Linear Accelerator (LINAC)

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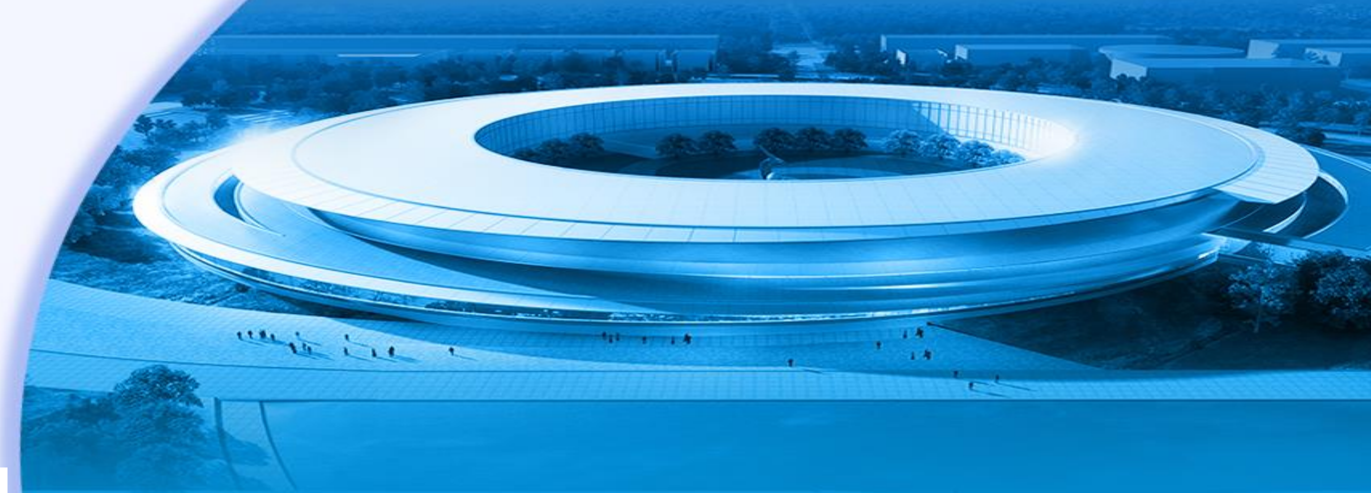

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12TH INTERNATIONAL ORGANIZATION OF CHINESE PHYSICISTS AND ASTRONOMERS ACCELERATOR SCHOOL
OCPA-2025

Outline

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01 Introduction and basic ideas
Basic definition and Brief history

02 RF parameters for SW or TW structures
Q, Shunt Impedance, Transient Factor...

03 Main parameters of a LINAC
Energy spread, emittance, ...

04 Basic Beam Dynamics
Beam Loading and Bunching

05 How to Make a Linac
Basic processes of manufacturing, assembly and commissioning

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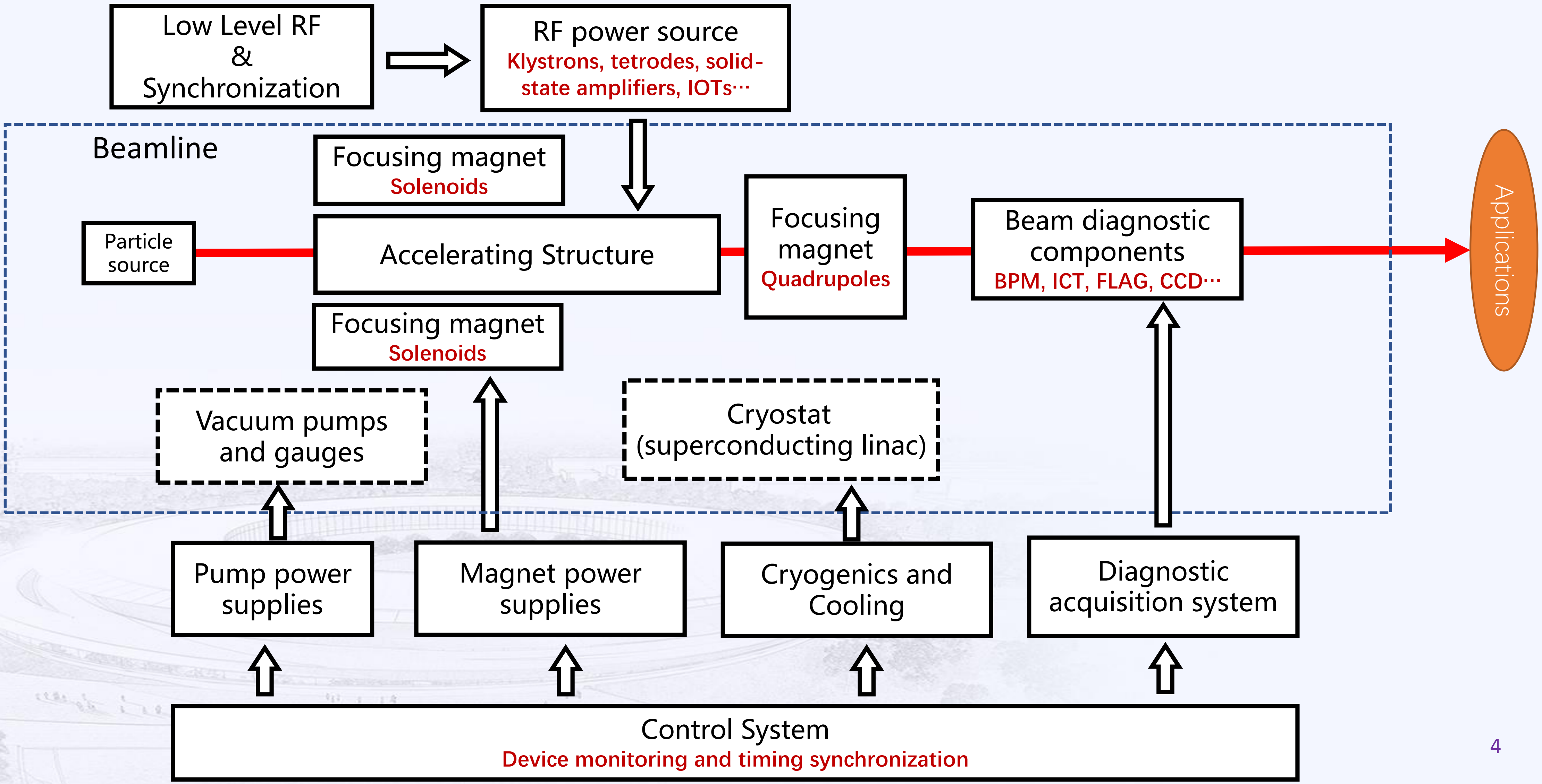
LINAC: Basic Definition and main components

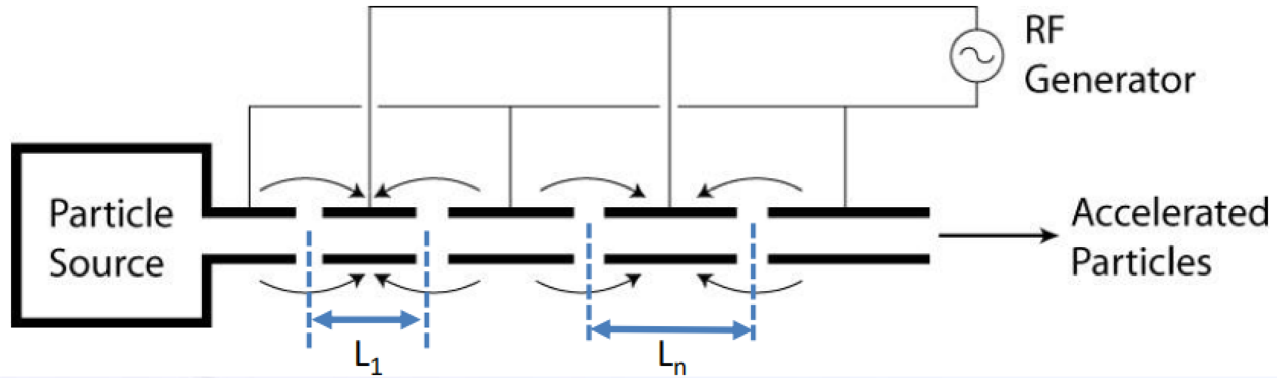
LINAC (linear accelerator): a system for accelerating charged particles **through a linear trajectory** using electromagnetic fields.



Early LINAC

- Wideroe "Drift Tube Linac" (first RF accelerator)
  - Basic idea: Particles are accelerated between the gaps of electrodes connected to the two poles of an **AC generator**.
  - Ising proposed the concept in 1924
  - Wideroe realized it in 1927
  - The particles do not see any force while travelling inside the tubes (equipotential regions) and are accelerated across the gaps.
  - If the length of the tubes increases with the particle velocity during the acceleration such that the time of flight is kept constant and equal to half of the RF period, the particles see a synchronous accelerating voltage and get an energy gain of $\Delta E = q\Delta V$ at each gap

Rolf Wideroe



Basic Idea -1

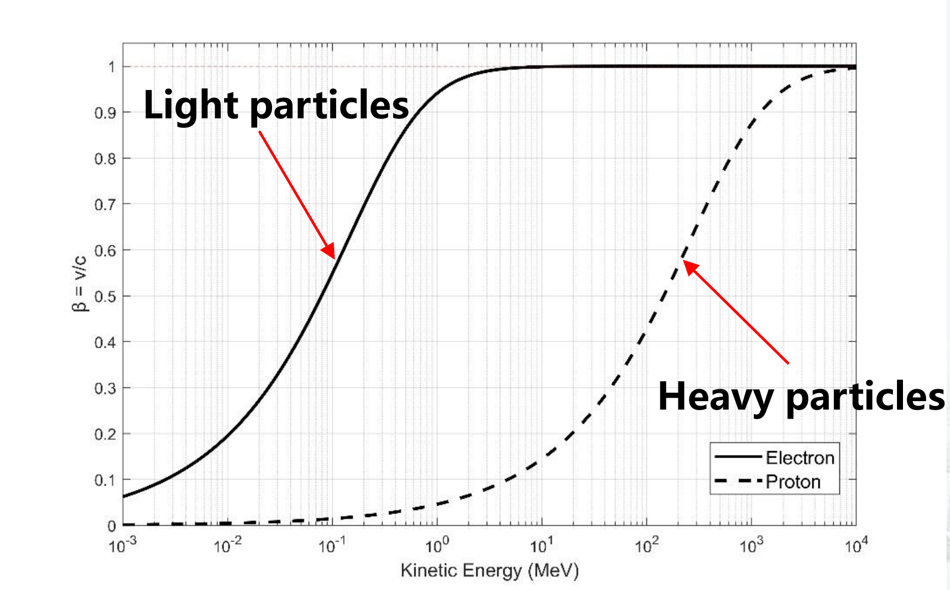
Particle velocity β and relativistic factor γ

Lactures on **Linear Accelerators**, by *David Alesini* (2016)

- rest energy E_0 (=m_0c^2)
- total energy E
- mass m
- velocity v
- Kinetic energy $W = E - E_0$

$$W = (\gamma - 1)m_0c^2 \approx \frac{1}{2}m_0v^2 \quad \text{if } \beta << 1$$

$$\beta = \sqrt{1-\frac{1}{\gamma^2}} = \sqrt{1-\left(\frac{E_0}{E}\right)^2} = \sqrt{1-\left(\frac{E_0}{E_0+W}\right)^2}$$



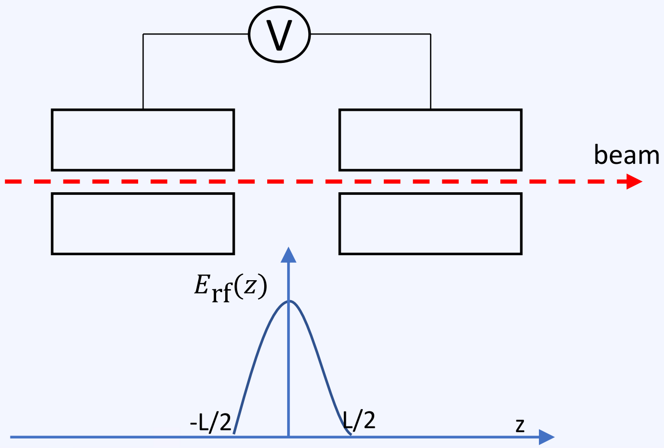
⇒ **Light particles** (as **electrons**) are practically fully relativistic (β≅1, γ>>1) at relatively low energy and **reach a constant velocity** (~c). The acceleration process occurs at constant particle velocity.

⇒ **Heavy particles** (**protons and ions**) are typically weakly relativistic and **reach a constant velocity only at very high energy.** The velocity changes a lot during acceleration process.

⇒ This implies **important differences** in the technical characteristics of the **accelerating structures**. In particular for protons and ions we need different types of accelerating structures, **optimized for different velocities** and/or the accelerating structure has to vary its geometry to take into account the velocity variation.

Basic Idea -2

Electric field and energy gain in a single accelerating gap



$$\Delta V = V_{RF}\cos(\omega_{RF}t) \quad \omega_{RF} = 2\pi f_{RF} = \frac{2\pi}{T_{RF}}$$

$$V_{RF} = \int_{gap} E_{RF}(z)dz \quad E_z(z,t) = E_{RF}(z)\cos(\omega_{RF}t)$$

$$E_z(z,t)\Big|_{\substack{\text{seen}\\\text{by}\\\text{particle}}} = E_{RF}(z)\cos\left[\omega_{RF}(t+t_{inj})\right] = E_{RF}(z)\cos(\omega_{RF}t+\phi_{inj}) \qquad \phi_{inj} = \omega_{RF}t_{inj}$$

This simplification assumes that the electric field distribution is symmetrical about the center.

$$\Delta E = q\int_{gap} E_z(z,t)\Big|_{\substack{\text{seen}\\\text{by}\\\text{particle}}} dz = q\int_{-L/2}^{+L/2} E_{RF}(z)\cos\left(\omega_{RF}\frac{z}{v}+\phi_{inj}\right)dz = q\int_{gap} E_{RF}(z)dz \, \frac{\int_{gap} E_{RF}(z)\cos\left(\omega_{RF}\frac{z}{v}\right)dz}{\int_{gap} E_{RF}(z)dz}\cos(\phi_{inj})$$

V_{RF} — *T*: Transit time factor — Injection phase

Transit time factor reflects the efficiency of particles obtaining energy from the electric field, it is a dimensionless coefficient (less than 1).

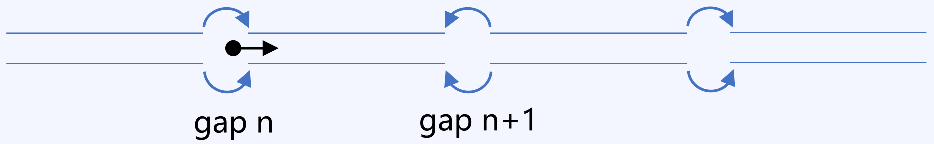
$$\Delta E = qV_{RF}T\cos(\phi_{inj}) = q\hat{V}_{acc}\cos(\phi_{inj}) = qV_{acc}$$

$\hat{E}_{acc} = \hat{V}_{acc}/L$ (Average accelerating field in the gap)

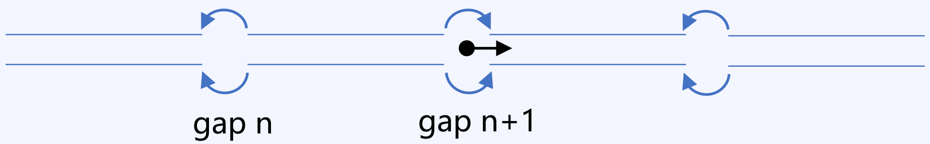
$E_{acc} = V_{acc}/L$ (Average accelerating field seen by the particle)

Basic Idea -3

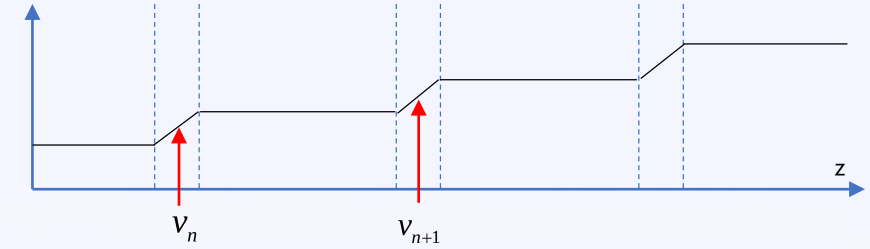
In a DTL structure, where the maximum energy obtained by each accelerating gap particle is $\Delta E_n = qV_{acc}$, and the speed of the particle increases step by step.



phase flips when the particles travel to the next gap



$$v_n = c\beta_n = c\sqrt{1-\frac{1}{\gamma_n^2}} = c\sqrt{1-\left(\frac{E_a}{E_n}\right)^2}$$



Synchronization conditions : $t_n = \frac{L_n}{\bar{v}_n} = \frac{T_{\text{RF}}}{2} \Rightarrow L_n = \frac{1}{2}\bar{v}_n T_{\text{RF}} = \frac{1}{2}\bar{\beta}_n c \frac{\lambda_{\text{RF}}}{c}$ ⇨ $L_n = \frac{1}{2}\bar{\beta}_n \lambda_{RF}$

$L_n \ll \lambda_{RF}$ for technical limitations (e.g. For f=1MHz, λ_{RF}=300m), so $\beta \ll 1$, can **not be applied to accelerate relativistic particles**

Acceleration gradient : $\frac{\Delta E}{\Delta L} = \frac{qV_{acc}}{L_n} = \frac{2qV_{acc}}{\lambda_{RF}\bar{\beta}_n}$

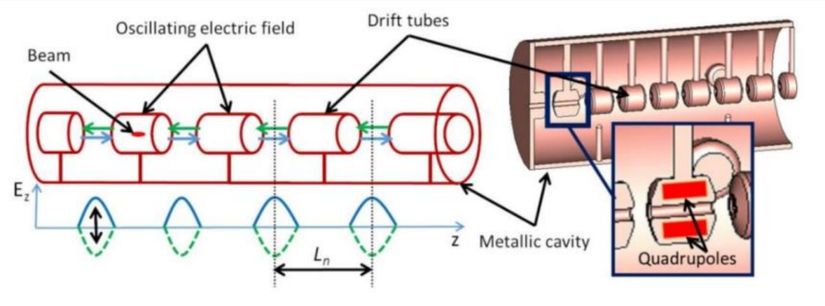
When the particle velocity becomes higher, the drife tube becomes longer and the average acceleration gradient decreases.

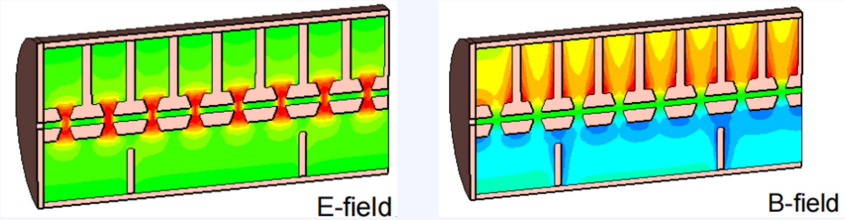
Increasing the acceleration gradient requires a small λ_{RF} (higher frequency).

Basic Idea -4

Solution: A closed cavity with a resonant freq. that matches the freq. of the RF generator

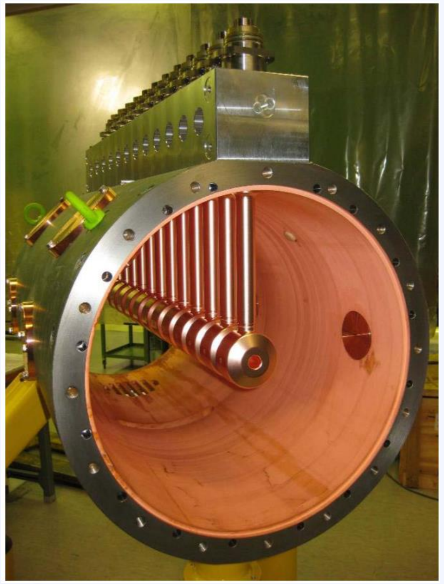
After WW-II, driven by military technology needs (such as radar), **high-frequency, high-power microwave power technology has developed** rapidly. However, **the concept of drift tubes is not applicable to small λ_{RF}** and its power loss is proportional to the RF frequency.





Alvarez structure diagram

- The Alvarez structure can be considered as a special DTL, where the electrodes are part of the resonant structure.
- The drift tube is connected to the inner wall of the cavity by metal rods, and the electric field is concentrated between the gaps (as shown in the figure above).
- Since the Wideroe structure is no longer used, the Alvarez structure is called as DTL.
- When the beam is in the "drift tubes", the electric field is in a deceleration state (green dotted line in the figure above).
- Works at '0-mode', so $L_n = \bar{\beta}_n \lambda_{RF}$
- Used to accelerate protons and ions, β=0.1-0.5, f=20-400MHz



CERN Linac4 (352 MHz)

Example : $\beta = 0.1$, $f_{RF} = 100\text{MHz}$, $\lambda_{RF} = 3\text{m}$, $L_n = 0.3\text{m}$

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RF parameters for SW structures -1

Basic parameters of a ‘naked’ cavity

ω_0: resonance frequency of the cavity

T : Transit time factor

V_{acc} : accelerating voltage

P_{diss} : dissipation power

$$P_{\text{diss}} = \iint_{\text{cavity wall}} \frac{1}{2} R_s H_{\tan}^2 \, dS$$

R_s : surface resistivity

NC cavity (Cu $R_s \approx$ 3 mΩ at 1 GHz)
SC cavity (Nb at 2 K $R_s \approx$ 10 nΩ at 1 GHz)

W : stored energy in cavity

$$W = \int_{\substack{\text{cavity}\\\text{volume}}} \left(\frac{1}{4}\varepsilon |\vec{E}|^2 + \frac{1}{4}\mu |\vec{H}|^2 \right) dV$$

R : Shunt impedance

$$R = \frac{\hat{V}_{\text{acc}}^2}{P_{\text{diss}}} \quad [\Omega]$$

Shunt impedance reflects the efficiency of the acceleration mode. It directly affects the cost of the accelerator

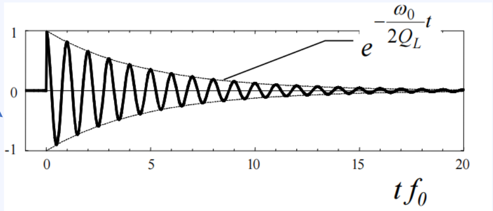
Other definitions

$$R = \frac{\hat{V}_{\text{acc}}^2}{2P_{\text{diss}}} \quad [\Omega]$$

$$Z = \frac{V_{\text{acc}}^2}{P_{\text{diss}}} \quad [\Omega]$$

Q : Quality factor

$$Q = \omega_0 \frac{W}{P_{\text{diss}}}$$



A quantity that evaluates the rate at which energy is dissipated within a cavity

R/Q : Only related to the structure and not to the material

$$\frac{R}{Q} = \frac{\hat{V}_{acc}^2}{\omega_0 W}$$

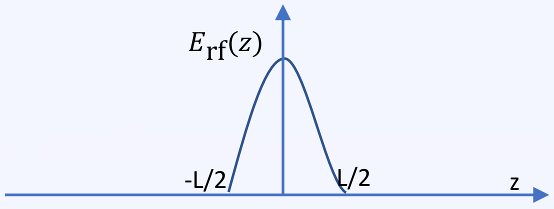
r : Shunt impedance per unit length

$$r = \frac{\left(\hat{V}_{\text{acc}} / L\right)^2}{P_{\text{diss}} / L} = \frac{\hat{E}_{\text{acc}}^2}{P_{\text{diss}} / L} \quad [\Omega / \text{m}]$$

RF parameters for SW structures -2

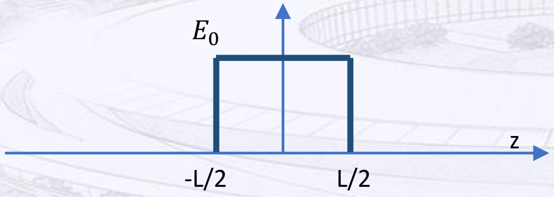
Transit time factor

- Transit time factor reflects the efficiency of particles obtaining energy from the electric field.
- Related to the field distribution in the gap and the particle velocity.
- T is different for each gap in DTL, and it is also a function of the time required to pass through the gap.

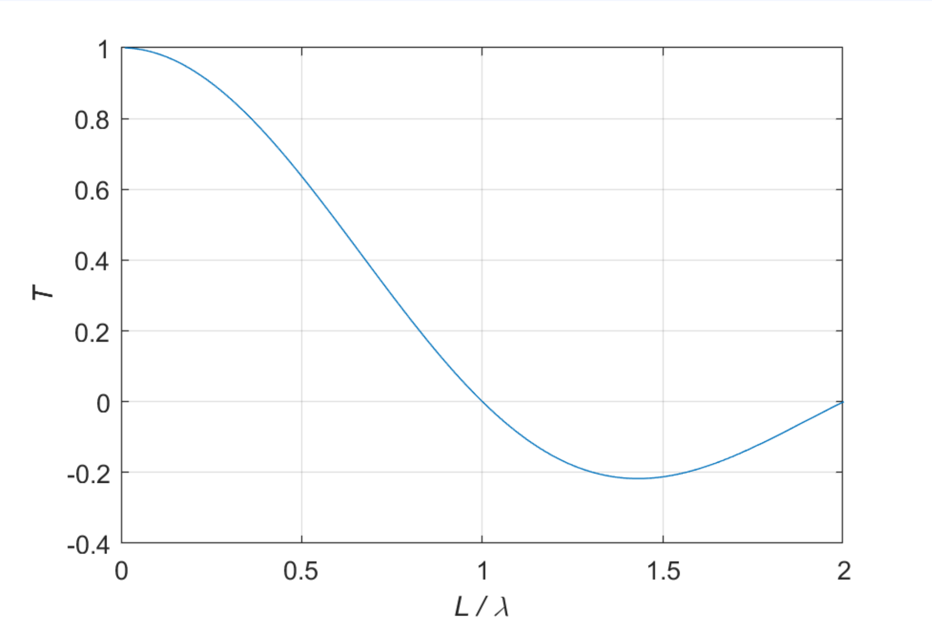


$$T = \frac{\int_{gap} E_{RF}(z)\cos\left(\omega_{RF}\frac{z}{v}\right)dz}{\int_{gap} E_{RF}(z)dz}$$

Assuming that the particle velocity in the gap is constant and the electric field distribution in the gap is uniform, T can be simplified to:



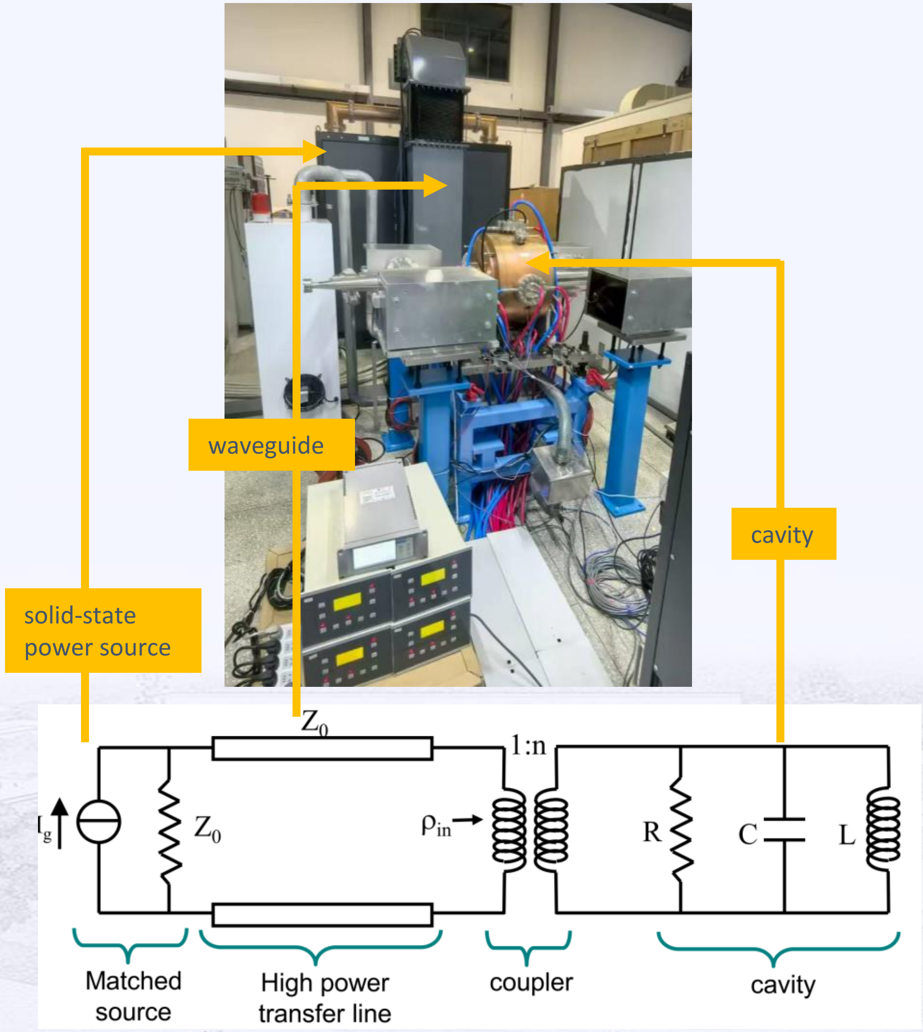
$$T = \sin\left(\frac{\pi L}{\lambda}\right) / \left(\frac{\pi L}{\lambda}\right)$$



T of each DTL unit is about 0.6-0.9 when the proton kinetic energy in the range of 0.75-100 MeV.

RF parameters for SW structures -3

Parameters of a ‘loaded’ cavity



equivalent circuit

No external power source

$$Q_0 = \omega_0 RC = \frac{R}{\omega_0 L}$$

Q_0 : Unloaded quality factor or intrinsic quality factor

With external power source

$$\frac{1}{Q_L} = \frac{P_{loss} + P_{ext} + \cdots}{\omega_0 W} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} + \frac{1}{\cdots}$$

Q_L : Loaded quality factor

Coupling coefficient $\beta = \frac{P_{ext}}{P_{loss}}$

$\beta \sim 1$ for NC

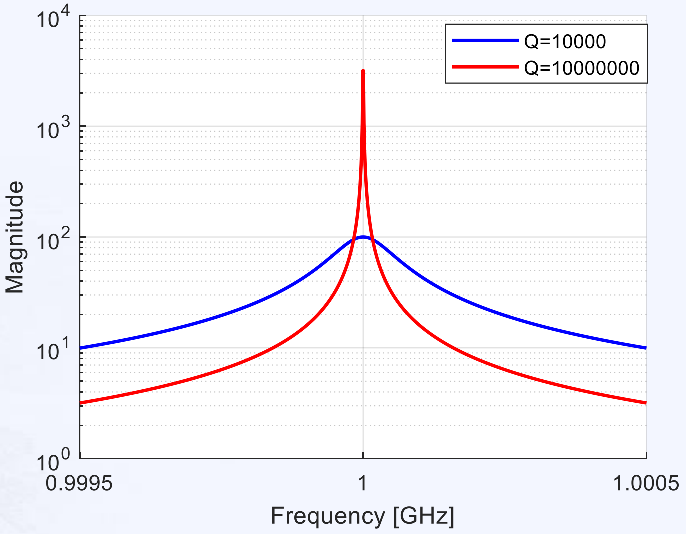
$\beta \sim O(10^4 \ldots 10^6)$ for SC

$$Q_L = \frac{Q_0}{1+\beta}$$

$$V_{acc} = \sqrt{2RP_{diss}} = \sqrt{2\left(\frac{R}{Q}\right)QP_{in}} \propto \sqrt{Q}$$

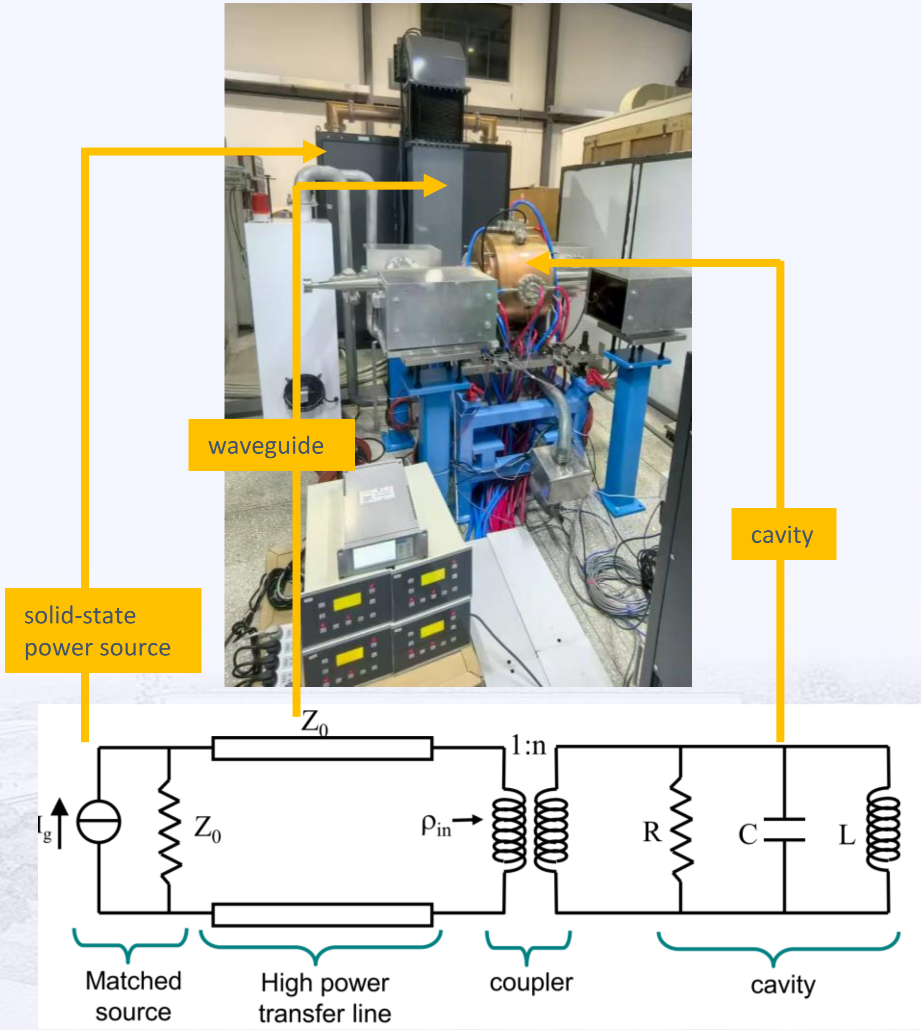
$$\left.\frac{\Delta f_{RF}}{f_{RF}}\right|_{3dB} = \frac{1}{Q_L} \Rightarrow \begin{cases} \Delta f_{RF}|_{3dB,NC} = 100\text{kHz} \\ \Delta f_{RF}|_{3dB,SC} < 1\text{Hz} \end{cases}$$

Susceptible to external disturbances, increasing bandwidth by reducing Q_{ext}



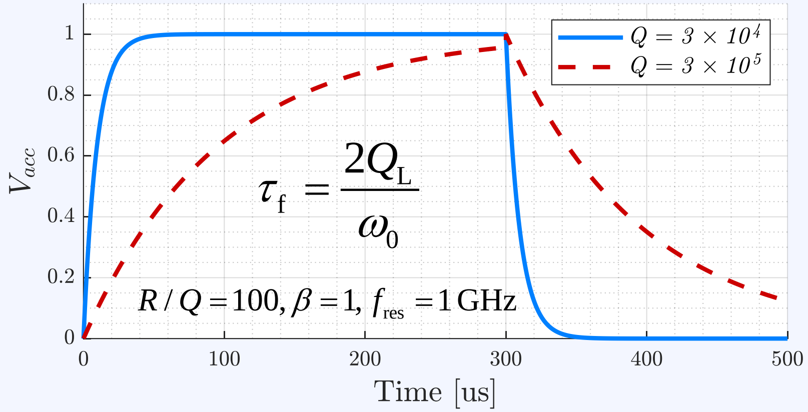
RF parameters for SW structures -4

Parameters of a ‘loaded’ cavity



equivalent circuit

$$U(t) = U_0(1 - e^{-(\omega_0/2Q_L)t}) = U_0(1 - e^{-t/\tau_f})$$



It takes several times the filling time factor to complete the field building up

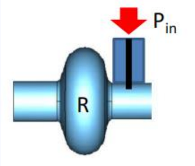
$$\tau_f|_{NC} \approx \mu s, \quad \tau_f|_{SC} > 100 ms$$

Filling time	$U(t)/U_0$
1 time of τ_f	63%
2 times of τ_f	86%
3 times of τ_f	95%
5 times of τ_f	99%

RF parameters for SW structures -5

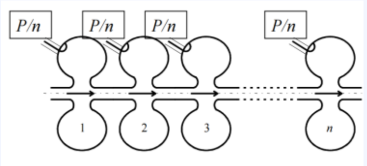
Multi-cell cavity

Single Cell + 1 power coupler (total RF power : P)



$$|V_{acc}| = \sqrt{RP}$$

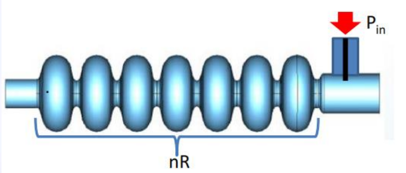
n independent cells + n RF couplers (total RF power is evenly distributed into n parts)



$$|V_{acc}| = n\sqrt{R\frac{P}{n}}$$

With the same power consumption, the beam energy is increased by $n^{1/2}$ times

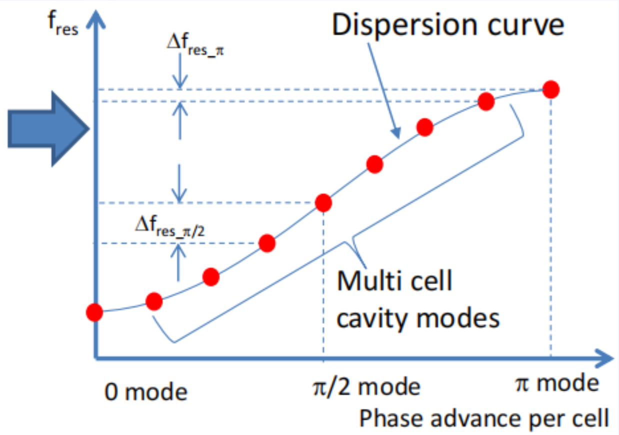
n coupling cells + 1 RF coupler



$$|V_{acc}| = \sqrt{nRP}$$

- When n cells are connected together, the impedance is about n times that of a single cavity;
- In a multi-cell structure, there is only one RF input coupler. The layout and cost can be simplified compared to the former.
- Involving the coupling between modes and cells.

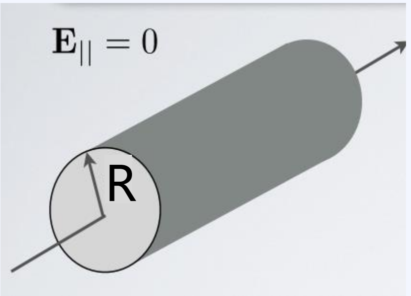
- The N-cell structure behaves like a system composed by N coupled oscillators with N coupled multi-cell resonant modes.
- The multi cell mode generally used for acceleration is the π, π/2 and 0 mode (DTL as example operate in the 0 mode) .
- It is possible to demonstrate that over a certain number of cavities (>10) working on the π mode, the overlap between adjacent modes can be a problem. (See reference 1 for the solution)



Basic principles of TW structures -1

Electromagnetic fields in a circular waveguide

Assuming an EM field travels in a uniform waveguide (WG), its fundamental mode TM_{01} has an maximum E_z on axis, thus is a most possible mode to accelerate particles.



$$E_z(r,z,t) = E_0 J_0(k_c r) e^{j\omega t - k' z}$$

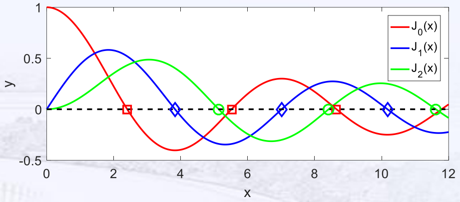
$k_c = \omega_c / \upsilon_p$ is the cut-off wave number, which has

$$\begin{cases} \omega = \omega_c & \omega_c \text{ -- waveguide cut-off frequency} \\ \upsilon_p = c & \upsilon_p \text{ -- phase velocity} \end{cases}$$

ω_c obtained from the boundary condition $E_z(r=R)=0$

by the first root of $J_0(k_c R) = 0$

$$\omega_c = 2.405 \frac{c}{R}$$



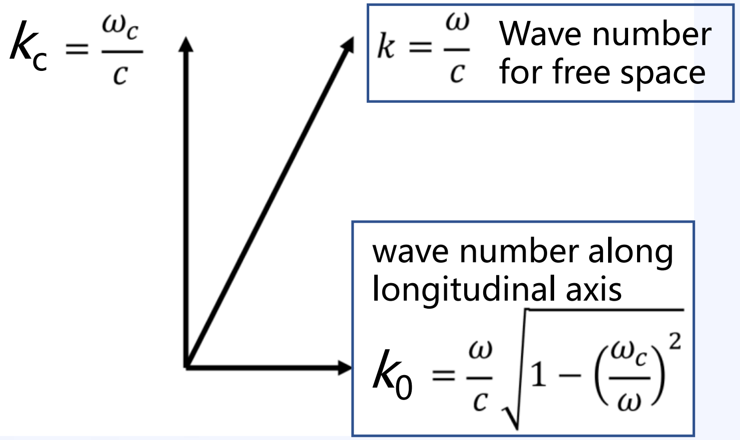
$k' = \alpha + jk_0$ α is field attenuation (RF loss)

Consider the case of no power loss ($\alpha = 0$) for simplification,
and using the Wave Equation (for TM waves):

$$\nabla^2 E_z + k^2 E_z = 0$$

then its propagation property (Dispersive Relation) is $k_0^2 = (\frac{\omega}{c})^2 - k_c^2 = (\frac{\omega}{c})^2 - (\frac{\omega_c}{c})^2$

cut-off wave number, only related to transverse size of waveguide



*Refers to the report of Shuhong Wang at 3rd OCPA Topical Accelerator School & Workshop, 2013.

Basic principles of TW structures -2

Electromagnetic fields in a circular waveguide

For TM_{01} to exist in WG, k_0 must be a real number, so that $\omega \geq \omega_c$

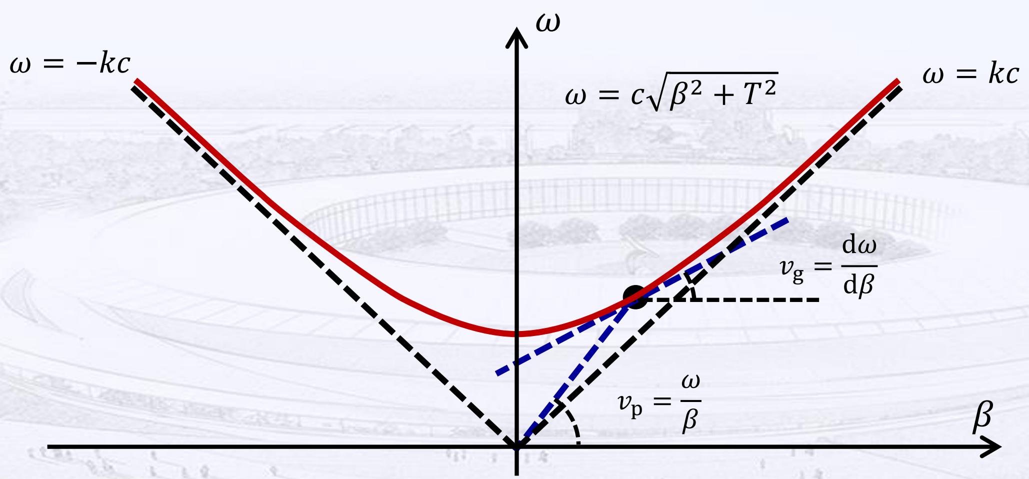
$$k_0^2 = (\frac{\omega}{c})^2 - k_c^2 = (\frac{\omega}{c})^2 - (\frac{\omega_c}{c})^2 > 0$$

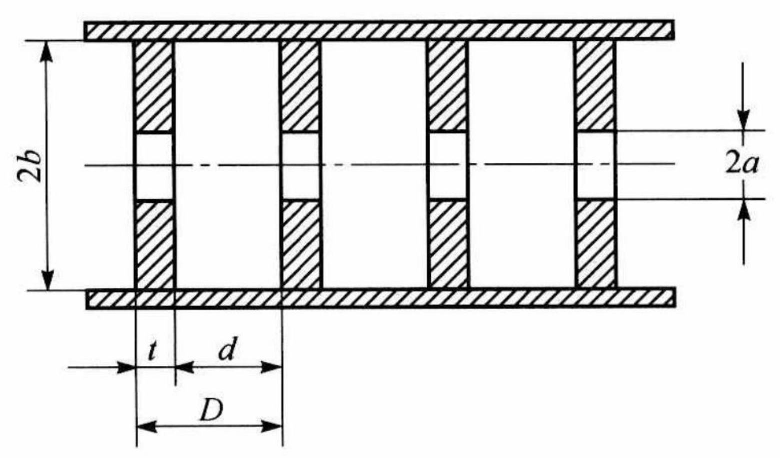
This means that only the waves with $\omega \geq \omega_c$ can be propagated in the waveguide, but their phase velocity

$$v_p = \frac{\omega}{k_0} = \frac{c}{\sqrt{1-(\frac{\omega_{cr}}{\omega})^2}} > c$$

Obviously, these waves can not resonantly accelerate particles.
(wave moves faster than particles)

For having $v_p \leq c$ $\Rightarrow$ by introducing a periodic structure e.g. disk-loaded structure .





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Electromagnetic fields in a periodic structure

Wave amplitude is periodically modulated

$$E_z(r,z,t)=E_{L_c}(r,z)e^{j(\omega t-k_0 z)} \Leftarrow \text{ Floquet Theorem}$$

here $E_{Lc}(r,z)$ is a periodic function with period L_c.

Expands $E_{Lc}(r,z)$ as a Fourier series (space harmonic components):

$$E_{L_c}(r,z)=\sum_{n=-\infty}^{\infty} E_n J_0(k_n r)e^{-j\frac{2\pi n}{L_c}z}$$

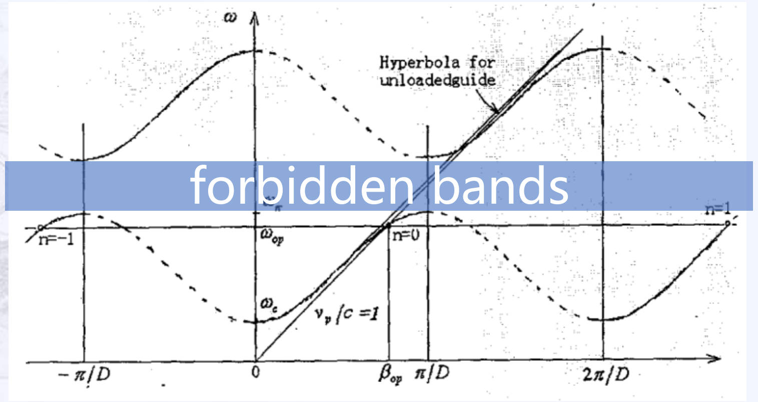
$$E_z(r,z,t)=\sum_{n=-\infty}^{\infty} E_n J_0(k_n r)e^{j(\omega t-k_n z)}$$

here k_n is the wave number of nth space harmonic wave,

$$k_n=k_0+\frac{2\pi n}{L_c}$$

which has the phase velocity $v_{n,p}=\frac{\omega}{k_n}=\frac{\omega}{k_0(1+\frac{2\pi n}{k_0 L})}\le c$

Due to the reflection and superposition of waves in the periodic disk-load structure, the original dispersion curve is split into a series of passbands (β_n : real number) and forbidden bands (β_n : imaginary number)



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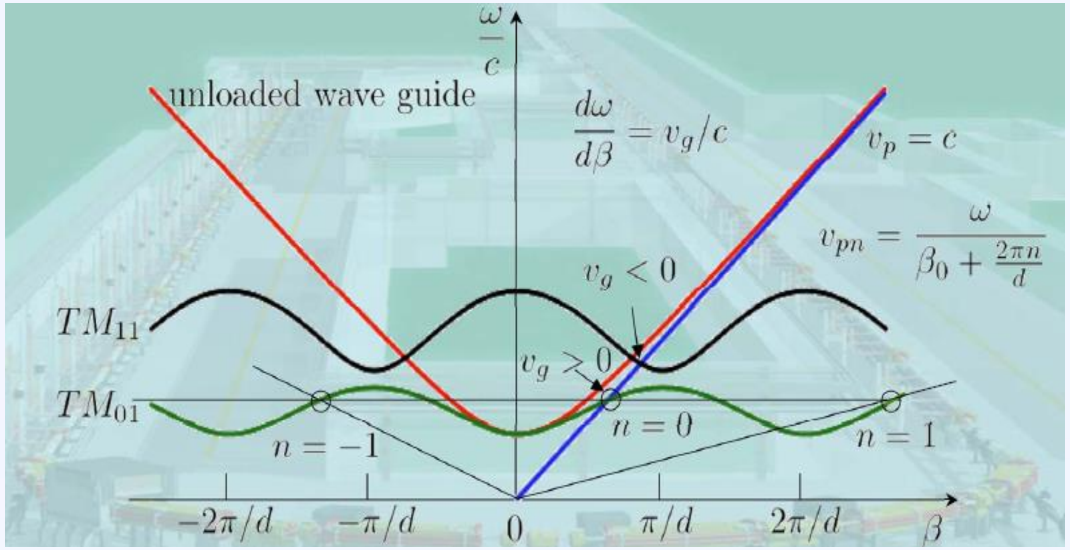
Electromagnetic fields in a periodic structure

A traveling wave consists of infinite space harmonic waves:



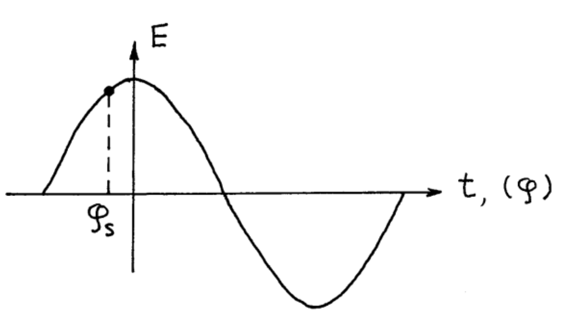
n ≥ 0 forward waves, $\upsilon_p \geq 0$
n < 0 back waves, $\upsilon_p < 0$

Only one of them, that $\omega = \omega_0$ and $\upsilon_p = \upsilon_e$ can be used to accelerate particles.

A particle that "rides" on the wave at a phase φ_s, its energy gain per period (L_c) is

$$\Delta W = e\int_0^{L_c} E_a(z)\cos\phi_s dz$$

$$\Delta W = \Delta W_m \cos\phi_s$$



*Refers to the report of Shuhong Wang at 3rd OCPA Topical Accelerator School & Workshop, 2013.

RF parameters for TW structures -1

Parameters In a single cell

acceleration voltage

$$\hat{V}_{\text{acc}} = \left| \int_0^D \hat{E}_{\text{acc}} \cdot e^{j\omega_0 \frac{z}{\beta c}} \mathrm{d}z \right|$$

average acceleration gradient

$$E_{\text{acc}} = \frac{\hat{V}_{\text{acc}}}{D}$$

power flow

$$P_{\text{w}} = \int_{\text{Section}} \frac{1}{2} \mathrm{Re}\left(\vec{E} \times \vec{H}^*\right) \cdot \hat{z} \mathrm{d}S$$

dissipation power

$$P_{\text{diss}} = \frac{1}{2} R_{\text{s}} \int_{\substack{\text{cavity}\\\text{wall}}} \left| H_{\tan} \right|^2 \mathrm{d}S$$

dissipation power per unit length

$$\frac{\Delta P_{\text{w}}}{\Delta z} = \frac{-P_{\text{diss}}}{D}$$

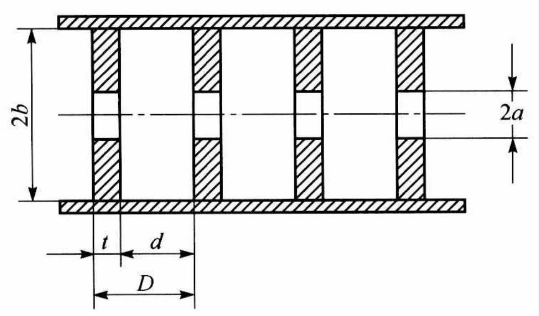
stored energy

$$U = \int_{\substack{\text{cavity}\\\text{volume}}} \left(\frac{1}{4} \varepsilon |\vec{E}|^2 + \frac{1}{4} \mu |\vec{H}|^2 \right) \mathrm{d}V$$

quality factor

$$Q = \frac{\omega U / D}{-\mathrm{d}P_{\text{w}} / \mathrm{d}z}$$

geometry parameters



$$Z = \frac{E_{\text{acc}}^2}{p_{\text{diss}}}$$

shunt impedance per unit length [Ω/m]

$$\alpha = \frac{-\Delta P_{\text{w}} / \Delta z}{2 P_{\text{w}}}$$

field attenuation factor

$$v_g = \frac{P_{\text{w}}}{U / D}$$

group velocity

$$\Delta\phi = k_0 D$$

Operation mode: phase shift between adjacent cells

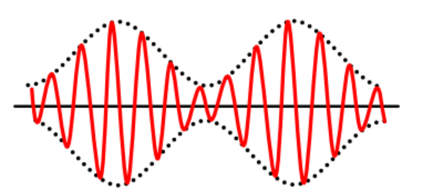
RF parameters for TW structures -2

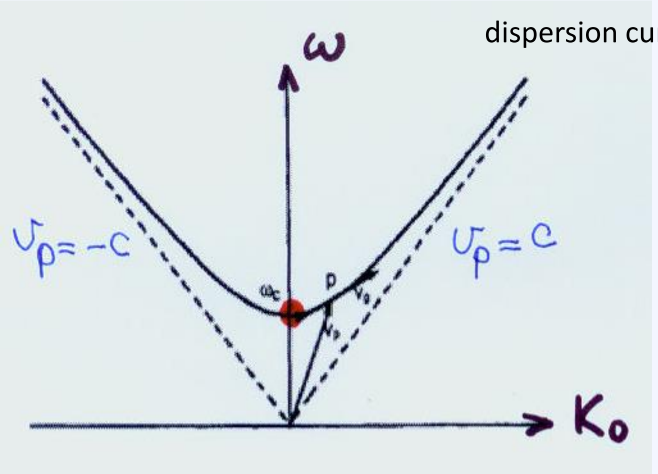
Group velocity and phase velocity

- Group velocity refers to the speed at which changes in the shapes of the wave amplitude ("wave packet") are transmitted in space.
- Phase velocity refers to the speed at which the phase of the wave is transmitted in space. You can select any specific phase of the wave to observe (such as the peak of the wave), and it will move forward at the phase velocity.
- Take the superposition of two waves with different frequencies as an example:

$$V(z,t) = e^{j(\omega_1 t - k_1 z)} + e^{j(\omega_2 t - k_2 z)}$$

$$= 2\cos\left[\frac{(\omega_1-\omega_2)t-(k_1-k_2)z}{2}\right] e^{j\left[\frac{(\omega_1+\omega_2)t-(k_1+k_2)z}{2}\right]}$$



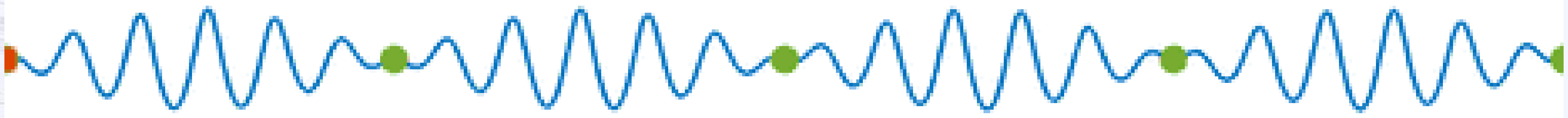


group velocity

phase velocity

$$v_g = \frac{\omega_1-\omega_2}{k_1-k_2} \to \frac{d\omega}{dk} \qquad v_p = \frac{\omega_1+\omega_2}{k_1+k_2} = \frac{\bar{\omega}}{\bar{k}}$$

For TM01 mode, $v_g = \frac{P_w}{U}$, $P_w = \int_0^a E_r H_\theta 2\pi r \mathrm{d}r$, $E_r \;\; r$, $H_\theta \propto r \Rightarrow v_g \propto a^4$ **a : the radius of iris**



The phase velocity can be greater than the speed of light, The group velocity is less than the speed of light

RF parameters for TW structures -3

Attenuation factor $\alpha(z)$

- The actual TW structure : considering the dissipation power
- Total dissipation factor: $\tau_0 = \int_0^{L_s} \alpha(z) dz$ 　 $\alpha(z)$ — attenuation / unit length, L_s — accelerating section length.
- τ_0 can be considered as an independent variable in the design of the TW structure
- **Generally**, given P_{in} and structure length, $\tau_0 \uparrow \Rightarrow P_{out} \downarrow \Rightarrow E_{acc} \uparrow$
- $\tau_0 \downarrow \Rightarrow \upsilon_g \uparrow \Rightarrow a \uparrow \Rightarrow$ Acceptance $\uparrow$
- τ_0 should make a compromise between the two effects

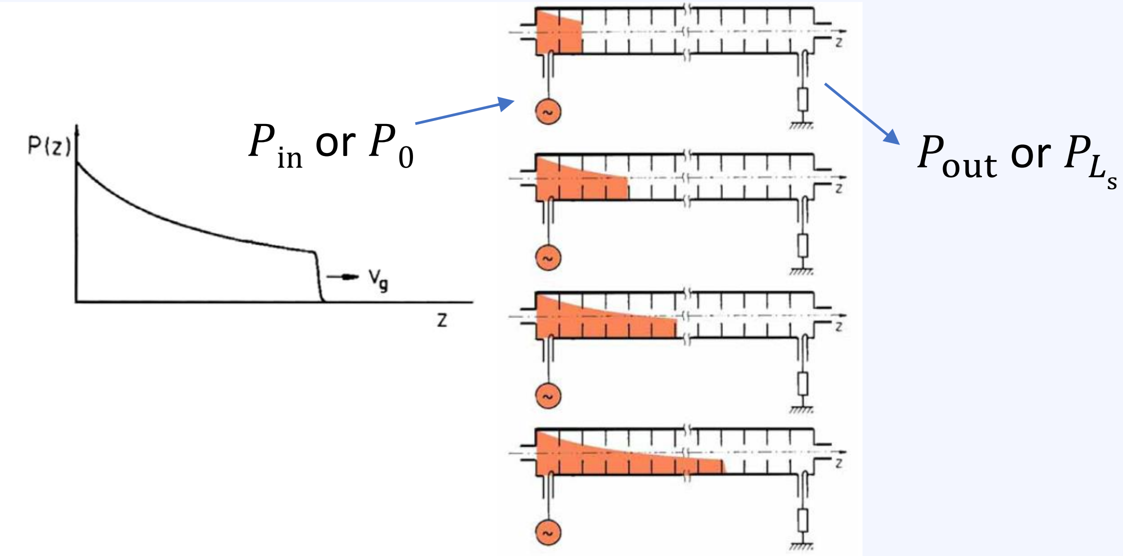
$$Q = \frac{\omega U/D}{-dP_w/dz}, \quad v_g = \frac{P_w}{U/D} \Rightarrow \frac{dP_w}{dz} = -\frac{\omega U/D}{Q} = -\frac{\omega P_w}{Q v_g} = -2\alpha_0 P_w \Rightarrow \frac{1}{P_w}\frac{dP_w}{dz} = -2\alpha_0 \Rightarrow P_{L_S} = P_0 e^{-2\tau_0}$$

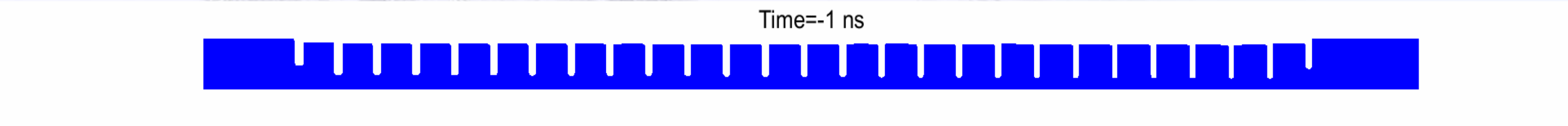
RF parameters for TW structures -4

Filling time T_f

- A real accelerating tube cannot be regarded as a transmission line with an infinite period structure, and there are mode converters at both ends.
- T_f : Time needed for power filling into a structure
- For TW:

$$t_F = \int_0^{L_s} \frac{dz}{v_g(z)}$$





CLIC-T24: t_f = 60 ns

* Refers to Hao Za ’ s report at HG2018

RF parameters for TW structures -5

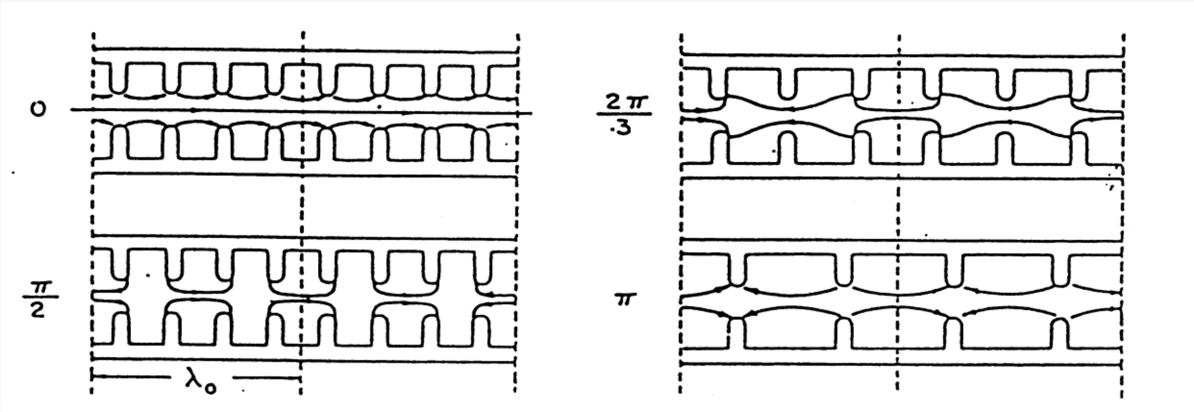
Working frequency f_0

- Shunt impedance $Z_s \sim f_0^{1/2}$, (Skin-depth ~ $f_0^{-1/2}$)
  - From the perspective of reducing high-frequency power loss, high frequency is beneficial.
- Quality factor $Q \sim f_0^{-1/2}$
- Power loss $-\mathrm{d}P_w/\mathrm{dz} \sim f_0^{-1/2}$
  - Higher frequency is beneficial to reduce power loss.
- Minimum energy storage required for field construction $Z_s/Q \sim f_0$
- High-frequency energy storage $U \sim f_0^{-2}$
  - For strong beams, the lower the frequency, the better.
- Power filling time $t_f \sim f_0^{-3/2}$ $(t_f = L_c/v_g)$
  - Higher frequency is beneficial to shorten the filling time.
- Geometry dimensions of the structure a 、 $b \sim f_0^{-1}$
  - Low frequency and larger aperture are beneficial to reducing beam loss.
- Longitudinal wakefield $\sim f_0^2$
- Transverse wakefield $\sim f_0^3$

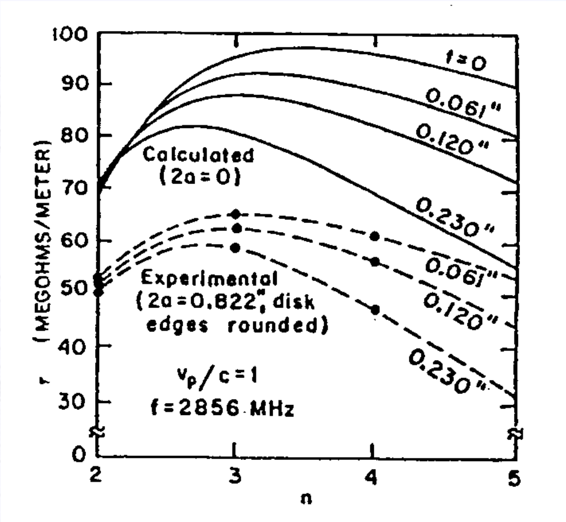
RF parameters for TW structures -6

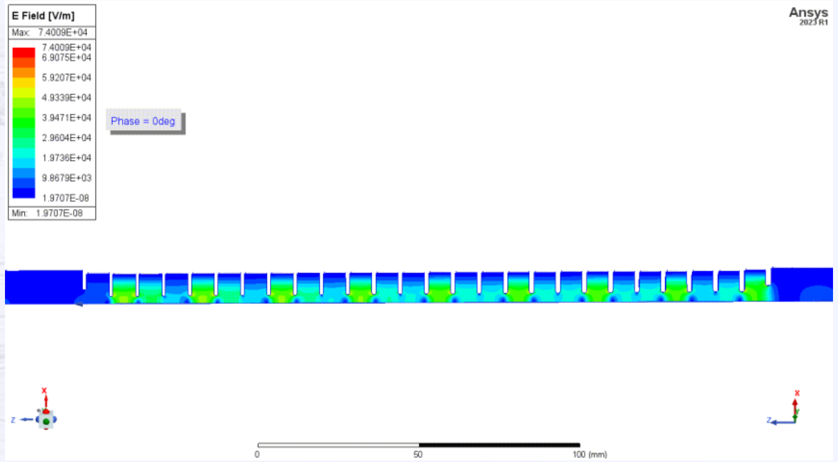
Operation mode

- Specified by the rf phase difference between adjacent cells.



- For Disk-loaded TW Structure, $2\pi/3$-mode: Z_s, max (2856MHz)



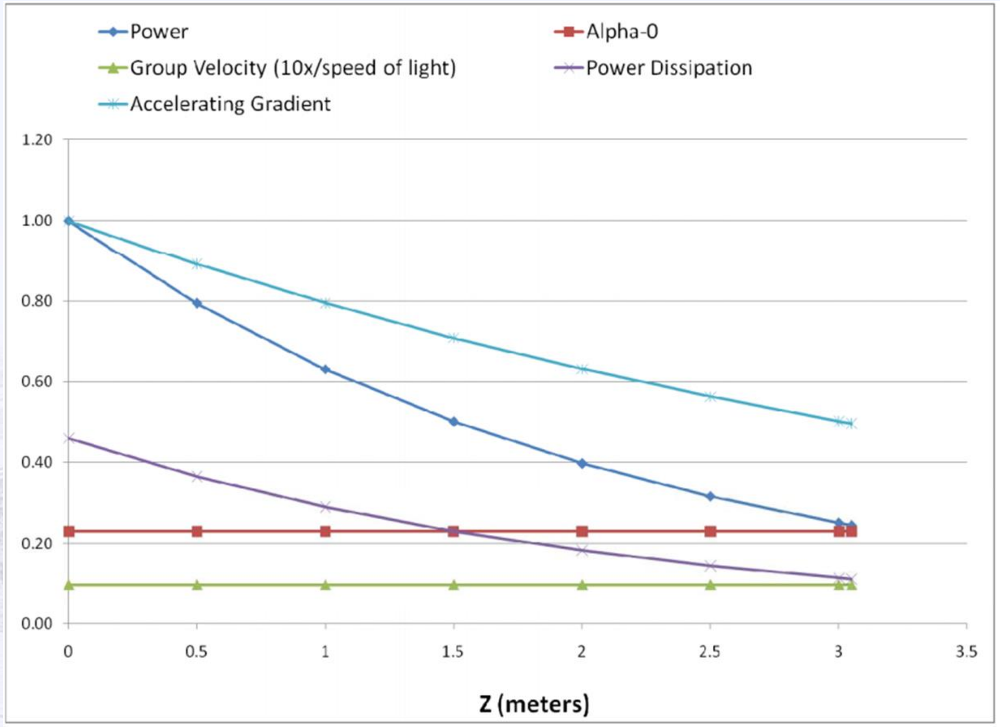


Constant Impedance Structure

- For each cell, a and b are the same, Q, v_g, Z_s and α_0 are all the same
- ⇨ constant impedance

$$\left.\begin{array}{l}\dfrac{dP_w}{dz} = -2\alpha_0 P_w \\ Z_s = \dfrac{E_a^{\ 2}}{-dP_w / dz}\end{array}\right\} \Rightarrow E_a^{\ 2} = 2\alpha_0 Z_s P_w(z) \xRightarrow{\alpha_0 = \frac{\omega}{2Qv_g}} \frac{dE_a}{dz} = -\frac{\omega E_a}{2Qv_g} = -\alpha_0 E_a \Rightarrow \begin{cases} P_w(z) = P_0 e^{-2\alpha_0 z} \\ E_a(z) = E_0 e^{-\alpha_0 z}\end{cases}$$

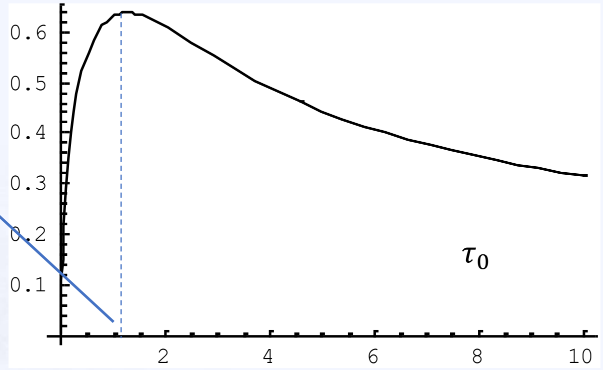
$$\Rightarrow \Delta W_m = e\sqrt{2Z_s P_0 L_s}\cdot\left(\frac{1-e^{-\tau_0}}{\sqrt{\tau_0}}\right)$$



To have a max. ΔW_m (to optimize the structure) , we should have :

(1) Z_s maximum

(2) $\left(\dfrac{1-e^{-\tau_0}}{\sqrt{\tau_0}}\right)_{max} \Rightarrow \tau_0 = 1.26$



On the other hand,

$$t_f = \frac{L_s}{v_g} = \frac{2Q\tau_0}{\omega}$$

to decrease t_F, then τ_0 should be compromised < 1.26

Commonly, τ_0 = 0.5 ~ 0.8

Constant Gradient Structure -1

- Electric field in the constant impedance has an exponential decay along z axis
- Constant gradient acceleration structure adjusts *a* and *b* of each cell to keep the accelerating electric field constant. (The constant gradient refers to the voltage gradient)
- v_g is sensitive to changes in aperture *a*, but Q and Z_s are not very sensitive to changes in *a* and are therefore assumed to be constants.

$\boldsymbol{E_a}$ **= const.** $\Rightarrow$ $\mathbf{d}\boldsymbol{P_w}\mathbf{/dz}$ **= const.**

$\Rightarrow \alpha(z) \neq$ **const.**

$$E_a^2 = -Z_s \frac{\mathrm{d}P_w}{\mathrm{d}z}$$

$$\frac{\mathrm{d}P_w}{\mathrm{d}z} = -2\alpha(z)P_w$$

$$\tau_0 = \int_0^{L_s} \alpha_0(z)dz \Longrightarrow P_{Ls} = P_0 e^{-2\tau_0}$$

$$\Rightarrow \quad P_w(z) = P_0 + \frac{P_{L_s} - P_0}{L_s} z = P_0\left[1 - \frac{1-e^{-2\tau_0}}{L_s} z\right]$$

The power decreases linearly along the z axis.

$$\Rightarrow \quad \frac{\mathrm{d}P_w}{\mathrm{d}z} = -\frac{P_0}{L_s}(1-e^{-2\tau_0}) \Rightarrow \alpha(z) = \frac{-\mathrm{d}P/\mathrm{d}z}{2P(z)} = \frac{\alpha_0}{1-2\alpha_0 z}$$

$$\alpha_0 = \frac{1-e^{2\tau_0}}{2L}$$ (1st cell)

$$v_g(z) = \frac{\omega}{2Q\alpha(z)} \Rightarrow v_g(z) = \frac{\omega L_s}{Q} \cdot \frac{1-(1-e^{-2\tau_0})z/L_s}{1-e^{-2\tau_0}}$$

Group velocity also decreases linearly along the z axis.

$$E_0^{\ 2} = -Z_s \frac{\mathrm{d}P_{L_s}}{\mathrm{d}z} = \frac{Z_s P_0}{L_s}(1-e^{-2\tau_0}) \Rightarrow \Delta W_m = eE_0 L_s = e\sqrt{Z_s P_0 L_s (1-e^{-2\tau_0})}$$

To obtain max. ΔW_m, need to maximize Z_s and τ_0.

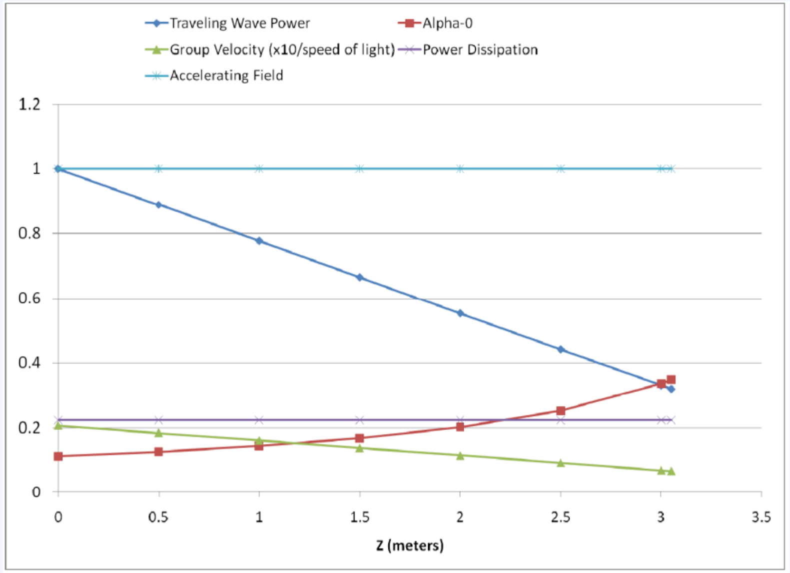
Constant Gradient Structure -2

$$t_f = \int_0^{L_s} \frac{dz}{v_g(z)} = \frac{Q}{\omega L_s}(1-e^{-2\tau_0})\int_0^{L_s} \frac{dz}{1-\frac{z}{L_s}(1-e^{-2\tau_0})} = \frac{2Q\tau_0}{\omega}$$

$$= \frac{2L_s\tau_0}{1-e^{-2\tau_0}}$$

$$\Delta W = eE_0L_s = e\sqrt{Z_sP_0L_s(1-e^{-2\tau_0})}$$

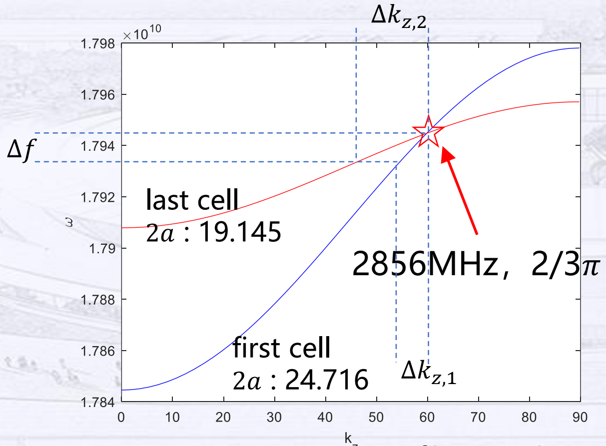
$\tau_0 \uparrow \ \Rightarrow \ E_{acc} \uparrow$



In addition to increasing the t_f and reducing RF utilization efficiency, increasing τ_0 also has two additional risks in engineering applications:

(1) Less a makes the phase shift more sensitive to geometry parameters (especially b) and therefore more sensitive to temperature, and also more difficult to tune.

(2) Smaller apertures reduce the vacuum pumping speed and increase the difficulty of obtaining high vacuum inside the TW structure.

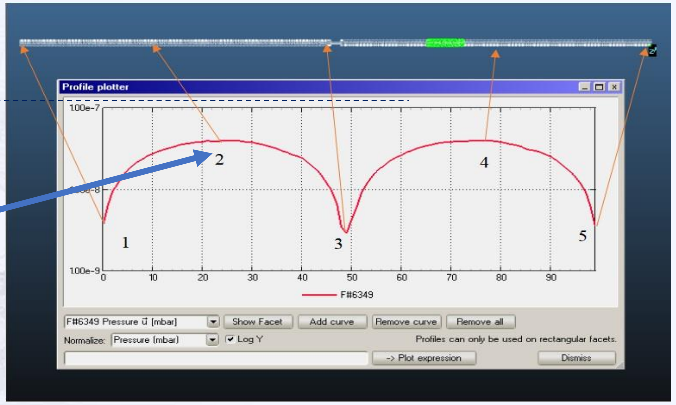


HALF 3-m TW structure dispersion curve

1E-7 Torr

$\tau_0 \uparrow \ \Rightarrow a \downarrow$

Engineering requirements: <5E-5Pa



Calculation results of vacuum pressure distribution inside the 2-section structure

Summary of CI and CG Structures

	Constant Impedance	Constant Gradient
Gradient	$E_a(z) = E_0 e^{-\alpha_0 z}$	E_a = const
Dissipation	$\frac{dP_w}{dz} \neq \text{const}$ $\frac{dP_w}{dz} = -2\alpha_0 P_0 e^{-2\alpha_0 z}$	$\frac{dP_w}{dz} \approx \text{const}$ $\frac{dP_w}{dz} = -\frac{P_0}{L_s}(1-e^{-2\tau_0})$
Attenuation factor	$\alpha(z)$ = const $\alpha(z) = \alpha_0$	$\alpha(z) \neq \text{const}$ $\alpha(z) = \frac{\alpha_0}{1-2\alpha_0 z}$
Total dissipation factor	$\tau_0 = \alpha_0 L_s$	$\tau_0 = \int_0^{L_s} \alpha(z)dz = -\frac{1}{2}\ln(1-2\alpha_0 L_s)$
Group velocity	v_g = const $v_g = \frac{\omega}{2Q\alpha_0}$	$v_g \neq \text{const}$ $v_g(z) = \frac{\omega L_s}{Q} \cdot \frac{1-(1-e^{-2\tau_0})z/L_s}{1-e^{-2\tau_0}}$
Energy gain with no beam loading	$\Delta W_m = e\sqrt{2Z_s P_0 L_s} \cdot (\frac{1-e^{-\tau_0}}{\sqrt{\tau_0}})$	$\Delta W_m = eE_0 L_s = e\sqrt{Z_s P_0 L_s(1-e^{-2\tau_0})}$ for SLAC 2856MHz Acc. structure: $\Delta W_m(\text{MeV}) \approx 10\sqrt{P_{in}(\text{MW})}$
Energy gain for steady-state beam loading (discuss later)	$\Delta W_b = -I_b Z_s L_s \cdot (1-\frac{1-e^{-\tau_0}}{\tau_0})$	$\Delta W_b = -I_b Z_s L_s \cdot (1-\frac{2\tau_0 \cdot e^{-2\tau_0}}{1-e^{-2\tau_0}})$
Filling time	$t_f = \frac{2Q\tau_0}{\omega}$	

Advantages of the CG structure :

- **uniform power loss.**
- **uniform peak surface field for lower RF breakdown rate.**

Most e- linacs designed as CG structure.

Outline

01 Introduction and basic ideas

Basic definition and Brief history

02 RF parameters for SW or TW structures

Q, Shunt Impedance, Transient Factor…

03 **Main parameters of a LINAC**

Energy spread, emittance, …

04 Basic Beam Dynamics

Beam Loading and Bunching

05 How to Make a Linac

Basic processes of manufacturing, assembly and commissioning

06 Application of Linacs

Scientific research, Medical, Industrial,…

07 Summary

NSRL

National Synchrotron Radiation Laboratory

国家同步辐射实验室

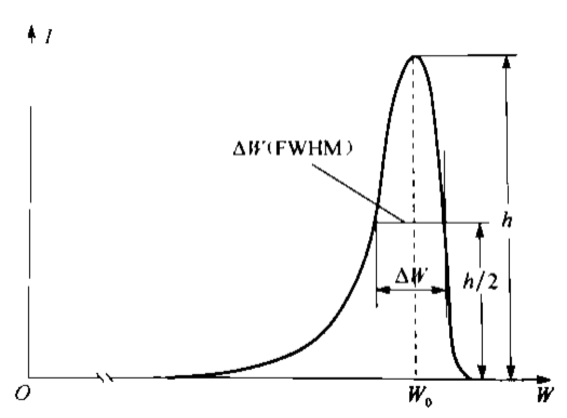
Main parameters of linear accelerator beam -1

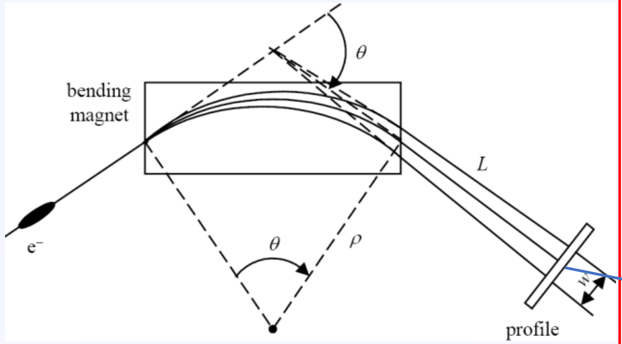
Beam Energy and Energy Spread

- Beam energy: $W = m_0 c^2 (\gamma - 1)$
- Energy spread: generally refers to relative energy spread $\dfrac{\Delta W}{W}$

Two definitions:

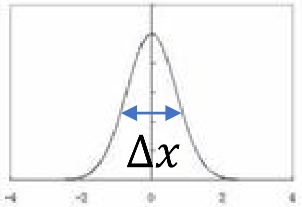
- half-width energy spread
- RMS energy spread





$$D_x = \rho(1 - \cos\theta) + L\sin\theta$$

$$\Delta x = D_x \frac{\Delta W}{W}$$



- **Measurement**: Using an energy analyzer magnet (Bending Magnet).
- With the measured electrons' distribution on the profile, one can get W and $\Delta W/W$.
- D_x = dispersion function.
- To measure a slice energy spread, need a deflecting cavity and a slit.

Main parameters of linear accelerator beam -2

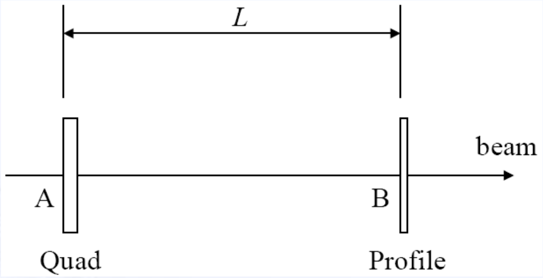
Emittance

- Parameters used to describe the particle distribution in the 6-dimensional phase space in the Cartesian coordinate system, **beam projection in the phase space**
- The concept corresponding to the transmittance: acceptance
- Some definitions:

Normalized emittance $\varepsilon_n = \pi \cdot m_e c \cdot \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x \cdot p_x \rangle^2}$

Geometrical emittance $\varepsilon = \pi \cdot \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2}$

- Measurements: **Quadruple scan method**



beam size at the profile:

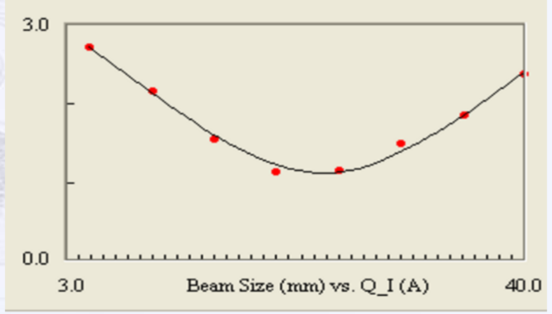
$$\sigma^2 = \varepsilon\left[(1+kL)^2 \beta - 2(1+kL)L\alpha + L^2\gamma\right]$$

k: quad' s focusing strength $\varepsilon, \beta, \alpha$: emittance parameters

$k = \frac{L_Q}{B\rho}\frac{\partial B}{\partial r}$ L_Q : quad' s length

By scanning G many times (>10), and fitting the curve

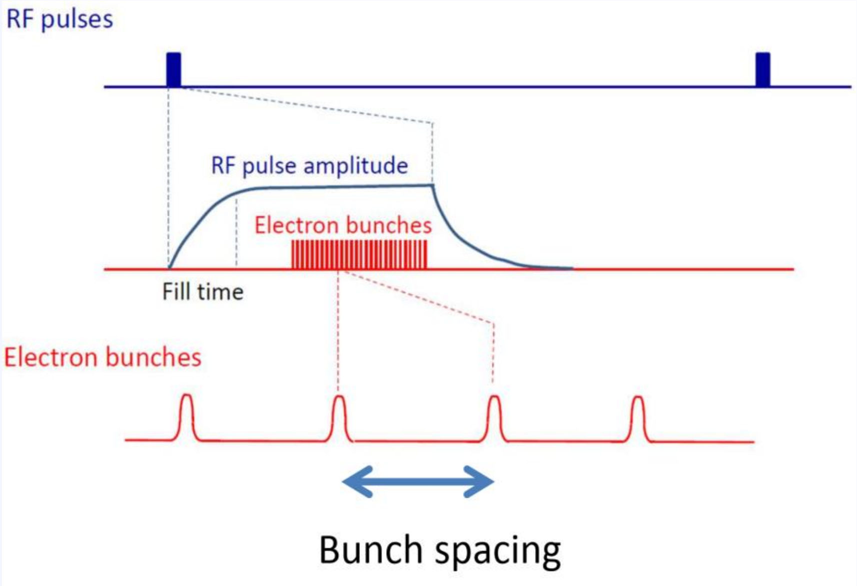
$$\sigma^2 = a(k_1 - b)^2 + c \qquad \varepsilon = \sqrt{\frac{ac}{L^2}} \qquad \alpha = \sqrt{\frac{a}{c}}\left(b + \frac{1}{L}\right) \qquad \beta = \sqrt{\frac{a}{c}}$$

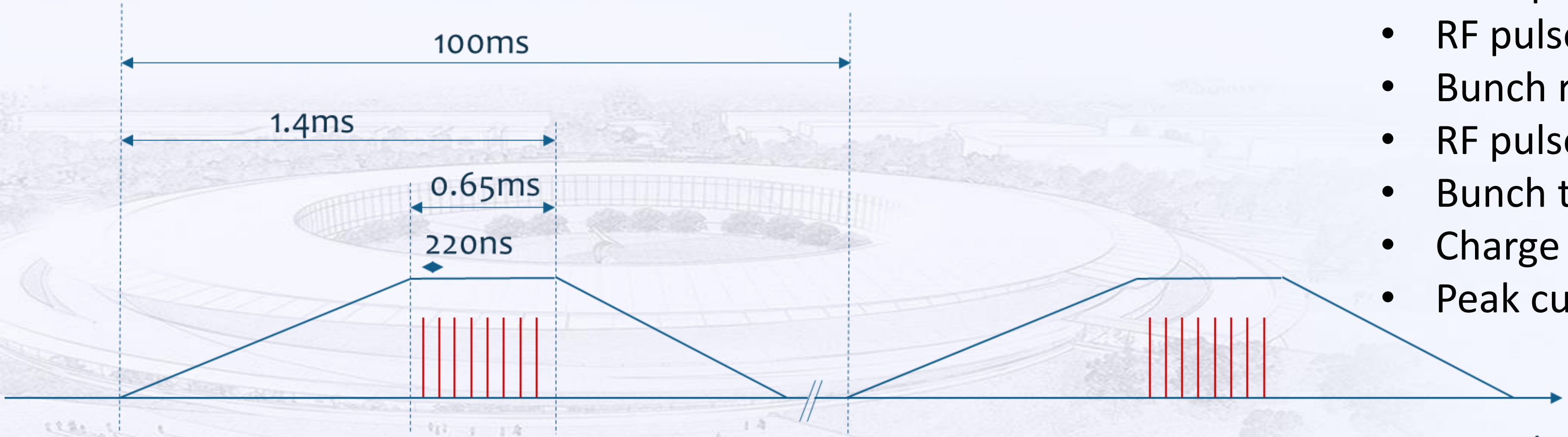


Main parameters of linear accelerator beam -3

Parameters related to pulse structure

- Peak current I_p
- Macro pulse current
  - $I_\mathrm{b} = C * f_\mathrm{b}$ (C: bunch charge, f_b : bunch repetition rate)
- Average current
  - $I = I_\mathrm{b} * \tau_\mathrm{bt} * f_\mathrm{p}$ (τ_bt : bunch train pulse width, f_p : RF pulse repetition rate)
- Duty factor: $DF = \tau_\mathrm{bt} * f_\mathrm{b}$





For European-XFEL

- RF pulse repetition rate : 10 Hz
- Bunch repetition rate : 4.5 MHz
- RF pulse width : 1.4 ms
- Bunch train pulse width : 0.65 ms
- Charge : 1 nC
- Peak current : 5 kA

* Eu-XFEL TDR

Outline

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Beam loading

- The beam is not simply a medium which absorbs radio frequency (RF) energy and adds an **additional resistive load** to the cavity, but is really **equivalent to a generator**, which can either absorb energy from the cavity modes or deliver energy to them.
- As the beam current increases, it becomes important to treat the effects of the interaction between the beam and the cavity more carefully.
  - When the average beam current is strong enough compared to the external generator current, the interaction needs to be taken seriously.
  - In the case of a single-shot pulse, the beam loading is often negligible.
- In this course, beam loading refers to the effects of the beam on the cavity fields in the **accelerating mode**.
- The most important effects of beam-induced fields in modes other than the accelerating mode, are higher-order-mode power losses, and the beam-breakup instability may be discussed in later course.

Beam loading for TW structures -1

- In this section, we only discuss **steady-state** beam loading effect of TW structure from the perspective of **power flow**.
- Considering beam loading, power dissipation expression adds a additional item:

$$\frac{dP_w}{dz} = -2\alpha(z)P_w - I_b E_a$$

The solution is derived as follows:

$$V_{total} = V_a - V_b \qquad V_a = \int_0^{L_s} E_a(z)dz$$

V_b:

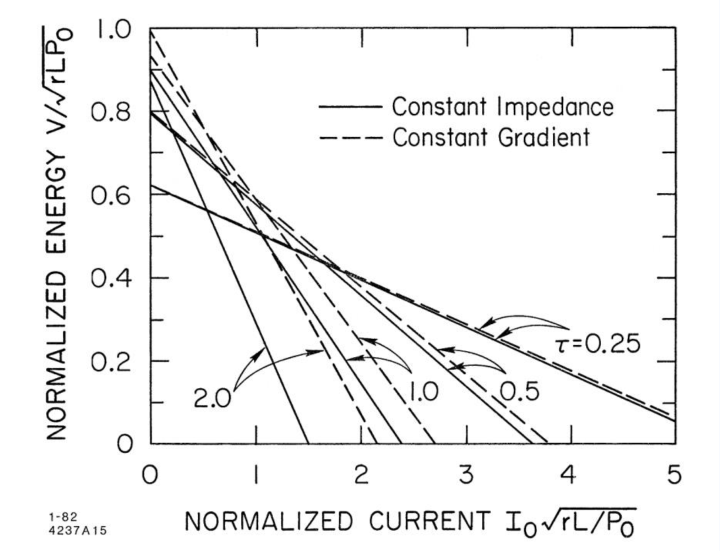
$$\left.\begin{aligned} \frac{dP_b}{dz} &= I_b \cdot E_b - 2\alpha P_b \\ E_b^{\,2} &= 2\alpha Z_s P_b \end{aligned}\right\} \quad \frac{dE_b}{dz} = \alpha \cdot I_b \cdot Z_s - \alpha E_b \Rightarrow E_b = I_b \cdot Z_s (1 - e^{-\alpha(z)z})$$

$$V_b = \int E_b dz \Rightarrow \begin{cases} \text{CZ} \quad V_b = I_b \cdot Z_s \cdot L_s (1 - \frac{1-e^{-\tau_0}}{\tau_0}) \\ \text{CG} \quad V_b = I_b \cdot Z_s \cdot L_s (1 - \frac{2\tau_0 \cdot e^{-2\tau_0}}{1-e^{-2\tau_0}}) \end{cases}$$

For case of CG:

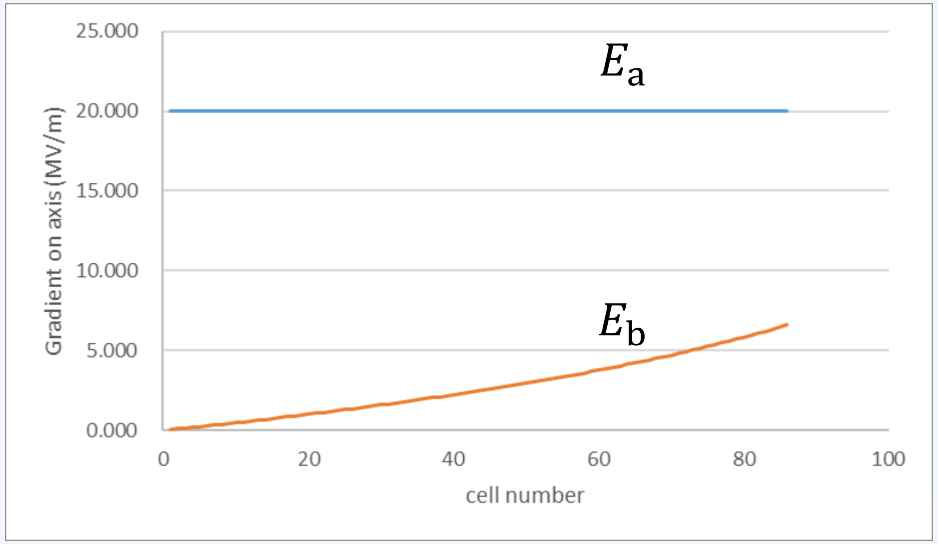
$$\Delta W = e\sqrt{Z_s P_0 L_s (1-e^{-2\tau_0})} - I_b Z_s L_s \cdot (1 - \frac{2\tau_0 \cdot e^{-2\tau_0}}{1-e^{-2\tau_0}})$$

Energy gain decreases linearly with beam current.



Beam loading for TW structures -2

HALF TW structure beam loading calculation for example



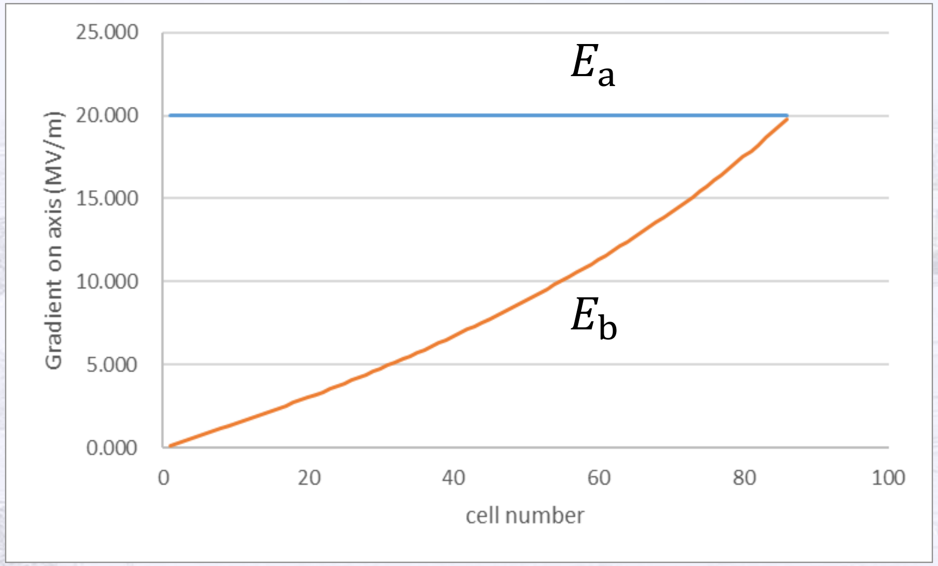
Parameters	Unit	Value
Number of cells		85 + 2
Input power	MW	30
Operational gradient	MV/m	20
Diameter of aperture, $2a$	mm	24.716–19.051
Diameter of cell, $2b$	mm	82.940–81.697
Shunt impedance, R_s	MΩ/m	57.34–65.32
Quality factor, Q		13 989–13 936
Length of cell, L	mm	34.99
Disk thickness	mm	5
Group velocity, v_g	m/s	(0.0184–0.0073)c[a]
Attenuation factor	Np	0.54
Filling time	ns	830
Length of structure	m	3.14
Peak-to-average ratio, E_{max}/E_0		2.12–1.96
Ratio of peak fields, B_{max}/E_{max}	mT/(MV/m)	1.401–1.397

I_b= 200mA

V_a= 59.5MeV $\Delta W_m(\mathrm{MeV}) = 10.86\sqrt{P_{in}(\mathrm{MW})}$

V_b= 8.1MeV (solve difference equation)

V_b= 8.3MeV (previous equation)



I_b= 600mA

V_a= 59.5MeV

V_b= 24.2MeV (solve difference equation)

V_b= 24.8MeV (previous equation)

Beam loading for TW structures -3

- RF to beam efficiency: $\eta = \Delta W \cdot I_b / P_0$
- Given the input power and beam current, how to design the accelerator to obtain max. η?

- $V = V_0 - mI_b$

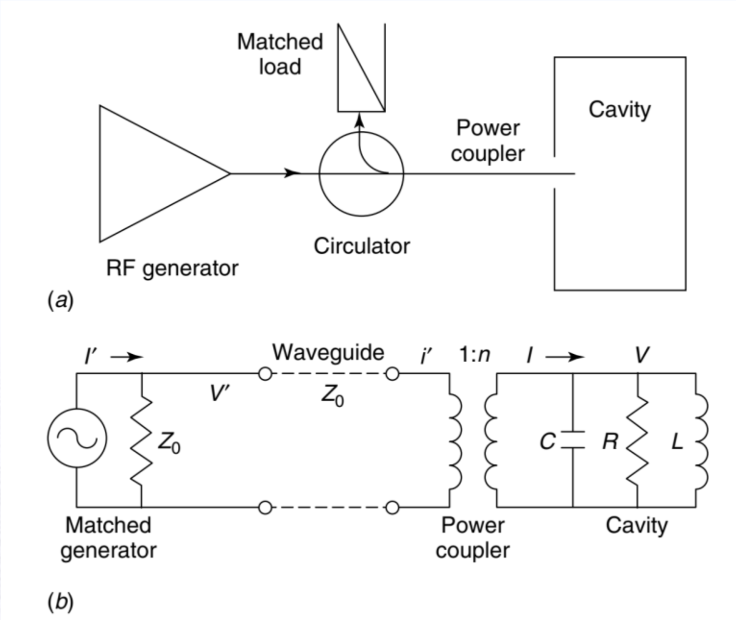
CZ $m = Z_s L_s \cdot (1 - \frac{1-e^{-\tau}}{\tau})$

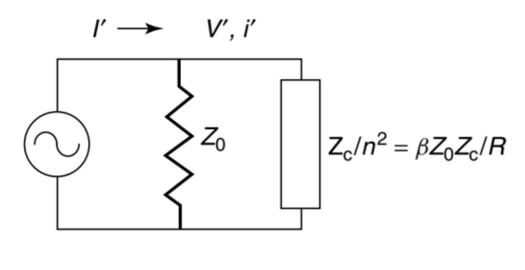
CG $m = Z_s L_s \cdot (1 - \frac{2\tau \cdot e^{-2\tau}}{1-e^{-2\tau}})$

- $P_b = V_0 I_b - m I_b^2$
- $\eta = P_b / P_0$
- When $I_b = V_0/2m$, η reaches the max., $V = V_0/2$, $\eta_m = (V_0/I_b)/4m$

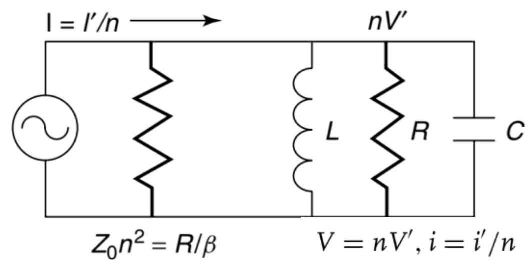
Beam loading for SW structures -1

- For SW structure: beam load analysis implemented using the equivalent circuit model.
- The ideal generator could be modeled as a matched current source
  - matched: the generator could be regarded as a match load from the load (cavity) perspective
  - current source: most RF output power from generator (amplifier) is generated by the electron flow, such as klystron, tetrode, MOSFET...

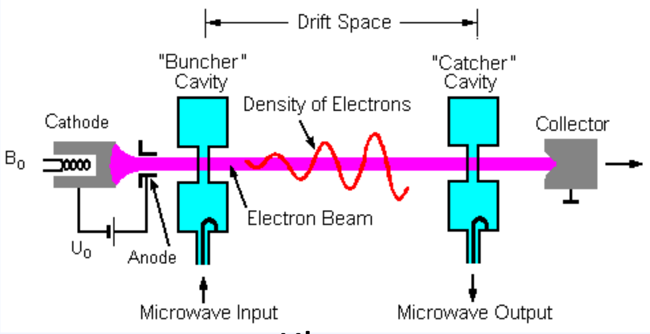




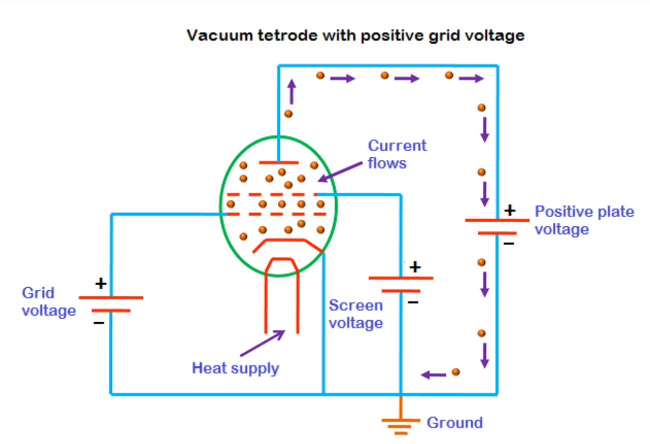
Generator circuit



Resonator circuit



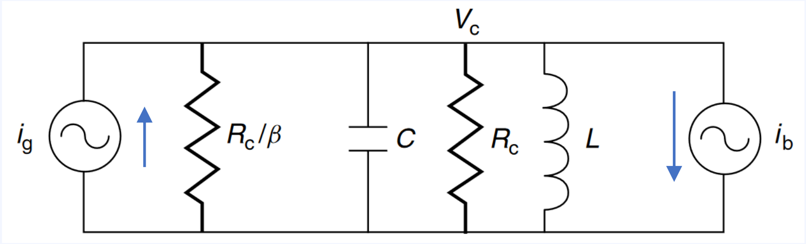
Klystron



Tetrode

Beam loading for SW structures -2

- Equivalent circuit for the beam-loaded cavity transformed into the resonator circuit (noting the definition of current direction)
- i_b : **first-order harmonic component of beam current**, twice as much as average current (I)
- ψ : Detuning angle, also **impedance rotation angle**
  - $\tan\psi = -2Q_L\delta$
- ϕ : the synchronous phase
- $R_c = V_c^2/2P_{diss}$ (Commonly used as parallel resistor in equivalent circuit model)
- $r_s = 2R_c$ effective shunt impedance (Commonly used in linac definition)
- $V_c = V_0 T$ effective cavity voltage
- $P_b = I \cdot V_c \cos\phi$: **the average power delivered to the beam**
- As defined before: $Q_L = Q_0/(1 + \beta)$
  waveguide-to-cavity coupling factor: $\beta = Q_0/Q_e$



$$Z_L = \frac{R_c e^{j\psi}}{(1+\beta)}\cos\psi \quad \delta \equiv \frac{\omega-\omega_0}{\omega_0}, \quad |\delta| \ll 1$$

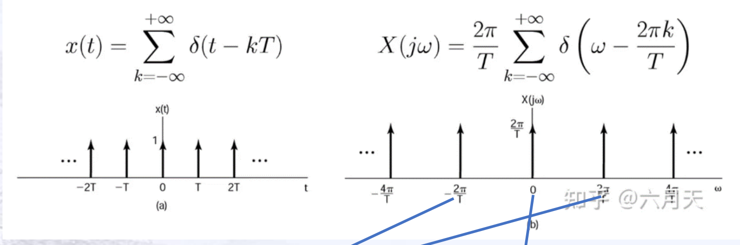
ω_0: Cavity Resonance frequency

ω: Beam and generator frequency

ψ can be changed by tuner on cavity

Tips: how the "twice" comes?

The spectrum of the periodic impulse sampling function is also an impulse sequence



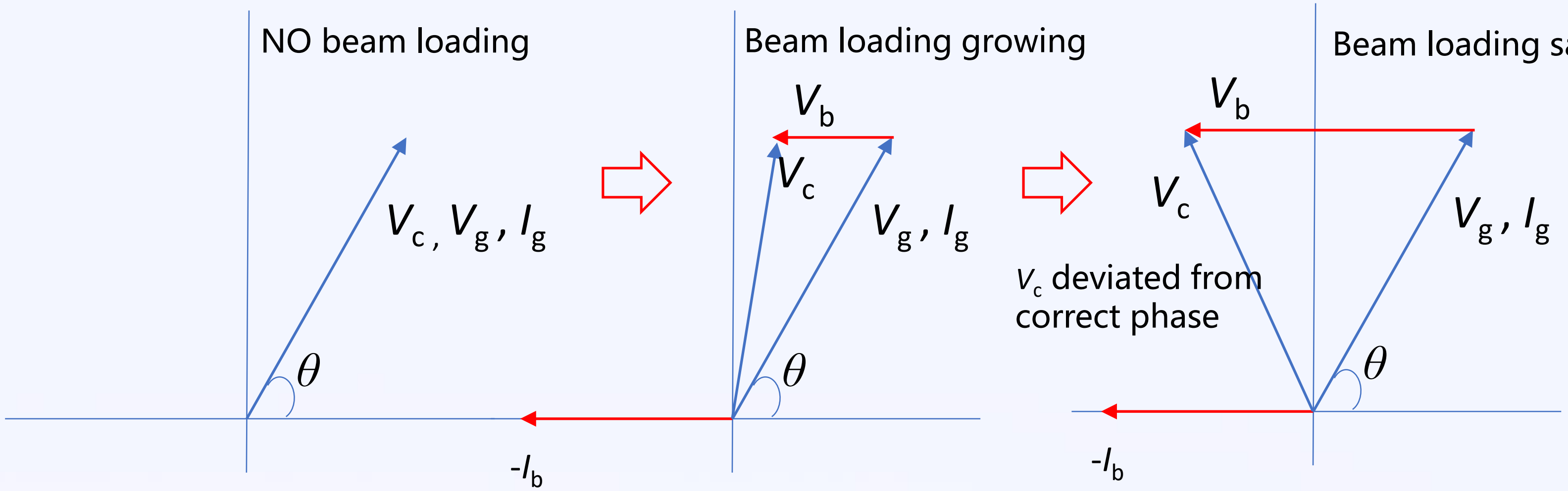
First-order harmonic component

DC component, usually regarded as average current in bunch train pulse width

Beam loading for SW structures -3

Question 1: How to maximize RF efficiency by tuning the cavity under heavy beam loading?

- SW cavity beam loading compensation for insufficient generator output through detuning



θ: phase of I_g and V_g

ϕ: phase of V_C

π : phase of V_b and $-I_b$

θ= ϕ with no beam loading and detuning

- Undetuned state

$-I_b$: induced current in the cavity

V_b and $-I_b$: in phase

V_g : the voltage applied by the transmitter on the cavity

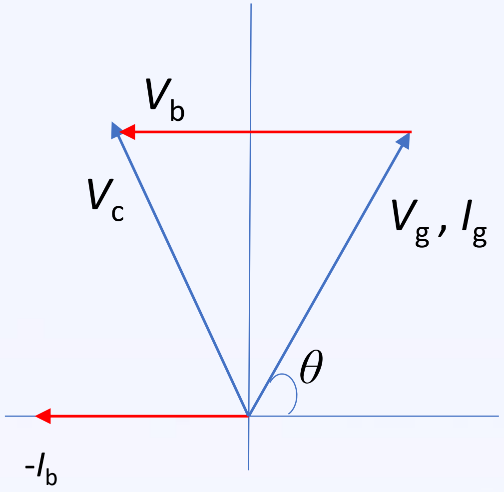
V_g and I_g are in phase

Beam loading for SW structures -3

Question 1: How to maximize RF efficiency by tuning the cavity under heavy beam loading?

- SW cavity beam loading compensation for insufficient generator output through detuning

θ: phase of I_g and V_c
$\pi + \psi$: phase of V_b
$\theta + \psi$: phase of V_g



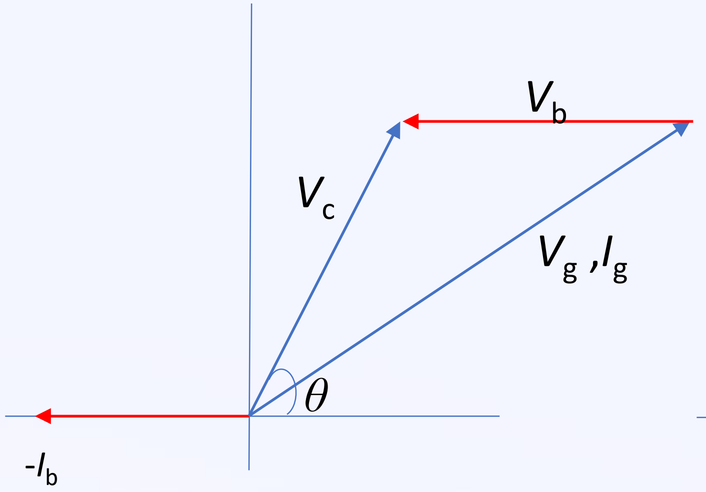
- Undetuned state

$-I_b$: induced current in the cavity

V_b and -I_b : in phase

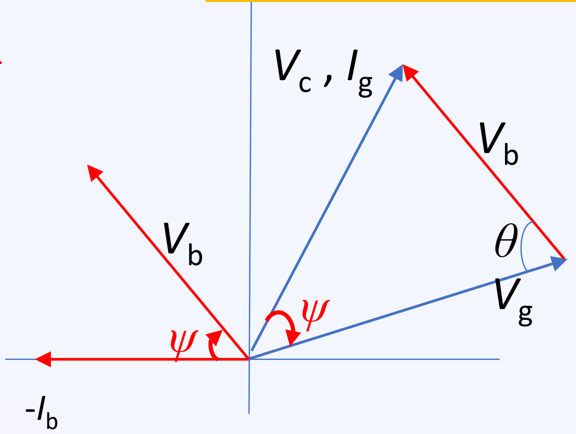
V_g : the voltage applied by the transmitter on the cavity

V_g and I_g are in phase.



- Undetuned state

In order to make V_c reach the preset phase, it is necessary to increase the generator output (amplitude of V_g) and compensate V_b .



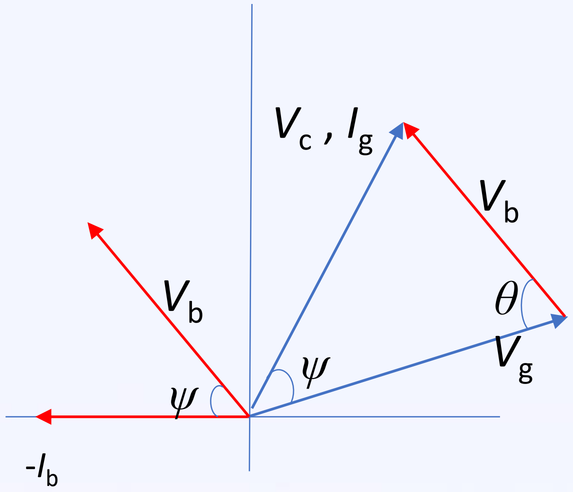
- detuned state

The impedance of the cavity changes, and V_b and V_g rotate simultaneously relative to -I_b and I_g by ψ (ψ has a negative value), The amplitude of V_b decreased.

Beam loading for SW structures -4

Question 1: How to maximize RF efficiency by tuning the cavity under heavy beam loading?

- Optimization of beam loading matching in SW cavity to meet acceleration requirements



Law of Sines $\dfrac{V_b}{V_c} = -\dfrac{\sin\psi}{\sin\phi}$

$$\tan\psi = -\frac{I r_s \sin\phi}{V_c(1+\beta)} = -\frac{P_b \tan\phi}{P_c(1+\beta)}$$

$$V_b = \frac{I r_s \cos\psi}{(1+\beta)}$$

$$\frac{P_b}{P_c} = \frac{I r_s \cos\phi}{V_c} \Leftarrow \begin{matrix} P_b = I\,V_c \cos\phi \\ P_c = V_c^2/r_s \end{matrix}$$

θ: phase of I_g and V_c

$\pi + \psi$: phase of V_b

$\theta + \psi$: phase of V_g

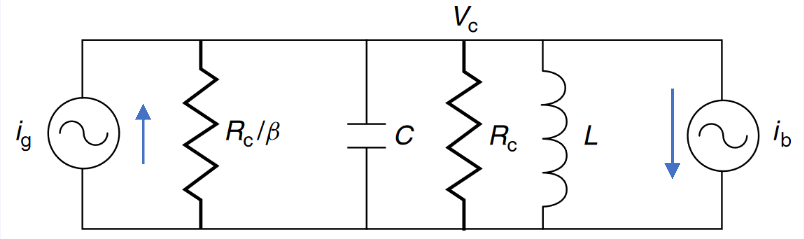
To minimize the generator power with respect to β, it is necessary to choose β, and therefore Q_e

$$\beta_0 = \frac{P_c + P_b}{P_c} = 1 + \frac{I r_s \cos\phi}{V_c} \Rightarrow \tan\psi_0 = -\frac{\beta_0 - 1}{\beta_0 + 1}\tan\phi$$

Beam loading for SW structures -5

Question 2: How to obtain the optimal β to maximize the acceleration voltage?

- Sometimes cannot detune the cavity, beam accelerated on-crest
- e.g. small-scale SW accelerator for medical or industrial use



$$V = \frac{2\sqrt{\beta}}{1+\beta}\sqrt{r_S P_+} - \frac{r_S}{1+\beta} I$$

Derivation as below:

$$V = (I_g - 2I)\cdot\frac{R_C}{1+\beta}$$

$$= \frac{I_g \cdot r_s}{2(1+\beta)} - \frac{I \cdot rs}{1+\beta}$$

$$= \frac{2\sqrt{\beta}}{1+\beta}\sqrt{r_s P_+} - \frac{r_s}{1+\beta}\cdot I$$

$$P_+ = I_g^2 \cdot \frac{R_c}{8\beta}$$

- Let $x = \sqrt{\beta}$ and find $\mathrm{d}V/\mathrm{d}x = 0$
- so optimal coupling coefficient :

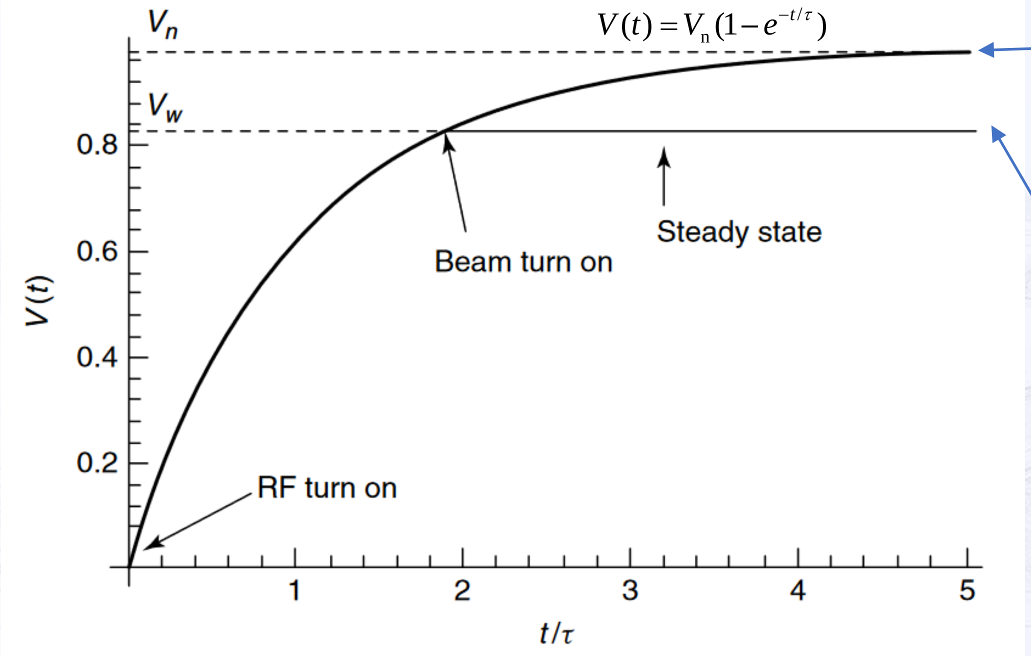
$$\beta_{\mathrm{m}} = \left(\frac{I}{2} + \sqrt{\left(\frac{I}{2}\right)^2 + 1}\right)^2$$

$$I = I_{\mathrm{b}}\sqrt{\frac{R_S}{P_0}}$$

Beam loading for SW structures -6

Transient Turn-On of a Beam-Loaded Cavity

- Consider the following method of **injecting beam in advance**, so that the field build-up by the beam and the generator **cancel each other and reach steady-state value in advance**, thereby reducing the generator output pulse width and improving power efficiency.
- τ and Q_L do not change when beam is turned on.
- When the design cavity field level is reached, the beam can be injected, provided that the field is not still increasing.



Steady state without beam loading

$$P_{cn}=P_+\frac{4\beta}{(1+\beta)^2}\qquad U_n=\frac{Q_0P_{cn}}{\omega}=\left(\frac{Q_0P_+}{\omega}\right)\left[\frac{4\beta}{(1+\beta)^2}\right]\qquad V_n\propto\sqrt{U_n}$$

Steady state with beam loading

$$P_+=P_{cw}+P_b=P_{cw}\left(1+\frac{P_b}{P_{cw}}\right)\qquad \beta=1+\frac{P_b}{P_{cw}}\quad \text{for } P_-=0$$

$$U_w=\frac{Q_0P_{cw}}{\omega}=\frac{Q_0P_+}{\omega\beta}\qquad V_w\propto\sqrt{U_w}$$

$$V_w=V_n(1-e^{-t_b/\tau})\longrightarrow t_b=-\tau\ln\left(1-\frac{V_w}{V_n}\right)$$

Bunching

- Background: The pulsed beam from the grid-controlled electron gun is a DC beam for the RF linear accelerator. Only by focusing in the initial stage of the accelerator, i.e. the bunching stage, can the beam be accelerated well in the subsequent acceleration process and have good beam quality.
- Purpose: Design the trajectory of ideal particles or reference particles, and make the transverse oscillation and longitudinal oscillation within a reasonable range.
- Bunching: Realize time/space compression in the longitudinal direction of the beam.
  - Velocity compression: $\beta<1$ The beam realizes velocity modulation at different phases of the RF field, and realizes longitudinal compression through drift or magnetic structure.
  - Magnetic compression: $\beta\approx1$ It is difficult to achieve velocity modulation. After energy modulation, it passes through a magnetic compressor to achieve longitudinal compression. (introduced briefly in this course)

Bunching - Velocity compression -1

- Simplest case: Electron gun directly connected to downstream TW buncher
- The solution to the bunching process can be achieved by solving the phase motion equation

$$\frac{\mathrm{d}\varphi}{\mathrm{d}z} = \frac{2\pi}{\lambda}\left(\frac{1}{\beta_\varphi} - \frac{1}{\beta}\right)$$

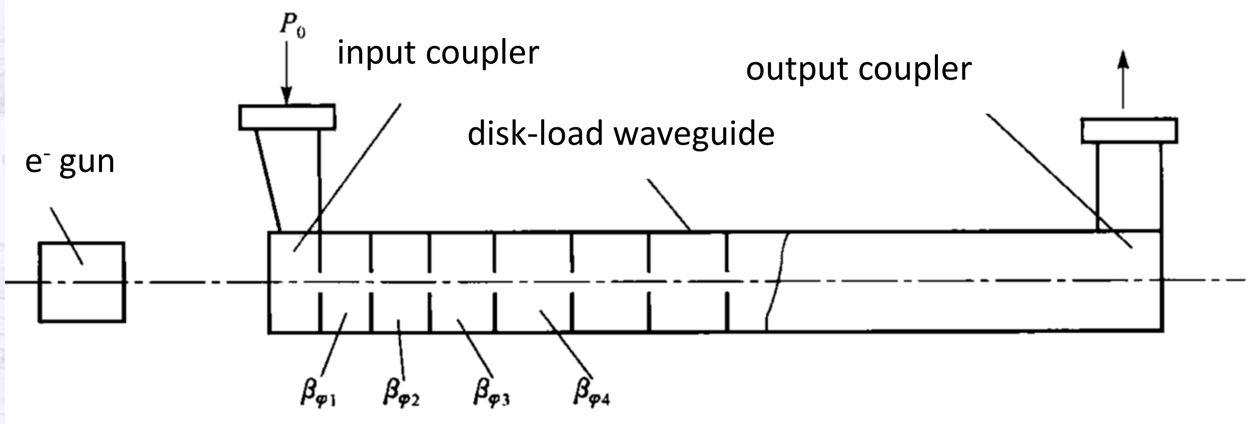
β_φ : phase velocity in the bunching cell

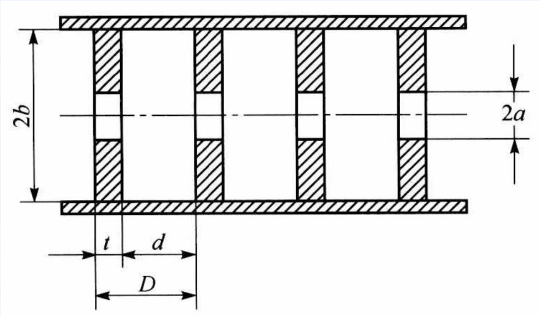
$\beta_\varphi = \frac{2\pi}{\Delta\phi}\frac{D}{\lambda_{RF}}$ $\Delta\phi$: operation mode D: length of bunching cell

  - Solving the difference equations
  - The one-dimensional model only considers the particles on the axis
  - Some useful equations:

$$\frac{\mathrm{d}\gamma}{\mathrm{d}z} = \frac{eE(z)}{m_0c^2}\cos\varphi \qquad E(z) = \sqrt{R_s\frac{\mathrm{d}P(z)}{\mathrm{d}z}} = \sqrt{2R_s(z)\alpha(z)P(z)} \qquad \frac{\mathrm{d}P}{\mathrm{d}z} = -2\alpha(z)P(z) - I_bE(z)$$

- The phase velocities of the first few cells need to be carefully chosen
  - Energy spread and capture efficiency need to make a trade-off





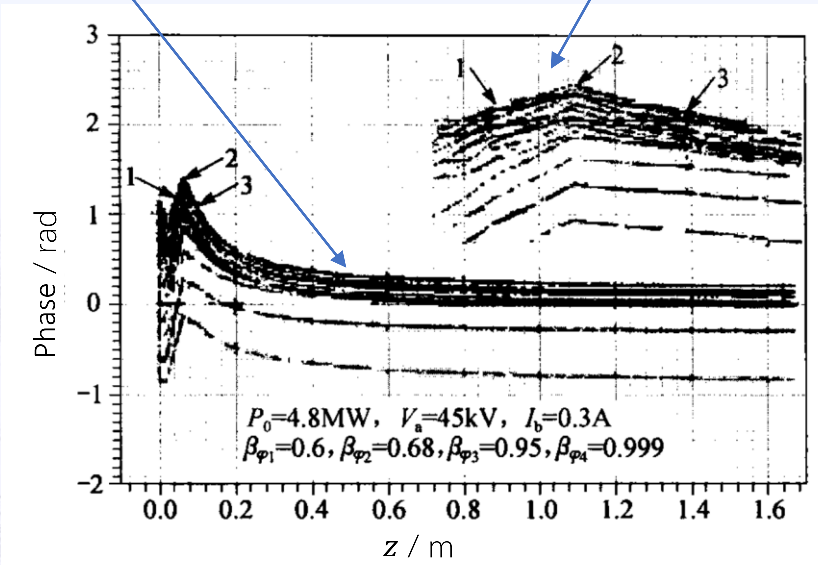
Bunching - Velocity compression -2

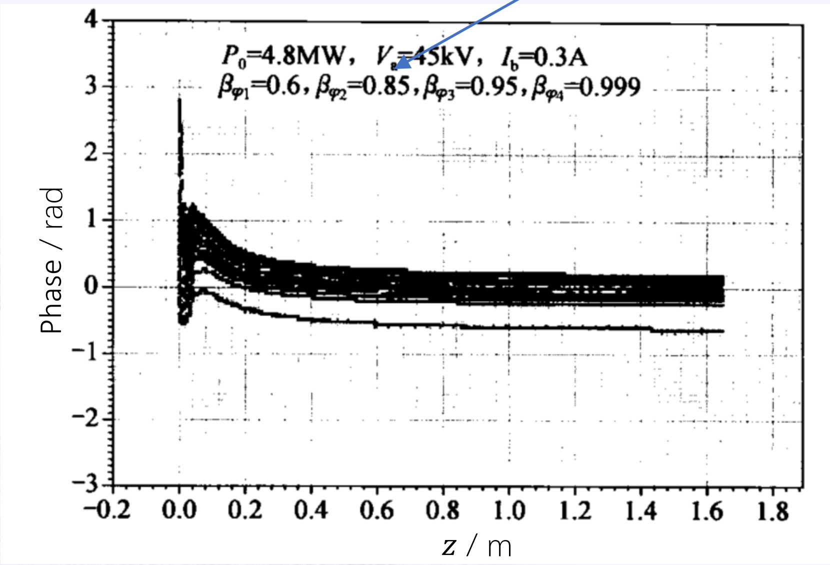
- Example: electron gun voltage 45kV, 3 special cells: β_φ=0.6, 0.68/0.85, 0.95, 45 regular cells β_φ = 0.999

Phase of the accelerated electron beam is mostly not at zero phase, so the energy obtained is not optimal.

Point 1 to point 2 is the phase orbit of 2nd bunching cell. the phase of the electron beam in the bunching cell is increasing, that is, the electron speed is faster than the phase speed of electric field.

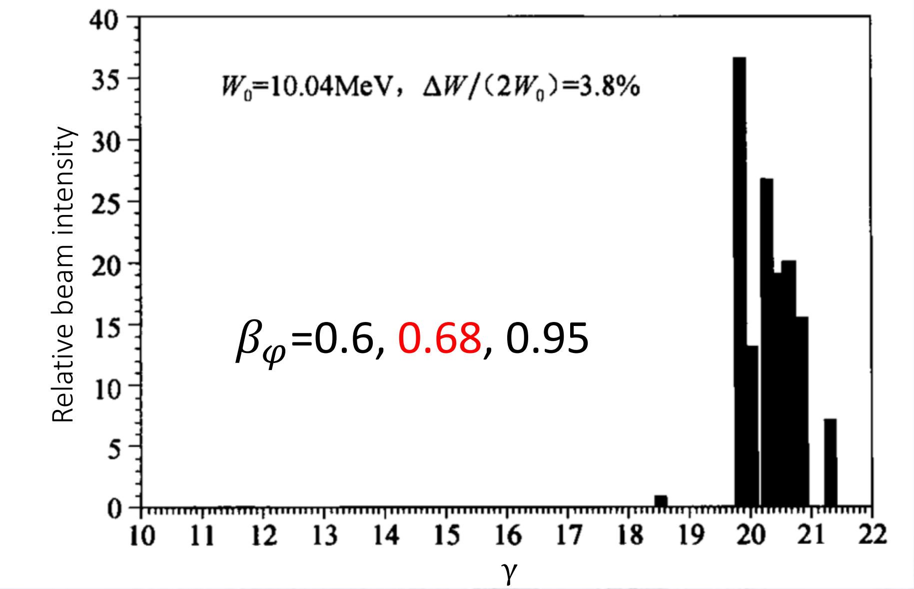
Increasing the phase speed of the 2nd bunching cell can reduce the phase of the electron beam, and finally it is possible to make the phase of the electron beam close to the "0" phase.

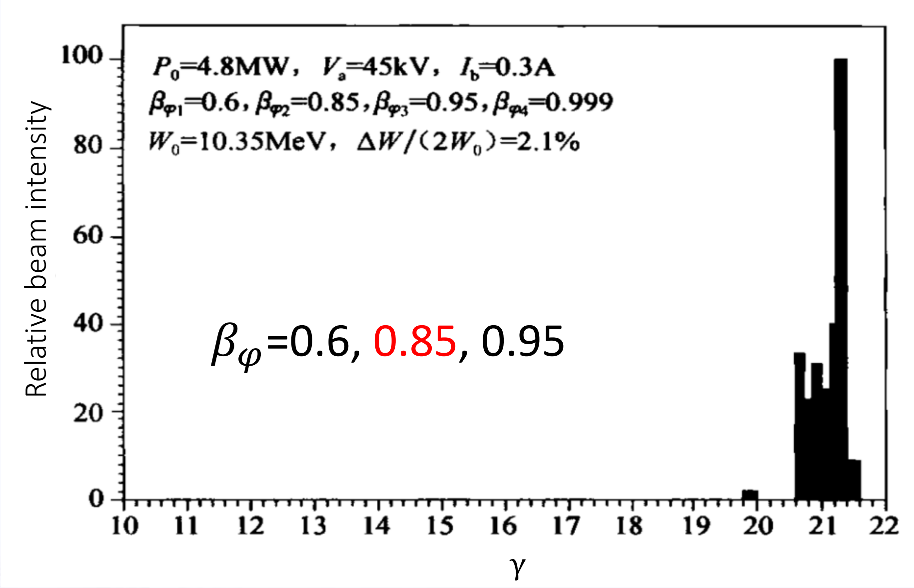




Bunching - Velocity compression -3

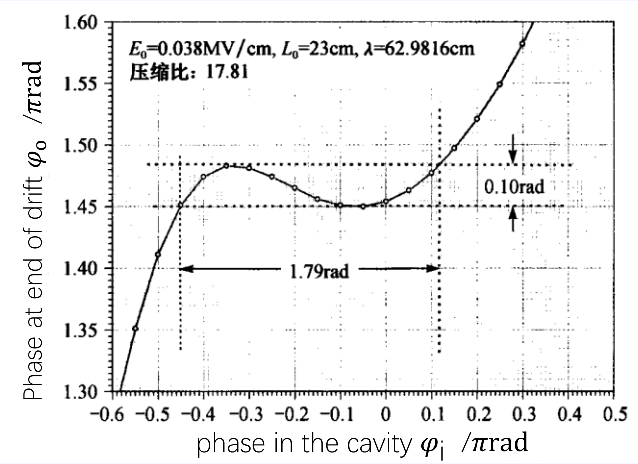
- After increasing the phase velocity of the second bunching cell, the energy gain is increased, and the energy spread is reduced.





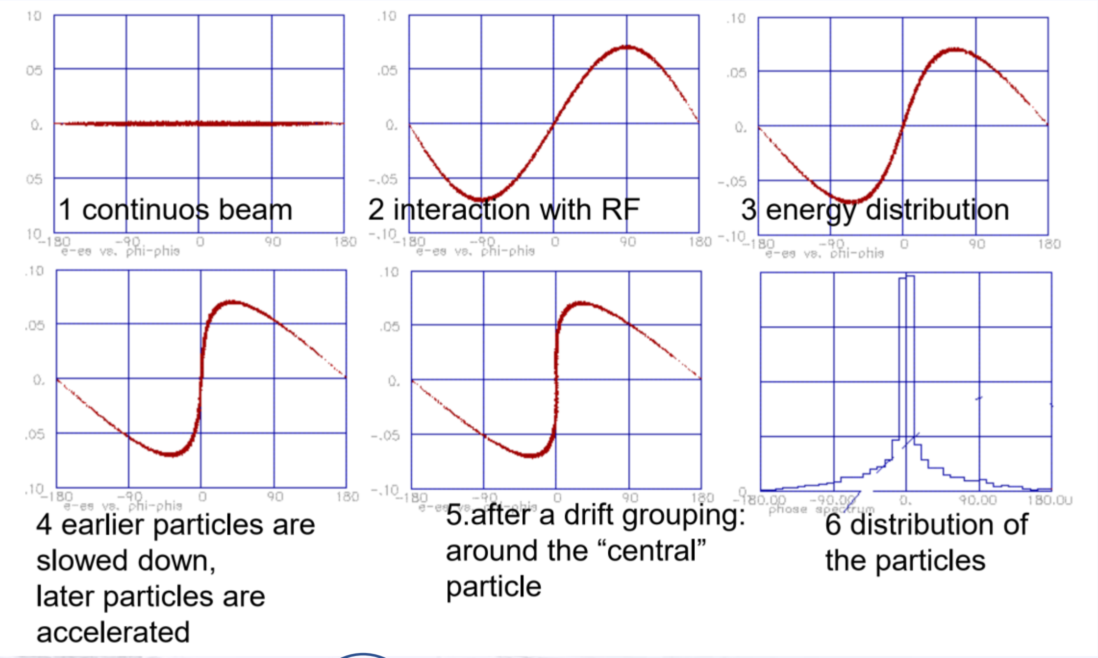
Bunching - Velocity compression -4

- Further reduce energy spread -> Separate buncher (pre-buncher)
- Generally a standing wave cavity.
- Sub-harmonics : increase the amount of charge in the captured bunch, be careful about the phase conversion with different frequencies.

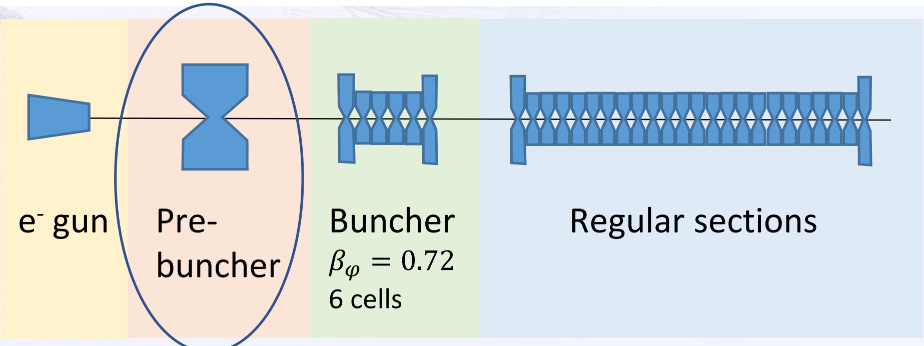


V_0=80kV, L_g=23cm, V_g=38kV, f_0=476MHz

Compression ratio:~18



Evolution of longitudinal phase space in the bunching process



Bunching - Velocity compression -4

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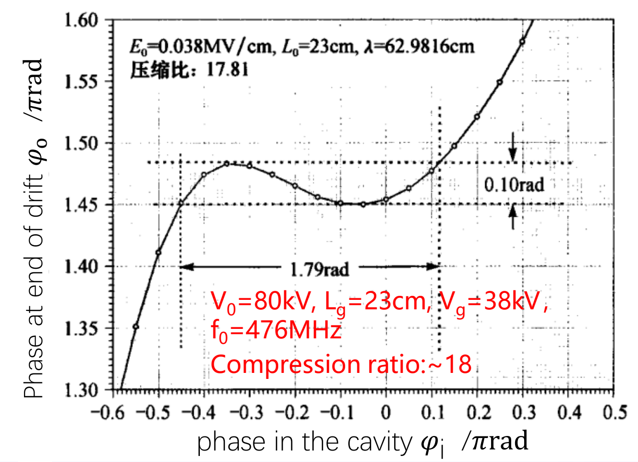
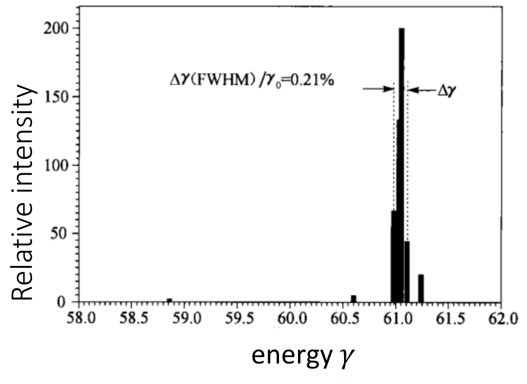
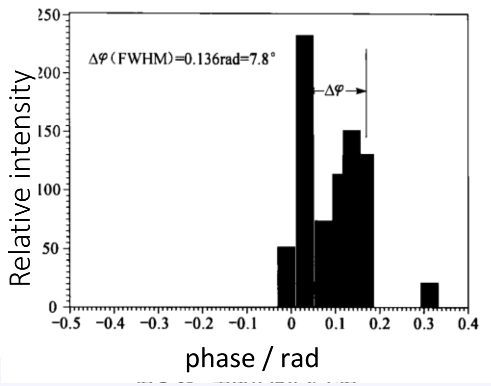
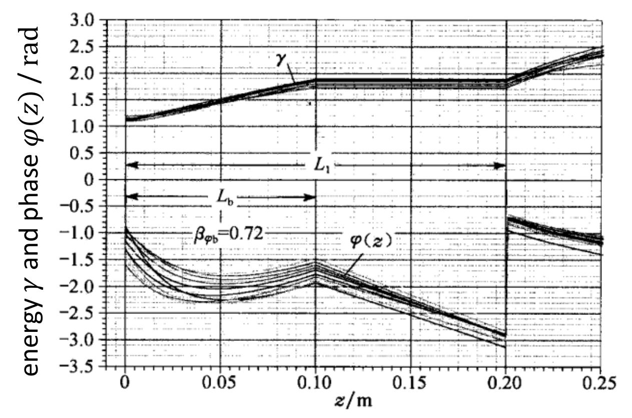
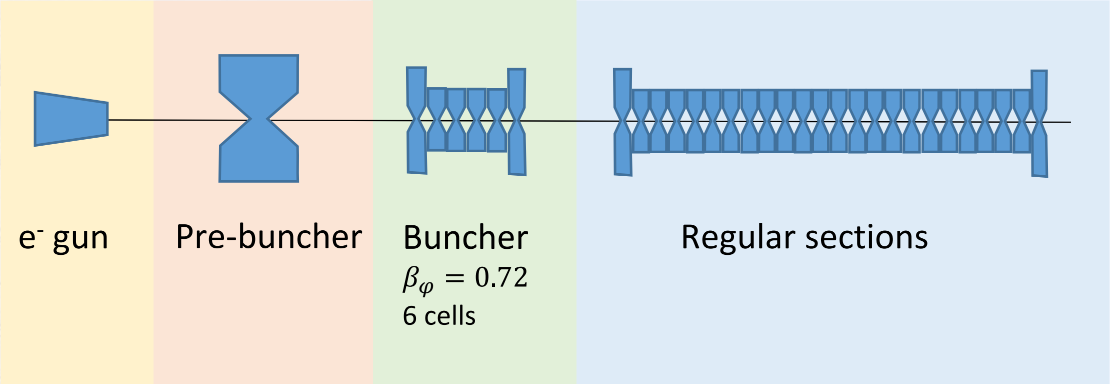








Phase trajectory and energy gain curve of buncher and drift section



Bunching - Magnetic compression

- Bunch gets energy chirp before entering compression system (low energy at the head, high energy at the tail)

$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xx'} & \sigma_{xs} & \sigma_{x\delta} \\ \sigma_{x'x} & \sigma_{x'x'} & \sigma_{x's} & \sigma_{x'\delta} \\ \sigma_{sx} & \sigma_{sx'} & \sigma_{ss} & \sigma_{s\delta} \\ \sigma_{\delta x} & \sigma_{\delta x'} & \sigma_{\delta s} & \sigma_{\delta\delta} \end{pmatrix} \qquad \Sigma_{\mathrm{f}} = R \cdot \Sigma_{\mathrm{i}} \cdot R^{\mathrm{T}}$$

Bunch length after compression

$$\sigma_{z_\mathrm{f}} = \sqrt{(1+kR_{56})^2\sigma_{z_\mathrm{i}}^2 + R_{56}^2\sigma_{\delta_\mathrm{i}}^2} \approx |1+kR_{56}|\ \sigma_{z_\mathrm{i}}$$

$$k(\varphi_0, \Delta\varphi) \equiv \frac{\partial \delta_f}{\partial z_i} = -\frac{2\pi}{\lambda}\left(1-\frac{E_{\mathrm{i}0}}{E_{\mathrm{f}0}}\right)\frac{\sin(\varphi_0+\Delta\varphi)}{\cos\varphi_0}$$

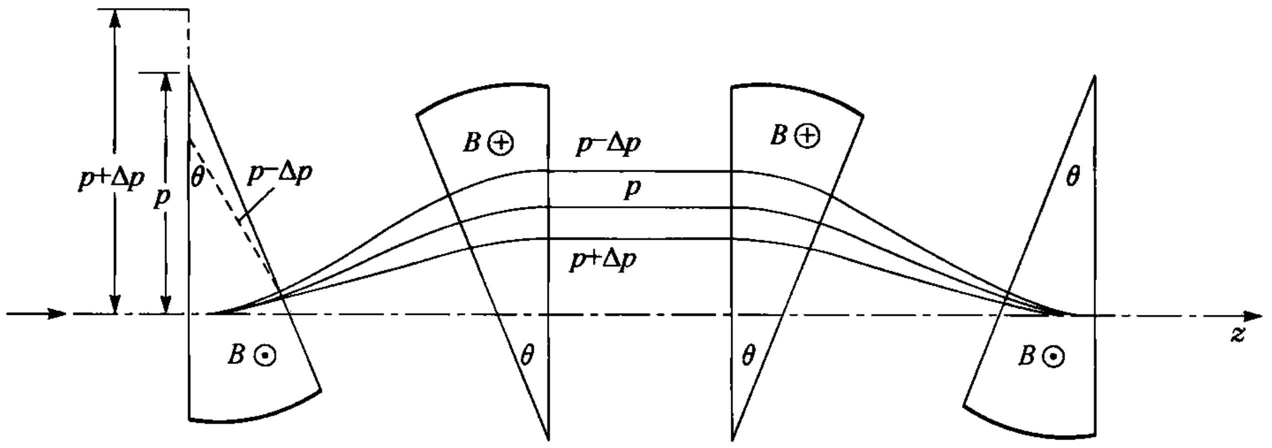
The compression ratio is highest when R_{56}=-1/k

The length of the compressed bunch is affected by the jitter of the acceleration phase and the arrival phase.
For example, when φ_0 = 20°, the compression ratio is 33, and the phase jitter is 0.1°, the bunch length jitter reaches 16%.

$$\frac{\Delta\sigma_{z_\mathrm{f}}}{\sigma_{z_\mathrm{f}}} \approx -\left(\frac{\sigma_{z_\mathrm{i}}}{\sigma_{z_\mathrm{f}}} \mp 1\right)\Delta\varphi\cot\varphi_0$$

Single Magnet Transfer Matrix

$$R(s) = \begin{pmatrix} 1 & s & 0 & -\rho\cdot\left(1-\cos\left(\frac{s}{\rho}\right)\right) \\ 0 & 1 & 0 & -\sin\left(\frac{s}{\rho}\right) \\ \frac{s}{\rho} & \frac{s^2}{2\rho} & 1 & \frac{s}{\gamma^2} - s + \rho\cdot\sin\left(\frac{s}{\rho}\right) \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Schematic diagram of the trajectories of particles with different momentum in a chicane

Outline

01 Introduction and basic ideas
Basic definition and Brief history

02 RF parameters for SW or TW structures
Q, Shunt Impedance, Transient Factor…

03 Main parameters of a LINAC
Energy spread, emittance, …

04 Basic Beam Dynamics
Beam Loading and Bunching

05 How to Make a Linac
Basic processes of manufacturing, assembly and commissioning

06 Application of Linacs
Scientific research, Medical, Industrial,…

07 Summary

USTC NSRL
NSRL
National Synchrotron Radiation Laboratory
国家同步辐射实验室

How to Make a Linac

- Design
  - beam dynamics design
    - 1) control the synchronization between the field and the particles
    - 2) insure that the beam is kept in the smallest possible volume during acceleration
  - cavity design
    - 1) control the field pattern inside the cavity
    - 2) minimize the ohmic losses on the walls / maximize the stored energy
- Subsystem design
  - Stability error analysis, allocate beam stability requirements to subsystems
- Manufacturing and test
- Assembly and alignment
- Commission
  - Beam energy to achieve the goal
  - Bunch charge (transmission efficiency)
  - Emittance optimization
  - Energy spread optimization
  - Orbit correction / Beam based alignment
  - Stability test
  - ….

Choice of frequency

Lactures on **Linear Accelerators**, by *David Alesini* (2016)

Structure dimensions	**Scales with** $f^{\frac{1}{2}}$
Shunt impedance (efficiency) per unit length r	**NC structures** r increases and this push to adopt **higher frequencies** $\propto f^{\frac{1}{2}}$
	SC structures the power losses increases with f^2 and, as a consequence, r scales with $1/f$, this push to adopt **lower frequencies**
Power sources	At very high frequencies (>10 GHz) **powersources** are less available
Mechanical realization	Cavity fabrication at very high frequency requires **higher precision** but, on the other hand, at low frequencies one needs more material and **larger machines**/brazing oven
Bunch length	**short bunches** are easier with higher f (FEL)
RF defocusing (ion linacs)	Increases with frequency ($\propto f$)
Cell length ($\beta\lambda_{\mathrm{RF}}$)	$1/f$
Wakefields	more critical at high frequency ($w_{\|\|} \propto f^2$, $w_{\perp} \propto f^3$)

Electron linacs tend to use higher frequencies (1-12 GHz) than ion linacs.
SW SC: 500 MHz-1500 MHz
TW NC: 3 GHz-12 GHz

Proton linacs use lower frequencies (100-800 MHz), increasing with energy (ex.: 350–700 MHz): compromise between focusing, cost and size.

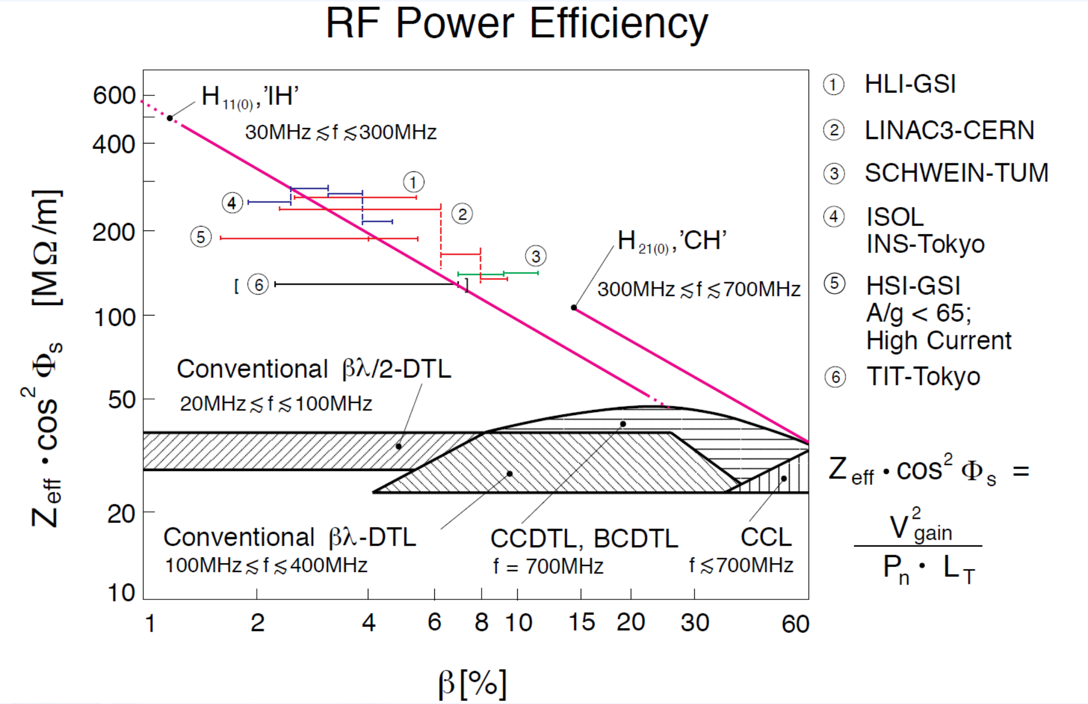
Heavy ion linacs tend to use even lower frequencies (30- 200 MHz), dominated by the low beta in the first sections.

Choice of accelerator structure

- In general **the choice of the accelerating structure depends on**:
  - ⇒ **Particle type**: mass, charge, energy
  - ⇒ **Beam current**
  - ⇒ **Duty cycle** (pulsed, CW)
  - ⇒ **Frequency**
  - ⇒ **Cost** of fabrication and of operation

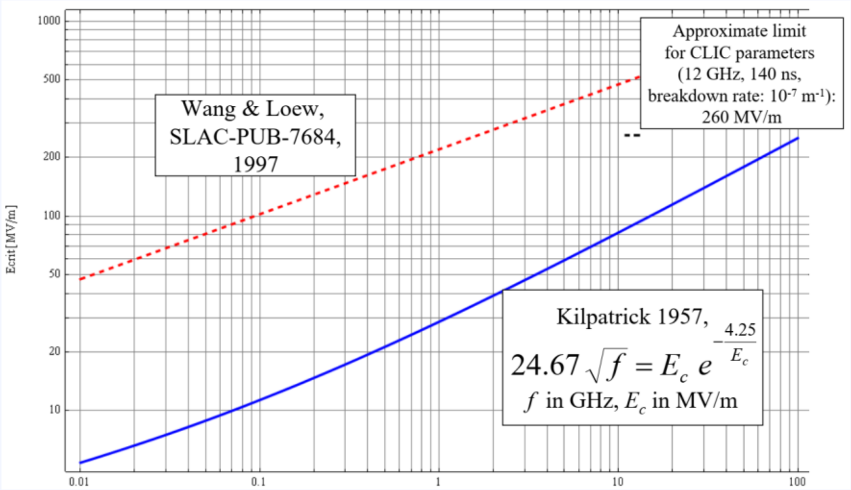
Moreover **a given accelerating structure has also a curve of efficiency** (shunt impedance) with respect to the particle energies and the choice of one structure with respect to another one depends also on this.
As example a very general scheme is given in the Table (absolutely not exhaustive).

Lactures on Linear Accelerators, by *David Alesini* (2016)

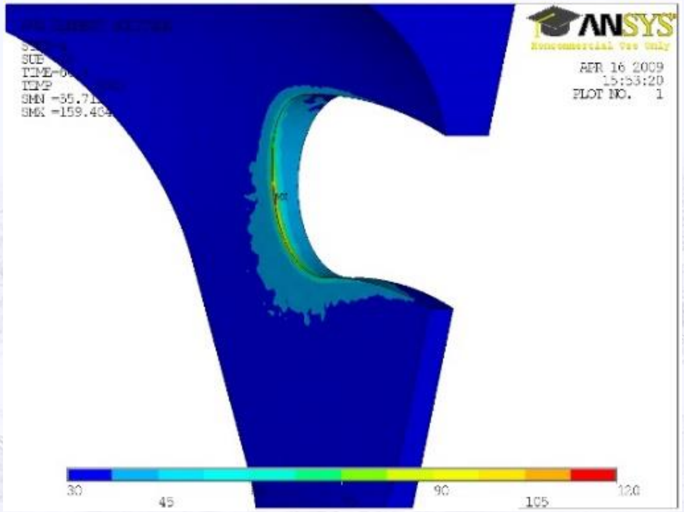


Cavity Type	β Range	Frequency	Particles
RFQ	0.01– 0.1	40-500 MHz	Protons, Ions
DTL	0.05 – 0.5	100-400 MHz	Protons, Ions
SCL	0.5 – 1	600 MHz-3 GHz	Protons, Electrons
SC Elliptical	> 0.5-0.7	350 MHz-3 GHz	Protons, Electrons
TW	1	3-12 GHz	Electrons

Limitation of gradient



Electric field limitation (NC)



Magnetic field limitation

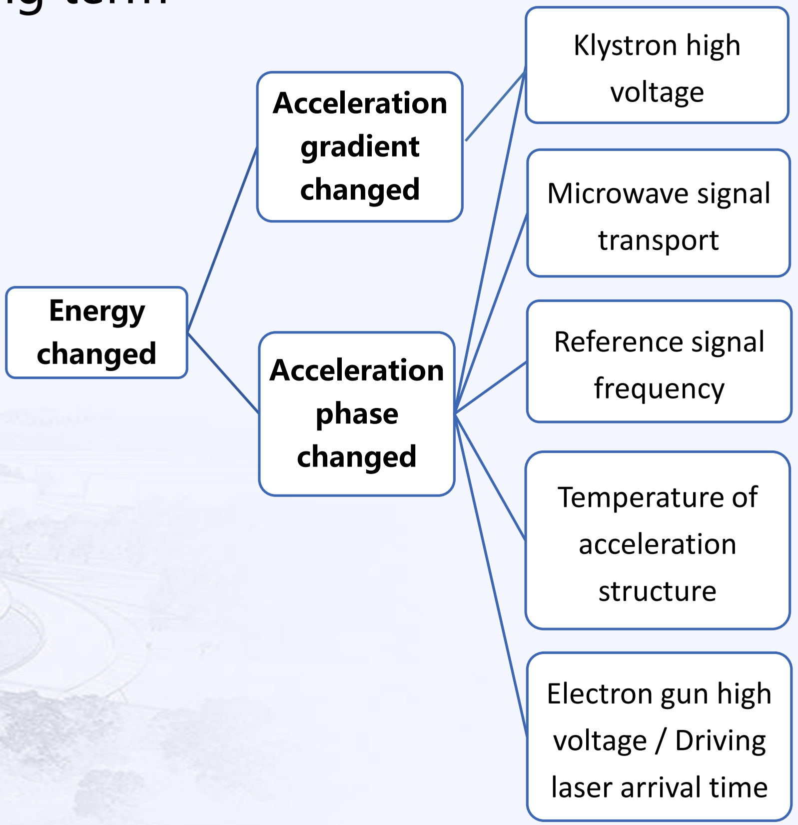
- When the electric field is too high, the probability of electric field breakdown increases rapidly, making it impossible to accelerate particles normally and increasing the possibility of damage.
- Kilpatrick criterion: empirical formula
- Technology improvements also improve the E-field limitation by: high-purity materials, low roughness precision machining, improved EM field simulation accuracy, ultra-high vacuum tech., dust-proof tech. …

- Coupled hole or weld seams: pulse heating, thermal deformation, and even melting
- Superconducting cavity: large magnetic field leads to quench

Beam stability analysis -1

- Two types of factors may affect beam trajectory deviation and parameter stability : Installation error and power supply stability.
- The former can be corrected through the corrector along the beamline.
- Here we discuss the factors that affect beam energy and energy spread.
- Consider the power and phase as well as the short and long term

Influence Factors	Gradient or Phase	Short-term or Long-term
TW structure manufacturing and tuning	Phase	Fixed Deviation
Reference signal frequency	Phase	Long-term
Water temperature	Phase	Long-term
Klystron high voltage amplitude	Gradient / Phase	Short-term
Reference signal line temperature drift	Phase	Long-term
Electron gun high voltage	Phase	Short-term



Beam stability analysis -2

- Reference signal frequency
  - Energy deviation in a single TW structure after considering frequency deviation (cannot be compensated):

$$\frac{\Delta W}{W_0}=\frac{K^2L^2}{6}\left[\frac{6}{(\alpha_0 l)^2}-\frac{3+\frac{6}{\alpha_0 l}}{e^{\alpha_0 l}-1}\right] \qquad K=\frac{2\pi}{\beta_e}\left(1-\beta_\varphi\frac{c}{v_g}\right)\frac{\Delta f}{f}$$

L: :Length of the TW structure in wavelength units
l: Length of the TW structure $L=l/(\beta_e\lambda)$

  - for SLAC 2856MHz TW struc.

$$\frac{\Delta W}{W_0}=-2.76\times10^8\times\left(\frac{\Delta f}{f}\right)^2$$

If $\Delta W/W<$1e-4 is required, then $\Delta f/f<$6e-7 is required. Commercial signal sources can easily meet the needs.

- Water temperature
  - for HALF TW struc., water temperature <±0.05°C, cumulative phase shift <±0.72°
  - For on-crest acceleration, $\frac{\Delta W}{W_0}=\frac{\Delta\varphi^2}{2}<$2E-5
  - When transmitting long-distance pick-up signals, the temperature fluctuation of the phase of cables will affect the acceleration phase.
- Klystron high voltage amplitude

$$\frac{\Delta W}{W_0}=\frac{5}{4}\frac{\Delta V_k}{V_k} \qquad \Delta\varphi_k=-2\pi\frac{f}{c}\left(\frac{eV_k}{m_0c^2}\right)\frac{l_k}{\left[\left(1+\frac{eV_k}{m_0c^2}\right)^2-1\right]^{\frac{3}{2}}}\frac{\Delta V_k}{V_k}$$

  - For a general S-band klystron, a 1% change in high voltage results in a 6-8 phase change.
  - For an 100ppm (rms) voltage fluctuation, the gradient fluctuation ~0.012% (rms) and additional phase fluctuation ~0.06° (rms)
  - In addition, the trigger pulse leading edge and the top-drop of the pulse should also be considered.

Beam stability analysis -3

- Allocate beam stability requirements to each subsystem

Table of tolerance requirements for each subsystem of the linear accelerator when the energy spread is less than 0.1%

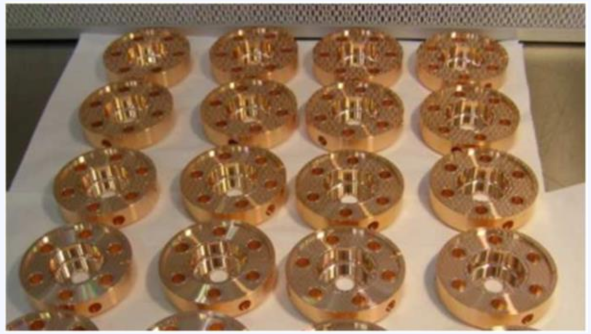
System Name	Tolerance Requirement Value	Impact on Energy Deviation
Frequency stability	$\Delta f/f \leq 1.0\times10^{-7}$	2.8×10^{-6}
Cooling water temperature stability	$\Delta T \leq 0.1^{\circ}C$	1.2×10^{-4}
Modulator pulse high - voltage stability	$\Delta V_k/V_k \leq 0.2\%$	3.8×10^{-4}
Phase stability	$\Delta\varphi \leq 1.0^{\circ}$	1.5×10^{-4}
Electron gun beam current stability	$\Delta I/I \leq 2\times10^{-3}$	2.5×10^{-4}
Root - mean - square value of above items	—	4.9×10^{-4}

* See reference 4 for details

Manufacturing and test

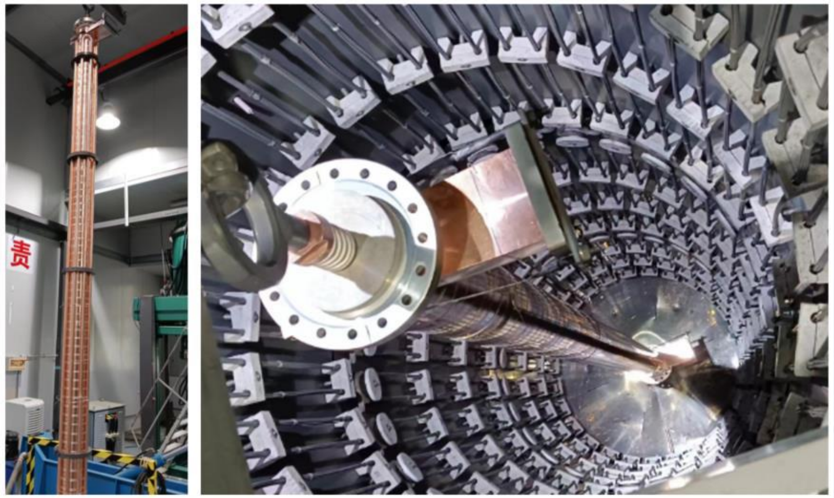
- Taking the manufacturing of traveling wave structure as an example

OFHC forged or laminated copper



Precision turning of cells, surface roughness <50 nm, precisions of the order of few um

Precision testing of mechanical dimensions of fabricated cells

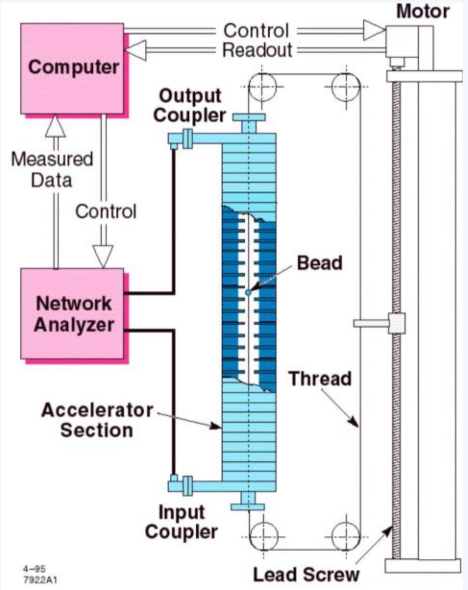


Brazing in vacuum or hydrogen furnace using different alloys at different temperatures (650-850 C) and/or in different steps

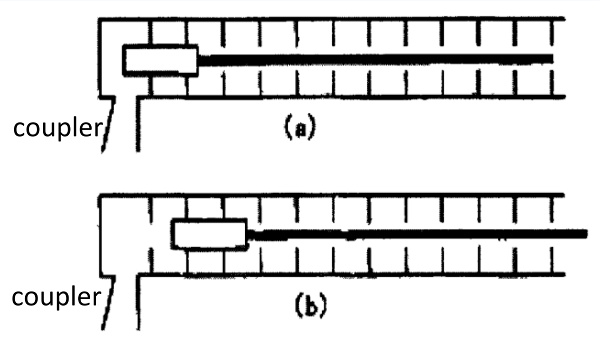
Vacuum leak test

Tuning method & Experimental setup

- Non-resonant perturbation method
  - Vector field solution
  - The main principle: A zero imaginary part of the local reflection coefficient indicates that the cavity frequency is well-tuned.
  - the n-th cell is calculated from the backward reflection difference between the (n-1)th and (n+1)th discs, which is derived from the S-parameter amplitude and phase recorded during the measurement
  - Advantage：Non-contact with the iris, preventing scratches.



- Nodal-shift method
  - Single-cell phase shift solution
  - Uses the phase difference of the S-parameter between adjacent cells to determine the inter-cell phase advance; correct tuning is confirmed when the measured phase advance equals the design value
  - Advantage：Greater precision in positioning and an easy and fast process for lower gradient requirements
- For both methods, the vacuum frequency must be calibrated against ambient conditions such as air pressure, temperature, and gas type.



*Shi J ,Grudiev A ,Wuensch W .Tuning of X-band traveling-wave accelerating structures[J].Nuclear Inst. and Methods in Physics Research, A,2013,704

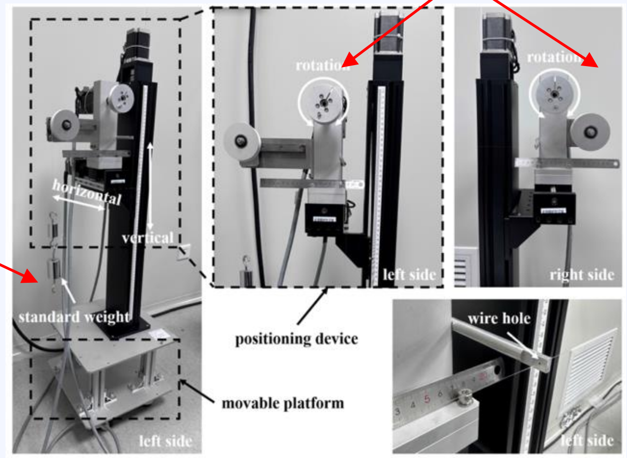
Tuning method & Experimental setup

NSRL National Synchrotron Radiation Laboratory

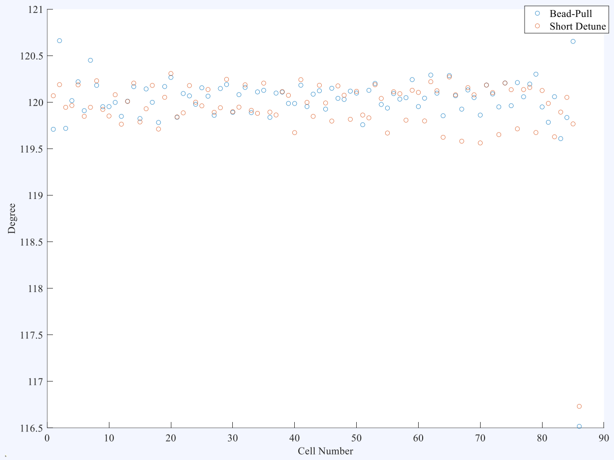
Tuning result

Servo motor

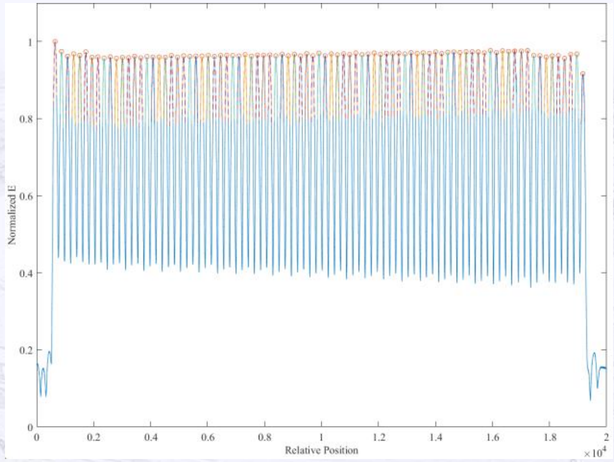
Counterweight

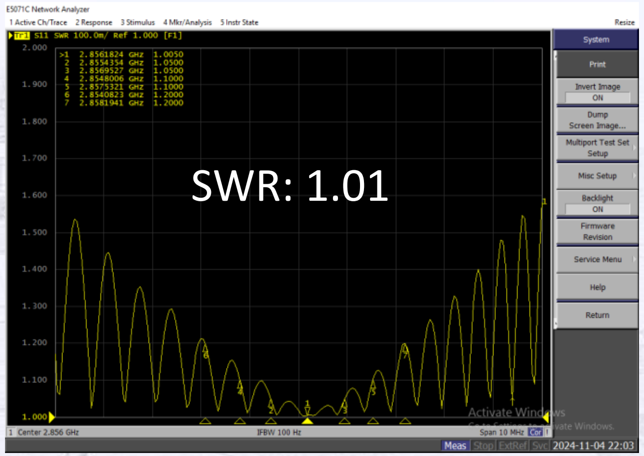


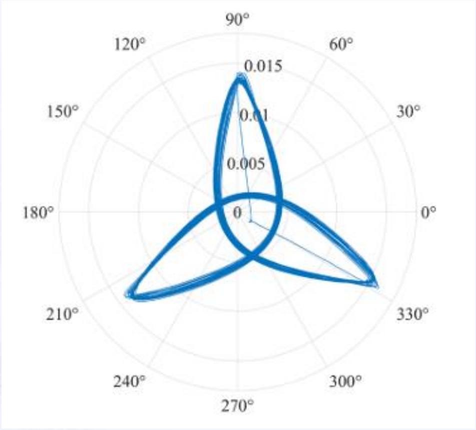
Horizontal bead-pull measurement of the long accelerating structure



The phase advances measured by both methods are in good agreement.

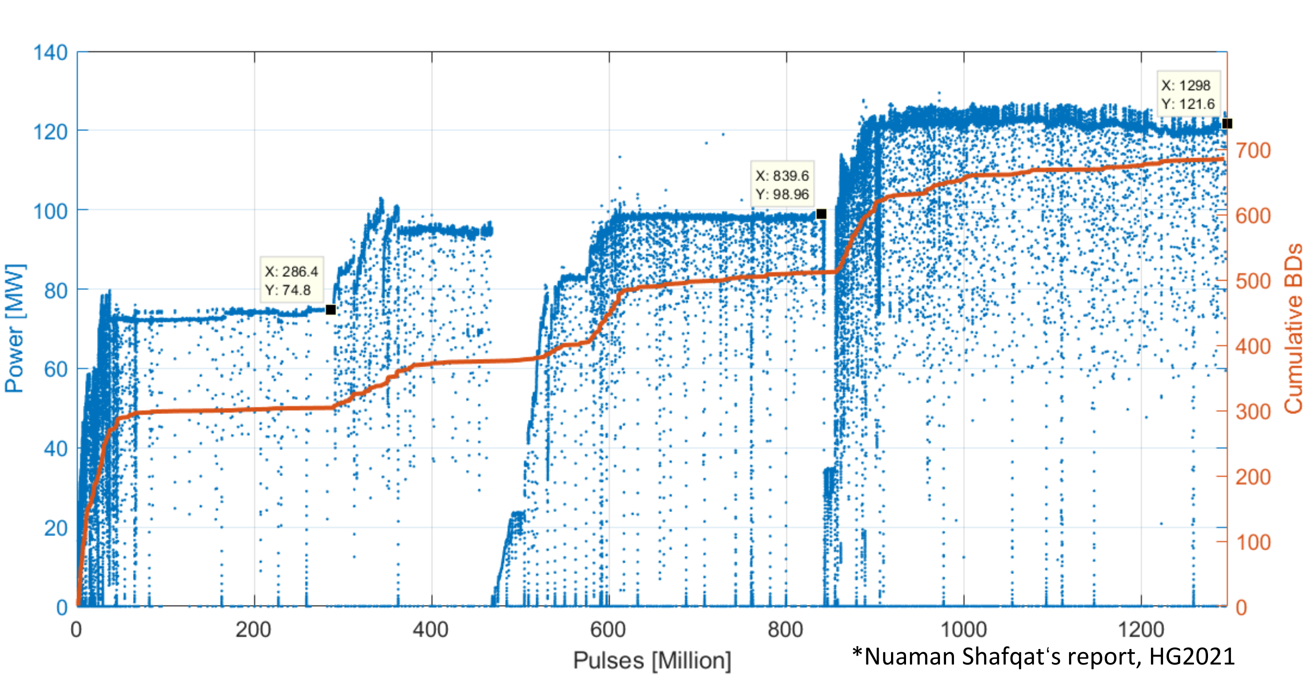






High-Power Conditioning

- Vacuum breakdown melts away tiny burrs or oxide layers, creating a smoother surface
- Local heating can release the internal stress of the material and reduce the risk of deformation in subsequent operation
- Gradually heat the surface to fully release the adsorbed gas and remove it by the vacuum system to stabilize the vacuum pressure.
- Multiple low-intensity breakdowns or electron bombardment can "clean" the surface (remove the adsorption layer), reduce the secondary electron emission coefficient, and reduce the risk of field distortion



*Nuaman Shafqat's report, HG2021

Continuously record vacuum and breakdown during conditioning

Outline

USTC NSRL

NSRL
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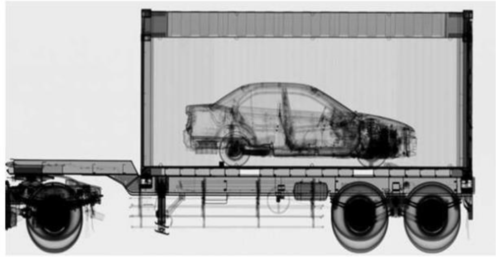
国家同步辐射实验室

Application of Linacs

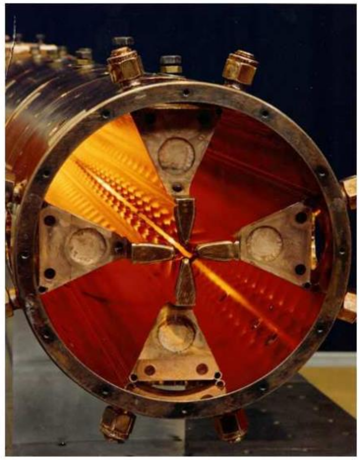
Medical applications

Neutron spallation sources

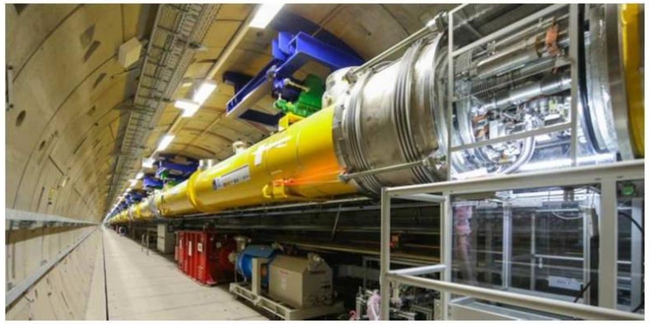
Security: Cargo scans

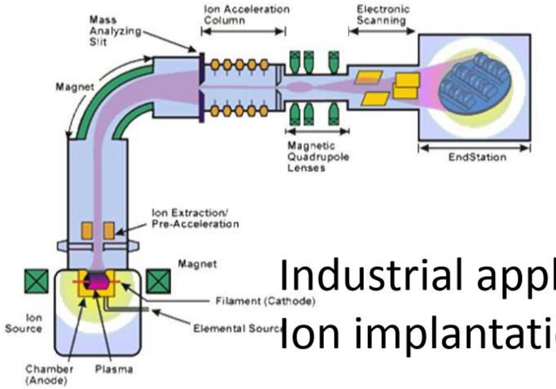


Injectors for colliders and synchrotron light sources



FEL





Industrial applications:
Ion implantation for semiconductors

LINAC for High-gain FELs

- High-gain FELs (such as SASE and seeded type) have extremely high requirements on electron beam parameters, the quality of the electron beam directly determines the gain rate, saturation power, coherence and stability of the radiation.

Radiation wavelength is directly related to the beam energy

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$ LCLS, e.g., 1 Å, 15 GeV

Emittance requirement:

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}$$ LCLS, e.g., ε_N < 1 μm at 1 Å, 15 GeV

Requirement of energy spread, peak current:

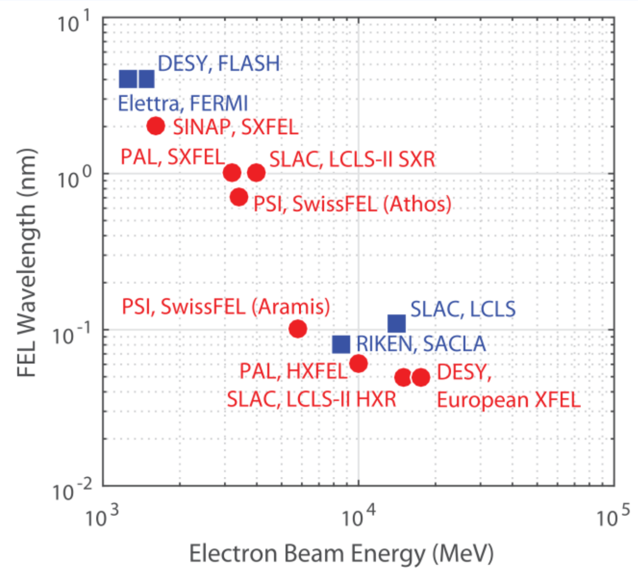
$$\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$ ρ : pierce parameter

σ_δ <0.04% at I_{pk} = 3 kA, $K \approx 3$, $\lambda_u \approx 3$ cm

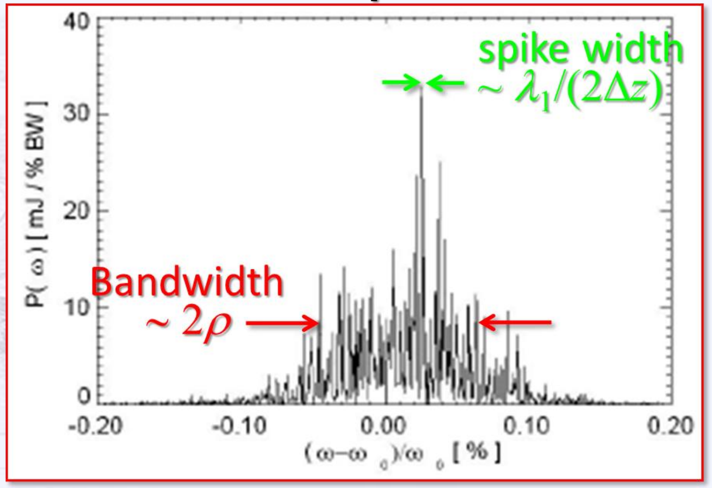
$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

FEL saturation length ~18L_g

18 $L_g \approx 60$ m for $\varepsilon_N \approx 0.5$ μm

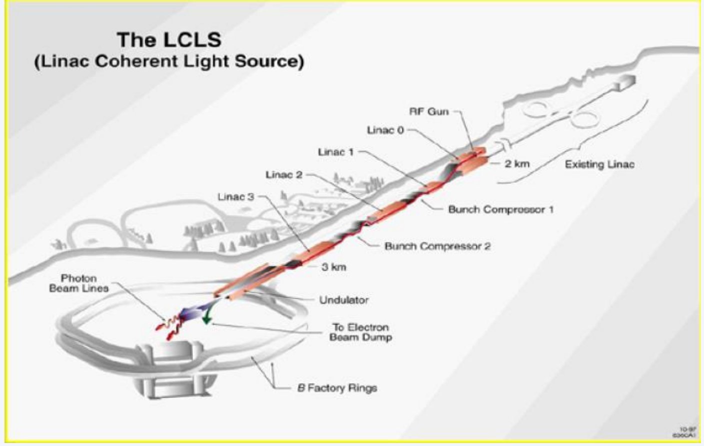


LCLS spectrum



LINACs for FEL -1

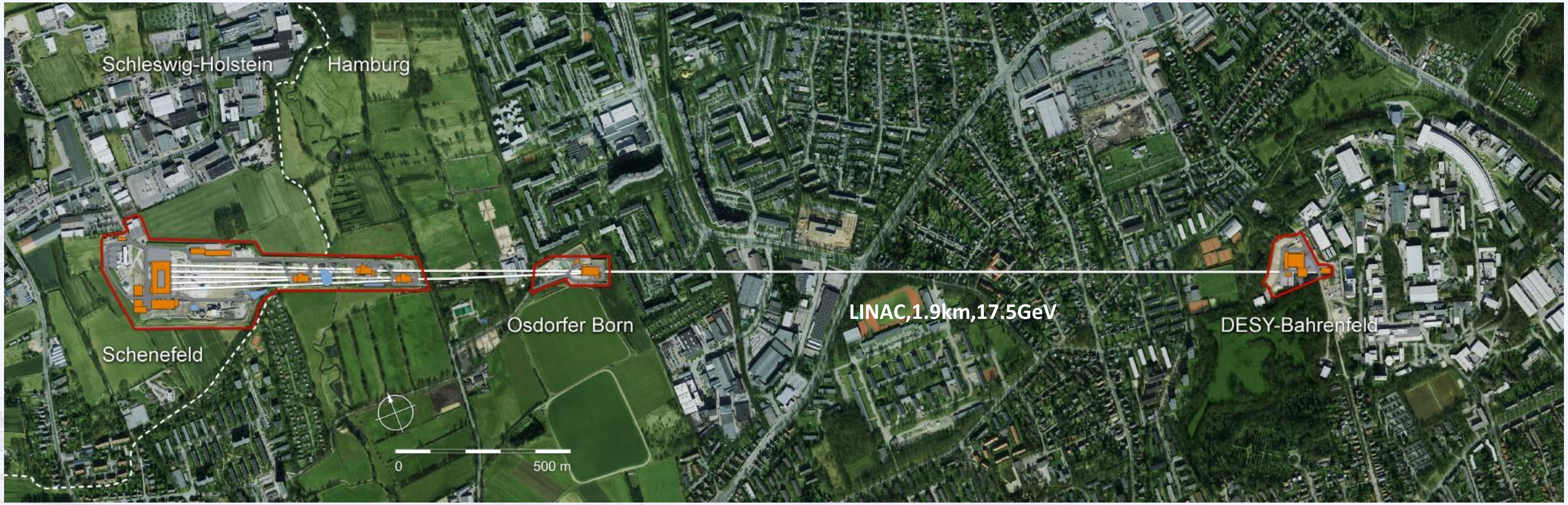
- **LCLS**: The first XFEL user device
- Construction period 2001-2009
- The main accelerator is the last kilometer of the SLAC 2-mile linear collider.
- Using the original accelerator tunnel
- Mainly modifying the injector and undulator beamline



- **SACLA** (SPring-8 Angstrom Compact free-electron LAser) : The first compact XFEL
- Built by RIKEN (in japan)
- Construction period 2006-2012
- Max energy : 8 GeV
- C-band chock-mode TW structure, operated above 35 MV/m
- 500kV DC gun for electron source
- Since 2020, SACLA has been used as a full-energy injector for the Spring-8 storage ring
- BL2 and BL3 beamlines cover a wavelength range from 0.062 nm to 0.31 nm

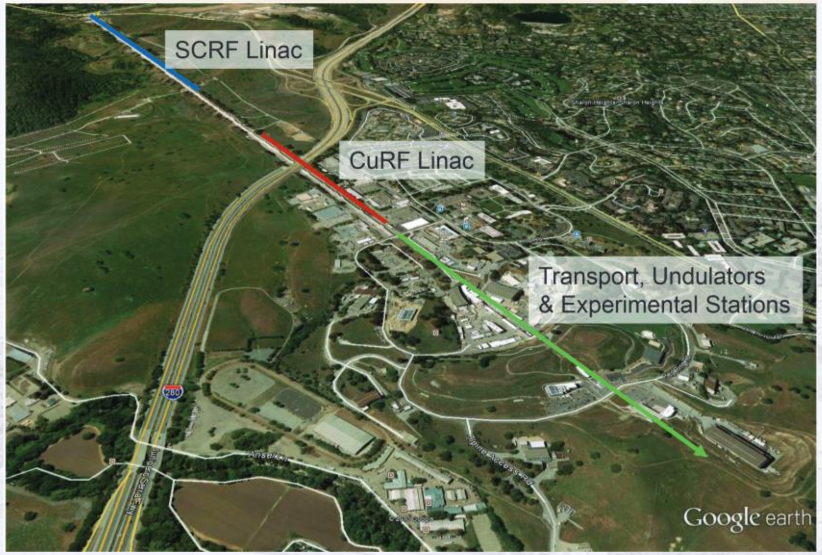
LINACs for FEL -2

- **European-XFEL**: The longest FEL (>3km)
- Jointly built by 12 countries, Germany (DESY) is the leading party
- Construction period 2009-2016
- A pulsed SC LINAC, actively promoting the upgrade to CW mode
- Max energy: 17.5 GeV
- Bunch repetition rate up to 4.5 MHz (pulse mode)
- Ultimate goal: full CW operation (No pulse interval, The average brightness of X-rays increased by 1-2 orders of magnitude)



LINACs for FEL -3

- **Swiss-FEL**: Another compact XFEL
- Built by PSI
- Construction period 2012-2017
- Operated at a higher repetition (100Hz)
- Lower energy (5.8GeV) than SACLA
- Wider adjustable radiation wavelength (0.1 nm~7 nm), adapt to different types of experiments

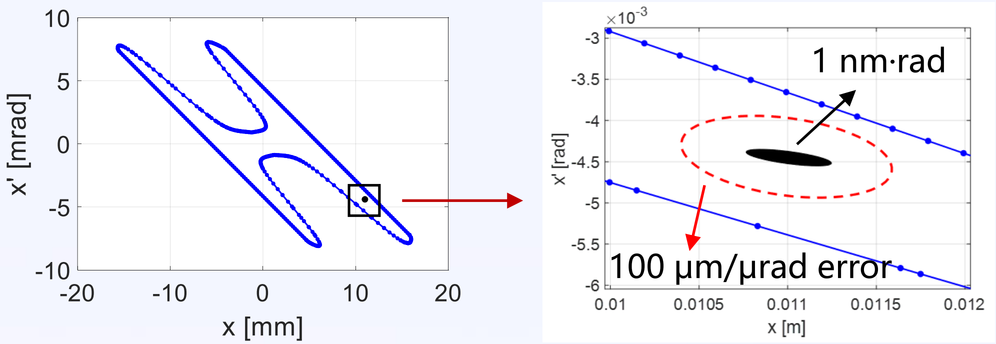


- **LCLS-II**: First CW-mode hard X-ray XFEL
- Construction lead by SLAC, in collaboration with Fermilab, ANL, and Cornell Univ.
- Construction period 2009-2023
- A CW SC LINAC, operated at 18-20 MV/m
- Max energy 4 GeV, the ongoing LCLS-II-HE (High Energy) upgrade will increase to 8 GeV
- Bunch repetition rate up to 1 MHz

SXFEL and SHINE facility will be introduced in detail in subsequent courses.

Injector for storage ring or circular collider

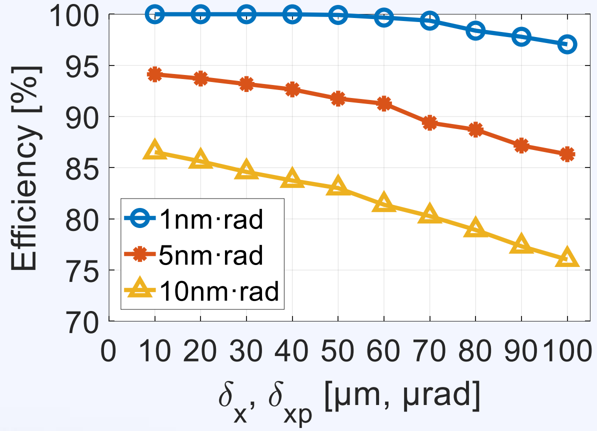
- Goal: To satisfy the storage ring's requirements for energy, bunch charge, repetition rate, emittance, stability, etc.
- Especially meet the injection acceptance requirements.
- For the circular collider injector, in addition to meeting the large charge injection requirements, the positron beamline design also needs to be considered.



Injection acceptance at the septum outlet

Parameter	Value
Emittance	< 1 nm·rad
Horizontal Position Deviation (rms)	≤ 100 μm
Angle Deviation (rms)	≤ 100 μrad
Energy Stability (rms)	≤ 0.1%
Energy Spread (rms)	≤ 0.1%

HALF storage ring requirements for injector beam parameters



Beam injection efficiency under different injection beam positions and angle errors. The different colored lines represent the beam injection efficiency under different injection beam emittances.

* Gangwen Liu, Internal Report

Linear collider

- The beam parameter requirements of the linear collider need to be designed around the three core goals of "high brightness", "high energy accuracy" and "high stability"
- Energy : Higgs particle research requires about 250 GeV, and new physics exploration may require TeV level, the energies of the two beams must be precisely matched (difference usually needs to be less than 0.1%)
- Luminosity : The core indicator for measuring collision efficiency, which directly determines the rate of physical events

High duty factor

repetition rate

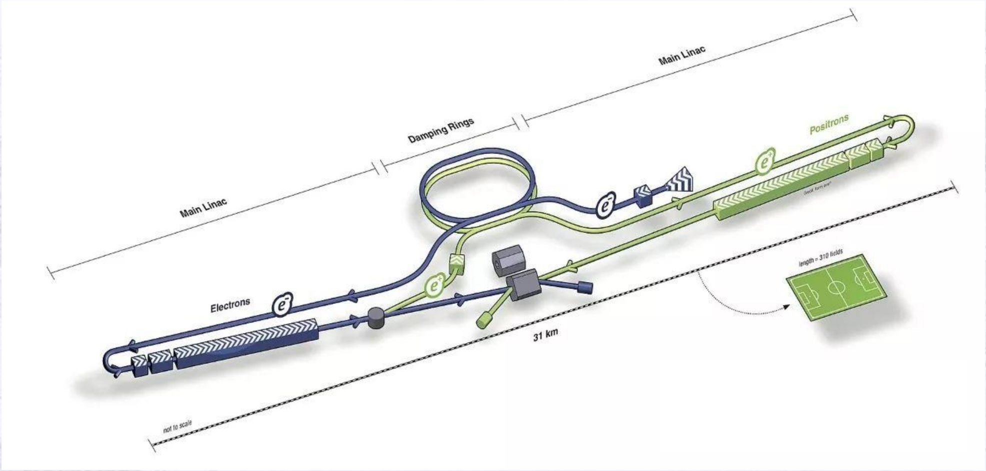
particle number

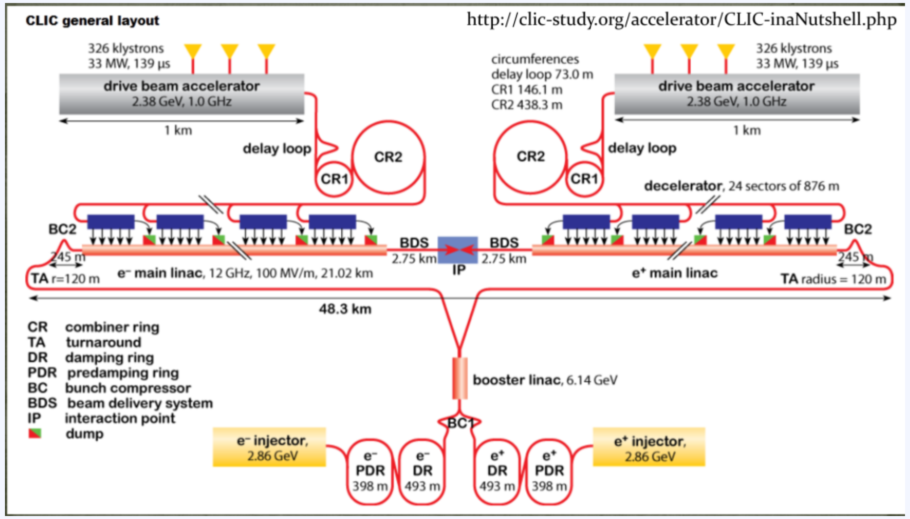
$$L = \frac{f \cdot N_1 \cdot N_2}{4\pi\sigma_x\sigma_y}$$

beam size at interception point → emittance, bunch length, stability...

Linear collider in proposal

- **International Linear Collider (ILC)**
- Technical plan determined in 2004, and pre-production research promoted through international cooperation.
- Budget ~ $10-13 billion.
- 2 SC LINAC, each ~12 kilometers
- Collision energy 500GeV with an option to upgrade to 1 TeV
- Collisions between electrons and positrons, in bunches of 5 nm in height each containing $2\text{x}10^{10}$ particles and colliding 14 kHz
- 16,000 cavities for 2K operation





- **Compact Linear Collider (CLIC)**
- The full TDR is expected to be completed before engineering design starts after 2030
- Budget ~ €10 billion
- 50 km of underground tunnel
- based on high-gradient, 100 MV/m, NC RF, low emittance beams and a two-beam accelerator
- e+ e- linear collider for the range of 380 GeV to 3 TeV

Medical applications -1

- Nuclide (radioisotope) production : designed for large beam power
- Short half-life, moderate dose, imaging for disease diagnosis
- Moderate half-life, large dose, emitting highly ionizing particles (β、α、e-) for therapy

Table: Radioisotope production by electrons irradiation

Year	Produced nuclide	Reaction channel	Irradiation conditions	Yield
2016	^{99}Mo	$^{100}Mo(\gamma,n)$	42 MeV, 8 kW, 6.5 d	12.4 Ci
2016	^{67}Cu	$^{68}Zn(\gamma,p)$	36 MeV, 3-10 kW	
2016	^{47}Sc	$^{48}Ti(\gamma,p)$	35 MeV, 2 kW, 3 hrs	1313.3 μCi for Ti foil
2008	^{225}Ac	$^{226}_{88}\mathrm{Ra}(n,\gamma)^{225}_{88}\mathrm{Ra}\xrightarrow{\beta^-}{}^{225}_{89}\mathrm{Ac}$	18 MeV, 26 uA, 2.9 h	11.5 mCi/h

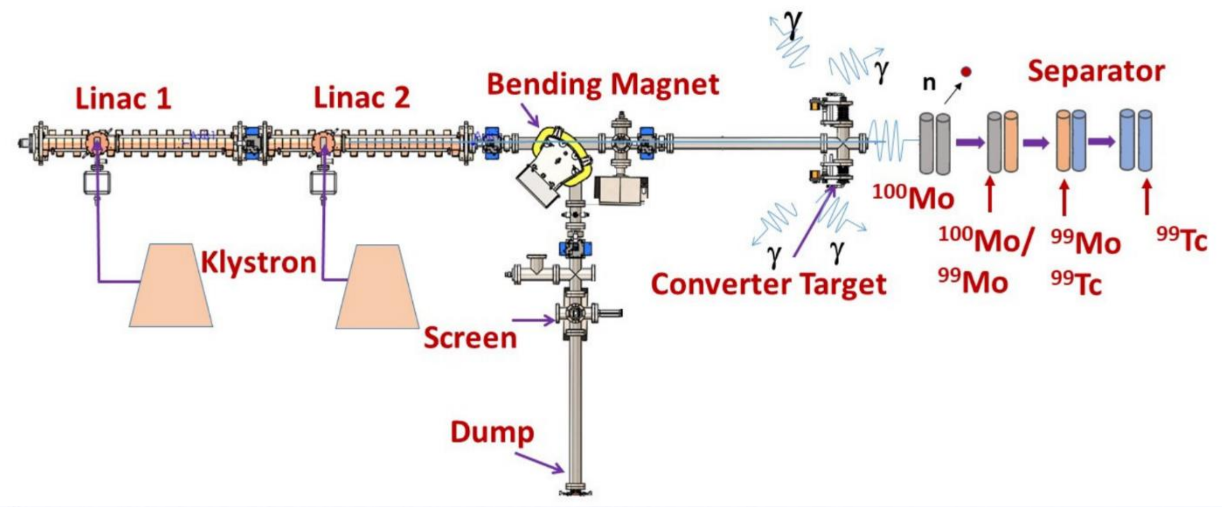
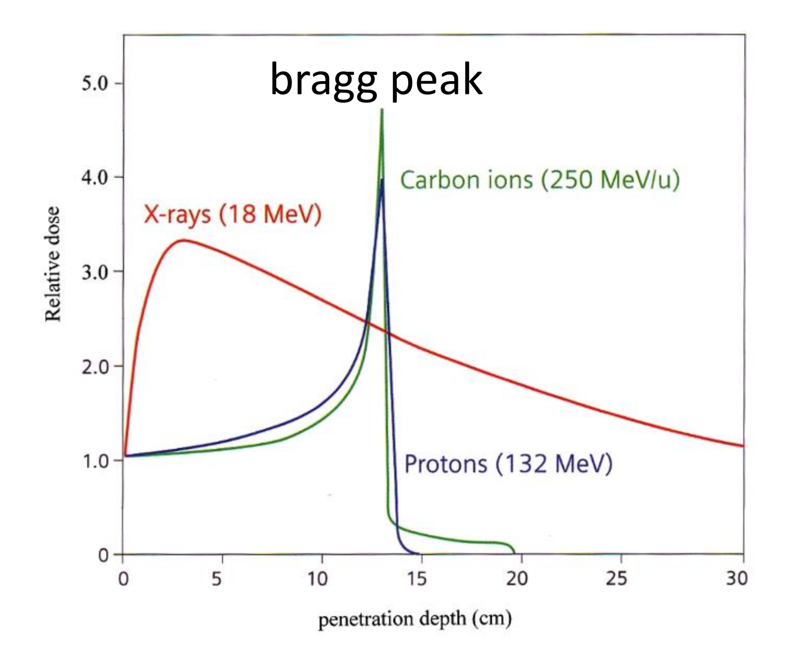


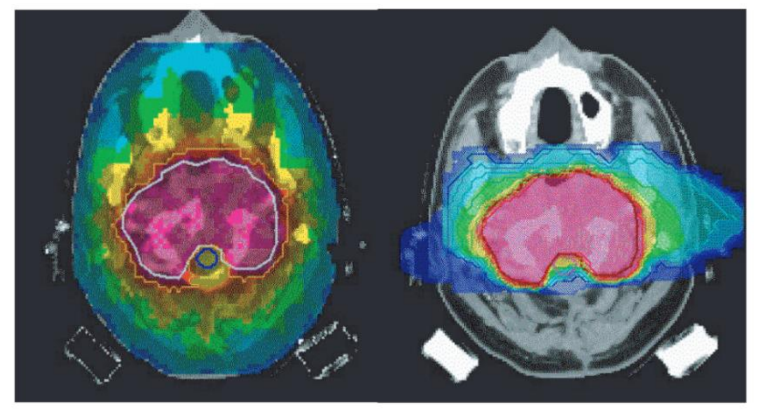
Table 1: Parameters for Thermal Estimation

Parameter	Value
Beam Energy	30 MeV
Beam Power	10 KW
Peak power	7.5 MW
Average power per linac	36 KW
Duty	0.00514
Type of flow	Parallel flow
Water flow, (for 5 °C rise)	64 lpm
Surface area	0.376 m^2
Heat Flux	2.6363 x 10^4 W/m^3

Medical applications -2

- Radiation therapy : Extremely high dose control accuracy
- **Ions have larger LET** (energy loss per unit distance) than photons.
- High LET criterion: >20eV/nm, an average of two DNA double-strand breaks in one cell, proton beam reaches its 20 eV/nm limit only in the last 50 μm of its trajectory.
- Most heavy ion/proton therapy facility is based on circular accelerators. In recent years, linear accelerators have also been developed for proton therapy.
- **Photons therapy**： produced by electron beam bombardment (usually generated by a SW linear accelerator), the energy is about 5-30MeV.
- From a doctor's view, photon therapy has greater universality





Photons in 9 direction　Carbon ions in 2 direction

Industrial applications

- Irradiation
  - Direct electron beam irradiation **or** conversion into x-ray irradiation.
  - Designer focus on power use efficiency, beam power, and compactness.
  - Different application occasions have different requirements for electron beam energy.
  - E.g. 5-10MeV electron beam, used for cross-linking, curing and polymerization of thicker materials, sterilization of medical products, food irradiation .....
- Ion implantation
  - The largest number of industrial accelerators.
  - In the early 1980s, the development of high current (>10mA) implanters made them the main tool for doping integrated circuit semiconductor production.
  - Now: covers a wide range of ion species, beam energies, from protons to antimony ions for implantation in silicon, energies from a few hundred eV to ~10 MeV.
- CT (computerized tomography)
  - Resolution is determined by the size of the electron beam under the same conditions.
  - LINAC based CT: Inspecting large metal castings and welded joints to locate defects.
  - Energy of electrons: 1-16 MeV.

*Robert W. Hamm, **Industrial Accelerators,** Reviews of Accelerator Science and Technology, Vol. 1 (2008) 163–184

Summary

- Principle of LINAC: synchronization, focusing…
- Parameters
- Different type of cavities: SW or TW
- Bunching, beam loading and compensation method
- Processes of making a LINAC
- Applications
- Designing and building an accelerator requires engineering services that meet the scientific goals of the facility.

Homework

- 1. Plot the transmission power P_w, accelerating electric field E_a, unit power loss $-\mathrm{d}P_W / \mathrm{d}z$, group velocity v_g, and attenuation constant $\alpha(z)$ of the two traveling wave acceleration structures mentioned below as a function of the longitudinal positon along the structure z, without considering the beam loading:

(1) Constant impedance traveling wave acceleration structure:

Operating frequency f = 12 GHz, structure length L_s = 0.8 meter, the input power P_0=50 MW, quality factor Q_0=8000, the shunt impedance Z_s =100 MΩ/m, and the group velocity v_g = 0.02c, where c is the speed of light.

(2) Constant gradient traveling wave acceleration structure:

Operating frequency f = 12 GHz, structure length L_s = 0.8 meter, the input power P_0=50 MW, quality factor Q_0=8000, the shunt impedance Z_s =100 MΩ/m, and the total attenuation constant τ_0=0.8.

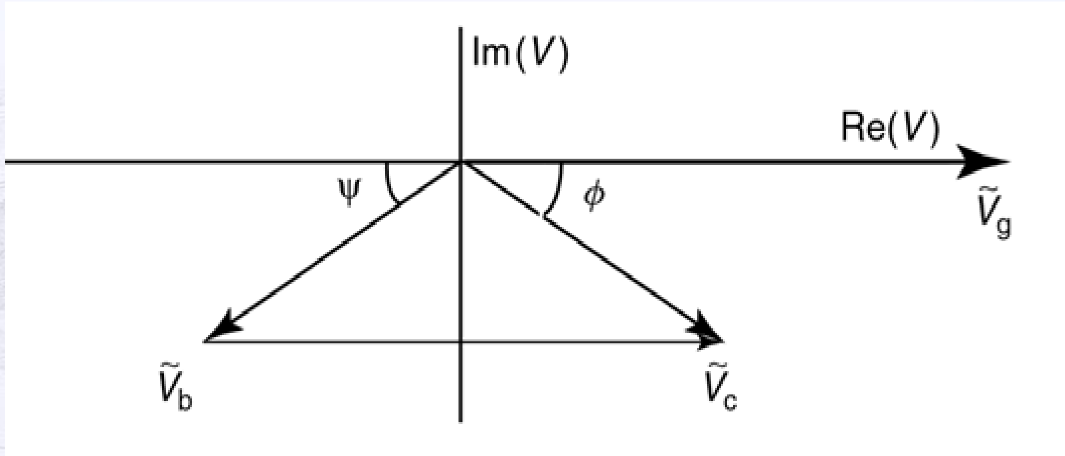
Homework

2. Consider a beam-loaded superconducting cavity in a proton linac with the following parameter values frequency $f = \omega/2\pi = 0.65$ GHz, beam current $I = 0.1$ A, effective shunt impedance $r_s = 1.6 \times 10^{12}\,\Omega$, loaded quality factor $Q_L = 3 \times 10^5$, synchronization phase $\phi = -33\,°$, effective cavity voltage (includes the transit-time factor) $V_c = 4 \times 10^6\ V$;

Calculate: (1) power delivered to the beam P_b and cavity wall-power loss P_c;

(2) optimal coupling coefficient β_0 and detuning angle ψ corresponding to yield zero reflected power when the beam is on;

(3) beam voltage V_b and transmitter voltage V_g and calculate the transmitter power P_g assuming $\beta = \beta_0$ and the detuning angle ψ from part (2).



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THANKS

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