An Introduction to Accelerators

Part II

Chuanxiang Tang (唐传祥)
Tsinghua University
tang.xuh@tsinghua.edu.cn

12TH INTERNATIONAL ORGANIZTION OF CHINESE PHYSICISTS AND ASTRONOMERS ACCELERATOR SCHOOL

OCPA-2025

KHAOYAI, NAKHON RATCHASIMA, THAILAND | 29 JULY - 7 AUGUST 2025

Outline

1. Principles of Accelerators
2. Contributions to science and others applications
3. A Simple Introduction of Accelerator Physics

2. Contributions to Science and Others Applications

2.1 Accelerators for Physics

Time	Event
1800	William Herschel discovers "heat rays"
1801	Johann Wilhelm Ritter made the hallmark observation that invisible rays just beyond the violet end of the visible spectrum were especially effective at lightening silver chloride-soaked paper. He called them "oxidizing rays" to emphasize chemical reactivity and to distinguish them from "heat rays" at the other end of the invisible spectrum (both of which were later determined to be photons). The more general term "chemical rays" was adopted shortly thereafter to describe the oxidizing rays, and it remained popular throughout the 19th century. The terms chemical and heat rays were eventually dropped in favor of **ultraviolet** and **infrared** radiation, respectively.[1]
1895	Discovery of the ultraviolet radiation below 200 nm, named **vacuum ultraviolet** (later identified as photons) because it is strongly absorbed by air, by the German physicist Victor Schumann[2]
1895	**X-ray** produced by Wilhelm Röntgen (later identified as photons)[3]
1897	**Electron** discovered by J. J. Thomson[4]
1899	**Alpha particle** discovered by Ernest Rutherford in uranium radiation[5]
1900	**Gamma ray** (a high-energy photon) discovered by Paul Villard in uranium decay[6]
1911	**Atomic nucleus** identified by Ernest Rutherford, based on scattering observed by Hans Geiger and Ernest Marsden[7]
1919	**Proton** discovered by Ernest Rutherford[8]
1932	**Neutron** discovered by James Chadwick[9] (predicted by Rutherford in 1920[10])
1932	**Antielectron** (or **positron**), the first antiparticle, discovered by Carl D. Anderson[11] (proposed by Paul Dirac in 1927 and by Ettore Majorana in 1928)
1937	**Muon** (or **mu lepton**) discovered by Seth Neddermeyer, Carl D. Anderson, J.C. Street, and E.C. Stevenson, using cloud chamber measurements of cosmic rays[12] (it was mistaken for the pion until 1947[13])
1947	**Pion** (or **pi meson**) discovered by C. F. Powell's group, including César Lattes(first author) and Giuseppe Occhialini (predicted by Hideki Yukawa in 1935[14])
1947	**Kaon** (or **K meson**), the first strange particle, discovered by George Dixon Rochester and Clifford Charles Butler[15]

1932	**Neutron** discovered by James Chadwick[9] (predicted by Rutherford in 1920[10])	isotopes
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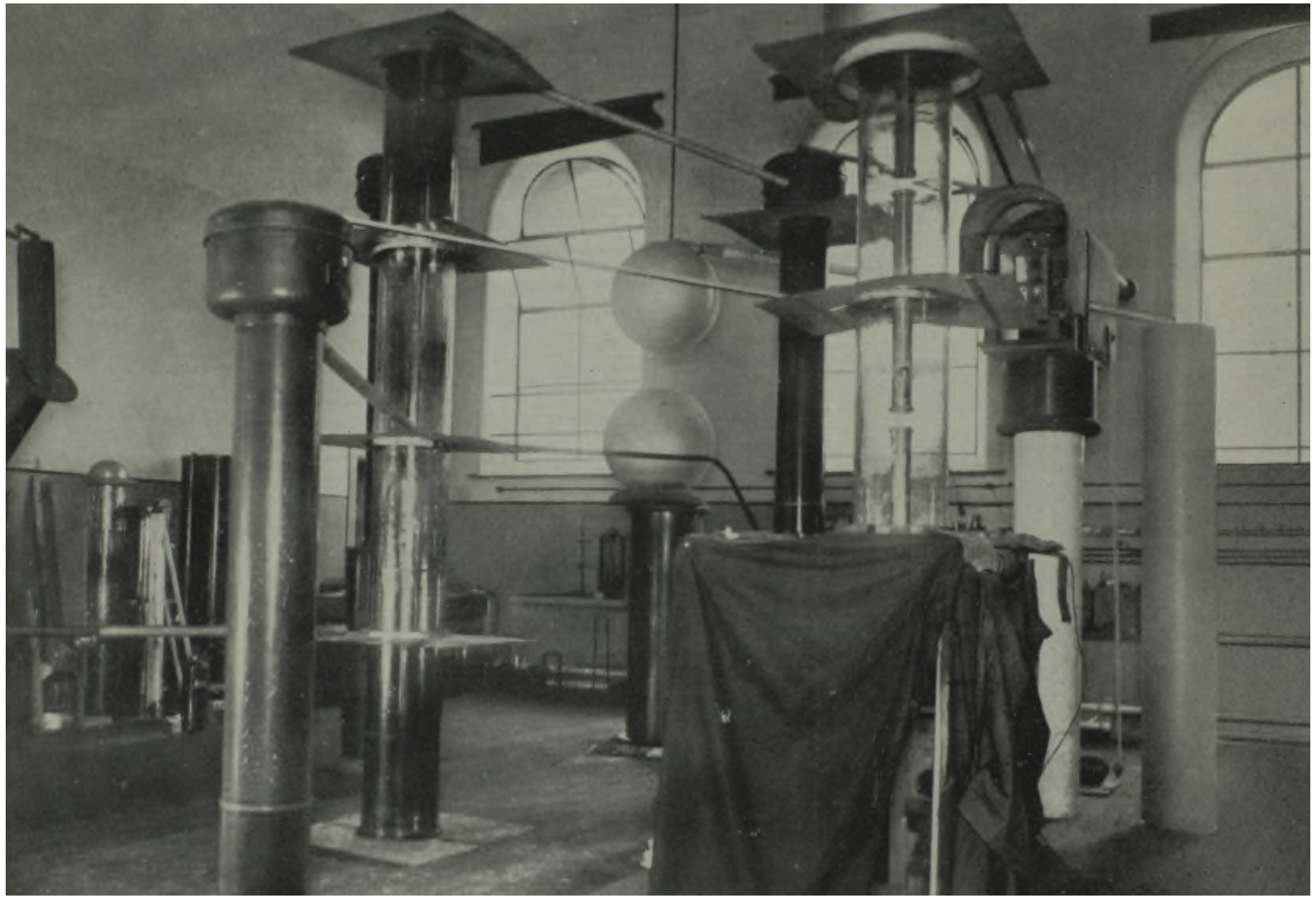
1947	**Kaon** (or **K meson**), the first strange particle, discovered by George Dixon Rochester and Clifford Charles Butler[15]	cosmic rays
1947	Λ^0 discovered during a study of cosmic-ray interactions[16]	cosmic rays
1955	**Antiproton** discovered by Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis[17]	Bevatron
1956	**Electron antineutrino** detected by Frederick Reines and Clyde Cowan (proposed by Wolfgang Pauli in 1930 to explain the apparent violation of energy conservation in beta decay)[18] At the time it was simply referred to as *neutrino* since there was only one known neutrino.	Nuclear reactor
1962	**Muon neutrino** (or **mu neutrino**) shown to be distinct from the electron neutrino by a group headed by Leon Lederman[19]	AGS
1964	**Xi baryon** discovery at Brookhaven National Laboratory[20]	AGS, Tevatron; cosmic rays
1969	**Partons** (internal constituents of hadrons) observed in deep inelastic scattering experiments between protons and electrons at SLAC;[21][22] this was eventually associated with the quark model (predicted by Murray Gell-Mann and George Zweig in 1964) and thus constitutes the discovery of the **up quark**, **down quark**, and **strange quark**.	2-mile Linac
1974	**J/ψ meson** discovered by groups headed by Burton Richter and Samuel Ting, demonstrating the existence of the **charm quark**[23][24] (proposed by James Bjorken and Sheldon Lee Glashow in 1964[25])	SPEAR; AGS
1975	**Tau** discovered by a group headed by Martin Perl[26]	SPEAR
1977	**Upsilon meson** discovered at Fermilab, demonstrating the existence of the **bottom quark**[27] (proposed by Kobayashi and Maskawa in 1973)	Tevatron
1979	**Gluon** observed indirectly in three-jet events at DESY[28]	DORIS
1983	**W and Z bosons** discovered by Carlo Rubbia, Simon van der Meer, and the CERN UA1 collaboration[29][30] (predicted in detail by Sheldon Glashow, Mohammad Abdus Salam, and Steven Weinberg)	SPS
1995	**Top quark** discovered at Fermilab[31][32]	Tevatron
1995	**Antihydrogen** produced and measured by the LEAR experiment at CERN[33]	PS, LEAR
2000	**Tau neutrino** first observed directly at Fermilab[34]	Tevatron
2011	**Antihelium-4** produced and measured by the STAR detector; the first particle to be discovered by the experiment	RHIC
2012	A particle exhibiting most of the predicted characteristics of the **Higgs boson** discovered by researchers conducting the Compact Muon Solenoid and ATLAS experiments at CERN's Large Hadron Collider[35]	LHC

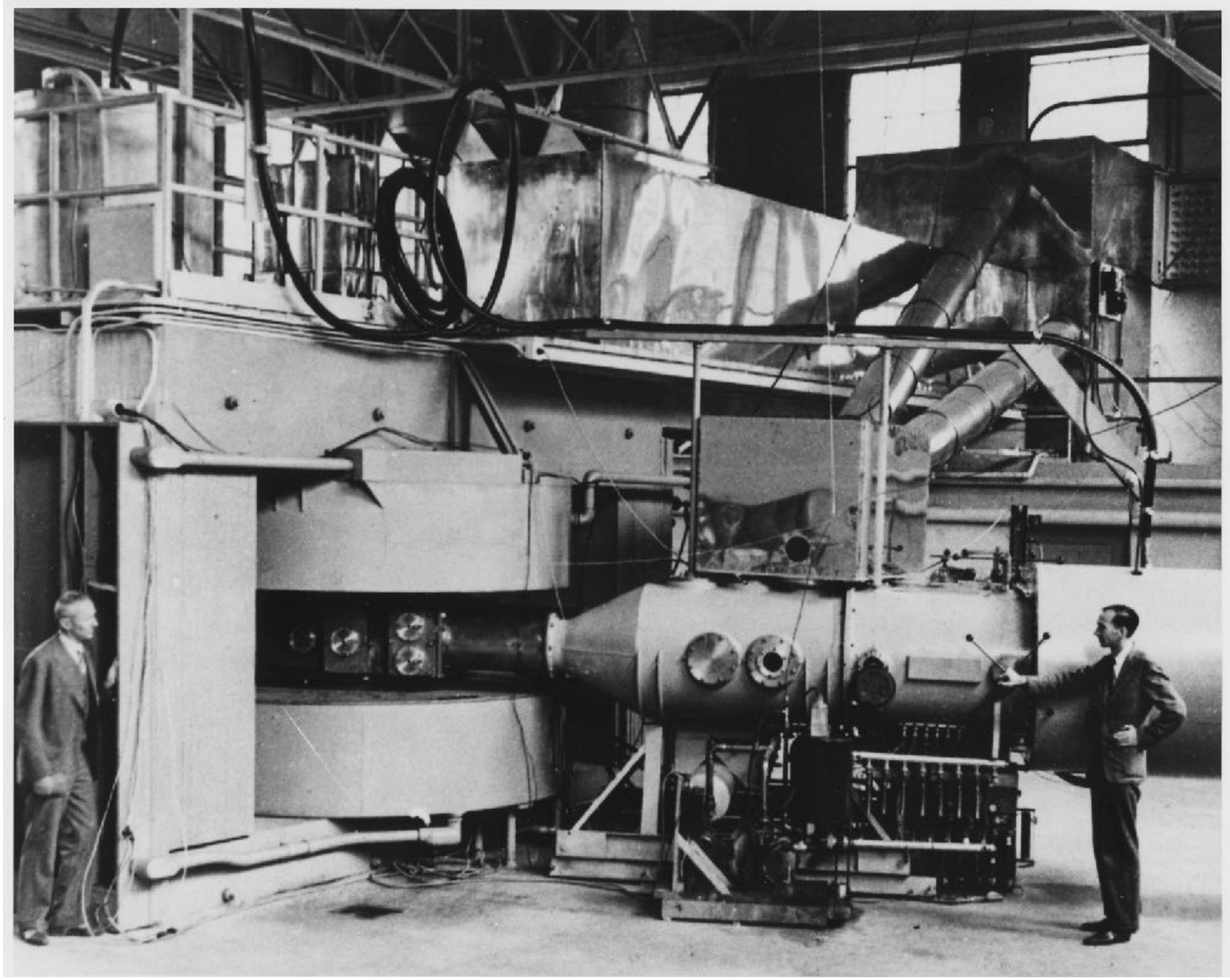
The first nuclear experiment by man-controlled particles



$$p +^{7}_{3} Li \rightarrow 2\alpha + 8.6 \text{ MeV}$$

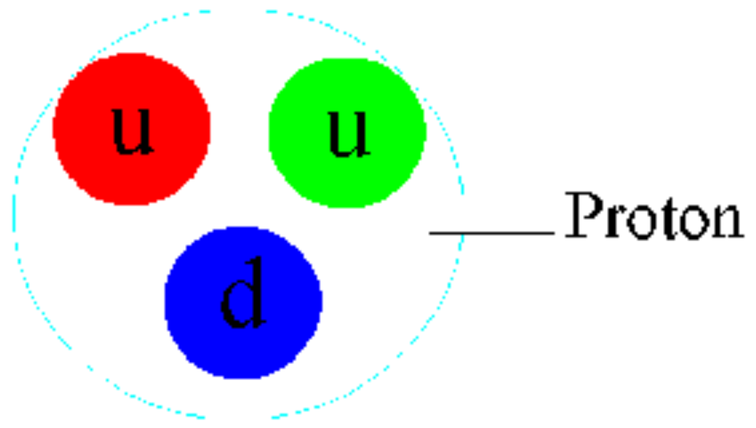
In 1932, the English physicist John Cockcroft and the Irish physicist Ernest Walton produced a nuclear disintegration by bombarding Lithium with artificially accelerated protons of 0.4MeV . The following reaction took place: This was the first artificial splitting of a nucleus. Both of them were awarded Nobel Prize in Physics in 1951

New Elements and Cyclotron



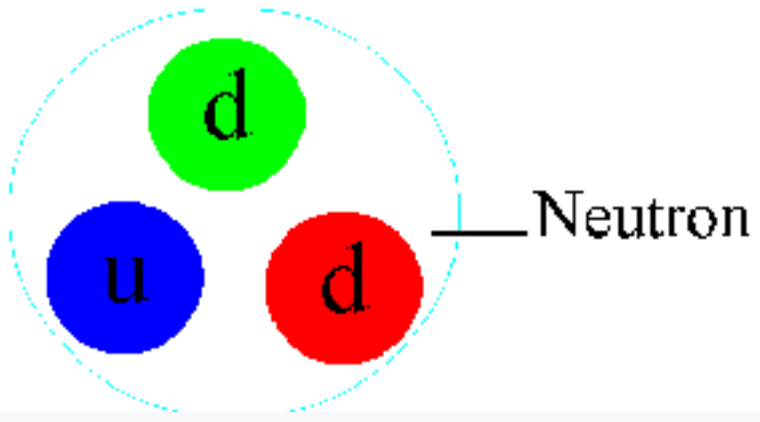
Lawrence's 60 inch cyclotron, with magnet poles 60 inches (5 feet, 1.5 meters) in diameter, at the University of California Lawrence Radiation Laboratory, Berkeley, in August, 1939, the most powerful accelerator in the world at the time. Glenn T. Seaborg and Edwin M. McMillan *(right)* used it to discover plutonium, neptunium and many other transuranic elements and isotopes, for which they received the 1951 Nobel Prize in chemistry.

Pi-meson and the 184” Cycoltron



Theoretical work by Hideki Yukawa in 1935 had predicted the existence of mesons as the carrier particles of the strong nuclear force.

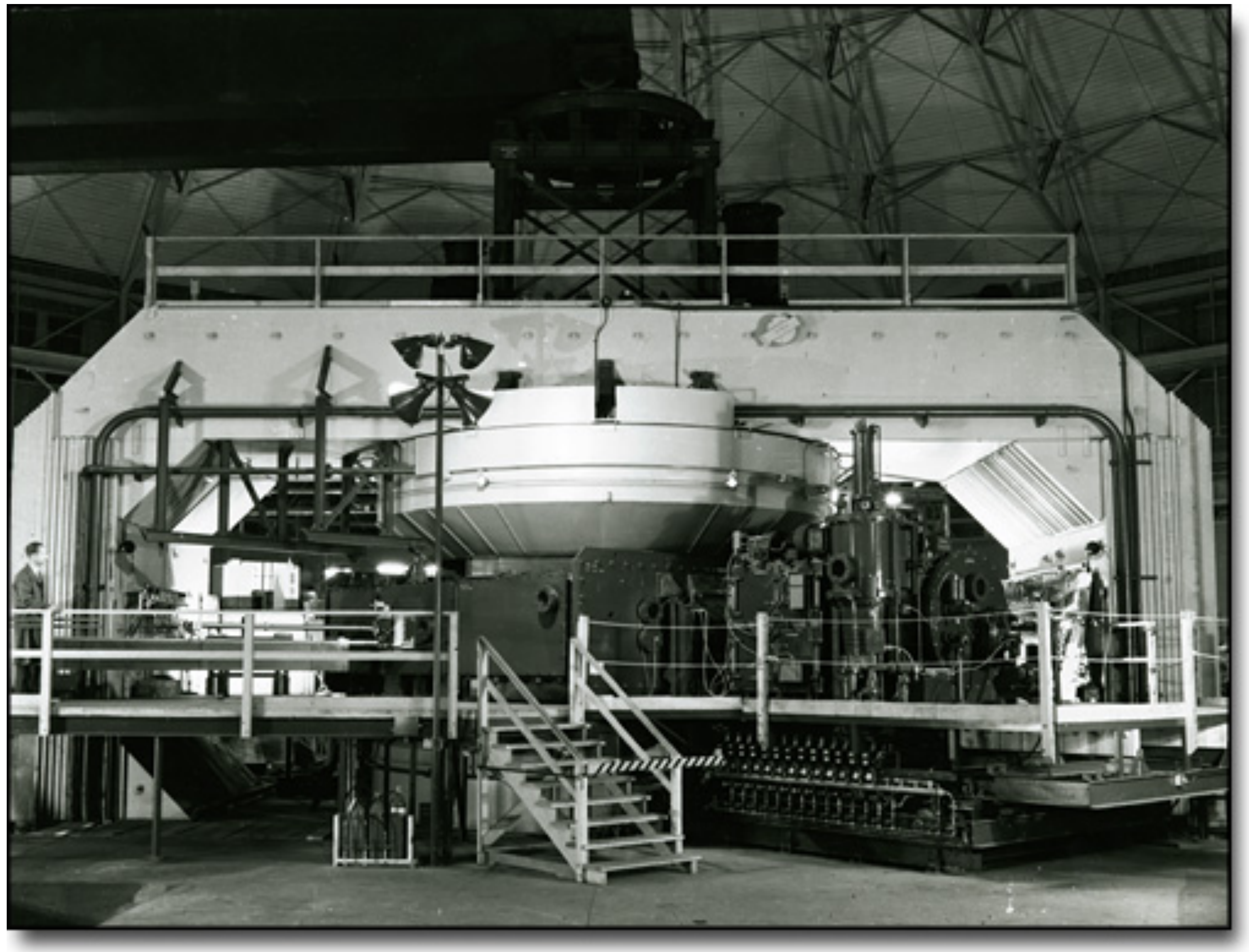
In 1947, the first true mesons, the charged pions, were found by the collaboration of Cecil Powell, César Lattes, Giuseppe Occhialini, *et al.*, at the University of Bristol, in England. Since the advent of particle accelerators had not yet come, high-energy subatomic particles were only obtainable from atmospheric cosmic rays.



An animation of the nuclear force (or residual strong force) interaction. The small colored double disks are gluons. Anticolors are shown as per this diagram

In 1948, Lattes, Eugene Gardner, and their team first artificially produced pions at the University of California's cyclotron in Berkeley, California, by bombarding carbon atoms with high-speed alpha particles.

Nobel Prizes in Physics were awarded to Yukawa in 1949 for his theoretical prediction of the existence of mesons, and to Cecil Powell in 1950 for developing and applying the technique of particle detection using photographic emulsions.

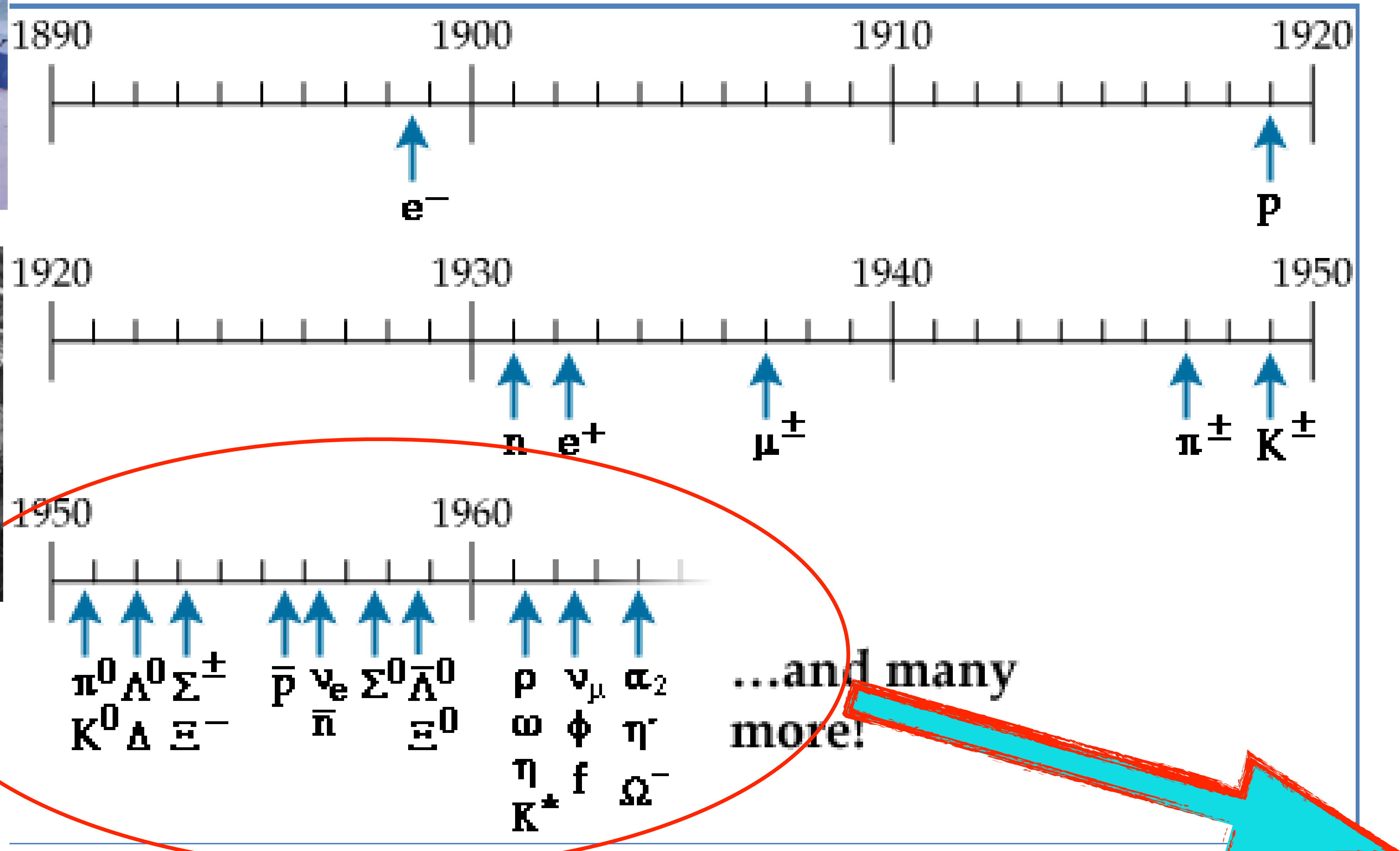


184" Cyclotron Before Installation of Fifteen-Foot-Thick Concrete Shielding, ca. 1940

Accelerators and the Zoo of Particles

If we only have electron, proton and neutron, the world is already good enough, for physicists.

Zoo of Particles



Quarks

1994 Nobel Prize Winner in Physics

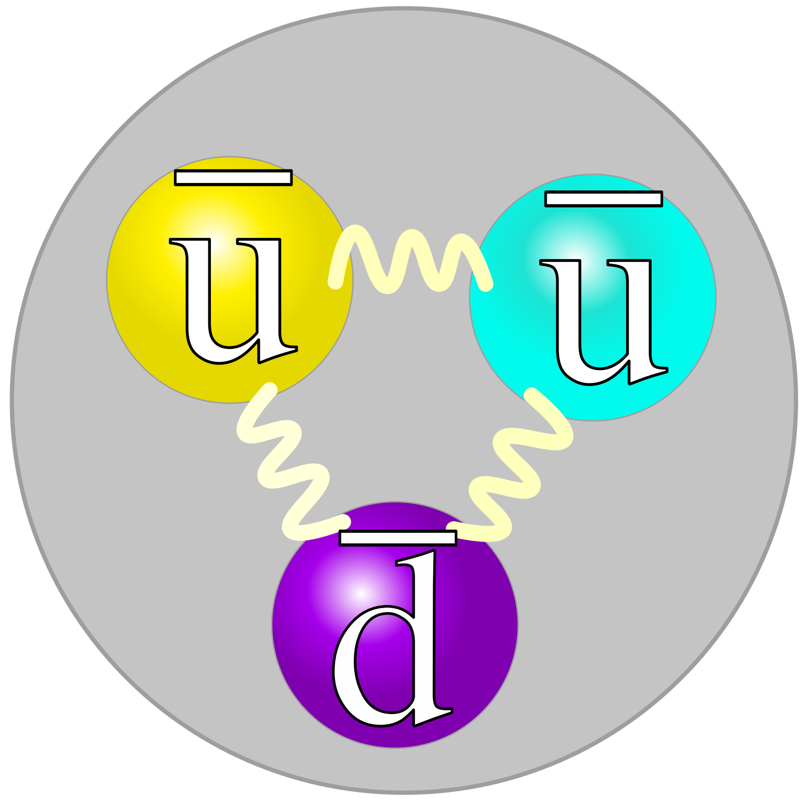
“Who ordered that?”

I. I. Rabi’s famous quote when the muon was discovered

Murray Gell-Mann had just been reading Finnegan's Wake by James Joyce which contains the phrase "three quarks for Muster Mark”. In 1964, Murray Gell-Mann and George Zweig came up with the idea that one could account for the entire “zoo of particles”, if there existed objects call quarks.

Antiproton and Bevatron

- The antiproton, is the antiparticle of the proton. Antiprotons are stable, but typically short-lived, since any collision with a proton will cause both particles to be annihilated in a burst of energy.
- The existence of the antiproton was predicted by Paul Dirac in his 1933 Nobel Prize lecture.
- The antiproton was first experimentally confirmed in 1955 at the Bevatron particle accelerator by University of California, Berkeley physicists Emilio Segrè and Owen Chamberlain, for which they were awarded the 1959 Nobel Prize in Physics.



Edwin McMillan and Edward Lofgren on the shielding of the Bevatron. The shielding was only added later, after initial operations.

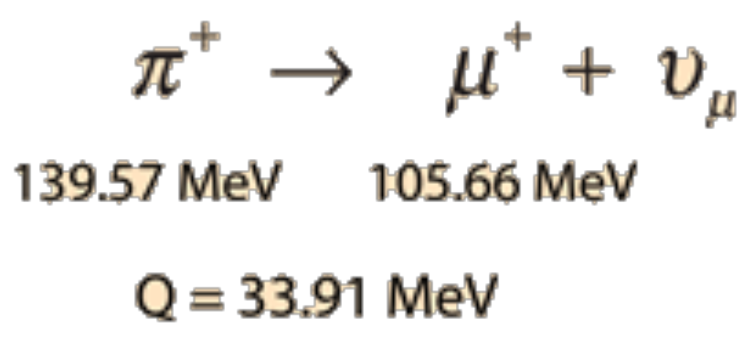
- The Bevatron — a weak-focusing proton synchrotron — LBNL, which began operating in 1954. It was designed to collide protons at 6.2 GeV, the expected optimum energy for creating antiprotons.

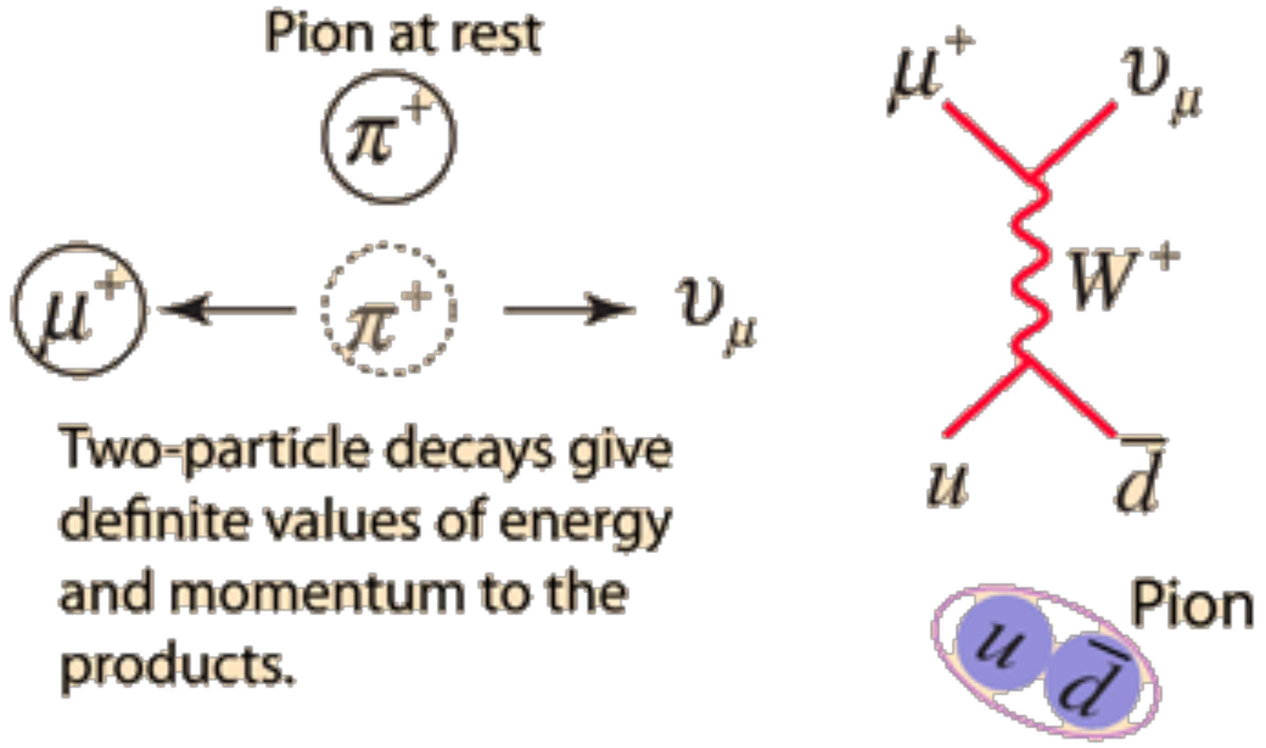
The Bevatron in 1958

Muon Neutrino and AGS

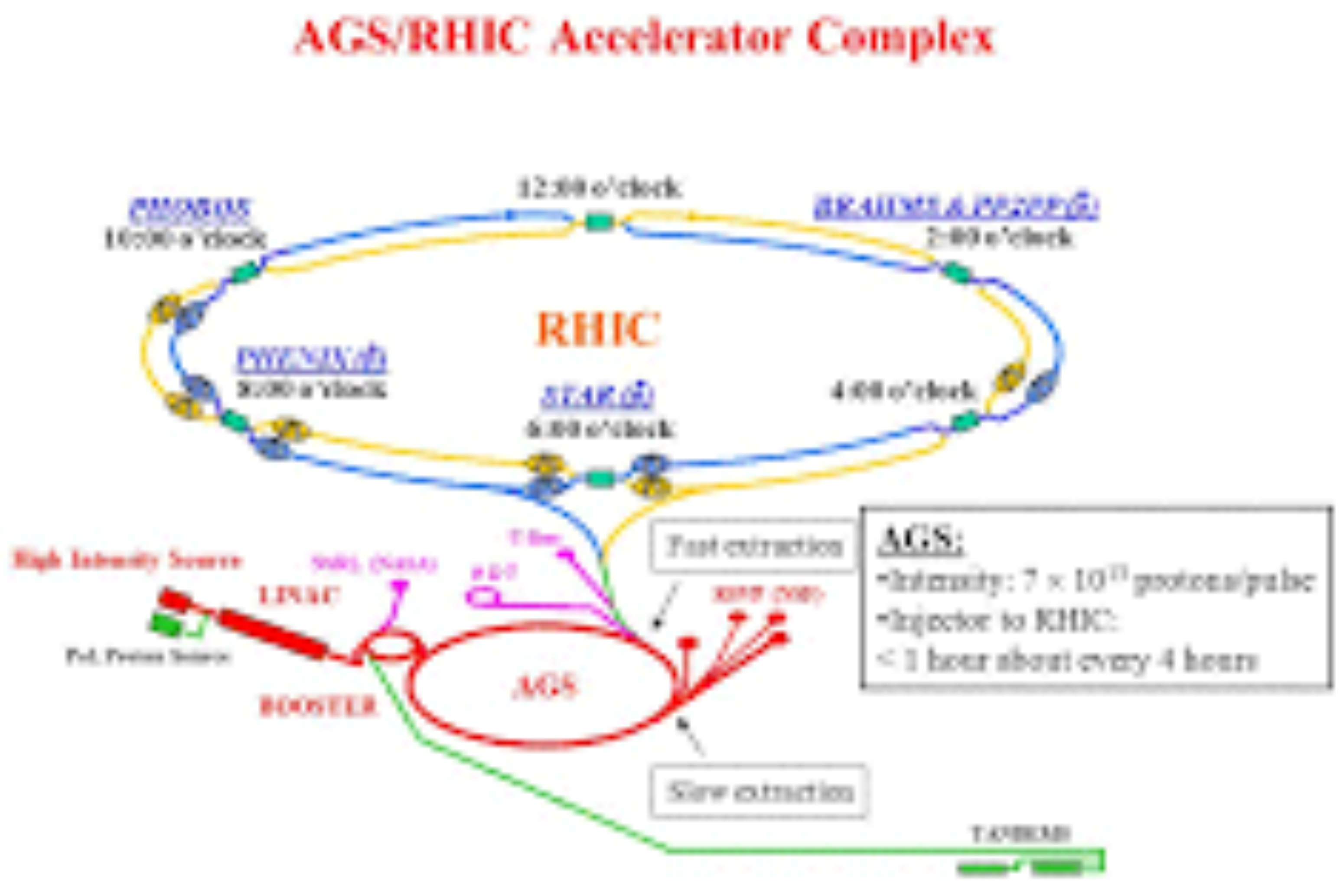
Leon Lederman, **Melvin Schwartz** and **Jack Steinberger**:

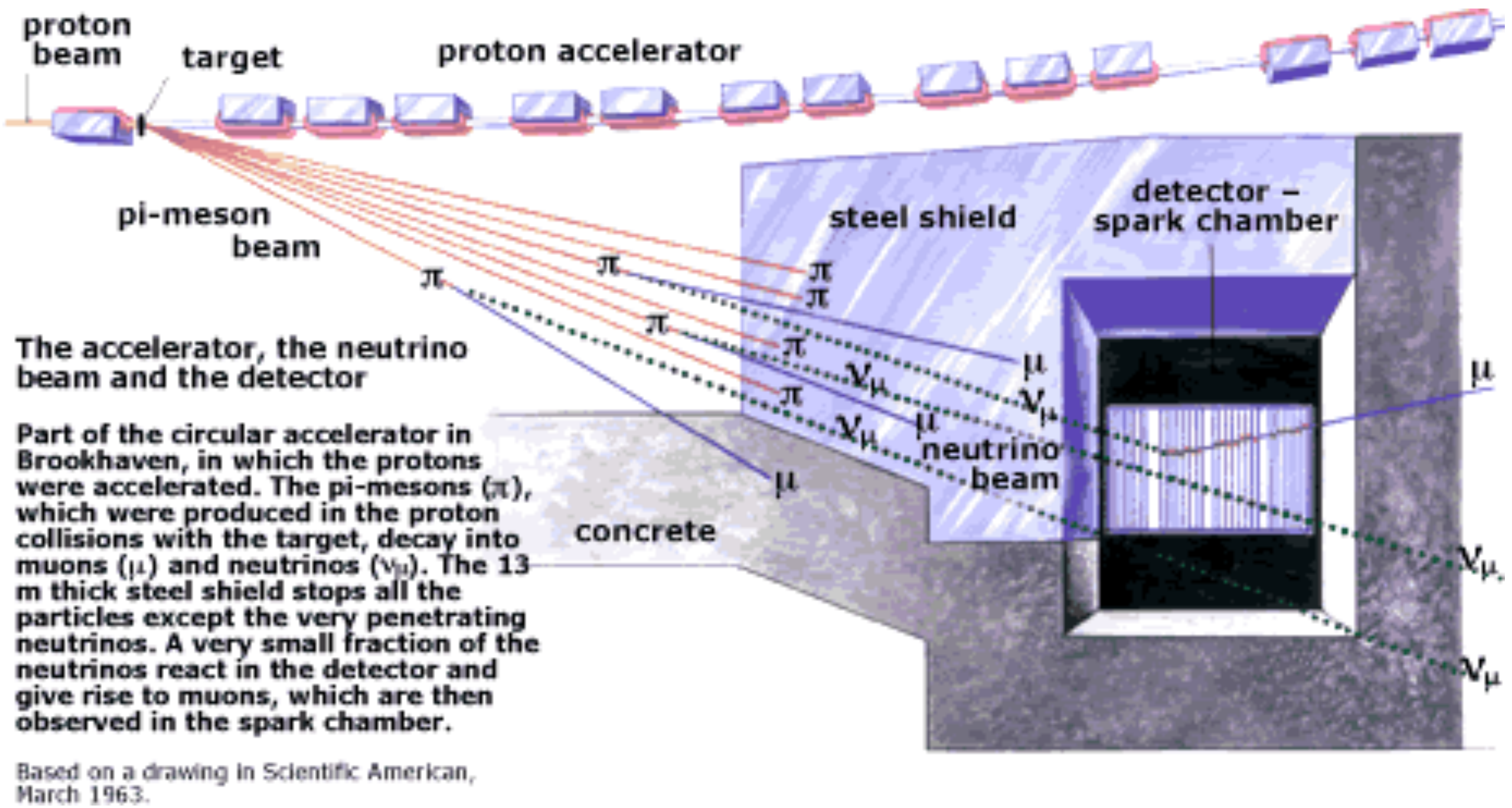
- Protons were accelerated to an energy of 15 GeV in the Brookhaven accelerator AGS on Long Island, USA.
- The intense proton beam was directed onto a target of beryllium. In each collision a handful of particles were produced, mainly pi-mesons.
- The many pi-meson decays



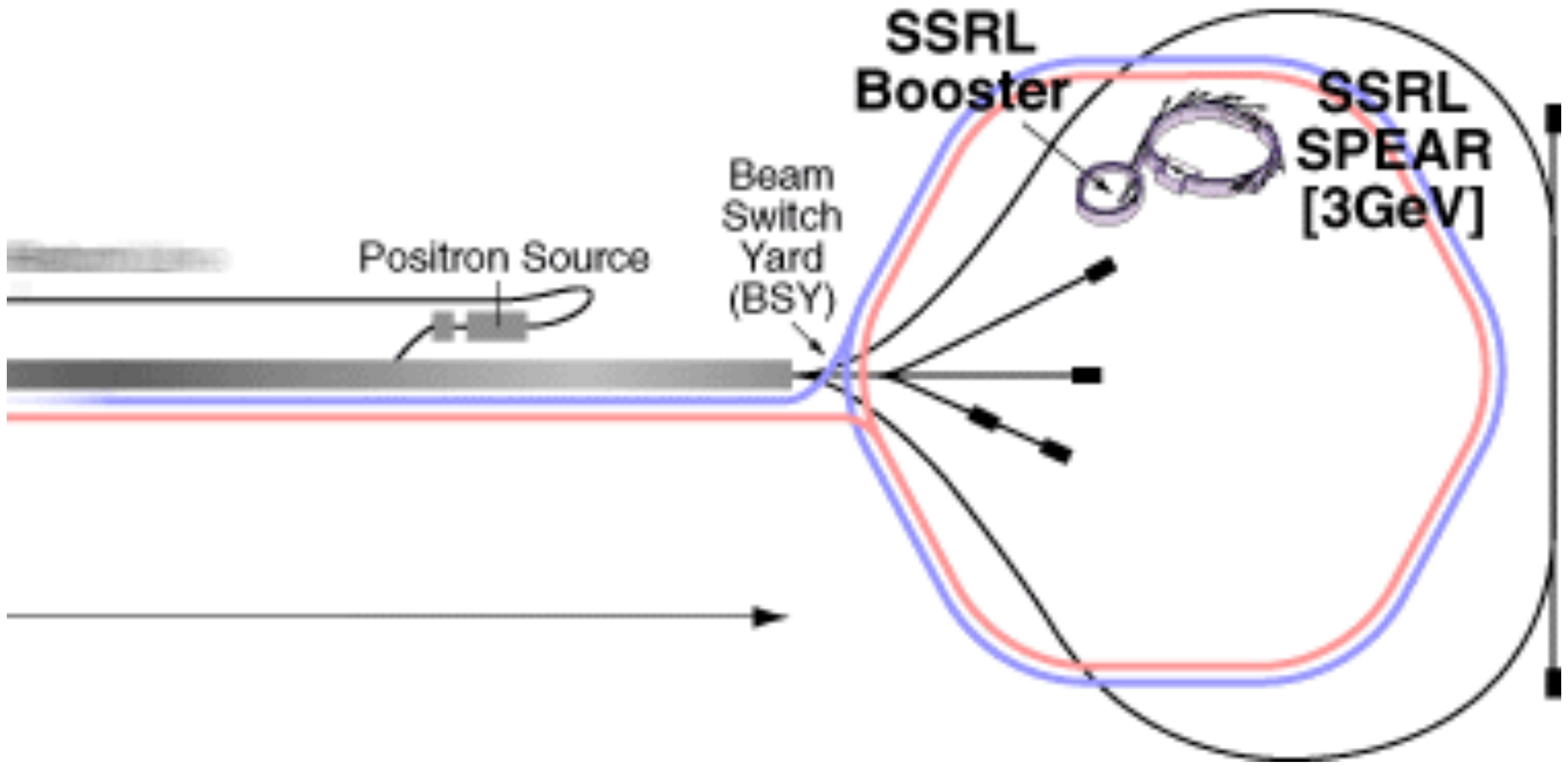


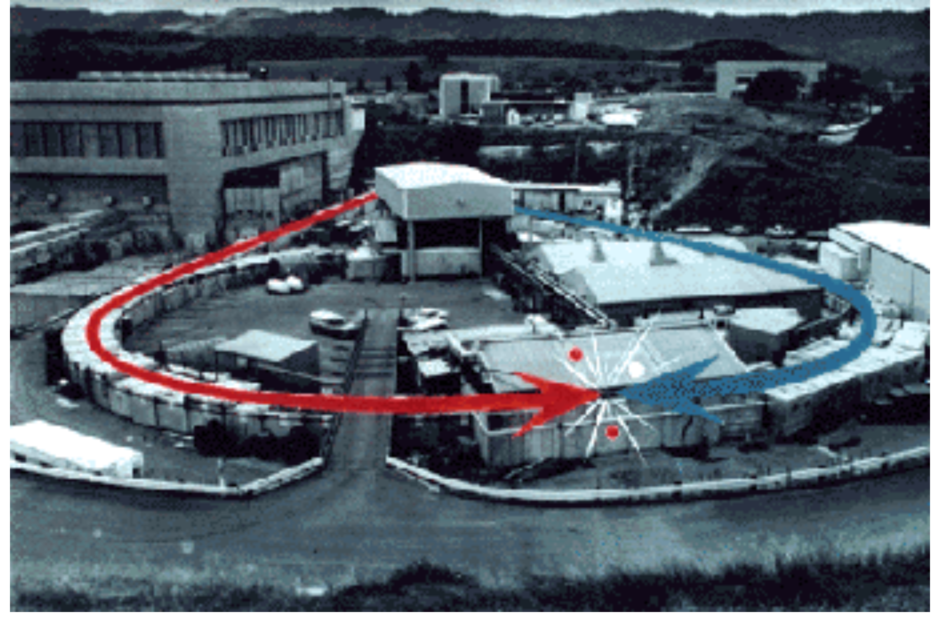
resulted in a collimated beam of muons and neutrinos.
- The neutrinos, the muons and the surviving pi-mesons crashed into a 13 m thick steel shield, which stopped all particles except the neutrinos.



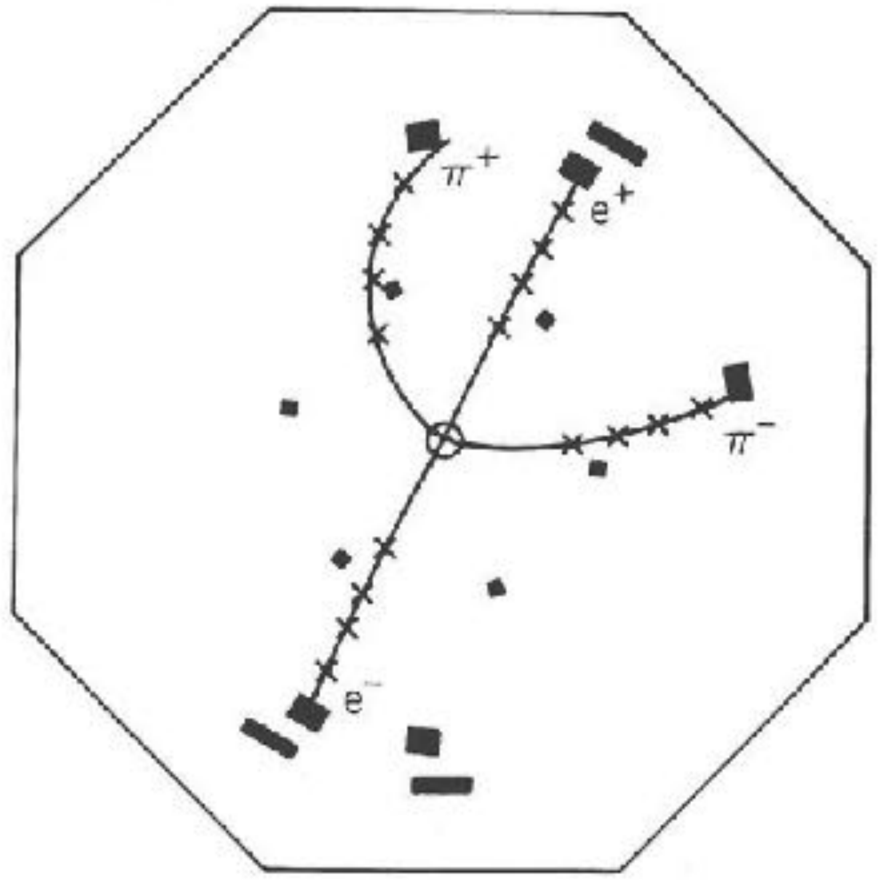


SPEAR and the Discovery of Psi and Tau

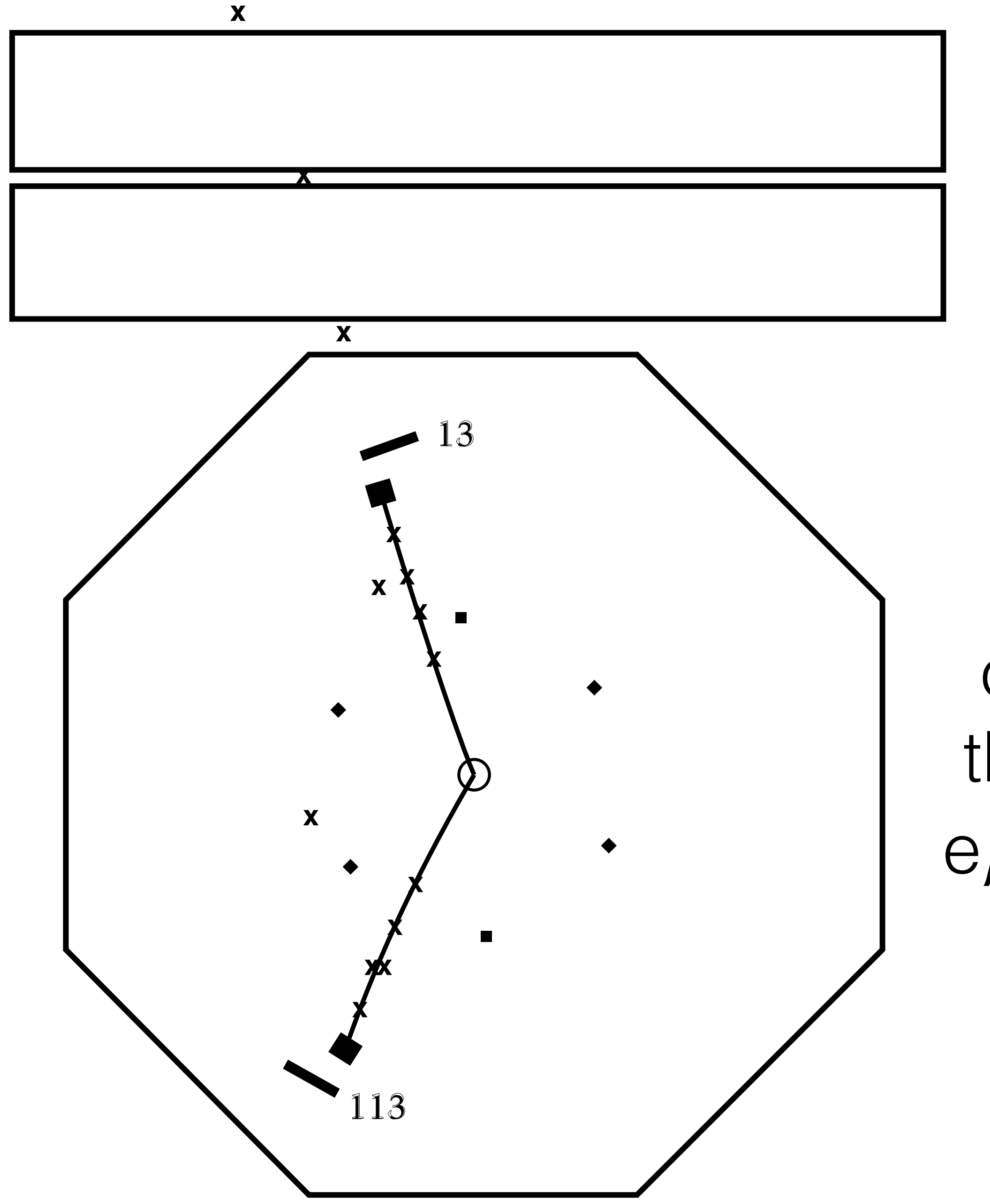




SLAC's signature of J/Psi resulted in an almost exact image of the greek letter Psi



SPEAR was a collider at the SLAC National Accelerator Laboratory. It began running in 1972, colliding electrons and positrons with an energy of 3 GeV. During the 1970s, experiments at the accelerator played a key role in particle physics research, including the discovery of the meson (awarded the 1976 Nobel Prize in physics), many charmonium states, and the discovery of the tau (awarded the 1995 Nobel Prize in physics).
Today, SPEAR is used as a synchrotron radiation source for the Stanford Synchrotron Radiation Lightsource (SSRL). The latest major upgrade of the ring in that finished in 2004 rendered it the current name SPEAR3.

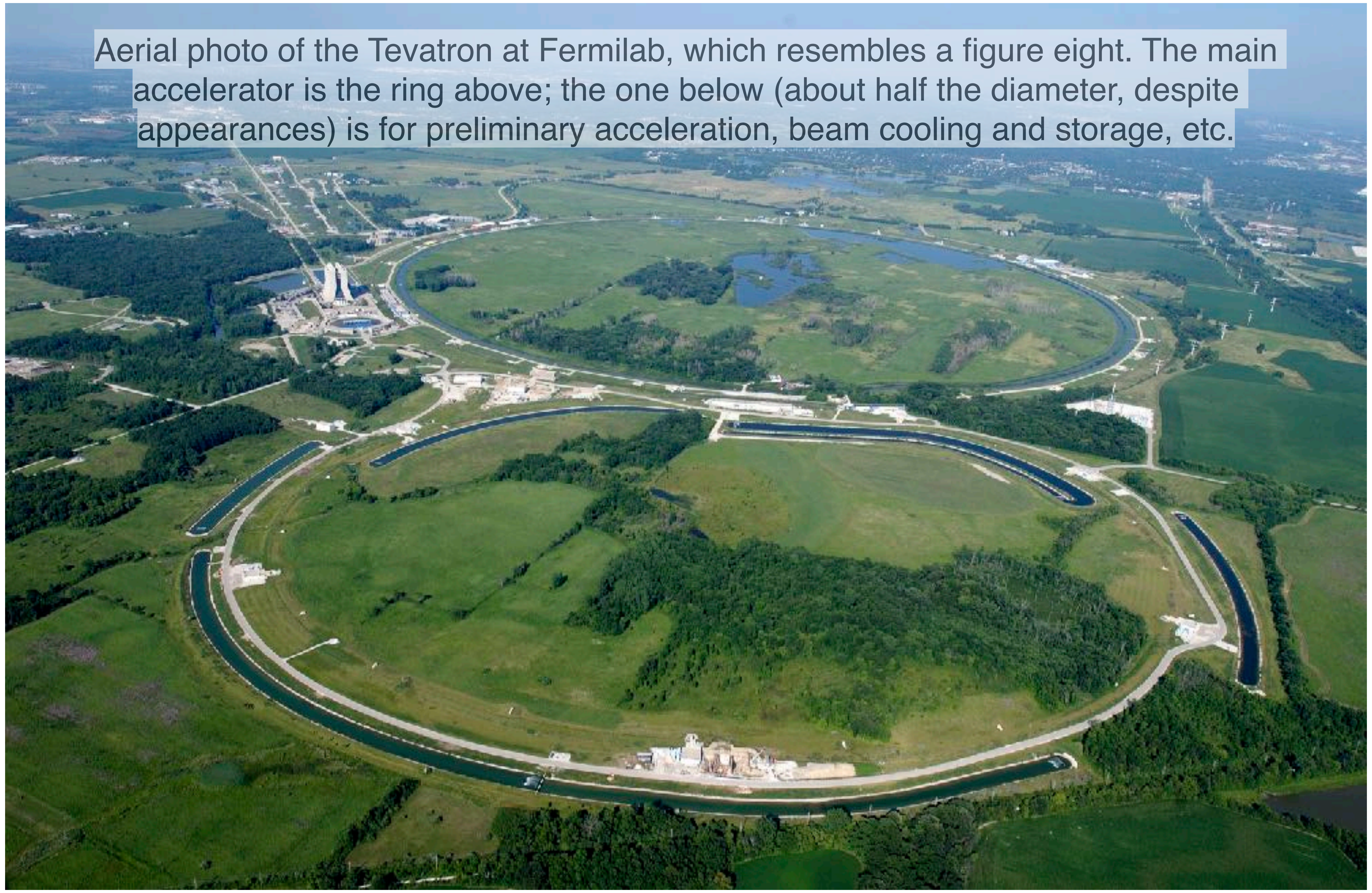


one of the first $e\mu$ event

Tevatron and the Discovery of b and t Quarks, tau neutrino

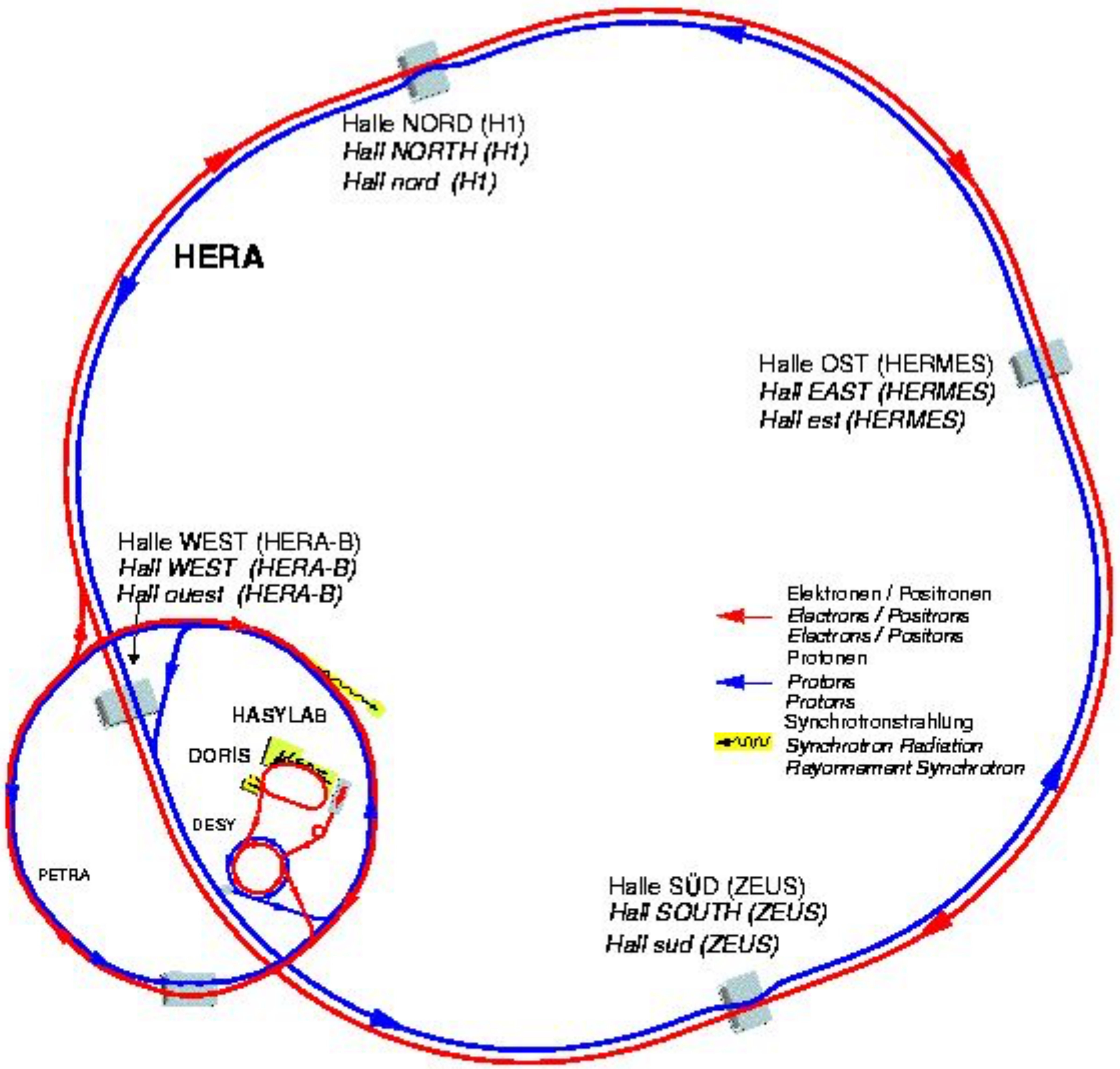
- The Upsilon meson (ϒ) is a quarkonium state (i.e. flavourless meson) formed from a bottom quark and its antiparticle. It was discovered by the E288 experiment team, headed by Leon Lederman, at Fermilab in 1977, and was the first particle containing a bottom quark to be discovered because it is the lightest that can be produced without additional massive particles. It has a lifetime of 1.21×10^{-20} s and a mass about 9.46 GeV/c^2 in the ground state.

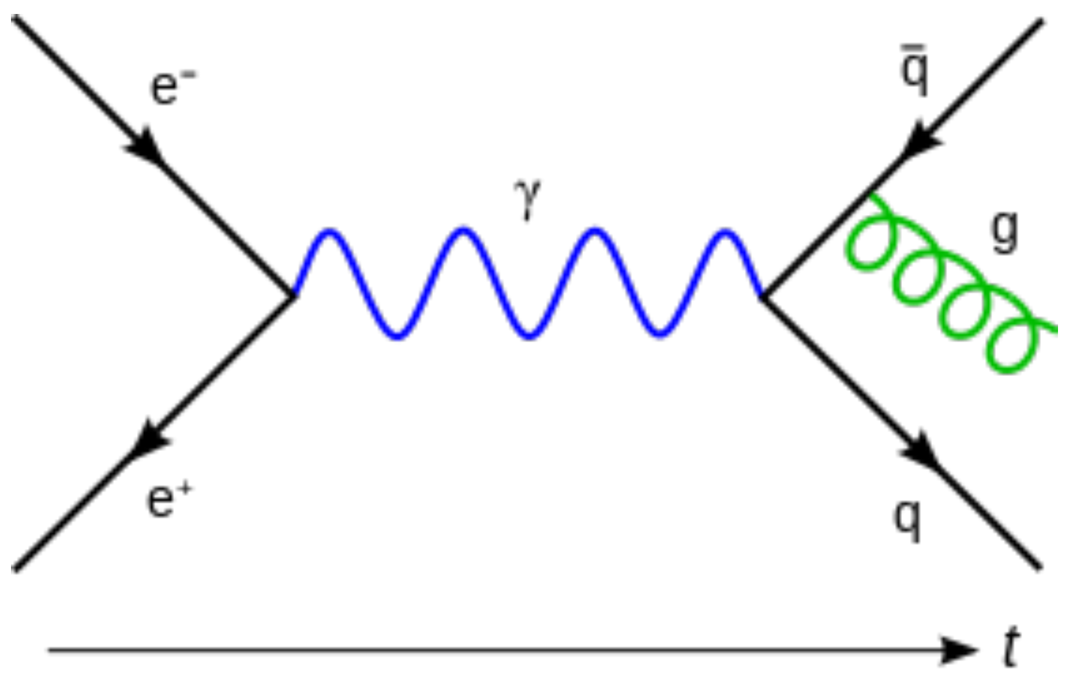
- The heaviest known elementary particle, the top quark, was discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton-antiproton collider at Fermilab.



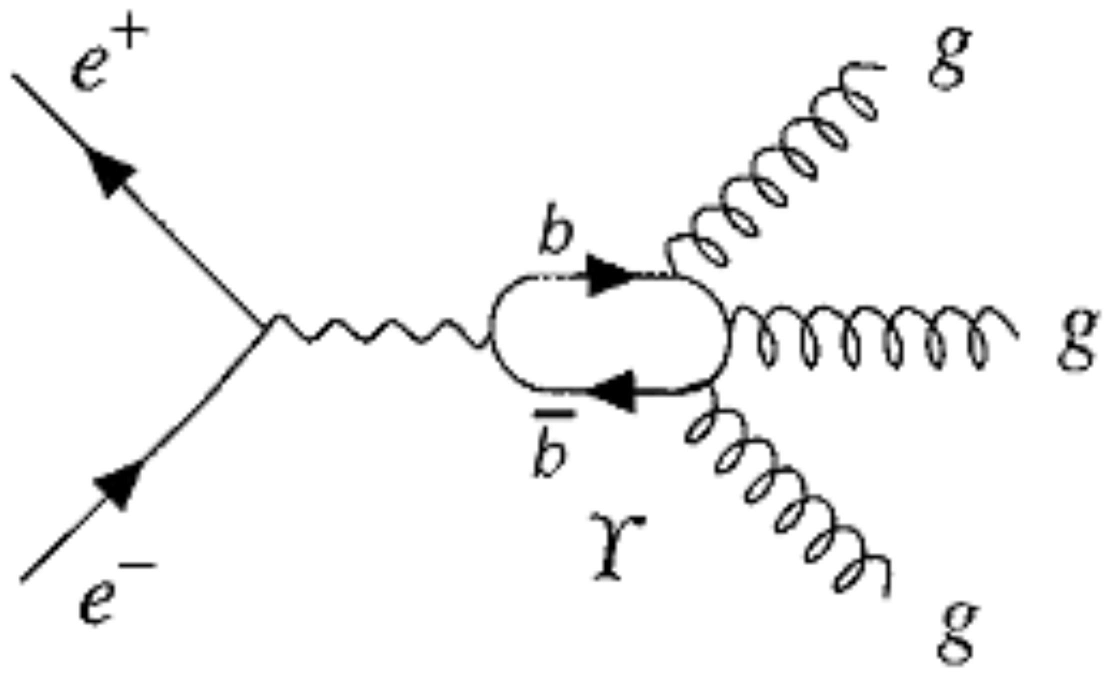
- DONUT (Direct observation of the nu tau, E872) was an experiment at Fermilab dedicated to the search for tau neutrino interactions. The detector operated during a few months in the summer of 1997, and successfully detected the tau neutrino. It confirmed the existence of the last lepton predicted by the Standard Model. The data from the experiment was also used to put an upper limit on the tau neutrino magnetic moment and measure its interaction cross section.

Doris, Petra and HERA -Gluon





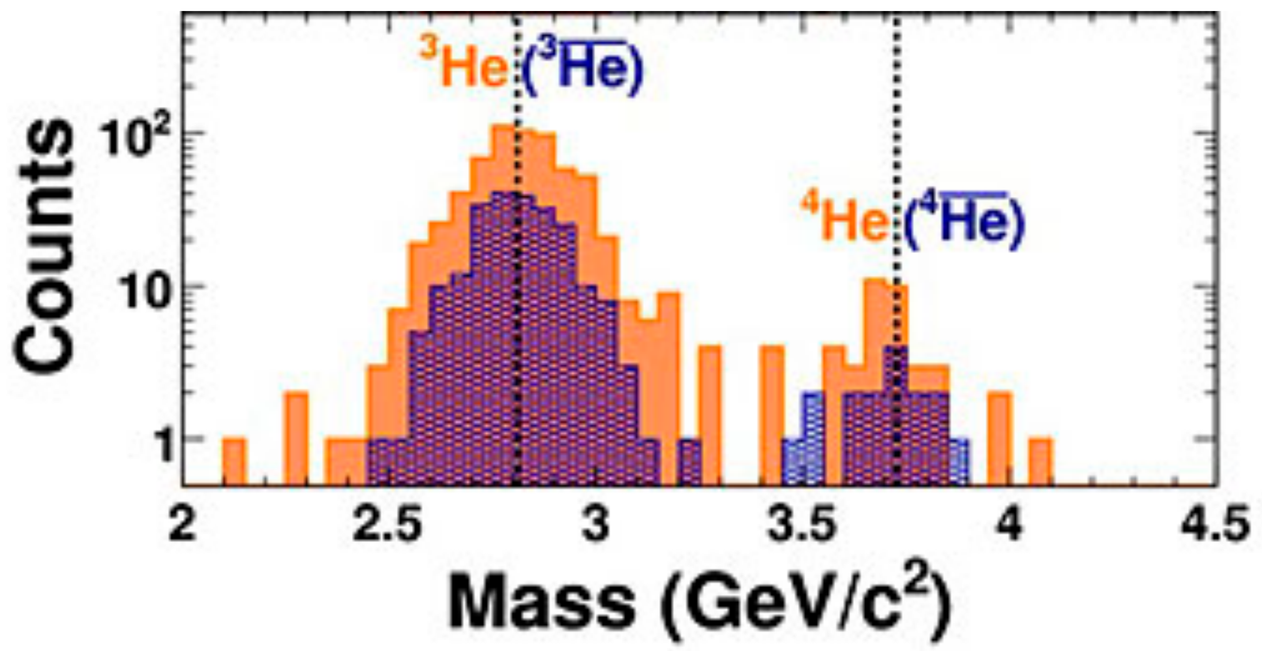
$e^+e^- \to q\bar{q}g$: 1979 at PETRA (DESY) by TASSO, MARK-J, JADE and PLUTO experiments

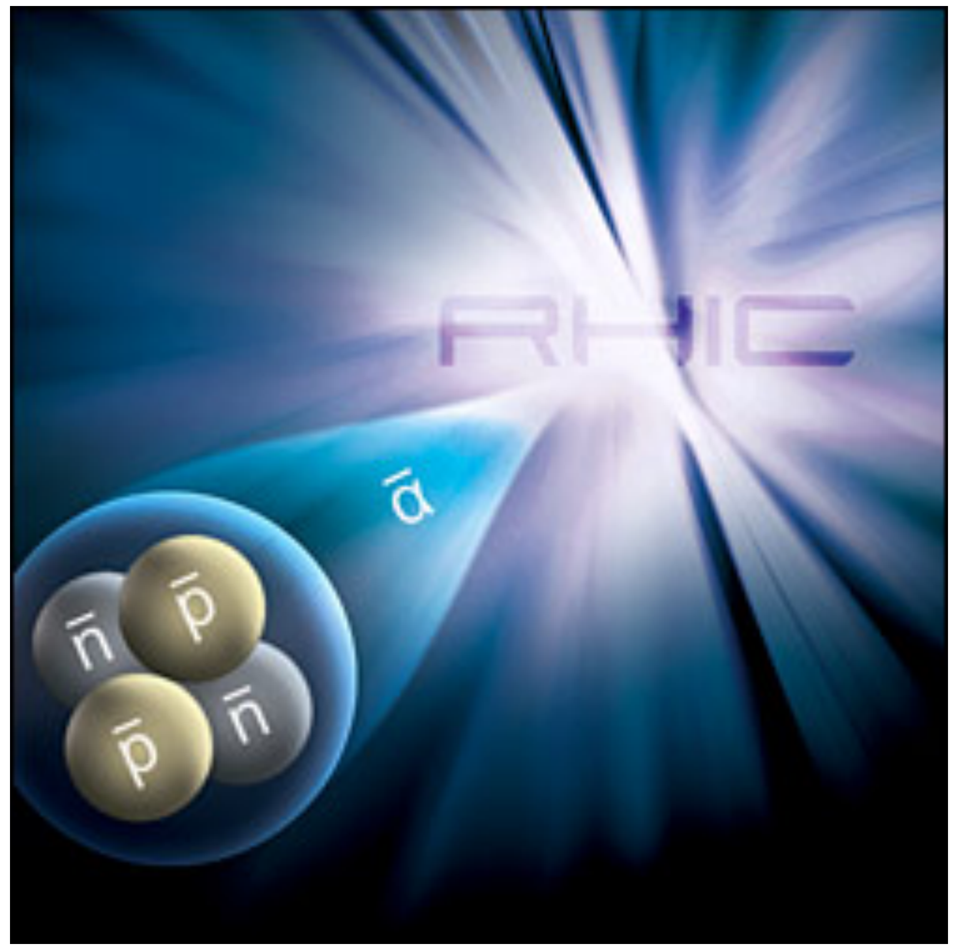


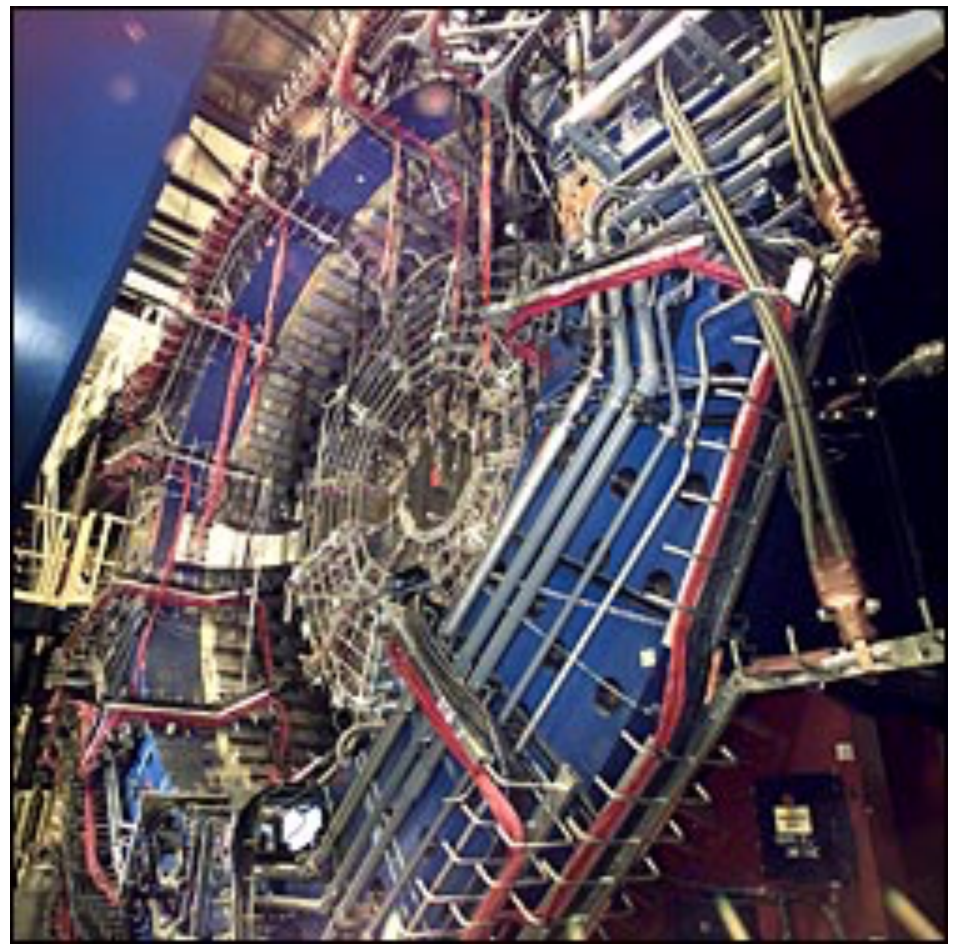
$e^+e^- \to \Upsilon(9.46) \to 3g$: 1978 at DORIS (DESY) by PLUTO experiments

Anti-mater and RHIC

The collider was constructed in an existing 3.834 km long ring tunnel, and is in operation since 2000. Its beam energy ranges up to 100 GeV/n for the heaviest ions, and for polarized protons are a maximum energy of 250 GeV .







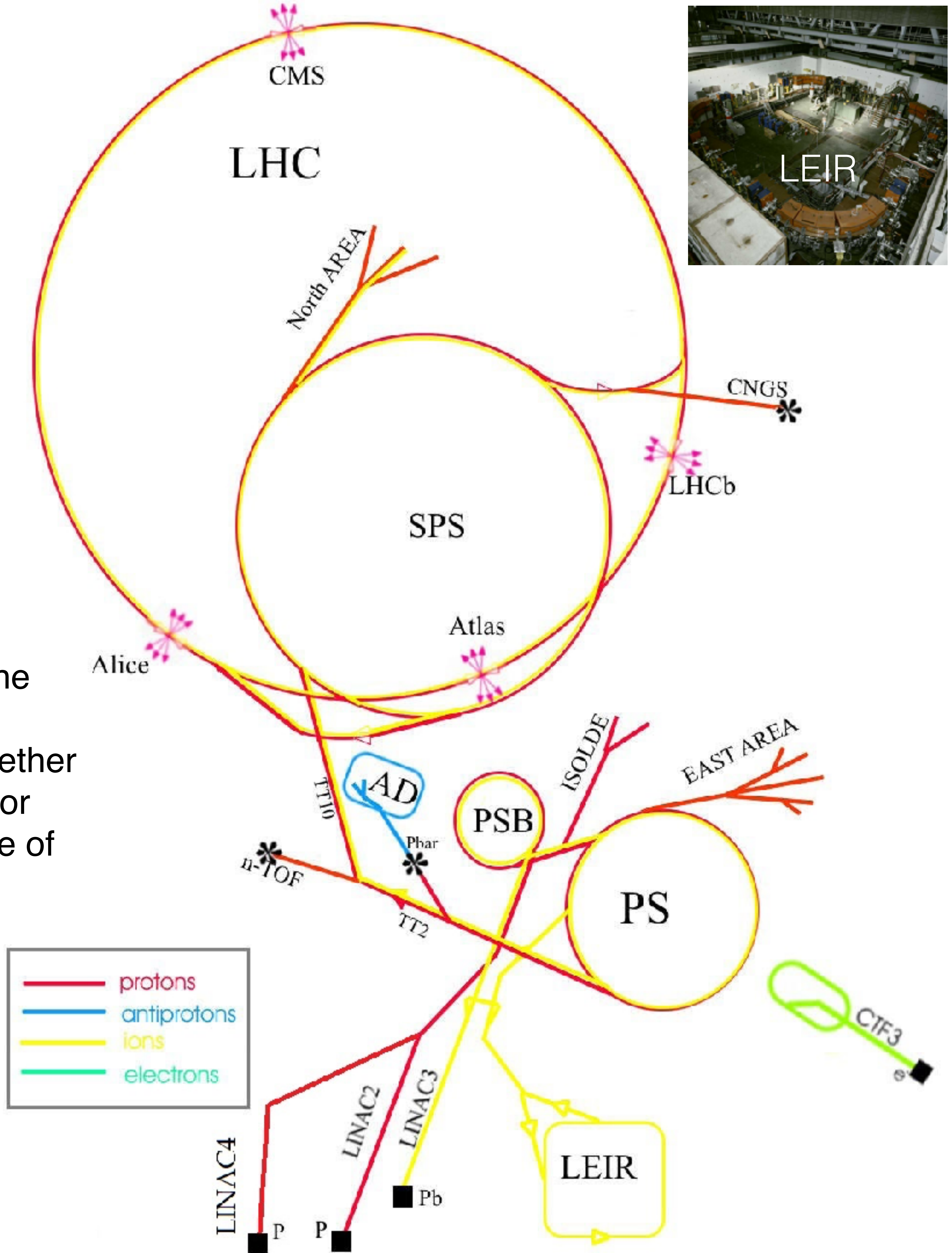
From W and Z Bosons, Anti-Hydrogen to Higgs in CERN

- 1983: The discovery of W and Z bosons in the UA1 and UA2 experiments.The 1984 Nobel Prize in physics was awarded to Carlo Rubbia and Simon van der Meer for the developments that led to this discovery.

- 1995: under the LEAR programme, four machines – the Proton Synchrotron (PS), the Antiproton Collector (AC), the Antiproton Accumulator (AA), and LEAR – worked together to collect, cool and decelerate antiprotons for use in experiments. The NASA gives a price of $62.5 trillion per gram of antihydrogen.

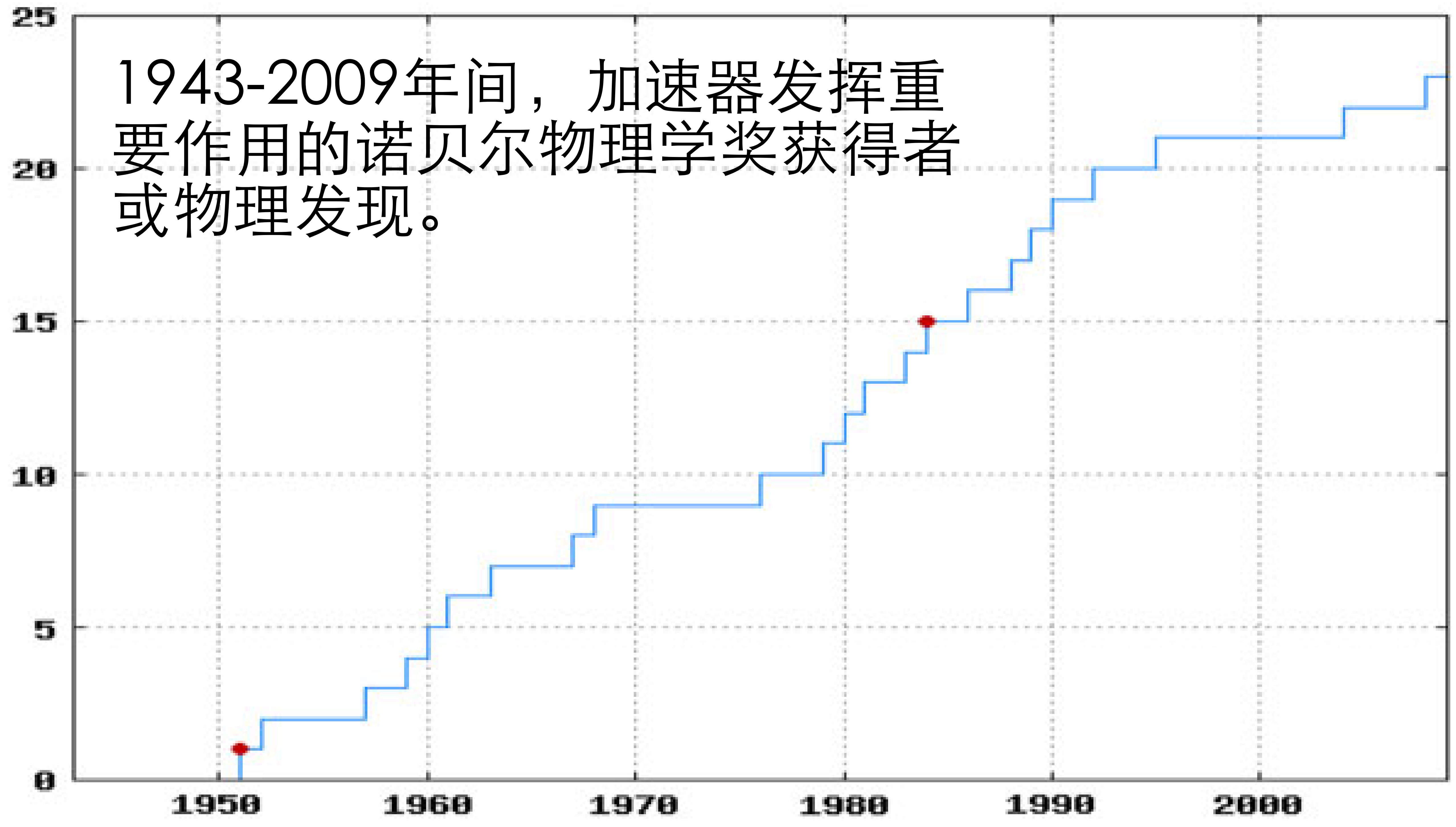
- 1999: The discovery of direct CP violation by the NA48 experiment

- 2012: The discovery of HIGGS boson at ATLAS and CMS of LHC.



The Influence of Accelerator Science on Physics Research

E. F. Haussecker, A. W. Chao Phys. Perspect. 13 (2011) 146–160



- 只是诺贝尔物理学奖，不含其它。
- 基于直接证据－文章分析得到结论。

"Our analysis indicates that accelerator science has played an integral role in influencing 28% of physicists working between 1939 and 2009 by either inspiring or facilitating their research. We also determined that 28% of the research in physics between 1939 and 2009 has been influenced by accelerator science, and that on average accelerator science contributed to a Nobel Prize for Physics every 2.9 years."

- International Linear Collider (**ILC**), Compact Linear Collier (**CLIC**), Future Circular Collider(**FCC**), Circular Electron Positron Collier(**CEPC**) are candidates of next big accelerator for “post-LHC” high energy particle physics.

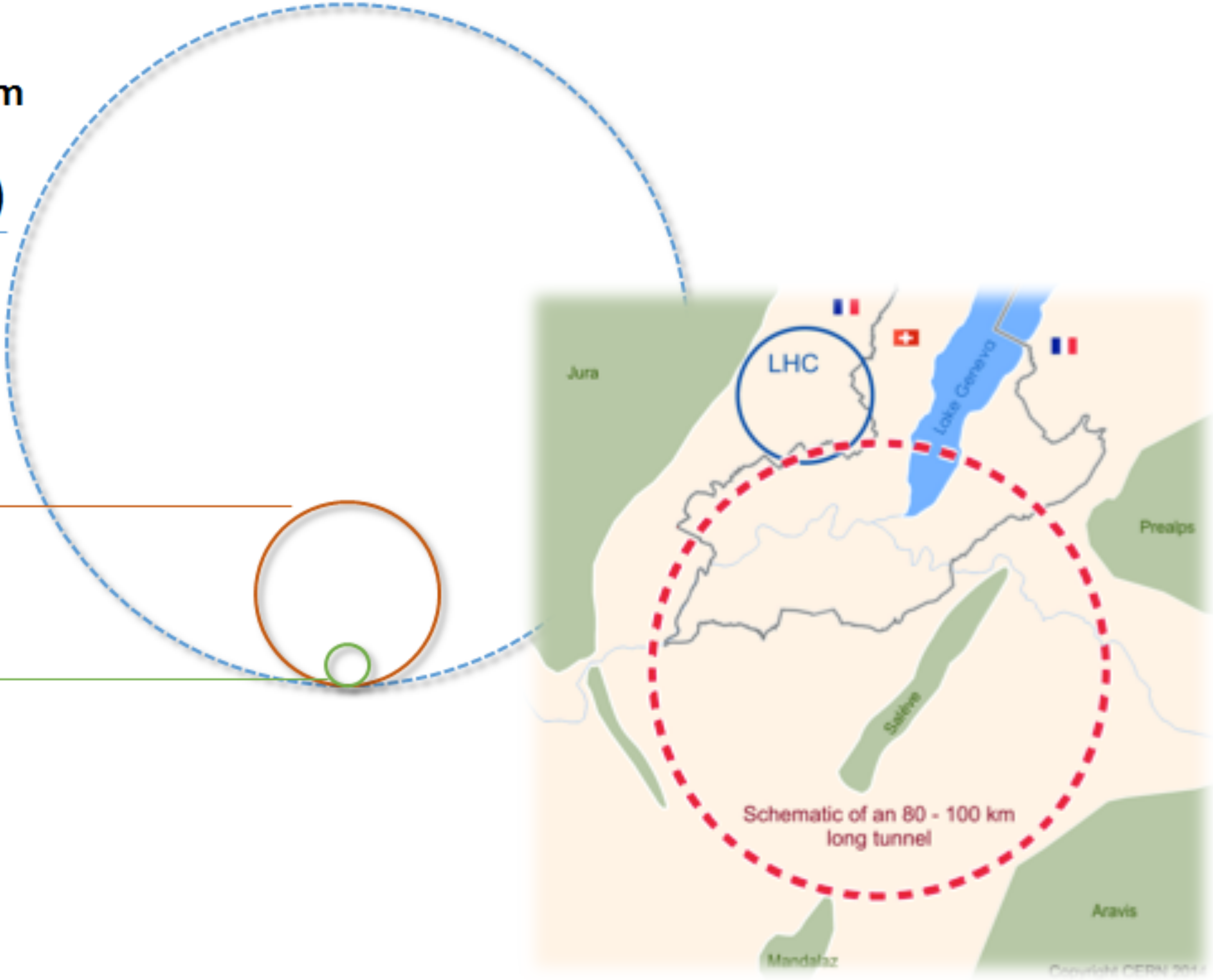
- They will be tens of kilometers long or circumstance, and tens of billion dollars needed.

Future Circular Collider

Future Circular Collider
Circumference: **80-100 km**
Energy: **100 TeV (pp)**
>350 GeV (e^+e^-)

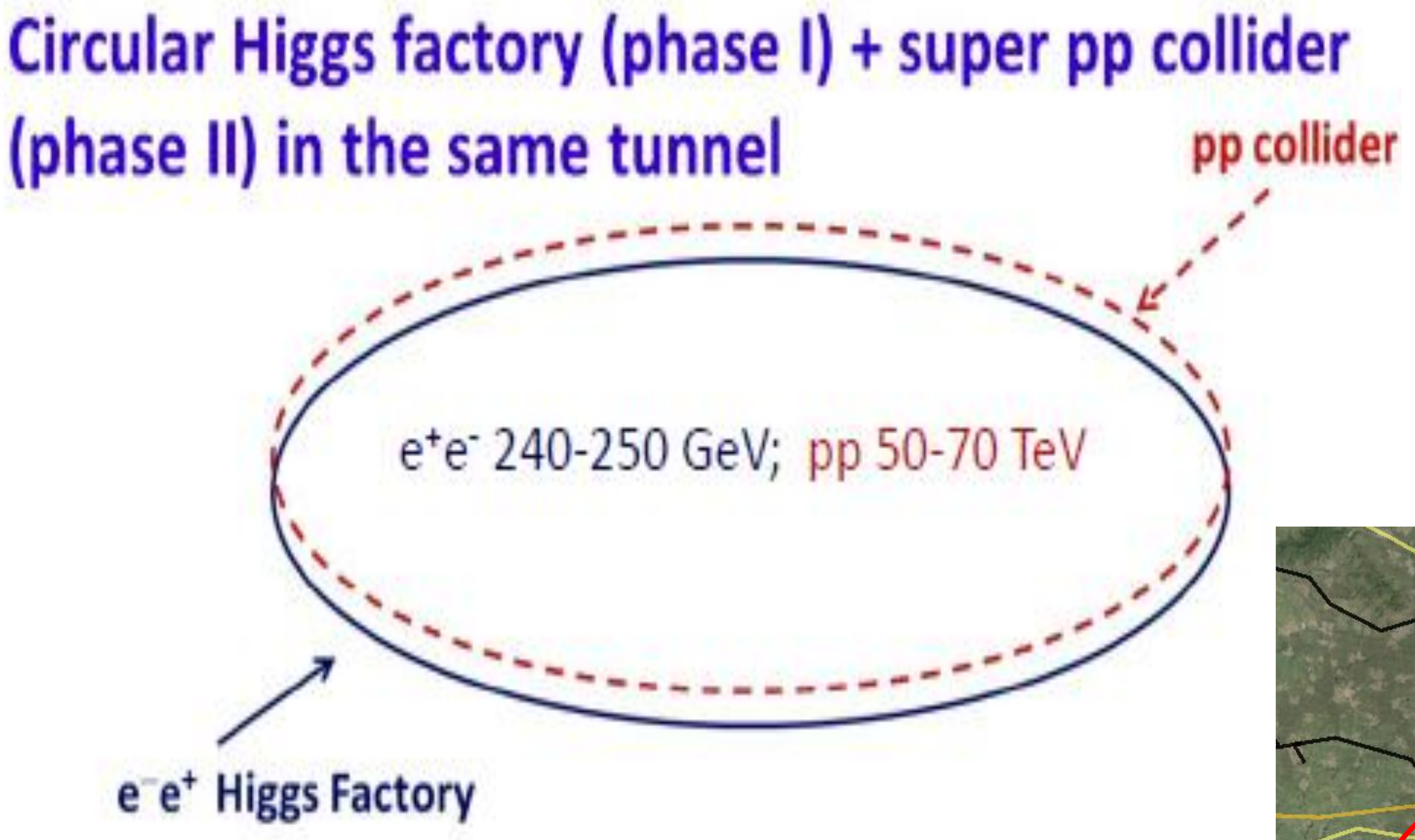
Large Hadron Collider
Circumference: **27 km**
Energy: **14 TeV (pp)**
209 GeV (e^+e^-)

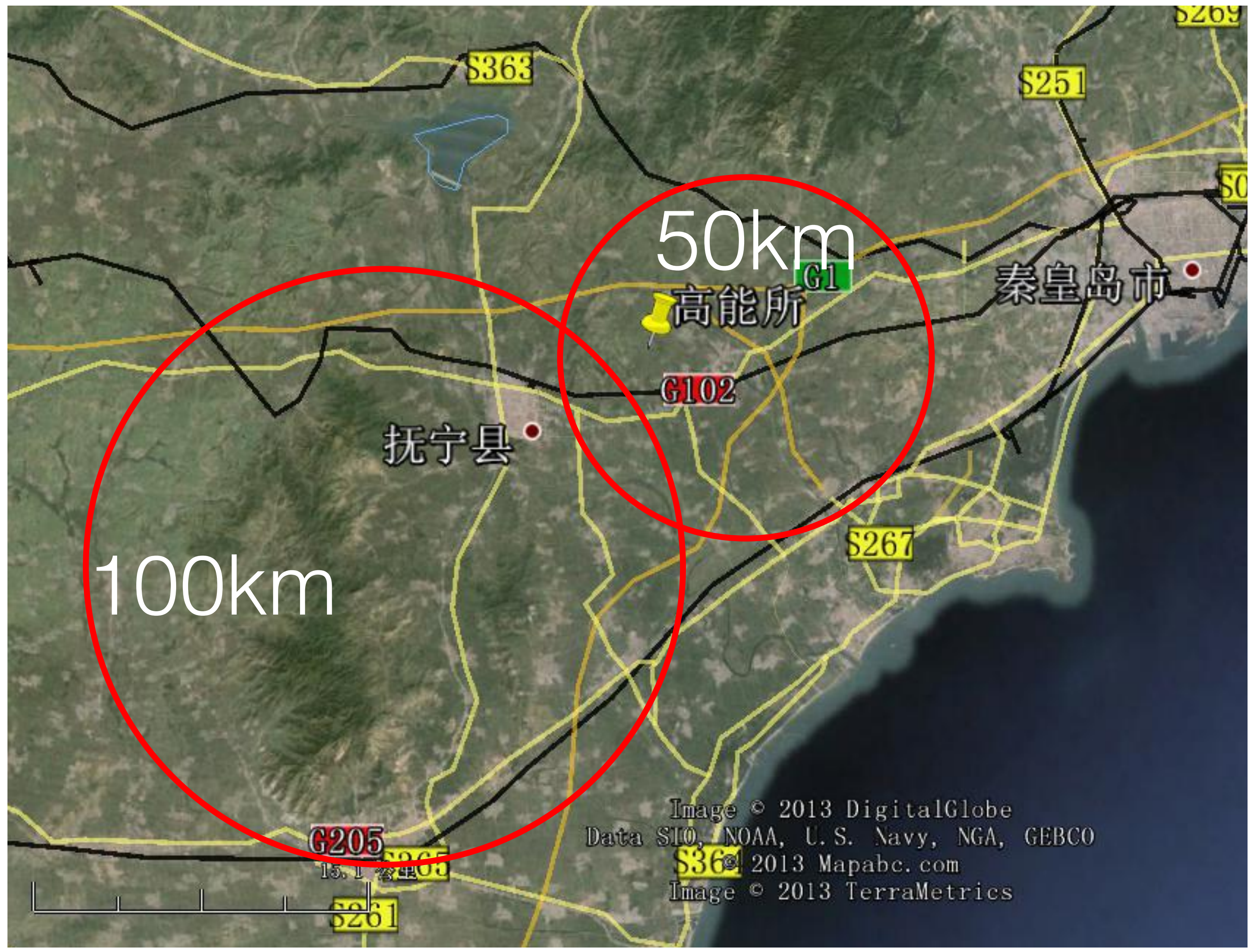
Tevatron (closed)
Circumference: **6.2 km**
Energy: **2 TeV**



fcc.web.cern.ch;2015

Circular Electron Positron Collider

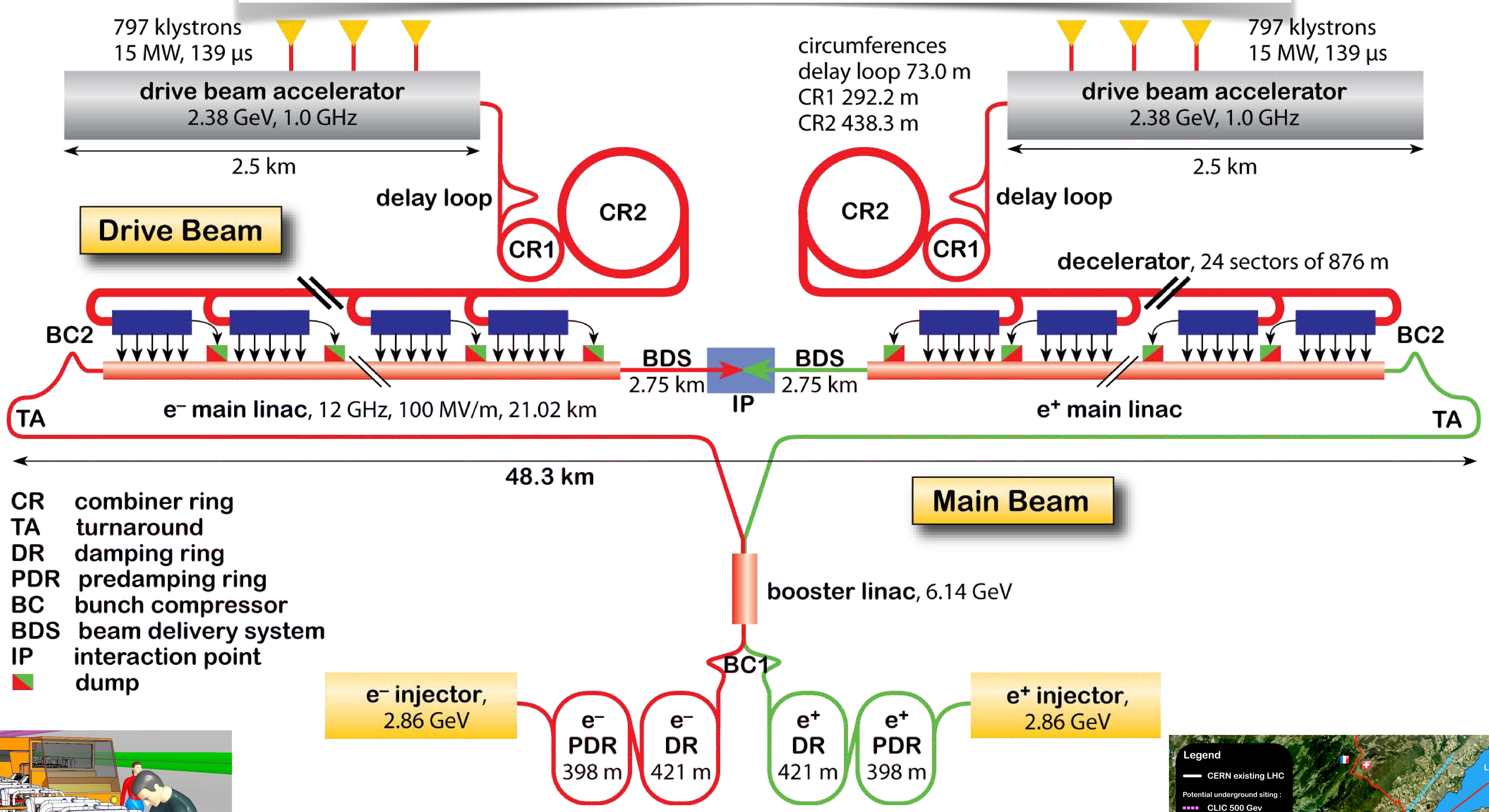


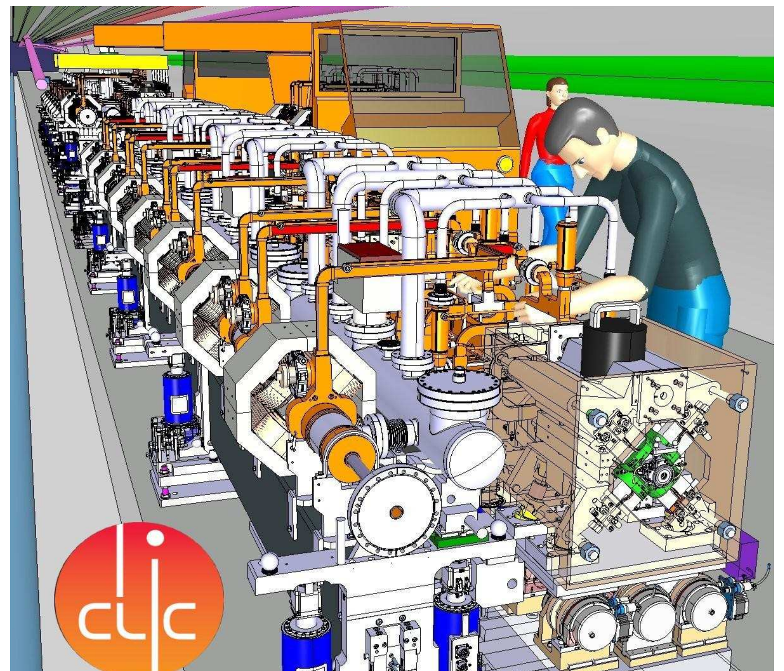


- Yifang Wang, Introduction of CEPC-SppC, Feb.13,2014, Geneve.
- CEPC-SPPC Preliminary Conceptual Design Report, IHEP-CEPC-DR-2015-01, IHEP-AC-2015-01

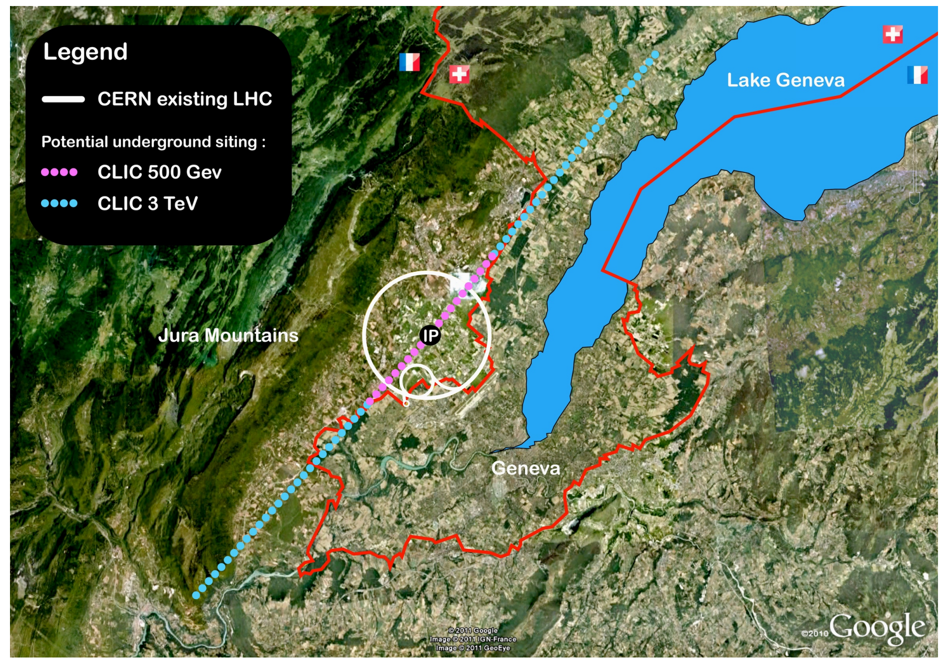
Compact Linear Collider

2x797 Klystrons of 15MW,139us, at 1.0GHz



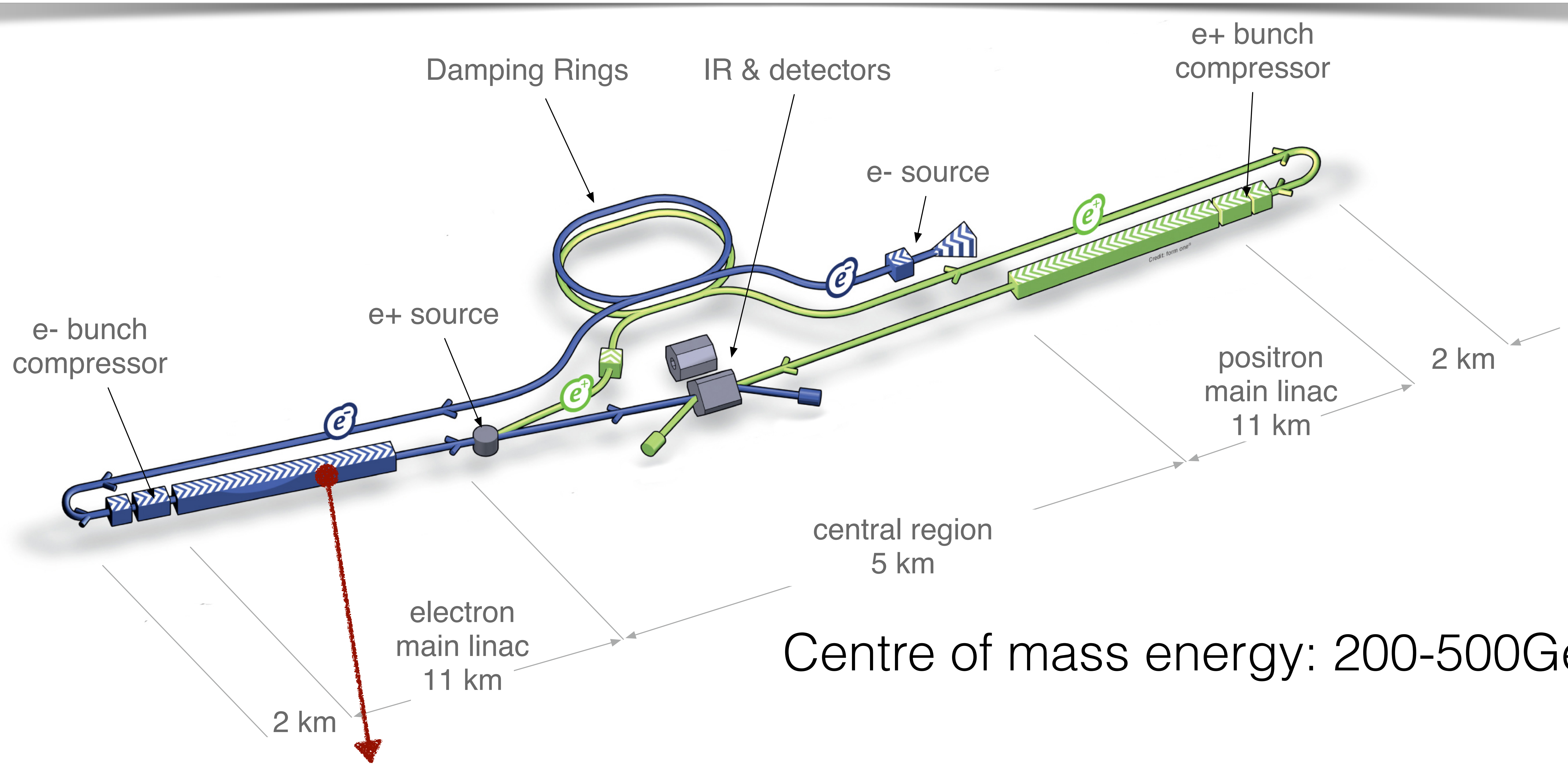


CLIC Concept Design Report, CERN-2012-007,
12 October 2012.

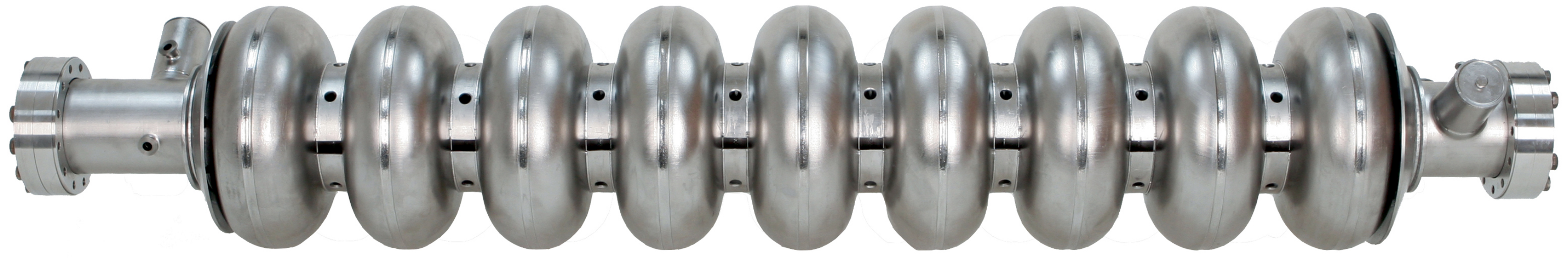


International Linear Collider

1.3GHz, 10MW,1.65ms, 5-10Hz, multi-beam klystron: 426/461—>567



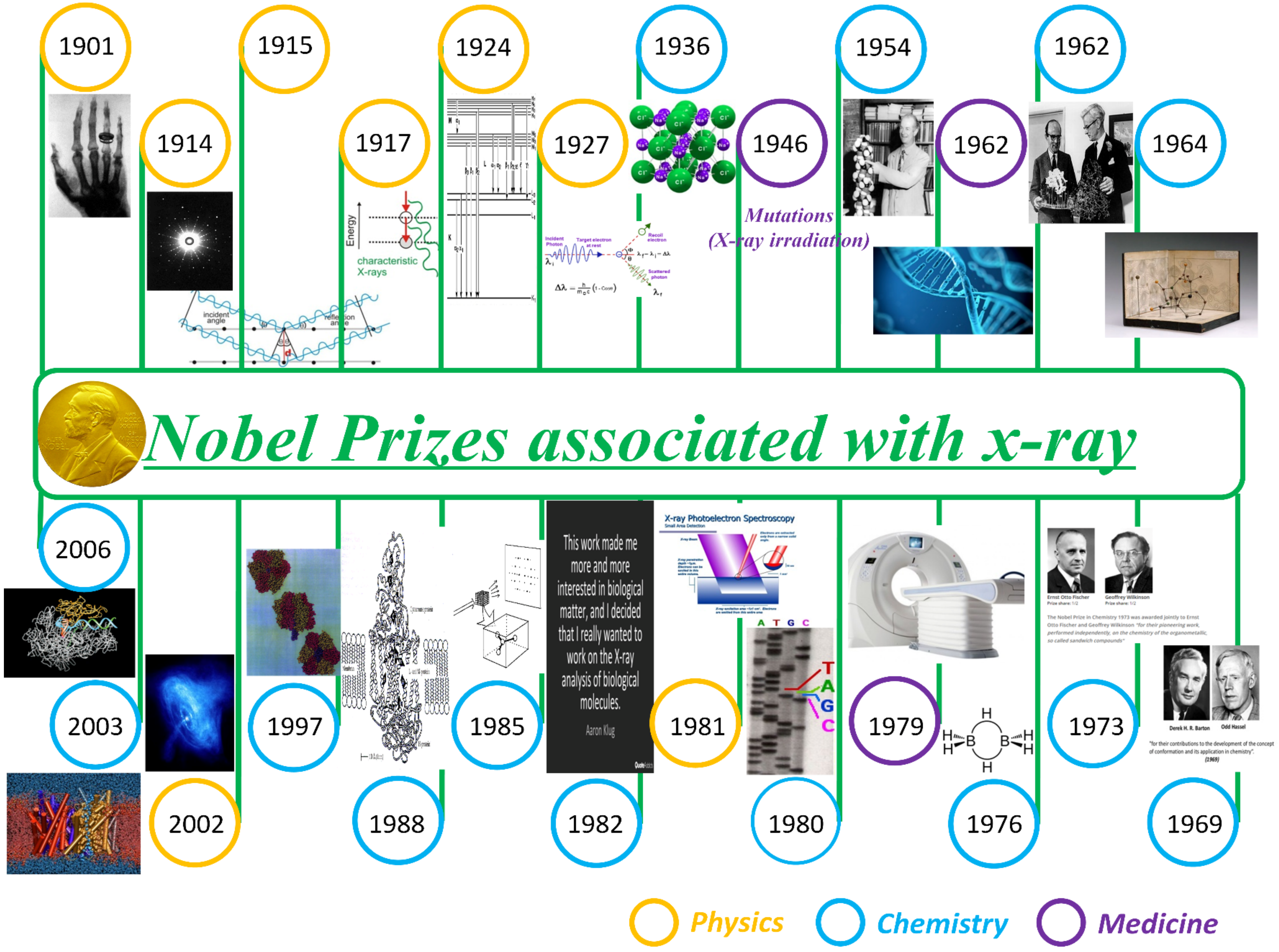
Centre of mass energy: 200-500GeV



1.3GHz, Nb SC cavity,
2K, ~1m each

The International Linear Collider Technical Design Report, 2013

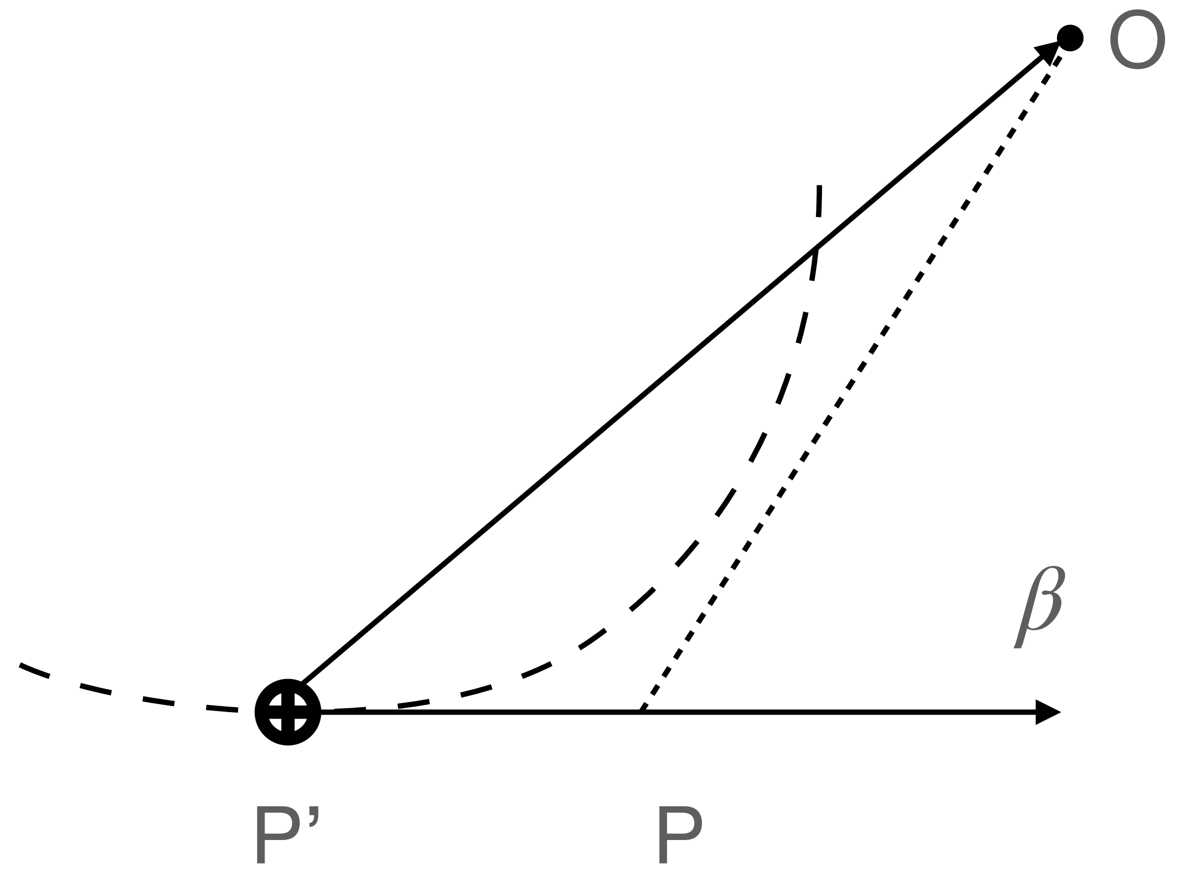
2.2 Light sources and spallation neutron sources



The electromagnetic fields from a moving charge

$$A^\mu = \left(\Phi/c, A_x, A_y, A_z\right) \qquad J^\mu = \left(c\rho, J_x, J_y, J_z\right)$$

$$A^\mu(x) = A^\mu_{\text{in}}(x) - \mu_0 \int \mathrm{d}^4x' D_r(x-x') J^\mu(x') = -\mu_0 \int \mathrm{d}^4x' D_r(x-x') J^\mu(x')$$



n: *unit vector in the direction of **x**-**r**(τ)*

Contra-variant form of Liénard-Wiechert Potentials

$$A^\mu(x) = -\frac{\mu_0 e c}{4\pi} \frac{V^\mu(\tau)}{V \cdot \left[x - r(\tau)\right]}\Bigg|_{\tau=\tau_0}$$

$$V^\mu = (\gamma c, \gamma \mathbf{v})$$

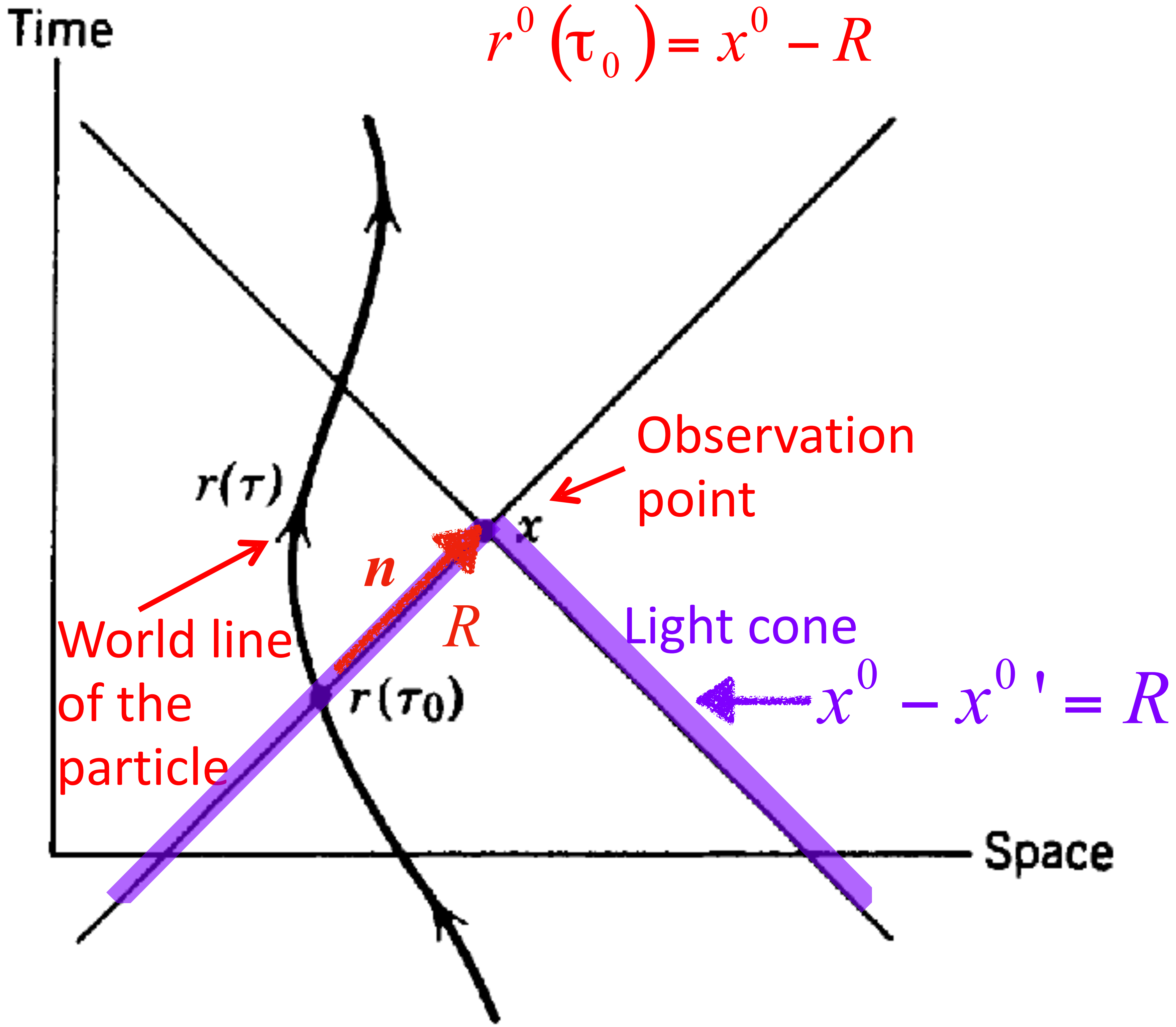
velocity 4-vector

$$r^\mu = \left[ct, \boldsymbol{r}(t)\right]$$

coordinate 4-vector

ret: *quantity in the square brackets is to be evaluated at the retarded time* τ_0, *given by*

$$r^0(\tau_0) = x^0 - R$$



Retarded Liénard-Wiechert Potentials and electromagnetic fields

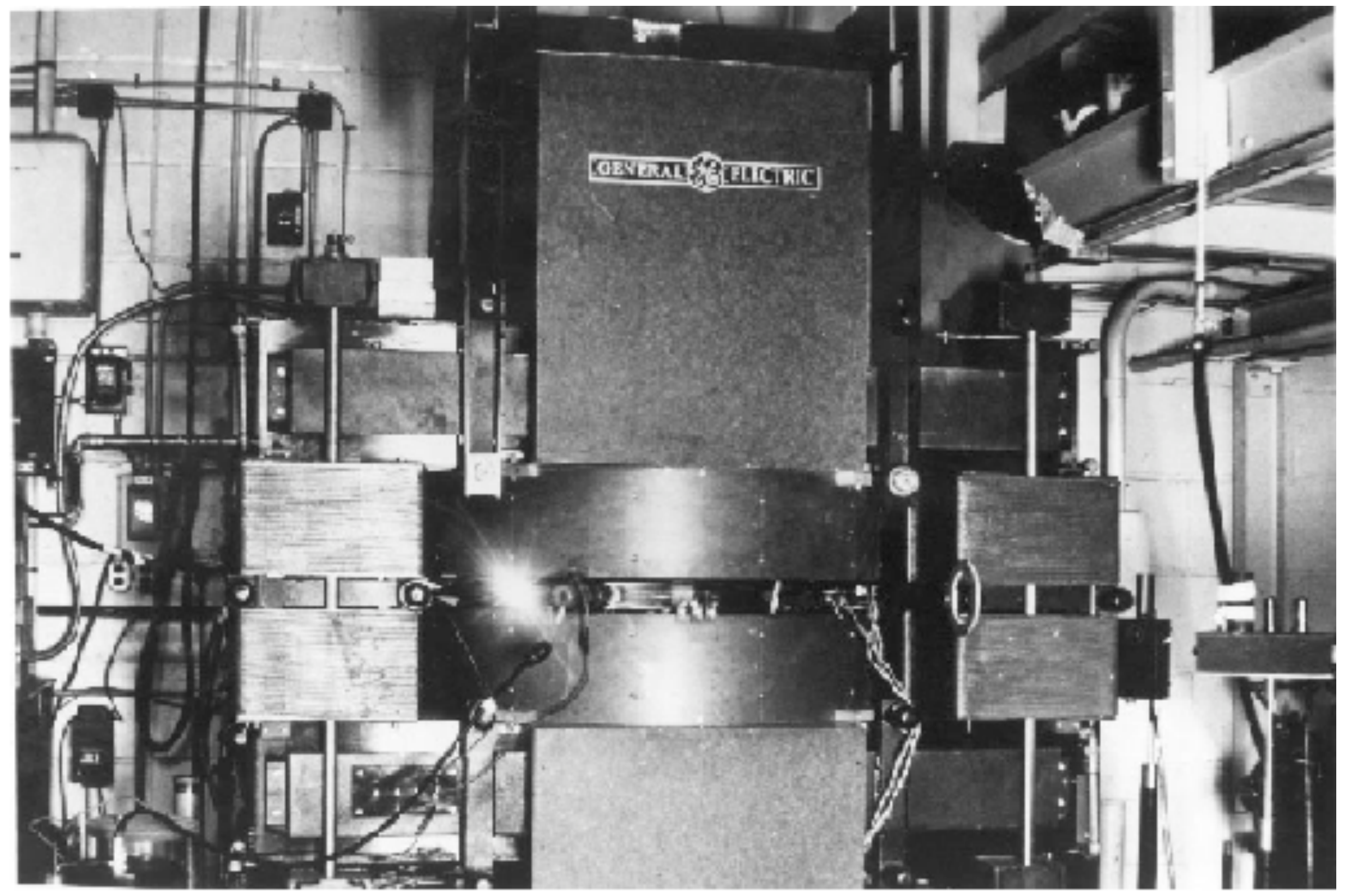
$$\begin{cases} \Phi(\boldsymbol{x},t) = cA^0(x) = \dfrac{\mu_0 e c}{4\pi\gamma R}\left[\dfrac{\gamma c}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})}\right]_{\text{ret}} = \dfrac{1}{4\pi\varepsilon_0}\left[\dfrac{e}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})R}\right]_{\text{ret}} \\ \boldsymbol{A}(\boldsymbol{x},t) = \dfrac{\mu_0 e}{4\pi\gamma R}\left[\dfrac{\gamma \boldsymbol{v}}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})}\right]_{\text{ret}} = \dfrac{1}{4\pi\varepsilon_0 c}\left[\dfrac{e\boldsymbol{\beta}}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})R}\right]_{\text{ret}} \end{cases}$$

$$\begin{cases} \boldsymbol{B} = \dfrac{1}{c}\left[\boldsymbol{n}\times\boldsymbol{E}\right]_{\text{ret}} \\ \boldsymbol{E} = \dfrac{e}{4\pi\varepsilon_0}\left[\dfrac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^3R^2}\right]_{\text{ret}} + \dfrac{e}{4\pi\varepsilon_0 c}\left[\dfrac{\boldsymbol{n}\times\left[(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right]}{(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^3 R}\right]_{\text{ret}} \end{cases}$$

Synchrotron Radiation

- Lectures on Accelerator Physics, by A. Chao (2020)

- 1883 — Hertz observes EM wave: EM fields can radiate like wave, and with constant speed c;
- 1887 — Maxwell equations
- 1895 — Roetgen discovers X-ray
- 1897 — Thomson discovers electron
- 1898 — Lienard-Wiechert potential: EM wave start to be connected to Point charges
- 1907 — Schott's classical analysis Of synchrotron radiation
- 1946 — Schwinger's quantum analysis of SR
- 1947 — Synchrotron radiation is observed at 70-MeV General Electric electron synchrotron
- 1970s — 1st generation of SR facilities
- 1980s — 2nd generation of SR facilities
- 1990s — 3rd generation of SR facilities
- 2010s — 4th generation of SR facilities
- 2030 — 5th : storage ring based with longitudinal manipulation?

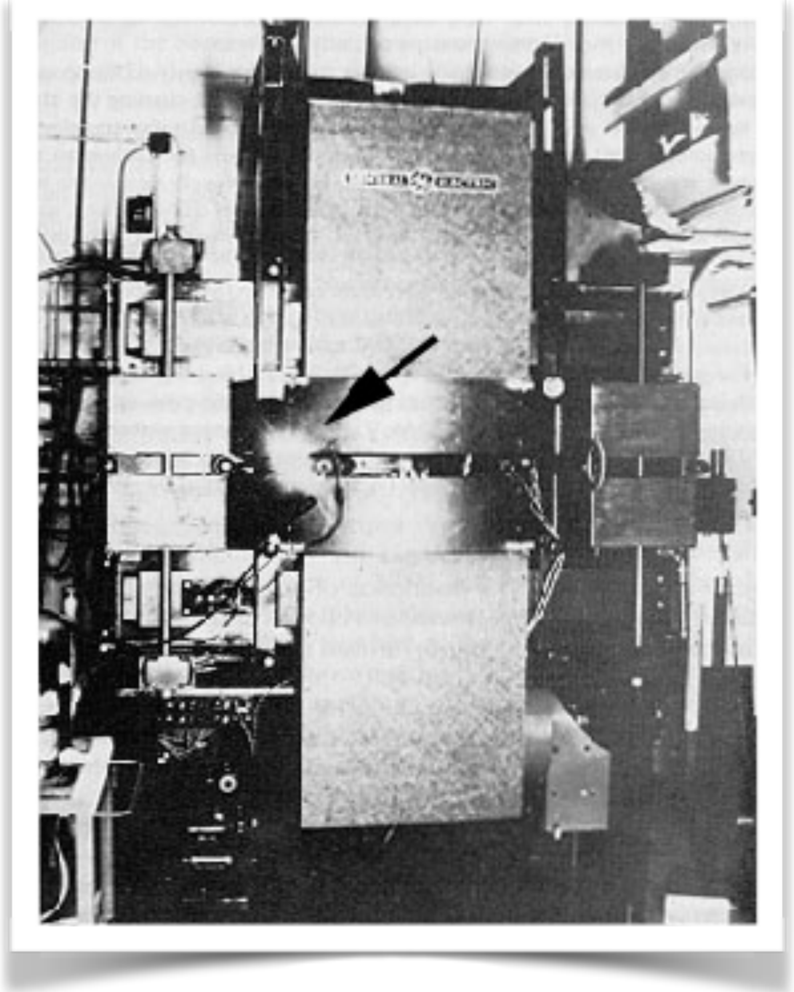


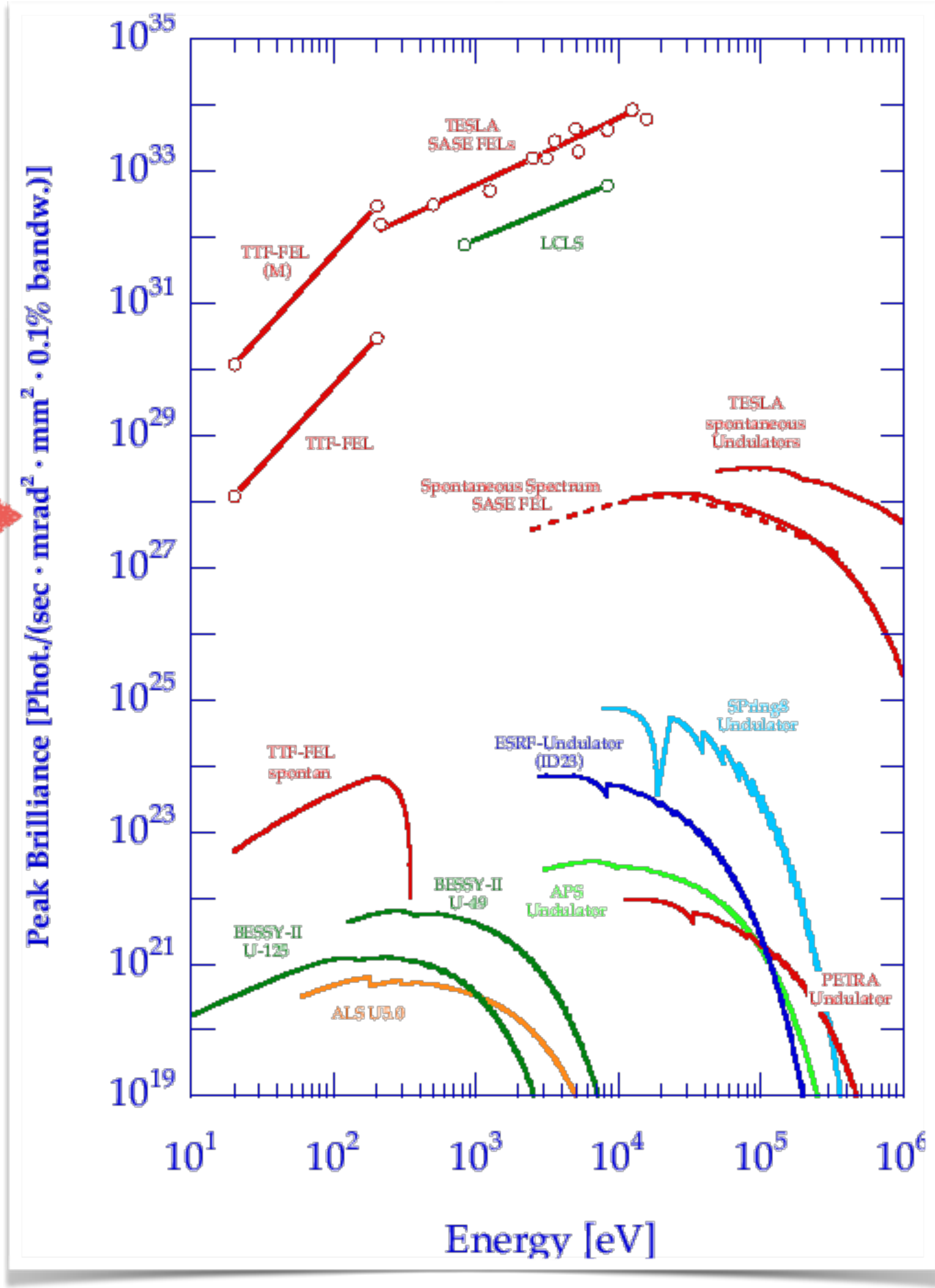
70MeV bluish-white, 40-yellow, 30-red,20-none

John P. Blewett , J. Synchrotron Rad. (1998). 5, 135-139

Accelerator Light Sources： Synchrotron Radiation and Free Electron Laser

- 1919 — Rutherford's plea for particle accelerators , and the start point of accelerators
- 1943 — Synchrotron
- 1946 — Synchrotron radiation was discovered at GE's 70MeV Synchrotron.
- 1946 — Electron Linac
- 1971 — Free Electron Laser (FEL) by J. Madey, at Stanford U,
- 1994 — ESRF
- 1996 — APS
- 1997 — Spring-8
- 2009 — First light of LCLS at SLAC



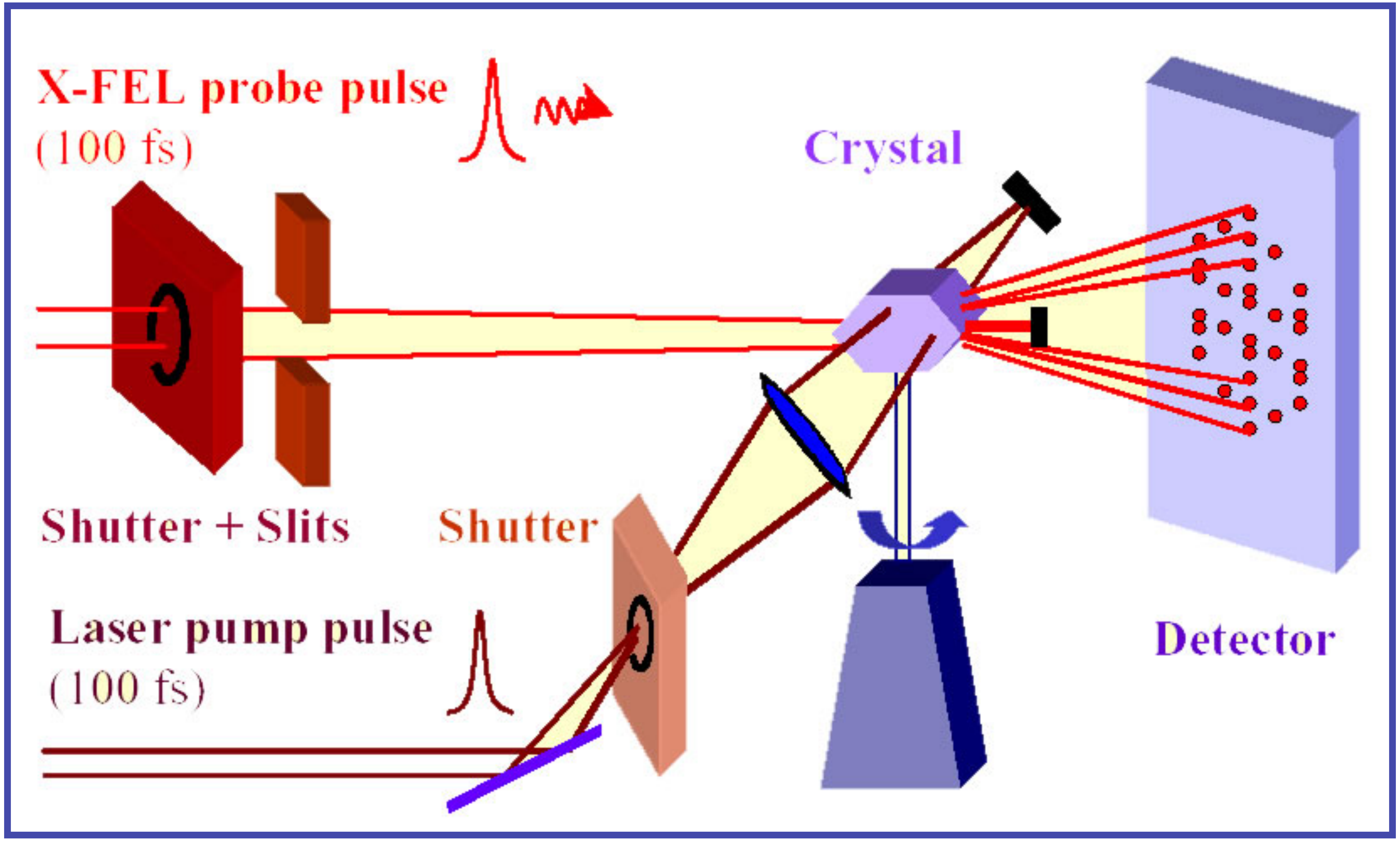


- Engines of Discovery-A Century of Particle Accelerators, by Andrew Sessler and Edmund Wilson, World Scientific, 2006
- A Brief History of Particle Accelerators, Poster, Review of Accelerator Science and Technology, by A. Chao and W. Chou

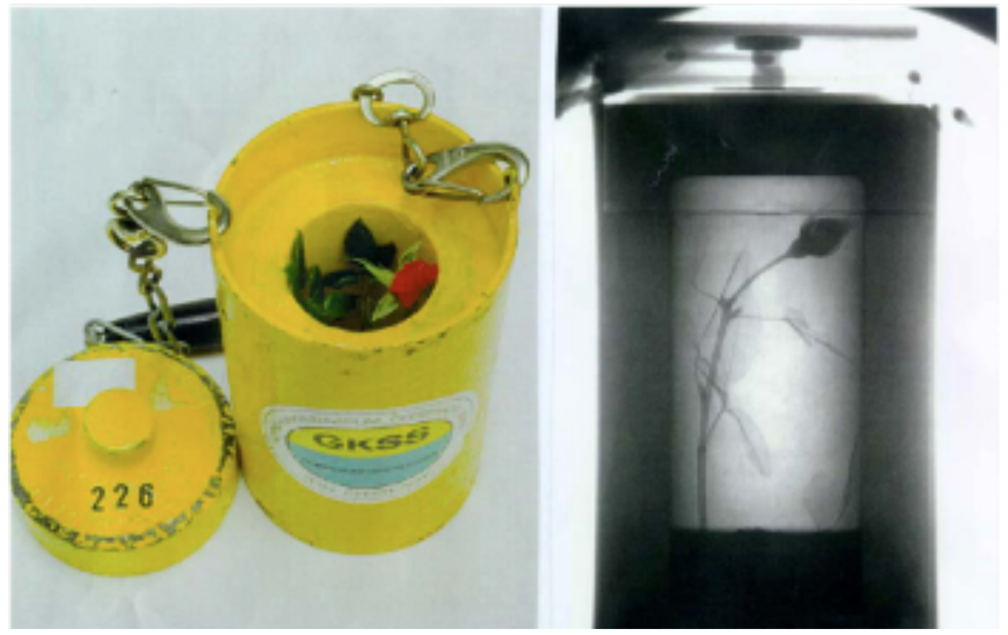
An example of the synchrotron radiation light source: Diamond

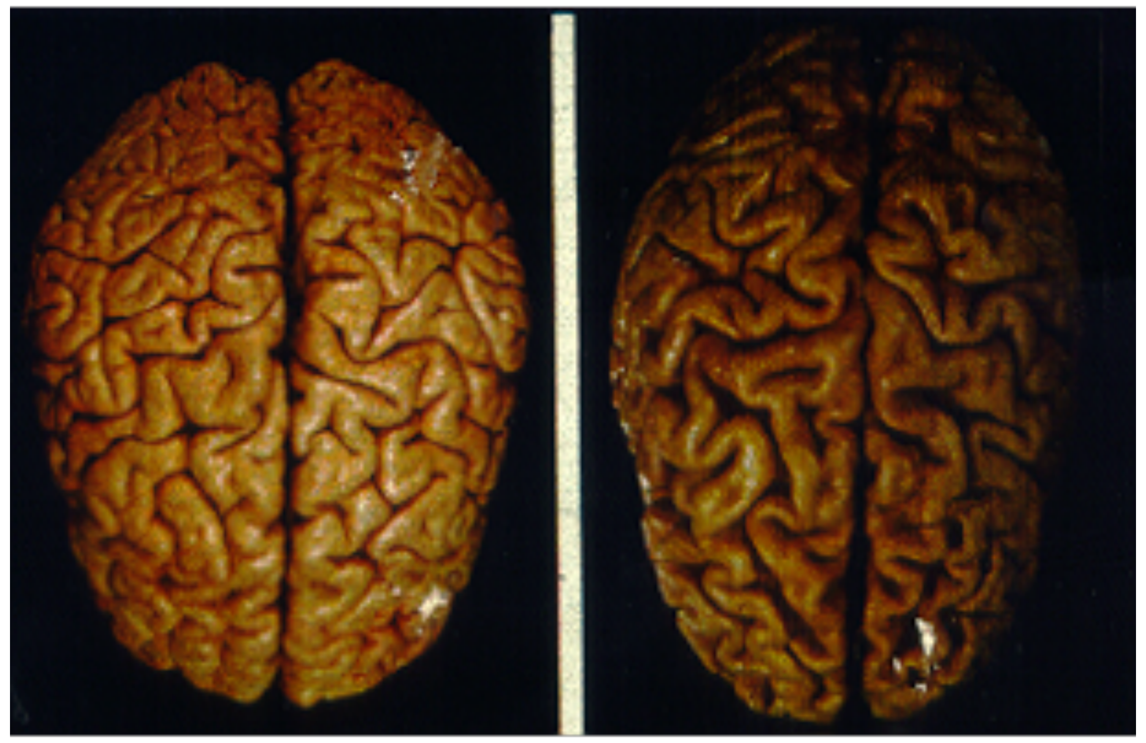
An example of the synchrotron radiation light source- LCLS

The pump-probe experiment at SR and FEL x-ray sources

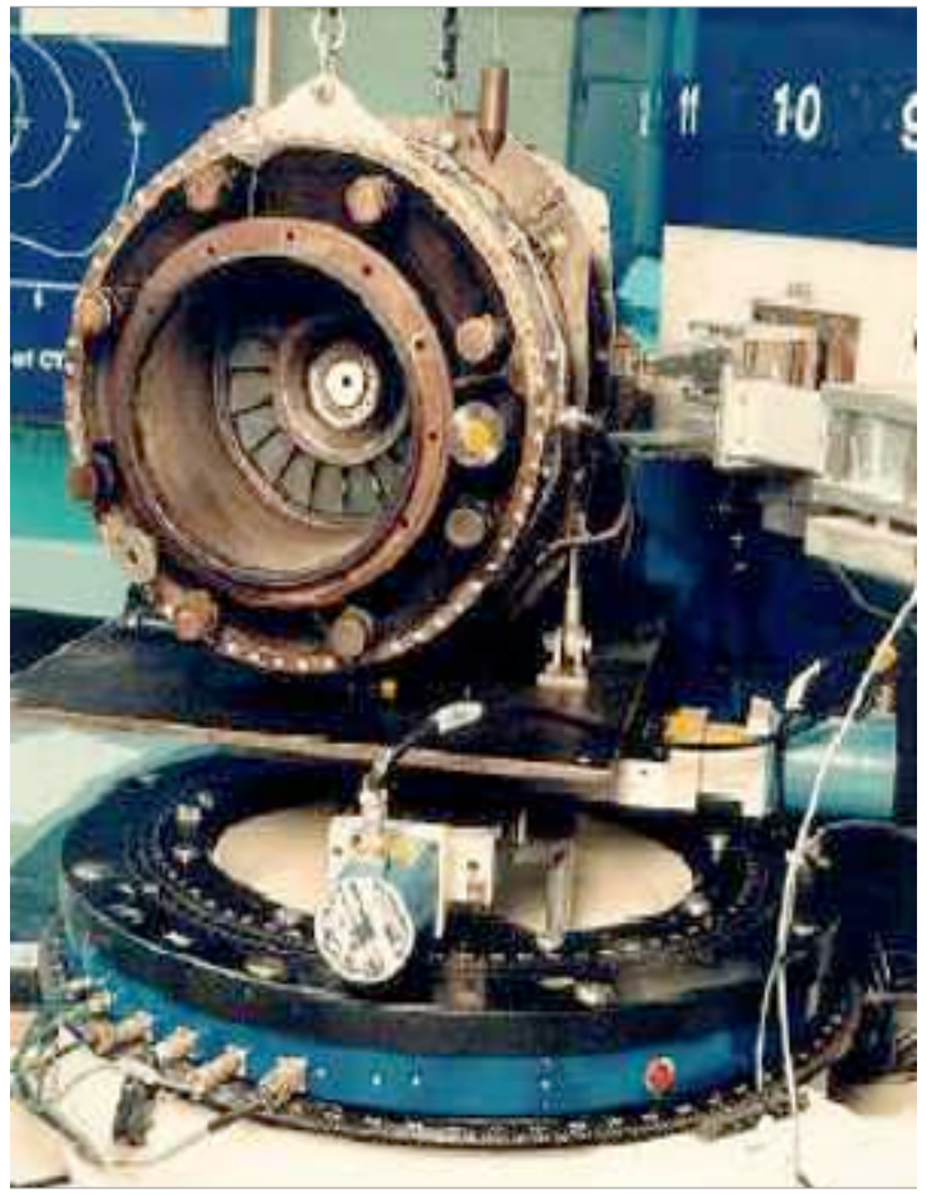


Spallation neutron sources

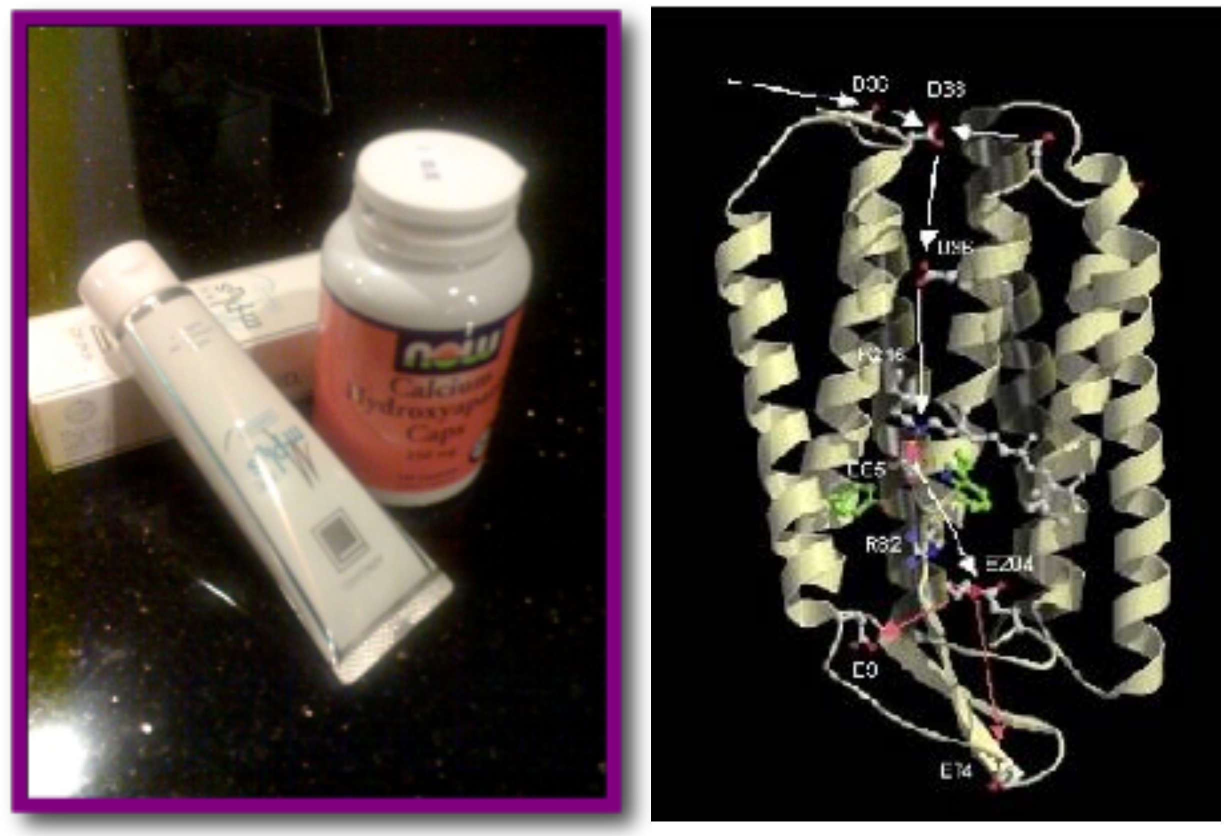




Neutron imaging

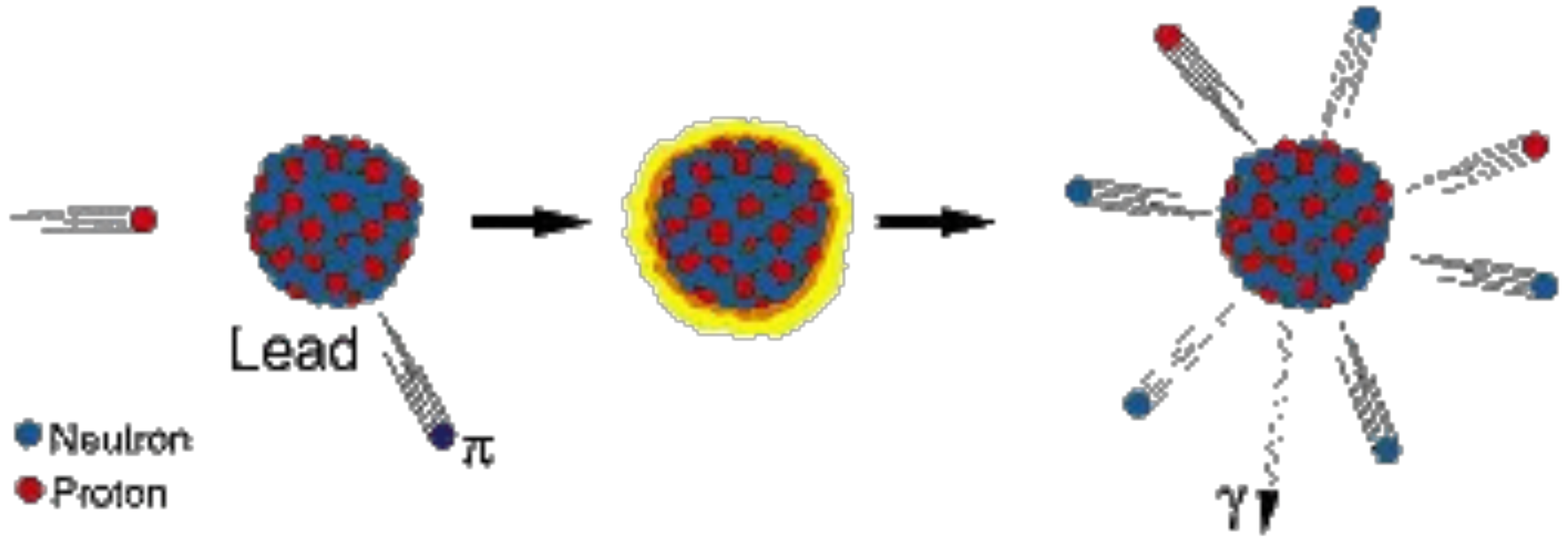


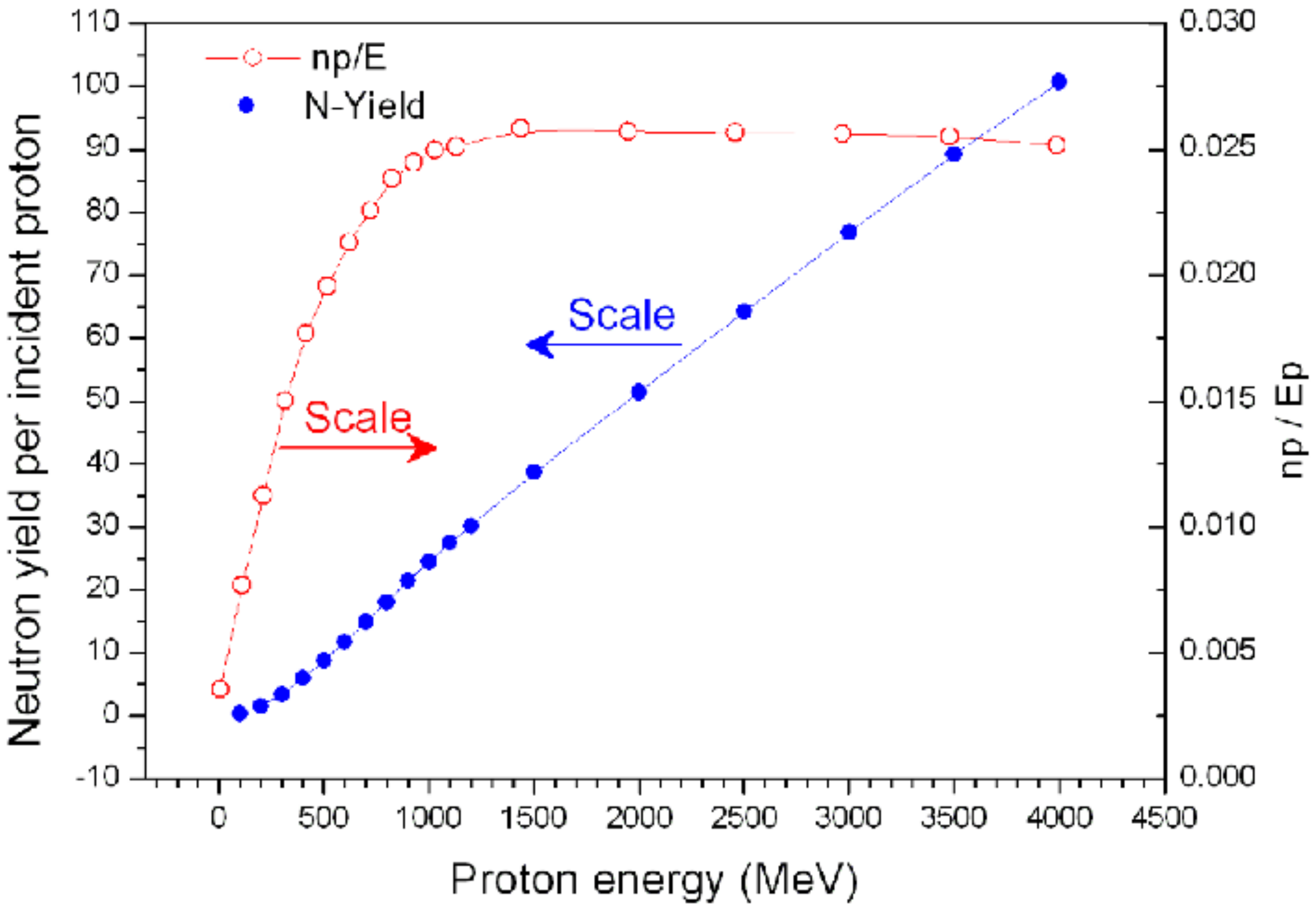
Neutron diffraction



Neutron small-angle scattering (SANS)

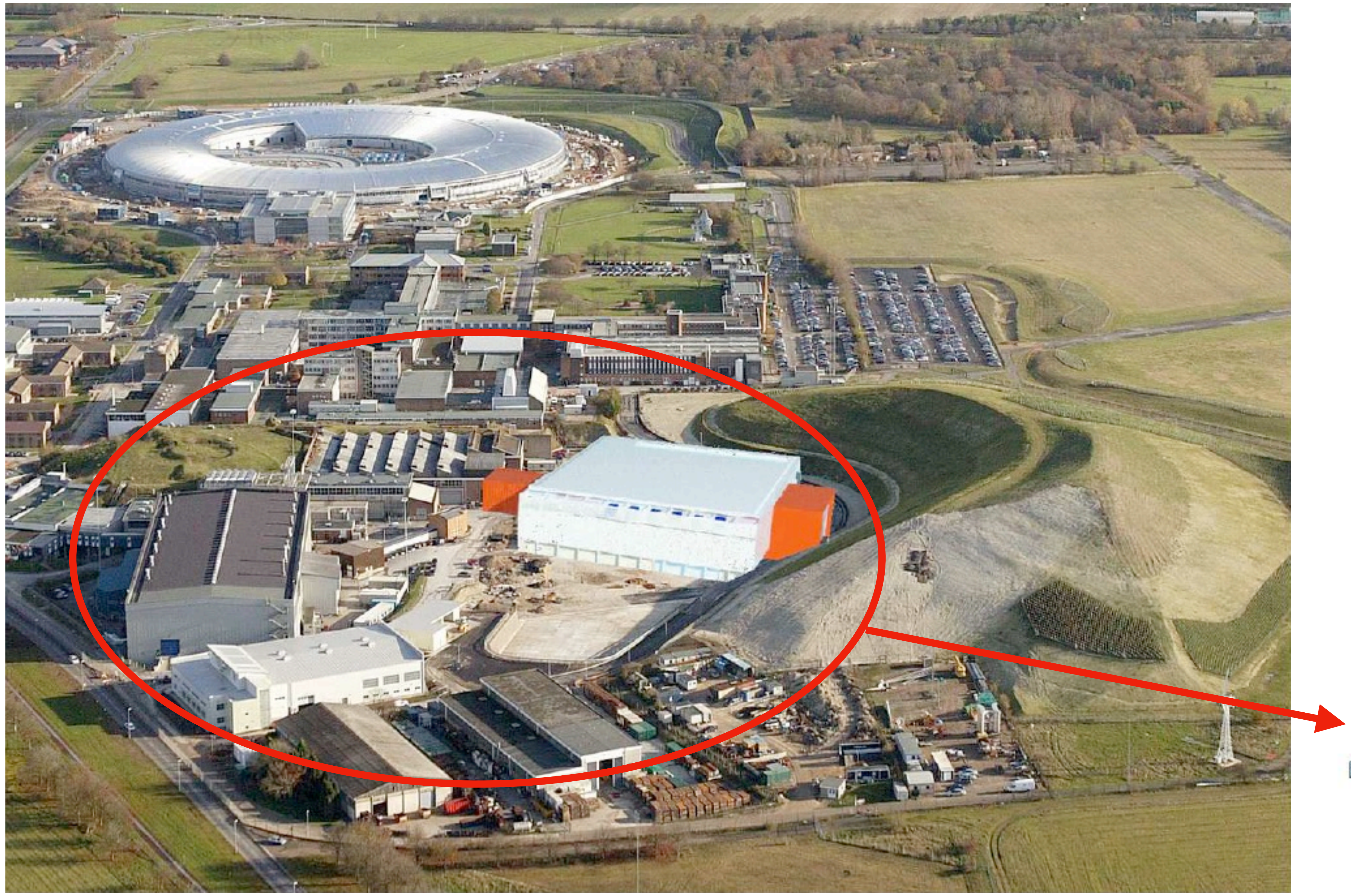
In nuclear physics, spallation is the process in which a heavy nucleus emits numerous nucleons as a result of being hit by a high-energy particle, thus greatly reducing its atomic weight.

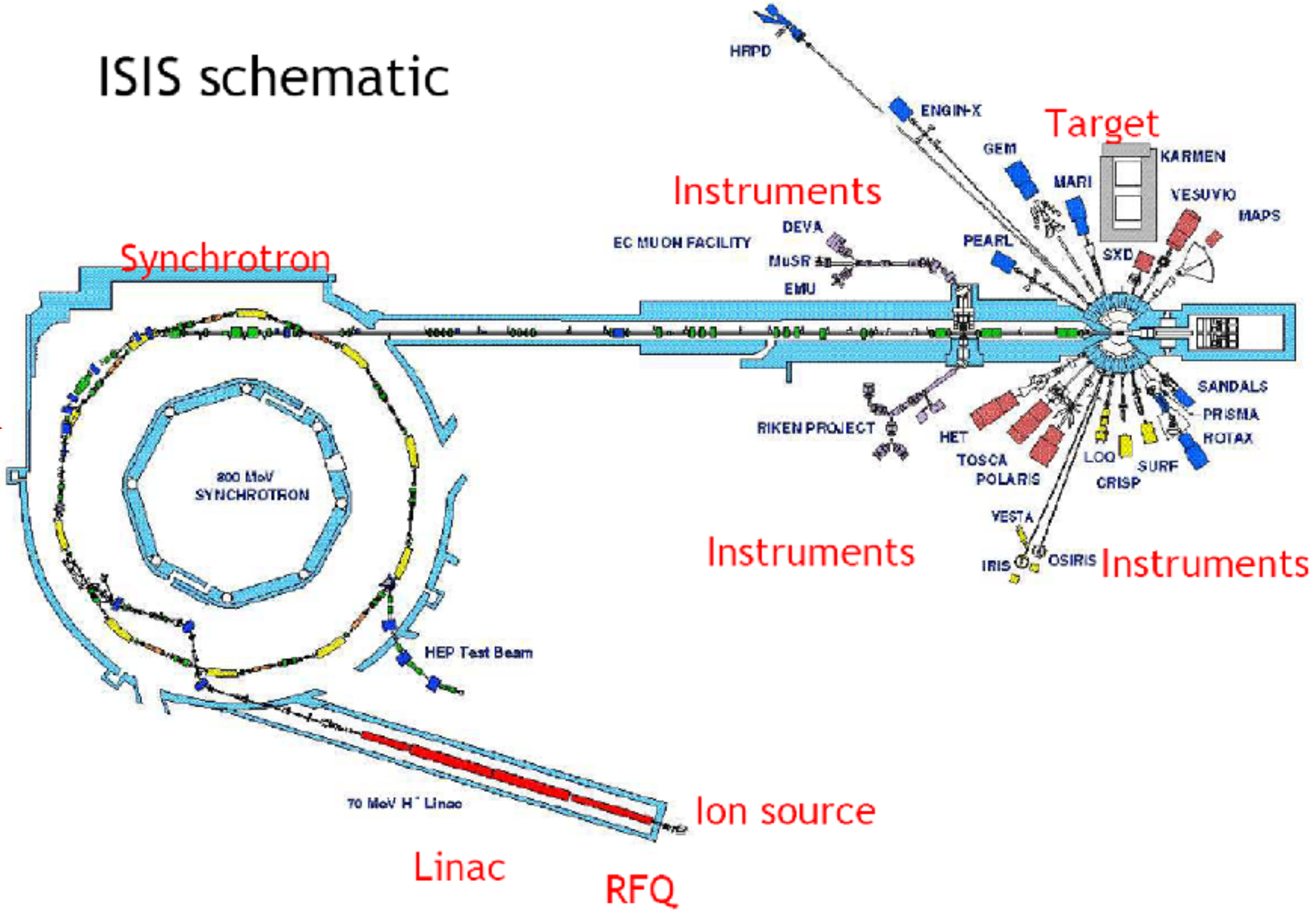




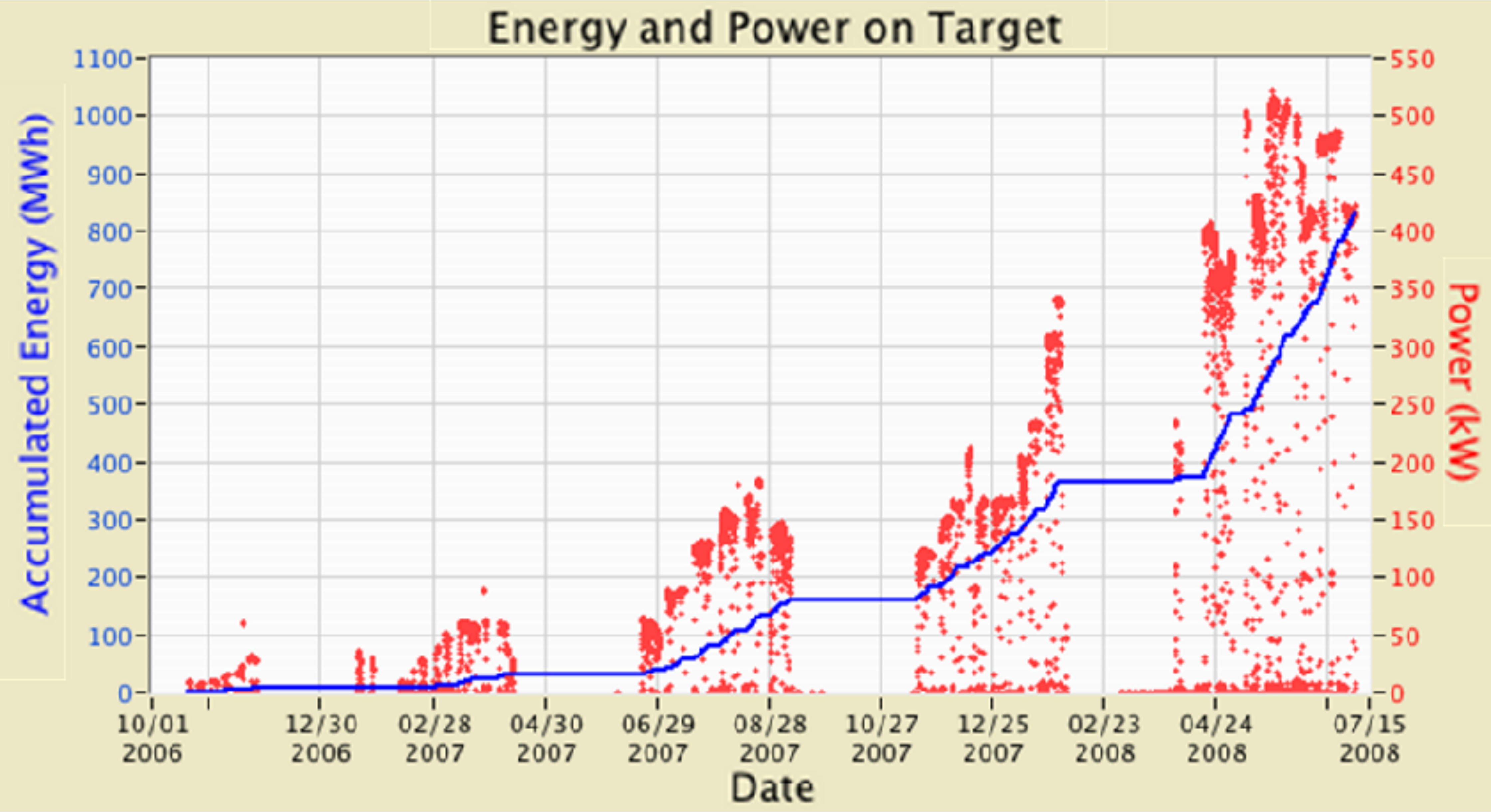
- Courtesy from CK Loong

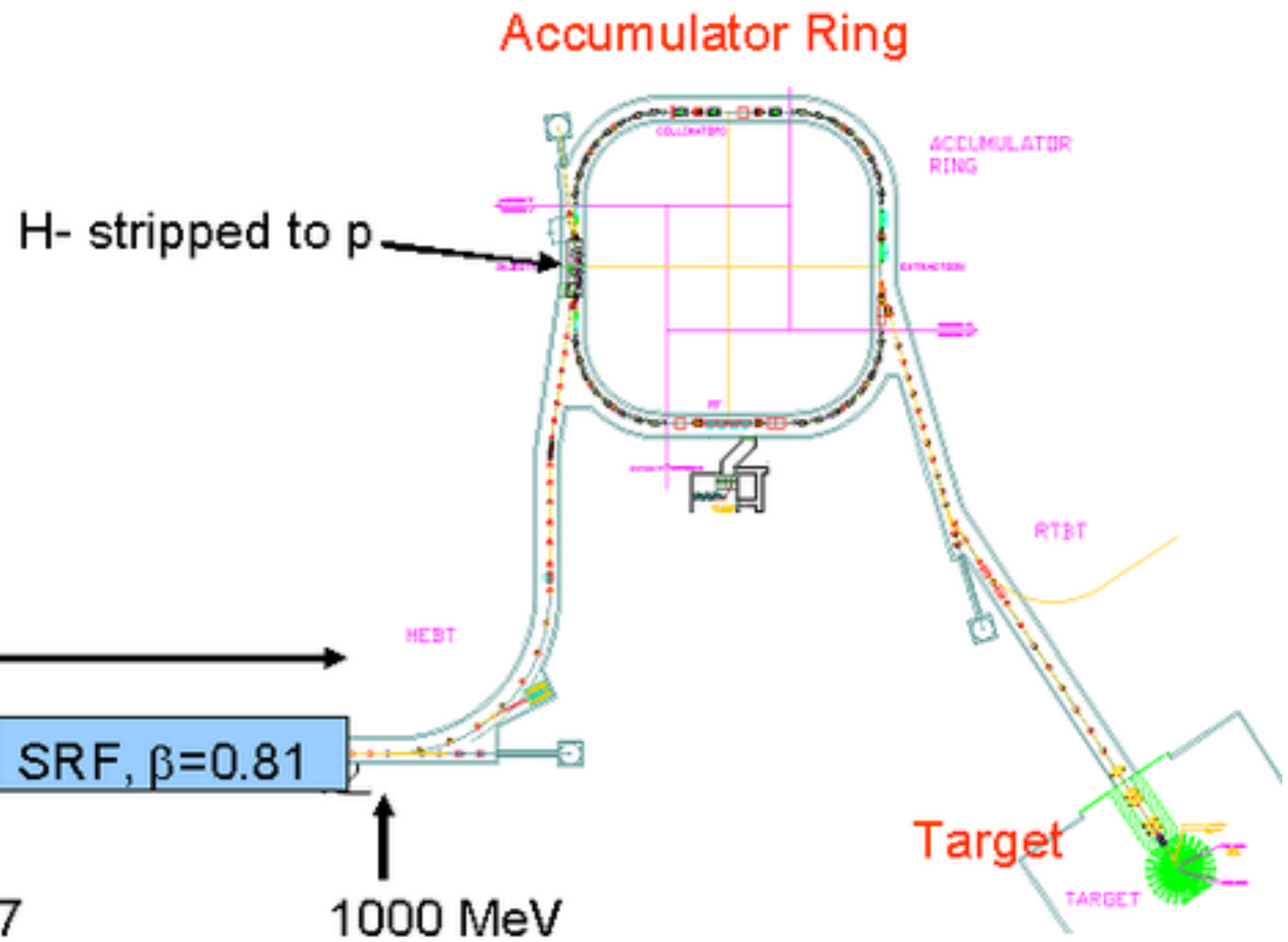
ISIS and DIAMOND (RAL, UK)

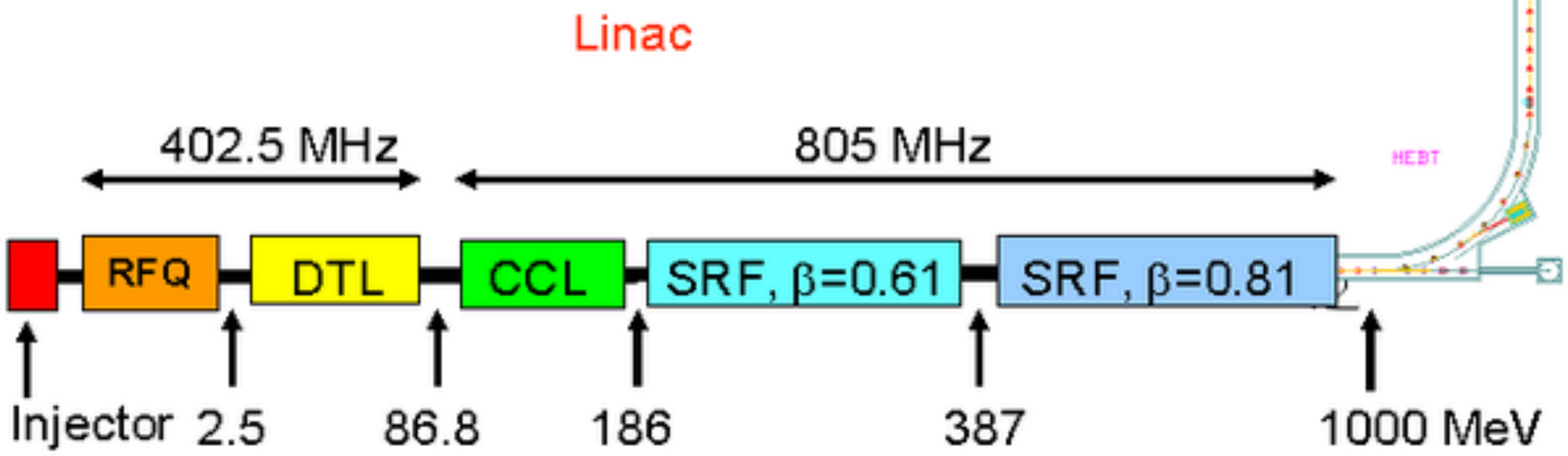




SNS

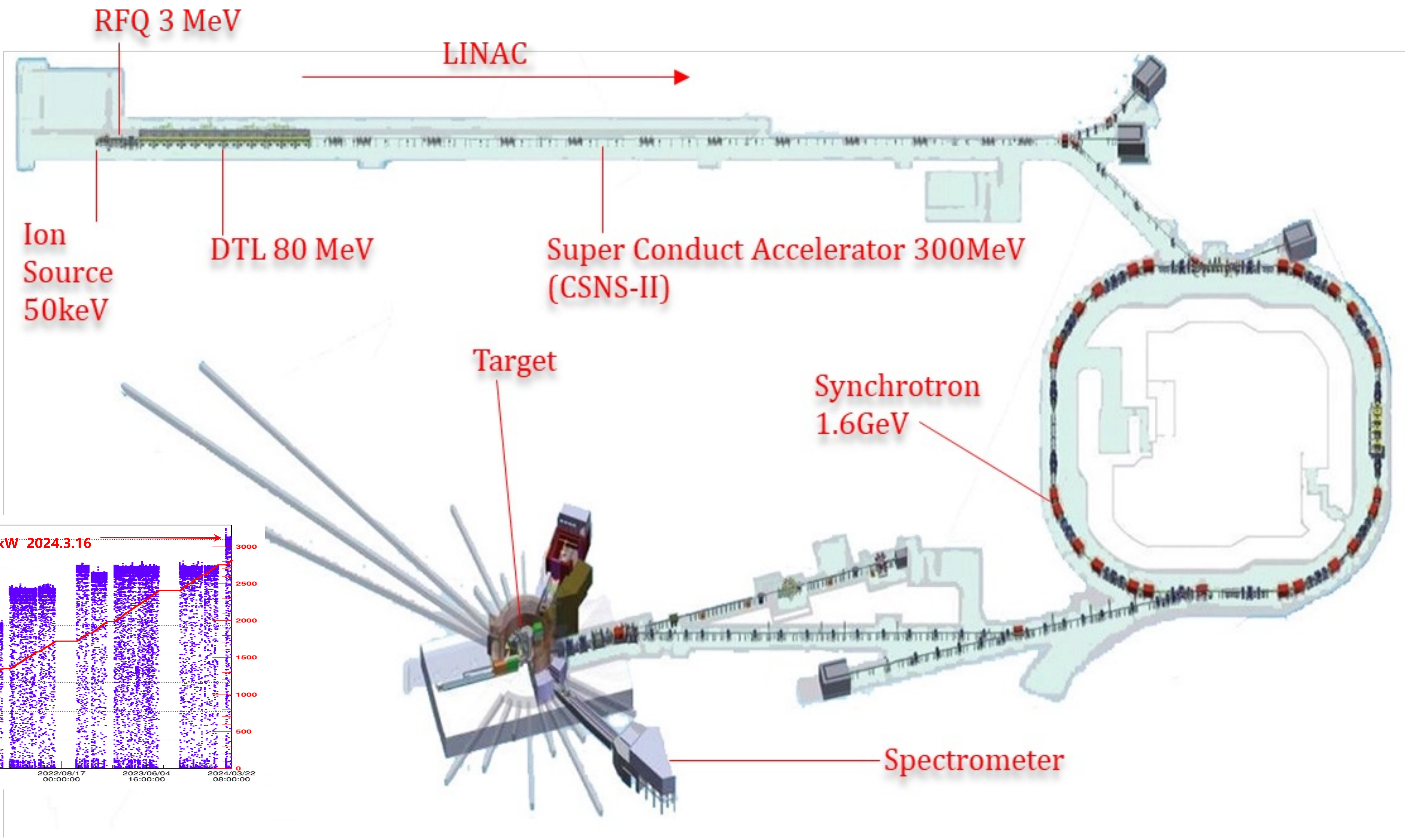


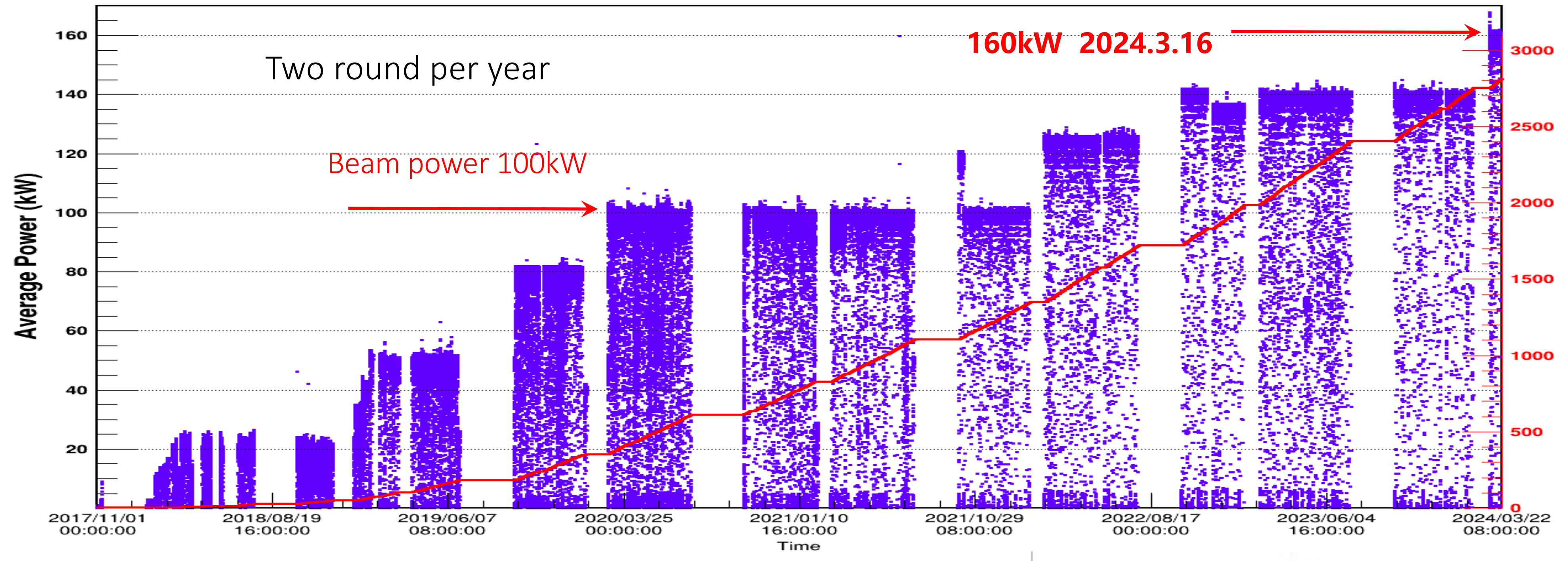




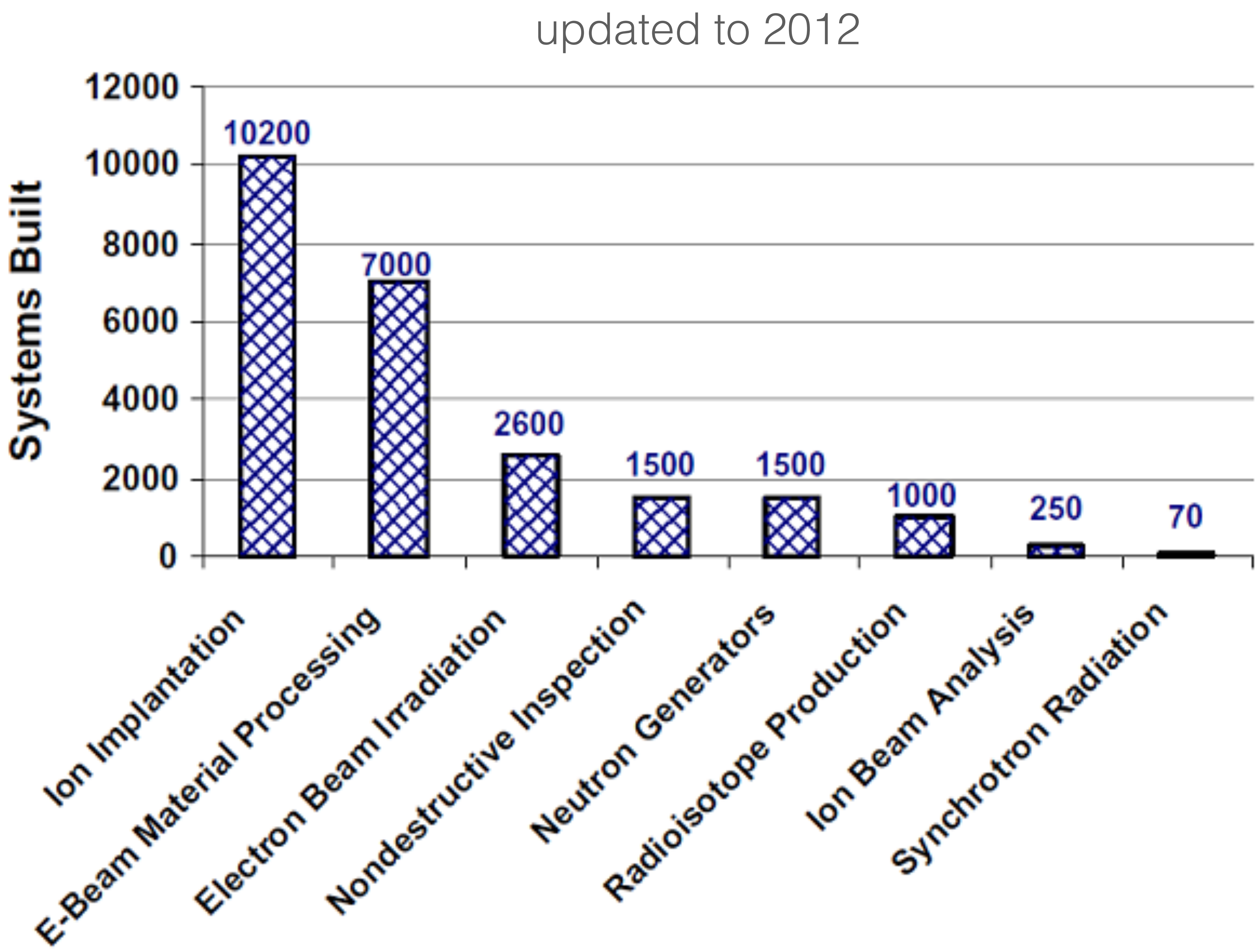
- Journal of the Korean Physical Society, Vol. 54, No. 5, May 2009, pp. 1925-1930

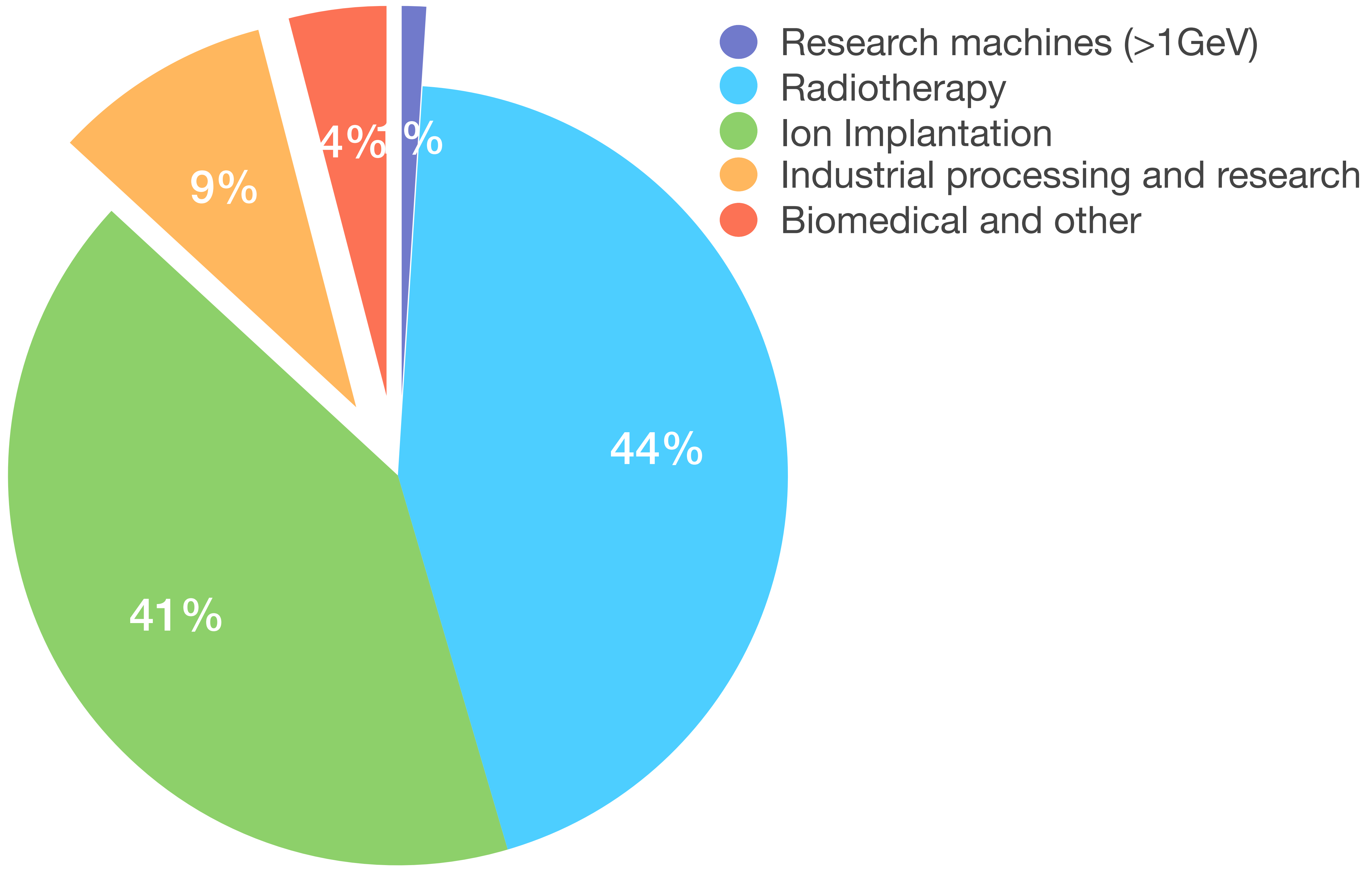
CSNS


RFQ 3 MeV
LINAC
Ion Source 50keV
DTL 80 MeV
Super Conduct Accelerator 300MeV (CSNS-II)
Target
Synchrotron 1.6GeV
Spectrometer


Two round per year
Beam power 100kW
160kW 2024.3.16
Average Power (kW)
Time
2017/11/01 00:00:00
2018/08/19 16:00:00
2019/06/07 08:00:00
2020/03/25 00:00:00
2021/01/10 16:00:00
2021/10/29 08:00:00
2022/08/17 00:00:00
2023/06/04 16:00:00
2024/03/22 08:00:00

2.3 Medical, industrial, radiation processing and security applications



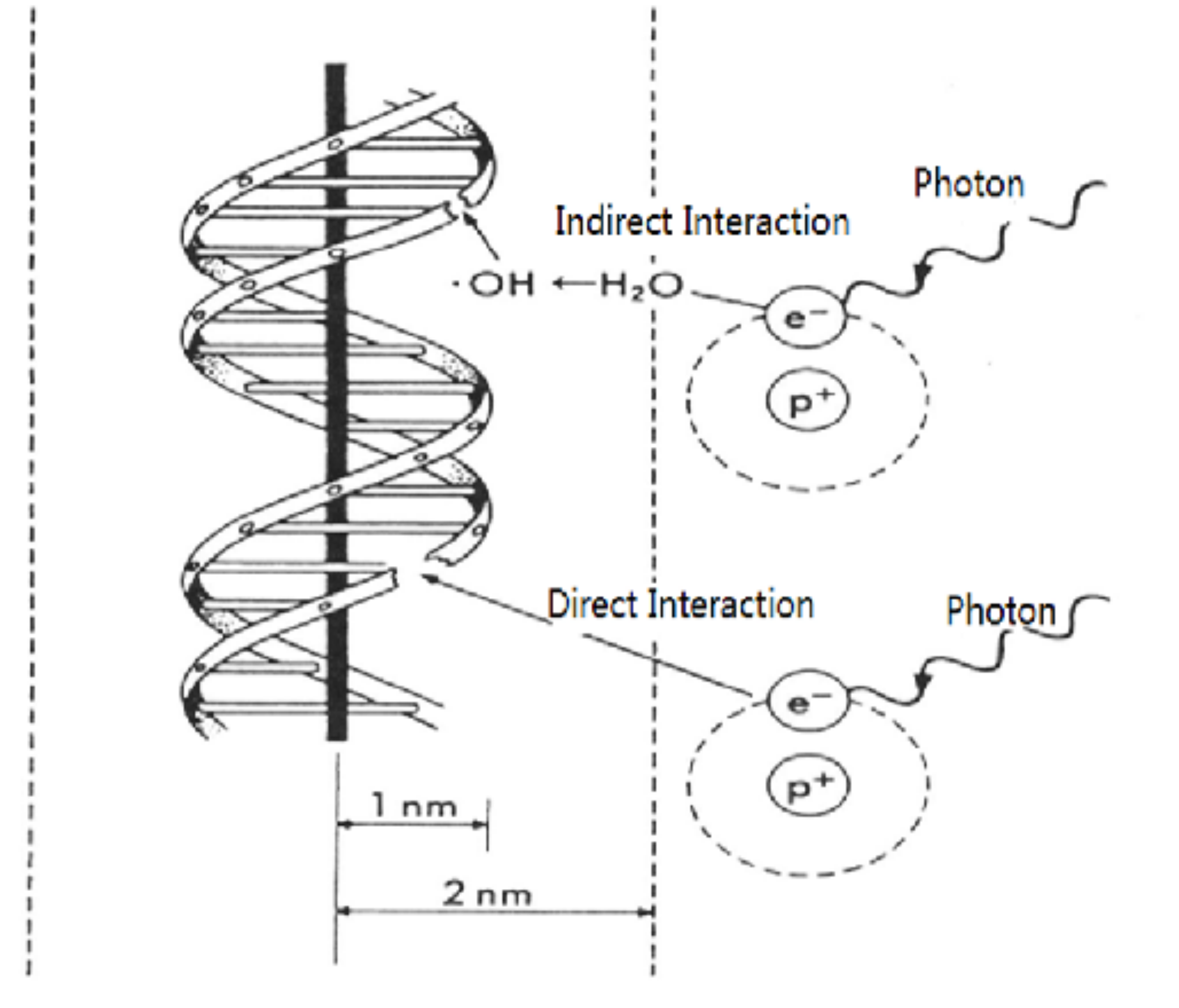


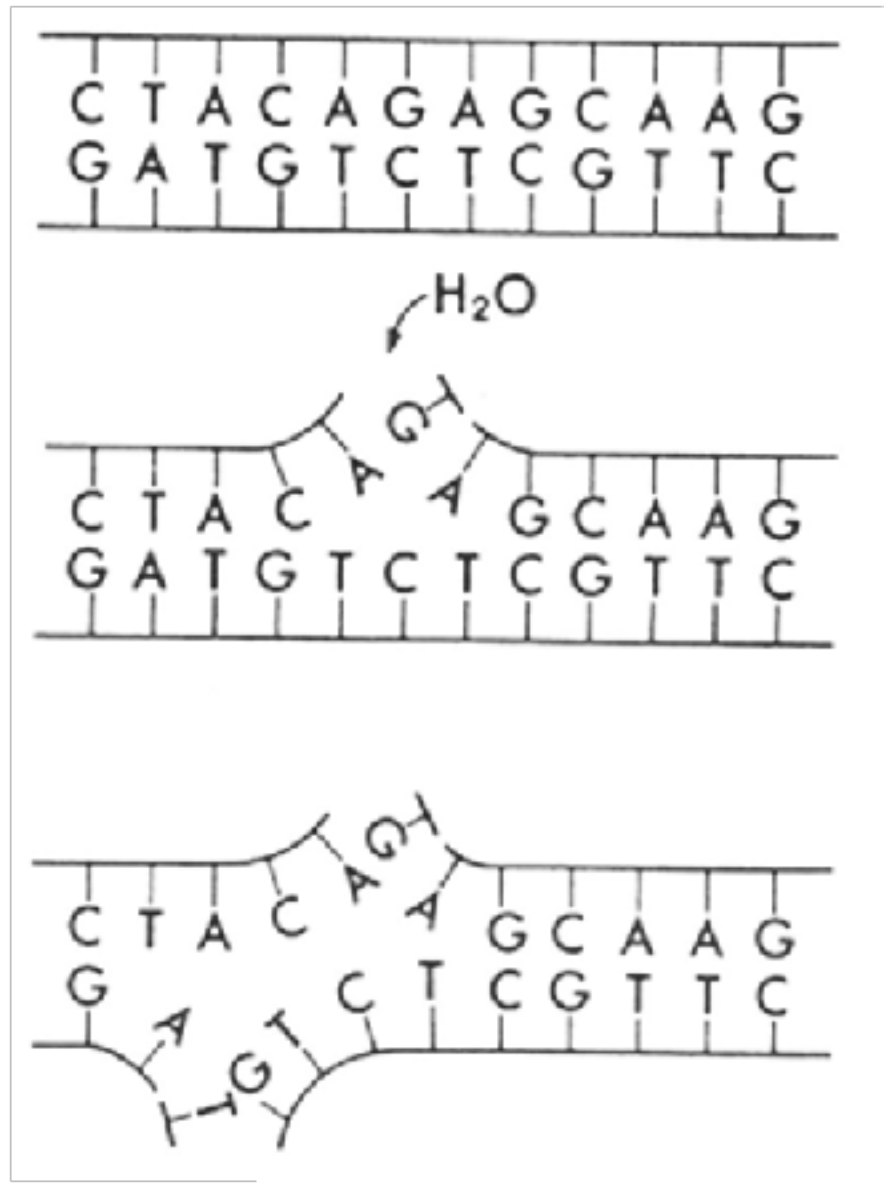
It has been estimated that there are approximately 30,000 accelerators worldwide

- Hamm, Robert W.; Hamm, Marianne E. (2012). Industrial Accelerators and Their Applications. World Scientific. ISBN 978-981-4307-04-8.
- Feder, T. (2010). "Accelerator school travels university circuit" . Physics Today. 63 (2): 20. Bibcode:2010PhT....63b..20F. doi:10.1063/1.3326981

Radiotherapy

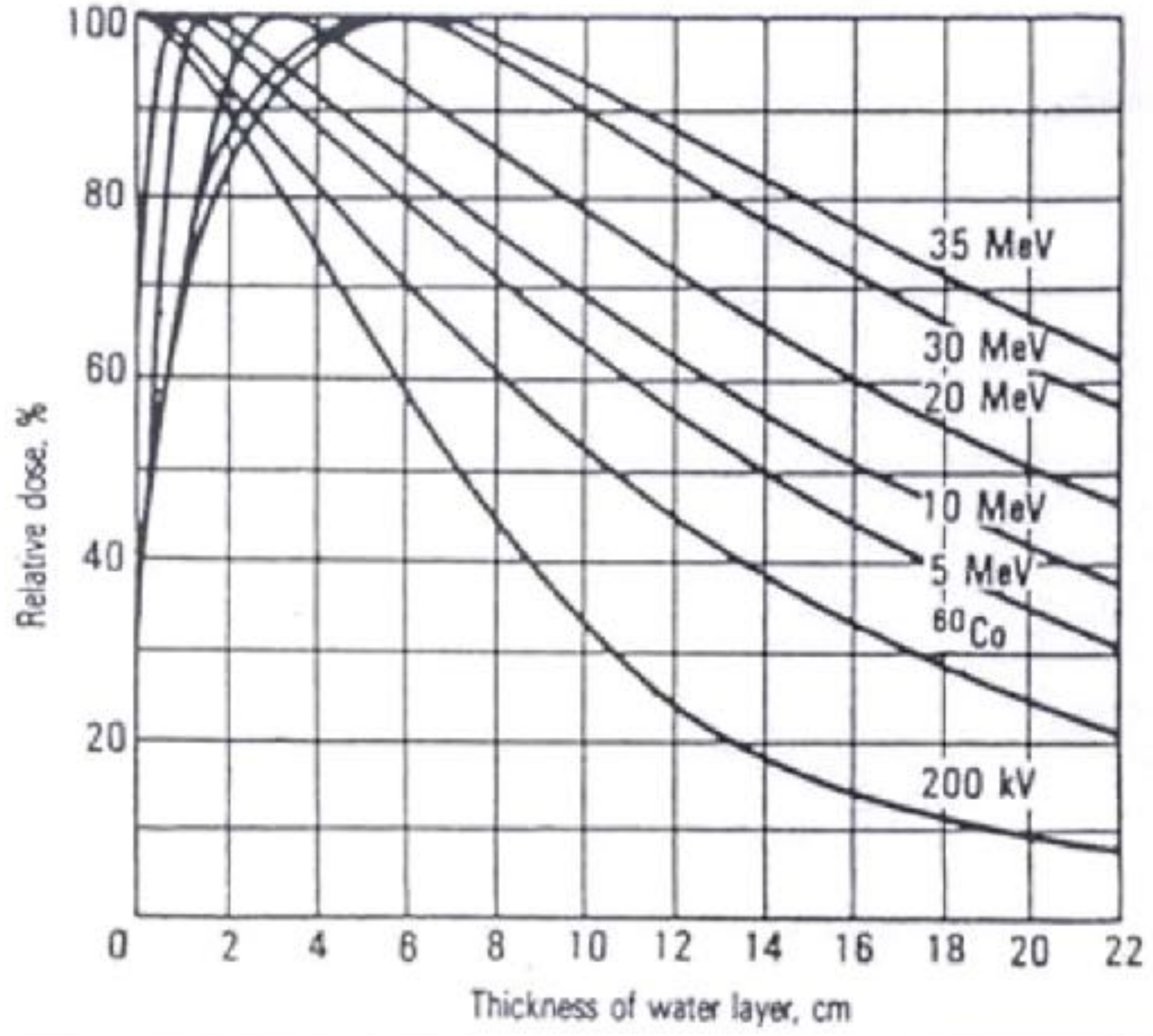
- X-ray or γ -ray
- Electron
- Proton
- Heavy ion (carbon)
- Neutron (BNCT)



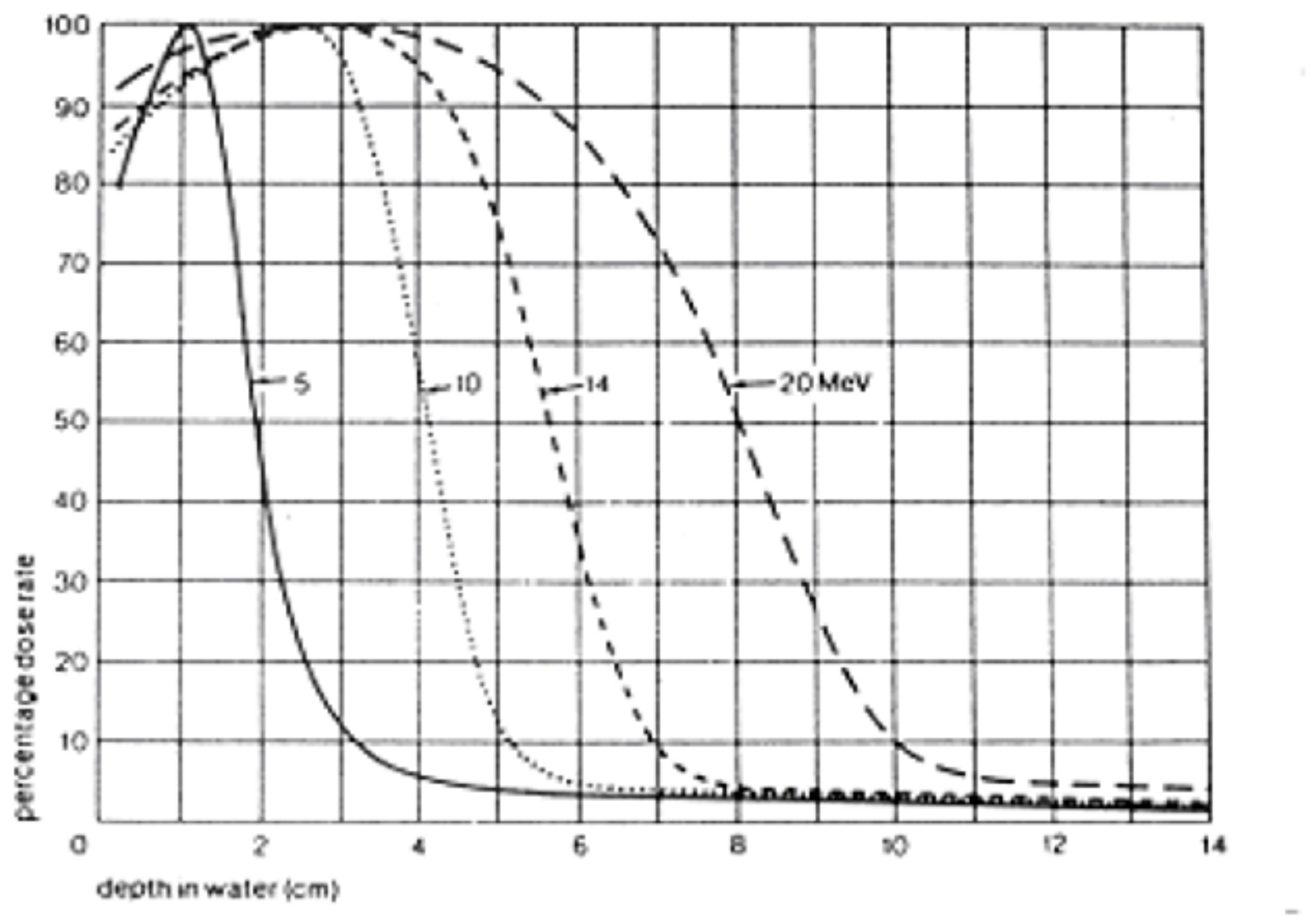


Single strand breaks

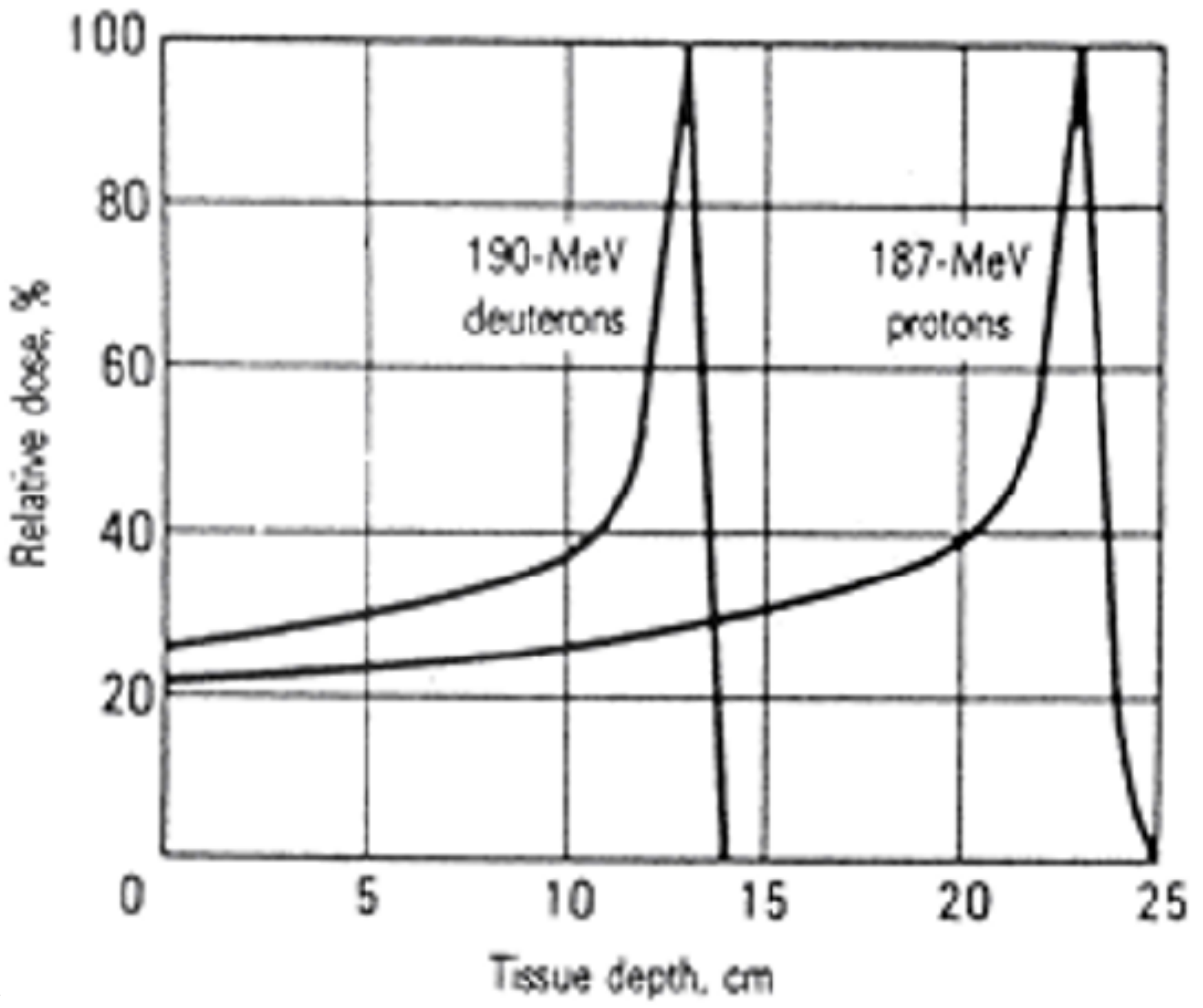
Double strand breaks



Depth-dose as a function of thickness of water layer for **X-rays** with energies of 5, 10, 20, 30 and 35 MeV



Depth-dose distribution in a water phantom for **electron** beams

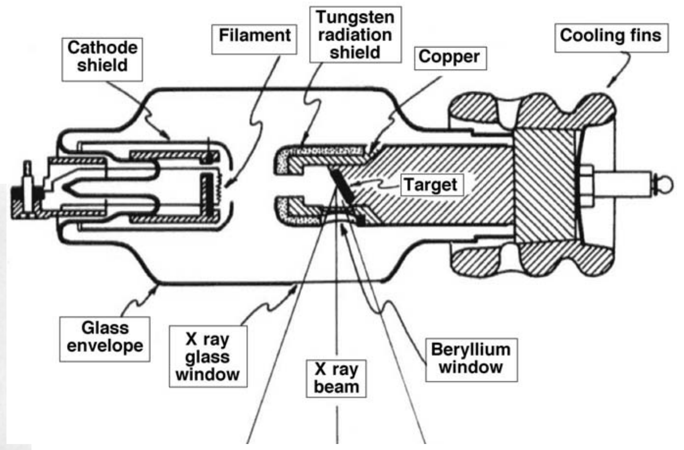


Depth dose in water for 190MeV deuterons and 187MeV protons

X-ray Radiotherapy

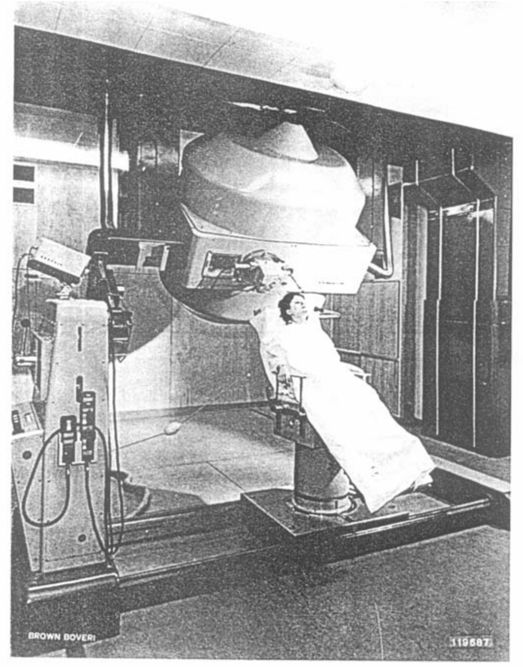
X-ray Discovery

View of a medical betatron mfd by Brown Bover (Switzerland)



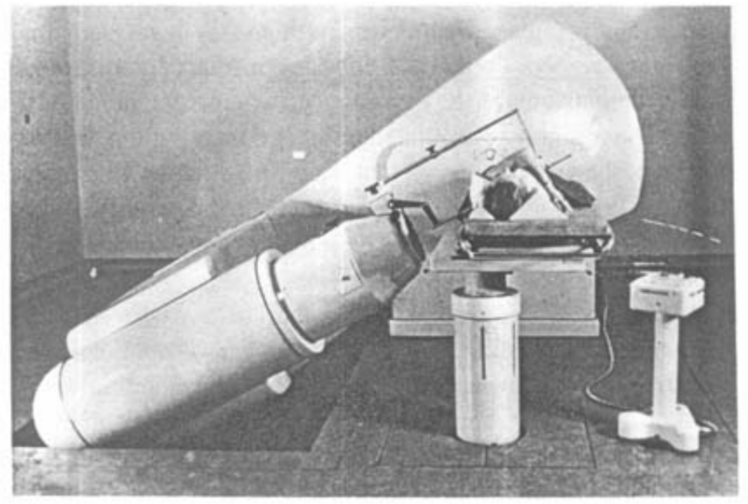
140keV X-ray Tube

400keV X-ray Tube



20-25 MeV Betatron

4-25 MeV Electron Linac



The first linear electron accelerator was installed at Hammersmith Hospital, England, in 1952, (8MeV); First orientable linear accelerator— the orthotron (1954, 4MeV)

~10,000Linacs(+IP,CT,MRI,PET…., and FLASH)

~200 Betatron

Microtron

1895 1910 1913 1937 1943 1951 1953 1970 1974 1980 1990 2000 2010 2016

~40 Van de Graff

1959

Radium-226 0.24 – 2.2 MeV gamma rays

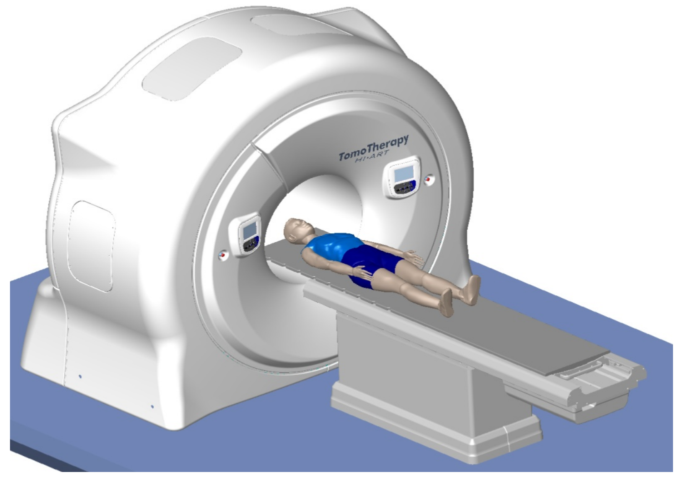
Van de Graff Accelerator 1 MeV, radiotherapy installed in Boston

Co-60 1.17-1.33 MeV gamma rays

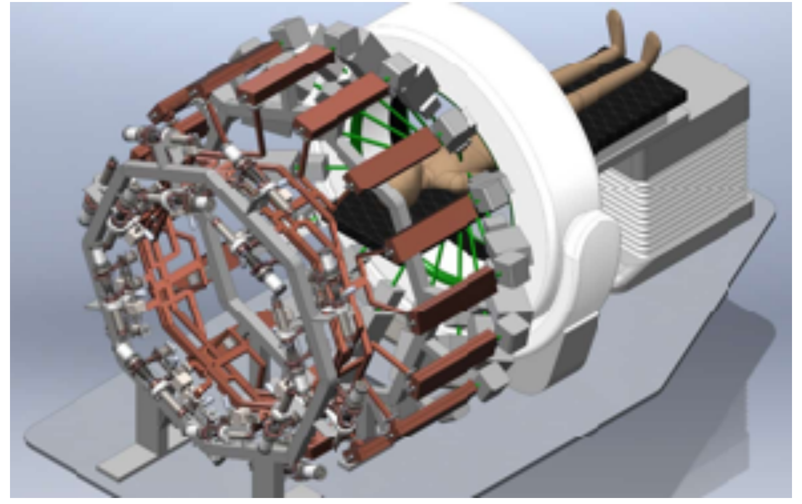
3D Imaging technologies CT MRI

IMRT

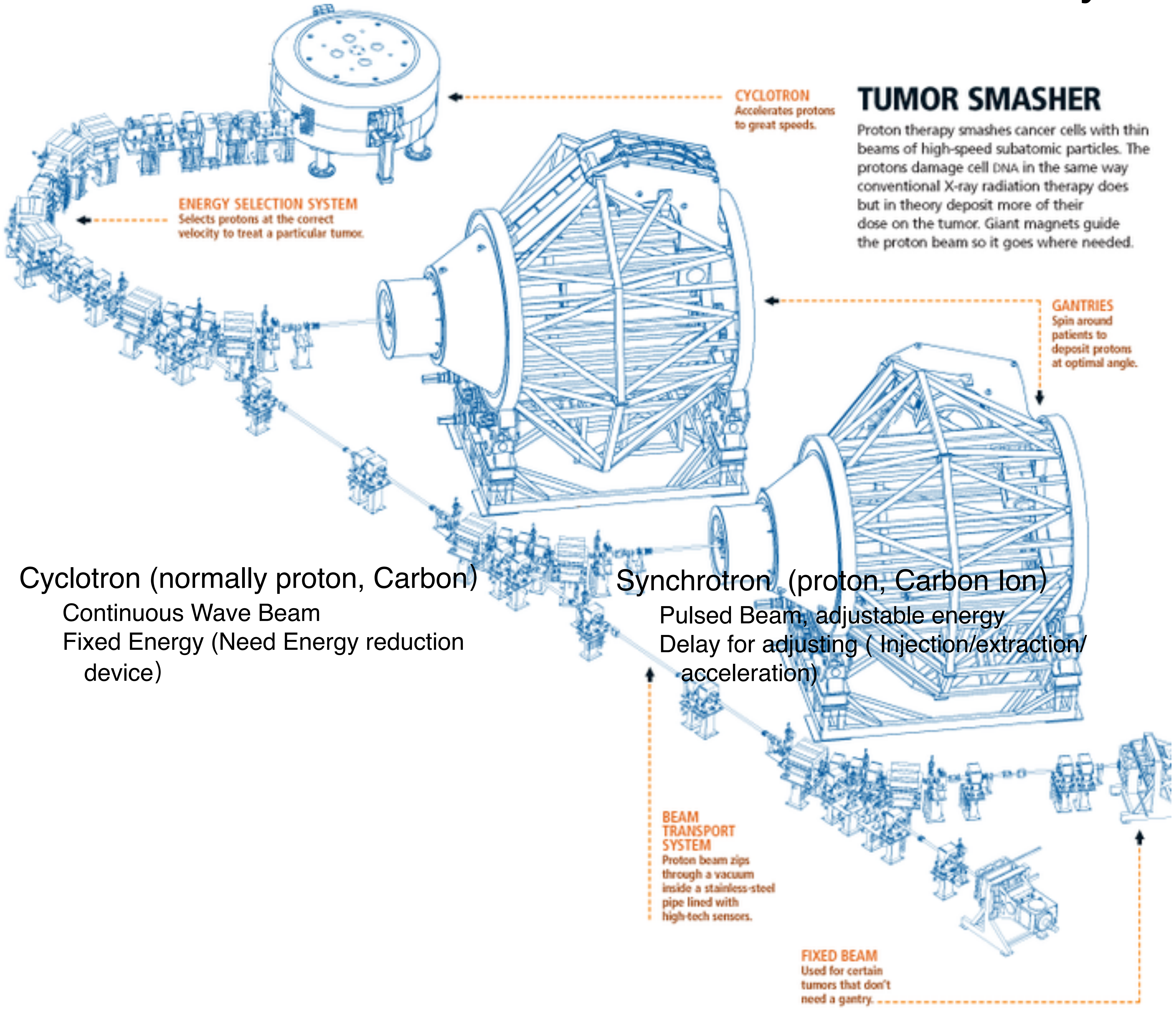
IGRT



FLASH with dose rate > 40Gy/s



Proton and Heavy Ion Radiotherapy



Cyclotron (normally proton, Carbon)

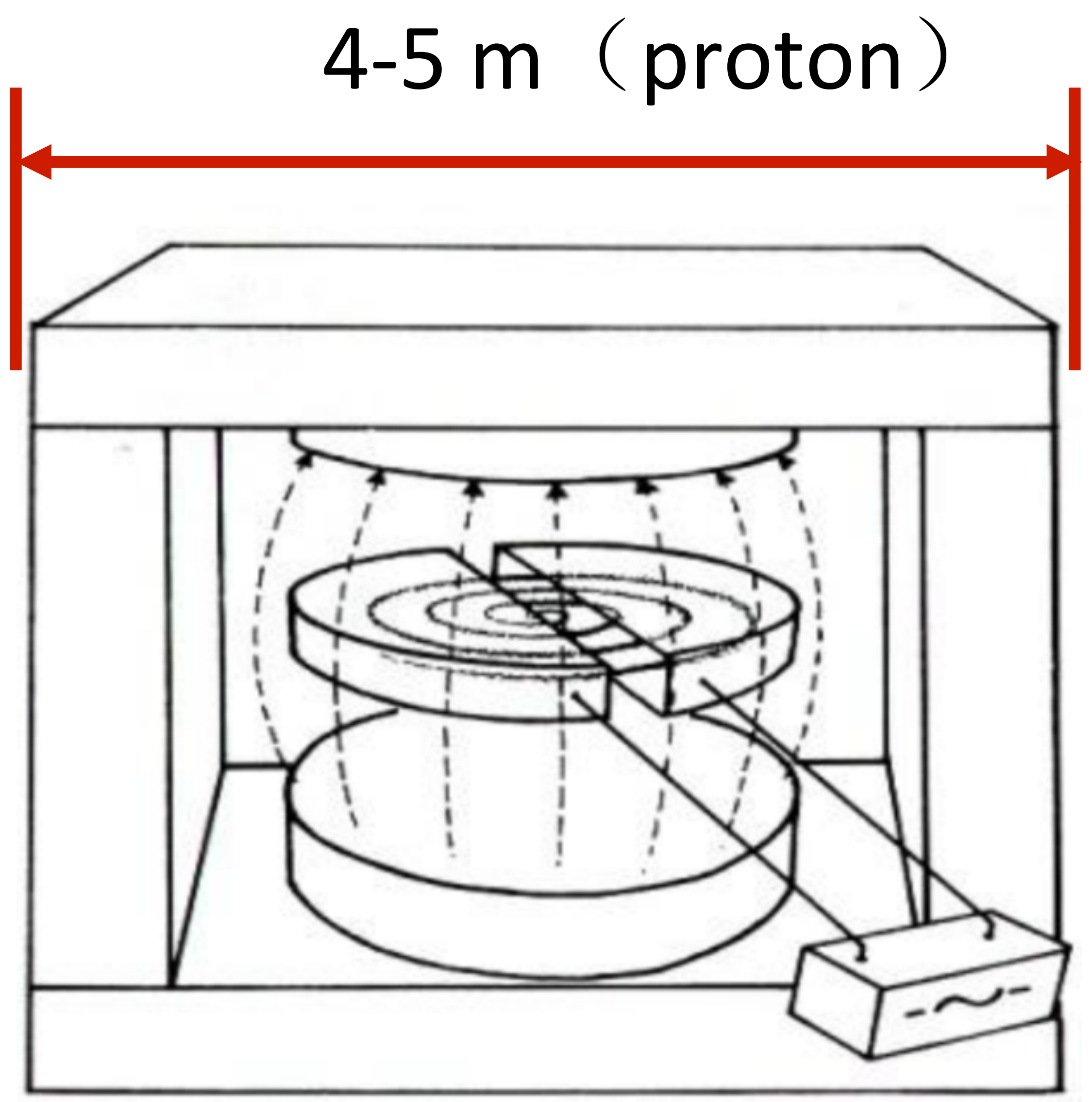
Continuous Wave Beam

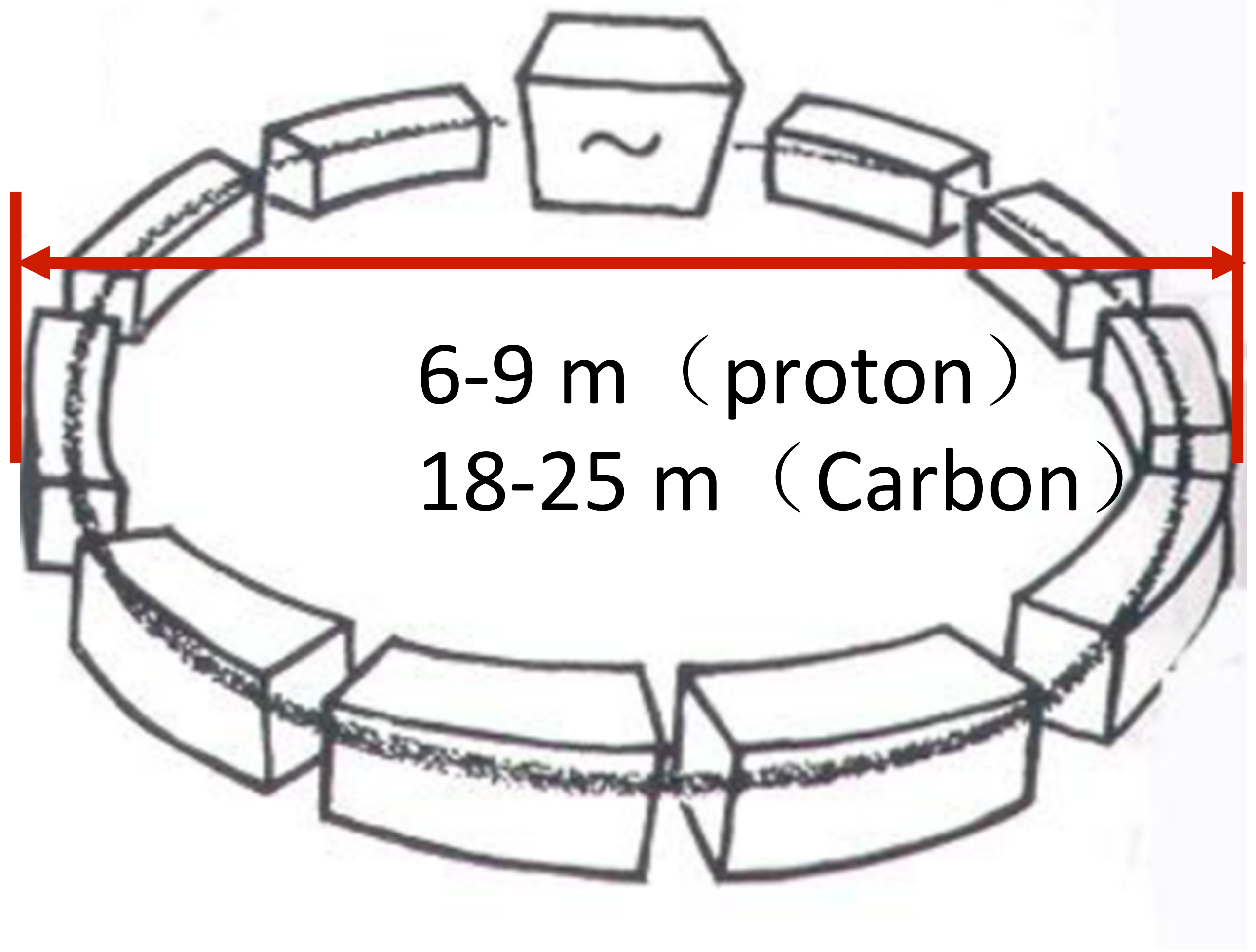
Fixed Energy (Need Energy reduction device)

Synchrotron (proton, Carbon Ion)

Pulsed Beam, adjustable energy

Delay for adjusting (Injection/extraction/ acceleration)

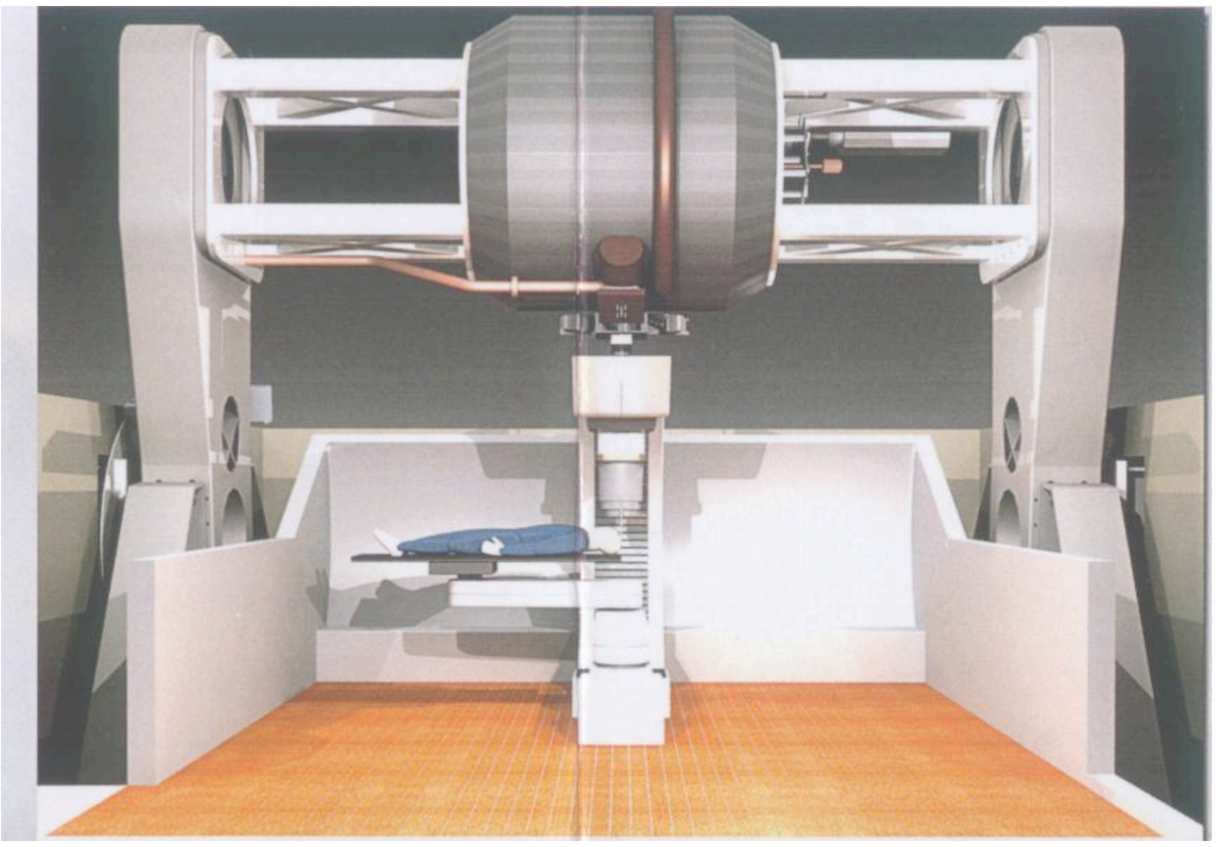




Accelerators for Proton and Heavy Ion Radiotherapy

Cyclotron therapy systems

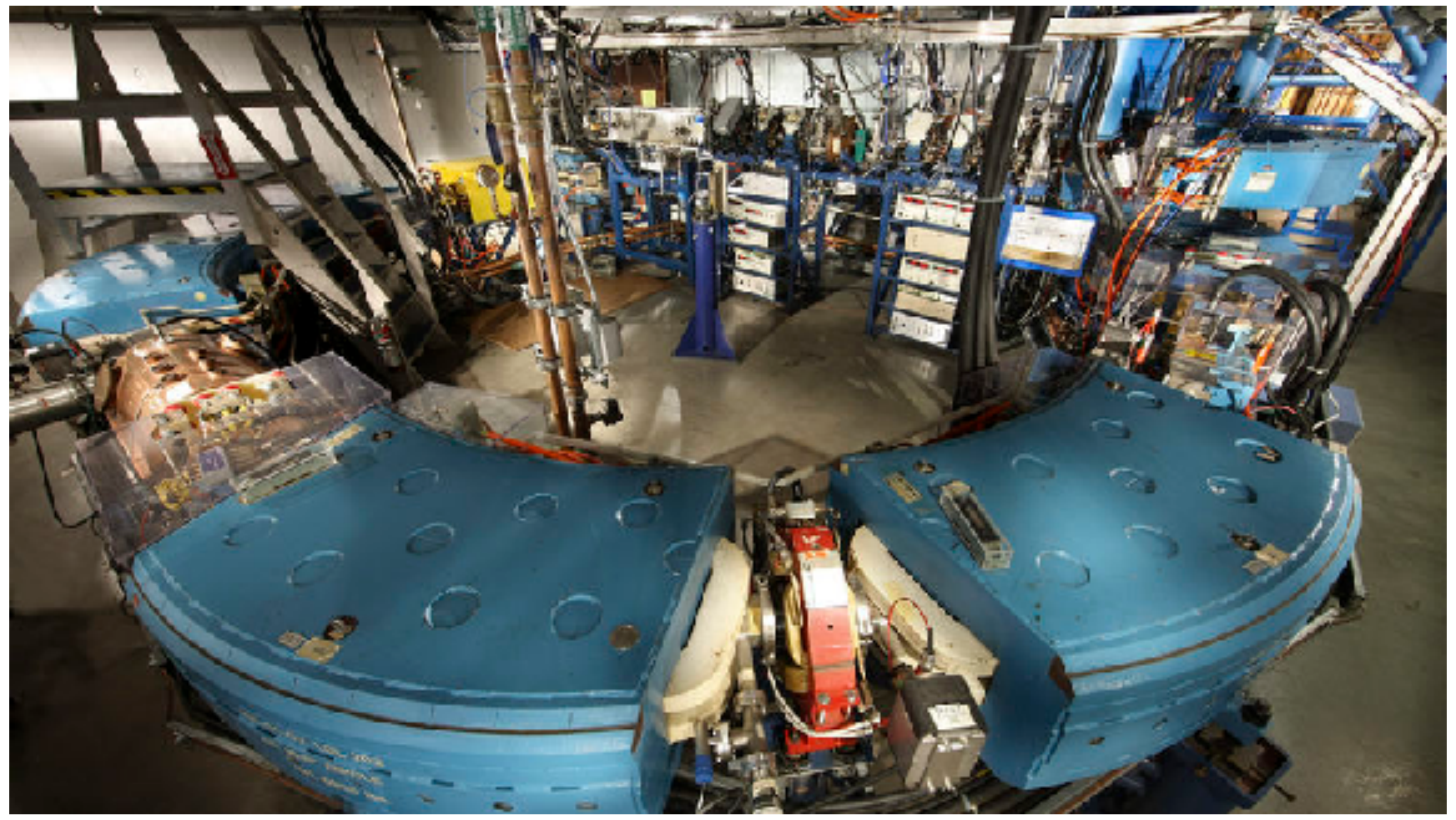
Mevion S250 with SC magnet
B=9T （20 tons）



Cyclotron on Gantry, B=11T（17 tons）
Still River Systems Inc.

Room Temp. Magnet, IBA C230 B=2.2T （200 tons）

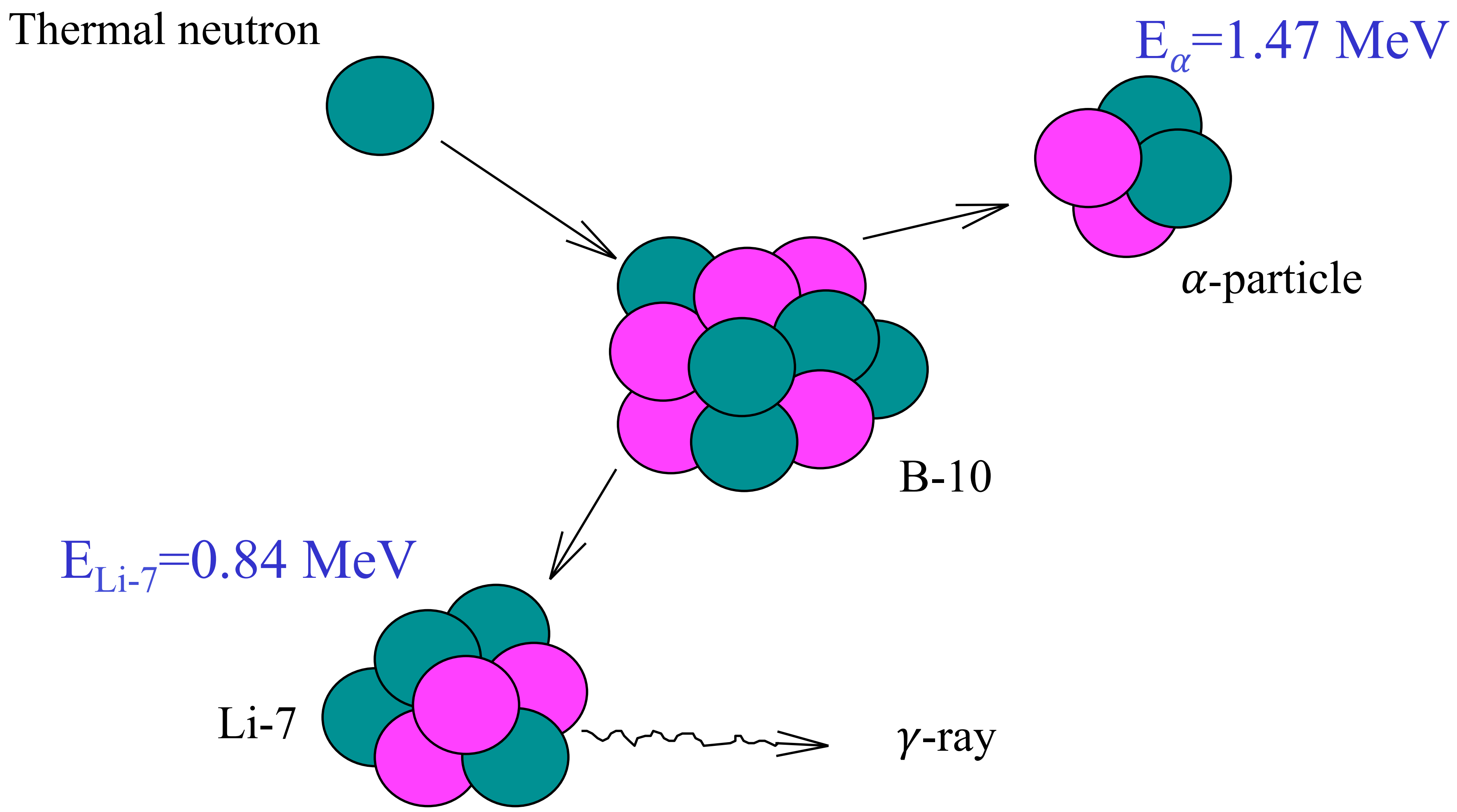
Synchrotron therapy systems

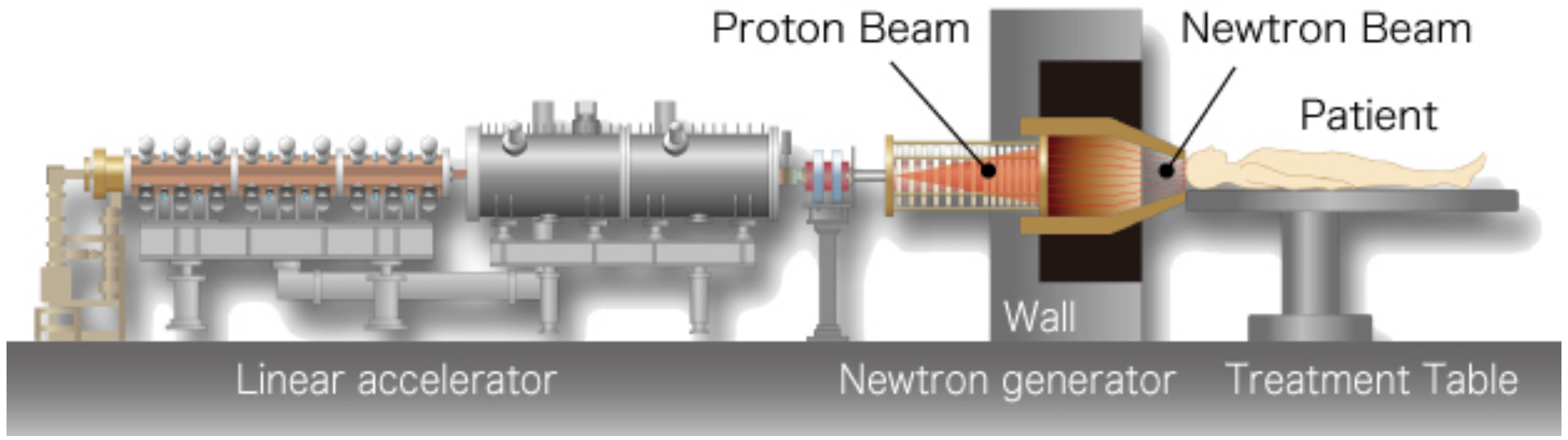


The Synchrotron of at Loma Linda University

Mitsubishi: Proton type (70 - 250 MeV)
Proton (70 - 250 MeV) /carbon (70 - 380 MeV/u) type.

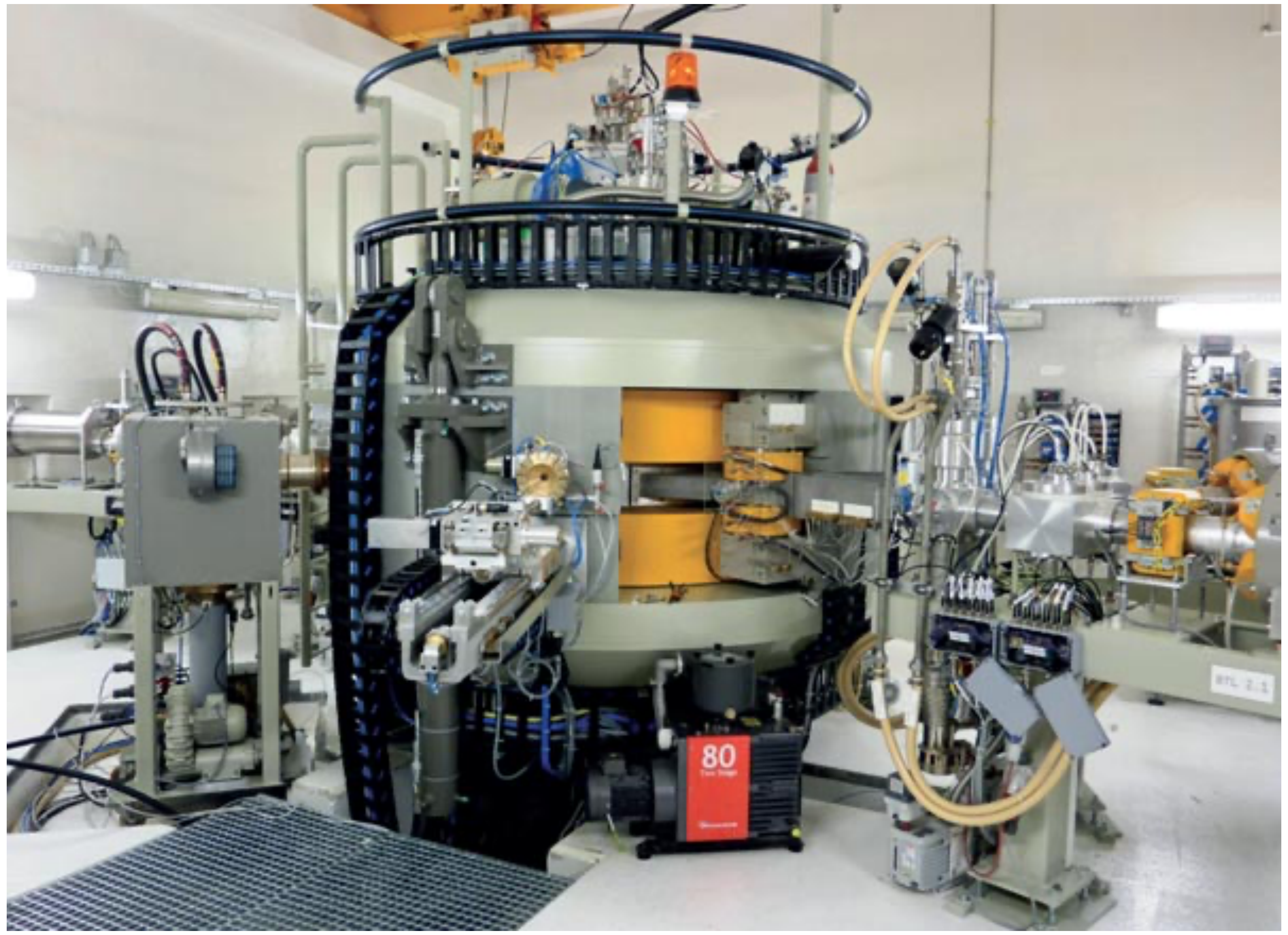
BNCT(Boron Neutron Capture Therapy)





Accelerators for radioisotope production

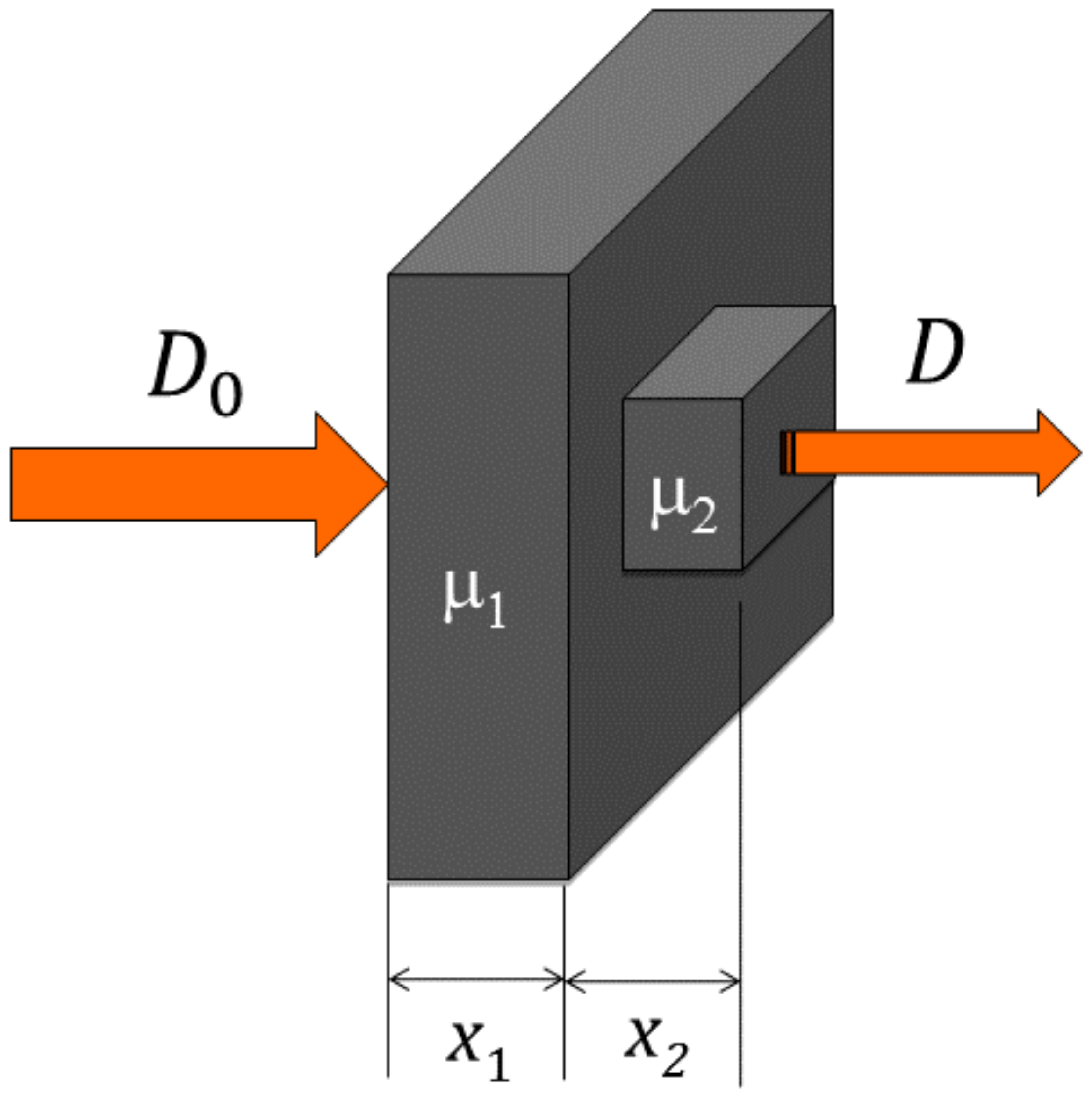
Cyclotron, linacs, FFAG and electrostatic machines are commonly used to produce isotope medicines.

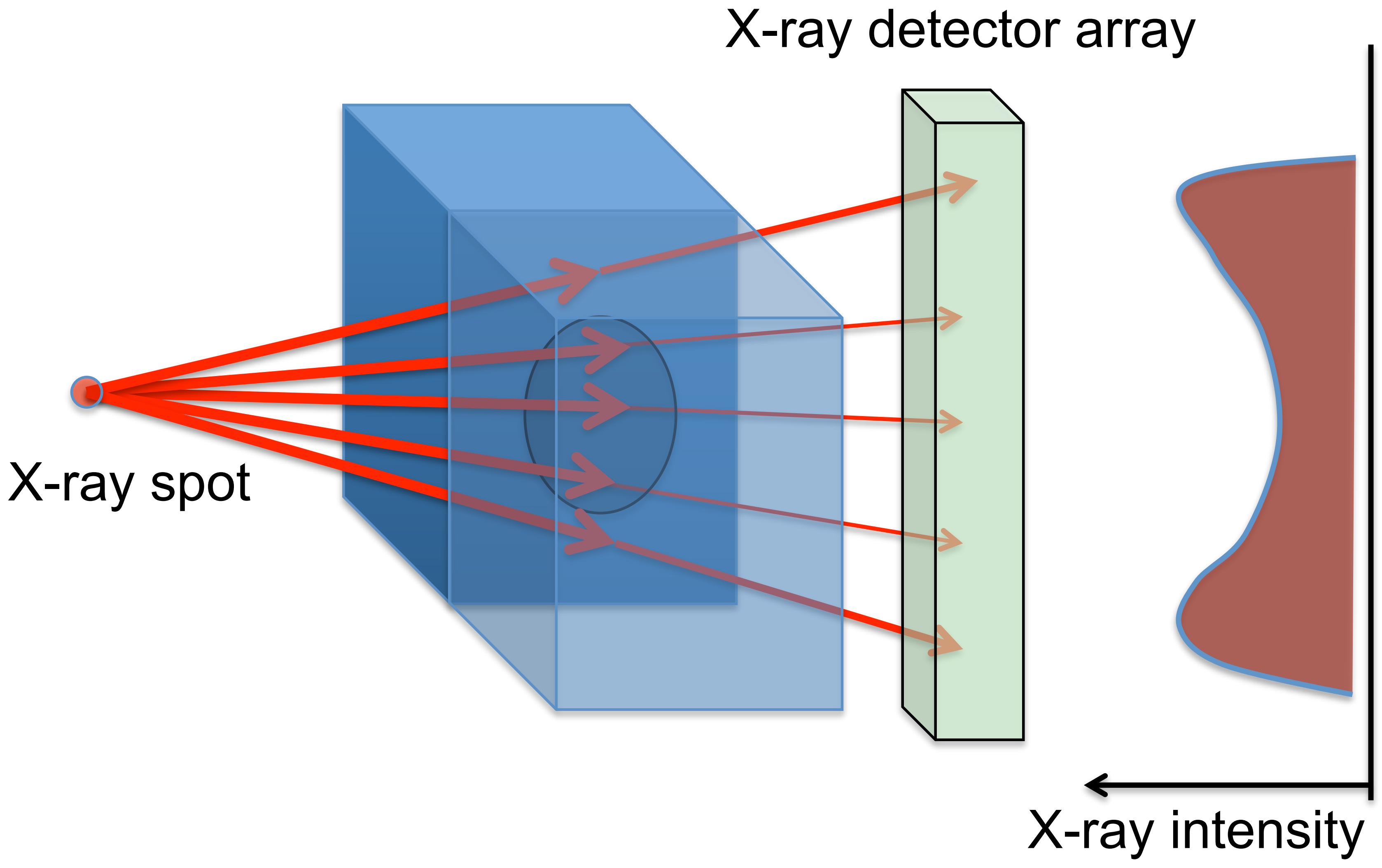


The power-efficient Cyclone-30 isotope-producing cyclotron, 2.7 m in diameter and 2.8 m high. Image credit: IBA.

Non-Destructive Test (NDT)

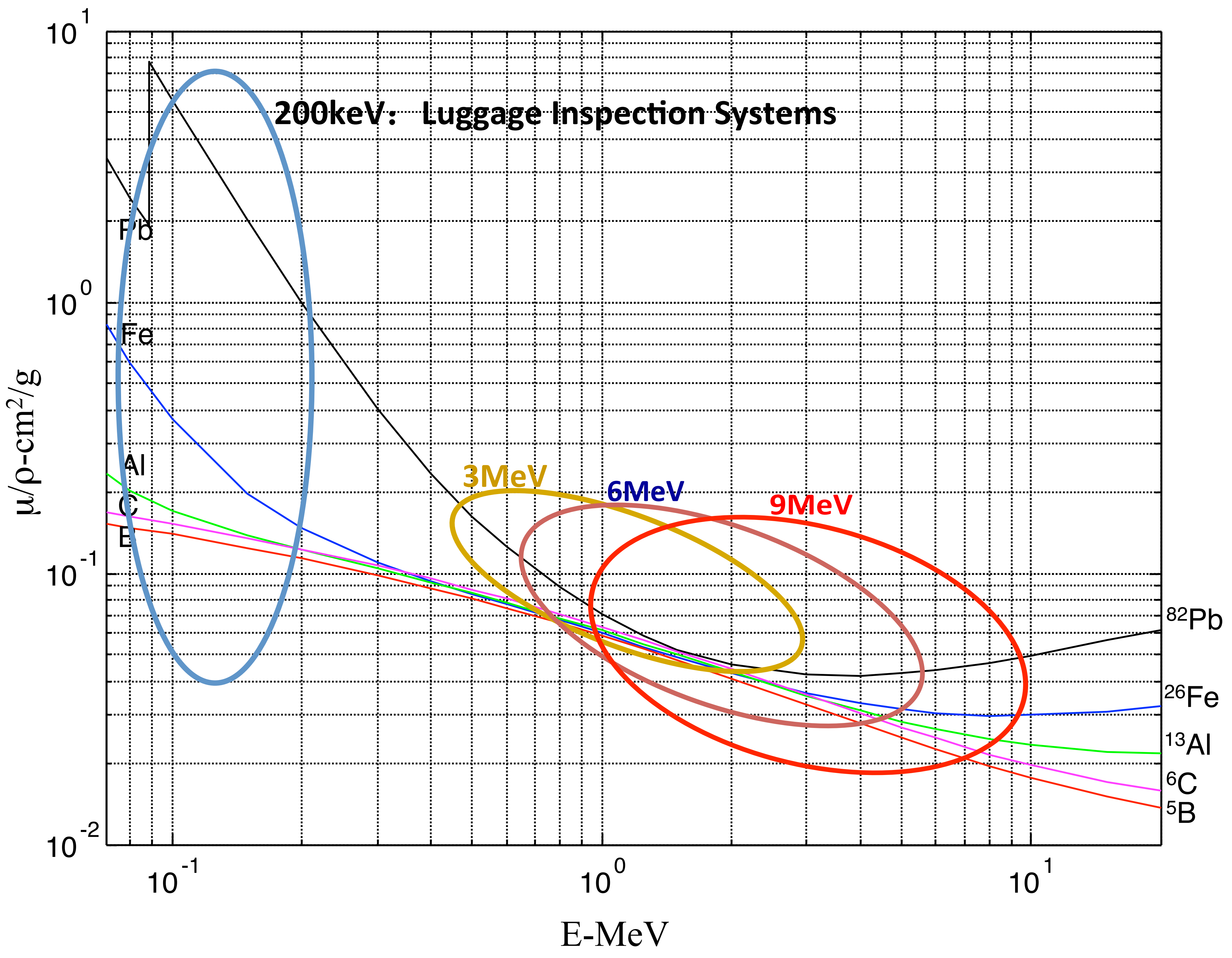
$$D = D_0 e^{-(\mu_1 x_1 + \mu_2 x_2)}$$



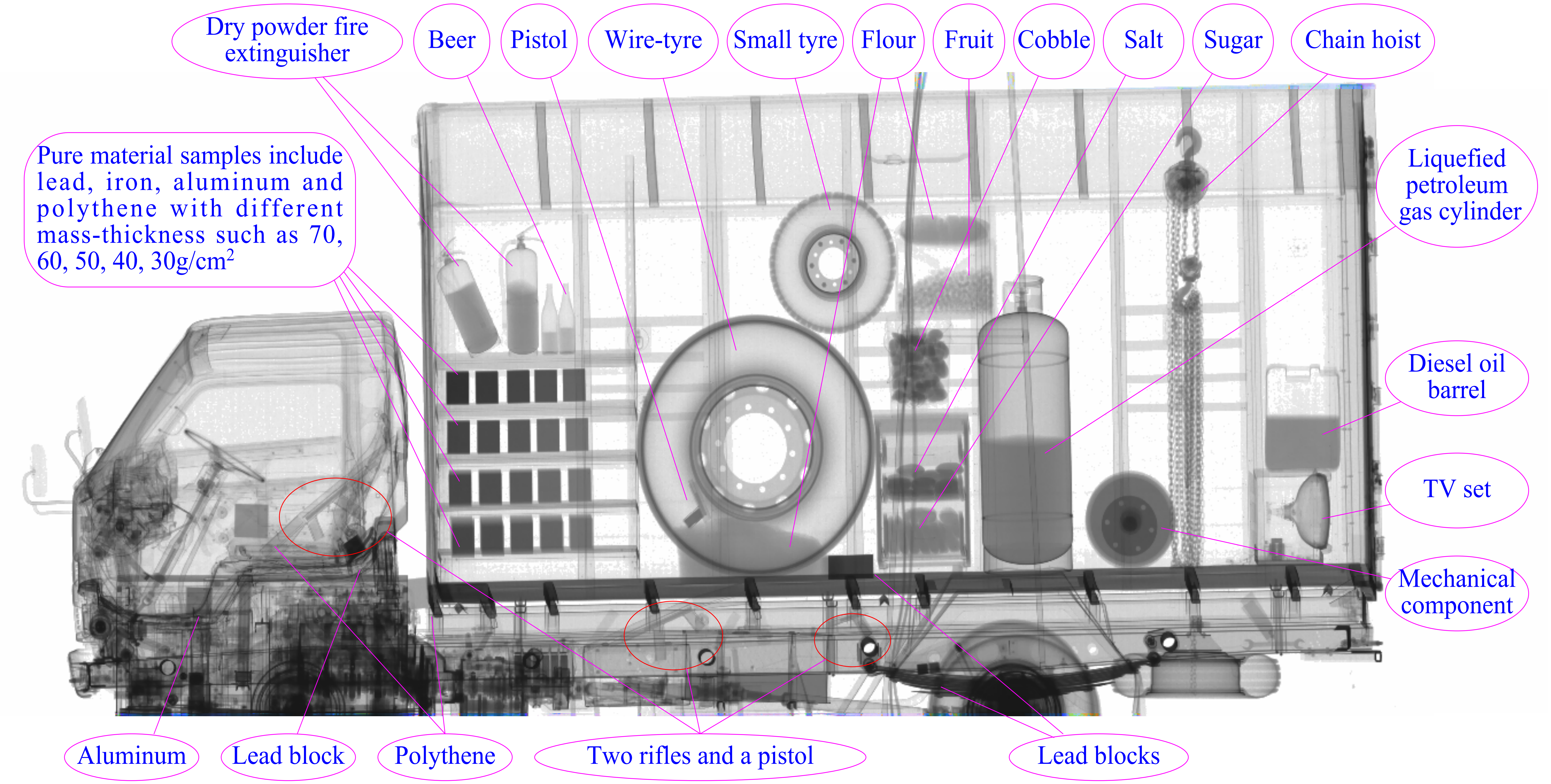


X-ray is mostly used for NDT, and linacs and betatrons are as the high energy (>MeV) x-ray sources. X-ray tubes can be considered as DC high voltage electron accelerators. They accelerate electrons, electron beams hit an target to generate x-ray.
Electrons, protons and neutrons can also be used to do imaging. And each of them has their special advantages.

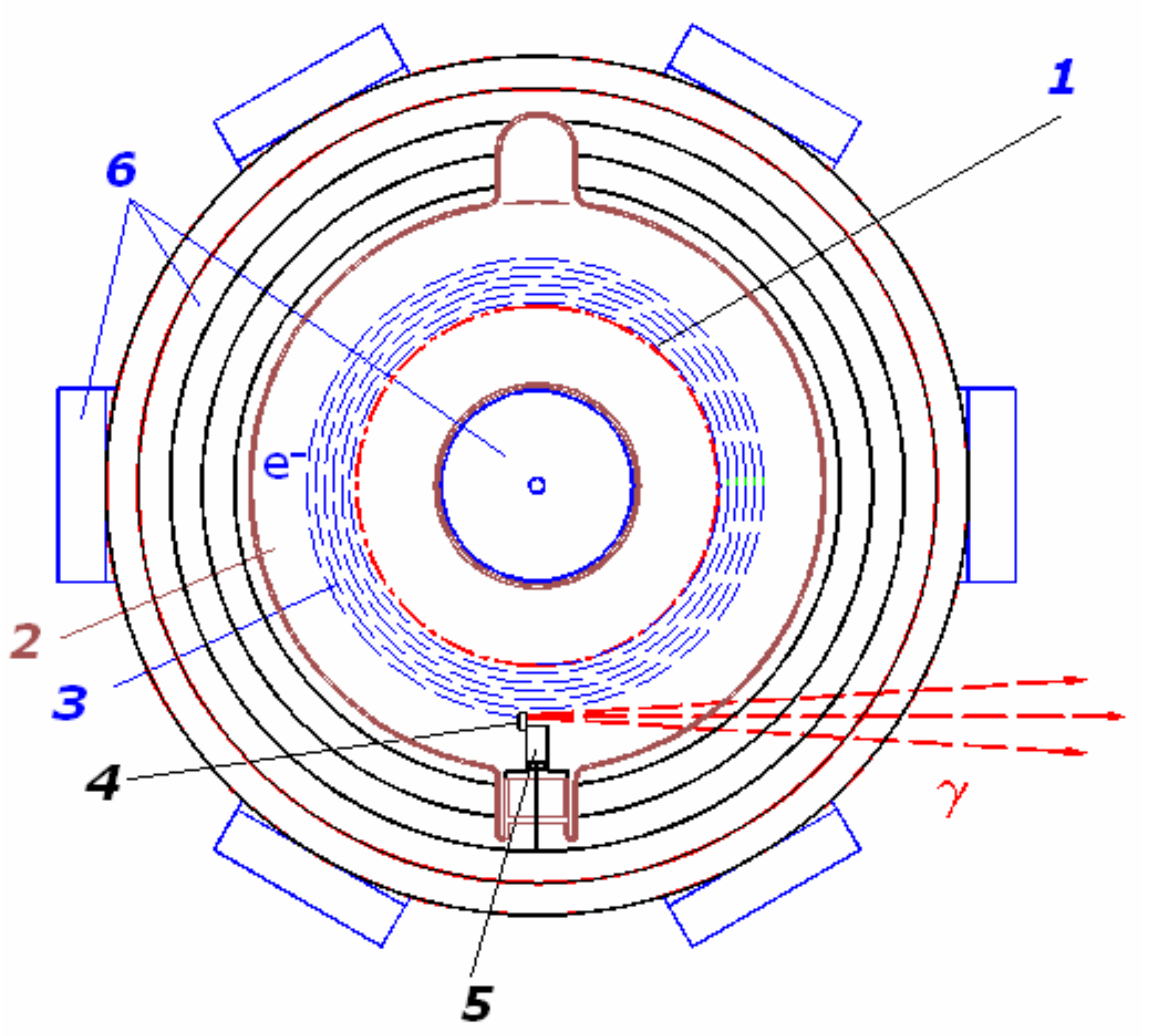
X-ray attenuation in materials

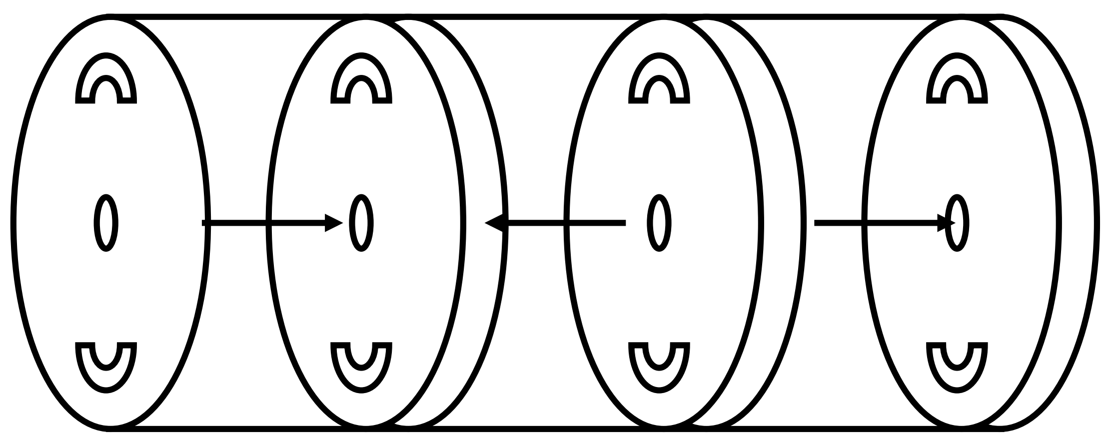


An image of dual energy cargo inspection

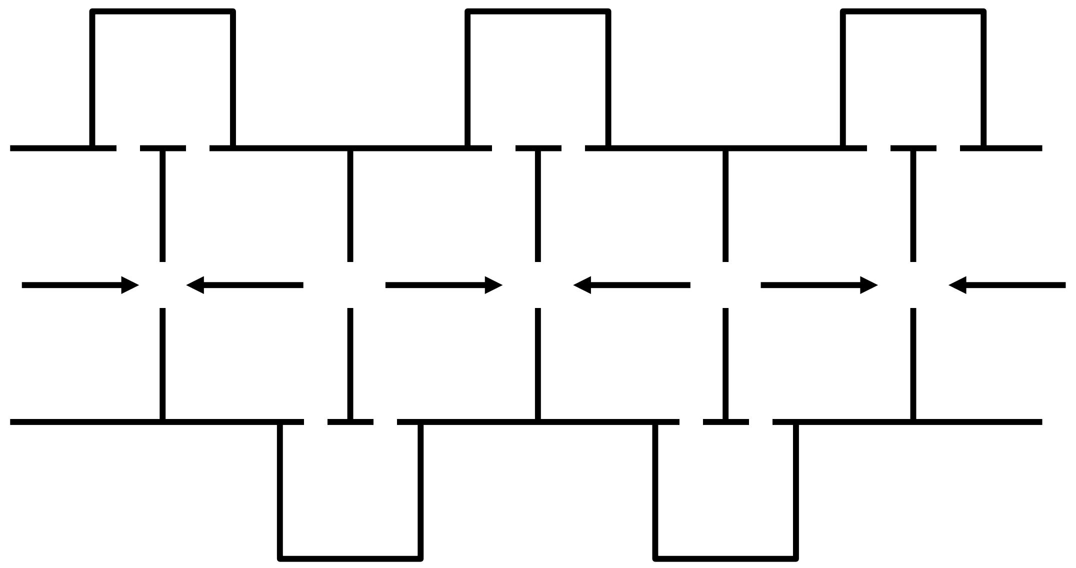


Accelerators as The X-ray Sources





On-axis magnetic coupled bi-period structures used in Tsinghua university



Side coupled structures

PXB - 6 by Tomsk Polytechnic University

Betatron

6 MeV SW Linac by THU

Linear Accelerator

Irradiation

What is irradiation?

- Irradiation is the process to change molecular structure of an item, which is exposed to radiation.
- In common usage it refers specifically to ionizing radiation, and to a level of radiation that will serve specific purpose.

Ray species: *X-rays, gamma rays, electron beam*

Classification:

Food irradiation,
Sterilization for medical devices,
Industrial irradiation

What's important for Irradiation?

- Beam Power: Processing capacity
- Plug to Beam efficiency: Processing capacity, Cost-effectiveness ratio
- Beam energy: depth of the product

Kinds of accelerators :

- High voltage DC accelerators
  Insulated core transformer, Dynamitron, High power (> 100kW), low energy (<1MeV)
- RF Linacs: high energy (>5MeV) , low power (<100kW)
- Rhodotron: 10MeV, 150kW. Low frequency RF, heavy beam loading can be helpful to increase the efficiency.

Food Irradiation

- The radiation of interest in food preservation is ionizing radiation, also known as irradiation. These shorter wavelengths are capable of damaging microorganisms such as those that contaminate food or cause food spoilage and deterioration.

- Two things are needed for the irradiation process.
  1) A source of radiant energy, and
  2) a way to confine that energy.

Treated with irradiation or Treated by irradiation

Industrial irradiation

Vulcanization of rubber , e.g. cross-link

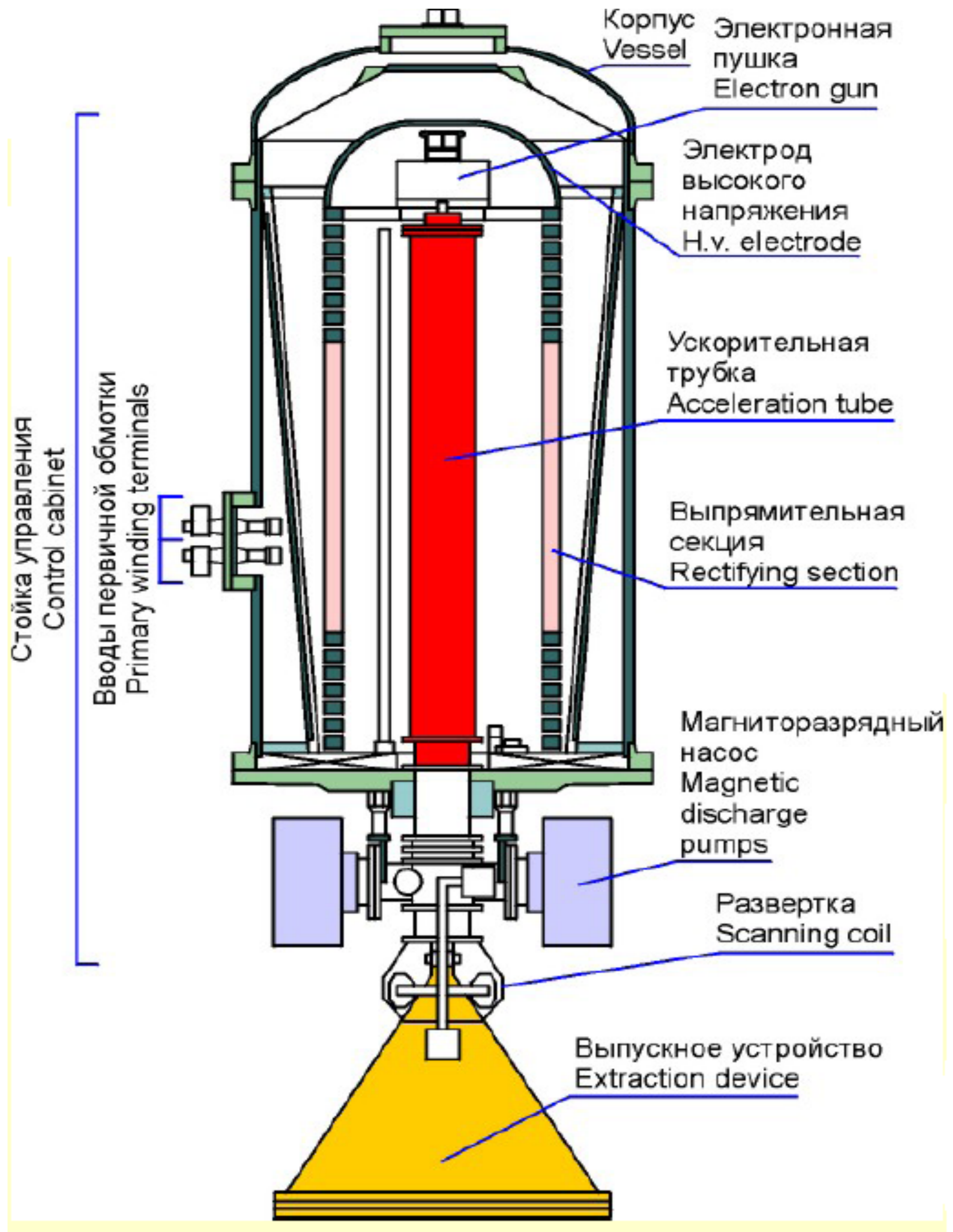
Pollution Control , e.g. NOx and SOx

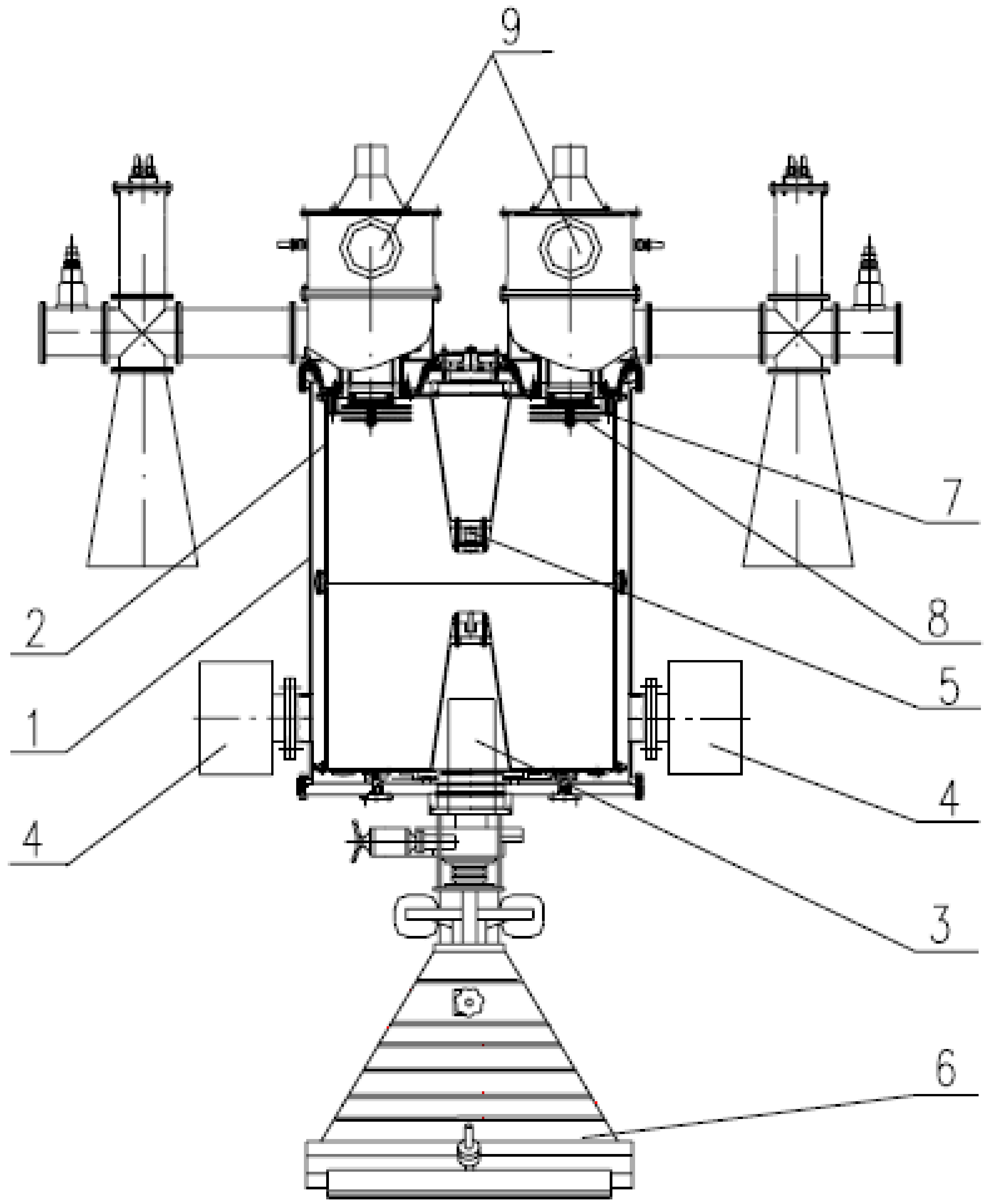
Material modification , e.g. carbon-fiber or semiconductor

Surface processing , e.g. Gem & Glass

ELV and ILU developed by BINP

Two kinds of widely used irradiation accelerators in Asia: ELV-DC high voltage type, and ILU based on RF acceleration.





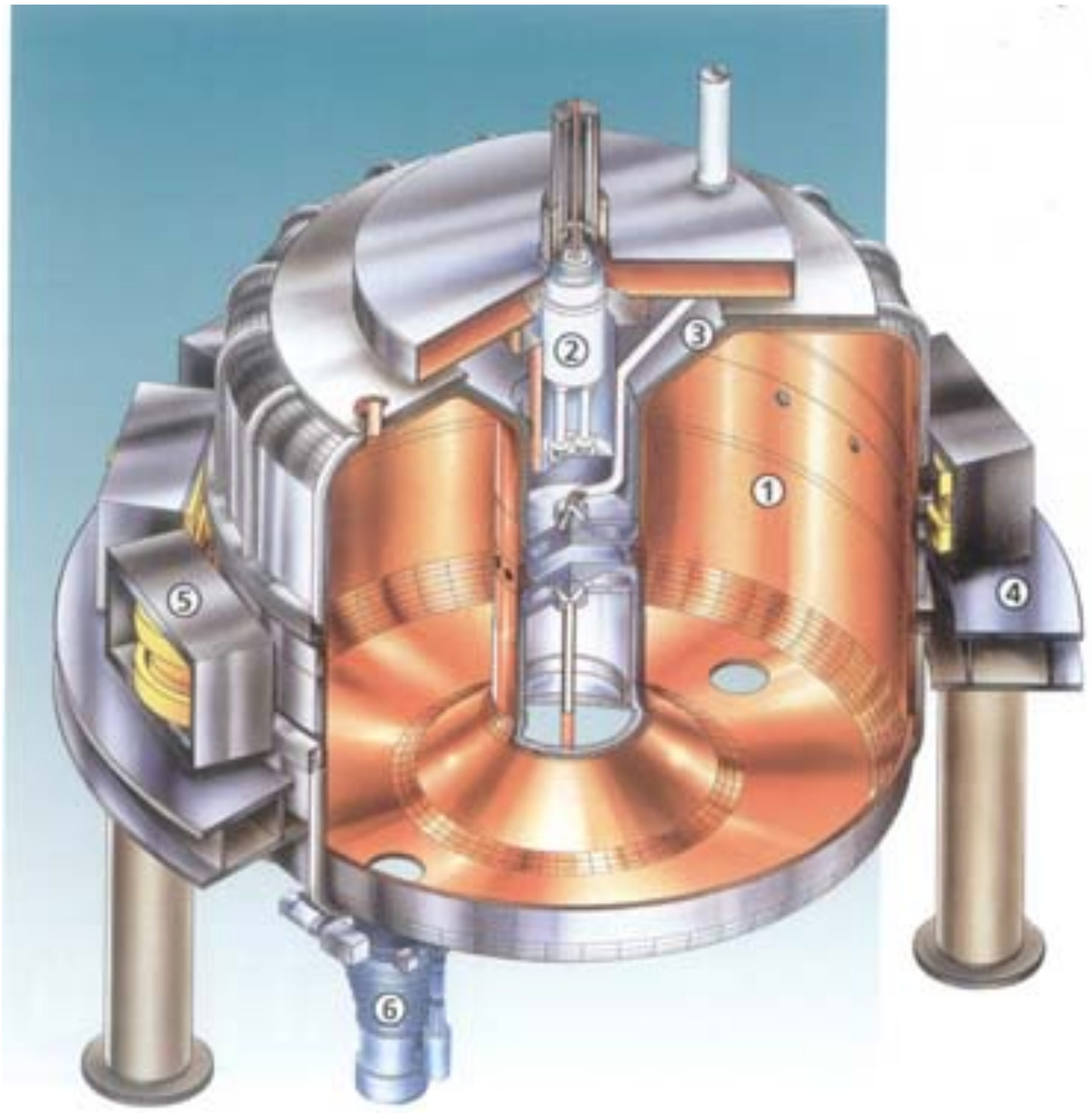
The electron beam power of ELV-12 can reach 400kW with electron energy of 0.6-0.9MeV, and the electron energy of ELV-8 can be 1.0-2.5MeV with beam power of 90kW .

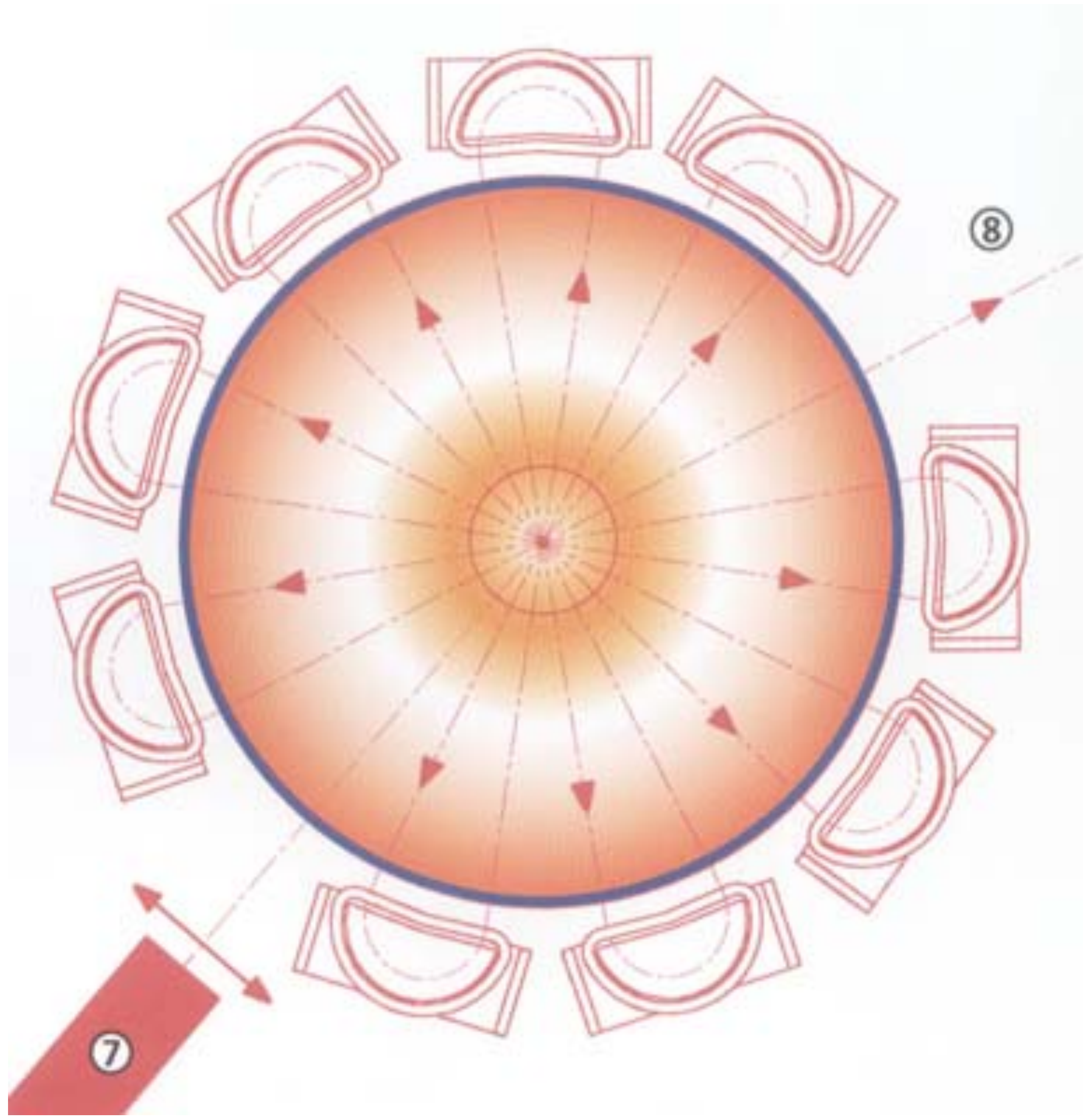
ILU covers the energy range from 0.6MeV to 5 MeV, and the maximum beam power is 50 kW. A 5MeV/300kW ILU accelerator is developing now.

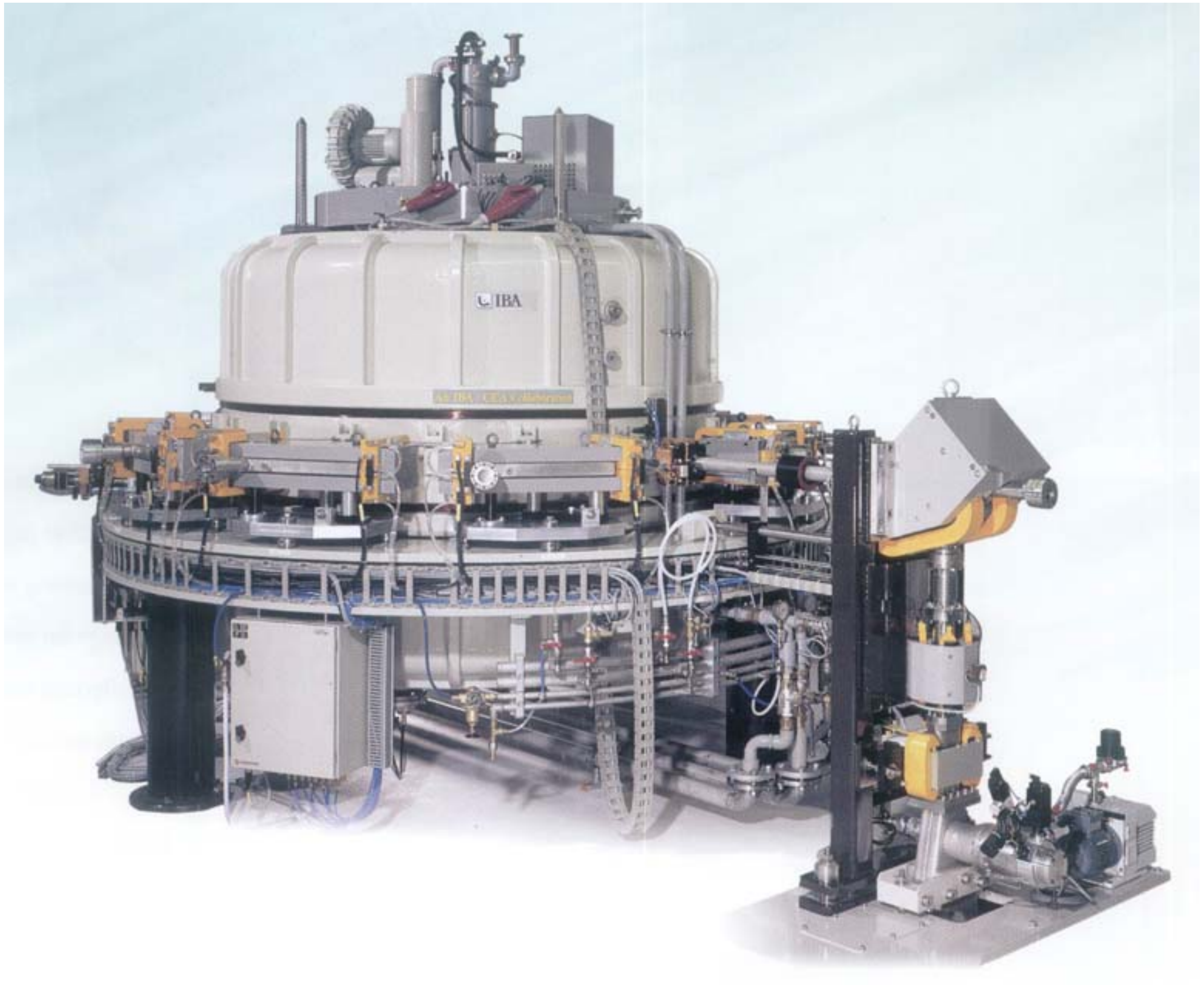
Yu.I. Golubenko, et al, "Electron Accelerator of ELV-Type And Their Worldwide Application", APAC2007,THPMA118.
V.L. Auslender, et al, "Industrial High Energy Electron Accelerators Type ILU", Proceedings of RuPAC 2008, P367(2008).

Rhodotron

Rhodotron is an IBA company's patent product. Its operating principle is shown in the following figures. The electrical field is radial and oscillates at a frequency of either 107.5 or 215 MHZ.







- Its beam power can reach 150 kW (10MeV)

Applications of Particle Accelerators