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Nuclear Physics and Applications: The Societal Impact – A Project for Greece

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Nuclear Physics and Applications: The Societal Impact – A Project for Greece

"An introduction to the third edition of the school "Rewriting Nuclear Physics Textbooks: one step forward" and future perspectives

Nicolas Alamanos, Eur. Phys. J. Plus (2020) 135:417.

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Medical and Societal Applications

Medical Applications

The Positron emission tomography (PET) and radioisotope production

Using radiations for therapy - the hadron-therapy

The MRI (Magnetic Resonance Imaging)

Societal Applications

Cultural heritage – Archeometry, Study of air pollution.

Neutron technique in civil Security Application

Reach for the stars by digging in the dirt

New developments – Compact sources

Wilhelm Conrad Röntgen - The discovery of the "X-rays" and the beginning of "Imaging"

A little bit of history : November 8, 1895, Röntgen was studying the phenomena accompanying the passage of an electric current through a gas of extremely low pressure. He found that, if the discharge tube is enclosed in a sealed thick black carton, to exclude all light, and if he worked in a dark room, a paper plate covered on one side with barium platinocyanide, placed in the path of the rays, become fluorescent even when it was as far as two meters from the discharge tube.

Wilhelm Conrad Röntgen - The discovery of the "X-rays" and the beginning of "Imaging"

Nearly two weeks after his discovery, he immobilized for some moments his wife Anna Bertha's hand in the path of the rays over a photographic plate. After development he observed an image of the hand.

A century ago, the living body, like most of the material world, was opaque. Then Wilhelm Roentgen captured an X-ray image of his wife's finger - her wedding ring 'floating' around a white bone and our vision changed forever.

The medical application of X-rays represents one of the most obvious benefits of nuclear physics in medicine.

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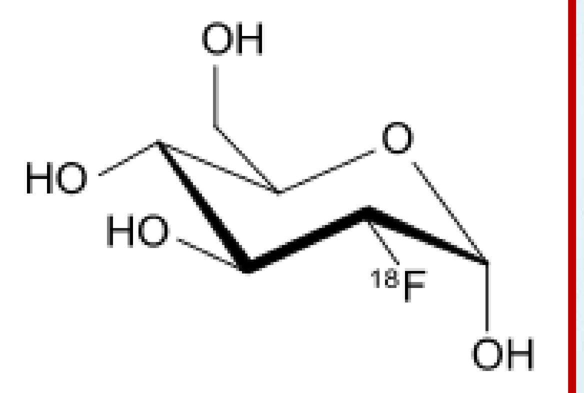
Imaging - Positron emission tomography (PET) and radio-isotopes

Cells to live, function and reproduced need energy in the form of glucose. Cancer cells require a lot of energy, and therefore have a very high glucose consumption.

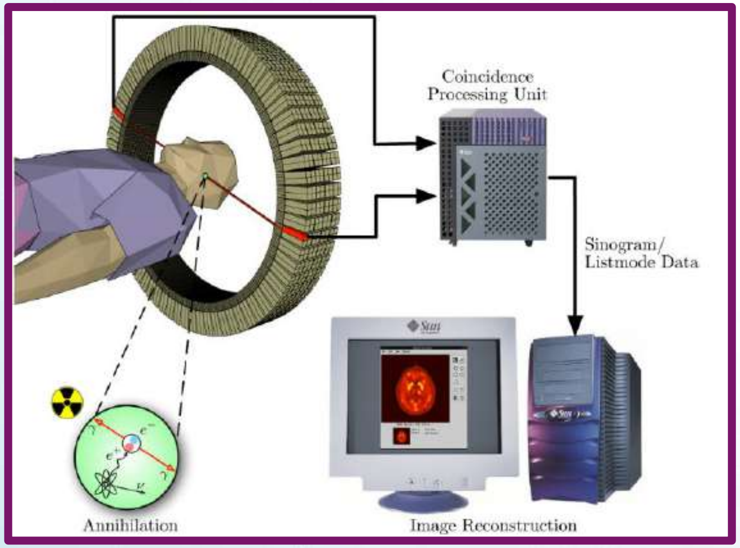
(PET) consists in administrating intravenously to the patient a marked molecule with a radioactive isotope of a relatively short lifetime. One of the most popular molecules is the *radioactive glucose*, labelled Fluor-18. It is an hydroxyl group (HO) where an ^{16}O is replaced by a nucleus of ^{18}F.



NuPECC : Nuclear Physics for Medicine

Imaging - Positron emission tomography (PET) and radio-isotopes

The ^{18}F is unstable and decreases by positron emission. The positron is immediately captured by an electron. The two particles annihilate each other. Their masses being 511 keV their annihilations is followed by the emission of two photons of 511 keV each. The annihilation takes place very close to ^{18}F.



Imaging - Positron emission tomography (PET) and radio-isotopes

The large majority of PET scanner installed in hospitals are hybrid system where a PET detector is combined with an X-ray Computer Tomography (CT).

……. *Makes use of computer-processed combinations of many X-rays measurements taken from different angles to produce cross-sectional images of specific areas of a scanned object…….*

According to medical specialists, PET/CT is a technical evolution that has led to a medical revolution.

Today, more than ~1000 hospital cyclotrons are used worldwide to produce radionuclides. Among these cyclotrons, ~350 are dedicated to the manufacture of radionuclides for Positron-emission tomography (PET) imaging.

Radioisotopes for Nuclear Medicine

Radioisotopes for Nuclear Medicine : Among them the most commonly used radionuclides are ^{18}F, or ^{11}C, ^{13}N, ^{123}I or ^{67}Ga… $^{99}Mo/^{99m}Tc$…

Established isotopes with industrial suppliers	*^{99m}Tc, ^{18}F, $^{123,125,131}I$, ^{111}In, ^{90}Y*
Emerging isotopes with small innovative suppliers	*^{68}Ga, ^{82}Rb, ^{89}Zr, ^{177}Lu, ^{188}Re*
R&D isotopes Research labs	*$^{44,47}Sc$, $^{64,67}Cu$, ^{134}Ce, ^{140}Nd, $^{149,152,155,161}Tb$, ^{166}Ho, ^{195m}Pt, ^{211}At, $^{212,213}Bi$, ^{223}Ra, ^{225}Ac…*

An example of research (PSI and ISOLD) in progress is the case of Terbium. Terbium offers four clinically interesting radioisotopes with complementary physical decay characteristics, the ^{149}Tb, ^{152}Tb, ^{155}Tb, and ^{161}Tb.

ARRONAX: Accélérateur pour la recherche en radiochimie et oncologie à Nantes-Atlantique

Is a cyclotron of high energy (70 MeV) and high intensity (750 µA)

As powerful as the SPES cyclotron !!

Inaugurated in 2008 it is expected to be specialized in the production of :

β+ emitters (Cancerology)

^{64}Cu, ^{44}Sc, ^{68}Ge, ^{82}Sr

β- emitters

^{67}Cu, ^{47}Sc, ^{166}Ho

α emitters (immunotherapy)

^{211}At

Radioisotopes and Radioisotope Production

For their production these short-lived isotopes require *cyclotrons, reactors and dedicated nuclear physics techniques* .

⇒ Reactors ?? Yes for the production of ^{99}Mo/^{99m}Tc.

Over 30,000 scans are performed with this isotope in the United States each day. However, one of the main problems in this domain is the shortage of ^{99}Mo/^{99m}Tc.

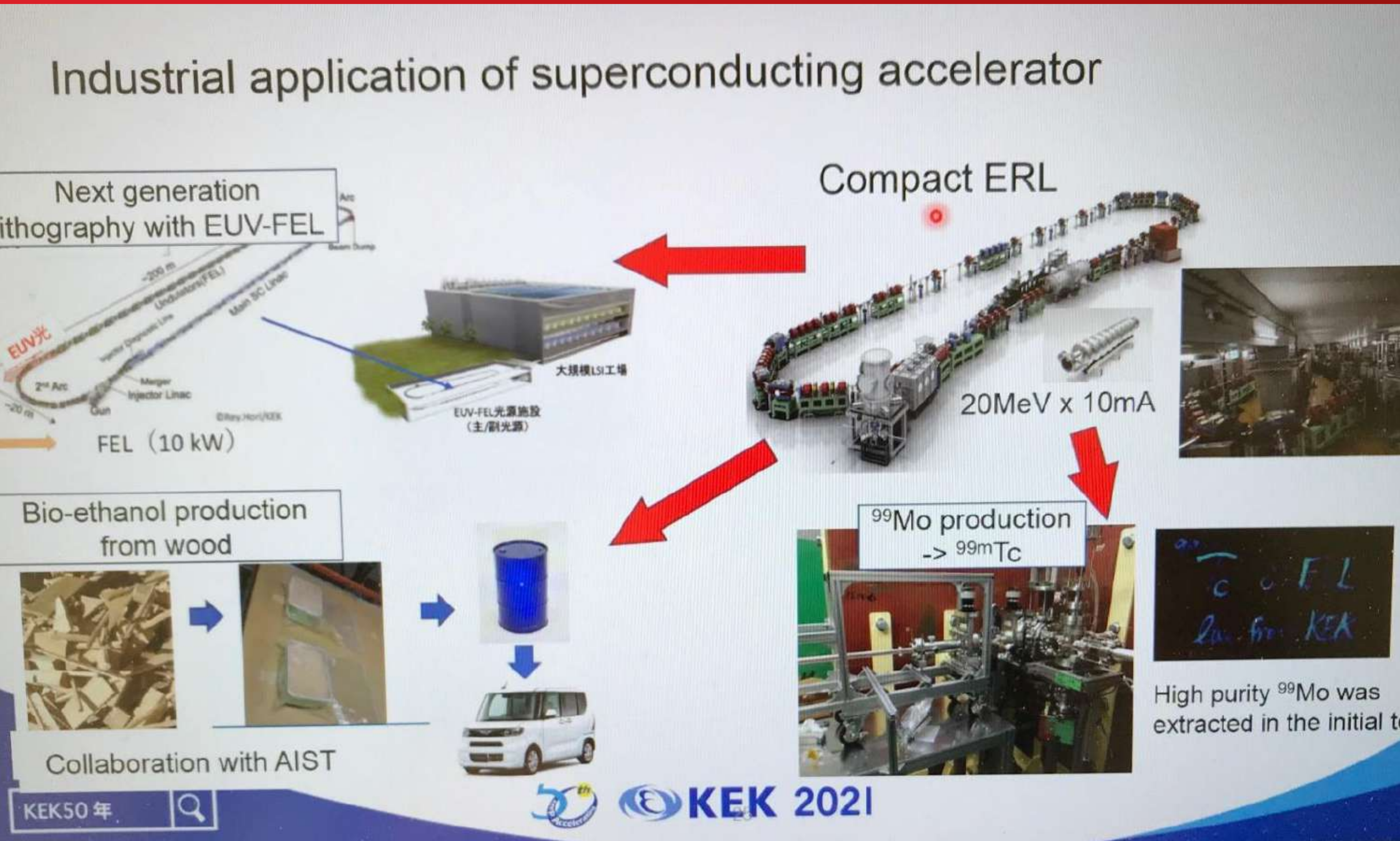
In 2013 eight research reactors were involved in the large scale production (>95% of world supply) of ^{99}Mo. Today some of them were shutdown. Others are expected to stop irradiating targets for ^{99}Mo production within the decade.

Radioisotopes and Radioisotope Production

These supply shortages raised interest in alternative production routes of ^{99}Mo and ^{99m}Tc.

Bombarding a Mo-100 target with a 22-MeV-proton beam seems to be the most effective way for its direct production. …. Cyclotron type "methods" stands as an invaluable tool for the production of ^{99m}Tc….

…. even if it seems necessary to pave the country with medical cyclotrons close to hospital complexes.


Industrial application of superconducting accelerator
Next generation
lithography with EUV-FEL
EUV光
FEL（10 kW）
大規模LSI工場
EUV-FEL光源施設
（主/副光源）
Compact ERL
20MeV x 10mA
Bio-ethanol production
from wood
Collaboration with AIST
99Mo production
-> 99mTc
High purity 99Mo was
extracted in the initial t
KEK50年
KEK 2021

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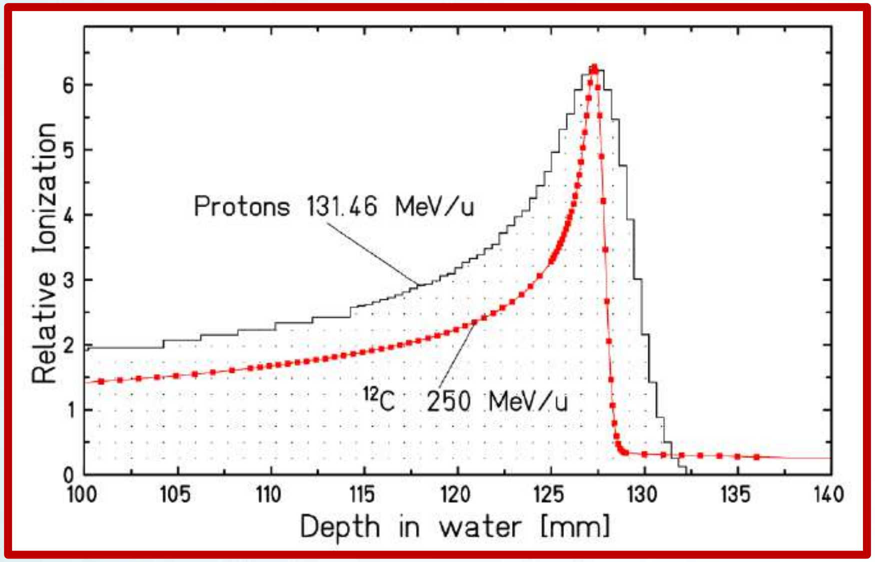
Radiation Therapy – Hadron Therapy

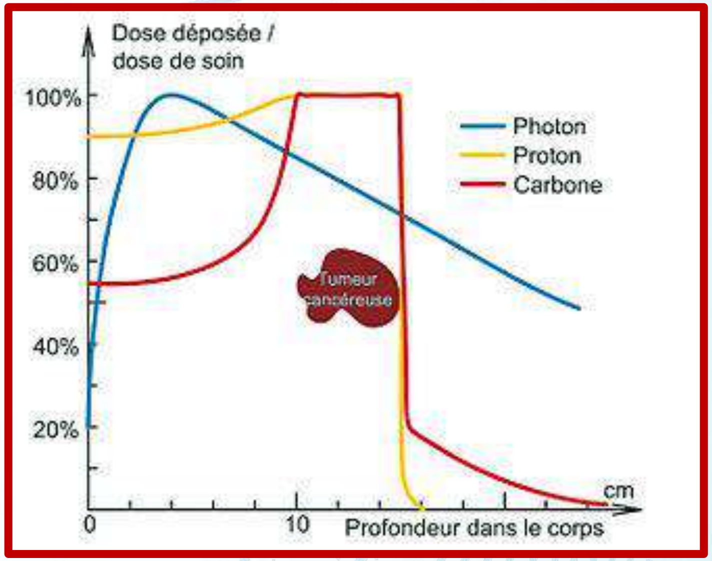
Radiation therapy is the medical use of ionizing radiation to treat cancer. Today, cancer is among the highest cause of death (before the COVID crisis) in developed countries and its treatment presents a real challenge.

In conventional radiation therapy, beams of X rays (high energy photons) or hadrons are produced and then delivered to the patient to destroy tumor cells. Using crossing beams from many angles, radiation oncologists irradiate the tumor target while trying to spare the surrounding normal tissues. Inevitably some radiation dose is always deposited in the healthy tissues.

Why Hadron-therapy

The strength of hadron-therapy lies in the unique physical and radiobiological properties of these particles.





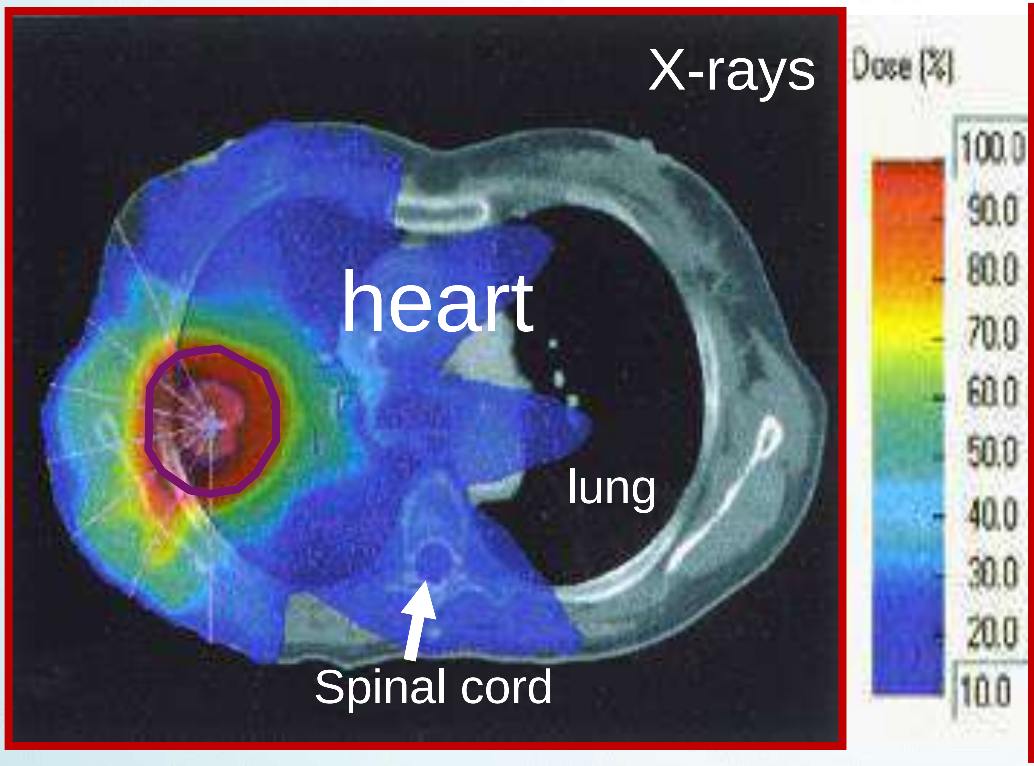
Measured Bragg peaks of protons and ^{12}C ions having the same mean range in water

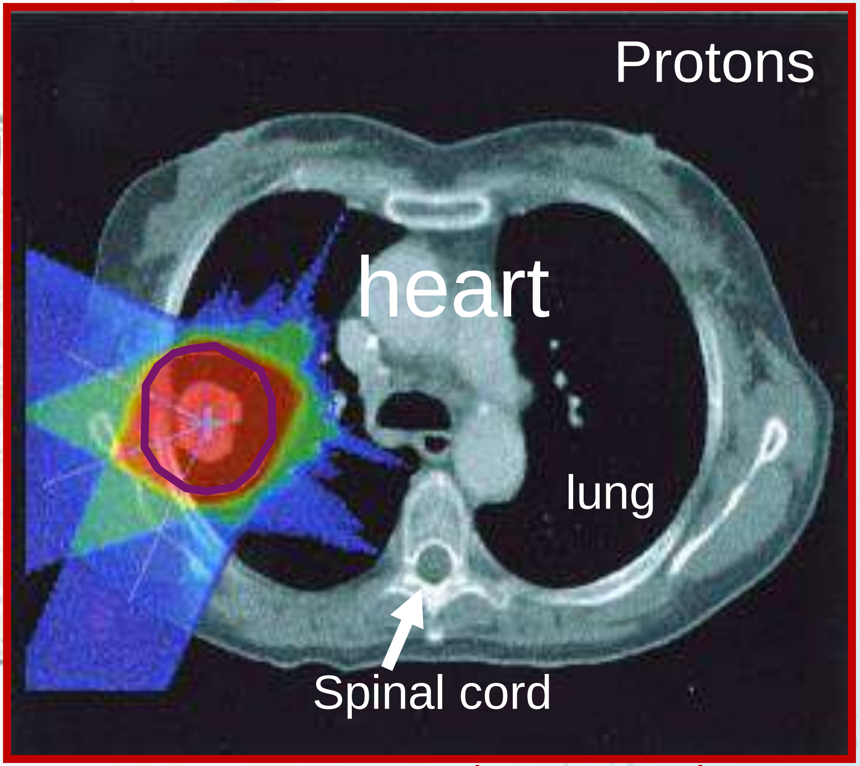
More precise ballistics: Depth efficiency curves of photons, protons and carbon ions.

Advantages of Hadron-therapy

X-ray beams
from 7 directions

Proton beams
from 3 directions





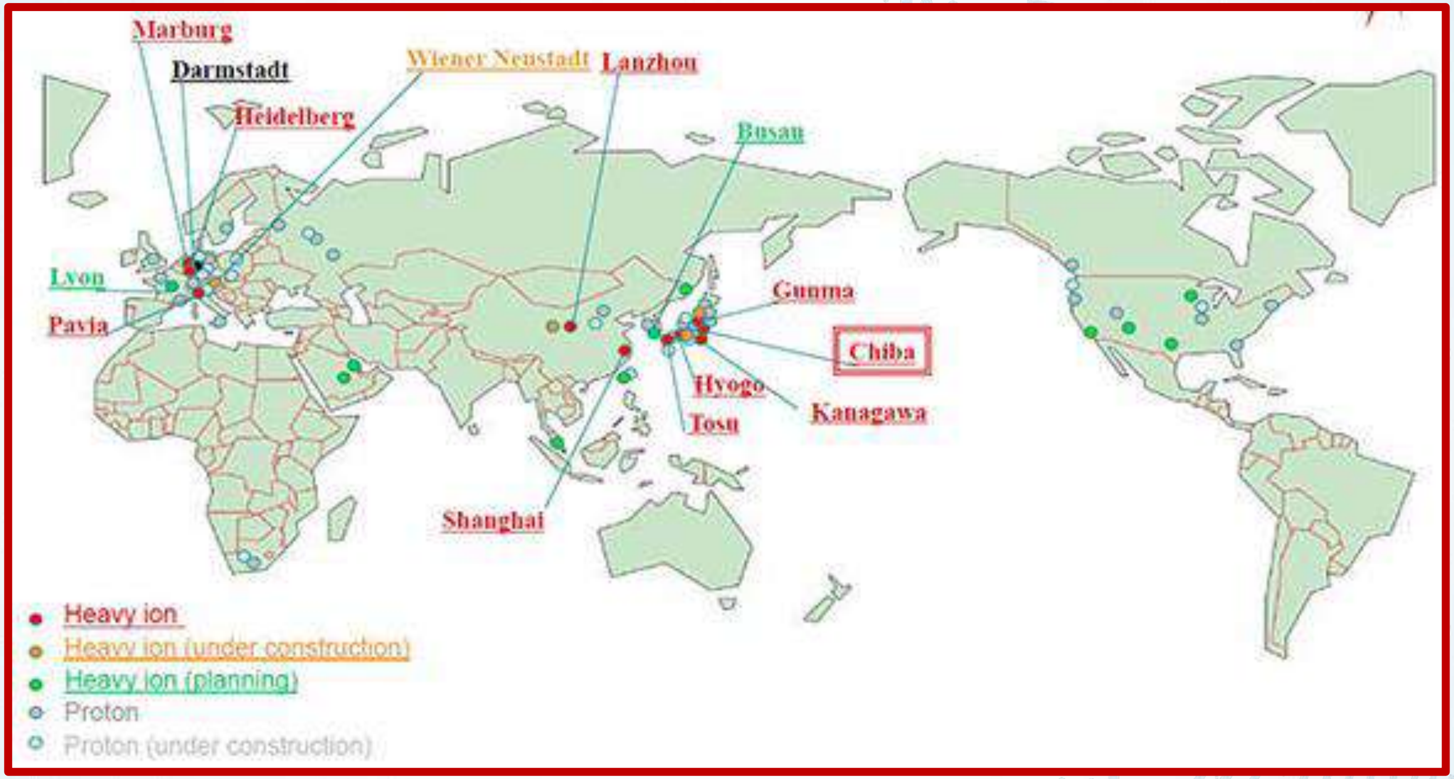
pictures: Medaustron

The carbon therapy has grown up only very recently. The leading country is Japan where the first treatment center in Chiba was build in 1994. The HIMAC (Heavy- Ion Medical Accelerator in Chiba) facility has treated around 10000 patients.

Advantages of Hadron-therapy

1) Carbon ion beams have physical properties enabling to concentrate radiation damage intensively on the cancer site.
2) It's biologically more effective in killing cancer cells.
3) The treatment period is shorter than other radiotherapy.

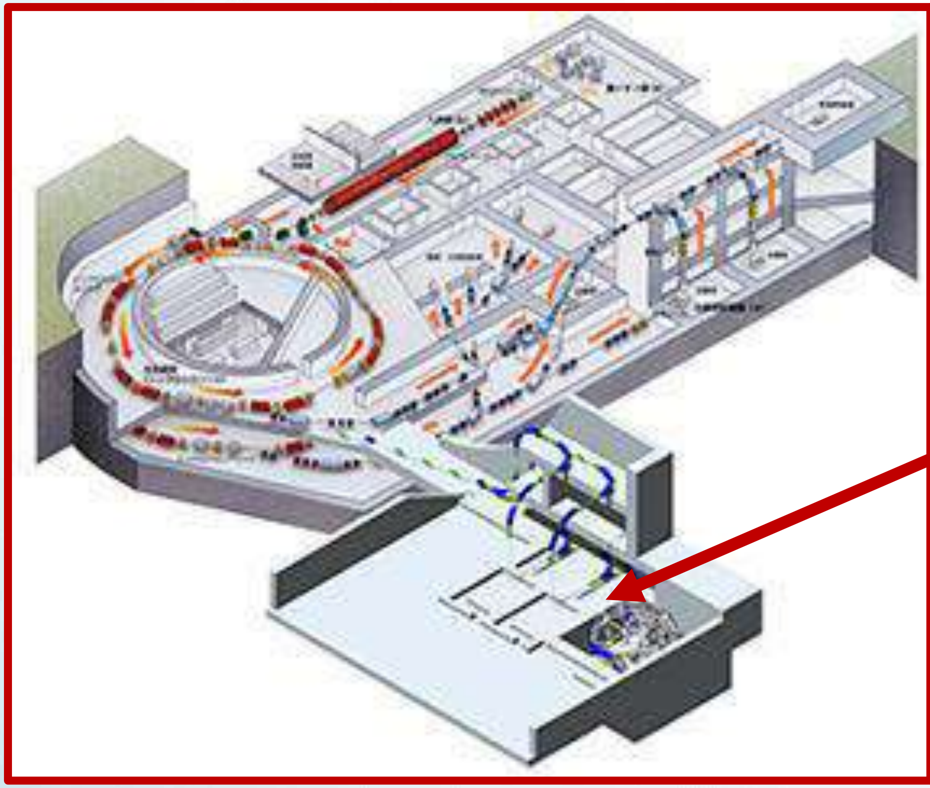
Hadron-therapy

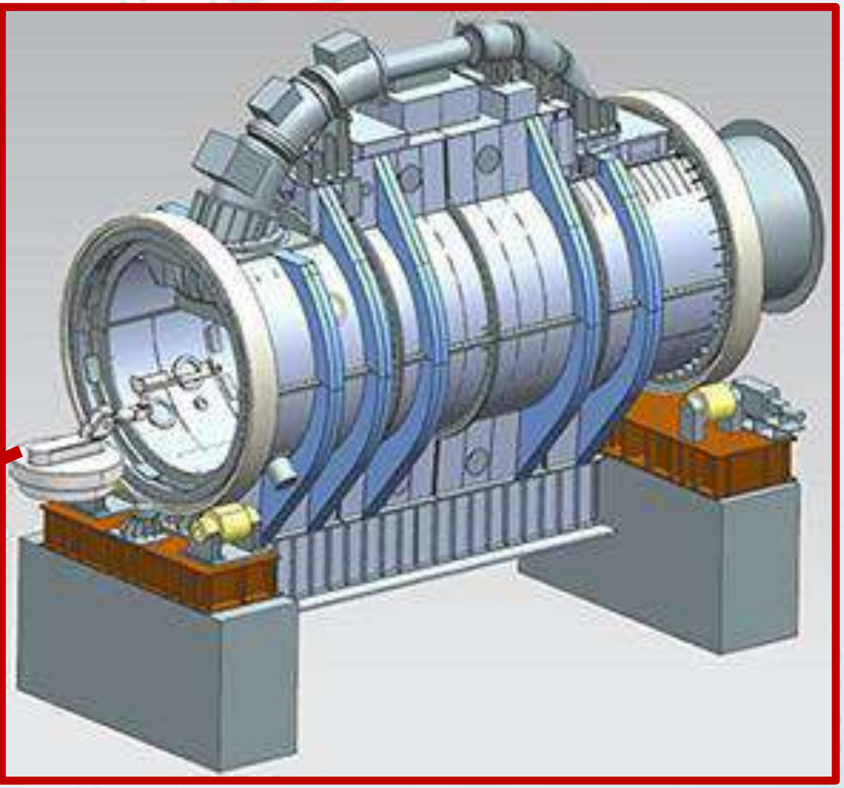


At the end of 2017, there were 63 centers worldwide for cancer treatment with protons (52 centers) or carbon ions (11 centers). This field benefits from the very strong interface between physics, biology and medicine.

The Heavy- Ion Medical Accelerator in Chiba (HIMAC)

HIMAC complex consists of a three ion sources, one linac, two synchrotron rings, and three treatment rooms. The new treatment facility has also three treatment rooms.





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Magnetic Resonance Imaging (MRI).

To perform a study, the person is positioned within an MRI scanner (~1.5 Tesla) that forms a strong magnetic field around the area to be imaged.

An oscillating magnetic field is temporarily applied to the patient at the appropriate resonance frequency. The excited hydrogen atoms emit a radio frequency signal, which can be measured.

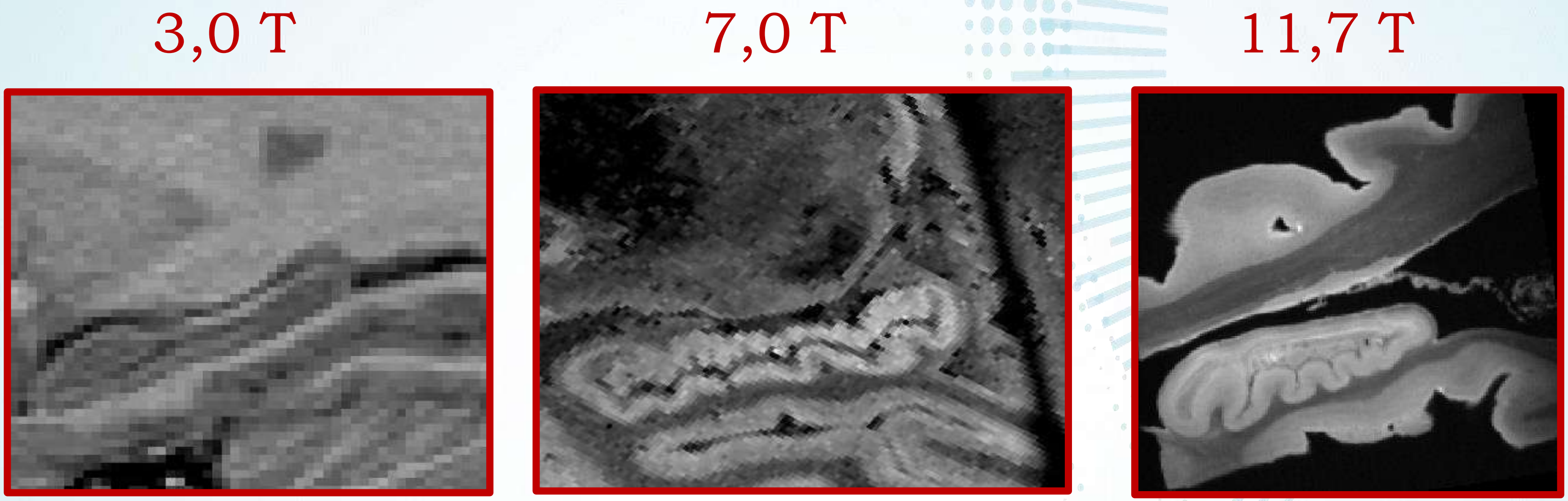
Magnetic Resonance Imaging (MRI).

MRI does not involve X-rays or the use of ionizing radiation. Is based on the fact that the spin of nuclei into a magnetic field is aligned either into the direction of the magnetic field either into the opposite direction.

The total magnetization of a sample is the difference of the number of nuclei between each spin direction. This difference is proportional to the applied field: the larger the field, bigger the magnetization, the more accurate the quality of the information.

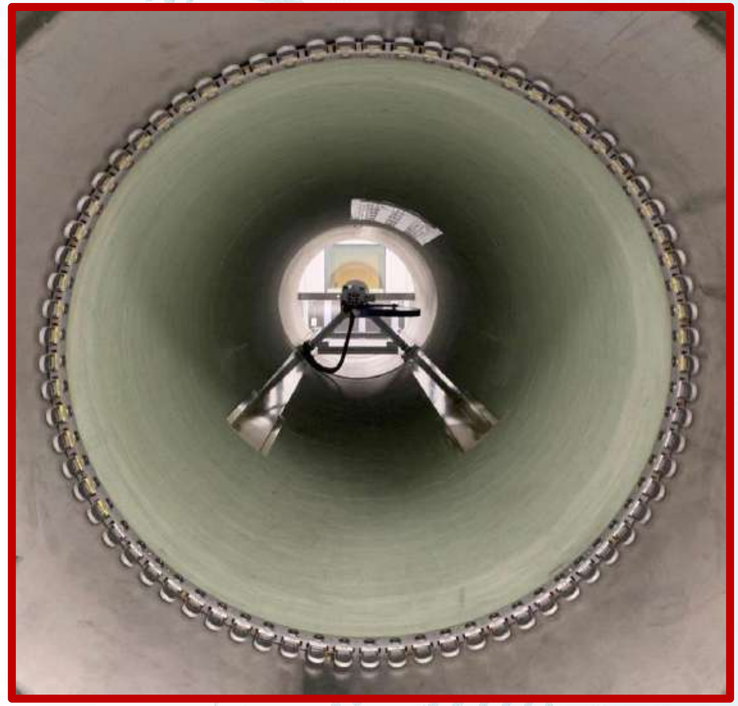
MRI is a water story !

Example of a human hippocampus image



With a 11,7 Tesla magnet high accuracy segmentation of the hippocampus becomes possible. Furthermore, clinical research into Alzheimer's disease, epilepsy and schizophrenia may become available. The future of scientific research in this domain also relies on high field magnets.

Imaging - MRI with 11.75 Tesla fields



The magnetic field must be homogeneous at 0.5 PPM (parts per million) around the patient's brain.

5904 pieces of shim (small iron pellets) were thus screwed onto their rails and installed inside the magnet tunnel.

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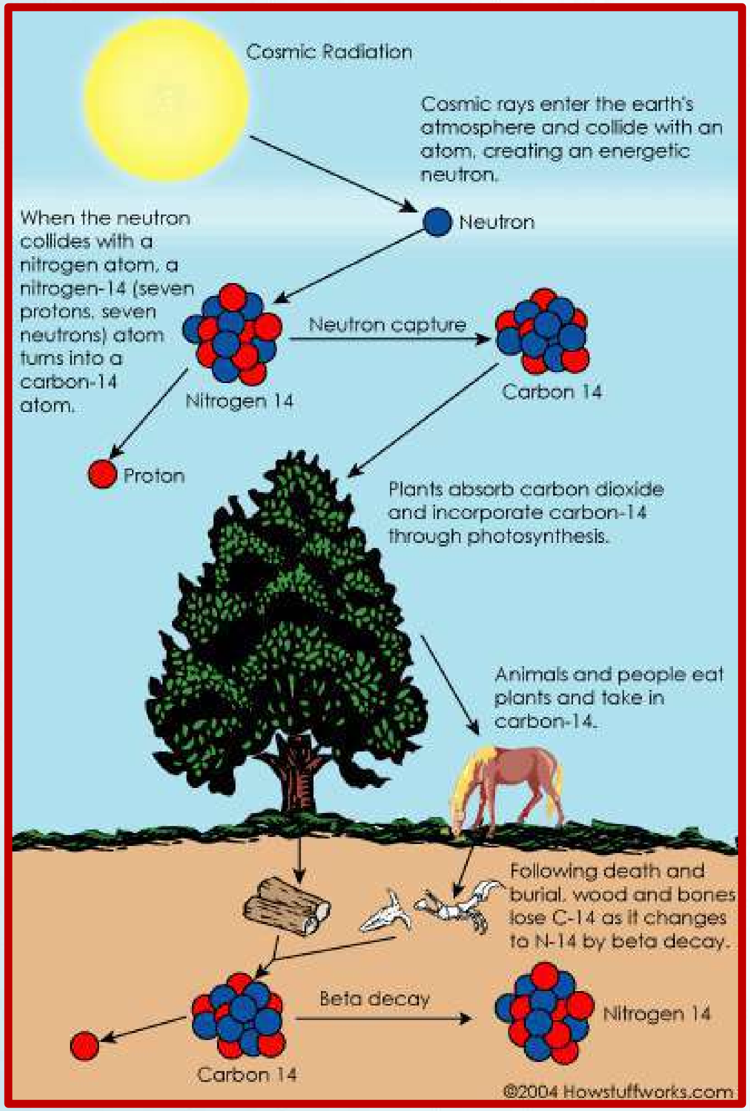
The ^{14}C method is a great contribution of Nuclear Physics to Archaeology



…. A cosmic rays collide with atoms creating energetic neutrons.

The neutrons collide with nitrogen atoms creating ^{14}C via the reaction ($n+^{14}N->p+^{14}C$).

Carbon-14 is radioactive, with a half-life of about 5,700 years.

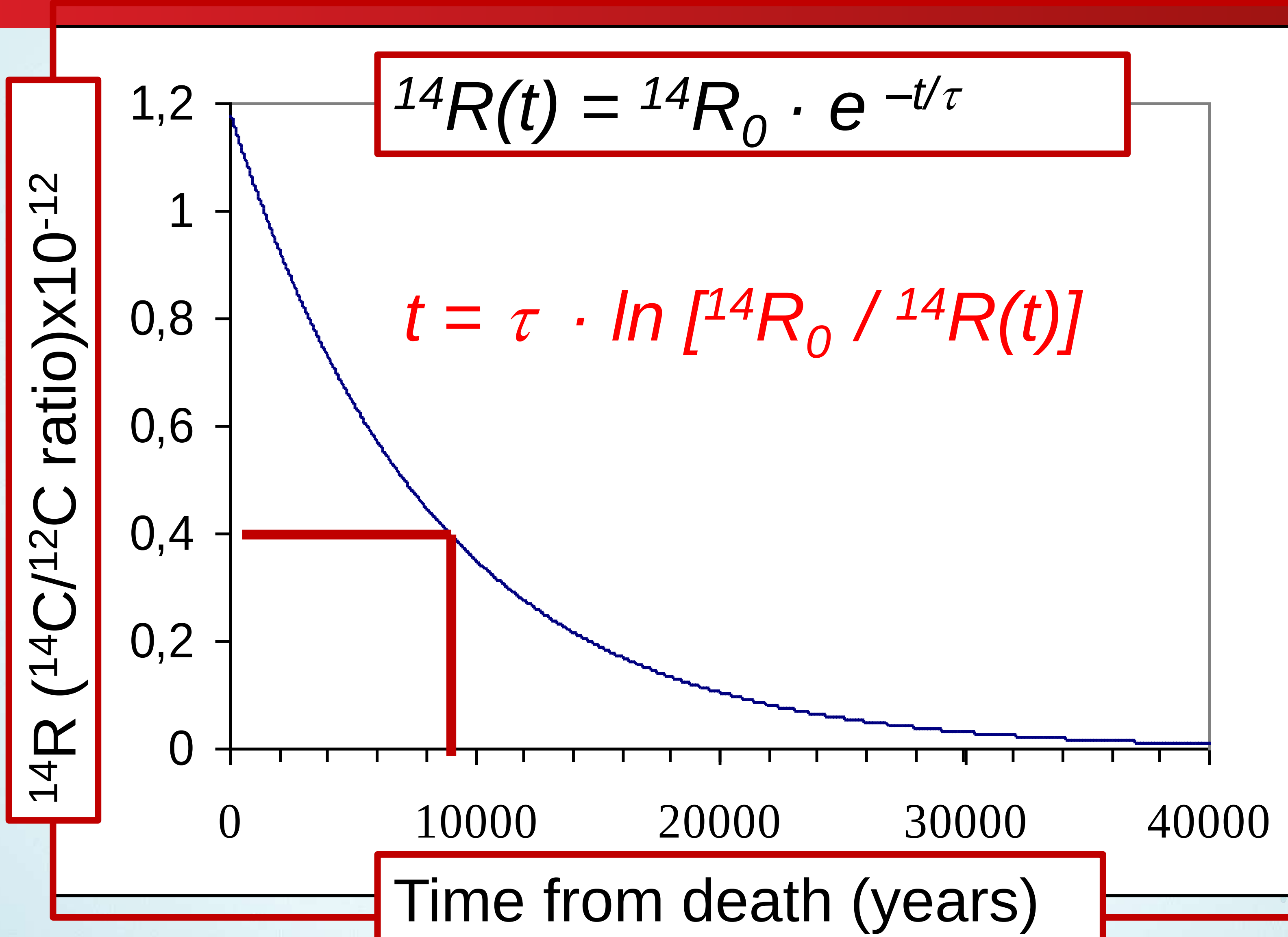
The ^{14}C method is a great contribution of Nuclear Physics to Archaeology

The carbon-14 atoms combine with oxygen to form carbon dioxide.

Plants absorb Carbon dioxide and incorporate carbon-14 trough photosynthesis..... Animals and people eat plants and take in carbon-14.

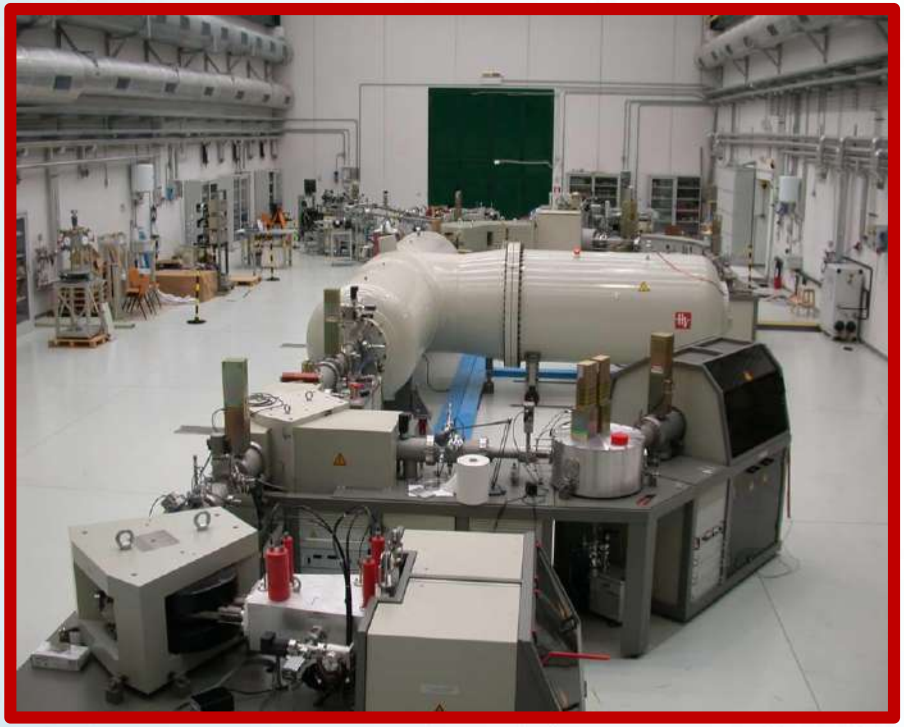
The ratio of carbon-12 to carbon-14 in the air and in all living things at any given time is nearly constant. At this moment, your body has a certain percentage of carbon-14 atoms in it, and all living plants and animals have the same percentage.

Following death and burial, wood and bones loose C-14 as it changes to N-14 by beta decay.



$^{14}R(t) = {}^{14}R_0 \cdot e^{-t/\tau}$
$t = \tau \cdot \ln [{}^{14}R_0 / {}^{14}R(t)]$
^{14}R ($^{14}C/^{12}C$ ratio)x10^{-12}
1,2
1
0,8
0,6
0,4
0,2
0
0
10000
20000
30000
40000
Time from death (years)

Accelerator mass spectrometry (AMS)



The Florence Laboratory of Nuclear Techniques for Environment and Cultural Heritage

The special strength of AMS is its power to separate a rare isotope from an abundant neighboring mass ("abundance sensitivity", e.g. ^{14}C from ^{12}C).

It makes possible the detection of naturally occurring, long-lived radio-isotopes such as ^{10}Be, ^{36}Cl, ^{26}Al and ^{14}C.

Accelerator mass spectrometry (AMS)

AGLAE

Every big museum has to dispose or to be associated with an accelerator for different type of studies

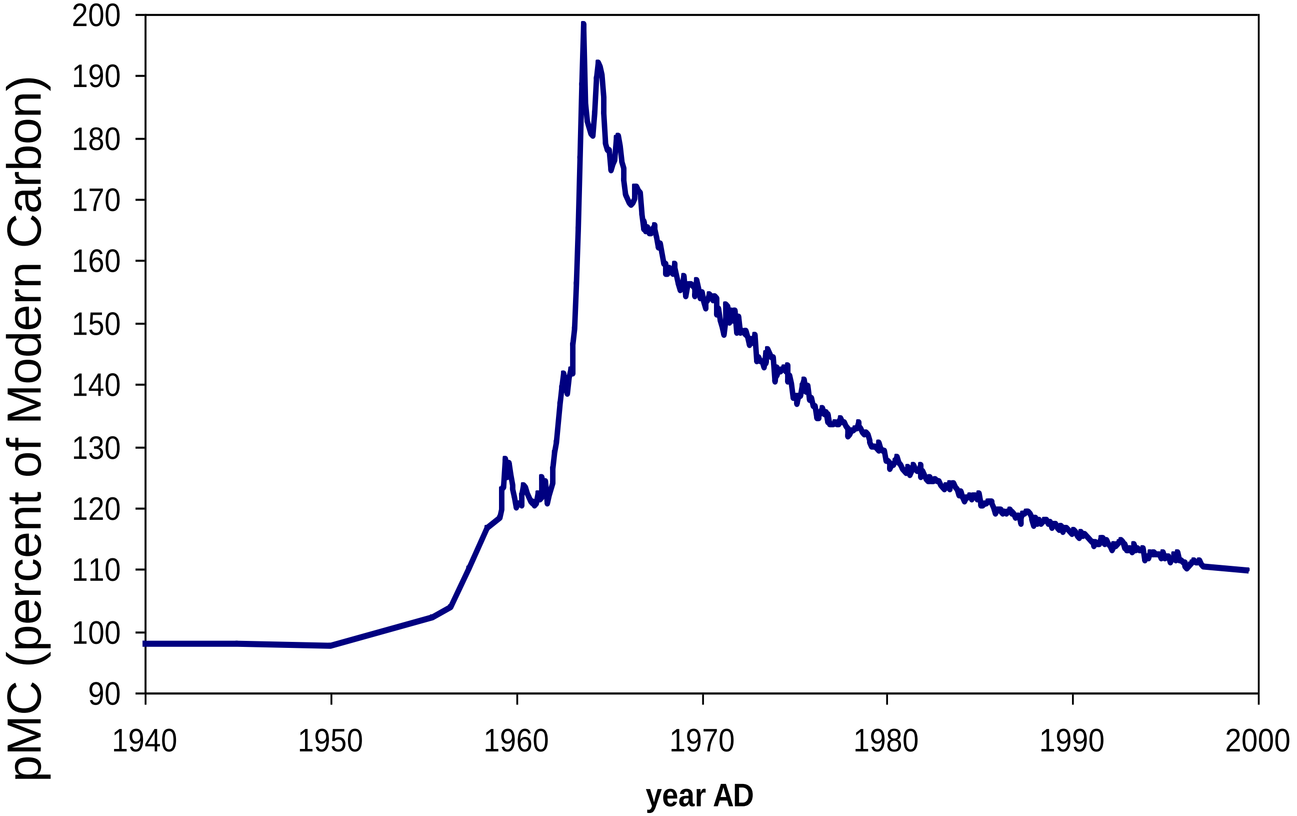
The traditional ^{14}C dating apply to old (or very old!) objects but not only

The shroud of Turin a linen cloth that tradition associates with the crucifixion and burial of Jesus, has undergone numerous scientific tests, the most notable of which is radioactive dating.

In 1988, scientists at three separate laboratories dated samples from the Shroud to a range of 1260–1390 AD, which coincides with the first certain appearance of the shroud in the 1350s and is much later than the burial of Jesus in 30 or 33 AD.

The traditional ^{14}C dating apply to old (or very old!) objects but not only

Nuclear test exposition performed after the second Wold Wor injected a large amount of neutrons in the atmosphere increasing the C-14 concetration.



M.E. Fedi, *et al*, *Nucl. Instr.&Meth.* *B* 294 (2013), 662

The traditional ^{14}C dating apply to old (or very old!) objects but not only

L. Caforio, et al, Eur. Phys. J. Plus (2014) 129: 6

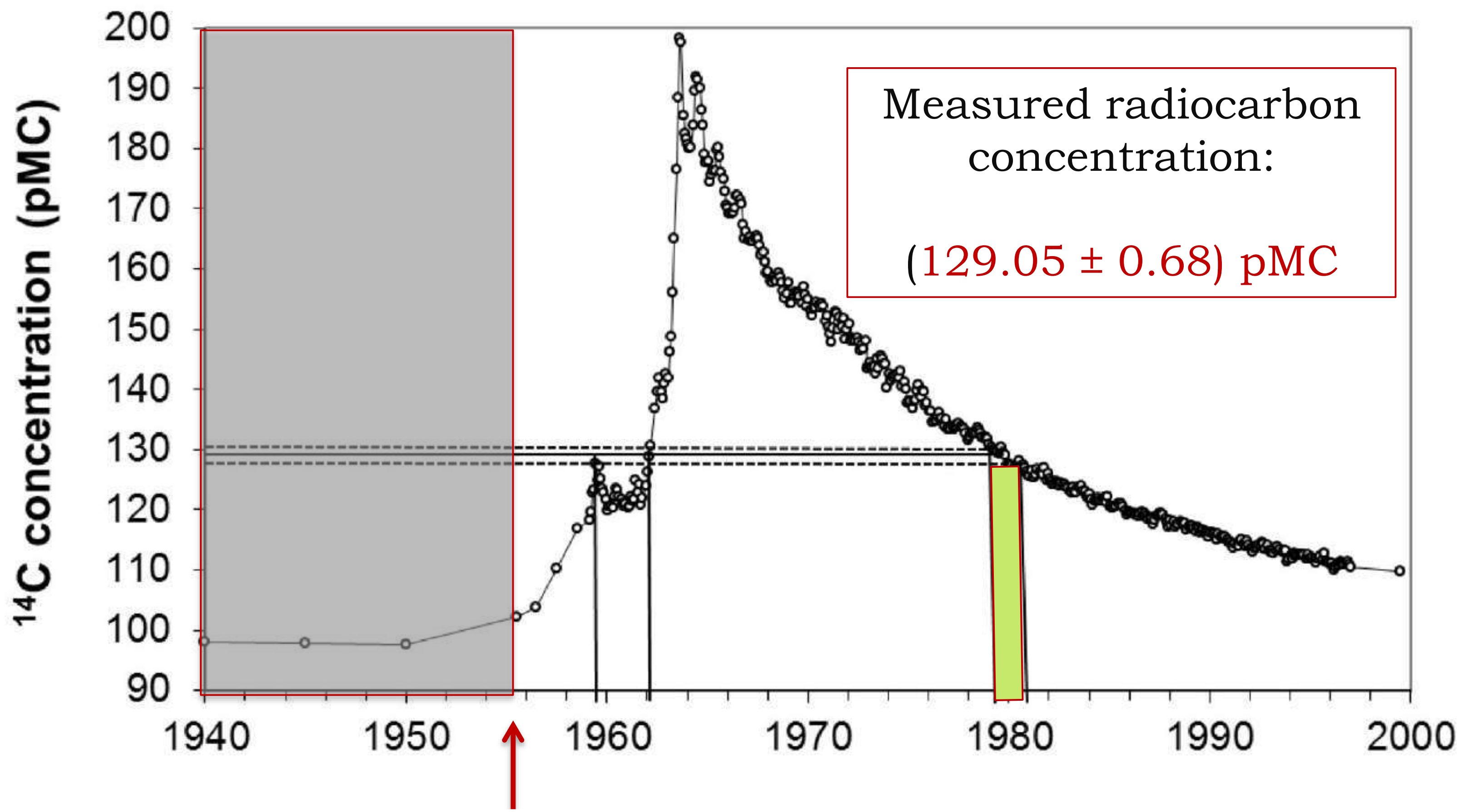
Fernand Léger, (Contraste de Formes)

allegedly painted in 1913-14

Bought by Peggy Guggenheim in the late 1960s

never on display to public because of early suspicions to be a forgery

The canvas was produced using cotton plants cut out in 1959, or 1962, or 1979-80



Léger's death → the painting is a fake

The archeometric methods are at the crossroad of several scientific fields. Supported by sophisticated technologies, refine our vision of the Cultural Heritage world.

C Scirè Calabrisotto, …, M.E. Fedi, *et al*, Radiocarbon, Vol 59, 2017,

This results into a renew interest in analytical pipelines, data management and preservation plan for cultural remains.

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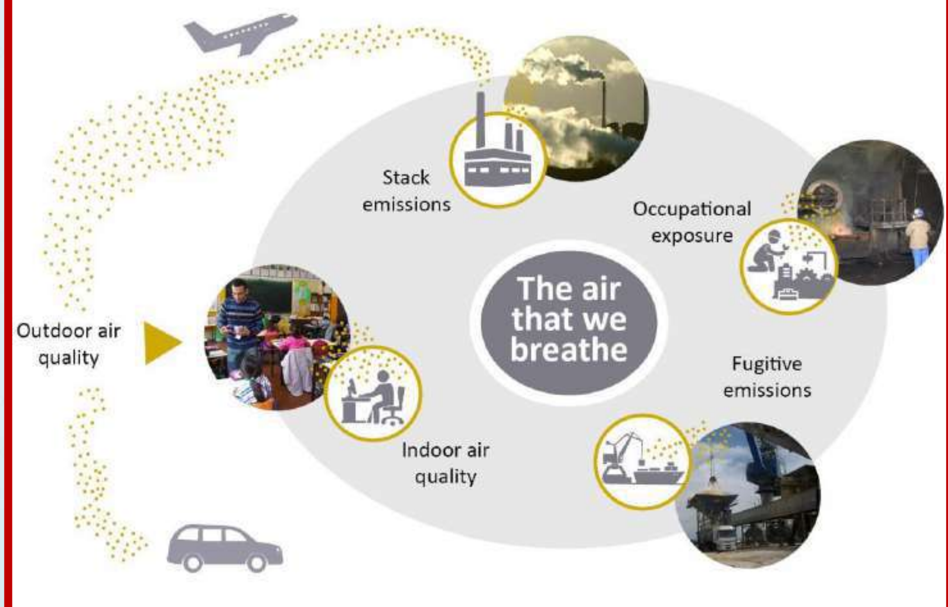
The study of air pollution.

The air that we breath



No matter where we are, indoors at home, school, work,…, the air that we breathe carries airborne particulate matter (APM) (*small particles with a diameter of less than 2.5 μm suspended in the air*) from a variety of sources.

Careful analysis of the APM granulometry and chemical composition can be used to "fingerprint" each source.

The study of air pollution - example France.

Air pollution is responsible for 48,000 deaths each year in France. It is the third leading cause of death in France, after tobacco (78,000 deaths) and alcohol (49,000 deaths).

At the origin of 9% of annual deaths in France, fine particles with a diameter of less than 2.5 micrometers – penetrate deep into the respiratory system and cause many pathologies - cause a loss of life expectancy, which can exceed two years in the most polluted cities

The study of air pollution

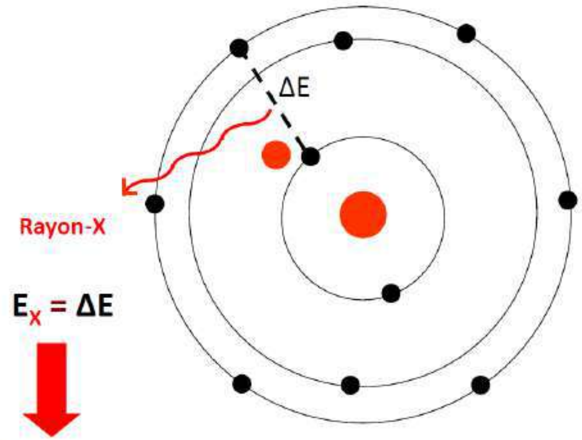
Particle Induced X-ray Emission (PIXE) and Neutron Activation Analysis (NAA) are very often used in air quality studies, due to their high sensitivity to metals and many other elements of interest, from 0.1 ng/m3 (nanogram per cubic meter of air) in favorable cases to 1000 ng/m3, and due to their ease of use.

The study of air pollution - PIXE

Particle Induced X-ray Emission: (PIXE), is sensitive (*to elements from Si to U*) in concentrations at ppm level (part per million).

PIXE belongs to the group of techniques known as Ion Beam Analysis. Beam of ions, normally protons, excites the atoms of the sample, leading to the emission of X-rays which are characteristic of each element.

PIXE: *Particle Induced X-Ray Emission*

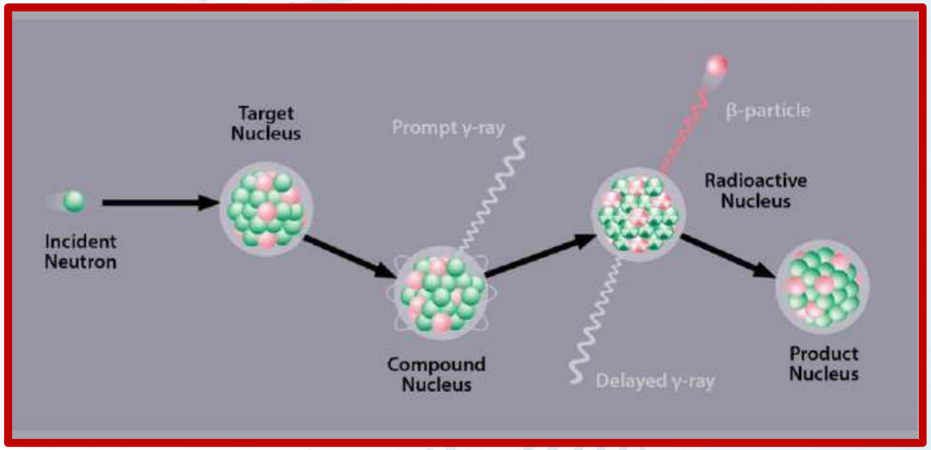


L'énergie des rayons-X est caraqueristique de l'élément.

Varying the energy of the protons, we can probe different depths of the sample.

The study of air pollution

Neutron Activation Analysis : (NAA) is a nuclear analytical technique capable of determining (*depending on the element and on the sample*), concentrations as low as (typically) 1 nanogram to 1 microgram per gram of sample.



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New developments – Compact sources

Neutron technique in civil Security Application

The effectiveness of the custom clearance calls for the balance between two trade-related constrains: *Fluidity and security.*

Until recently only a small fraction of the containers was scanned with X-rays . The X-ray measurements are not able, some times, to solve doubts about the possibility of illicit trafficking, so that unloading and physical inspections are required, with additional costs and time delays.

In case of suspect cargos, the reconciliation between fluidity and security can be achieved implementing new technologies as the neutron based scanning systems as integral part of the custom inspection methodology.

The EURopean Illicit TRAfficking Countermeasures Kit (EURITRACK) inspection system

Explosives are identified by means of fast neutron interrogation given their peculiar carbon-to-oxygen (C/O) and carbon-to-nitrogen (C/N) chemical ratios

In the d+t->α+n fusion reaction, a 14MeV neutron and an alpha particle are emitted almost back to back.

Reflection-set: the neutron generator, the associated particle detector, ….

Top-set: Shielded γ-ray detectors

Transmission-set: Shielded γ-ray detectors and a liquid scintillator,….

The C-BORD helping customs to inspect containerized freight

Within the framework of the C-BORD project, a new generation container inspection system is foreseen, combining advanced X-ray techniques capable of locating objects inside a large volume (cargo container) at a high rate, as well as additional techniques more sensitive to specific substances, such as advanced passive detection technologies, a tagged neutron inspection system, photo-fission technology and artificial sniffing. The data generated by the five technologies is collated in a single graphic user interface for customs decision-making.

This project has received funding from the European Union's Horizon 2020 research and innovation programme. With a budget of 11.8M€, involves 18 partners from nine countries.

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The Australopithecus 2-3myr Ago

Imagine the surprise of the prehistoric man of 2 million years ago suddenly seeing a new sun appearing in the sky much brighter than the everyday one.

The ^{60}Fe story - nucleosynthesis-clock isotope in galactic cosmic rays

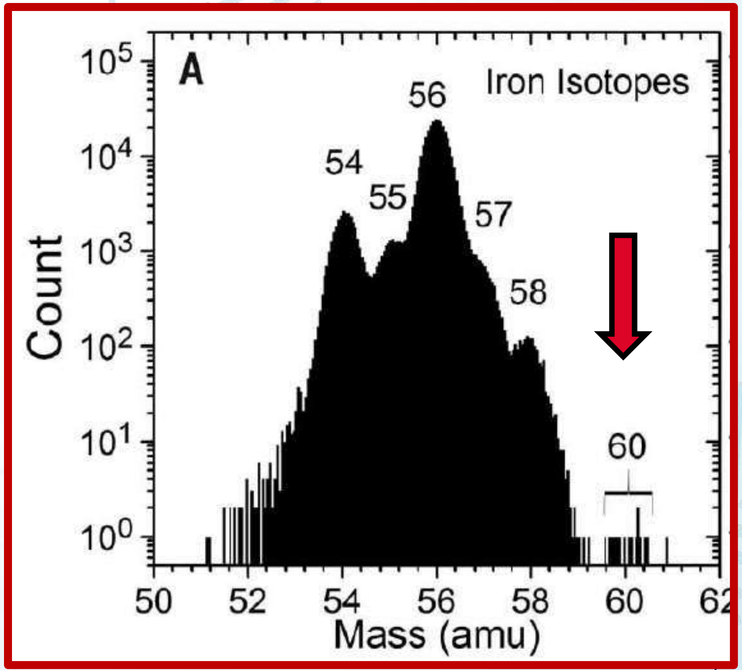
Signature of recent nucleosynthesis: The radioactive isotope ^{60}Fe is expected to be synthesized in core-collapse supernovae of massive stars with mass M > ~10 solar masses and ejected into space by supernovae, and thus be present in galactic cosmic rays near Earth, depending upon the time elapsed since nucleosynthesis and the distance of the supernovae.

It is the only primary radioactive isotope with atomic number Z ≤ 30 produced with a half-life long enough (2,62x10^{6} years) to potentially survive the time interval between nucleosynthesis and detection at Earth.

The ^{60}Fe story - nucleosynthesis-clock isotope in galactic cosmic rays

Deep-sea manganese crusts have been found to harbor elevated ^{60}Fe levels in all major oceans of the world . Analysis of crust layers using accelerator mass spectrometry showed significant increases in the ^{60}Fe/Fe ratio 2.8 million years (My) ago.

It was also detected in lunar samples and in cosmic rays after a long period of data collection (17 years) achieved by the Cosmic Ray Isotope Spectrometer (CRIS) aboard NASA's Advanced Composition Explorer (ACE) space mission.



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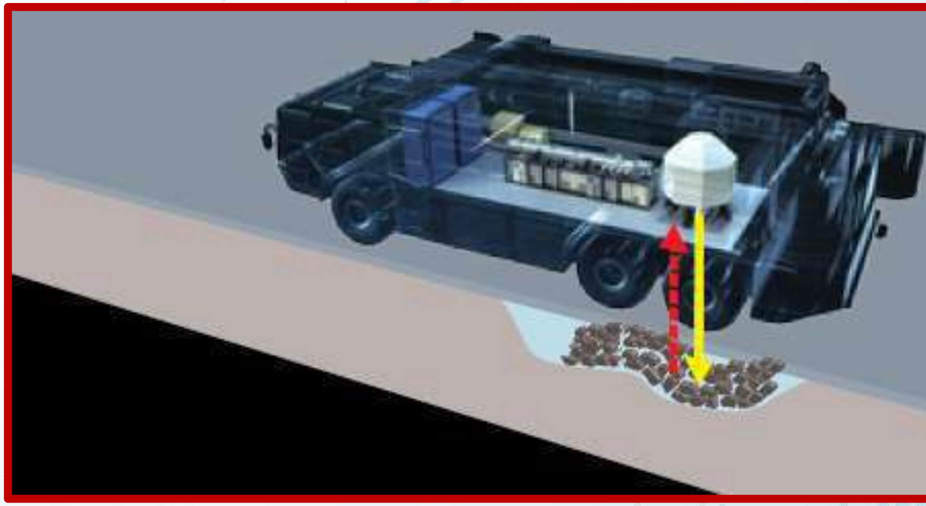
Moradi (Italy) bridge collapse
（2018.8.14） Salt damage

In France at least 25,000 bridges (out of 250,000 bridges) are in poor structural condition and pose safety and availability problems for users

Development of Compact Neutron Sources and Neutron Applications

Development of Compact neutron systems for practical use ! neutrons, anytime, anywhere !!

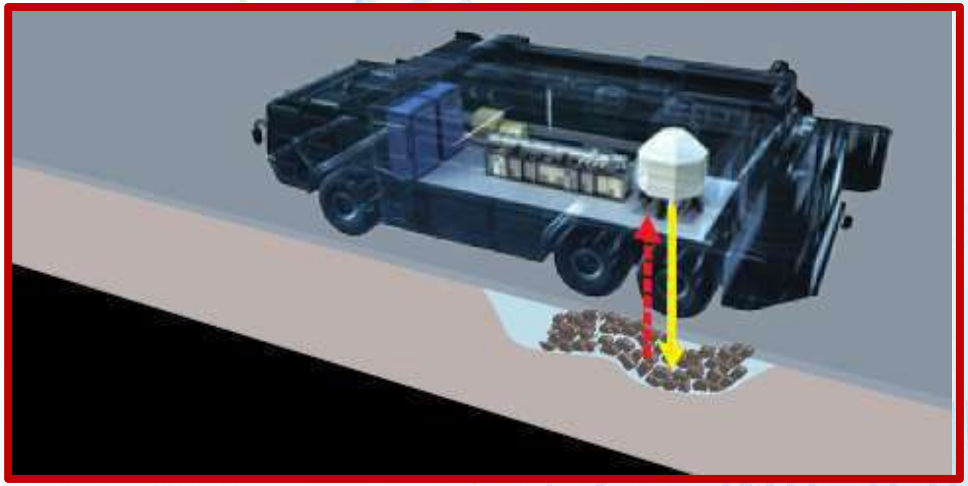
Source and instrumentation are inextricably associated



Non-destructive inspection of large scale infrastructures on-site, out-door.

Transmission neutron measurement

Back scattered neutron measurement



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Emerging facilities in Europe: a Possible project for Greece

www.cea.fr

In the world many new accelerator based facilities are under construction – See two presentations

Commemorative ceremony of the 50th Anniversary of the Physics Department of the University of Ioannina

http://www.physics.uoi.gr/node/1153

In workshops of the Hellenic Institute of Nuclear Physics:

http://hinp.physics.uoi.gr/Workshops.htm

and more specifically in:

http://hinp.physics.uoi.gr/HINPW5/Workshop2019.htm

New facilities around the World.....

http://hinp.physics.uoi.gr/Workshop_2017/Workshop2017.htm

http://hinp.physics.uoi.gr/Workshop_2014/Workshop2014.htm

In Europe many new accelerator based facilities are under construction

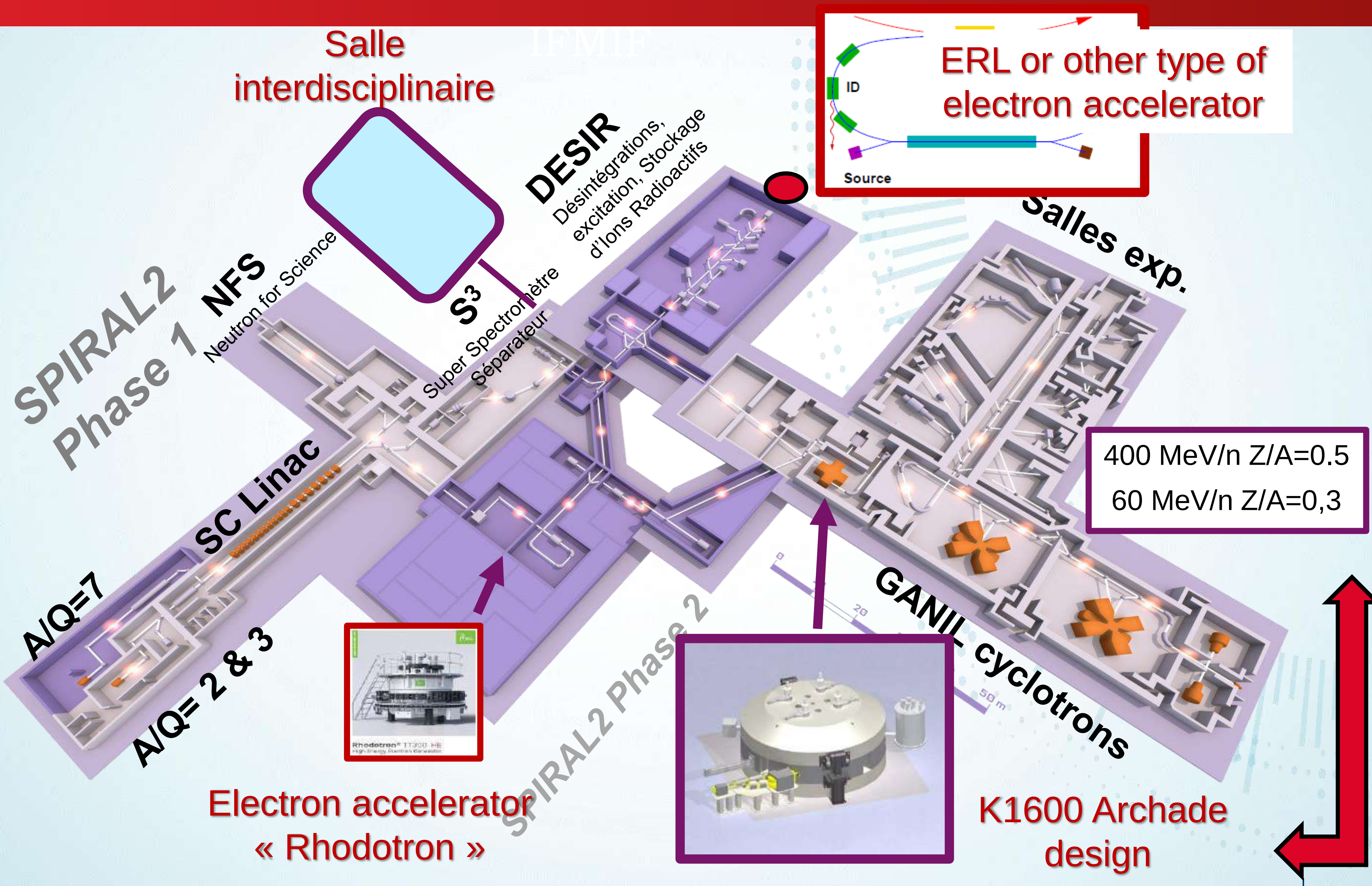
New facilities for fundamental research in nuclear physics *FAIR, GANIL, LEGNARO, ... {……………….}*

For production of radioisotopes or radiation for medical treatment (MYRRHA, …)

Accelerators for neutron production – (SARAF, The Saclay project, DONES, SONATE, ….)

A project for Greece ??

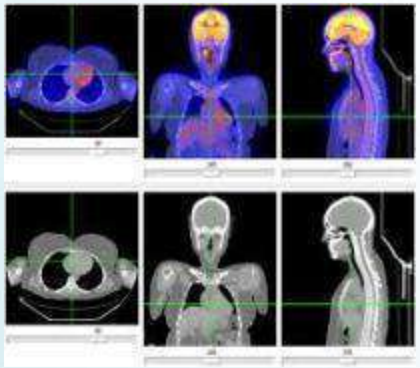
The future du GANIL project



A new paradigm for emerging accelerators –

Accelerator satisfying multiple communities

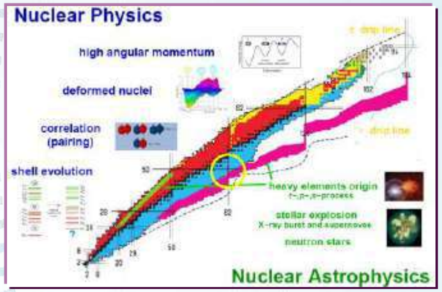
Cyclotron



Radioisotopes for Nuclear Medicine

By Diego Bettoni

SPES at its best



Production of neutron–rich ions from p-induced Fission on UCx (10^{13} f/s)

Accelerator based neutron sources

From this example one can identify the needs in the different domains

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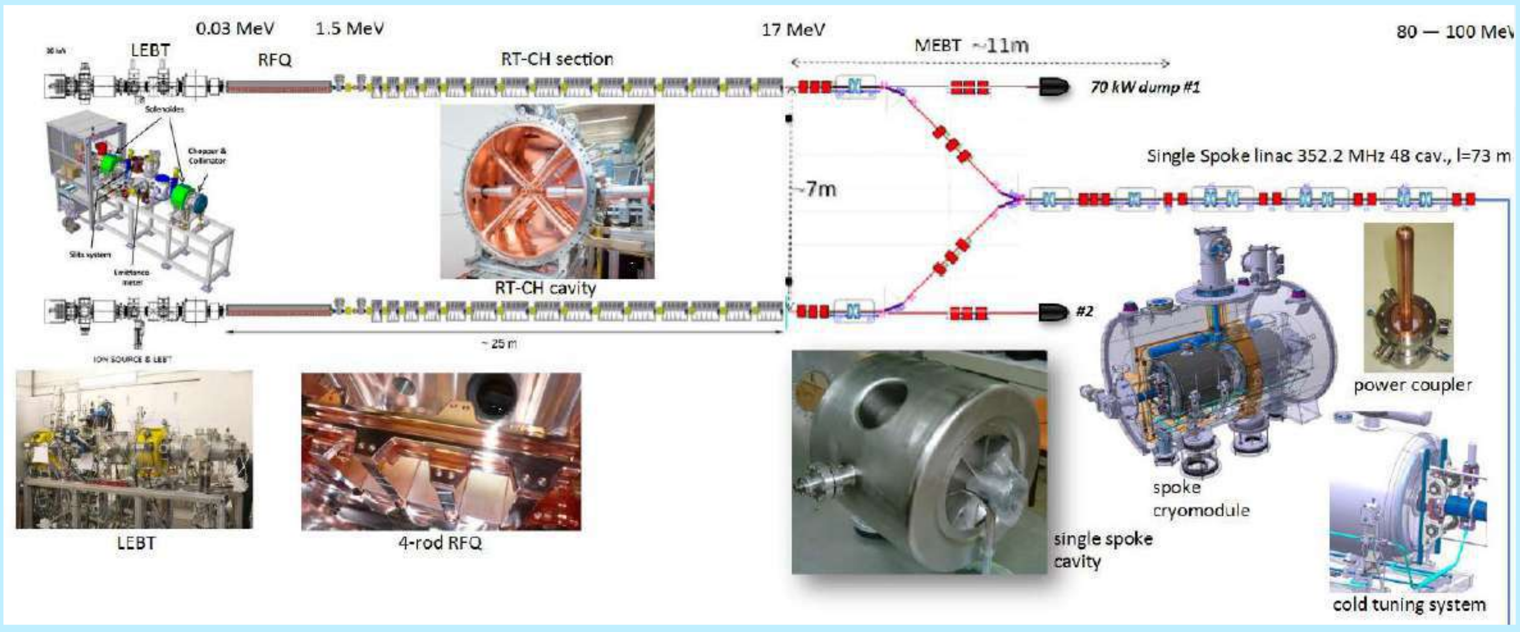
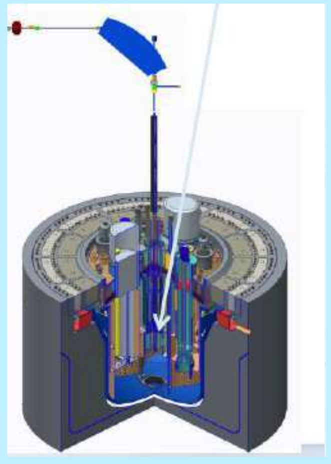
The MYRRHA Facility (Proton beam first step 100MeV final step of ~600MeV of 4mA)

The (ADS), are subcritical reactors, where the missing neutrons are supplied by an external source.

MYRRHA





Phase 1 ('18-'24) – 100 MeV accelerator & ISOL Target Station

Phase 2 ('25-'30) – 600 MeV extension and Reactor

Approved: Phase 1, 100MeV Accelerator and ISOL Target station

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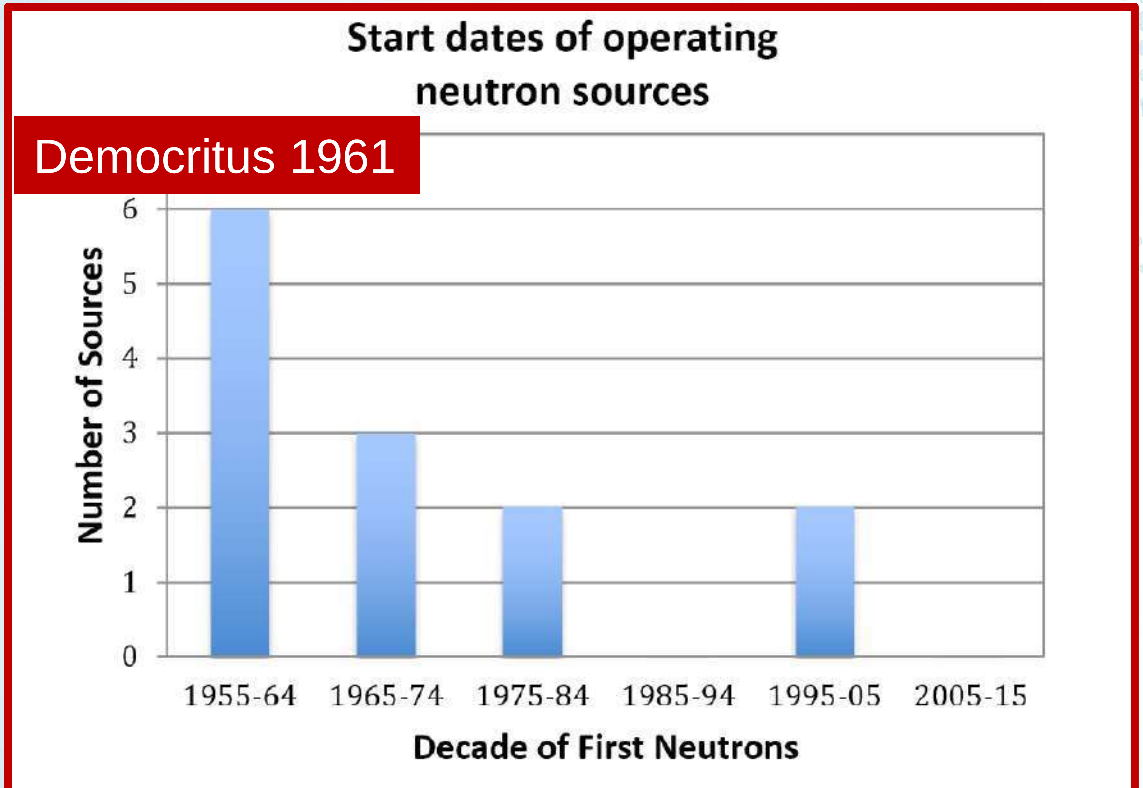
ESFRI Physical Sciences and Engineering Strategy : Neutron Land scape Group/2016



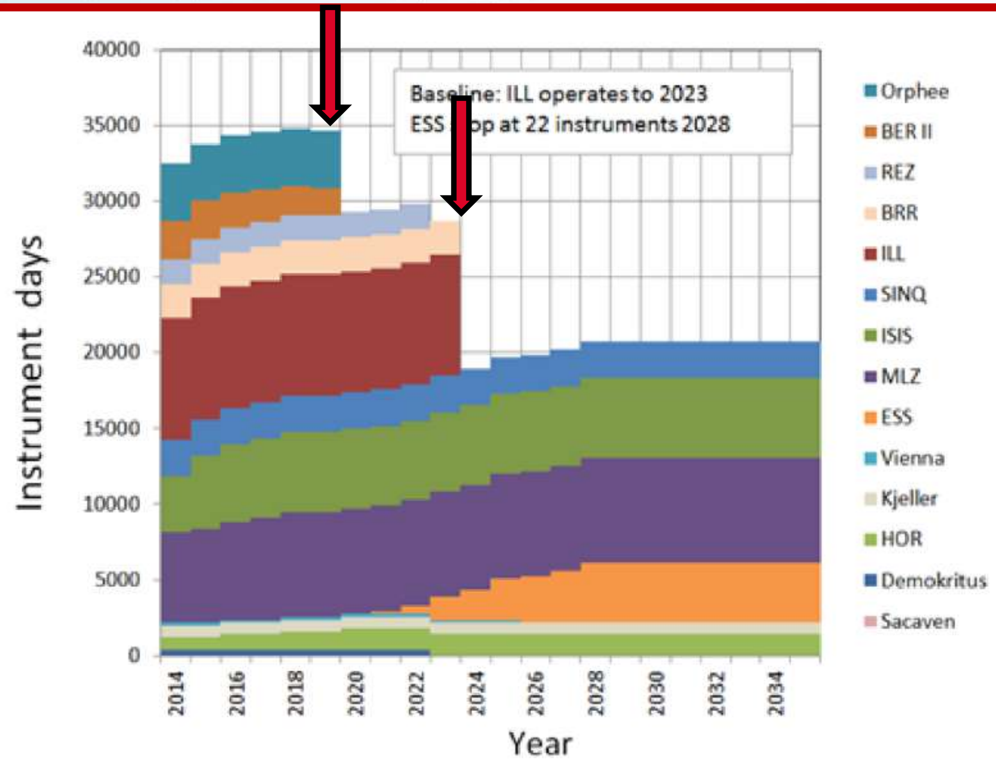
Among the more recent neutron sources

1998 - SINQ: The Swiss Spallation Neutron Source
And
2004 - FRM II (MLZ)
The Heinz Maier-Leibnitz Zentrum

Replacement value for the sources build before 1985: ~ <5000M€

The estimation is difficult, for instance the price of Democritus was evaluated at ~50M€

Neutron Sources



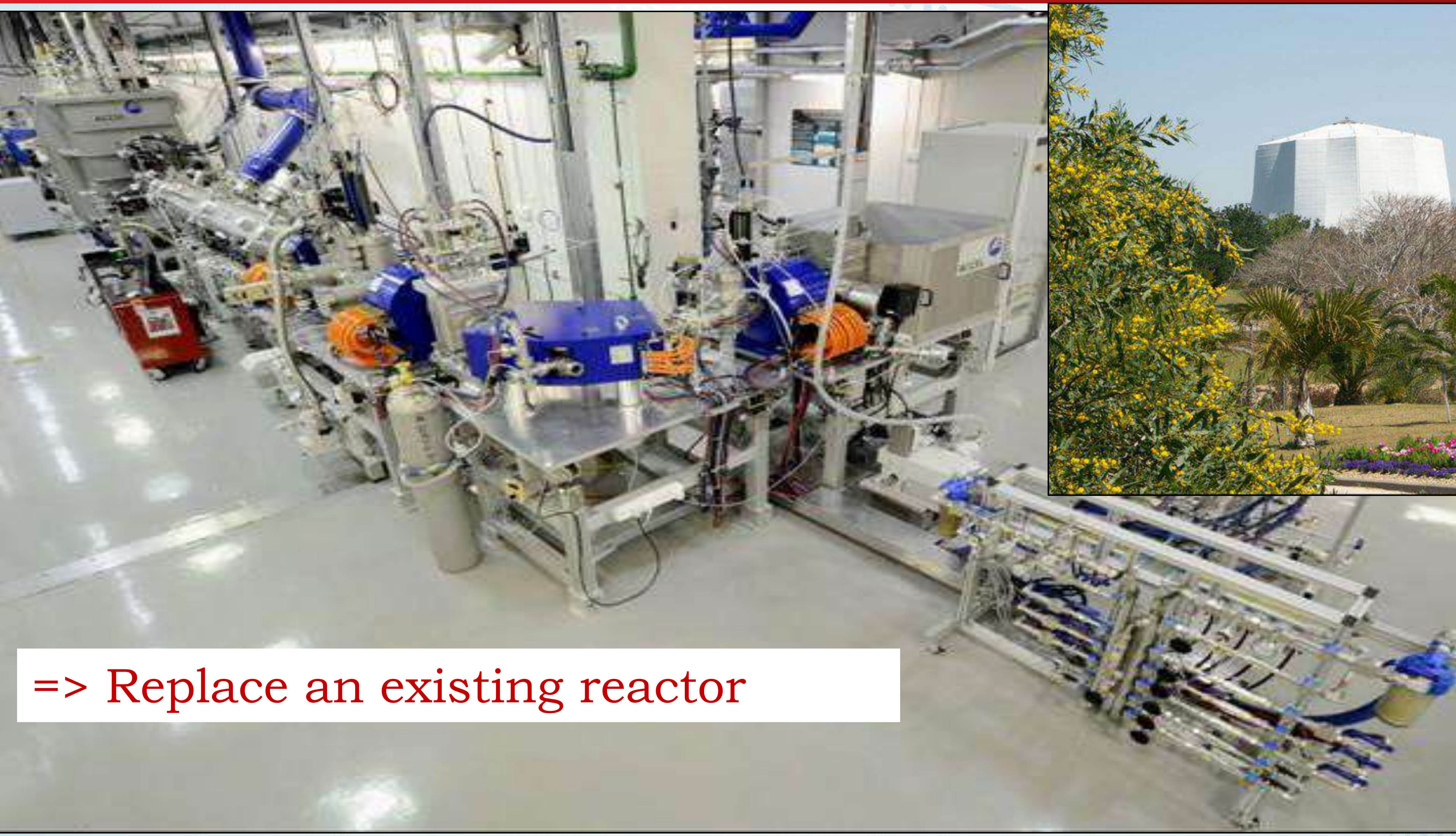
The predicted delivery of instrument beam days in the baseline scenario

The 2020 drop is due to the closure of the Berlin and Saclay reactors.

The 2020- 2023 drop is due to the closure of Budapest, Rez and ILL.

Note that extensions to the lifetime of these facilities, depend upon financial and political considerations

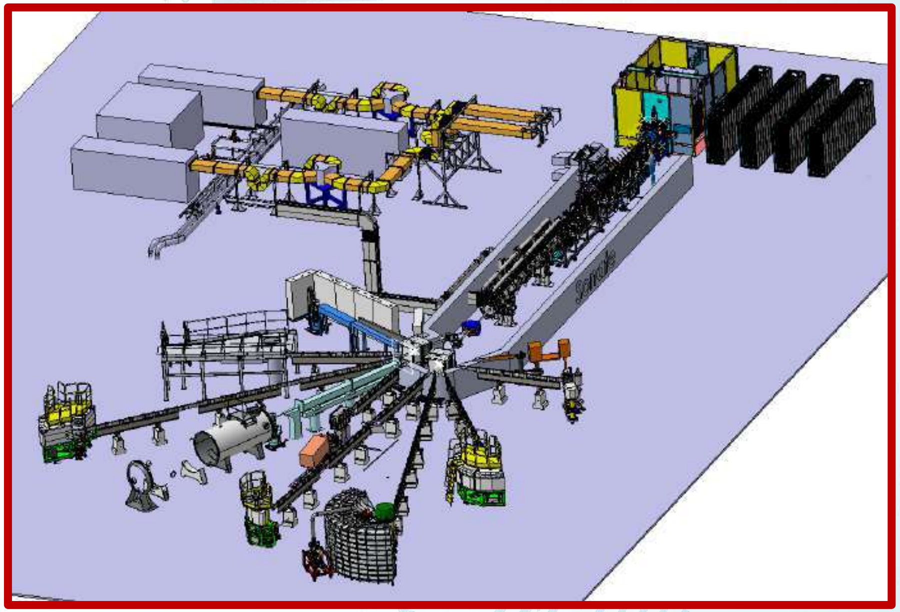
SARAF TLR : beams: p, and d (5mA, 40MeV)



=> Replace an existing reactor

Replacing aging reactors by compact accelerator neutron sources

IPHI at SACLAY (~3MeV, 100 mA, cw/pulsed) will replace the ORPHE reactor



A. Sgouros, V. Soukeras and Prof. A. Pakou have evaluated for low energy proton beams impinging on thick ^{7}Li and ^{9}Be targets the neutron production rates, validating our empirical IPHI neutron beam calculations. *A letter to the editor Eur. Phys. J. A, 57 4 (2021) 125.*

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An accelerator for Greece?

I really think that the nuclear physics community in Greece could well seize this very favorable situation around nuclear physics and its applications in Europe and propose a national project that could be financed in large part by European budgets and built through European collaborations ….

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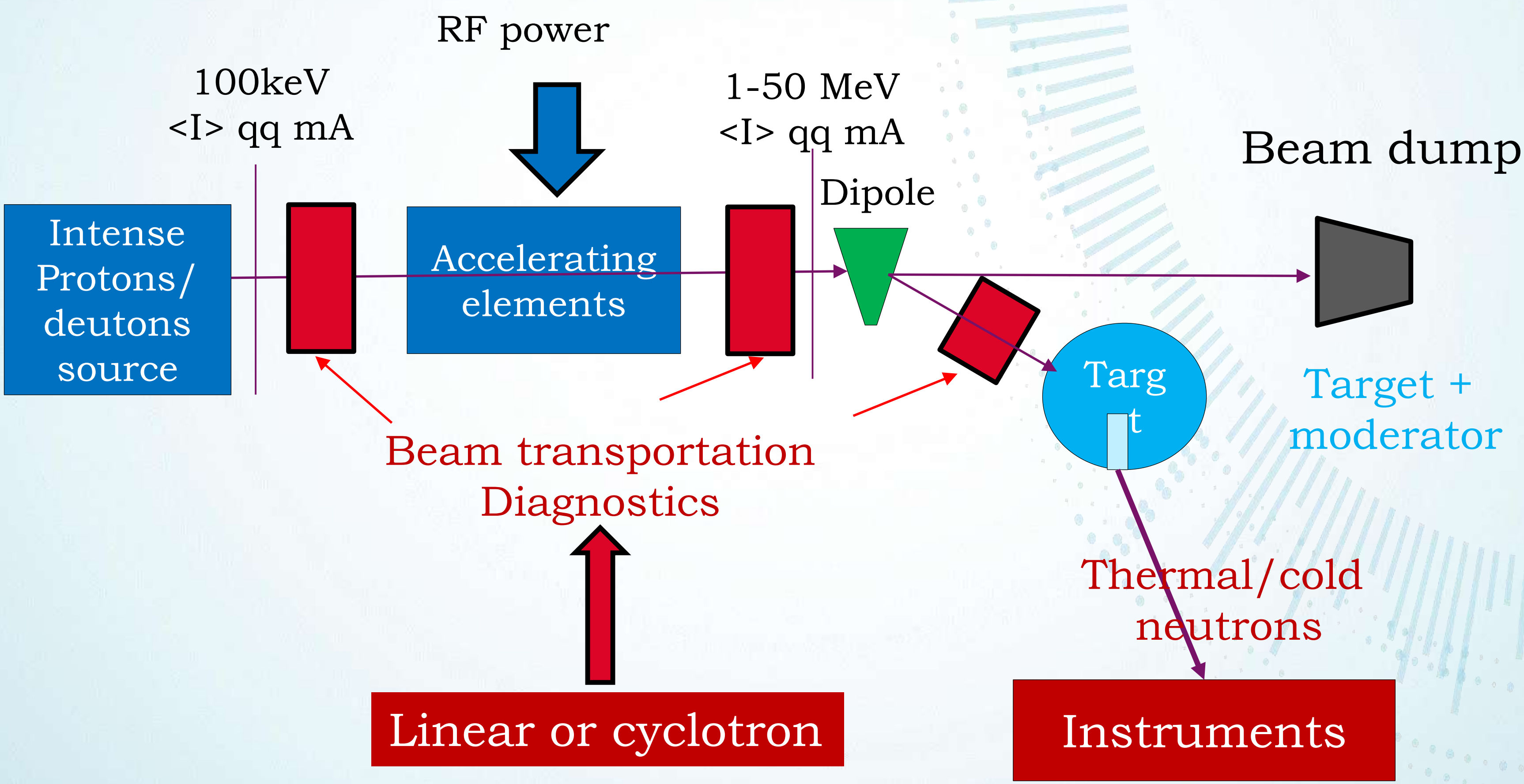
I really think that the nuclear physics community in Greece could well seize this very favorable situation around nuclear physics and its applications in Europe and propose a national project that could be financed in large part by European budgets and built through European collaborations ….

A project of this nature should boost not only nuclear physics but the ensemble of the communities that use its techniques. It would help to create a multicultural center and keep young scientists in Greece! In Democritus or elsewhere ? it is up to the community and the politicians to decide?

An accelerator in Greece for the replacement (partially) of Democritus (1961) and other activities



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Thank you