Accelerating Structures

Alberto DEGIOVANNI

Accelerators for Medical Applications
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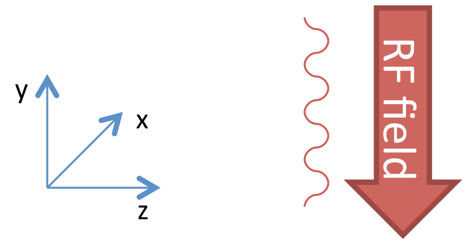
RF accelerating structures

Accelerating structures are **resonant** structures used to **accelerate** (or increase energy) of a beam of **charged** particles.



$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial}{\partial t}\vec{E} = 0 \qquad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} + \frac{\partial}{\partial t}\vec{B} = 0 \qquad \nabla \cdot \vec{E} = 0$$

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

Since $\vec{v} = v_x \cdot \hat{i} + v_y \cdot \hat{j} + v_z \cdot \hat{k} \approx \beta c \cdot \hat{k}$, **only** the electric field can change the particle energy!
To accelerate the beam along the axis we need a **longitudinal component** of the **electric field, E_z**.

Outline

- **EM waves in structure and RF frequency**
  - RF basics
  - Travelling wave
  - Standing wave
- **Structures characteristics**
  - Accelerating voltage
  - Losses and quality factor
  - Structure efficiency - R/Q
  - Shunt impedance
- **Example of structures**
  - Low Beta structures
  - Intermediate beta structures
- **Linacs for medical applications**

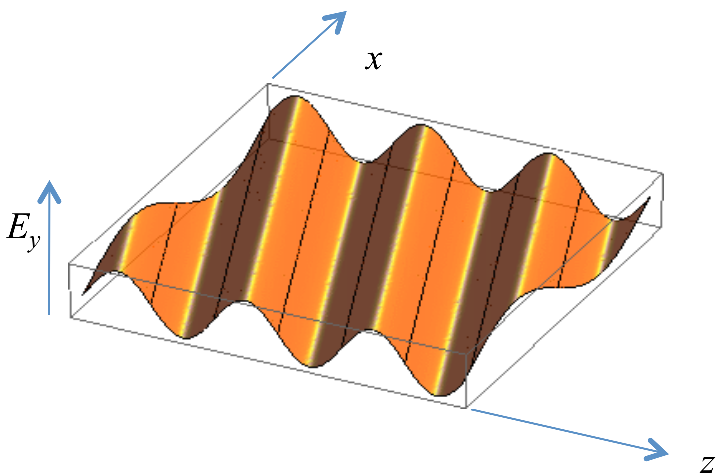
EM WAVES IN STRUCTURES

EM waves in waveguides

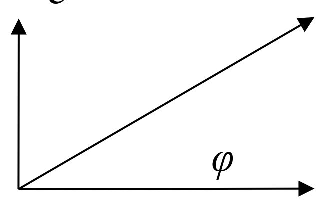
- EM waves can propagate in cylindrical and rectangular pipes, called **waveguides**
- In a waveguiding system, we are looking for **solutions of Maxwell's equations** that are propagating along the guiding direction (the z direction) and are confined in the near vicinity of the guiding structure and can be described mathematically by:

$$E(x,y,z,t) = E(x,y)e^{j\omega t - jk_z z}$$
$$H(x,y,z,t) = H(x,y)e^{j\omega t - jk_z z}$$

- These are homogenous plane waves characterized by a wave vector **k:**



$$k_\perp = \frac{\omega_c}{c} \qquad k = \frac{\omega}{c}$$



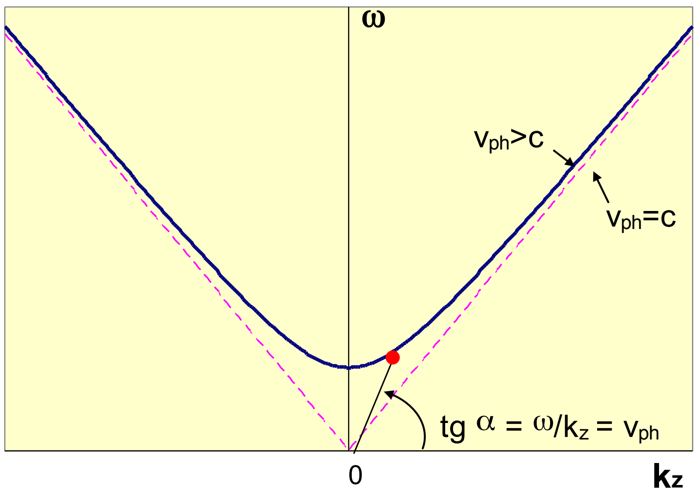
$$k_z = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}$$

The dispersion relation and wave velocitiy

- The precise relationship between ω (angular frequency) and k_z (waveguide propagation constant) is called **dispersion relation:**

M. Vretenar (CERN), CAS2013

$$k_z = \frac{1}{c}\sqrt{\omega^2 - \omega_c^2} \qquad \omega = \sqrt{\omega_c^2 + k_z^2 c^2}$$

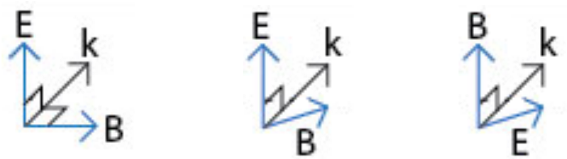


- ω_c is the so-called "**cut-off frequency**". The boundary conditions for each waveguide type force ω_c to take on certain values.
- At each excitation frequency is associated a phase velocity, the velocity at which a certain phase travels in the waveguide.
- To be synchronized all the time with an accelerating E-field, a particle traveling inside the waveguide has to travel at $v = v_{ph} > c$!
- Energy and information travel at the group velocity ($v_g < c < v_{ph}$)

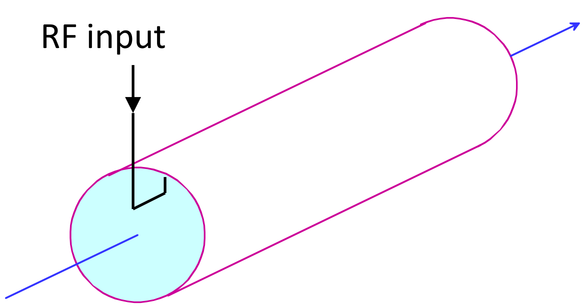
$\lambda_p = v_{ph} / f$	guide wavelength
$k_z=2\pi/\lambda_p$	guide wave number
$v_{ph}=\omega/k_z = (c^2+\omega_c^2/k_z^2)^{1/2}$	phase velocity
$v_g=d\omega/dk_z$	group velocity

EM propagating modes

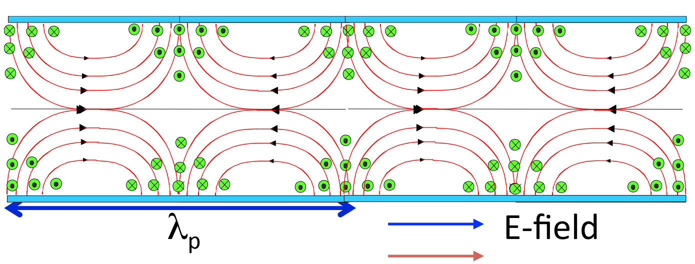
TEM mode | TE mode | TM mode



Transverse Electric and Magnetic | Transverse Electric | Transverse Magnetic



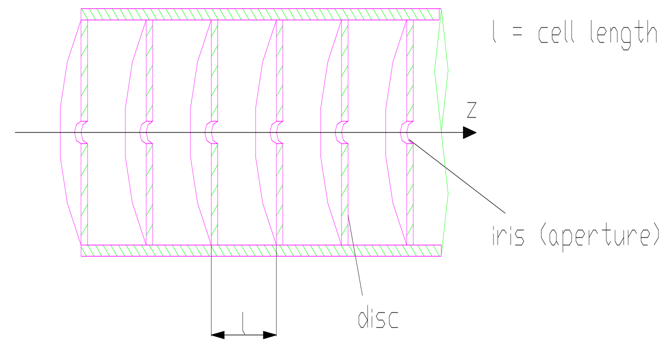
TM01 field configuration

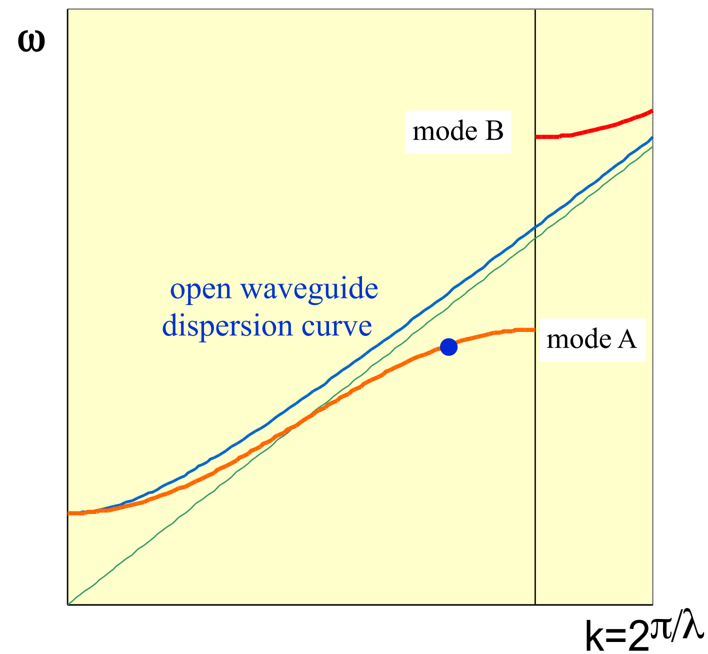


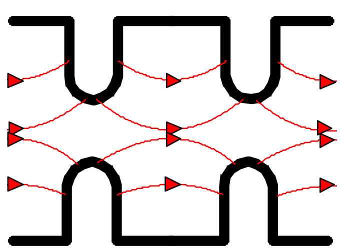
- Solutions of Maxwell's equations can be classified in three families (TEM, TE, TM) depending on whether both, one, or none of the longitudinal components are zero.
- To accelerate particles, we need a mode with **longitudinal E-field** component on axis: a TM mode (**Transverse Magnetic, B_z=0**). The simplest is TM01.
- We inject RF power at a frequency exciting the TM01 mode, but as we have seen before **v_{ph} > c**
- We need to "slow down" the wave in order to use the pipe as an **accelerating structure**

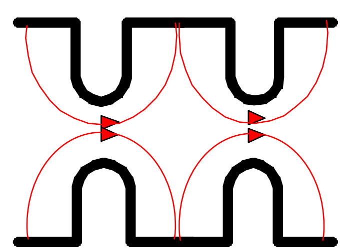
The disc loaded waveguide: an accelerating tube for electrons!

- Discs inside the cylindrical waveguide, spaced by a distance l , will induce **multiple reflections** between the discs.
- for λ_p=0 and $\lambda_p=\infty$ the wave does not see the discs, i.e. the dispersion curve remains that of the empty cylinder.
- At $\lambda_p/2$= l , 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: the dispersion curve splits into 2 branches, separated by a stop band.



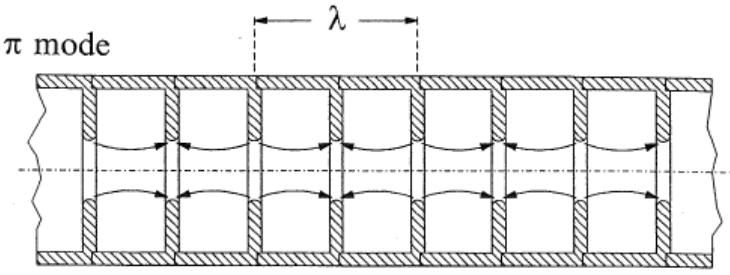


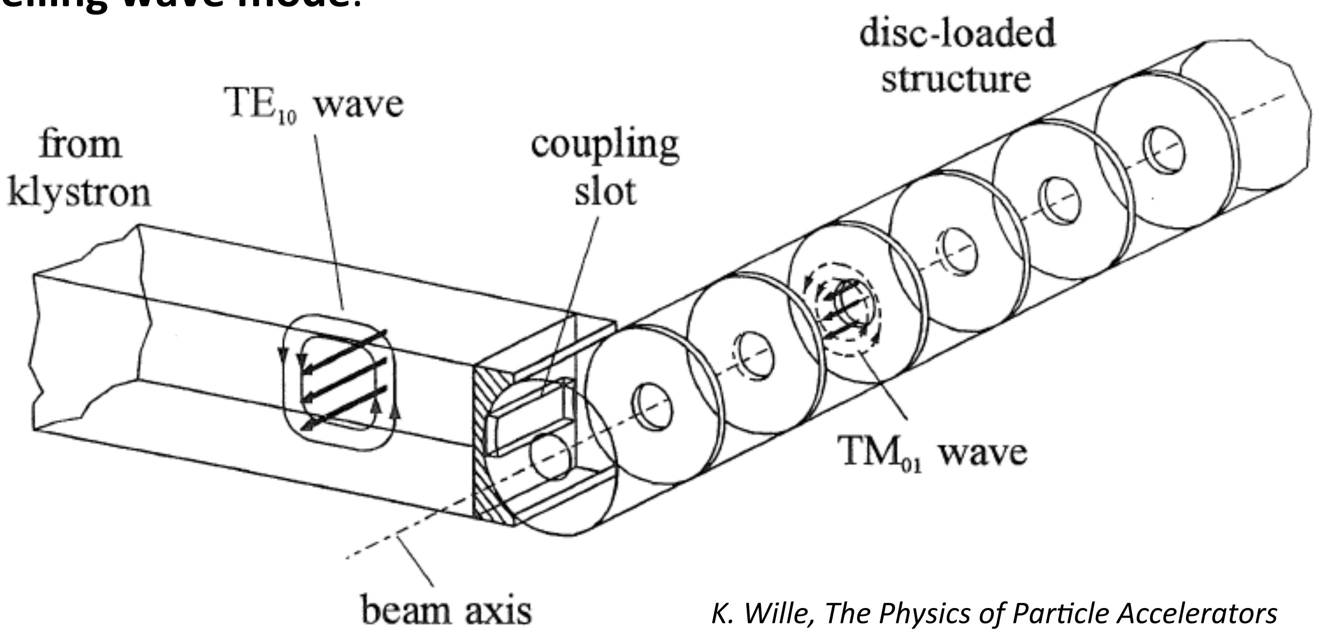

electric field pattern - mode A


electric field pattern - mode B

Travelling wave structures

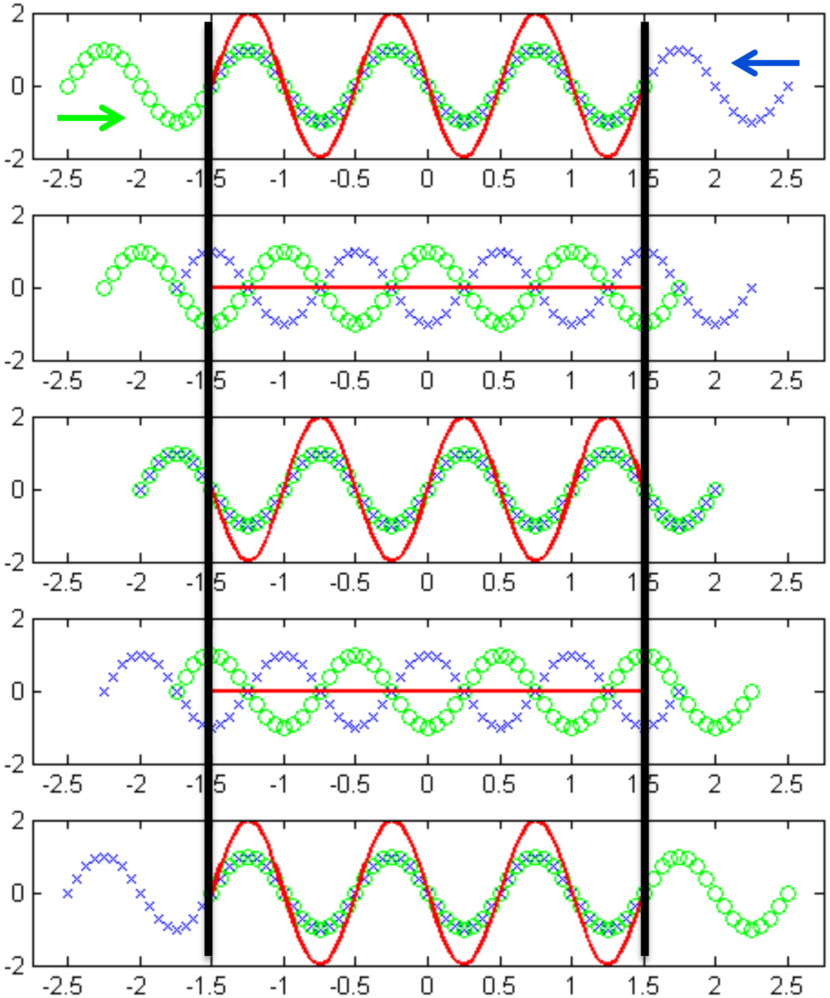
- In an electron linac velocity is practically constant v = c (i.e. $\beta = 1$).
- The linac structure is made of a sequence of identical cells (except for the gun) of length $d = \beta \lambda / 2 = \lambda / 2$.
- The cells are grouped in cavities operating in **travelling wave mode**.



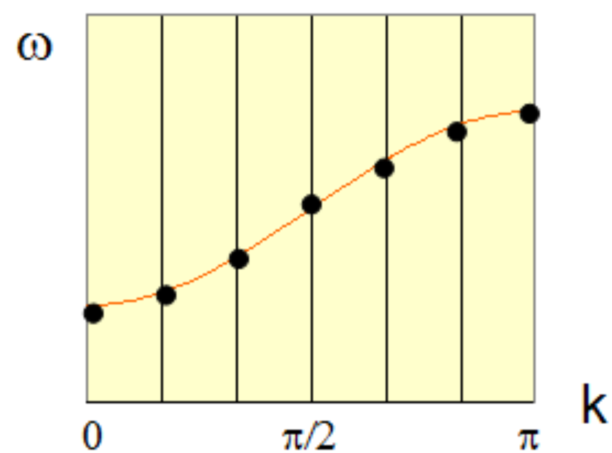


K. Wille, The Physics of Particle Accelerators

Standing wave structures



- **Standing wave modes** are generated by the **sum of 2 waves traveling in opposite directions**, adding up in the different cells
- Boundary condition at both ends is that electric field must be perpendicular to the cover → Only some modes on the disc-loaded dispersion curve are allowed



Standing wave modes

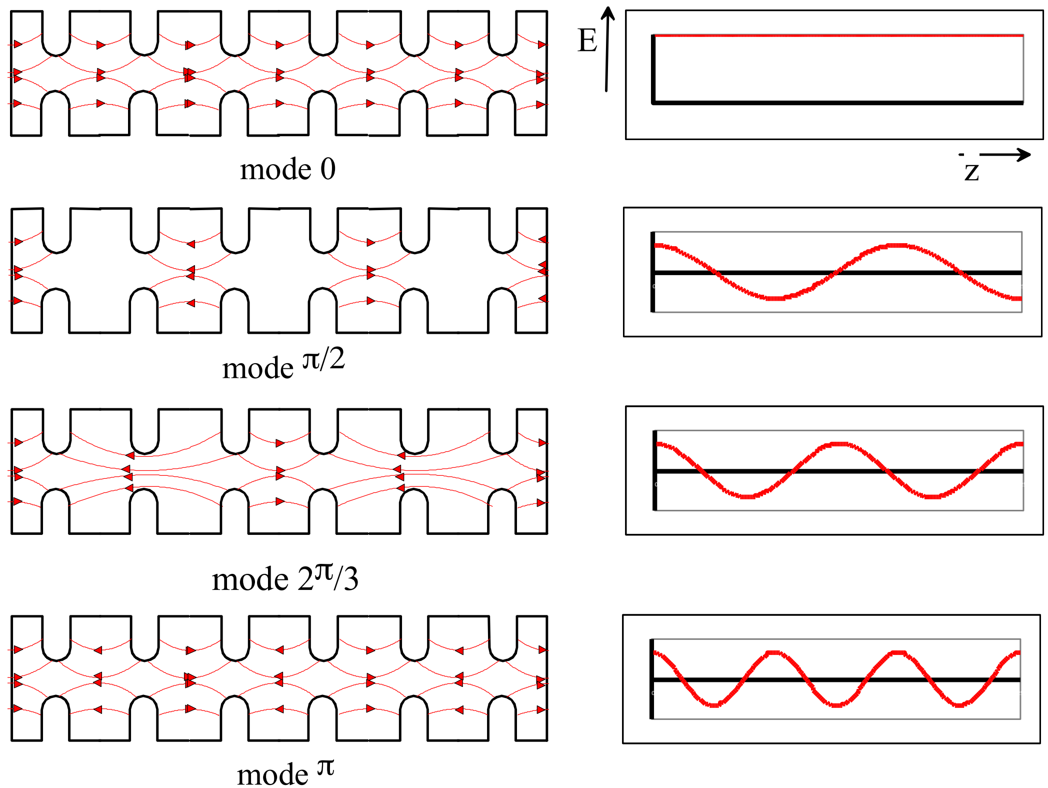
- Standing wave modes are named from the phase difference between adjacent cells: in the example below, mode 0, π/2, 2π/3, π.

- For acceleration, the particles must be in phase with the E-field on axis. We have already seen the π mode:

Synchronism conditions:
0-mode : l = $\beta\lambda$
π/2 mode: l = $\beta\lambda/4$
π mode: l = $\beta\lambda/2$

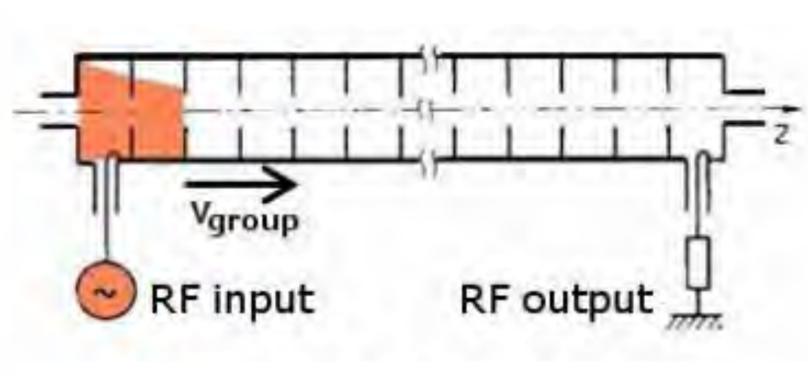
- In standing wave structures, cell length can be matched to the particle velocity!

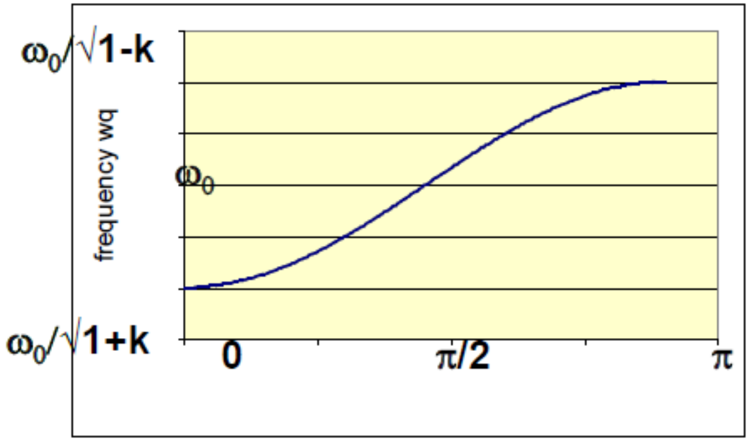
M. Vretenar (CERN), CAS2013



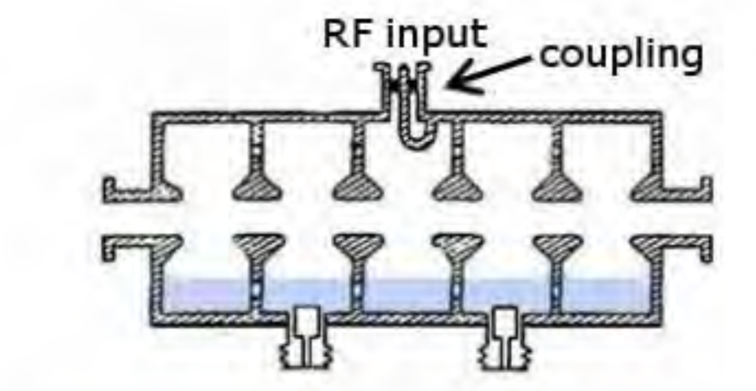
RF accelerating structures

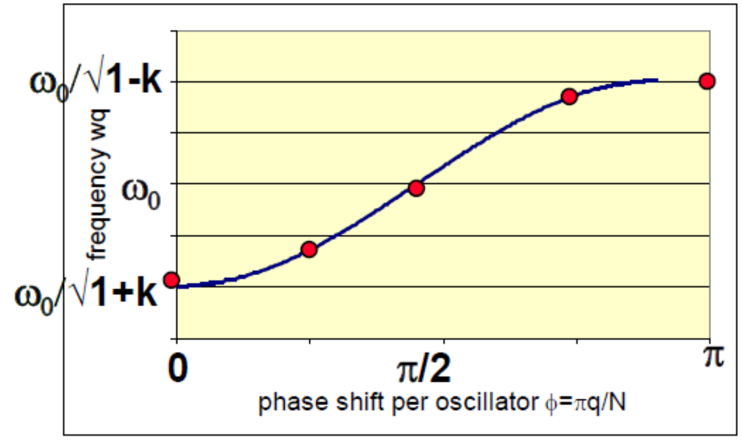
Travelling wave





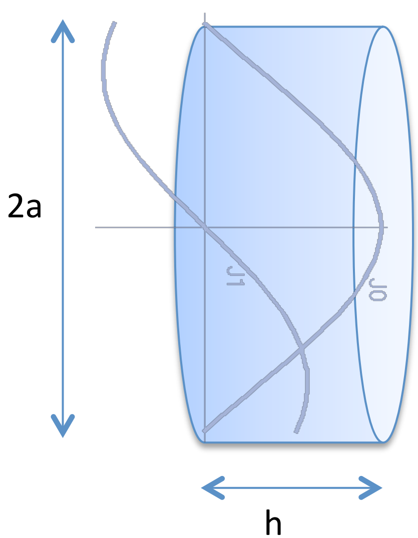
Standing wave

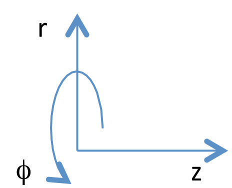




The Pillbox cavity

- The linac we have seen before is composed of an array of accelerating gaps. Each gap can be seen as a **'pill box' cavity**.
- The boundary conditions on the cavity walls ($E_{//} = 0$) force the fields to exist only at certain quantized resonant frequencies → **an integer multiple of half-wavelengths must fit along each direction.**
- Simplest mode is TM_{010} . Indexes indicate number of half wavelength in ϕ, r and z direction → no dependence on z and ϕ, 1 half wavelength in r direction





$$E_z = E_0 J_0(k_r r)\cos(\omega t)$$

$$B_\phi = -\frac{E_0}{c} J_1(k_r r)\sin(\omega t)$$

$$k_r = \frac{2.405}{a} = \frac{\omega_0}{c}$$

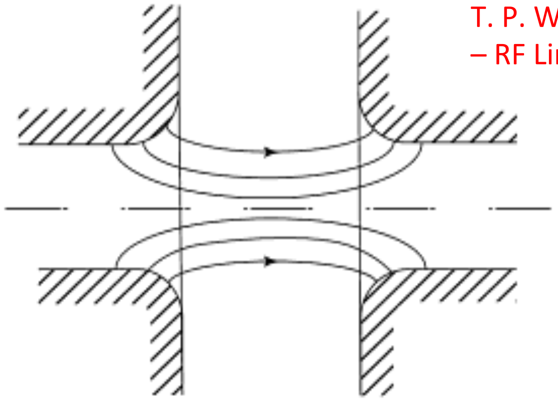
STRUCTURES CHARACTERISTICS

1. Accelerating voltage and energy gain

- The **accelerating voltage** in a gap is defined as:

$$V_{acc} = \int E_z\, e^{j\frac{\omega}{\beta c}z}\,\mathrm{d}z = V_0 T$$

The exponential factor accounts for the variation of the field while particles with velocity βc are traversing the gap.



T. P. Wangler – RF Linacs

- The **transit time factor** is the ratio of the acceleration voltage to the (non-physical) voltage a particle with infinite velocity would see (→ see also Transit time factor next lecture):

$$T = \frac{|V_{acc}|}{\left|\int E_z \mathrm{d}z\right|} = \frac{\left|\int E_z\, e^{j\frac{\omega}{\beta c}z}\mathrm{d}z\right|}{\left|\int E_z \mathrm{d}z\right|}$$

- The **energy gain** of an arbitrary particle with charge q travelling through the gap is:

$$\Delta W = q V_0 T \cos\phi$$

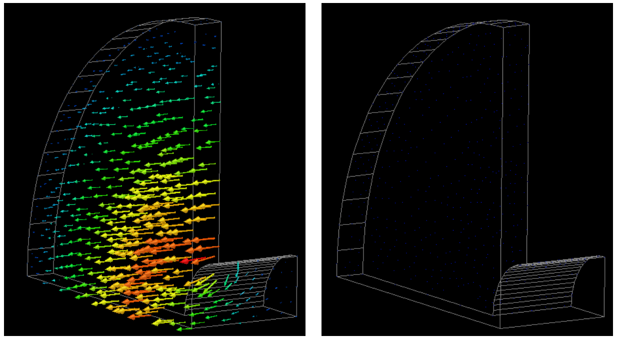
The CERN Accelerator School

2. Stored energy and losses

- The **losses** P_{loss} are proportional to the stored energy W. In steady state, the total stored energy is:

$$W = \iiint_{cavity} \left(\frac{\varepsilon}{2} \left| \vec{E} \right|^2 + \frac{\mu}{2} \left| \vec{H} \right|^2 \right) \mathrm{d}V$$

- The energy into the cavity is stored in the electric and magnetic field. Since E and H are 90° out of phase, the stored energy continuously swaps from electric energy to magnetic energy. The (imaginary part of the) **Poynting vector** describes this energy flux



- `
- In a vacuum cavity, losses are dominated by the **ohmic losses** due to the finite conductivity of the cavity walls

$$\frac{dP_{\text{loss}}}{dA} = \frac{1}{2} R_s |J_s|^2$$

- Surface resistance R_s is related to the **skin depth** δ, which is function of material and frequency:

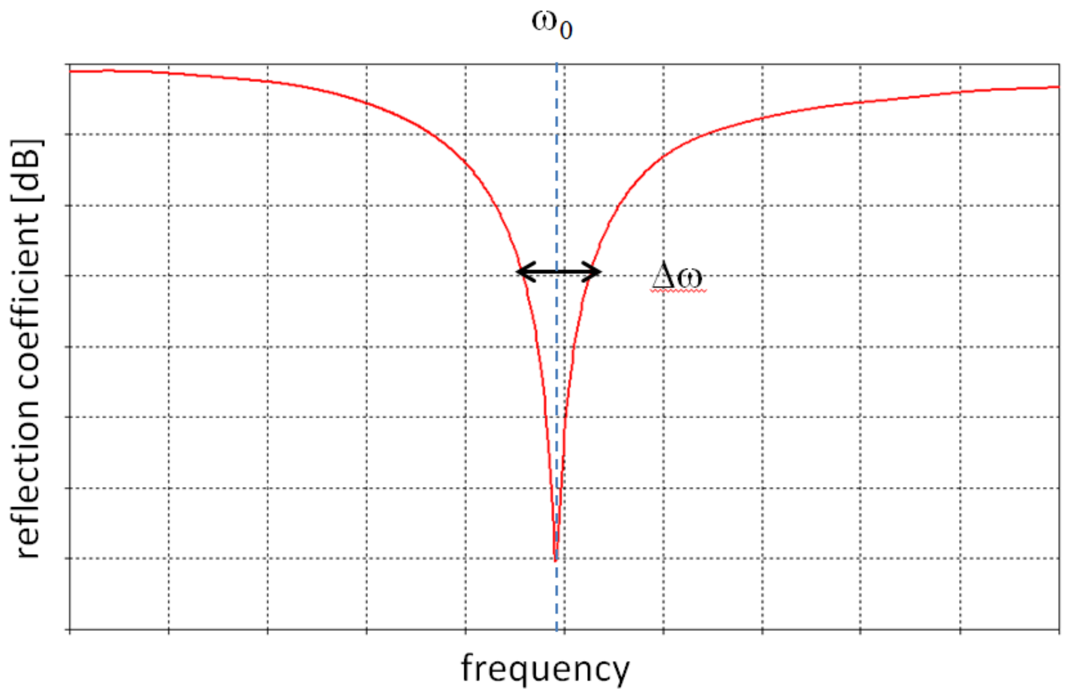
$$R_s = \frac{1}{\sigma\delta} \qquad \delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

3. The quality factor

- The cavity **quality factor** Q is defined as the ratio: $$Q = \frac{\omega_0 W}{P_{loss}}$$
- But, how does a resonance look like?
- We can identify the ratio:

$$\Delta\omega = \frac{P_{loss}}{W}$$

as the FWHM of the resonance centred at frequency ω



- Therefore we have:

$$Q = \frac{\omega_0}{\Delta\omega}$$

4. Structure efficiency:R, Z and R/Q

- The relation between gap voltage and power is characterized by the so-called **shunt impedance**:

$$RT^2 = \frac{|V_{acc}|^2}{P_{loss}} = \frac{(V_0 T)^2}{P_{loss}}$$

- Let L be cavity length, the average axial electric field is:

$$E_0 = \frac{V_0}{L}$$

- Then we can define the effective cavity **shunt impedance per unit length (p.u.l.):**

$$ZT^2 = \frac{RT^2}{L} = \frac{E_0^2 T^2}{P_{loss}/L}$$

- Taking the ratio between R and Q, we can define the quantity R/Q.
- This quantity represents the proportionality constant between the square of the acceleration voltage and the stored energy. It is **independent of cavity losses** (it only depends on the geometry) and it gives a measure of structure efficiency.

$$\frac{R}{Q} = \frac{\dfrac{V_0^{\,2}}{P_{loss}}}{\dfrac{\omega_0 W}{P_{loss}}} = \frac{V_0^{\,2}}{\omega_0 W}$$

Shunt impedance…

- Shunt impedance per unit length Z (measured in Ω/m) is defined as the ratio of the average electric field squared (E0) to the power (P) per unit length (L) dissipated on the wall surface.

$$Z = \frac{E_0^2}{\quad} \cdot \frac{L}{P} \qquad Z = \frac{E_0^2}{\quad} \cdot \frac{dL}{dP} \text{ for TW}$$

- Physically it measures how well we concentrate the RF power in the useful region.
- NOTICE that it is **independent of the field level** and **cavity length**, it depends on the cavity mode (frequency) and geometry (shape).

- IMPORTANT: beware definition of shunt impedance !!! some people use a factor 2 at the denominator (we will see why later); some (other) people use a definition dependent on the cavity length (the R introduced in the previous slide).

… and Effective shunt impedance

- If we want to take into account the **effect on the beam** (this is what we are interested in, isn't it?) we need to include the effect of transit time factor T!

- From shunt impedance (p.u.l.) to **EFFECTIVE SHUNT IMPEDANCE (p.u.l.)**

$$Z = \frac{E_0^2}{\cdot} \cdot \frac{L}{P} \quad \Rightarrow \quad ZT^2 = \frac{(E_0 T)^2}{\cdot} \cdot \frac{L}{P}$$

optimum RF design $\neq$ **optimum structure design adapted to the velocity of the particle to be accelerated**

Summary: structure characteristics

Gap accelerating voltage

$$V_{acc} = V_0 T$$

R*-upon-*Q

$$\frac{RT^2}{Q} = \frac{|V_{acc}|^2}{2\,\omega_0 W}$$

Shunt impedance

$$RT^2 = \frac{|V_{acc}|^2}{2\,P_{loss}}$$

Energy stored inside the cavity

$$W$$

Power lost in the cavity walls

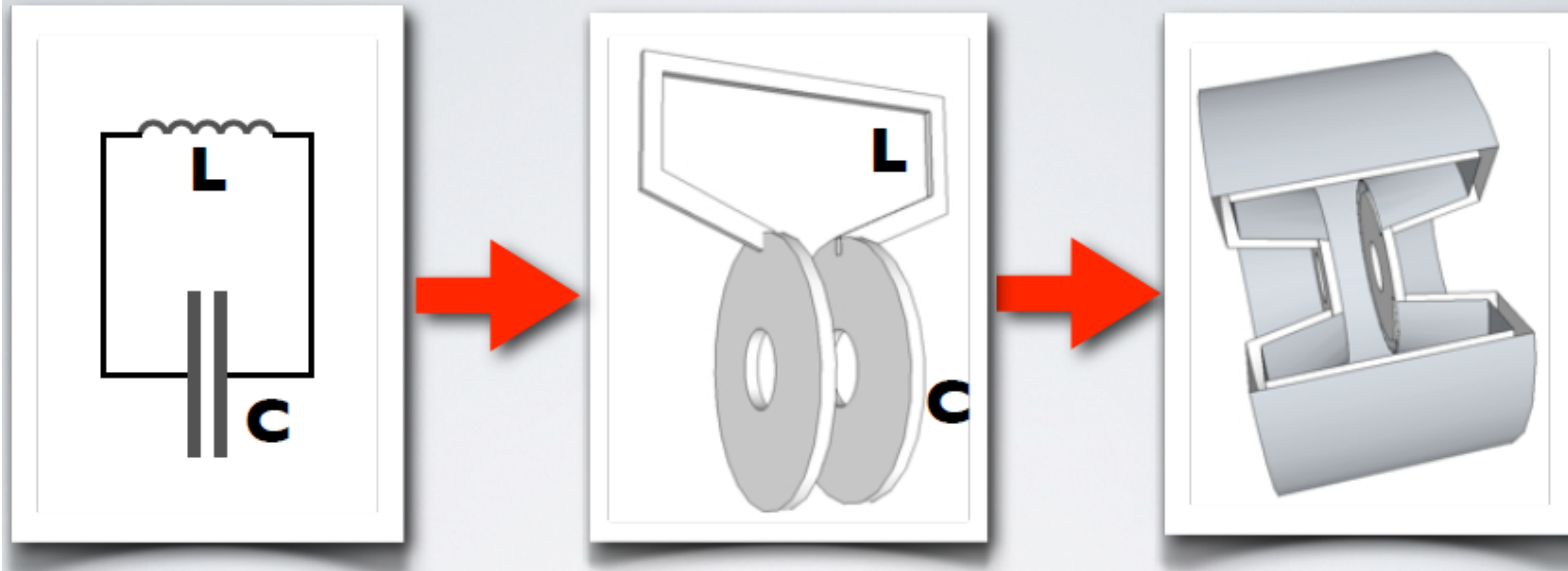
$$P_{loss}$$

***Q* factor**

$$Q = \frac{\omega_0 W}{P_{loss}}$$

Lumped elements circuit model

F. Gerigk (CERN), CAS2010



$$\omega_{res} = 2\pi f_{res} = 1/\sqrt{LC}$$

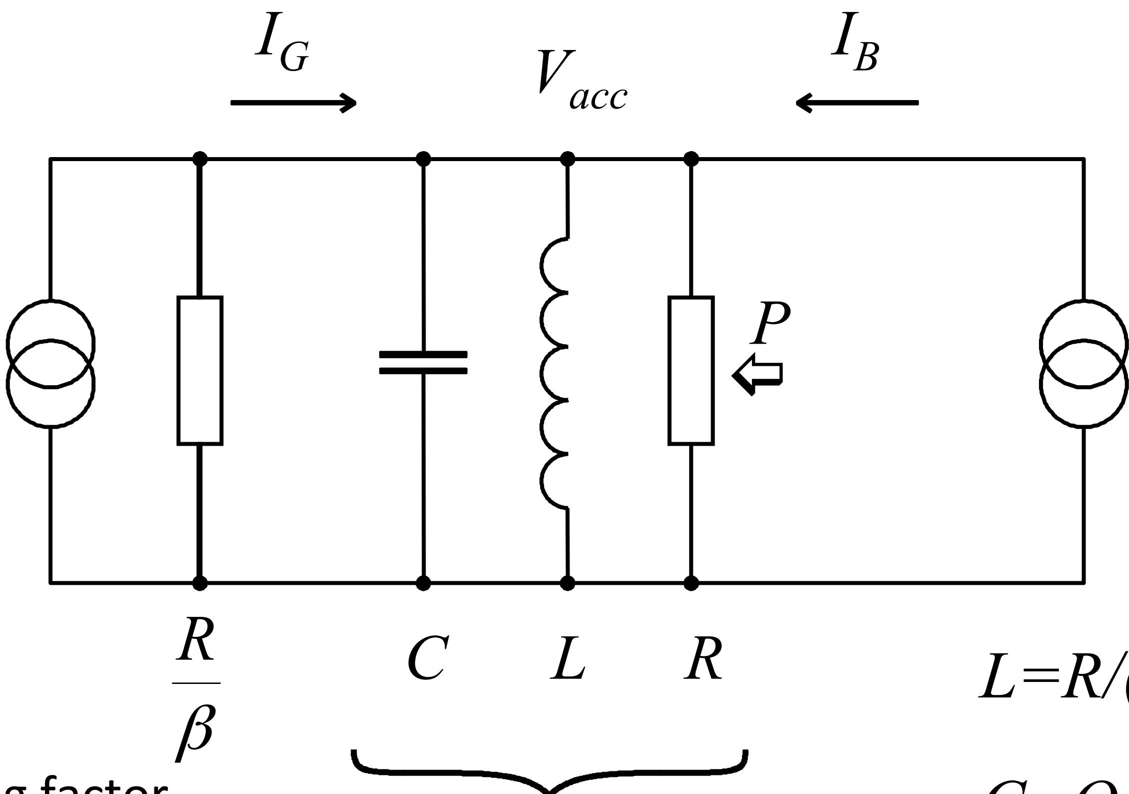
A lumped element resonator transformed into a pillbox cavity

Equivalent circuit

E. Jensen (CERN), CAS2011

Simplification: single mode (given frequency)

Generator



Beam

β : coupling factor

Cavity

$L=R/(Q\omega_0)$

$C=Q/(R\omega_0)$

R: Shunt impedance

$\sqrt{L/C}$: *R*-upon-*Q*

Cavities characteristics

- Resonance frequency $$\omega_0 = \frac{1}{\sqrt{L \cdot C}}$$
- Transit time factor $$\frac{\left| \int E_z e^{j \frac{\omega}{\beta c} z} \mathrm{d}z \right|}{\left| \int E_z \mathrm{d}z \right|}$$

	Circuit definition	Linac definition
Shunt impedance	$\left\|V_{acc}\right\|^2 = 2\,R\;P_{loss}$	$\left\|V_{acc}\right\|^2 = R\;P_{loss}$
Structure quality factor	$\omega_0 W = Q P_{loss}$	$\omega_0 W = Q P_{loss}$
Structure efficiency R/Q	$\frac{R}{Q} = \frac{\left\|V_{acc}\right\|^2}{2\,\omega_0 W} = \sqrt{\frac{L}{C}}$	$\frac{R}{Q} = \frac{\left\|V_{acc}\right\|^2}{\omega_0 W}$

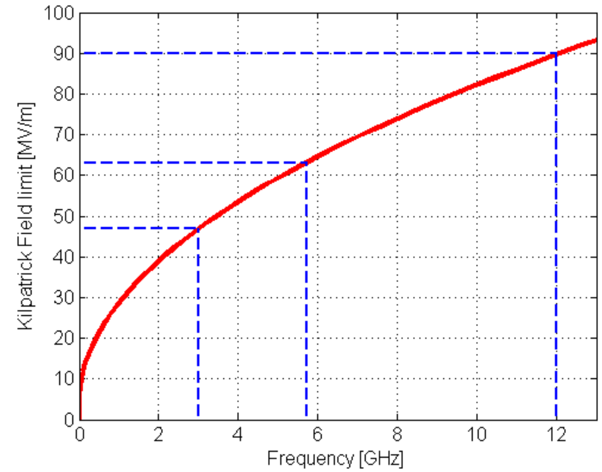
Field limiting quantities

- The peak to average field ratio E_{max}/E_0 of a cavity is defined as the ratio between the maximum Surface electric field E_{max} and the average axial electric field E_0:

$$\frac{E_{max}}{E_0}$$

- The **Kilpatrick criterion** is used as the basis for the peak surface electric-field limit at low frequencies (f < 1 GHz).

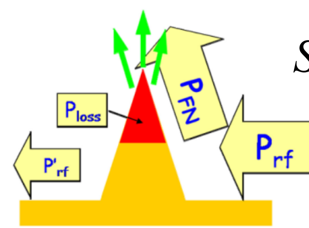
$$f = 1.64 E_K^2 e^{-8.5/E_K}$$



- Experimental evidence supports the model that a combination of electric and magnetic fields at the surface correlate well with the measured breakdown probability.

$$BDR \propto E_0^{30} t_p^5$$

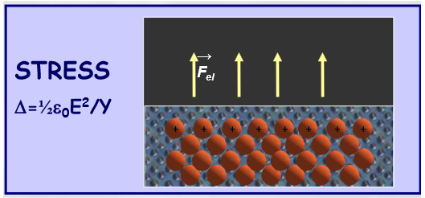
$$BDR \propto S_c^{15} t_p^5$$



$$S_c = \mathrm{Re}(\mathbf{S}) + 1/6\,\mathrm{Im}(\mathbf{S})$$

Grudiev at al., *Phys. Rev. ST Accel. Beams* 12 (2009)

$$BDR \propto e^{a(E_0^2 + kT)}$$



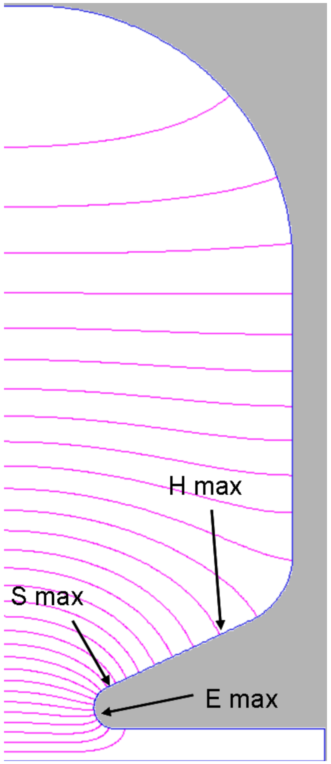
Djurabekova et al., *Phys. Rev. ST Accel. Beams* 15 (2012)

Accelerating cavities optimization

GOALS
1. Energy gain
2. Power consumption
3. Final dose rate
4. **Acceptable cost**

CONSTRAINTS
1. Number of RF sources
2. Repetition rate
3. Mechanical constraints
4. Beam dynamics

DESIGN OPTIMIZATION
1. Structure geometry
2. Tuning features
3. Linac layout (see next lecture)



$$Z' \equiv ZT^2 = \frac{(E_0 T)^2}{P/L}$$

$$W = q(E_0 T) L \cos\phi_S$$

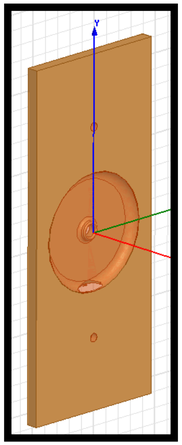
$$W \propto \sqrt{Z' \cdot P \cdot L}$$

Maximum surface field limit: $E_{max} \propto f^{0.45}$

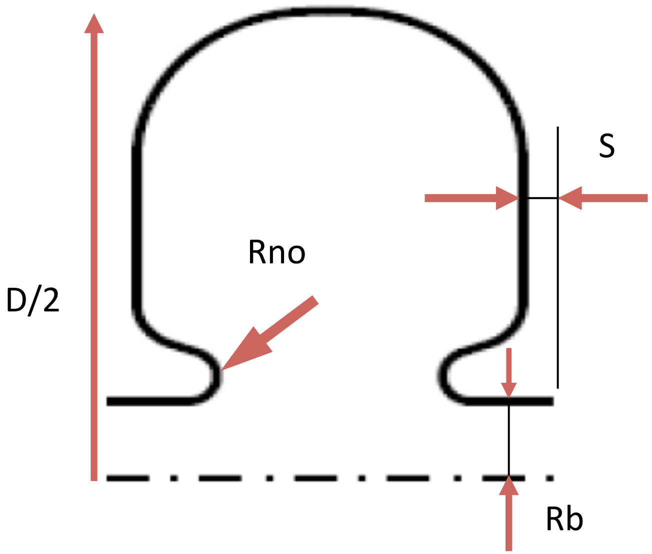
Break-Down Rate (*BDR*): $BDR \approx S_c^{15} t_p^5$

Modified Poynting vector (*Sc*)*: $S_c = \mathrm{Re}\{S\} + g_c \cdot \mathrm{Im}\{S\}$

Example: optimization of a cell



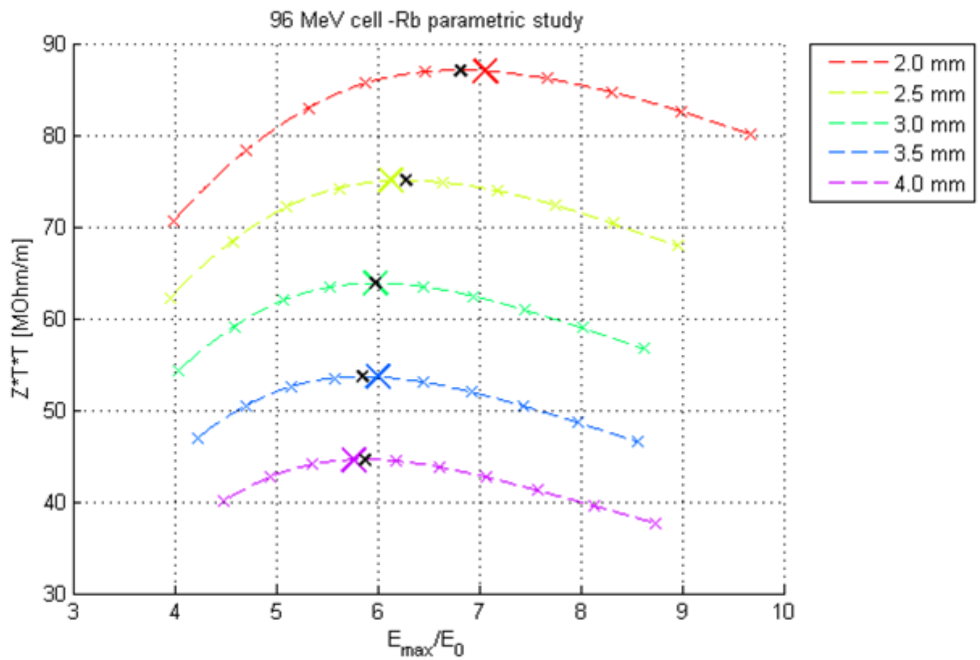
Parameter	
Diameter	D
Bore radius	**Rb**
Septum	S
Outer nose radius	Rno



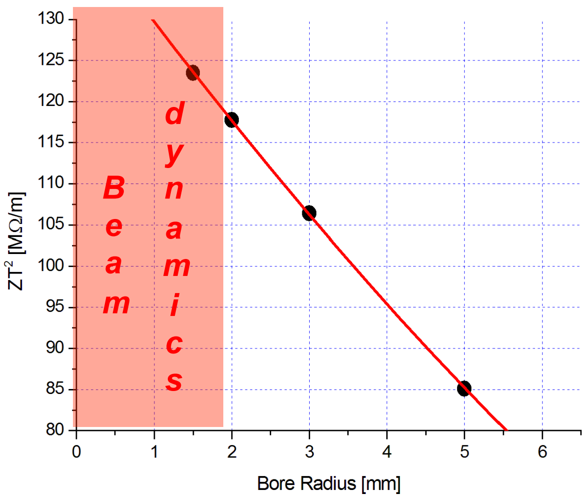
- Optimization of the acc. cell geometry
  - maximize the shunt impedance

$$ZT^2 = \frac{(E_0 T)^2}{P/L} \qquad \Delta W \propto \sqrt{ZT^2 \cdot P \cdot L}$$

  - keep the ratio Emax/E0 < 5
  - resonant freqeuncy at 3 GHz !

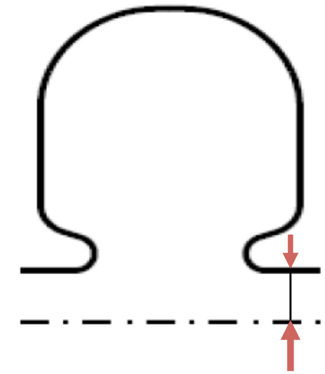


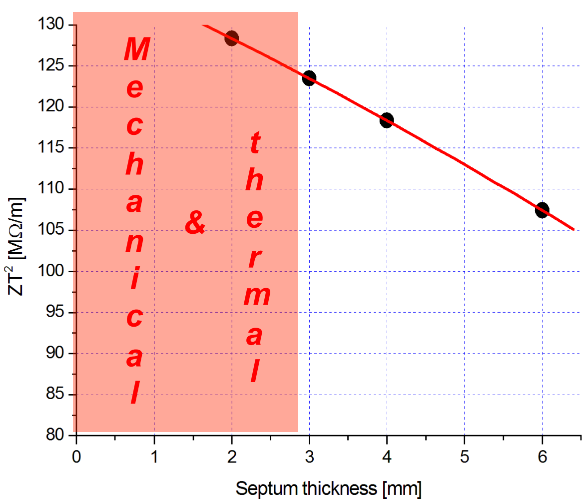
Example of optimization study



+1 mm ~ -10%

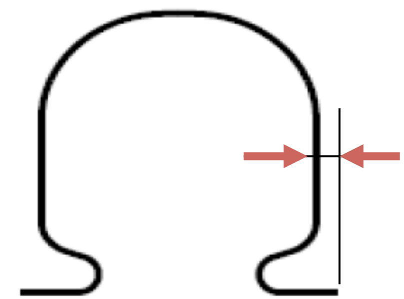
Bore Radius
influence on ZT^2





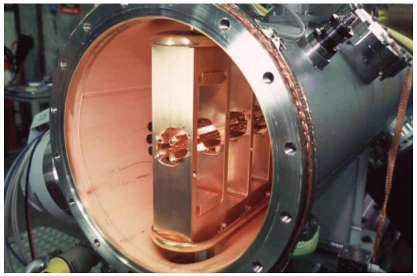
+1 mm ~ -4%

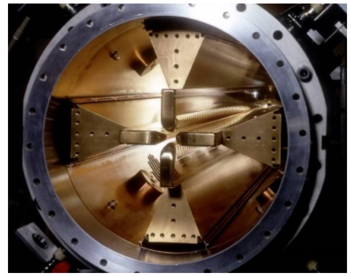
Septum
influence on ZT^2



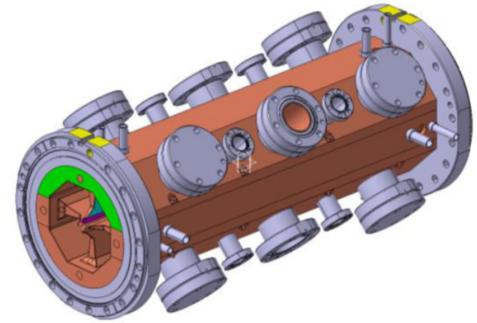
EXAMPLE OF STRUCTURES

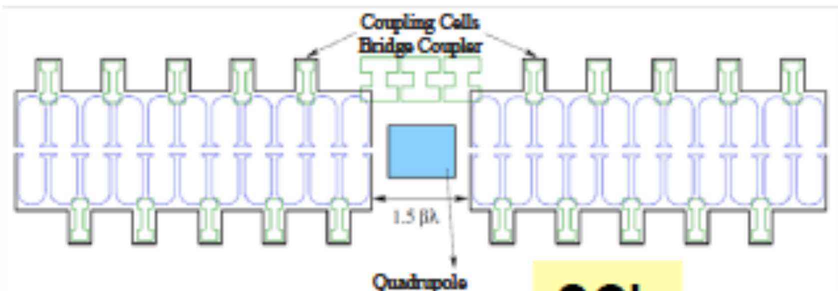
Standing wave normal conducting structures



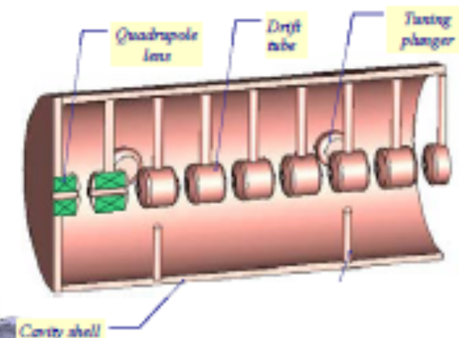


RFQ

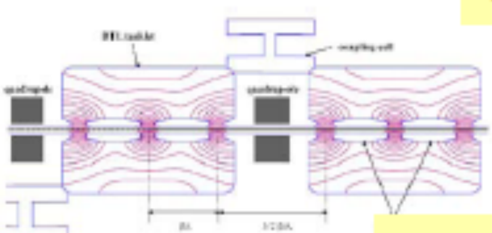




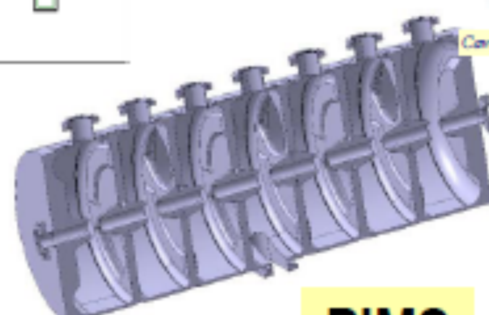
SCL



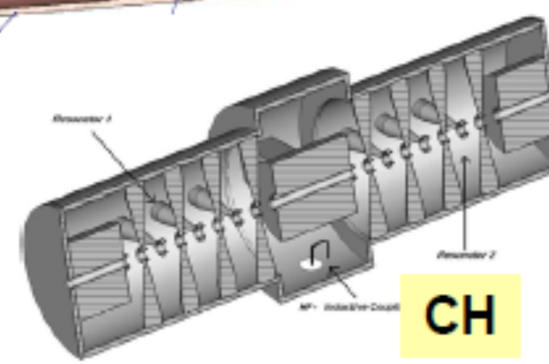
DTL



CCDTL



PIMS



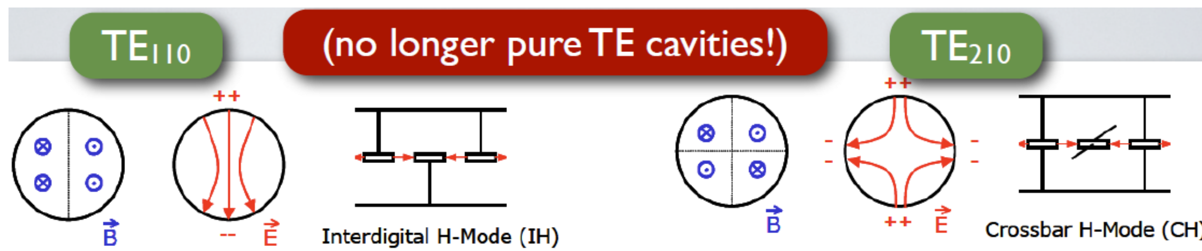
CH

M. Vretenar (CERN), CAS2013

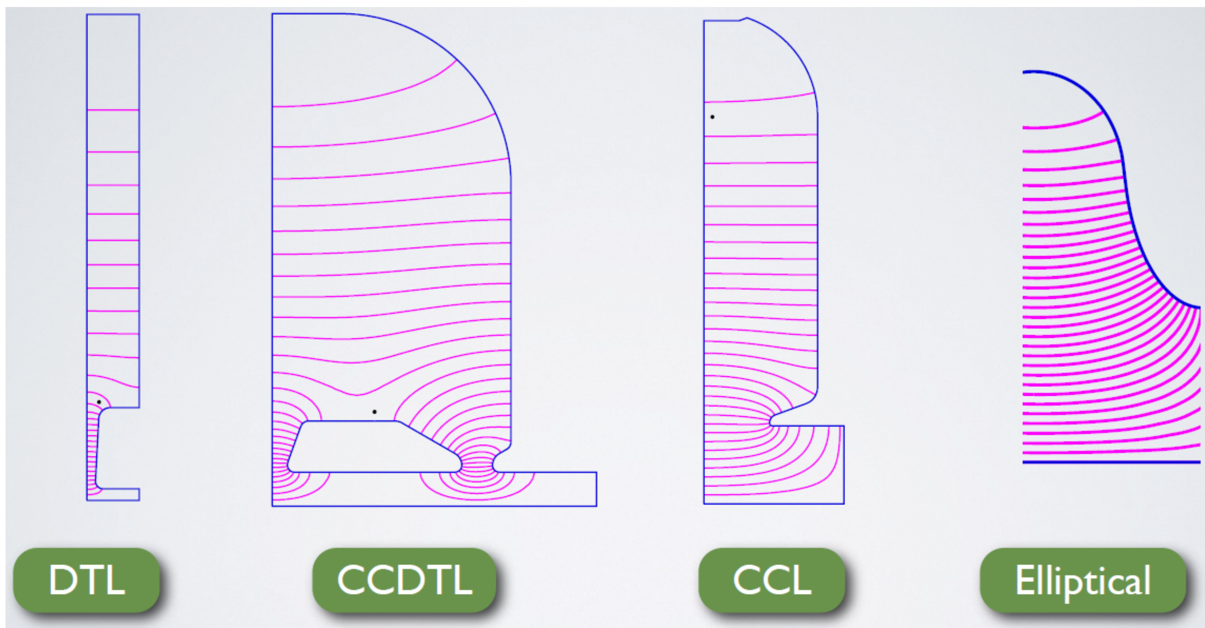
Examples of practical structures

F. Gerigk (CERN), CAS2010

- **TE mode** like structures:
  - RFQ
  - Interdigital H-mode
  - Crossbar H-mode

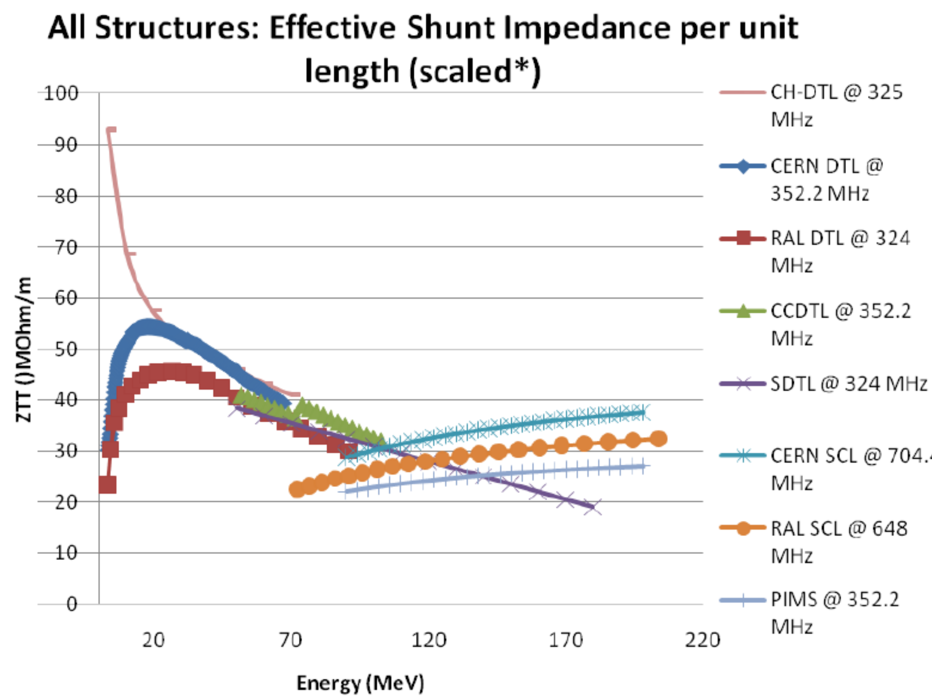


- **TM mode** like structures:
  - Drift Tube Linac
  - Cell Coupled Drift Tube Linac
  - Cell Coupled Linac
  - Elliptical



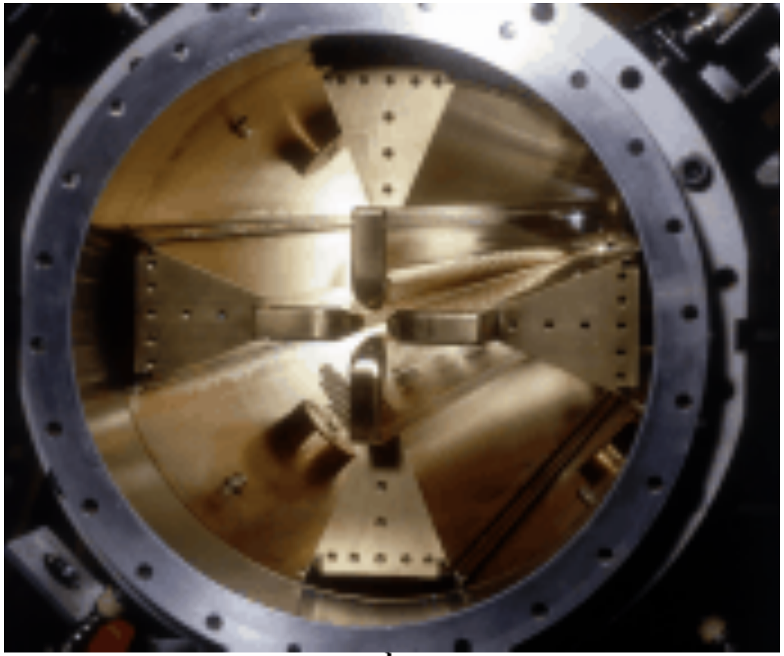
Linac structures layout

- The accelerating efficiency is strongly dependent on the type of structure used and on the beam energy
- For proton linac, several structures are used in sequence to adapt to the increasing particle velocity β
- In order of increasing β typical structures are:
    1. RFQ
    2. DTL or SCDTL
    3. CCL

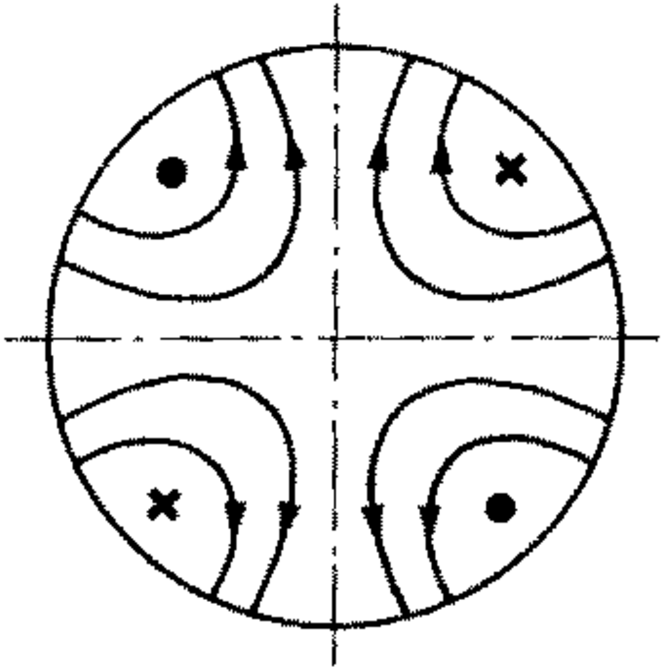


CARE-Report-2008-071-HIPPI (2008)

Back to TE modes: the RFQ



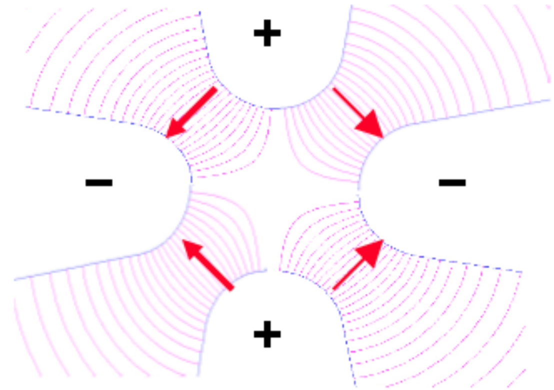
Cavity with vanes

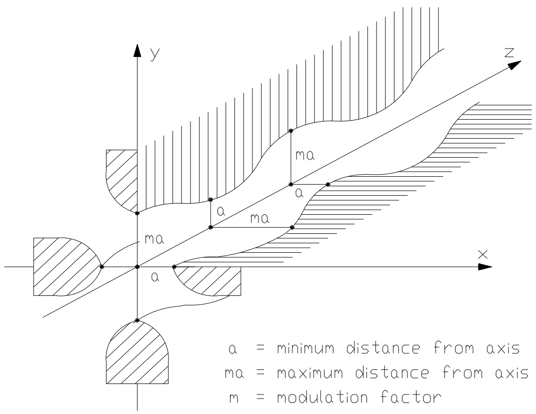


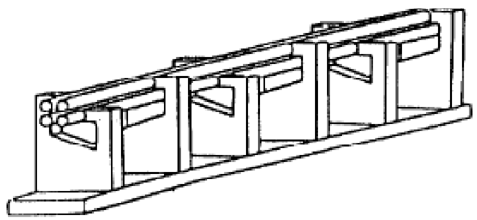
Empty cavity; mode TE_{21}

The Radio Frequency Quadrupole

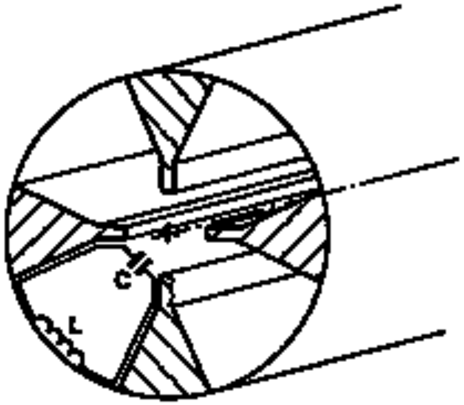
- The Radio Frequency Quadrupole is a special RF structure used for acceleration of low β protons and ions
- It uses a quadrupolar electric field to:
    1. **bunch** the beam adiabatically
    2. **focusing** the beam transversally
    3. **accelerating**
- There are 2 types: 4 vanes and 4 rods
- Typical frequencies used 10-350 MHz!
- Machining tolerances and related frequency errors limit scaling up in frequency

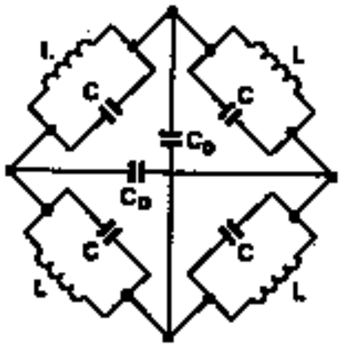


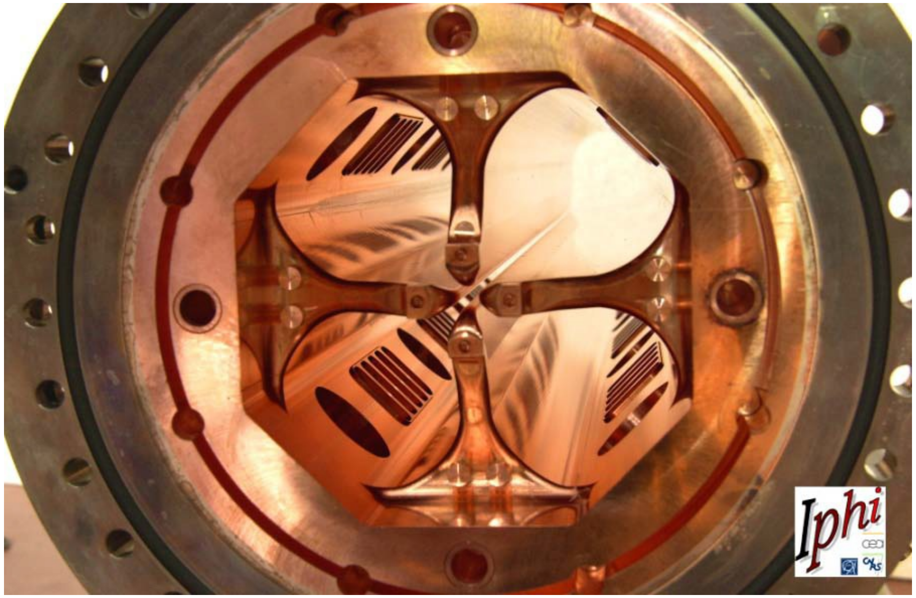




The 4 vane-structure



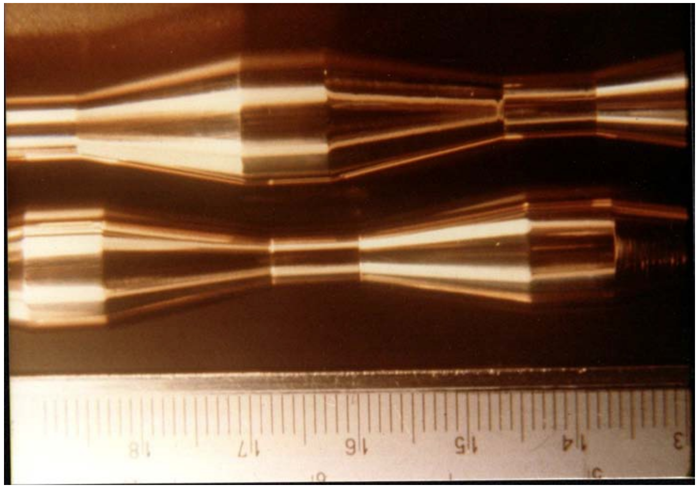




- **Capacitance** between vane tips, **inductance** in the inter-vane space
- Each **vane** is a resonator!
- Frequency **depends on cylinder dimensions** (good at frequency of the order of 200MHz, at lower frequency the diameter of the tank becomes too big)
- Vane tip are machined by a computer controlled milling machine.
- **Need stabilization** (problem of mixing with dipole modeTE110)

The 4 rod-structure

- **Capacitance** between rods, **inductance** with holding bars (remember the circuit model!)
- **Each cell** is a resonator!
- Cavity dimensions are independent from the frequency
- Easy to machine (better access)
- Problems with end cells, less efficient than 4-vane due to strong current in the holding bars

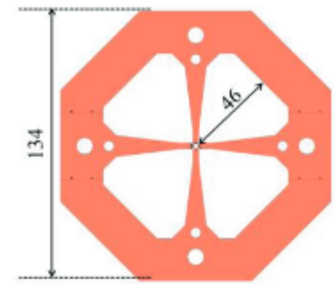


The CERN Accelerator School

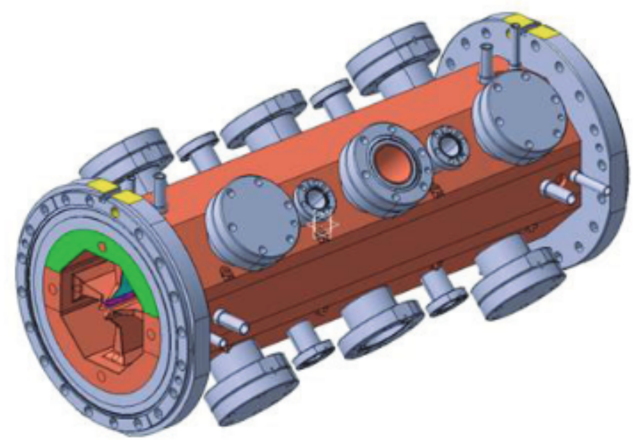
The High Frequency RFQ for medical applications

CERN

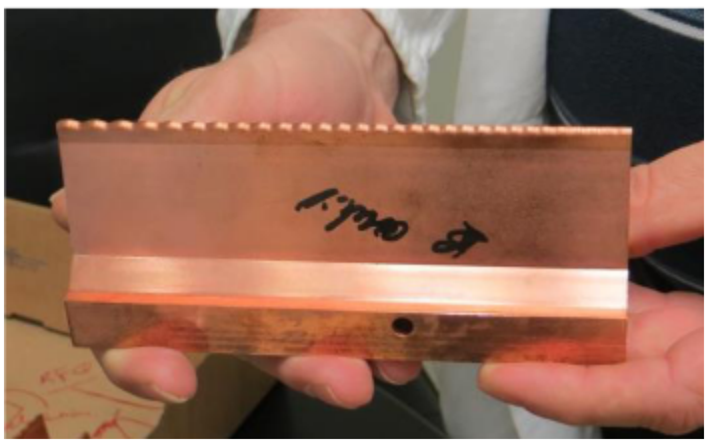
750 MHz RFQ - 4 MODULES
40 keV-5 MeV in 2 meter

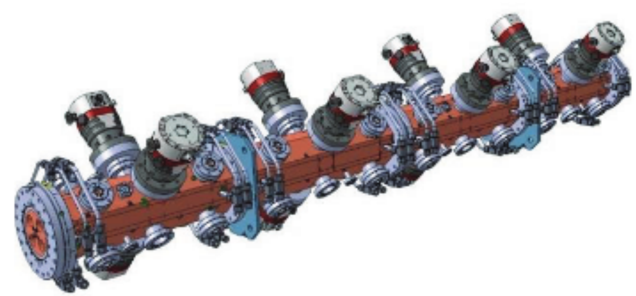


1. Injector for proton therapy linac
2. Two units (10 MeV) for radioisotope production



Modulation machining test on a minor vane



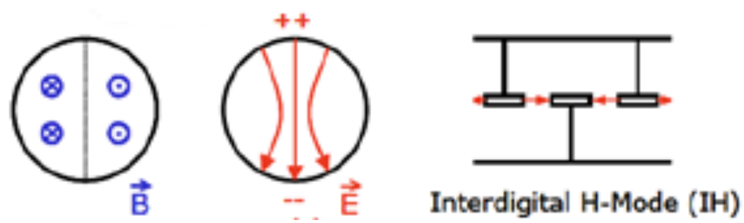


LINAC Conference 2014,
M. Vretenar et al.
A COMPACT HIGH-FREQUENCY RFQ FOR MEDICAL APPLICATIONS

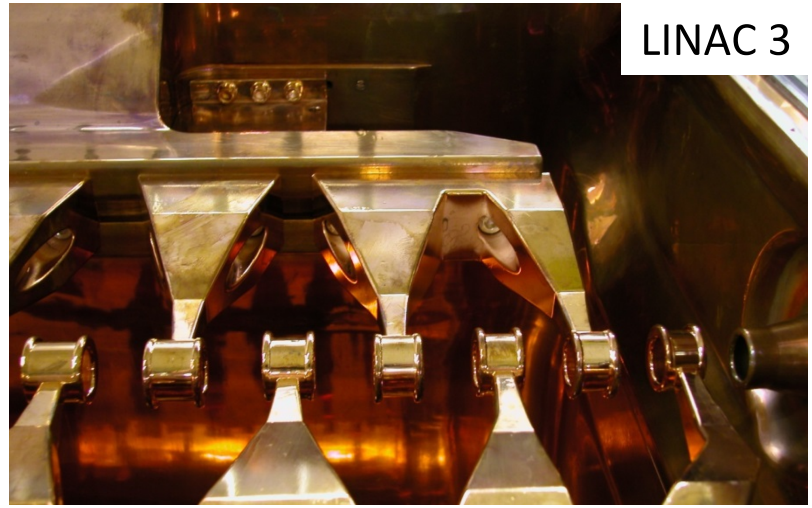
IPAC Conference 2015,
A. Lombardi et al.
BEAM DYNAMICS IN A HIGH FREQUENCY RFQ

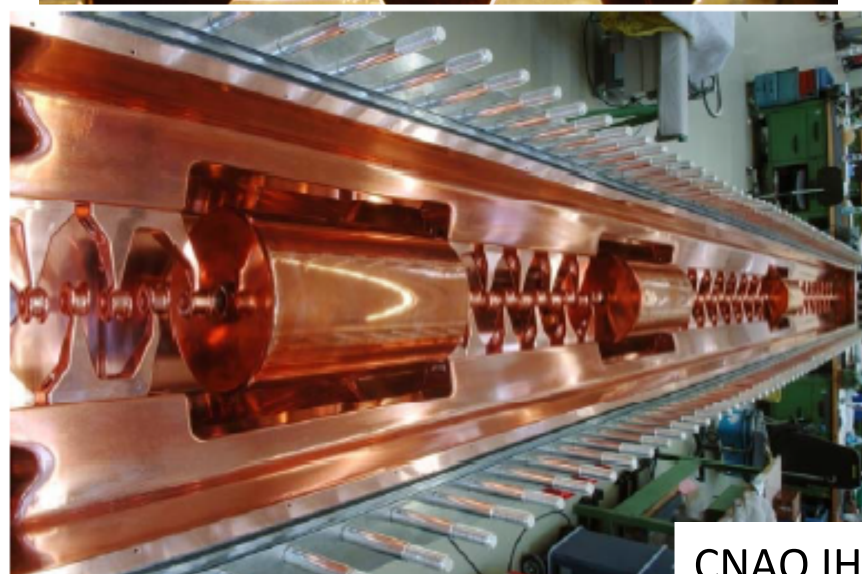
Interdigital H structure

- TE mode (also called H mode)
- Transverse electric field is pushed along the axis by the presence of the stems



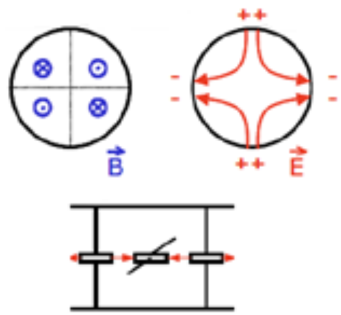
- Good ZT^2 for **very low β** (0.02-0.08) and **low frequency** (f ~ 200 MHz)
- Low intensities beam


LINAC 3


CNAO IH

CLUSTER: a CH structure for proton therapy

- Another **TE mode** like structure!
- Two stems per drift tube alternated from one cell to the next

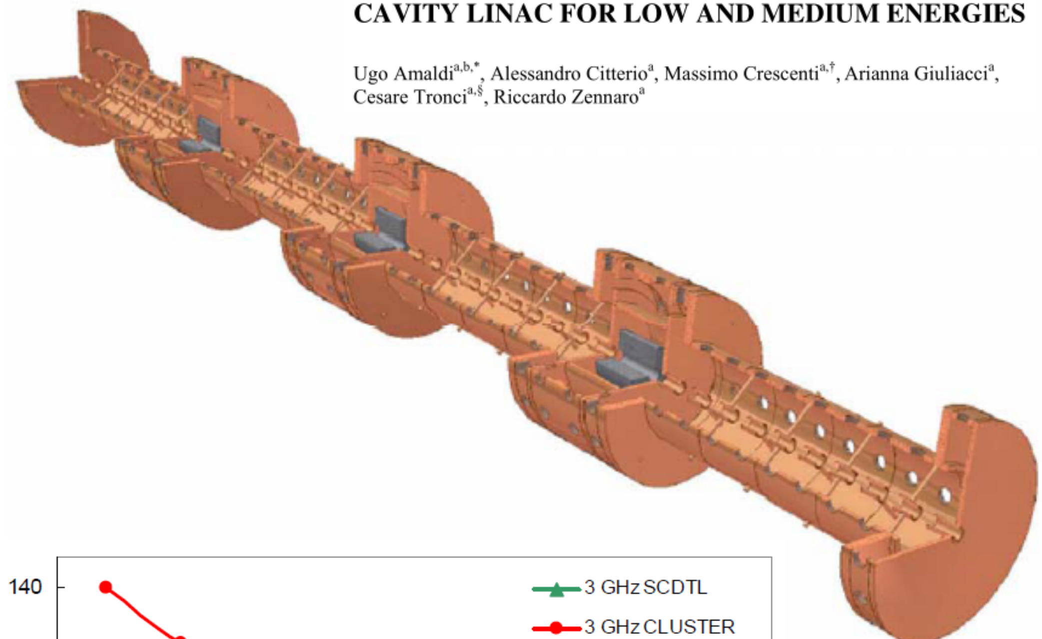


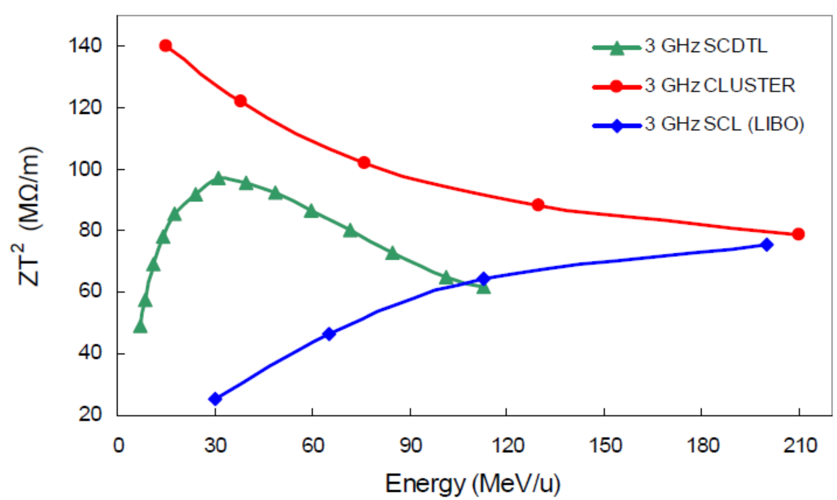
Crossbar H-Mode (CH)

- H-mode structures are more efficient at low beta than SCDTL and SCL

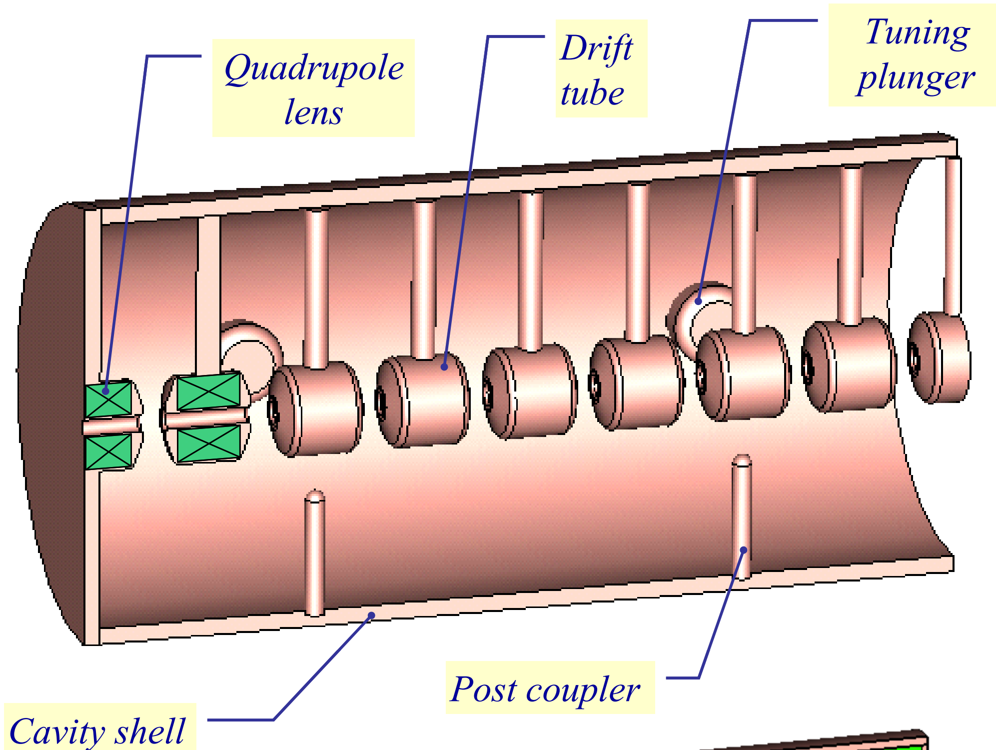
CLUSTER: A HIGH FREQUENCY H-MODE COUPLED CAVITY LINAC FOR LOW AND MEDIUM ENERGIES

Ugo Amaldi[a,b,*], Alessandro Citterio[a], Massimo Crescenti[a,†], Arianna Giuliacci[a], Cesare Tronci[a,§], Riccardo Zennaro[a]

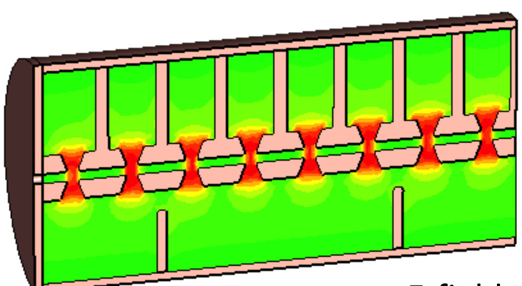


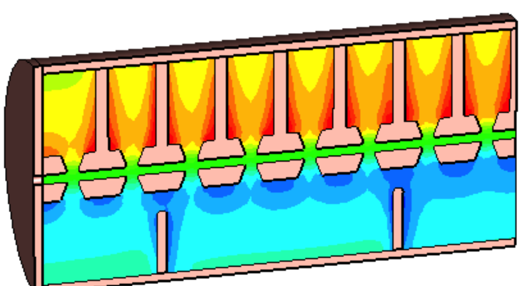


The Drift Tube Linac (DTL)

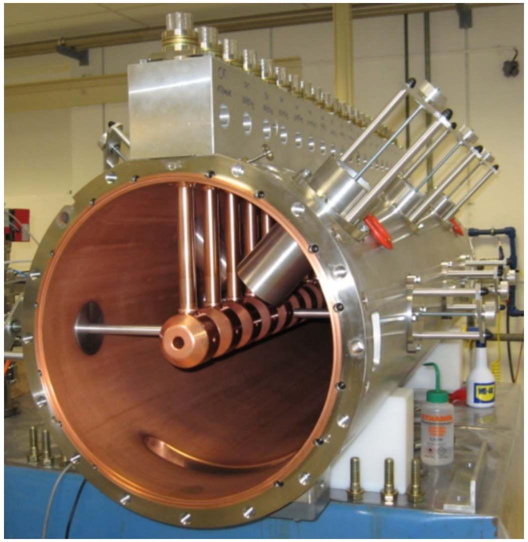


- Standing wave linac structure for protons and ions
- β=0.1-0.5, f=20-400 MHz
- Drift tubes are suspended by stems
- Coupling between cells is maximum (no slot, fully open!)
- The 0-mode allows a long enough cell (d=βλ) to house focusing quadrupoles inside the drift tubes

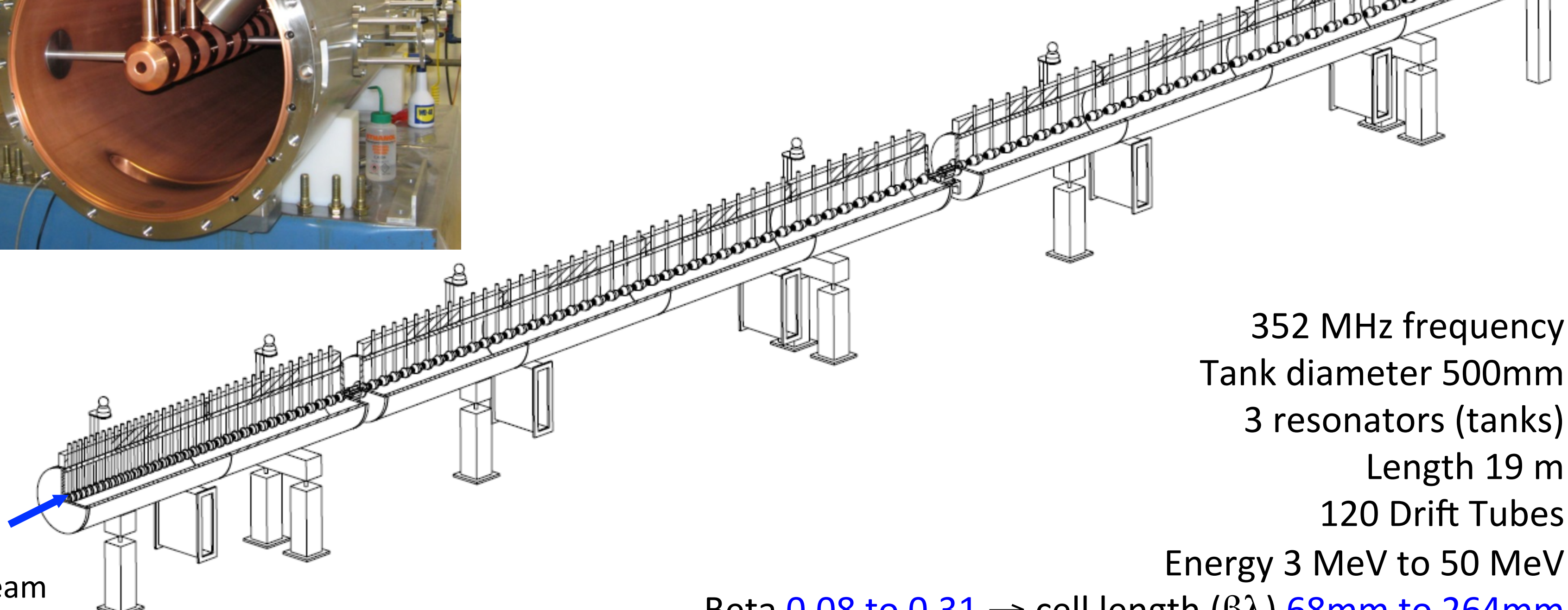




Example: the Linac4 DTL



DTL tank 1 fully equipped: focusing by small permanent quadrupoles inside drift tubes.



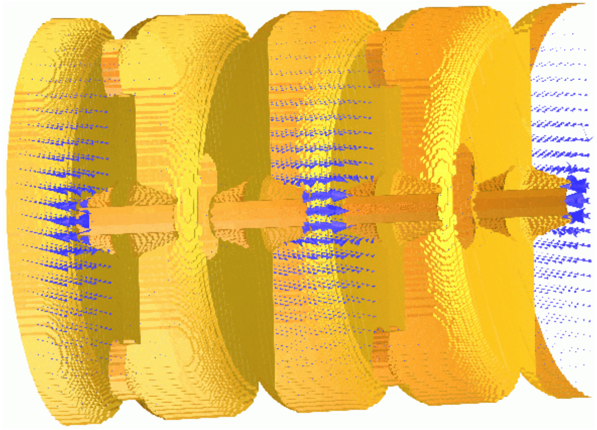
beam

M. Vretenar (CERN), CAS2013

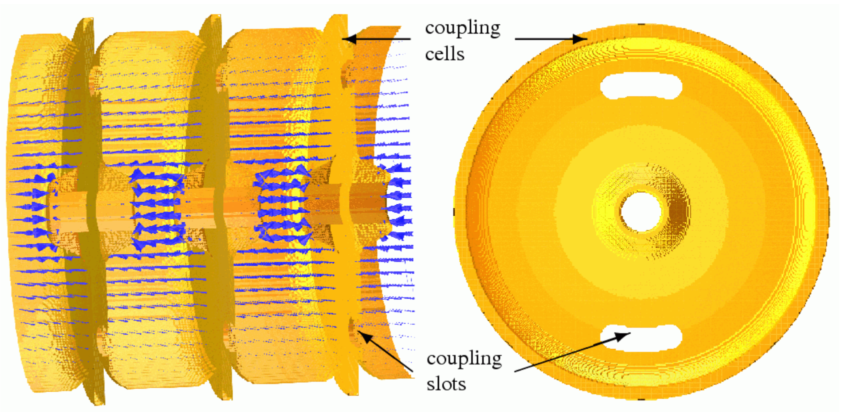
352 MHz frequency
Tank diameter 500mm
3 resonators (tanks)
Length 19 m
120 Drift Tubes
Energy 3 MeV to 50 MeV
Beta 0.08 to 0.31 → cell length ($\beta\lambda$) 68mm to 264mm
→ factor 3.9 increase in cell length

Example of Cell Coupled Linacs

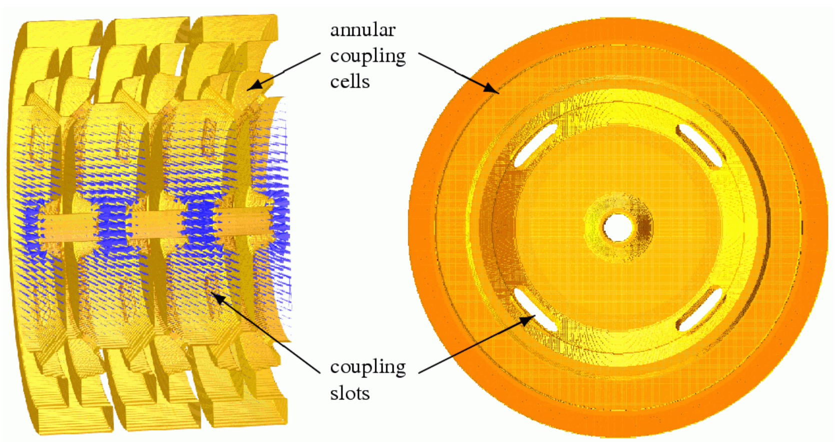
π/2-mode in a coupled-cell structure



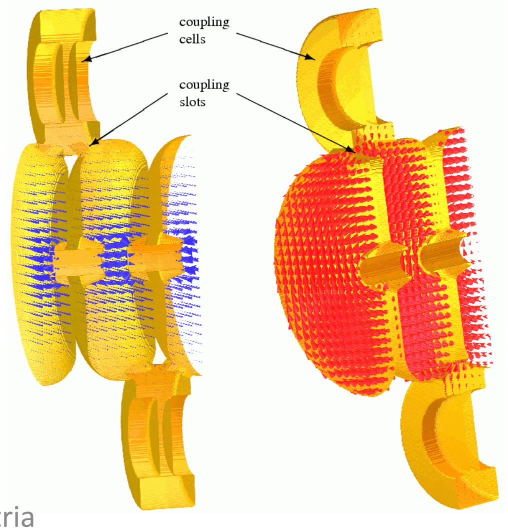
On axis Coupled Structure (OCS)



Annular ring Coupled Structure (ACS)

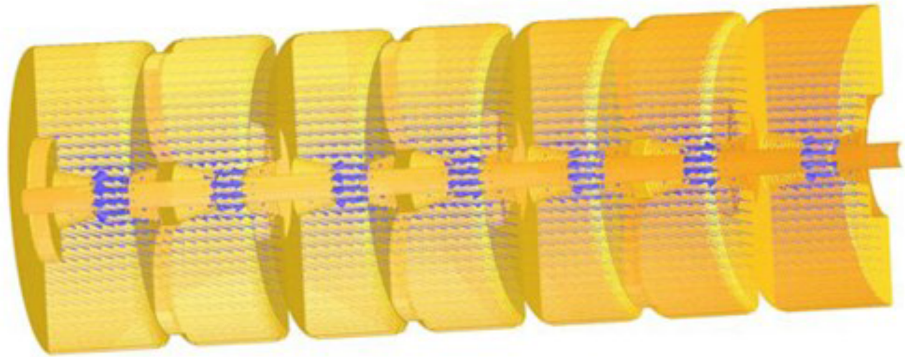


Side Coupled Structure (SCS)

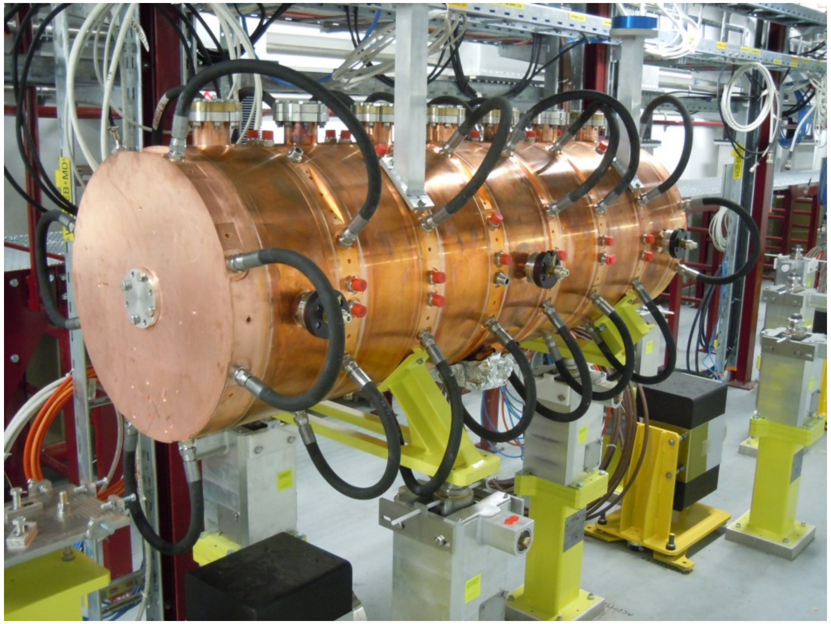


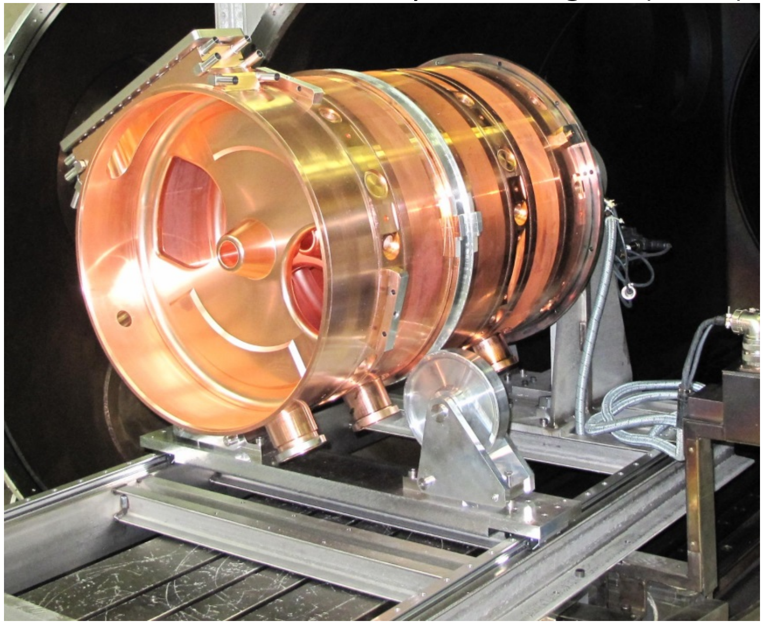
PIMS structure for LINAC 4

352 MHz PI Mode Structure
intermediate β structure
102-160 MeV - **22 meter**
12 Modules 7 cells

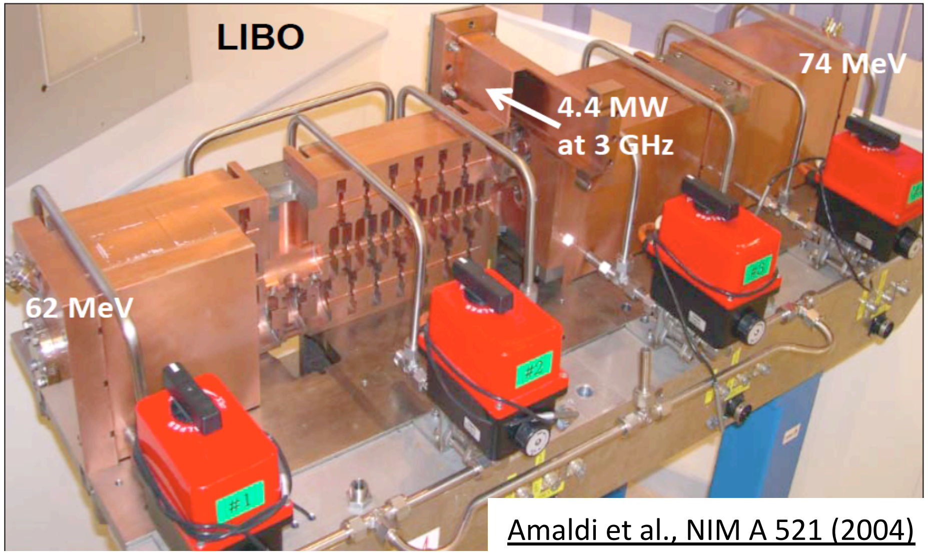


courtesy of R. Wegner (CERN)



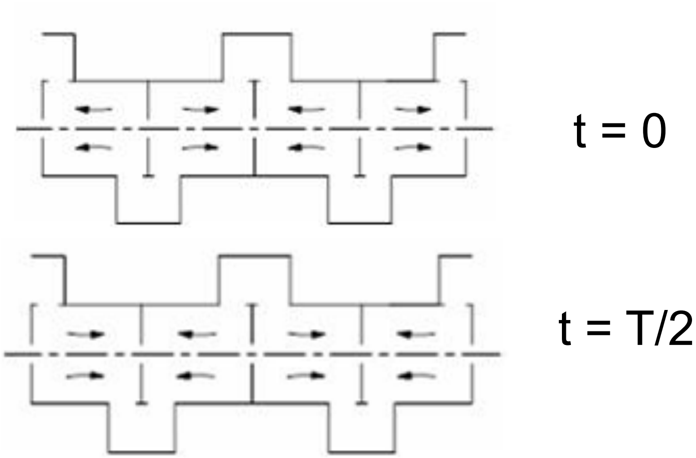


LIBO (Linac Booster): the first 3 GHz SCL for proton therapy



Amaldi et al., NIM A 521 (2004)

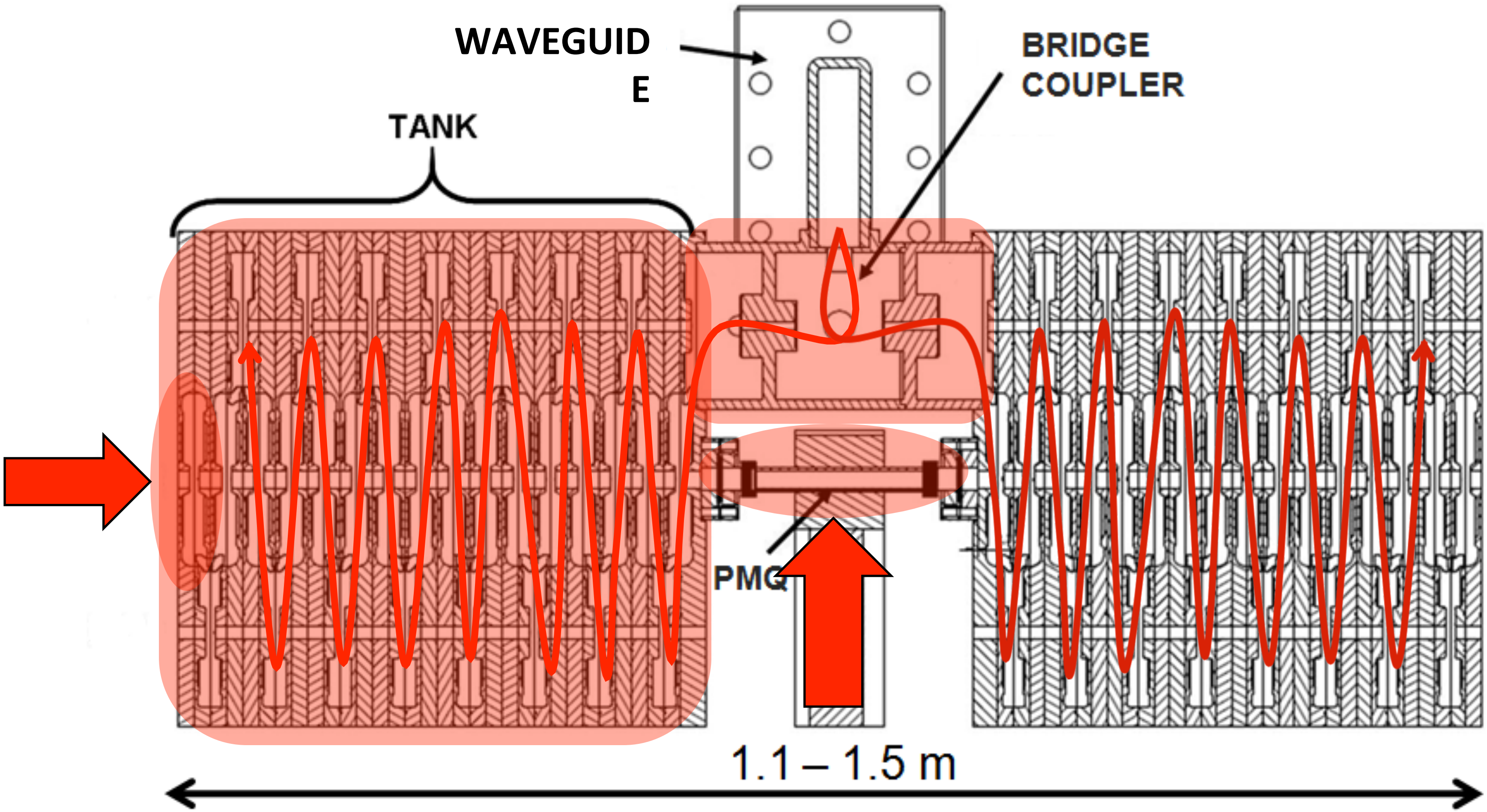
- Linear accelerating structure:
  - *Standing wave*
  - *π/2 mode*
  - *Biperiodic structure (off-axis coupling cavities)*



- Synchronism condition:

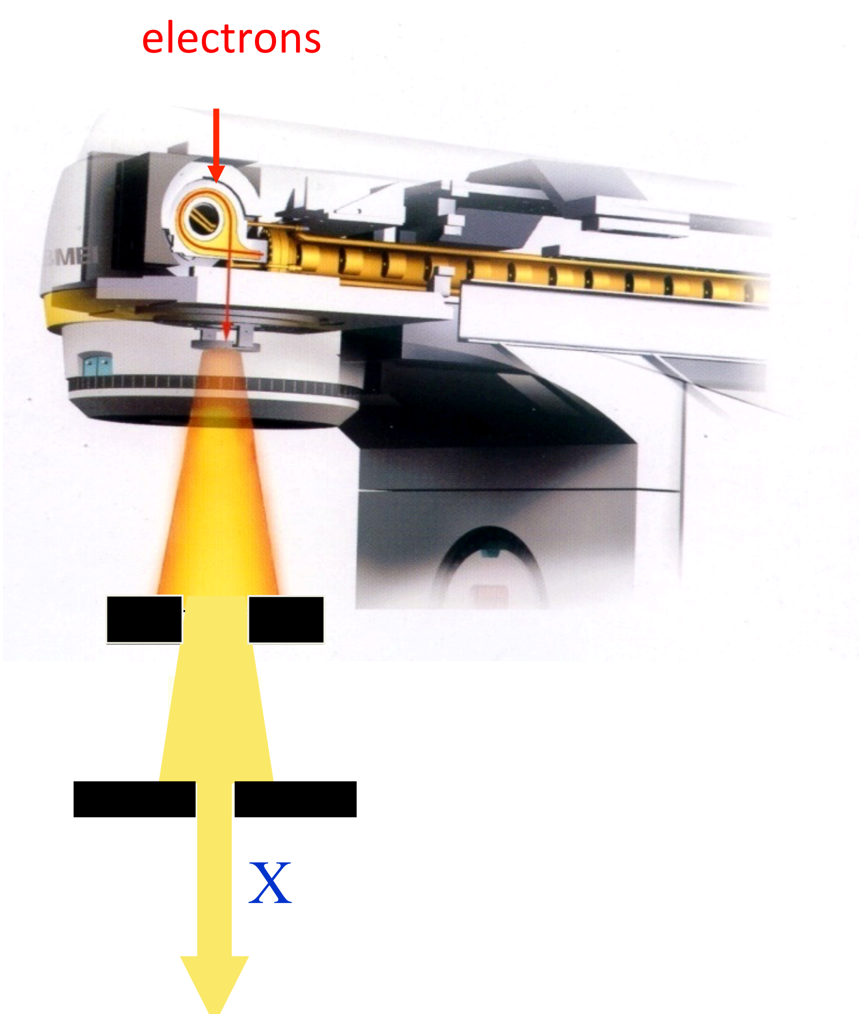
$$L = v \cdot \frac{T}{2} = \beta c \frac{\lambda}{2c} = \frac{\beta \lambda}{2}$$

Accelerating unit
Side Coupled Linac

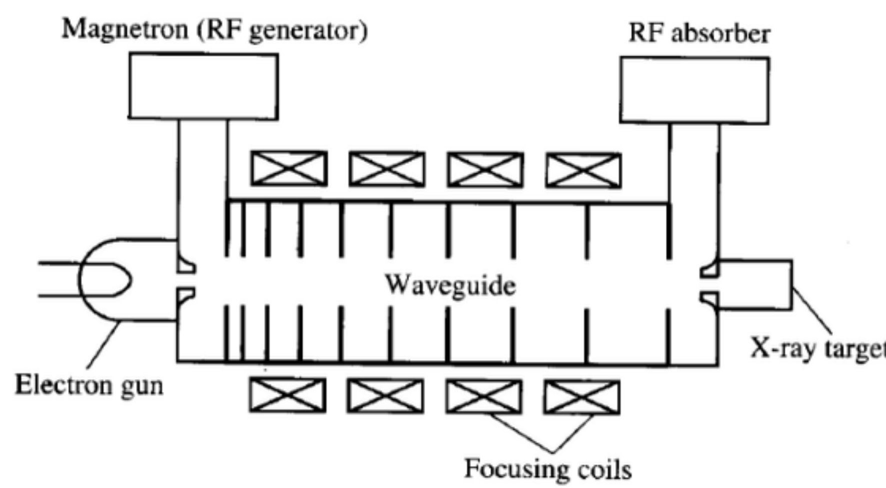


LINACS FOR MEDICAL APPLICATIONS

Linacs for medical applications!



- The most used linacs with E > 1 MeV in the world are radiotherapy linacs!
- About 10’000 e- linacs are used daily for radiotherpay
- Electron tubes can be both SW or TW
- RF sources: magnetrons or klystrons in the 5 MW range



Typical configuration of a linear accelerator

Electron linacs

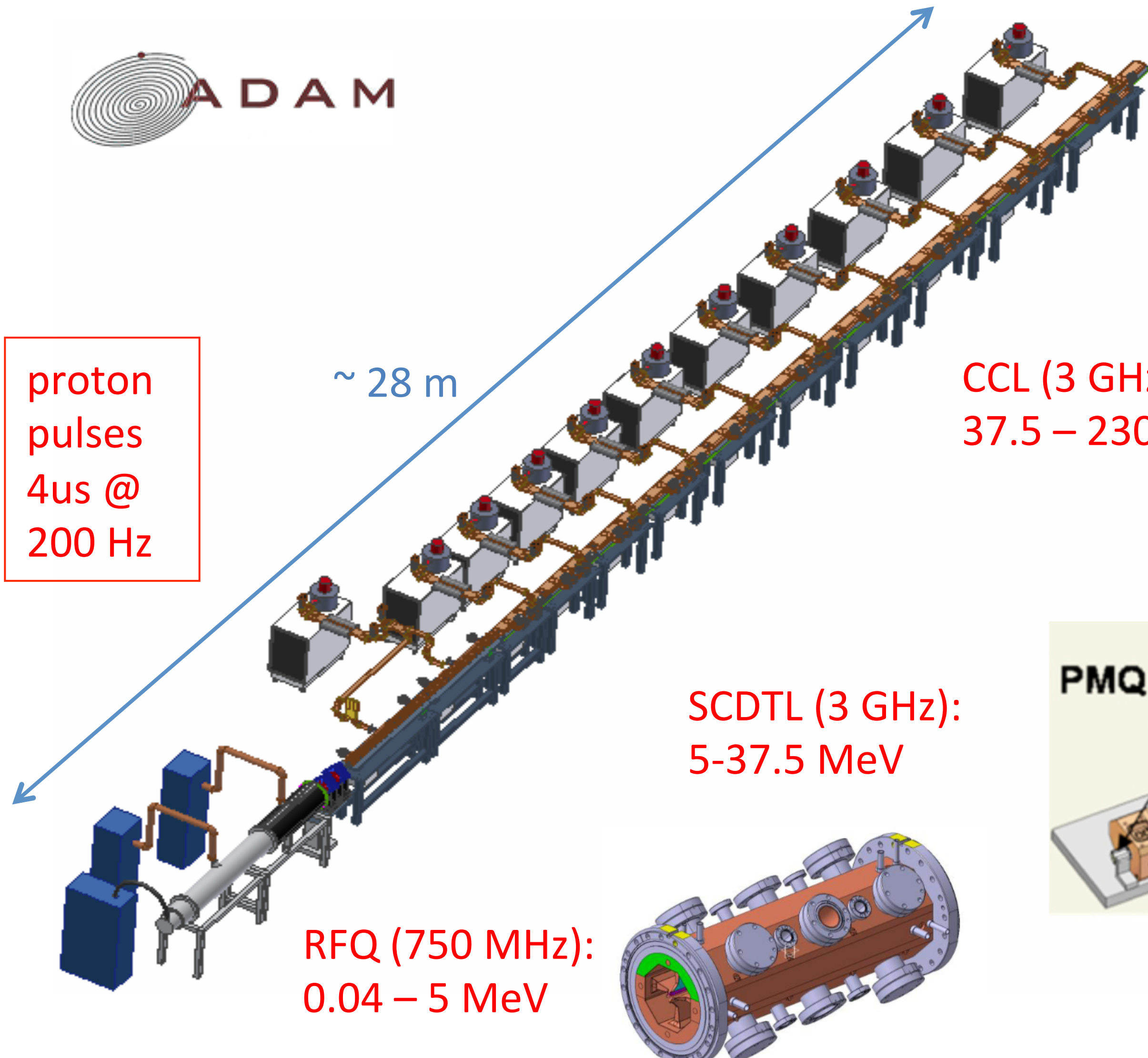
[To order these specialized brazed products contact us today](#).

- **Energy range of linacs: 4-25 MeV**
- **Electrons are accelerated by microwaves (10^3-10^4MHz)**
- **Philips SL-75/5: S-band 2856 MHz, MW cavities dimensions - lenght 3 cm, radius 5 cm, electrons 5 MeV, tungsten target**

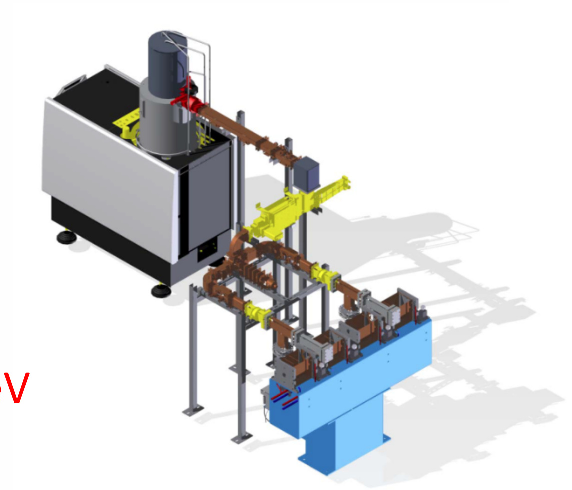
An example of full linac solution for proton therapy by A.D.A.M. SA.

ADAM

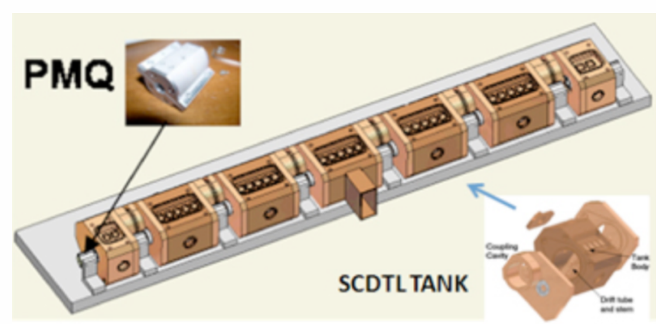
proton pulses
4us @
200 Hz



CCL (3 GHz):
37.5 – 230 MeV



SCDTL (3 GHz):
5-37.5 MeV



RFQ (750 MHz):
0.04 – 5 MeV

Bibliography

General Introductions to linear accelerators

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P. Lapostolle, M. Weiss, **Formulae and Procedures useful for the Design of Linear Accelerators**, CERN-PS-2000-001 (DR), 2000

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T. P. Wangler, **Principles of RF Linear Accelerators** (Wiley, New York, 2008)

S. J. Orfanidis, **Electromagnetic Waves and Antennas** (2014)
http://www.ece.rutgers.edu/~orfanidi/ewa/

D. M. Pozar, **Microwave engineering** (Wiley, 2012)

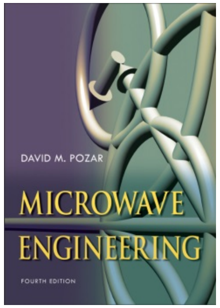
Yellow books:

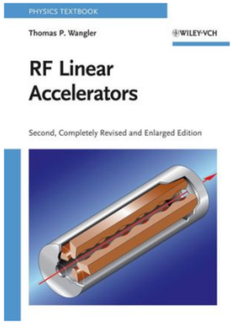
M. Weiss, Introduction to RF Linear Accelerators, CERN-94-01 (1994), p. 913

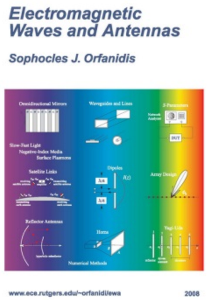
N. Pichoff, Introduction to RF Linear Accelerators, CERN-2005-04 (2005)

M. Vretenar, Differences between electron and ion linacs, CERN-2006-012

Proc. of specialized CAS: **RF for accelerators**, R. Bailey ed., CERN-2011-007







Acknowledgements

Material used from:

- E. Jensen, RF Cavity Design (CAS 2011 - Chios)
- M. Vretenar, Introduction to RF Linear Accelerators (CAS 2009 - Divonne)
- M. Vretenar, Linear Accelerators (CAS 2013 - Trondheim)
- F. Gerigk, Cavity types (CAS 2010 - Ebeltoft)

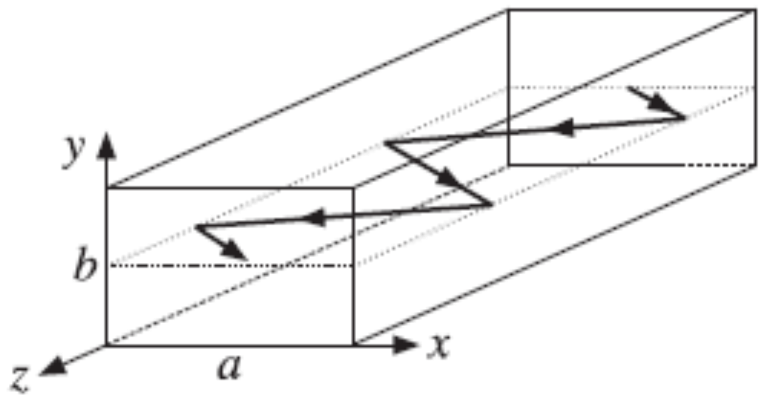
- *S. J. Orfanidis,* **Electromagnetic Waves and Antennas** (2014)
- *T. P. Wangler*, **Principles of RF Linear Accelerators** (Wiley, New York, 2008).

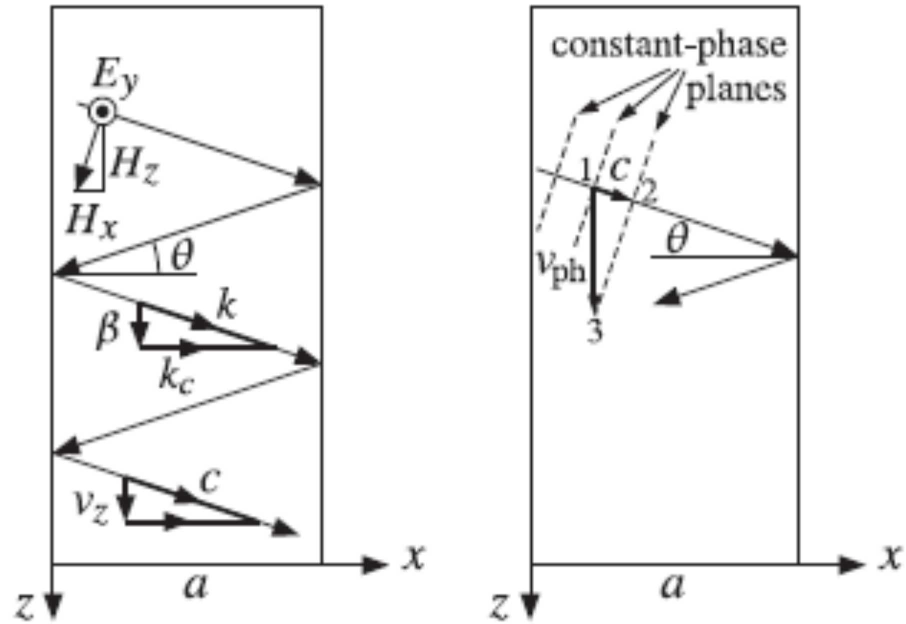

THANK YOU!

EXTRA

Reflection model of waveguide propagation

$$\cos\theta = \frac{\omega_c}{\omega}, \quad \sin\theta = \sqrt{1 - \frac{\omega_c^2}{\omega^2}}$$



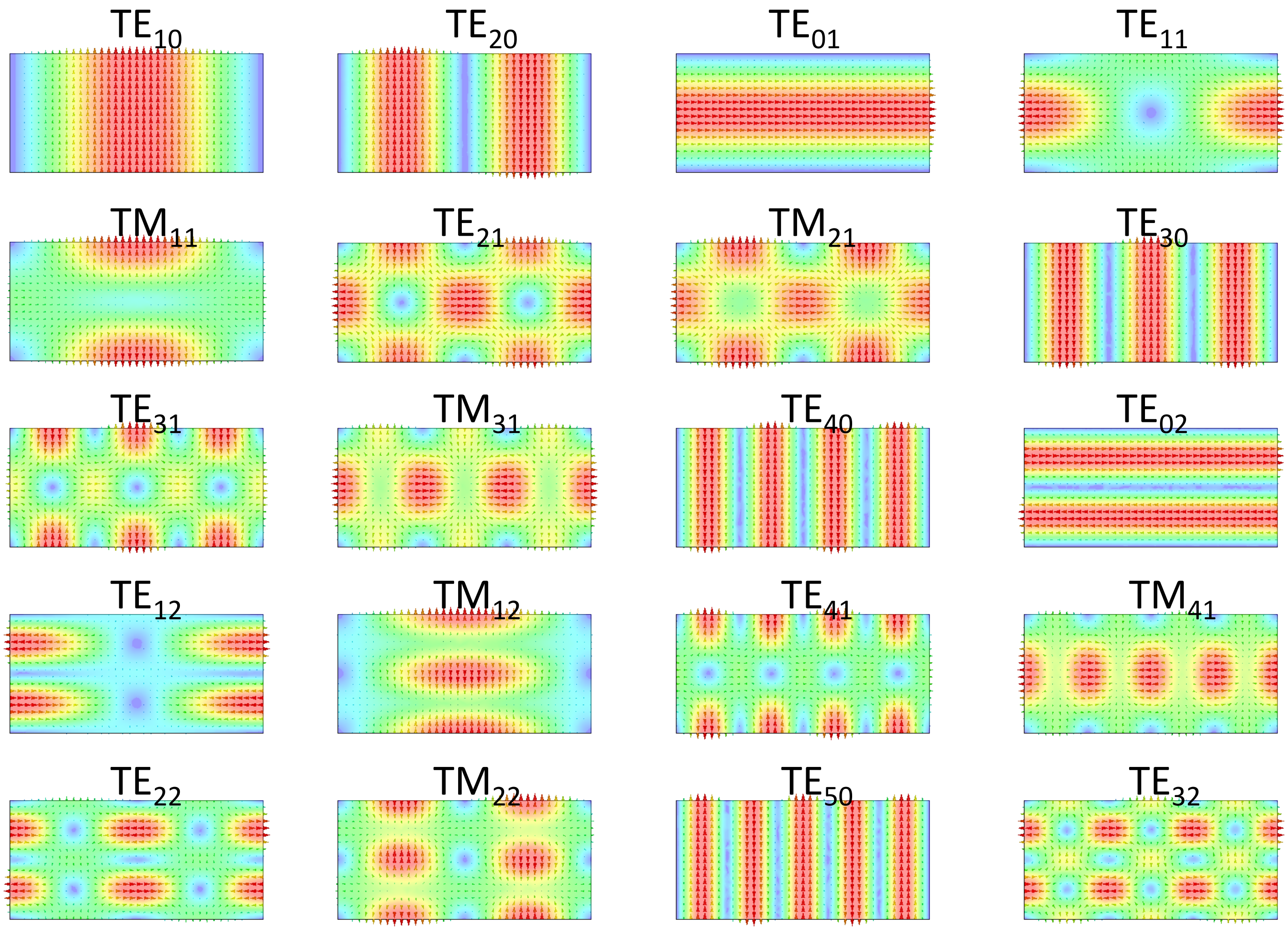


This model clarifies also the meaning of the group velocity. The plane wave is bouncing left and right with the speed of light c. However, the component of this velocity in the z-direction will be $v_z = c\sin\theta$. This is equal to the group velocity. Indeed, it follows from Eq. (9.9.3) that:

$$v_z = c\sin\theta = c\sqrt{1 - \frac{\omega_c^2}{\omega^2}} = v_{gr} \qquad (9.9.5)$$

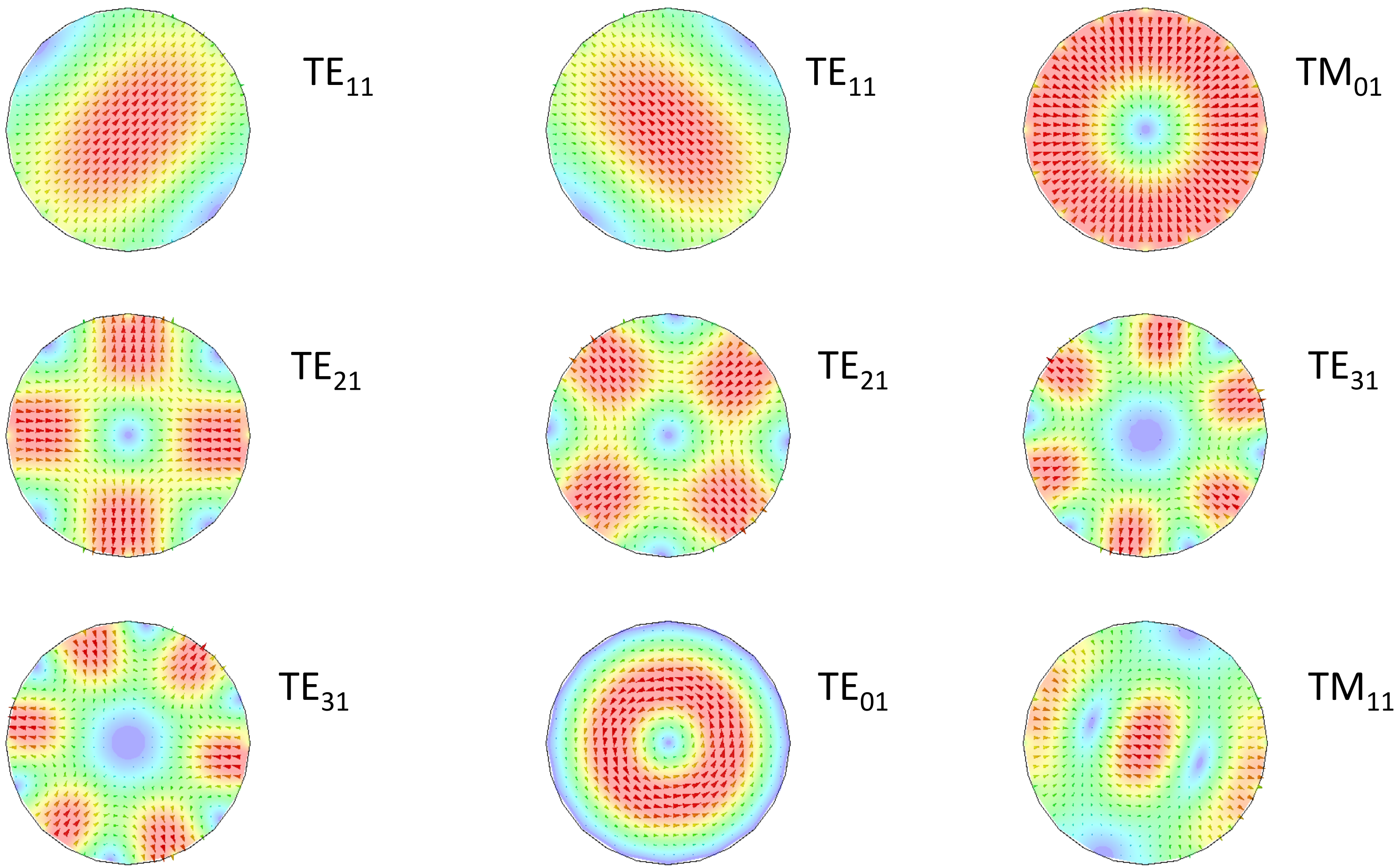
the effective speed in the z-direction of the common-phase points will be $v_{ph} = c/\sin\theta$ so that $v_{ph}v_{gr} = c^2$.

Rectangular waveguide modes



plotted: *E*-field

Circular waveguide modes



plotted: *E*-field