# The Radio Frequency Quadrupole

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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

# Low-energy acceleration of protons and ions

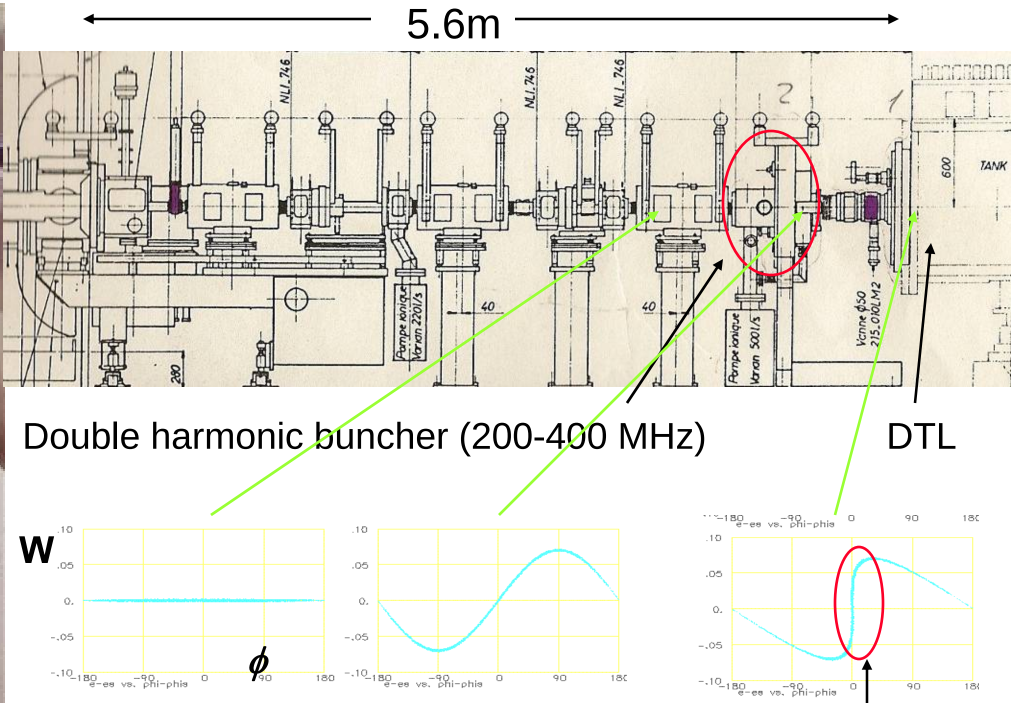
***Low energy*** →

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. (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: 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

- 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), presented by a Czech refugee.

- 1977-1980: the Los Alamos team, enthusiastic about this idea, 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.

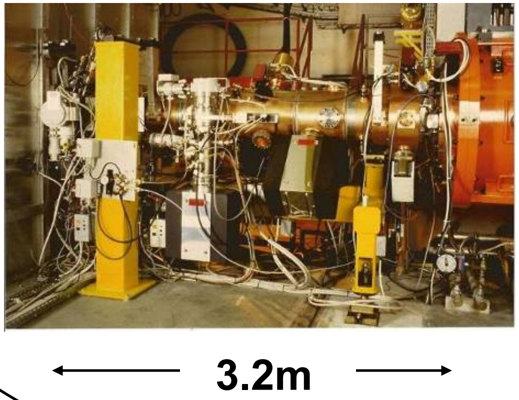
- 1980's: the RFQ principle spreads around the world, more RFQs are built in the USA and in Europe (1st CERN RFQ: 1984).

- 1985-1995 : RFQs progressively replace the old pre-injectors in most of the 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, for example high intensity (CW, high current).

# RFQ compared to the old pre-injectors

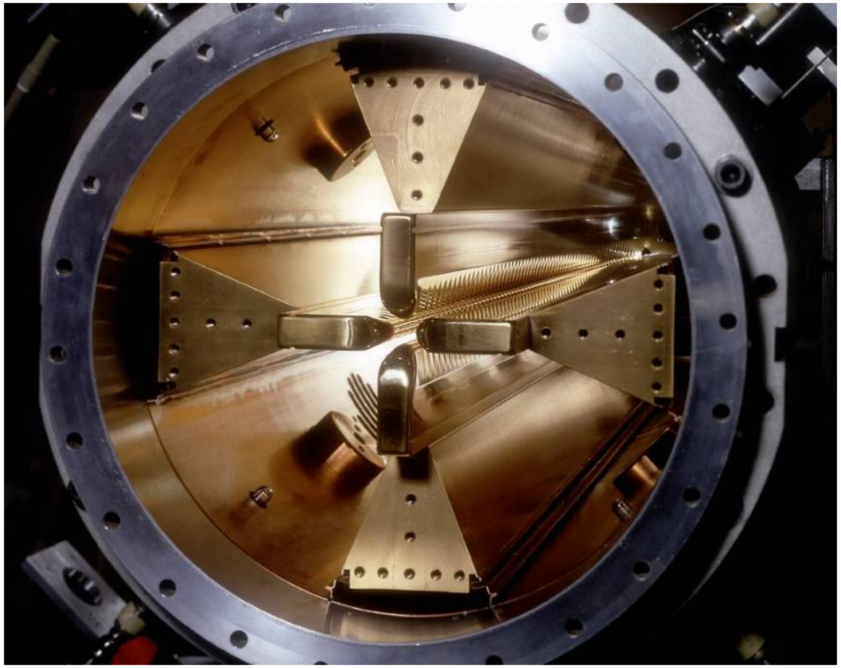
The old pre-injector at CERN (1976): Source+ Cockroft Walton +line+bunching

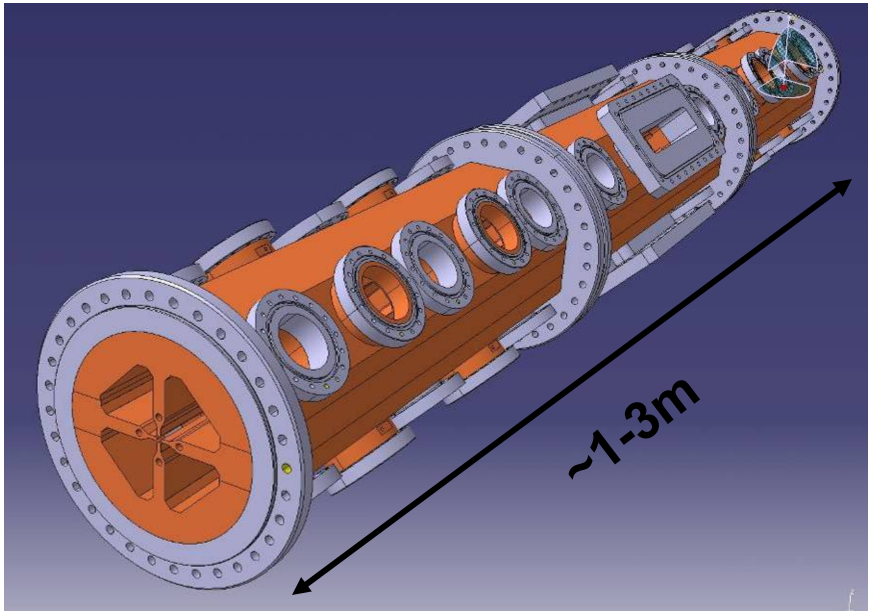


The new RFQ2 pre-injector at CERN (1993): Source+LEBT +RFQ

# The Radio Frequency Quadrupole (RFQ)

RFQ = Electric quadrupole focusing channel + bunching + acceleration

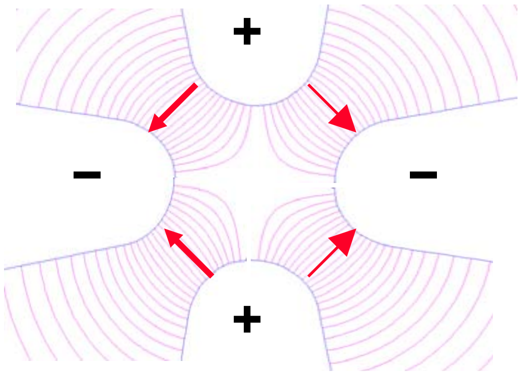


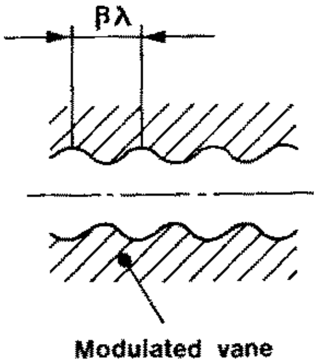


New and performing accelerator.
Compact and critical structure, where beam dynamics, RF and mechanical aspects are closely interconnected.

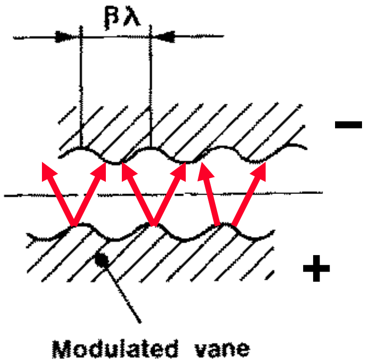
# The basic RFQ principle

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

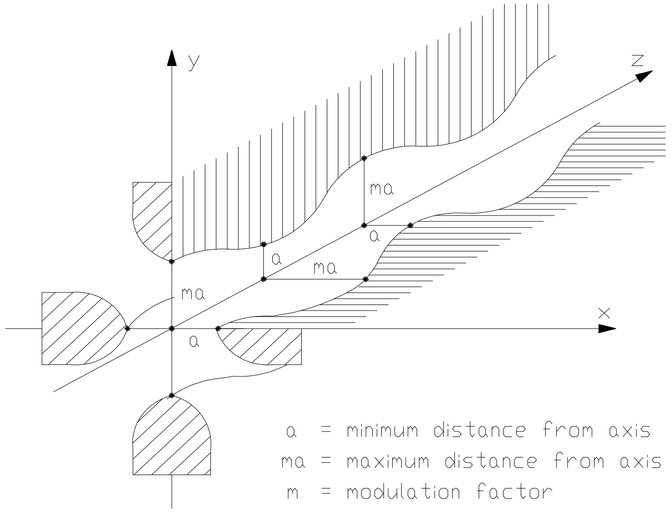




**Opposite vanes (180º)**



**Adjacent vanes (90º)**



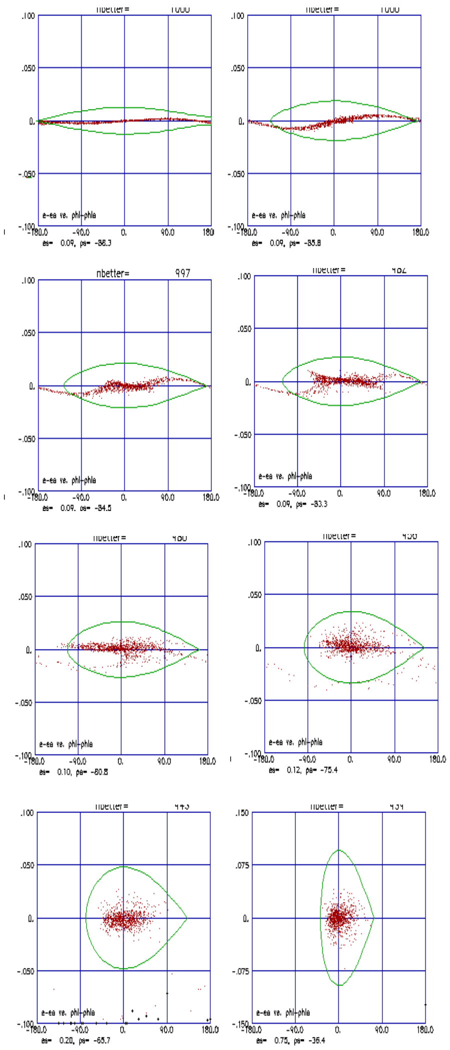
a = minimum distance from axis
ma = maximum distance from axis
m = modulation factor

# Bunching and acceleration

3. The <u>modulation period</u> (distance between maxima) can be slightly adjusted to change the phase of the beam inside the RFQ cells, and the <u>amplitude of the modulation</u> can be changed to change the accelerating gradient → we can start at -90° phase (linac) with some bunching cells, progressively bunch the beam (<u>adiabatic bunching channel)</u>, and only in the last cells switch on the acceleration.

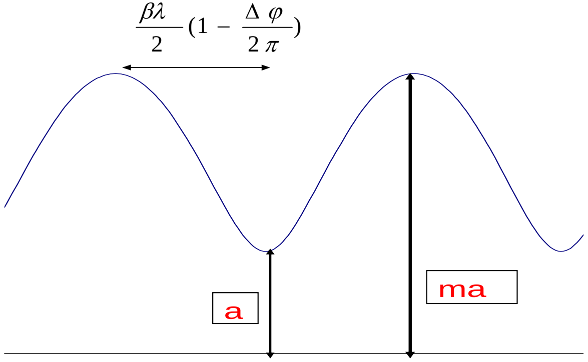
☞ An RFQ has 3 basic functions:

1. Adiabatically <u>bunching</u> of the beam.
2. <u>Focusing</u>, on electric quadrupole.
3. <u>Accelerating</u>.



**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



The modulation is defined by 2 parameters:

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

plus the cell length (depending on particle $\beta$ and phase)

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.

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

k=2π/βλ

*Transverse quadrupole term*

*"Longitudinal" term*

# CAS RFQ beam dynamics - 2

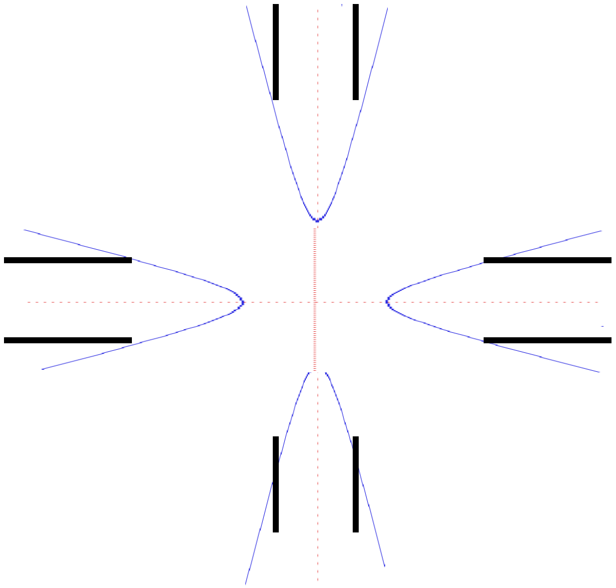
$$V(r,\vartheta,z) = A_0 r^2 \cos 2\theta + A_{10} I_0(kr) \cos kz$$

→ The electrodes have to follow equipotential surfaces of this solution

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:

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

# 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**

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

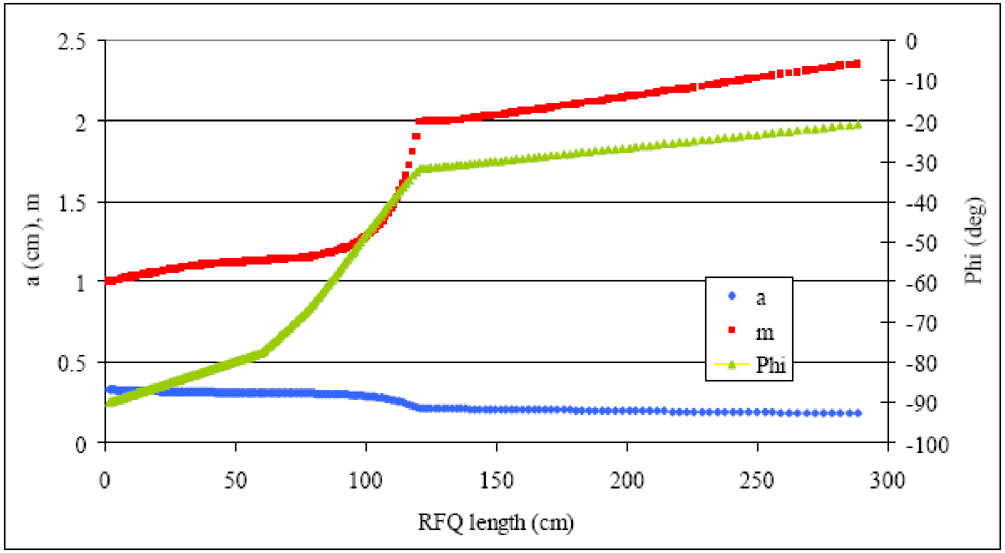
Accelerating efficiency : fraction of the field deviated in the longitudinal direction (=0 for un-modulated electrodes)

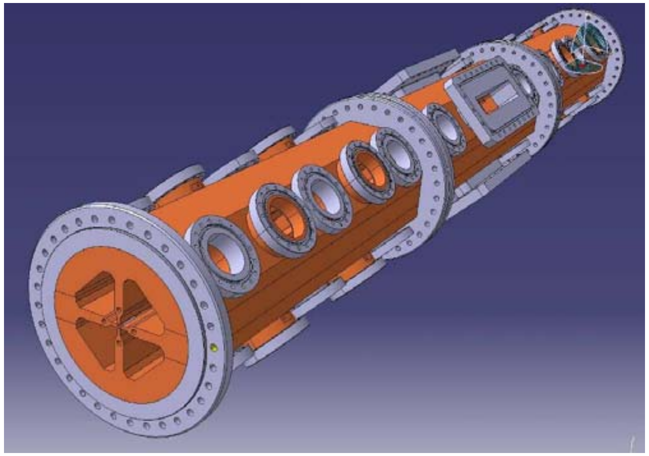
cell length

# Example of an RFQ Beam Dynamics design

The new CERN Linac4 RFQ:

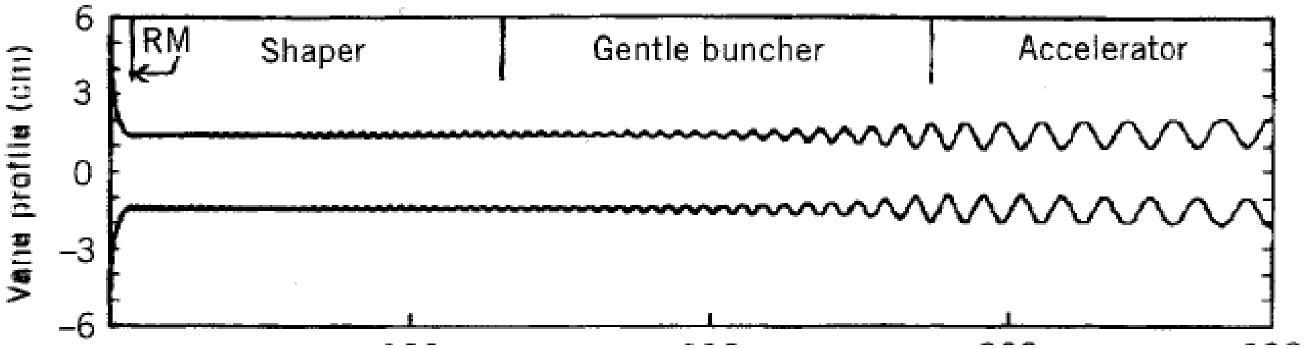
352 MHz, 45 keV to 3 MeV, 303 cells, 3 m length, 70 mA beam current
Beam transmission 93 % (calculated)





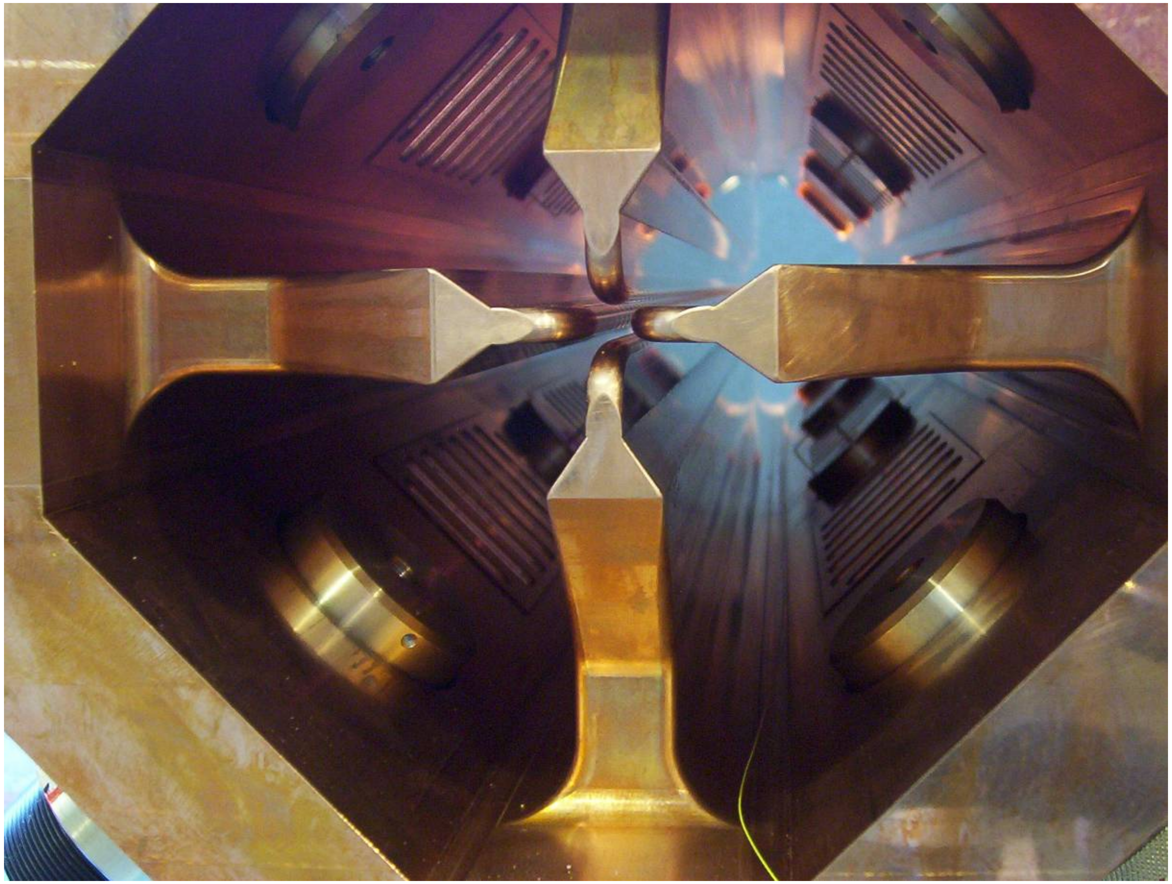
The first ~200 cells are used for adiabatic bunching of the beam: the synchronous phase is slowly increased from -90 to -20 deg → bunching with low beam loss!

# 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. | | |
| | | |

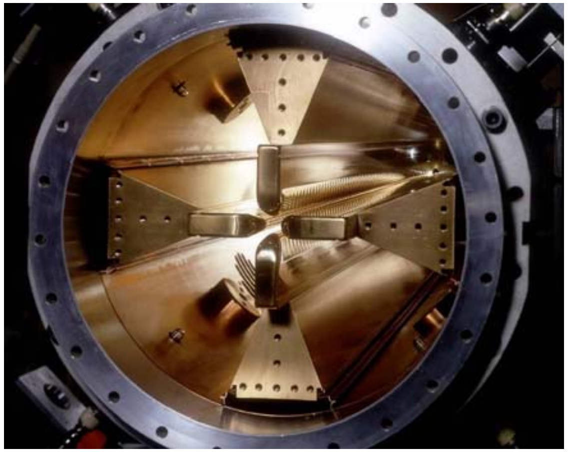
# RFQ movie

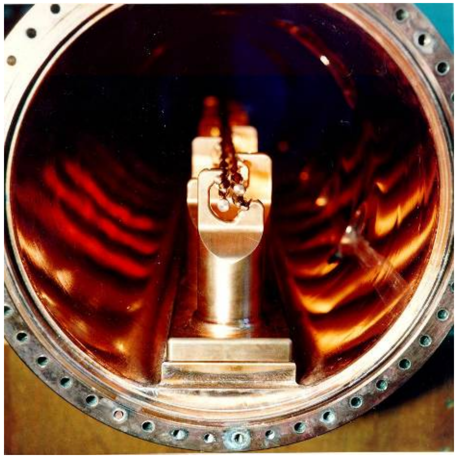


# The RFQ resonator

**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.)

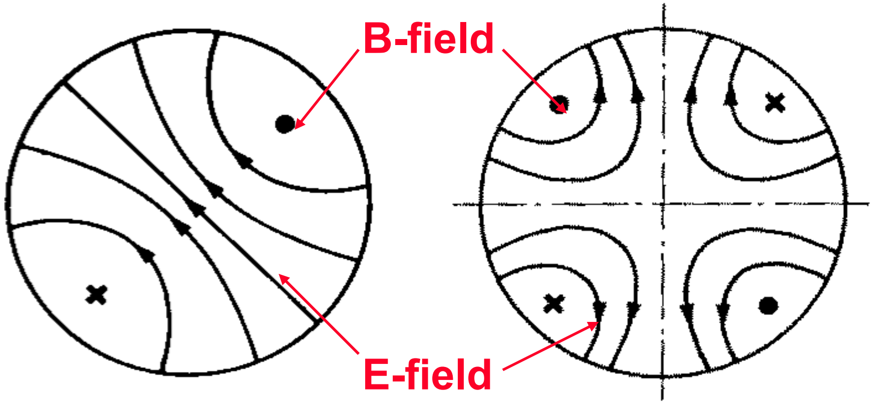
**Remark:**
what is the ideal frequency for an RFQ?

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

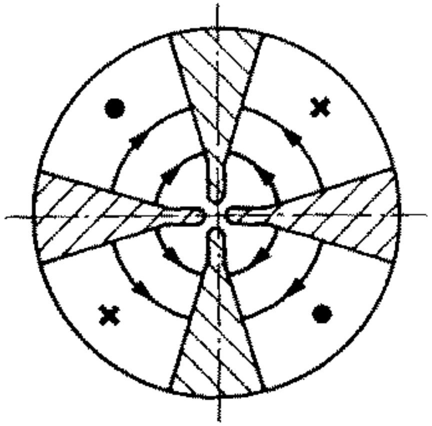
For heavy ions,
$\beta \sim 10^{-4} – 10^{-3}$
corresponding to
f~ 10 – 100 MHz

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

# The “4-vane” RFQ



Empty cavity; mode $TE_{11}$ Empty cavity; mode $TE_{21}$



Cavity with vanes

Basic idea:

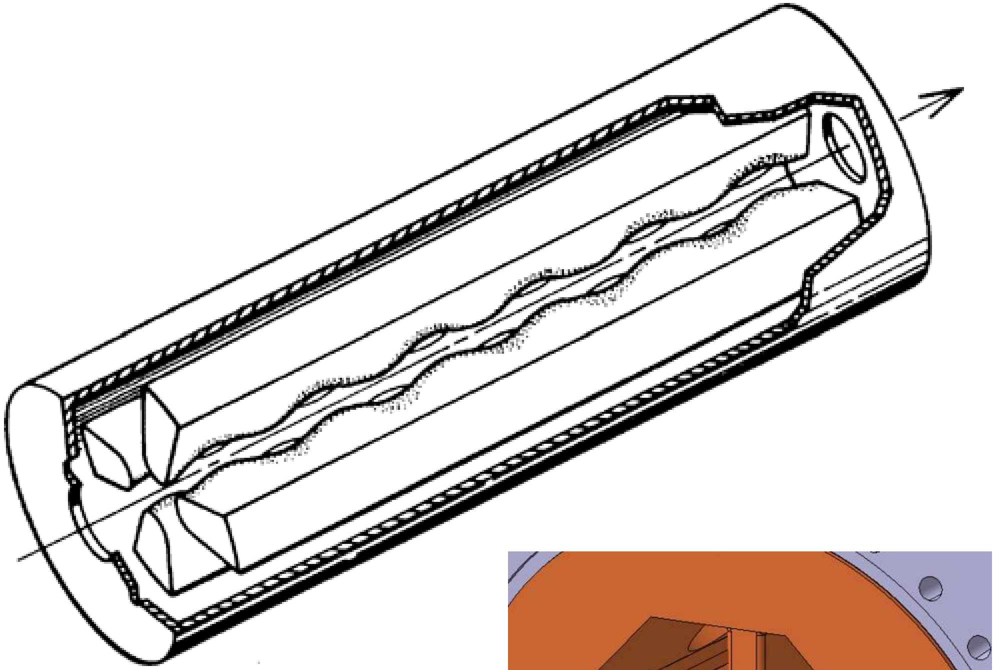
An empty cylindrical cavity can be excited on different modes.
Some of these modes have only transverse electric field (the TE modes), and in particular going up in frequency one can find a “quadrupole” mode, the TE210.

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

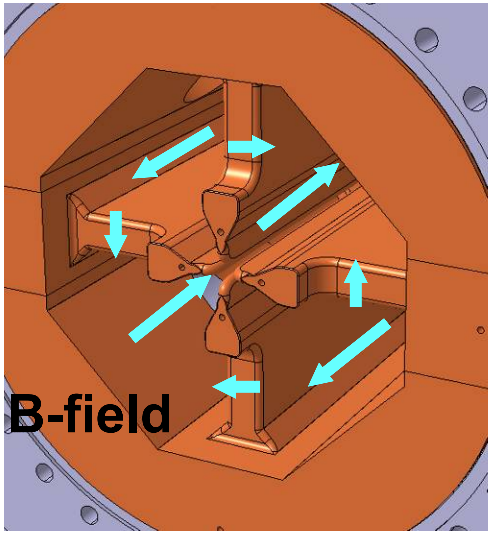
- Concentrate the electric field on the axis, increasing the efficiency.
- Lower the frequency of the TE210 mode, separating it from the other modes of the cylinder.

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

# The 4-vane RFQ

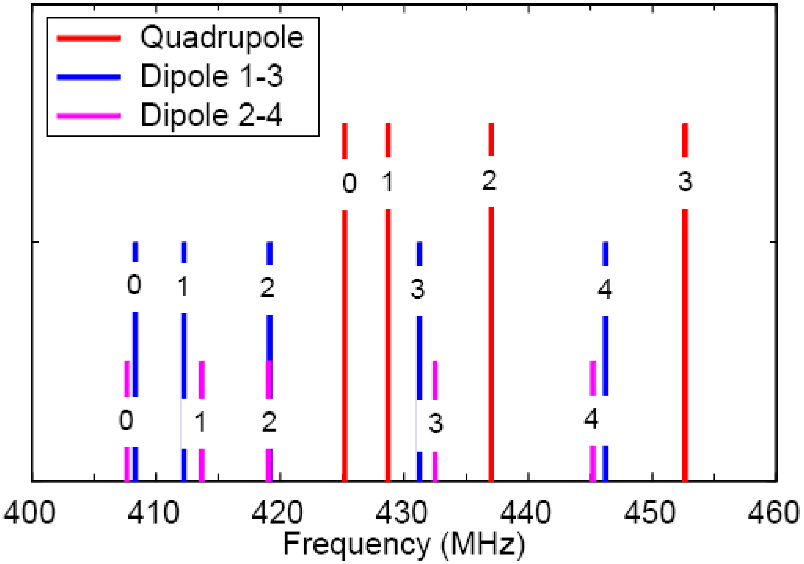


The RFQ will result in cylinder containing the 4 vanes, which are connected (large RF currents!) to the cylinder along their length.



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!

# Length of an RFQ



*Mode spectrum (after tuning) of a 425 MHz, 2.75m long RFQ (3.9 $\lambda$)*

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)

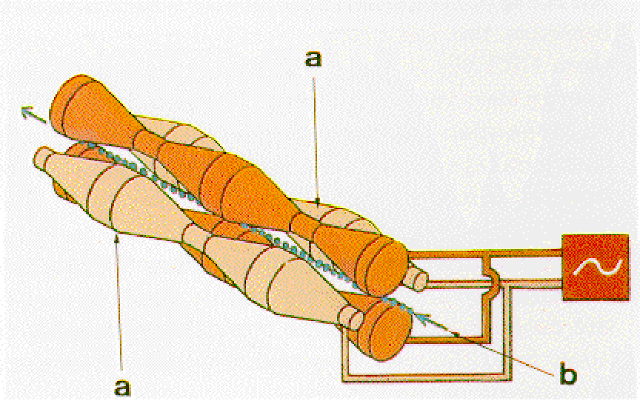
The difference in frequency between the higher order modes ($n \geq 1$) and the modes at n=0 is inversely proportional to $(\text{length}/\lambda)^2$ → the longer the RFQ, the closer the higher-order modes come to the operating mode.

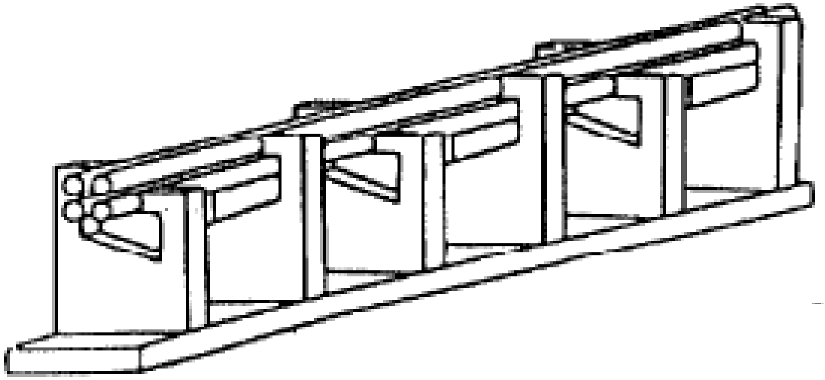
The closer the modes, the higher is the effect on the E-field of machining or alignment errors → the quadrupole field is no longer constant along the RFQ, and flattening the field (“tuning”) becomes difficult.

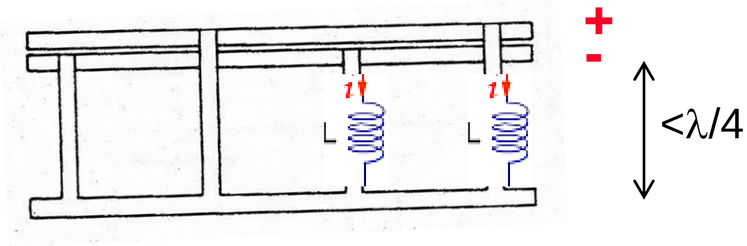
→ to have shorter RFQs, choose the minimum injection energy allowed by space charge !

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

# 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).

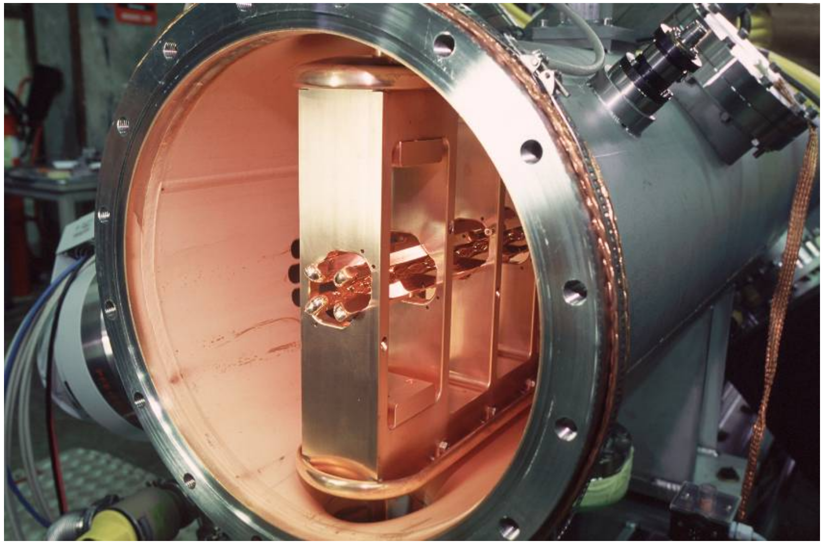
The rods can then be brought to the correct quadrupole potential by an arrangement of quarter-wavelength transmission lines. The set-up is then inserted into a cylindrical tank.

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 $\lambda/4$ parallel plate lines to create the correct fields.



# Mechanical aspects – tolerances

2 main problems define the RFQ mechanical construction:

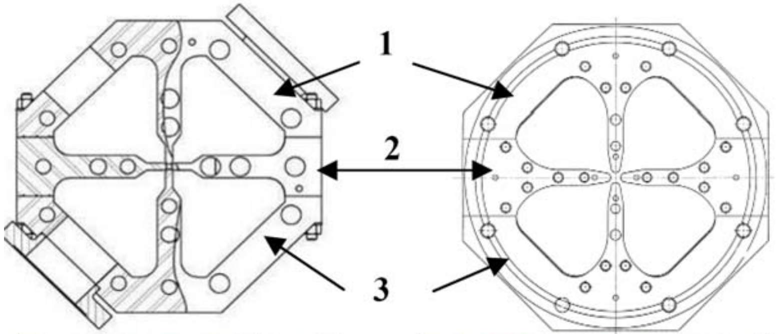
1. The need to achieve tight tolerances in vane machining and positioning (small aperture → small tolerances for field quality, more critical in presence of an RF dipole mode).
   ~ 0.05 mm on the vane tips, can be less if high RF field quality is required.

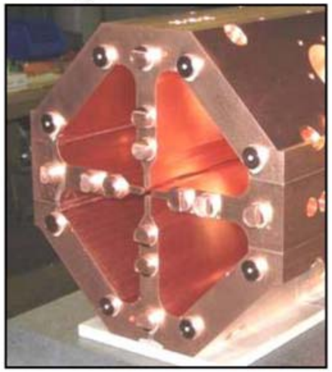
*Machining of a vane for the new CERN RFQ (linac4)*

# Mechanical aspects – joining RFQ parts

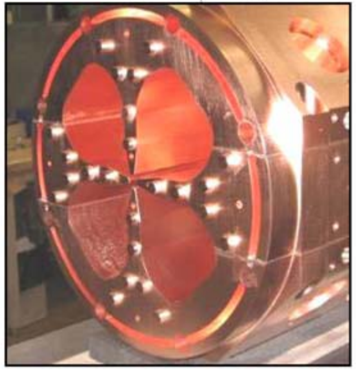
2. An RFQ is a LEGO8 of many components (tanks, vanes or rods, supports, etc.) that have to be assembled together keeping the tolerances and providing a good quality RF contact (large currents flowing!).

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



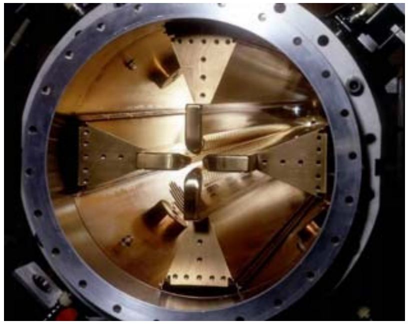


TRASCO, LNL, Italy



IPHI, CEA-CNRS, France

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



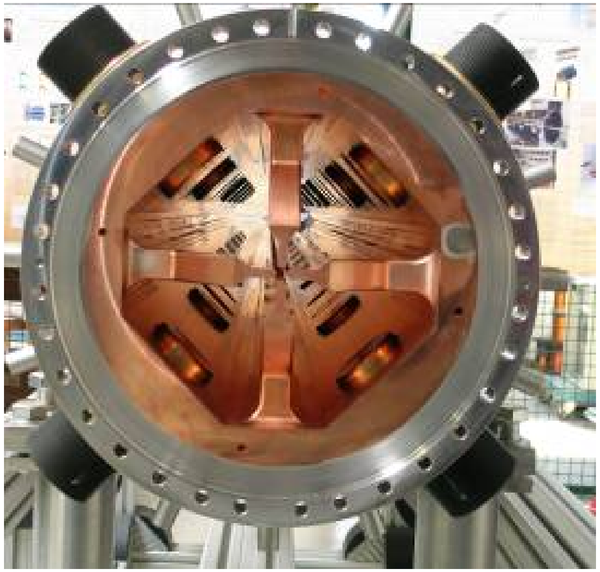
RFQ1 and RFQ2, CERN

SPIRAL2, CEA-CNRS, France

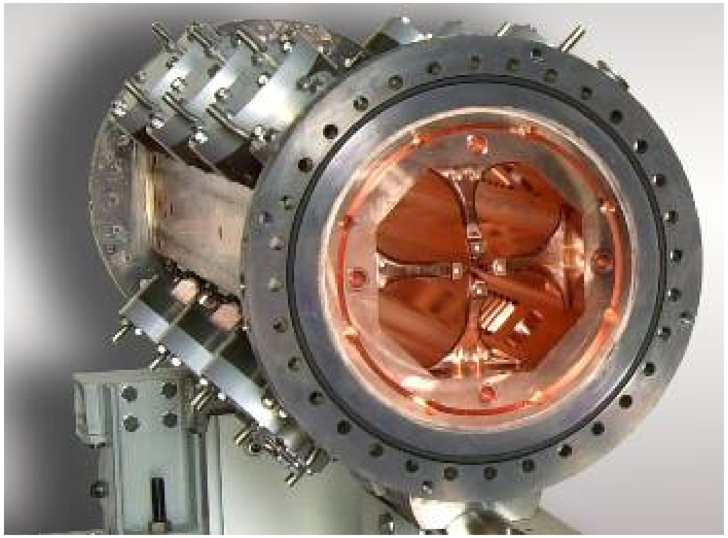
# Examples of RFQs - 1

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

2 RFQs in construction in Europe:

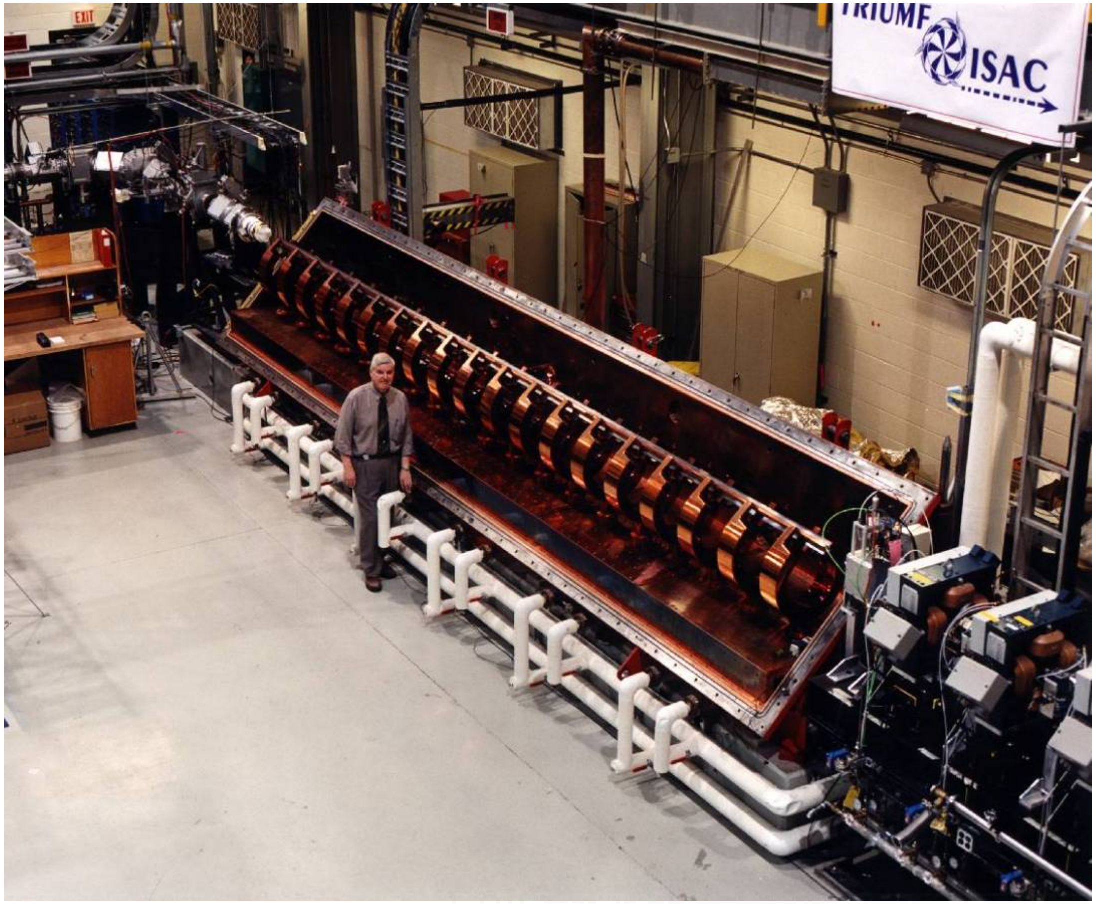


TRASCO@LegnaroINFN



IPHI@Saclay.CEA

# Examples of RFQs - 2



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

The ISAC-II RFQ at TRIUMF (Canada)

# Examples of RFQ - 3

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

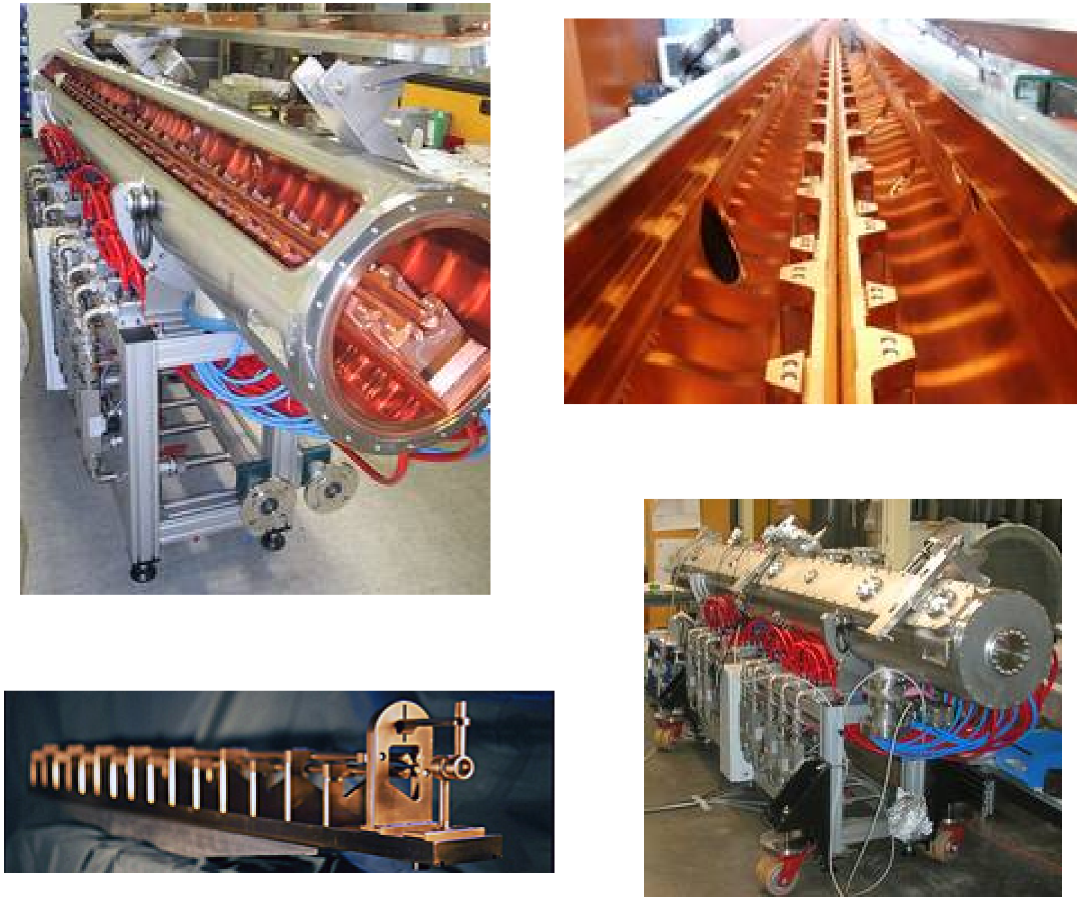
**Superconducting RFQs:**

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

# Examples of RFQ - 4

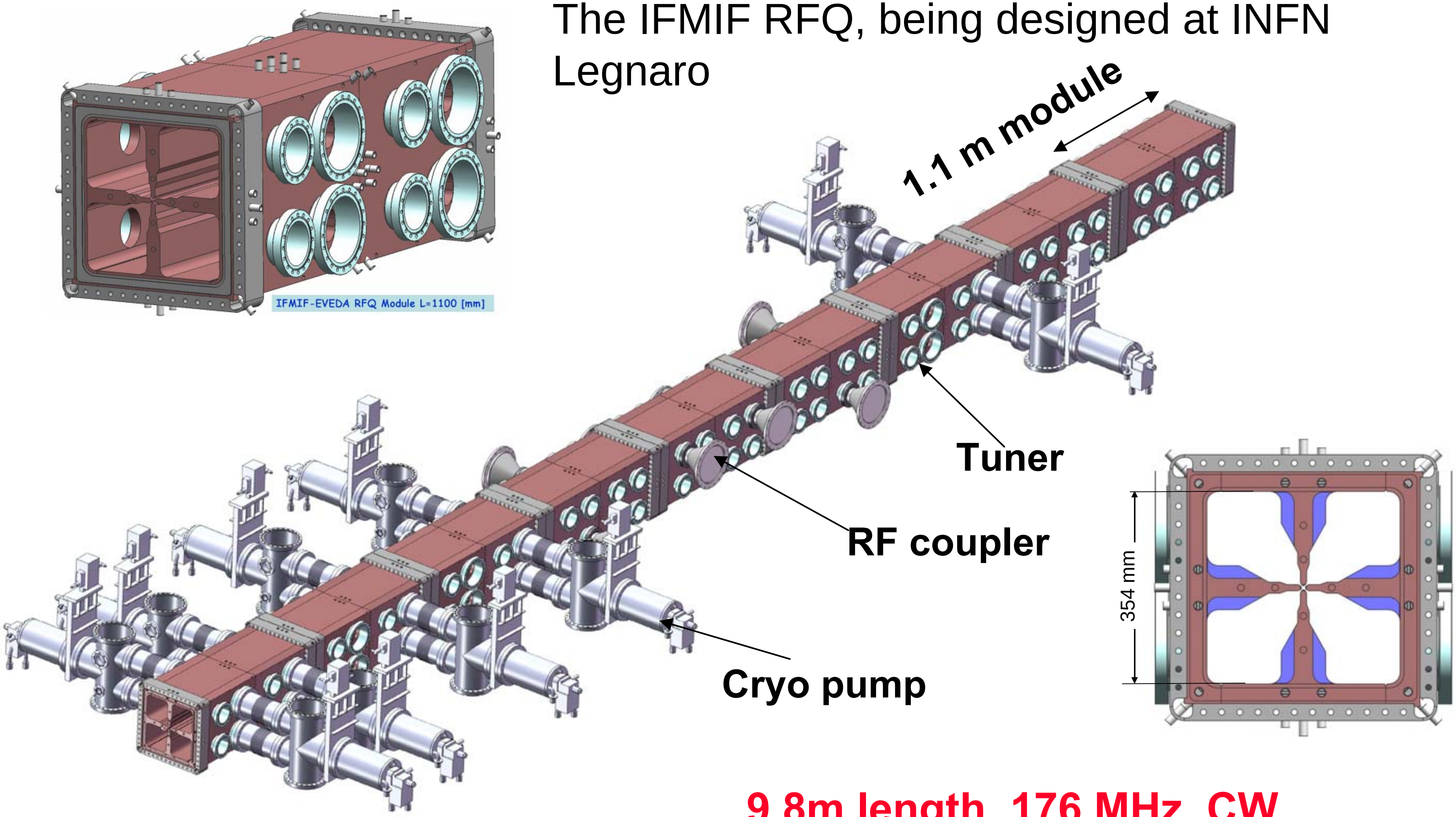


Medium frequency (176 MHz), high duty cycle (CW),
4-rod design
for high-intensity deuteron and proton acceleration.

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

# Examples of RFQ - 5

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**

+ many thanks to A.M. Lombardi, C. Rossi, A. Pisent for their help in preparing the material for this lecture.


TR 02