Tecnologie e applicazioni degli acceleratori lineari: verso l'acceleratore in miniatura ?

Maurizio Vretenar, DG Department, 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)

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

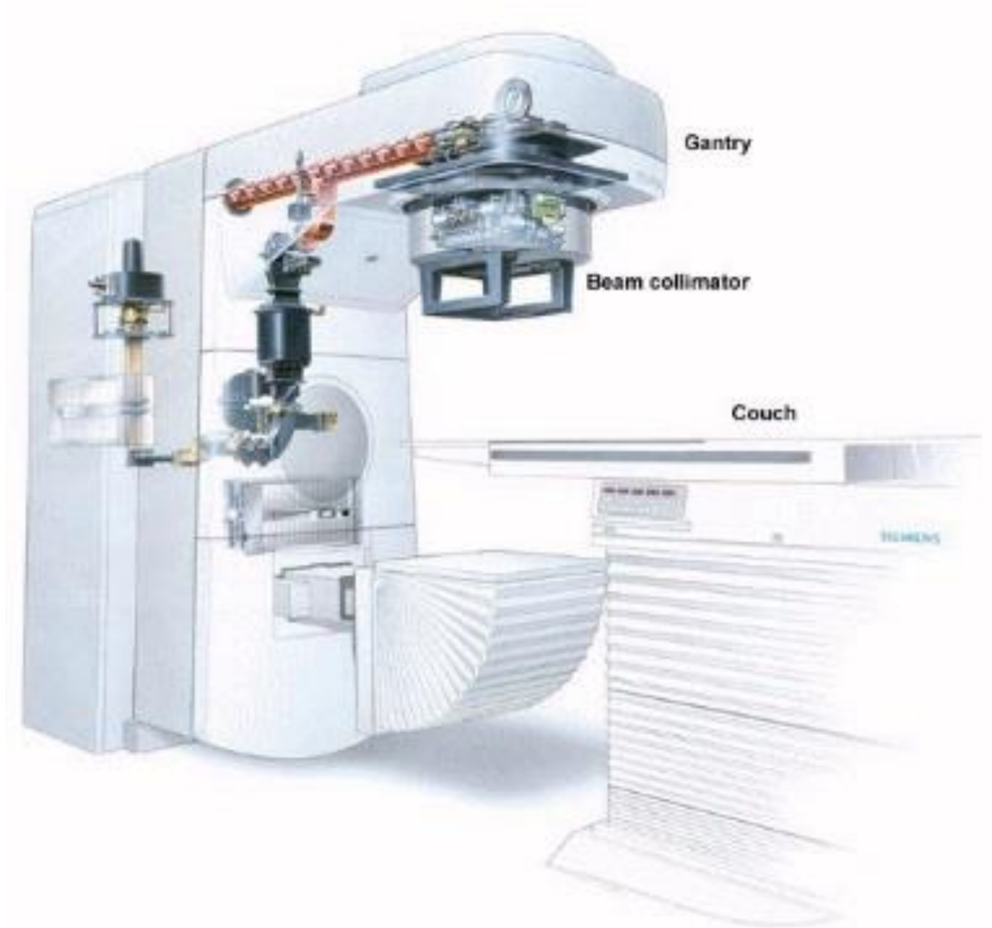
Linac (acceleratore lineare) di elettroni per la radioterapia (trattamento del cancro con raggi X)

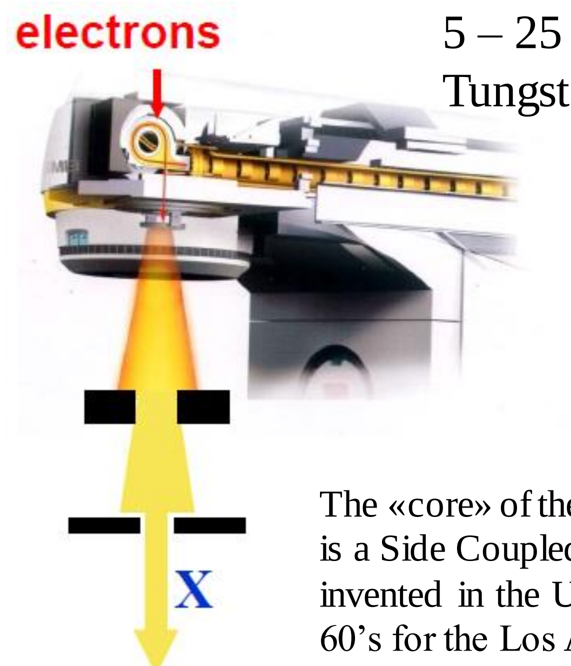
Circa 8’000

(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

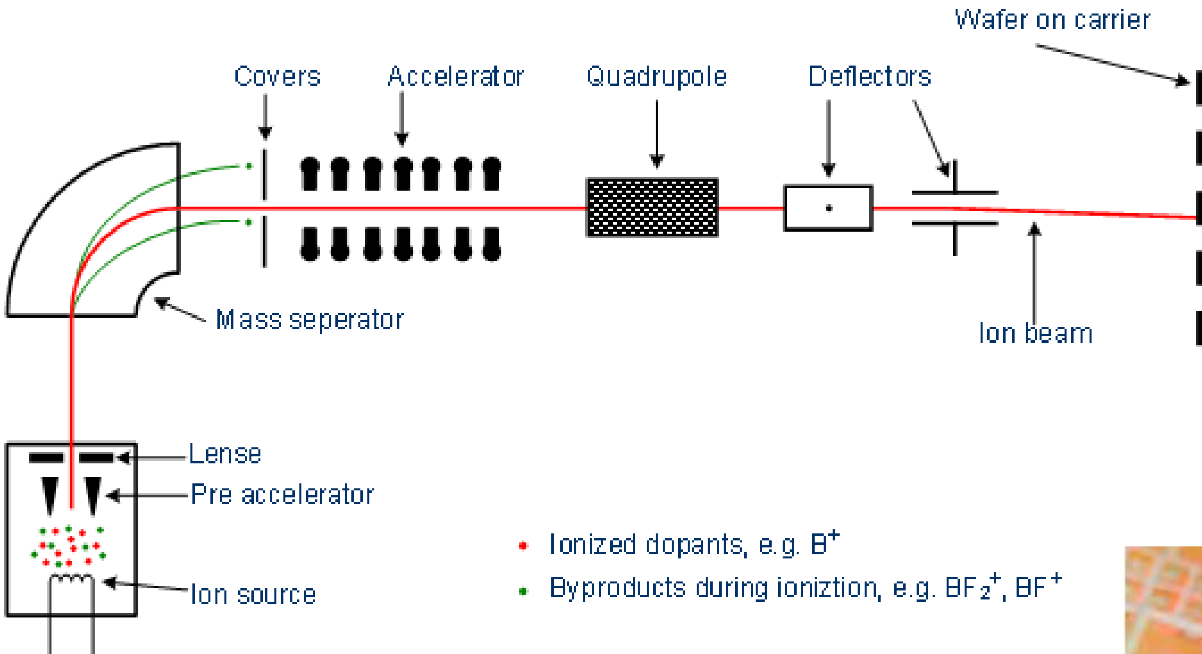
Commercialised by several companies, available in all major hospitals

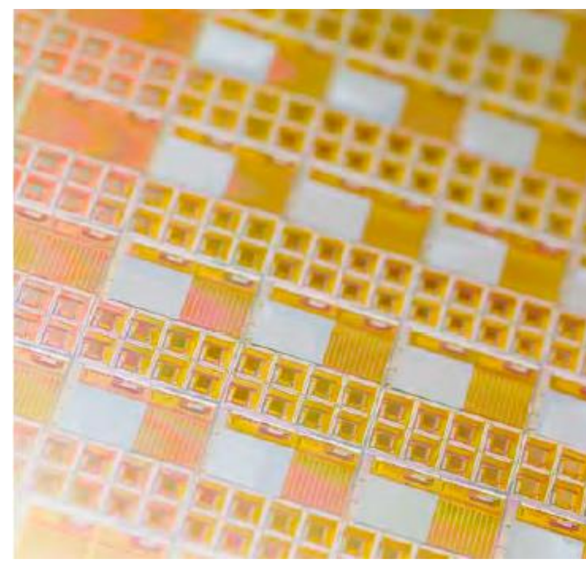
Industrial applications of linacs

	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

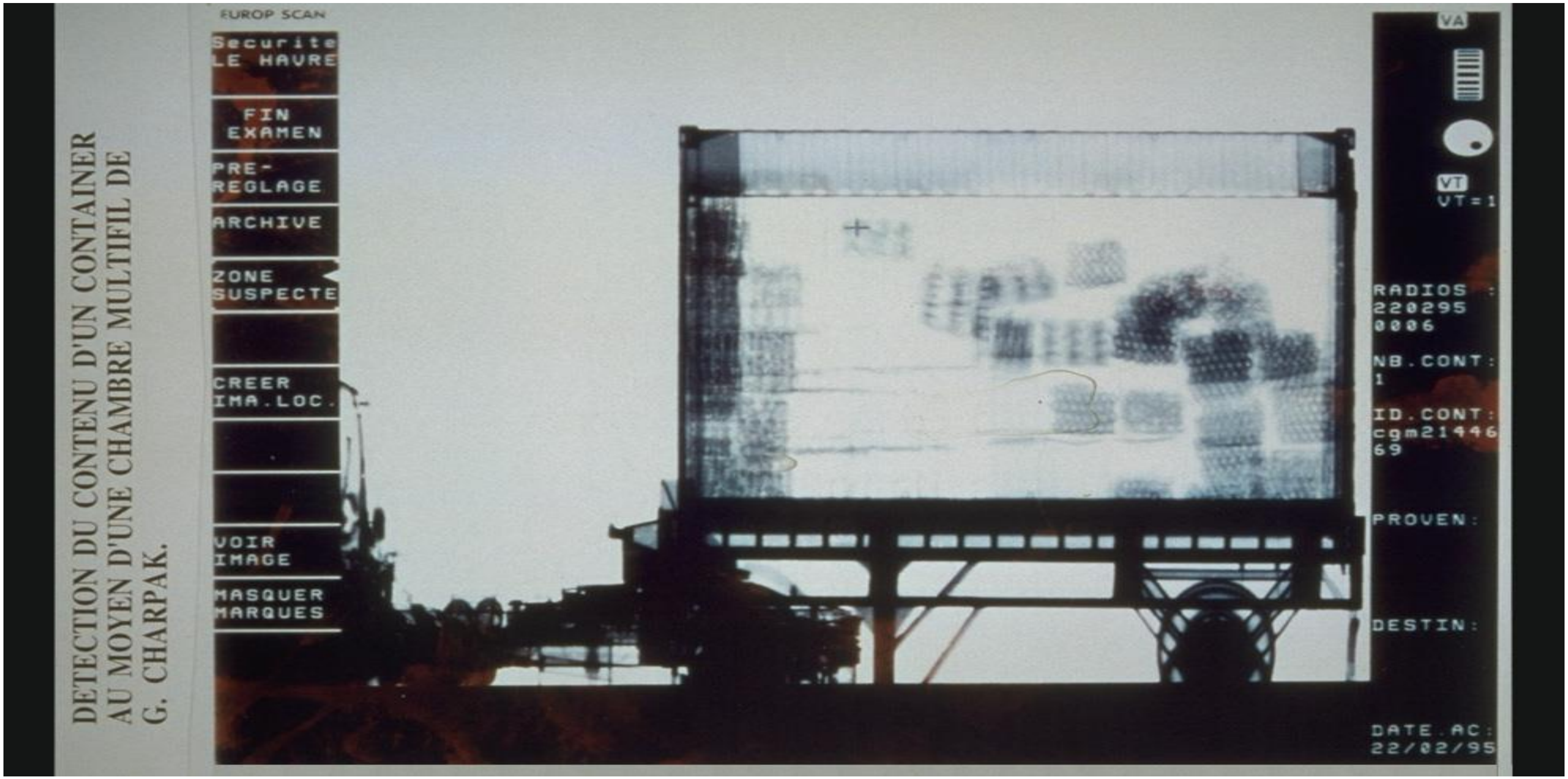
A large fraction is made of small electrostatic machines for ion implantation.

Ion implantation system





Cargo screening



Key questions: what does the man in the street need?

More and better science – we all agree!
More and better life – we all agree, too…

APAE kick-off meeting

"THE APPLICATIONS OF PARTICLE ACCELERATORS IN EUROPE"

http://indico.cern.ch/e/APAE-2015.html

Royal Academy of Engineering
London, 18-19 June 2015

International Organising Committee:

Roy Aleksan (CEA)
Oliver Boine-Frankenheim (GSI & TU Darmstadt)
Phil Burrows (Oxford)
Angeles Faus-Golfe (IFIC Valencia) - Chair
Steve Myers (CERN)
Andrea Pisent (INFN LNL)
Rob Edgecock (Huddersfield & STFC) - WP4 coordinator
Agnes Szeberenyi (CERN) - EuCARD2 Communications

EuCARD²

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.

June 2015: Kick-off meeting of APAE: document for policy-makers on applications of interest in Europe and for which technology developed for research can have an impact.

Acceleratori lineari

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

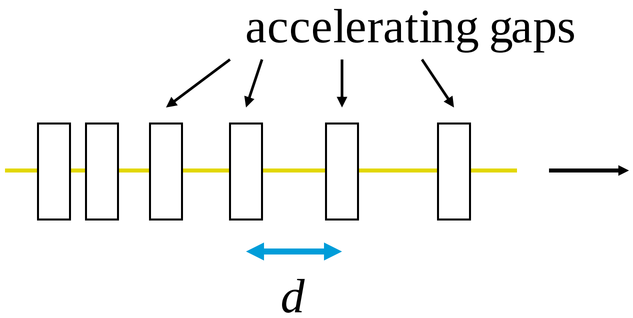
Gli acceleratori lineari coprono la parte iniziale del processo di accelerazione di un fascio di particelle, fino a energie dell’ordine di 10-500 MeV per protoni e 1 GeV per elettroni.

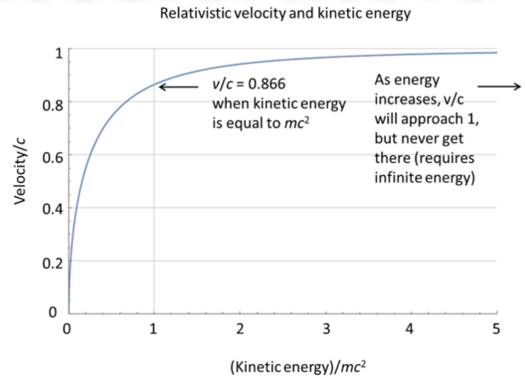
Assieme ai ciclotroni, sono gli acceleratori piu’ adatti per le applicazioni mediche e industriali che richiedono energie non molto elevate.

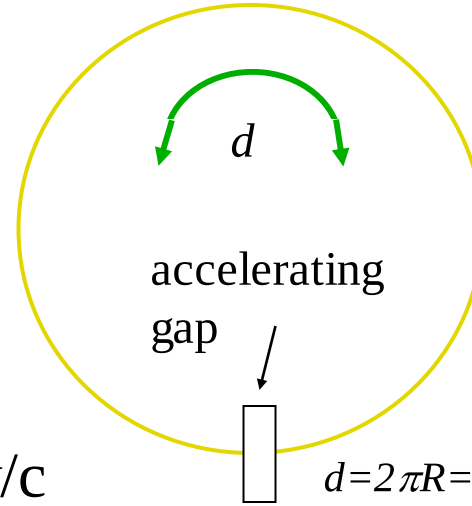
LHC = energia piu’ alta possibile (massa delle nuove particelle prodotte)
intensità piu’ alta possibile (numero delle nuove particelle prodotte)

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







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

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

$\beta=v/c$

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

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:

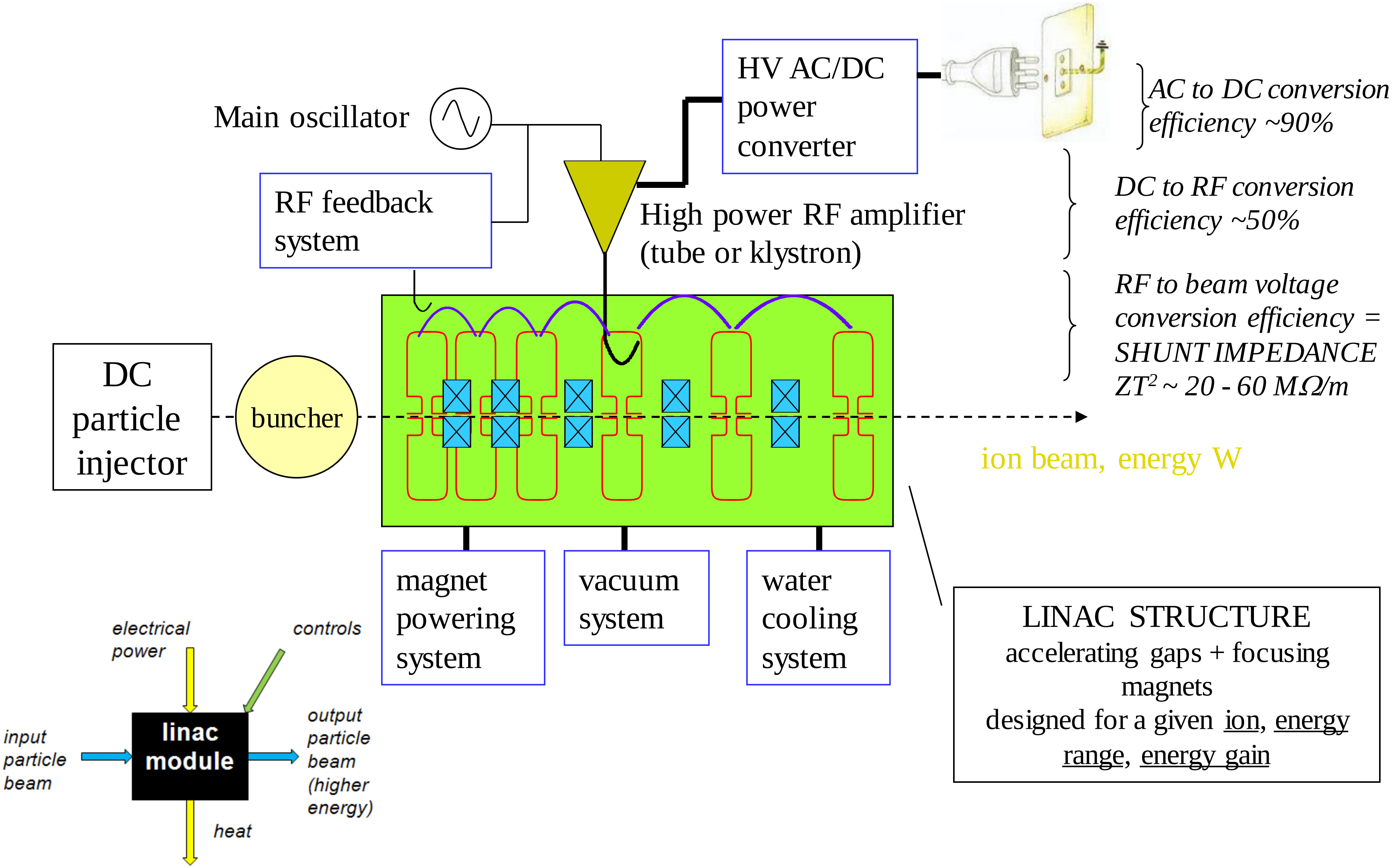
Particles accelerated by one (or more) gaps at given positions in the ring.

Distance between gaps is fixed. Synchronicity only for β~const, or varying (in a limited range!) the RF frequency.

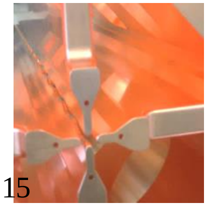
Used in the range where β is nearly constant. "Einstein" machine

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

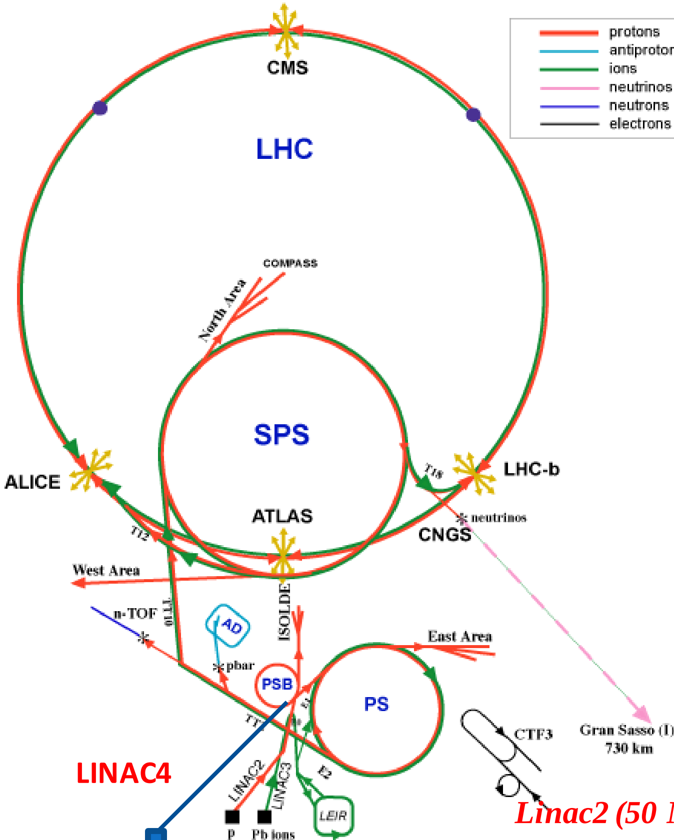
Linac building blocks



Il progetto Linac4



The LHC injection chain



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

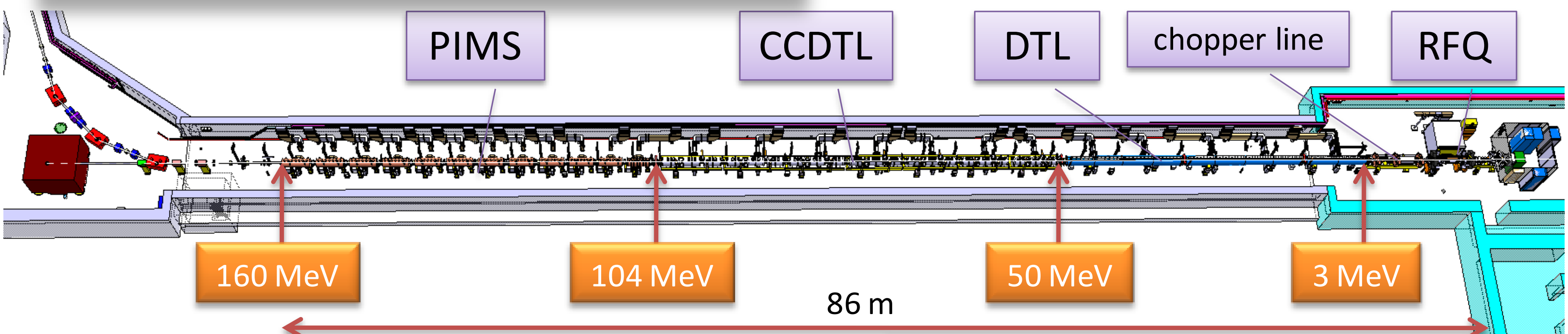
Linac2 (50 MeV)
↓
PS Booster (1.4 GeV)
↓
PS (25 GeV)
↓
SPS (450 GeV)
↓
LHC

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

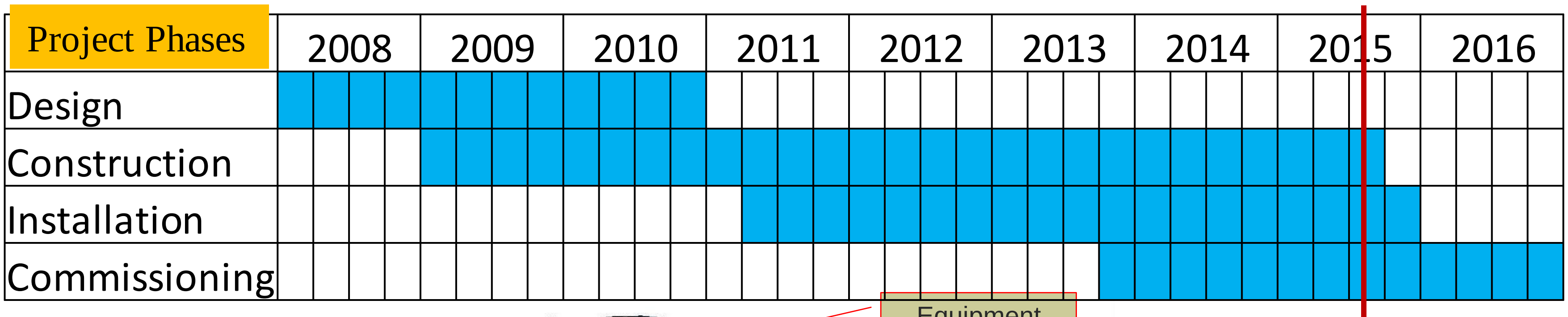
	Energy [MeV]	Length [m]	RF Power [MW]	Focusing
RFQ	0.045 - 3	3	0.6	RF
DTL	3 - 50	19	5	112 PMQs
CCDTL	50 - 102	25	7	14 PMQ, 7 EMQs
PIMS	102 - 160	22	6	12 EMQs

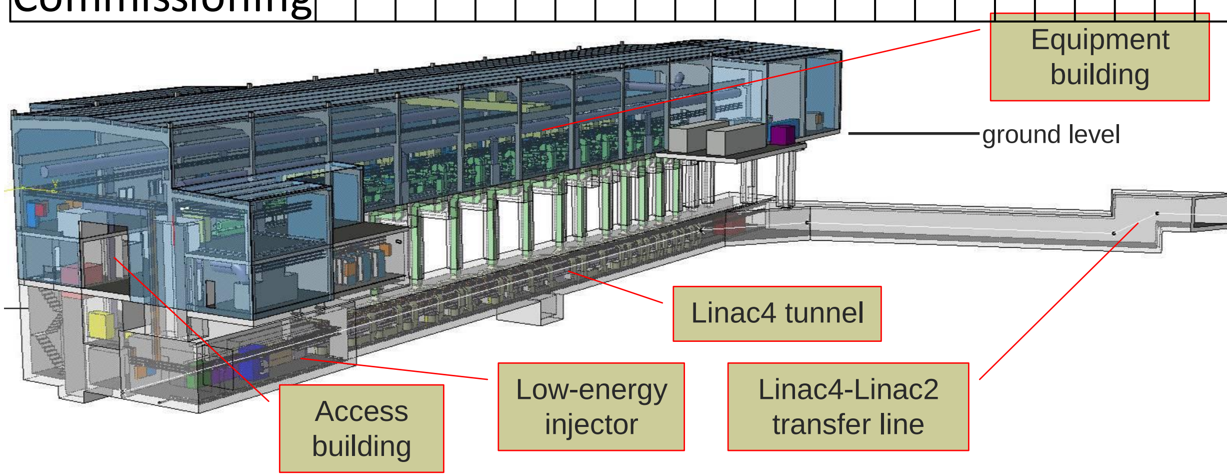


The Linac4 Project

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).



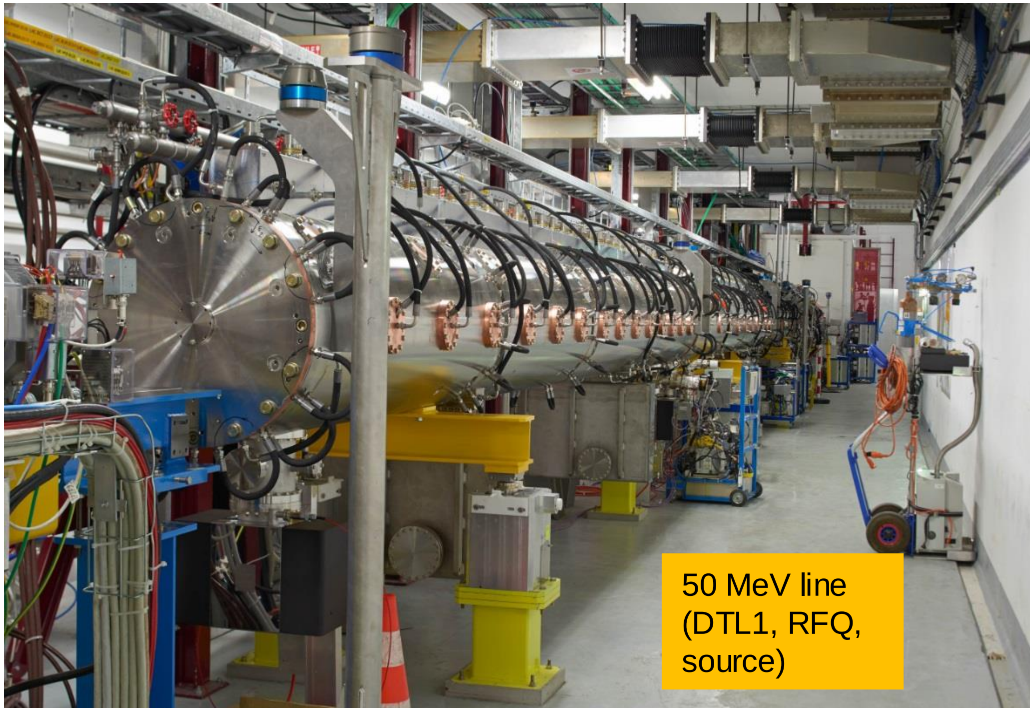


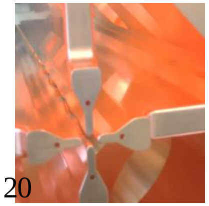
- About 100m in length, connection to the PSB and option of a future extension to higher energy.
- Linac tunnel 12 m underground, surface building for RF and other equipment, access module at low energy.

Linac4 Status - building

Installation in surface hall completed

Linac4 Status - tunnel

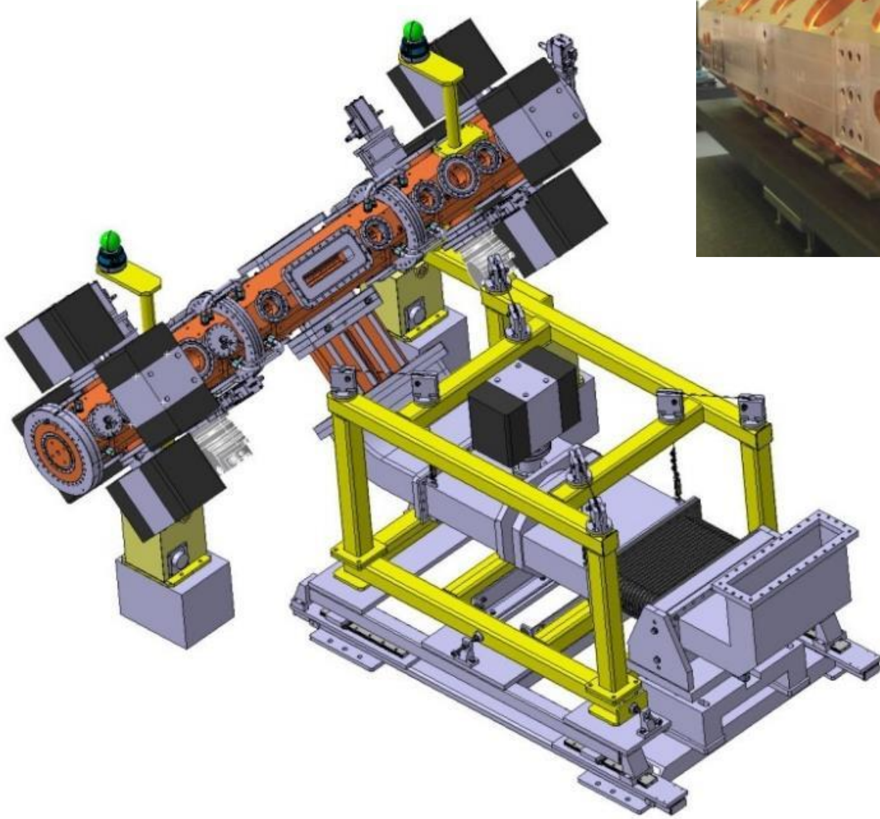




The Linac4 Radio Frequency Quadrupole (RFQ)

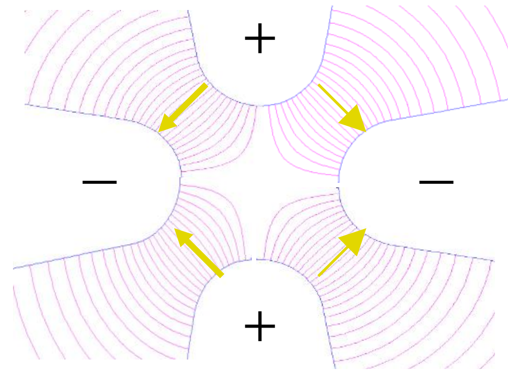
RFQ = Focusing channel + bunching + acceleration

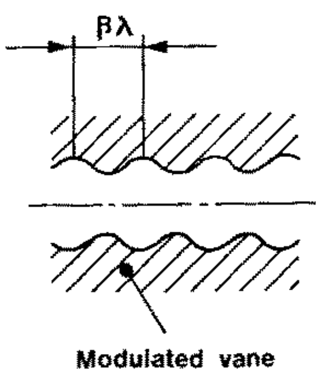
The Radio Frequency Quadrupole (RFQ) is the first accelerator in Linac4 (3m, up to 3 MeV). It focuses bunches and accelerates the beam in a quadrupole channel inside an RF resonator.



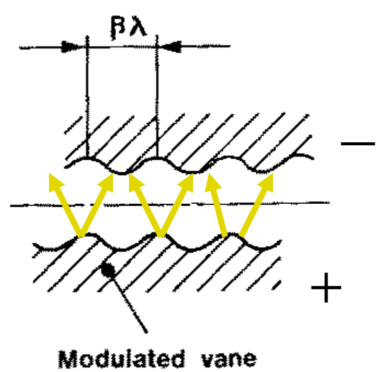
RFQ properties

1. Four electrodes (vanes) between which we excite an RF Quadrupole mode (TE210) → 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 provides acceleration and bunching.

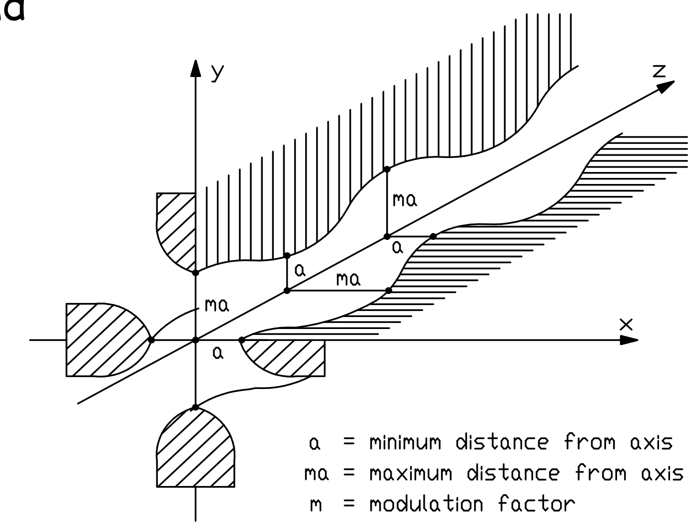




Opposite vanes (180°)



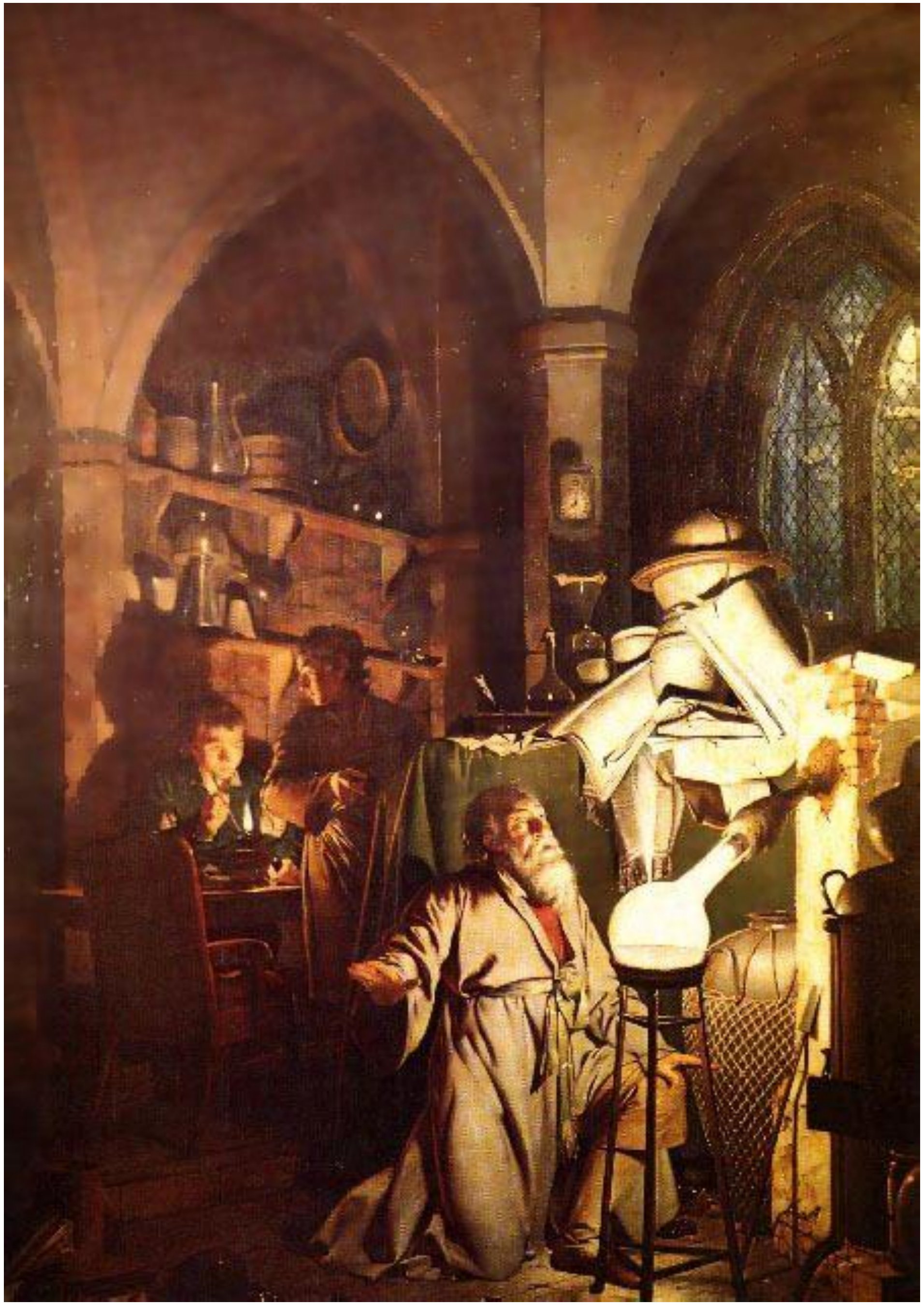
Adjacent vanes (90°)



From Linac4 to society…

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).



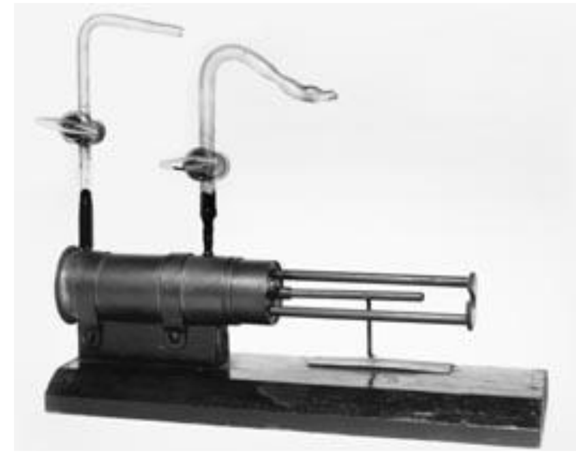
The alchemists of the XXI century!

Back to the Rutherford and to the origins of accelerators

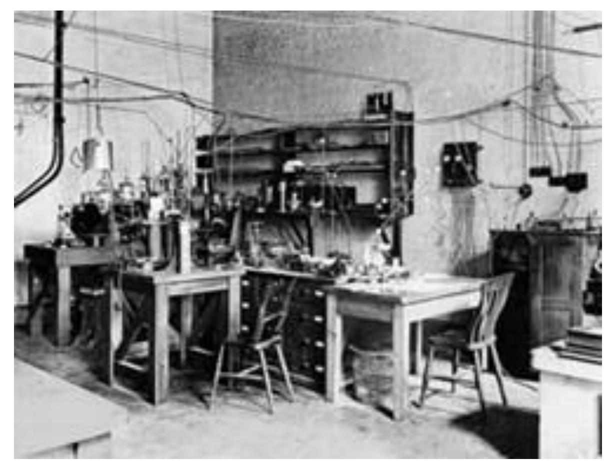
1919: Ernest Rutherford's historical experiment: some nitrogen nuclei are disintegrated by α-particles coming from radioactive decay of Ra and Th → start of a new era for science! But only few light atoms can be modified using particles from radioactive decays .

Men can transform the matter, the dream of the ancient alchemists!

1927: Rutherford in a famous speech at the Royal Society asks for "accelerators" capable to disintegrate heavy nuclei. Theory predicts the threshold for penetration of the nucleus at ~500 keV → from 1929, various labs start developing "particle accelerators" for >500 keV.



Reproduction of the Rutherford chamber: Bombardment of nitrogen atoms with alpha particles, producing oxygen and hydrogen nuclei.



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.

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.

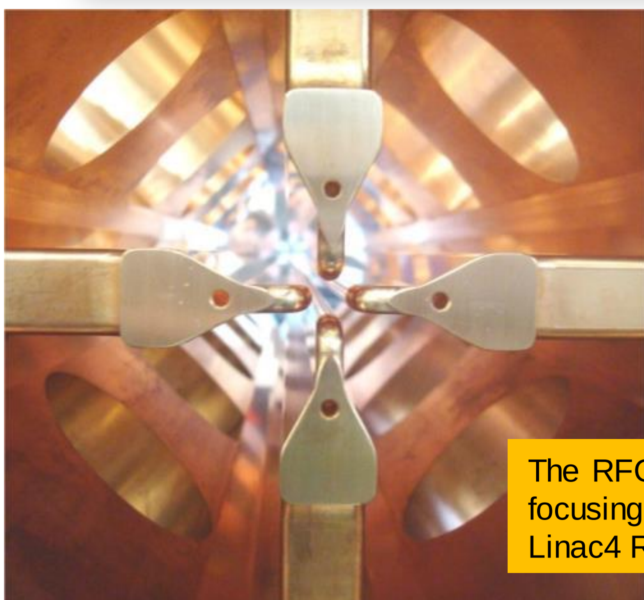
Compact RFQs

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

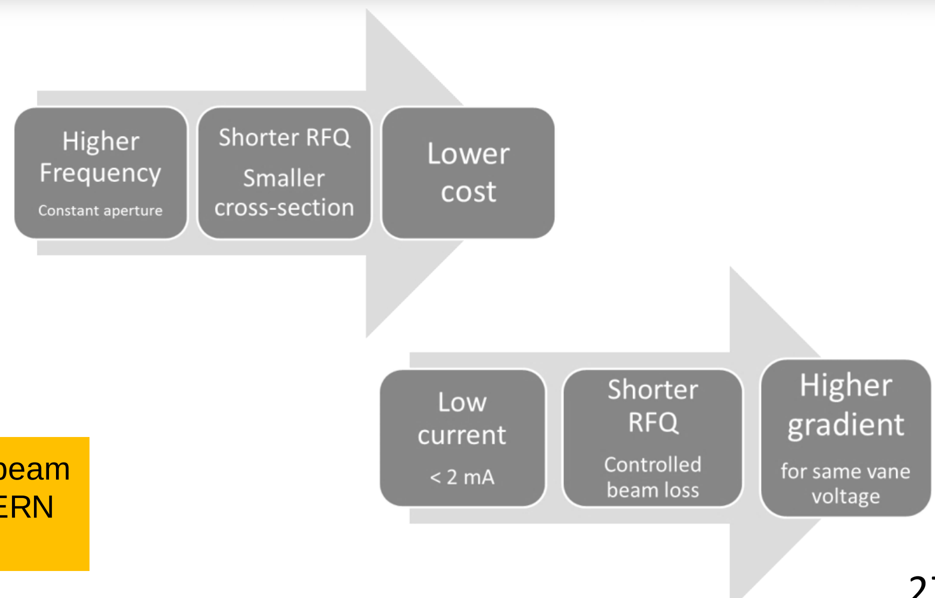
Relatively new technology (invented in Russia in the 70's, first prototype RFQ in the USA 1980, becomes the standard low-energy linac in scientific laboratories from the 90's).

THE KEY TO SMALLER DIMENSIONS : HIGHER FREQUENCY

Initial RFQs in the 200 MHz frequency range, later, 400 MHz range (Linac4).
The new compact RFQ needs to go to a new frequency range 700 – 800 MHz !



The RFQ cross-like beam focusing channel (CERN Linac4 RFQ, 2012).



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

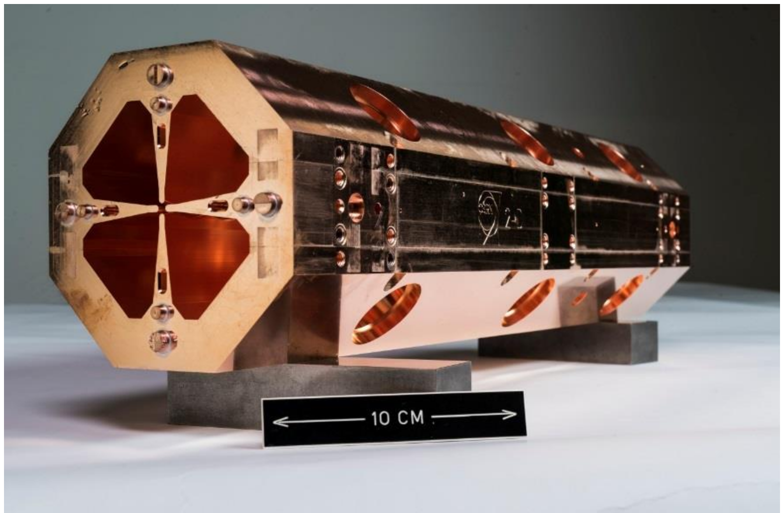
- 20 MeV
- Includes DTL linac
- High current
- High duty cycle (10%)
- Preliminary design

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 Status

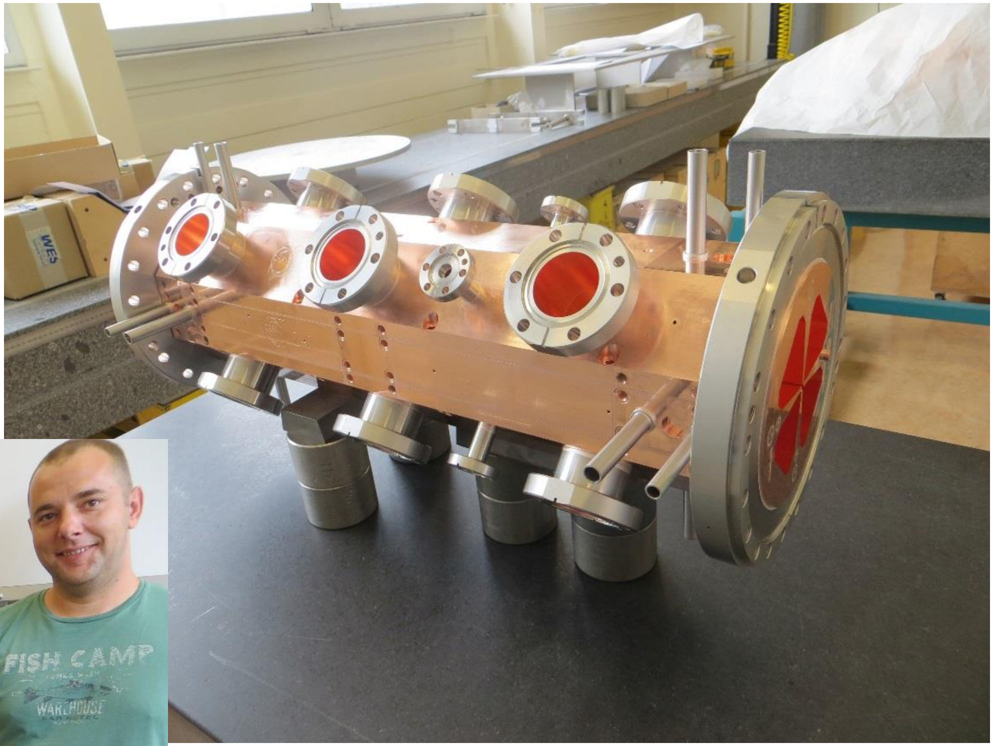


The first RFQ module with S. Mathot, in charge of the mechanical construction.

Two out of 4 modules have been completed; production of the others is progressing and final assembly is foreseen for April 2016, to be followed by high-power and beam tests.

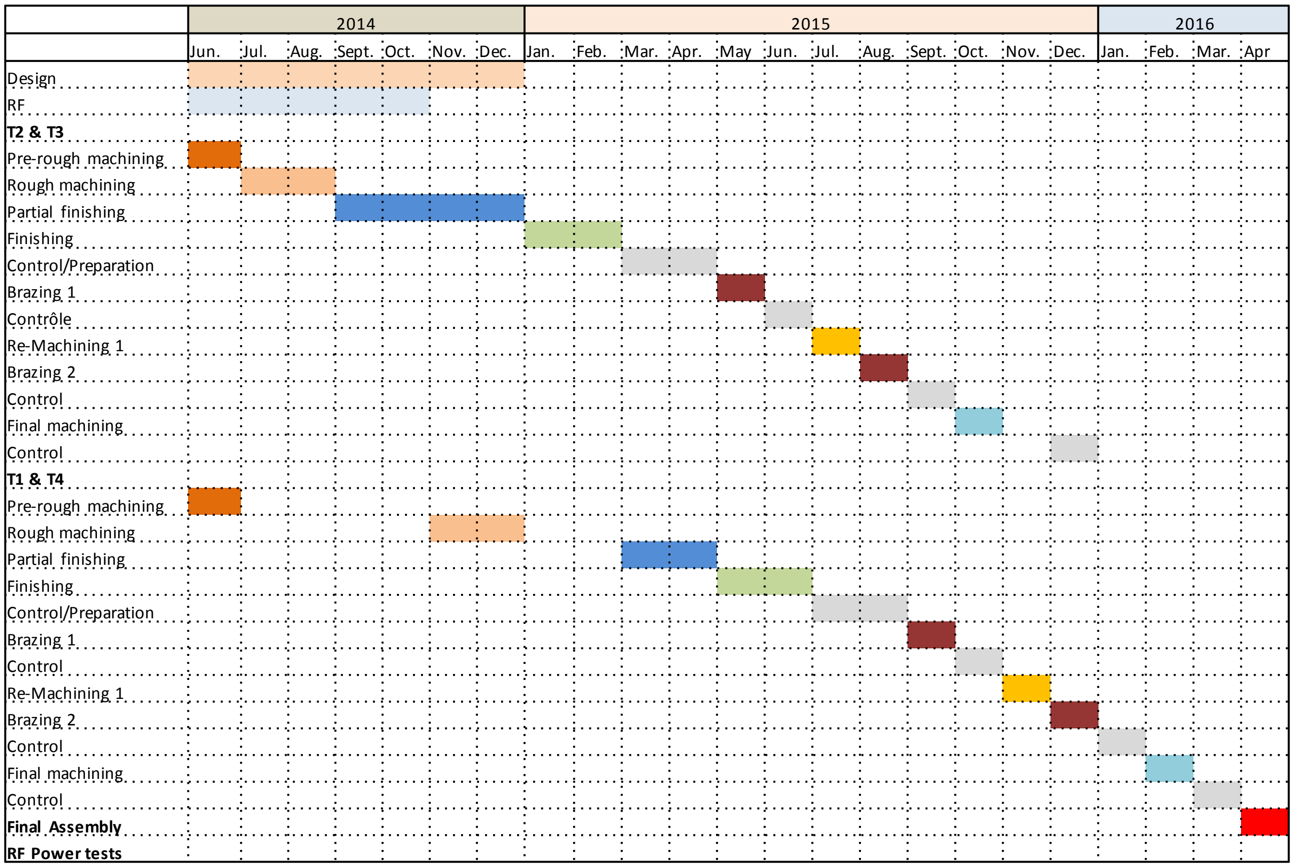
In summer 2016 the technology will be completely validated.

Assembled RFQ module



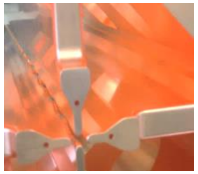
Construction and testing

HF-RFQ Production Planning, version 20 Mars 2015

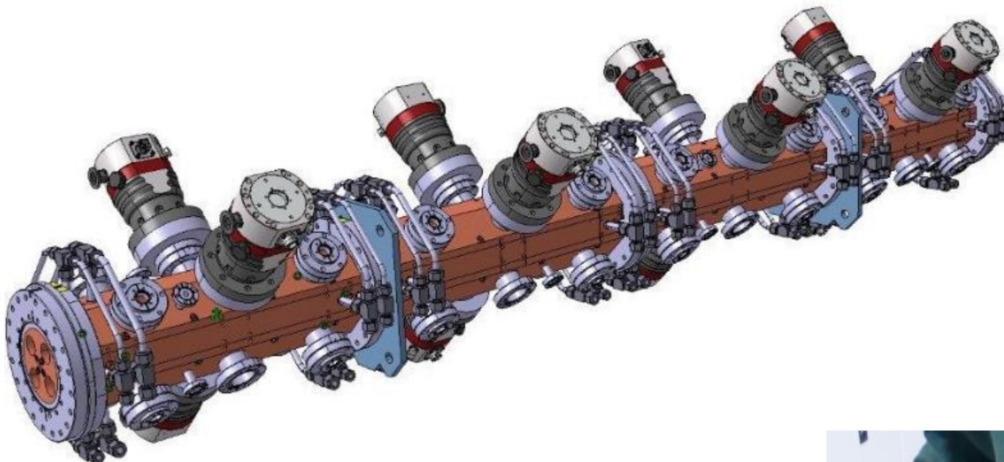


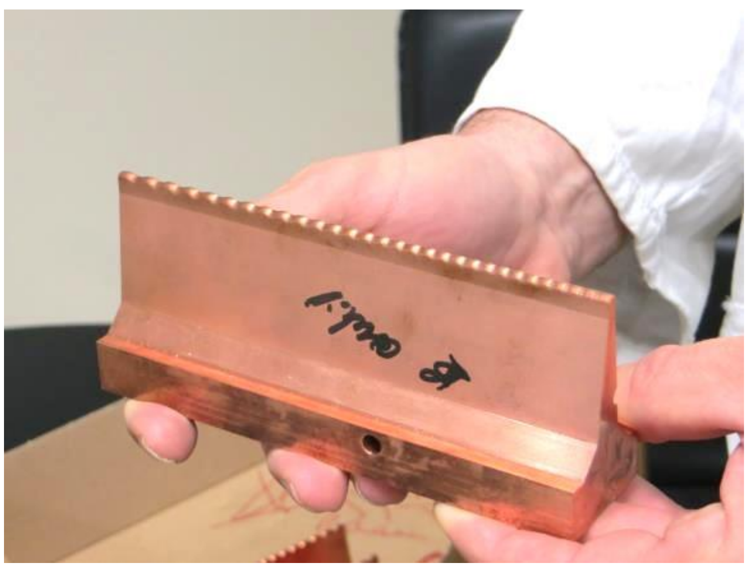
Final assembly foreseen for April 2016.

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



A small RFQ...





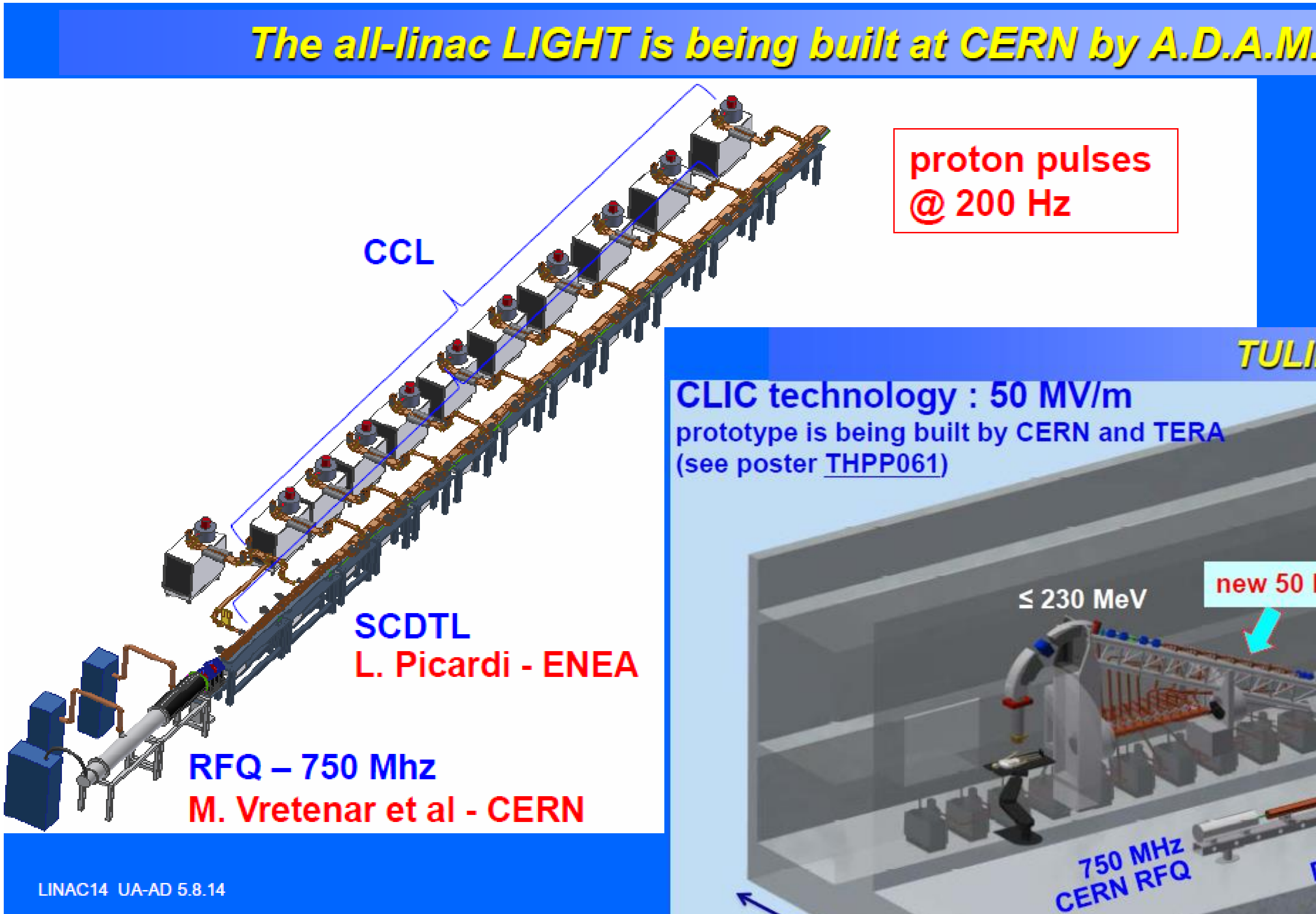
Modulation test machining

Major electrode, rough machined

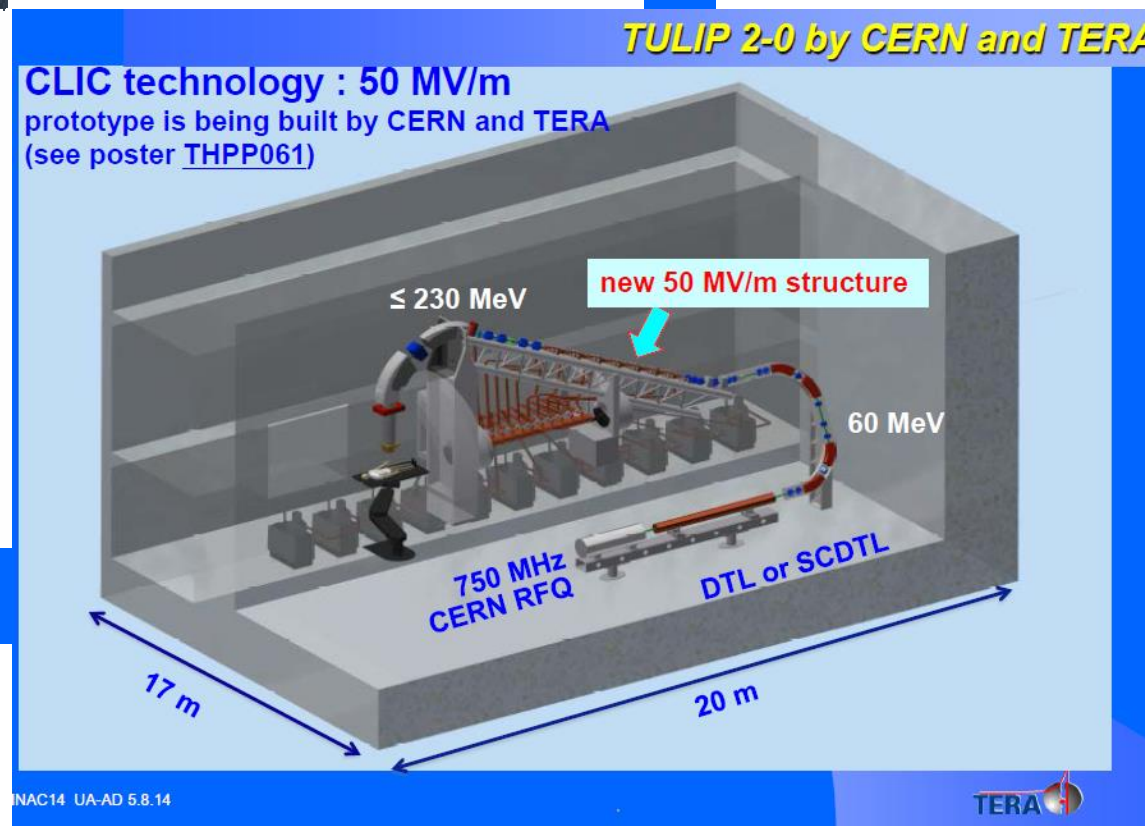
Basic parameters

	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

RFQ for Proton therapy

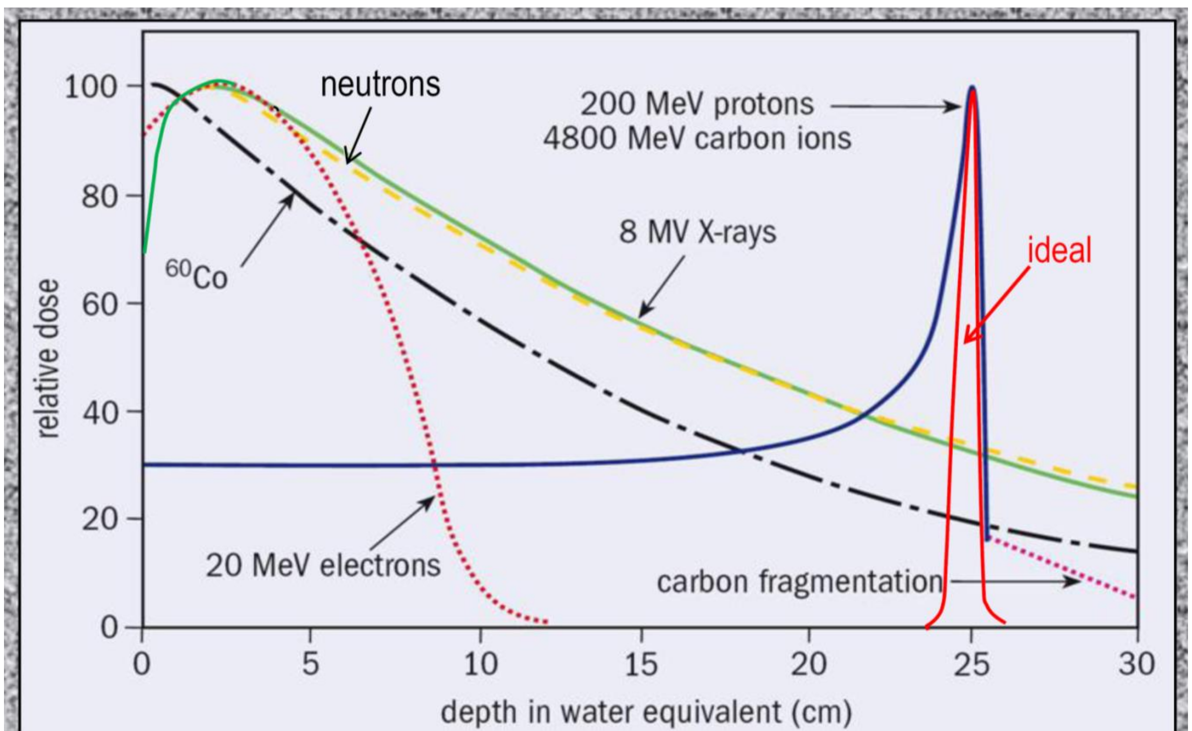


2 examples of proton therapy linacs using the HF-RFQ as injector



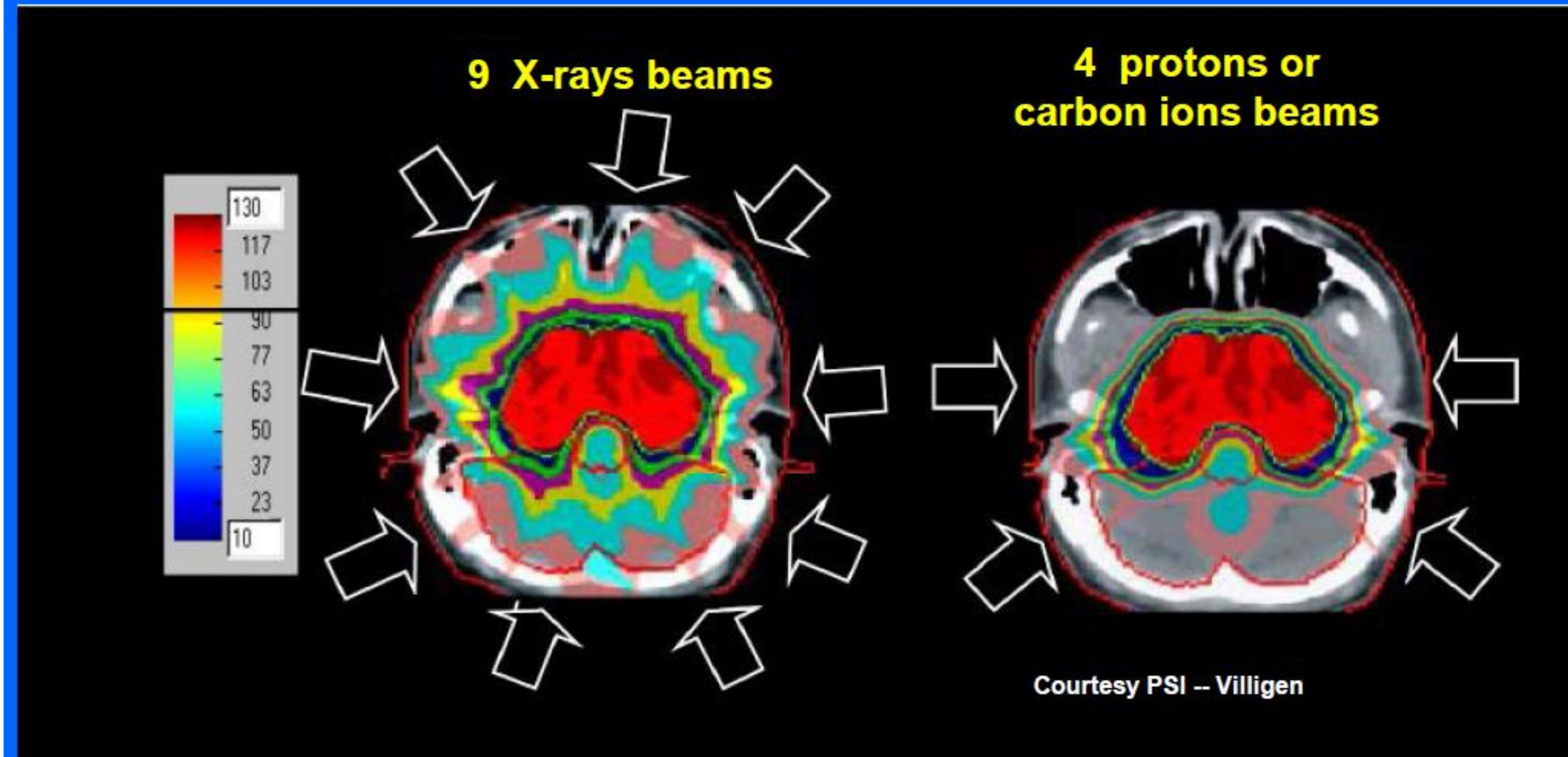
Hadrontherapy

‘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.

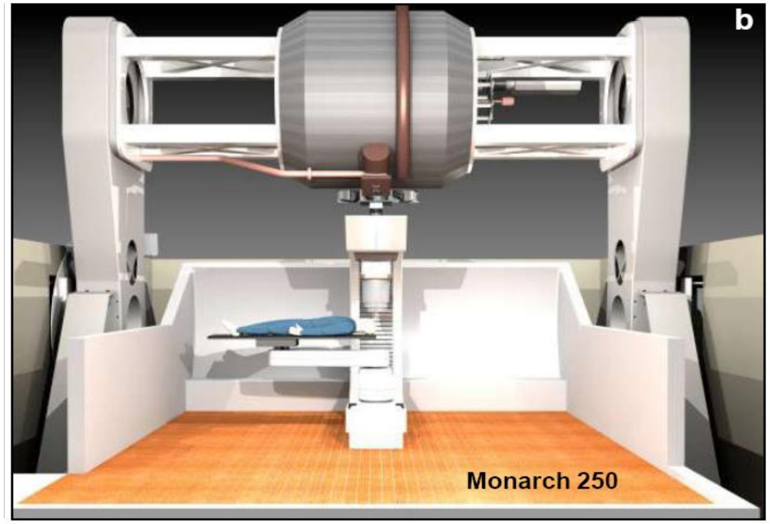
Advantages of hadrontherapy: 1. normal tissues are speared



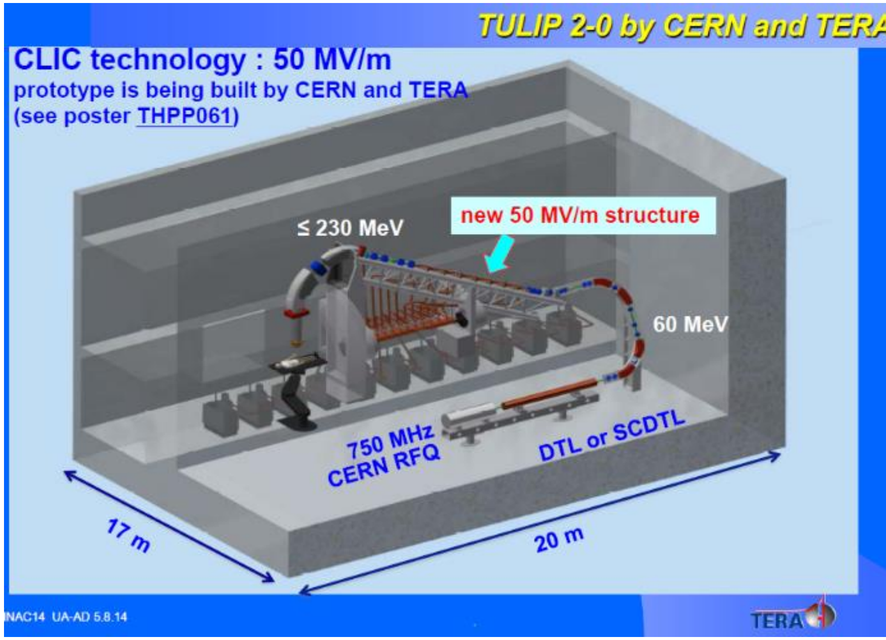
New challenges in hadrontherapy accelerators

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.



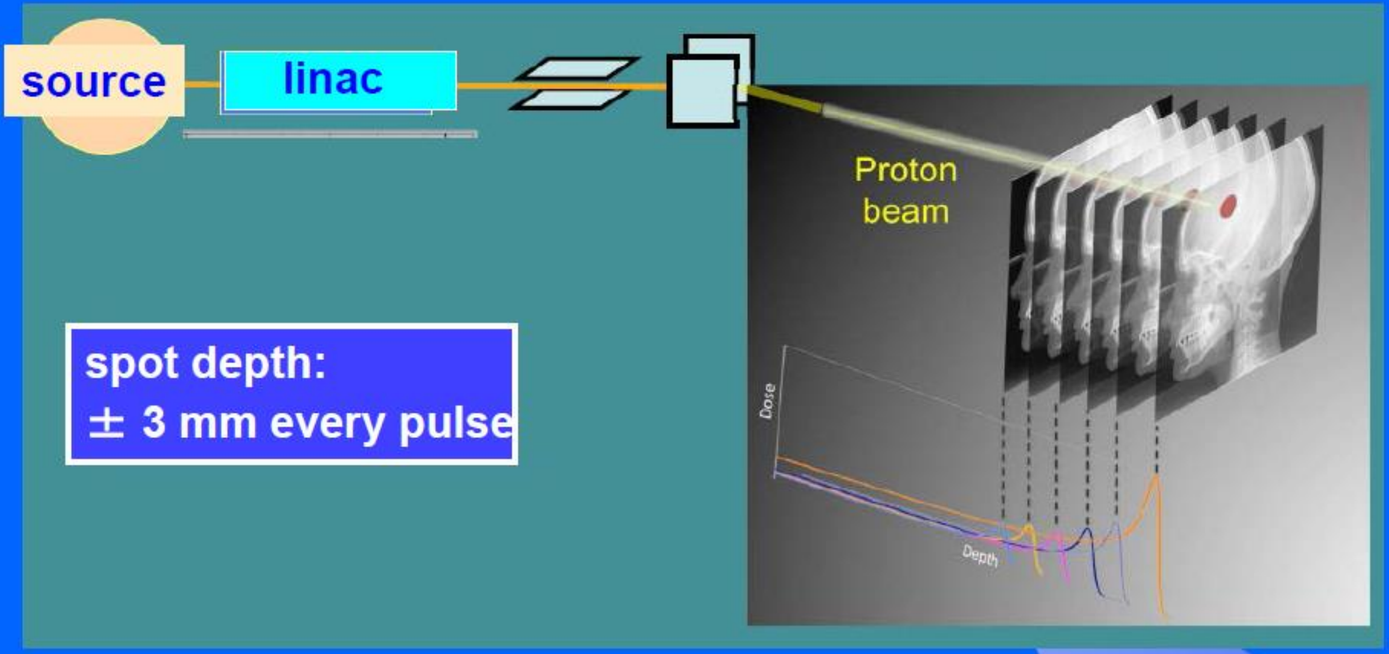
First single room facility: Still River synchrocyclotron rotating around the patient



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

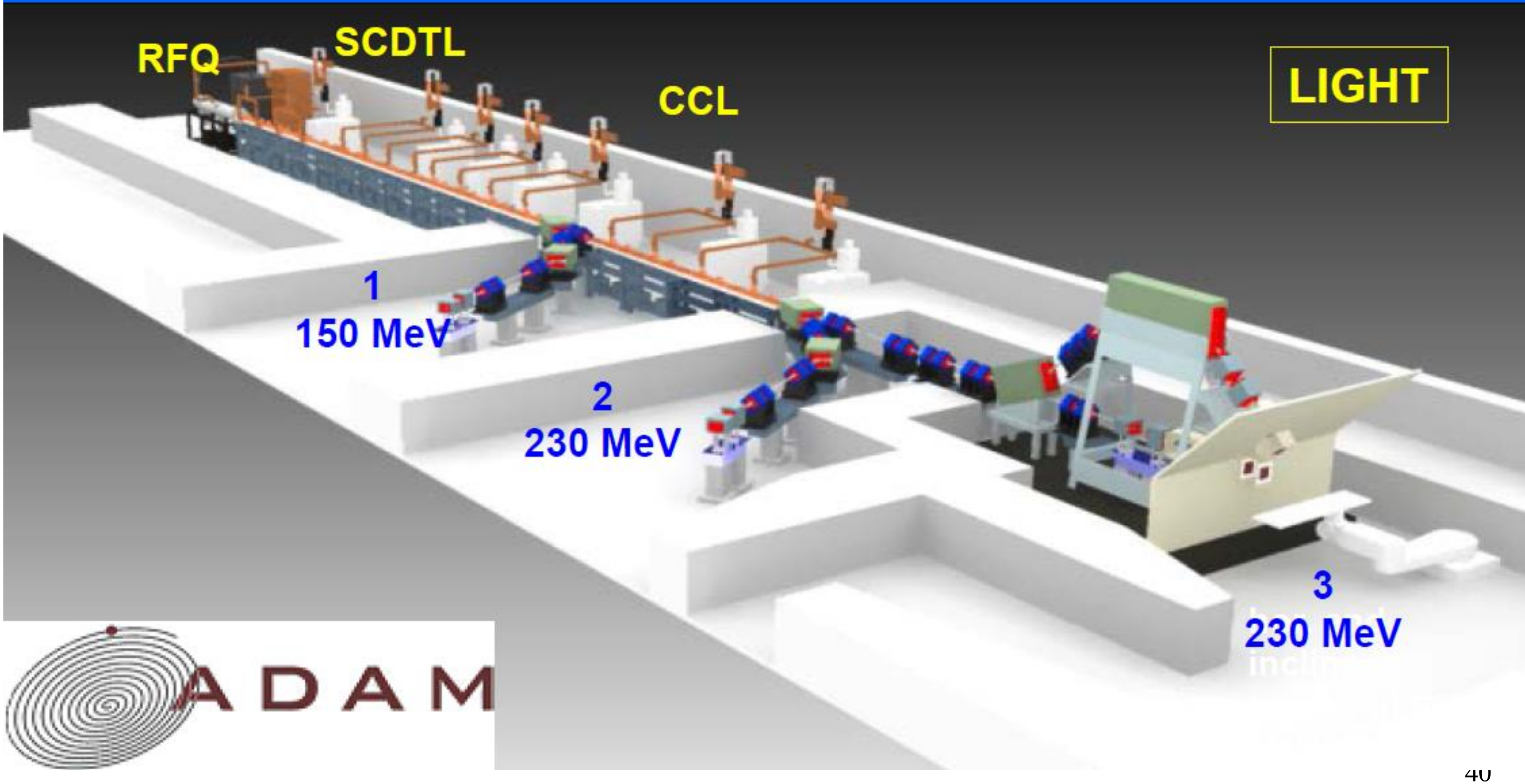
The dose deposition depth can be adjusted every 3 ms

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

The all-linac LIGHT is being built at CERN by A.D.A.M.



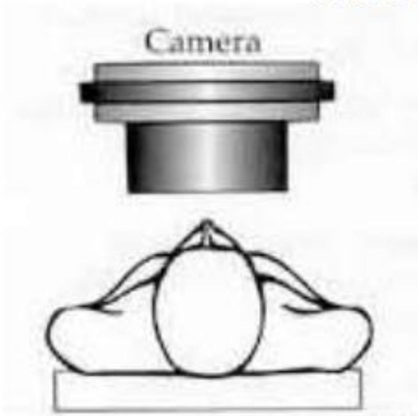
ADAM

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.

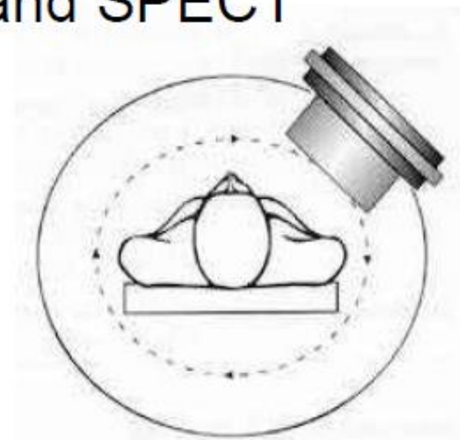
Recently (contract signed in August 2015) ADAM has purchased from CERN a license to use the compact RFQ technology for the construction of proton therapy linacs.

Tomography

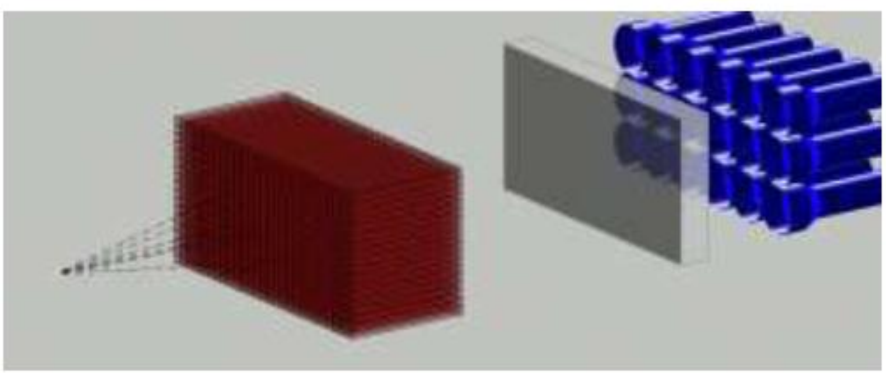
Scintigraphy and SPECT



2D: planar scan
(Gamma camera)

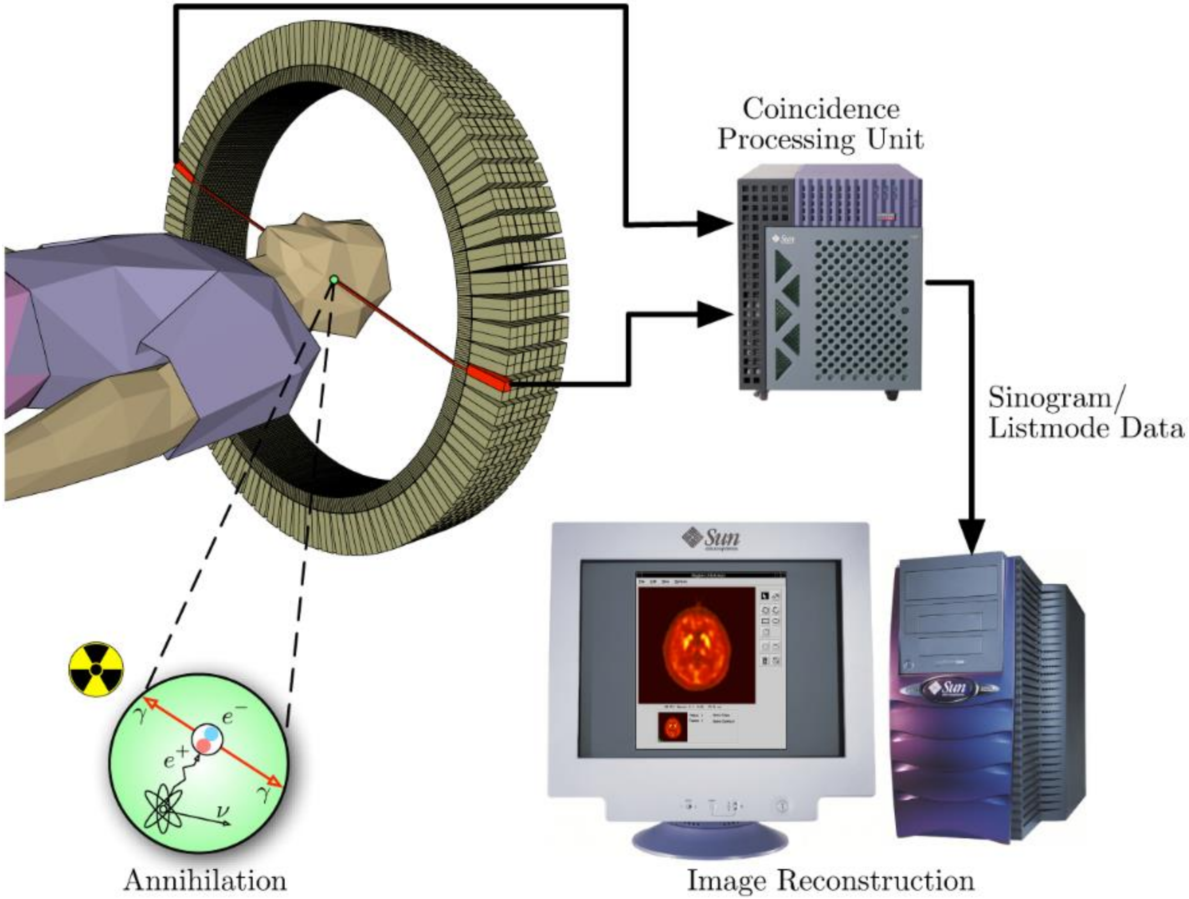


3D: SPECT: Single Photon Emission Computer Tomography



E_γ > 60 keV
E_γ < 400 keV

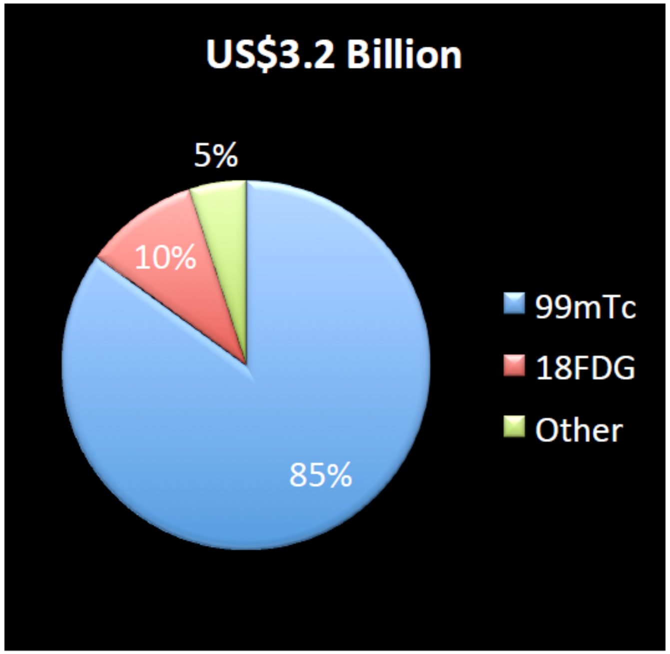
Positron Emission Tomography



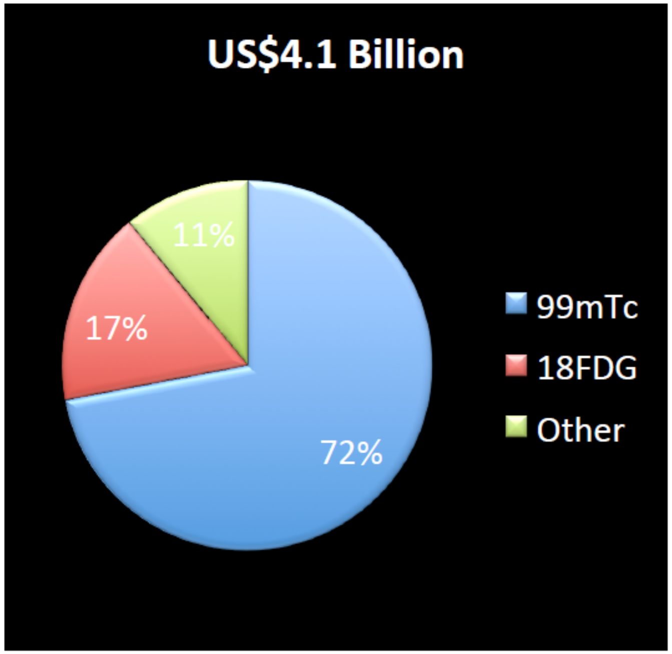
Isotope production

Global Radiopharmaceutical Diagnostic Market [1,2,3]

2010



2017

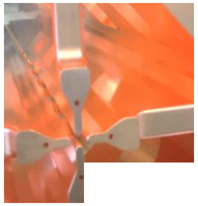


1 Global Radiopharmaceuticals Market (PET/SPECT Imaging & Therapy) – Current Trends & Forecasts (2010 – 2015); MarketsandMarkets, August 2011
2 BMI - Business Monitor International Ltd, Molybdenum-99: Privatising Nuclear Medicine, Special Report 2011
3 Interim Report on the OECD/NEA High-Level Group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

Courtesy of H. Owen

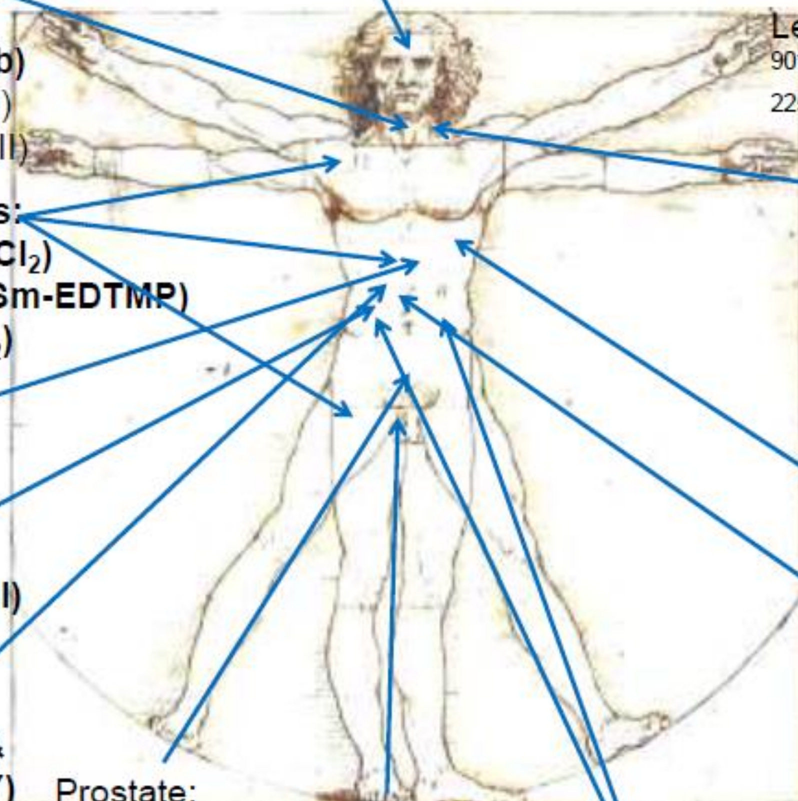
The Cockcroft Institute of Accelerator Science and Technology

MANCHESTER 1824

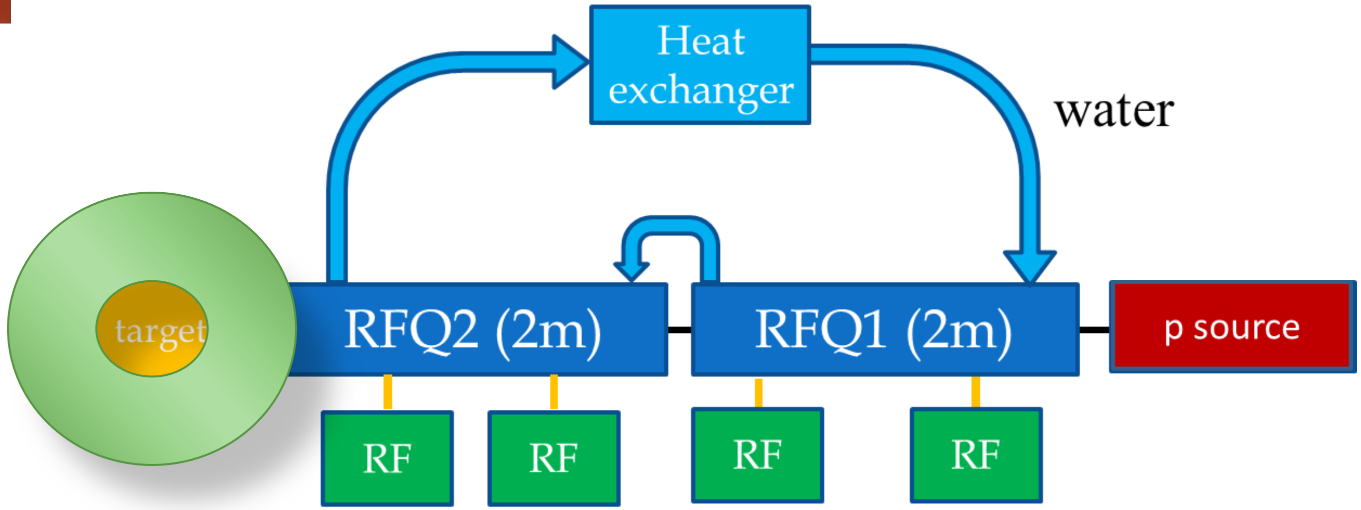


Advanced Radiotheraphy

Targeted radionuclide therapies in the clinic



The isotope RFQ system



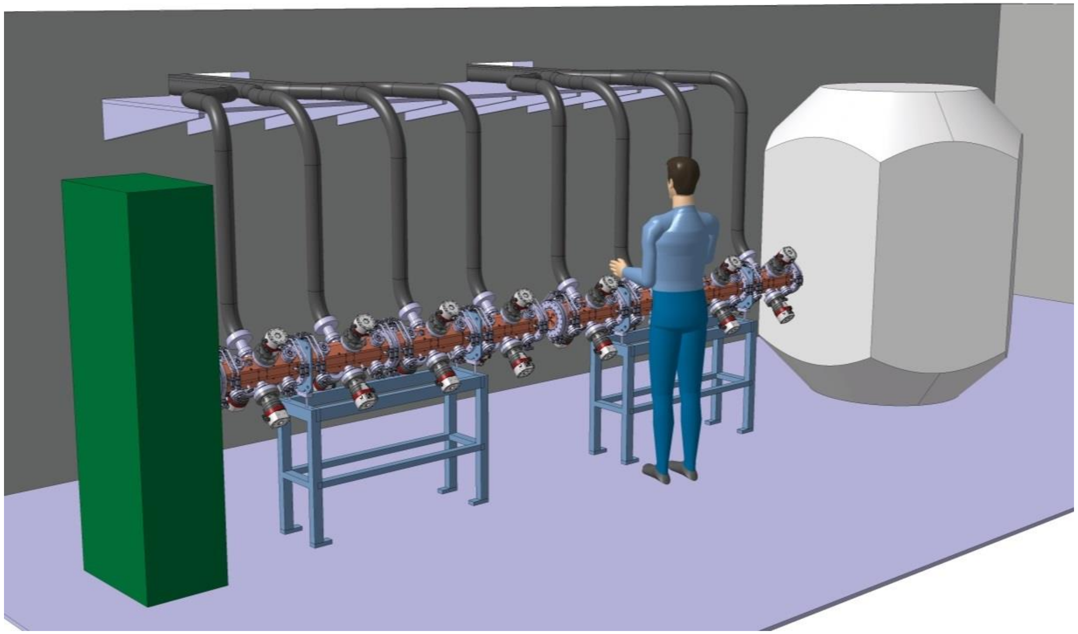
To be installed in hospitals

2 (or more) movable targets.

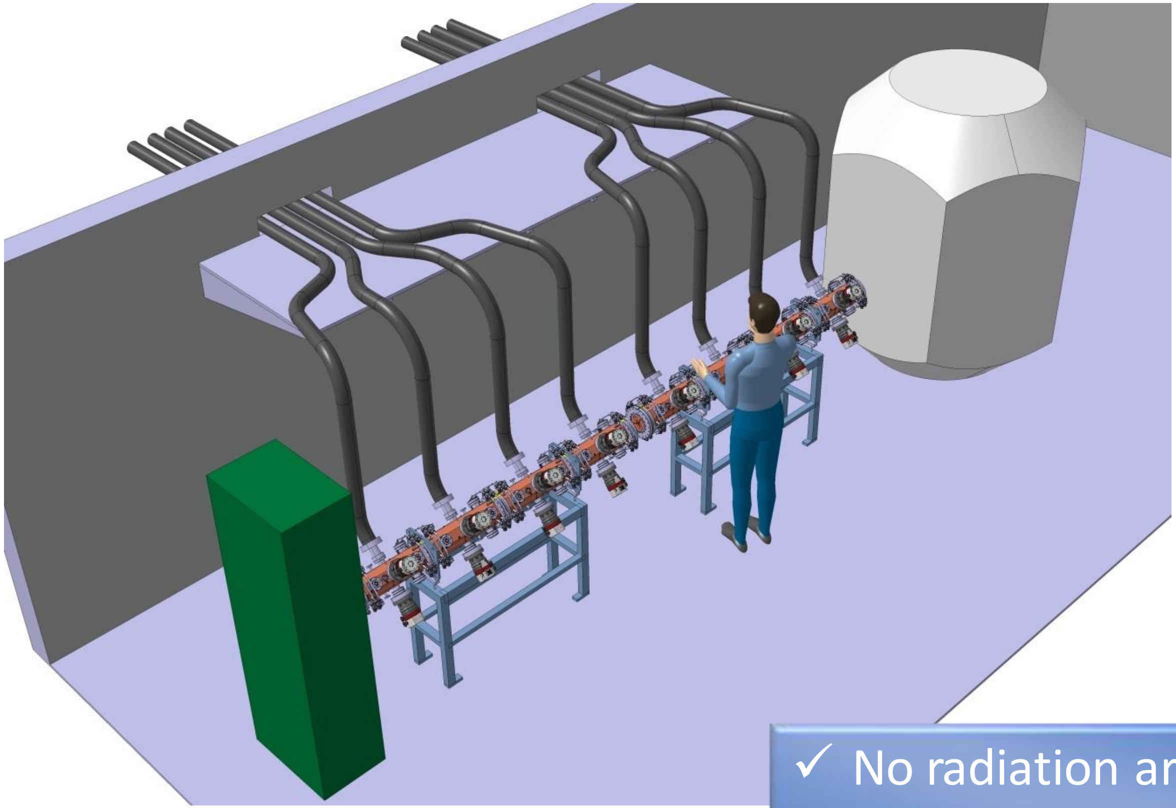
Target shielded by layers of iron and borated (6%) polyethylene, overall radius <0.9 m.

Maximum calculated dose at shielding 2 μSv/h

Weight: 400 kg total (2 RFQs)



Parameters for compact isotope RFQ system



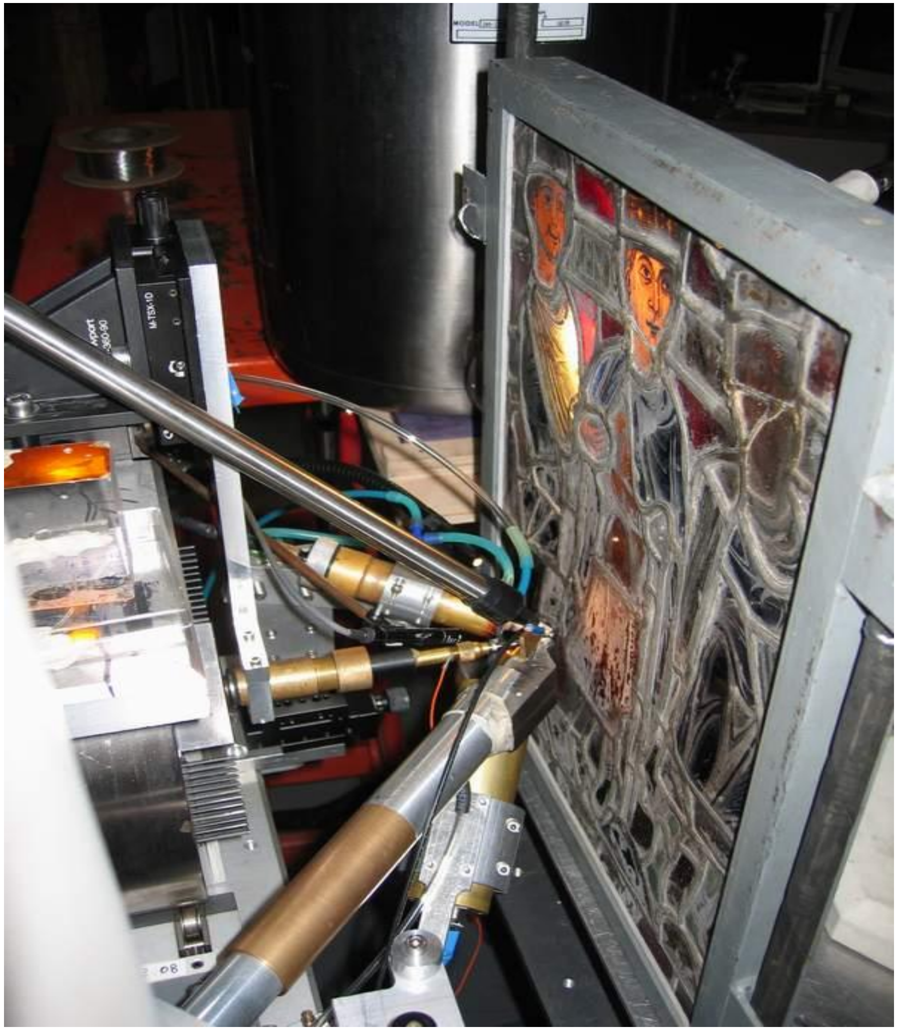
2 RFQs
Input energy = 40 KeV
Total Length = 4.0 m
Output Energy = 10 MeV
Frequency 750 MHz
Average current = 20 μA
Peak current = 500 μA
Duty cycle = 4 %
Peak RF power < 800 kW
Total weight (RFQ): 500 kg
Mains power < 65 kW
Cooling ~ 100 l/min

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)

Other applications

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



RFQ at 3 MeV
Length 1.5 m
Weight 150 kg

Can become a portable accelerator for the analysis of artwork in museums or archeological sites

Ion Beam Analysis of Cultural Heritage with a portable RFQ

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Issue No. 26-27/2015 - Monday 22 June 2015

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THE MINIATURE ACCELERATOR

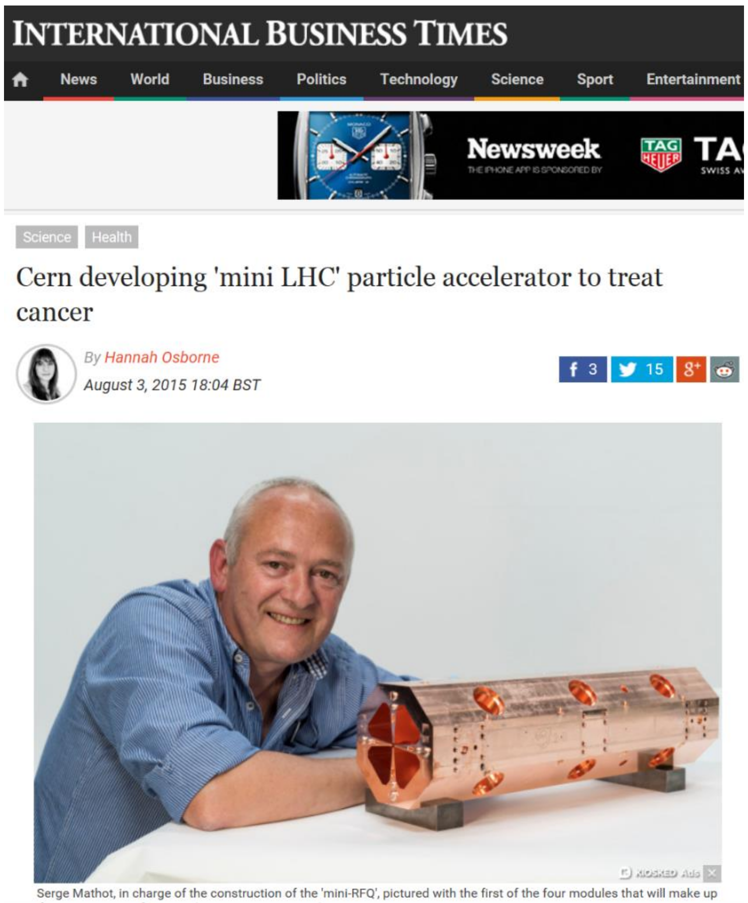
The image that most people have of CERN is of its enormous accelerators and their capacity to accelerate particles to extremely high energies. But thanks to some cutting-edge studies on beam dynamics and radiofrequency technology, along with innovative construction techniques, teams at CERN have now 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

Spreading over the internet…

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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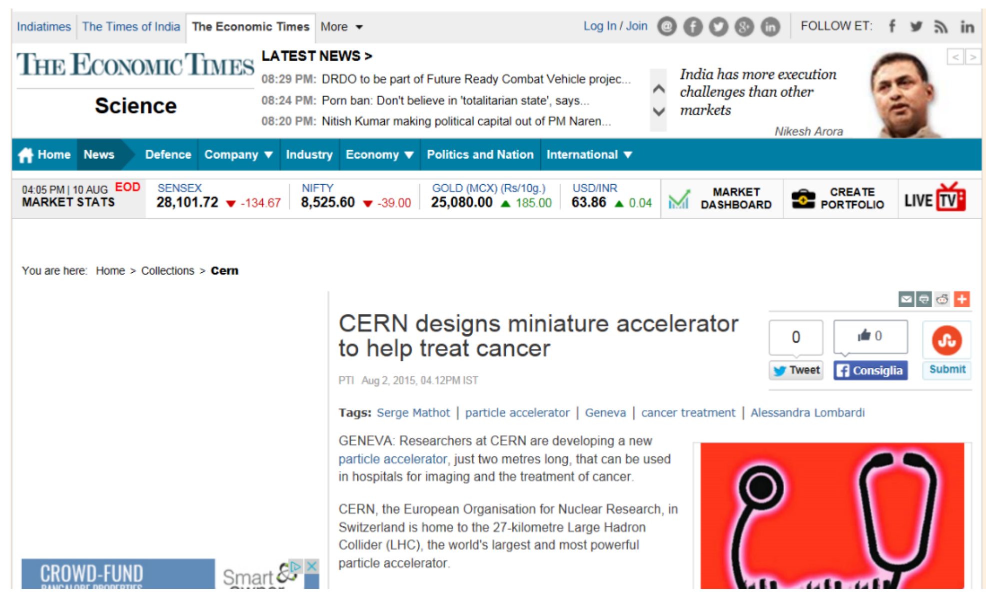
Science Health

Cern developing 'mini LHC' particle accelerator to treat cancer

By Hannah Osborne

August 3, 2015 18:04 BST

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



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CERN designs miniature accelerator to help treat cancer

PTI Aug 2, 2015, 04.12PM IST

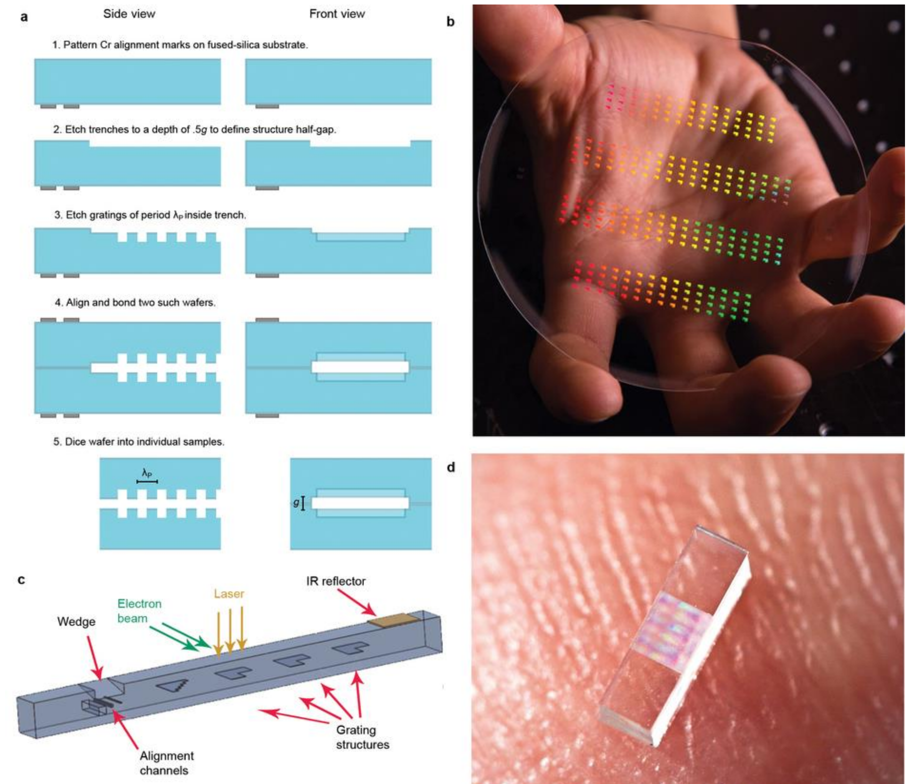
Tags: Serge Mathot | particle accelerator | Geneva | cancer treatment | Alessandra Lombardi

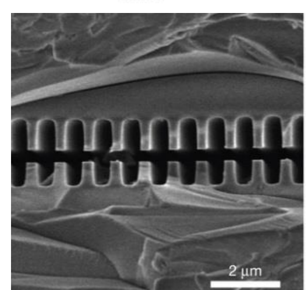
GENEVA: Researchers at CERN are developing a new particle accelerator, just two metres long, that can be used in hospitals for imaging and the treatment of cancer.

CERN, the European Organisation for Nuclear Research, in Switzerland is home to the 27-kilometre Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator.

Other roads to the miniature accelerator

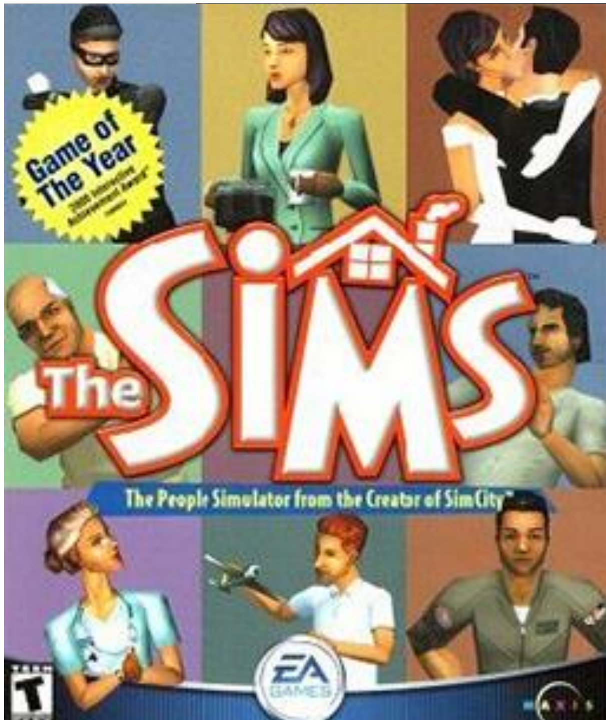
AMIT superconducting cyclotron
(CIEMAT, Spain, with CERN contribution)

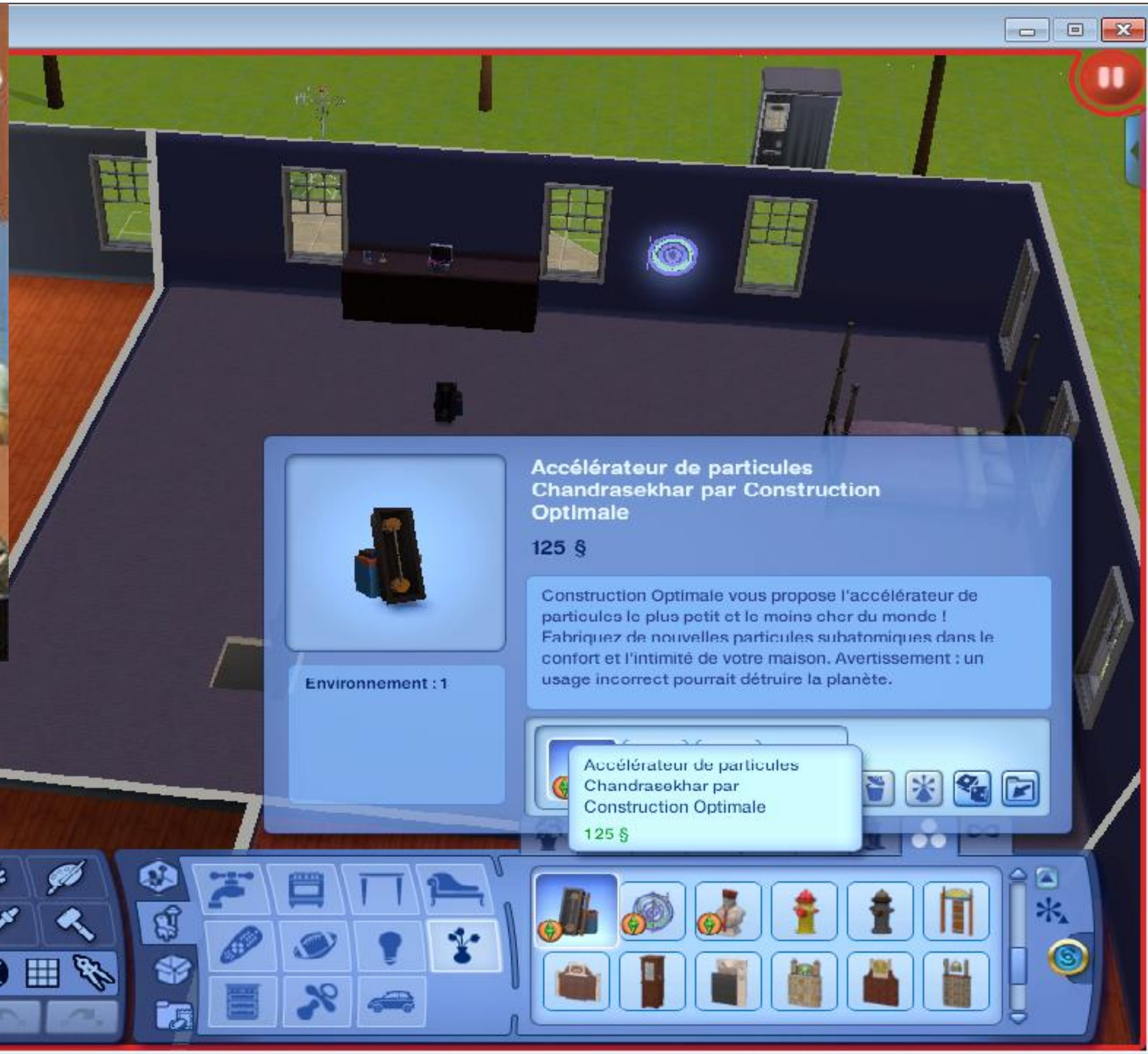




Dielectric Laser Accelerator,
electrons (Stanford)

The miniature accelerator in the virtual world





Grazie per la vostra attenzione

Maurizio.Vretenar@cern.ch