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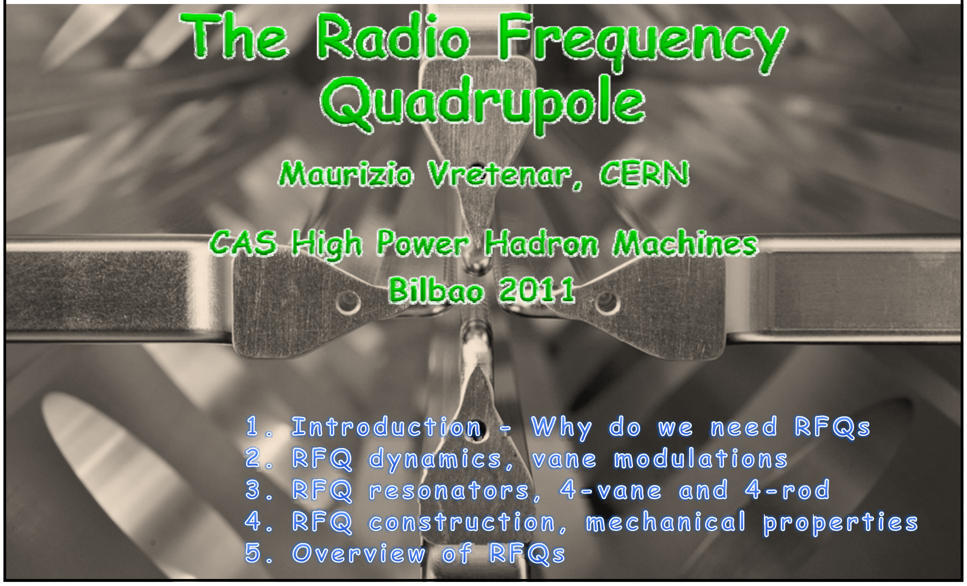

The Radio Frequency Quadrupole

Maurizio Vretenar, CERN

CAS High Power Hadron Machines
Bilbao 2011

1. Introduction - Why do we need RFQs
2. RFQ dynamics, vane modulations
3. RFQ resonators, 4-vane and 4-rod
4. RFQ construction, mechanical properties
5. Overview of RFQs

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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 β = 0.01 – 0.10

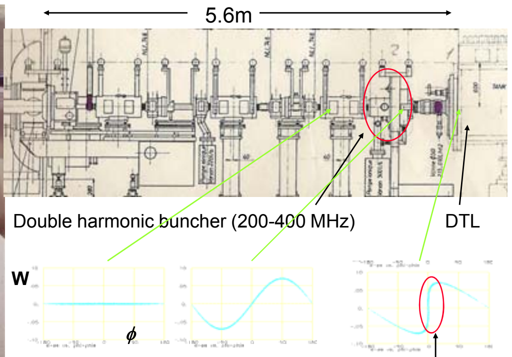
Why it is a problem?

1. (from previous lecture): need strong focusing (strong space charge!), but the short cell length (~$\beta\lambda$) limits the length of quadrupoles, for ex. $\beta\lambda$(1MeV,352MHz) = 3.9cm
2. in this region the beam needs to be bunched → standard bunching systems are quite ineffective (~50% beam loss…).
3. At low energy, the usual accelerating structures have low efficiency (low shunt impedance).

The classical 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



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

New ideas – an history of the RFQ

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): 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 very high intensity (CW, high current).

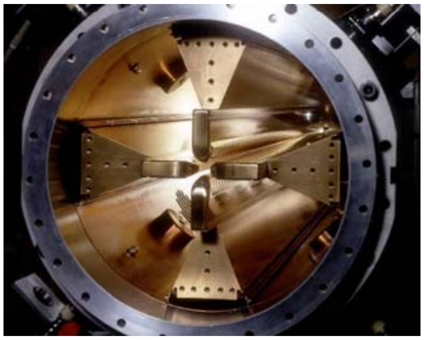
RFQ compared to the old pre-injectors

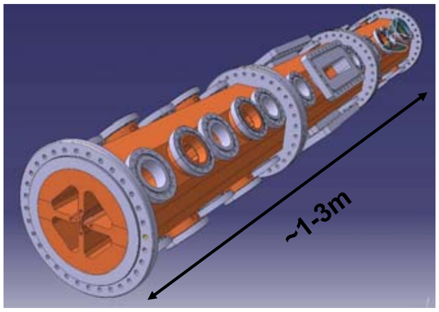
The old pre-injector at CERN (1976): Source+ Cockroft Walton +line+bunching

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

The Radio Frequency Quadrupole (RFQ)

RFQ = Electric quadrupole focusing channel + bunching + acceleration

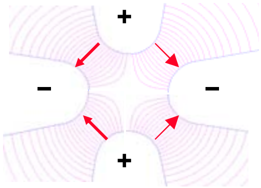


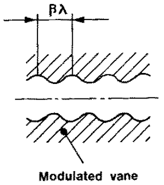


New and performing accelerator.
Compact and critical structure, where beam dynamics, RF and mechanical aspects are closely interconnected.

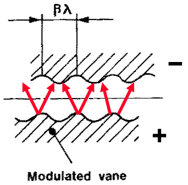
CAS The basic RFQ principle

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.

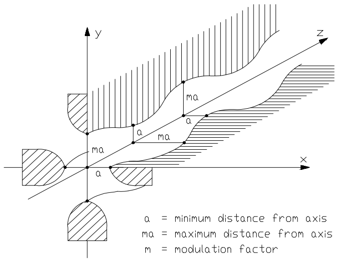




Opposite vanes (180º)



Adjacent vanes (90º)



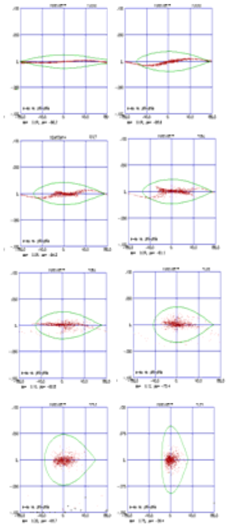
CAS Bunching and acceleration

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. →

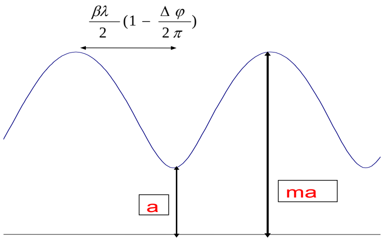


RFQ beam dynamics

An RFQ is made of a sequence of cells (length βλ → 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 with much less freedom): the RF voltage V.



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

cell length/βλ = 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.

The Kapchinski potential

Kapchinski derived an analytical expression for the fields in an RFQ channel :

- The region between the vanes is small w.r.t. the wavelength → static approximation, we can use the formulae for static fields.
- The potential in the intervane region is then a solution of the Laplace equation, which in cylindrical coordinates can be solved by a series of Bessel functions.
- Kapchinski's idea: of all the terms in the series, take only the 2 that are interesting for us (*the transverse quadrupole term + a longitudinal focusing and accelerating term*) and try to build some electrodes that give only those 2 terms.

$$\underbrace{V(r,\vartheta,z) = A_0 r^2 \cos 2\theta}_{\text{Transverse quadrupole term}} + \underbrace{A_{10} I_0(kr)\cos kz}_{\text{“Longitudinal” term}}$$

k=2π/βλ

→ an RFQ cell is defined by the 2 parameters, A_0 and A_{10} (plus the phase)
→ the 3 dimensional profile of an RFQ electrode must correspond to an equipotential surface of V(r,theta,z)

RFQ beam dynamics - 2

$$V(r,\vartheta,z) = A_0 r^2 \cos 2\theta + A_{10} I_0(kr) \cos kz$$

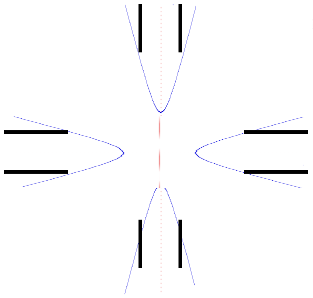
→ The electrodes have to follow equipotential surfaces of this equation

Sample 1

The equipotential surfaces giving the 2-term RFQ potential are hyperbolic surfaces with a longitudinal sinusoidal modulation.

→ The vanes in the 1st generation of RFQs were perfect truncated hyperbolae.

V=voltage applied between 2 adjacent vanes



The constants A0, A10 depends on the geometry, and can be related to the modulation factors and to the intervane voltage V:

$$A_0 = \frac{V_0}{2a^2} \frac{I_0(ka) + I_0(kma)}{m^2 I_0(ka) + I_0(kma)} \qquad A_{10} = \frac{V_0}{2} \frac{m^2 - 1}{m^2 I_0(ka) + I_0(kma)}$$

RFQ beam dynamics - 3

But:

1. Truncated hyperbolic surfaces are difficult to machine (require a precise 3D milling).
2. Modern field calculation codes allow to use vane profiles that cannot be analyzed analytically.

→ after the first generation of RFQs, the designers are now using simplified vane profiles with constant curvature radius.

→ introduction of multipoles (additional terms with respect to Kapchinski potential), can be calculated and their effect on the beam kept within acceptable limits.

Sample 2

Parameters of the RFQ

Transverse focusing coefficient

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

limited by sparking

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

Longitudinal bunching and accelerating field

$$E_0T=\frac{m^2-1}{m^2 I_o(ka)+I_o(mka)}\cdot V\frac{2}{\beta\cdot\lambda}\frac{\pi}{4}$$

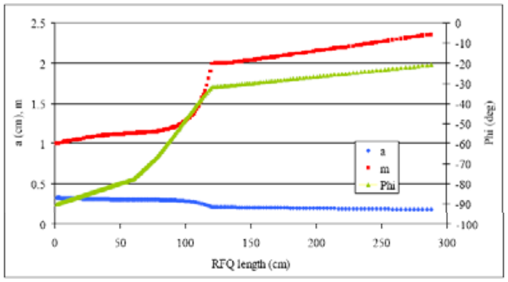
Accelerating efficiency : fraction of the field deviated in the longitudinal direction (=0 for un-modulated electrodes)

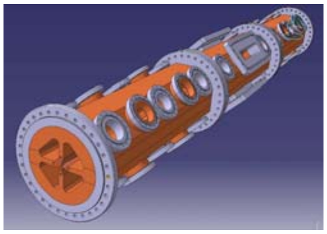
cell length

Example of an RFQ Beam Dynamics design

The new CERN Linac4 RFQ:

352 MHz, 45 keV to 3 MeV, 303 cells, 3 m length, 70 mA beam current
Beam transmission 93 % (calculated)





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!

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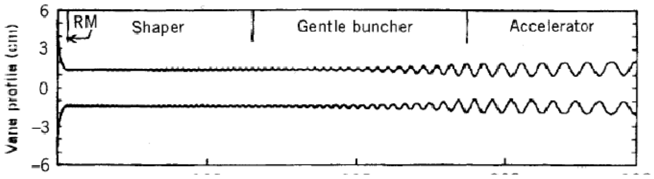
RFQ sections



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.		

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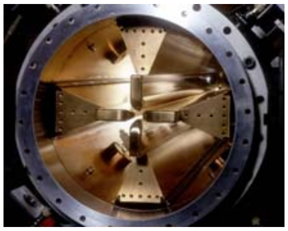
RFQ movie

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

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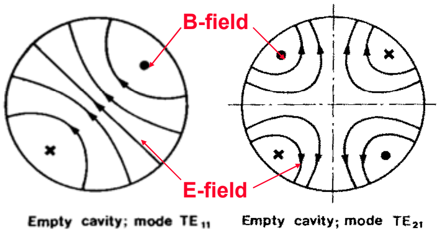
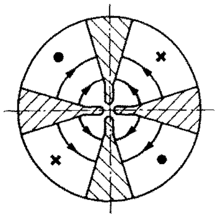
The “4-vane” RFQ



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



Cavity with vanes

Basic idea:

An empty cylindrical cavity can be excited on different 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.

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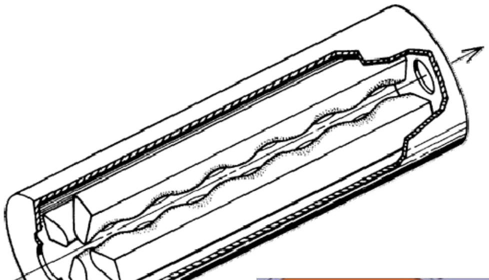
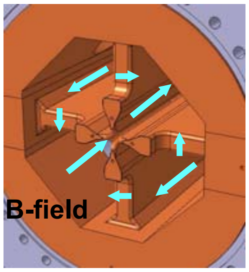
The 4-vane RFQ



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!

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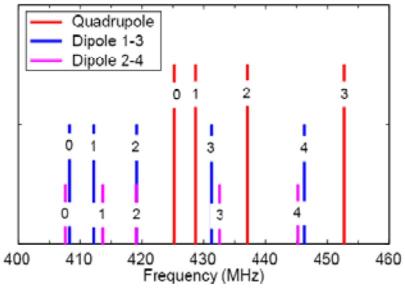
Length of an RFQ



Mode spectrum (after tuning) of a 425 MHz, 2.75m long RFQ (3.9 λ)

→to have shorter RFQs, choose the minimum injection energy allowed by space charge !
(counterintuitive…)

The length of an RFQ is limited by field errors:

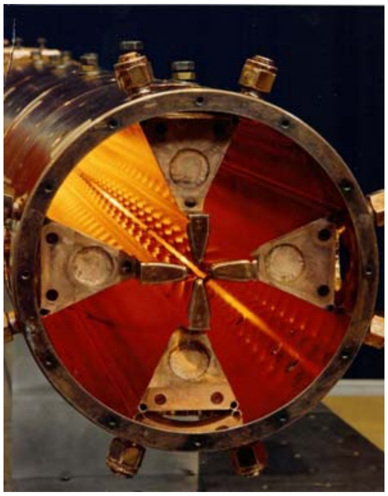
The TE210 mode is not the only one in a 4-vane RFQ: TE21 band (quadrupoles) + TE11 band (dipoles)

The difference in frequency between the higher order modes (n≥1) and the modes at n=0 is inversely proportional to (length/λ)^2 → the longer the RFQ, the closer the higher-order modes come to the operating mode.

The closer the modes, the higher is the effect on the E-field of machining or alignment errors → the quadrupole field is no longer constant along the RFQ, and flattening the field (“tuning”) becomes difficult.

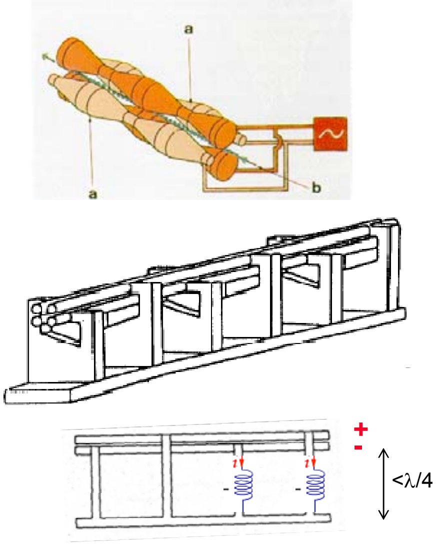
Rule of thumb:
length < 2λ → no problem
2λ < length < 4λ → need particular care
length > 4λ → require segmentation and resonant coupling

The 1st 4-vane RFQ



Proof of Principle (POP) RFQ, Los Alamos
1980 – the 1st vane-type RFQ
100 KeV - 650 KeV, 30 mA , 425 MHz

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 (simple machining on a lathe).

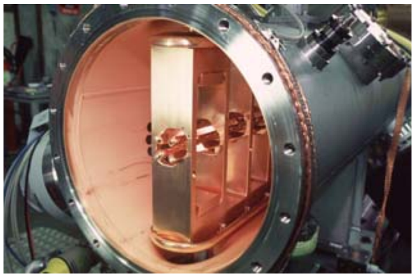
The rods can then be brought to the correct quadrupole potential by an arrangement of quarter-wavelength transmission lines. The set-up is then inserted into a cylindrical tank.

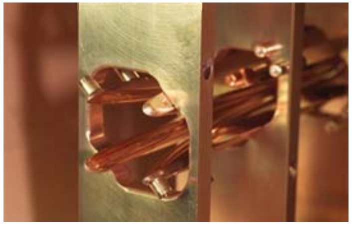
Cost-effective solution, becomes critical at high frequencies → dimensions become small and current densities go up.

This structure is commonly used for ions at low frequency – low duty cycle.
(frequency <200 MHz)

Other 4-rod geometries

The electrodes can also be “vane-like” in structures using doubled λ/4 parallel plate lines to create the correct fields.





Mechanical aspects – tolerances

2 main problems define the RFQ mechanical construction:

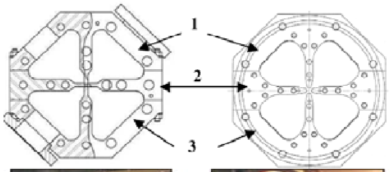
1. The need to achieve tight tolerances in vane machining and positioning (small aperture → small tolerances for field quality, more critical in presence of an RF dipole mode).
   ~ 0.05 mm on the vane tips, can be less if high RF field quality is required.

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

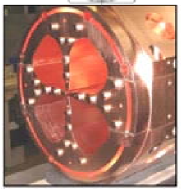
Mechanical aspects – joining RFQ parts

2. An RFQ is a LEGO of many components (tanks, vanes or rods, supports, etc.) that have to be assembled together keeping the tolerances and providing a good quality RF contact (large currents flowing!).

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

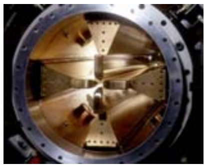


TRASCO, LNL, Italy



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

RFQ – thermal aspects

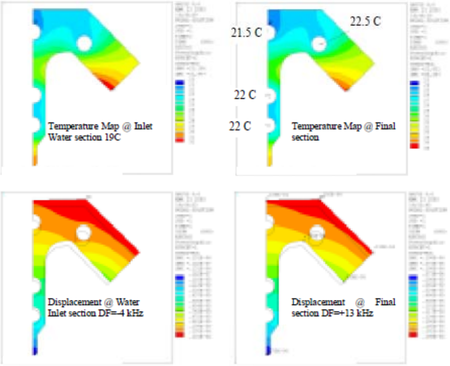


Fig. 6: Top: temperature maps at begin (left) and at the end (right) of one RFQ section. Bottom: deformation maps and frequency shifts.

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

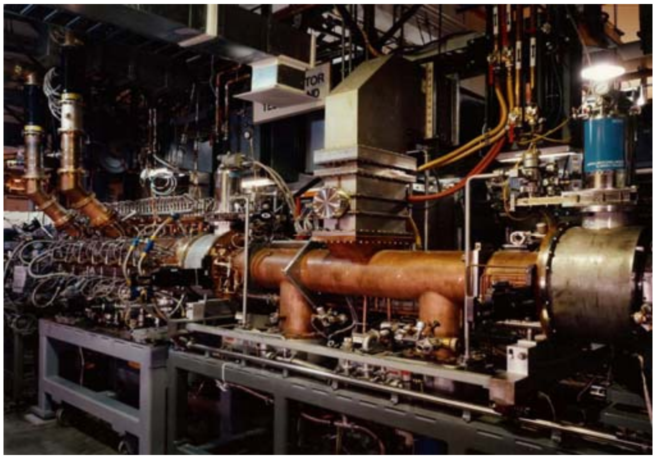
1. High (beam) power RFQs need to dissipate large amounts of RF power in small volumes (vanes are “thin” to maximize shunt impedance).
2. Thermal deformations can lead to large voltage variations and to beam loss.

⬇

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).
1. Thermal deformations can lead to large voltage variations and to beam loss.

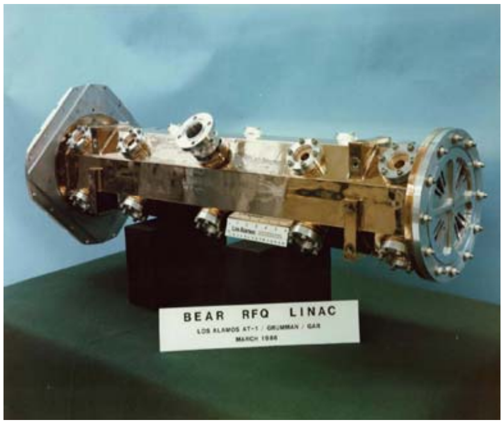
Examples of RFQs – 1

“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



Examples of RFQs - 2

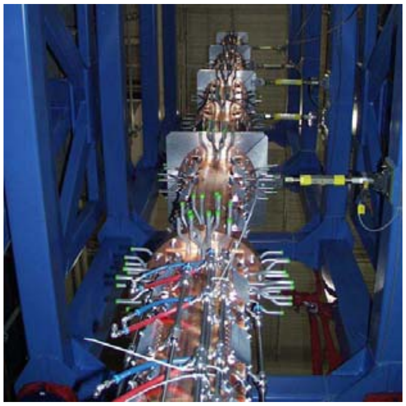
“BEAR” RFQ (beam experiment aboard a rocket)(partly classified) 1989
30 KeV – 1 MeV, 20 mA, <1% duty H-minus
425 MHz, solid-state RF system
Cu plated Al quadrants, joined by electroforming, 55 kg
Operated in sub-orbital flight with a “neutral” beam, LANL



Examples of RFQs - 3

The first high-beam-power RFQ

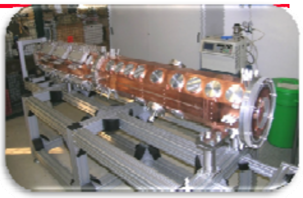
LEDA RFQ (low energy demonstration accelerator)
1999 - 2000
75 keV-6.7 MeV, 100 mA cw protons
350 MHz
Brazed OFE Cu quadrants
Resonantly coupled, 8 m long, LANL

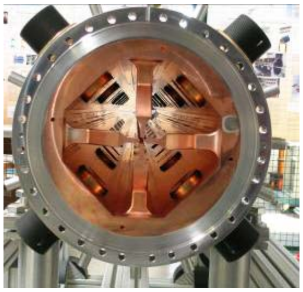


Examples of RFQs - 4

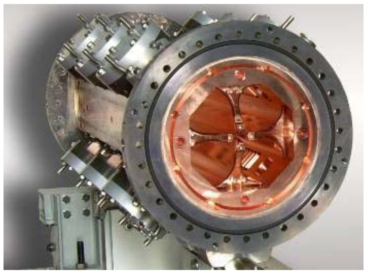
High frequency (352 MHz), high duty cycle (CW) for ADS studies and other applications.

2 RFQs in construction in Europe:





TRASCO@LegnaroINFN



IPHI@Saclay.CEA

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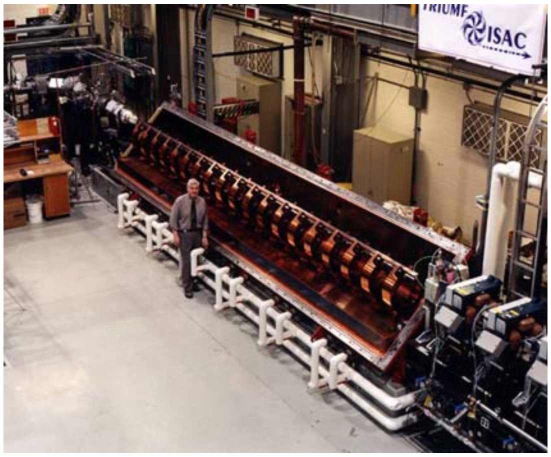
Examples of RFQs - 5



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

The ISAC-II RFQ at TRIUMF (Canada)

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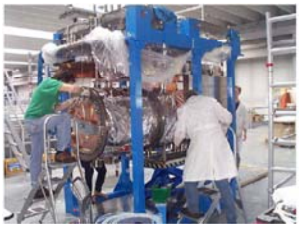
Examples of RFQ - 6

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



Superconducting RFQs:

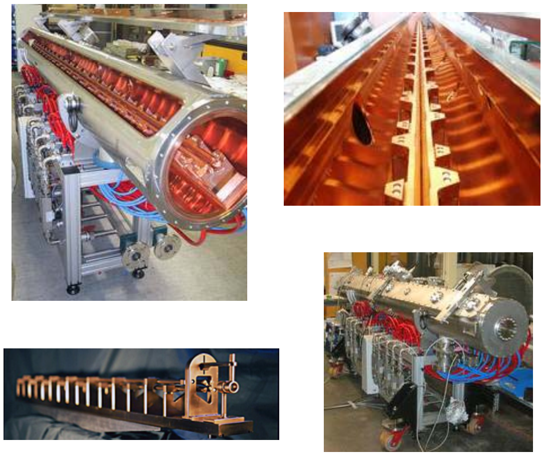
Only 2 Superconduting RFQs built so far in the world (Argonne, USA and Legnaro, Italy).

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 - 7

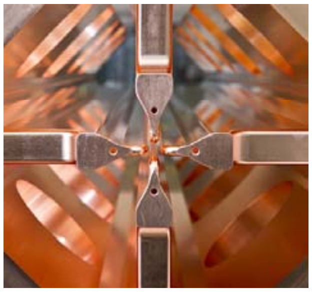


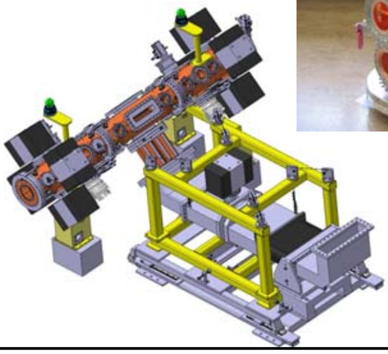
Medium frequency (176 MHz), high duty cycle (CW),
4-rod design
for high-intensity deuteron and proton acceleration.

The SARAF RFQ, built by NTG and A. Schempp (IAP Frankfurt) for the Soreq Nuclear Research Center in Israel.

Examples of RFQs - 8

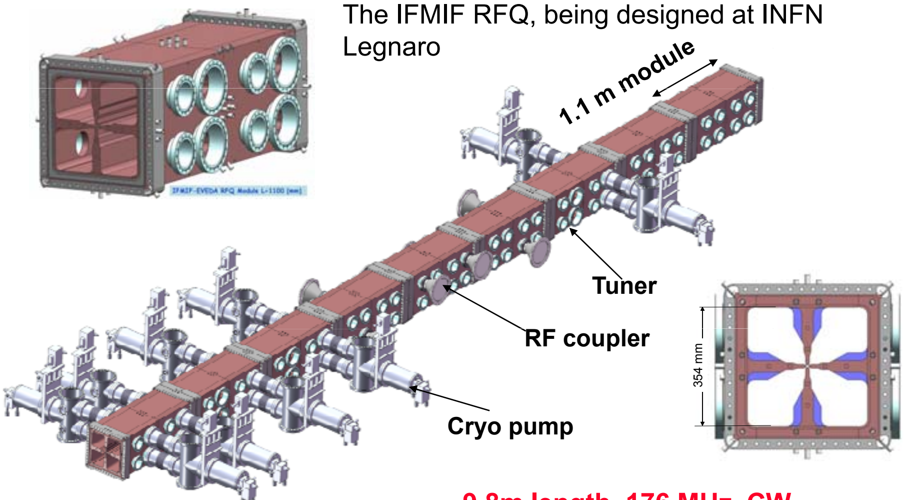
The CERN Linac4 RFQ
In construction at the CERN Workshop
First beam expected end 2011
45 keV – 3 MeV, 3 m
80 mA H-, max. 10% duty cycle





Examples of RFQ - 9

The IFMIF RFQ, being designed at INFN Legnaro



9.8m length, 176 MHz, CW

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)**
- **M. PUGLISI, "Radio Frequency Quadrupole", CERN 87-03 (CAS Oxford, 1985)**
- **RFQ chapter in Wangler, RF Linear Accelerators**

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