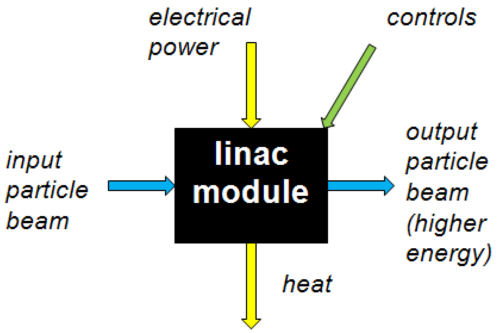
Maurizio Vretenar CERN

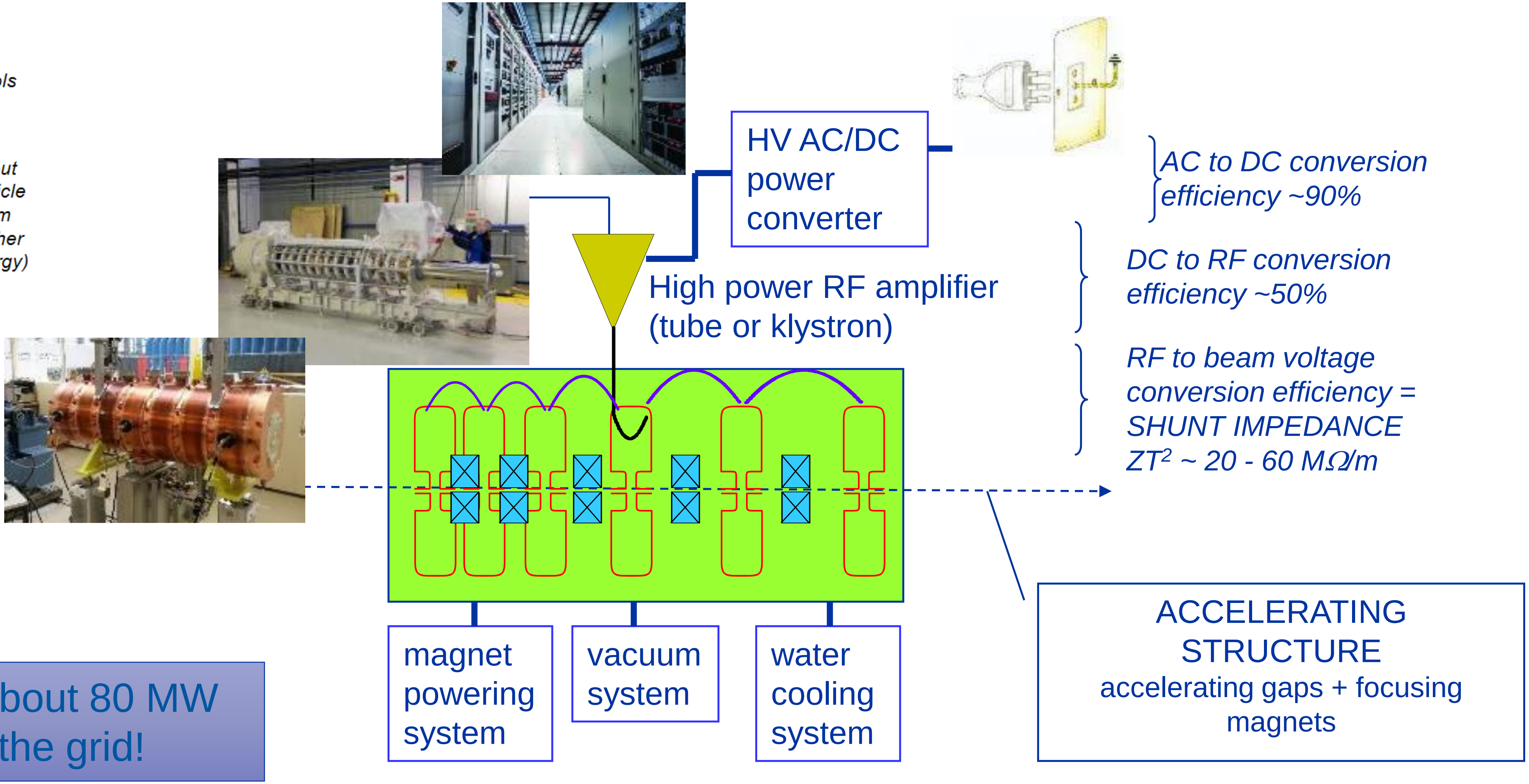
LECTURE 4: Technology and RFQ

August 2021

Introduction to Particle Accelerator Science and Technology

Where does the energy come from: from wall plug to particles




HV AC/DC power converter

AC to DC conversion efficiency ~90%

High power RF amplifier (tube or klystron)

DC to RF conversion efficiency ~50%

RF to beam voltage conversion efficiency = SHUNT IMPEDANCE $ZT^2 \sim 20 - 60\ M\Omega/m$

magnet powering system

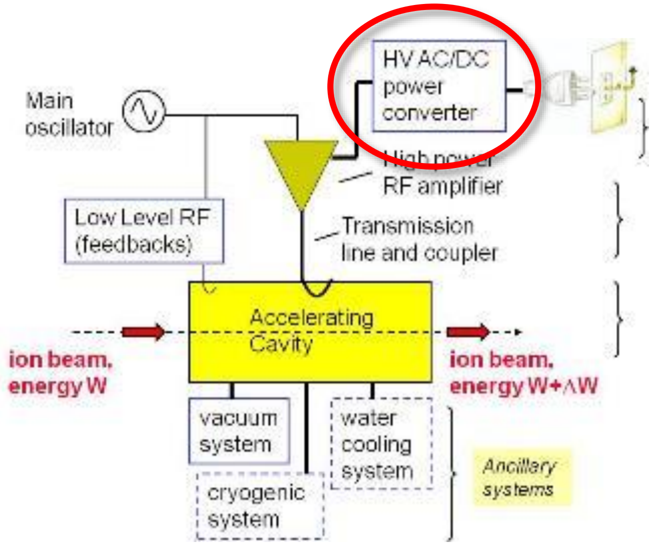
vacuum system

water cooling system

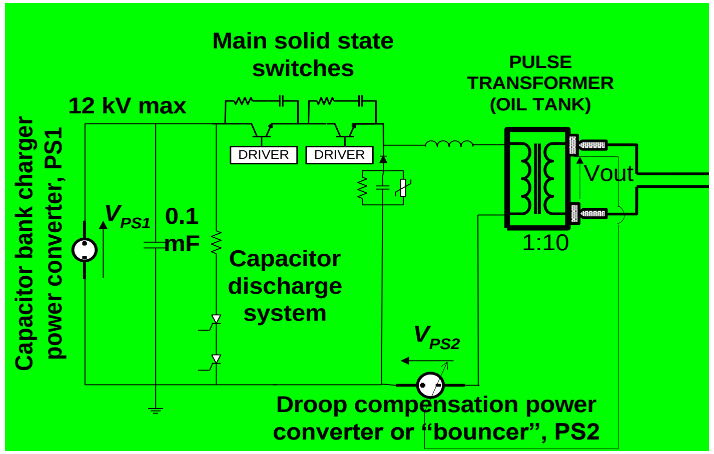
ACCELERATING STRUCTURE
accelerating gaps + focusing magnets

The LHC needs about 80 MW of electricity from the grid!

Other ancillary systems – power converters



The Power Converter
An essential ingredient for the reliability (high voltages!), stability (noise) and cost of an accelerator!
For linacs, made of rectifiers + HV transformer + energy storage when pulsed (can be a PFN).
If pulsed and HV, called “modulator”.



Topology and layout of the Linac4 modulator

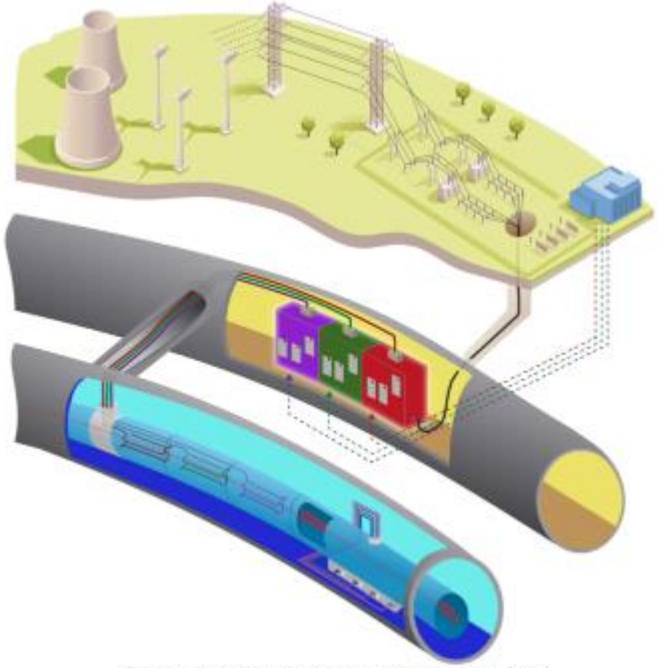
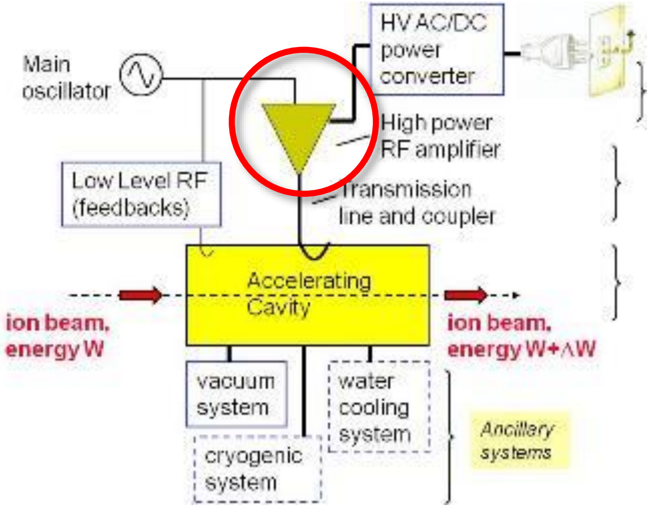


Fig. 1: Particle accelerator powering chain

Powering of magnets, with high currents and very low noise

Other ancillary systems – RF amplifiers



The RF Amplifier
Usually an amplifier chain (sometimes called “transmitter”).
Provides the RF power, is based on an active device: RF tube (tetrode or triode), klystron or RF transistor (solid state).

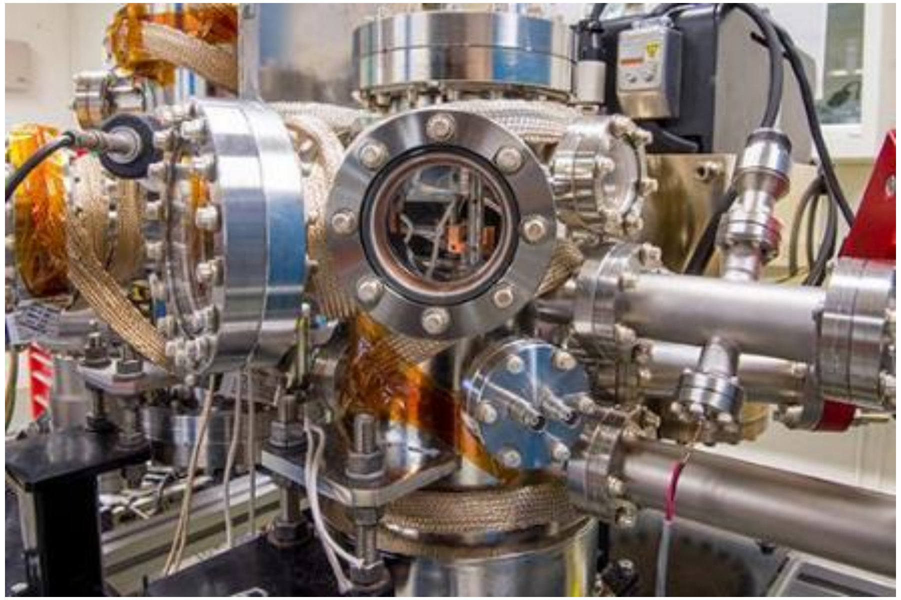
The CERN Linac4 klystrons

The CERN Linac1 triode amplifiers (2 MW, 202 MHz) in a photo of 1959

New solid-state RF power system for the CERN SPS

Accelerator vacuum

- To avoid particle loss by collision with air molecules, the accelerator beam pipe has to be kept at extreme vacuum levels: 10^{-7} – 10^{-10} mbar. Synchrotrons and colliders in particular have very stringent vacuum requirements.
- All accelerator components have to be built with a well-defined vacuum envelope, sealed with special gaskets and containing only material with low degassing rate.
- Different types of vacuum pumps generate and maintain the vacuum.



Going back to low-energy acceleration

The Radio-Frequency Quadrupole as a good example of integration of beam optics, radio frequency, and mechanical aspects

Low-energy acceleration of protons and ions

Low energy →
for protons, between ~ 50 keV (source extraction) and ~ 3 MeV (limit for an effective use of the DTL)
→ range $\beta = 0.01 - 0.10$

Why it is a problem?

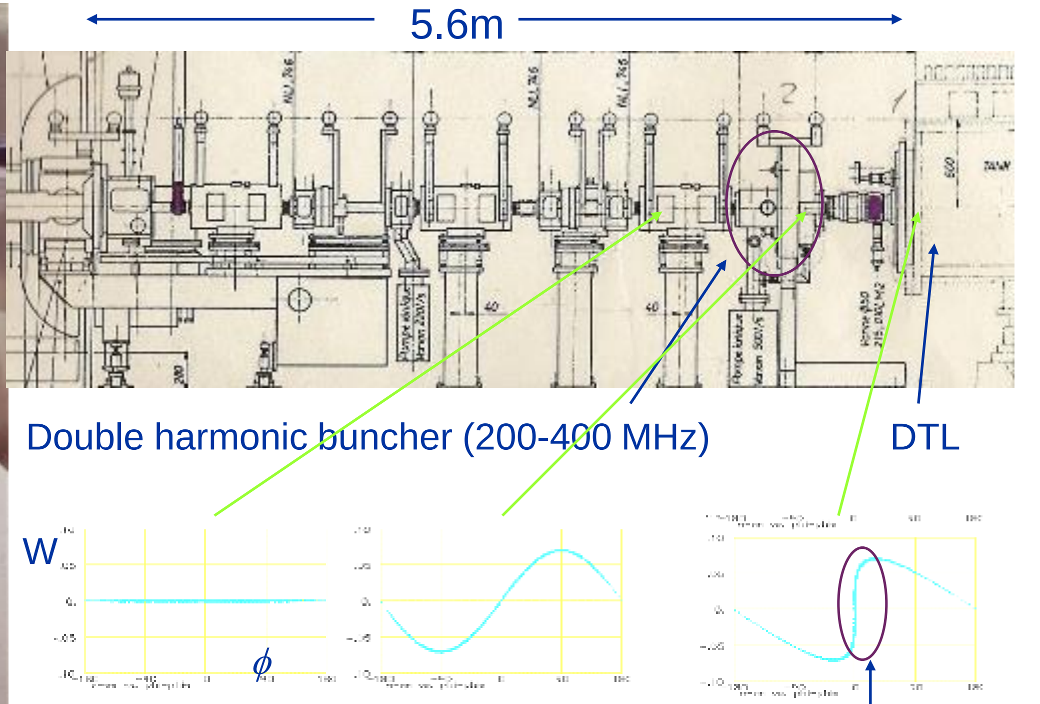
1. At low energy we need strong focusing (strong space charge!), but the short cell length (~$\beta\lambda$) limits the length of the quadrupoles, for ex. $\beta\lambda$(1MeV,352MHz) = 3.9cm
2. this is where we need to bunch the continuous beam out of the ion source, and usual bunching systems are quite ineffective (~50% beam loss…).
3. At low energy, the usual accelerating structures have low efficiency (low shunt impedance).

The "old" solution:

1. Increase as much as possible the extraction voltage from the source → huge HV installations, up to the maximum of some 800 kV.
2. Add a bunching section (1 or 2 cavities) after the source extraction.
3. Start the first accelerating structure (usually a Drift Tube Linac) from the minimum possible energy.

The classical solution: HV column + LEBT + bunching

The old CERN pre-injector (1978)



Double harmonic buncher (200-400 MHz)

DTL

Principle of single-harmonic bunching

Useful beam (inside DTL acceptance)

Drawbacks:

-Large and expensive HV column
-Reliability (800 kV…)
-Bunching efficiency (~50%)
-Long line with inefficient magnetic focusing ($\propto \beta$)
-Difficult DTL at low energy (short tubes and quads)
-Large emittances for high currents

RFQ compared to the old pre-injectors

The old pre-injector at CERN (1976): Source+ Cockroft Walton +line+bunching

The new RFQ2 pre-injector at CERN (1993): Source+LEBT +RFQ

← 3.2m →

A new idea – the Radio Frequency Quadrupole

The driving force for the development of something new for the low-energy section was the research in URSS and USA on high-current proton accelerators. The idea is to break the limitation to current coming from *space charge in the beam transport* and from *bunching losses*.

- 1960's: Early works of I. Kapchinski at ITEP (Moscow, URSS): idea to *use at low energy an electric quadrupole focusing channel, excited at RF frequency, and modulated to add a longitudinal field component providing adiabatic bunching and acceleration*.

- 1969: an RF resonator is designed around Kapchinski's electrodes by V. Tepliakov (IHEP). First paper on the RFQ by Kapchinski and Teplyakov (in Russian). First experimental RFQ in Russia (1974).

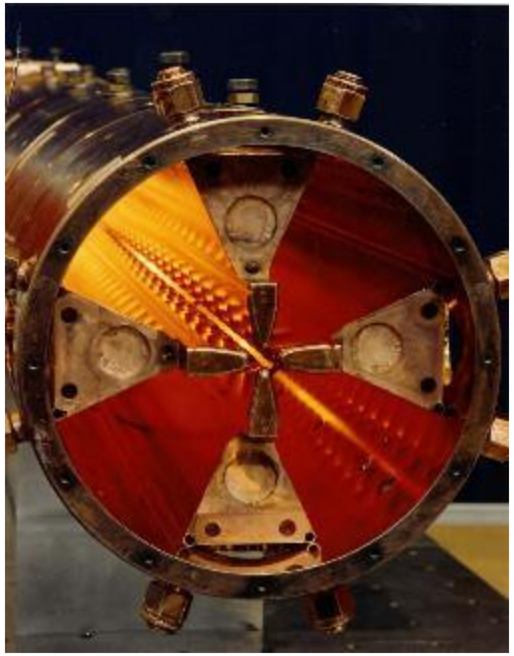
- 1977: the idea arrives at Los Alamos (USA), introduced by a Czech refugee.

- 1977-1980: the Los Alamos team is enthusiastic about this idea (for their Fusion Material Irradiation), makes some improvements to the original Kapchinski structure and develops a new resonator design. The first complete RFQ is built at Los Alamos and successfully operated (for a few hours…) in 1980.

- 1980's: the RFQ principle spreads around the world, more RFQs are built in the USA and in Europe (1st CERN RFQ: 1984). Long and difficult learning curve (RFQs are not simple devices…).

- 1985-1995 : reliable RFQ designs exist and progressively replace the old pre-injectors in most accelerator laboratories (CERN: 1993). Different design and applications are proposed all over the world.

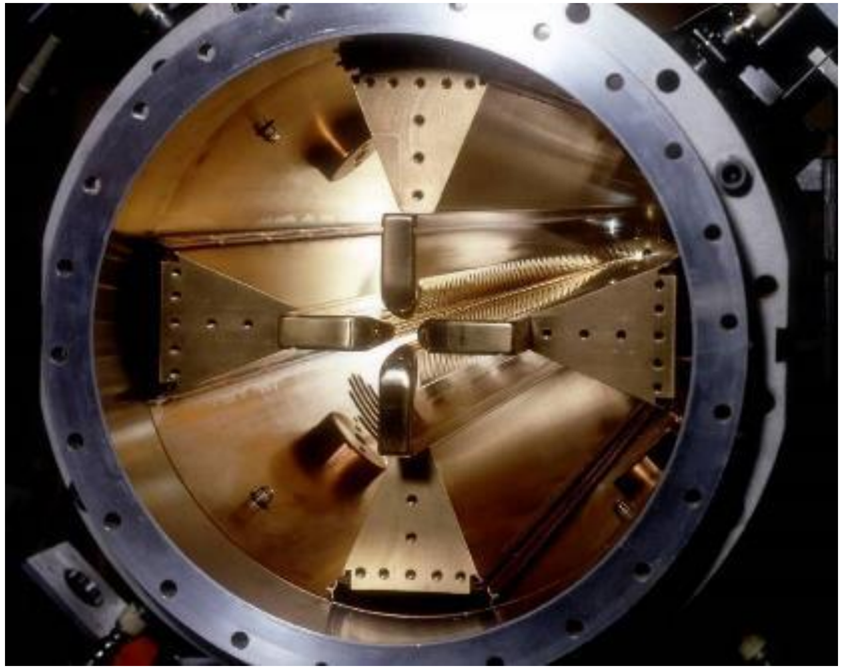
- 1995-now : new RFQs are designed and built for extreme applications, like high intensity (CW, high current) or compact high-frequency.

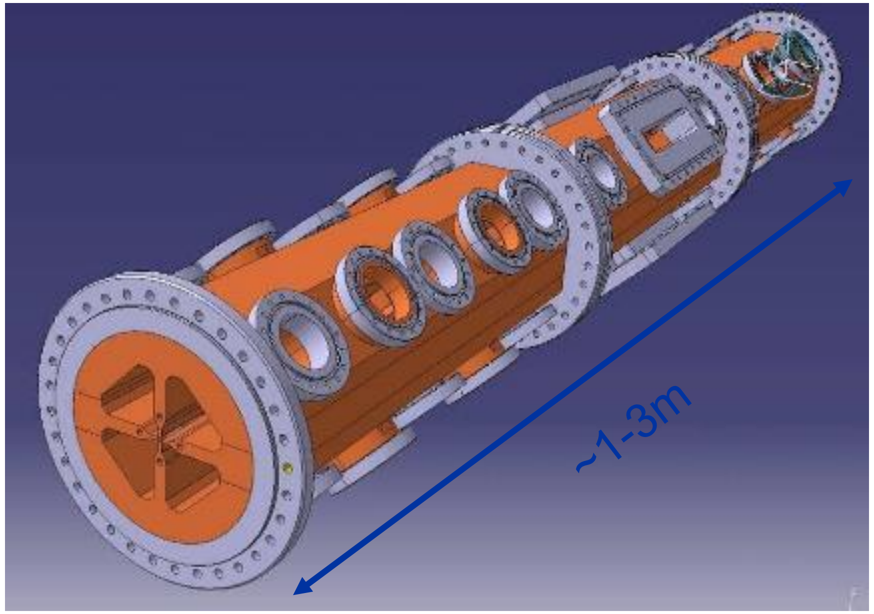


Proof of Principle (POP) RFQ, Los Alamos 1980

The Radio Frequency Quadrupole (RFQ)

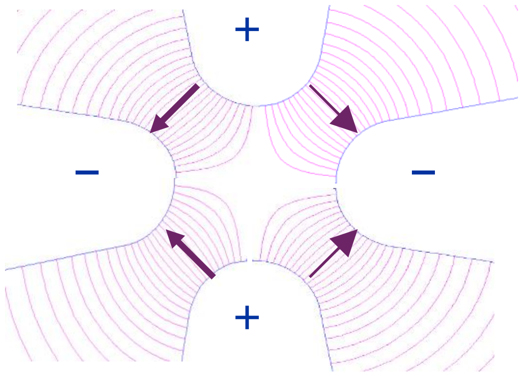
RFQ = Electric quadrupole focusing channel + bunching + acceleration





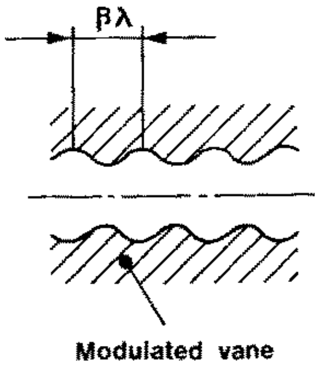
New and performing accelerator.
Compact and critical structure, where beam dynamics, RF and mechanical aspects are closely interconnected.

The basic RFQ principle

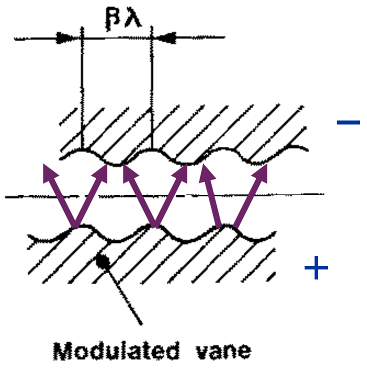


1. Four electrodes (called vanes) between which we excite an RF Quadrupole mode → Electric focusing channel, alternating gradient with the period of the RF. Note that electric focusing does not depend on the velocity (ideal at low β!)

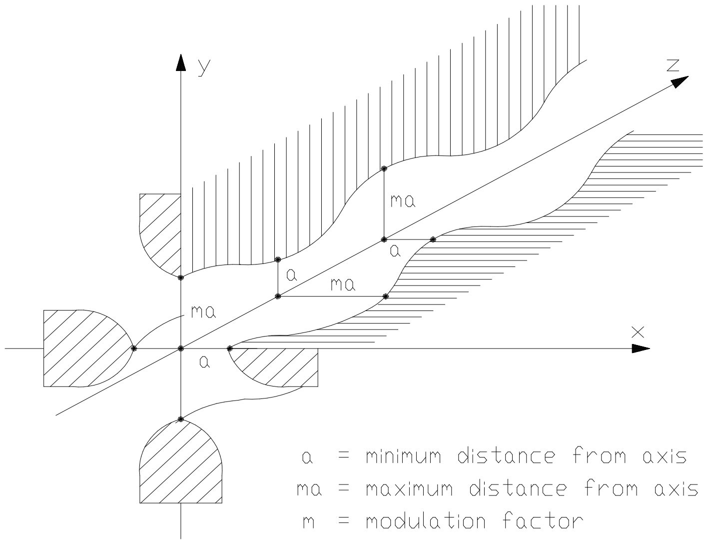
2. The vanes have a longitudinal modulation with period = βλ → this creates a longitudinal component of the electric field. The modulation corresponds exactly to a series of RF gaps and can provide acceleration.



Opposite vanes (180º)



Adjacent vanes (90º)



a = minimum distance from axis
ma = maximum distance from axis
m = modulation factor

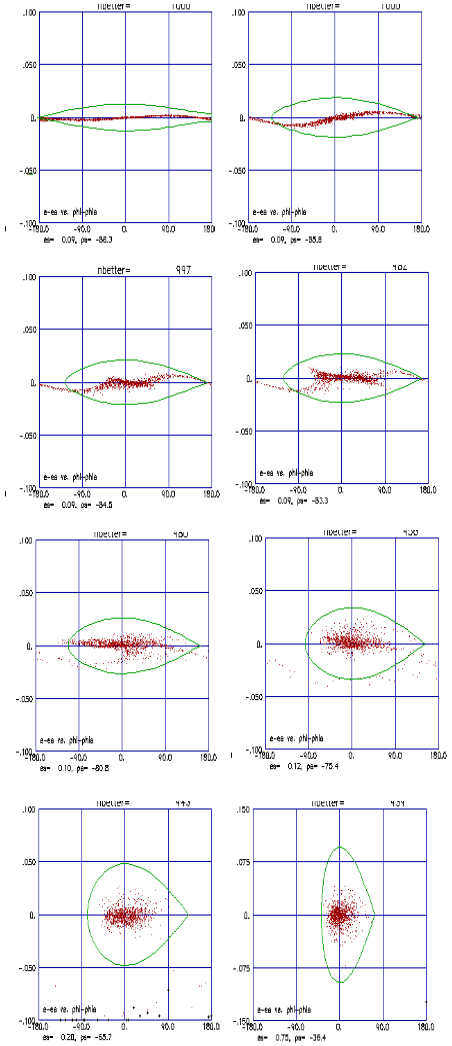
Bunching and acceleration

3. The modulation period (distance between maxima) 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 at -90° phase (linac) with some bunching cells, progressively bunch the beam (adiabatic bunching channel), and only in the last cells switch on the acceleration.

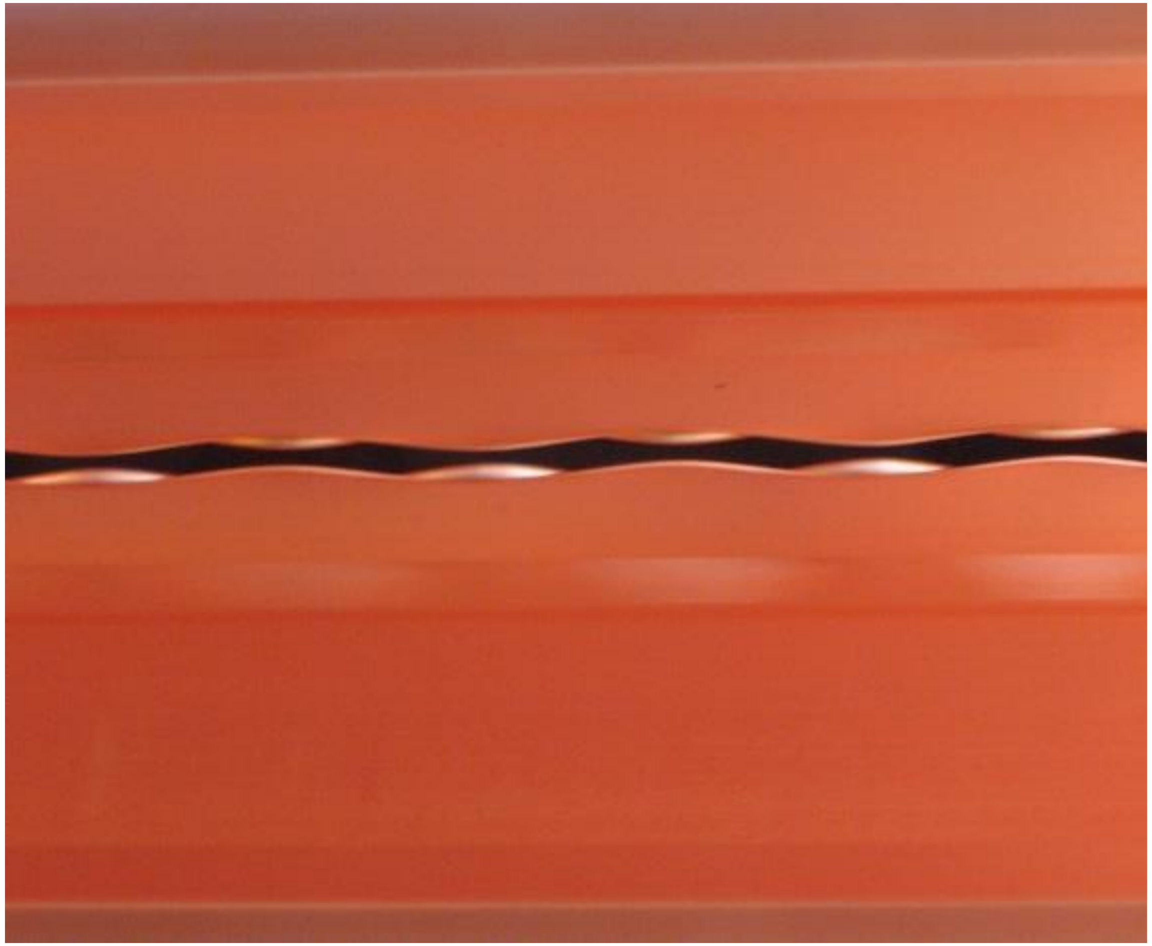
☞ An RFQ has 3 basic functions:

1. Adiabatically bunching of the beam.
2. Focusing, on electric quadrupole.
3. Accelerating.

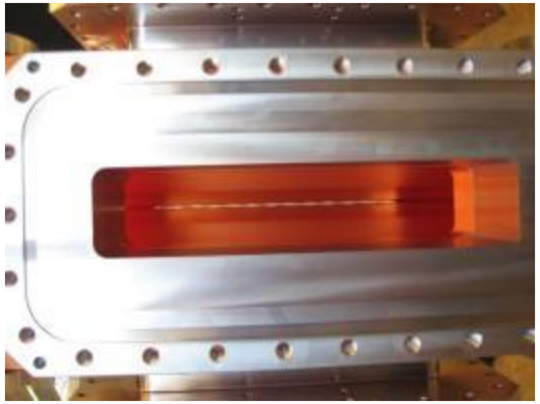
Longitudinal beam profile of a proton beam along the CERN RFQ2: from a continuous beam to a bunched accelerated beam in 300 cells. →



Peeping into an RFQ…



Looking from the RF port
into the new CERN RFQ
(Linac4, 2011)

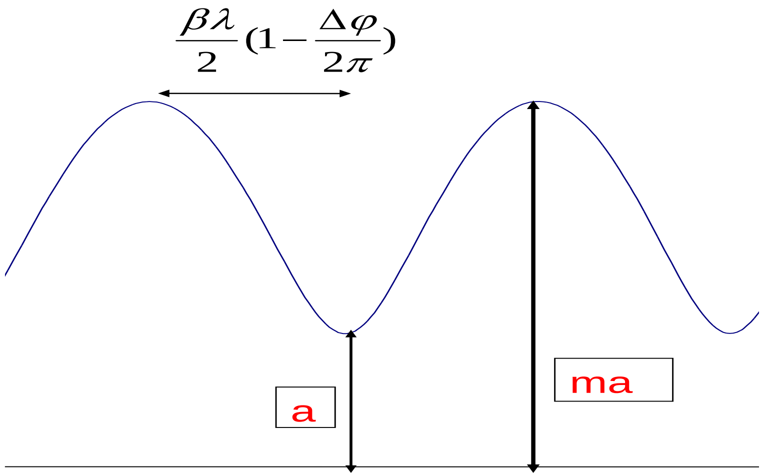


RFQ beam dynamics

An RFQ is made of a sequence of cells (length $\beta\lambda$ → in 1 m we can have > 100 cells) where the beam dynamics designer can vary 3 parameters for each cell:

1. Aperture a (defines the focusing strength)
2. Modulation factor m (defines the longitudinal component)
3. The beam phase ϕ, phase difference between bunch center and RF wave (defines the bunching and/or accelerating action).

+ 1 more parameter that is common to all cells or can be changed only smoothly: the RF voltage V.



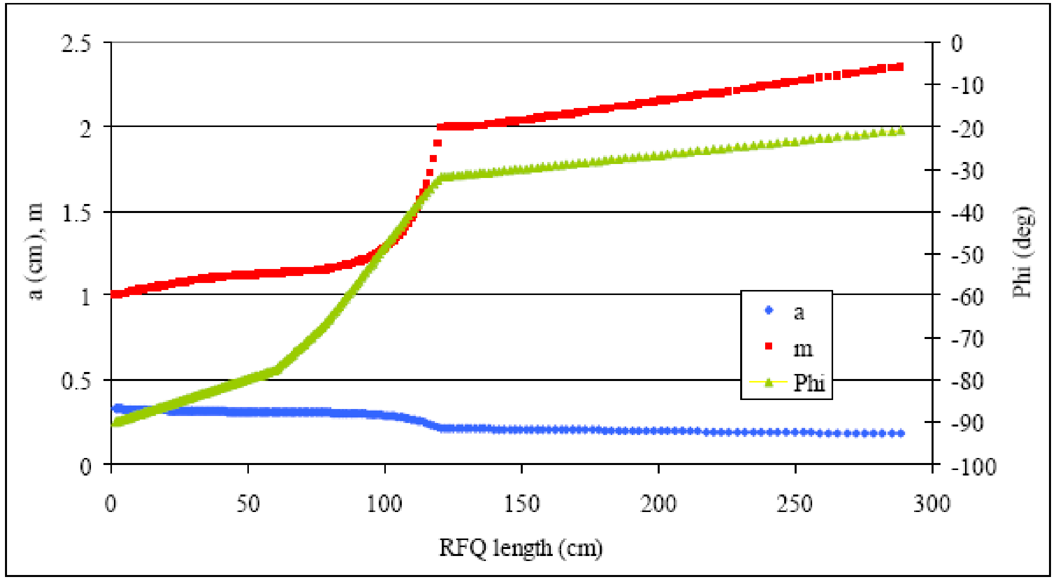
a = minimum aperture
m = modulation factor (ratio bw. max and min aperture)

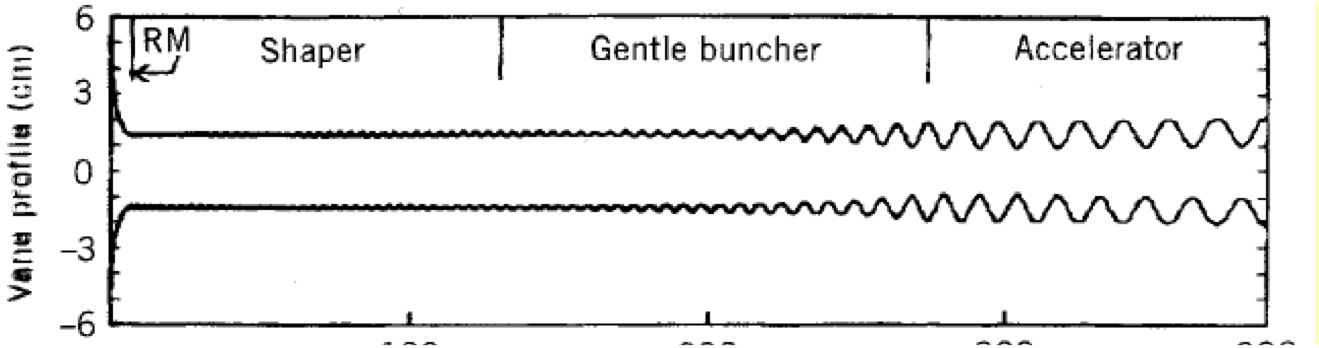
cell length/$\beta\lambda$ = changing the length of the cell with respect to the optimum length for a given beta will change the RF phase seen by the beam.

All these parameters can be adiabatically changed from one cell to the other, to achieve a smooth bunching, focusing and acceleration.

Example of an RFQ Beam Dynamics design

The CERN Linac4 RFQ:
352 MHz, 45 keV to 3 MeV, 303 cells, 3 m length, 70 mA beam current
Beam transmission 95 %



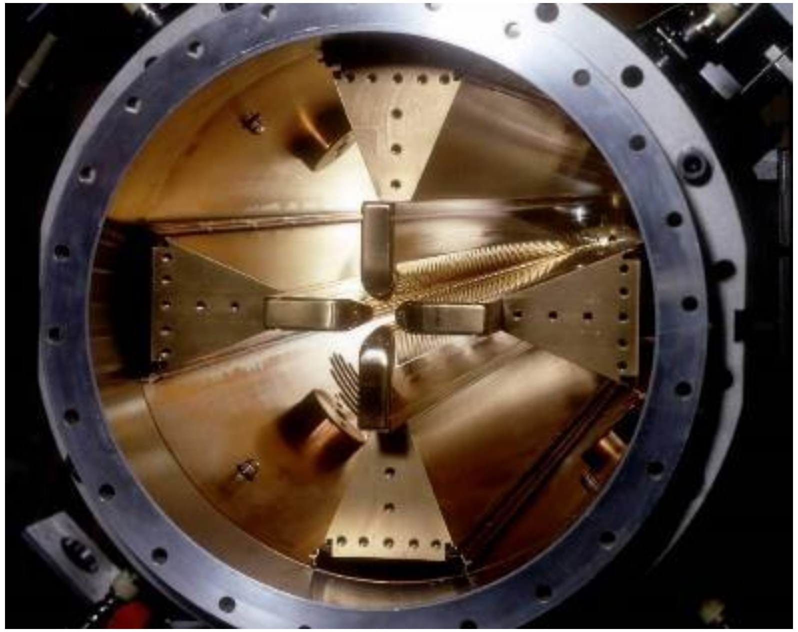


The first ~200 cells are used for adiabatic bunching of the beam: the synchronous phase is slowly increased from -90 to -20 deg → bunching with low beam loss!

The RFQ resonator

Problem:
How to produce on the electrodes the quadrupole RF field?

2 main families of resonators: 4-vane and 4-rod structures



plus some more exotic options
(split-ring, double-H, etc.)

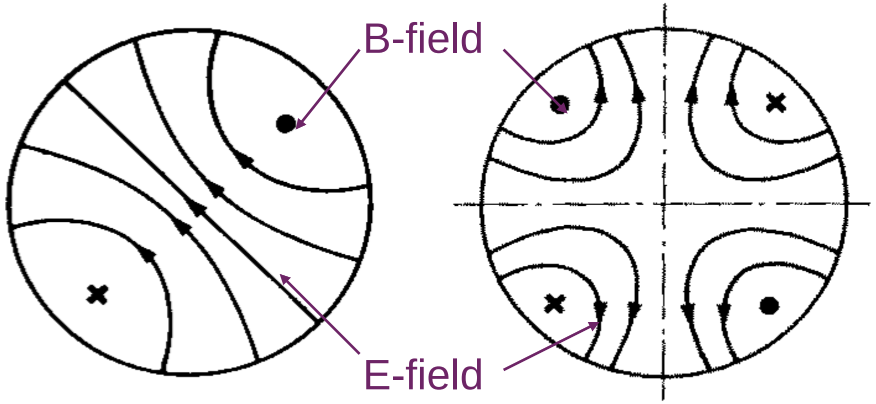
Remark:
what is the ideal frequency for an RFQ?

Cell length $\beta\lambda/2$ at injection should be mechanically achievable, of the order of few mm.

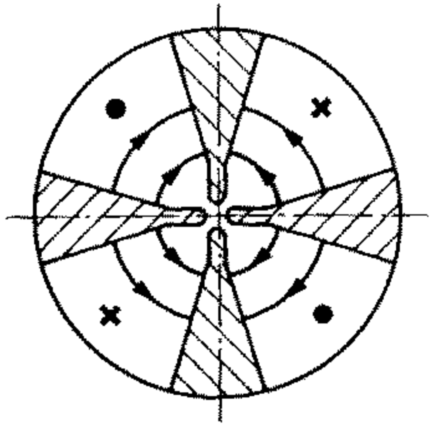
For heavy ions,
$\beta \sim 10^{-4} - 10^{-3}$
corresponding to
f~ 10 – 100 MHz

For protons,
$\beta \sim 10^{-2}$ makes higher frequencies possible, but beam dynamics (focusing $\sim f^{-2}$) and technology limit to
f ~ 200 – 400 MHz

The “4-vane” RFQ



Empty cavity; mode TE$_{11}$ Empty cavity; mode TE$_{21}$



Cavity with vanes

Basic idea:

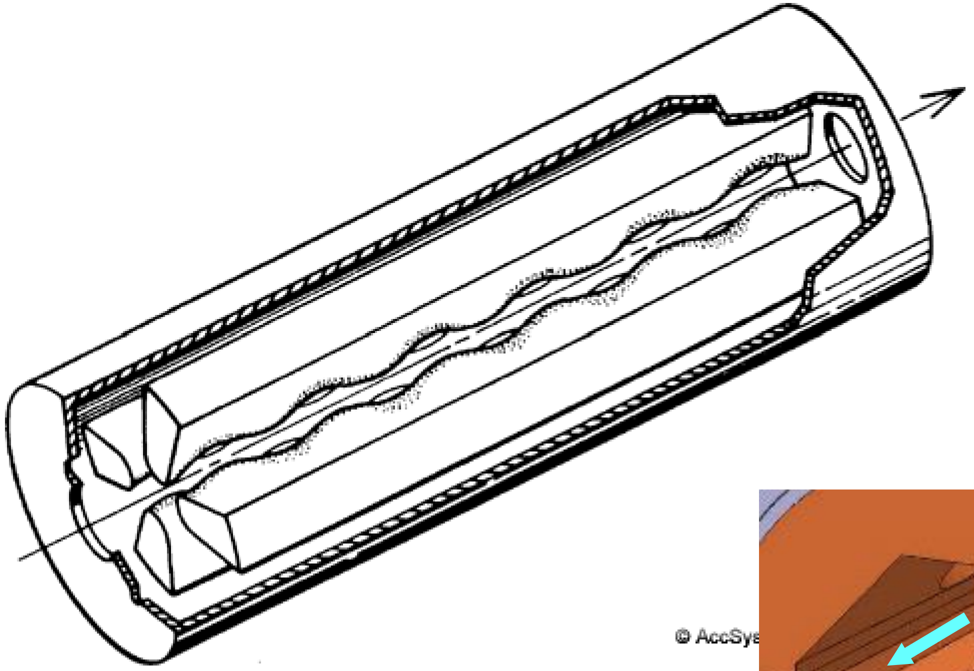
An empty cylindrical cavity can be excited on different RF modes.
Some of these modes have only transverse electric field (the TE modes), and in particular going up in frequency one can find a “quadrupole” mode, the TE210.

The introduction of 4 electrodes (the vanes) can then “load” the TE210 mode, with 2 effects:

- Concentrate the electric field on the axis, increasing the efficiency.
- Lower the frequency of the TE210 mode, separating it from the other modes of the cylinder.

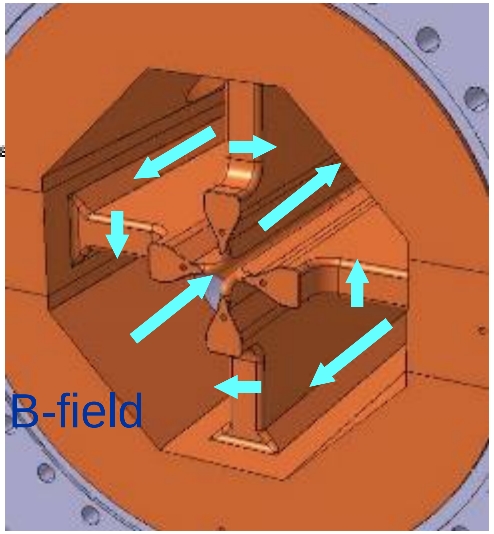
Unfortunately, the dipole mode TE110 is lowered as well, and remains as a perturbing mode in this type of RFQs.

The 4-vane RFQ



© AccSys

The RFQ will result in cylinder containing the 4 vanes, which are connected (large RF currents!) to the cylinder along their length.



Field excitation via a loop or an iris in one (or more) quadrants

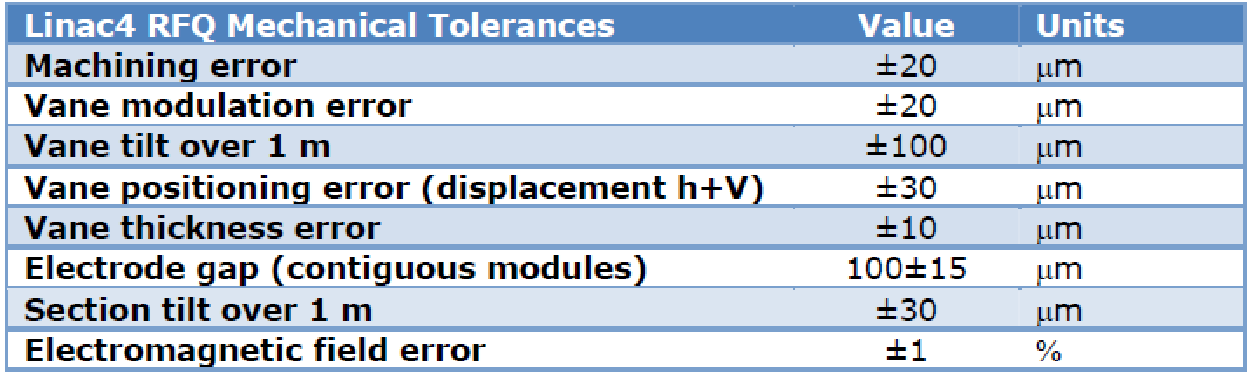
A critical feature of this type of RFQs are the end cells:
The magnetic field flowing longitudinally in the 4 “quadrants” has to close its path and pass from one quadrant to the next via some openings at the end of the vanes, tuned at the RFQ frequency!

Mechanical aspects – tolerances

Two main mechanical problems:
1. The need to achieve the tight tolerances in vane machining and positioning required by beam dynamics and RF.

Machining of a vane for the new CERN RFQ (linac4)

RF and beam dynamics both require tight tolerances in the position of the electrodes (Linac4 RFQ: <30 μm).
RF: presence of dipole and/or longitudinal components.
Beam dynamics: introduction of multipoles (Linac4 RFQ average aperture r_0 = 3.3 mm, 1% of aperture is ~30 μm). Minimum aperture a = 1.8 mm !!

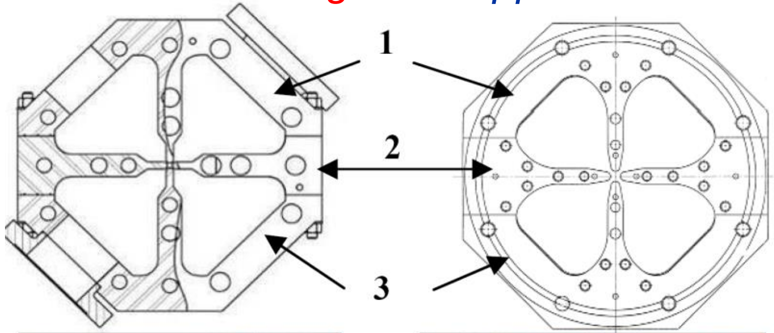


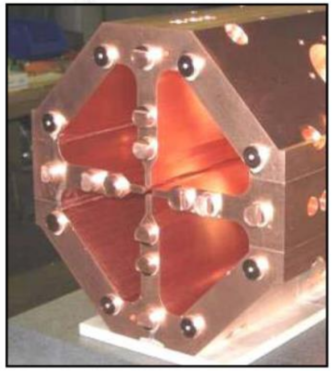
Linac4 RFQ Mechanical Tolerances	Value	Units
Machining error	±20	μm
Vane modulation error	±20	μm
Vane tilt over 1 m	±100	μm
Vane positioning error (displacement h+V)	±30	μm
Vane thickness error	±10	μm
Electrode gap (contiguous modules)	100±15	μm
Section tilt over 1 m	±30	μm
Electromagnetic field error	±1	%

Mechanical aspects – joining RFQ parts

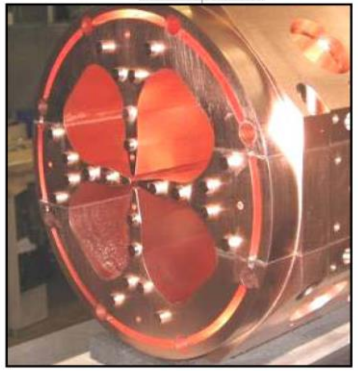
2. The need to assemble a LEGO®8 of several components (tanks, vanes or rods, supports, etc.) that have to fit together keeping the tolerances and providing a good quality RF contact (large currents flowing!).

4-vane, high frequency: furnace brazing of 4 copper elements



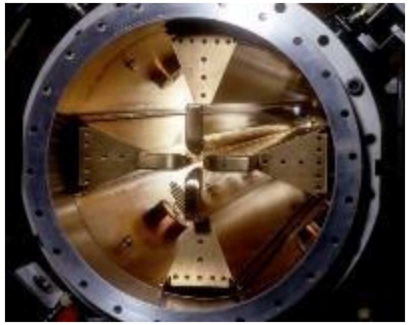


TRASCO, LNL, Italy



IPHI, CEA-CNRS, France

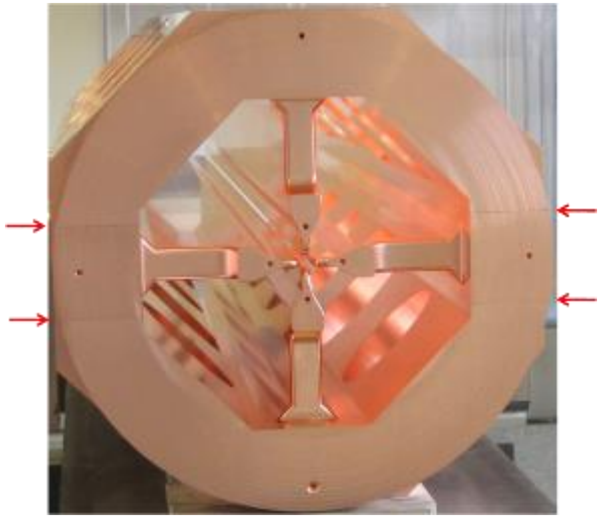
4-vane, low frequency: EB welding or bolting of copper or copper plated elements



RFQ1 and RFQ2, CERN

SPIRAL2, CEA-CNRS, France

Errors before and after brazing

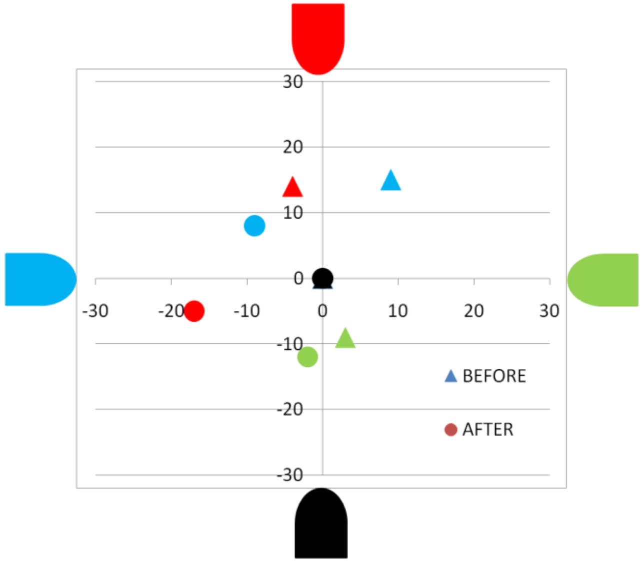


Linac4 RFQ:

☞ 3 segments of 1 m, each formed by 4 parts brazed together

☞ Required error in vane positions <30 μm

☞ Achieved by a) precise machining of the contact surfaces and b) appropriate thermal treatments to minimize vane deformation during brazing.



RFQ – thermal aspects

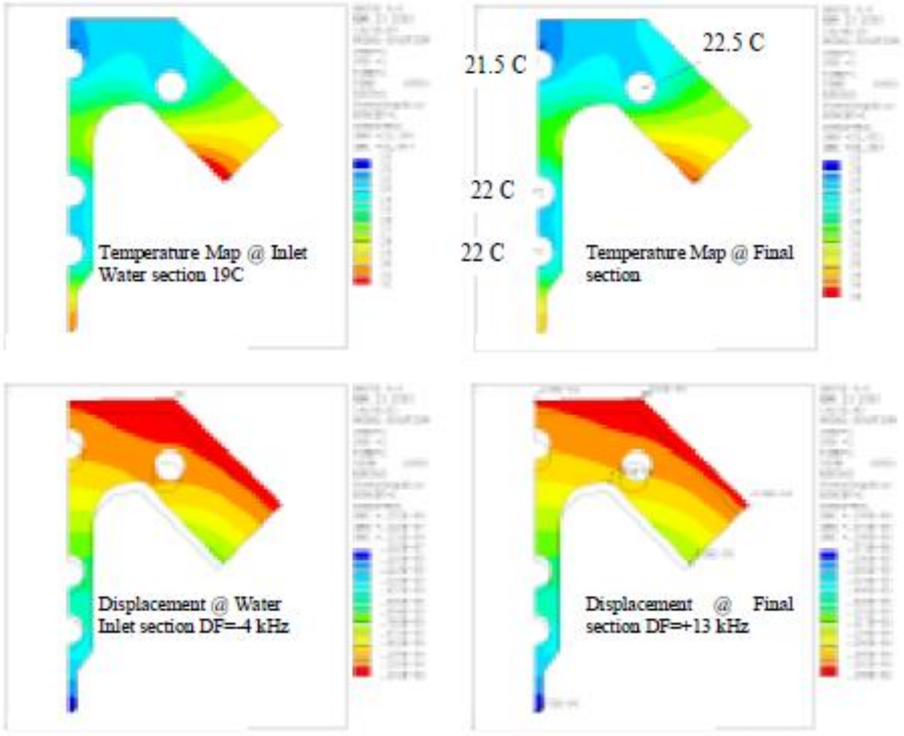


Fig. 6: Top: temperature maps at begin (left) and at the end (right) of one RFQ section. Bottom: deformation maps and frequency shifts.

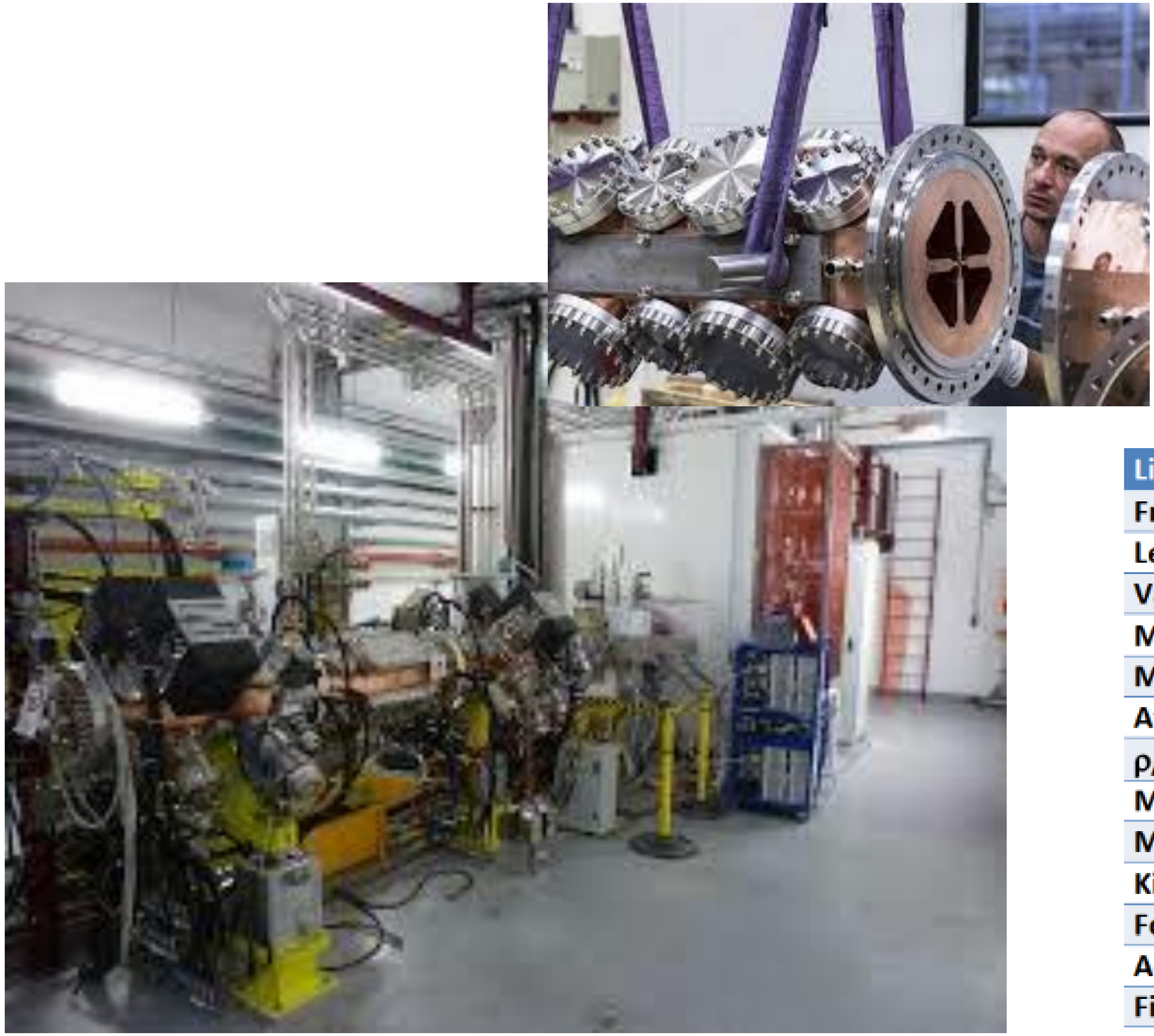
Example: thermal study of the TRASCO RFQ (CW, 352 MHz, 1 kW/cm) – courtesy of LNL, Legnaro

1. High (beam) power RFQs need to dissipate large amounts of RF power in small volumes (vanes are “thin” to maximize shunt impedance).
2. Thermal deformations can lead to large voltage variations and to beam loss.

⇓

Need to carefully design and dimension the cooling channels to keep High (beam) power RFQs need to dissipate large amounts of RF power in small volumes (vanes are “thin” to maximize shunt impedance).
Thermal deformations can lead to large voltage variations and to beam loss.

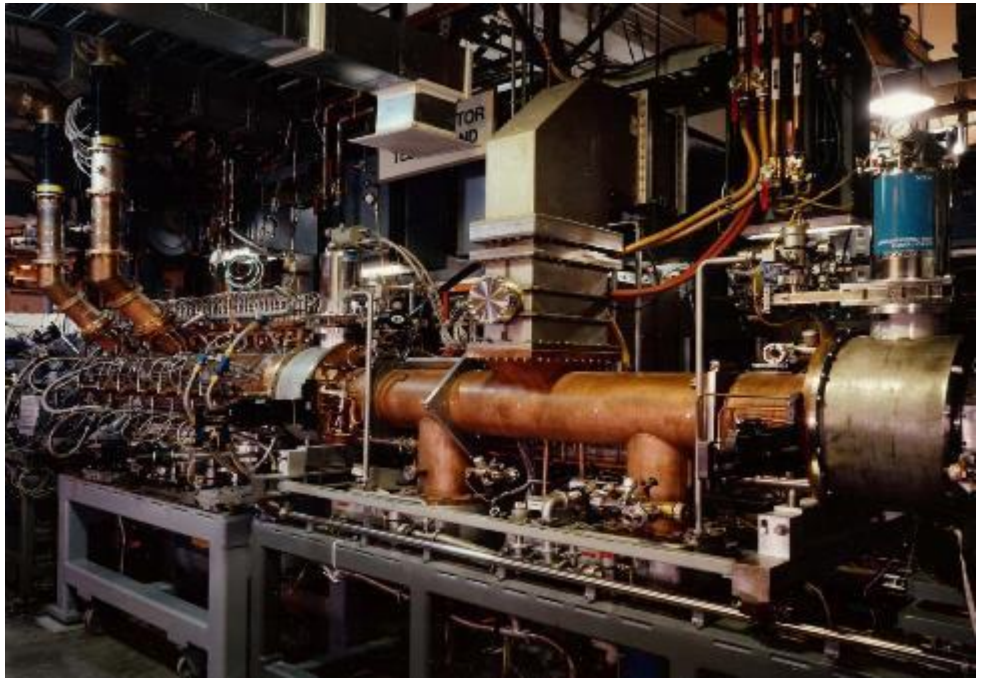
Examples of RFQ – the RFQ for CERN Linac4

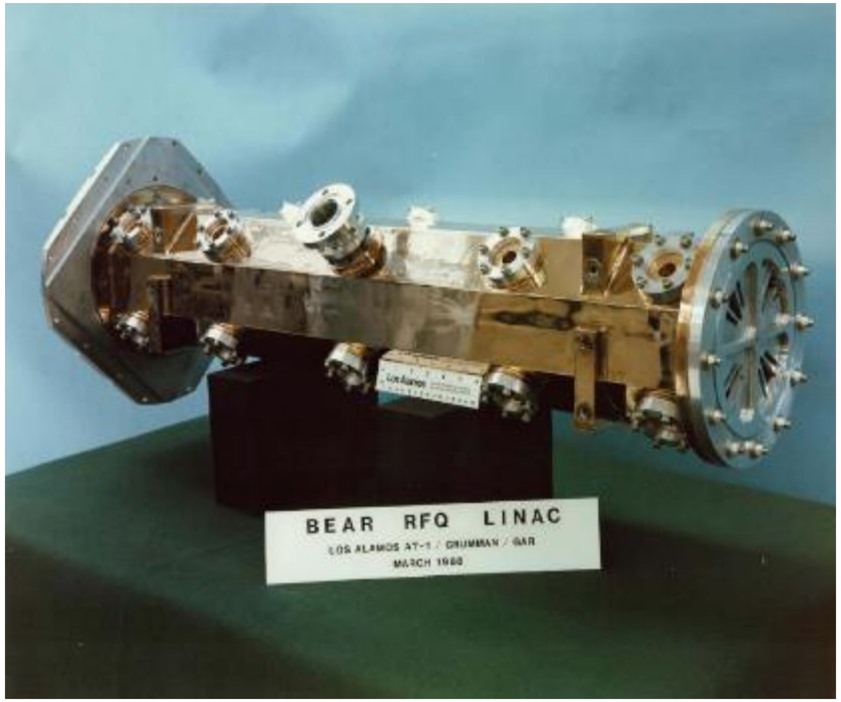


Linac4 RFQ Parameter	Value	Units
Frequency	352.20	MHz
Length	3.06	m
Vane voltage	78.27	kV
Minimum aperture a	0.18	cm
Maximum modulation	2.36	
Average aperture r0	0.33	cm
ρ/r0	0.85	
Minimum longitudinal radius	0.9	cm
Max field on pole tip	34	MV/m
Kilpatrick value	1.84	
Focusing parameter	5.7	
Acceptance at zero current	1.7	π mm mrad
Final synchronous phase	-22	deg

Examples of RFQs – military applications…

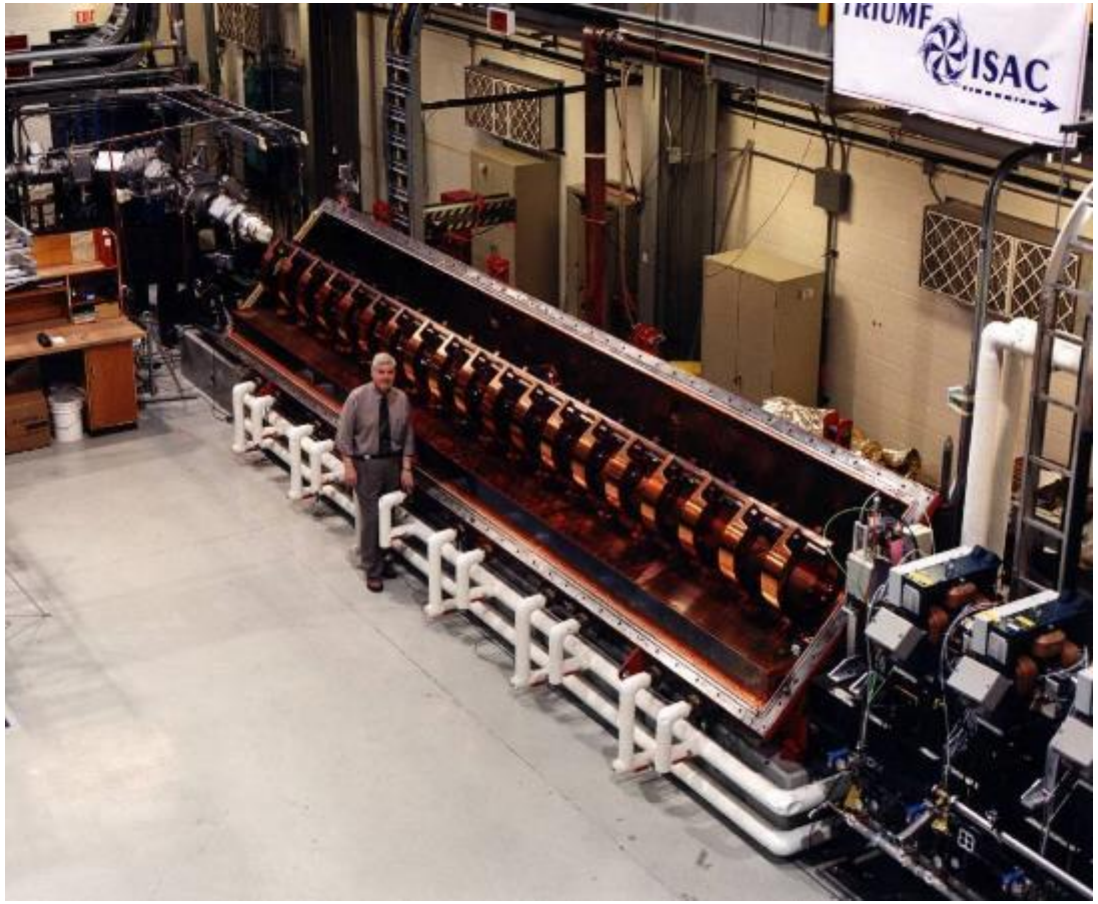
“Star Wars” RFQ (now de-classified), 1983, LANL
2 MeV, 100 mA, ~5% duty, H-minus, 425 MHz
Cu plated carbon steel vanes and cavity, manifold coupled
Demonstrated very small emittance H-minus beams





“BEAR” RFQ (beam experiment aboard a rocket)(partly classified) 1989
30 KeV – 1 MeV, 20 mA, <1% duty H-minus
425 MHz, solid-state RF system
Cu plated Al quadrants, joined by electroforming, 55 kg
Operated in sub-orbital flight with a “neutral” beam, LANL

Examples of RFQs – The large ones



Low frequency (35 MHz), high duty cycle (CW)
for post-acceleration of radioactive ions.

The ISAC-II RFQ at TRIUMF (Canada)

Examples of RFQ – Superconducting RFQ

Al prototype and the final installation of the superconducting RFQ at LNL, Italy

Superconducting RFQs:

Only one operating Superconducting RFQs built so far in the world (INFN Legnaro, Italy).

The modulation is extremely difficult to realise in Nb → a superconducting RFQ is limited to few cells at low frequency → heavy ions.

LNL superconducting RFQ: 2 separate structures, 1.4 m and 0.8 m, 41 and 13 cells

On proton RFQs with high intensity, the unavoidable beam loss during the bunching process would be very dangerous for a superconducting structure.

Examples of RFQ - the CERN mini-RFQ

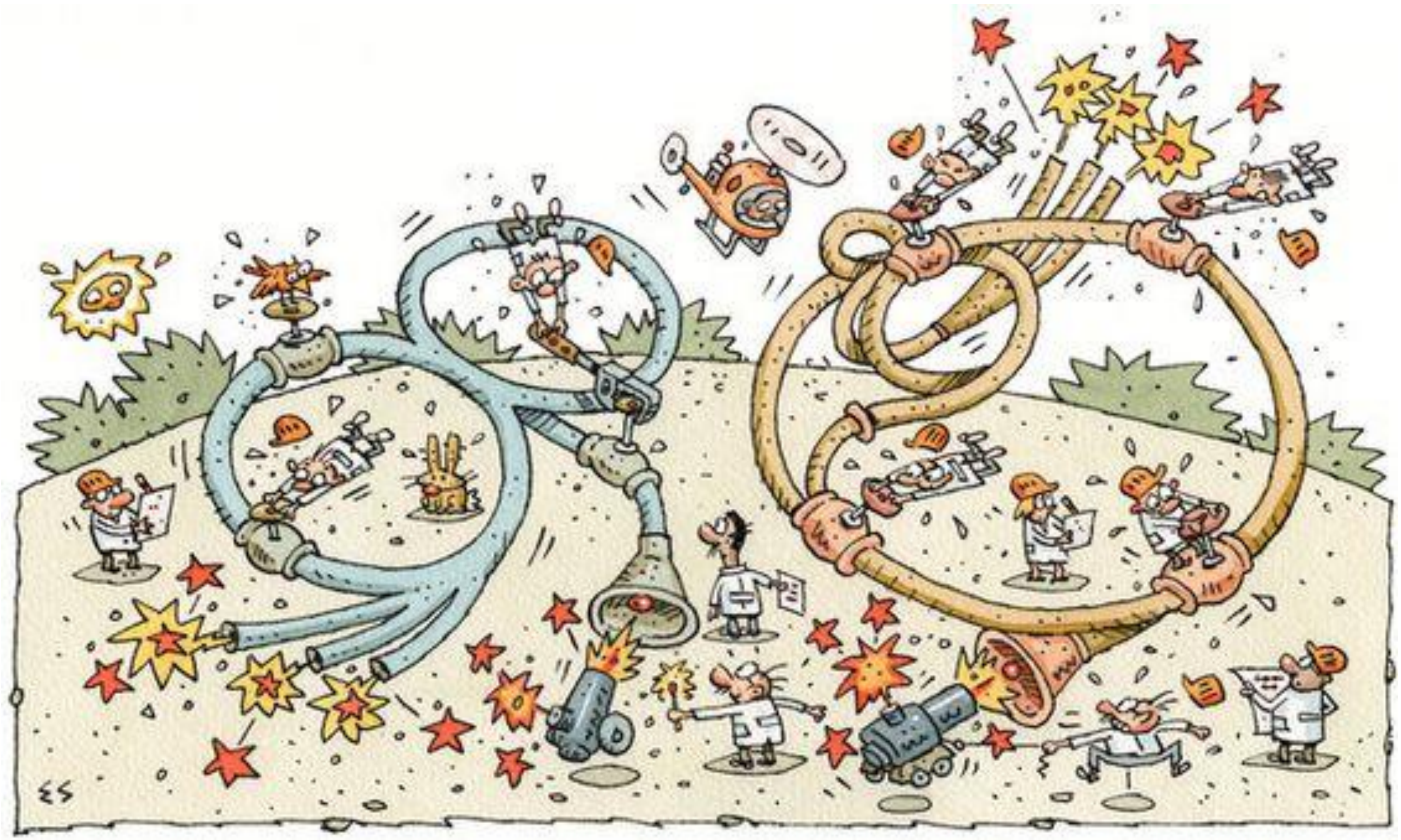
CERN has developed and built a «mini-RFQ» (Radio Frequency Quadrupole) at 750 MHz, extending to higher frequencies and applications outside science the experience of the recent Linac4 RFQ.

RFQ (the first element of any ion acceleration chain) at high frequency – targeted at low current applications requiring small dimensions, low cost, low radiation emissions, up to portability

	Frequency	Energy	Length	Gradient	Current
Linac4 RFQ	352 MHz	3 MeV	3 m	1 MeV/m	90 mA
HF-RFQ	750 MHz	5 MeV	2 m	2.5 MeV/m	400 µA

Fabrication cost per meter about 50% for HF-RFQ

The prototype unit (5 MeV protons) has been built at the CERN Workshops and is now used in front of the LIGHT proton therapy prototype linac of ADAM/AVO.



End of Lecture 4

Thank you for your attention!

Some RFQ bibliography

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

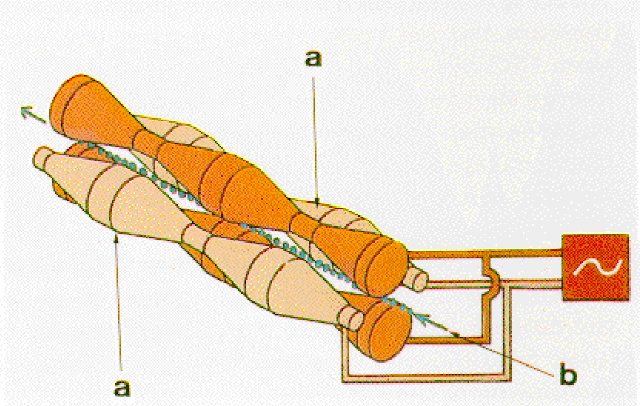
K.R. CRANDALL,R.H.STOKES and T.P.WANGLER, “ RF Quadrupole Beam dynamics Design study”,1979 Linear Accelerator Conference

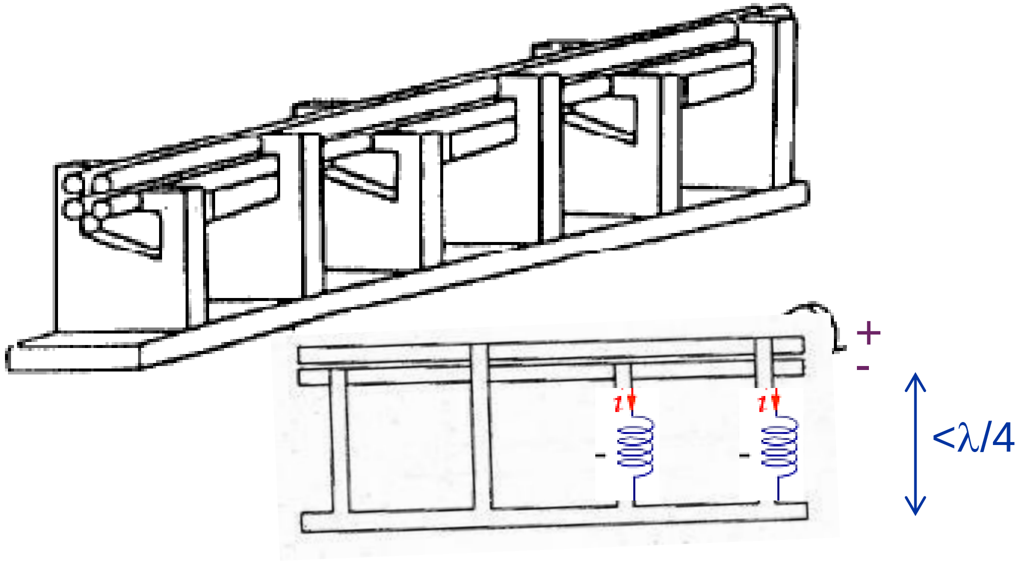
M.WEISS, “ Radio Frequency Quadrupole” , CERN-PS/87-51 (CAS Aarhus,1986)

M. PUGLISI, “Radio Frequency Quadrupole”, CERN 87-03 (CAS Oxford, 1985)

RFQ chapter in Wangler, RF Linear Accelerators

The 4-rod RFQ





An alternative solution is to machine the modulation not on the tip of an electrode, but on a set of rods (machining on a lathe, old design) or on some small “vanelets”.

The 4 electrodes are then brought to the correct quadrupole potential by an arrangement of quarter-wavelength transmission lines. The set-up is then inserted into a cylindrical tank.

Cost-effective solution, becomes critical at high frequencies → dimensions become small and current densities go up.

Power densities are higher than in the 4-vane → more problems for high power applications.

Commonly used for heavy ions and protons at low frequency – low duty cycle (f <200 MHz).