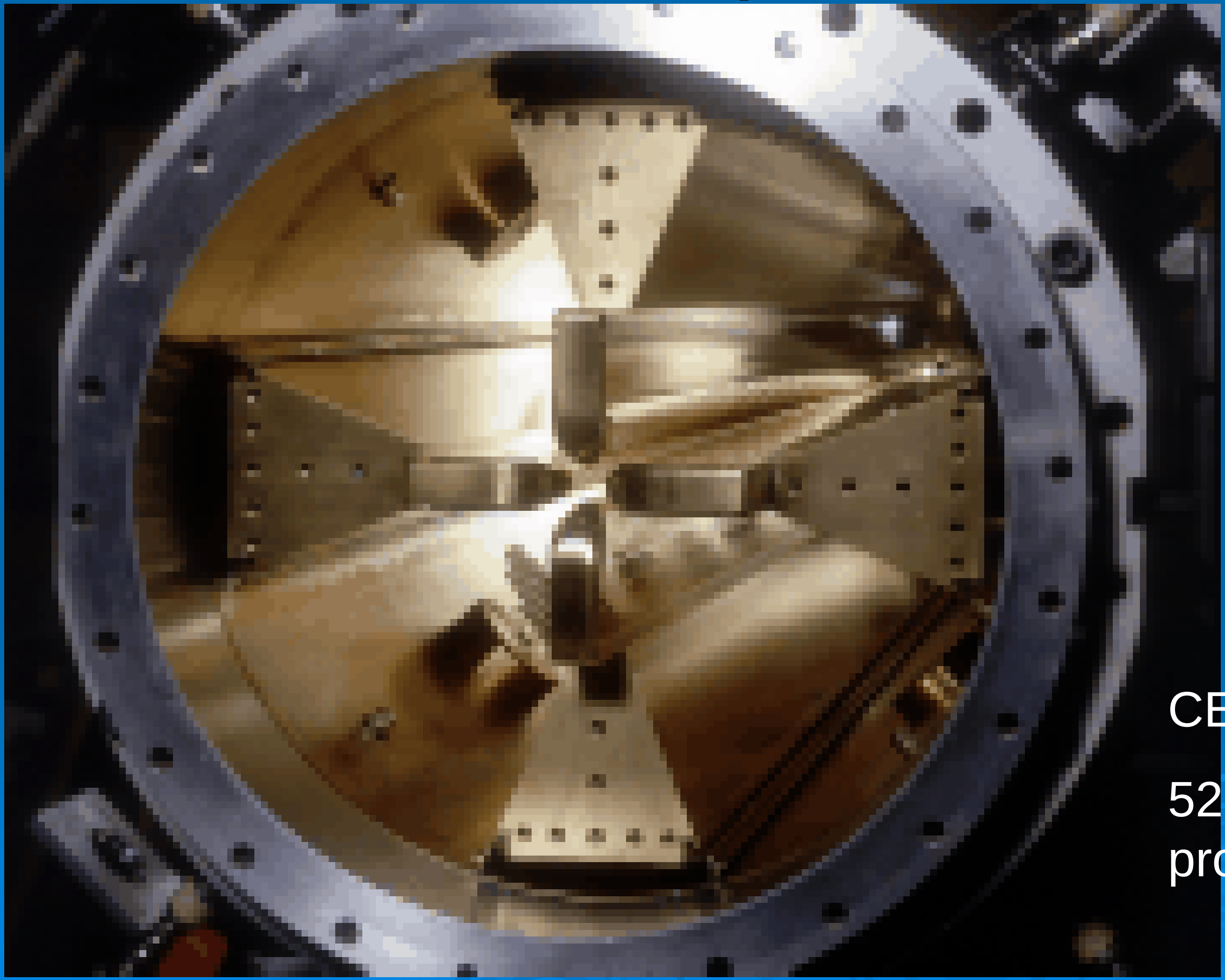
Radio Frequency Quadrupole

Alessandra Lombardi

Radio Frequency Quadrupole is on the school poster!



CERN RFQ1

520 keV protons

Contents

- Motivation and historical introduction
- What is a radio frequency quadrupole (RFQ) ?
- Designing a RFQ
- Frequently asked questions

RFQ history

- 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)).
- 1974 experimental test of K&T idea at USSR Institute for High Energy Physics in Protvino. A 148.5-MHz RFQ accelerated 100-KeV protons to 620 KeV with an efficiency of 50%.
- 1977 RFQ concept is published in the western world. Strong interest in Los Alamos National Laboratory (USA). Decision to test the RFQ principle for possible application in development of high-current low-emittance beams. Developments of computer codes for rfq design.
- 1979 Start of P.O.P. (Proof-of-principle experiment) at Los Alamos . 425 MHz RFQ accelerates a 100-keV proton beam to 640 keV with an efficiency of 90%, as predicted by the codes. (14 Feb. 1980)
- Nowadays hundreds of RFQ accelerator are operating in the world

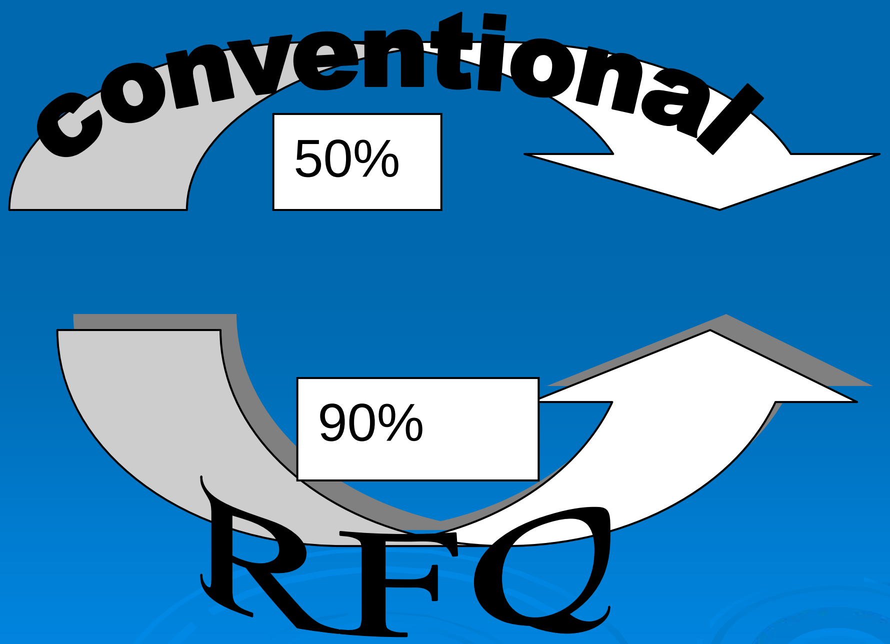
RFQ represented the "missing link" to high power beam

•High current and small emittance (powerful source)
•High energy (powerful and efficient accelerators)

POWERFUL SOURCE :

200 mA proton beam

Emittance 1 pi mm mrad



POWERFUL

ACCELERATOR

Link between source and efficient accelerator

The **R**adio **F**requency **Q**uadrupole is a linear accelerator which

- focuses
- bunches
- accelerates

a continuos beam of charged particles with high efficiency and preserving the emittance

Both the focusing as well as the bunching and acceleration are performed by the RF field

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 :

$$\vec{E}_{//}=\vec{0}$$

$$\vec{B}_{\perp}=\vec{0}$$

TE or TM modes

- TE (=transverse electric) : the electric field is perpendicular to the direction of propagation. in a cylindrical cavity

$$TE_{nml}$$

n : azimuthal,

m : radial

l longitudinal component

- TM (=transverse magnetic) : the magnetic field is perpendicular to the direction of propagation

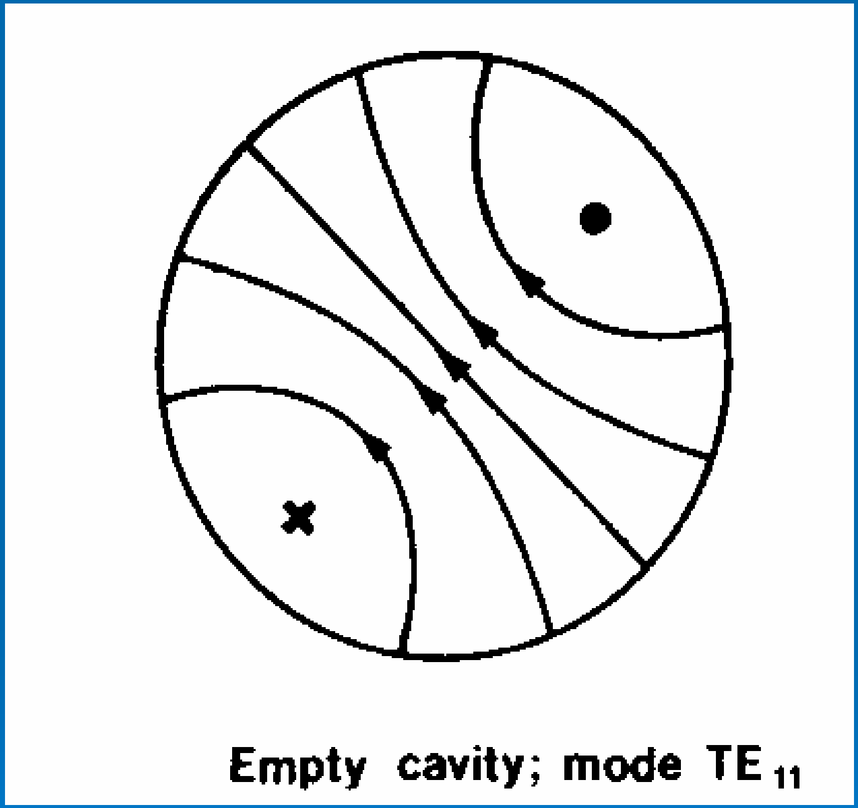
$$TM_{nml}$$

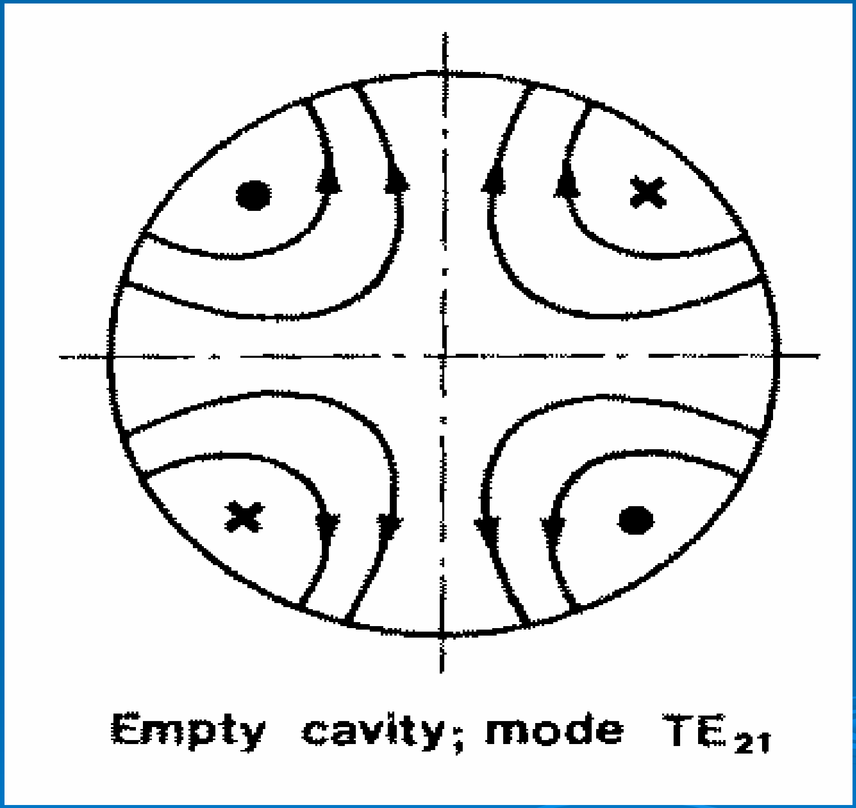
n : azimuthal,

m : radial

l longitudinal component

TE modes

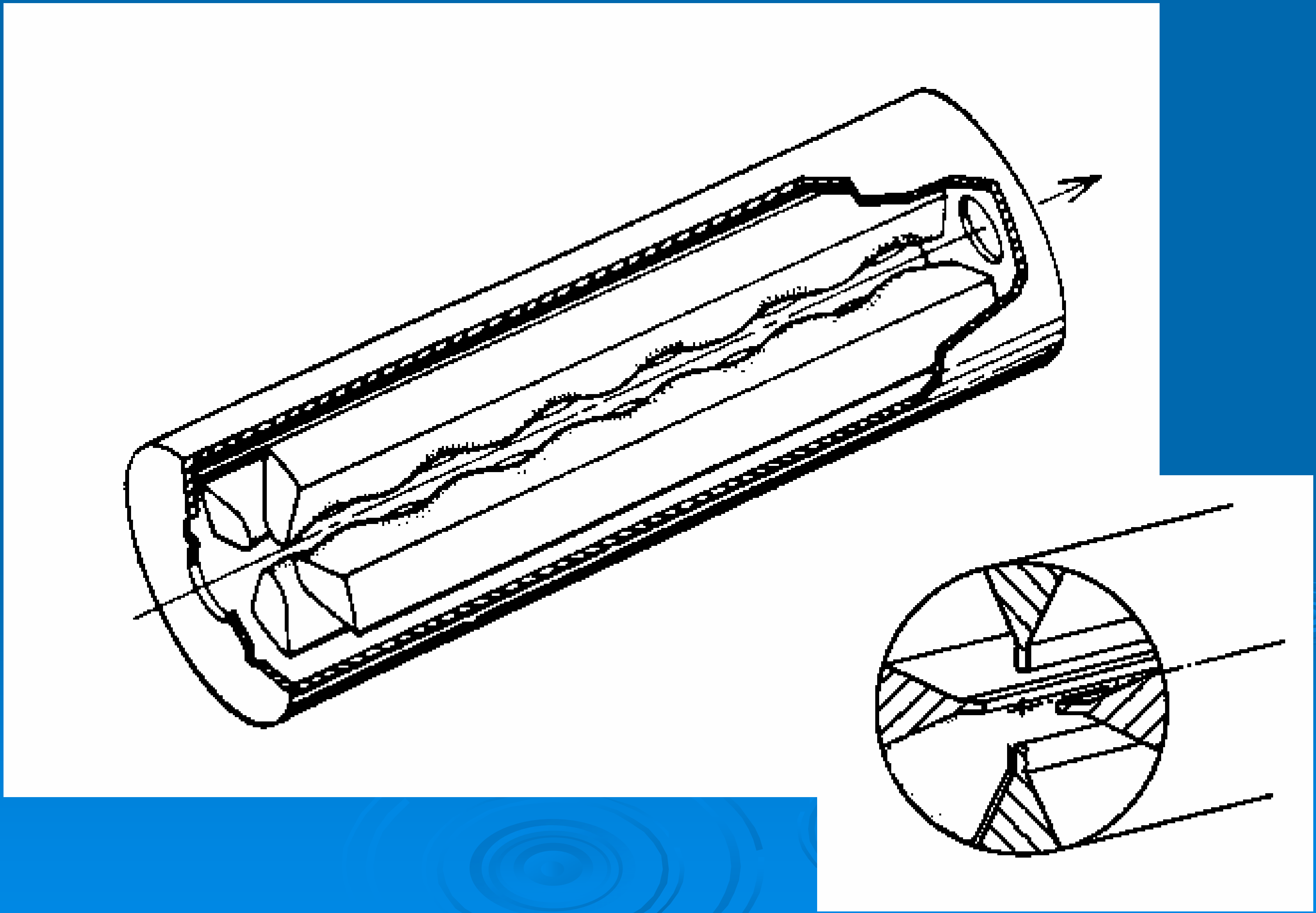




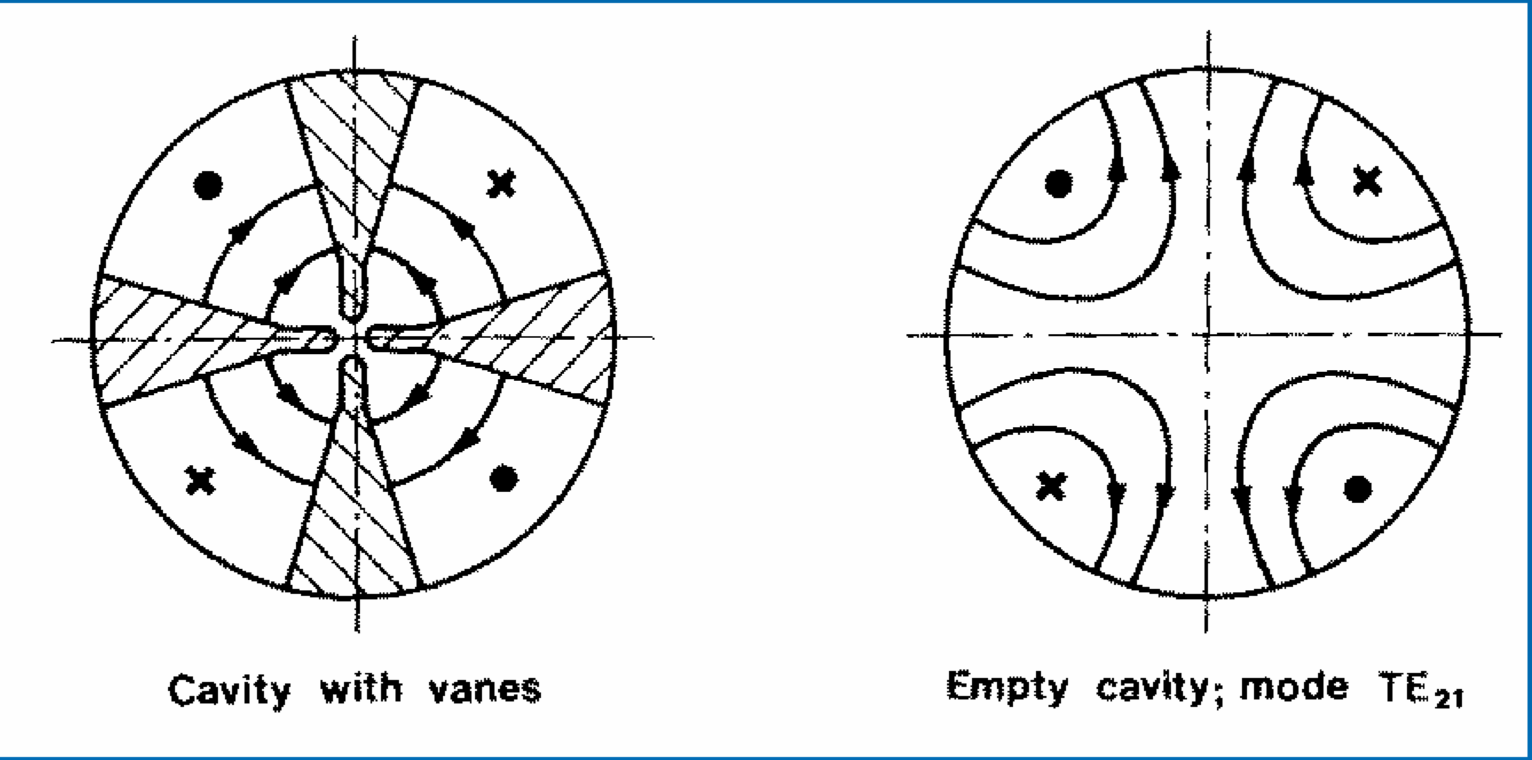
dipole mode

quadrupole mode used in Radio Frequency Quadrupole

Radio Frequency Quadrupole



Radio Frequency Quadrupole



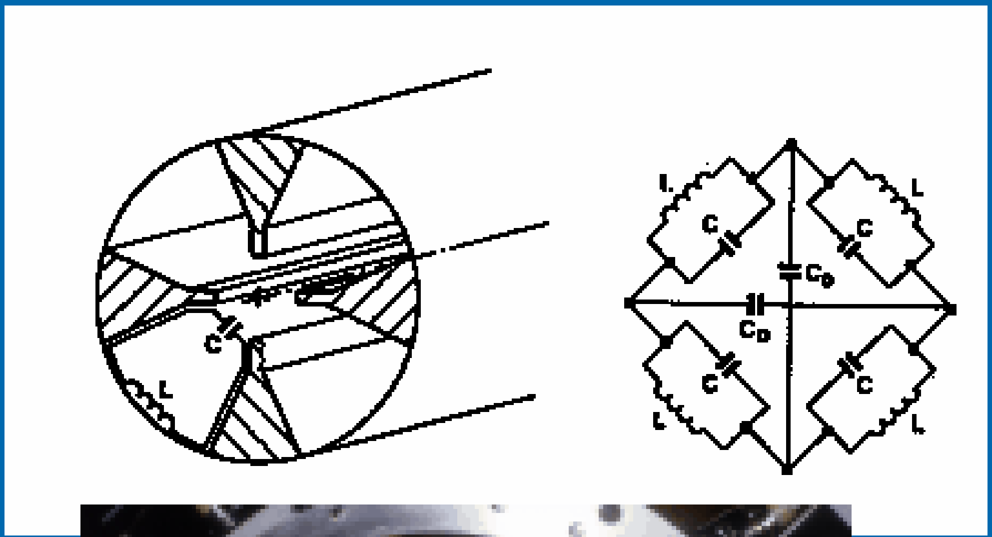
cavity loaded with 4 electrodes

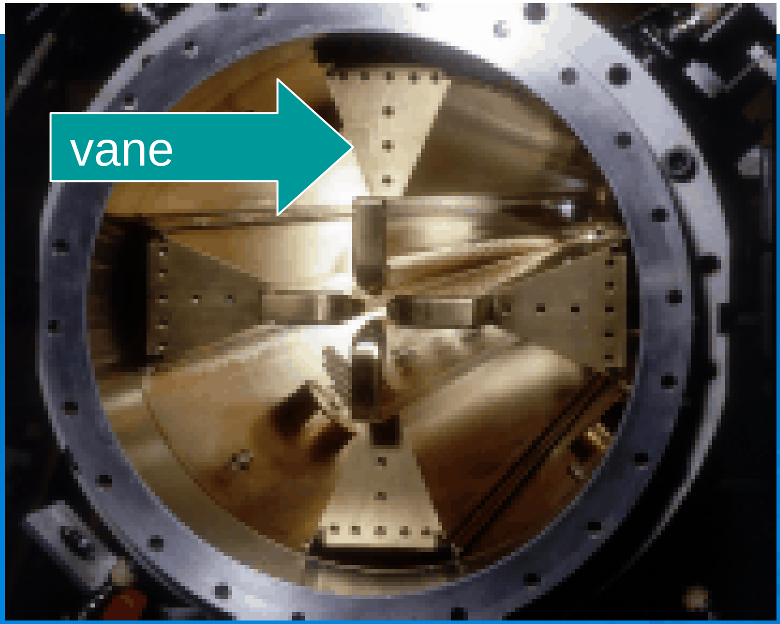
TE210 mode

RFQ Structures

- four-vane
- four-rod
- others (split coaxial,double H)

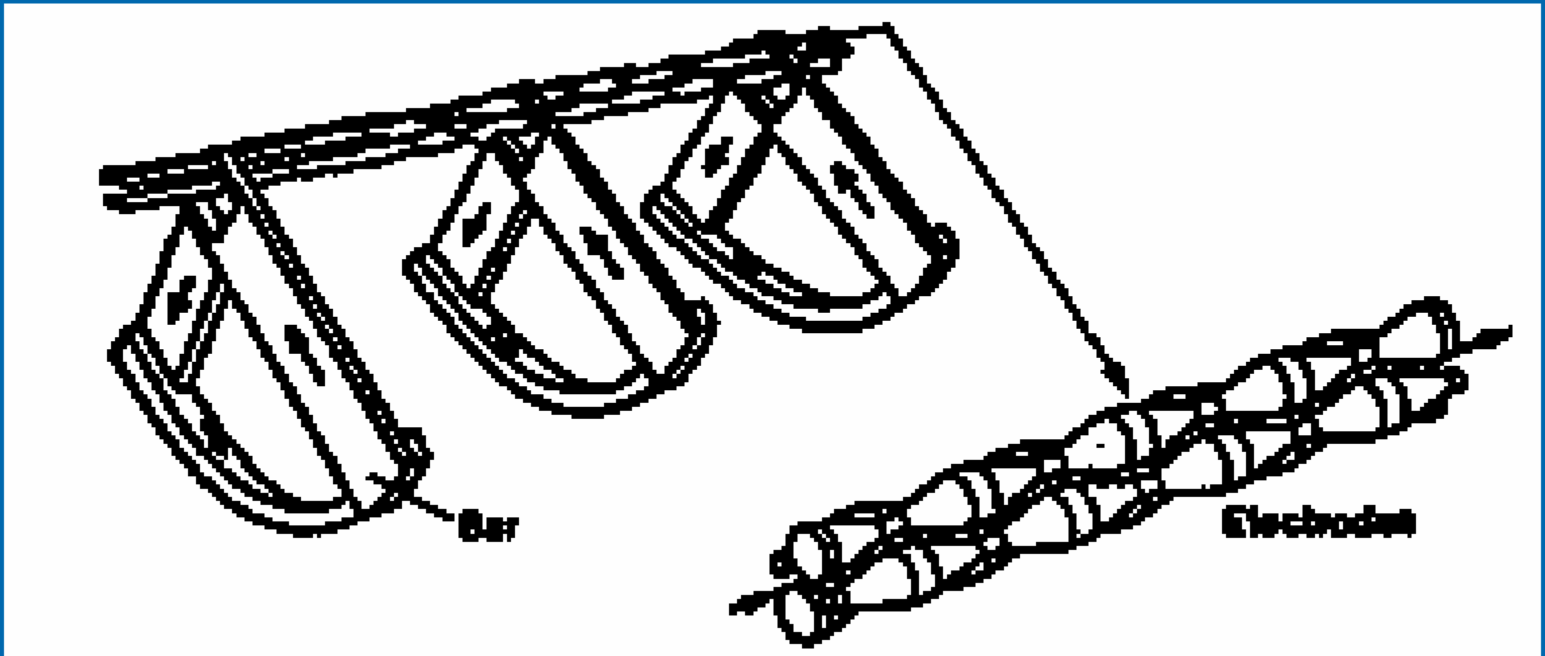
four vane-structure





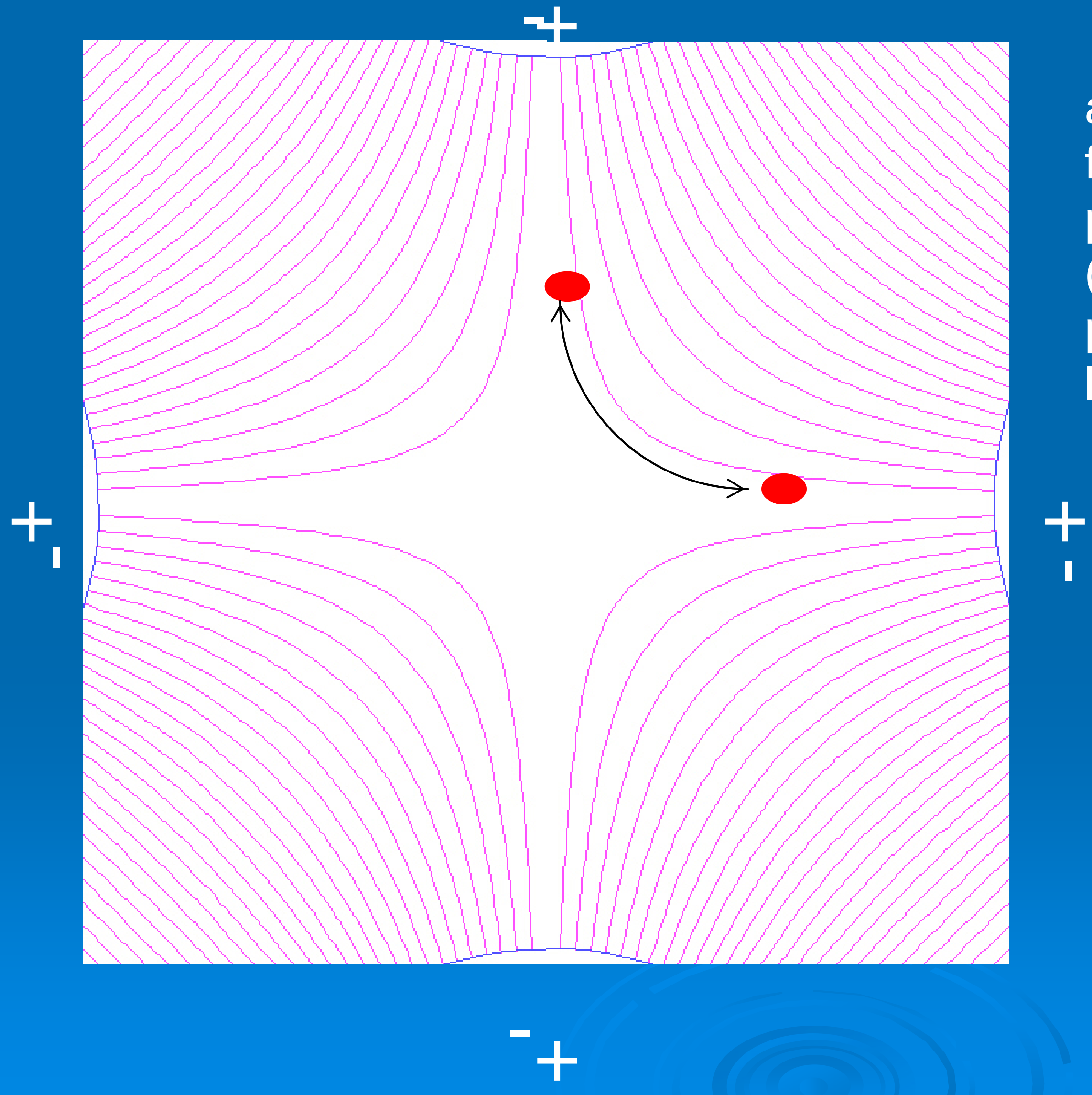
1. capacitance between vanetips, inductance in the intervane space
2. each vane is a resonator
3. frequency depends on cylinder dimensions (good at freq. of the order of 200MHz, at lower frequency the diameter of the tank becomes too big)
4. vane tip are machined by a computer controlled milling machine.
5. need stabilization (problem of mixing with dipole modeTE110)

four rod-structure



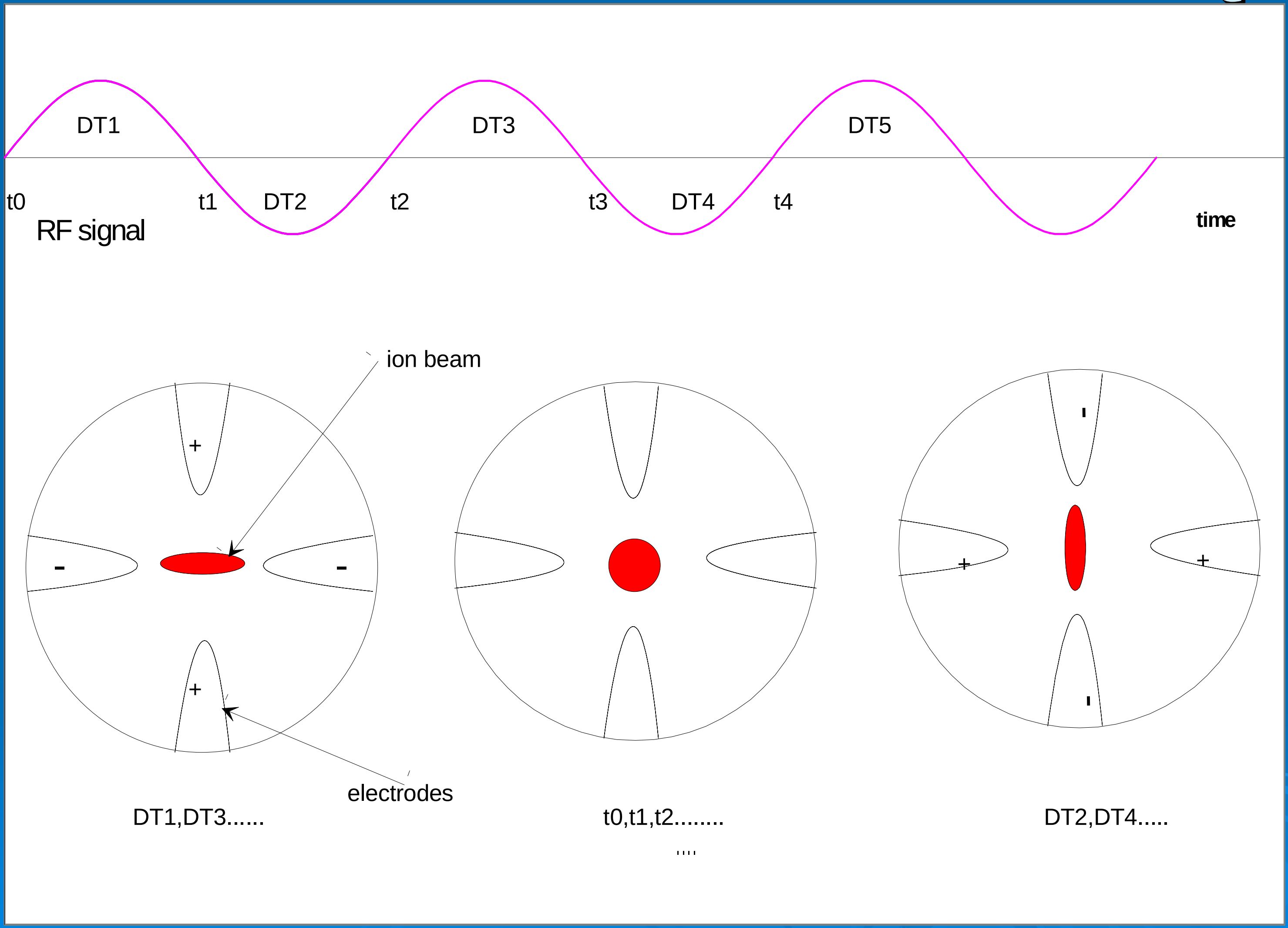
- capacitance between rods, inductance with holding bars
- each cell is a resonator
- cavity dimensions are independent from the frequency,
- easy to machine (lathe)
- problems with end cells, less efficient than 4-vane due to strong current in the holding bars

transverse field in an RFQ

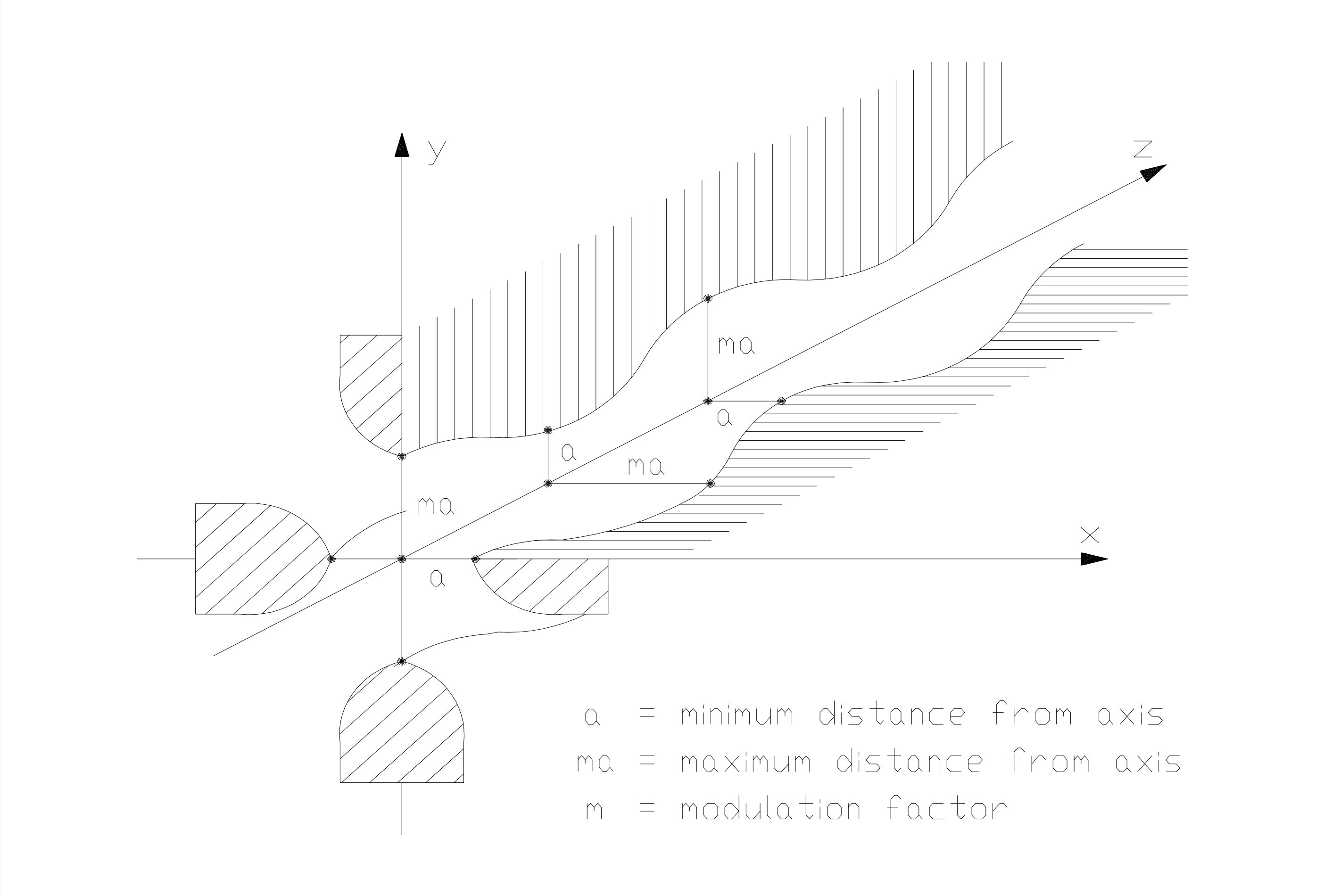


alternating gradient focussing structure with period length $\beta\lambda$
(in half RF period the particles have travelled a length $\beta\lambda/2$)

transverse field in an RFQ



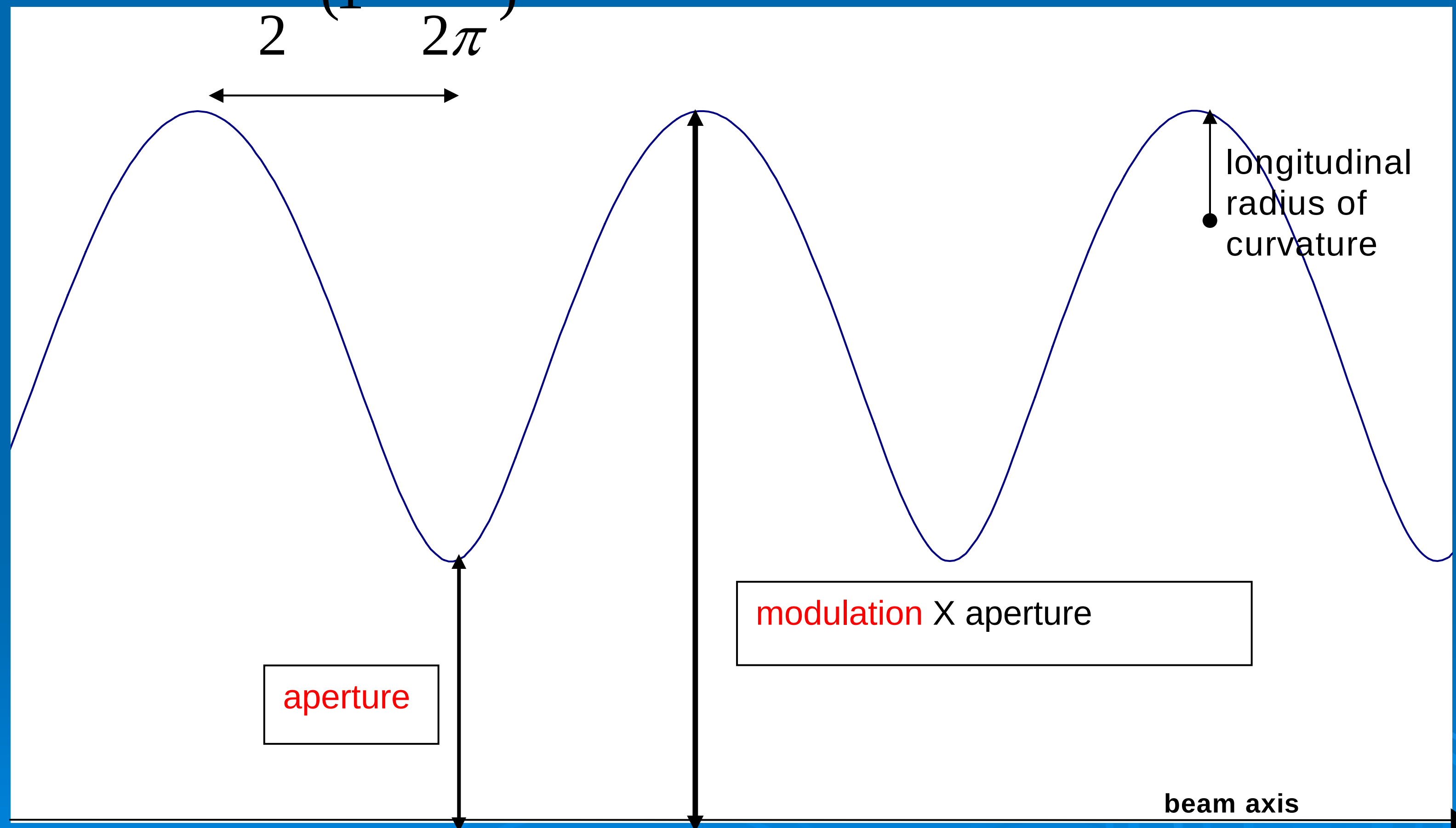
acceleration in RFQ



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

acceleration in an RFQ

$$\frac{\beta\lambda}{2}\left(1-\frac{\Delta\varphi}{2\pi}\right)$$



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

Beam dynamics design
(very first approach)

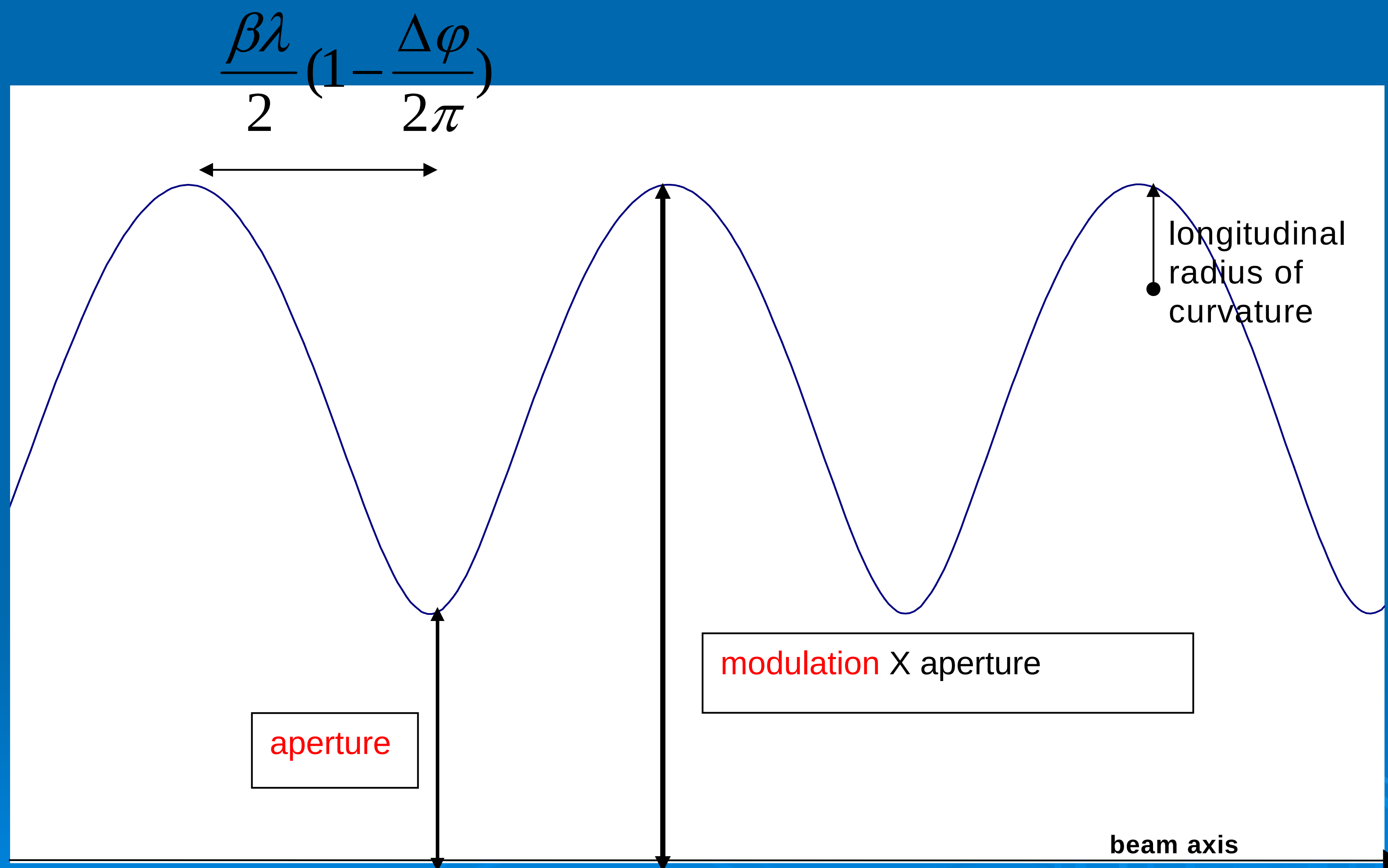
The beam dynamics in an RFQ determined by the geometrical parameter of the electrode structure

Aperture : determines the focusing strenght and the acceptance.

Depth of the modulation : determines the field availible for acceleration

Distance between the peaks and the trough of the modulation determines the synchronicity between the field and the particles

Electrode structure



Transverse plane-focusing

- quadrupole focusing (1)

- RF defocusing (modulation) (2)
- space charge defocusing (3)

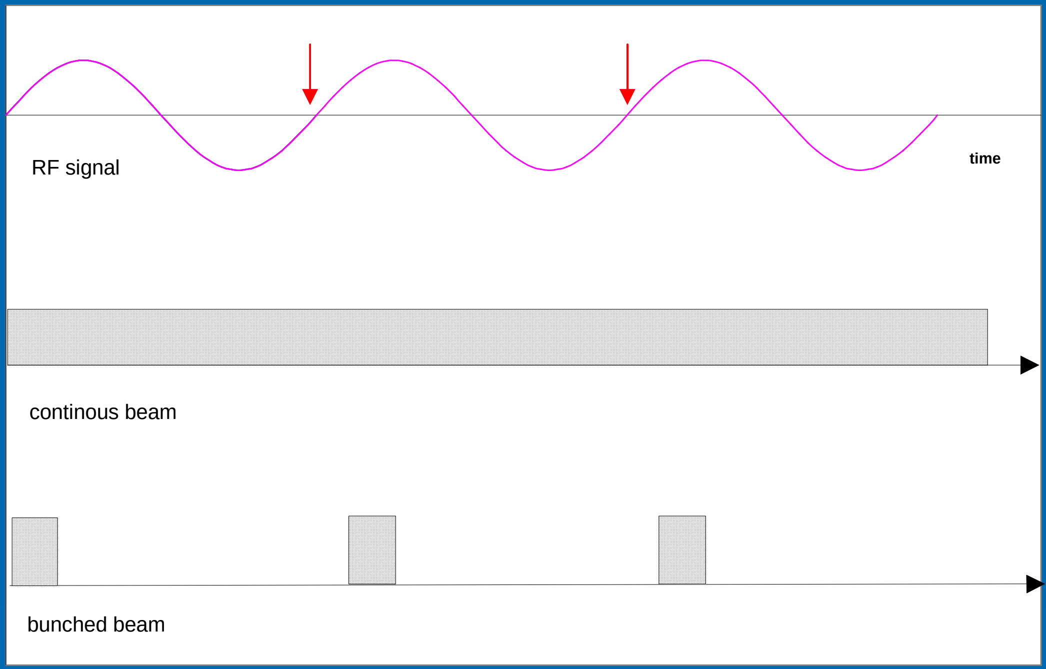
$$\sigma = \sqrt{\frac{B^2}{8\pi^2} - \frac{\pi q E_0 T \sin(\varphi)\lambda}{mc^2 \beta\gamma^3} - \frac{3Z_0 q I \lambda^3 (1 - f(p))}{8\pi mc^2 \gamma^3 r^2 b}}$$

(1) (2) (3)

$$0 \,\square\, \sigma < 90\,\mathrm{deg}$$

Z0 is the free-space impedance (376.73 Ohm),
I is the beam current,
f(p) is a geometrical factor
p is the ratio of the transvese beam dimensions,
r is the average transverse beam dimension, b the longitudinal .

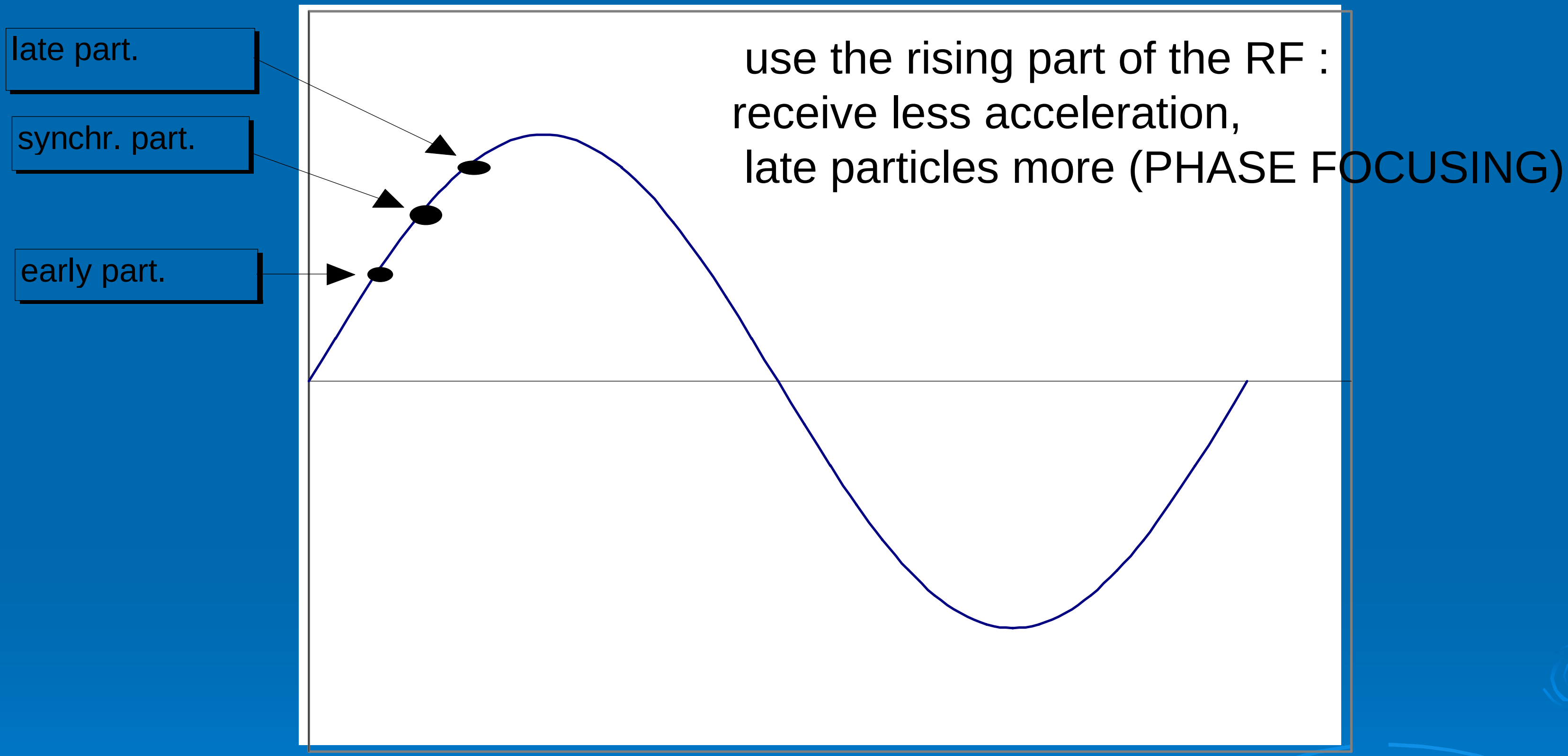
Longitudinal plane-bunching



Smootly change the velocity profile of the beam without changing its average energy

$$\varphi_s = -90\,\mathrm{deg}$$

Longitudinal plane-acceleration



$$-90\,\mathrm{deg} < \varphi_s < 0$$

RFQ sections

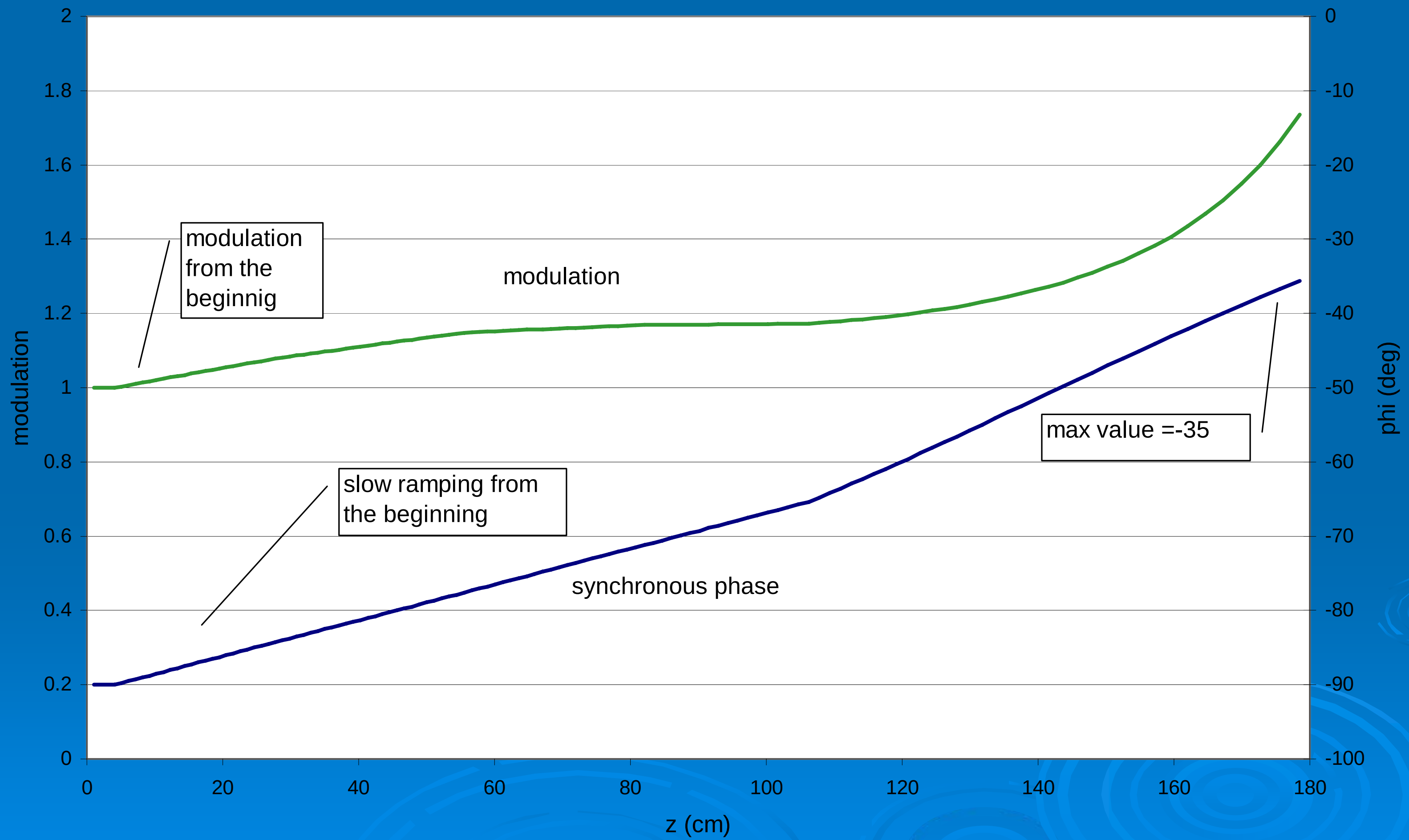
Radial matching to adapt the beam to a time-varying focusing system		
		aperture smoothly brought to the average value
shaping to give the beam a longitudinal structure		
Taper phase to –80,–60 deg	start modulation	aperture such that focusing is constant
bunching to bunch and begin acceleration		
Taper phase to –30,-20 deg	modulation to max	aperture such that focusing is constant
acceleration to bring the beam to the final energy.		
Constant phase	Constant modulation	Constant aperture
output matching to adapt the beam to the downstream user's need.		

High intensity vs. low intensity

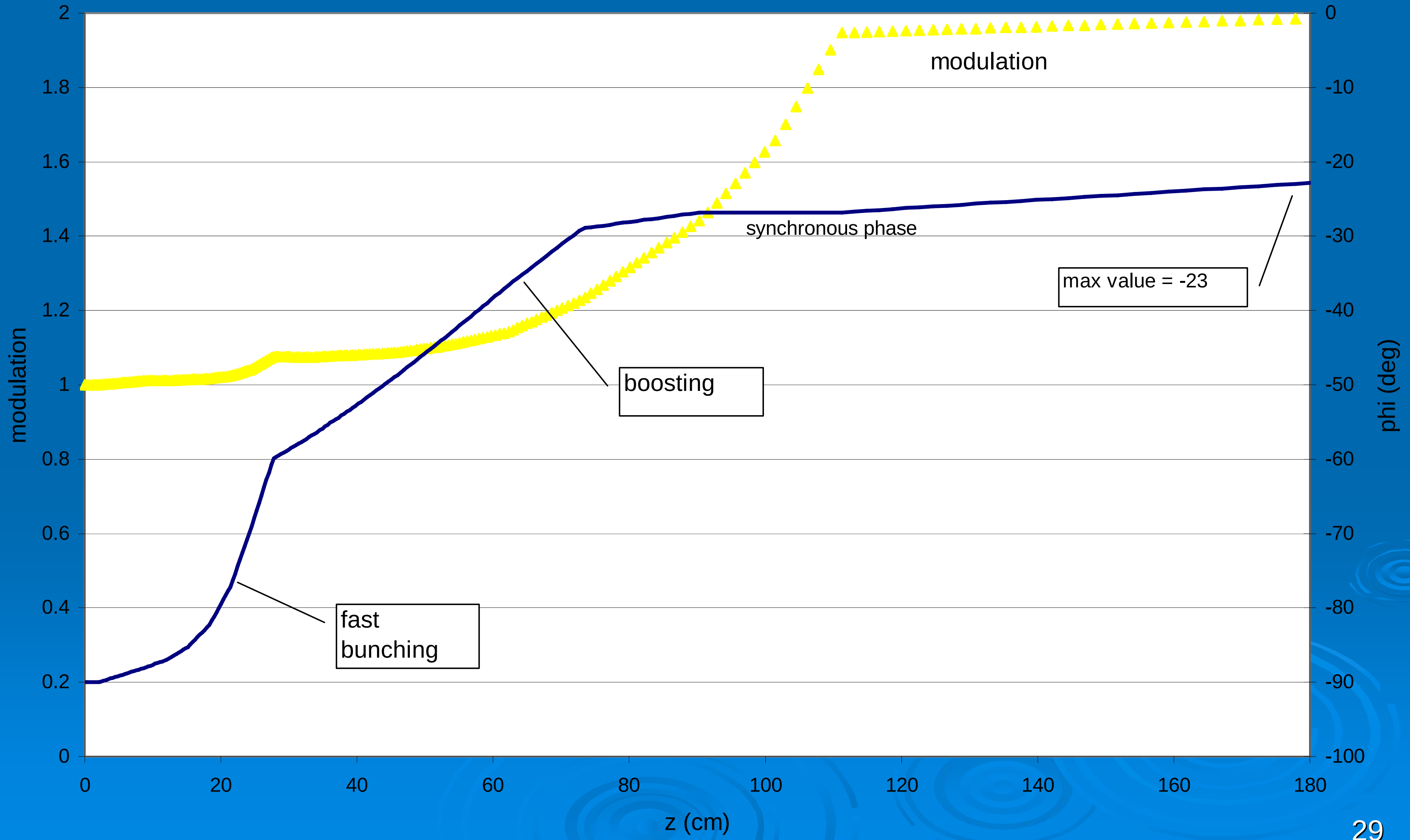
Emittance dominated		Space charge dominated
	RMS	
over many cells w/o acceleration	SHAPER	shaping and acceleration
fast bunching	PRE-BUNCHER	
complete the bunching (almost no energy increase up to here)	GENTLE BUNCHER	bunching and acceleration
fast transition to accelerating phase	BOOSTER	
beam strongly bunched (φ=-20,-15)	ACCELERATOR	beam bunched around φ=-35,-30
	EXIT MATCHER	

LOW INTENSITY RFQS CAN BE MADE SHORTER THAN THE CORRESPONDING HIGH INTENSITY ONES

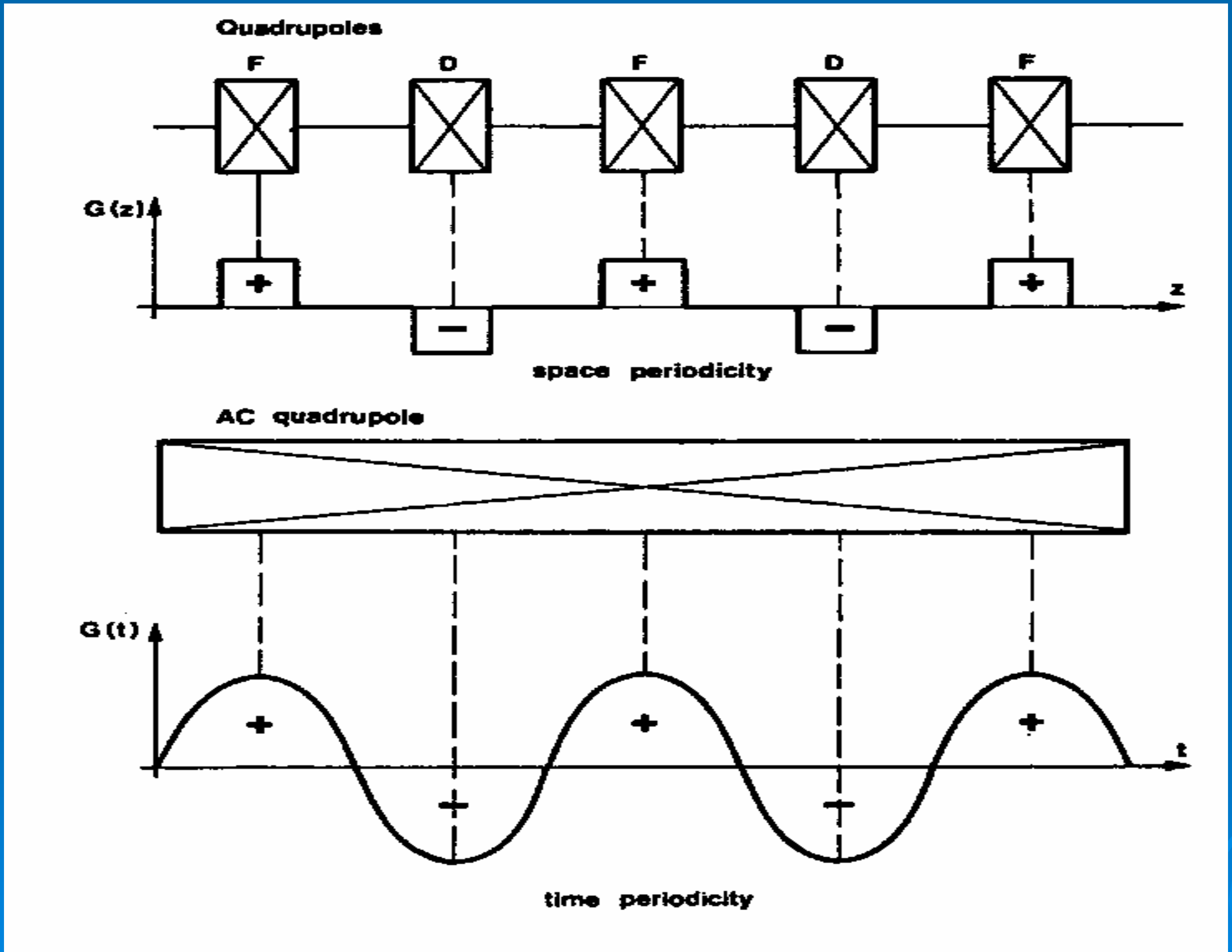
HIGH INTENSITY RFQ2 (200 mA protons)



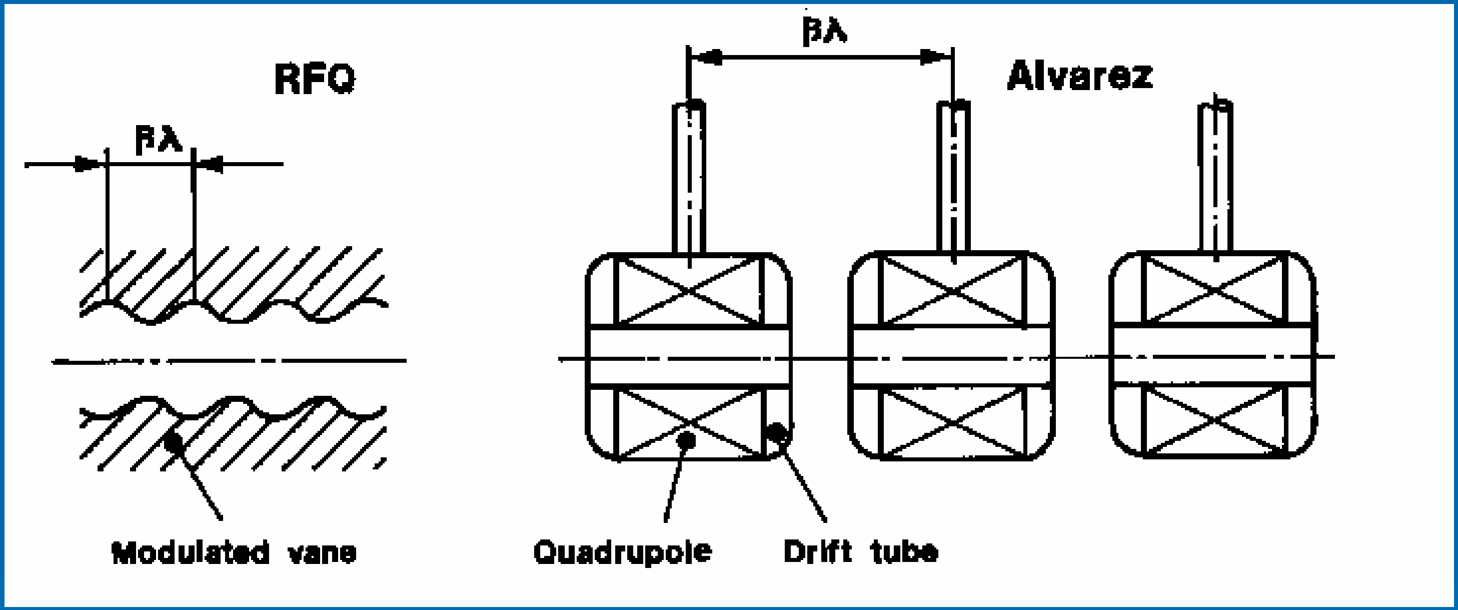
LOW INTENSITY
LEAD ION RFQ (100 μA)



Why is the RFQ such a good focusing channel for low energy ions



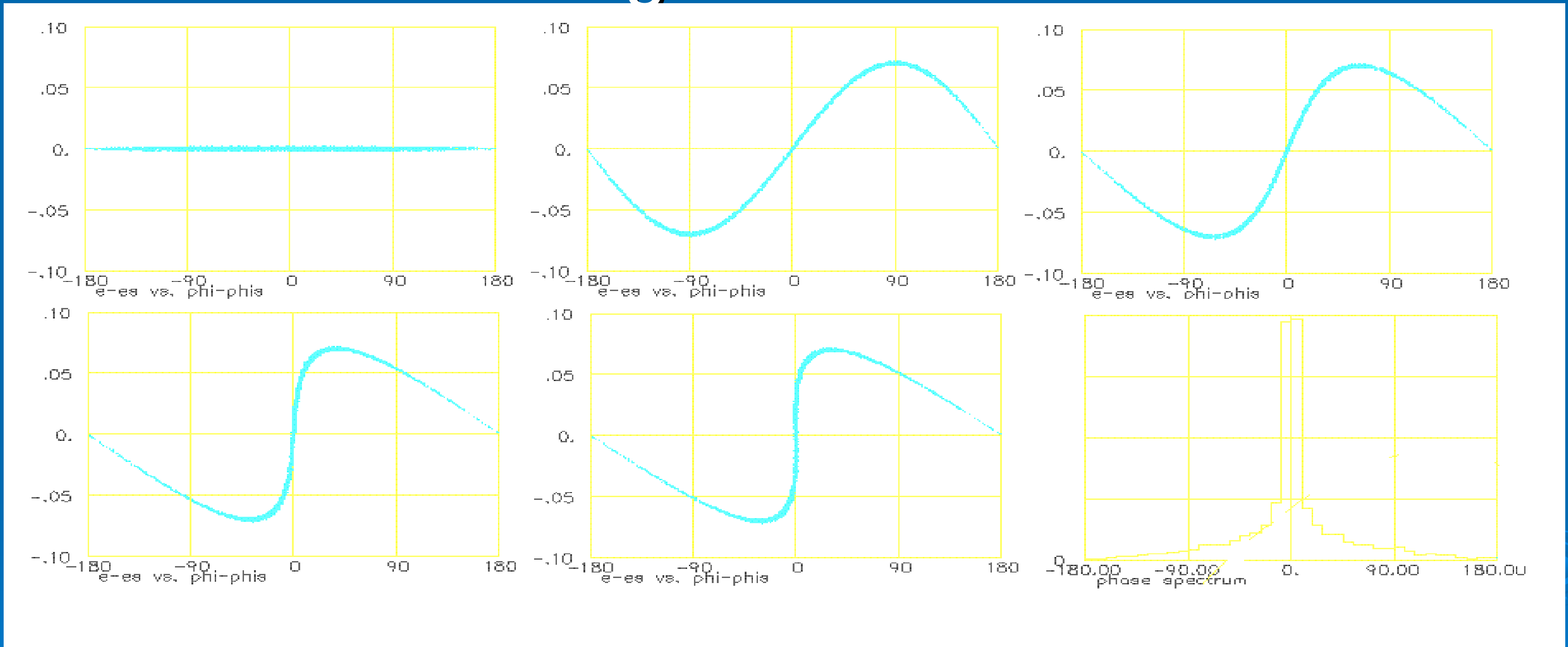
RFQ vs. DTL



DTL can't accept low velocity particles, there is a minimum injection energy in a DTL due to mechanical constraints

Why is the RFQ so efficient in bunching a beam

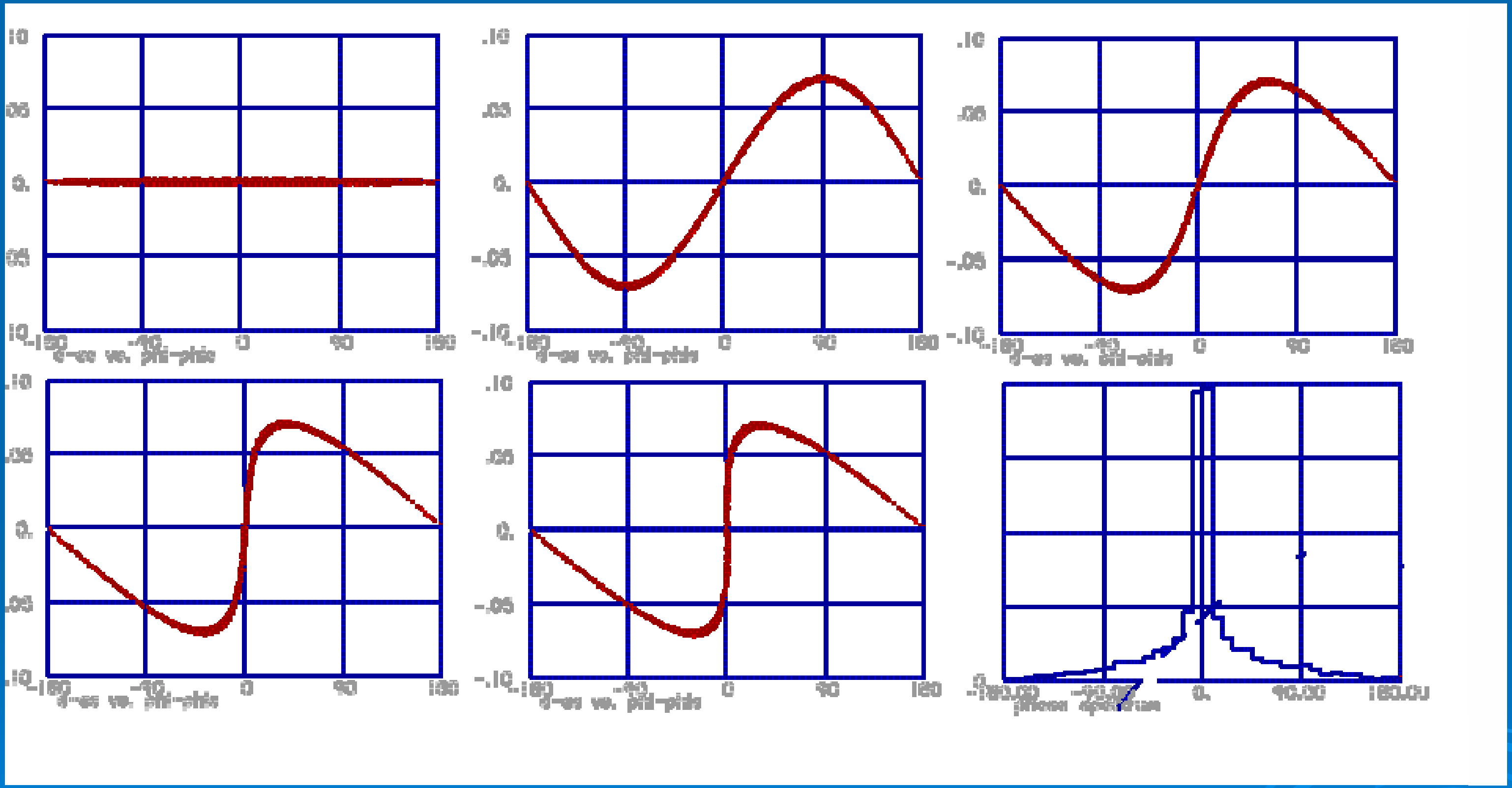
- Discrete bunching



- Vs adiabatic bunching : movie

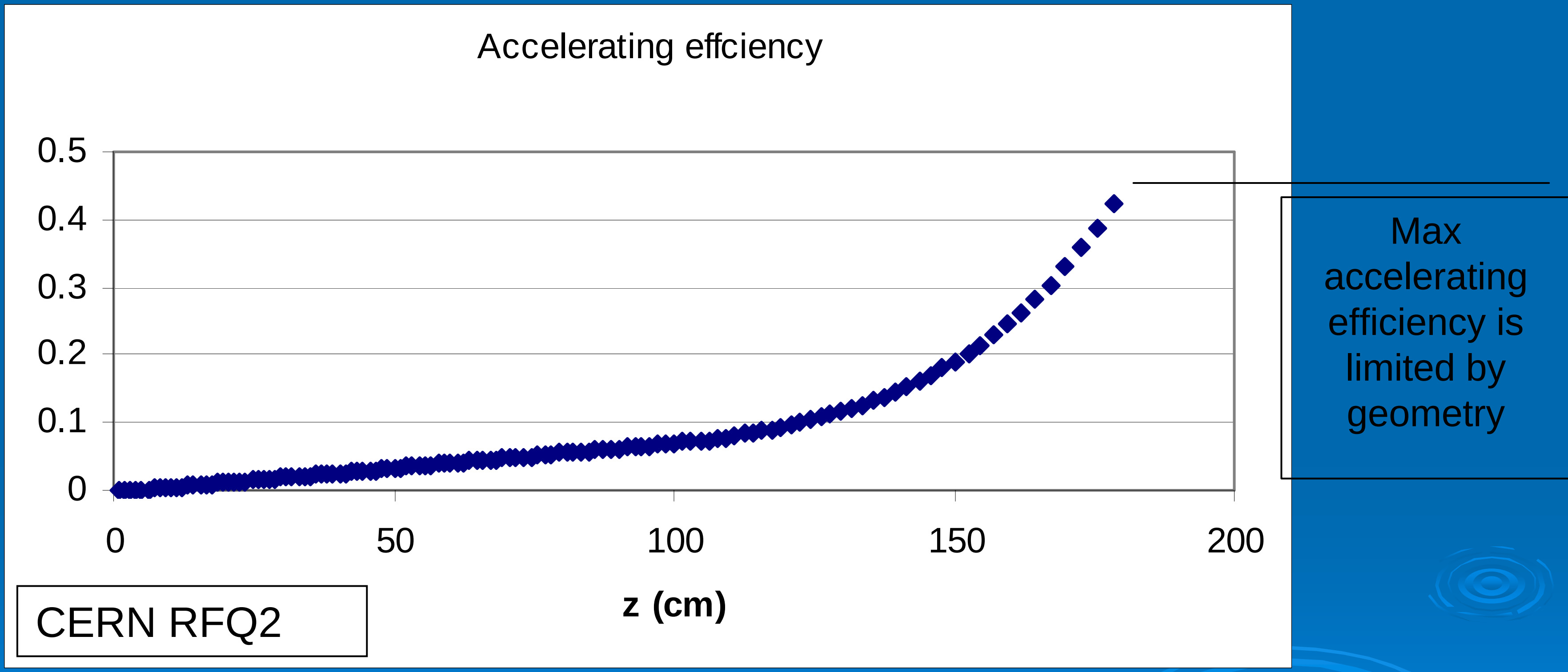
Why is the RFQ so efficient in bunching a beam

- Discrete bunching



- Vs adiabatic bunching : movie

Why don't we accelerate to the final energy by using only RFQs ?



RFQ-summary

- The resonating mode of the cavity is a focusing 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

- The RFQ is the only linear accelerator that can accept a low energy CONTINOUS beam of particles

RFQ-highlights

- electric focusing : accept low energy beam
- adiabatic bunching : preserve beam quality, high capture (~90%) vs. 50% of discrete bunching
- “one button” machine, easy to operate (the transverse and longitudinal dynamics are machined in the electrode microstructure)

Further reading

- T.P.WANGLER, ”Space charge limits in linear accelerator”,LA-8388 (Los Alamos)
- R.H.STOKES and T.P.WANGLER, ”Radio Frequency Quadrupole and their applications”,Annual Review of Nuclear and Particle Science , 1989
- K.R. CRANDALL,R.H.STOKES and T.P.WANGLER, “ RF Quadrupole Beam dynamics Design study”,1979 Linear Accelerator Conference
- M.WEISS, “ Radio Frequency Quadrupole” , CERN-PS/87-51 (CAS Aarhus,1986)

Some Codes

- PARMTEQM-Los Alamos
- TOUTATIS- CEA Saclay
- LIDOS-MRTI Moscow
- DYNAMION-ITEP Moscow