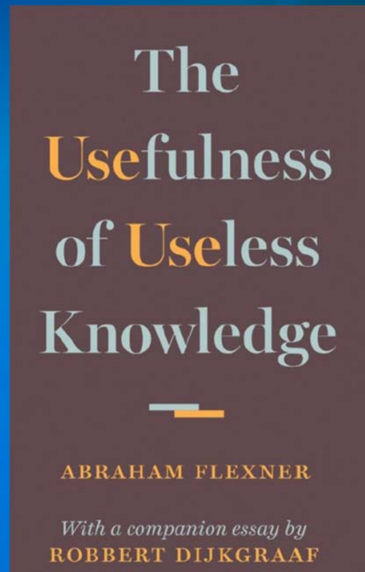
The Unreasonable Effectiveness of Physics in Society*

(part II)

Tadeusz Lesiak

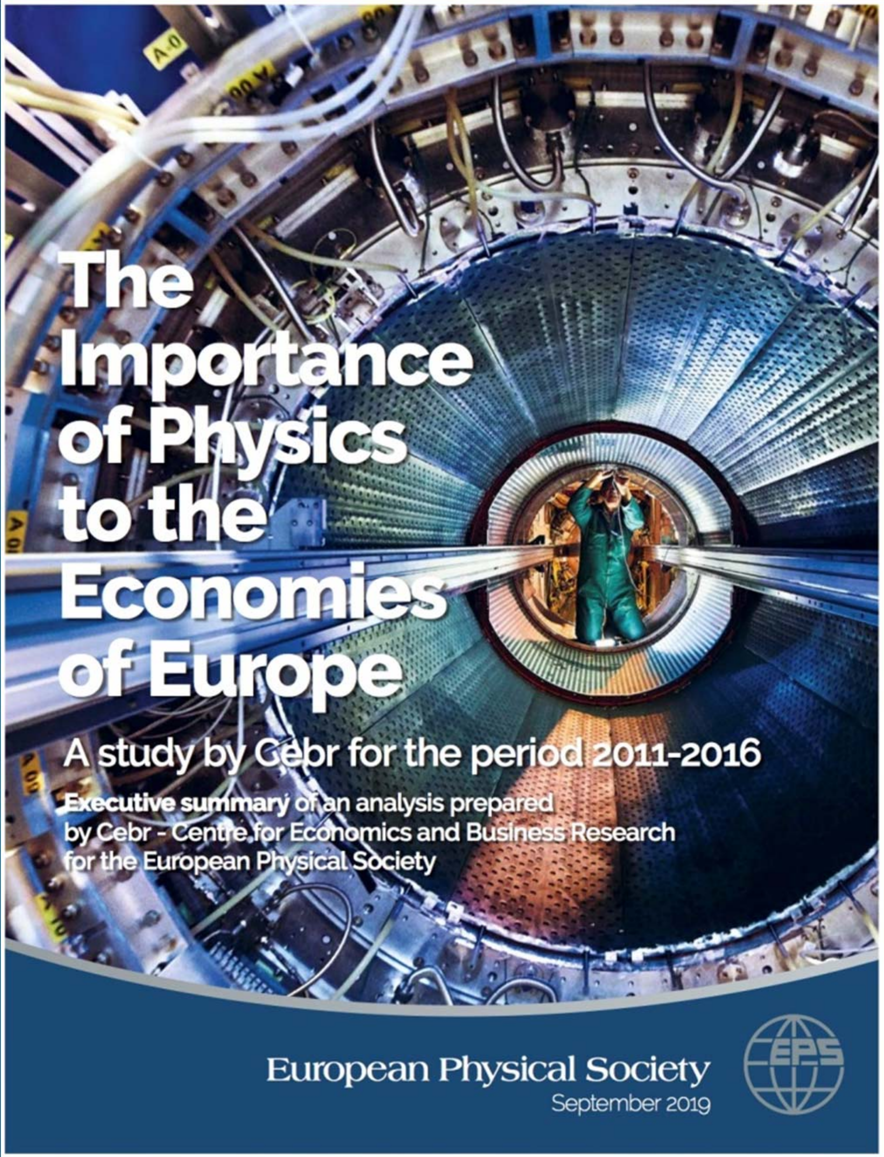


(*) „The Unreasonable Effectiveness of Mathematics in the Natural Sciences”

Eugene Wigner

A.D. 1939 !

The Importance of Physics to the Economies of Europe



https://www.eps.org/page/policy_economy

The previous report:

https://cdn.ymaws.com/www.eps.org/resource/resmgr/policy/EPS_economyReport2013.pdf

EPS – European Physical Society

CEBR – Centre for Economics and Business Research

„Europe" = 31 countries:
EU (28 countries) + Iceland, Norway and Switzerland (EFTA members)

The Importance of Physics to the Economies of Europe

- ✓ **„Physics"** – branch of science concerned with the nature, structure and properties of matter, ranging from the smallest scale of elementary particles to the Universe as a whole

- ✓ **Physics** includes experiment and theory and **involves both fundamental research driven by curiosity, as well as applied research linked to technology**

- ✓ Physics often provides the foundations for other disciplines, and plays a central role in many different sectors of industries
- ✓ **ALL THE ABOVE-WRITTEN STATEMENTS ARE FROM THE CEBR REPORT**

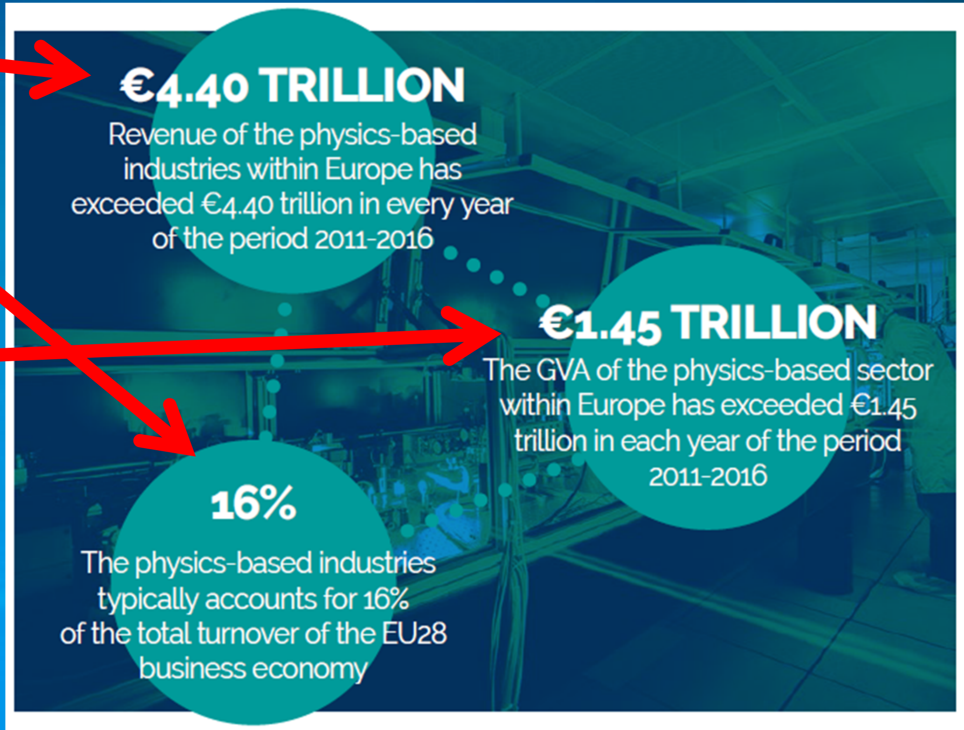
- ✓ **„Physics based industries" (PBIs)** – those sectors where workers with some training in physics would be expected to be employed and where the activities would be expected to rely heavily on the theories and results of physics to achieve their commercial goals

- ✓ → 72 branches out of over 700, spanning the range from electrical, civil and mechanical engineering, energy, information technology and communications, design and manufacturing, transportation, medicine and related life-science fields and technologies used in space

The Importance of Physics to the Economies of Europe

- ✓ „Physics Based Industries" (PBIs) contribute significantly to the economies of European countries and to the European economy as a whole (E-PBIs)
- ✓ **The revenue** of E-PBIs
- ✓ **The fraction of E-PBI's revenue** w.r.t. the total one
- ✓ **The Gross Value Added (GVA)** – a measure of the value generated in the production of goods and services

  The GVA of E-PBIs is a greater fraction than either the construction, financial or retail sectors



- ✓ **The employment** in E-PBIs: **17 millions people** (12% of Europe's total business economy employment)
- ✓ **The relative workforce productivity** [GVA/employee/yr]: **90 800 EUR** for PBIs, i.e. higher than for manufacturing sector and substantially higher than the construction and retail sectors
- ✓ **The revenue/employee: 253 000 EUR/year**

The Importance of Physics to the Economies of Europe

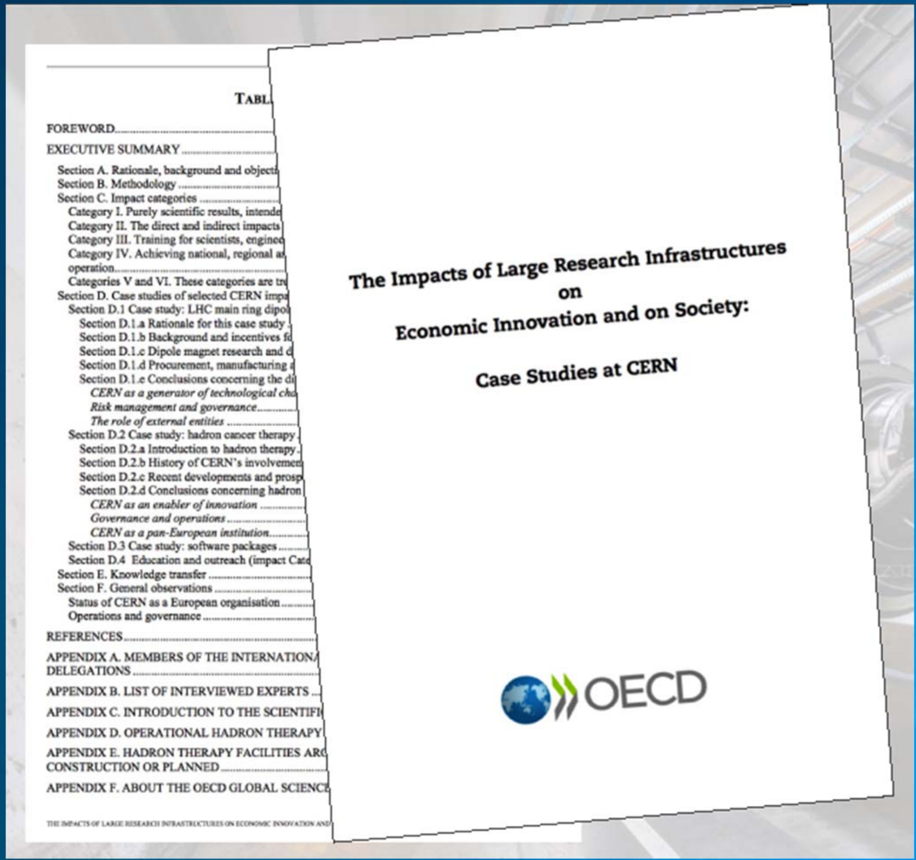
FOR EVERY €1 OF PHYSICS-BASED GVA, THE EU28 ECONOMY GAINS €2.64

The Importance of Physics to the Economies of Europe

- ✓ The activities of the PBIs also impact the wider economy, thus creating a multiplier effect, impacting employment, GVA and output
- ✓ Example: a physics-based enterprise purchases other goods and services as inputs of their own business.
- ✓ For this „indirect" impact every 1 EUR generates 2.49 EUR
- ✓ The employment multiplier: 3.34 (for every single job in E-PBI, a total of 3.34 jobs are supported in European economy)
- ✓ Physics-based goods & services contributed to 44 % of all European export

The physics-based sector is a highly productive part of the European economy

The Importance of Physics to the Economies of Europe


TABL

The Impacts of Large Research Infrastructures
on
Economic Innovation and on Society:

Case Studies at CERN

OECD

OECD – The Organization of Economic Co-operation and Development

http://www.oecd.org/sti/inno/CERN-case-studies.pdf

The impact of CERN analysed in four (related) categories:

1. **Innovations needed for major CERN component development**
2. **Innovations unrelated to the facility needs**
3. **Software applications**
4. **Education and public outreach**

omitted due to the lack of time

Cost Benefit Analysis of the LHC

Cost-Benefit Analysis of the Large Hadron Collider to 2025 and beyond

Massimo Florio[1], Stefano Forte[2], and Emanuela Sirtori[3]

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[2] *TIF Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[3] *CSIL, Centre for Industrial Studies Corso Monforte 15, I-20122 Milano, Italy*

Abstract

Social cost-benefit analysis (CBA) of projects has been successfully applied in different fields such as transport, energy, health, education, and environment, including climate change. It is often argued that it is impossible to extend the CBA approach to the evaluation of the social impact of research infrastructures, because the final benefit to society of scientific discovery is generally unpredictable. Here, we propose a quantitative approach to this problem, we use it to design an empirically testable CBA model, and we apply it to the the Large Hadron Collider (LHC), the highest-energy accelerator in the world, currently operating at CERN. We show that the evaluation of benefits can be made quantitative by determining their value to users (scientists, early-stage researchers, firms, visitors) and non-users (the general public). Four classes of contributions to users are identified: knowledge output, human capital development, technological spillovers, and cultural effects. Benefits for non-users can be estimated, in analogy to public goods with no practical use (such as environment preservation), using willingness to pay. We determine the probability distribution of cost and benefits for the LHC since 1993 until planned decommissioning in 2025, and we find there is a 92% probability that benefits exceed its costs, with an expected net present value (NPV) of about 3 billion €, not including the unpredictable economic value of discovery of any new physics. We argue that the evaluation approach proposed here can be replicated for any large-scale research infrastructure, thus helping the decision-making on competing projects, with a socio-economic appraisal complementary to other evaluation criteria.

We determine the probability distribution of cost and benefits for the LHC since 1993 until planned decommissioning in 2025, and we find there is a **92% probability that benefits exceed its costs, with an expected net present value of about 3 billion euro, not including the unpredictable economic value of discovery of any new physics.**

Additional reading:
Schopper, Herwig, 2016. "Some remarks concerning the cost/benefit analysis applied to LHC at CERN," Technological Forecasting and Social Change, Elsevier, vol. 112(C), pages 54-64.

E Pugliese, G Cimini, A Patelli, A Zaccaria, L Pietronero, A Gabrielli, Unfolding the innovation system for the development of countries: co-evolution of Science, Technology and Production, arXiv preprint arXiv:1707.05146

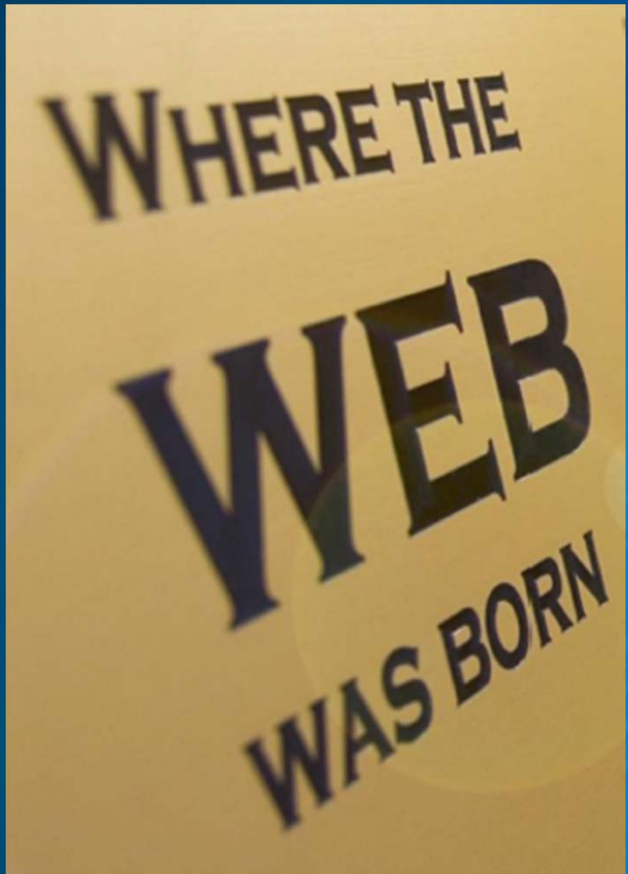
A Patelli, G Cimini, E Pugliese, A Gabrielli, The scientific influence of nations on global scientific and technological development, Journal of Informetrics 11, 1229-1237 (2017)

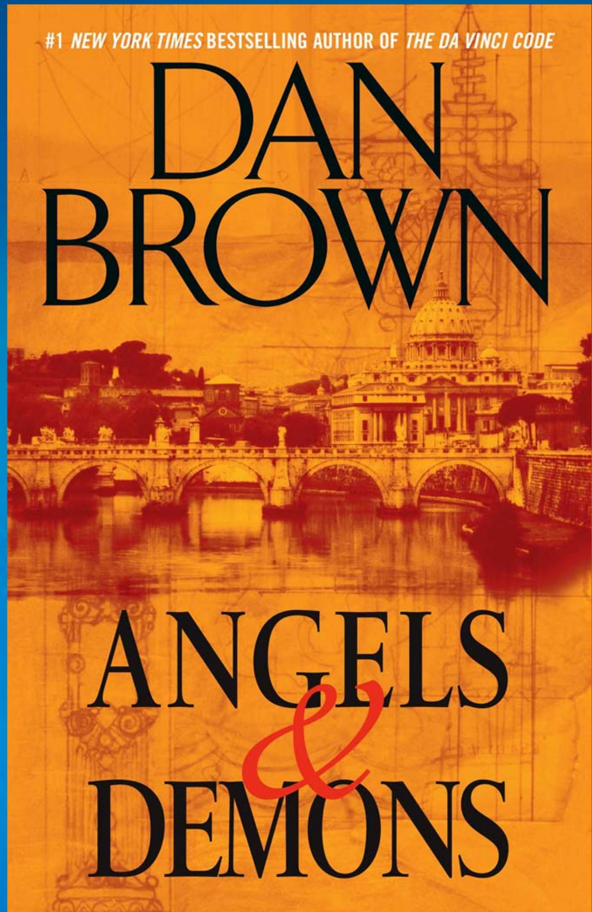
arXiv:1507.05638

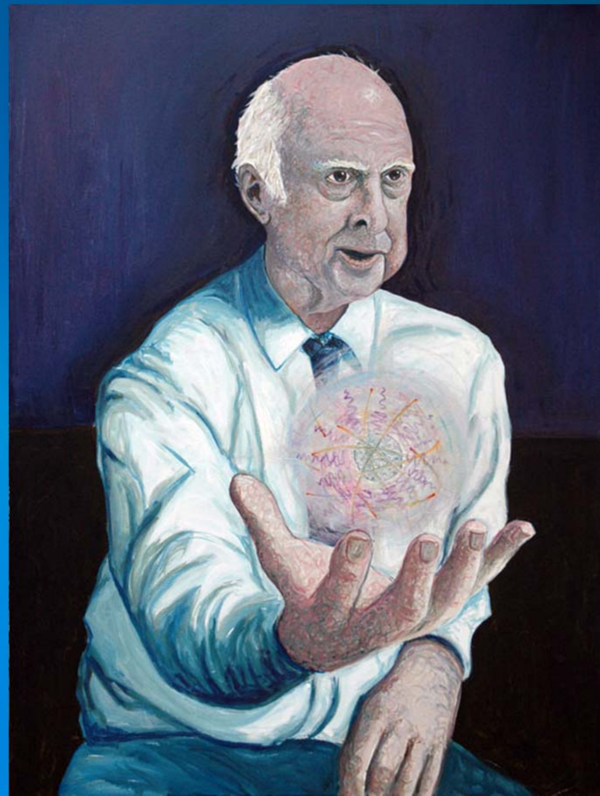
The Importance of Particle Physics and Accelerator Technology to the Economies in Europe

http://apae.ific.uv.es/apae/wp-content/uploads/2015/04/EuCARD_Applications-of-Accelerators-2017.pdf

Three Faces of CERN for the General Public







Accelerators Had an Impact on a Wide Range of Materials…

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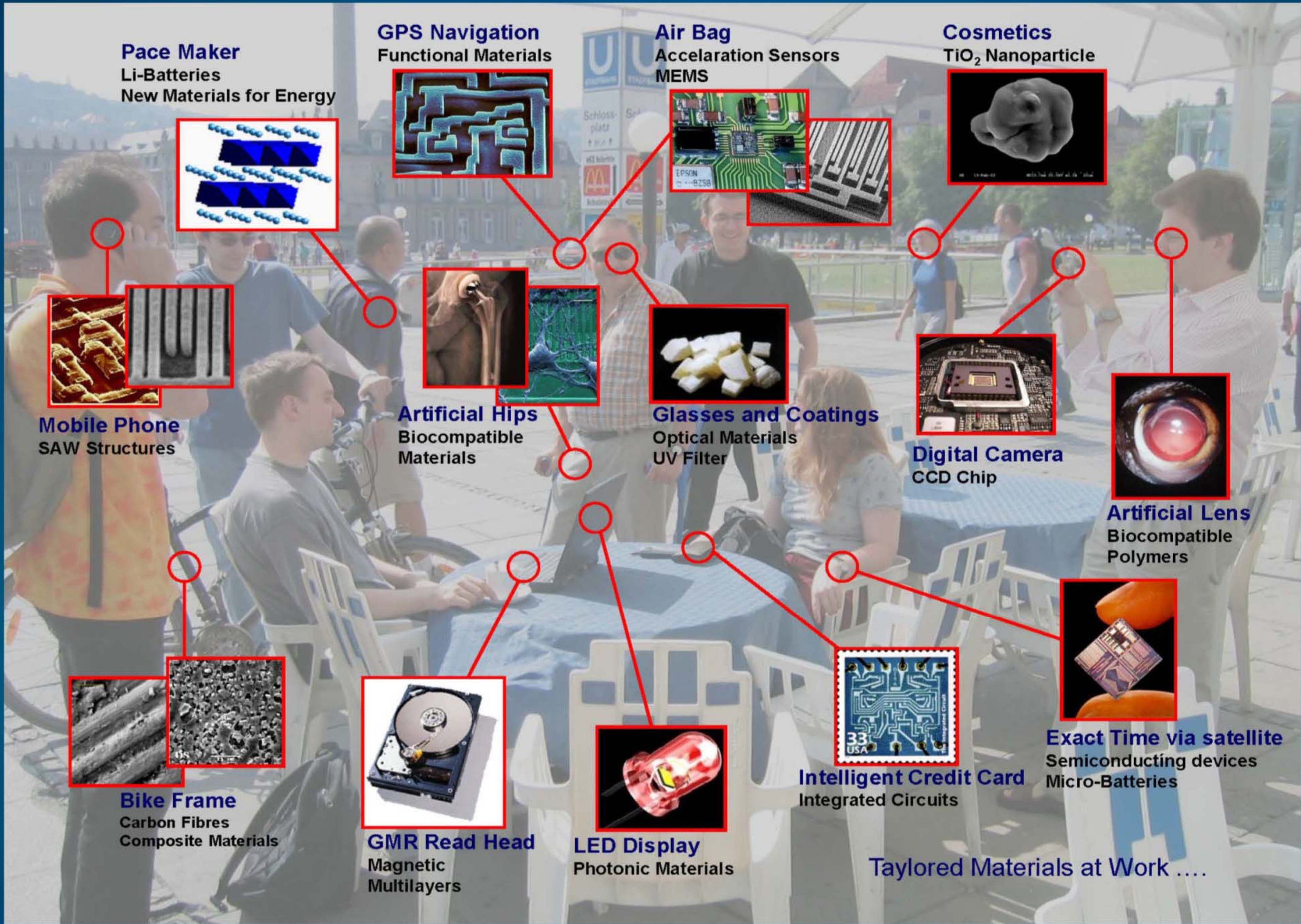
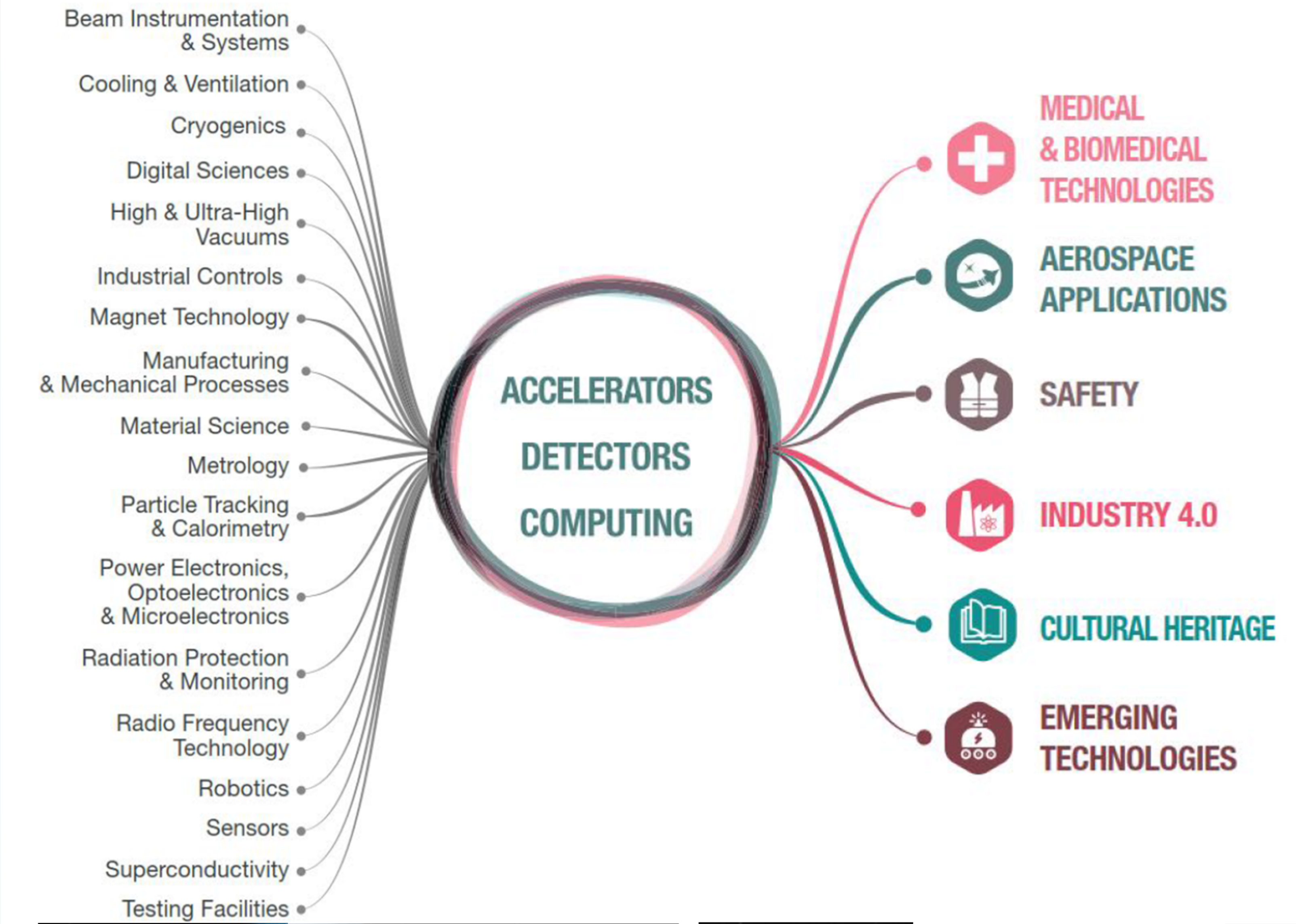


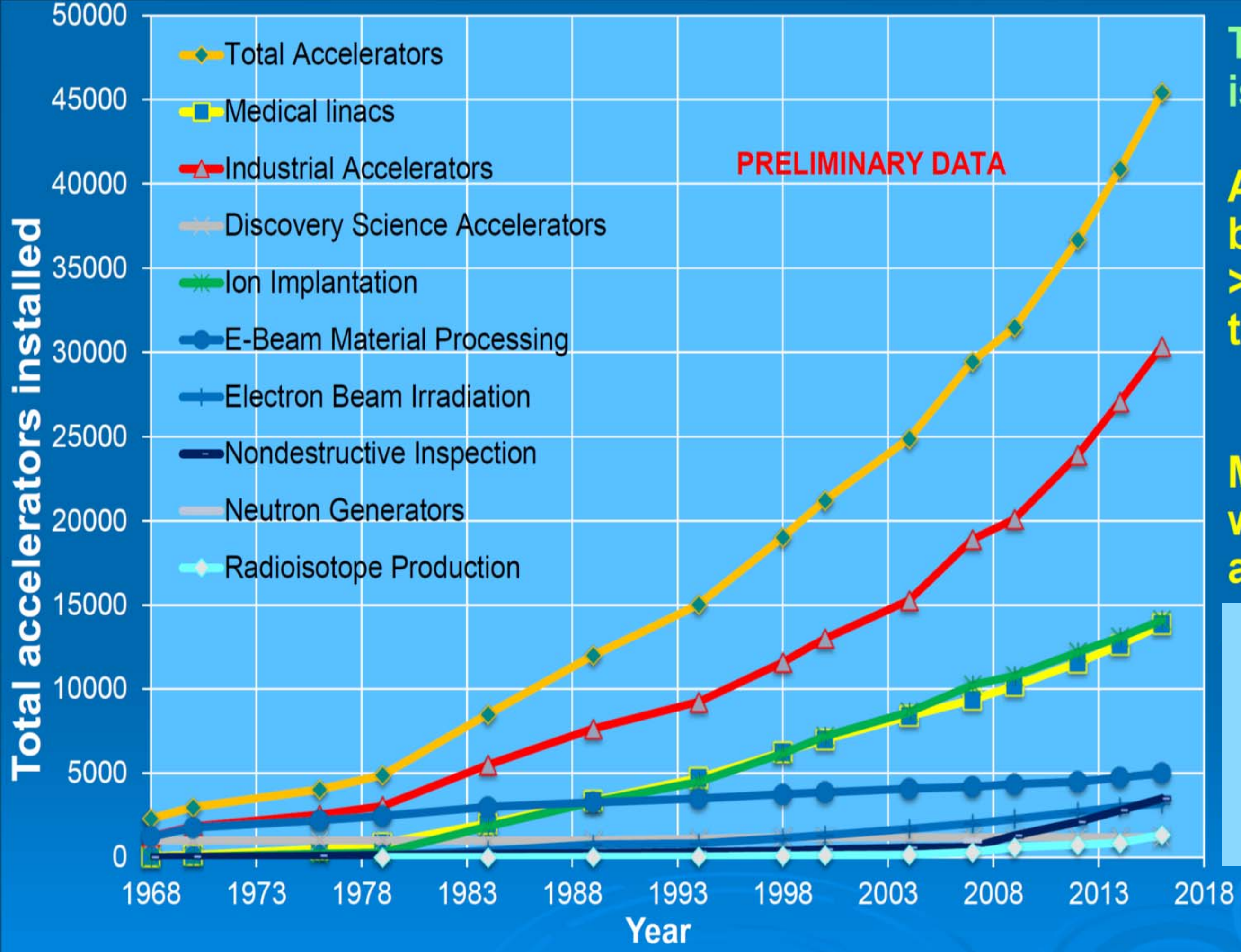
From Particle Physics Technologies…



… to Society

Particle Accelerators as a Business

64% accelerators in industry, **33%** for medical purposes, **3%** for basic science



Total sales of accelerators is ~US$5B annually

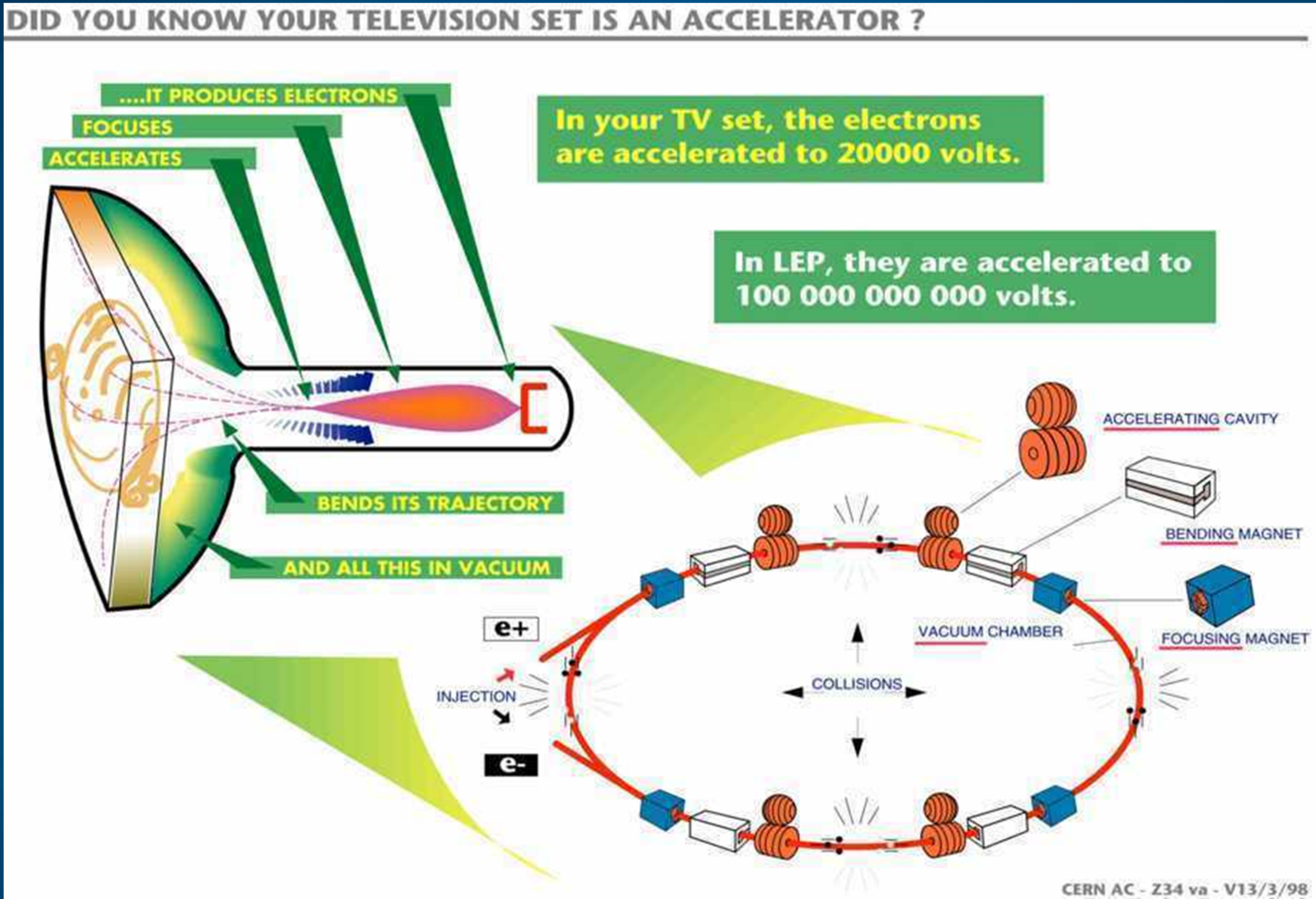
About 47,000 systems have been sold,
> 40,000 still in operation today

More than 100 vendors worldwide are in the accelerator business.

Accelerators are now involved in the creation of over **US$500B year** in products

R. Hamm, Accelerator-Industry Co-Innovation Workshop, Feb 6, 2018, Brussels, Belgium

What (the Hell) is the Accelerator?



Accelerators: Essential Tools in Industry

Market value US$2.2B

➢ **Exploitation of electron and ion beams**

❑ **Electron-beams (EB):**

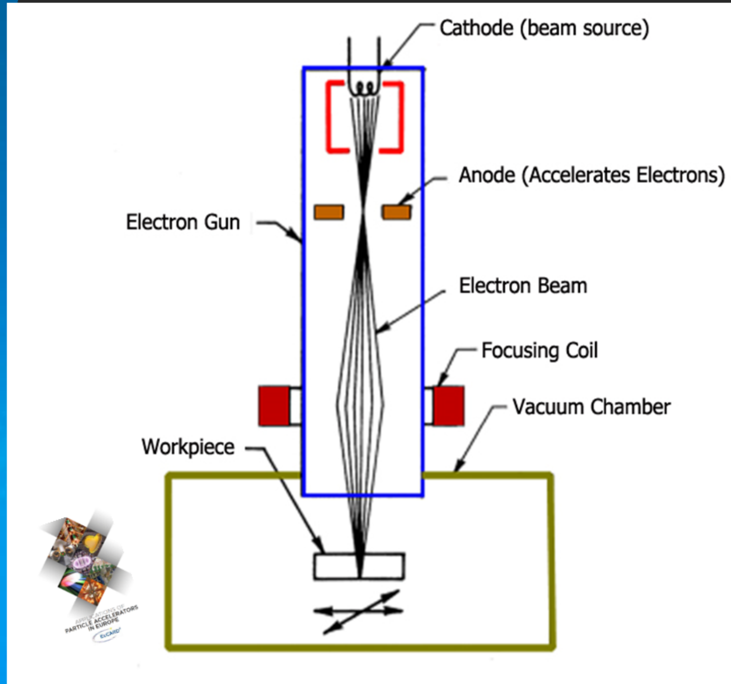
- VLE - Very low energy (<320 keV)
- LE - Low energy (320 keV – 10 MeV)

✓ The accelerated electrons interact with matter by ionizing atoms and/or exciting the atomic electrons

✓ This results in the emission of X-rays and secondary electrons together with the breaking of molecular bonds and heating up

✓ The VLE beam is used in one of the two configurations as:

EB gun – the simplest accelerator

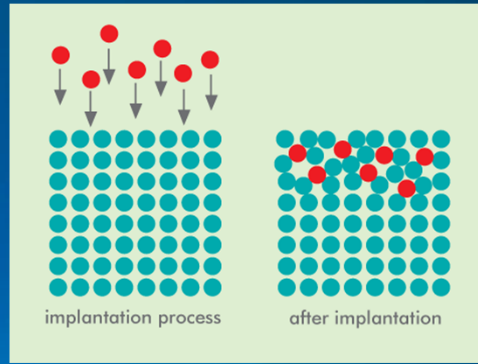


- **Non-thermal:** an expanded electron „shower" at the upper level of energy range (~>80 keV), but low power density – to change a material's chemistry under atmospheric conditions, and virtually no heating
- **Thermal:** a focused beam with a very high power density up to 10^8 W/cm^2, but lower level of the energy range, under vacuum conditions to heat up a material

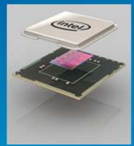
Accelerators in Industry: Non-Thermal Beams

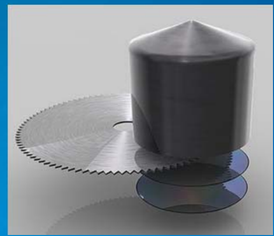
➢ Ion implantation

- over 11 000 (electrostatic) accelerators (< 1 MeV)



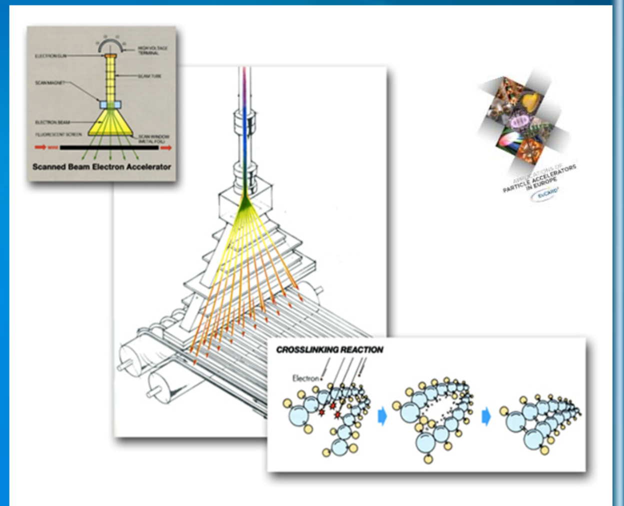
- ✓ Accelerators can precisely deposit ions modifying materials and their electric properties (boron, phosphorus…)
- ✓ Vast applications in:
  - semiconductors (CMOS,CCD…),
  - metals (hardening cutting tools,reducing friction, biomaterials for implants),





➢ Material processing

– 7500 electron accelerators (< 10 MeV)



- Modifying polymeric materials, polymerizing…
- Cross linking (the electrons brake molecular bonds, creating radicals i.e. molecules with unpaired electrons, which are highly reactive; the molecular bonds may stay permanently broken („cutting”) or, the radicals that are generated on one section of the polymer chain may react with another part of the chain, causing „cross linking”)
- Cross linking applications: insulating cables, pre-vulcanisation of automobile tyres (92% of them are treated this way)… → stability against heat, resistance to cracking, abrasion…

- Improve the color in gem stones; beam exposure changes crystal’s structure (e.g. colorless topaz → blue topaz)

Accelerators in Industry: Non-Thermal Beams

➢ **Sterilisation** - 3000 electron accelerators (< 10 MeV)

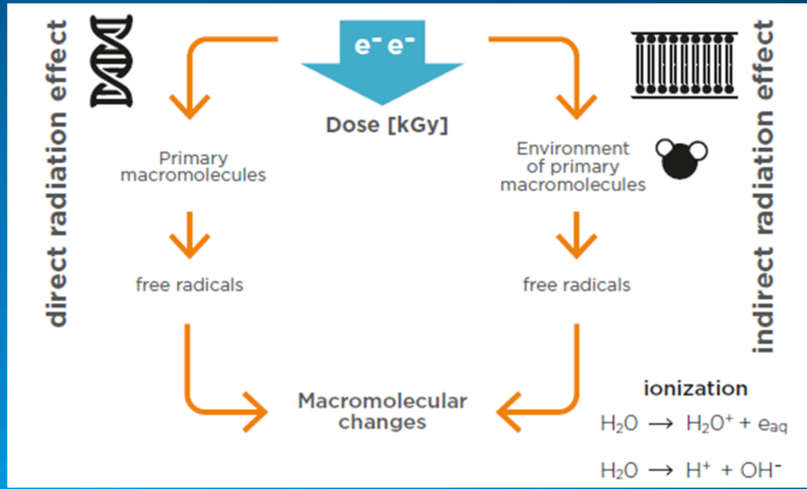
✓ **Medical disposables, surgical instruments, medical implants, pharmaceutical packages…**

- killing the germs without altering the material itself

- mechanism: breaking of molecular bonds associated with the water and DNA in microbial cells

(+) takes only a few seconds (gamma irradiation – hours)

(-) limited penetration depth; works best on simple, low-density products



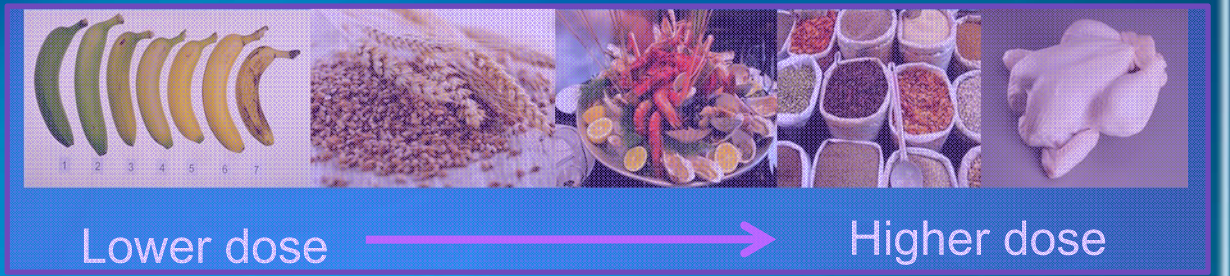
sterilizer

The IBA rhodotron – a commercial accelerator used for e-beam sterilisation

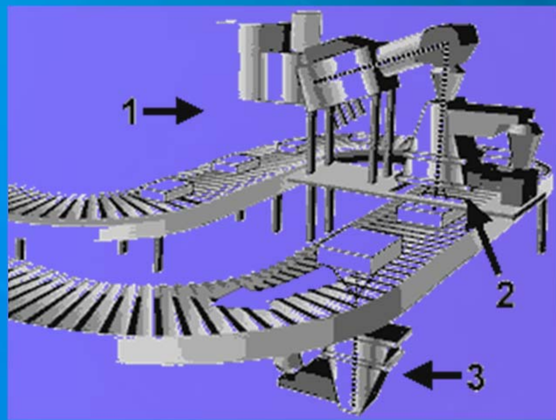
Accelerators in Industry: Non-Thermal Beams

➢ **Food irradiation** („cold” or „electronic „ pasteurisation)

- ✓ (20-30) % of food harvested never even reaches the first processing step, because it is lost to rotting and insect infestation
- ✓ irradiation kills pathongens in the environment-friendly, purely-physical way
- ✓ Few examples:



- ✓ Seed treatment
  - by precisely adjusting the electron-beam energy, contamination on the seed surface can be treated without damaging the DNA of the seed grain



- ✓ The disinfection of grains, nuts, spices….
- ✓ The main limitation is regulatory
- ✓ The words „irradiated” or „treated with ionising radiation” must appear on the label packaging

More than **400 B€** of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

Accelerators in Industry: Thermal Beams

✓ Melting and evaporation

- Mainly melting/re-meting of metals, to produce high purity metals (Ti, Nb) and alloys (e.g. nickel based ones)
- Material is melted, impurities outgassed/separated → re-melting
- Applications for the aerospace and power-plant industries
- Typical power densities of 10^6 W/cm^2
- Molten materials can be evaporated by overheating under vacuum conditions and then condensed onto a surface for layer deposition (PVD – Physical Layer Deposition)

A re-melting furnace of ALD Vacuum Technolgies

✓ Electron Beam Welding (EBW) and joining

- With EBW the energy put into a workpiece concentrated and influences the material only in a very restricted region
- → weld deformations are avoided

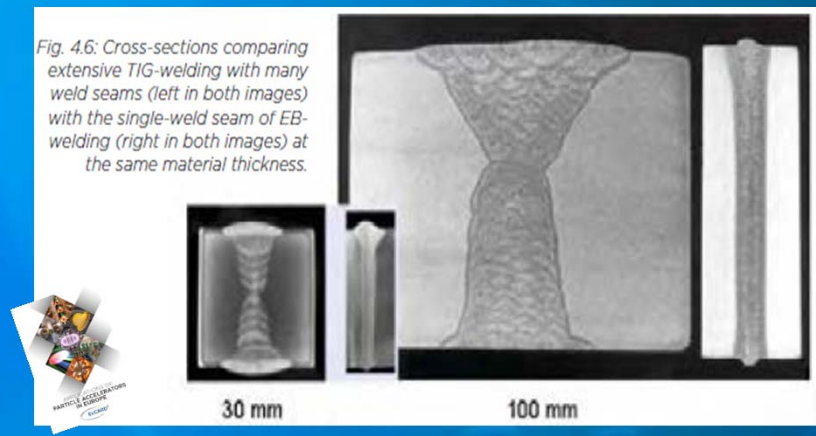


Fig. 4.6: Cross-sections comparing extensive TIG-welding with many weld seams (left in both images) with the single-weld seam of EB-welding (right in both images) at the same material thickness.

- The EBW can be used for deep welds without the need for grooves
- It works without any filler material

Accelerators in Industry: Micro-Machining

- **A high-energy (MeV)proton beam can be employed to scan a deep, sub-micrometre pattern over a suitable resist material**
- The proton beam, interacting with matter, follows an almost straight path
- Thus, smooth 3D features can be directly written into resist materials with very sharply defined lines (aspect ratio of almost 40)
- Proton-beam writing is able to define „large" 3D structures in silicon at a **spatial resolution limited only by the proton beam-spot size, and which can approach 20 nm**

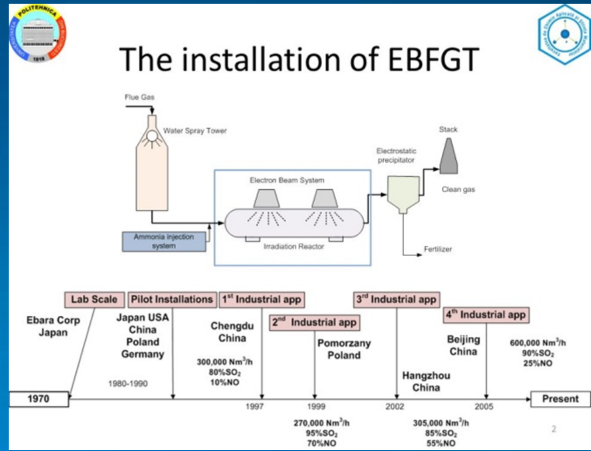
Fig. 4.26: In this micro-machined Stonehenge-like structure, which is 80 micrometres in diameter, the horizontal 'stones' are fabricated by a beam of 500-keV protons (range in silicon about 6 micrometres) and the vertical 'stones' by 2-MeV protons (range about 48 micrometres). (Reproduced from F. Watt et al., Materials Today, 2007, ***10****, 20.)*

Accelerators in Industry: Environmental Applications

✓ **Flue gas treatment**

- E-Beam Flue-Gas Treatment (EBFGT)
  - dry scrubbing process that removes SO_2 and NO_x pollutants simultaneously

- No waste products are generated apart from a byproduct, which is a good fertilised component



- Pomorzany power plant (Szczecin, Poland)

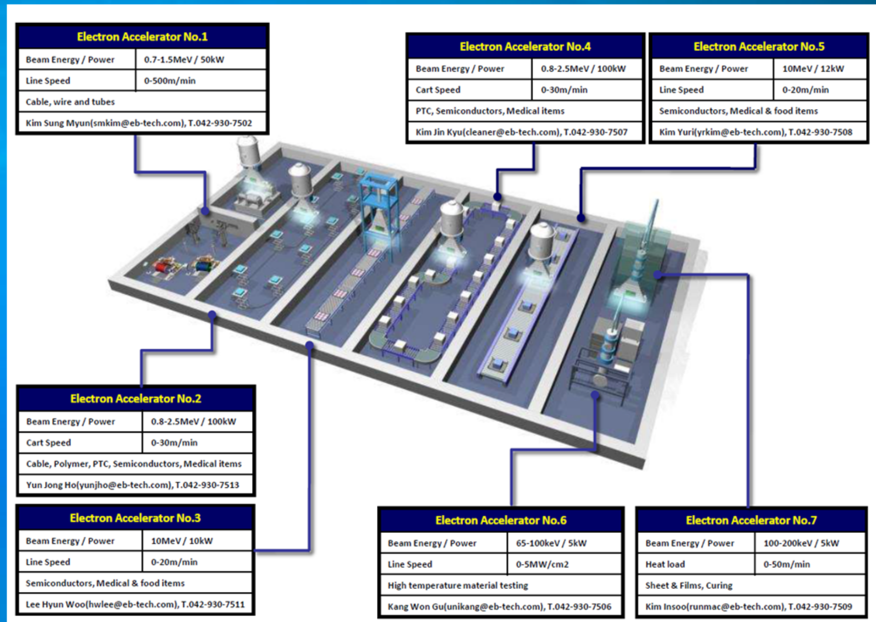
✓ **Treatment of waste-water and sewage**

- The current liquid waste loads exceed the self-purification capacity of receiving streams…

- A high-power e^- accelerator (1 MeV, 400kW) was applied in Sth Korea; it treats up to 10 000 m^3/day of waste water from textile-dyeing

- The e-beam is also applicable to sludge, breaking log-chain organic molecules

- The irradiated sludge is 99.99% pathogen free and can be used as manure in agriculture

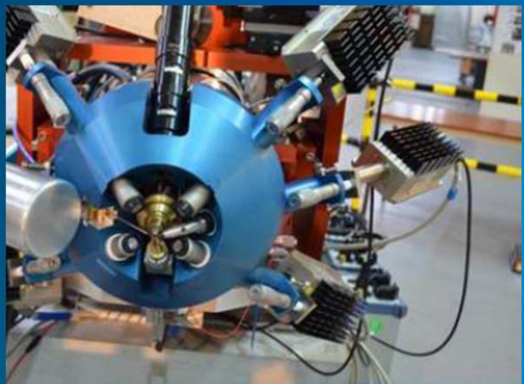


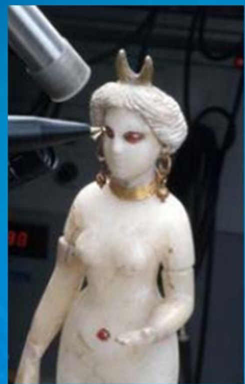
Bumsoo Han /EB TECH Co., Ltd

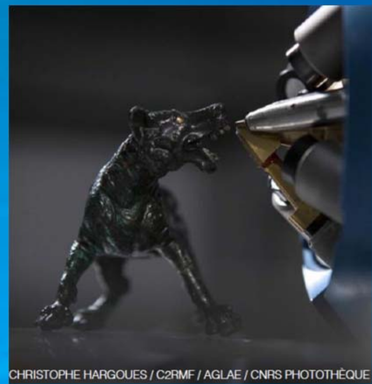
Accelerators for Cultural Heritage

AGLAE – Accelerateur Grand Louvre d'analyse elementaire

- The accelerator 15m under Louvre
- Beam time for more than 1200 French museums
- Uses IBA (Ion Beam Analysis); PIXE,PIGE, Rutherford Backscattering Spectroscopy (RBS)…







- Studies of museum artefacts:
  - How old is it ?
    → production centres, workshops…
  - How was it made ?
    → making process and technique history…
  - Where does it come from ?
    → provenance, trade routes…
  - Is it a fake ?
    → authenticacation…
  - Why is it degraded ?
    → degradation mechanism…
  - Will the restoration process be worse than doing nothing ?

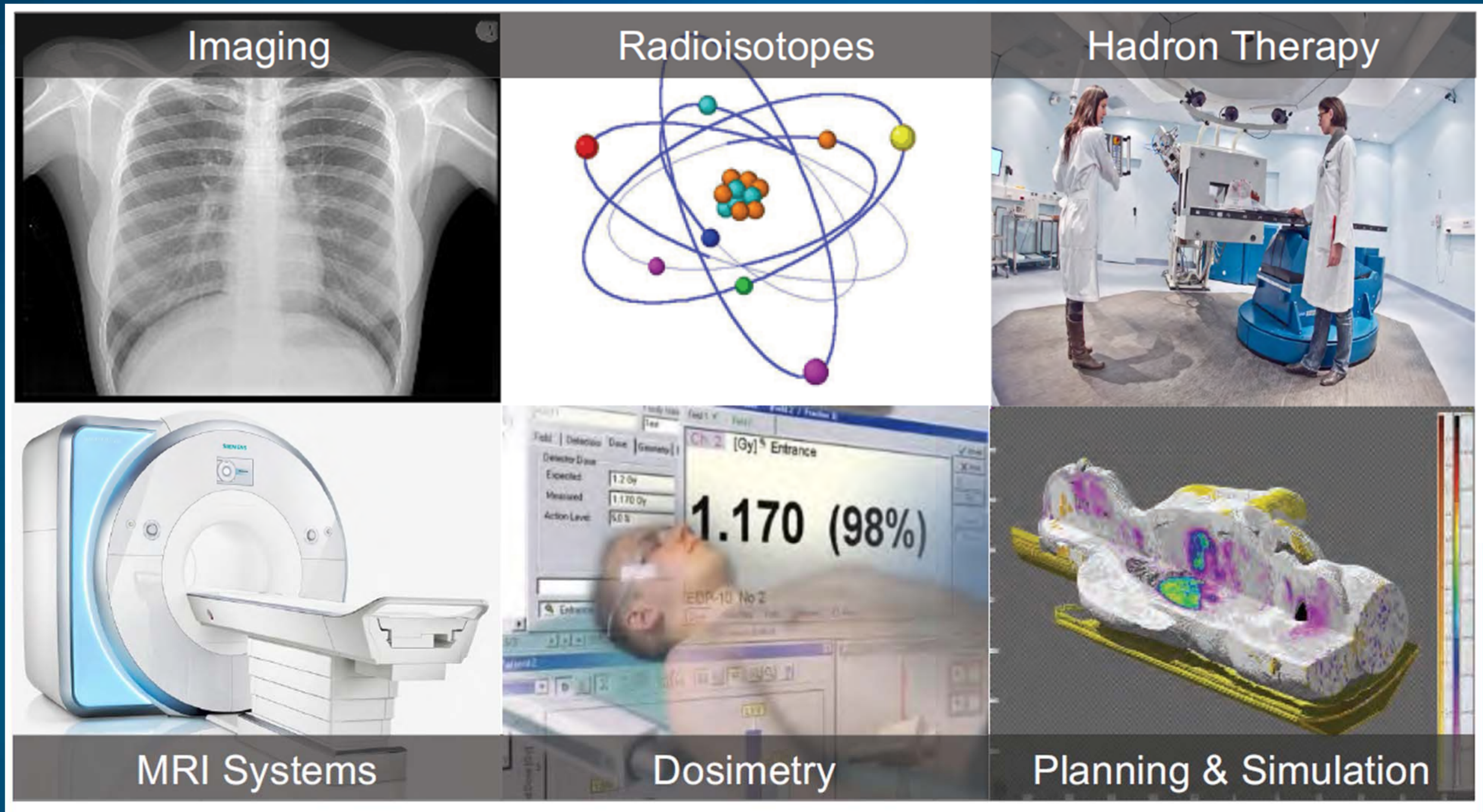
Accelerators for Cultural Heritage

Length 2m; weight: 300 kg, fully movable;

Host location: Laboratories of the *Opificio delle Pietre Dure (OPD) in Florence*

- ✓ **Accelerators harnessed for the protection of books, archives and artefacts from destruction caused by insects and microorganisms (electron beams)**

Medical Applications of Particle Physics

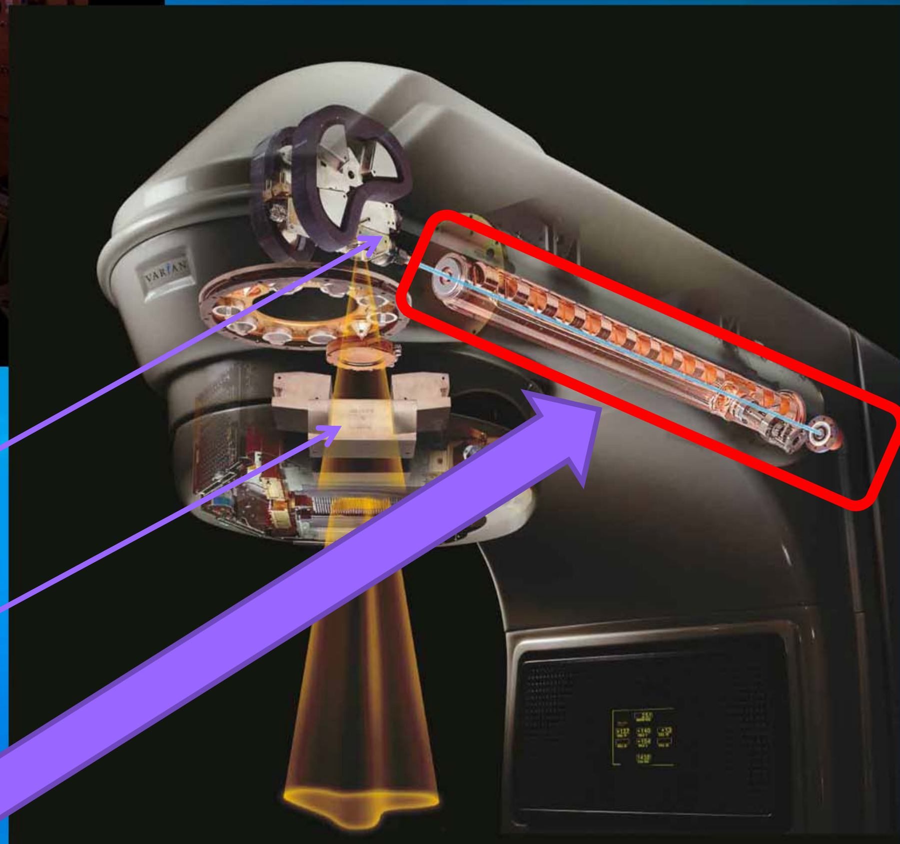


LCWS 2016, Morioka --- M. Demarteau

(almost) omitted due to the local know-how and lack of time

Accelerators for Medical Purposes

Manuela Cirilli JENAS 2019



Target (tungsten)
to produce x-rays

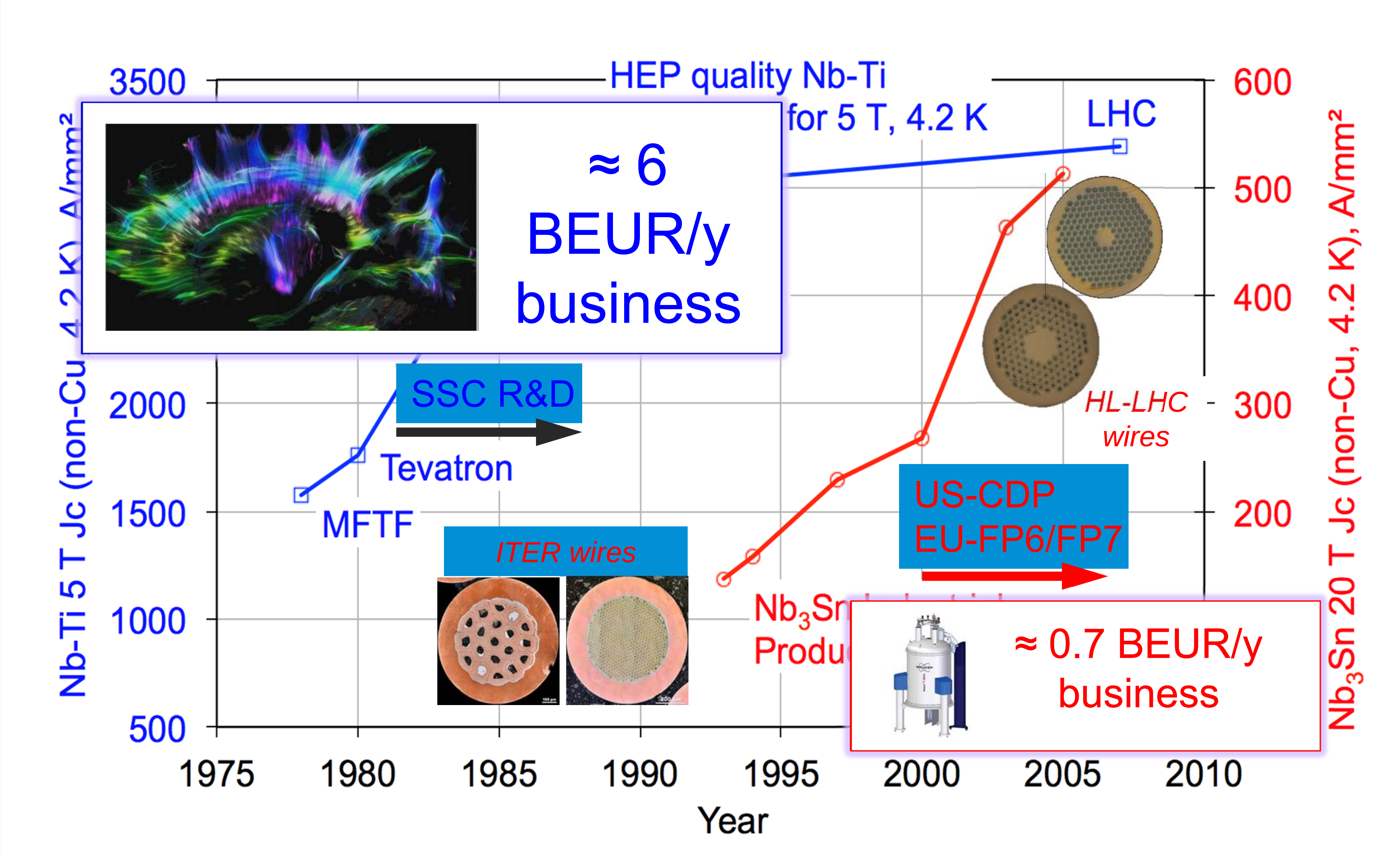
Collimation system

Linac
e^- beam
(4-20) MeV

Image: copyright Varian medical systems

Suzie Sheehy PECFA session Nov. 2015

On the Unreasonable Request of High J_c ...

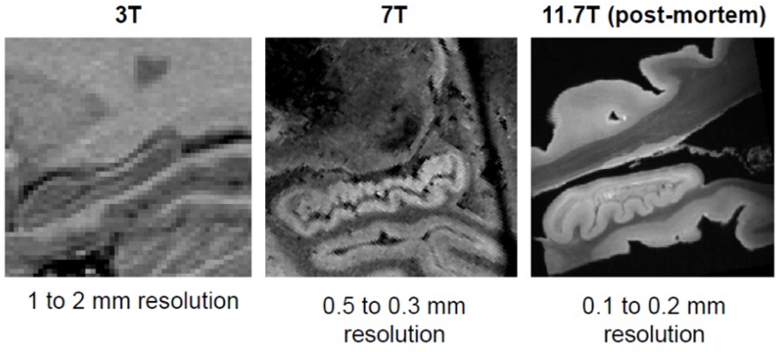


HL-LHC → HE-LHC → FCC accelerators

On the Unreasonable Request of High J_c …

✓ The number of Teslas matters…

Example of a human hippocampus image - Courtesy Neurospin/CEA



Cooperation Saint-Aubin/Saclay; Aim to push a.f.a.p. the limits of Magnetic resonance Imaging (MRI); **Neurospin** facility opened in CEA Saclay in 2007

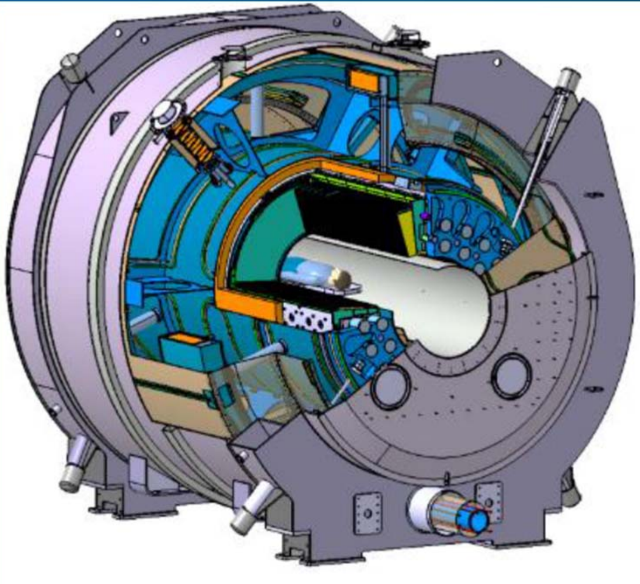
A very tight specification:
- **B0 / Aperture 11.72T (500 MHz for proton resonance)**
- **Aperture 900mm**
- **Field stability 0.05 ppm/h**

Innovative solutions for a MRI magnet
- **170 NbTi double pancakes** for the main coil
- **2 NbTi shielding coils** to reduce the fringe field
- Cryostat for **superfluid helium at 1.8 K**, 1.25 bars
- **Dedicated cryorefrigerator** (80 l/h + 40 W @ 4.2 K)
- **Driven mode operation**, with two 1500 A power supplies

11.72T – JULY 18TH 2019

The ISEULT magnet

- 180 km of Nb-Ti SC wires
- Wires wound in double pancake coils
- 5000 liters of superfluid He as coolant

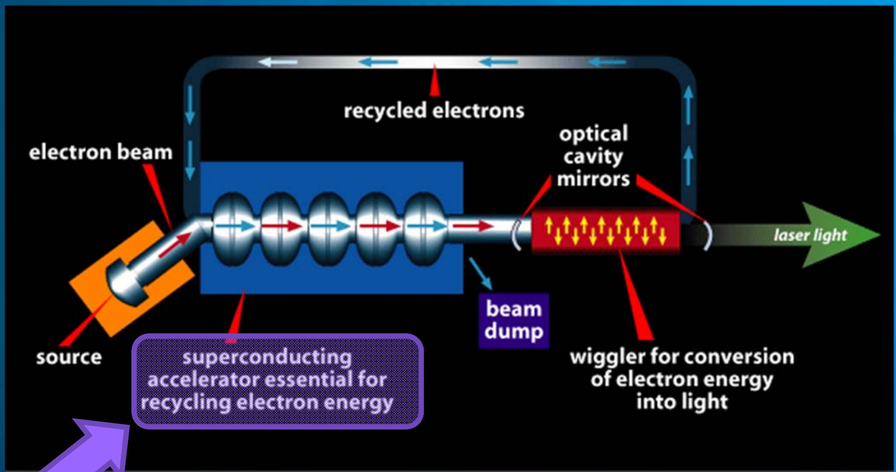


11.7 T magnet section : in orange the windings, in blue the mechanical structure at 1.8 K and in violet the cryostat

- The ISEULT is capable of scanning the patient's entire body
- Will enable a deeper understanding of the brain by improving the images by a factor of 10

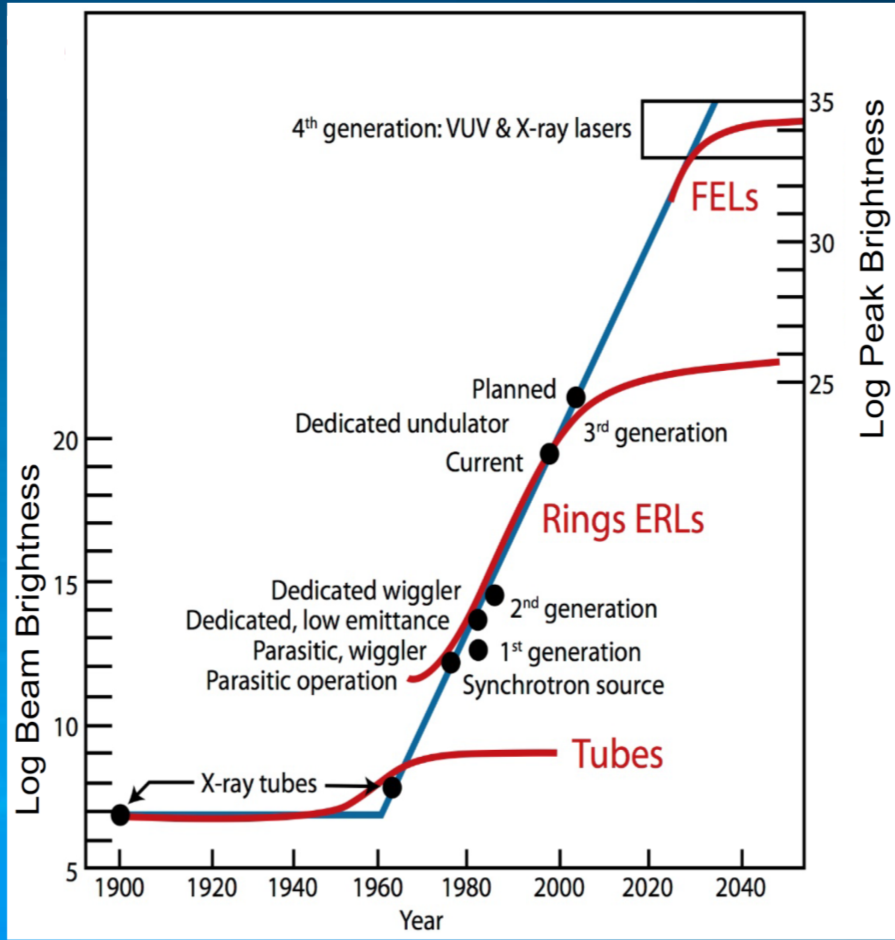
Light Sources

- X-ray tubes
- Storage rings
- Free Electron Lasers (FELs)



https://www.jlab.org/FEL/feldescrip.html

- ...



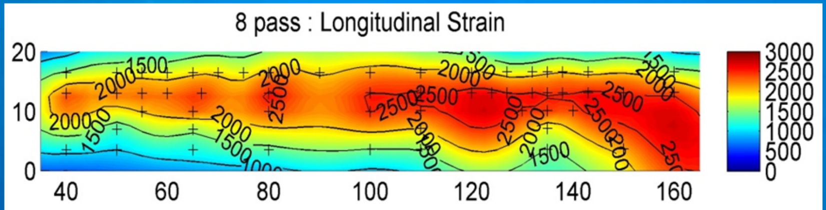
(almost) omitted due to the local know-how and lack of time

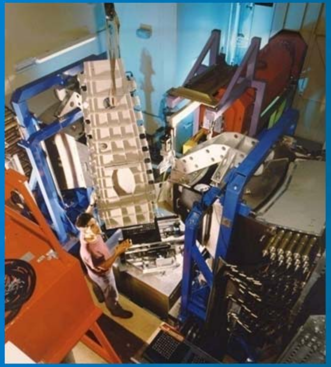
Neutron Spallation Sources

https://youtu.be/VESMU7JfVHU?t=21

'Neutrons tell you where atoms ***are*** and what atoms ***do***'

- Neutrons attraverse the material and are detected when they come out
- The directions in which the neutron emerge tell us about the arrangement of the atoms inside – „neutron diffraction method"
- The amount of energy lost by the neutrons as they travel through the material tells us about the atomic dynamics – „neutron spectroscopy"
- Example: stresses in Airbus A380 wing





(almost) omitted due to the local know-how and lack of time

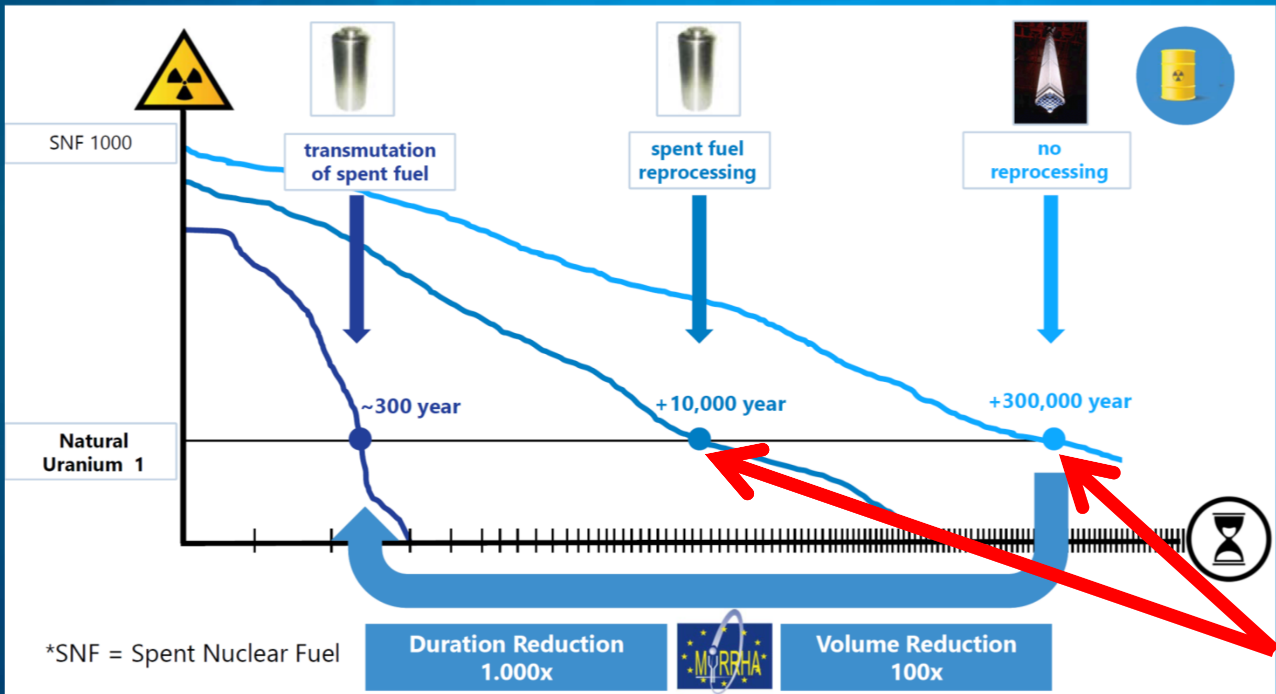
Accelerator Driven Subcricital Reactors (ADSRs)

➢ Transmutation of nuclear waste isotopes or energy generation

- The nuclear electricity is currently produced in pressurised water reactors (PWRs) or boiling water reactors (BWRs), both based on a fission chain reaction induced by **slow neutrons**
- The fission by slow neutrons in PWRs and BWRs is always in competition with the neutron capture by actinides (also present in the fuel)

- Instead of fission, this proces yields so called **MAs – minor actinides**, which are typically long-lived and highly radio-toxic (neptunium, americium, curium…)
- Only the US nuclear industry generates over 2000 tons of nucluear wastes annually; MAs – 1% of them)

1 The urgent need for the efficient method for transmutation of MAs



https://satisfactory.gamepedia.com/Nuclear_Waste

unacceptable

Accelerator Driven Subcricital Reactors (ADSRs)

- If the MAs are bombarded with **fast neutrons**, fission becomes the dominant proces
- → in this way MAs can be transmuted into fission products tht are radioactive isotopes in the medium mass range → the associated cooling time of „only 300 years" - **acceptable**

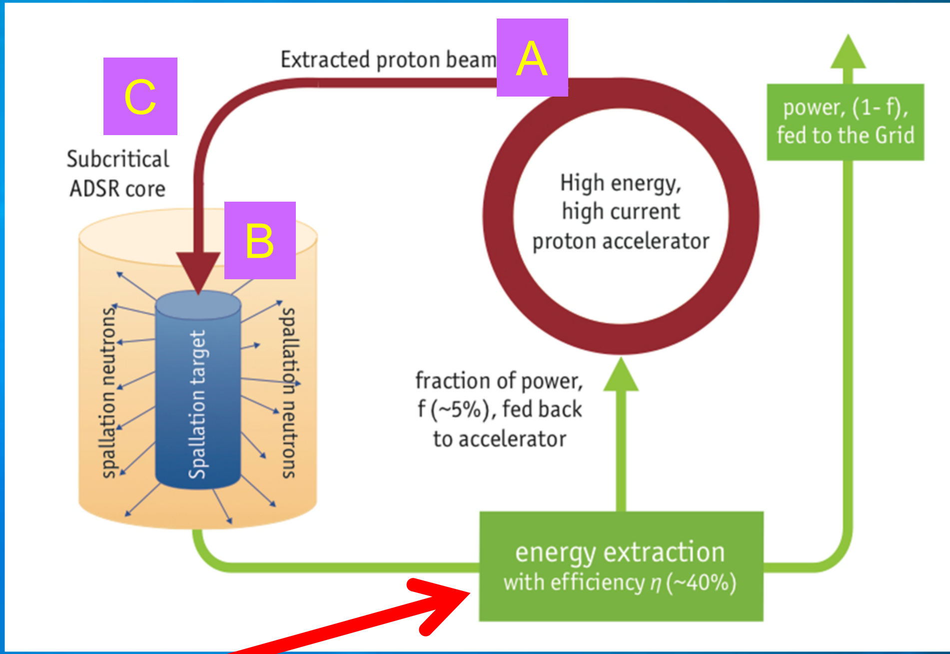
2 For an efficient transmutation of MAs a fast-neutron system is crucial

3 The incineration of MAs must be safe

- In an subcritical reactor (k < 1), MAs can be loaded safefy up to 40% of the core content
- k < 1 → the fission is not sustained on its own → Use **accelerator** to supply extra FAST neutrons
- → The incineration of MAs is safe
  – in danger just turn off the accelerator

(1 & 2 & 3) + particle accelerator =
= Accelerator Driven Subcritical Reactor (ADSR)

A – proton accelerator & beam
B – spallation target (MAs)
C – subcritical reactor core



➢ ADSRs are NOT constructed for electricity production (although power is an available byproduct)

Accelerator Driven Subcricital Reactors (ADSRs)

MYRRHA – Multi-purpose hYbrid Research Reactor for High-tech Applications

High power proton beam (up to 2.4 MW)

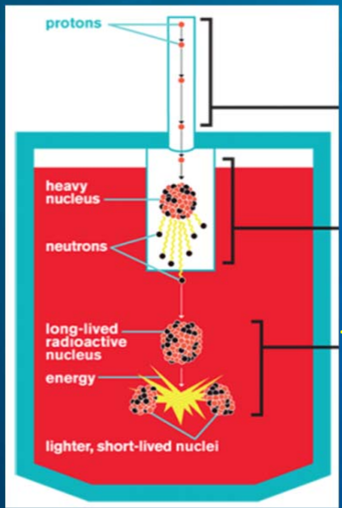
Proton energy	600 MeV
Beam current	0.1 to 4.0 mA
Repetition rate	CW, 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
Beam footprint on reactor window	Circular ∅85mm
Beam footprint stability	< ± 10% on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

Extreme reliability level: MTBF > 250 hrs

SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

CW – continuous wave beam (instead of bunch structure)

Commissioning by 2033



https://www.symmetrymagazine.org/article/february-2012/taking-the-heat-out-of-nuclear-waste

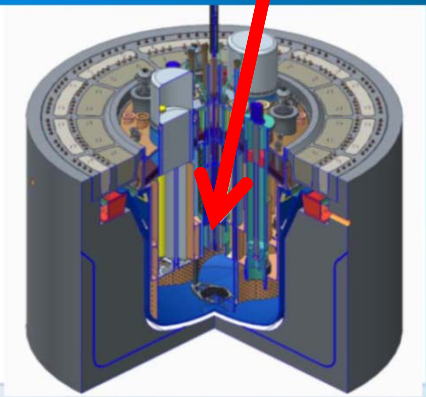
Accelerator

Spallation target

Transmutation

Target	
main reaction	spallation
output	$2 \cdot 10^{17}$ n/s
material	LBE (coolant)

Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast
coolant	LBE Lead Bismuth Eutectic (liquid)



Finally, Just One More Application…. detecting wine fraud

How Wine Fraud Is Destroying the Rare Wine Business

Wine experts recently gathered in New York City to talk about wine fraud. Eater NY wine editor Levi Dalton was on the scene.

by Levi Dalton | Oct 14, 2014, 1:39pm EDT

https://www.eater.com/2014/10/14/6974265/how-wine-fraud-is-destroying-the-business-of-selling-rare-bottles

- 2015 – Rudy Kurniawan – fined $48 millions and sentenced to 10 years in jail
- His crime making and selling countefeit wine (refilling bottles in his kitchen)

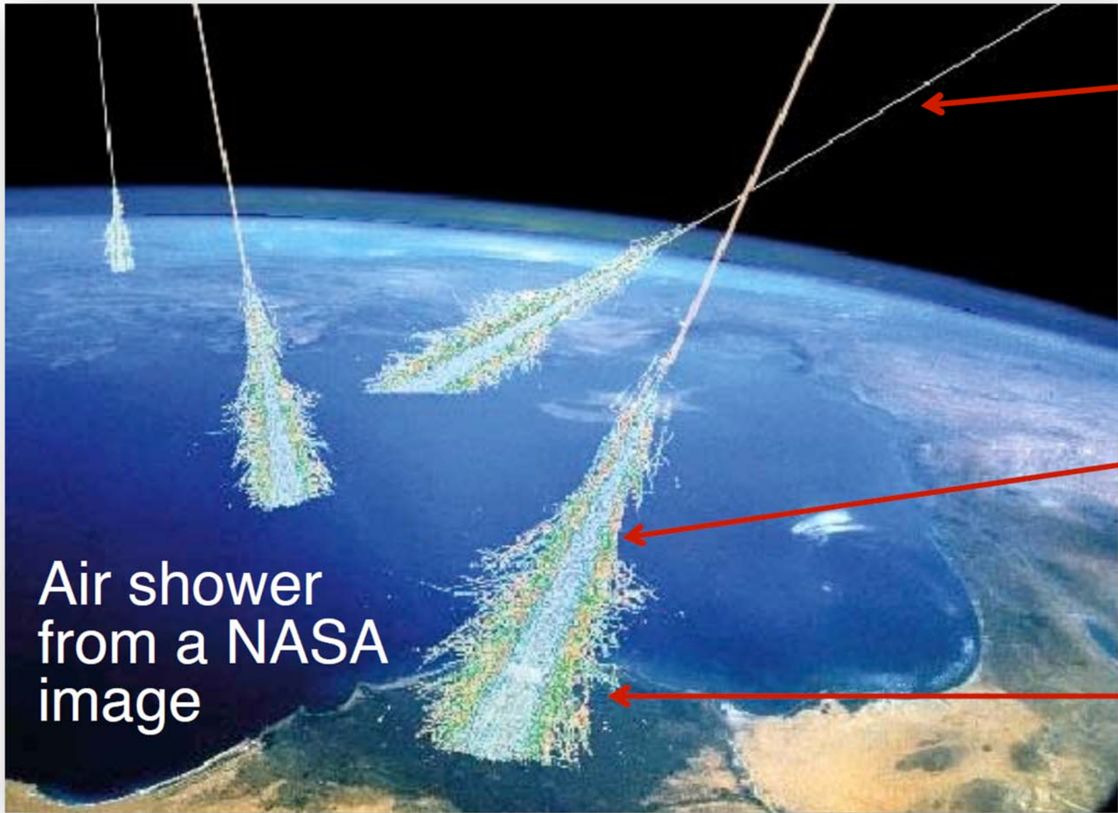
Accelerator Mass Spectrometry (AMS) using a cyclotron or a tandem van de Graaf setup

- The direct ^{14}C dating using accelerated negative ions of graphite.
- The sample (wine) is converted to graphite and ionized negatively by bombarding it with Cesium ions (important since ^{14}N does not form a negative ions)

- The beam of „wine" i.e. of „graphite negative ions" is accelerated and subjected to the separation in magnetic and electric fields
- → ^{14}C atoms are counted

- The AMS method: 10^3-10^4 more sensitive than decay counting;
- moreover the measurement time is drastically reduced.

Muons from the Cosmic Accelerator



Primary cosmic rays
99% are **hydrogen and helium** nuclei from the sun

Air shower.
Particle cascade: it originates from the interaction of the cosmic ray with the atmosphere

Sea-level cosmic rays.
At sea level most of the surviving rays are ***muons*** **(μ)**

EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017
Germano Bonomi

The flux:

✓ 10 000 cosmic rays/minute/m² hit the ground
– one of them cross our hand every second

✓ At sea level, most cosmic rays ARE MUONS, with mean energy of (3-4) GeV

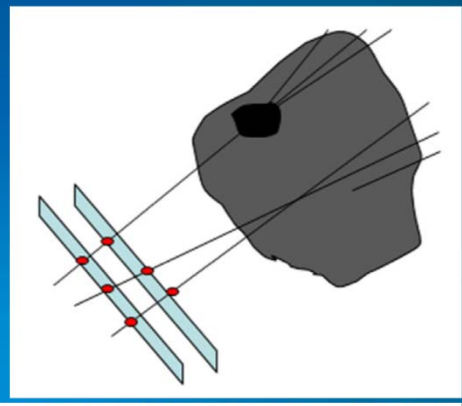
Interaction of Muons with Matter

✓ **Muons can pass through hundreds of meters of solid material before they are absorbed**

✓ **Two major kinds of interactions with matter:**

1. Energy loss (slow down or absorption)

„muon radiography"



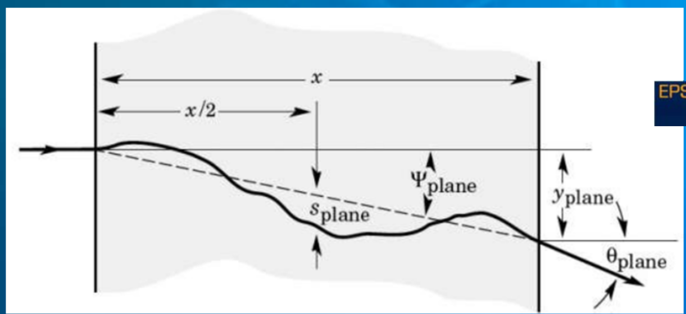
Nuclear Inst. and Methods in Physics Research, A 878 (2018) 169–179

- Excitation or ionization of the medium

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$

- Bremsstrahlung (emission of photons) – only at very high energies

2. Trajectory deviation (multiple Coulomb scattering)

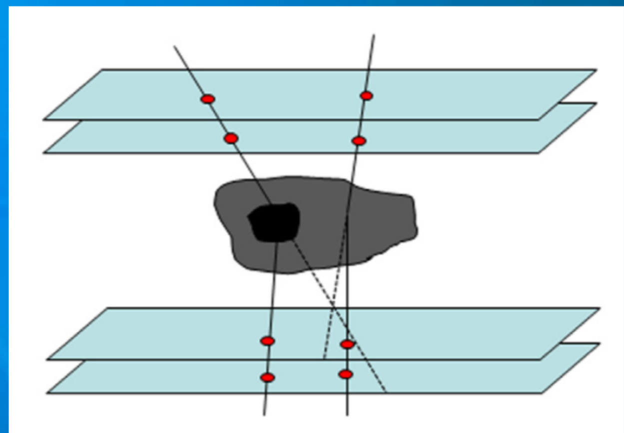


Germano Bonomi

EPS Conference on High Energy Physics
Venice, Italy 5-12 July 2017

✓ Valid only for modest opacity – the diffusion centre reconstruction is irrelevant when multiple diffusions occur

„muon tomography"



Nuclear Inst. and Methods in Physics Research, A 878 (2018) 169–179

Detection Techniques of Muons

1. **Plastic scintillators** – use the light created by de-excitation of atoms interacting with the incoming muons; photons are collected, converted into electrons which are then amplified in a photo-multiplier or Silicon PM; very robust, easy to built, relatively cheap, practically insentitive to environmental conditions; detection efficiency close to 100%; the main drawback – spatial resolution

2. **Nuclear emulsion plates** – reconstruct the muon trajectory in 3D and with a high granularity, resulting in a sub-micron resolution; the data analysis can take place after the exposure and is preceded by a time consuming, automatic scanning to reconstruct the tracks and form the final image (Hyper Track Selector from Nagoya University); no time information is recorded by the plates which only accumulate the muons during the whole exposure, preventing from any dynamical monitoring of the structure

3. **Gaseous detectors** – can achieve resolutions of a few hundreds of microns (10x better than scintillators), at still a reasonable cost; they allow for dynamical studies, thus combining the advantages of 1) and 2); TPCs are also being developed as the ultimate instrument for muography

Muon Radiography & and Giza's Great Pyramid

- **Idea: use the information about muon absorption to measure the thickness of the material crossed by the muon themselves**

- The first ever civil application of the cosmic rays to inspect large volumes dates back to 1955: determination of the thickness of rock above an underground tunnel (E.P.George, „Cosmic rays measure overburden of tunnel" Commonwealth Engineer, (1955), 455)

- The first ever radiography - of Giza's Great Pyramid (also known as Cheops's or Khufu's or Chevren's - 2500 BC) by L.W. Alvarez et al., (Science 167 (1970) 832) in search for hidden chambers – null result; detection of muons in spark-chambers (digital readout)

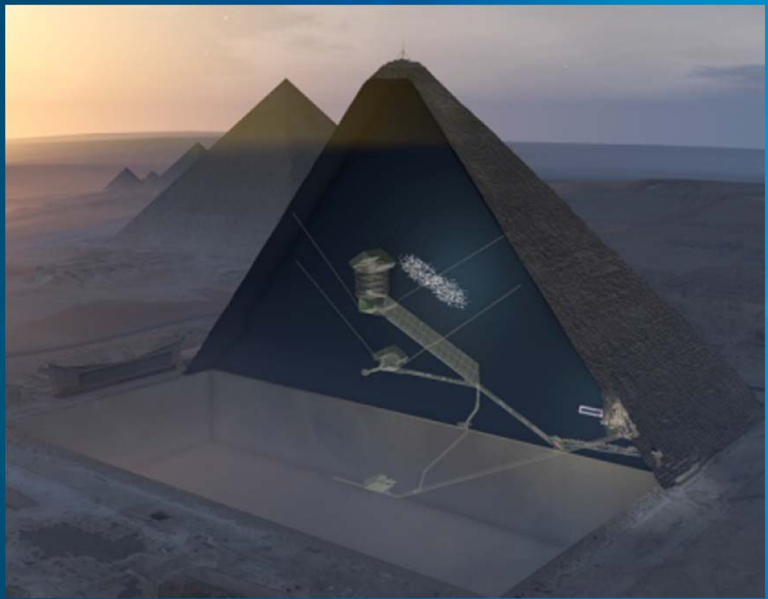
Muon Radiography & and Giza's Great Pyramid

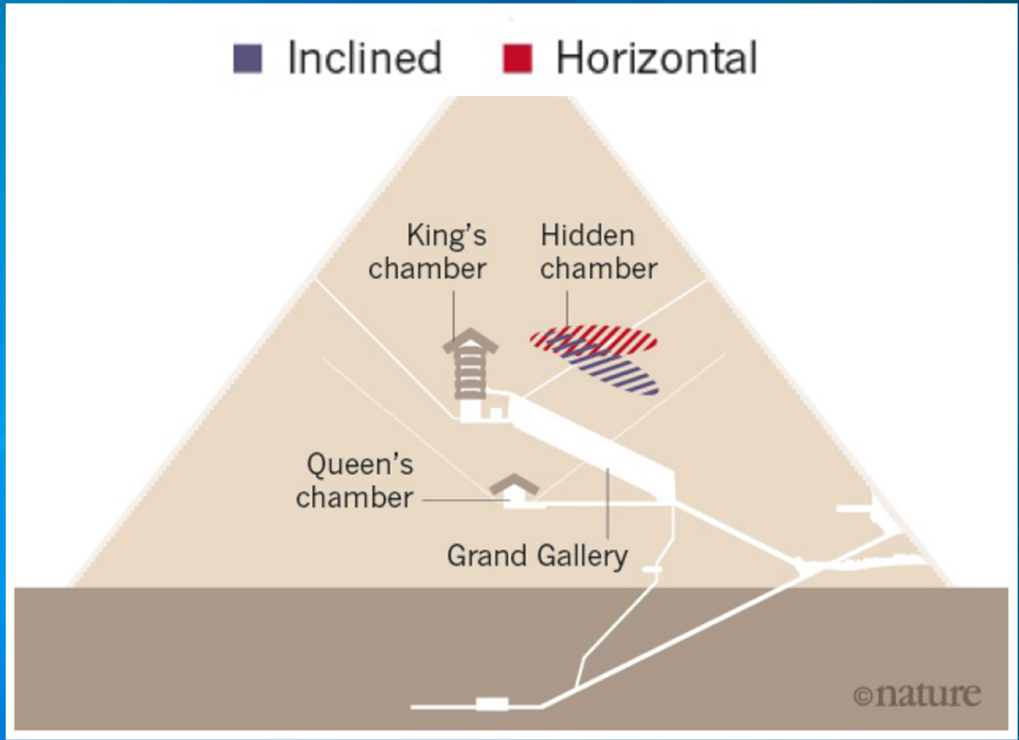
- **The second radiography of Giza's Great Pyramid in 2017**

  K.Morishima et al., http://dx.doi.org/10.1038/nature24647 (2017)

- **Observation of a secret, hidden chamber – 30 m long void**

- Two possible orientations of void:

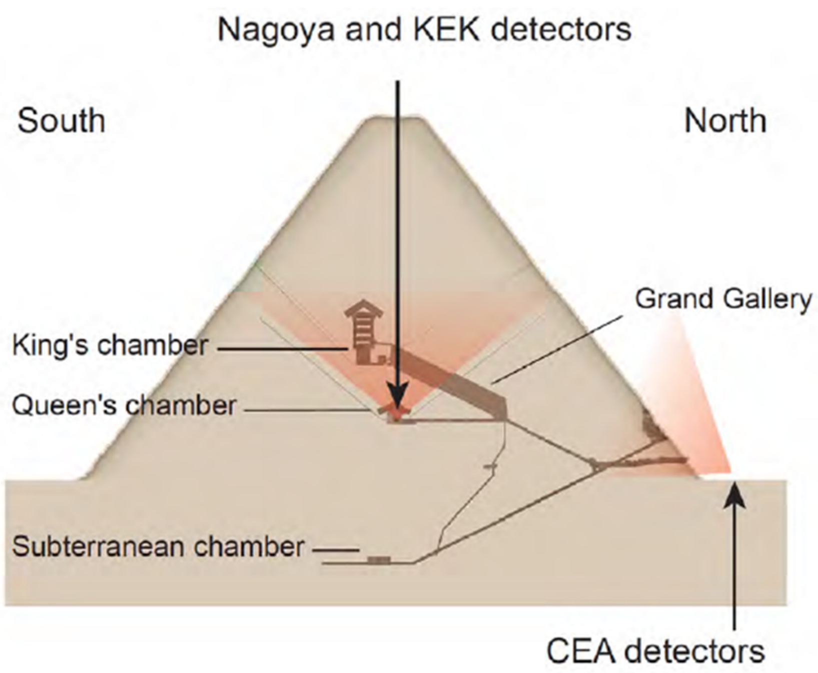




The birth of **„muography"** – usage of cosmic muons to probe the innards of dense structures – thus building a 3D profile of the density of the interior

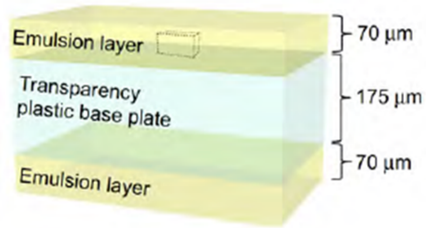
Tomography with Cosmic Ray Muons (selected)

Three different particle physics detector technologies have been harnessed

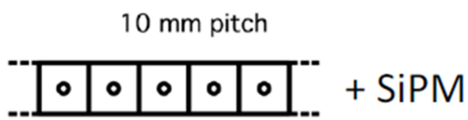


https://www.nytimes.com/2017/11/02/science/pyramids-giza-void.html
Nature: doi:10.1038/nature24647

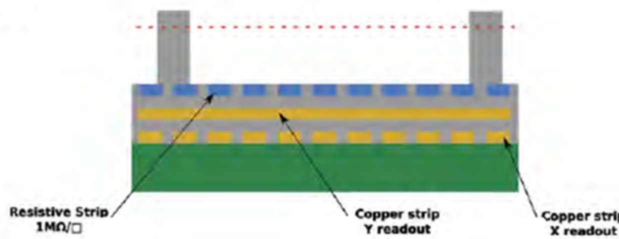
Emulsions (Nagoya)



Scintillator Strips (KEK)



Micromegas (CEA)



Similar study: Arturo Menchaca et al. (2011): usage of MWPCs to reconstruct the internal structure of the Mexicana Pyramid of the Sun at Teotichuacan (3 years of data taking)

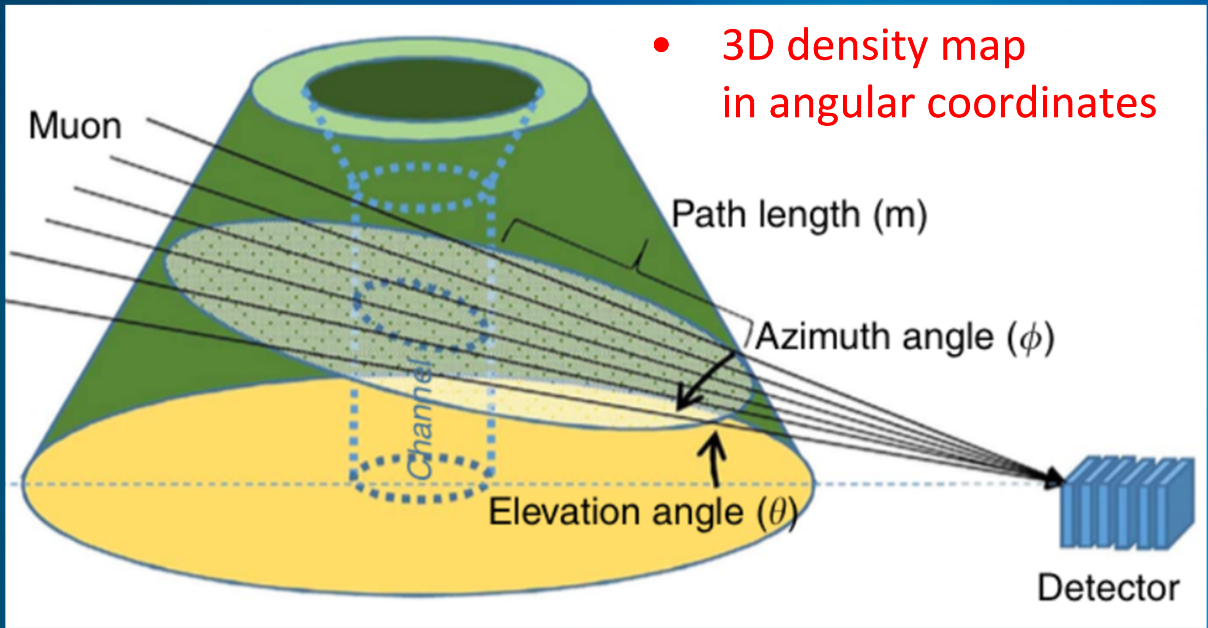
Tomography with Cosmic Ray Muons (selected)

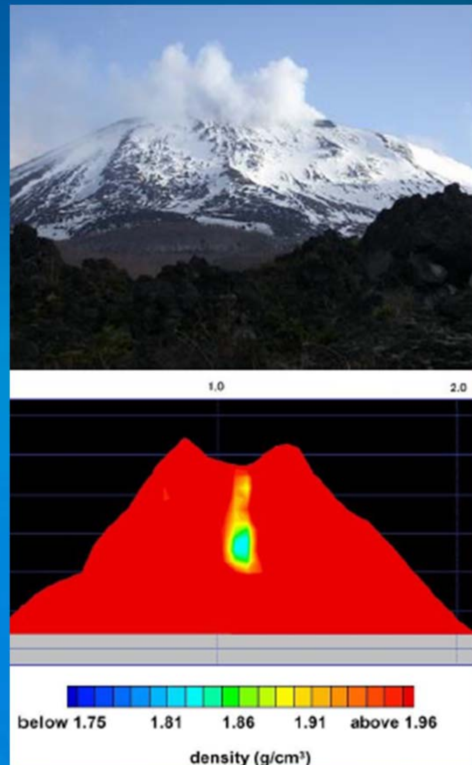
The lesson:

refinement of particle physics detectors can lead to new exciting discoveries

Muon Radiography of Vulcanoes

- **Mapping lava channels, which absorb less energy from muons than does the dense surrounding rock**
- Ambitious goal: contribute significantly in forecasting the eruptions



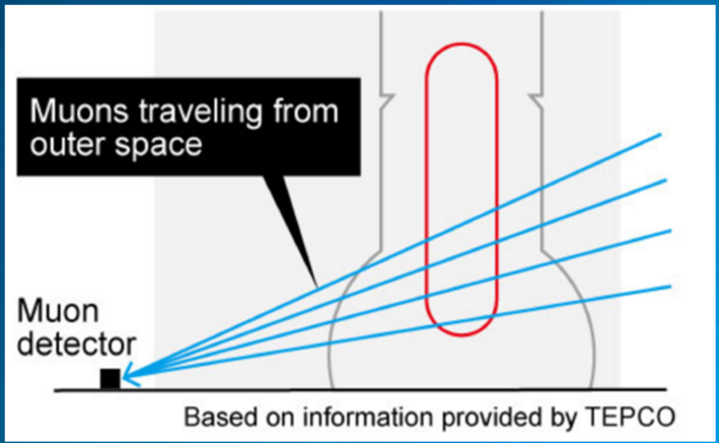


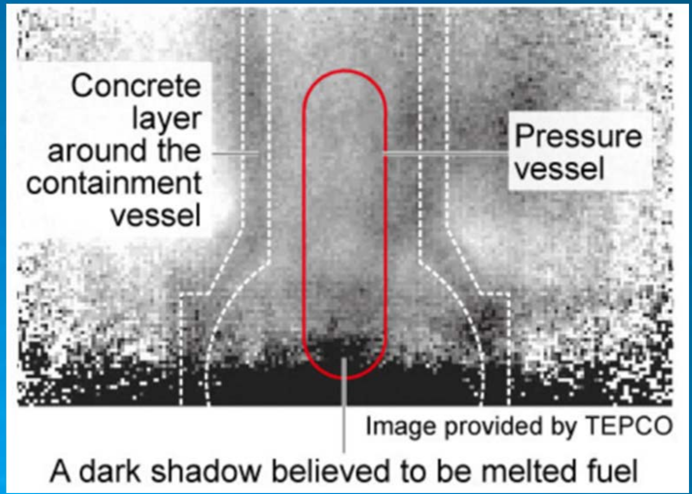
- Studies in Japan, France and Italy
- The recent example: studies of Stromboli in 2011: Scientific Reports 9, No 6695 (2019); detectors: emulsions of 0.96 m^2 area

K. Nagamine et al., "Method of probing inner-structure of geophysical substance with the horizontal cosmic ray muons and possible application to volcanic eruption prediction", Nucl. Inst. Meth. A 356 (1995), 585.
L. Oláh et al., "Cosmic Muon Detection for Geophysical Applications", Advances in High Energy Physics Volume 2013, Article ID 560192

Muon Radiography of the Fukushima Damaged Unit 3

- The Unit 3 has melted and dropped into the primary containment vessel
- **Nuclear materials such as uranium and plutonium are very dense and are therefore relatively easy to identify**





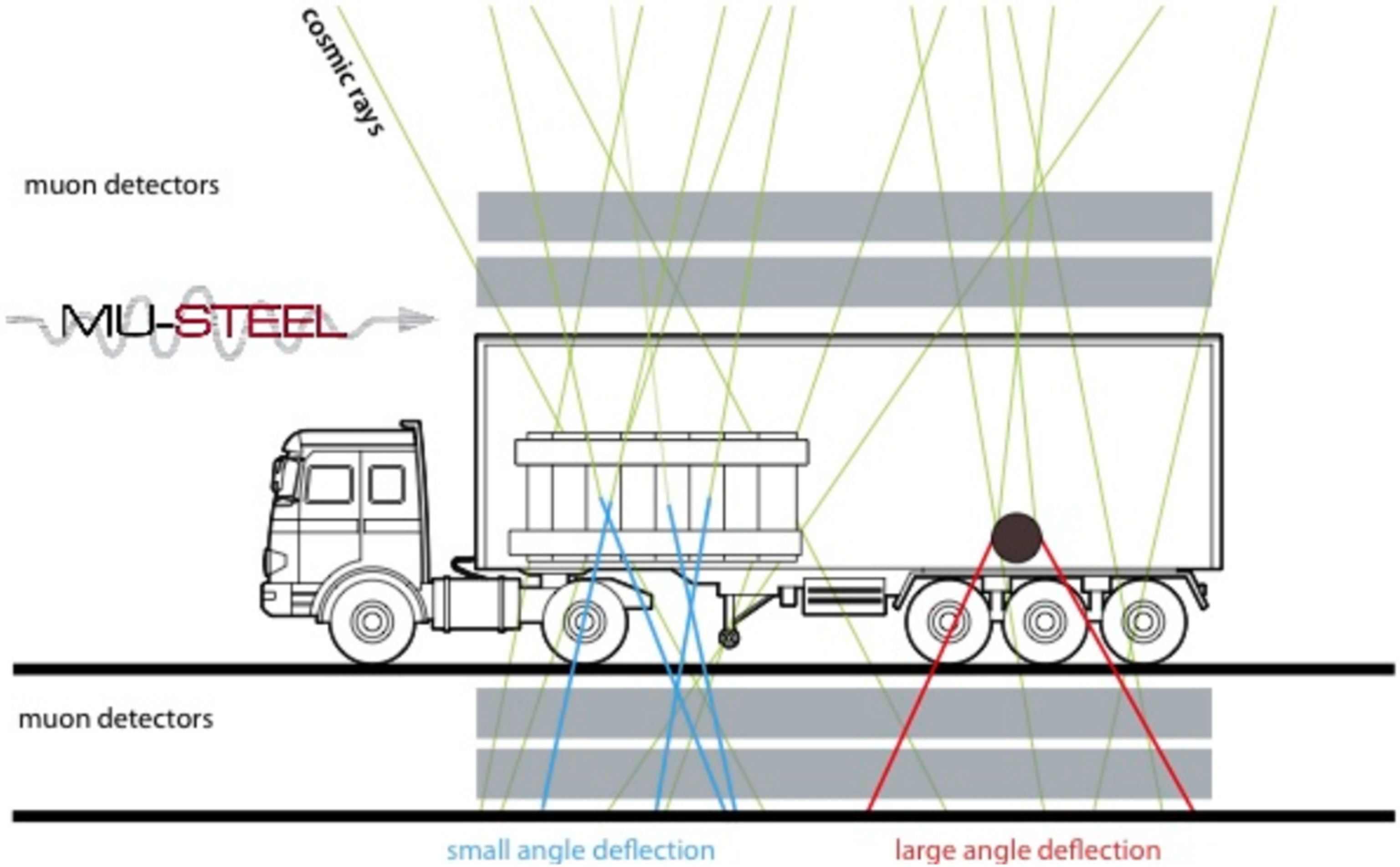
http://www.world-nuclear-news.org/RS-Muons-suggest-location-of-fuel-in-unit-3-0210174.html

- The TEPCO company installed a muon detection system (drift tube detectors 7x7 m2; 6 x-planes and 6 y-planes) on the unit 3's turbine building; 4 months of data taking in 2017
- **The results:**
- **- structures within the reactor building are clearly visible**

  - most of the fuel has melted and dropped from its original position within the core
- Similar studies for exploration of soils (muon detectors can be deployed within boreholes during the search for new ore sites → reductions the number of drillings → cost reduction

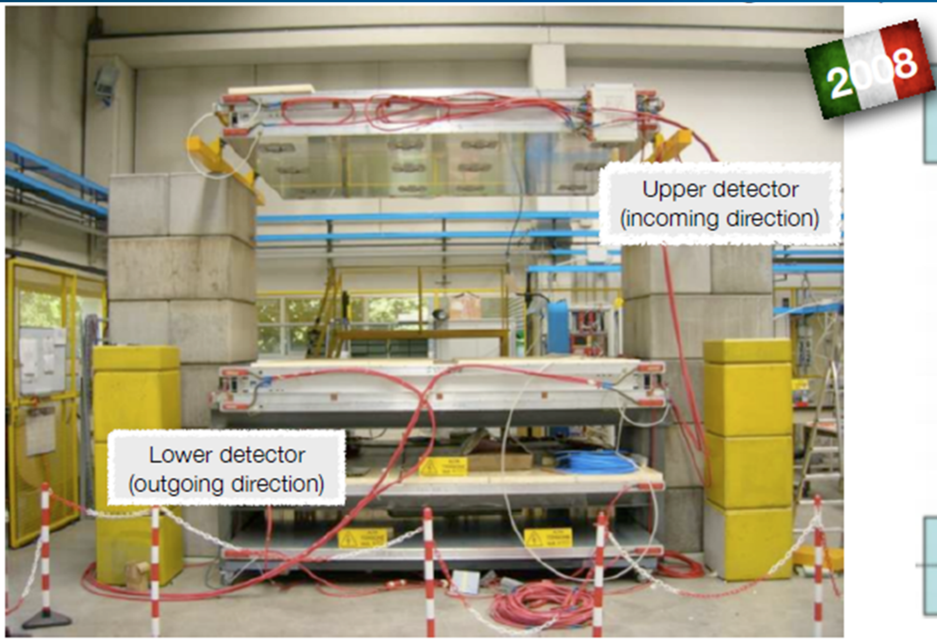
Muon Tomography – Basic Principle

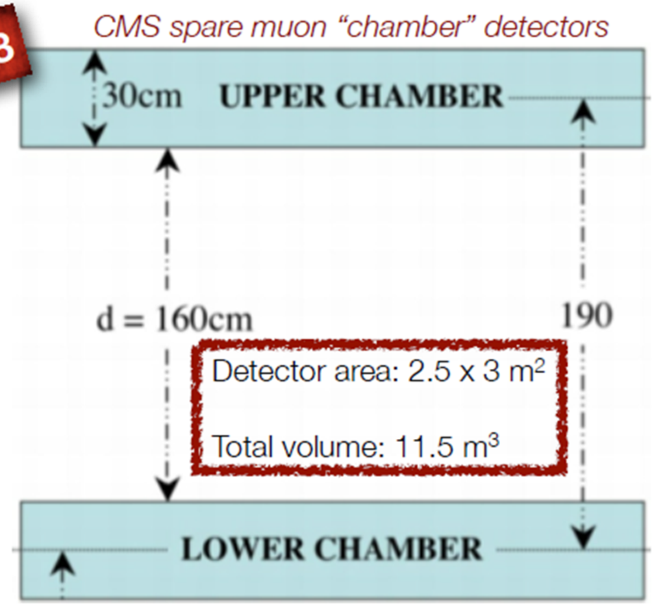
two detectors (**above** and **below**) the volume under study
to measure the muon trajectory **deviation** from a straight line



Muon Tomography (MT) cont.

The first „large scale” MT ever built – INFN-LBL Legnaro, 2008





First results

Contents lists available at ScienceDirect

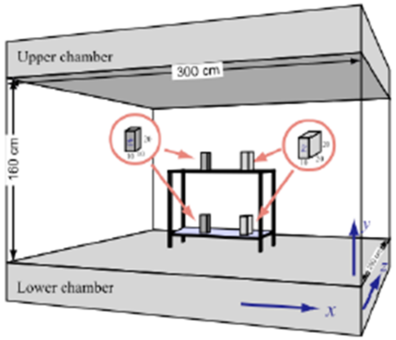
Nuclear Instruments and Methods in Physics Research A

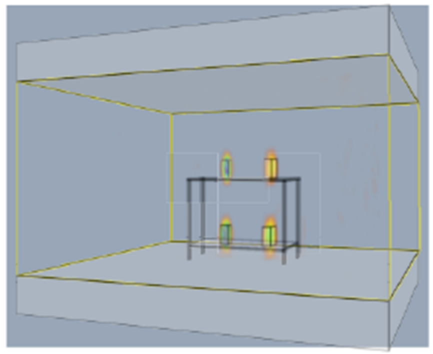
journal homepage: www.elsevier.com/locate/nima

First results on material identification and imaging with a large-volume muon tomography prototype

S. Pesente[a], S. Vanini[a,*], M. Benettoni[a], G. Bonomi[b], P. Calvini[c], P. Checchia[a], E. Conti[a], F. Gonella[a], G. Nebbia[a], S. Squarcia[c], G. Viesti[d], A. Zenoni[b], G. Zumerle[d]

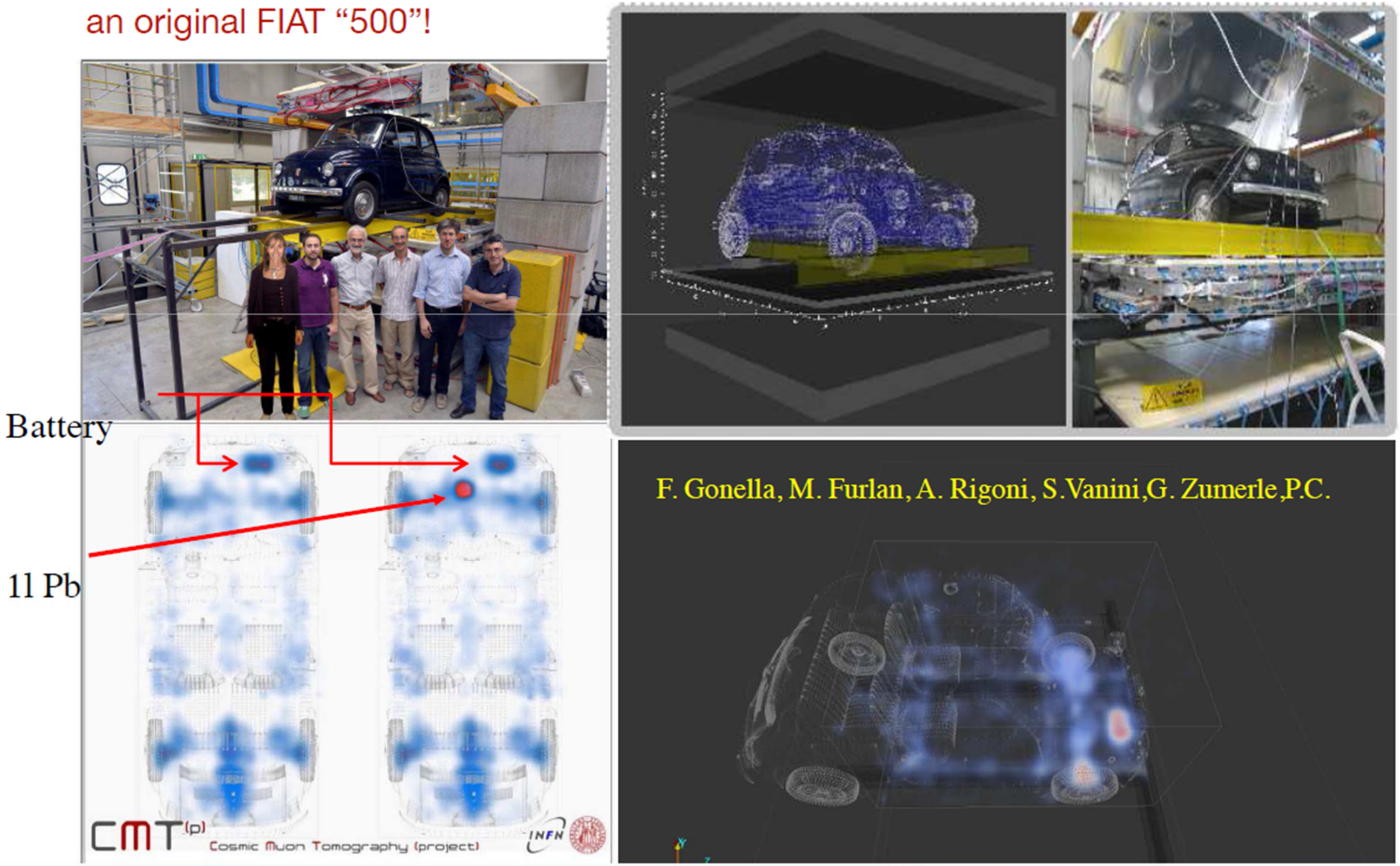
Nucl. Instr. and Meth. A 604 (2009) 738





Muon Tomography (MT) cont.

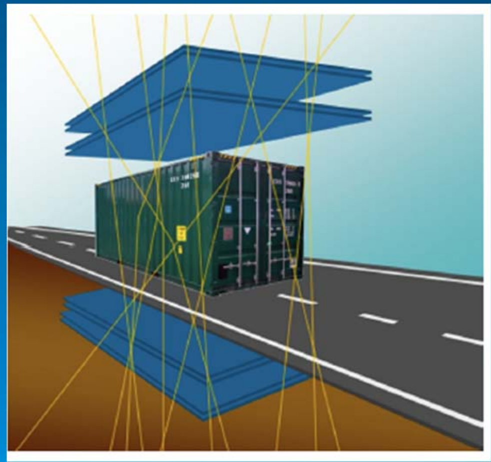
A tomographic image of
an original FIAT "500"!



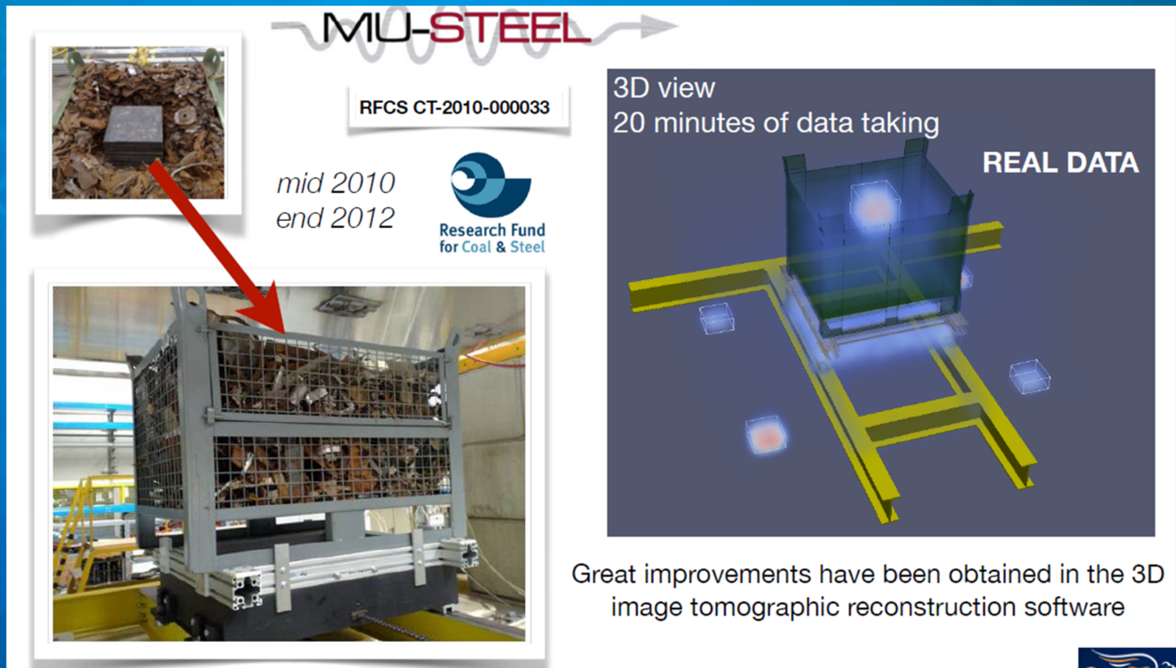
Muon Tomography: Safety/Security Applications

Muon-Portal Project (Catania)

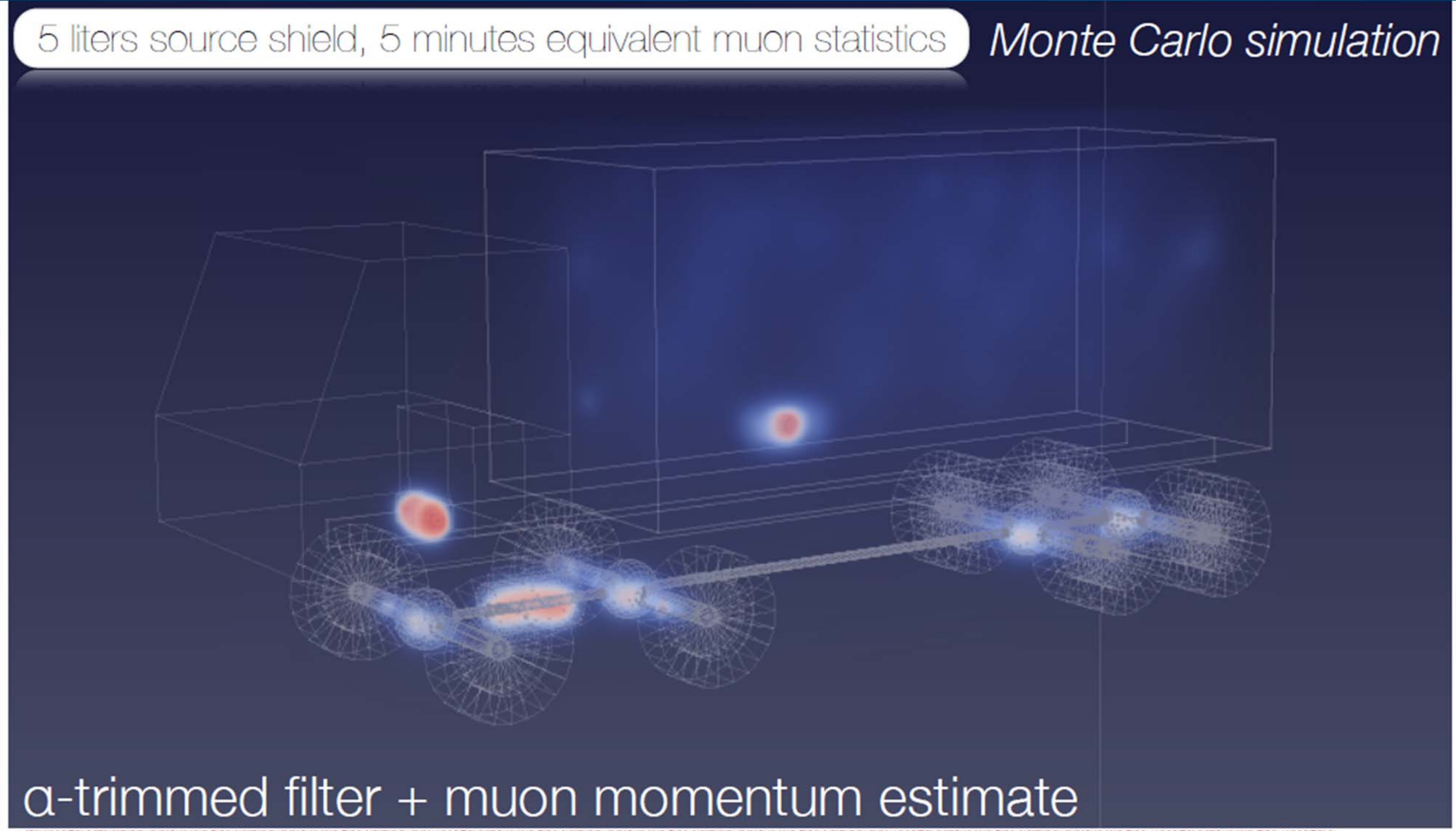
- large area detectors (tens of squared meters)
- good angular resolution (~ 10 mrad)



Control of trucks when entering steel foundries to detect hidden radioactive sources that, if melted, can cause huge environmental and economical damages

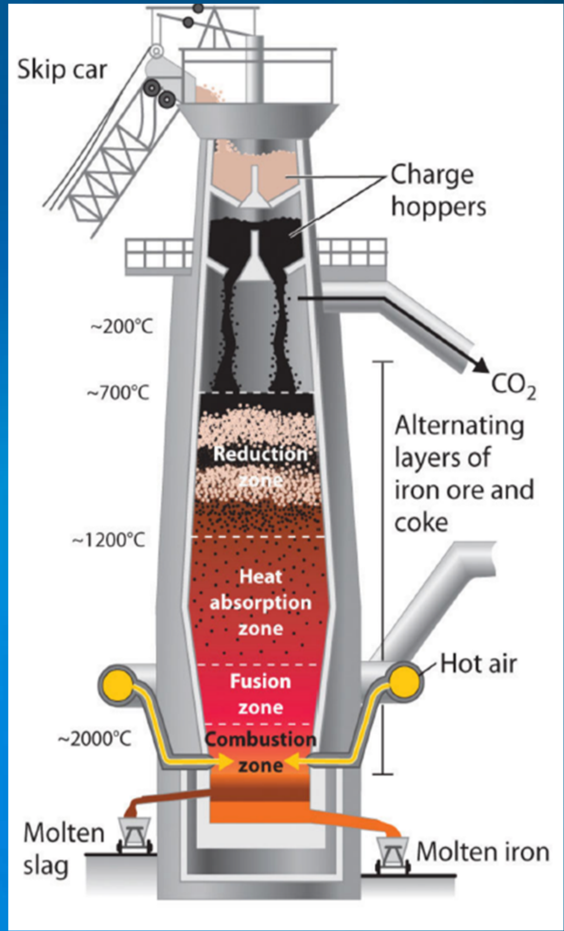


Muon Tomography: Safety/Security Applications

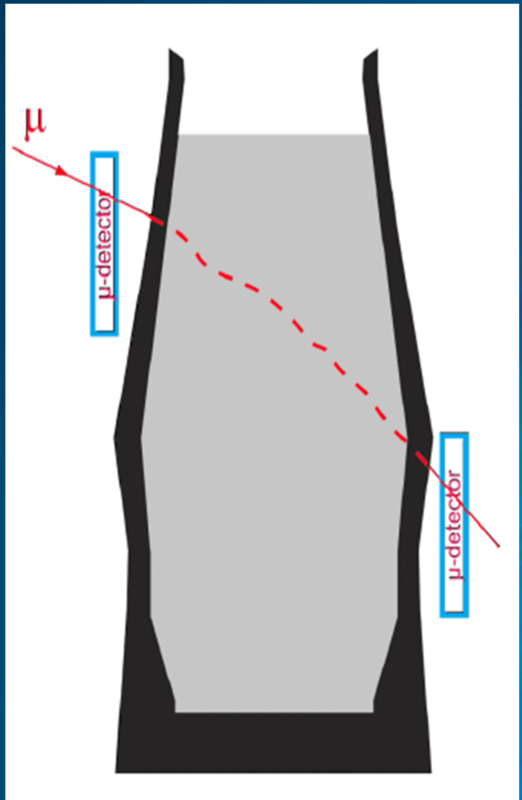


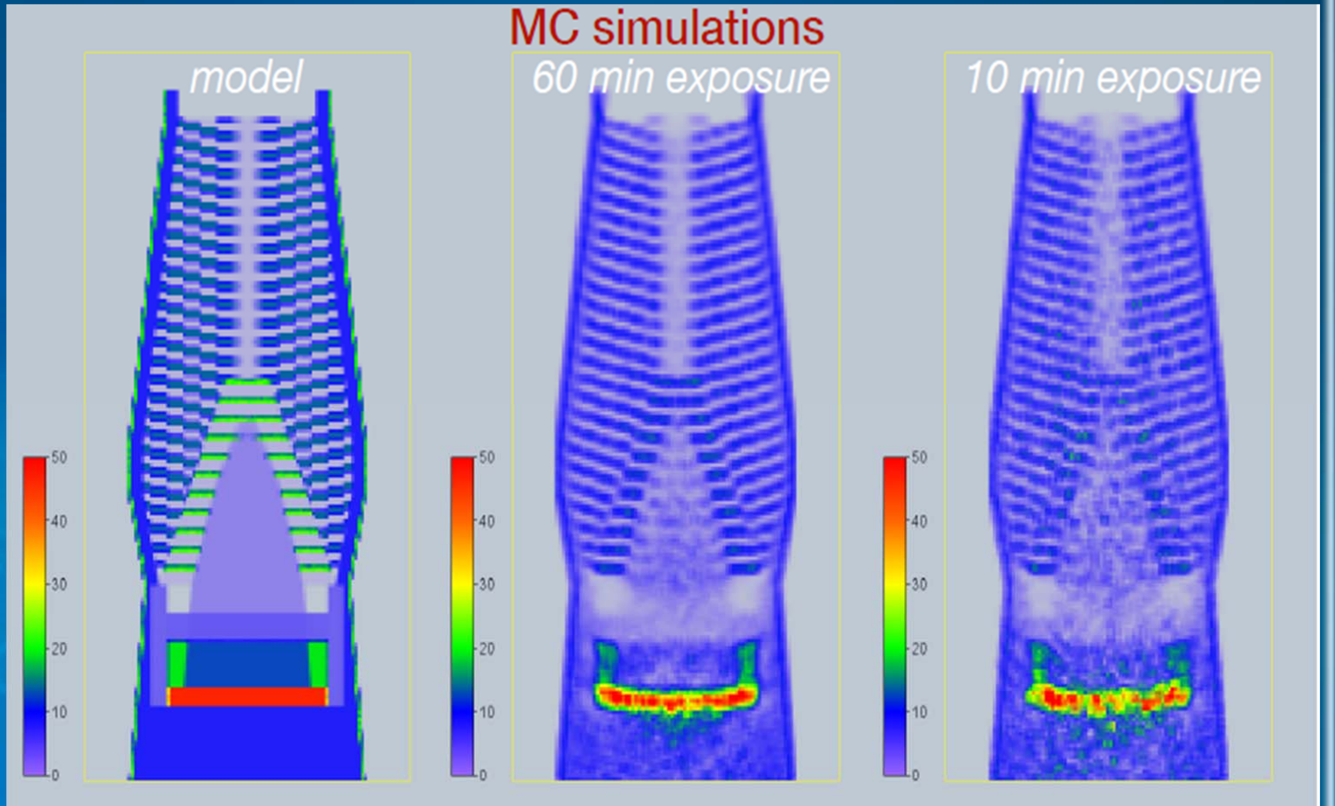
5 liters [2 liters] source shield ($17x17x17\ cm^3$ [$13x13x13\ cm^3$]) is detected in **4 [7] minutes** with 100% efficiency and 0% false alarms [MC estimates]

Muon Tomography in Industry



Muon Tomography in Industry





Despite the low number of „almost horizontal" muons and the movement of the burden, the MT imaging of the interior of a blast furnace is possible

Mu-Blast - RFCS CT-2014-00027

mid 2014- mid 2016

Research Fund for Coal & Steel

INFN swerea MEFOS LKAB

Particle Physics Software Matters…

GEANT4
A SIMULATION TOOLKIT

Space applications

European Space Agency

- Geant4 Space Users' Home Page
- ESA Project Support
- XMM-Newton Radiation Environment.
- Space Environment Information System (SPENVIS)
- Dose Estimation by Simulation of the ISS Radiation Environment (DESIRE)
- Physics Models for Biological Effects of Radiation and Shielding
- Geant4 Radiation Analysis for Space (GRAS)
- MUlti-LAyered Shielding SImulation Software (MULASSIS)

GLAST

- Gamma Ray Large Area Space Telescope

MEGAlib

- Medium Energy Gamma-ray Astronomy library

Medical applications

G4DNA
Geant4-DNA project

G4MED (in Japanese)
Geant4 Medical Physics in Japan

G4NAMU
Geant4 North American Medical User Organization

GAMOS
Geant4-based Architecture for Medicine-Oriented Simulations

GATE
Geant4 Application for Tomographic Emission

GHOST
Geant4 Human Oncology Simulation Tool

TOPAS
Geant4 Monte Carlo Platform for Medical Applications

+ industrial applications
Notably, non-destructive testing

Manuela Cirilli CERN Knowledge Transfer Group JENAS 2019

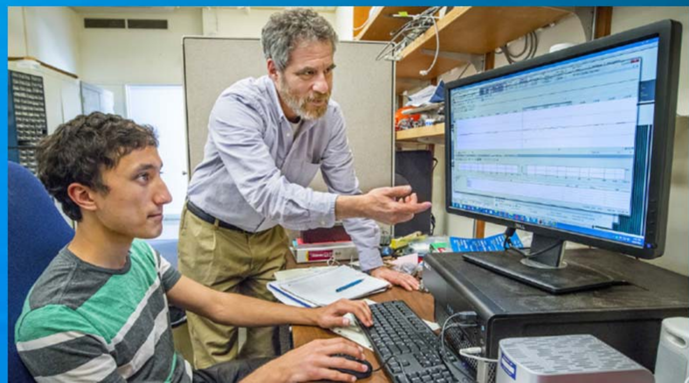
The Medical Community is currently a larger user of GEANT than the Particle Physics Community

LHC Software & Preservation of Native American Voices

- Hundreds of thousands of various old recordings are storied in various libraries worldwide
- Most of them old, fragile, noisy if not completely unplayable
- Typically they are stored on wax or aluminium cylinders
- They were recorded mechanically e.g. by using a diaphragm attached to a needle: when a diaphragm felt a sound wave generated by a voice or instrument it vibrated. These vibrations moved the needle which inscribed the motions into a soft, rotating, material

Symmetry Magazine

- Idea: scan the recording (with a confocal microscope) to create a digital, high resolution map of the surface of the recording
- **Harness the ATLAS detector reconstruction software**



- Berkeley: Carl Haber & Vitaliy Fadeyev: scanning and extracting sound of the 2700 wax cylinders stored in the University of California Phoebe Hearst Museum of Antropology

http://www.newyorker.com/magazine/2014/05/19/a-voice-from-the-past
http://www.symmetrymagazine.org/article/june-2015/lhc-physicists-preserve-native-american-voices

The Human Capital

Instead of Summary…

Gravitational waves and black holes now have become part of pop culture. Below a brief overview of some of the manifestations

https://shenovafashion.com/products/gravitational-waves-dress

We should not be too shy, and speak openly about benefits of particle physics and accelerators

Summary:

✓ Particle physics is costly BUT it yields impressive profits, not only scientific, but also economic, societal etc.

✓ Accelerators are essential for science and society

✓ It is enough to state just three reasons:

- Tens of millions of patients receive accelerator based diagnoses and treatment each yesr in clinics and hospitals around the world

- All products that are processed, treated or inspected by particle beas have a collective annual value of more than 500 B$

- A significant fraction of the nobel prizes are directly connected to the use of accelerators

ECFA
European Committee for Future Accelerators

Key elements of the updated European Strategy

Two key documents made public:
(main website http://europeanstrategyupdate.web.cern.ch/welcome)

1. a document including all recommendation:
   https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

2. a deliberation document elaborating on the recommendations in a context:
   https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Deliberation%20Document%20European%20Strategy.pdf

Scientific priorities

- Full exploitation of LHC physics potential → successful completion of the high-luminosity upgrade of accelerators and experiments → going well, according to (revised) schedule
- e^+e^- Higgs factory as the highest-priority next collider
- Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc. Develop accelerator R&D roadmap under LDG's supervision → starting
- Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
  → to be completed by next Strategy update (~ 2026).
- Support to long-baseline neutrino projects in US and Japan
  → in particular, successful implementation of DUNE at LBNF
- Support to high-impact scientific diversity programme complementary to high-E colliders (role of national labs emphasised, as well as participation in experiments outside Europe)
- Theory, detector R&D (develop roadmap under ECFA's supervision → starting), SW and computing

Preliminary implementation in this year's Medium-Term Plan of CERN
(draft presented in June, final version for approval by the Council in September)

Initial views on the European Strategy implementation

Fabiola Gianotti, ECFA, 13/7/2020

Jak fizyka podstawowa służy społeczeństwu?

„Physics is like sex: sure, it may give some practical results, but that's not why we do it.”

Richard Feynman

Naukę (i seks) można uprawiać na dwa sposoby:

1) Dla „prokreacji” – użytkowo, „dla zastosowań”, jako obowiązek względem społeczeństwa oraz używanie dostępnej wiedzy i narzędzi.

2) Dla „twórczości” – kreatywnie, budując nowe jakościowo teorie (trwałe związki międzyludzkie).

Można także zrezygnować z nauki (i nie tylko z niej… ), niestety przynosi to wymierne straty na wszystkich płaszczyznach życia

Accelerators: Instead of Summary – page 1

Area	Application	Beam	Accelerator	Beam energy/MeV	Beam current/ mA	Number
Medical	Cancer therapy	e	linac	4-20	10^{-2}	>14000
		p	cyclotron, synchrotron	250	10^{-6}	60
		C	synchrotron	4800	10^{-7}	10
	Radioisotope production	p	cyclotron	8-100	1	1600
Industrial	Ion implantation	B, As, P	electrostatic	< 1	2	>11000
	Ion beam analysis	p, He	electrostatic	<5	10^{-4}	300
	Material processing	e	electrostatic, linac, Rhodatron	≤10	150	7500
	Sterilisation	e	electrostatic, linac, Rhodatron	≤10	10	3000
Security	X-ray screening of cargo	e	linac	4-10	?	100?
	Hydrodynamic testing	e	linear induction	10-20	1000	5
Synchrotron light sources	Biology, medicine, materials science	e	synchrotron, linac	500-10000		70

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Area	Application	Beam	Accelerator	Beam energy/MeV	Beam current/mA	Number
Neutron scattering	Materials science	p	cyclotron, synchrotron, linac	600-1000	2	4
Energy - fusion	Neutral ion beam heating	d	electrostatic	1	50	10
	Heavy ion inertial fusion	Pb, Cs	Induction linac	8	1000	Under development
	Materials studies	d	linac	40	125	Under development
Energy - fission	Waste burner	p	linac	600-1000	10	Under development
	Thorium fuel amplifier	p	linac	600-1000	10	Under development
Energy - bio-fuel	Bio-fuel production	e	electrostatic	5	10	Under development
Environmental	Water treatment	e	electrostatic	5	10	5
	Flue gas treatment	e	electrostatic	0.7	50	Under development