Ionising radiation, its measurement and interactions

The Foundation Course on Physics

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Revisiting Basic Knowledge – Atomic Nucleus

Composition of the atomic nucleus:
Particles inside the atomic nucleus – neutrons and protons = nucleons.
Attracted by the „strong interaction“.
Nuclei are characterised mainly by:
Atomic (or **proton**) **number** *Z* – number of protons inside a nucleus.
Neutron number *N* – number of neutrons inside a nucleus.
Atomic mass (or **nucleon**) **number** *A* – number of nucleons inside a nucleus.

$$A = Z + N$$

Example: $^{235}_{92}U$

The electric charge of a nucleus is:
$Q_{nuc} = Z \cdot e$,
where e is the elementary charge (electric charge of one electron or proton, 1.602×10^{-19} C).

Revisiting Basic Knowledge – Atomic Nucleus

An **element** is a substance the nuclei of which are made up of the same number of protons (number Z is the same in all the nuclei).

A **nuclide** is a substance the nuclei of which are of identical composition (numbers Z and N have the same values in all the nuclei).

Isotopes are nuclides the nuclei of which have the same number Z but they differ in number of neutrons.

Isotopes have very similar chemical properties because they possess identical electron shells.

Isotopes are often denoted by the name of the chemical element followed by the respective nucleon number A. For example:

carbon-12, carbon-14 or uranium-235, uranium-238 etc.

Revisiting Basic Knowledge – Atomic Nucleus

The nucleons are bound by the “strong interaction”. The **binding energy** E_{nuc} is the energy just necessary to disintegrate the nucleus into individual nucleons. During synthesis of nuclei *the same* amount of energy is liberated.

The greater the binding energy the more stable is the nucleus.

This energy can be calculated from the mass difference (defect or excess):

$$\Delta m = Zm_p + Nm_n - m_{nuc}$$ *and*

Einstein’s formula of **mass – energy equivalence:**

$$E_b = \Delta mc^2$$

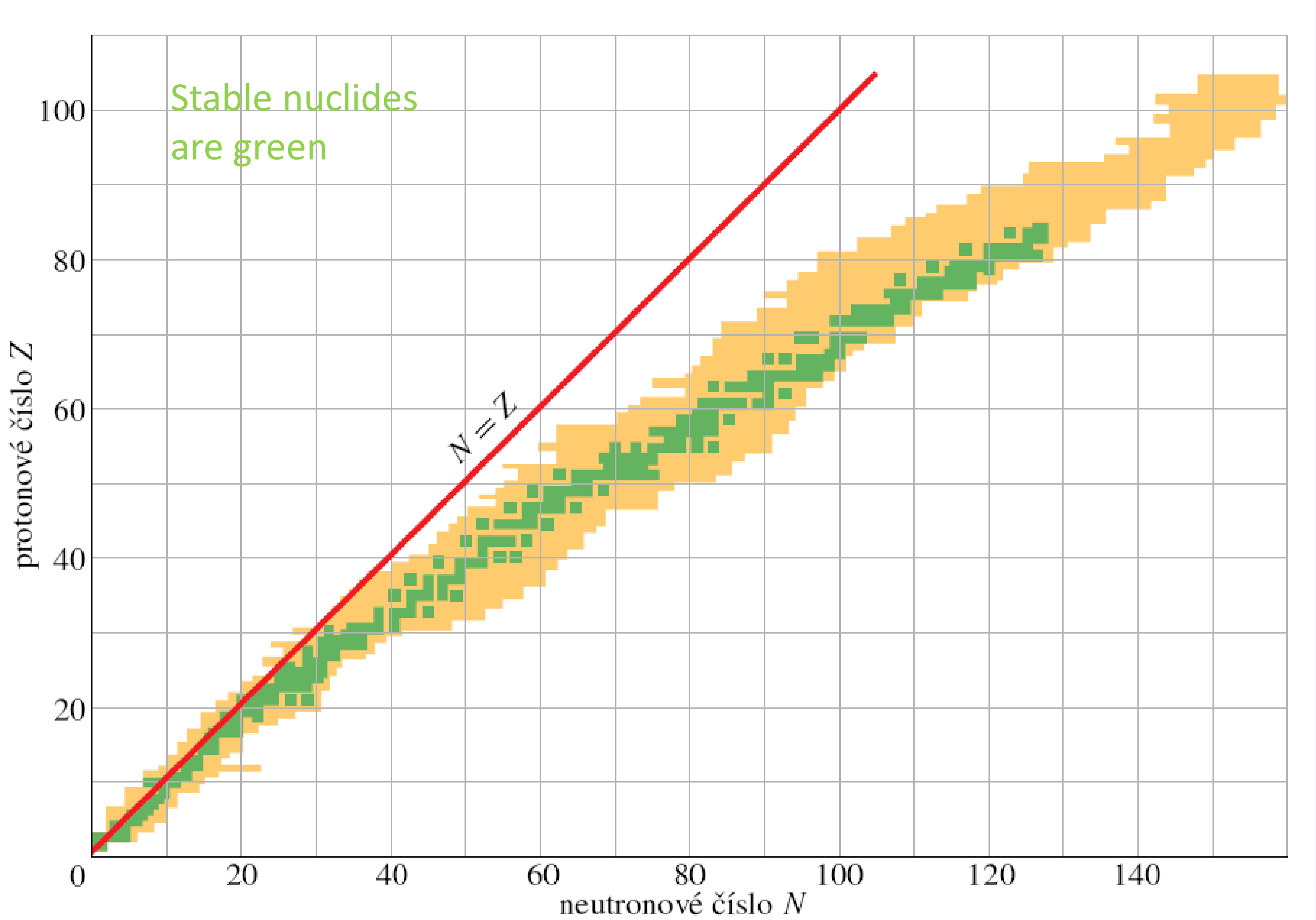
Revisiting the Basic Knowledge – Atomic Nucleus

Nuclear fission – chain reaction – nuclear reactor
Importance for production of energy and also some radionuclides used in medicine

Natural and artificial radioactivity:
Radioactivity is the ability of a nucleus to emit particles or quanta of energy. This process is also called **radioactive decay** or disintegration.

Radioactive nuclides are called **radionuclides** (about 2000 radionuclides have been identified in nature or prepared artificially). The radioactivity is accompanied by **nuclear transformation**. It means that during the radioactive decay new (daughter) nuclei arise.

Stability of the Nucleus



Revisiting the Basic Knowledge – Atomic Nucleus

We distinguish several types of radioactive decay according to the particles produced:

α (alpha)-radiation: Helium nuclei. They are electrically charged (+2*e* charge) and cause direct ionization of ambient atoms, and have very short track. It means that this radiation is little penetrating.

β^- (beta-minus)-radiation: Electrons. One neutron is transformed into a proton, an electron and a very light particle "electron antineutrino". Interaction of β^- particles with matter is like origin of X-rays. They have relatively low ionization ability hence they penetrate easier into matter in comparison with α-particles.

β^+ (beta-plus)-radiation: Positrons - antiparticles of the electrons. One proton is transformed into a neutron, a positron and "positron neutrino"

γ (gamma)-radiation: High energy photons. A nucleus with some excess energy emits a photon. The γ-emission often accompanies other types of radioactive decay. Its ionization ability is relatively low hence it penetrates deep into matter. Remember photoelectric effect and Compton scatter.

Neutron radiation: A neutron is emitted from a radionuclide or can be liberated after collision of two accelerated nuclei. Neutrons ionize matter indirectly. Fast neutrons transmit their energy by impacts. This process is highly effective in collisions with light nuclei. Moderated (slow, thermal) neutrons can enter some heavy nuclei and cause their disintegration – fission.

Proton radiation: Protons are emitted from a radionuclide, or liberated after collision of two accelerated nuclei.

Revisiting the Basic Knowledge – Atomic Nucleus

Laws valid for radioactive decay

- Law of mass-energy conservation
- Law of electric charge conservation
- Law of nucleon number conservation
- Law of momentum conservation

Law of Radioactive Decay

The activity *A* of a radioactive sample at a given time ($A = \Delta N/\Delta t$) is proportional to the total number of *undecayed* nuclei present in the sample. Then we can obtain by integration:

$$N_t = N_0 . e^{-\lambda . t}$$

A more useful equation for medicine is (obtained by dividing the above equation by Δt on both sides):

$$A_t = A_0 . e^{-\lambda . t}$$

λ is the decay or transformation constant, *A is activity.* The negative sign indicates that the number of *undecayed* nuclei is decreasing.

Unit of *A* is **becquerel (Bq) [1 disintegration per second, s^{-1}]**

(in the past: curie, 1 Ci = 3.7×10^{10} Bq)

Physical Half-Life

T_f – time in which the sample activity A_t decreases to one half of the initial value A_0. Derivation:

$$A_0/2 = A_0.e^{-\lambda.T_f} \quad \text{thus} \quad ½ = e^{-\lambda.T_f}$$

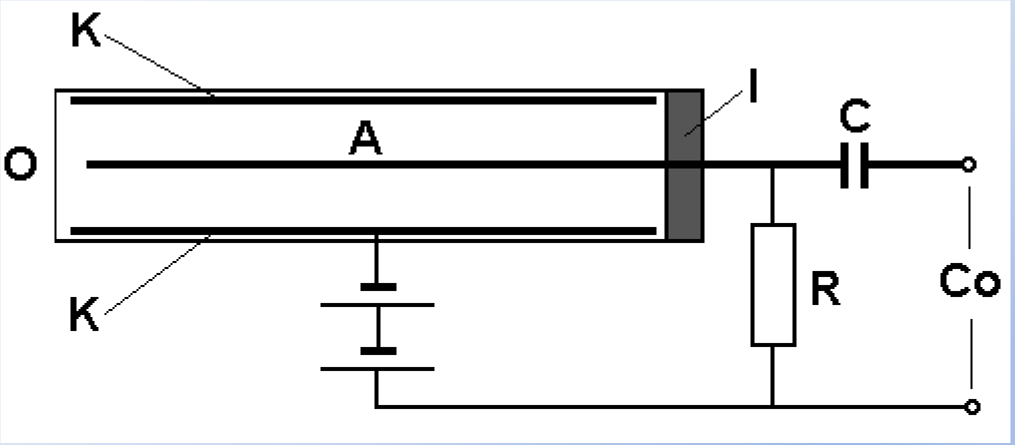
- taking logarithm of both sides of the equation and rewriting:

$$T_f = \ln 2/\lambda_f \qquad \text{thus} \quad T_f = 0{,}693/\lambda_f$$

Detection and Measurement of Ionizing Radiation

- We will briefly mention some of the most important **dosimetric methods** and **detectors** of ionizing radiation. All of them are based on the ability of radiation to ionize or to form free radicals.
- Medicine, industry, environmental applications ....

Geiger-Müller Counter



K - cylindrical cathode, A - anode central wire, O - window, I - insulator, R - working resistor, C - capacitor of the capacity coupling, Co - counter connectors.

The Geiger-Müller (GM) counter consists of a GM tube, a source of high direct voltage, and an electronic counter of pulses. The GM tube is a metallic hollow cylinder which acts as a cathode. The central wire is the positively charged anode. The GM tube is usually filled by argon and 10 % of the **quenching agent**. This agent stops (quenches) the ion multiplication process, and so prevents the formation of an electric discharge between the anode and cathode. The duration of ion avalanche is short, about 5 ms. However, during this time the tube is not able to detect another particle of ionising radiation. This **dead time** is an important characteristic of GM tubes.

Scintillation Counter

The **scintillation counter** consists of a **scintillator** – a crystal which produces light after irradiation by ionizing radiation. The scintillator is in a light-proof housing. One side of the housing is transparent, hence the originating photons can come to a **photomultiplier**, which measures low-intensity light.

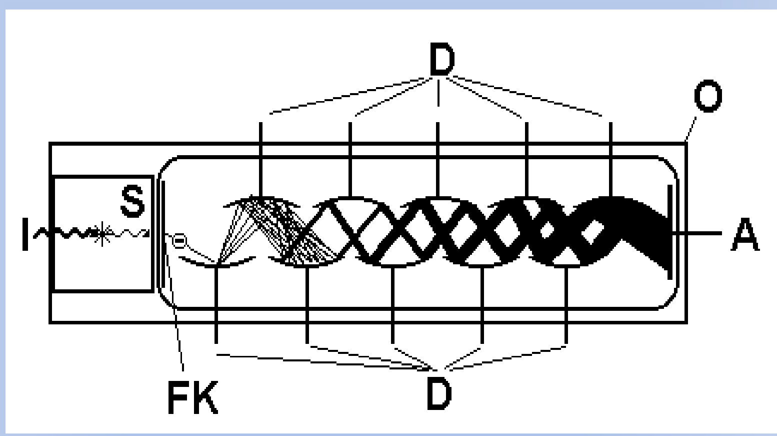


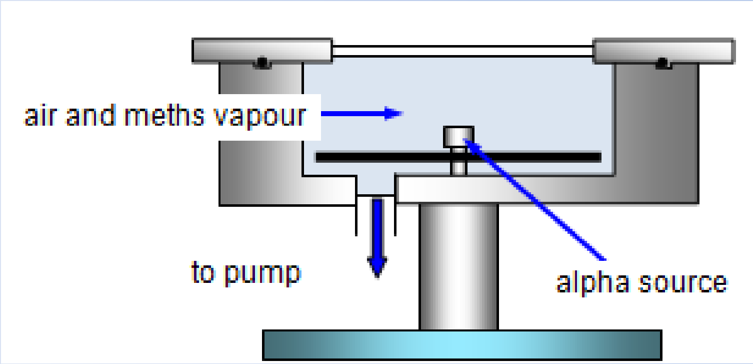
Fig. 38. The scintillation detector. I - ionising radiation particle (photon), S - scintillator, FK - photocathode, D - dynodes, A - anode, O - light-proof housing.

The photons hit the **photocathode** – a thin layer of a metal like caesium. Ejected electrons are accelerated towards the closest positively charged electrode, the first **dynode**. There are some more electrons ejected. These secondary electrons are attracted to the next dynode, where the process is repeated. Resulting voltage pulses are counted in the electronic part. The magnitude of the pulse depends on by the *energy* of the ionising particle!

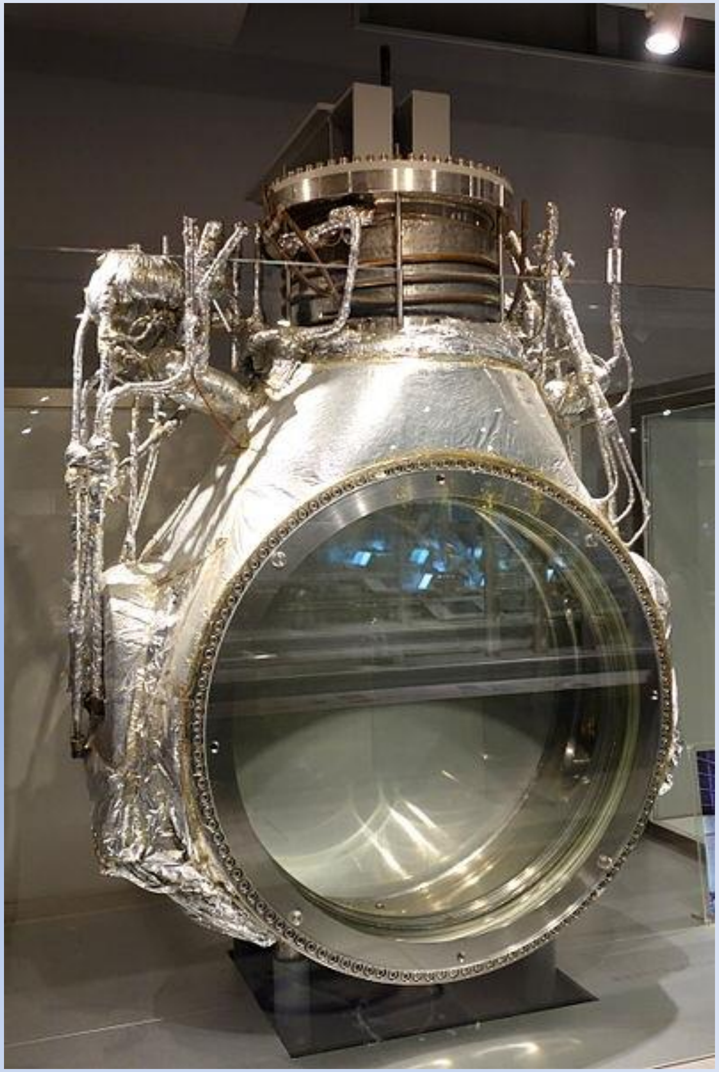
Cloud and Bubble Chambers

- **Wilson cloud chamber** (or **fog trail apparatus**) is used for visualization of the trajectory of ionizing particles. These chambers are filled with an *oversaturated* vapour (water or alcohol). The ions formed along the particle trajectory serve as centres of condensation. So the particle trail can be seen as a series of small droplets – the fog trail. It is possible to follow collisions of particles with neutral atoms, their disintegration etc. The magnetic or electric field in the chamber enables to determine the charge and velocity of the particle.
- In the **bubble chamber**, a similar principle is exploited. The particles of ionizing radiation move in a vessel filled by an *overheated* liquid. The ions formed serve as centres of evaporation. It is possible to see the trajectory of the particle as a series of small bubbles.

Cloud and Bubble Chambers



Video:
https://www.youtube.com/watch?v=NeydrHKvpYM

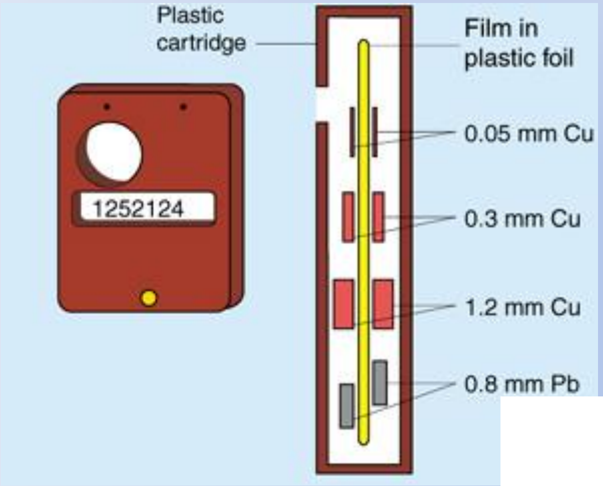


Hydrogen bubble chamber, diameter 1 meter, National Laboratory for High Energy Physics (KEK), built 1971-1975 - National Museum of Nature and Science, Tokyo - DSC07799.JPG

Personal Dosimeters

- **Photographic films** are sensitive to the action of ionizing radiation which causes a local blackening of the film. These (thick-layered) films were also used in scientific research to follow trajectories of ionizing particles. Blackening of the film can be used also for determination of the dose of radiation absorbed by people working with sources of ionizing radiation.
- Some contemporary **personal dosimeters** are based on **thermoluminescence** principle. The irradiated material is heated and light is produced which amount depends on the dose of radiation absorbed in the material.

Personal Dosimeters - Badges



Interaction of Ionising Radiation with Matter

- The interaction of radiation with matter is usually accompanied by the formation of **secondary radiation** which differs from the primary radiation in lower energy and often also in kind of particles.
- Primary or secondary radiation directly or indirectly **ionises** the medium, and creates also **free radicals**.
- A big portion of the radiation energy is always transformed into **heat**.
- The energy loss of the particles of primary radiation is characterised by means of LET, **linear energy transfer,** i.e. energy loss of the particle in given medium per unit length of its trajectory. The higher the LET the more damaging is the radiation to humans.

Attenuation of X / Gamma Radiation

When a beam of X or gamma radiation passes through a substance:

absorption + scattering = attenuation

$$I = I_0 . e^{-\mu . x}$$

I is intensity of radiation passed through the layer of thickness *x*, I_0 is the intensity of incident radiation, μ is **linear coefficient of attenuation** [m^{-1}] (depending on photon energy, atomic number of medium and its density).

Electron - Positron Pair Production

- **WE KNOW ALREADY: Photoelectric effect and Compton scatter!!!**

- **For very high energy photons only:** The energy of the photon is transformed into mass and kinetic energy of an electron and positron. The mass-energy E in each particle:

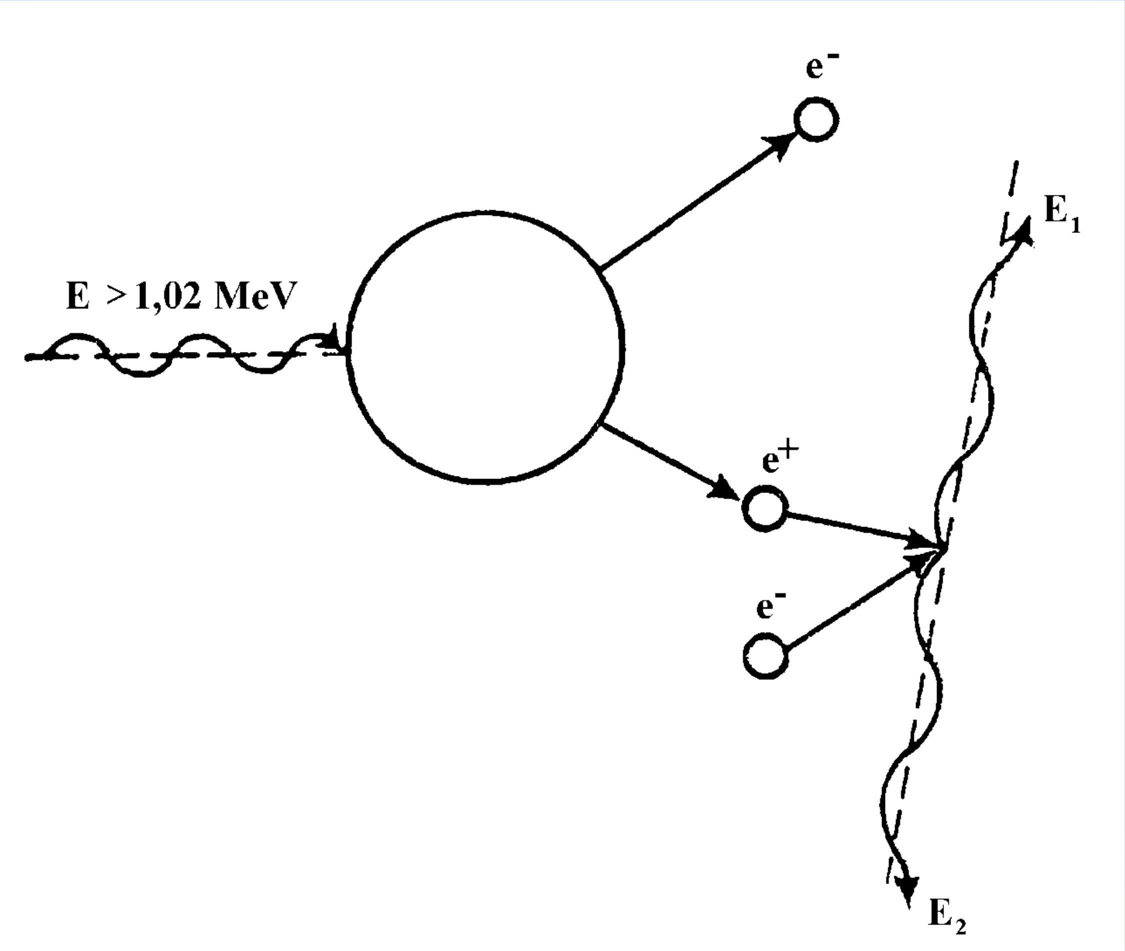
  $$E = m_0 c^2 \text{ (= 0,51 MeV)},$$

  m_0 is rest mass of an electron or positron, c is speed of light in vacuum. Energy of the photon must be higher than *twice* the energy calculated above (1.02 MeV). Thus:

  $$E = h.f = (m_0.c^2 + E_{k1}) + (m_0.c^2 + E_{k2})$$

- Terms in brackets: mass-energies of created particles, E_{k1} a E_{k2} kinetic energies of these particles.
- The positron quickly interacts (annihilates) with any nearby electron, and two photons originate, each with energy of 0.51 MeV.

Electron - Positron Pair Production



Interaction of Corpuscular Radiation with Matter

- β **radiation** = fast electrons or positrons – ionise the medium as in X-ray production. Trajectory of a β particle is some mm or cm in water.

- α **radiation** ionises directly by impacts. There are formed many ions along its very short trajectory in medium (μm) – it loses energy very quickly (= very high LET) .

- **Neutrons** ionise by *elastic* and *non-elastic* impacts (scatter) with atom nuclei. When a **fast neutron** hits the nucleus of a heavy element, it bounces off almost without energy loss. Collisions with light nuclei lead to big energy losses. In **non-elastic scatter**, the slow **(moderated, thermal) neutrons** penetrate into the nucleus. Among others, they can lead to the emission of other particles or fission of heavy nuclei.

Main Quantities and Units for Measurement of Ionising Radiation

A single particle energy is very small → the **electron volt** (eV) was introduced.

1 eV is the kinetic energy of an electron accelerated from rest by electrostatic field of the potential difference of 1 volt.

$$1\ eV = 1.602 \times 10^{-19}\ J.$$

Energy absorbed by the medium is described by **absorbed dose (D)** - unit **gray, Gy**). It is the amount of energy absorbed per 1 kg of matter. Gray = $J.kg^{-1}$

Dose rate is the absorbed dose in unit time [$J.kg^{-1}.s^{-1}$]. The same absorbed dose can be reached at different dose rates during in different times.

The biological radiation hazard depends mainly on the absorbed dose and kind of radiation. The **radiation weighting factor** is a number indicating how hazardous a type of radiation is (the higher the LET the higher the radiation weighting factor).

Equivalent dose D_e is defined as the product of the absorbed dose and the radiation weighting factor. The unit of Equivalent dose is the **sievert (Sv).**

Biological Effects of Ionising Radiation

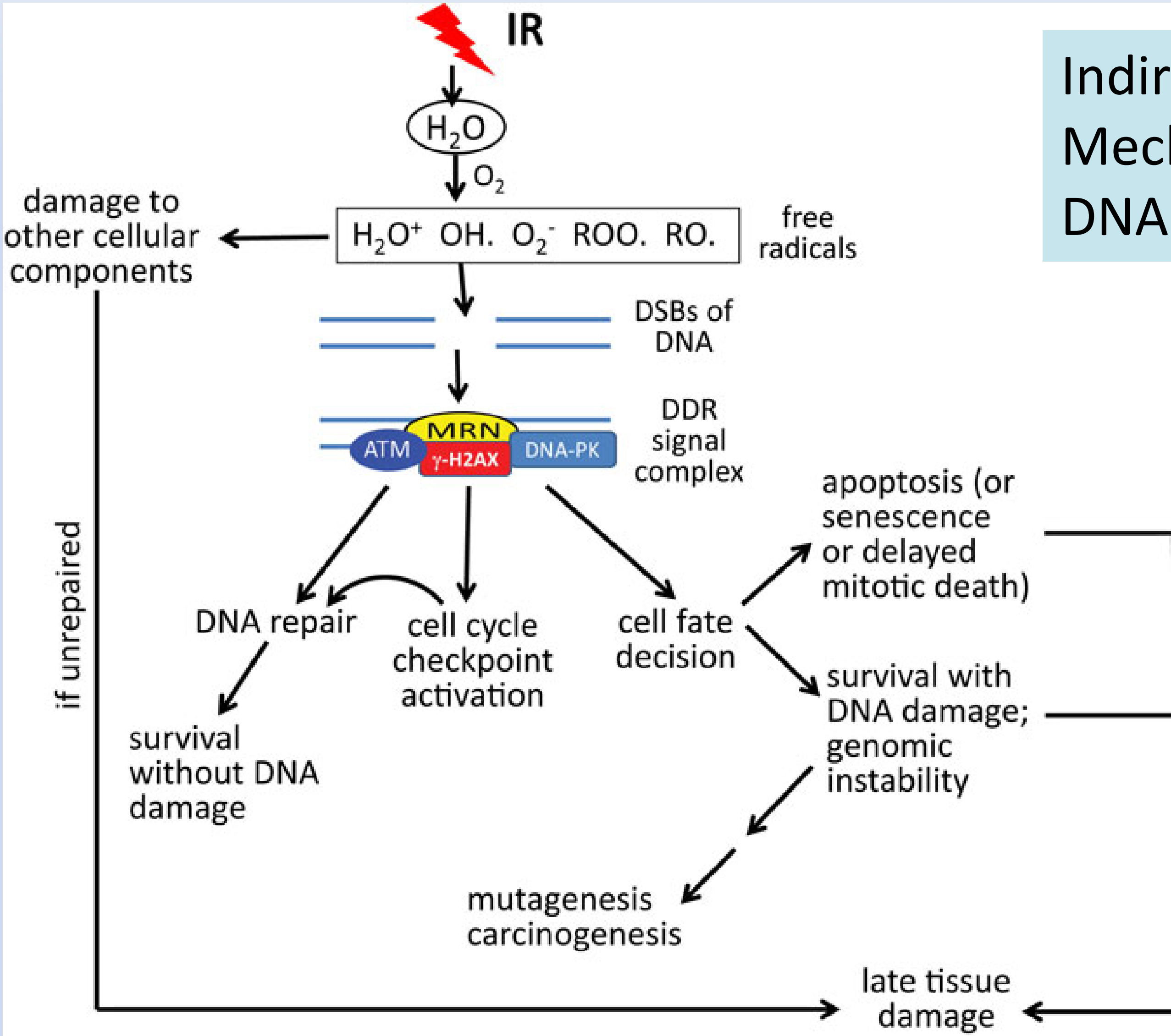
- All kinds of nuclear radiation, together with X-rays, are called **ionizing radiation** because they ionize atoms along their tracks (trajectories) through matter. Even more dangerous products of ionising radiation are the **free radicals** which can cause chemical changes of various substances including DNA.

Biological Effects of Ionising Radiation

- **Direct action (hits) –** physical and physical-chemical process of radiation energy absorption, leading directly to changes in important cellular structures. It is the most important action mechanism in cells with low water content. Theory of direct action is called **target theory**. It is based on physical energy transfer.

- **Indirect effects** are mediated by water radiolysis products, namely by free radicals H* a OH*. It is most important in cells with high water content. The free radicals have free unpaired electrons which cause their high chemical reactivity. They attack chemical bonds in biomolecules and degrade their structure. Theory of indirect action – **radical theory** – is based on chemical energy transfer.

Indirect Mechanism of DNA Damage



http://www.frontiersin.org/files/Articles/111103/fonc-04-00381-HTML-r1/image_m/fonc-04-00381-g001.jpg

Effects on the Cell

In proliferating cells we find these levels of radiation damage:

- **Transient stopping of proliferation**
- **Reproductive death of cells** (vital functions are kept but proliferation ability is lost)
- **Instantaneous death of cells**

Cell sensitivity to ionising radiation (radiosensitivity), or its resistance (radioresistance) depends mainly on the repair ability.

Main factors influencing biological effects:

- **Physical and chemical:** equivalent dose, dose rate, temperature, spatial distribution of absorbed dose, presence of water and oxygen.
- **Biological:** species, organ or tissue, degree of cell differentiation, physiological state, spontaneous ability of repair, repopulation and regeneration.

Sensitivity of cells is influenced by:

- **Cell cycle phase** (S-phase!)
- **Differentiation degree**. Differentiated cells are less sensitive.
- **Water and oxygen content**. Direct proportionality (+,+)

Very sensitive are e.g. embryonic, generative, epidermal, bone marrow and **tumour cells**.

Tissue Sensitivity and Radiation Sickness

Arranged according to the decreasing radiosensitivity:

lymphatic
spermatogenic epithelium of testis
bone marrow
gastrointestinal epithelium
ovaries
cells of skin cancer
connective tissue
liver
pancreas
kidneys
nerve tissue
brain
muscle

Typical symptoms of radiation sickness:

1. Non-lethal – damage to the erythropoiesis (bone marrow), effects on gonads

2. Lethal – gastrointestinal syndrome (damaged epithelium), skin burning, damage to suprarenal glands, damaged vision, nerve syndrome (nerve death)

Late sequels – cumulative – **genetic damage,** cancer

It is not radiation sickness but some other effect of irradiation or nuclear bomb explosions!!!

Accelerators

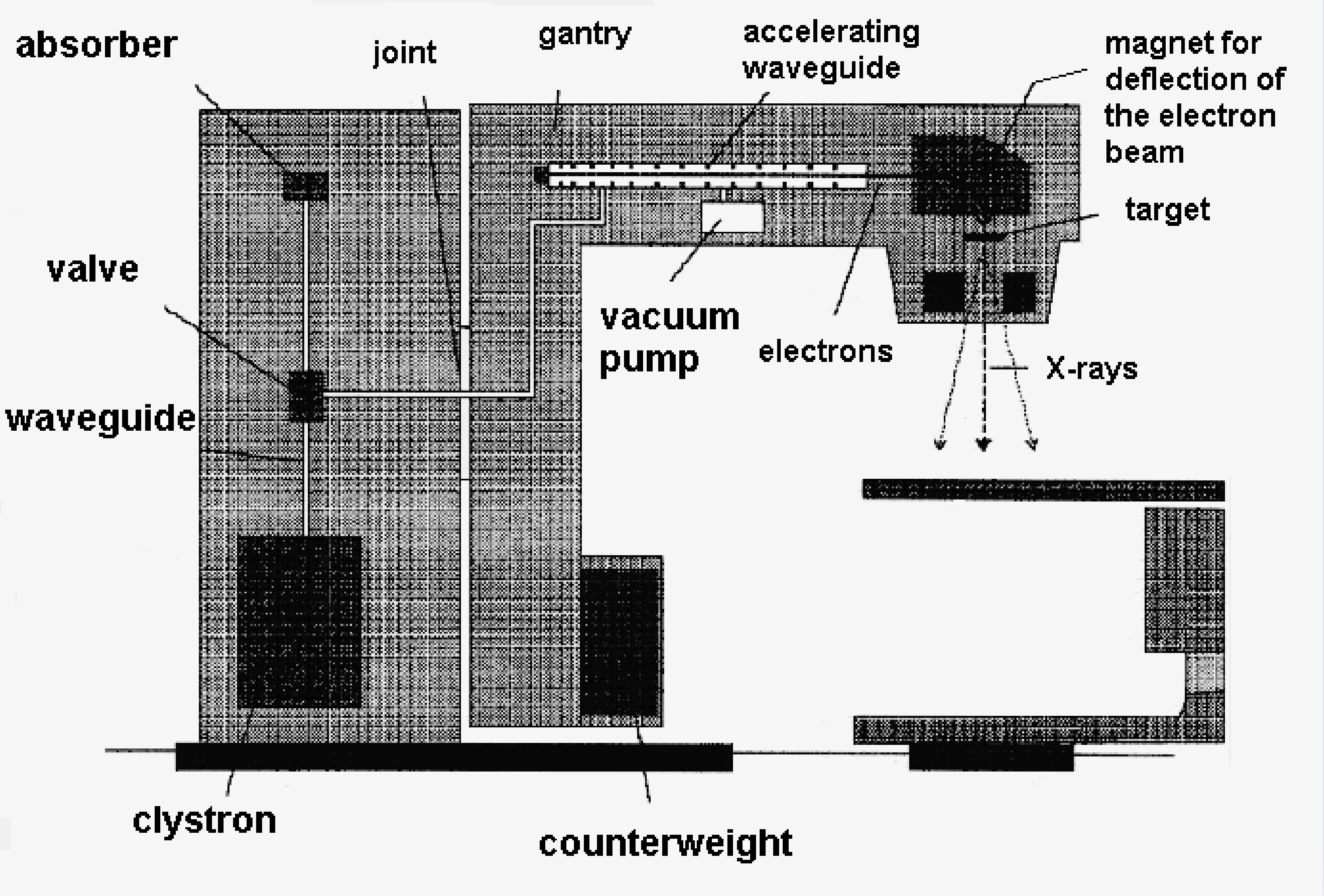
- Accelerators are electronic devices by means of which some charged particles (electrons, protons, ions) are accelerated to reach energies comparable or higher than the energies of particles emitted during natural radioactivity processes.
- Linear accelerators are used for electrons.
- Cyclotrons can accelerate protons or ions.
- Synchrotrons accelerate mainly electrons to very high energies.

The Linear Accelerator

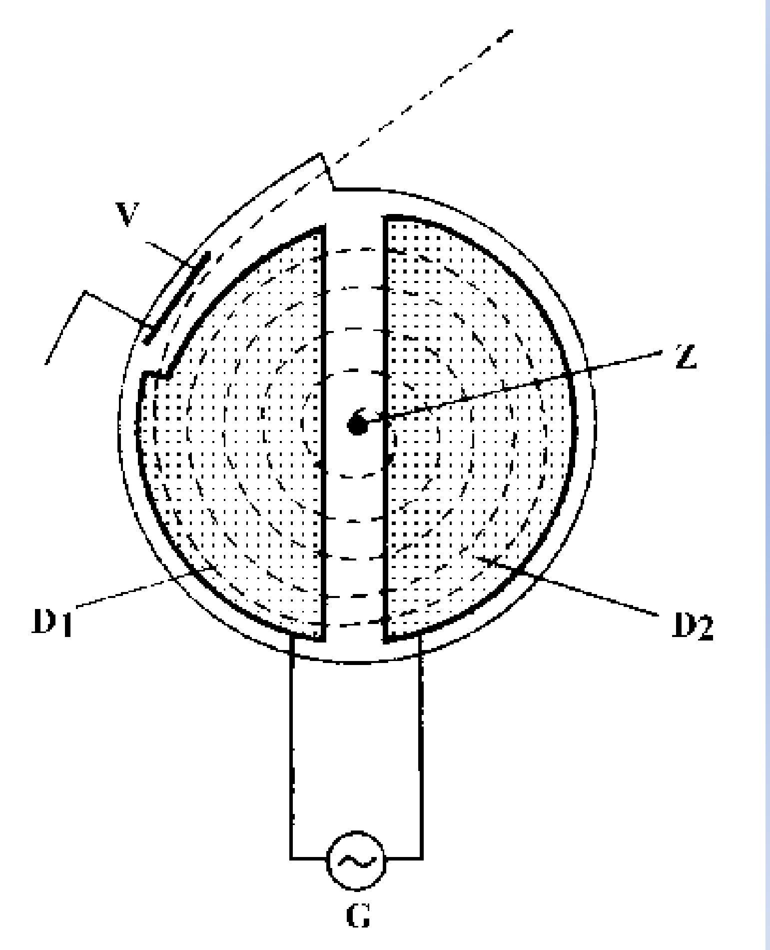
CLINAC 2100C in Masaryk Memorial Institute of Oncology in Brno

The Linear Accelerator - Scheme

http://www.cs.nsw.gov.au/rpa/pet/RadTraining/MedicalLinacs.htm



The Cyclotron



Z – source of the accelerated particles (protons),

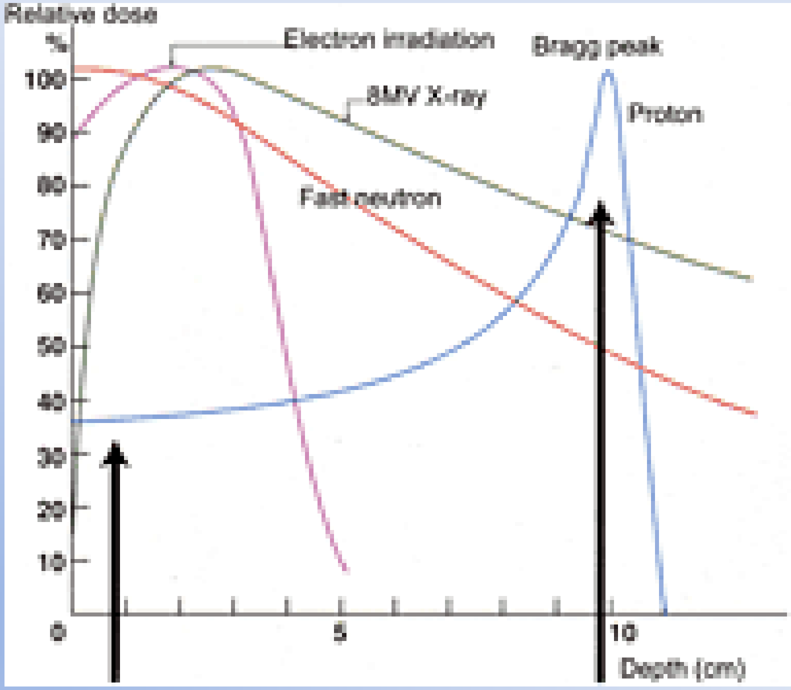
D_1 and D_2 – duants or dees,

G - generator of high-frequency voltage.

$$f = \frac{B.q}{2\pi.m}$$

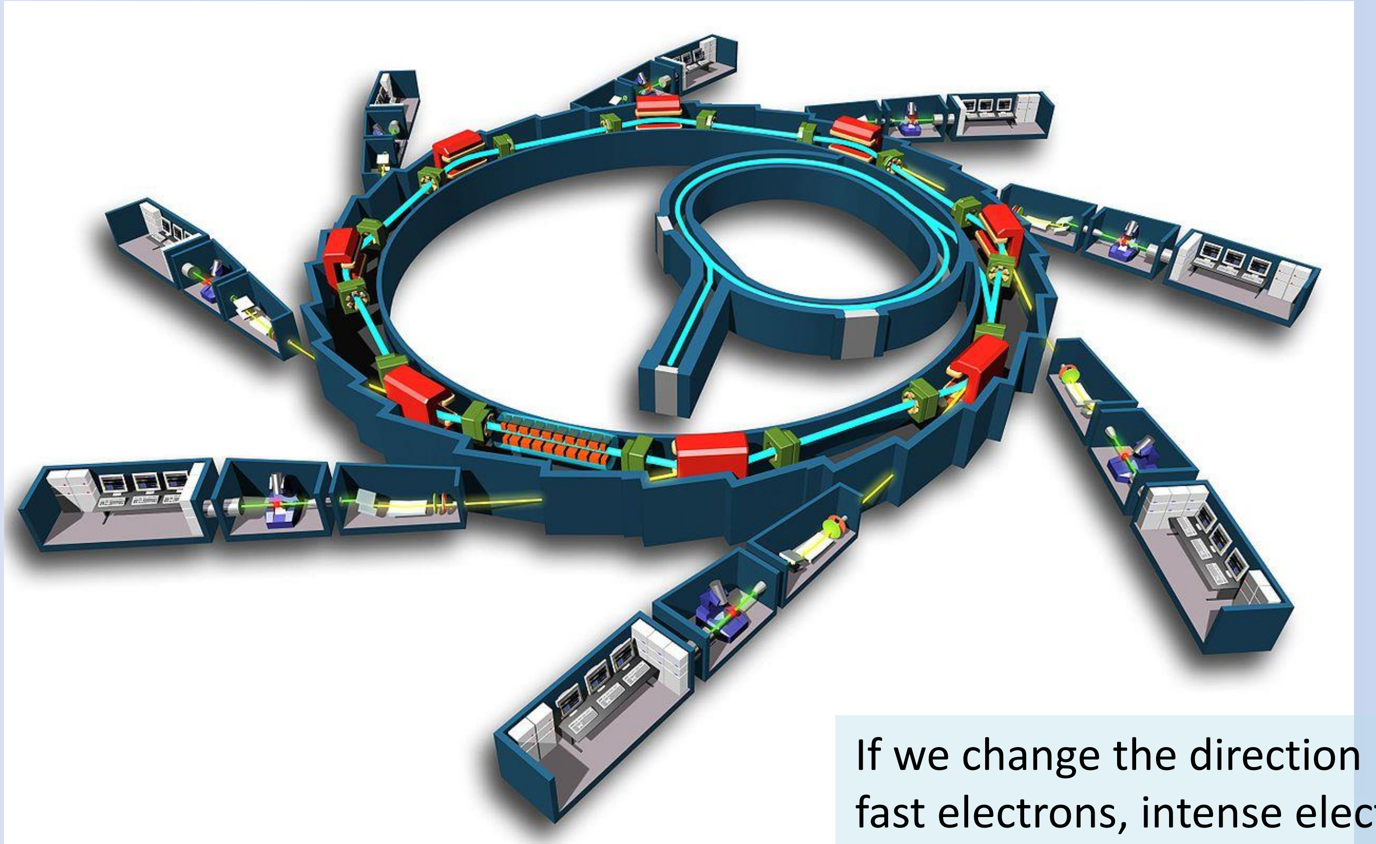
Cyclotron frequency – condition for circular trajectory of accelerated particles.

The Cyclotron in Oncology – Proton (Hadron) Therapy



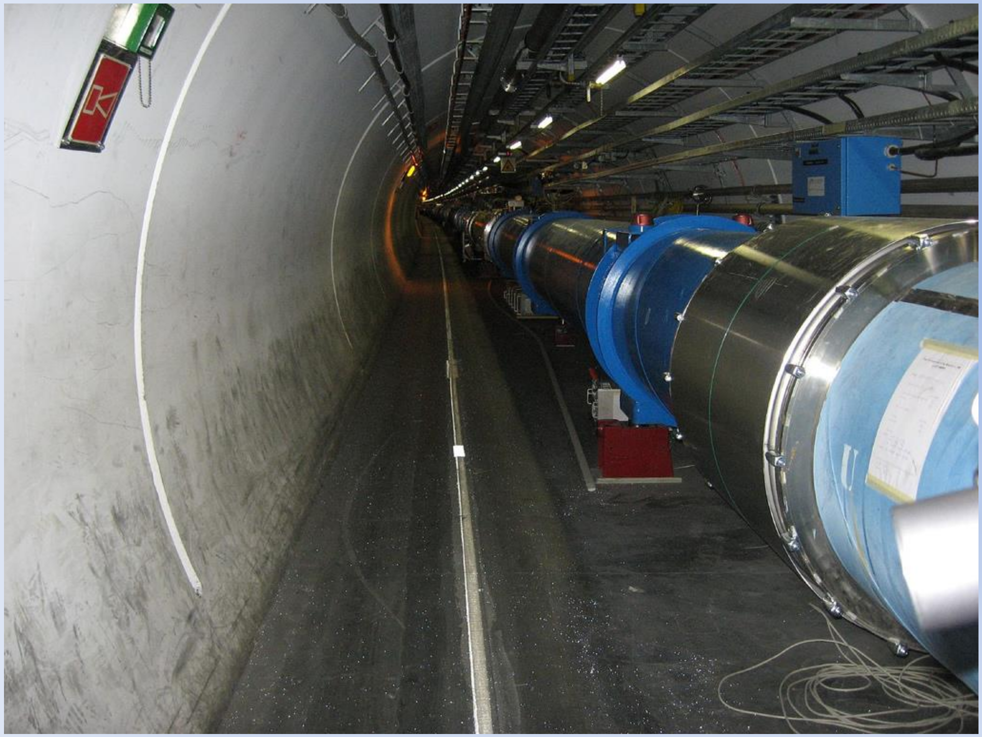
The Sumitomo cyclotron

Synchrotron Research Facility



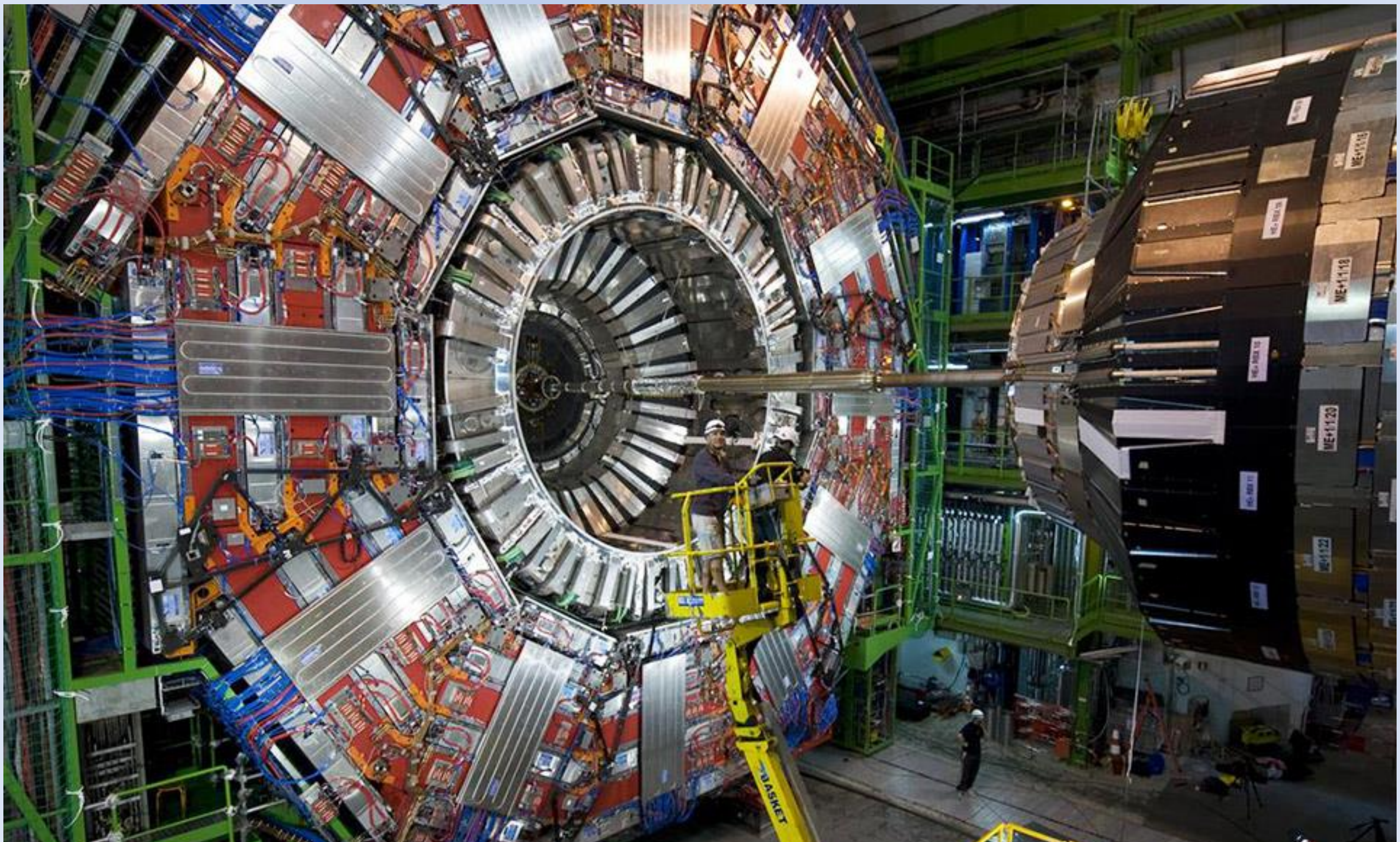
If we change the direction of a beam of very fast electrons, intense electromagnetic radiation (VIS, UV, X-RAY) can be produced. Many experimental labs are connected to a single synchrotron.

CERN Collider
the Strongest Accelerator with Collision Energy of Two Particles of about 10 TeV

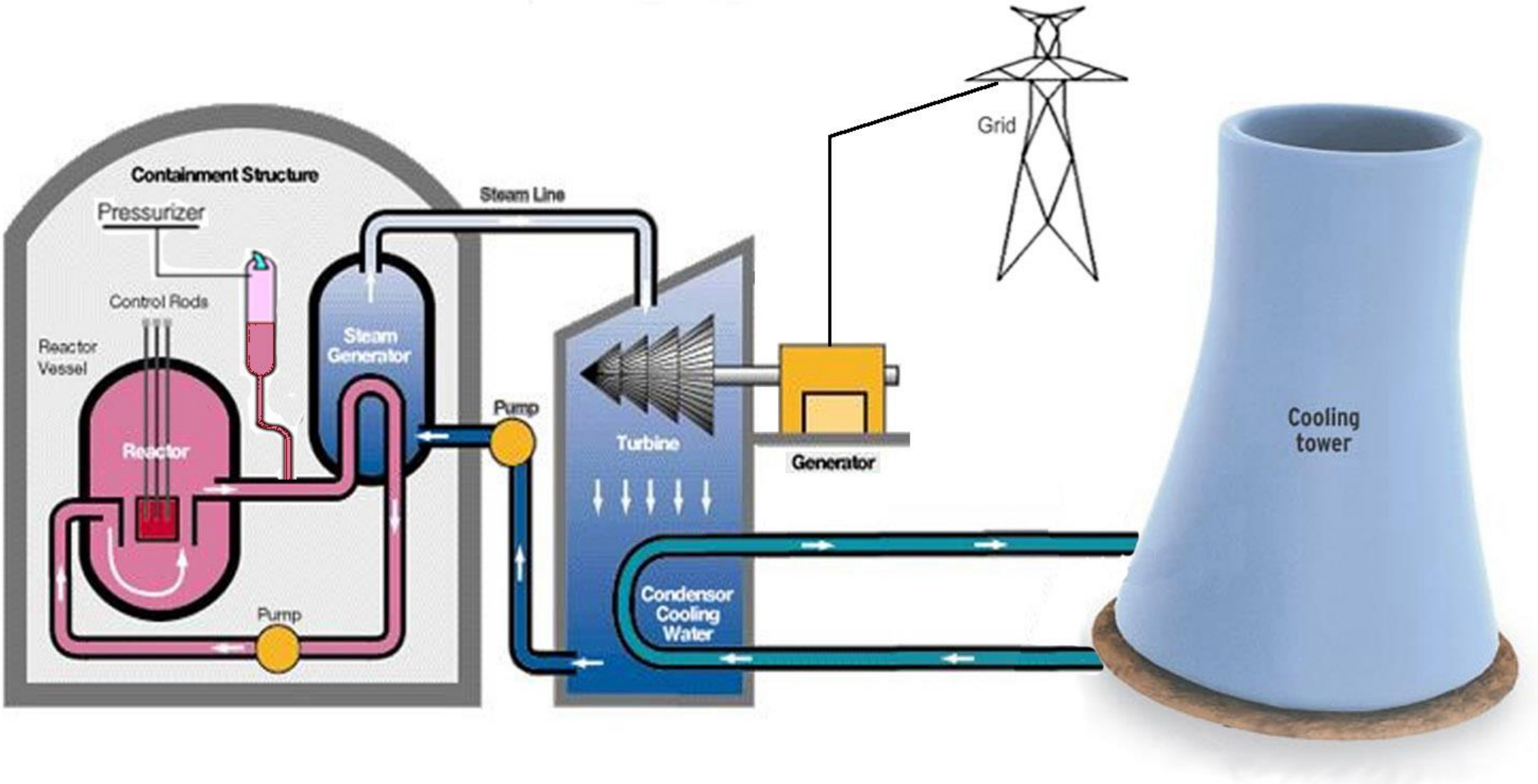


A very small part of the 27 km long underground device
By alpinethread - Flickr, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=4538468

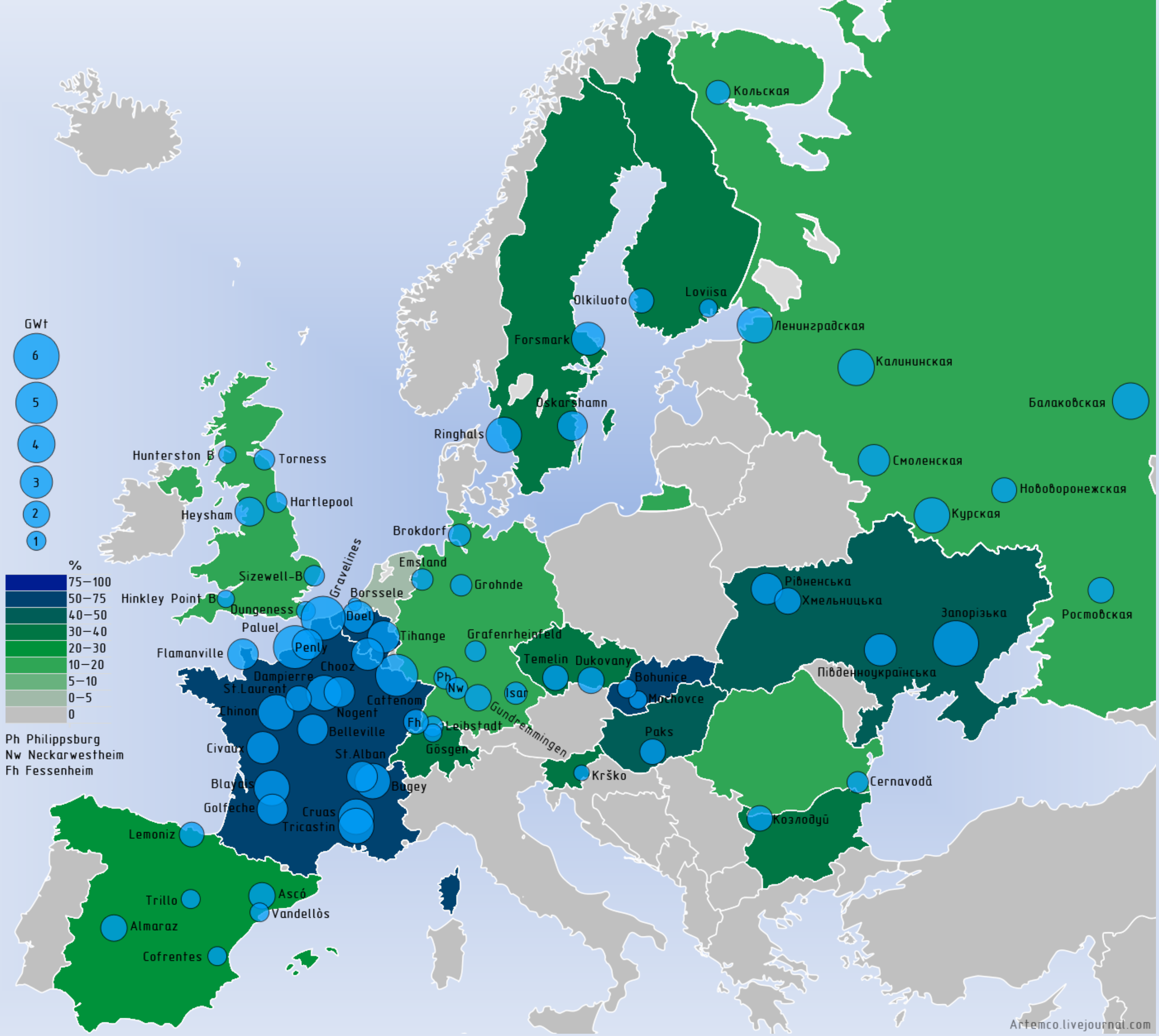
CERN Hadron Collider
(one of the collision product detectors)



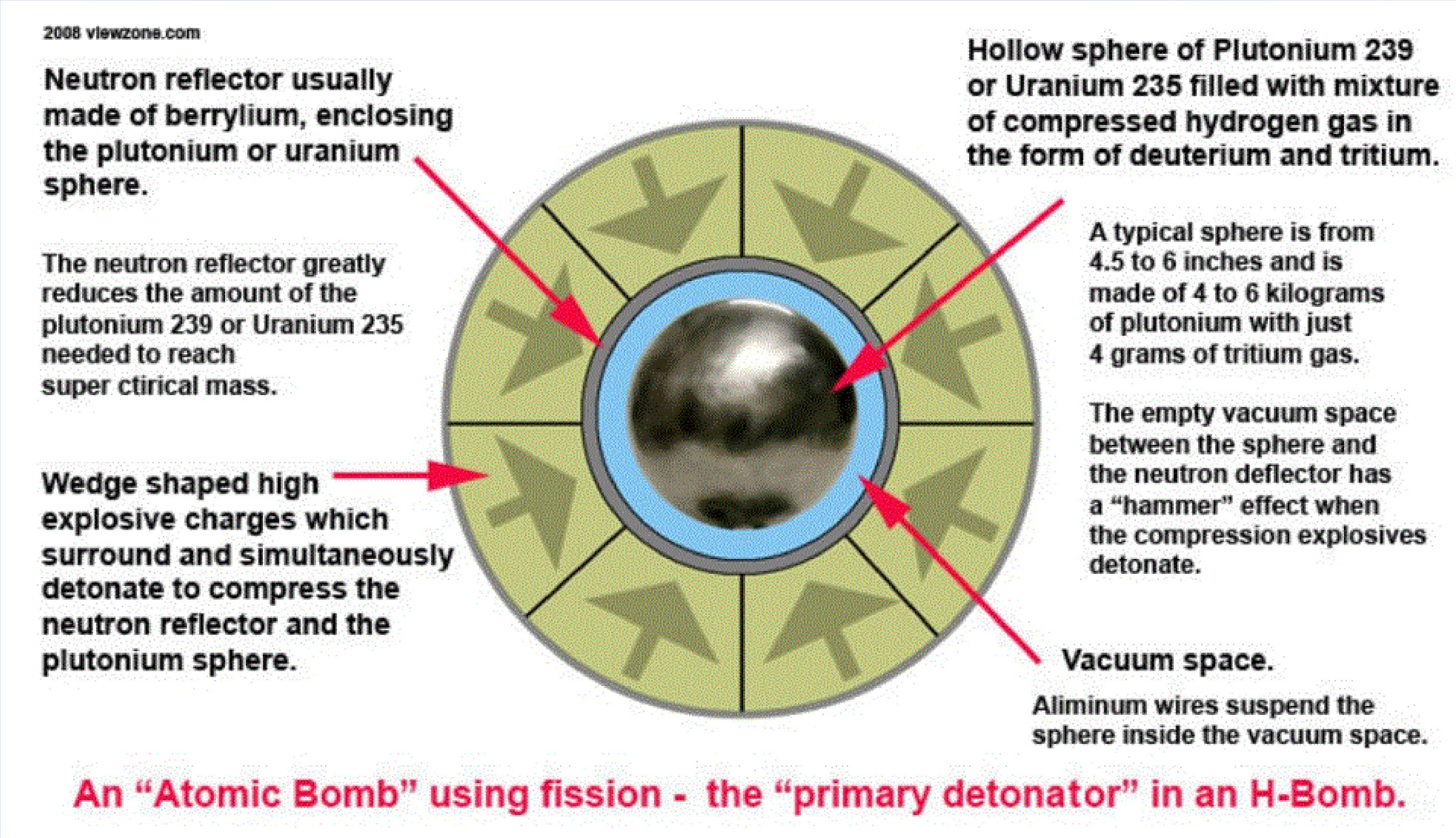
Nuclear Reactor and Power Plant



Nuclear Power Plants in Europe



Nuclear Bomb



See you next year in Medical Biophysics!!!!

It is not English but I hope you understand it!!