Heavy Ion Therapy Research Integration

Heavy Ion Therapy MasterClass School, 17-21 May 2021

Linear accelerators

G. BISOFFI, CERN AND INFN

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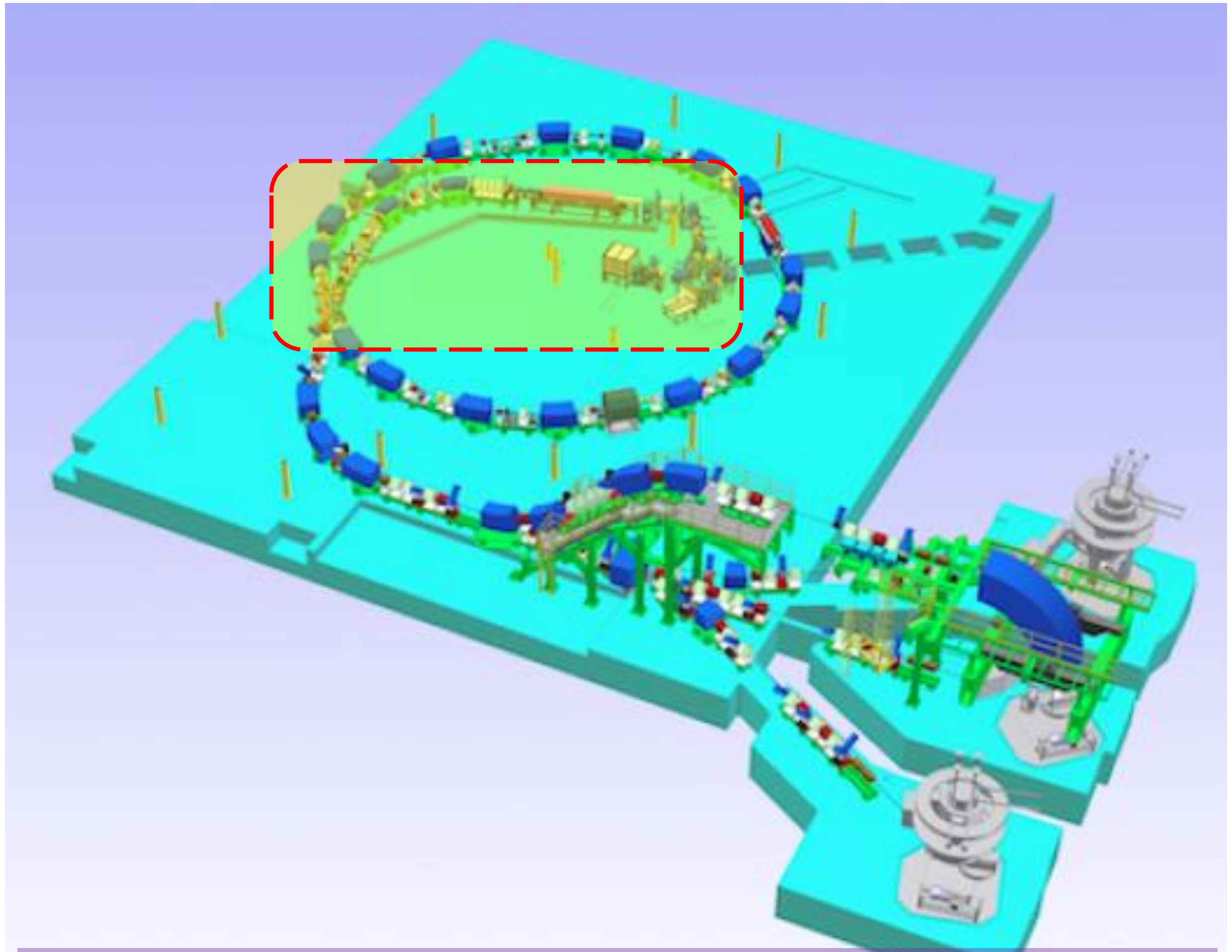
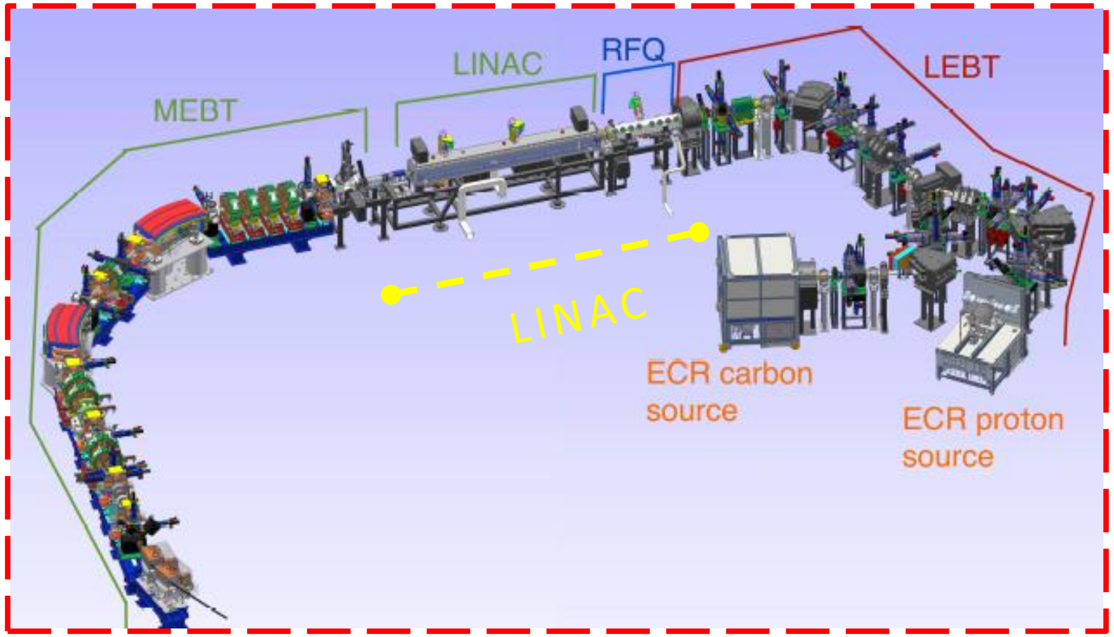
An example: the CNAO LINear ACcelerator



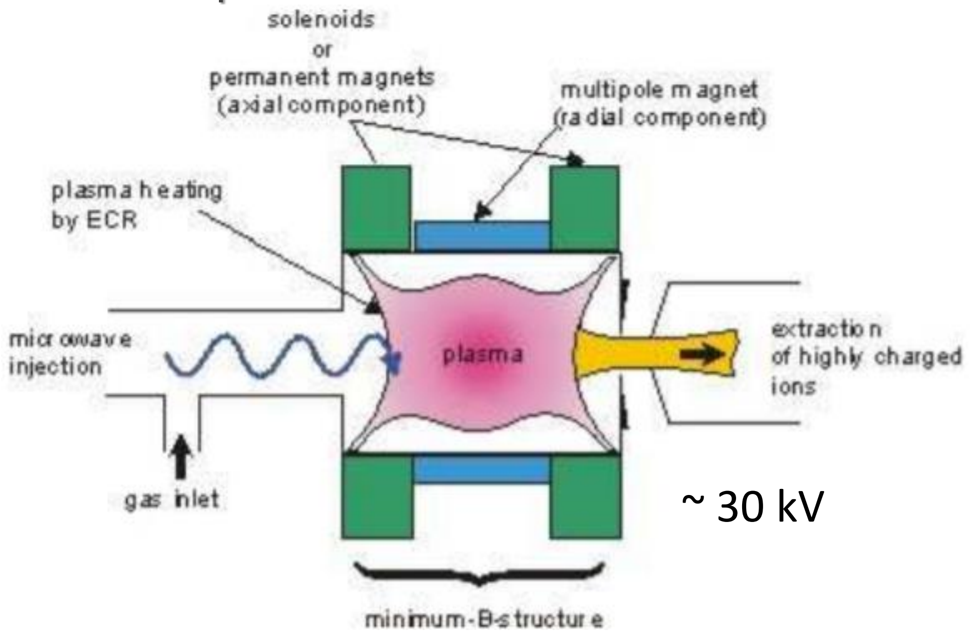


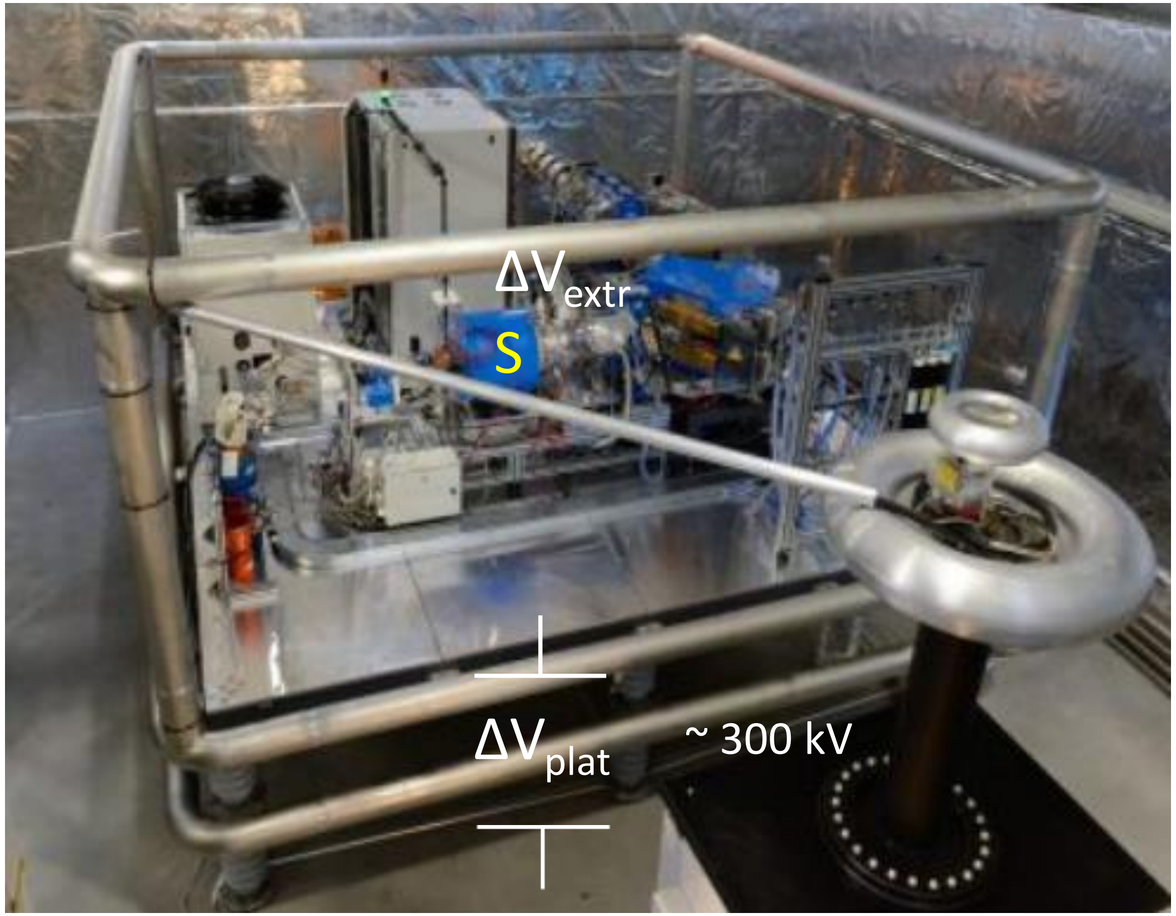
Terminology: in this lecture a LINAC is the part of the synchrotron injector (including the RFQ) **where the beam gets accelerated**. The injector includes the ion source and extraction, low and medium energy transport sections (LEBT, MEBT).

DISCLAIMER: most of the lecture will be on hadron LINACs; in lepton linacs many similarities and a few differences

Preparation to acceleration: generate and extract the beam

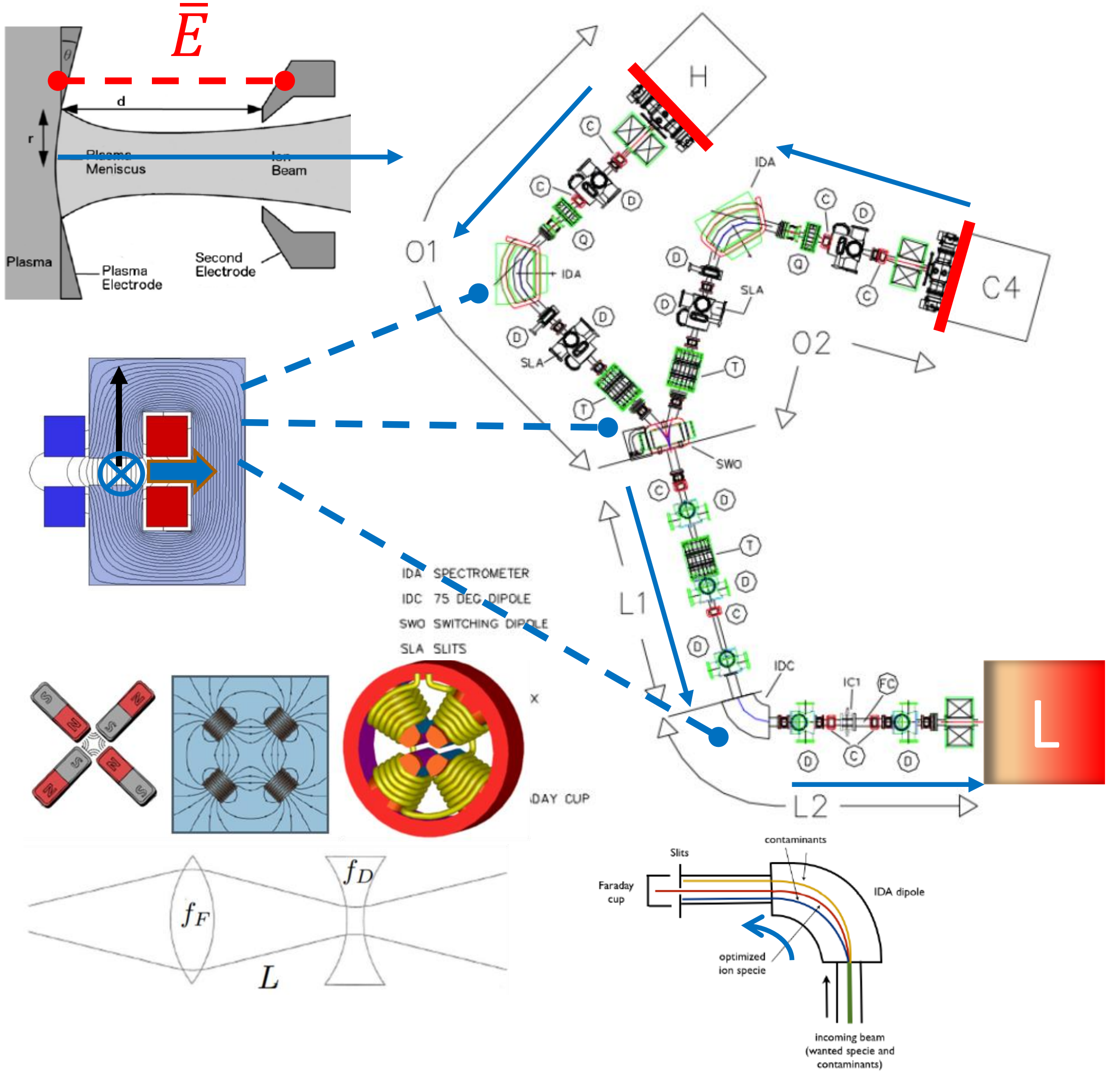
Ion sources: create a plasma ("4th state of matter", **hot ensamble of electrons and ions**); optimising heating, confinement and loss mechanisms, to produce the desired ion type. Remove ions from the plasma via an aperture and an electric field.





See N. Gambino, 18-05-2021

Source and LEBT – the LINAC injector – the LINAC front end



Indeed, acceleration starts right after beam generation at the source (**source extraction**), where a DC voltage (**20÷50 kV**) is applied (high enough to minimize space charge forces...). Then bending and focusing magnets provide beam transportation the the LINAC.

<u>**LORENZ FORCE**</u>: Linacs (and accelerator in general) use electromagnetic forces to accelerate, bend, focus **charged** particles (electrons, protons, heavier nuclei). $F = m\frac{d\bar{v}}{dt} = m\ddot{\boldsymbol{x}} = \boldsymbol{q}e(\bar{\boldsymbol{E}} + \bar{v}x\bar{\boldsymbol{B}})$

with **q** – charge state (positive value = number of missing electrons from the neutral atom) as extracted from the source.

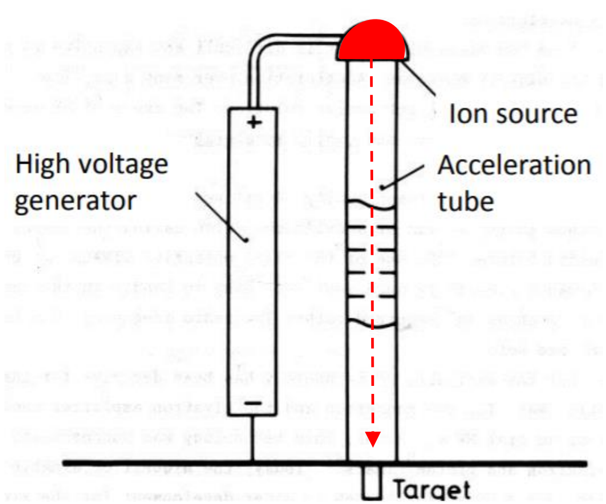
The LEBT has the very important function of **selecting the A/q ratio of interest**, from all the ion species and values of q extracted by the source.

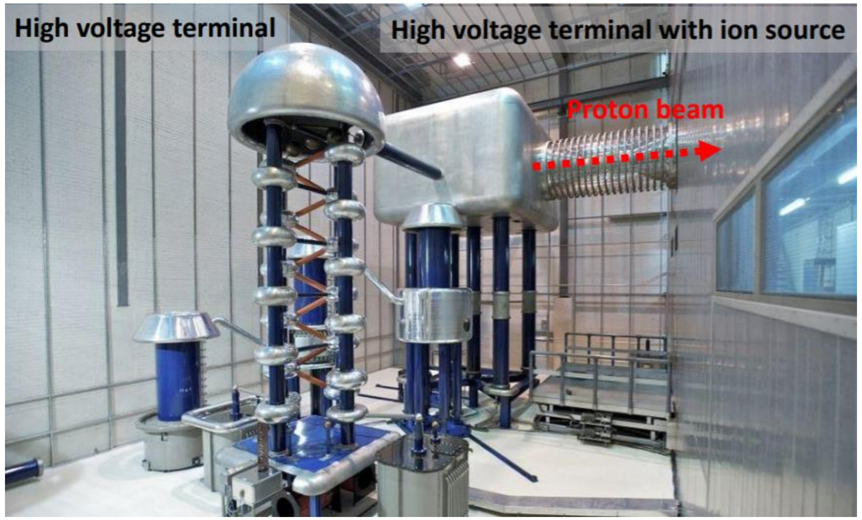
By simply playing with the Lorenz force (your exercise!) $\mathbf{R} = \frac{\mathbf{A}m_0 v}{\mathbf{q}eB}$, in the same B particles with different A/q will have different trajectories

In the following q often means q*e: apologies!

Electrostatic accelerators and their limits

1.





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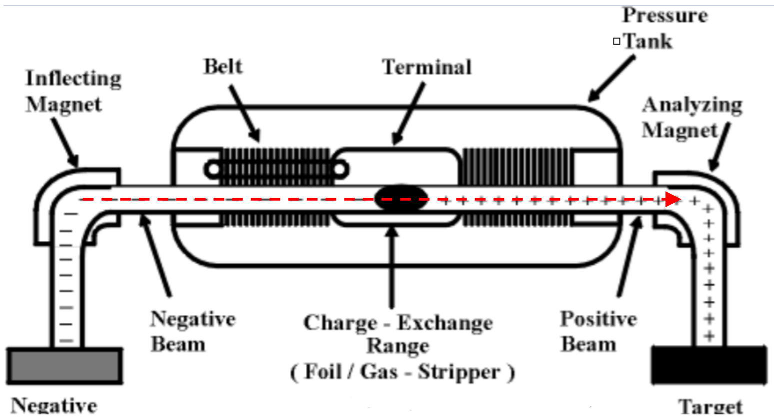


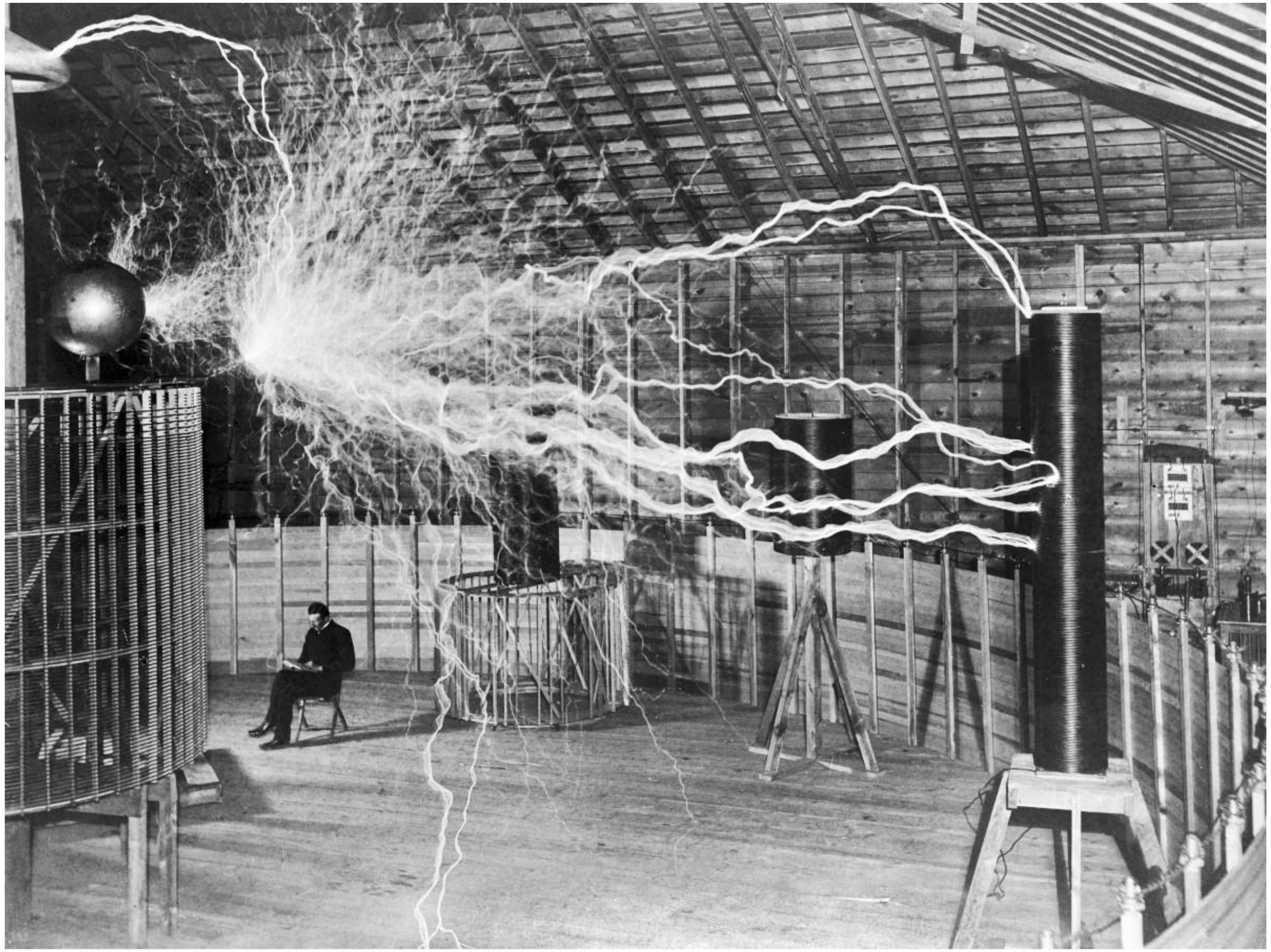
1. Cockroft-Walton: up to 1 MV in the head, cointaining the ion source, before discharge. $\boldsymbol{\Delta W_{fin}=q\ (1\ MV)}$

2. Tandem Van de Graaf: internal terminal in a big tank with insulating gas. ~16 MV achievable, with a

TRICK: charge change along path!

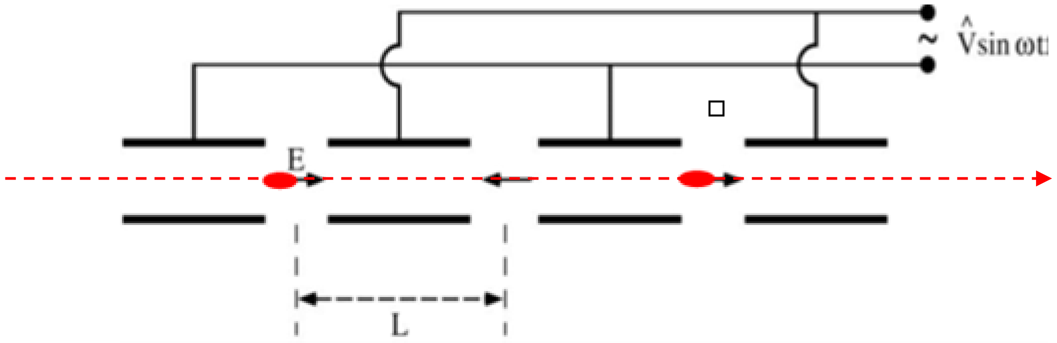
Inject neg. ions (**1-**), accelerate and strip them of many electrons (**q+**) in the 16 MV + terminal, have them repelled to $\boldsymbol{\Delta W_{fin}=(1+q)(16\ MV)}$

No matter how well designed, electrical discharges limit V_{max} in accelerators

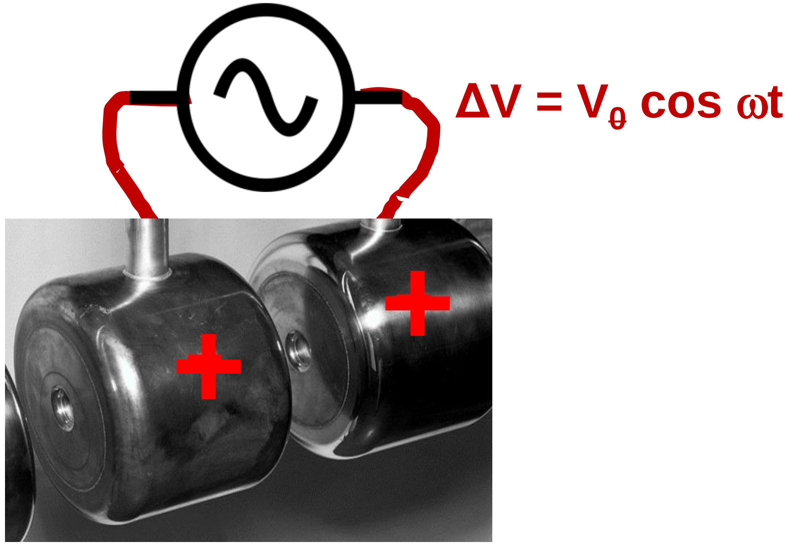


From the electrostatic accelerator to the RF linac

Alternative to changing polarity of the charge (which can be done only once): change polarity of the E field repeatedly along the beam path. The Wideroe Drift Tube Linac. Particles are subject to a synchronous accelerating voltage and experience an energy gain of **$\Delta W = q\Delta V$** at each gap crossing.



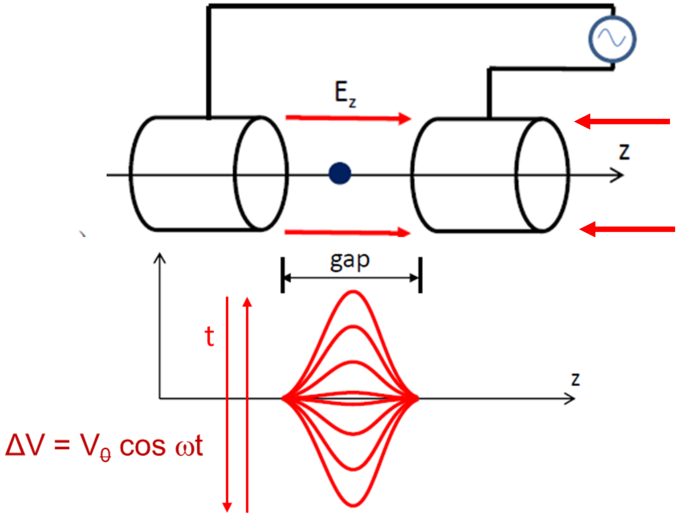
Coupling an RF genator to a closed resonator improves the efficiency, increases the E field, ... avoids dispersion of RF waves.



Linac4 DTL (CERN)

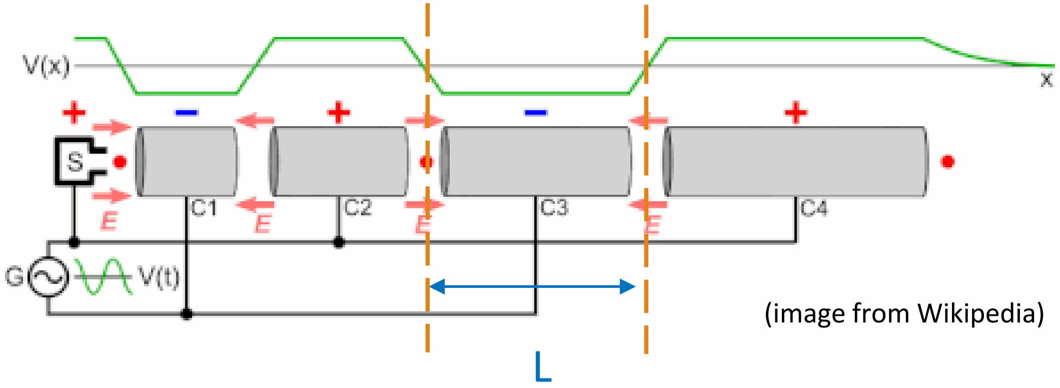
RF acceleration requires a beam in bunches and synchronous with E_{acc}

To be synchronous with AC field along $\bar{Z}$, particles must be gathered in a bunched (=non-uniform) time structure.



$\omega = 2\pi f$

Shape of the electric field along the gap (**z**) alternating according to the angular frequency ω=2πf
Field polarity is made to change when the beam is inside the Drift Tubes (~ Faraday cages).



(image from Wikipedia)

Phase btw bunch and field: a bunch meets the field only in the accelerating direction at each gap.

At each gap v_{beam} increases. So, the DT length L has to increase accordingly

(time to travel 2L) = T_{RF} = 1/f $\rightarrow \frac{2L}{v} = \frac{1}{f}$

$$L = \frac{v}{2f} = \frac{\beta c}{2\frac{c}{\lambda}} = \frac{\beta\lambda}{2} \qquad \left(\beta = \frac{v}{c};\ \lambda = \frac{c}{f}\right)$$

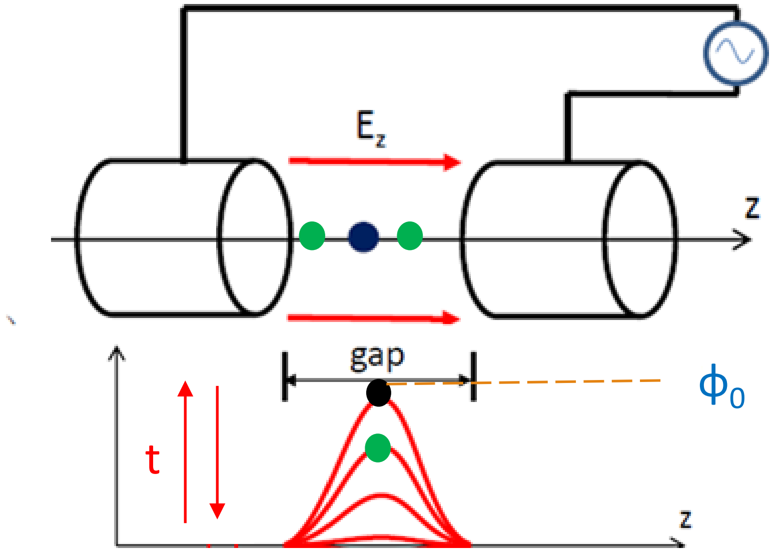
How much energy can you gain at each gap?

From Lorenz force with only E field:

$$\frac{dp}{dt} = qE_z \Rightarrow v\frac{dp}{dz} = qE_z \Rightarrow \frac{dT}{dz} = \boldsymbol{qE_z}$$ (rate of T gain per unit length)

$$\Delta \boldsymbol{T} = \int_{gap} \frac{dT}{dz} dz = q \int_{gap} E_z dz = q\Delta V = \boldsymbol{qV_0 T cos\varphi_0}$$

is the energy gain per gap between electrodes.

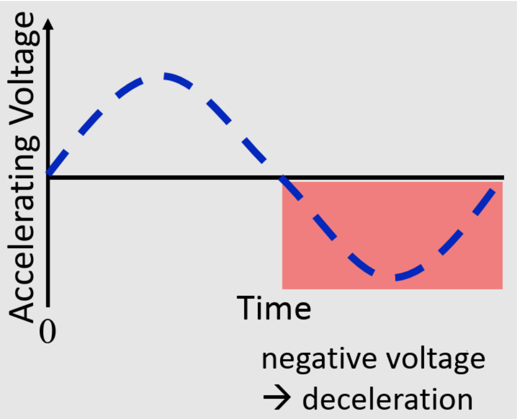


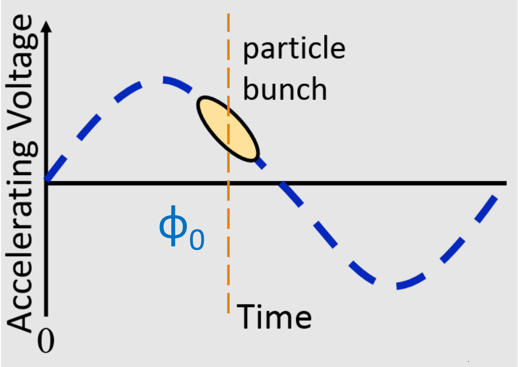
$\Delta V = V_0 \cos \omega t$

ϕ_0 is the phase of the bunch at the gap center; **V_0** is the maximum rf accelerating voltage in the gap; **T** (transit time factor) **< 1** accounts for the fact that V changes in time as long as the bunch crosses the gap.

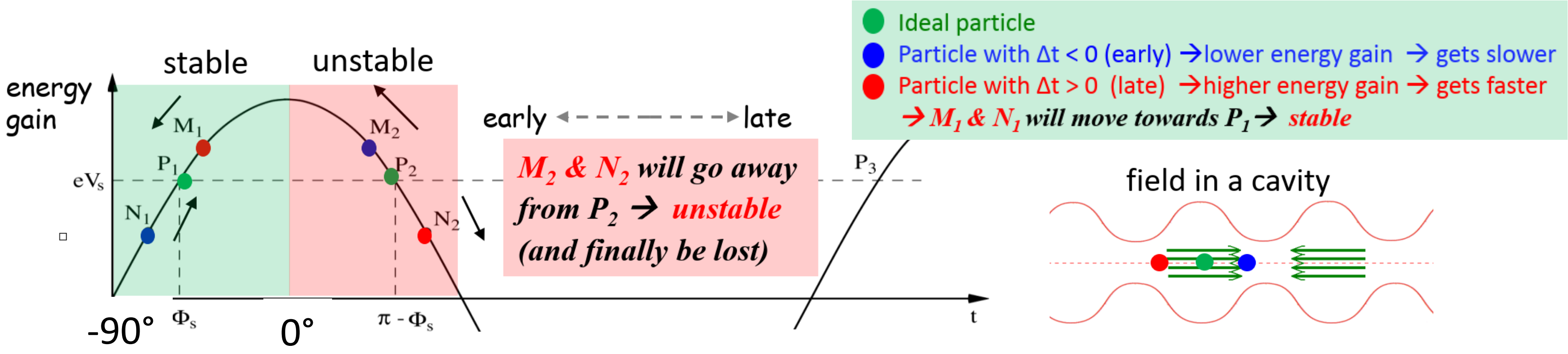
SC resonator, 0.2 m long with Ea=6 MV/m → **ΔV ~ 1.2 MV**,
13 resonators for 16 MV and ... length and € are the only limits!

The choice of φ_0 is important ! (a bunch is made by many particles...)





Beam bunches, centered at ϕ_0, must avoid decelerating phases



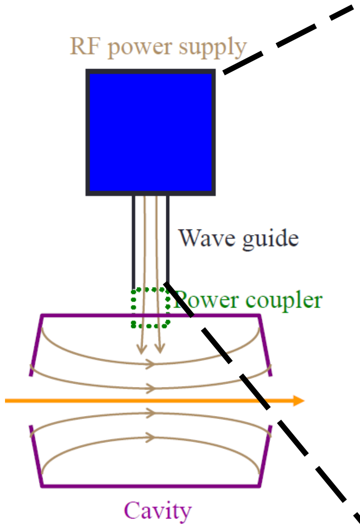
Take the **three dots** of the previous slides as “**different particles of the same bunch**”, arriving at different times and not gaining the same energy.

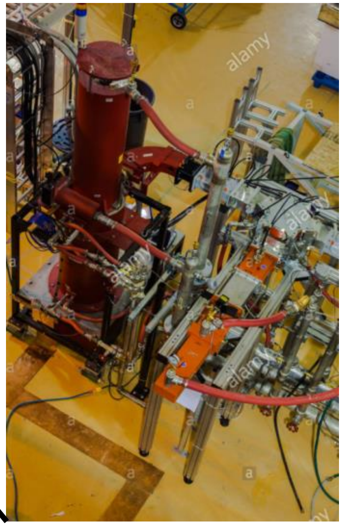
Versus the beam center (green dot):

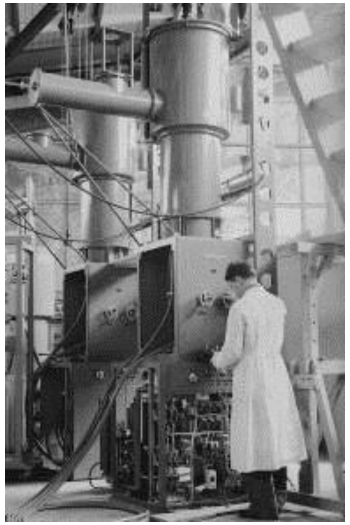
On the t-growing side, early particles (lower t, or φ) gain less and get delayed, while late particles (higher t, or φ) gain more and anticipate - POTENTIAL WELL, STABLE

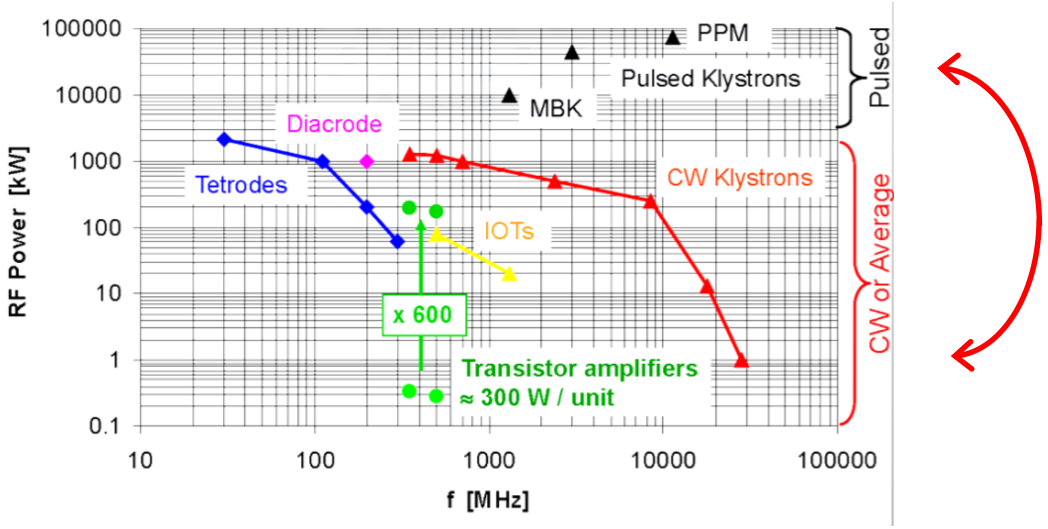
On the t-decreasing side – UNSTABLE

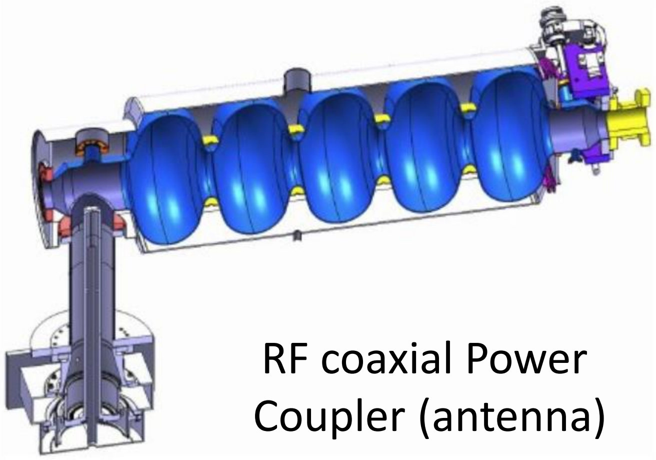
RF Power sources: how to provide the RF power to the cavities







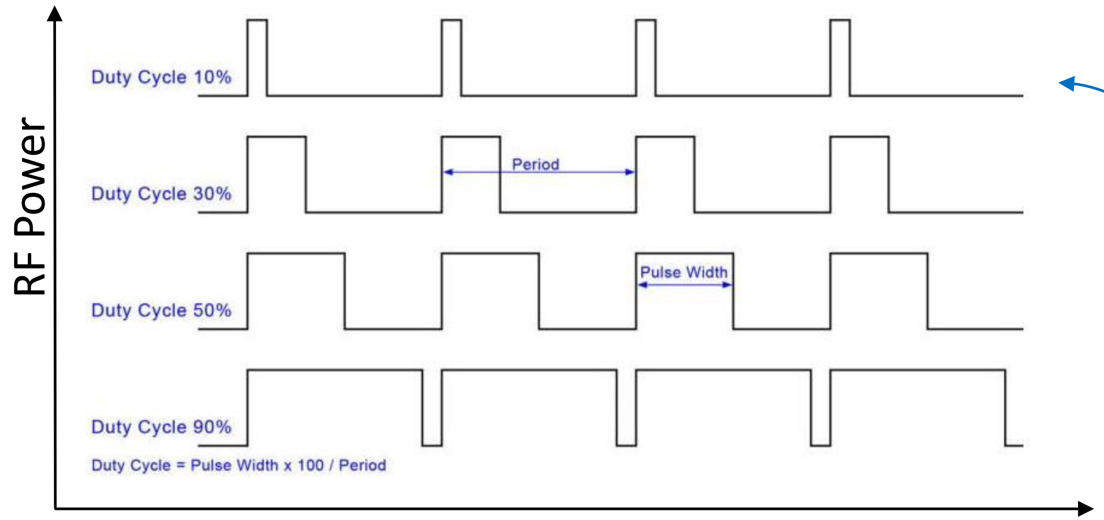


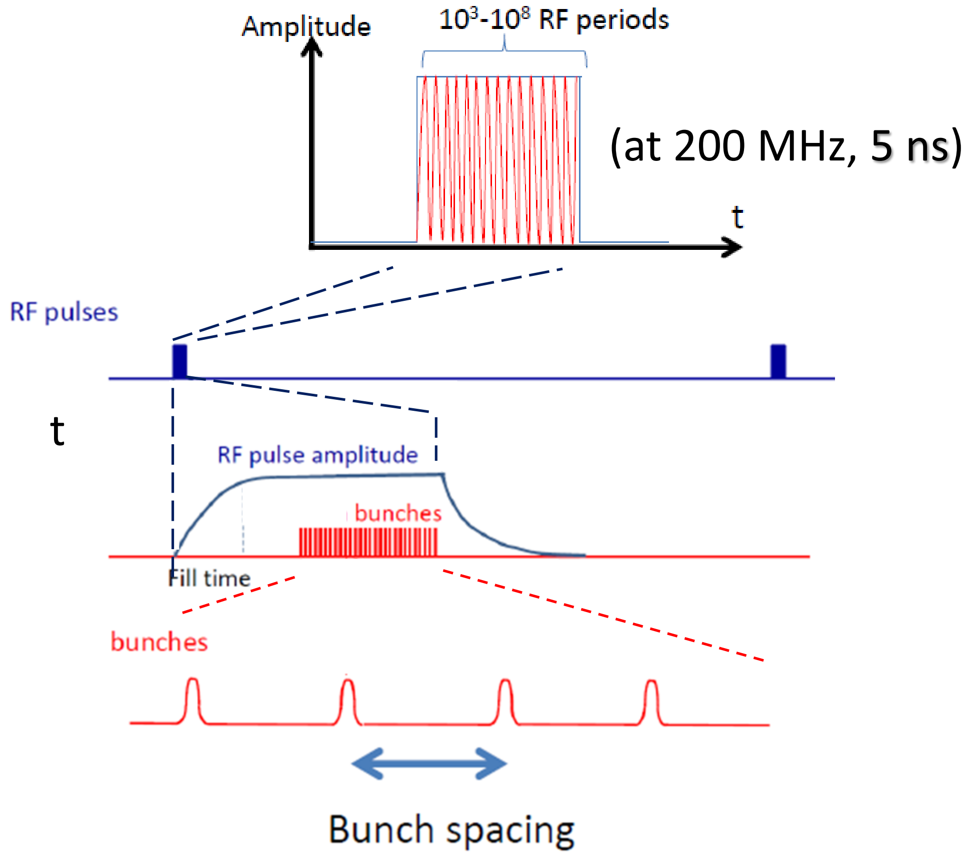


RF coaxial Power Coupler (antenna)

Power sources are hystorically produced for the broadcasting industry and used and adapted to the needs of particle accelerators. They may be very large and may need (and deliver) large **powers to cavities**, through **waveguides** and **power couplers** (antennas providing transition btw transmission line and cavity).

RF structure and beam structure





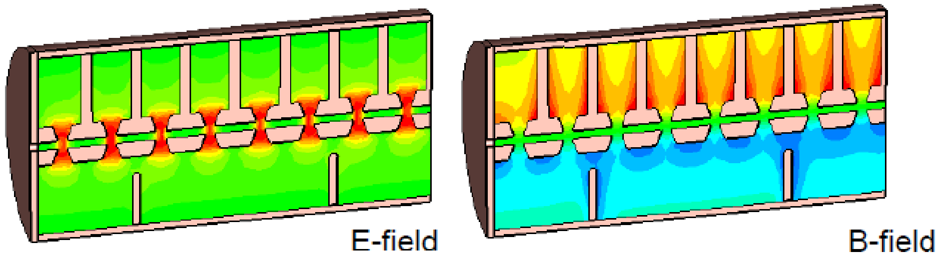
To feed RF power to a cavity all the time (continuous wave-CW mode, or "duty cycle"-d.c.=100%) is expensive (big amplifier systems, lot of power from the electrical network) and heats up the structure considerably, forcing to design big water cooling schemes. So, the **RF is kept on for barely the d.c. required by the user** (unless superconductivity is used). **At CNAO**: 0,5 ms pulse every 100 ms (**0,5%**).

Each "RF-on" period comprises several RF periods, filled with beam bunches.

The two main pathways to a linac design

Cavity design

- Control the **field pattern** inside a cavity
- **Minimize** ohmic **losses** on the walls (P_{diss}), while **maximizing** the stored energy (**U**), or the accelerating field (V_{acc})



3D EM Simulation codes

$$R_{sh} = \frac{\hat{V}_{acc}^2}{P_{diss}}\ [\Omega] \qquad Q = \omega_{RF}\frac{U}{P_{diss}}$$

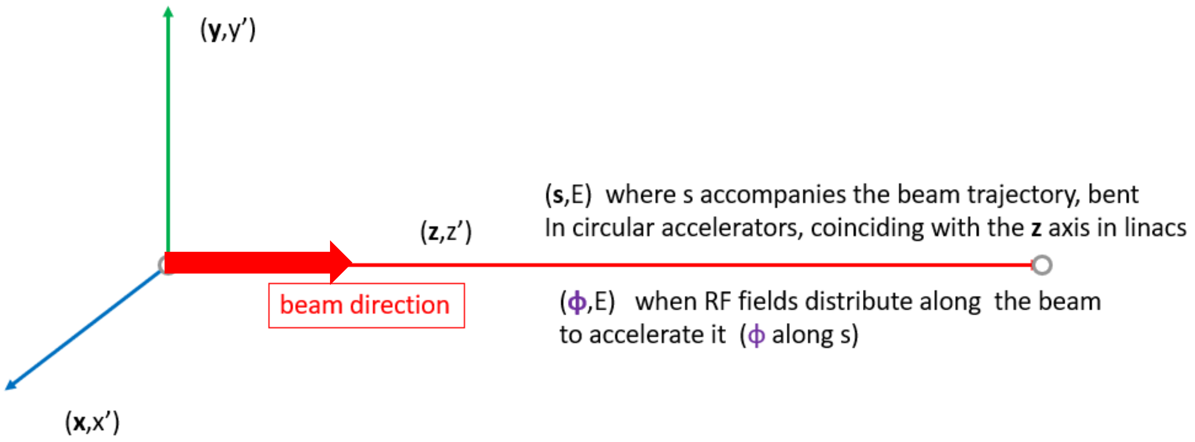
R_{sh} – shunt impedance *Q – quality factor*

V_{acc} is limited by electrical discharge (similarly to electrostatic accelerators). P_{diss} limited by the cooling capacity of water (room T) or the critical T of Nb (SC)

Beam dynamics design

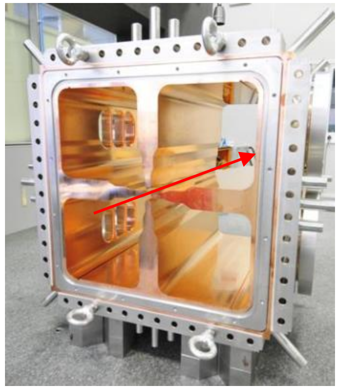
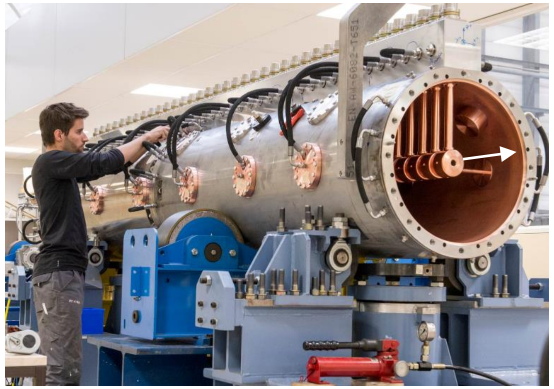
There are many particles in the beam. They have to be kept together

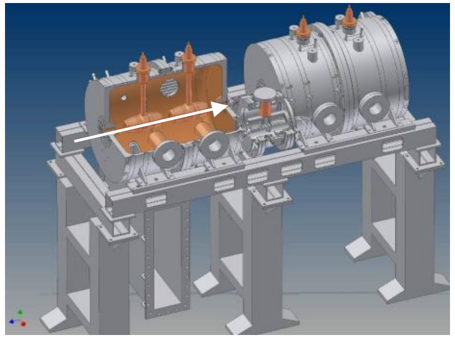
- Control the synchronization between the field and the bunch of particles
- Ensure the **beam is kept in the smallest possible «volume»** during acceleration



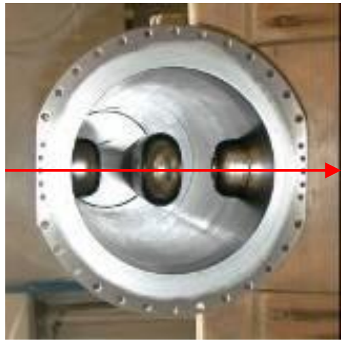
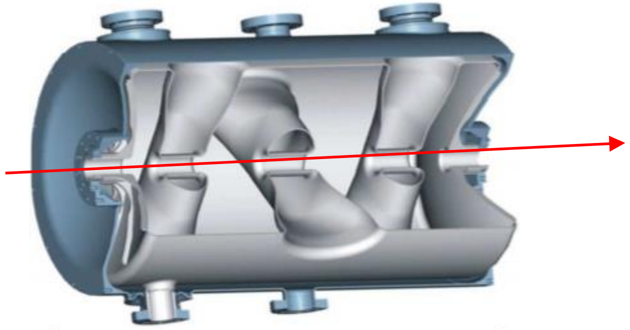
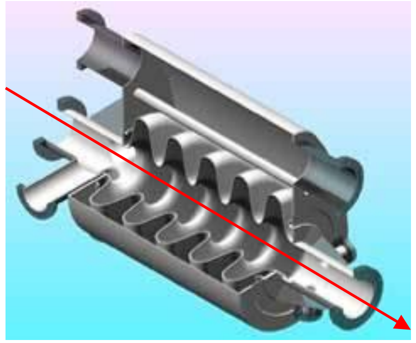
Accelerating cavity design

Realization in **Cu**, often brazed to an external structure in stainless steel, is the standard for low velocity and low duty cycle (cheap and reliable).



At **high E_{acc}**, high **E_{beam}**, high **d.c.**, the very low RF dissipation of SC is a clear advantage. Bulk **Nb** (SC below 9,2K) and a Nb onto a Cu layer are adopted.


Little Physics basics needed for the beam dynamics design

SPECIAL RELATIVITY:

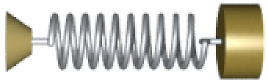
$$\cancel{T = \frac{1}{2} m\, \beta^2 c^2} \qquad \boldsymbol{\beta = \frac{v}{c}}$$

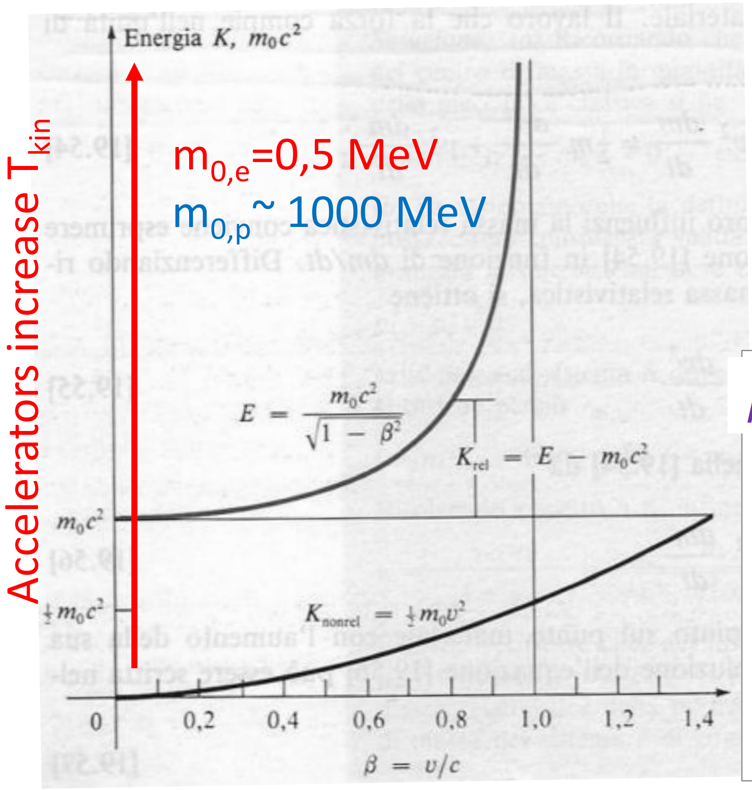
$$E = (\dots)mc^2 = \gamma mc^2 = \frac{mc^2}{\sqrt{(1-\beta^2)}} = \frac{mc^2}{\sqrt{\left(1-\left(\frac{v}{c}\right)^2\right)}}$$

$$\boldsymbol{\gamma = \frac{1}{\sqrt{1-\beta^2}}}$$

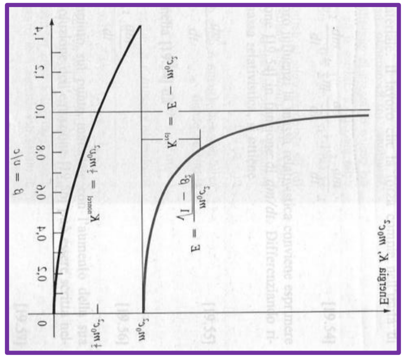
HARMONIC OSCILLATION: describing basic stable motion in physics

$$\bar{F} = -k\bar{x}\,; \qquad m\ddot{x} + \mathrm{k}x = 0$$

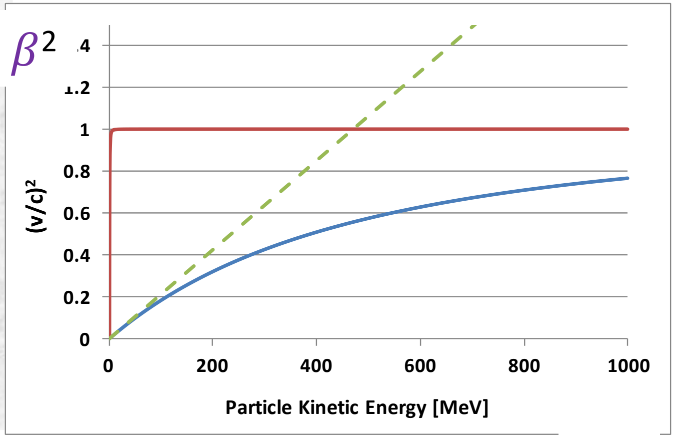




$$\beta = \frac{v}{c}$$



E_{tot}



E_{kin}

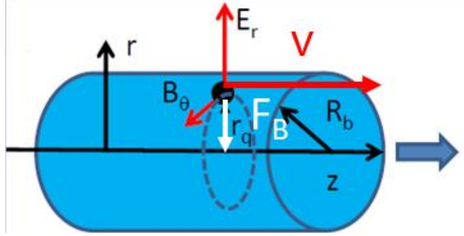
It is much easier to increase the velocity of electrons, with electric fields, than of protons or heavier nuclei, starting from their rest mass: v~c is achieved with a much smaller accelerator

Space charge and transverse beam dynamics

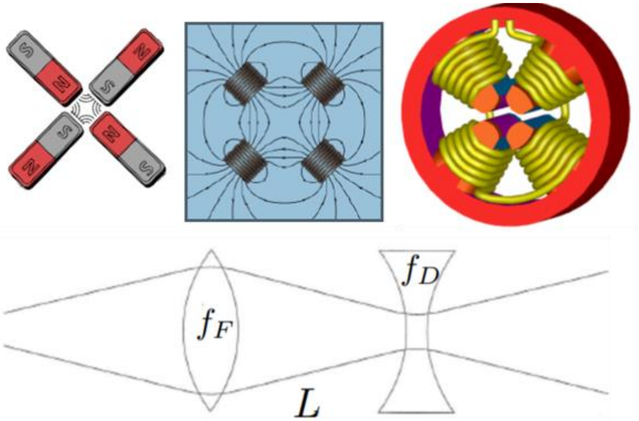
Bunches can contain many particles (~10^{10}).

Coulomb repulsion between particles (space charge) plays an important role at low β, low R_b, high I, high q.

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



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



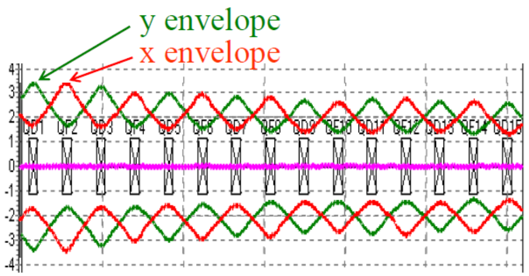
$$\begin{cases} B_x = G\cdot y \\ B_y = G\cdot x \end{cases} \Rightarrow \begin{cases} F_y = qvG\cdot y \\ F_x = -qvG\cdot x \end{cases}$$

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

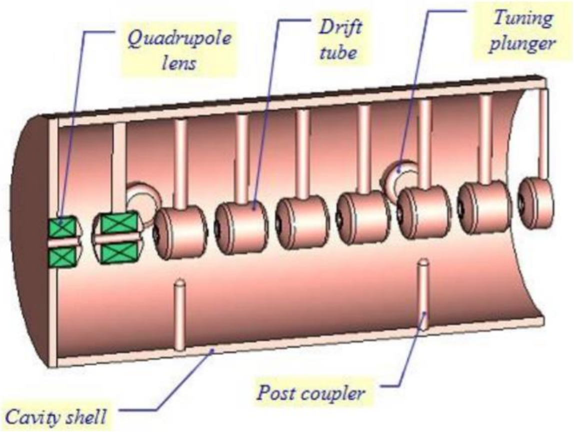
A sequence of EM lenses keep the beam together (L<f)

Unless kept together by a sequence of EM lenses, the beam would disperse transversally.

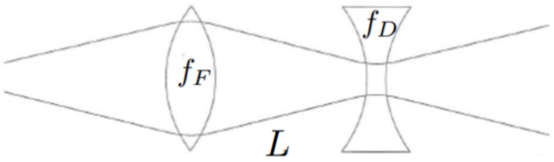
NOTABENE: At high velocities, γ^2 dominates and F_{sc} tends to vanish (=perfect equilibrium between Coulomb repulsion and magnetic attraction).

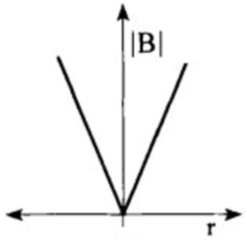


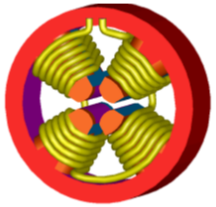
sequence of focusing and defocusing quadrupoles



Transverse beam dynamics 1







$B_y = K \cdot x \qquad B_x = K \cdot y$

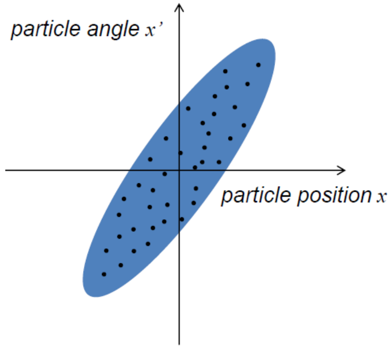
For each transverse direction (x and y), a sequence of lenses with L<f ensures control of the transverse beam size.

Playing with the Lorenz force:

General equation of motion (Hill's equation)

$$x''(s) + K(s)x(s) = 0$$

$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\psi(s) + \phi)$$



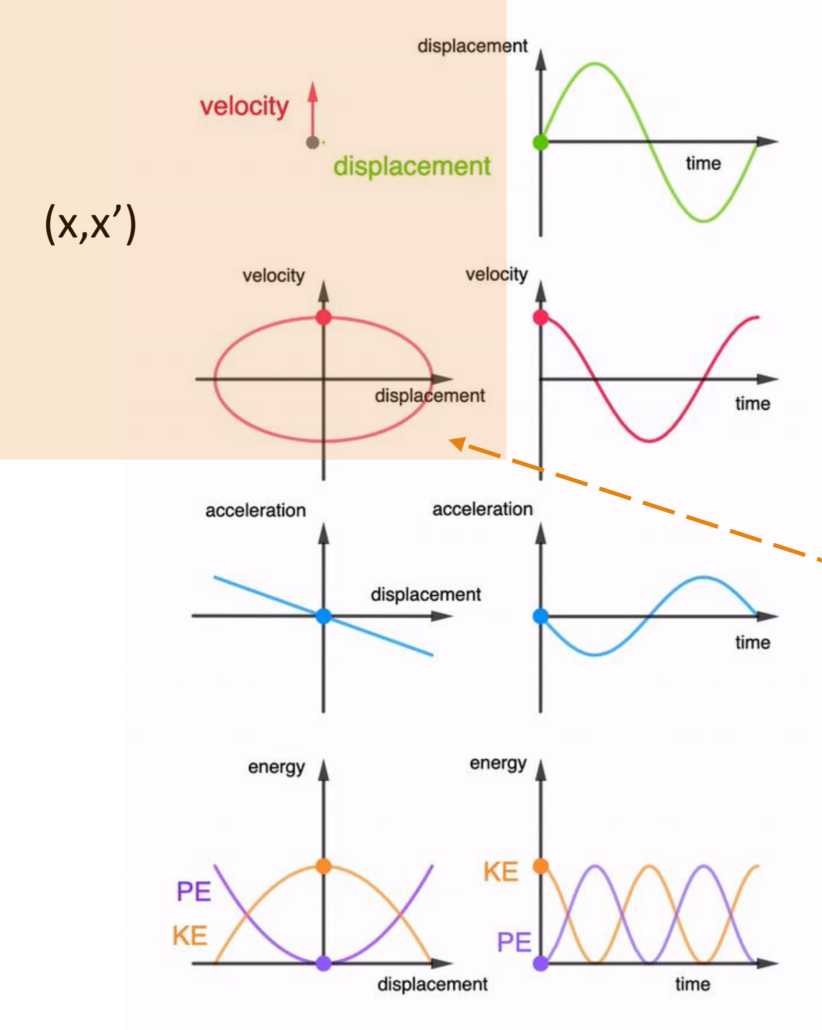
Along the linac (or a sychrotron...) particles are confined in an elliptical area in the (x,x') space, $x' = \frac{dx}{ds}$ being v_x along the direction of motion ($\bar{s}$ or $\bar{z}$)

Not too awkward... This looks VERY similar to a **harmonic oscillator**, like a spring, where k is K(s) – i.e. changes along the linac.

$$\bar{F} = -k\bar{x} \qquad m\ddot{x} + \mathrm{kx} = 0$$

"system that, when displaced from its equilibrium position, experiences a restoring force F proportional to the displacement"

Transverse beam dynamics 2

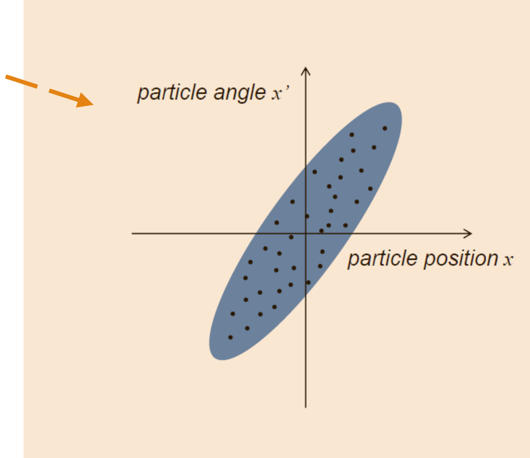


If k is constant, the system undergoes sinusoidal oscillations about the equilibrium point, with a constant amplitude and a constant frequency (which does not depend on the amplitude).

General equation of motion (Hill’s equation)

$$x''(s) + K(s)x(s) = 0$$

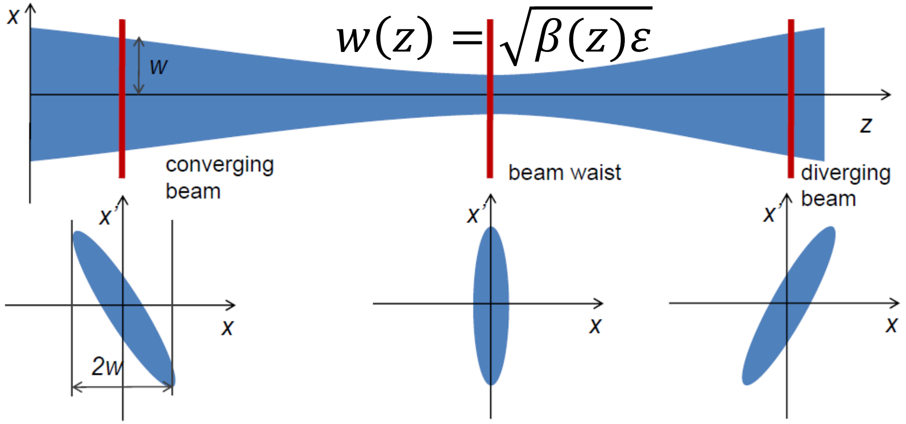
$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\psi(s) + \phi)$$



In our case K(s) varies along the linac, and so does the shape of the ellipse.

It is the way in which nature grants stable equilibrium around a reference position. This applies also to particle accelerators, in the three phase spaces of particle trajectories.

Transverse beam dynamics 3

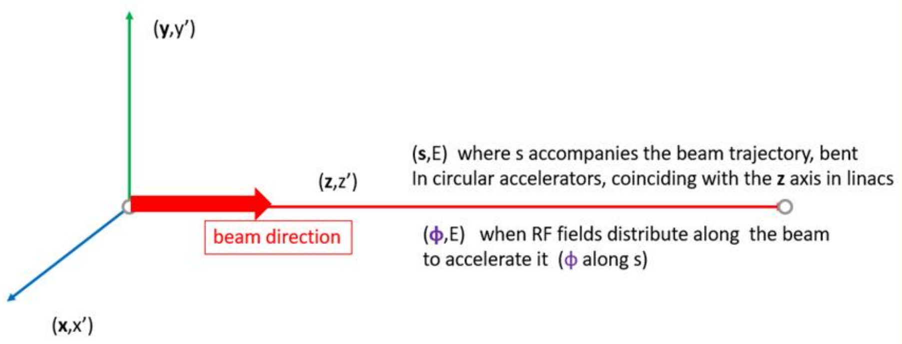


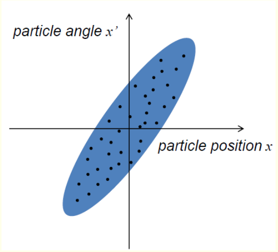
As K varies along the beam line (K(s) ... or K(z)), so does the amplitude of the **beam envelope 2*w(z), comprising all particles**, and also the ellipse «rotates» along s (or z).

In $w(z) = \sqrt{\beta(z)\varepsilon}$, β(z) depends on the accelerator design. ε, (**beam emittance**) is a measure of the ellipse area. $\varepsilon_N = \beta\gamma\varepsilon$ (normalized emittance) is constant during acceleration. Indeed it may increase along the linac.

To start at the source with a small ε is essential for the linac design, e.g. for efficient injection into a synchrotron.

The same applies to (y,y′)

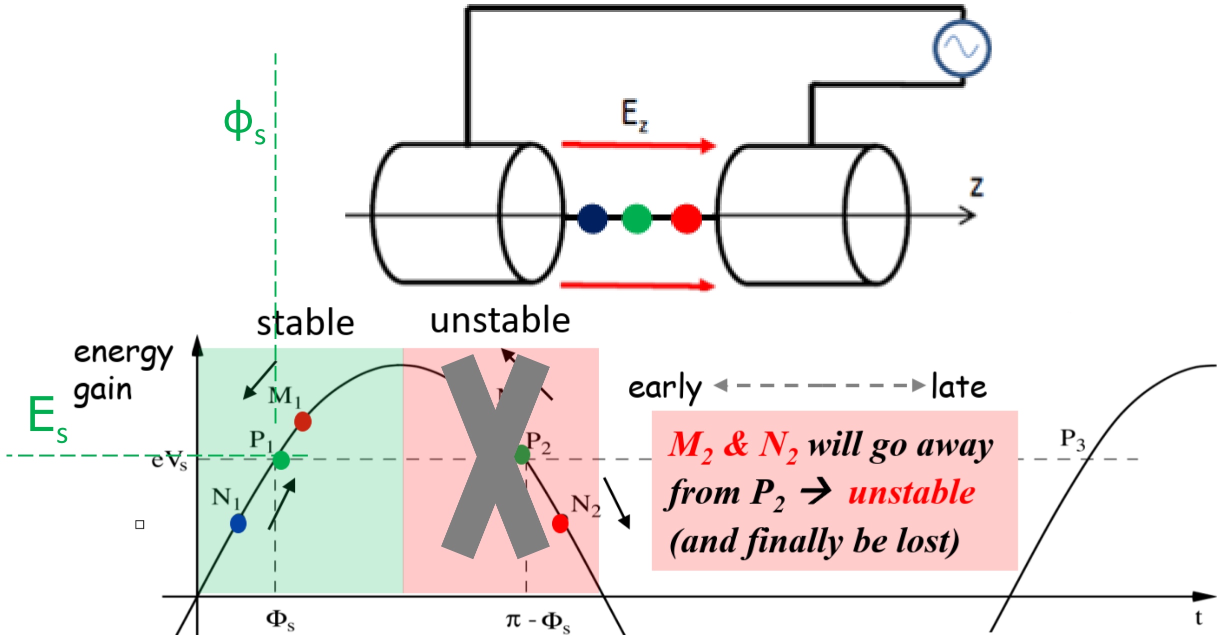




"It is the way in which nature grants stable equilibrium around a reference position. This applies also to particle accelerators, **in the three phase spaces** of particle trajectories."

A harmonic motion is found also in the (z,z′) or (φ,E) phase space

Longitudinal beam dynamics 1



- Ideal particle
- Particle with $\Delta t < 0$ (early) →lower energy gain → gets slower
- Particle with $\Delta t > 0$ (late) →higher energy gain → gets faster

→ *M_1 & N_1 will move towards P_1 → stable*

We already anticipated the **stability** in the (z,z′) or (φ,E) phase space.

In formulas (just a tiny bit) ...

We play with the variables $\varphi=\phi-\phi_s$, $w=E-E_s$ relating a generic particle wit the "s" (synchronous) particle (= center of the bunch).

From $\Delta\phi_s=\omega_{RF}\Delta t_s$, $\Delta\phi=\omega_{RF}\Delta t$ and $\Delta\phi = \Delta\phi - \Delta\phi_s$ we get:

$$\frac{\Delta\varphi}{\Delta L} = \frac{d\varphi}{dz} = \omega_{RF}\left(\frac{\Delta t}{\Delta L} - \frac{\Delta t_s}{\Delta L}\right) = \cdots = -\frac{\omega_{RF}}{cE_0\beta_s^3\gamma_s^3}w$$

Similarly with $w=E-E_s$.

\- -

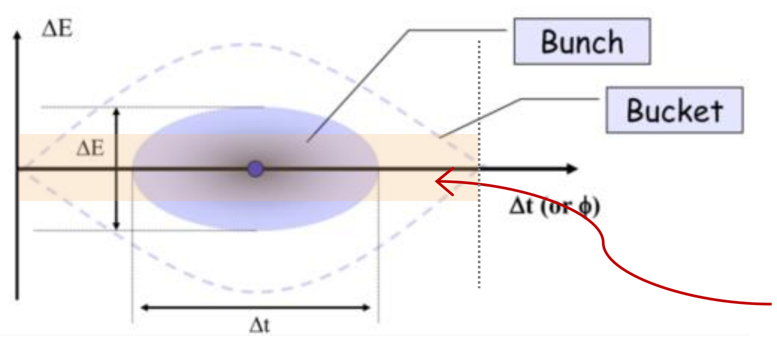
A relation is established between the canonically conjugate variables φ and w, leading to

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

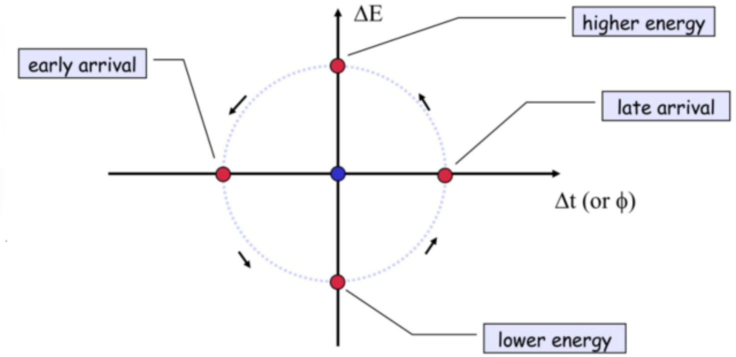
which is again the **equation of a harmonic oscillator**.

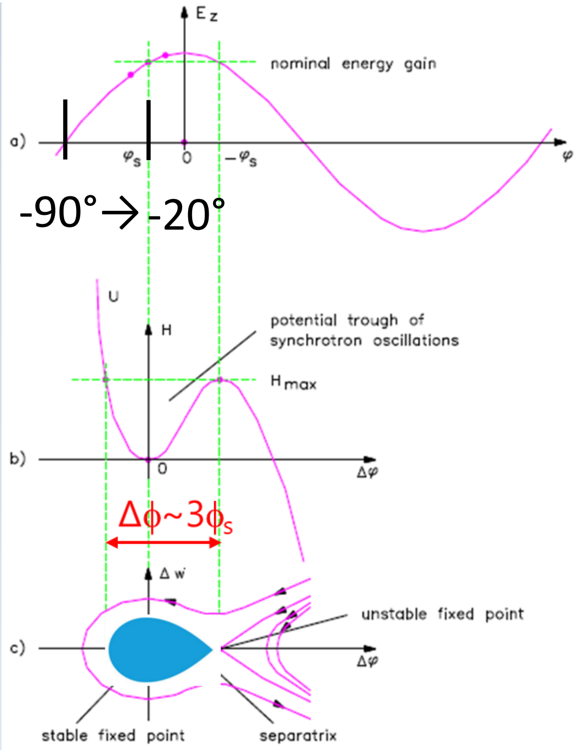
in (x,x′) $\quad (\bar{F} = -k\bar{x}; \quad m\ddot{x} + kx = 0)$

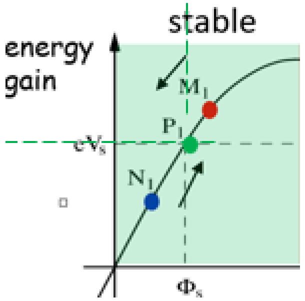
Longitudinal beam dynamics 2



initially continuous beam







$$\omega_l^{\ 2} = \omega_0^{\ 2}\,\frac{qE_0T\sin(-\varphi)\lambda}{2\pi\, mc^2\,\beta\gamma^3}$$

frequency of small oscillations around the center: at high β,γ oscillation stops...

By **switching on a RF field** on a continuous beam, we introduce a **potential well** (in the «bucket»), and a **harmonic motion** also in the phase space **(φ,E)** (it does not apply to a continuous beam !)

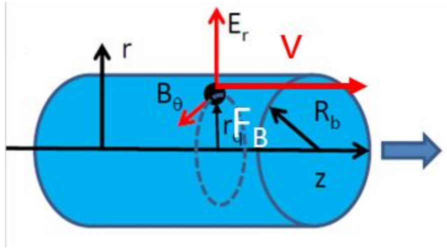
Moving φ_s then from **-90° towards -20°** (not to 0°!) we give **net acceleration** to the whole «stable» bunch. Choice of φ_s : the stability area shrinks towards 0° (fewer particles inside) but the energy gain is larger.

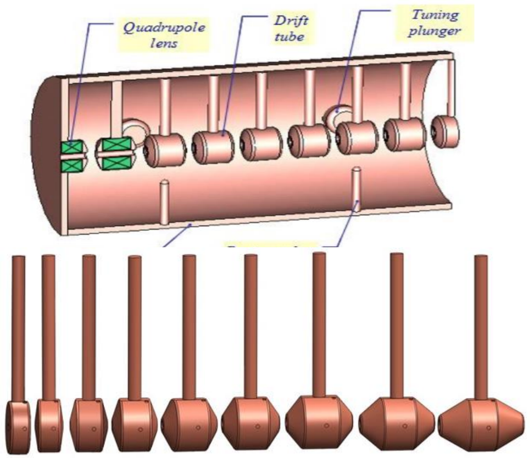
How to handle space charge right after the ion source? β is VERY low...

Problem: beam dynamics is very tough to solve at low ion velocities …

1. We noted already that Coulomb repulsion is highest at low velocities (low β), and small R_{beam}, high I_{beam} and q.

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

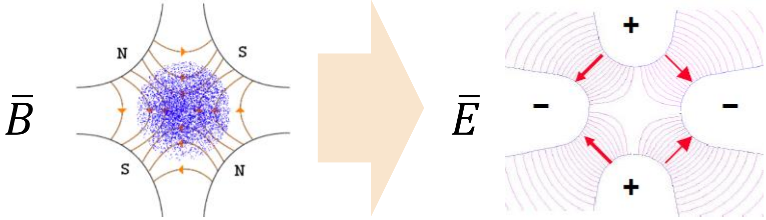




2. At low velocity, in DTL drift tubes ($L \propto \beta\lambda$) are too short to host a focusing magnet.

3. From $F = q(\bar{E} + \bar{v}x\bar{B})$: B is less effective at small v.

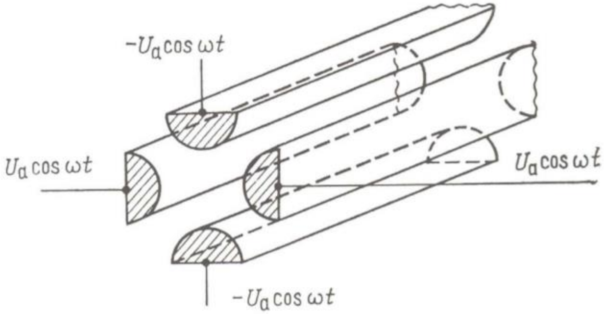
Solution: use electrostatic rather than magnetostatic quadrupoles!



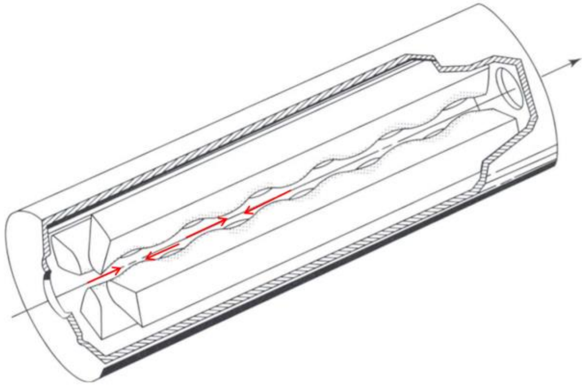
Fine, to keep just a low velocity beam focused, but indeed … we want to accelerate!

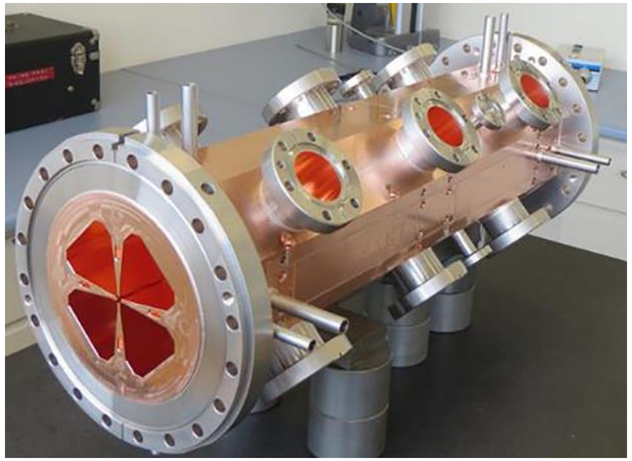
How to handle space charge right after the ion source? With an RFQ!

Idea: use a long electrical quadrupole channel in a RF cavity (**polarity alternates with RF as the beam goes along the axis**, as if in a sequence of short F and D quads) – Transverse beam dynamics



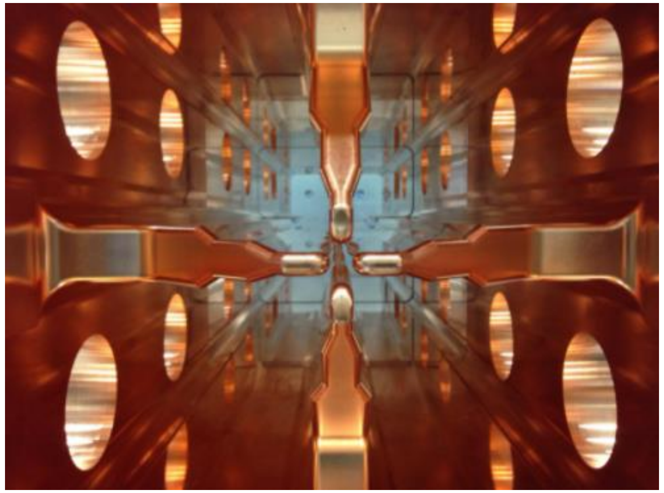
Then, **apply a deformation on the q-pole horizontal and vertical vanes, alternating hills and valleys**, generating a small but crucial field along the axis in «gaps» of increasing length ($\beta\lambda$) following the increase of v_{beam}! – Longitudinal b.d.

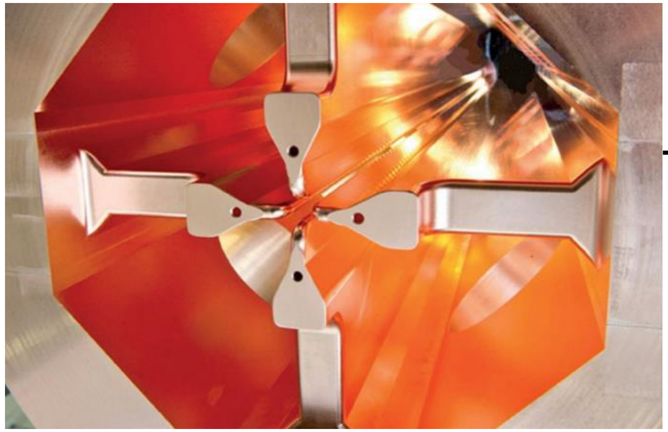




You have made an RFQ! At the end v has increase enough that F_{SC} is much less a problem.

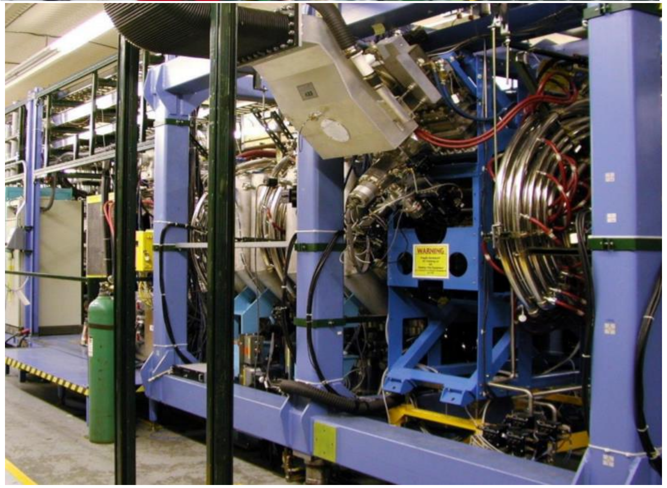
RFQs are indeed not so simple…





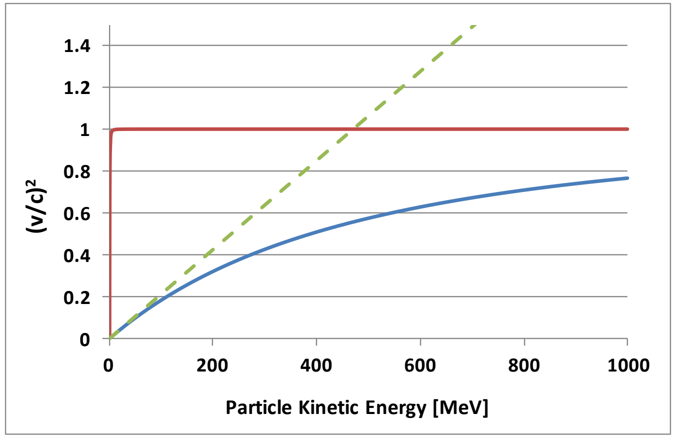
Before accelerating (while keeping focused) the beam, RFQ electrodes are designed for gradually increased transverse focusing of the beam coming from the source, then to provide very gradual bunching: in both the transverse (x,x') (y,y') planes and in the longitudinal plane (φ,E) the beam is treated very gently. The emittance of the source (~ density of particles) is very well preserved and delivered for further acceleration.

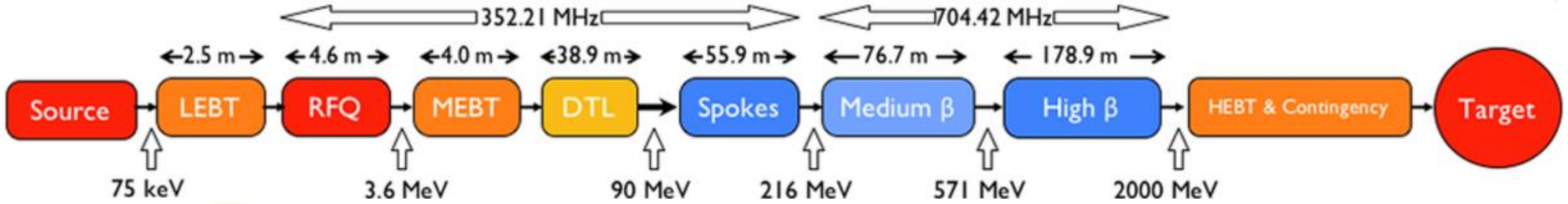
They can be **compact** (high frequency), small energy (1 MeV), small duty cycle (0.1%) and average RF power, as well as **massive** (7 MeV, 100% duty cycle). Hidden behind equipment!



Credits to Kapchinsky and Tepliakov (former USSR).

Now you have your linac…





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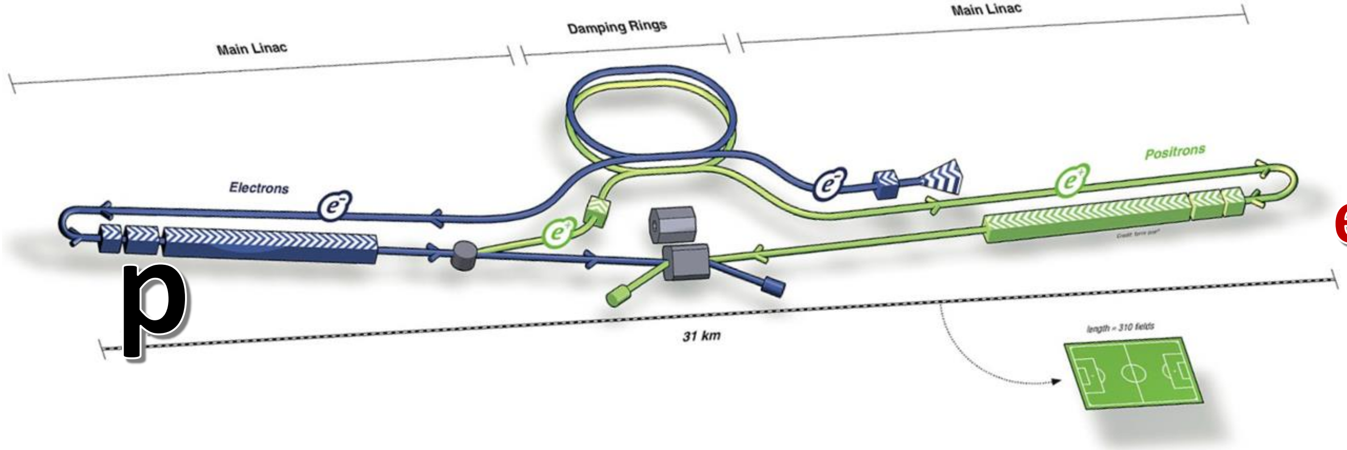

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e

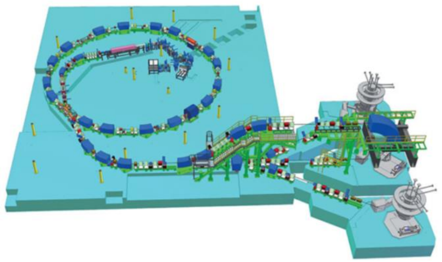
Proton/ion linac: v=c is approached only at some GeV (very few exist): **design will be adapted to the increase in particle velocity** - **sections of different type** (ion source, RFQ, DTL, …).

Electron linac: v=c is approached after few MeV of energy (in ~1m of acceleration) → then, **identical accelerating structures** can be adopted for the rest of the accelerator. But to achieve **high energies** for particle physics e- and e+ linear colliders still requires **very long distances**!

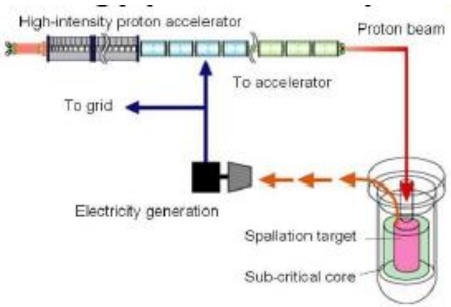
Uses of electron and proton/ion linacs

- Science of nucleus and elementary particles

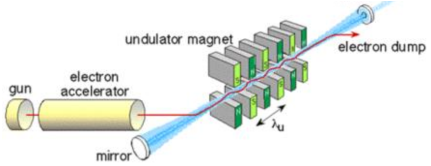
- Injectors for synchrotrons
- Radiotherapy, hadron therapy



- Spallation sources for neutron production (material, energy, health ...)
- Nuclear waste treatment and controlled fission for energy production (ADS)

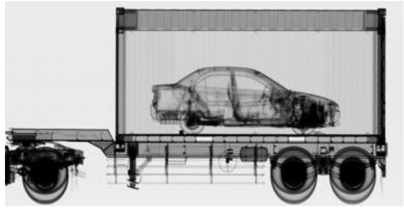


- Free Electron Lasers (x-ray imaging, ...)



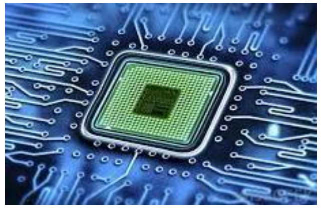
Industrial applications:

- National security (w/ photons, neutrons)



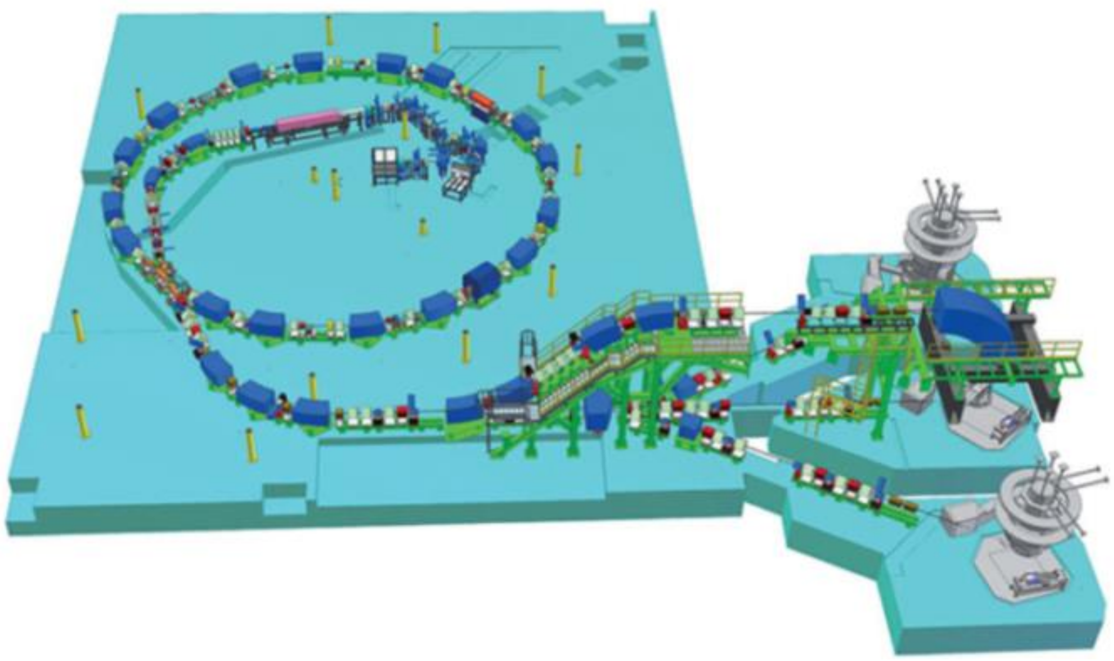
- Material treatment, analysis

- Ion implantation



- Food sterilization

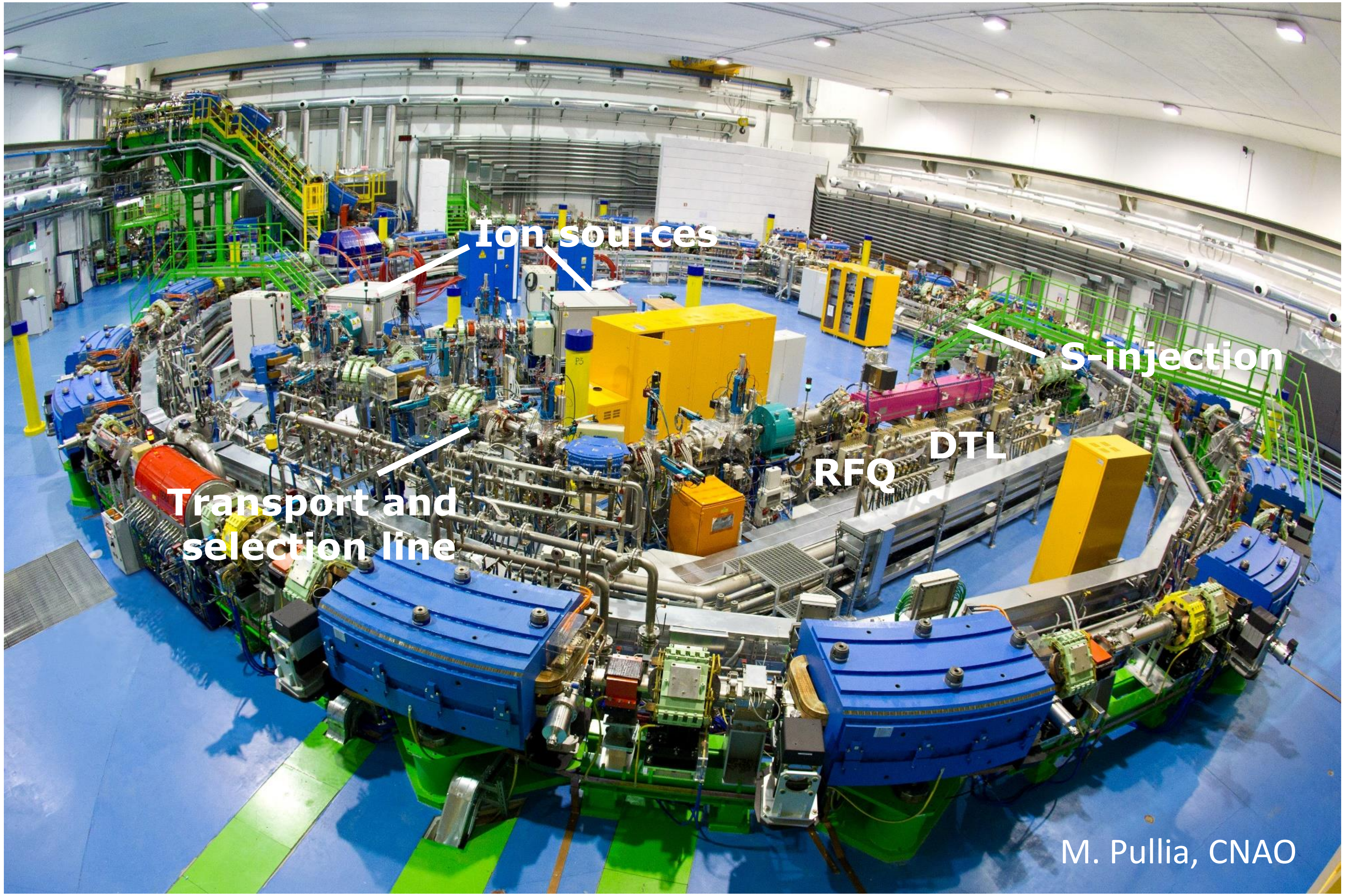
In conclusion...



In the context of this master class, the LINAC is the first section of a chain, eventually delivering a well-focused beam, of desired intensity and size, to be scanned very precisely, at various energies through the patient’s tumor.

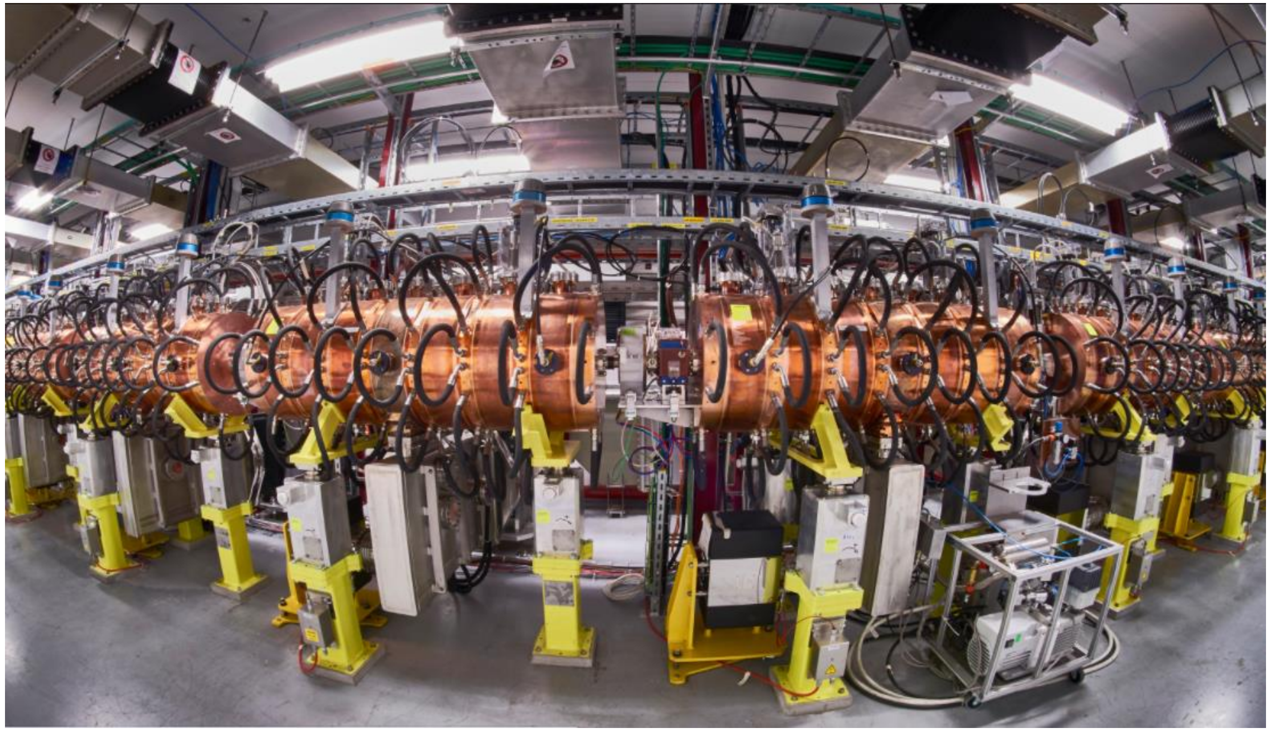
It passes the beam to the synchrotron, into which it has to be «injected» (topic of the next lecture by Elena Benedetto).

For the synchrotron, a linac duty cycle of only 0,1% is needed. It is relatively easy to build linacs for 5-10% duty cycle: we are investigating competitive ways of producing radioactive isotopes for nuclear medicine in the remaining time! (A. Mamaras, Friday at 4.50 pm)



HITRI plus
Heavy Ion Therapy Research Integration

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548



THANKS!

Much material taken from CERN Accelerator Schools and US Particle Accelerator Schools

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