Particle Physics A Driver for Knowledge and Technology: Sharing with Society

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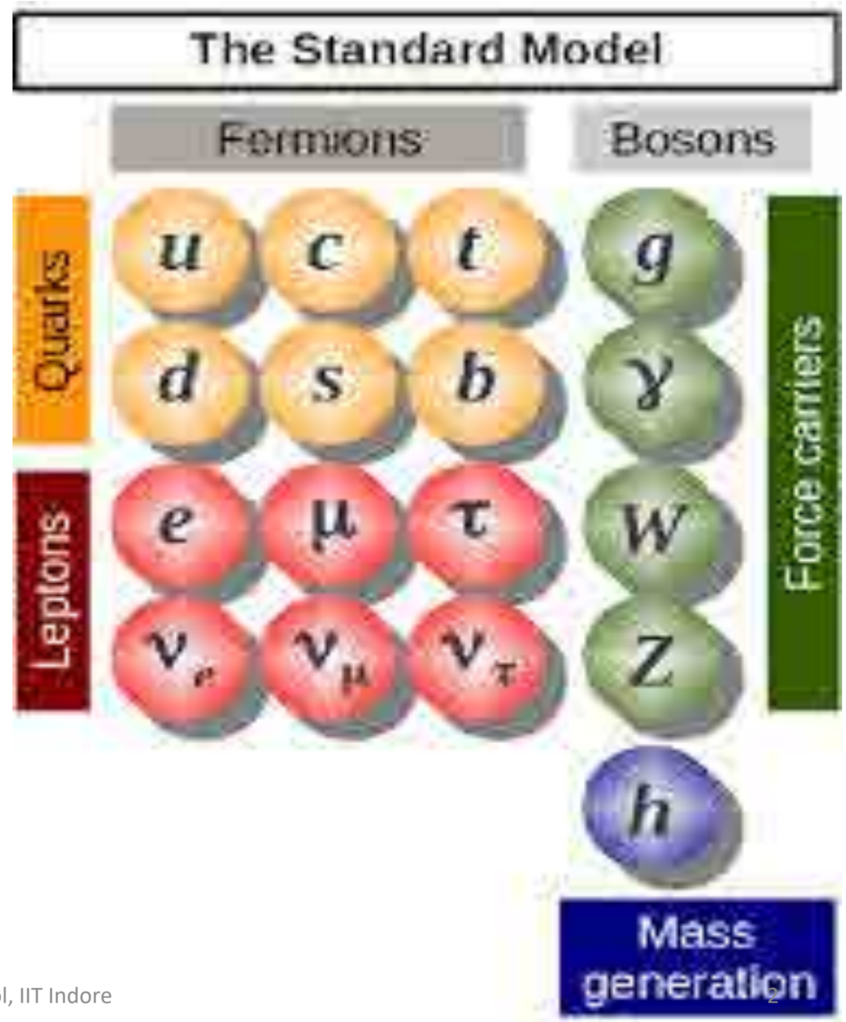
Advancing human progress through **basic knowledge**

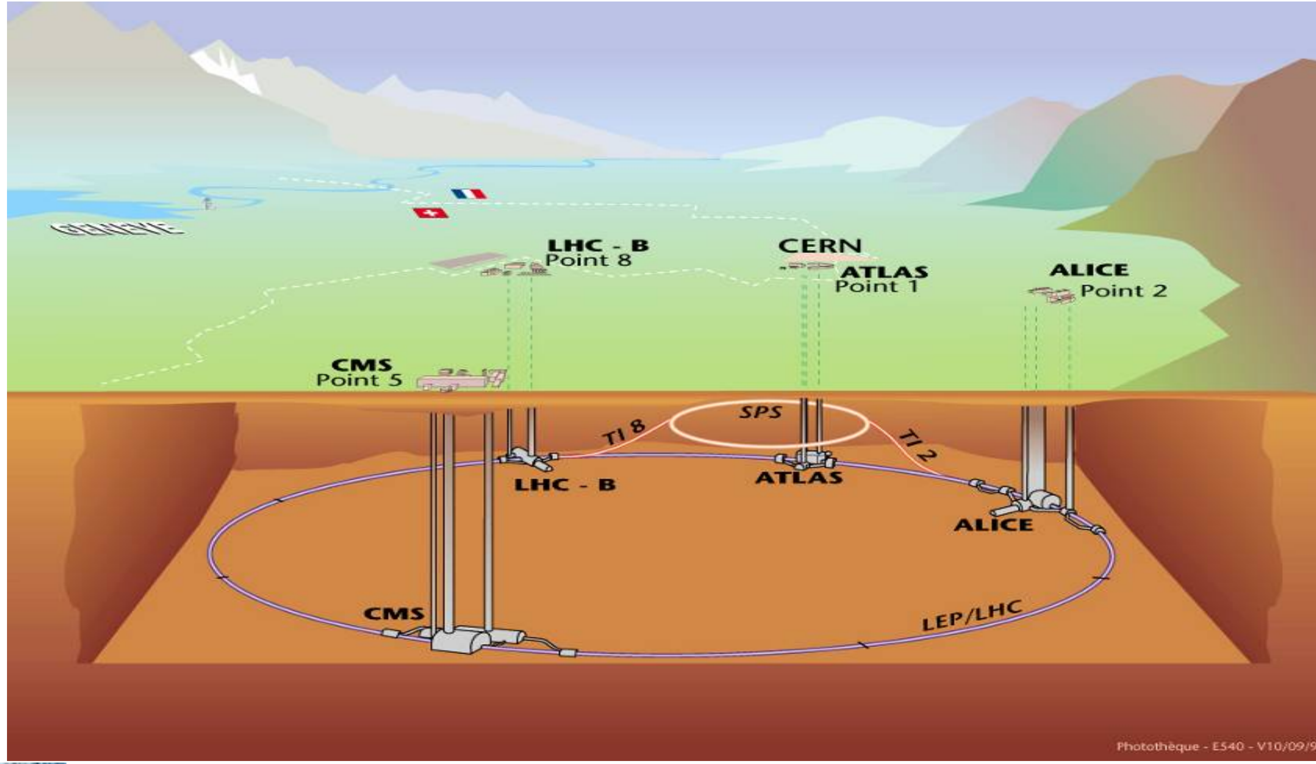
Research into the forces and building blocks of matter is a key area of modern physics

The Standard Model of particles and forces is one of the cornerstones of modern physics

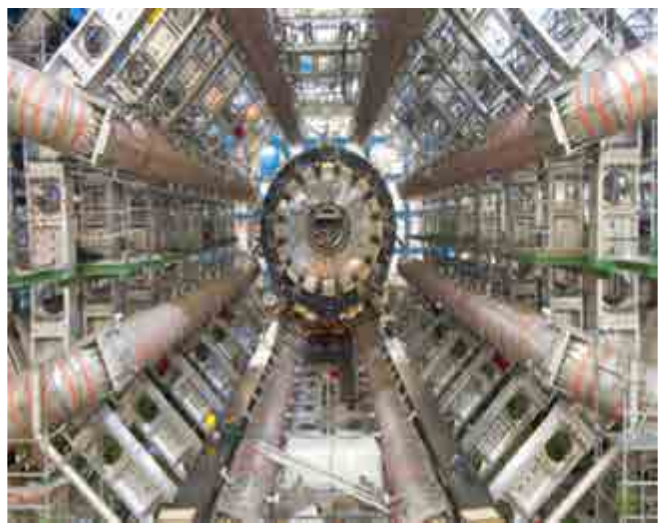
- **MATTER PARTICLES**
  - Quarks
  - Leptons
- **FORCE PARTICLES**
  - Gravitational Force
  - Weak Force
  - Electromagnetic Force
  - Strong Force



Tools of the trade



Accelerators



Detectors

Computing

Scientific Challenges: New frontiers in **basic science**

Particle physicists have exciting plans to push back the frontiers of knowledge over the next decade

New experimental projects aim to answer major questions that will take the Standard Model of particles and forces much further; they may even lead to an entirely new description of Nature.

- **Where does mass come from?**
- **Where is the missing antimatter?**
- **What is darkmatter?**
- **Are there extra spatial dimensions?**

The experiments

Large Hadron Collider (LHC)

Ultra-cold neutrons - EDM experiment

The SuperNEMO detector, measures the energy of the electrons from beta-decay with unprecedented accuracy. This scintillator has achieved the world's best energy-resolution for observing such decays

LHCb experiment

Neutrino factory

Despite being the second most abundant particle in the Universe, neutrinos are the most elusive of the elementary particles because they have hardly any mass and are difficult to detect. They are now a key probe of phenomena such as the disappearance of antimatter. The T2K and MINOS experiments currently taking data are using sub-MW neutrino beams. The construction of a multi-MW neutrino source, obtained using a very high power proton beam, is now a major priority in particle-physics research.

Super LHC

After a decade of operation, the international teams running the LHC plan to upgrade the collider to produce much more intense proton beams. This will allow them to obtain more precise data, and focus on rarer phenomena already identified as significant. Candidate theories explaining initial LHC data can then be put under scrutiny and further developed.

International Linear Collider (ILC)

A post-LHC machine colliding electrons and their antimatter partners, positrons, is being planned. This would allow the properties of new particles discovered at the LHC to be

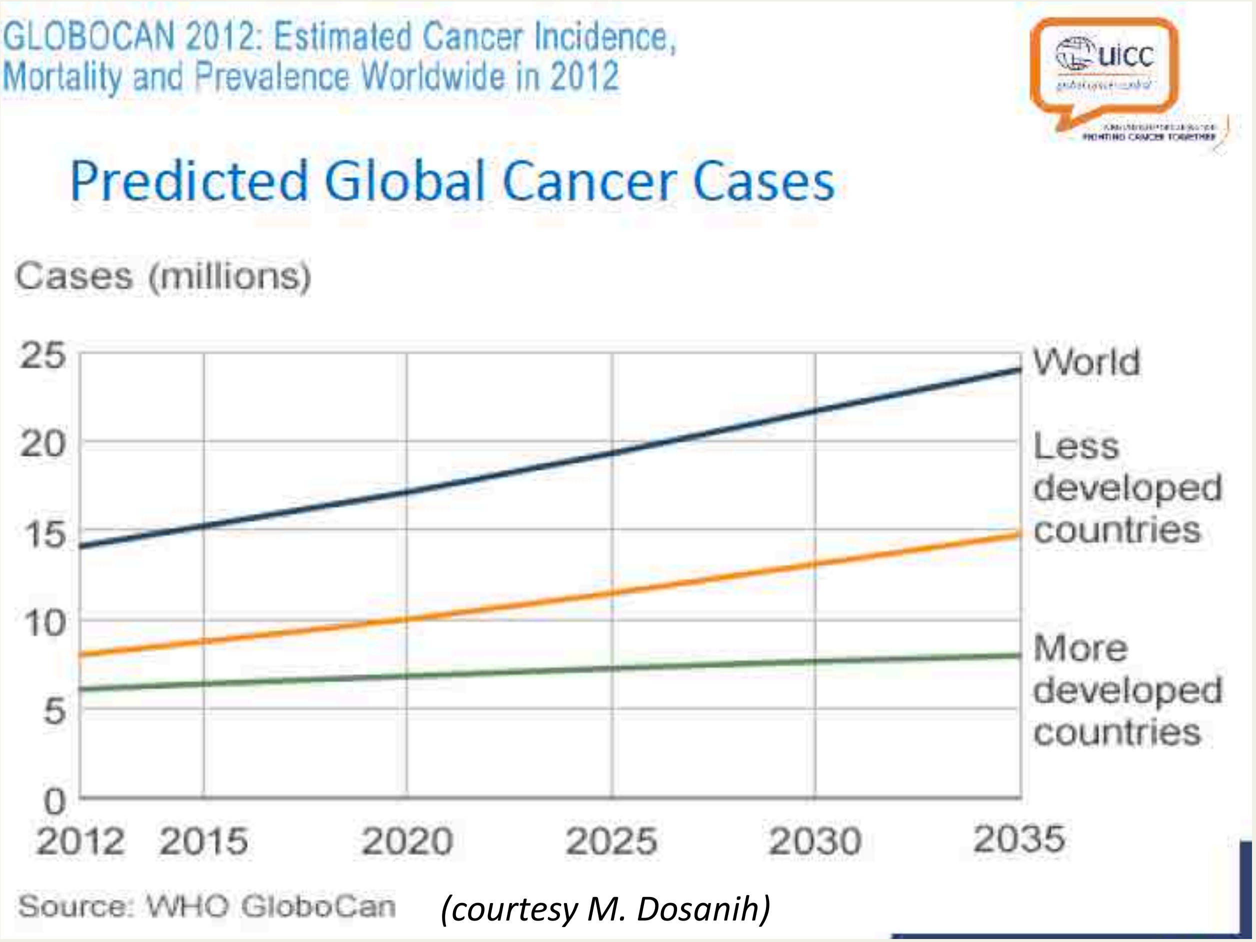
How particle physics **benefits society**

Are there any benefits to mankind from studying particle physics apart from just gaining knowledge?

Research in curiosity-driven science is an important driver for technological innovation and economic success.

Impact of cancer on world population

Cancer is the second leading cause of death globally, and was responsible for 8.8 million deaths in 2015. Globally, nearly 1 in 6 deaths is due to cancer (WHO).



(courtesy M. Dosanih)

Increase of cancer cases due to:

- ➢ Increasing age of population
- ➢ Aggressive environmental and living conditions in developing countries.

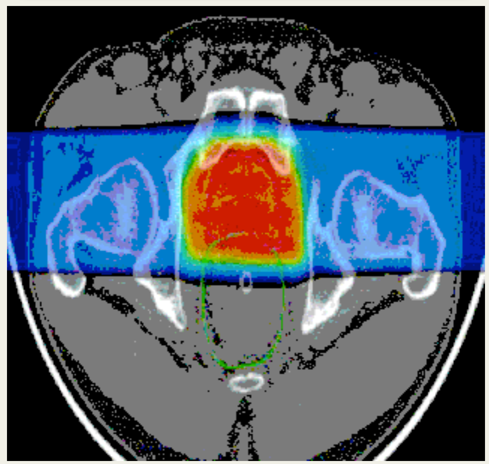
Nowadays, the standard protocol for treatment of most cancers is based on:

1. Surgery
2. **Radiotherapy** (accelerator-based)
3. Chemiotherapy
4. (Immunotherapy)

Treatment options

Surgery

Radiotherapy



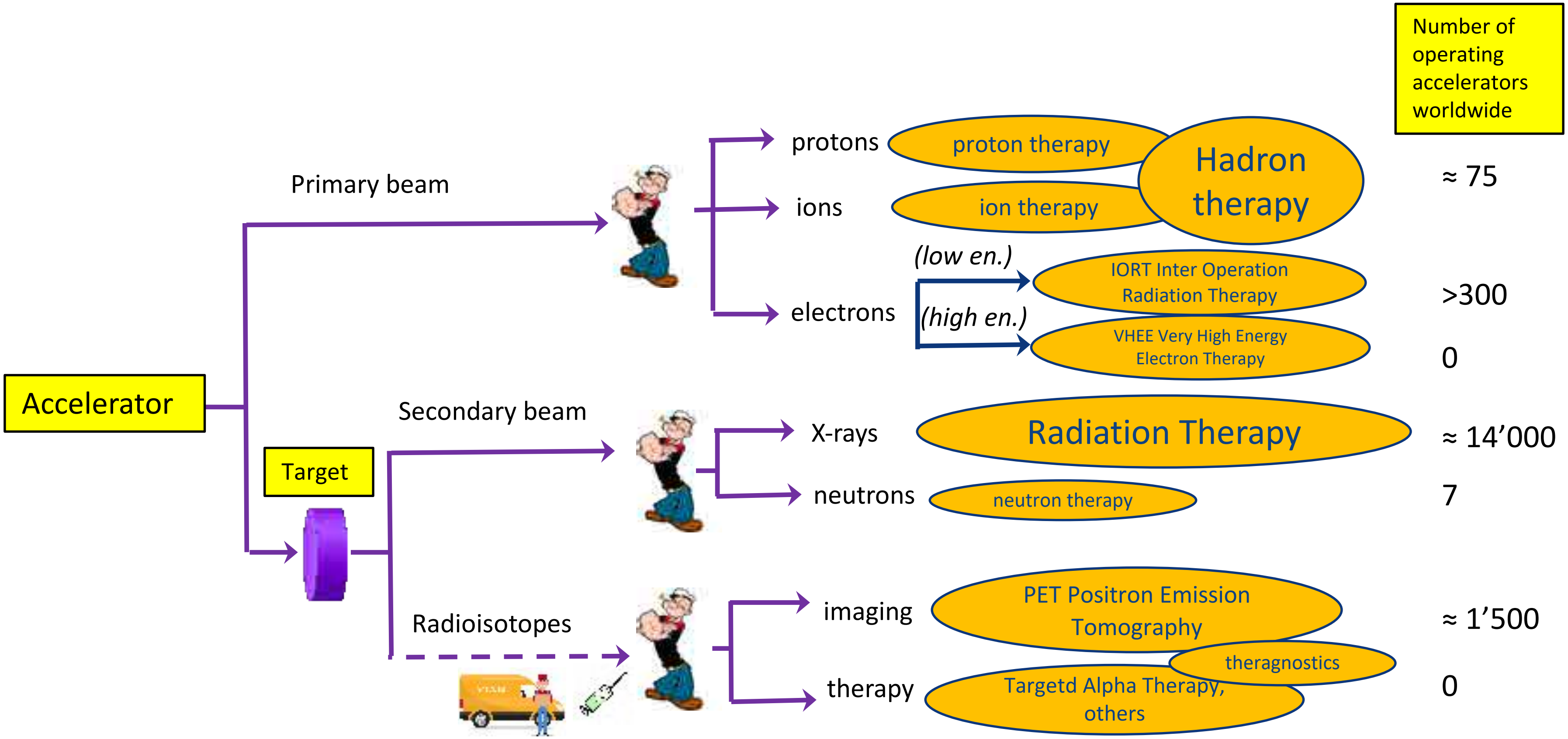
X-ray, IMRT, Brachytherapy, Hadrontherapy

Chemotherapy (+ others)

Hormones; Immunotherapy; Cell therapy; Genetic treatments; Novel specific targets (genetics..)

AIM:
Survival, Quality of life

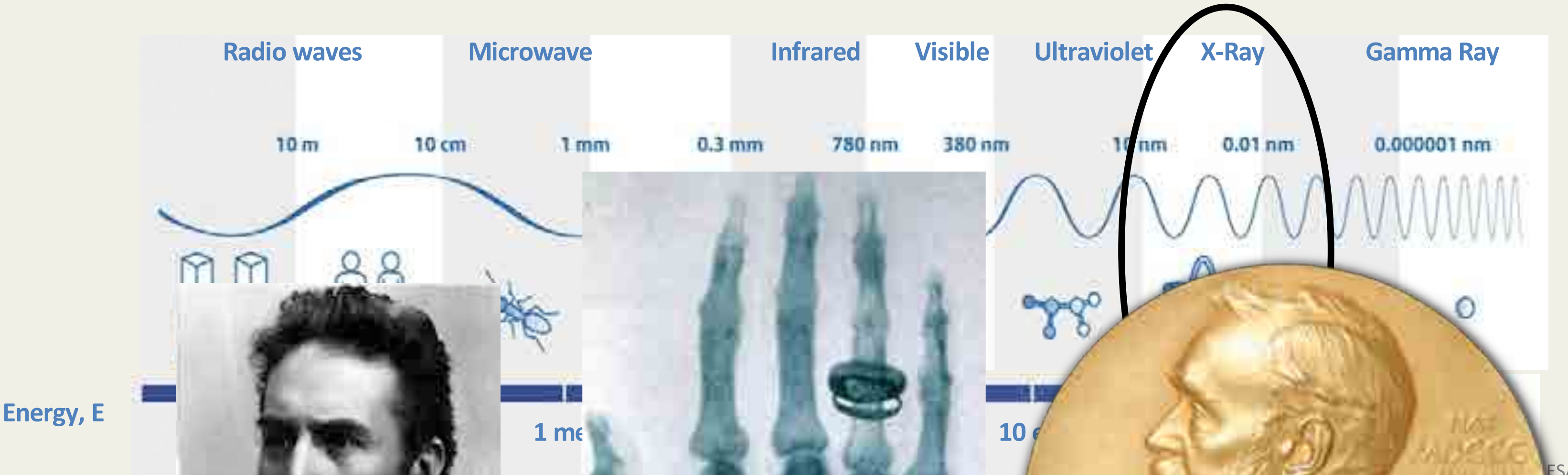
Particle physics and healthcare
Accelerator as Medicine



Total: ≈ 16’000 particle accelerators operating for medicine

First step: Detection

Curiosity and the future – X-rays



Wilhelm Röntgen

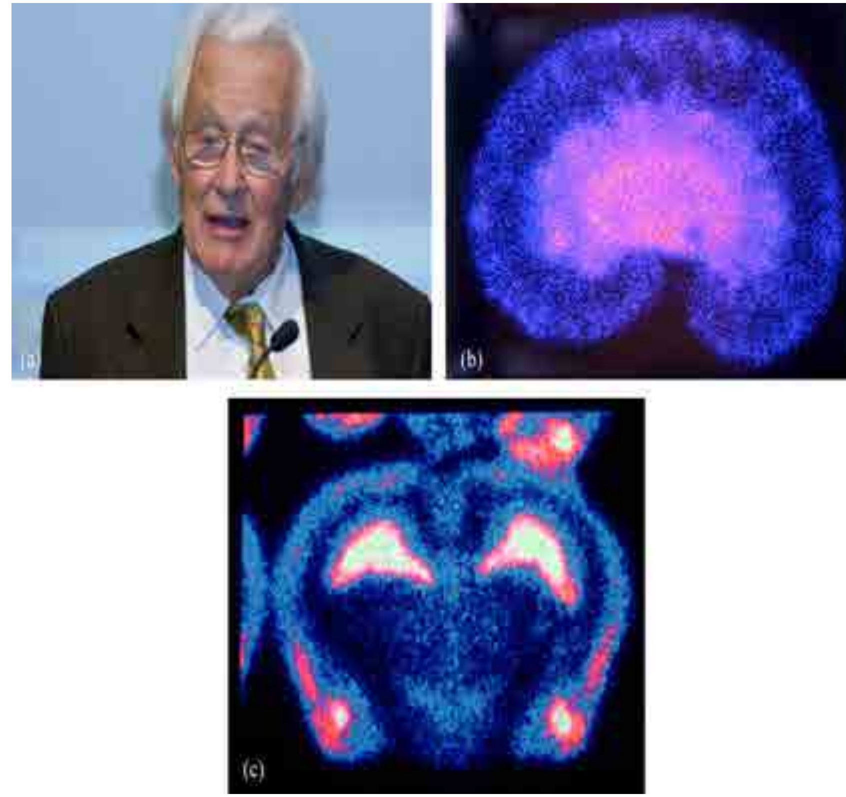
8/11/1895

22/12/1895

1901

https://en.wikipedia.org/wiki/X-ray

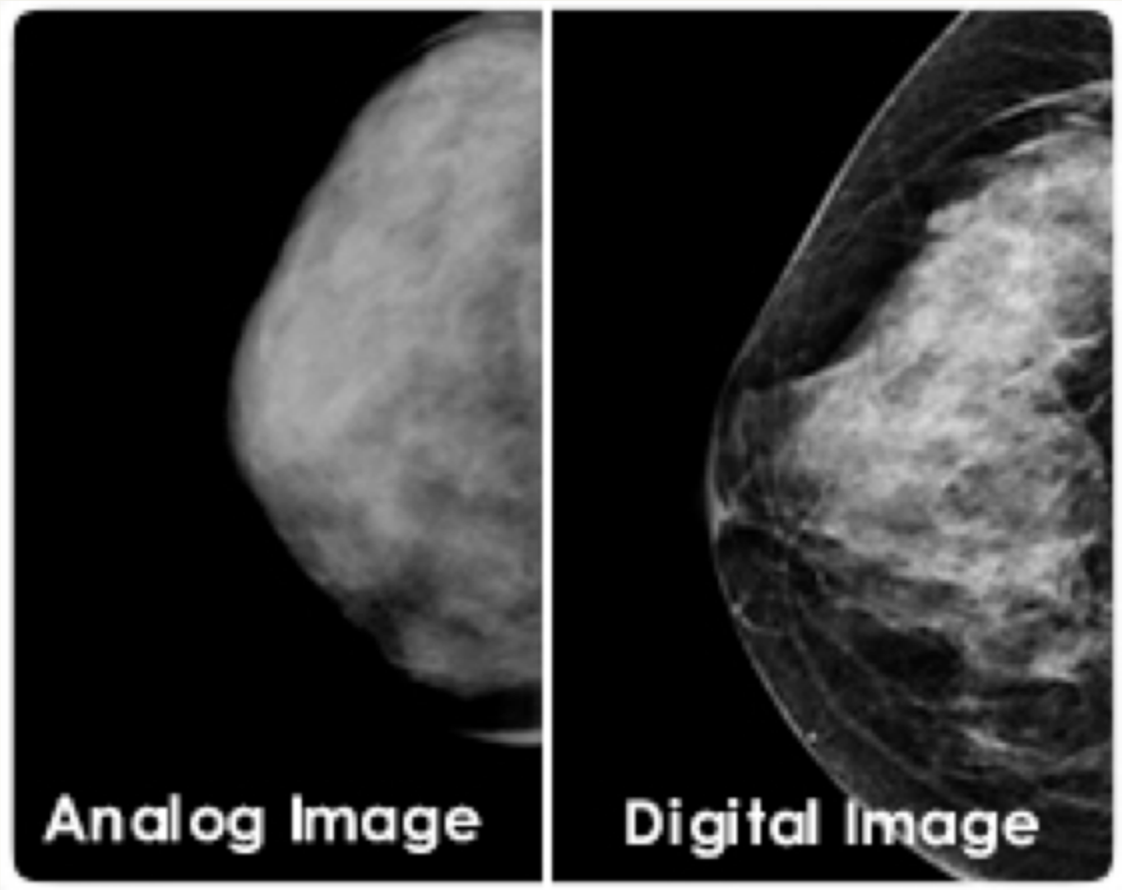
Medical Imaging: Charpak and the multiwire proportional chamber



These images of (b) a rat kidney and (c) a rat brain were produced using Charpak's multiwire detector, called the parallel plate avalanche chamber (PPAC). © CERN 1993–2017.

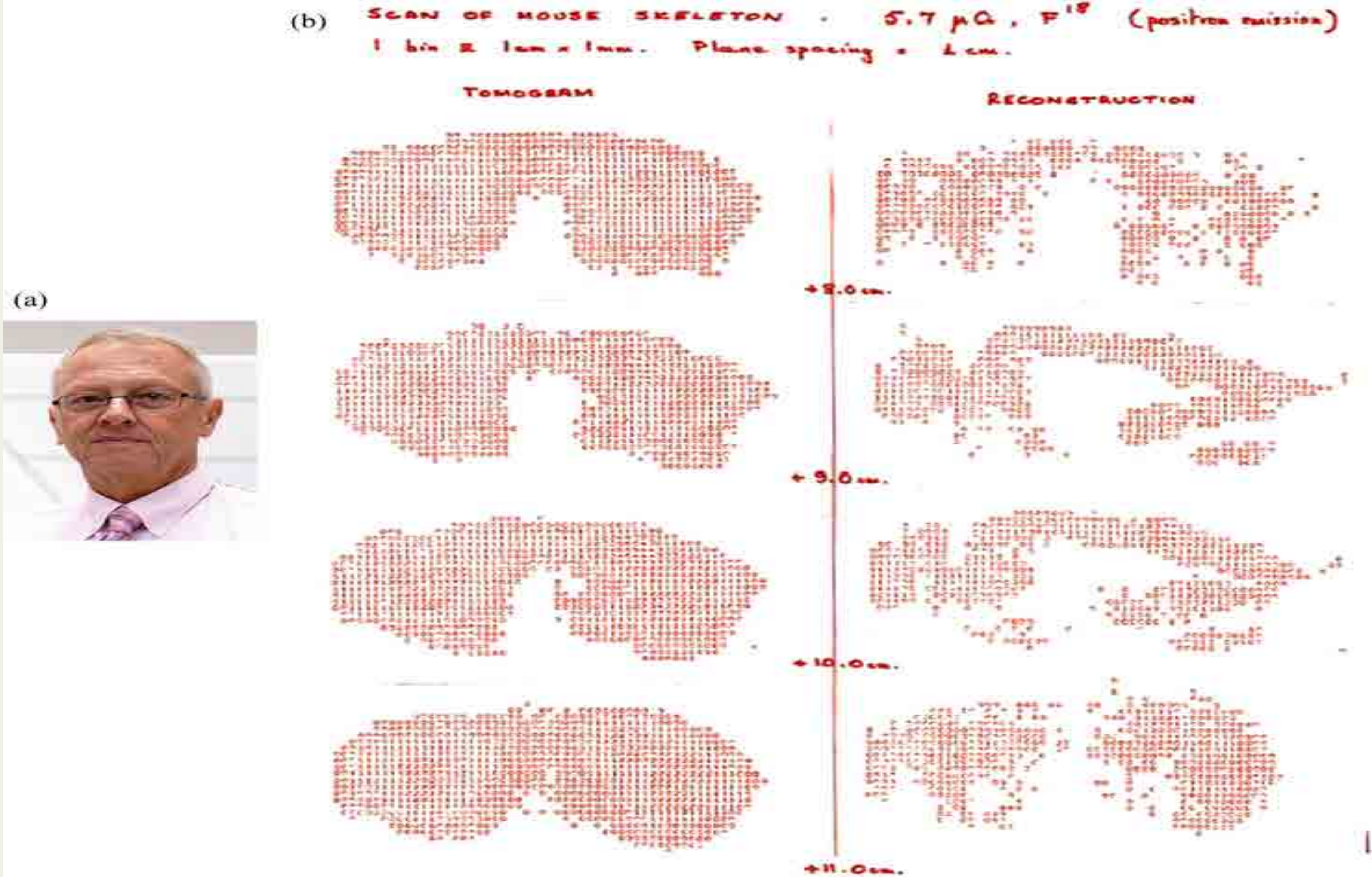
- Charpak's innovative design for the MWPC enabled physicists
  - to detect thousands of ionizing particles per second for the first time, unlike previous techniques, such as the bubble chamber, which could only record a few photographs per second.
  - made it much easier to track the path of individual particles, where previously a series of proportional counters had to be deployed to follow particles as they moved through large areas.
- Charpak devoted considerable effort to ensuring that these detectors could be exploited in medical radiology.
- Here the trend is for digital read-out to replace photographic film, since this improves both sensitivity and spatial resolution. Increasing the recording speed also enables faster scanning and lower body doses when using medical diagnostic tools based on radiation or particle beams.

Towards digital imaging



Antimatter – ~~science fiction~~?

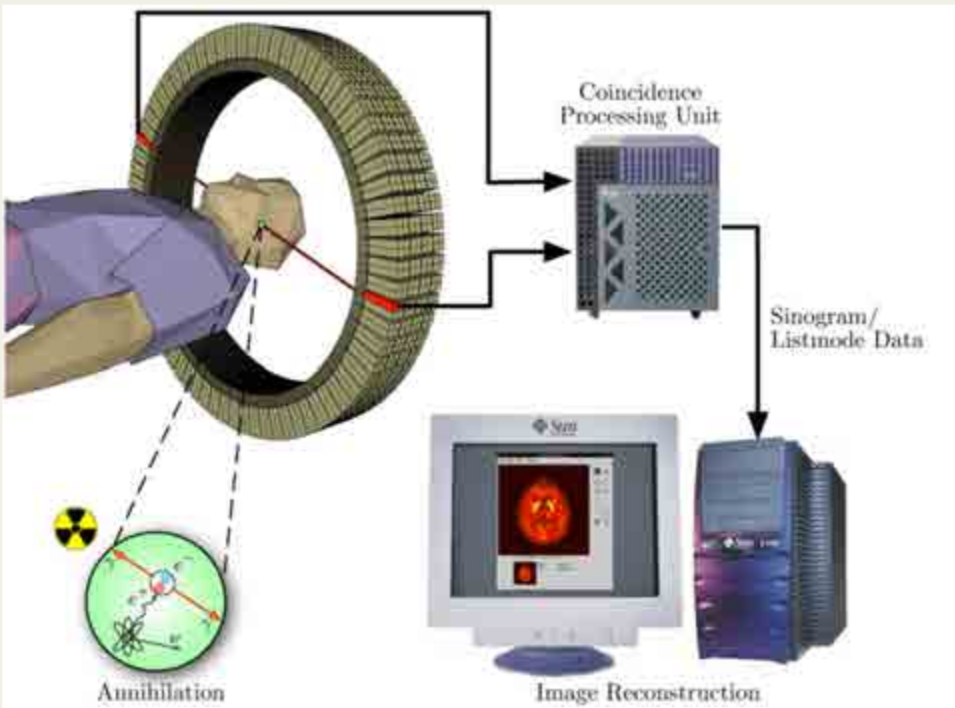
PET

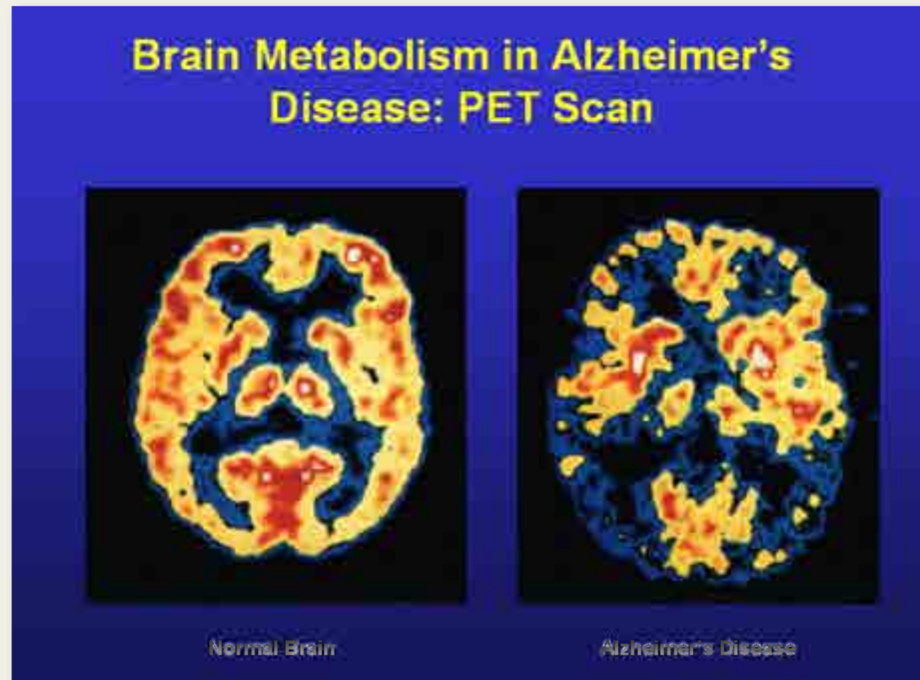


David Townsend (a) produced the first PET image of a mouse (b) in collaboration with the University Hospital of Geneva. The PET data were obtained with high-density avalanche chambers developed at CERN. © CERN 2005.

PET – How it works

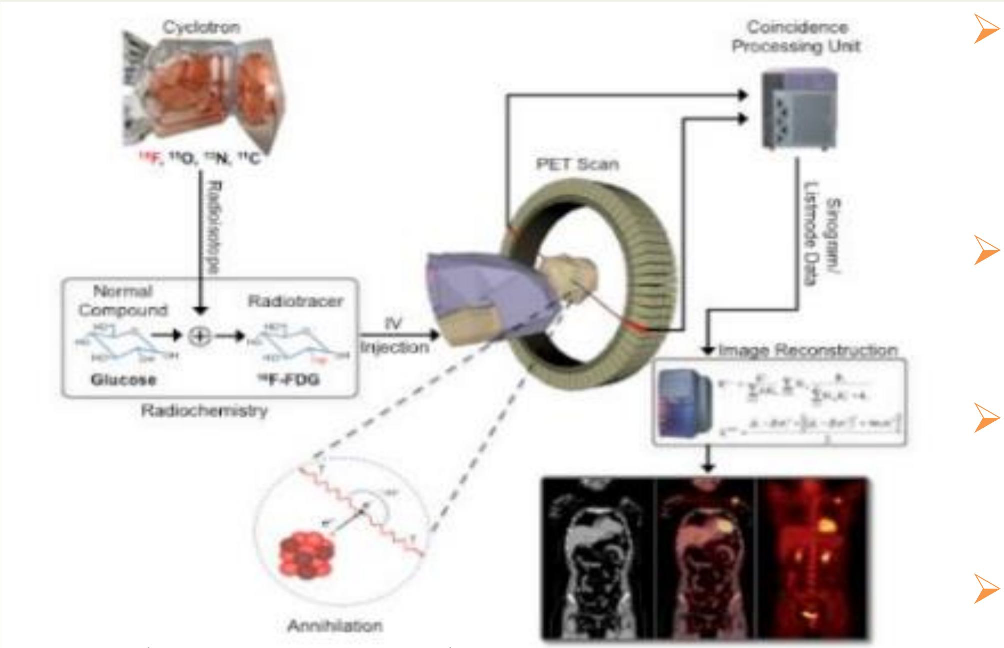
PET Scan


Coincidence
Processing Unit
Sinogram/
Listmode Data
Annihilation
Image Reconstruction

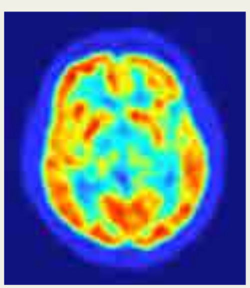

Brain Metabolism in Alzheimer's
Disease: PET Scan
Normal Brain
Alzheimer's Disease

Safer Medical Isotopes:

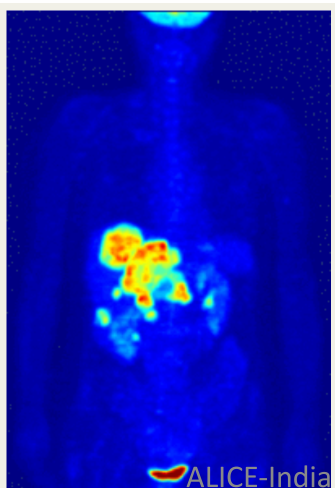
Radioisotope-based tomographies



(source: Huntsman Cancer Institute)

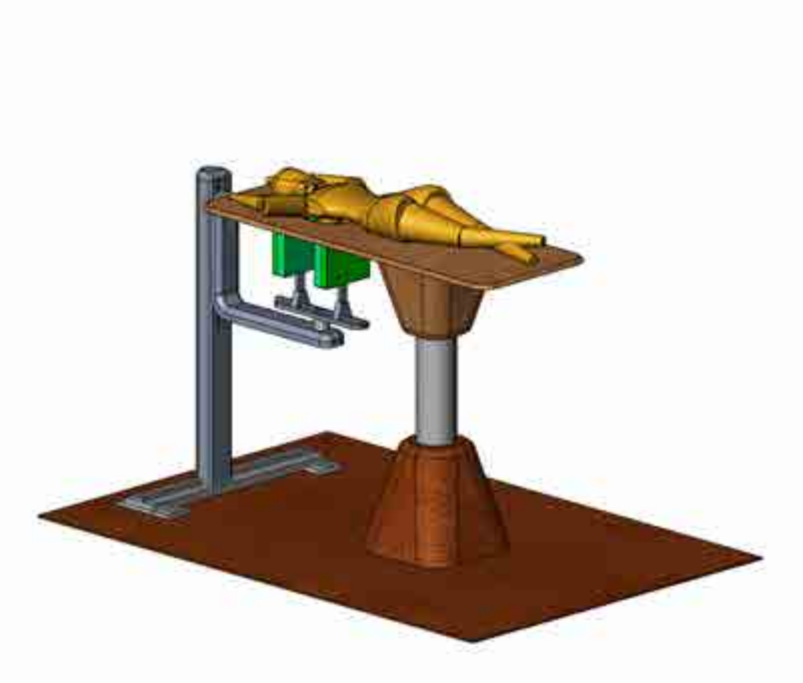


90% of PET scans are in clinical oncology



- A **radioisotope** (radiotracer) is produced by an accelerator (usually a cyclotron) and attached to a normal chemical compound, usually a glucose, in a radiopharmaceutical unit.
- The compound is injected to the patient and accumulates in tissues with high metabolic activity, as tumours – and metastasis.
- When the radioisotope decays, the emitted particles are detected by a scanner allowing a precise mapping of the emitting areas.
- In **SPECT** (single photon emission computed tomography) is used Technetium-99 (6 hours half-life) that emits a photon. 99-Te is generated in the hospital by Molybdenum-99 (66 hours half-life) produced at a nuclear plant.
- In the much more precise **PET** (Positron Emission Tomography) is used Fluorine-18 (1h50’ half-life) attached to Fludeoxyglucose (FDG) molecules, which emits positrons that annihilates with electrons producing 2 gamma rays in opposite directions.

ClearPEM

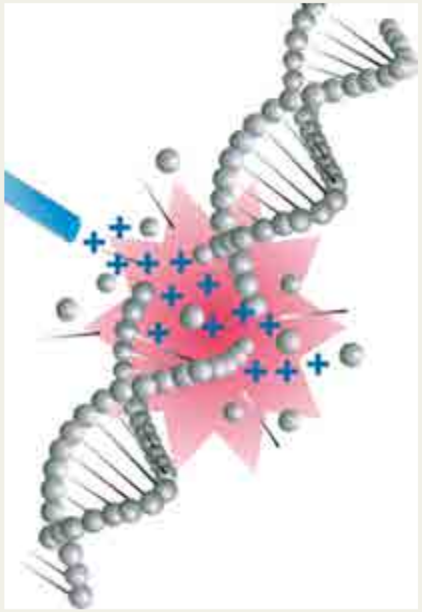


Extremely sensitive to small tumour masses

Conventional radiotherapy

- least expensive cancer treatment method
- most effective
- no substitute for RT in the near future
- rate of patients treated with RT is increasing

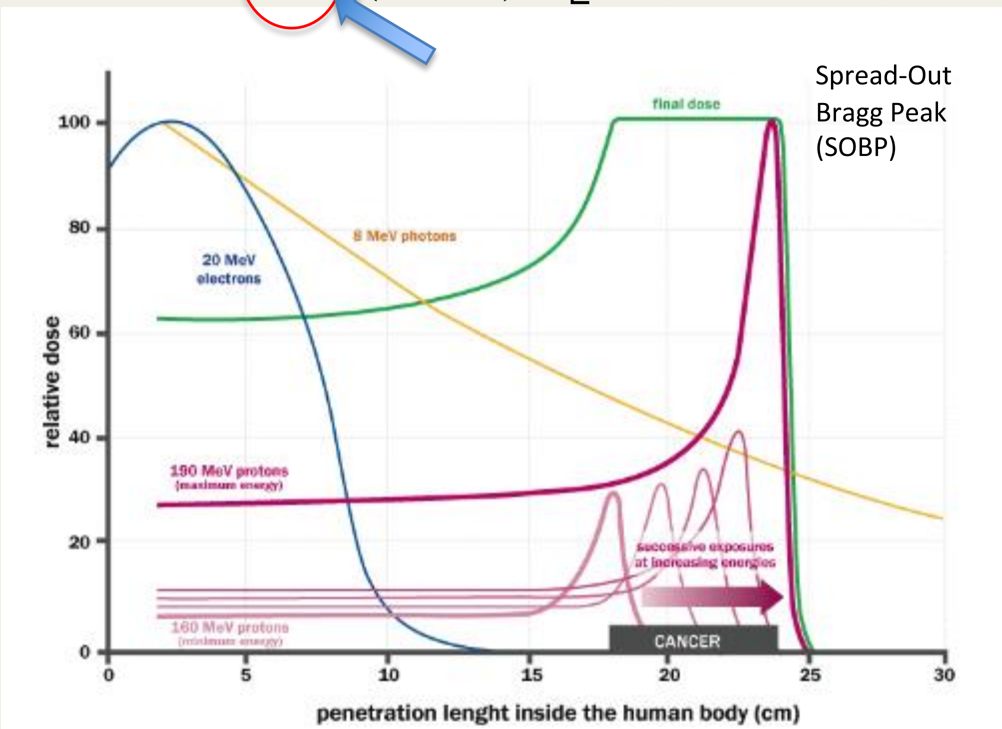
30% of patients cancer comes back in the same location after RT



The beauty of the Bragg peak

Bethe-Bloch equation of ionisation energy loss by charged particles

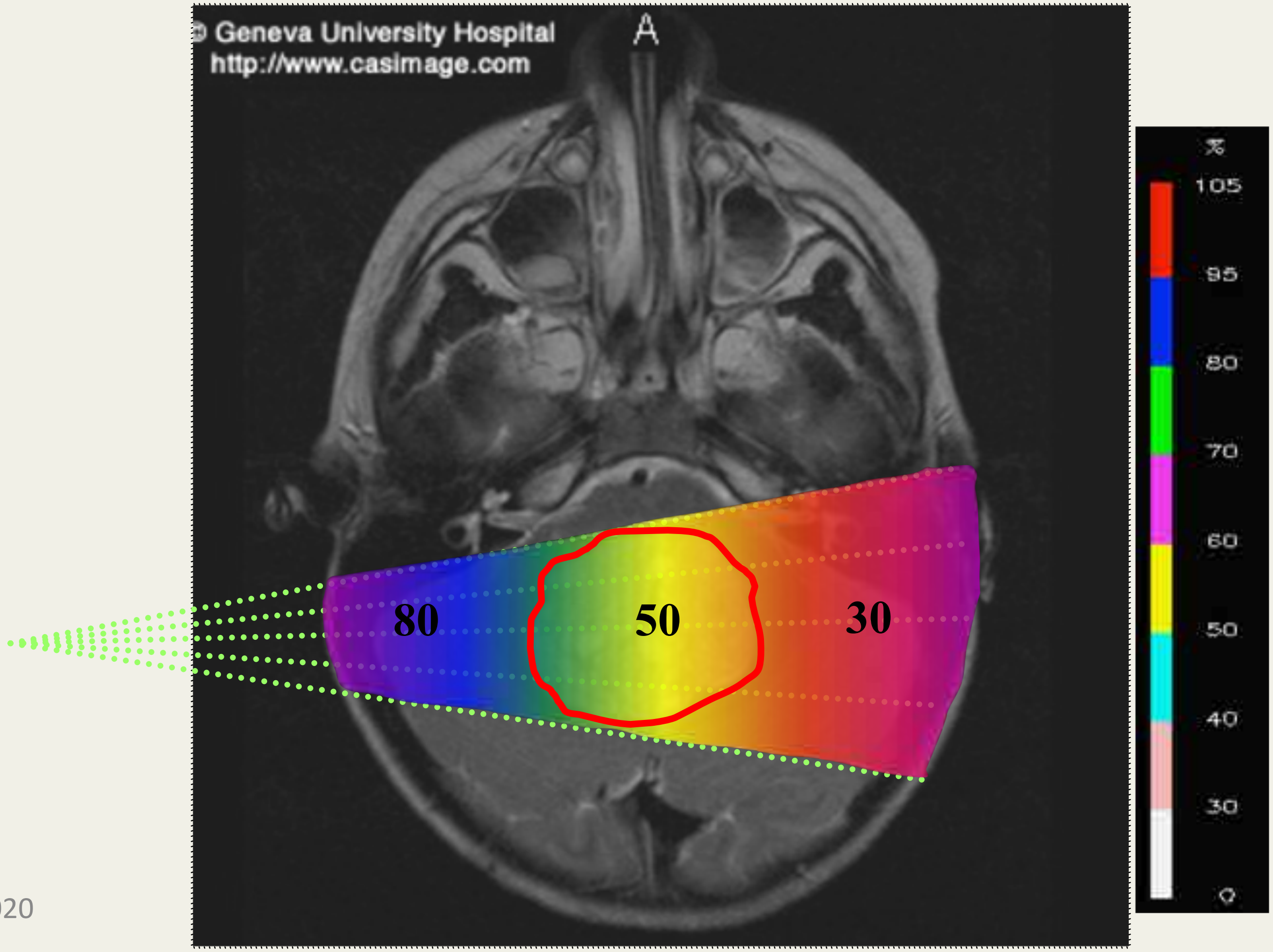
$$-\frac{dE}{dx}=\frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I.(1-\beta^2)}\right)-\beta^2\right]$$



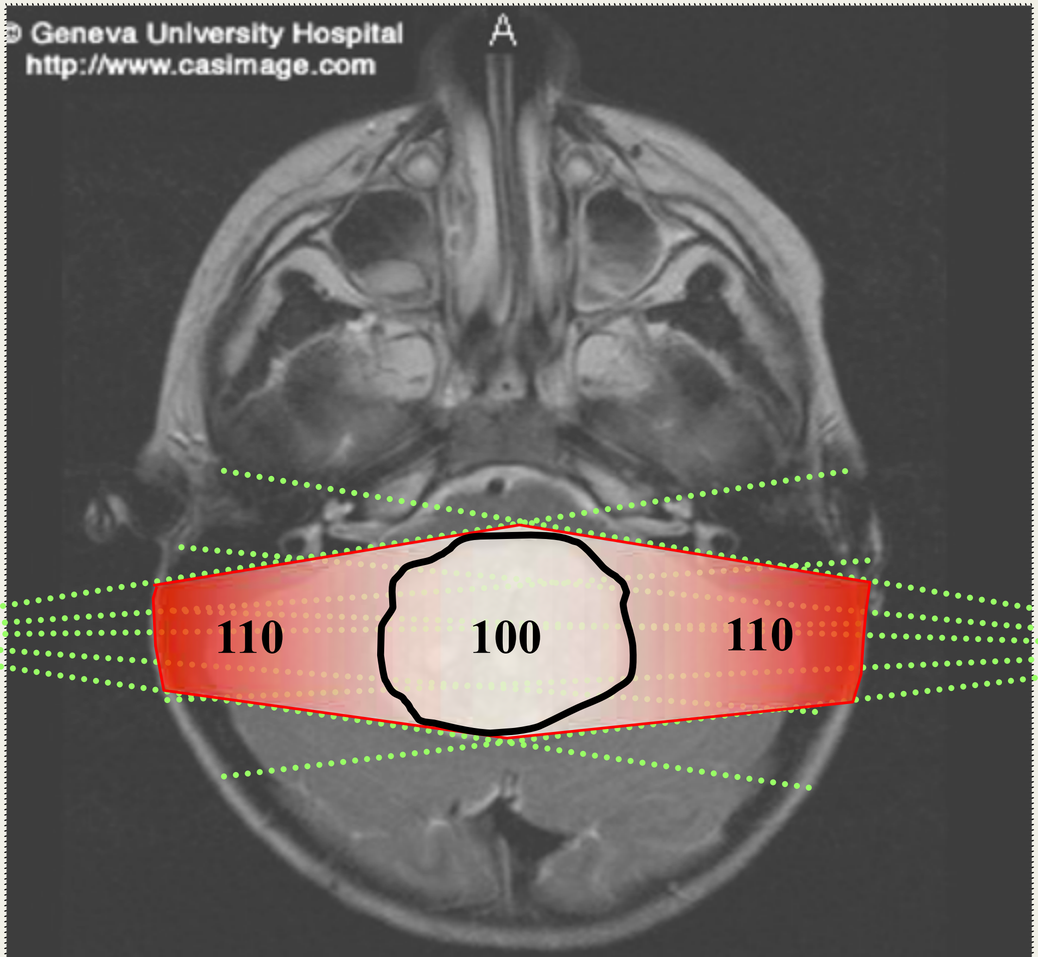
accelerators-for-society.org

Single beam of photons

X-rays (i.e. photons) have a Bragg peak at a slightly greater depth than electrons but doesn’t fall off so quickly meaning there is a good chance health organs could be effected. Bragg peak really needs to be precise



2 opposite photon beams



Accelerators for cancer diagnosis and treatment

There are today about 16’000 accelerators in hospitals or working for hospitals, but we have to consider that the requirements for a medical accelerator are very different from those of a scientific accelerator:

- The beam must be perfectly known, stable and reliable.
- The accelerator (as the radiopharmaceutical unit in case of production of isotopes) have to follow strict Quality Assurance procedures.

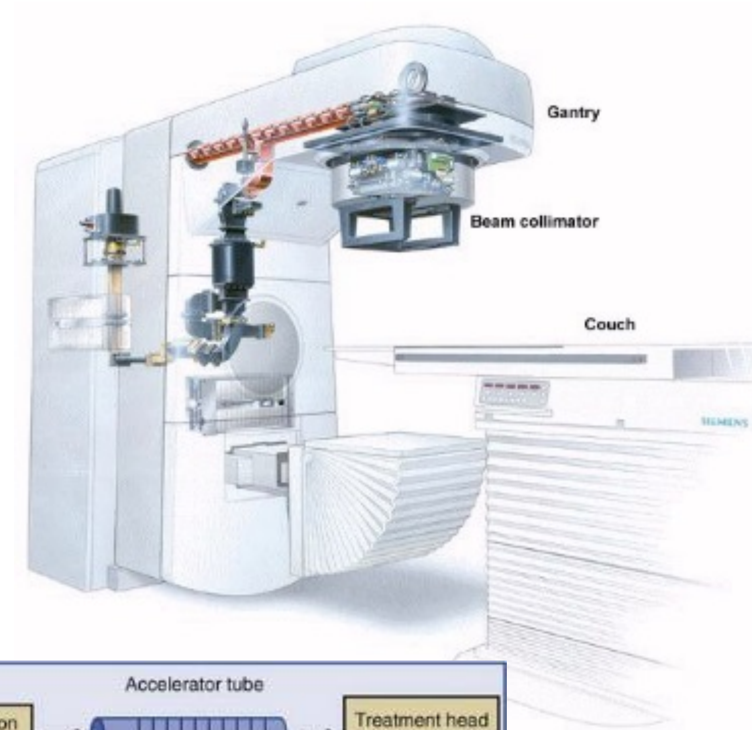
Example: factor 4 in the complexity and cost of the control system for a medical accelerator as compared to a scientific one.

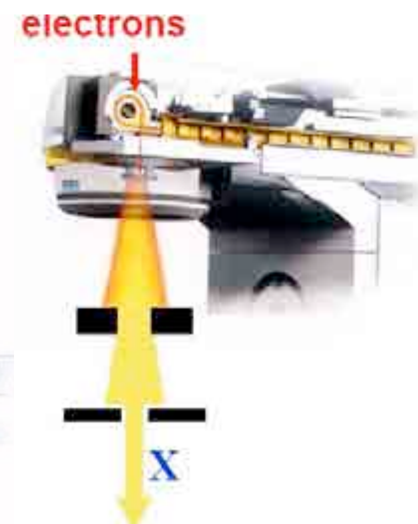
The role of the medical physicist is essential in planning the treatment and in guaranteeing the delivered dose.

IntegraLab® PLUS combined radiopharmaceutical production centre from IBA.
The accelerator is the small box in the upper right corner, all the rest is what is needed to shield the accelerators and to provide radiopharmaceuticals compliant with quality control procedures (purity, sterility, etc.).

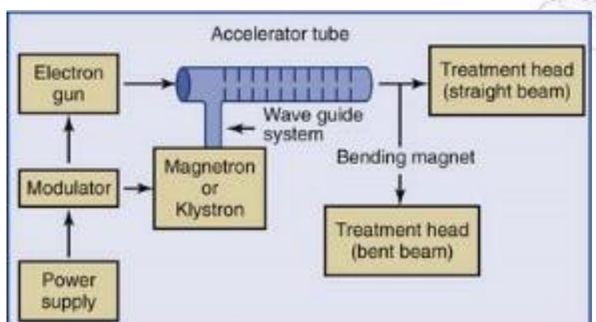
The most successful accelerator

Electron Linac (linear accelerator) for radiotherapy
(X-ray treatment of cancer)





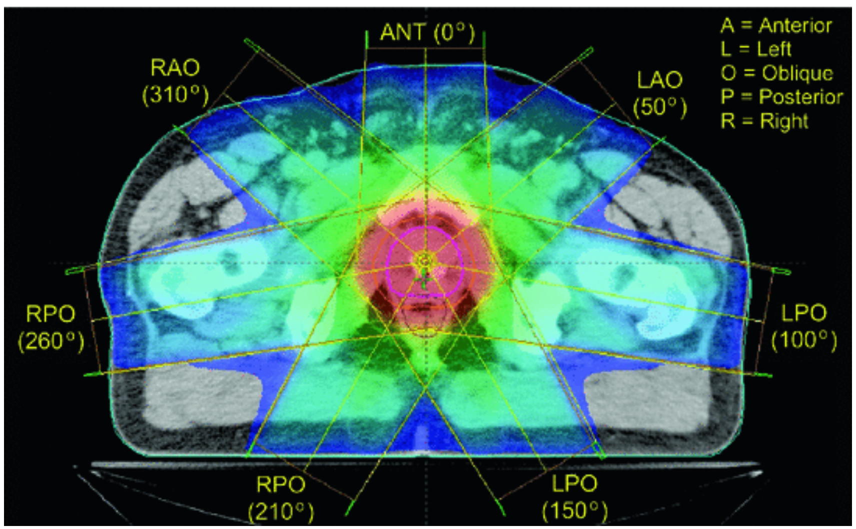
5 – 25 MeV e-beam
Tungsten target



14,000 in operation worldwide!

Modern radiotherapy

X-rays are used to treat cancer since last century. The introduction of the electron linac has made a huge development possible, and new developments are now further extending the reach of this treatment.



Accurate delivery of X-rays to tumours

To spare surrounding tissues and organs, computer-controlled treatment methods enable precise volumes of radiation dose to be delivered. The radiation is delivered from several directions and transversally defined by multi-leaf collimators (MLCs).

Combined imaging and therapy

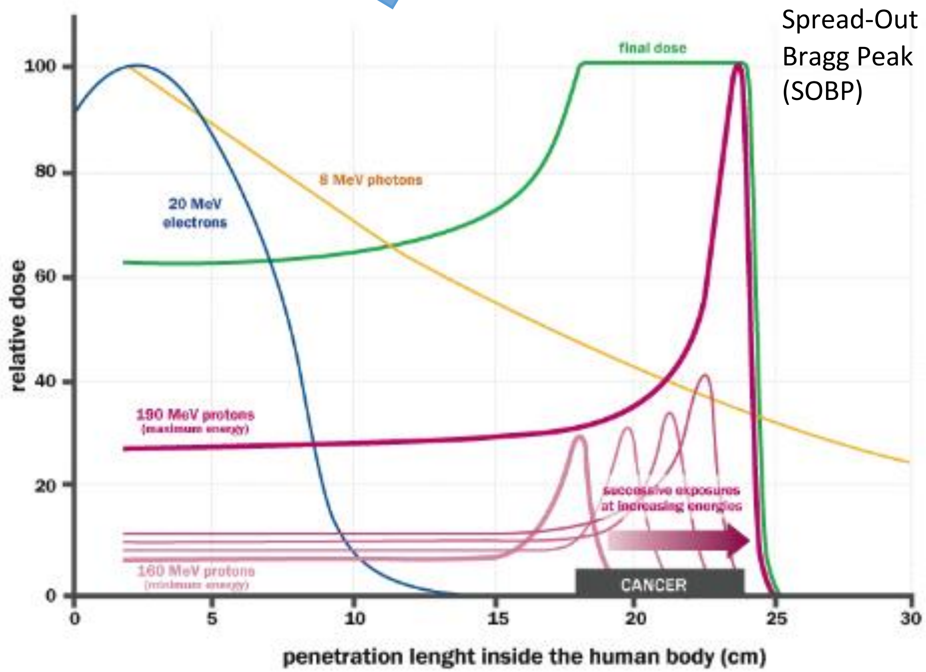
Modern imaging techniques (CT computed tomography, MRI magnetic resonance imaging, PET positron emission tomography) allow an excellent 3D (and 4D, including time) modelling of the region to be treated.
The next challenge is to combine imaging and treatment in the same device.

Fig. 3.4: The MR-linac, developed by Elekta, consists of a linear accelerator equipped with multi-leaf collimator technology for accurate radiotherapy dosage, combined with a high-field MR imaging system. The MR-linac is work in progress and is not available for sale or distribution (courtesy of Elekta).

The beauty of the Bragg peak

Bethe-Bloch equation of ionisation energy loss by charged particles

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I.(1-\beta^2)}\right) - \beta^2\right]$$



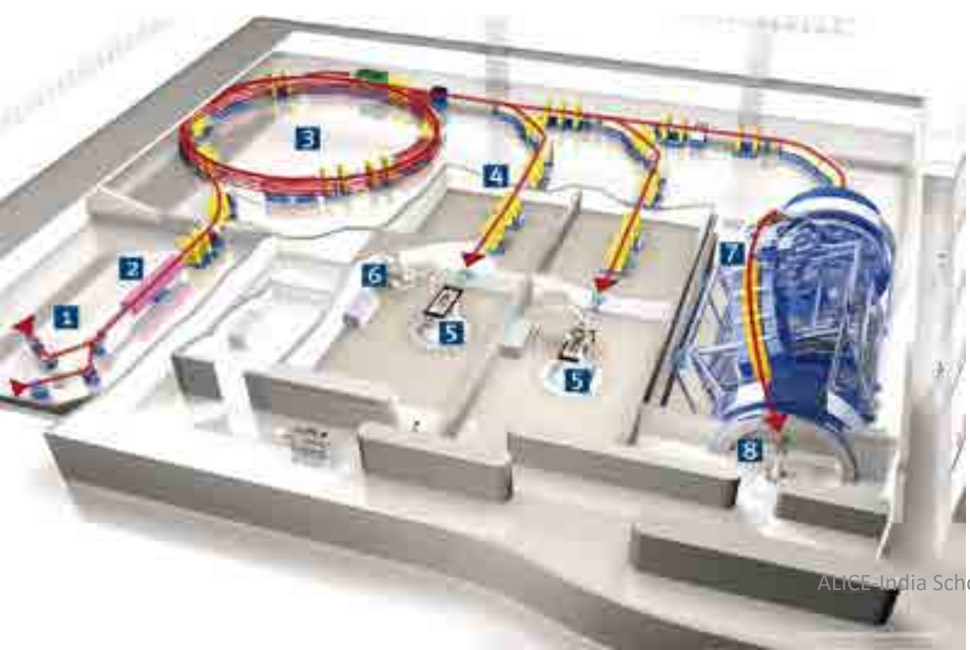
Spread-Out Bragg Peak (SOBP)

accelerators-for-society.org

Different from X-rays or electrons, protons (and ions) deposit their energy at a given depth inside the tissues, **minimising the dose to the organs close to the tumour**.

Required energy (protons) about 230 MeV, corresponding to 33 cm in water.
Small currents: 10 nA for a typical dose of 1 Gy to 1 liter in 1 minute.

The rise of particle therapy

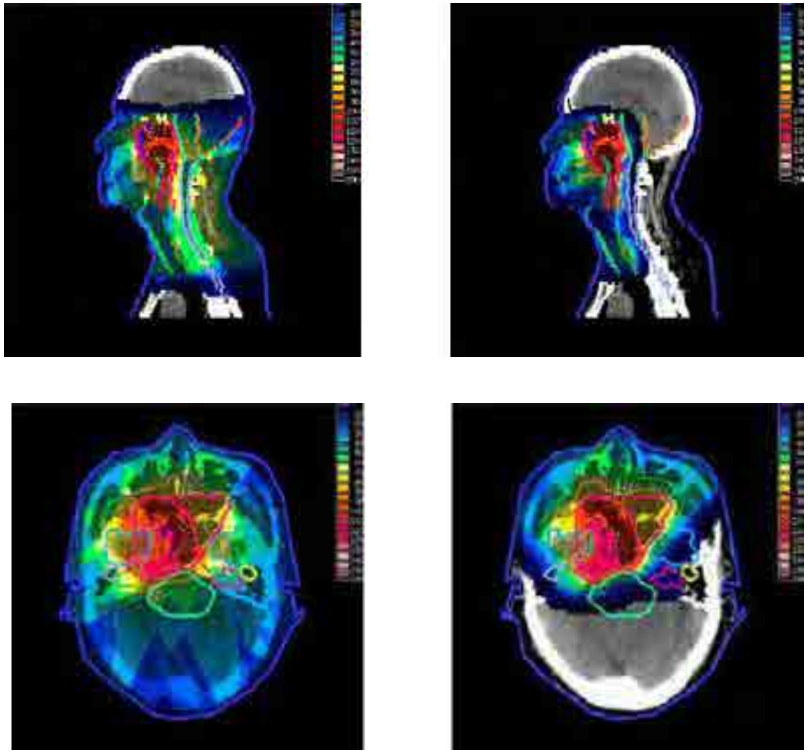


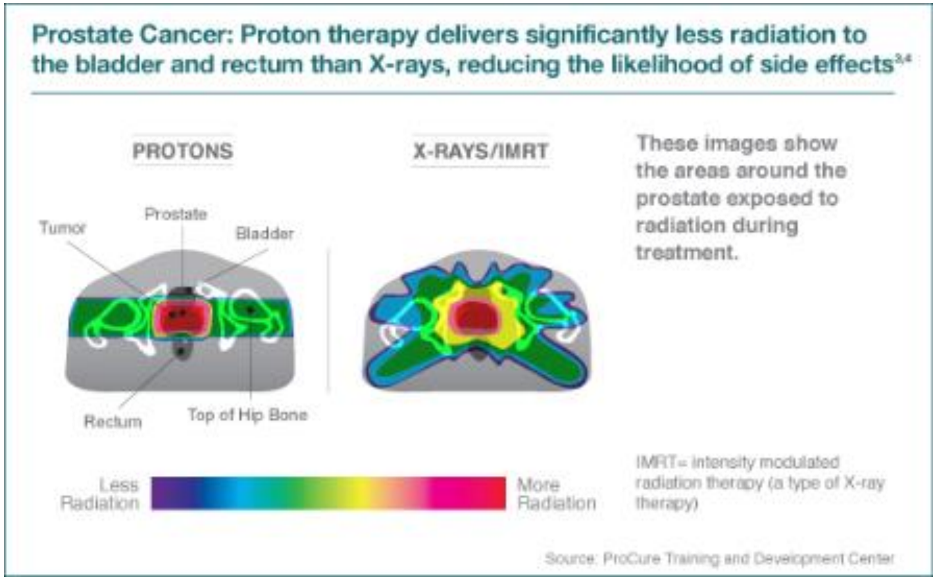
- First experimental treatment in 1954 at Berkeley.
- First hospital-based proton treatment facility in 1993 (Loma Linda, US).
- First treatment facility with carbon ions in 1994 (HIMAC, Japan).
- Treatments in Europe at physics facilities from end of '90s.
- First dedicated European facility for proton-carbon ions in 2009 (Heidelberg).
- From 2006, commercial proton therapy cyclotrons appear on the market (but Siemens gets out of proton/carbon synchrotrons market in 2011).
- Nowadays 3 competing vendors for cyclotrons, one for synchrotrons (all protons).
- More centres are planned in the near future.

A success story, but …

- many discussion on effectivness, cost and benefits.
- Some negative experiences from some running centers (lack of patients, increasing costs,…)

Comparing proton and X-ray therapy





The main recognised advantage of proton therapy are for:

- **Pediatric tumours**, where surrounding tissues are more delicate and the risk of secondary tumours is higher.
- **Tumours close to vital organs**: base of skull, central nervous system, head and neck.

-Protontherapy is rapidly developing: more than 65'000 patients treated worldwide, 5 companies offer turn-key solutions.

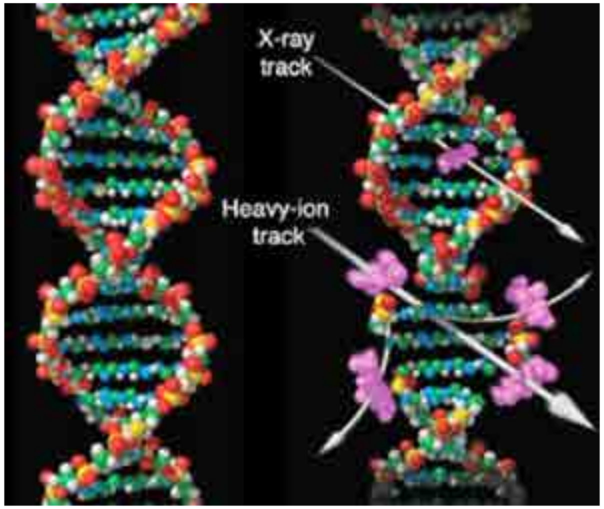
- Carbon ions have been used to treat about 6000 patients worldwide

Ion therapy: advantages

Heavy ions are **more effective than protons or X-rays** in attacking cancer.

The particle (or X-ray) breaks the DNA; multiple breaks kill the tumour cell. However, the key mechanism is DNA self-repair by the body cells.

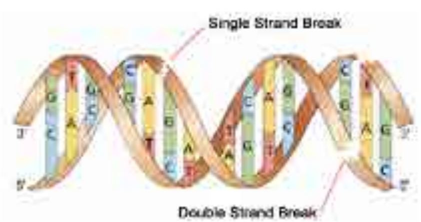
- Protons and X-rays cause single-strand breaks that are easy to repair.
- Ions produce more ionisations per length and may cause double-strand breaks that are much more difficult to repair.



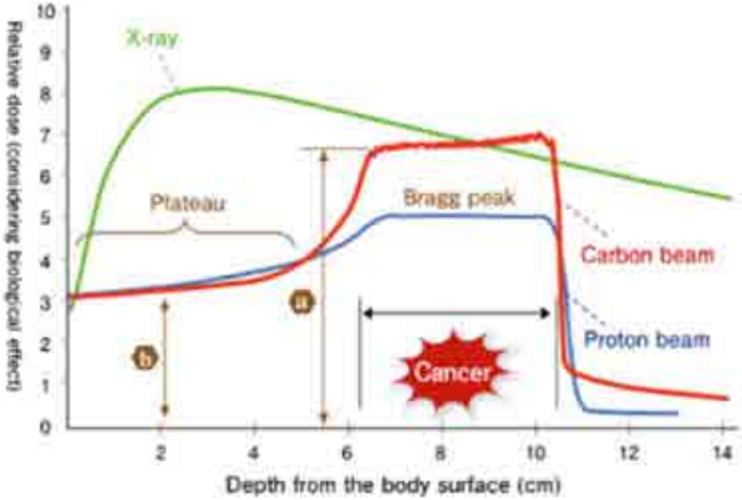
Heavy ions allow for lower doses, are effective with radio-resistant tumours (low oxygen content), and might reduce metastasis that are the main cause of mortality.

So far, 2/3 of cases treated at the mixed facilities (CNAO, etc.) are with carbon.

Fragmentation is what makes ions more effective in treating cancer



Radio Biological Effectiveness (RBE) is higher for Carbon than for protons.
1.1 for protons
3 for C ions
(reference 1 for Co X-rays)

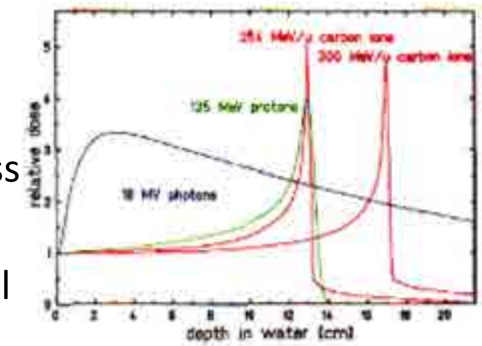


Ion therapy: cost and perspectives

For practical and historical reasons, all ion accelerators operate with fully stripped **Carbon ions**.

Bethe energy loss goes as z^2, z=charge of the incident particle → the energy loss is higher for ions → we need a higher energy (per atomic mass unit) to fully penetrate inside the body → around **440 MeV/u**.

The accelerator is more complex than for protons: magnetic rigidity at full energy is 2.76 times that of proton at full treatement energy.



$$B\rho[T.m] = 3.3356 \cdot pc[GeV]$$

Particle	H^+		C^{6+}		
Ring 1	inj	ext	inj	ext	
Ring 2				inj	ext
Energy [MeV/u]	31 MeV	250	7.9	68.8	440
$B\rho$ [T-m]	0.811	2.432	0.811	2.432	6.716

For a given magnet field, in a medical ion synchrotron with respect to a proton one accelerator and gantries have to be almost 3 times larger.

The HIT gantry has a mass of 600 tons for a dipole bending radius of 3.65 m.

All existing ion medical accelerators are large synchrotrons.
Cyclotrons cannot be easily used because of the dimensions and complexity (needs superconductivity) and because of the complexity of ion extraction from cyclotrons.

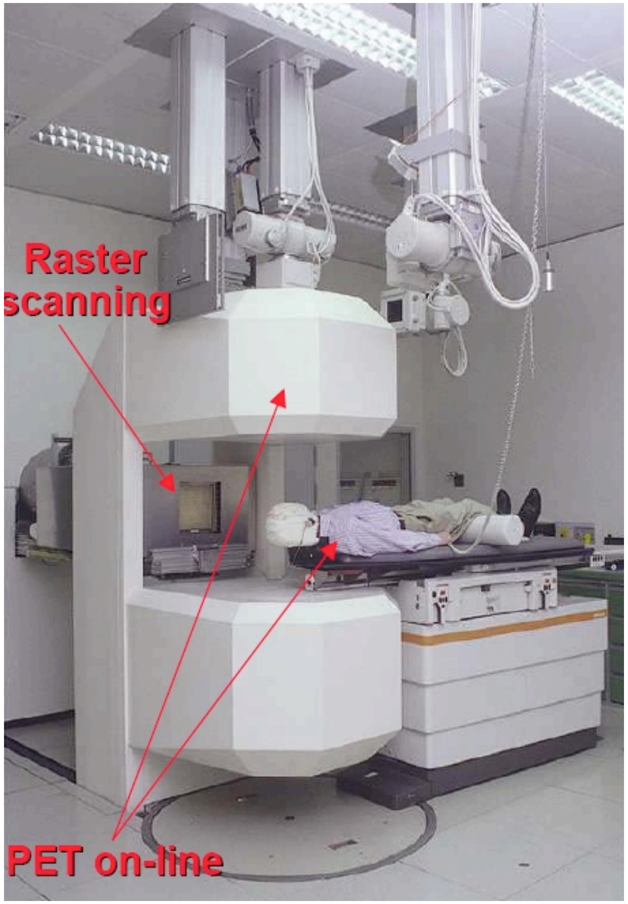
Alternative ions are being considered and extensive studies are ongoing

cern.ch/virtual-hadron-therapy-centre

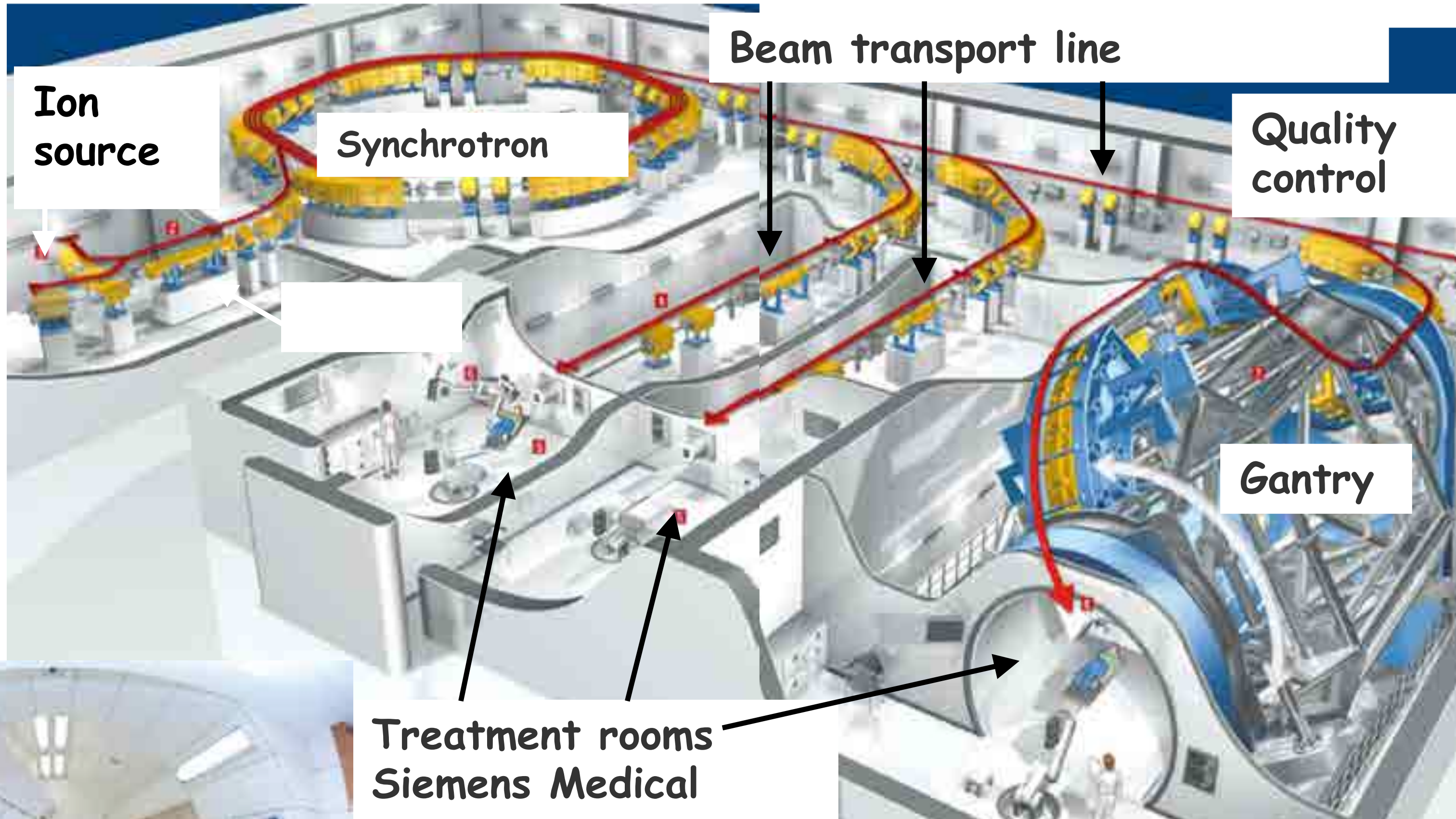
Carbon ions: pilot project in Europe

GSI & Heidelberg

- 450 patients treated

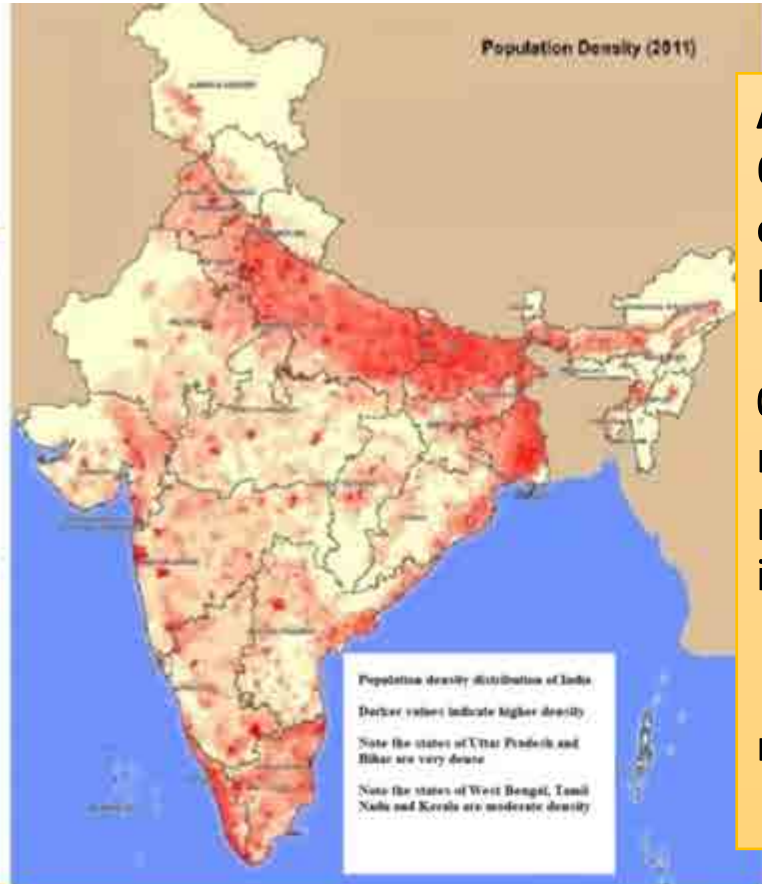


HIT - Heidelberg



CNAO – Italy (Pavia)

Radiation Oncology in India



AERB:
689 machines in 478 centres with 464 linear accelerators.

0.53 machines per million population.(Required is 1 machine/1M)

deficiency of 0.47 machines.

According to WHO machines required is 1280 (1 machine per 1 million population)
Radiation Therapy is underutilized in India ➔ Only 36.3% patients have access to radiation facility
Hardly accessible to rural population (see map)
Most of these are private➔ thus expensive and there is lack of manpower and training

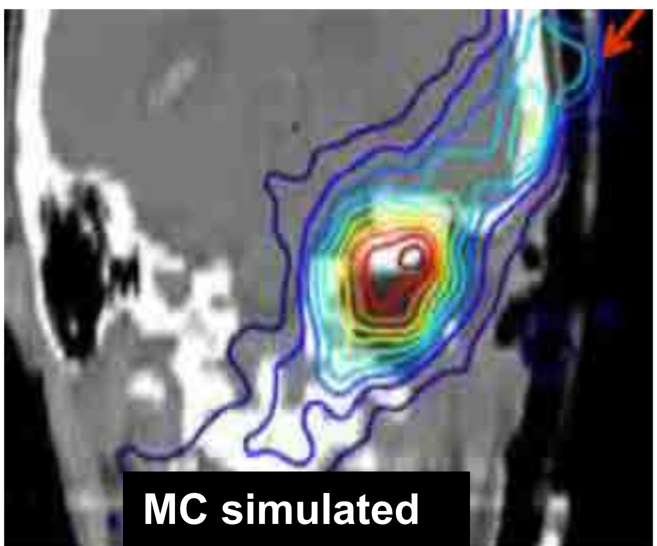
Initiatives by GOI

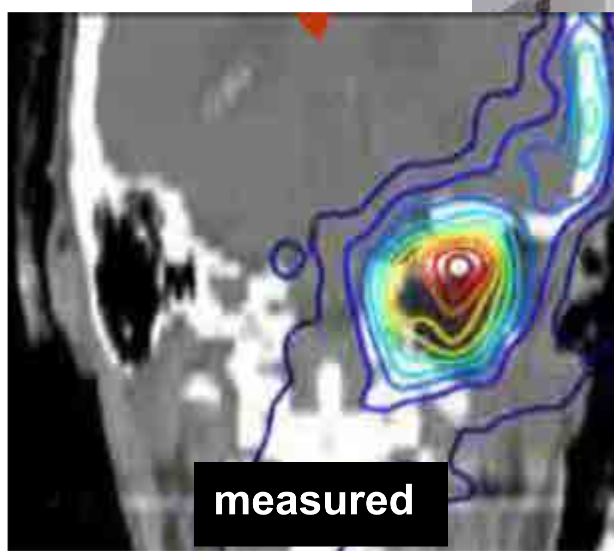
- Multi step plan proposed in 12^{th} Plan
- To reduce the cost of machine and thereby increase the number
  - Indigenization by BARC
    - Developed Telecobolt Unit Babhatronics, Babhatronics Ii and Babhatronics 3I
    - Radiothherpy Simulator IMAGIN Developed
    - 6MV Linac being Developed by SAMEER (under DOE)
    - Plan to introduce screening to catch the cancer in early stage→ more radiation machines and other infrastructure are thus required
- Manage Skewed Demand and Supply
    - Impetus on novel radiation oncology research to reduce number of radiation treatments. brachytherapy and hypofractioned radiotherapy needs to be undertaken


ENVISION
European NoVel Imaging Systems
for ION therapy

Challenges

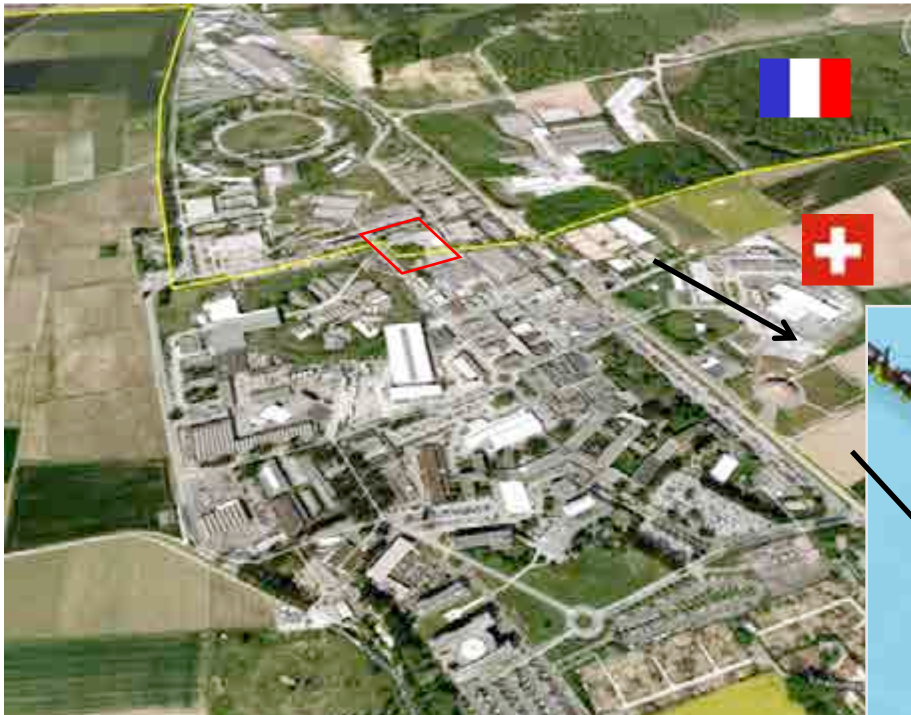
- In-beam PET @ GSI (Germany)
- MonteCarlo simulations
- Organ motion

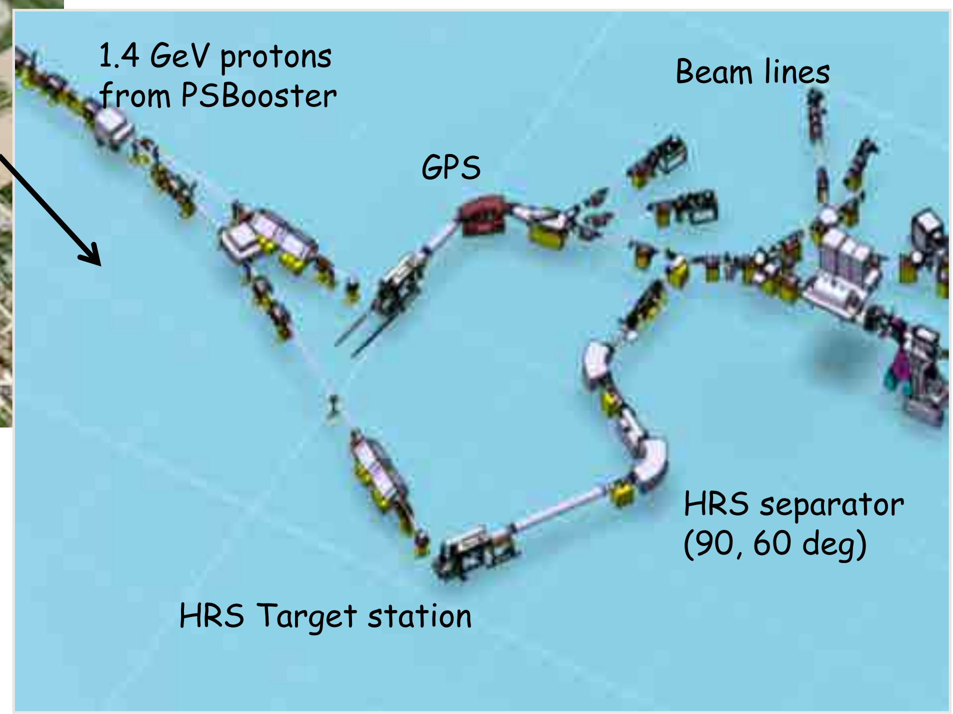




ISOLDE

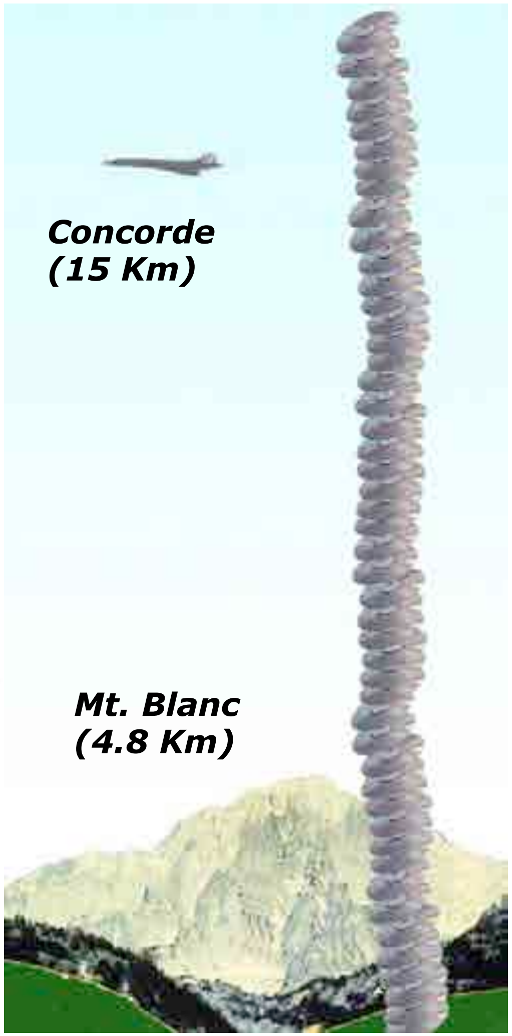
isotopes for detection & treatment



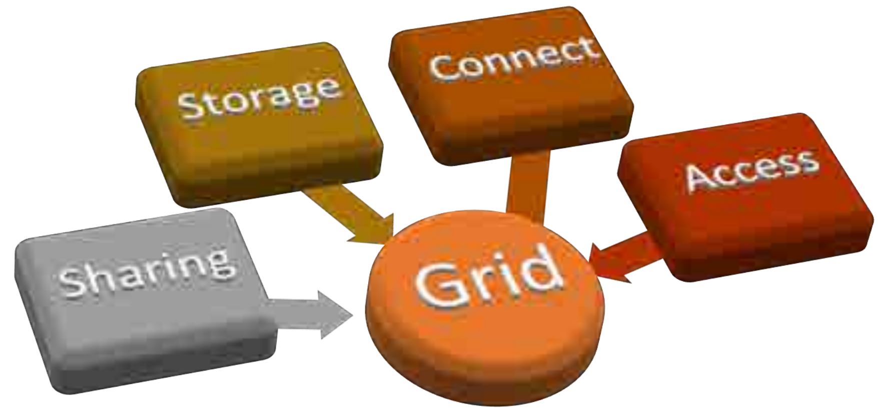


In collaboration with
University Hospital Geneva

Computing for medical applications



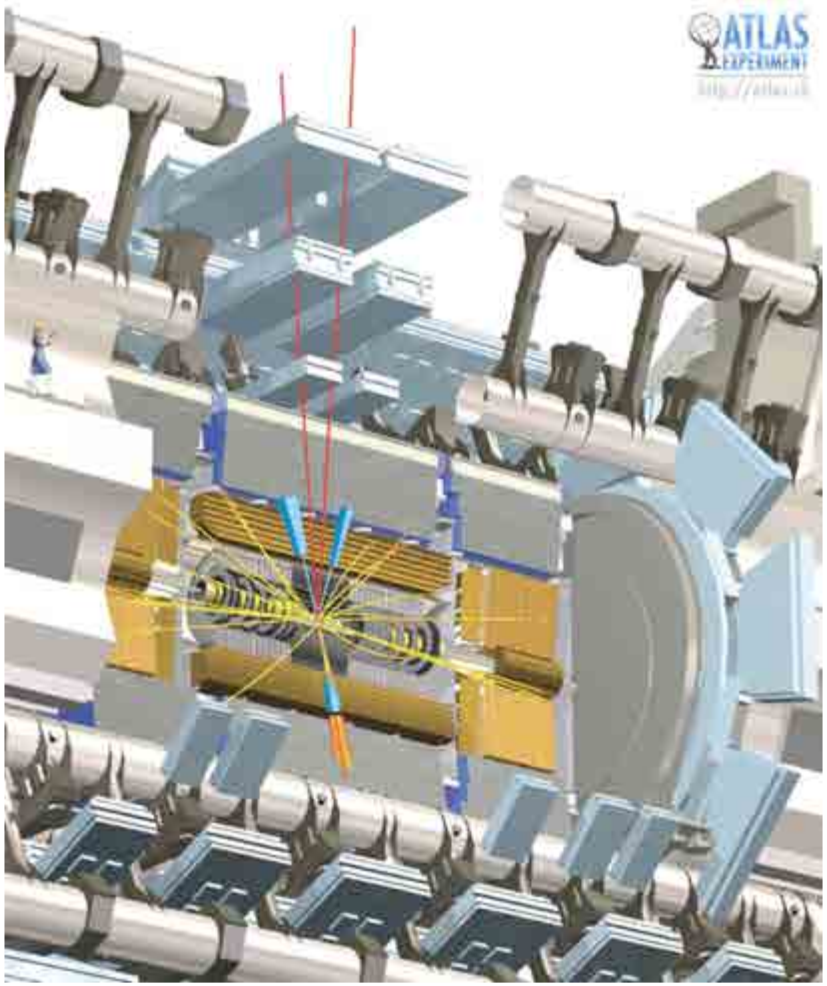
Computing

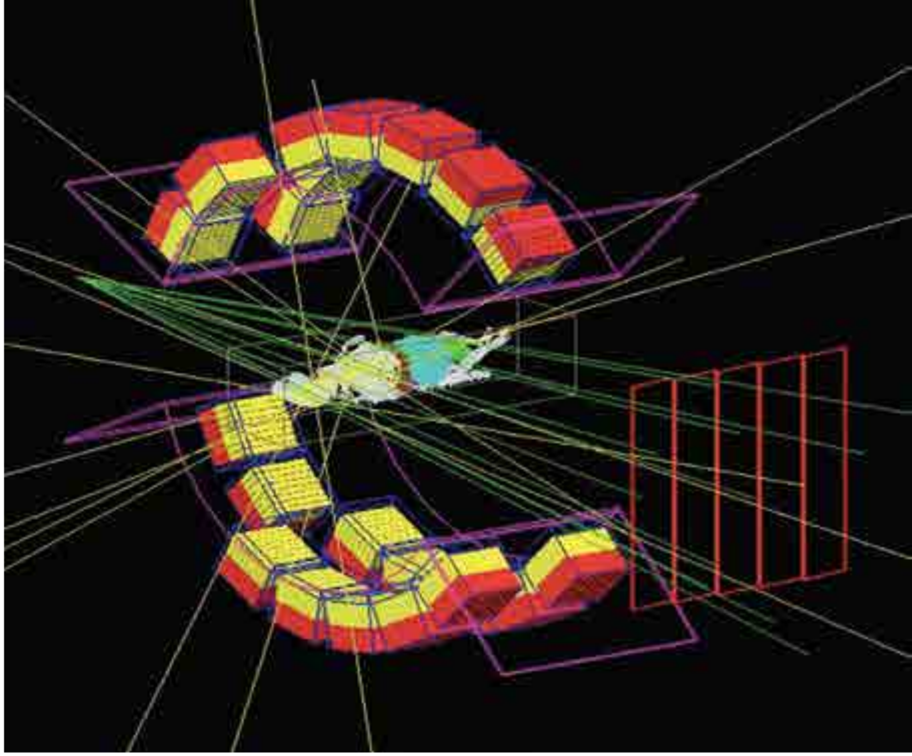


CASE STUDY

Image repositories are now commonplace on the internet, with content ranging from personal photographs to historical archives. Grid technology developed for the LHC has allowed the company Imense Ltd, working with particle physicists at the University of Cambridge, to increase its search capabilities 100-fold, as it seeks to become the pre-eminent image search portal.

Simulation



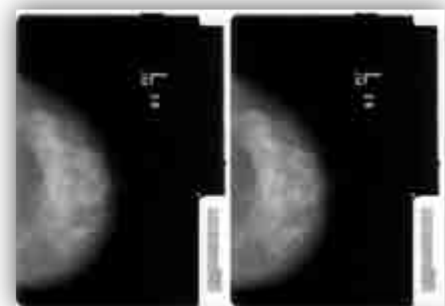


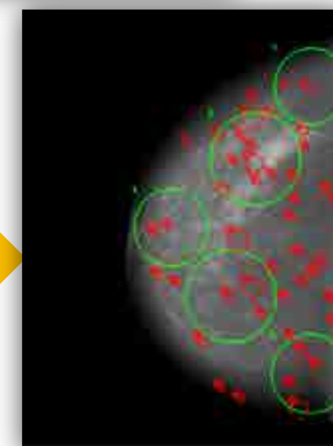
Medical imaging software

OpenGATE is an extension of GEANT4, a software tool for the simulation of the penetration of particles through matter, originally developed for the design of physics experiments. OpenGATE provides a complete environment for simulating the behaviour of the next generation of nuclear medicine scanners, which may be used in clinics or for the development of drugs.

Mammogrid - a grid mammography database

- Second Opinion
- Cancer Screening
- Education and Training
- Reference Database / Repository

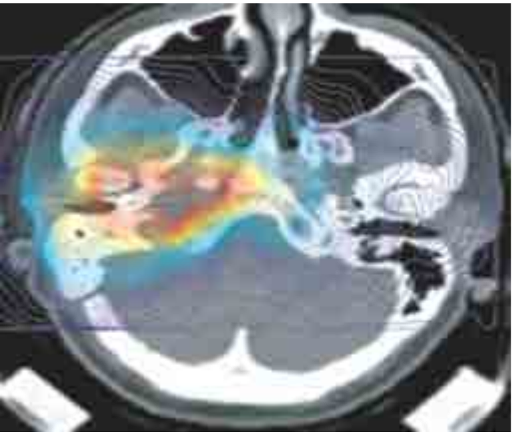




From: David MANSET, CEO MAAT France, www.maat-g.com

Detector applications

Novel 'bionic' implants
A new type of active pixel sensor developed for the LHC has many applications but the most exciting are retinal implants which have the potential to restore partial sight to the blind.



- Several advanced silicon devices, such as the Medipix hybrid pixel detector developed by a CERN collaboration, will lead to faster X-ray imaging and CT-scanning, with clearer images at lower X-ray doses, which can be used to monitor cancer therapy in real time.

- Originally developed for particle physics and astronomy, charge coupled devices (CCDs), found in digital cameras, are also used in dental X-ray machines. A new generation of large-area X-ray detectors based on technology being developed for the International linear Collider could be used to image the heart for example.

- Gas-filled particle detectors have been incorporated in a new whole-body PET scanner, which is significantly cheaper and quicker than the current PET systems.

Manufacturing and business

- Particle-physics experiments represent a formidable engineering challenge, virtually always requiring novel hardware, electronics, and software developments.
- Particle accelerators are essential tools in fabricating the layouts of electronic circuit boards, using ion implantation, and more than 10 000 are used in the semiconductor industry

Engineering
CERN engineers have developed efficient cryogenic and vacuum technology that can be applied in many industrial areas.

The SuperconductingRF Cavities technology is likely to be exploited in accelerators such as light sources used in biomedical and materials research.

Electronics
major collaborations with electronics manufacturers resulting in radiation-hard, highly parallel and three-dimensional chips, as well as connectors that allow fast read-out and data acquisition.

Global challenges

World Wide Web (WWW),designed at CERN to help its transnational teams communicate, has **revolutionised the global economy**. **Google's revenue alone was more than $20 bn in 2008.**

Software

Software tools employed in particle physics also provide an enabling technology to the financial-services and engineering sectors.

Based on computer software designed to analyse LHC results, **UK particle physicists set up a company, Axomic, which markets Web-based tools to architects, engineering and construction companies for managing image catalogues and 3-D plans.**

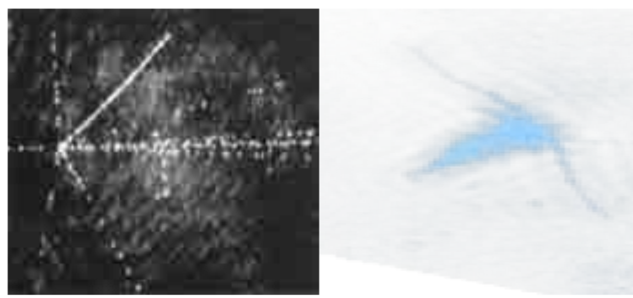
National security

Particle detectors are used

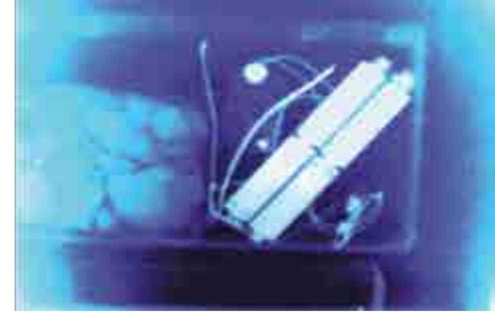
- monitor nuclear reactor cores
- checking whether weapons-grade enriched uranium or plutonium are present.
- to detect radioactive materials at airports

Energy

- Novel accelerator technology has the potential to **dispose of nuclear waste.**
- **Nuclear fusion** is another future energy source that can benefit from particle-physics technology, as it requires ultra-high vacuums and powerful magnets.



A holographic camera, originally designed to image particle tracks in bubble chambers, was adapted to record clouds of plankton in the sea in pollution and global-warming studies.



Scintillating crystals that respond to X-rays and gamma-rays are components in particle-detection systems.

A partnership between the company Corus and the University of Sheffield is developing large-area **scintillation detectors to detect fissile material.**

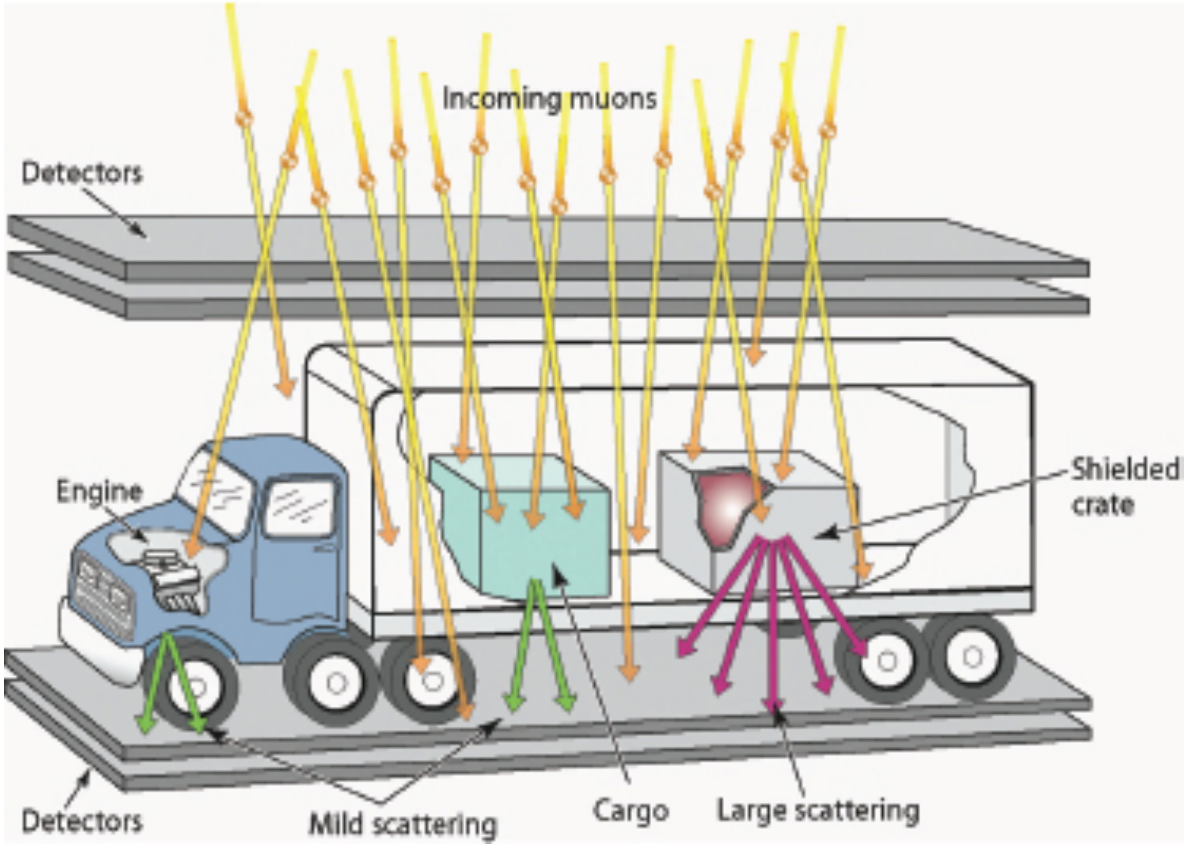
Physicists have also developed devices that generate neutrons which, when combined with **scintillators, can identify the characteristic signatures of explosives and drugs in air cargo.**

Greener industrial processes

- Electron-beam technology reduces energy consumption by as much as 90% compared to conventional thermal techniques.
- Replacement of steel with X-ray-cured carbon composites in cars, including the chassis, can reduce vehicle weight by 80% and energy consumption by 50%

Cultural heritage

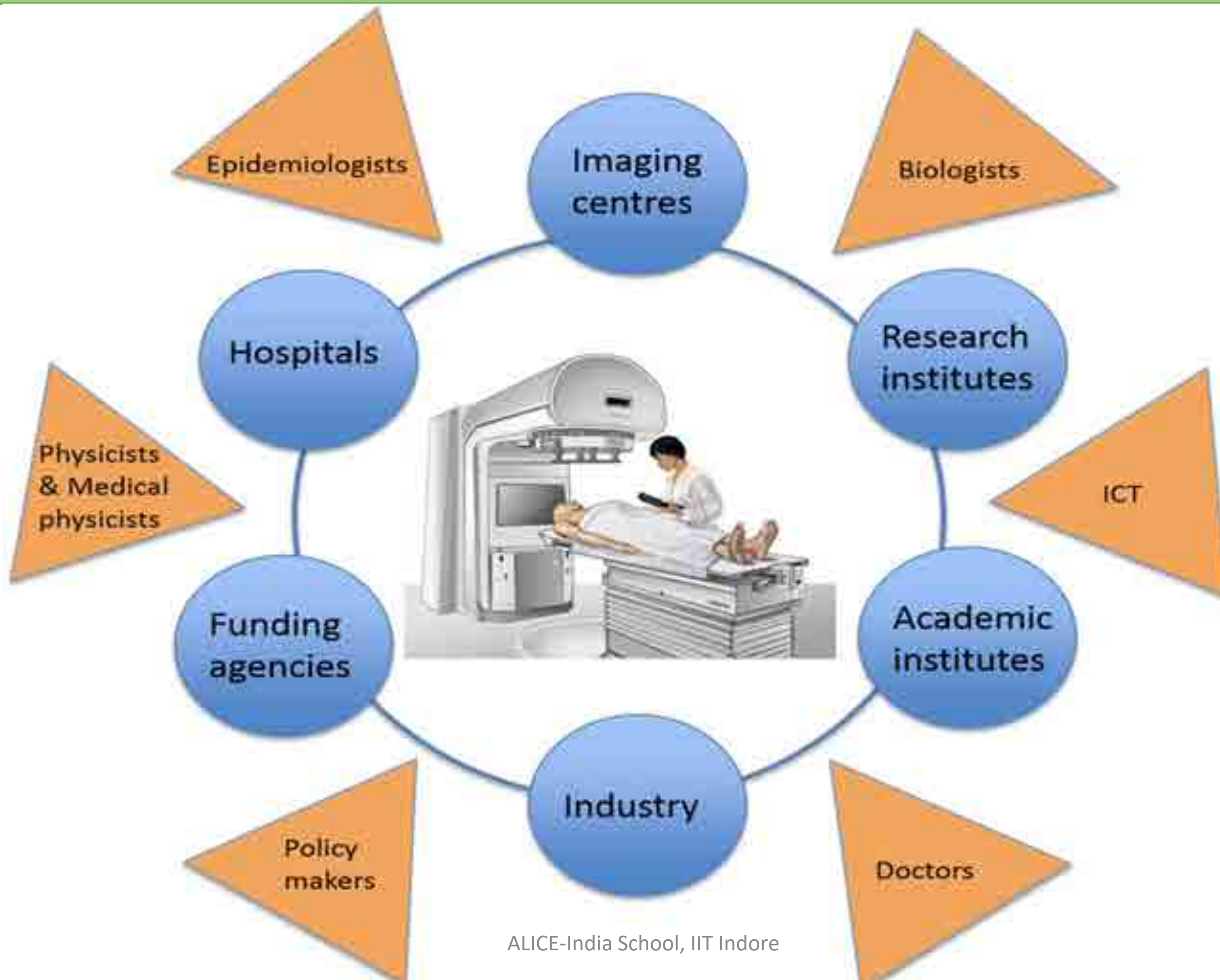
Accelerator Mass Spectroscopy (AMS) can also be used to date paintings and detect fraudulent copies.



Muons passing through high-Z materials (like uranium and plutonium) are scattered more than those passing through other materials (such as steel or water). Cosmic ray muons can therefore be used as an active interrogation probe of nuclear materials by detecting muons above and below a truck.

4th pillar of technology - collaboration

ENLIGHT is a multidisciplinary network that brings together physicists, physicians, radiobiologists,, engineers and information technology experts, and one of its key purposes is to enable collaboration between academic, research and industrial partners in particle therapy



Collaborations & Partnerships

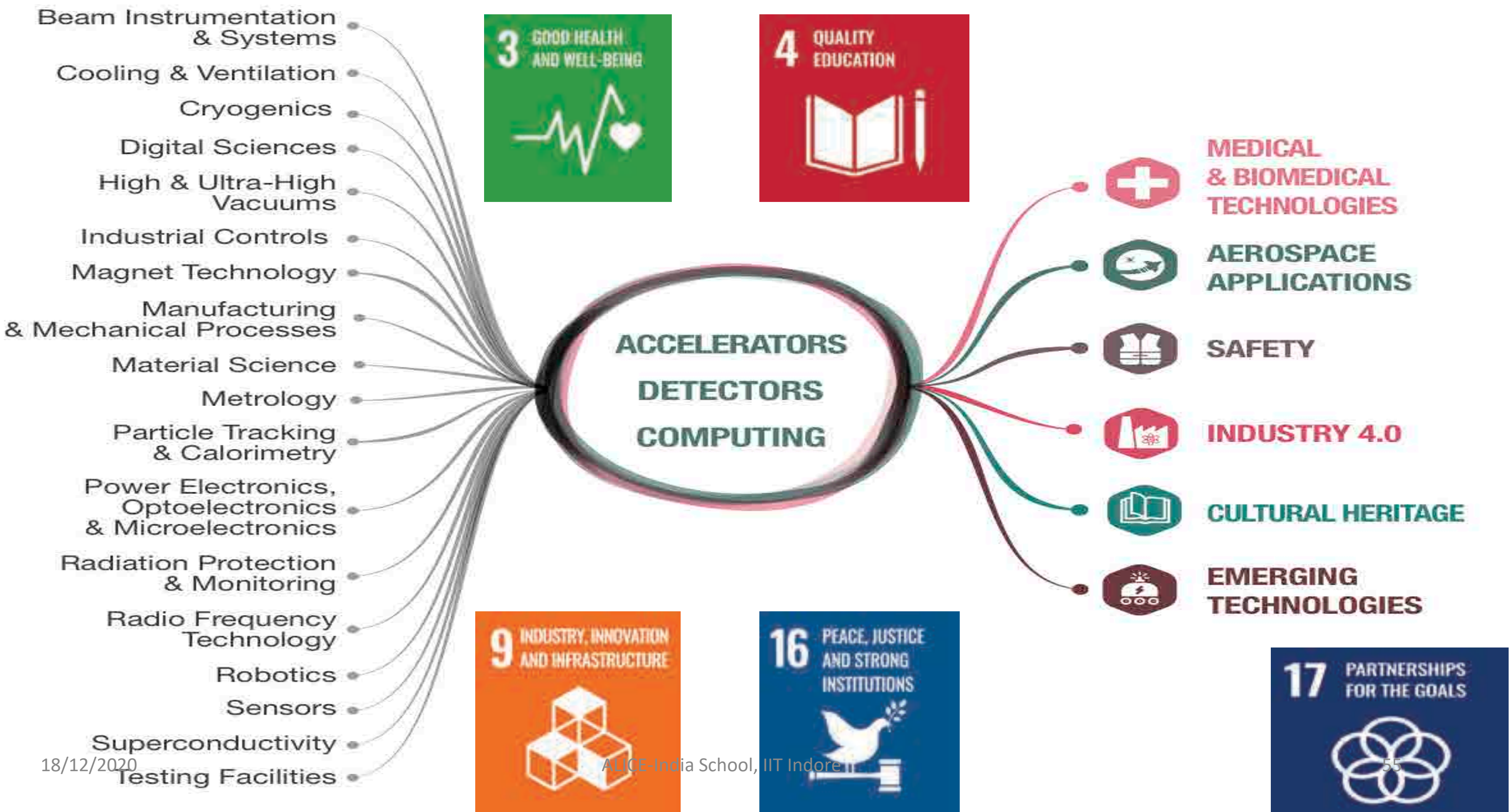
The G-20 nations—Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, Saudi Arabia, South Africa, South Korea, Turkey, the United Kingdom, and the United States, plus the European Union—include countries with advanced economies and countries with emerging economies that are working together toward worldwide financial stability and the achievement of sustainable growth and development.

Examples of this include the ITER fusion reactor project and the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN).

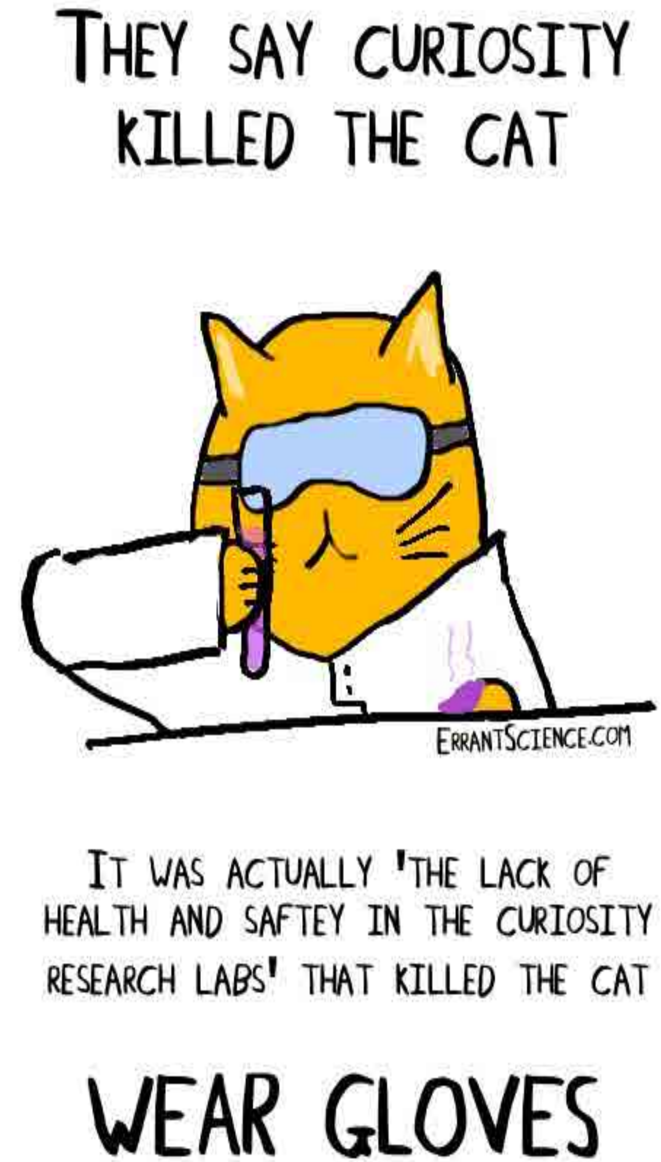
Curiosity in Basic Science: Advancing Frontiers of Technology

A myriad of engineers, technicians and scientists develop novel technology and expertise that can be applied to fields other than high-energy physics

- develops the expertise and shares it with society.
- Collaboration with industry – including large companies, SMEs or recent start-ups – and engages with other stakeholders, such as policy makers.




CURIOSITY IS THE ESSENCE OF THE SCIENTIFIC MIND.

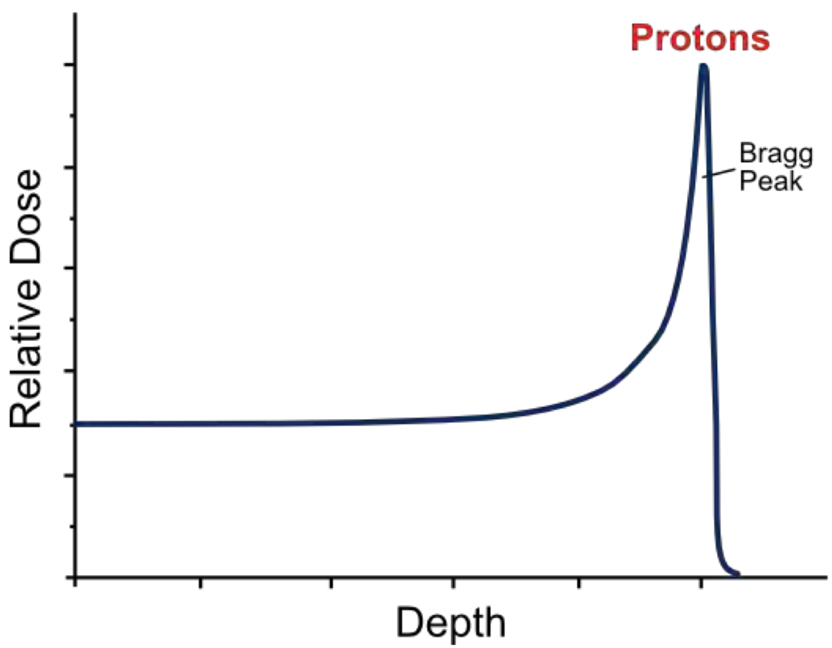

THEY SAY CURIOSITY KILLED THE CAT
ERRANTSCIENCE.COM
IT WAS ACTUALLY 'THE LACK OF HEALTH AND SAFTEY IN THE CURIOSITY RESEARCH LABS' THAT KILLED THE CAT
WEAR GLOVES

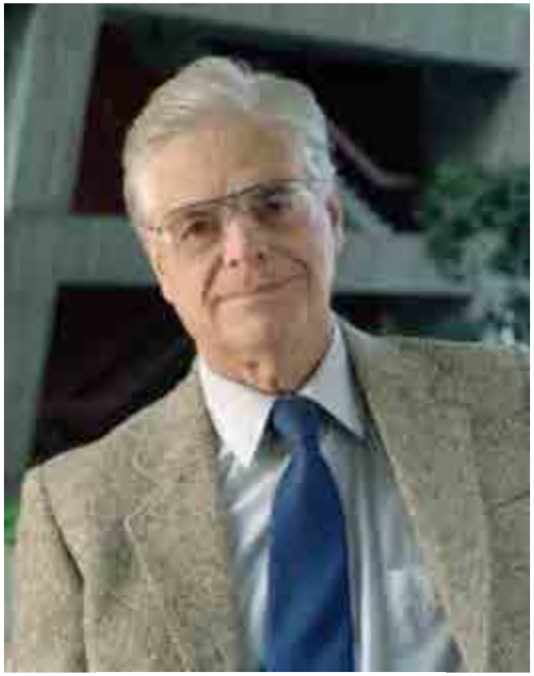
Backup Slides

Alternative – Hadron Therapy

- 1946: Robert Wilson

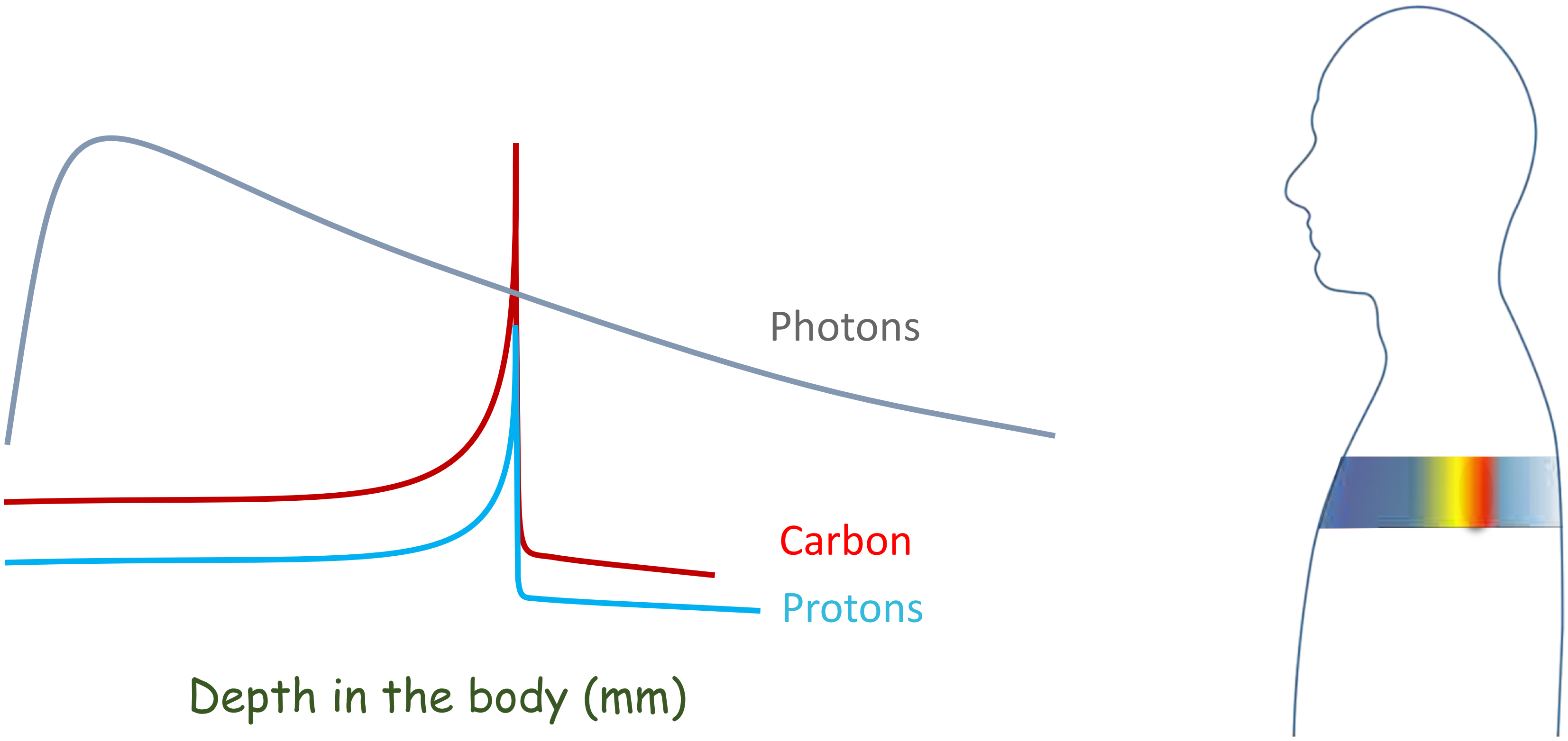
  Protons can be used clinically





Robert Wilson

Why hadron therapy



Tumours near critical organs
Tumours in children
Radio-resistant tumours

Accelerator and Society

Over 30'000 particle accelerators are in operation world-wide.

Only ~1% are used for fundamental research.

Medicine is the largest application with more than 1/3 of all accelerators.

Research		**6%**
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,2 - 0,9%
	Biology	5%
Medical Applications		**35%**
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0,1%
Industrial Applications		**<60%**
	Ion implantation	34%
	Cutting and welding with electron beams	16%
	Polymerization	7%
	Neutron testing	3.5%
	Non destructive testing	2,3%