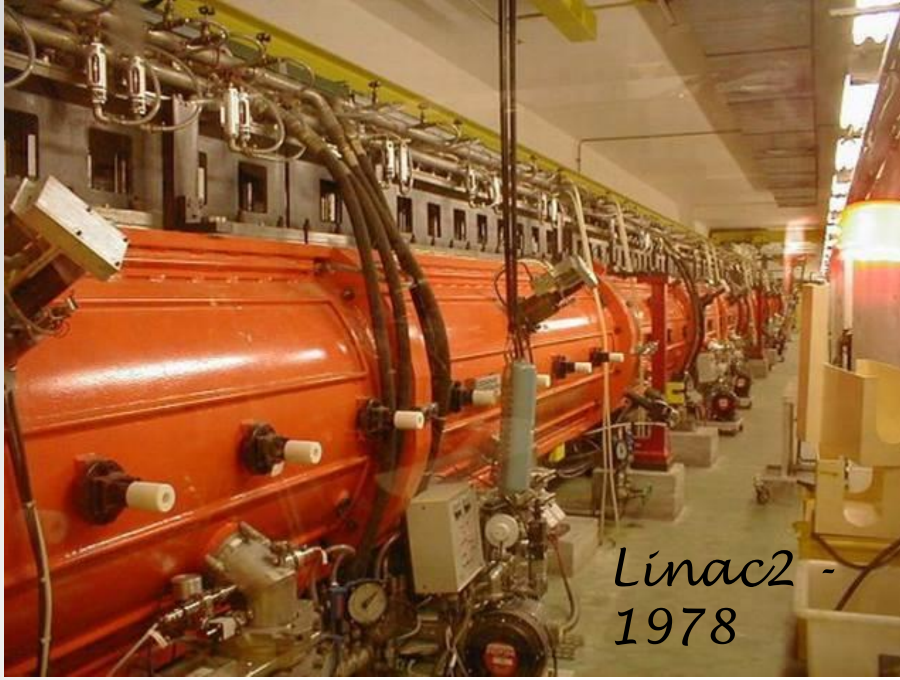
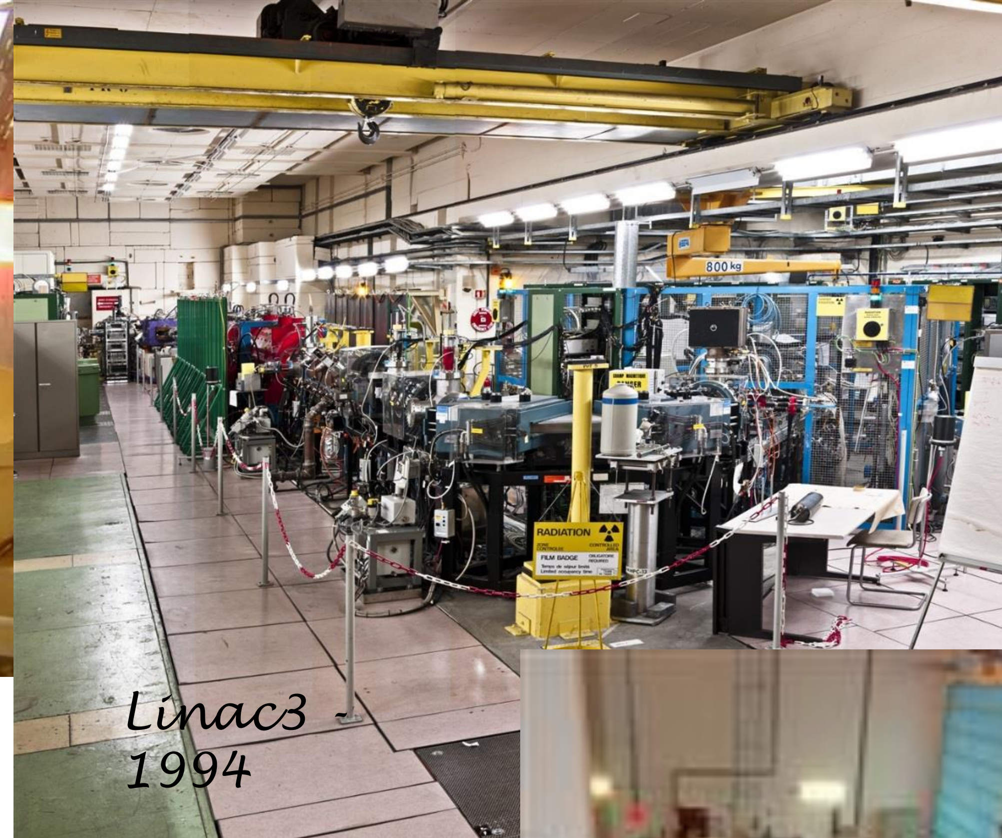




Linacs

Alessandra M. Lombardi
CERN BE/ABP

- Basics of Accelerator Science and Technology at CERN

outline

- Introduction and focus of the lecture
  - WHAT is a LINAC, WHEN was it invented and HOW does it work
- A selection of the CERN LINACS
  - Linac2,3,4 : hadron linacs injecting into a synchrotron
  - (Rex) – will not talk about this
  - (Clic/ctf3)- will not talk about this
- LINAC building blocks
  - Acceleration : Radio Frequency Cavities
  - Focusing : Quadrupoles

What is a linac

- LINear ACcelerator : single pass device that increases the energy of a charged particle by means of a (radio frequency) electric field and it is equipped with magnetic elements (quadrupoles, solenoids, bending magnets) to keep the charged particle on a given trajectory.
- Motion equation of a charged particle in an electromagnetic field

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

$$\vec{p} = momentum = \gamma m_0 \vec{v}$$

$$q, m_0 = charge, mass$$

$$\vec{E}, \vec{B} = electric, magnetic field$$

$$t = time$$

$$\vec{x} = position vector$$

$$\vec{v} = \frac{d\vec{x}}{dt} = velocity$$

What is a linac-cont'ed

Relativistic or not

$$\frac{d}{dt}\left(\gamma \frac{d\vec{x}}{dt}\right) = \frac{q}{m_0} \cdot \left(\vec{E} + \frac{d\vec{x}}{dt} \times \vec{B} \right)$$

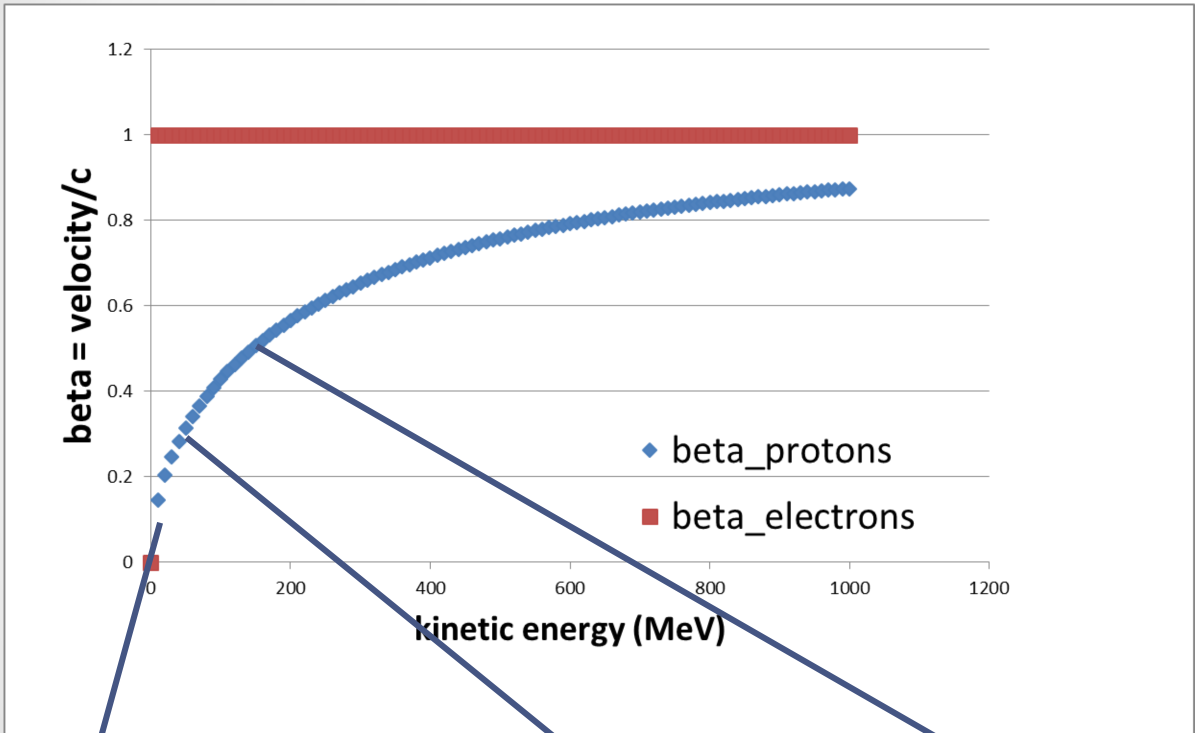
type of particle : charge couples with the field, mass slows the acceleration

type of RF structure

type of focusing

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

Type of particles



- electron, mass 0.511 MeV, quickly relativistic, easi(er) to accelerate
- proton, mass 938.28 MeV, q/m=1
- lead ions , mass 195.16 GeV , q/m=1/8.32 (in the linac,)
- Xenon ions , mass 122 GeV, q/m=1/5.8

At 0.1 MeV
beta =0.015,
gamma= 1

At 50 MeV
beta =0.3 ,
gamma=1.05

At 160 MeV
beta =0.52 ,
gamma=1.17

Velocity of the particles

Synchronicity with the accelerating electric field

(accelerator is single purpose)

1) Geometry of the accelerator has to be adapted step-by-step
2) The phase of the radio frequency field has to be optimised independently

Space charge effects

(more severe the lower the velocity)

1) The beam cannot be compressed in a small volume
2) The beam quality degradation is more severe

When ? A short history

- Acceleration by time varying electromagnetic field overcomes the limitation of static acceleration
- First experiment towards an RF linac : Wideroe linac 1928 on a proposal by Ising dated 1925. A bunch of potassium ions were accelerated to 50 keV in a system of drift tubes in an evacuated glass cylinder. The available generator provided 25 keV at 1 MHz.
- First realization of a linac : 1931 by Sloan and Lawrence at Berkeley laboratory
- From experiment to a practical accelerator : Wideroe to Alvarez
    - to proceed to higher energies it was necessary to increase by order of magnitude the frequency and to enclose the drift tubes in a RF cavity (resonator)
    - this concept was proposed and realized by Luis Alvarez at University of California in 1955 : A 200 MHz 12 m long Drift Tube Linac accelerated protons from 4 to 32 MeV.
    - the realization of the first linac was made possible by the availability of high-frequency power generators developed for radar application during World War

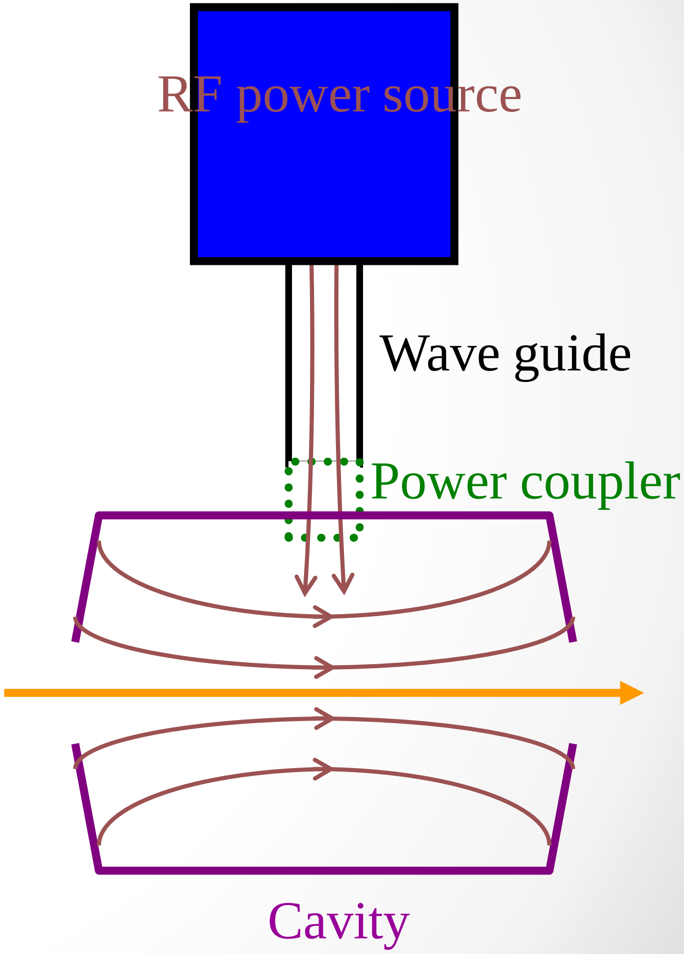
Why not an electrostatic field?

750 kV Cockcroft-Walton

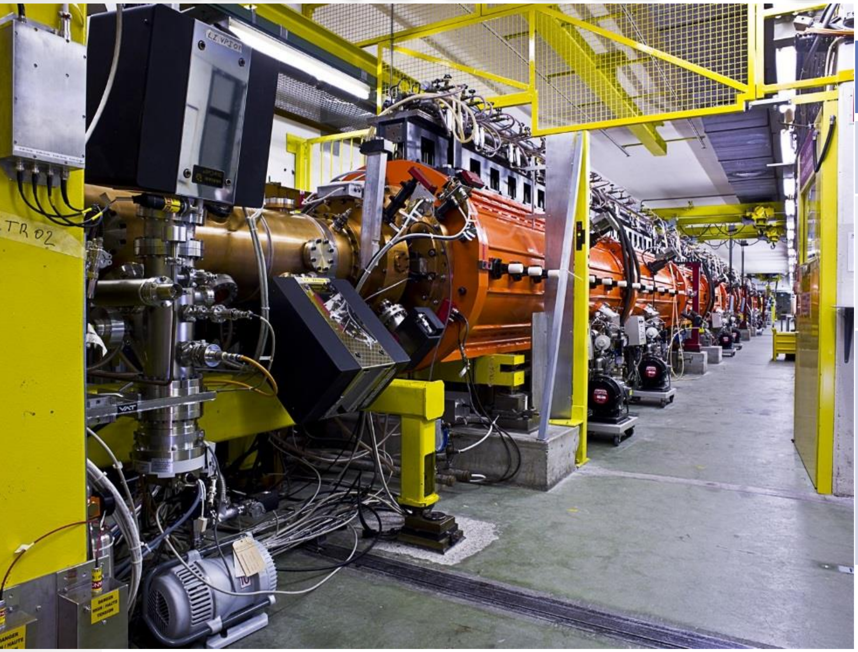
750 keV Radio Frequency accelerator (2m long, 0.5 m across)

How? principle of an RF linac

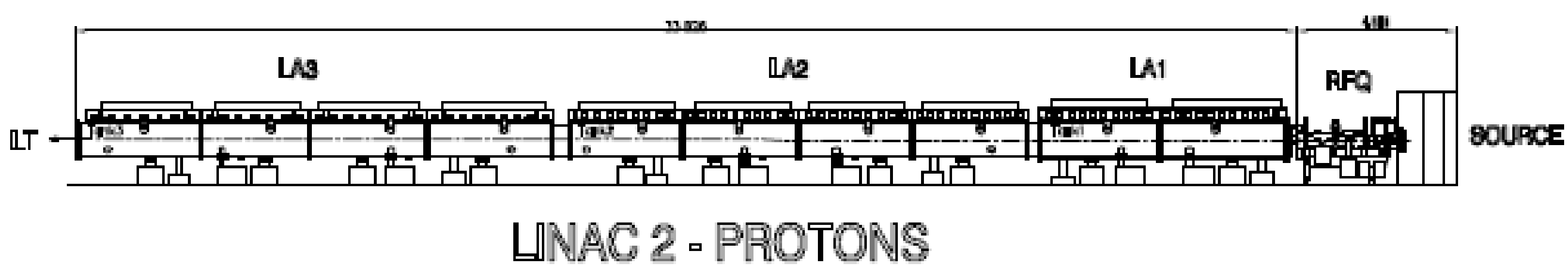
1) RF power source: generator of electromagnetic wave of a specified frequency. It feeds a
2) Cavity : space enclosed in a metallic boundary which resonates with the frequency of the wave and tailors the field pattern to the
3) Beam : flux of particles that we push through the cavity when the field is maximized as to increase its
4) Energy.



LINAC2 - 50 MeV protons

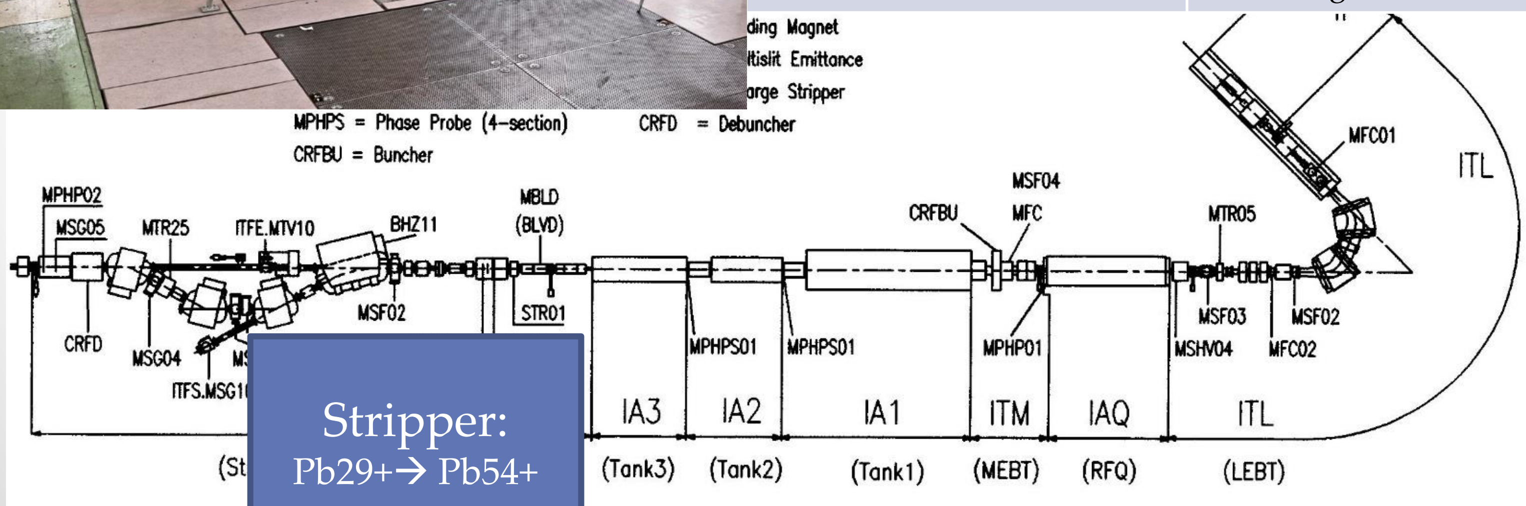


LINAC2 machine layout- 200MHz	
Drift Tube Linac	Pre-injector
50 MeV (beta=0.3)	0.750 MeV (beta=0.04)
34 m 3 Tanks 3 rf power source:5 MW 130 quadrupoles 2 steerers	5 m Source 2 solenoids Radio Frequency Quadrupole 4 EM Quadrupoles 2 Cavities



LINAC3- heavy ions

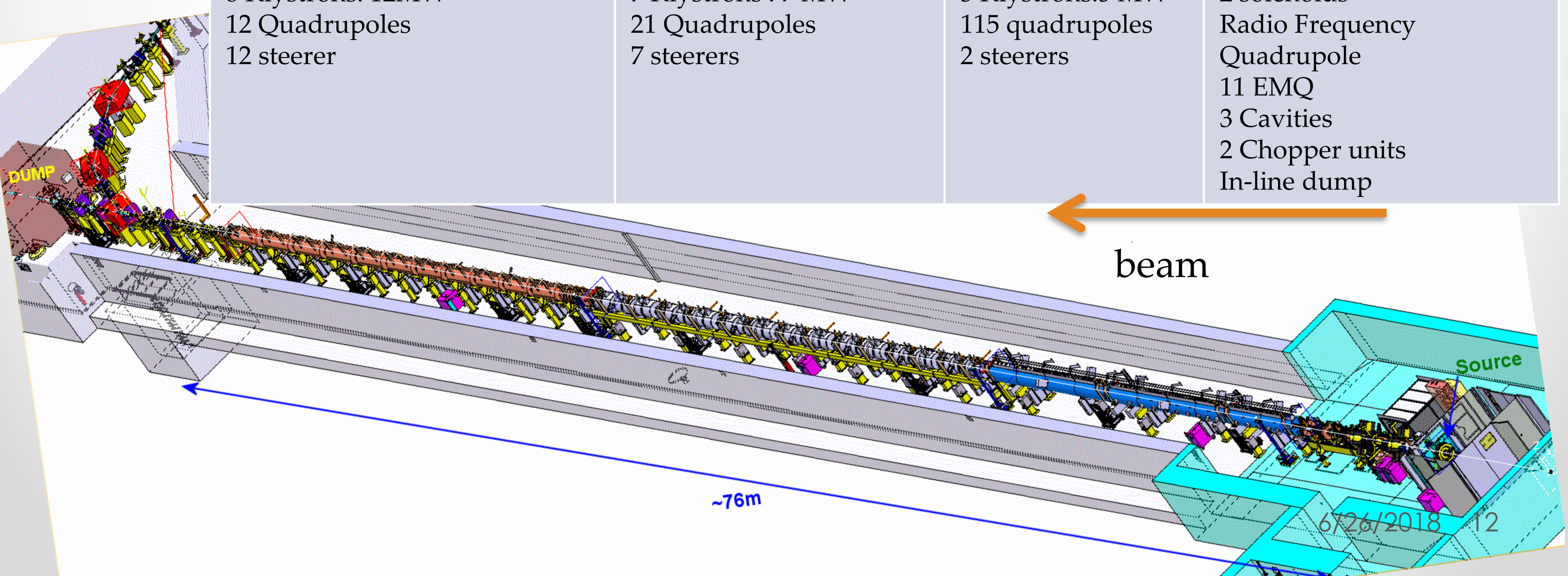
LINAC3 machine layout- 100 and 200MHz	
IH –LINAC	Pre-injector
4.2 MeV/u (beta=0.094)	0.0025 MeV /u (beta=0.0023)
7 m 3 Tanks 3 rf power source:5 MW 12 quadrupoles 2 steerers	10 m ECRIS Source with multiple charges 2 solenoids Radio Frequency Quadrupole 8 EMQuadrupoles 2 Cavities 2 bendings



Stripper:
Pb29+→ Pb54+

LINAC4 – 160MeV

LINAC4 machine layout- 352MHz			
Π-mode	CC-DTL	Drift Tube L	Pre-injector
160 MeV (beta=0.52)	100 MeV (beta=0.42)	50 MeV (beta=0.3)	3MeV (beta=0.08)
23 m 12 Modules 8 Klystrons: 12MW 12 Quadrupoles 12 steerer	25 m 7 Modules 7 Klystrons : 7 MW 21 Quadrupoles 7 steerers	19 m 3 Tanks 3 Klystrons:5 MW 115 quadrupoles 2 steerers	9 m Source(s) 2 solenoids Radio Frequency Quadrupole 11 EMQ 3 Cavities 2 Chopper units In-line dump



What is a linac-cont'ed

From 1 to 1.17

$$\frac{d}{dt}\left(\gamma \frac{d\vec{x}}{dt}\right) = \frac{q}{m_0} \cdot \left(\vec{E} + \frac{d\vec{x}}{dt} \times \vec{B} \right)$$

q/m=1/1 to q/m=1/8

type of RF structure

type of focusing

Types of RF structures

Type of structure	Used at CERN in
Radio Frequency Quadrupole	LINAC2,LINAC3,LINAC4,LINAC5, REX-ISOLDE
Interdigital-H structure	LINAC3 , REX-ISOLDE
Drift Tube Linac	LINAC2,LINAC4, LINAC5
CellCoupled DTL	LINAC4
PIMS	LINAC4

wave equation -recap

- Maxwell equation for E and B field:

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E}=0$$

- In free space the electromagnetic fields are of the *transverse electro magnetic,* TEM, type: the electric and magnetic field vectors are ⊥ to each other and to the direction of propagation.

- In a bounded medium (cavity) the solution of the equation must satisfy the boundary conditions : $\vec{E}_{//}=\vec{0} \quad \vec{B}_{\perp}=\vec{0}$

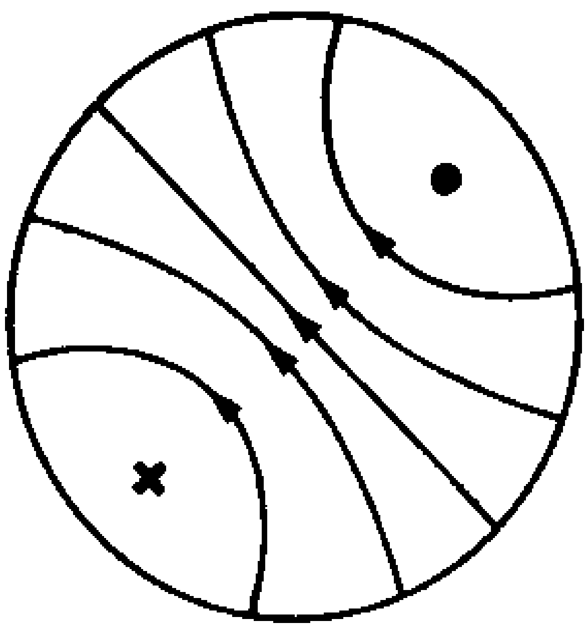
- In a cavity we have Tranverse Electric (TE modes) or Transverse magnetic (TM modes)

TE_{nml}

n : azimuthal,

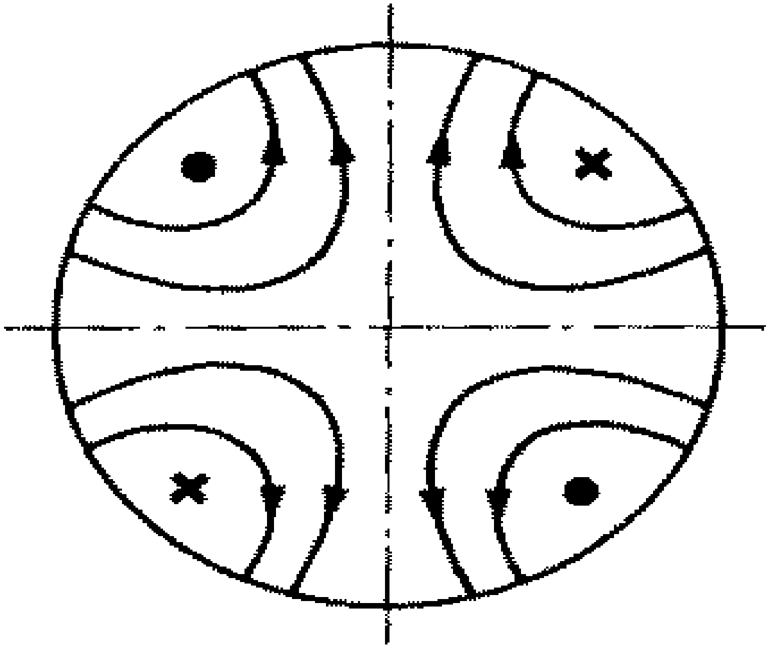
m : radial

l longitudinal component



Empty cavity; mode TE_{11}

dipole mode used in the IH structures



Empty cavity; mode TE_{21}

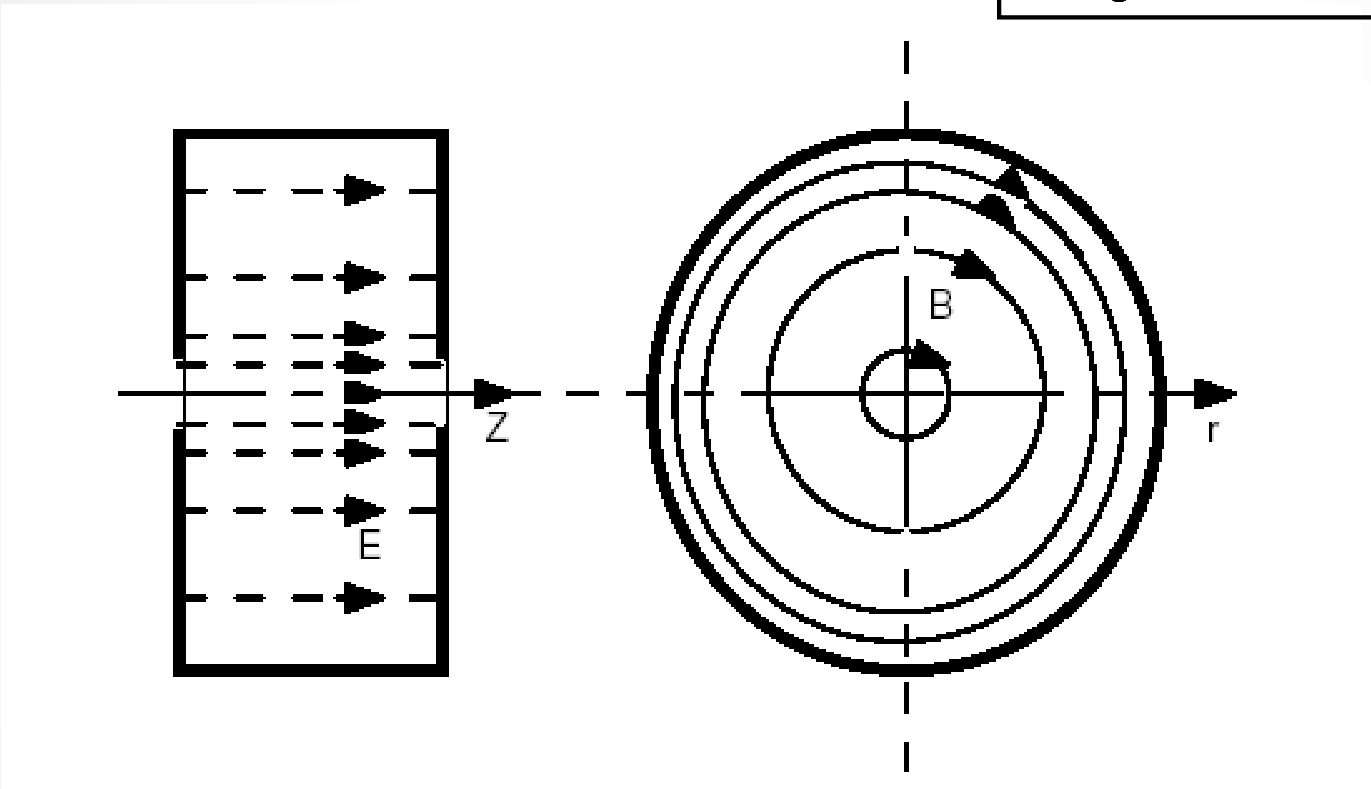
quadrupole mode used in Radio Frequency Quadrupole

TM_{nml}

n : azimuthal,

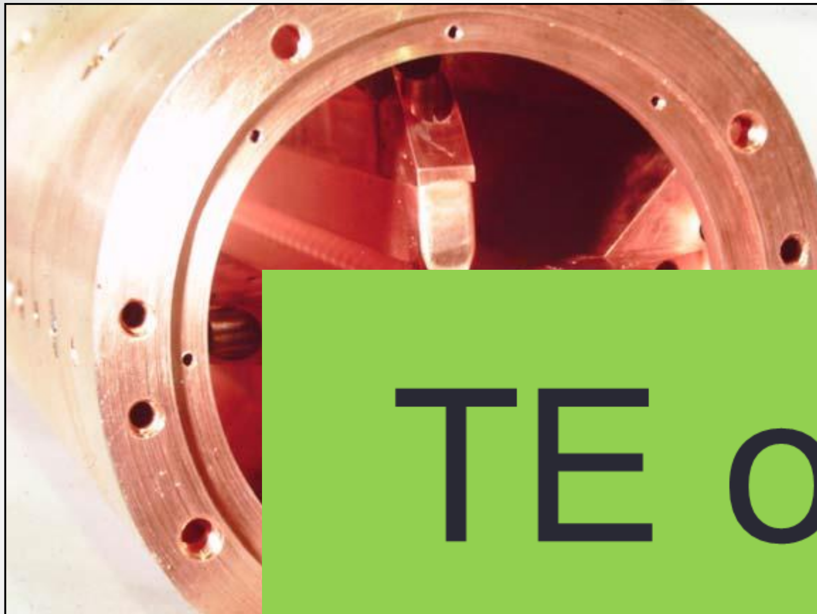
m : radial

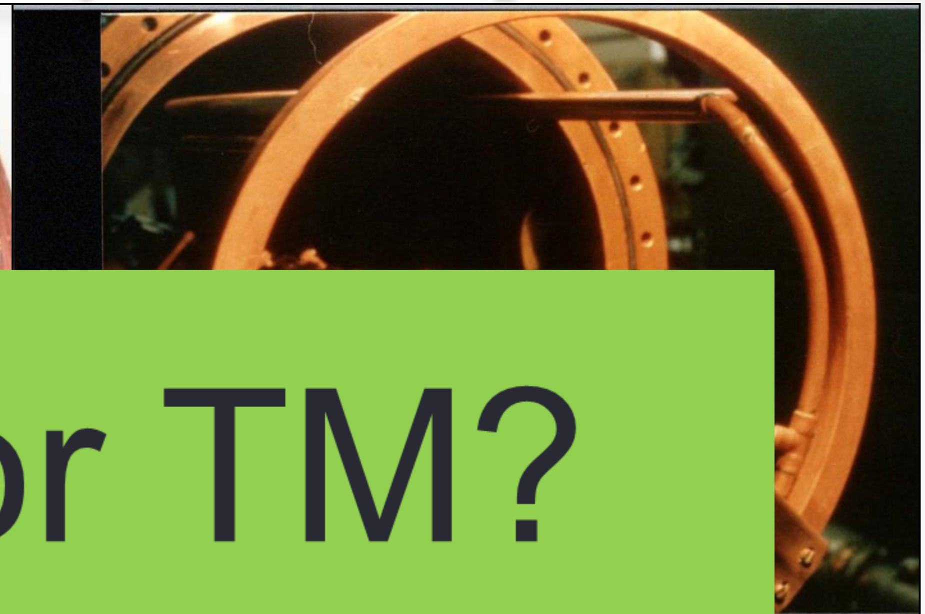
l longitudinal component



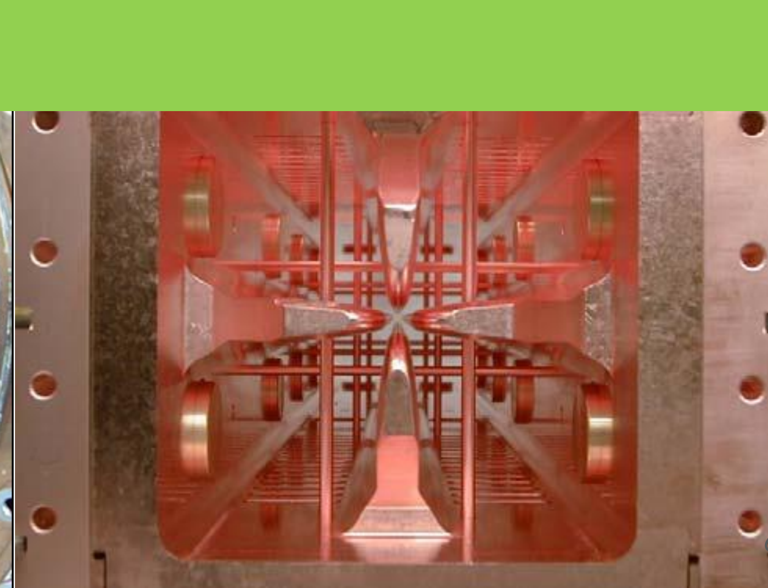
TM010 mode , most commonly used accelerating mode

Radio Frequency Quadrupoles

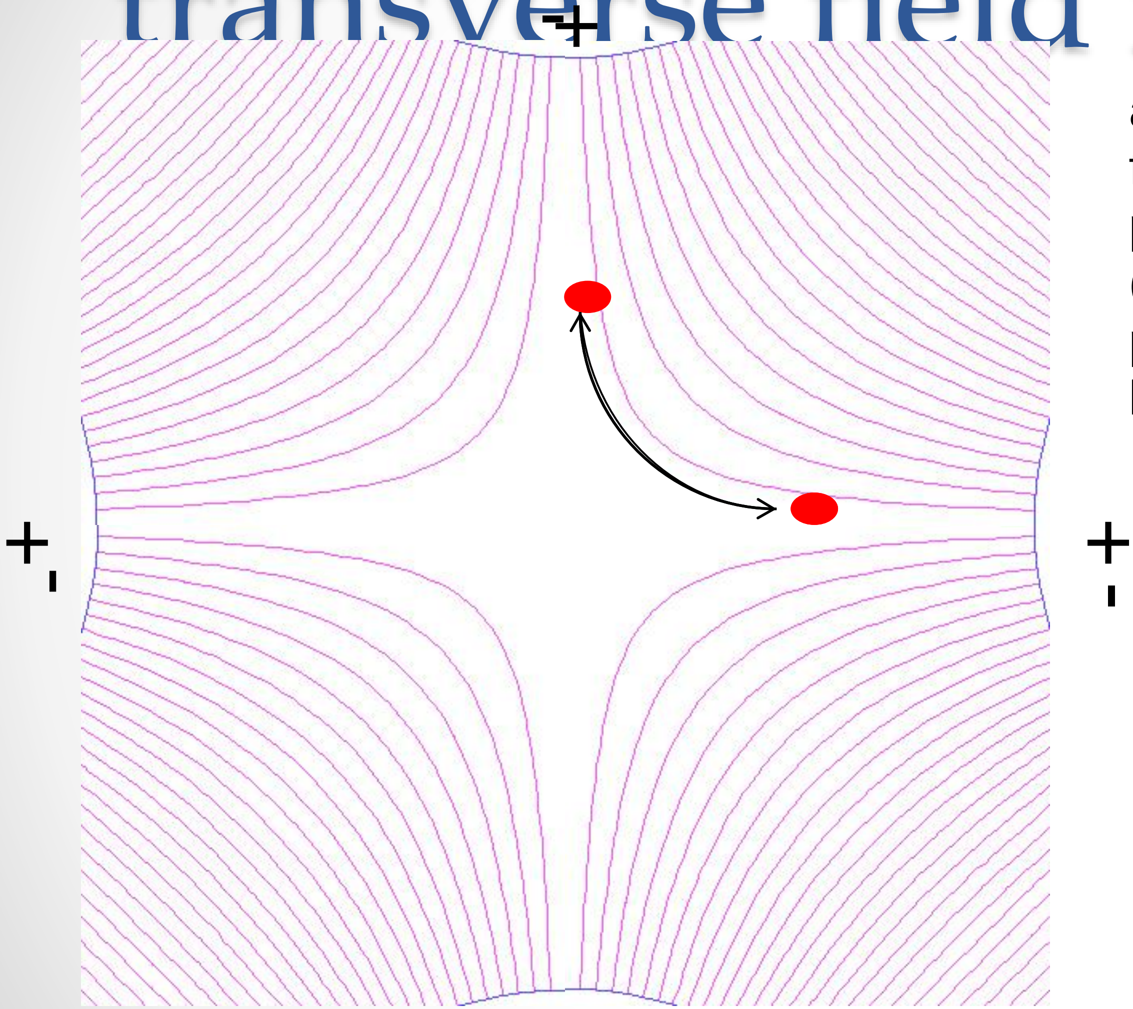




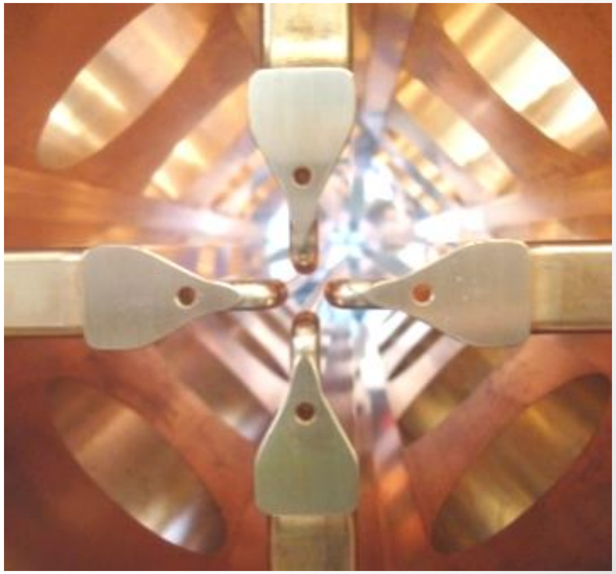
TE or TM?



transverse field in an RFQ

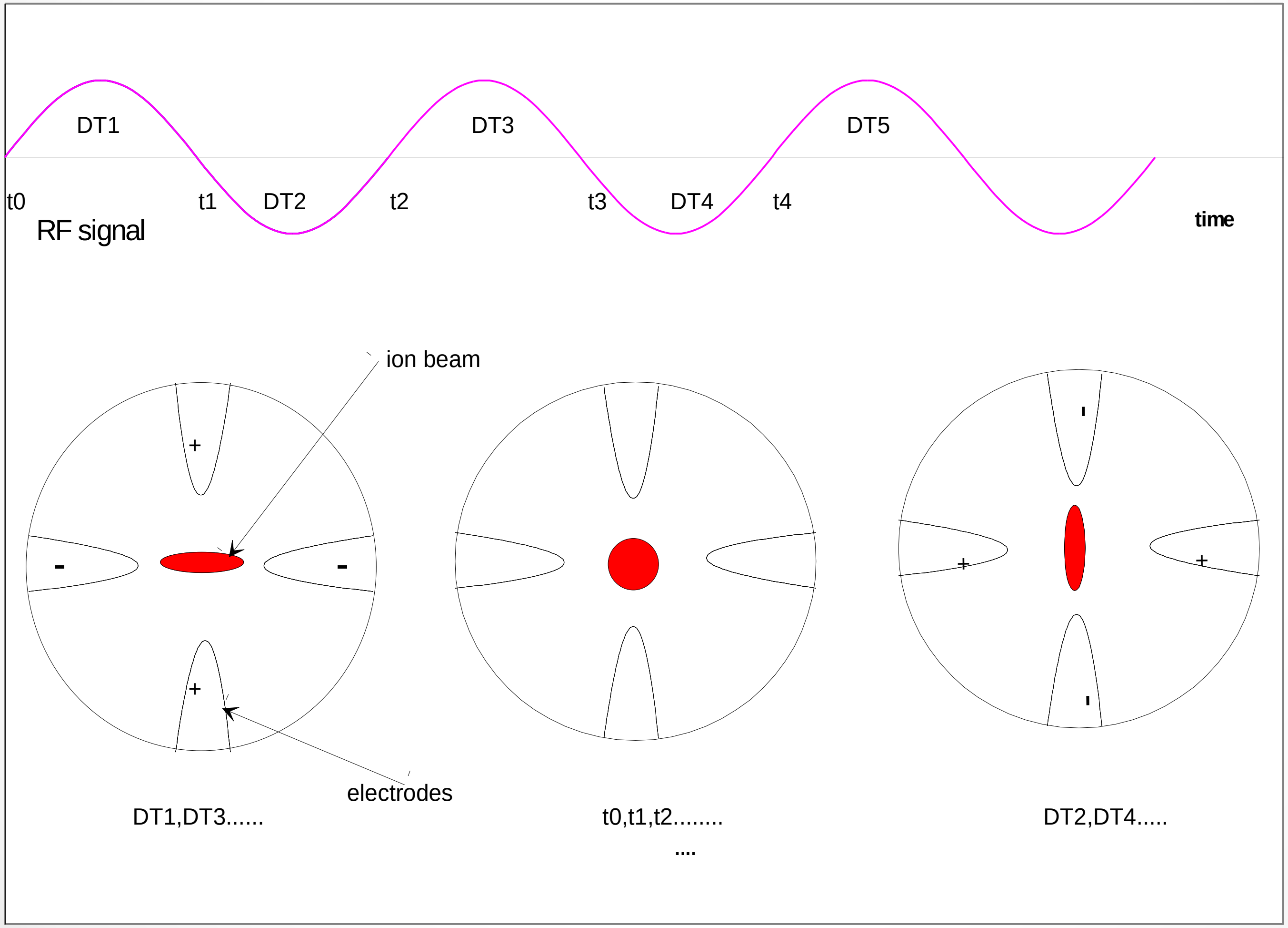


alternating gradient focussing structure with period length βλ
(in half RF period the particles have travelled a length βλ/2)

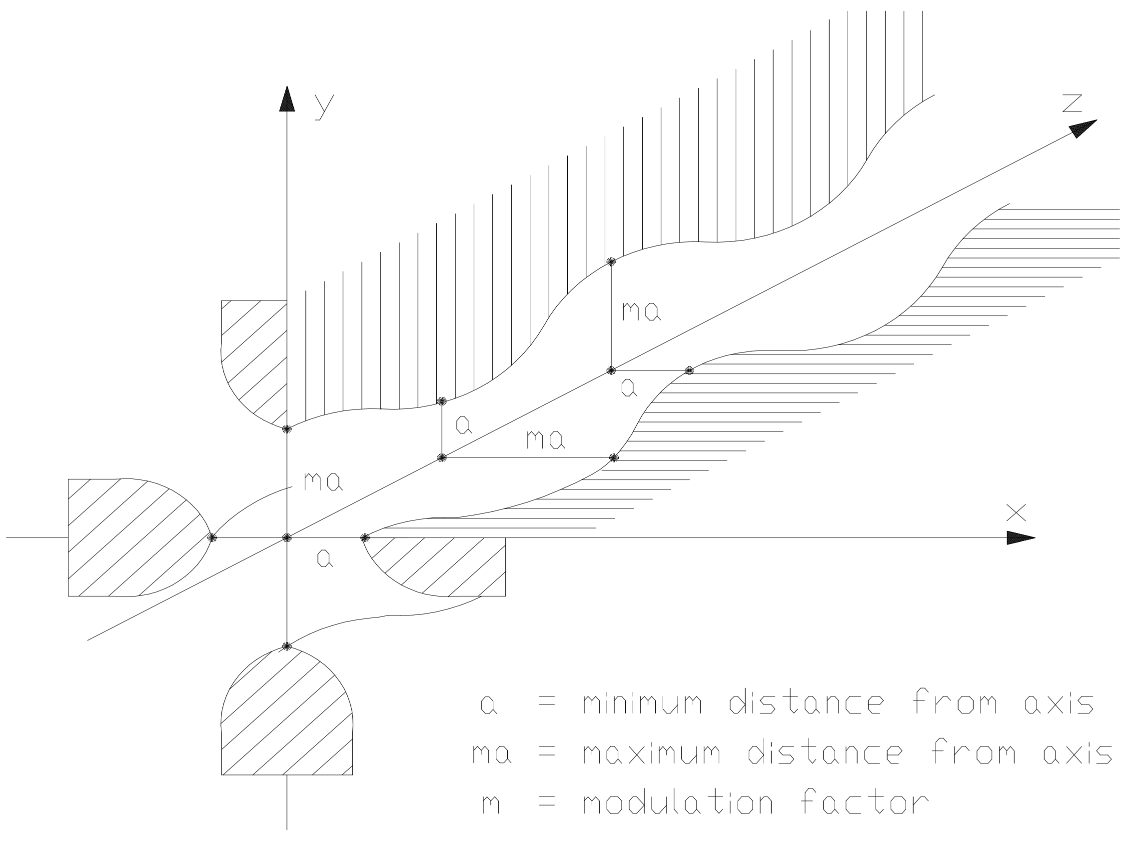


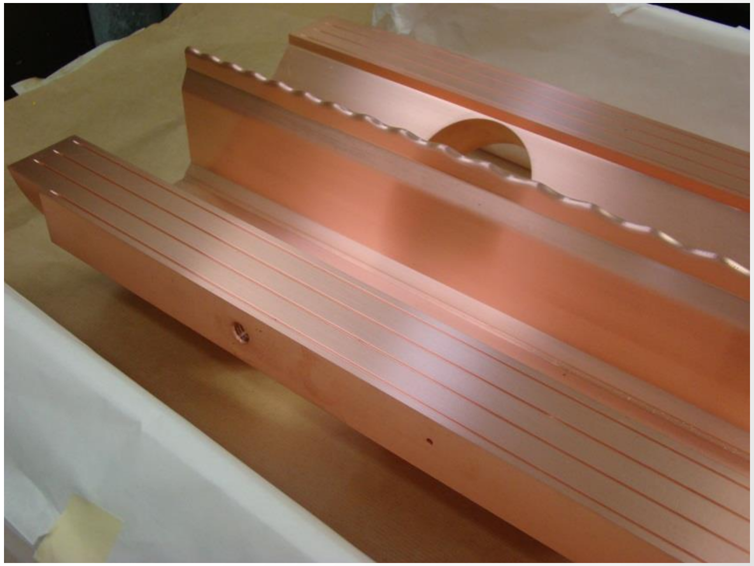
Beam goes into the paper in between the 4 vanetips

transverse field in an RFQ



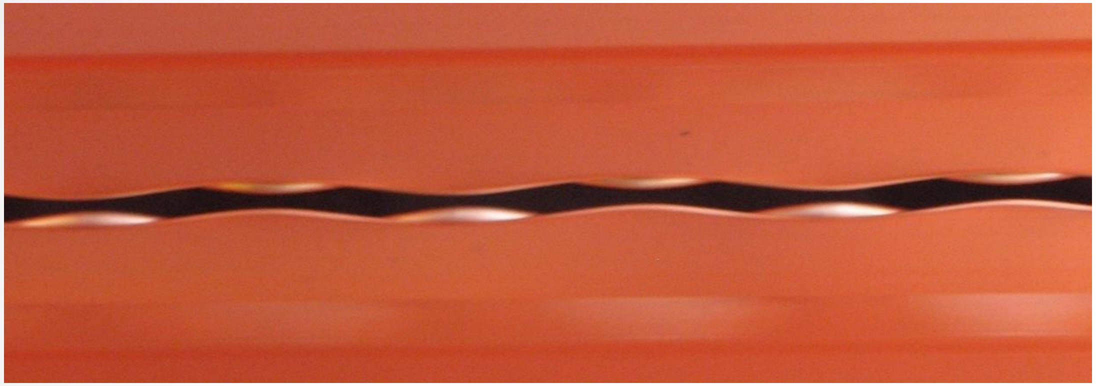
acceleration in RFQ



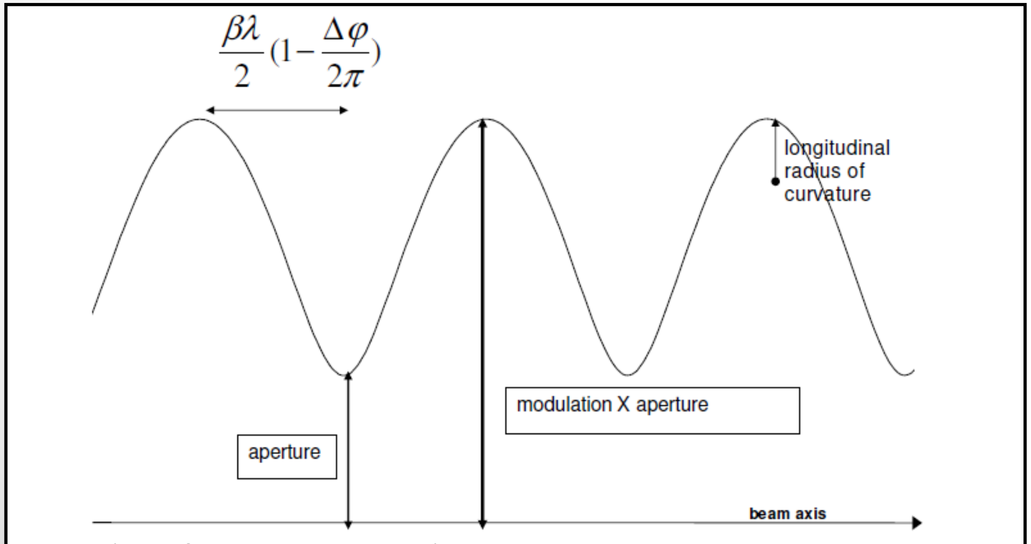


longitudinal modulation on the electrodes creates a longitudinal component in the TE mode

Modulation and Rhol



Looking in from the RF port : these are adjacent



important parameters of the RFQ

$$B = \left(\frac{q}{m_0}\right)\left(\frac{V}{a}\right)\left(\frac{1}{f^2}\right)\frac{1}{a}\left(\frac{I_o(ka)+I_o(mka)}{m^2 I_o(ka)+I_o(mka)}\right)$$

type of particle

limited by sparking

Transverse field distortion due to modulation (=1 for un-modulated electrodes)

$$E_0 T = \frac{m^2 - 1}{m^2 I_o(ka) + I_o(mka)} \cdot V \frac{2}{\beta \cdot \lambda} \frac{\pi}{4}$$

Accelerating efficiency : fraction of the field deviated in the longitudinal direction (=0 for un-modulated electrodes)

cell length

transit time factor

.....and their relation

$$\left(\frac{I_o(ka)+I_o(mka)}{m^2 I_o(ka)+I_o(mka)}\right)+\frac{m^2-1}{m^2 I_o(ka)+I_o(mka)}\cdot I_0(ka)=1$$

focusing efficiency

accelerating efficiency

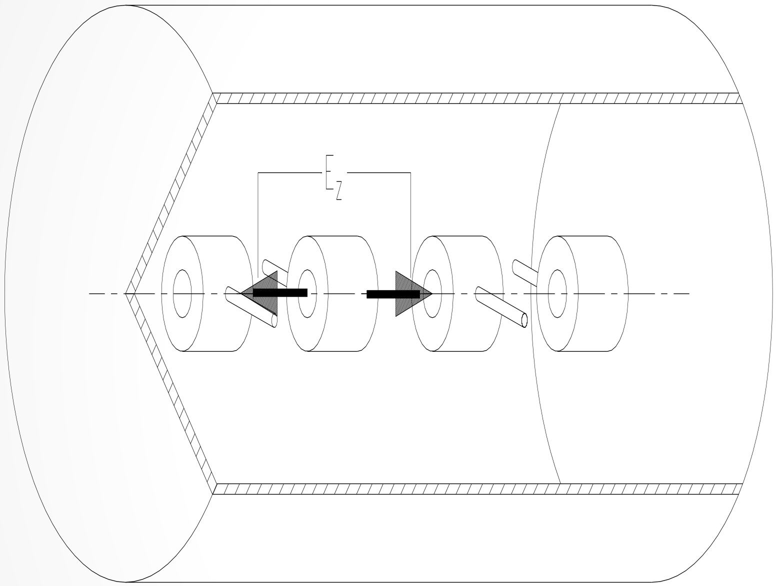
a=bore radius, β,γ=relativistic parameters, *c*=speed of light, *f*= rf frequency, *I0,1*=zero,first order Bessel function, *k*=wave number, λ=wavelength, *m*=electrode modulation, *m0*=rest *q*=charge, *r*= average transverse beam dimension, *r0*=average bore, *V*=vane voltage

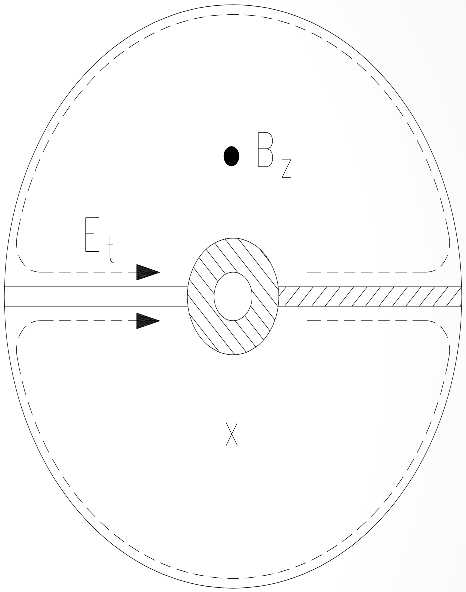
RFQ

- The resonating mode of the cavity is a focusing mode (TE mode)
- Alternating the voltage on the electrodes produces an alternating focusing channel
- A longitudinal modulation of the electrodes produces a field in the direction of propagation of the beam which bunches and accelerates the beam
- Both the focusing as well as the bunching and acceleration are performed by the RF field
- Not very efficient accelerator
- The RFQ is the only linear accelerator that can accept a low energy CONTINOUS beam of particles
- 1970 Kapchinskij and Teplyakov propose the idea of the radiofrequency quadrupole (I. M. Kapchinskii and V. A. Teplvakov, Prib.Tekh. Eksp. No. 2, 19 (1970))

Interdigital H structure

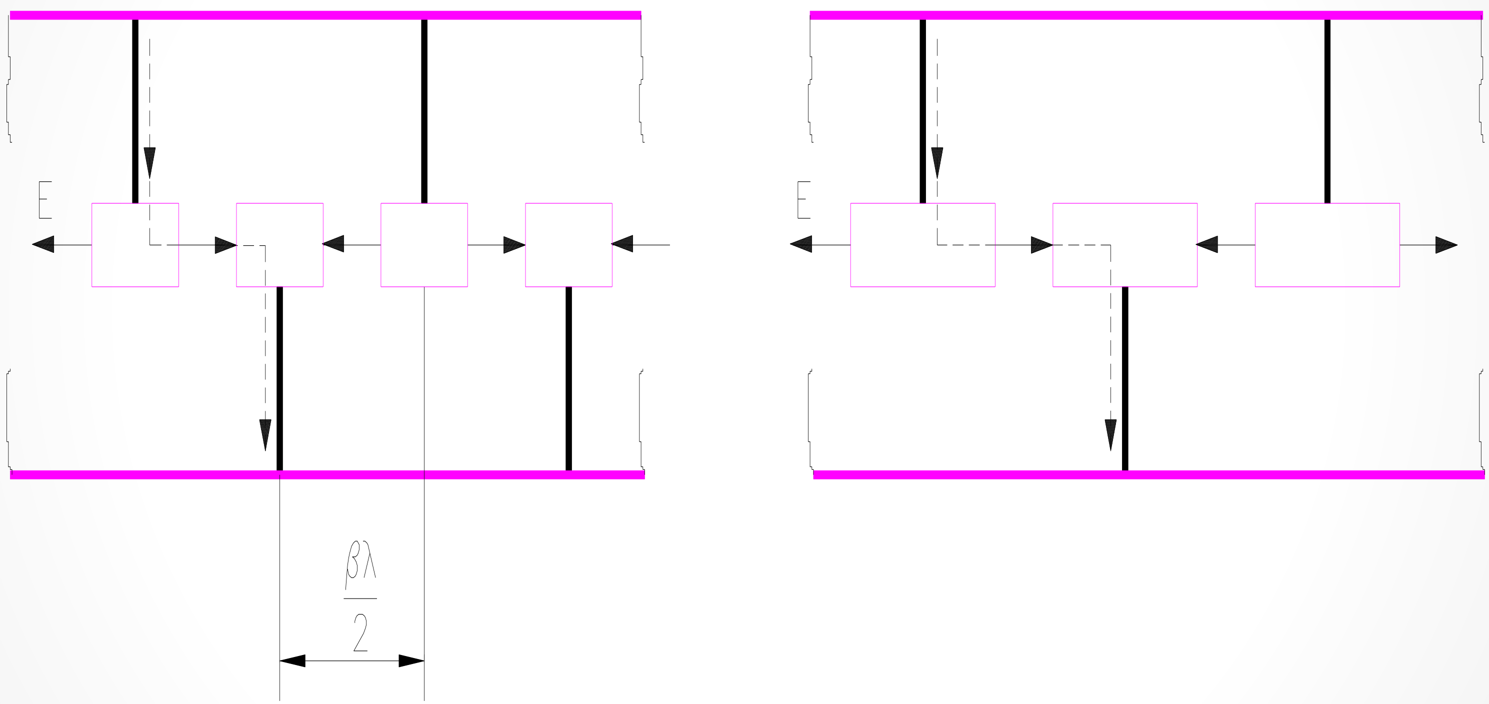
Interdigital H structure





the mode is the TE110

Interdigital H structure



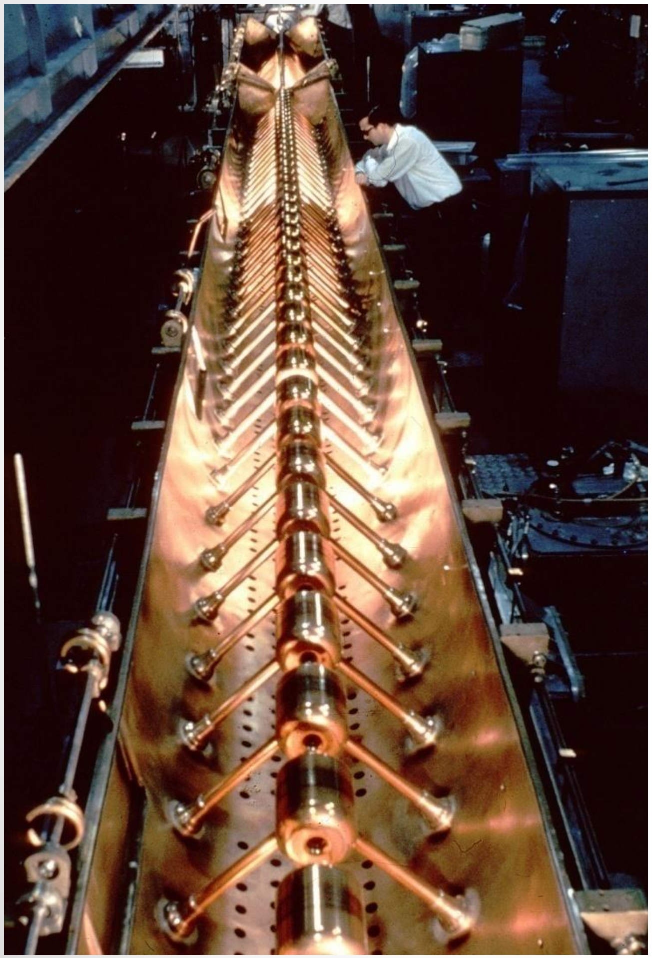
•stem on alternating side of the drift tube force a longitudinal field between the drift tubes

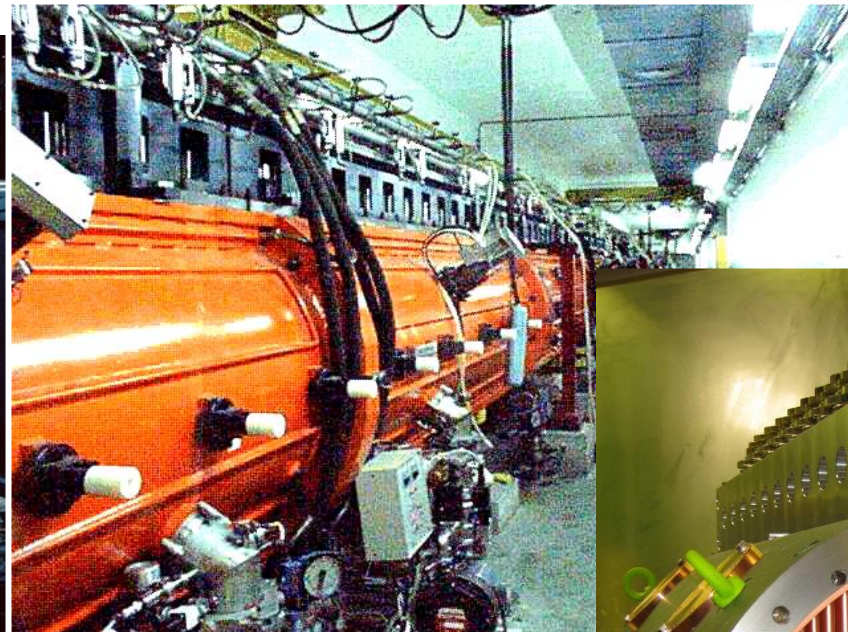
•focalisation is provided by quadrupole triplets places OUTSIDE the drift tubes or OUTSIDE the tank

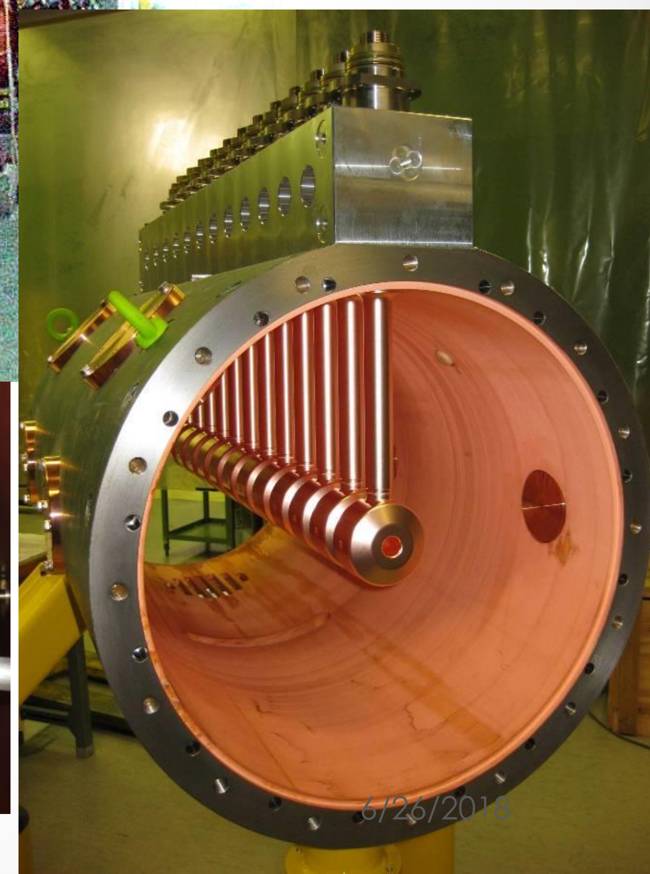
IH

- The resonating mode of the cavity is a dipole mode mode
- The cavity is equipped with thin drift tubes.
- Alternating the stems on each side of the drift tubes produces a field in the direction of propagation of the beam which accelerates the beam
- Focusing is provided by quadrupole triplets located inside the tank in a dedicated section
- Very efficient in the low beta region (($\beta \cong 0.02$ to 0.08) and low frequency (up to 200MHz)
- not for high intensity beam due to long focusing period
- ideal for low beta ion acceleration

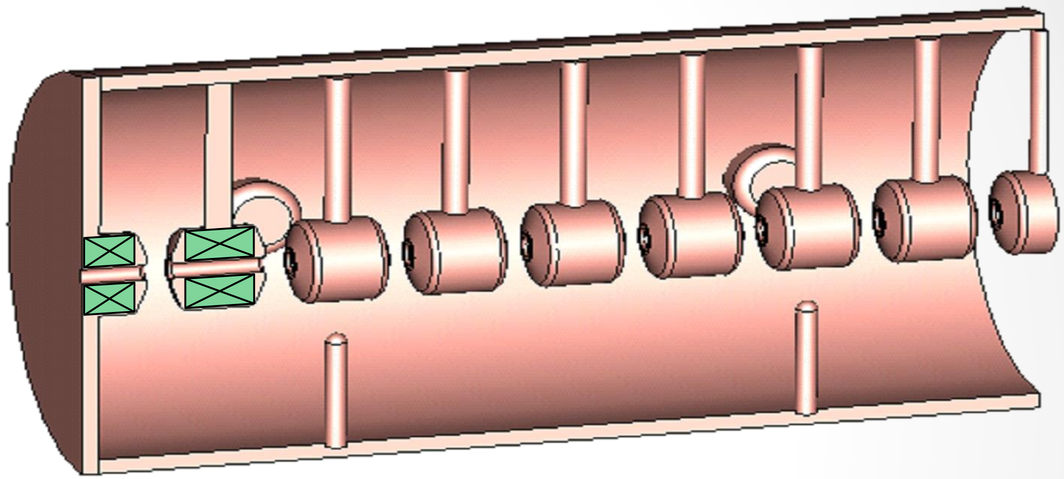
Drift Tube Linac



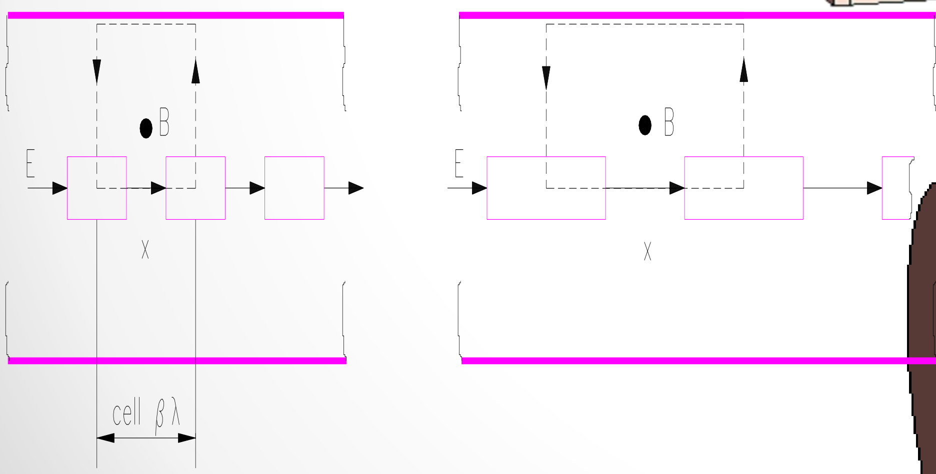


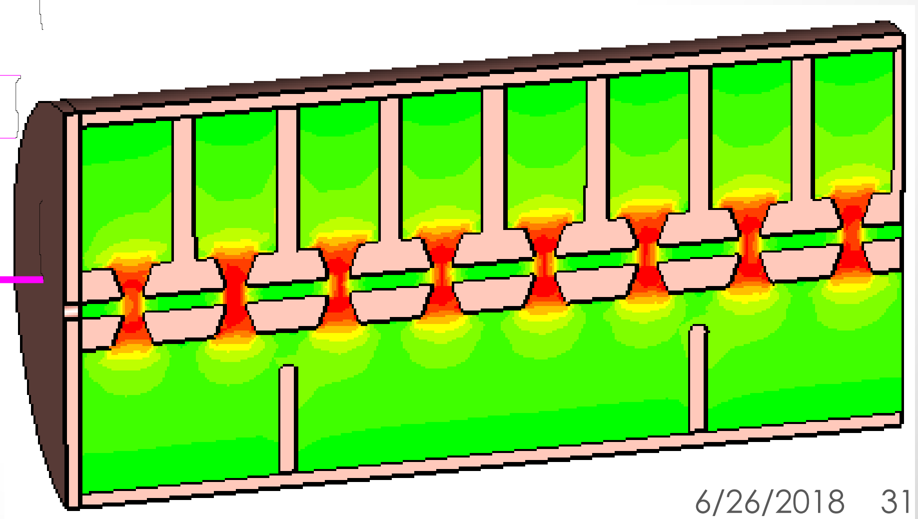


DTL : electric field

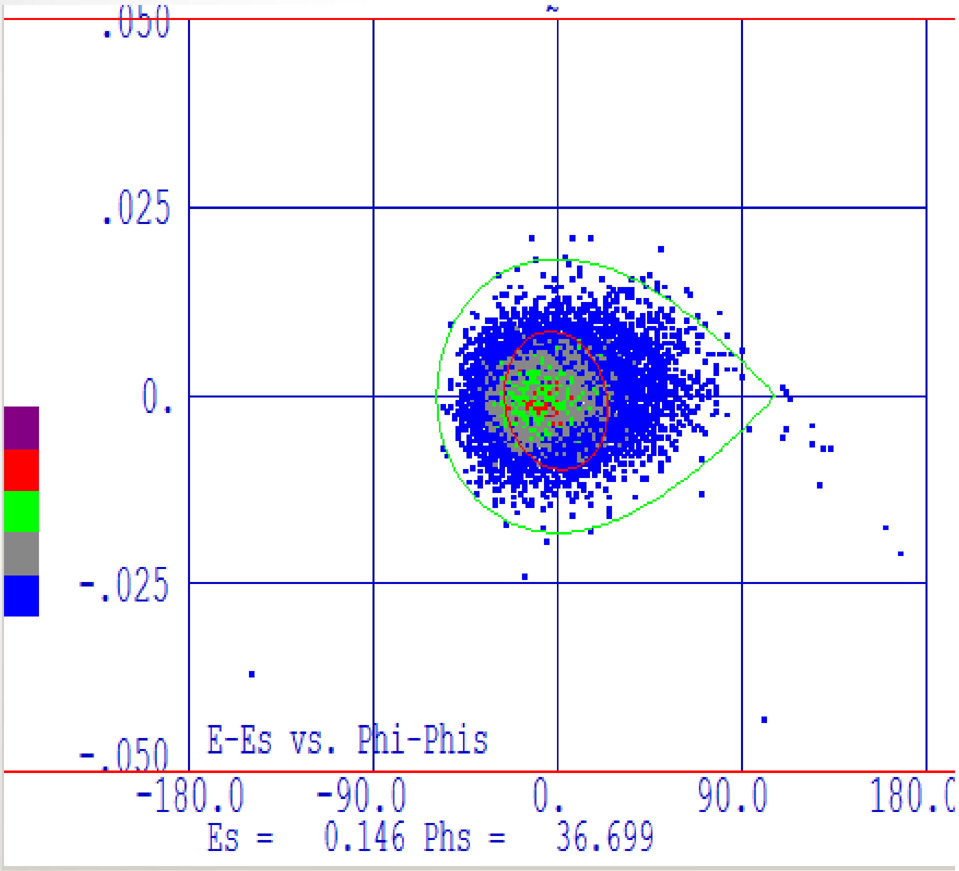


Mode is TM010





Synchronous particle



- it's the (possibly fictitious) particle that we use to calculate and determine the phase along the accelerator. It is the particle whose velocity is used to determine the synchronicity with the electric field. Design for that particle and provide longitudinal focusing so that the other stick with it!

Perfect synchronicity

- The length of the accelerating gap is either
$$L = {}^{\beta\lambda}/_{2} \text{ or } L = \beta\lambda$$
- Each cavity is adapted to the speed of the particle
- Best possible longitudinal beam dynamics
- Full control of the longitudinal phase space

Perfect synchronicity

- The absolute phase φ_i and the velocity β_{i-1} of this particle being known at the entrance of cavity i, its RF phase ϕ_i is calculated to get the wanted synchronous phase ϕ_{si}, $\phi_i = \varphi_i - \phi_{si}$
- the new velocity β_i of the particle can be calculated from, $\Delta W_i = qV_0T \cdot \cos\phi_{si}$

  ① if the phase difference between cavities i and $i+1$ is given, the distance D_i between them is adjusted to get the wanted synchronous phase ϕ_{si+1} in cavity $i+1$.

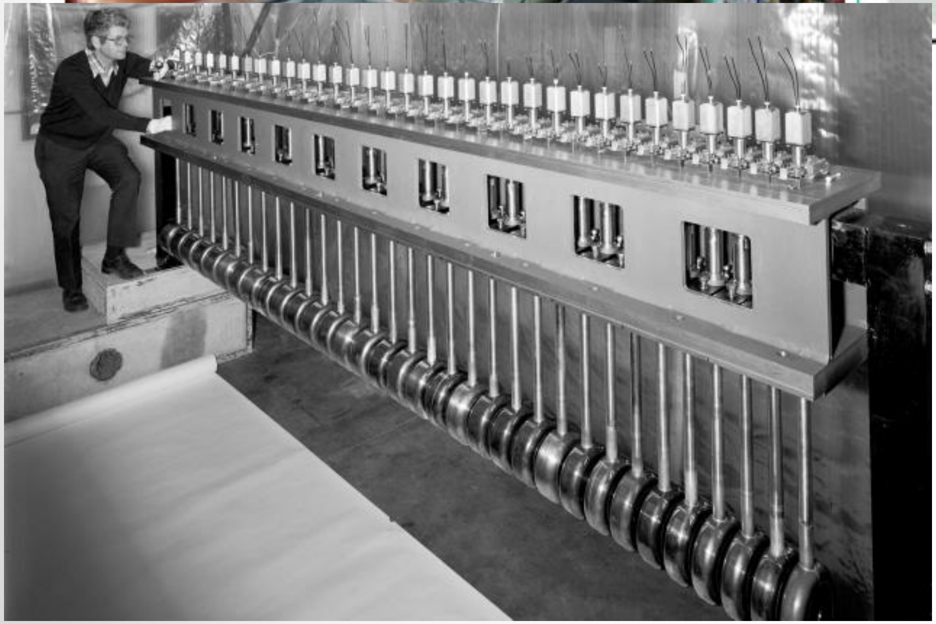
  ② if the distance D_i between cavities i and $i+1$ is set, the RF phase ϕ_i of cavity $i+1$ is calculated to get the wanted synchronous phase ϕ_{si+1} in it.

RF phase	ϕ_{i-1}		ϕ_i		ϕ_{i+1}
Particle velocity		β_{si-1}		β_{si}	
Distances		D_{i-1}		D_i	
Synchronous phase	ϕ_{si-1}		ϕ_{si}		ϕ_{si+1}
Cavity number	$i-1$		i		$i+1$

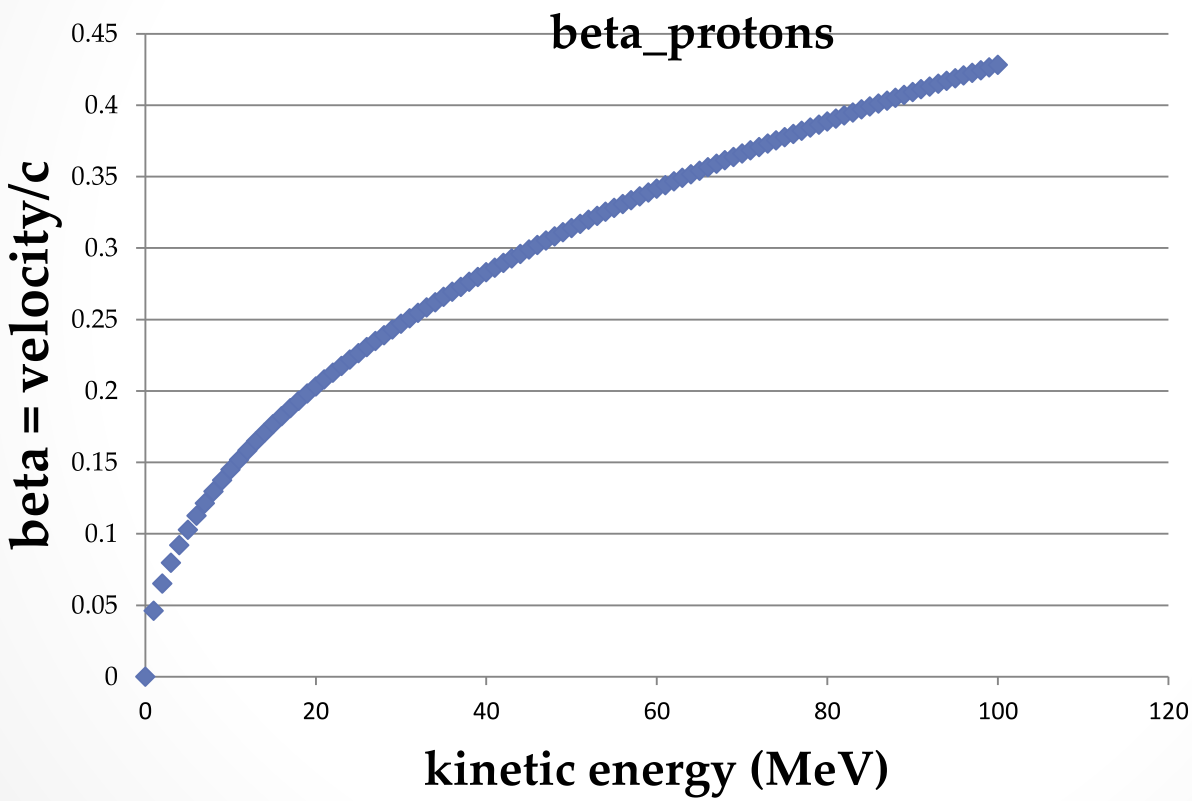
Synchronism condition :

$$\phi_{si+1} - \phi_{si} = \omega \cdot \frac{D_i}{\beta_{si}\, c} + \phi_{i+1} - \phi_i + 2\pi n$$

Synchronous structures



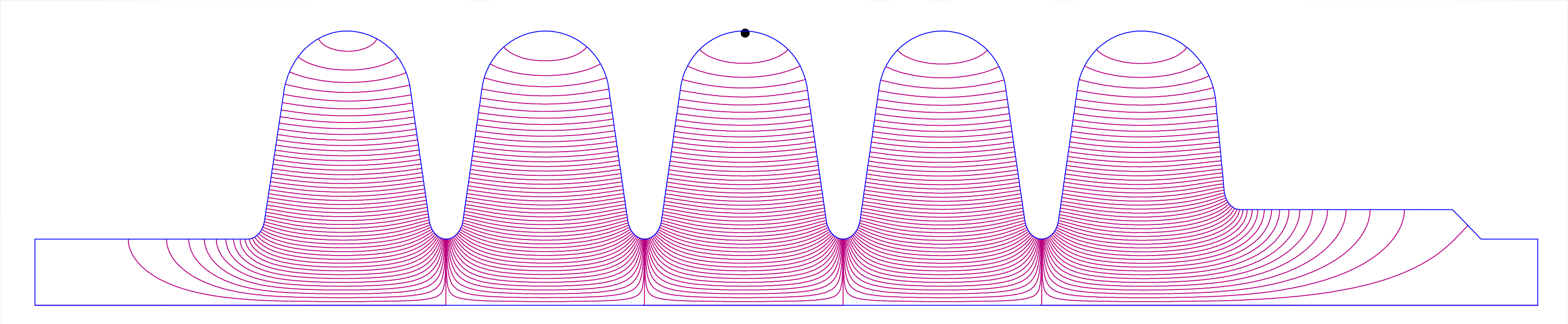
Beta vs W


beta_protons
beta = velocity/c
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
kinetic energy (MeV)

Almost perfect synchronicity

- for simplifying construction and therefore keeping down the cost, cavities are not individually tailored to the evolution of the beam velocity but they are constructed in blocks of identical cavities (tanks). several tanks are fed by the same RF source.
- This simplification implies a "phase slippage" i.e. a motion of the centre of the beam . The phase slippage is proportional to the number of cavities in a tank and it should be carefully controlled for successful acceleration.

phase slippage



Lcavity = $\beta_g \lambda/2$

particle enters the cavity with $\beta_s < \beta_g$. It is accelerated

the particle has not left the cavity when the field has changed sign : it is also a bit decelerated

the particle arrives at the second cavity with a “delay”

........and so on and so on

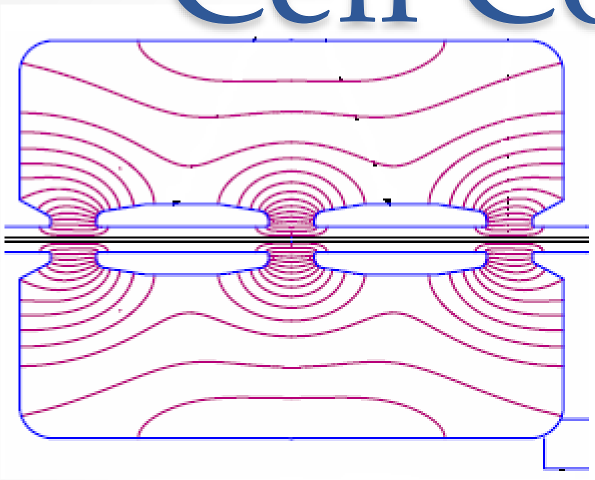
we have to optimize the initial phase for minimum phase slippage

for a given velocity there is a maximum number of cavity we can accept in a tank

Adapting the structure to the velocity of the particle

- Case1 : the geometry of the cavity/structure is continuously changing to adapt to the change of velocity of the "synchronous particle"
- Case2 : the geometry of the cavity/structure is adapted in step to the velocity of the particle. Loss of perfect synchronicity, phase slippage.
- Case3 : the particle velocity is beta=1 and there is no problem of adapting the structure to the speed.

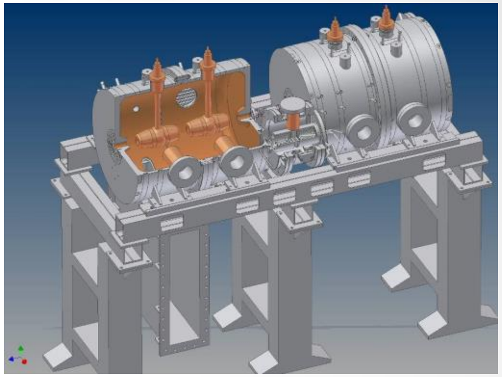
Cell Coupled-DTL



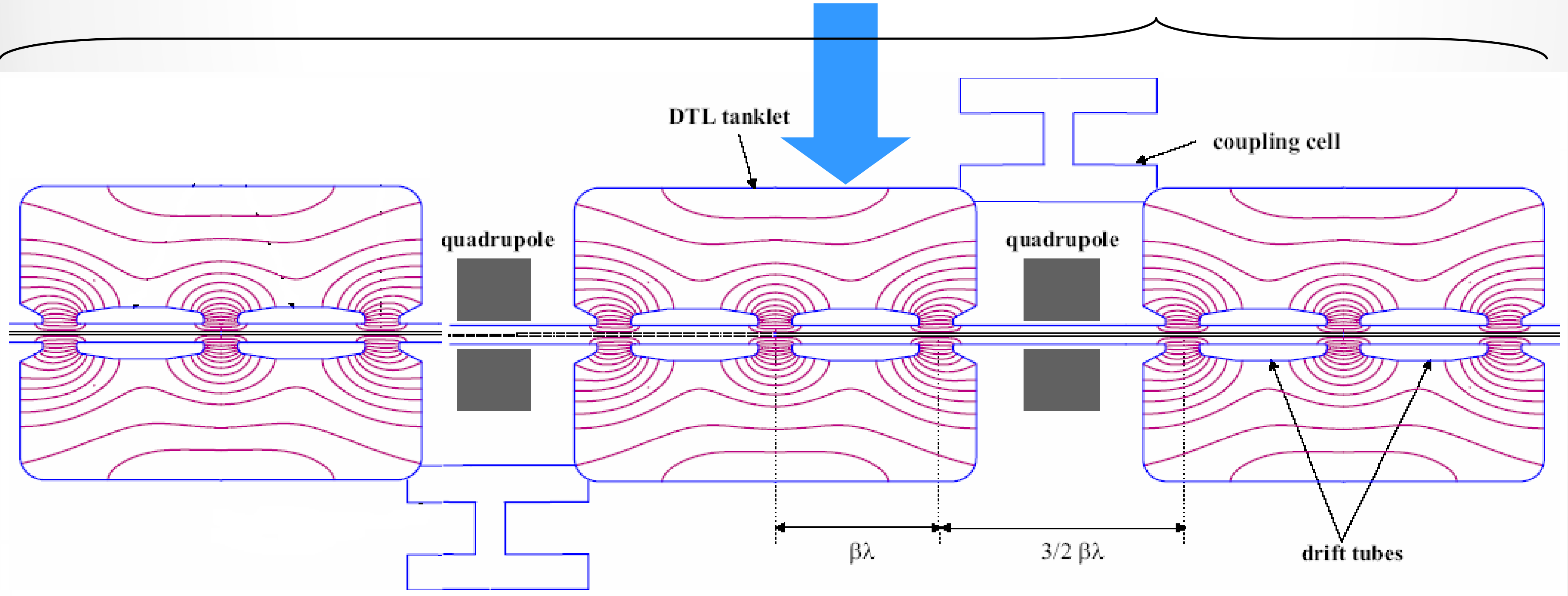
Single Accelerating

CCDTL tank

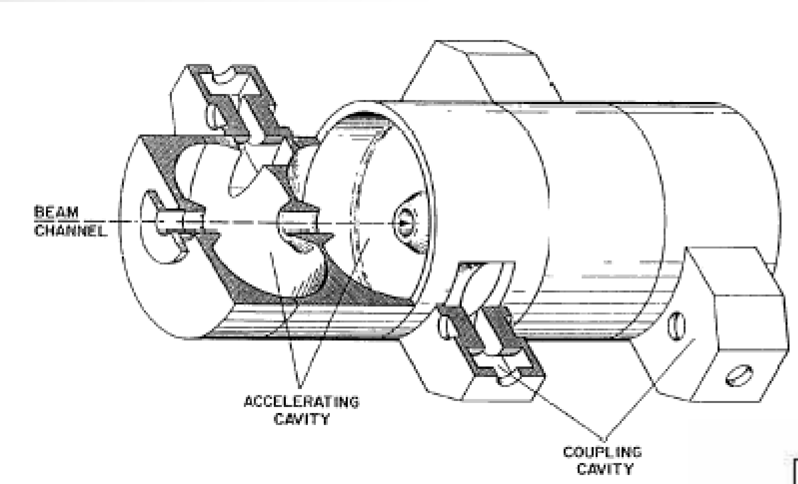
1 Power coupler / klystron



Module

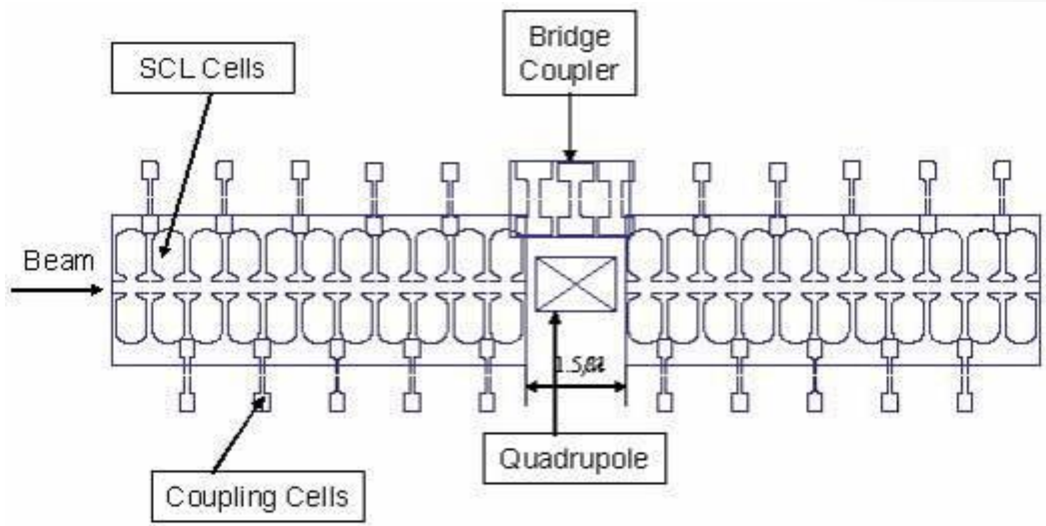


Side Coupled Linac

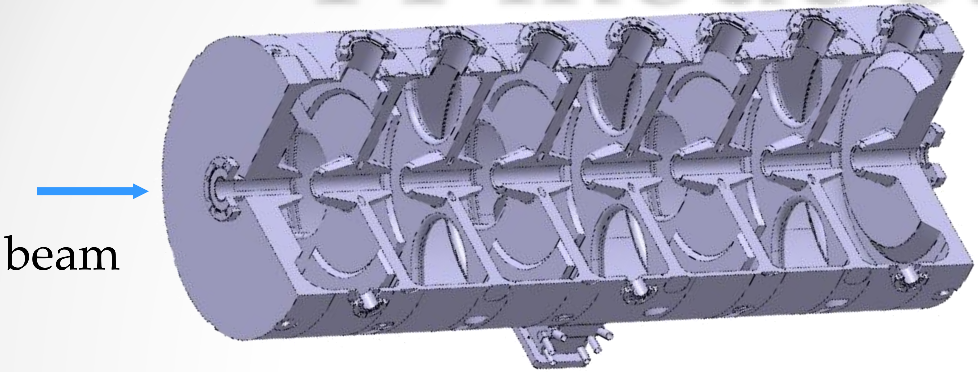


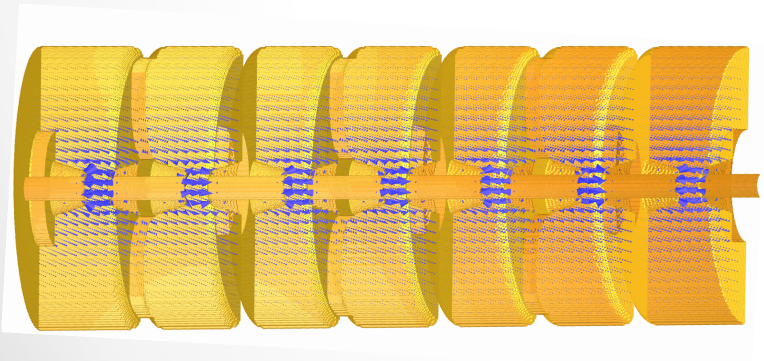
Chain of cells, coupled via slots and off-axis coupling cells.
Invented at Los Alamos in the 60's.
Operates in the $\pi/2$ mode (stability).

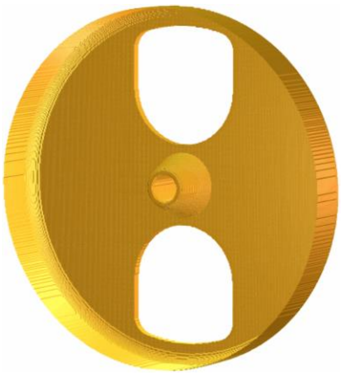
CERN SCL design:
Each klystron feeds 5 tanks of 11 accelerating cells each, connected by 3-cell bridge couplers.
Quadrupoles are placed between tanks.



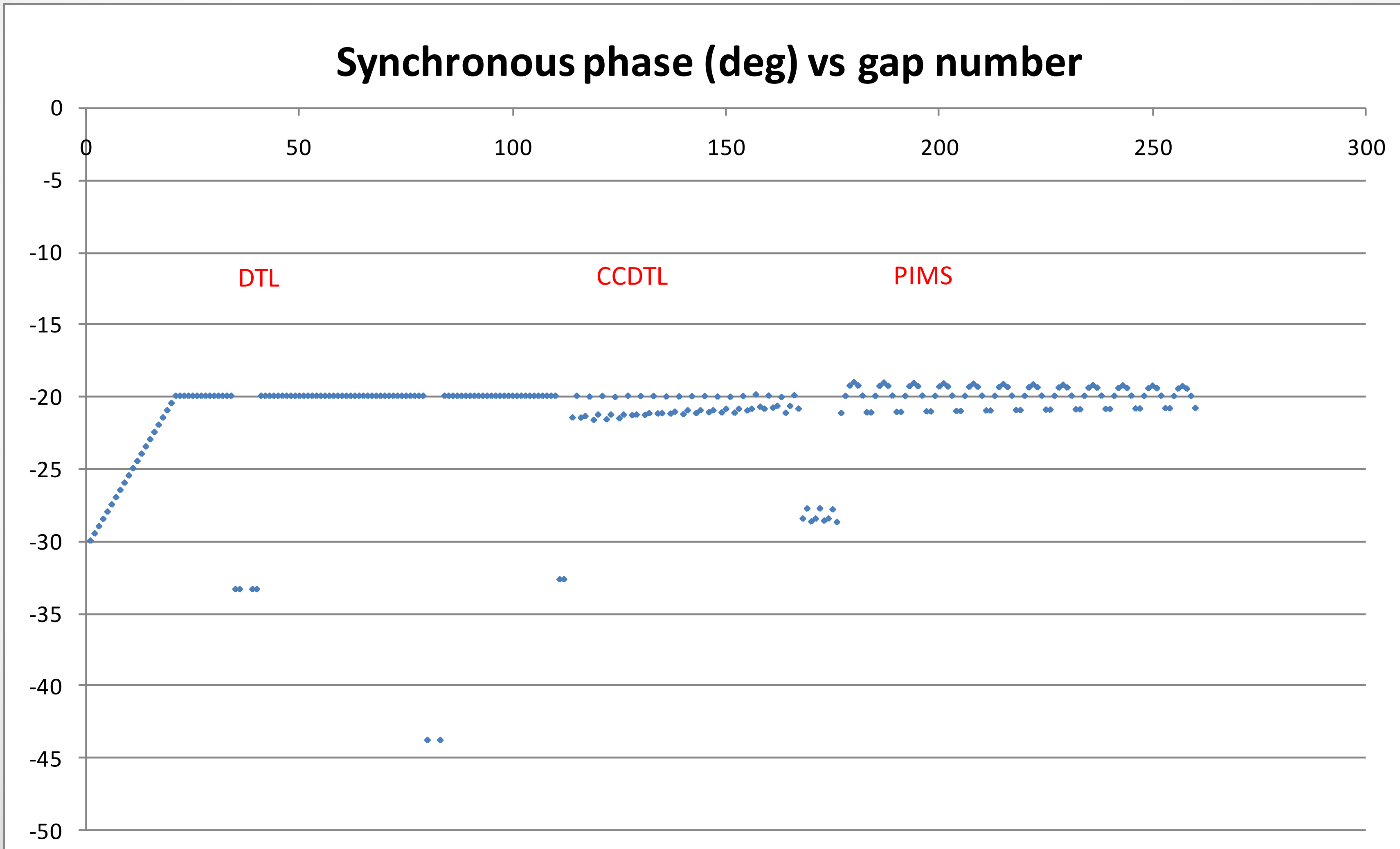
PI-mode structure





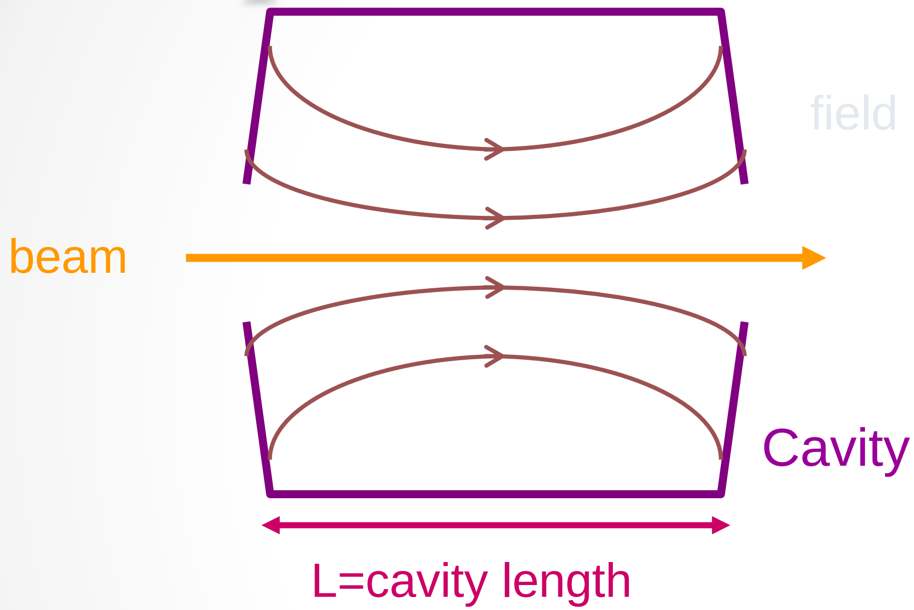


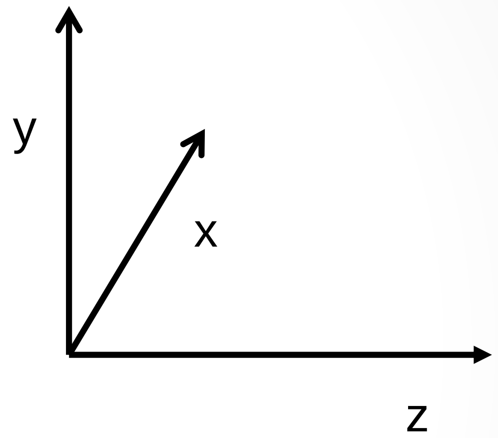
Beam centre phase in LINAC4



How to choose

cavity geometry and related parameters definition





1-Maximum field/average field

2-Shunt impedance

3-Quality factor

4-Filling time

5-Transit time factor

6-Effective shunt impedance

Average electric field

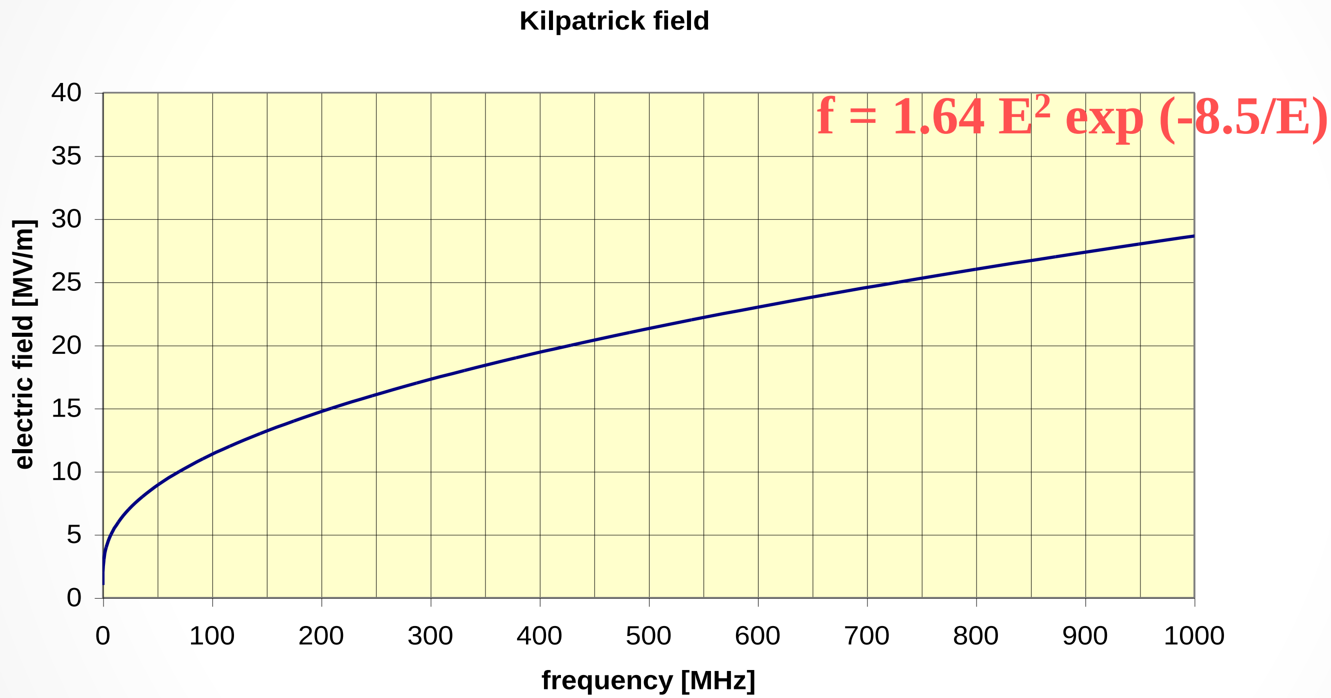
- Average electric field (E_0 measured in V/m) is the space average of the electric field along the direction of propagation of the beam in a given moment in time when F(t) is maximum.

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

$$E_0 = \frac{1}{L}\int_0^L E_z(x=0,y=0,z)\,dz$$

- physically it gives a measure how much field is available for acceleration
- it depends on the cavity shape, on the resonating mode and on the frequency

Kilpatrick sparking criterion

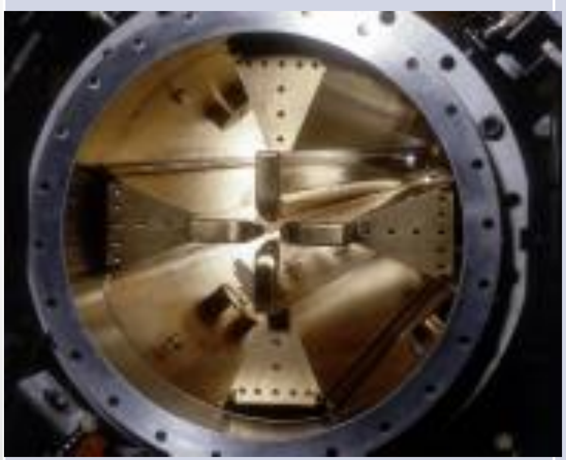
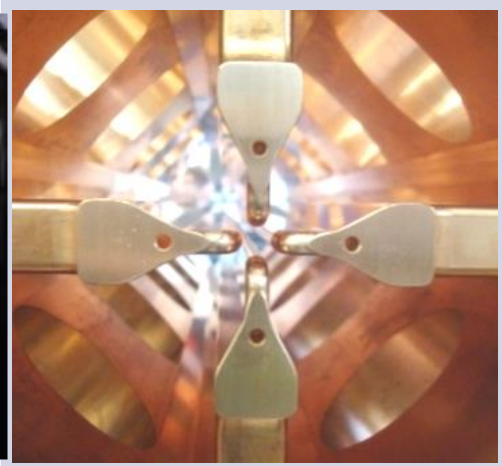
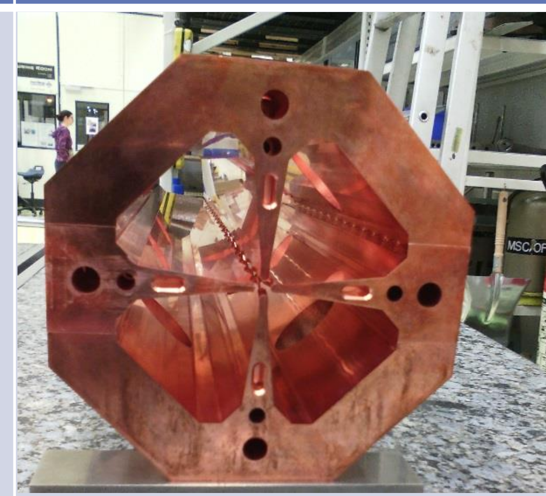


GUIDELINE nowadays : peak surface field up to 2*kilpatrick field

Quality factor for normal conducting cavity is E_{peak}/E_oT

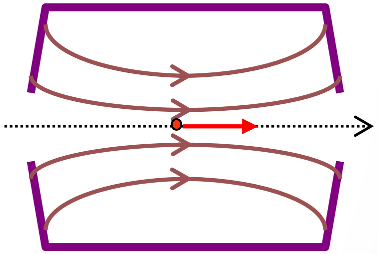
The higher the frequency

1990 LINAC2 RFQ2 200 MHz 0.5 MeV /m Weight : 900kg/m Ext. diametre : ~45 cm Beam current: 200 mA	2007 LINAC4 RFQ 352 MHz 1MeV/m Weight : 400kg/m Ext. diametre : 29 cm Beam current : 80 A	2014 HF RFQ 750MHz 2.5MeV/m Weight : 100 kg/m Ext. diametre : 13 cm Beam current : 0.1 mA

Transit time factor

- transit time factor (T, dimensionless) is defined as the maximum energy gain per charge of a particles traversing a cavity over the average voltage of the cavity.
- Write the field as $Ez(x,y,z,t) = E_z(x,y,z)e^{-i(\omega t)}$



- The energy gain of a particle entering the cavity on axis at phase φ is
- $$\Delta W = \int_0^L qE_z(o,o,z)e^{-i(\omega t+\phi)}dz$$

cavity parameters-5

- assume constant velocity through the cavity (APPROXIMATION!!) we can relate position and time via

$$z = v \cdot t = \beta c t$$

- we can write the energy gain as

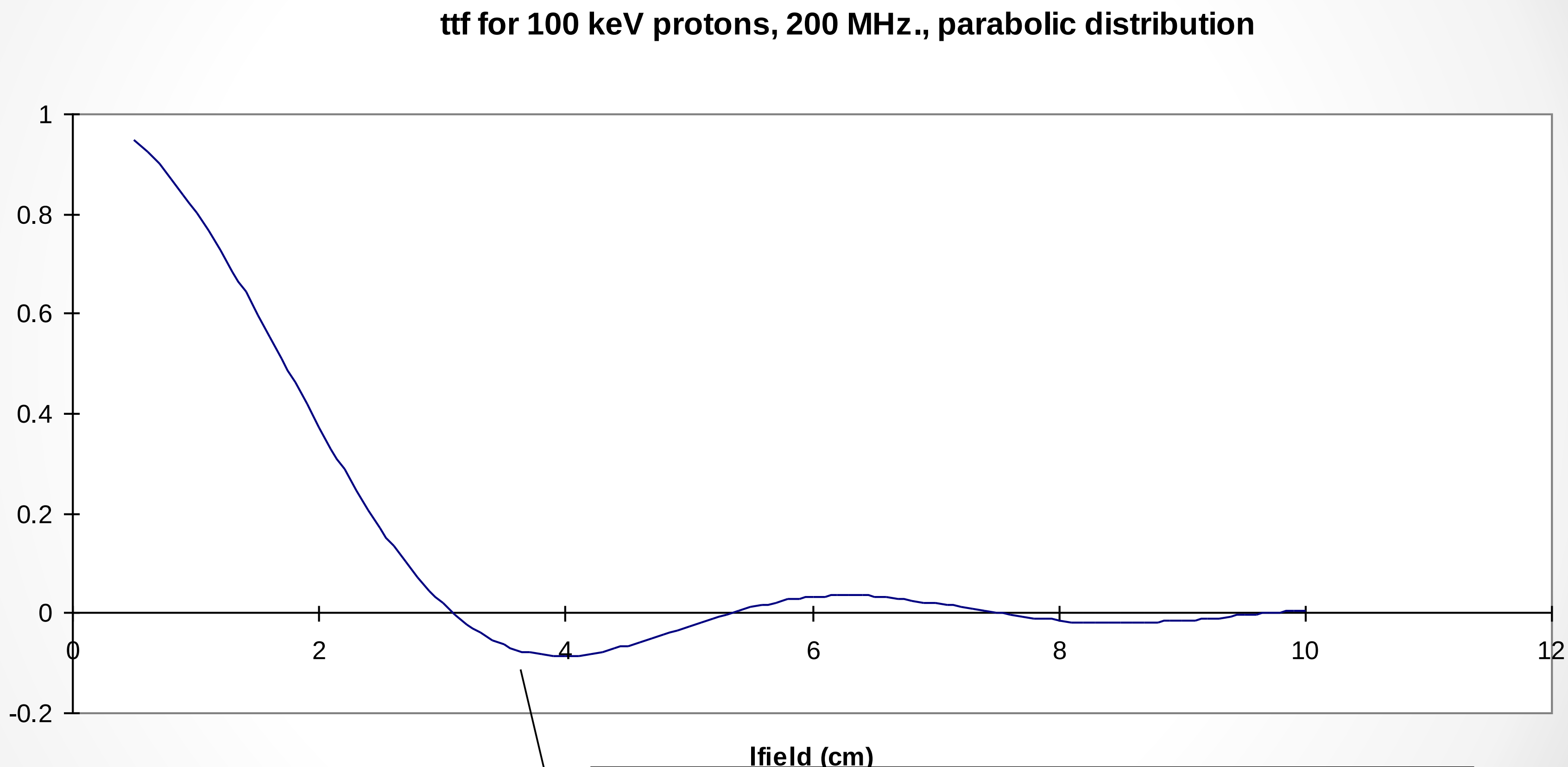
$$\Delta W = qE_0 LT\cos(\phi)$$

- and define transit time factor as

$$T = \frac{\left| \int_0^L E_z(z) e^{-j\left(\frac{\omega z}{\beta c}\right)} dz \right|}{\int_0^L E_z(z) dz}$$

T depends on the particle velocity and on the gap length. IT DOESN"T depend on the field

Transit time factor



if we don't get the length right we can end up decelerating!!!

effective shunt impedance

- Effective shunt impedance (Z measured in Ω/m) is defined as the ratio of the average effective electric field squared (E0T) to the power (P) per unit length (L) dissipated on the wall surface.
- it is independent of the field level and cavity length, it depends on the cavity mode and geometry and on the velocity of the particle to be accelerated

$$ZTT = \frac{(E_0 T)^2}{} \cdot \frac{L}{P}$$

measure if the structure is optimized and adapted to the velocity of the particle to be accelerated

Measure of how much energy a charged particle can gain for 1 w of power when travelling over 1 m of structure.

overview

take with CAUTION!

	Ideal range of beta	frequency	Effective gradient	[illegible]
RFQ	Low!!! - 0.05	40-400 MHz	1 MV/m (350MHz)	[illegible]
IH	0.02 to 0.08	40-200 MHz	4.5 MV/m (200MHz)	Ions and also protons
DTL	0.04-0.5	100-400 MHz	3.5 MV/m (350MHz)	Ions / protons
SCL	Ideal Beta=1 But as low as beta 0.3	800 - 3000 MHz	20 MV/m (3000MHz)	protons

What is a linac-cont'ed

Relativistic or not

$$\frac{d}{dt}\left(\gamma \frac{d\vec{x}}{dt}\right) = \frac{q}{m_0} \cdot \left(\vec{E} + \frac{d\vec{x}}{dt} \times \vec{B} \right)$$

type of particle : charge couples with the field, mass slows the acceleration

type of RF structure

type of focusing

Magnetic quadrupoles

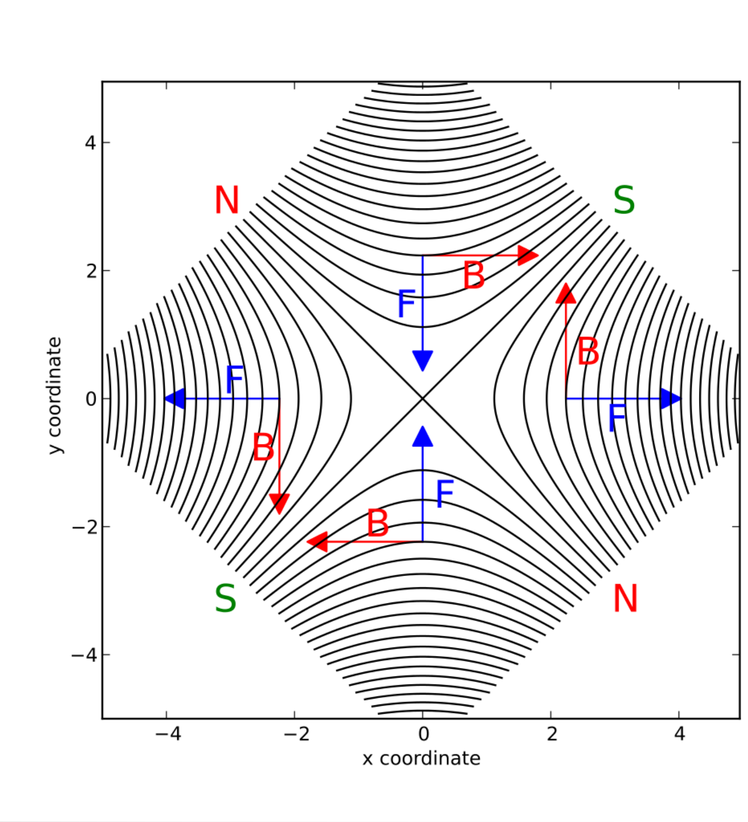
ElectroMQ

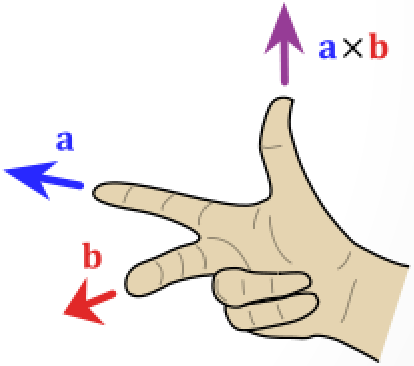
Permanent MQ

Focusing force

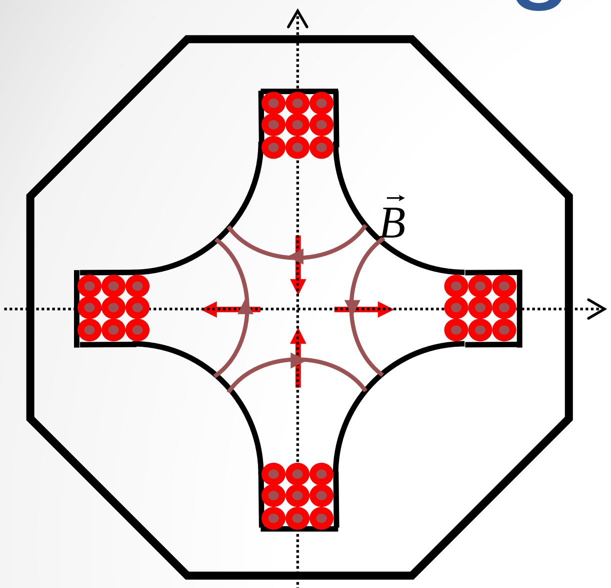
B=magnetic field/F=force

Positively charged particles going into the screen





Magnetic quadrupole



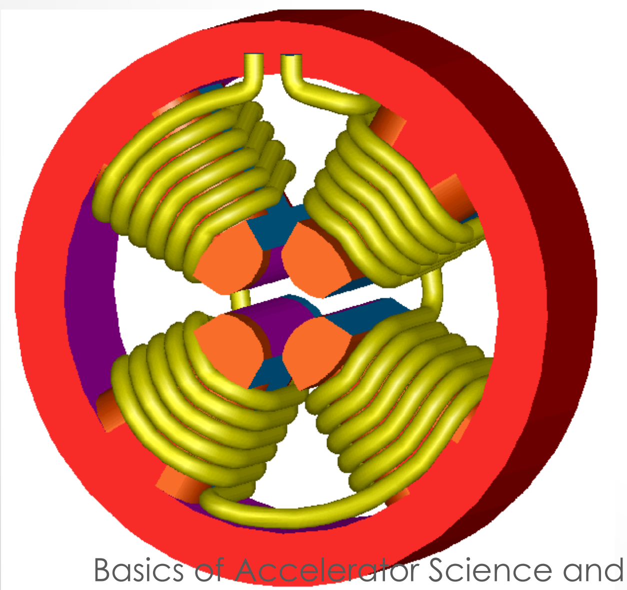
Magnetic field

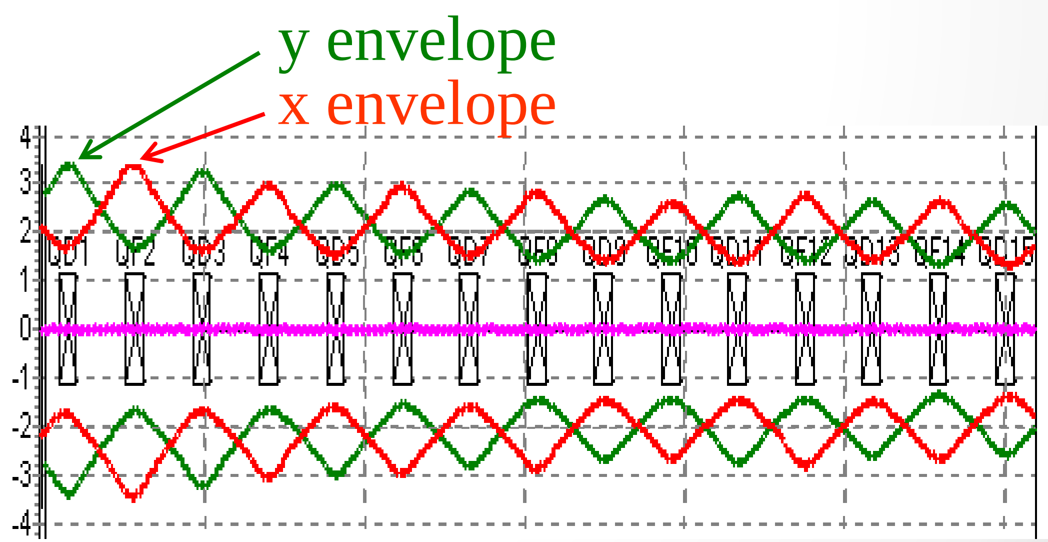
$$\begin{cases} B_x = G \cdot y \\ B_y = G \cdot x \end{cases}$$

Magnetic force

$$\begin{cases} F_x = -q \cdot v \cdot G \cdot x \\ F_y = q \cdot v \cdot G \cdot y \end{cases}$$

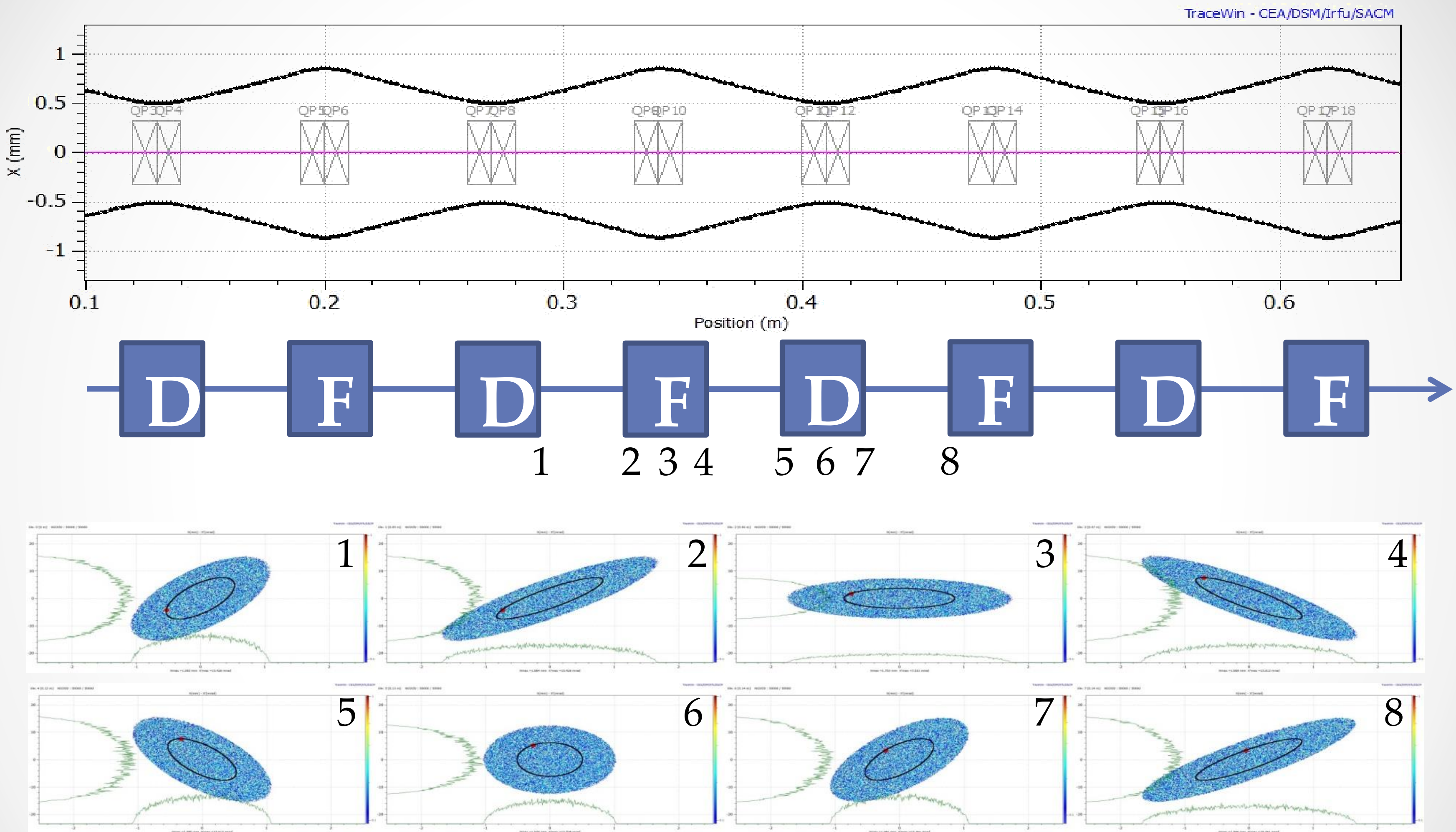
Focusing in one plan, defocusing in the other





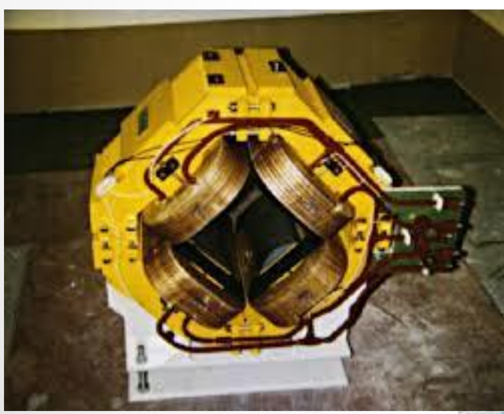
sequence of focusing and defocusing quadrupoles

F0D0 focusing



The beam is matched, after every period, the twiss parameters are identical.

Building blocks-recap



Choices / Questions

Frequency?	Frequency and size Frequency and acceptance Frequency and maximum accelerating field Frequency and duty cycle
RFQ output energy?	Into which structure do we inject How long is the RFQ (compared to wavelenght)
Continue with TE mode or switch to TM mode?	Start thinking about transverse focusing Think about the final energy Think about the energy at the transition (NB treshold for copper activation is around few MeV)
At what energy we start standardising the RF structures	Quasi-synchronous condition
PMQ or EMQ?	Cheap and easy or maximum flexibility