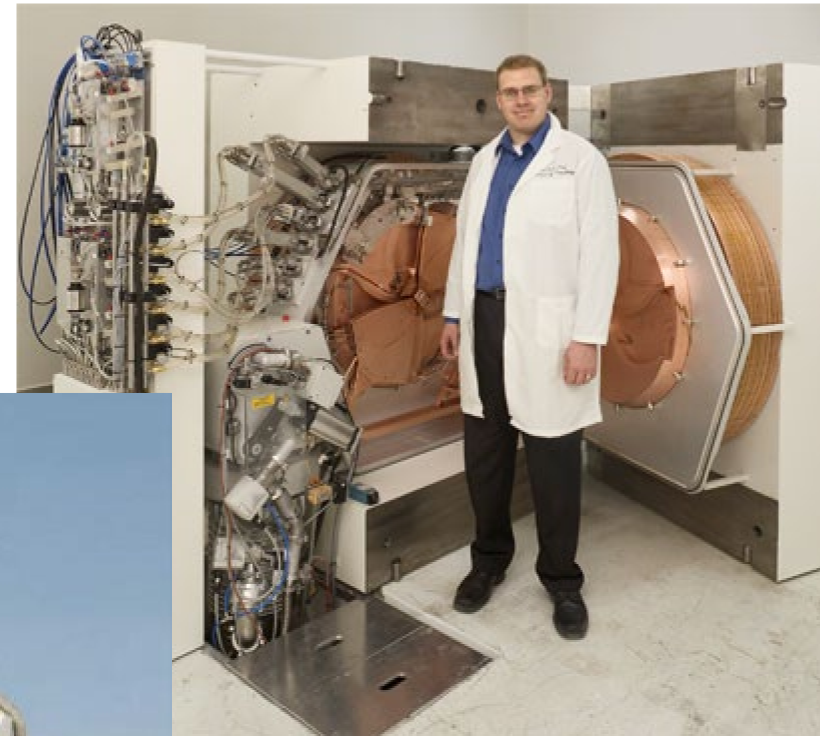
- minimize chromatic and geometric beam abberations
- new concepts with light s.c. magnets

Fast Energy Change with Gantry II



compact cyclotrons for Isotope production

CYCLONE 30 (IBA) : H^- 15 à 30 MeV



Vertical setup

Medical Isotopes

radioactive isotopes are used for variety of diagnostic and therapeutic purposes:

- imaging of cancers and neurological problems
- cancer therapy by enriching radioactive material around tumor cells

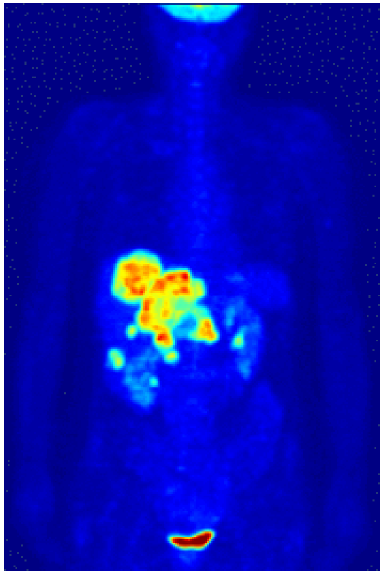


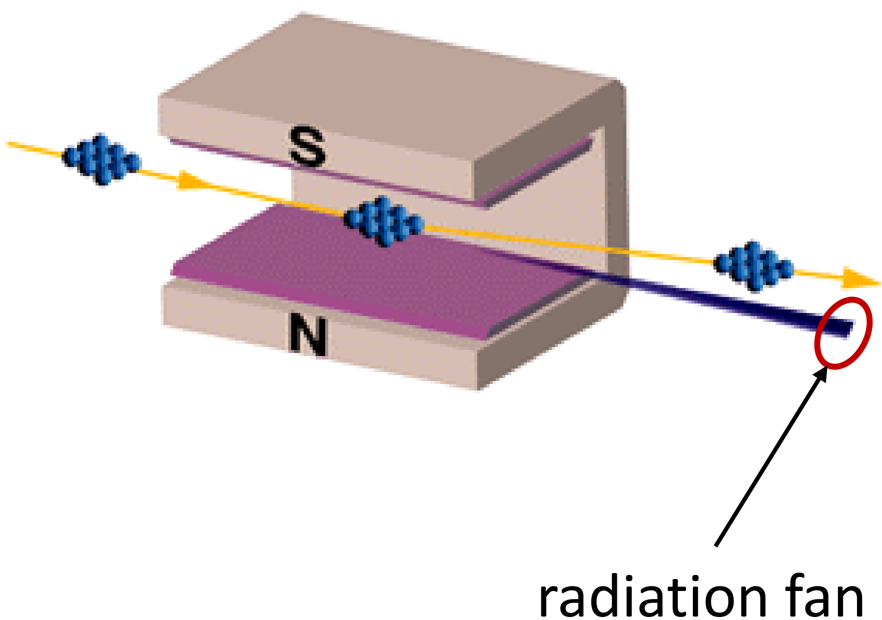
image of a PET scan using ^{18}F

Next: Accelerators for Condensed Matter Research

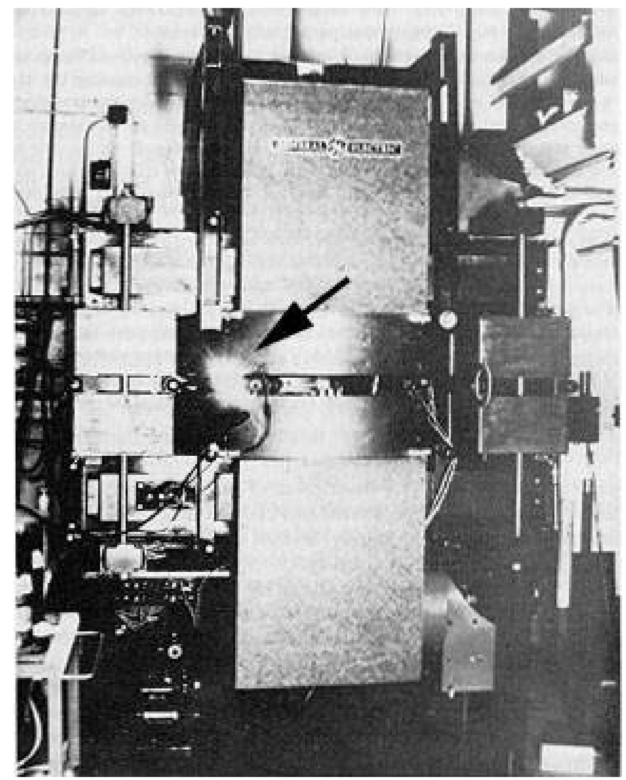
- Synchrotron Light Sources
- Free Electron Lasers
- Neutron Sources

EPFL

Synchrotron radiation from electrons in a bending magnet

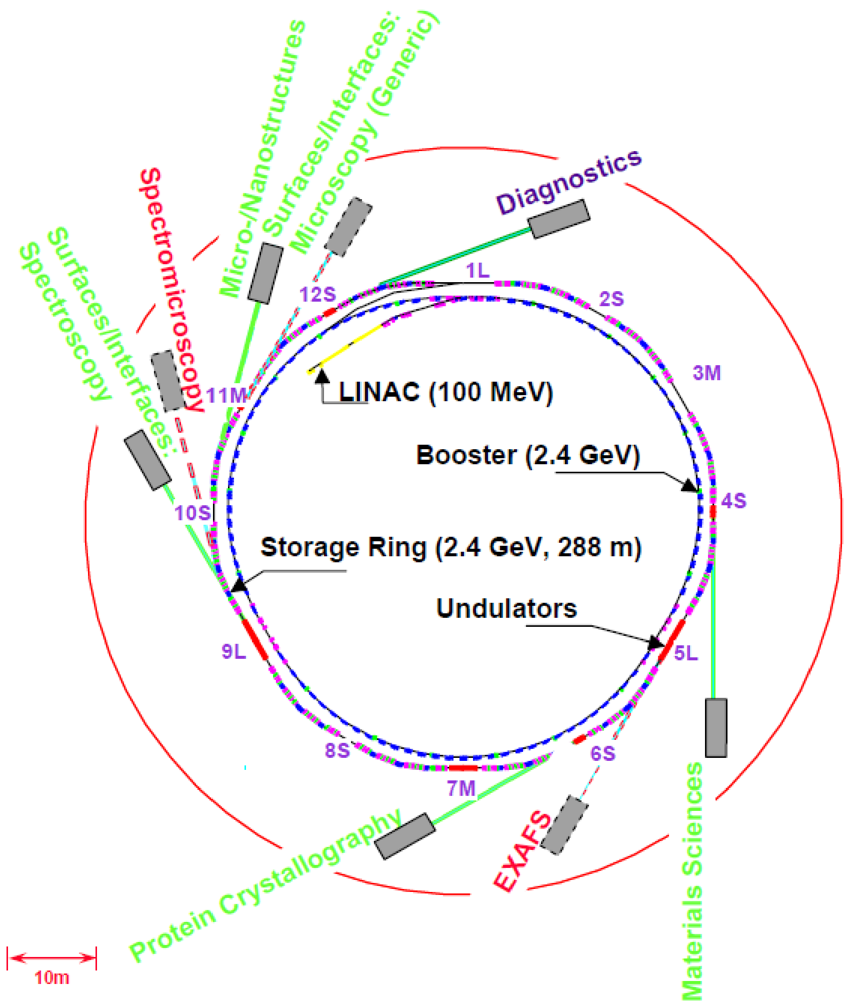


GE Synchrotron
New York State



First light observed 1947

Swiss Light Source (SLS) – a synchrotron



circumference:	288 m
energy:	2.4 GeV
beam current:	400 mA
beam lines:	21

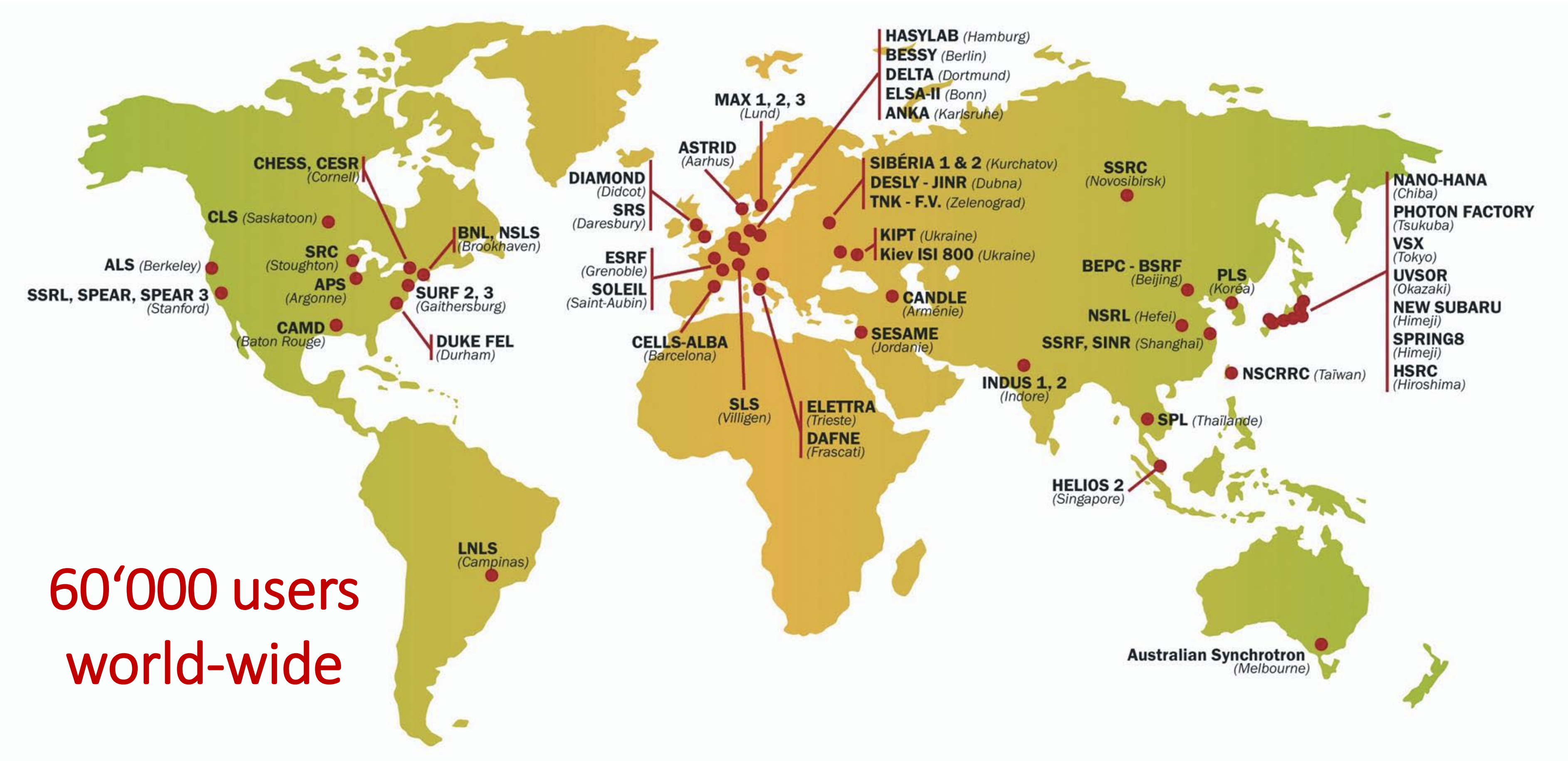
integrated booster ring → Top-Up operation

magnet lattice:

12 TBA cells
(triple bend achromat)

12 straight sections for undulators

Synchrotron Light Sources:
about 50 storage ring based

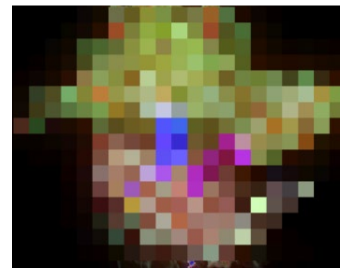
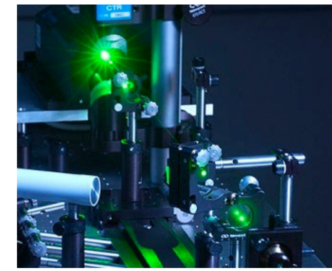


60‘000 users world-wide

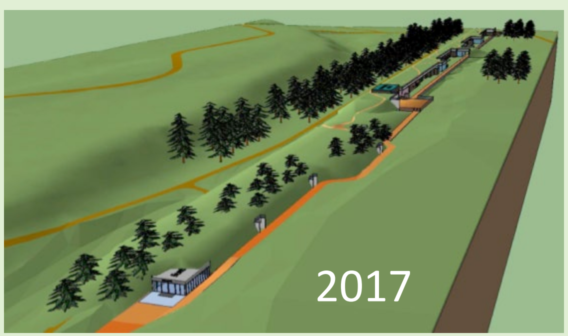
SwissFEL – a new accelerator based Research Infrastructure

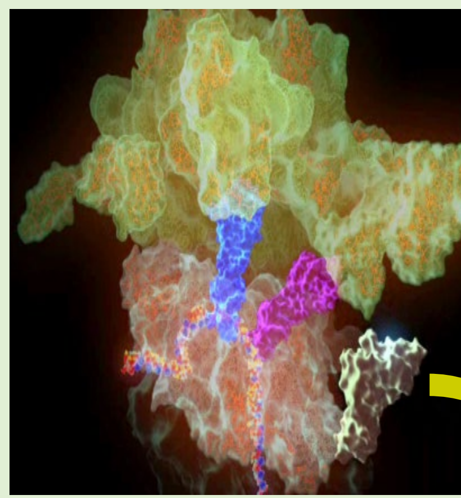
3rd gen. synchrotron
fine, slow


optical lasers
fast, coarse

SwissFEL fine **and** fast
at extreme high intensity






new direct insights into chemical, physical, biological mechanisms governing our daily-life

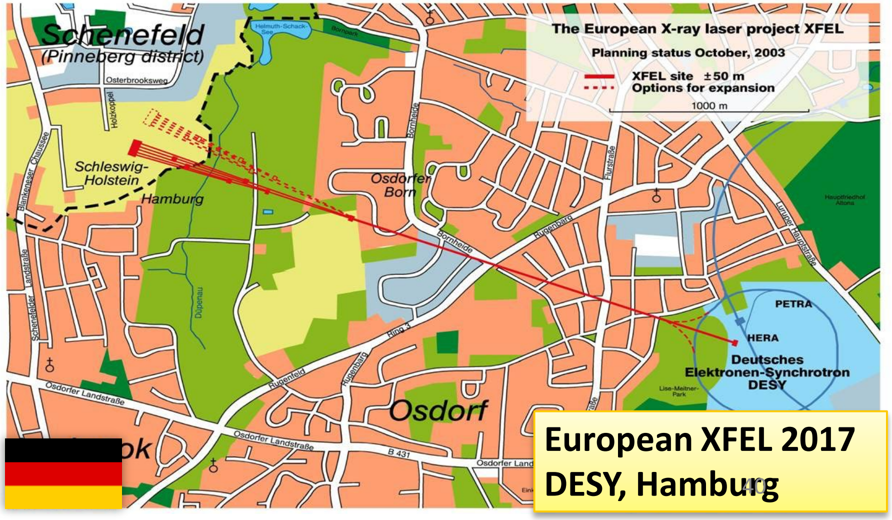
X-Ray Free Electron Lasers

PAL XFEL 2016

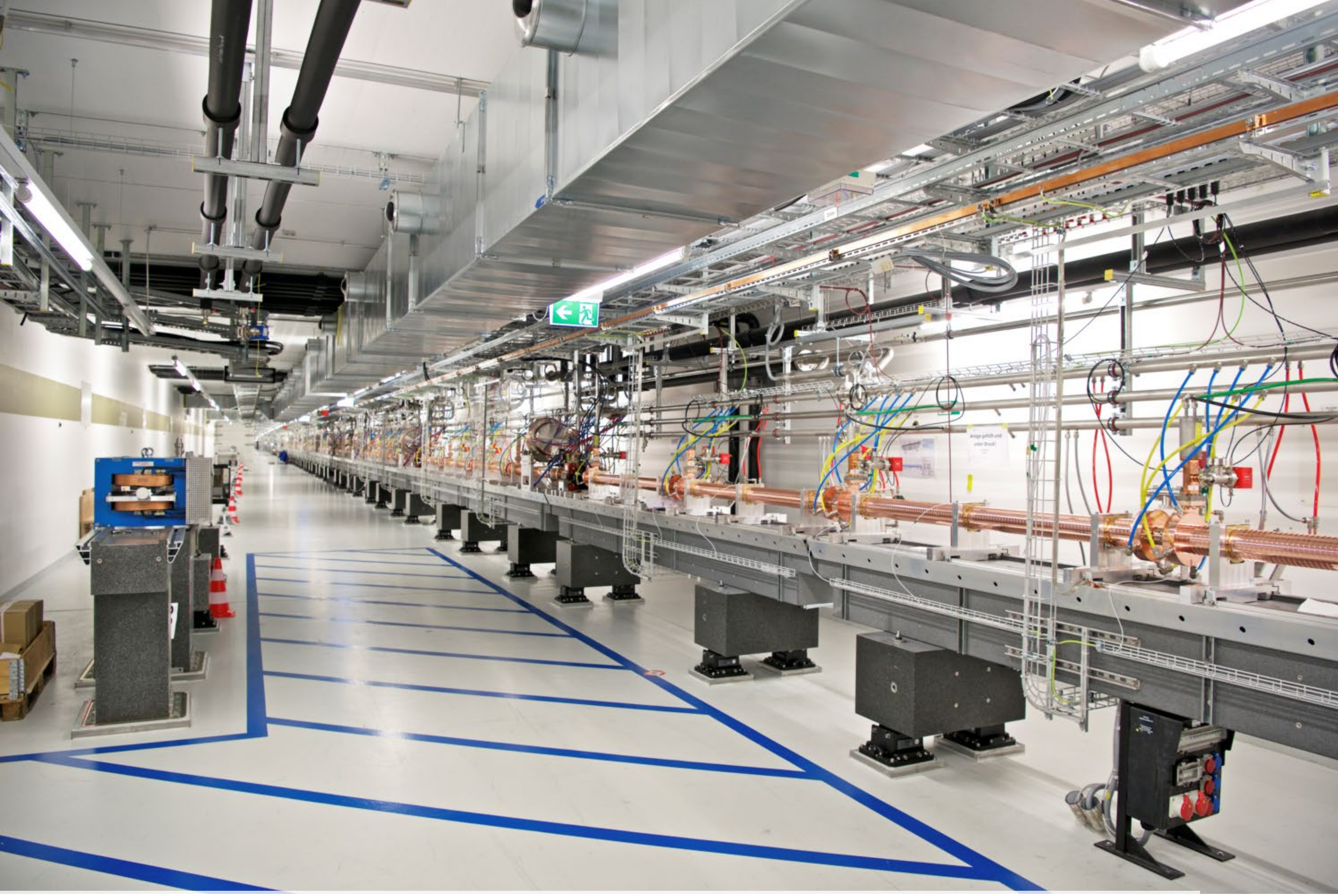
SwissFEL 2017

LCLS I, II 2009, 2022

SACLA 2011
8.5 GeV, 60 Hz NC



European XFEL 2017
DESY, Hamburg

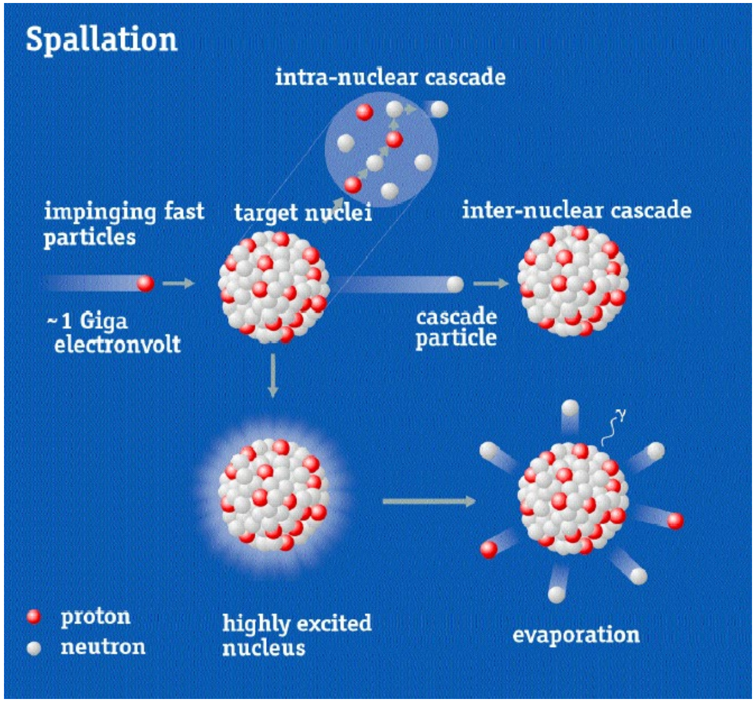


SwissFEL Linac (C-Band Frequency, 6GHz)

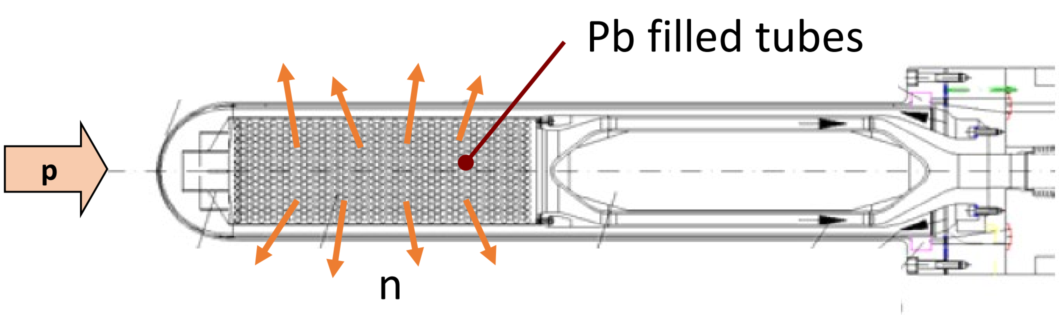
Spallation Neutron Sources

use **proton beam** on a target → safe process but need high power beam, **MW class accelerators**

neutron energy around 1 MeV → to high
→ use moderators:
for thermal spectrum D_2O/H_2O, (ambient temperature): 0.025 eV

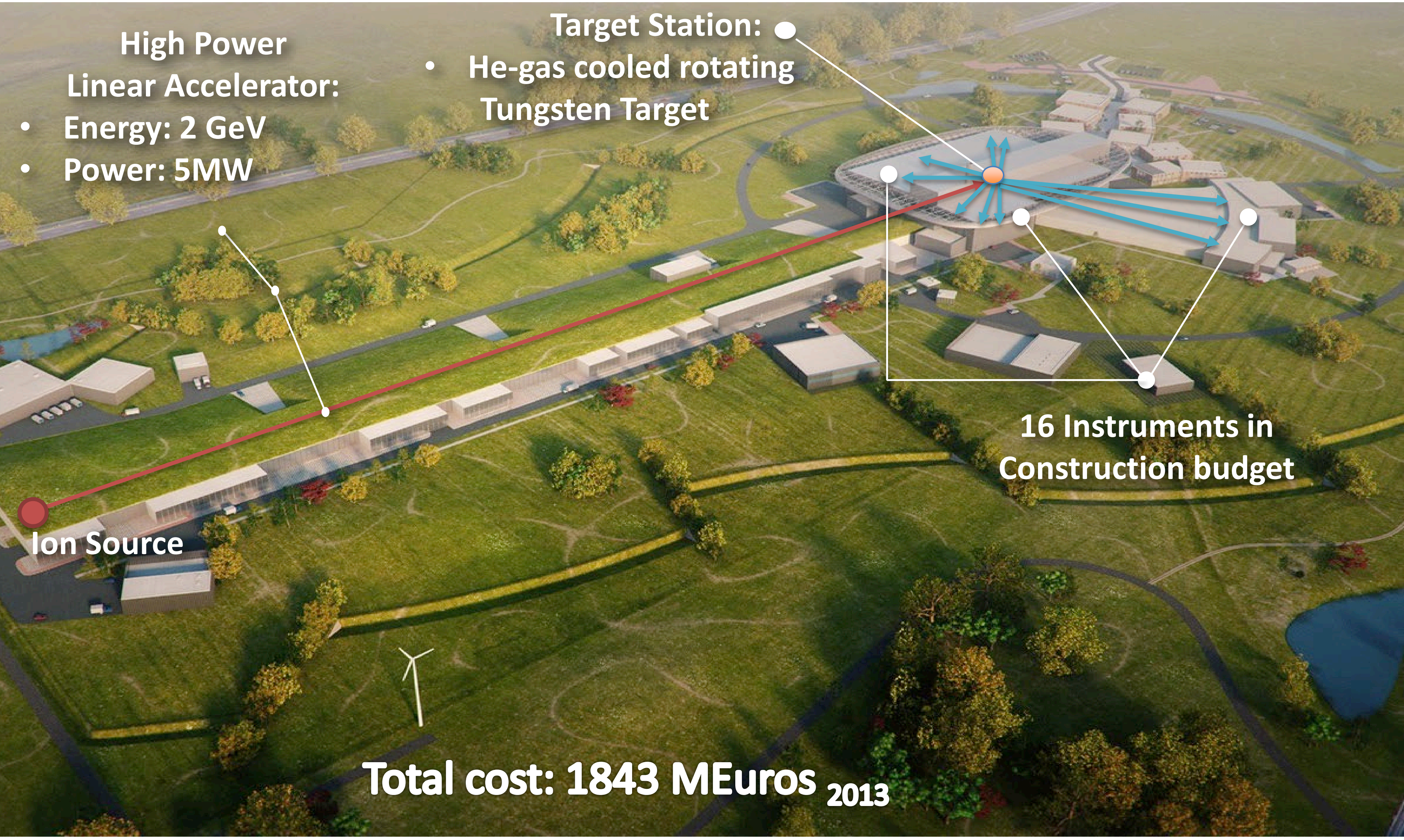


example: PSI-HIPA target

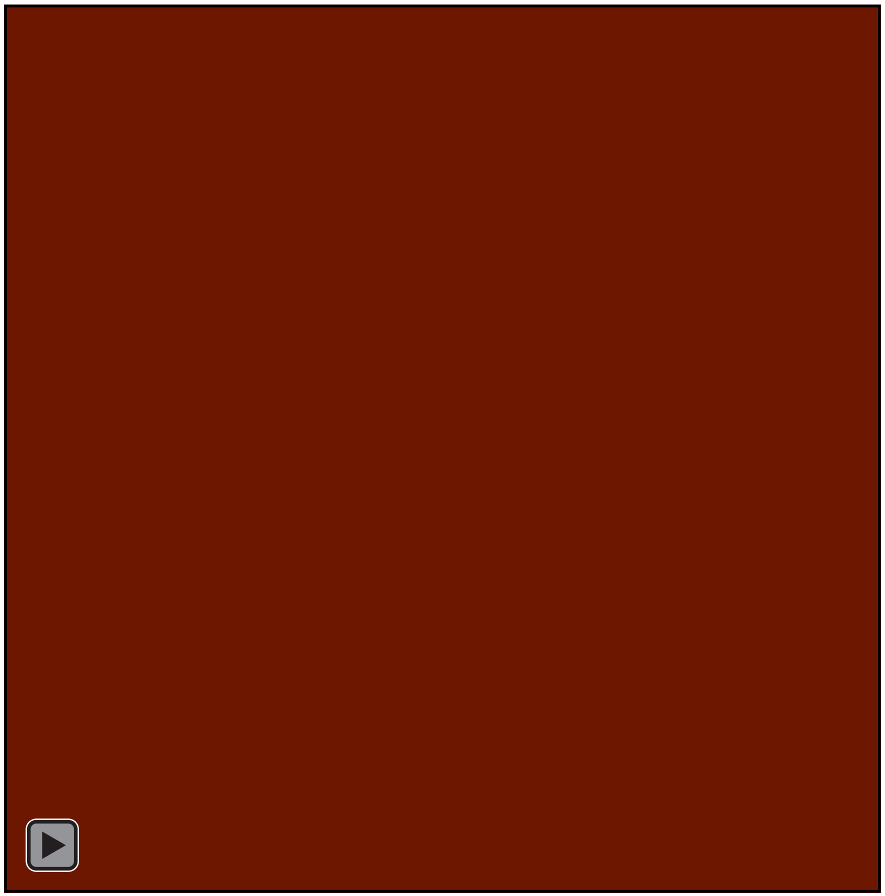


Example: European Spallation Source

[M.Lindroos, ESS]



time resolved neutron scattering – making coffee

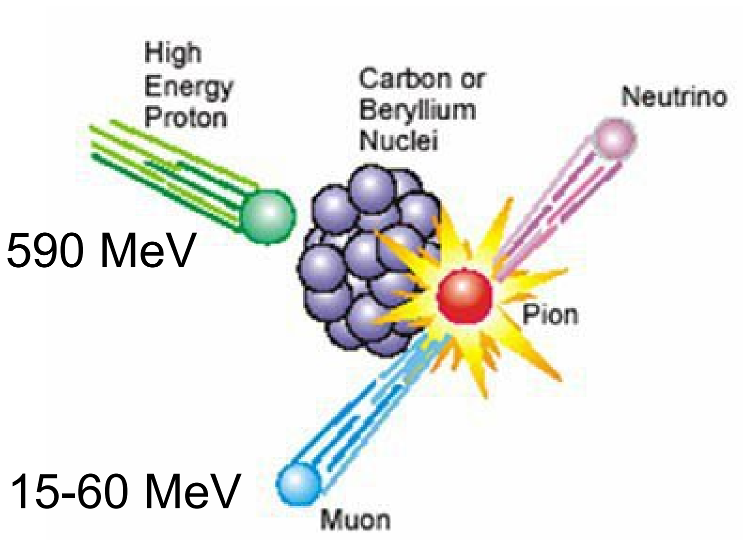


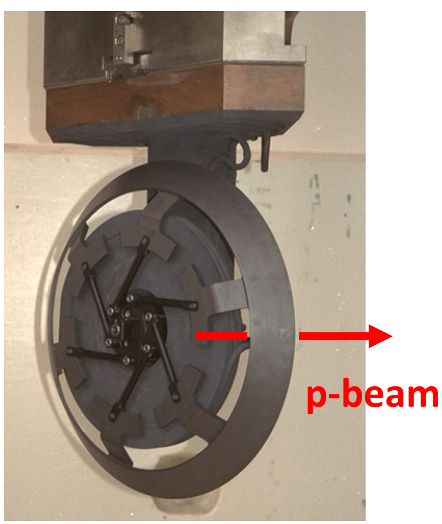
neutron radiography

[courtesy: PSI]

Muon production using targets

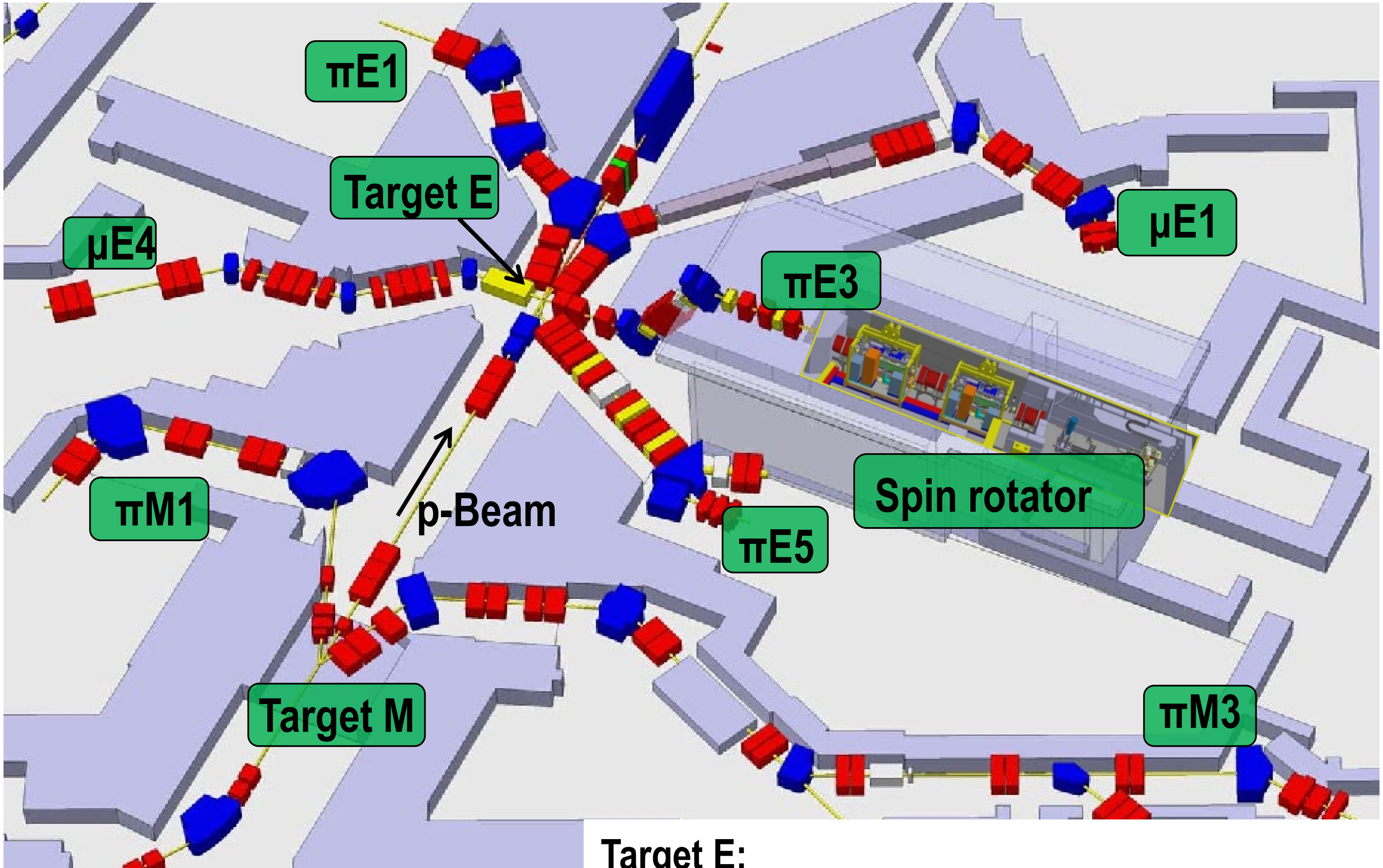
Production of muons:





Graphite TARGET CONE	
Mean diameter:	450 mm
Operating Temperature:	1700 K
Rotational Speed:	1 Turn/s
Target thickness:	40 mm
Power deposition:	50 kW

PSI μ/π Secondary Beam Lines



Target E:
πE1: 10 - 500 MeV/c High Intensity Pions und Muons
μE1: Polarized Muon Beam
πE3: 28MeV/c Surface polarized Muons
μE4: 30 - 100 MeV/c High Intensity Polarized Muons
πE5: 10 - 120 MeV/c High Intensity Muons

Target M:
πM1: 100-500 MeV/c Pions
πM3: 28 MeV/c Surface Muons

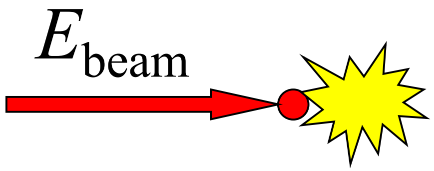
Next: Accelerators for Particle Physics Research

EPFL

Fixed target vs collisions

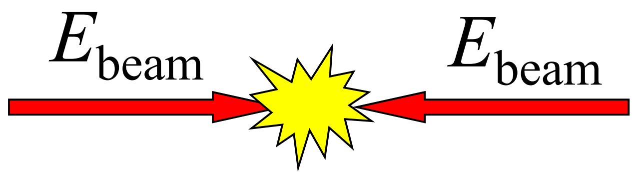
What energy is available in collisions (center-of-mass energy)?

fixed target geometry:



$$E_{\mathrm{cm}} = \sqrt{2mc^2} \cdot \sqrt{E_{\mathrm{beam}}}$$

Colliding beams:



$$E_{\mathrm{cm}} = 2 \cdot E_{\mathrm{beam}}$$

The energy gain with collisions is enormous!
LHC: 14TeV vs. 0.15TeV

the first collider facility AdA was built 1961 in Frascati by Bruno Touschek

LHC – the largest accelerator today

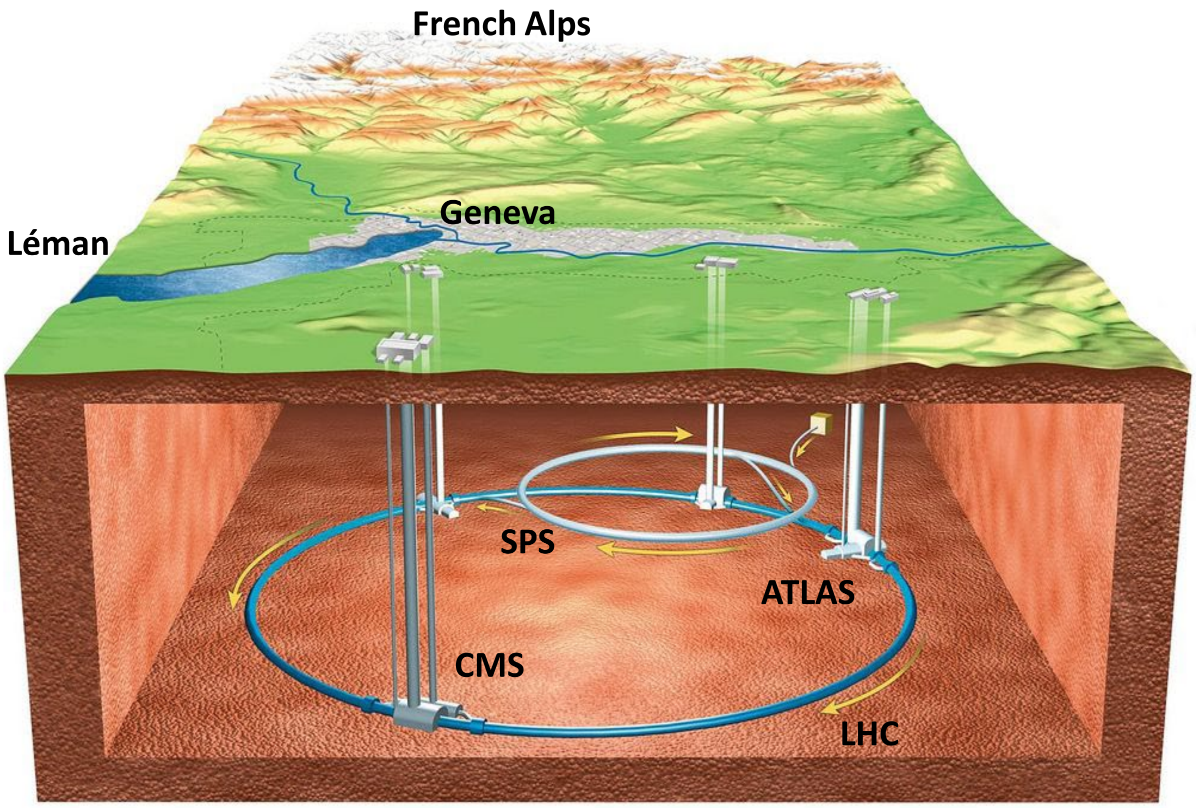
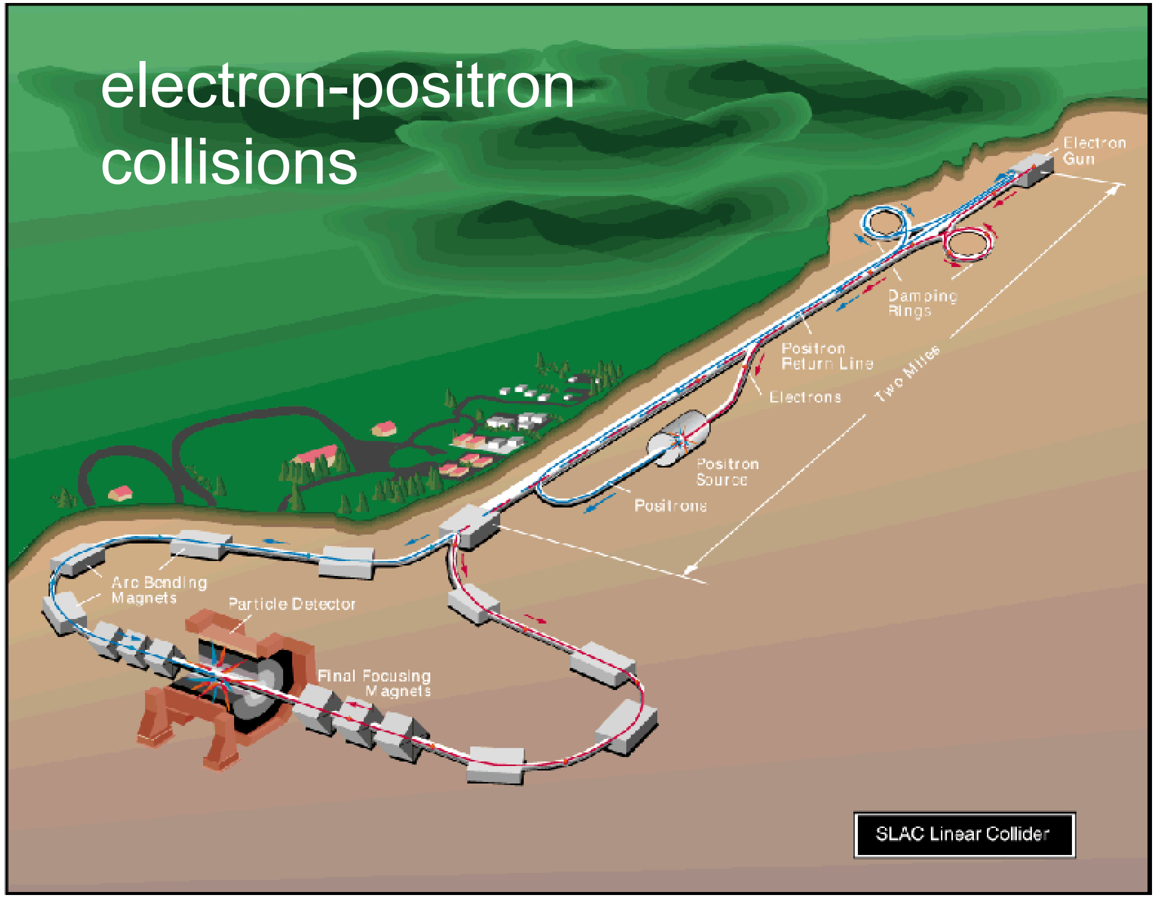
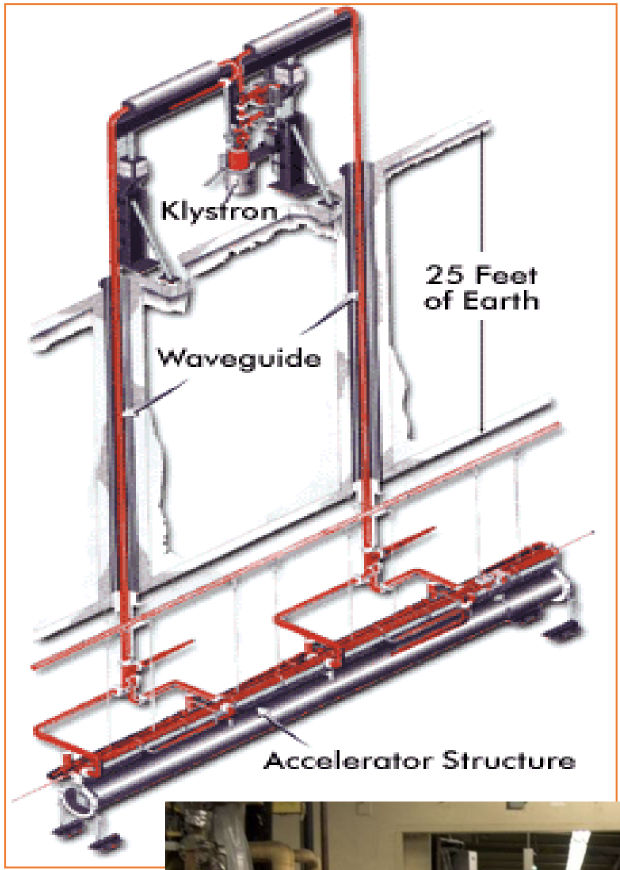


Image: Philippe Mouche

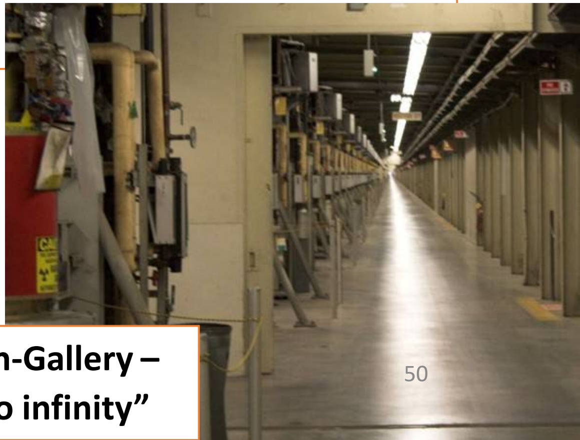
- **27 km circumference**
- **100 m below ground**
- **7 TeV per beam**
- **99,9999991% of c**
- **CMS/ATLAS:** local generation of Big Bang conditions, Higgs etc.
- **LHCb**: CP violation in B-Meson-Systems
- **ALICE**: Heavy Ions, Quark-Gluon-Plasma

Stanford Linear Collider (SLC, till 1997)





only linear collider in world, Menlo Park/California/USA
Linac: 3km length
2x50GeV e^+/e^- collisions, polarised!



Klystron-Gallery – "view to infinity"

24 Nobel Prizes in Physics with direct contributions from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

2013: François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at **CERN's Large Hadron Collider**"

Particle Accelerators

Next: about this course …

References and accessible Reading Material

available on the internet:

P. Schmüser & J. Rossbach, Basic course on accelerator optics:

https://cds.cern.ch/record/247501/files/p17.pdf

F.Tecker, Longitudinal Dynamics:

https://arxiv.org/pdf/1601.04901.pdf

L.Rivkin, Electron dynamics in rings in the presence of radiation :

https://cds.cern.ch/record/375974/files/p45.pdf

Book, H.Wiedemann, Particle Accelerators, download pdf !:

https://link.springer.com/book/10.1007%2F978-3-319-18317-6

CERN Accelerator School (CAS) proceedings homepage (huge!)
https://cas.web.cern.ch/previous-schools

CERN Accelerator School on Medical Applications:

https://cds.cern.ch/record/2271793/files/33-8-PB.pdf

books, papers:

S.Peggs, T.Satogata, *Introduction to Accelerator Dynamics*, Cambridge University Press, 2017

A. Wolski, *Beam Dynamics in high energy particle accelerators*, Imperial College Press, 2014

A. W. Chao, M. Tigner, *Handbook of Accelerator Physics and Engineering*, World Scientific 1999

E. D. Courant and H. S. Snyder, Annals of Physics: **3**, 1-48 (1958)

M. Sands, SLAC-121, 1969

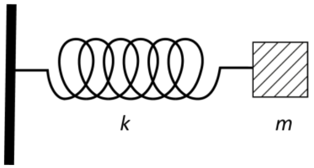
Physics of Electron Storage Rings: An Introduction.

https://digital.library.unt.edu/ark:/67531/metadc865991/

Mathematical Prerequisites

linear differential equations:

$$\ddot{x} + \omega^2 x = 0,\ \ x(t) = A \sin \omega t$$

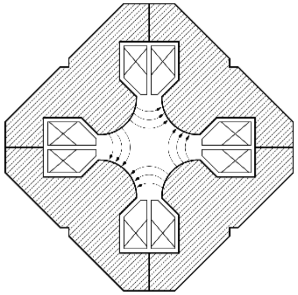


$$x'' + K(s)x = 0$$

$$\frac{\Delta x}{\Delta t} \propto x \ \longrightarrow\ \dot{x} = \alpha x,\ \ x(t) = A \exp \alpha t$$

vector differential equations:

$$\boldsymbol{\nabla} \times \vec{B} = 0, B_z = 0, \ \to\ \frac{\partial}{\partial x} B_y - \frac{\partial}{\partial y} B_x = 0$$



More Mathematical Prerequisites

linearization and Taylor expansion:

$$B_z(R+x) \approx B_z(R) + \frac{dB_z}{dR}x$$

$$\frac{1}{R+x} \approx \frac{1}{R} \cdot \left(1 - \frac{x}{R}\right)$$

R = position of beam center
x = particle, distance to center

matrix calculations:

$$\vec{x}_2 = \boldsymbol{M} \cdot \vec{x}_1$$

$$\det \boldsymbol{M}_1 = 1, \det \boldsymbol{M}_2 = 1 \quad \longrightarrow \quad \det\left(\boldsymbol{M}_1 \cdot \boldsymbol{M}_2\right) = 1$$

matrix eigenvalues, eigenvectors:

$$\boldsymbol{M}\vec{v} = \lambda\vec{v}, \;\; \det\left(\boldsymbol{M} - \lambda\boldsymbol{I}\right) = 0$$

eigenvalue equation, characteristic polynomial

$$\boldsymbol{M}^n = \boldsymbol{v}\boldsymbol{\lambda}^n\boldsymbol{v}^{-1}$$

$\boldsymbol{\lambda}$ = diagonal matrix of eigenvalues
$\boldsymbol{v}$ = matrix with eigenvectors in cols.

Outline of LPAP Accelerator Physics Course

Lectures	Dates
Accelerator Concepts, their History and their Applications	12.09.2024
An Overview on Physics and Technology of Accelerators	19.09.2024
Transverse Dynamics :: Equation of Motion and Solutions	26.09.2024
Transverse Dynamics :: Lattice Design and Beam Properties	03.10.2024
Transverse Dynamics :: Lattice Imperfections and Hamilton Formalism	10.10.2024
Longitudinal Beam Dynamics	17.10.2024
Synchrotron Radiation and Electron Dynamics	31.11.2024
Synchrotron Light Sources	07.11.2024
Medical Application (Marco Schippers, PSI)	14.11.2024
Particle Colliders	21.11.2024
CERN Visit	28.11.2024
Collective Effects (Tatiana Pieloni, EPFL)	05.12.2024
Accelerator Case Studies	12.12.2024
Recap and exam example	19.12.2024

special tutorial mid-term test-exam

special tutorial exam preparation

Possibilities for TPs, Master thesis

CERN (postdocs, doctoral students)

- LHC and its upgrades (high luminosity, energy)
- Future Circular Collider study
- Muon Collider Study

PSI (postdocs, graduate students)

- SwissFEL: X-Ray Free Electron Laser
- Swiss Light Source (SLS)
- neutron, muon beams
- medical applications: cancer proton therapy

Other accelerator labs around the world

Why learn about accelerators?

Accelerator is a challenging **part** of experimental setups.

It is important to understand

Its limitations

Its potential

You can be user or designer of future machines

Help to specify, design them

It's fun!

Appendix: Magnetic Rigidity (proton)

Lorentz force $\vec{F}_B = e \cdot \vec{v} \times \vec{B}$

B, v perpendicular $F_B = evB$

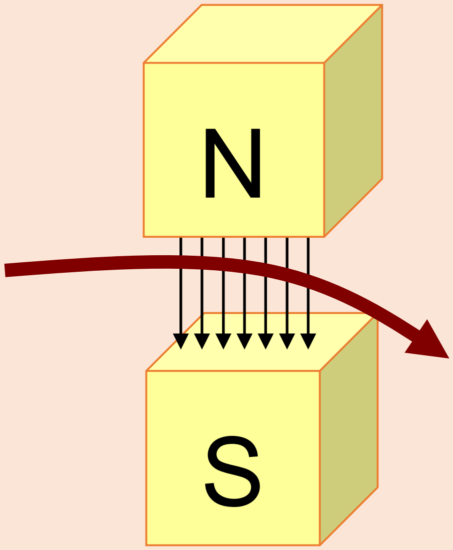
centrifugal force $F_c = -m\frac{v^2}{\rho}$

$$F_B + F_c = 0 \longrightarrow evB = m\frac{v^2}{\rho}$$

$$B\rho = \frac{mv}{e}$$

Magnetic rigidity

$$B\rho = \frac{p}{e}$$



B = magnetic field

ρ = local bending radius

p = momentum

e = elementary charge

Appendix: Magnetic Rigidity in Practical Units

$$B\rho = \frac{p}{e} = \frac{mv}{e} = \beta\gamma\frac{m_0 c}{e}$$

$$= \beta\gamma\ \frac{m_0 c^2}{ce}$$

$$= \beta\ \frac{E_{\text{tot}}}{ce}$$

$$= \beta\ \frac{10^9}{c} E_{\text{tot}}[\text{GeV}]$$

$$\downarrow$$

$$B\rho[\text{Tm}] \approx 3.3356 \cdot E_k[\text{GeV}]$$

$$B\rho[\text{Tm}] = 3.3356 \cdot p[\text{GeV/c}]$$

B = magnetic field
ρ = local bending radius
p = momentum
e = elementary charge
E_k = kinetic energy

total energy:

$$E_{\text{tot}} = E_k + m_0 c^2$$

approximations:

$$\beta \approx 1, cp \approx E_k$$

$$\text{for } E_k \gg m_0 c^2$$

see also Wiedemann, p.101, eq.5.6