
Introduction to RF Linear Accelerators

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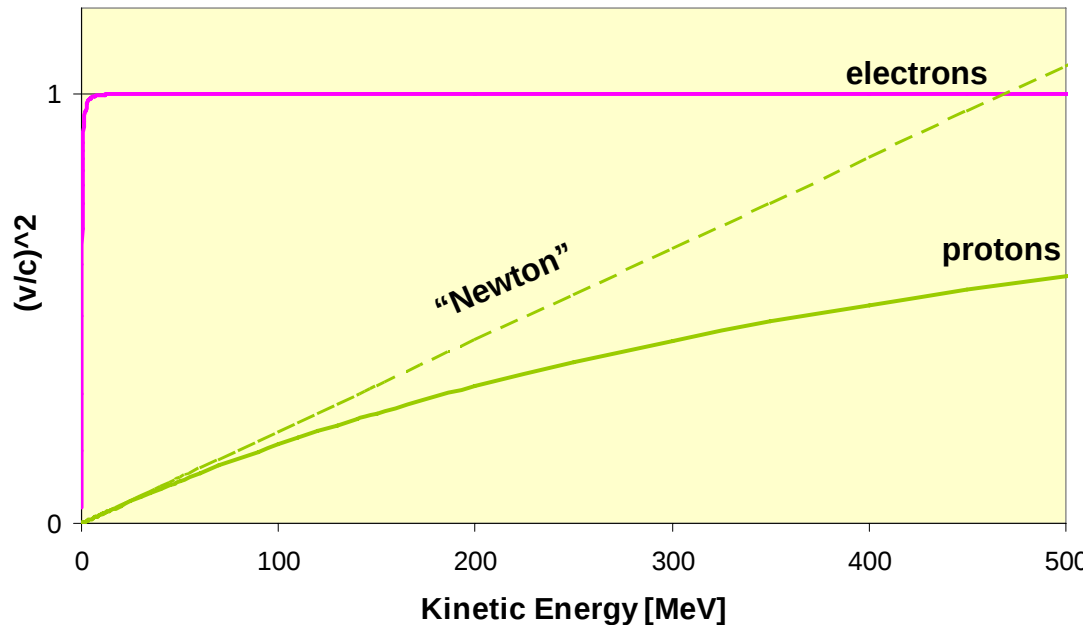
1. Why linear accelerators - basic concepts
2. Periodic Accelerating Structures
3. Overview of linac structures
4. Basics of linac beam dynamics
5. More on periodic structures
6. The RFQ
7. Linac Technology

Linacs are used for:

- Low-Energy accelerators (injectors to synchrotrons or stand-alone)
- Production of High-intensity proton beams
- High energy lepton colliders

For protons and ions, linear accelerators are required to be synchronous with the RF fields in the region where velocity increases with energy. As soon as velocity is $\sim$ constant, synchrotrons are more efficient (multi-pass instead of single pass). However, in comparison with synchrotrons linacs can go to higher repetition rate, are less affected by resonances and have losses more distributed $\rightarrow$ linacs are more suitable for high intensity beams (where they are in competition with cyclotrons).

For electrons, main advantage is the absence of synchrotron radiation (but there is no synchrotron radiation damping).



$\beta^2 = (v/c)^2$ as function of kinetic energy T for protons and electrons.

Relativistic (Einstein) relation:

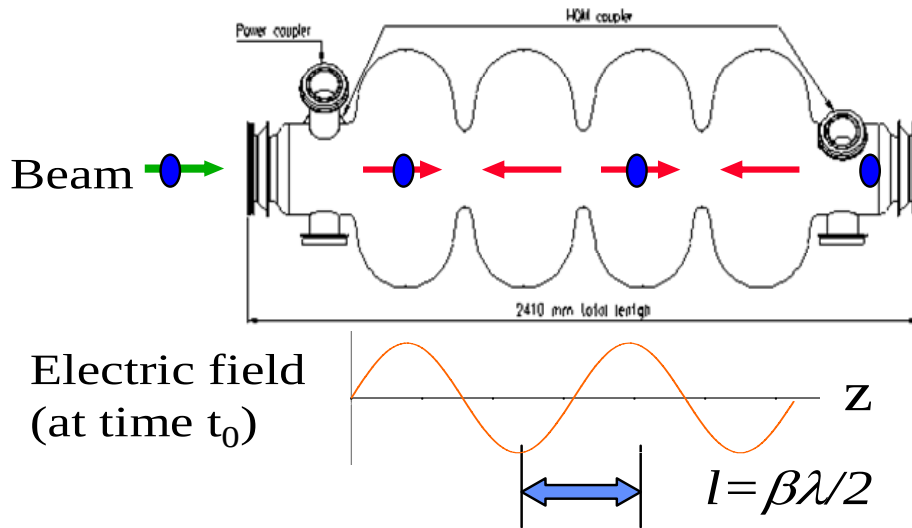
$$T = m_0 c^2 \left(\frac{1}{\sqrt{1 - v^2/c^2}} - 1 \right) = m_0 c^2 (\gamma - 1)$$

Classic (Newton) relation:

$$T = m_0 \frac{v^2}{2} = m_0 c^2 \left(\frac{1}{2} \frac{v^2}{c^2} \right)$$

- Protons (rest energy 938.3 MeV): follow "Newton" mechanics up to some **tens of MeV** ($\Delta v/v < 1\%$ for $W < 15$ MeV) then slowly become relativistic, and from the **GeV range** velocity is nearly constant ($v \sim 0.95c$ at 2 GeV) → linacs can cope with the increasing particle velocity, synchrotrons are more efficient for v nearly constant.
- Electrons (rest energy 511 keV, 1/1836 of protons): relativistic from the **keV range** ($v \sim 0.1c$ at 2.5 keV) then increasing velocity up to the **MeV range** ($v \sim 0.95c$ at 1.1 MeV) → $v \sim c$ after few meters of acceleration in a linac (typical gradient 10 MeV/m).

Remember the synchronism condition: for multigap acceleration, cell length is proportional to particle velocity



Example: a linac superconducting 4-cell accelerating structure

Synchronism condition:

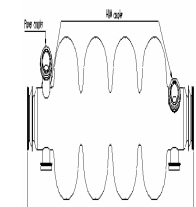
t (travel between centers of cells) = $T/2$

$$\frac{l}{\beta c} = \frac{1}{2f} \quad l = \frac{\beta c}{2f} = \frac{\beta\lambda}{2}$$

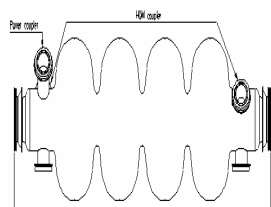
Conclusion:

1. For electron linacs, $\beta=1$, $l=\lambda/2 \rightarrow$ An electron linac will be made of an **injector** + a **series of identical accelerating structures**, with cells all the same length
2. In an ion linac cell length has to increase (up to a factor 200 !) and the linac will be made of a **sequence of different accelerating structures** (changing frequency, operating mode, etc.) matched to the ion velocity.

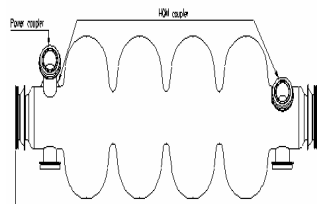
The same Superconducting cavity design can be used for different proton beta's, just changing the cell length accordingly to beta.



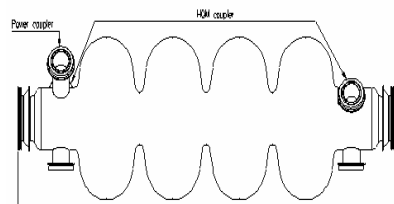
$$\beta=0.52$$



$$\beta=0.7$$

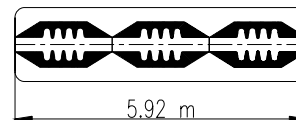


$$\beta=0.8$$

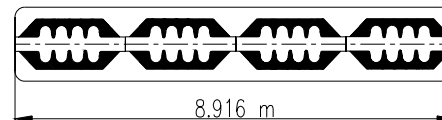


$$\beta=1$$

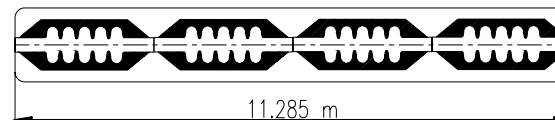
A). $\beta=0.52$



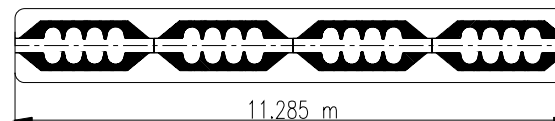
B). $\beta=0.7$



C). $\beta=0.8$, LEP cryostat

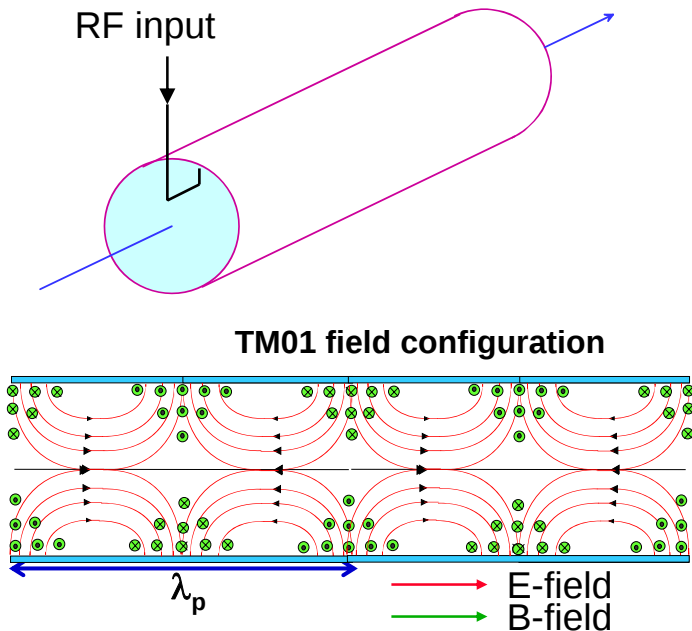


D). $\beta=1$, LEP cryostat

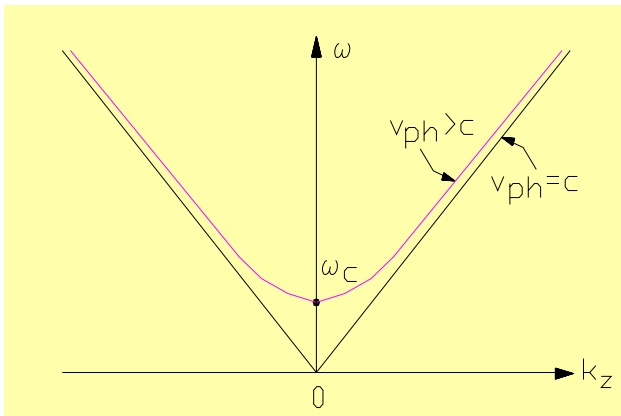


2 - Periodic Accelerating Structures

Wave propagation in a cylindrical pipe



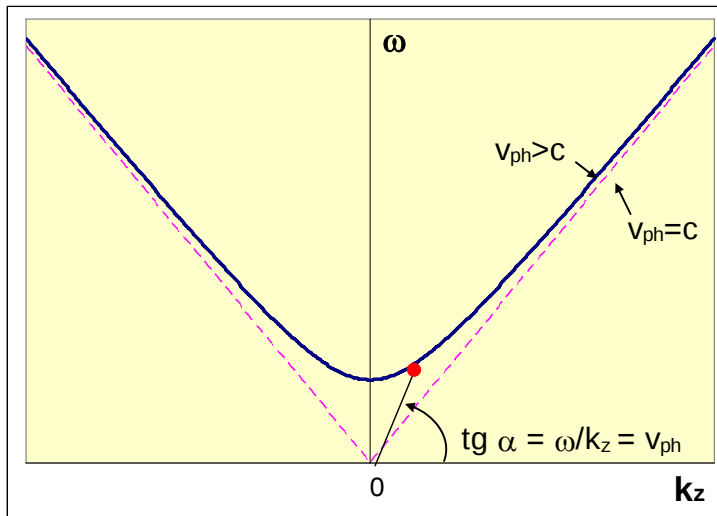
- In a cylindrical waveguide different **modes** can propagate (=Electromagnetic field configurations, transmitting power and/or information). The field is the superposition of waves reflected by the metallic walls of the pipe → velocity and wavelength of the modes will be different from free space (c , λ)
- To accelerate particles, we need a mode with longitudinal E-field component on axis: a TM mode (Transverse Magnetic, $B_z=0$). The simplest is TM01.
- We enter RF power at a frequency exciting the TM01 mode: E-field periodic on axis, wavelength λ_p depends on frequency and on cylinder radius. Wave velocity (called "phase velocity") is $v_{ph} = \lambda_p / T = \lambda_p f = \omega / k$ with $k = 2\pi / \lambda_p$
- The relation between frequency ω and propagation constant k is the **DISPERSION RELATION** (red curve on plot), a fundamental property of waveguides.



The relation $\omega(k)$ can be calculated from the standard theory of waveguides:

$$\omega^2 = k^2 c^2 + \omega_c^2$$

Plotting this curve (hyperbola), we see that:

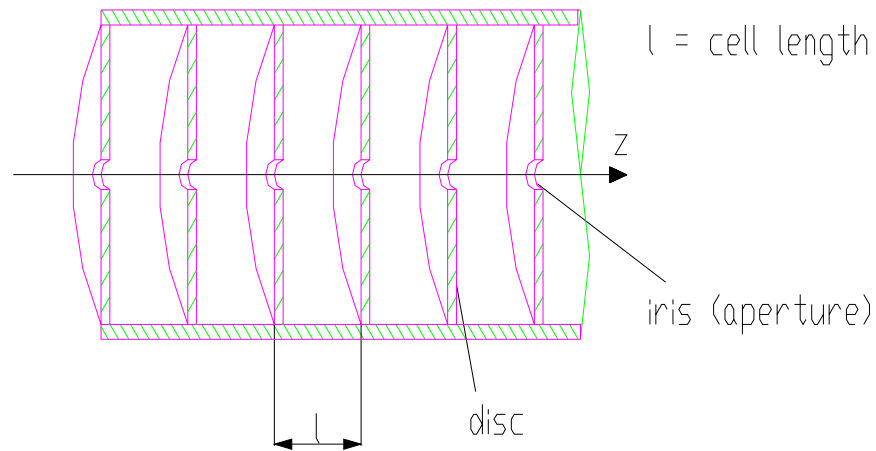


$$k = 2\pi/\lambda_p$$

$$v_{ph} = \omega/k = (c^2 + \omega_c^2/k^2)^{1/2}$$

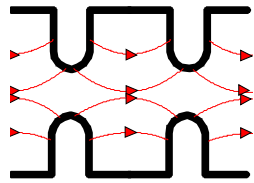
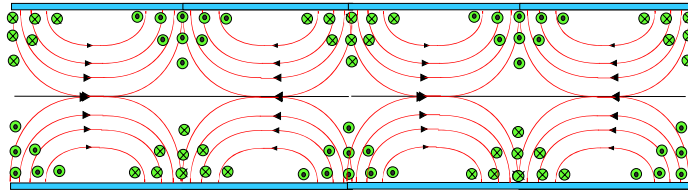
$$v_g = d\omega/dk$$

- 1) There is a "cut-off frequency", below which a wave will not propagate. It depends on dimensions ($\lambda_c = 2.61a$ for the cylindrical waveguide).
- 2) At each excitation frequency is associated a **phase velocity**, the velocity at which a certain phase travels in the waveguide. $v_p = \infty$ at $k=0$, $\omega=\omega_c$ and then decreases towards $v_p=c$ for $k, \omega \rightarrow \infty$.
- 3) Energy (and information) travel at **group velocity** $d\omega/dk$, which is between 0 and c . This velocity has to respect the relativity principle!
- 4) A particle traveling inside our cylinder has to travel at $v = v_{ph}$ to see a constant accelerating E-field $\rightarrow$ should travel at $v > c$!!!
- 5) To use the waveguide to accelerate particles, we need a "trick" to slow down the wave.

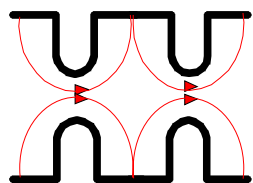


Discs inside the cylindrical waveguide, spaced by a distance ℓ , will induce multiple reflections between the discs.

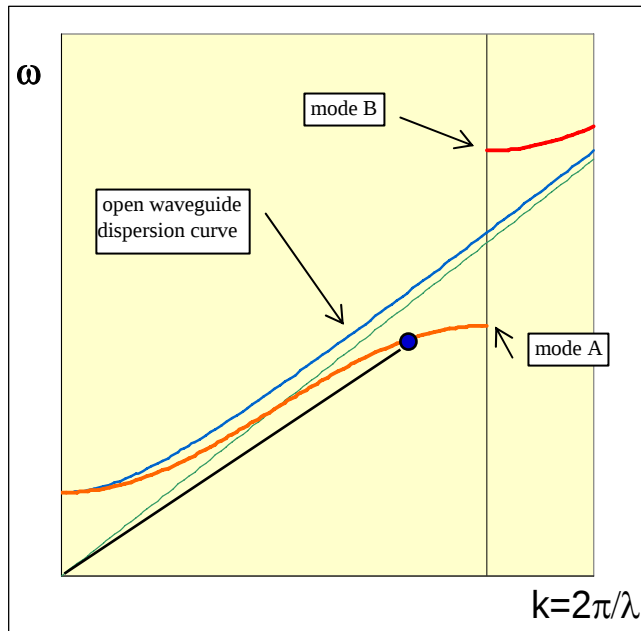
Dispersion relation for the disc-loaded waveguide



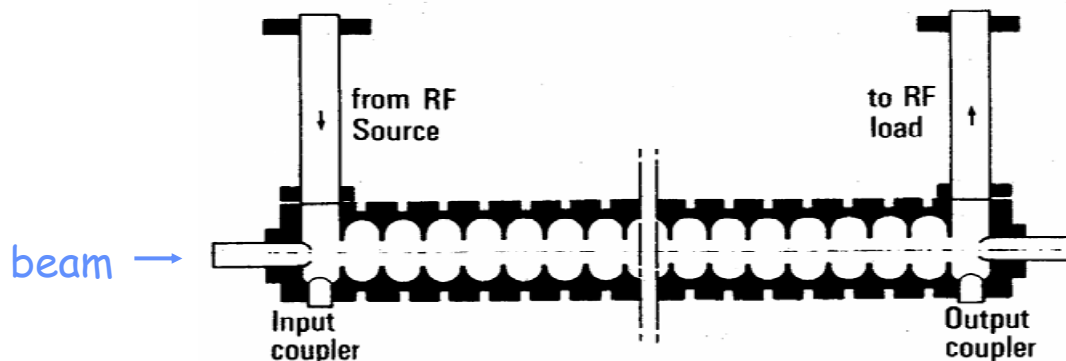
electric field pattern - mode A



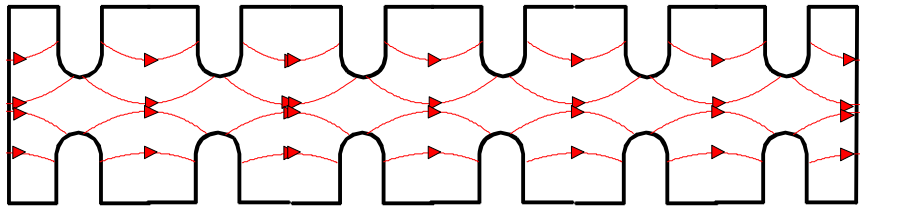
electric field pattern - mode B



- Wavelengths $\lambda_p \sim \ell$ will be most affected by the discs. On the contrary, for $\lambda_p = 0$ and $\lambda_p = \infty$ the wave does not see the discs $\rightarrow$ the dispersion curve remains that of the empty pipe.
- At $\lambda_p = \ell$, the wave will be confined between the discs, and present 2 "polarizations" (mode A and B in the figure), 2 modes with same wavelength but different frequencies $\rightarrow$ the dispersion curve splits into 2 branches, separated by a stop band.
- In the disc-loaded waveguide, the lower branch of the dispersion curve is now "distorted" in such a way that we can find a frequency such that $v_{ph} = c \rightarrow$ we can use it to accelerate a particle beam!
- We have built a linac for $v \sim c \rightarrow$ a **TRAVELING WAVE** (TW) ELECTRON LINAC



- Disc-loaded waveguide designed for $v_{ph}=c$ at a given frequency, equipped with an input and an output coupler.
- RF power is introduced via the input coupler. Part of RF power is dissipated in the structure, part is taken by the beam (beam loading) and the rest is absorbed in a matched load at the end of the structure. Usually, structure length is such that $\sim 30\%$ of power goes to the load.
- The “traveling wave” structure is the standard linac for electrons from $\beta \sim 1$.
- Can not be used for ions at $v < c$:
 1. constant cell length does not allow synchronism
 2. efficiency requires long structures, with little space for transverse focusing

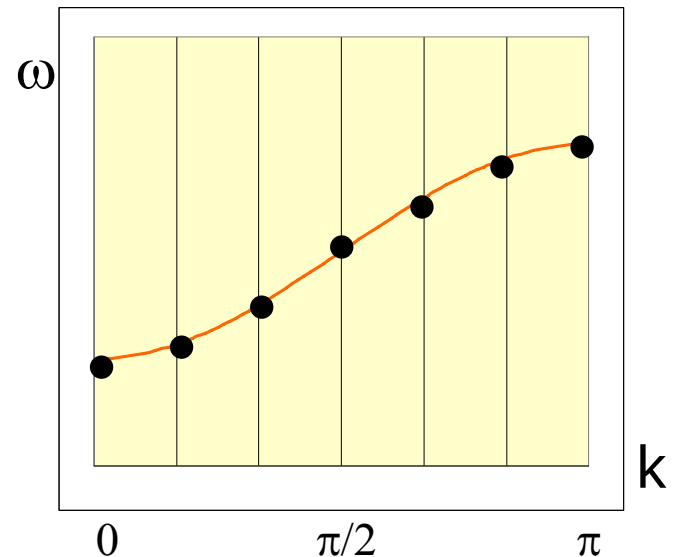


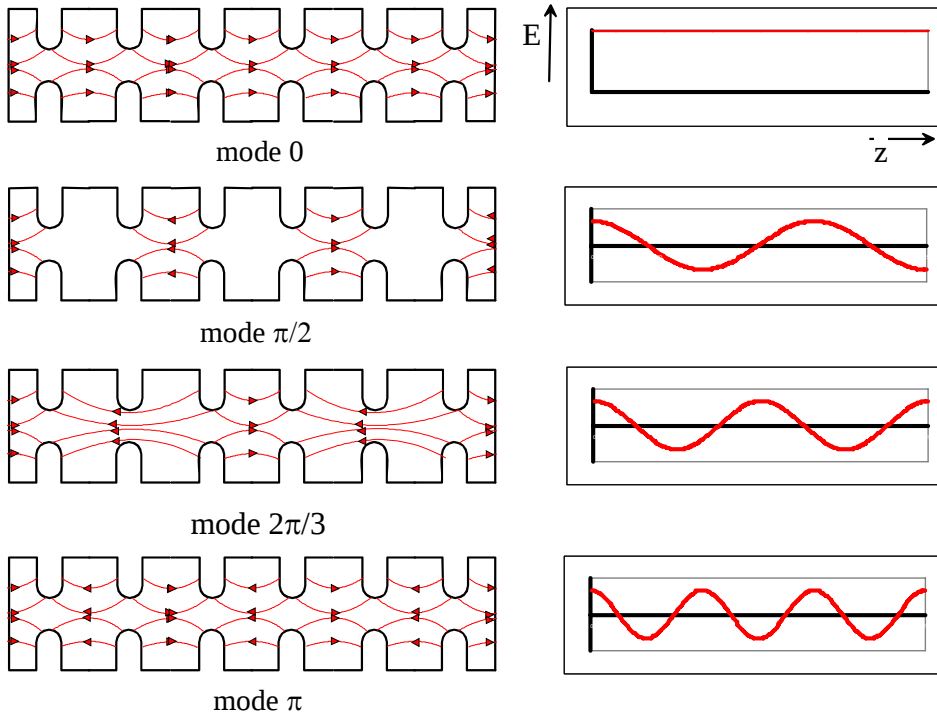
To obtain an accelerating structure for ions we close our disc-loaded structure at both ends with metallic walls $\rightarrow$ multiple reflections of the waves.

Boundary condition at both ends is that electric field must be perpendicular to the cover $\rightarrow$ Only **some modes on the disc-loaded dispersion curve** are allowed $\rightarrow$ only some frequencies on the dispersion curve are permitted.

In general:

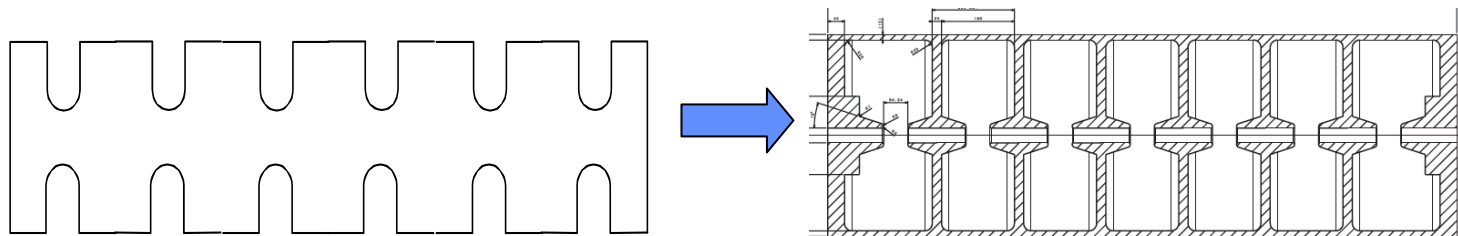
1. the modes allowed will be equally spaced in k
2. The number of modes will be identical to the number of cells (N cells $\rightarrow N$ modes)
3. The k represents the phase difference between the field in adjacent cells.





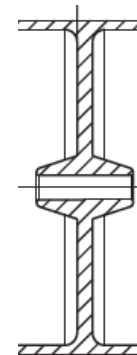
Standing wave modes are named from the phase difference between adjacent cells: in the example above, mode 0, $\pi/2$, $2\pi/3$, π .

- These **STANDING WAVE MODES** are generated by the sum of 2 traveling waves in opposite directions, adding always in the same way in the different cells.
- For acceleration, the particles must be in phase with the E-field on axis. We have already seen the π mode: synchronism condition for cell length $\ell = \beta\lambda/2$.
- Standing wave structures can be used for **any β** (→ ions and electrons) and can follow the **increase in β** of the ions.

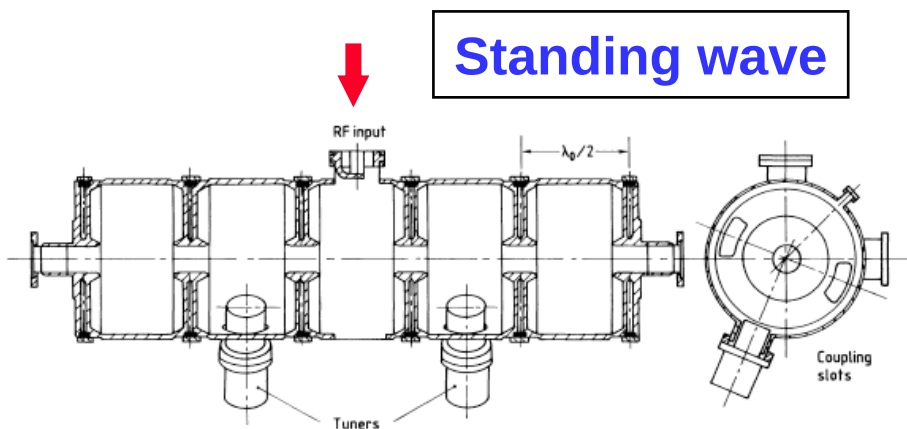


From **disc-loaded structure** to a **real cavity** (Linac4 PIMS, Pi-Mode Structure)

1. To increase acceleration efficiency (=shunt impedance ZT^2 !) we need to concentrate electric field on axis ($Z \uparrow$) and to shorten the gap ($T \uparrow$) → introduction of "noses" on the openings.
2. The smaller opening would not allow the wave to propagate → introduction of "coupling slots" between cells.
3. The RF wave has to be coupled into the cavity from one point, usually in the center.



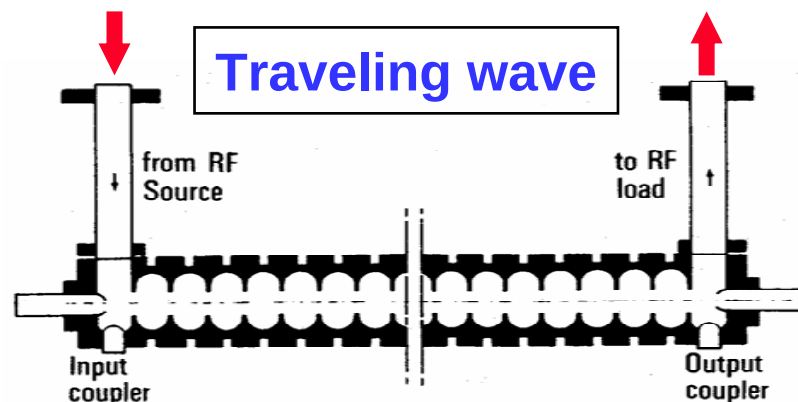
Comparing traveling and standing wave structures



Standing wave

Chain of coupled cells in SW mode.
Coupling (bw. cells) by slots (or open). On-axis aperture reduced, higher E-field on axis and power efficiency.
RF power from a coupling port, dissipated in the structure (ohmic loss on walls).
Long pulses. Gradients 2-5 MeV/m

Used for Ions and electrons at all energies



Traveling wave

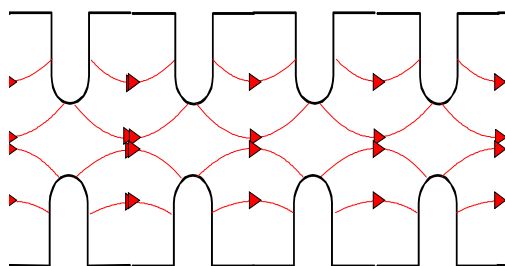
Chain of coupled cells in TW mode
Coupling bw. cells from on-axis aperture.
RF power from input coupler at one end, dissipated in the structure and on a load.
Short pulses, High frequency.
Gradients 10-20 MeV/m

Used for Electrons at $v \sim c$

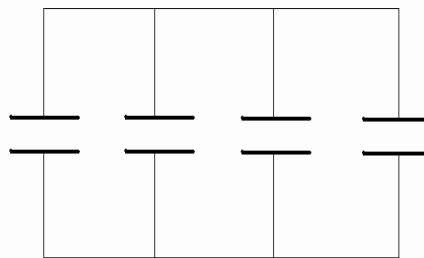
Comparable RF efficiencies

3 - Examples of linac accelerating structures

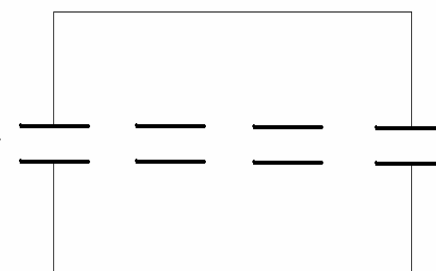
The Drift Tube Linac (Alvarez)



Disc-loaded structures operating in 0-mode



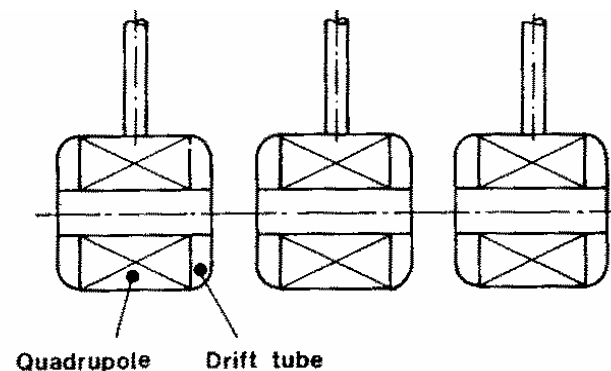
Add tubes for high shunt impedance

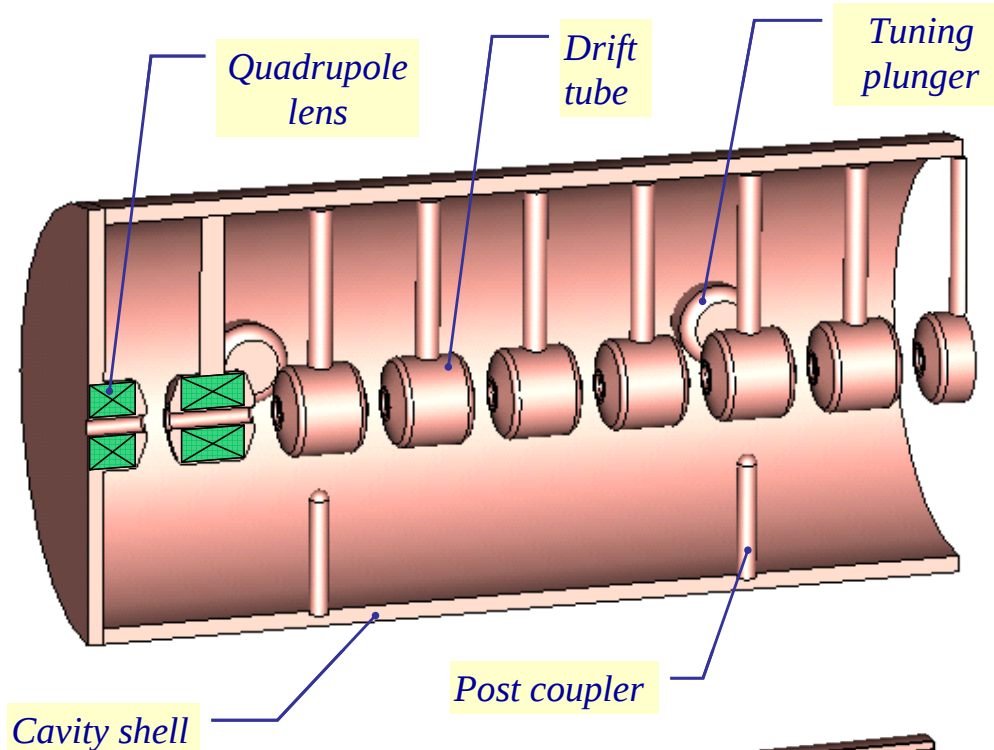


Add maximum coupling between cells → remove completely the walls

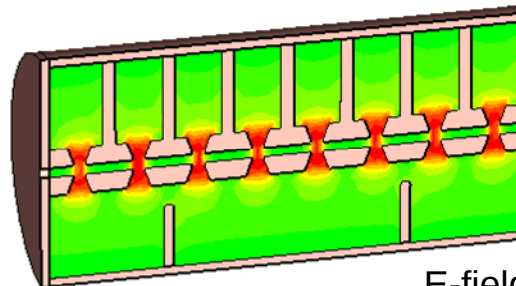
2 advantages of the 0-mode:

1. the fields are such that if we eliminate the walls between cells the fields are not affected, but we have less RF currents and higher shunt impedance.
2. The tubes can be long, the particles are inside the tubes when the electric field is decelerating, and we have space to introduce focusing elements (quadrupoles) inside the tubes.

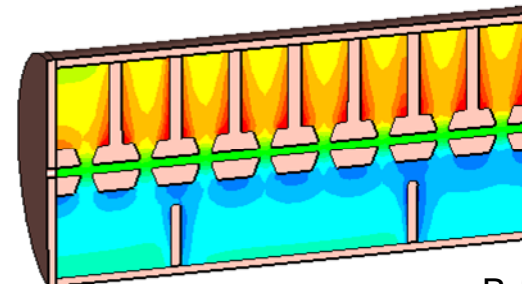




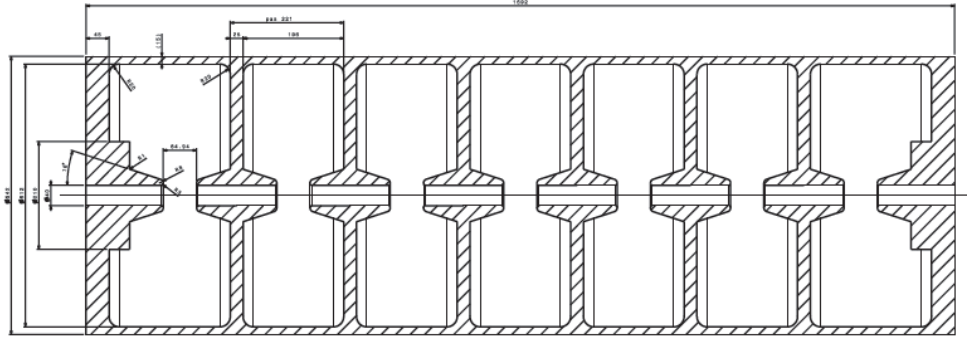
Standing wave linac structure for protons and ions,
 $\beta=0.1-0.5$, $f=20-400$ MHz
Chain of coupled cells, completely open (no walls), maximum coupling.
Operating in 0-mode, cell length $\beta\lambda$.
Drift tubes are suspended by stems (no net current)
Drift tubes contain focusing quadrupoles.



E-field

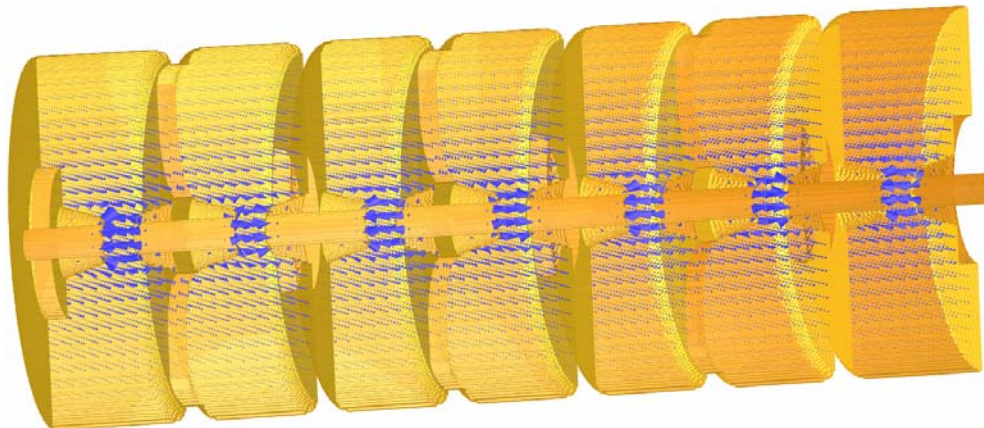


B-field

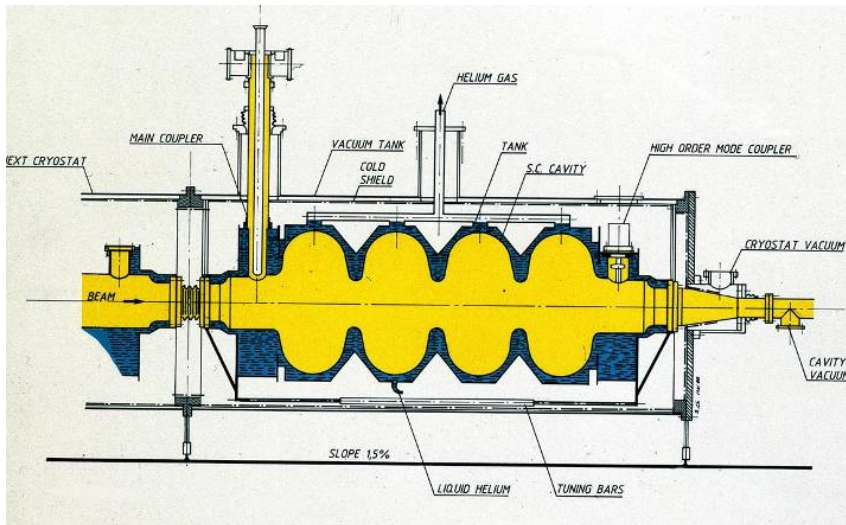


7-cell pi-mode cavity, 352 MHz

PIMS=PI Mode Structure
Standing wave linac structure
for protons, $\beta > 0.4$
Chain of coupled cells with
coupling slots in walls.
Operating in π -mode, cell
length $\beta\lambda/2$.



Multi-gap Superconducting Cavities (elliptical)



Widely used for proton linacs (SNS, etc.) and electron linacs (TESLA, etc.)

Standing wave structures for particles at $\beta > 0.5 - 0.7$, widely used for protons (SNS, etc.) and electrons (TESLA, etc.)
 $f = 350 - 700$ MHz (protons),
 $f = 350$ MHz - 3 GHz (electrons)

Chain of cells electrically coupled, large apertures (ZT^2 not a concern).

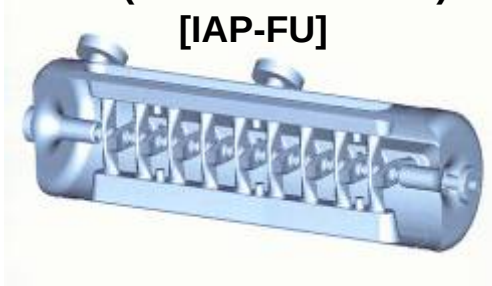
Operating in π -mode, cell length $\beta\lambda/2$
 Input coupler placed in one of the "cut-off" tubes.



Spoke (low beta)
[FZJ, Orsay]



CH (low/medium beta)
[IAP-FU]



QWR (low beta)
[LNL, etc.]



HWR (low beta)
[FZJ, LNL, Orsay]

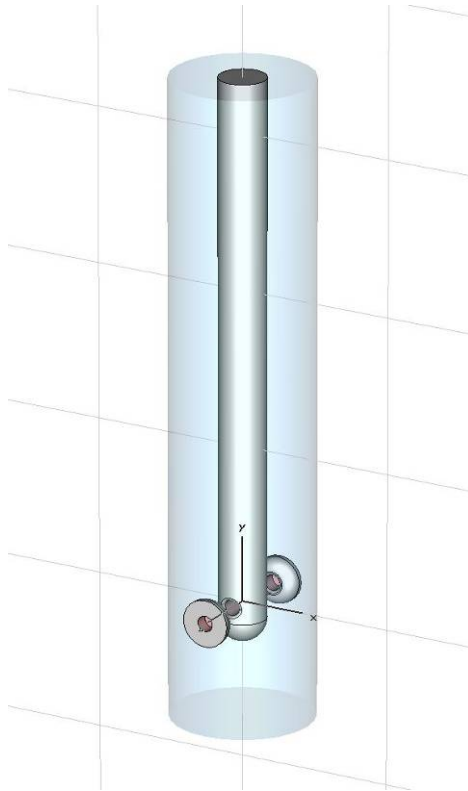


Re-entrant
[LNL]



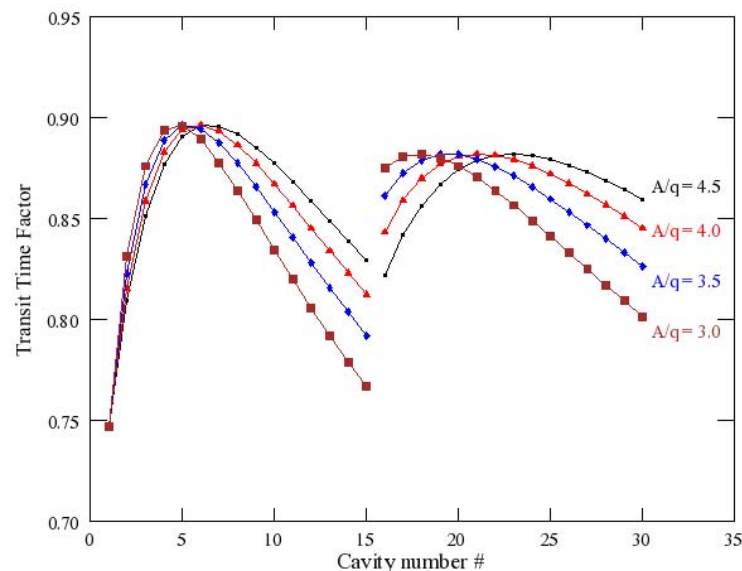
Superconducting linacs for low and medium beta ions are made of multi-gap (1 to 4) individual cavities, spaced by focusing elements. Advantages: can be individually phased → linac can accept different ions
Allow more space for focusing → ideal for low β CW proton linacs

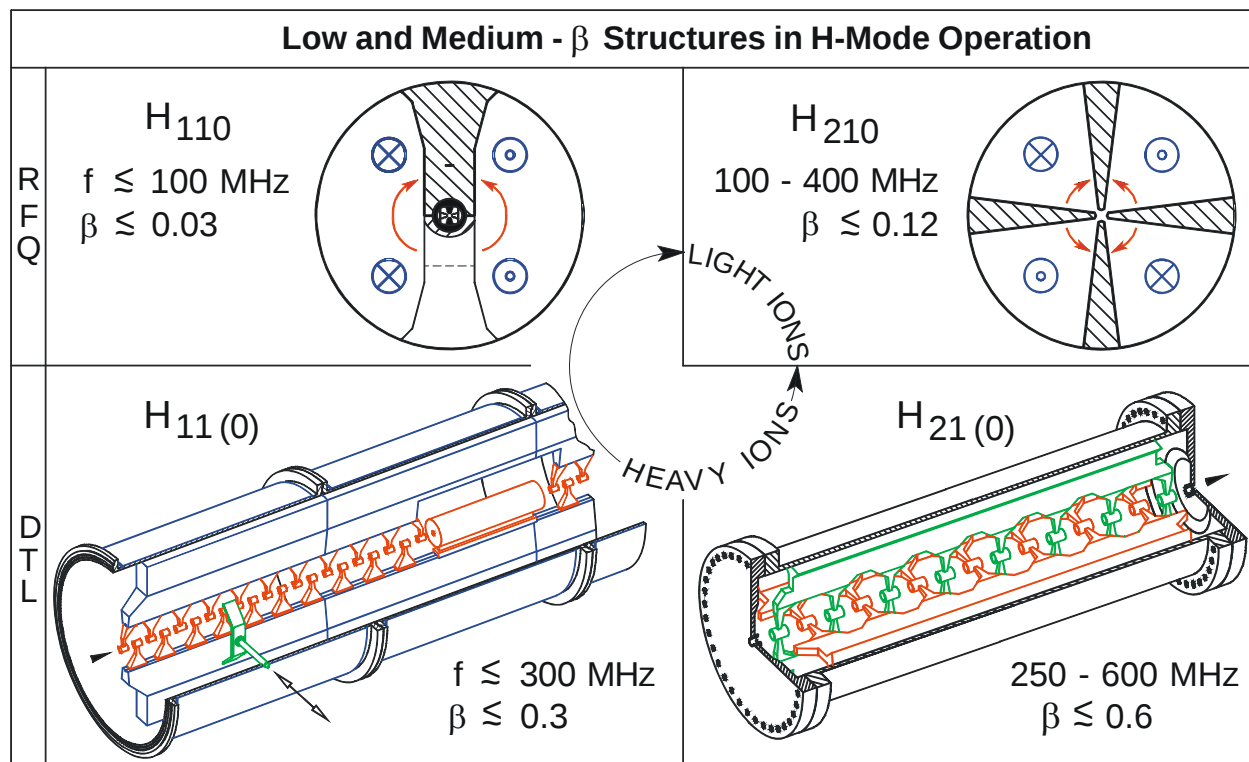
CAS Quarter Wave Resonators



Simple 2-gap cavities commonly used in their superconducting version (lead, niobium, sputtered niobium) for low beta protons or ion linacs, where $\sim$ CW operation is required.

Synchronicity (distance $\beta\lambda/2$ between the 2 gaps) is guaranteed only for one energy/velocity, while for easiness of construction a linac is composed by series of identical QWR's $\rightarrow$ reduction of energy gain for "off-energy" cavities. Transit Time Factor curves as below.

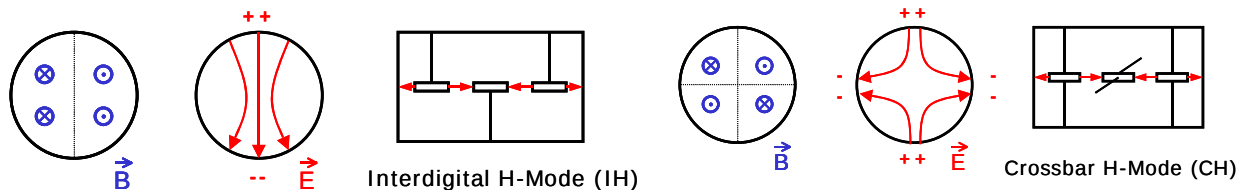




Interdigital-H Structure Operates in TM₁₁₀ mode
 Transverse E-field
 "deflected" by adding drift tubes
 Used for ions, $\beta < 0.3$

CH Structure operates in TM₂₁₀, used for protons at $\beta < 0.6$

High ZT^2 but more difficult beam dynamics (no space for quads in drift tubes)



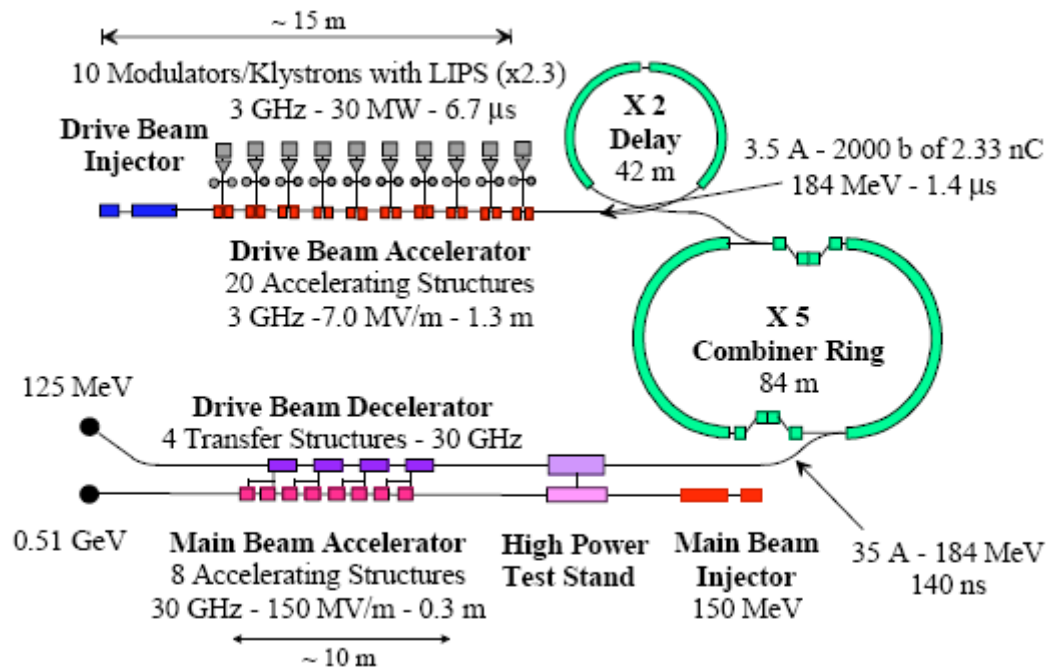
HSI - IH DTL, 36 MHz



CAS Electron linac architecture

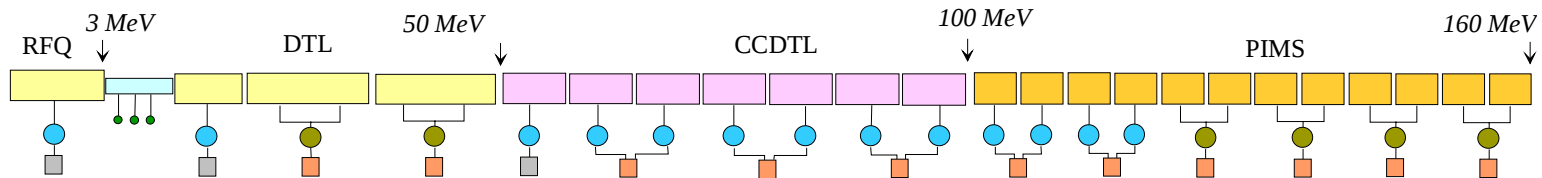


EXAMPLE: the **CLIC Test facility (CTF)** at **CERN**: drive linac, 3 GHz, 184 MeV.
An injector + a sequence of 20 identical multi-cell traveling wave accelerating structures.
Main beam accelerator: 8 identical accelerating structures at 30 GHz, 150-510 MeV

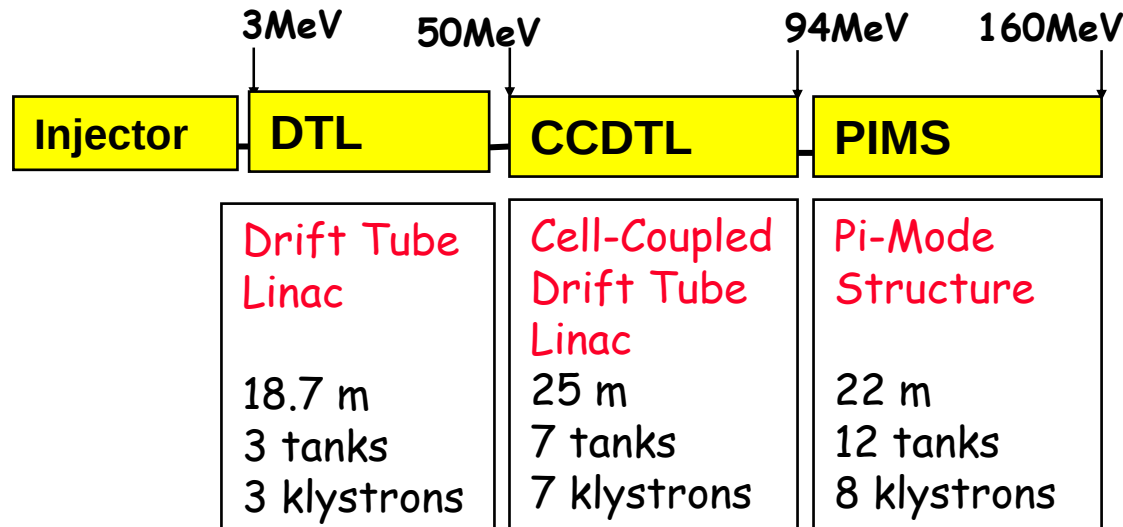


EXAMPLE: the **Linac4 project at CERN**. H⁻, 160 MeV energy.

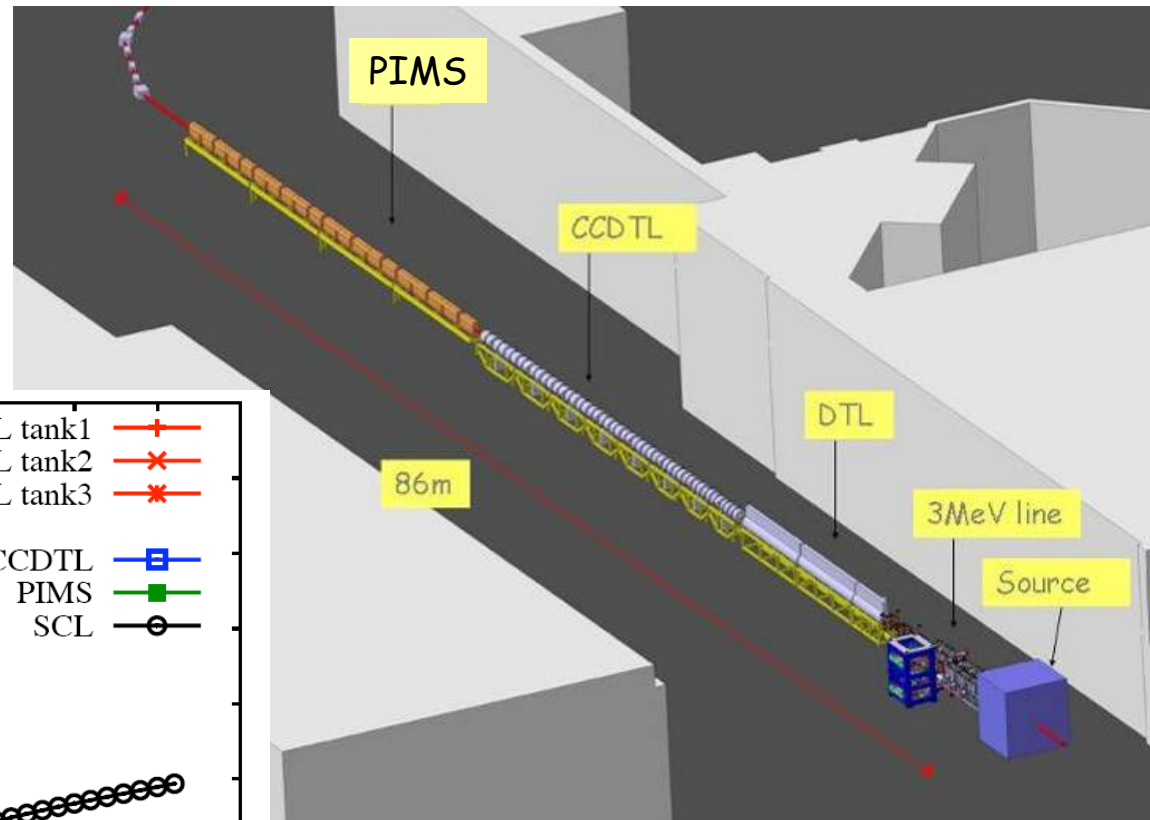
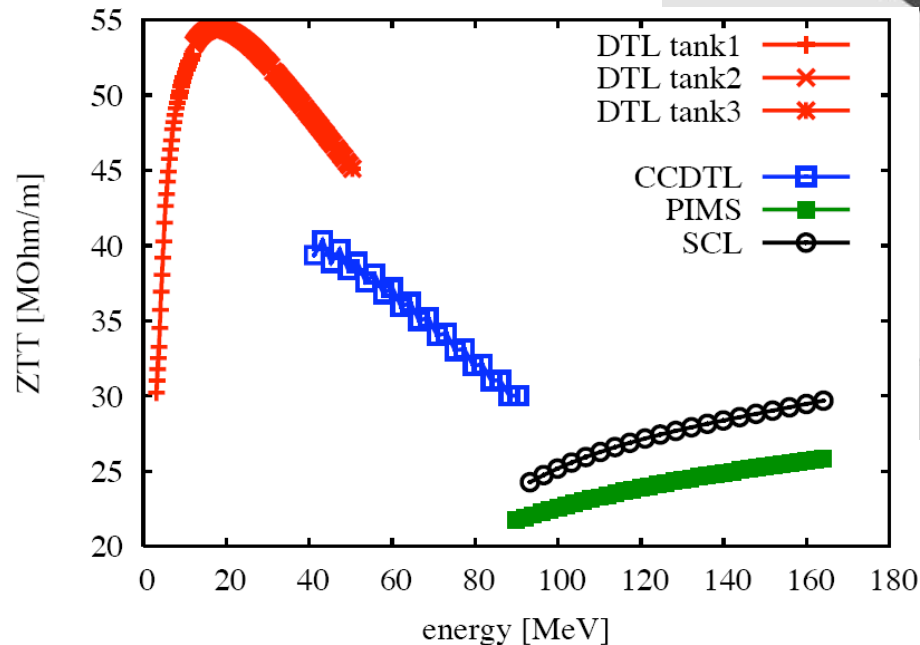
A 3 MeV injector + a sequence of 22 multi-cell standing wave accelerating structures at 352 MHz, each with cell length adapted to the beam velocity profile



- 1.3 MW klystron (LEP, CW)
- 2.5 MW klystron (pulsed)
- Modulator for 1.3 MW RF
- Modulator for 2.5 MW RF



Every proton linac structure has a characteristic curve of shunt impedance (=acceleration efficiency) as function of energy.

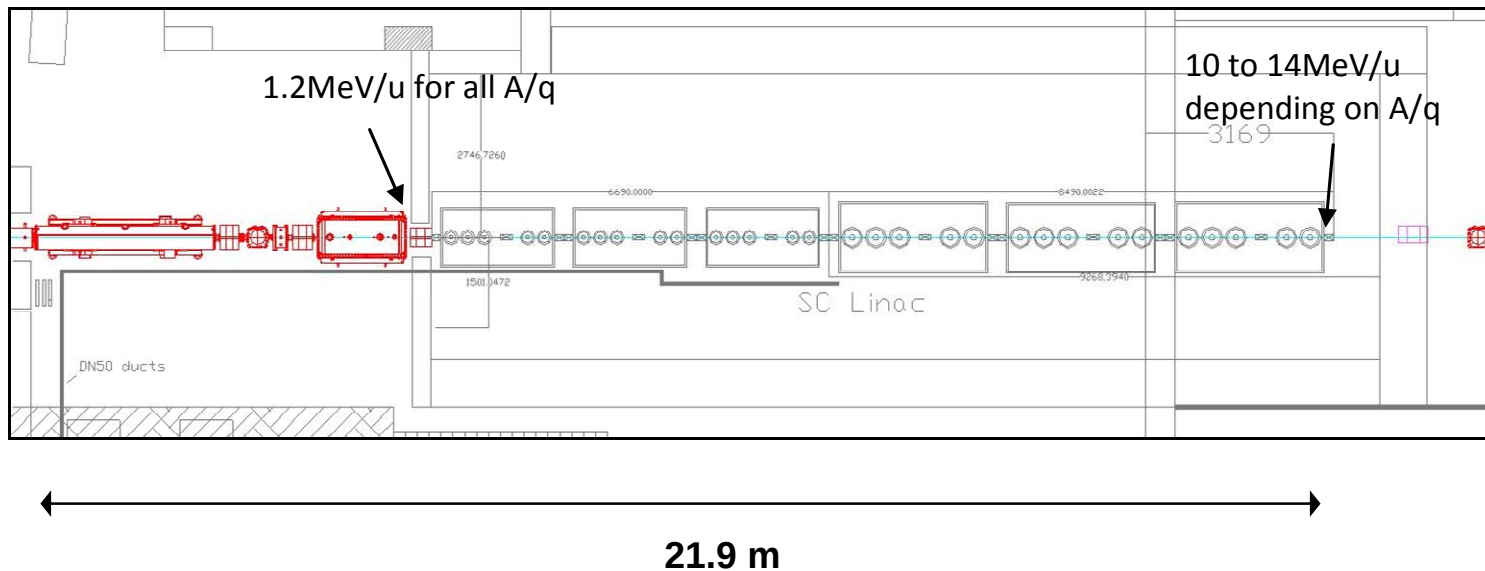


The choice of the best accelerating structure for a certain energy range depends on **shunt impedance**, but also on **beam dynamics** and construction **cost**.

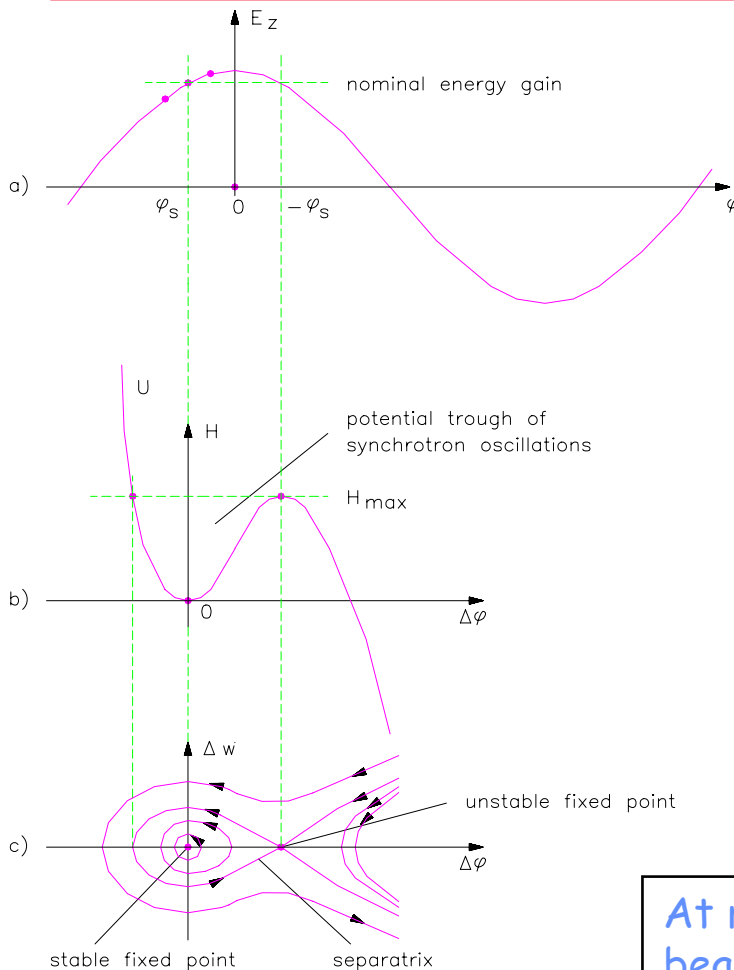
CAS Heavy Ion Linac Architecture



EXAMPLE: the **REX upgrade project at CERN-ISOLDE**. Post-acceleration of radioactive ions with different A/q up to energy in the range 2-10 MeV. An injector (source, charge breeder, RFQ) + a sequence of short (few gaps) standing wave accelerating structures at frequency 101-202 MHz, normal conducting at low energy (Interdigital, IH) and superconducting (Quarter Wave Resonators) at high energy.



4 - Beam Dynamics of Ion and Electron Linacs



- Ions are accelerated around a (negative) synchronous phase.
- Particles around the synchronous one perform oscillations in the longitudinal phase space.
- Frequency of small oscillations:

$$\omega_l^2 = \omega_0^2 \frac{qE_0 T \sin(-\varphi)\lambda}{2\pi mc^2 \beta\gamma^3}$$

- Tends to zero for relativistic particles $\gamma \gg 1$.
- Note phase damping of oscillations:

$$\Delta\varphi = \frac{\text{const}}{(\beta\gamma)^{3/4}} \quad \Delta W = \text{const} \times (\beta\gamma)^{3/4}$$

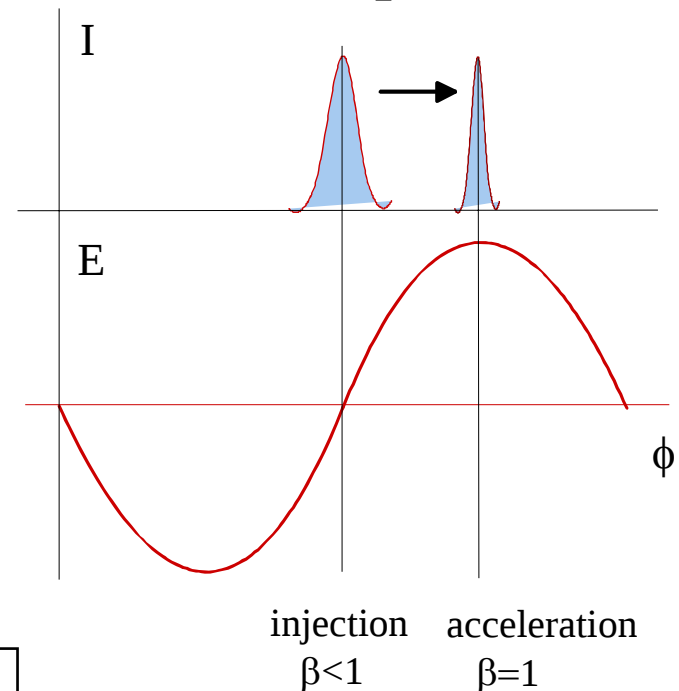
At relativistic velocities phase oscillations stop, the beam is compressed in phase around the initial phase. The crest of the wave can be used for acceleration.

- Electrons at $v=c$ remain at the injection phase.
- Electrons at $v < c$ injected into a TW structure will move from injection phase φ_0 to an asymptotic phase φ , which depends only on gradient and β_0 at injection.
- The beam can be injected with an offset in phase, to reach the crest of the wave at $\beta=1$
- Capture condition, relating E_0 and β_0 :

$$\frac{2\pi}{\lambda_g} \frac{mc^2}{qE_0} \left[\sqrt{\frac{1-\beta_0}{1+\beta_0}} \right] = 1$$

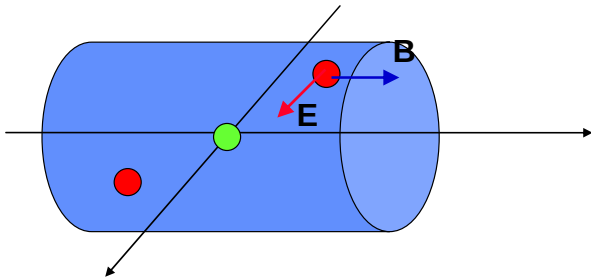
Example: $\lambda=10\text{cm}$, $W_{\text{in}}=150\text{ keV}$ and $E_0=8\text{ MV/m}$.

$$\sin \varphi = \sin \varphi_0 + \frac{2\pi}{\lambda_g} \frac{mc^2}{qE_0} \left[\sqrt{\frac{1-\beta_0}{1+\beta_0}} - \sqrt{\frac{1-\beta}{1+\beta}} \right]$$



In high current linacs, a bunching and pre-acceleration sections up to 4-10 MeV prepares the injection in the TW structure (that occurs already on the crest)

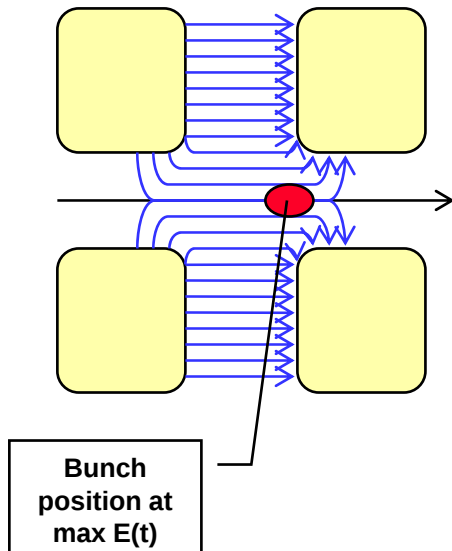
- Large numbers of particles per bunch ($\sim 10^{10}$).
- Coulomb repulsion between particles (space charge) plays an important role.
- But **space charge forces $\sim 1/\gamma^2$ disappear at relativistic velocity**



Force on a particle inside a long bunch with density $n(r)$ traveling at velocity v :

$$E_r = \frac{e}{r} \int_0^r n(r) r dr \quad B_\phi = \frac{ev}{r} \int_0^r n(r) r dr$$

$$F = e(E_r - vB_\phi) = eE_r \left(1 - \frac{v^2}{c^2}\right) = eE_r (1 - \beta^2) = \frac{eE_r}{\gamma^2}$$



- RF defocusing experienced by particles crossing a gap on a longitudinally stable phase.
- In the rest frame of the particle, only electrostatic forces → no stable points (maximum or minimum) → radial defocusing.
- Lorentz transformation and calculation of radial momentum impulse per period (from electric and magnetic field contribution in the laboratory frame):

$$\Delta p_r = -\frac{\pi e E_0 T L r \sin \varphi}{c \beta^2 \gamma^2 \lambda}$$

- Transverse defocusing $\sim 1/\gamma^2$ disappears at relativistic velocity (transverse magnetic force cancels the transverse RF electric force).
- Important consequence: in an electron linac, transverse and longitudinal dynamics are decoupled !

The equilibrium between external focusing force and internal defocusing forces defines the **frequency of beam oscillations**.

Oscillations are characterized in terms of *phase advance per focusing period* σ_t or *phase advance per unit length* k_t

Ph. advance = Ext. quad focusing - RF defocusing - space charge - Instabilities

$$k_t^2 = \left(\frac{\sigma_t}{N\beta\lambda} \right)^2 = \left(\frac{qGl}{2mc\beta\gamma} \right)^2 - \frac{\pi q E_0 T \sin(-\varphi)}{mc^2 \lambda \beta^3 \gamma^3} - \frac{3qI\lambda(1-f)}{8\pi\epsilon_0 r_0^3 mc^3 \beta^2 \gamma^3} - \dots$$

Approximate expression valid for:
FODO lattice, smooth focusing approximation, space charge of a uniform 3D ellipsoidal bunch.

Electron Linac:

Ph. advance = Ext. focusing + ~~RF defocusing~~ + ~~space charge~~ + Instabilities

For $\gamma \gg 1$ (electron linac): RF defocusing and space charge disappear, *phase advance* $\rightarrow 0$.

External focusing is required only to control the emittance and to stabilize the beam against instabilities (as **wakefields** and **beam breakup**).

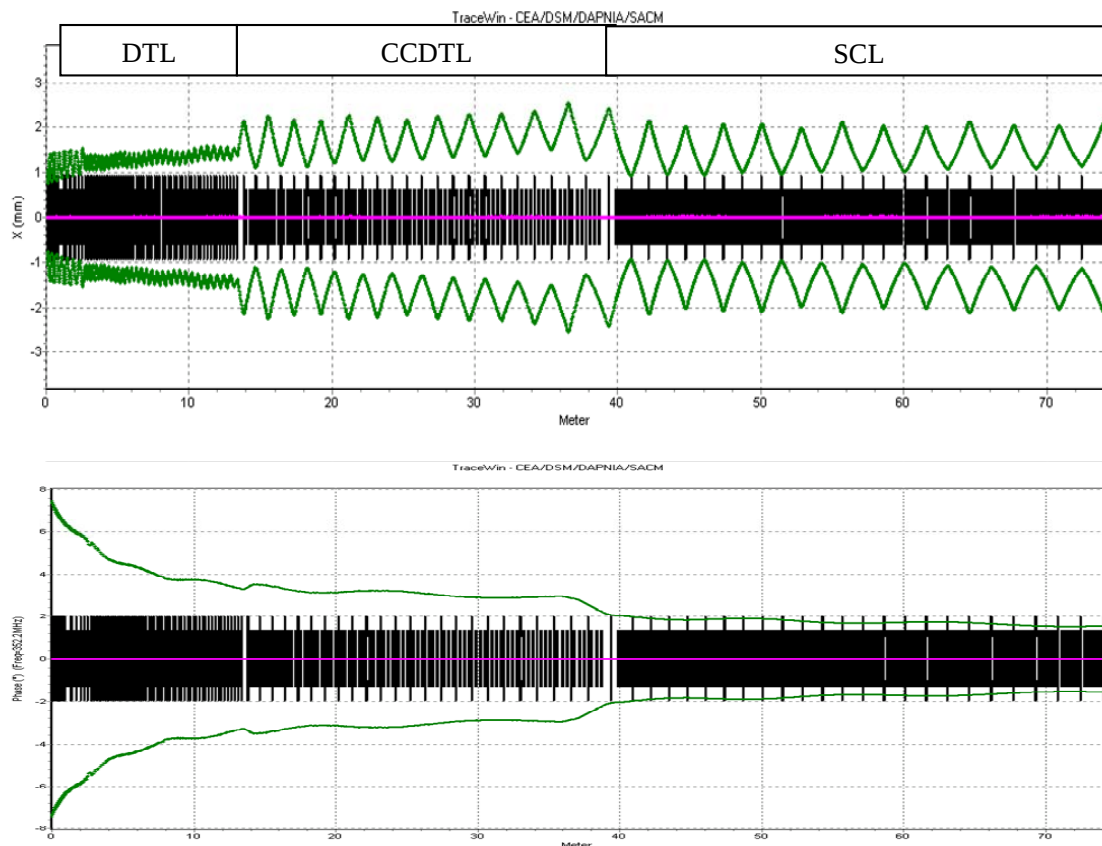
Focusing provided by quadrupoles (but solenoids for low β !).

Different **distance between focusing elements** (=1/2 length of a FODO focusing period)! For the main linac accelerating structure (after injector):

Protons, (high beam current and high space charge) require short distances:
 $\beta\lambda$ in the main linac, from $\sim 70\text{mm}$ (3 MeV, 352 MHz) to $\sim 250\text{mm}$ (40 MeV),
can be increased to $4-10\beta\lambda$ at higher energy (>40 MeV).

Heavy ions (low current, no space charge):
 $2-10 \beta\lambda$ in the main linac ($>\sim 150\text{mm}$).

Electrons (no space charge, no RF defocusing):
up to several meters, depending on the required beam conditions. Focusing is
mainly required to control the emittance.



Example: beam dynamics for Linac4@CERN.

High intensity protons (60 mA bunch current, duty cycle could go up to 5%)

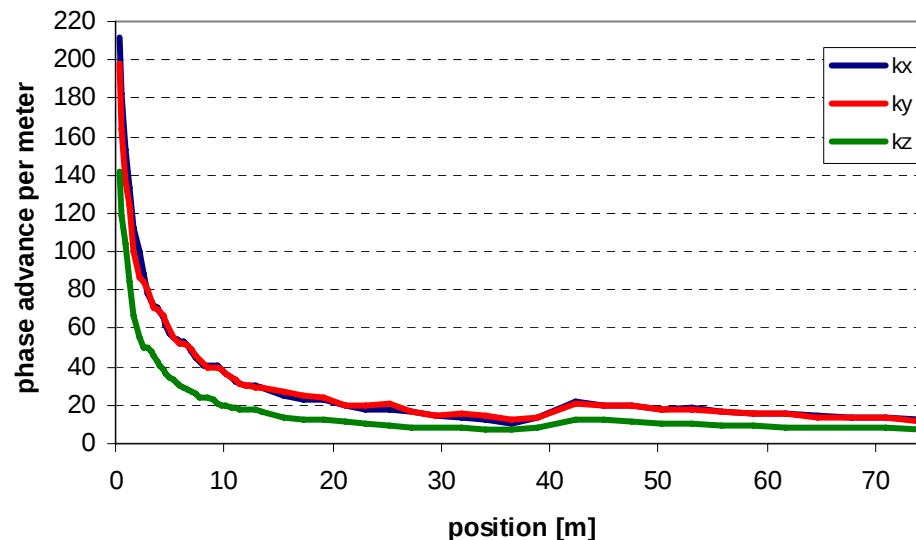
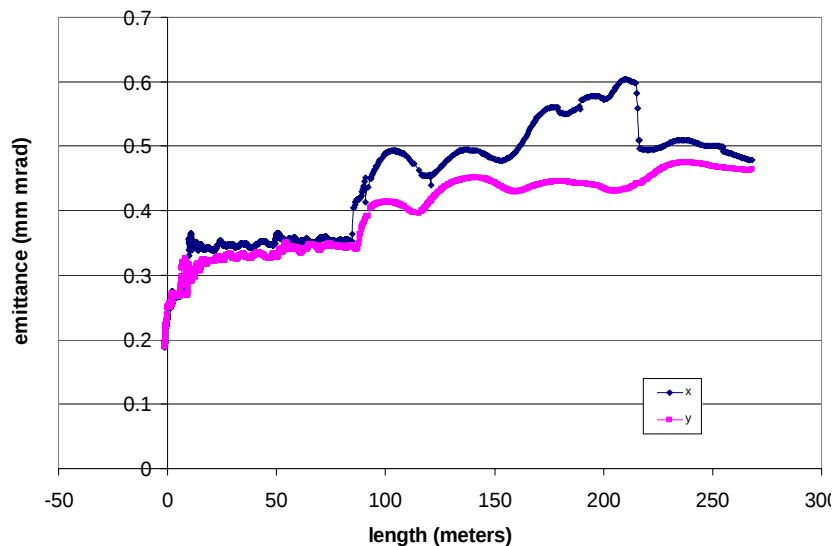
Goal of beam dynamics design is to minimise emittance growth and halo development in order to:

1. **avoid uncontrolled beam loss** (activation of machine parts)
2. **preserve small emittance** (high luminosity in the following accelerators)

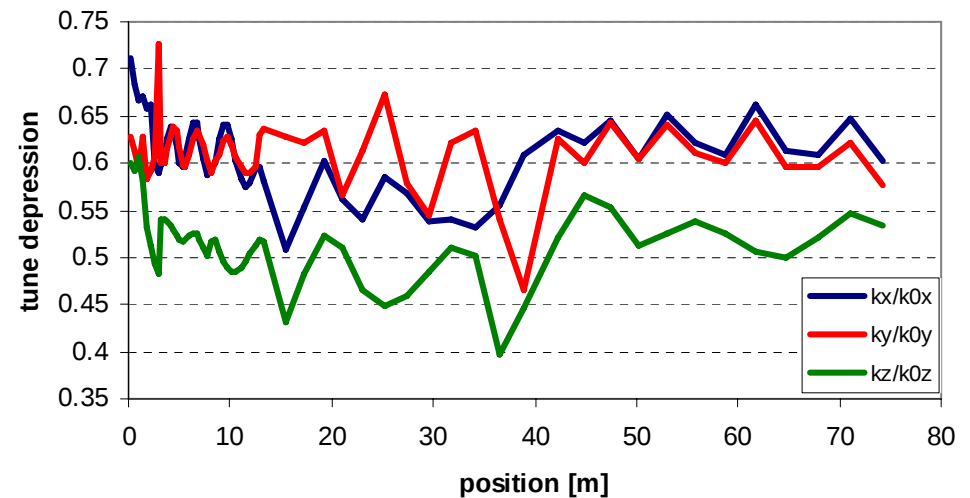
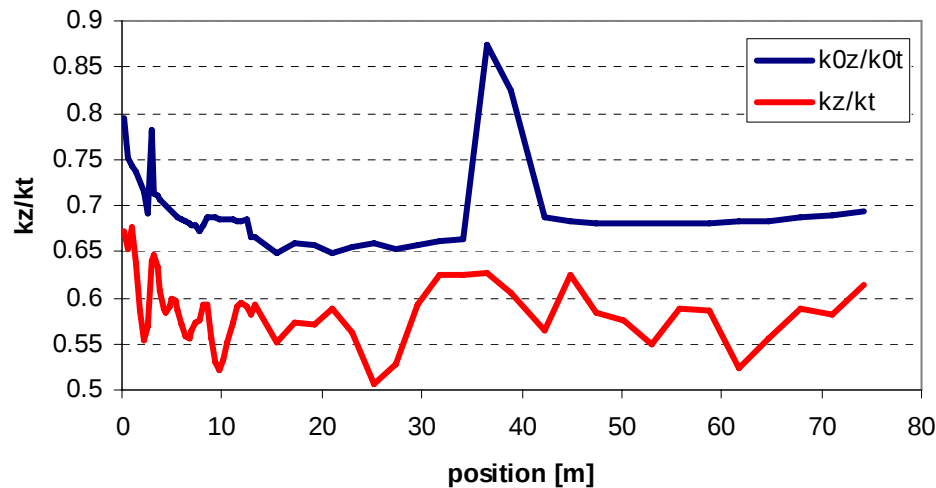
Transverse (x) and phase r.m.s. beam envelope along the DTL-CCDTL-SCL

Prescriptions:

1. Keep zero current phase advance always below 90° , to avoid resonances
2. Keep longitudinal to transverse phase advance ratio 0.5-0.8, to avoid emittance exchange
3. Keep a smooth variation of transverse and longitudinal phase advance per meter.
- (4. Keep sufficient safety margin between beam radius and aperture)

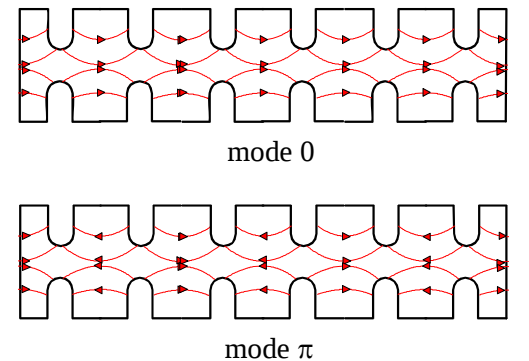
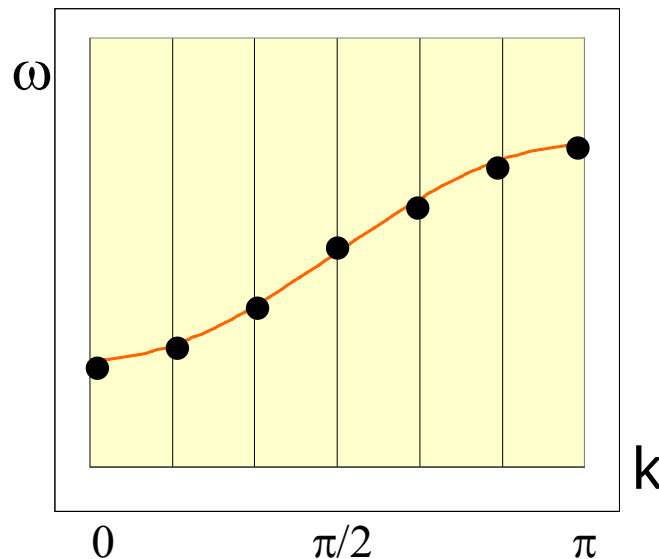


Transverse r.m.s. emittance and phase advance along Linac4 (RFQ-DTL-CCDTL-SCL)



5. Double periodic accelerating structures

- ➡ To reduce RF cost, linacs use high-power RF sources feeding a large number of **coupled cells** (DTL: 30-40 cells, other high-frequency structures can have >100 cells).
- ➡ Long linac structures operating in the 0 or π modes are extremely **sensitive to mechanical errors**: small machining errors in the cells can induce large differences in the accelerating field between cells.

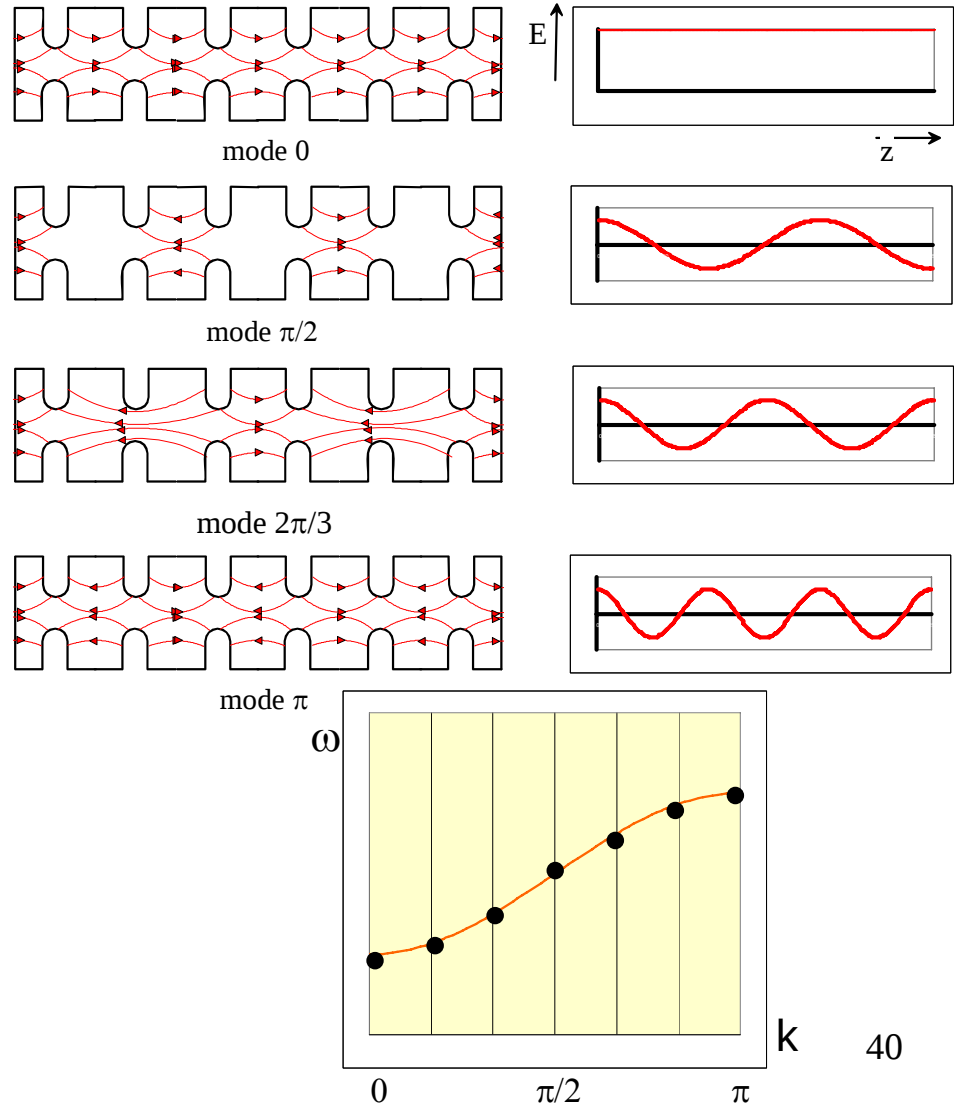


Mechanical errors $\rightarrow$ differences in frequency between cells $\rightarrow$ to respect the new boundary conditions the electric field will be a linear combination of all modes, with weight

$$\frac{1}{f^2 - f_0^2}$$

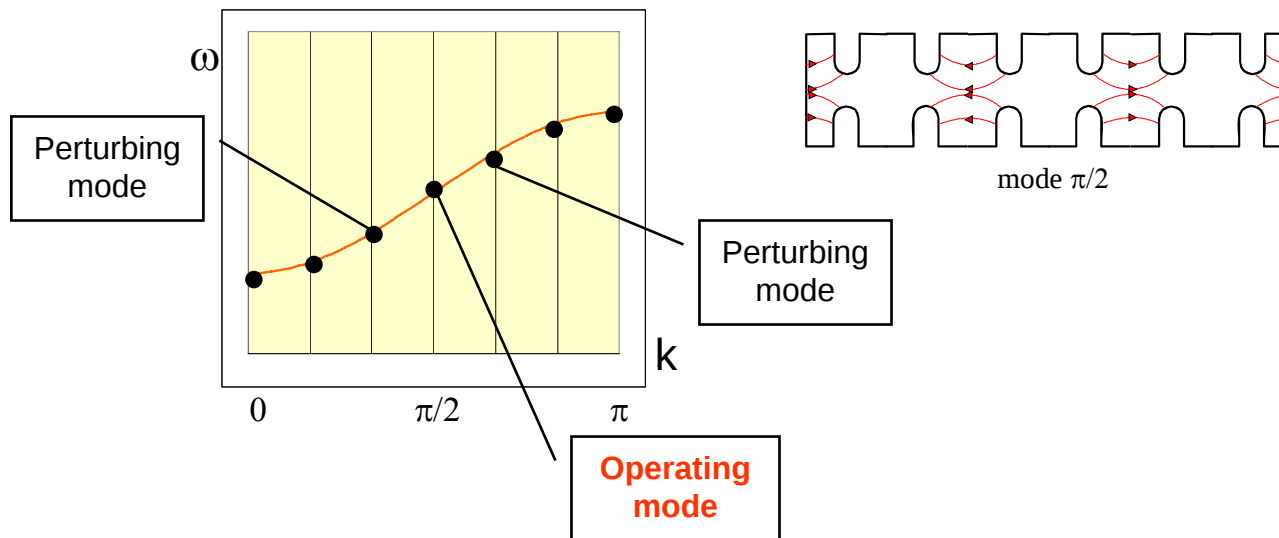
(general case of small perturbation to an eigenmode system, the new solution is a linear combination of all the individual modes)

The nearest modes have the highest effect, and when there are many modes on the dispersion curve (number of modes = number of cells !) the difference in E-field between cells can be extremely high.



Solution:

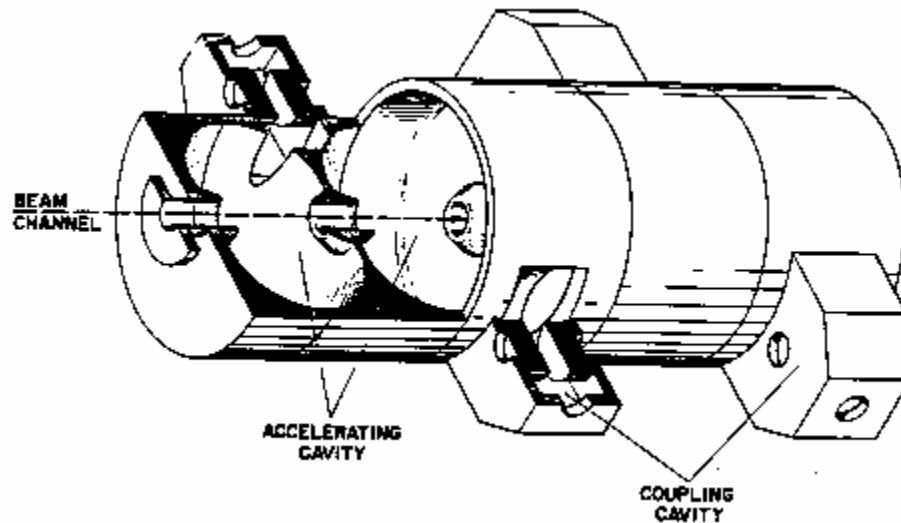
Long chains of linac cells are operated in the $\pi/2$ mode, which is **intrinsically insensitive** to differences in the cell frequencies.



Contribution from adjacent modes proportional to $\frac{1}{f^2 - f_0^2}$ **with the sign !!!**

Contribution from equally spaced modes in the dispersion curve will cancel each other.

To operate efficiently in the $\pi/2$ mode, the cells that are not excited can be removed from the beam axis $\rightarrow$ they become coupling cells, as for the **Side Coupled Structure**.



Example: the Cell-Coupled Linac at SNS, >100 cells/module

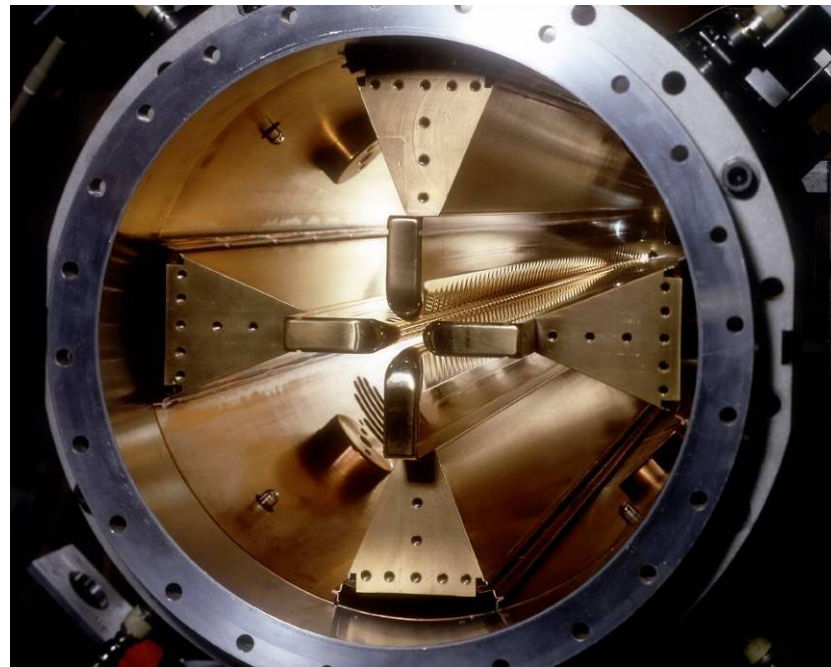
multi-cell Standing Wave
structure in **$\pi/2$ mode**
frequency 800 - 3000 MHz
for protons ($\beta=0.5 - 1$)



6. The Radio Frequency Quadrupole

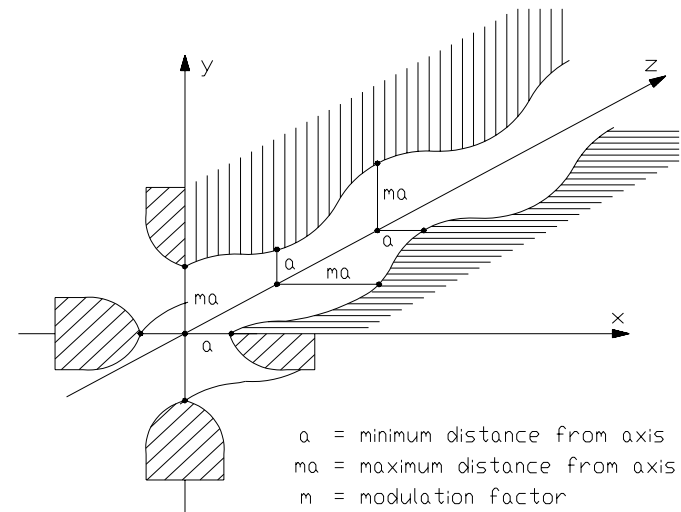
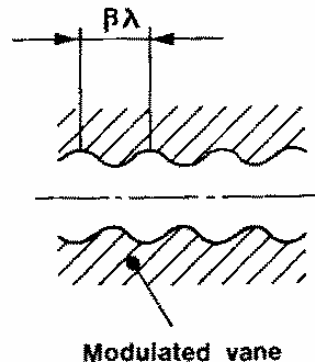
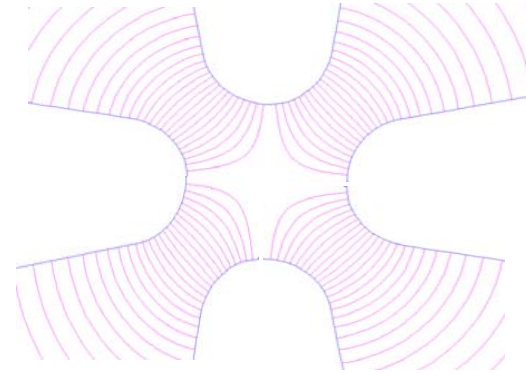
The Radio Frequency Quadrupole (RFQ)

At low proton (or ion) energies, space charge defocusing is high and quadrupole focusing is not very effective, cell length becomes small → conventional accelerating structures (Drift Tube Linac) are very inefficient → use a (relatively) new structure, the Radio Frequency Quadrupole.



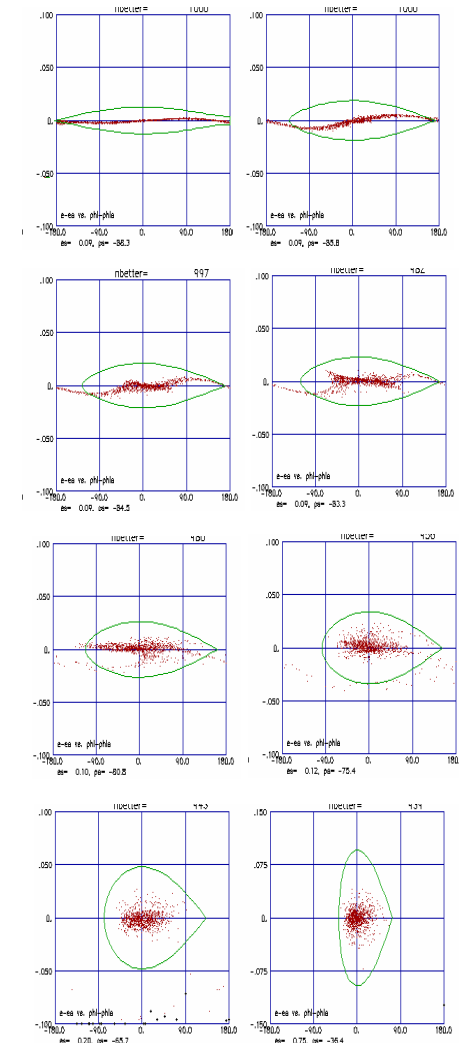
RFQ = Electric quadrupole focusing channel + bunching + acceleration

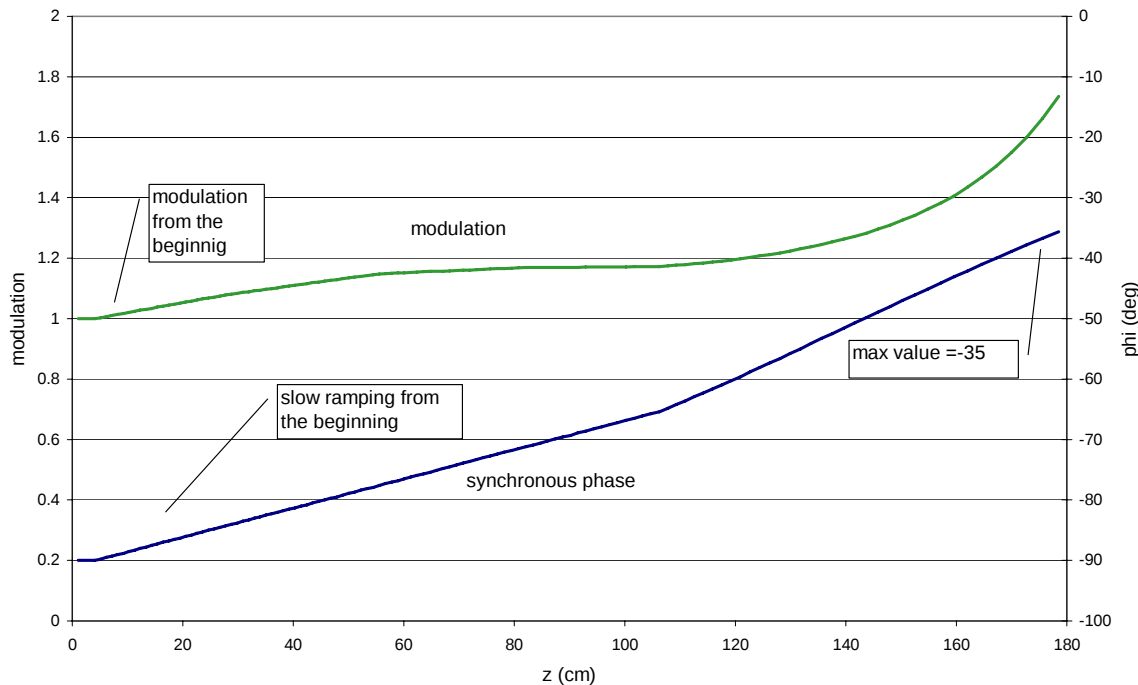
1. Four electrodes (vanes) between which we excite an RF Quadrupole mode (TE₂₁₀) → Electric focusing channel, alternating gradient with the period of the RF.
2. The vanes have a longitudinal modulation with period = $\beta\lambda$ → this creates a longitudinal component of the electric field. The modulation corresponds exactly to a series of F gaps and can provide acceleration.



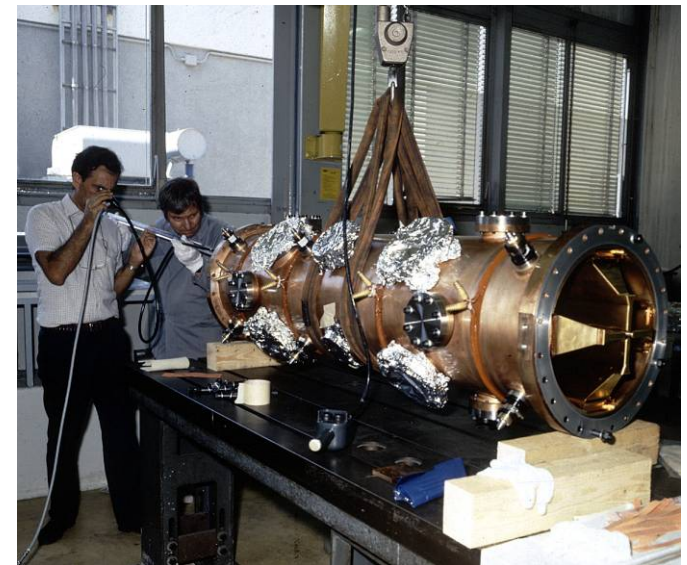
3. The distance between peaks of the modulation can be slightly adjusted to change the phase of the beam inside the RFQ cells, and the amplitude of the modulation can be changed to change the accelerating gradient → we can start on the zero phase (linac) with some bunching cells, create an adiabatic bunching channel, and then slowly switch on the acceleration.

Longitudinal beam profile of a proton beam along the CERN RFQ: from a continuous beam to a bunched accelerated beam in 300 cells.

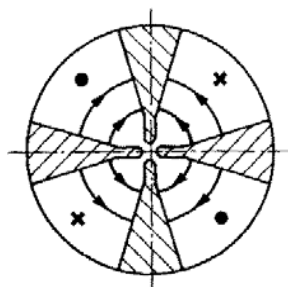




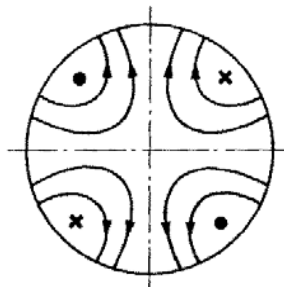
CERN High intensity RFQ
(RFQ2, 200 mA)



How to create a quadrupole RF mode ?



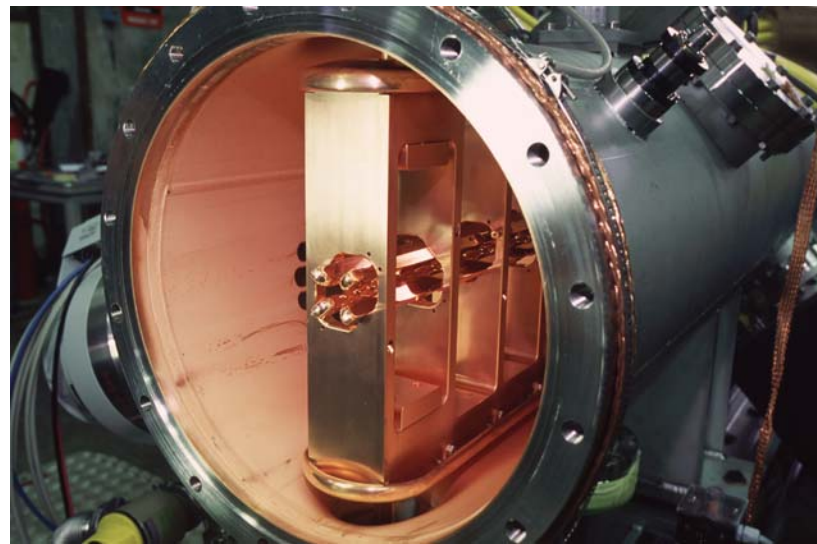
Cavity with vanes



Empty cavity; mode TE_{21}

The TE_{210} mode in the “4-vane” structure and in the empty cavity

An alternative resonator design is the “4-rod” structure, where an array of $\lambda/4$ parallel plate lines load four rods, connected in such a way as to provide the quadrupole field.



7. Linac Technologies

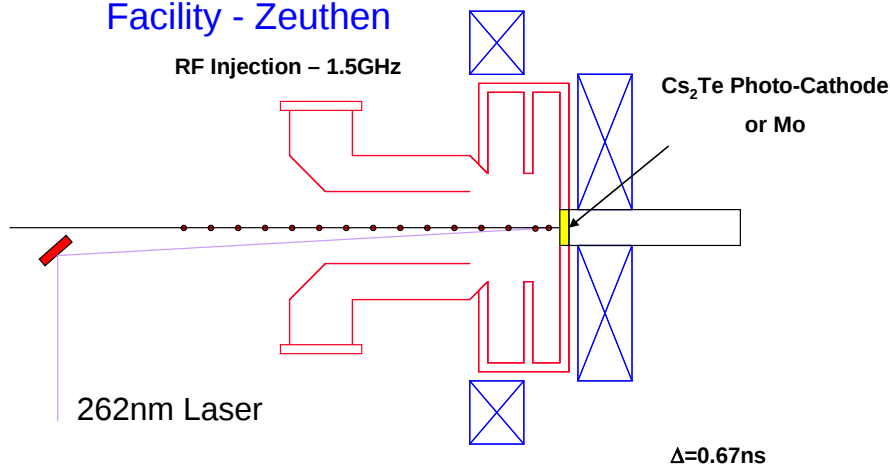
Electron sources:

give energy to the free electrons inside a metal to overcome the potential barrier at the boundary.

Used for electron production:

- thermoionic effect
- laser pulses
- surface plasma

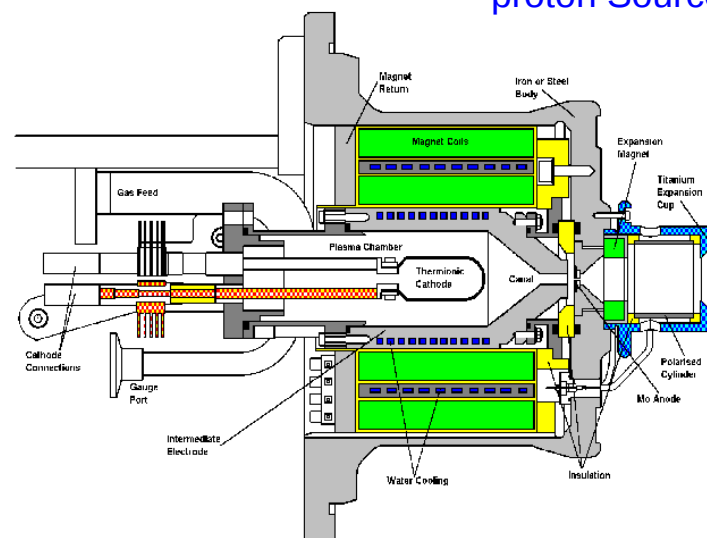
Photo Injector Test Facility - Zeuthen



Ion sources:

create a plasma and optimise 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.

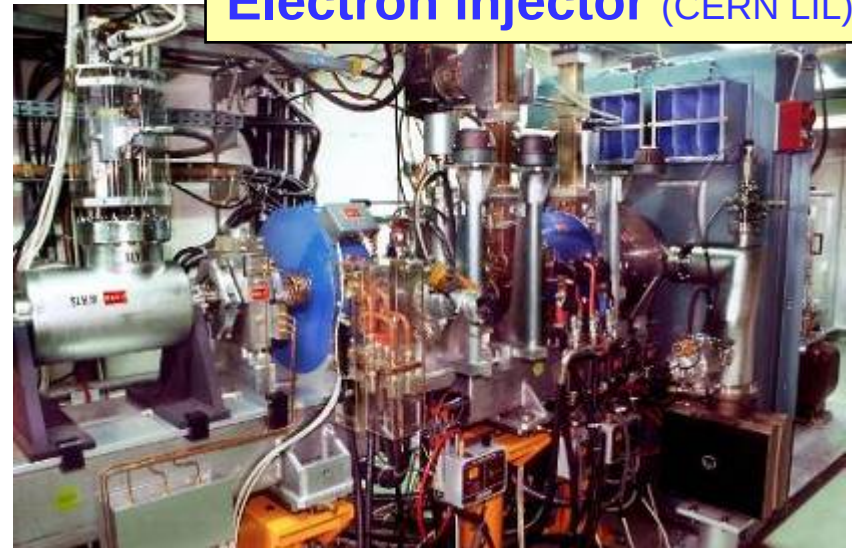
CERN Duoplasmatron proton Source



Ion injector (CERN Linac1)



Electron injector (CERN LIL)



3 common problems for protons and electrons after the source, up to ~ 1 MeV energy:

1. large space charge defocusing
2. particle velocity rapidly increasing
3. need to form the bunches

Solved by a special **injector**

Ions: RFQ bunching, focusing and accelerating.

Electrons: Standing wave bunching and pre-accelerating section.

☞ For all particles, the injector is where the emittance is created!

approximate scaling laws for linear accelerators:

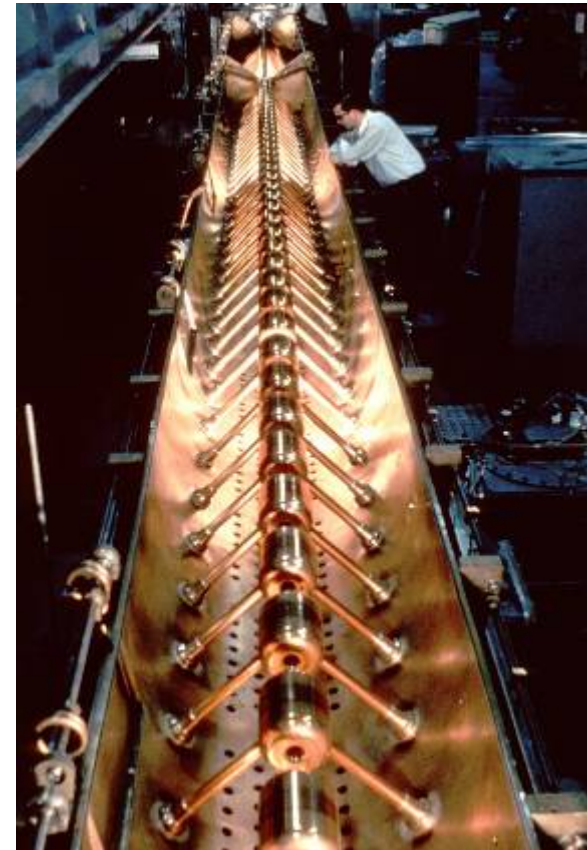
➤ RF defocusing (ion linacs)	$\sim \text{frequency}$
➤ Cell length ($=\beta\lambda/2$)	$\sim (\text{frequency})^{-1}$
➤ Peak electric field	$\sim (\text{frequency})^{1/2}$
➤ Shunt impedance (power efficiency)	$\sim (\text{frequency})^{1/2}$
➤ Accelerating structure dimensions	$\sim (\text{frequency})^{-1}$
➤ Machining tolerances	$\sim (\text{frequency})^{-1}$

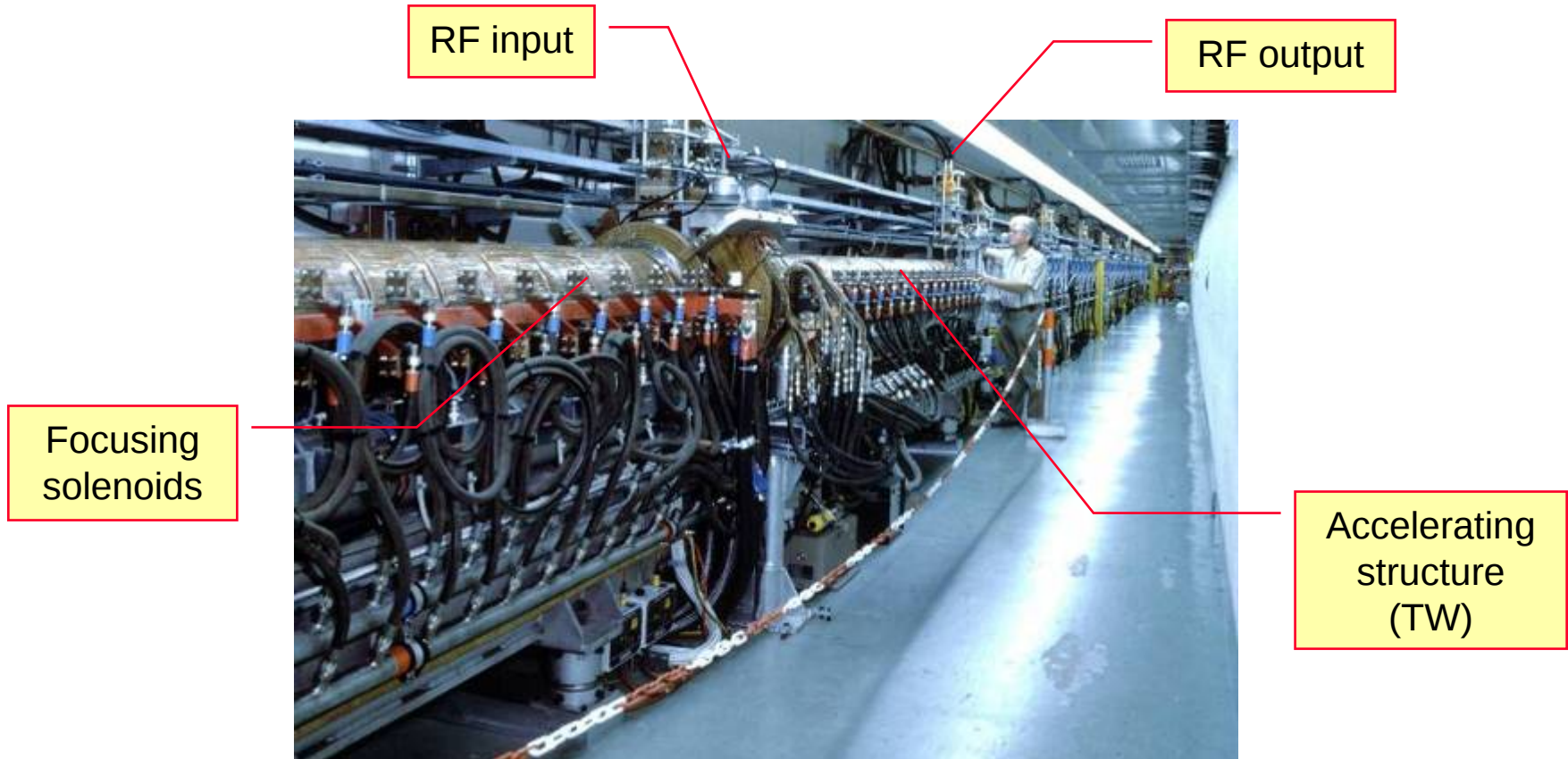
- **Higher frequencies** are economically convenient (shorter, less RF power, higher gradients possible) but the limitation comes from **mechanical precision** required in construction (tight tolerances are expensive!) and **beam dynamics** for ion linacs.
- **Electron linacs** tend to use **higher frequencies** than ion linacs (0.5-30 GHz), usual frequency 3 GHz (10 cm wavelength). No limitations from beam dynamics, iris in TW structure requires less accurate machining than nose in SW structure.
- **Proton linacs** use **lower frequencies** (100-800 MHz), increasing with energy (ex.: 350 - 700 MHz): compromise between focusing, cost and size.
- **Heavy ion linacs** tend to use **even lower frequencies** (30-200 MHz), dominated by the low beta in the first sections (CERN RFQ at 100MHz, 25 keV/u: $\beta\lambda/2=3.5\text{mm}$!)



**CERN Linac2 Drift Tube Linac accelerating tank 1 (200 MHz).
The tank is 7m long (diameter 1m) and provides an energy
gain of 10 MeV.**

**Focusing is provided by (small) quadrupoles inside drift
tubes (right). Length of drift tubes (cell length) increases
with proton velocity.**





The old CERN LIL (LEP Injector Linac) accelerating structures (3 GHz). The TW structure is surrounded by focusing solenoids, required for the positrons.

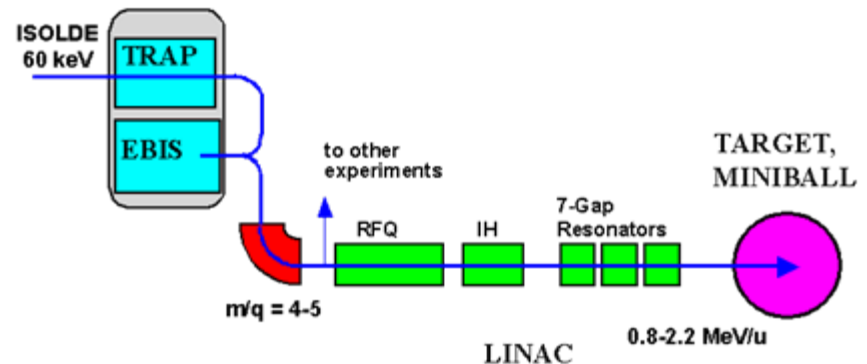
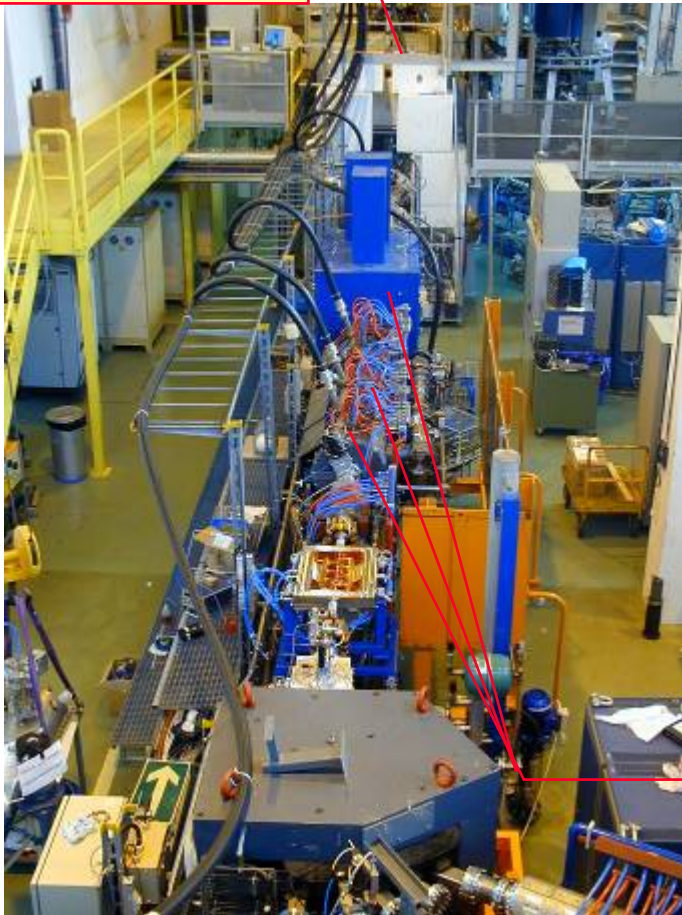


A 3 GHz LIL accelerating structure used for CTF3. It is 4.5 meters long and provides an energy gain of 45 MeV. One can see 3 quadrupoles around the RF structure.

CAS Examples: a heavy ion linac

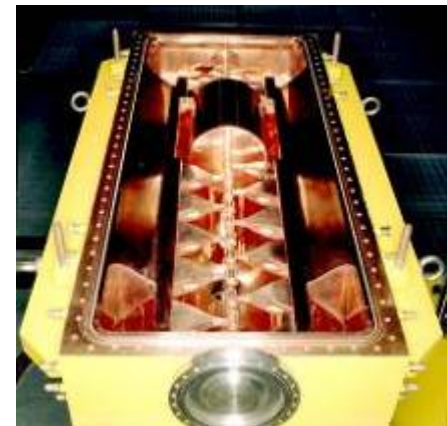


Particle source



The REX heavy-ion post accelerators at CERN. It is made of 5 short standing wave accelerating structures at 100 MHz, spaced by focusing elements.

Accelerating structures



- Type of **RF power source** depend on frequency:
 - ☞ Klystrons (>350 MHz) are used for electron linacs and modern proton linacs. RF distribution via waveguides.
 - ☞ RF tube amplifiers (<400 MHz) are used for proton and heavy ion linacs. RF distribution via coaxial lines.
- **Construction technology** depends on dimensions ($\rightarrow$ on frequency):
 - ☞ brazed copper parts (>500 MHz) are commonly used for electron linacs.
 - ☞ copper or copper plated welded/bolted parts are commonly used for ion linacs (<500 MHz).



**3 GHz klystron
(CERN LPI)**

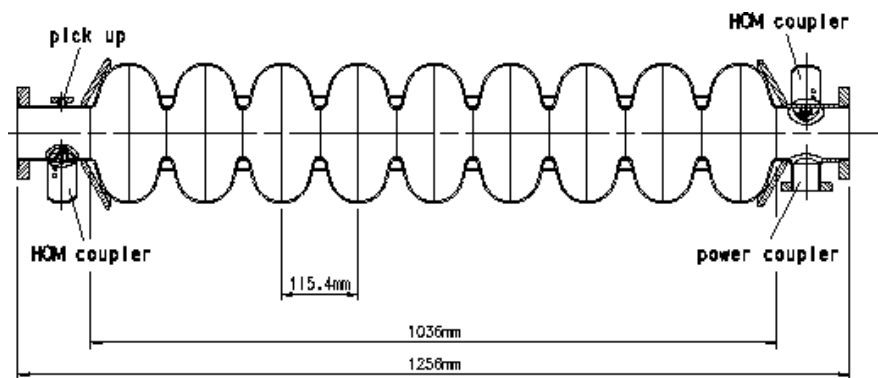
**200 MHz triode amplifier
(CERN Linac3)**

What is new (& hot) in the field of linacs?

1. Frequencies are going up for both proton and electron linacs (←less expensive precision machining). Modern proton linacs start at 350-400 MHz, end at 800-1300 MHz. Modern electron linacs in the range 3-30 GHz.
2. Superconductivity is progressing fast, and is being presently used for both electron and ion linacs → standing wave structures in the frequency range from ~100 MHz to 1300 MHz.

Superconductivity is now **bridging the gap between electron and ion linacs**.

The 9-cell TESLA SC cavities at 1.3 GHz for electron linear colliders, are now proposed for High Power Proton Accelerators (Fermilab 8 GeV linac) !



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