L’acceleratore in miniatura

Un viaggio nel mondo degli acceleratori lineari e delle loro applicazioni: come la società può approfittare delle tecnologie sviluppate per l’LHC e per i grandi acceleratori

Maurizio Vretenar, CERN

- Quanti acceleratori di particelle ci sono al mondo (quelli veri, non i tubi catodici)?

Piu' di 30'000 !

- E quali sono i 2 campi di applicazione piu’ comuni (circa 10’000 acceleratori ciascuno)?

La medicina (diagnosi e trattamento con raggi X o elettroni)
L’industria dei semiconduttori (drogaggio per implantazione di ioni)

1. Applicazioni degli acceleratori

Existing accelerators

Recherche		**6%**
	Physique des particules	0,5%
	Physique nucléaire, de l'état solide, des matériaux	0,2 a 0,9%
	biologie	5%
Applications médicales		**35%**
	Diagnostic/traitement par X ou électrons	33%
	Production de radio-isotopes	2%
	Traitement par protons et ions	0,1%
Applications industrielles		**60%**
	Implantation d'ions	34%
	Découpage et soudure par électrons	16%
	Polymérisation, …	7%
	Traitement par neutrons	3.5%
	Tests non destructifs	2,3%

L'acceleratore piu' diffuso

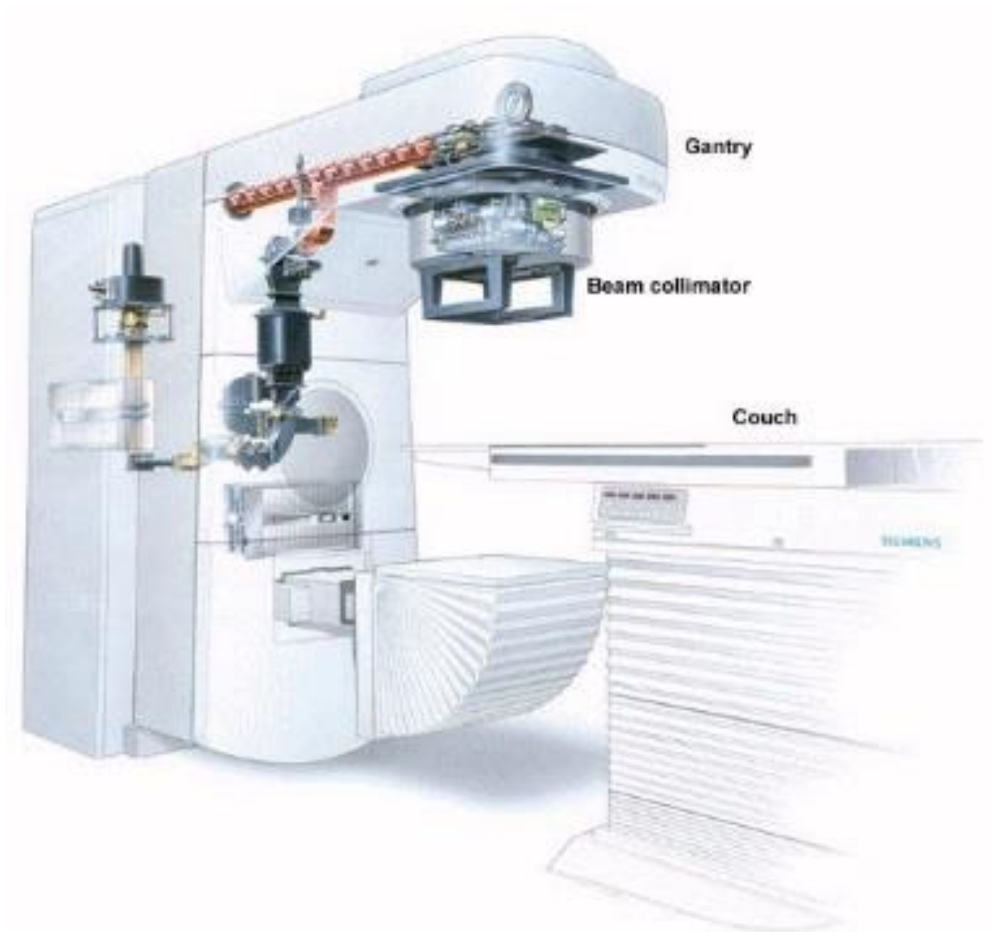
Linac (acceleratore lineare) di elettroni per la radioterapia (trattamento del cancro con raggi X)

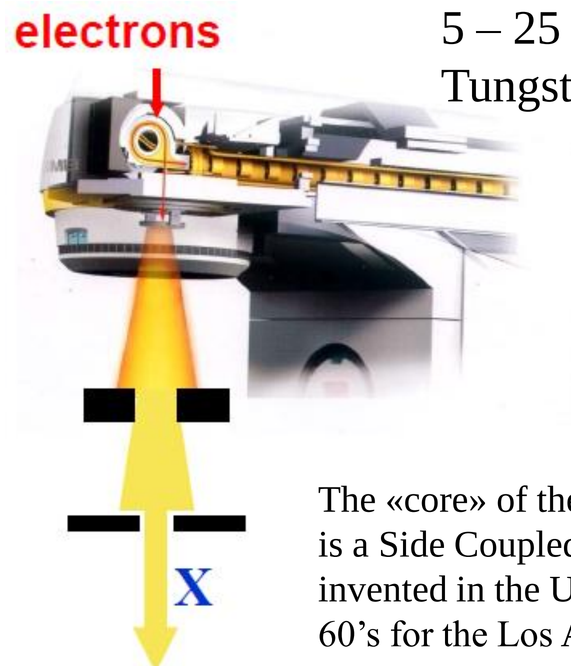
Circa 8'000

(Linac = Linear Accelerator)

La maggioranza degli acceleratori utilizzati al di fuori del campo della ricerca sono lineari: la bassa energia richiesta non rende necessario l'uso di grandi acceleratori circolari.

Radiotherapy linac





5 – 25 MeV
Tungsten target

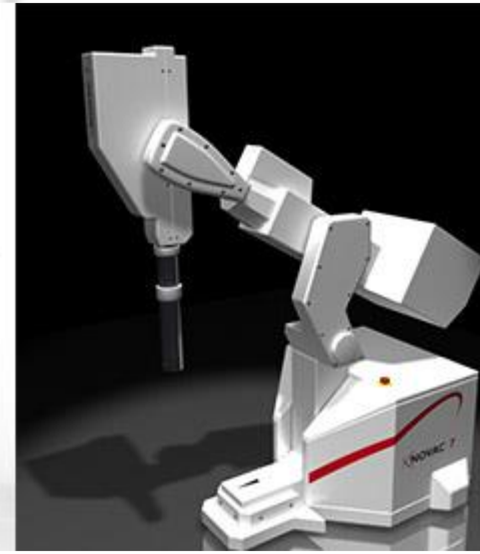
The «core» of the system is a Side Coupled Linac invented in the US in the 60’s for the Los Alamos Meson Factory

2000 patients/year every in 1 million inhabitants

Commercialised by several companies, available in all major hospitals

IORT = Interoperative Radiation Therapy

Un esempio di applicazione avanzata degli acceleratori alla medicina (e un'eccellenza italiana!)



Tecnica radioterapica che permette di erogare una dose elevata di radiazioni subito dopo l'asportazione del tumore, nel corso dell'intervento chirurgico.

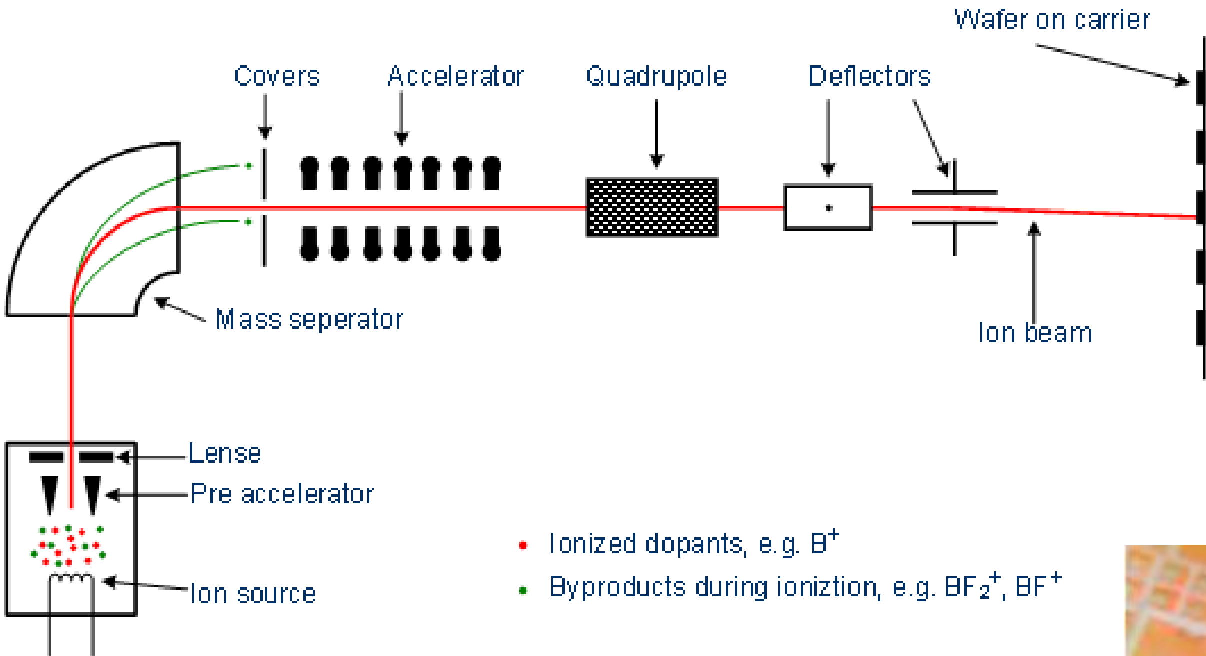
Acceleratore compatto sviluppato dall'ENEA a Frascati negli anni '90 in collegamento con il gruppo di oncologia del Prof. Veronesi, ora commercializzato dalla Sordina (Vicenza). Si sta affermando in tutto il mondo, in particolare per il trattamento del tumore al seno.

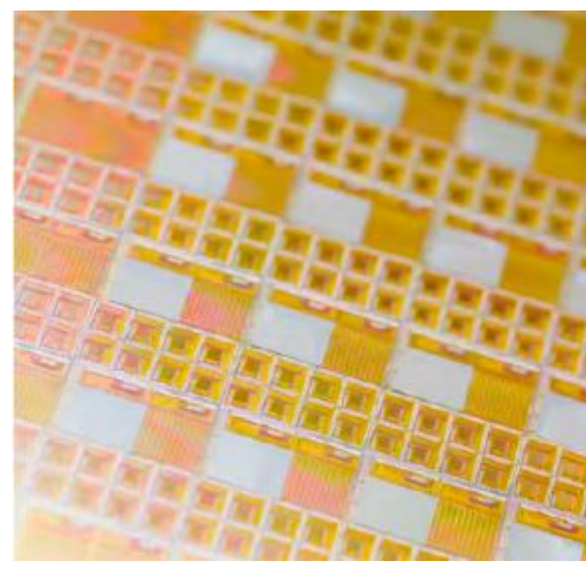
Energia	3 - 9 MeV
Corrente di picco	1.5 mA
Frequenza di ripetizione	1-30 Hz
Durata dell'impulso	4 μsec
Frequenza RF	2.998 GHz
Tipo di Struttura	SW in rame OFHC brasata
Modo di operazione	π/2
No. cavità acceleranti	11
Lenti magnetiche	nessuna
Lunghezza	50 cm
Peso	25 Kg

Industrial applications of linacs

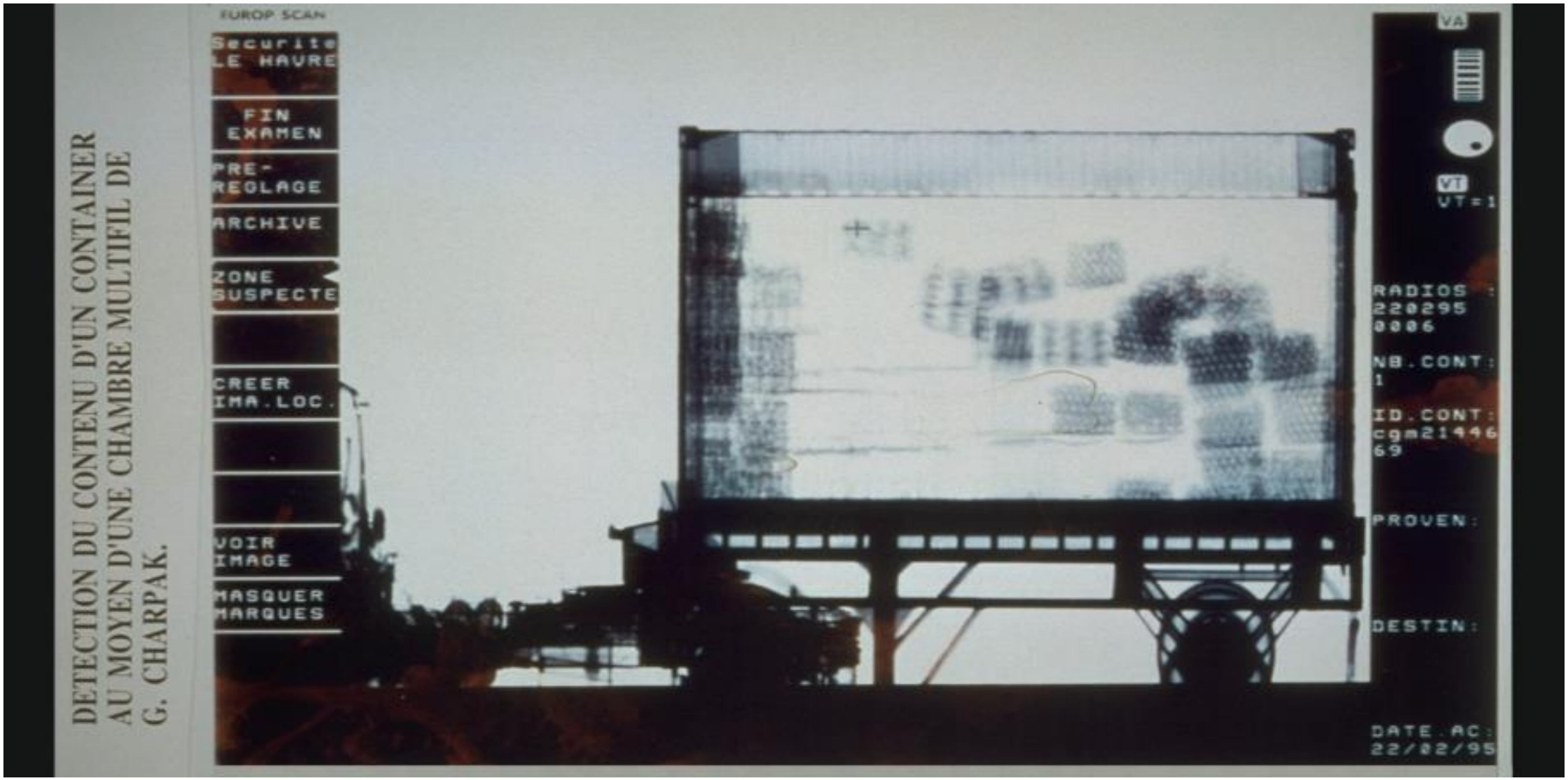
	Goal	Examples	Accelerator
Material processing (electrons)	Improve polymer resins inducing cross-linking of polymer chains → higher stress resistance	Heat-shrinkable films for food packaging, tires and cable insul. Gemstone irradiation	Electrons, 100 keV-10 MeV
Sterilization	Kill microroganisms	Sterilization of medical products Food processing (public acceptance!)	Electrons, ~10 MeV
Wastewater treatment	Distruction of organic compounds	Russia, Korea, USA, Brazil	Electrons, ~10 MeV
Non-destructive testing	Detect discontinuities in a material (cracks, etc.)	Inspection of pipelines, ships, bridges, etc. (depth + variable energy)	Electrons for X-rays, 1-15 MeV, portable (9 GHz)
Cargo inspection	Screening of trucks or containers for illegal objects	Many ports, customs, etc.	Electrons for X-rays, 3-6 MeV
Ion implantation	Alter near-surface properties of semiconductors (doping)	Semiconductor industry (arsenic, boron, indium, phosphorus,…)	Ions, from low to high energy (5 MeV)
PET isotope production	Production of radiotracers for Positron Emission Tomography	Linacs are smaller and have less res. activation than cyclotrons	Protons, 7 MeV
Neutron testing	Neutron generation for non-destructive inspection	Inspection of materials, cargo, etc.	Protons, 1-10 MeV

Ion implantation system





Cargo screening



Accelerators for society

what does the man in the street need?
More and better science – we all agree –
but the priority is more and better life


"THE APPLICATIONS OF PARTICLE ACCELERATORS IN EUROPE"

Activity within Integrated Projects supported by the European Union: EuCARD2, ARIES.

People in the street need the LHC (and now the FCC…) but need as well more and better medical isotopes, better materials, better semiconductors, improved security, etc.

The new ARIES Project

ARIES

Accelerator
Research and
Innovation for
European
Science and Society

- Integrated Activity project aiming at developing technologies for the next generation of particle accelerators.
- Consortium of 42 Laboratories, Universities and Industries from 18 EU countries (+CERN).
- Approved in August 2016 by the European Commission (Horizon2020) for the period 2017/21 with a contribution of **10 M€.**

Includes an «Application» Network concentrated on 2 specific applications:

1. Technology of compact low-energy electron accelerators and their applications for environment and industry (treatment of water and flue gases, treatment of agricultural waste, etc.)
2. Radioisotope production with accelerators: compact accelerators for PET isotope production in hospital, accelerator production of Tc for SPECT tomography and of therapeutic isotopes.

2. Acceleratori Lineari

Acceleratori lineari

Acceleratori Lineari a Radio-Frequenza: un elemento dove delle particelle elementari acquistano energia muovendosi su una traiettoria rettilinea sotto l'azione di campi elettrici variabili a frequenza radio (da qualche MHz a qualche GHz).

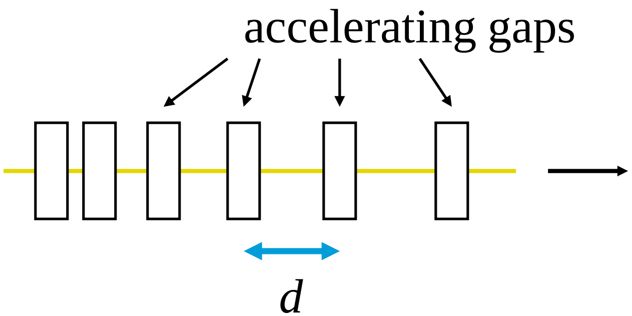
Gli acceleratori lineari coprono la parte iniziale del processo di accelerazione di un fascio di particelle, fino a energie dell'ordine di 10-500 MeV per protoni e 1 GeV per elettroni.

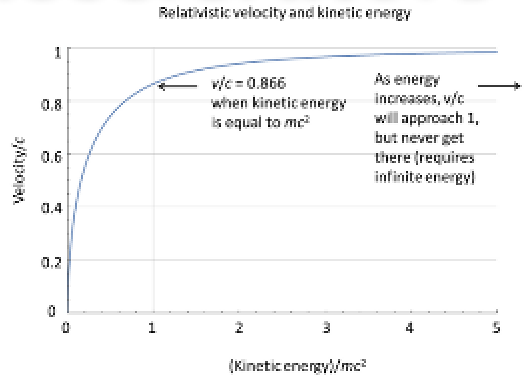
Assieme ai ciclotroni, sono gli acceleratori piu' adatti per le applicazioni mediche e industriali che richiedono energie non molto elevate.

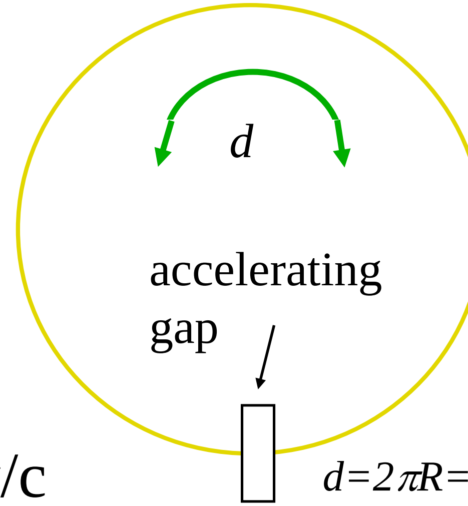
LHC = energia piu' alta possibile (massa delle nuove particelle prodotte)
intensità piu' alta possibile (numero delle nuove particelle prodotte)

Applicazioni = energia appena sufficiente a interagire con i nuclei atomici,
basse intensità per evitare danni ai tessuti e/o ai materiali.

Linear and circular accelerators







$d=\beta\lambda/2=$variable
$f=$constant

$$d = \frac{\beta c}{2f} = \frac{\beta\lambda}{2}, \quad \beta c = 2d\,f$$

$\beta = v/c$

$d=2\pi R=$constant
$f=\beta c/2d=$variable

Linear accelerator:

Particles accelerated by a sequence of gaps (all at the same RF phase).

Distance between gaps increases proportionally to the particle velocity, to keep synchronicity.

Used in the range where β increases.
"Newton" machine

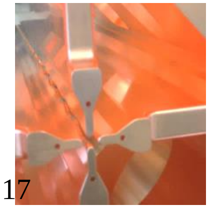
Circular accelerator:

Particles accelerated by one (or more) gaps at given positions in the ring.

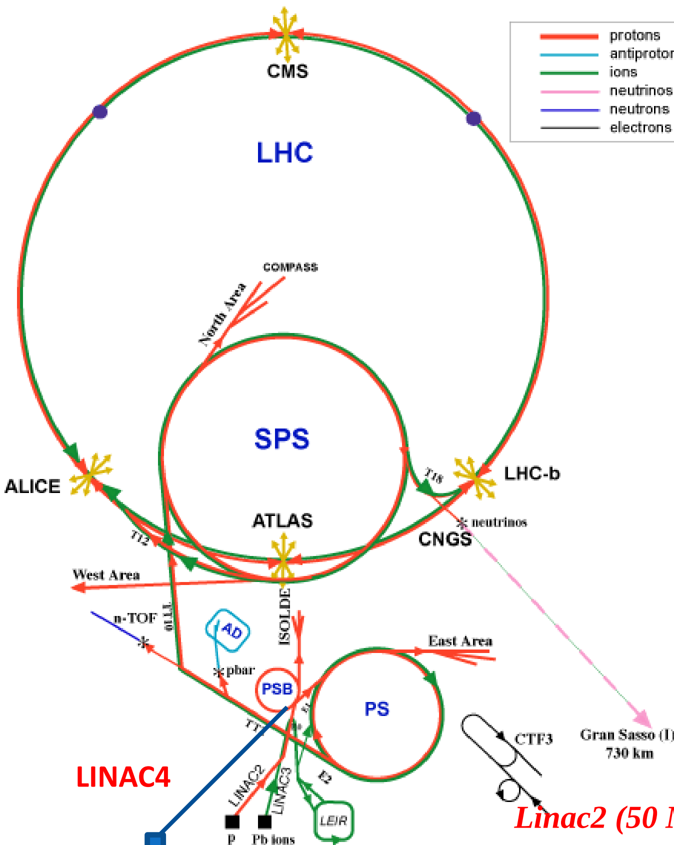
Distance between gaps is fixed. Synchronicity only for $\beta\sim$const, or varying (in a limited range!) the RF frequency.

Used in the range where β is nearly constant.
"Einstein" machine

Note that only linacs are real «accelerators», synchrotrons are «mass increaser»!



Linac4, the new LHC injector



LHC Injection chain: 4 accelerators. The first one is a 30 m linear accelerator, Linac2 (commissioned in 1978), accelerating protons at 50 MeV for injection into the PS Booster. Linac2:

1. Has a low energy that limits the intensity in the PSB (and the LHC luminosity);
2. Experiences persistent vacuum problems (leaks) rising concerns for its future;
3. Is one of the 2 last injectors in the world still using protons: all modern machines went to H- ions (easier injection, less expensive linac, lower beam loss)

→ decision in 2007 to build a new linac, Linac4

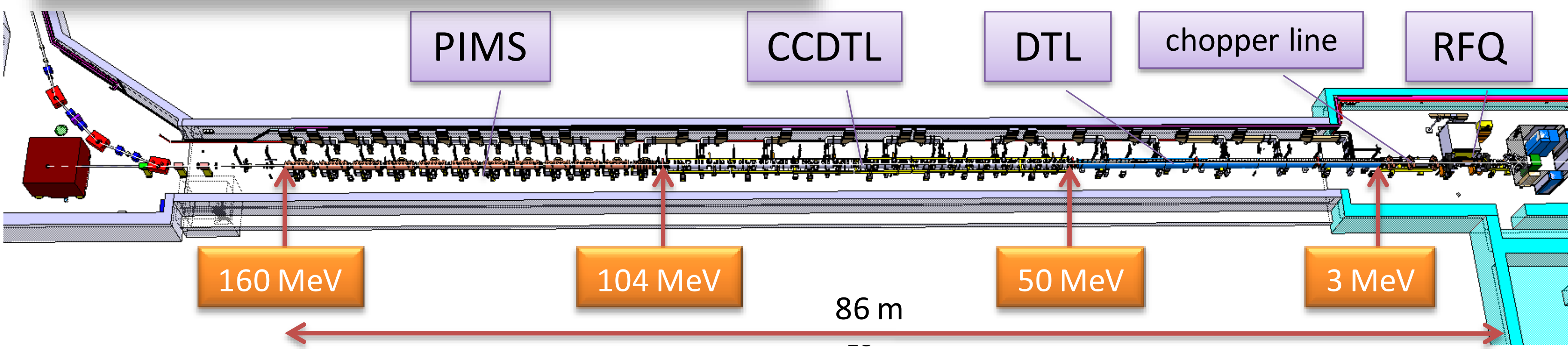
Linac2 (50 MeV)
↓
PS Booster (1.4 GeV)
↓
PS (25 GeV)
↓
SPS (450 GeV)
↓
LHC

Linac4 Parameters and Layout

Pre-injector (source, magnetic LEBT, 3 MeV RFQ, chopper line), 3 types of accelerating structures at 352 MHz (Drift-Tube Linac 50 MeV, Cell-Coupled Drift Tube Linac 102 MeV, Pi-Mode Structure 160 MeV), beam dump at linac end with switching magnet towards transfer line to PSB.

Ion species	H^-	
Output Energy	160	MeV
Bunch Frequency	352.2	MHz
Max. Rep. Frequency	2	Hz
Max. Beam Pulse Length	0.4	ms
Max. Beam Duty Cycle	0.08	%
Chopper Beam-on Factor	65	%
Chopping scheme:	222 transmitted /133 empty buckets	
Source current	80	mA
RFQ output current	70	mA
Linac pulse current	40	mA
Tr. emittance (source)	0.25	π mm mrad
Tr. emittance (linac exit)	0.4	π mm mrad

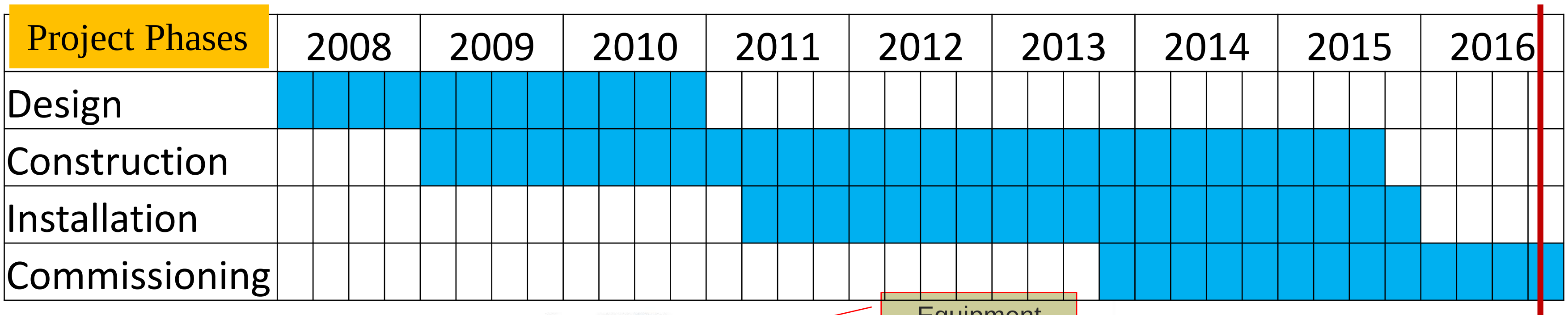
	Energy [MeV]	Length [m]	RF Power [MW]	Focusing
RFQ	0.045 - 3	3	0.6	RF
DTL	3 - 50	19	5	112 PMQs
CCDTL	50 - 102	25	7	14 PMQ, 7 EMQs
PIMS	102 - 160	22	6	12 EMQs

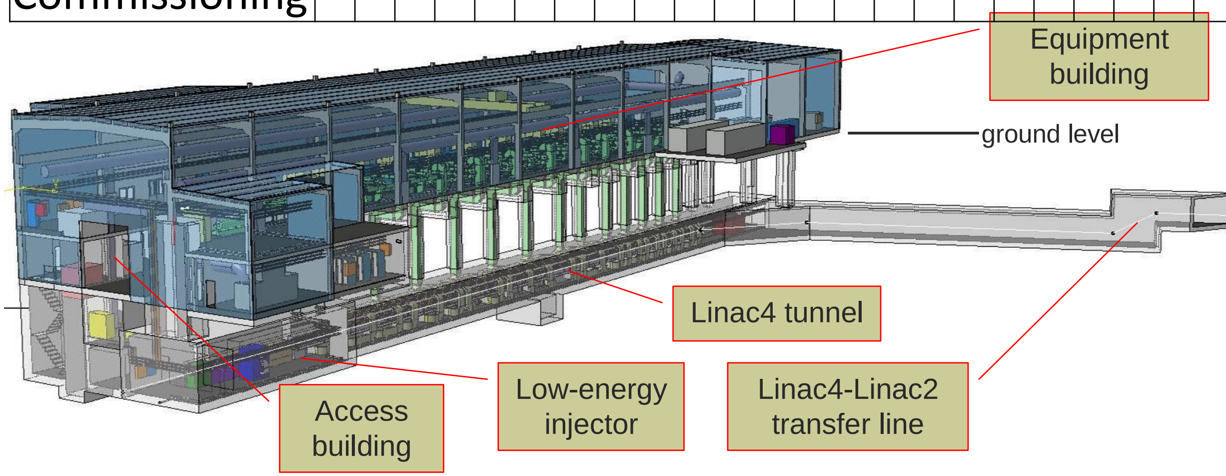


The Linac4 Project

Approved by CERN Council in June 2007, started on 1 January 2008 first step of the LHC Luminosity upgrade

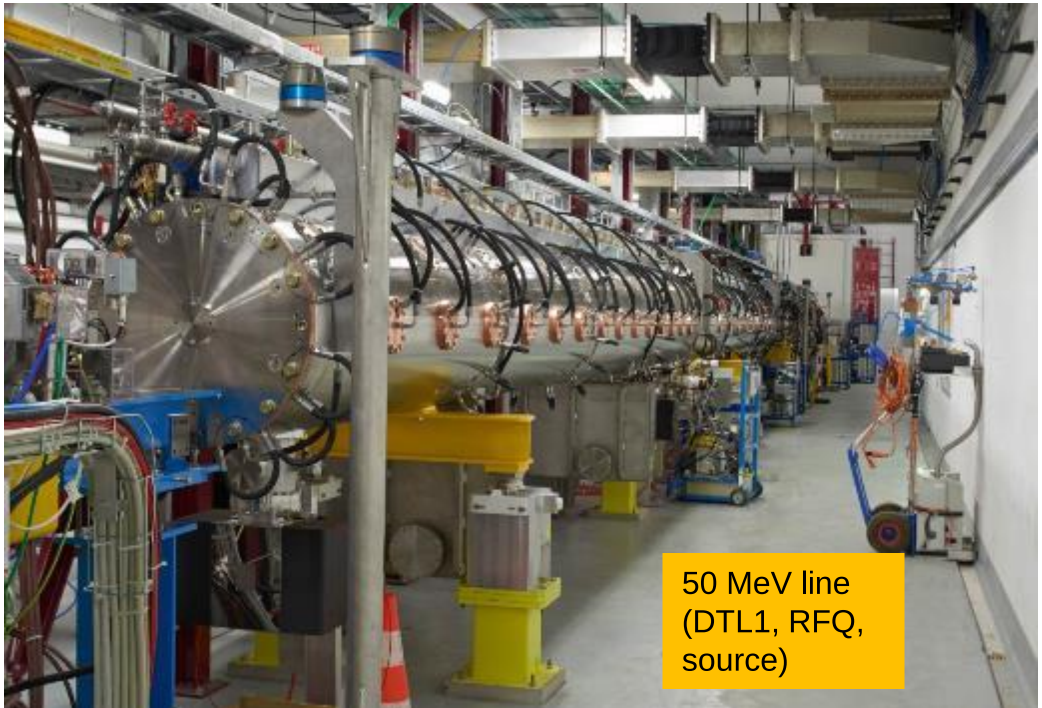
Scope: 160 MeV H− linear accelerator replacing Linac2 as injector to the PS Booster (PSB), to increase beam brightness (current/emittance) out of the PSB by a factor of 2 for the benefit of LHC (low current/low emittance) and of high-intensity beam users (high current/high emittance).





- About 100m in length, connection to the PSB and option of a future extension to higher energy.
- Linac tunnel 12 m underground, surface building for RF and other equipment, access module at low energy.

Some views of Linac4

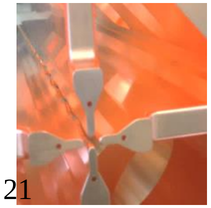


50 MeV line (DTL1, RFQ, source)

PIMS section

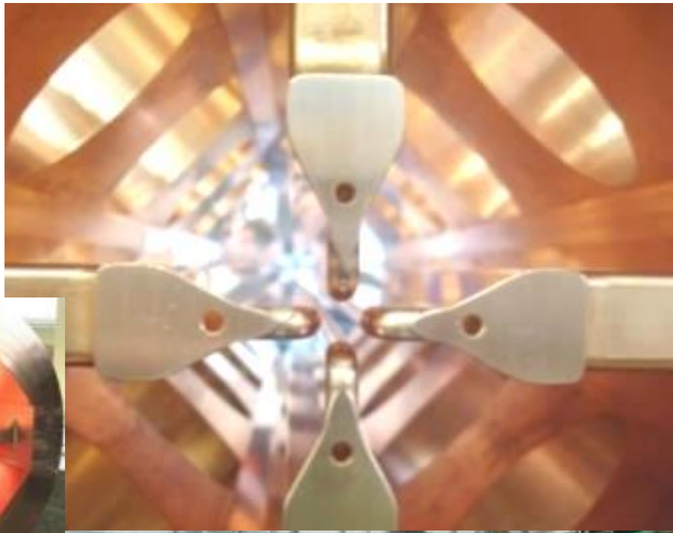
CCDTL (100 MeV)

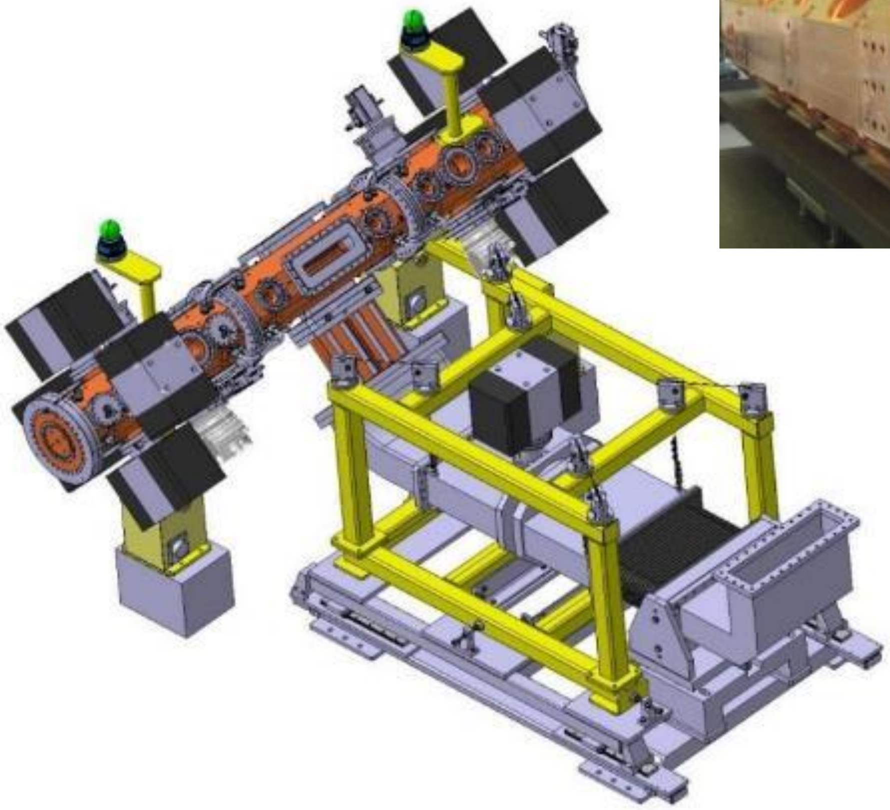
Hot news (November 2016):
Reached the full energy (160 MeV)



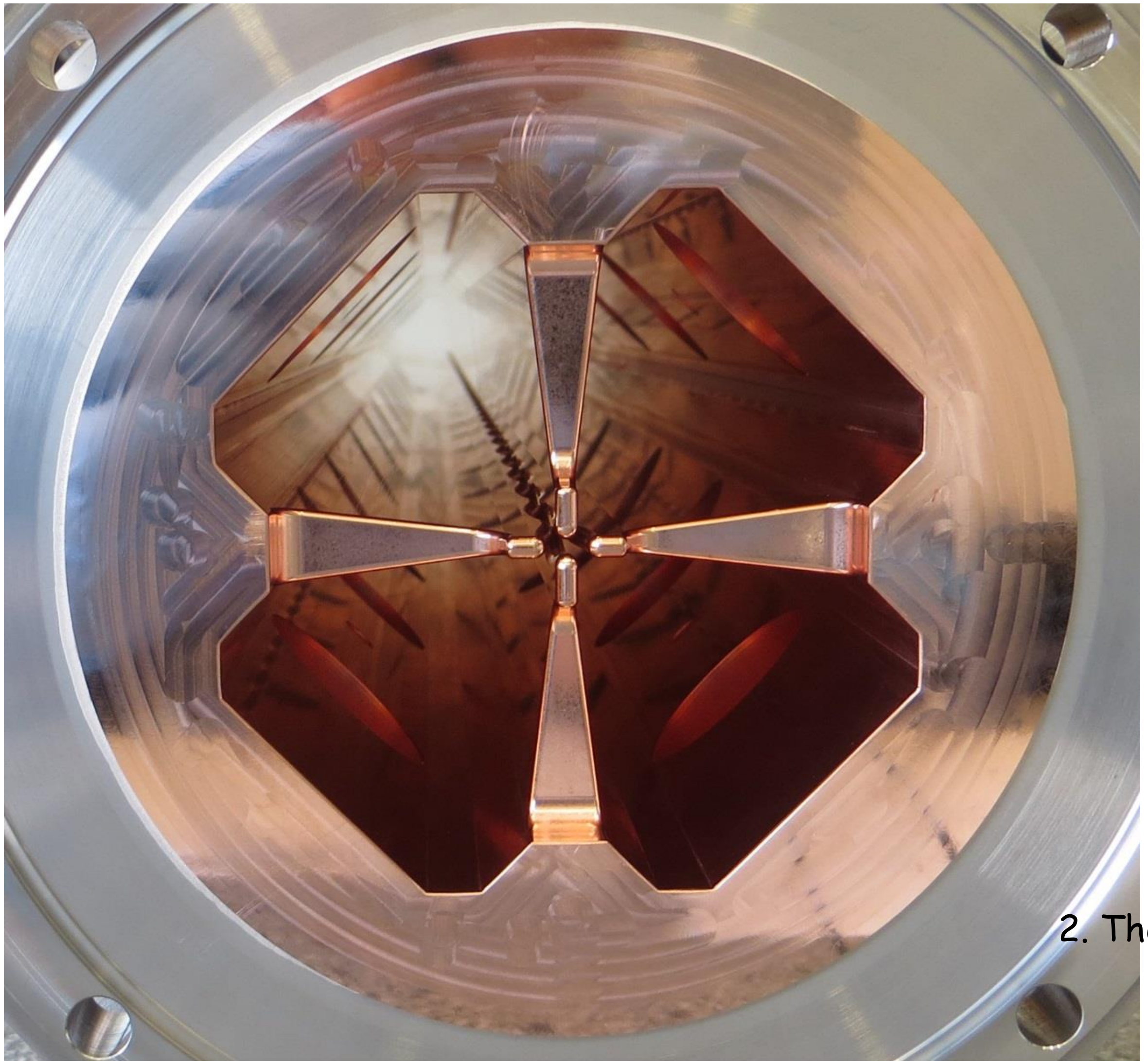
The Linac4 Radio Frequency Quadrupole (RFQ)

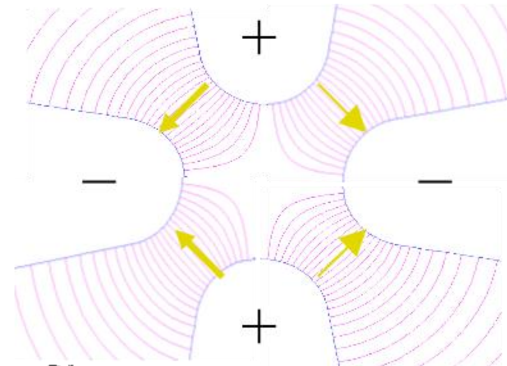
The Radio Frequency Quadrupole (RFQ) is the first accelerator in Linac4 (3m, up to 3 MeV). It focuses bunches and accelerates the beam in a quadrupolar focusing channel inside an RF resonator.

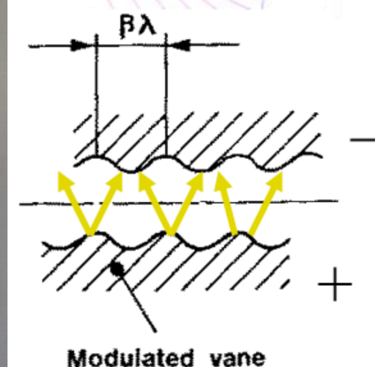


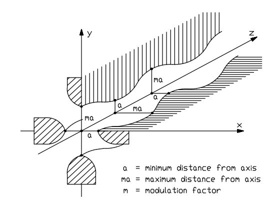


Looking into an RFQ









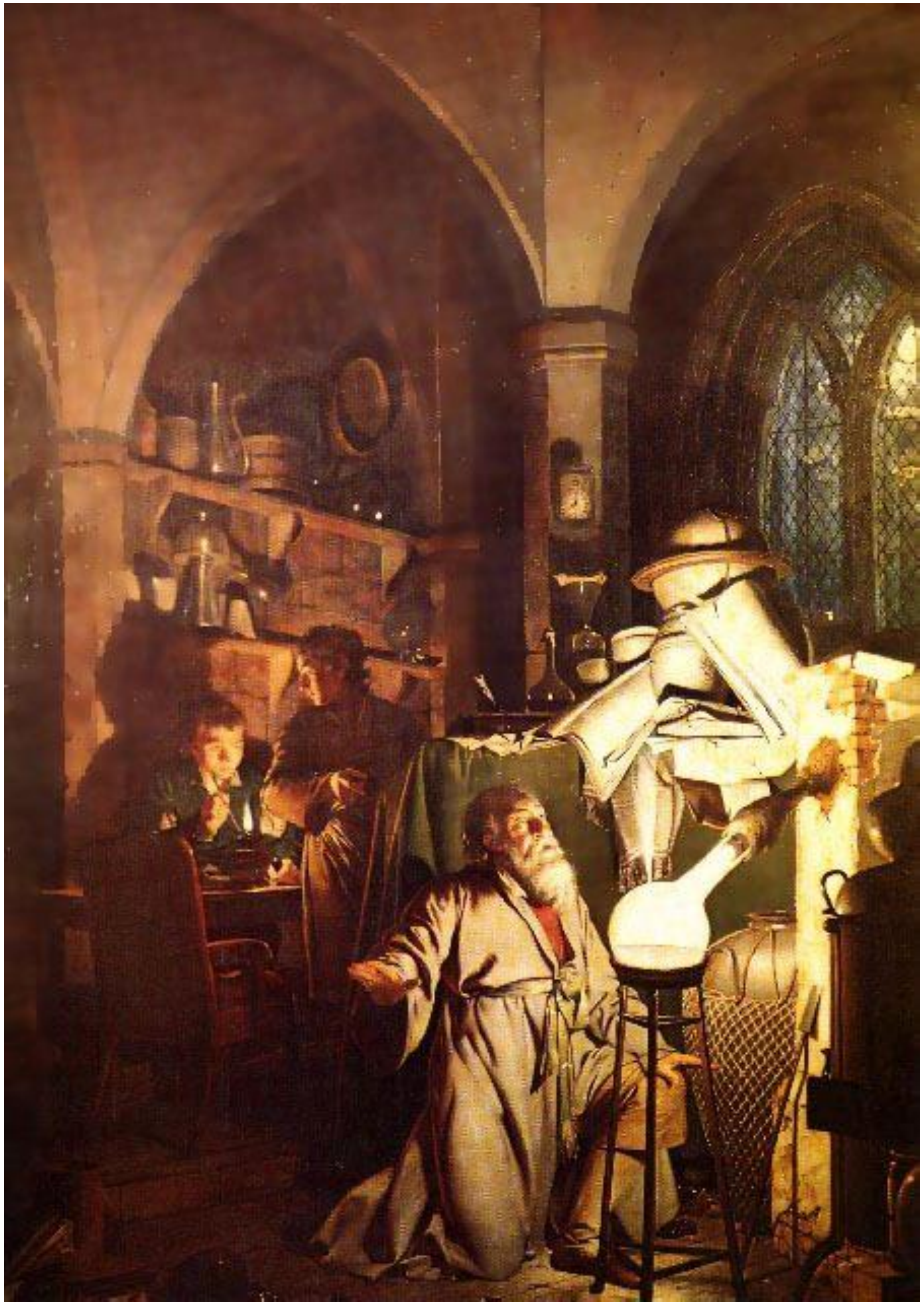
Adjacent vanes (90º)

1. Four electrodes (vanes) excited in an RF Quadrupole mode → Electric focusing channel.
2. The vanes have a longitudinal modulation with period = βλ → longitudinal component of the electric field for acceleration and bunching.

3. Dal Linac4 alla società…

Starting with a 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.
- There are now 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).

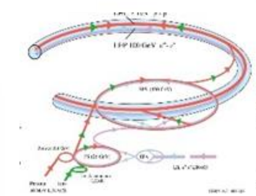


Particle accelerators can realise the dream of the ancient alchemists: transform the matter!

The miniature accelerator

The **miniature particle accelerator** should:

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



The best accelerator corresponding to these specification is the **Radio Frequency Quadrupole linear accelerator** :

- Energies up to 10-15 MeV.
- Linear, small dimensions, limited weight.
- Controlled beam optics with no beam loss outside of the target: only the target needs to be locally shielded.
- Not expensive if built on large scale, one-piece device with virtually no maintenance.

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

Cyclotrons, the accelerators presently used for isotope production, are limited by beam loss and induced radiation and need large concrete shielding and/or an underground installation.

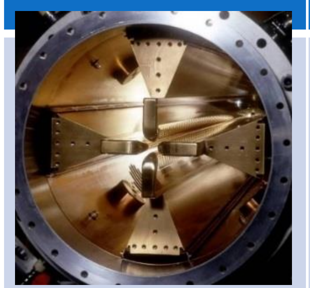
Pushing the RFQ limits

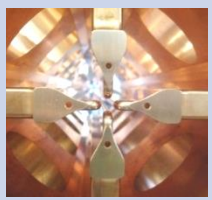
THE KEY TO SMALLER DIMENSIONS : HIGHER FREQUENCY

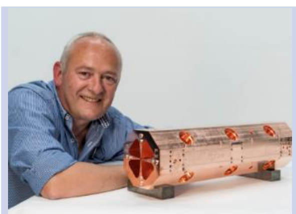
Initial RFQs in the 200 MHz frequency range, later, 400 MHz range (Linac4).

A new compact RFQ reaching the high frequency range 700 – 800 MHz

1988-92	2008-13	2014-16
Linac2 RFQ2	LINAC4 RFQ	HF-RFQ
202 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







200 MHz → 350 MHz → 750 MHz

Higher Frequency (Constant aperture) → Shorter RFQ (Smaller cross-section) → Lower cost

Low current (< 2 mA) → Shorter RFQ (Controlled beam loss) → Higher gradient (for same vane voltage)

	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

Technological Roadmap

Develop a modular high-frequency RFQ covering 3 medical 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

Additional step outside of medical applications:
Portable 3 MeV accelerator for PIXE and PIGE spectrometric analysis of artwork in museums or of components in an industrial environment

After ideas… you need people and money

- The construction of the compact RFQ has been funded by the new CERN Office for Medical Applications.
- A competent part-time team has been adventurously set up
- Design and construction of the prototype compact RFQ has started at the end of 2013.
- Construction has been completed in summer 2016.
- The RFQ is now on loan to a proton therapy company (a CERN start-up) that will use it in front of a new compact proton therapy linac to be installed in hospitals worldwide.
- Beam tests will start before the end of 2016.

The RFQ for proton therapy design and challenges

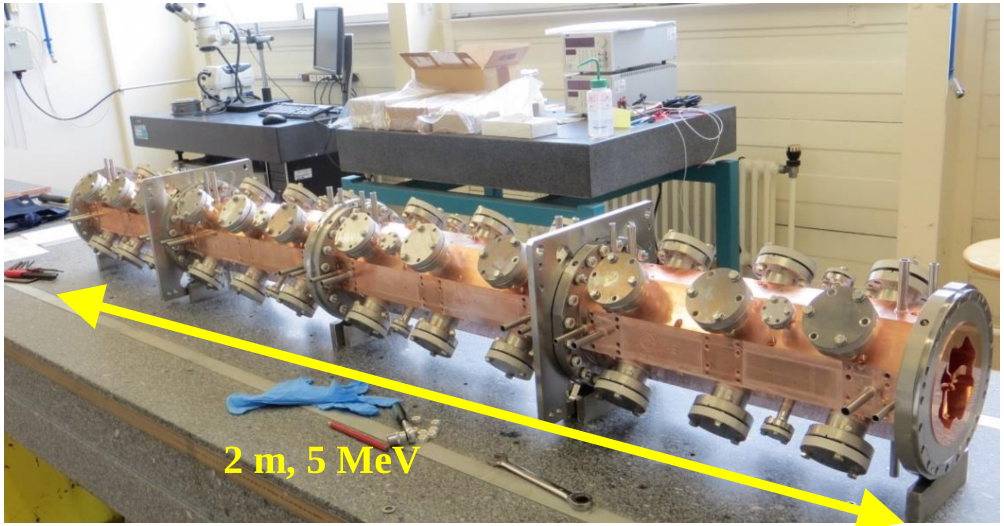
Long list of **challenges**:

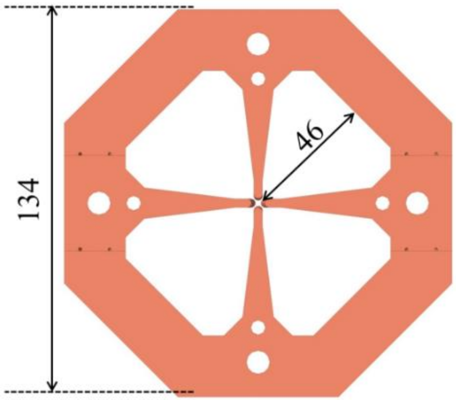
- Provide enough focusing, maximize acceptance.
- Best compromise length / transmission: accelerate only what can be captured, eliminate the rest at low energy
- Machining the modulation in the short initial cells.
- Reduce sensitivity to errors to keep conventional machining tolerances.
- Limit the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

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 µA
Transv. emittance 90%	0.1 π mm mrad
Average aperture (r0)	2 mm

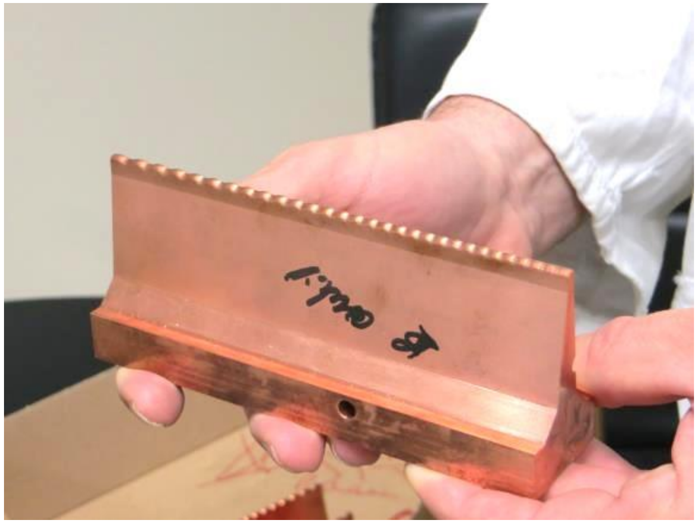
Approaching an unexplored frequency!

General design – a multi-purpose RFQ





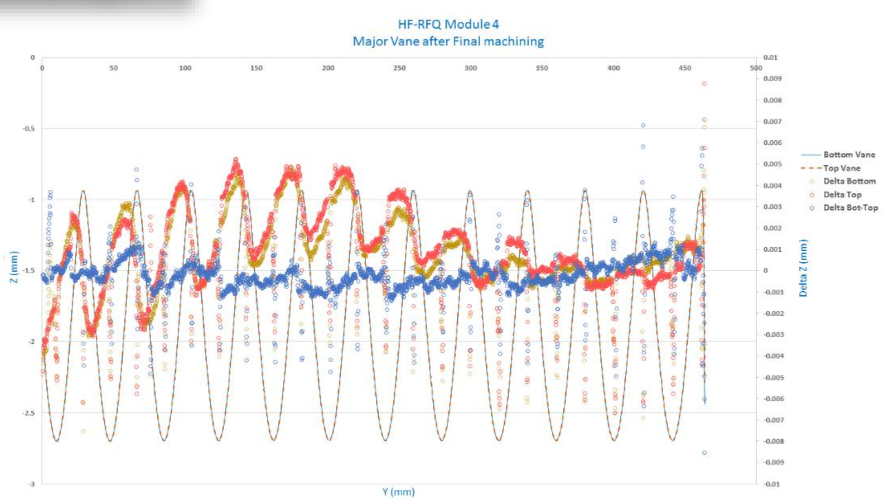
Machining tolerances ±20 µm (cavity), ±10 µm (vane tip).
Assembly tolerance for the four vanes ±15 µm.



- 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).

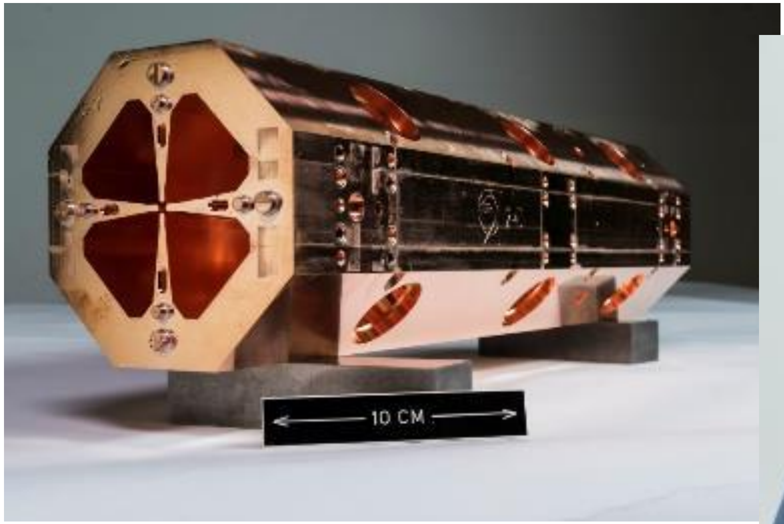
Machining

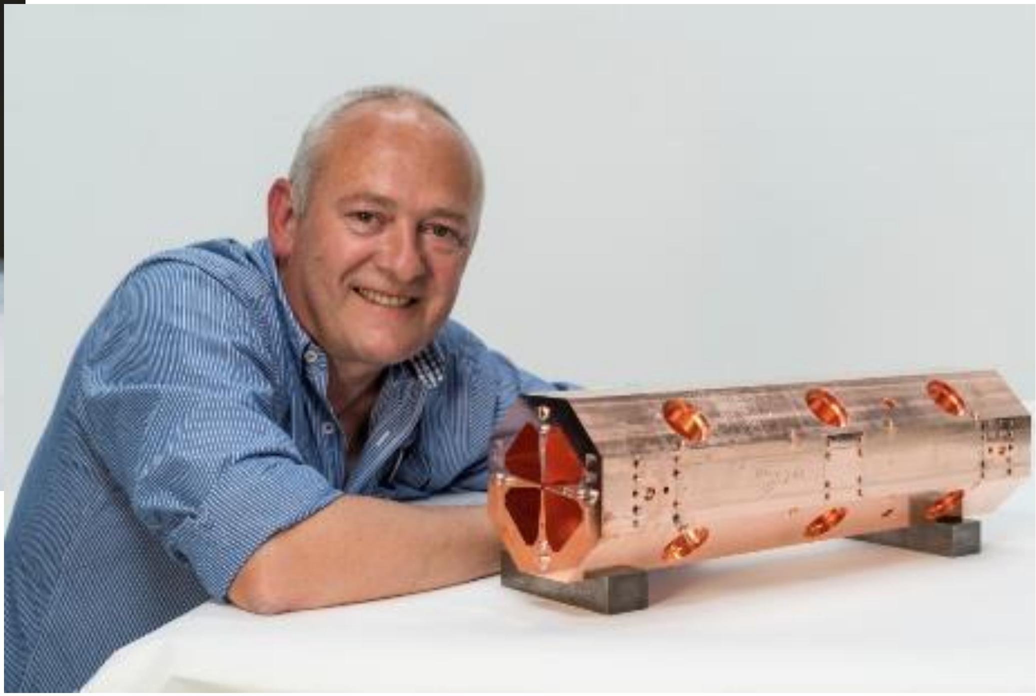
Fabrication entirely done in the CERN Workshop!



Machining errors on vane tips within ±5 μm (specs ±10 μm)

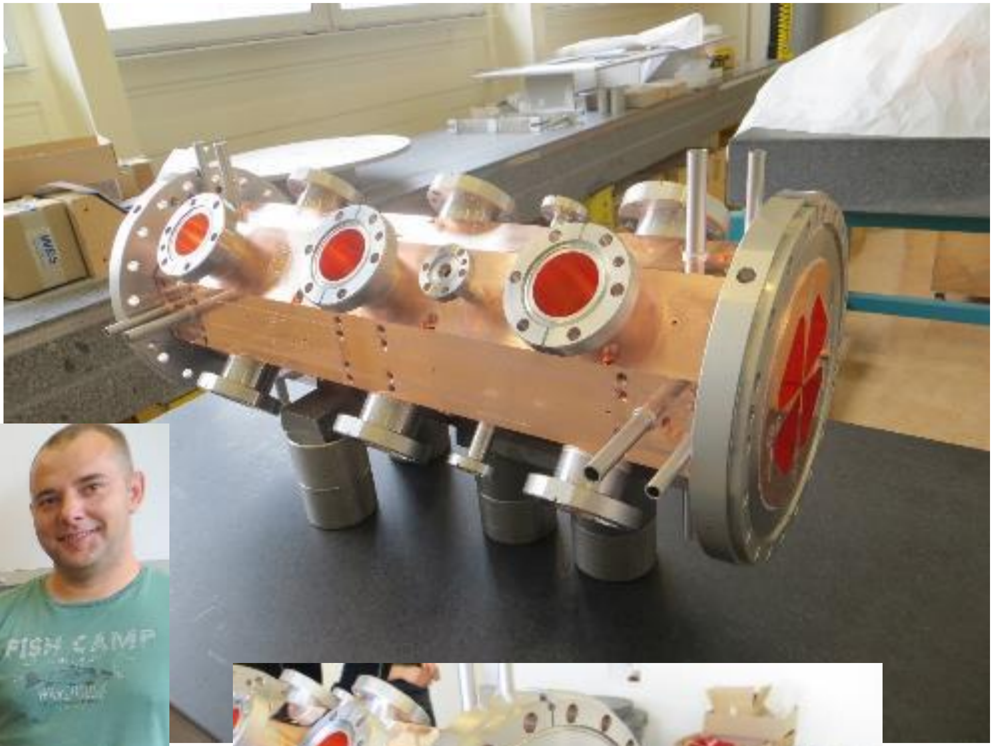
The first completed module





The first RFQ module with S. Mathot, in charge of the mechanical construction.

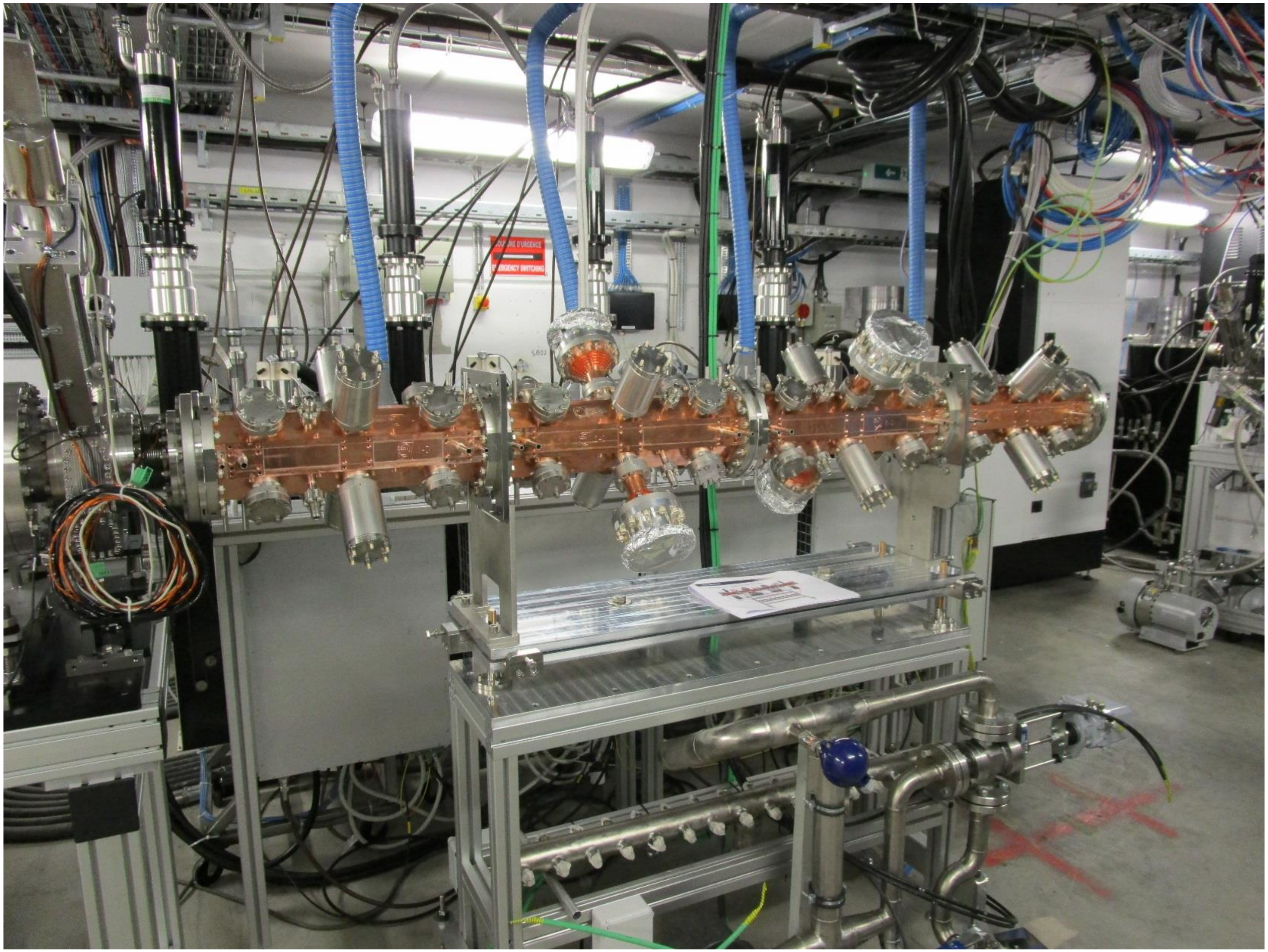
First fully equipped modules



Transport of the 5 MeV RFQ to the beam testing area

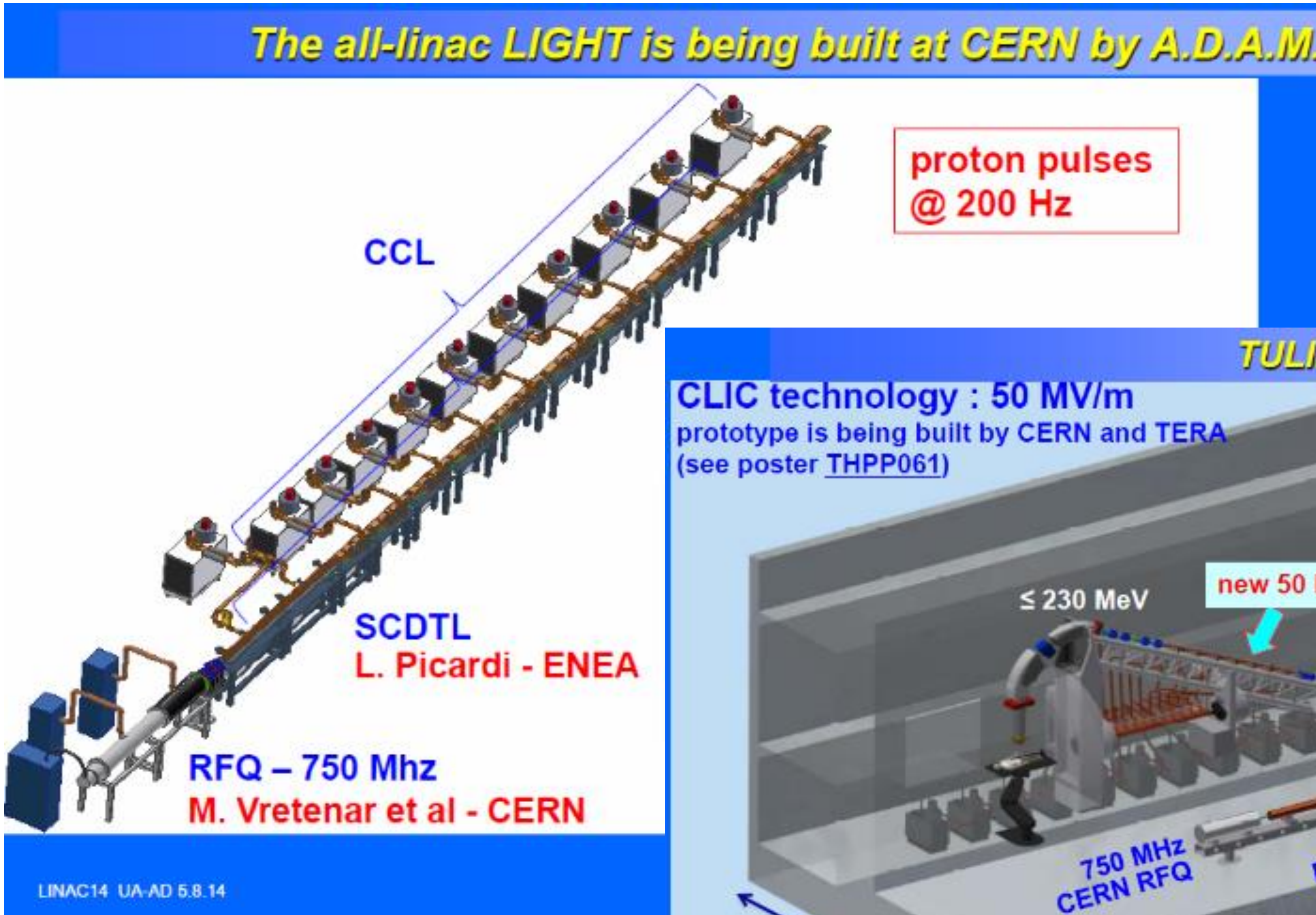
14 September 2016

The RFQ installed in the beam test area

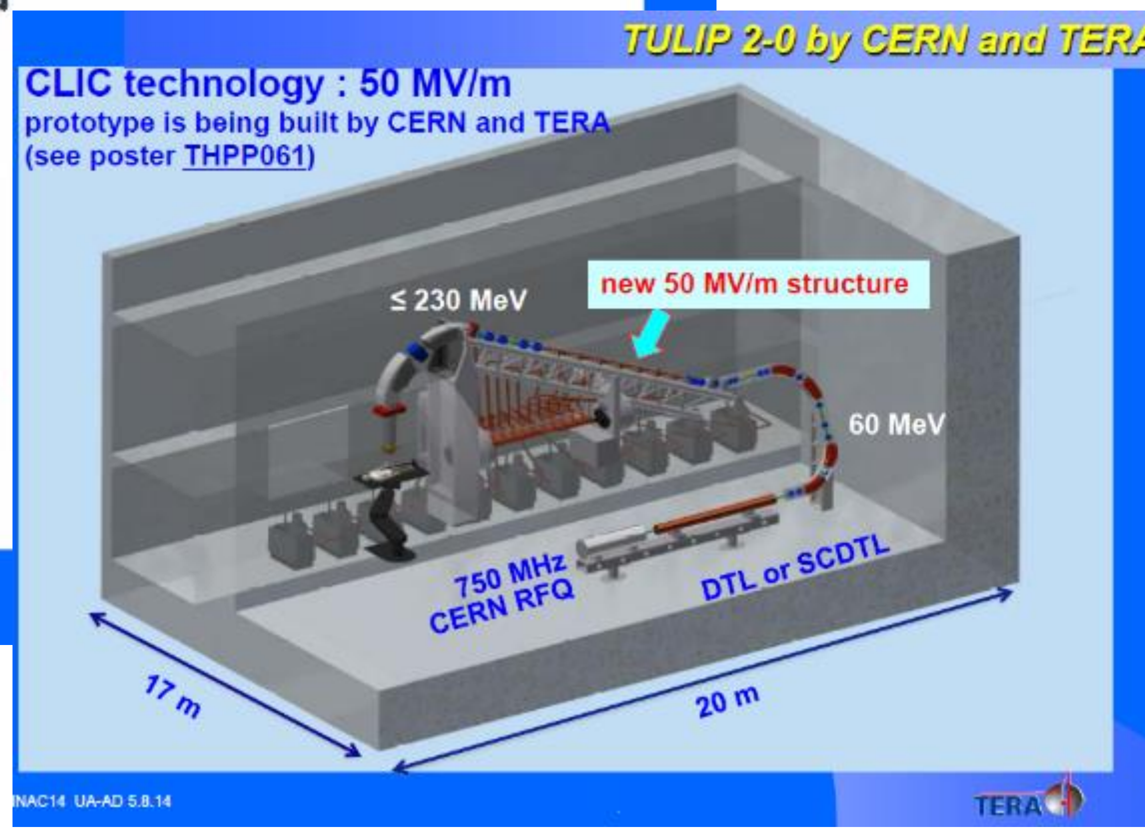


4. Applicazioni del mini-RFQ

RFQ for Proton therapy

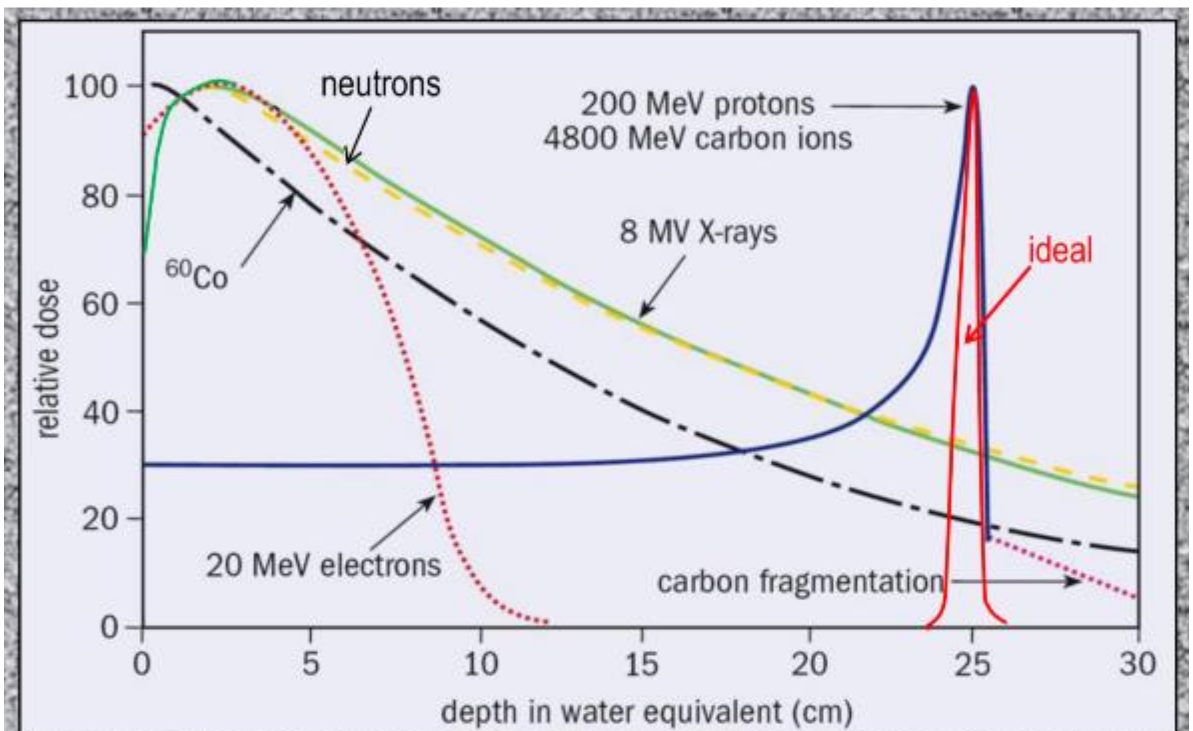


2 examples of proton therapy linacs using the HF-RFQ as injector



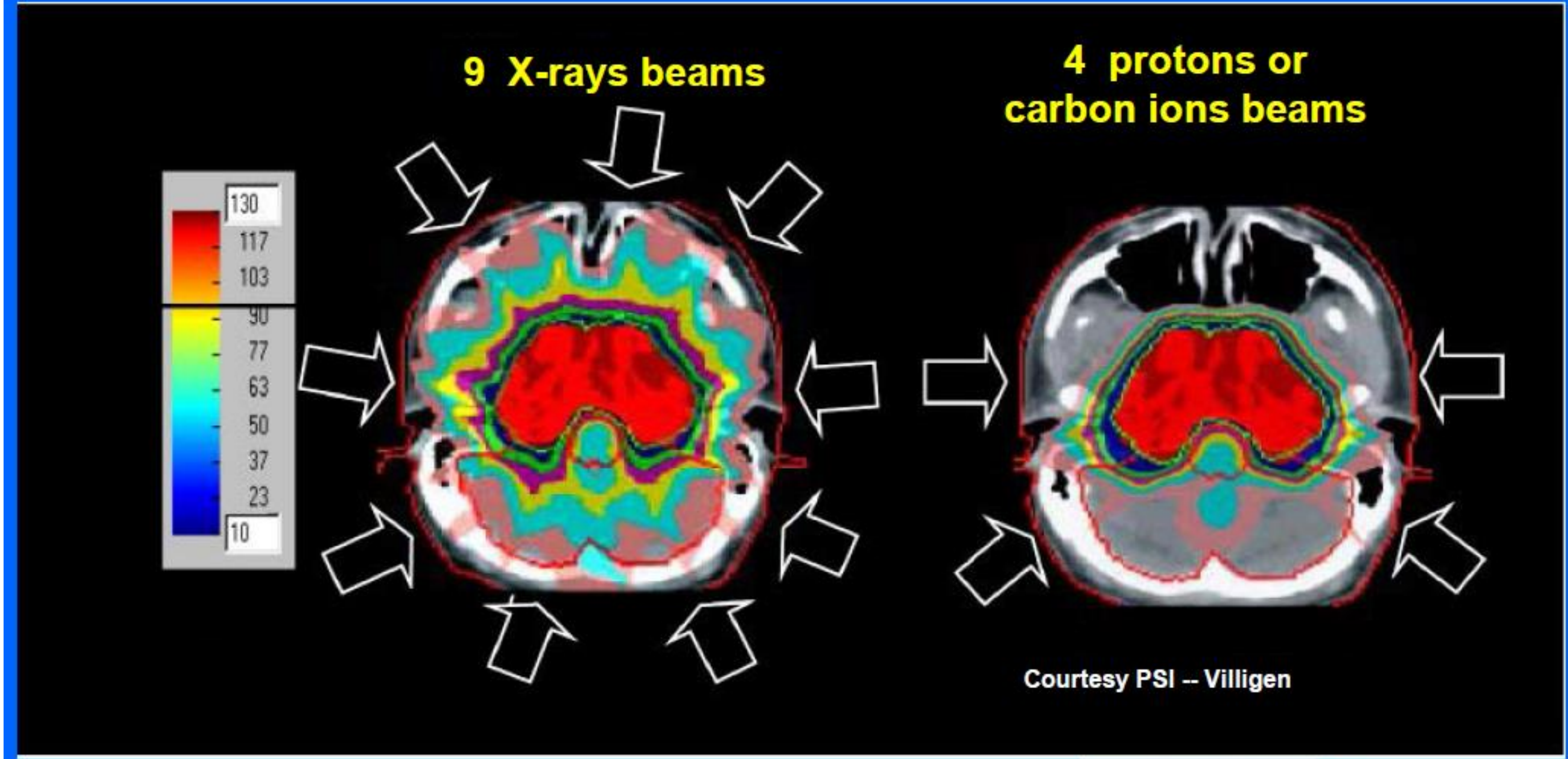
Hadrontherapy

‘Hadrontherapy’: cancer therapy modalities which irradiate patients with beams of hadrons. The “Bragg peak” allows to concentrate the radiation dose on a deep tumour, minimising the dose to the adjacent tissues.
Hadrontherapy is an alternative to usual irradiation with X-rays from e-linacs.



Most used hadrons: protons and carbon ions.
- Protontherapy is rapidly developing: more than 65'000 patients treated, 5 companies offer turn-key solutions.
- Carbon ions, used for about 6000 patients, have a larger radiobiological effectiveness and require more radiobiological and clinical studies to define the best tumour targets.

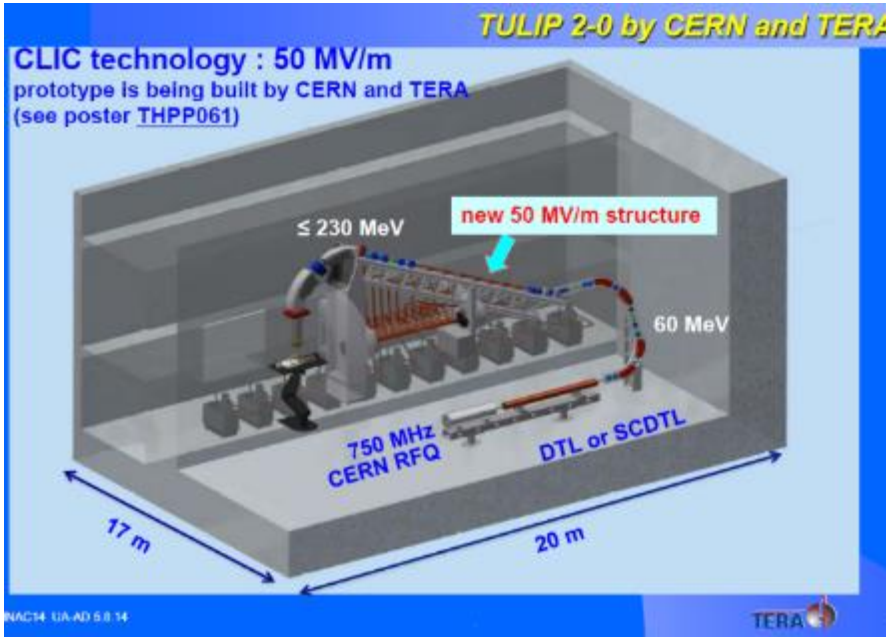
Advantages of hadrontherapy: 1. normal tissues are speared



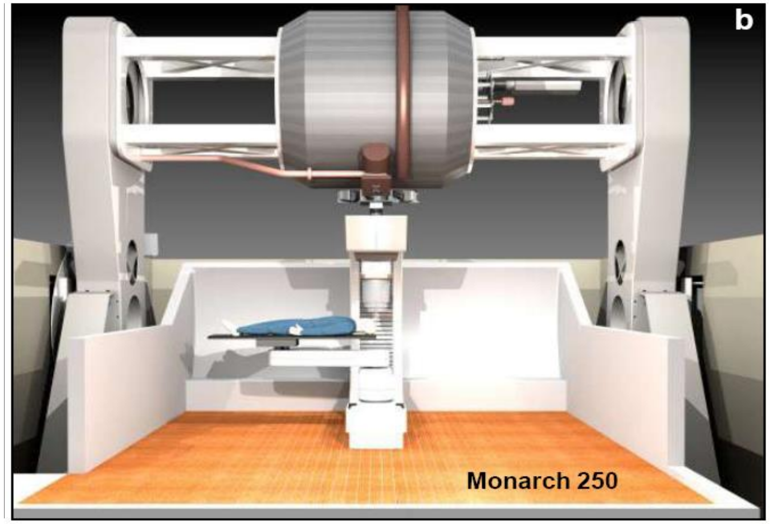
New challenges in hadrontherapy accelerators

Challenges for the new generation machines:

1. More compact (to fit in conventional hospitals): often cyclotron based, trend to single-room facilities.
2. Avoid complicated and expensive gantries.



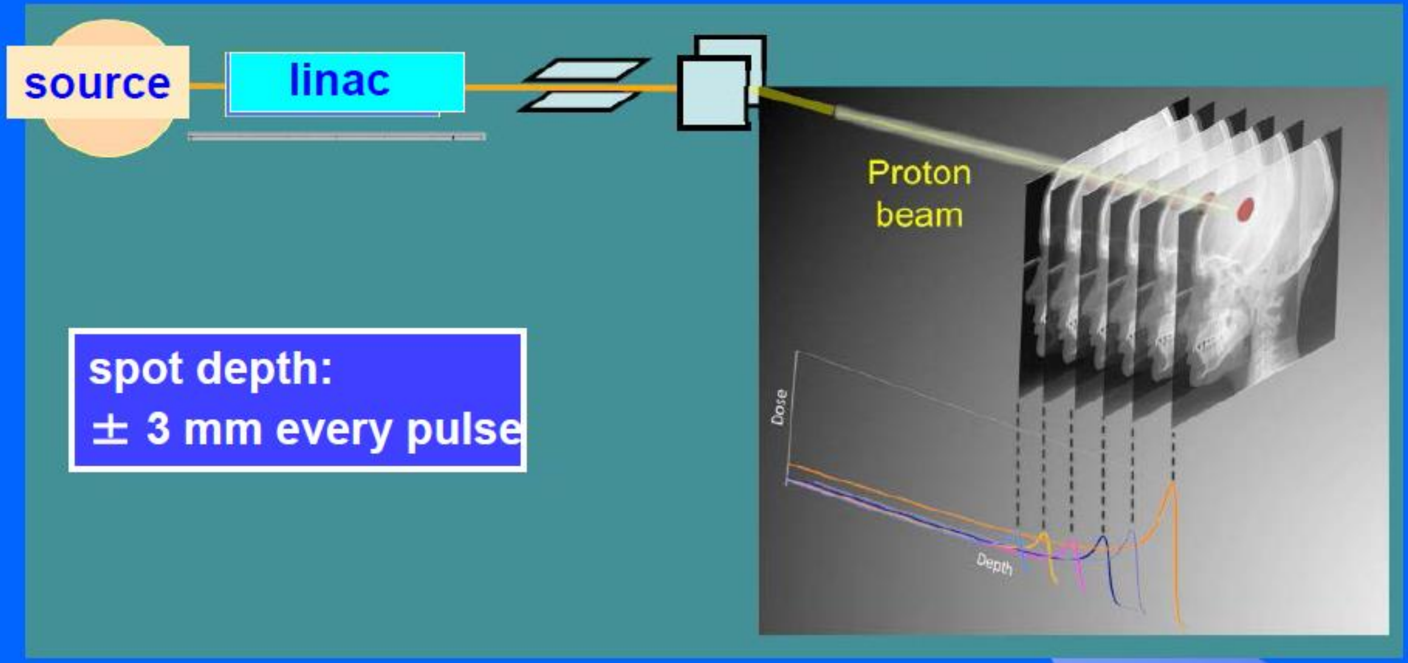
The TULIP concept (TERA Foundation), compact linac rotating around the patient.



First single room facility: Still River synchrocyclotron rotating around the patient

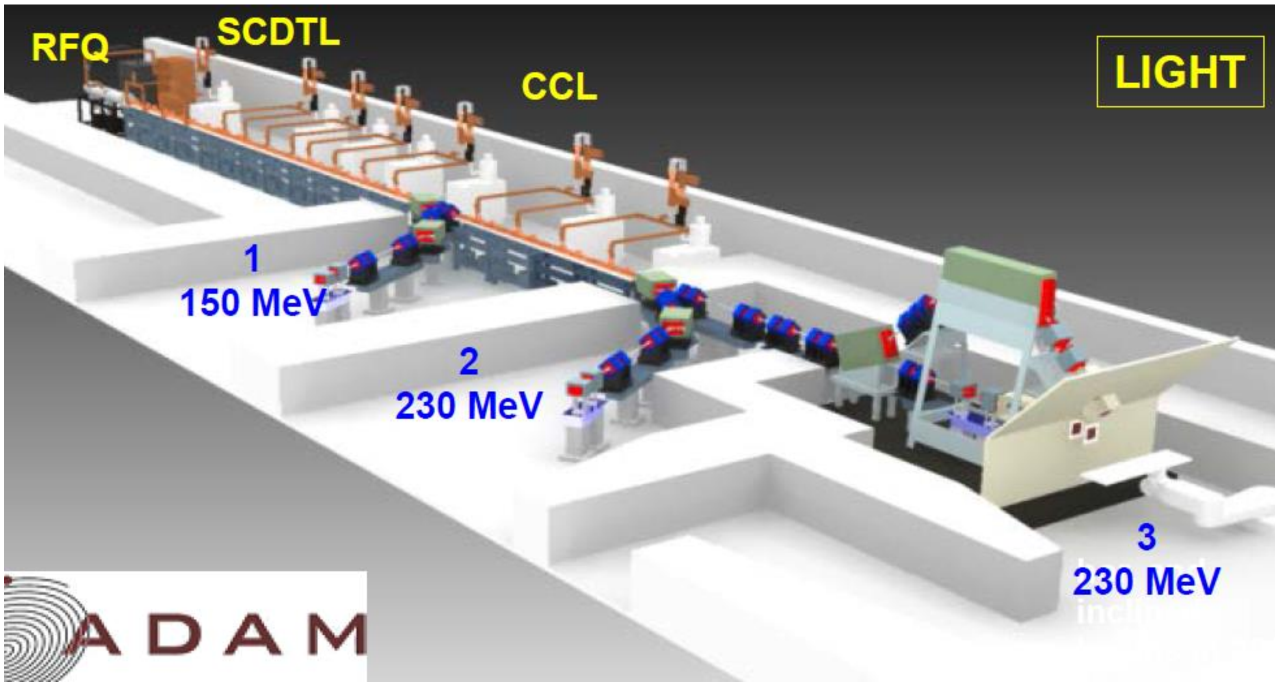
The dose deposition depth can be adjusted every 3 ms

The linac pulses 200-300 times per second



To follow moving organs in 4D - with spot scanning, motion feedback and more than 10 paintings - the beam time structure of linacs is better than the ones of cyclotrons and synchrotrons

ADAM and CERN



- ADAM, a spin-off company of CERN initially started by Ugo Amaldi and his TERA Foundation, is building a prototype proton therapy linac (LIGHT).
- CERN contributes with the RFQ.
- Beam commissioning of the RFQ at the ADAM test stand at CERN

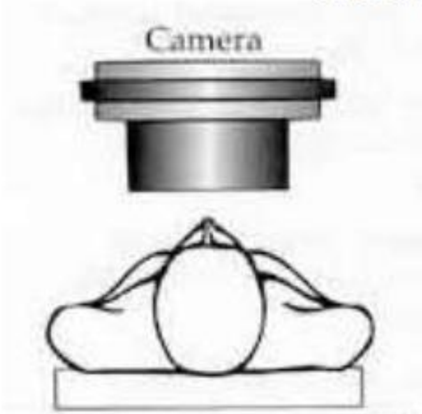
Interest for smal proton therapy facilites to be installed in existing hospitals. Linacs allow fast cycling with energy variability (precision 4D scanning of a moving organ).
3 GHz structures take the beam only from ≈ 5 MeV energy → need a high-frequency injector.

In 2014 CERN has signed an agreement with the ADAM Company (Application of Accelerators and Detectors to Medicine, part of the AVO – Advanced Oncotherapy – group from UK) to allow them using the prototype RFQ in their LIGHT proton therapy linac.

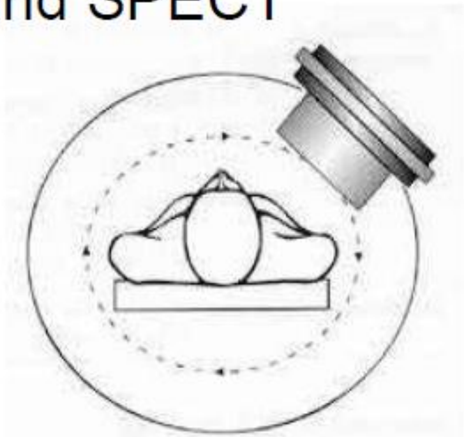
Recently (contract signed in August 2015) ADAM has purchased from CERN a license to use the compact RFQ technology for the construction of proton therapy linacs.

Tomography

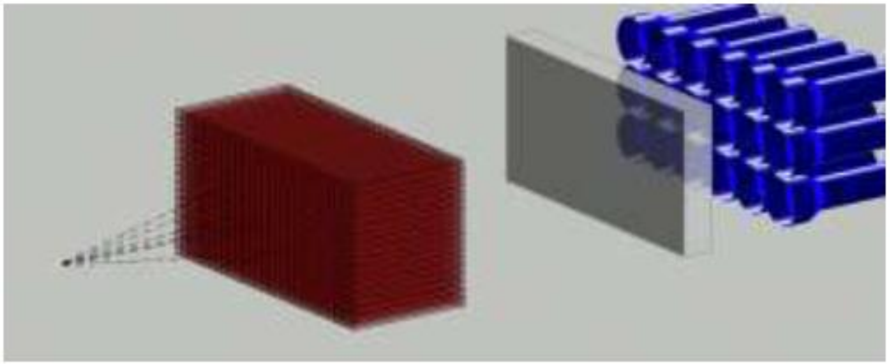
Scintigraphy and SPECT



2D: planar scan (Gamma camera)



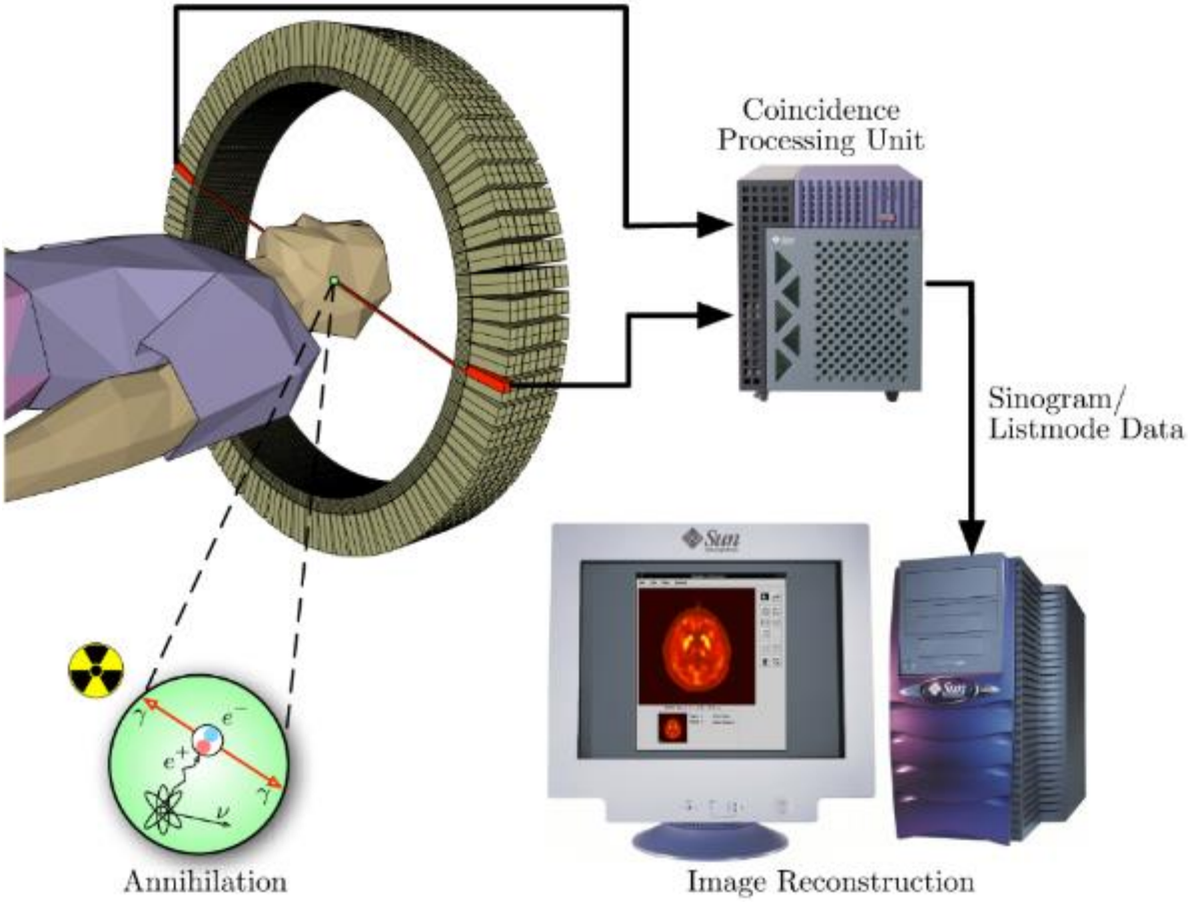
3D: SPECT: Single Photon Emission Computer Tomography



E_γ > 60 keV

E_γ < 400 keV

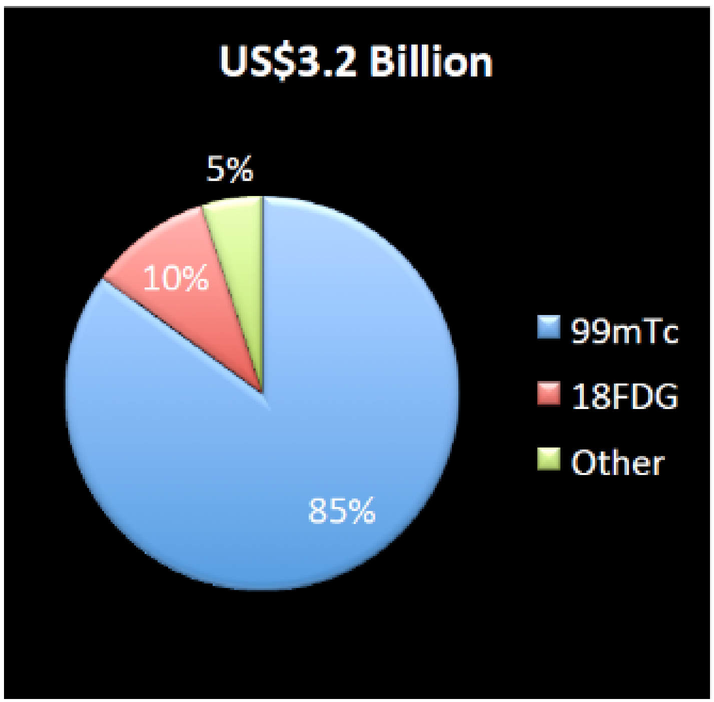
Positron Emission Tomography



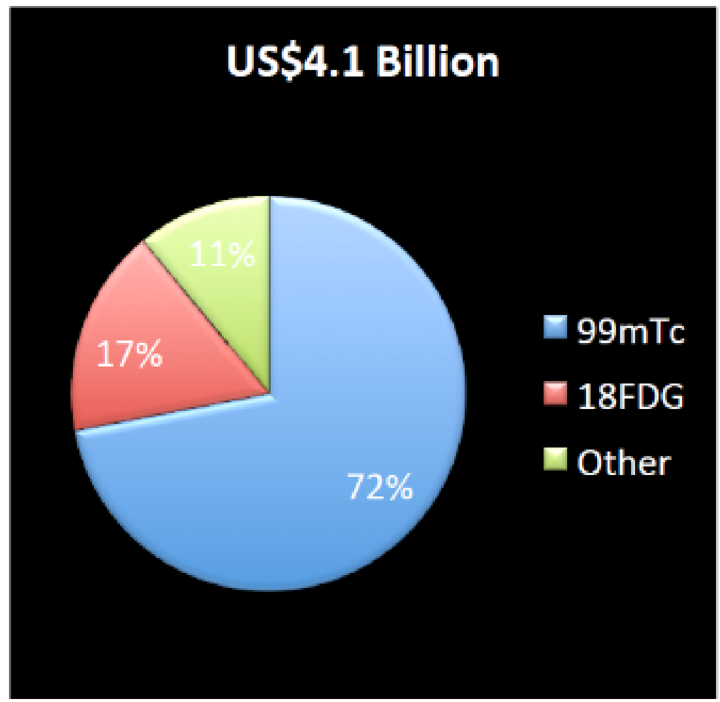
Isotope production

Global Radiopharmaceutical Diagnostic Market [1,2,3]

2010



2017



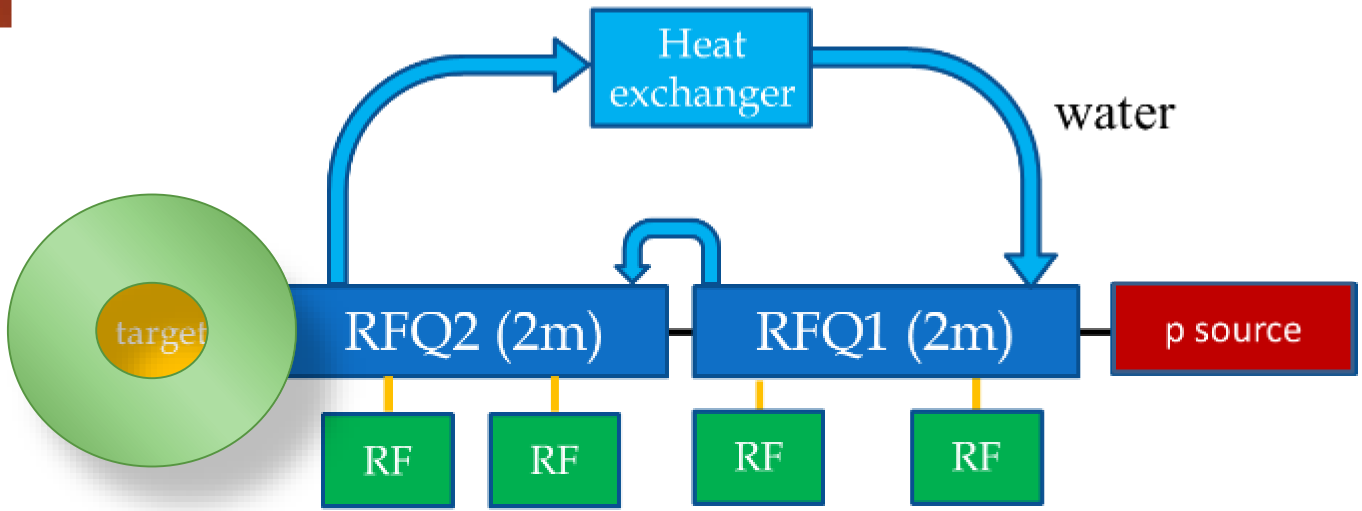
1 Global Radiopharmaceuticals Market (PET/SPECT Imaging & Therapy) – Current Trends & Forecasts (2010 – 2015); MarketsandMarkets, August 2011
2 BMI - Business Monitor International Ltd, Molybdenum-99: Privatising Nuclear Medicine, Special Report 2011
3 Interim Report on the OECD/NEA High-Level Group on Security of Supply of Medical Radioisotopes, The Supply of Medical Radioisotopes, OECD 2012

Courtesy of H. Owen, Manchester University

The Cockcroft Institute

MANCHESTER 1824

The isotope RFQ system



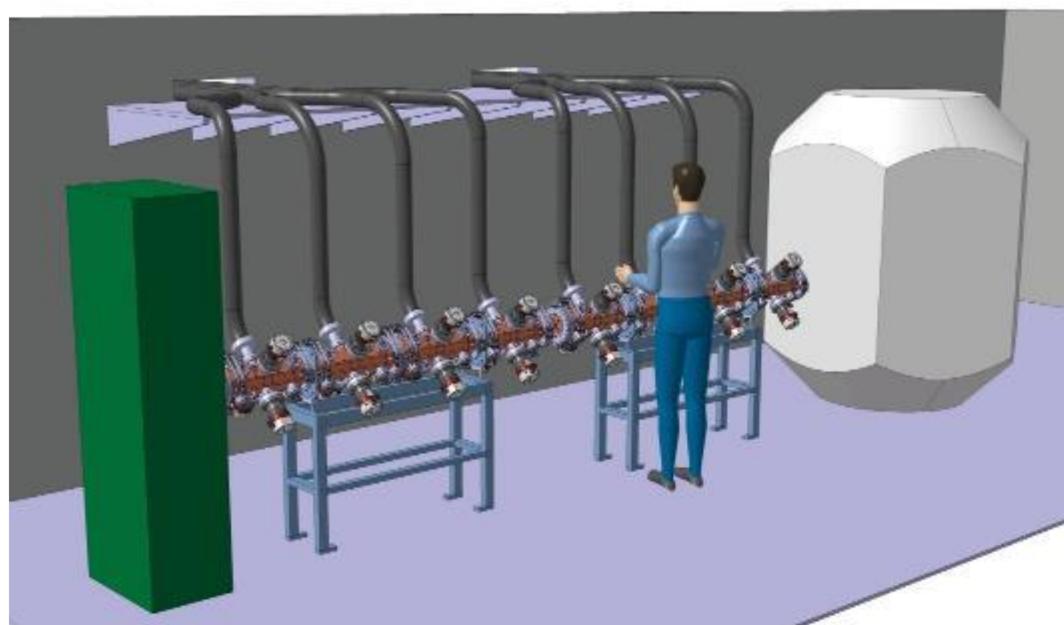
To be installed in hospitals

2 (or more) movable targets.

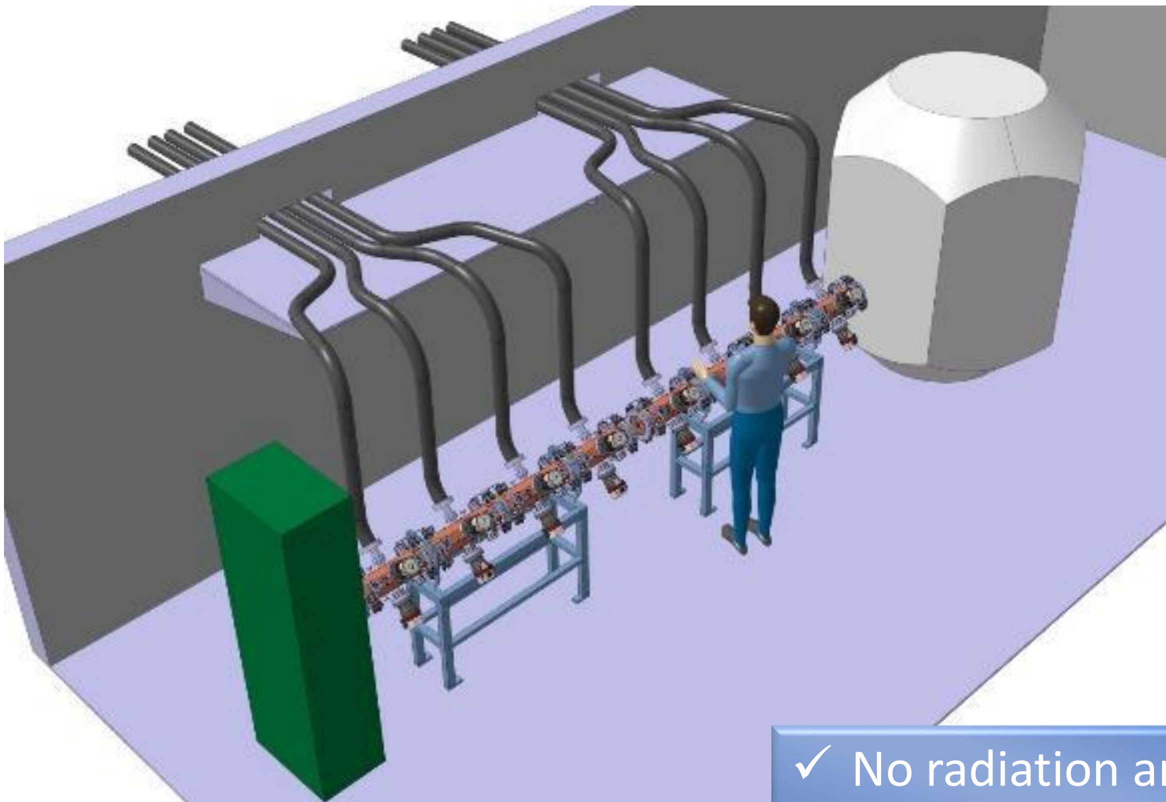
Target shielded by layers of iron and borated (6%) polyethylene, overall radius <0.9 m.

Maximum calculated dose at shielding 2 μSv/h

Weight: 400 kg total (2 RFQs)



Parameters for compact isotope RFQ system



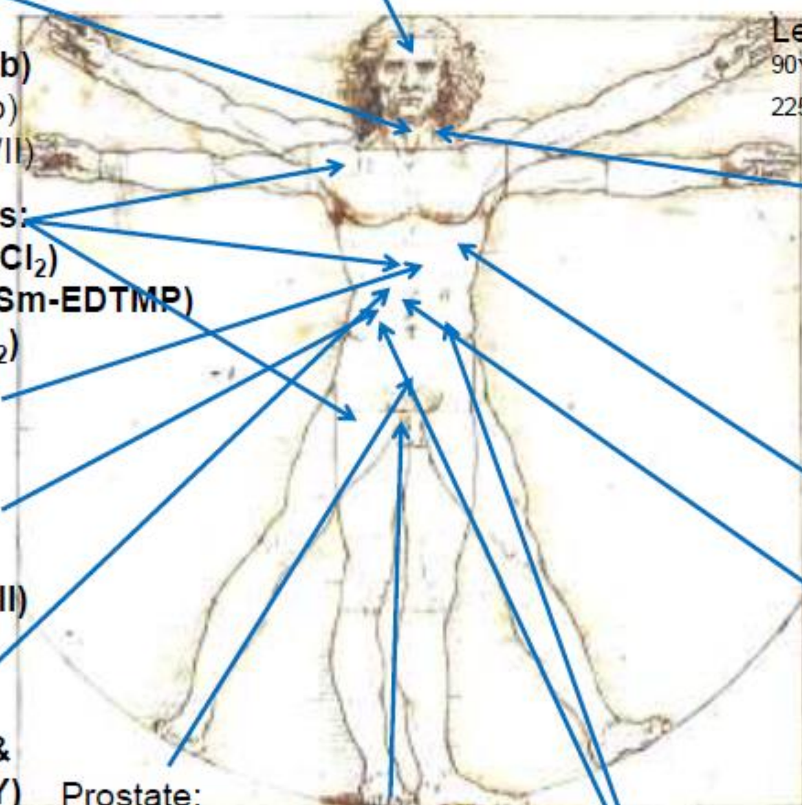
2 RFQs
Input energy = 40 KeV
Total Length = 4.0 m
Output Energy = 10 MeV
Frequency 750 MHz
Average current = 20 μA
Peak current = 500 μA
Duty cycle = 4 %
Peak RF power < 800 kW
Total weight (RFQ): 500 kg
Mains power < 65 kW
Cooling ~ 100 l/min

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

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

Advanced Radiotheraphy

Targeted radionuclide therapies in the clinic



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.

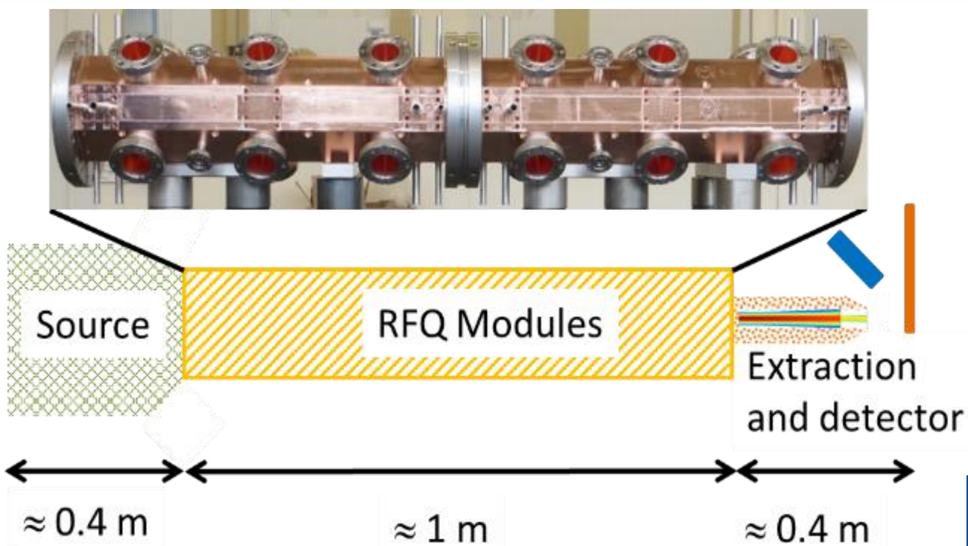
Ion beam analysis

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, …)

Ion Beam Analysis is presently performed with large electrostatic accelerators based in research centres. An RFQ-based portable accelerator 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



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

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

Starting a collaboration with INFN (Florence)

Ion Beam Analysis of Cultural Heritage with a portable RFQ

5. L'acceleratore in miniatura: dal sogno alla realtà?

CERN Accelerating science

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The miniature accelerator

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Michele Ferro-Luzzi (1938-2015)

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THE MINIATURE ACCELERATOR

The image that most people have of CERN is of its enormous accelerators and their capacity to accelerate particles to extremely high energies. But thanks to some cutting-edge studies on beam dynamics and radiofrequency technology, along with innovative construction techniques, teams at CERN have now created the first module of a brand-new accelerator, which will be just 2 metres long. The potential uses of this miniature accelerator will include deployment in hospitals for the production of medical isotopes and the treatment of cancer. It's a real David-and-Goliath story.

Serge Mathot, in charge of the construction of the "mini-RFQ", pictured with the first of the four modules that will make up the miniature accelerator.

The miniature accelerator consists of a radiofrequency quadrupole (RFQ), a component found at the start of all proton accelerator chains around the world, from the smallest to the largest. The LHC is designed to produce very high-intensity beams at a very high energy, but its little brother is content to produce beams at low speeds, containing particles which, after travelling two metres, have an energy of 5 MeV. "When we took up the challenge of creating the first high-frequency compact RFQ accelerator, with the support of the

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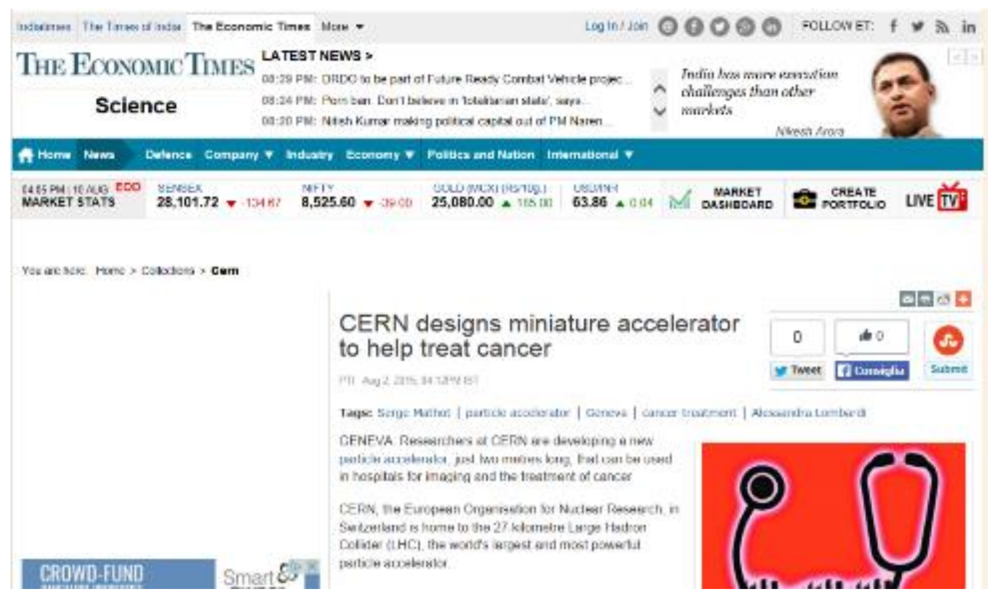
Cern developing 'mini LHC' particle accelerator to treat cancer

By Hannah Osborne

August 3, 2015 18:04 BST

Since a first article on this activity was published on the CERN Bullettin in June, the information has been retwetted more than 1’000 times and reported by dozens of on-line science journals and blogs…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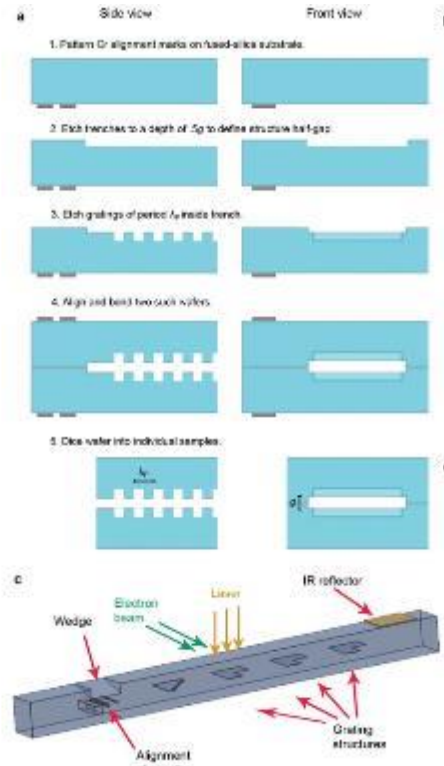
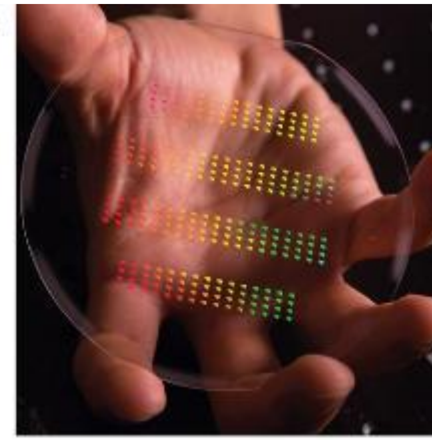
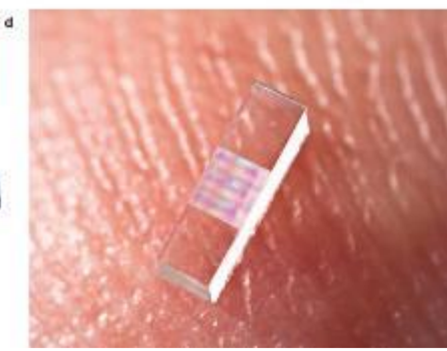
CERN designs miniature accelerator to help treat cancer

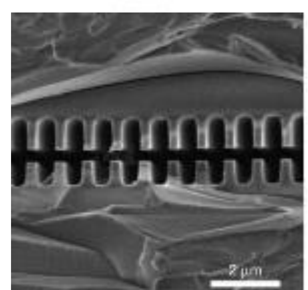
Other roads to the miniature accelerator

AMIT superconducting cyclotron
(CIEMAT, Spain, with CERN contribution)









Dielectric Laser Accelerator,
electrons (Stanford)

The miniature accelerator in the virtual world

Grazie per la vostra attenzione

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