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Electron Linac

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Linac = <u>Lin</u>ear <u>Ac</u>celerator

Outline – Electron Linac –

- Introduction

  Roles, Types, Beams, Length…of linacs are described so that you could get some image of linear accelerators.

- Principles of Particle Acceleration in RF Linacs

  Basic knowledge of electromagnetism, mechanics, special relativity is assumed.

  Problems concerning principles of acceleration are categorized into three items through

  "intuitive explanation"

  two of which are clarified by

  "rigorous treatment"

- Electron Linear Accelerator

  Remained problems concerning

  "bunching mechanism"

  "transverse motion"

  are discussed in detail.

  KEK electron / positron linac is introduced as an example.

- (Advanced Concepts)
- Conclusion

Introduction

•Roles of Electron Linacs

1. Injection into circular accelerators
   for various applications
   SPring8, PF(SR) KEKB, PEPII(high energy physics)...

2. Low-emittance linac for advanced light source
   FEL, ERL(Energy Recovery Linac)...

3. Linear collider for future high energy physics

4. Medical applications (the most familiar?)

key issue :
"accelerate charged particles efficiently"

Introduction (cont'd)

• Two Basic Elements of Linacs (G. A. Loew)

1. Accelerating Structure
2. Particle Beam

1. Accelerating Structure – It depends on types of linacs.

DC linacs
- DC electric field to accelerate beams
- Limited to a few tens of MeV

Induction linacs
- Based on Faraday's law
  Changing magnetic fluxes to generate the accelerating electric fields
- Used in medium-energy high-current pulsed applications

Introduction (cont'd)

1. Accelerating Structure (cont'd)

RF linacs : Main subject in this lecture

- Frequency
  UHF, Microwave (L, S, C, X-band), Laser...
- CW or Pulsed
- Traveling-wave or Standing-wave
- Room Temperature or Superconducting
- Utilize Cavity (Resonance) Structure
- Used for a wide spectrum of applications
  from injectors to high-energy accelerators,
  medical accelerators...

Introduction (cont'd)

2. Particle Beam

Protons and Heavier Particles :

- Main particles in early developments of RF linacs
  - High-frequency efficient RF devices did not exist.
  - Imagine a maximum frequency of 1 MHz.
    - Relativistic particles travel 300 m in a single period!! –> Too large apparatus.
- Nowadays: RF frequency >= 200 MHz

Electrons and Positrons : Main subject in this lecture

- Technological innovation during the war :
  - Invention of high power klystrons made it possible that electrons can be accelerated in realistic sizes. (e.g. 2856 MHz high-power klystrons)

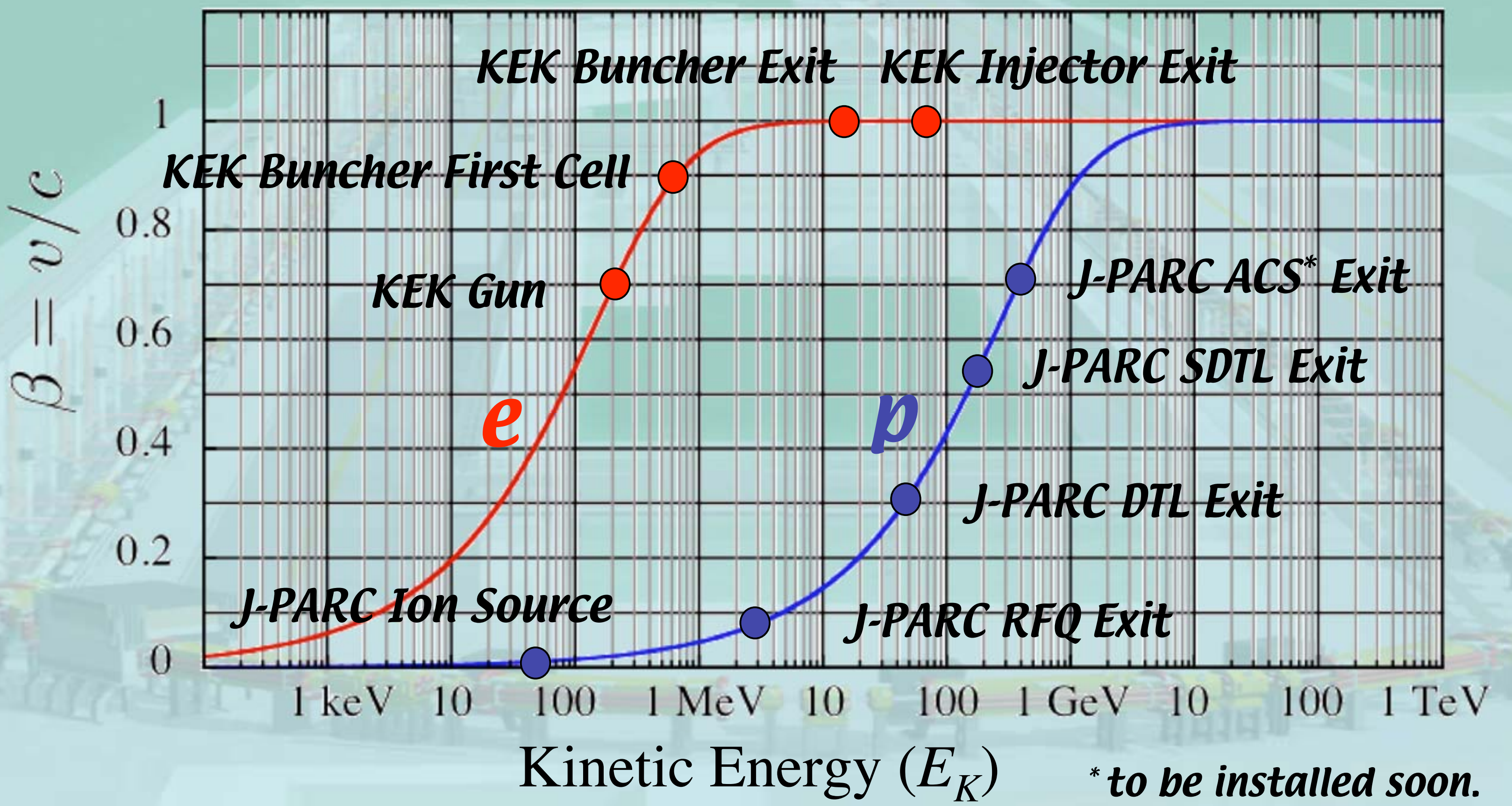
Introduction (cont'd)

Kinetic Energy vs Velocity

$$E_K = \frac{m_0 c^2}{\sqrt{1-\beta^2}} - m_0 c^2$$

$\beta = v/c$: normalized velocity $\quad v$: velocity

c : velocity of light $\quad m_0$: rest mass



* to be installed soon.

Introduction (cont'd)

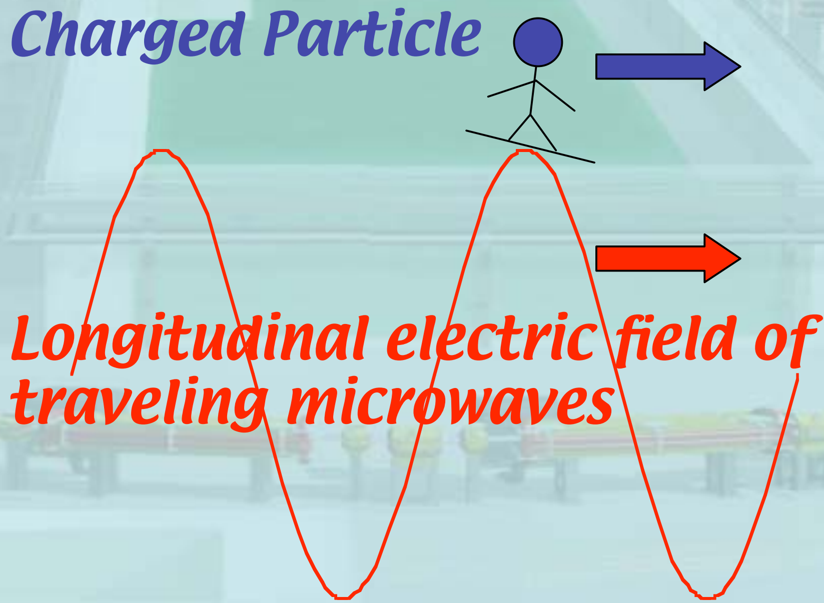
- **Length of Electron Linacs**

Longer linacs, higher energy.

- SLAC : Longest in the world
  3-km linac –> SLC 50 GeV (1989)
- KEK : 600-m J-shaped linac –> KEKB linac 8 GeV (1998)
- LAL : 230-m linac, 2.3 GeV (1968)

Principles of Particle Acceleration in RF Linacs

- Intuitive Explanation
  - [1] Assume the existence of "longitudinal electric fields of traveling microwaves".
  - [2] Imagine charged particles surf on "a crest of traveling microwaves".
  - [3] The velocity of the charged particles should equal the phase velocity of microwaves for continuous acceleration.



Principles of Particle Acceleration in RF Linacs

- ***Equation of motion***

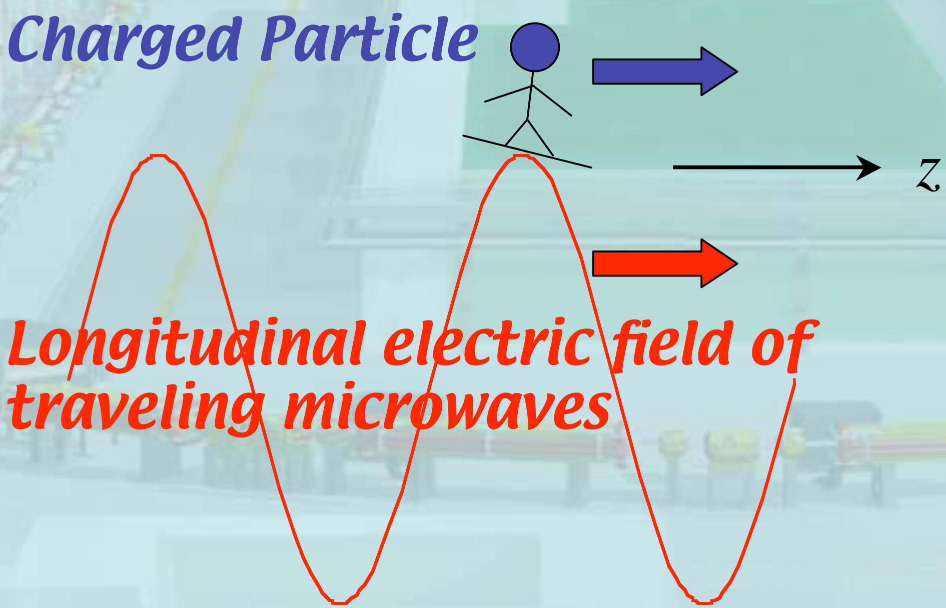
$$\frac{dp_z}{dt} = eE_z(z,t)$$

Longitudinal electric field of traveling microwaves

$$E_z(z,t) = E_{z0} \sin\left[\omega\left(t - \int_0^z \frac{dz'}{v_p}\right)\right]$$

v_p : phase velocity

ω : angular frequency



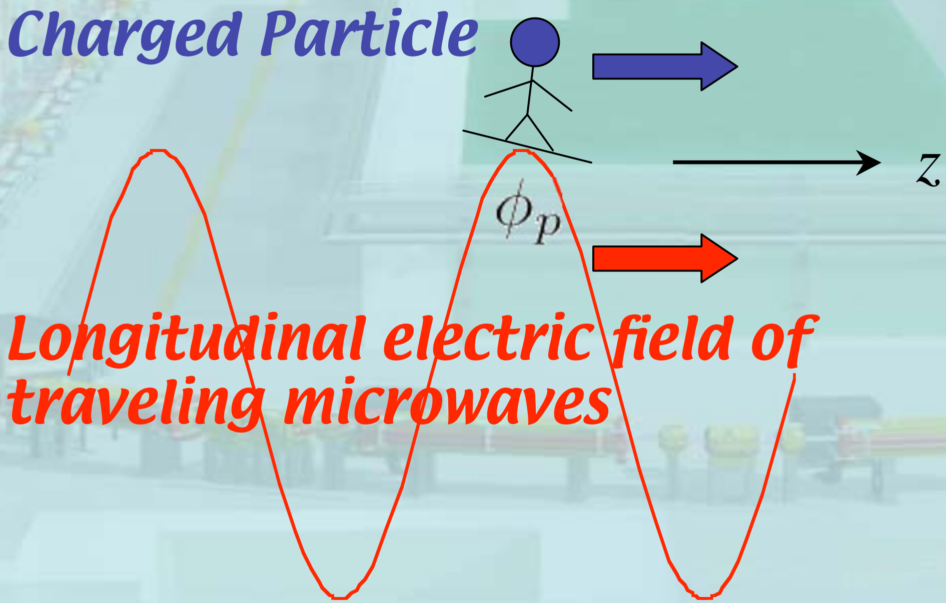
Principles of Particle Acceleration in RF Linacs

- ***Synchronized Particles*** **if** $v_{zp} = v_p$

$$\frac{dp_{zp}}{dt} = eE_{z0} \sin \phi_p$$

$$\phi_p \equiv \omega \left(t - \int_0^z \frac{dz'}{v_p} \right) = \text{constant}$$

Particles on the synchronized phase ϕ_p
can be efficiently accelerated.



v_p : phase velocity

ω : angular frequency

Principles of Particle Acceleration in RF Linacs

- The story, however, does not end:
  The intuitive explanation is apparently right and easy to understand, but actually not enough,
  even superficial for serious students.

- There are many fundamental and technical issues to be resolved.

Can you point out what the problems are?

[1] Electromagnetic waves are "transverse" in free space.
How do you make "longitudinal" waves?

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

[3] How do you make many particles localized in a very short length so as to be uniformly accelerated on a crest of the wave? ===> next section

Principles of Particle Acceleration in RF Linacs

[1] Electromagnetic waves are "transverse" in free space.
How do you make "longitudinal" waves?

Before going into detail, you should notice that the electric field in vacuum must satisfy

$$\mathrm{div}\vec{E} = 0$$

How about our longitudinal electric field?

$$E_z(z,t) = E_{z0} \sin\left[\omega\left(t - \int_0^z \frac{dz'}{v_p}\right)\right]$$

E_{z0} must depend on transverse coordinates.

$$E_{z0}(x,y)$$

One needs to go back to the principle of the issue:
"Electromagnetism"

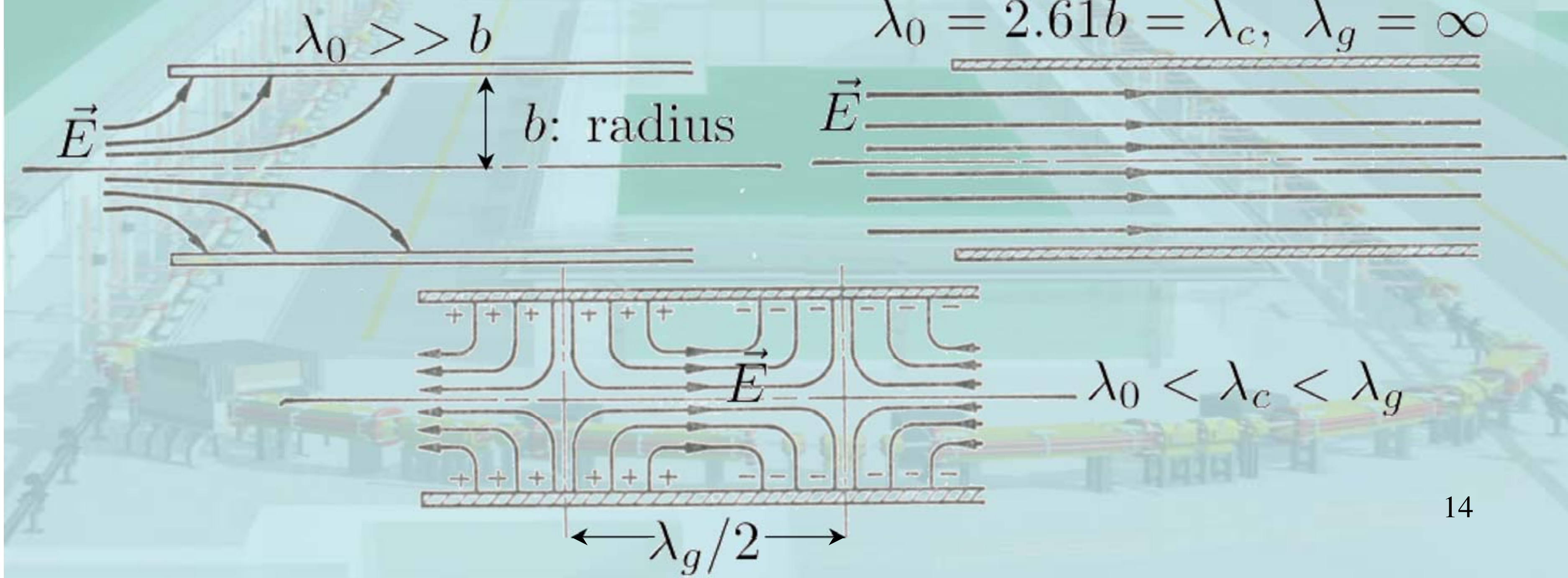
Principles of Particle Acceleration in RF Linacs

[1] Electromagnetic wave are "transverse" in free space.
How do you make "longitudinal" waves?

"Acceleration by guided wave" is one solution.
Electromagnetic waves in a wave guide could have a longitudinal electric field component.

Example: Circular wave guide

TM_{01} mode : Transverse Magnetic Wave



Principles of Particle Acceleration in RF Linacs

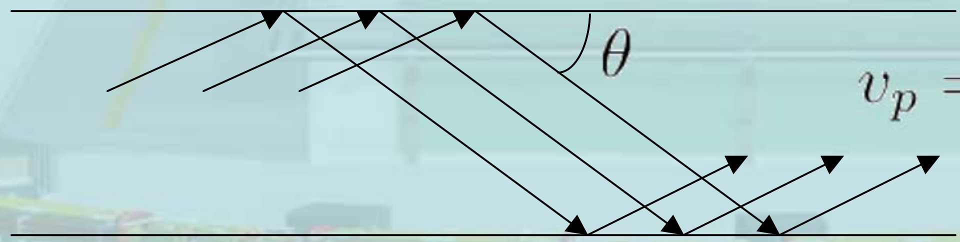
[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Example: Circular wave guide

TM_{01} mode : Transverse Magnetic Wave

A longitudinal electric field exists!
But how about the phase velocity?
The wave and the particles must be synchronous.

The phase velocity seems greater than the velocity of light.



$$v_p = \frac{c}{\cos\theta}$$

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Example: Circular wave guide

Let's start with a wave equation in cylindrical coordinates

$$\frac{\partial^2 E_z}{\partial r^2} + \frac{1}{r}\frac{\partial E_z}{\partial r} + \gamma^2 E_z = -\frac{\omega^2}{c^2} E_z \qquad E_z \propto e^{i\omega t - \gamma z}$$

γ : complex wave number

Solutions for axial symmetric TM_{01} mode are written as:

$$E_z = C J_0(k_c r) e^{-\gamma z}$$

$$H_\theta = \frac{j\omega\epsilon_0}{k_c} C J_1(k_c r) e^{-\gamma z} \qquad k_c^2 = \gamma^2 + (\frac{\omega}{c})^2$$

$$E_r = \frac{\gamma}{k_c} C J_1(k_c r) e^{-\gamma z}$$

$$E_z = 0 \text{ at } r = b \Longrightarrow J_0(k_c b) = 0 \Longrightarrow k_c b = \frac{2\pi}{\lambda_c} b = 2.405$$

$$\Longrightarrow \lambda_c = 2.61b : \text{ cut-off wavelength}$$

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Example: Circular wave guide

Dispersion relation for an axial symmetric TM_{01} mode

If there is no attenuation,

$$\gamma = j\beta = j\frac{2\pi}{\lambda_g}$$

the dispersion relation is written as

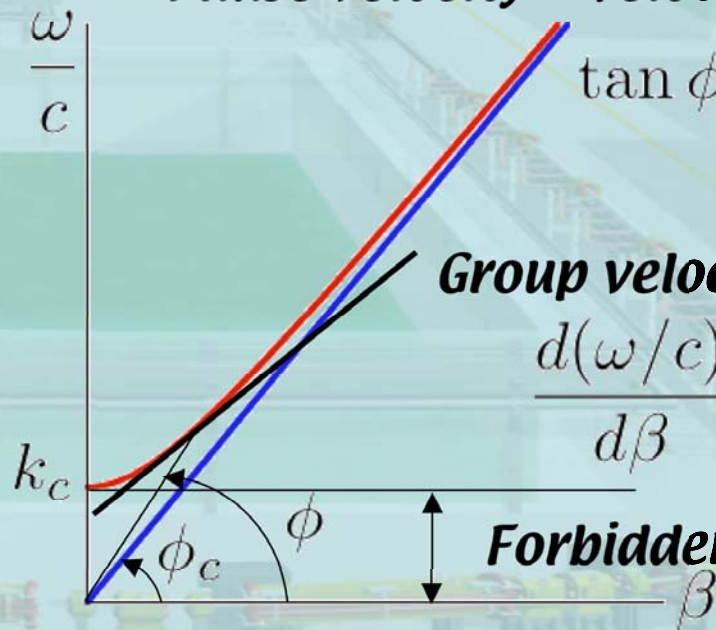
$$\left(\frac{\omega}{c}\right)^2 = k_c^2 + \beta^2$$

Velocity of light

$$\tan\phi_c = 1$$

Phase velocity > Velocity of light

$$\tan\phi = \frac{v_p}{c} > 1$$



Group velocity

$$\frac{d(\omega/c)}{d\beta} = \frac{v_g}{c} < 1$$

Forbidden band

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Example: Circular wave guide

The dispersion relation for the axial symmetric TM_{01} mode tells us that the phase velocity is greater than the velocity of light. The relation :

$$v_p > c > v_g$$

is always valid for electromagnetic waves traveling in uniform wave guides.

The particle velocity can not exceed the velocity of light. Therefore we can not accelerate the charged particles by using uniform wave guides.

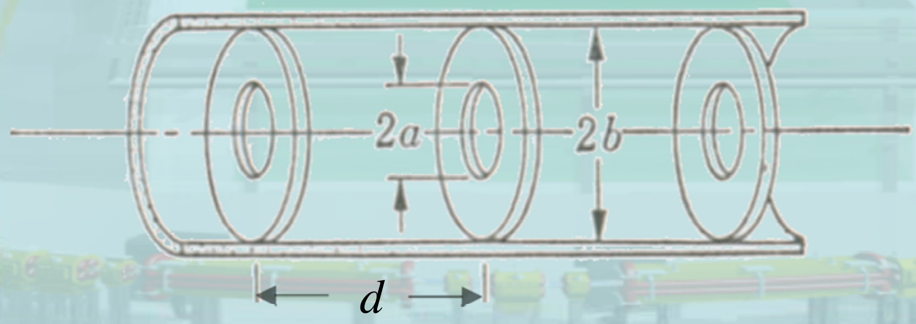
Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

How do we slow down the phase velocity in a wave guide?

A quick thought:
Introduce some obstacles in wave guides to slow down the phase velocity: non-uniform wave guide.

The simplest and frequently-used structure is the disk-loaded wave guide: "slow-wave structure".

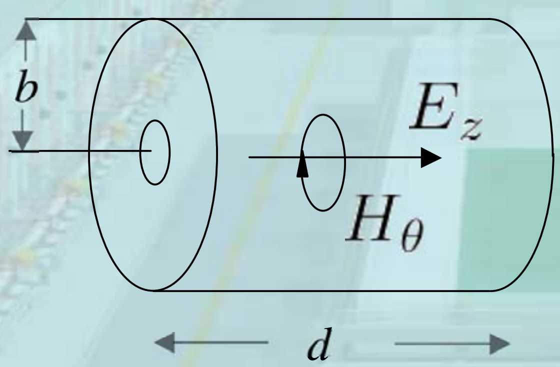


Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Disk-loaded wave guide: Pillbox resonator chain

Before going into detail, we investigate a single pillbox resonator.



The lowest mode TM_{010}

$$E_z = C J_0(k_c r)$$

$$H_\theta = i \frac{C}{Z_0} J_1(k_c r)$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\ \Omega\ :\ \text{impedance of free space}$$

$$\omega = \omega_c = k_c c = 2.405 \frac{c}{b}$$

The frequency is independent of the length "d".

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Disk-loaded wave guide: Pillbox resonator chain

The lowest mode TM_{010} of the pillbox resonator has the resonant frequency which is independent of the resonator length.

Then the chained resonators can be phased independently in the weak coupling limit so that the phase velocity could be adjusted to the particle velocity…

But our disk-loaded wave guides have larger iris holes: larger coupling.

Let's treat the irises as perturbations and see what happens to the wave guide modes.

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Disk-loaded wave guide: Pillbox resonator chain

The electromagnetic wave experiences a lot of reflections at each iris and interferes either destructively or additively.

Destructive case:
The irises have a minor effect. It's OK.

Additive case:
Standing waves are created. $v_g = 0$
This could make the dispersion curve flattened at the condition ("Bragg" reflection):

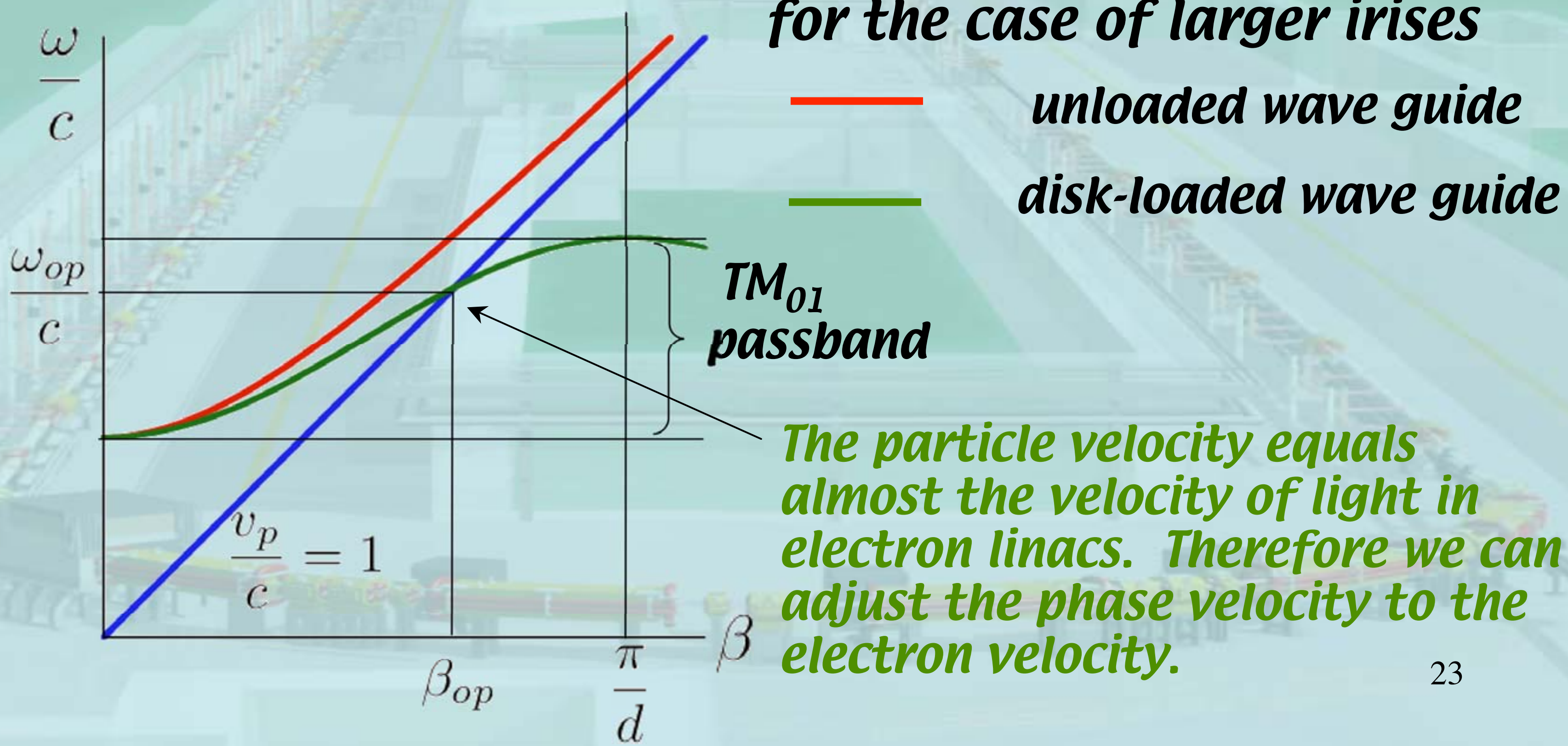
$$2\beta d = 2n\pi \longrightarrow \beta = \frac{\pi}{d}n \quad n = 0, 1, 2, \ldots$$

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Disk-loaded wave guide: Pillbox resonator chain

Schematic dispersion curves of disk-loaded wave guides for the case of larger irises



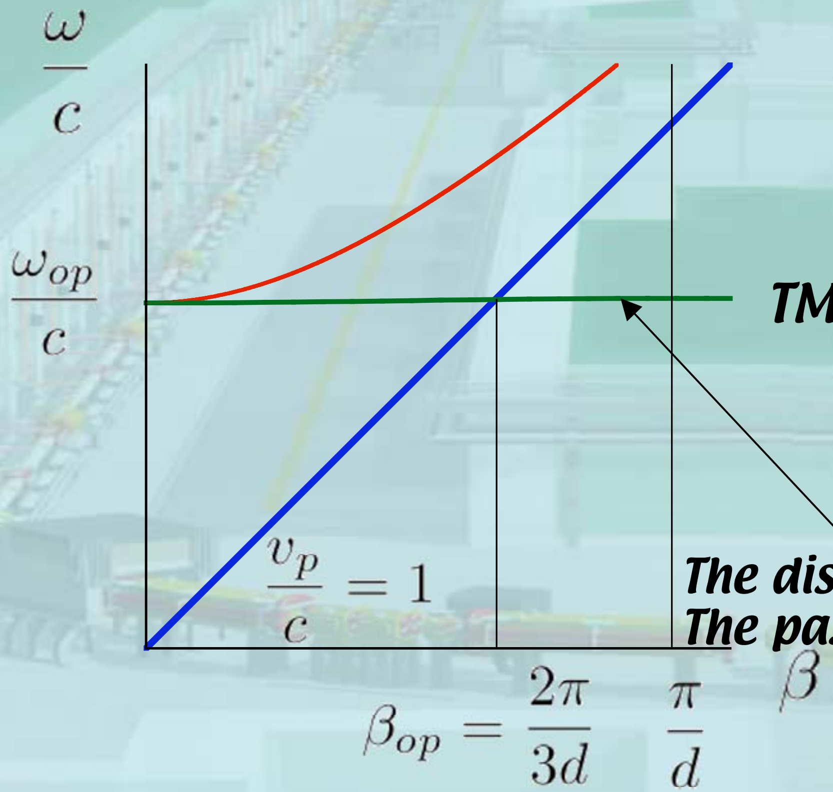
The particle velocity equals almost the velocity of light in electron linacs. Therefore we can adjust the phase velocity to the electron velocity.

Principles of Particle Acceleration in RF Linacs

[2] How do you adjust the phase velocity of the electromagnetic wave to the particle velocity?

Disk-loaded wave guide: Pillbox resonator chain

Actual dispersion curves of disk-loaded wave guides for the case of larger irises



unloaded wave guide

disk-loaded wave guide

TM_{01} 2856 MHz

KEK electron linac
S-band structure
$2\pi/3$ mode

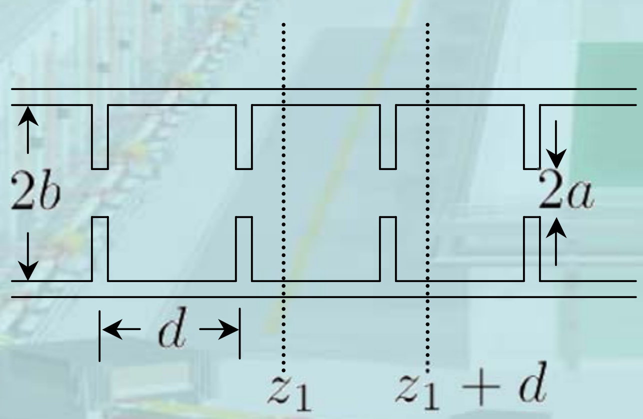
The dispersion curve is significantly depressed.
The passband is actually very narrow.

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

We have verified that a slow-wave structure exists.

More theoretical treatment is based on the
"Floquet's Theorem"
for wave propagation in a periodic structure.



Floquet's theorem for TM_{01} mode

$$E(r, z_1 + d, t) = e^{-i\beta_0 d} E(r, z_1, t)$$

The theorem comes from the fact that when a structure of infinite length is displaced along its axis by one period, it can not be distinguished from its original self.

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

Electromagnetic fields of TM_{01} mode can be expanded in a spatial Fourier series (space harmonics) by using Floquet's theorem.

$$E_z(r,z,t) = \sum_{n=-\infty}^{\infty} a_n J_0(k_{rn} r) e^{i(\omega t - \beta_n z)}$$

$$E_r(r,z,t) = i \sum_{n=-\infty}^{\infty} a_n \frac{\omega}{k_{rn} v_{pn}} J_1(k_{rn} r) e^{i(\omega t - \beta_n z)}$$

$$B_\theta(r,z,t) = i \sum_{n=-\infty}^{\infty} a_n \frac{\omega}{k_{rn} c^2} J_1(k_{rn} r) e^{i(\omega t - \beta_n z)}$$

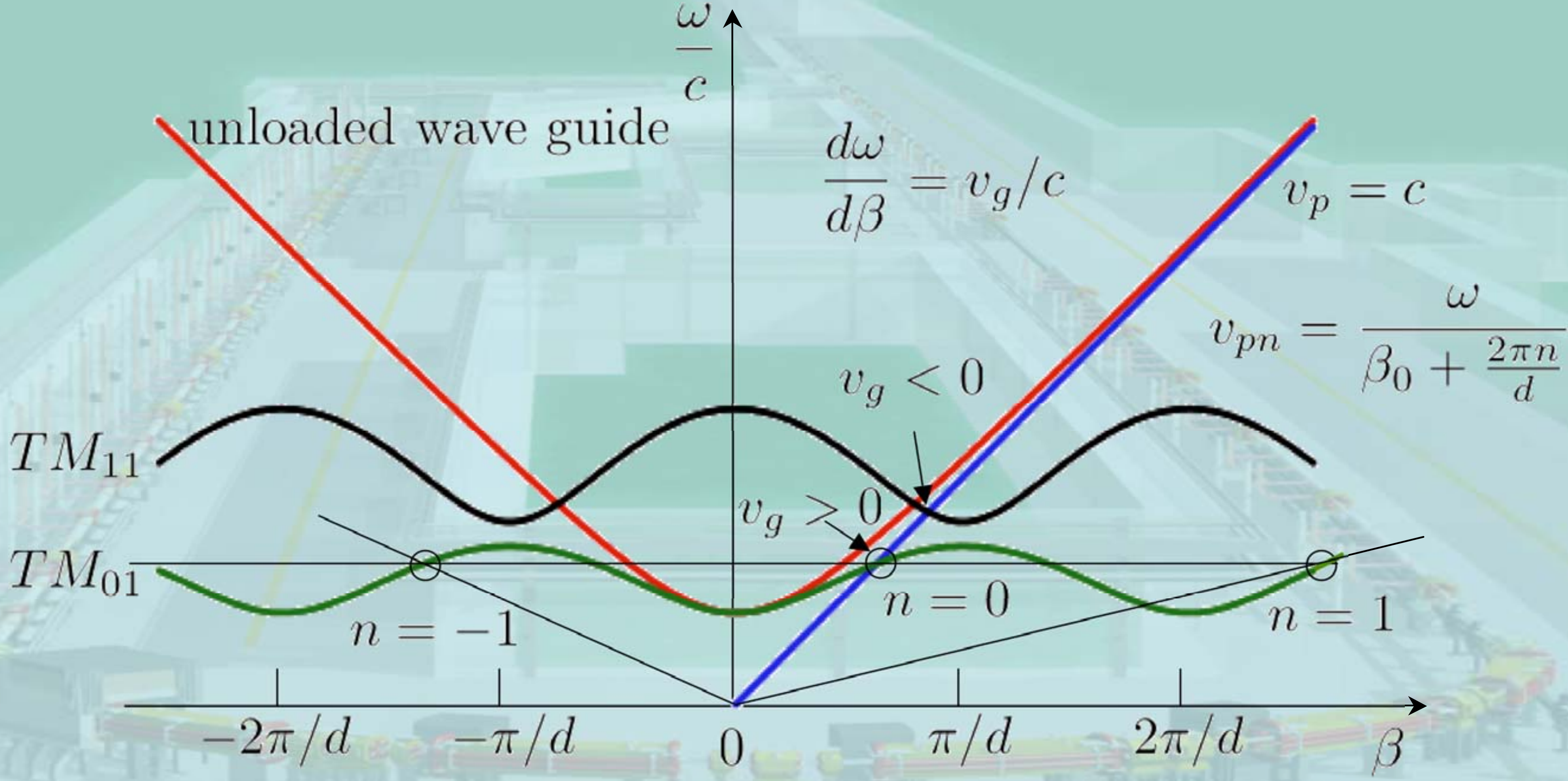
$$k_{rn} = i \frac{\omega}{v_{pn}} \sqrt{1 - \left(\frac{v_{pn}}{c}\right)^2}$$

$$v_{pn} = \frac{\omega}{\beta_n} = \frac{\omega}{\beta_0 + \frac{2\pi n}{d}}$$

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

Brillouin diagram for a disk-loaded wave guide



Basically only the intersections of the dispersion curves and the line of $v_p = c$ affect beam dynamics.

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

Distinctive characteristics

[1] There are "space harmonics". $n = 0,\ n = \pm 1, \ldots$

(a) Each has a different propagation constant. β_n

(b) Each has a different phase velocity. $v_{pn} = \dfrac{\omega}{\beta_n} = \dfrac{\omega}{\beta_0 + \frac{2\pi n}{d}}$

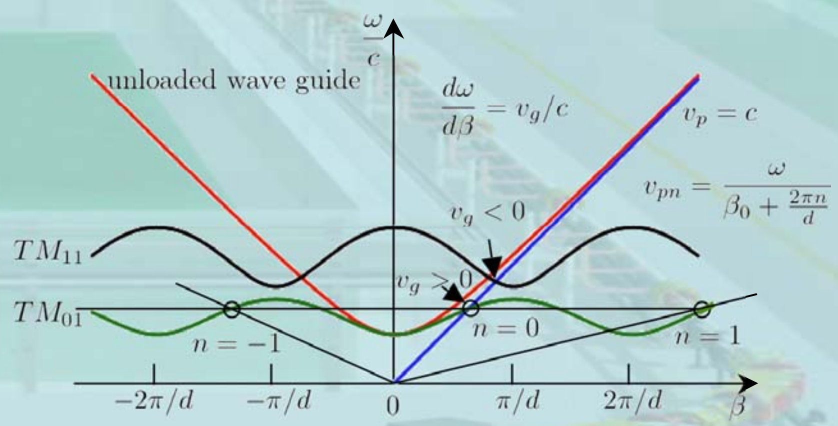
Example:

TM_{01} : $2\pi/3$ mode ($\beta_0 = 2\pi/3d$)

$n = 0 : v_p = c$

$n = 1 : v_p = -c/4$

$n = -1 : v_p = -c/2$



Brillouin diagram for a disk-loaded wave guide

==>We can adjust the phase velocity to the velocity of light.

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

Distinctive characteristics

[2] When $n = 0$ and $v_p = c$,
the forces acting on the charged particle are simply expressed by:

$$F_z(r, z, t) = ea_0 e^{i\omega(t-z/c)}$$

$$F_r(r, z, t) = e(E_r - vB_\theta) = i\frac{ea_0\omega}{2c}(1 - v/c)re^{i\omega(t-z/c)}$$

$$k_{r0} = 0 \Longrightarrow J_0(k_{r0}r) = 1\ ,\ J_1(k_{r0}r)/k_{r0} \to r$$

☺ The accelerating force is independent of the radial position of the synchronous particle.

☺ The radial force is proportional to the radial position and divergent, but becomes zero as the particle velocity approaches the velocity of light.

==>Extremely fortunate for the operation of electron linacs!!!

Principles of Particle Acceleration in RF Linacs

Disk-loaded wave guide: Pillbox resonator chain

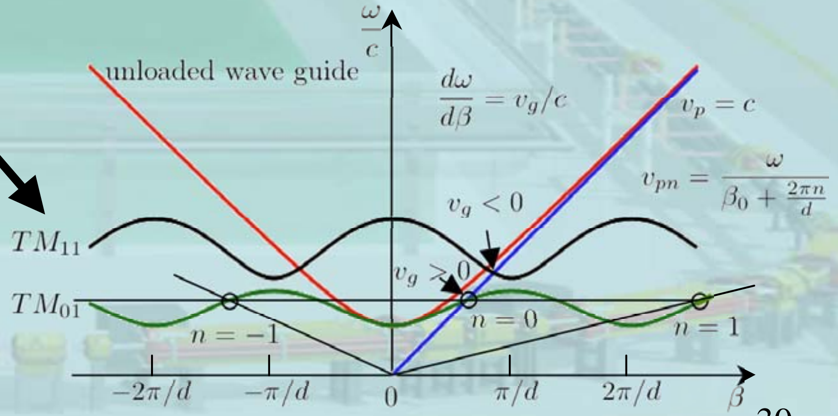
Remarks: Some important items not investigated in this lecture.

[1] How the choice of the phase shift per period of the fundamental mode (TM_{01}) is made?

It is made empirically...

$2\pi/3$ mode is mostly chosen for traveling-wave linacs because
acceleration efficiency is high, and
it is robust against the instability due to higher modes.

[2] The existence of higher pass bands such as TM_{11} mode may be responsible for serious instabilities in the linac operation.



Brillouin diagram for a disk-loaded wave guide

Electron Linear Accelerator

Remaining problem in the preceding section:

[3] How do you make many particles localized in a very short length so as to be uniformly accelerated on a crest of the wave?
==> "bunching mechanism in electron linacs"

Start with a longitudinal equation of motion:

$$\frac{dp_z}{dt} = eE_z(z,t)$$

where a longitudinal electric field of traveling microwaves:

$$E_z(z,t) = E_{z0}\sin\left[\omega\left(t - \int_0^z \frac{dz'}{v_p}\right)\right]$$

Assume synchronous particles:

$$\frac{dp_{zp}}{dt} = eE_{z0}\sin\phi_p$$

$$\phi_p \equiv \omega\left(t - \int_0^z \frac{dz'}{v_p}\right) = \text{constant}$$

Electron Linear Accelerator

"bunching mechanism in electron linacs"

Define a small displacement from the synchronous particle:

$$z = z_p + \xi \qquad \dot{z} = v_p + \dot{\xi}$$

The equation of motion is represented by ξ and ϕ_p .

$$\frac{dp_z}{dt} = eE_{z0} \sin\left(\phi_p - \omega \int \frac{d\xi}{v_p}\right)$$

Since the right-hand side does not explicitly depend on time, we can consider an energy integral so that a potential energy could be defined by:

$$U(\xi) = -\int eE_{z0} \sin\left(\phi_p - \omega \int \frac{d\xi}{v_p}\right) d\xi$$

Then we can calculate a Lagrangian:

$$L = -mc^2\sqrt{1-\beta^2} - U(\xi) \ , \ \beta \equiv \frac{v_p + \dot{\xi}}{c}$$

Electron Linear Accelerator

"bunching mechanism in electron linacs"

In an approximation of slow displacement variation:

$$\left|\dot{\xi}/v_p\right| \ll 1$$

The Lagrangian is expanded to a second order of $\dot{\xi}$.

$$L = -mc^2\sqrt{1-\beta_p^2} + p_{zp}\dot{\xi} + \frac{1}{2}m_l\dot{\xi}^2 - U(\xi)$$

$$\beta_p \equiv v_p/c \qquad p_{zp} \equiv \frac{mc\beta_p}{\sqrt{1-\beta_p^2}} \qquad m_l \equiv \frac{m}{\left(1-\beta_p^2\right)^{3/2}}$$

where m_l is a so-called longitudinal mass.
Defining a longitudinal momentum $p_l \equiv m_l\dot{\xi}$, and using a canonical momentum:

$$p_\xi = \frac{\partial L}{\partial \dot{\xi}} = p_{zp} + p_l$$

Electron Linear Accelerator

"bunching mechanism in electron linacs"

The Hamiltonian is obtained as

$$H = mc^2\sqrt{1-\beta_p^2} + \frac{1}{2m_l}\left(p_\xi - p_{zp}\right)^2 + U(\xi)$$

For simplicity, assume v_p is treated as a constant, then redefine a longitudinal potential energy:

$$U_l(\xi) \equiv U(\xi) + eE_{z0}\xi\sin\phi_p$$

The new Hamiltonian concerning a particle motion is written as:

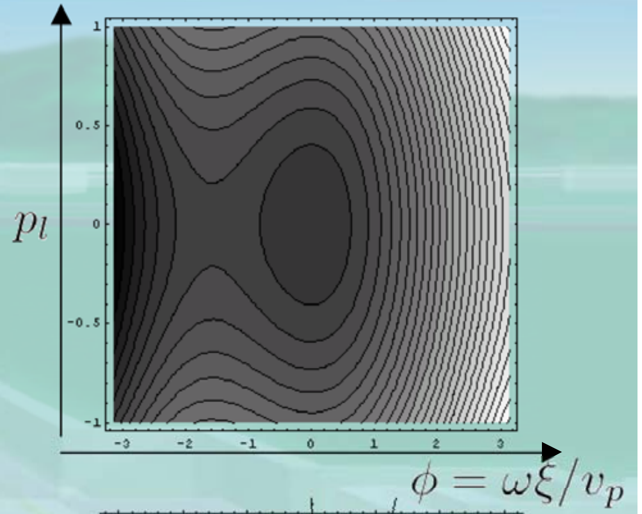
$$H = \frac{p_l^2}{2m_l} + U_l(\xi)$$

$$U_l(\xi) = -eE_{z0}\left[\frac{v_p}{\omega}\cos\left(\phi_p - \frac{\omega\xi}{v_p}\right) - \xi\sin\phi_p\right]$$

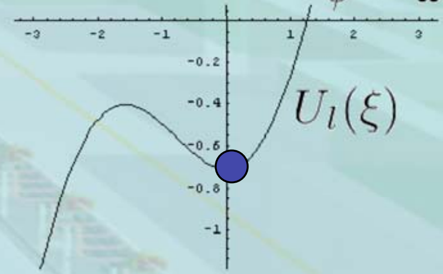
Electron Linear Accelerator

"bunching mechanism in electron linacs"

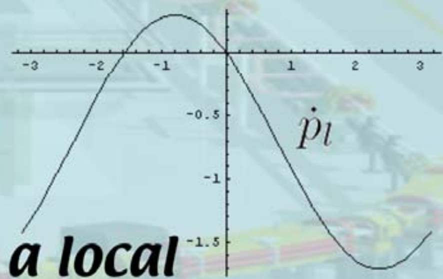
The phase space, the longitudinal potential and the generalized force are shown in the figure.



$$H = \frac{p_l^2}{2m_l} + U_l(\xi)$$



$$U_l(\xi) = -eE_{z0}\left[\frac{v_p}{\omega}\cos\left(\phi_p - \frac{\omega\xi}{v_p}\right) - \xi\sin\phi_p\right]$$



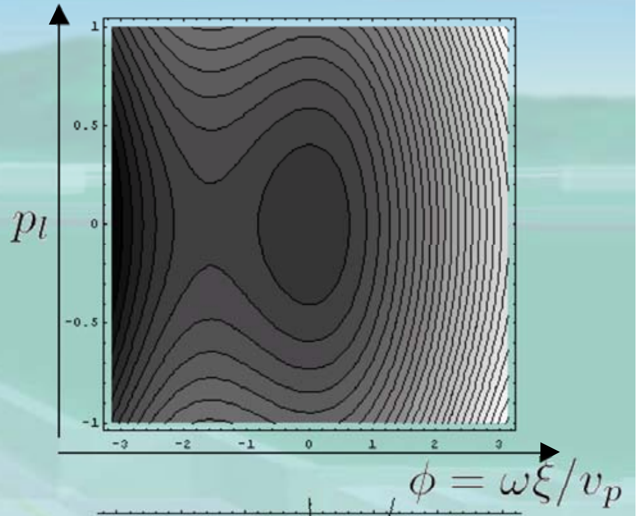
$$\dot{p}_l = -\frac{\partial U_l}{\partial \xi}$$

The electrons could be trapped in a potential well: a local minimum, oscillating in a relatively narrow region.

Electron Linear Accelerator

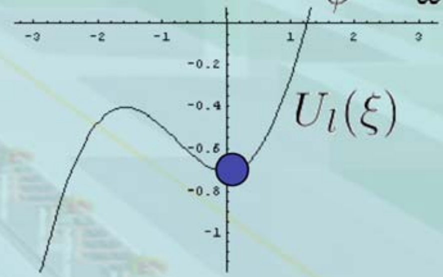
“bunching mechanism in electron linacs”

To get “bunched beam”, we increase the phase velocity of the microwave and the electric field adiabatically.



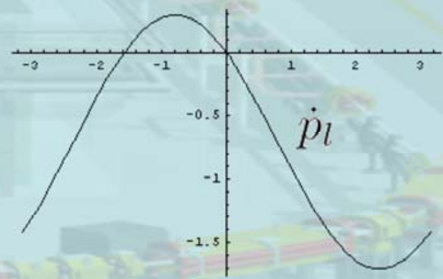
Adiabatic theorem of Ehrenfest:

An action variable of a mechanical system in periodic motion is conserved when the system changes adiabatically.



$$J = \frac{1}{2\pi}\oint pdq = \text{constant}$$

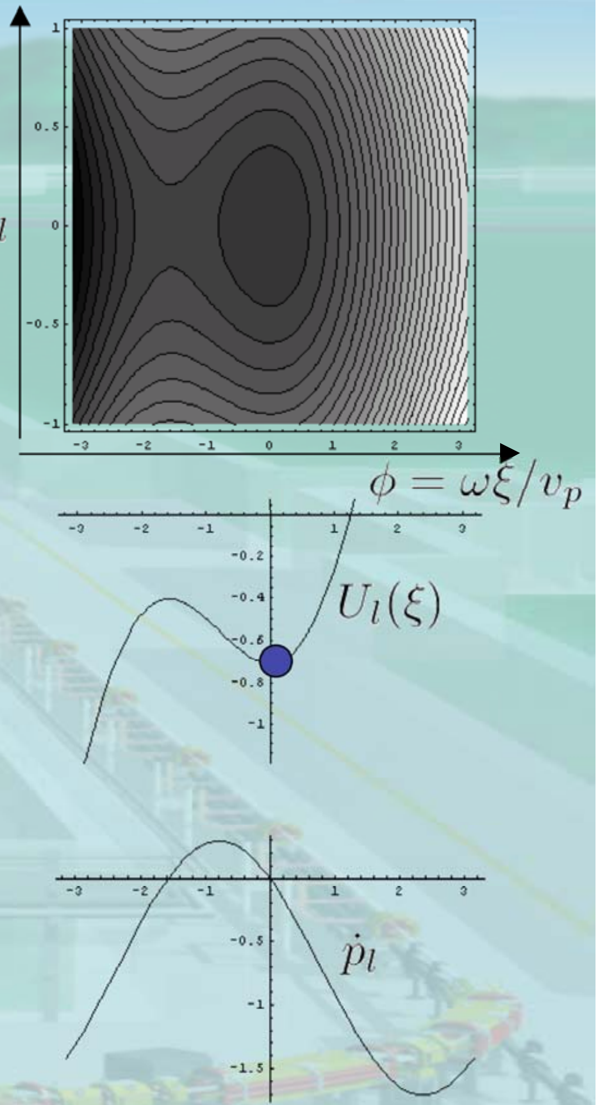
$$(q,p)\ :\ \text{canonical variables}$$



Electron Linear Accelerator

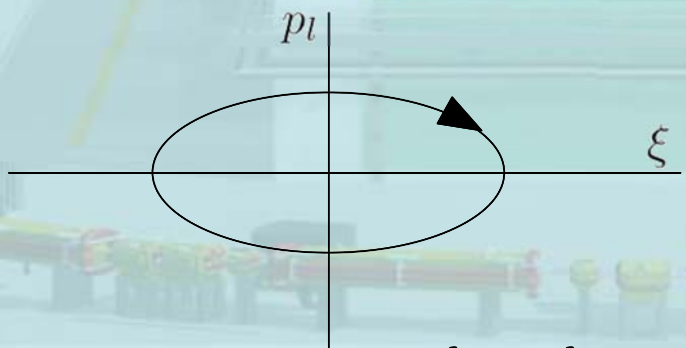
"bunching mechanism in electron linacs"

Before using the Ehrenfest's theorem, write down the Hamiltonian for electrons trapped in a potential well, which is undergoing small oscillations.
The Hamiltonian is written as:



$$H_l = \frac{1}{2m_l}\left(p_l^2 + m_l^2\omega_p^2\xi^2\right)$$

$$\omega_p = \sqrt{\frac{eE_{z0}\omega\cos\phi_p}{m_l v_p}}$$

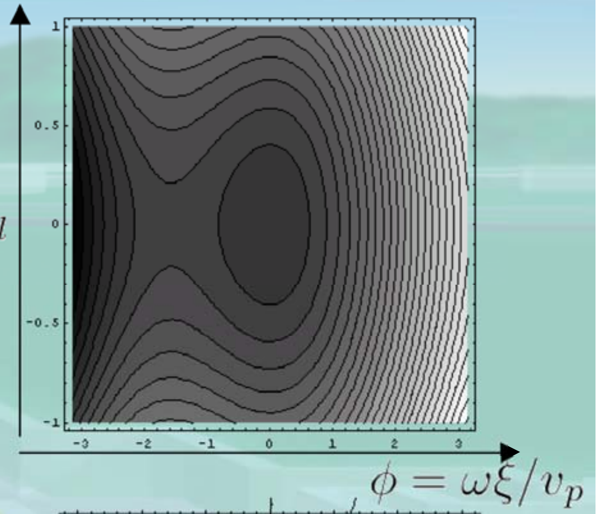


Electrons move along an ellipse in the phase space.

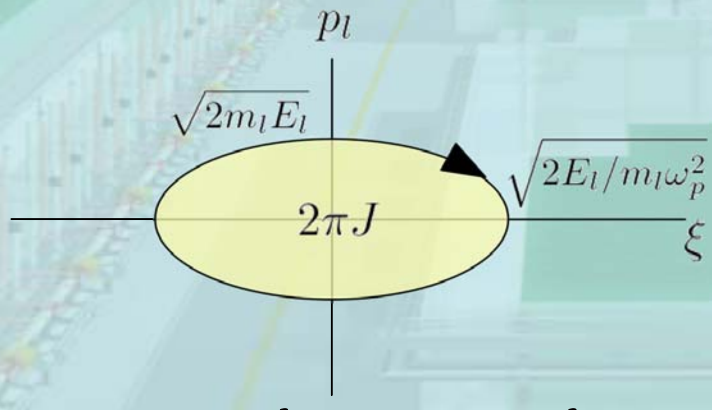
Electron Linear Accelerator

"bunching mechanism in electron linacs"

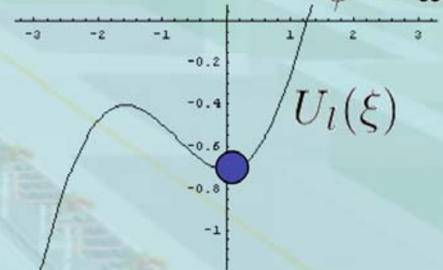
Calculation of the action variable:
If the total energy is E_l,
the area of the phase space is expressed as

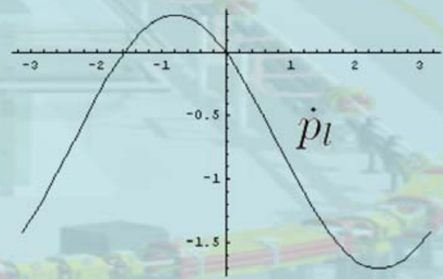


$$2\pi J = \pi\sqrt{2m_l E_l}\sqrt{2E_l/m_l\omega_p^2} = 2\pi E_l/\omega_p$$



$$\omega_p = \sqrt{\frac{eE_{z0}\omega\cos\phi_p}{m_l v_p}}$$





Then we obtain the relation:

$$E_l/\omega_p = J = \text{constant}$$

===The Ehrenfest's adiabatic theorem===

Electron Linear Accelerator

"bunching mechanism in electron linacs"

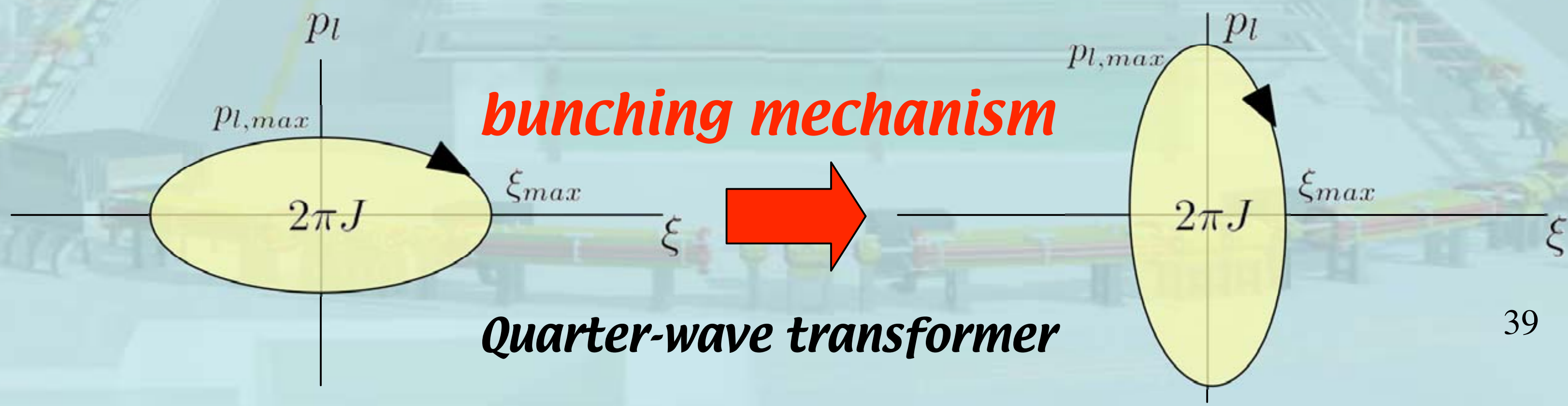
Maximum amplitude and momentum are derived:

$$\xi_{max} = \sqrt{2E_l/m_l\omega_p^2} = \sqrt{J}\left(\frac{v_p}{em_l E_{z0}\omega\cos\phi_p}\right)^{1/4}$$

$$p_{l,max} = \sqrt{2m_l E_l} = \sqrt{J}\left(\frac{em_l E_{z0}\omega\cos\phi_p}{v_p}\right)^{1/4}$$

$$m_l \equiv \frac{m}{\left(1-\beta_p^2\right)^{3/2}}$$

Adiabatically increasing the phase velocity and the longitudinal electric field,
the bunch shrinks down, while
the momentum spread stretches out.



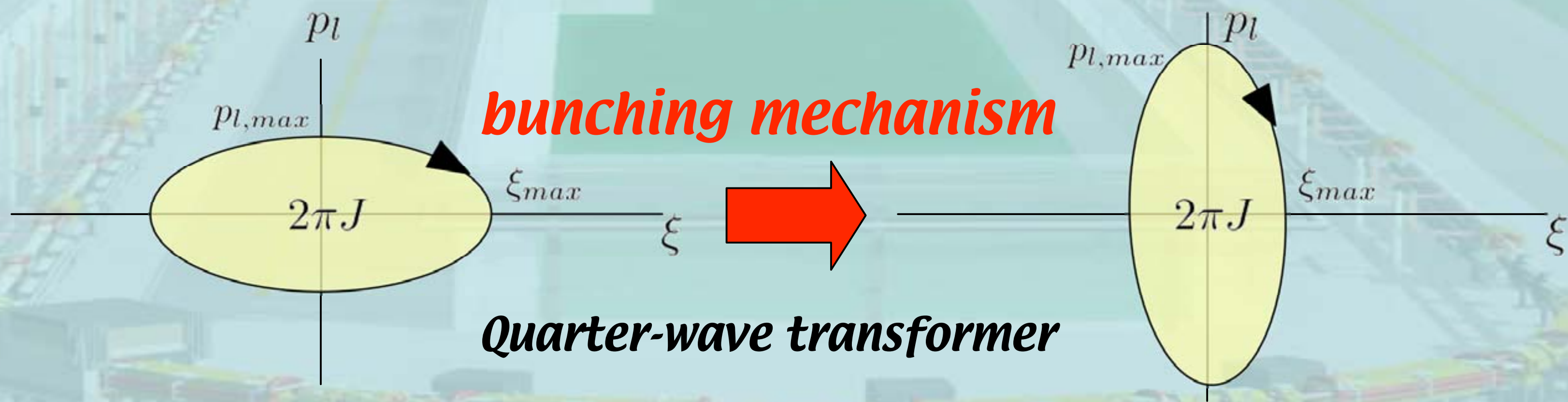
Electron Linear Accelerator

"bunching mechanism in electron linacs"

Remarks:

Even the momentum spread, which stretches out in the bunching process, is damped in the sense that we are usually interested in the fractional momentum spread:

$$\delta p/p \rightarrow \ \text{smaller as } p \rightarrow \ \text{larger(accelerated)}$$



bunching mechanism

Quarter-wave transformer

In the actual bunching mechanism for electrons, the bunching process is quite rapid even without any oscillation, since electrons are too light...The above figure is rather appropriate for protons.

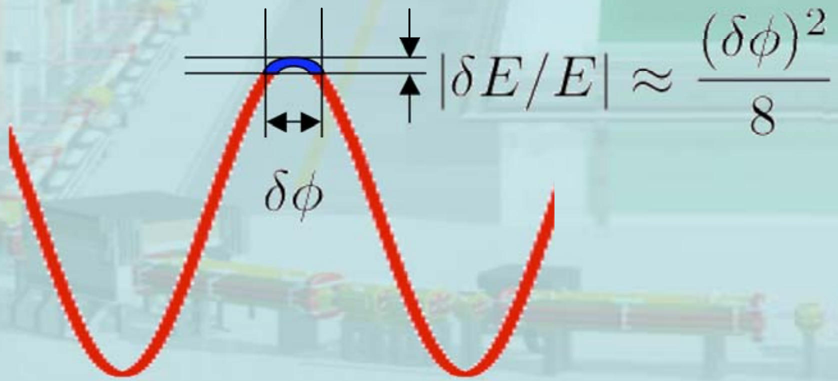
Electron Linear Accelerator

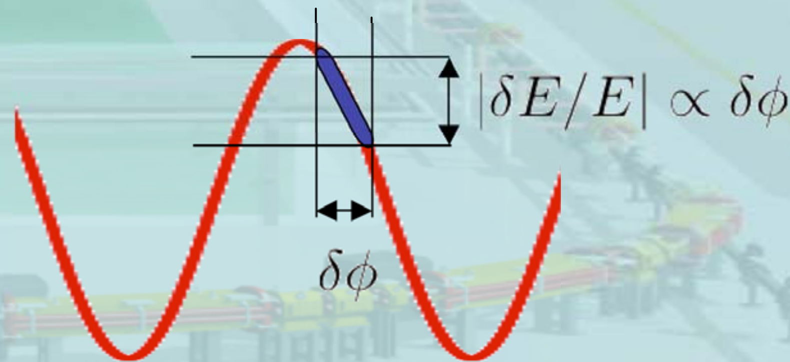
We have studied a longitudinal motion of electrons in linacs with particular emphasis on the bunching process.

After sufficiently bunched and accelerated to several tens of MeV, the electrons can be treated as rigid particles in a longitudinal direction. The relativistic beta is very close to one.

As a consequence of this favorable fact, you can just put the electrons on a crest of the microwave for efficient acceleration.

Comment: The electron bunch has a finite length, which causes the energy spread depending on the phase of the microwave on which you put it.





In the case of a high-current beam, the situation changes...

Electron Linear Accelerator

How about a transverse motion of electrons?

Next subject: "transverse motion in electron linacs"

In the relativistic region $v \to c$ *, the transverse force caused by the microwave (TM_{01} mode) vanishes.*

$$F_r(r, z, t) = e(E_r - vB_\theta) = i\frac{ea_0\omega}{2c}(1 - v/c)re^{i\omega(t-z/c)} \Longrightarrow 0$$

Transverse equation of motion (x):

$$\frac{dp_x}{dt} = F_x$$

where

$$p_x = \frac{m}{\sqrt{1-\beta^2}}\frac{dx}{dt} = m\gamma\frac{dx}{dt}$$

$$c\beta = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{mc^2}$$

Electron Linear Accelerator

"transverse motion in electron linacs"

The transverse equation of motion is rewritten as

$$m\frac{d}{dt}\left(\gamma\frac{dx}{dt}\right)=F_x$$

Changing the independent variable: $ds=c\beta dt$

$$m\frac{d}{ds}\left(\beta\gamma\frac{dx}{ds}\right)=\frac{F_x}{\beta mc^2}$$

For ultra relativistic case (electrons): $\beta\rightarrow 1$

$$m\frac{d^2x}{ds^2}+\frac{\gamma'}{\gamma}\frac{dx}{ds}=\frac{F_x}{\gamma mc^2}$$

We have a damping term: $\frac{\gamma'}{\gamma}\frac{dx}{ds}$ "adiabatic damping"

which is fortunate in operating electron linacs.
"More accelerate, more stable in a transverse motion."

Electron Linear Accelerator

"transverse motion in electron linacs"

Adiabatic Damping

To be precise, the term of "damping" might be inappropriate, because there is actually no dissipation.

Solve the equation of motion in the conditions of:

constant acceleration gain: $\gamma = \gamma_0 + gs \quad \gamma' = g = \text{constant}$
no external focusing force: $F_x = 0$

$$\frac{d^2x}{ds^2} + \frac{g}{\gamma_0 + gs}\frac{dx}{ds} = 0$$

The solution is:

High-energy region

$$x = x_0 + x_0' \frac{\gamma_0 + gs}{g} \ln \frac{\gamma_0 + gs}{\gamma_0 + gs_0} \quad \Longrightarrow x = x_0 + x_0' s_0 \ln \frac{s}{s_0}$$

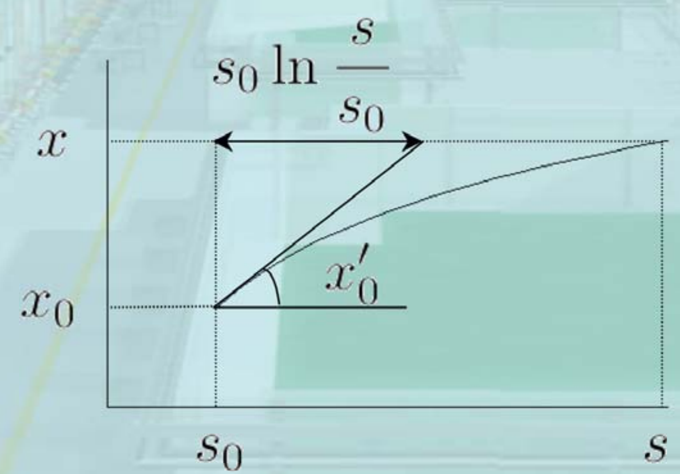
$$x' = x_0' \frac{\gamma_0 + gs_0}{\gamma_0 + gs} \quad \Longrightarrow x' = x_0' \frac{s_0}{s}$$

Electron Linear Accelerator

"transverse motion in electron linacs"

Adiabatic Damping

Electron orbits are logarithmic.



It is as if the length $s - s_0$ has been contracted to $L_{eff} = s_0 \ln \frac{s}{s_0}$.

Example: KEK linac $s_0 = 10$ m $s = 600$ m

$$\gamma' = g = 39.14 \ /\mathrm{m} \qquad \Longrightarrow L_{eff} = 40.9 \ \mathrm{m}$$

Electron Linear Accelerator

"transverse motion in electron linacs"

Transverse emittance is defined as a phase space area: $u_x \equiv \int\int dx dp_x$

Liouville's theorem states that u_x might be conserved if only non-dissipative forces act on the particles.

Comment: The general definition of phase space volume is written as

$$U_6 \equiv \int\int\int\int\int\int dx dp_x dy dp_y d\theta d\gamma$$

This must be conserved. Usually the coupling between different components, however, is weak so that the sub-phase space, e.g., the projected phase space volume is conserved.

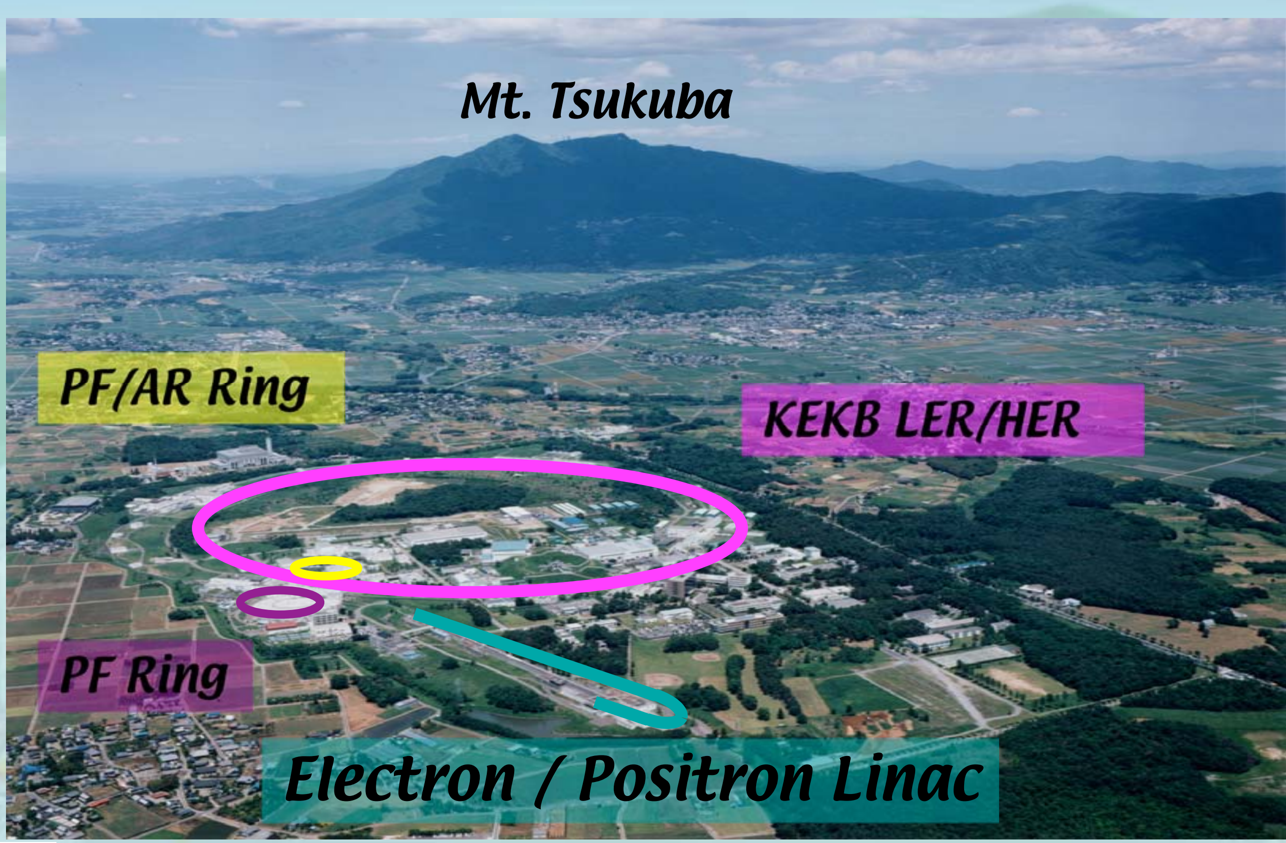
Transverse emittance in accelerators is defined as:

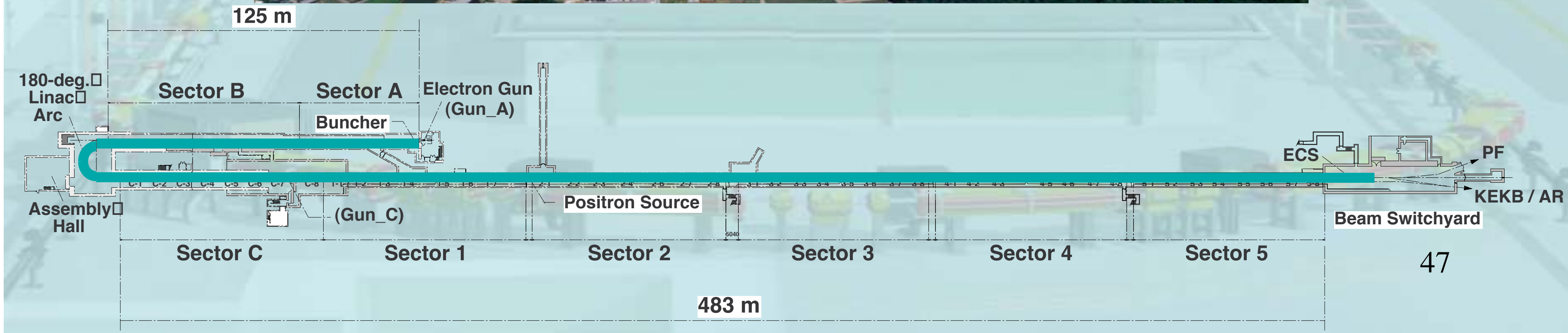
$$\pi\epsilon_x = \int\int dx dx' \qquad x' = p_x/p_z = p_x/\gamma\beta mc$$

Therefore $\gamma\beta\epsilon_x$, "normalized emittance" is conserved.

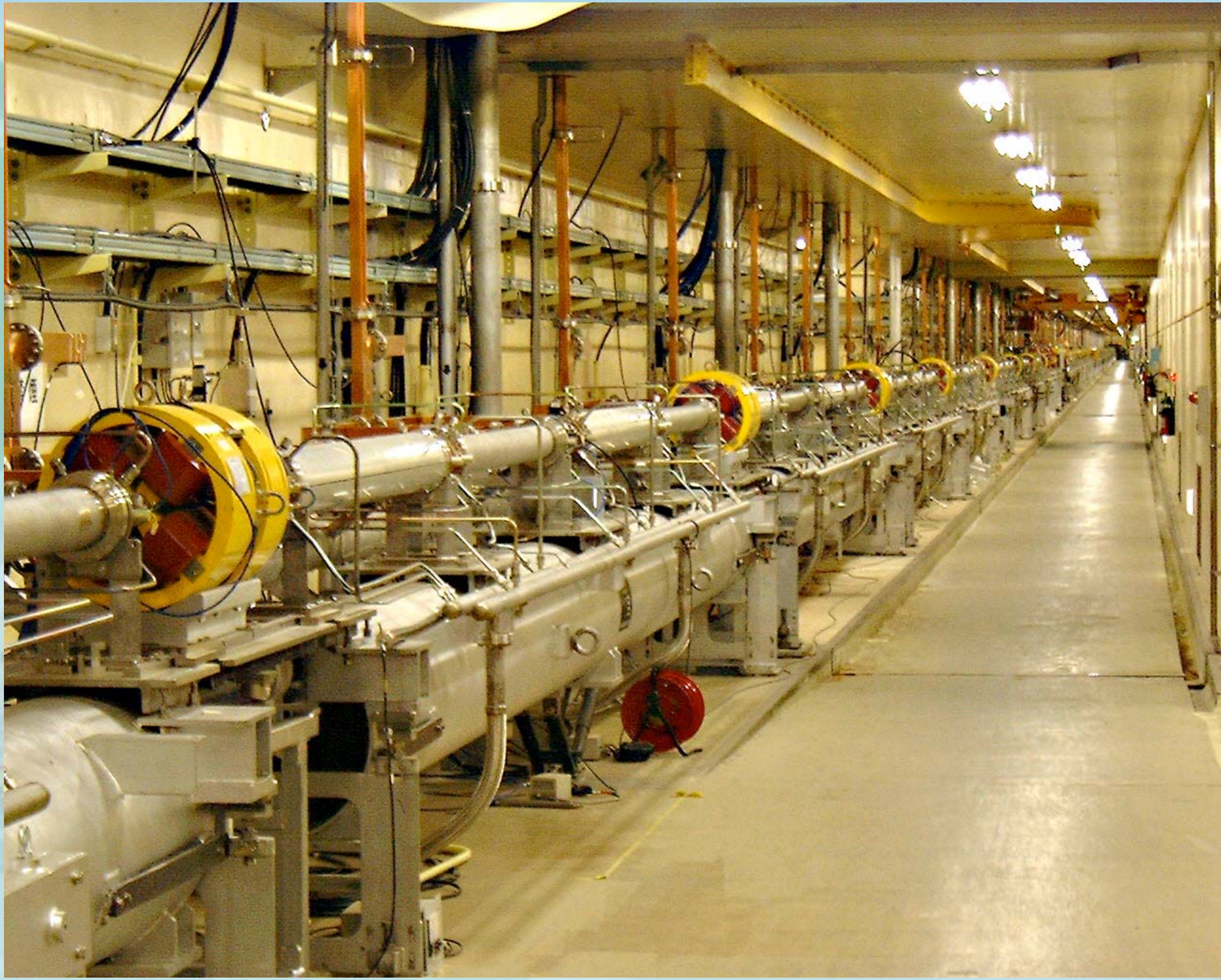
KEK Accelerator Complex

Cheiron School
Spring-8 Sep 13 2007





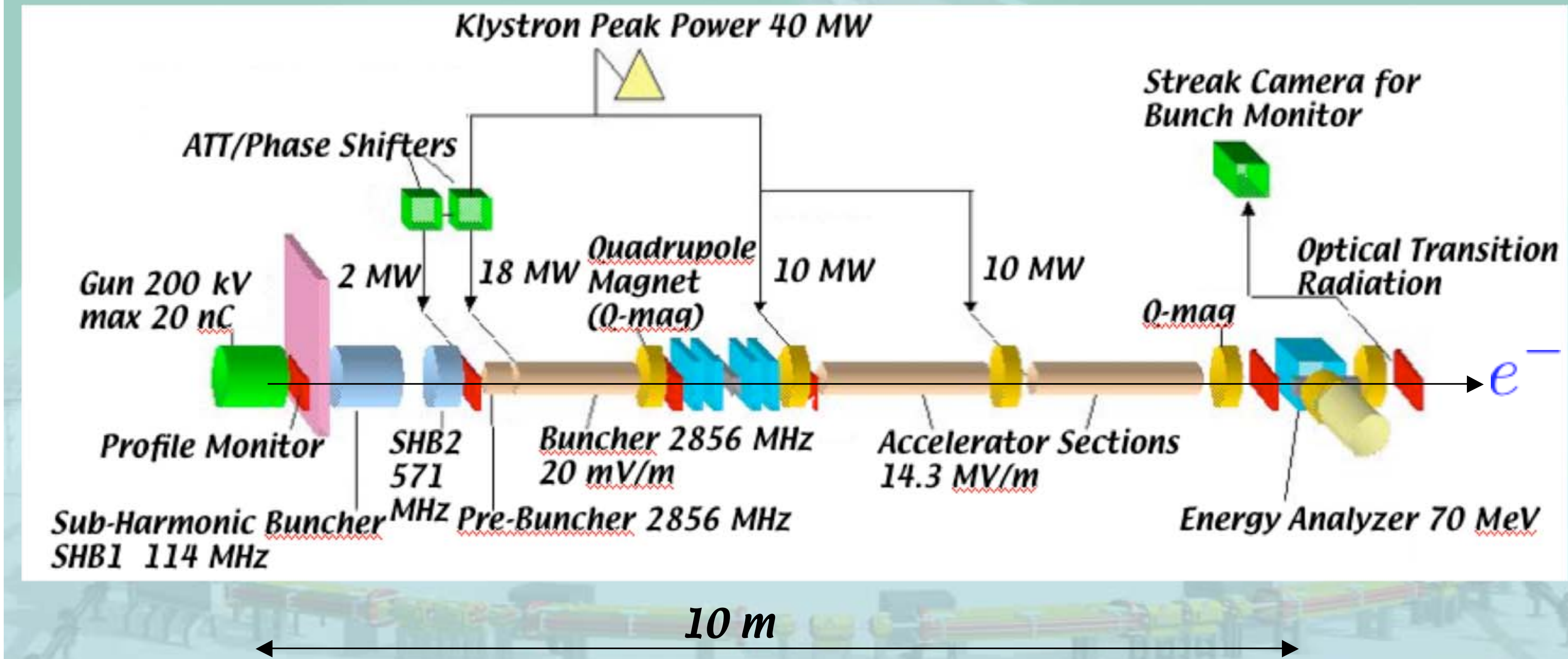
KEK electron / positron linac



Electron Linear Accelerator

KEK electron / positron linac

Injector

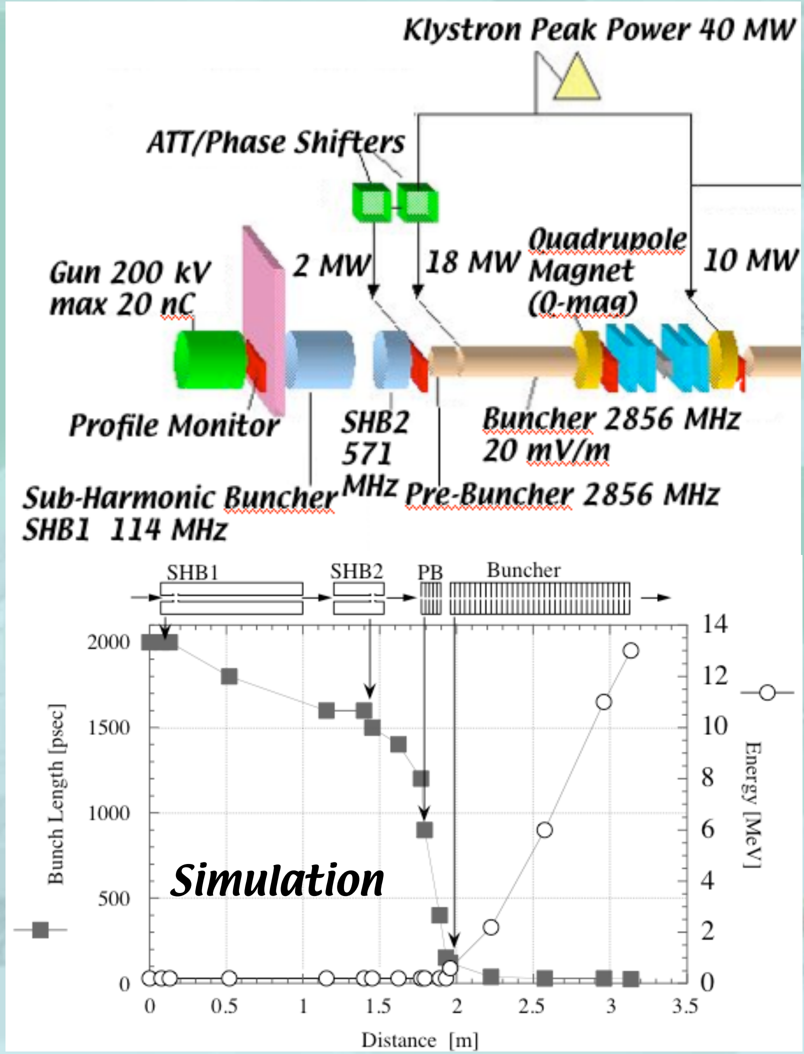


The beam dynamics "drama" (G.A.Loew) takes place in the injector.

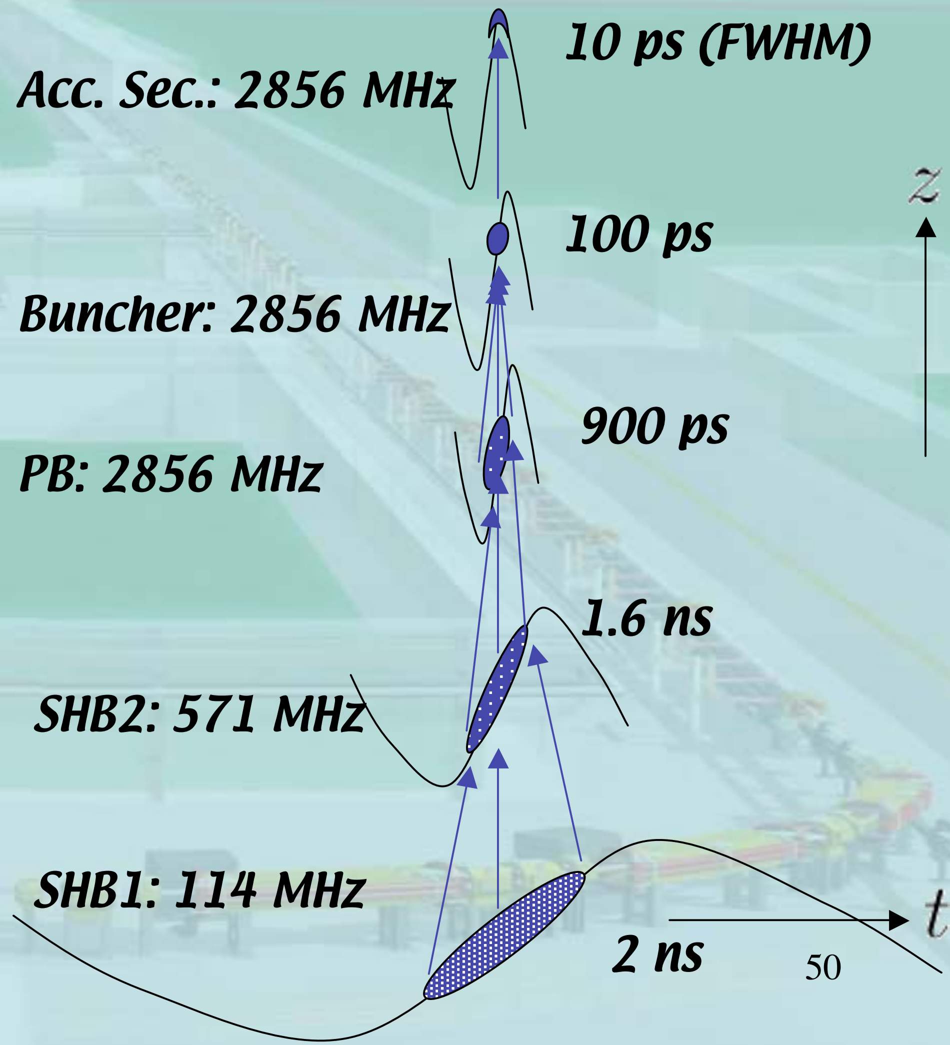
Electron Linear Accelerator

KEK electron / positron linac

Pre-Injector



The beam dynamics drama: velocity bunching & acceleration



Electron Linear Accelerator

KEK electron / positron linac

Main Elements

Electron Gun, Positron Source

Bunching Section: Sub-Harmonic Buncher, Pre-buncher, Buncher

RF System: Klystron, Modulator, RF Monitor

Accelerator Sections

Magnet System (inc. power supply):
Magnetic Lens, Solenoid, Quadrupole, Bend, Steering, Sextupole

Beam Monitor System
Profile (Screen / Wire) , Position, Bunch, Radiation

Vacuum System

Control System: Computer, Trigger, Software...

Alignment system

Safety interlock system

Facility: Power Supply, Water, Air, Room Temperature...

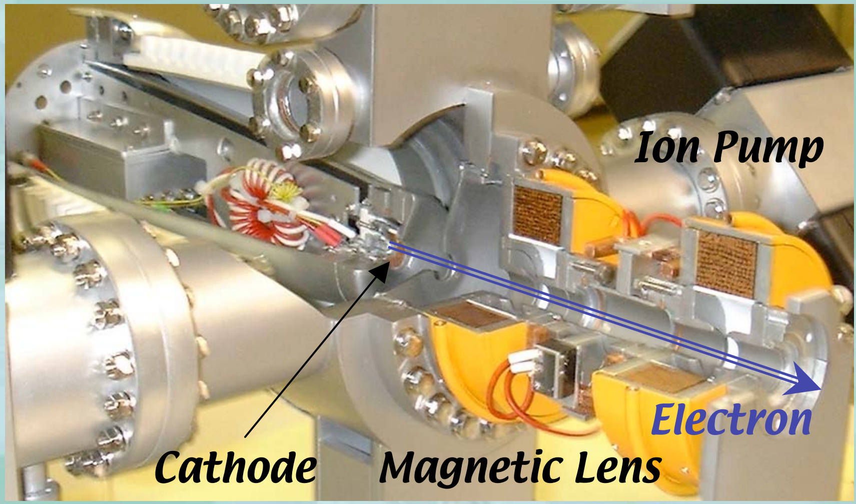
Electron Linear Accelerator

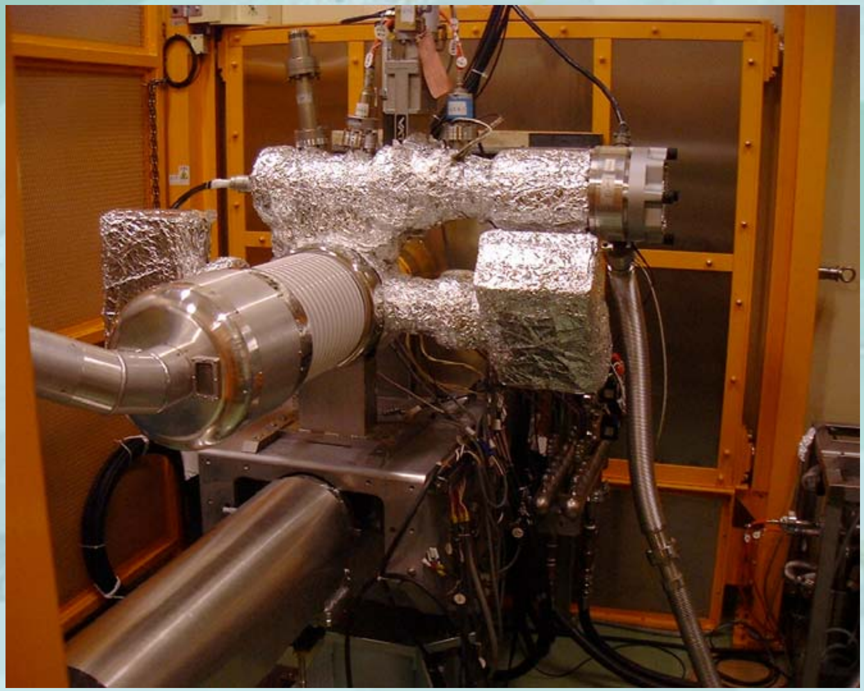
KEK electron / positron linac

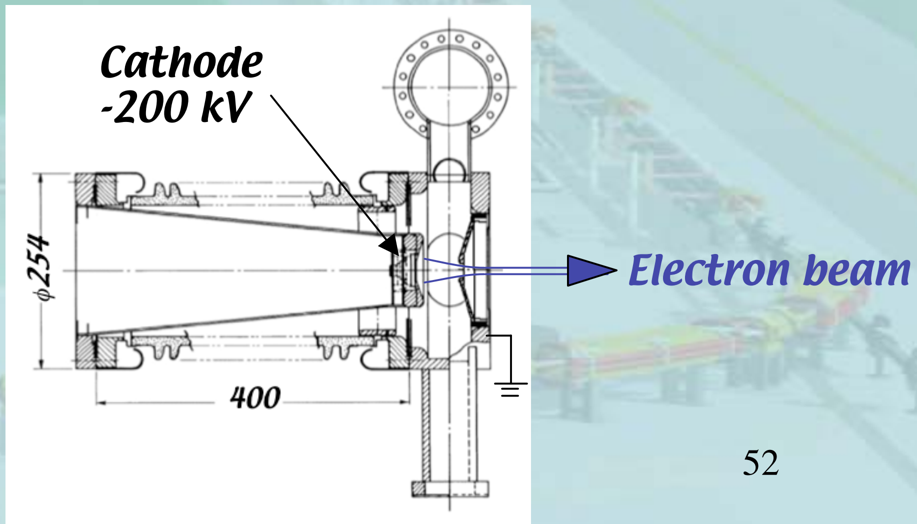
KEK Electron Gun

Thermoionic triode
Acceleration voltage: 200 kV
Pulse length: 1-2 ns
Maximum charge: 20 nC

The model of the electron gun





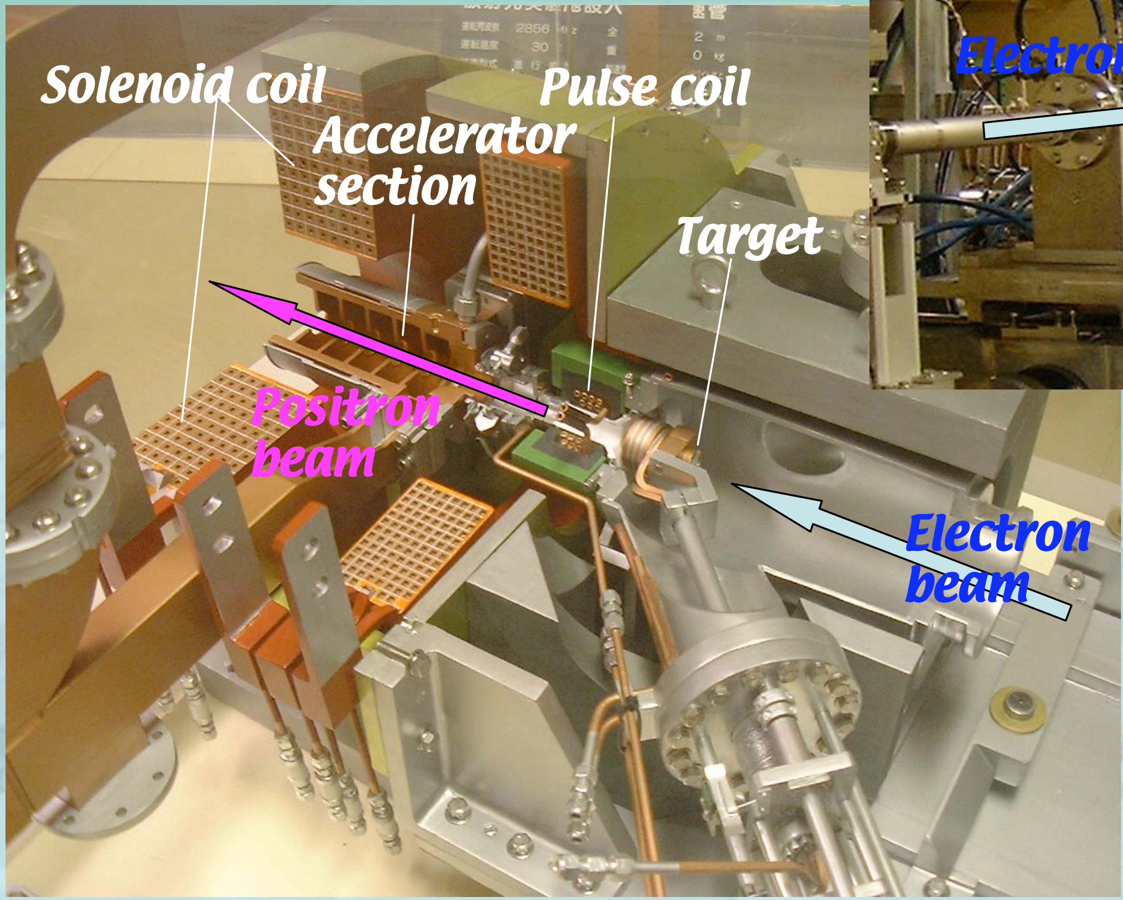


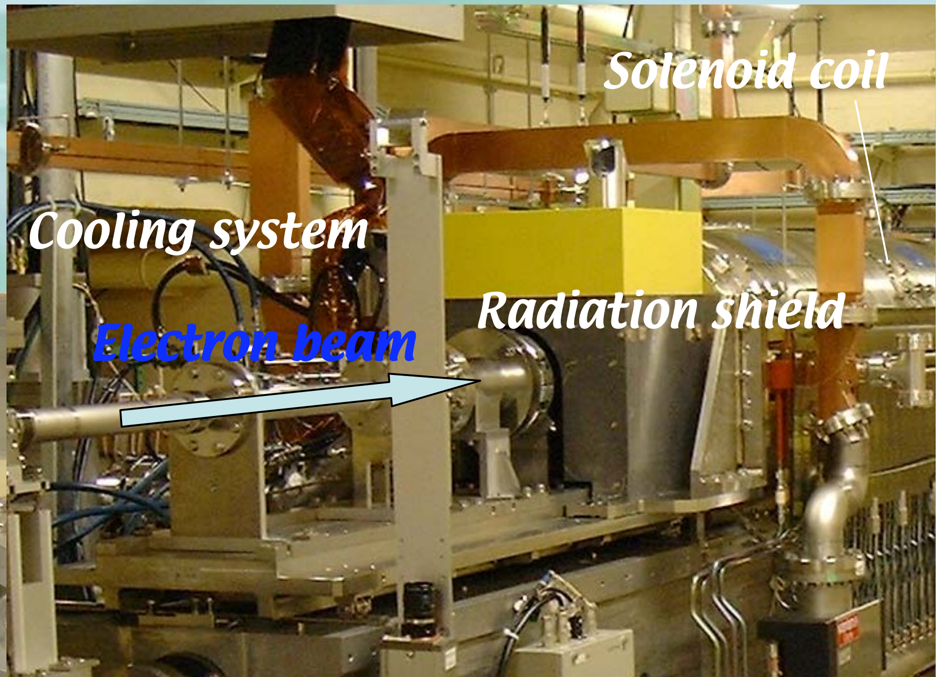
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Positron Source

tungsten target
pulse & solenoid coils

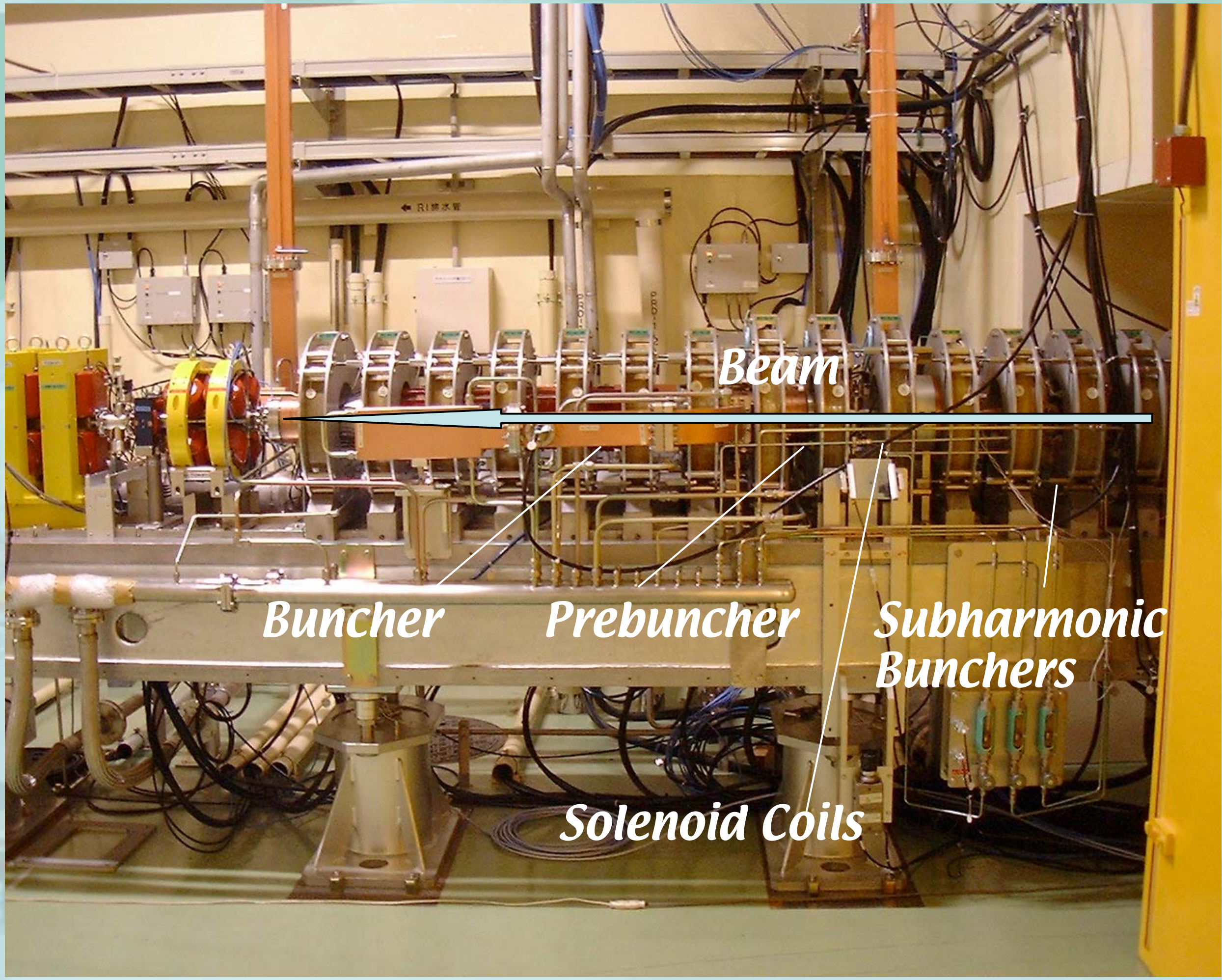




Electron Linear Accelerator

KEK electron / positron linac

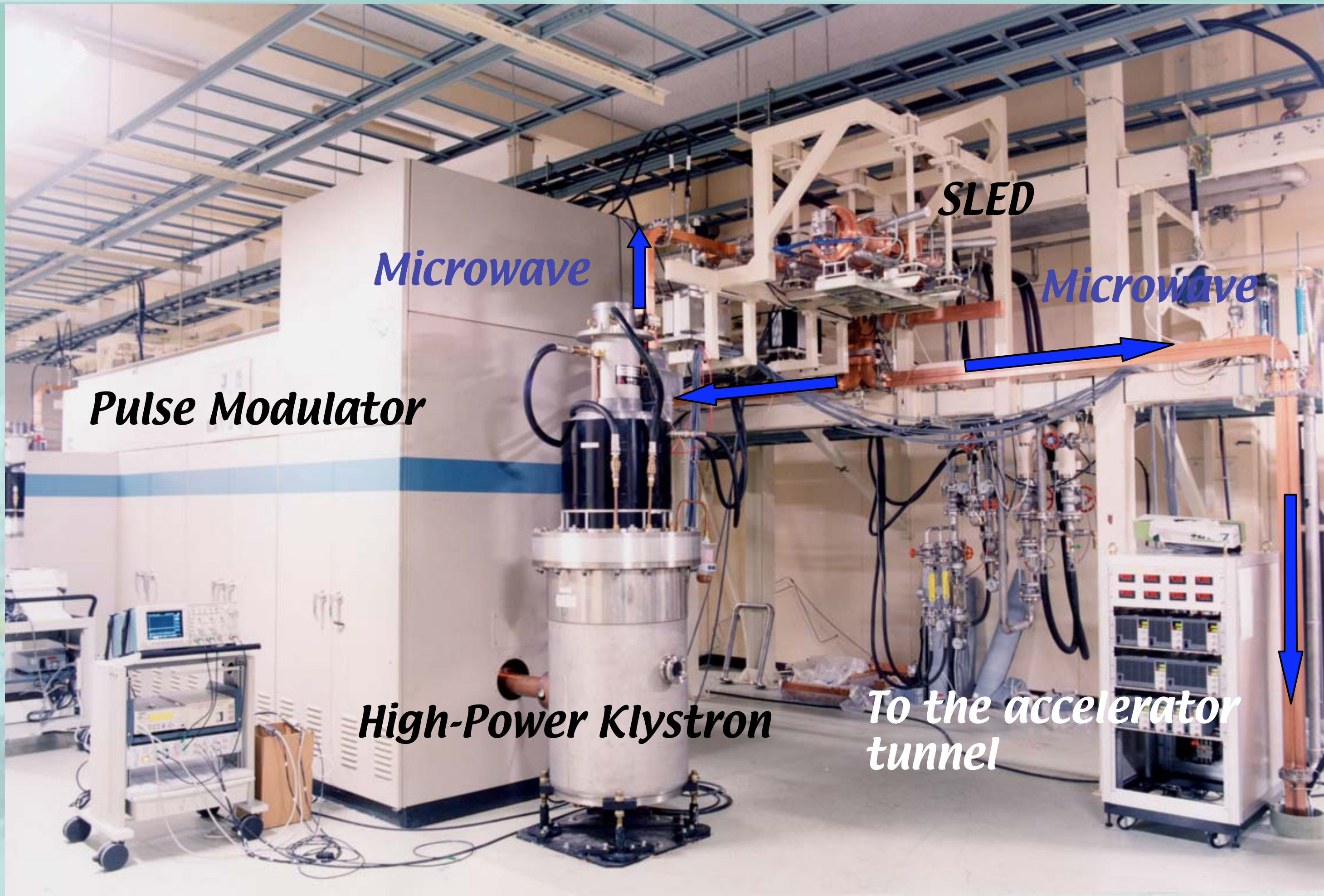
KEK Linac Bunching Section



Electron Linear Accelerator

KEK electron / positron linac

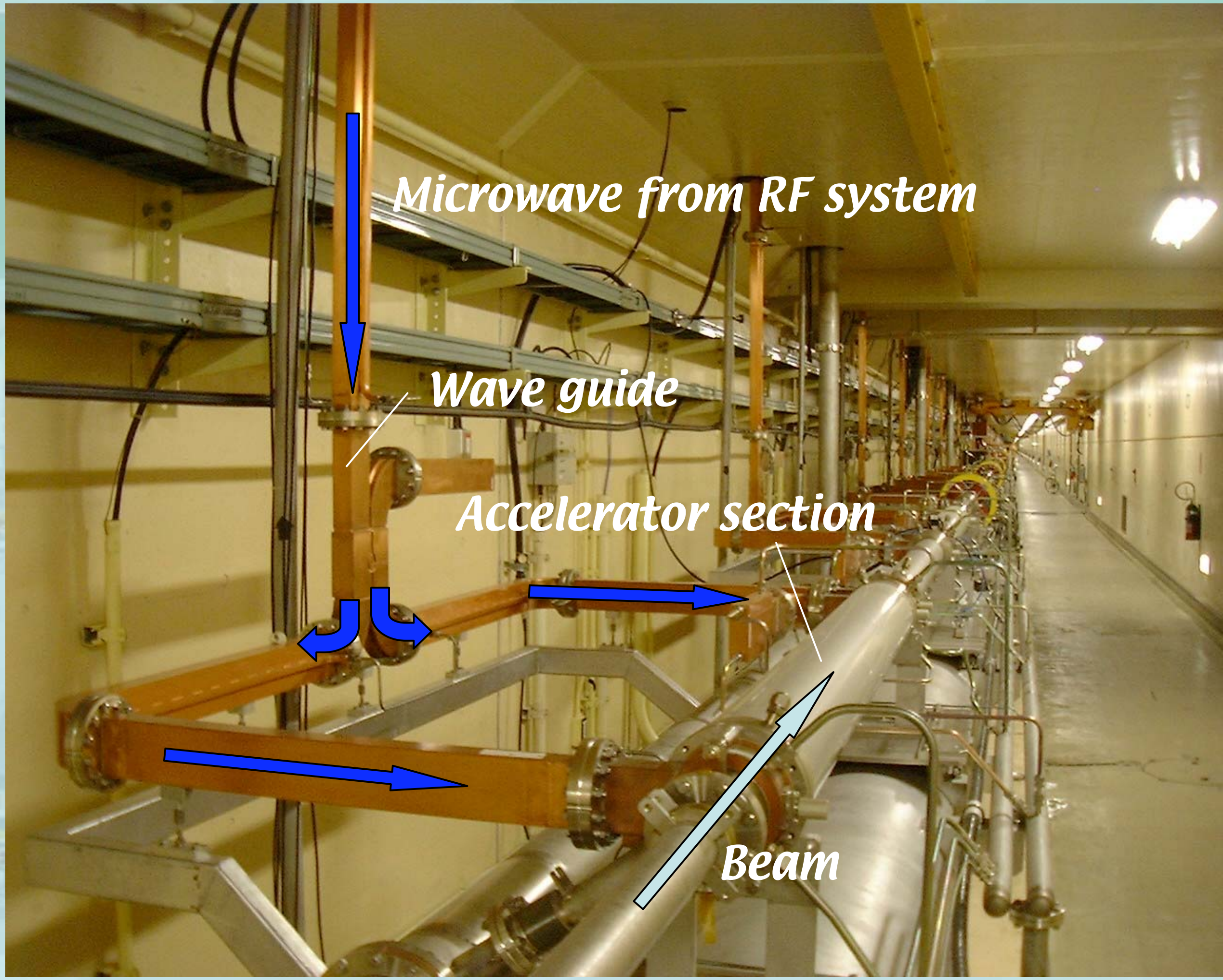
KEK Linac RF system : 60 units (klystron, Modulator, SLED...)



Electron Linear Accelerator

KEK electron / positron linac

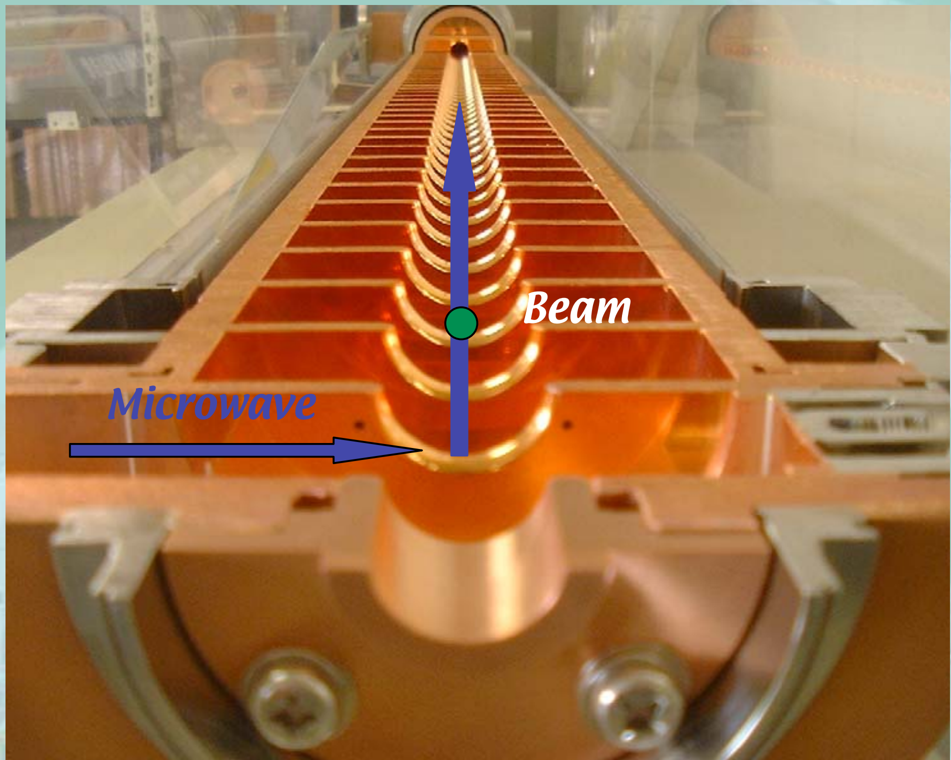
KEK Linac Acceleration System in Tunnel : 240 accelerator sections



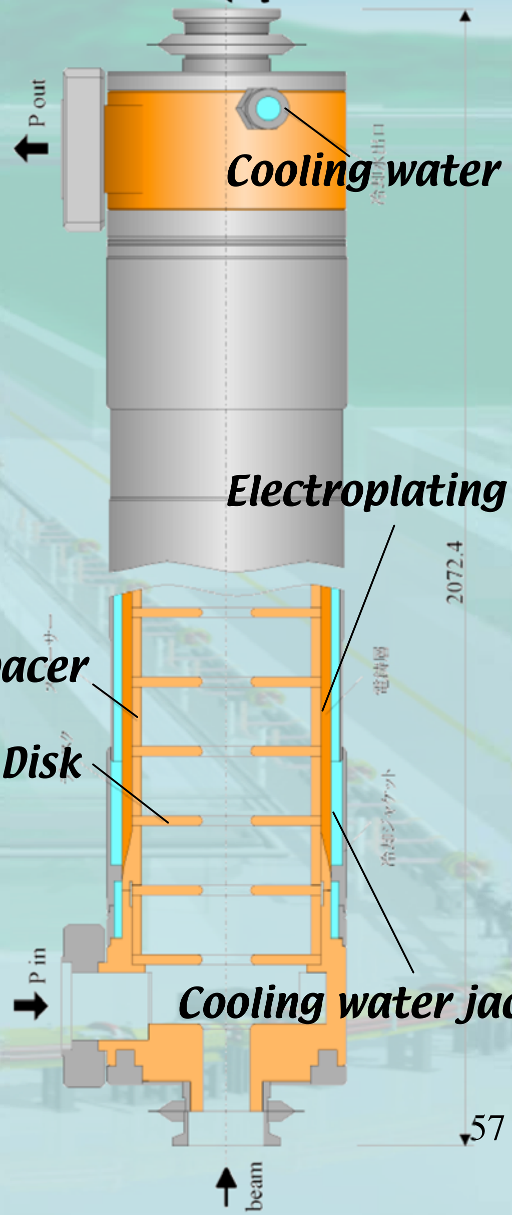
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Accelerator Sections



Half-cut two-meter long accelerator section

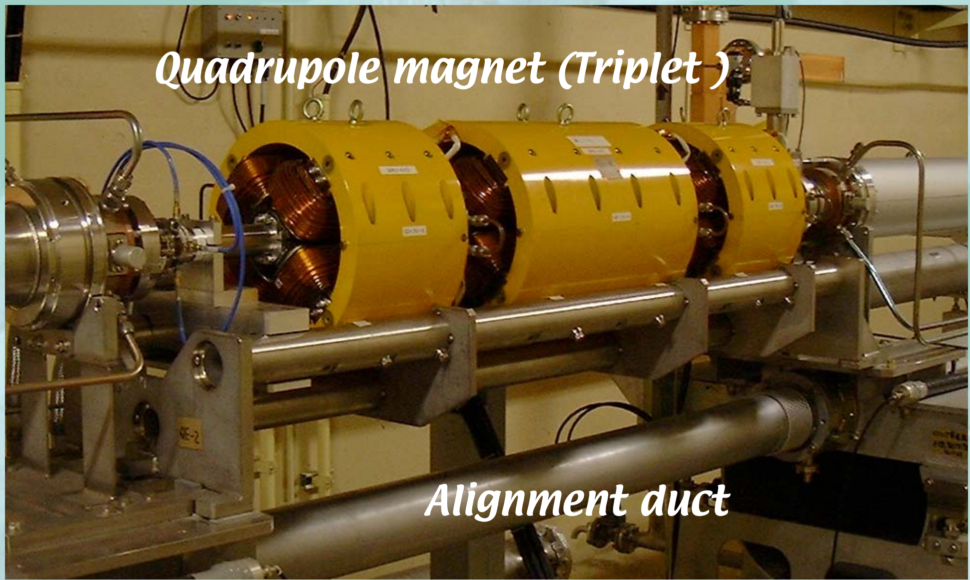


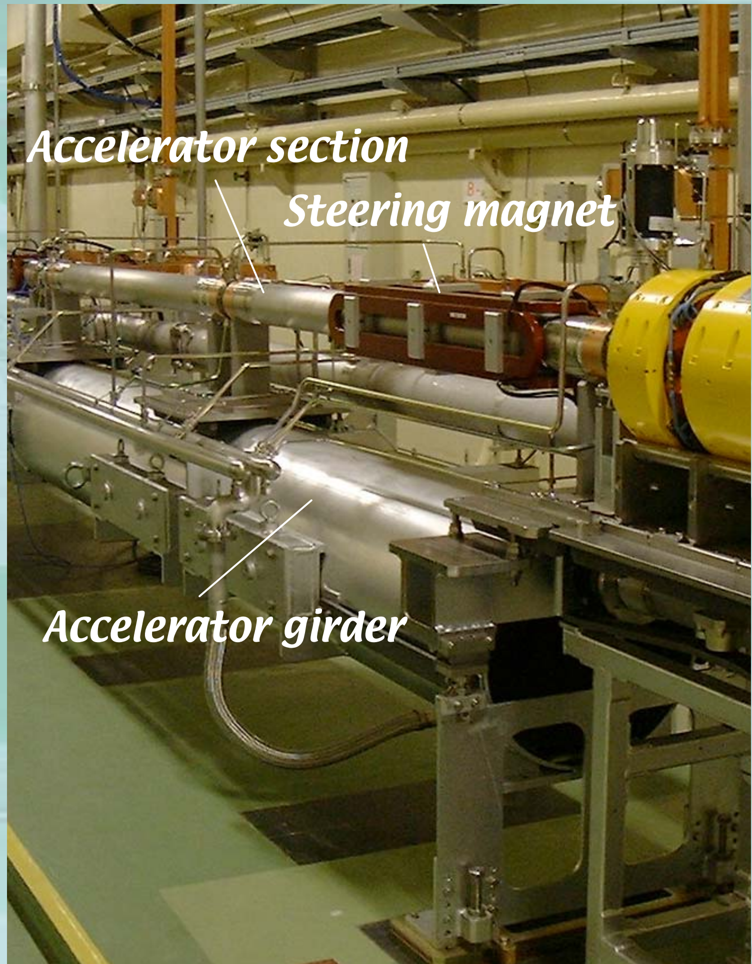
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Magnet System: total 390 sets

100 quadrupoles
(triplet 50, doublet 20, singlet 30)
17 bends, 240 steerings
30 solenoids, 1 pulse coil for positrons



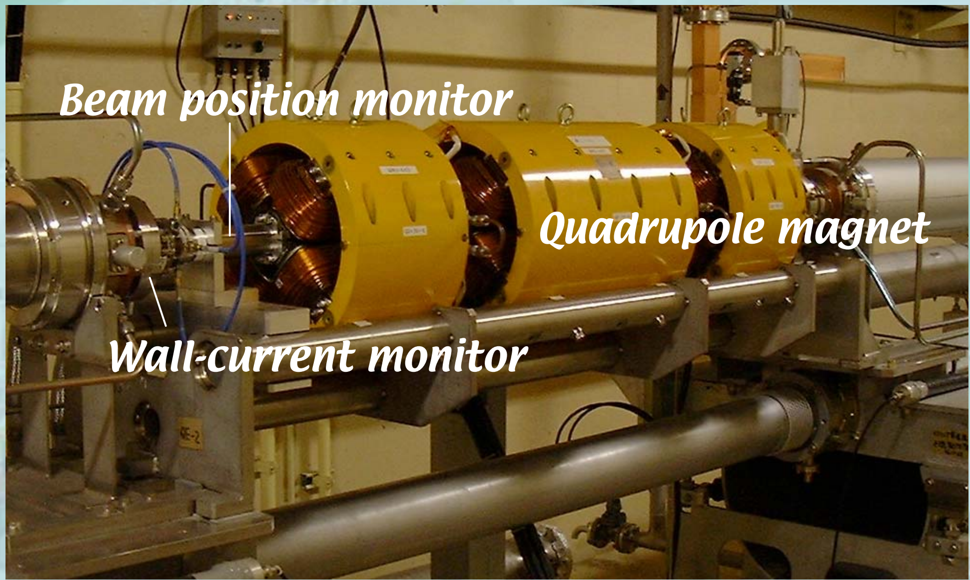


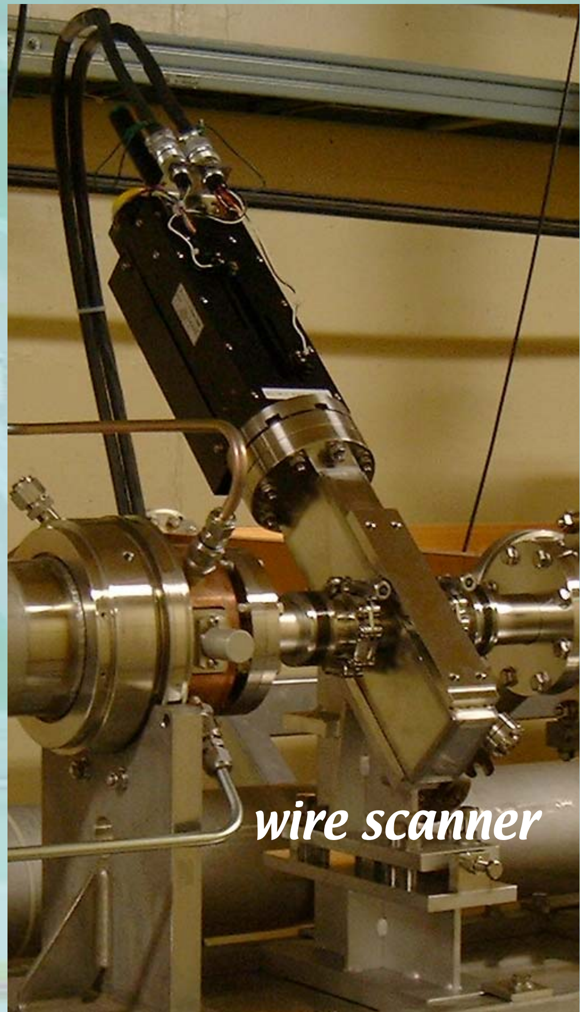
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Beam Monitor System:

100 beam position monitors
4 bunch monitors (OTR monitors)
132 profile monitors
(12 wire scanners, 120 screens)
5 current monitors
(for charge-limit regulations)



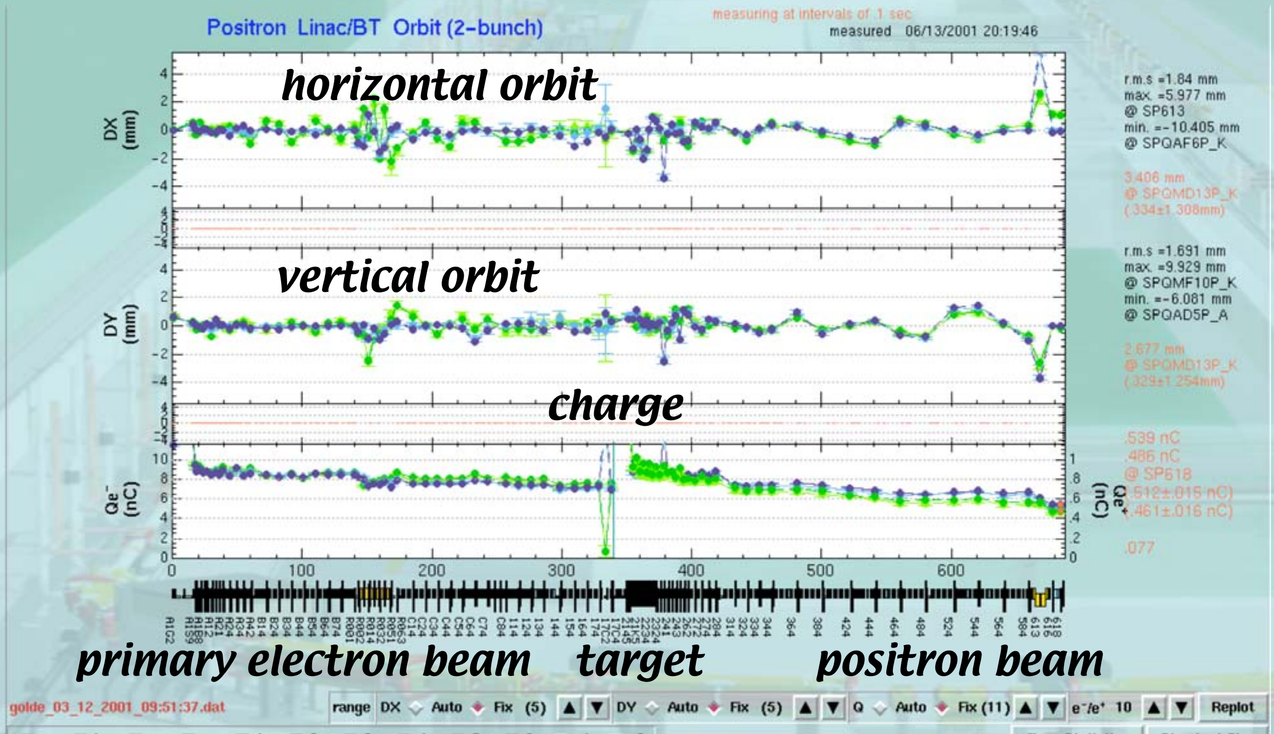


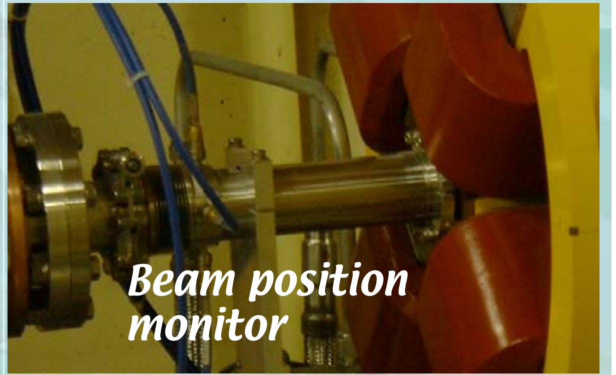
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Beam Monitor System:

Beam diagnosis : beam orbit measurements
Example : high-current electron beam
positron beam



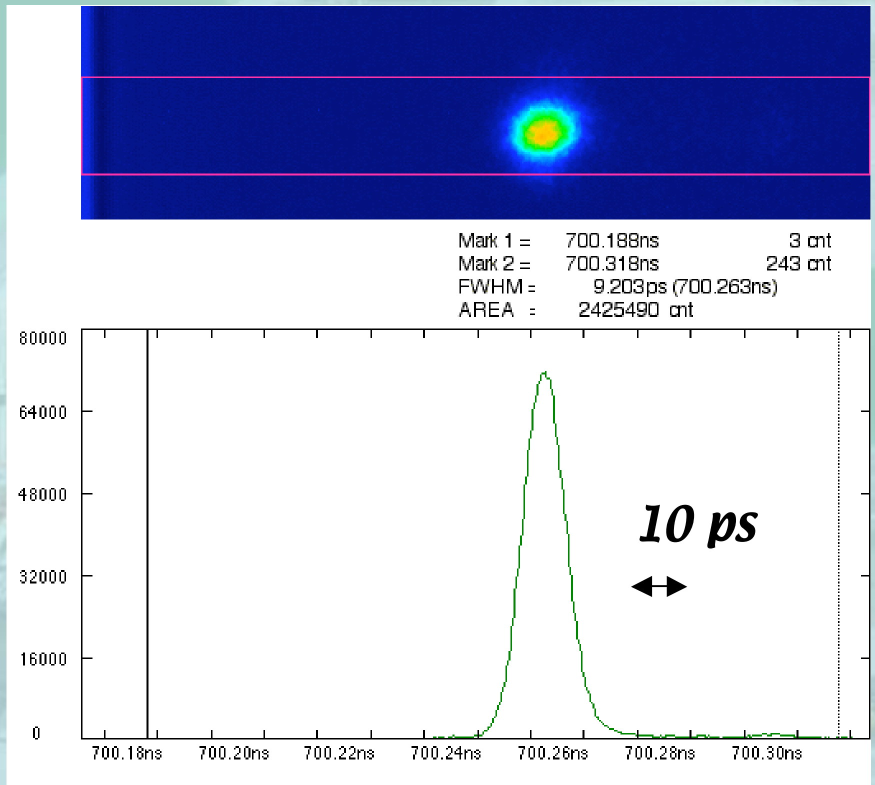


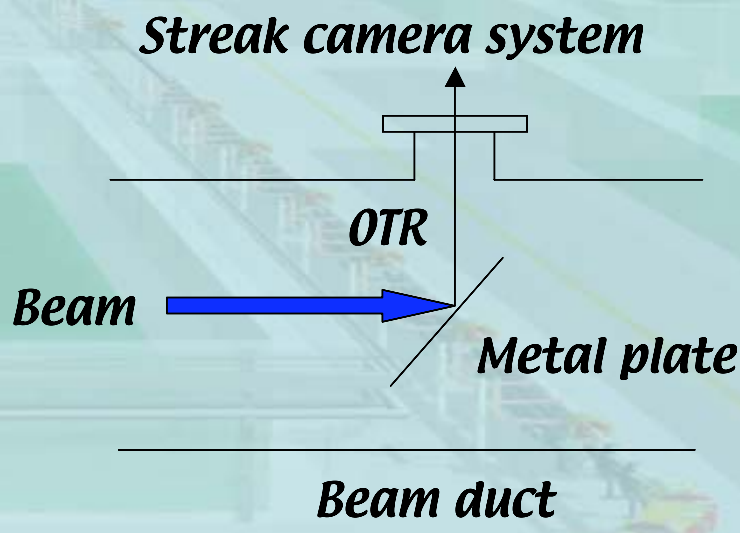
Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Beam Monitor System:

Beam diagnosis : bunch-length measurements by ORT & streak camera
Example : high-current electron beam for positron production





OTR: Optical Transition Radiation

10-nC, single-bunched beam with a bunch length of 3.9 ps (σ)

Example: Beam Diagnosis of KEKB linac

Beam Characteristics for KEKB Sep. 2006 - Jun. 2007

	Electron	Positron
Beam Energy	8 GeV	3.5 GeV
Charge (BT End)	0.9 nC/pulse (×2)	0.5×2 nC/pulse
Emittance ($\gamma\varepsilon$) (ε)	1.1×10^{-4} m 7.0×10^{-9} m	1.7×10^{-3} m 2.5×10^{-7} m
$\Delta E/E$ (1σ) (90%)	0.05 % 0.17 %	0.15 % 0.50 %
Injection Rate (CIM: 10 Hz)	0.4 - 0.6 mA/sec (×2)	0.3 mA/sec

CIM: Continuous Injection Mode

Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Vacuum System:

222 ion pumps
85 vacuum gauges
59 gate valves

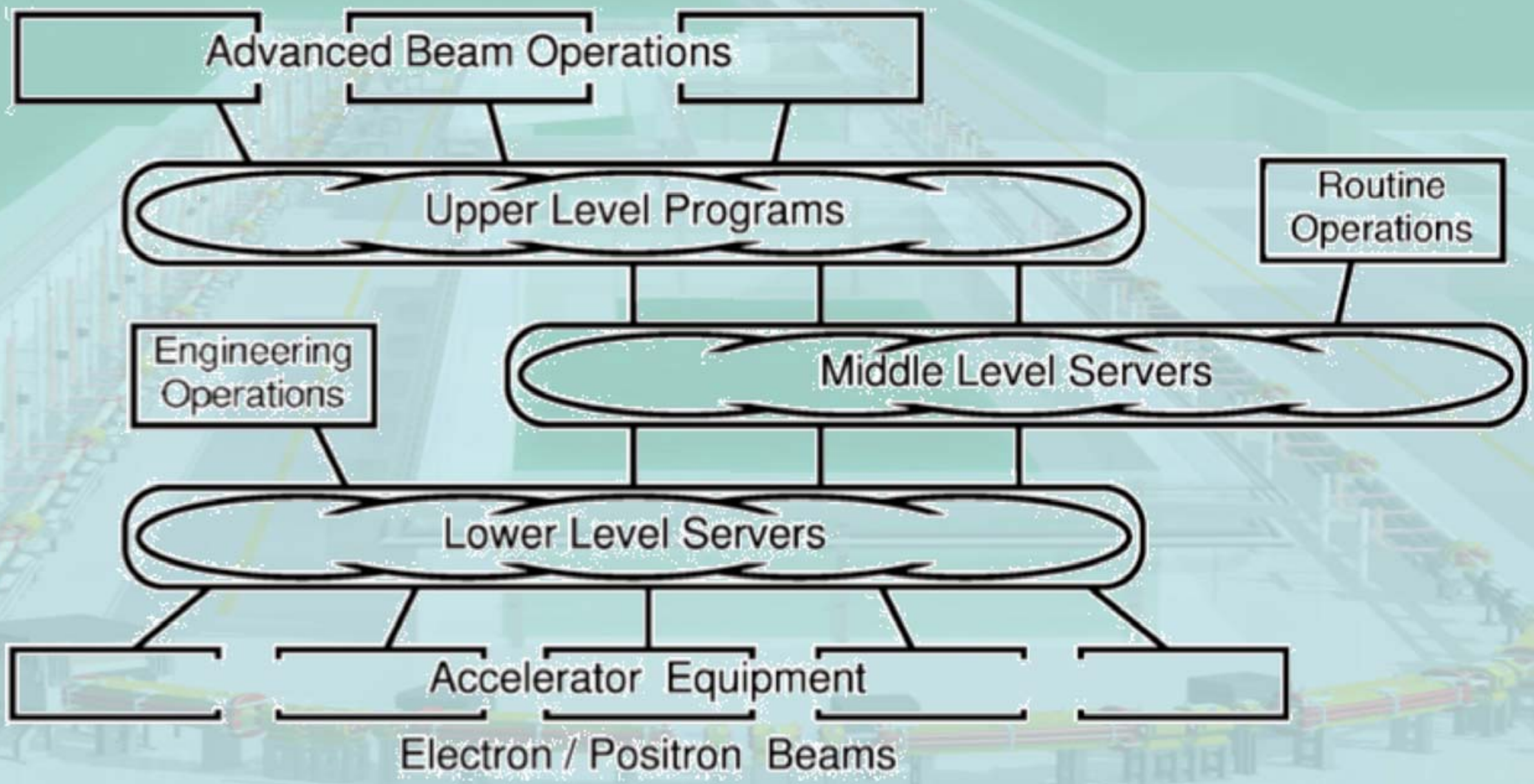
Total length : 645 m
Total surface area: 750 m^2
Total volume: 16 m^3
Pressure in beam lines : 10^{-6} Pa
(< 10^{-8} Pa for the electron gun)
In linacs, the conductance is generally small in beam lines.

Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Control System: UNIX and device controllers with home-made RPCs (Remote Procedure Call) for communication

Control architecture: Three software layers



Logical view of control system processes

Electron Linear Accelerator

KEK electron / positron linac

KEK Linac Control System:

Beam control by many feedback loops (>30):

- Gun high voltage
- Energy
- Orbit
- RF power/phase
- Trigger timing

File Checktime — Linac Feedback Status — 18:31 v1.3.0

summay — Thu Jan 31 18:29:34 2002

Title	Name	Display	Hostname	Start	Status1	Status2	Status3	LastGet	LastPut		
	tkfb-arc.tcl	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	Denied		17:28:34	17:26:05	start	stop
Energy AR	tkfb-are	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		17:28:35	17:28:29	start	stop
GU_A1_G HV	tkfb-guna1	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:07	18:29:42	start	stop
GU_A1_G Delay e-	tkfb-guna1dle #2	xp400d:0	plum.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:23	18:15:23	start	stop
GU_A1_G Delay e+	tkfb-guna1dlp	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:18	18:29:19	start	stop
GU_CT_G HV	tkfb-gunct	xp400d:0	plum.kek.jp	Run	Satisfied	---		18:29:39	---	start	stop
Energy KEKB e- 58	tkfb-kbe	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		17:06:36	17:06:29	start	stop
Energy KEKB e- BT	tkfb-kbebt	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:38	17:46:01	start	stop
Energy KEKB e+ 61	tkfb-kbp	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:46	18:29:48	start	stop
Energy KEKB e+ BT	tkfb-kbpbt	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 1XY KEKB e+	tkfb-orbit1XYpk	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 2XY KEKB e-	tkfb-orbit2XYek	xp400g:0	poplar	Run	Beam elepos Denied	---		18:15:35	18:15:27	start	stop
Orbit 5X KEKB e-	tkfb-orbit5Xek	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:31	18:15:31	start	stop
Orbit 5X KEKB e+	tkfb-orbit5Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:42	18:29:42	start	stop
Orbit 5Y KEKB e-	tkfb-orbit5Yek #2	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:36	18:15:27	start	stop
Orbit 5Y PF/AR	tkfb-orbit5Ypa	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:30	17:26:02	start	stop
Orbit 5X PF/AR	tkfb-orbit5pfar	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:23	17:28:10	start	stop
Orbit 6X KEKB e+	tkfb-orbit6Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:45	start	stop
Orbit 6Y KEKB e+	tkfb-orbit6Ypk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Denied		18:29:45	18:29:44	start	stop
Orbit A0X KEKB e+	tkfb-orbitA0Xpk	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit A0Y KEKB e+	tkfb-orbitA0Ypk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1X KEKB e+	tkfb-orbitA1Xpk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1Y KEKB e+	tkfb-orbitA1Ypk	xp400d:0	poplar	Stop	Satisfied	---		Jan 29	Jan 29	start	stop
Orbit BX KEKB	tkfb-orbitBX	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit BY KEKB	tkfb-orbitBY	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit RX KEKB	tkfb-orbitRX	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:48	18:29:48	start	stop
Orbit RY KEKB	tkfb-orbitRY	xp400g:0	poplar	Run	Satisfied	---		18:29:44	18:29:43	start	stop
Orbit 57-61 PF	tkfb-orbitpf #2	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:35	16:48:41	start	stop
Energy PF BT	tkfb-pfe #2	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:36	09:12:22	start	stop
Energy R0 e-	tkfb-r0	xp400g:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:49	18:29:48	start	stop
SH_A1_S1 Power	tkfb-shb1 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:40	18:29:29	start	stop
SH_A1_S1 Phase e-	tkfb-shb1phe	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S1 Phase e+	tkfb-shb1php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S8 Power	tkfb-shb2 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:43	18:29:33	start	stop
SH_A1_S8 Phase e+	tkfb-shb2php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop

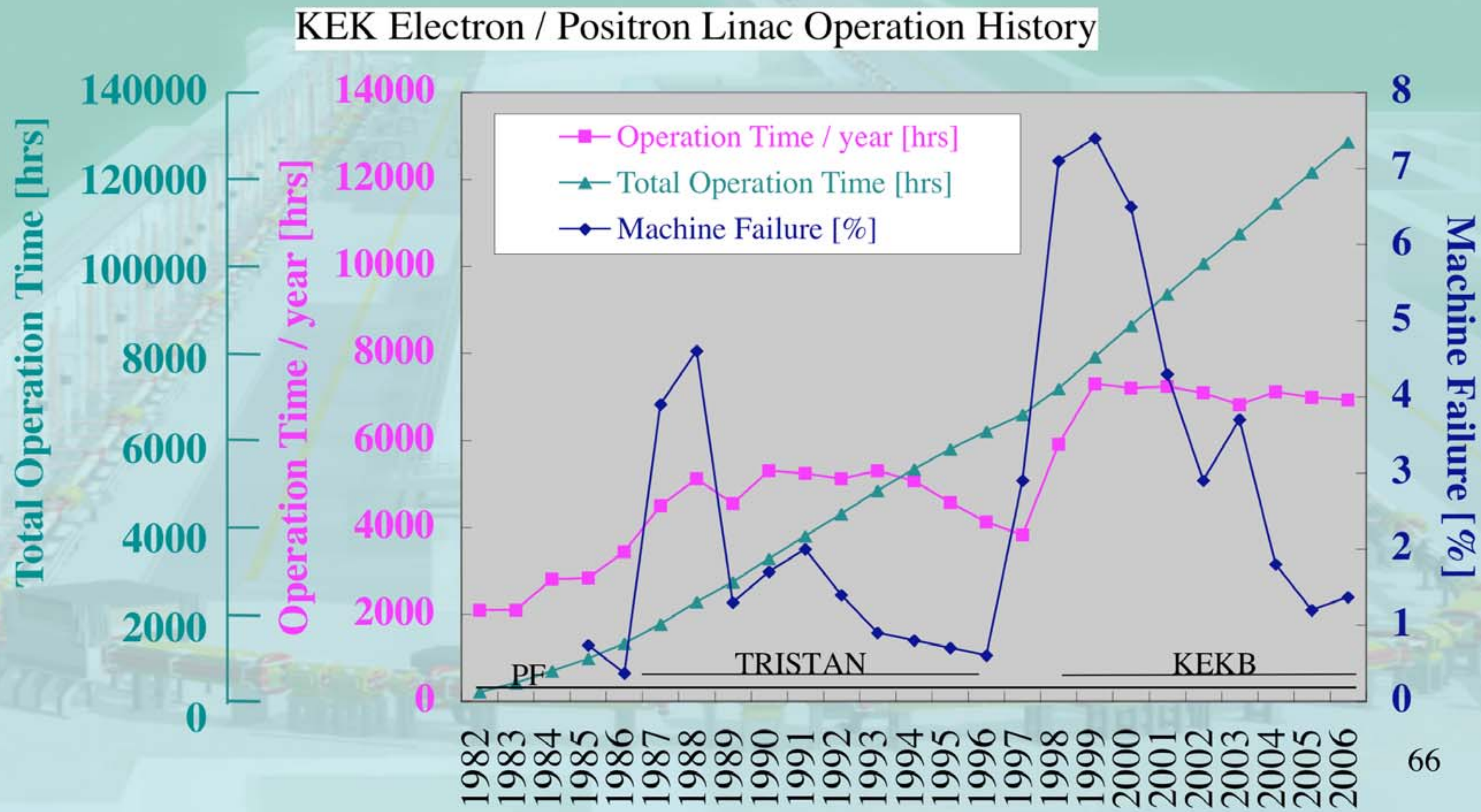
Last Update: Jan 31 18:29:49 — Update

Electron Linear Accelerator

KEK electron / positron linac

KEK Linac operation statistics:

Annual operation time: >7000 hours = 10 months
High availability of 98 % has been maintained.



(Advanced Concepts)

High-gradient acceleration:
- *Laser plasma acceleration*
- *Electron beam driven acceleration*

High-brightness electron-beam generation: (Shintake's lecture)
- *XFEL(LCLS SLAC, SCSS Spring8)*
- *RF Gun*

ERL: Energy Recovery Linac: (Shintake's lecture)

Instead of stating my Conclusion

Important lessons:

[1] Injector performances determine the beam characteristics in linacs.

"How it ends depends on how it begins"

[2] The accelerator is just one of the science instruments, but without knowing science, especially physics very well, it can not be even constructed and operated stably so that it could not really serve as a good and efficient tool for science experiments.

At first there was no wall between accelerator and science.
Users used to construct and operate accelerators.
Today we need mutual exchange for future development.

"We build too many walls and not enough bridges."
(Isaac Newton)

=====>Please join us to develop new accelerators.