Office for CERN Medical Applications

A compact RFQ for radio isotope production in hospitals

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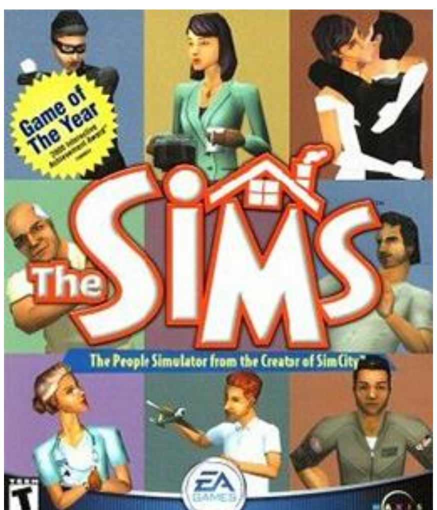
A long-term vision…

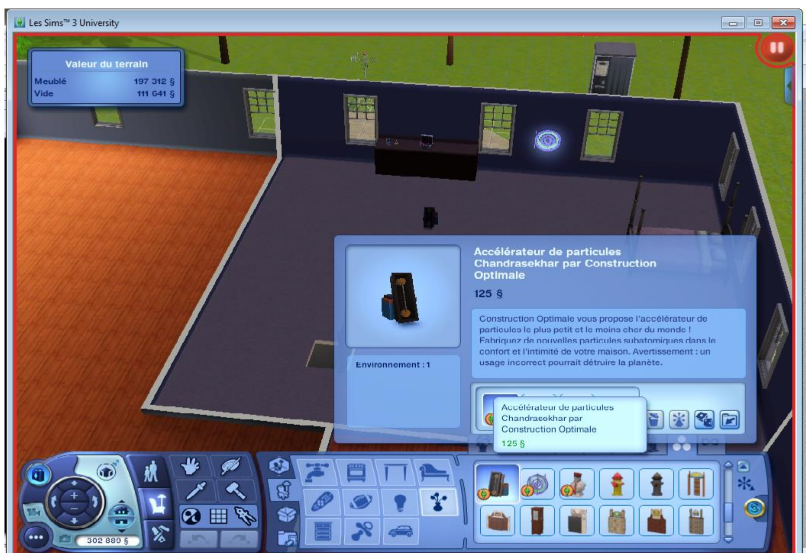
- Particle accelerators are not only scientific instruments, they are unique tools to interact with atomic nuclei and subatomic particles.
- The technologies related to manipulations of the atomic structure of the matter offer many opportunities for society that are only partially exploited, because of cost, of “radiophobia”, and of lack of contacts between laboratories and industry.
- New opportunities: cost of key technologies is decreasing, better regulation and understanding of radiation are slowly increasing the social acceptance of nuclear-related technologies, more attention is given to technology transfer from science to society.
- There is space for bringing more accelerator technology out of scientific laboratories to society: what is needed are compact, easy to operate, low radiation and low cost proton (and ion) accelerators able to cover several medical and industrial applications.
- Among the different applications, medicine has the priority. Medicine is becoming the main technology driver of 21st century (as defense was the technology driver of 20th century).

Specifications

Dreaming of the pocket-size accelerator:

- Brings protons above Coulomb barrier
- Fits in your kitchen (or in a standard industrial environment)
- Allow you to stay in (or next to) your kitchen while it works (low radiation!)
- Cheap, reliable and maintenance-free





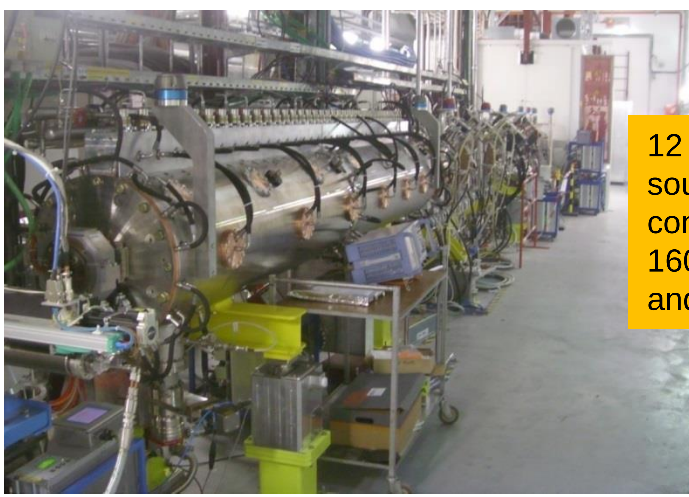
AVAILABLE IN THE VIRTUAL WORLD: In "The SIMS" (life simulation video game) you can already buy: *"the smallest and cheapest particle accelerator in the world. Produce new subatomic particles in the comfort and intimacy of your home. Notice: a wrong usage could destroy the planet."*

Linacs vs. cyclotrons

- Industrial and medical applications: standard low-energy accelerator is the **cyclotron**.
- Most of scientific applications: low-energy acceleration provided by **linear accelerators**.

Two different (competing?) technologies coming from the same origin, the work of Ernest O. Lawrence team at Berkeley in the 30's – great success of the cyclotron, interest for linacs came only after WWII when high RF frequencies became available.

	Principle	Operation	Focusing	Extraction	Beam quality	RF power	Cost	Maintenance
CYCLOTRON	Cyclic (magnet based)	CW	Weak	Lossy	Average	**Low**	**Low**	Higher
LINAC	Linear (RF based)	Pulsed	**Strong**	**Clean**	**Good**	High	High?	**Lower**



12 MeV section (from left, DTL1, RFQ, source) of the CERN Linac4 under commissioning at CERN. Linac4 is 80 meters, 160 MeV, 80 MEUR (500 kEUR/MeV building and infrastructure included)

E. O. Lawrence

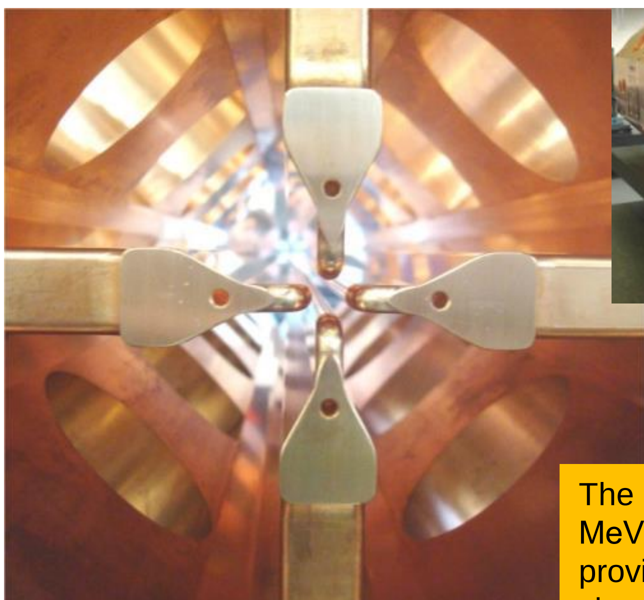
Modern linacs: the RFQ

Acceleration up to 5 – 10 MeV by the **RFQ = Radio Frequency Quadrupole**

A relatively new technology (invented in Russia in the 70’s, first prototype RFQ in the USA 1980, becomes the standard low-energy linac from the 90’s).

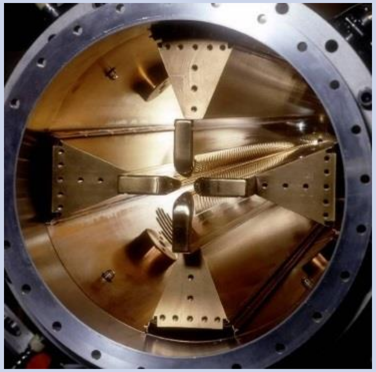
Follows the ion source and can simultaneously accelerate, focus and bunch large currents of protons and ions up to several MeV’s without beam loss and with excellent output beam quality.

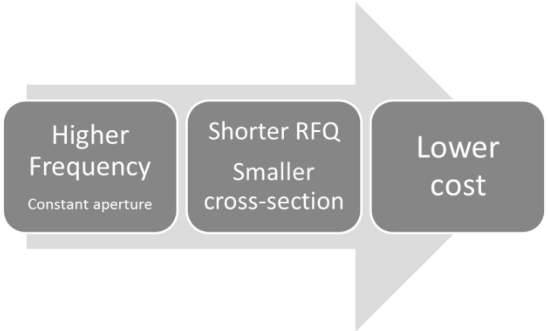
Reliable (one-button machine), no maintenance, but relatively high construction cost

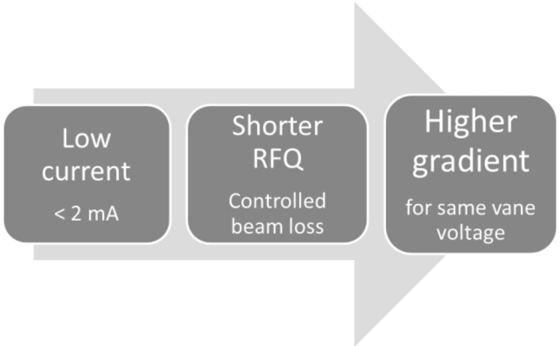


The CERN Linac4 RFQ, 0.05 to 3 MeV, 3 m. Four electrodes (“vanes”) provide a quadrupole focusing field, a sinusoidal profile machined on the vane tips provides acceleration.

Pushing the RFQ limits

1990	2007	2014
RFQ2	LINAC4 RFQ	HF RFQ
200 MHz	352 MHz	750MHz
0.5 MeV /m	1MeV/m	2.5MeV/m
Weight : 1000 kg/m	Weight : 400kg/m	Weight : 100 kg/m
Ext. diameter : 45 cm	Ext. diameter : 29 cm	Ext. diameter : 13 cm
		





HIGHER FREQUENCY

Initial RFQs in the 200 MHz frequency range
Later, 400 MHz range (Linac4, 352 MHz).
New frequency range 700 – 800 MHz

New development at 750 MHz
-Smaller, less expensive construction
-More cells/unit length, shorter
But:
-Lower current capability
-Same range of RF power

Fabrication cost per meter about **50%** at 750 MHz w.r.t. 350 MHz

Why linacs ?

The HF-RFQ team at the CERN Linac2
the source of all protons for the LHC

Behind the group, the Linac2 RFQ (0.09-0.75 MeV), to the right the orange DTL Tank1 (10 MeV).

- **Note 1**: in Alessandra Lombardi's hands, a pole of the new RFQ (50 cm), providing the same energy gain of the Linac2 RFQ (1989, 1.8 m).

- **Note 2**: during the photo session, Linac2 was accelerating protons for the LHC with a peak current of 180 mA (18 μA average) present in the linac. There is no shielding towards the high-energy side. Linacs are virtually loss-free, all beam loss is concentrated in the target.

Technological Roadmap

Develop a modular high-frequency RFQ design covering 3 applications:

1. Injector for proton therapy linac

- 5 MeV
- Low current
- Low duty cycle (<1%)

- In construction

2. Isotope production in hospitals

- 10 MeV
- Low current
- Medium duty cycle (<5%)

- Design

3. Brachytherapy isotopes or Technetium production in dedicated centers

- 20 MeV
- Includes DTL linac
- High current
- High duty cycle (10%)

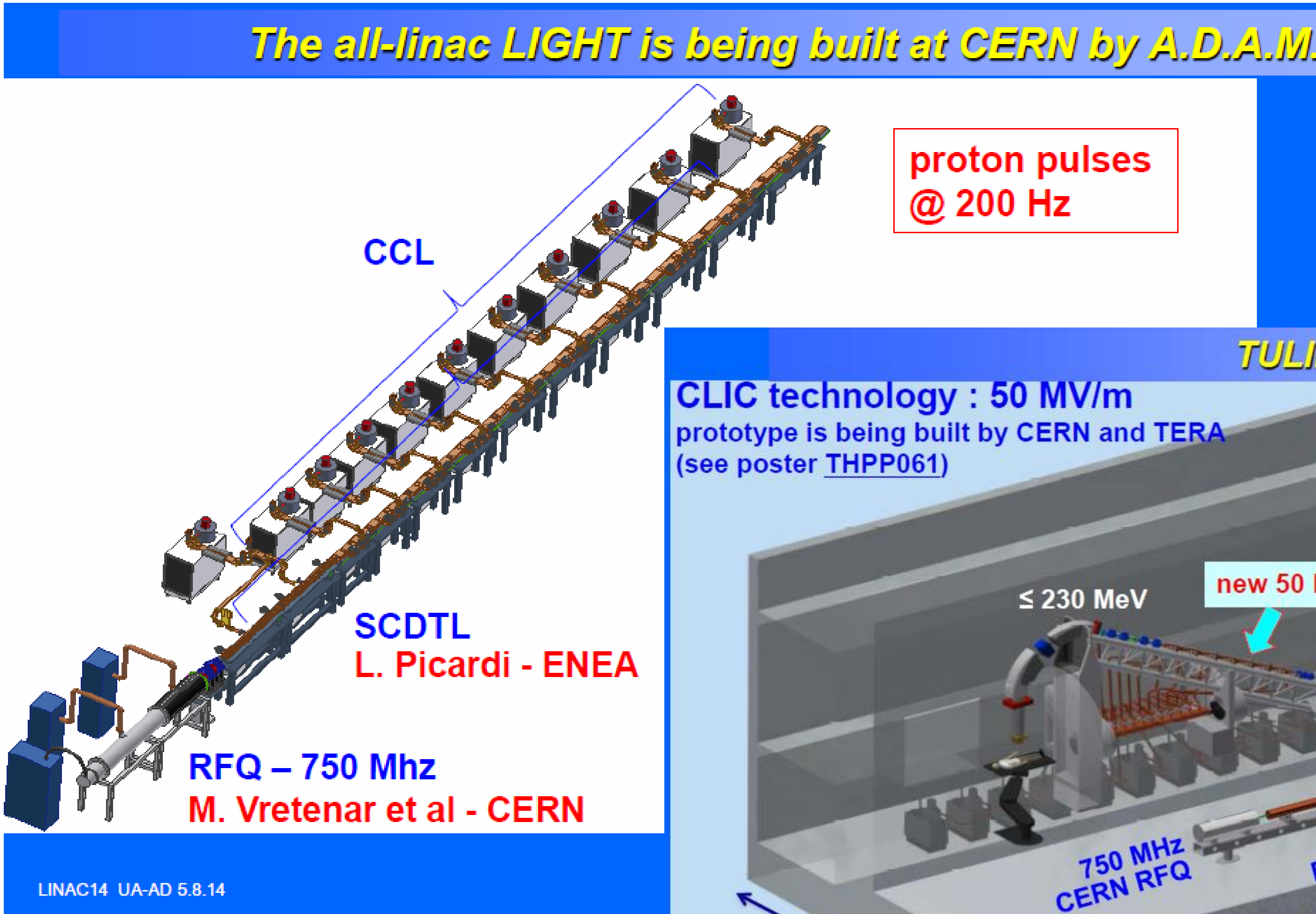
- Preliminary design

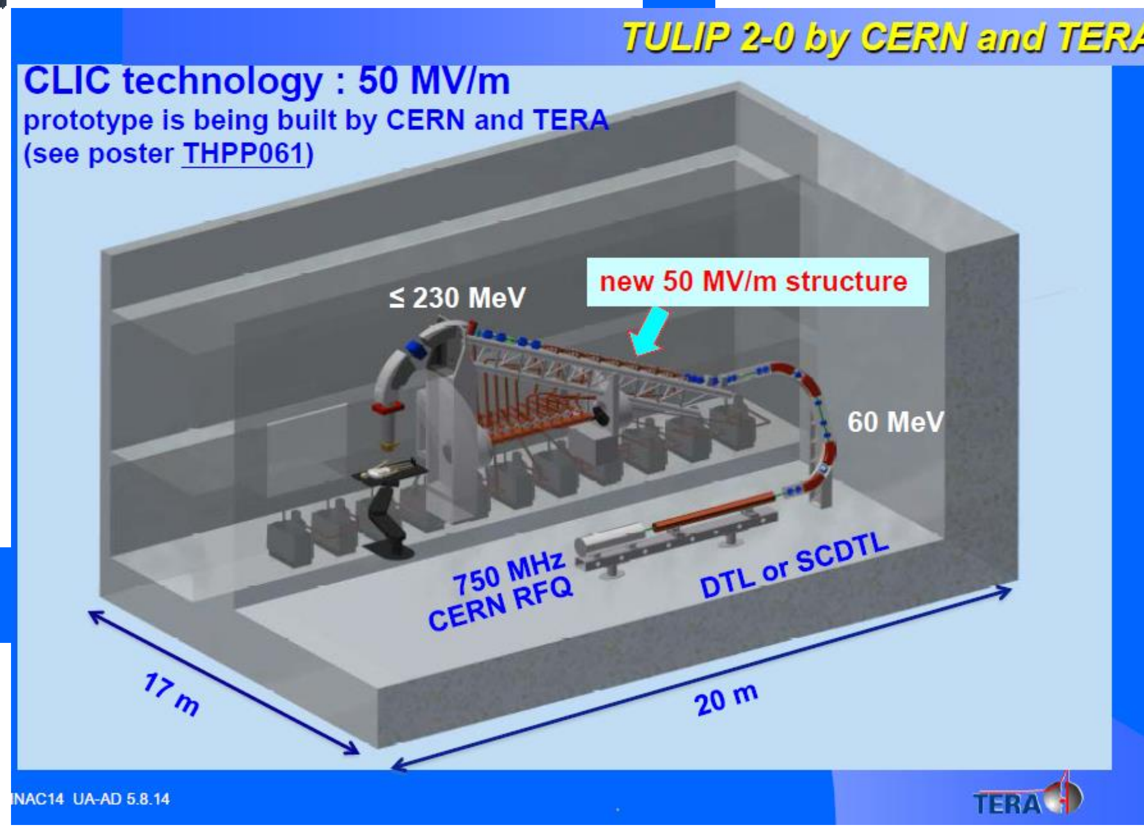
Increasing complexity from one step to the next, will profit of experience from previous step

Proton therapy RFQ at 750 MHz (submultiple of 3 GHz), others in range 700-800 MHz

RFQ for Proton therapy

2 examples of proton therapy linacs using the HF-RFQ as injector



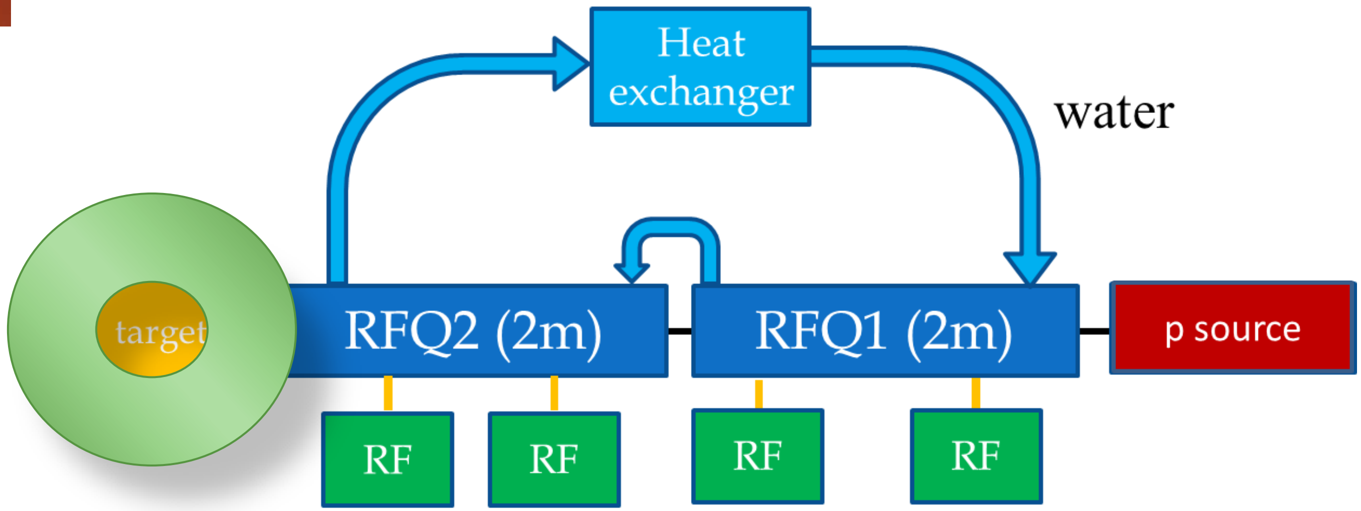


Basic parameters

	Step 1	Step 2	Step 3	
Application:	Injector for Hadron Therapy Accelerator	PET Isotope Production	^{99m}Tc Production	Isotope Production for Brachytherapy
Particle:	p^+	p^+	p^+	α / d^+
Beam energy (MeV)	5	10	18	20
Accelerator length (m)	2	4	≈10	≈10
Average current (mA)	0.015	0.02	1	~0.1
Peak current (mA)	0.3	0.5	10	~1
RF Frequency (MHz)	750	750	704	704
Duty Cycle (%)	< 1	4	10	10
Peak RF Power (kW)	400	800	≈1500	≈1500

Note: higher current (~10 mA) can be obtained with a lower frequency RFQ (eg. 350 MHz)

The isotope RFQ system

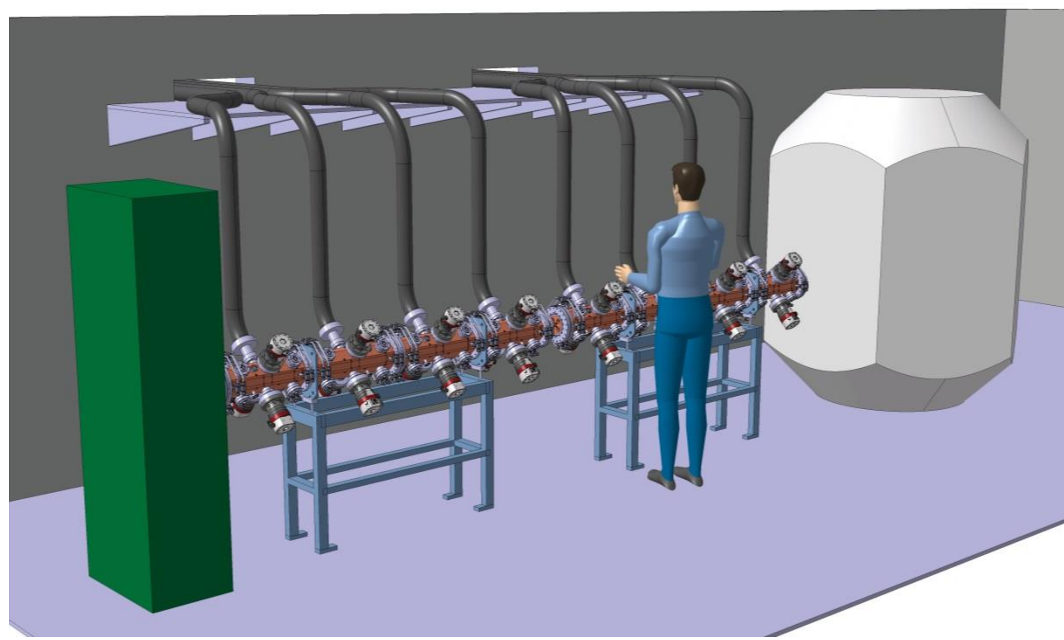


To be installed in hospitals (or movable on a lorry?)

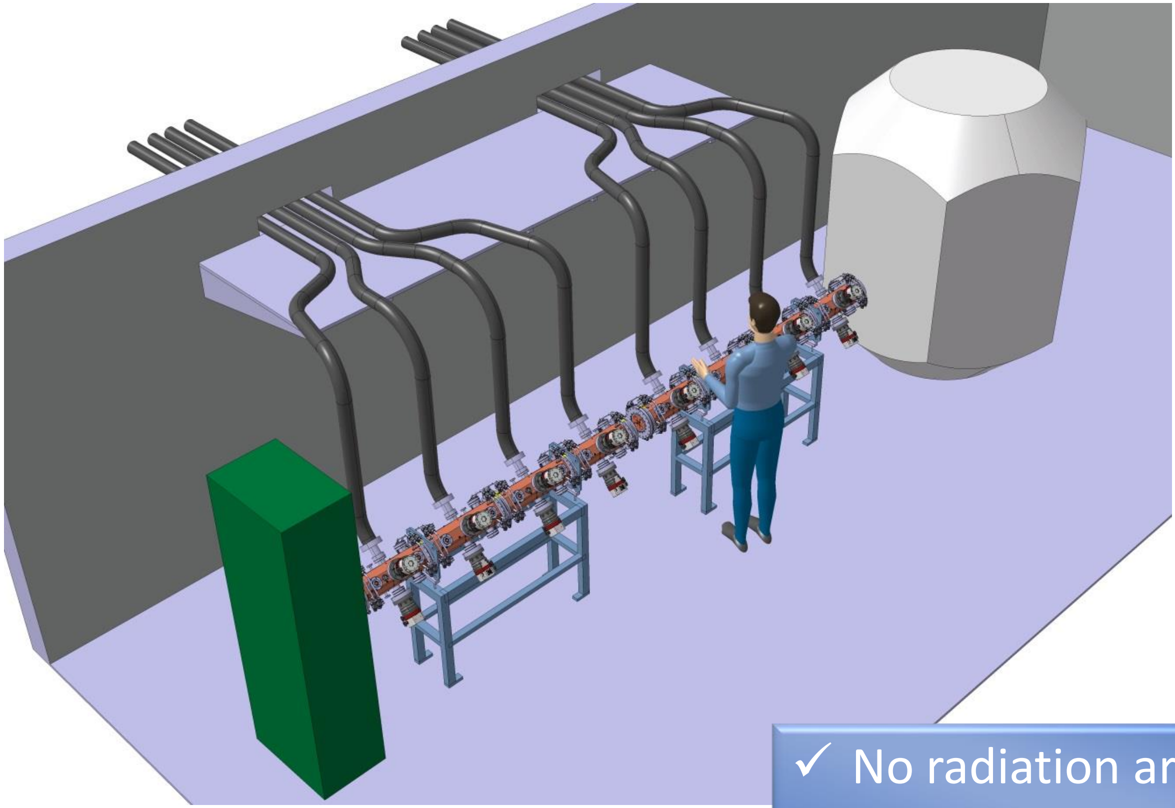
2 (or more) movable targets.

Target shielded by layers of iron and borated (6%) polyethylene, overall radius <0.9 m.

Maximum calculated dose at shielding 2 μSv/h



Parameters for compact isotope RFQ system



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

Production for PET scans of ^{18}F and ^{11}C

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

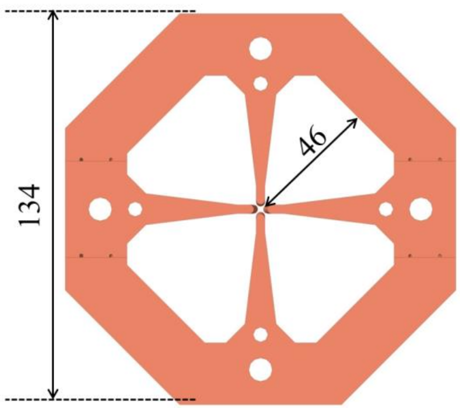
Industrial partnerships

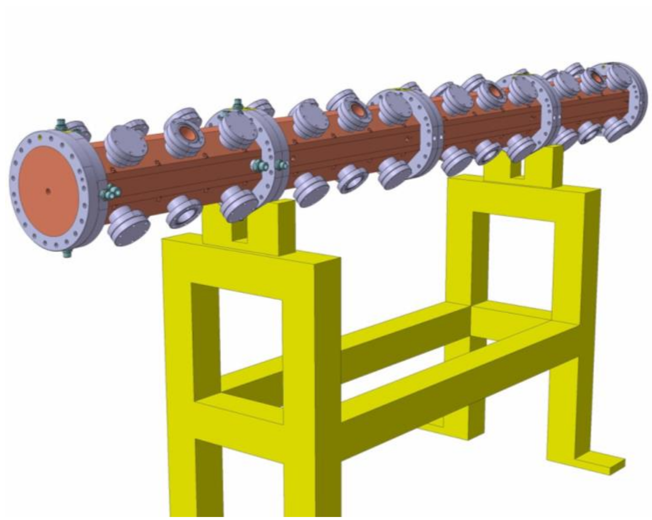
- Step 1: Initial development and RFQ construction financed by CERN Office for Medical Applications. Testing and validation under partnership agreement with ADAM (Application of Detectors and Accelerators to Medicine, part of the UK Group AVO Advanced Oncotheraphy). ADAM provides the components and infrastructure for testing the RFQ with beam and will test the RFQ in front of its prototype hadron therapy linac (the LIGHT project).
- Step 2, isotope production: CERN is developing the design of RFQ and target shielding, and is planning innovative designs for the RF power sources. ***Presently looking for partners*** (scientific and industrial, option of using the SME instrument of Horizon 2020).
- Step 3, brachytherapy: to be developed in a collaborative environment (European project?).

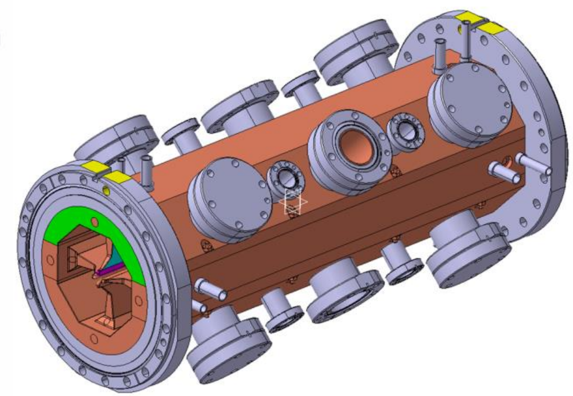
In parallel: Intellectual property related to the novel RFQ is open for licensing

RFQ Mechanical design

Mechanical design and construction procedure based on the Linac4 RFQ: 4-vane structure with 2 brazing steps. Inner radius 46 mm; total weight 220 kg.
Mechanical tolerances ±20 μm (cavity), ±10 μm (vane tip).
Assembly tolerance for the four vanes ±15 μm. Surface finishing Ra=0.4 μm.

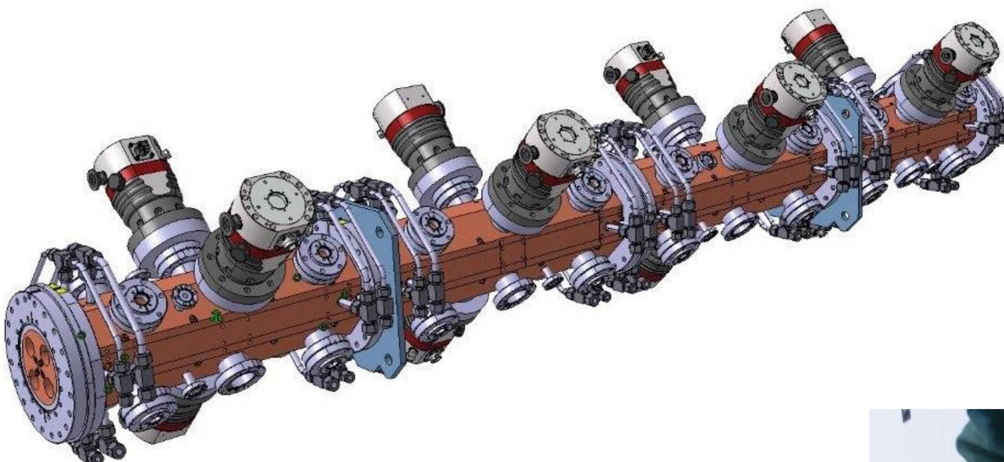






Modular design: assembly of four 0.5 m long modules, each with 8 tuning ports and 4 combined tuner/power coupler ports. The modules differ only by the vane modulation (and for the end cells at both ends).

A small RFQ…



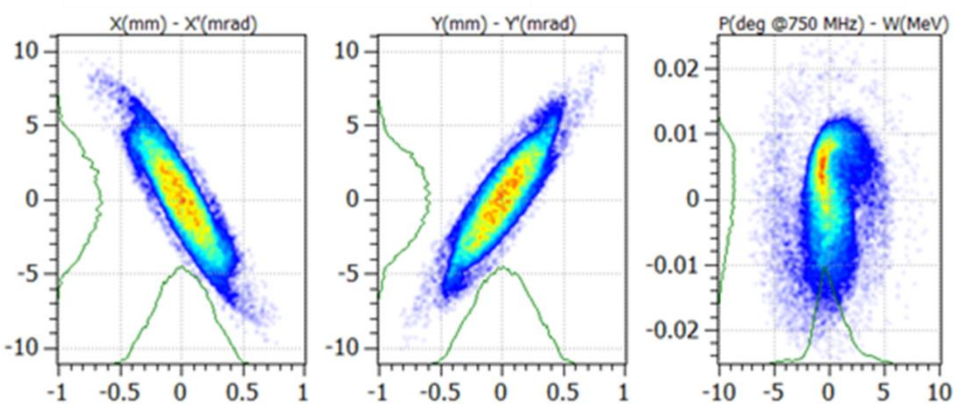
Modulation test machining

Major Vane, rough machined

Beam dynamics

Input/Output Energy	40 keV / 5 MeV
Length	1.964 m
Vane voltage	67.6 kV
Min aperture radius	1 mm
Maximum modulation	3
Final synchronous phase	-15 deg
Output current (max.)	300μA
Beam transmission	30 %
Output transv. rms emit.	0.027 p.mm.mrad
Output phase spread	± 2 deg
Output energy spread	± 20 keV

Compromise between transmission efficiency and acceleration per unit length; controlled beam loss at energies < 500 keV (transmission efficiency only 30%); 99.5% of the lost particles have an energy below 100 keV.



Output Phase Spaces

Controlled particle loss:
The design is such that particles that could be lost at high energy are instead eliminated at low energy, below the activation threshold.

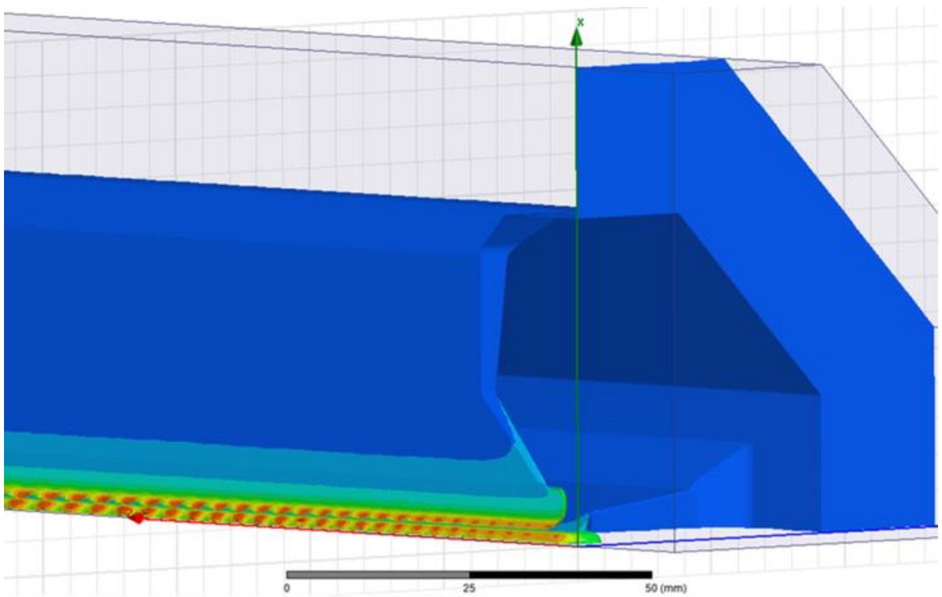
RF Cavity design

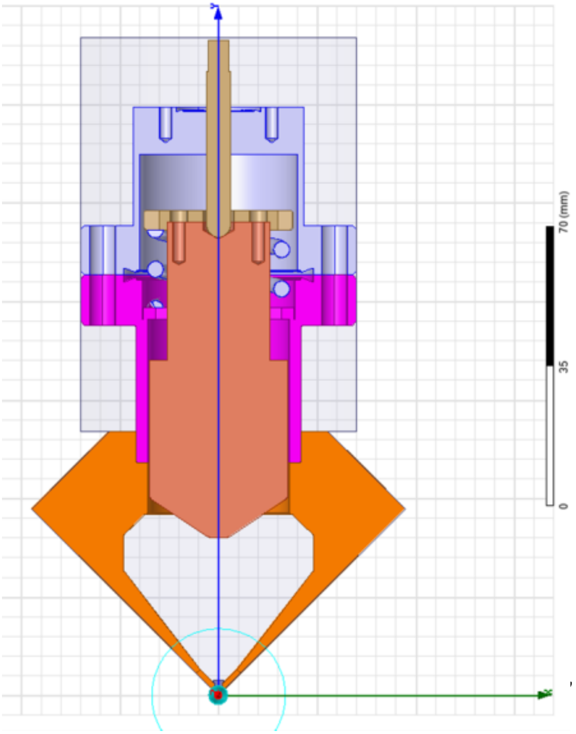
Set of detailed 3D simulations; developed a strategy for tuning long RFQs (5λ).

Minimised power consumption (optimization of the transverse cross-section, reduction of vane voltage).

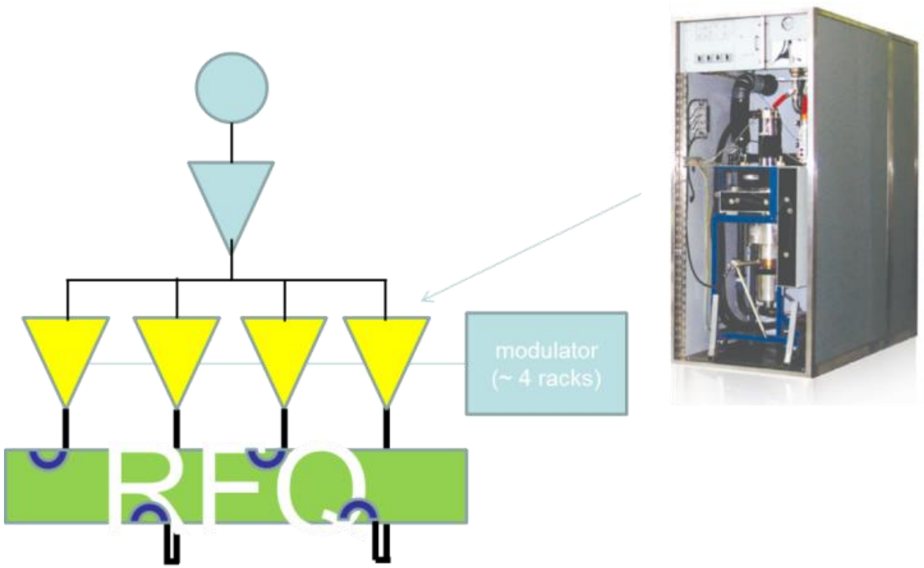
Conservative power factor of 1.5 as a margin for all 3D and surface effects → RF power 400 kW.

Detailed and innovative design of tuners (low power consumption).





RF amplifiers



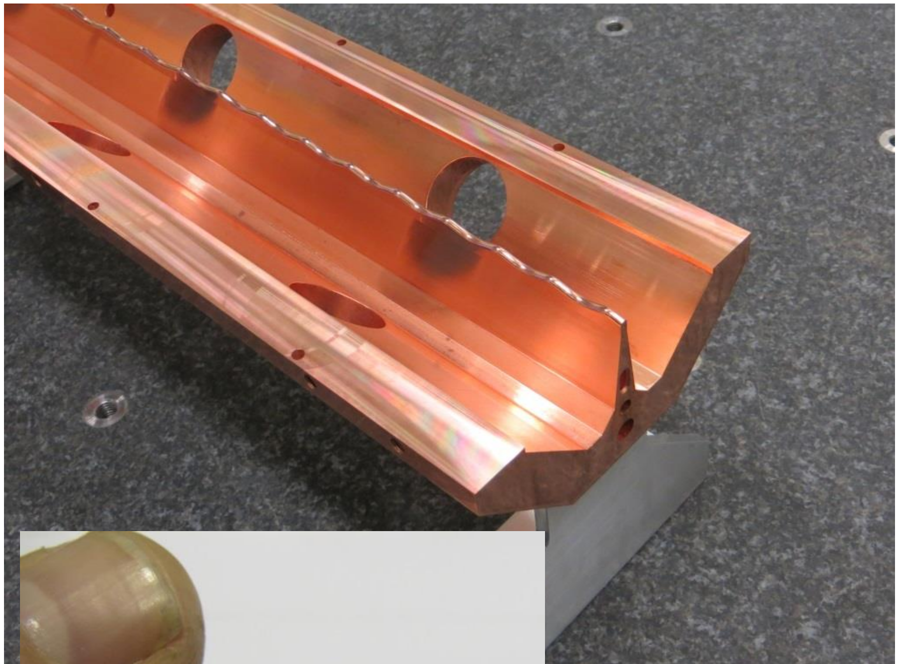
Basic concept:
Combine several small RF amplifiers into the RFQ (that acts like a combiner).

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. Most economic and easier to procure option.

For the isotope production RFQ, **solid-state amplifiers** will be used for reduced cost and increased reliability (no HV, hot exchange of faulty modules).

- *Profit of the rapid increase of power and decrease of cost of RF transistors.*
- *Develop «stripped-down» units with minimum control and electronics.*
- *Use innovative architectures.*

Construction Status



First completed major vane

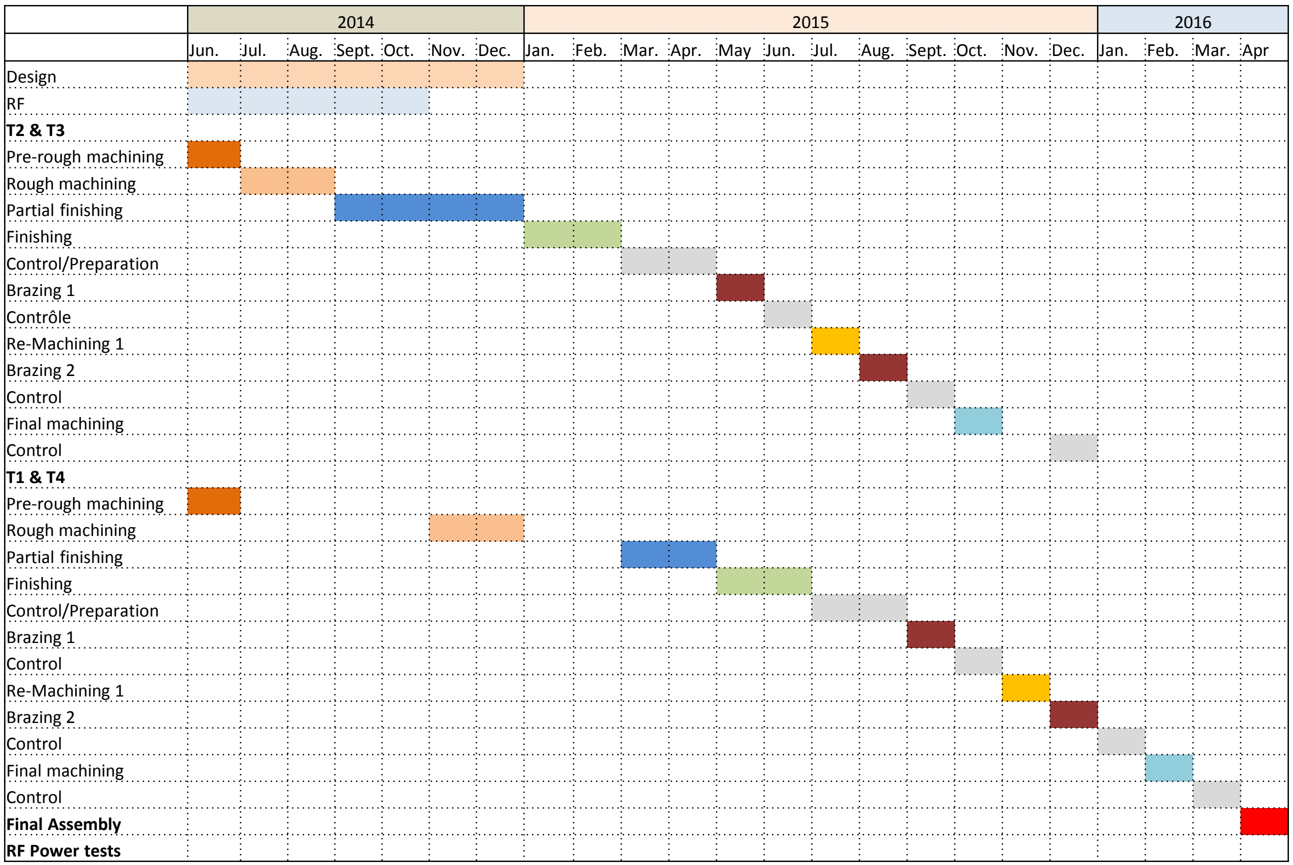
Shape tools made by the company BOUDON-FAVRE, Feillens (F)e
Precision machining obtained with a CNC grinding machine ANCA type mx7 with camera control Iview

Minor vanes

Rough to Final Machining

Construction and testing

HF-RFQ Production Planning, version 20 Mars 2015



Final assembly foreseen for April 2016.

Low-power and high-power RF tests will follow in 2016.

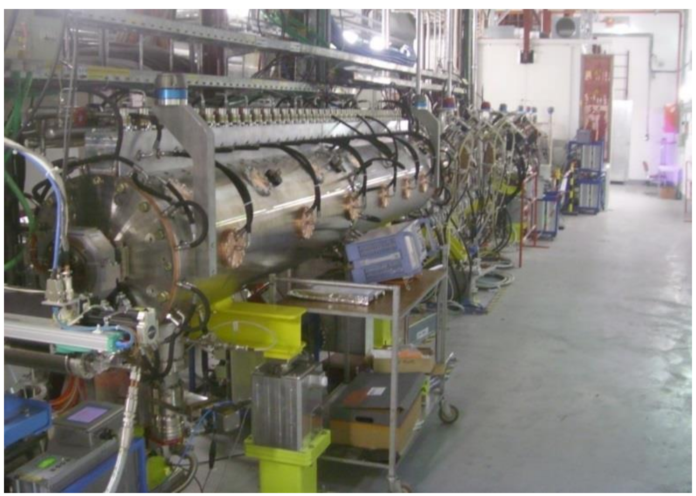
Technetium production

Energy of 20 MeV for production of ^{99m}TC

1. High-frequency RFQ option (low cost, low current)

704 MHz
2 RFQs + 1 DTL
Source W = 90 KeV
L = 10 m
Output W = 18 MeV
Average current = 1 mA
Peak current = 10 mA
Duty cycle = 10 %

2. Conventional RFQ option: copy of Linac4



352 MHz
1 RFQs + 2 DTL tanks
Source W = 45 KeV
L = 12 m
Output W = 20 MeV
Average current = 10 mA
Peak current = 100 mA
Duty cycle = 10 %
2 klystrons @ 352 MHz
Hands-on maintenance on accelerator (<1 W/m beam loss)

Conclusions

For the production of radio isotopes, modern linear accelerators can be a viable alternative to cyclotrons, in particular in environments requiring limited radiation levels and/or presenting constraints in terms of space and shielding and thanks to their qualities of ease of operation and limited maintenance.

We welcome scientific and industrial partners for the next step: build and test with beam the isotope version of the RFQ.

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