Accelerator technology

Mika Masuzawa (KEK)

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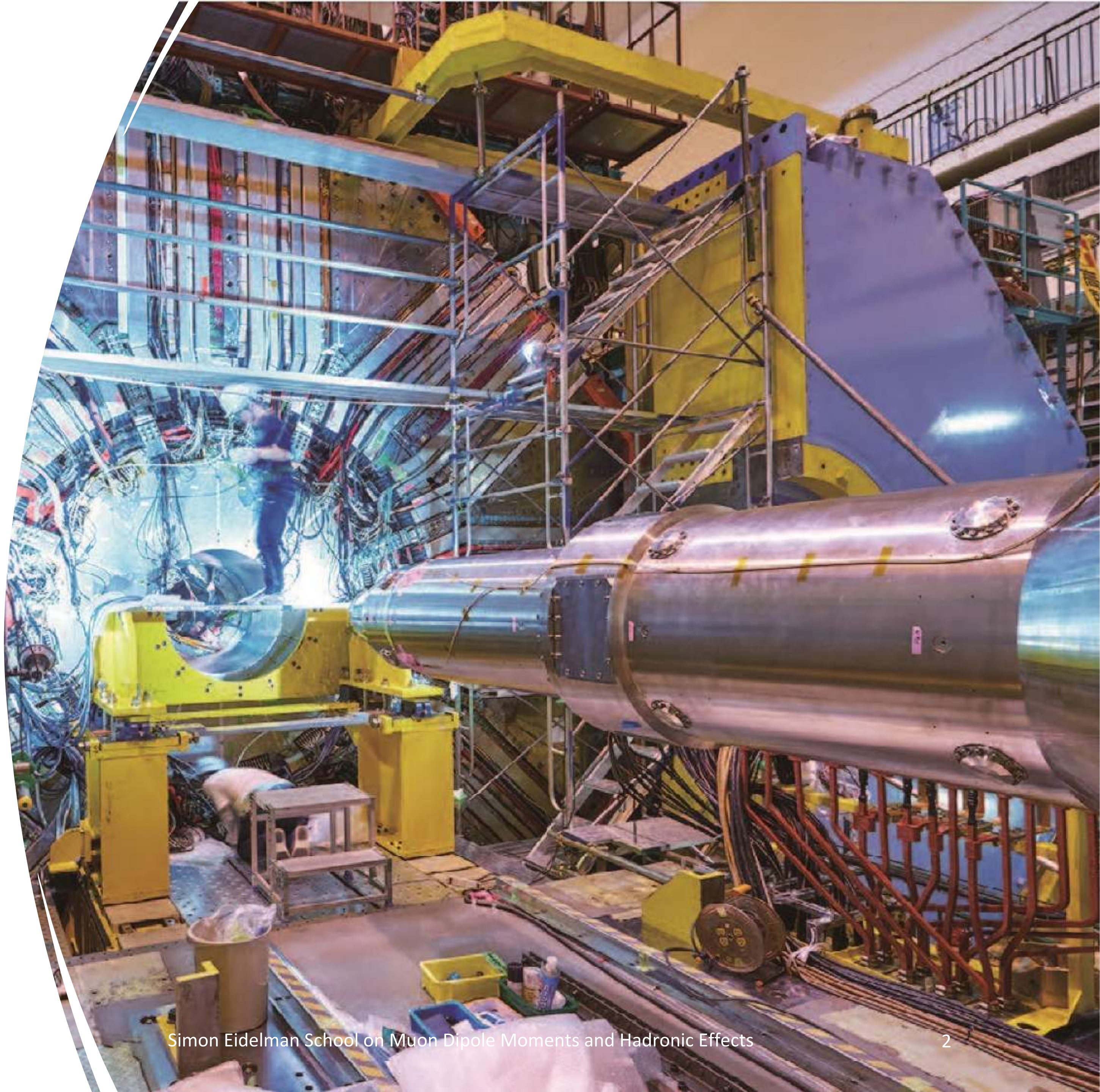
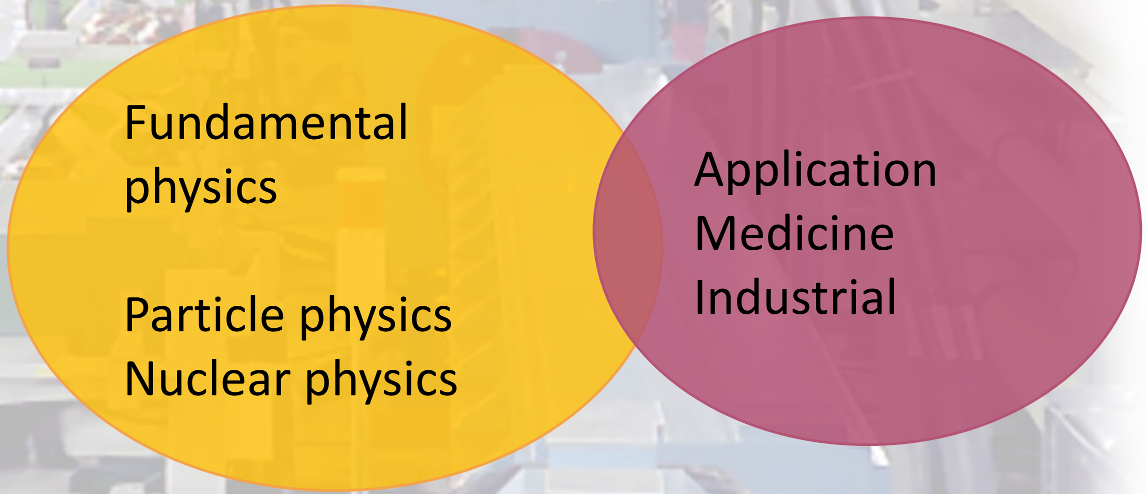


Introduction

- An accelerator propels charged particles, such as protons or electrons, at high speeds, close to the speed of light.
- The accelerated particles are smashed either onto a target (“Fix target experiment”) or against other particles coming from the opposite direction(“Collider experiment”)
- By studying these collisions, physicists are able to probe the world of the infinitely small and solve the mysteries



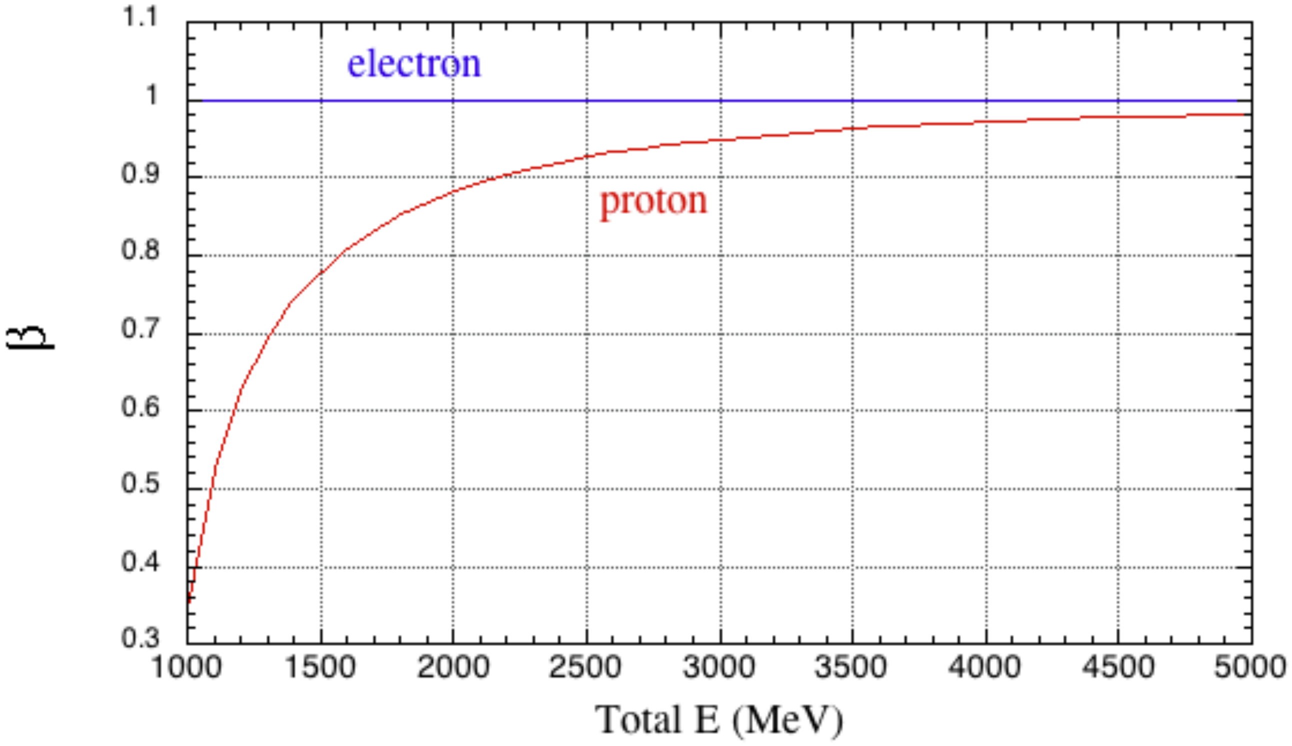
Introduction

- An accelerator accelerates particles,
- $\beta \equiv {}^{v}/_{c} \rightarrow\rightarrow 1$ (close to speed of light c)

- Then total energy E_T of a particle is the sum of its rest energy E_0 and its kinetic energy T

- $E_T = E_0 + T = mc^2 + T$

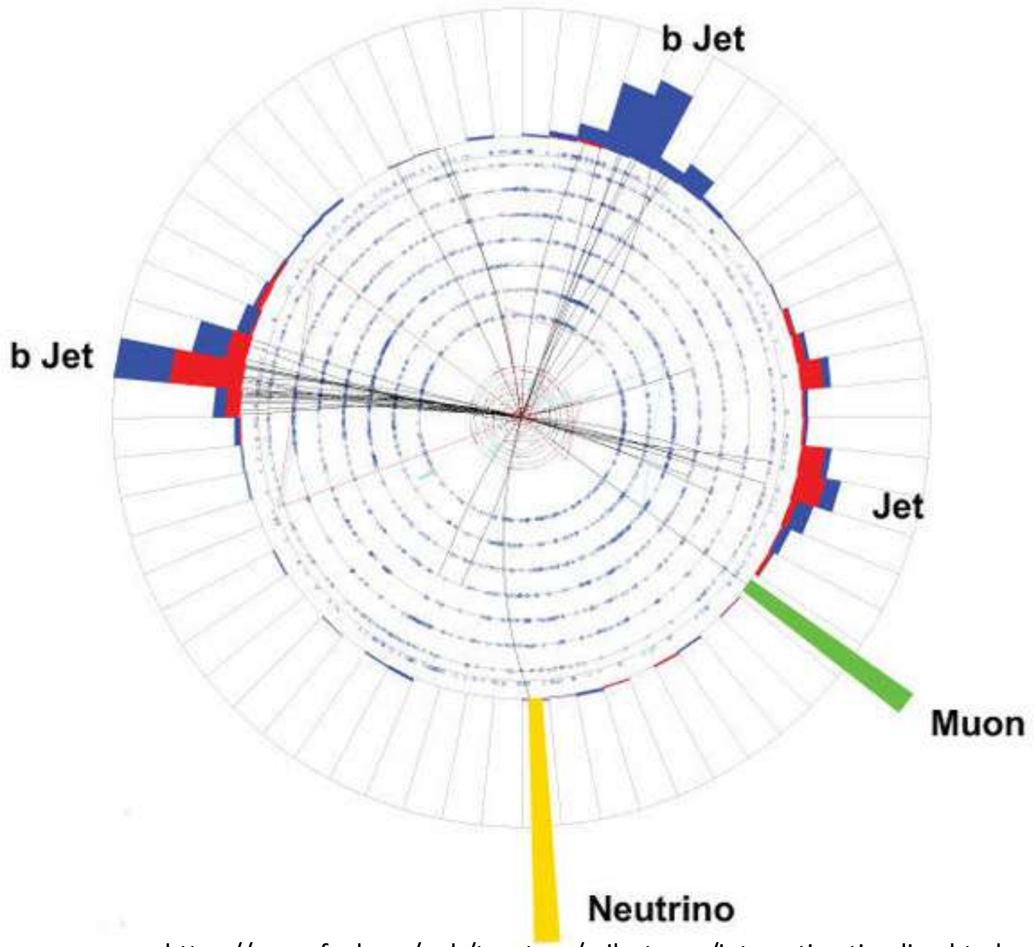
- The total energy E_T can also be expressed in terms of the gamma factor
- $E_T = \gamma mc^2, \quad \text{where} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$



Introduction

Particle	Symbol	E_0
electron	e	0.511 (MeV)
muon	μ	105.659 (MeV)
proton	p	938.26 (MeV)
b quark	b	4735 (MeV)
upsilon	$\Upsilon(4S)$	10580 (MeV) 10.58 (GeV)
t quark	t	172.76 (GeV)

Top quark signature recorded at Tevatron



https://www.fnal.gov/pub/tevatron/milestones/interactive-timeline.html

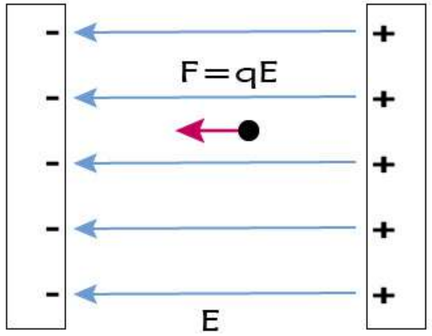
High(er) energy accelerator is needed to generate heavy (heavier) particles

Introduction

(1) How to accelerate particles

A particle of velocity $\vec{v}$, charge q, passes through magnetic field $\vec{B}$ and an electric field $\vec{E}$, it receives the Lorentz force, the combination of electric and magnetic force.

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



The energy change ΔU when a particle moves from point $\vec{r_1}$ to $\vec{r_2}$ is

$$\Delta U = \int_{\vec{r_1}}^{\vec{r_2}} \vec{F}\cdot d\vec{r} = q\int_{\vec{r_1}}^{\vec{r_2}} (\vec{E} + \vec{v}\times\vec{B})\cdot d\vec{r} = q\int_{\vec{r_1}}^{\vec{r_2}} \vec{E}\cdot d\vec{r}$$

$\because d\vec{r} // d\vec{v}$

Acceleration by the use of electric fields

Introduction

(2) How to control the particle path

A particle of velocity $\vec{v}$, charge q, passes through magnetic field $\vec{B}$ and an electric field $\vec{E}$, it receives the Lorentz force, the combination of electric and magnetic force.

$$\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

Path control by the use of magnetic fields

Path control

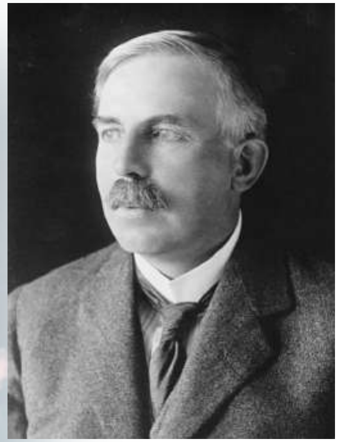
- Passage of the particles is called orbit
- Orbit control → to deflect, to focus, to defocus …

Magnet technologies

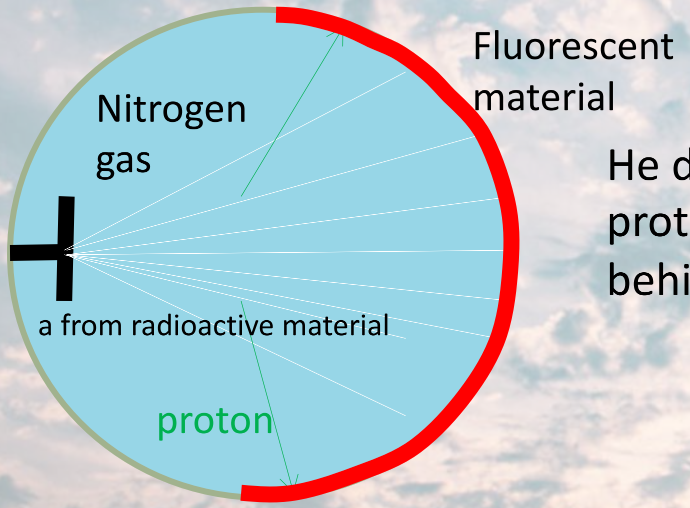
Dawn

The first nuclear reaction by Rutherford

$$\alpha + {}^{14}_{7}N \rightarrow p + {}^{17}_{8}O$$



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



He demonstrated in 1919, that alpha particle could knock protons out of nitrogen nuclei and merge with what was left behind.

This inspired physicists to seek more nuclear reaction using an accelerator

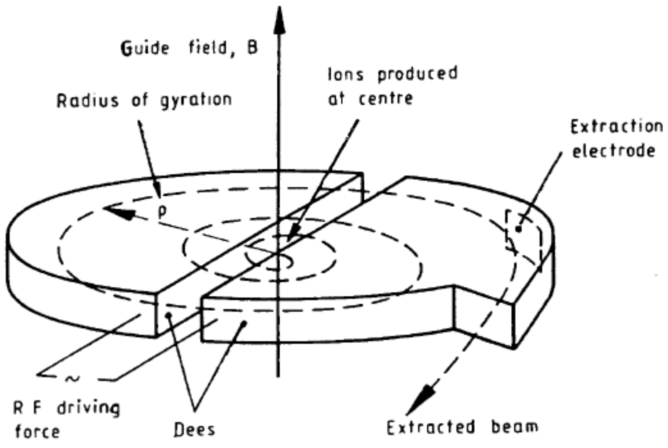
Brief history & major inventions

"The early history of accelerators can be traced from three separate roots. Each root is based on an idea for a different acceleration mechanism and all three originated in the twenties"

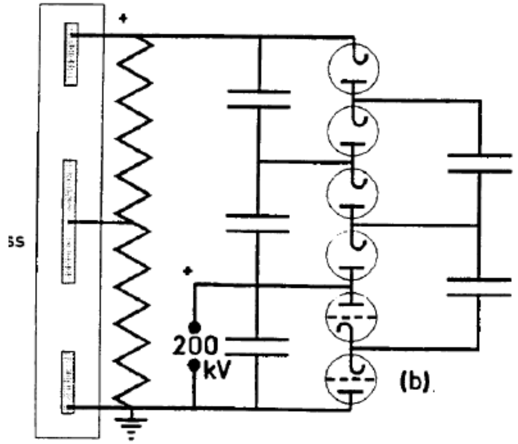
A BRIEF HISTORY AND REVIEW OF ACCELERATORS
P.J. Bryant, CERN

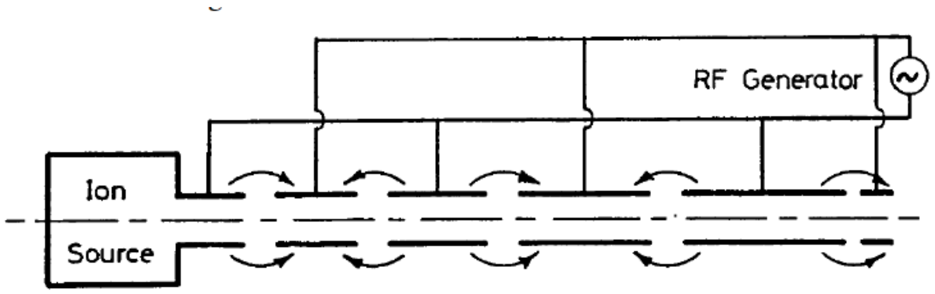
"The early history of accelerators can be traced from three separate roots. Each root is based on an idea for a different acceleration mechanism and all three originated in the twenties"

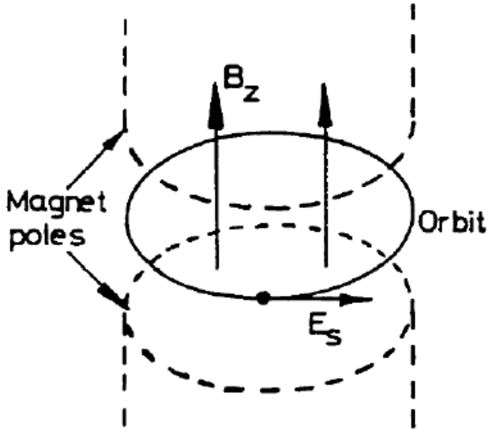
Three separate roots



1. DC generators
2. RF acceleration
   - Linear
   - circular
3. Betatron







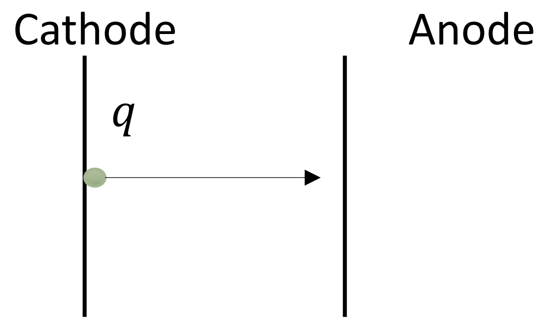
A BRIEF HISTORY AND REVIEW OF ACCELERATORS
P.J. Bryant, CERN

1^{st} root

DC generators for providing electric fields for acceleration

DC Generators：two major methods

- Cockcroft & Walton's 800 kV voltage-multiplier circuit with capacitors and rectifier tubes
- Van de Graaff's 1.5 MV belt-charged generator (1931)



$$\Delta U = \int_{\vec{r_1}}^{\vec{r_2}} \vec{F} \cdot d\vec{r} = q \int_{\vec{r_1}}^{\vec{r_2}} \vec{E} \cdot d\vec{r}$$

1st root

Cockcroft-Walton:
First disintegration of atomic nuclei with accelerator

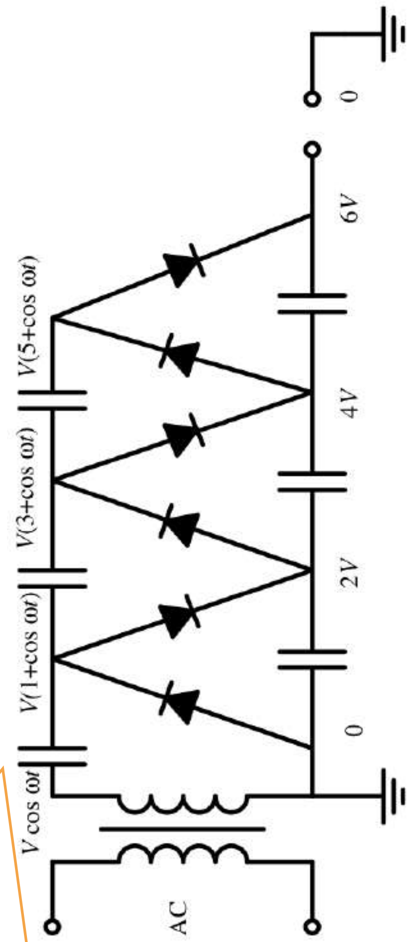
750 keV Cockcroft-Walton at KEK

1st root

Cockcroft-Walton:
First disintegration of atomic nuclei with accelerator

Cavendish Laboratory
1932, Cockcroft and Walton used their machine to accelerate protons,and directed the beam of protons at a sample of lithium. This resulted in changing lithium atoms into two helium atoms. They had disintegrated – “smashed” – the lithium atom by means of artificially accelerated protons.

$$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He + energy$$



High voltage is provided by charging capacitors and discharging them in series.

1st root

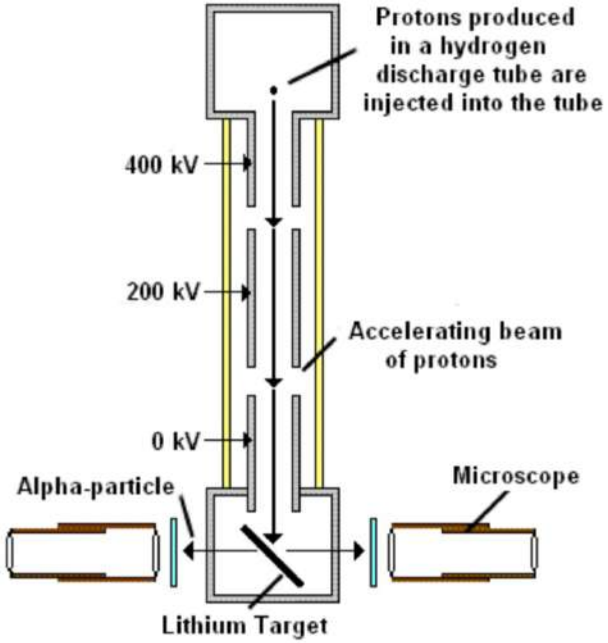
Cockcroft-Walton:

"Transmutation of atomic nuclei by <u>artificially</u> accelerated atomic particles"

$$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He + energy$$

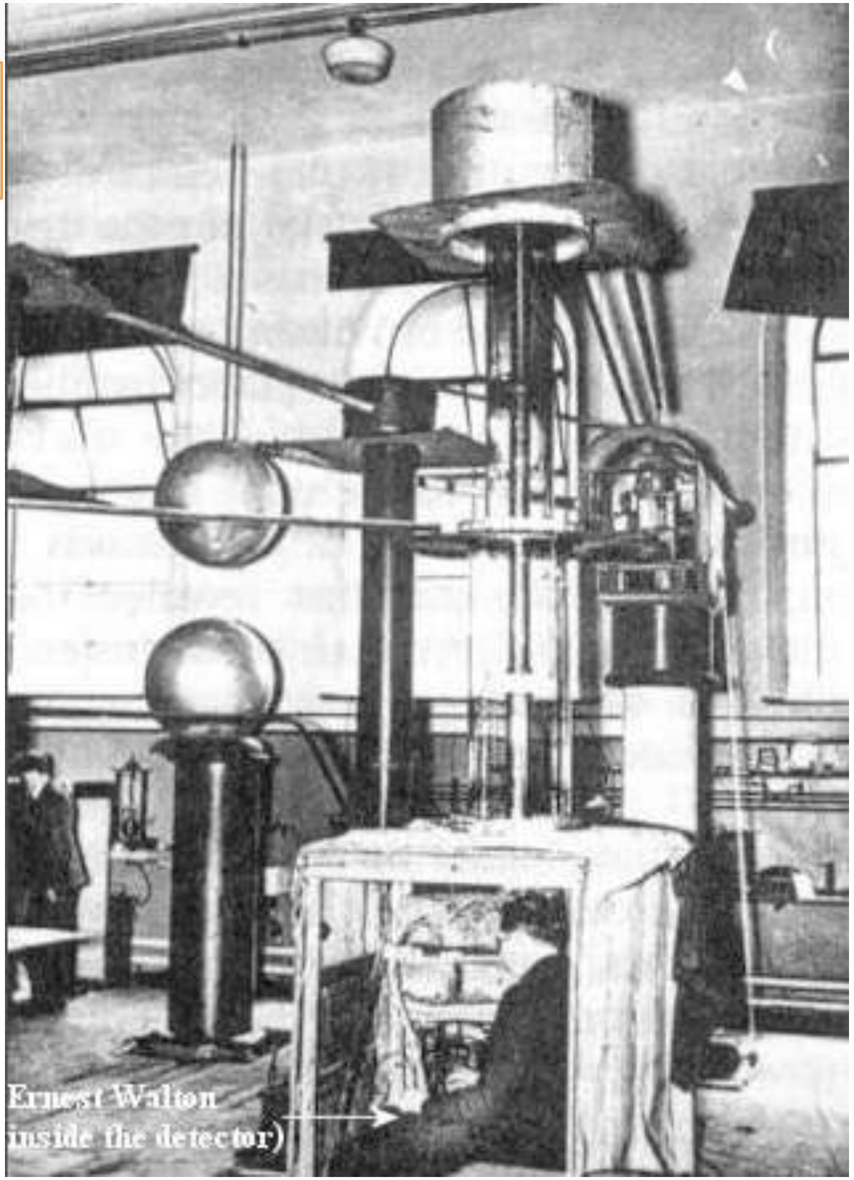
On 14 April 1932 Walton set up the tube and bombarded lithium with high energy protons. He then crawled into the little observation cabin set up under the apparatus and immediately saw scintillations of the fluorescent screen.

The reaction was giving off a particles.



http://www-outreach.phy.cam.ac.uk/camphy/cockcroftwalton/cockcroftwalton9_1.htm

The Nobel Prize in Physics 1951
John Cockcroft, Ernest T.S. Walton



1^{st} root

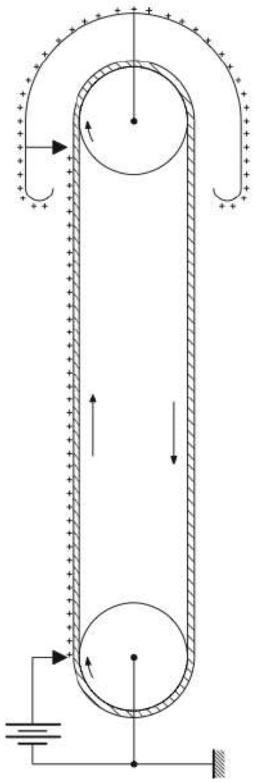
Van de Graaf:
The Van de Graaff generator was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University.

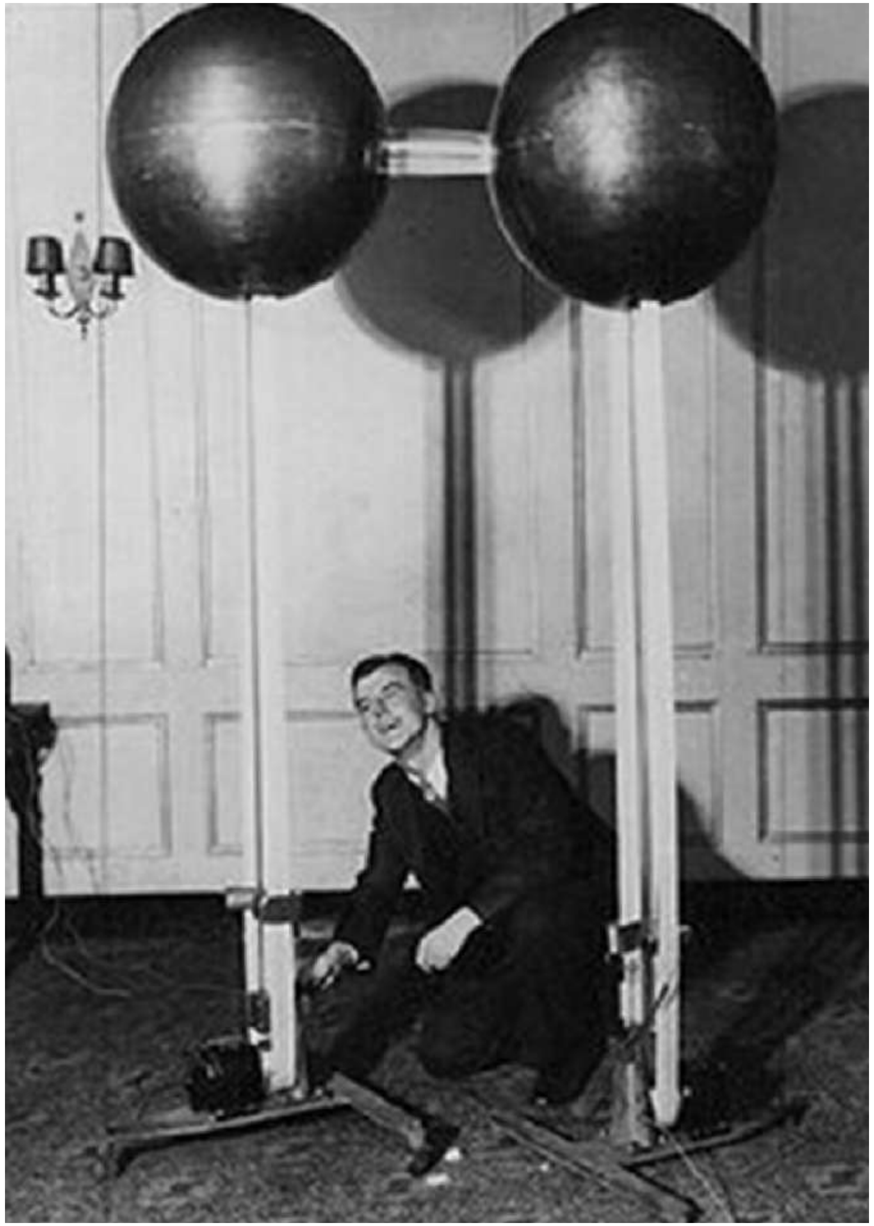
1st root

An electrostatic generator which uses a moving belt to accumulate very high voltages on a hollow metal globe on the top of the stand.

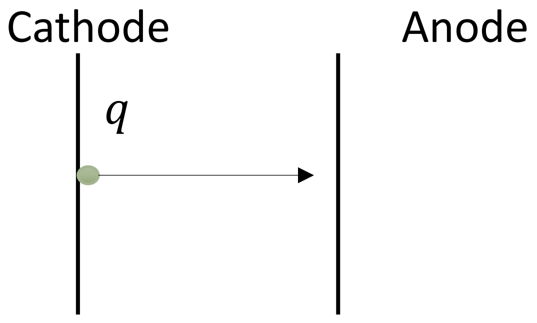
Van de Graaff:
The Van de Graaff generator was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University.

Today, up to ~10MV.





1^{st} root



$$\Delta U = \int_{\vec{r_1}}^{\vec{r_2}} \vec{F} \cdot d\vec{r} = q \int_{\vec{r_1}}^{\vec{r_2}} \vec{E} \cdot d\vec{r}$$

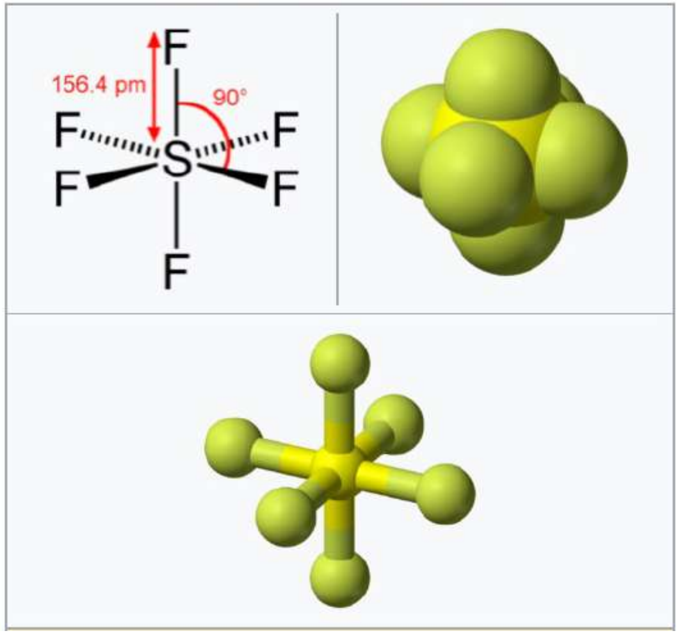
Limits on Electrostatic Accelerators
DC acceleration is limited by high-voltage breakdown

Typical breakdown voltage for a 1cm gap of parallel metal plates

Ambience	Breakdown voltage
Air 1atm	~30 kV
SF6 (Sulfur hexa-fluoride) 1atm	~80 kV
SF6 7atm	~360 kV
Transformer oil	~150 kV
UHV (10^{-5}~10^{-8} Pa)	~220 kV

From K. Takata "Fundamental Concepts of Particle Accelerators"http://research.kek.jp/people/takata/home.html

Sulfur hexafluoride



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

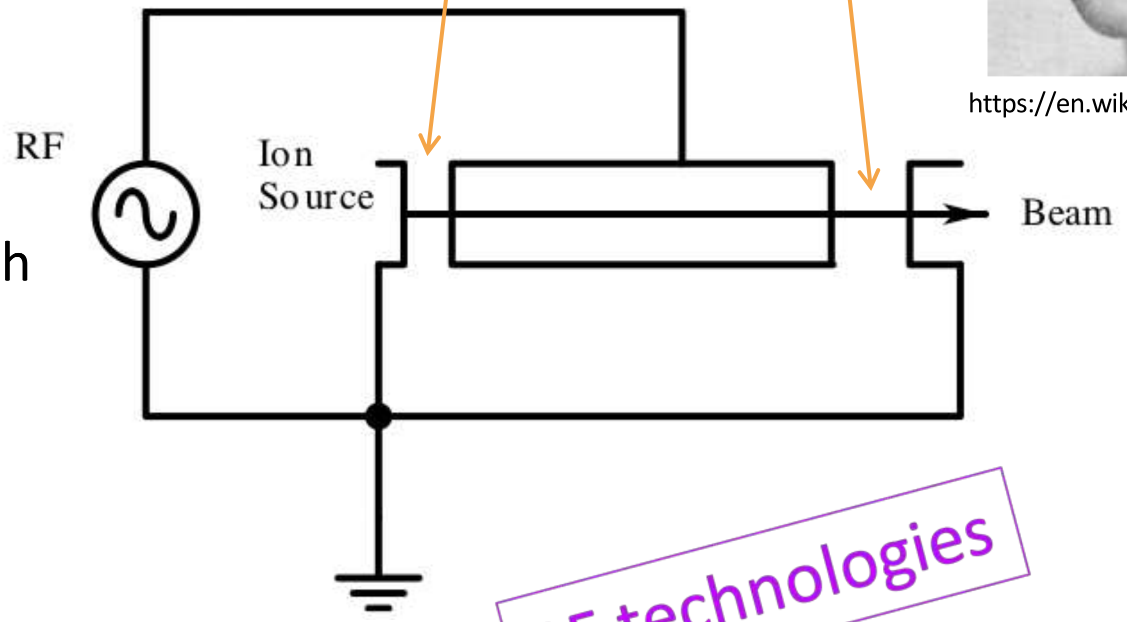
2^{nd} root

Drift tube: From DC to AC

Radio-Frequency "RF" accelerators

- The principle of the acceleration with <u>alternating fields</u> was proposed by G.Ising in 1924.

The particles must be synchronized with the RF fields in the accelerating sections.



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

RF technologies

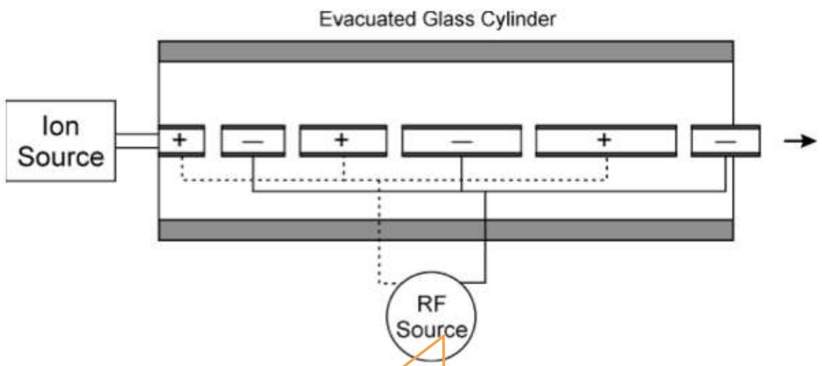
2^{nd} root

Drift tube: From DC to AC

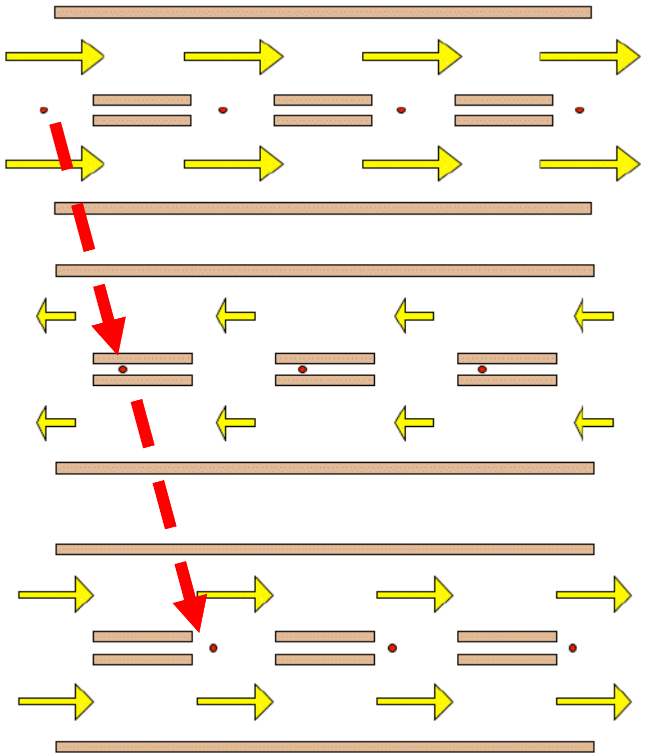
Radio-Frequency "RF" accelerators

- R. Wideröe accelerated alkali ions (K+, Na+) up to 50 keV (25kV × 2) using the accelerator based on alternating fields (1 MHz) and drift tubes in 1928.

Concept of Wideröe accelerator



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



Prototype of the linear accelerators.
The idea of RF acceleration is also inherited to the circular accelerators.

We need longer tubes and gaps as energy increases

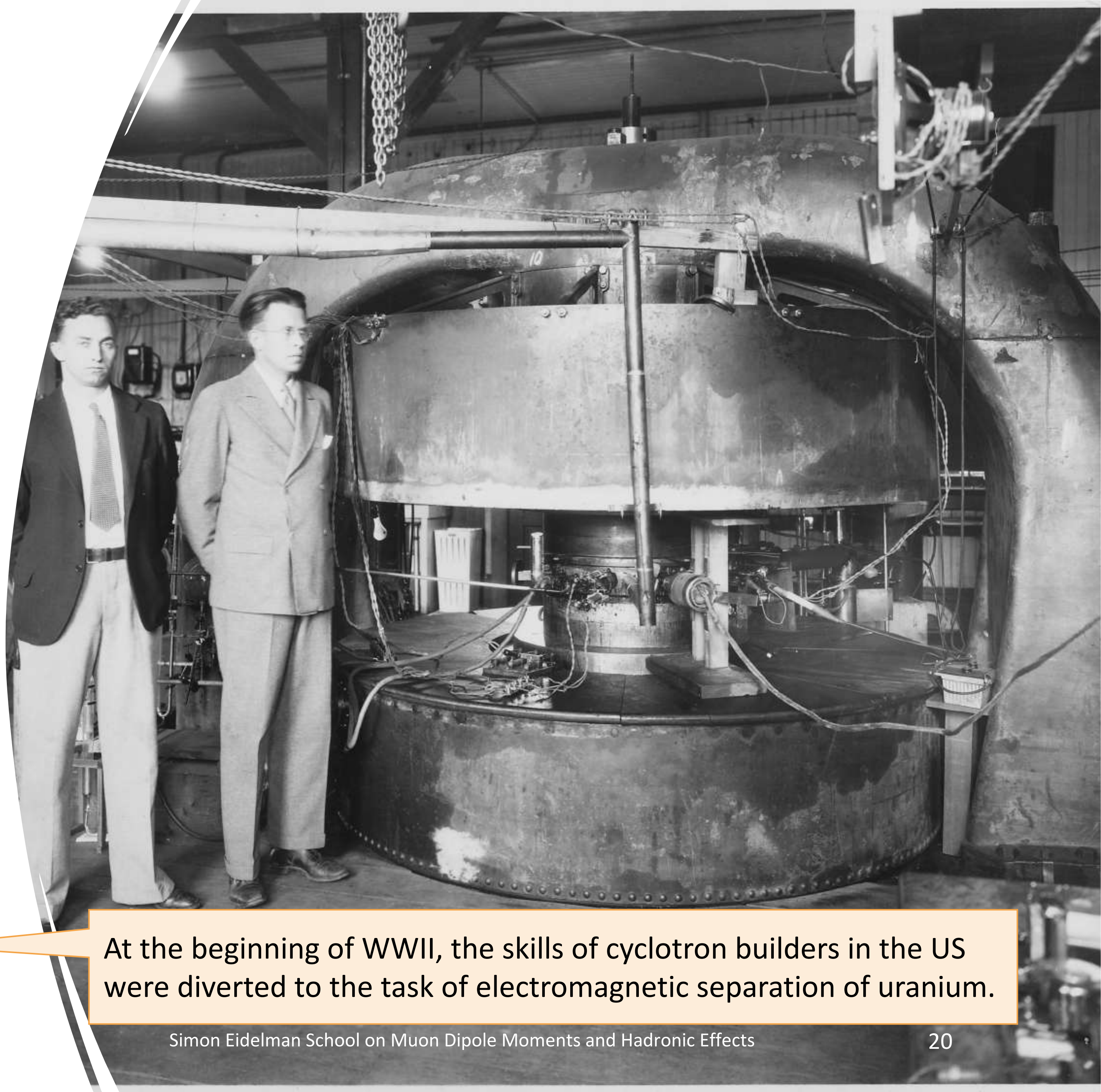
2^{nd} root

Cyclotron: From DC to AC

Radio-Frequency “RF” accelerators

- Wideroe's linear scheme inspired Earnest Lawrence to think about how one could use the same potential multiple times instead of just once.

- Using a magnetic field to bend charged particles into circular trajectories and thus pass them through the same accelerating region over and over again. (Lawrence’s cyclotron, 1931)



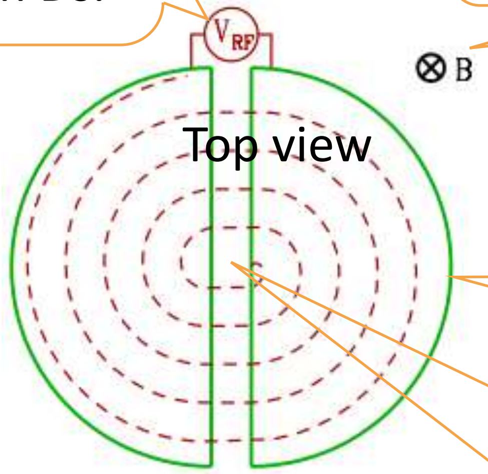
At the beginning of WWII, the skills of cyclotron builders in the US were diverted to the task of electromagnetic separation of uranium.

Cyclotron: How it works

1st circular accelerator (TOP View)

(2) An oscillating voltage was applied to produce an electric field across the gap between Ds.

(0) Now we need magnetic field for controlling the orbit



(1) A cyclotron consisted of two large dipole magnets (Ds) designed to produce a semi-circular region of uniform magnetic field.

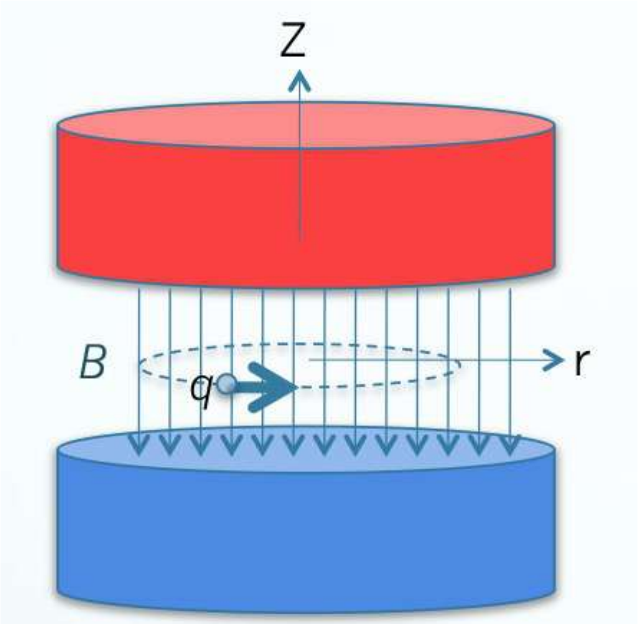
The Lorentz Force
$\vec{F} = q\vec{v}\times\vec{B}$

(4) The electric field in the gap then accelerates the particles as they pass across it.

(3) Particles injected into the magnetic field region of a D trace out a semicircular path until they reach the gap.

Cyclotron: How it works

Suppose uniform magnetic induction B is applied perpendicular to the velocity v of a particle with mass m, charge q:
The Lorentz Force $\vec{F} = q\vec{v}\times\vec{B}$ produces a circular track.
Relationship between momentum p and radius r:



For non-relativistic case:
$p = mv$

Cyclotron frequency f_{rev} and radius r:

$$f_{rev} = {}^{v}/_{2\pi r} = {}^{qB}/_{2\pi m}$$ ←frequency is independent of velocity

$$r = {}^{mv}/_{qB}$$ ←radius is proportional to velocity

The particles can be excited at a fixed RF frequency and the particles will remain in resonance throughout acceleration.

2^{nd} root

Limits on Cyclotron
When particles become relativistic the mass of the particle increases as

$$m \rightarrow m\gamma$$

which results in decrease of $\omega_{rev}(2\pi f_{rev})$

Some attempts made:

- Magnetic field distribution
- Changing RF frequency so that …

But no drastic improvement beyond 20 MeV with protons.

~~The particles can be excited at a fixed RF frequency and the particles will remain in resonance throughout acceleration.~~

Livingston's curve : Energy vs. time

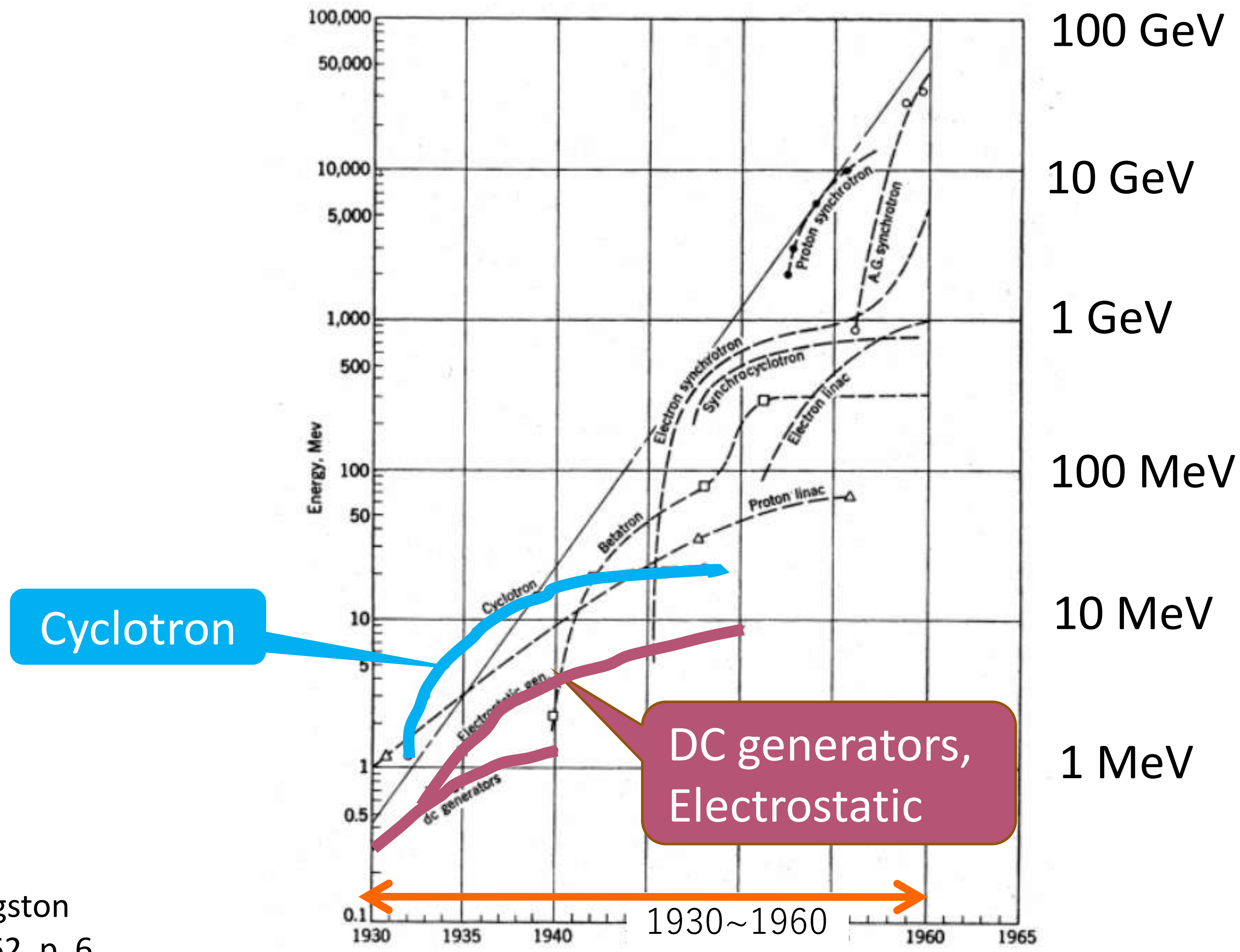
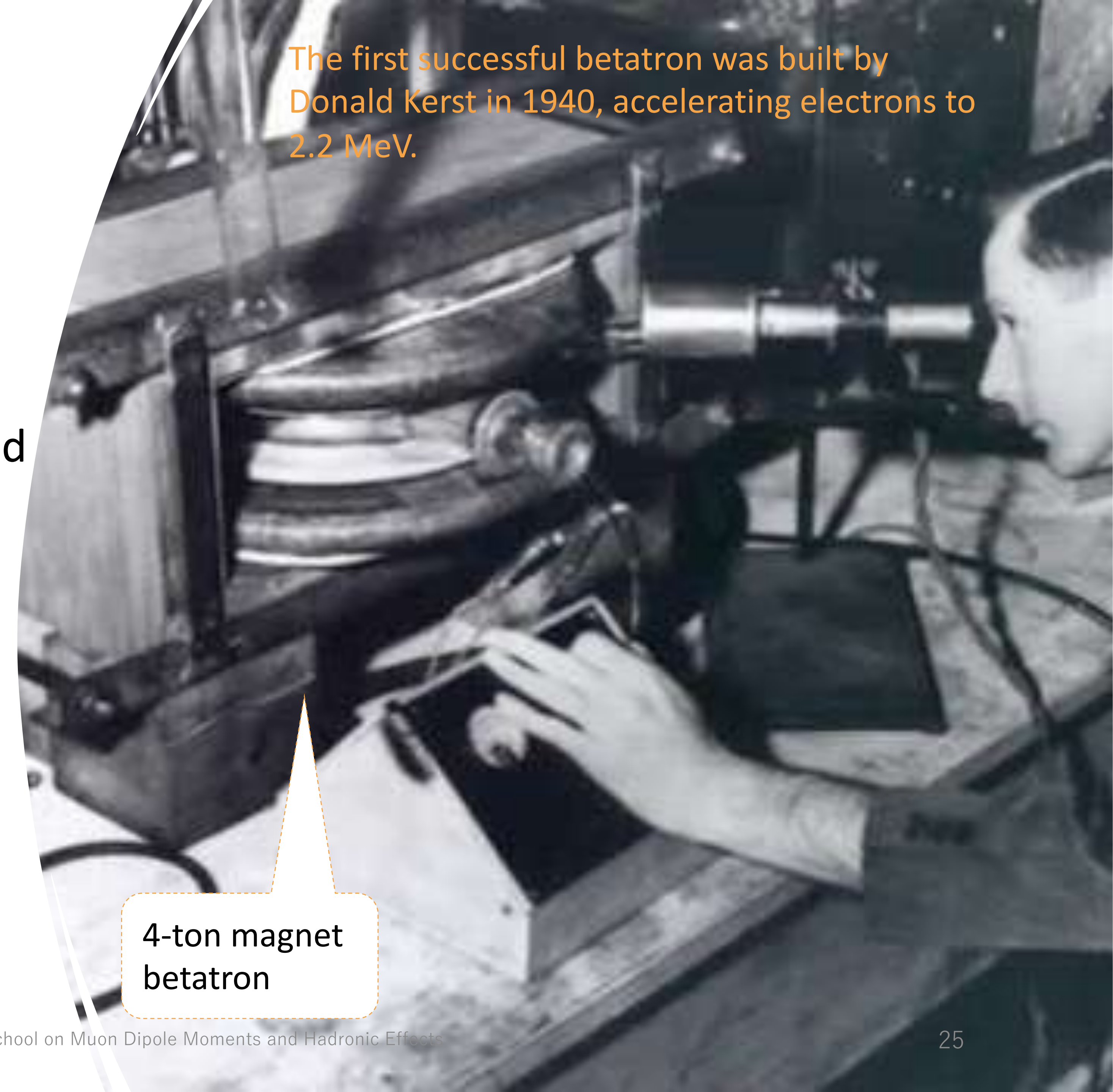


Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

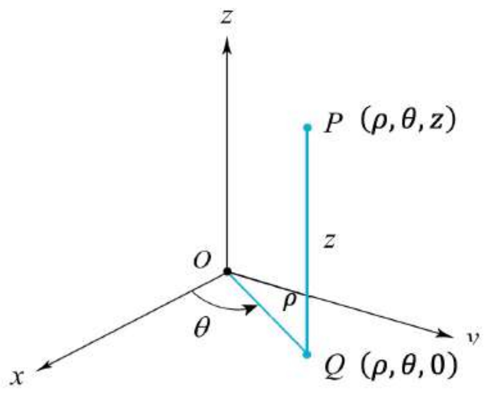
From PARTICLE ACCELERATORS by Livingston and John P. Blewett, 1962, p. 6.

3^{rd} root

Betatron: use of electric field induced by magnetic field



The first successful betatron was built by Donald Kerst in 1940, accelerating electrons to 2.2 MeV.



Betatron:

$$\oint \vec{E} \cdot d\vec{l} = \int \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = -\frac{\partial \Phi}{\partial t}$$

The electric field induced by a varying magnetic field is used for acceleration

$$2\pi\rho E_\theta = -\frac{\partial \Phi}{\partial t} = \pi\rho^2 \frac{d\overline{B_z}}{dt}$$

$$\frac{dp}{dt} = -qE_\theta = \frac{1}{2} q\rho \frac{d\overline{B_z}}{dt} \quad (1)$$

$$F_\theta = qE_\theta = \frac{d(mv)}{dt} = \frac{d}{dt}(q\rho B_z) = q\rho \frac{dB_z}{dt} \quad (2)$$

From (1) and (2) we obtain the condition for constant orbit for betatron.

$$\frac{dB_z}{dt} = \frac{1}{2} \frac{d\overline{B_z}}{dt}$$

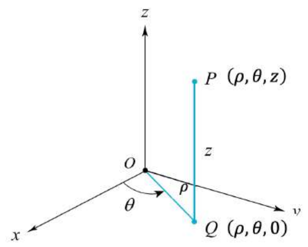
→The magnetic field at the orbit must be half the average magnetic field over its circular cross section

“2:1 rule” or “Betatron two for one condition”

Not dependent on mass.
Good for relativistic (light mass) particles!

Different from Cyclotron

Non RF

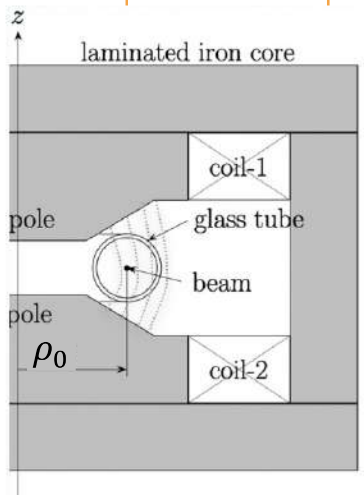


Betatron

When magnetic field is written with "field index" n as

$$B(\rho) = B_0\rho^{-n}$$

$$n \equiv -\frac{\Delta B/B}{\Delta\rho/\rho}$$



And tweaking the equations, we obtain eq. of motion for hor. direction x as

$$\ddot{x} + \omega^2(1-n)x = 0$$

for the vertical direction z as

$$\ddot{z} + \omega^2 nz = 0$$

The oscillation is stable if 0<n<1 , in both horizontal and vertical directions.

The change in the magnetic field is slow, thus the change in momentum upon the effect of the azimuthal induction electric field is weak. → "weak focusing"

Betatron

From the analysis of transvers
oscillations, we

- obtained an understanding of the orbit
- developed the theory of betatron oscillations of today

Betatron oscillation

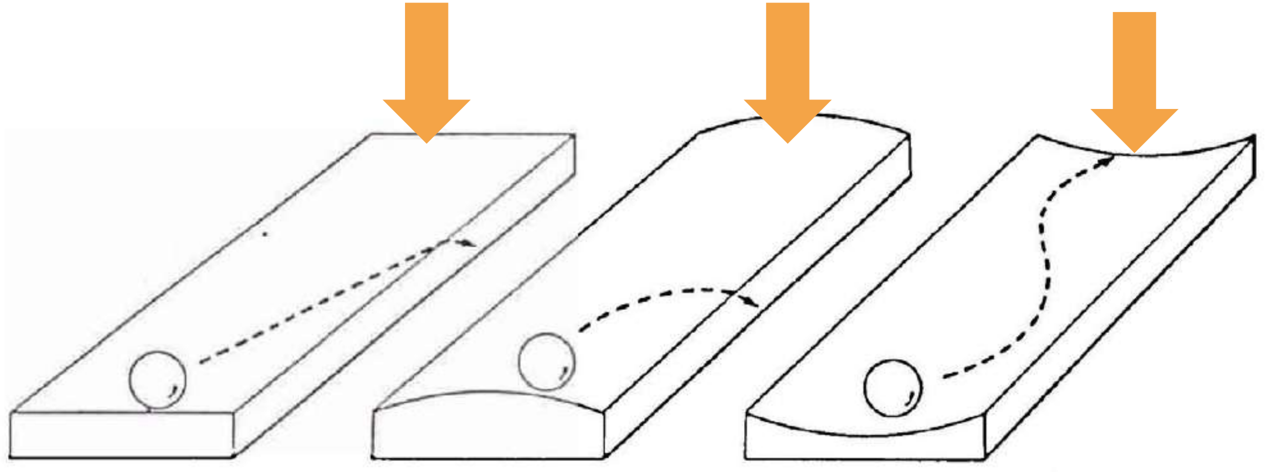


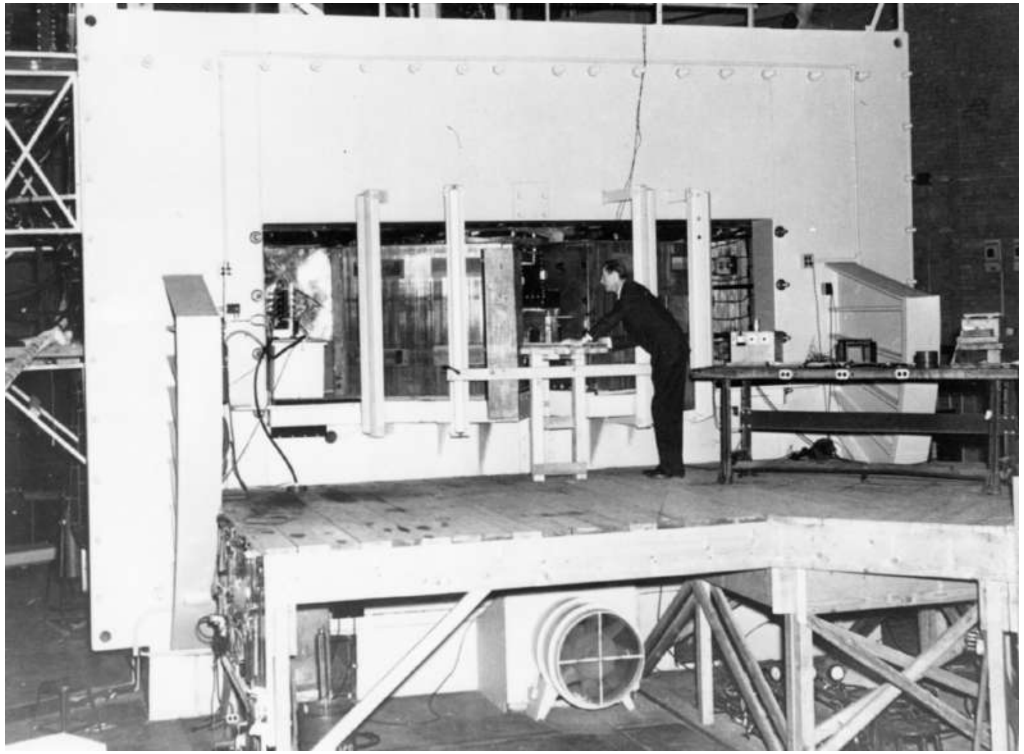
Fig. 2-1. Bowling alley analogy of systems of forces which produce neutral, unstable, or stable orbits.

$B(\rho) = B_0 \rho^{-n}$

- $n = 0$ → A uniform field with no focusing
- $n > 1$ → B cannot provide enough centripetal force to keep the particles in a circular orbit, unstable.
- $0 < n < 1$ → B can provide restoring forces, results in a stable orbit.

Betatron

- Betatron: Limit
  - You need a large magnet to generate magnetic field to cover the beam path.
  - Reachable energy is limited by the size of the magnet yoke.



Operation of a 300-Mev Betatron*

D. W. Kerst, G. D. Adams, H. W. Koch,† and C. S. Robinson
Physics Department, University of Illinois, Urbana, Illinois
March 20, 1950

GEIGER counter yield trials of our new betatron were successful on the first attempt. After a few minutes of operation, the yield was read on an ionization chamber. The present yield which can be held at 315 Mev is about 1000 r/min. at one meter behind ⅛-in. Pb at 6 PPS and 80-kv injection. Injecting with a rising voltage wave form has increased the output

"The flux magnet contains 275 tons and the six-field magnets contain 11 tons each"

pensation for the 9 percent orbital radiation loss is achieved by supplying a shaped flux pulse in a separate package of iron which links the orbit but not the flux-forcing circuit. This peaked flux pulse is also used to expand the electron beam out to the x-ray target.

3rd root

Betatron: use of electric field induced by magnetic field

A circular accelerator

- dedicated to electrons (beta particles) and
- uses a completely different principle than conventional accelerators.

Betatrons are not used much today (in high energy experiments), but we learned

- their accelerating principle and
- focusing conditions in a magnetic field

Livingston's curve : Energy vs. time

Discovery of “strong focusing”

1949 by N. Christofilos
1952 by E.D.Courant, M.S.Livingston and H.Snyder

→Synchrotron

☹ does not work well for relativistic particles

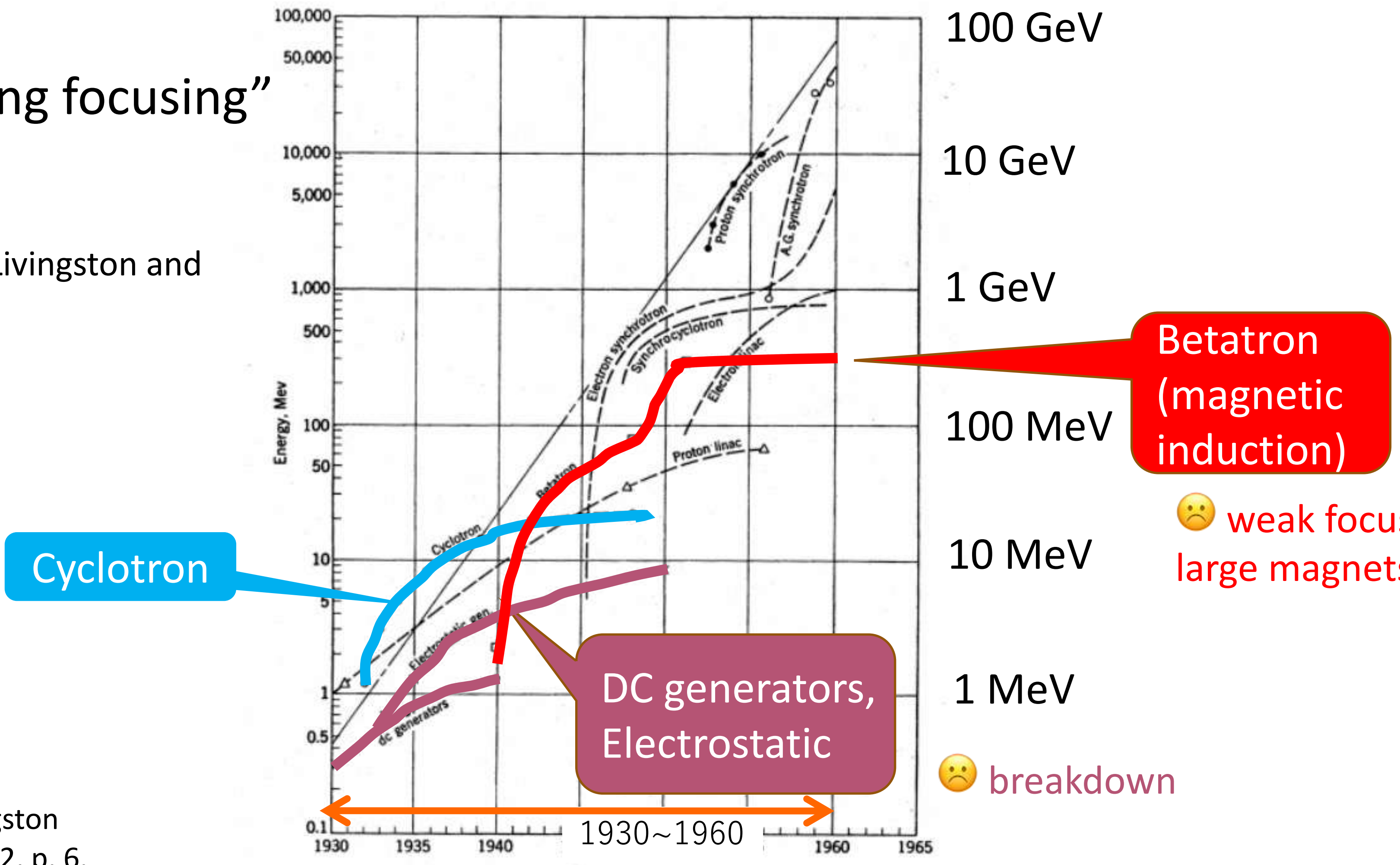


Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

☹ weak focusing, large magnets needed

From PARTICLE ACCELERATORS by Livingston and John P. Blewett, 1962, p. 6.

Synchrotron

1. Strong focusing

2. Bunch and Phase stability

The synchrotron is one of the first accelerator concepts to enable the construction of large-scale facilities, since bending, beam focusing and acceleration can be separated into different components.

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

Synchrotron

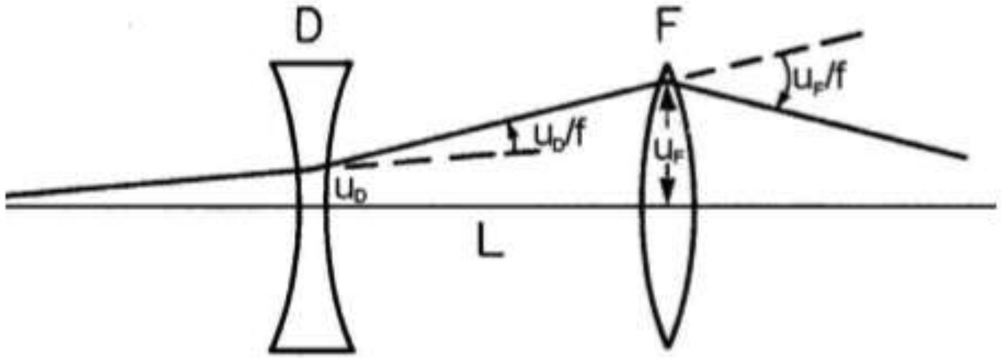
1. Strong focusing

also known as
Alternating-Gradient (AG)
focusing

For weak focusing, there is a constraint on n as
$0 < n < 1$

$$n \equiv \frac{\Delta B/B}{\Delta r/r} \quad (fied\ index)$$

Analogy with optical thin lens



$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{1}{f_1 f_2}$$

$$\therefore F = \frac{f_1 f_2}{f_1 + f_2 - L}$$

Obtaining a net focus by combining F- and D- magnets
is called “strong focus”,
as no constraints on the field index n.

Entire orbit does not need to be covered by magnets😀.
Each magnet can be smaller.

If $f_1 = -f_2 \equiv -f$

The overall focal length is

$$F = \frac{f_2}{L} > 0$$

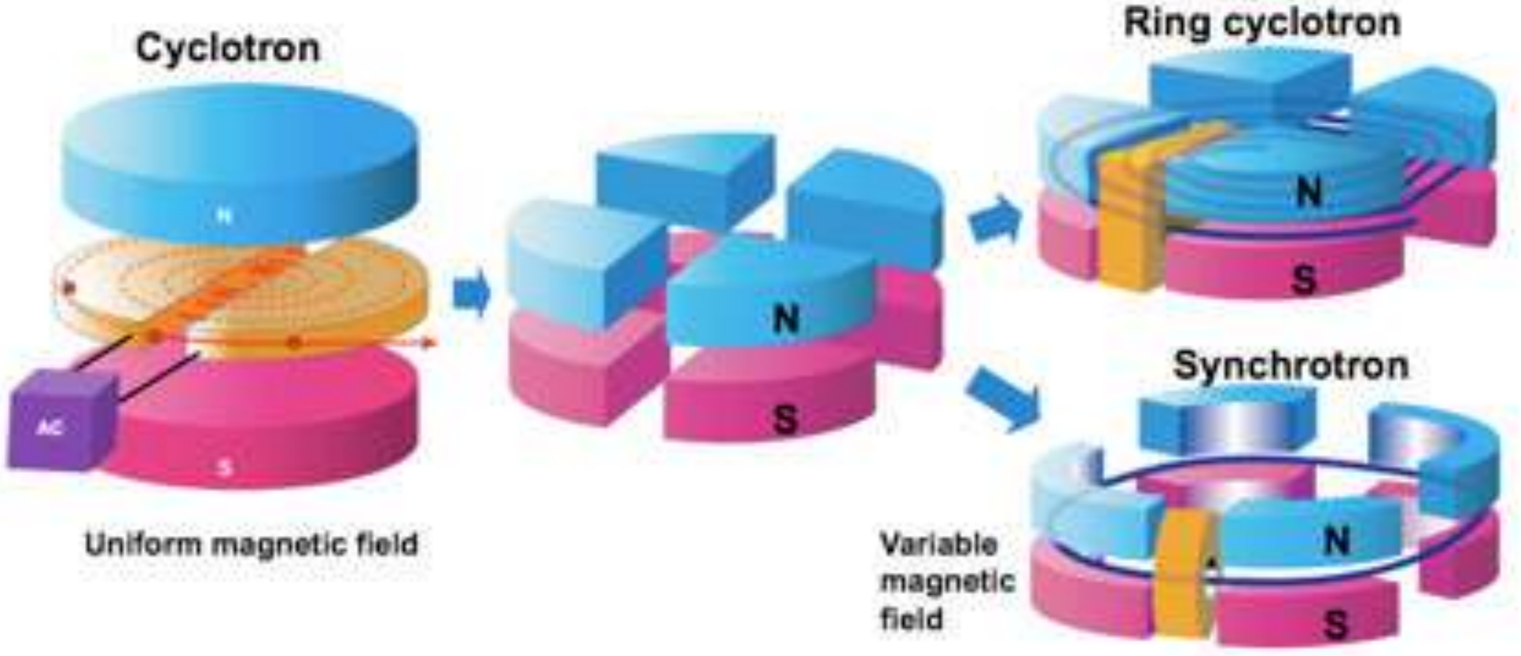
Since it is positive, net focus

Synchrotron

Synchrotron: concept of Strong focusing, also known as Alternating-Gradient (AG) focusing

For weak focusing, there is a constraint on n as $0 < n < 1$

“Advanced”

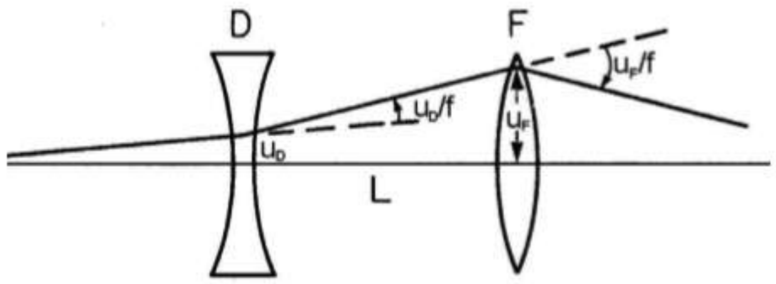


https://www2.kek.jp/proffice/archives/feature/2010/DigitalAccelerator.html

- Ring accelerator evolved from cyclotron in which particles spirals out as they are accelerated by alternating current voltage in a uniform magnetic field.
- Synchrotron confines beam orbit at a fixed radius.

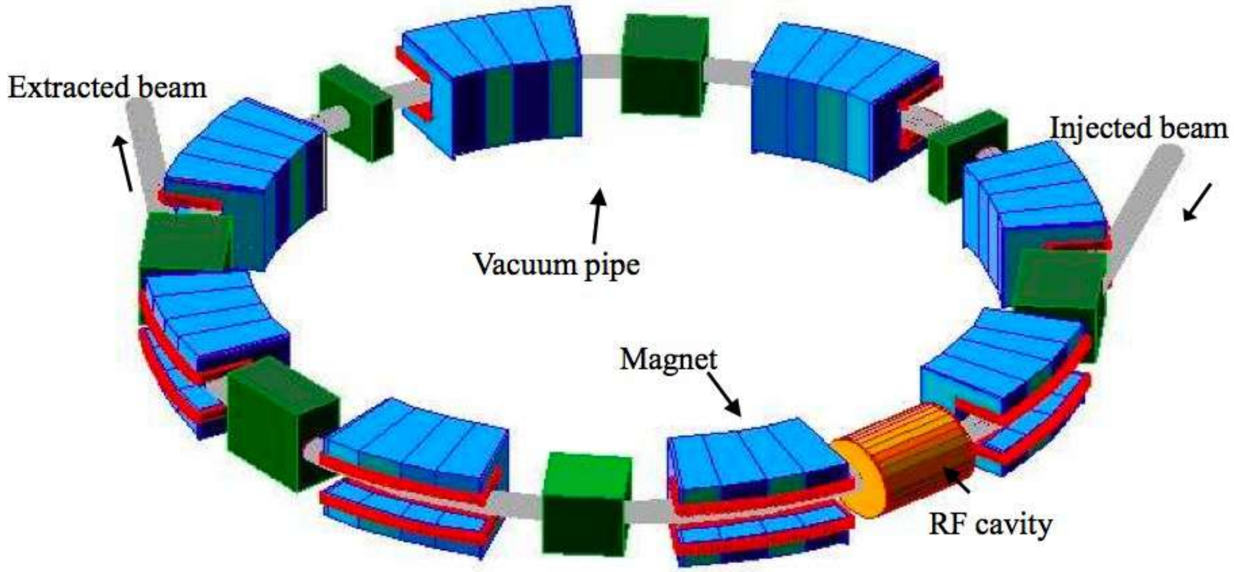
Synchrotron

Synchrotron:
Alternating-Gradient (AG) focusing



Synchrotron basic components

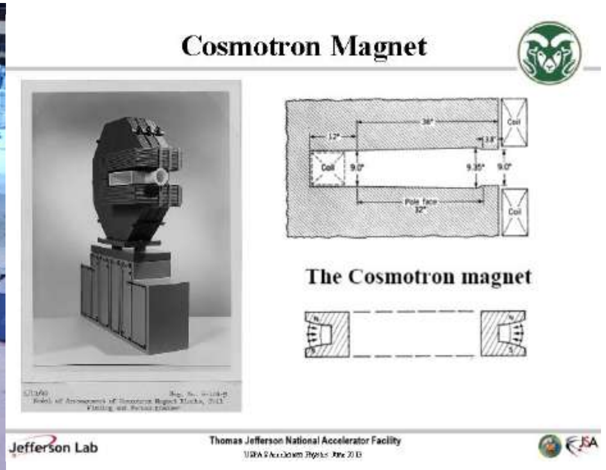
Vacuum pipes
To cover the beam passage



Magnets
Dipole magnets for bending
Quadrupole magnets for focusing

RF cavities
To accelerate/compensate for lost energy

Strong focus vs. weak focus



The strong-focusing principle had a big impact on the accelerator design

10 times higher energy was obtained with <u>only</u> 2 times larger amount of steel

Energy

Weak focus

strong focus

Steel

3.3GeV Cosmotron

33GeV AGS

33GeV AGS

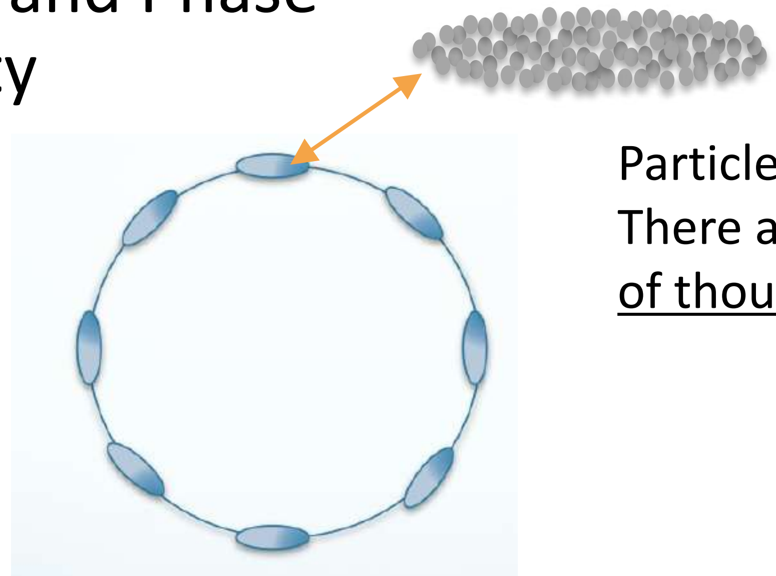
http://www.bnl.gov/bnlweb/history/focusing.asp

Synchrotron

2. Bunch and Phase stability

The RF field has a restoring force at a certain phase, around which asynchronous particles be captured, that is to say "bunched."

→ This enables a stable, continuous acceleration of the whole particles in a bunch to high energies.



Particles are "bunched"
There are many particles in a bunch, circulating many turns tens of thousands, for example.

"Storage ring"

Circular accelerators based on this principle are called "synchrotron."

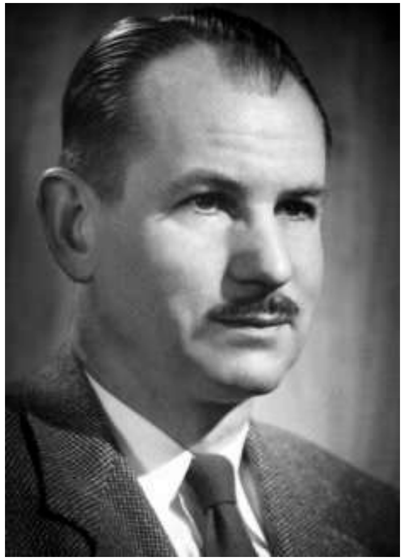
Discovery of Phase stability:

Synchrotron

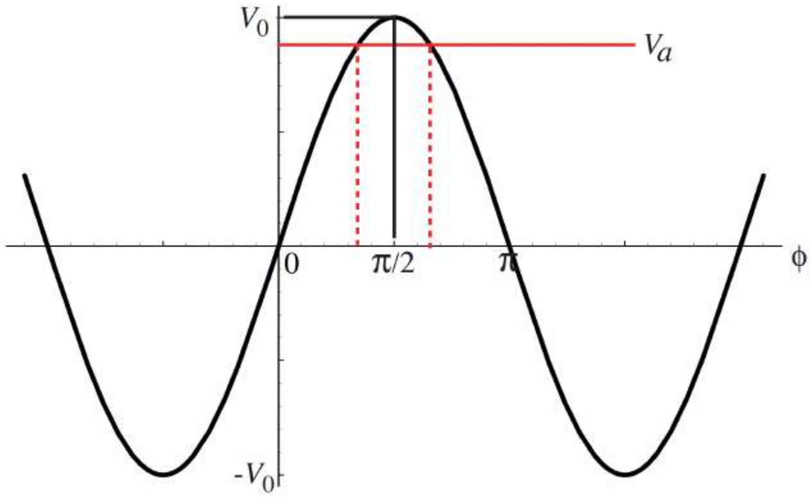
2. Bunch and Phase stability

Breakthrough in 1945
Phase stability principle
Vladimir Veksler (1944) and
Edwin M. McMillan (1945)
proposed Synchrotron

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



https://www.nobelprize.org/prizes/chemistry/1951/mcmillan/biographical/



Sinusoidal RF Wave

Phase stability
The RF field has a “restoring force” at a certain phase

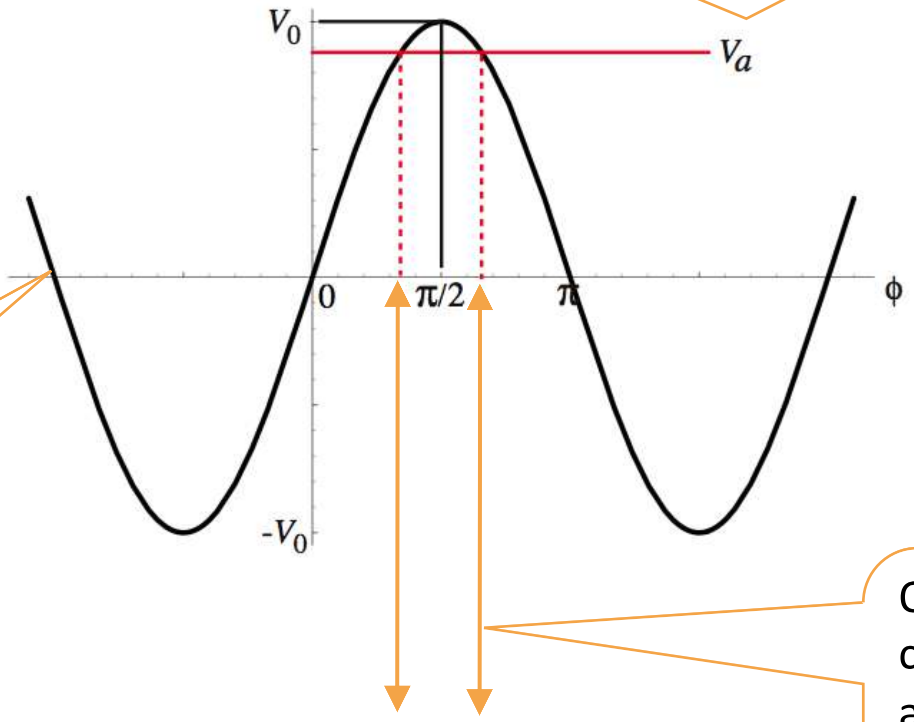
The particles stay “synchronous”

Synchrotron

2. Bunch and Phase stability

There are two ϕ which satisfy $V_a = V_0 \sin \phi$ in one RF period

when
V_a is acceleration voltage



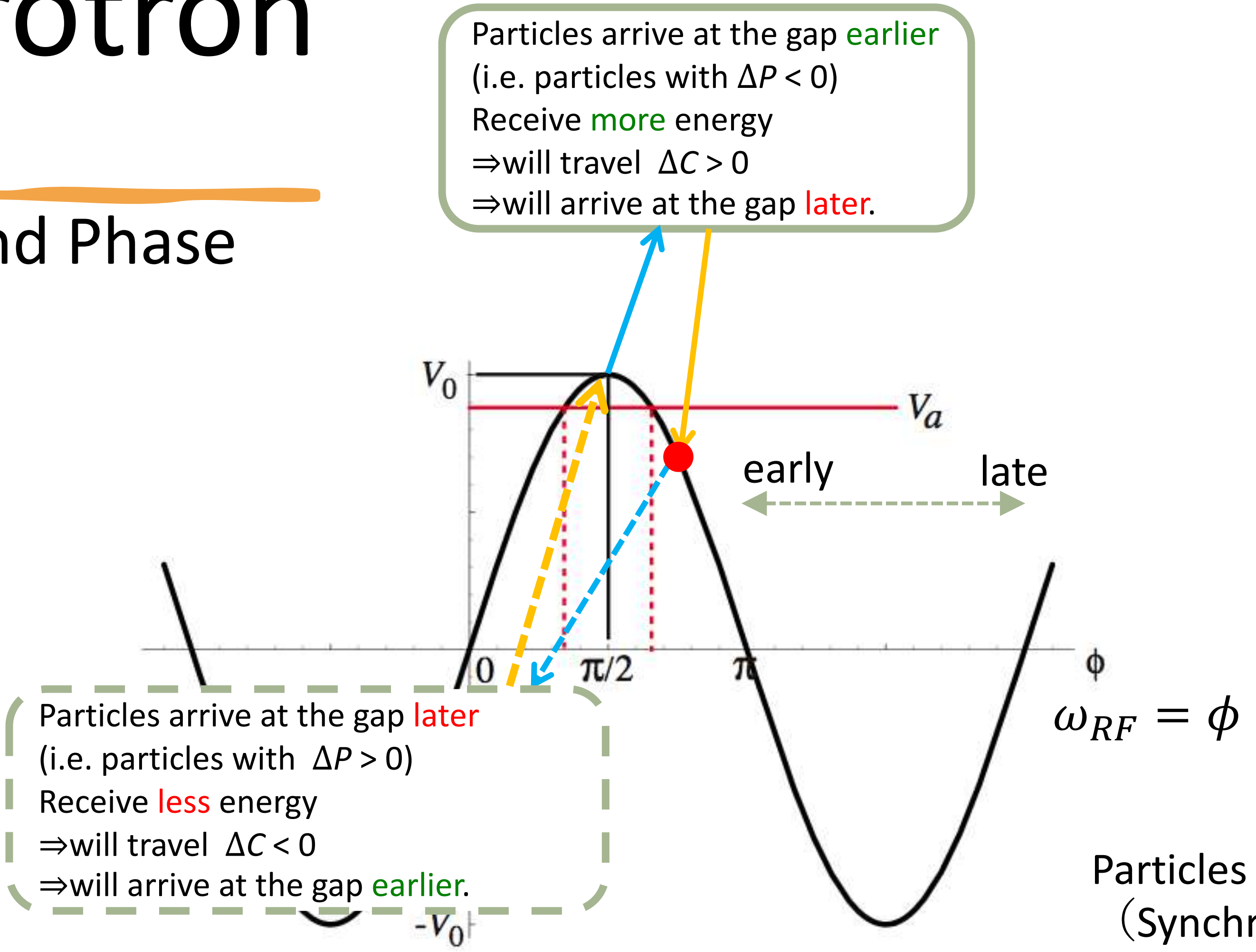
Assume RF electric field $V = V_0 \sin \omega t$

Only one of them can capture particles and make oscillations around the phase.

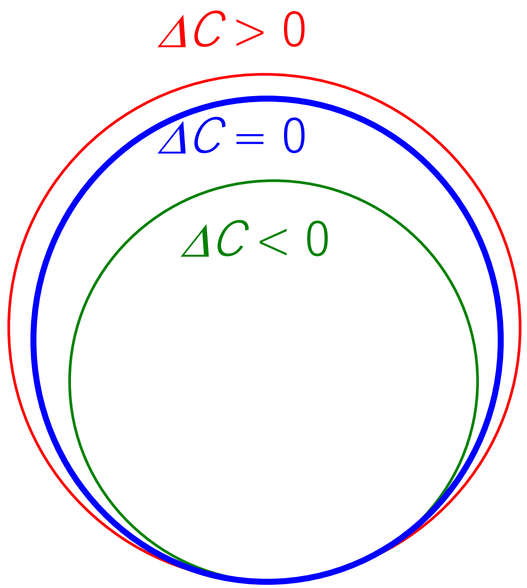
Phase stability: “restoring force” at a certain phase

Synchrotron

2. Bunch and Phase stability



For the case where particles with $\Delta P > 0$ travel $\Delta C > 0$

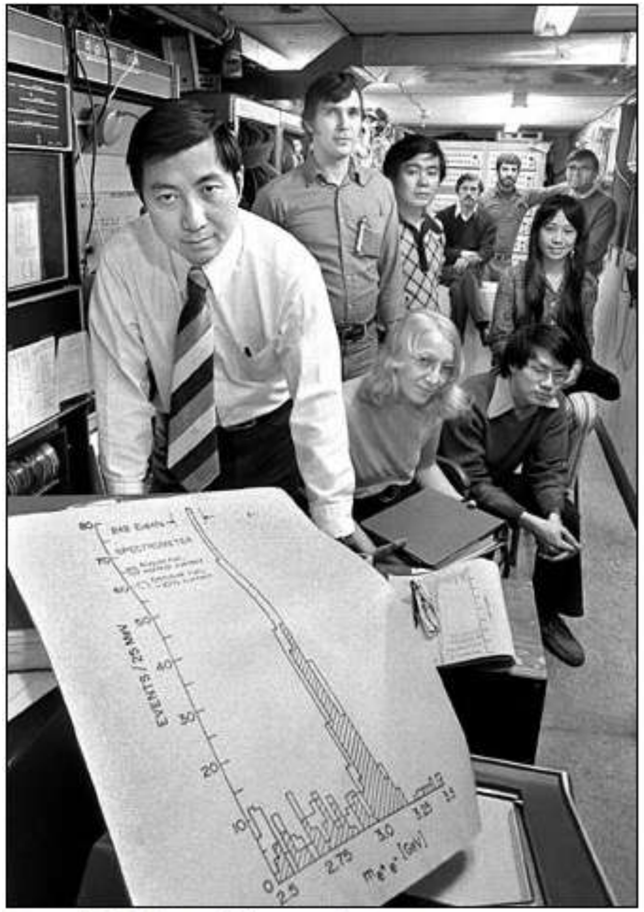


Example of a circular orbit

Particles oscillations around ϕ_s
（Synchrotron phase）

Alternating gradient synchrotron (AGS)

http://www.bnl.gov/bnlweb/history/nobel/nobel_76.asp



Samuel C.C. Ting and his research team.

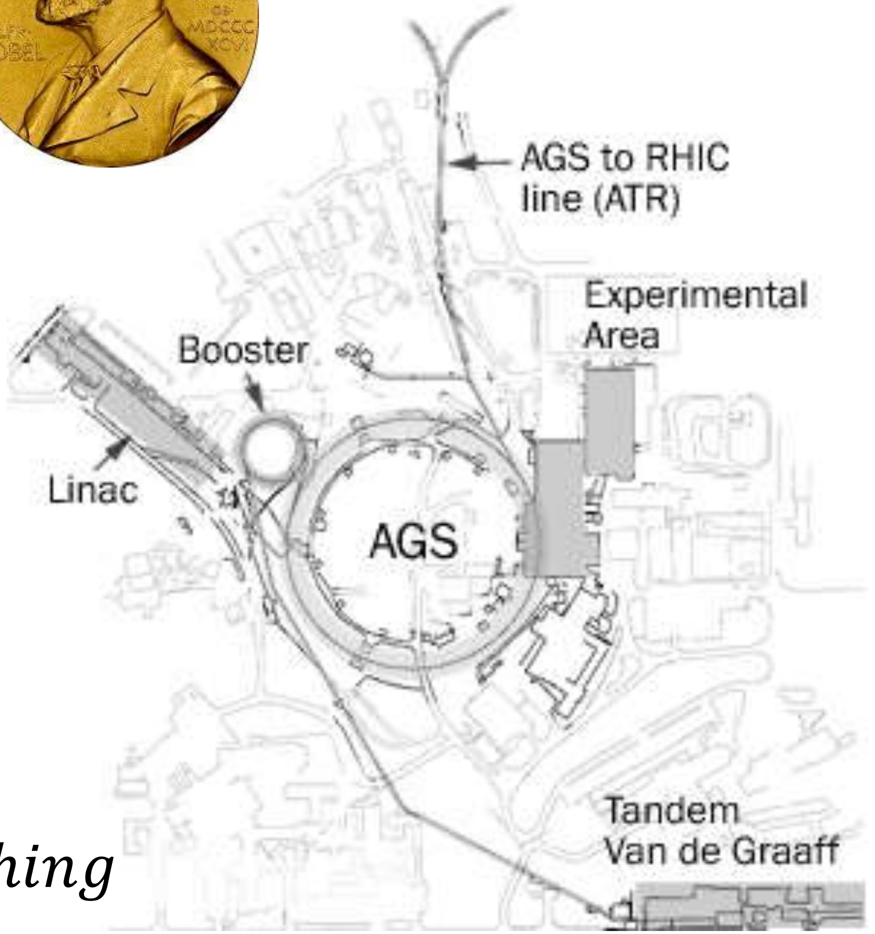
Discovery of the J/psi Particle

The 1976 Nobel Prize in physics was shared by a Massachusetts Institute of Technology researcher who used Brookhaven's Alternating Gradient Synchrotron (AGS) to discover a new particle and confirm the existence of the charmed quark.

Samuel C.C. Ting (at left, with his research team) was credited for finding what he called the "J" particle, the same particle as the "psi" found at nearly the same time at the Stanford Linear Accelerator Center by a group led by Burton Richter. The particle is now known as the J/psi.

Ting's experiment took advantage of the AGS's high-intensity proton beams, which bombarded a stationary target to produce showers of particles that could be detected by complex detectors. A strong peak in electron and positron production at an energy of 3.1 billion electron volts (GeV) led Ting to suspect the presence of a new particle, the same one found by Richter.

Their discoveries not only won the Nobel Prize; they also helped confirm the existence of the charmed quark -- the J/psi is composed of a charmed quark bound to its antiquark.



$$p + Be \rightarrow J/\psi + anything$$

28 GeV protons on a beryllium target

Livingston's curve : Energy vs. time

Discovery of "strong focusing"
1949 by N. Christofilos
1952 by E.D.Courant,
M.S.Livingston and H.Snyder

→Synchrotron

☹ does not work well for relativistic particles

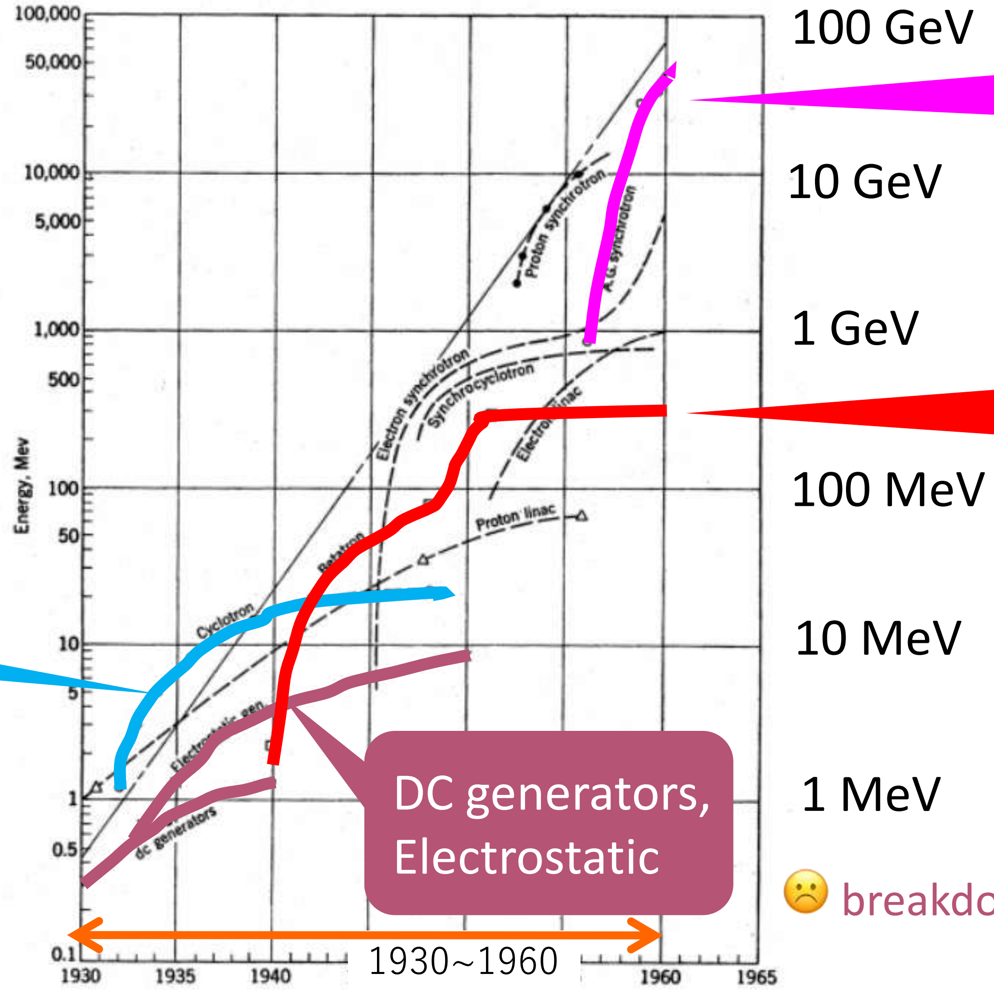


Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

☹ weak focusing, large magnets needed

☹ breakdown

From PARTICLE ACCELERATORS by Livingston and John P. Blewett, 1962, p. 6.

Brief history and inventions before 1960

Collider

Cyclotron
- Multiple acceleration by RF, Orbit changes with energy
- Entire orbit covered by magnets
- Synchronization becomes difficult as particles become relativistic.

Discovery of <u>Phase stability principle</u> in1945
→ Synchronization issue is solved.

Betatron
- Acceleration by magnetic induction
- <u>Constant orbit</u>
- Entire orbit covered by magnets

Discovery of <u>Strong focusing</u> In 1952

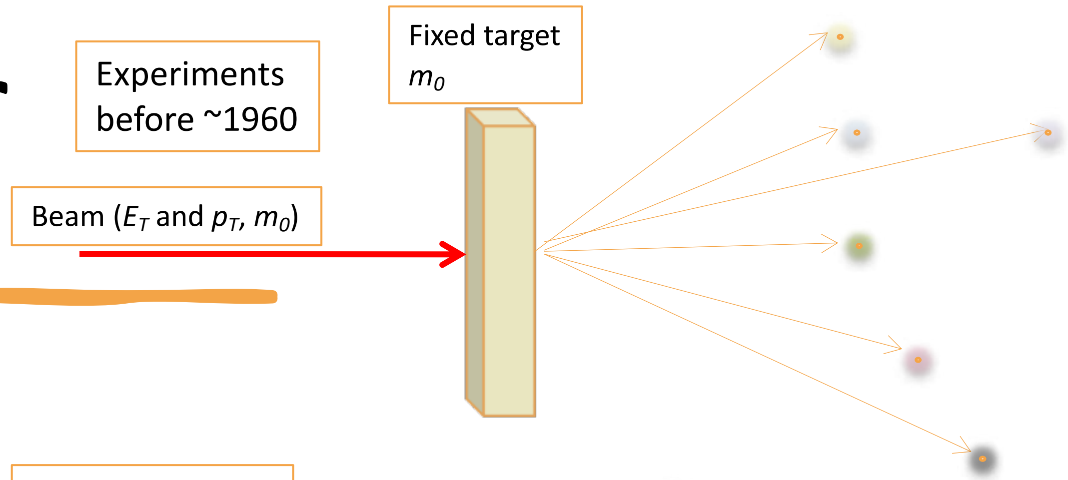
Orbit stability/theory
Betatron oscillation, <u>Weak focusing</u>
We learned a lot from Betatron

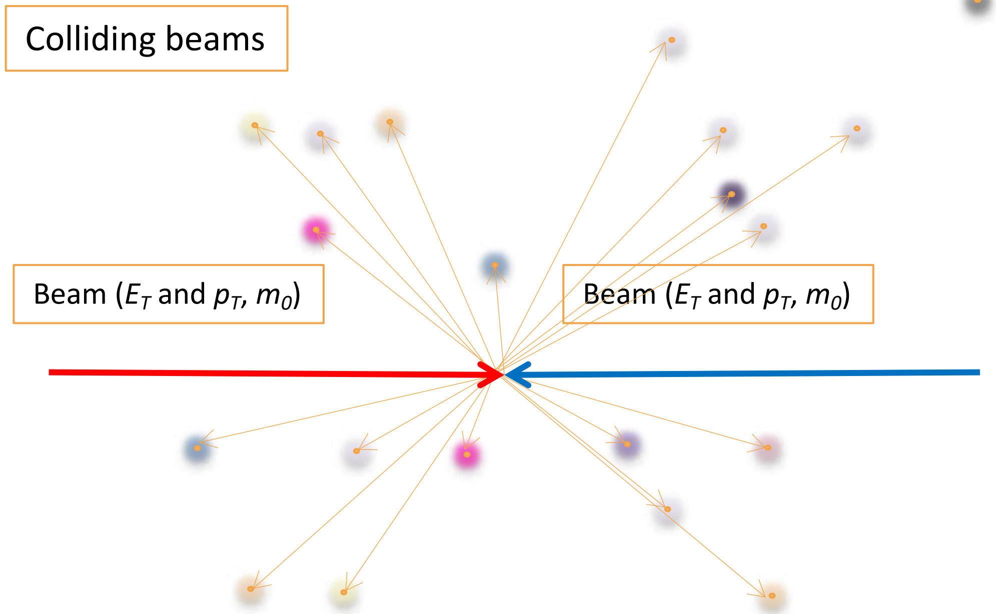
Birth of <u>Synchrotron</u>
- Entire orbit is <u>not</u> needed to be covered by magnets.
- Can reach much higher energy >10 GeV

→ Can go Even higher in energy? Can we get larger $E_{c.m.}$?

Collider

Collider





$$E_T = (1+\gamma)mc^2$$
$$P_T = \beta\gamma m_0 c$$
$$\therefore -E_{C.M.}^2 = (P_T c)^2 - E_T^2$$
$$= (\beta\gamma m_0 c \cdot c)^2 - [(1+\gamma)m_0 c^2]^2$$
$$= -2(1+\gamma)(m_0 c^2)^2$$
$$\therefore E_{C.M.} = \sqrt{2(1+\gamma)}m_0 c^2 \approx \sqrt{2\gamma}m_0 c^2$$

$$E_{C.M.} = 2\gamma m_0 c^2 > \sqrt{2\gamma}m_0 c^2$$

collider

Fixed target

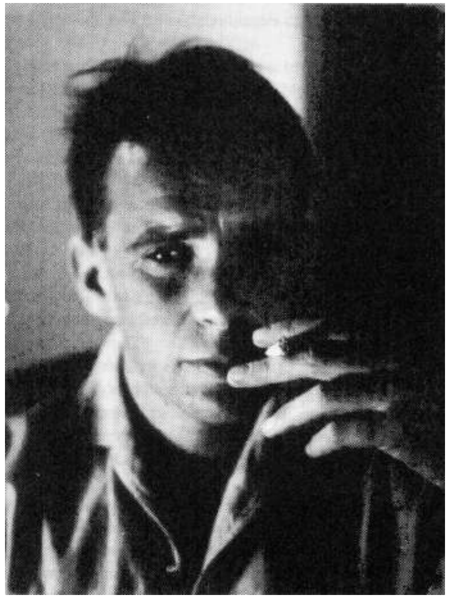
Collider🙂
Higher energy than fixed target

Collider😔
Collision rate is lower

The 1st collider (e^-e^+):AdA
(Anello di Accumulazione) and happened to be Bruno Touschek's aunt's name

Collider

Collider:
1st collider "AdA"



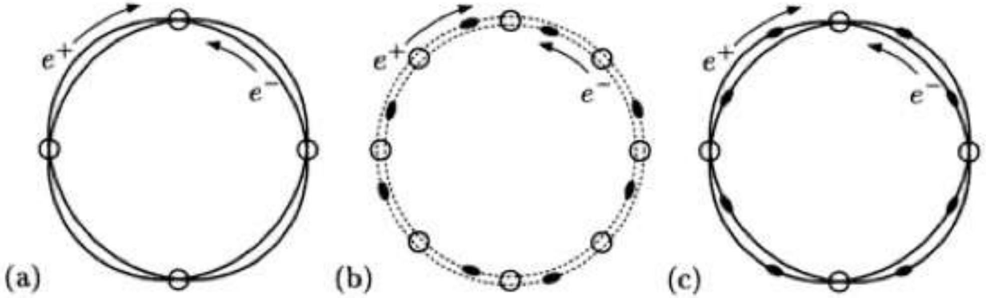


Fig. 1.11. (a) Beam routing. Small distortions to the circular trajectories make the two beams overlap only at a few selected places. The small circles denote the collision sites, at which the detectors will be aimed. (b) Beam bunching. Here particles come in concentrated volleys or "bunches" (the grey blobs); being evenly spaced, the bunches from the two beams will meet only at certain regular intervals. (c) By combining routing and bunching, one can further customize where and when collisions may take place.

Collision-based computing, Andrew Adamatzky (2002)

ADONE (big AdA) 1969
C=105 m, E_{cm} < 3 GeV
no J/ψ (3.1 GeV)...

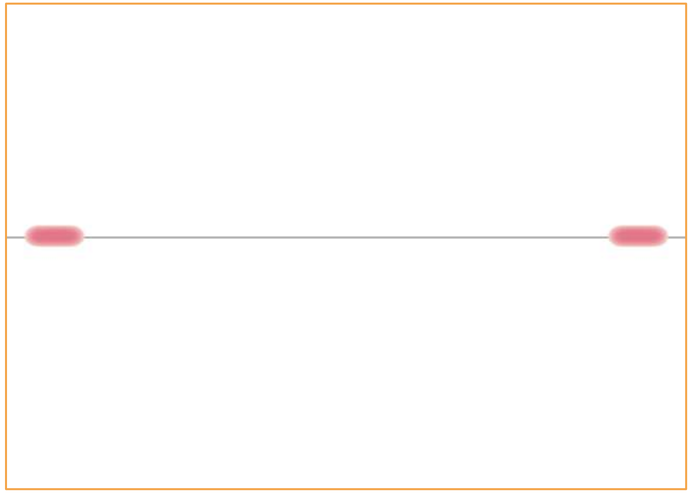
Orbit radius = 65 cm,
250MeV × 250 MeV
Operated 1961-1964.
Many feasibility experiments with this working model.
Followed by a full-size collider ADONE

Era of large circular colliders : Energy Frontier

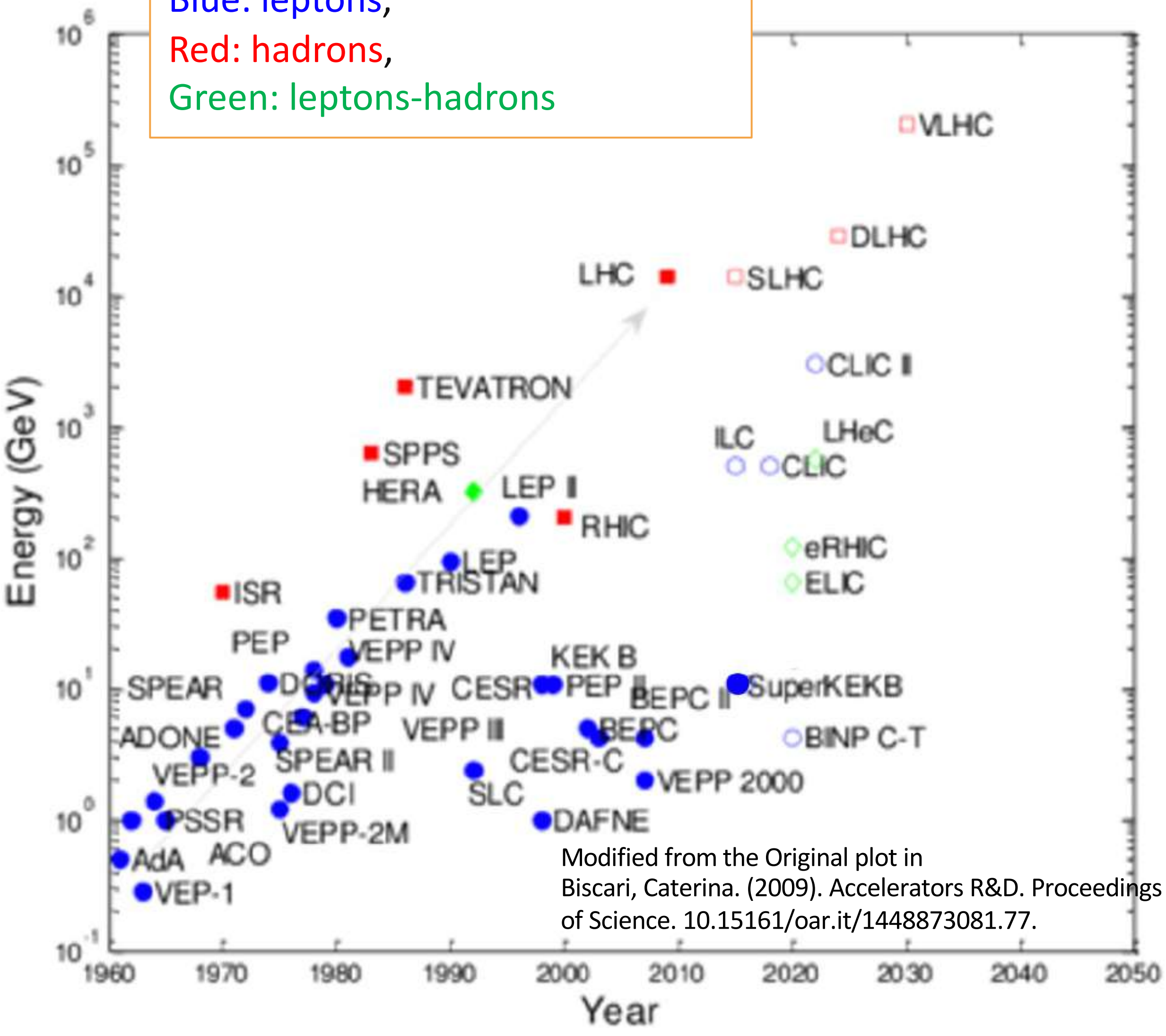
Collider

Era of large circular colliders

- Energy frontier machines
- Luminosity frontier machines



Full symbol: past and present
Empty symbols: future.
Blue: leptons,
Red: hadrons,
Green: leptons-hadrons



Modified from the Original plot in
Biscari, Caterina. (2009). Accelerators R&D. Proceedings of Science. 10.15161/oar.it/1448873081.77.

Tevatron

Tevatron(Fermilab)
1TeV P $\times$ 1TeV $\bar{P}$
6.3km circumference
4.2 T superconducting magnets
Operated 1983~2011.9.30
Discovery of top quark in 1995.

The first large-scale use of superconducting magnets enabled the construction of the Tevatron. By 1985, the Tevatron achieved energy above 1 Tera electron-volt (TeV) in proton-antiproton collisions, making it the most powerful particle collider in the world until 2009. The Tevatron construction established the superconducting wire manufacturing infrastructure that made applications such as Magnetic Resonance Imaging (MRI) viable.

https://news.fnal.gov/2017/12/ieee-honors-game-changing-tevatron-technology/

Tevatron

The main ring is 2 km in diameter & contains two accelerators, one on top of the other. The top accelerator, which employs ordinary magnets (red & blue), accelerates protons up to 150 GeV. It then passes them to the lower accelerator, which has superconducting magnets (yellow), & which is designed to accelerate the protons up to 1000 GeV.

https://atlas.cern/updates/blog/tevatron-goodnight-not-goodbye

Tevatron

Alvin Tollestrup who provided the leadership in developing superconducting magnets that could be used in a particle accelerator; Rich Orr who served as Head of the Double Section and so ably managed the other three (no mean feat); Dick Lundy who developed and ran the "magnet factory" at which approximately 1000 superconducting magnets were constructed on the Fermilab site; and Helen Edwards who provided the technical leadership for the design, construction, and commissioning of the Tevatron.

Figure 3: Alvin Tollestrup, Rich Orr, Dick Lundy, and Helen Edwards receiving the National Medal of Technology in 1989.

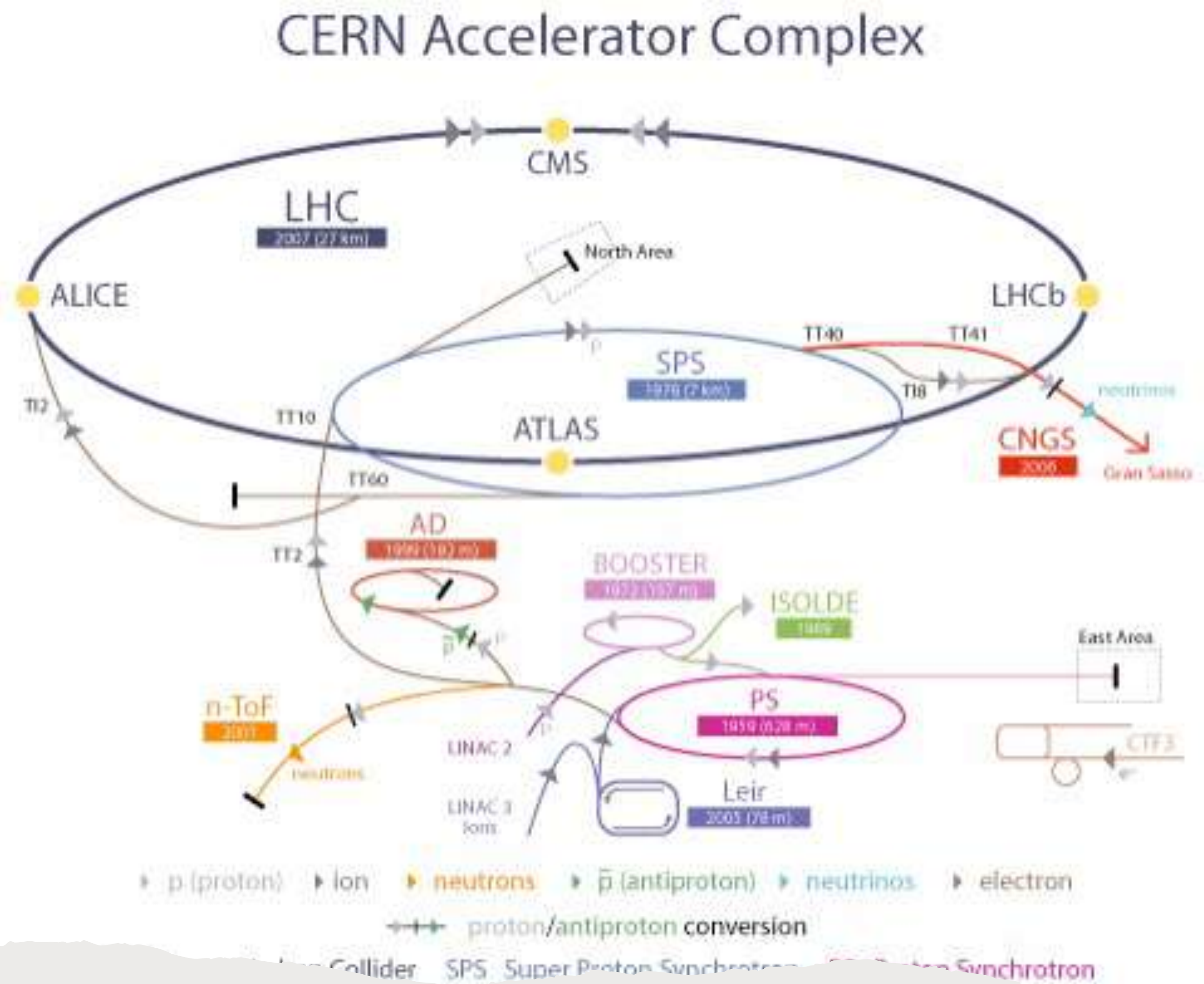
https://arxiv.org/pdf/1109.2937

Era of large circular colliders : Energy Frontier

LHC

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon



Era of large circular colliders : Energy Frontier

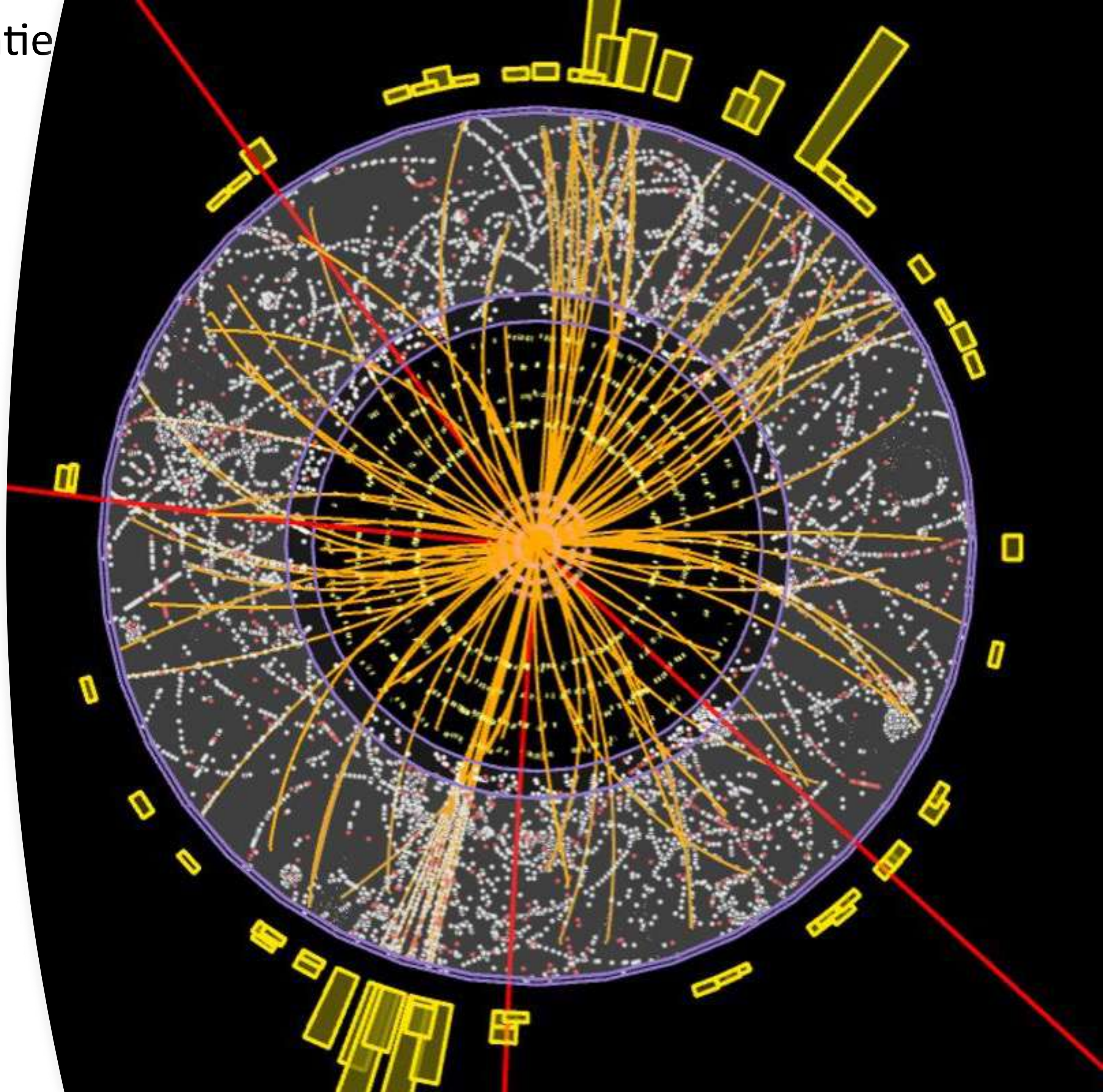
LHC

https://home.cern/news/news/accelerators/record-luminosity-well-done-lhc

LHC

Results of a proton-proton collision with four identified muons, a possible signature of a Higgs boson (Image: CERN)

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

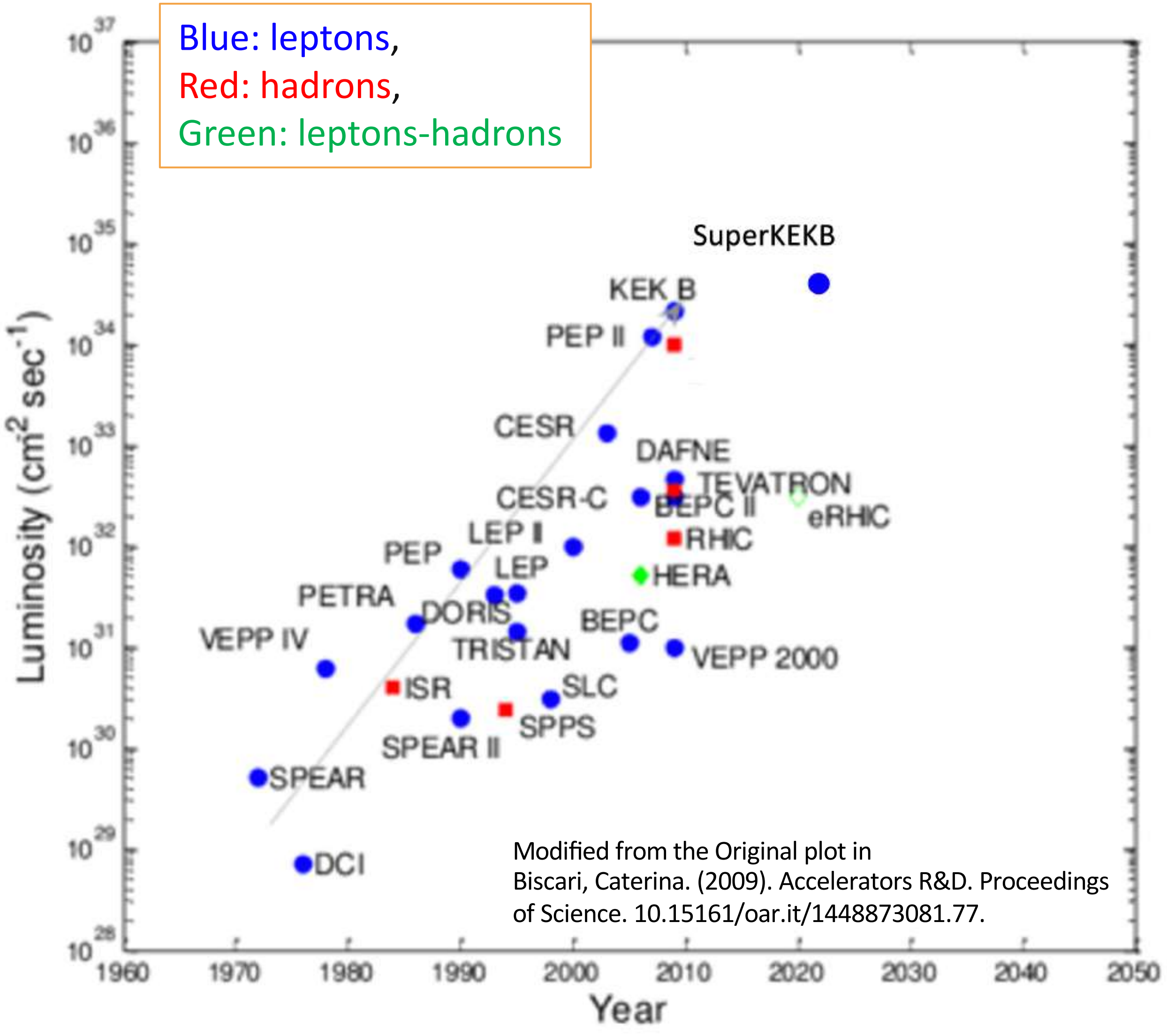


Era of large circular colliders : Luminosity Frontier

Collider

Era of large circular colliders

- Energy frontier machines
- Luminosity frontier machines



Modified from the Original plot in Biscari, Caterina. (2009). Accelerators R&D. Proceedings of Science. 10.15161/oar.it/1448873081.77.

Collider

Era of large circular colliders

- Energy frontier machines
- Luminosity frontier machines

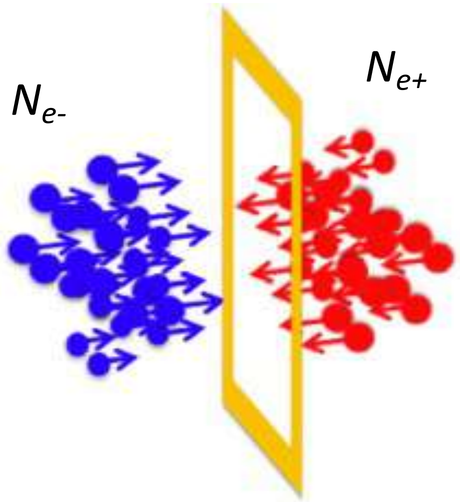
E_{CM} is an important parameter.

Another important key parameter is

Luminosity

Luminosity gives a measure of how many collisions are happening in a particle accelerator.

Collider: Luminosity



$$Y = L\sigma$$

$$L = \frac{N_{e+}N_{e-}f}{A}$$

the number of particles per unit area per unit time

$$dN_{\pm} = \frac{N_{\pm}}{2\pi\sigma_x^*\sigma_y^*} exp\left(-\frac{x^2}{2\sigma_x^{*2}} - \frac{y^2}{2\sigma_y^{*2}}\right) dxdy$$

$$L = \int dL = \frac{N_+N_-f}{(2\pi\sigma_x^*\sigma_y^*)^2}\int_{-\infty}^{+\infty} exp\left(-\frac{x^2}{\sigma_x^{*2}}\right) dx = \frac{N_+N_-f}{4\pi\sigma_x^*\sigma_y^*} \to \frac{N_+N_-f}{4\pi\sigma_x^*\sigma_y^*}R$$

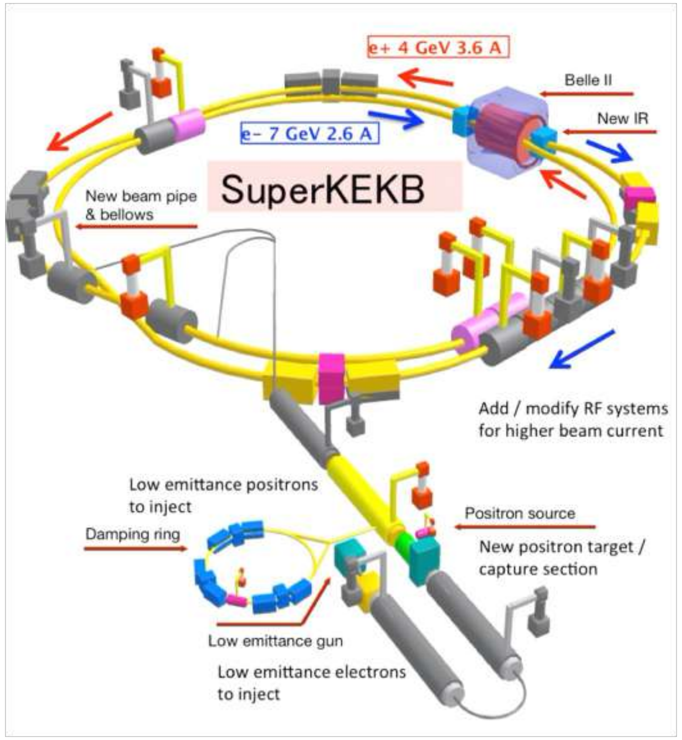
- More particles in a bunch
- Frequent collision
- Smaller beam

→ Higher luminosity

SuperKEKB

Luminosity frontier e^+e^- collider

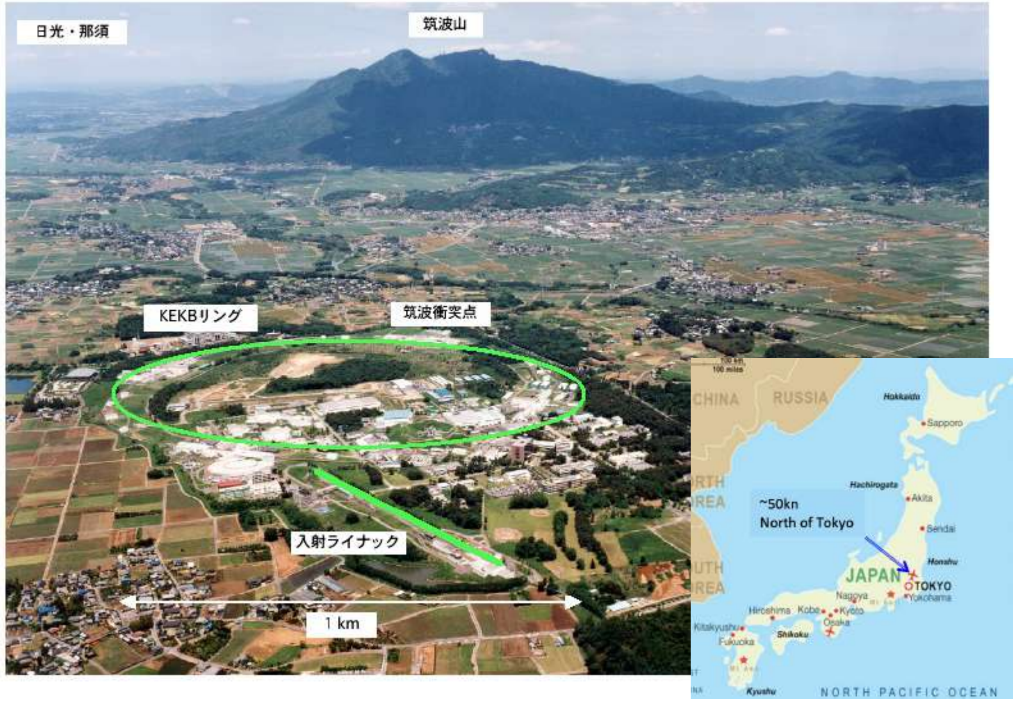
More, later



SuperKEKB complex consists of

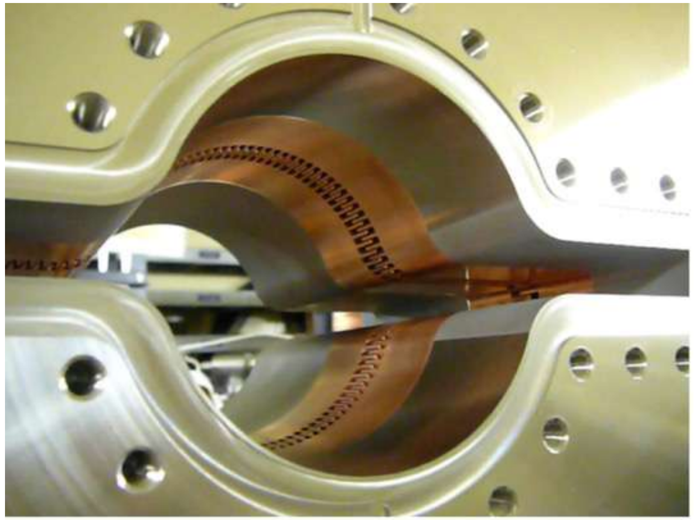
- a 7-GeV electron ring (the high-energy ring, HER)
- a 4-GeV positron ring (the low-energy ring, LER)
- $E_{CM} = 10.58\ GeV\ (\Upsilon(4S))$, the same as KEKB
- an injector linear accelerator (linac)
- a 1.1-GeV positron damping ring (DR)

Upgraded from KEKB (1998~2010)
Using the same tunnel, 3 km in circumference
11m below the ground level



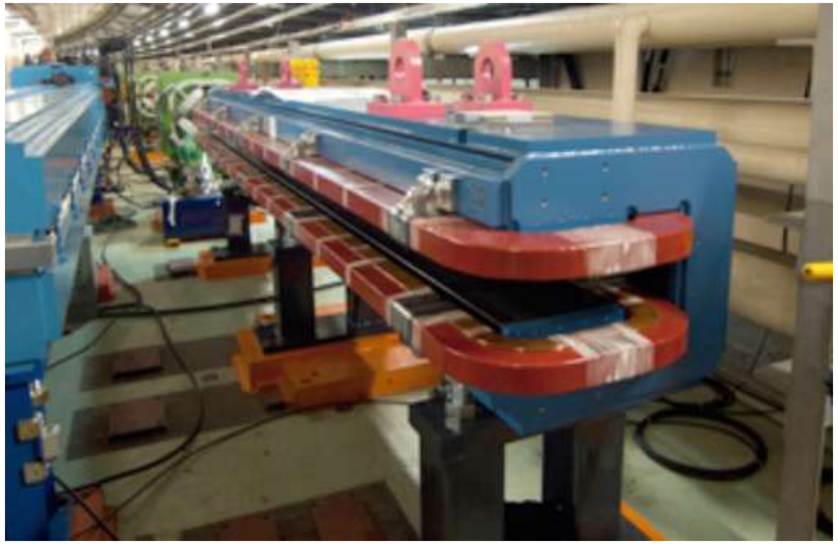
Accelerator components

Various technologies

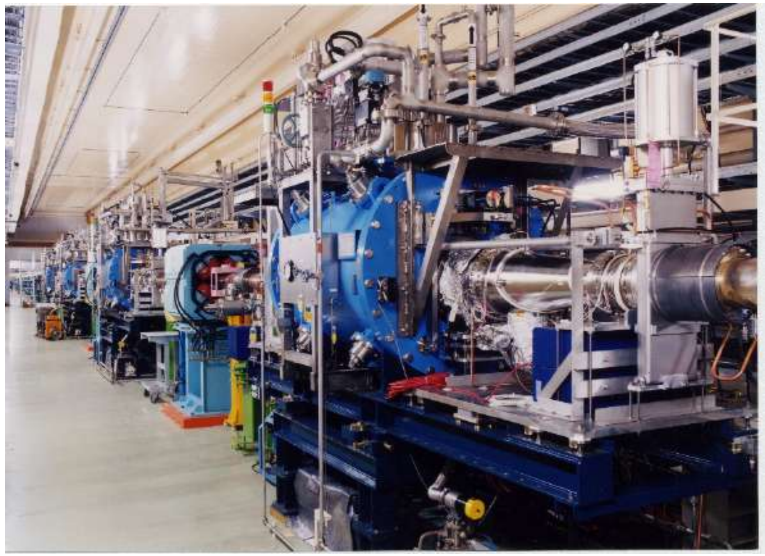


Bellow with a comb-type RF shield

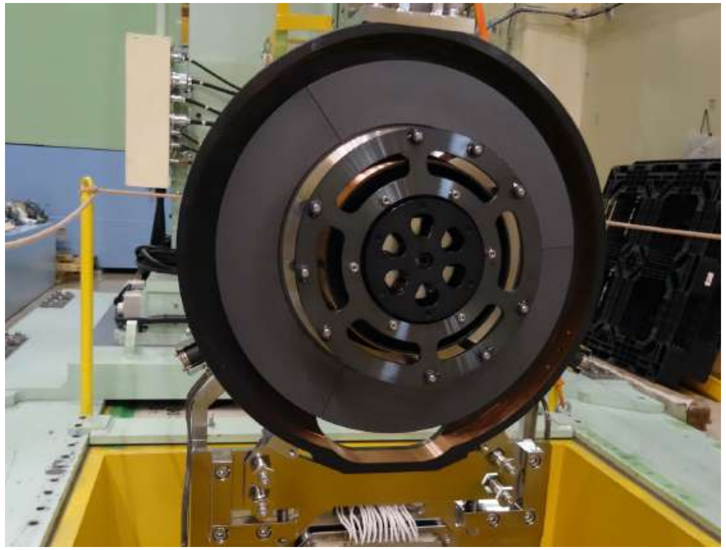
SuperKEKB Cryostat at IR



Dipole magnet



Superconducting RF cavity

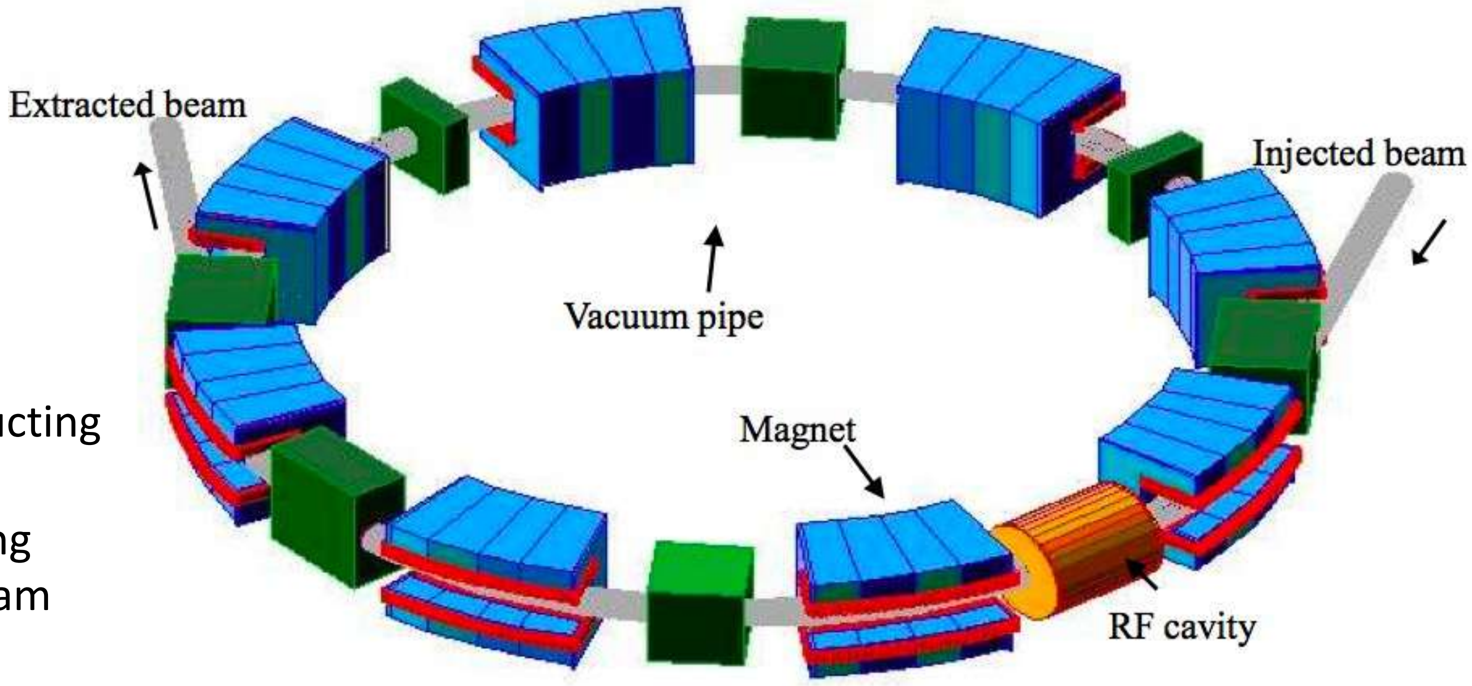


Muon target

Accelerator components

Various technologies

(2) Vacuum components
- To cover the beam passage
- Bellows
- Collimators
- Gate valves



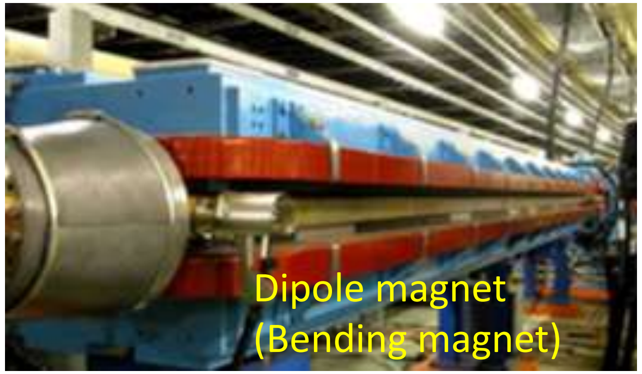
(1) Magnets
- Normal conducting, superconducting
- Dipole magnets for bending
- Quadrupole magnets for focusing
- Kicker magnets for injection/beam aborts

(4) Monitors
- Beam Position Monitors (BPM)
- Beam profile monitors
- Beam current monitors

(3) RF system
- Normal conducting, superconducting
- To accelerate/compensate for lost energy

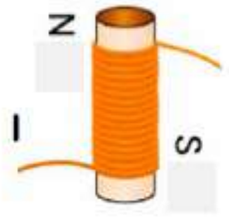
Accelerator components

(1) Magnets (Normal conducting)

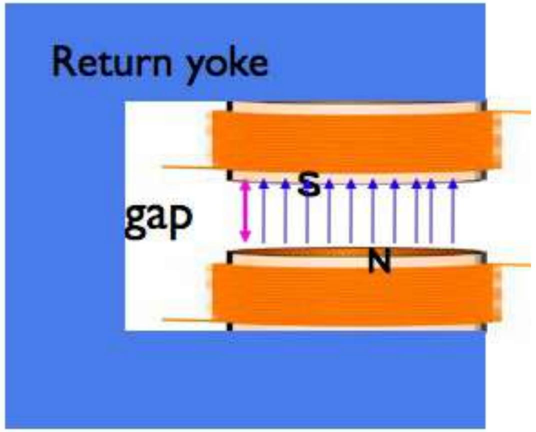


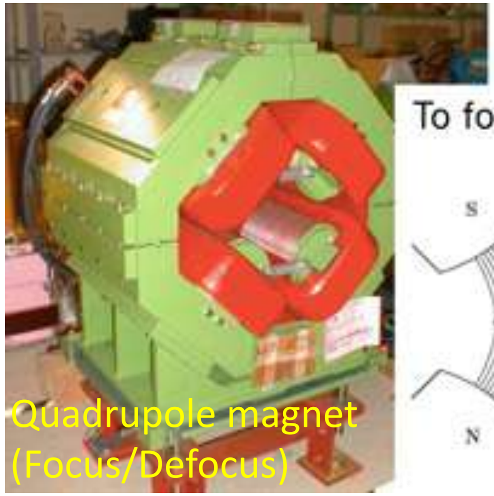
Charged particles traveling through the field receive a deflecting (bending) force.

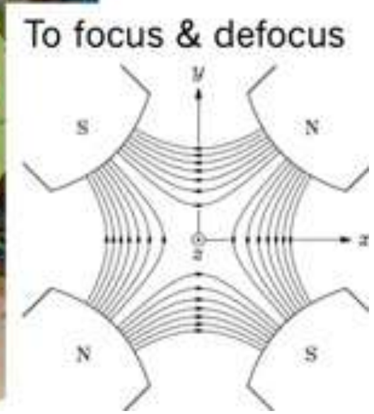
Wind a wire on an iron bar.
Flow current through the wire and the bar will be magnetized. Polarity changes when current direction is changed.

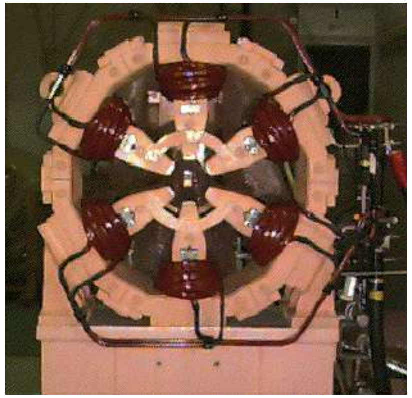


Coils on the pole
+ return yoke
→dipole magnet!









Sextupole magnet
(SPring-8)

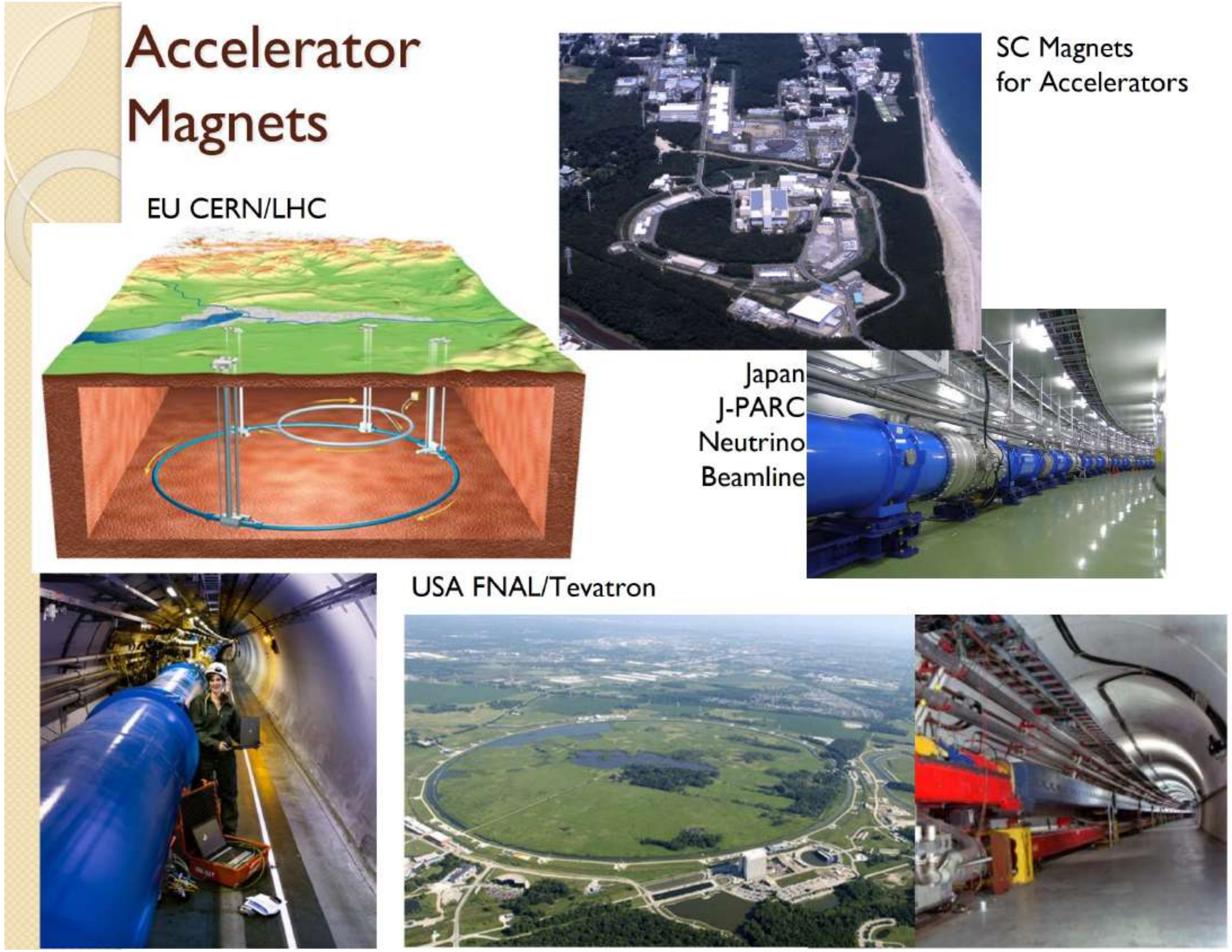
Chromatic correction

Accelerator components

(1) Magnets (superconducting)

Higher currents can be applied and higher magnetic field can be generated than iron core/copper conductor “normal” conducting magnets.

Also allows more compact magnet design.



https://conference-indico.kek.jp/event/18/sessions/114/attachments/134/141/ASSCA-SCMag1.pdf

Discovery of Superconductivity

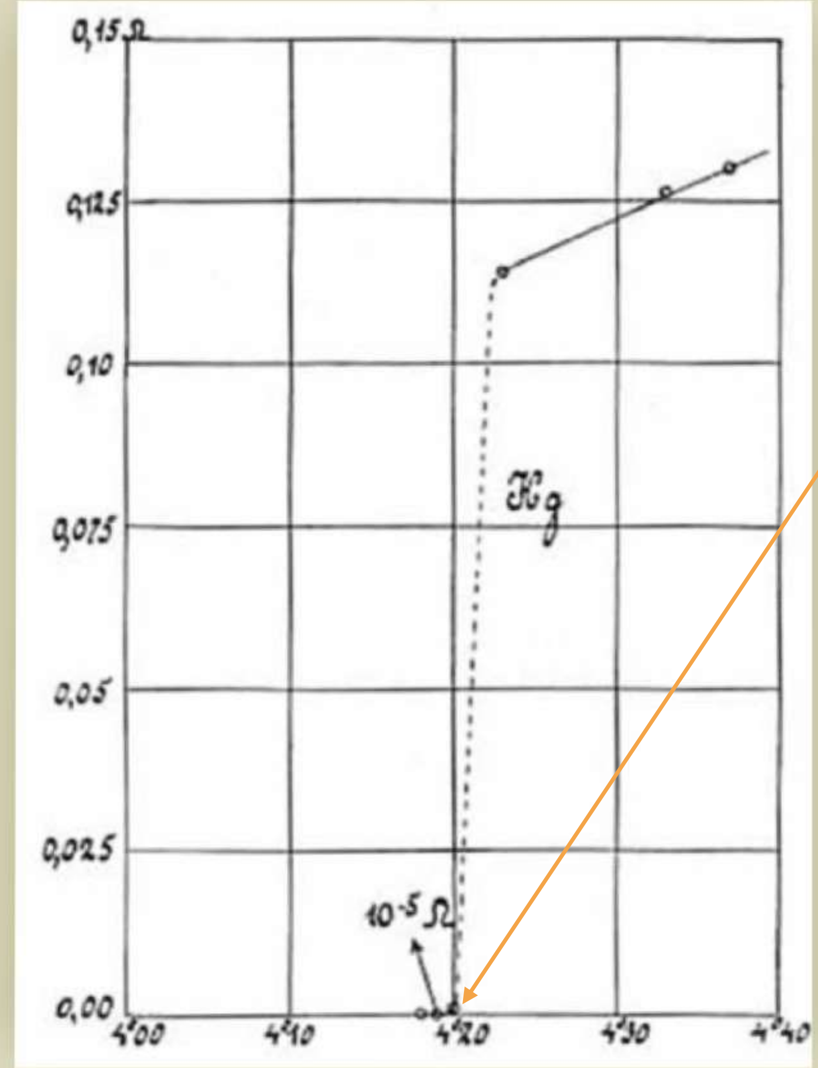
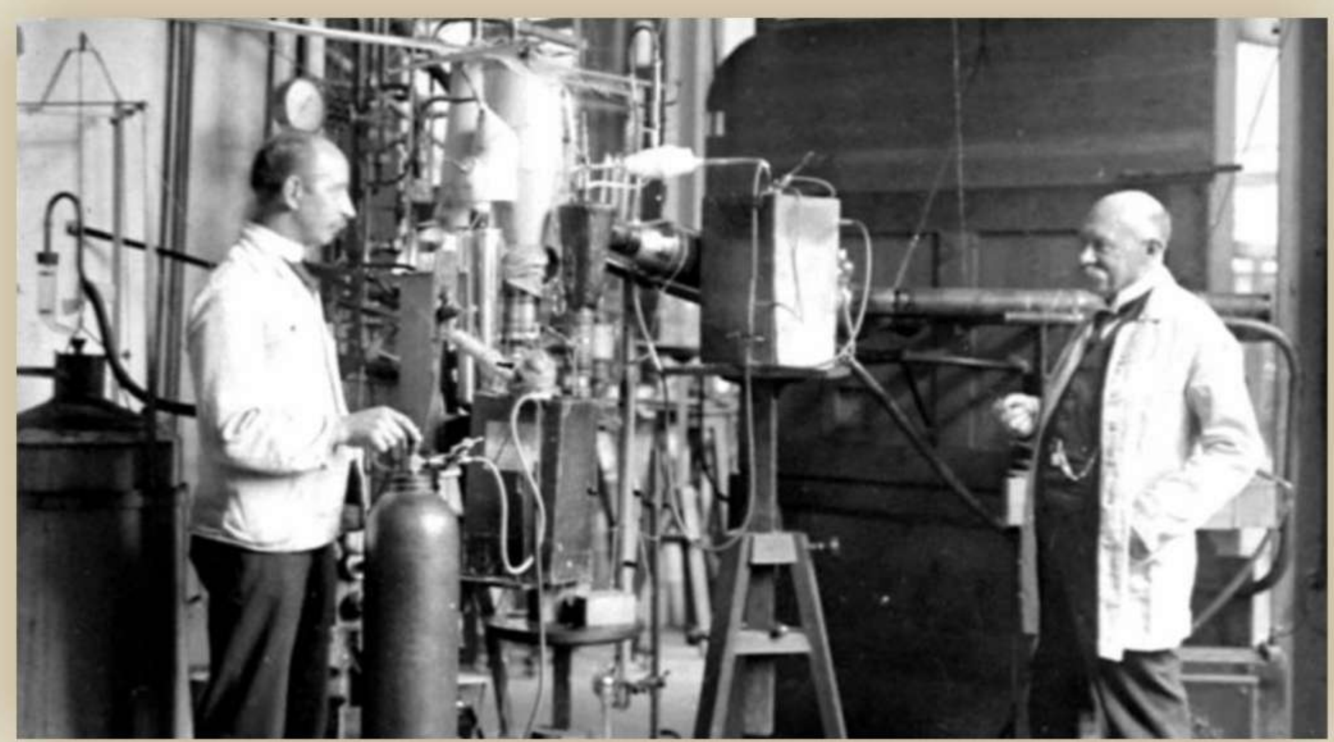


Figure 4. Historic plot of resistance (ohms) versus temperature (kelvin) for mercury from the 26 October 1911 experiment shows the superconducting transition at 4.20 K. Within 0.01 K, the resistance jumps from unmeasurably small (less than 10^{-6} Ω) to 0.1 Ω. (From ref. 9.)

Superconductivity discovered in 1911 by K. Onnes
ZERO resistance of mercury wire at 4.2 K

https://www.lorentz.leidenuniv.nl/history/cold/DelftKes_HKO_PT.pdf



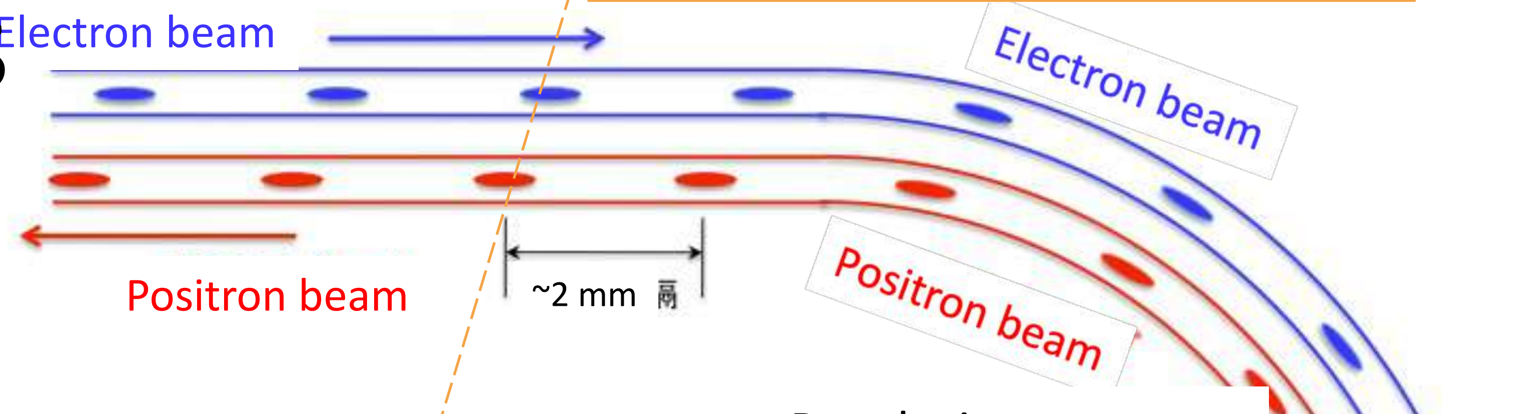
LEIDEN INSTITUTE OF PHYSICS

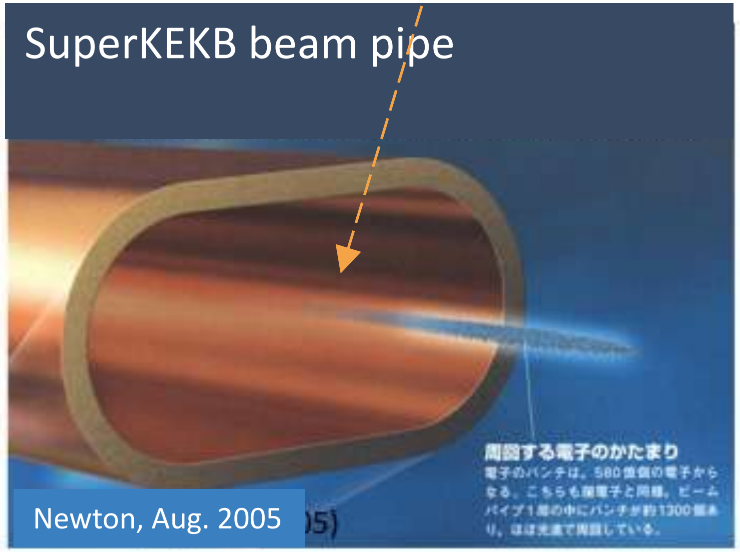
Figure 1. Heike Kamerlingh Onnes (right) and Gerrit Flim, his chief technician, at the helium liquefier in Kamerlingh Onnes's Leiden laboratory, circa 1911.

Accelerator components

(2)Vacuum component

10^{-7}~10^{-8} Pa
1/10^{12} of the atmospheric pressure



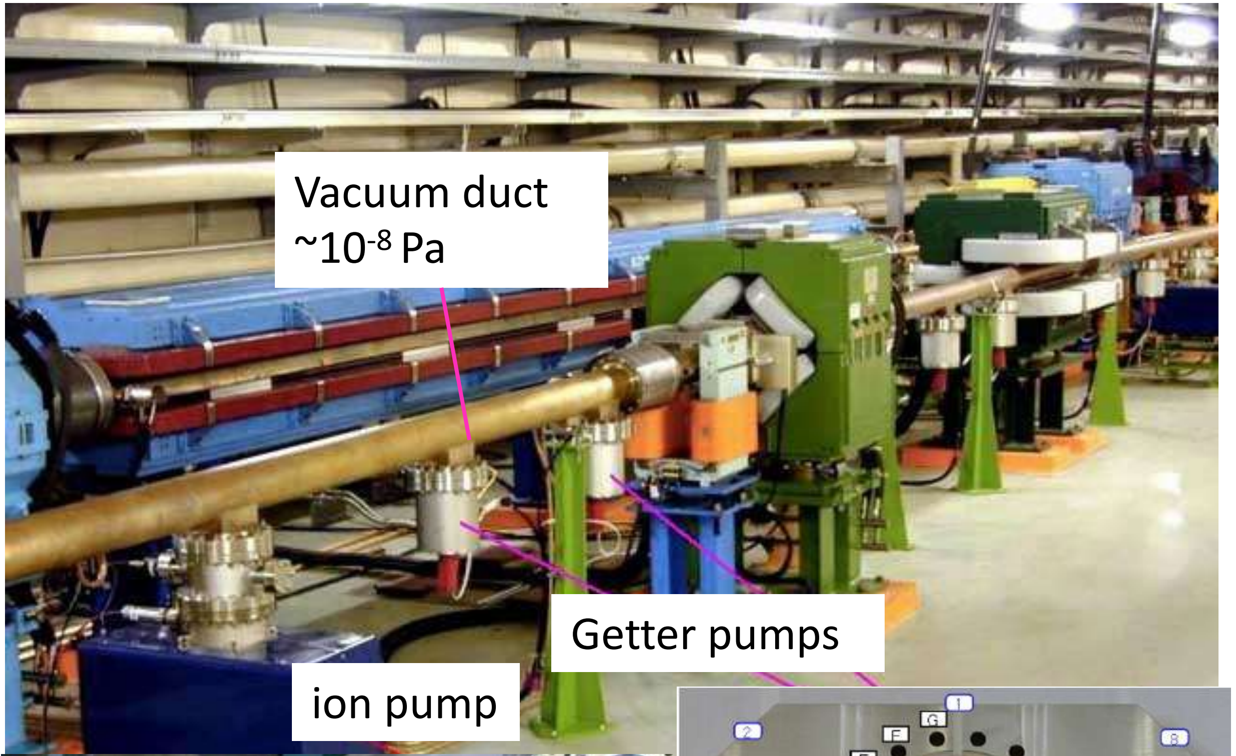


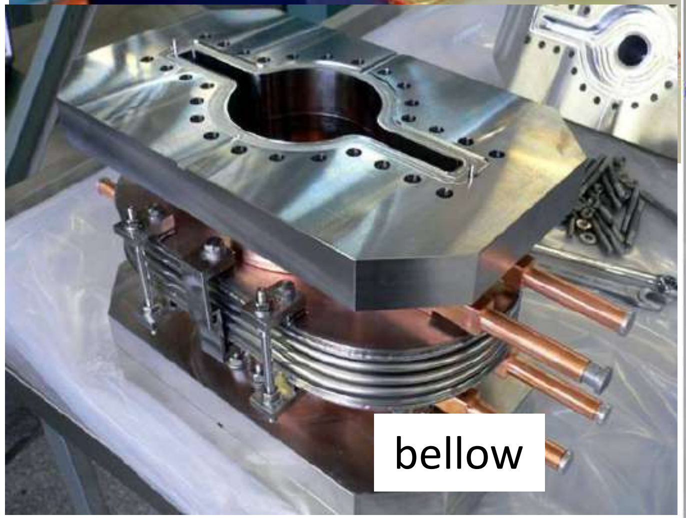
Bunch size
~ 12 mm in length
~ several 100 mm in width

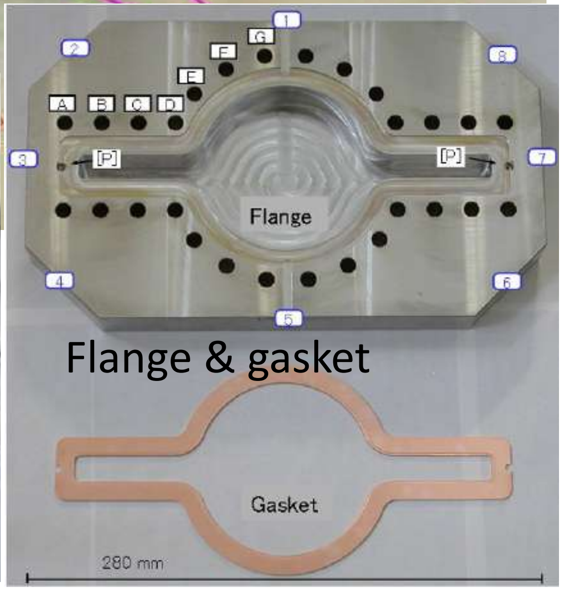
~70 billion electrons/positrons in a bunch

There are ~1500 bunches in a ring

(2) Vacuum components





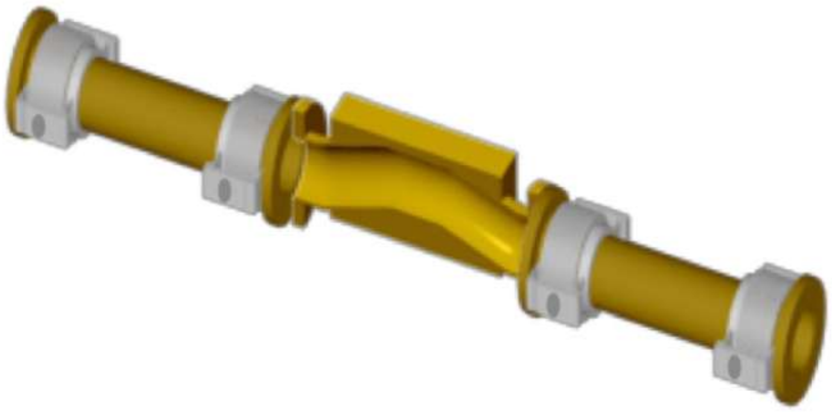


Gate Valve

(2) Vacuum components

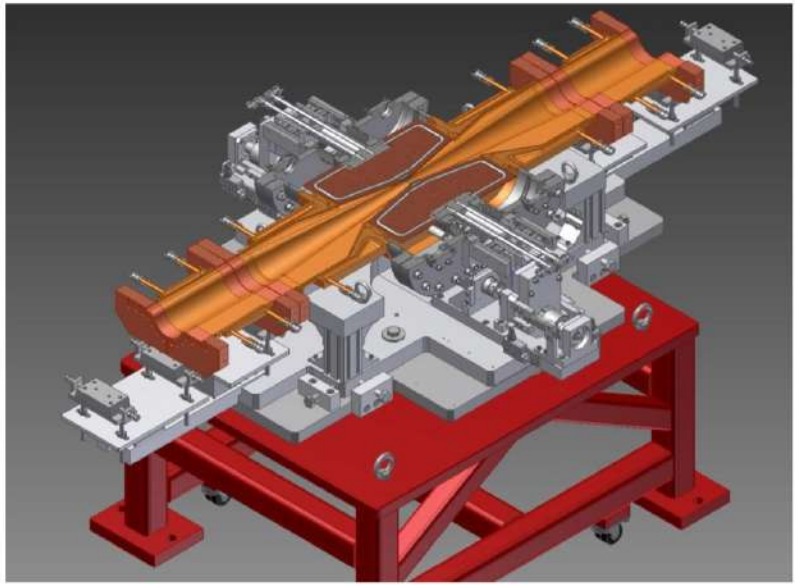
Collimators for
- controlling radiation background
- beam cleaning
- machine protection

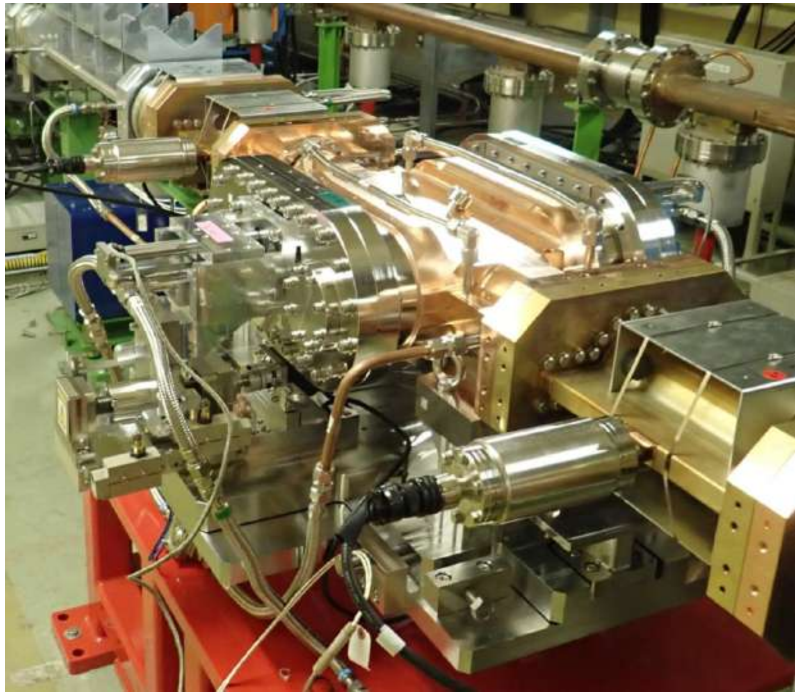
Used to be very important for hadron machines
But now high energy and high luminosity machines need collimation system



KEKB type

[Y. Suetsugu et al., NIM A 513, 465 (2003)]





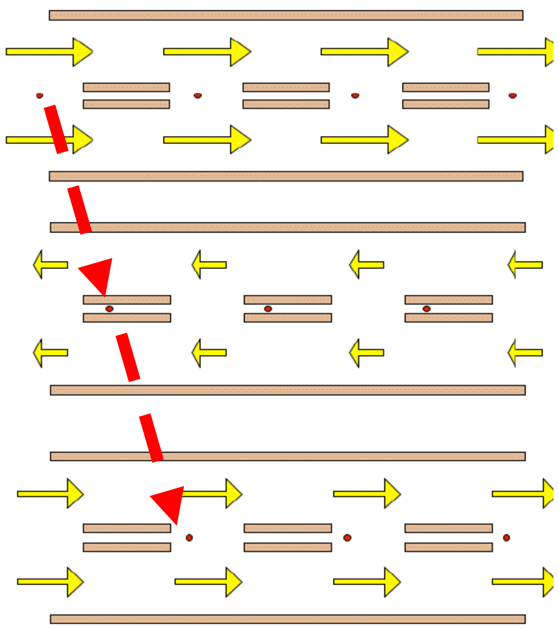
SuperKEKB type

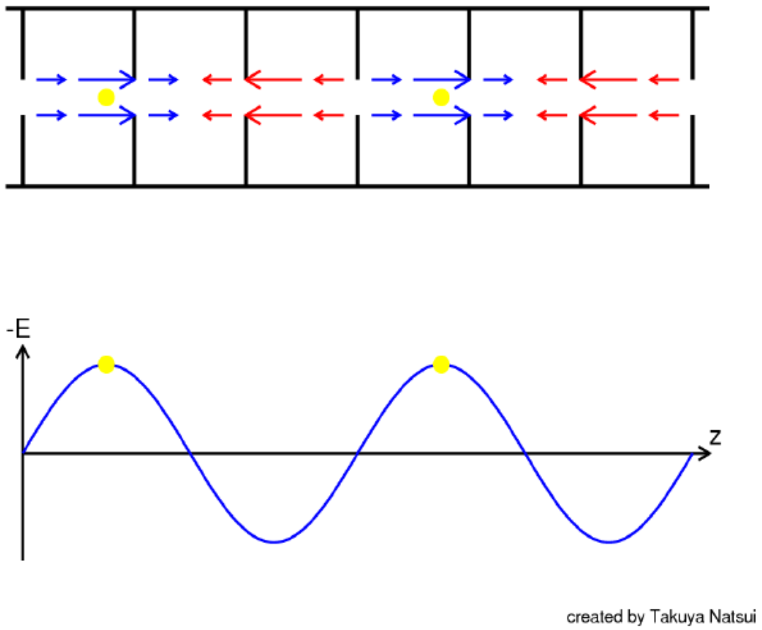
[T. Ishibashi et al., PRAB 23, 053501 (2020)]

Basic hardware components

(3)RF system

RF cavities are used to
- Store energy for accelerating beam
- Extract beam energy (for example as a beam pickup)
- Modulate beam energy or position as a beam kicker

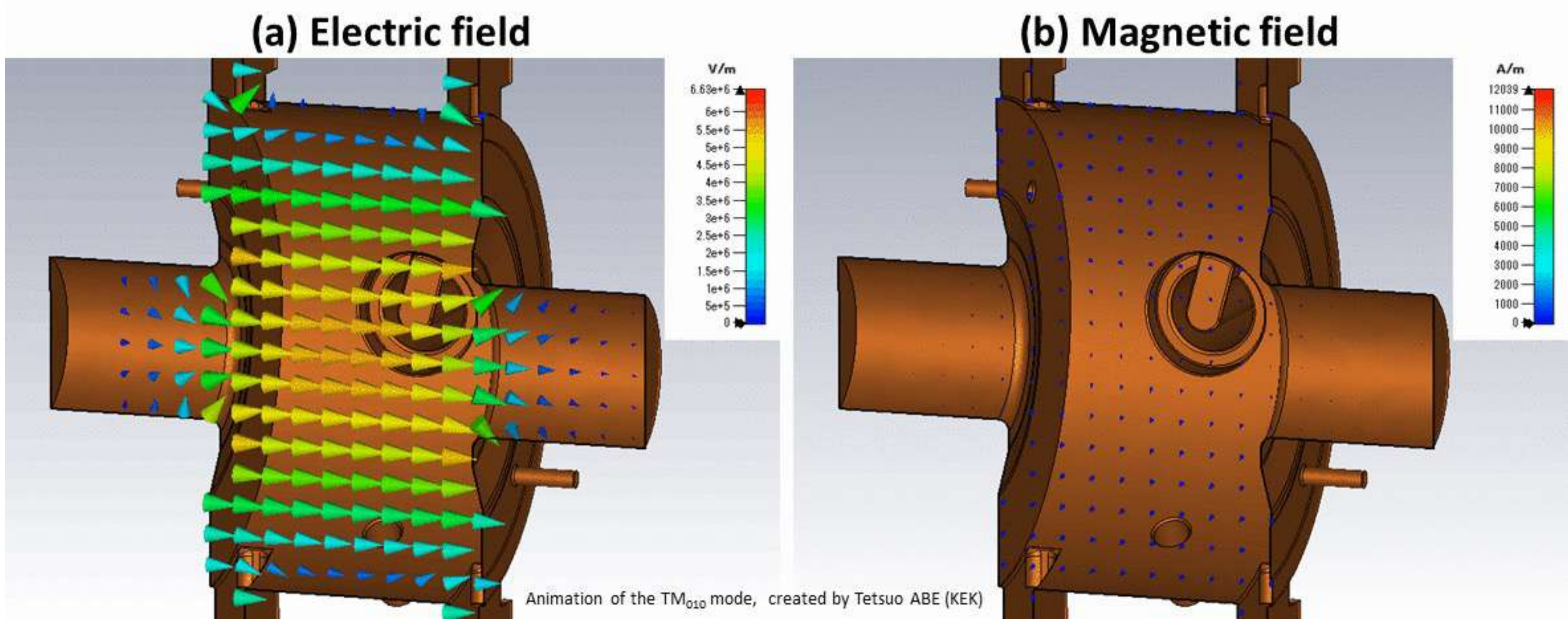




https://uspas.fnal.gov/materials/14UNM/RF_Structures.pdf

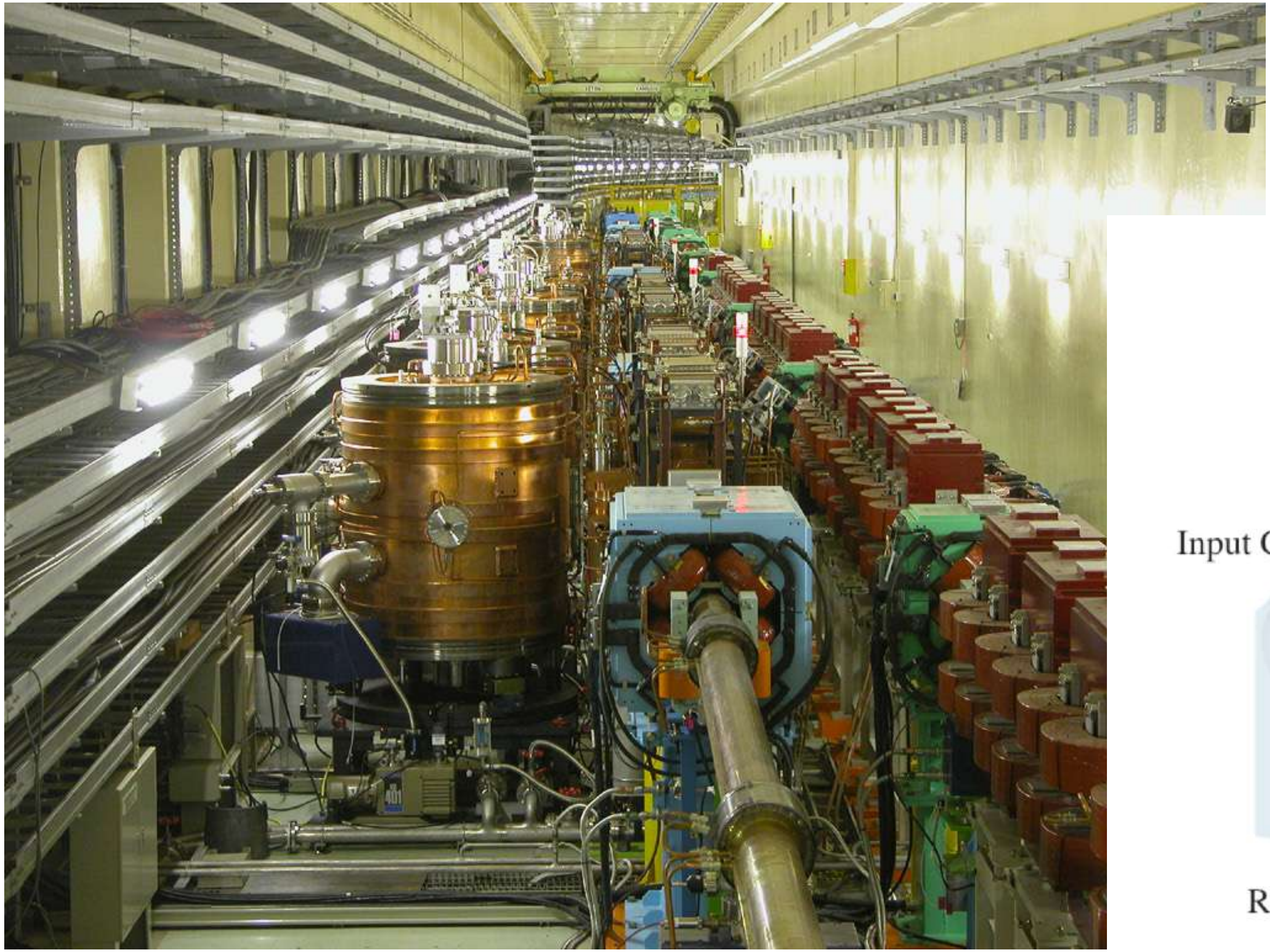
Basic hardware components

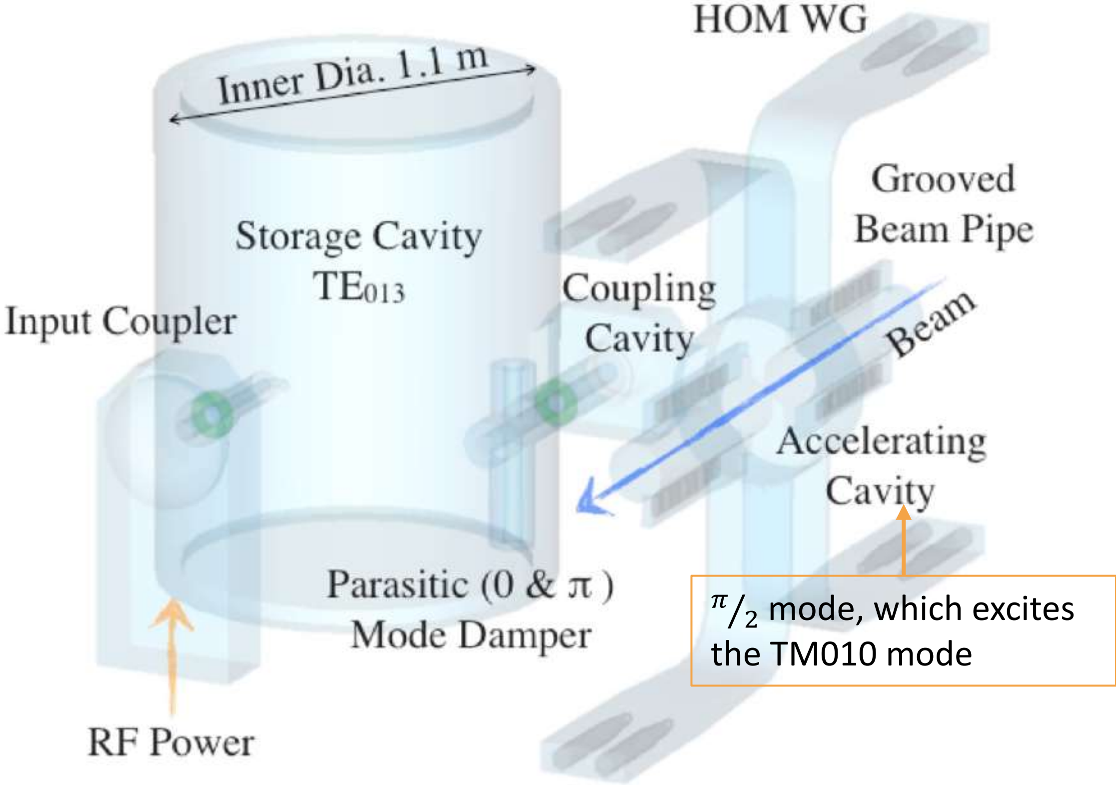
(3)RF system



An example of a pillbox cavity (“TM010” mode)
(SuperKEKB Damping Ring)

Normal conducting RF





$^{\pi}/_{2}$ mode, which excites the TM010 mode

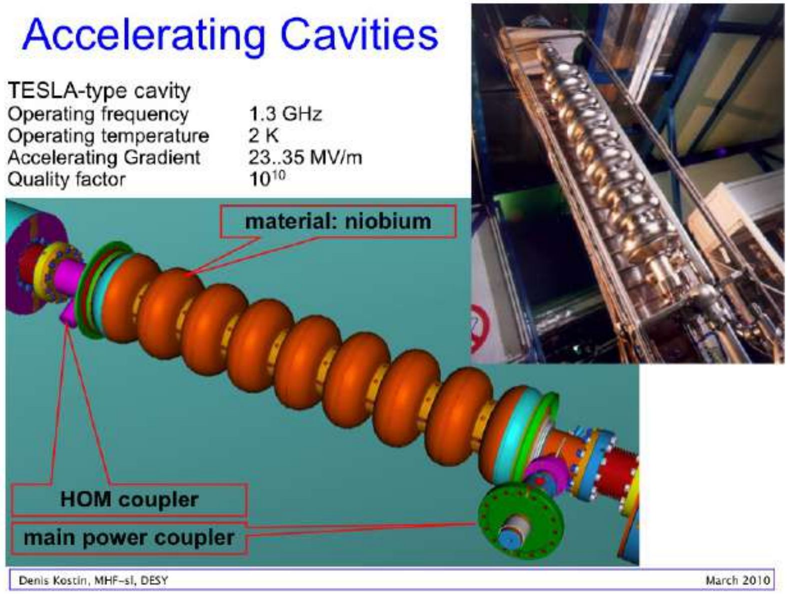
Superconducting RF

The main advantage

- The RF losses at the inner surface of the cavity are very small.
- Almost all of the input power can be supplied to the beam.
- Continuous ("CW") operation at high acceleration fields is possible, which is difficult with normal-conducting cavities.

In the case of normal-conducting cavities
- about half of the RF power provided externally is consumed as heat due to electric resistance
- only the other half is transferred to the beam.

https://aaa-sentan.org/ILC/about_collider/scrf.html



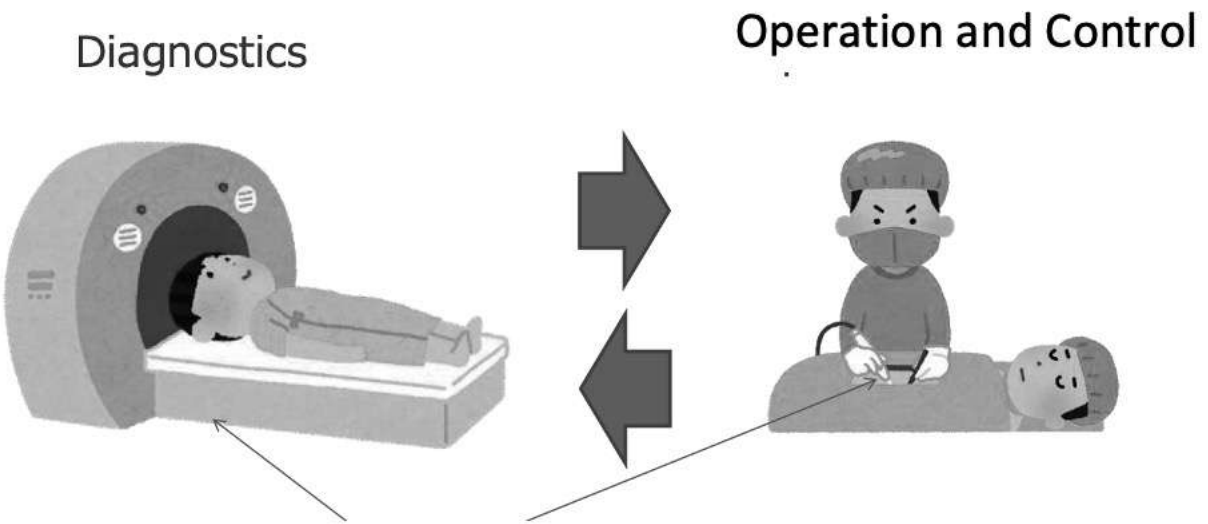
R&D Superconducting cavity for ILC

ILC GDE Meeting at IHEP, Beijing 8/19 zongzg@ihep.ac.cn

Accelerator components

(4) Monitors (beam diagnostics)

- Beam position monitor (BPM) provides information on the position of the beam in the vacuum chamber
- BPMs detect the electric or magnetic field excited by beam passing by.

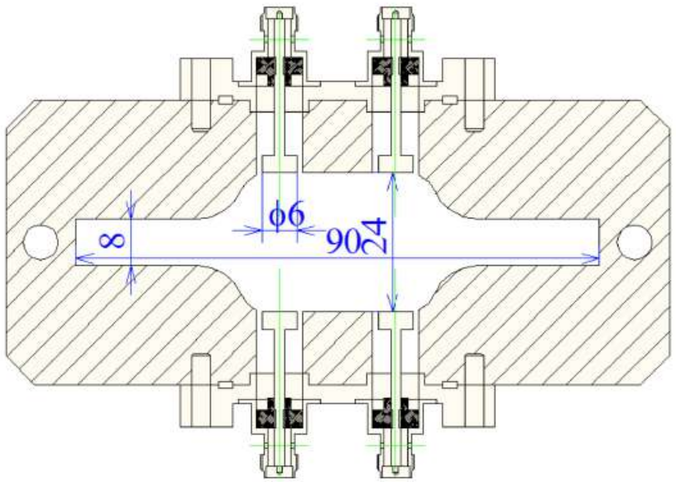


Without correct beam diagnostics, accelerators cannot be operated or controlled. Development of more advanced diagnostic systems

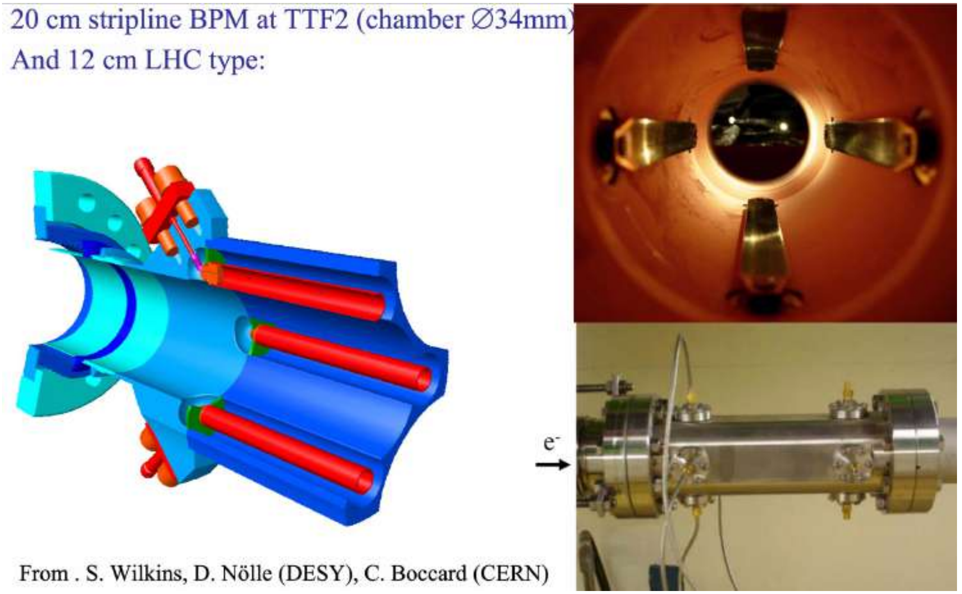
http://accwww2.kek.jp/oho/OHOtxt/OHO-2020/01_Obina_Takashi.pdf

- Types of BPM
  - Electrostatic: 'button' pick-ups
  - Electromagnetic: stripline couplers,
  - Resonant cavity
  - etc

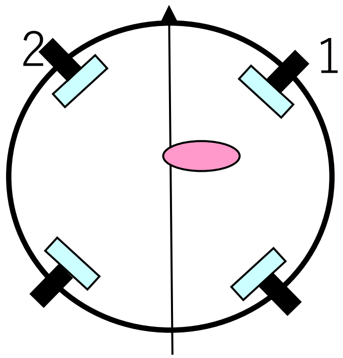
(4) Monitors (beam diagnostics)

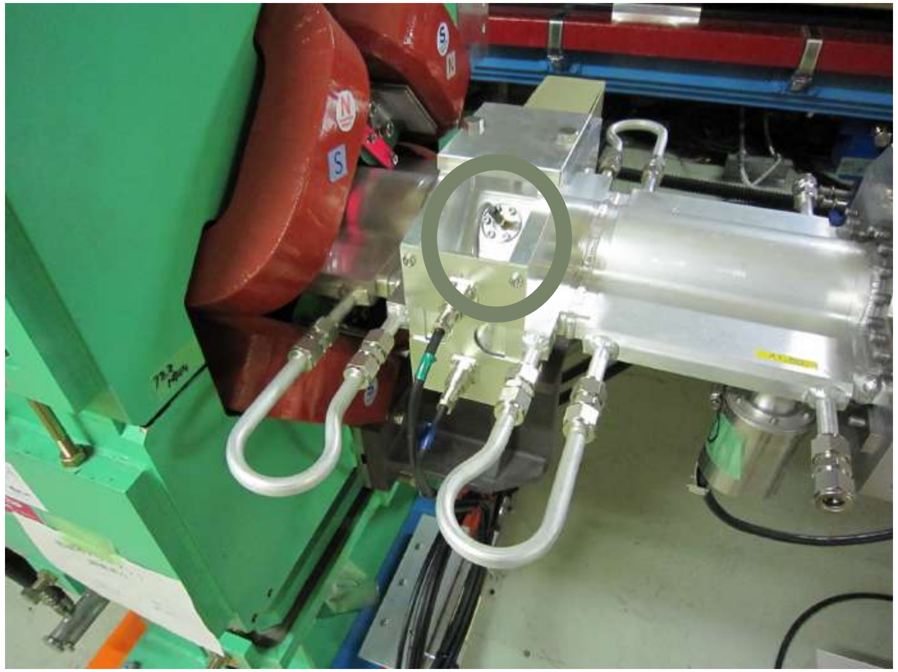


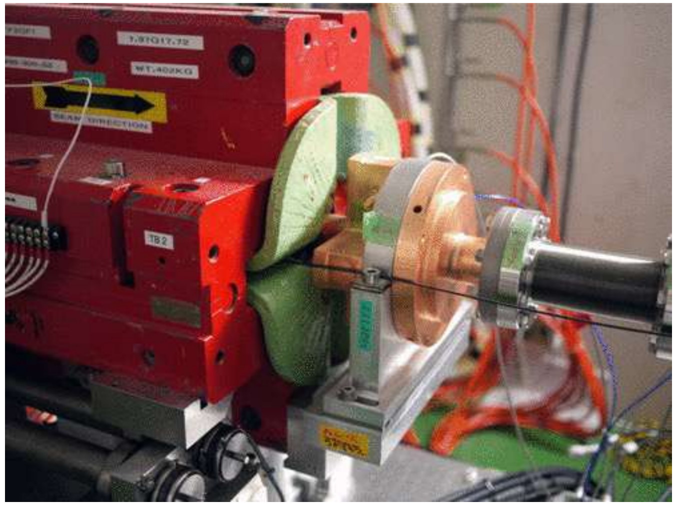
Button BPM (KEK)



Stripline BPM (LHC)







Resonant monitors detect the excitation of a certain field configurations by an off-center beam (AFT)

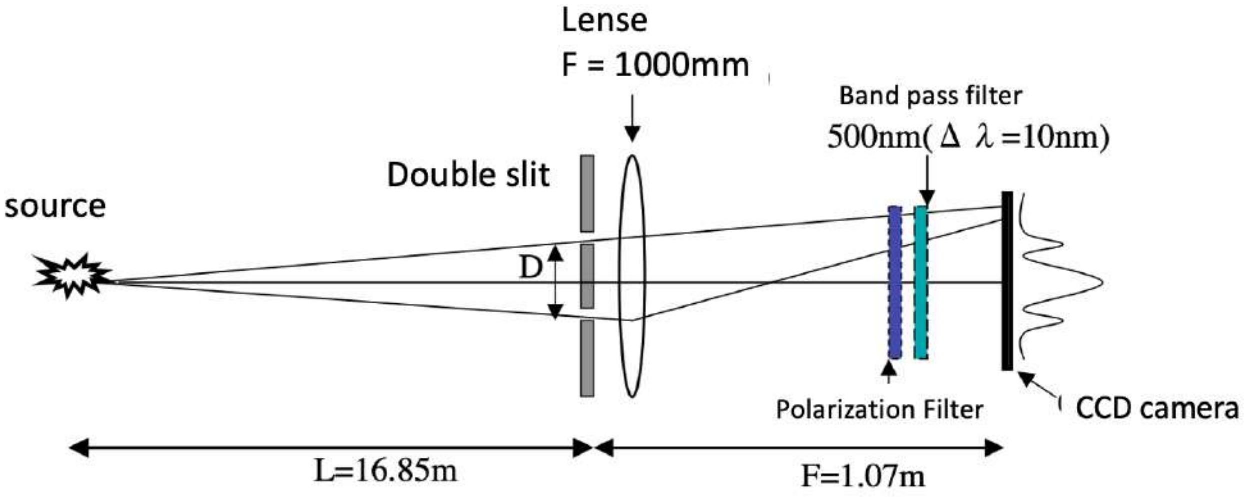
Accelerator components

(4)Monitors

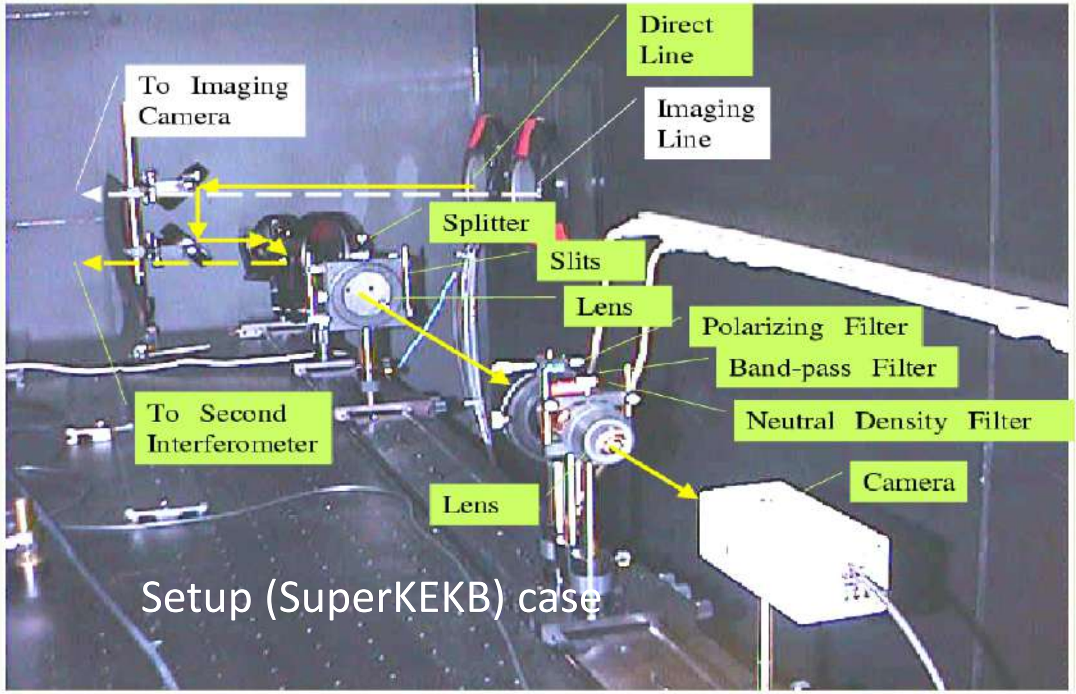
Beam size/profile monitor

- **S**ynchrotron **R**adiation Monitor
- Screen monitor

SR interferometer for measuring beam size



http://www.pasj.jp/web_publish/pasj2_lam30/Proceedings/21P048.pdf

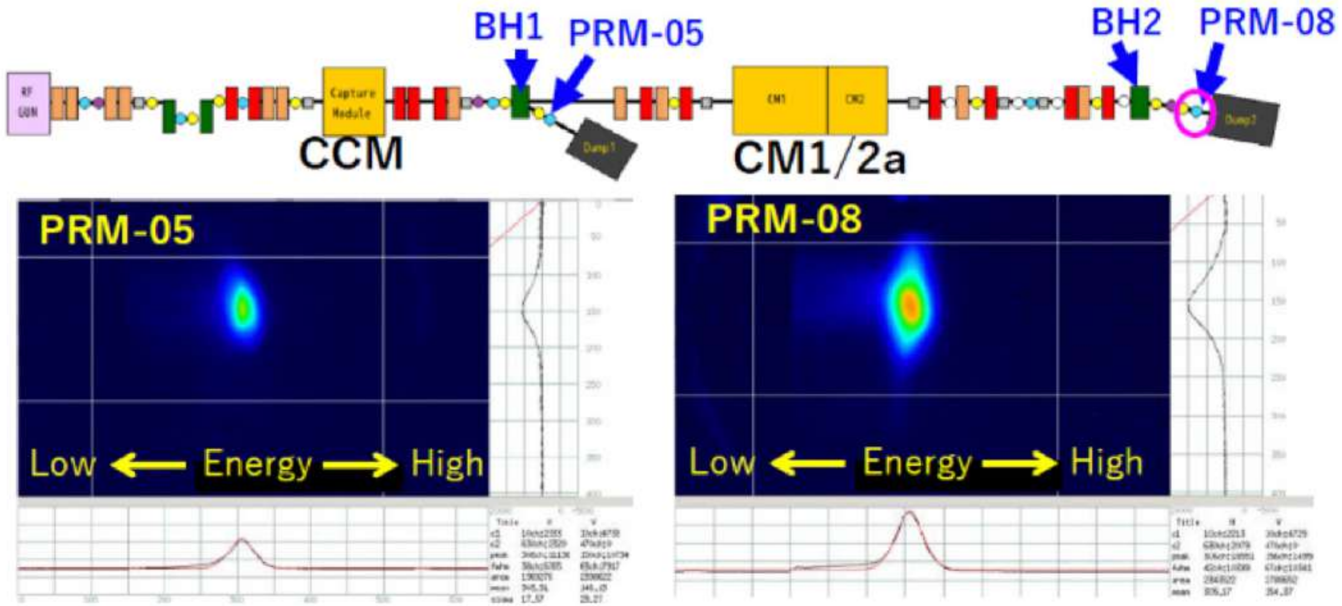


Accelerator components

(4)Monitors

Beam size/profile monitor

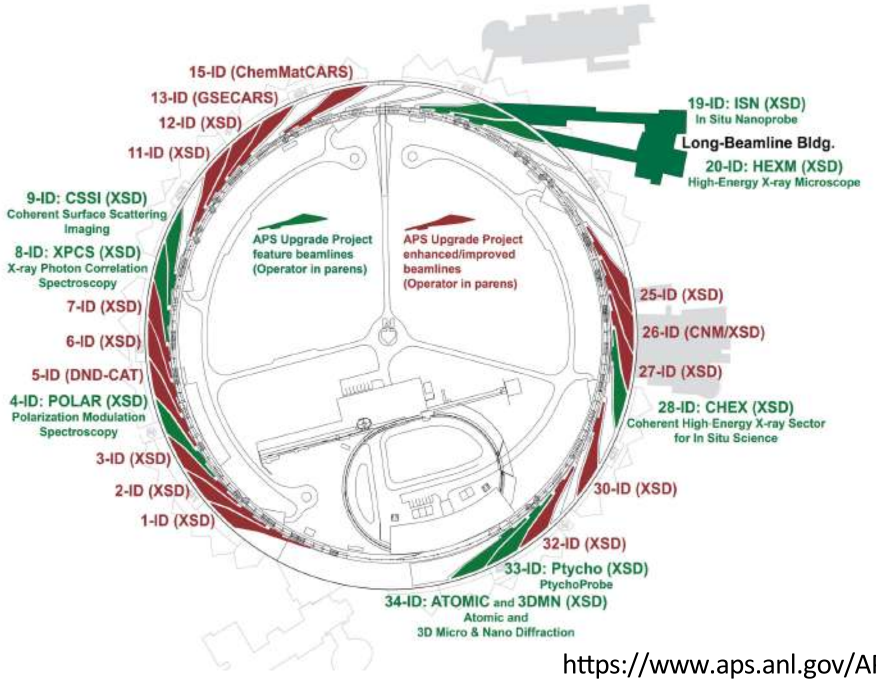
- Synchrotron Radiation Monitor
- Screen monitor



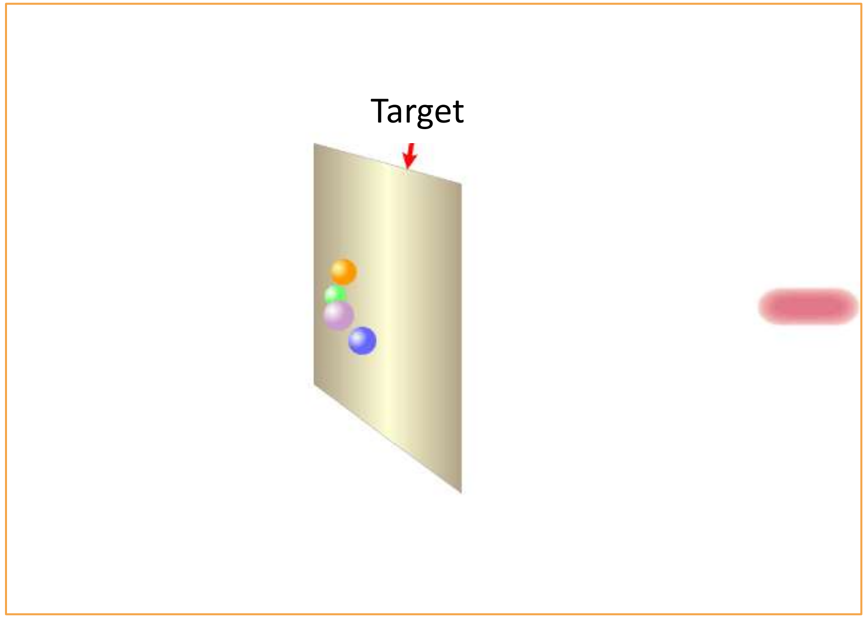
Beam profile measurementhttps://beam-physics.kek.jp/mirror/www.pasj.jp/web_publish/pasj2021/proceedings/PDF/THP0/THP029.pdf

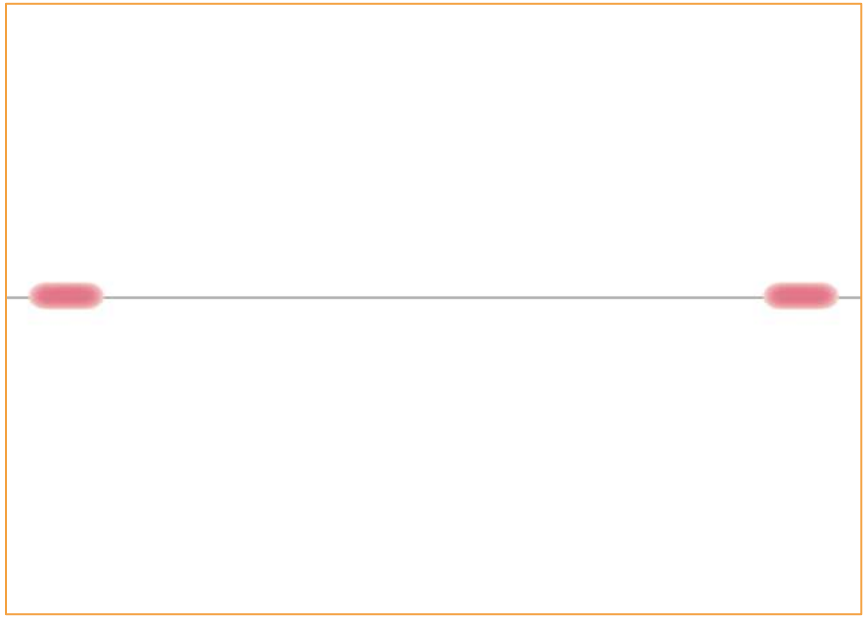
Various types of accelerators

- Light sources
- Synchrotron
  - J-PARC
- Colliders
  - SuperKEKB
- Many other
  - Application



https://www.aps.anl.gov/APS-Upgrade/Feature-Beamlines

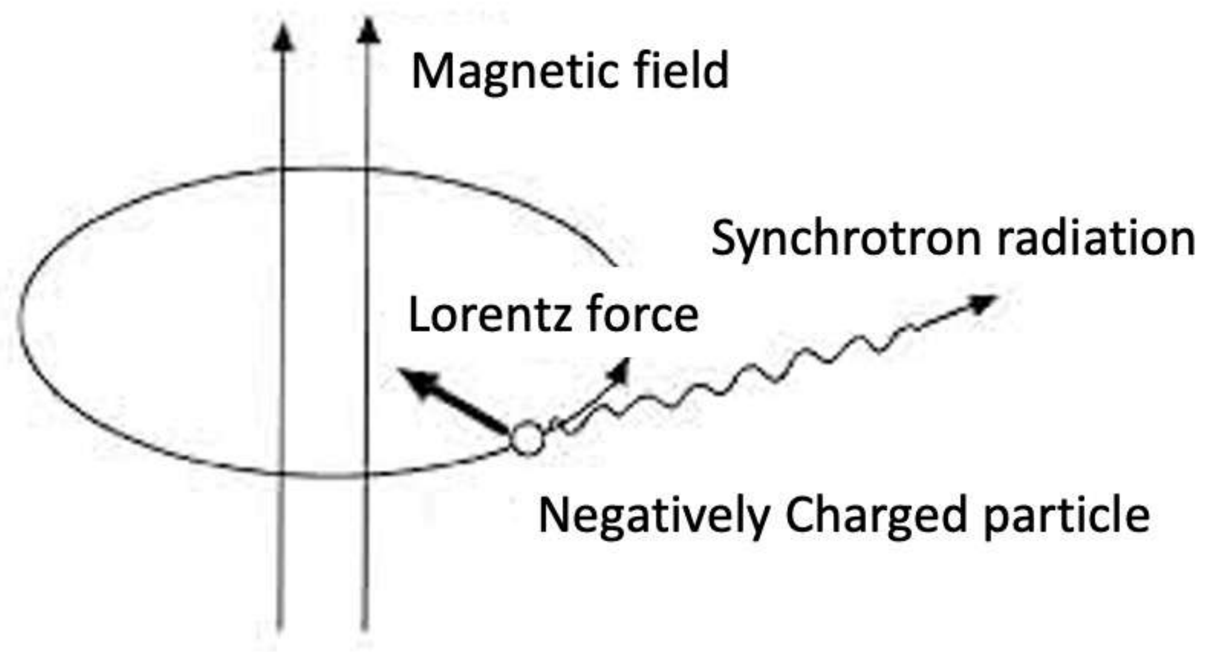




https://www2.kek.jp/ja/newskek/2005/novdec/beam.html

Various types of accelerators

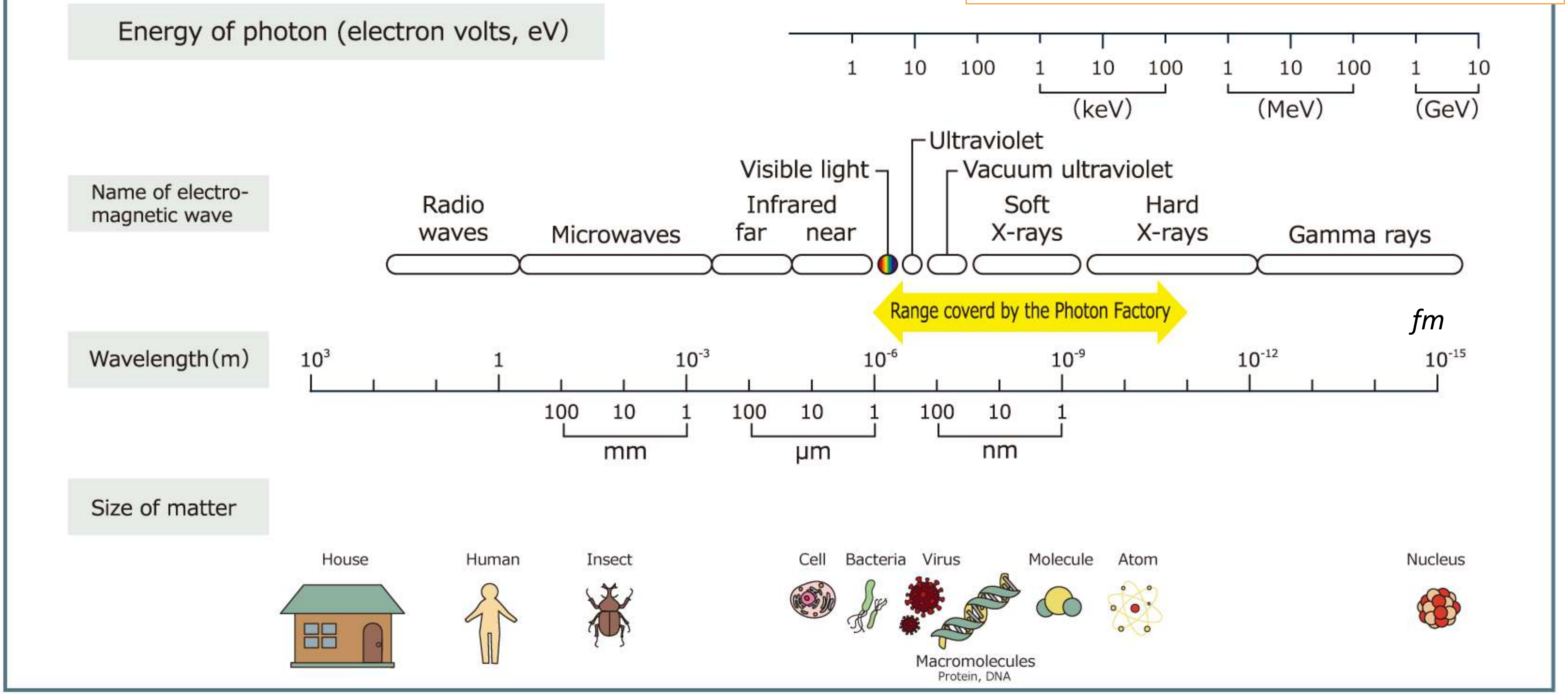
- Light sources
- Synchrotron
  - J-PARC
- Colliders
  - SuperKEKB
- Many other
  - Application



Light sources (Photon Factory)
- Keeps the beam for hours, 260 billion km, ~87 round trips between the earth and the sun.
- A radiation facility where various phenomena caused by the interaction of light and matter are studied.

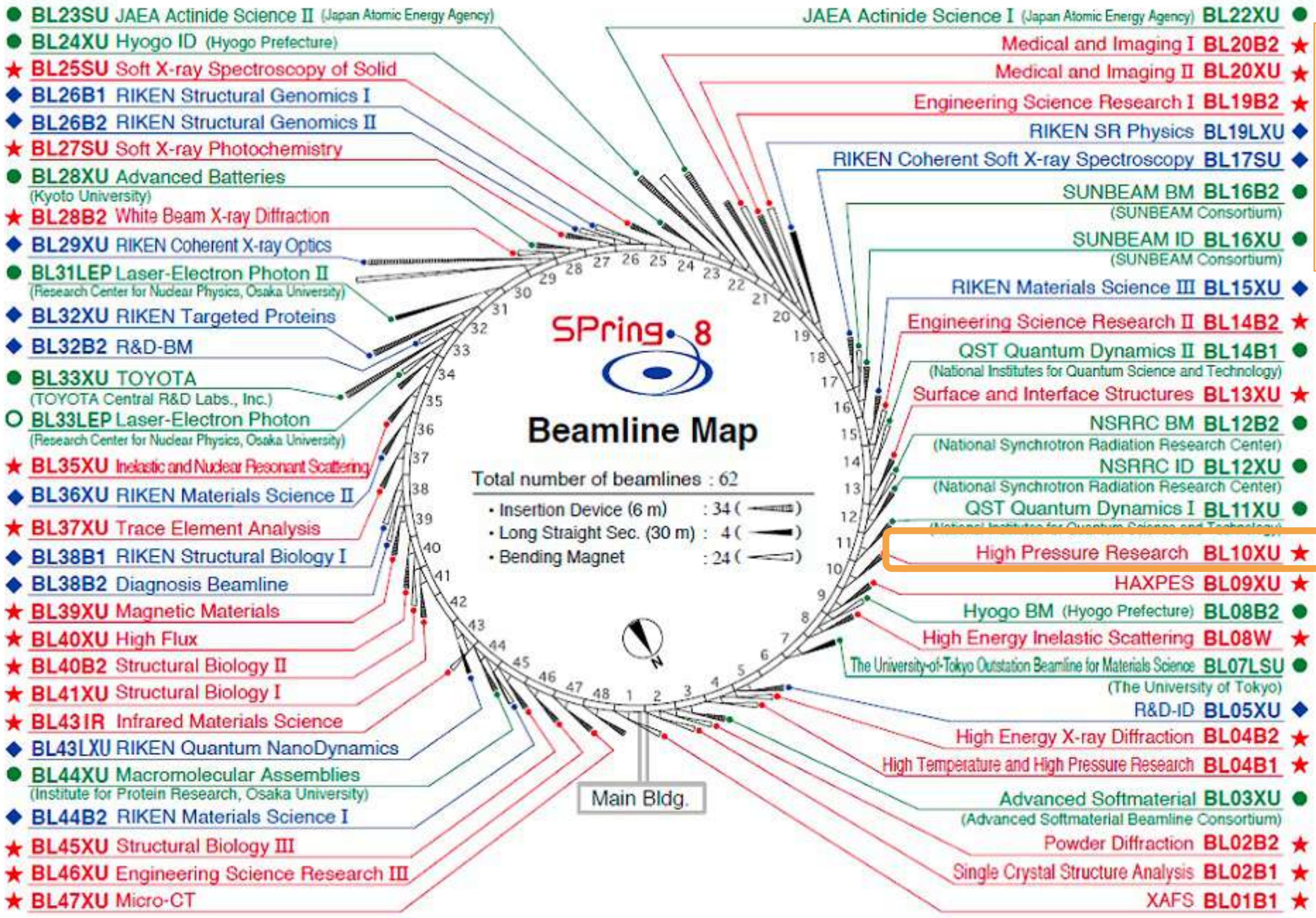
Electromagnetic Spectrum

Light from the KEK Photon Factory
- continuous spectrum from ultraviolet to X-rays
- highly collimated, polarized light
- pulsed light with the pulse widths about 100 ps.



https://www2.kek.jp/imss/pf/eng/about/sr/lightspectrum2020_en.png

Example : SPring-8



https://new.spring8.or.jp/index.php/spring8/bl?lang=ja#

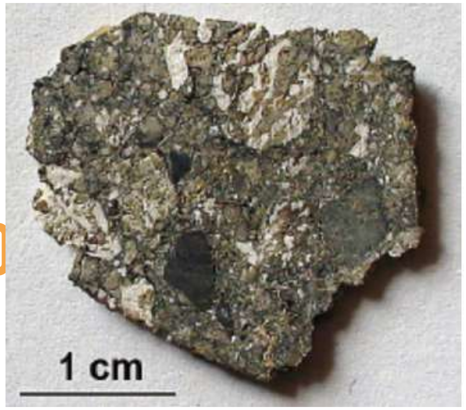
SCIENCE ADVANCES | RESEARCH ARTICLE

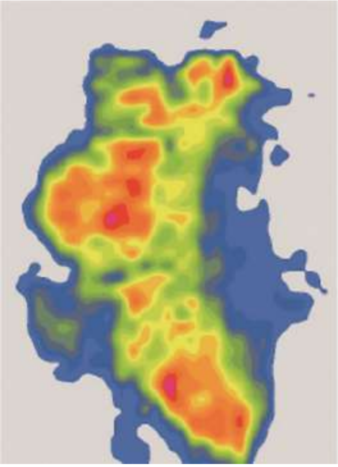
PLANETARY SCIENCE

Discovery of moganite in a lunar meteorite as a trace of H_2O ice in the Moon's regolith

Masahiro Kayama,[1,2]* Naotaka Tomioka,[3] Eiji Ohtani,[1] Yusuke Seto,[4] Hiroshi Nagaoka,[5] Jens Götze,[6] Akira Miyake,[7] Shin Ozawa,[1] Toshimori Sekine,[8,9] Masaaki Miyahara,[8] Kazushige Tomeoka,[4] Megumi Matsumoto,[4] Naoki Shoda,[4] Naohisa Hirao,[10] Takamichi Kobayashi[11]

lunar meteorite "NWA2727"





Micro-Raman spectroscopy

Moganite (reddish color) indicates existence of water beneath the Moon's surface

Various types of accelerators

- Light sources
- Synchrotron
  - J-PARC
- Colliders
  - SuperKEKB
- Many other
  - Application

The synchrotron is one of the first accelerator concepts to enable the construction of large-scale facilities, since bending, beam focusing and acceleration can be separated into different components.

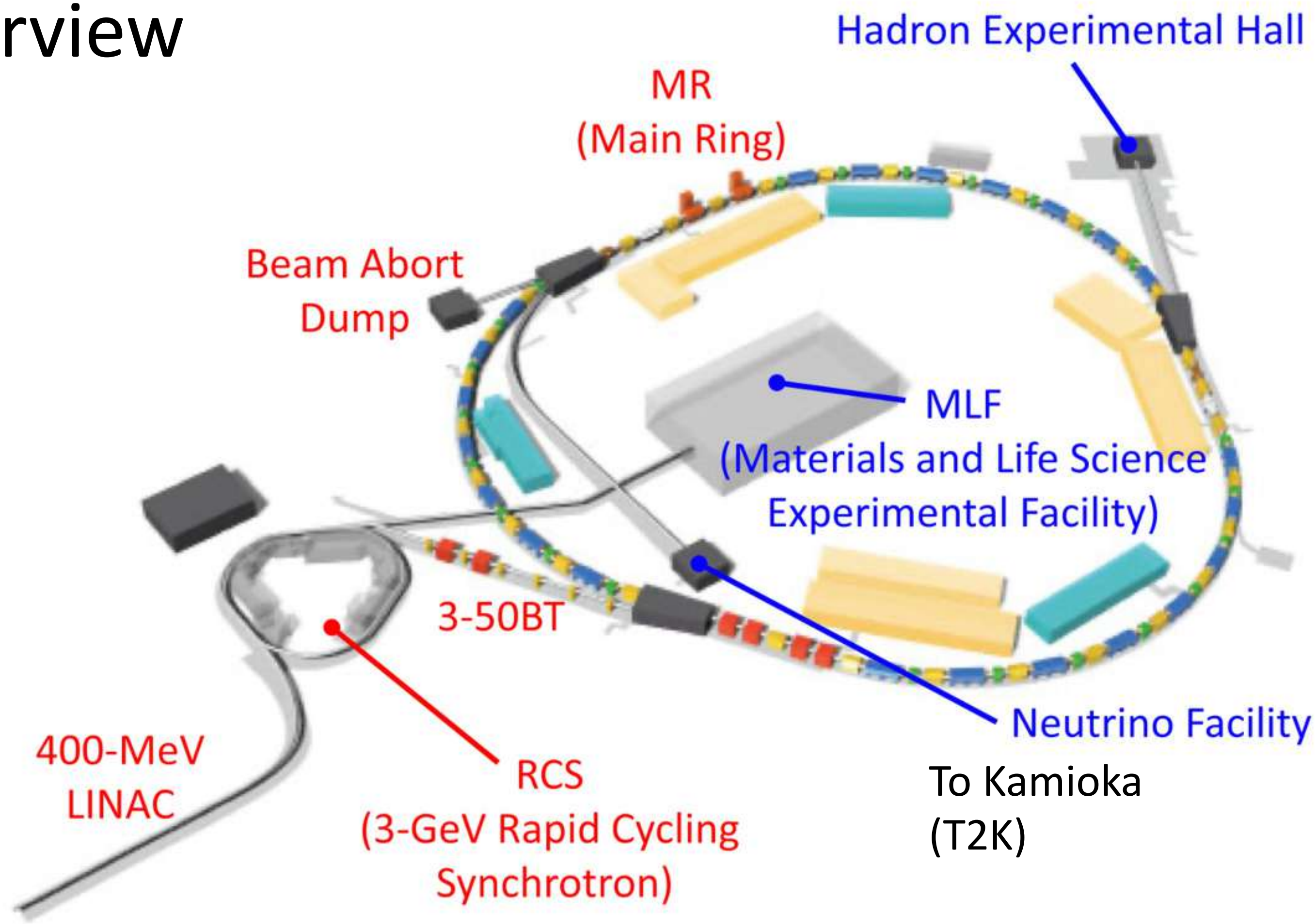
https://en.wikipedia.org/wiki/Synchrotron

J-PARC/ SuperKEKB

J-PARC Fixed Target

- Key words : Storage Ring, Proton Synchrotron, high-energy proton beam, High-Intensity Proton Accelerator Facility Project
- J-PARC is a multi-purpose facility. It can deliver varieties of secondary-particle beams. Neutron, pion, kaon and neutrino beams are all produced at J-PARC via collisions between the proton beams and target materials.
- Goals
  - Research in fundamental nuclear and particle physics, materials and life science
  - Development in nuclear technology.

Overview

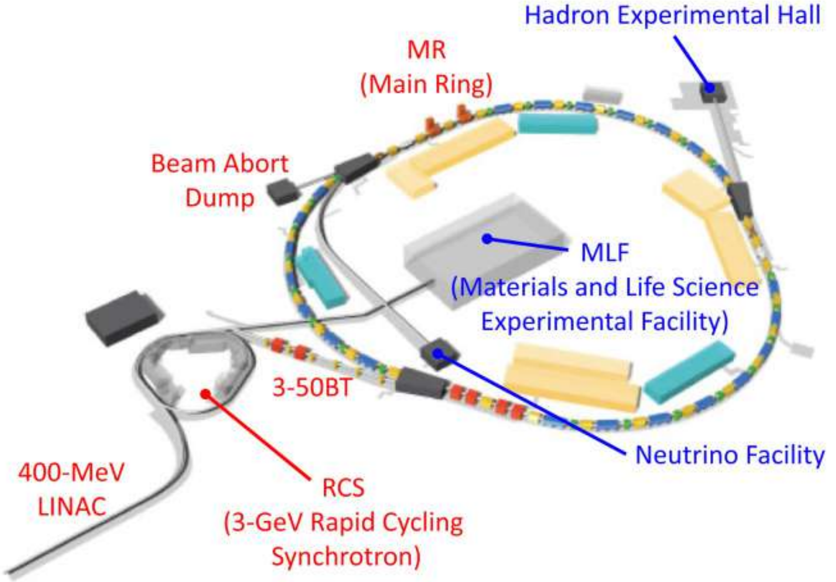


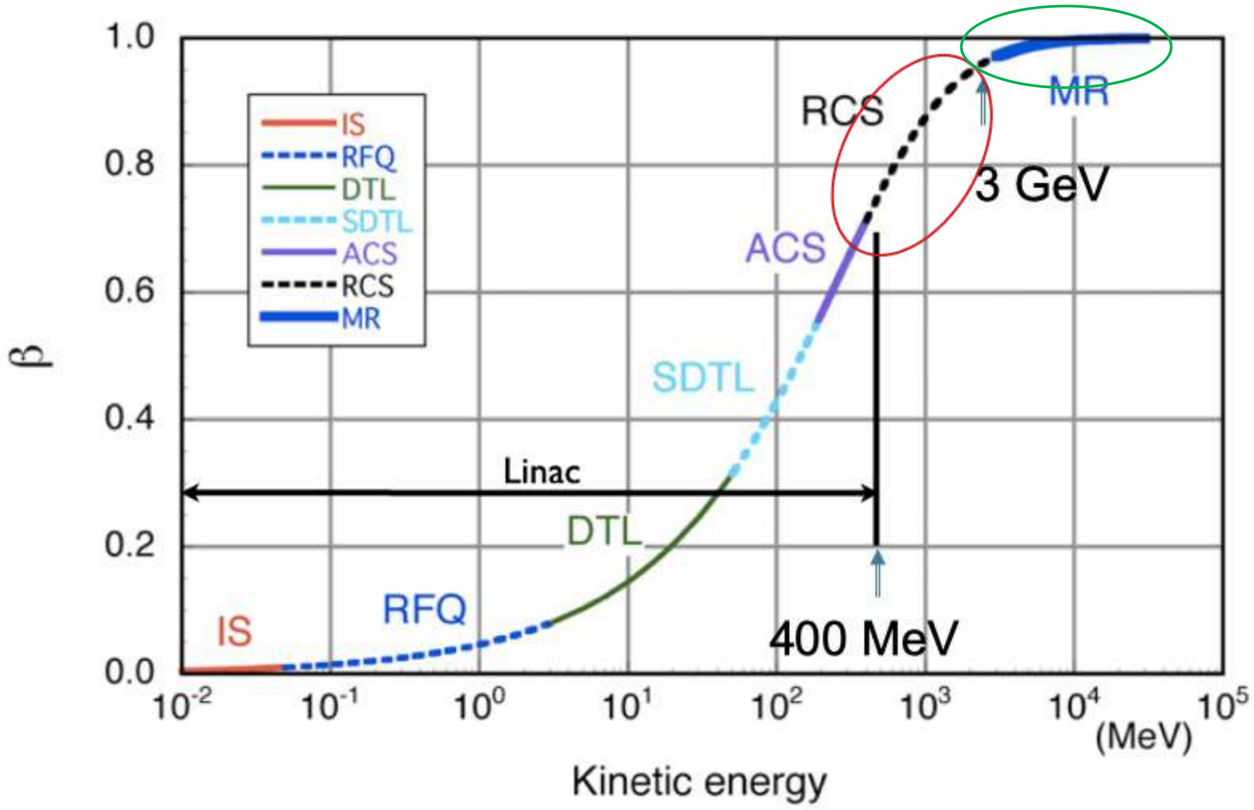
J-PARC has three proton accelerators:

- a 400 MeV linear accelerator
- a 3 GeV rapid-cycling synchrotron (RCS)
- a 50 GeV (currently 30 GeV) main ring (MR)

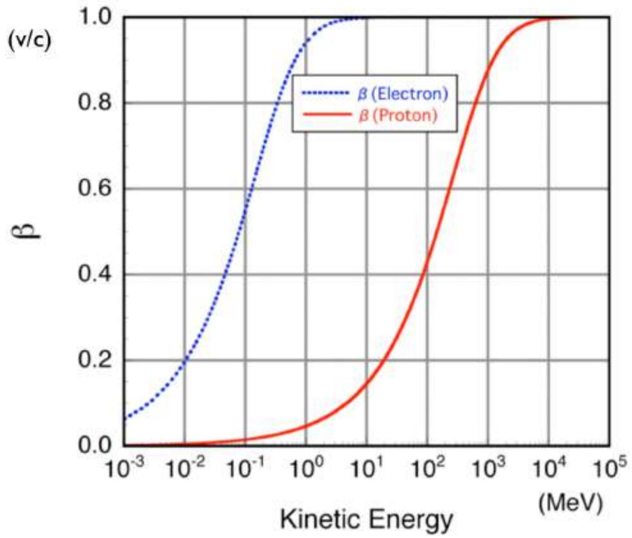
Provides the desired secondary particle beam to each facility

Overview



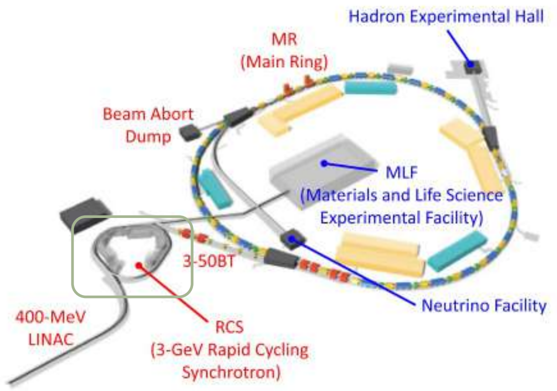


- The RF frequency has to be changed by ~30% as the protons are accelerated (β increases) and circulate faster in RCS.
- Even in the MR, the speed changes (β increases) by about 3% and the RF frequency needs to be changed.

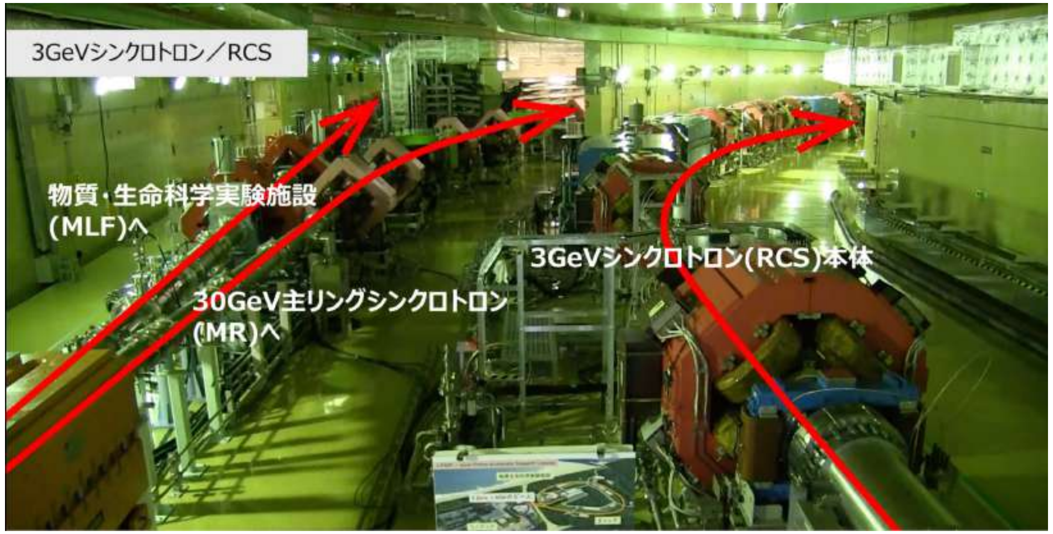


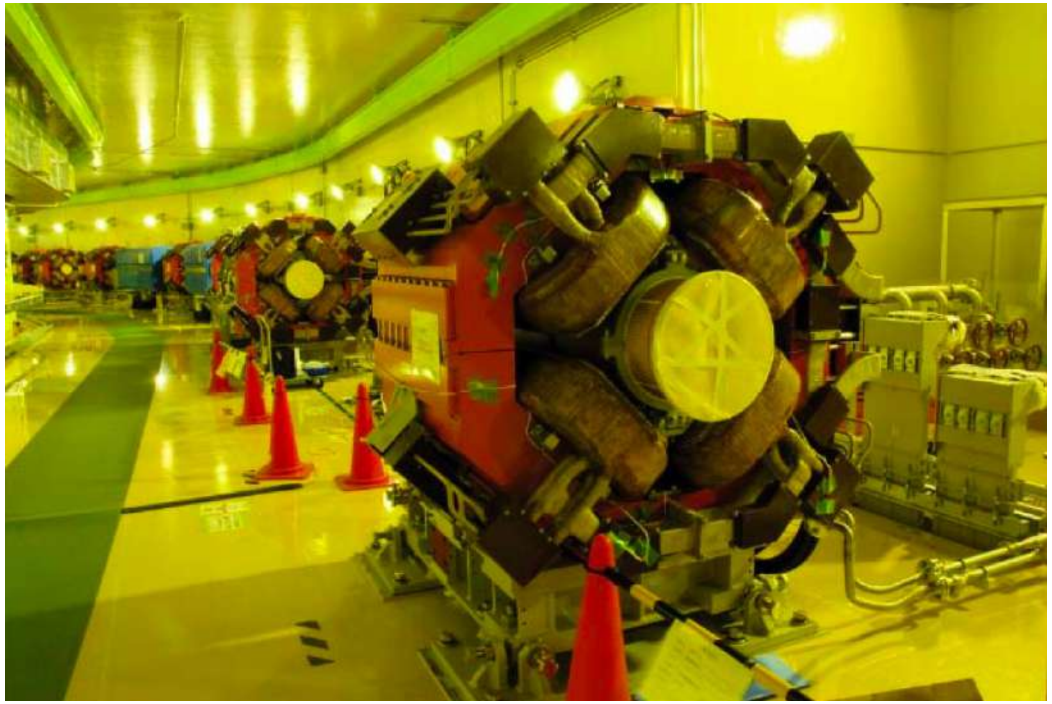
Very complicated operation is needed as β increases, which is quite different from an electron machine.

RCS



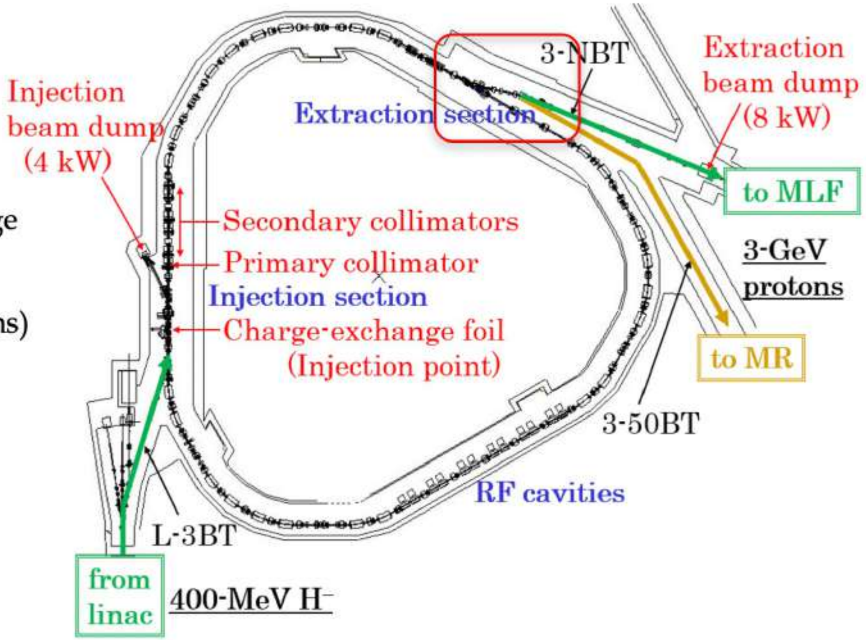
RCS (Rapid-Cycling Synchrotron)



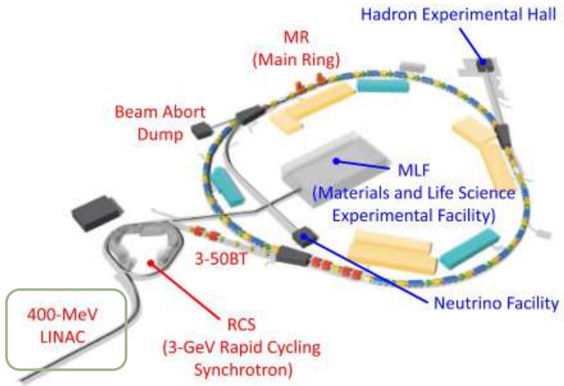


J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

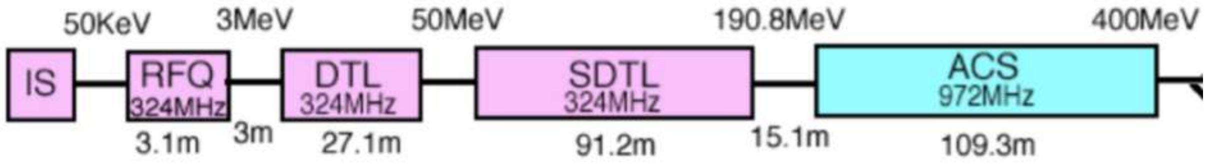
Circumference	348.333 m
Superperiodicity	3
Harmonic number	2 (2 bunches)
Injection	Multi-turn, charge-exchange
Injection energy	400 MeV
Injection period	0.5 ms (307 turns)
Injection peak current	50 mA
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	8.33 x 10^{13}
Beam power	**1 MW**



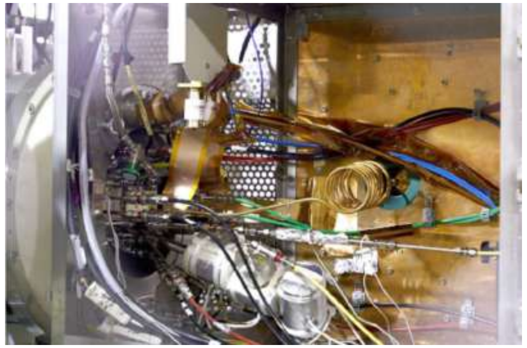
LINAC



Accelerating RF structures



Ion source (H-)



Drift Tube Linac (DTL)
Up to 3 MeV

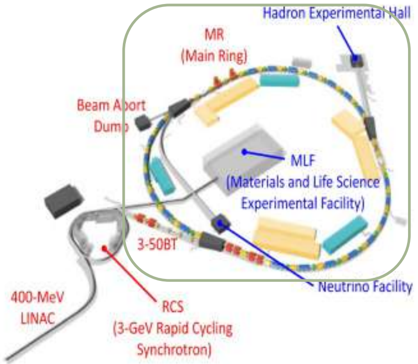
RFQ (Radio Frequency Quadrupole Linac)
Up to 50 MeV

SDTL（Separated DTL）
Up to 190 MeV

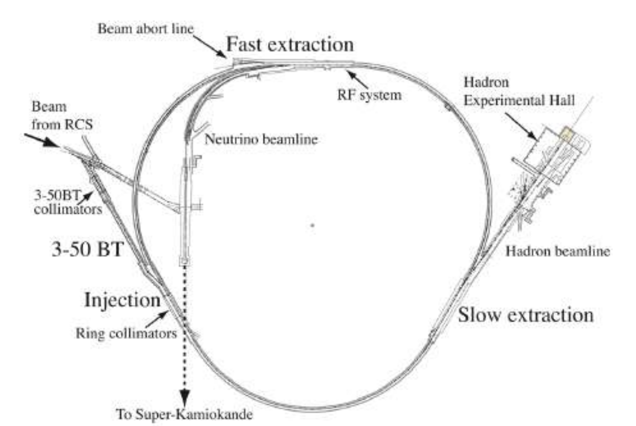
ACS（Annular-ring Coupled Structure Linac）
Up to 400 MeV

Various types of accelerating RF structures are needed to accelerate protons efficiently in the LINAC.

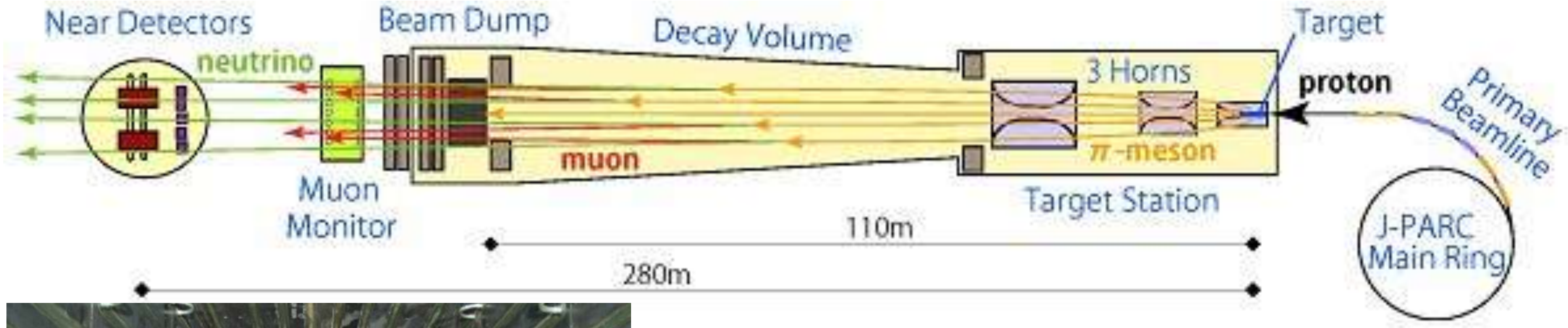
Main Ring (MR)

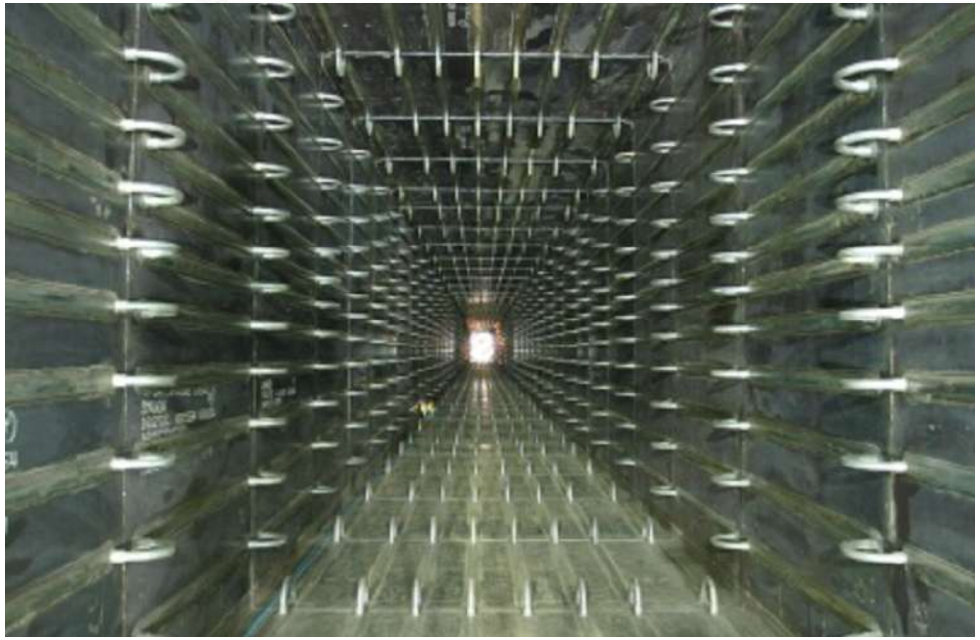


Circumference [m]	1567.5
Superperiodicity	3
Typical cycle time for FX [s]	2.56
Typical cycle time for SX [s]	6.0
Injection energy [GeV]	3
Extraction energy [GeV]	30
Harmonic number	9
Number of bunches	8
Typical transition gamma	j31
Physical aperture [π mm-mrad]	>81
Collimator aperture [π mm-mrad]	54–81
Number of bending magnets	96
Number of quadrupole magnets	216
Number of sextupole magnets	72
rf frequency [MHz]	1.67–1.72
Number of rf systems	9



Neutrino





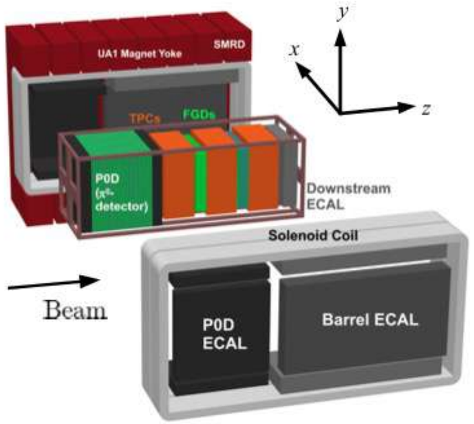
Protons are extracted from the MR
Protons collide with a graphite target and produce many particles
Among many particles, π^+'s go forward under the effect of magnetic horns. Magnetic horns are magnets designed to focus π^+'s by applying a few hundred thousand amperes of pulsed current synchronized with each beam shot.

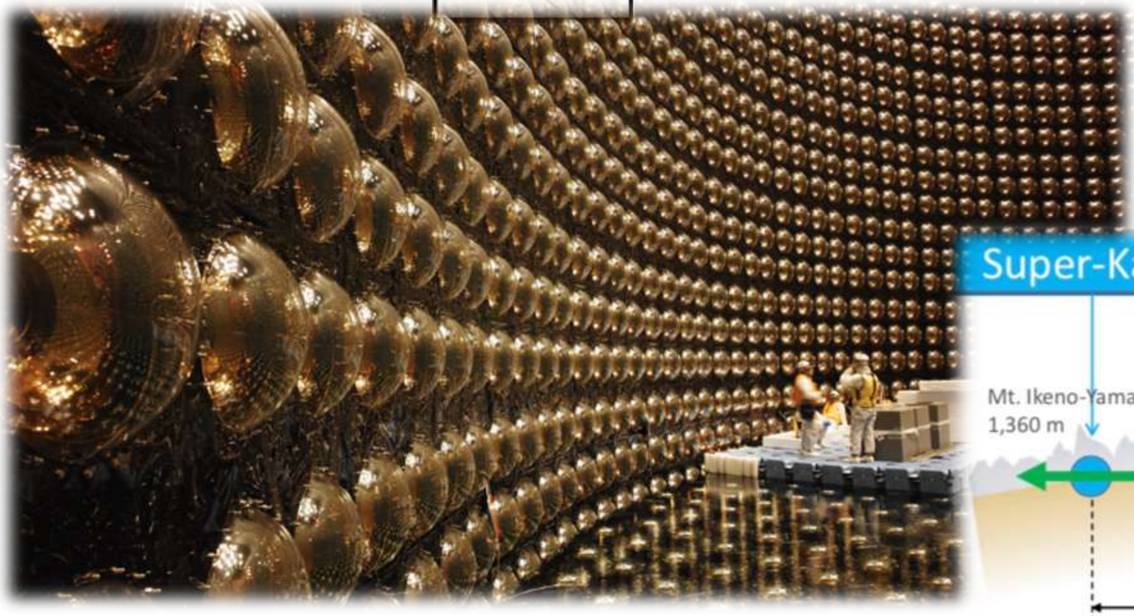
In the 100m long tunnel (decay volume) π^+'s decay primarily

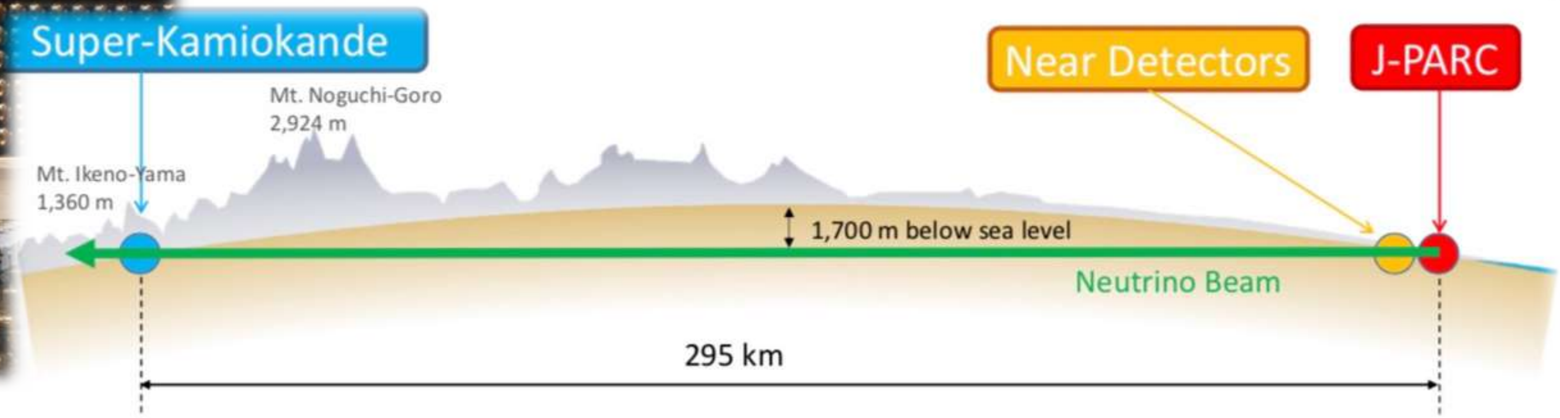
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Neutrino

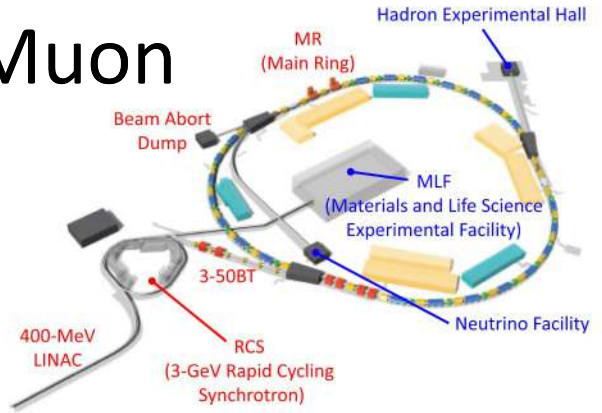
T2K is a neutrino experiment designed to investigate how neutrinos change from one flavour to another as they travel (neutrino oscillations).
An intense beam of muon is measured once before it leaves the J-PARC site, using the near detector ND280, and again at Super-K: the change in the measured intensity and composition of the beam is used to provide information on the properties of neutrinos.
https://t2k-experiment.org



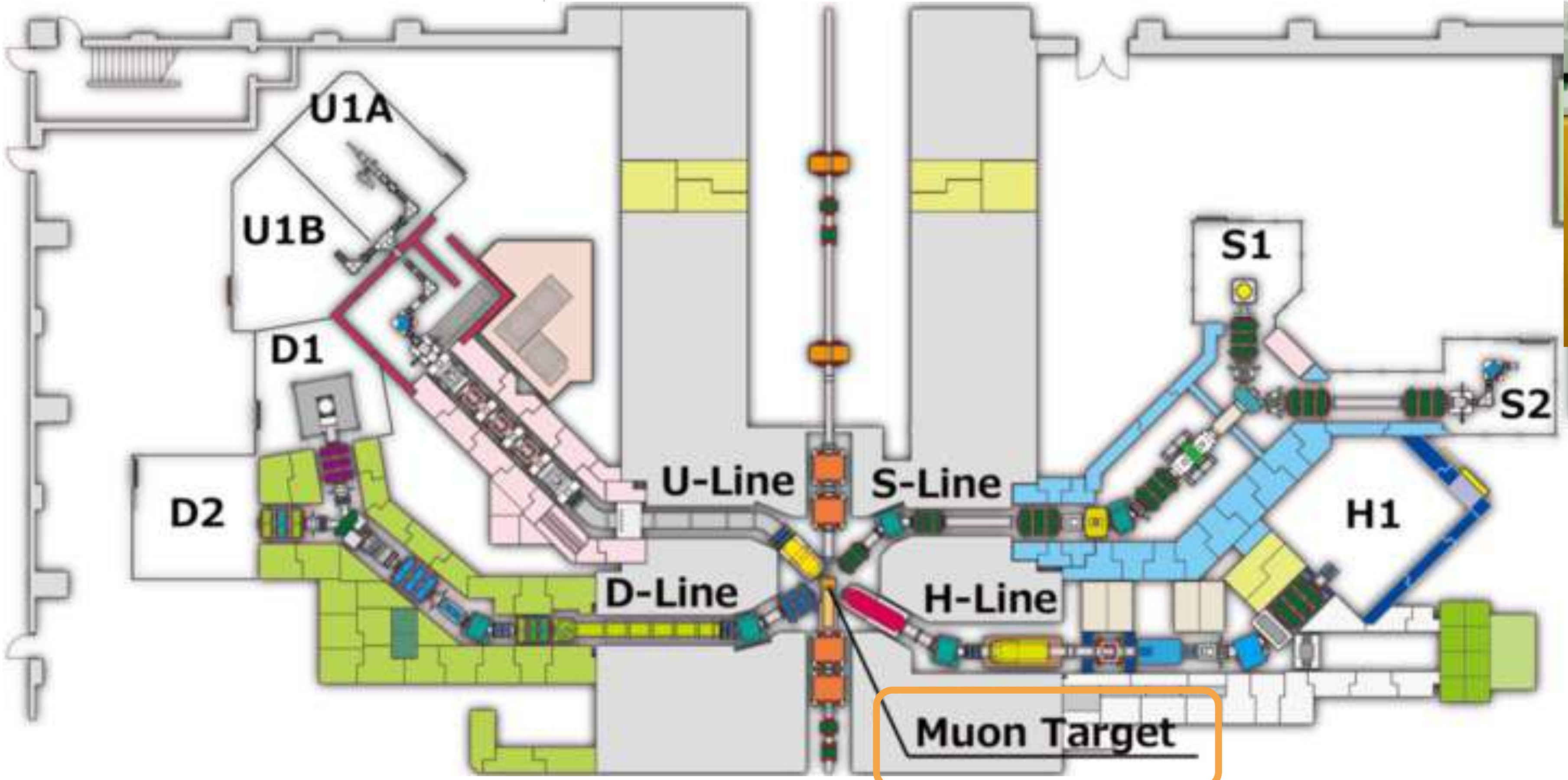




Muon

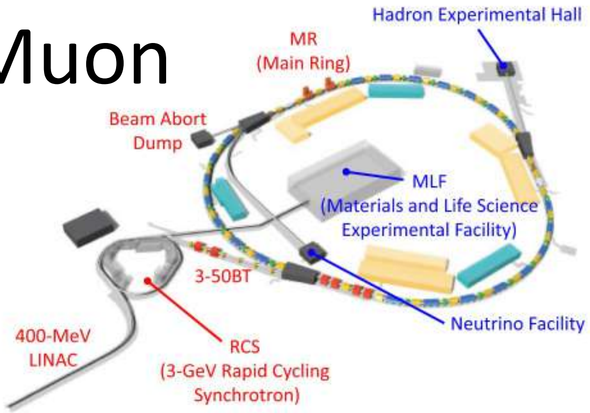


Muon Facility in MUSE

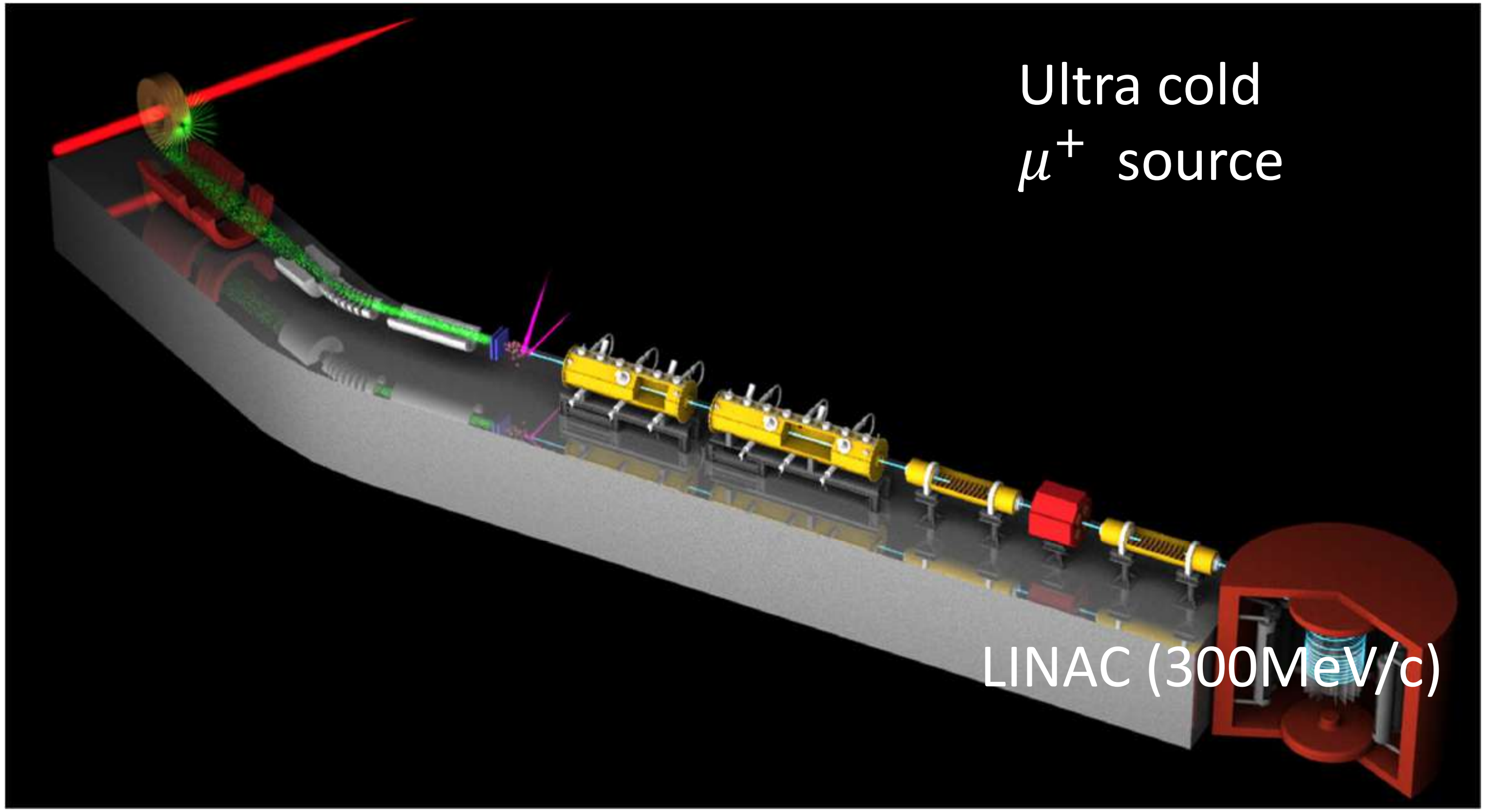


H-Line
High Momentum
Muon Beam Line
→g-2

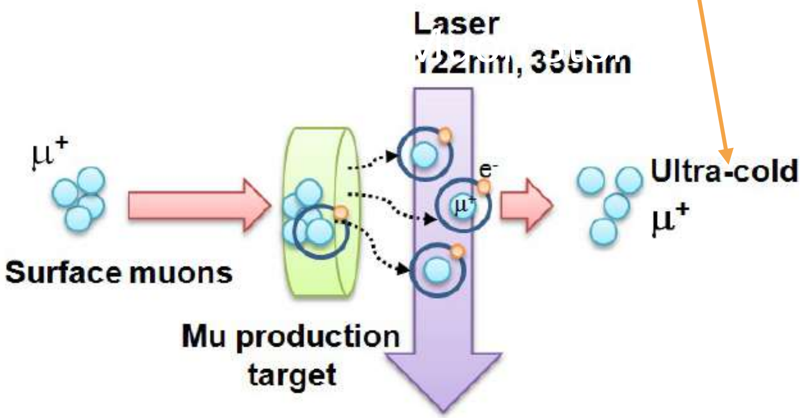
Muon



- μ^+ having a speed of about 30% the speed of light produced in a proton accelerator are shot into a material called silica aerogel.
- μ^+s combine with e^-s in silica aerogel to form muoniums.

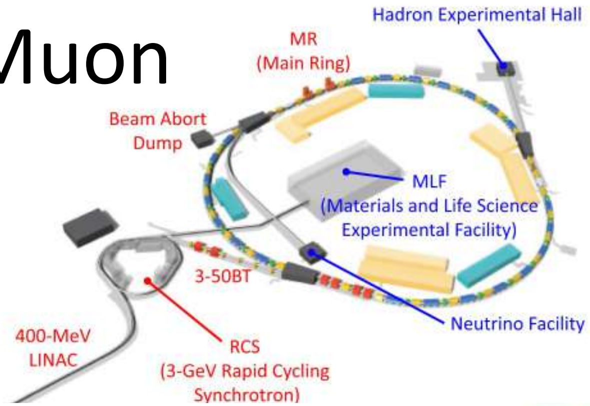


- Irradiating the muonium with a laser to strip off an electron, we obtain μ^+s that have been cooled to a nearly stopped velocity at around 0.002% of the speed of light.



https://j-parc.jp/c/en/press-release/2024/05/23001341.html

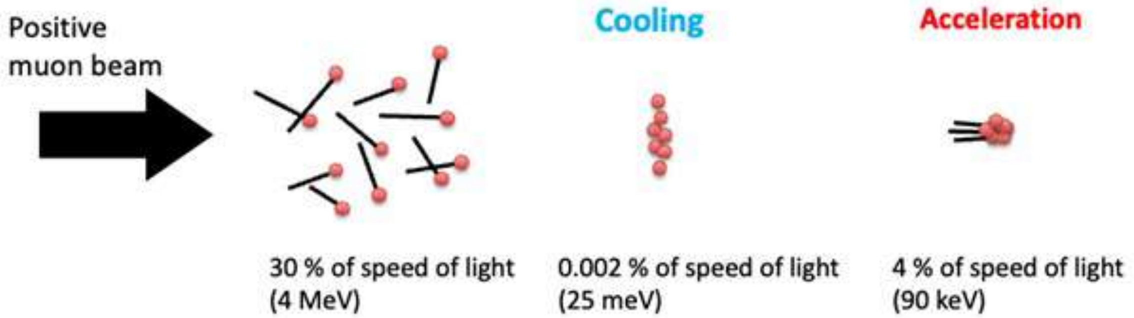
Muon

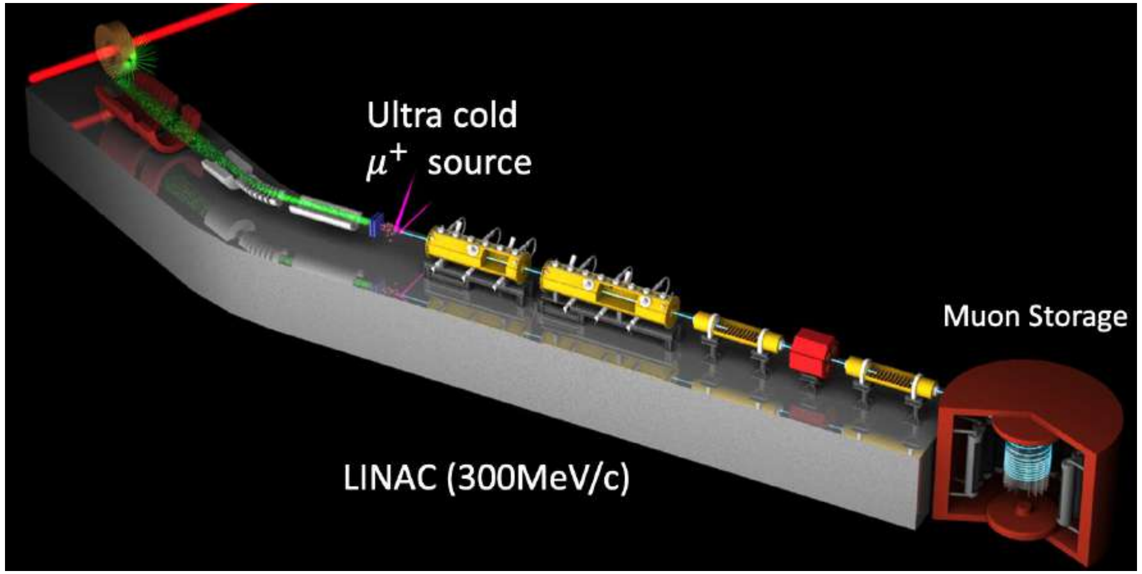


2024.05.23

Congratulations !

World's first cooling and acceleration of muon
- The first muon accelerator finally coming to a reality. -





https://j-parc.jp/c/en/press-release/2024/05/23001341.html

World first The experimental set up for muon cooling and acceleration at J-PARC. A beam of antimatter muons enters the apparatus from the right. Credit: J-PARC

Various types of accelerators

- Light sources
- Synchrotron
  - J-PARC
- Colliders
  - SuperKEKB
- Many other
  - Application

https://www2.kek.jp/ilc/en/

https://fccis.web.cern.ch/host-states-gear-work-fcc

Linear or circular?

SR is an electric dipole radiation from a charged particle in acceleration $\dot{\vec{v}}$
Radiation power in the rest frame is given by Larmor's formula:

$$P = \frac{2r_e m_e}{3c}\left(\frac{d\vec{v}}{dt}\right)^2, \text{ where } r_e \equiv \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.82\times10^{-15}(m)$$

The radiated energy per turn ΔE for a ring of radius r

$$\frac{\Delta E}{m_e C^2} = \frac{4\pi}{3}\frac{r_e}{\rho}\beta^3\gamma^4$$

Practical formula
$\Delta E(keV) \approx 88.5[E(GeV)]^4/\rho(m)$

For relativistic protons and electrons of the same momentum, the energy loss is in the ratio $(m_e/m_p)^4$~10^{13}.

It is 10^{13} times smaller for protons than for electrons.

When it comes to SR loss

- Proton has an advantage $\left(\frac{938.26}{0.511}\right)^4 \sim 10^{13}$!!!
- Large ring radius (large circular machine) has an advantage

Various types of accelerators

- Light sources
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  - J-PARC
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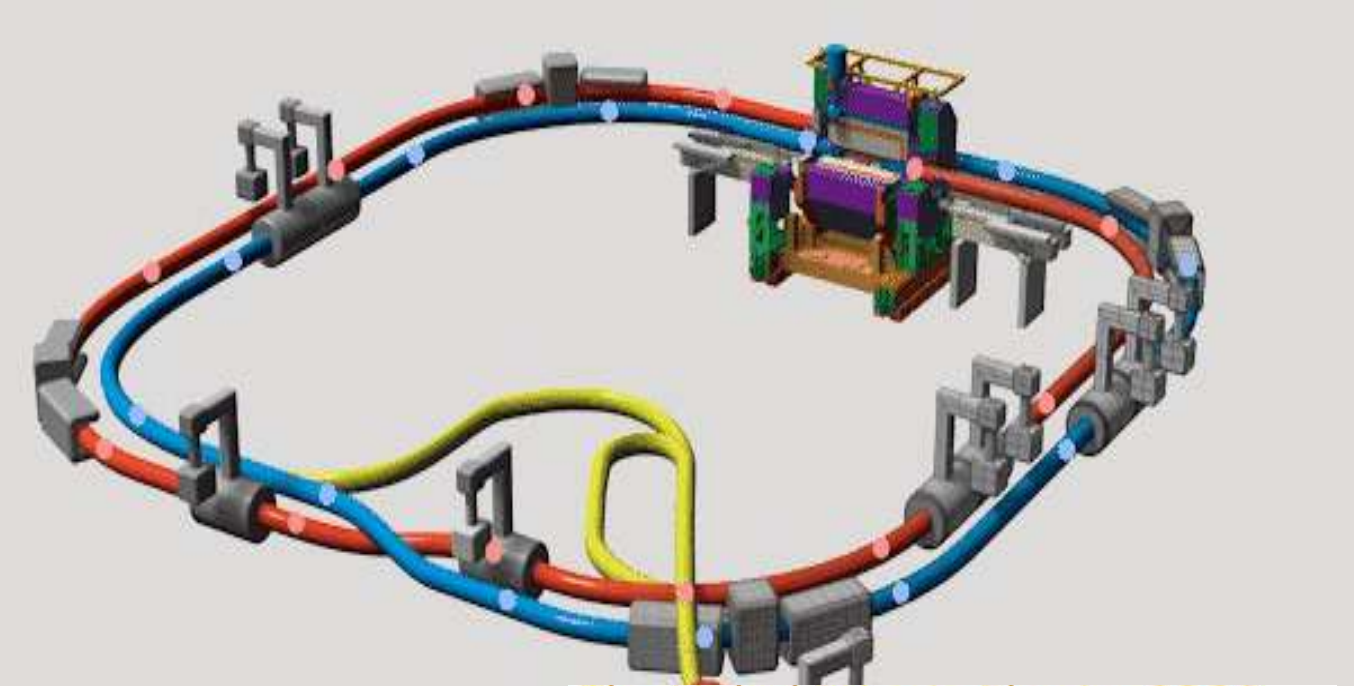
  - Application

J-PARC/ SuperKEKB

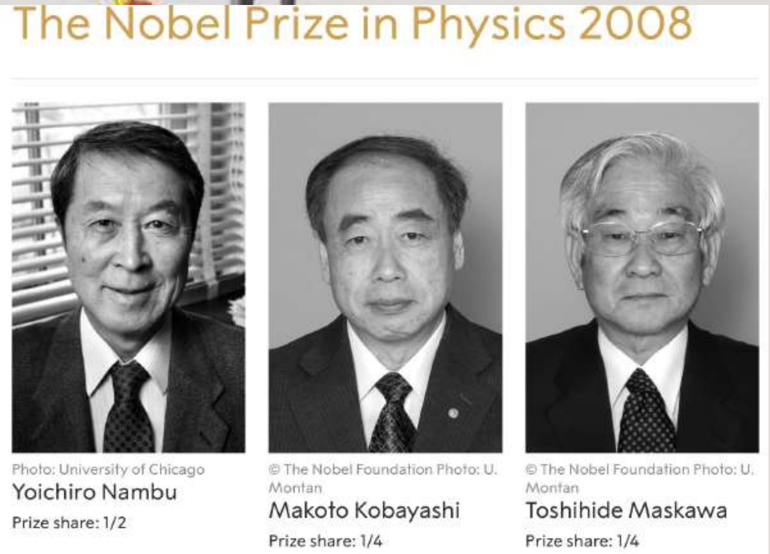
SuperKEKB Luminosity frontier



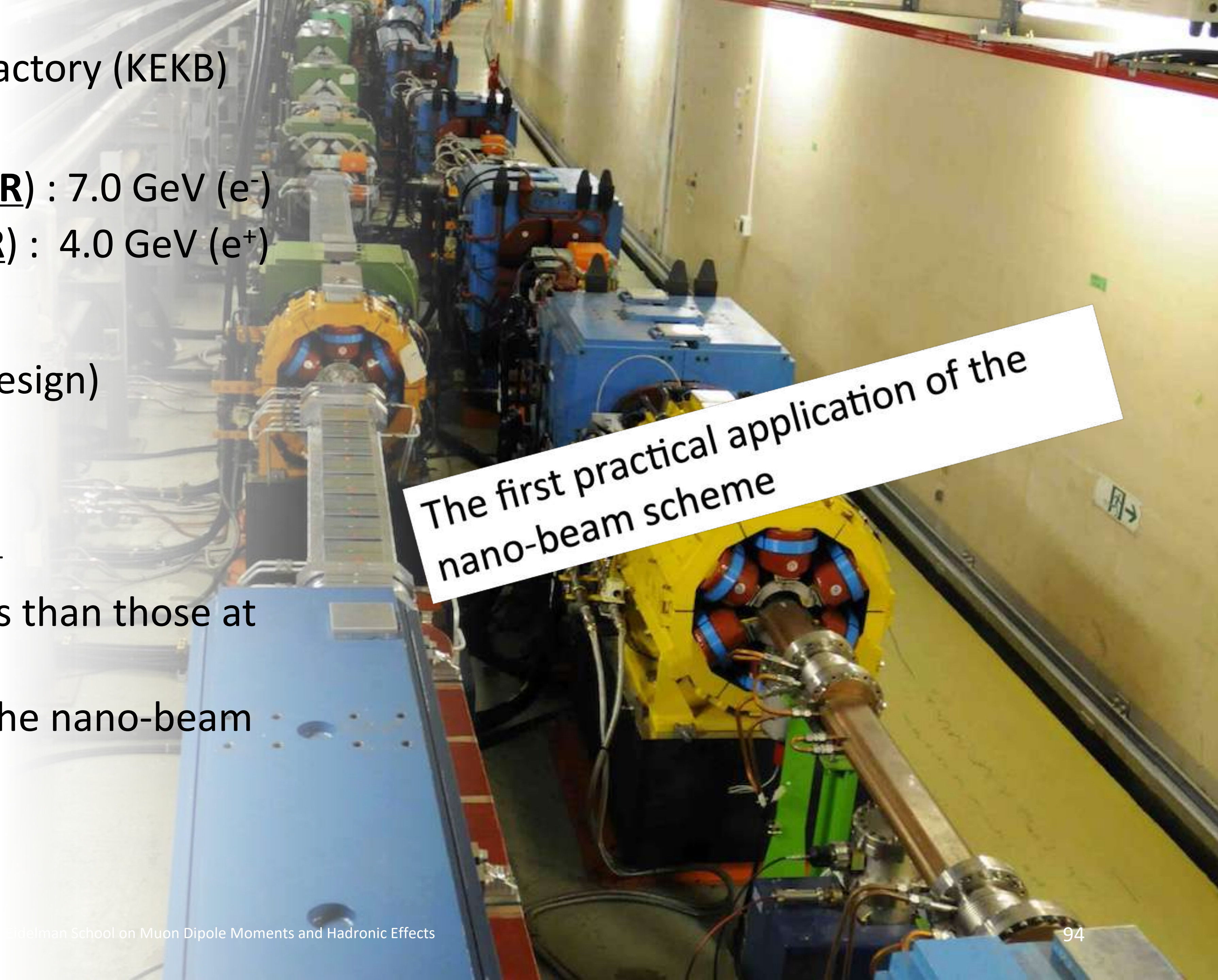
Key words : Storage Ring, Synchrotron, luminosity frontier, small beam, KEKB

- Background
- KEKB collider, which was SuperKEKB's predecessor, generated sooooooo many e^+e^- collisions with very high luminosity (2.11×10^{34} cm^{-2} s^{-1}) and demonstrated the CP violation proposed by Dr. Kobayashi and Dr. Maskawa, who received the 2008 Nobel Prize in Physics.
- Goal

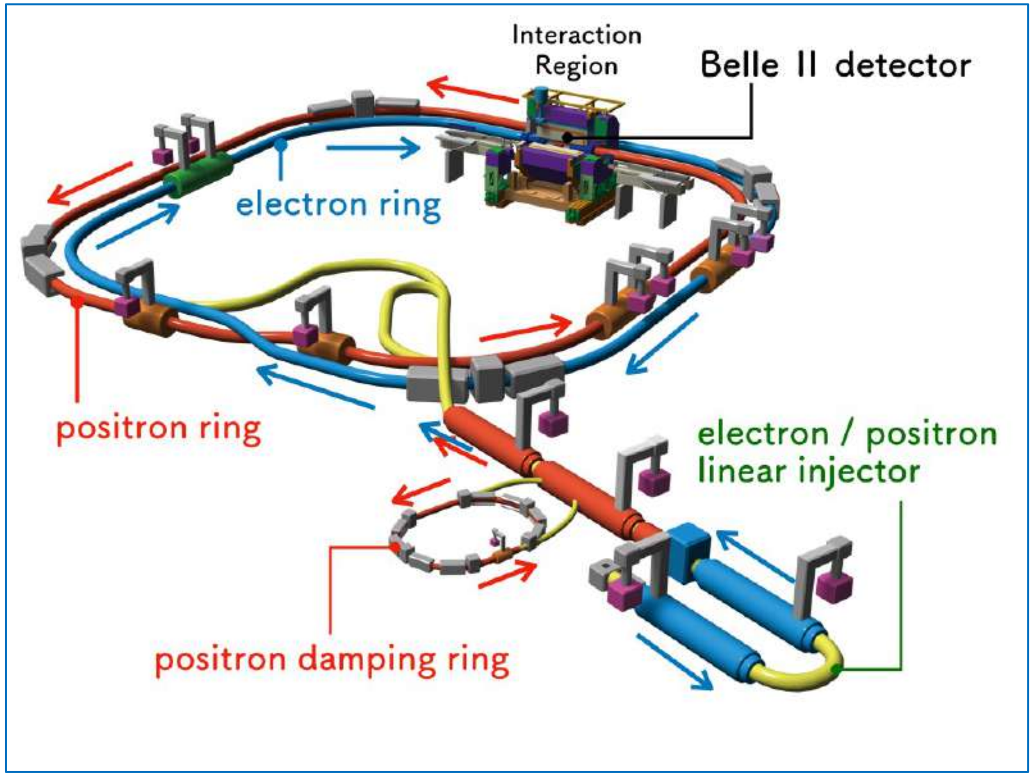
The next target is several tens of times higher luminosity, to discover new physics beyond the Standard Model.



- Upgraded from KEKB B-factory (KEKB)
- Stored-beam energies
  - **<u>H</u>**igh **<u>E</u>**nergy **<u>R</u>**ing (**<u>HER</u>**) : 7.0 GeV (e^-)
  - **<u>L</u>**ow **<u>E</u>**nergy **<u>R</u>**ing (**<u>LER</u>**) : 4.0 GeV (e^+)
- $E_{\mathrm{cms}} \approx M_{\Upsilon(4S)}$
- Stored-beam currents (design)
  - HER : 2.6 A
  - LER : 3.6 A
- Toward $6.0\times10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Higher beam currents than those at KEKB
  - Squeezing β_y^* with the nano-beam collision scheme



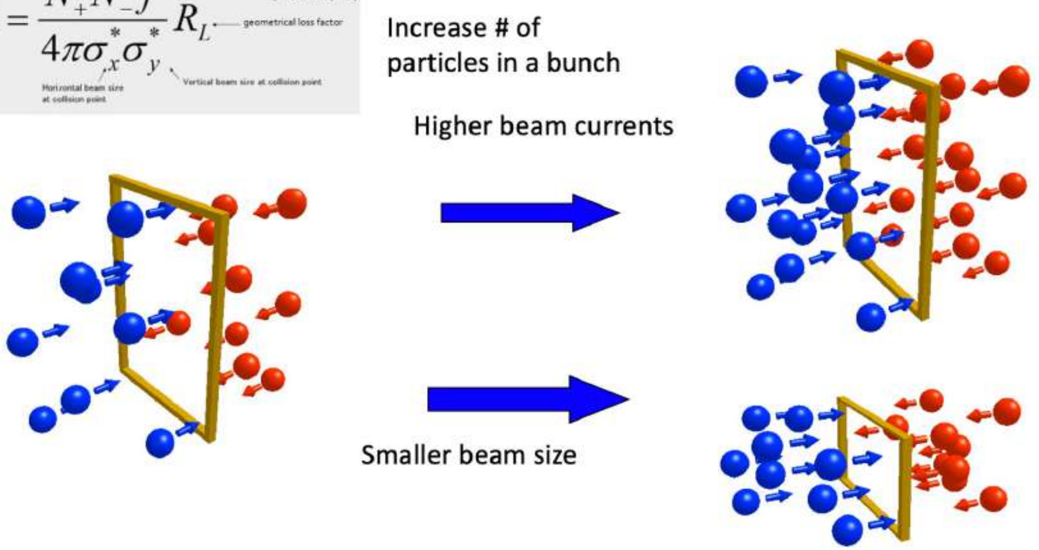
The first practical application of the nano-beam scheme



Strategy for higher luminosity than its predecessor KEKB

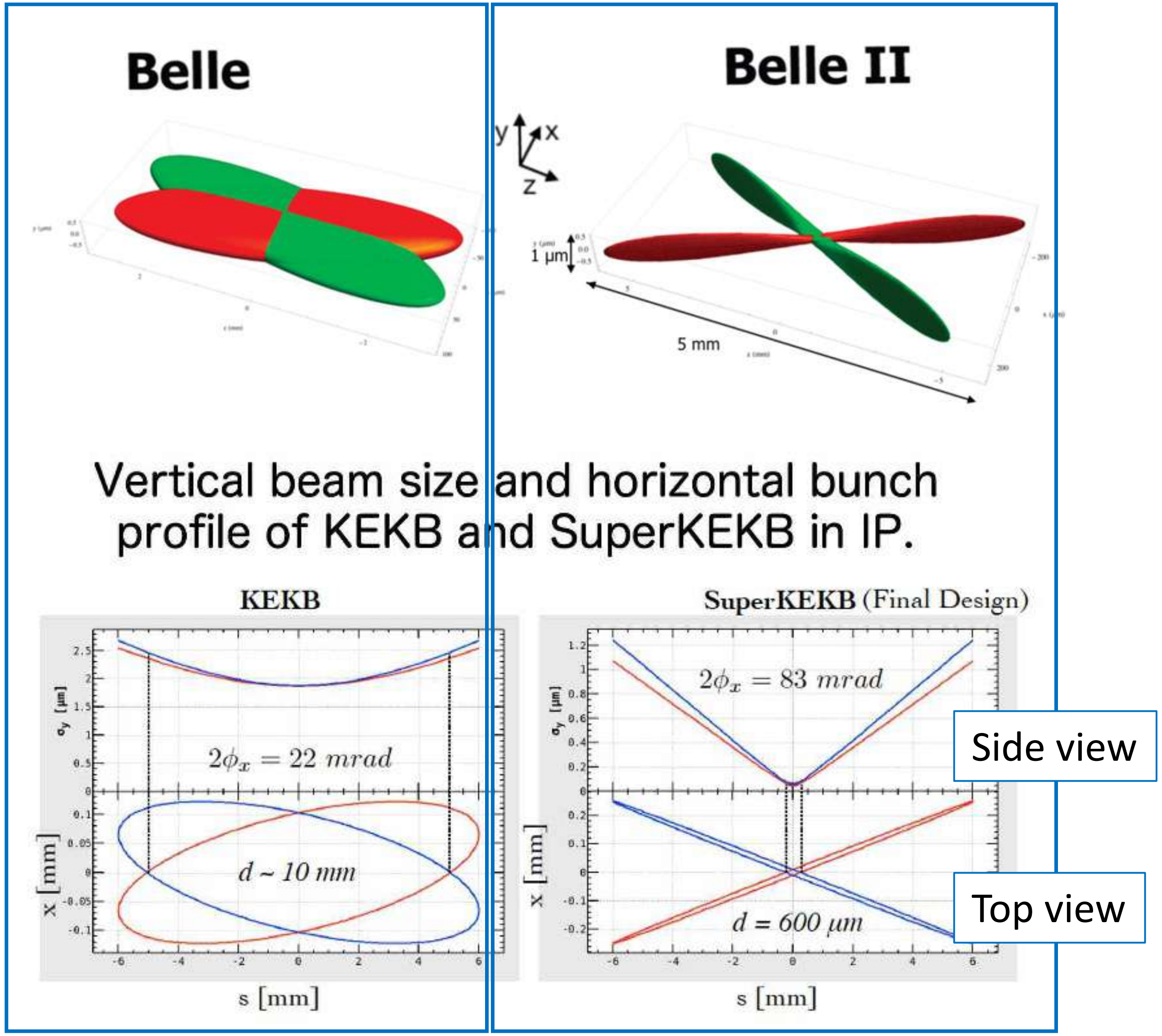
$$L = \frac{N_+ N_- f}{4\pi\sigma_x^* \sigma_y^*} R_L$$

Number of positrons in a bunch
Number of electrons in a bunch
Collision frequency of bunches
$f = n_b f_0$ — n_b: No. of bunches, f_0: rotation frequency
R_L: geometrical loss factor
Horizontal beam size at collision point
Vertical beam size at collision point

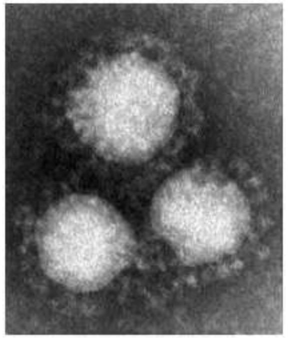


7 GeV Electron beam (High Energy Ring HER) and 4 GeV Positron beam (Low Energy Ring)
Colliding at one interaction point at E_{cm} = 10.58 GeV Υ(4S)
~3 km in circmferece

Innovative “Nano-beam scheme” of SuperKEKB

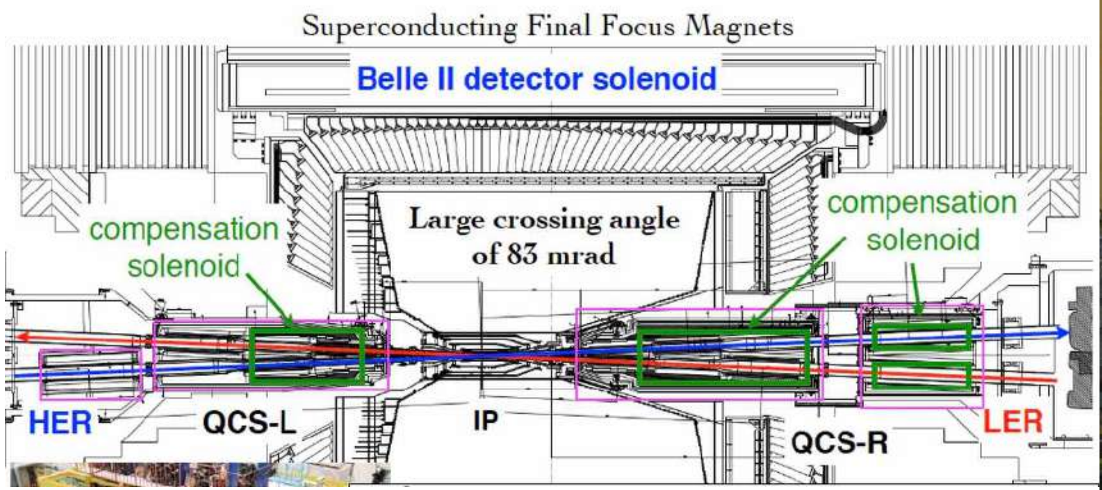


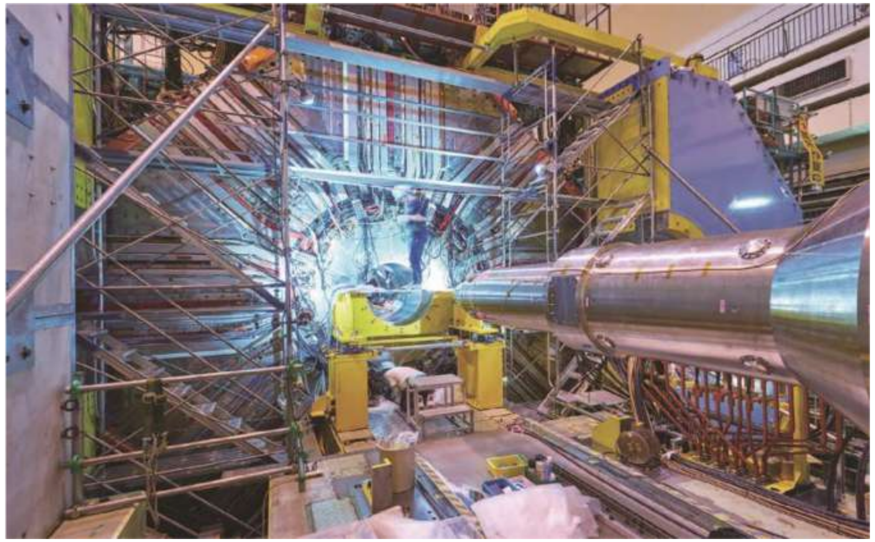
- Narrow and thin beam
- Vertical size is 50-60 nm at the IP
- Larger crossing angle of about degree.



Design vertical beam size ~COVID19 virus

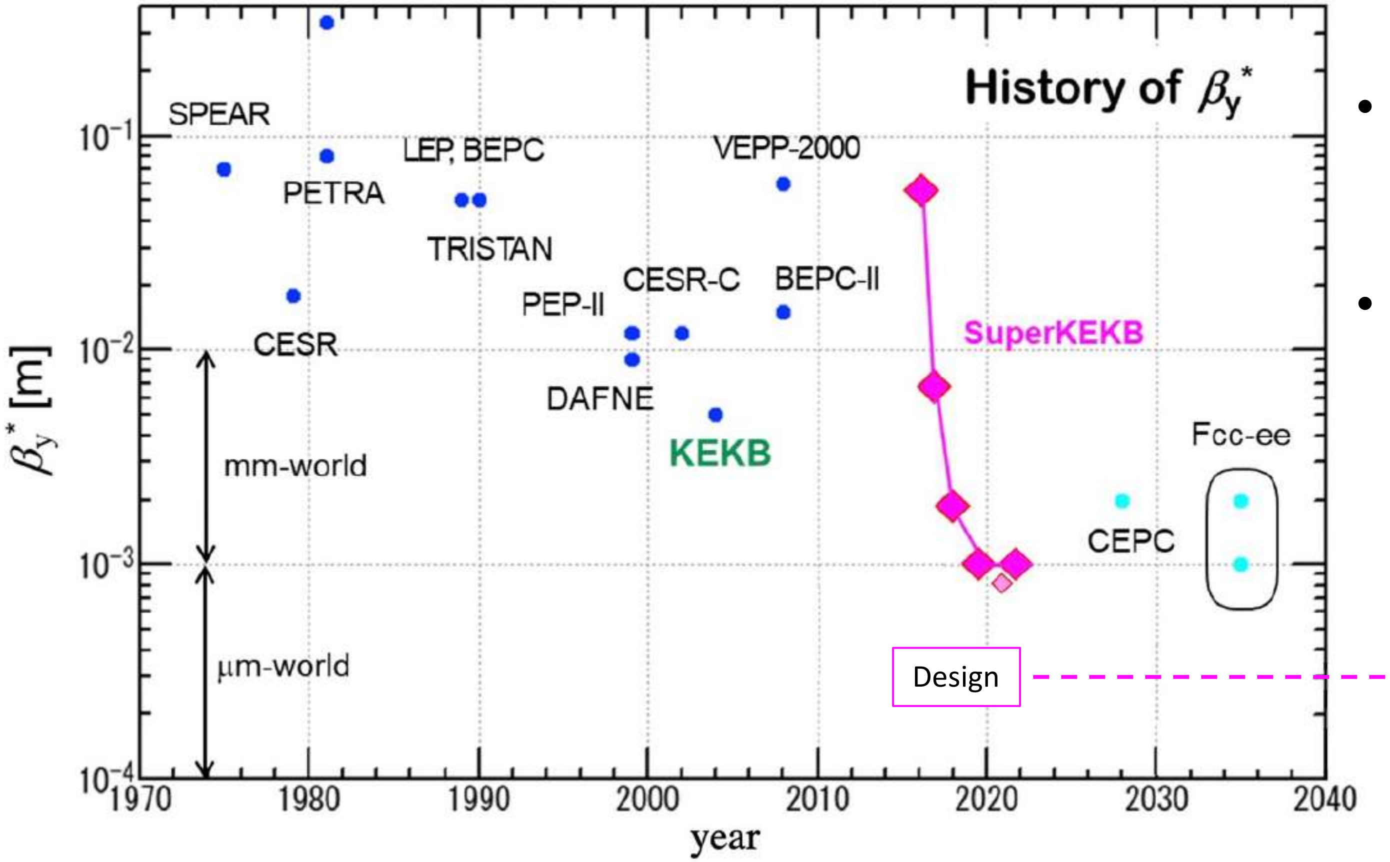
Innovative "Nano-beam scheme" of SuperKEKB



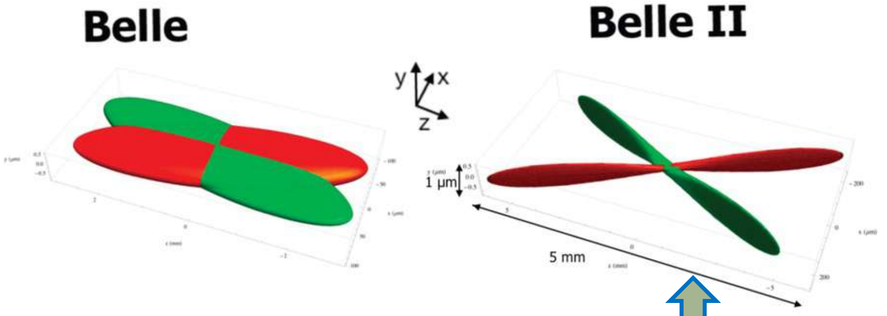


Superconducting final focusing magnet system (QCS)
provides strong focusing to the HER/LER beams.

Beam squeezing



- In 2022 run, the vertical beta-function at the interaction point, β_y^* , was 1.0 mm.
- A β_y^* of 0.8 mm was tried in preparation for a future operation with smaller β_y^* , toward the design values of 0.27 mm and 0.3 mm for LER and HER, respectively.



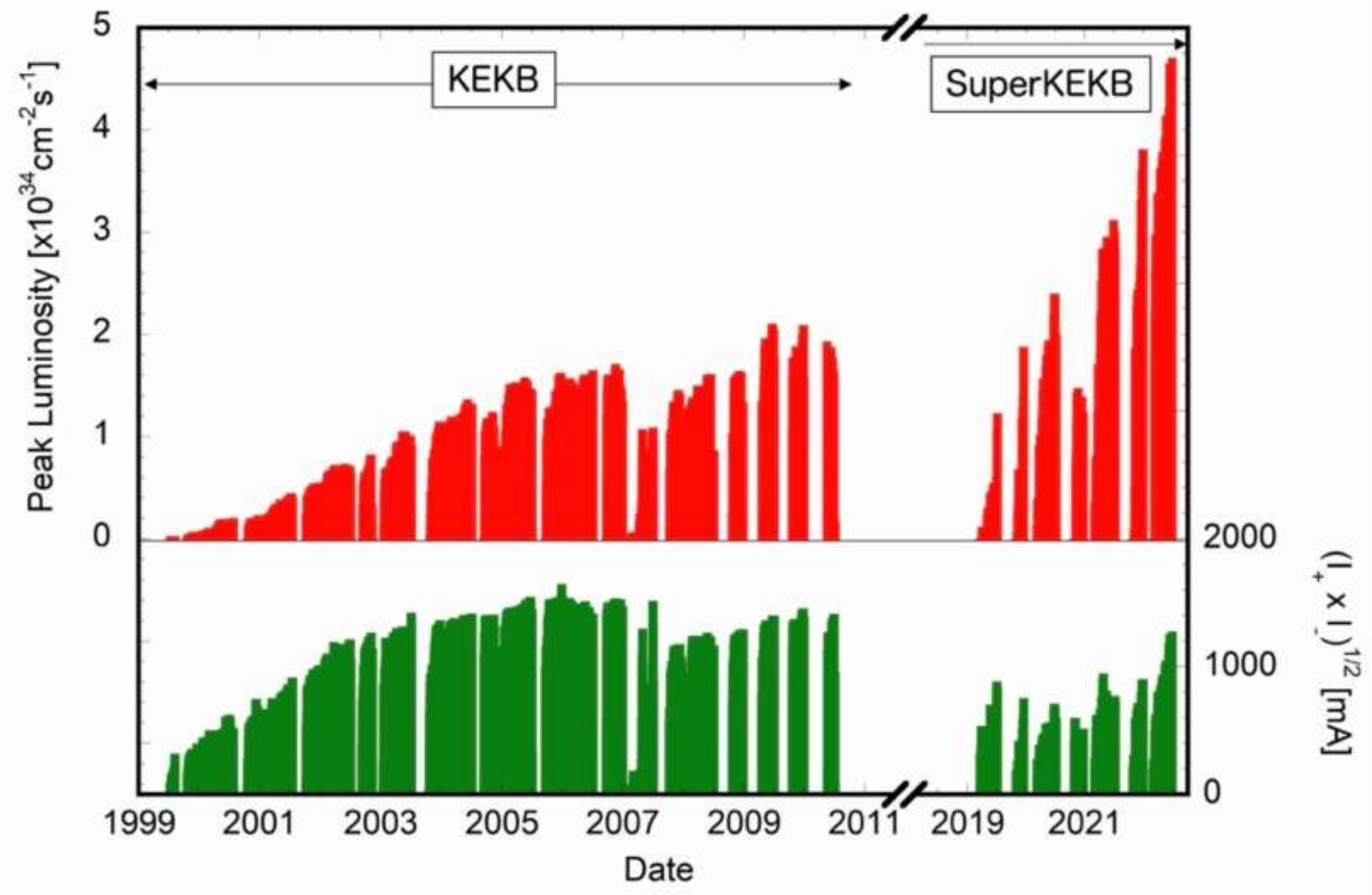
Nano-beam scheme
Squeeze the two beams in both the horizontal and vertical directions to achieve higher luminosity

$$L = \frac{N_+ N_- f}{4\pi\sigma_x^* \sigma_y^*} R_L$$

Number of positrons in a bunch; Number of electrons in a bunch; Collision frequency of bunches; $f = n_b f_0$ — n_b: No. of bunches, f_0: rotation frequency; R_L: geometrical loss factor; σ_x^*: Horizontal beam size at collision point; σ_y^*: Vertical beam size at collision point

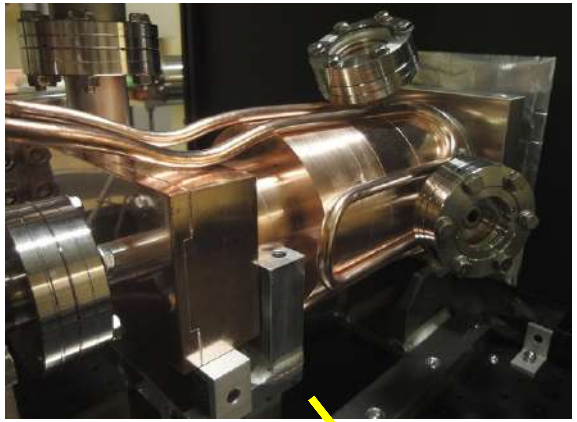
$$\sigma = \sqrt{\epsilon\beta}$$

Higher luminosity with lower beam current→ "eco" machine



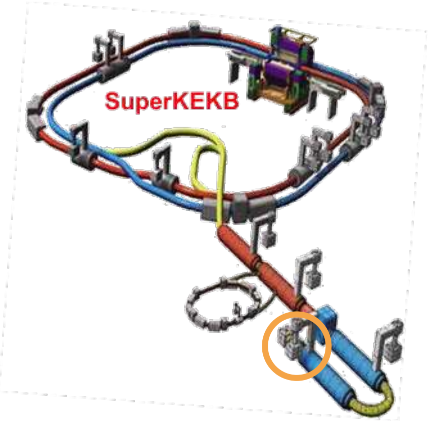
Photocathode RF gun system

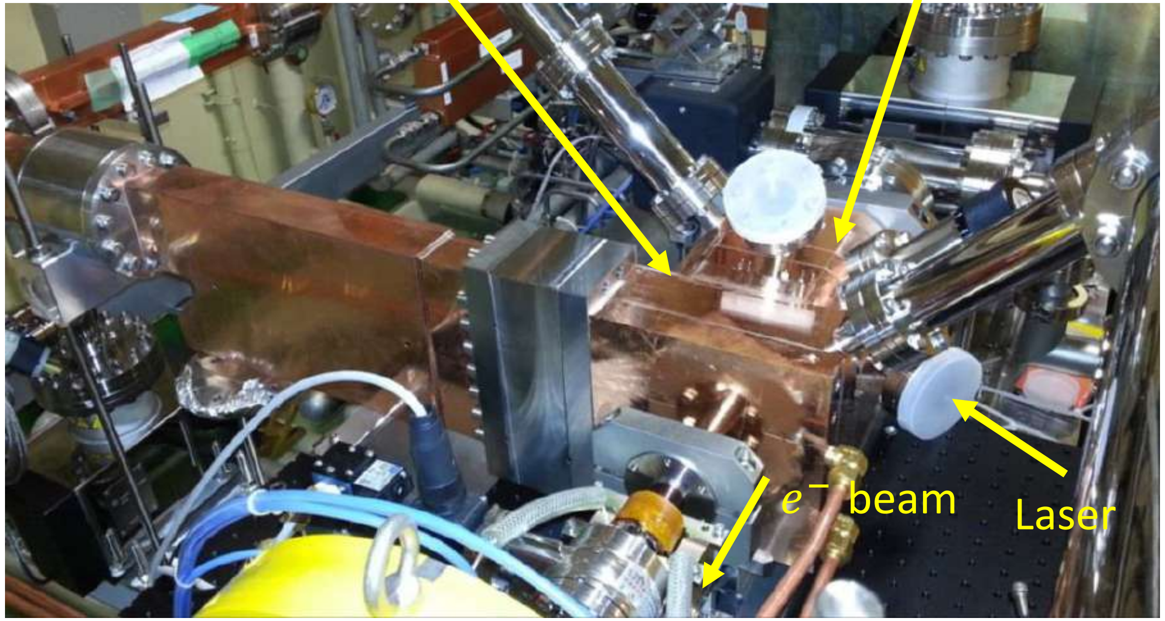
DAW-type cavity



Ir_5Ce cathode

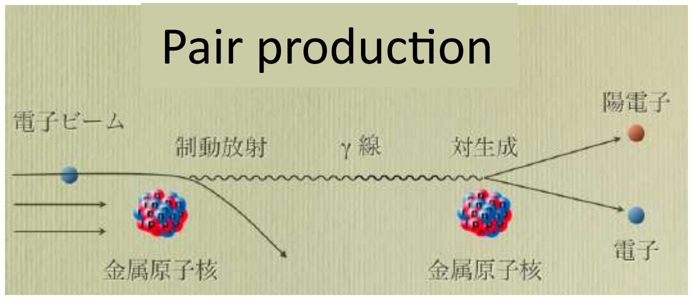
SuperKEKB tour

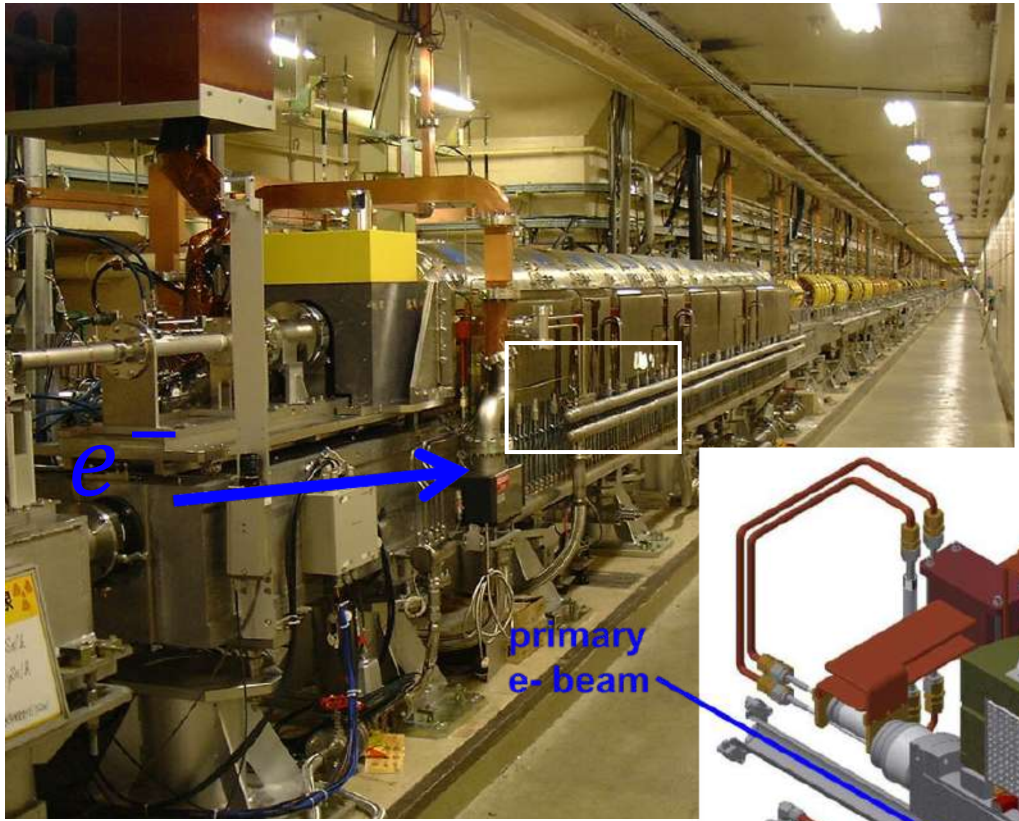


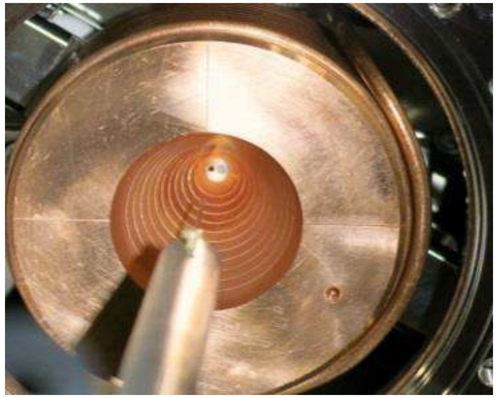


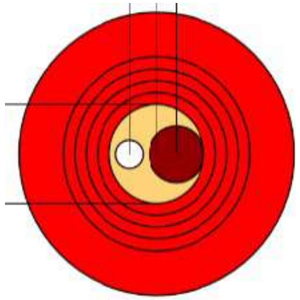
- An electron gun is capable of producing a high-quality electron beam.
- Materials have the property of emitting photoelectrons when irradiated with light above a certain energy.
- Photoelectrons generated by laser injected into a photocathode are accelerated as an electron beam by a high-frequency accelerating electric (RF) field.

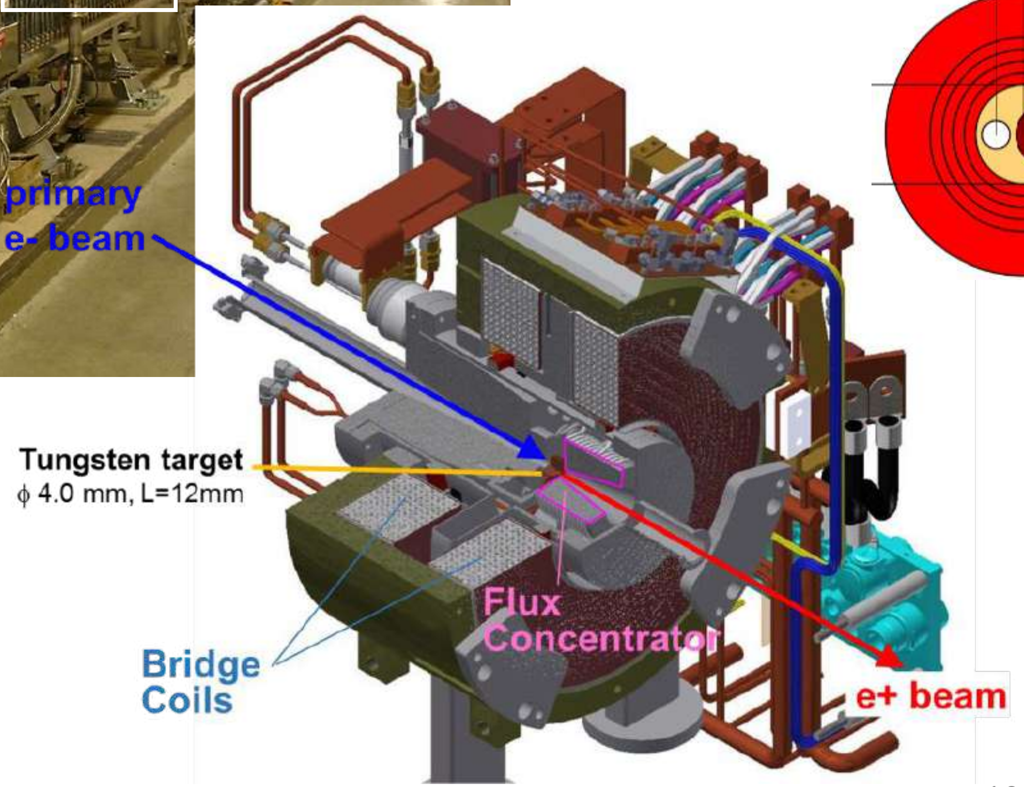
Positron production on tungsten target



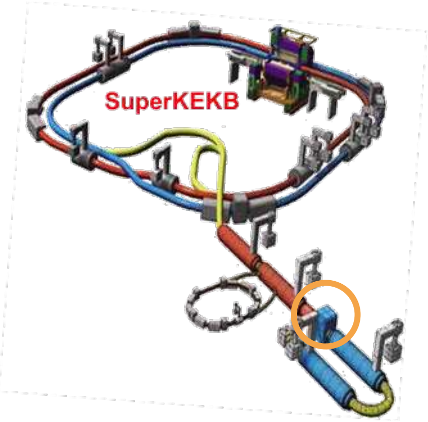






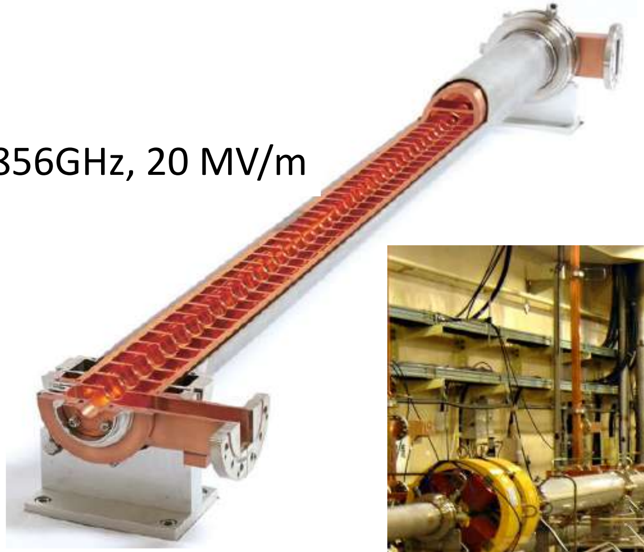


SuperKEKB tour



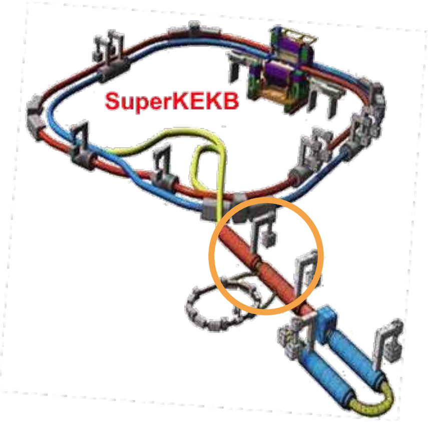
Accelerating section

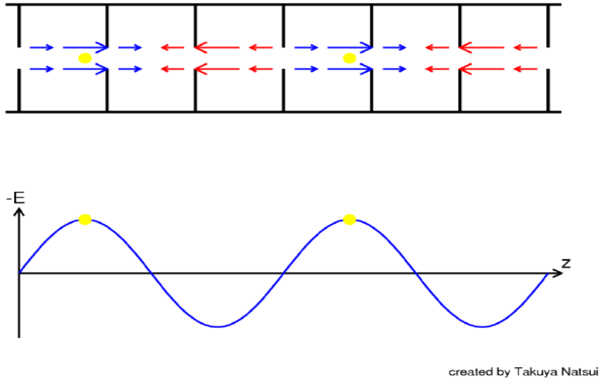
2.856GHz, 20 MV/m



SuperKEKB tour

500m linear accelerating section(LINAC). Bicycle is handy.

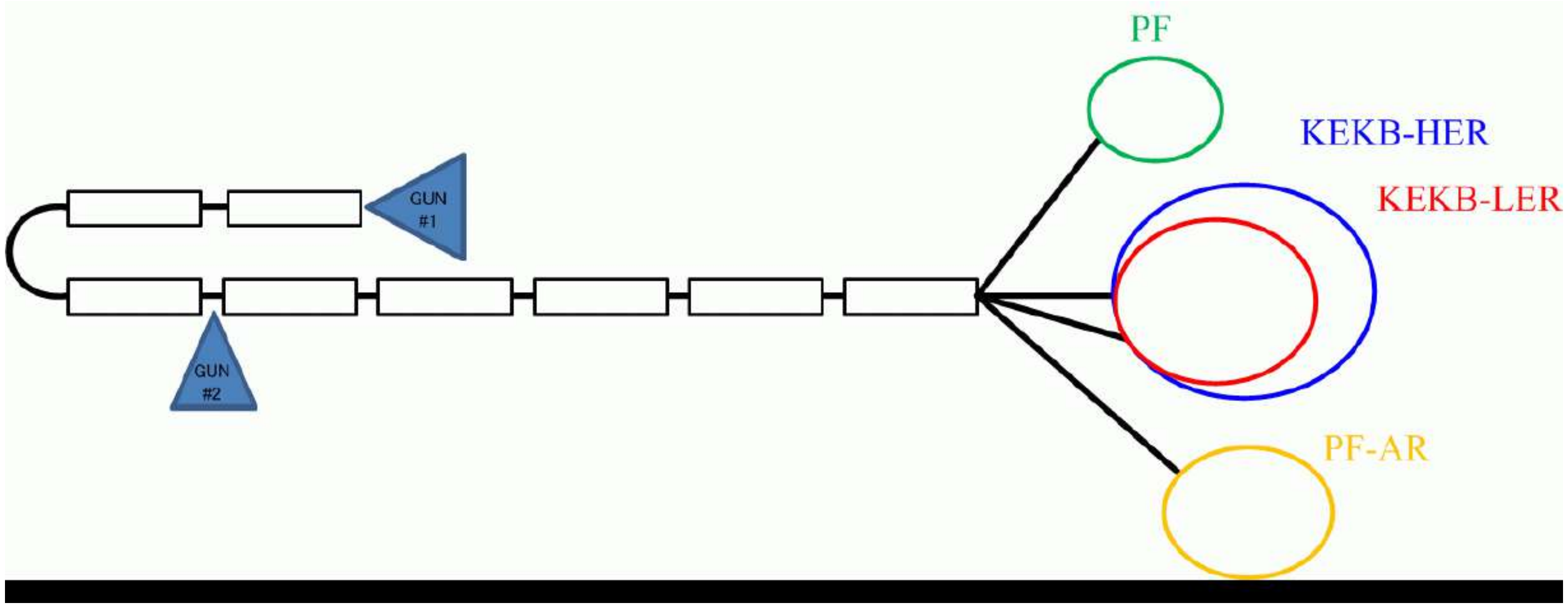




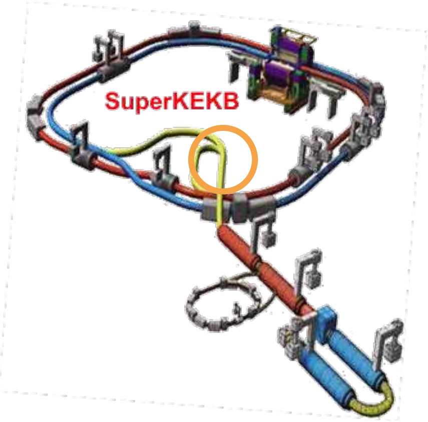
$e^-$and e^+ are accelerated to the target energy (7 GeV for e^- and 4 GeV for e^+) and transferred.

Simultaneous injection to the 4 rings (PF, HER, LER and PF-AR)

SuperKEKB tour



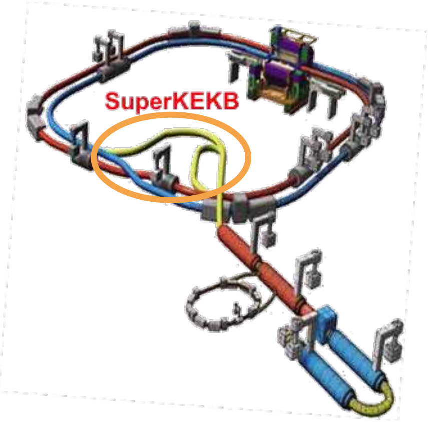
https://www2.kek.jp/accl/legacy/topics/topics100830.html

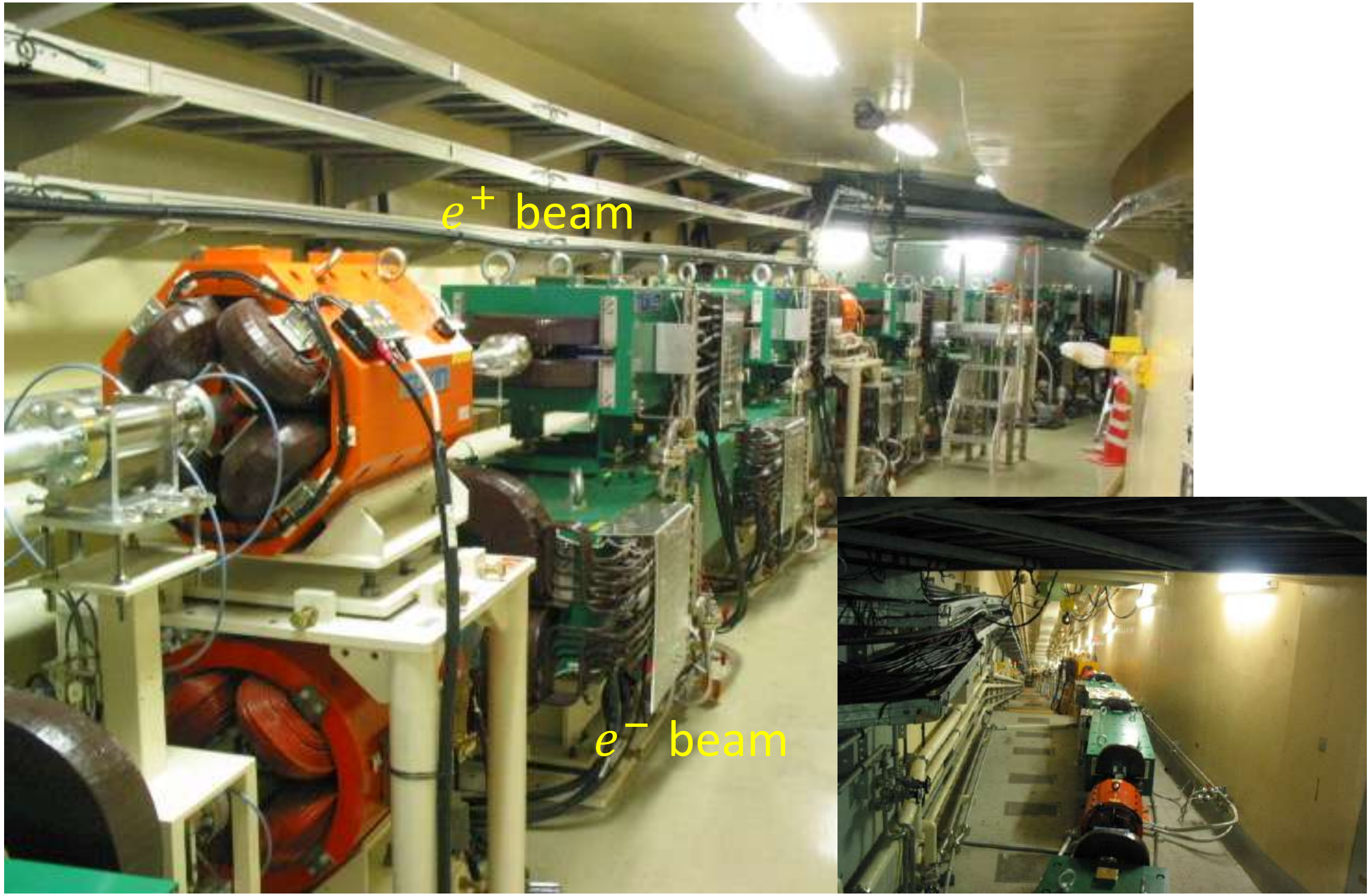


PF: Photon Factory 3.5 GeV
HER: SuperKEKB High Energy Ring (electron ring) 7 GeV
LER: SuperKEKB Low Energy Ring (positron ring) 4 GeV
PF-AR: Photon Factory Advanced Ring) 6.5 GeV

Beam Transport Line
From the LINAC to Main Ring,
from 5m below G.L. to 11m below.

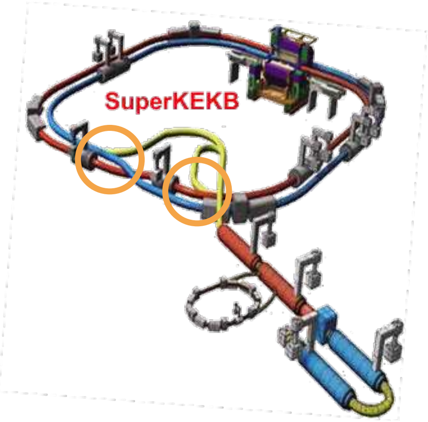
SuperKEKB tour

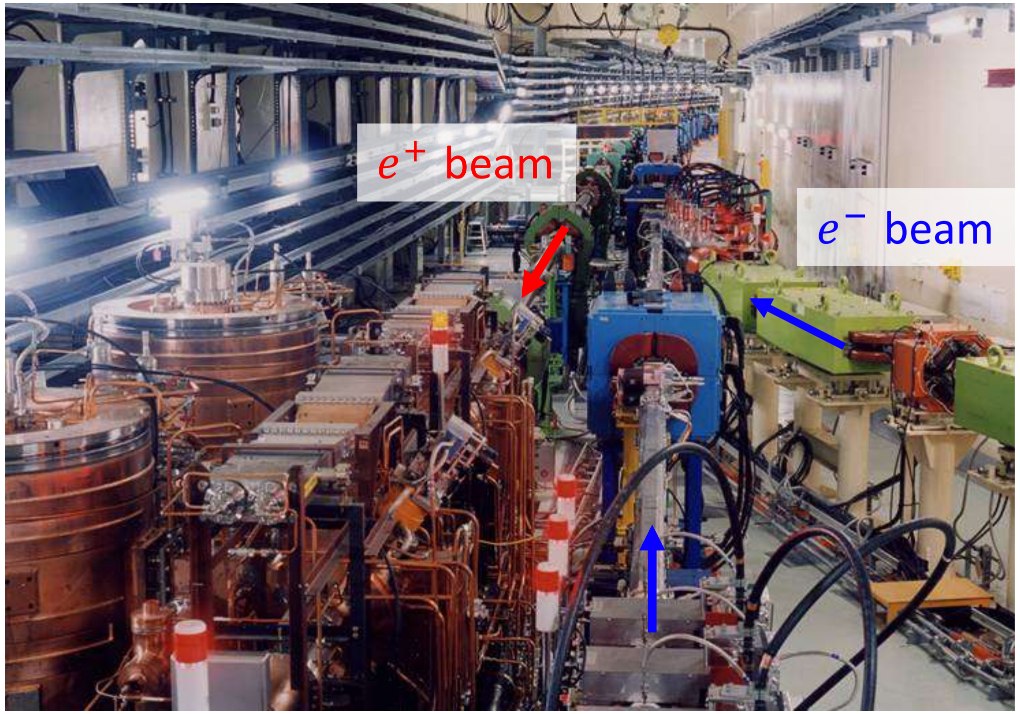


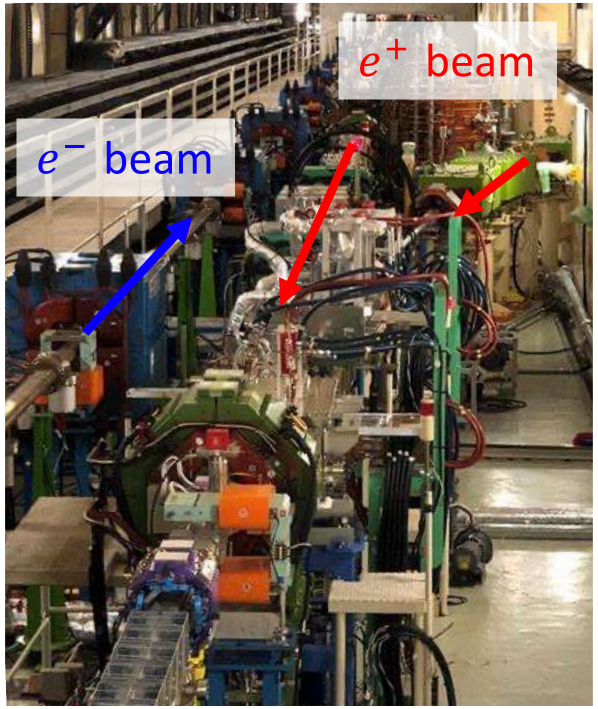


From Beam Transport Line to the Main Ring

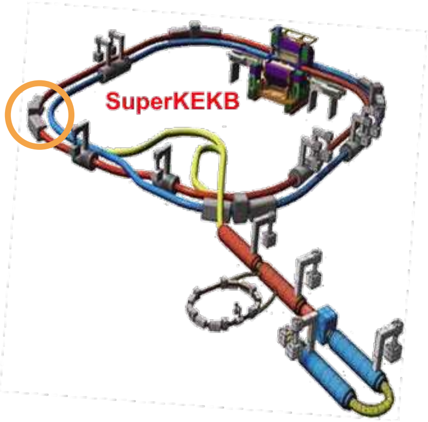
SuperKEKB tour

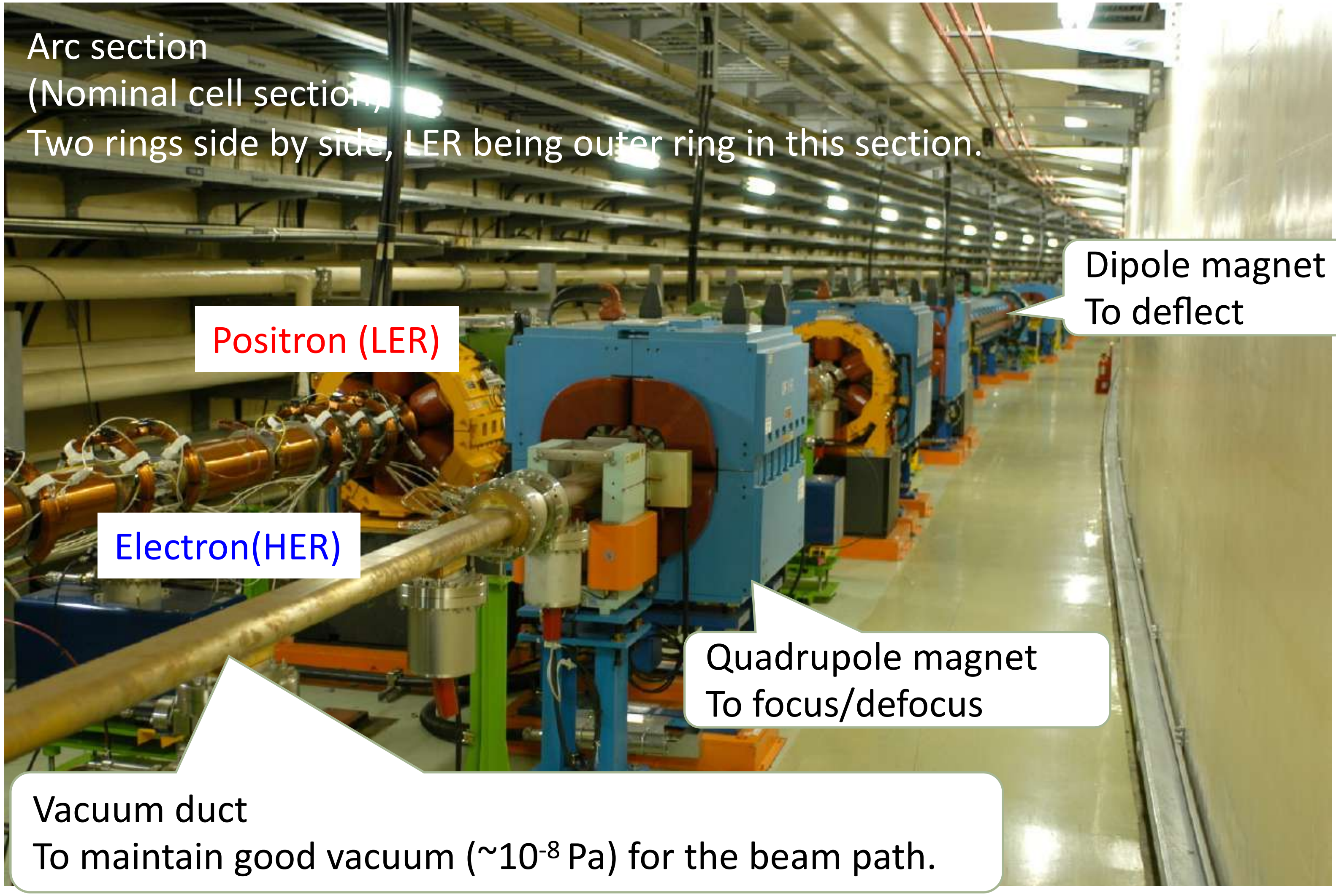




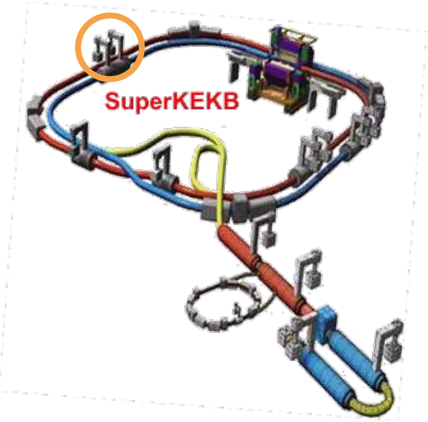


SuperKEKB tour

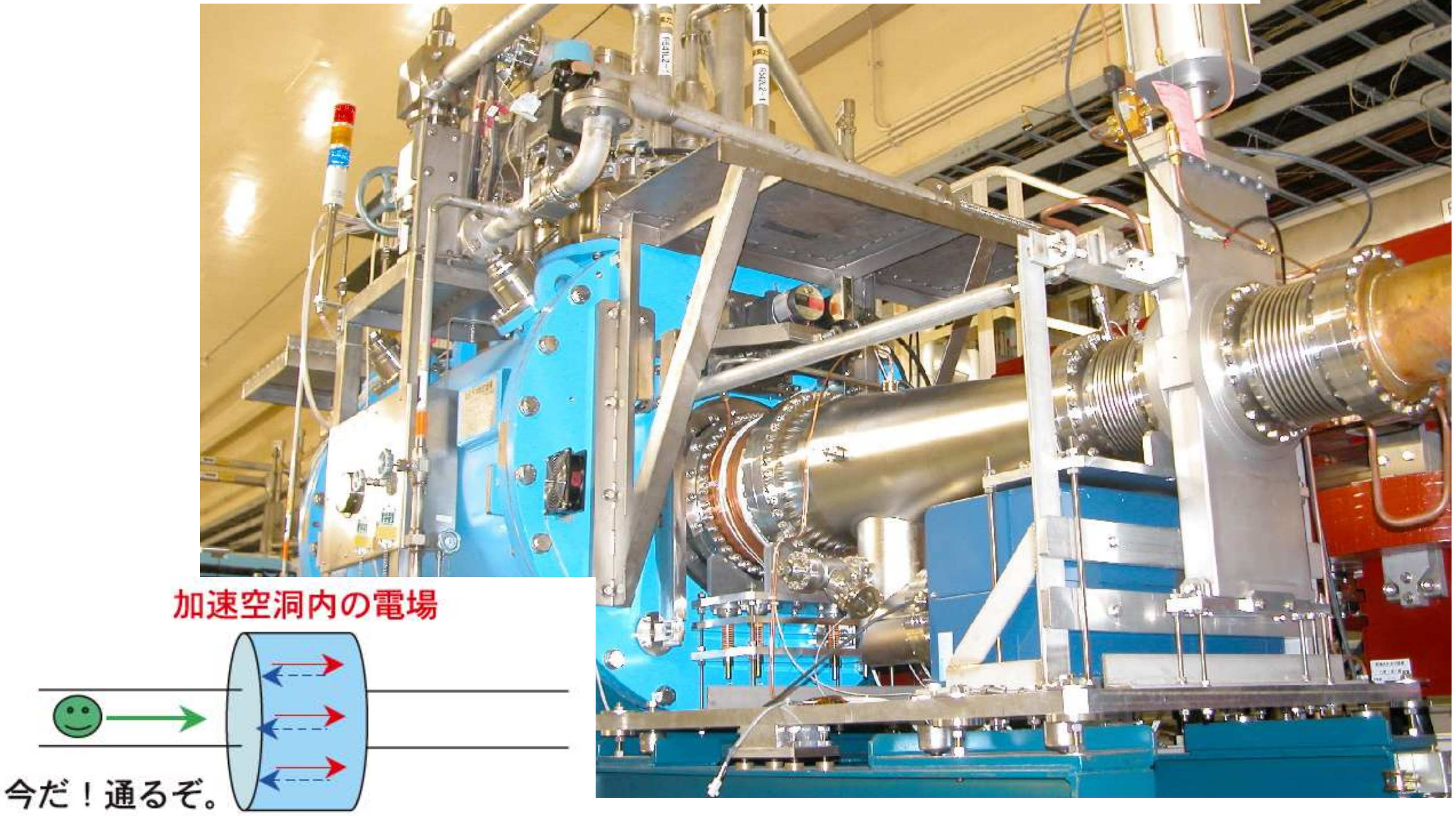




SuperKEKB tour

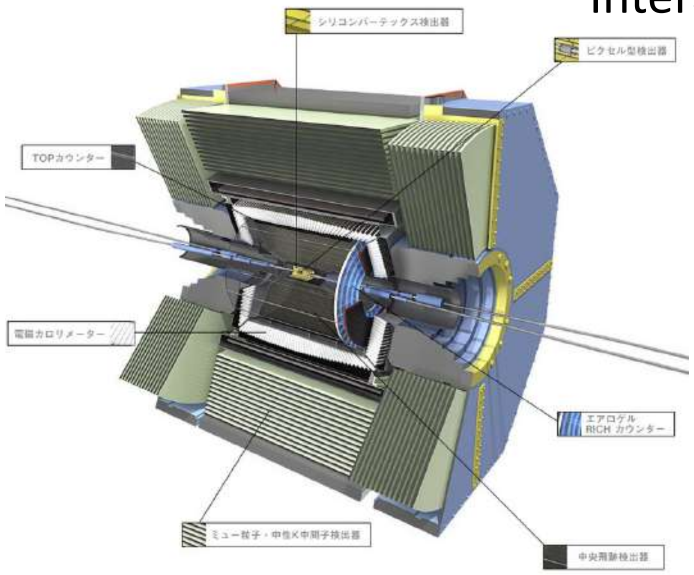


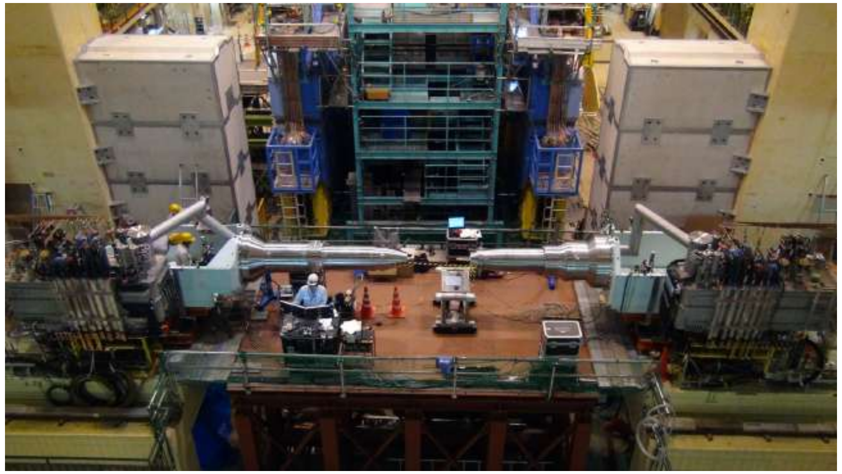
SCC (Single-cell Superconducting cavity) for HER
Highest beam current stored (1.45A) in the world.



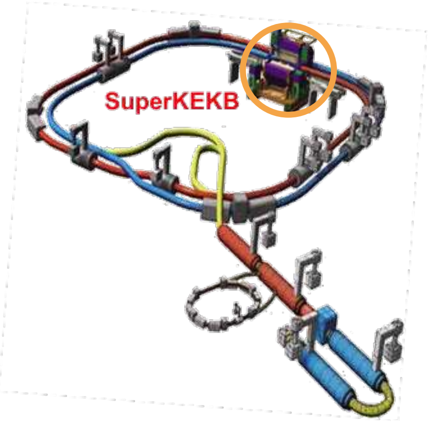
TM010 mode

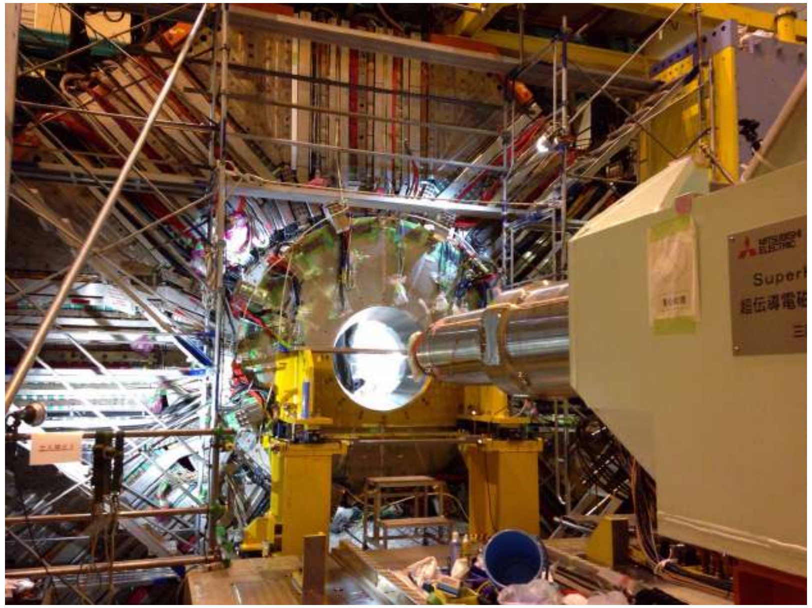
Interaction Region

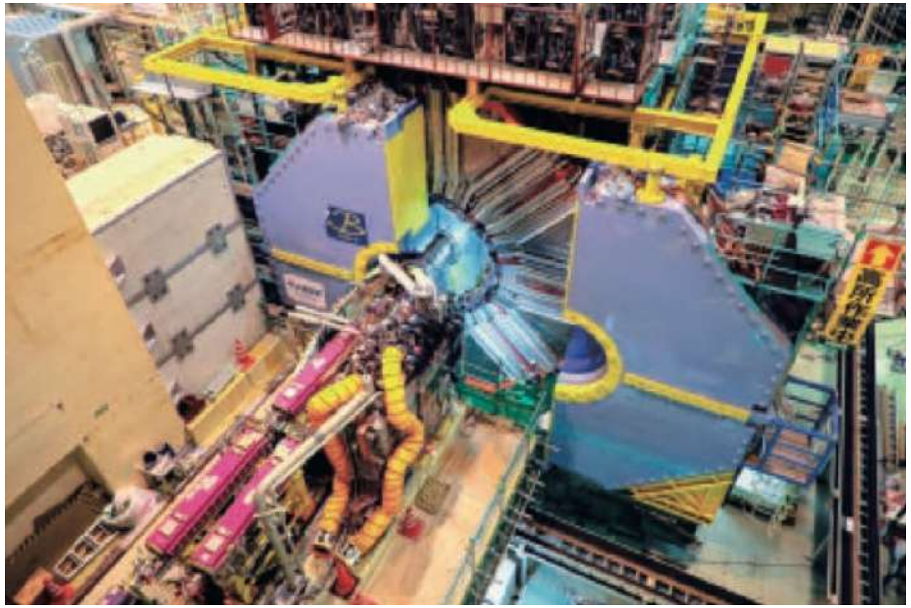




SuperKEKB tour

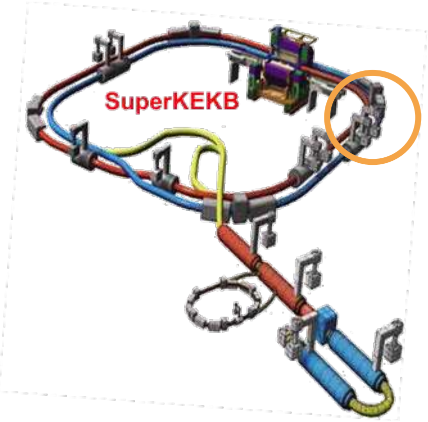




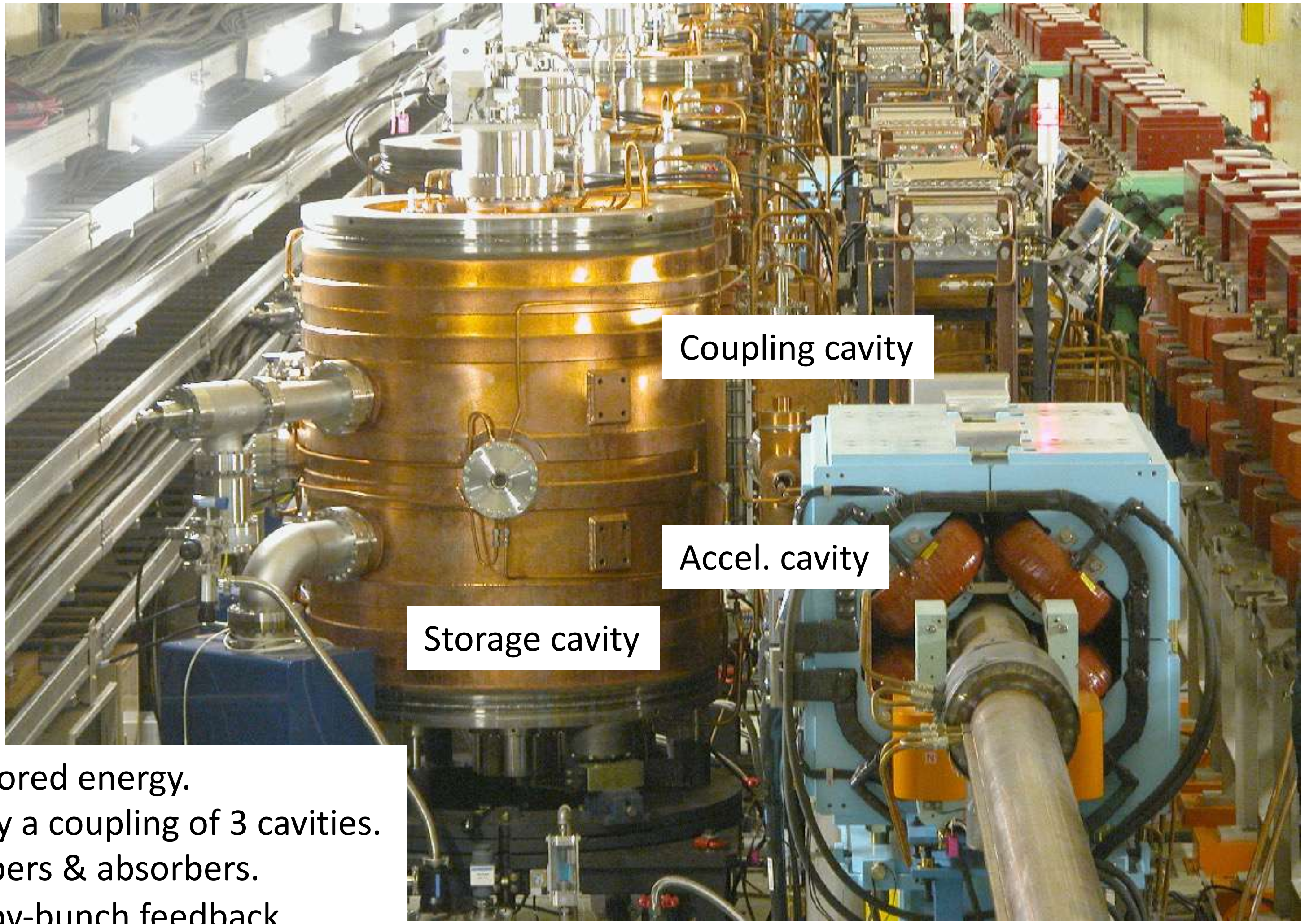


Arc section (Nominal cell section)
Two rings side by side, LER being inner ring in this section.

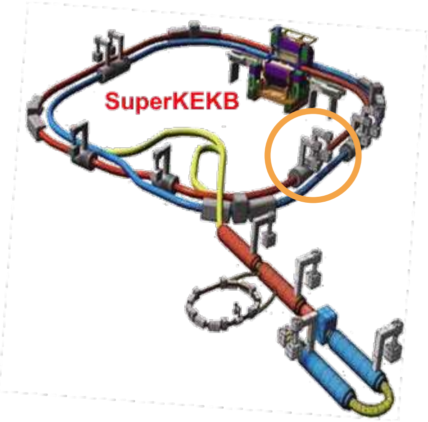
SuperKEKB tour



ARES (The Accelerator Resonantly coupled with an Energy Storage)
Normal conducting Cavity



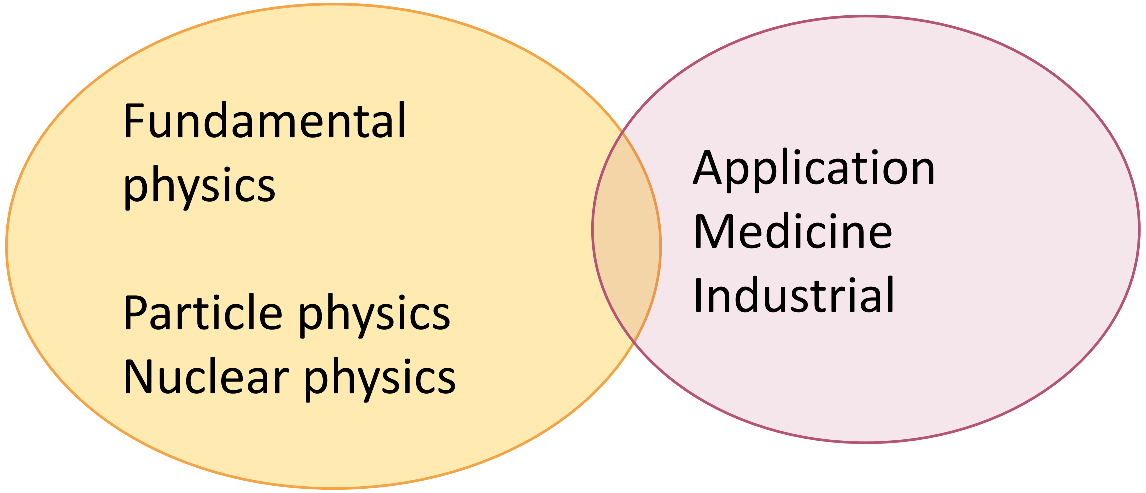
SuperKEKB tour



Passive stabilization with huge stored energy.
Eliminates unnecessary modes by a coupling of 3 cavities.
Higher Order Mode (HOM) dampers & absorbers.
No need for longitudinal bunch-by-bunch feedback.
No transverse instabilities arises from the cavities.

Various types of accelerators

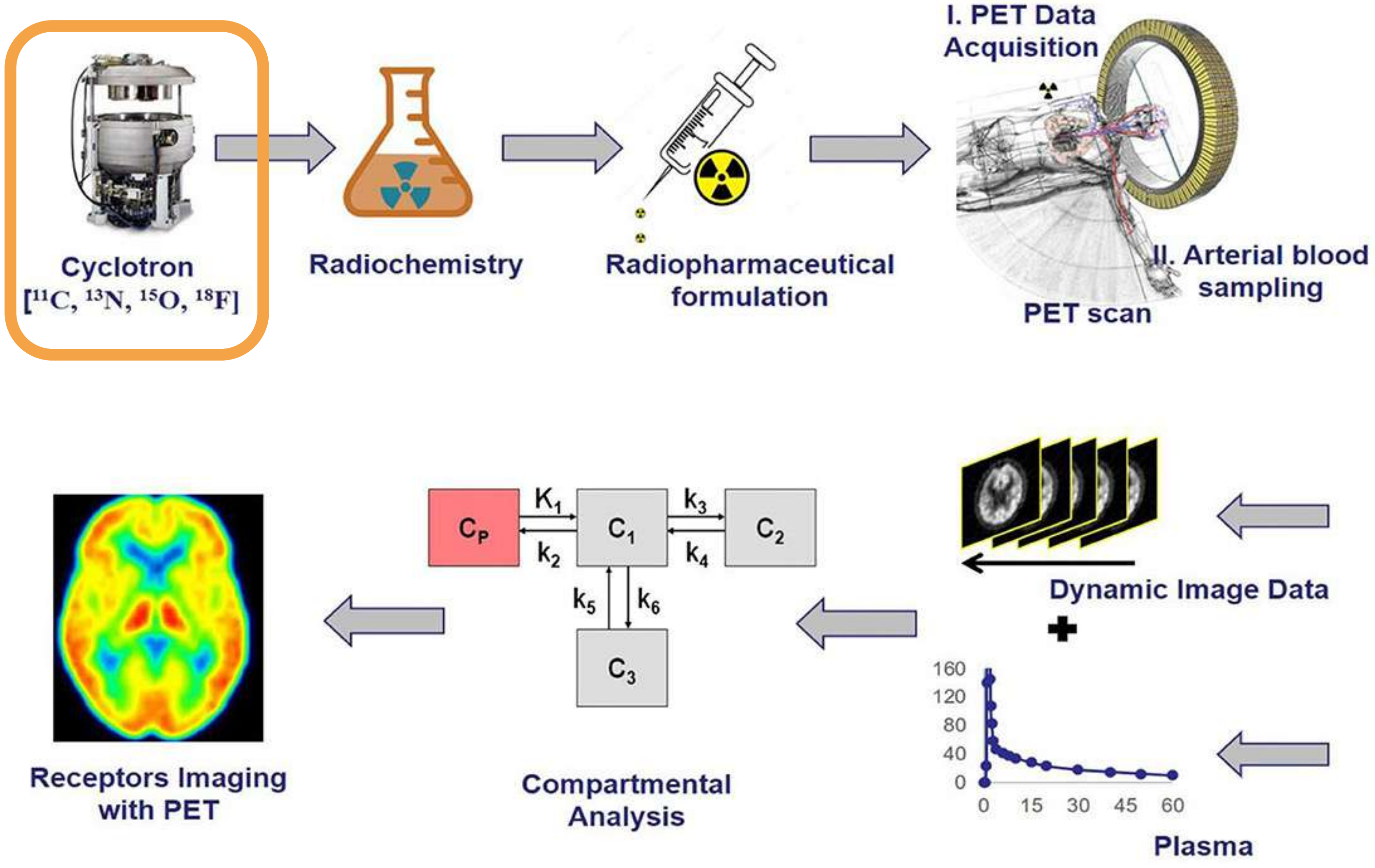
- Light sources
- Synchrotron
  - J-PARC
- Colliders
  - SuperKEKB
- Many other
  - Application



Medical application

Used for diagnosis or direct treatment

- Diagnostics
  - Accelerate electrons to produce X-rays (X-rays, CT scans)
- Cancer treatment
  - Irradiation with X-rays, protons, heavy ions, neutrons, etc.



https://www.frontiersin.org/files/Articles/812270/fmed-09-812270-HTML-r2/image_m/fmed-09-812270-g001.jpg

PET (Positron Emission Tomography)

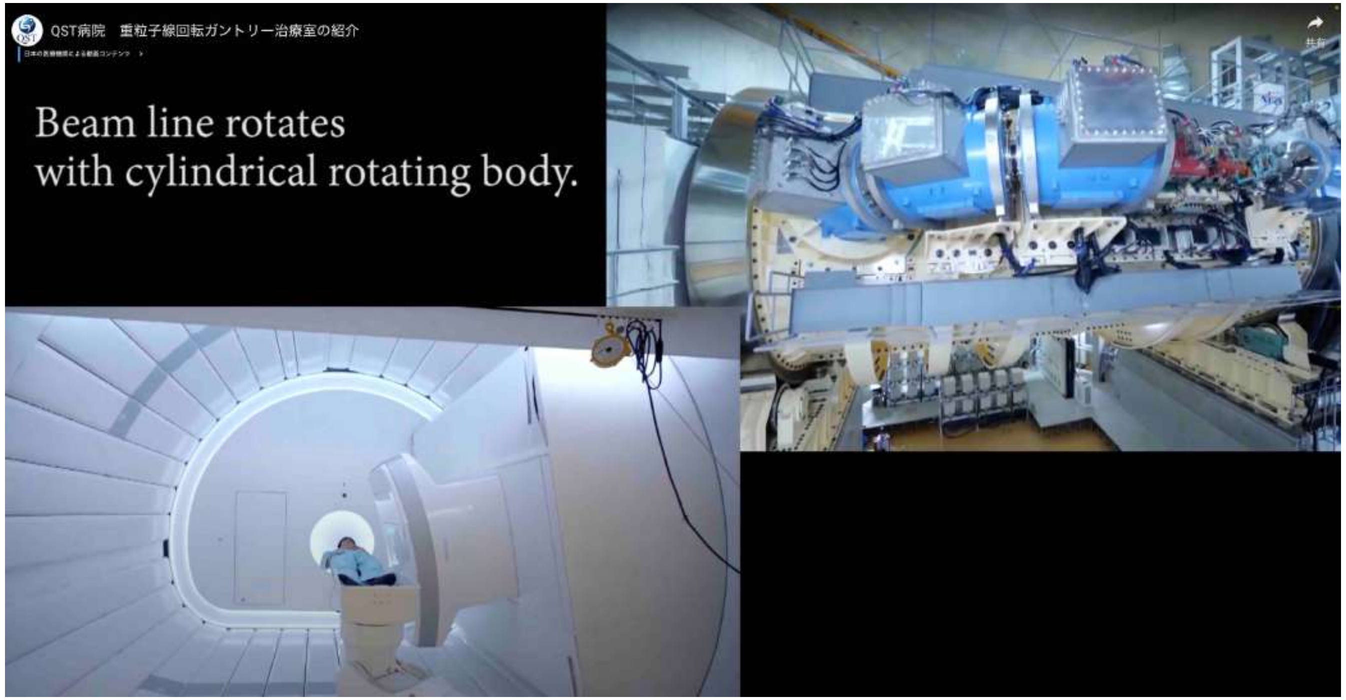
- Diagnosis for early detection of cancer. Uses a tracer. (Isotopes such as O, N, C, and F emit positrons)
- Cancer takes in more glucose. After administration of a drug containing tracers,
- Radiation is observed from outside the body.
- Tracers have a short lifespan and must be produced by an accelerator.

Medical application

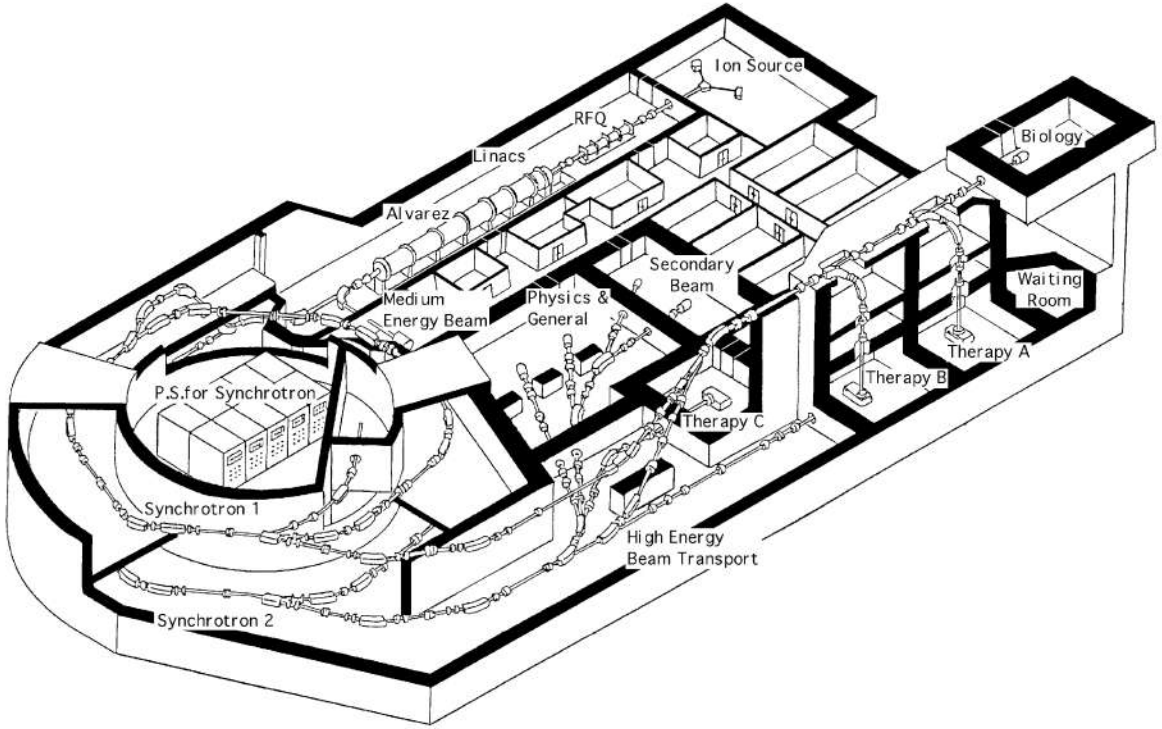
Used for diagnosis or direct treatment

- Diagnostics
  - Accelerate electrons to produce X-rays (X-rays, CT scans)
- Cancer treatment
  - Irradiation with X-rays, protons, heavy ions, neutrons, etc.

A bird's-eye view of the HIMAC facility A unique double-synchrotron ring heavy-ion accelerator system dedicated for medical use was designed and constructed. It consists of two ion sources, an RFQ (radio frequency quadrupole) linear accelerator (linac), an Alvarez linear accelerator (linac), two synchrotron rings, a high-energy beam transport system, and an irradiation system.



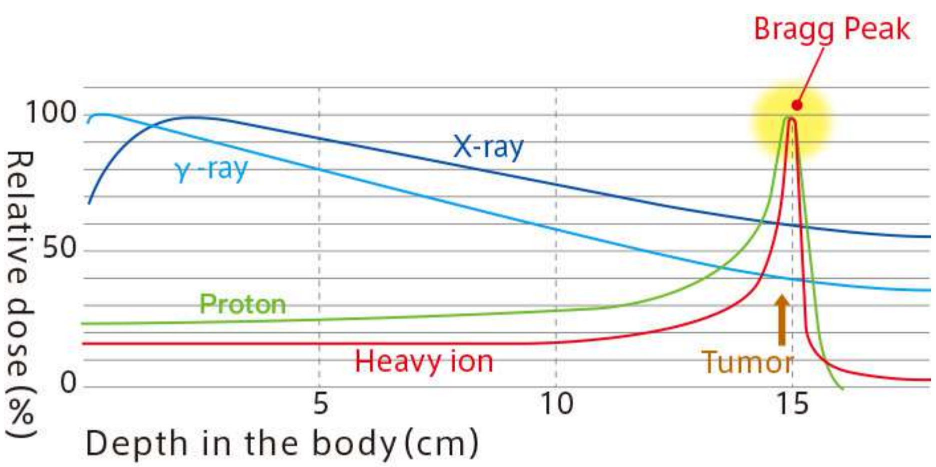
https://www.qst.go.jp/site/iqms-english/accelerator-medical-physics.html



https://accelconf.web.cern.ch/p95/ARTICLES/MAD/MAD03.PDF

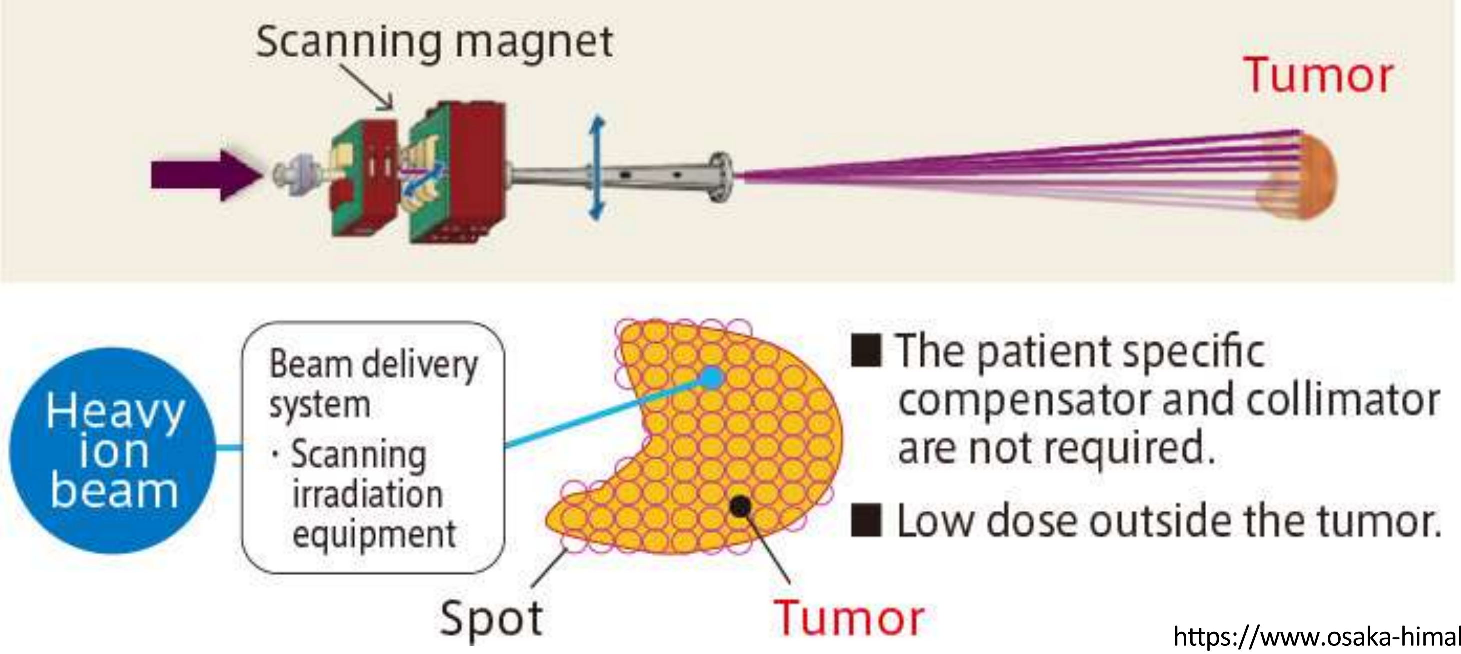
Medical application

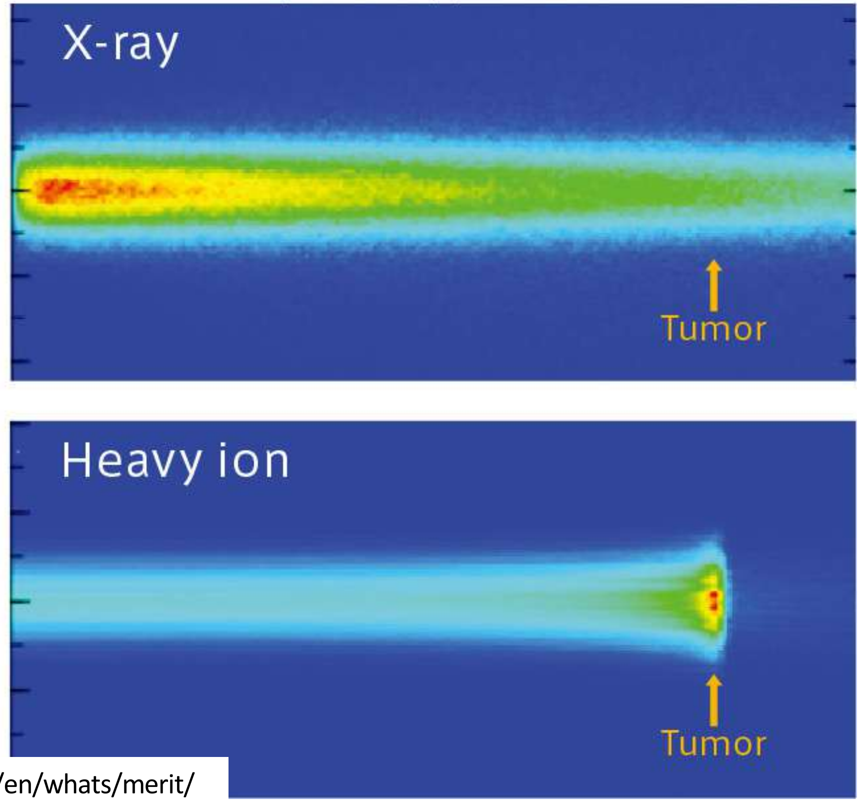
- With conventional X-rays and γ-rays, a large radiation dose is inevitably deposited near the surface of the body.
- Deep-seated tumors will not receive sufficient damage and healthy tissue will also be irradiated.
- Heavy ion and proton beams have characteristic called "Bragg Peak" which enables a high dose to be administered to the tumor while limiting the dose to the surface of the patient's body.



Reference: Website of the Association for Nuclear Technology in Medicine, http://www.hirt-japan.info/medical/about/merit.html

Example (scanning method)





https://www.osaka-himak.or.jp/en/whats/merit/

Industrial application

Cargo inspection at port

- The contents of the vast amount of cargo (containers) brought in daily are checked.
- X-rays, which are the most convenient and have the widest application area among particle beams, are mainly used. X-rays with energies of several tens to several hundreds keV are often used for relatively small objects such as airline baggage and small cargo.
- Containers, which are the main source of trade cargo at ports and harbors, often use X-rays with energies up to 10 MeV.

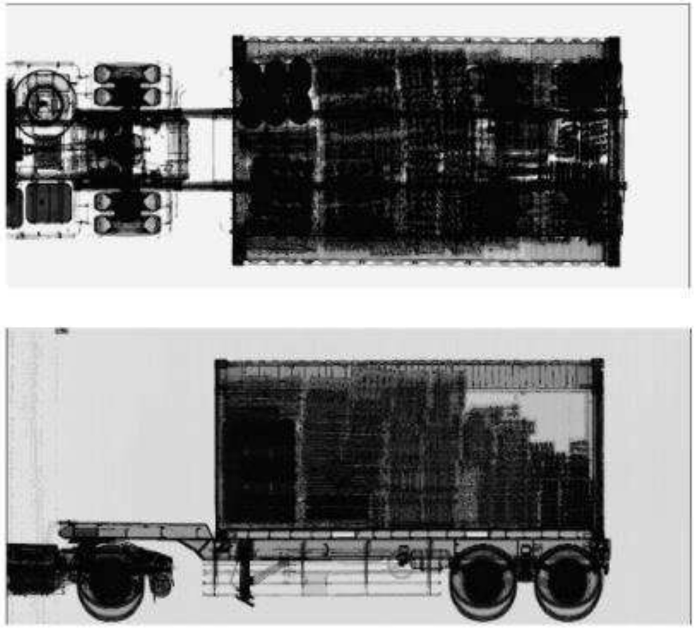
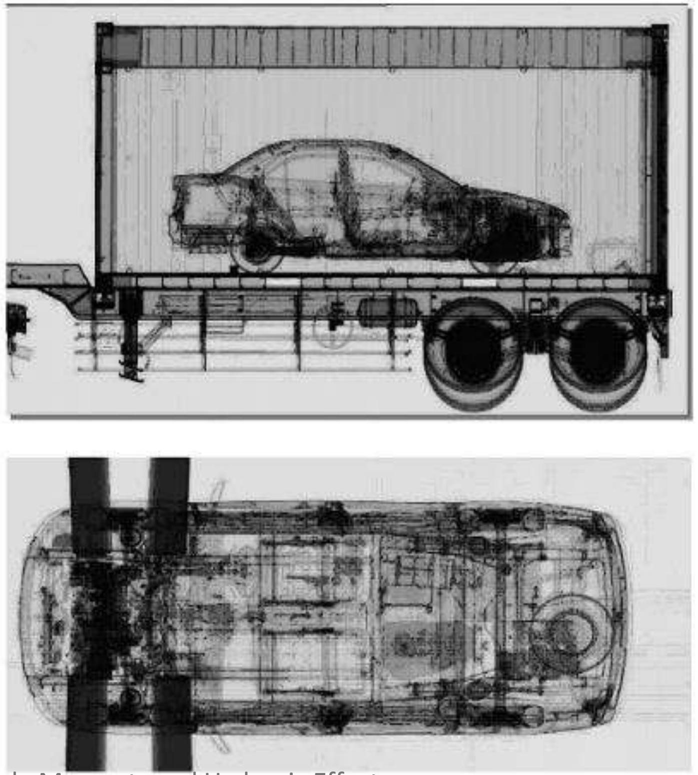
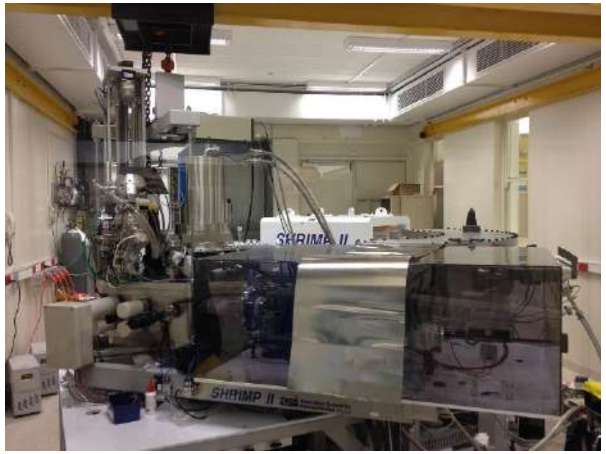


図 5　X 線画像例



Industrial application

- Food irradiation: prevention of mold on soybeans and citrus fruits; only prevention of potato germination permitted in Japan (1972, 60Co)
- Pest control: eradication of cucurbit fly (1993, 60Co, Nansei Islands):
- Breeding: disease-resistant Koshihikaririce, pears (1960)
- Dating: Measuring carbon content of organisms: 14C separation by accelerator: (1.8~2.5MV), Nagoya University : **A**ccelerator **M**ass **S**pectrometry
- Nondestructive testing: X-rays (electron density distribution), neutron beams (distribution of light elements)



RADIOCARBON, Vol 46, Nr 1, 2004, p 219–230

AMS ^{14}C DATING OF IRON ARTIFACTS: DEVELOPMENT AND APPLICATION

Hiroki Enami[1] • Toshio Nakamura[1,2] • Hirotaka Oda [1] • Tetsuya Yamada[3] • Toshio Tsukamoto[3]

Summary

- A Brief history and major inventions and principles are introduced along with some basic hardware components.
- Accelerator technology has contributed to the development of particle physics
- Some slides on J-PARC and SuperKEKB are presented.
- Examples of applications of accelerator technology are presented.
- There are many things that you can contribute to in this field.

Virtual tour, SuperKEKB

https://360camera.space/kek/

KEK Open House

Sep.7, 2024