The CERN Accelerator School

Mechanical Materials Engineering for Particle Accelerators and Detectors

The RFQ’s

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CERN | EN ENGINEERING DEPARTMENT

The RFQ's

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Outline:

1) RF – RF accelerator – RFQ

2) RFQ Manufacturing

3) RFQ Applications

1) RF – RF accelerator – RFQ

<u>Reference documents:</u>

M. Weiss, “Radio-Frequency Quadrupole”, CERN Accelerator School, Aarhus, p. 196 (1986).

A. Lombardi, “Radio Frequency Quadrupole”, CERN Accelerator School, Zeegse, (2005).

A. Lombardi et al., “Beam Dynamics in a High Frequency RFQ”, IPAC15, Newport News, (2015).

M. Vretenar, “Introduction to RF Linear Accelerators”, CERN Accelerator School, Frascati, (2008).

M. Vretenar, “Low-Beta Structures”, CERN Accelerator School, Ebeltoft, (2010).

F. Gerigk, “Cavity Types”, CERN Accelerator School, Ebeltoft, (2010).

M. Weiss†

A. Lombardi

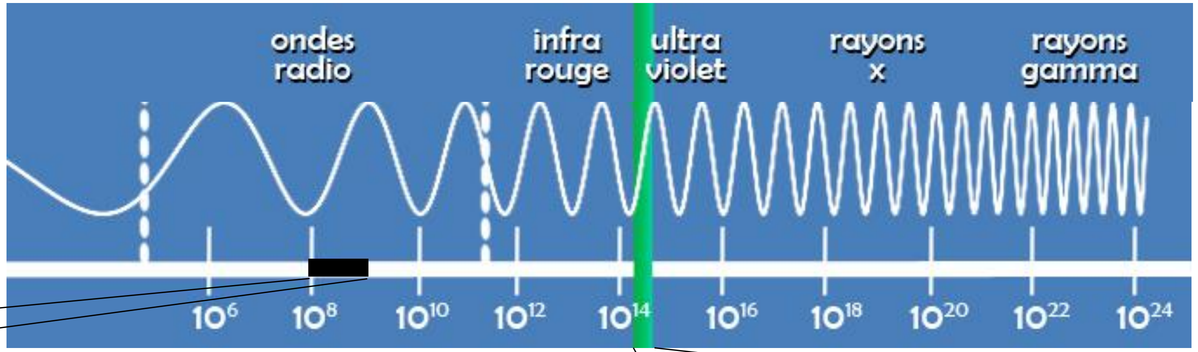
M. Vretenar

F. Gerigk

+ A. Grudiev, E. Montesinos, C. Rossi, M. Timmins, ….

1) RF – RF accelerator – RFQ

1.1: Electromagnetic waves in a free space:



Frequency (Hz)

(Mhz)	(m)	(cm)
100	3.00	300
200	1.50	150
350	0.86	86
750	0.40	40
1000	0.30	30

Accelerators

ν	λ (Wavelength)						
(Hz)	(m)	(cm)	(mm)	(µm)	(nm)	(pm)	(fm)
1.00E+06	300.0						
1.00E+08	3.0	300.0	3000.0				
1.00E+10		3.0	30.0	30000.0			
1.00E+12			0.3	300.0			
1.00E+14				3.0	3000.0		
1.00E+16					30.0	30000.0	
1.00E+18					0.3	300.0	
1.00E+20						3.0	3000.00
1.00E+22							30.00
1.00E+24							0.30

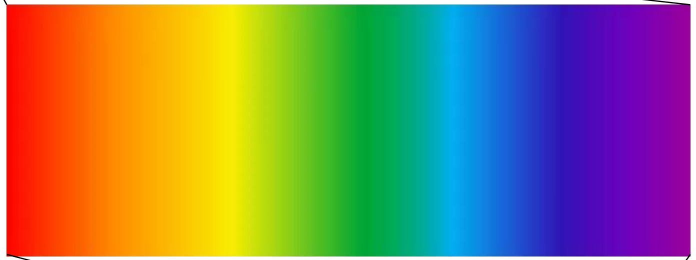
Radio-wave

Micro-wave

Infra-red

X-Rays

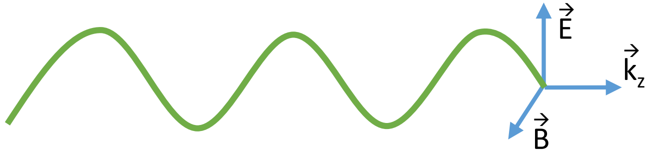
Gamma Rays



(nm)	(Hz)
800	3.8E+14
700	4.3E+14
600	5.0E+14
500	6.0E+14
400	7.5E+14
300	1.0E+15

1.1: Electromagnetic waves in a free space:

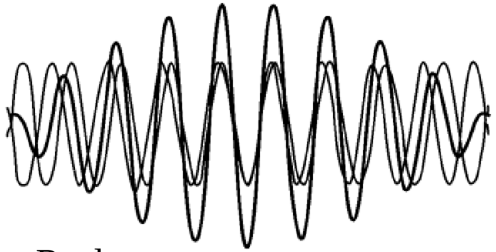
- In a free space: the electromagnetic waves are TEM (Transverse Electric and Magnetic fields)



$\omega = 2\pi f$ *where f* is the frequency (*ω is often called frequency as well)*

$k_z = \frac{\omega}{v_p}$ is the wave number or propagation constant.

v_p is the phase velocity

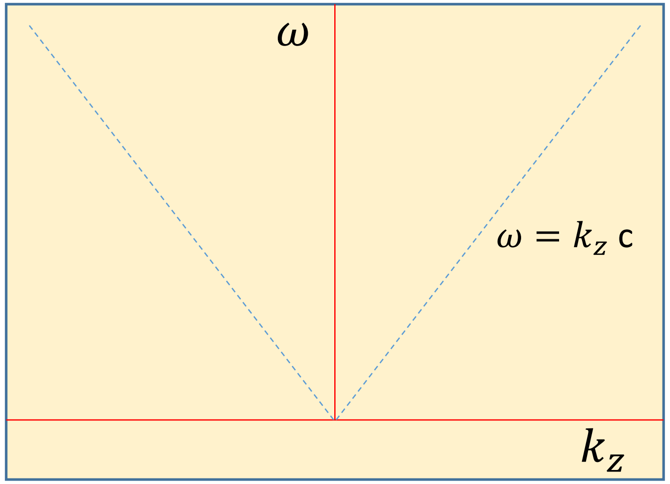


Real wave = wave group

$$v_p = \frac{\omega_1 + \omega_2}{k_1 + k_2}$$

$$v_g = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{d\omega}{dk}$$

v_g is the group velocity



Dispersion curve

In vacuum and free space, v_p = c

1.2: Electromagnetic waves in a tube:

- In a tube: we have modes with $\vec{E}$ // $\vec{k}_z$ (Transverse Magnetic, TM) or $\vec{B}$ // $\vec{k}_z$ (Transverse Electric, TE)

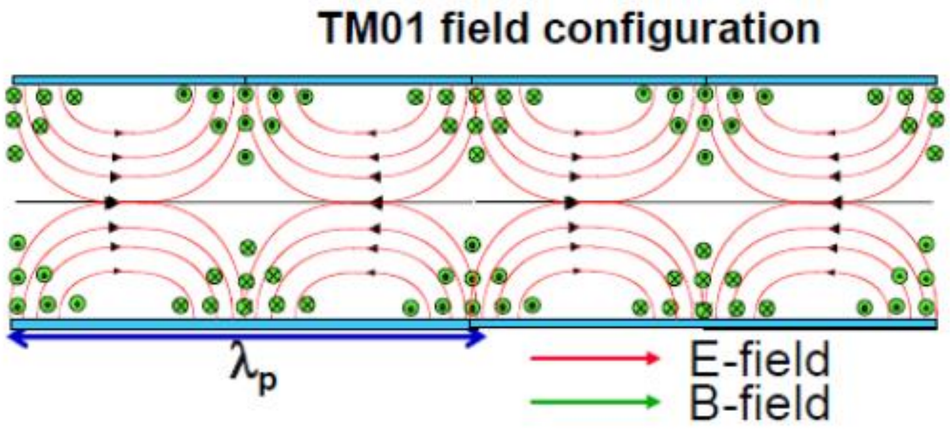
Can be used for the acceleration of the particles (ions)

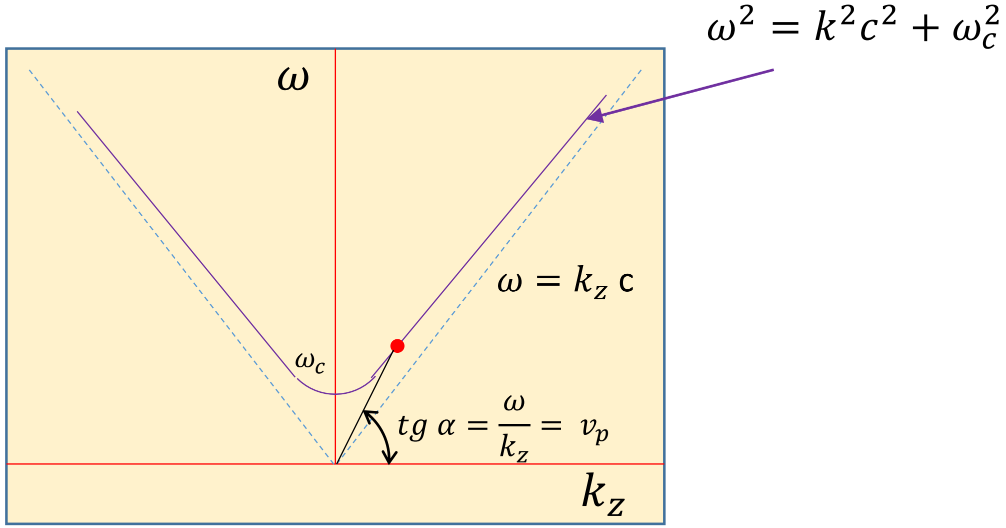
But:

$$v_p = \frac{\omega}{k_z} > c$$

A particle traveling in the tube must be at a speed

$v = v_p > c$ to see a constant accelerating E field !!!





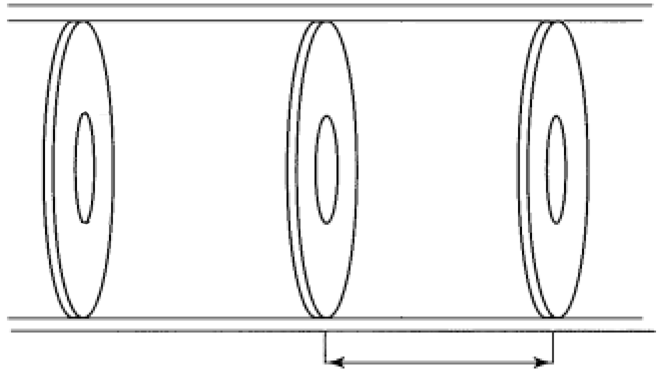
Dispersion curve
For a uniform waveguide
(Infinite tube)

ω_c is a cut−off frequency ($\lambda_c = 2.61a$ *for a cylinder*)

1) RF – RF accelerator – RFQ

1.3: Electromagnetic waves in a periodic structure:

- In a "loaded" cavity: we have modes with $v_{ph} < c$: $\vec{E}$ can be used for the acceleration of ions.

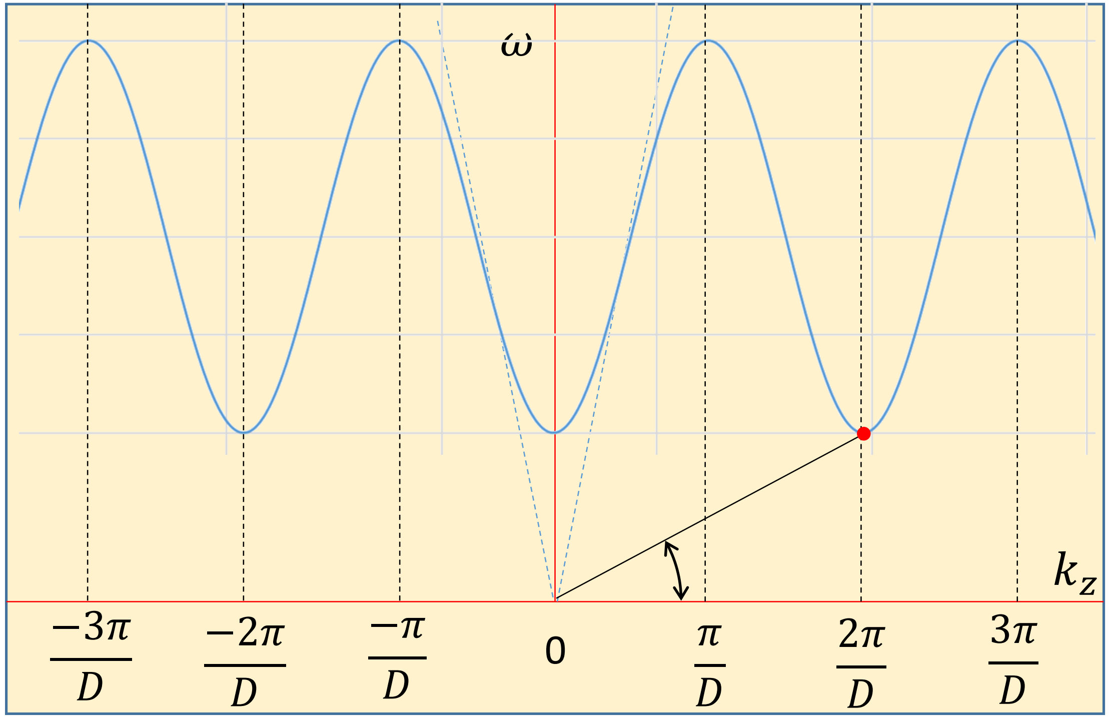


$$For\ k_z = \frac{2\pi}{D} = \frac{\omega}{v_p} = \frac{2\pi f}{v_p}$$

$$with\ \ c = \lambda f$$

$$\frac{2\pi}{D} = \frac{2\pi c}{\lambda v_p}$$

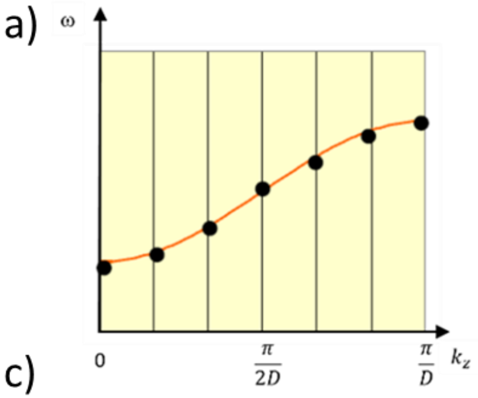
$$D = \frac{\lambda v_p}{c} = \beta\lambda$$

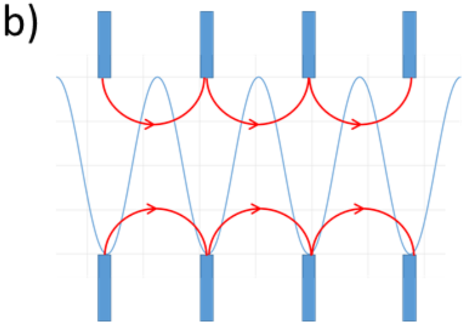


Dispersion curve
For an infinite periodic structure

1.4: Electromagnetic waves in a finite structure:

- In a finite cavity: the longitudinal wave number is restricted to discrete values (modes) required to satisfy the boundary conditions.

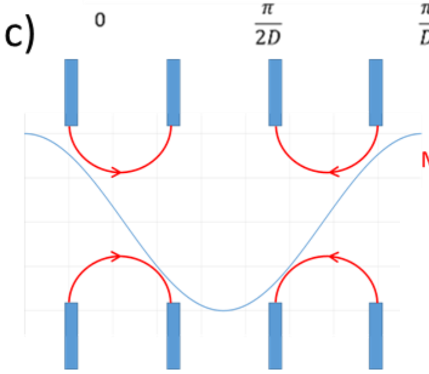




Mode 0:

$$k_z = \frac{2\pi}{D}$$

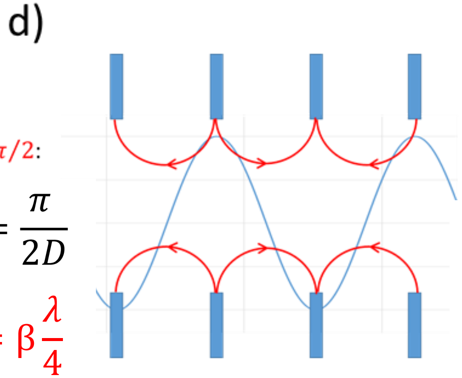
$$D = \beta\lambda$$



Mode $\pi/2$:

$$k_z = \frac{\pi}{2D}$$

$$D = \beta\frac{\lambda}{4}$$

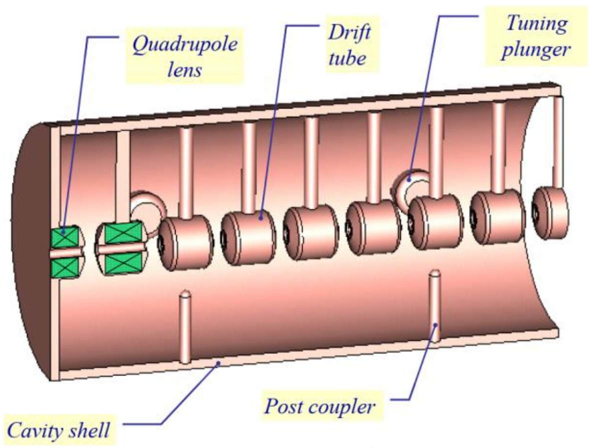


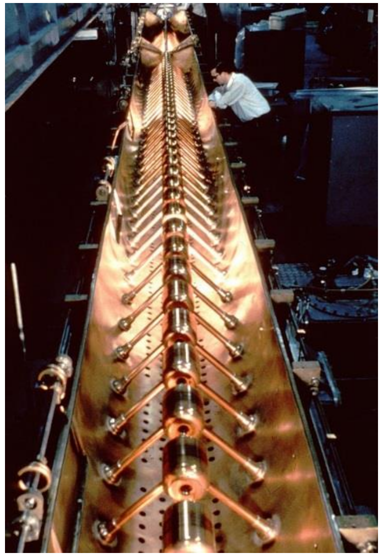
Mode π:

$$k_z = \frac{\pi}{D}$$

$$D = \beta\frac{\lambda}{2}$$

The DTL (Drift Tube Linac) is an example of "Mode 0" TM cavity

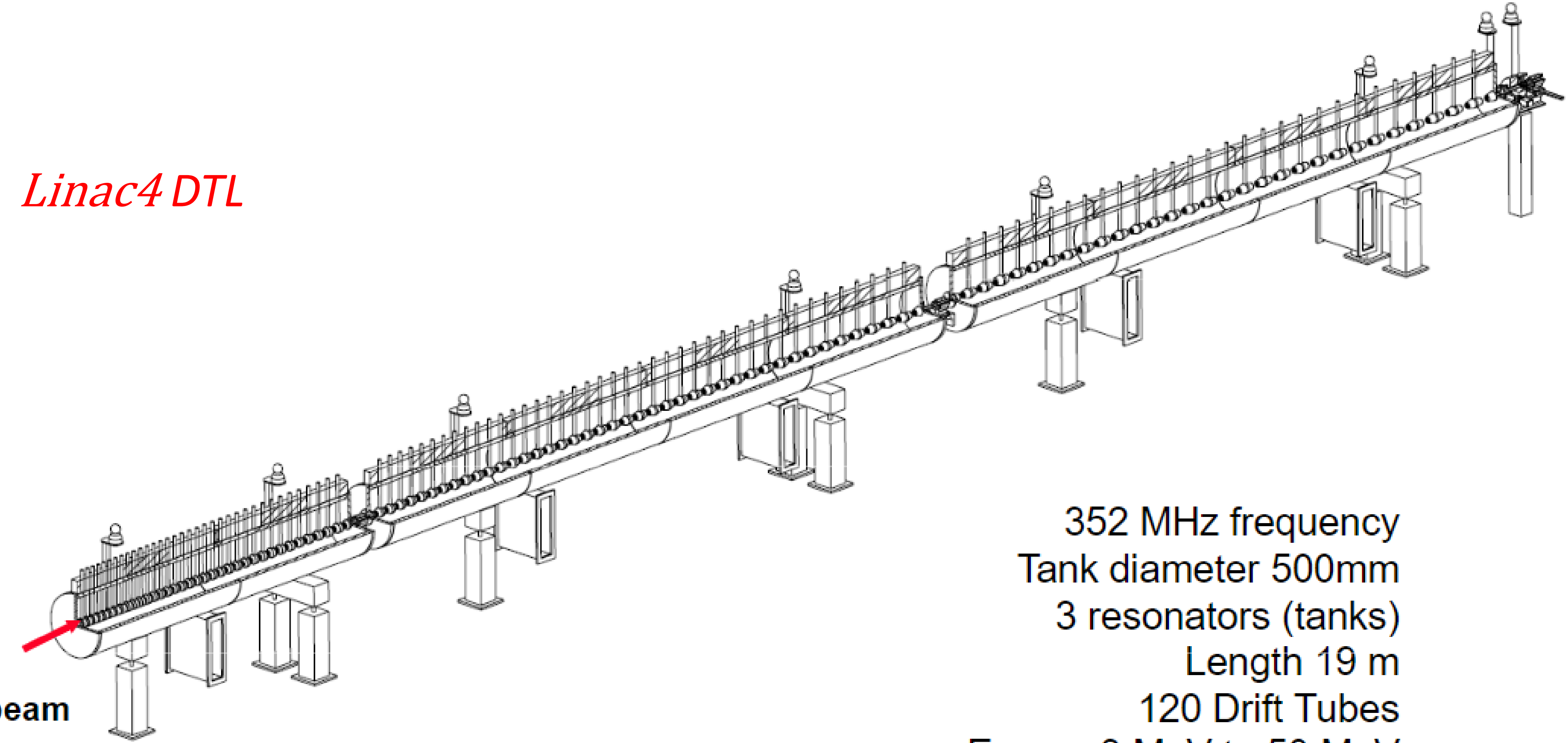




DTL Linac 1
(CERN, 1958)
202 MHz, for protons
up to 50 MeV

Note: In an RF accelerator, the particle beam is bunched!

Linac4 DTL

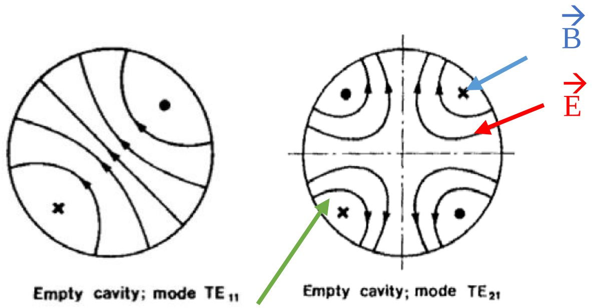


352 MHz frequency
Tank diameter 500mm
3 resonators (tanks)
Length 19 m
120 Drift Tubes
Energy 3 MeV to 50 MeV
Beta 0.08 to 0.31 → cell length ($\beta\lambda$) 68mm to 264mm
→ factor 3.9 increase in cell length

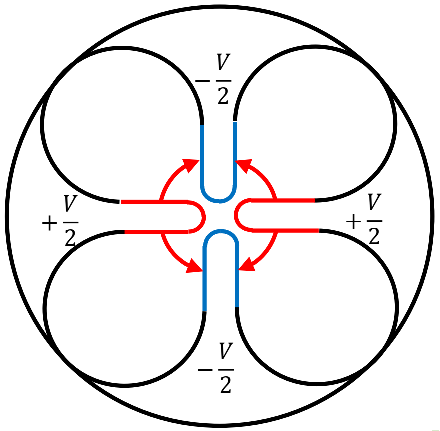
M. Vretenar – CAS 2008

1) RF – RF accelerator – RFQ

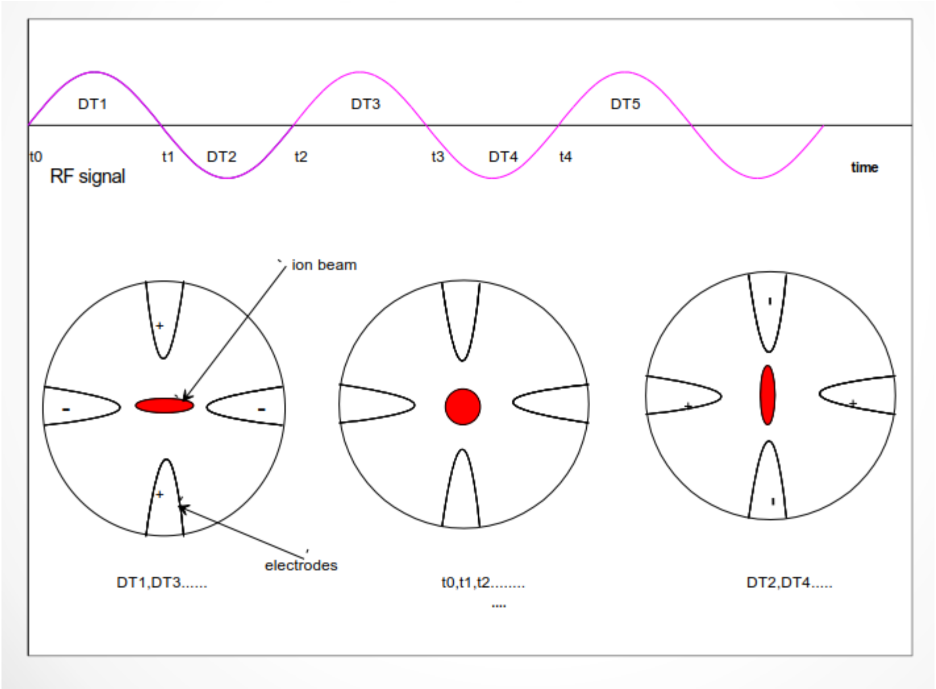
1.5: The use of Transverse Electric Mode (TE)



Quadrupolar mode



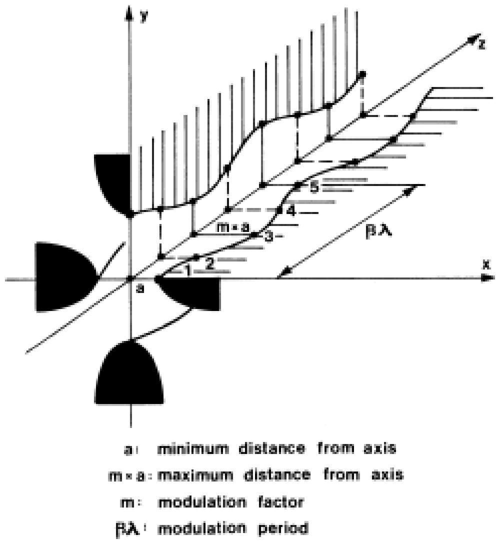
With Electrodes (Vanes)

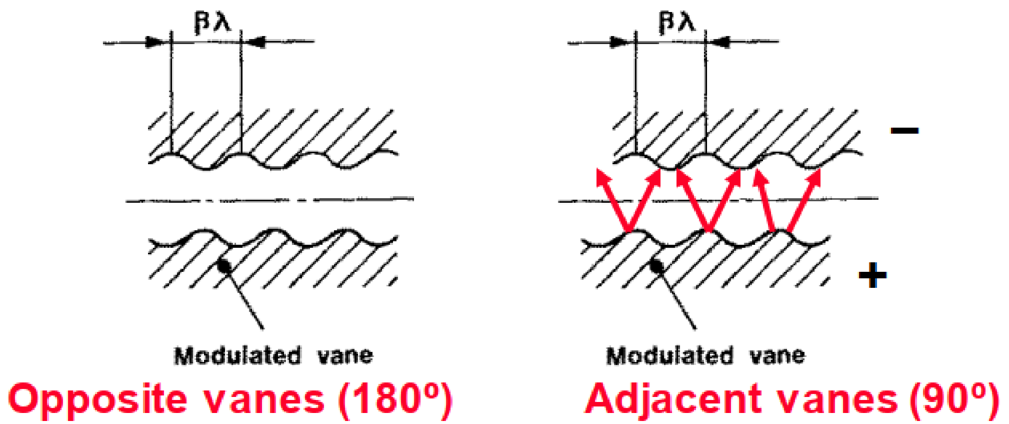


→ RF Field produces alternating gradient focusing (Electric Quadrupole)

1) RF – RF accelerator – RFQ

1.6: Electromagnetic wave in an RFQ (Radio Frequency Quadrupole)





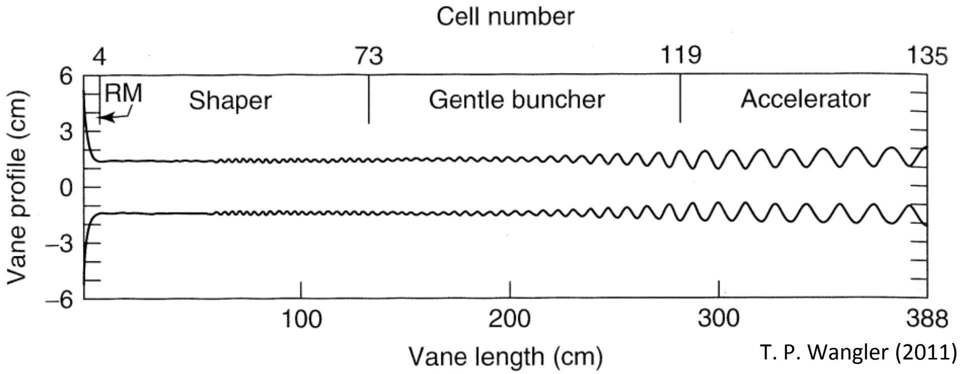
Perturbation (Modulation*) of the Electrodes (Vanes) produces a longitudinal electric field for the acceleration of the ions.

RFQ Performances:

- The RF field allows the Focusing, Bunching and Acceleration

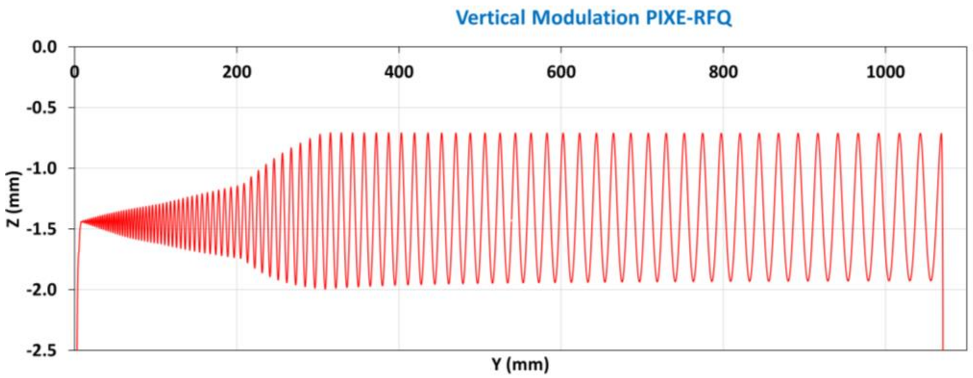
- Is the only linear accelerator accepting a low energy continuous beam

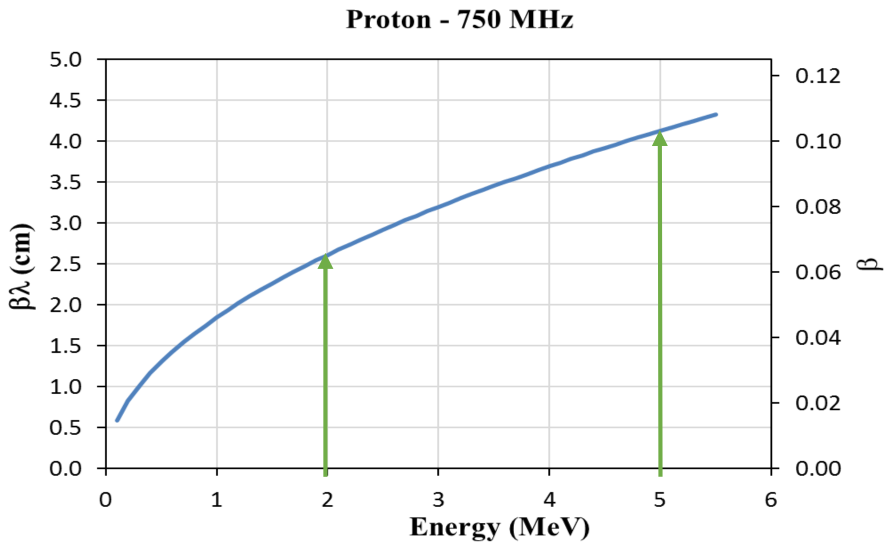
- Acceleration up to 5 - 10 MeV for protons



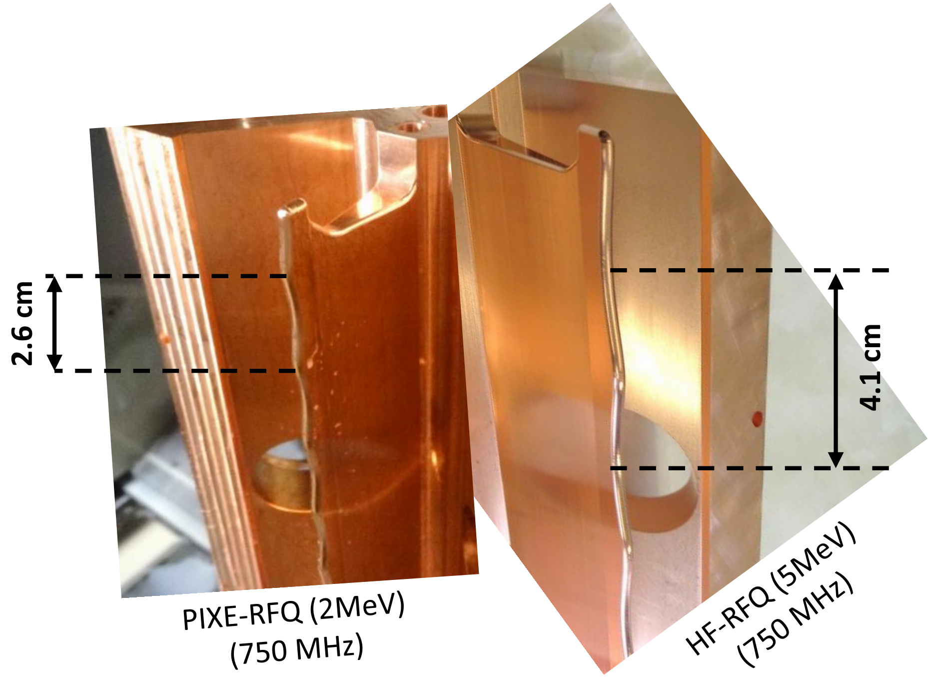
1) RF – RF accelerator – RFQ

1.7: Synchronism between the modulation and the velocity of the particle in an RFQ



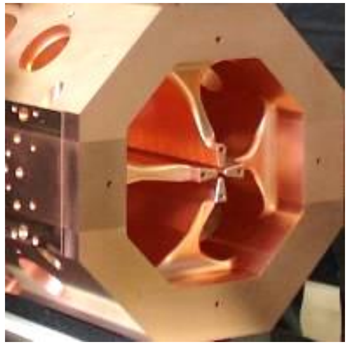


Views of the high energy side of the vane for two RFQ's at same frequency, same ion but different end-energy.

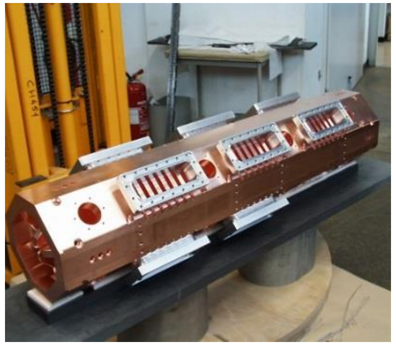


1.8: RFQ gallery

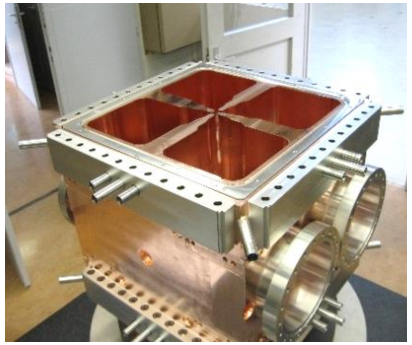
4-Vanes RFQ's: Higher frequency, higher duty cycle (or CW), light ions



IPHI (2005)

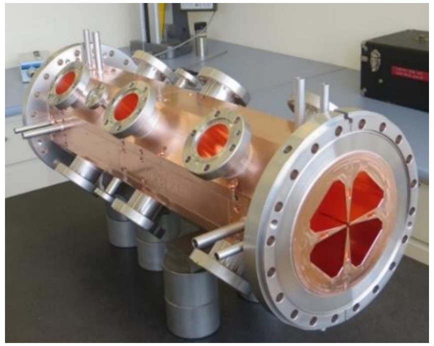


TRASCO (2003)

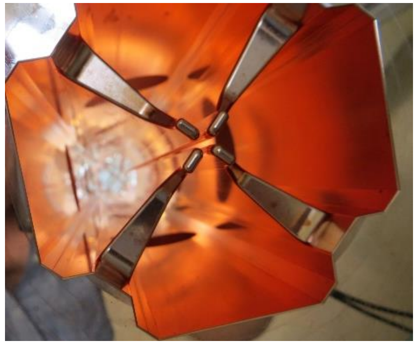


IFMIF (2010)

Linac4 (2010)

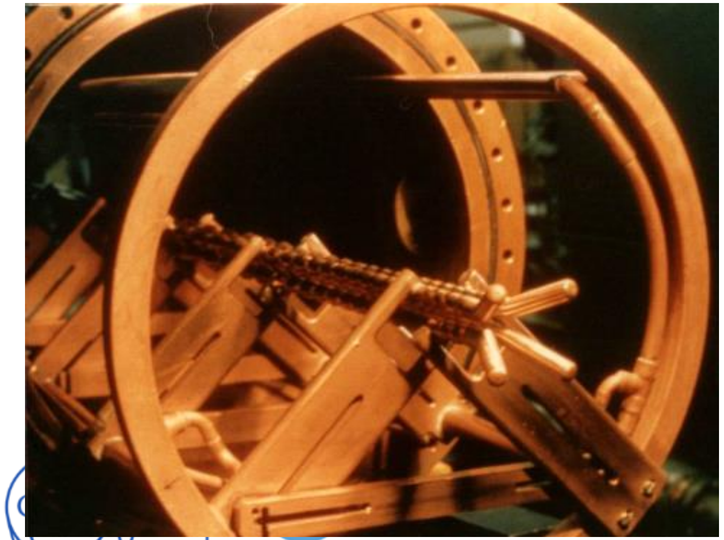


HF-RFQ (2016)



PIXE-RFQ (2019)

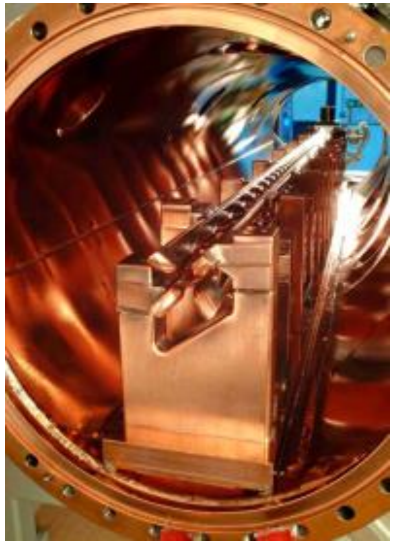
4-Rods RFQ's: lower frequency, lower duty cycle, heavy ions



Frankfurt (1981)

Frankfurt (1988)

INFN, Legnaro (2002)



ISIS (UK) (2004)

2) RFQ Construction (4-Vane)

2.1: Principle

Four vanes: top and bottom major vanes,
left and right minor vanes.

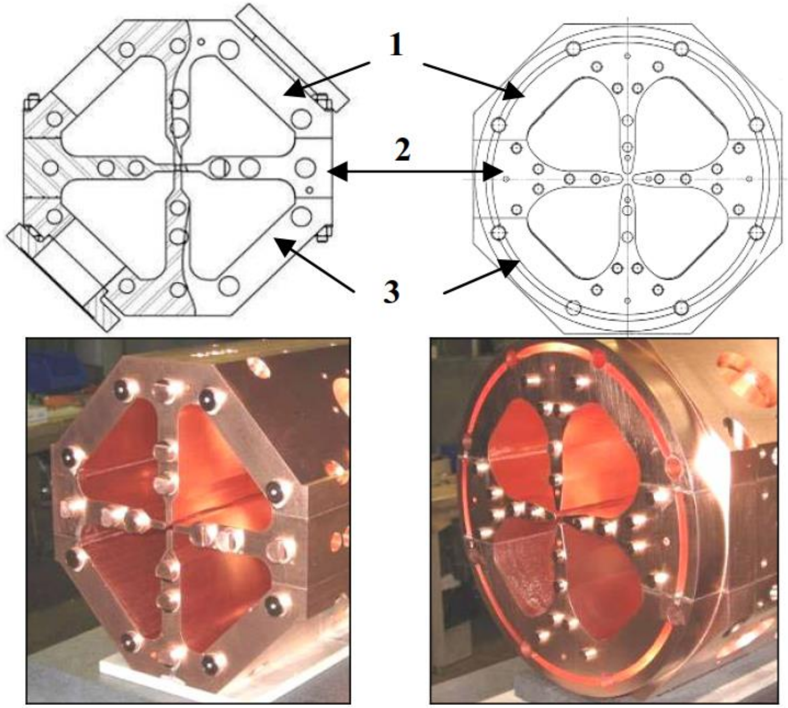
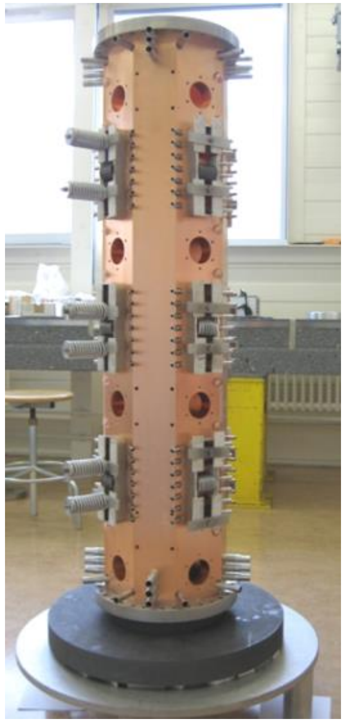


Figure 1: Transverse views of the TRASCO (left) and IPHI RFQ modules. 1 & 3 : major vanes, 2 : minor vanes.

- → Machining of the four vanes
- → Assembly by vacuum brazing
- → Flat surfaces for the brazing planes, between the minors and major vanes
- → Brazing in two steps:
  - Horizontal for the vanes
  - Vertical for the flanges



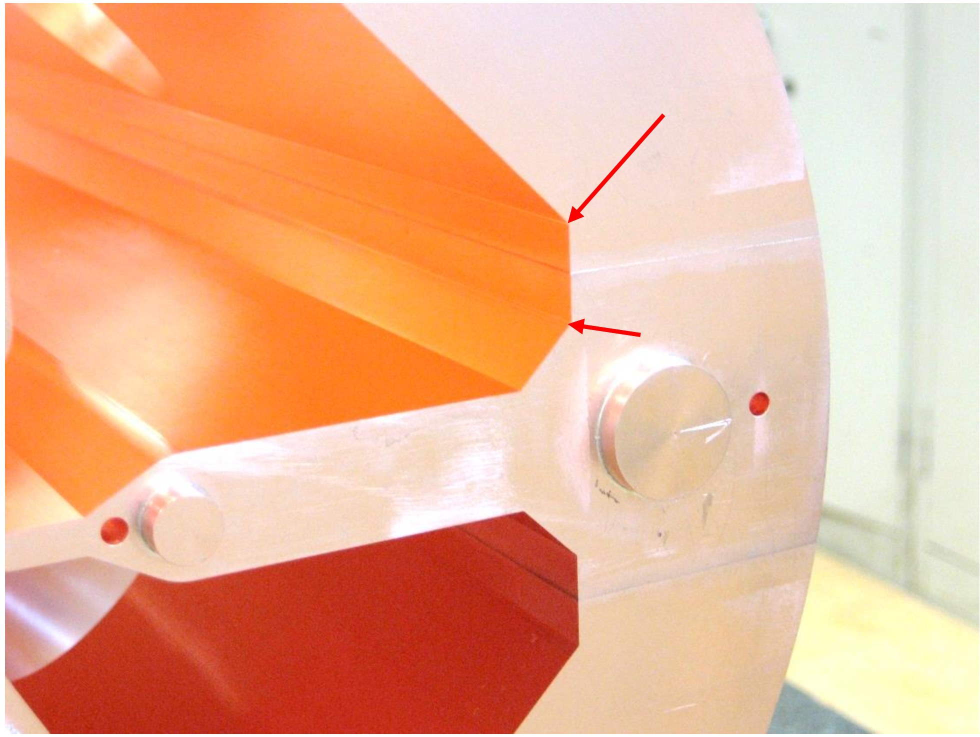
2) RFQ Construction

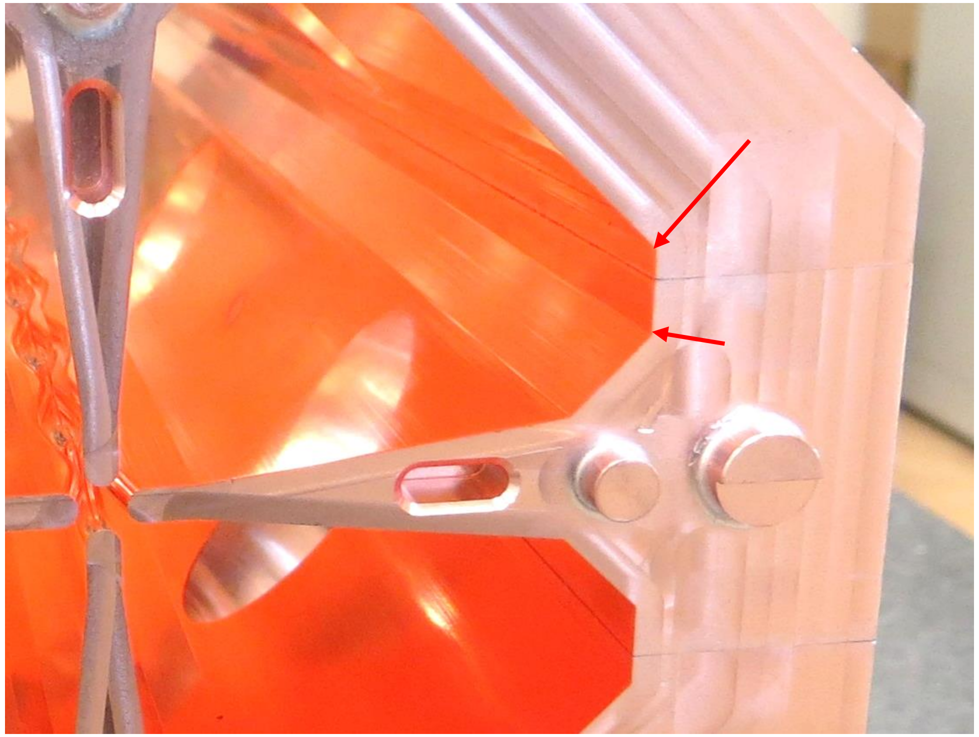
2.1: Principle

Since Linac4 and HF-RFQ:

→ Brazing surfaces "between" edges of the cavity!

→ "2D" machining for the cavity!

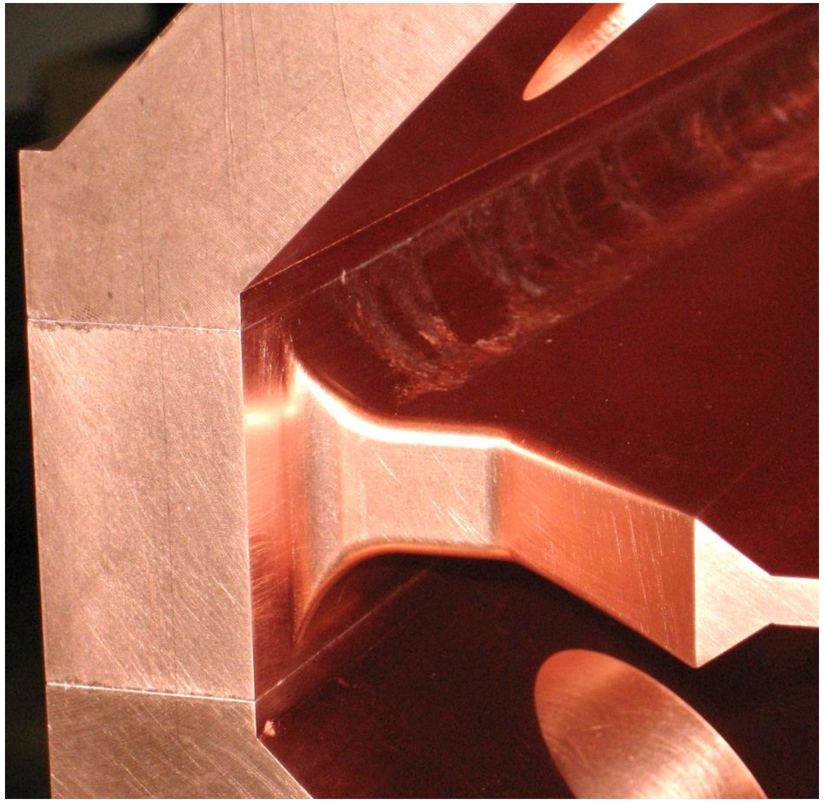


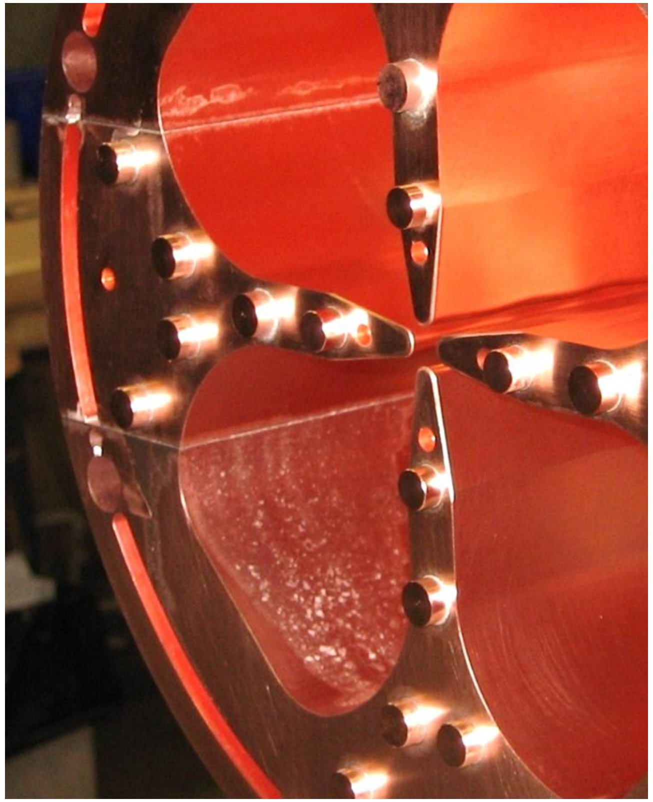


2) RFQ Construction

2.1: Principle

(Without edges)





2) RFQ Construction

2.2: Material

1) Copper:

Cu OFE Dia. 150 mm, multi-way forged + hammer hardened – SCEM 44.09.47.610.0

2) Stainless Steel:

Forged blanks – 1.4429 (316LN) – UHV applications - SCEM 18.60.19.202.6

Technical Specification

N° 2001 - Ed. 8
EDMS No: 790779

Oxygen-Free Electronic copper
Bars/blanks/ingots

Cu-OFE

This document specifies the CERN technical requirements for Cu-OFE bars/blanks/ingots, equivalent to UNS C10100 Grade 1, according to ASTM B224 with a maximum oxygen content of 5 ppm.

Technical Specification

N° 1001 - Ed. 5
EDMS N°: 790775

Stainless steel forged blanks
for ultra-high vacuum applications

1.4429

X2CrNiMoN17-13-3

AISI 316LN

This document specifies the CERN technical requirements for 1.4429 (X2CrNiMoN17-13-3, AISI 316LN) stainless steel blanks for ultra-high vacuum applications (UHV) at CERN requiring vacuum firing at 950°C.

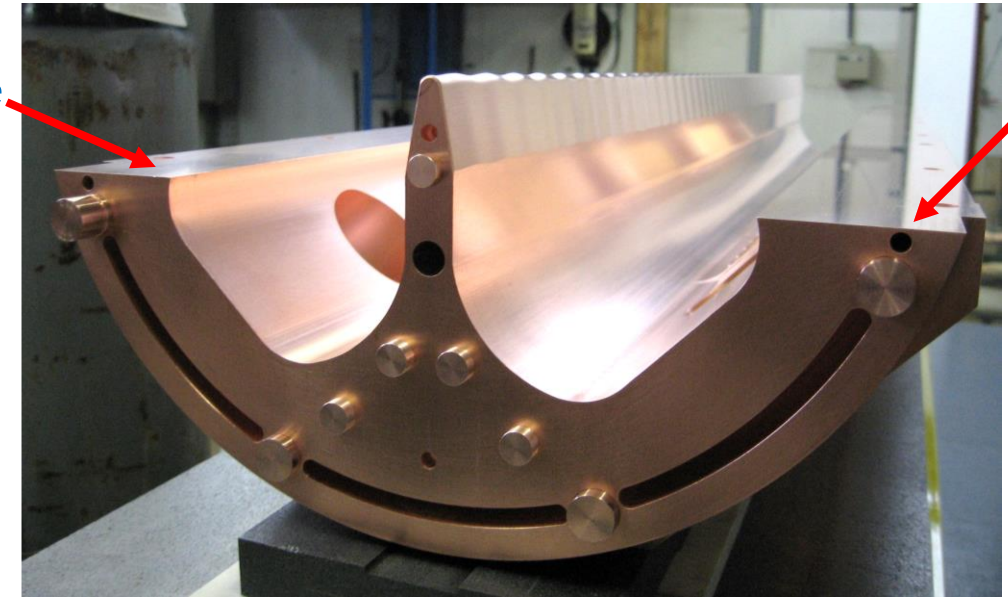
2.3: Procedure

The machining procedure is governed by the presence of a high temperature thermal cycle for the brazing.
The thermal cycle releases the internal stresses of the material and thus the presence of internal stresses leads to deformation.
The machining itself produces internal stresses.

→ One stabilization before machining is not sufficient.
→ It is necessary to alternate machining and heat treatments.

Demonstration with a major vane:
(IPHI project - 2007)

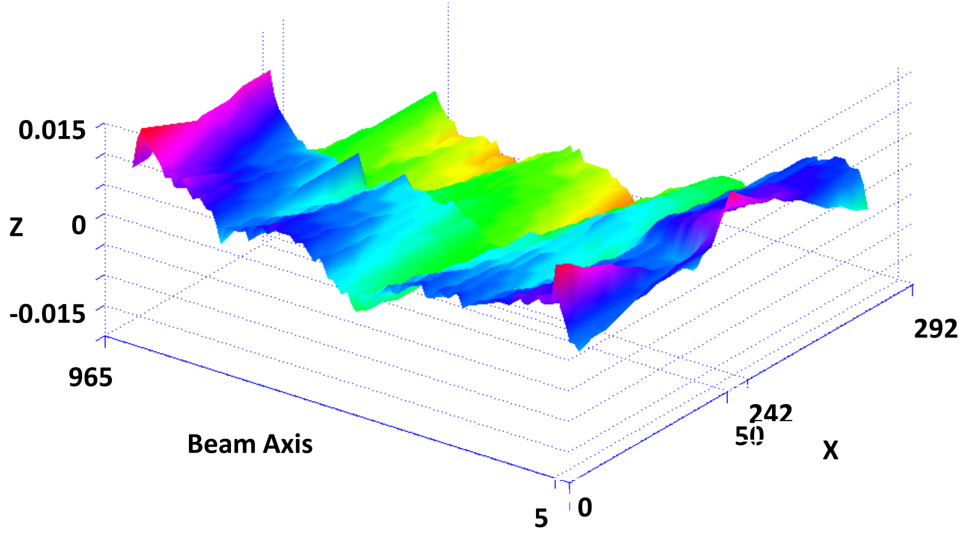
Brazing plane



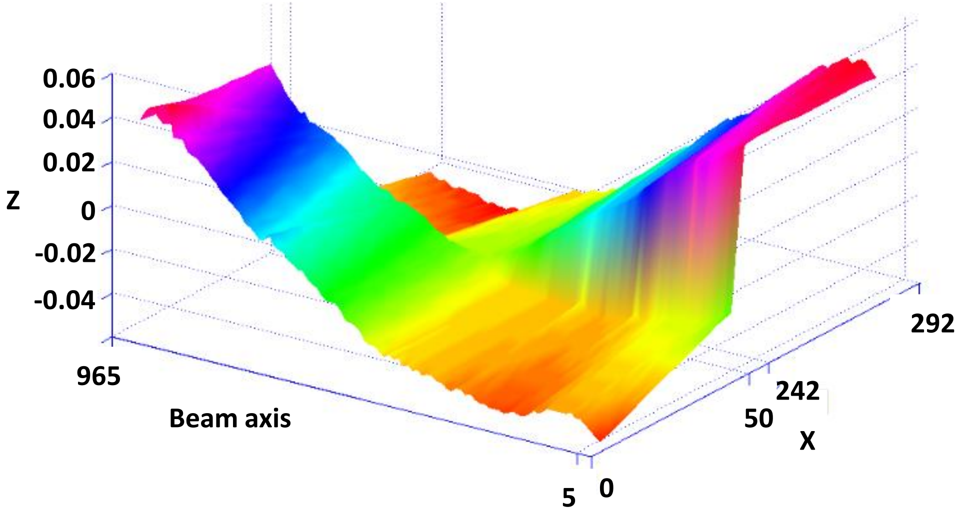
Brazing plane

2) RFQ Construction

2.3: Procedure



Geometry of the brazing planes after machining.
Dimensions are in mm. The flatness is better than 10 µm over one meter.
(Note: This major vane has been rough machined and heat treated at 600 °C before final machining)

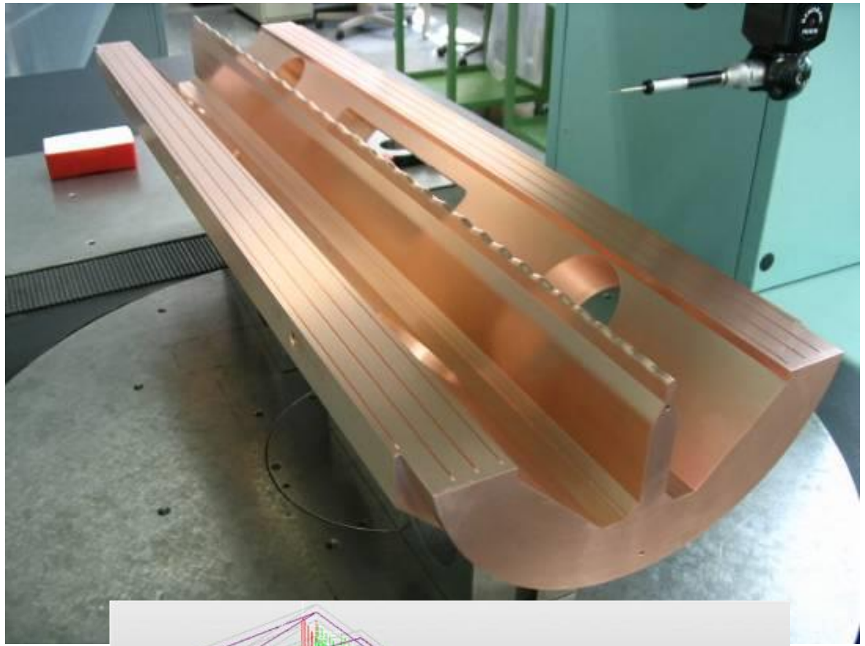


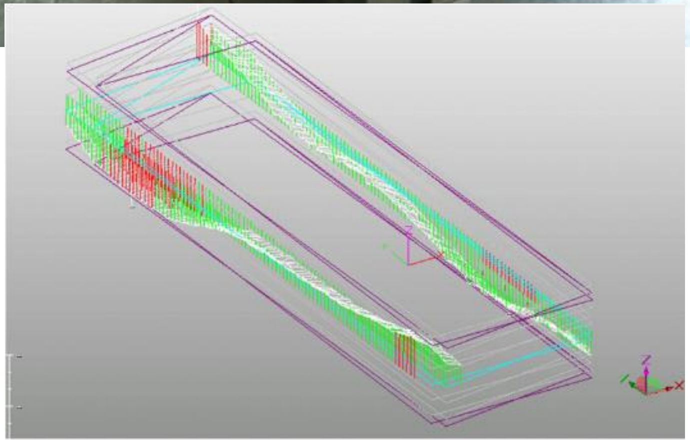
Geometry after a heat treatment at 800 °C.
The deformation is more than 80 µm, not acceptable for vacuum brazing! (≈ 20 µm)

2) RFQ Construction

2.3: Procedure

Additional tests of a LINAC4 major vane:





Ecart de planeite = 0.028

Flatness measured for the brazing surface :

After final machining:	**28 µm**
After first heat treatment at 800 °C :	65 µm
After second heat treatment at 800 °C :	60 µm
After re-machining of the brazing planes :	15 µm
After a new treatment at 800 °C :	28 µm

A stabilisation even at 600 °C is not sufficient before the final machining of the piece.

The last stabilisation should be at the brazing temperature (800 °C) and the following finishing machining should be as limited as possible to avoid the creation of residual stress.

2) RFQ Construction

2.3: Procedure

PIXE-RFQ – Manufacturing procedure
rev 1 – July 12, 2017

1. Machining of the raw material – Copper rods.
1.1 L = L_f + several cm.
1.2 Over thickness: 1 mm on all external surfaces.
1.3 Wire cut of the rod.

2 Pre-rough machining; Over thickness >3 mm on all internal surfaces.
2.1 Vane length unchanged, L = L_f + several cm.
2.2 Pre-rough machining.
2.3 Drilling of the cooling channels.
2.4 Degreasing and 1° heat treatment (600°C).

3 Rough machining; Over thickness 1 mm on all surfaces.
3.1 Vane length adjustment : L = L_f + 2 mm (1mm per side)
3.2 Rough machining of the internal and external profiles, pumping and RF ports, input and output coupling cells; over thickness 1 mm.
3.3 Rough machining of the modulation profile, with a cylindrical cutter.
3.4 Rough machining of the reference surfaces for metrology.
3.5 Degreasing and 2° heat treatment (600°C).

4 Pre-finishing; Over thickness of 0.15 mm for the modulation profiles and brazing surfaces.
4.1 Machining of the inlet and outlet sides, L = L_f + 1.5 mm (0.75 mm per side).
4.2 Finishing for the external and internal surfaces, opening for the pumping and RF port.
4.3 Finishing of the 7° slopes.
4.4 Finishing of the metrology reference surfaces.
4.5 Finishing for the water plugs.
4.6 Finishing of the brazing grooves but with a depth of 1.3 mm.
4.7 Pre-finishing of the input and output coupling cells, over thickness 0.15 mm.
4.8 Pre-finishing for the CF 40/CF 16 flange boring holes and water tubes, over thickness 0.5 mm.
4.9 Pre-finishing for the brazing surfaces, over thickness 0.15 mm.
4.10 Pre-finishing for the modulation profile using a shape tool, over thickness 0.15 mm.
4.11 Pre-finishing of the straight part of the modulation (z>-8), over thickness 0.15 mm.
4.12 Degreasing and 3° heat treatment (800°C).
4.13 1° 3-D vane metrology.

5 Finishing; except input and output faces and bore holes for the flanges.
5.1 For all vanes, machining on a same plane the three reference surface at the back side.
5.2 The vane length is **NOT** machined now, L = L_f + 1.5 mm (0.75 mm per side).
5.3 Finishing of the major vanes.
5.4 Metrology of the major vanes, measure of the optimum beam axis, measure of references point on the internal and external surfaces.
5.5 Finishing of the modulation and coupling cells for the minor vanes.
5.6 Metrology of the minor vanes, measure of the optimum beam axis.
5.7 Finishing for the brazing surfaces for the ninor vanes.

6 Assembly before first brazing.
6.1 Four vanes assembly using the external reference points, blocking in position.
6.2 Machining of common side reference surfaces.
6.3 Machining of the input and output sides, L = L_f + 1 mm (0.5 mm per side).
6.4 Metrology of the vane positions.
6.5 Vanes disassembly and chemical etching.

7 First brazing.
7.1 First brazing in horizontal position.
7.2 Vanes and water plugs brazing.

8 Machining after first brazing (alcohol lubrication).
8.1 First metrology of the module.
8.2 Machining of the input and output faces, L = L_f + 0.70 mm (0.35 mm per side).
8.3 Finishing for the CF 40/CF16 flange and water tubes boring holes.
8.4 Finishing for the diameters and depths for the input and output flanges (CF 150).
8.5 Machining of the flanges
8.6 Surface treatment of the flanges.

9 Second brazing
9.1 Degreasing with alcohol and acetone, heat treatment at 700 °C.
9.2 Brazing in vertical position for the flanges and cooling pipes.
9.3 Vacuum test.
9.4 Second metrology of the module, determination of the over thickness on the inlet and outlet faces, optimum module beam axis and external reference surfaces for final machining of the inlet and outlet flanges.

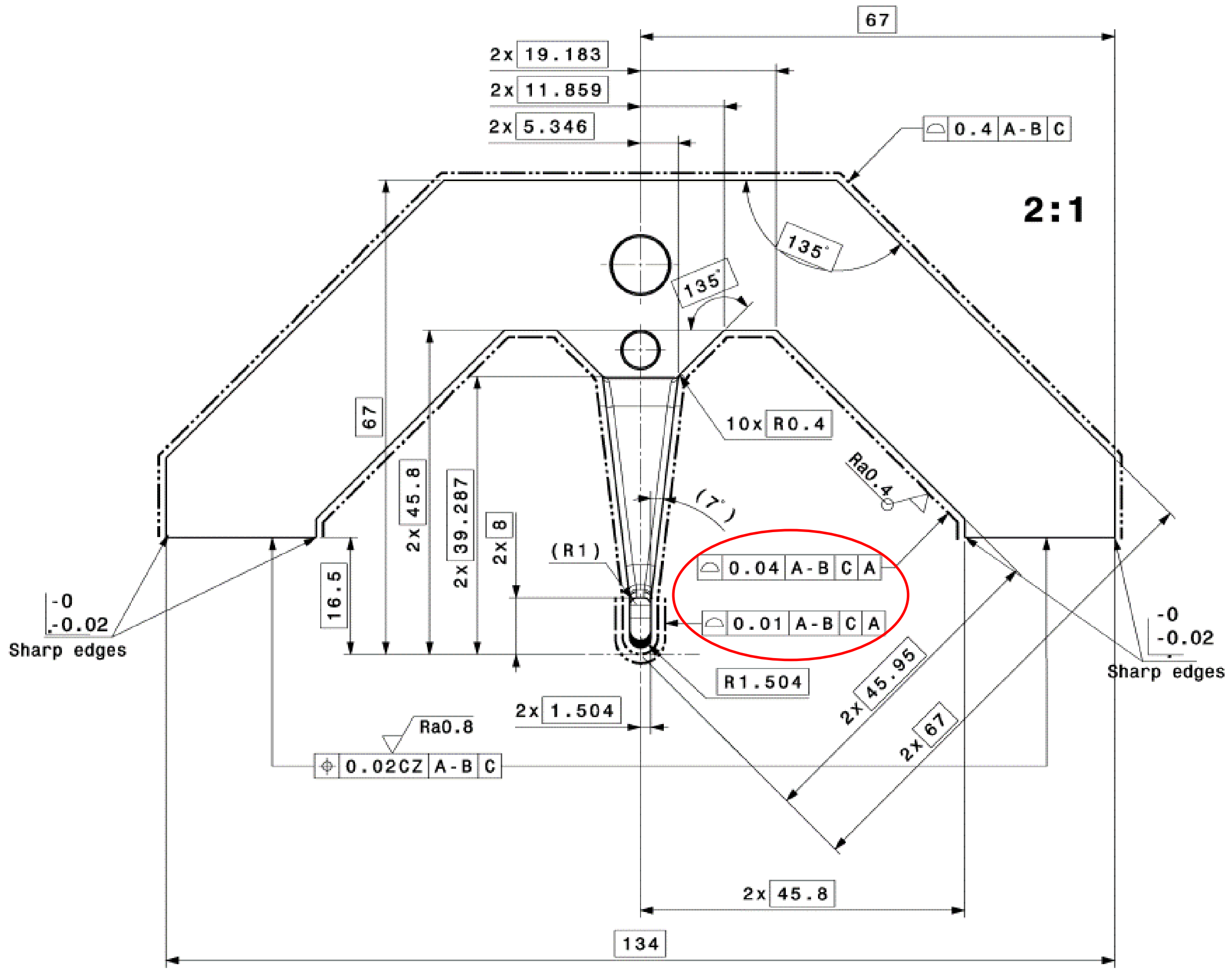
10 Reprise finale
10.1 Machining with alcohol lubrication and dust protections.
10.2 Finishing of the inlet and outlet sides, L = L_f.
10.3 Machining of the CF 150 flange contact surface, over thickness for the 0.1 mm gap, diameter for the centring ring, groove for the rotation pin and flange flat surfaces.
10.4 3° and final module metrology.
10.5 RF measure of the module.

11 RFQ assembly
11.1 Machining of the centring rings and pins.
11.2 Assembly, also with coupling flanges.
11.3 Vacuum test.
11.4 RF measure of the RFQ.

2) RFQ Construction

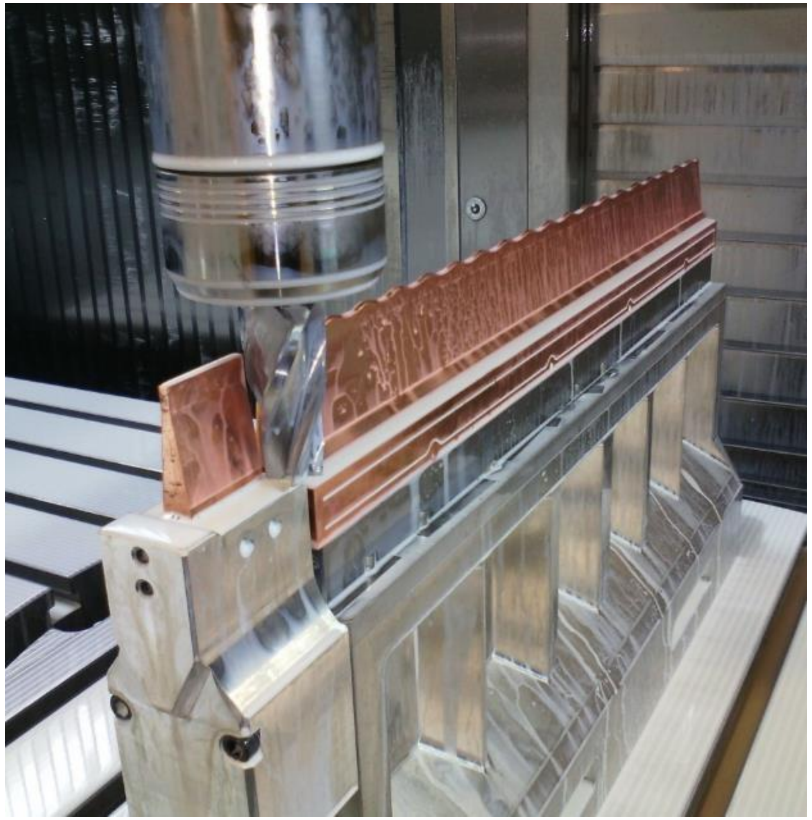
2.4: Tolerances

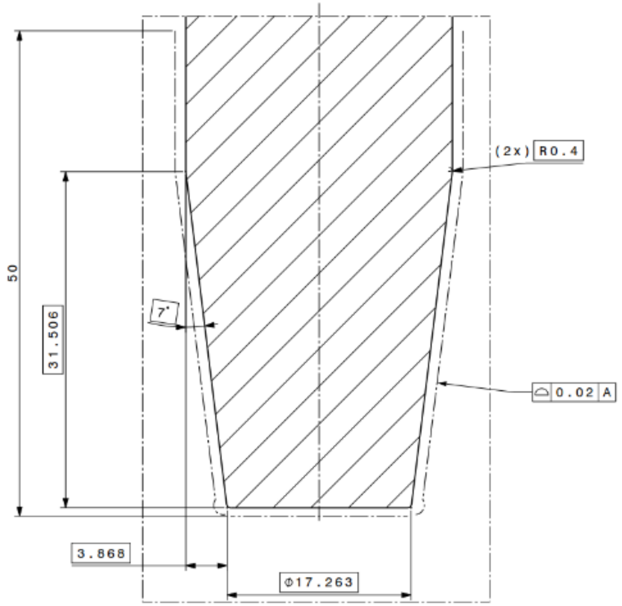
	HF-RFQ 750 MHz	Linac4 RFQ 350 MHz
Vane shape	± 5 µm	± 10 µm
Vane relative position	± 15 µm	± 30 µm
Cavity shape	± 20 µm	± 20 µm
Displacement max (X-Y)	± 50 µm	± 25 µm
Displacement max. (Z)	± 50 µm	± 20 µm
Gap between modules	± 10 µm	± 15 µm

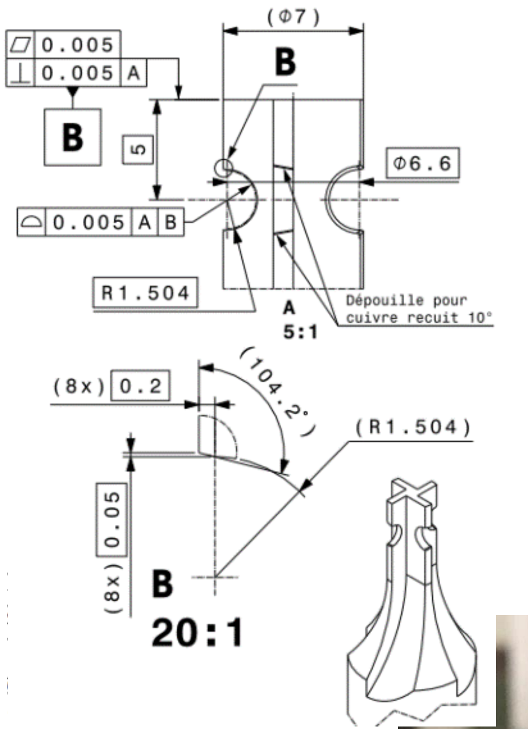


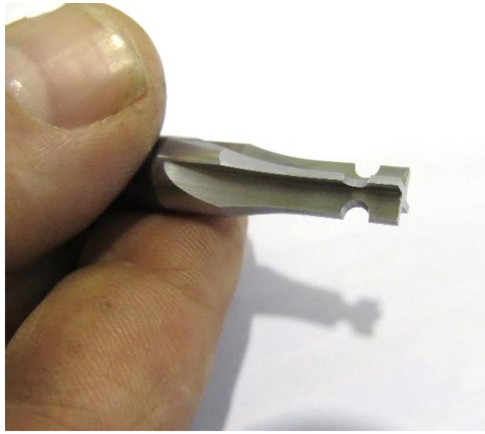
2) RFQ Construction

2.5: Toolings







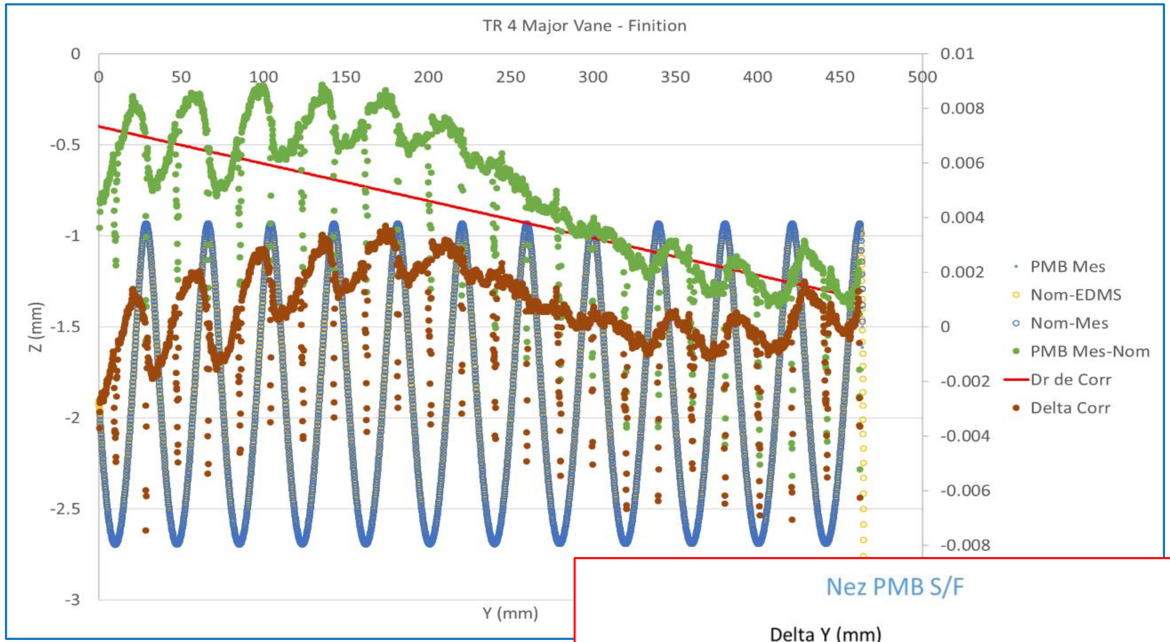


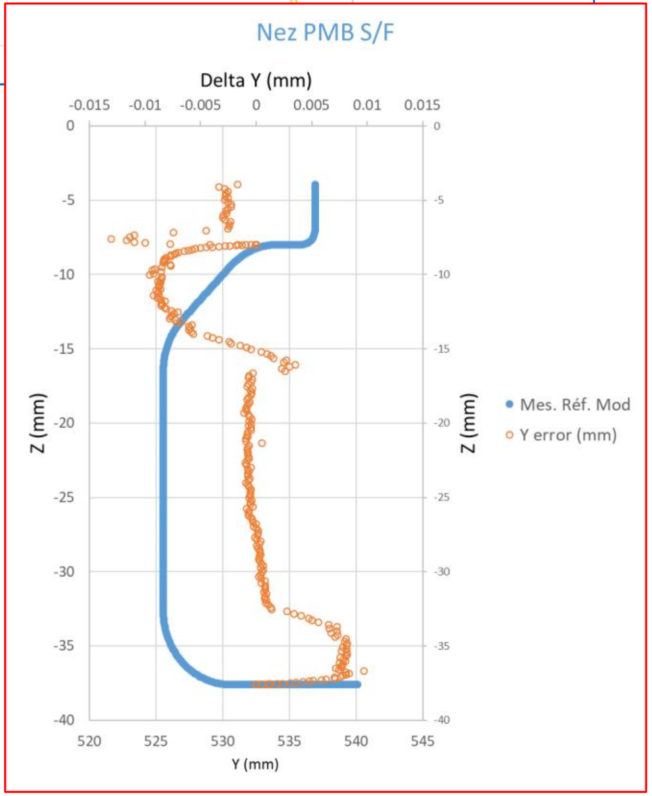
Diamond tool

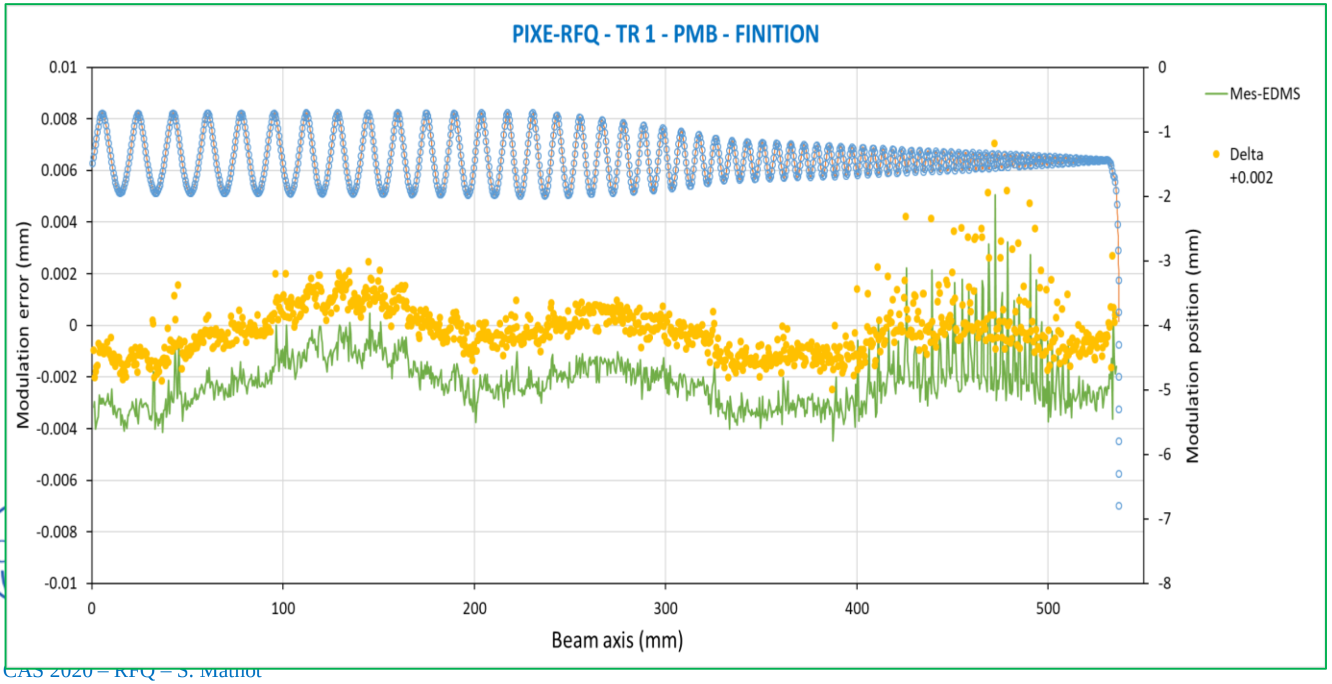
2) RFQ Construction

2.6: Metrology

Metrology of the vane modulation is used to determine the “optimum beam axis” of the vane, where the errors for the modulation are minimum.
All other points of the vane are measured relative to this beam axis.

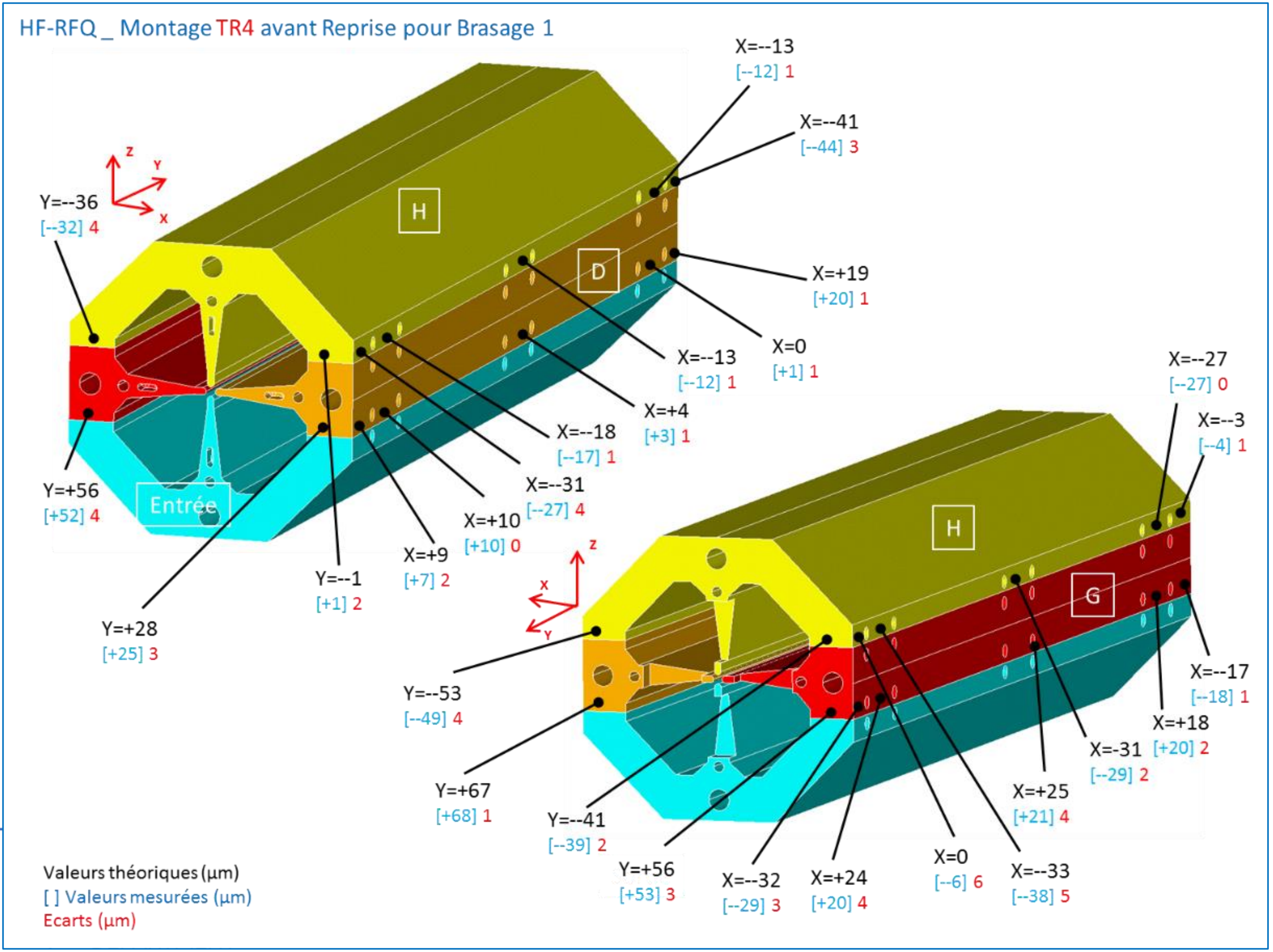






2) RFQ Construction

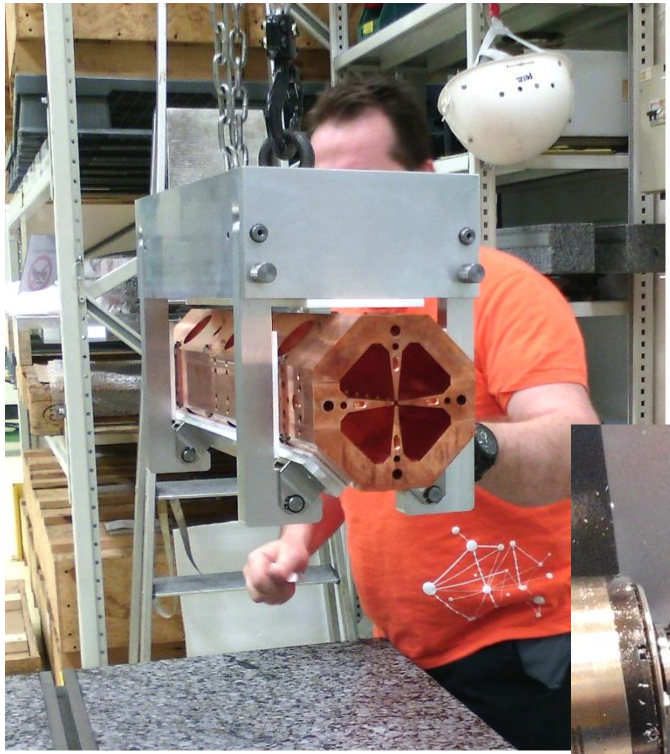
2.7: Module alignment before brazing

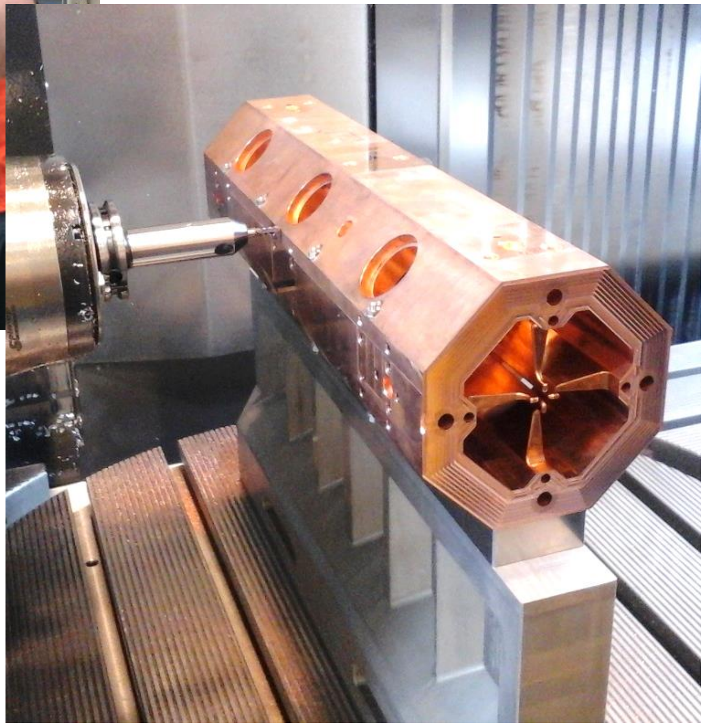


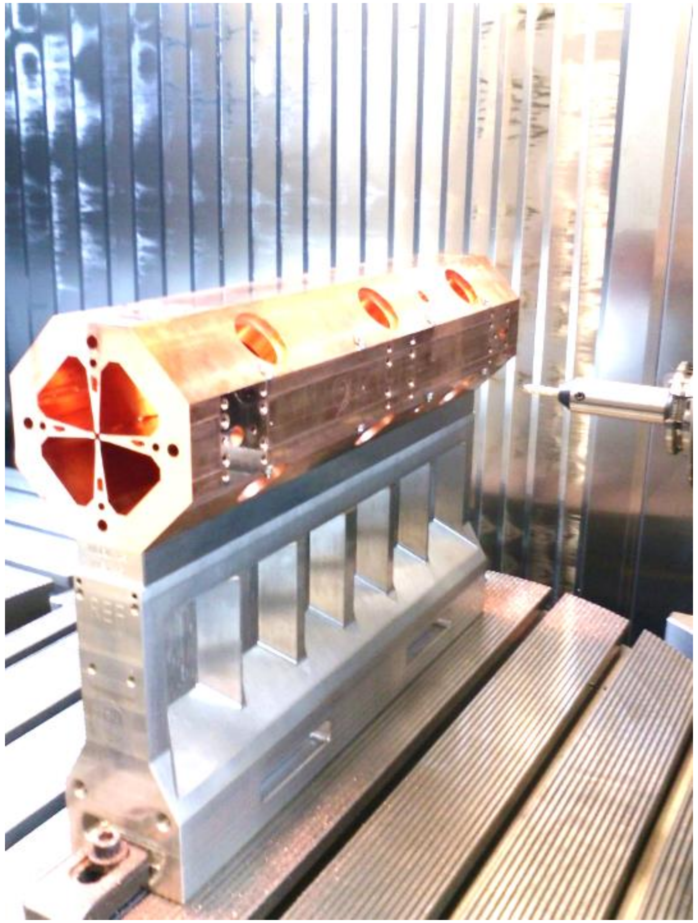
- Reference points measured outside the cavity on the vanes after finishing are used to align the module.
- The optimized beam axis for each vane must be on a same line!

2) RFQ Construction

2.8: Module machining before the first brazing



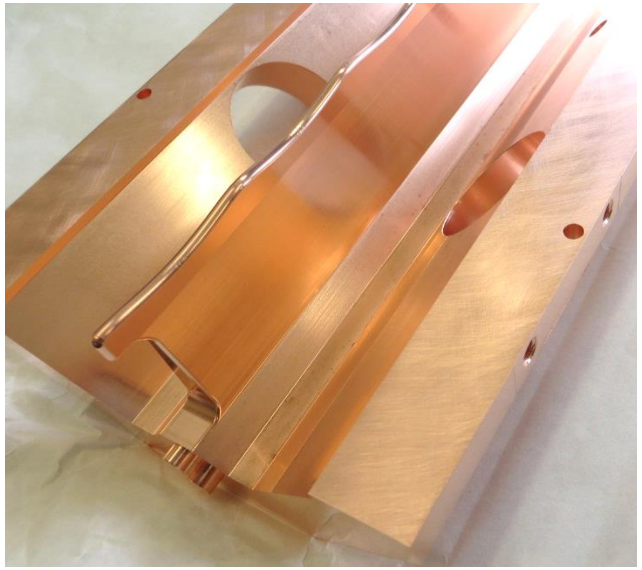


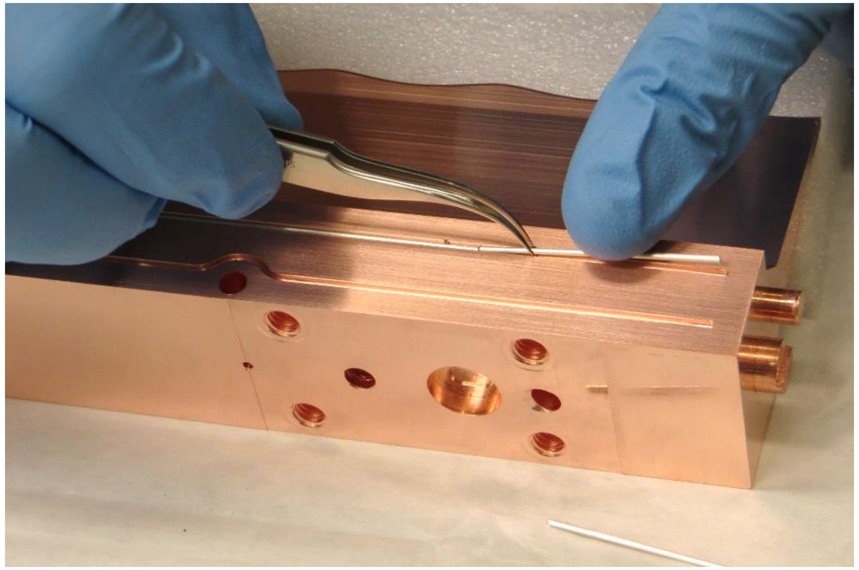


2) RFQ Construction

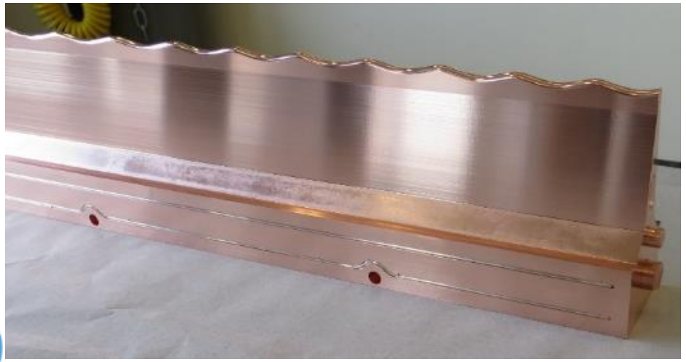
2.9: First brazing

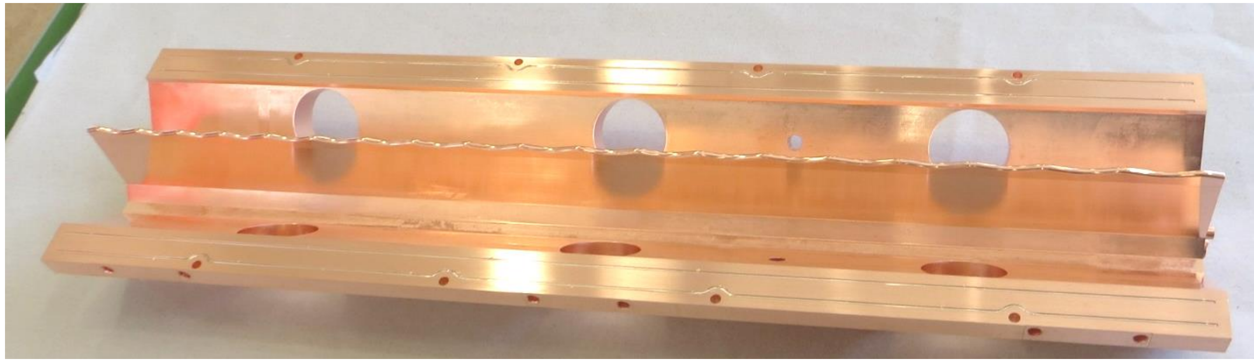
Copper surface treatment: Chemical etching – Cr passivation
Brazing surface preparation
Brazing alloy: Pd5Ag68.5Cu26.5 (PD1V following BS 1845; PD106 following EN 1044), solidus 807°C, liquidus 810°C





(Grooves on one side for the minor vanes and on the brazing surface of the top major vane)

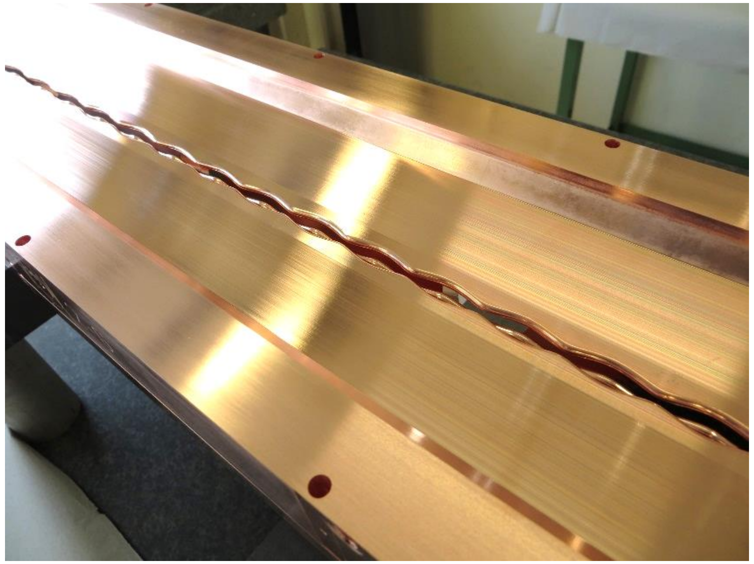


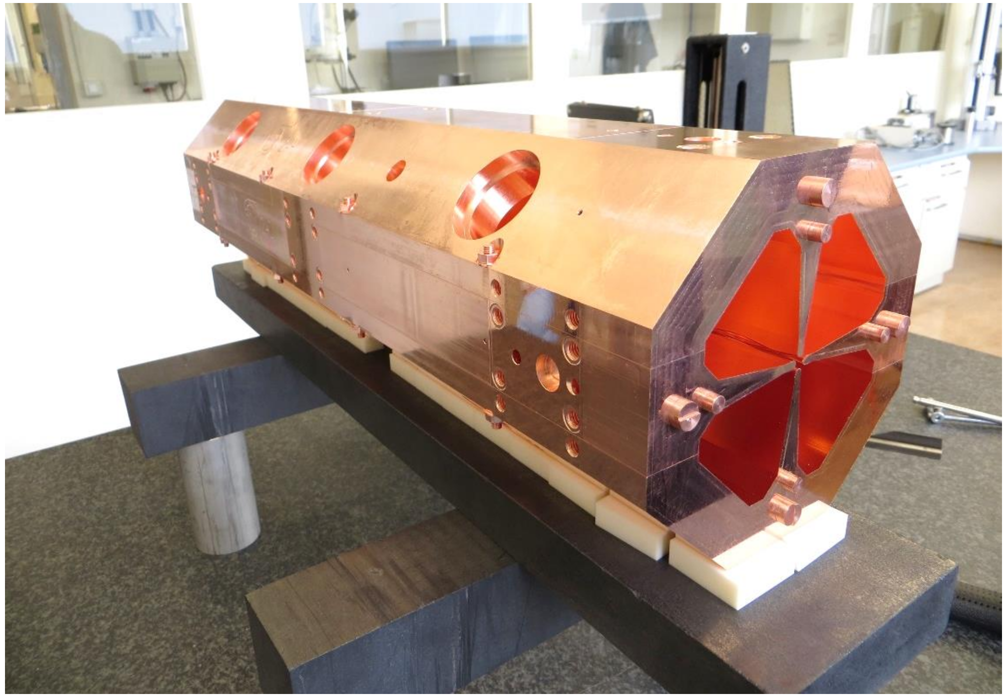


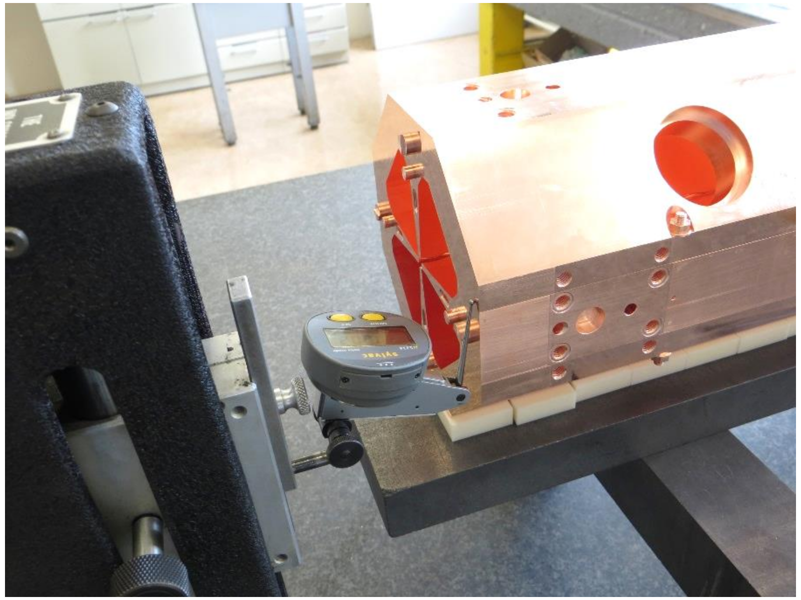
2) RFQ Construction

2.9: First brazing

Assembly and alignment:

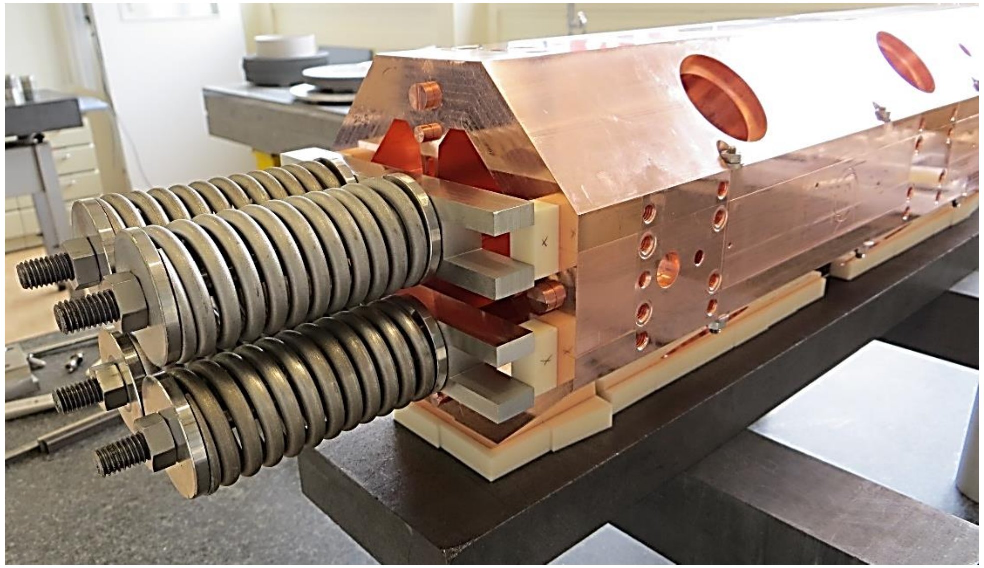


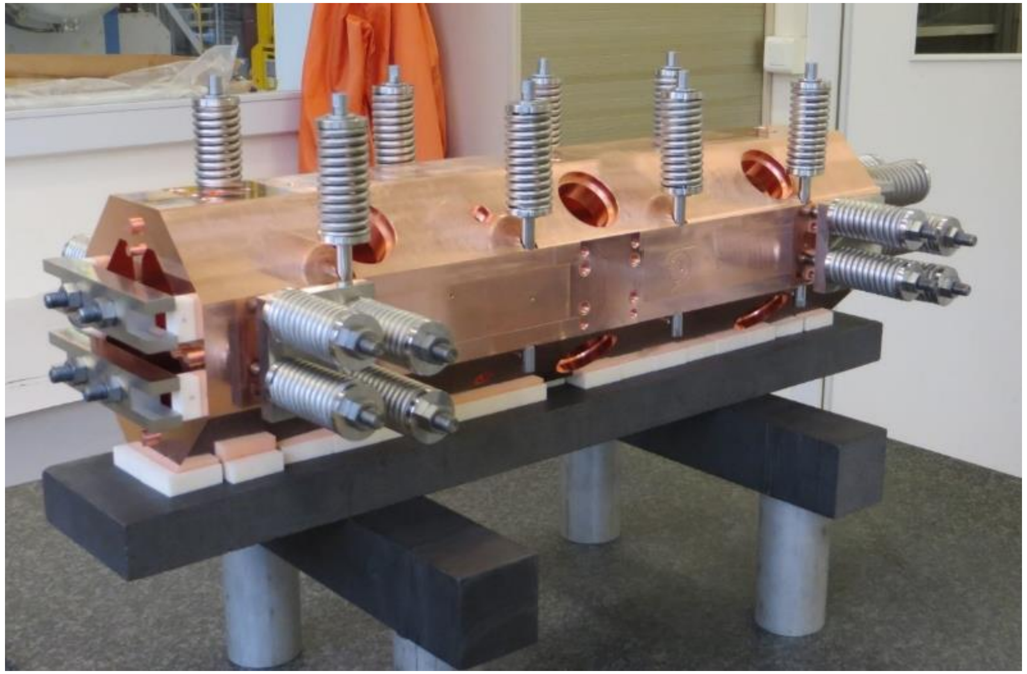




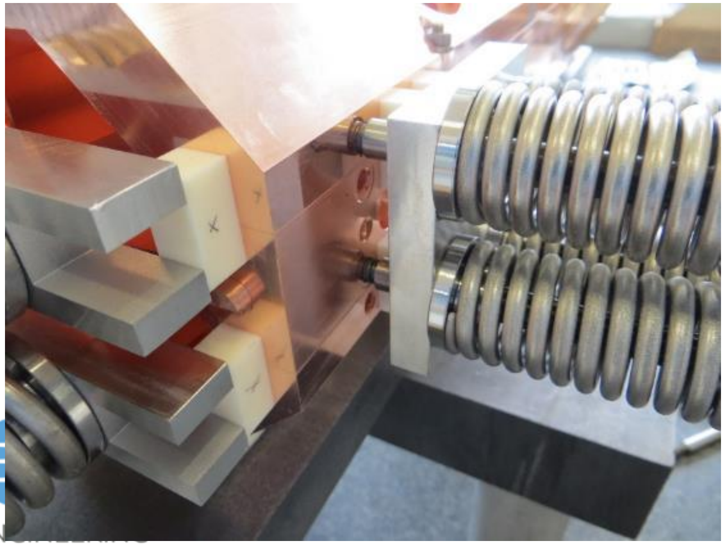
2) RFQ Construction

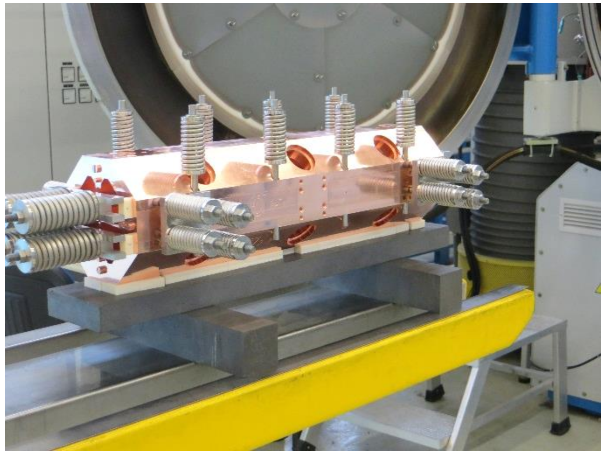
2.9: First brazing





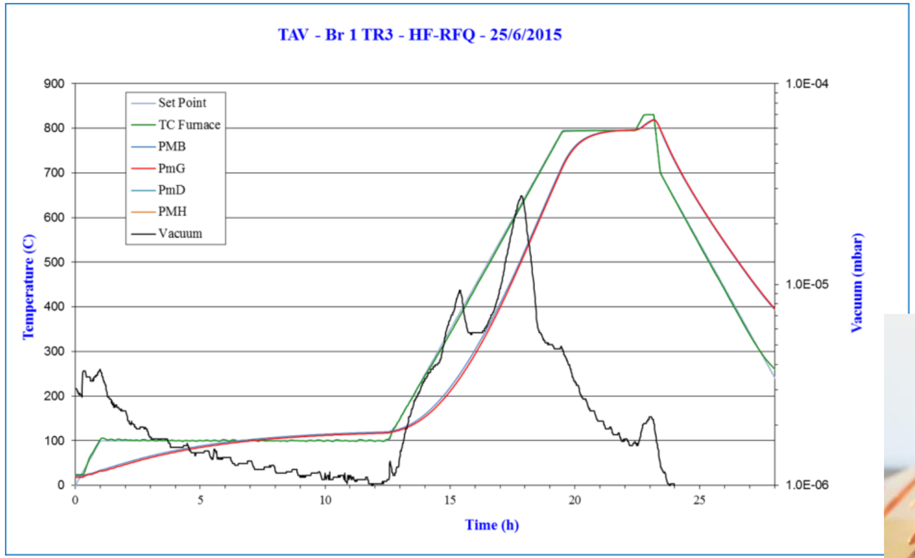
Brazing fixtures

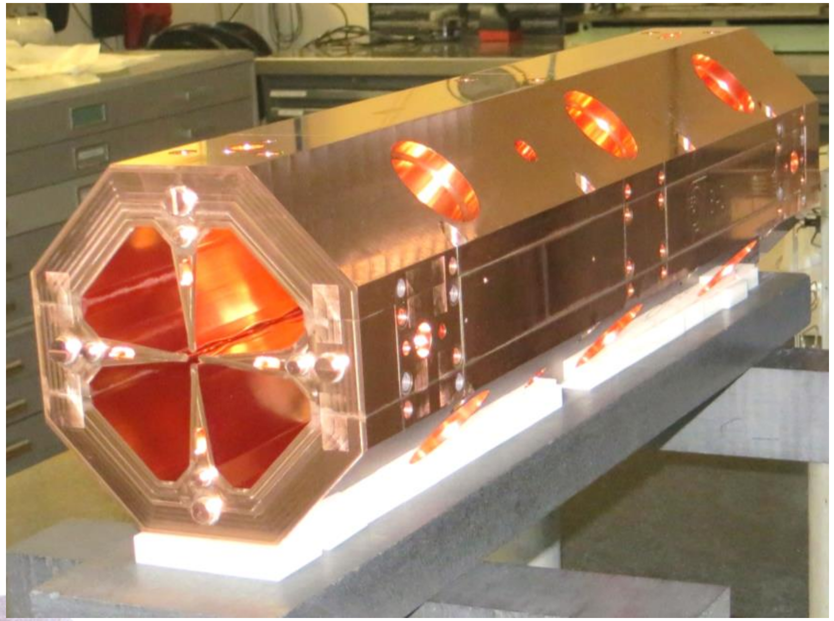


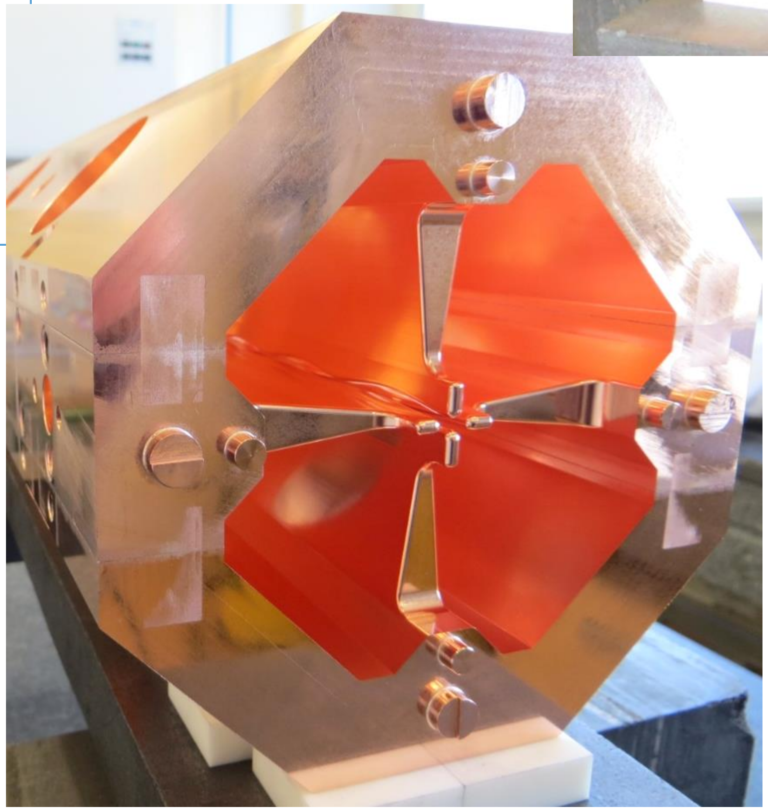


2) RFQ Construction

2.9: First brazing

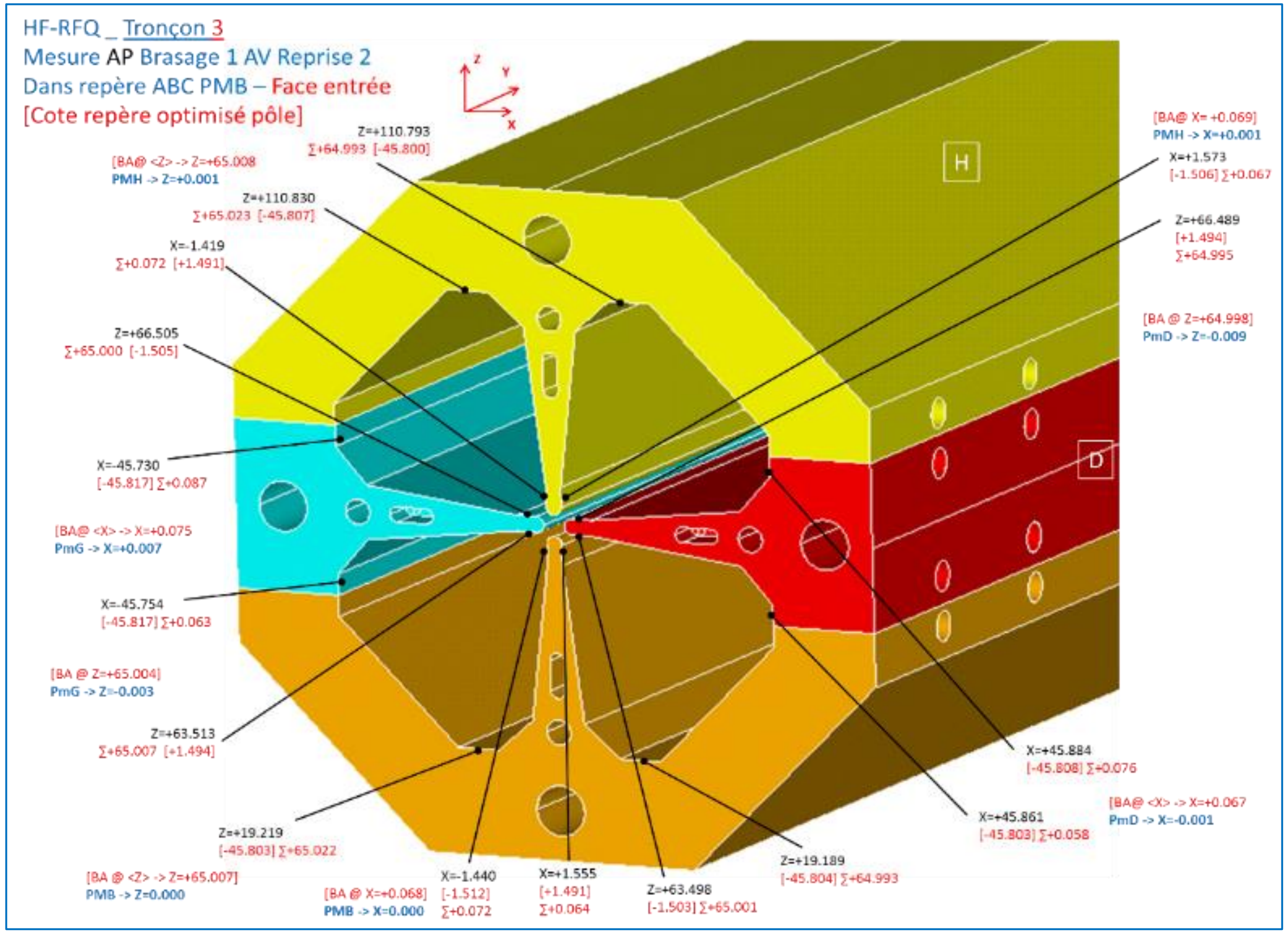


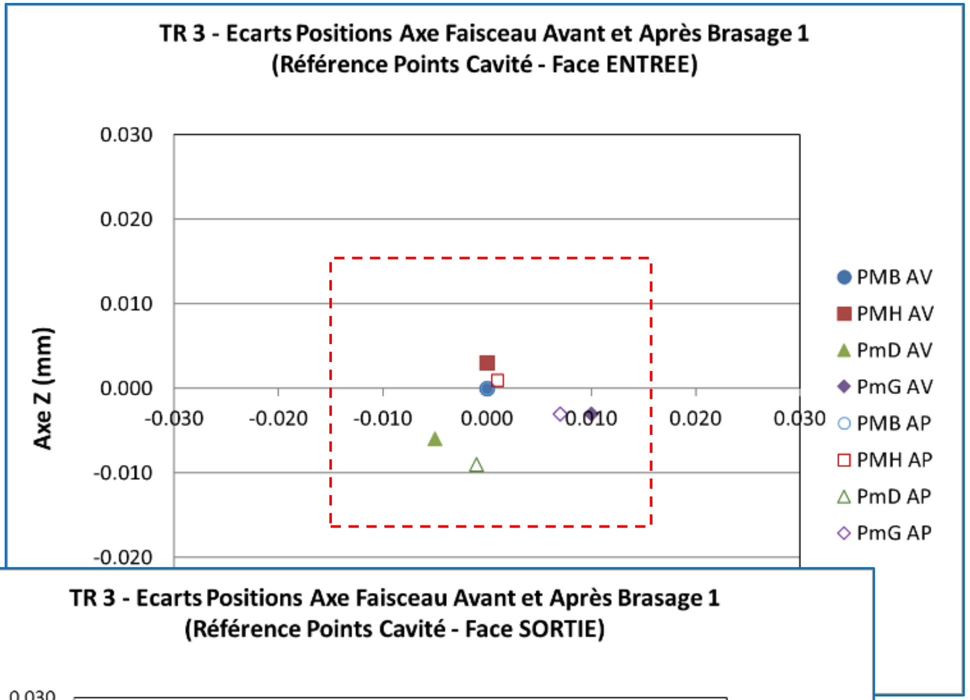


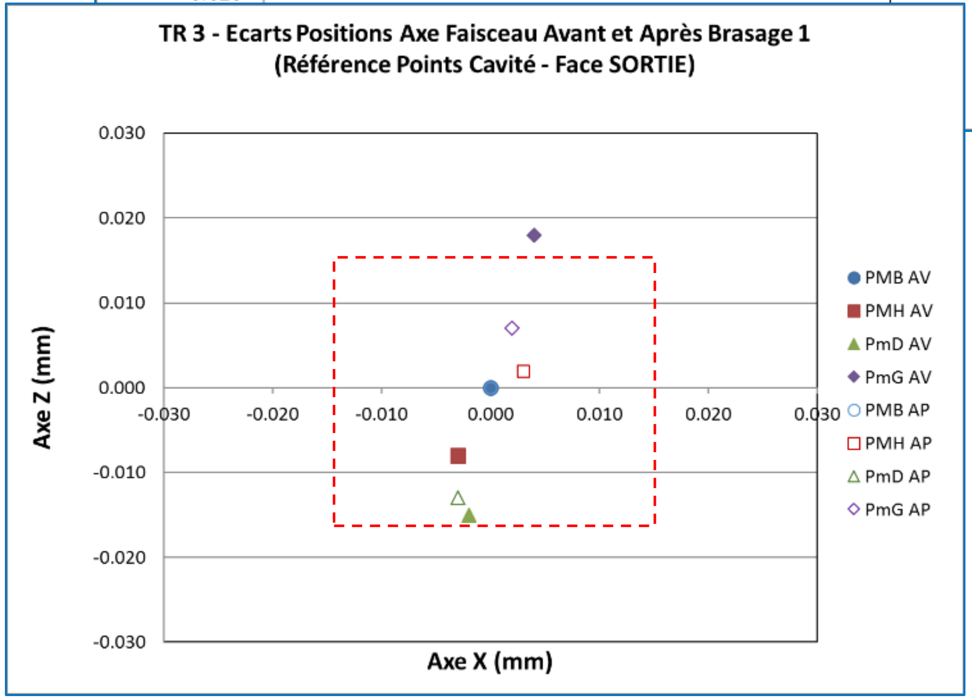


2) RFQ Construction

2.10: Metrology after first brazing







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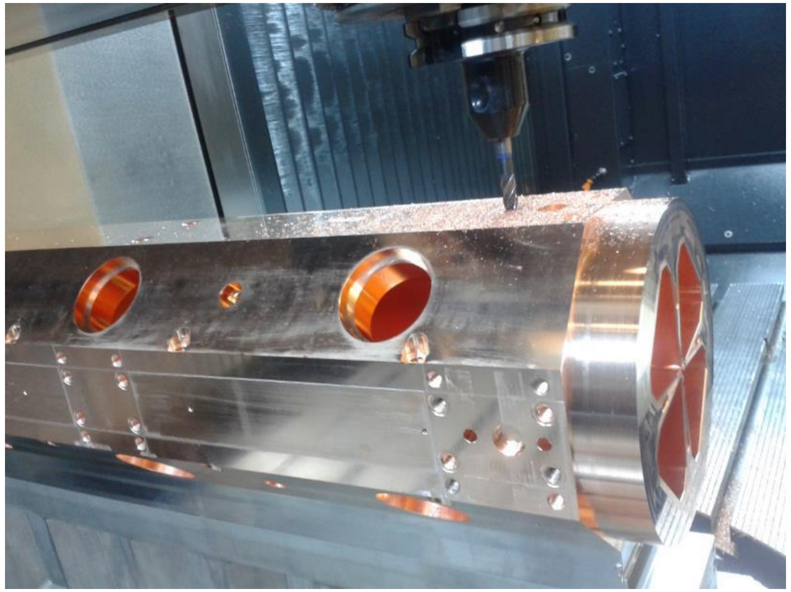
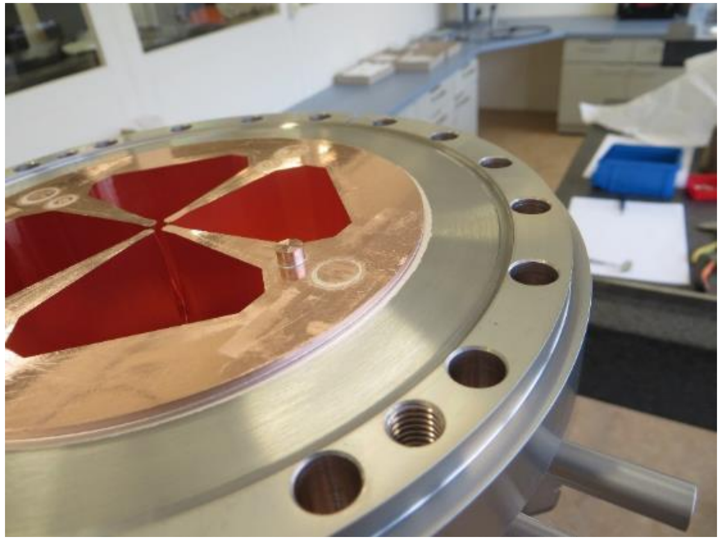
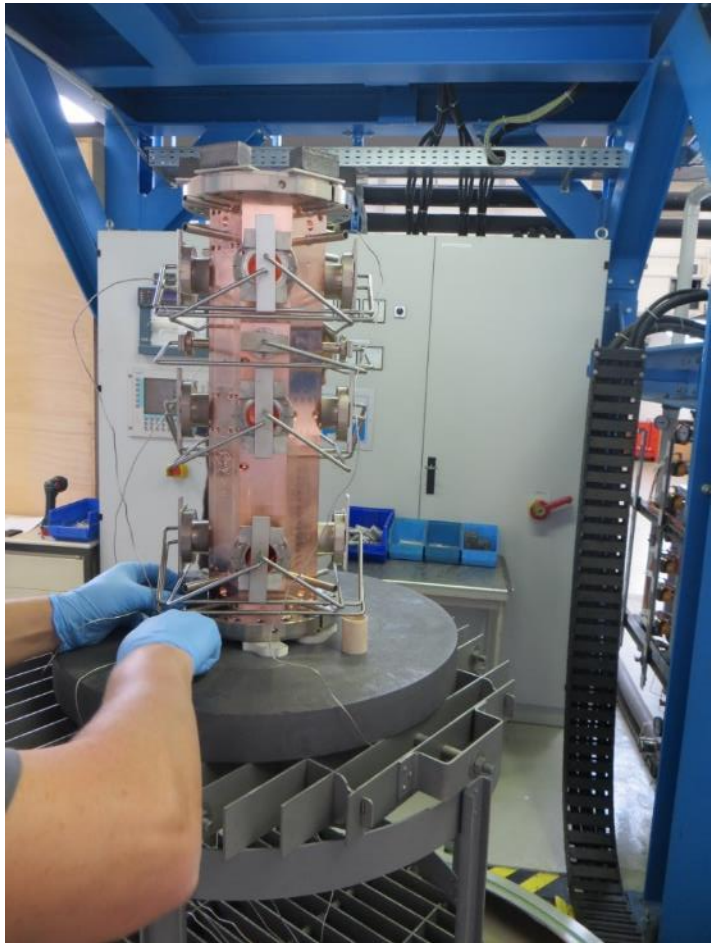
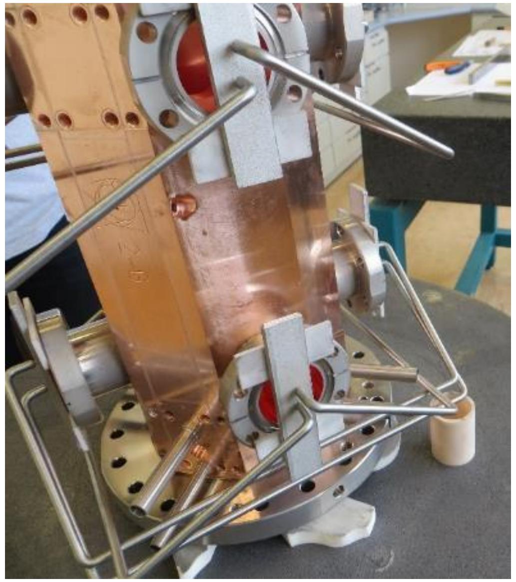
2) RFQ Construction

2.11: Re-machining and second brazing



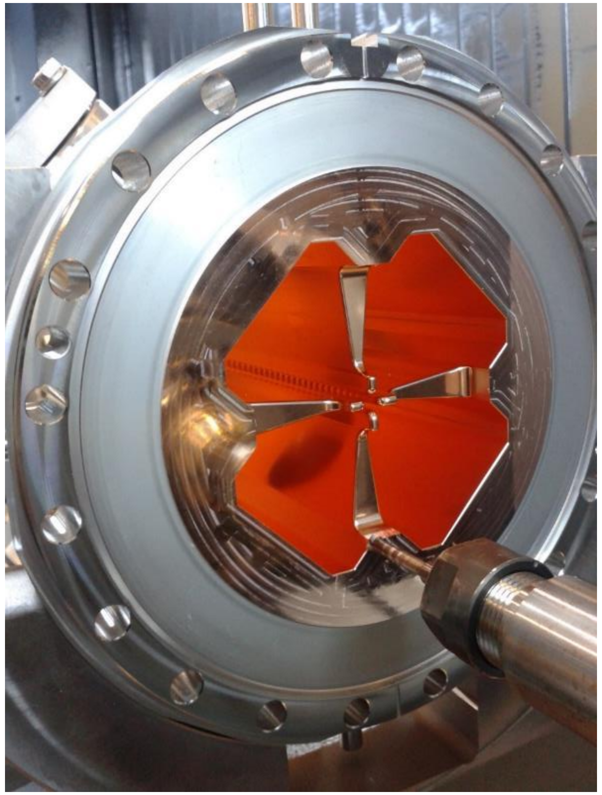


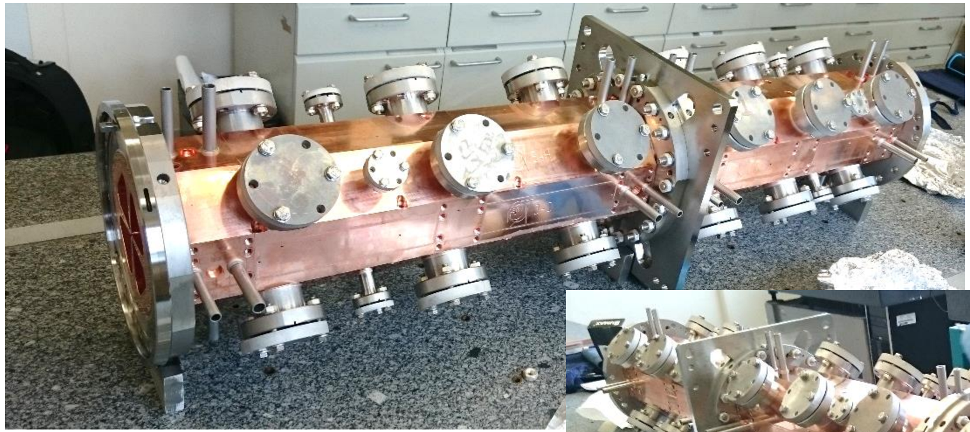


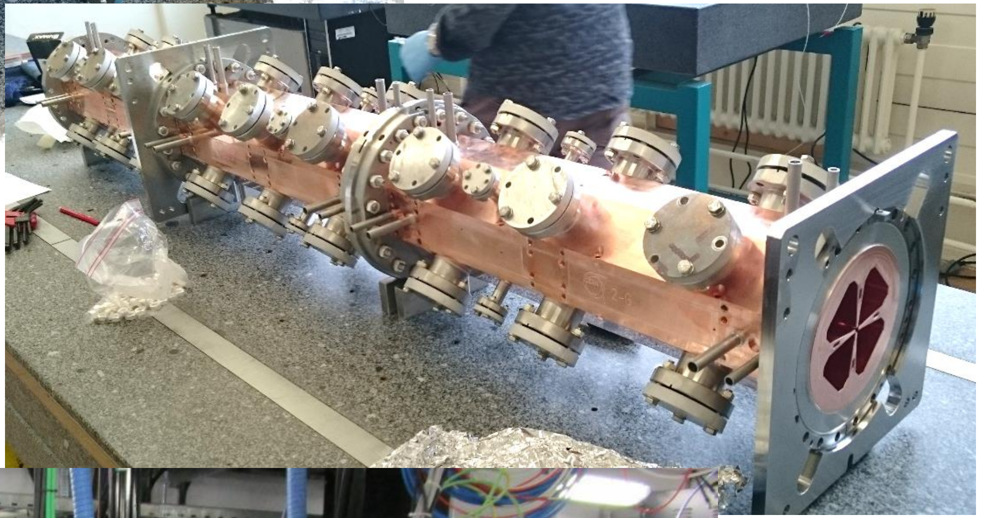


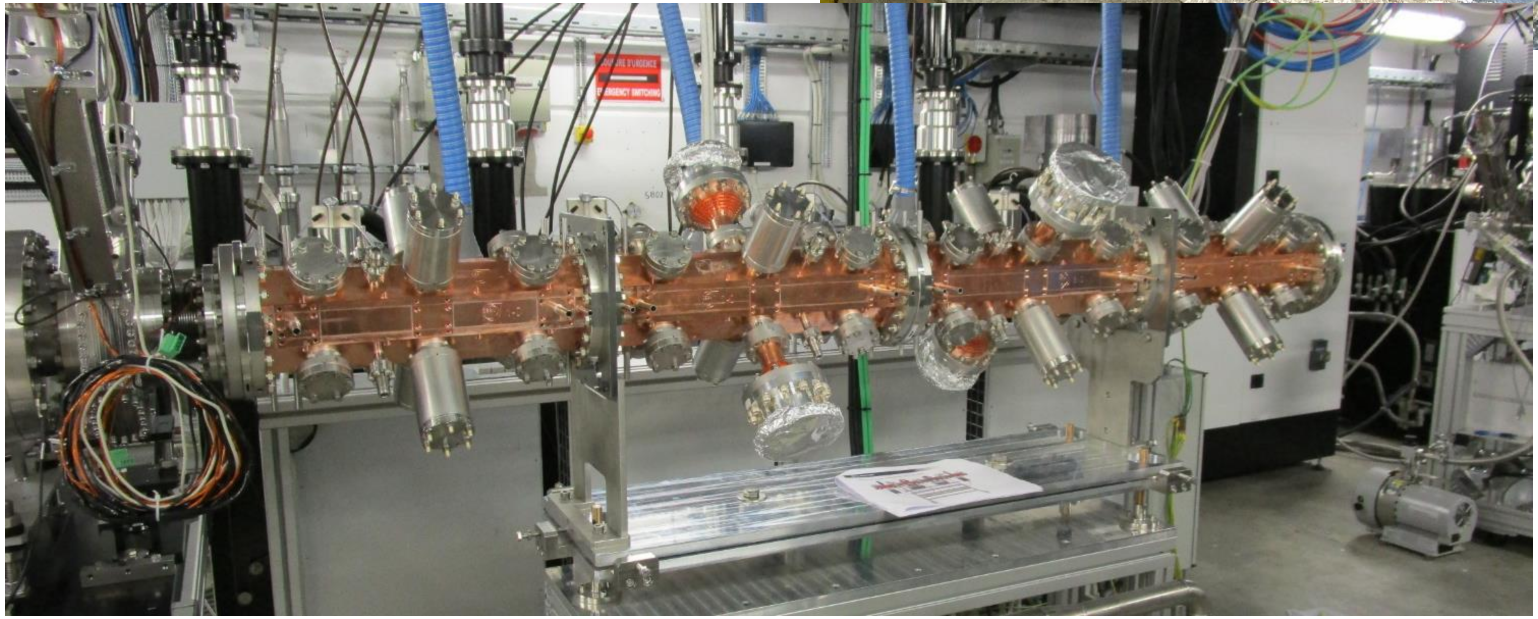
2) RFQ Construction

2.12: Final machining and module assembly









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3) RFQ Applications

3.1: High energy physic – The RFQ as an injector

CERN Cockcroft-Walton (1976-1993)

The RFQ is a single cavity able to Accelerate, Focus and Bunch an ion beam.

Ion sources produce a beam with a few tens of keV in energy. The acceleration up to a few MeV, where the beam is then accelerated with an RF cavity (DTL for example) is one of the most complicate part of a high energy, high intensity accelerator.

Before the RFQ, the solution was to increase as much as possible the end energy of the source, for example with an electrostatic accelerator (750 keV – 130 mA Cockcroft Walton at CERN up to 1993). But the buncher cavities needed after have an efficiency of 50 to 65 %.

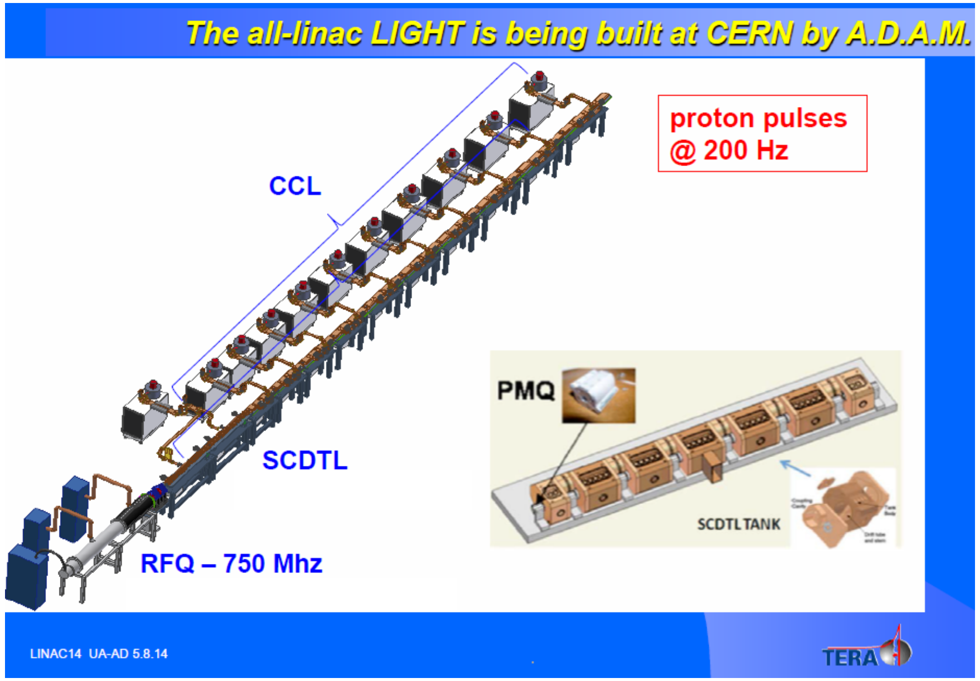
The RFQ, which is the sole RF accelerating cavity that we can connect directly after the ion source, can have an efficiency of more that 95% ....

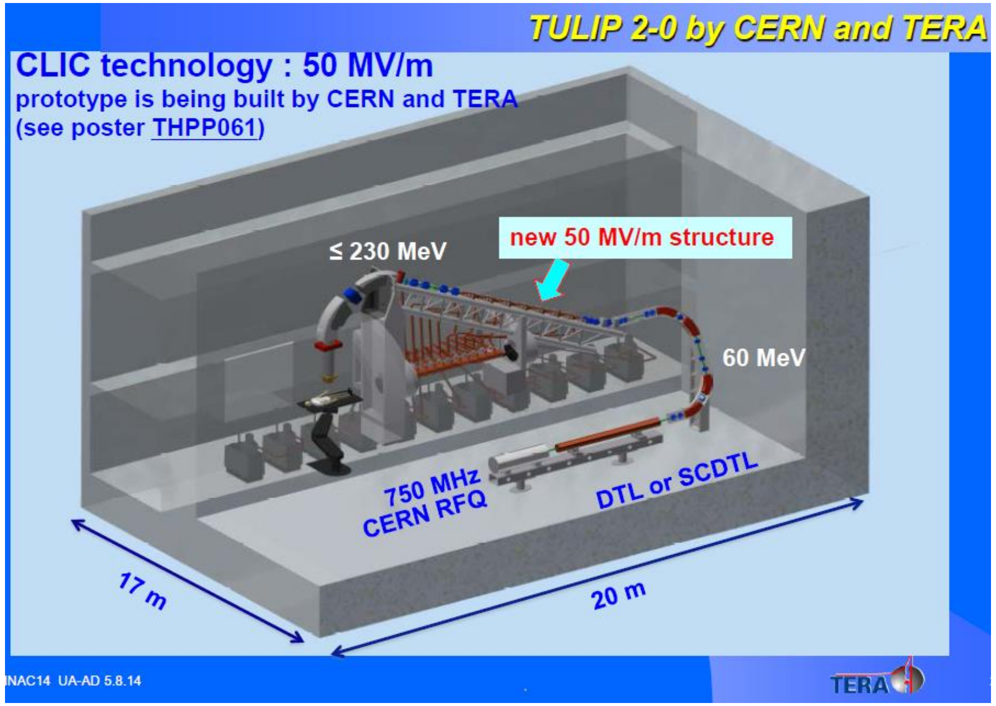
With the RFQ, the high energy accelerators have been able to profit of the high intensity ion sources.

CERN Linac2 RFQ (1993-2018)

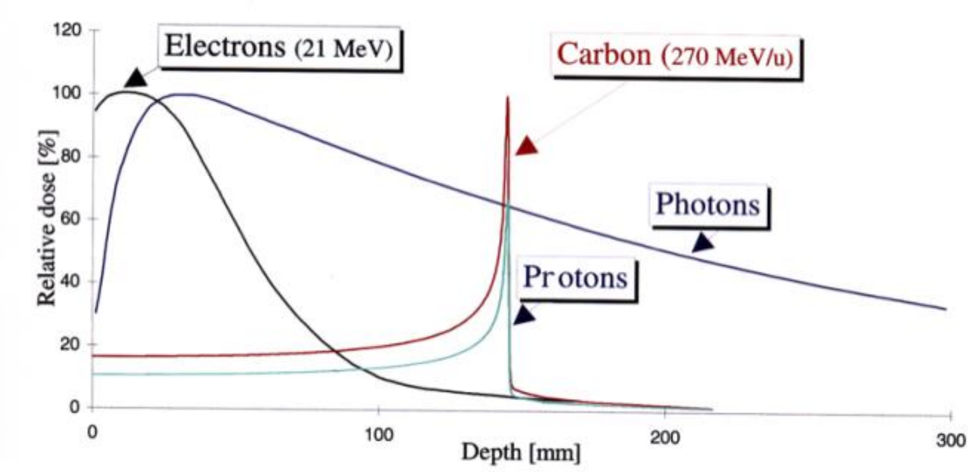
3) RFQ Applications

3.2: Medium energy accelerator – The RFQ as an injector





The RFQ: A compact injector for Linac used for hadrontherapy



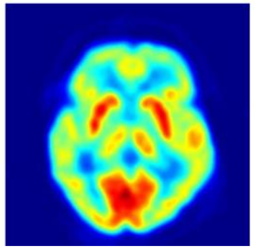
3) RFQ Applications

3.2: Low energy accelerator – The RFQ alone!

3.2.1 Isotope production

Positron emitters

- Cancer Metabolism and Functional Imaging
  - F-18-fluorodeoxyglucose (FDG) glucose analog, measures hexokinase activity (glucose metabolism), phosphorylated by hexokinase to F-18-FDG-6-PO4, elevated in tumor cells, chemically trapped in cells
  - F-18-amino acids (phenylalanine, tyrosine) image metastatic lesions
  - F-18-fluorothymidine measures thymidine kinase activity (DNA synthesis)
  - F-18-flouromisonidazol (FMISO) images tumor hypoxia
  - F-18-estradiol breast tumor detection



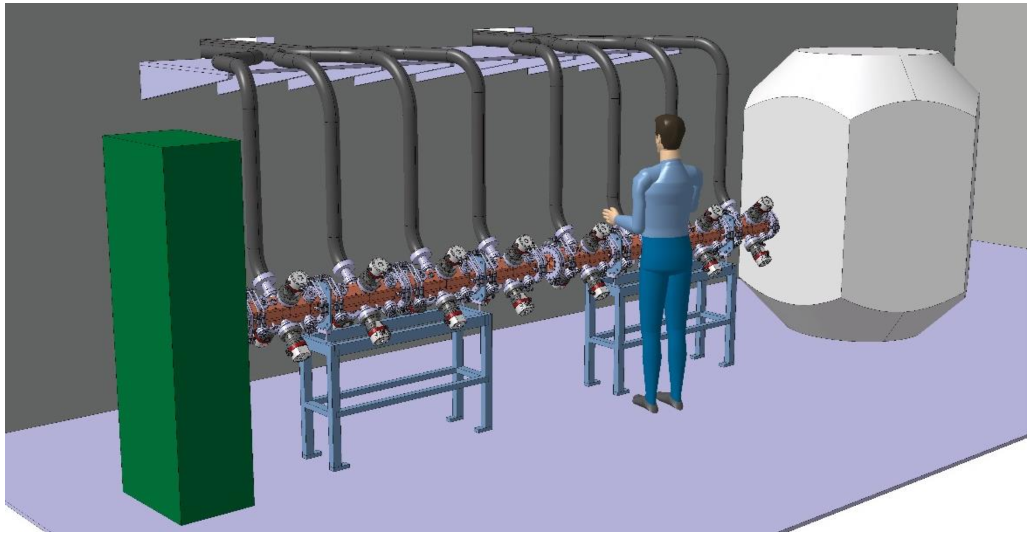
PET radiopharmaceuticals other than fluorine-18

- C-11-thymidine incorporates in DNA, indicates rapid metabolism
- C-11-choline incorporates in cell membrane phospholipids
- C-11-carbon monoxide indicates blood flow
- C-11-methionine amino acid uptake and protein metabolism
- C-11-acetate measures oxidative activity

PET brain imaging

- Neuroimaging
  - F-18-FDG glucose metabolism, brain activity
  - F-18-PIB binds amyloid placque in Alzheimer's disease
  - F-18-fallypride targets dopamine receptors in neuropsychiatric disease and addiction
  - C-11-raclopride dopamine receptors in addiction, alcoholism

Isotopes for PET scan:



Advantages vs cyclotron:

- ✓ No radiation around accelerator and target, no casemate!
- ✓ Easy operation (one button machine).
- ✓ High reliability
- ✓ Minimum footprint (15 m2)

2 RFQs
Input energy = 40 KeV
Total Length = 4.0 m
Output Energy = 10 MeV
Frequency 750 MHz
Average current = 20 μA
Peak current = 500 μA
Duty cycle = 4 %
Peak RF power < 800 kW
Total weight (RFQ): 500 kg
Mains power < 65 kW
Cooling ~ 100 l/min

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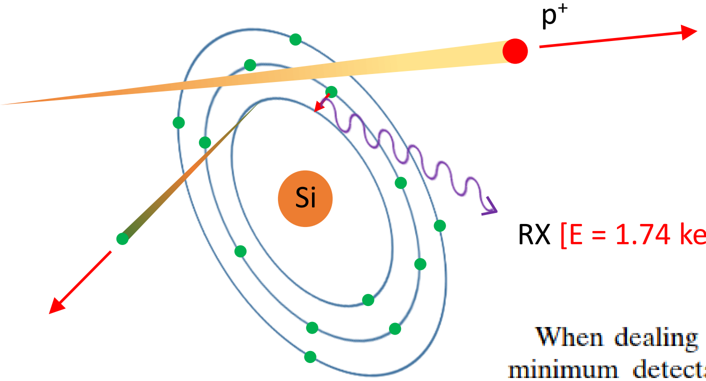
3) RFQ Applications

3.2: Low energy accelerator – The RFQ alone!

3.2.2 Material analysis … with a transportable accelerator

MeV proton beams are commonly used for the analysis of materials using the PIXE technic.



RX [E = 1.74 keV]

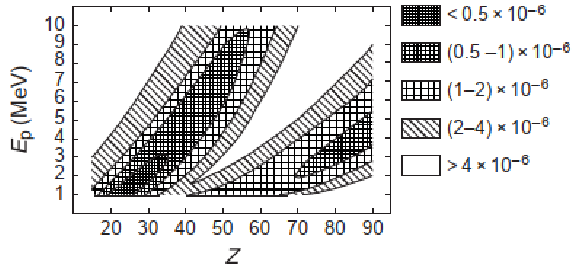


Figure 10 Attainable MDL as a function of proton bombarding energy and atomic number, in typical conditions. (Reproduced by permission from Johansson and Johansson.(17))

When dealing with MDLs, both relative (in terms of minimum detectable mass over the total mass of the sample) and absolute values should be considered. Indeed another great quality of PIXE is that absolute quantities as small as picograms of the elements in the detectable range can be quantified in measurements lasting only a few minutes. This makes PIXE a very useful technique when nondestructivity is a mandatory requirement (as in the case of precious items such as works of art), or when the quantity of material to be analyzed is very small (as in some applications related to environmental pollutants).

P. A. Mandò (2000)

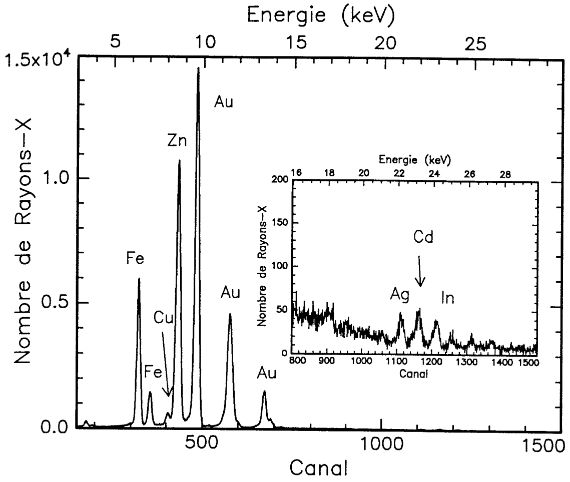
6.6.6 Recent developments

During the period between the writing and the printing of this book the interest in ion beam analysis has considerably increased. Indeed, several meetings have been completely or partially devoted to this subject [35, 36, 37, 38].

Amongst other techniques, the analysis by proton induced X-ray emission (now called PIXE), has shown a striking development. In [35], fifty papers can be found on the subject. The most spectacular development is probably the use of external proton beams for the analyses. In this method a beam of 2.5 MeV protons is used, in open air, or in a helium atmosphere at atmospheric pressure, the beam is extracted from the high vacuum region in the tube extension of the accelerator through a thin beryllium or aluminium window. The sample is positioned on the beam path which is clearly visible either in air or in helium. X-rays are then detected in a Si(Li) detector as described in Section 2.2.2. The sensitivity is the same as the sensitivities achieved in analysis made in vacuum, but samples which could not withstand high vacuum conditions can be analysed; this is so in the case of liquids and biological sample [35, 36, 37].

G. Deconninck, "Introduction to radioanalytical physics", LARN (BE) (1978)

tomic No.	Element	K series					L series							
		K_{ab}	$K\beta_2$	$K\beta_1$	$K\alpha_1$	$K\alpha_2$	L_{Iab}	L_{IIab}	L_{IIIab}	$L\gamma_1$	$L\beta_2$	$L\beta_1$	$L\alpha_1$	$L\alpha_2$
76	Os	73.860	73.393	71.404	62.991	61.477	12.965	12.383	10.869	12.094	10.596	10.354	8.910	8.840
77	Ir	76.097	75.605	73.549	64.886	63.278	13.413	12.819	11.211	12.509	10.918	10.706	9.173	9.098
78	Pt	78.379	77.866	75.736	66.820	65.111	13.873	13.268	11.559	12.939	11.249	11.069	9.441	9.360
79	Au	80.713	80.165	77.968	68.794	66.980	14.353	13.733	11.919	13.379	11.582	11.439	9.711	9.625



AGLAE – external 3 MeV proton beam

from Burma or Sri Lanka. These results are in agreement with Sanskrit texts written in IV–Xth century B.C. [16,17] stating that rubies were extracted from deposits in India and Sri Lanka.

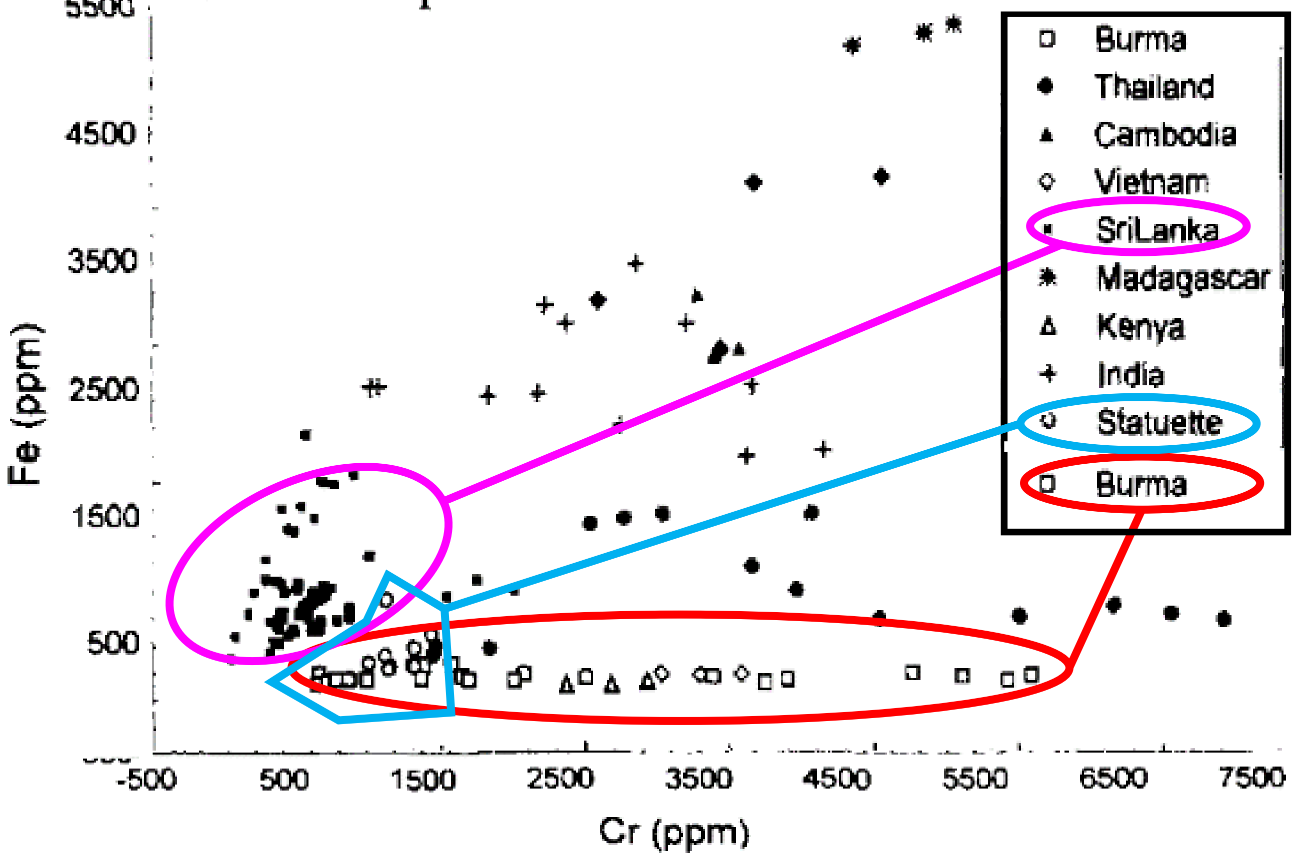


Fig. 4. Plot of Fe vs. Cr for different locations.

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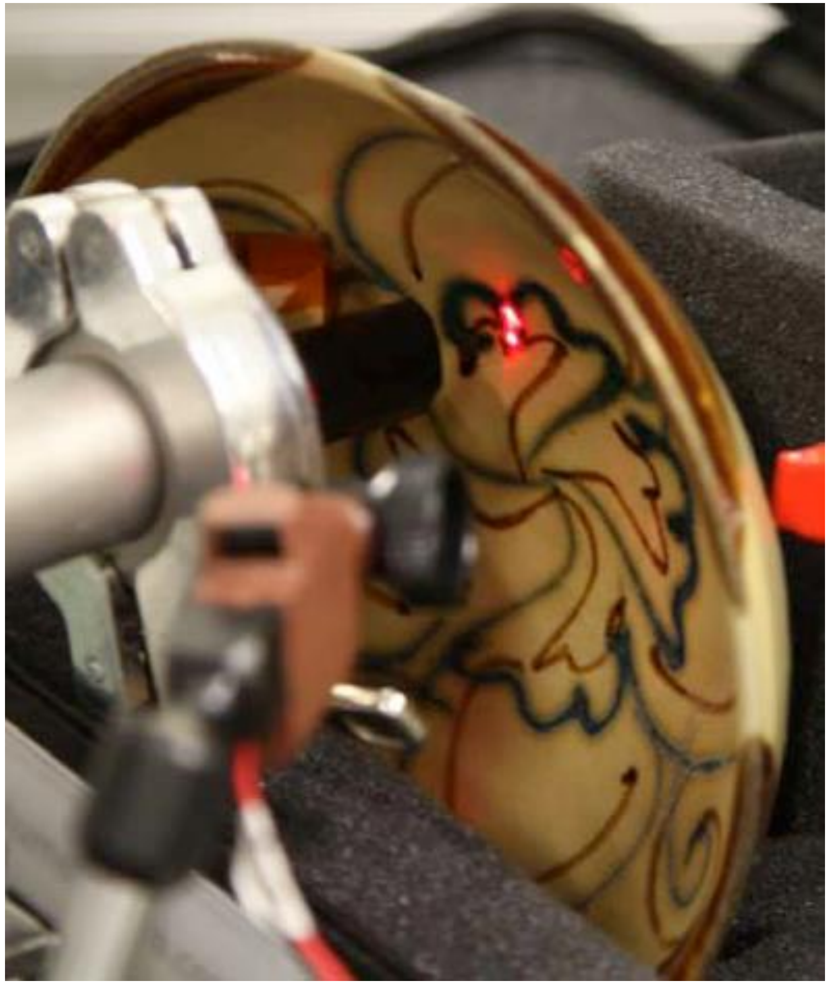
PIXE examples

Questions:

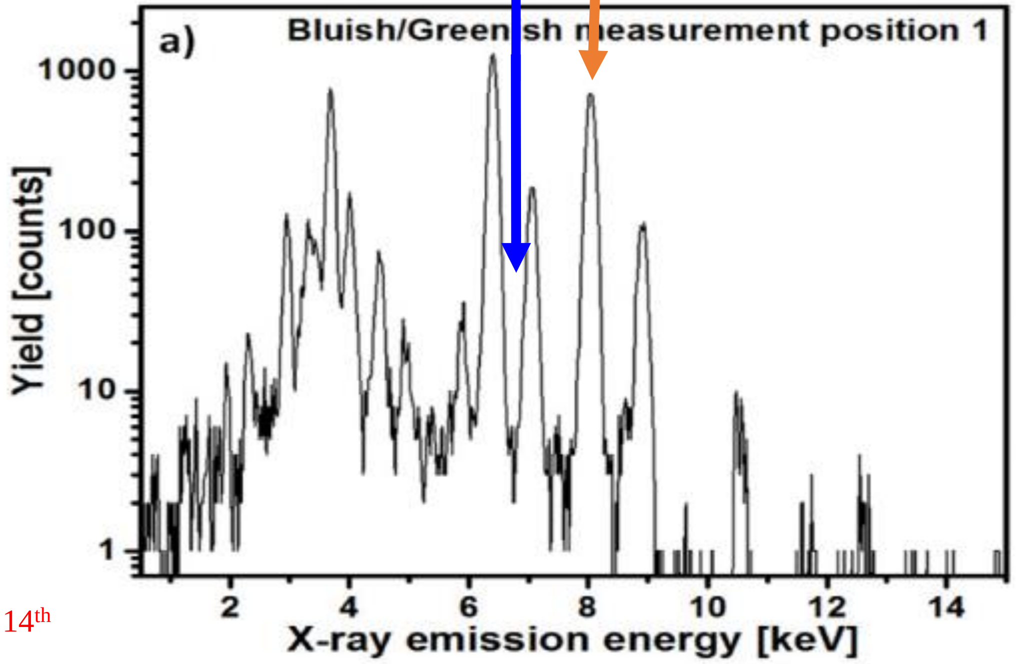
1. Tongguan origin?
2. Tang period?
3. Co-blue?

Answers:

1. Tongguan area
2. Tang period
3. No Co-blue: Cu-blue!



Jyväskylä - 3 MeV proton PIXE bowl from Tang Dynasty



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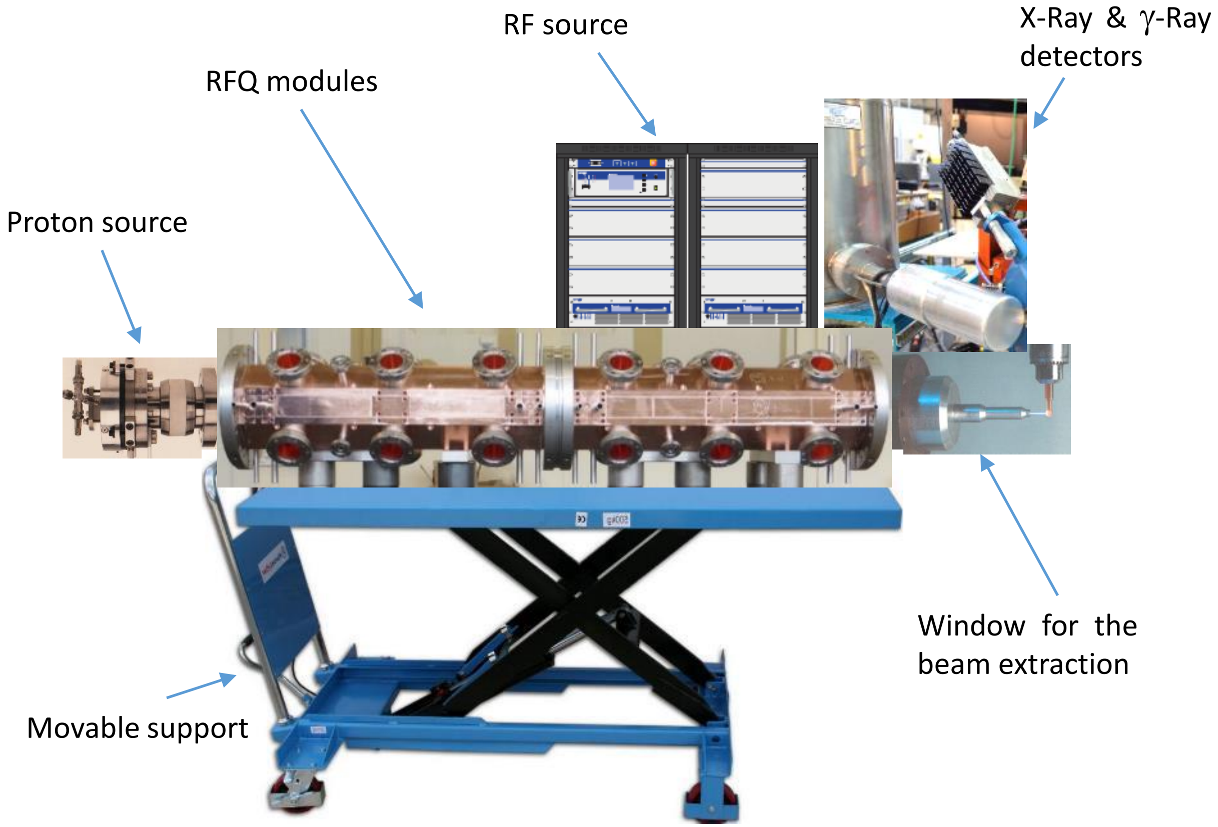
The PIXE-RFQ / MACHINA project

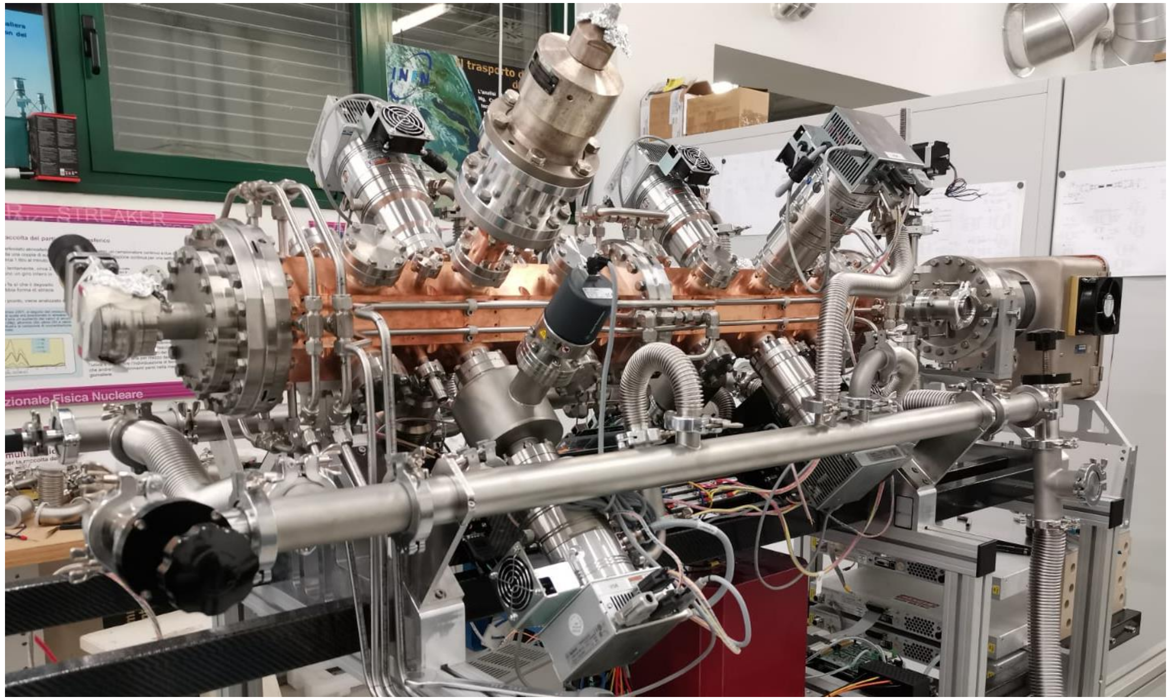
PIXE-RFQ construction accepted in March 2017



Main parameters for the HF-RFQ

RF Frequency (MHz)	750
Length (mm)	1000
Input Energy (MeV)	0.02
Output Energy (MeV)	2

MACHINA (Movable Accelerator for Cultural Heritage In-situ Non destructive Analysis) kick-off meeting – Opificio delle Pietre Dure – Florence – April 2018



MACHINA (Decembre 2020)

The ELISA project @ Science Gateway

3.2: Low energy accelerator – The RFQ alone!

3.2.3 Accelerator for education

EDMS Document Number: 2433889
Rev: 1.0- Status: RELEASED

Technical Note
20 November 2020

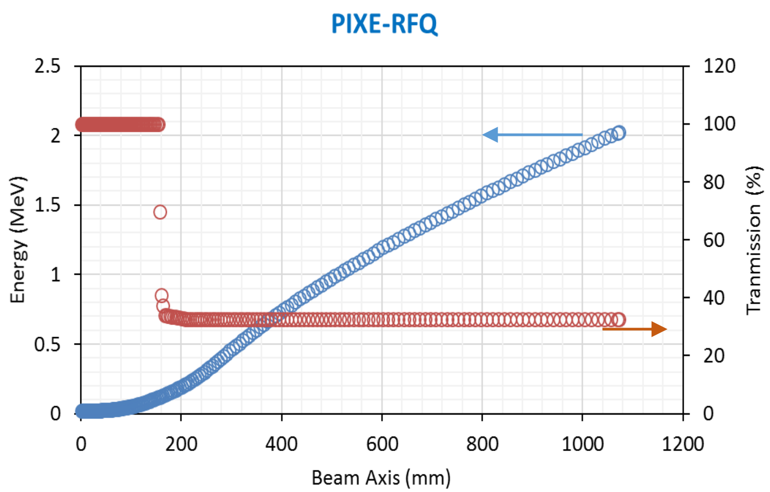
Radiation protection assessment of the ELISA low energy proton accelerator

prepared by:	verified by:	approved by:
M. Widorski (HSE-RP)		H. Vincke (HSE-RP)

The PIXE-RFQ designed at CERN is a very safe accelerator:

- Source HV limited at 20 keV : No X-Ray, reduced protection
- Vane voltage limited at 35 kV: No X-ray out of the cavity
- Final energy limited at 2 MeV : No neutron
  ➔ < 2.17 MeV, E_{th} $^{65}Cu(p,n)^{65}Zn$
- Vane voltage limited at 35 kV: No X-ray out of the cavity
- Beam dynamics ensuring no lost particle at high energy
  ➔ No radiation

March 2019, proposition for the construction at CERN of a new PIXE-RFQ, which will produce a proton beam of 2 MeV which will be extracted in air.
This accelerator will be installed for a permanent exhibition at Science Gateway. For the first time in the world, the public will be able to approach at a few tens of centimetres, without barrier, and see with their eyes a beam of particles entering the atmosphere.
→ *Accepted in January 2020 and currently under construction!*

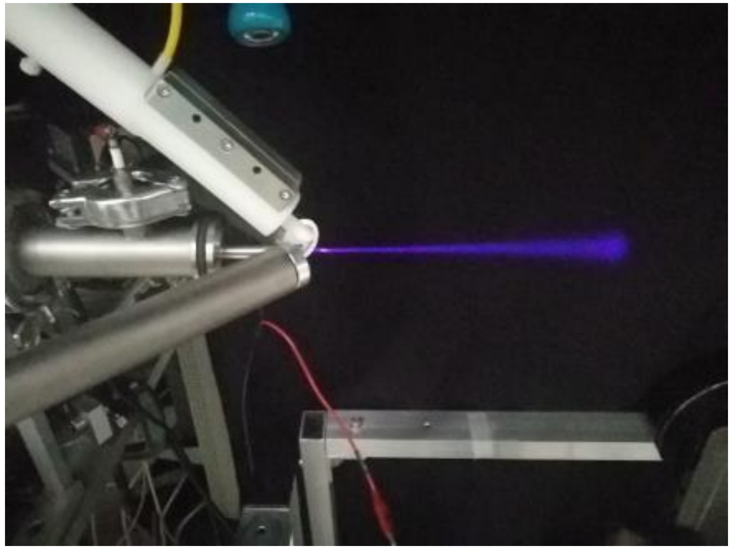


ELISA

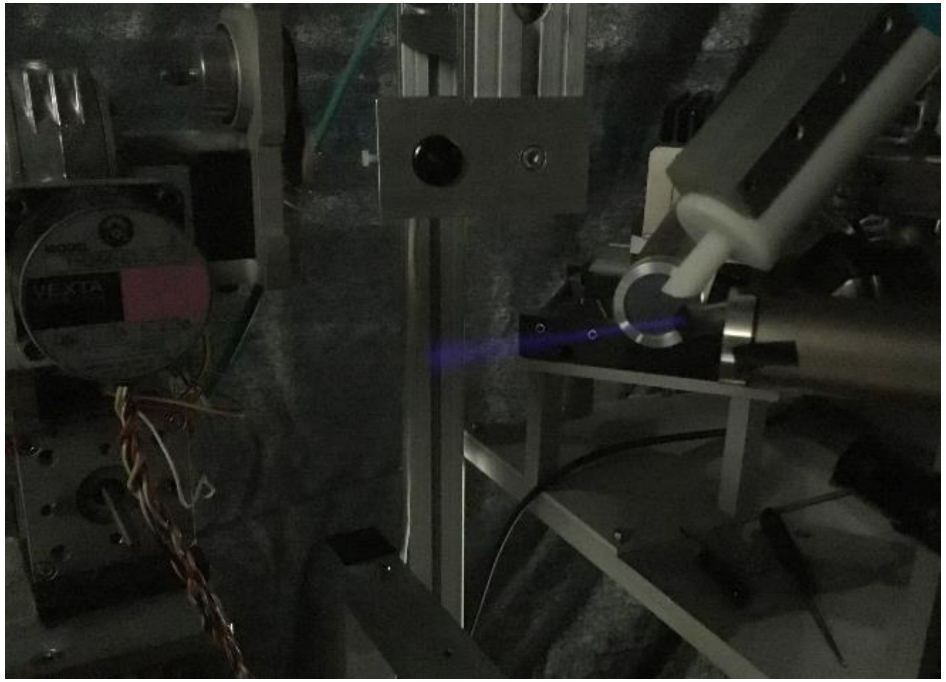
Experimental Linac for Surface Analysis

A compact proton accelerator for Science Gateway

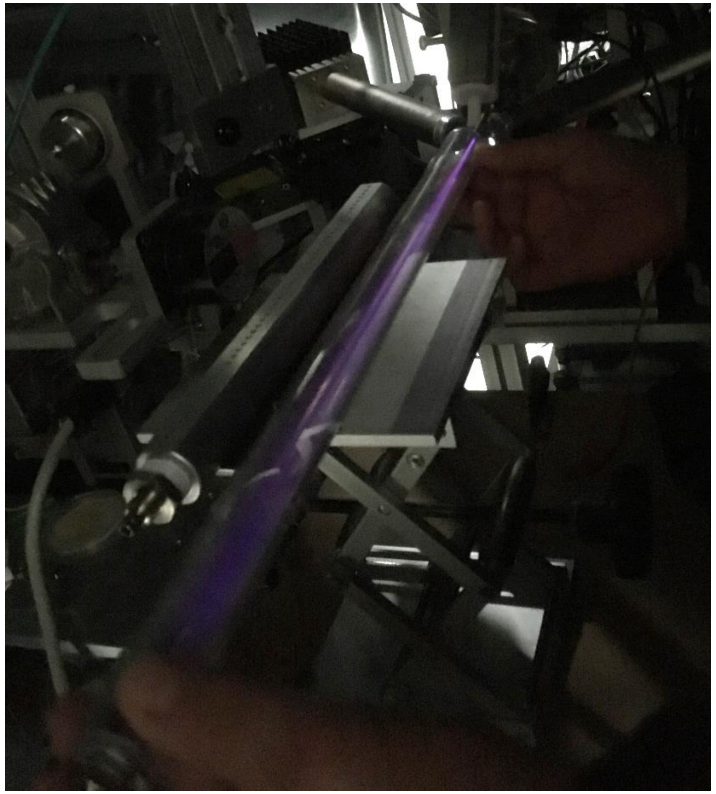
What we want to show:



2 MeV - 200 nA continuous in air
(Distance 75 mm)



2 MeV - 30 nA continuous in air (Distance 75 mm)

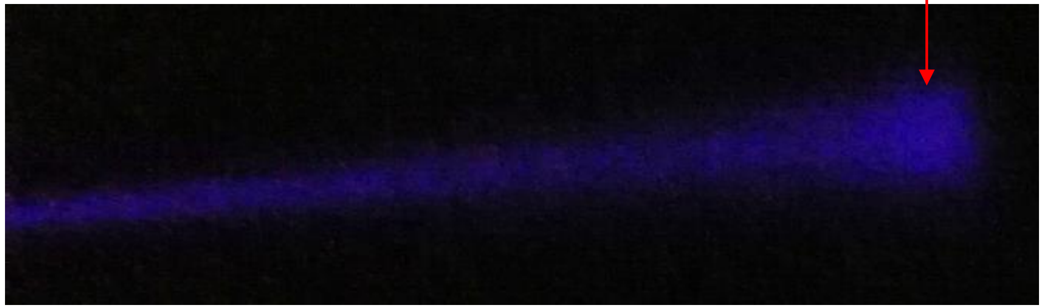


2 MeV - 30 nA continuous in Helium
(Distance 385 mm)

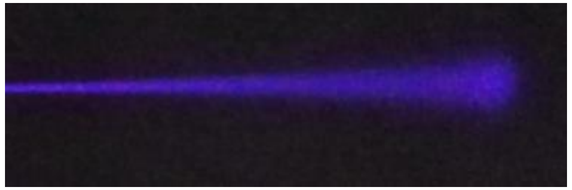
CERN | EN ENGINEERING DEPARTMENT

ELISA

Experiments with the beam:



Observation of the Bragg peak: The beam is more visible at the end of the trajectory. This explains the advantages of the hadrontherapy!



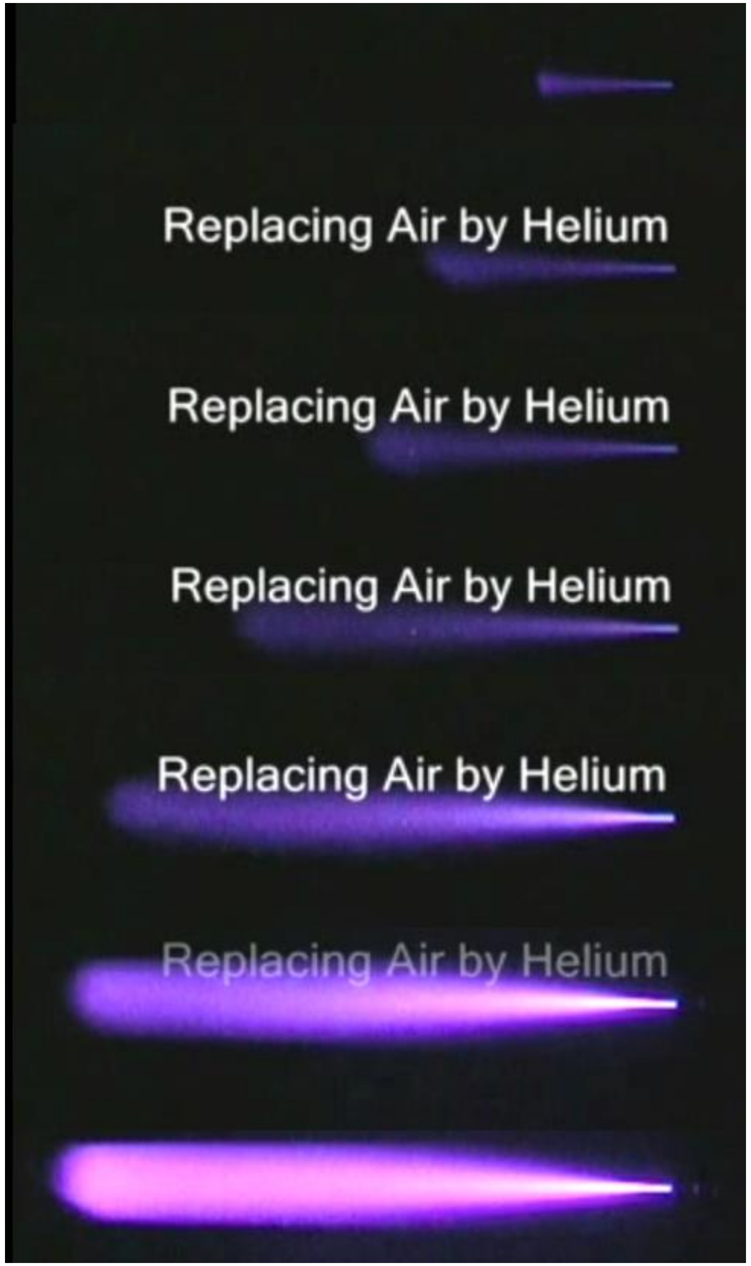
Air (Nitrogen)

Different colours with different gas: as observed in the stars …

Argon

Helium

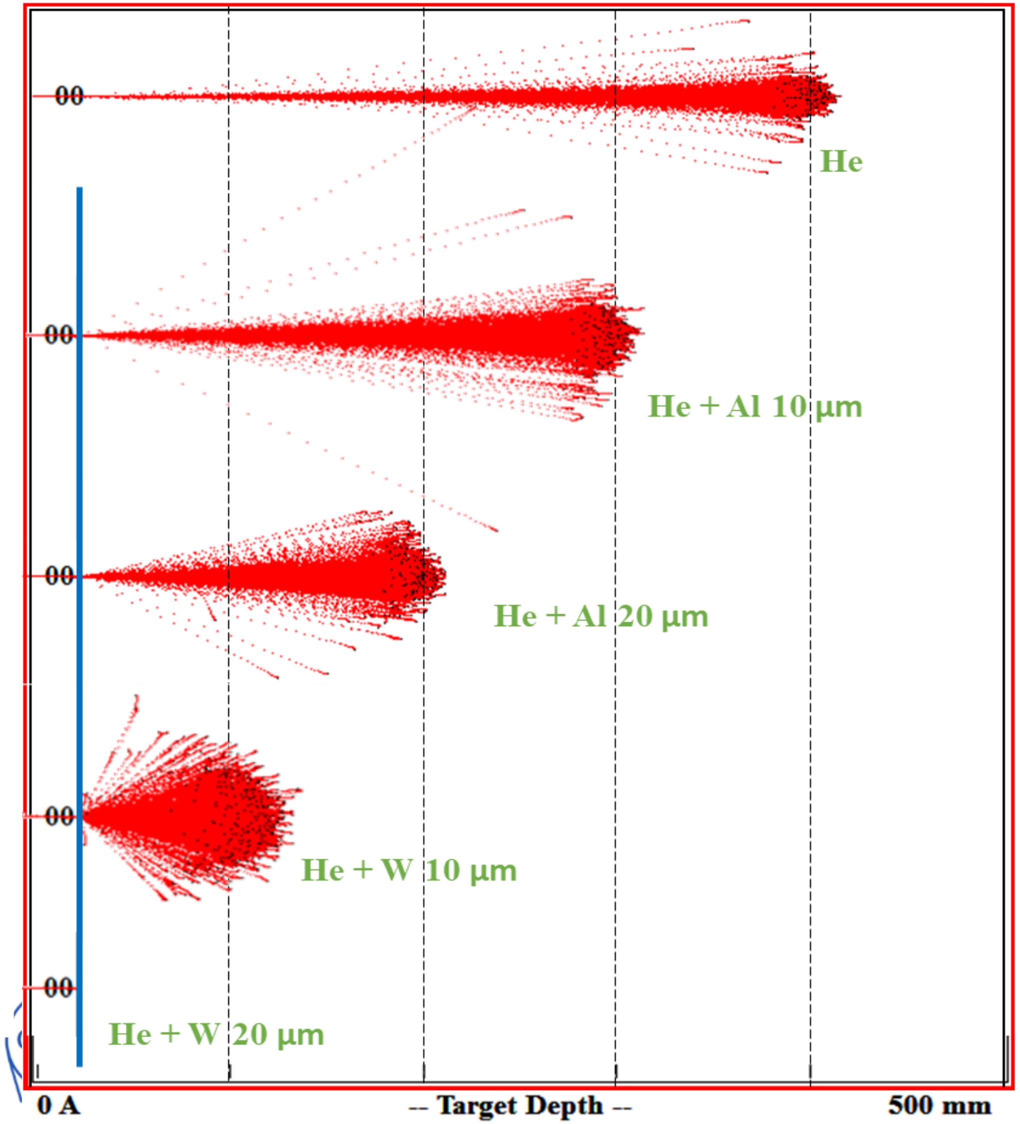
Effects of gas / pressure / density



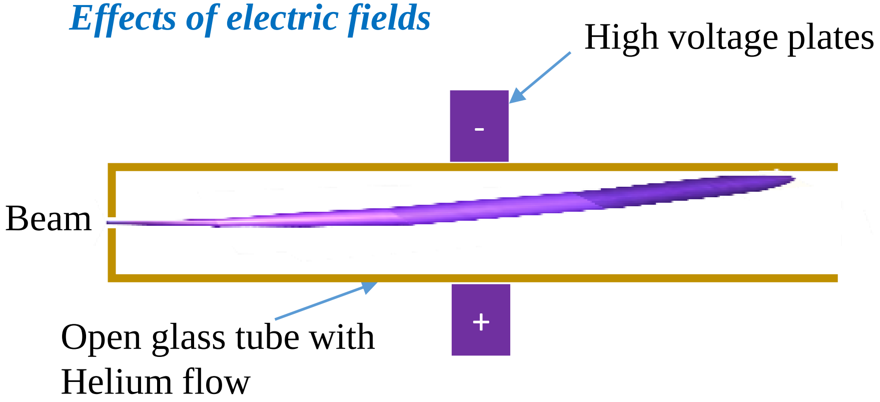
ELISA

Experiments with the beam:

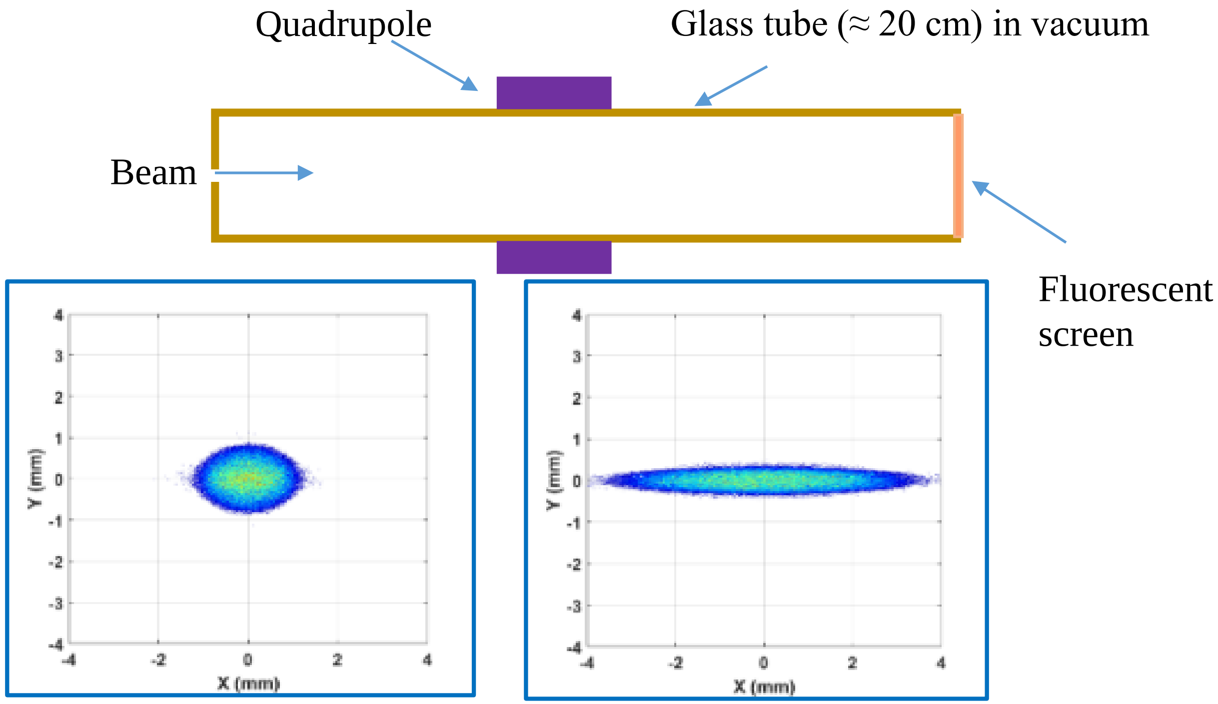
Effects of absorbers / materials



Effects of electric fields



Effects of magnetic fields (Quadrupole ,…



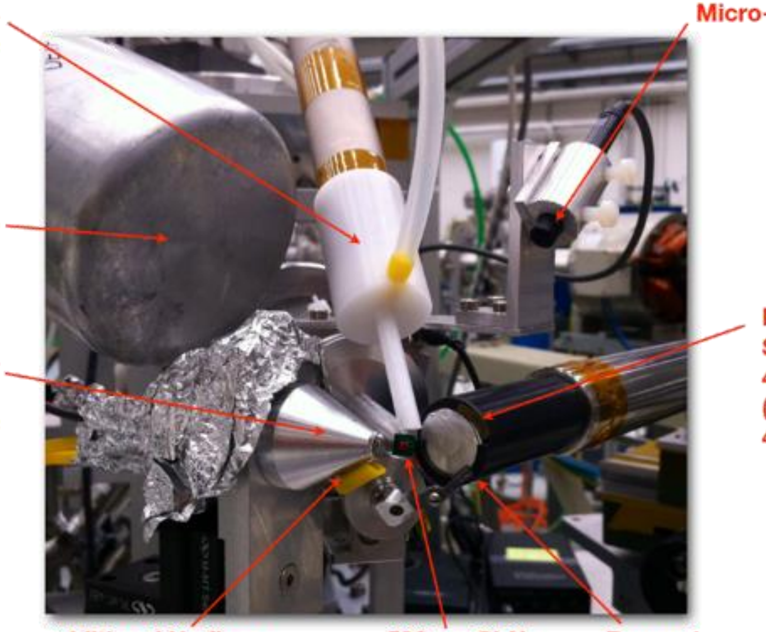
Beam without quadrupole

Beam with quadrupole

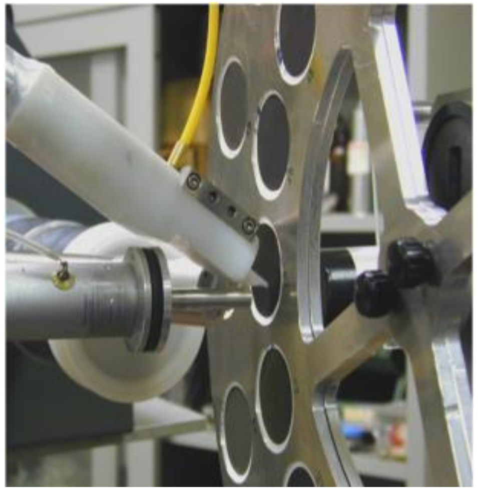
ELISA

"Surface Analysis" is on the name of ELISA …

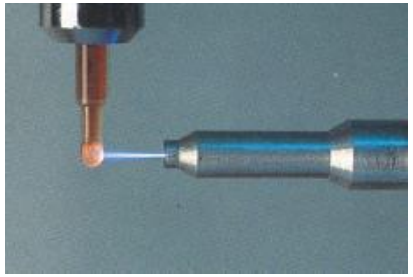
The ELISA accelerator is the exact copy of the MACHINA accelerator.
We will set up some detectors to perform live analysis for ***public demonstrations and also for <u>scientific collaborations</u>***.



Madonna dei Fusi, Leonardo da Vinci, courtesy OPD, Florence

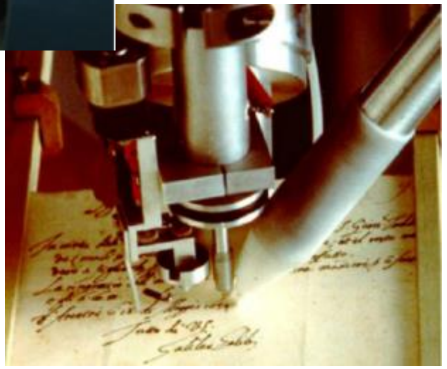


Aerosols, courtesy LABEC, Florence



Liquid. courtesy LARN, Namur

Jewellery, courtesy AGLAE, Paris



Ink, courtesy LABEC, Florence

The RFQ's

Conclusions

The RFQ's are fantastic accelerating cavities. They are the sole RF accelerators than we can connect directly after an ions source. With the capability of focusing, accelerating and bunching, these cavities have open the doors of high intensity RF accelerators.

The construction is however challenging. Vacuum brazing is often the critical step in the manufacturing process. At CERN, we have developed a procedure alternating machining and heat treatments to minimize the deformations during brazing.
This development was only possible thanks to open discussions between RF & beam dynamics design and construction and this from the beginning of the project.

With the recent development of a high frequency RFQ at CERN, compact ion accelerators can be designed for a large variety of applications.