# Accelerator physics

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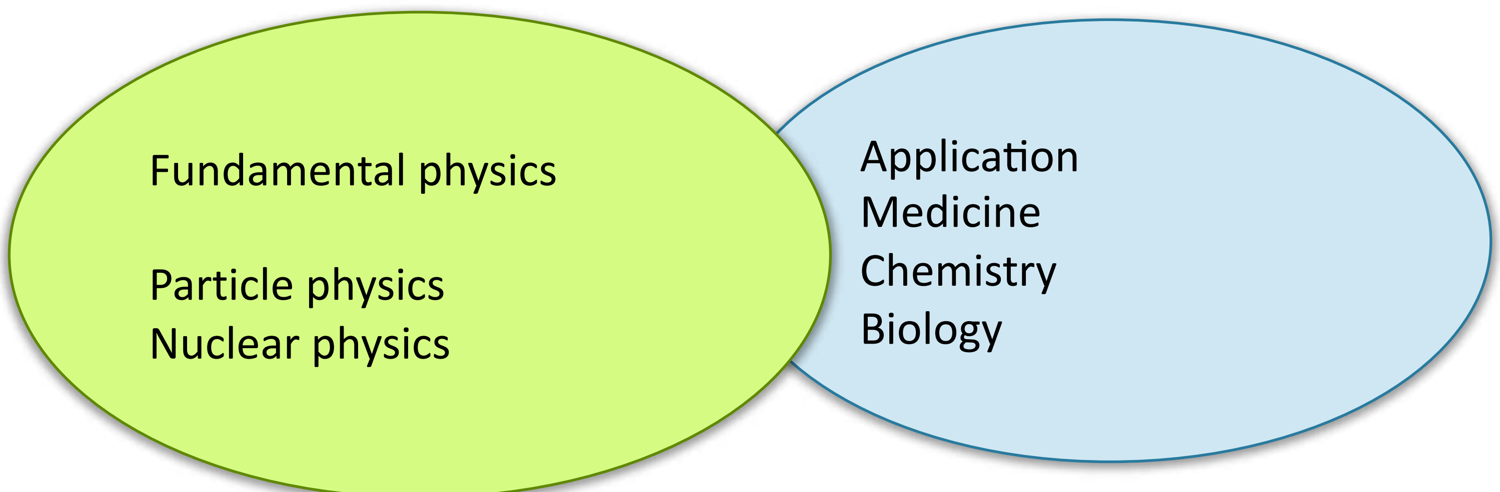
  - SuperKEKB (BELLE II)

- Summary

The 2021 JENNIFER2 will introduce you to particle physics research at KEK, focusing on the research of Belle II (SuperKEKB) and T2K (J-PARC)

# 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, $\beta \equiv {}^{v}/_{c} \to\to 1$ (close to speed of light $c$)

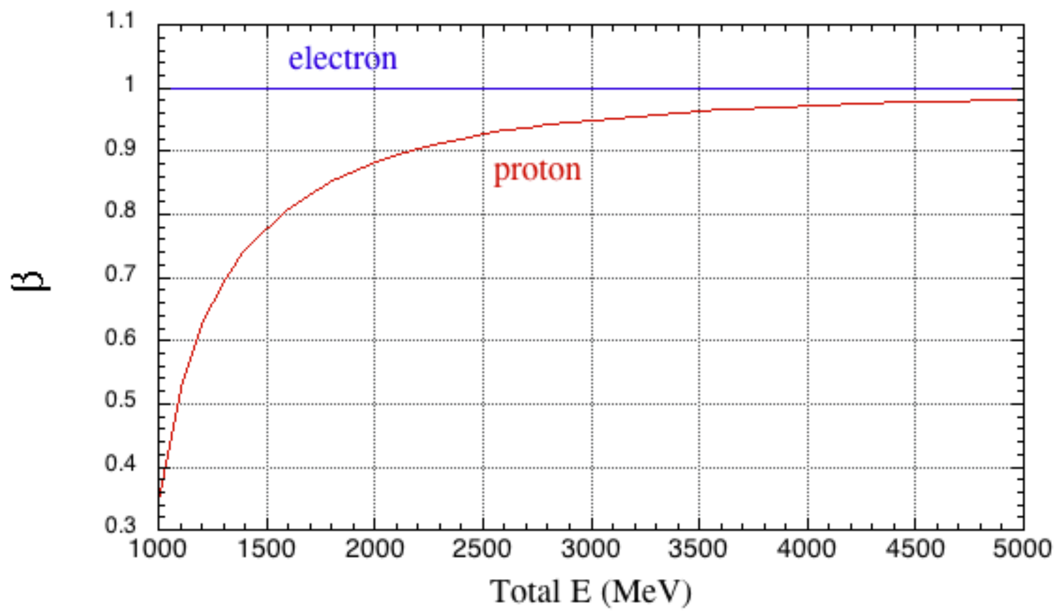
Then total energy $E_T$ of a particle is the sum of its rest energy $E_0$ and its kinetic energy $T$

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

$E_0$ for some particles are shown in the next page.

The total energy $E_T$ can also be expressed in terms of the gamma factor

$$E_T = \gamma mc^2, \qquad \text{where} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$



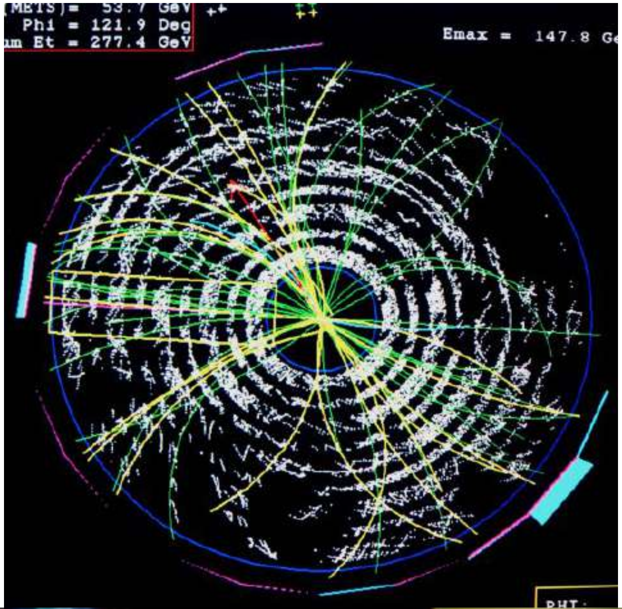
# Introduction

Rest energy: $E_0\ (example)$

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

Heavier particle

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

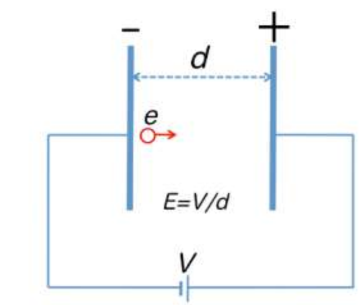



THIS IMAGE, COURTESY OF FERMILAB, SHOWS A COLLIDER DETECTOR EVENT THAT CAPTURED A POSSIBLE TOP QUARK PAIR CANDIDATE. TRACKS SHOWN ARE FROM THE DECAYS OF TWO TOP QUARKS PRODUCED IN A COLLISION. DEEPER KNOWLEDGE ABOUT THE CHARACTERISTICS OF THE TOP QUARK COULD BOOST OUR UNDERSTANDING OF THE FATE OF OUR UNIVERSE.

# Introduction

Energy units often used

The kinetic energy gained by an electron accelerating from rest through an electric potential difference of 1 volt in vacuum.




When $V = 1V \rightarrow 1\ eV$

Units used in accelerators

| | |
|---|---|
| $10^3$ eV | 1 keV |
| $10^6$ eV | 1 MeV |
| $10^9$ eV | 1 GeV |
| $10^{12}$ eV | 1 TeV |

# Introduction

## 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 $\Delta U$ when a particle moves from point $\overrightarrow{r_1}$ to $\overrightarrow{r_2}$ is

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

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

Acceleration by the use of electric fields

# Introduction

## 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.

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

Path control by the use of <u>magnetic fields</u>

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

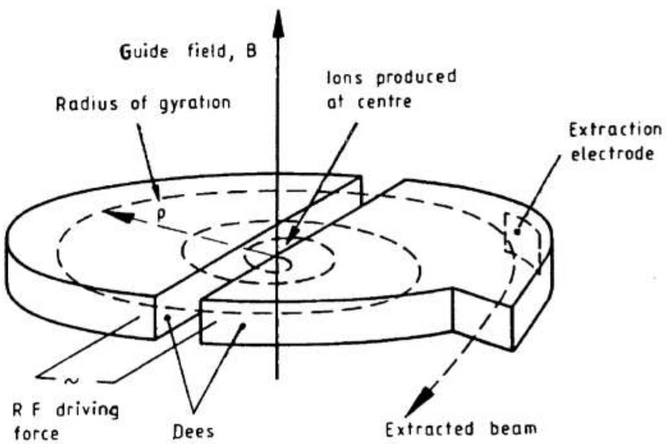
→Next : History of acceleration technique
(i.e. various electric fields)

# Brief history & major inventions

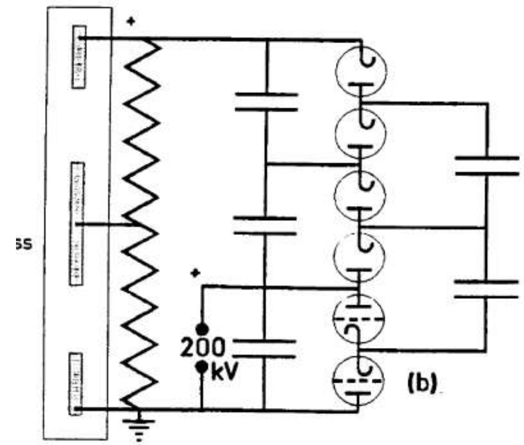
"The early history of accelerators can be traced from three separate roots. Each root is based on an idea for a different acceleration mechanism and all three originated in the twenties"

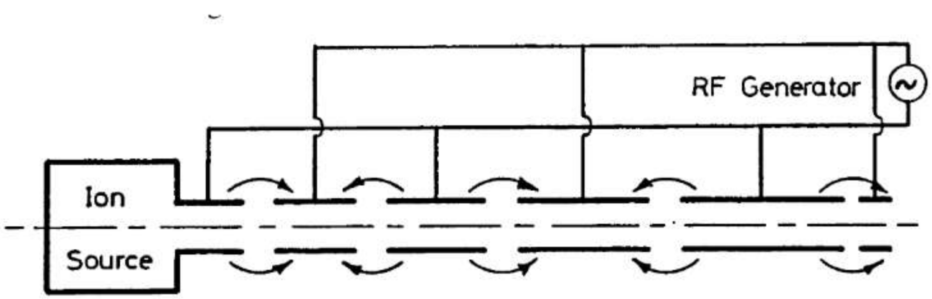
A BRIEF HISTORY AND REVIEW OF ACCELERATORS
P.J. Bryant, CERN

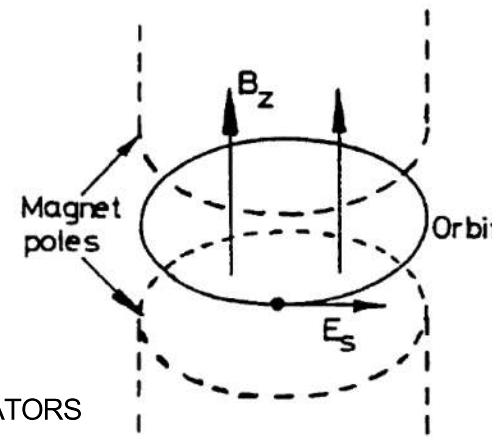
# Three separate roots




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




A BRIEF HISTORY AND REVIEW OF ACCELERATORS
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# Brief history & major inventions

## Livingston's curve : Energy vs. time

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

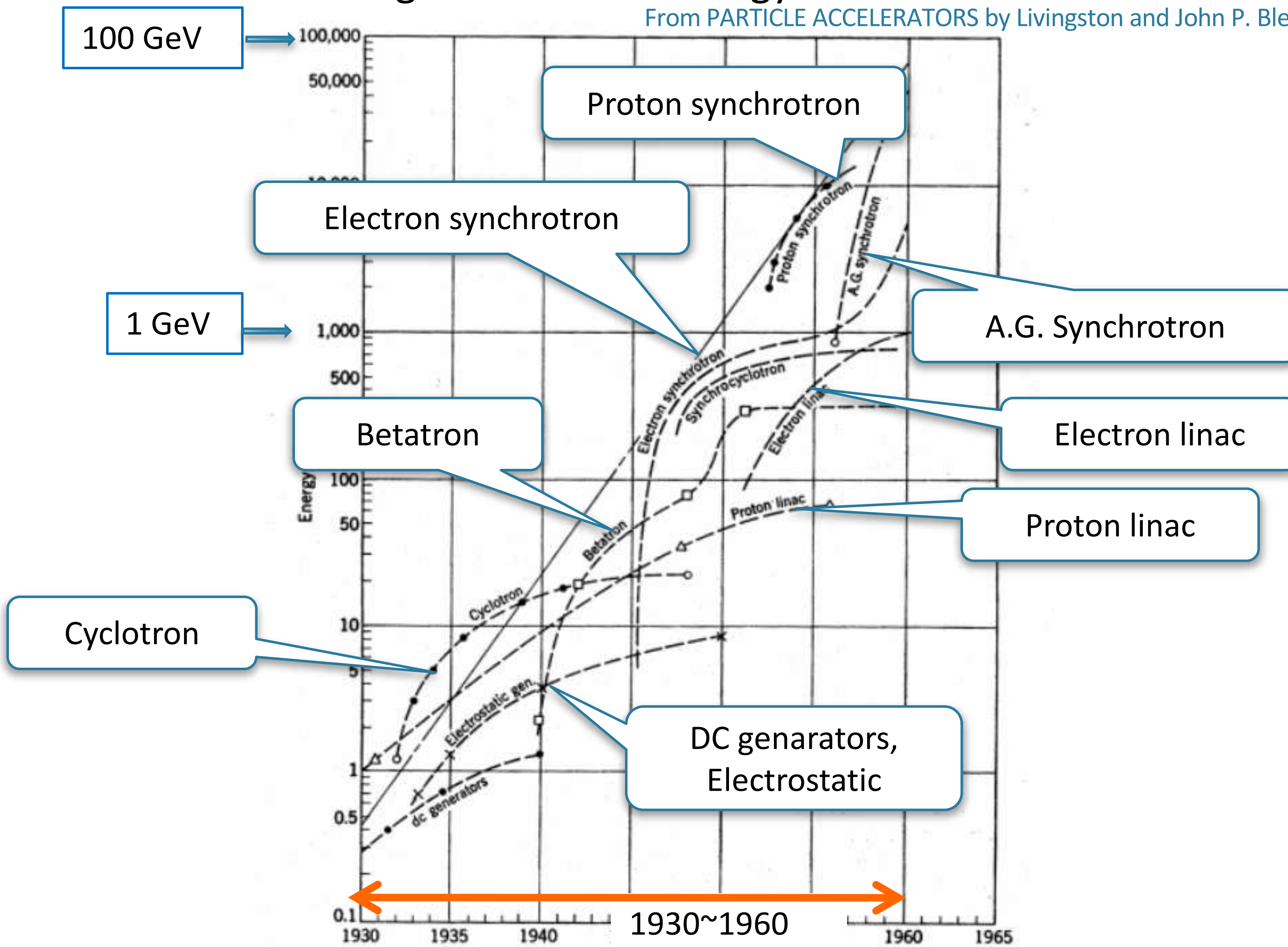
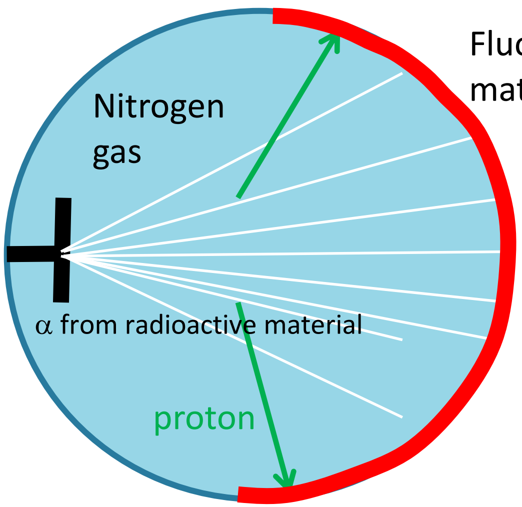


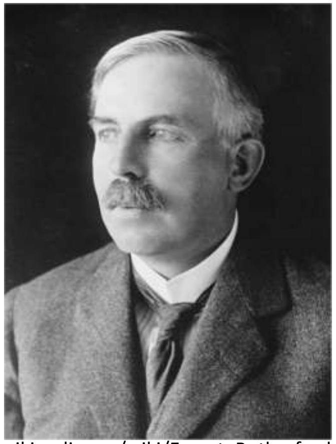

**Fig. 1-1.** Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

# 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

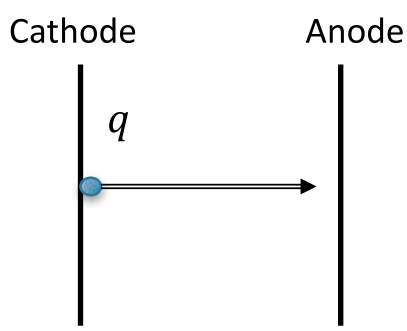
Next: the first root

# 1st root

## DC generators for providing electric fields for acceleration

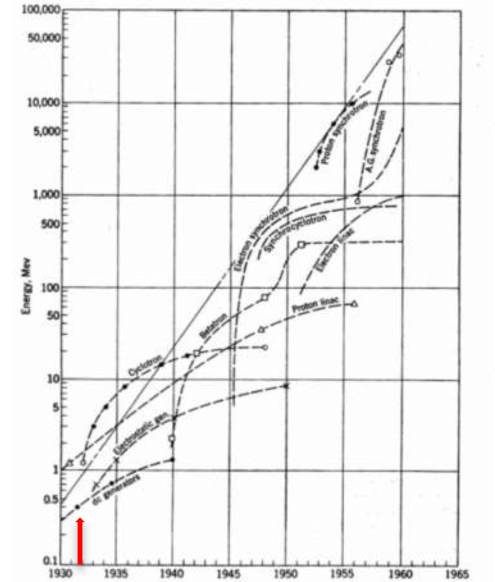
DC Generators : two major methods

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




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

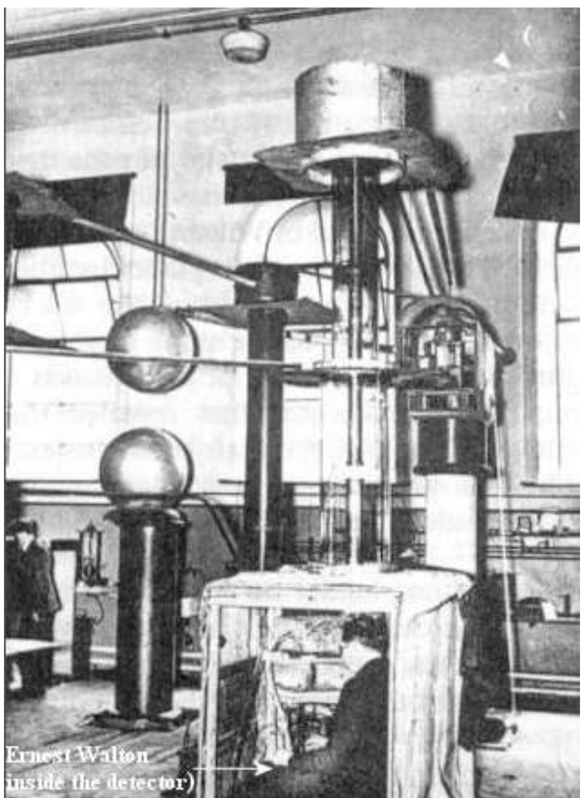
# Cockcroft-Walton:
# First disintegration of atomic nuclei with accelerator



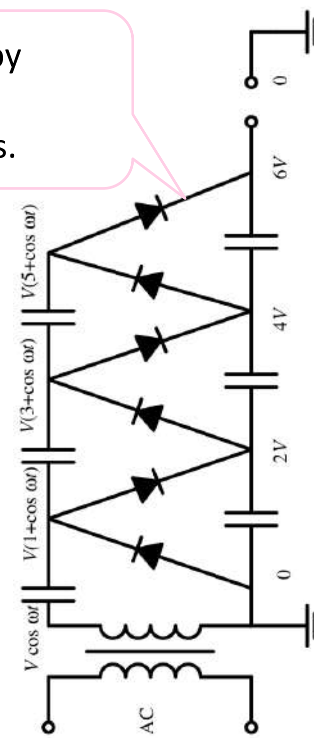

Cavendish Laboratory

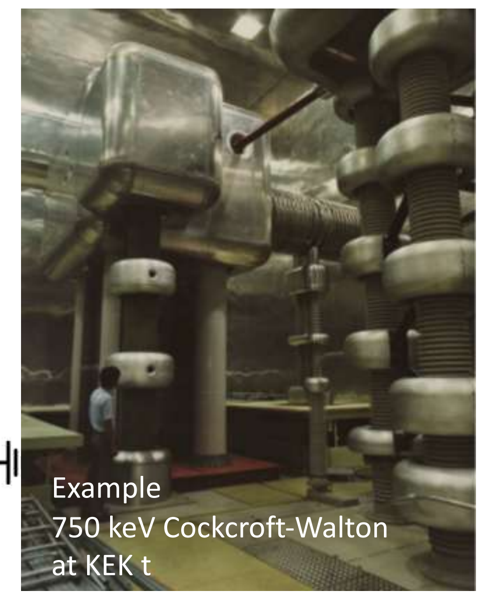
1932, Cockcroft and Walton used their machine to accelerate protons, and directed the beam of protons at a sample of lithium. This resulted in changing lithium atoms into two helium atoms. They had disintegrated – "smashed" – the lithium atom by means of artificially accelerated protons.

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

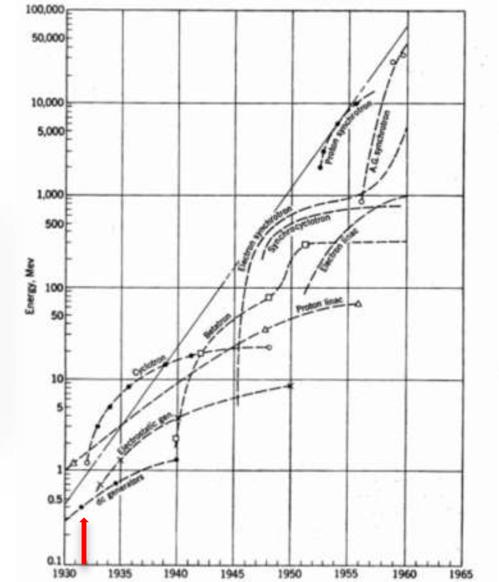



High voltage is provided by charging capacitors and discharging them in series.



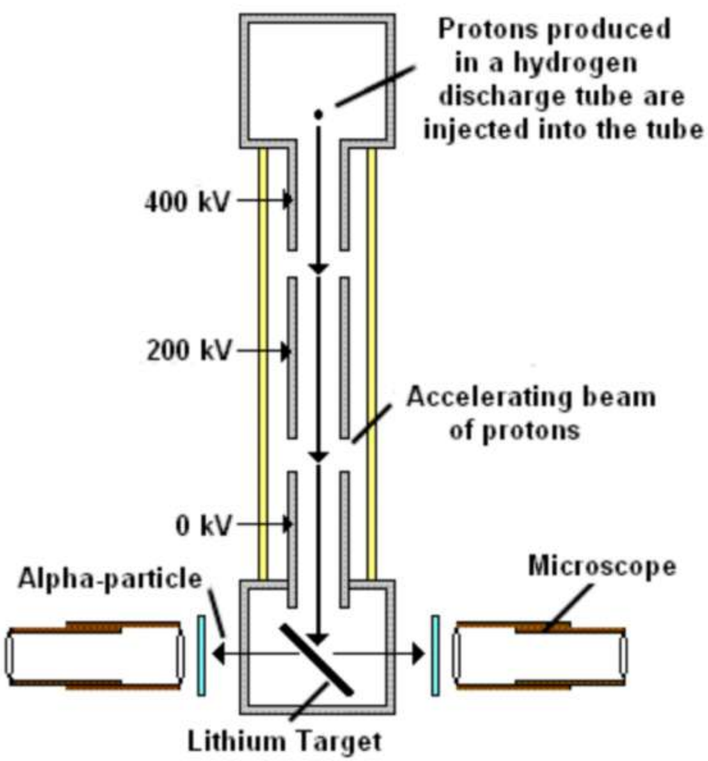



# Cockcroft-Walton: First disintegration of atomic nuclei with accelerator




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

"Transmutation of atomic nuclei by artificially accelerated atomic particles"



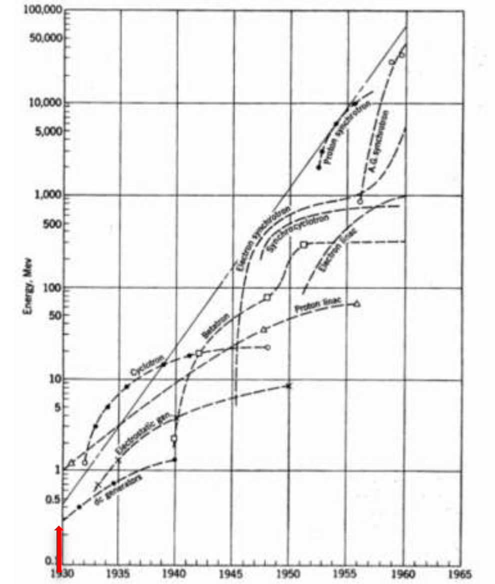

$$^{7}_{3}Li + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{4}_{2}He + energy$$

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 $\alpha$ particles.

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

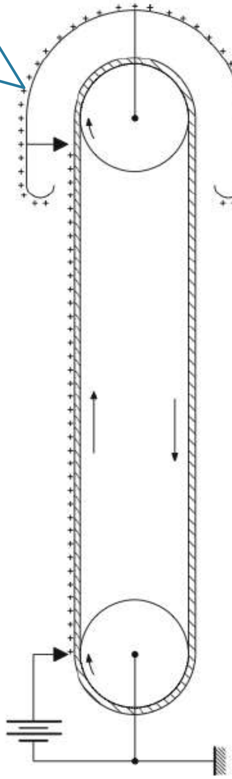
# Van de Graaff

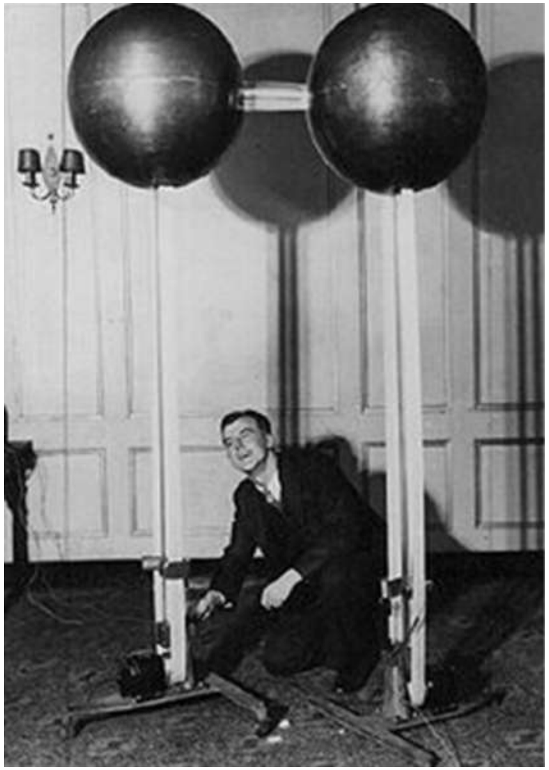



The Van de Graaff generator was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University.

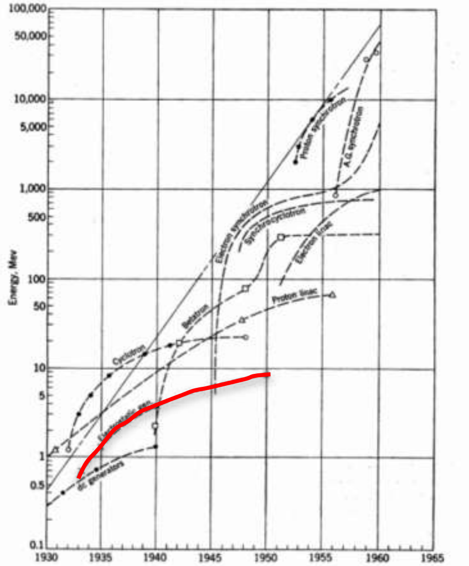
Today, up to ~10MV.

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





# Limits on Electrostatic Accelerators



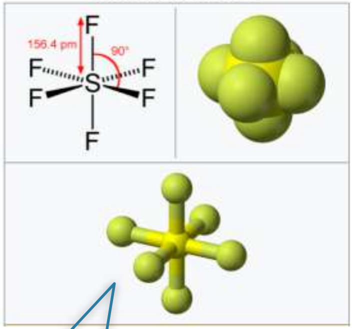

DC acceleration is limited by high-voltage breakdown

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 | ~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

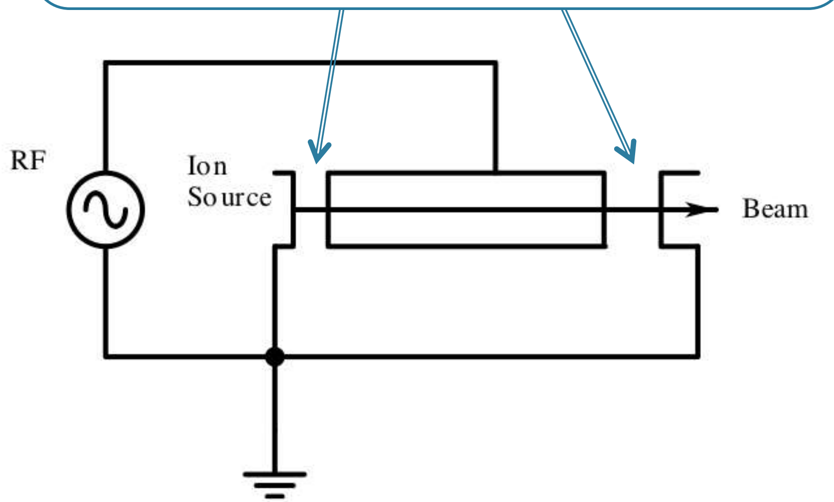
Main use
Gas circuit breakers for electrical insulation, gas insulated substations, electron beam accelerators, electrical transformers, tracers

# 2nd root

## Drift tube: From DC to AC, Radio-Frequency "RF" accelerators

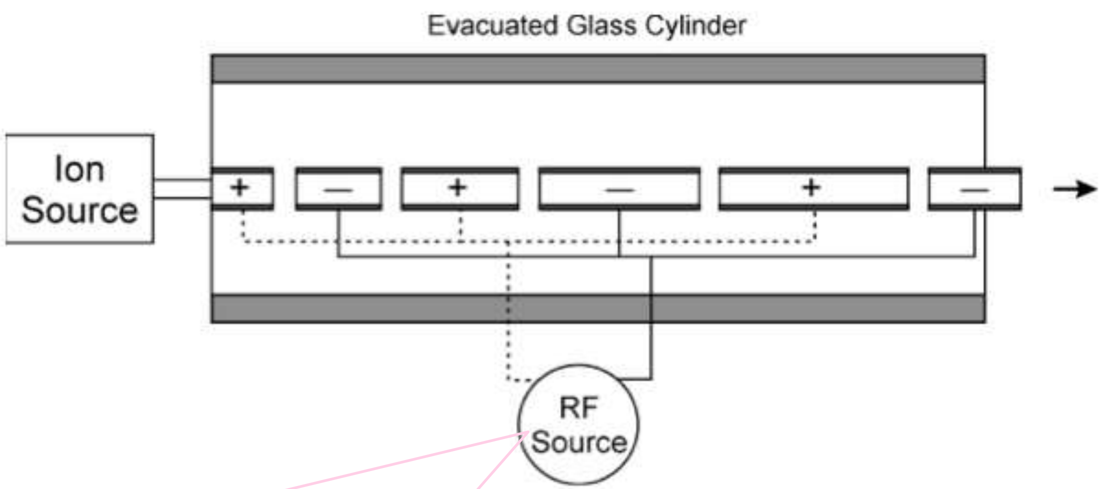
The principle of the acceleration with alternating fields was proposed by G.Ising in 1924.
R. Wideröe accelerated alkali ions (K+, Na+) up to 50 keV (25kV × 2) using the accelerator based on alternating fields (1 MHz) and drift tubes in 1928.

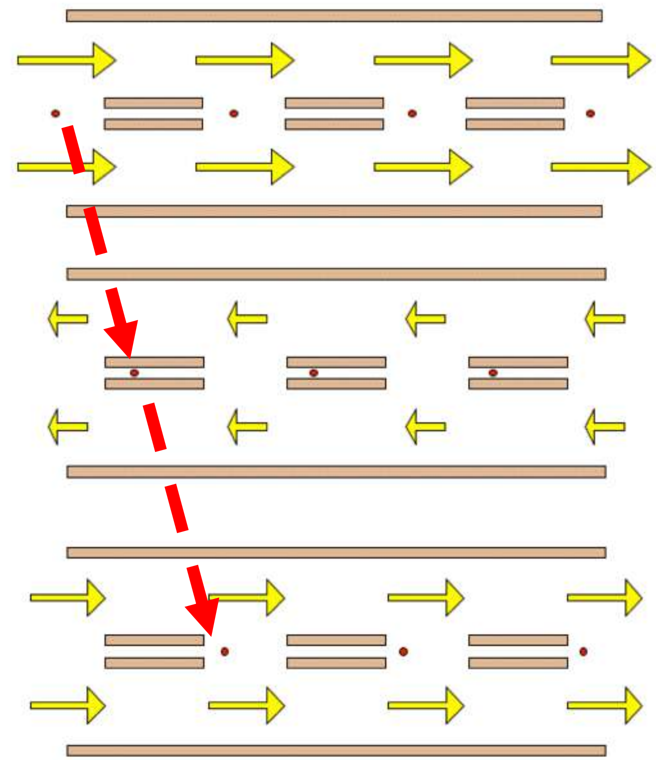
The particles must be synchronized with the rf fields in the accelerating sections.



# Drift tube: From DC to AC, Radio-Frequency Accelerators

## Concept of Wideröe accelerator



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

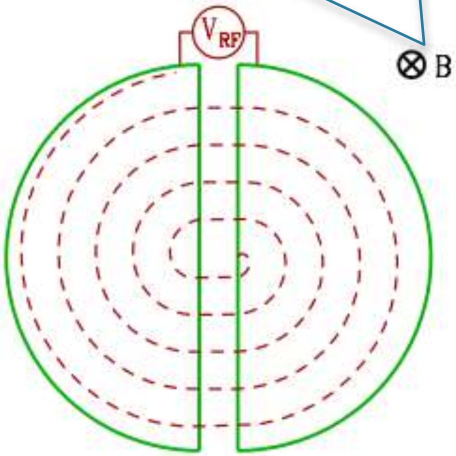
We need longer tubes and gaps as energy increases

# Cyclotron: From DC to AC, Radio-Frequency Accelerators

## First "circular" accelerator

https://www.aps.org/publications/apsnews/200306/history.cfm

Now we need magnetic field for controlling the orbit




Top view

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)

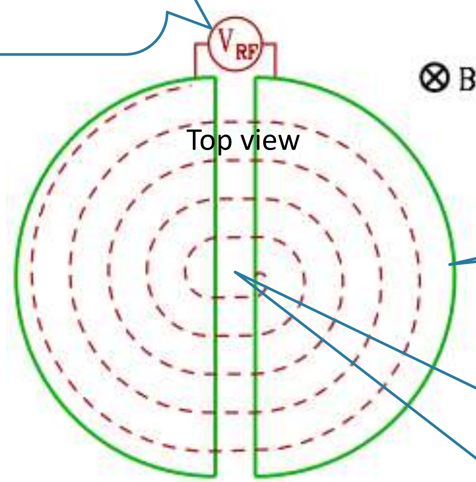
At the beginning of WWII, the skills of cyclotron builders in the US were diverted to the task of electromagnetic separation of uranium.
"FIFTY YEARS OF SYNCHROTRONS, E. J. N. Wilson, CERN, Geneva, Switzerland"

# Cyclotron: From DC to AC, Radio-Frequency Accelerators

## First “circular” accelerator

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

(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.

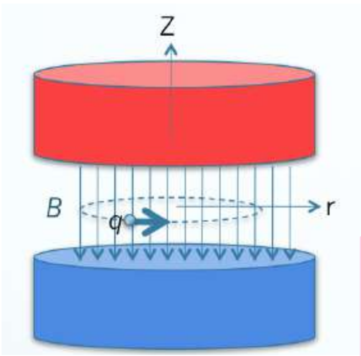
# Cyclotron: From DC to AC, Radio-Frequency Accelerators

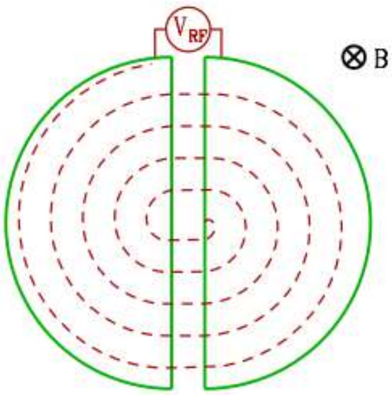
## First “circular” accelerator

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:

$$p = mv$$

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

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

# Cyclotron: From DC to AC, Radio-Frequency Accelerators

First "circular" accelerator

## Limits

When particles become relativistic the mass of the particle increases as

$$m \rightarrow m\gamma$$

which results in

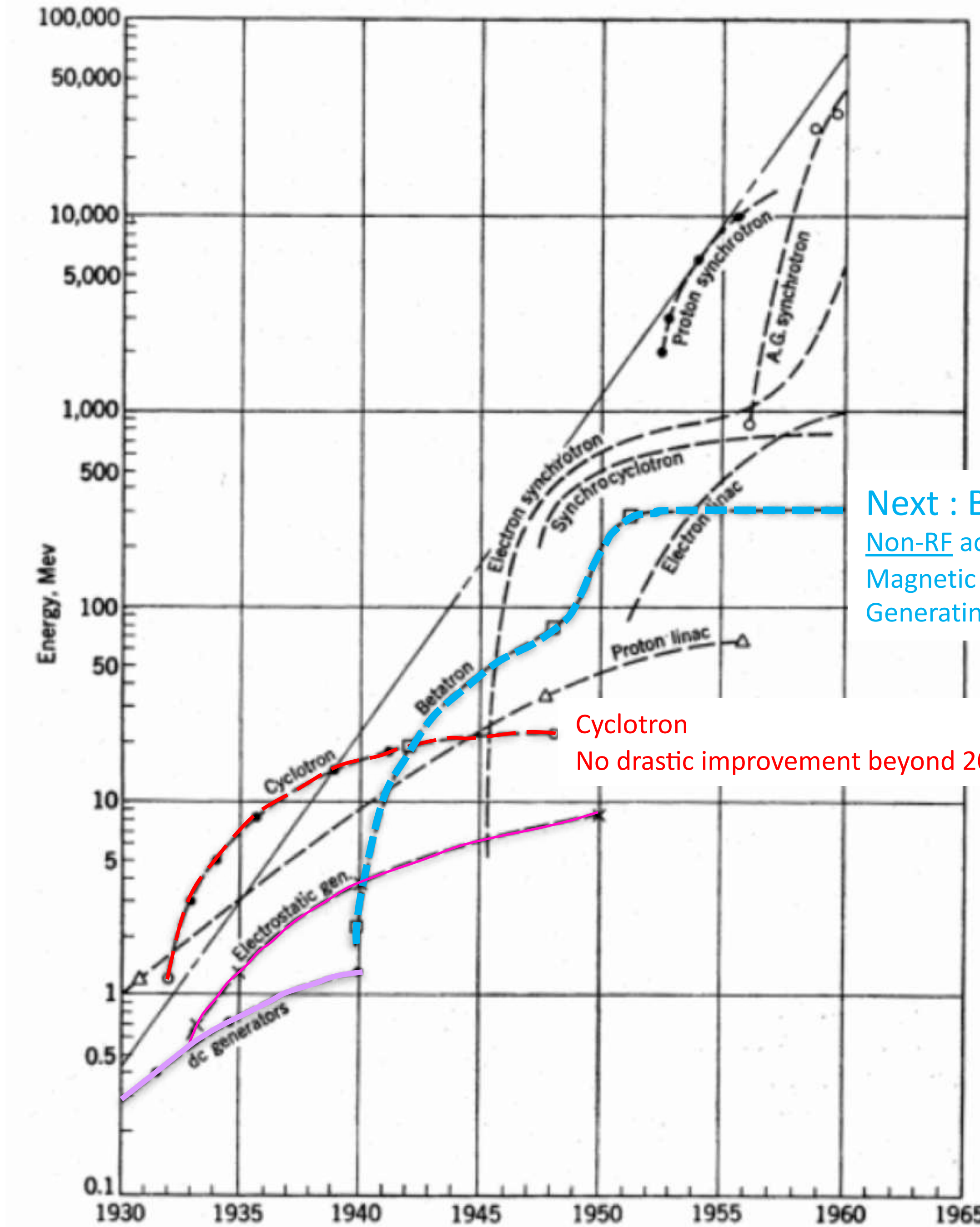
→ decrease of $\omega_{rev}(2\pi f_{rev})$

→ asynchronism with RF

Some attempts made:

- Magnetic field distribution
- Changing rf freuquency so that …

But no drastic improvement beyond 20 MeV with protons.




Next : Betatron

Non-RF acceleration

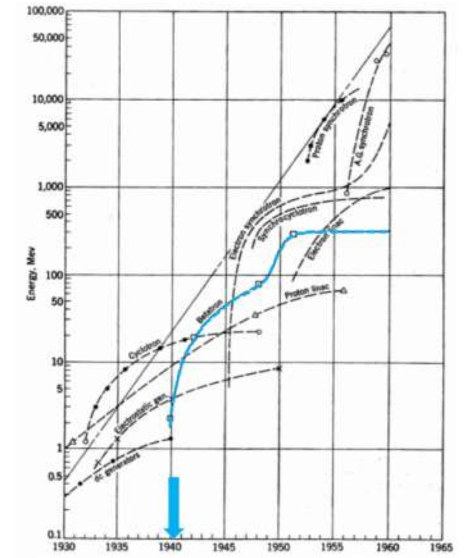
Magnetic induction is used for Generating the electric field

Cyclotron

No drastic improvement beyond 20 MeV with protons.

# 3rd root

## Betatron: use of electric field induced by magnetic induction

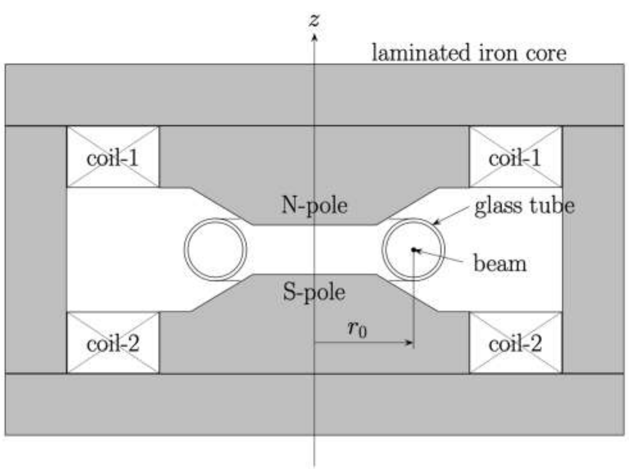



http://physics.illinois.edu/history/Betatron.asp

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

$$\nabla\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0$$ Maxell's eq.

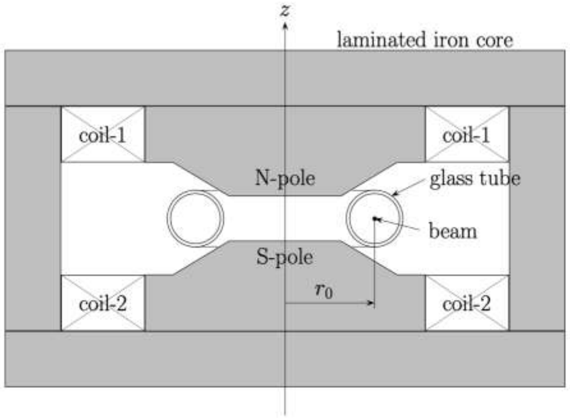
$$\oint\vec{E}\cdot d\vec{l}=\int\frac{\partial\vec{B}}{\partial t}\cdot d\vec{S}=-\frac{\partial\Phi}{\partial t}$$

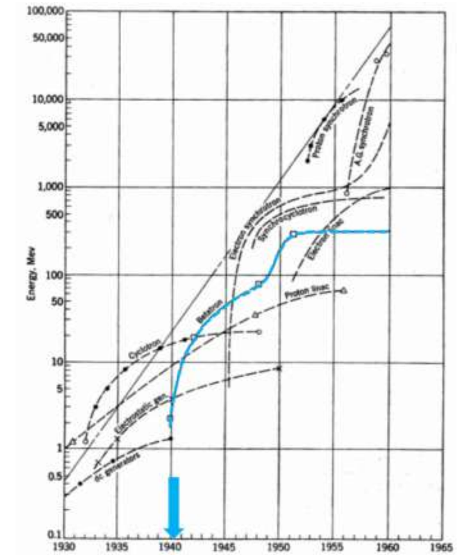



The electric field induced by a varying magnetic field is used for acceleration

Faraday's law of induction

# Betatron: non RF, accelerate electrons (beta particles)




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

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

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

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

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

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

Different from Cyclotron

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

From (1) and (2) we obtain the condition for constant orbit for betatron.
"2:1 rule" (Wideröe, 1928) or "Betatron two for one condition"
The magnetic field at the orbit must be half the average magnetic field over its circular cross section

# Betatron: what we learned from betatron (1)

From the analysis of transverse oscillations of particles we

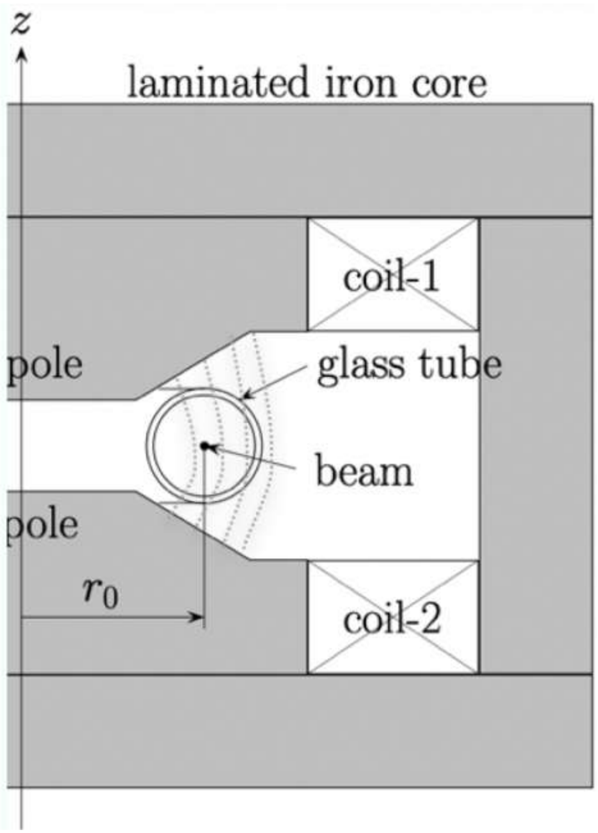
→obtained an understanding of the orbit
→developed the theory of betatron oscillations of today

Orbit theory
➜ We learned about conditions for a stable orbit from betatron

# Betatron: what we learned from betatron (2)

Magnetic field by this magnet is not uniform but still cylindrically symmetric.

Therefore it can be written as




$$B_z(r,z) = \frac{B_\rho}{\left[{}^{r}/_{\rho}\right]^n} \qquad n \equiv \frac{\Delta B/B}{\Delta r/r} \qquad (fied\ index)$$

If the particle passage (orbit) is near the central orbit, $r = \rho$

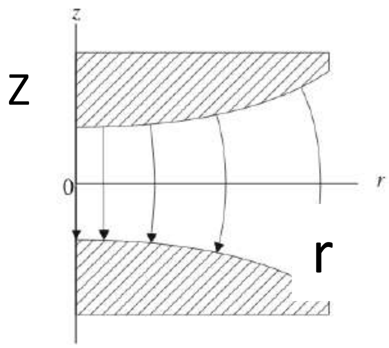
$$B_z(\rho + x, z) = \frac{B_\rho}{\left[{}^{(\rho + x)}/_{\rho}\right]^n} \cong B_\rho\left(1 - \frac{n}{\rho}x\right)$$

From Maxwell's equation

$$\frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r} = 0$$

$$\therefore B_r(r,z) = -\frac{nB_\rho}{\left[{}^{r}/_{\rho}\right]^{n+1}} z \cong B_\rho\left(-n\frac{z}{\rho}\right)$$

# Betatron: what we learned from betatron (2)




$$B_z(\rho + x, z) = \frac{B_\rho}{\left[ {(\rho + x)}/{\rho} \right]^n} \cong B_\rho \left( 1 - \frac{n}{\rho} x \right) \qquad B_r(r, z) = -\frac{nB_\rho}{\left[ {r}/{\rho} \right]^{n+1}} z \cong B_\rho \left( -n \frac{z}{\rho} \right)$$

Using the first order approximation of the field above

we obtain eq. of motion for horizontal direction $x$ as

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

for the vertical direction $z$ as

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

$$\omega_x \equiv \omega \sqrt{1 - n}$$
$$\omega_z \equiv \omega \sqrt{n}$$

The oscillation is stable if 0<n<1

$$\nu_x \equiv \sqrt{1 - n}$$
$$\nu_z \equiv \sqrt{n}$$

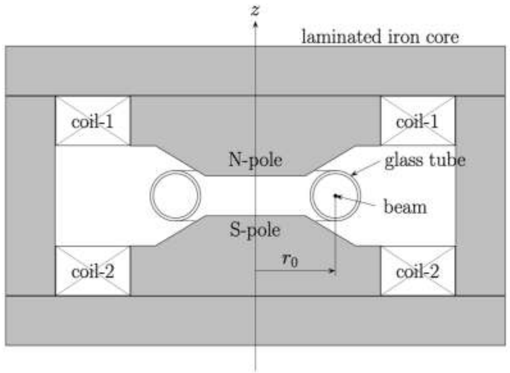
# Betatron: what we learned from betatron (2)

## Concept of Weak Focusing

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

If 0<n<1, stable oscillation in BOTH horizontal and vertical plane!
But n<1 …. This is why this scheme is called "Weak" focusing.

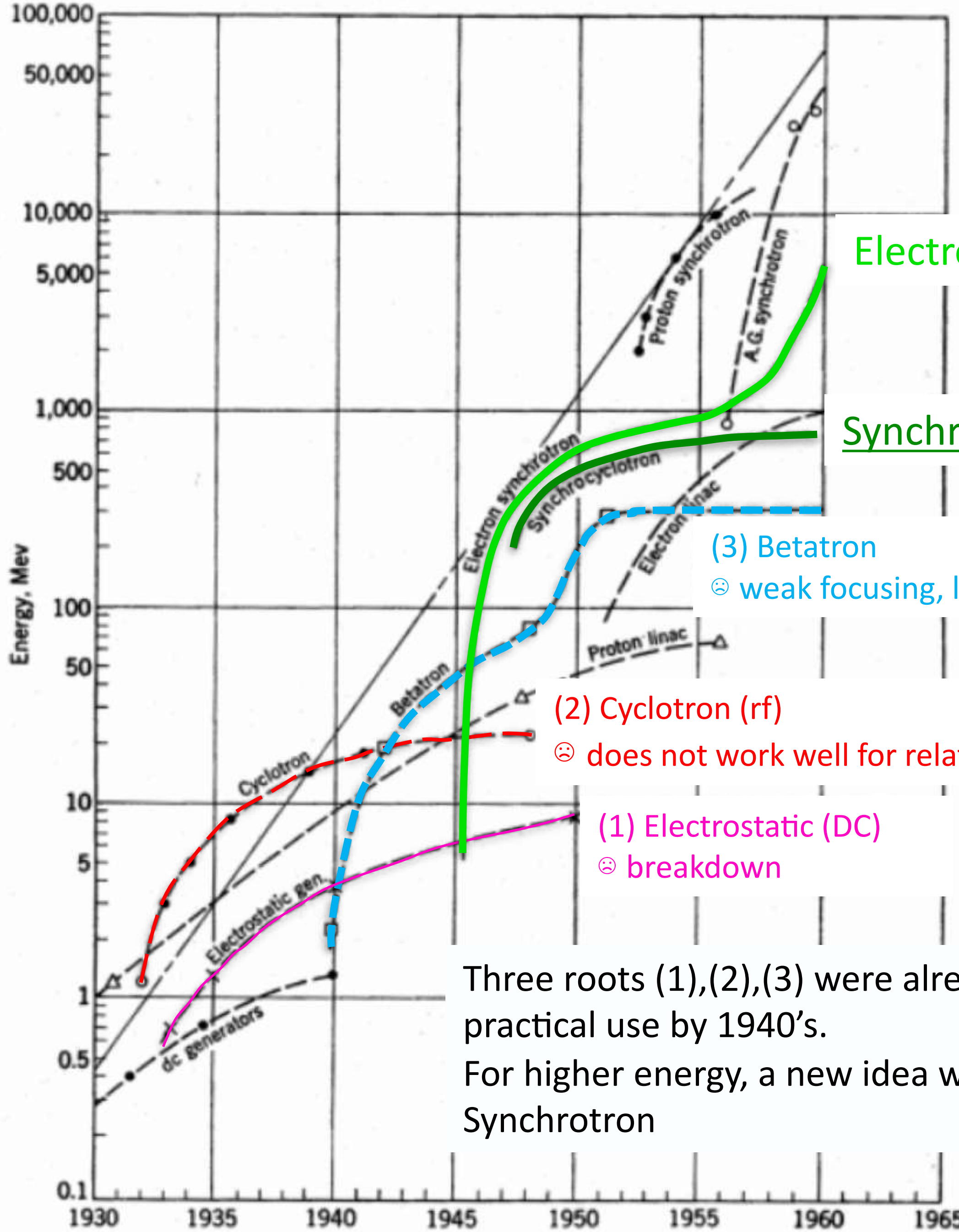
If you want to achieve higher energy, stronger focus is needed.
And you need a large magnet to generate magnetic field to cover the beam path.




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

Explain about strong focusing in a couple slides later

Next Synchrotron




Electron Synchrotron

Synchrocyclotron

(3) Betatron
☹ weak focusing, large magnets needed

(2) Cyclotron (rf)
☹ does not work well for relativistic particles

(1) Electrostatic (DC)
☹ breakdown

Three roots (1),(2),(3) were already put into a practical use by 1940's.
For higher energy, a new idea was needed ➜ Synchrotron

# Synchrotron : Radio-Frequency (RF) Accelerators

RF acceleration → the arrival time of the particles to the RF gap is important

Limiting factor was
Particles of different energies (larger or smaller) energies have differences in velocity and in orbit length;

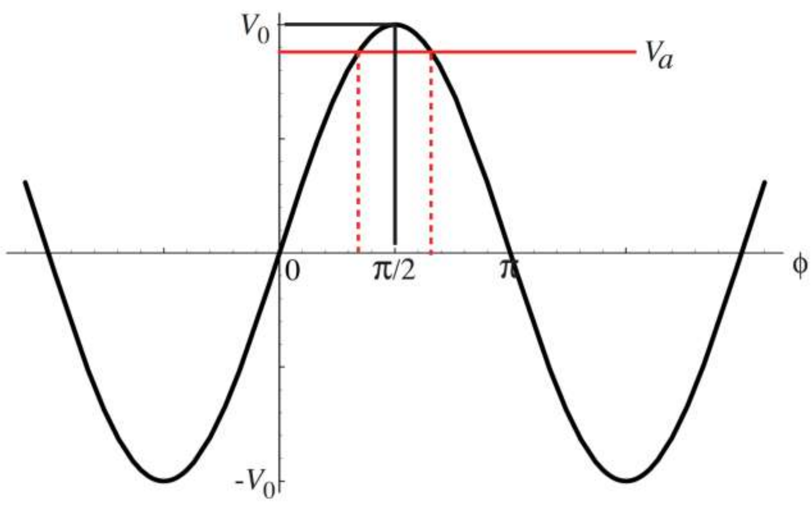
→particles may be asynchronous (😔) with the RF frequency

Discovery of Phase stability🙂

# Discovery of Phase stability:

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

Sinusoidal RF Wave



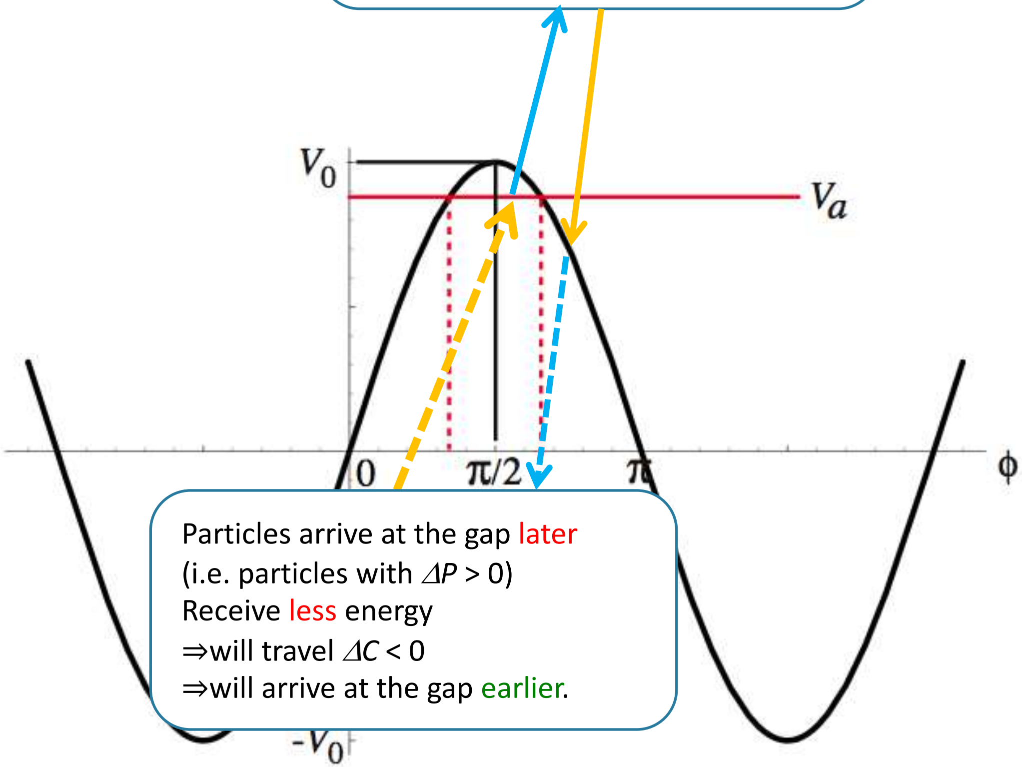

Phase stability
The RF field has a “restoring force” at a certain phase

The particles stay synchronous

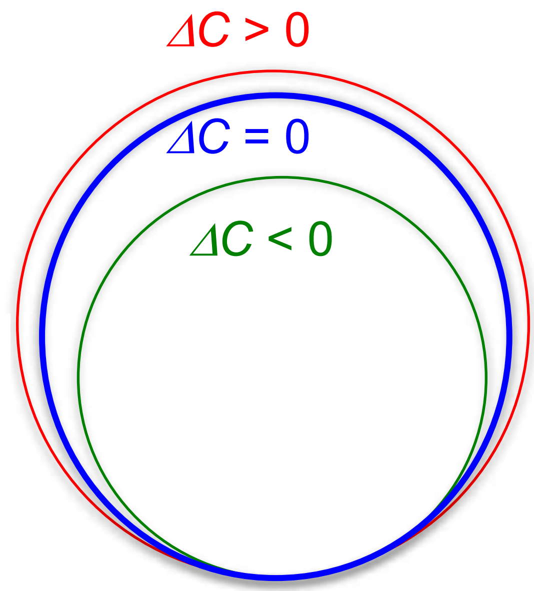
# Phase stability: "restoring force" at a certain phase

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

Particles arrive at the gap earlier
(i.e. particles with $\Delta P < 0$)
Receive more energy
$\Rightarrow$will travel $\Delta C > 0$
$\Rightarrow$will arrive at the gap later.




Particles arrive at the gap later
(i.e. particles with $\Delta P > 0$)
Receive less energy
$\Rightarrow$will travel $\Delta C < 0$
$\Rightarrow$will arrive at the gap earlier.




Example of a circular orbit

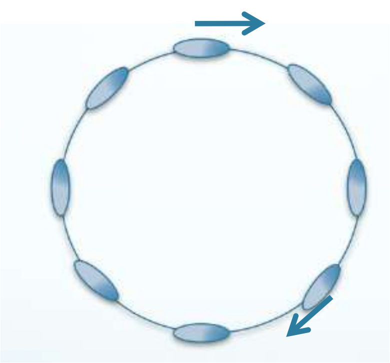
Particles oscillations around $\phi_s$
(Synchrotron phase)

"Synchrotron oscillations"
in the longitudinal direction

# Phase stability: "restoring force" at a certain phase

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.

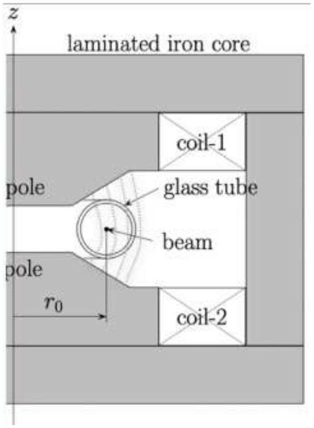


Particles are bunched
There are many particles in a bunch, <u>circulating many turns tens of thousands</u>, for example.

"Storage ring"

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

# Proposal of strong focusing/ alternating-gradient (AG) focusing




Before strong focusing, it was "weak focusing"
0<n<1

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

Magnetic field to cover the entire region
Focusing in both horizontal and vertical plane is possible

Nicholas C. Christofilos (1950)
E. Courant, M. Livingston and H. Snyder (1952)
proposed strong focusing, also known as alternating-gradient (AG) focusing.

## What are different from "weak focusing"?

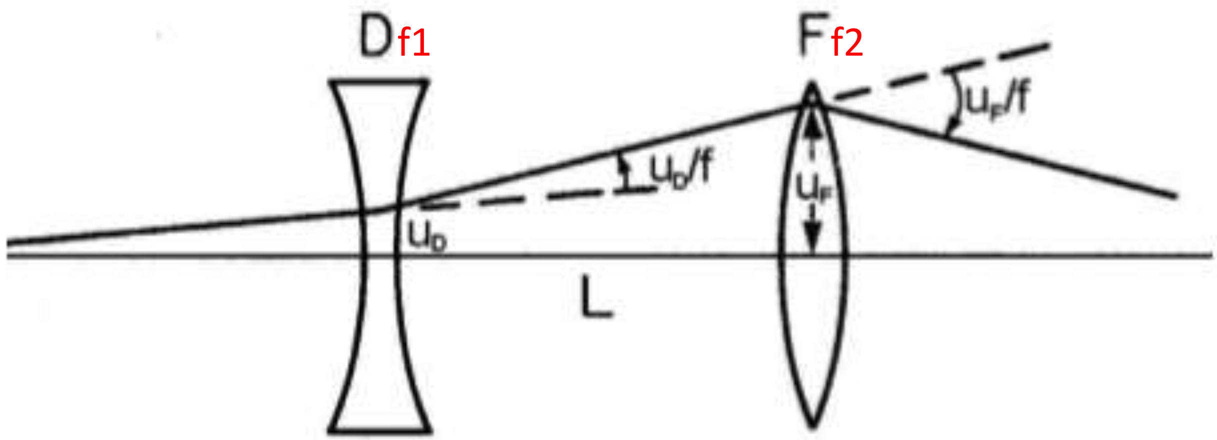
- No limitations for the n value.
- Focusing in one direction, defocusing in the other.

Is this a problem?

# Strong focus: Alternating gradient synchrotron

No, it is not a problem, because

Analogy with optical thin lens




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

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

The deflection (u) is always greater at F than D.

If $f_1 = -f_2 \equiv -f$

The overall focal length is

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

Since it is positive, net focus

Obtaining a net focus by combining F- anf D- magnets is called "strong focus", as no constraints on $n$.

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

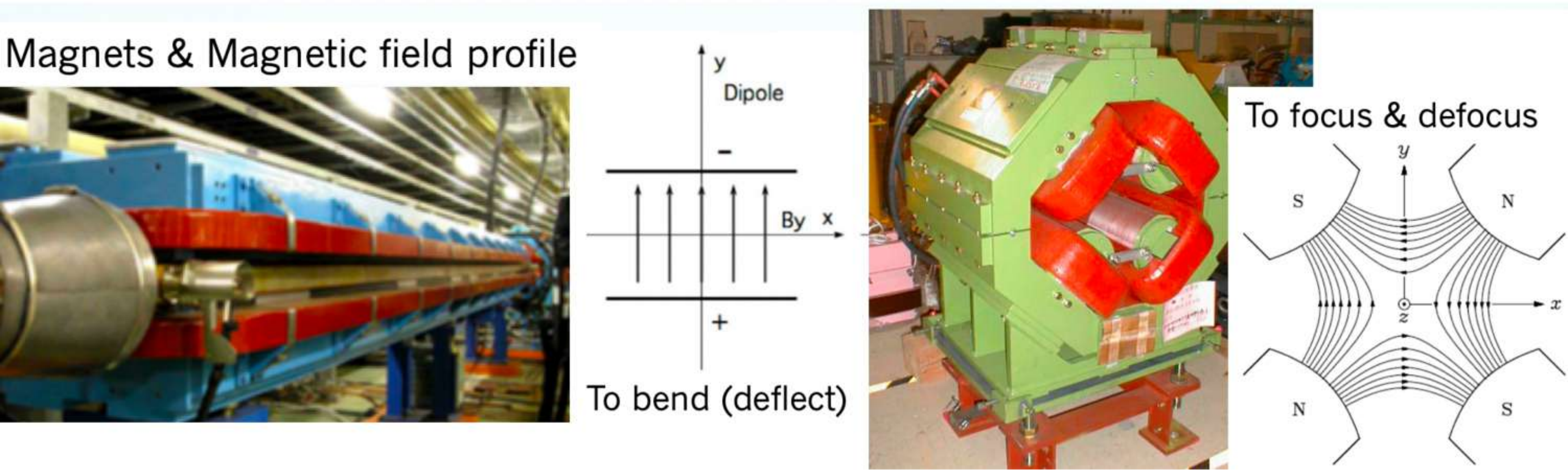
# Strong focus: Alternating gradient synchrotron

For very high energy particles, magnetic force is much larger than electric

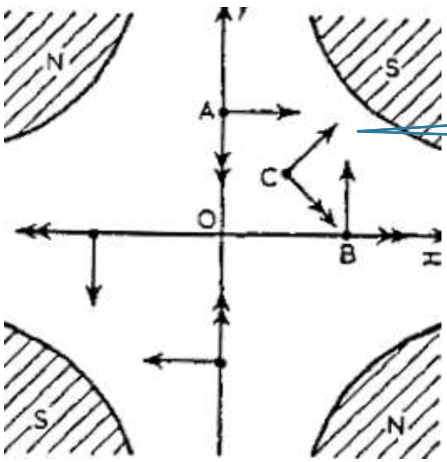
$$\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

For example, compare
B=2[Tesla] and 10kV/mm (10MV/m)

Both are reasonable numbers for today's accelerators.
Use 2 [T] = 2 [Wb/m$^2$]=2 [V ・ s/m$^2$]
The magnetic term is 2 [V・s/m$^2$] × 3 ・ 10$^8$[m/s]=6 ・ 10$^8$V/m=600MV/m >> 10 MV/m



# Strong focus: Alternating gradient synchrotron




Positively charged particle moving into this paper.

Quiz) What is the force on the particle at points A, B and C?

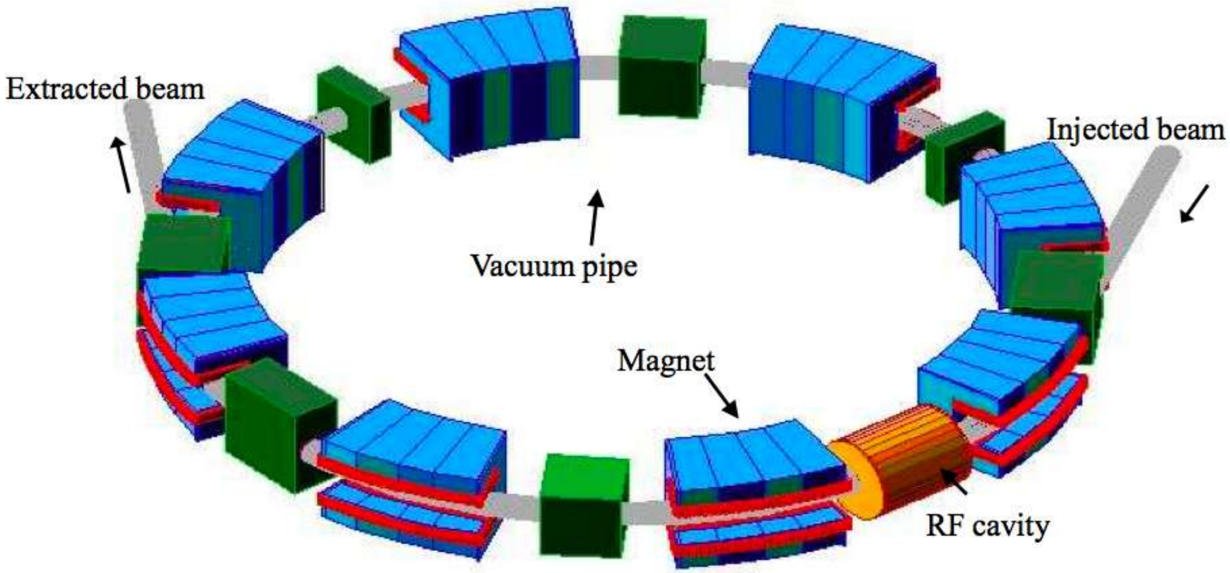
Focusing in horinzontal direction and defocusing in vertical direction.
Let's call it "Focusing" or "F-type" quadrupole magnet.

If the polarity is reversed (N and S are reversed), defocusing in horizontal and focusing in vertical.
We call it "Defocusing" or "D-type" quadrupole magnet.

# Strong focus: Alternating gradient synchrotron

Synchrotron basic components

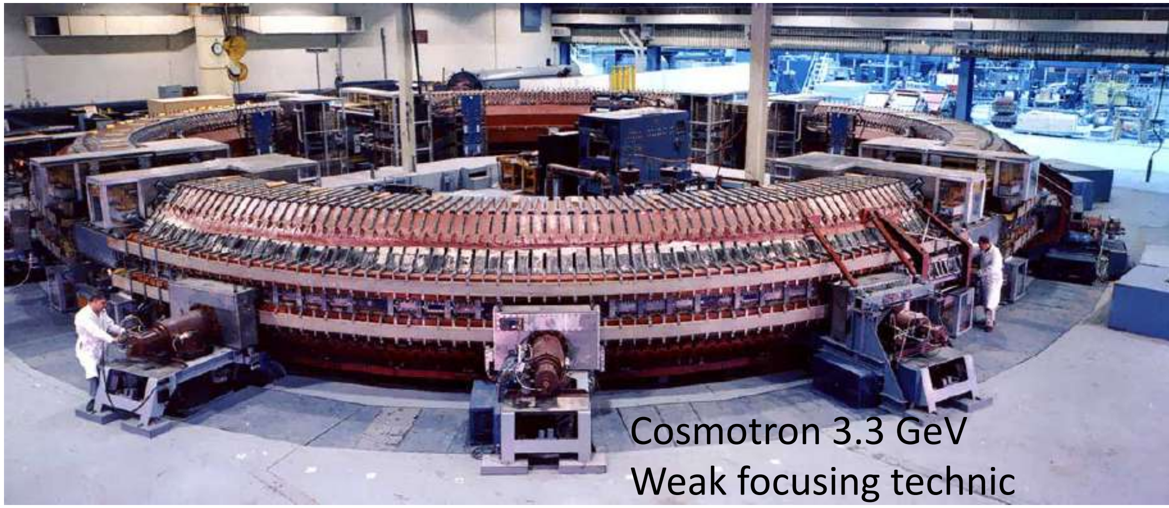
Vacuum pipes
To cover the beam passage



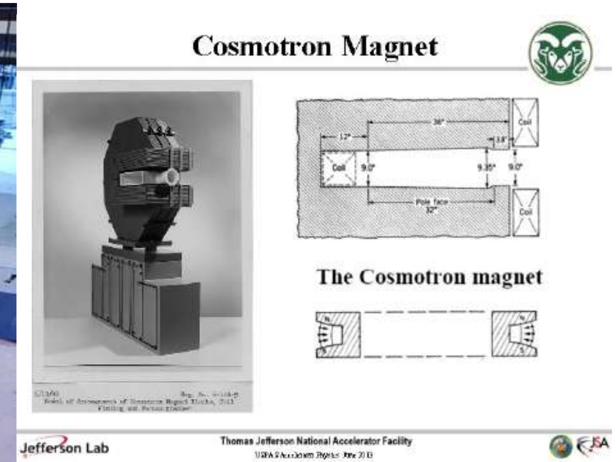

Magnets
Dipole magnets for bending
Quadrupole magnets for focusing

RF cavities
To accelerate/compensate for lost energy

# Strong focus vs. weak focus

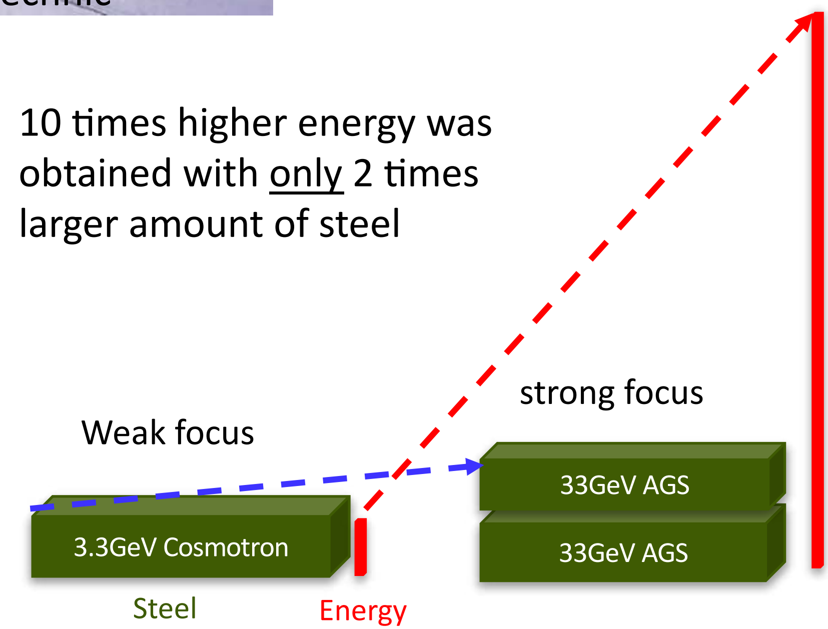


Cosmotron 3.3 GeV
Weak focusing technic




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

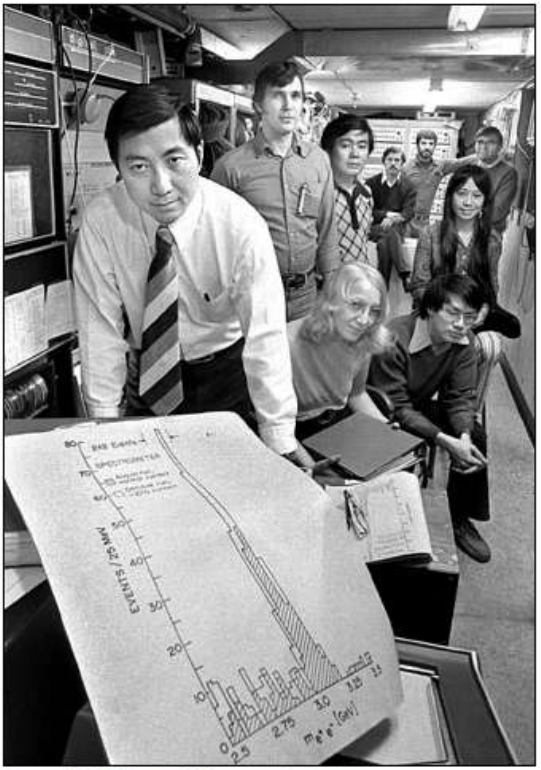
10 times higher energy was obtained with <u>only</u> 2 times larger amount of steel




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

# Alternating gradient synchrotron (AGS)

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



Samuel C.C. Ting and his research team.

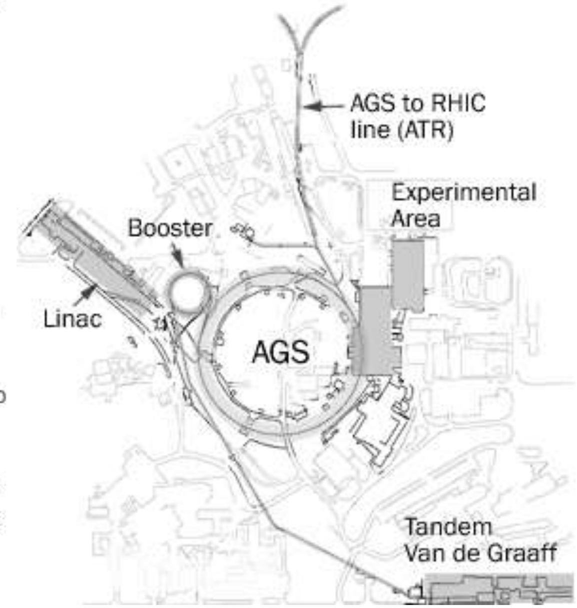
## Discovery of the J/psi Particle

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

# Brief history & major inventions
# collider

# Brief history and inventions before 1960

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

✓ Discovery of Phase stability principle in1945
→ Synchronization issue is solved.
Weak focusing

Betatron
•Acceleration by magnetic induction
•Constant orbit
•Entire orbit covered by magnets

✓ Discovery of Strong focusing
In 1952

✓ Orbit stability/theory
Betatron oscillation, Weak focusing
We learned a lot from Betatron

Birth of Synchrotron
•Entire orbit is not needed to be covered by magnets.
•Can reach much higher energy >10 GeV
→ Can go Even higher in energy?

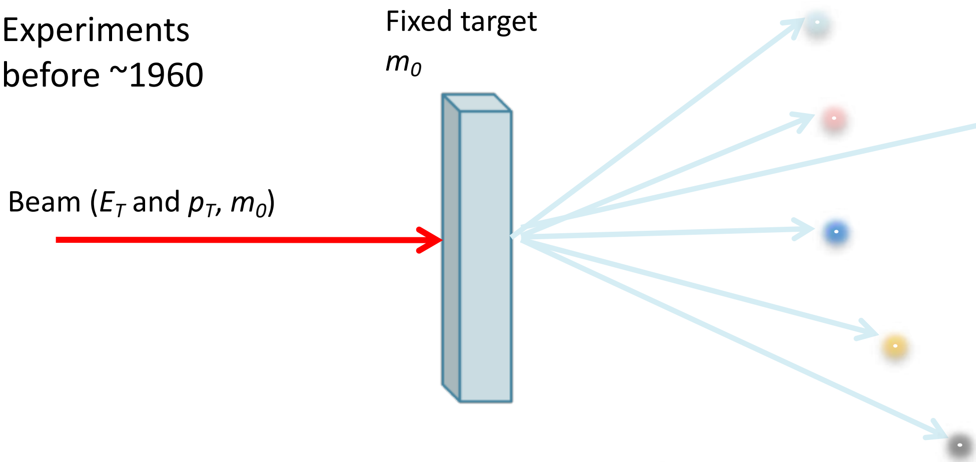
Collider

Storage Ring

Keeps particles stored at a constant energy for a long time (storage).

# Collider

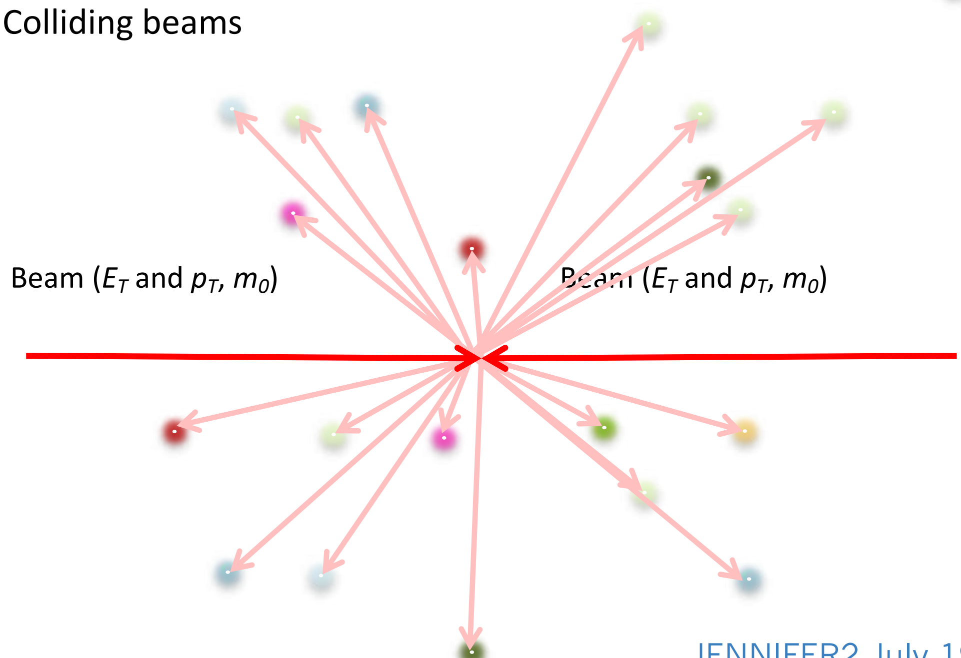
Experiments before ~1960




Lorentz invariant

$$E_T = (1+\gamma)mc^2$$
$$P_T = \beta\gamma m_0 c$$
$$\therefore -E_{C.M.}^2 = (P_T c)^2 - E_T^2$$
$$= (\beta\gamma m_0 c \cdot c)^2 - [(1+\gamma)m_0c^2]^2$$
$$= -2(1+\gamma)(m_0c^2)^2$$
$$\therefore E_{C.M.} = \sqrt{2(1+\gamma)}m_0c^2 \approx \sqrt{2\gamma}m_0c^2$$

Colliding beams




$$E_{C.M.} = 2\gamma m_0c^2 > \sqrt{2\gamma}m_0c^2$$

collider

Fixed target

Collider🙂
Higher energy than fixed target

Collider😔
Collision rate is lower

# Collider: the first collider ($e^-e^+$):AdA

(Anello di Accumulazione) and happened to be Bruno Touschek's aunt's name.

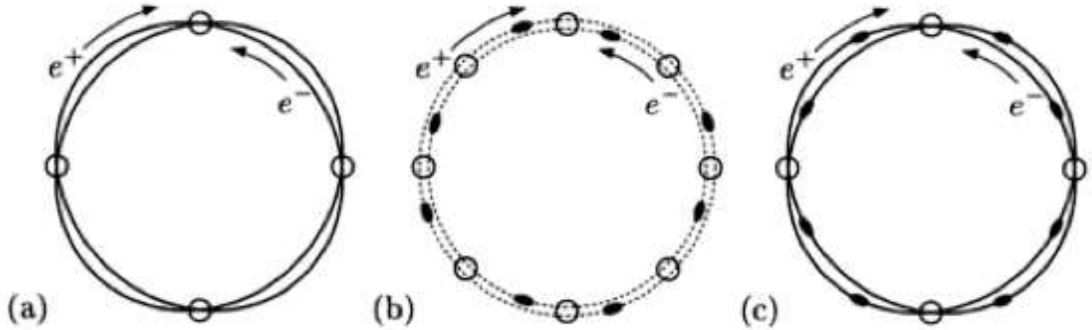
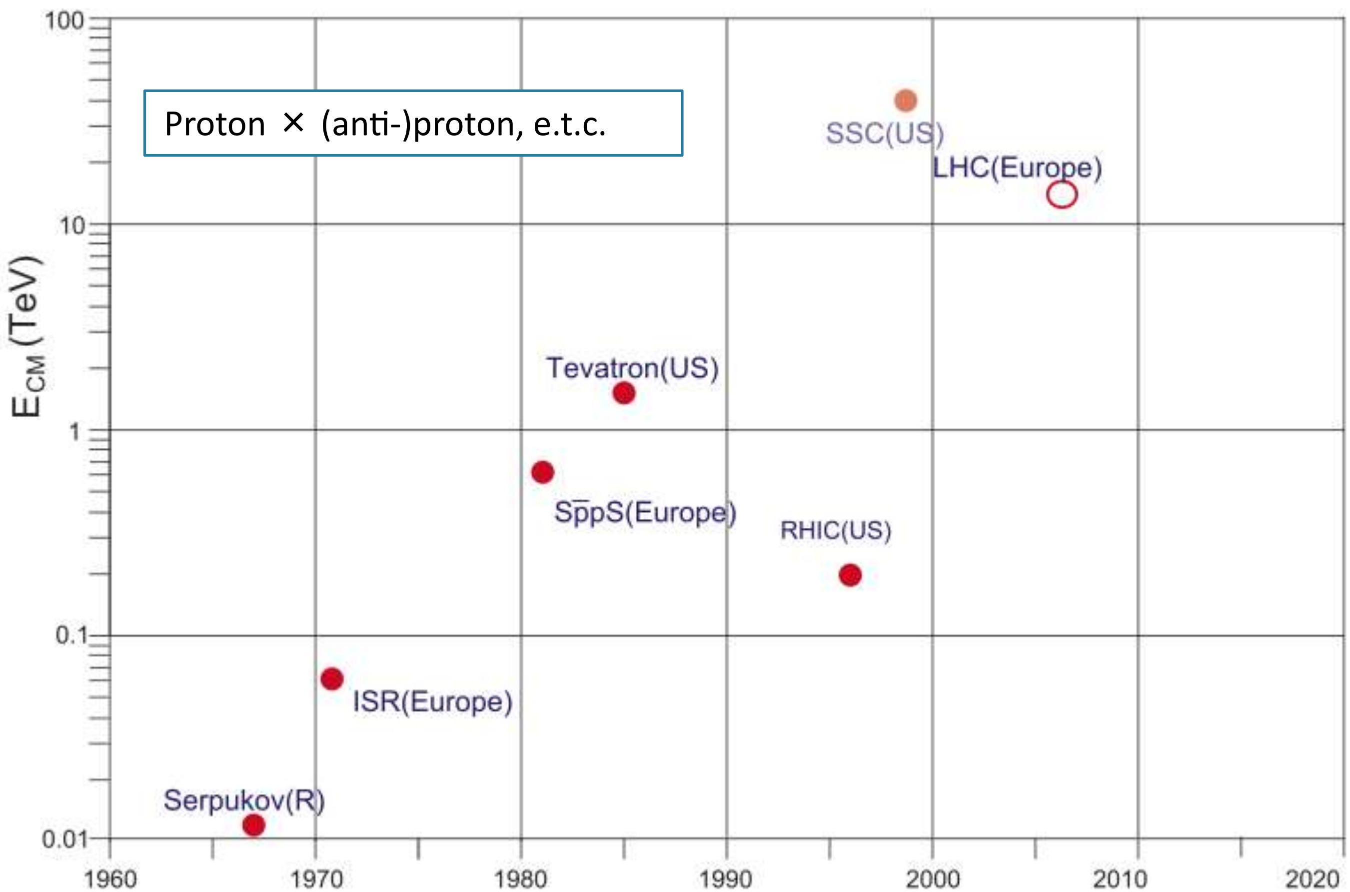



**Fig. 1.11.** (a) Beam routing. Small distortions to the circular trajectories make the two beams overlap only at a few selected places. The small circles denote the collision sites, at which the detectors will be aimed. (b) Beam bunching. Here particles come in concentrated volleys or "bunches" (the 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 1969
C=105 m
$E_{cm}$ < 3 GeV
no J/ψ …

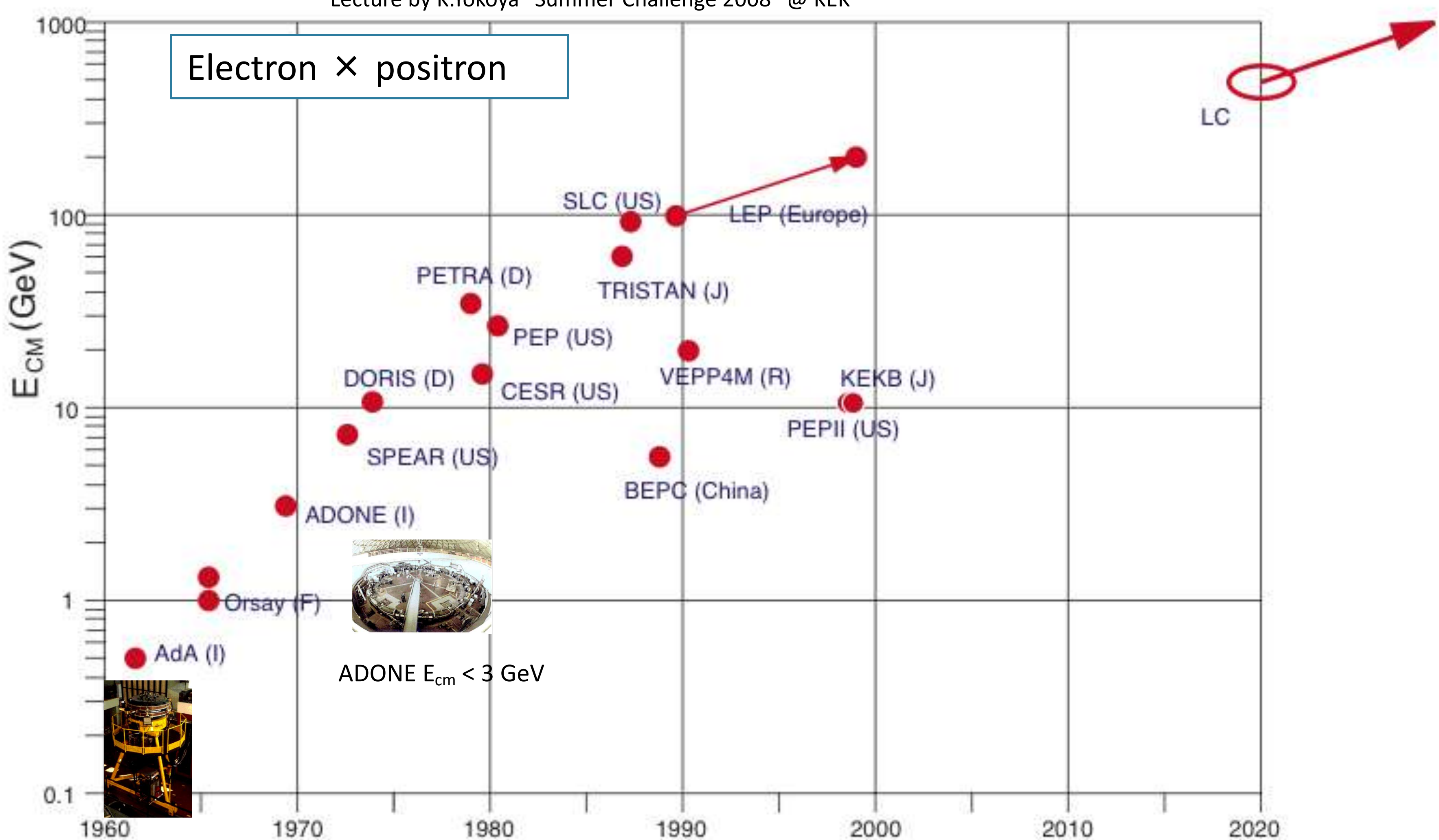
# Collider: Era of large circular colliders, energy frontier machines




Lecture by K.Yokoya "Summer Challenge 2008" @ KEK

# Collider: Era of large circular colliders, energy frontier machines

Lecture by K.Yokoya "Summer Challenge 2008" @ KEK




AdA (250MeV × 250 MeV)

# Collider: Era of large circular colliders, energy frontier machines (Tevatron)

**Tevatron (Fermilab)**

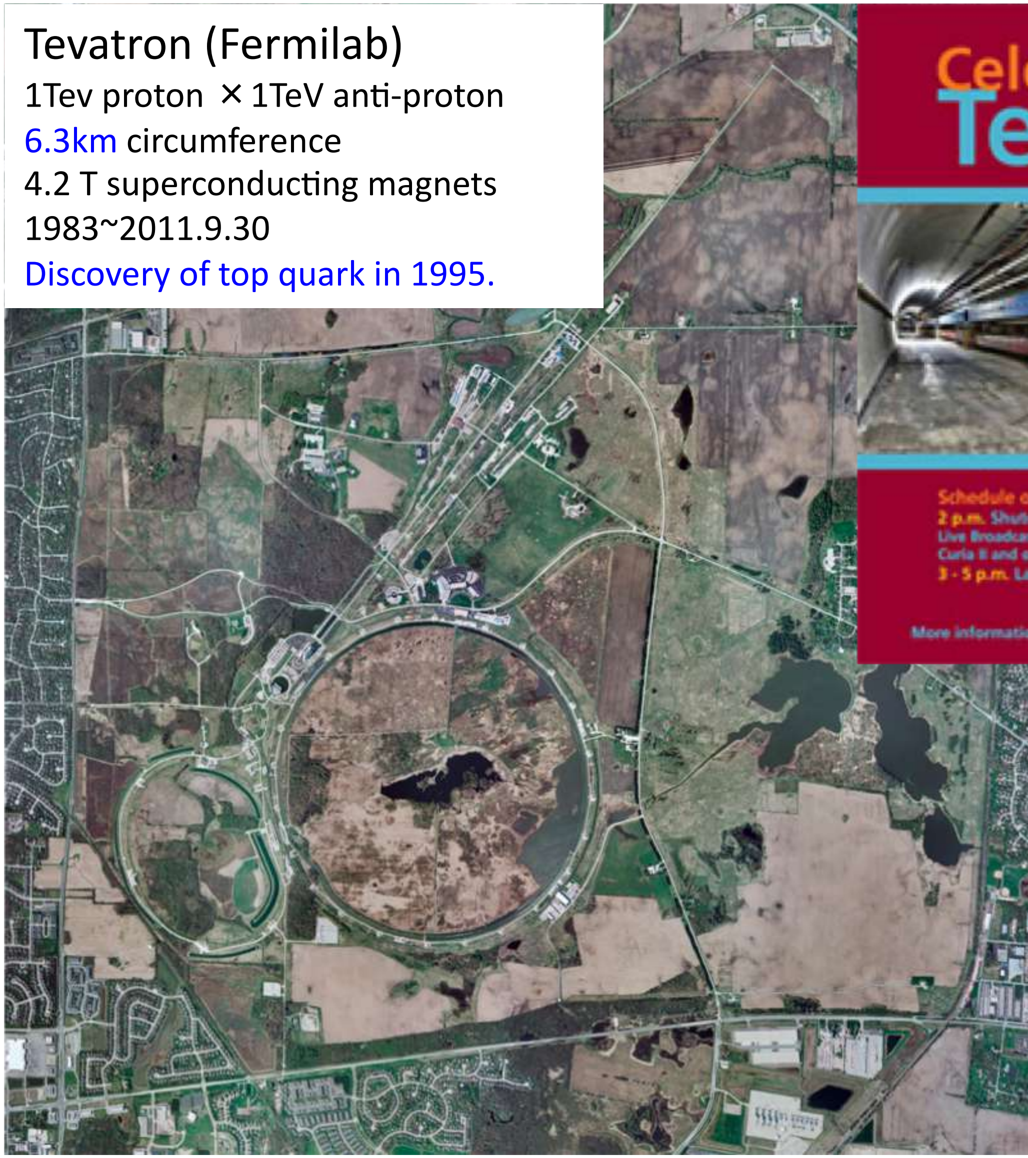
1Tev proton × 1TeV anti-proton

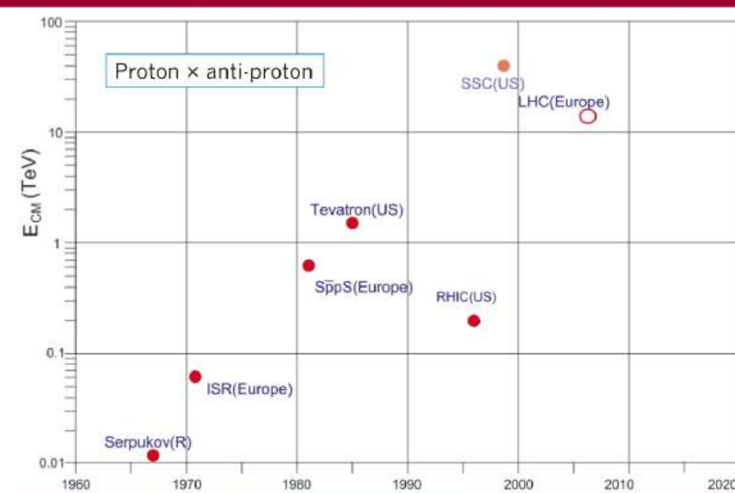
6.3km circumference

4.2 T superconducting magnets

1983~2011.9.30

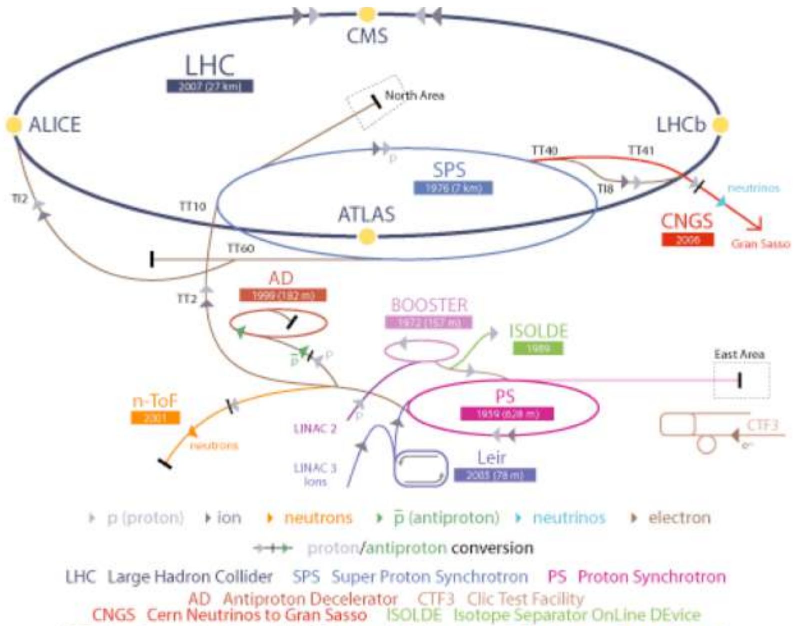
Discovery of top quark in 1995.



# Collider: Era of large circular colliders, energy frontier machines

SPS (Super Proton Synchrotron) →
SppS(Super Proton Anti-Proton Synchrotron) @CERN



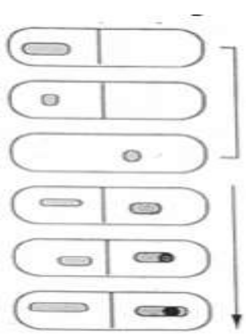

http://public.web.cern.ch/public/en/Research/UA1_UA2-en.html

SPS (Super Proton Synchrotron)
~7km in circumference
1976 commissioning

From a one-beam accelerator into a two-beam collider, SppS. D. Cline, P.McIntyre and C. Rubbia
Collision of a beam of protons with a beam of antiprotons, greatly increasing the available energy in comparison with a single beam colliding against a fixed target.

1981 SppS $\sqrt{s} = 540\ GeV$

Rev. Mod. Phys. 57, 689–697 (1985)
Stochastic cooling and the accumulation of antiprotons



Stochastic cooling
a way of producing and storing dense beams of protons or antiprotons
S. Van der Meer

## 1983 Discovery of $W^{\pm}$ & $Z^0$

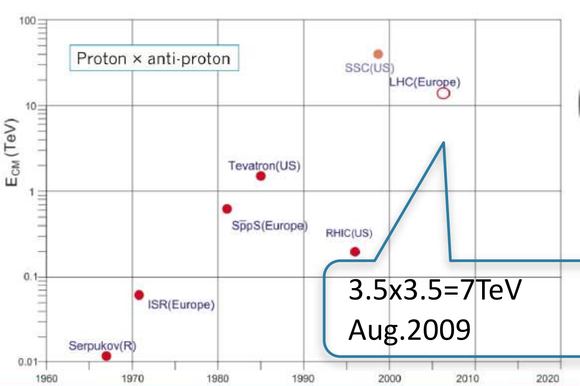
Nobel prize for Van der Meer and Rubbia

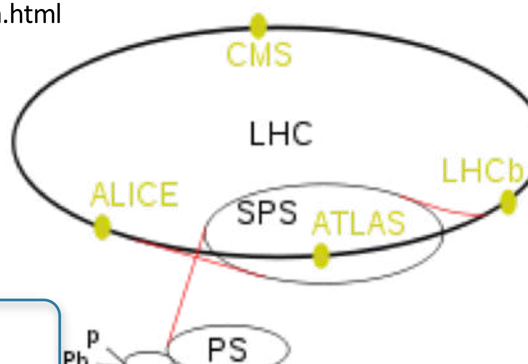
# Collider: Era of large circular colliders, energy frontier machines (LHC)

| 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 |

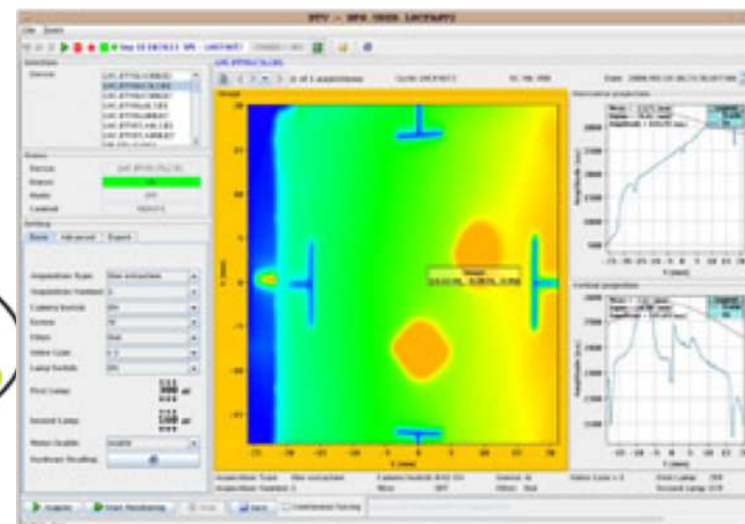
27 km!!!

http://public.web.cern.ch/public/en/LHC/LHC-en.html




Celebrating the first beam in the ATLAS control room, Sep.2008.



# Collider: Era of large circular colliders

$E_{CM}$ is important parameter for a collider
But there is another important key parameter for a particle accelerator

## Luminosity

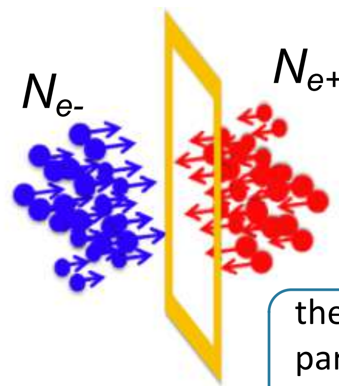
Luminosity gives a measure of how many collisions are happening in a particle accelerator, so we're often asked why we don't just say collision rate. It's a very reasonable question. The answer is because luminosity isn't strictly speaking the collision rate: it measures how many particles we're able to squeeze through a given space in a given time. That doesn't mean that those particles will all collide, but the more we can squeeze into a given space, the more likely they are to collide.

https://home.cern/news/opinion/cern/luminosity-why-dont-we-just-say-collision-rate

# Collider: Luminosity

Fixed target
Beam on solid (usually) target
Collision guaranteed

Collider
Bunch against bunch
Some (most) stream through the other




$$Y = L\sigma$$

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

the number of particles per unit area per unit time

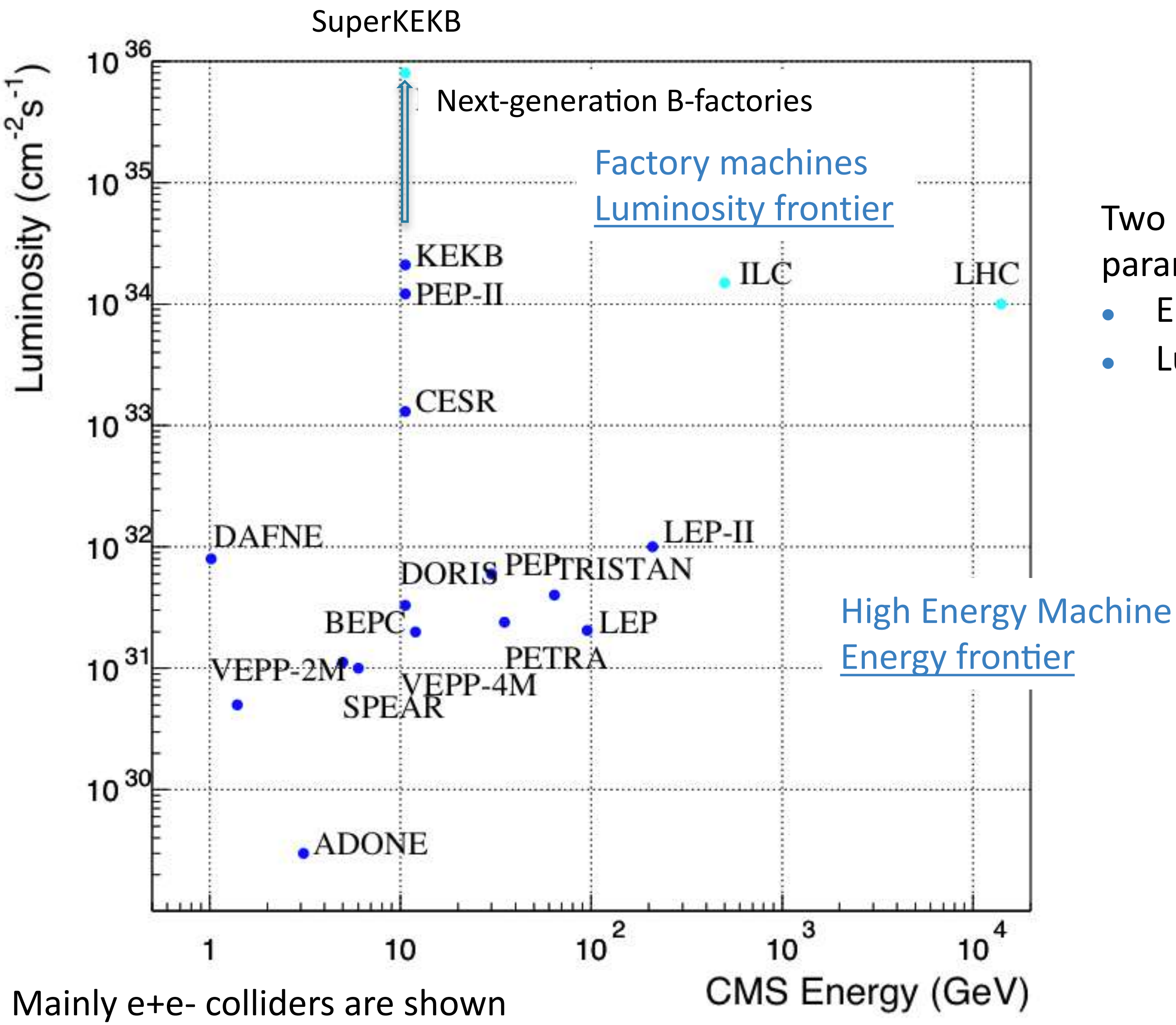
$$dN_{\pm} = \frac{N_{\pm}}{2\pi\sigma_x^*\sigma_y^*} exp\left(-\frac{x^2}{2\sigma_x^{*2}} - \frac{y^2}{2\sigma_y^{*2}}\right) dxdy$$

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

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

⇨ Higher luminosity

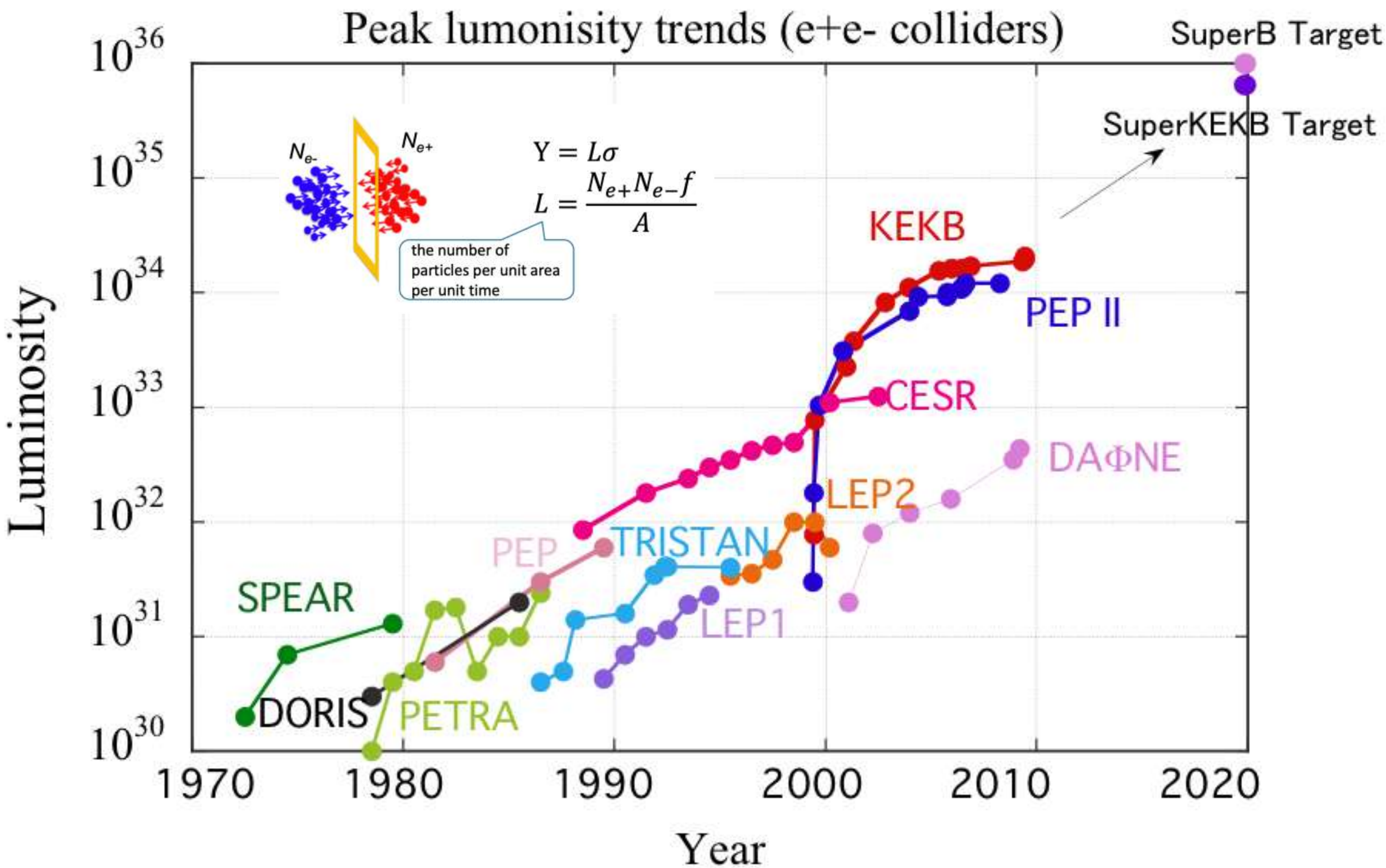
# Collider: Era of large circular colliders




Two important parameters
- Energy
- Luminosity*

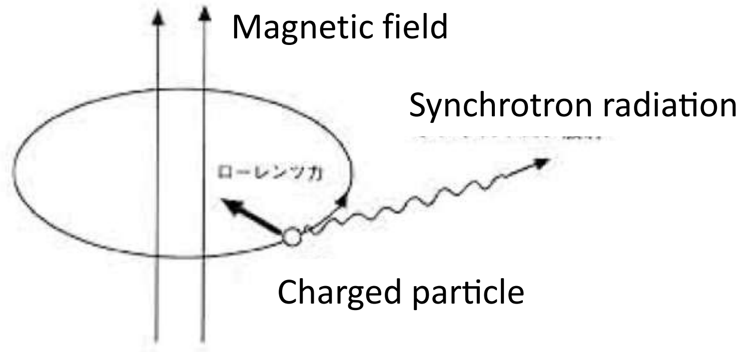
Mainly e+e- colliders are shown

# Collider: Era of large circular colliders, luminosity frontier machines



# Collider: Era of large circular/linear colliders

1. Circular ? Linear?
   Synchrotron radiation



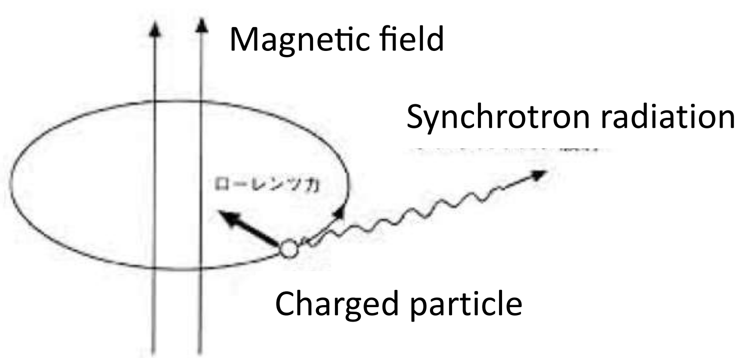

2. Types of accelerators

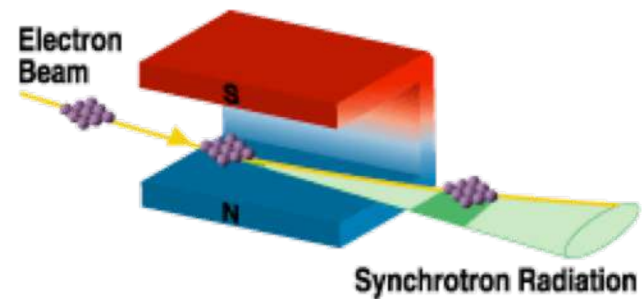
# 1. Synchrotron radiation

•Synchrotron radiation (SR) is emitted from an electron (a charged particle) traveling at almost the speed of light when its path is bent by a magnetic field. As it was first observed in a synchrotron in 1947, it was named "synchrotron radiation".

•Stored electrons run on a circular orbit and emit synchrotron radiation with a continuous spectrum when they encounter the bending magnet, which results in loss in energy.

•Recovery by RF is possible but eventually as you go higher in energy the loss and gain balances.




http://www.spring8.or.jp/en/news_publications/publications/sp8_brochure/sr.html/publicdocument_view

# 1. Synchrotron radiation

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:

$$P = \frac{2r_e m_e}{3c}\left(\frac{d\vec{v}}{dt}\right)^2$$

$$r_e \equiv \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.82\times10^{-15}(m)$$

classical electron radius

$$P = \frac{2r_e m_e}{3c}\gamma^2\left\{\left[\frac{d(\gamma\vec{v})}{dt}\right]^2 - \left[\frac{d(\gamma c)}{dt}\right]^2\right\}$$

The radiated energy per turn $\Delta E$ for a ring of radius $\rho$

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

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.
For electrons of energy 10 GeV circulating *r*=1 km, the SR energy loss is 0.9 MeV/turn. How much is it for 20 GeV, 30 GeV electron?

$$\left(\frac{20}{10}\right)^4 = 16, \quad \left(\frac{30}{10}\right)^4 = 81$$

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

# Linear collider

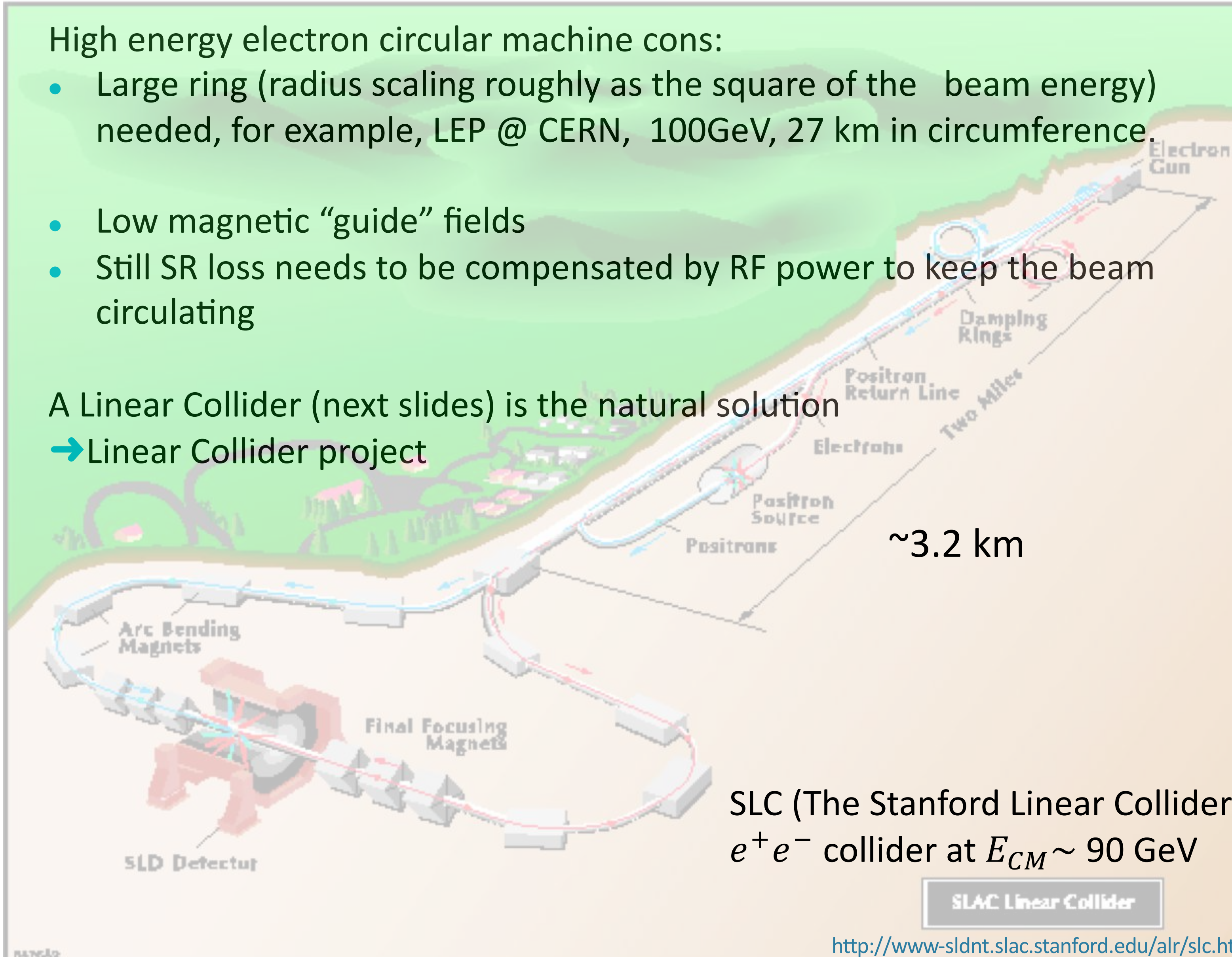
High energy electron circular machine cons:

- Large ring (radius scaling roughly as the square of the beam energy) needed, for example, LEP @ CERN, 100GeV, 27 km in circumference.

- Low magnetic “guide” fields
- Still SR loss needs to be compensated by RF power to keep the beam circulating

A Linear Collider (next slides) is the natural solution

➜Linear Collider project

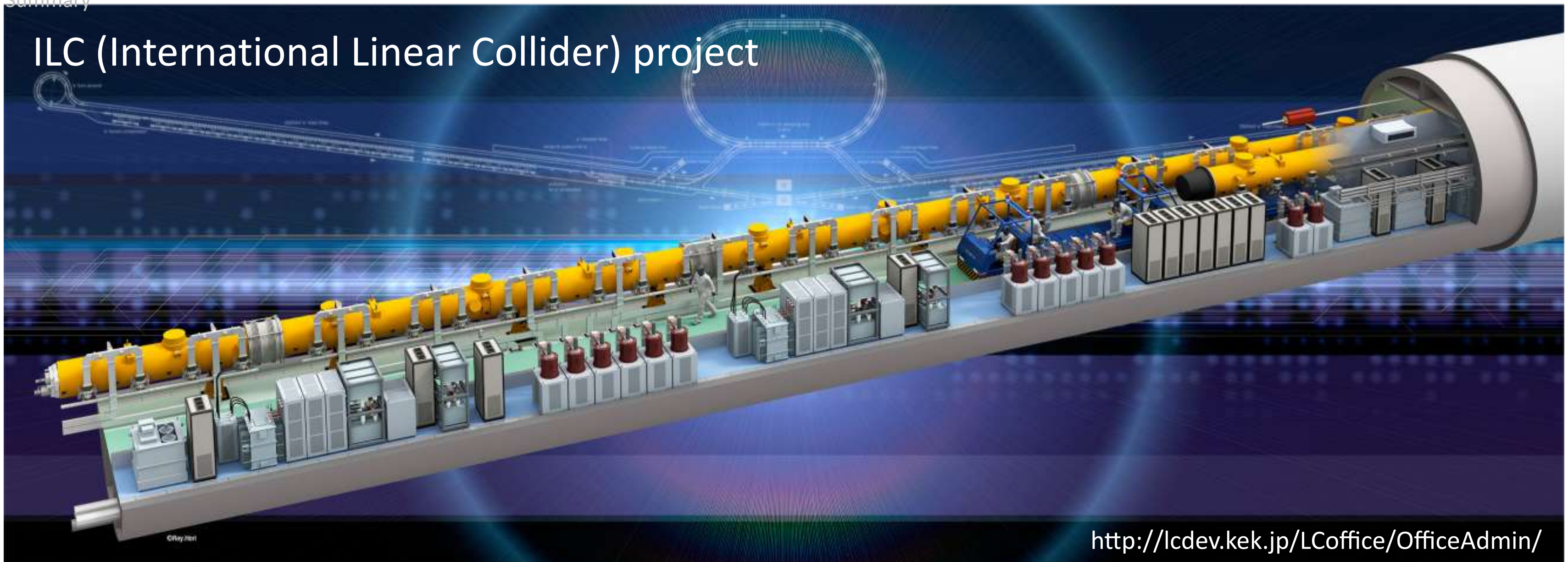



SLC (The Stanford Linear Collider)

$e^+e^-$ collider at $E_{CM}\sim$ 90 GeV

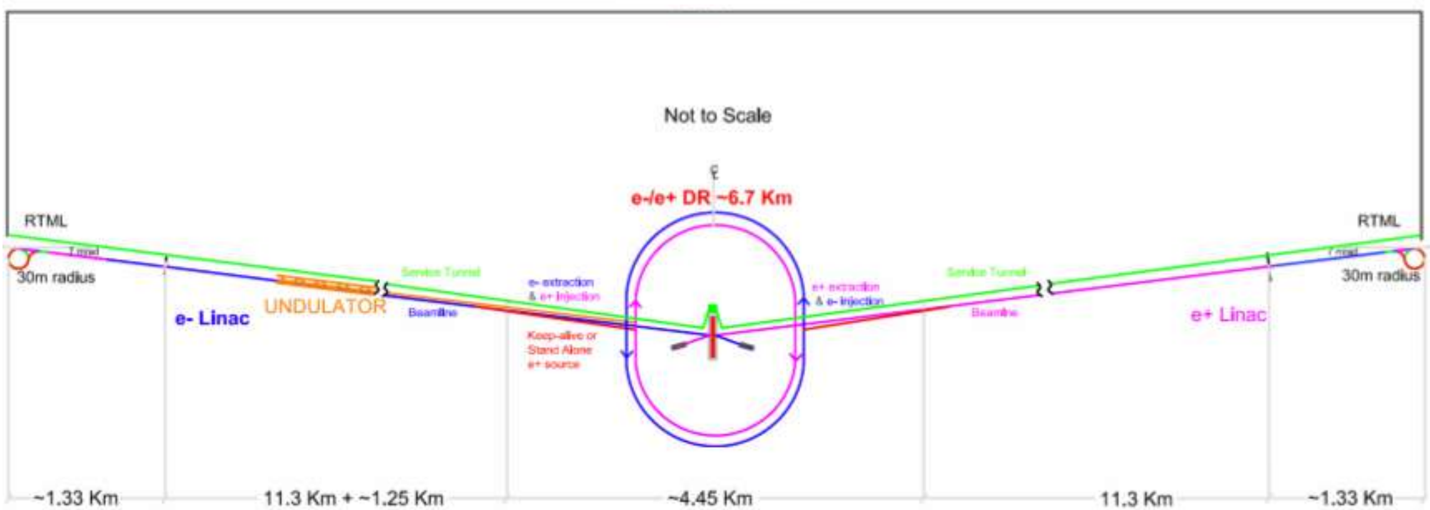
http://www-sldnt.slac.stanford.edu/alr/slc.htm

# Linear Collider (LC)




1st Stage: 500 GeV

~31 km




Schematic Layout of the 500 GeV Machine

# Linear Colliders: parameters

SLC at SLAC
operated from 1989 to 1998

The Compact Linear Collider
(CLIC) at CERN

| | SLC | ILC | CLIC | Unit |
|---|---|---|---|---|
| Technology | NC | SC | NC | |
| CMS Energy | 92 | 500 | 500 | GeV |
| Energy extension | - | 0.5 → 1 | 0.5 → 1 → 3 | TeV |
| Total length | 3.2+arc | 31 → 53 | 13 → 20 → 48 | km |
| Gradient | 20 | 31.5 | 80-100 | MV/m |
| RF frequency | 2.8 | 1.3 | 12 | GHz |
| Charge/pulse | 6.4 | 8400 | 386 | nC |
| Repetition | 120 | 5 | 50 | Hz |
| Luminosity | $3x10^{30}$ | $2x10^{34}$ | $2.3x10^{34}$ | $cm^{-2}s^{-1}$ |
| Power consumption | ? | 230 | 129 (x2?) | MW |

# 2. Types of accelerators

**Collider experiment**

- Circular
  - Energy frontier collides
    - LHC :
      - energy is ramped up from the injection energy to the target energy at first but kept constant for the experiment.
      - RF cavities are used to accelerate particles
  - Luminosity frontier colliers
    - SuperKEKB (BELLE II)
      - keeps particles stored at a constant energy for while (storage).
      - RF cavities are only used to replace energy lost through synchrotron radiation and other processes
- Linear collider

Particles are bunched

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

"Storage ring"

The 2021 JENNIFER2 will introduce you to particle physics research at KEK, focusing on the research of Belle II (SuperKEKB) and T2K (J-PARC)

**Fixed target experiment**

- delivering beam for other facilities, experiment
  - J-PARC T2K

**Light source (Photon Factory)**

Keeps the beam for hours, 260 billion km,

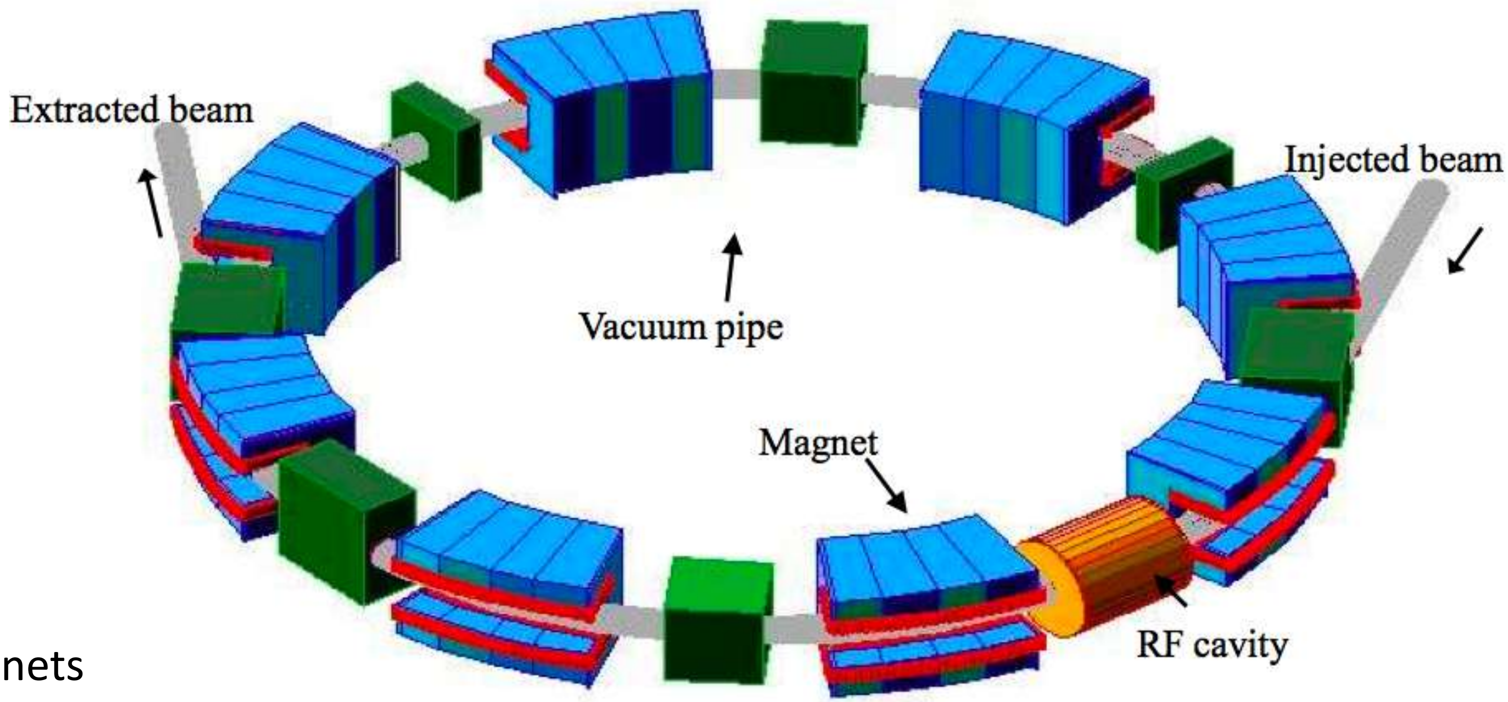
~87 round trips between the earth and the sun

There are pros and cons

1. Synchrotron radiation loss
2. One pass (LC) vs storage (Circular)

# Basic hardware 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

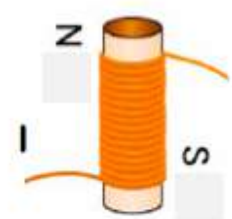
Monitors
Beam Position Monitors (BPM)

# Basic Components: Magnets

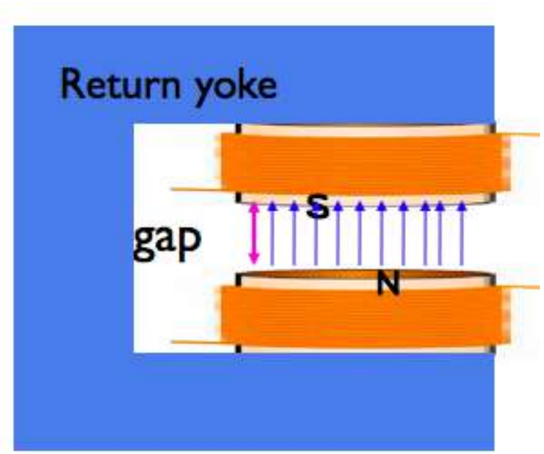
Dipole magnet
(Bending magnet)

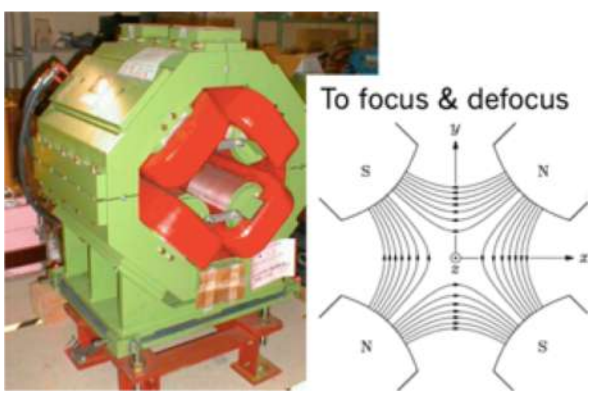
Two poles to generate a uniform magnetic field. Charged particles traveling through the field receive a deflecting (bending) force.

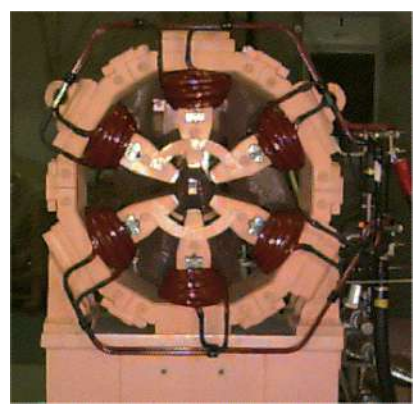
Wind a wire on an iron bar.
Flow current through the wire and the bar will be magnetized. Polarity changes when current direction is changed.




Coils on the pole
+ return yoke
→dipole magnet



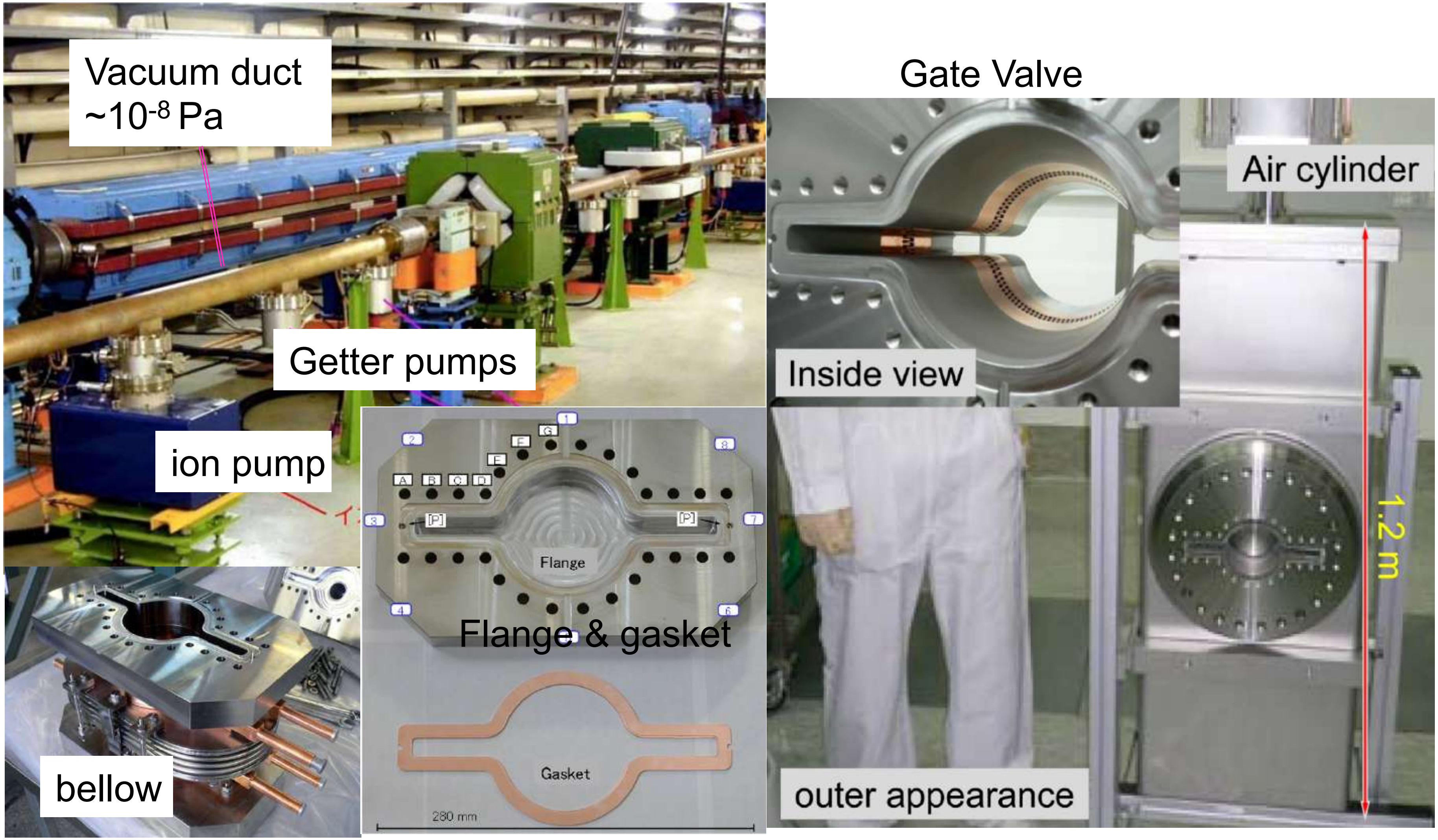



Sextupole magnet
(Spring-8)

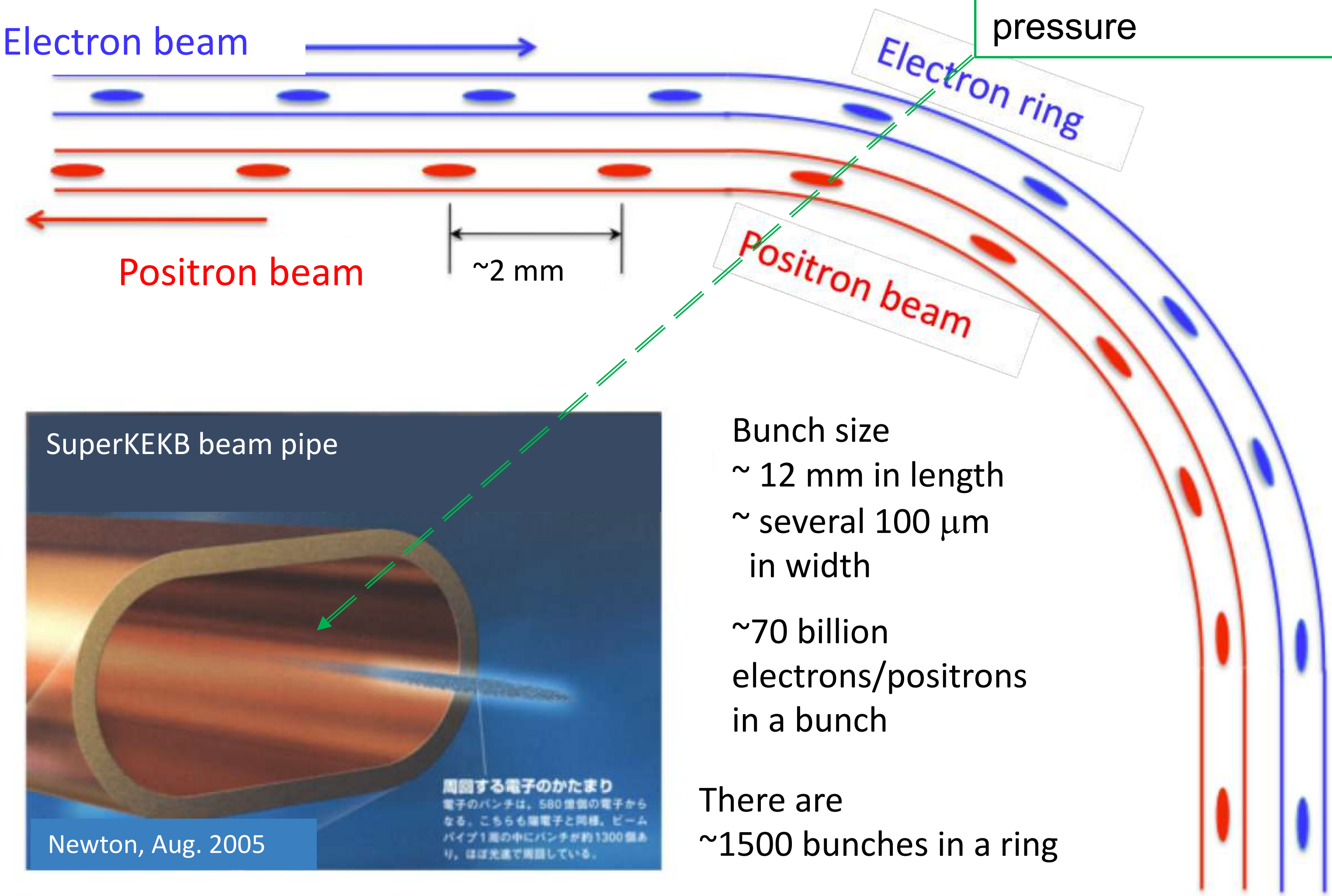
Chromatic correction

# Basic Components: Vacuum components



# Basic Components: SuperKEKB vacuum

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




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

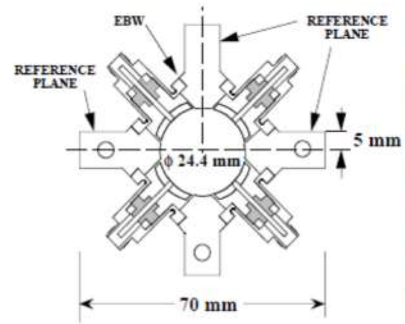
~70 billion electrons/positrons in a bunch

There are ~1500 bunches in a ring

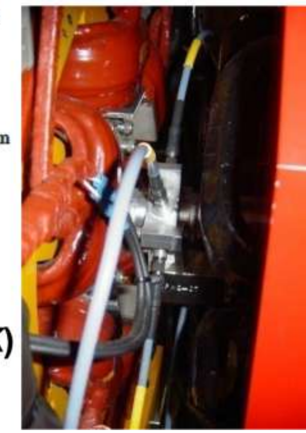
# Basic Components: Beam instrumentation

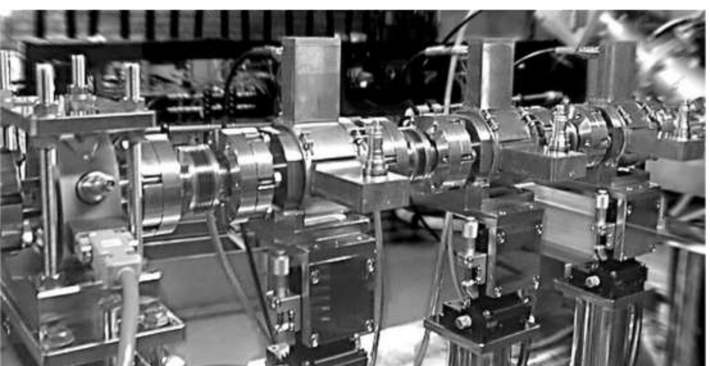
Beam position monitor (BPM)
provides information on the position of the beam in the vacuum chamber
BPMs detect the electric or magnetic field excited by beam passing by

- Electrostatic: ‘button’ pick-ups, for example
- Electromagnetic: stripline couplers, for example
- Resonant cavity
- etc

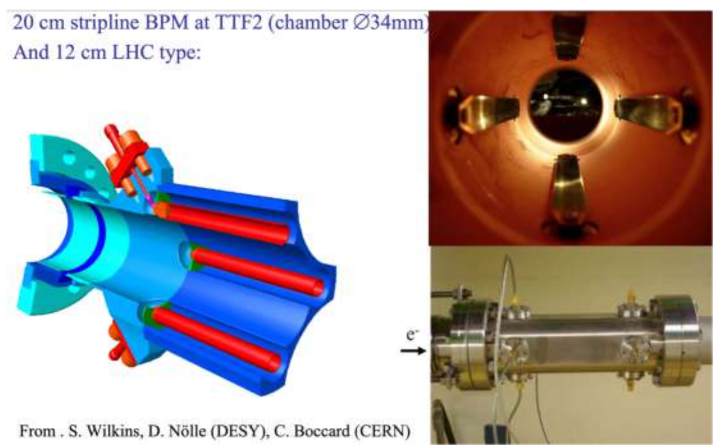



ATF Button BPM (*KEK*)

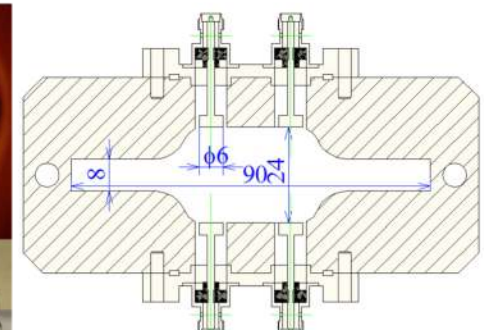




Resonant monitors detect the excitation of a certain field configurations by an off-center beam (AFT)



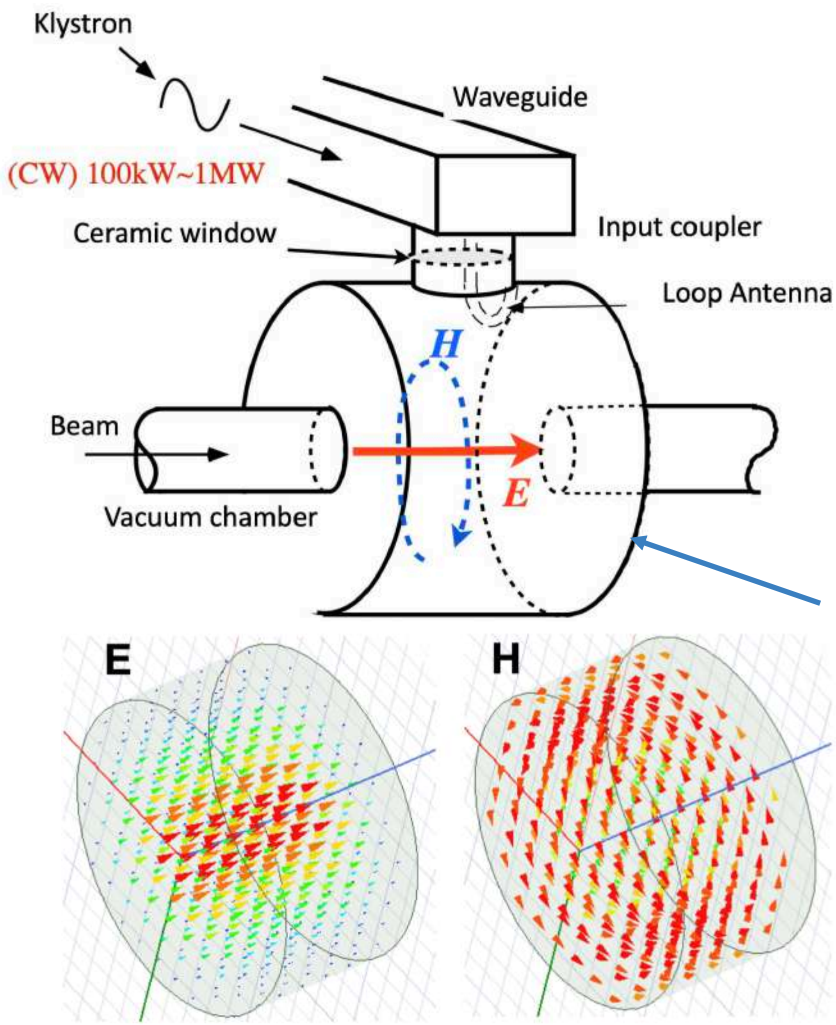

Stripline BPM (LHC)




Button BPM (KEK)

# Basic Components: RF cavities

TM01 mode




Resonant cavity
Various types, shape

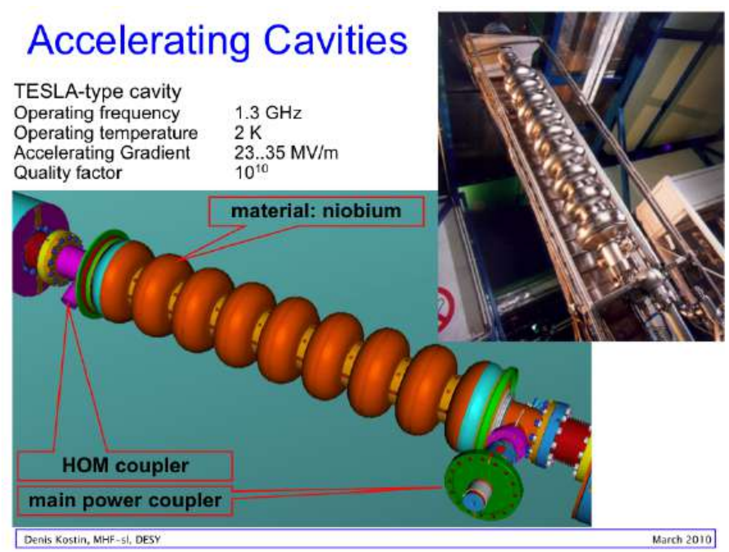
# Basic Components: RF cavities

SAGA-Light Source RF cavity
499.8 MHz
500 kV, 90kW

Load

| | |
|---|---|
| SR loss | 31.8 kW |
| Wiggler | 10.2 kW |
| Wall loss | 35.7 kW |
| Other | 7.8 kW |
| Total | 85.5 kW |

lam29.lebra.nihon-u.ac.jp/WebPublish/4P31.pdf

# Accelerator today
# J-PARC (T2K)
# SuperKEKB (BELLE II)

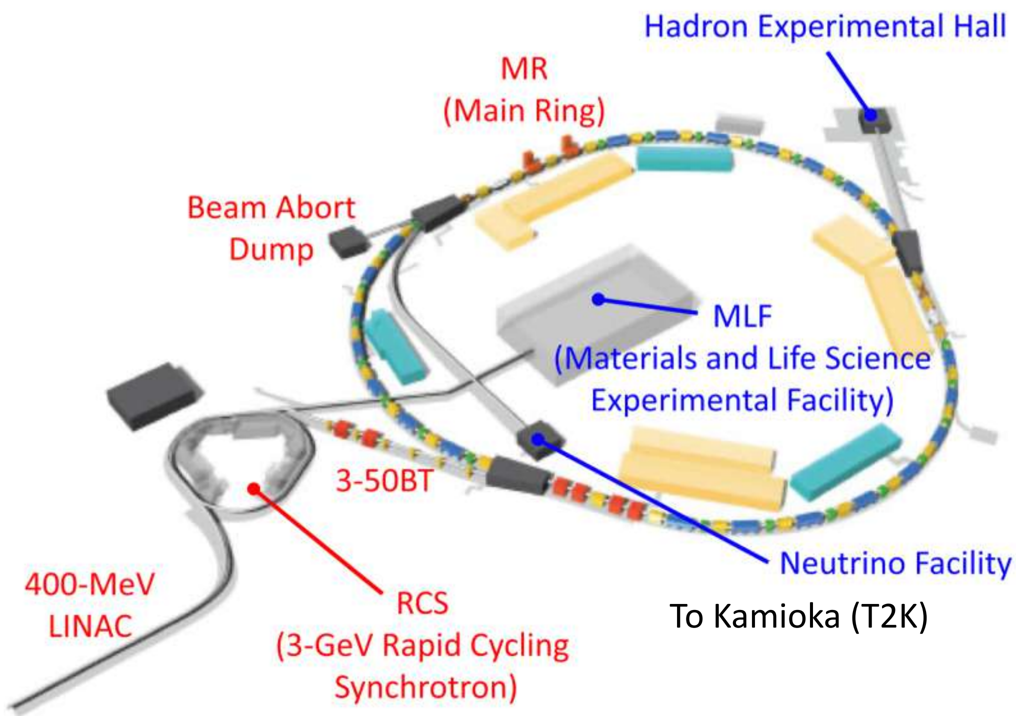
# Accelerator today
# J-PARC (T2K)
# SuperKEKB (BELLE II)

Key words : Storage Ring, Proton Synchrotron, high-energy proton beam, High-Intensity Proton Accelerator Facility Project

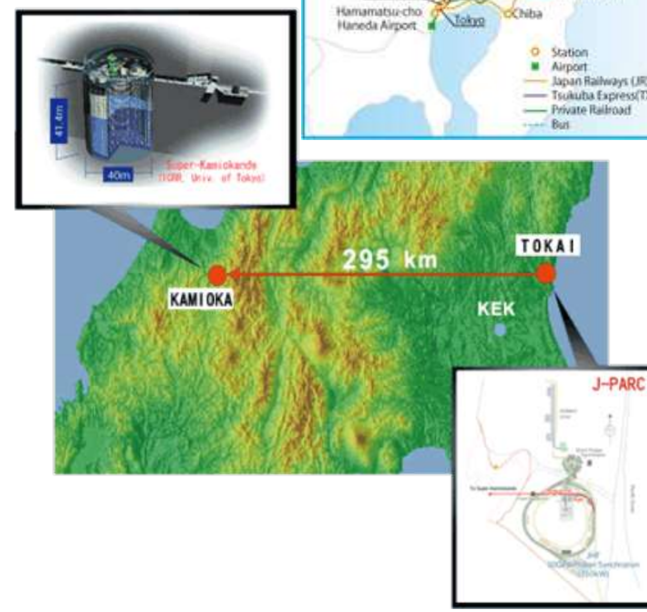
What is J-PARC?
J-PARC is a multi-purpose facility. It can deliver varieties of secondary-particle beams. Neutron, pion, kaon and neutrino beams are all produced at J-PARC via collisions between the proton beams and target materials.

Goals
Research in fundamental nuclear and particle physics, materials and life science
Development in nuclear technology.

# J-PARC



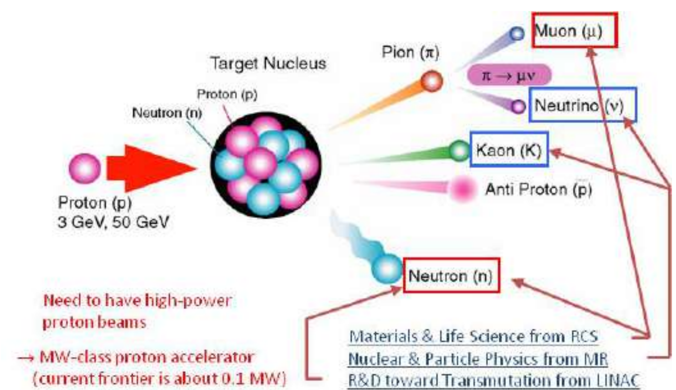




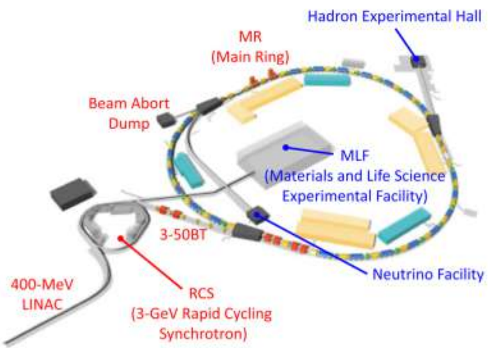

J-PARC has three proton accelerators:

- ✓ 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



# J-PARC




J-PARC has three proton accelerators:

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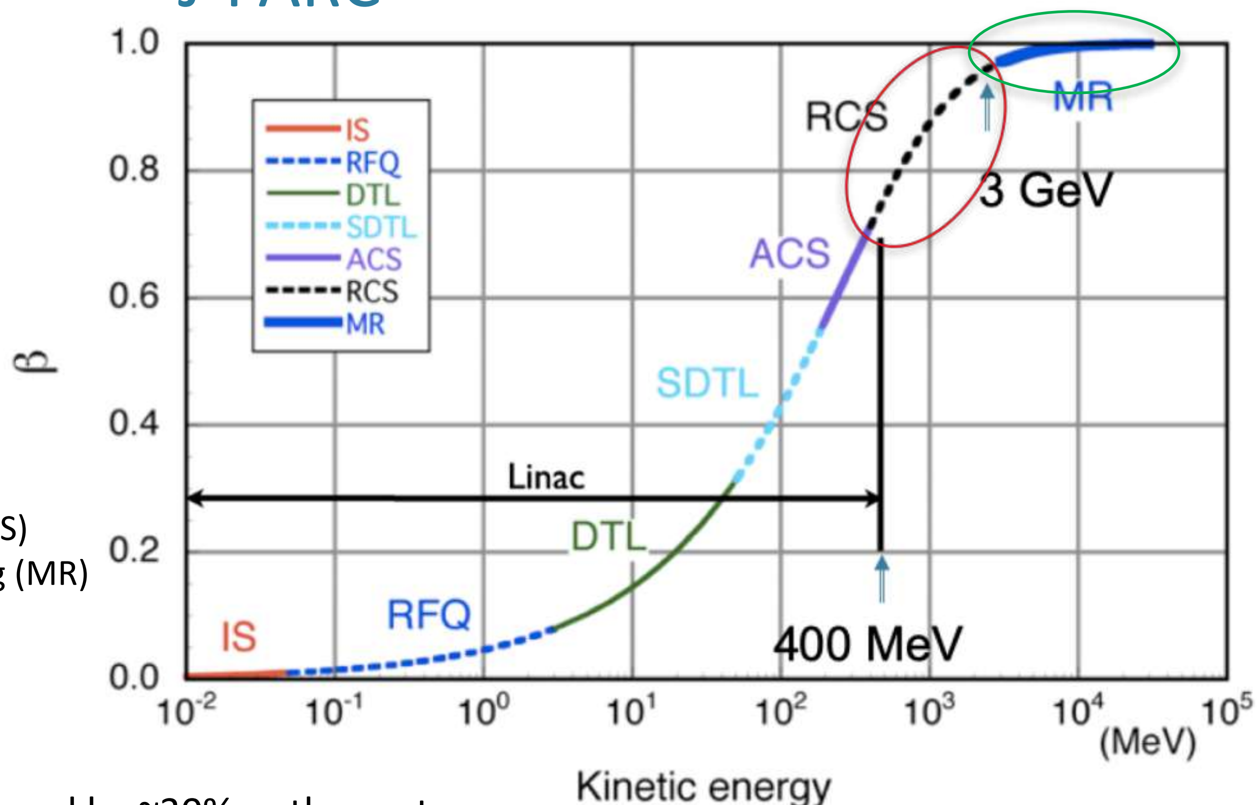
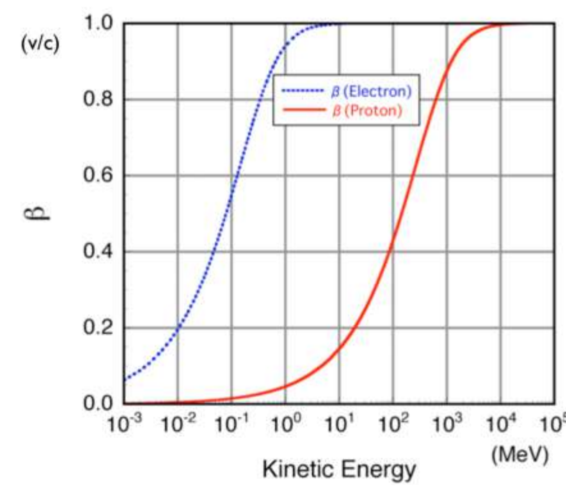
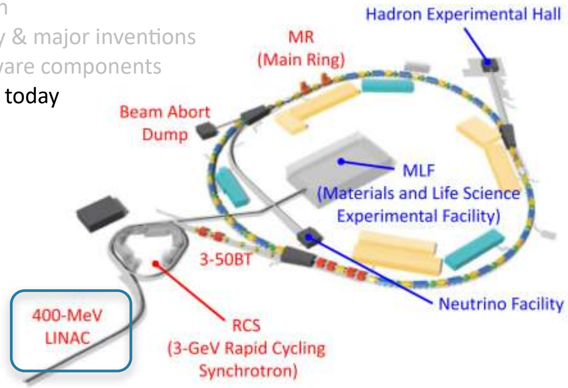


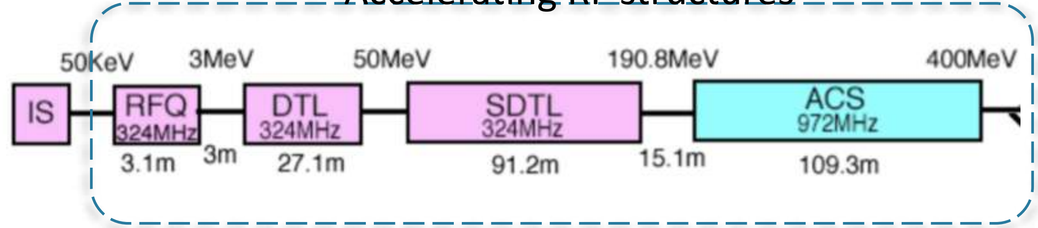

- ✓ The RF frequency has to be changed by ~30% as the protons are accelerated ($\beta$ increases) and circulate faster in RCS.
- ✓ Even in the MR, the speed changes ($\beta$ increases) by about 3% and the RF frequency needs to be changed.



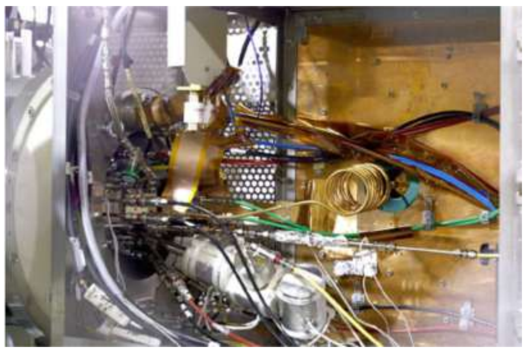

> Very complicated operation is needed as $\beta$ increases, which is quite different from an electron machine.




## Accelerating RF structures




Ion source (H-)



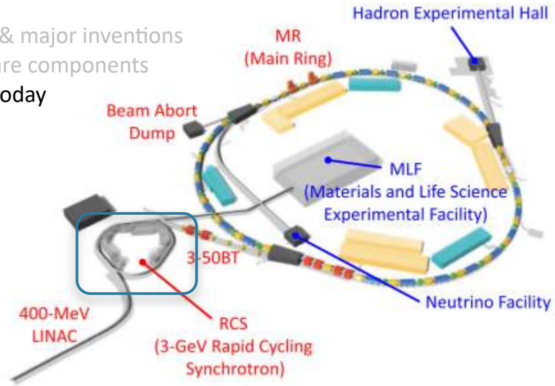
Drift Tube Linac (DTL)
Up to 3 MeV

RFQ (Radio Frequency Quadrupole Linac)
Up to 50 MeV

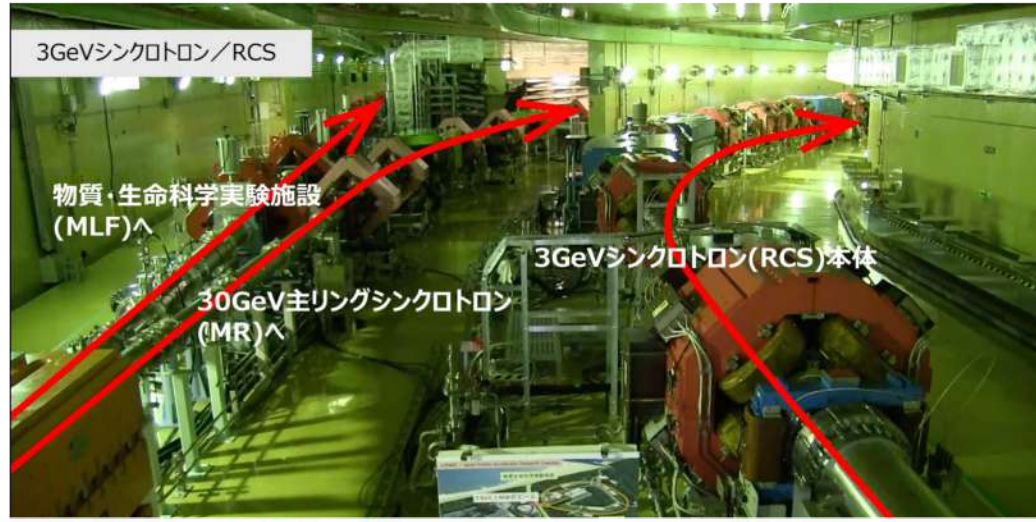
SDTL（Separated DTL）
Up to 190 MeV

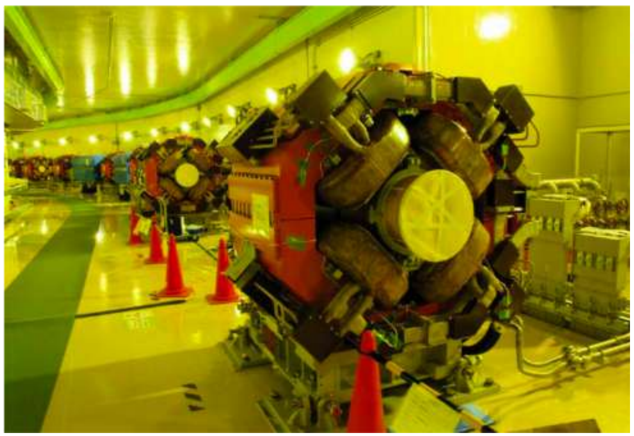
ACS（Annular-ring Coupled Structure Linac）
Up to 400 MeV

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



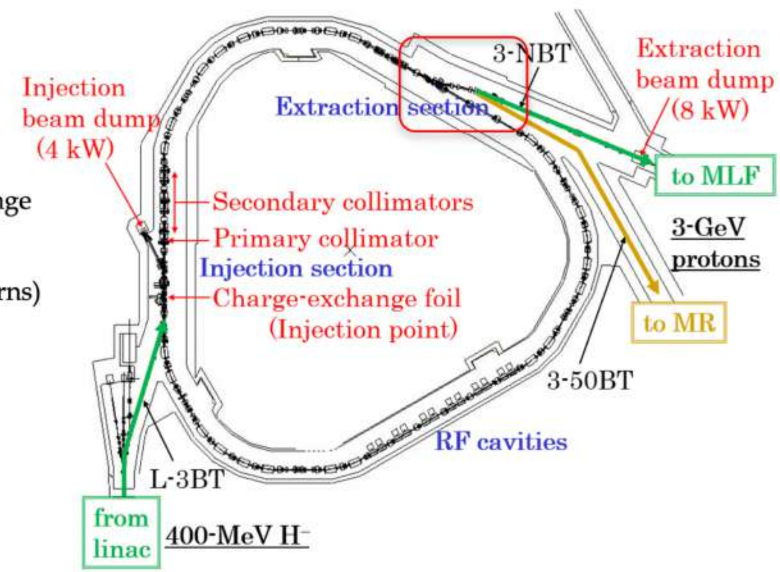

RCS (Rapid-Cycling Synchrotron)

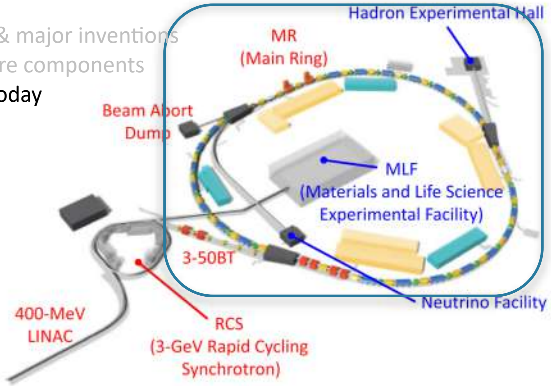


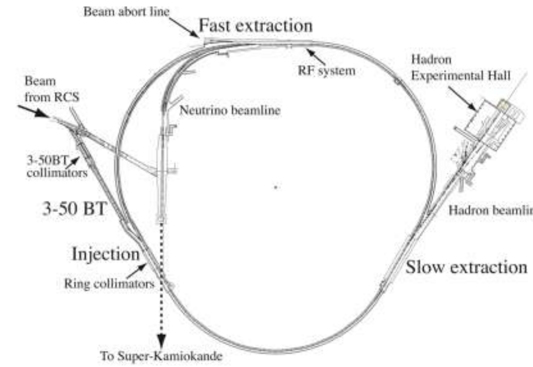



## J-PARC 3-GeV Rapid Cycling Synchrotron (RCS)

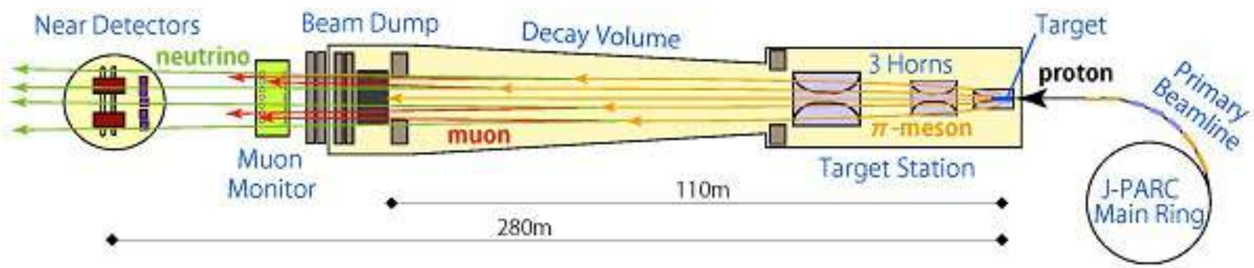
| | |
|---|---|
| Circumference | 348.333 m |
| Superperiodicity | 3 |
| Harmonic number | 2 (2 bunches) |
| Injection | Multi-turn, charge-exchange |
| Injection energy | 400 MeV |
| Injection period | 0.5 ms (307 turns) |
| Injection peak current | 50 mA |
| Extraction energy | 3 GeV |
| Repetition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





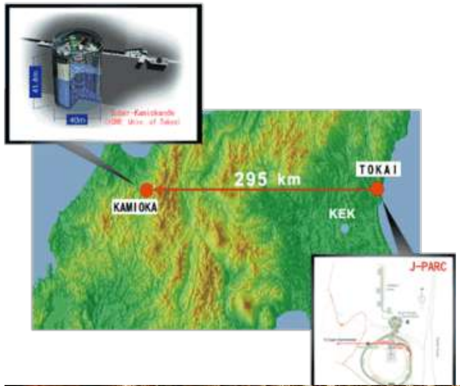

| | |
|---|---|
| Circumference [m] | 1567.5 |
| Superperiodicity | 3 |
| Typical cycle time for FX [s] | 2.56 |
| Typical cycle time for SX [s] | 6.0 |
| Injection energy [GeV] | 3 |
| Extraction energy [GeV] | 30 |
| Harmonic number | 9 |
| Number of bunches | 8 |
| Typical transition gamma | j31 |
| Physical aperture [$\pi$ mm-mrad] | >81 |
| Collimator aperture [$\pi$ 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 |

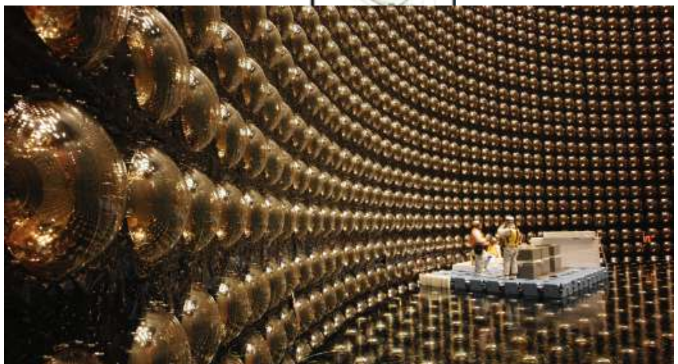


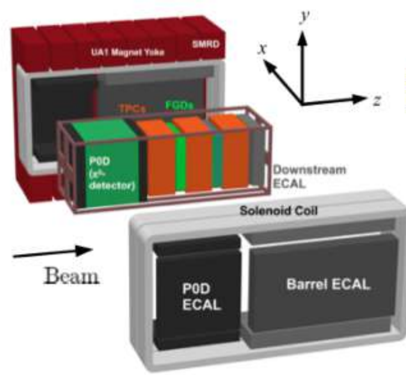

Protons are extracted from the MR
Protons collide with a graphite target and produce many particles
Among many particles, $\pi^+$'s go forward under the effect of magnetic horns. Magnetic horns are magnets designed to focus $\pi^+$'s by applying a few hundred thousand amperes of pulsed current synchronized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

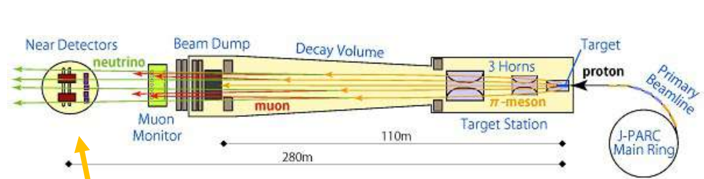
In the 100m long tunnel (decay volume) $\pi^+$'s decay primarily $\pi^+ \rightarrow \mu^+ + \nu_\mu$

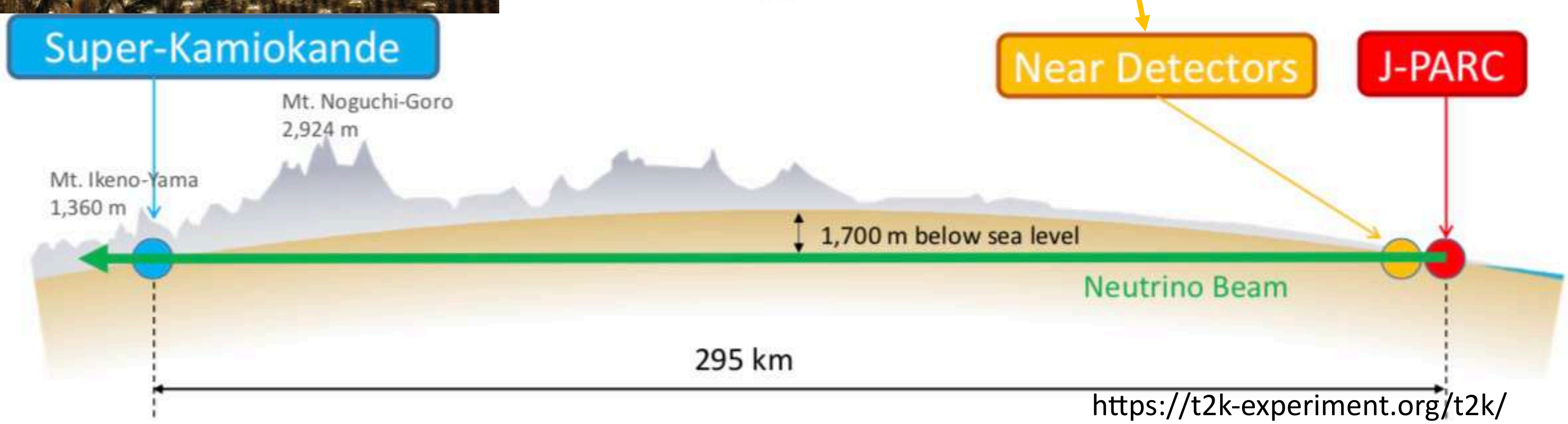
T2K is a neutrino experiment designed to investigate how neutrinos change from one flavour to another as they travel (neutrino oscillations).
An intense beam of muon is measured once before it leaves the J-PARC site, using the near detector ND280, and again at Super-K: the change in the measured intensity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





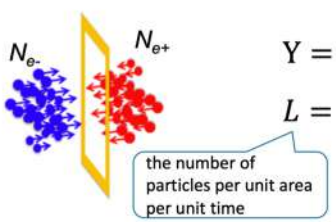




https://t2k-experiment.org/t2k/

# Accelerator today

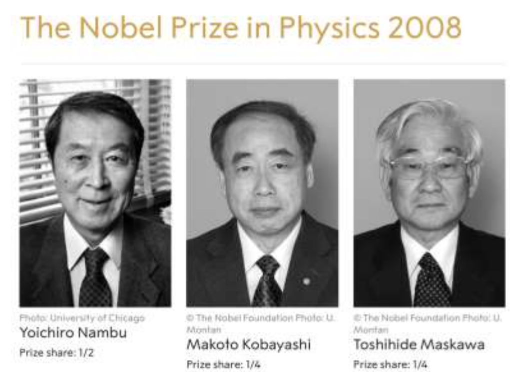
## J-PARC (T2K)

## SuperKEKB (BELLE II)




$$Y = L\sigma$$

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




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

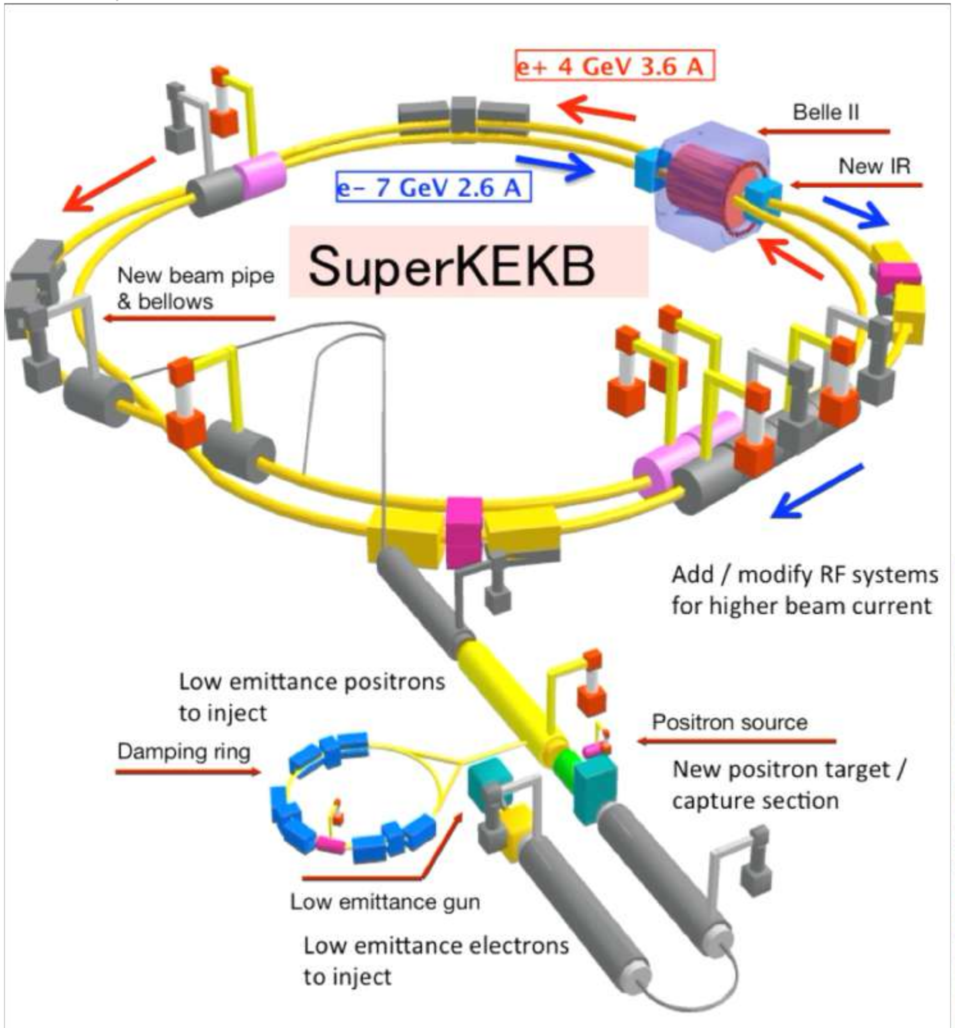
Background

KEKB collider, which was SuperKEKB's predecessor, generated sooooooo many $e^+e^-$ collisions with very high luminosity ($2.11 \times 10^{34}$ 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.

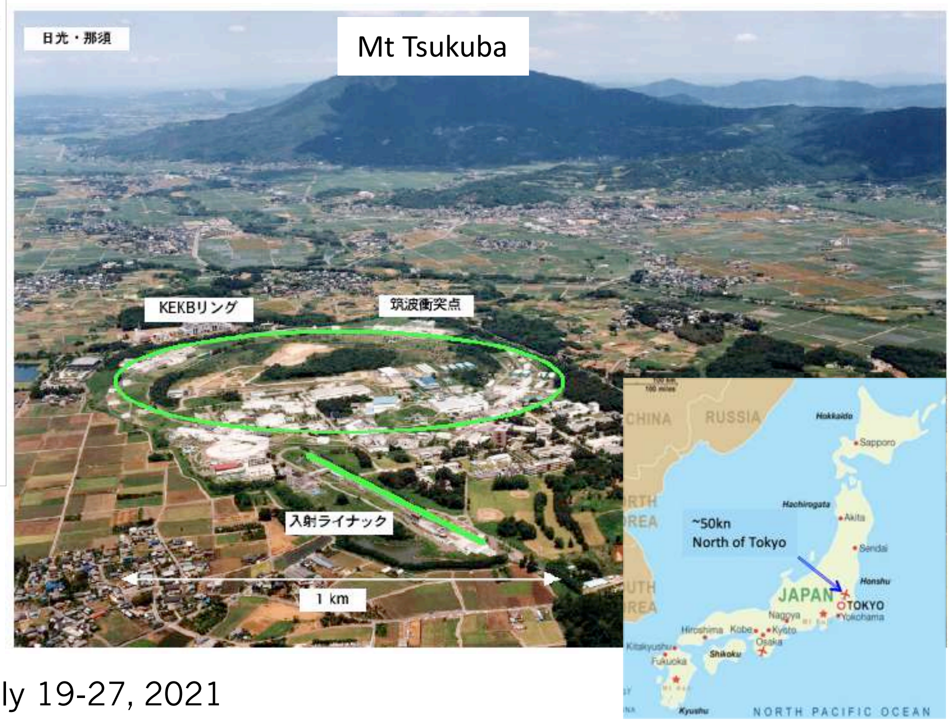
# SuperKEKB




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



# SuperKEKB

New beam collision method called the "nano-beam scheme" is used for the 1st time in the world.

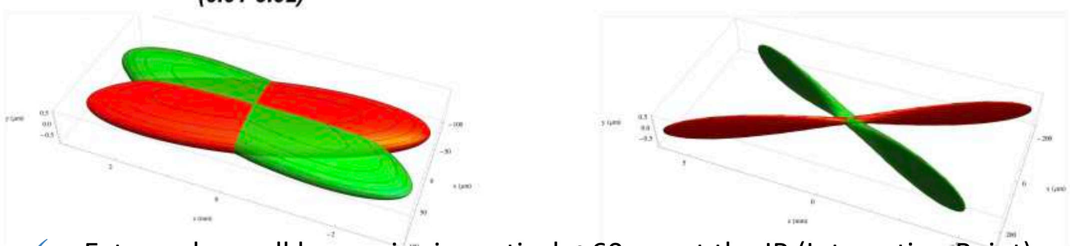
Lorentz factor — Beam current — Beam-Beam parameter

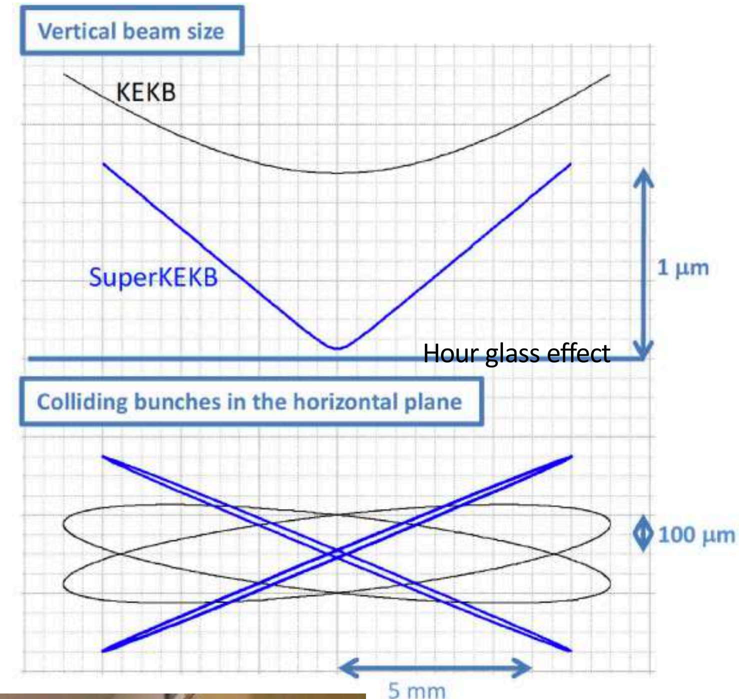
$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Vertical beta function at IP

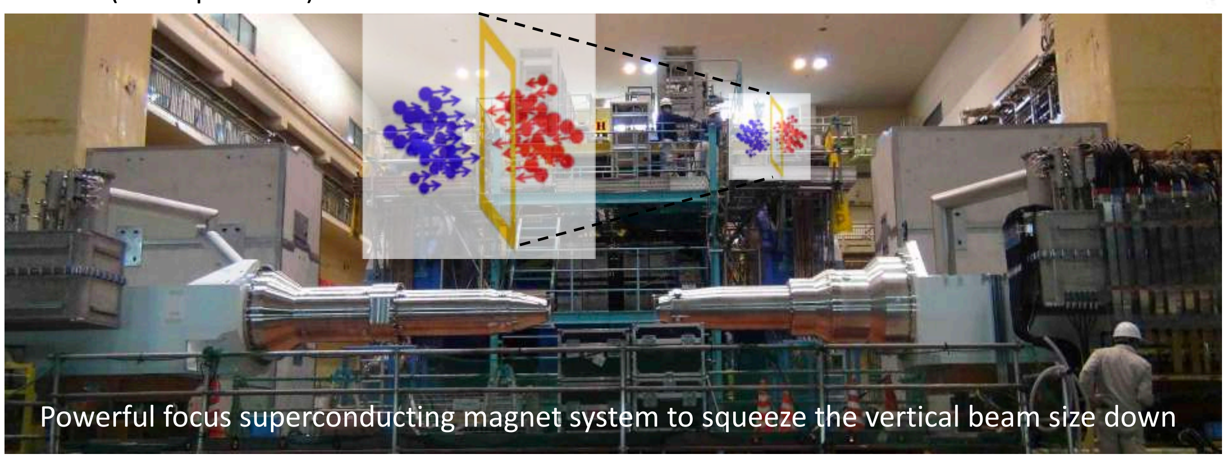
Beam aspect ratio at IP
***(0.01-0.02)***

$I$ ↑ x 2
$\beta^*_y$ ↓ x 1/20

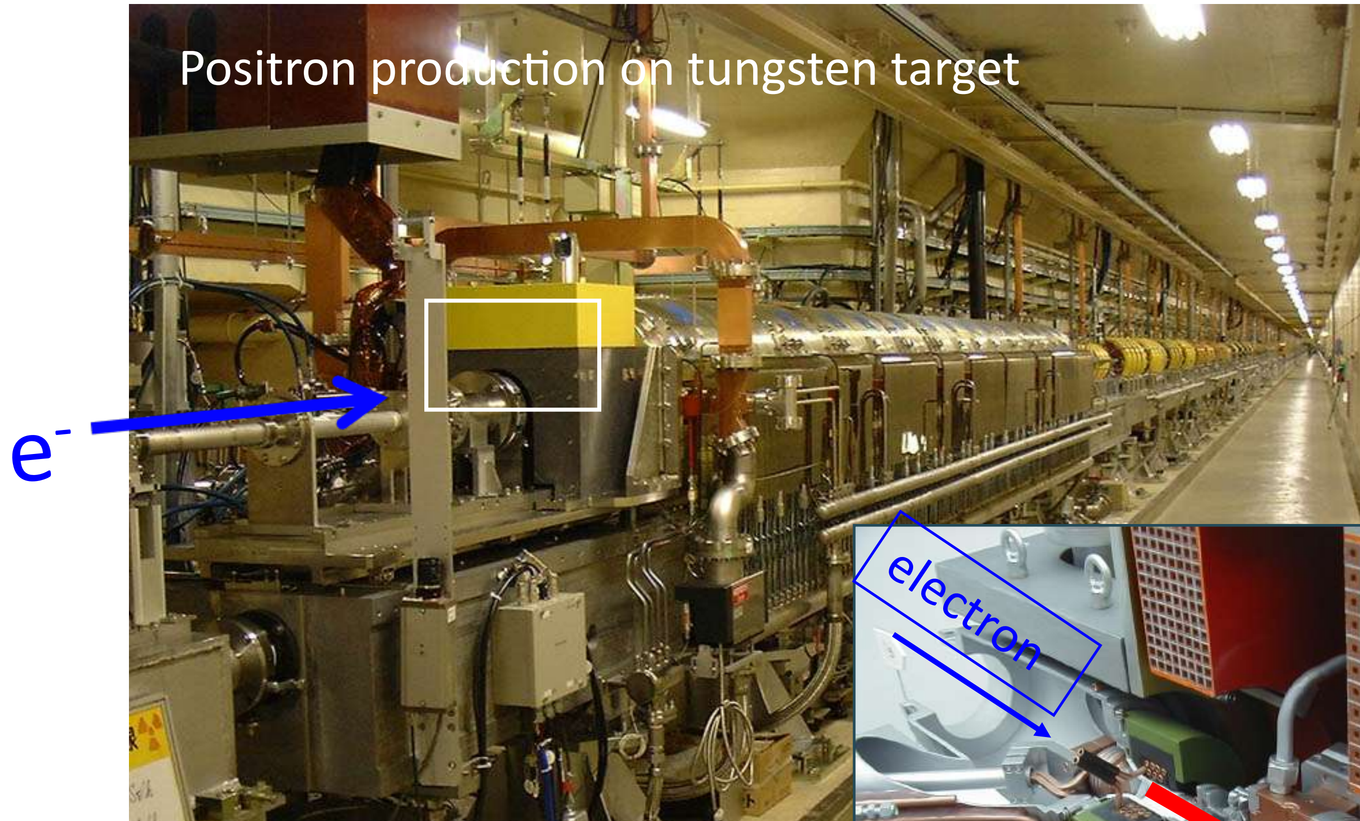


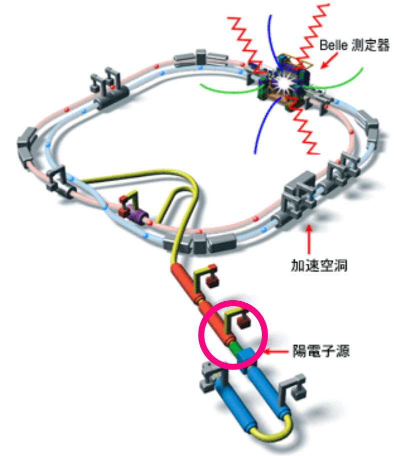


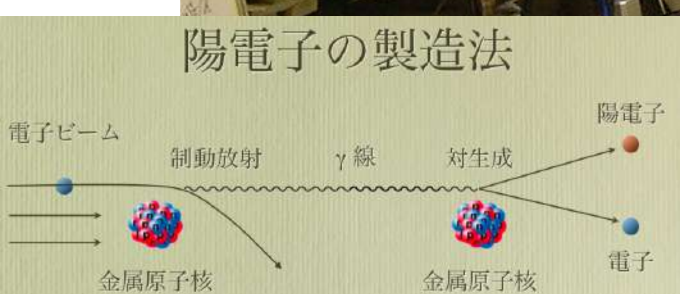

- ✓ Extremely small beam size in vertical, ~60 nm at the IP (Interaction Point)
- ✓ Large crossing angle
- ✓ Higher beam current (more particles)

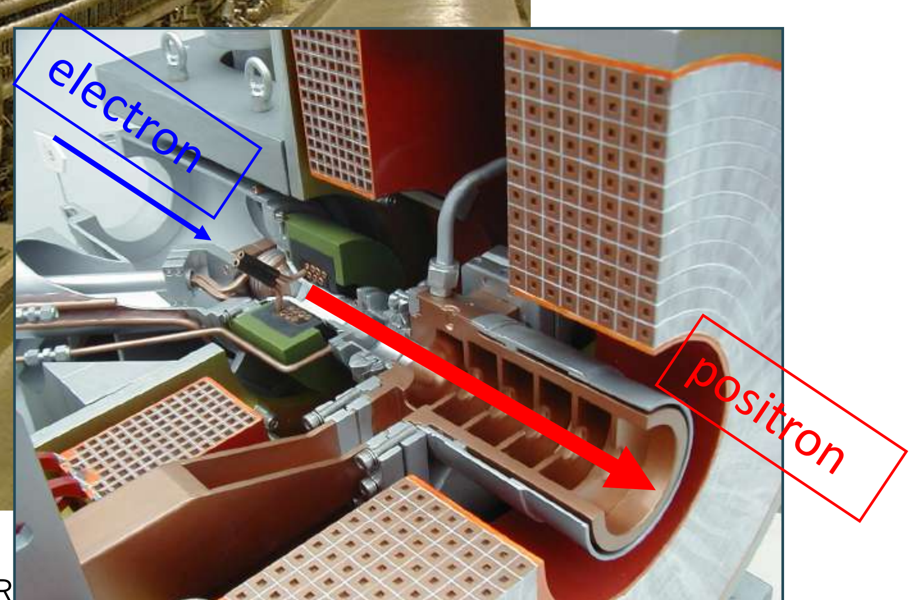


# Virtual Tour of SuperKEKB



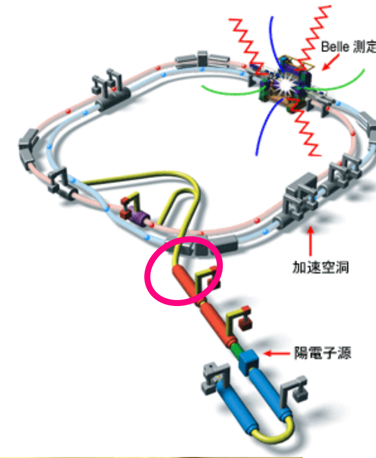



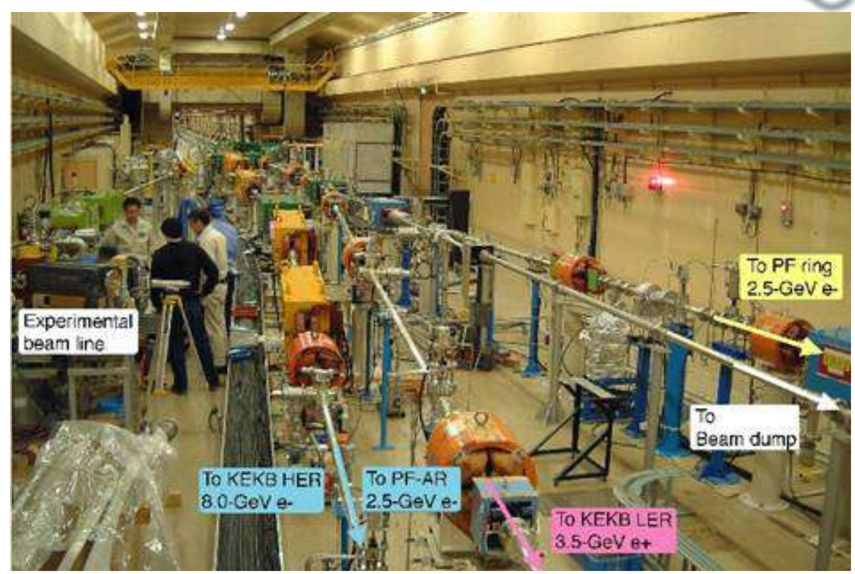



# Virtual Tour of SuperKEKB

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

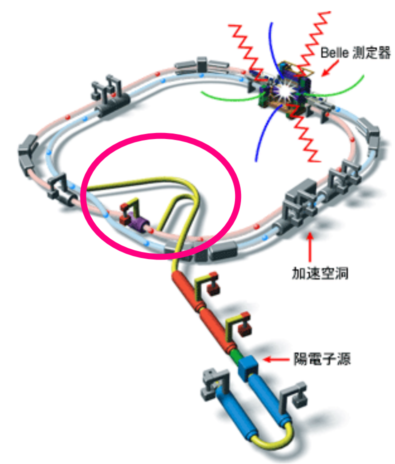



Electrons and positrons are accelerated to the target energy and transferred to many beam lines.

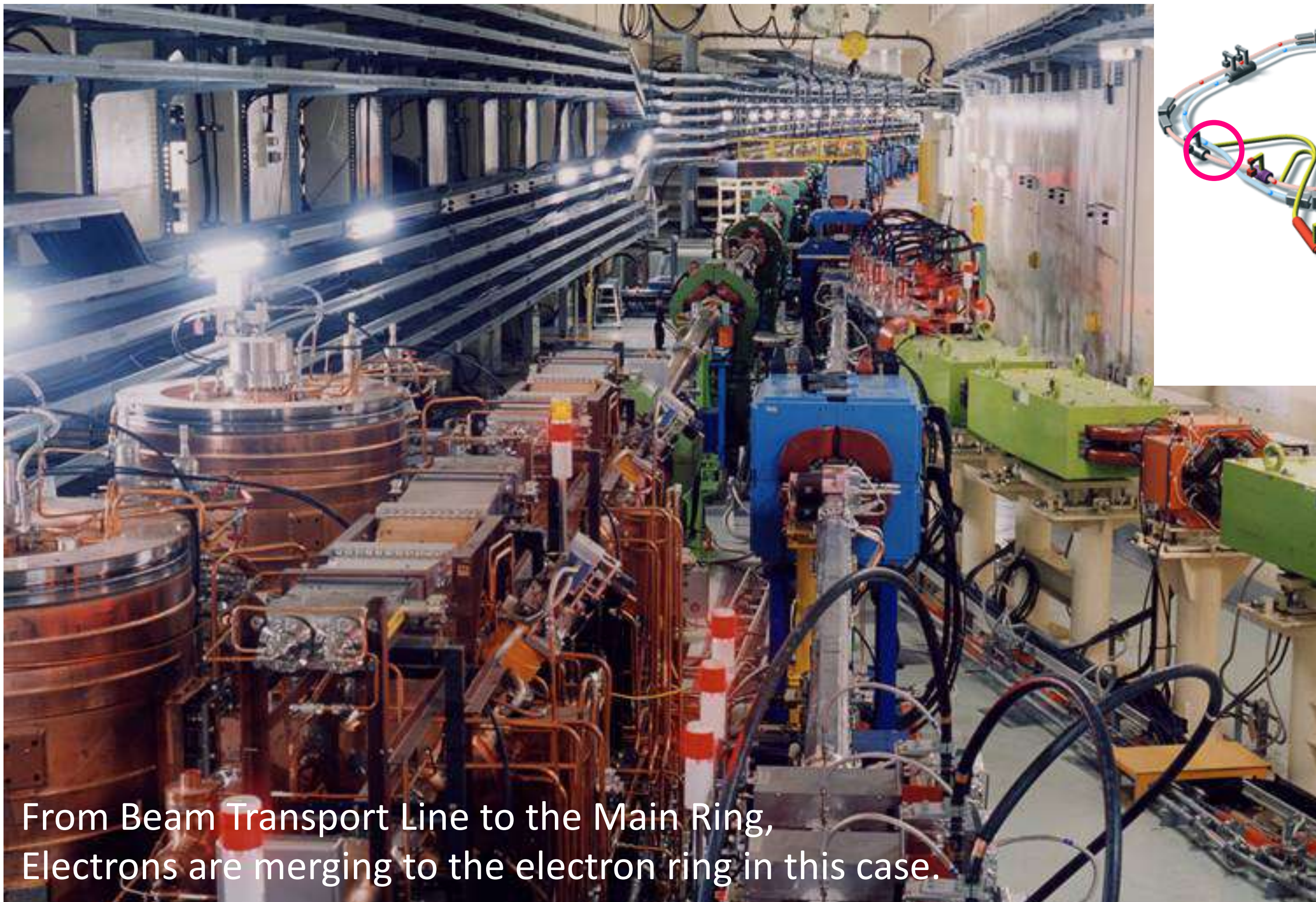


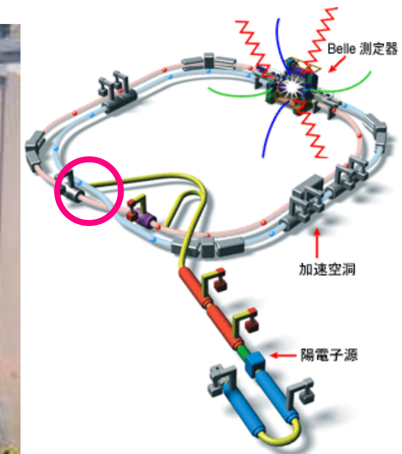
# Virtual Tour of SuperKEKB

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

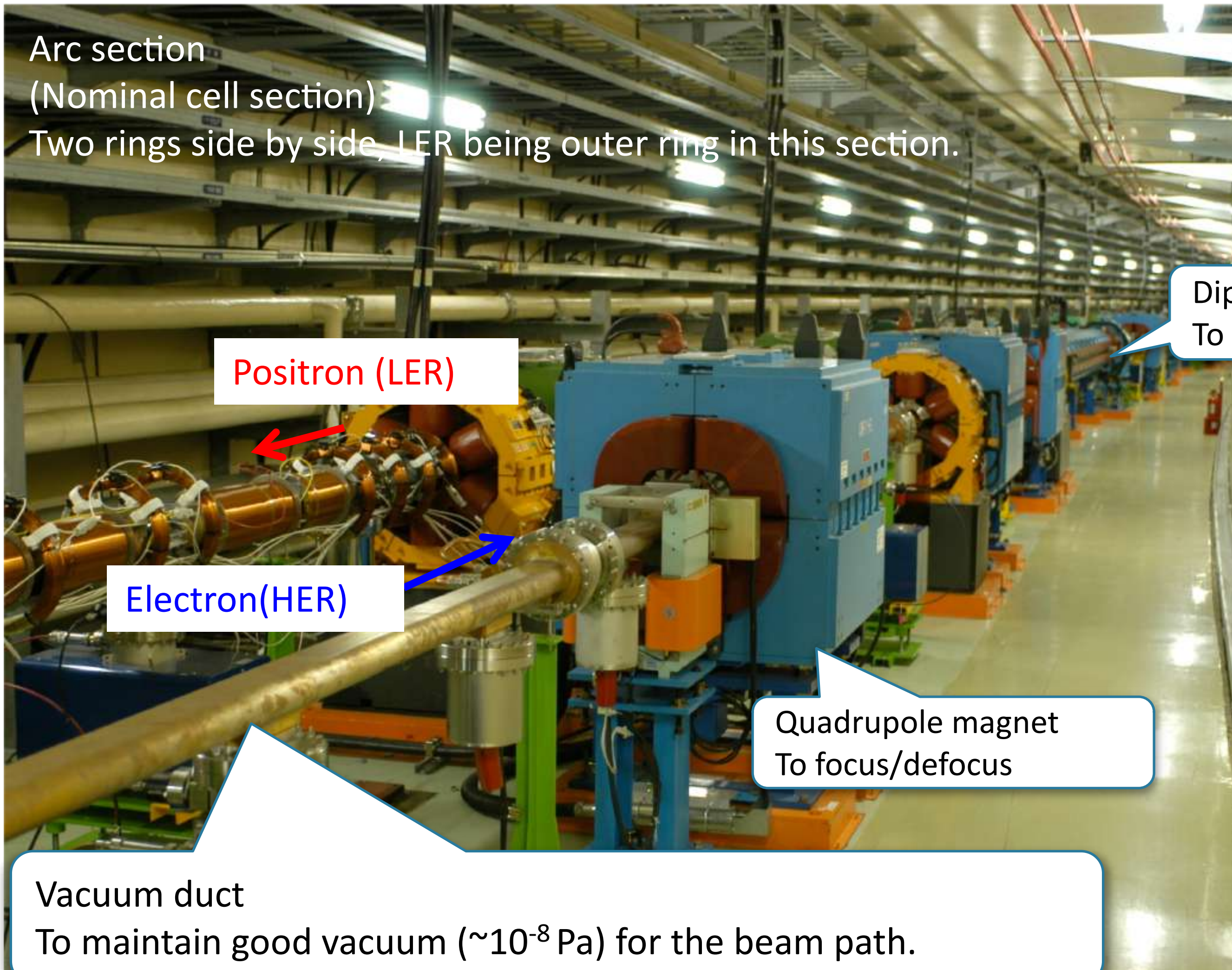


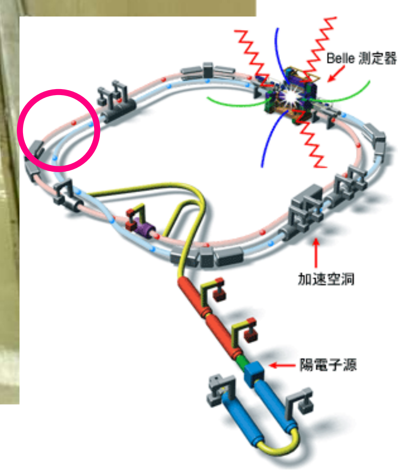
# Virtual Tour of SuperKEKB



# Virtual Tour of SuperKEKB



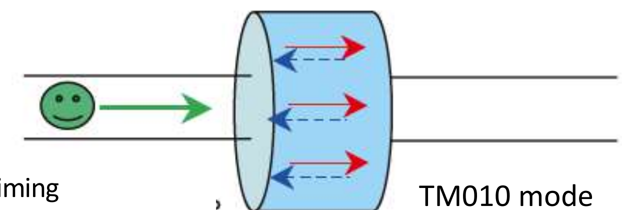



# Virtual Tour of SuperKEKB

SCC (Single-cell Superconducting cavity) for HER

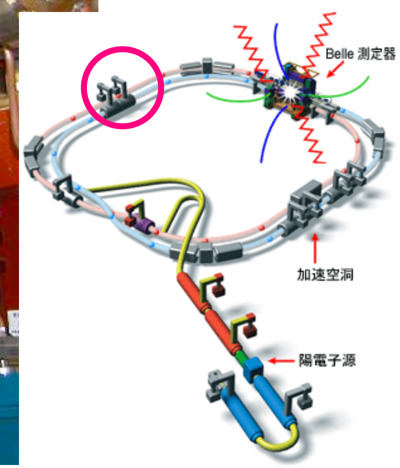
Highest beam current stored (1.45A) in the world.

Electric field in the cavity

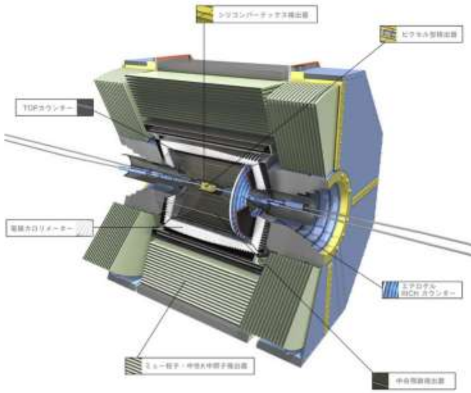


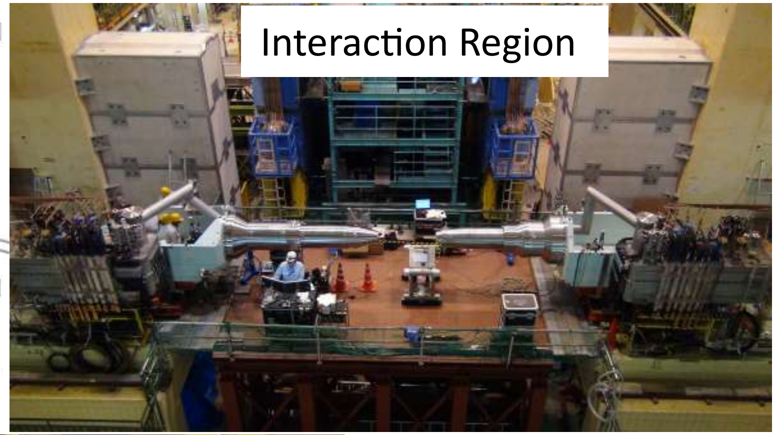
Timing important

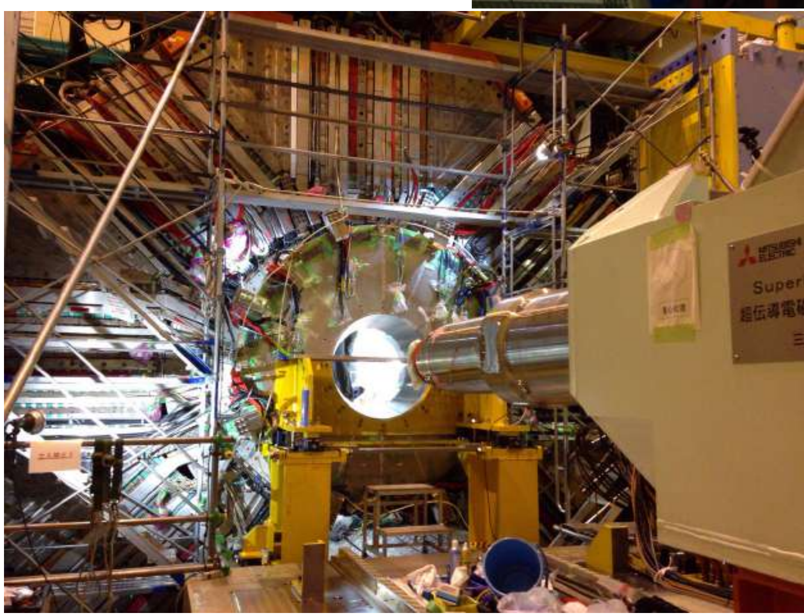
TM010 mode

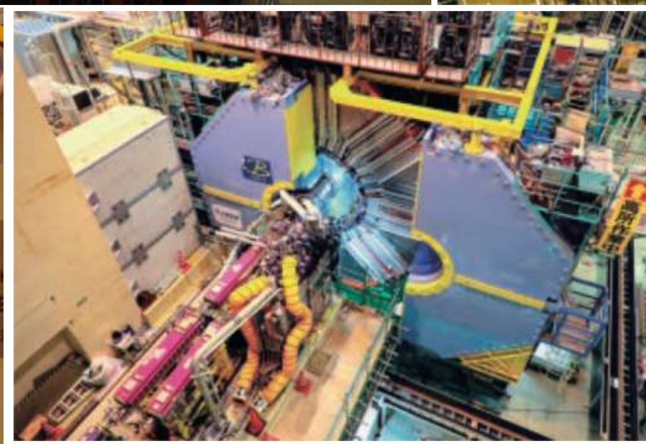


# Virtual Tour of SuperKEKB



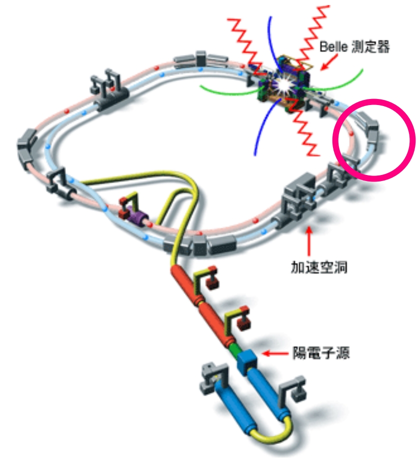




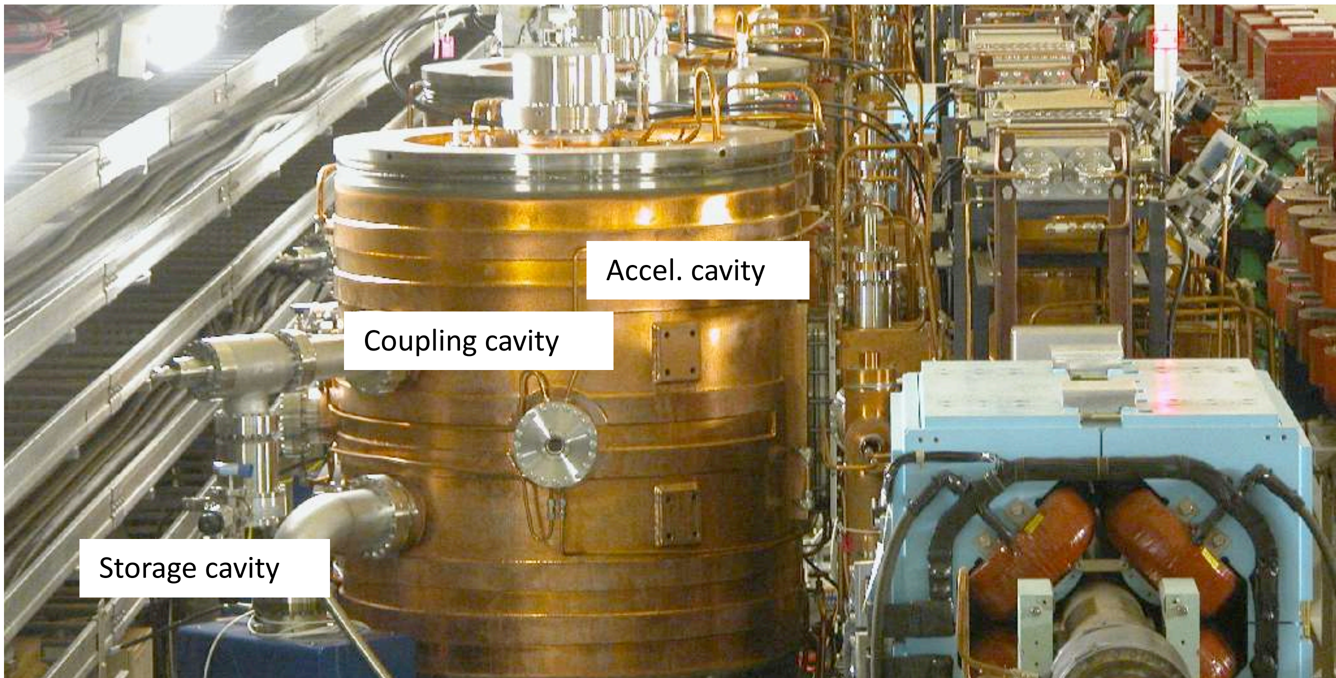
# Virtual Tour of SuperKEKB

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



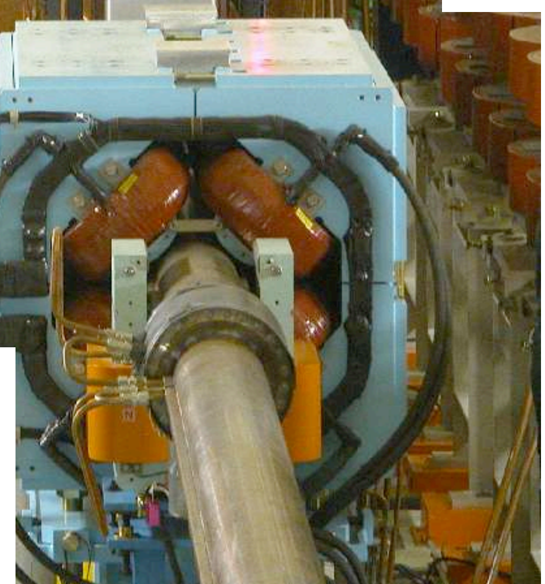
# Virtual Tour of SuperKEKB

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





KEKB
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.



# Summary

- A Brief history and major inventions and principles are introduced along with some basic hardware components.
- Some slides on J-PARC and SuperKEKB are presented.
- There are many things that you can contribute to in this field.
  See you around!