Introduction to Accelerators

Mika Masuzawa (KEK)

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Contents

- Brief history & major inventions
  - 1930~1960
    - Introduction
    - DC: Cockcroft-Walton, Van de Graaff
    - AC: Drift tube, Cyclotron
    - Betatron
      - Betatron oscillation, weak focus
    - A.G. Synchrotron
      - phase stability, strong focus, synchrotron radiation, (Linear collider)
  - 1960~
    - Collider
    - New era of large circular colliders
    - Energy frontier, Luminosity frontier
- Virtual tour of KEKB
- Challenges
  - SuperKEKB as an example
  - Future accelerators
- Final thoughts

Brief history & major inventions 1930~1960

- 1930~1960

  Introduction

  DC: Cockcroft-Walton, Van de Graaff,

  AC: Drift tube, Cyclotron

  Betatron

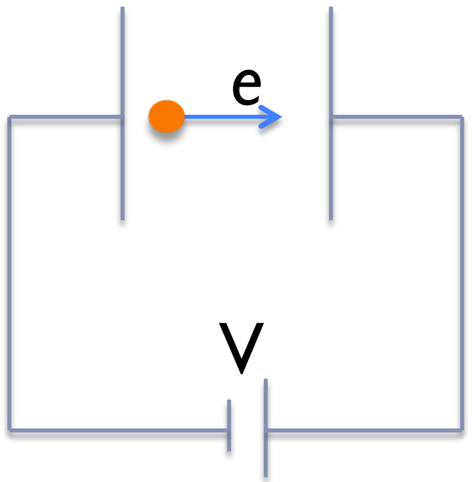
      Betatron oscillation, weak focus

  A.G. Synchrotron

      phase stability, Strong focus, synchrotron radiation

  (Linear collider)

Introduction: units



U=eV

Unit for energy

[eV] electron volt

➔Energy unit charge [e] receives from potential difference of 1 [V].

Why not [J] ?

[J] Joule

➔Energy unit charge [C] receives from potential difference of 1 [V]

1 kV = 10 ^{3} eV
1 MeV = 10 ^{6} eV
1 GeV = 10 ^{9} eV
1 TeV = 10 ^{12} eV

$$1[eV] = 1.602 \times 10^{-19} [J]$$

"Joule" is too large

Introduction

Livingston's curve : The beam energy of accelerators vs. time.

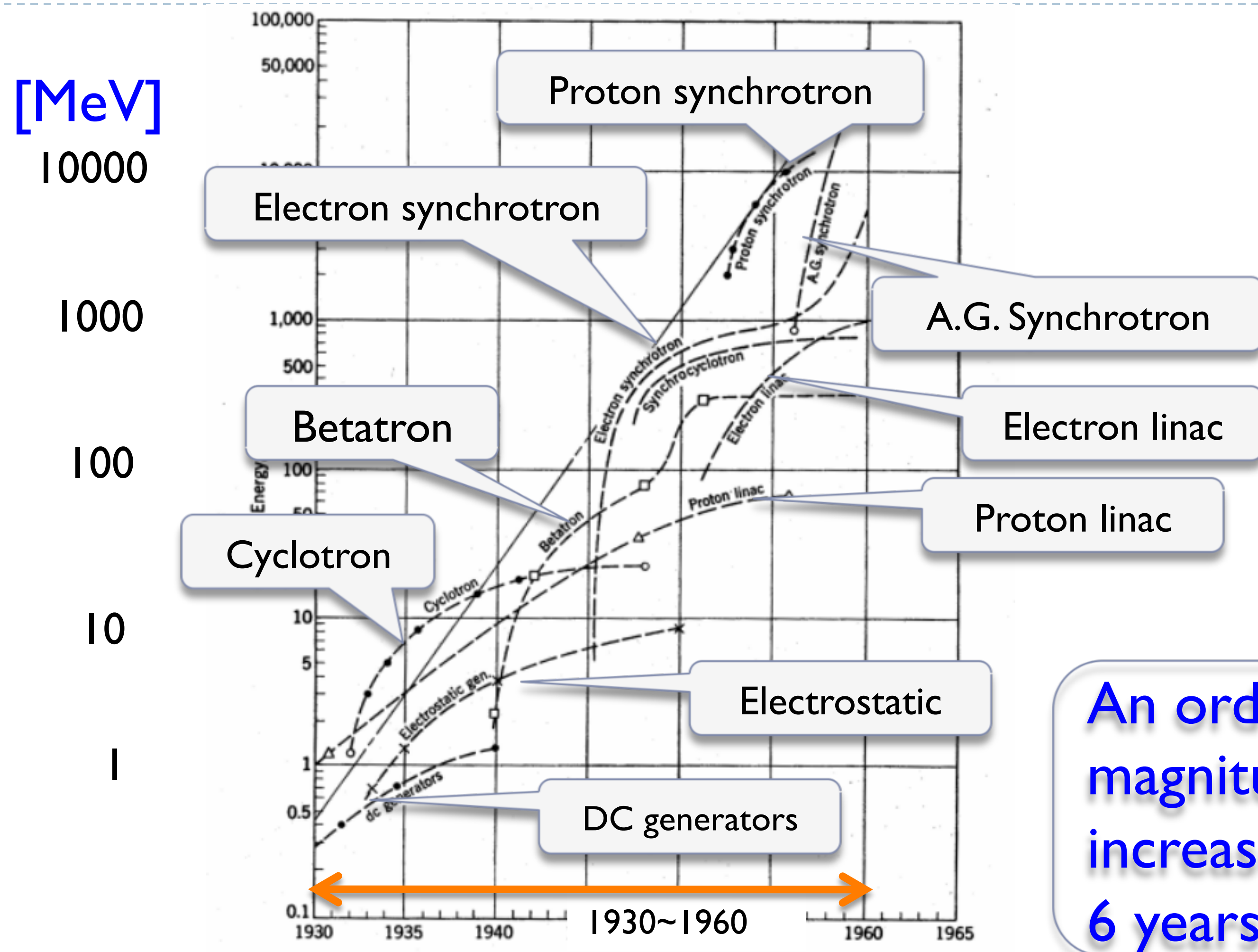


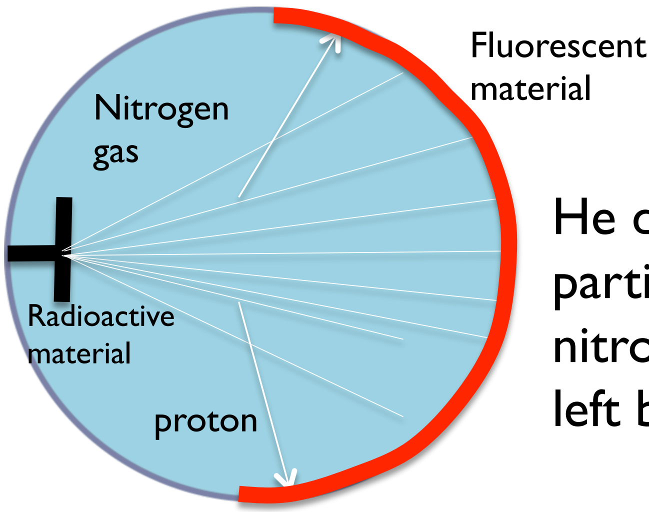
Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope

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

An order of magnitude increase every 6 years!

Introduction

Dawn: The first nuclear reaction by Rutherford



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

E. Rutherford

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

This provoked strong demand for generating high energy beams to study nuclear disintegration phenomena in more detail.

A race to develop high energy accelerators started.

Cockcroft-Walton:

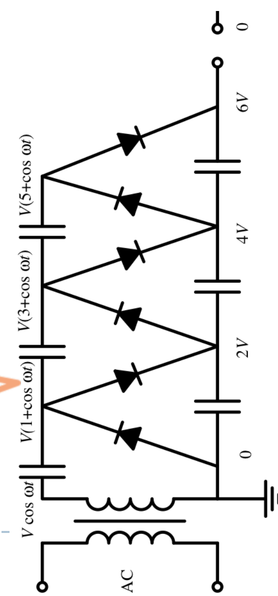
First disintegration of atomic nuclei with accelerator

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.

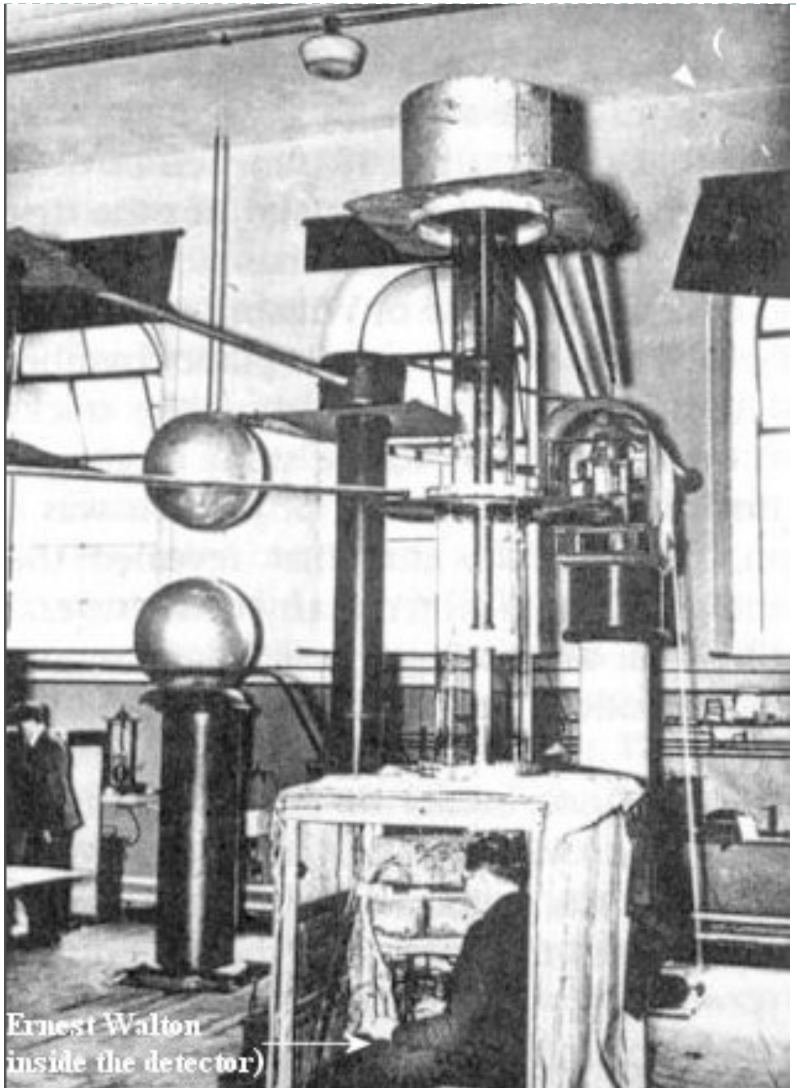
$$p + {}^{7}_{3}Li \rightarrow \alpha + \alpha$$

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"

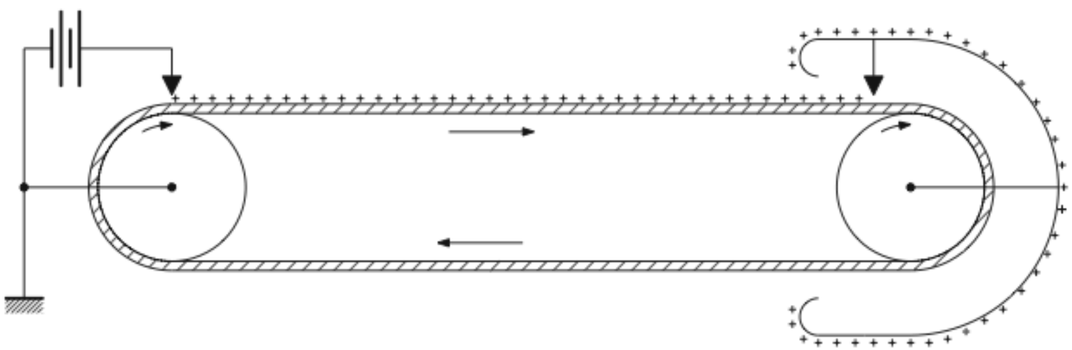
On 14 April 1932 Walton set up the tube and bombarded lithium with high energy protons. He then crawled into the little observation cabin set up under the apparatus and immediately saw scintillations of the fluorescent screen. The reaction was giving off alpha-particles.

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

- http://www.daviddarling.info/encyclopedia/C/Cockcroft.html

Van de Graaff

Van de Graaff generator (1931)
An electrostatic generator which uses a moving belt to accumulate very high voltages on a hollow metal globe on the top of the stand.



R. Van de Graaff

The Van de Graaff generator was developed, starting in 1929, by physicist Robert J. Van de Graaff at Princeton University.
~10MV.

Limits on Electrostatic Accelerators

DC acceleration is limited by high-voltage breakdown.

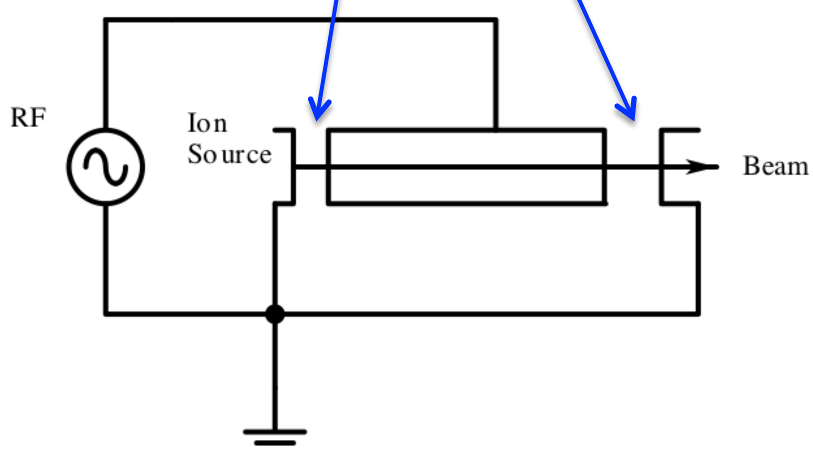
Ambience	Breakdown voltage
Air 1atm	~30 kV
SF6 (Sulfur hexa-fluoride) 1atm	~80 kV
SF6 7atm	~360 kV
Transformer oil	~150 kV
UHV	~220 kV

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

Drift tube: From DC to AC, Radio-Frequency 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.

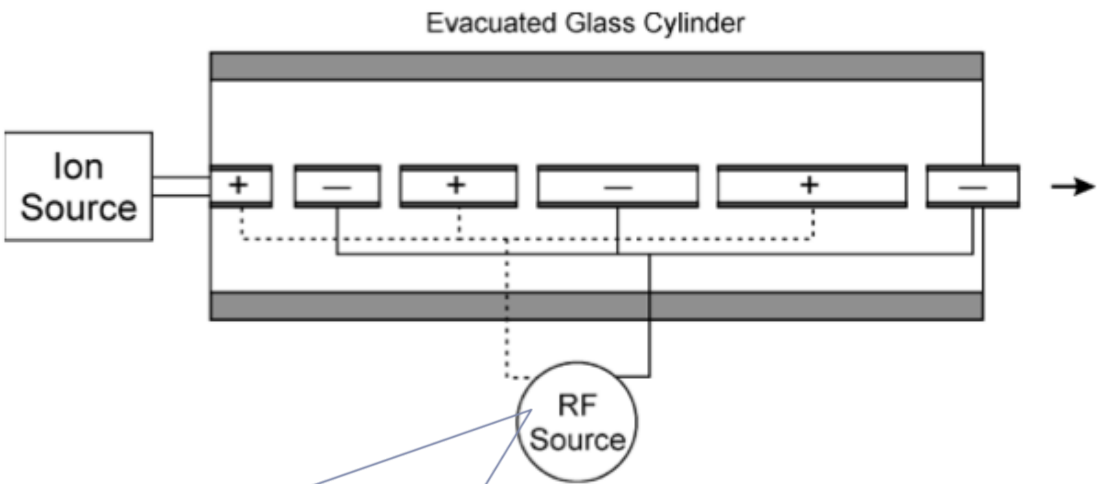
The particles must be synchronized with the rf fields in the accelerating sections.

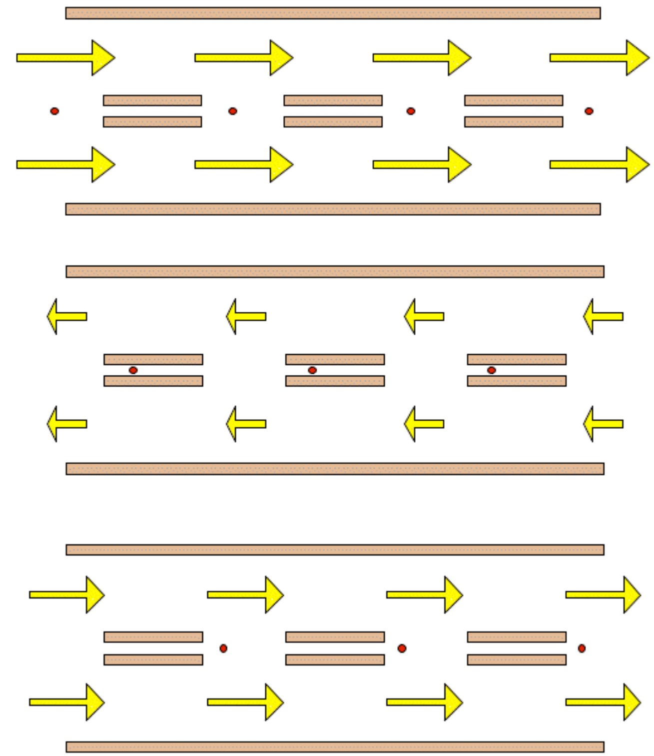


R. Wideröe

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

Concept of Wideröe accelerator





Prototype of linear accelerator. The idea of rf acceleration is also used by circular accelerators.

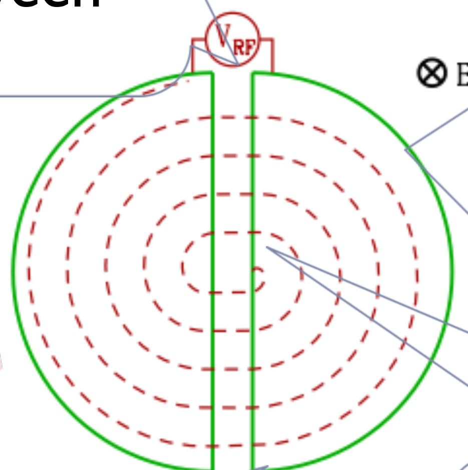
Need longer tubes and gaps as energy increases.

Cyclotron: From DC to AC, Radio-Frequency Accelerators

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

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

Lorentz Force
$F = q\, v \times B$



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

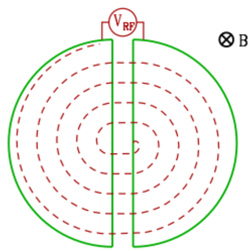
(4) The electric field in the gap then accelerates the particles as they pass across it.

Cyclotron: Frequency and orbit radius how it works.

Suppose a uniform magnetic induction B is applied perpendicular to the velocity v of a particle with mass m, charge q:

The Lorentz Force $F = q\, v \times B$ produces a circular track.

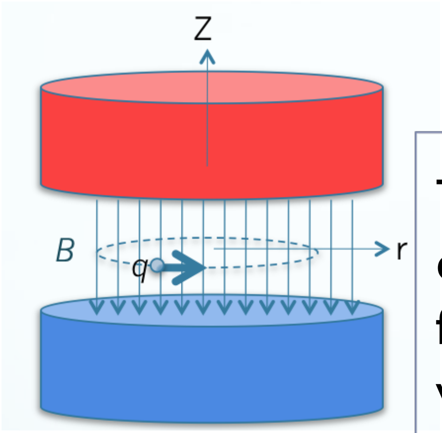
Force, relationship between momentum p and radius ρ:



Centrifugal force

$F = qvB$

$p = qB\rho$ (since $mv^2/\rho = qvB$)



and 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.

We obtain cyclotron frequency and radius as:

$f_{rev} = v/2\pi\rho = qB/2\pi m$

$\rho = mv/qB$

Frequency is independent of velocity and radius is proportional to velocity

Cyclotron: limits

When particles become relativistic the mass of the particle increases as

$$m \rightarrow m\gamma$$

which results in

→ decrease of ω_{rev}

→ asynchronism with RF

Some methods to overcome this limit tried:

- Magnetic field distribution
- Changing rf frequency with particle energy…

But no drastic improvement beyond 20 MeV with protons.

Recall

$f_{rev}=v/2\pi\rho=qB/2\pi m$

Breakthrough in 1945

Phase stability principle

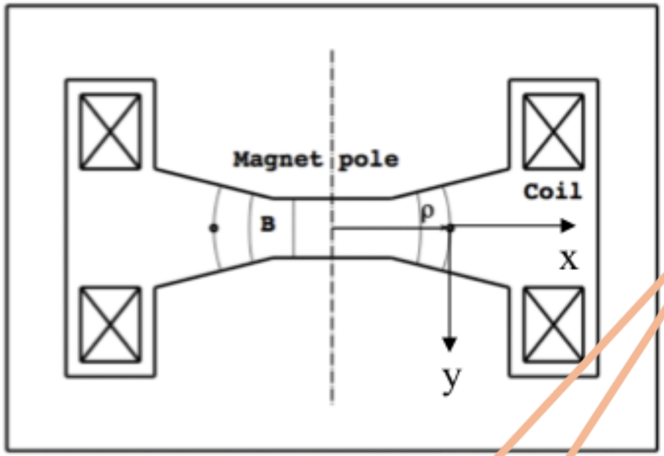
Vladimir Veksler (1944) and Edwin M. McMillan (1945)

⇒Synchrotron

(some slides later)

Betatron: non RF, accelerate electrons (beta particles)

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



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

Principle: Electromagnetic induction, not RF.

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

Maxell's eq.

$$\oint_C \vec{E} \cdot d\vec{l} = \int_s \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = -\frac{\partial \phi}{\partial t}$$

Stoke's theorem

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

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

Not dependent on mass.
Good for relativistic particles!

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

$$\frac{d\overline{B_y}}{dt} = 2\frac{dB_y}{dt}$$

From (1) and (2) we obtain the condition for constant orbit for betatron.
"2:1 rule" (Wideröe, 1928)

Eq. of motion
For ρ = const.

Constant orbit, good for relativistic particles but…

Betatron: limits of accelerating particles by magnetic induction.

We can accelerate particles by increasing the magnetic field, keeping the orbit radius constant. This means, we still need to cover the entire region with a magnetic field (magnets). And this also means that the maximum energy we can obtain is limited by the magnetic field (saturation of the iron core).

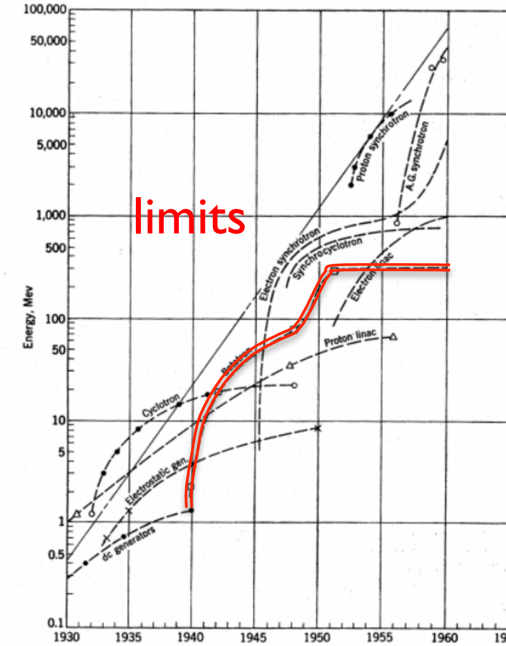


Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

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

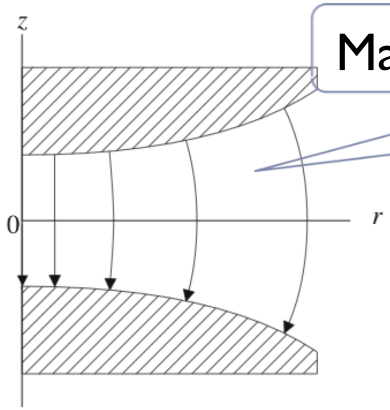
GEIGER counter yield trials of our new betatron were successful on the first attempt. After a few minutes of operation, the yield was read on an ionization chamber. The present yield which can be held at 315 Mev is about 1000 r/min. at one meter behind $\frac{1}{8}$-in. Pb at 6 PPS and 80-kv injection. Injecting with a rising voltage wave form has increased the output by a factor of about 5 over that using a flat-topped pulse. The field at the 122-cm orbit radius rises sinusoid +9200 gauss with a 60 c.p.s. wave form. The f core changes from −14 to +16 kilogauss simu pensation for the 9 percent orbital radiation l supplying a shaped flux pulse in a separate pac links the orbit but not the flux-forcing circuit. pulse is also used to expand the electron bean target.

The magnets[2] are all stacked with high quality transformer laminations. The flux magnet contains 275 tons and the six-field magnets contain 11 tons each. The field magnets are excited by two coils outside the pole rim and a coil in the gap, connected in series opposing so as not to excite the flux core. The energy stored in the capacitor bank is about 170,000 joules, of which about 85 percent is used to energize the field magnet gap and 15 percent is used to energize the flux magnet. Unidirectional pulsing is used and a synchronous mechanical switch is employed to reverse the connections to the capacitor bank.

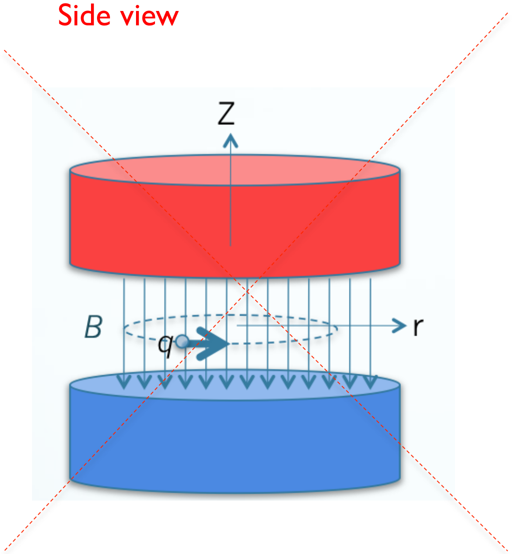
The flux core has a bias winding of 2600 ampere-turns empirically distributed to minimize leakage flux. The choke coil in the bias circuit is also designed for particle analysis.

Phys. Rev. 78, 297–297 (1950)

Betatron: Basis of today's betatron oscillation theory



Side view



Magnetic field, not uniform but still cylindrically symmetric.

$$B_z(r,z) \equiv \frac{B_\rho}{\left[r/\rho \right]^n}$$

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

Field index

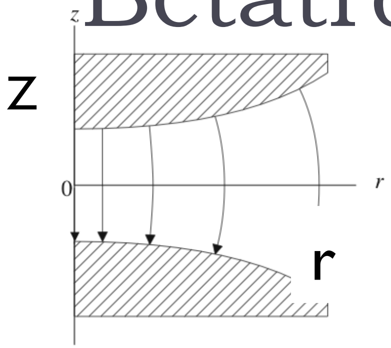
$$B_z(\rho + x, z) = \frac{B_\rho}{\left[\rho + x/\rho \right]^n} \cong B_\rho \left(1 - \frac{n}{\rho} x\right)$$

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

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

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

Betatron: betatron oscillation



$$m\frac{d\vec{v}}{dt} = q(\vec{v}\times\vec{B})$$

Use cylindrical coordinate

$$m(\ddot{r} - r\dot{\theta}^2) = q(r\dot{\theta}B_Z - \dot{z}B_\theta) \Rightarrow \ddot{r} = r\dot{\theta}(\dot{\theta}-\omega) = \frac{qv}{m}B_Z + \frac{v^2}{r} \Rightarrow (1)$$

$$m\ddot{z} = q(\dot{r}B_\theta - r\dot{\theta}B_r) \Rightarrow \ddot{z} = -qr\dot{\theta}B_r = -\frac{qv}{m}B_r \Rightarrow (2)$$

For the passage near the central orbit $r=r_0$

recall

$$B_z(r_0 + x, z) = \frac{B_0}{\left[r_0 + x/r_0\right]^n} \cong B_0\left(1 - \frac{n}{r_0}x\right) \Rightarrow (3)$$

From (1) and (3) and using $v=r_0\omega$, we obtain eq. of motion for x as

$$\ddot{x} + \omega^2(1-n)x = 0 \Rightarrow (4)$$

and similarly (sort of) for z as

$$\ddot{z} + \omega^2 nz = 0 \Rightarrow (5)$$

Equation of motion for betatron oscillation in an axisymmetric field.

Stable oscillation in horizontal plane: 1-n>0
in vertical plane: n>0

Betatron frequency

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

Betatron tune

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

Betatron: "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.

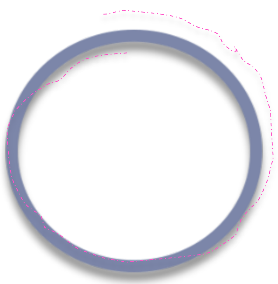
Motion in Betatron
Tune is less than 1, meaning betatron wave length is larger than the circumference.

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

$$\omega_z \equiv \omega\sqrt{n}$$

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

$$\nu_z \equiv \sqrt{n}$$



Betatron
Progress in understanding particle orbits in a magnetic field was made.
Basis of today's betatron oscillation theory was established.

If you achieve higher energy, will need large magnets as mentioned in the previous slide.
Stronger focus with more compact scheme is needed.

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

Betatron: concept of emittance

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

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

$$y = a_1 \cos(\nu s / R + \phi)$$

Horizontal position

Betatron amplitude

phase

Betatron tune

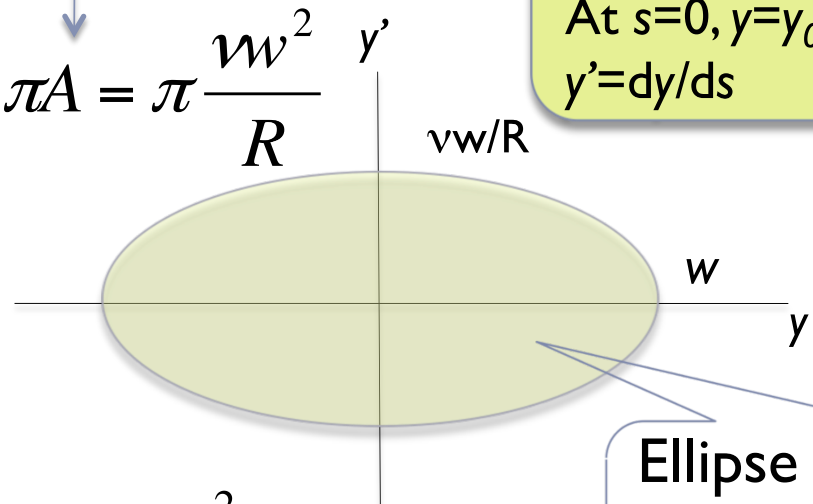
Radius of the design orbit

Instead of *t*, use *s*, the distance along the path. At *s*=0, *y*=*y₀* and *y'*=*y'₀* and *y'*=dy/ds

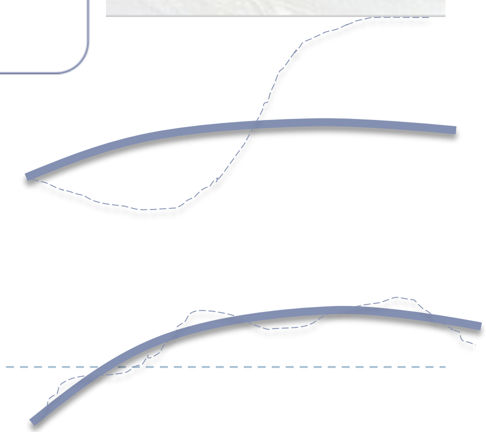
$$a_1 = \sqrt{y_0^2 + \left(y_0' R / \nu\right)^2}$$

Acceptance

$$\pi A = \pi \frac{\nu w^2}{R}$$



Larger ν results in smaller a_1

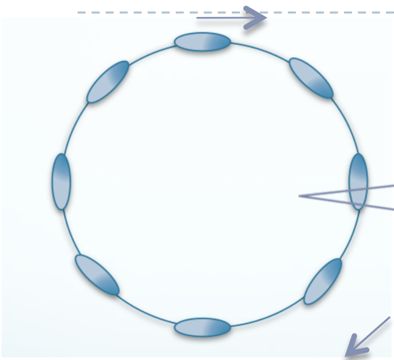


$$W \equiv a_1^2 \nu / R$$

Ellipse indicates the phase space condition for stable circulation

emittance

Phase stability: the concept of "bunch" & the Synchrotron



Many particles in a bunch, circulating many turns (tens of thousands, for example.

Particles of different energies have differences in velocity and in orbit length;

➔Particles may be asynchronous with the RF frequency.

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

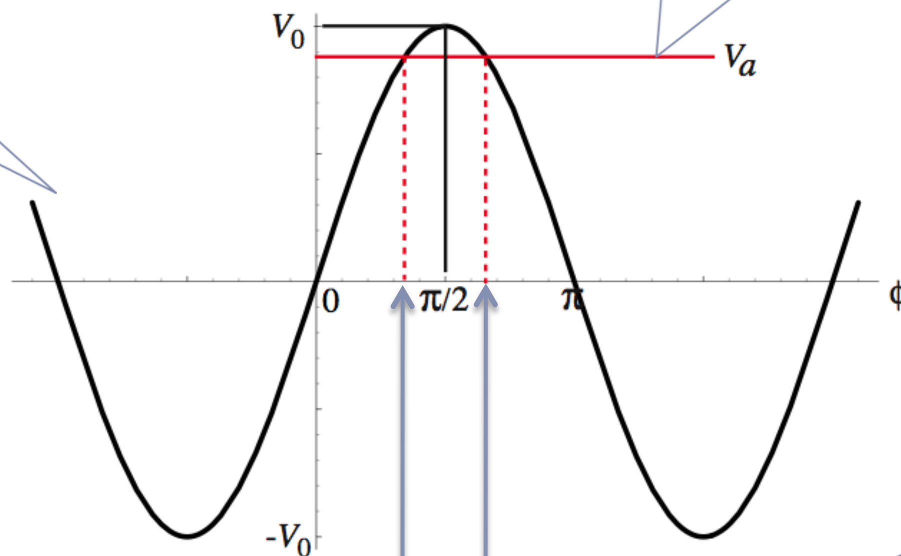
➔This enables a stable, continuous acceleration of the whole particles in a bunch to high energies.

➔Circular accelerators based on this principle are called "synchrotrons."

Phase stability: a concept of "bunch"

Va acceleration voltage

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



Which one?

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

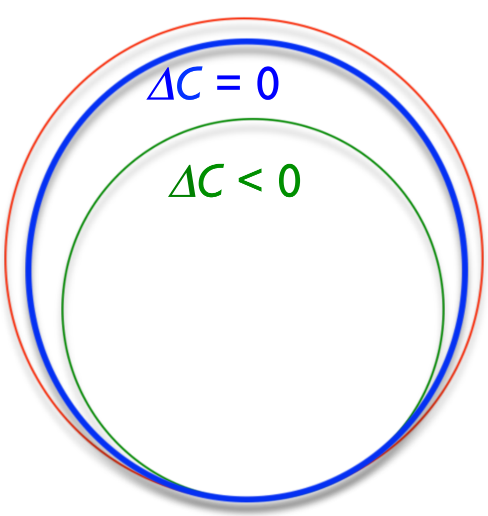
There are there are two ϕs which satisfy Va = $V_0 \sin \phi$ in one RF period

Phase stability: a concept of “bunch”

Case (1) Particles with $\Delta P > 0$ travel $\Delta C > 0$

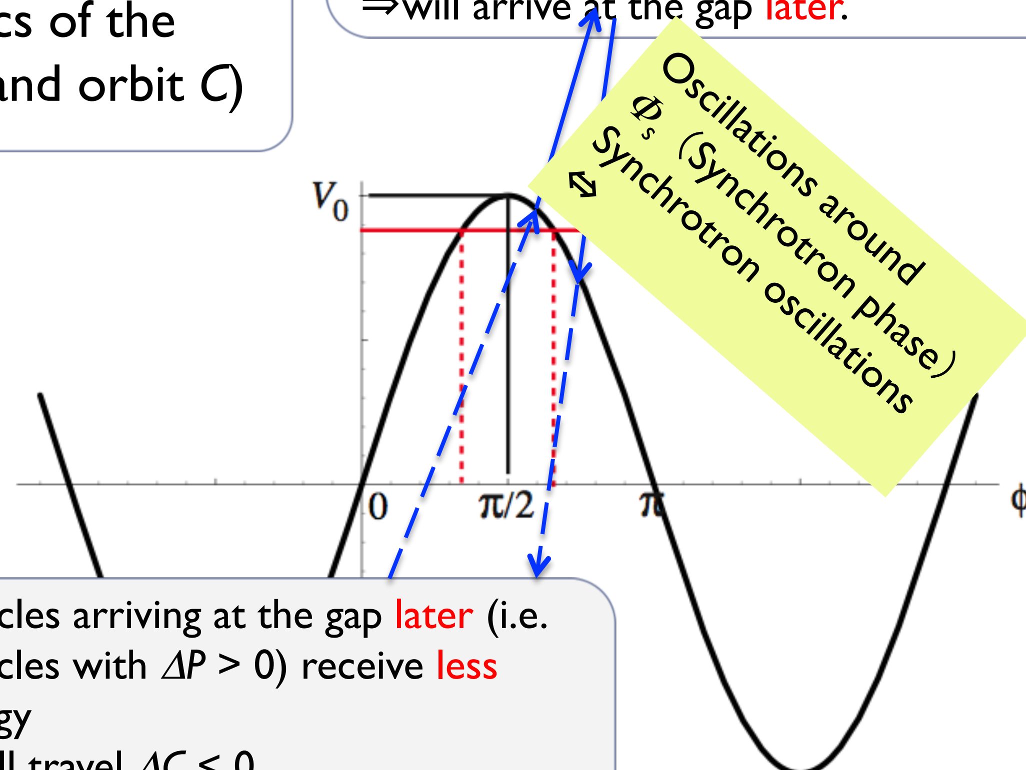
Which phase gives stable oscillations?

Depends on the characteristics of the orbit. (Particle momentum P and orbit C)



Example of a circular orbit

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

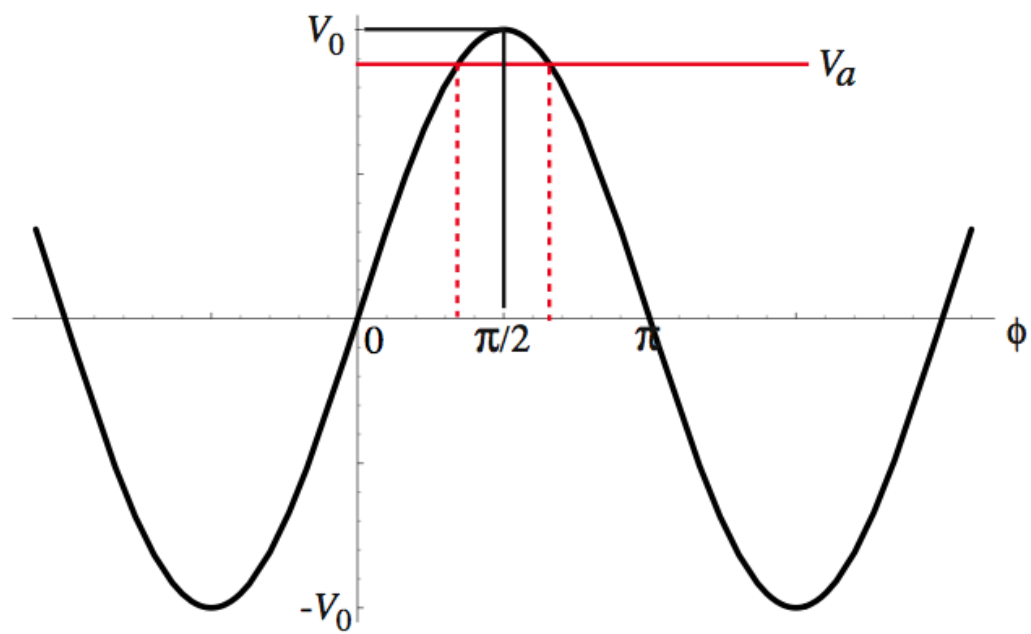


Particles arriving at the gap later (i.e. particles with $\Delta P > 0$) receive less energy
⇒will travel $\Delta C < 0$
⇒will arrive at the gap earlier.

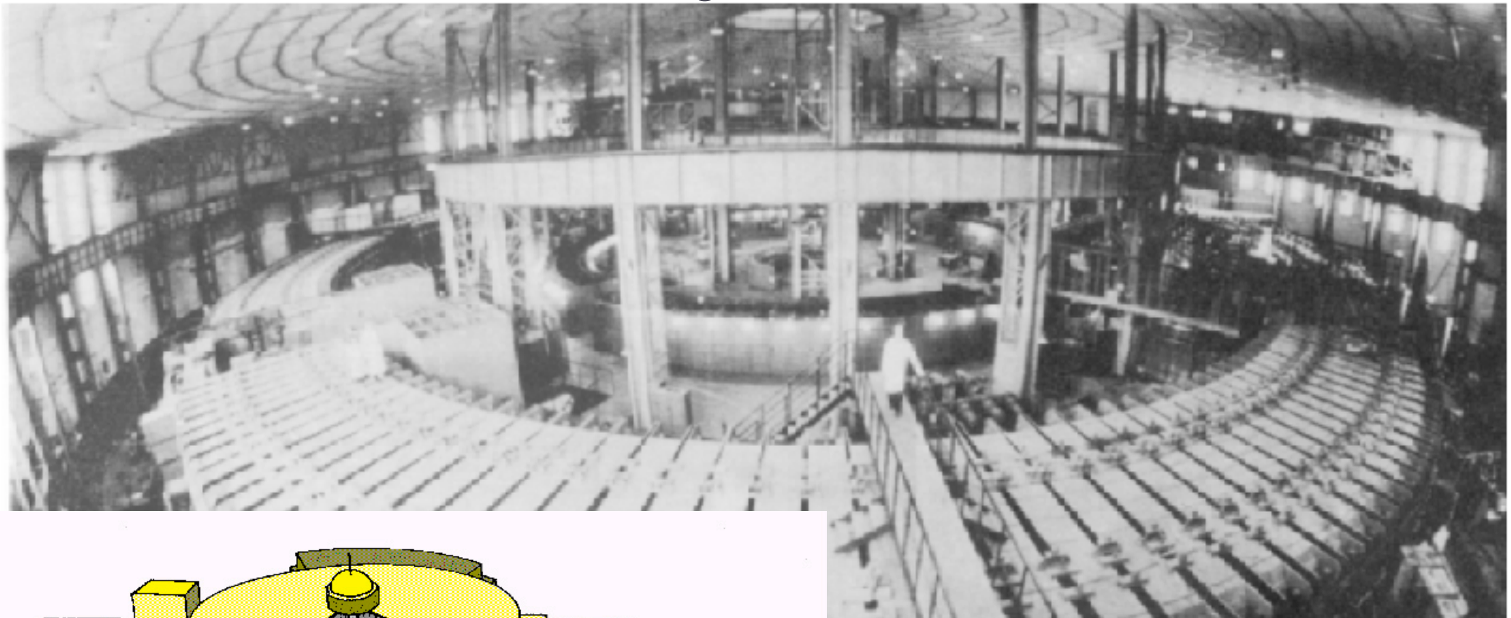
Phase stability: a concept of "bunch"

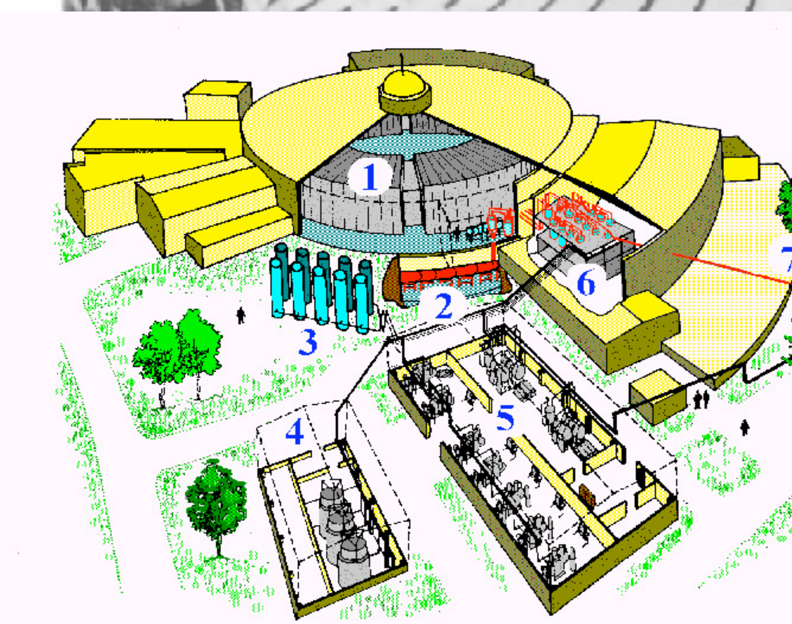
Case (2) Particles with $\Delta P > 0$ travel $\Delta C < 0$

Quiz: Which phase give stable oscillation?



Phase stability: the concept of “bunch” & the Synchrotron





Synchrophasotron:

1 - accelerator ring Nuclotron
2 - accelerator ring
3-7 - cryogenic supply system

The Synchrophasotron is included in Guiness Book of records as the largest electromagnet in the world. The magnetic system consists of four quadrants with a radius of the orbit of 28 m and weight of 36000 tons.

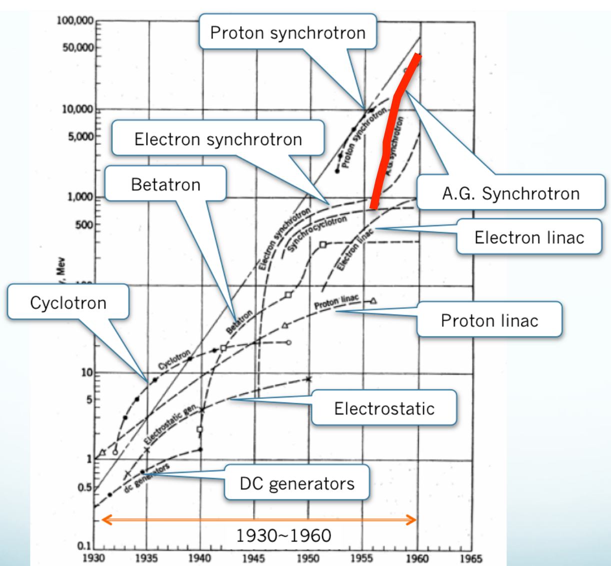
http://lhe.jinr.ru/english/img_01.htm

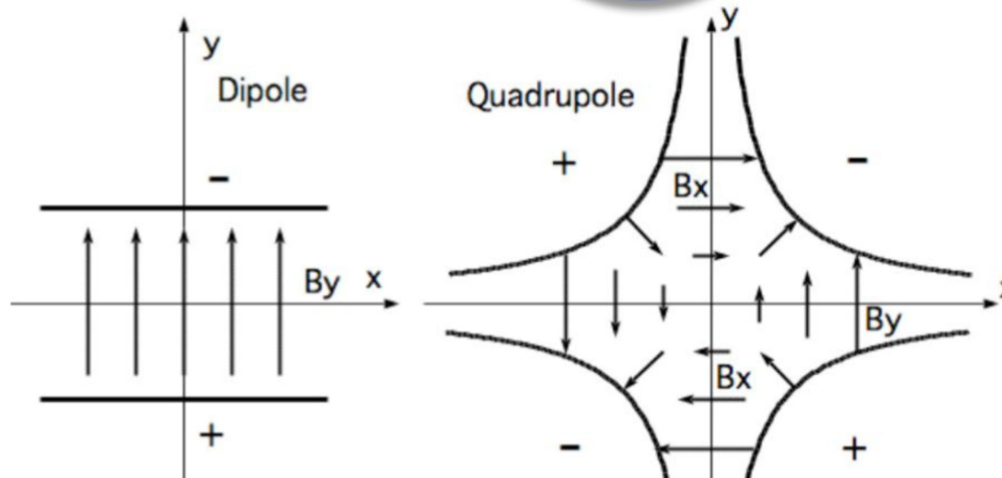
Strong focus: Alternating Gradient synchrotron

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

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

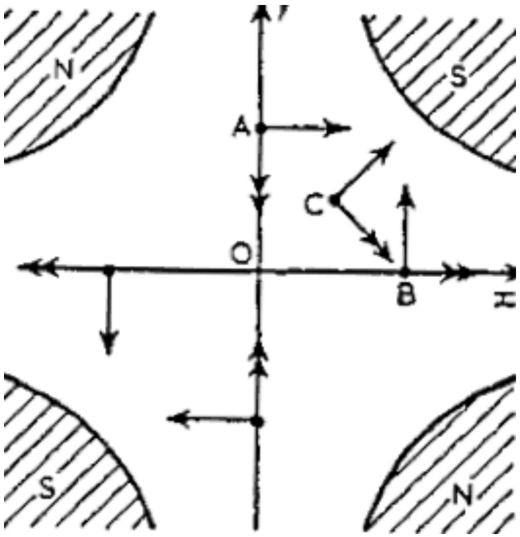
Why do we use magnetic field to deflect, focus,, not electric?





Magnetic fields
To bend (deflect) To focus & defocus

Strong focus: Alternating gradient synchrotron



Positively charged particle
Moving into this paper.

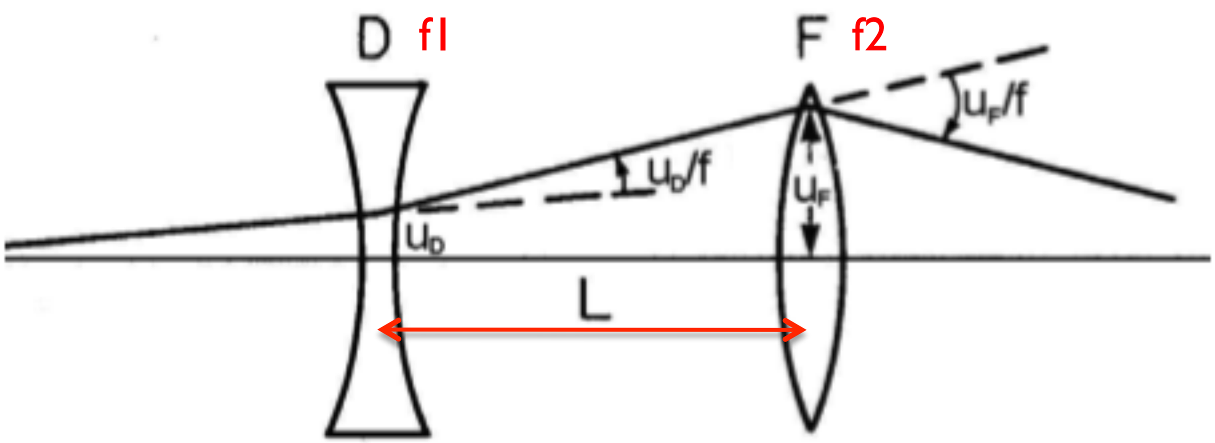
Quiz: What is the force (which one is the correct arrow representing the force) on the particle at points A, B and C?

Focusing in horizontal direction and defocusing in vertical direction -- let's call it a Focusing or F-type quadrupole magnet.
If the polarity is reversed (N and S are reversed), it becomes defocusing in horizontal and focusing in vertical: a Defocusing or D-type quadrupole magnet.

A big difference from weak focusing case, where focusing is obtained in both directions simultaneously.
By alternating F- and D- , we can obtain a net focusing effect.
Nicholas C. Christofilos (1950), E. D. Courant, M. S. Livingston, and H. S. Snyder (1952)

Strong focus: Alternating gradient synchrotron

Analogy with optical thin lens



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

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

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

$$f_1 = -f_2 \equiv -f$$

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

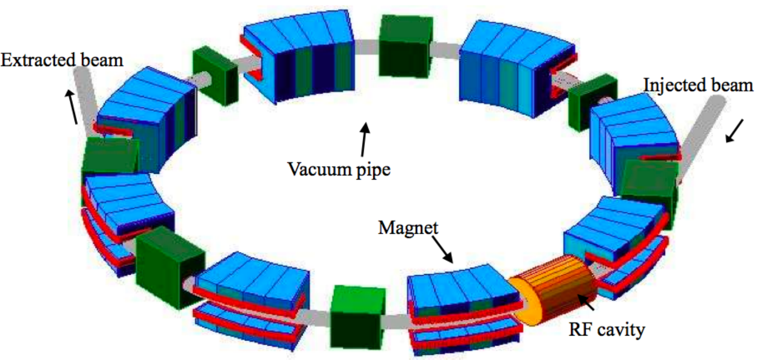
Net focus

Obtaining a net focus by combining F- and 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



Basic components
Magnets
- Dipole magnets for bending
- Quadrupole magnets for focusing

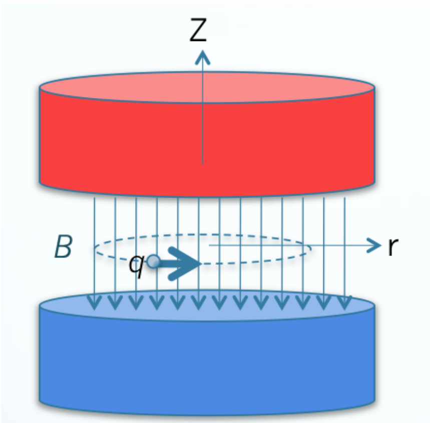
Vacuum pipes
- covers the beam passage

RF cavities

Let me take a
Side trip here…

Some photos
Next slides

Strong focus:
Magnet weight proportional to r



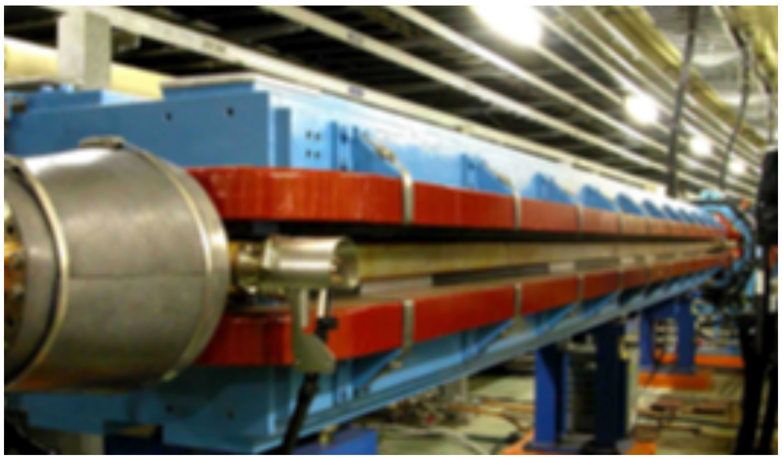
Weak focus:
Magnet weight proportional to r^2

The strong-focusing principle revolutionized accelerator design. The principle's practicality was demonstrated in 1954, when Cornell's 1.3-GeV electron accelerator began operation. Then the new technology was applied to larger machines. In 1959, the 25-GeV Proton Synchrotron went into operation at CERN, the European high energy physics laboratory, and in 1960, the 33 -GeV AGS was commissioned. These alternating gradient synchrotrons were constructed using only twice the amount of steel (4,000 tons) needed to construct the weak-focusing, 3.3-GeV Cosmotron.

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

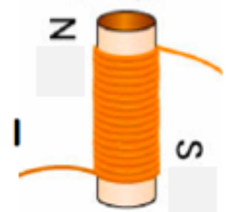
Basic components: Magnets

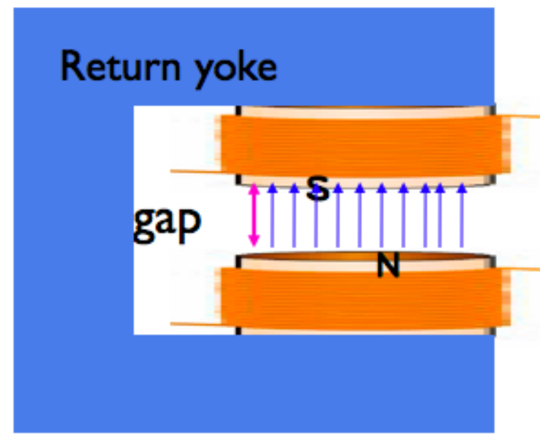
Dipole magnet
(Bending magnet)



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

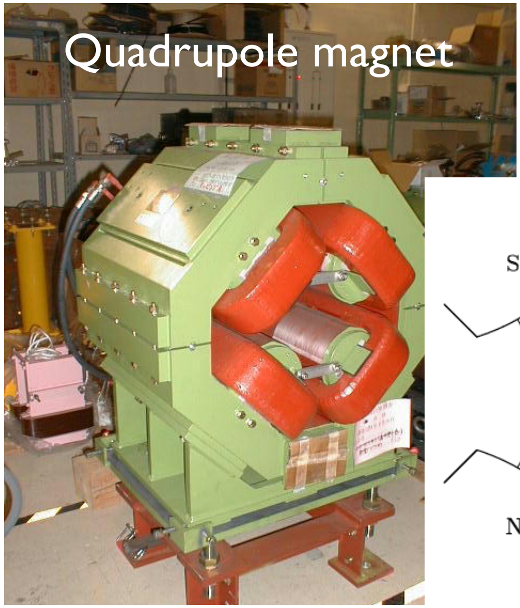
Wind a wire on an iron bar.
Flow current through the wire and the bar will be magnetized. Polarity changes when current direction is changed.

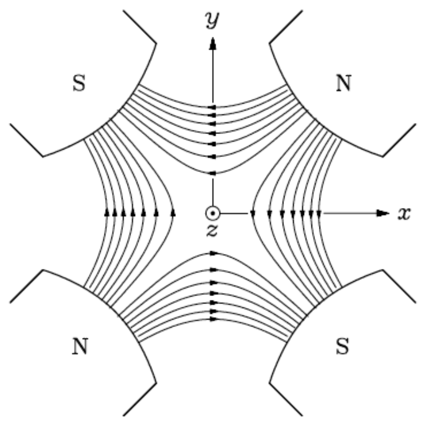


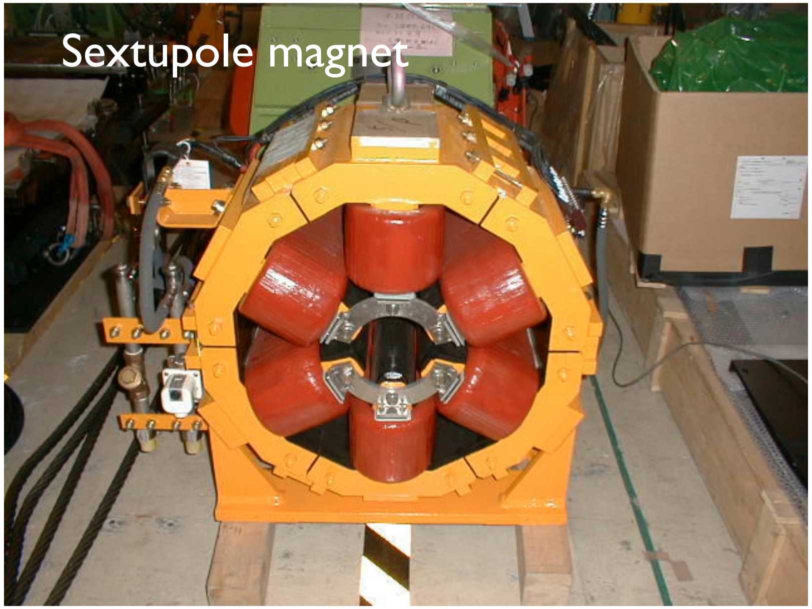


Coils on the pole
+ return yoke
→dipole magnet!

Basic components: Magnets



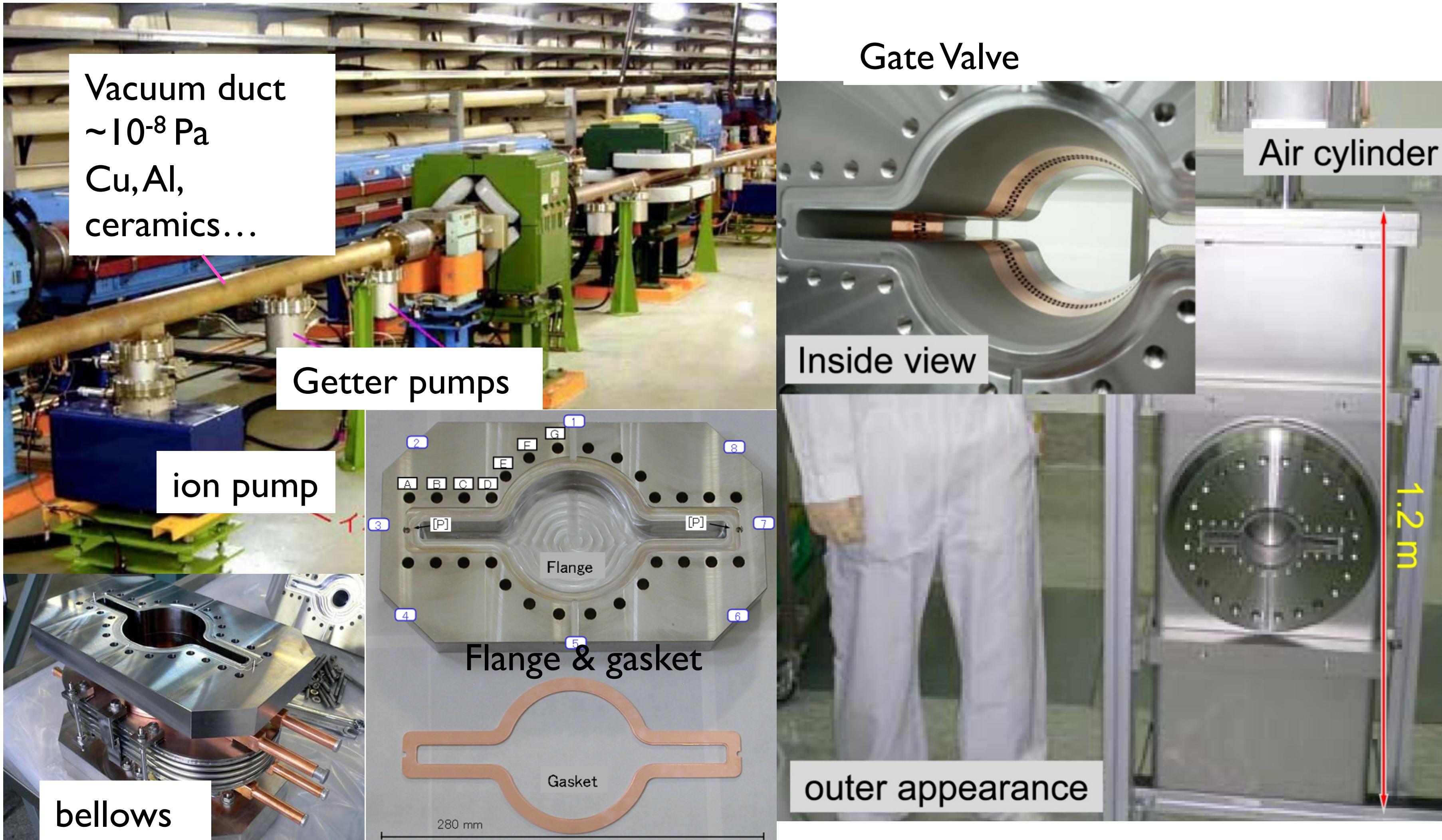




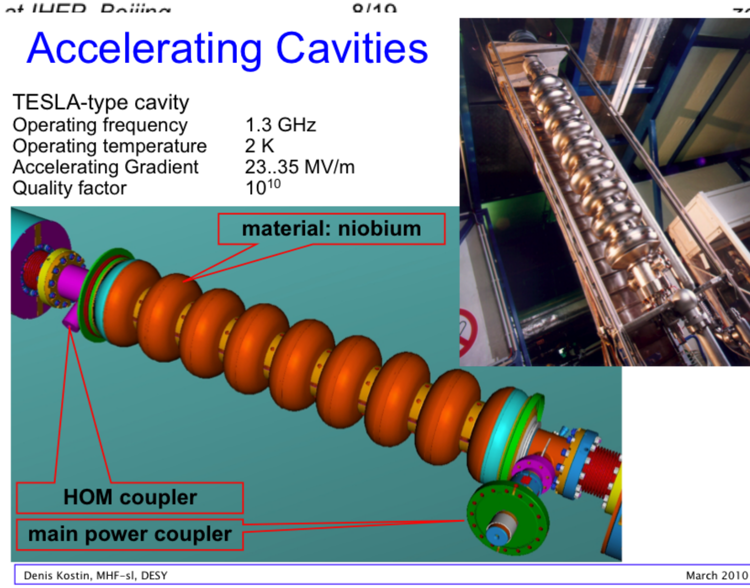
Generates a focusing/defocusing field. The charged particles that travel through the quadrupole magnet receive a focusing/defocusing force. The force is proportional to the distance from the magnet center. (no force if the beam goes though the center)

Sextupole fields have a focal length that is inversely proportional to the distance from the centre of the magnet. Used for correcting the effects of focusing dependence on momentum.

Basic components: Vacuum components



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

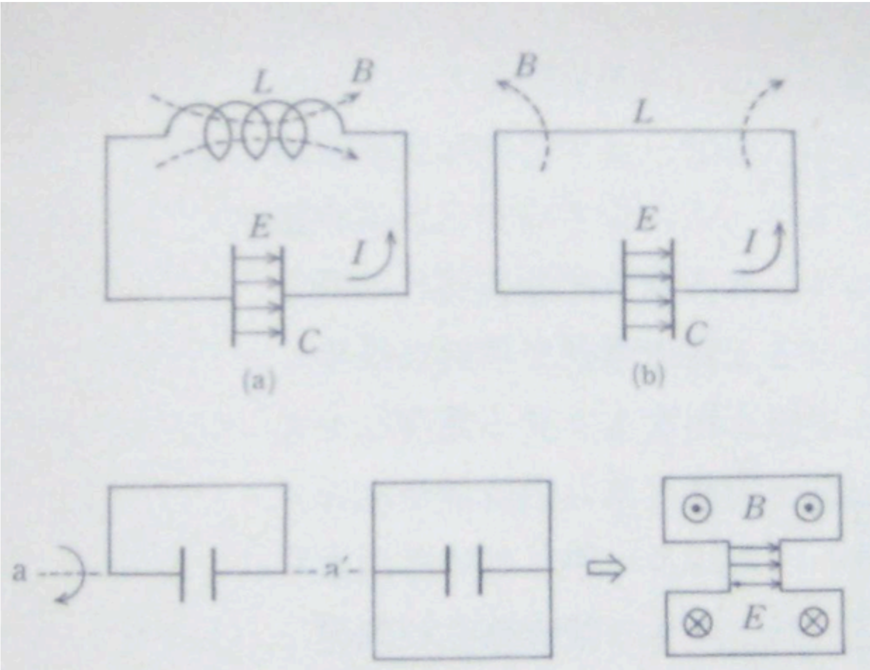
Wall loss 35.7 kW

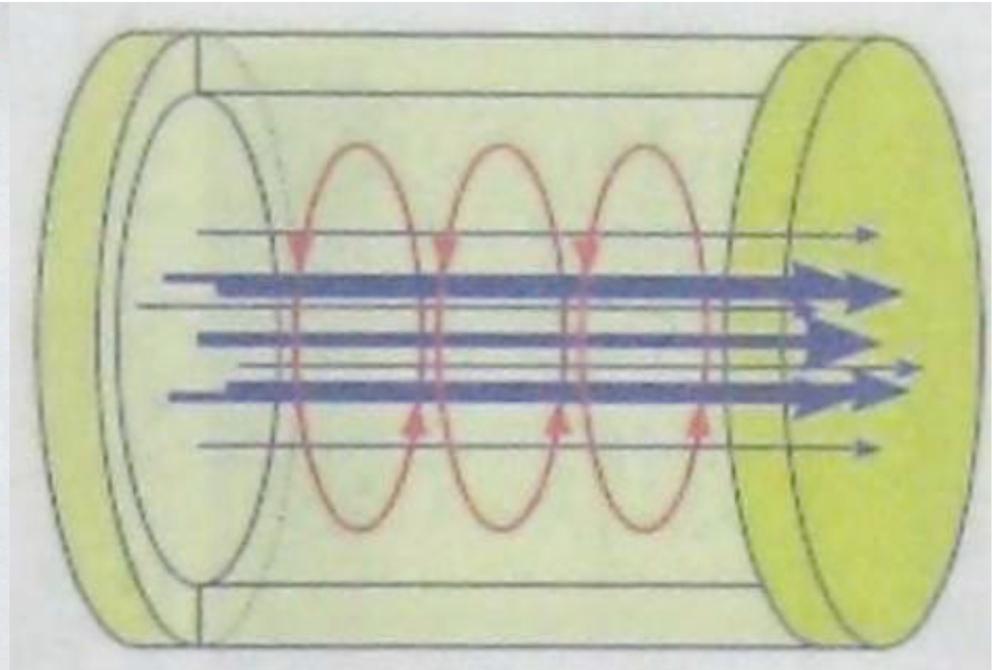
Other 7.8 kW

Total 85.5 kW

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

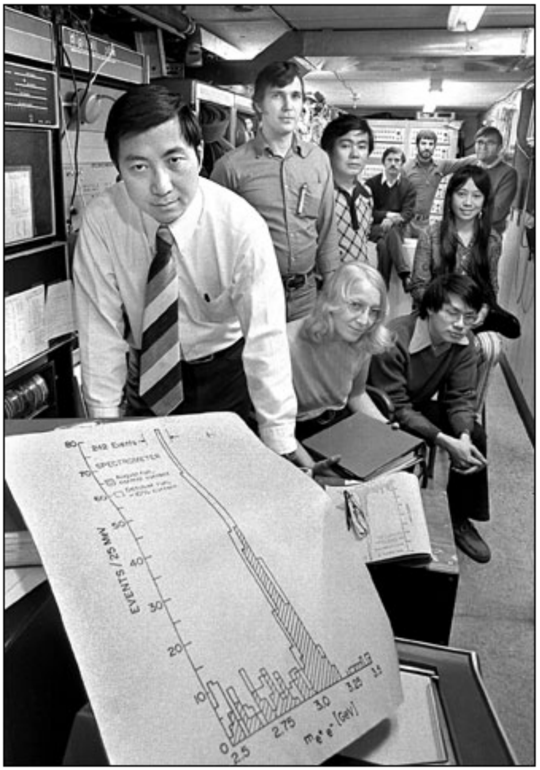
Basic components: RF cavities





Pillbox cavity
TM010 mode

Alternating Gradient Synchrotron (Brookhaven)



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.

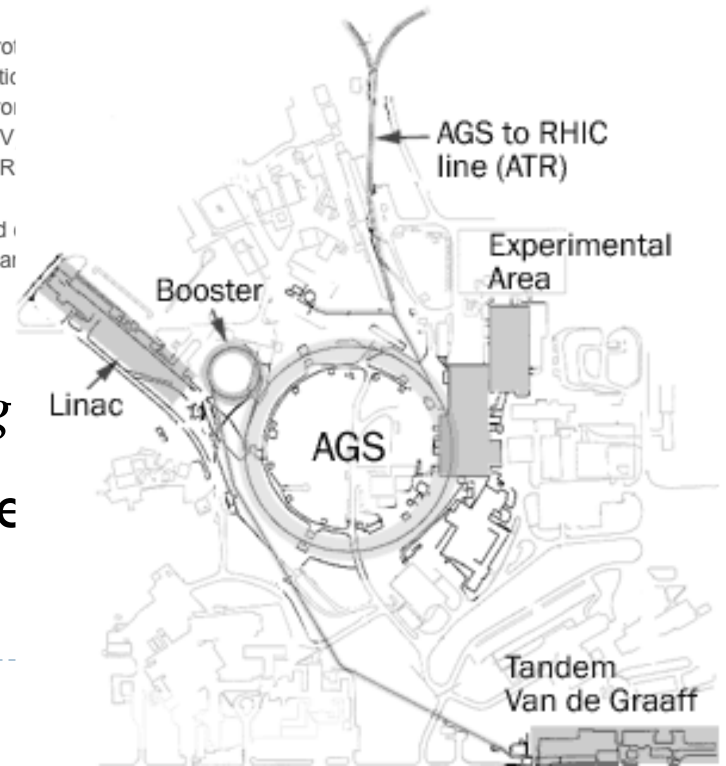
Ting's experiment took advantage of the AGS's high-intensity prot
which bombarded a stationary target to produce showers of partic
could be detected by complex detectors. A strong peak in electro
positron production at an energy of 3.1 billion electron volts (GeV
suspect the presence of a new particle,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

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

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

28 GeV protons on a beryllium targe

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

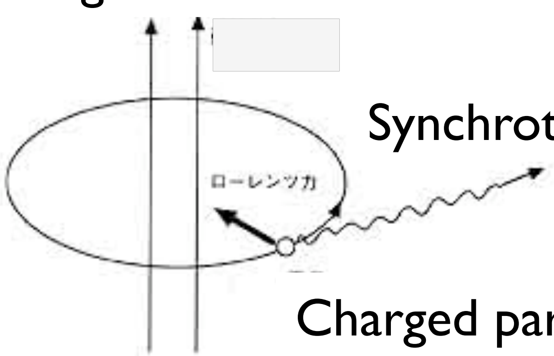


Synchrotron radiation:

•Synchrotron radiation (SR) is emitted from a charged particle traveling near 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".

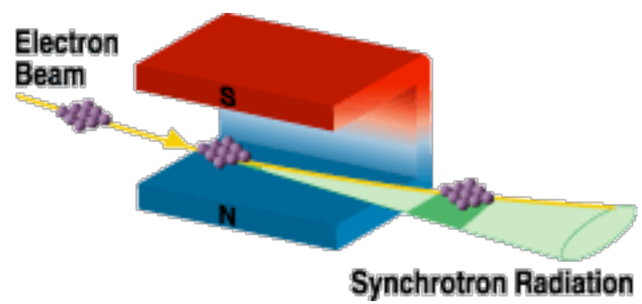
•Synchrotron radiation is emitted in a continuous spectrum.

Magnetic field



Synchrotron radiation

Charged particle



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

Synchrotron radiation: lighter particles suffer more.

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:

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

$$r_e \equiv e^2/\left(4\pi\varepsilon_0 m_e c^2\right) = 2.82\times10^{-15}$$

Can you derive this?

In the laboratory frame, *P* becomes

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

The radiated energy per turn *ΔE* for a ring of radius *ρ*

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

Practical formula

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

For relativistic protons and electrons of the same momentum, the energy loss is in the ratio $(m_e/m_p)^4 \sim 10^{13}$. It is 10^{13} times smaller for protons than for electrons. For electrons of energy 10 GeV circulating with ρ=1 km, the SR energy loss is 0.9 MeV/turn. How much is it for 20 GeV electron?

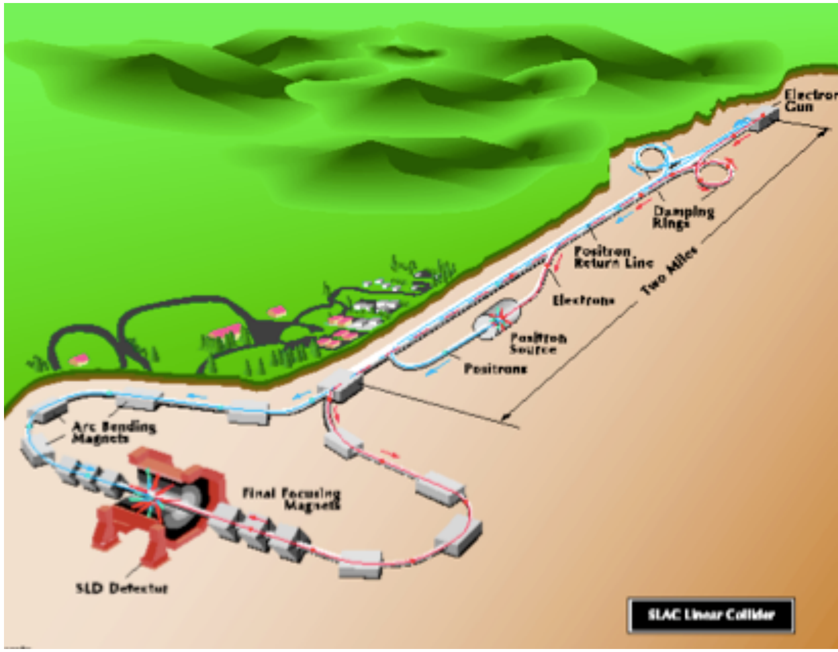
Synchrotron radiation:

SR loss is 10^{13} times smaller for protons than for electrons.
For a high energy electron circular machine, a large ring (radius scaling roughly as the square of the beam energy) is needed.
➔LEP @ CERN, 100GeV, 27 km in circumference.
Low magnetic "guide" fields
➔Still loss needs to be compensated by RF power to keep the beam circulating.

A linear accelerator is the natural solution to the scaling problems of a circular collider.

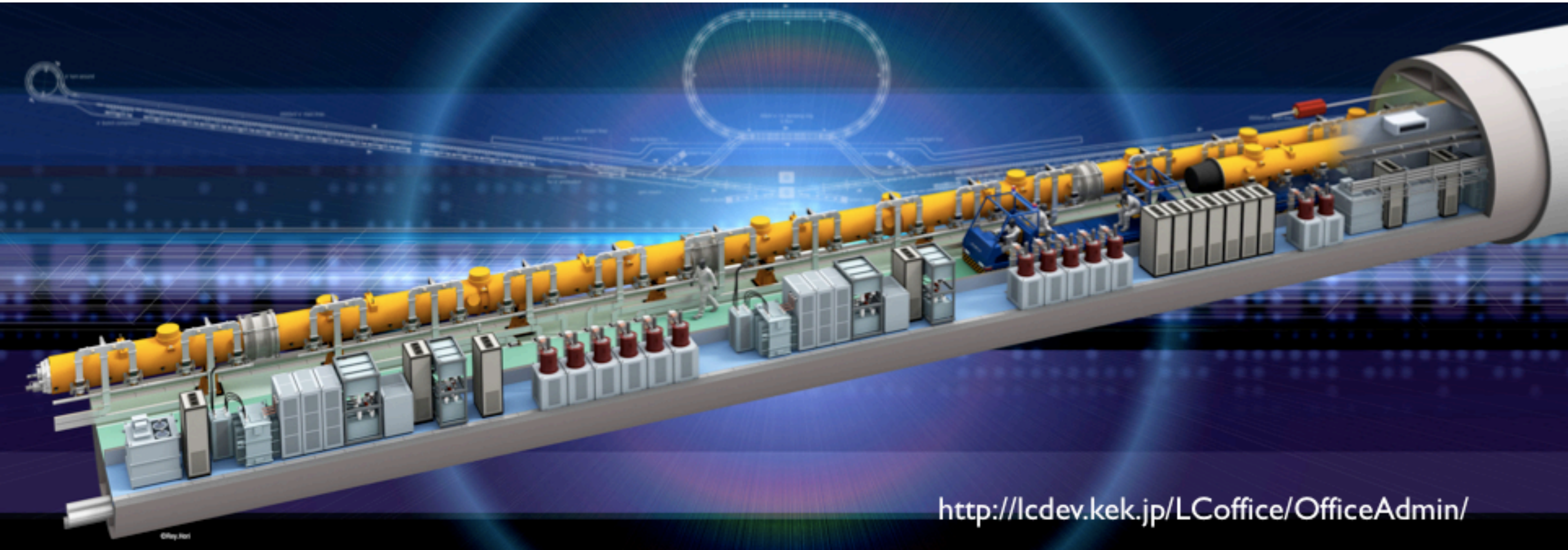
SLC (~50 GeV electron-positron beams, Ecm~91 GeV, lose some at the arcs).

➔Linear Collider project (following slides)

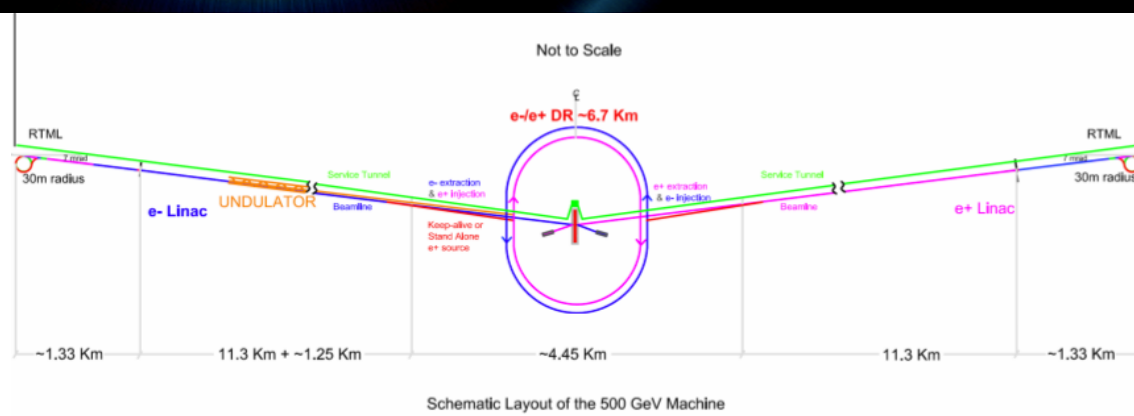


http://www-sldnt.slac.stanford.edu/alr/slc.htm

Linear Collider:



1 st stage 500 GeV



Linear Collider:

	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	3×10^{30}	2×10^{34}	2.3×10^{34}	$cm^{-2}s^{-1}$
Power consumption	?	230	129 (x2?)	MW

Brief history & major inventions 1960~

Collider

New era of large circular colliders

Energy frontier

(side trip: storage ring)

Luminosity frontier

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.

(2)Phase stability principle in1945
Synchronization issue is solved.

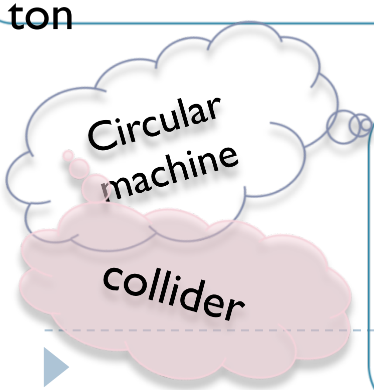
Betatron
•Acceleration by magnetic induction
•Constant orbit
•Entire orbit covered by magnets

Early Synchrotron
•Acceleration by RF
•Huge magnets Synchrophasotron 10 GeV, 39000 ton

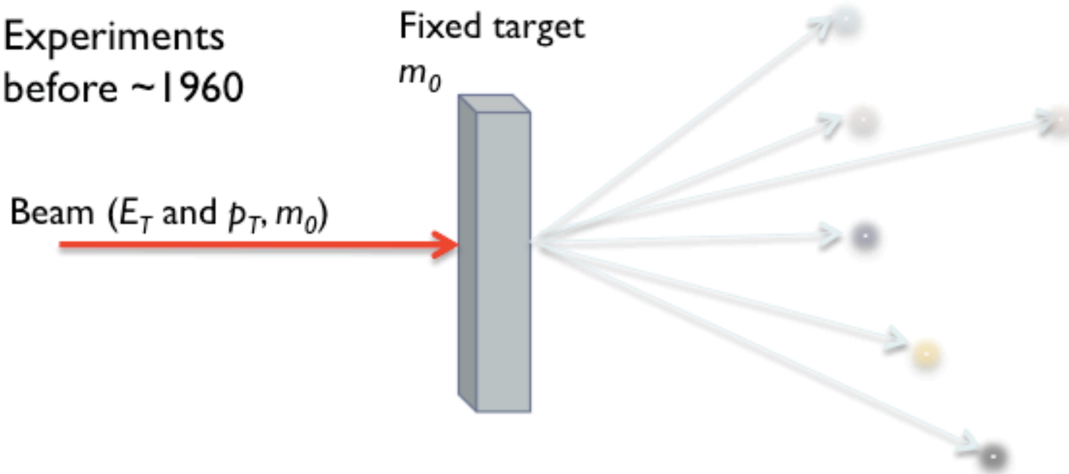
(1)Orbit stability
Betatron oscillation
Weak focusing

(3)Strong focusing
1952

Synchrotron
•Entire orbit not covered by magnets.
•Much higher energy
>10 GeV (10000 MeV)



Collider



$$E_T = (1+\gamma)m_0c^2$$

$$p_T = \beta\gamma m_0 c$$

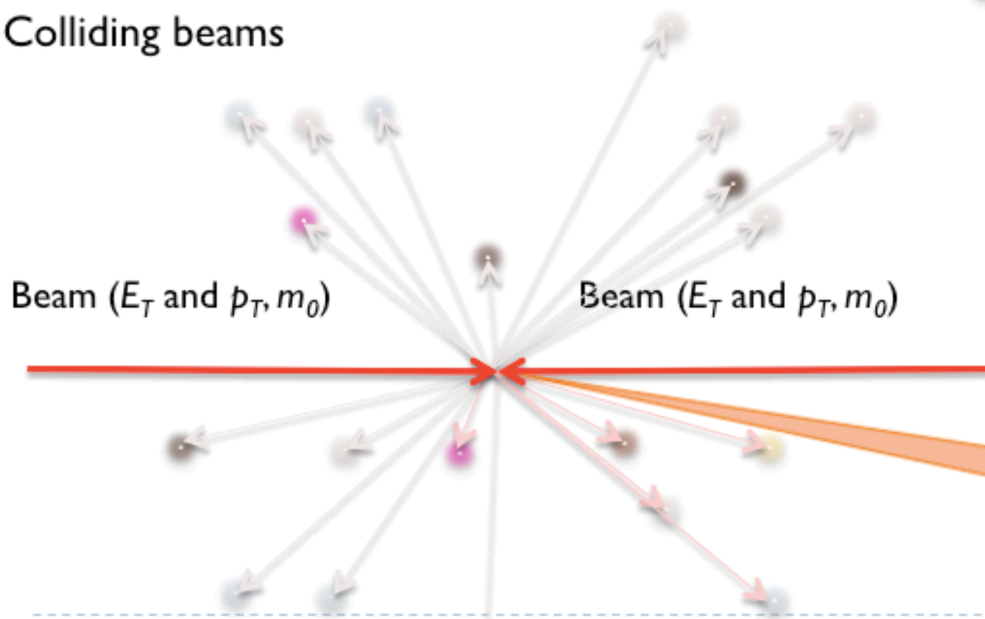
$$\therefore -E_{C.M.}^2 = (p_T c)^2 - E_T^2$$

$$= (\beta\gamma m_0 c \cdot c)^2 - \left[(1+\gamma)m_0c^2\right]^2$$

$$= -2(1+\gamma)\left(m_0c^2\right)^2$$

$$\therefore E_{C.M.} = \sqrt{(2\gamma+2)}m_0c^2 \approx \sqrt{2\gamma}m_0c^2$$

Lorentz invariant



Advantage:
Much larger center-of-mass energy available for the creation of particles.

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

Disadvantage:
Stable collision needed.
Collision rate is lower.

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

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

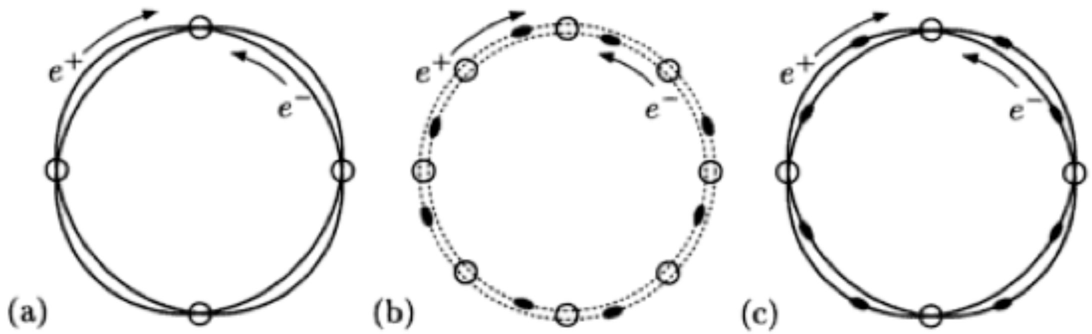
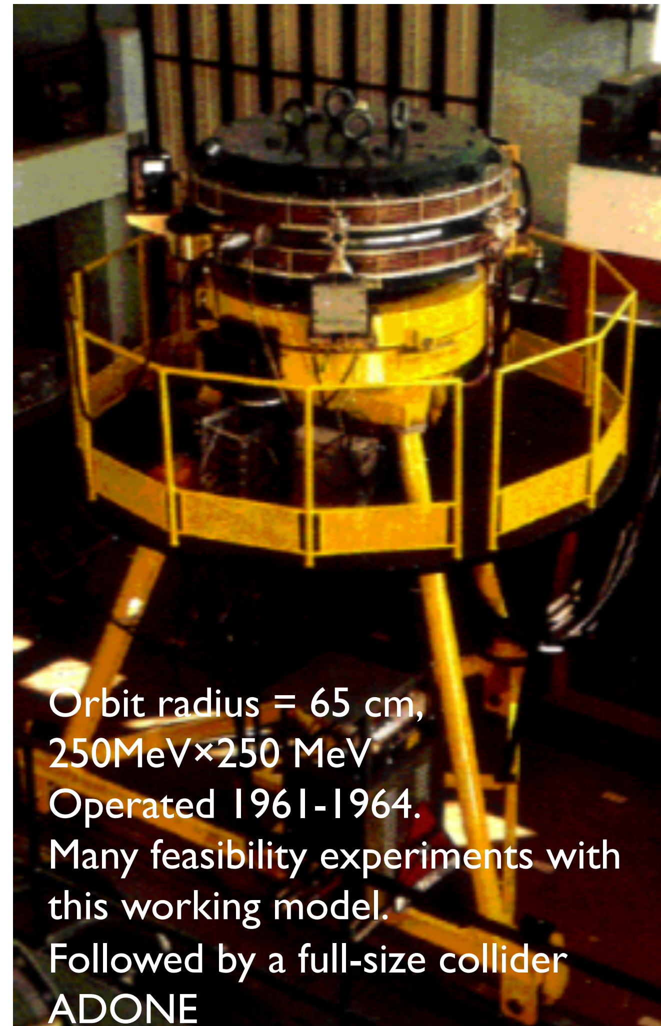


Fig. 1.11. (a) Beam routing. Small distortions to the circular trajectories make the two beams overlap only at a few selected places. The small circles denote the collision sites, at which the detectors will be aimed. (b) Beam bunching. Here particles come in concentrated volleys or "bunches" (the grey 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.

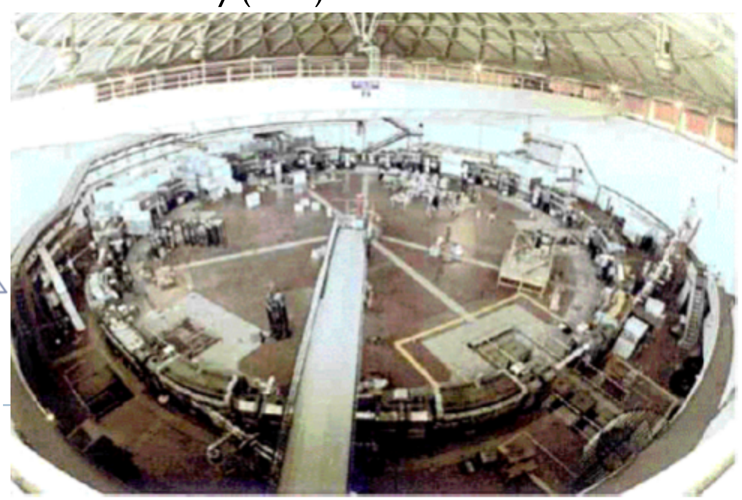
Collision-based computing, Andrew Adamatzky (2002)



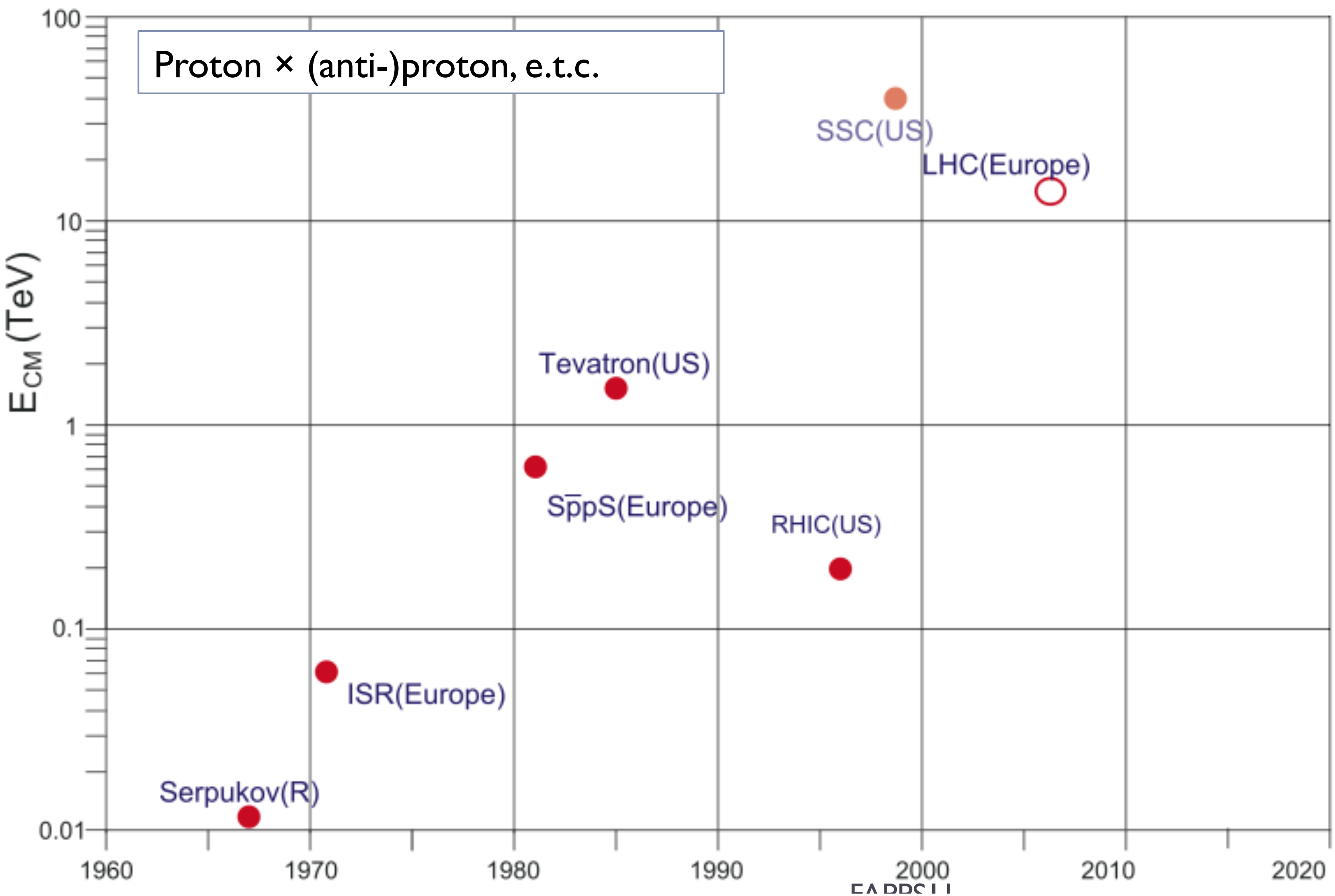
Orbit radius = 65 cm,
250MeV×250 MeV
Operated 1961-1964.
Many feasibility experiments with this working model.
Followed by a full-size collider ADONE

The First Electon-Positron Collider
Carlo Bernardini
Phys. Perspect. 6(2004) 156-183

ADONE 1969
C=105 m
E_{cm} < 3 GeV
no J/ψ …

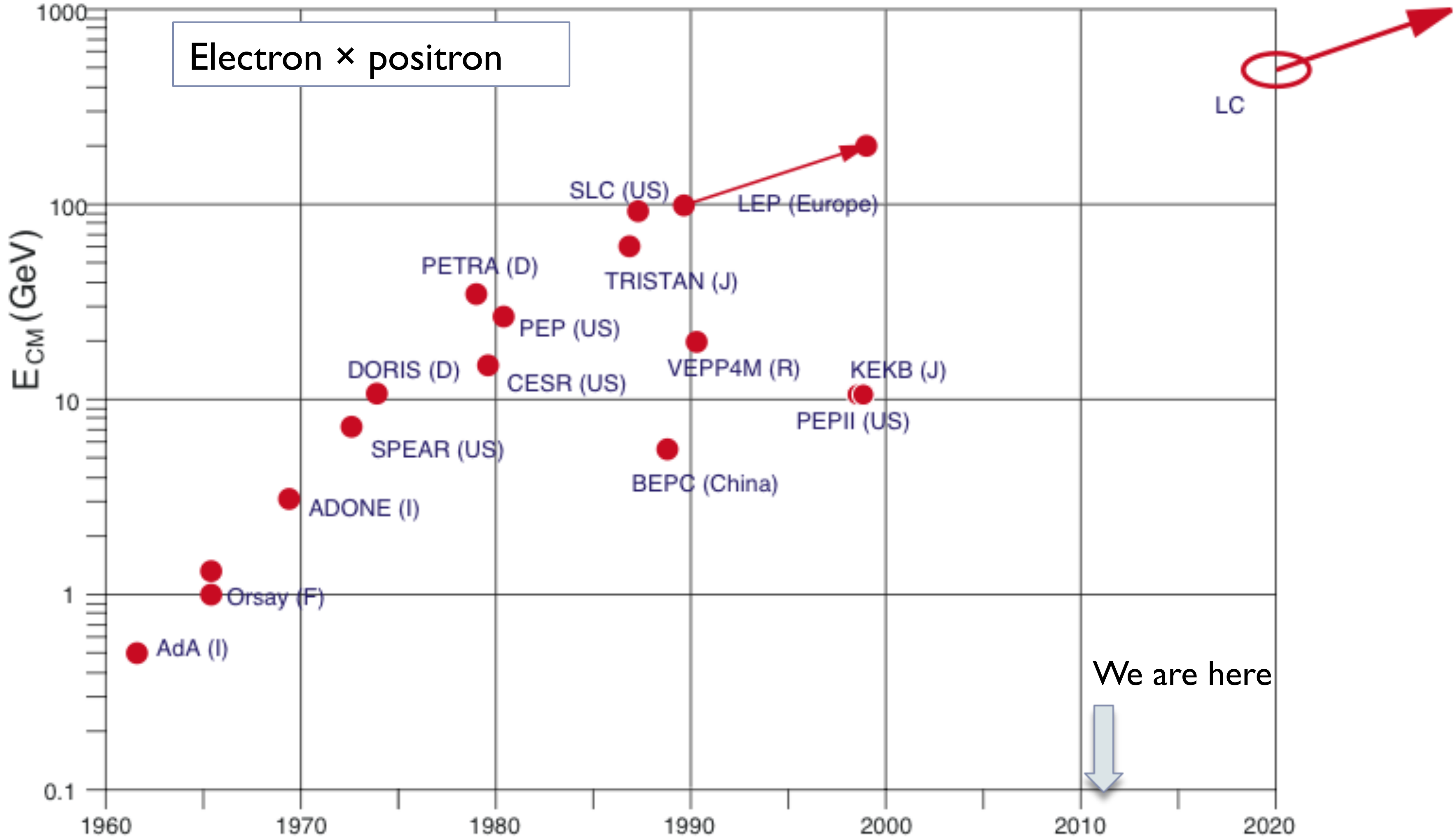


Collider: Era of large circular colliders, energy frontier machines



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

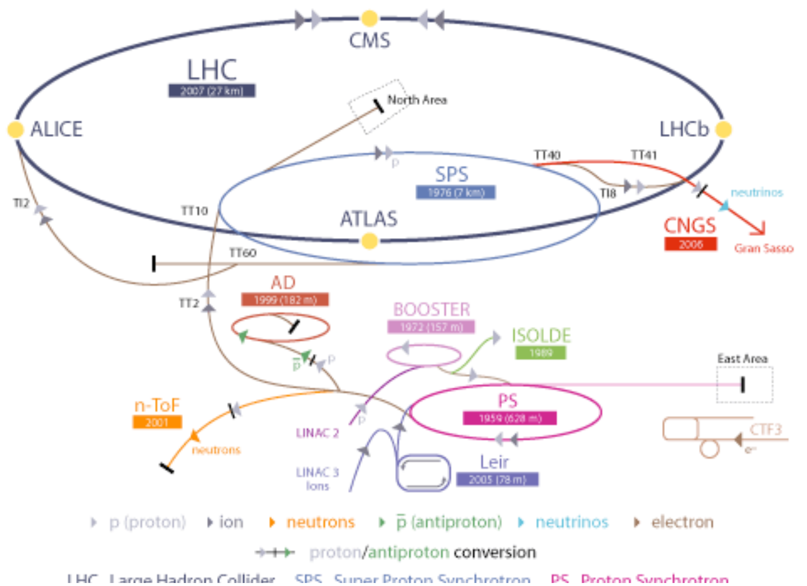
Collider: Era of large circular colliders



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

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

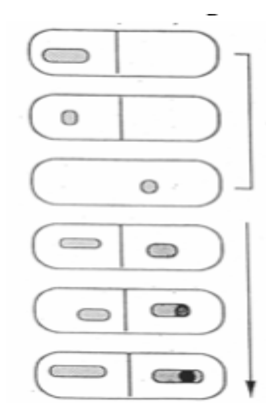
~7km in circumference
1976 commissioning

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

Tevatron (Fermilab)

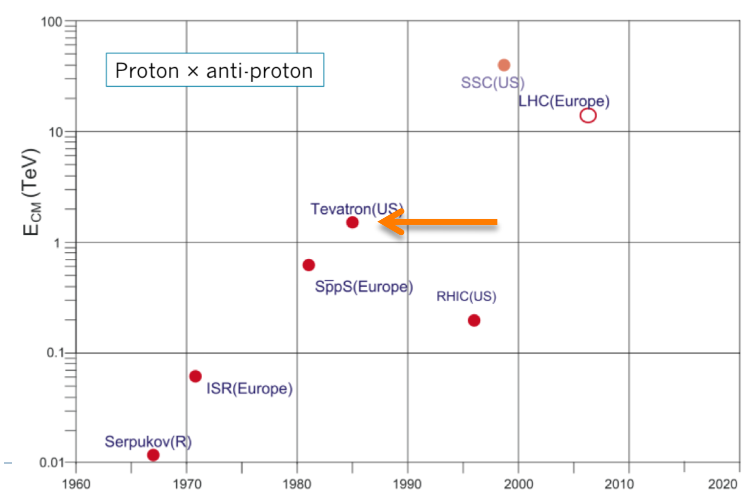
1 Tev proton × 1 TeV anti-proton

6.3km circumference

4.2 T superconducting magnets

1983~2011.9.30

Discovery of top quark in 1995.



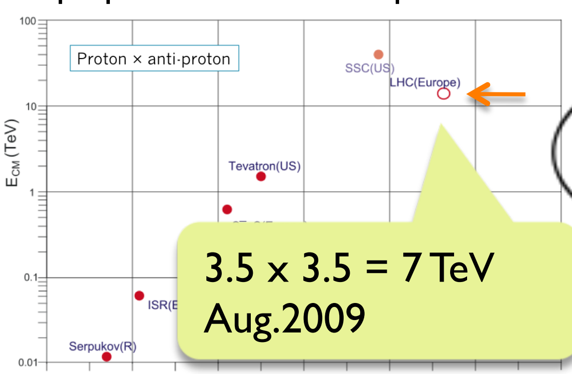
http://www.fnal.gov/pub/tevatron/

Collider: Era of large circular colliders, energy frontier machines

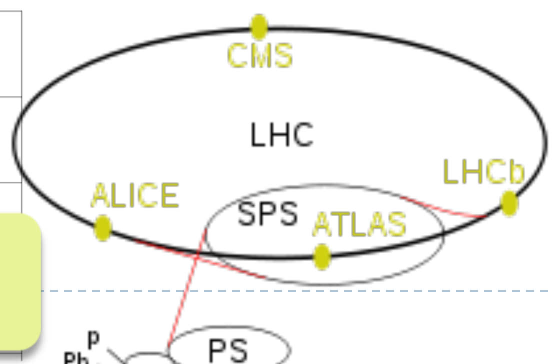
LHC (CERN)

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)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

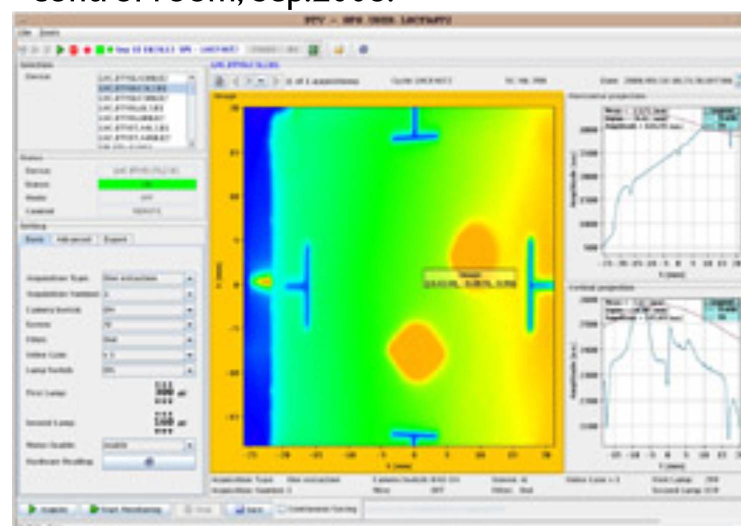
http://public.web.cern.ch/public/en/LHC/LHC-en.html



3.5 x 3.5 = 7 TeV
Aug.2009

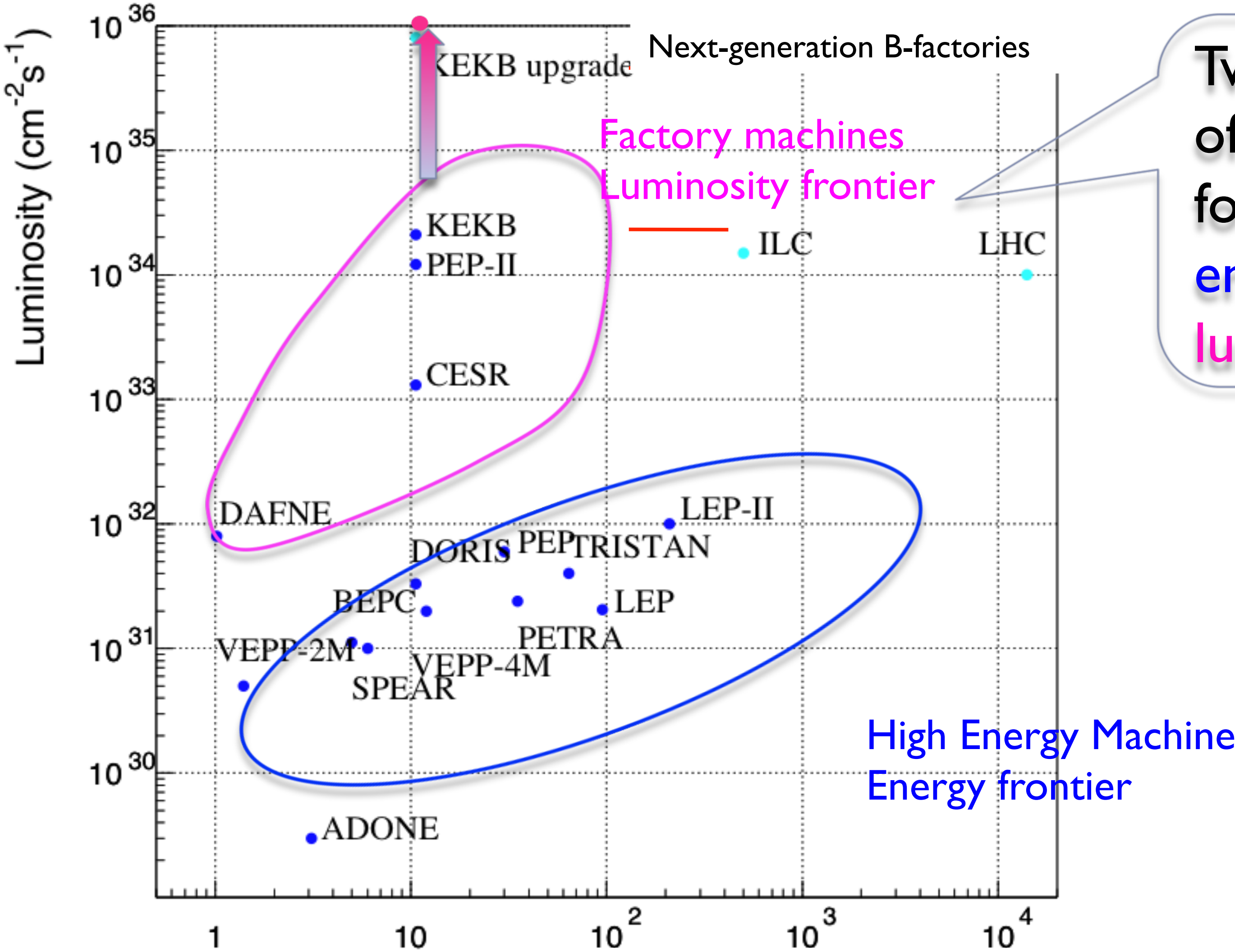


Celebrating the first beam in the ATLAS control room, Sep.2008.



http://legacy.kek.jp/newskek/2009/janfeb/LHC_ATLAS.html

Collider: Era of large circular colliders



Two major goals of accelerators for HEP: energy and luminosity

Mainly e+e- colliders are shown

Storage ring:

A storage ring is a type of synchrotron.

- Conventional synchrotron
  - Accelerates particles from low to high energy.
  - RF cavities are used to accelerate particles.

- Storage ring
  - Keeps particles stored at a constant energy for a long time (storage).
  - RF cavities are only used to replace energy lost through synchrotron radiation and other processes.

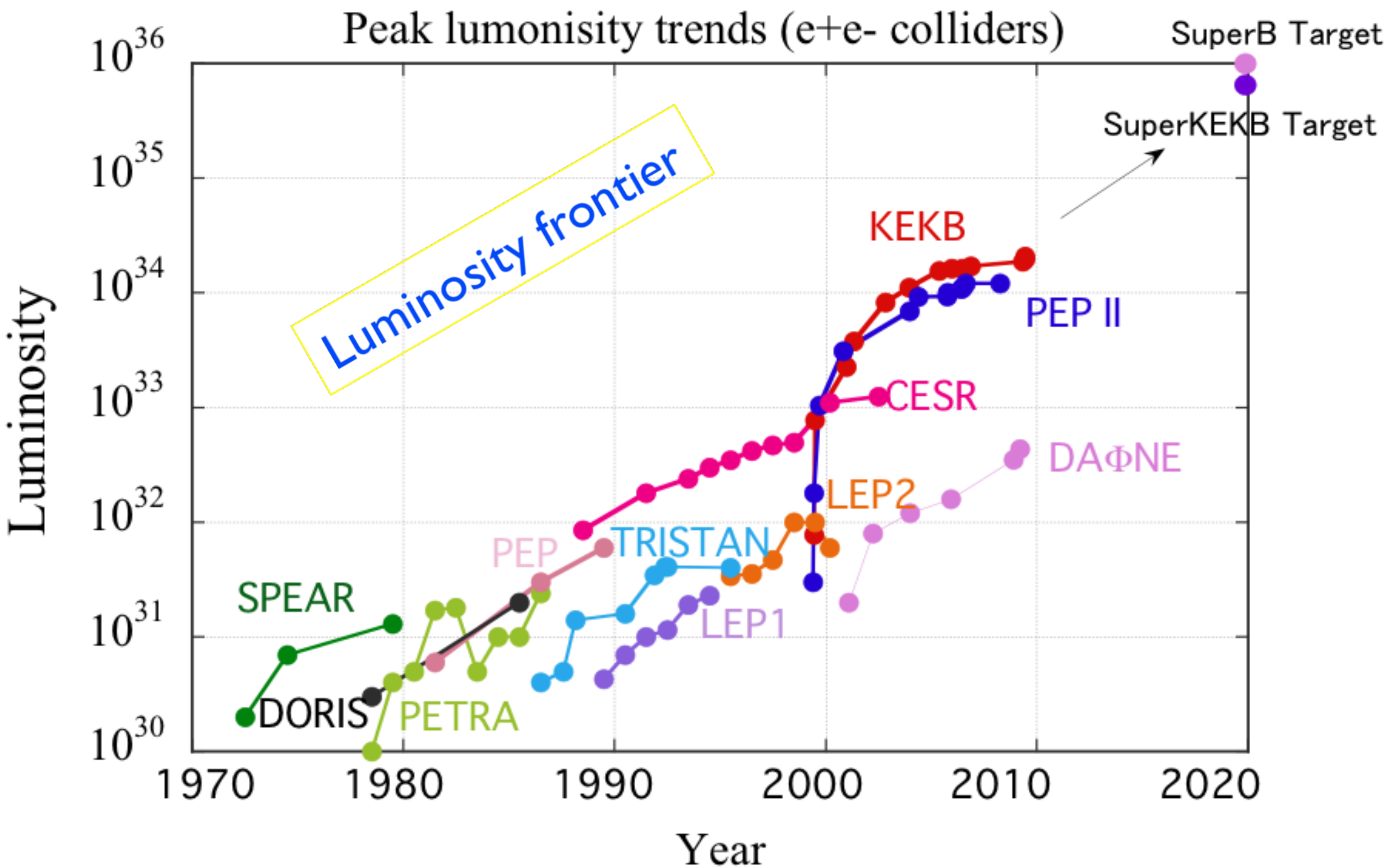
Storage ring:

A storage ring

- Collider for HEP
  - B-factories (PEP-II, KEKB)
  - Tevatron, LHC: energy is ramped up from the injection energy to the target energy at first, but then kept constant for the experiment.

- Synchrotron facilities for applied field
  - Keeps particles stored at a constant energy for a long time (storage).
  - RF cavities are only used to replace energy lost through synchrotron radiation and other processes.

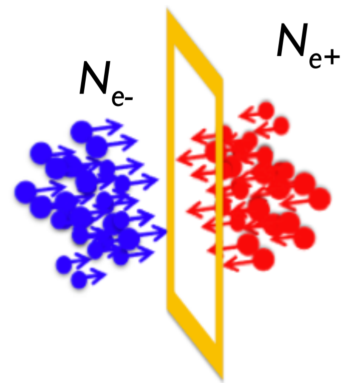
Collider: Era of large circular colliders, luminosity frontier machines



Collider: Luminosity

Fixed target
Beam on solid (usually) target
Collision guaranteed

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



$$Y = L\sigma$$

Event yield — Luminosity — Cross section

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

The number of particles per unit area per unit time

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

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

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

→ Higher luminosity

Collider: realizing small beam for higher luminosity

Beam size
emittance

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$$

For non-dispersive place

Often we write emittance as ε
Some more on emittance for the strong focusing in the next slides.

How can we squeeze down the beam size?

Collider: realizing small beam for higher luminosity

"Weak focus" case

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

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

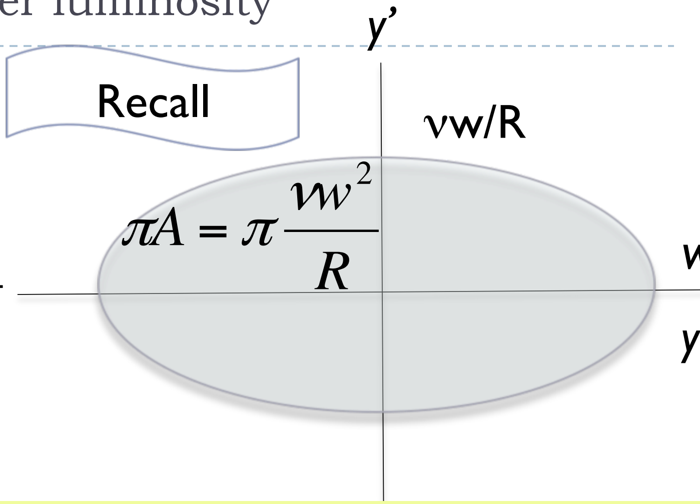
$$y = a_1 \cos(\nu s / R + \phi)$$

Recall

emittance

$$W \equiv a_1^{\,2} \nu / R$$

$$a_1 = \sqrt{WR/\nu} \equiv \sqrt{W \langle \beta \rangle}$$



"Strong focus" (n >> 1) case;

$$\ddot{y} + g(s) y = 0$$

$$y(s) = a w(s) \cos[\varphi(s) + \delta]$$

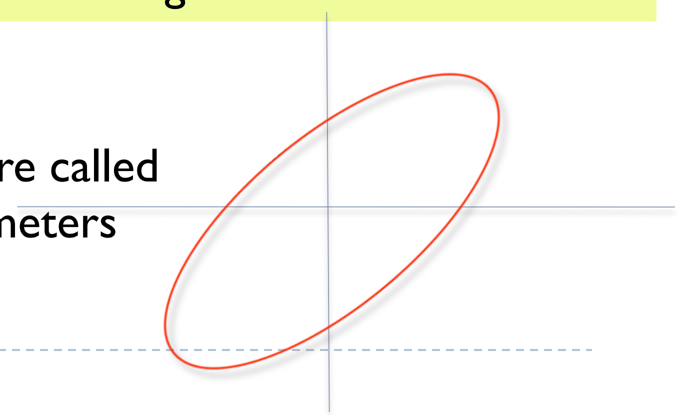
$$\Rightarrow y(s) = a \sqrt{\beta(s)} \cos[\nu \phi(s) + \delta]$$

β-function describes the amplitude of the motion of the particles:

- Constant in "weak focus"
- Function of *s* in "strong focus"

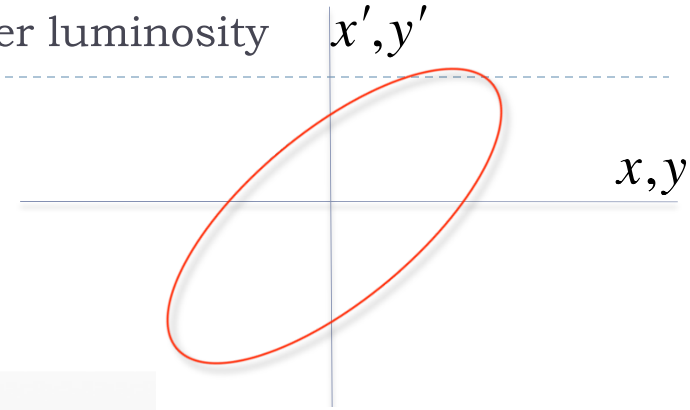
$$W = \gamma y^2 + 2\alpha y y' + \beta y'^2$$

α, β and γ are called Twiss parameters

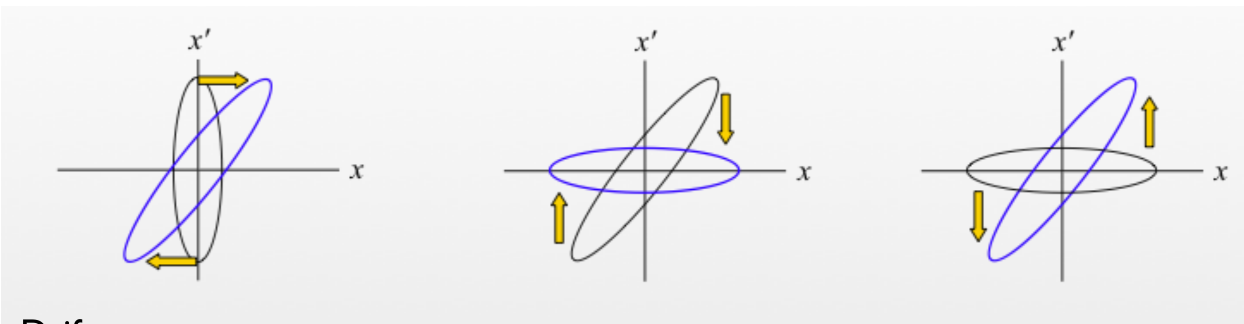


- The area is constant, independent of s also in strong focusing case.

Collider: realizing small beam for higher luminosity



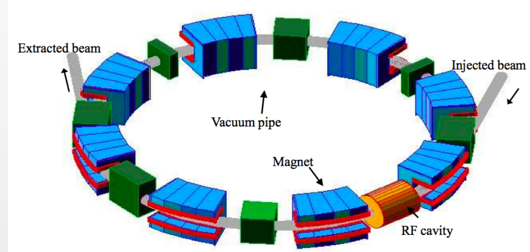
Particles move in an ellipse in phase space.
Ellipse rotates and change in shape in magnets.
The area of the ellipse is often represented as $2\pi J$ and this is conserved.



Drift space (between magnets)

Focusing magnets

Defocusing magnets



From lecture by Y. Ohnishi at OHO 2006

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$$

Keys for small collision spot size:
- Design a machine with small emittance.
- Squeeze the beta-function at the collision point.

I would like to introduce you our project SuperKEKB, as an example of a small beam machine.

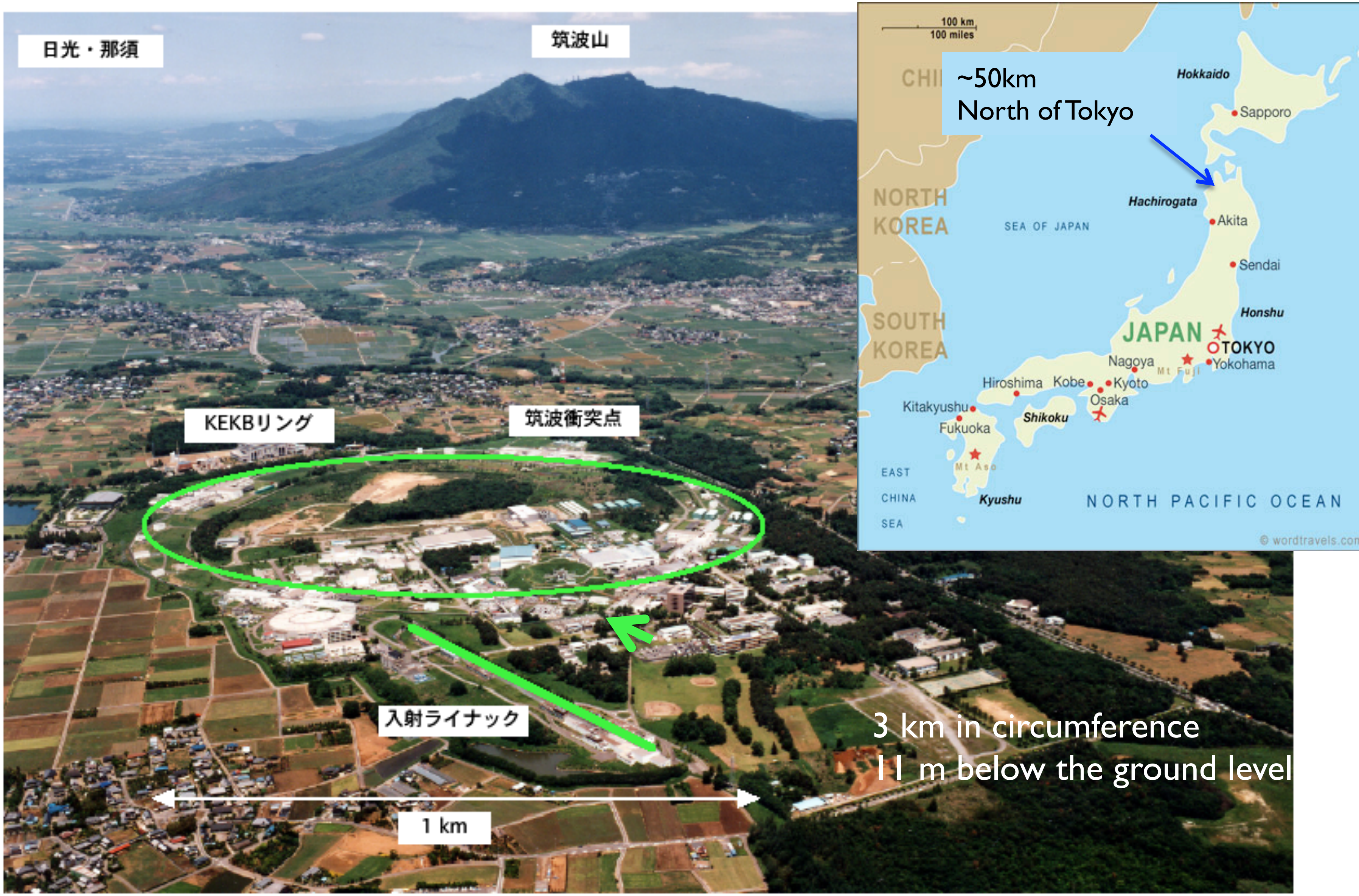
Virtual Tour of KEKB: e+e- double ring collider 1999~2010

SuperB
Italy

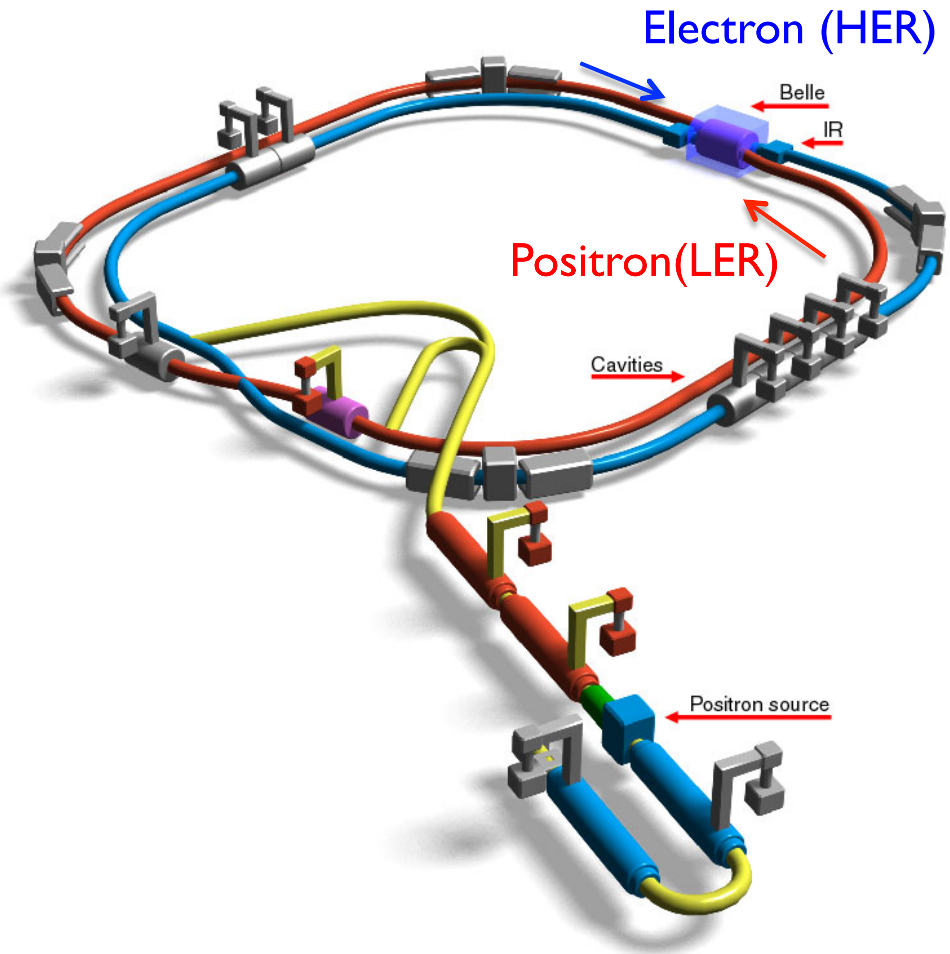
KEKB &
SuperKEKB
Japan

Global efforts for Next Generation B-factories

Virtual Tour of KEKB: e+e- double ring collider 1999~2010



Virtual Tour of KEKB: e+e- double ring collider 1999~2010



•3.5 GeV positron (LER) × 8 GeV electron (HER) to produce many B-mesons at 10.58 GeV.

➔That is why it is called "B-factory"

•Energy is fixed by physics goals.

•Look for very rare events.

➔This is why we need to have high rate collision (high luminosity)

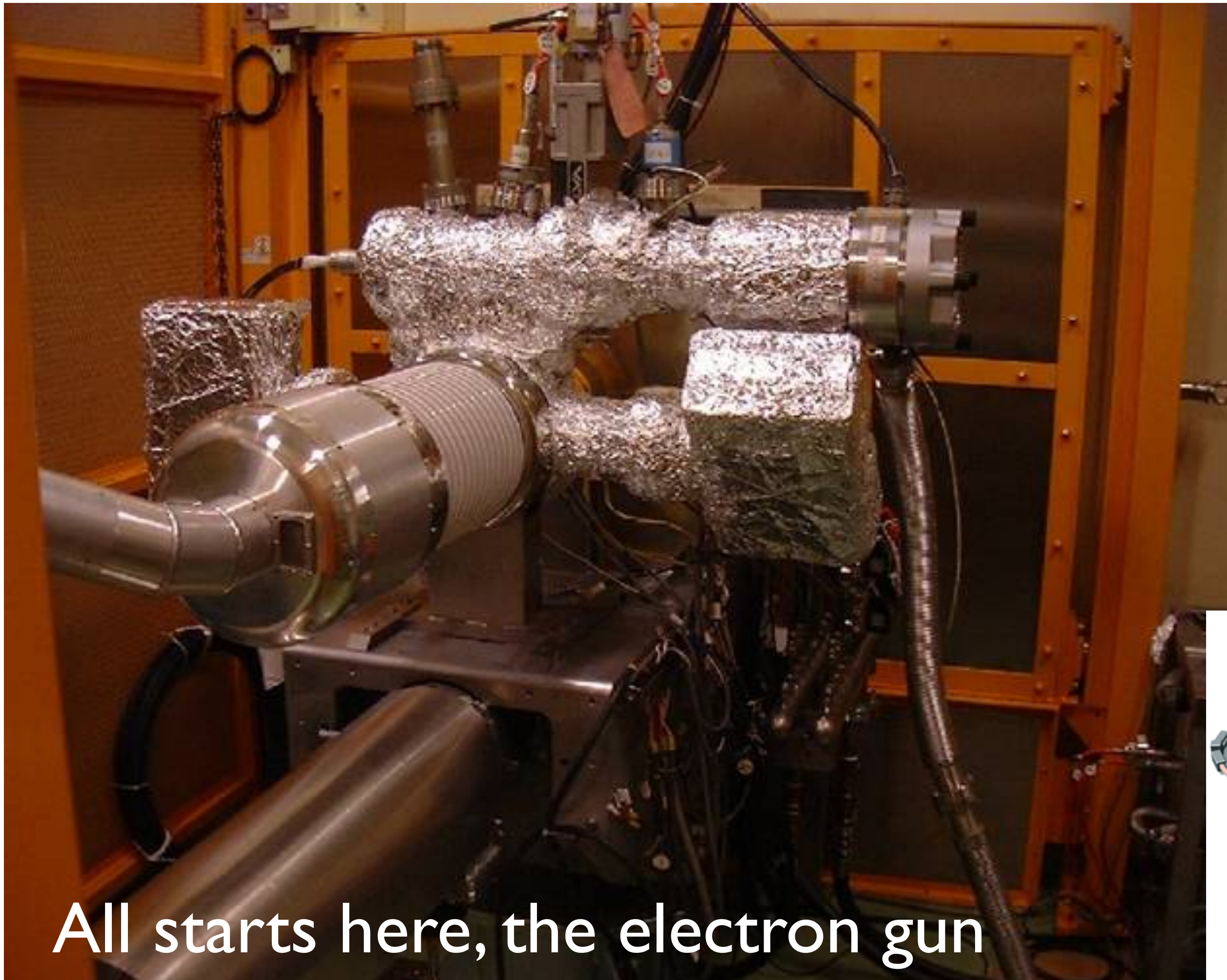
•Double ring, because the beam energy is asymmetric.

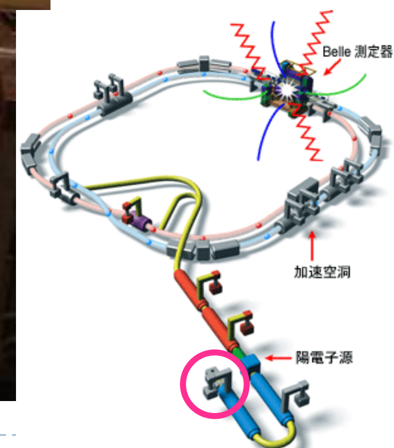
•3 km circumference, reuse of the previous machine called TRISTAN.

•Collide at one Interaction Point (IP).

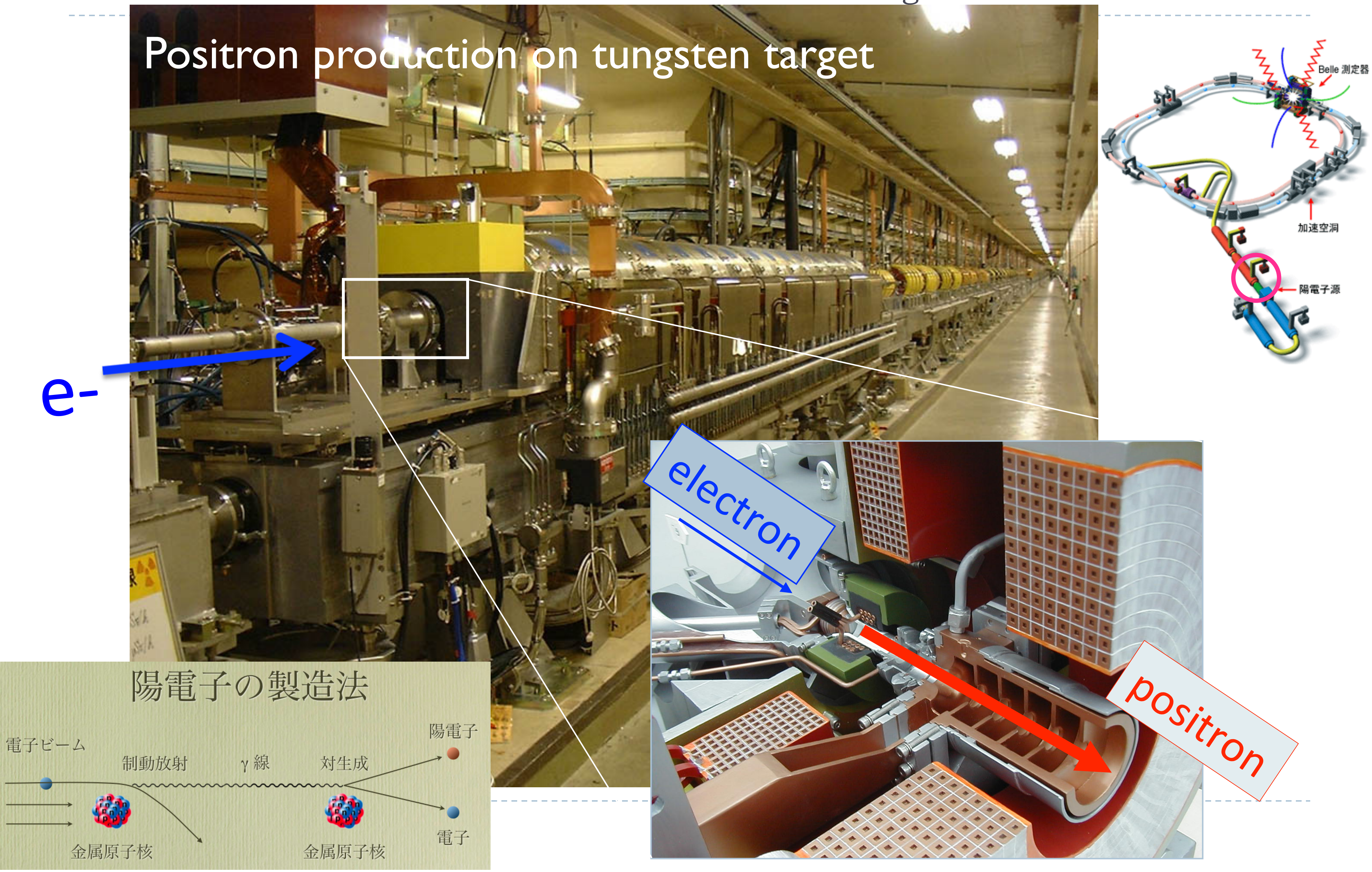
•Belle detector collects data at the IP.

Virtual Tour of KEKB: e+e- double ring collider 1999~2010

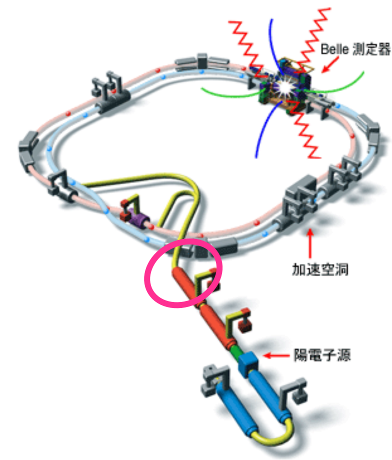




Virtual Tour of KEKB: e+e- double ring collider 1999~2010

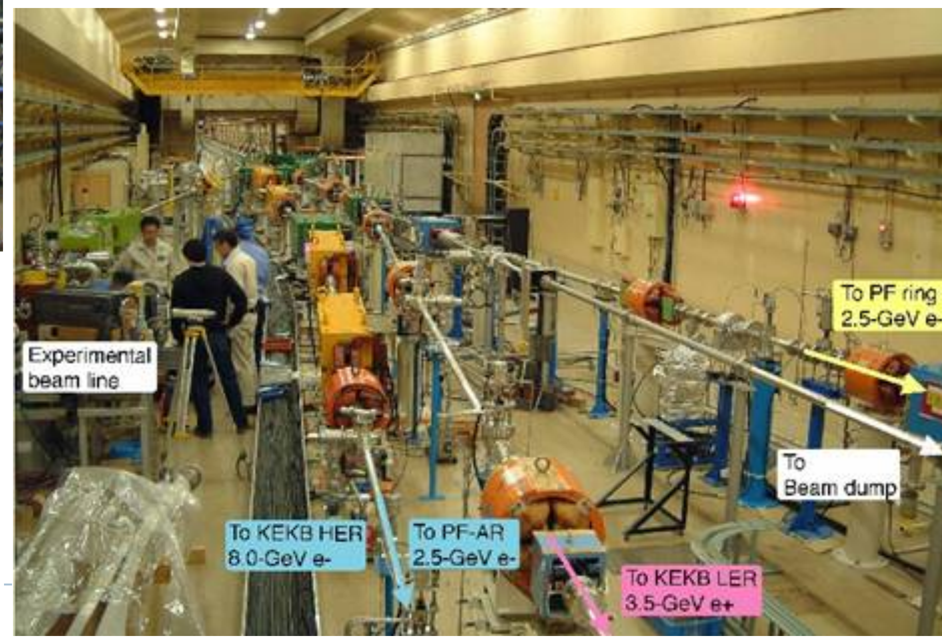


Virtual Tour of KEKB: e+e- double ring collider 1999~2010

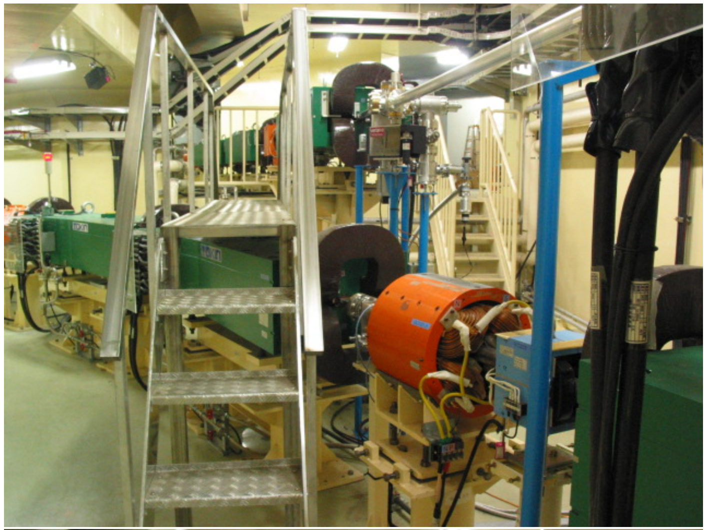


500 m linear accelerating section (LINAC).
Bicycle is handy.

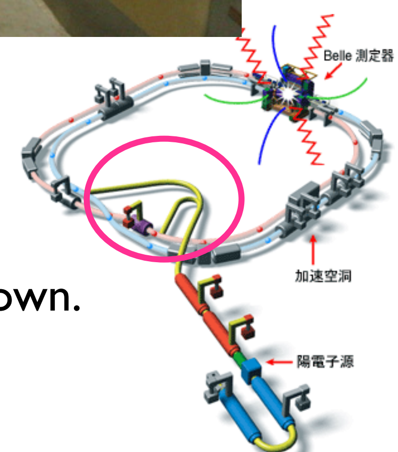
Electrons and positrons are accelerated to the target energy and transferred to many beam lines.



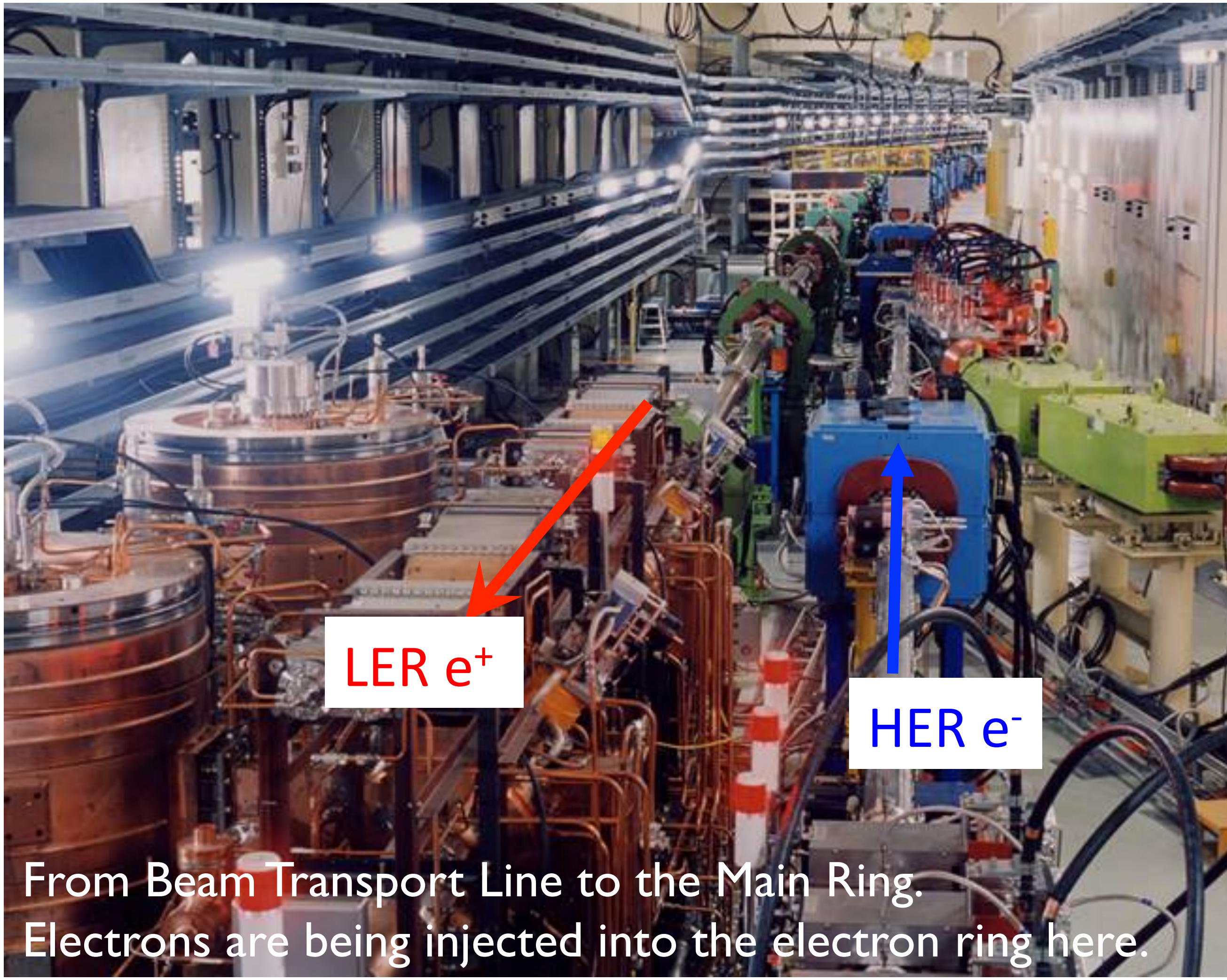
Virtual Tour of KEKB: e+e- double ring collider 1999~2010

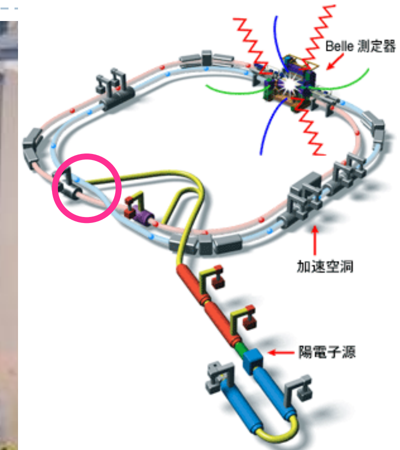


Beam Transport Line
From the LINAC to Main Ring,
From 5 m below G.L. to
11m G.L., going down, down, down.

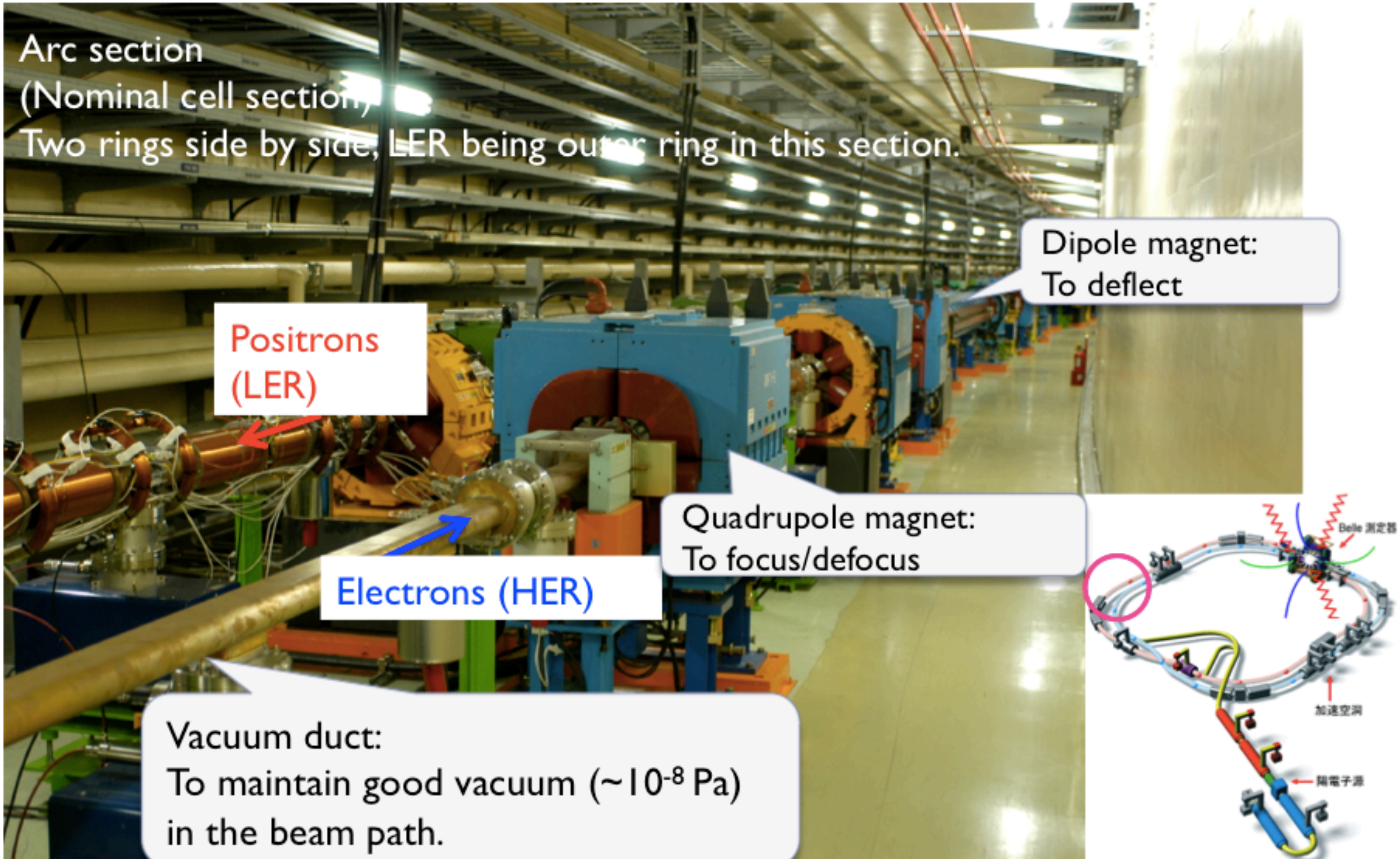


Virtual Tour of KEKB: e+e- double ring collider 1999~2010



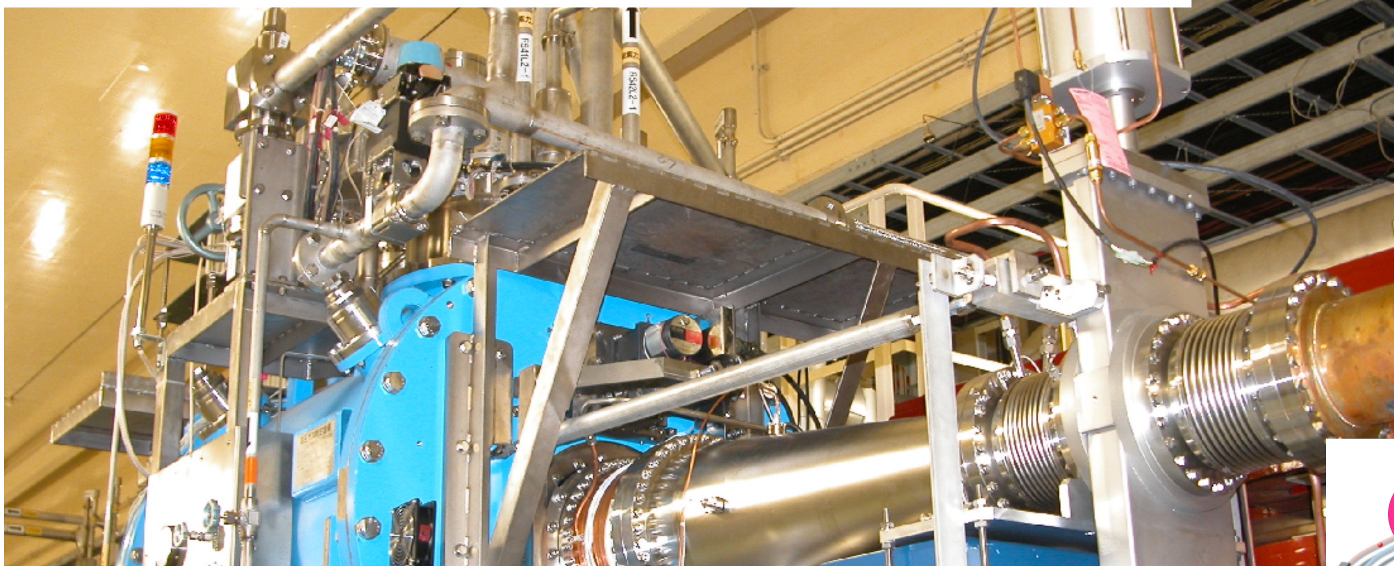


Virtual Tour of KEKB: e+e- double ring collider 1999~2010

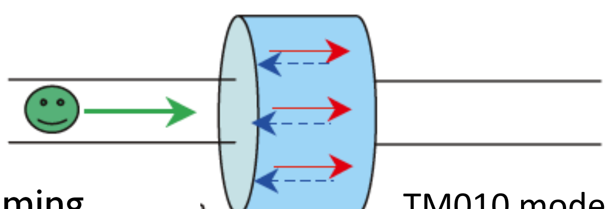


Virtual Tour of KEKB: e+e- double ring collider 1999~2010

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

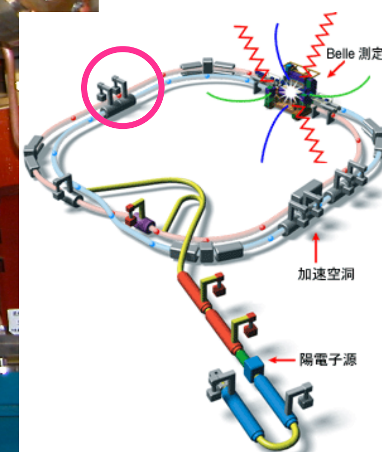


Electric field in the cavity

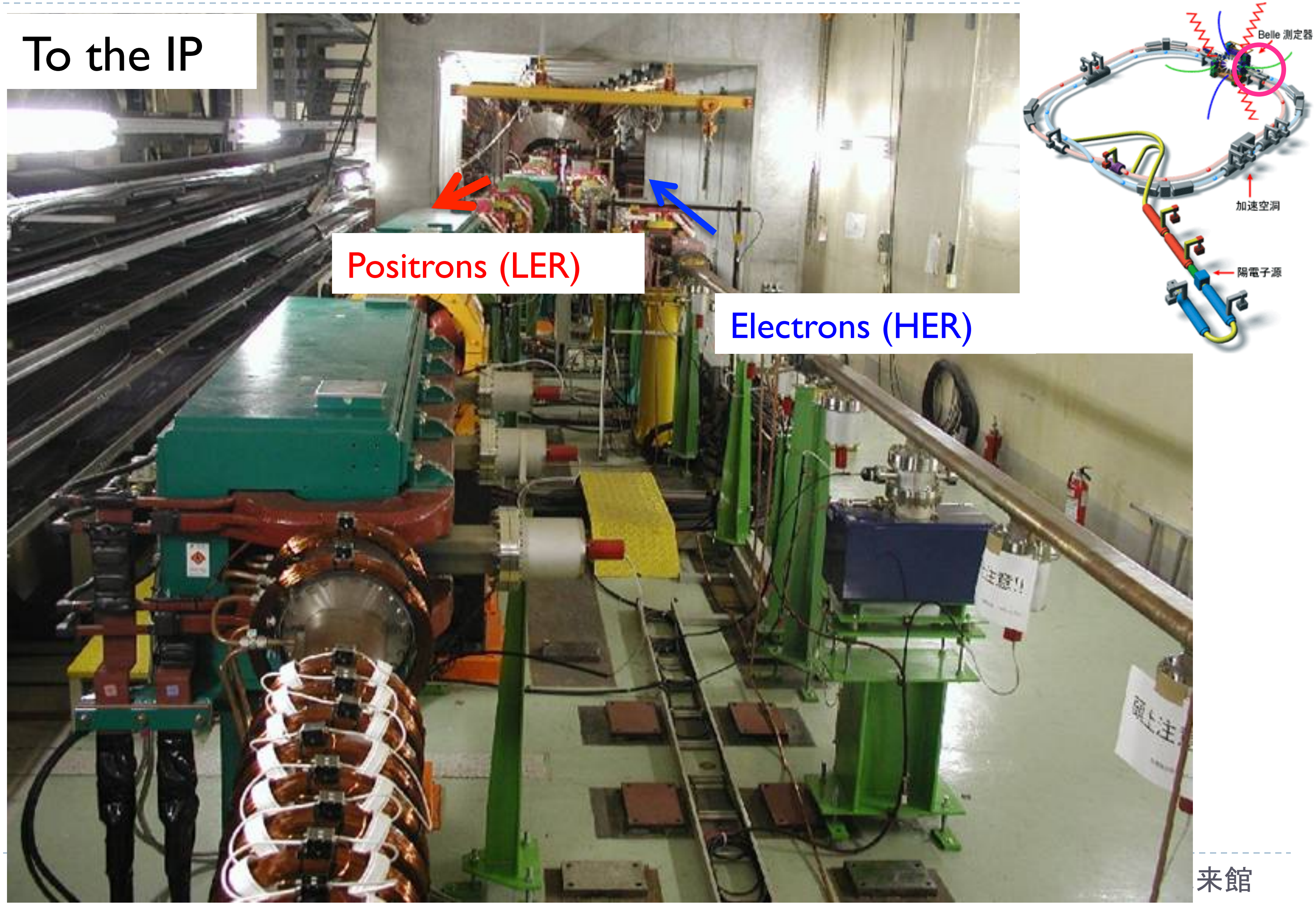


Timing important

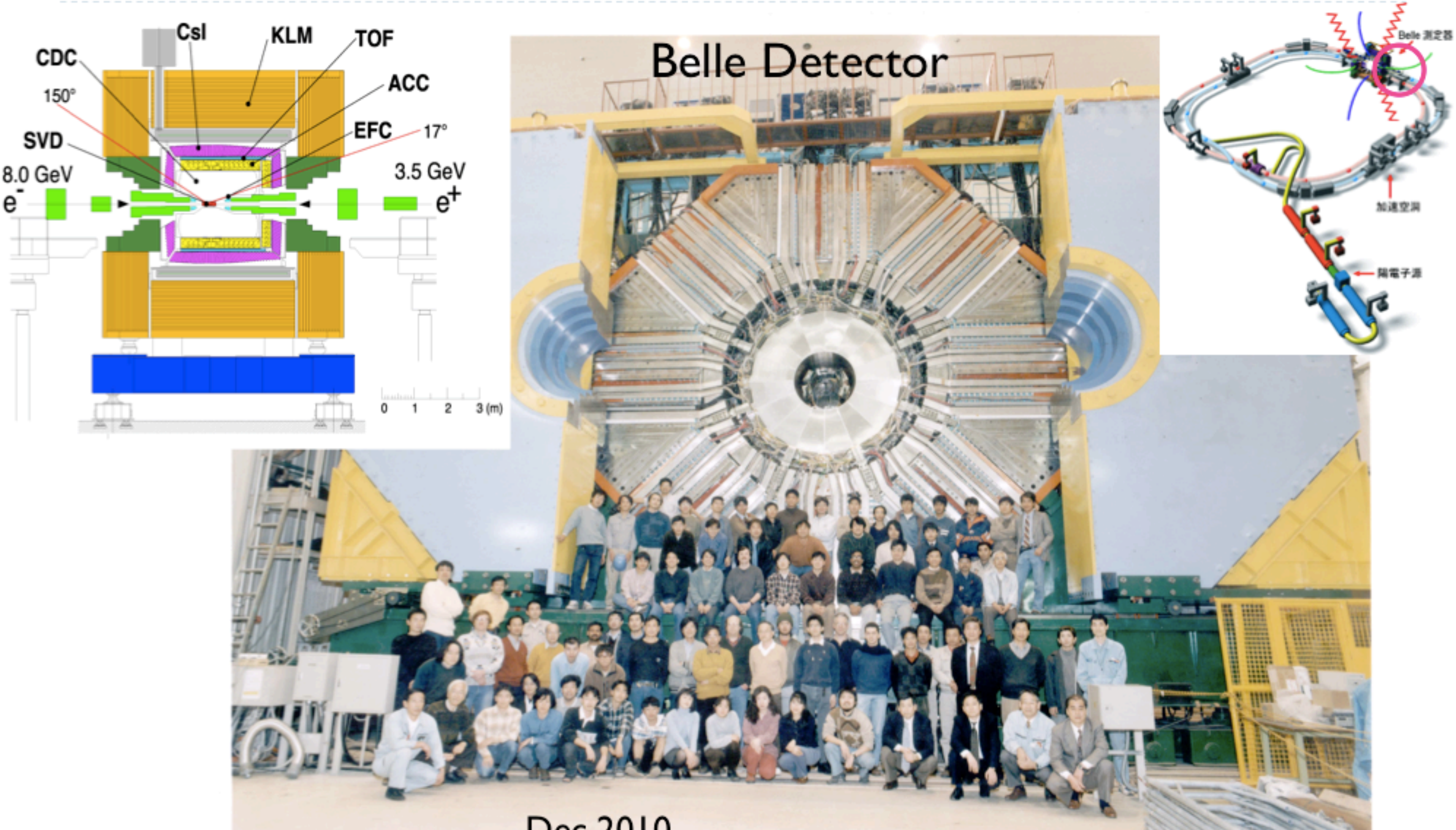
TM010 mode



Virtual Tour of KEKB: e+e- double ring collider 1999~2010

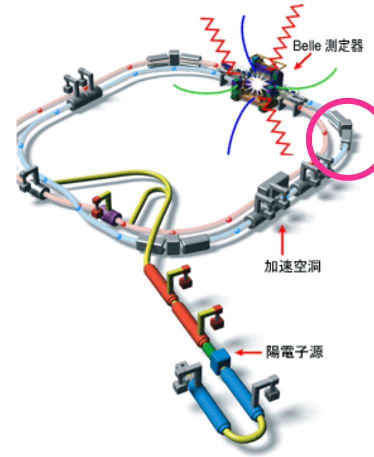


Virtual Tour of KEKB: e+e- double ring collider 1999~2010



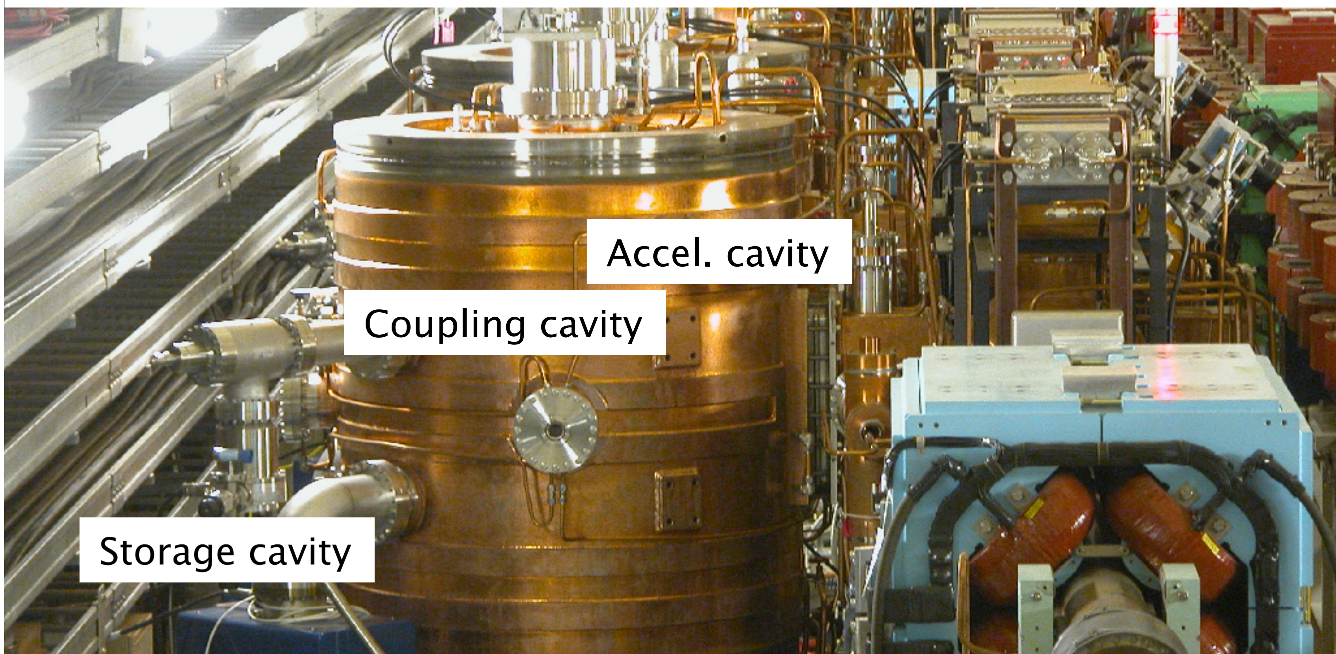
Virtual Tour of KEKB: e+e- double ring collider 1999~2010

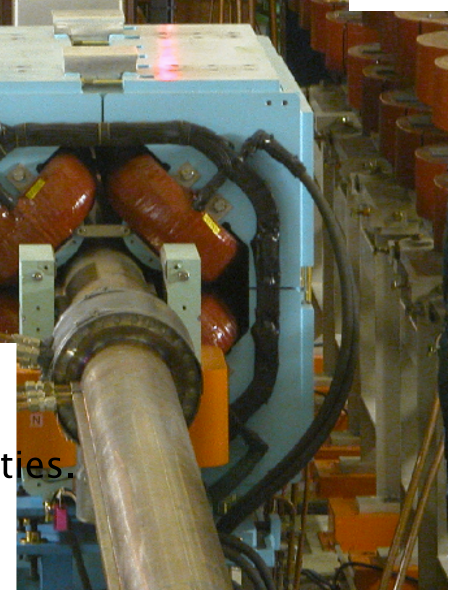
Arc section
(Nominal cell section)
Two rings side by side, LER being inner ring in this section.



Virtual Tour of KEKB: e+e- double ring collider 1999~2010

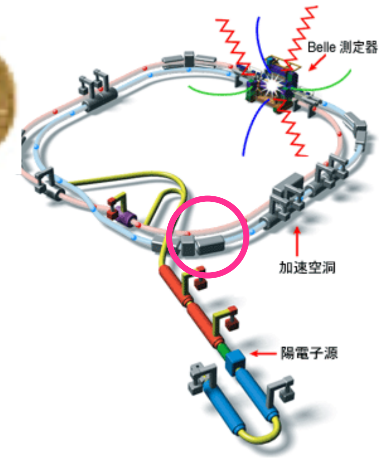
ARES (The Accelerator Resonantly coupled with an Energy Storage)
Normal conducting Cavity





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 arise from the cavities.

Virtual Tour of KEKB: e+e- double ring collider 1999~2010



http://legacy.kek.jp/nobel/photos/photosample/nobel1022.jpg

Virtual Tour of KEKB: e+e- double ring collider 1999~2010

KEKB control room.
We did not usually have this many people there.

Challenges: SuperKEKB as an example

Need for even higher luminosity machine
Q: How many years would we need to accumulate 50 ab^{-1}
(the target given by the physics community)
IF we kept running the present KEKB?

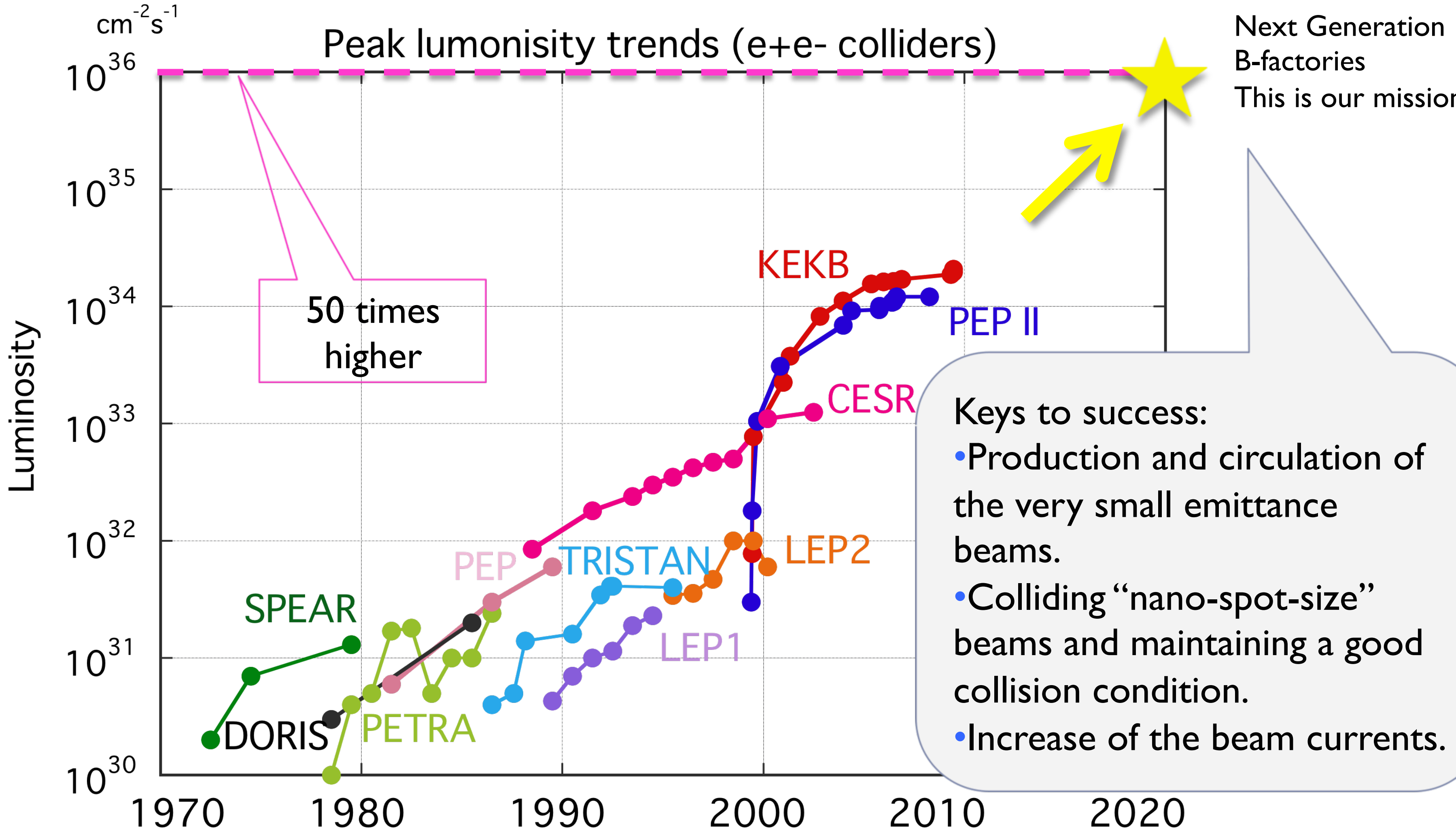
A: With the current peak luminosity of $2x10^{34}$ $cm^{-2}s^{-1}$
$\Rightarrow$0.3 ab^{-1}/year (assuming 1.5×10^{7} seconds/year running)
$\Rightarrow$167 years.

I will introduce this one today.

Need for much higher luminosity machines:
Next Generation B-factories

Two projects are being pursued: **SuperB and SuperKEKB**

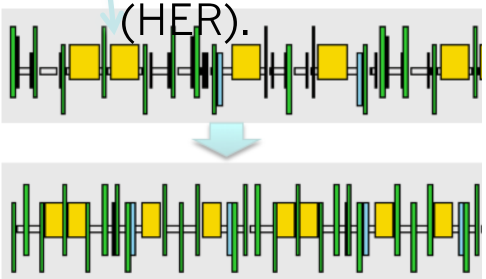
Challenges: SuperKEKB as an example



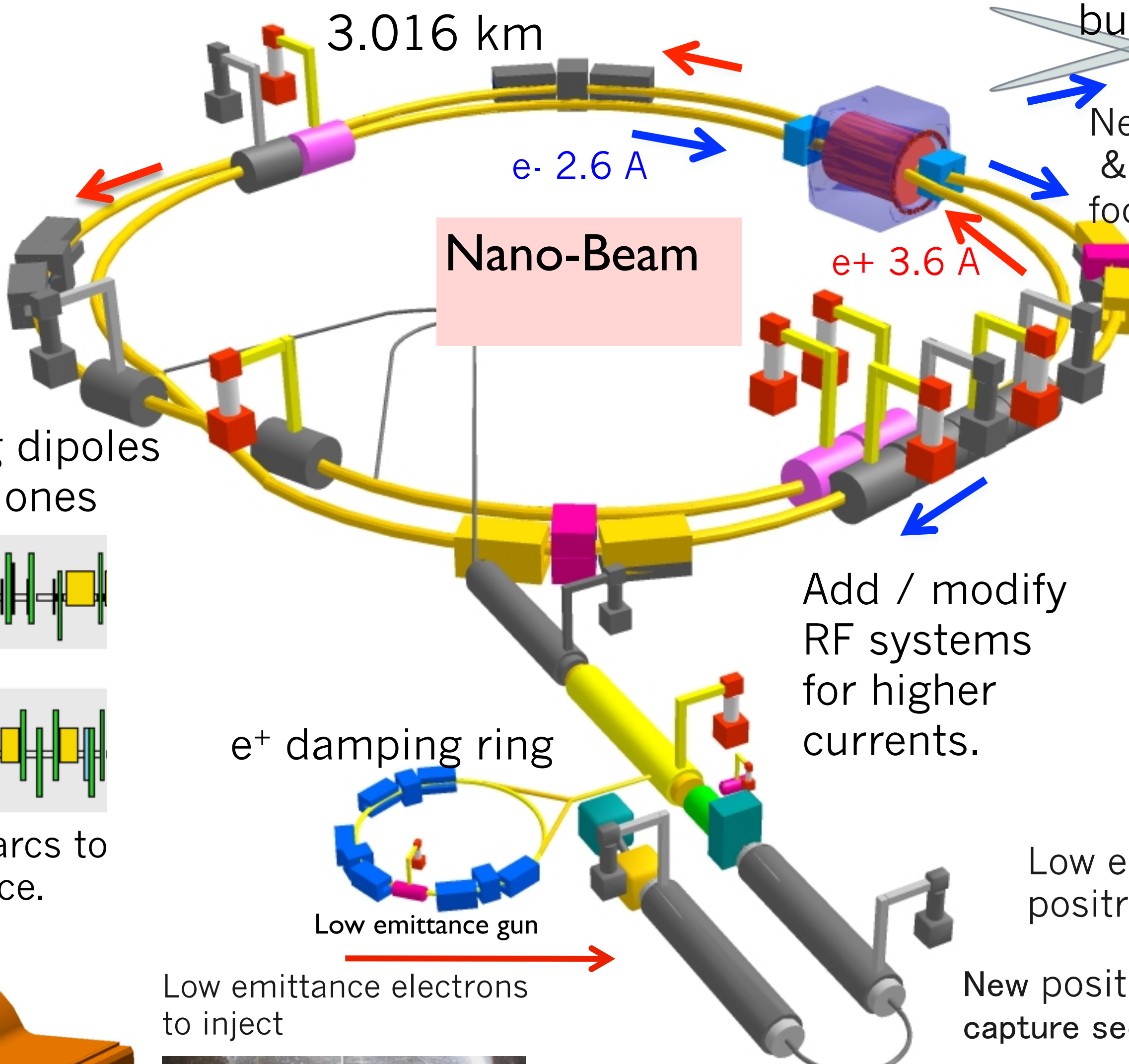
Keys to success:

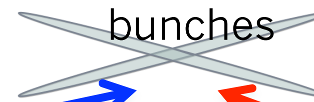
- Production and circulation of the very small emittance beams.
- Colliding "nano-spot-size" beams and maintaining a good collision condition.
- Increase of the beam currents.

Replace long dipoles with shorter ones (HER).

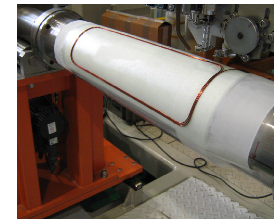


Redesign the HER arcs to reduce the emittance.





New IR with S.C. & P.M. final focusing quads

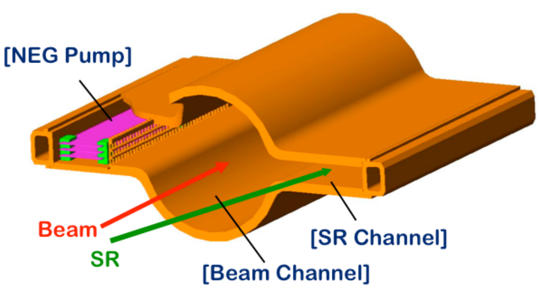


Add / modify RF systems for higher currents.

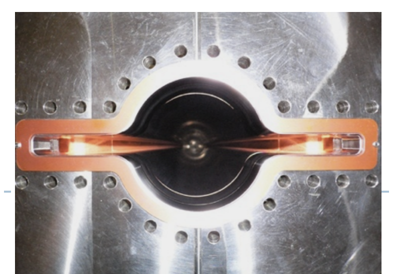
Low emittance positrons to inject

New positron target / capture section

Low emittance electrons to inject



TiN coated beam pipe with antechambers



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

~40 times gain in luminosity

Hardware challenges
Vacuum components as examples.

Challenges: SuperKEKB as an example

Higher beam currents
(a factor of 2 larger than KEKB)

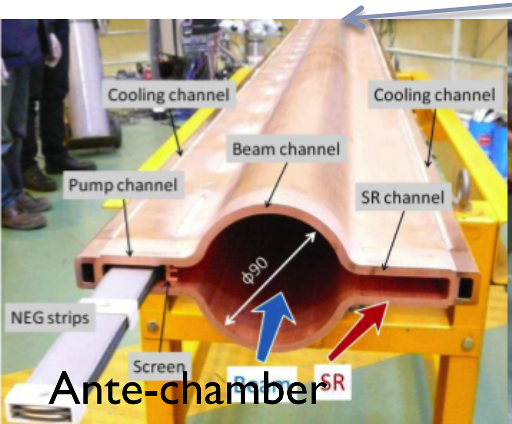
Higher bunch current
Short bunch length
(though the same as KEKB)

Synchrotron radiation power
Higher photon density
Higher heat & gas load

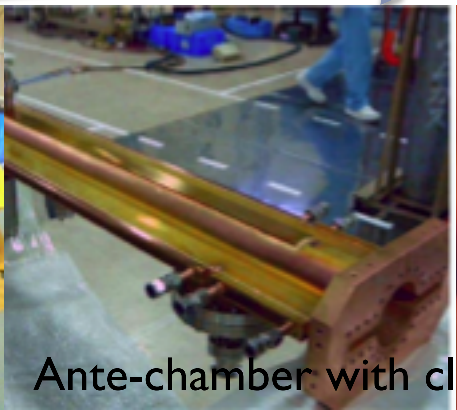
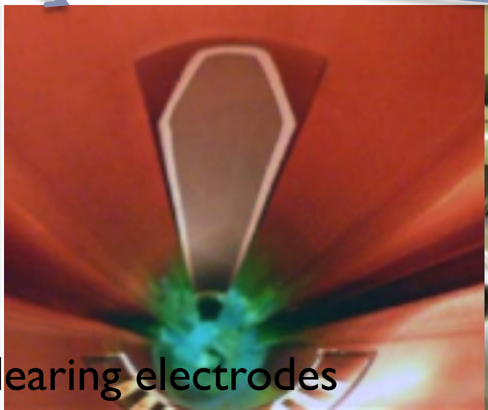
Higher Oder Mode
(HOM) heating

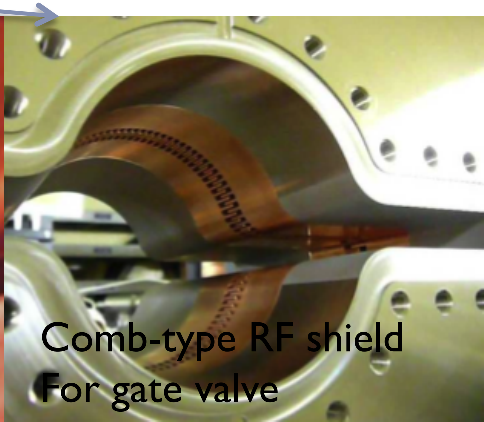
Electron cloud instability, heating of components, etc.

Damaged RF finger

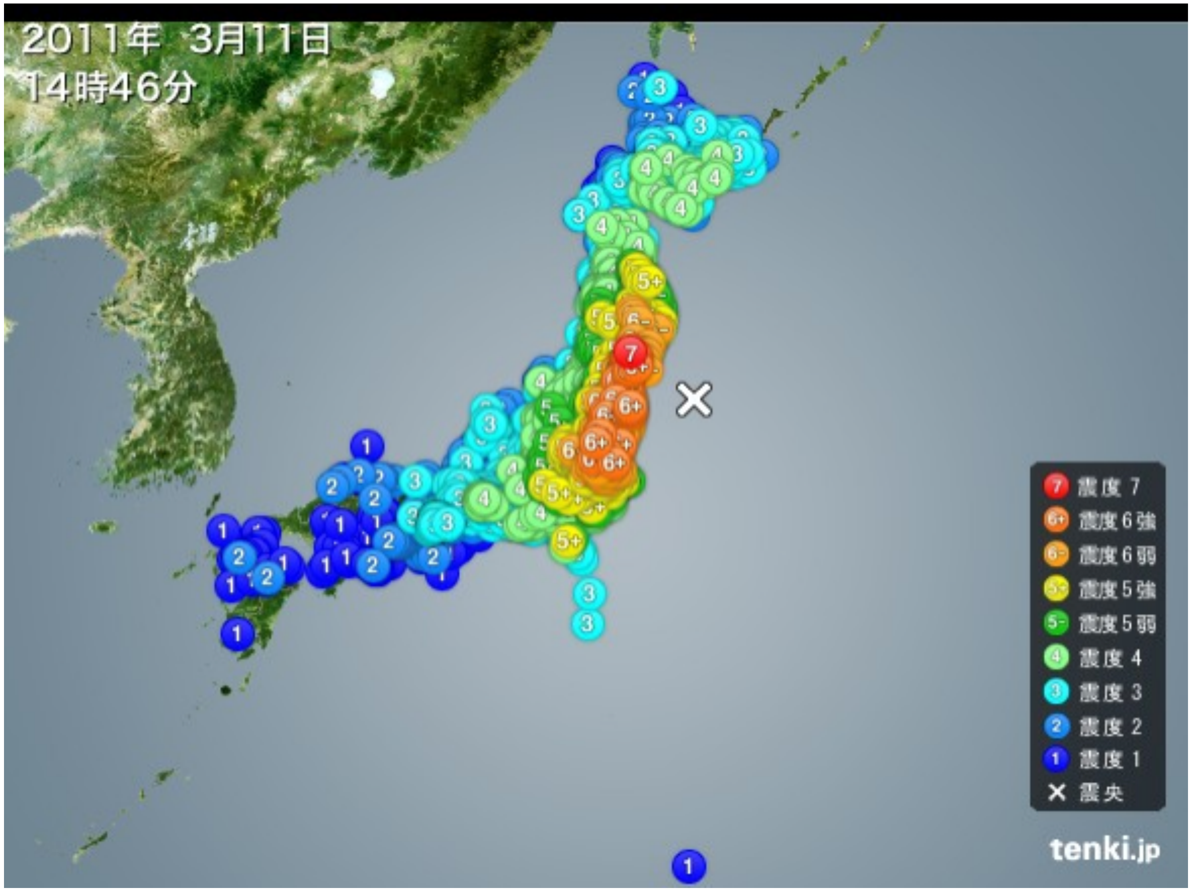


Ante-chamber



Ante-chamber with clearing electrodes

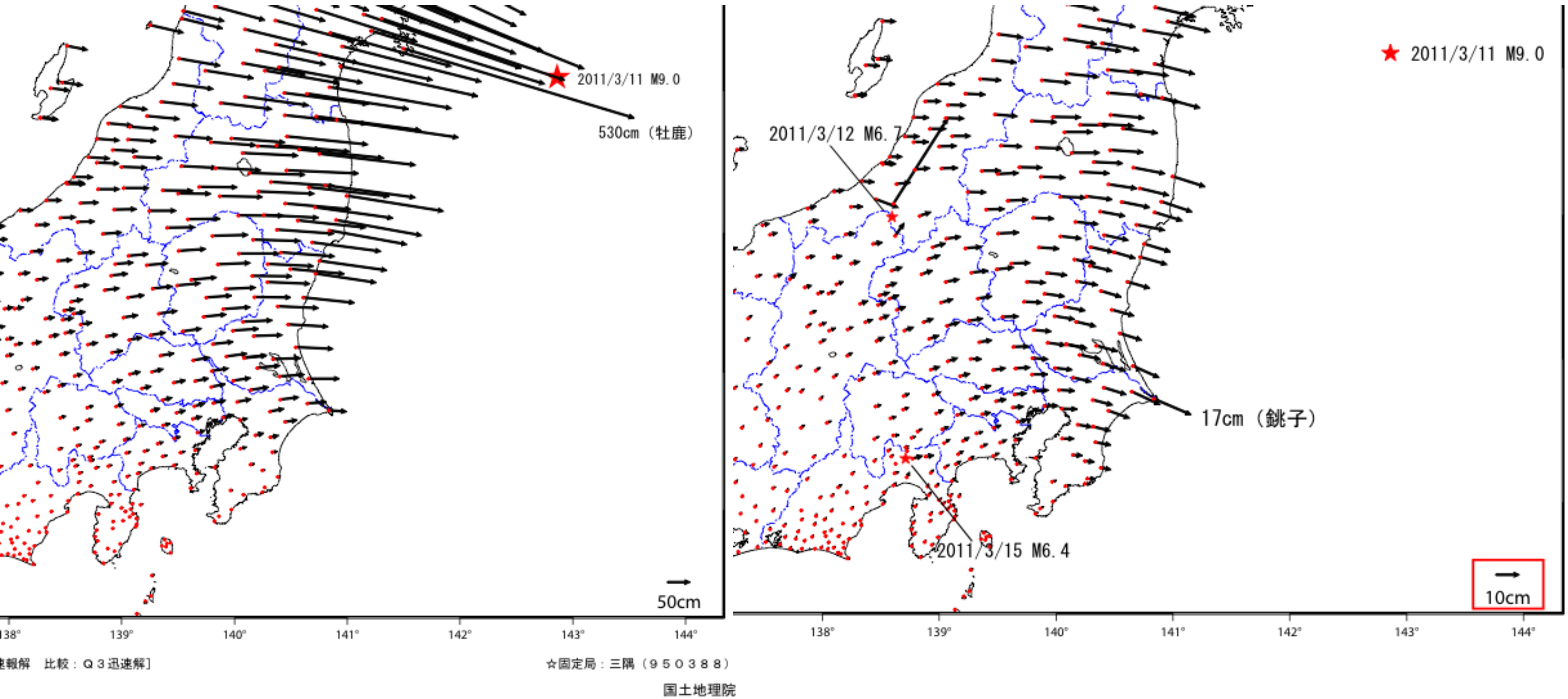

Comb-type RF shield
For gate valve

Challenges: Recovery from the earthquake



Magnitude 9.0

Challenges: Recovery from the earthquake

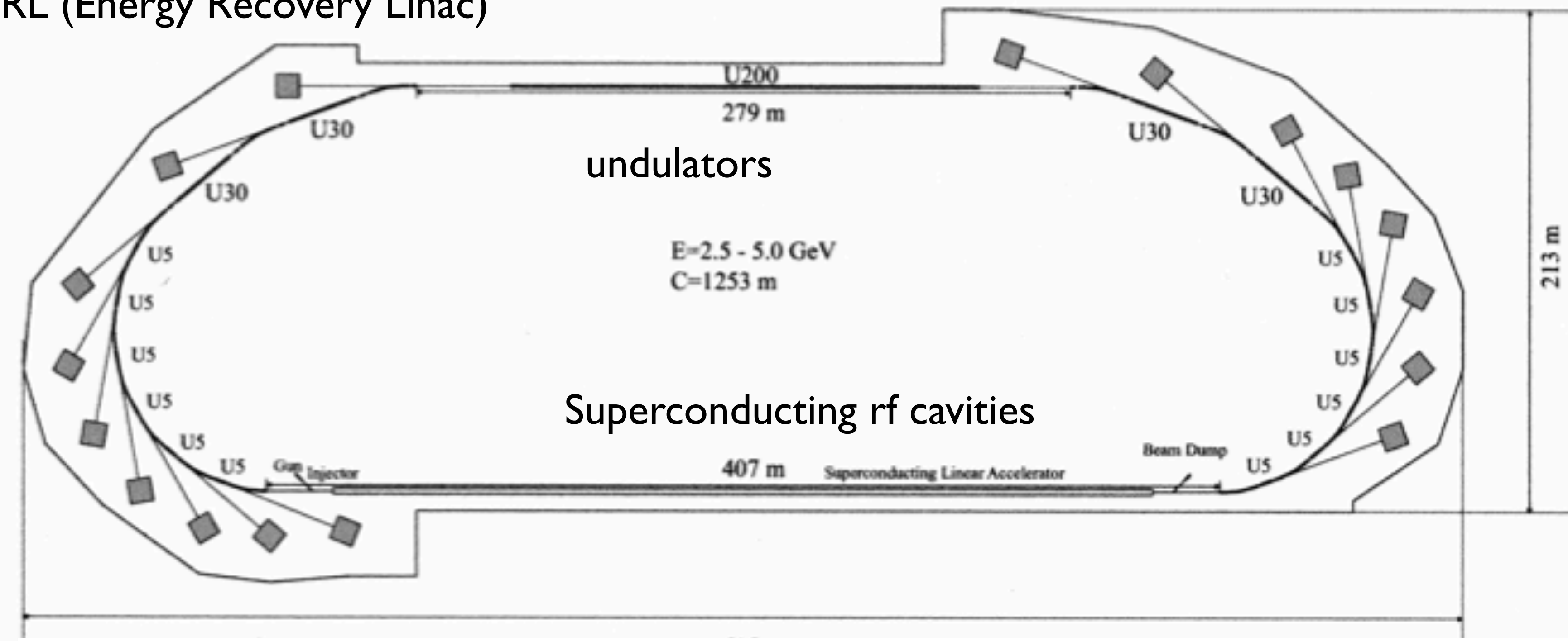


Challenges: Future Accelerators

- ERL: Energy Recovery Linac
- LC : Linear Collider
- μ - μ Collider and/or μ - Factory
- Laser-plasma acceleration

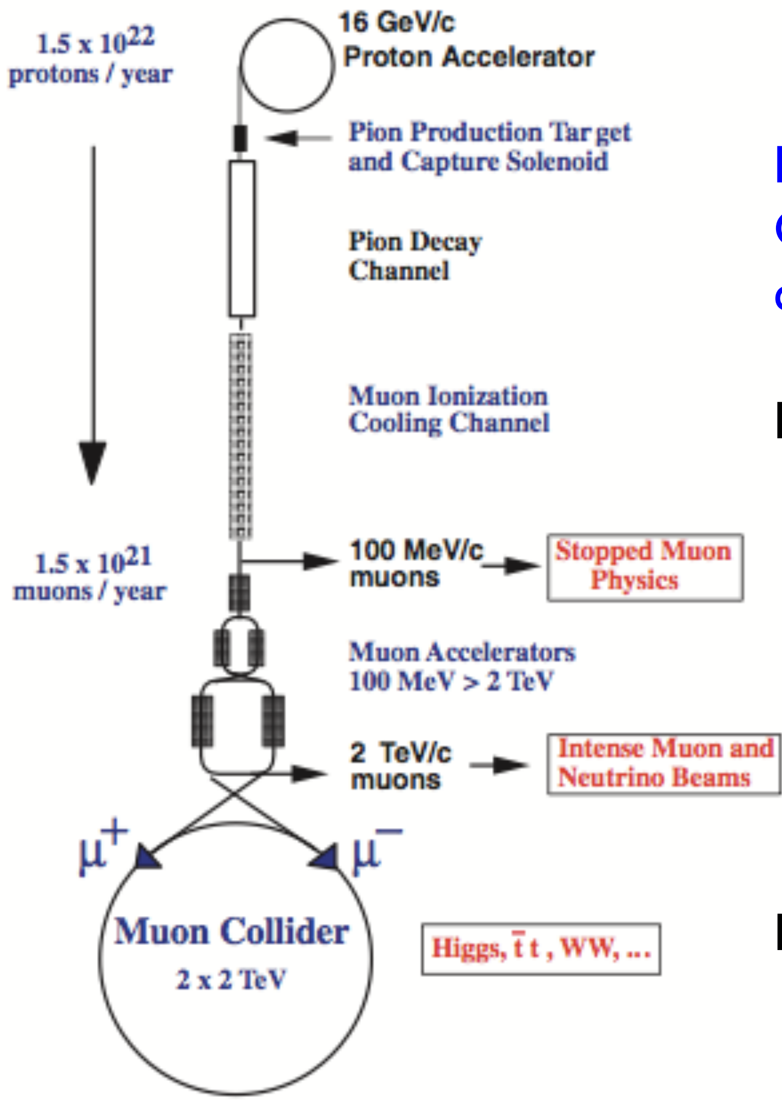
Challenges: Future Accelerators

ERL (Energy Recovery Linac)



While an electron storage ring stores the same electrons for hours in an equilibrium state, an ERL stores the energy of the electrons.
Basic idea: Bring the beam through the accelerating structures timed in a way so that the second-pass beam is decelerated, i.e. delivering its energy to the cavity fields.
Required RF power becomes nearly independent of beam current.

Challenges: Future Accelerators



μ - μ Collider and/or μ -Factory

Muon is heavier than electrons
Can accelerate to higher energy with a circular machine than electrons.

How to make a strong muon beam?

- Muon life time is only 2.2 μs.
- We need to accelerate them quickly.
- Use pion decay to generate muons.
  - But such muons have wide energy spread…
  - Stochastic cooling is needed.

Neutrino factory?

Challenges: Future Accelerators

Final thoughts

The development of accelerators has required developments in many technical fields, such as rf technologies, vacuum technologies, monitoring technologies, surface treatments, beam stabilization, and magnetic field shaping.

Accelerators for high energy physics continue to push new limits.

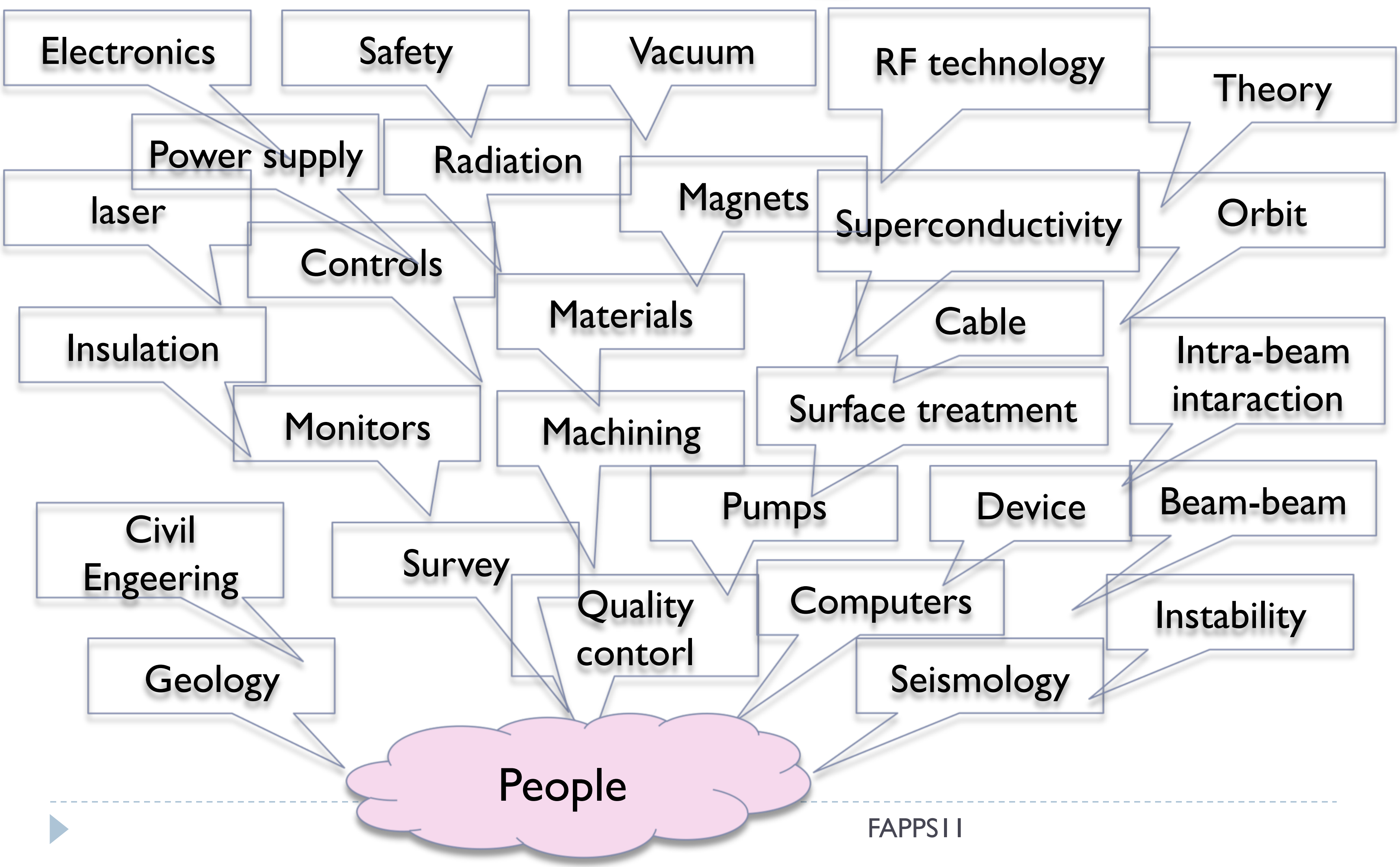
Accelerators for other uses have also become a very active field, with different metrics for performance than luminosity and energy:

- Synchrotron light sources for biological and materials sciences
- Medical applications
- Heavy ion machines…

The field of accelerator science is still expanding and diversifying.

Final thoughts

New ideas



Thank you
Merci
謝々
고마웠습니다

Spare

Synchrotron radiation:

$$\Delta E' = \gamma \Delta E$$

$$\Delta t' = \gamma \Delta t$$

$$\therefore P' \equiv \frac{\Delta E'}{\Delta t'} = \frac{\gamma \Delta E}{\gamma \Delta t} = P$$

$$(d\vec{p})^2 \rightarrow (d\vec{p})^2 - \frac{(dE)^2}{c^2}$$

$$d\tau = dt / \gamma = \frac{mc^2}{E} dt$$

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