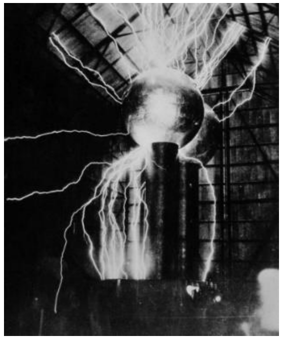
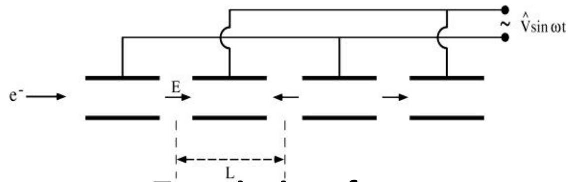
SUMMARY OF THE FIRST PART

ELECTROSTATIC ACCELERATORS



WIDERÖE DTL

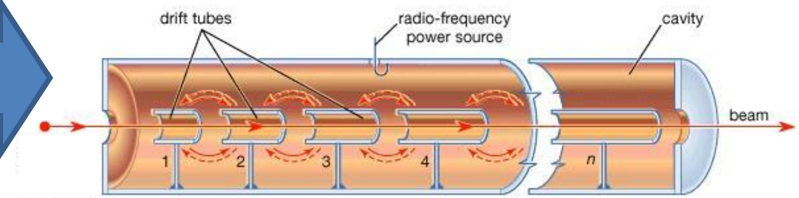


Transit time factor

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

ALVAREZ

β=0.05-0.5, f_{RF}=50-400 MHz

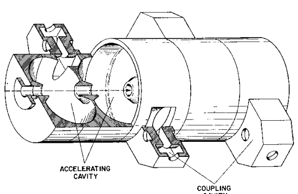


$$L_n = \bar{\beta}_n \lambda_{RF}$$

$$\Delta E_n = q\Delta V_n$$

RF CYLINDRICAL CAVITIES (PILLBOX-LIKE)

π/2 MODE



$$\tau_F = \frac{2Q}{\omega_{RF}}$$

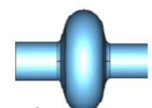
$$V_{acc}(t) = \hat{V}_{acc}\left(1 - e^{-\frac{t}{\tau_F}}\right)$$

$$\hat{V}_{acc} = \sqrt{\left(\frac{R}{Q}\right)QP_{diss}}$$

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

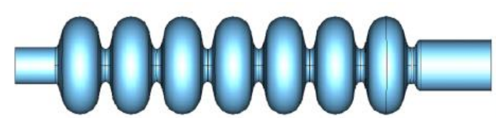
π MODE

β>0.5, f_{RF}=0.3-3 GHz (or above)



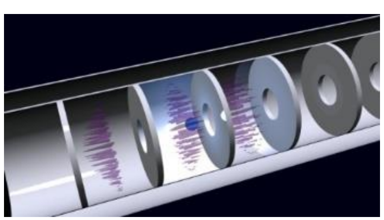
$$d = \frac{\beta\lambda_{RF}}{2}$$

d ↔



nR

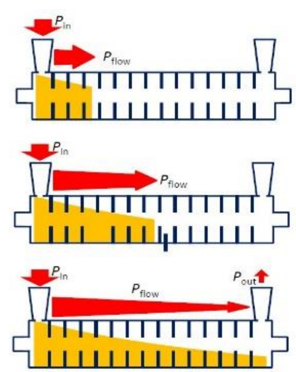
TW CAVITIES: IRIS LOADED STRUCTURES
(electrons, β=1)



$$r = \frac{\hat{E}_{acc}^2}{p_{diss}}$$

$$\alpha = \frac{p_{diss}}{2P_F}$$

$$v_g = \frac{P_F}{w}$$



$$E_{acc}(z) = E_{INPUT}e^{-\alpha z} \qquad V_{acc} = E_{INPUT}\frac{1-e^{-\alpha L}}{\alpha}$$

$$P_F(z) = P_{INPUT}e^{-2\alpha z} \qquad P_{OUT} = P_{INPUT}e^{-2\alpha L}$$

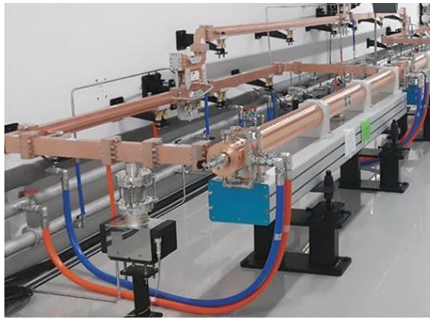
$$\tau_F = \frac{L}{v_g}$$

LINAC TECHNOLOGY

ACCELERATING CAVITY TECHNOLOGY

⇒The cavities (and the related LINAC technology) can be of different material:

- copper for **normal conducting (NC, both SW than TW)** cavities;
- Niobium for **superconducting cavities (SC, SW)**;



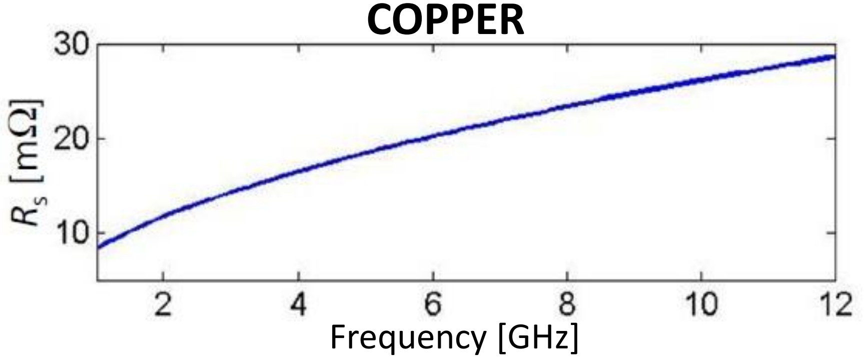
⇒We can choose between NC or the SC technology depending on the required performances in term of:

- **accelerating gradient** (MV/m);
- **RF pulse length** (how many bunches we can contemporary accelerate);
- **Duty cycle (see next slide)**: pulsed operation (i.e. 10-100 Hz) or continuous wave (CW) operation;
- **Average beam current**.
- …

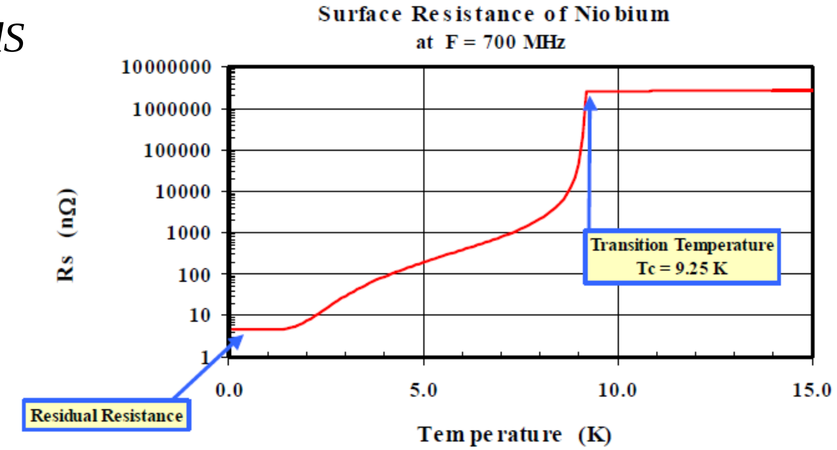
Dissipated power into the cavity walls is related to the surface currents

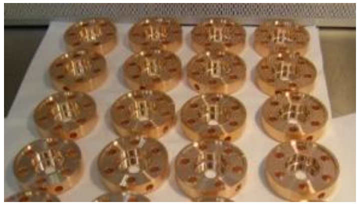
$$P_{diss} = \int_{cavity\ wall} \overbrace{\frac{1}{2} R_s H_{tan}^2}^{\text{power density}} dS$$

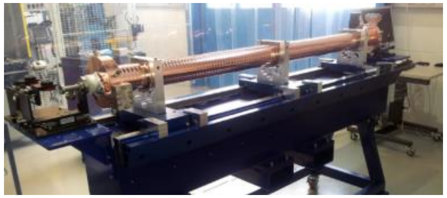
COPPER



NIOBIUM





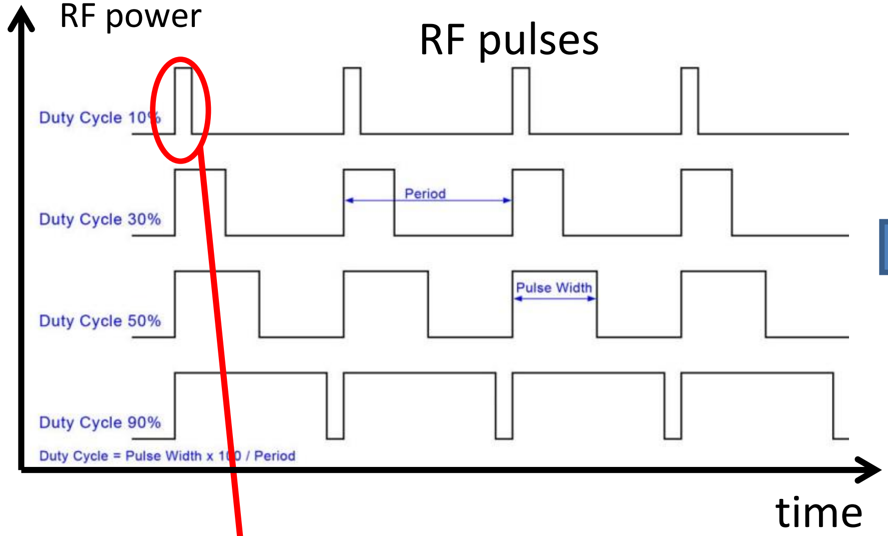


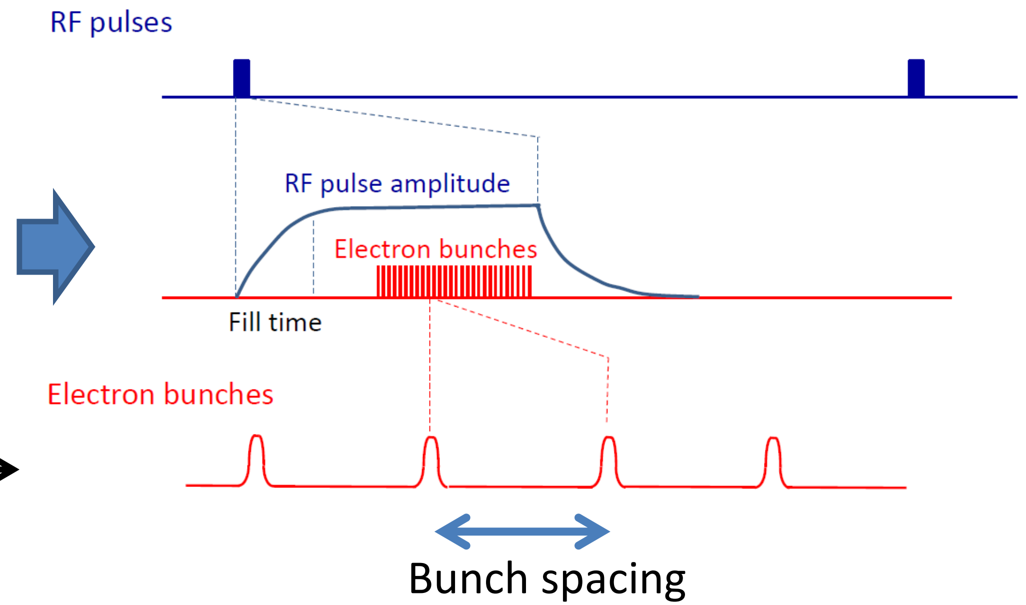
Between copper and Niobium there is a factor 10^5-10^6

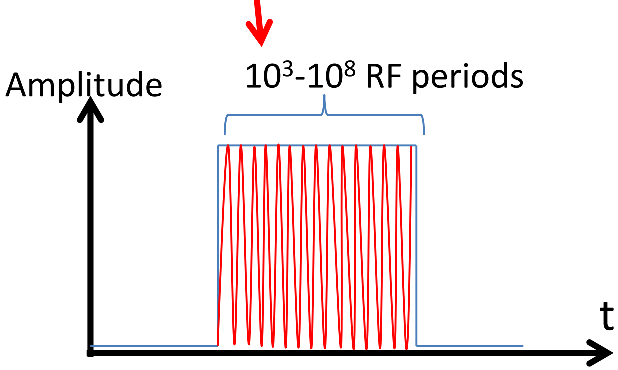
RF STRUCTURE AND BEAM STRUCTURE: NC vs SC

The "**beam structure**" in a LINAC is directly related to the "**RF structure**". There are two possible type of operations:

- **CW** (Continuous Wave) operation ⇒ allow, in principle, to operate with a continuous (bunched) beam
- **PULSED** operation ⇒ there are RF pulses at a certain repetition rate (**Duty Cycle (DC)=pulsed width/period**)







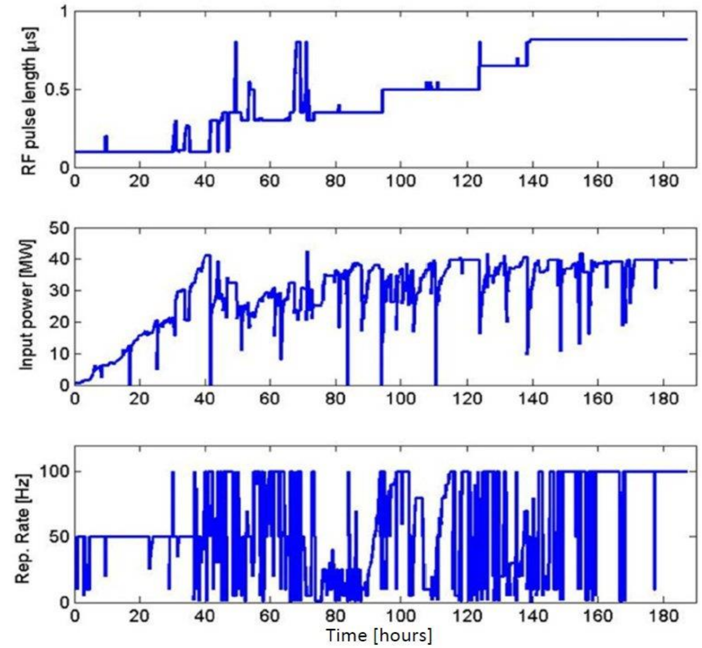
⇒**SC structures allow operation at very high Duty Cycle (>1%) up to a CW operation (DC=100%)** (because of the extremely low dissipated power) **with relatively high gradient (>20 MV/m)**. This means that a continuous (bunched) beam can be accelerated.

⇒**NC structures can operate in pulsed mode** at **very low DC** (10^{-2}-10^{-1} %) (because of the higher dissipated power) with, in principle, **larger peak accelerating gradient**(>30 MV/m). This means that one or few tens of bunches can be, in general, accelerated. NB: NC structures can also operate in CW but at very low gradient because of the dissipated power.

PERFORMANCES NC vs SC: MAXIMUM E_{acc}

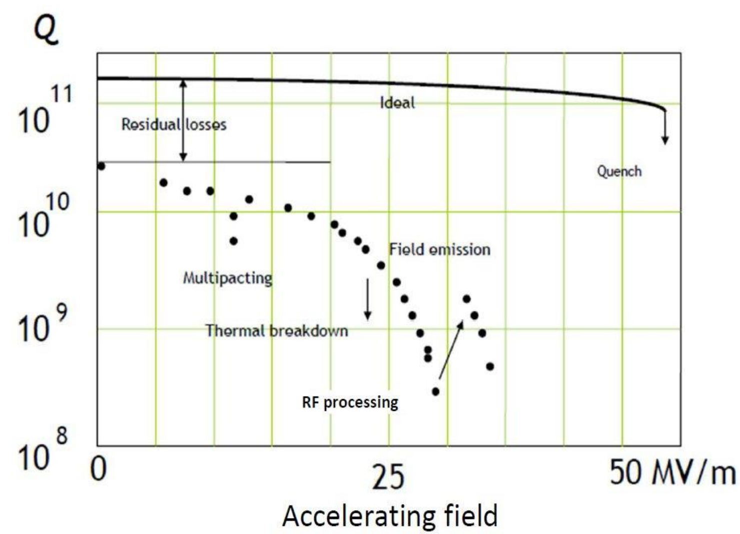
NC

- ⇒ If properly cleaned and fabricated, NC cavities can quite easily reach relatively high gradients (>**40 MV/m**) at rep. rate up to 100-200 Hz and pulse length of few µ.
- ⇒ Longer pulses or higher rep. rate can be reached but in this case the gradient has to be reduced accordingly (~MV/m).
- ⇒ The main limitation comes from **breakdown phenomena**, whose physics interpretation and modelling is still under study and is not yet completely understood.
- ⇒ **Conditioning is necessary** to go in full operation



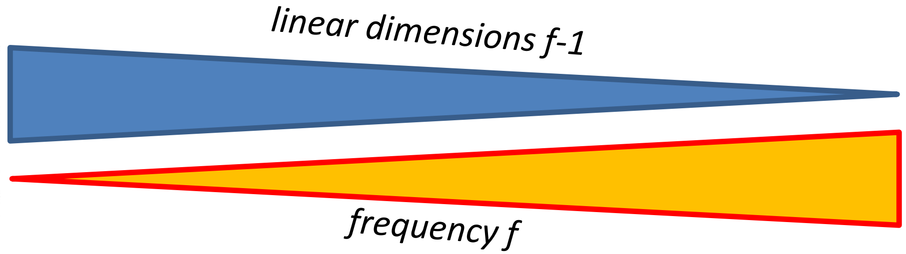
SC

- ⇒ SC cavities also need to be conditioned
- ⇒ Their performance is usually analyzed by plotting the behavior of **the quality factor as a function of the accelerating field**.
- ⇒ The ultimate gradient (~ **50 MV/m**) is given by the limitation due to the critical magnetic field (150-180 mT) .



PARAMETERS SCALING WITH FREQUENCY

We can analyze how all parameters (r, Q) scale with frequency and what are the advantages or disadvantages in accelerate with low or high frequencies cavities.



parameter	NC	SC
R_s	$\propto f^{1/2}$	$\propto f^2$
Q	$\propto f^{-1/2}$	$\propto f^{-2}$
r	$\propto f^{1/2}$	$\propto f^{-1}$
r/Q	$\propto f$	
$w_{//}$	$\propto f^2$	
$w_{\perp}$	$\propto f^3$	

Wakefield intensity: related to BD issues

⇒**r/Q increases at high frequency**

⇒for **NC structures** also r increases and this push to adopt **higher frequencies**

⇒for SC structures the power losses increases with f^2 and, as a consequence, r scales with 1/f this push to adopt **lower frequencies**

⇒On the other hand at very high frequencies (>10 GHz) **power sources** are less available

⇒Beam interaction (**wakefield**) became more critical at high frequency

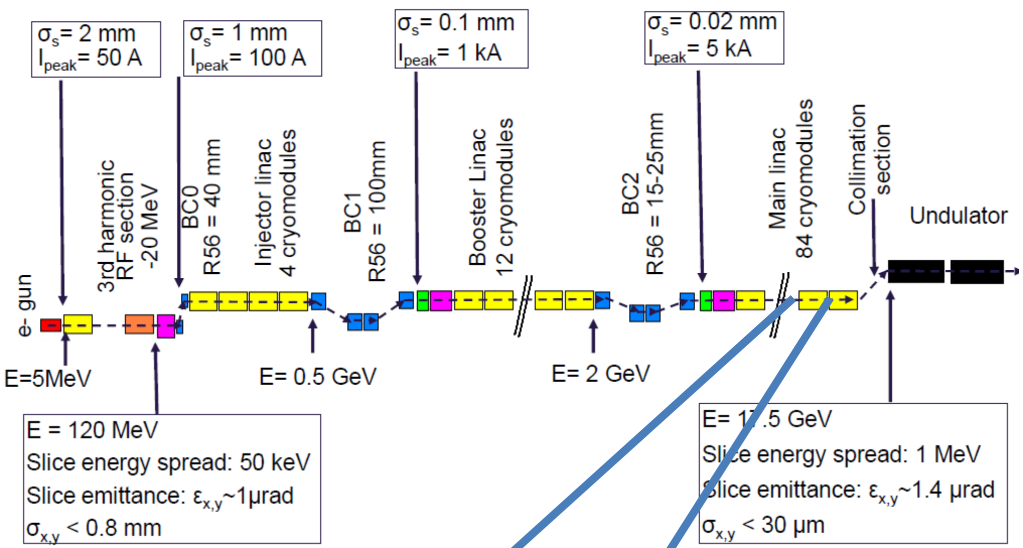
⇒Cavity fabrication at very high frequency requires **higher precision** but, on the other hand, at low frequencies one needs more material and **larger machines**

⇒**short bunches** are easier with higher f

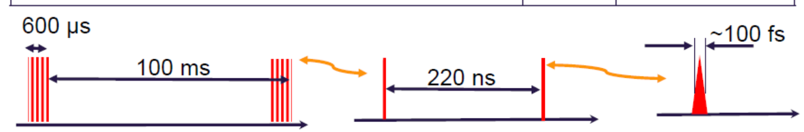
Compromise between several requirements

SW SC: 500 MHz-1500 MHz
TW NC: 3 GHz-6 GHz
SW NC: 0.5 GHz-3 GHz

EXAMPLES: EUROPEAN XFEL

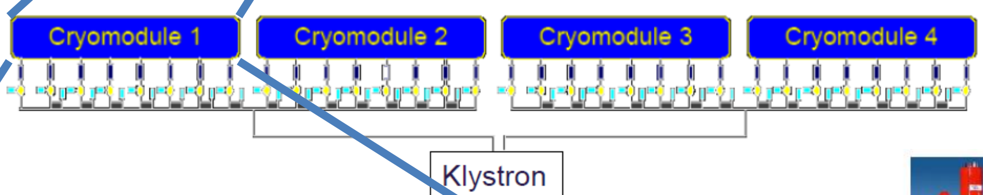


Nominal Energy	GeV	17.5
Beam pulse length	ms	0.60
Repetition rate	Hz	10
Max. # of bunches per pulse		2700
Min. bunch spacing	ns	220
Bunch charge	nC	1
Bunch length, σ_z	µm	< 20
Emittance (slice) at undulator	µrad	< 1.4
Energy spread (slice) at undulator	MeV	1



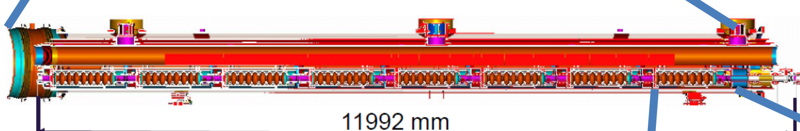
101 cryomodules in total

RF- system: 25 RF units. The unit = 4 cryomodules + RF-power source (klystron)



25 RF stations
5.2 MW each

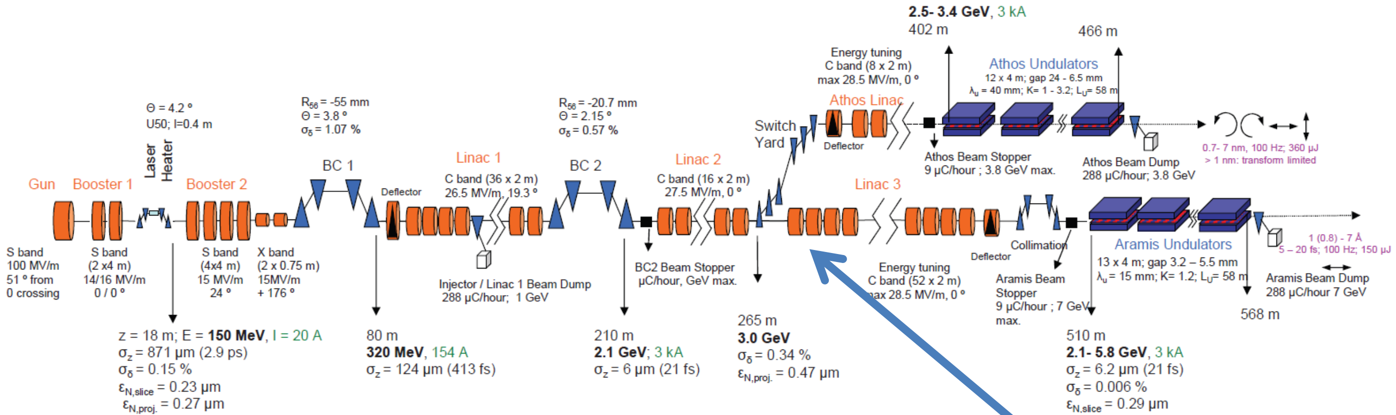
Cryomodule housing: 8 cavities, quadrupole and BPM

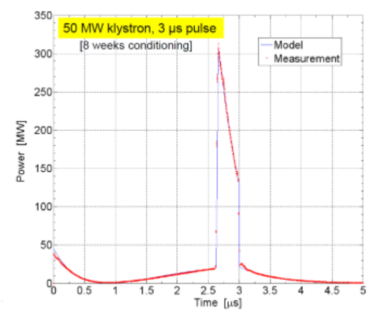


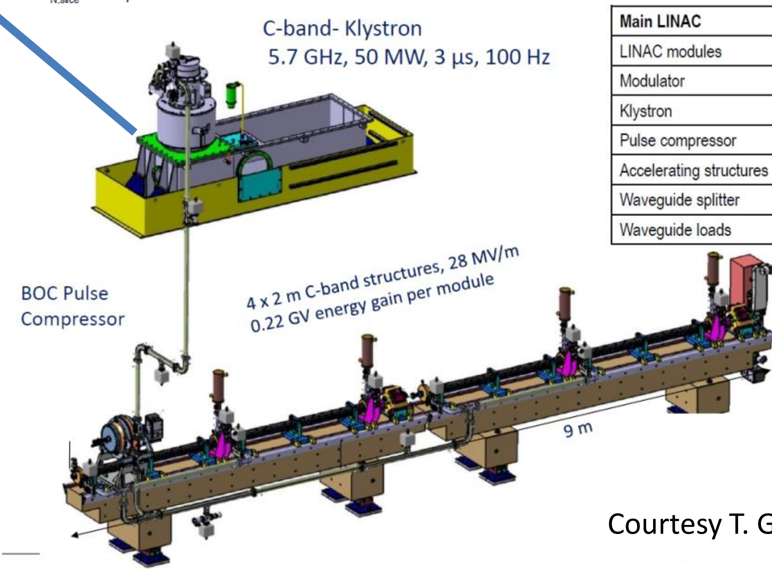
800 accelerating cavities

1.3 GHz / 23.6 MV/m

EXAMPLE: SWISSFEL LINAC (PSI)

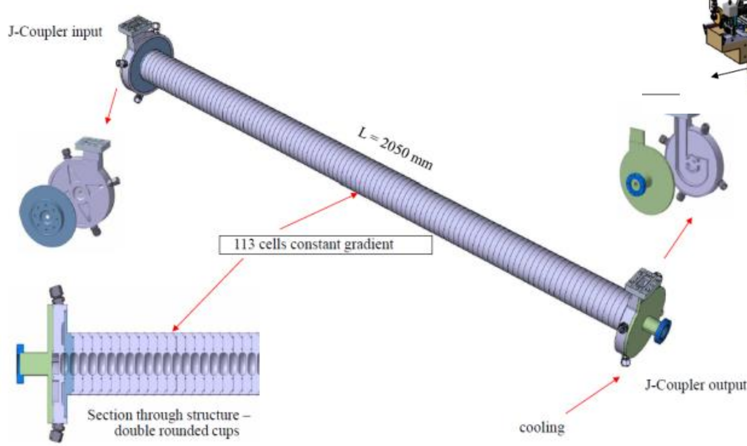


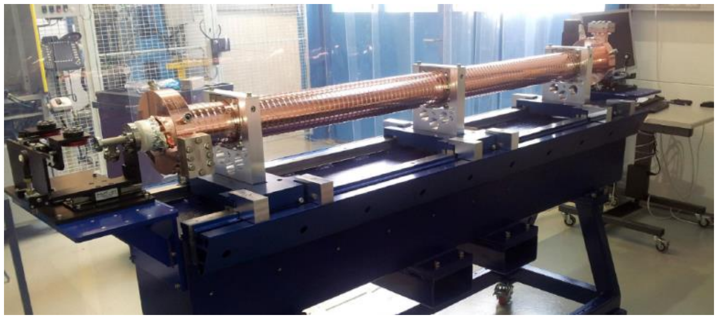




Main LINAC	#
LINAC modules	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structures	104
Waveguide splitter	78
Waveguide loads	104

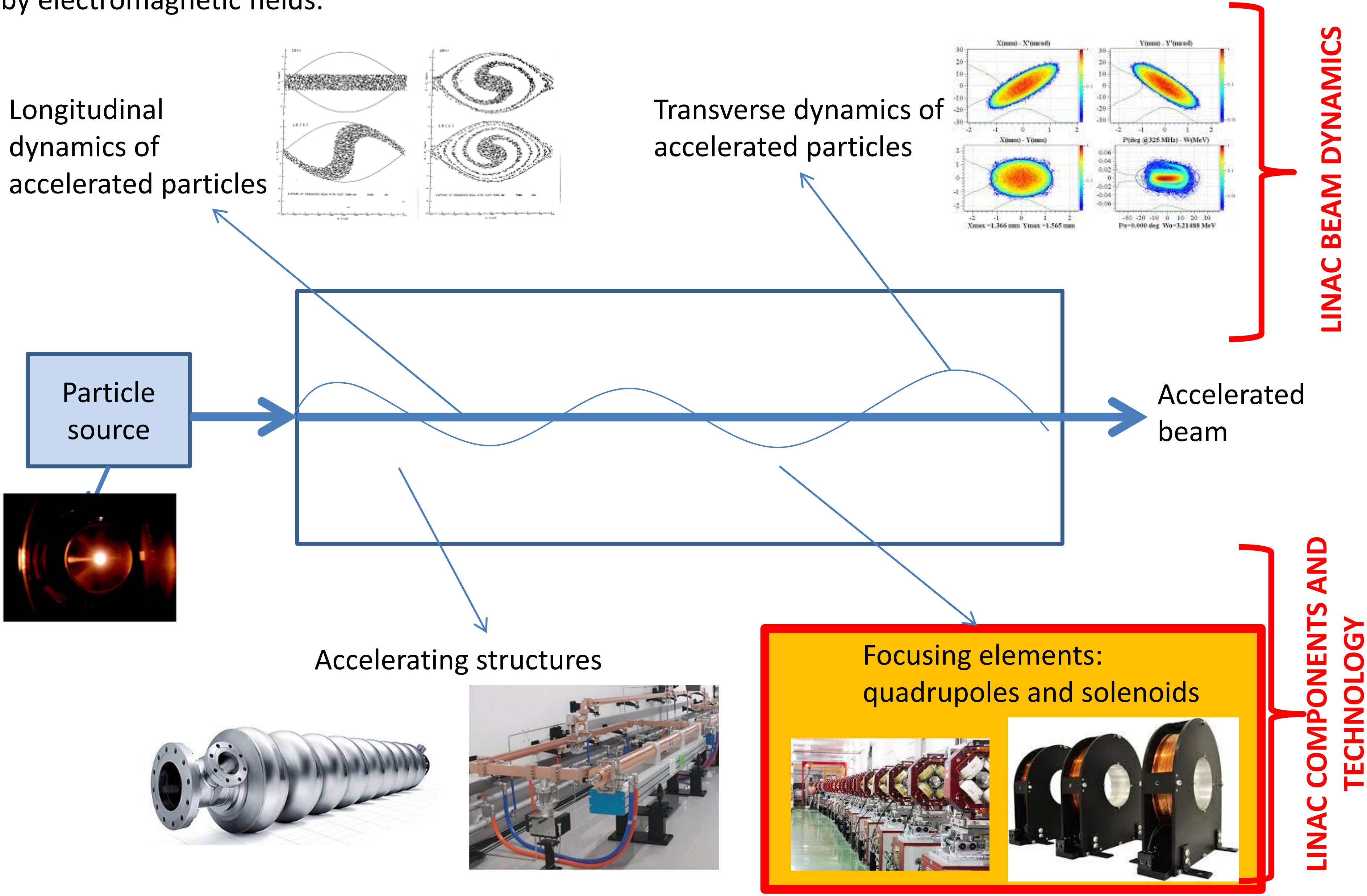
Courtesy T. Garvey





LINAC: BASIC DEFINITION AND MAIN COMPONENTS

LINAC (linear accelerator) is a **system that allows to accelerate charged particles through a linear trajectory** by electromagnetic fields.



LORENTZ FORCE: ACCELERATION AND FOCUSING

Particles are accelerated through electric field and are bended and focalized through magnetic field. The basic equation that describe the acceleration/bending /focusing processes is the **Lorentz Force**.

$\vec{p} = momentum$

$m = mass$

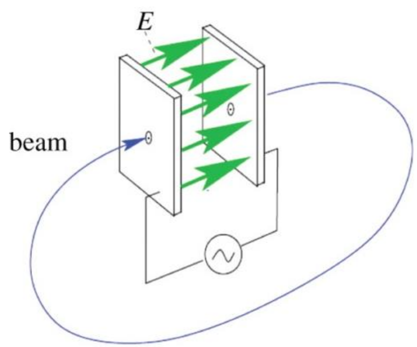
$\vec{v} = velocity$

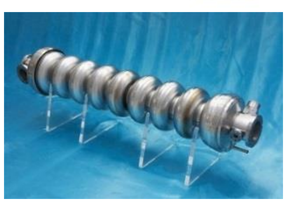
$q = charge$

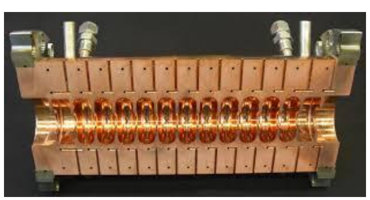
$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

ACCELERATION

To accelerate, we need a force in the direction of motion



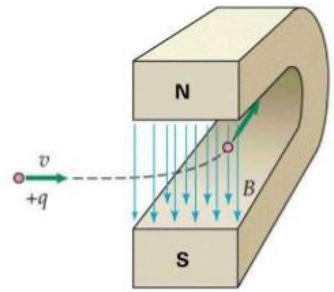


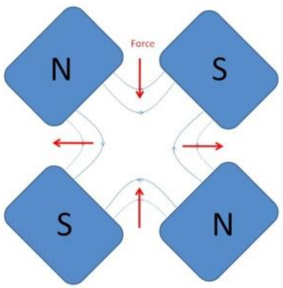


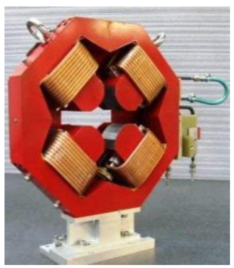
Longitudinal Dynamics

BENDING AND FOCUSING

2nd term always perpendicular to motion => no energy gain







Transverse Dynamics

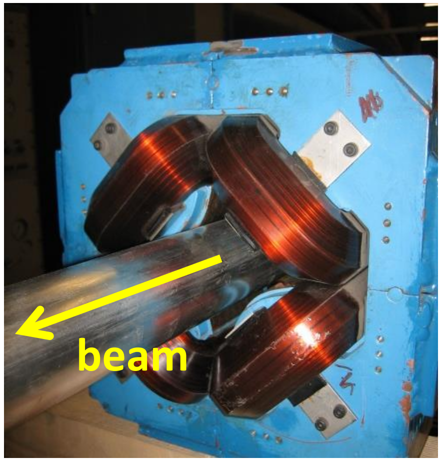
MAGNETIC QUADRUPOLE

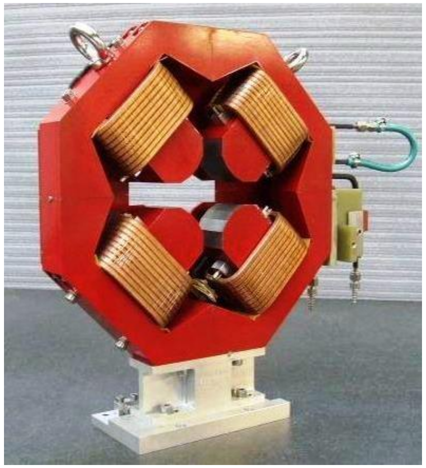
Quadrupoles are used to **focalize the beam in the transverse plane**. It is a **4 poles magnet**:

⇒**B=0 in the center of the quadrupole**

⇒The **B intensity increases linearly** with the off-axis displacement.

⇒If the quadrupole is **focusing in one plane is defocusing in the other plane**



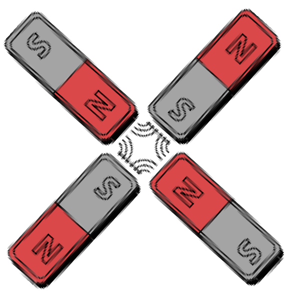


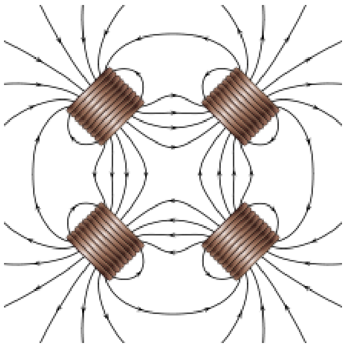
$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG \cdot y \\ F_x = -qvG \cdot x \end{cases}$$

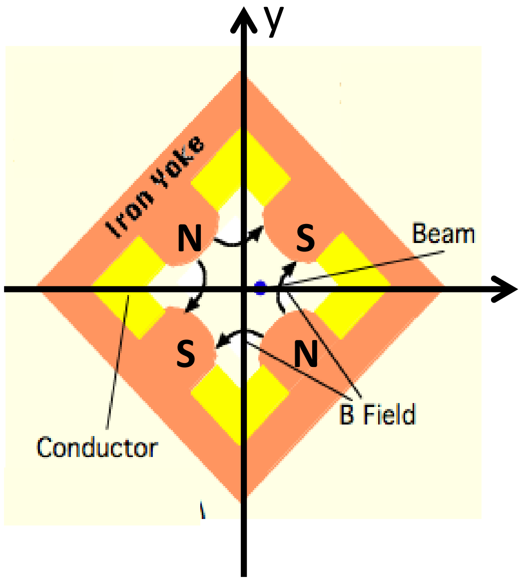
$$G = \text{quadrupole gradient} \left[\frac{T}{m} \right]$$

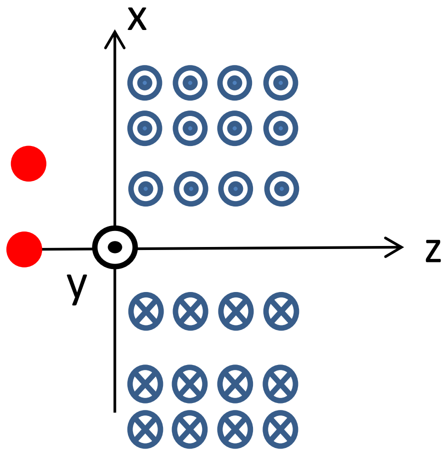
Electromagnetic quadrupoles G <50-100 T/m

$$\frac{F_B}{F_E} \propto v \Rightarrow \begin{cases} F_B(1T) = F_E\left(300 \frac{MV}{m}\right) @ \beta = 1 \\ F_B(1T) = F_E\left(3 \frac{MV}{m}\right) @ \beta = 0.01 \end{cases}$$









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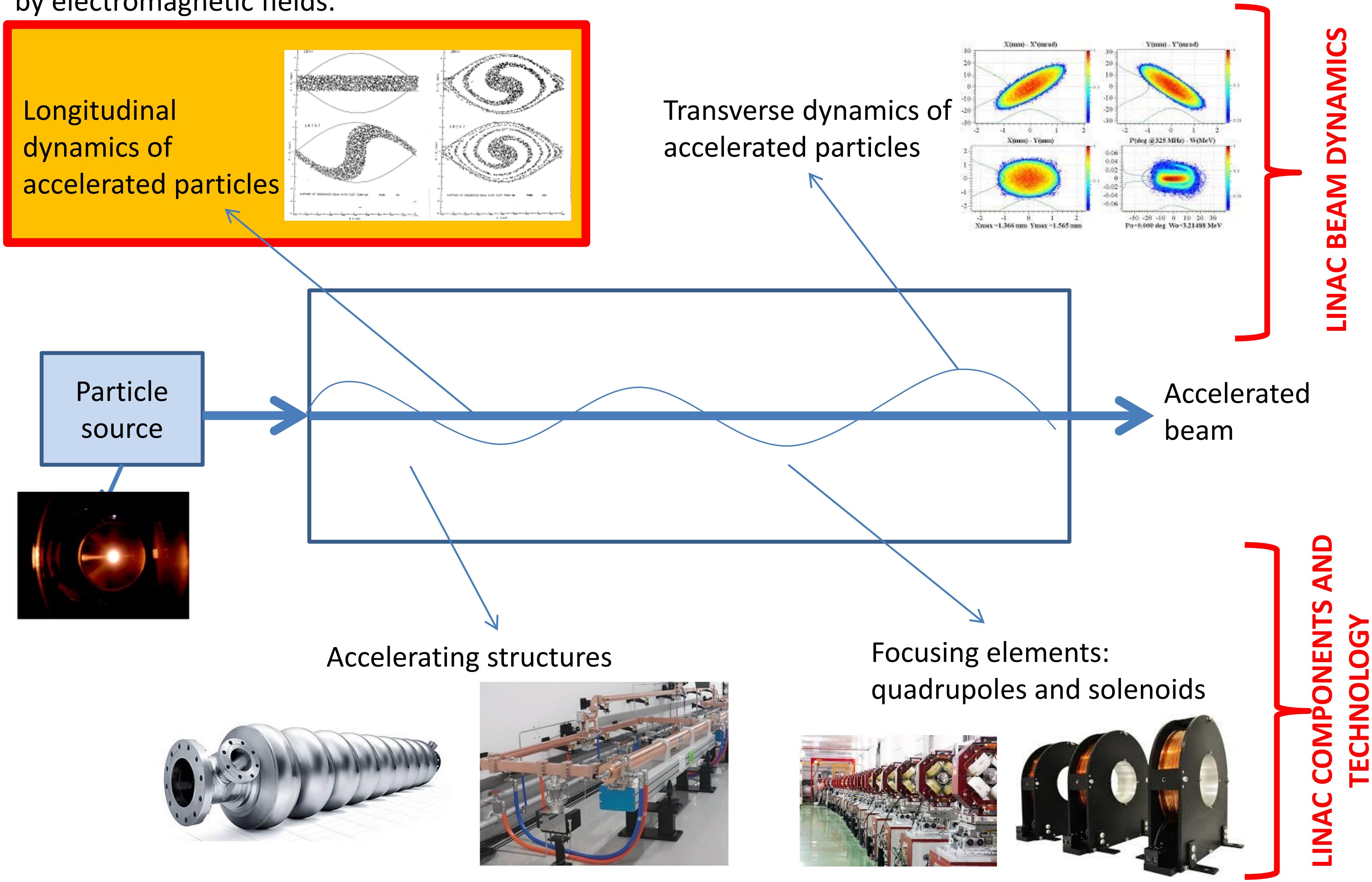
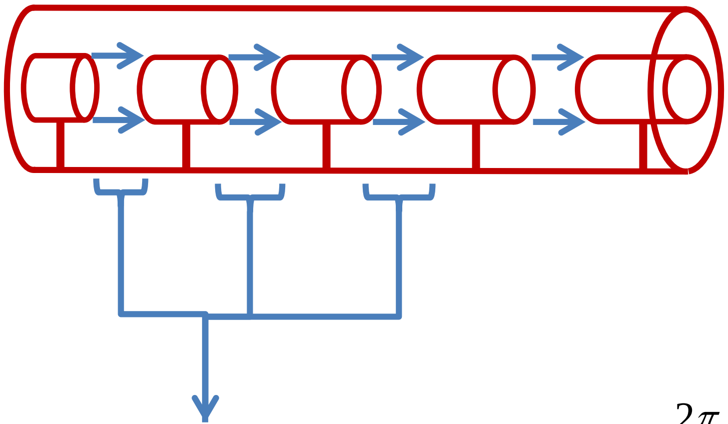
LINAC (linear accelerator) is a **system that allows to accelerate charged particles through a linear trajectory** by electromagnetic fields.



SYNCHRONOUS PARTICLE/PHASE

⇒Let us consider a **SW linac structure** made by accelerating **gaps** (like in DTL) or **cavities**.

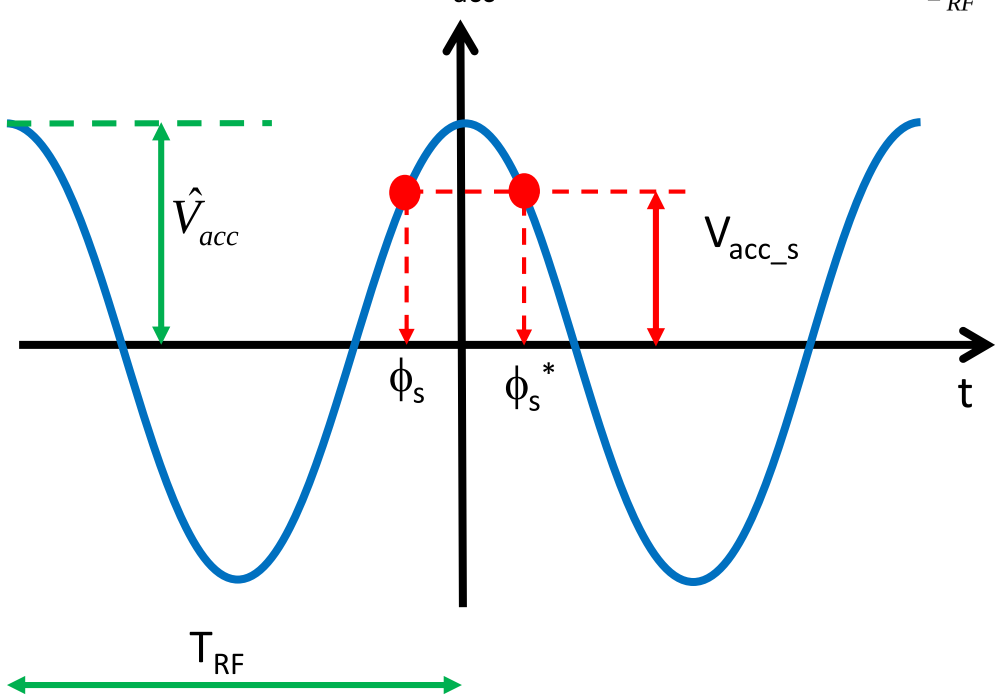


⇒In **each gap we have an accelerating field** oscillating in time and an integrated accelerating voltage (V_{acc}) still oscillating in time than can be expressed as:

$$V_{acc} = \hat{V}_{acc}\cos(\omega_{RF} t)$$

$$\omega_{RF} = 2\pi f_{RF} = \frac{2\pi}{T_{RF}}$$

⇒Let's assume that **the "perfect" synchronism condition is fulfilled for a phase ϕ_s** (called ***synchronous phase***). This means that a particle (called ***synchronous particle***) entering in a gap with a phase ϕ_s ($\phi_s=\omega_{RF} t_s$) with respect to the RF voltage receive an **energy gain** (and a consequent change in velocity) that allow entering in the subsequent gap with the **same phase ϕ_s** and so on.



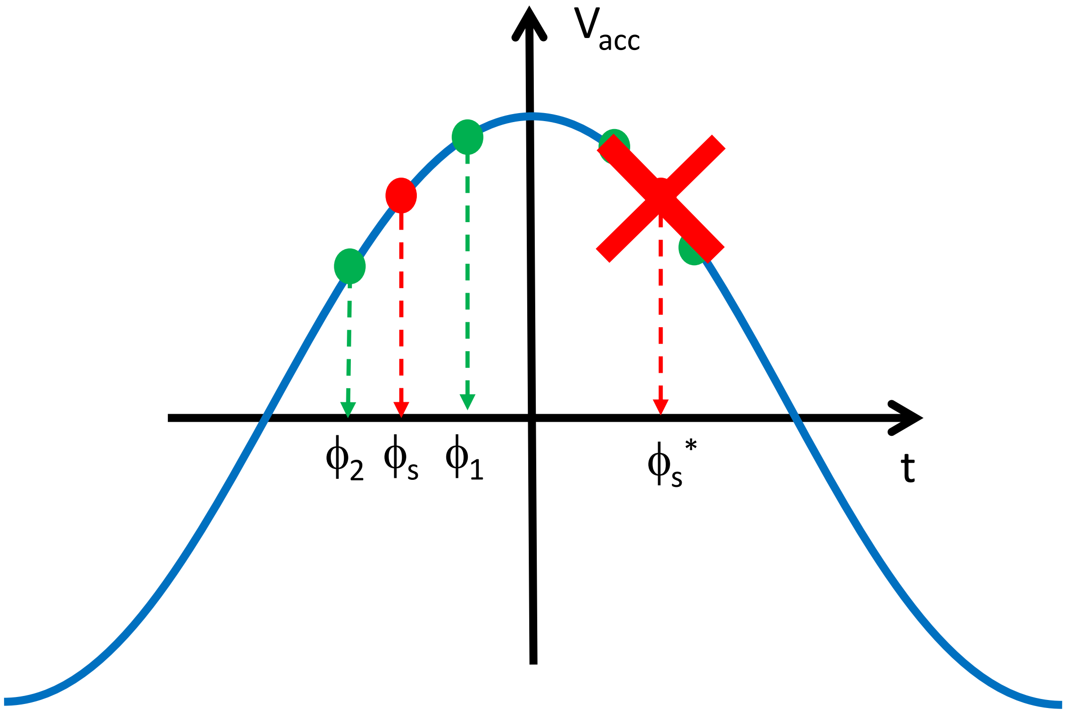
⇒for this particle the energy gain in each gap is:

$$\Delta E = q\underbrace{\hat{V}_{acc}\cos(\phi_s)}_{V_{acc\_s}} = qV_{acc\_s}$$

⇒obviously both ϕ_s and ϕ_s^* are synchronous phases.

PRINCIPLE OF PHASE STABILITY

(protons and ions or electrons at extremely low energy)



⇒Let us consider now the first synchronous phase ϕ_s (on the positive slope of the RF voltage). If we consider **another particle** "near" to the synchronous one **that arrives later in the gap** ($t_1>t_s$, $\phi_1>\phi_s$), it will see an higher voltage, it will gain an higher energy and an higher velocity with respect to the synchronous one. As a consequence its time of flight to next gap will be shorter, partially **compensating its initial delay**.

⇒**Similarly** if we consider another particle "near" to the synchronous one that arrives before in the gap ($t_1<t_s$, $\phi_1<\phi_s$), it will see a smaller voltage, it will gain a smaller energy and a smaller velocity with respect to the synchronous one. As a consequence its time of flight to next gap will be longer, compensating the initial advantage.

⇒**On the contrary** if we consider now the synchronous particle at phase ϕ_s^* and another particle "near" to the synchronous one that arrives later or before in the gap, it will receive an energy gain that will increase further its distance form the synchronous one

⇒The choice of the synchronous phase in the positive slope of the RF voltage provides longitudinal focusing of the beam: **phase stability principle**.

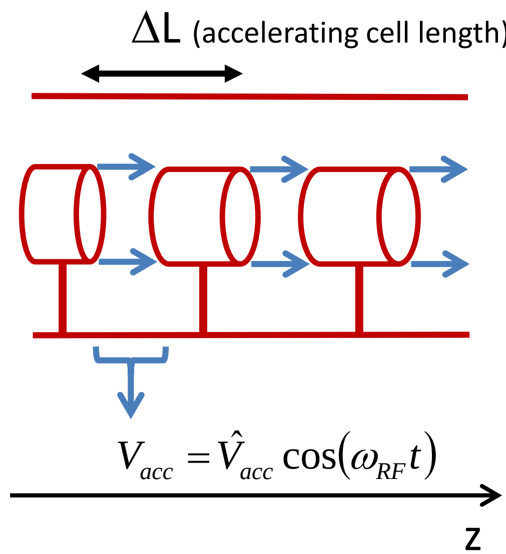
⇒The synchronous phase on the negative slope of the RF voltage is, on the contrary, **unstable**

⇒Relying on particle velocity variations, **longitudinal focusing does not work for fully relativistic beams** (electrons). In this case acceleration "on crest" is more convenient.

ENERGY-PHASE EQUATIONS (1/2)

(protons and ions or electrons at extremely low energy)

In order to study the **longitudinal dynamics in a LINAC**, the following variables are used, which describe the generic particle **phase** (time of arrival) and **energy with respect to the synchronous particle**:



Arrival time (phase) of a **generic particle** at a certain gap (or cavity)

Arrival time (phase) of the **synchronous particle** at a certain gap (or cavity)

$$\begin{cases} \varphi = \phi - \phi_s = \omega_{RF}(t - t_s) \\ w = E - E_s \end{cases}$$

Energy of the **synchronous particle** at a certain position along the linac

Energy of a **generic particle** at a certain position along the linac

The **energy gain per cell (one gap + tube in case of a DTL)** of a generic particle and of a synchronous particle are:

$$\begin{cases} \Delta E_s = q\hat{V}_{acc}\cos\phi_s \\ \Delta E = q\hat{V}_{acc}\cos\phi = q\hat{V}_{acc}\cos(\phi_s + \varphi) \end{cases}$$

subtracting

$$\Delta w = \Delta E - \Delta E_s = q\hat{V}_{acc}\left[\cos(\phi_s + \varphi) - \cos\phi_s\right]$$

Dividing by the accelerating cell length ΔL and assuming that:

$$\frac{\hat{V}_{acc}}{\Delta L} = \hat{E}_{acc}$$

Average accelerating field over the cell (i.e. average accelerating gradient)

$$\frac{\Delta w}{\Delta L} = q\hat{E}_{acc}\left[\cos(\phi_s + \varphi) - \cos\phi_s\right]$$

Approximating

$$\frac{\Delta w}{\Delta L} \approx \frac{dw}{dz}$$

$$\frac{dw}{dz} = q\hat{E}_{acc}\left[\cos(\phi_s + \varphi) - \cos\phi_s\right]$$

ENERGY-PHASE EQUATIONS (2/2)

(protons and ions or electrons at extremely low energy)

On the other hand we have that the **phase variation per cell** of a generic particle and of a synchronous particle are:

$$\begin{cases}\Delta\phi_s = \omega_{RF}\Delta t_s \\ \Delta\phi = \omega_{RF}\Delta t\end{cases}$$

Δt is basically the time of flight between two accelerating cells

subtracting

$$\Delta\varphi = \omega_{RF}\left(\Delta t - \Delta t_s\right)$$

Dividing by the accelerating cell length ΔL

v, v_s are the average particles velocities

$$\frac{\Delta\varphi}{\Delta L} = \omega_{RF}\left(\frac{\Delta t}{\Delta L} - \frac{\Delta t_s}{\Delta L}\right) = \omega_{RF}\left(\frac{1}{v} - \frac{1}{v_s}\right) \underbrace{\cong}_{MAT} -\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}w$$

Approximating

$$\frac{\Delta\varphi}{\Delta L} \cong \frac{d\varphi}{dz}$$

This system of coupled (non linear) differential equations **describe the motion of a non synchronous particles** in the longitudinal plane with respect to the synchronous one.

$$\frac{d\varphi}{dz} = -\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}w$$

$$\frac{dw}{dz} = q\hat{E}_{acc}\left[\cos(\phi_s + \varphi) - \cos\phi_s\right]$$

MAT

$$\omega_{RF}\left(\frac{1}{v} - \frac{1}{v_s}\right) = \omega_{RF}\left(\frac{v_s - v}{vv_s}\right) \underbrace{\cong}_{\substack{vv_s \cong v_s^2 \\ v - v_s \cong \Delta v}} -\frac{\omega_{RF}}{v_s^2}\Delta v = -\frac{\omega_{RF}}{c}\frac{\Delta\beta}{\beta_s^2} \quad \text{remembering that} \quad \beta = \sqrt{1\text{-}1/\gamma^2} \Rightarrow \beta d\beta = d\gamma/\gamma^3 \Rightarrow -\frac{\omega_{RF}}{c}\frac{\Delta\beta}{\beta_s^2} \cong -\frac{\omega_{RF}}{c}\frac{\Delta\gamma}{\beta_s^3\gamma_s^3} = -\frac{\omega_{RF}}{c}\frac{\overbrace{\Delta E}^{w}}{E_0\beta_s^3\gamma_s^3}$$

SMALL AMPLITUDE ENERGY-PHASE OSCILLATIONS

(protons and ions or electrons at extremely low energy)

$$\begin{cases} \dfrac{dw}{dz} = q\hat{E}_{acc}\left[\cos(\phi_s + \varphi) - \cos\phi_s\right] \\ \dfrac{d\varphi}{dz} = -\dfrac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3} w \end{cases}$$

Assuming **small oscillations** around the synchronous particle that allow to approximate $\cos(\phi_s + \varphi) - \cos\phi_s \cong \varphi \sin\phi_s$

Deriving both terms with respect to z and assuming an **adiabatic acceleration** process i.e. a particle energy and speed variations that allow to consider

$$\frac{d\left(\dfrac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}\right)}{dz} w << \frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}\frac{dw}{dz}$$

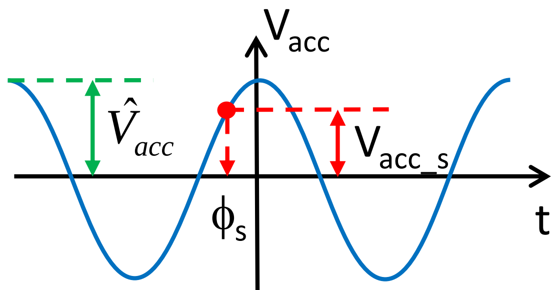
$$\frac{d^2\varphi}{dz^2} = -\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}\frac{dw}{dz}$$

$$\frac{d^2\varphi}{dz^2} + \underbrace{q\frac{\omega_{RF}\hat{E}_{acc}\sin(-\phi_s)}{cE_0\beta_s^3\gamma_s^3}}_{\Omega_s^2}\varphi = 0$$

harmonic oscillator equation

⇒The condition to have stable longitudinal oscillations and acceleration at the same time is:

$$\left.\begin{array}{l} \Omega_s^2 > 0 \Rightarrow \sin(-\phi_s) > 0 \\ V_{acc} > 0 \Rightarrow \cos\phi_s > 0 \end{array}\right\} \Rightarrow -\frac{\pi}{2} < \phi_s < 0$$



if we accelerate on the rising part of the positive RF wave we have a **longitudinal force keeping the beam bunched** around the synchronous phase.

$$\begin{cases} \varphi = \hat{\varphi}\cos(\Omega_s z) \\ w = \hat{w}\sin(\Omega_s z) \end{cases}$$

⇒ The angular frequency is simply: $\Omega_T = \Omega_s\beta_s c$;

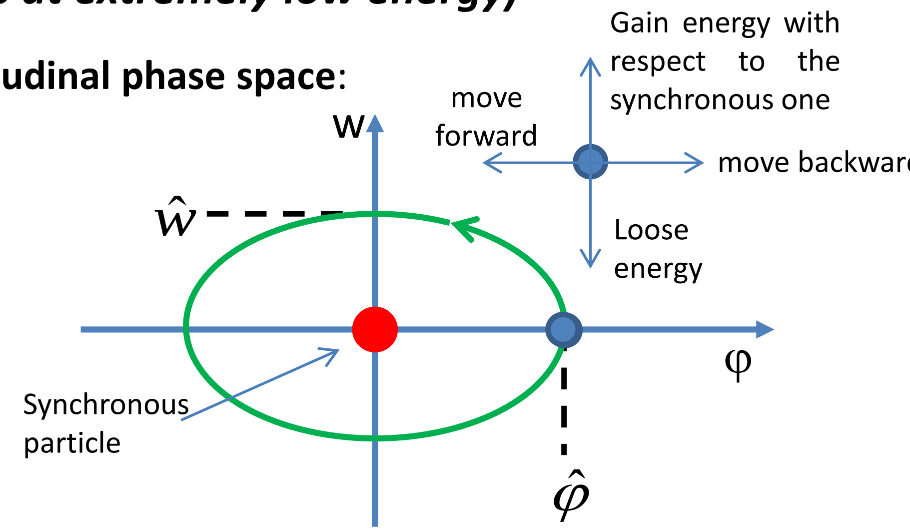
⇒ **The angular frequency scale with $1/\gamma^{3/2}$** that means that for ultra relativistic electrons shrinks to 0 (the beam is frozen)

ENERGY-PHASE OSCILLATIONS IN PHASE SPACE

(protons and ions or electrons at extremely low energy)

The energy-phase oscillations can be drawn in the **longitudinal phase space**:

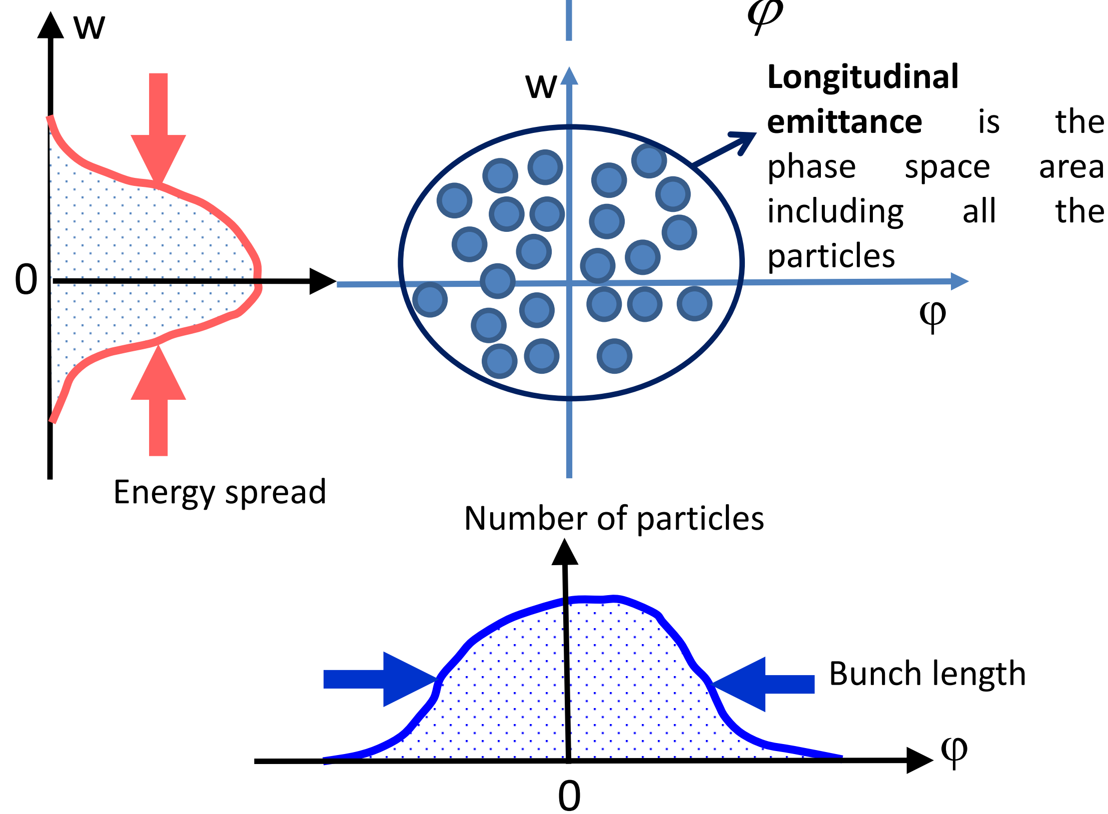
$$\begin{cases} \varphi = \hat{\varphi}\cos(\Omega_s z) \\ w = \hat{w}\sin(\Omega_s z) \end{cases}$$



⇒The trajectory of a generic particle in the longitudinal phase space is an **ellipse**.

⇒The **maximum energy deviation** is reached at φ=0 while the **maximum phase excursion** corresponds to w=0.

⇒the bunch occupies an area in the longitudinal phase space called **longitudinal emittance** and the projections of the bunch in the energy and phase planes give the **energy spread** and the **bunch length**.



APPENDIX: LARGE OSCILLATIONS AND SEPARATRIX

To study the longitudinal dynamics **at large oscillations**, we have to consider the **non linear system of differential equations** without approximations. In the **adiabatic acceleration** case it is possible to easily obtain the following relation between w and φ that is the **Hamiltonian of the system** related to the total particle energy:

$$\frac{1}{2}\left(\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}\right)^2 w^2 + \frac{\omega_{RF}\, q\hat{E}_{acc}}{cE_0\beta_s^3\gamma_s^3}\left[\sin(\phi_s+\varphi)-\varphi\cos\phi_s-\sin(\phi_s)\right]=\text{const}=\text{H}$$

⇒**For each H we have different trajectories** in the longitudinal phase space

⇒the oscillations are **stable** within a region bounded by a special curve called **separatrix**: its equation is:

$$\frac{1}{2}\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}w^2 + q\hat{E}_{acc}\left[\sin(\phi_s+\varphi)-(2\varphi_s+\varphi)\cos\phi_s+\sin(\phi_s)\right]=0$$

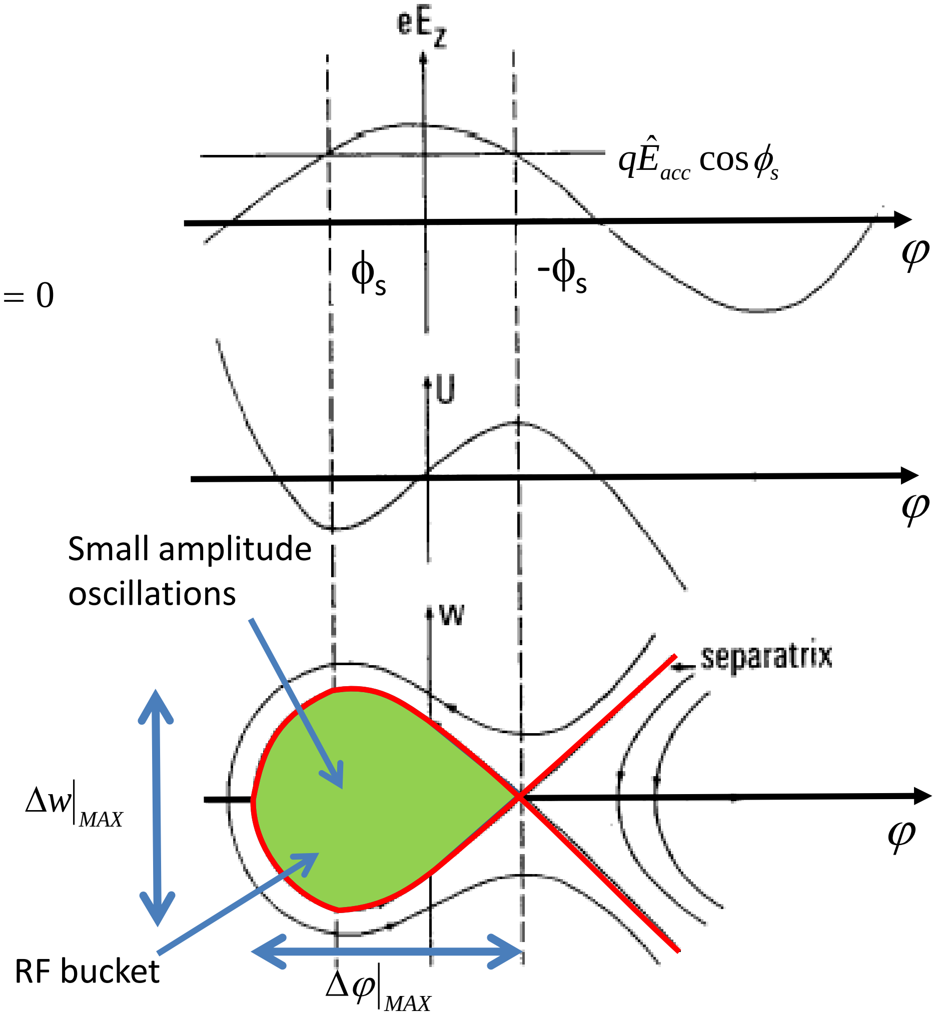
⇒the region inside the separatrix is called **RF bucket**. The dimensions of the bucket shrinks to zero if ϕ_s=0.

⇒trajectories outside the RF buckets are **unstable**.

⇒we can define the **RF acceptance** as the maximum extension in phase and energy that we can accept in an accelerator:

$$\Delta\varphi\big|_{MAX} \cong 3\phi_s$$

$$\Delta w\big|_{MAX} = \pm 2\left[\frac{qcE_o\beta_s^3\gamma_s^3\hat{E}_{acc}(\phi_s\cos\phi_s-\sin\phi_s)}{\omega_{RF}}\right]^{\frac{1}{2}}$$



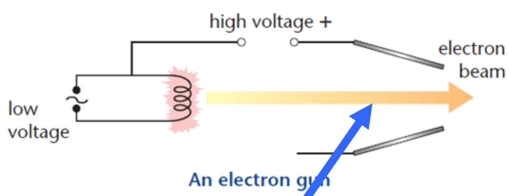
LONGITUDINAL DYNAMICS OF LOW ENERGY ELECTRONS

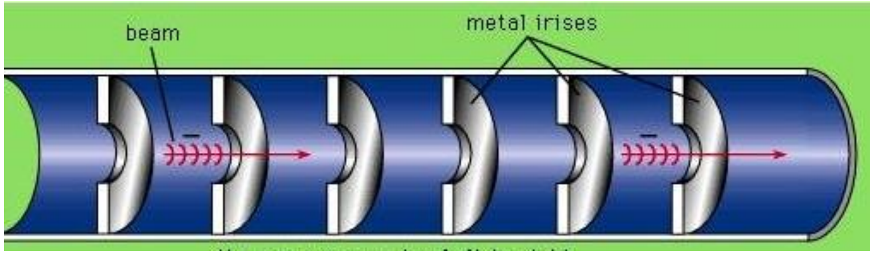
From previous formulae it is clear that there is **no motion in the longitudinal phase plane for ultrarelativistic particles** (γ>>1).

⇒This is the case of **electrons** whose **velocity is always close to speed of light c** even at low energies.

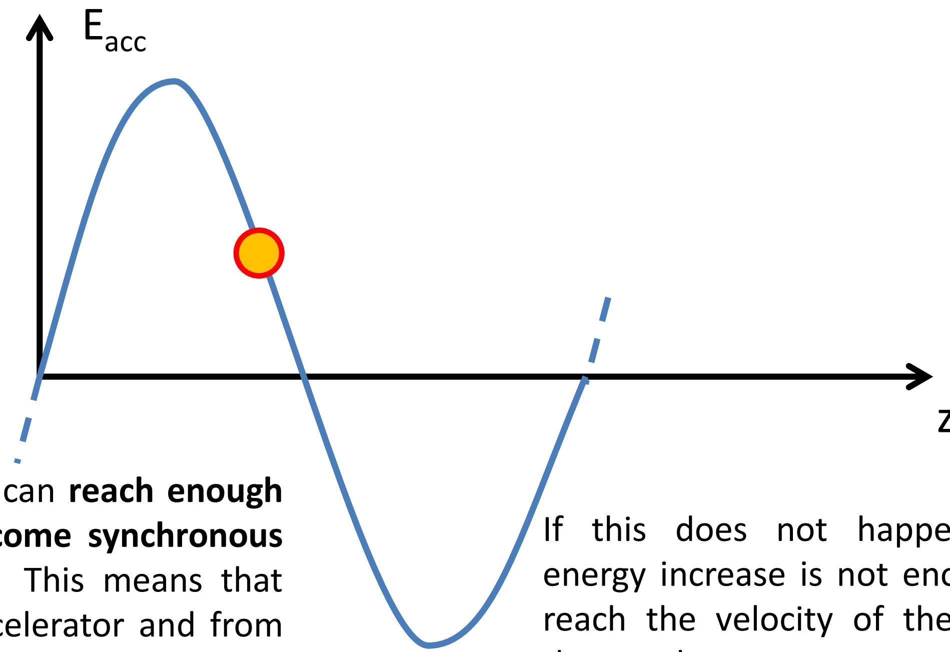
⇒Accelerating structures are designed to provide an accelerating field synchronous with particles moving at v=c. like **TW structures with phase velocity equal to c**.

It is interesting to analyze what happen if we **inject an electron beam produced by a cathode (at low energy) directly in a TW structure** (with v_{ph}=c) and the conditions that allow to **capture** the beam (this is equivalent to consider instead of a TW structure a SW designed to accelerate ultrarelativistic particles at v=c).





Particles enter the structure with velocity **v<c** and, initially, they are **not synchronous with the accelerating field** and there is a so called slippage.



After a certain distance they can **reach enough energy (and velocity) to become synchronous** with the accelerating wave. This means that they are captured by the accelerator and from this point they are stably accelerated.

If this does not happen (the energy increase is not enough to reach the velocity of the wave) they are lost

LONGITUDINAL DYNAMICS OF LOW ENERGY ELECTRONS: PHASE SPLIPPAGE

The **accelerating field** of a TW structure can be expressed by

$$E_{acc} = \hat{E}_{acc}\cos\underbrace{(\omega_{RF}t - kz)}_{\phi(z,t)}$$

The **equation of motion of a particle with a position z at time t accelerated by the TW** is then

$$\frac{d}{dt}(mv) = q\hat{E}_{acc}\cos\phi(z,t) \Rightarrow m_0 c\frac{d}{dt}(\gamma\beta) = m_0 c\gamma^3\frac{d\beta}{dt} = q\hat{E}_{acc}\cos\phi$$

It is useful to find which is the relation between β and φ from an initial condition (in) to a final one (fin)

$$\sin\phi_{fin} = \sin\phi_{in} + \frac{2\pi E_0}{\lambda_{RF} q\hat{E}_{acc}}\left(\sqrt{\frac{1-\beta_{in}}{1+\beta_{in}}} - \sqrt{\frac{1-\beta_{fin}}{1+\beta_{fin}}}\right)$$

Suppose that the particle reach asymptotically the value β_{fin}=1 we have:

Should be in the interval [-1,1] to have a solution for ϕ_{fin}

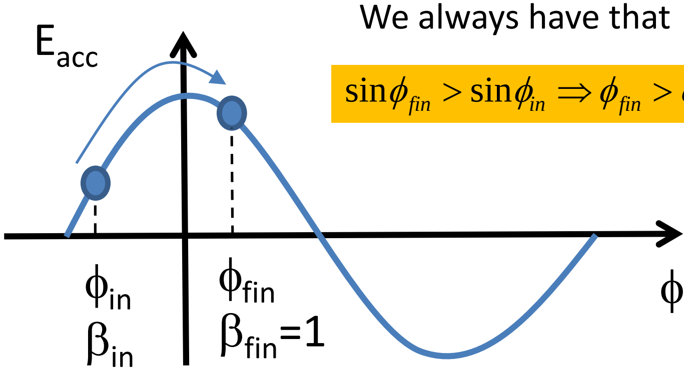
$$\sin\phi_{fin} = \sin\phi_{in} + \frac{2\pi m_0 c^2}{\lambda_{RF} q\hat{E}_{acc}}\sqrt{\frac{1-\beta_{in}}{1+\beta_{in}}}$$

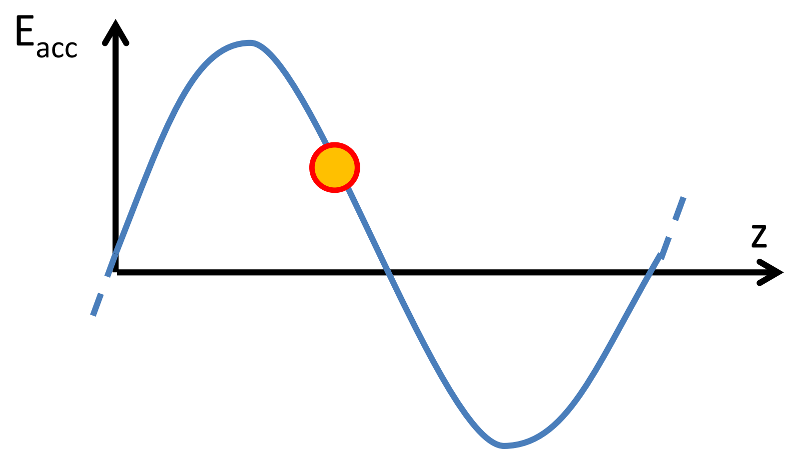
This limits the possible injection phases (i.e. the phase of the electrons that is possible to capture)

This quantity is >0

We always have that

$$\sin\phi_{fin} > \sin\phi_{in} \Rightarrow \phi_{fin} > \phi_{in}$$





LONGITUDINAL DYNAMICS OF LOW ENERGY ELECTRONS: CAPTURE ACCELERATING FIELD

$\Rightarrow$For a given injection energy (β_{in}) and phase (ϕ_{in}) we can find which is the accelerating field (E_{acc}) that is necessary to have the completely relativistic beam at phase fin (that is necessary to **capture the beam at phase fin**)

$$\hat{E}_{acc} = \frac{2\pi E_0}{\lambda_{RF} q \left(\sin\phi_{fin} - \sin\phi_{in}\right)} \sqrt{\frac{1-\beta_{in}}{1+\beta_{in}}}$$

Example:
E_{in} = 50 keV, (kinetic energy), ϕ_{in} =-π/2,
ϕ_{fin} =0$\Rightarrow$ $\gamma_{in} \approx$ 1.1; $\beta_{in} \approx$ 0.41
f_{RF}= 2856 MHz$\Rightarrow\lambda_{RF}\approx$ 10.5 cm

We obtain $E_{acc} \cong$20MV/m;

The **minimum value of the electric field (E_{acc}) that allow to capture a beam**. Obviously this correspond to an injection phase
ϕ_{in} =-π/2 and ϕ_{fin}=π/2.

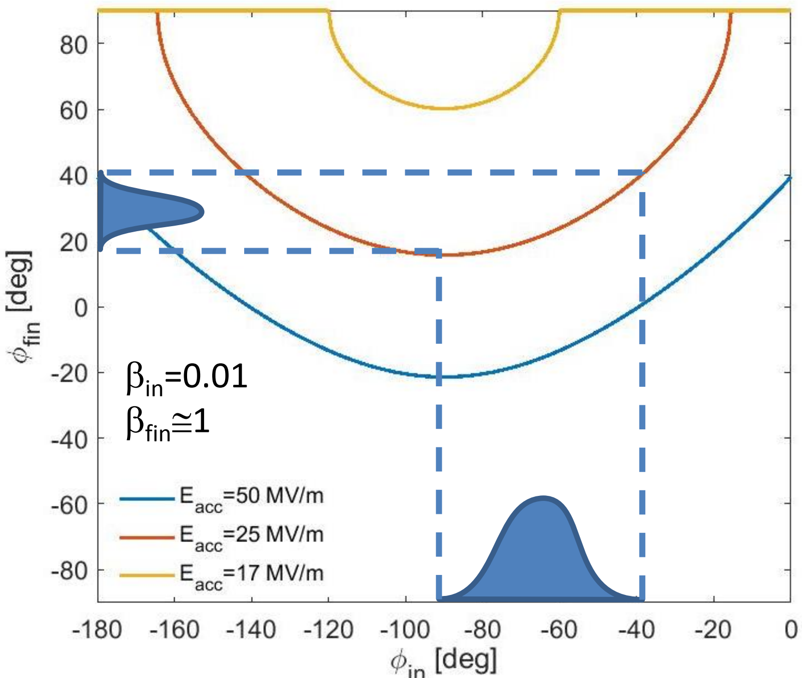
$$\hat{E}_{acc\_MIN} = \frac{\pi E_0}{\lambda_{RF} q} \sqrt{\frac{1-\beta_{in}}{1+\beta_{in}}}$$

Example: For the previous case we obtain: $E_{acc_min} \cong$10MV/m;

LONGITUDINAL DYNAMICS OF LOW ENERGY ELECTRONS: CAPTURE EFFICIENCY AND BUNCH COMPRESSION

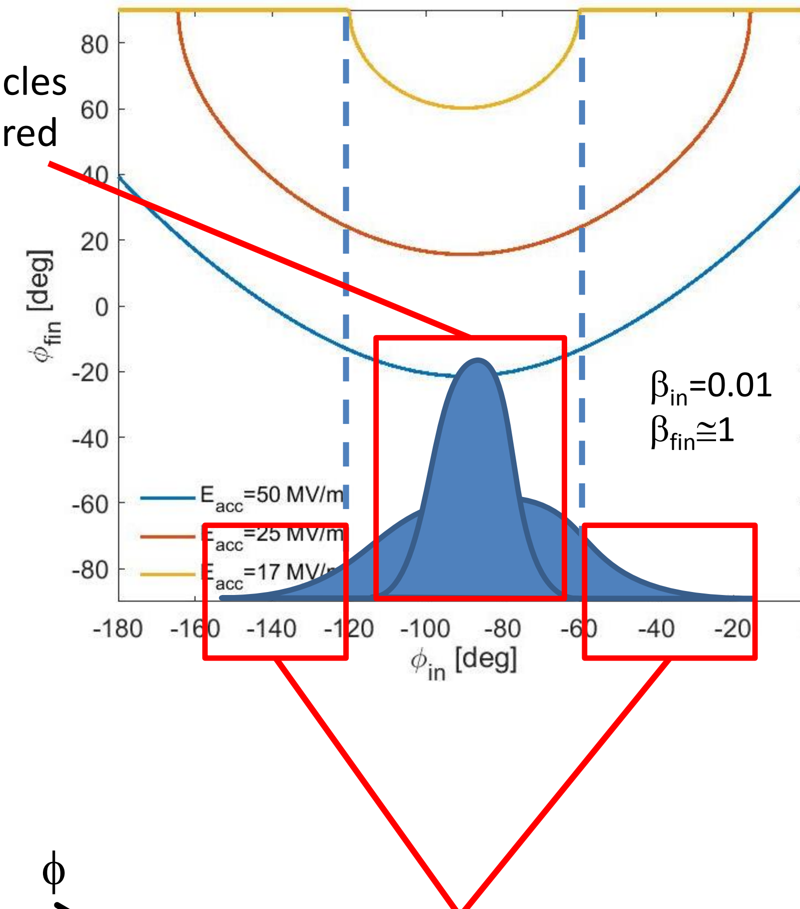
During the capture process, as the injected beam moves up to the crest, the beam is also bunched, which is caused by **velocity modulation** (velocity bunching). This mechanism can be used to compress the electron bunches (FEL applications).

BUNCH COMPRESSION



CAPTURE EFFICIENCY

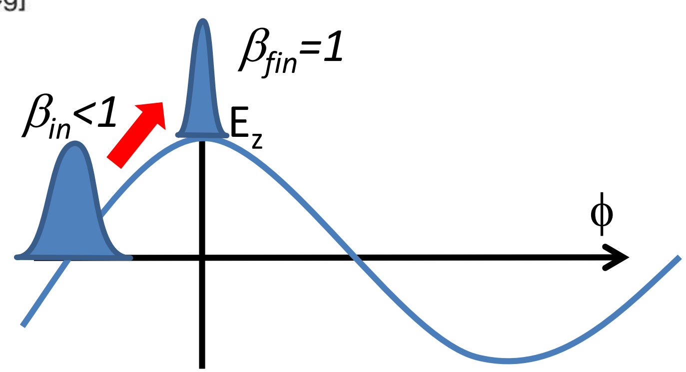
All particles are captured



These particle are lost during the capture process

Bunch length variation

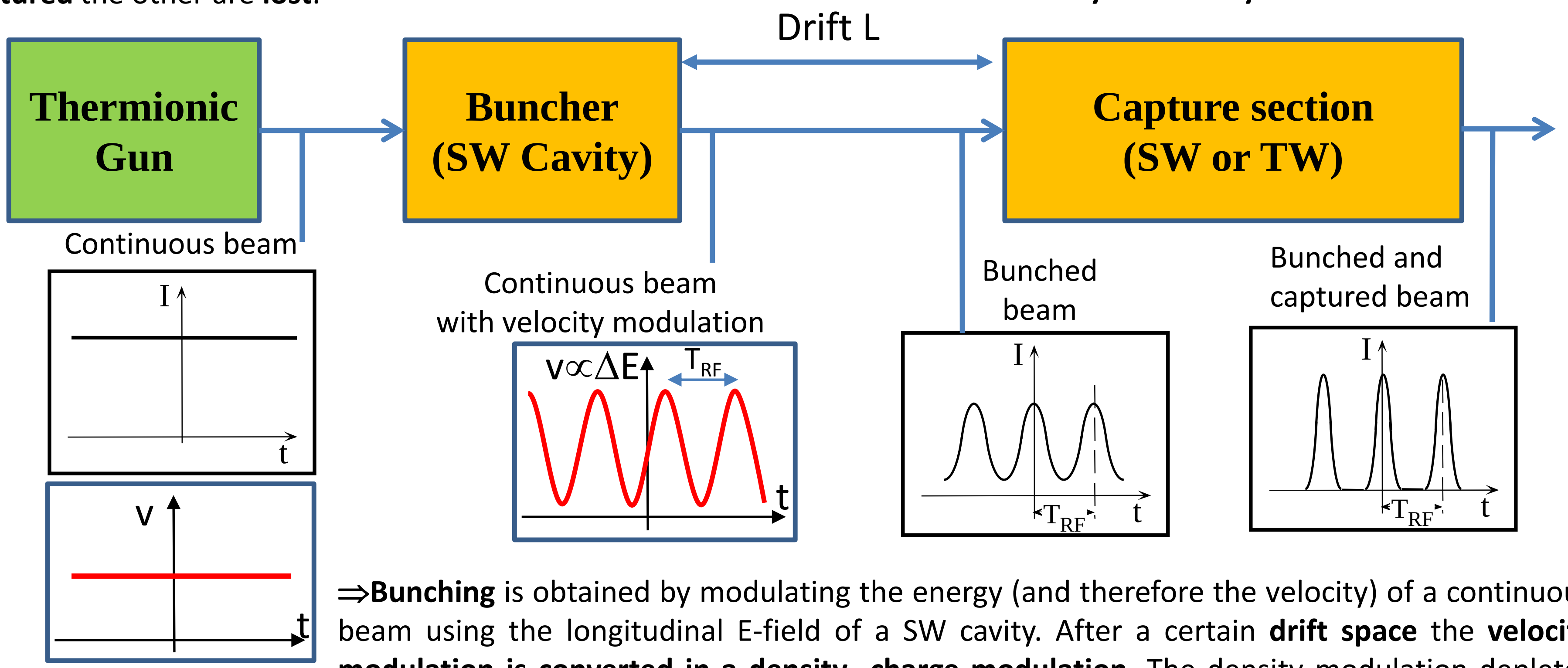
$$\Delta\phi_{fin} = \Delta\phi_{in} \frac{\cos\phi_{in}}{\cos\phi_{fin}}$$



BUNCHER AND CAPTURE SECTIONS
(electrons)

Once the capture condition $E_{RF}>E_{RF\_MIN}$ is fulfilled the fundamental equation of previous slide sets the **ranges of the injection phases ϕ_{in} actually accepted**. Particles whose injection phases are within this range can be **captured** the other are **lost**.

In order **to increase the capture efficiency** of a traveling wave section, **pre-bunchers** are often used. They are SW cavities aimed at **pre-forming particle bunches gathering particles continuously emitted by a source.**

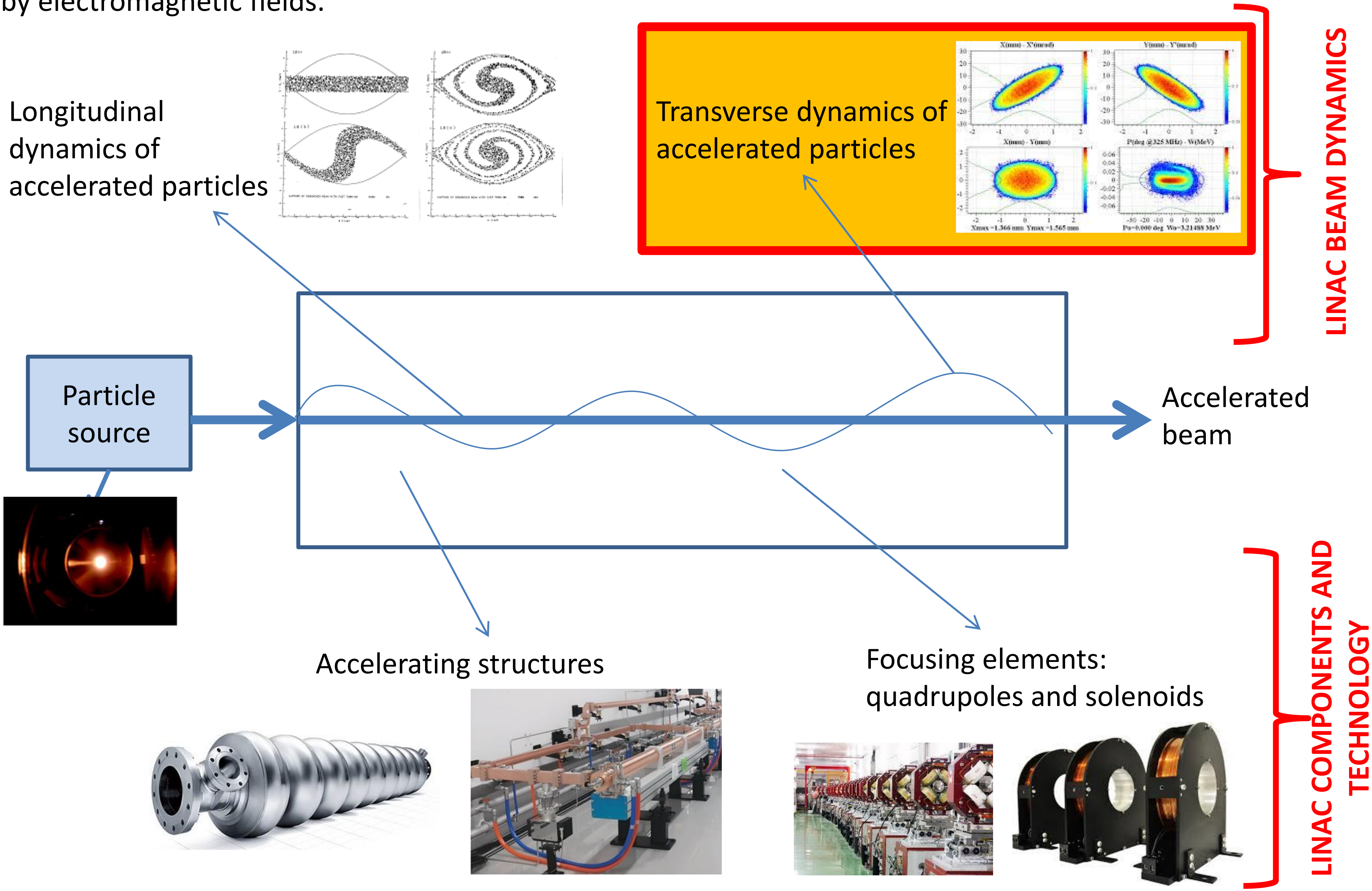


⇒**Bunching** is obtained by modulating the energy (and therefore the velocity) of a continuous beam using the longitudinal E-field of a SW cavity. After a certain **drift space** the **velocity modulation is converted in a density charge modulation**. The density modulation depletes the regions corresponding to injection phase values incompatible with the capture process

⇒A TW accelerating structure (**capture section**) is placed at an **optimal distance from the pre-buncher**, to capture a large fraction of the charge and accelerate it till relativistic energies. The **amount of charge lost is drastically reduced**, while the capture section provide also further beam bunching.

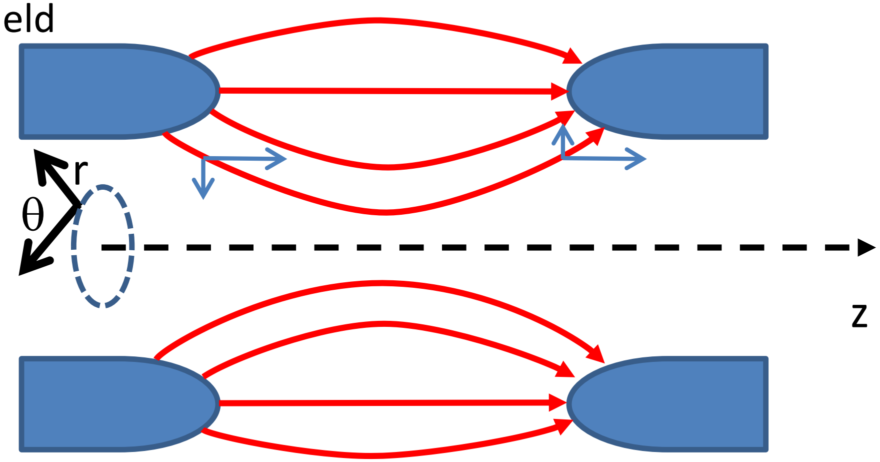
LINAC: BASIC DEFINITION AND MAIN COMPONENTS

LINAC (linear accelerator) is a **system that allows to accelerate charged particles through a linear trajectory** by electromagnetic fields.



RF TRANSVERSE FORCES

The **RF fields act on the transverse beam dynamics** because of the transverse components of the E and B field



$\Rightarrow$According to Maxwell equations the **divergence of the field is zero** and this implies that in traversing one accelerating gap there is a focusing/defocusing term

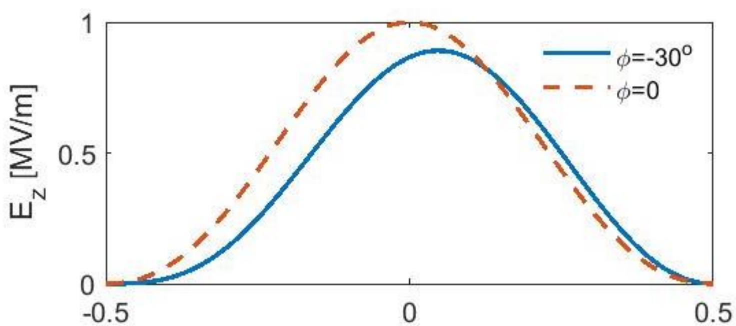
$$E_z(z,t) = E_{RF}(z)\cos(\omega_{RF} t)$$

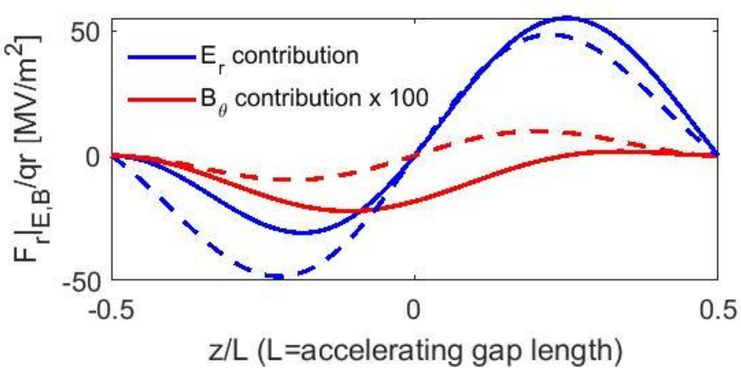
$$\begin{matrix} \nabla \vec{E} = 0 \\ \nabla \times \vec{B} = \dfrac{1}{c^2}\vec{E} \end{matrix} \Rightarrow \begin{cases} E_r = -\dfrac{r}{2}\dfrac{\partial E_z}{\partial z} \\ B_\theta = \dfrac{r}{2c^2}\dfrac{\partial E_z}{\partial t} \end{cases}$$

$$F_r = q(E_r - vB_\theta) = -q\frac{r}{2}\left(\frac{\partial E_z}{\partial z} + \frac{\beta}{c}\frac{\partial E_z}{\partial t}\right)$$

$$F_r\big|_E = -q\frac{r}{2}\frac{\partial E_{RF}(z)}{\partial z}\cos\left(\omega_{RF}\frac{z}{\beta c} + \phi_{inj}\right)$$

$$F_r\big|_B = q\frac{r}{2}\omega_{RF}\frac{\beta}{c}E_{RF}(z)\sin\left(\omega_{RF}\frac{z}{\beta c} + \phi_{inj}\right)$$





f_{RF}=350 MHz
β=0.1
L=3cm

RF DEFOCUSING/FOCUSING

From previous formulae it is possible to calculate the **transverse momentum increase** due to the RF transverse forces. Assuming that the velocity and position changes over the gap are small we obtain to the first order:

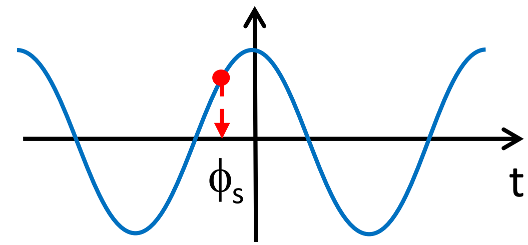
Transverse momentum increase

Defocusing force since sinϕ<0

Gap length

Defocusing effect

$$\Delta p_r = \int_{-L/2}^{+L/2} F_r \frac{dz}{\beta c} = -\frac{\pi q \hat{E}_{acc} L \sin\phi}{c\gamma^2\beta^2\lambda_{RF}} r$$



⇒ transverse **defocusing scales as ~1/γ²** and **disappears at relativistic regime (electrons)**

⇒ At relativistic regime (**electrons**), moreover, we have, in general, **ϕ=0 for maximum acceleration** and this completely cancel the defocusing effect

⇒ Also in the **non relativistic regime** for a correct evaluation of the defocusing effect we have to:

⇒ take into account the **velocity change across the accelerating gap**

⇒ the **transverse beam dimensions changes across the gap** (with a general reduction of the transverse beam dimensions due to the focusing in the first part)

Both effects give a **reduction of the defocusing force**

RF FOCUSING IN ELECTRON LINACS

-RF defocusing is negligible in electron linacs.

-There is a **second order effect** due to the non-synchronous harmonics of the accelerating field that give a **focusing effect**. These harmonics generate a **ponderomotive force i.e.** a force in an inhomogeneous oscillating electromagnetic field.

MECHANISM

The Lorentz force is linear with the particle dispacement

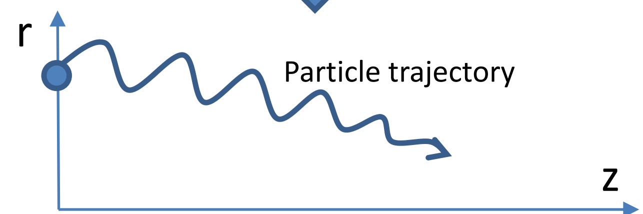
$$F_r = -q\frac{r}{2}\left(\frac{\partial E_z}{\partial z} + \frac{\beta}{c}\frac{\partial E_z}{\partial t}\right)$$

$\Longrightarrow$ Transverse equation of motion

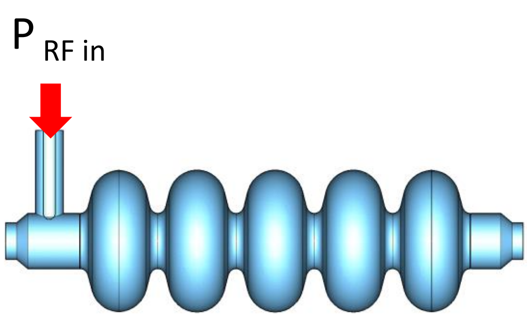
$$\ddot{r} = \frac{1}{\gamma m_0} r \sum_n a_n \cos(n\omega t)$$

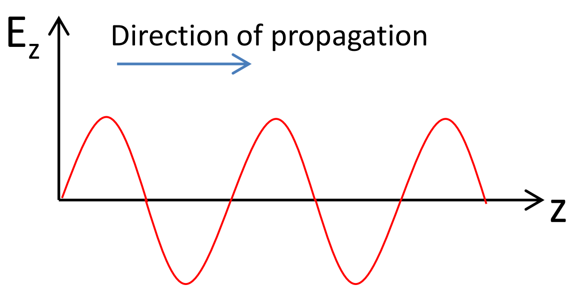
RF harmonics

This generate a global focusing force

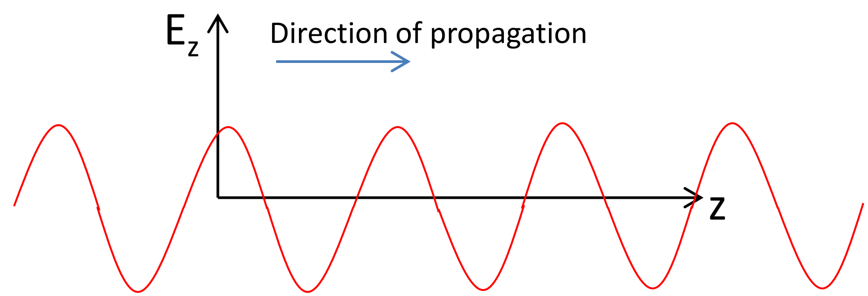


NON-SYNCHRONOUS RF HARMONICS: SIMPLE CASE OF SW STRUCTURE





Is equivalent to the **superposition of two counterpropagating TW waves**



The **forward wave only contribute to the acceleration** (and does not give transverse effect).

The **backward wave** does not contribute to the acceleration but generates an **oscillating transverse force** (ponderomotive force)

Average focusing force

$$\overline{F}_r = -rq\frac{\hat{E}_{acc}^2}{8\gamma\, m_0 c^2/e}\eta(\phi)$$

With accelerating gradients of few tens of MV/m can easily reach the level of MV/m²

APPENDIX: PONDEROMOTIVE FORCE

Let us consider a particle under the action of a **non-uniform force oscillating at frequency** ω in the radial direction. The equation of motion in the transverse direction is given by:

$$\ddot{r} = g(r)\cos(\omega t)$$

We are searching for a solution of the type:

$$r \cong r_s(t) + r_f(t)$$

Where r_s represents a slow drift motion and r_f a fast oscillation. Assuming $r_f \ll r_s$ we can proceed to a Taylor expansion of the function g(r) writing the equation as:

$$\ddot{r}_s + \ddot{r}_f \cong \left[g(r_s) + r_f \left.\frac{dg}{dr}\right|_{r=r_s} \right] \cos(\omega t)$$

assuming

$$\ddot{r}_s \ll \ddot{r}_f$$

$$g(r_s) \gg r_f \left.\frac{dg}{dr}\right|_{r=r_s}$$

$$\ddot{r}_f = g(r_s)\cos(\omega t)$$

On the time scale on which rf oscillates r_s is essentially constant, thus, the equation can be integrated to get:

$$r_f = -\frac{g(r_s)}{\omega^2}\cos(\omega t)$$

Substituting in the main equation and averaging over the one period

$$\ddot{r}_s \cong -\frac{g(r_s)}{2\omega^2}\left.\frac{dg}{dr}\right|_{r=r_s} = -\frac{1}{4\omega^2}\left.\frac{dg(r)^2}{dr}\right|_{r=r_s}$$

Thus, we have obtained an expression for the drift motion of a charged particle under the effect of a non-uniform oscillating field

In the case of the Lorentz force due to the harmonics of the accelerating field g(r)=Ar and we obtain:

$$\ddot{r}_s + \frac{A}{2\omega^2} r_s \cong 0$$

We have then an exponential decay of the amplitude due to a constant focusing force

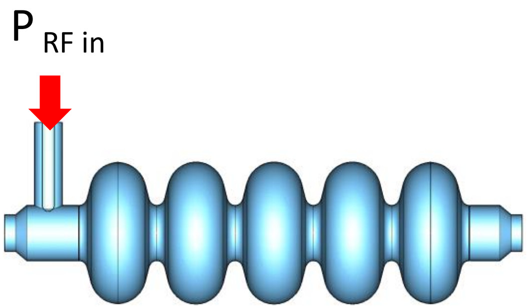
APPENDIX: RF NON-SYNCRONOUS HARMONICS

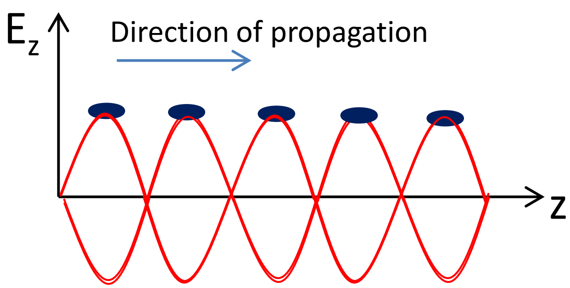
Let us consider the case of a multi-cell SW cavity working on the π-mode. The Accelerating field can be expressed as:

$$E_z = \hat{E}_{RF}\cos(kz)\cos(\omega_{RF}t)$$

In order to have synchronism between the accelerating field and and ultrarelativistic particle we have to satisfy the following relation:

$$k = \frac{2\pi}{\lambda_{RF}} = \frac{\omega_{RF}}{c} \quad , \quad \lambda_{RF} = cT_{RF}$$





The accelerating field seen by the particle is given by:

$$E_z\Big|_{\substack{seen\\by\\particle\\z=ct}} = \hat{E}_{RF}\cos(kz)\cos\left(\omega_{RF}\frac{z}{c}\right) = \hat{E}_{RF}\cos^2(kz) = \frac{\hat{E}_{RF}}{2} + \frac{\hat{E}_{RF}}{2}\cos(2kz)$$

The SW can be written as the sum of two TWs in the form:

$$E_z = \underbrace{\frac{\hat{E}_{RF}}{2}\cos(\omega_{RF}t - kz)} + \underbrace{\frac{\hat{E}_{RF}}{2}\cos(\omega_{RF}t + kz)}$$

Synchronous wave co-propagating with beam

NON-Synchronous wave (called RF harmonic) counter-propagating with beam (opposite direction)

The accelerating field seen by the particle is given by:

$$E_z\Big|_{\substack{seen\\by\\particle\\z=ct}} = \frac{\hat{E}_{RF}}{2}\cos\left(\omega_{RF}\frac{z}{c} - kz\right) + \frac{\hat{E}_{RF}}{2}\cos\left(\omega_{RF}\frac{z}{c} + kz\right) = \frac{\hat{E}_{RF}}{2} + \frac{\hat{E}_{RF}}{2}\cos(2kz)$$

Synchronous wave: acceleration

$$E_z\Big|_{\substack{seen\\by\\particle\\z=ct}} = \frac{\hat{E}_{RF}}{2} + \frac{\hat{E}_{RF}}{2}\cos(2kz) = \frac{\hat{E}_{RF}}{2} + \frac{\hat{E}_{RF}}{2}\cos(2\omega_{RF}t)$$

Oscillating field that does not contribute to acceleration but that gives RF focusing

COLLECTIVE EFFECTS: SPACE CHARGE AND WAKEFIELDS

Collective effects are **all effects related to the number of particles** and they can play a crucial role in the longitudinal and transverse beam dynamics of intense beam LINACs

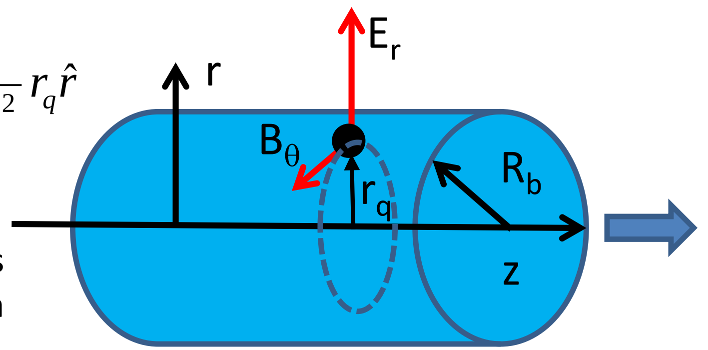
SPACE CHARGE

⇒ **Effect of Coulomb repulsion between particles** (**space charge**).

⇒ These effects cannot be neglected especially at **low energy and at high current** because the space charge forces **scales as $1/\gamma^2$ and with the current I.**

EXAMPLE: Uniform and infinite cylinder of charge moving along z

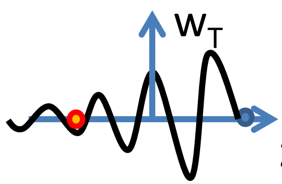
$$\vec{F}_{SC} = q\frac{I}{2\pi\varepsilon_0 R_b^2 \beta c \gamma^2} r_q \hat{r}$$

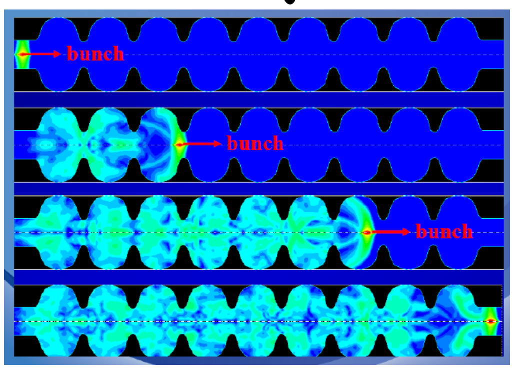


In this particular case it is linear but in general it is a **non-linear force**

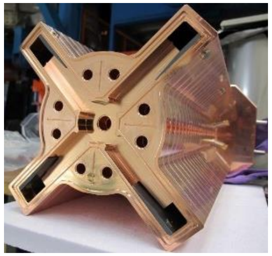
WAKEFIELDS

The other effects are due to the **wakefield**. The passage of bunches through accelerating structures excites electromagnetic **field**. This field can have longitudinal and transverse components and, interacting with subsequent bunches (long range wakefield), **can affect the longitudinal and the transverse beam dynamics**. In particular the **transverse wakefields**, can drive an instability along the train called **multibunch beam break up** (BBU).





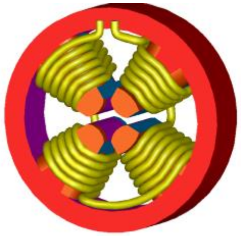
Several approaches are used to absorb these field from the structures like **loops** couplers, **waveguides**, Beam pipe **absorbers**



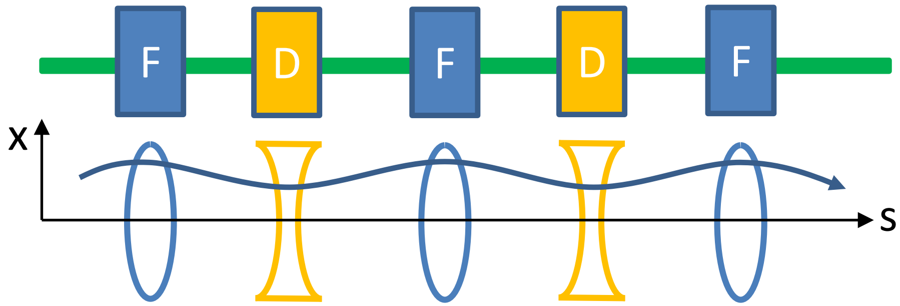
MAGNETIC FOCUSING AND CONTROL OF THE TRANSVERSE DYNAMICS

⇒**Defocusing RF forces, space charge** or the natural divergence (emittance) of the beam need to be **compensated** and controlled by **focusing forces**.

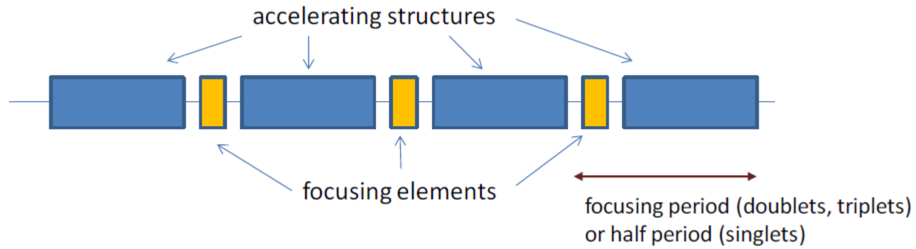
This is provided by **quadrupoles** along the beam line.
At low energies also **solenoids** can be used



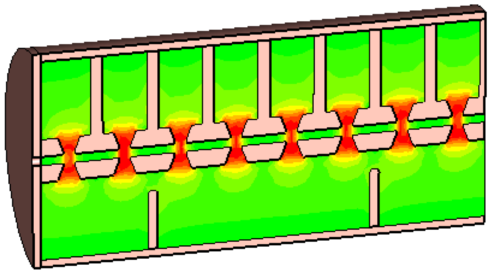
⇒Quadrupoles are focusing in one plane and defocusing on the other. A global focalization is provides by **alternating quadrupoles** with opposite signs



⇒In a linac one **alternates accelerating structures with focusing sections**.

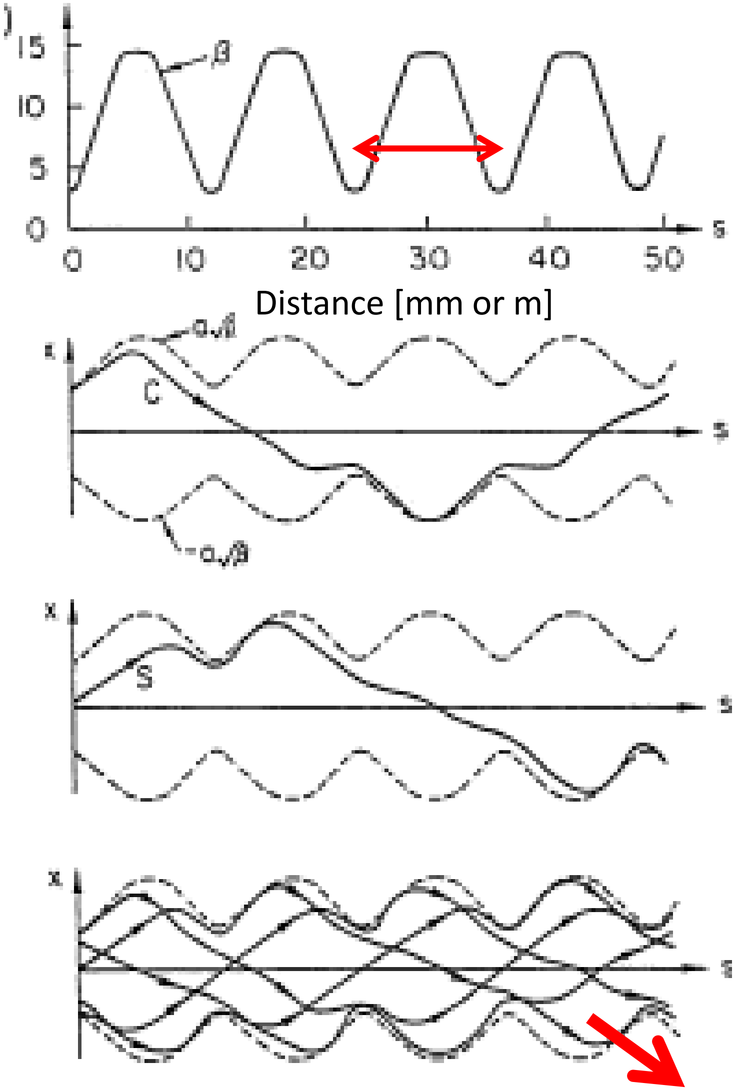


⇒The type of magnetic configuration and magnets type/distance depend on the type of particles/energies/beam parameters we want to achieve.



TRANSVERSE OSCILLATIONS AND BEAM ENVELOPE

Due to the **alternating quadrupole focusing system** each particle perform transverse oscillations along the LINAC.



Focusing period (L_p)= length after which the structure is repeated (usually as Nβλ).

The **equation of motion in the transverse plane** is of the type:

Term depending on the magnetic configuration

RF defocusing/focusing term

$$\frac{d^2x}{ds^2} + \underbrace{\left[\kappa^2(s) + k_{RF}^2(s)\right]}_{K^2(s)} x - F_{SC} = 0$$

Space charge term

The **single particle trajectory is a pseudo-sinusoid** described by the equation:

$$x(s) = \sqrt{\varepsilon_o \beta(s)} \cos\left[\int_{s_o}^{s} \frac{ds}{\beta(s)} + \phi_0\right]$$

Characteristic function (Twiss β-function [m]) that depend on the magnetic and RF configuration

Depend on the initial conditions of the particle

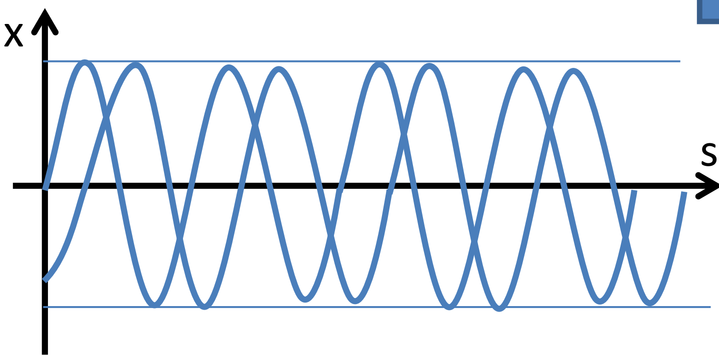
$$\sigma = \int_{L_p} \frac{ds}{\beta(s)} \approx \frac{L_p}{\langle \beta \rangle}$$

Transverse phase advance per period L_p. For stability should be $0<\sigma<\pi$

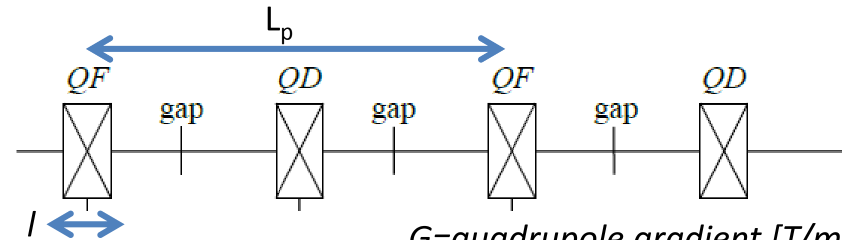
The final transverse beam dimensions ($\sigma_{x,y}(s)$) vary along the linac and are contained within an **envelope**

SMOOTH APPROXIMATION OF TRANSVERSE OSCILLATIONS

⇒In case of "**smooth approximation**" of the LINAC (we consider an average effect of the quadrupoles and RF) we obtain a simple harmonic motion along s of the type (β is constant):



$$x(s) = \sqrt{\varepsilon_o}\,\sqrt{1/K_0}\,\cos(K_0 s + \phi_0)$$



G=quadrupole gradient [T/m]
l=quadrupole length

Phase advance per unit length (σ/L_p)

$$K_0 = \sqrt{\left(\frac{qGl}{2m_0c\gamma\beta}\right)^2 - \frac{\pi q\hat{E}_{acc}\sin(-\phi)}{m_0c^2\lambda_{RF}(\gamma\beta)^3}}$$

Magnetic focusing elements (for a FODO)

RF defocusing term

NB: the RF defocusing term ∝f sets a higher limit to the working frequency

If we consider also the **Space Charge contribution** in the simple case of an **ellipsoidal beam** (linear space charges) we obtain:

$$K_0 = \sqrt{\left(\frac{qGl}{2m_0c\gamma\beta}\right)^2 - \frac{\pi q\hat{E}_{acc}\sin(-\phi)}{m_0c^2\lambda_{RF}(\gamma\beta)^3} - \frac{3Z_0qI\lambda_{RF}(1-f)}{8\pi m_0c^2\beta^2\gamma^3r_xr_yr_z}}$$

Space charge term

I= average beam current (Q/T_{RF})
$r_{x,y,z}$=ellipsoid semi-axis
f= form factor (0<f<1)
Z_0=free space impedance (377 Ω)

For ultrarelativistic **electrons RF defocusing and space charge disappear** and the external focusing is required to control the emittance and to stabilize the beam against instabilities.

GENERAL CONSIDERATIONS ON LINAC OPTICS DESIGN (1/2)

PROTONS AND IONS

⇒ Beam dynamics dominated by **space charge and RF defocusing forces**

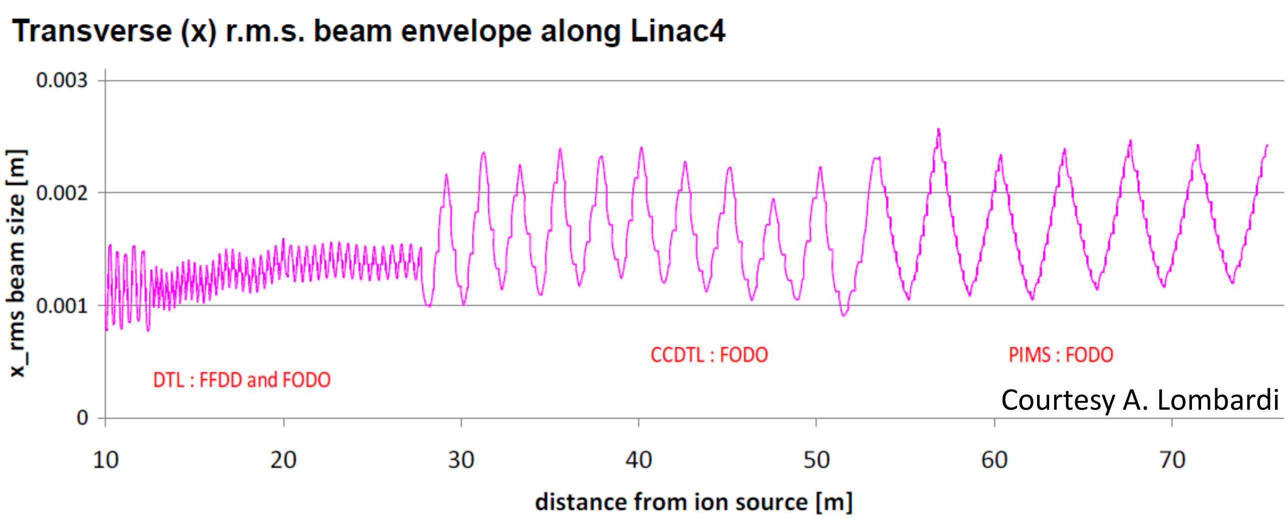
⇒ Focusing is usually provided by **quadrupoles**

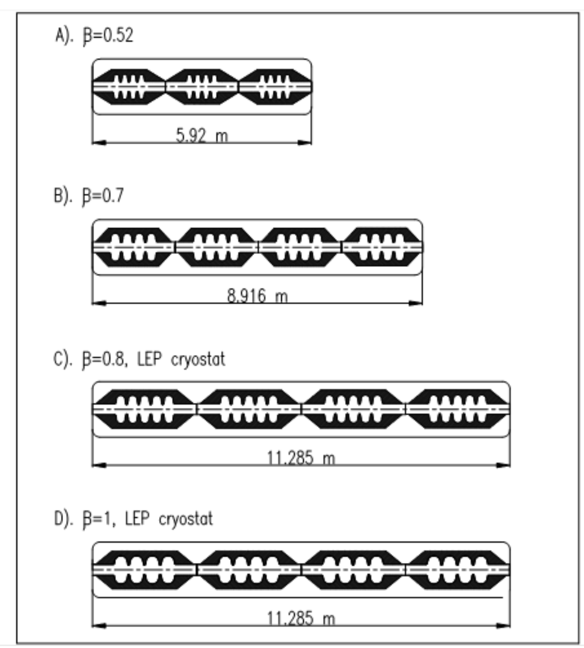
⇒ Phase advance per period (σ) should be, in general, in the range 30-80 deg, this means that, at low energy, we need a strong focusing term (**short quadrupole distance and high quadrupole gradient**) to compensate for the rf defocusing, but the limited space ($\beta\lambda$) limits the achievable G and beam current

⇒ **As β increases, the distance between focusing elements can increase** ($\beta\lambda$ in the DTL goes from ~70mm (3 MeV, 352 MHz) to ~250mm (40 MeV), and can be increased to 4-10$\beta\lambda$ at higher energy (>40 MeV).

⇒ A linac is made of a **sequence of structures, matched to the beam velocity**, and where the length of the focusing period increases with energy. As β increases, longitudinal phase error between cells of identical length becomes small and we can have **short sequences of identical cells** (lower construction costs).

⇒ Keep sufficient safety **margin between beam radius and aperture**





GENERAL CONSIDERATIONS ON LINAC OPTICS DESIGN (2/2)

ELECTRONS

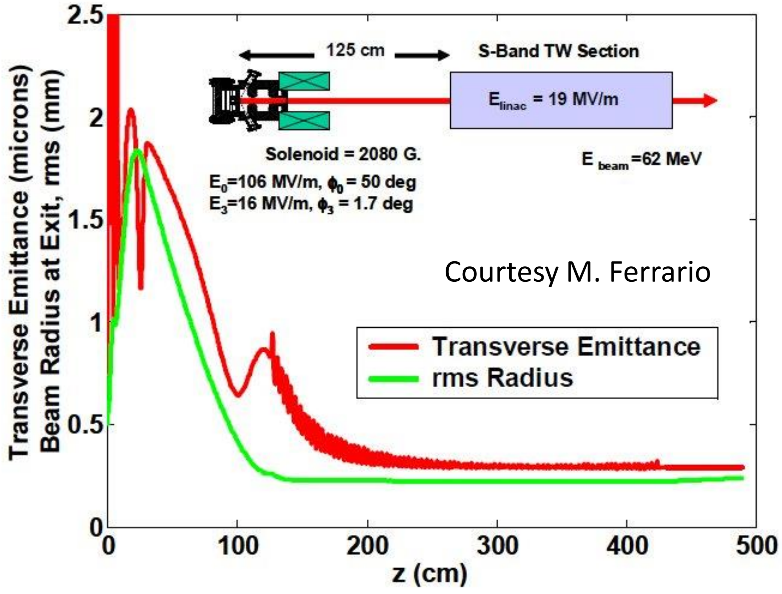
⇒ **Space charge only at low energy and/or high peak current**: below 10-20 MeV (injector) the beam dynamics optimization has to include emittance compensation schemes with, typically solenoids;

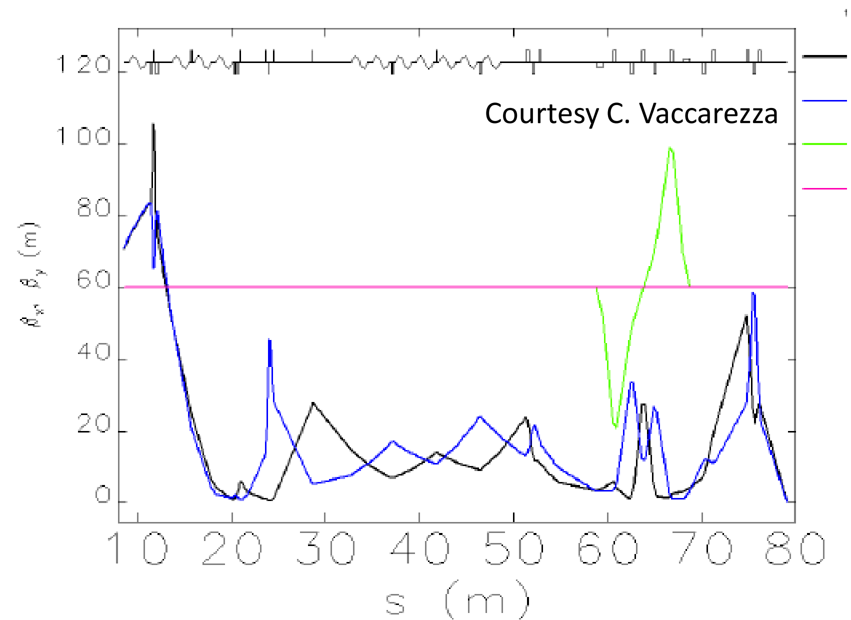
⇒ At higher **energies no space charge and no RF defocusing effects** occur but we have **RF focusing due to the ponderomotive force: focusing periods up to several meters**

⇒ Optics design has to take into account **longitudinal and transverse wakefields** (due to the **higher frequencies used for acceleration**) that can cause energy spread increase, head-tail oscillations, multi-bunch instabilities,…

⇒ Longitudinal bunch compressors schemes based on magnets and chicanes have to take into account, for short bunches, the interaction between the beam and the emitted synchrotron radiation (**Coherent Synchrotron Radiation effects**)

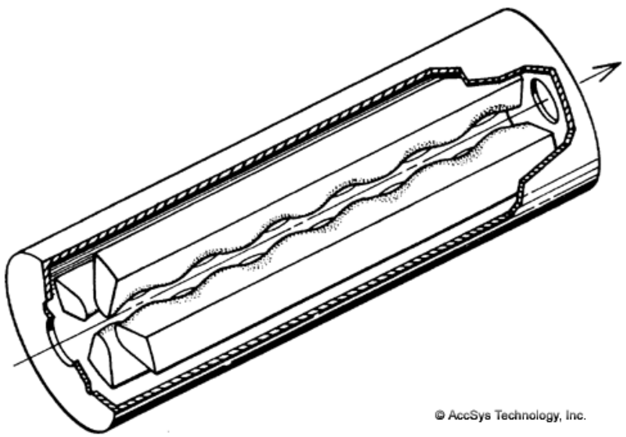
⇒ All these effects are important especially in LINACs for **FEL that requires extremely good beam qualities**



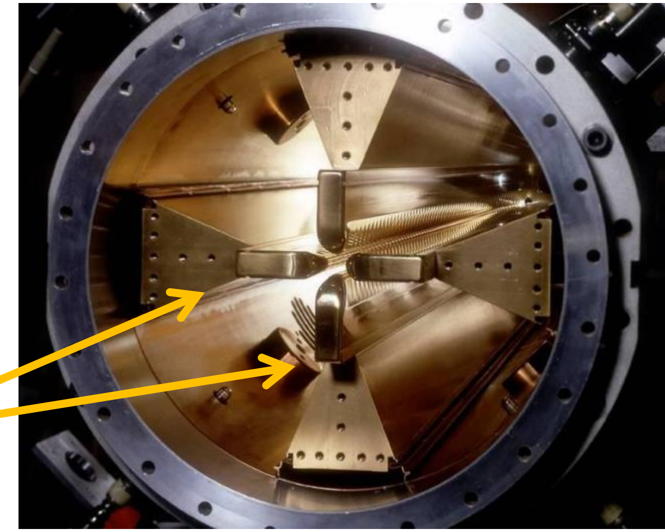


RADIO FREQUENCY QUADRUPOLES (RFQ)

At low proton (or ion) energies (β~0.01), **space charge defocusing is high and quadrupole focusing is not very effective**. Moreover cell length becomes small and conventional accelerating structures **(DTL) are very inefficient**. At this energies it is used a (relatively) new structure, the **Radio Frequency Quadrupole** (1970).



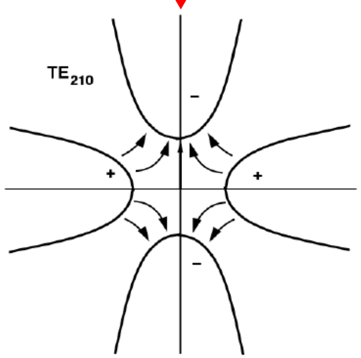
Electrodes



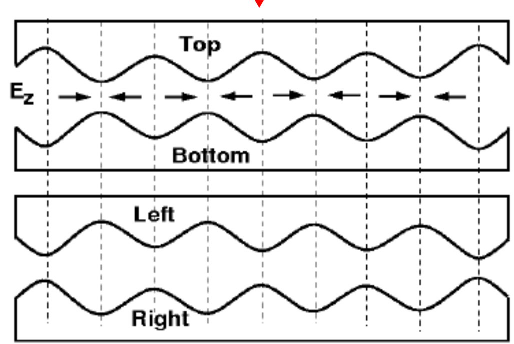
Courtesy M. Vretenar

These structures allow to simultaneously provide:

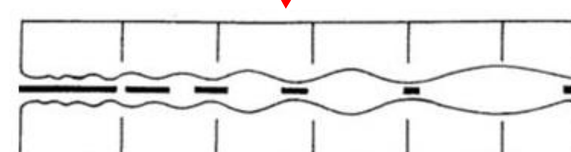
Transverse Focusing



Acceleration



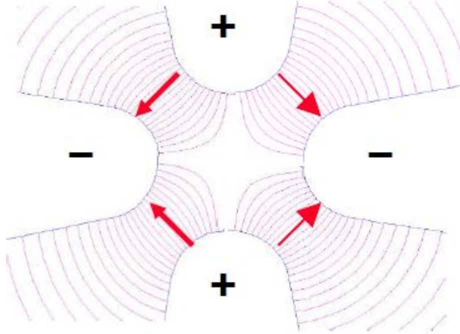
Bunching of the beam

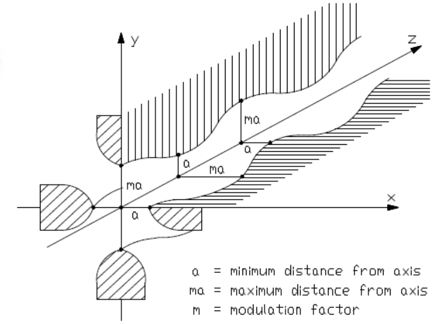


RFQ: PROPERTIES

1-Focusing

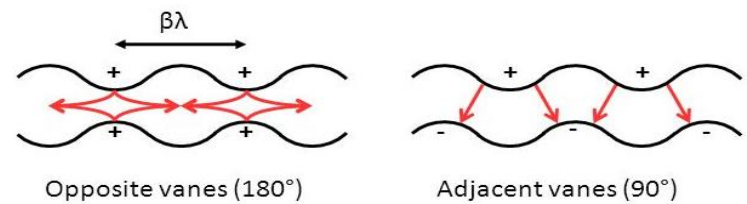
The resonating mode of the cavity (between the four electrodes) is a **focusing mode**: **Quadrupole mode (TE_{210})**. The alternating voltage on the electrodes produces an **alternating focusing channel** with the period of the RF (**electric focusing** does not depend on the velocity and is ideal at low β)





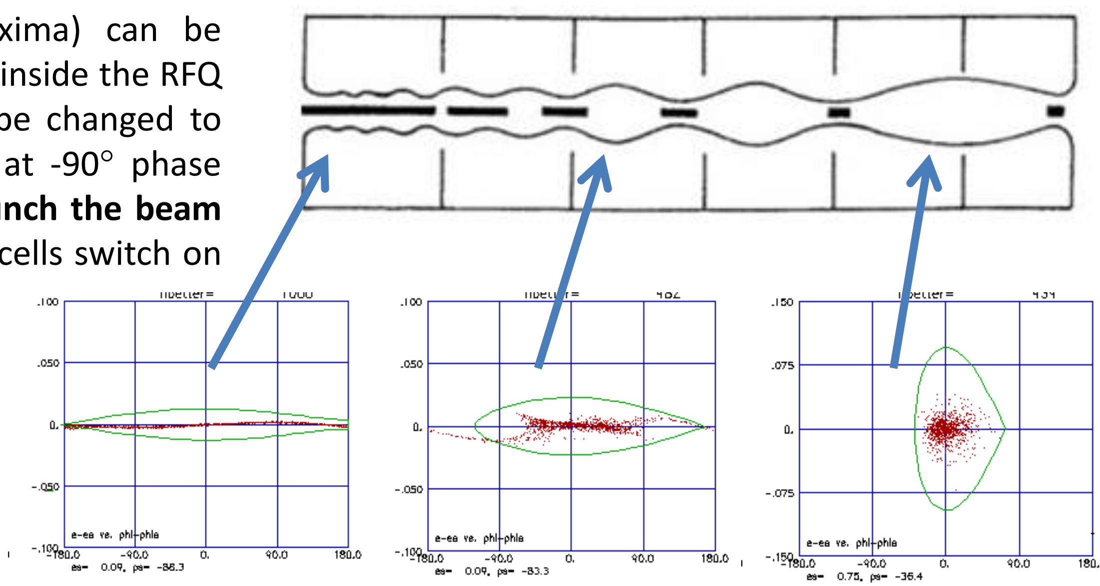
2-Acceleration

The vanes have a **longitudinal modulation** with period = $\beta\lambda_{RF}$ this creates a **longitudinal component of the electric field** that accelerate the beam (the modulation corresponds exactly to a series of RF gaps).



3-Bunching

The modulation period (distance between maxima) can be slightly adjusted to change the phase of the beam inside the RFQ cells, and the amplitude of the modulation can be changed to change the accelerating gradient. One can start at -90° phase (linac) with some **bunching cells**, progressively **bunch the beam** (adiabatic bunching channel), and only in the last cells switch on the **acceleration**.

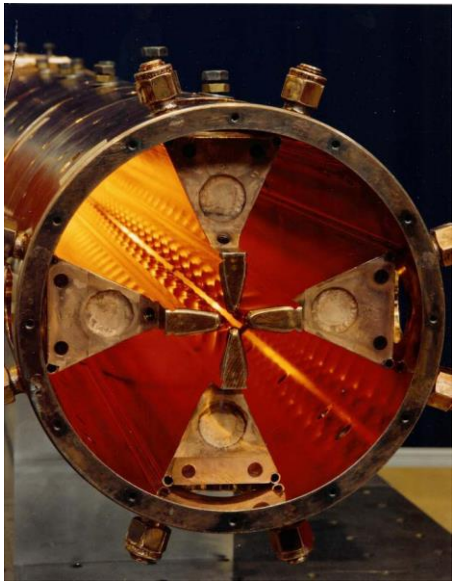



Courtesy A. Lombardi

The RFQ is the only linear accelerator that can accept a low energy continuous beam.

Courtesy M. Vretenar and A. Lombardi

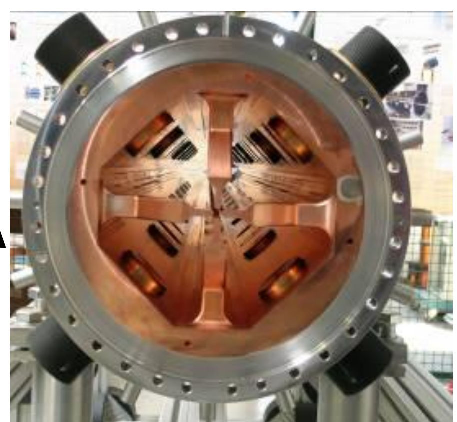
RFQ: EXAMPLES



The 1st 4-vane RFQ, Los Alamos
1980: 100 KeV - 650 KeV, 30 mA , 425 MHz

The CERN Linac4 RFQ
45 keV – 3 MeV, 3 m
80 mA H-, max. 10% duty cycle

TRASCO @ INFN Legnaro
Energy In: 80 keV
Energy Out: 5 MeV
Frequency 352.2 MHz
Proton Current (CW) 30 mA



THE CHOICE OF THE ACCELERATING 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

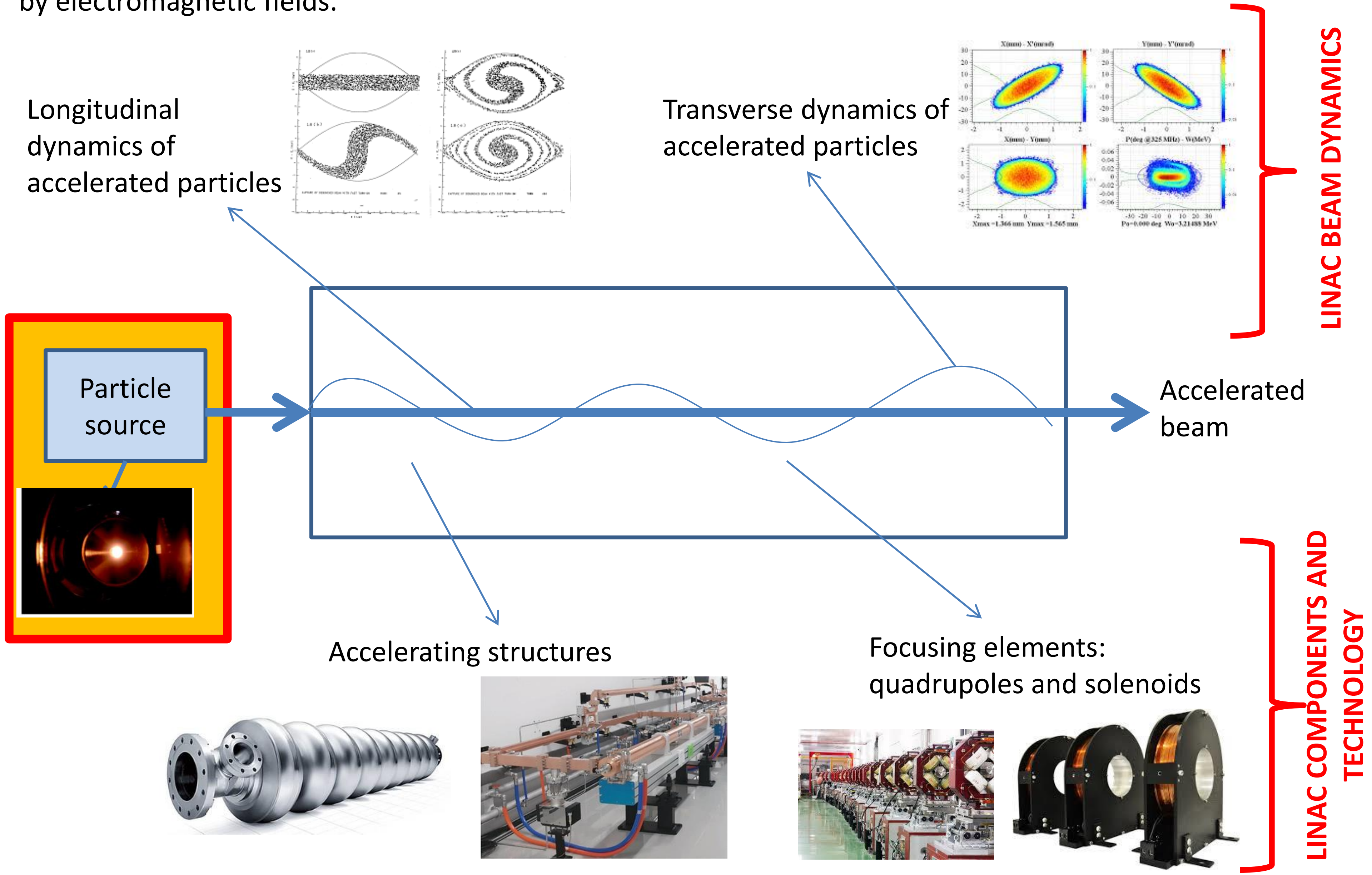
Moreover **a given accelerating structure has also a curve of efficiency** (shunt impedance) with respect to the particle energies and the choice of one structure with respect to another one depends also on this.

As example a very general scheme is given in the Table (absolutely not exhaustive).

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

LINAC: BASIC DEFINITION AND MAIN COMPONENTS

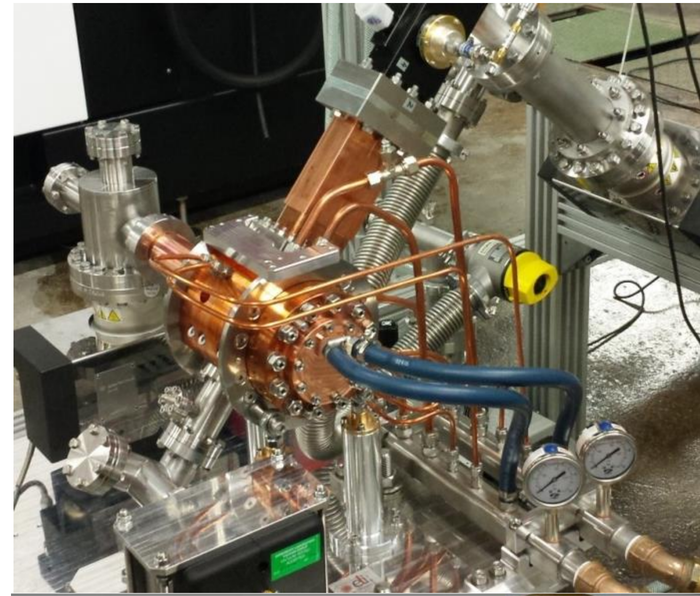
LINAC (linear accelerator) is a **system that allows to accelerate charged particles through a linear trajectory** by electromagnetic fields.

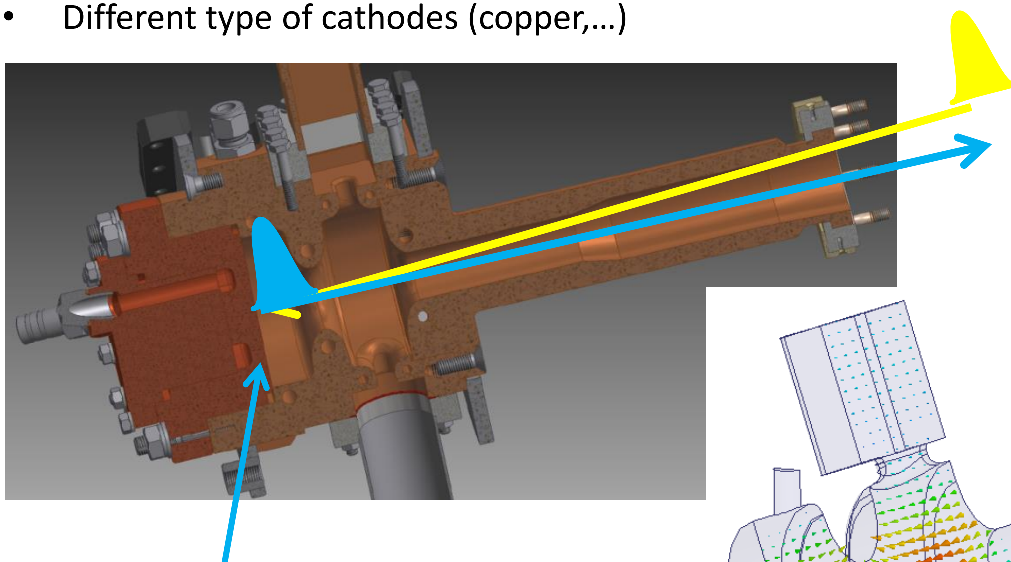


ELECTRON SOURCES: RF PHOTO-GUNS

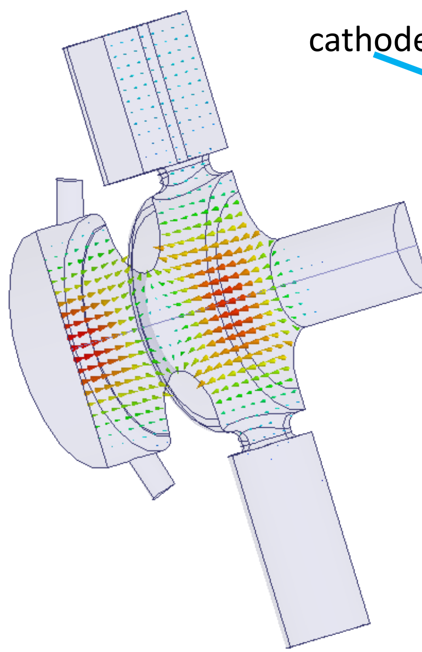
RF guns are used in the first stage of electron beam generation in FEL and acceleration.

- Multi cell: typically 2-3 cells
- SW π mode cavities
- operate in the range of 60-120 MV/m cathode peak accelerating field with up to 10 MW input power.
- Typically in L-band- S-band (1-3 GHz) at 10-100 Hz.
- Single or multi bunch (L-band)
- Different type of cathodes (copper,…)

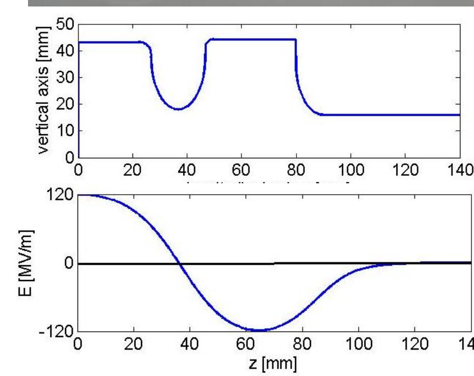




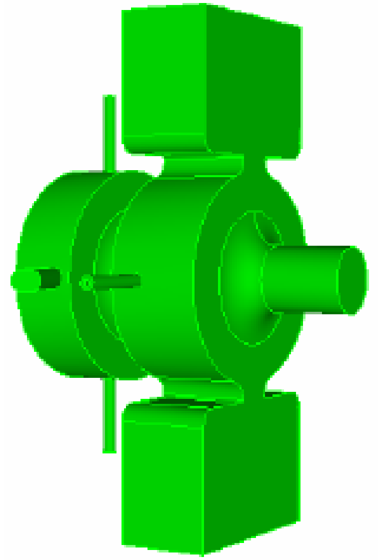
The electrons are emitted on the **cathode** through a laser that hit the surface. They are then accelerated trough the electric field that has a longitudinal component on axis TM_{010}.



cathode

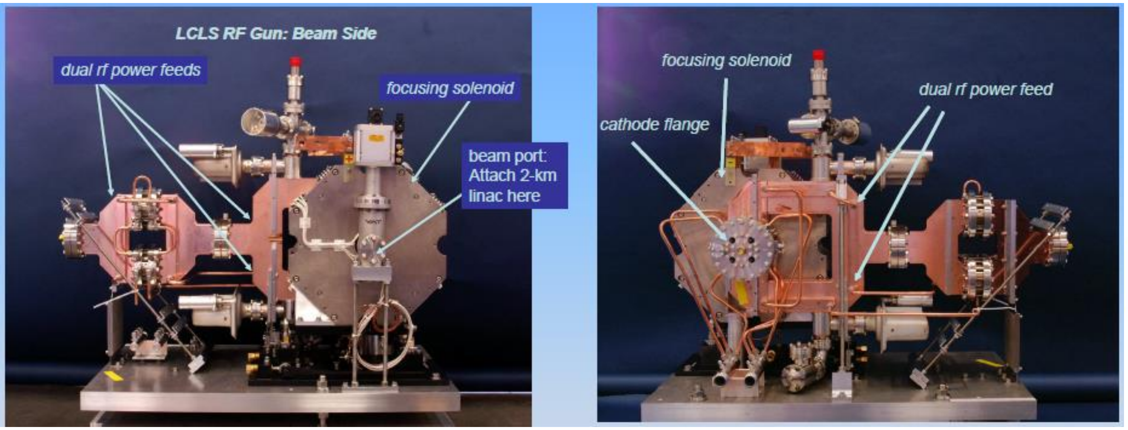


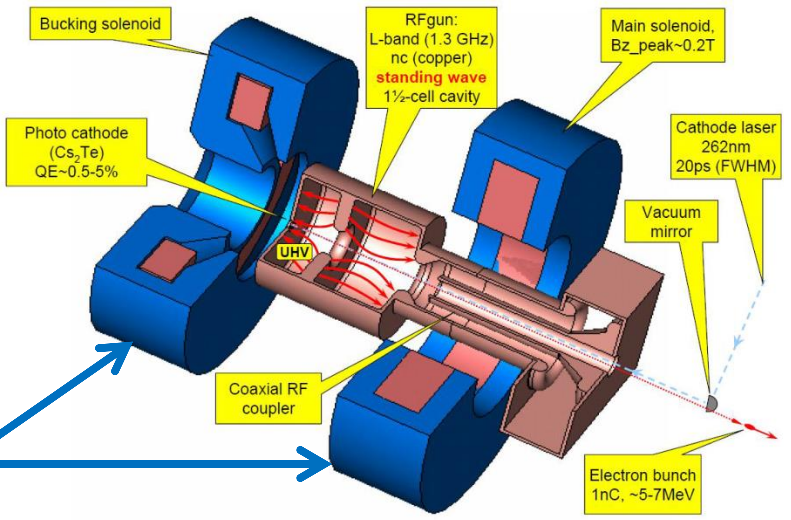
RF PHOTO-GUNS: EXAMPLES



LCLS
Frequency = 2,856 MHz
Gradient = 120 MV/m
Exit energy = 6 MeV
Copper photocathode
RF pulse length ~2 μs
Bunch repetition rate = 120 Hz
Norm. rms emittance
0.4 mm·mrad at 250 pC

PITZ L-band Gun
Frequency = 1,300 MHz
Gradient = up to 60 MV/m
Exit energy = 6.5 MeV
Rep. rate 10 Hz
Cs_2Te photocathode
RF pulse length ~1 ms
800 bunches per macropulse
Normalized rms emittance
1 nC 0.70 mm·mrad
0.1 nC 0.21 mm·mrad

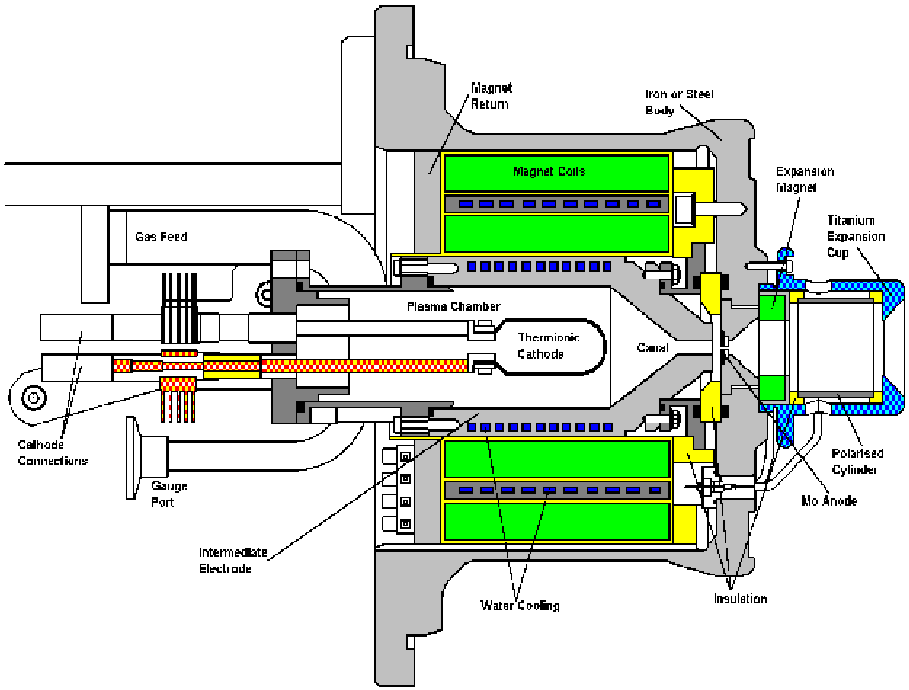


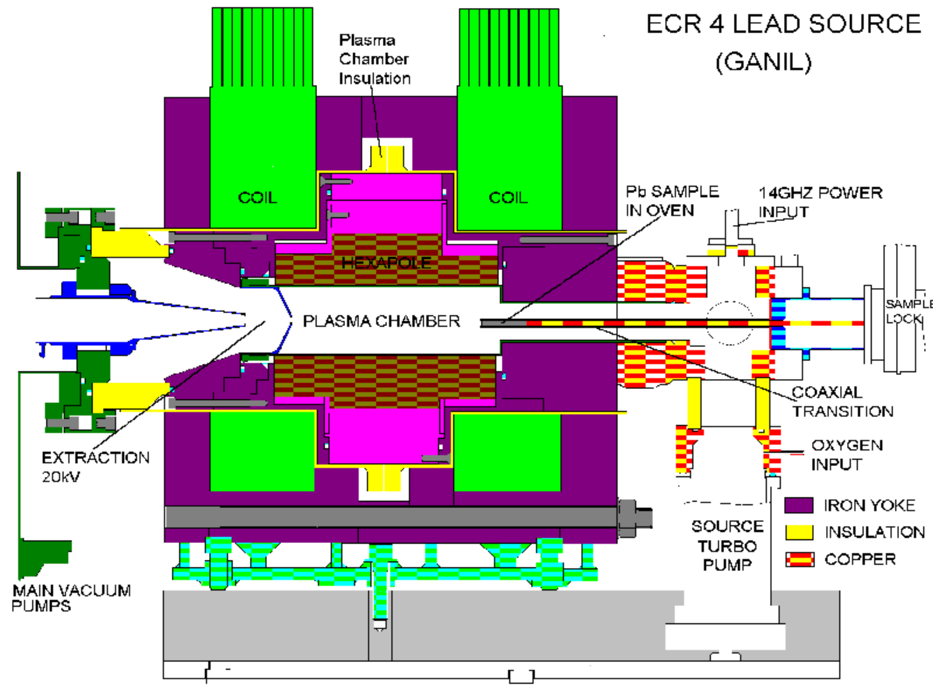


Solenoids field are used to compensate the space charge effects in low energy guns. The configuration is shown in the picture

ION SOURCES

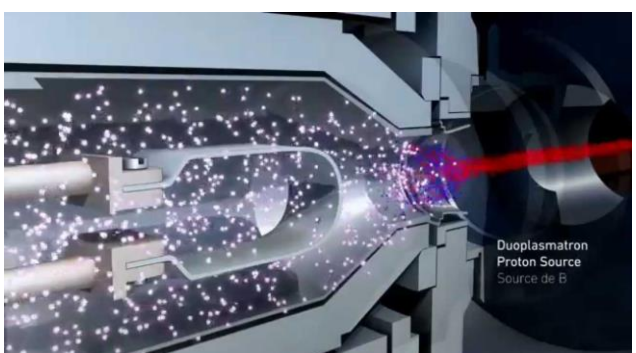
Basic principle: create a plasma and optimize its conditions (heating, confinement and loss mechanisms) to produce the desired ion type. Remove ions from the plasma via an aperture and a strong electric field.

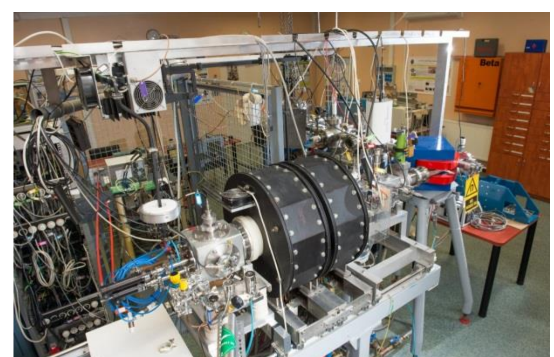




CERN Duoplasmatron proton Source

Electron Cyclotron Resonance (ECR) ECR



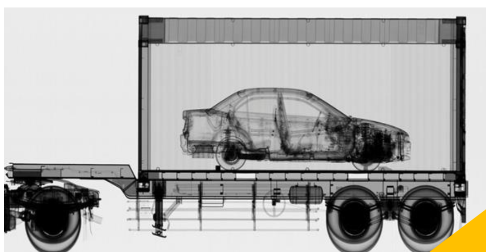


THANK YOU FOR YOUR ATTENTION AND….

Medical applications

Neutron spallation sources

Security: Cargo scans



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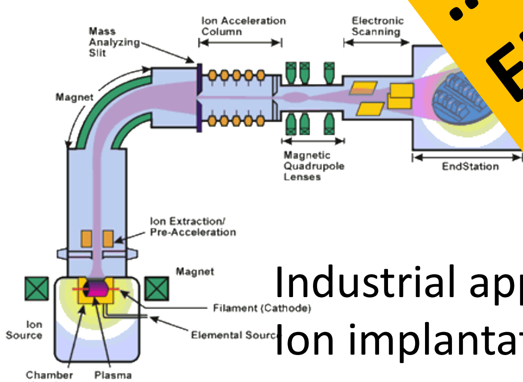
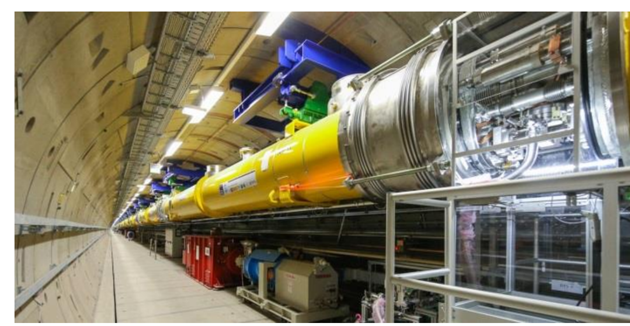
FEL



Industrial applicat ns:

Ion implantation for semiconductors



…ENJOY WITH THE ENORMOUS DIFFERENT APPLICATIONS OF LINEAR ACCELERATORS!

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T. Wangler, Principles of RF Linear Accelerators (Wiley, New York, 1998).
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