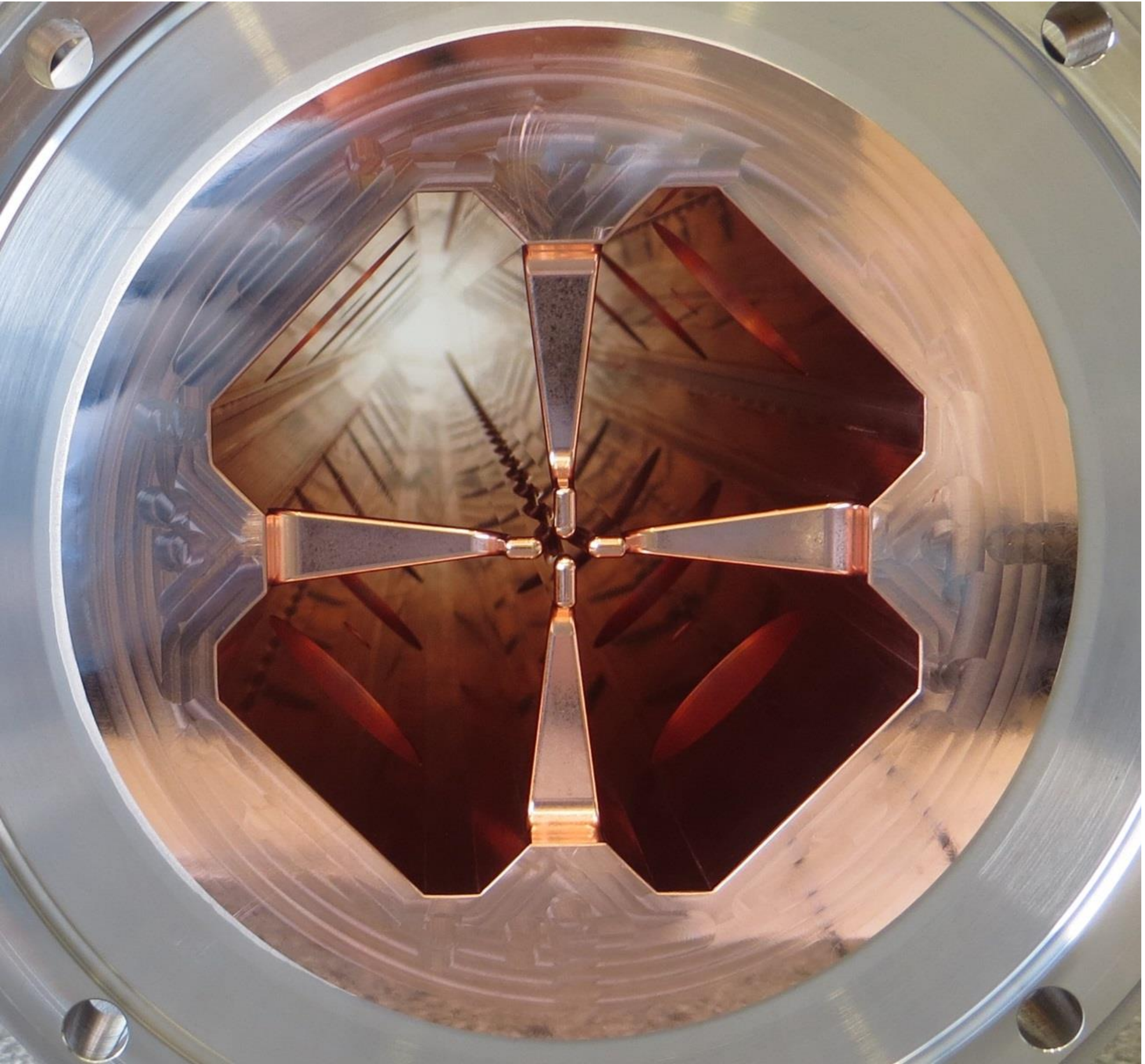

Compact Radio Frequency Quadrupoles for medical and industrial applications

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for the HF-RFQ Working Group

1. What is an RFQ

The Radio Frequency Quadrupole

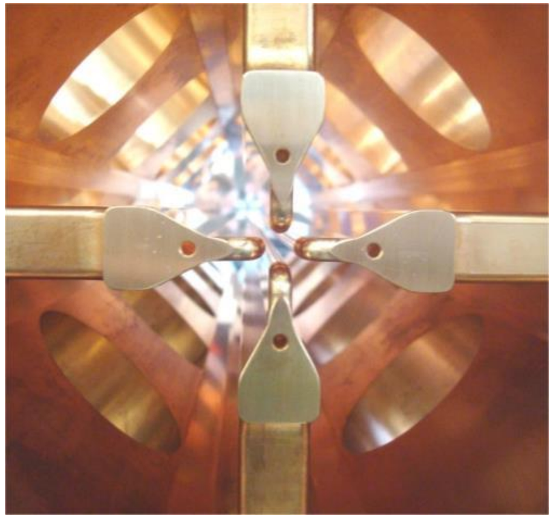
Protons and Ion acceleration up to few MeV energy by the **RFQ = Radio Frequency Quadrupole.**

A small linear accelerator (length ≈3 m, can go up to 10m), is the first element in any proton or ion accelerator chain (not used for electrons!)

A relatively young technology (invented in Russia in the 70s, first prototype in the USA 1980, becomes the standard low-energy linac from the 90s – present RFQ design and production capability limited to 6 laboratories in Europe, 3 in the US, some in Japan and China, 2 or 3 companies).

Follows the ion source and can simultaneously accelerate, focus and bunch (= create the "bunches" required for high-frequency acceleration) without beam loss and with excellent output beam quality.

Reliable (one-button machine), no maintenance, but complex structure with relatively high construction cost.



The CERN Linac4 RFQ, 0.05 to 3 MeV, 3 m.

Why do we need an RFQ?

Low energy →
for protons, between ~ 50 keV (source extraction) and ~ 3 MeV (limit for an effective use of the following DTL)
→ particle velocity range between 0.01c to 0.10c (c=speed of light)

3 problems:

1. Strong repulsion between particles of same sign (the repulsion will go down with energy!). A strong focusing is needed, but usual magnetic quadrupoles are not effective at low energy.
2. Particles need to be grouped in "bunches" to be accelerated by high-frequency fields (to be "on the top of the wave"). Usual "bunching" cavities induce high beam loss (~50%).
3. Standard accelerating structures have low power efficiency because the cell length is very short (usual cells $\beta\lambda/2$, with λ=RF wavelength and β=relative particle velocity. At the entrance of a 352 MHz RFQ $\beta\lambda/2 \approx 4$ mm).

Replacement in 1993 of the old CERN pre-injector with an RFQ

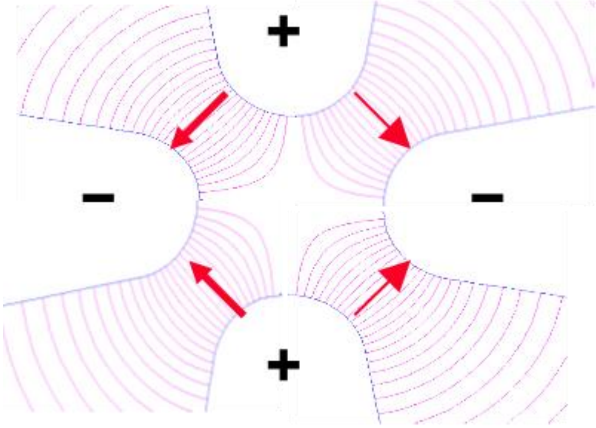
← 3.2m →

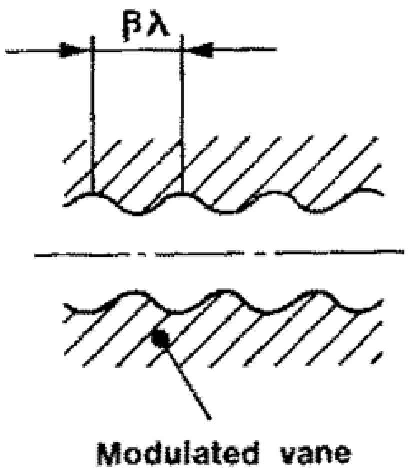
How does it work?

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!)

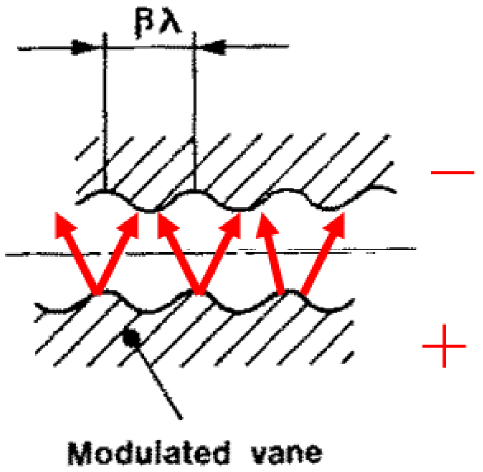
2. The vanes have a longitudinal modulation with period = $\beta\lambda$ → this creates a longitudinal component of the electric field. The modulation corresponds exactly to a series of RF gaps and can provide acceleration.

3. The period and amplitude of the modulation can be adjusted to change the longitudinal force and the acceleration of the particles, to progressively bunch the beam (adiabatic bunching channel), and then switch to full acceleration.

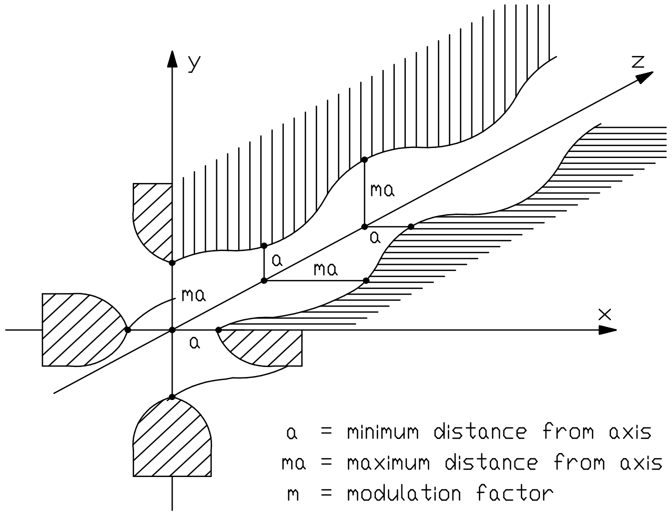




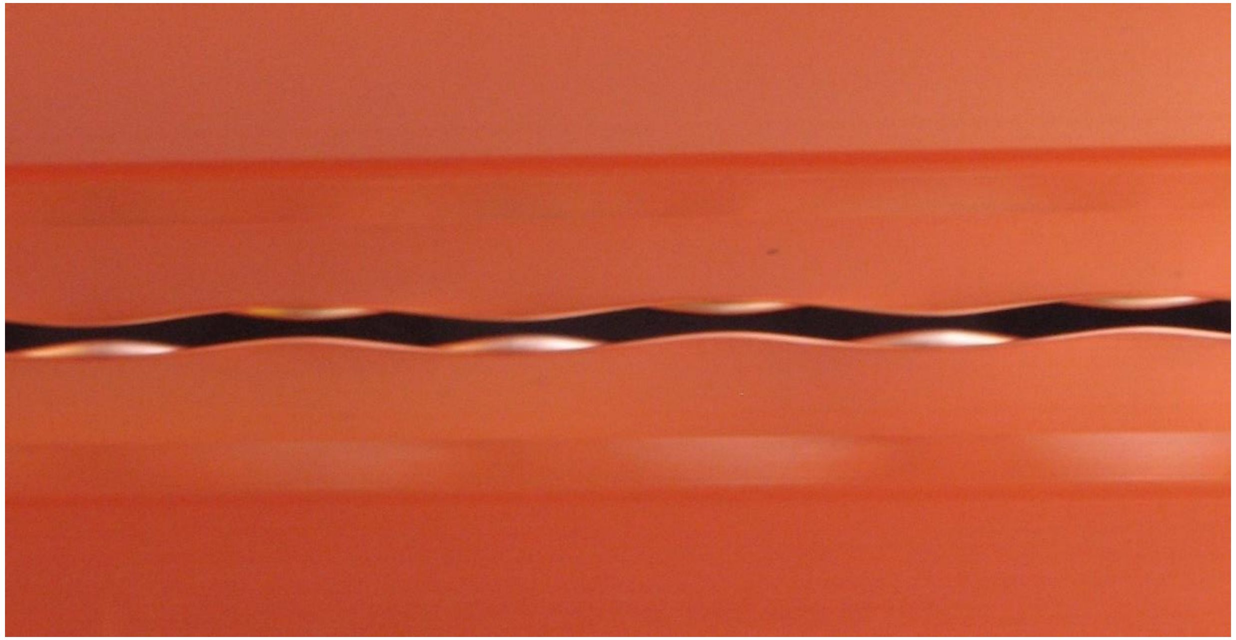
Opposite vanes (180°)



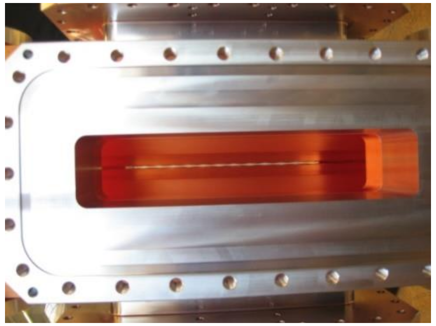
Adjacent vanes (90°)

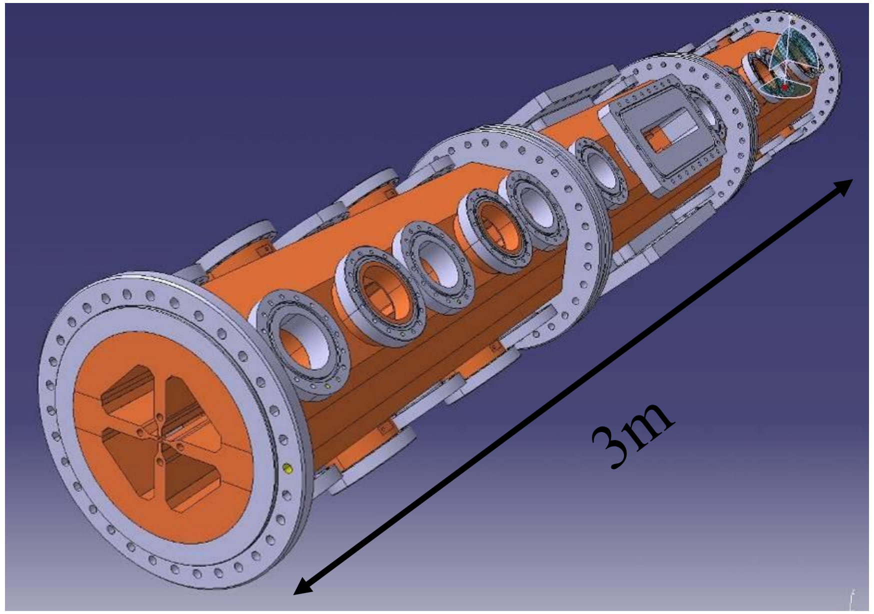


Looking into the RFQ

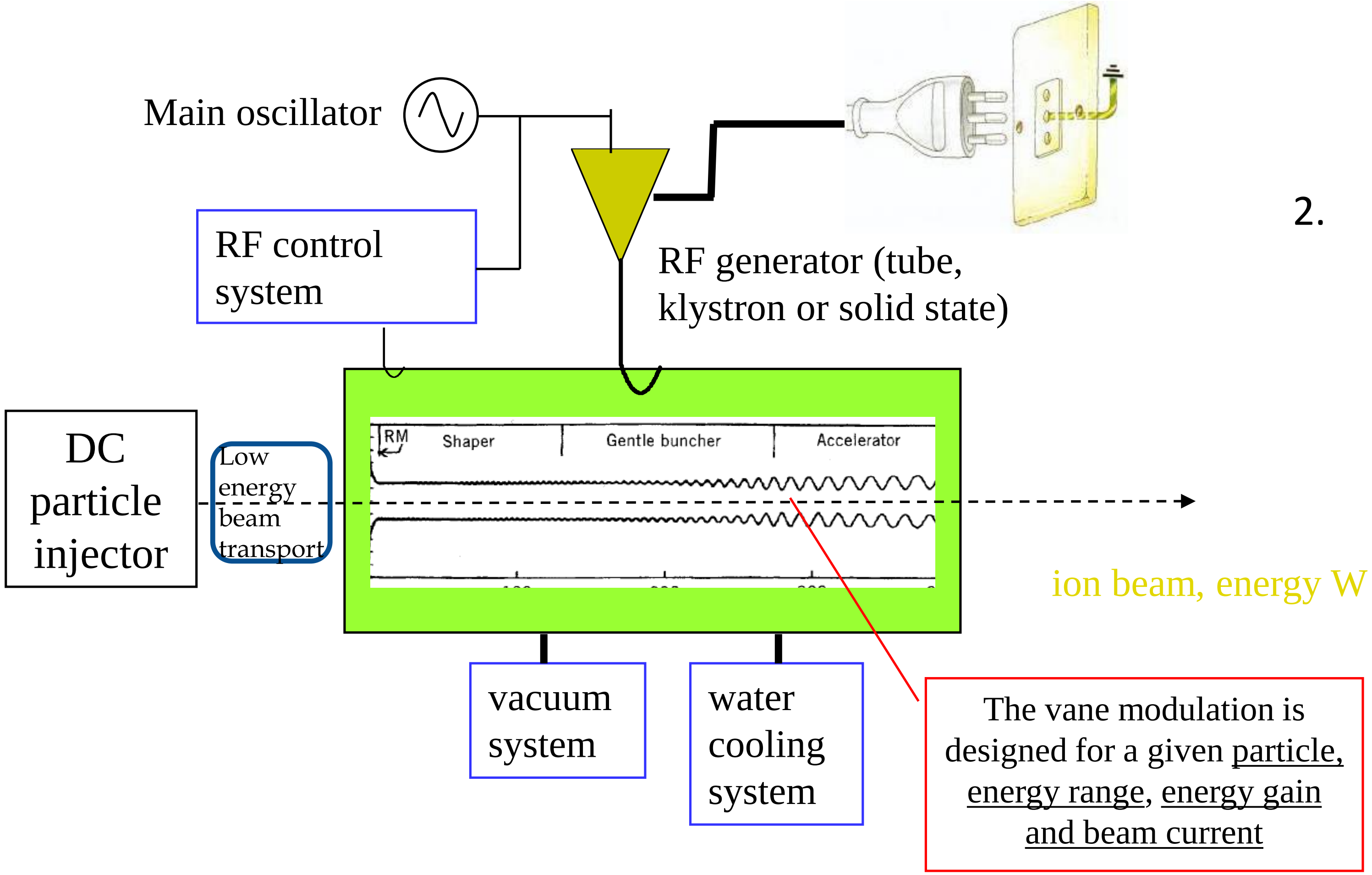


Looking from the RF port into the new CERN RFQ (Linac4, 2011, 352 MHz)

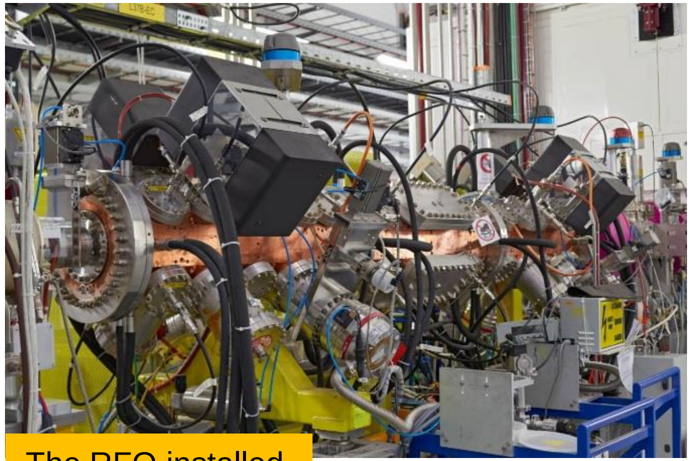




Elements of an RFQ system

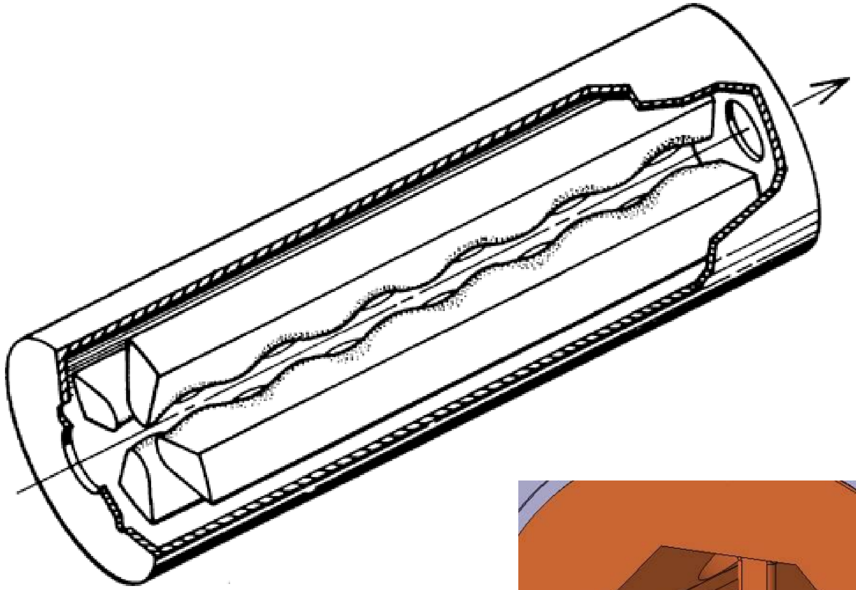


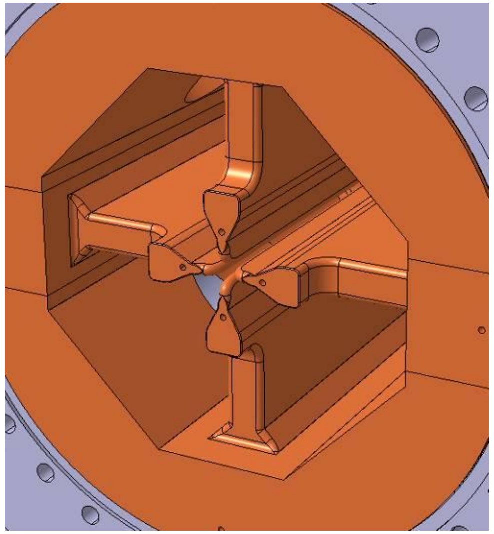
1. The **RFQ itself** is an RF cavity that contains a vane profile specifically designed for acceleration of one type of particle, at a given current and for a given energy range (input and output energy).
2. The **RFQ system** is made of all what is needed to produce a low-energy beam: ion source and beam transport, RFQ cavity, RF generator. Additional ancillary systems are RF control, vacuum, cooling.



The RFQ installed at Linac4

Tuning of an RFQ



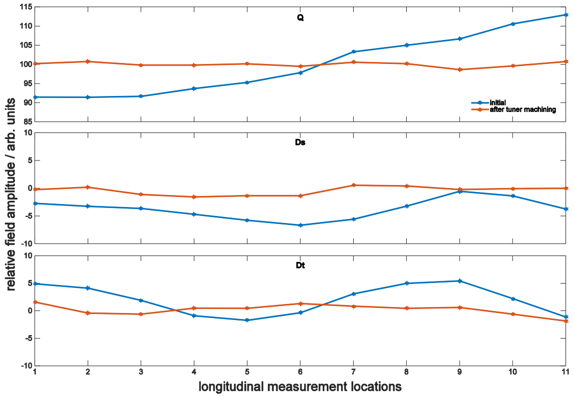


The RFQ is a cylindrical resonator containing the 4 vanes, which has to resonate at a precisely defined frequency, with a constant voltage along its length.

To ensure this requirement:

1. the cross-section and the vane terminations are carefully designed with 3D RF simulation codes.
2. Some ports are foreseen along the length for small cylinders (called "tuners") that are cut a length defined after a series of electric field measurements done in the RF laboratory after the final brazing of the RFQ.

The iterative process of adjusting the tuners is called "tuning" of the RFQ.



2. What is new in our design

Our vision

Particle accelerators have a wide potential to expand beyond their present boundaries: they are our **unique tool to access the atomic and subatomic world**.

Our technological processes are slowly moving from the **chemical dimension** to the **atomic and subatomic dimension**, and only accelerators provide a (controlled) way to access to and interact with this dimension.

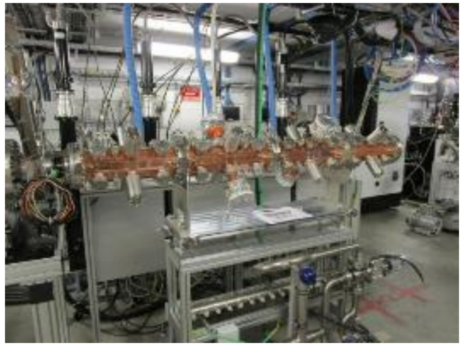
Bring accelerators out of scientific laboratories into medical and industrial environments

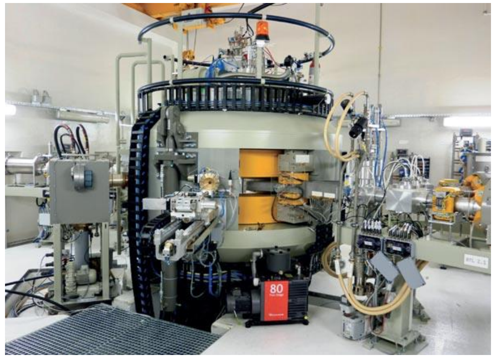
We need a **“miniature” accelerator** that:

- Brings protons above the Coulomb barrier (energy > few MeV)
- Fit in a standard size room, with no concrete bunker
- Allow you to stay next to it while it works (low radiation)
- Be low-cost, reliable and maintenance-free

A **high-frequency RFQ** is an ideal compact accelerator:

- Energies up to 10-15 MeV.
- Small dimensions, limited weight.
- Controlled beam optics, beam loss can be kept to virtually zero.
- One-piece device, zero maintenance.

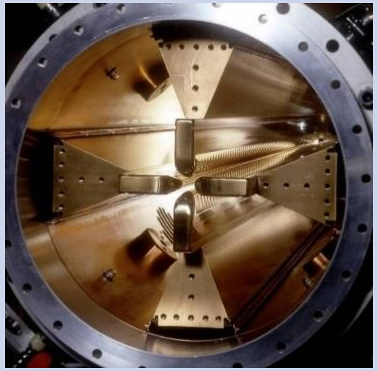
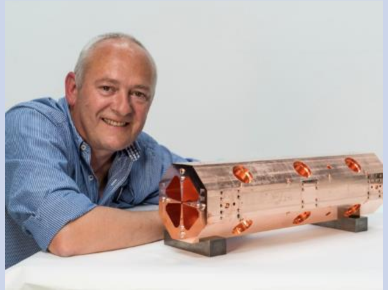




Cyclotrons, the present workhorse of low-energy medical and industrial applications, are limited by the **weight** of the magnet and by the **shielding** required by their high level of induced radiation.

RFQs have an advantage over cyclotrons for applications requiring: a) **low energy and/or low current**; b) **low radiation** or **transportability**; c) acceleration of **ions** (e.g. alpha particles).

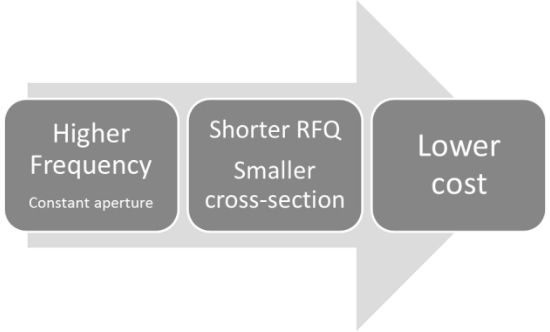
Pushing the RFQ limits

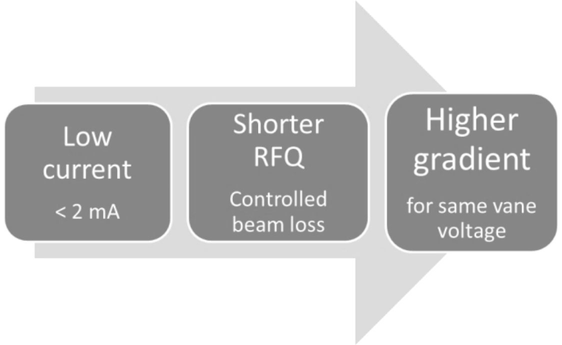
1988-92	2008-13	2014-16
Linac2 RFQ2 202 MHz 0.5 MeV /m Weight : 1000 kg/m Ext. diameter : 45 cm	LINAC4 RFQ 352 MHz 1MeV/m Weight : 400kg/m Ext. diameter : 29 cm	HF-RFQ 750MHz 2.5MeV/m Weight : 100 kg/m Ext. diameter : 13 cm
		

200 MHz → 350 MHz → 750 MHz

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

Fabrication cost per meter about 50% for HF-RFQ



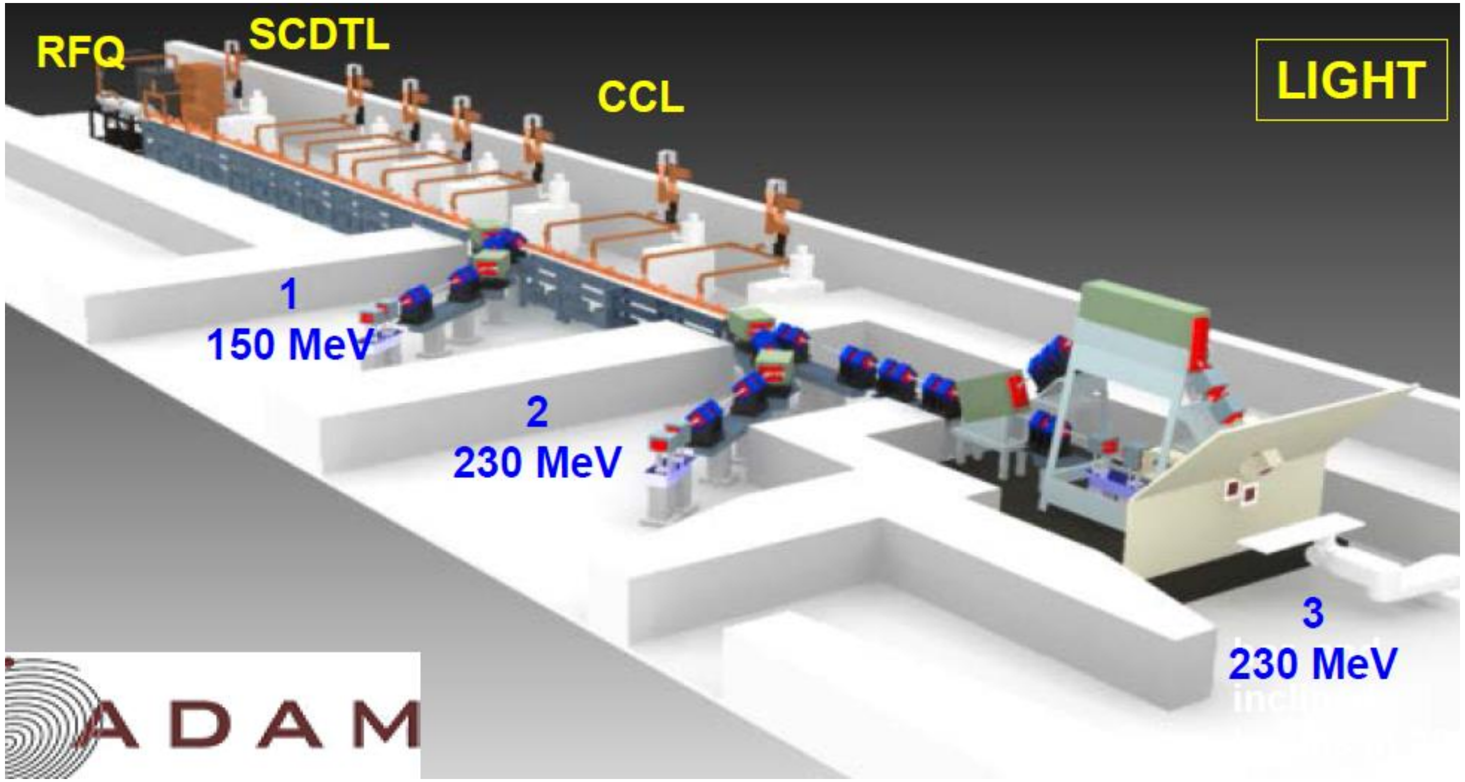


New High-Frequency (HF) RFQ at 750 MHz

ADVANTAGES:
- Smaller, less expensive construction
- Shorter, can have more cells/unit length

LIMITATIONS:
- Beam current limited by the small aperture
- Similar power requirements as conventional RFQs

Initial Application: Proton therapy



- ADAM, a spin-off company of CERN-TERA is building a proton therapy linac
- CERN contributes with an RFQ to their LIGHT project.
- Beam commissioning of the RFQ at the ADAM test stand at CERN

Interest for smal proton therapy facilites to be installed in hospitals. Linacs allow fast cycling with energy variability (precision 4D scanning of a moving organ).

RFQ has to inject into 3 GHz accelerating structures.

The first high-frequency RFQ for proton therapy

Approaching an unexplored frequency!

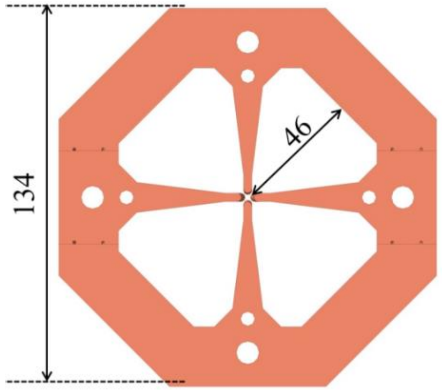
Long list of **challenges**:

- Provide enough focusing, maximize beam acceptance.
- Best compromise length / transmission: accelerate only what can be captured, eliminate the rest at low energy
- Machining the modulation in the short initial cells.
- Reduce sensitivity to errors to keep conventional machining tolerances.
- Limit the peak RF power.
- Achieve the required RF field symmetry in presence of longitudinal modes related to the short length.

Features of the new design:

- Novel “unconventional” beam dynamics design (modulation) for high-frequency.
- Full modularity: 500 mm identical modules, different only by the vane modulation (different RFQs can be composed changing # of modules).
- Multiple RF inputs (1/module) to use multiple low-power amplifiers.
- Brazed technology, based on the thermal treatment procedure developed for Linac4 to avoid deformations.
- Machining tolerances at the same level as the Linac4 RFQ, to use conventional CNC machines in a standard workshop.
- New design for RF couplers and tuners.

RF Frequency	750 MHz
Input Energy	40 keV
Output Energy	5 MeV
Length	2 m



3. RFQ Applications

Technological Roadmap

The modular high-frequency RFQ design can cover different applications. Specific beam dynamics design with different lengths covered by standard modules.

1. Injector for proton therapy linac
- 5 MeV
- Low current
- Low duty cycle (<1%)
- Completed

2. Portable accelerator for Ion Beam Analysis
- 3 MeV
- Low current
- Medium duty cycle (1-2%)
- Design completed
- In construction

3. Isotope production in hospitals
- 10 MeV
- Medium current
- Higher duty cycle (5%)
- Preliminary design

4. Ions with q/m=1/2 (alpha, deuterons, carbon 6+)
- 5 MeV/u
- Low/ Medium current
- Beam dynamics design completed

Ion Beam Analysis – PIXE and PIGE

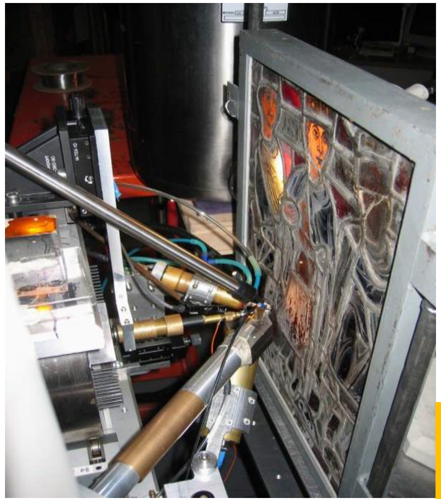
Design and build a small **transportable accelerator** delivering 2 MeV protons equipped with a **PIXE detector** (Proton Induced X-ray Emission), used for non-destructive non-invasive elementary analysis of samples, for:

- Archeometry (surface composition of cultural artefacts: paintings, jewellery, etc.)
- Environmental studies and air pollution (liquids & aerosols analysis)
- Tests and quality control in industry (metallurgy, thin films and polymer testing, pharmaceuticals,…)

Could be installed in museums, or for artefacts that cannot be displaced.

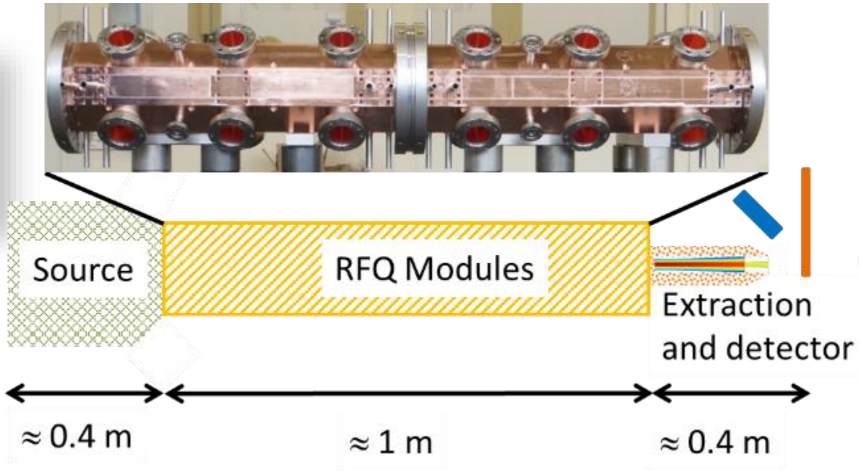
Tranportable PIXE-RFQ
Main Parameters @ 2 MeV

RF Frequency (MHz)	750
Length (mm)	1000
Input Energy (MeV)	0.02
Output Energy (MeV)	2
Average Current (nA)	100
Peak Current (μA)	1
Repetion Rate (Hz)	200
Pulse Duration (μs)	500
Duty Cycle (%)	10
Vane Voltage (kV)	35
Min Aperture (mm)	0.7
Max Modulation	2
Ro (mm)	1.4
Rho (mm)	1.4
Rhol (mm)	1.7
Transmission (%) (for matched beam)	30
Output Beam Size (mm)	± 0.1
Acceptance (π mrad mm) (Total norm.)	0.15
Output Energy Spread (keV)	10
RF Peak Power (kW)	50
RF Efficiency (%)	35
Coupleur number (#)	1
Plug Power (Total) (KVA)	14.3
Plug Number (#)	2
Power per Plug (kVA)	7.1



Stained glass panel analysed by PIXE/PIGE/RBS with 3-MeV protons

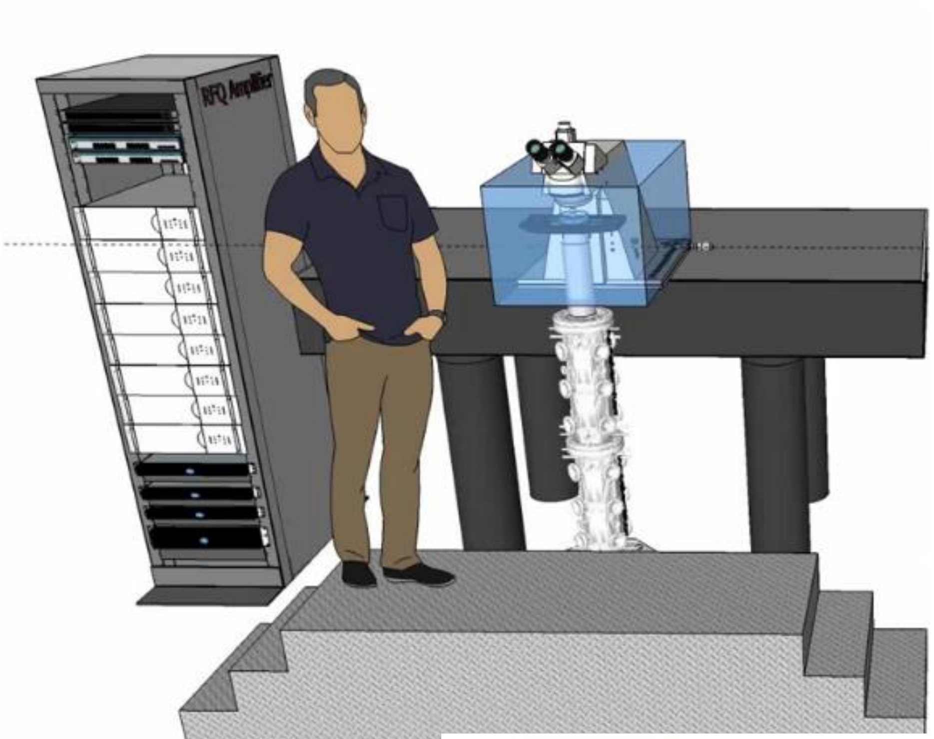
2 MeV - 1 m
Weight 110 kg
(+ 2 racks for the RF system)



An artist's view…

Real-time imaging of cellular response to proton radiation

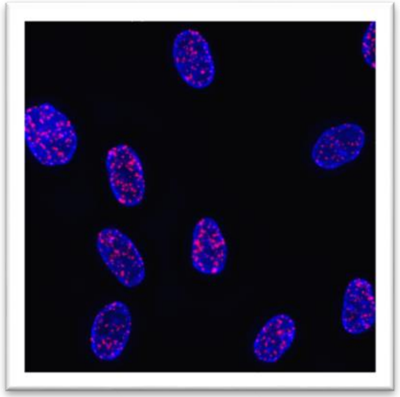
CERN

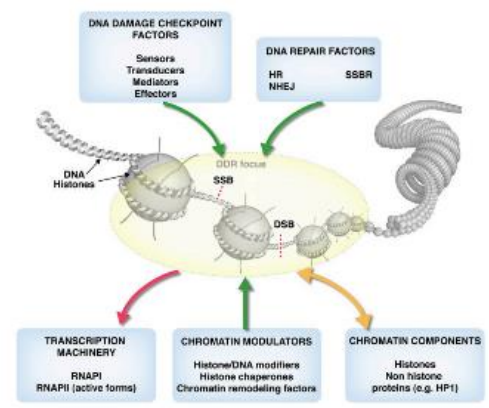


Proposal submitted by the Amsterdam Medical Centre to the Netherlands Organisation for Scientific Research

Install a 2 MeV RFQ (1m, 2 modules) in the hospital laboratory for real-time imaging of cellular response to proton radiation.
The Netherlands is strongly investing in proton therapy (4 centres in construction) but little data exist on the DNA repair mechanisms after irradiation.

This project if approved would provide a wealth of data on the effect of proton therapy that would allow optimisation of the treatment.

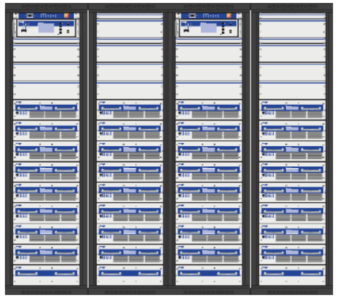




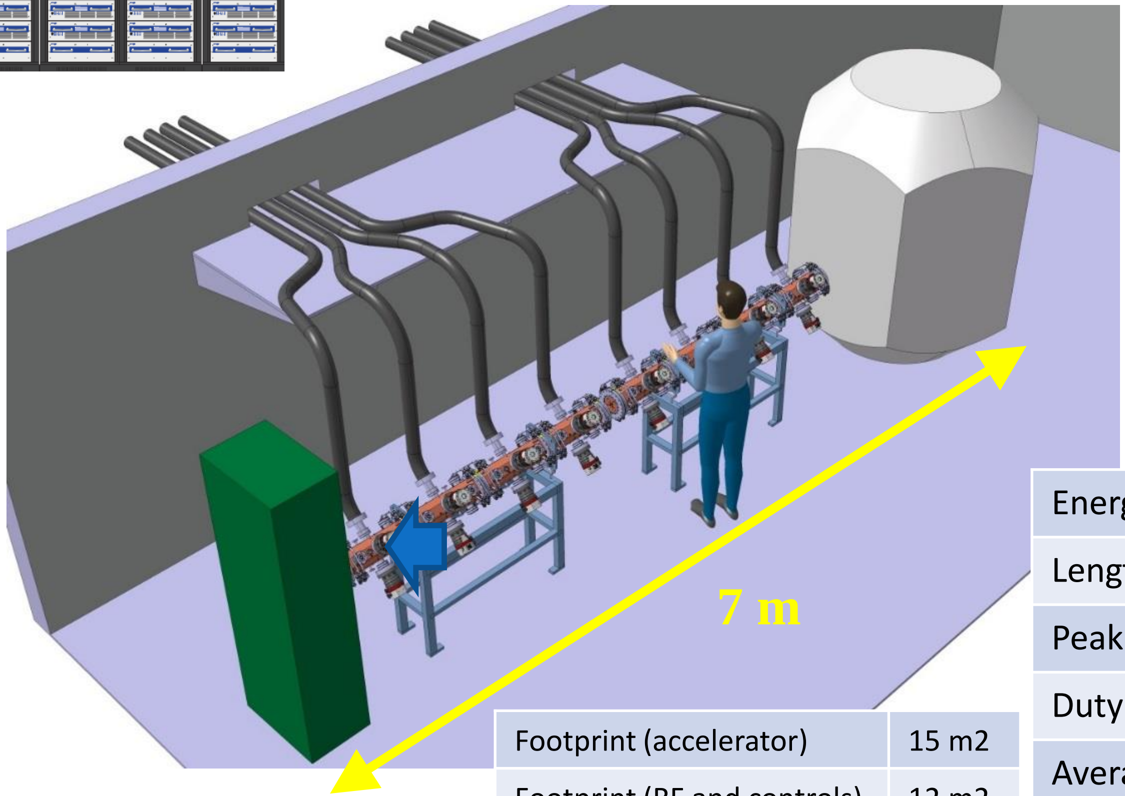
For this type of applications the competitors are the **large electrostatic accelerators** installed in several laboratories.

Isotope production

- The RFQ with a new beam dynamics design can go to to higher energy and duty cycle to make a compact **PET isotope production system**. Two consecutive RFQs for 10 MeV in a length of 4 m.
- Controlled beam loss and low weight makes it possible having the PET production unit next to the scanner **inside the hospital**, without concrete bunkers and heavy shielding.
- Simplifies logistics for isotope distribution; paves the way to a wider use of short-living isotopes (e.g. C11).



RF room



Target shielded by layers of iron and borated (6%) polyethylene, overall radius <1m (2 μSv/h at contact).

Footprint (accelerator)	15 m2
Footprint (RF and controls)	12 m2
Total weight of accelerator	500 kg
Mains power	35 kW

Energy	10 MeV
Length	4 m
Peak current	500 μA
Duty cycle	4 %
Average current	20 μA
RF power, peak	400 kW
RF power, average	16 kW

Production of ions with q/m = 1/2

The RFQ modulation can be designed for the acceleration of **charge-to-mass ½ ions** for 3 fields of application:

- Acceleration of **alpha particles** for advanced brachytherapy (local irradiation by an alpha emitter on the tumour). Techniques considered to be the new frontier of nuclear medicine; large scale production will require dedicated linacs.
- Acceleration of **fully stripped Carbon ions** (C^{6+}) to inject in an advanced (linac or synchrotron) accelerator for Carbon ion therapy. Only carbon ions can treat radio-resistant tumours.
- Acceleration of **deuterons** for neutron production, with a wide range of applications in the field of inspection and of nuclear security.