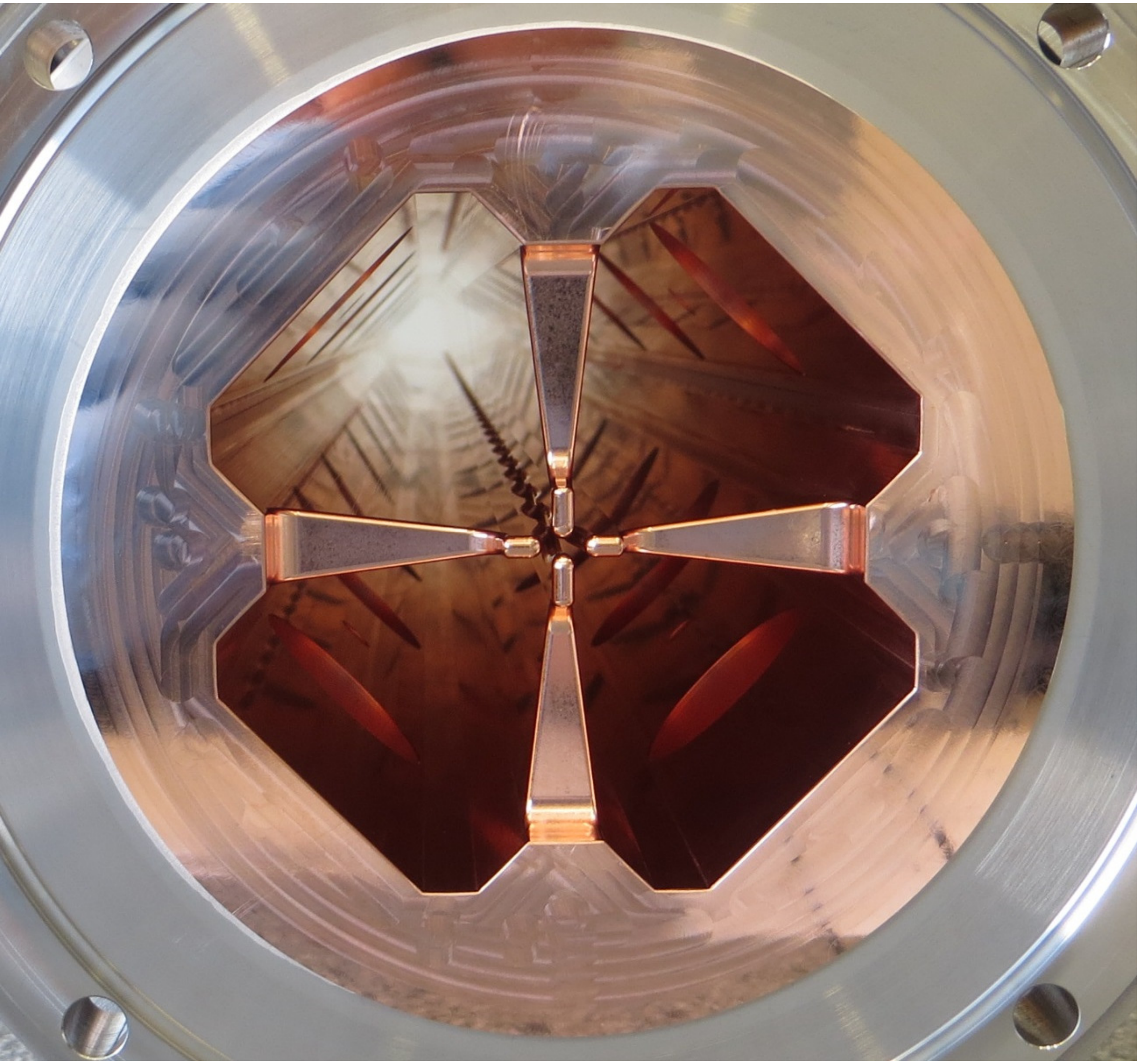
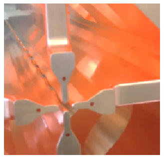


# High-Frequency Compact RFQs for medical and industrial applications


**M. Vretenar, CERN**

**for the HF-RFQ Working Group**
**(V.A. Dimov, M. Garlasché, A. Grudiev, B. Koubek, A.M. Lombardi, S. Mathot, D. Mazur, E. Montesinos, M. Timmins, M. Vretenar)**



# Pushing the RFQ limits

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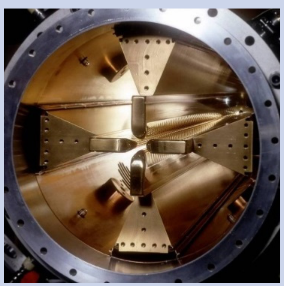
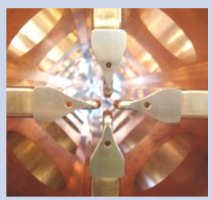
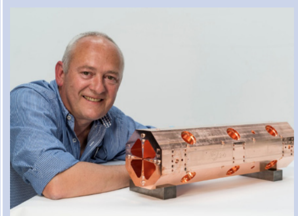
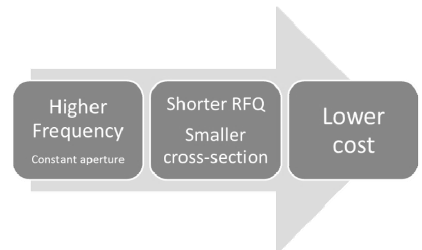
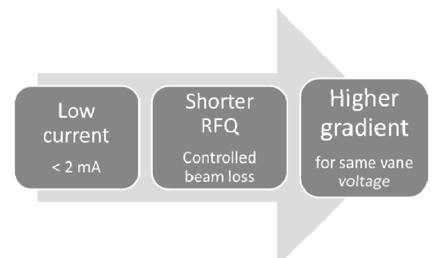
|  |  |  |

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**



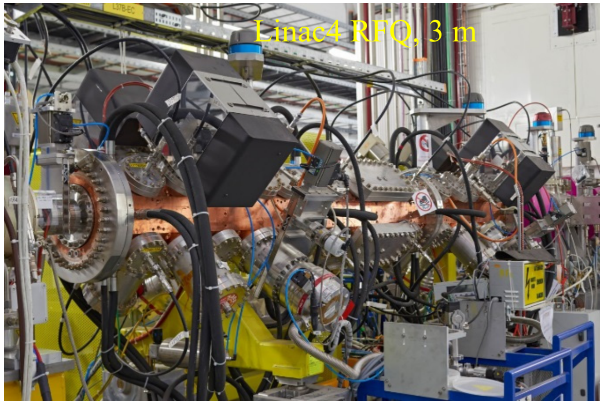

New High-Frequency (HF) RFQ at 750 MHz
ADVANTAGES:
- Smaller, less expensive construction
- Shorter, more cells/unit length

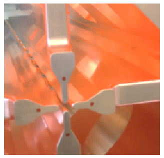
LIMITATIONS:
- Limited current
- Shunt impedance as in conventional RFQs

# Why at CERN?

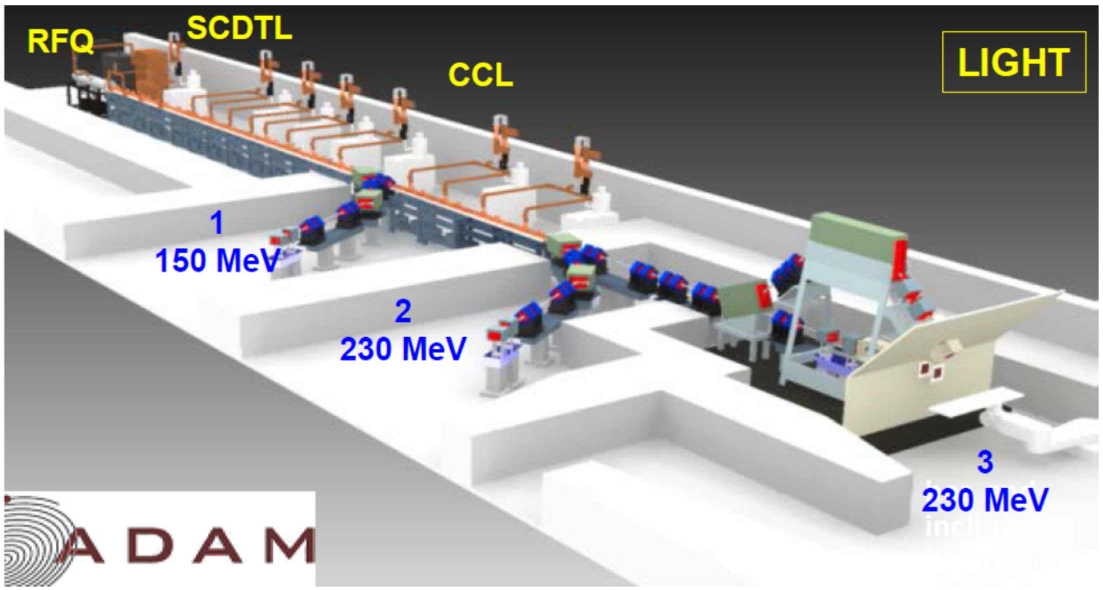
- Unique concentration of competences and experience in designing and manufacturing accelerator systems, and in operating them with high reliability.
- But the mandate of CERN is limited to particle physics.
- An opening in 2013 with the creation of the CERN Office for medical applications, with the aim for CERN to become an important facilitator of medical physics in Europe.
- Among the different applications of accelerators, in Europe there is a clear priority for medicine, which is becoming the main technology driver of 21st century.

+ large experience in linear accelerators after the completion of **Linac4**.



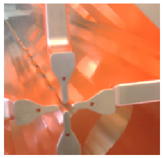


# Initial Application: Proton therapy




- 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 existing hospitals. Linacs allow fast cycling with energy variability (precision 4D scanning of a moving organ).*
*3 GHz structures take the beam only from ≈ 5 MeV energy → need a high-frequency injector.*



# A wider vision

Step towards the **"miniature" accelerator** that should:
- Bring protons above 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

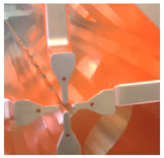
Keywords: high RF frequency, high gradient, low beam loss

A **high-frequency RFQ** is an ideal compact accelerator:
- Energies up to 10-15 MeV.
- Linear, small dimensions, limited weight.
- Controlled beam optics, beam loss outside of target can be kept to virtually zero.
- One-piece device, zero maintenance.

Broader goal: bring accelerators out of scientific laboratories into medical and industrial environments

**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.

# RFQ Design and Construction



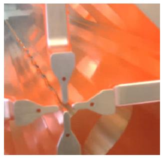
# The RFQ for proton therapy design and challenges

Long list of **challenges**:

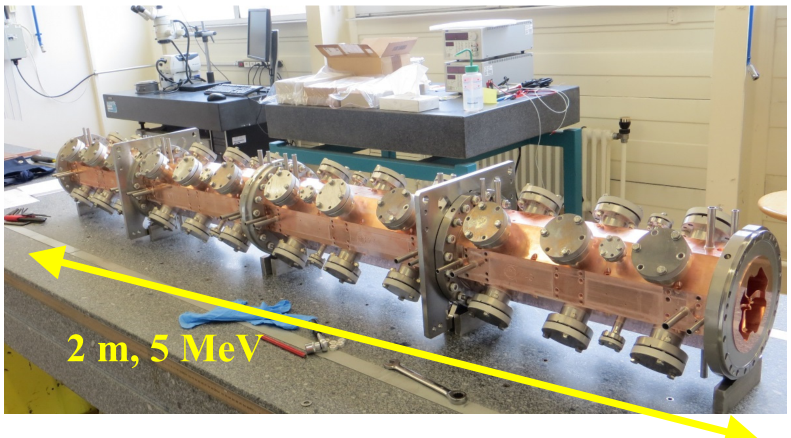
- Provide enough focusing, maximize acceptance.
- Best compromise length / transmission: accelerate only what can be captured, eliminate the rest at low energy
- Machining the modulation in the short initial cells.
- Reduce sensitivity to errors to keep conventional machining tolerances.
- Limit the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

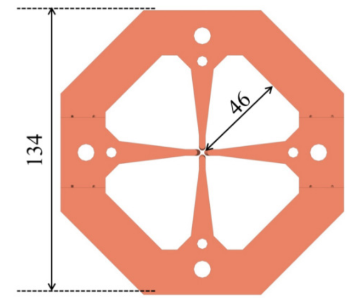
| Source and RFQ parameters | |
|---|---|
| RF Frequency | 750 MHz |
| Input Energy | 40 keV |
| Output Energy | 5 MeV |
| Length | 2 m |
| Vane voltage | 65 kV |
| Peak RF power | 400 kW |
| Duty cycle / max | 0.4 % / (5 %max) |
| Input/Output Pulse Current in 3 GHz acceptance | 100/30 $\mu$A |
| Transv. emittance 90% | 0.1 $\pi$ mm mrad |
| Average aperture (r0) | 2 mm |

*Approaching an unexplored frequency!*



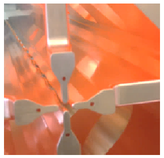
# General design – a multi-purpose RFQ



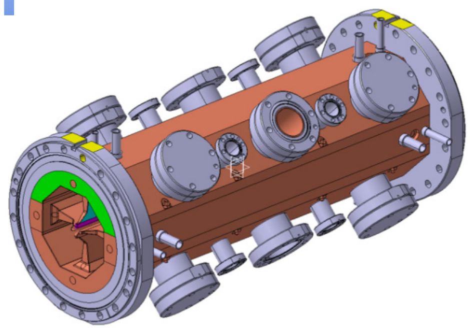

Machining tolerances **±20 μm (cavity), ±10 μm (vane tip).**
Assembly tolerance for the four vanes ±15 μm.

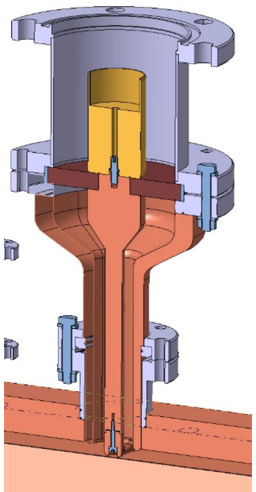
- Full modularity: 500 mm identical modules, different only by the vane modulation.
- Multiple RF inputs (1/module) to use multiple low-power amplifiers (using the RFQ as RF combiner).
- Brazed technology, based on the thermal treatment procedure developed for Linac4 to avoid deformations.
- Machining tolerances at the same level as the Linac4 RFQ, to use conventional CNC machines in a standard workshop.
- Design the module for the maximum duty cycle allowed by a simple cooling design (2 channels/vane).



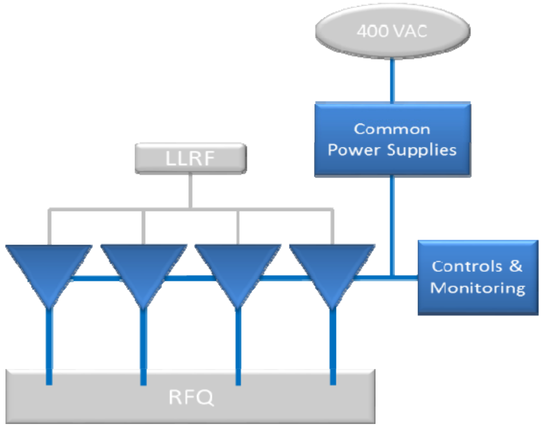
# RF design and powering system

RFQ length 5 $\lambda$
Tuning & field adjustment 8 tuners / module
Optimised tuner shape for low loss
RF coupler with PEEK window



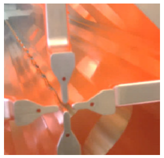


RF system:
Combine RF amplifiers into the RFQ acting as a combiner.



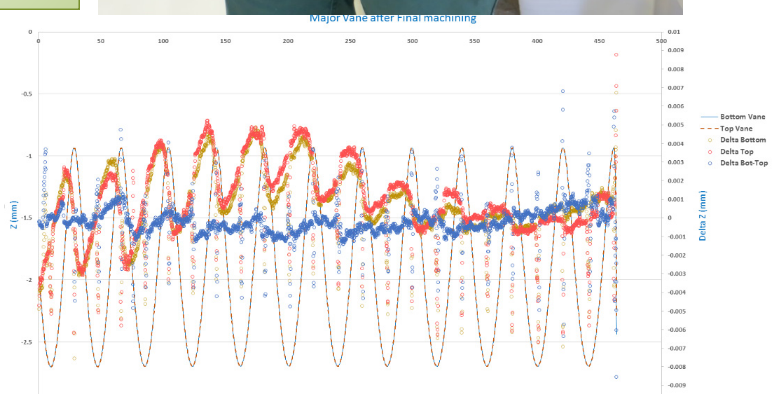

The RFQ for proton therapy will be fed by an arrangement of 4 IOT-based amplifiers on a common modulator, each connected to an RF coupler. Economic and easier to procure option.

RFQ design optmised for the use of **solid-state amplifiers,** multiple units combined into the RFQ (high reliability, no HV, low cost)

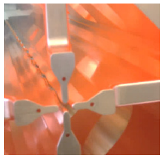


# Machining

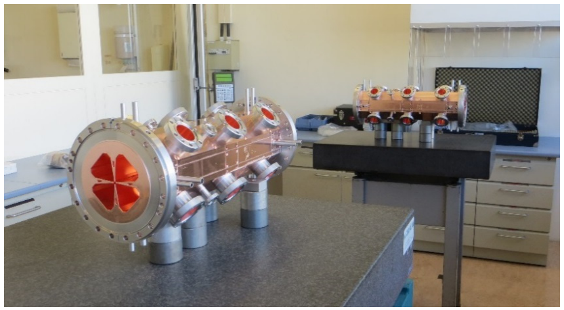
Fabrication entirely done in the CERN Workshop!



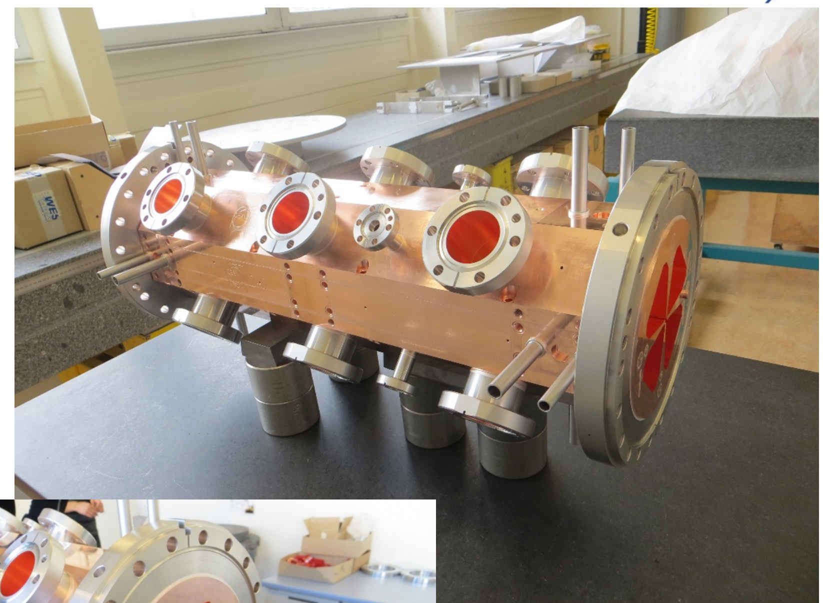

Machining errors on vane tips within ±5 $\mu$m (specs ±10 $\mu$m)

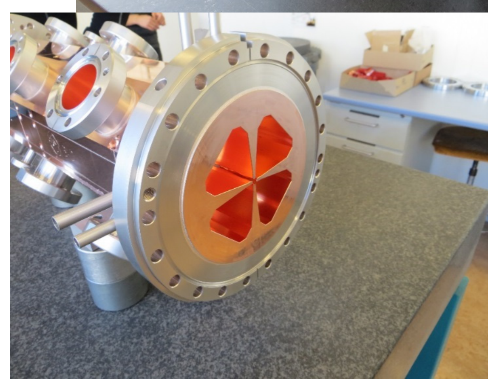


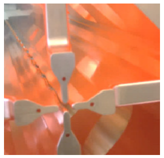
# First completed modules











# RF tuning

RF tuning completed in a record time: only **2 weeks** for field and frequency tuning!

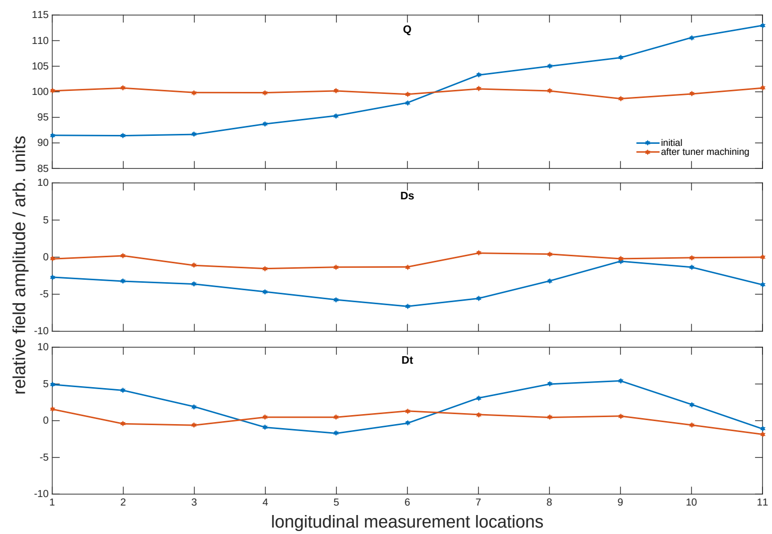
**Details on poster THPLR055 today (with oral presentation)**

| Component | Initial | Final |
|---|---|---|
| Quadrupole | ± 10.8% | ± 1.0% |
| Dipole-s | ± 3.0% | ± 1.0% |
| Dipole-t | ± 3.6% | ± 1.7% |

Excellent agreement

3Dcomputed/measured Q-value

6440 / 6570



# Transport of the 5 MeV RFQ to the beam testing area


**14 September 2016**

# Other Applications

# Technological Roadmap

The modular high-frequency RFQ design can cover different applications.
Specific beam dynamics 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

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

**Ions with q/m=1/2**

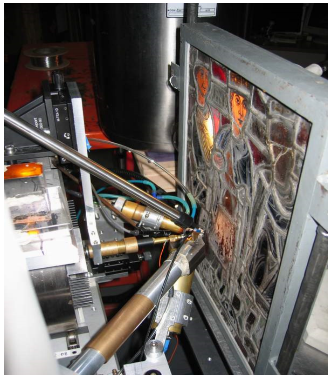
. . .

# Ion beam analysis – PIXE and PIGE

A small **portable accelerator** delivering 3 MeV protons equipped with a PIXE detector (Proton Induced X-ray Emission), used for non-destructive in-situ analysis in the domains of:

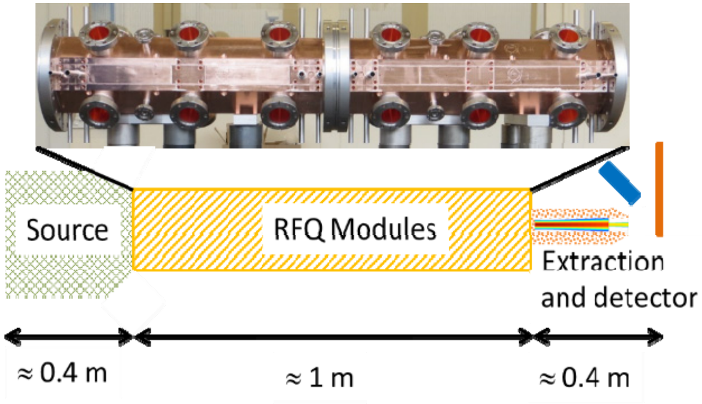
- Archeometry (surface composition of cultural artefacts: paintings, jewellery, etc.)
- Liquids & aerosols analysis
- Continuous quality control in industry (Metallurgy, thin films, …)

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



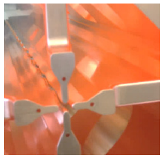
Stained glass panel analysed by PIXE/PIGE/RBS with 3-MeV protons

3 MeV - Length 1 m
Weight 100-150 kg
(+ 2 or 3 racks for the RF system)



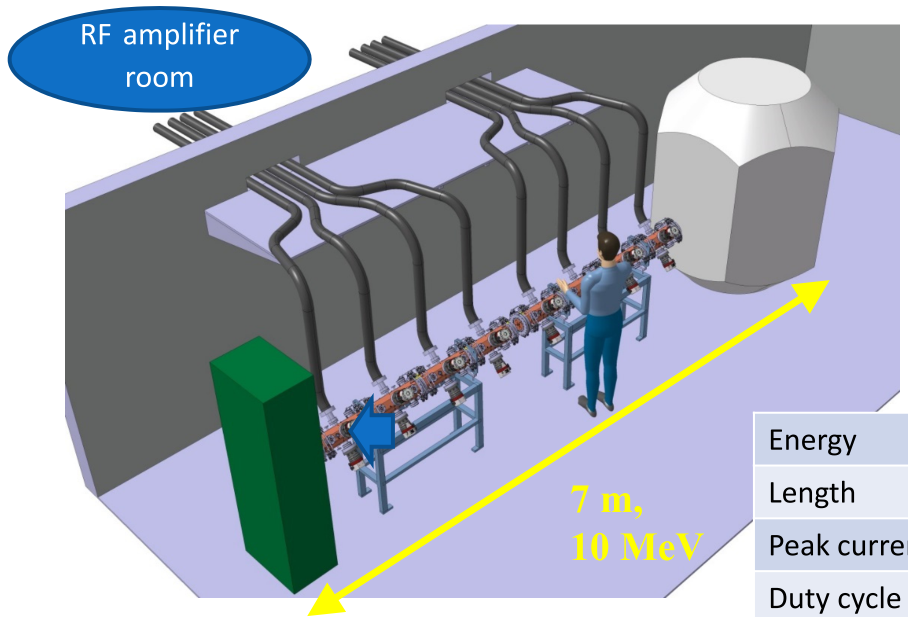

| | |
|---|---|
| Energy | 3 MeV |
| Length | 1 m |
| Peak current | 100 µA |
| Duty cycle | 1 % |
| Average current | 1 µA |
| RF power, average | 2 kW |

# An artist's view…



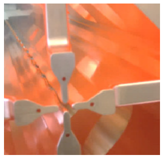
# Isotope production

- The RFQ design can be used for higher energy and maximum duty cycle for 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).




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

| | |
|---|---|
| Energy | 10 MeV |
| Length | 4 m |
| Peak current | 500 μA |
| Duty cycle | 4 % |
| Average current | 20 μA |
| RF power, peak | 700 kW |
| RF power, average | 28 kW |

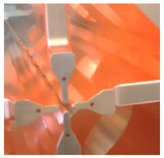


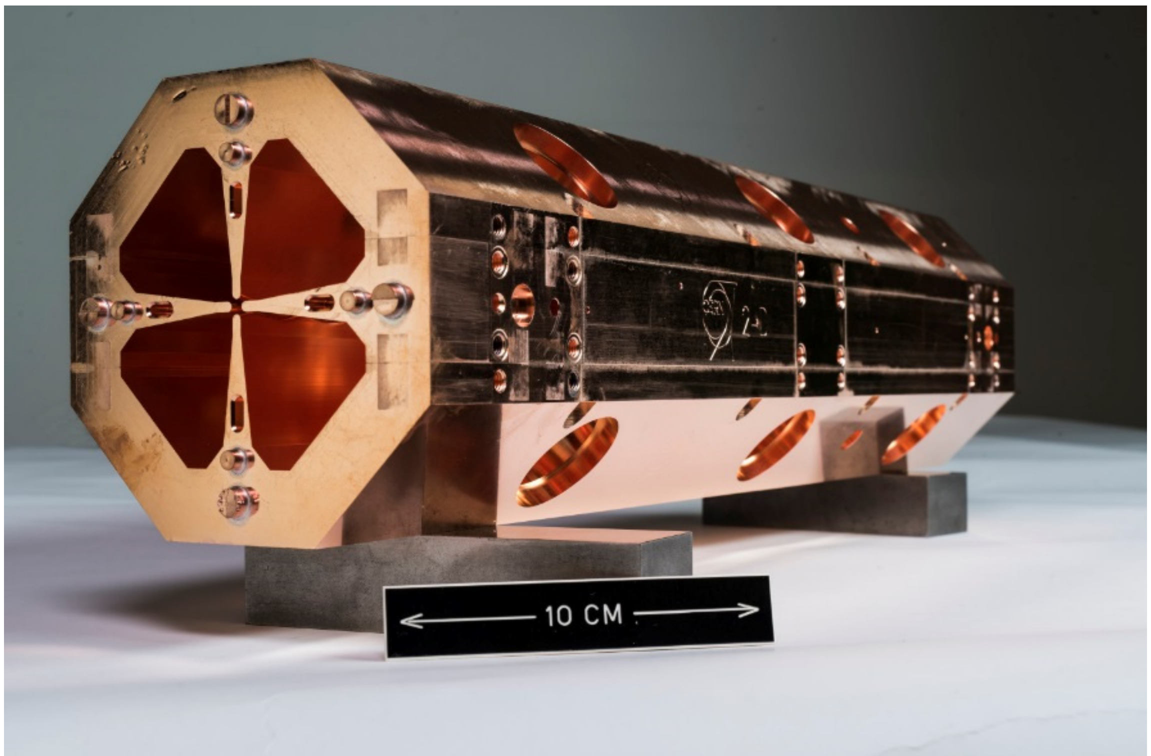
# Ions with q/m = 1/2

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** (C6+) 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 several fields.

# Conclusions and Outlook






- The beam tests foreseen this year will **fully validate** this novel RFQ design.
- In 2017 we will continue on our **technological roadmap** and address other applications; we are open to collaborations and industrial partnerships.
- This design is a small step in the direction of the **miniature / portable accelerator**, a subject with **several promising applications** and a **strong impact on public and society**.