Biomedical Applications of Particle Accelerators

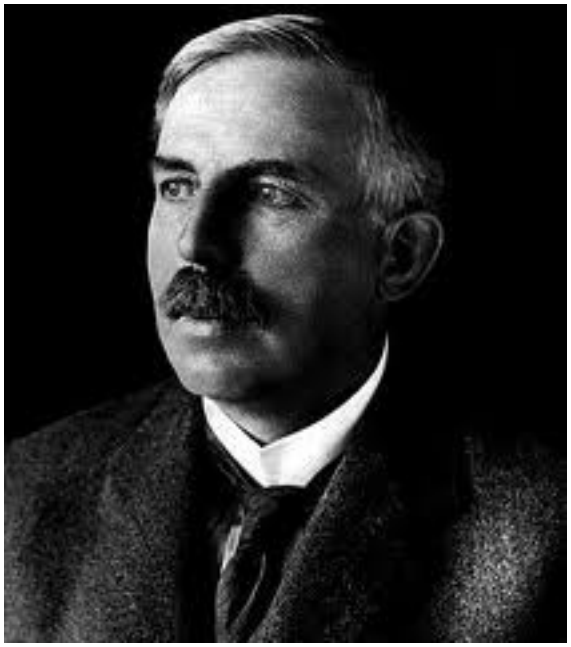
"I, as an accelerator builder, have found great satisfaction in relating to the men who built cathedrals in the 13th Century. When Ernest Lawrence built his cyclotron with a dedicated passion, he was not that different from Suger, also with a dedicated passion, building the cathedral at St. Denis [France]. The Abbot Suger was expressing a devotion to the church with his exalted structure, a structure that transcended all contemporary knowledge of strength of materials. And Lawrence, too, expressed in his fashion a devotion to the discovery of truth. He, too, transcended contemporary technology in attaining his dizzying heights of energy." **Robert Wilson** in *The Humaneness of Physics, Fermilab 25th anniversary symposium brochure.*

Layout of the Lecture

1. Why Accelerators?
2. Introduction to Accelerators
3. Superconducting Magnets - MRI
4. Hadron Therapy
5. Radioactive Isotopes for Nuclear Medicine
6. Synchrotron Light Sources
7. The Future

"I must confess that one reason we have undertaken this biological work is that we thereby have been able to get financial support for all of the work in the laboratory. As you know, it is much easier to get funds for medical research." - Ernest Lawrence to Niels Bohr, 1935

Rutherford and Me



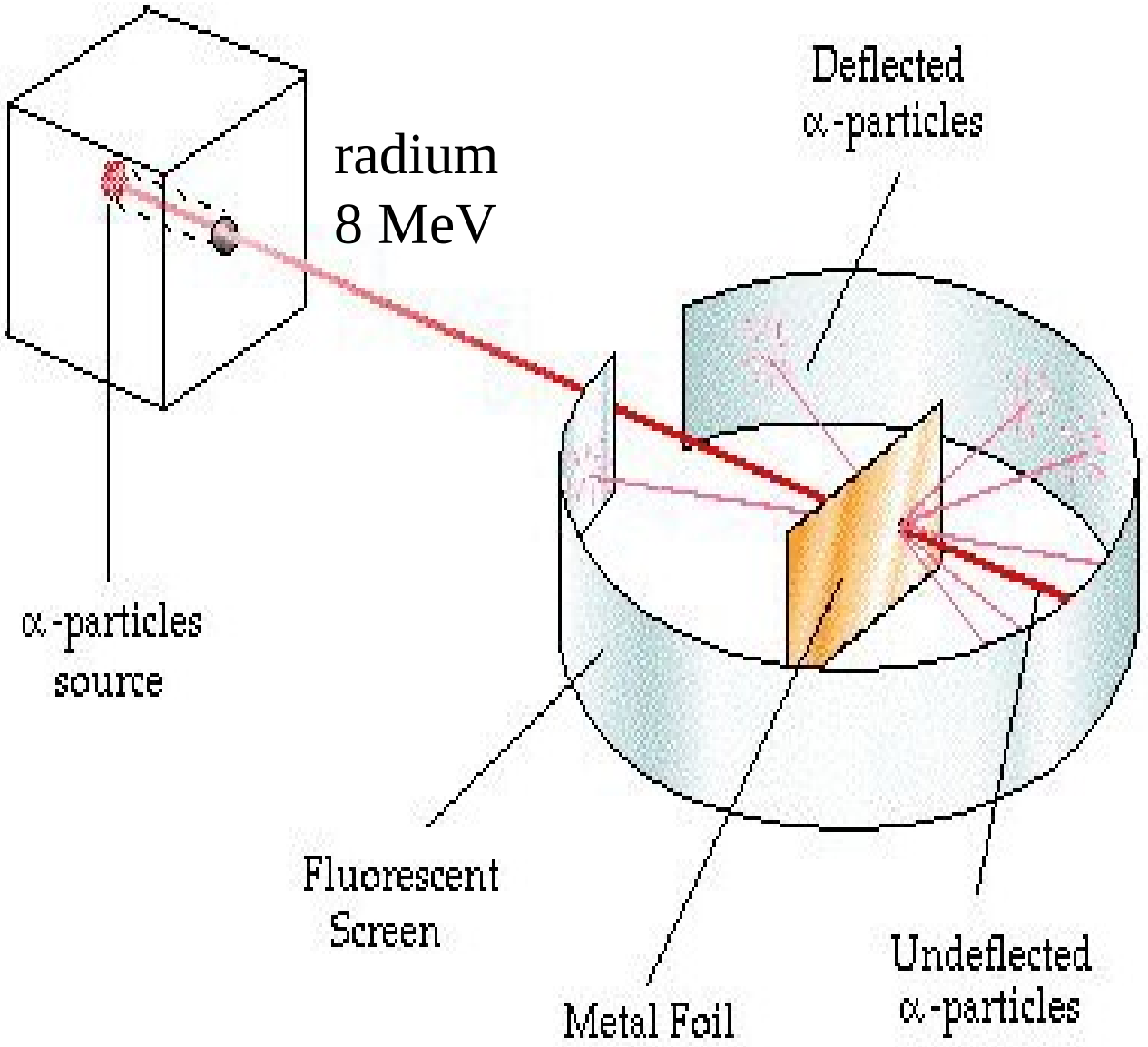
As with everything in particle physics, it begins with Ernest Rutherford (1871-1937).
- Nobel Prize for Chemistry(!) in 1908

Me at Westminster Abbey in London having finally found Rutherford's tombstone.

Rutherford Scattering

Geiger and Rutherford in 1911

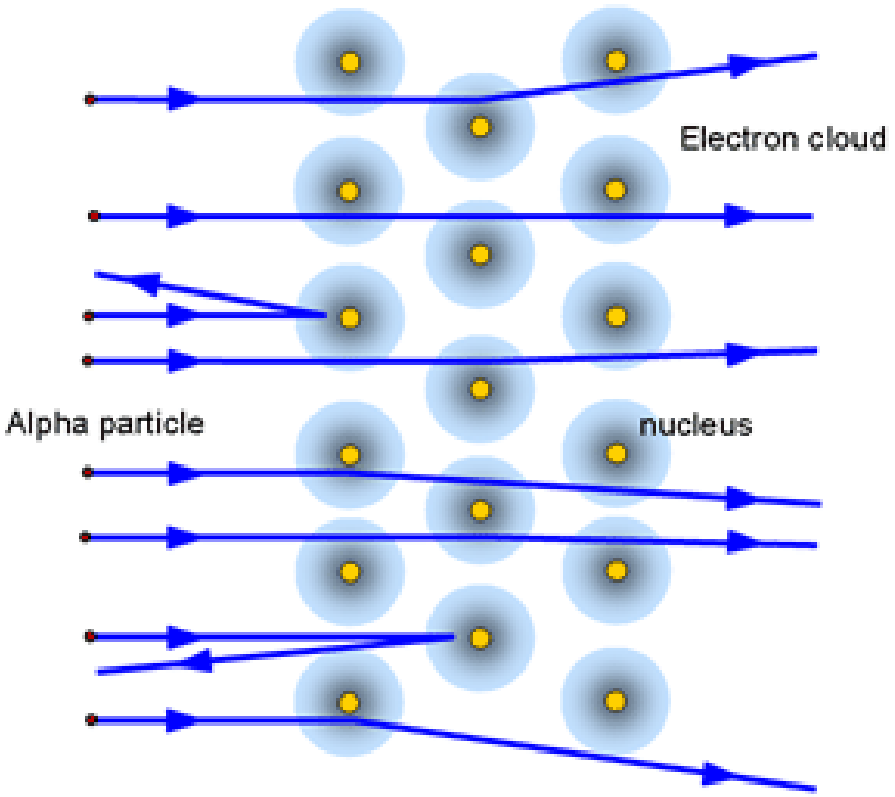
Radium is radioactive. It is a source of alpha particles (helium nuclei). Rutherford and Geiger created a “beam” of alpha particles and pointed it at a thin gold foil.



Why We Need an Accelerator

The alpha particle and gold nucleus are both positively charged (Z=2 and Z=79) so the electric force is repulsive. How close the alpha particle can get to the nucleus of a gold atom is directly related to the kinetic energy of the alpha.

For an 8 MeV (million eV) alpha on gold, this closest distance is 28 fm (a fm is 10^{-15} m). This happens to be 4 times the radius of the gold nucleus. In other words, the alpha does not have enough energy to penetrate ("get inside") the nucleus.



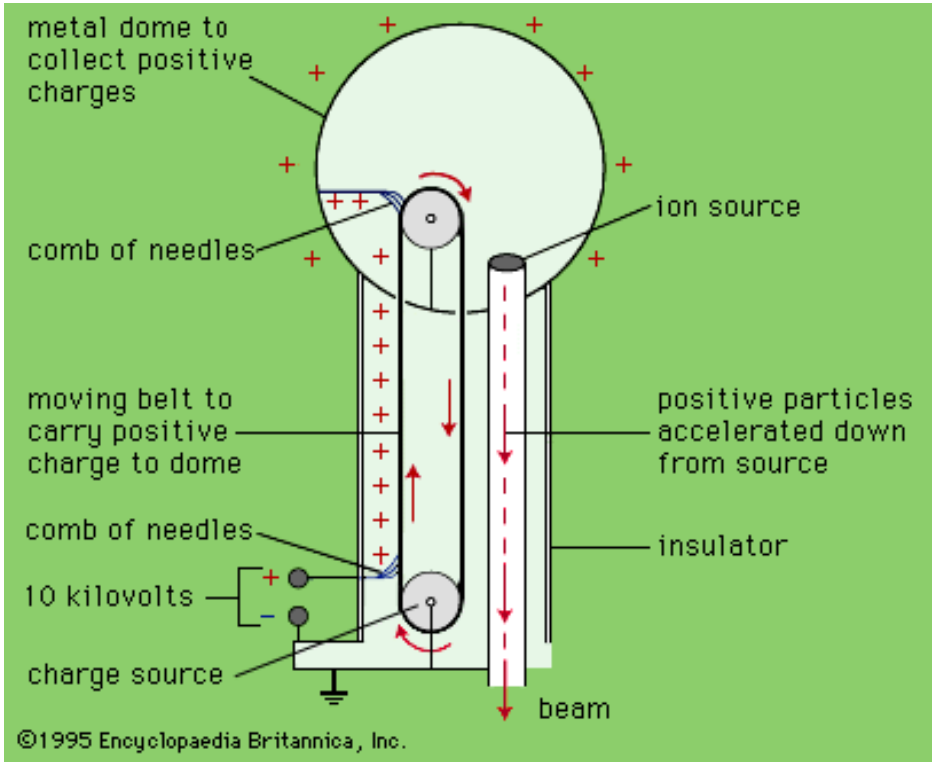
1 eV (electron-volt) = 1.6 X 10^{-19} J

It takes 13.6 eV to ionize hydrogen

Early Accelerators

Cockcroft and Walton (here with Rutherford) used a voltage multiplier circuit to accelerate protons through 800 kV (so they had a kinetic energy of 800 KeV) which could break apart lithium in 1932. They won the Physics Nobel prize in 1951.

The Van de Graaff generator was developed, starting in 1929, by physicist Robert Van de Graaff. It could accelerate to 1.5 MeV.



The Next Advance
Bending in a Magnetic Field

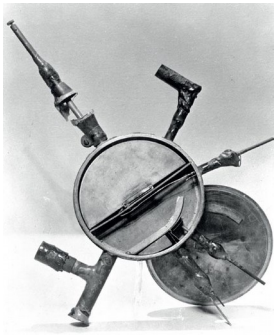
This “linear” accelerator technique had reached its potential. The key point to the next advance was to make the particle path circular using magnetic fields.

$$R = p/qB$$

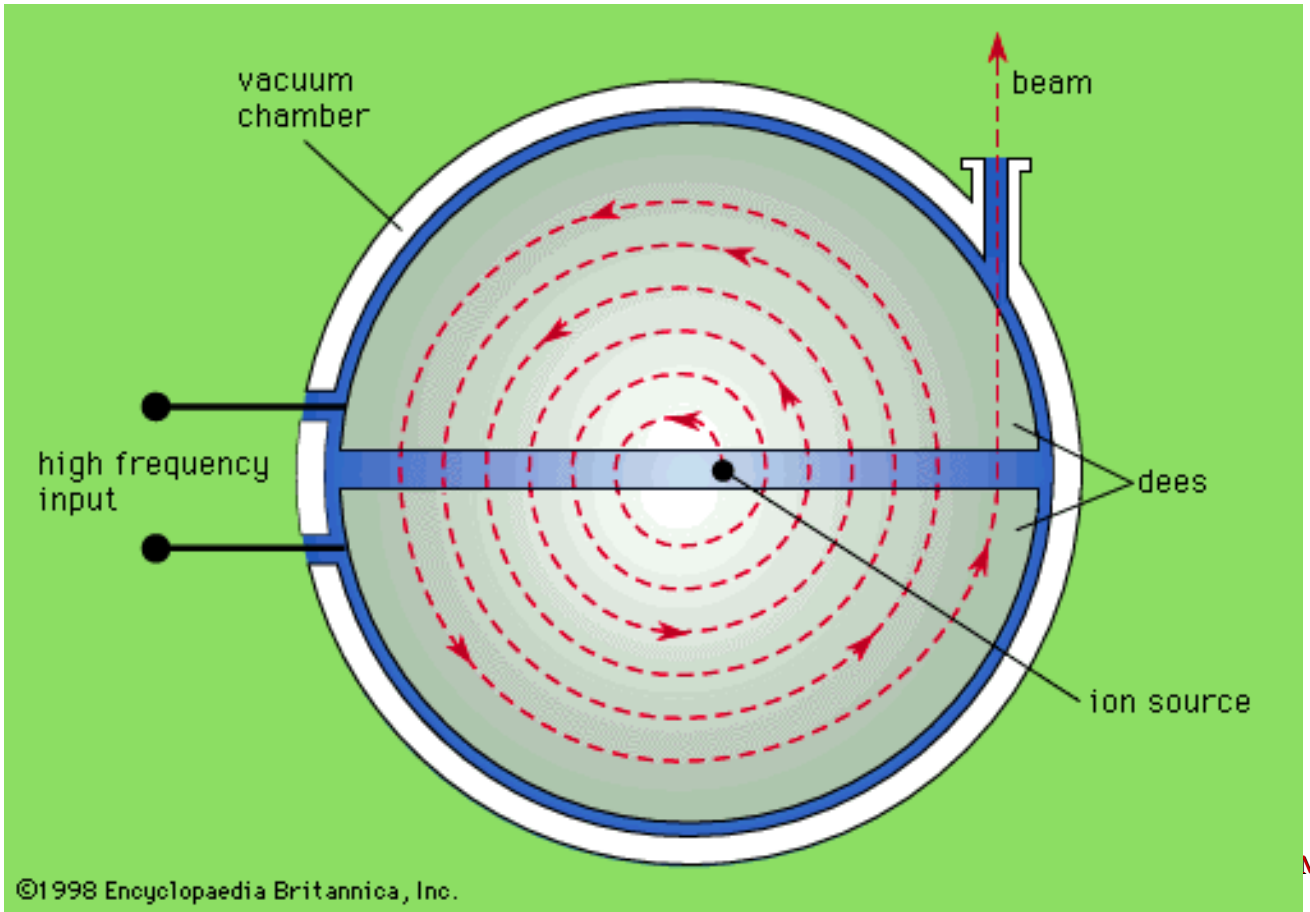
where R is the path's radius of curvature, p is momentum, q is charge, B is magnetic field

A beam of electrons bent into a circular path in a magnetic field

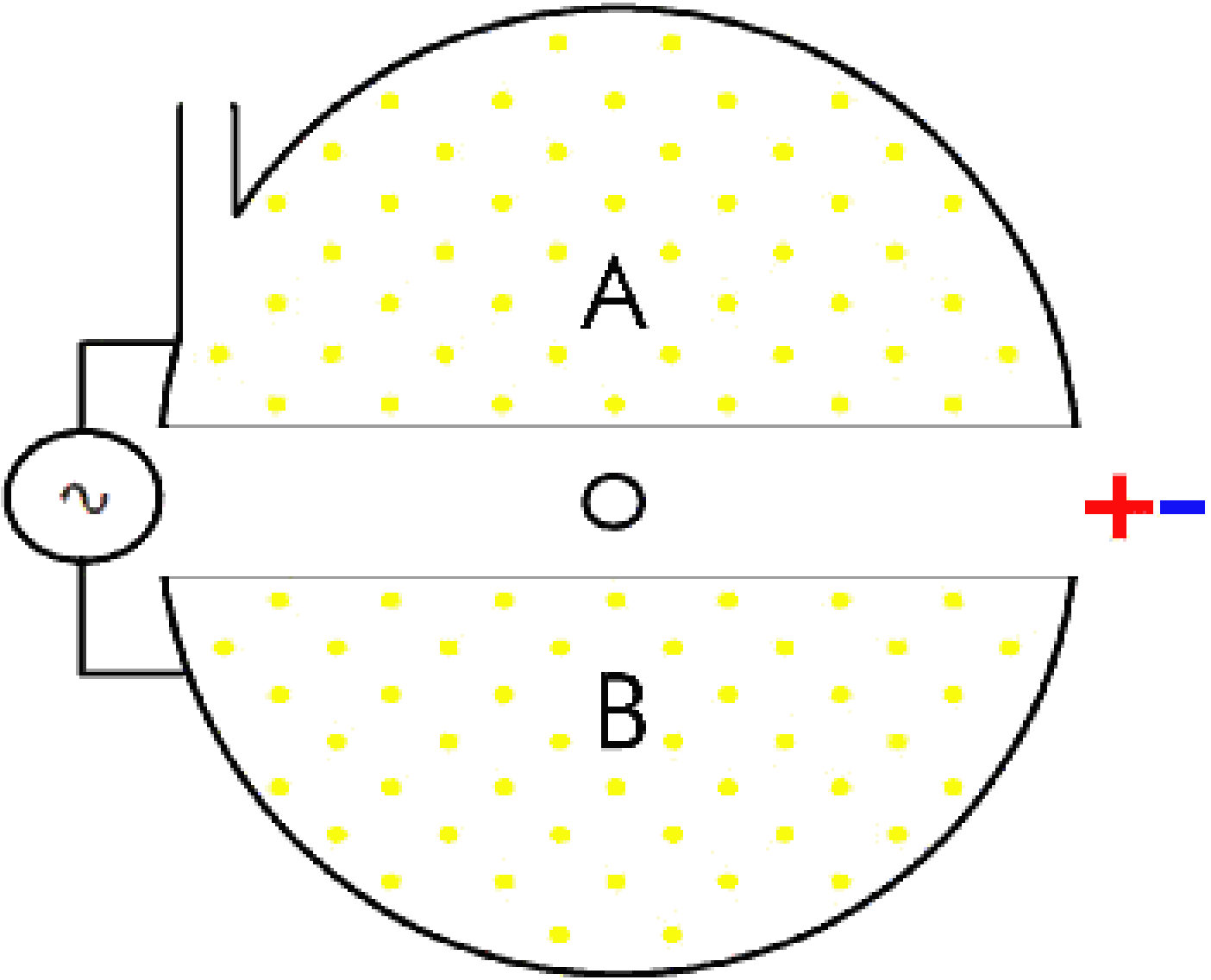
The Cyclotron



Ernest Orlando Lawrence invented the cyclotron in the early 1930's (Nobel Prize for Physics, 1939). Ultimately could only get protons to kinetic energies of about 10 MeV.



The key idea is to accelerate the charged particle each time it crosses the gap. The radius of its trajectory then gets larger until it exits.

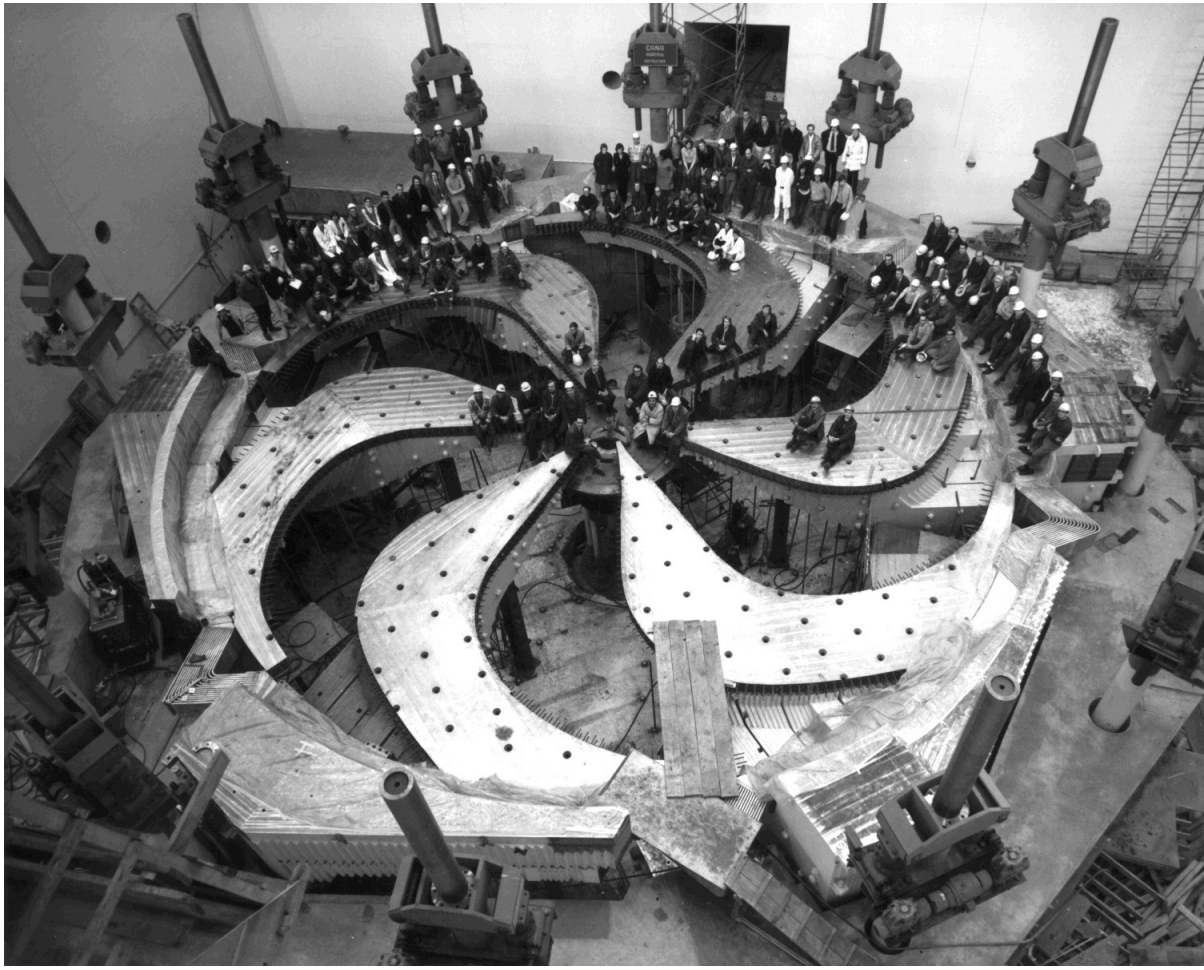

A
B

TRIUMF (TriUniversity Meson Facility)

The world's largest cyclotron is at the TRIUMF laboratory located on the UBC campus in Vancouver.

- Total magnet weight: 4000 Tons
- Magnet diameter: 18 m
- Magnetic field: 5.6 Tesla
- Magnet current: 18.5 kA
- Electric field frequency: 23 MHz
- Time for acceleration: 326 μs
- Particles accelerated/sec: 10^{15}

Previous Director Nigel Lockyer is a York physics graduate!



The TRIUMF cyclotron under construction

Getting to Higher Energies

The Synchrocyclotron - To overcome the energy limitation of the cyclotron, Veksler in Dubna and McMillan at Berkeley independently showed that by adjusting the frequency of the applied voltage to the decreasing frequency of the rotating protons it was possible to accelerate protons to several hundred MeV.

1909 100 ans 2009

institutCurie

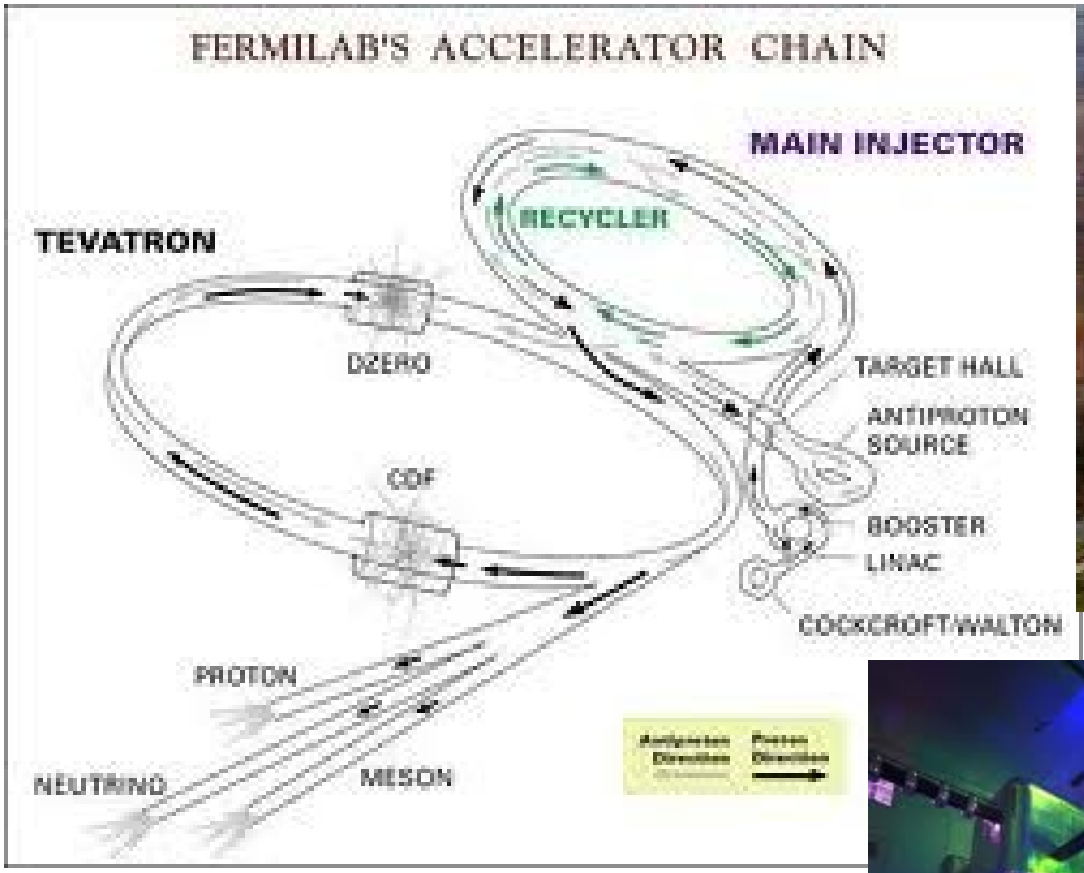
Ensemble, prenons le cancer de vitesse.

The synchrocyclotron (designed by Irene Joliot-Curie!) used in the proton therapy facility UNIVERSITÉ PARIS-SUD 11 in Orsay.

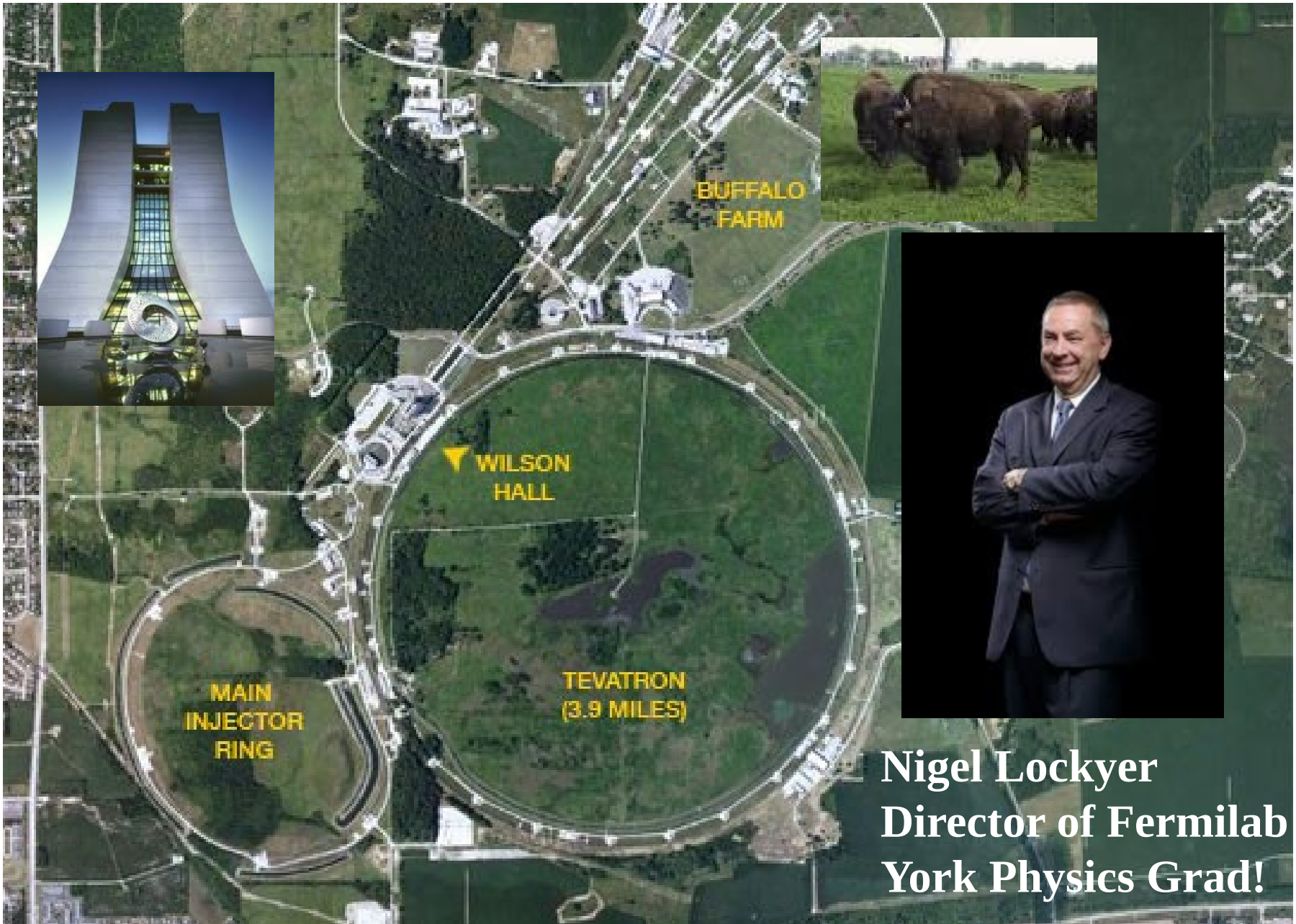
The Synchrotron

Rearrange R=p/qB to p=qBR. In the cyclotron, the magnetic field B is fixed so the path radius R increases with increasing momentum p (related to kinetic energy K). In a synchrotron, charged particles are accelerated along a circular path of fixed radius. The magnets, necessary for bending and focusing, are placed around the particle orbit. The magnetic fields are adjusted during acceleration from a low to a high value, matched to the increasing energy of the particles, so that the orbit remains essentially constant. The particles are accelerated by high voltages across one or several gaps along the circumference.

Fermilab Accelerator Complex

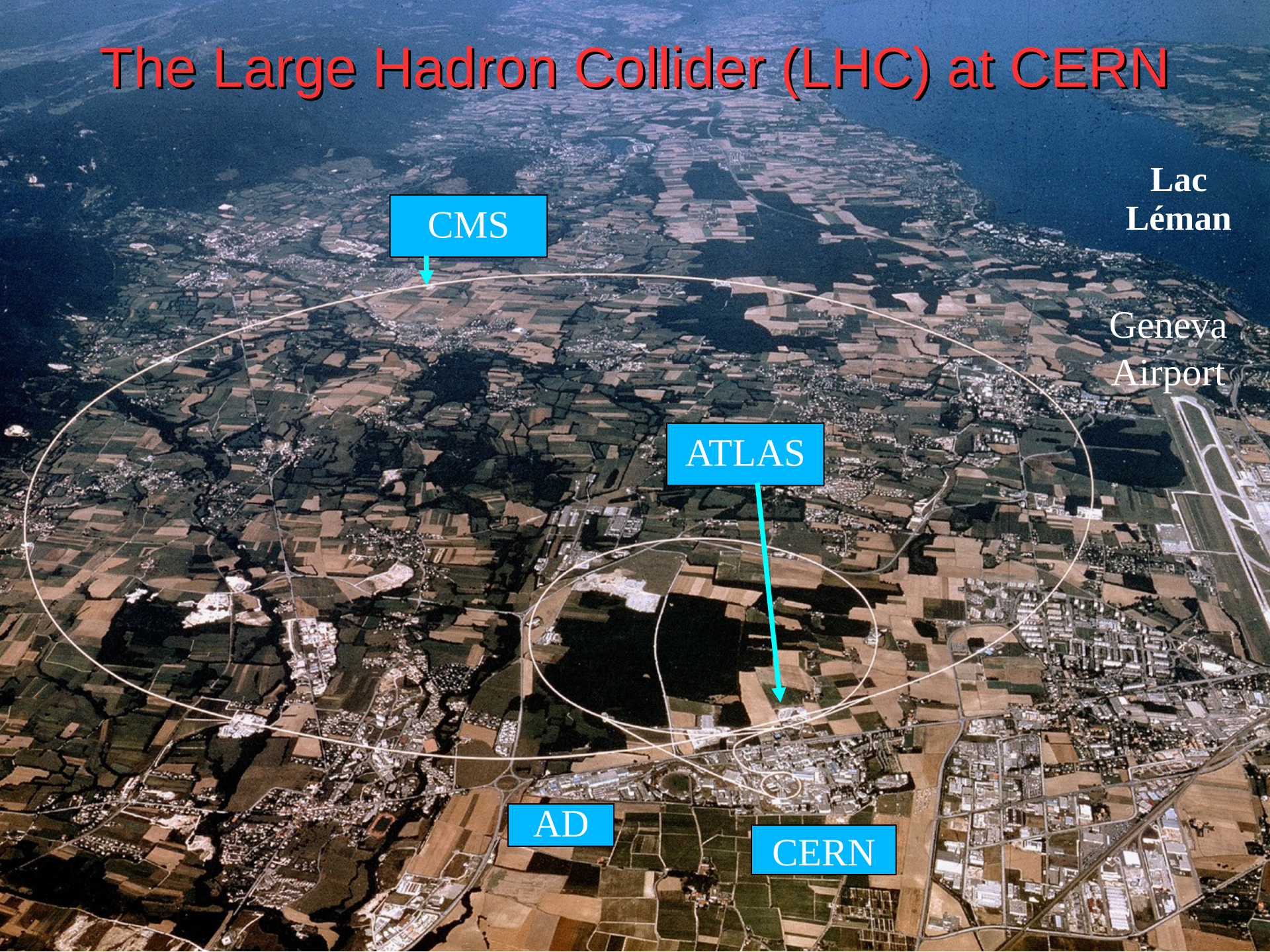


Fermilab from Above



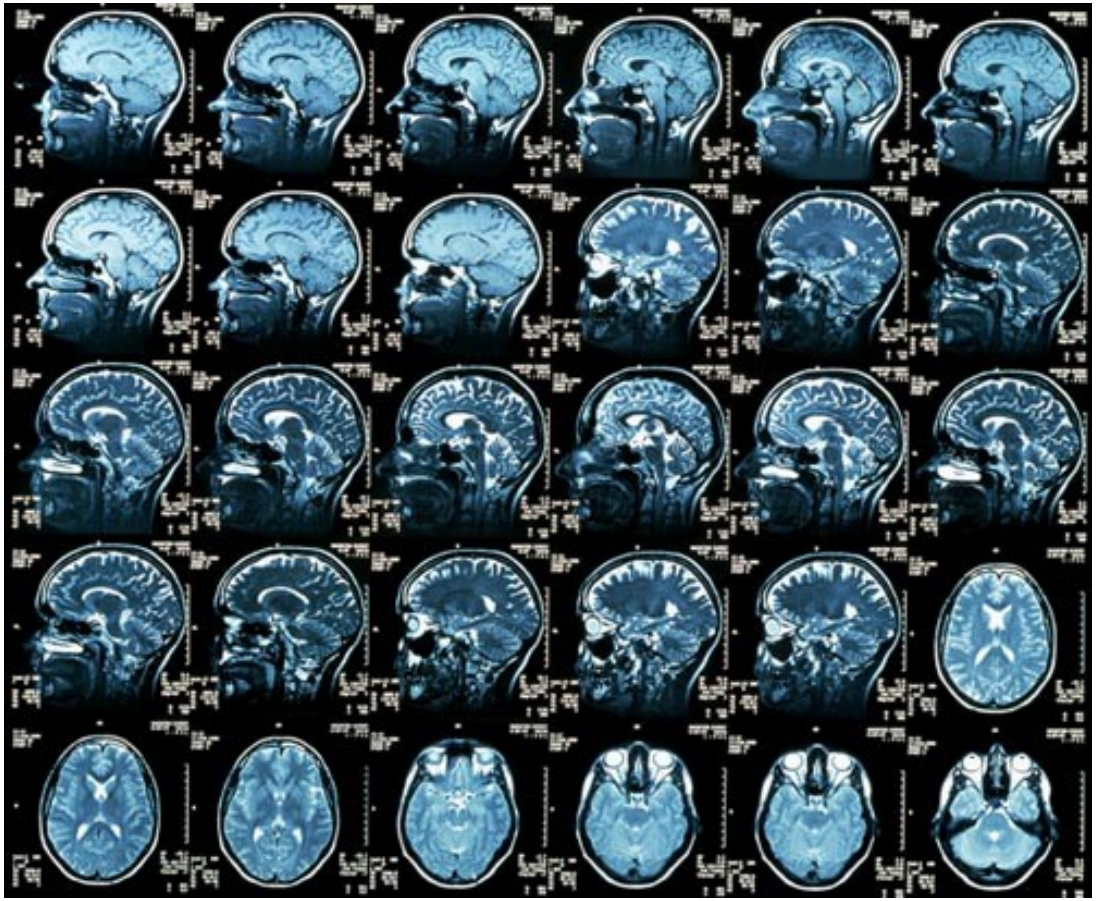
Nigel Lockyer
Director of Fermilab
York Physics Grad!

The Large Hadron Collider (LHC) at CERN



New Technologies from Accelerators

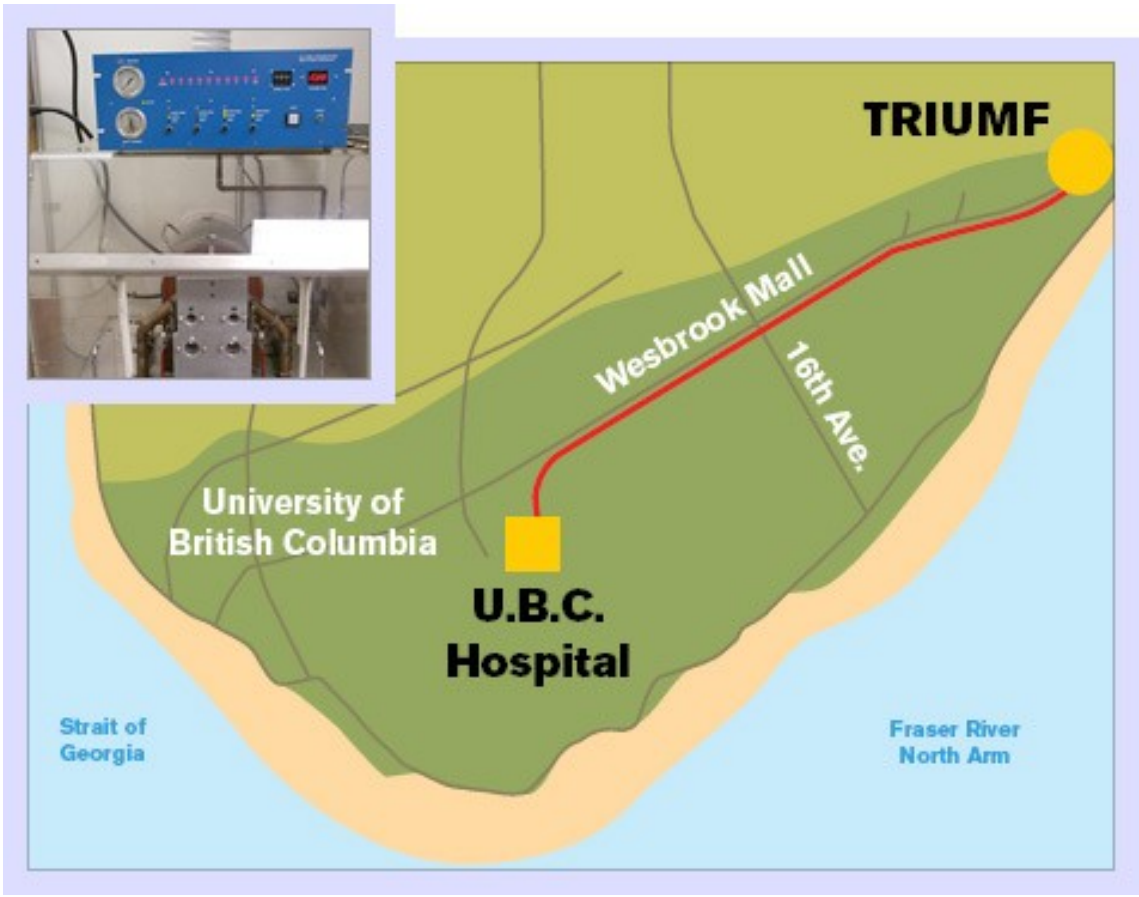
At the heart of MRI technology are powerful magnets made of superconducting wire and cable first developed in the 1970's to build Fermilab's proton synchrotron.



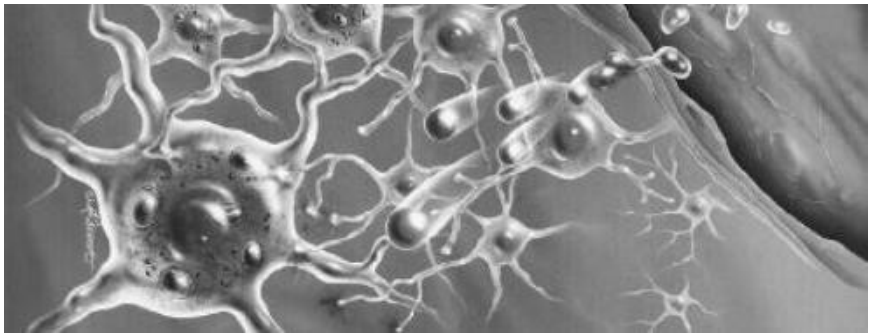
"Every program in superconductivity that there is today owes itself in some measure to the fact that Fermilab built the Tevatron and it worked."
Robert Marsh, of ATI Wah Chang, in Albany, Oregon, world's largest supplier of superconducting alloys.

Radioactive Sources for Nuclear Medicine

Radioactive elements have a wide range of medical uses. For example, β emitters are used in PET (Positron Emission Tomography) scans. In Vancouver they are produced at TRIUMF and then sent in an pneumatic tube 2.5 km to the hospital.



Research Breakthrough in the Study of Parkinson's-related Disease (2009-01-22). In partnership with TRIUMF, Dr. Jon Stoessl uses PET to explore the effect of dopamine release on Parkinson's, and to study the natural history and progression of the disease.



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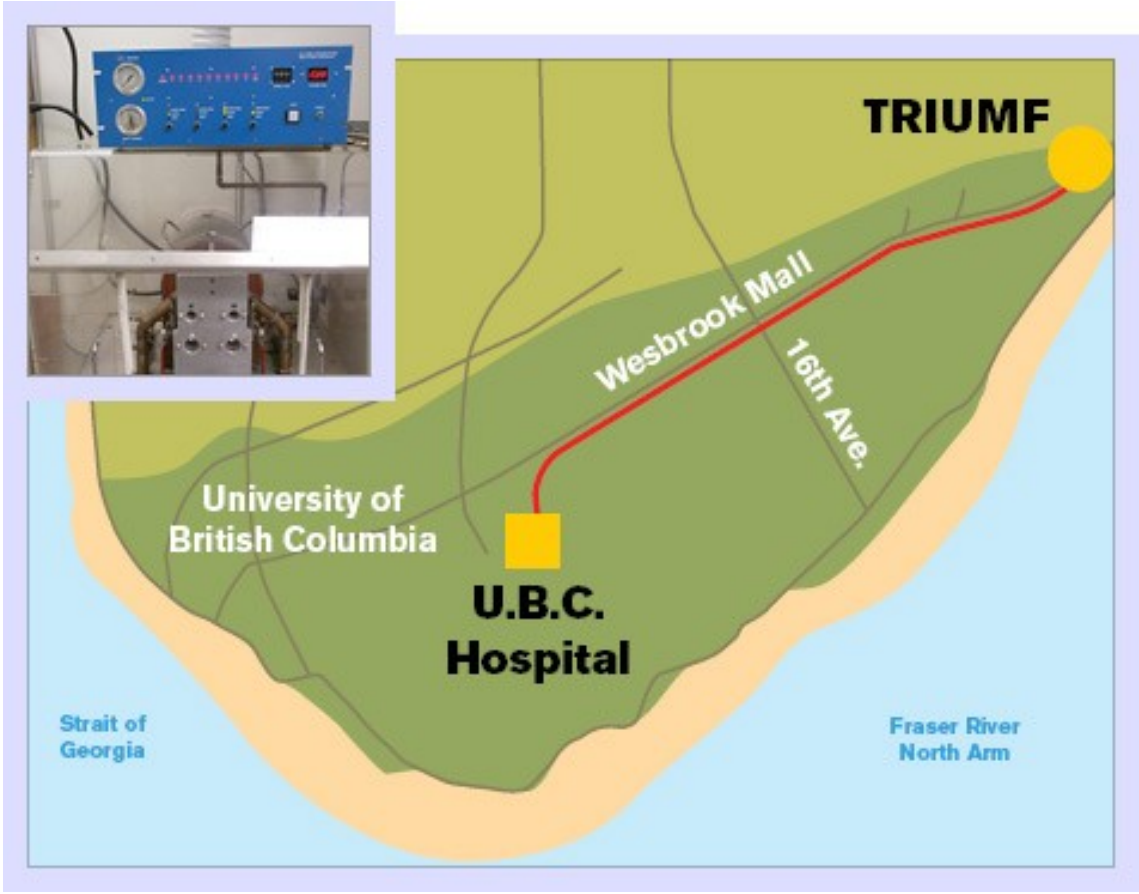

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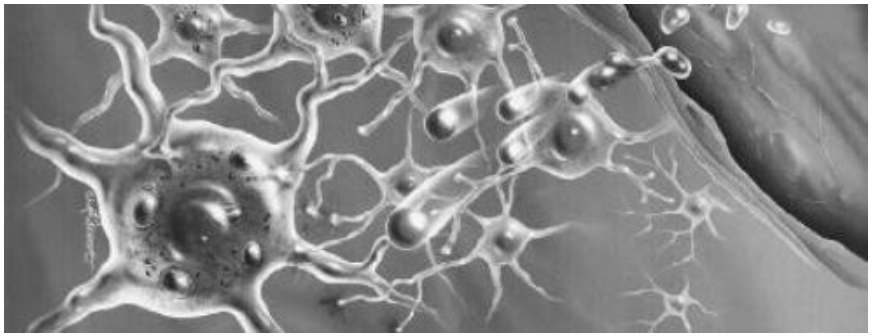


TRIUMF

is also pioneering a new technique for making the most commonly used medical isotopes with accelerators thus eliminating the need for reactors.

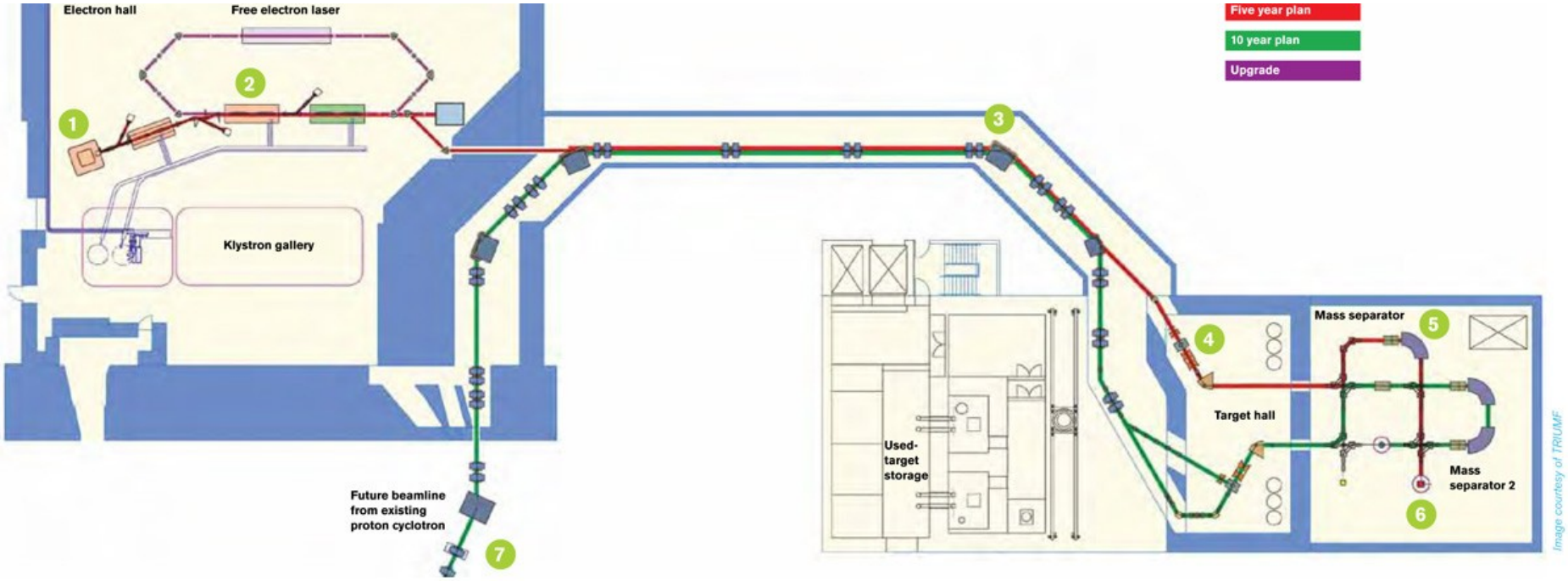
Report Explores Alternatives to Nuclear Reactors for Medical Isotopes (2008-11-15)

The Task Force on Alternatives for Medical-Isotope Production today released its final report in prepublication form at URL http://admin.triumf.ca/facility/5yp/comm/Report-vPREPUB.pdf

. Task Force was convened by TRIUMF, the University of British Columbia, and Advanced Applied Physics Solution, Inc., with support from Natural Resources Canada.

The Task Force examined accelerator-based methods for producing Molybdenum-99, the chief medical isotope used around the world in about 40 million procedures each year. The Task Force looked closely at a technology using accelerator-driven photo-fission with natural uranium that is based on an emerging core competency at TRIUMF in superconducting radiofrequency accelerators.

New Facility at TRIUMF for Producing Medical Isotopes

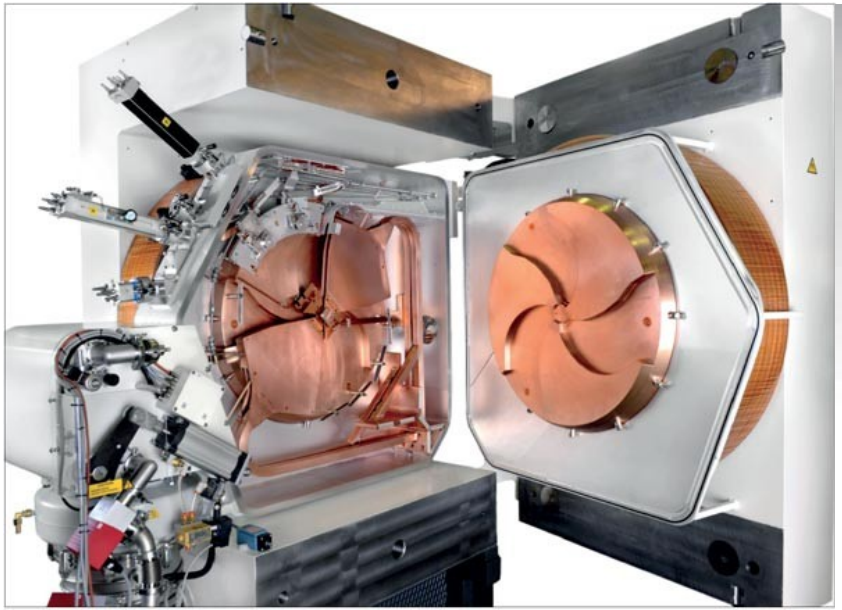


ARIEL starts with electrons and ends with isotopes. How does it work?

1) First, an electron gun strips electrons from atoms and gives the electrons an initial kick of energy.
2) The electrons proceed to the e-linac, where devices known as superconducting radio-frequency cavities propel them to nearly light speed.
3) Magnets steer the electron beam into an underground target hall, where robotic equipment handles thin slabs of target material.
4) The beam strikes a target, producing a shower of photons that shatter atomic nuclei in the target material, creating isotopes.
5) The isotopes travel to separator magnets that sort them by charge and mass, according to experimenters' needs.
6) Magnets focus the separated isotopes into particle beams, which travel up one story to the experimental halls.
7) A future beamline will bring protons from TRIUMF's cyclotron, the largest one in the world, into ARIEL to produce isotopes.

The Need for Smaller Cyclotrons

- **An important radionuclide for use in PET is ^{18}F which has a half-life of only 2 hours. The good thing is that it only needs production energies in the 5 to 20 MeV range.**
- **To be able to be used at hospitals that aren't near major cyclotron facilities requires that more compact cyclotrons need to be designed.**
- **There has been much progress in the last decade or so.**

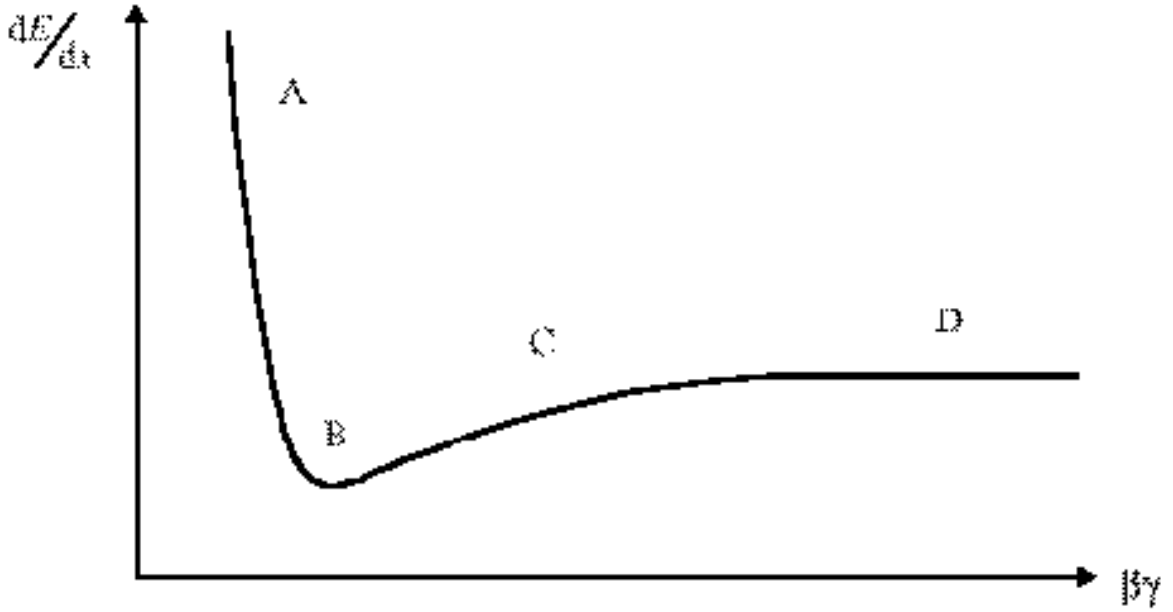


Hadrotherapy

Robert Wilson pointed out in 1946 how protons could be very effective for fighting cancer because of how they deposit their energy

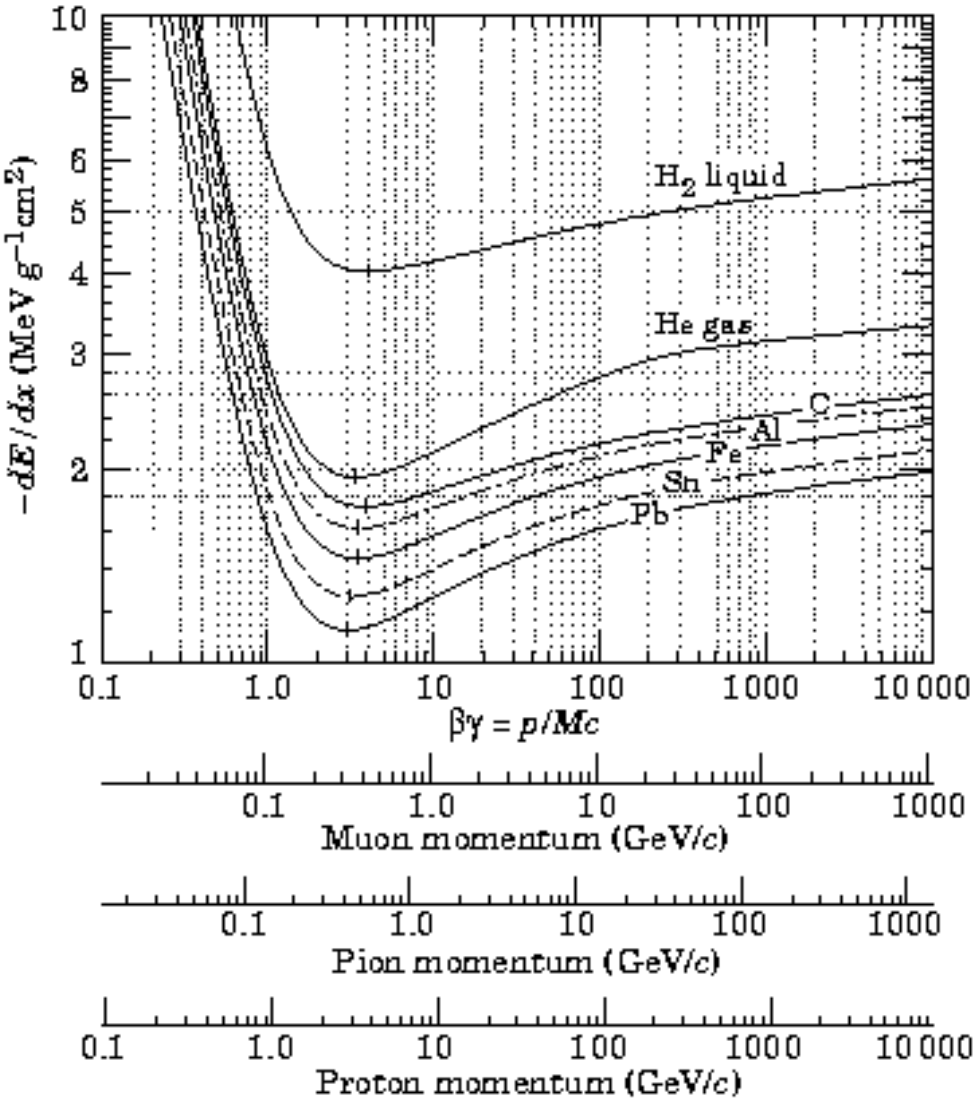
The Bethe-Bloch formula relates how a charged particle loses energy as it passes through matter (dE/dx)

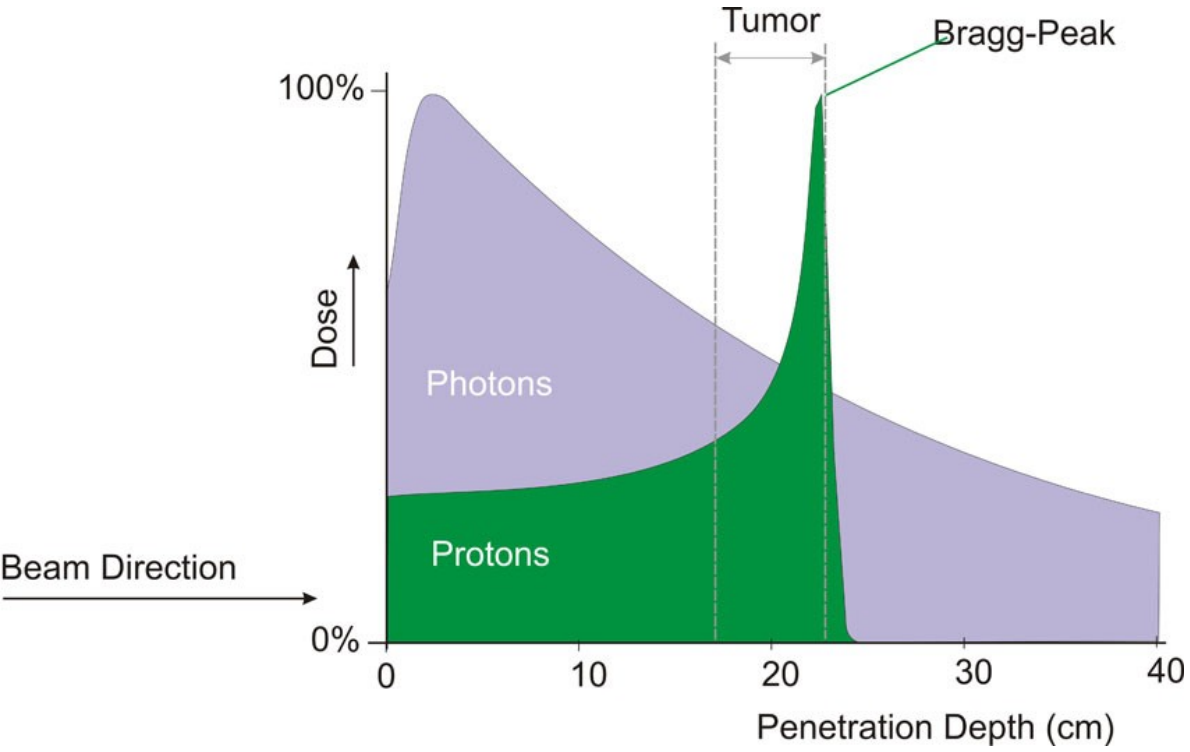
$$-\frac{dE}{dx} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

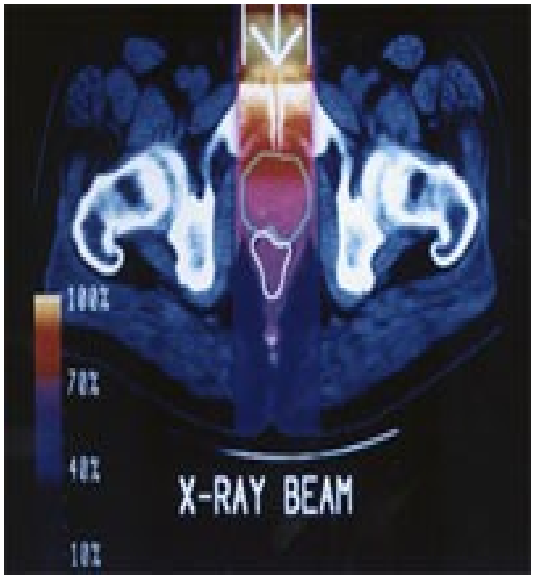


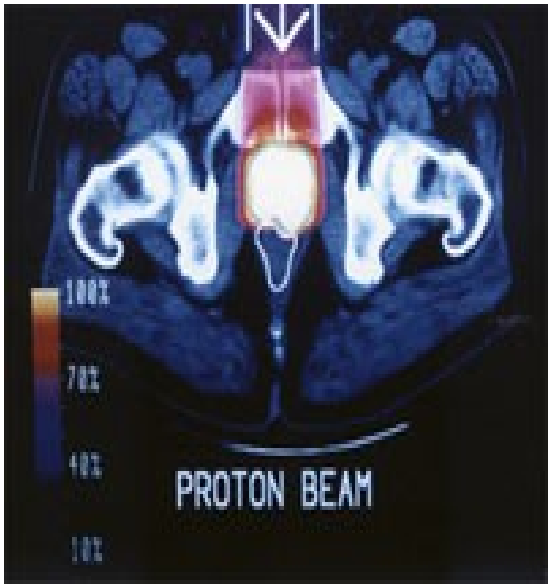
Energy Loss in Matter

The energy loss formula is a function of the relativistic variables $\beta\gamma$ which are related to the velocity of the object. An electron and proton having the same velocity have very different momenta because of the lower mass of the electron.









Facilities utilizing proton, neutron, and carbon ion beams for fighting a number of cancers resistant to other treatments are sprouting up all over the world.

Synchrotron Light Sources

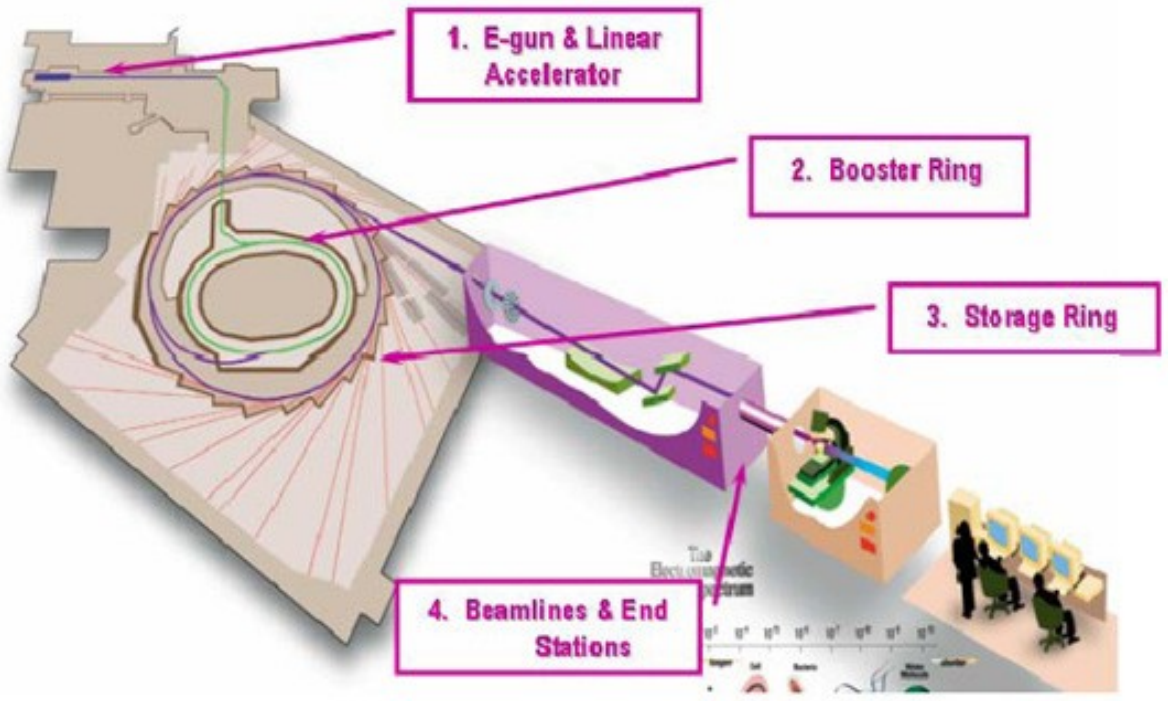
When an electron is accelerated (stopped or made to change direction) it radiates electromagnetic radiation (e.g., light, X-rays). This is bad for circular accelerators but is a nice source of intense X-rays which find a wide range of uses. The radiated power P is:

$$P=2Ke^2\gamma^4v^4/3c^3r^2$$

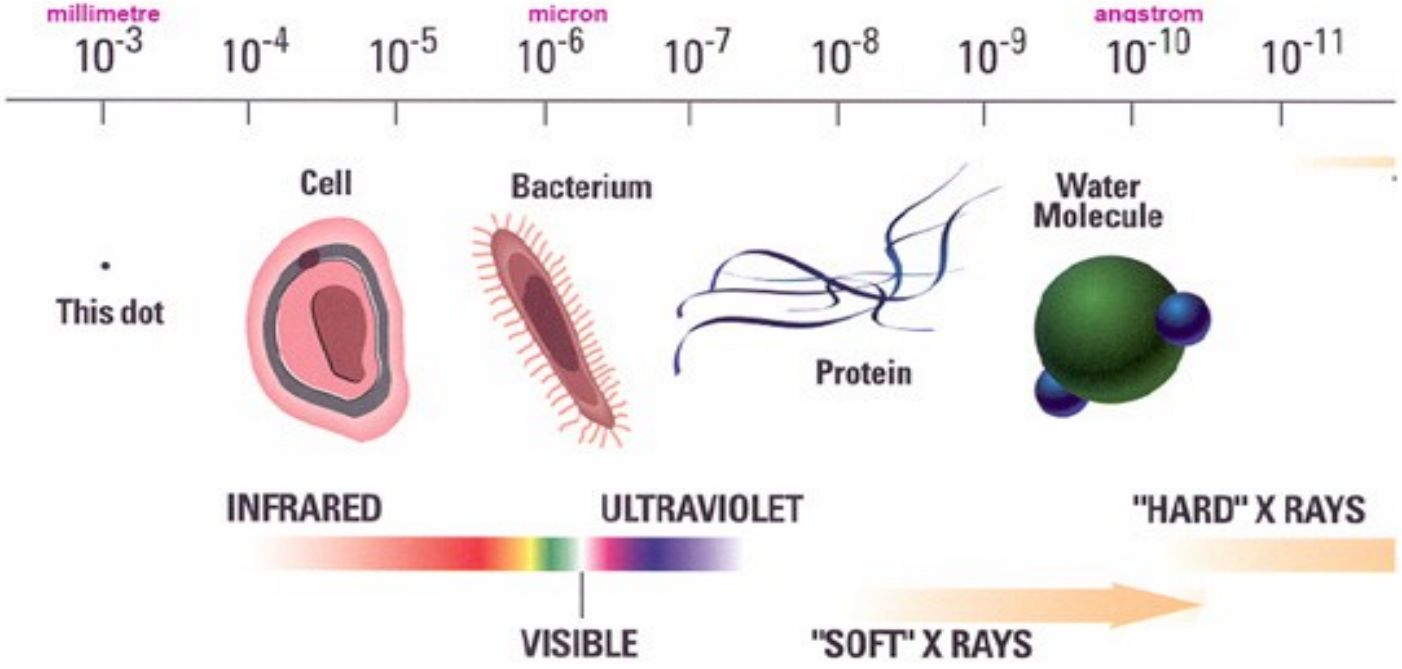
where K is the kinetic energy, e is the electron charge, γ is the relativistic Lorentz factor, v is the particle speed, c is the speed of light, and r is the radius of the accelerator. For relativistic particles v~c so it is γ~K/m is the important factor. That is, the power goes like $1/(\text{mass})^4$ – so it is hugely important for electrons but essentially negligible for protons since $M_p \sim 2000m_e$.

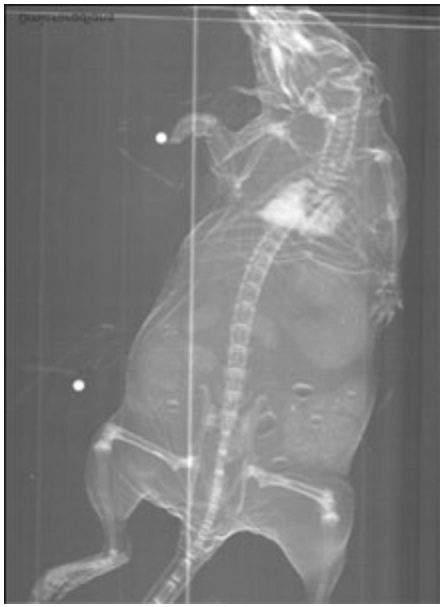
The Canadian Light Source

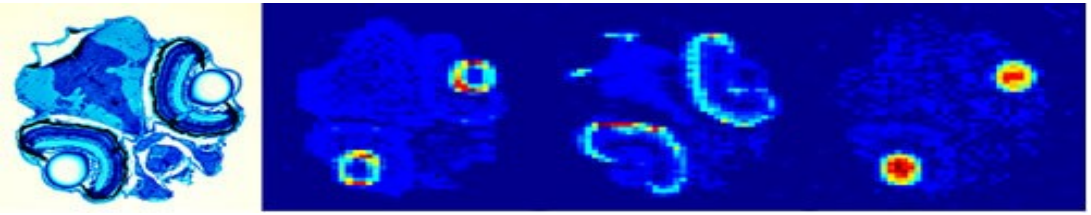
A 174 M$ light source started in 2004 in Saskatoon with beamlines for:
Biomedical Imaging and Therapy (BMIT), $17M;
Soft X-Ray Beamline for Microcharacterization of Materials, $4M;
Very Sensitive Elemental and Structural Probe Employing Radiation from a Synchrotron (VESPERS), $4.5M;
Resonant Elastic and Inelastic Soft X-Ray Scattering, $8.3M;
High-Throughput Macromolecular Crystallography, $10.4M.

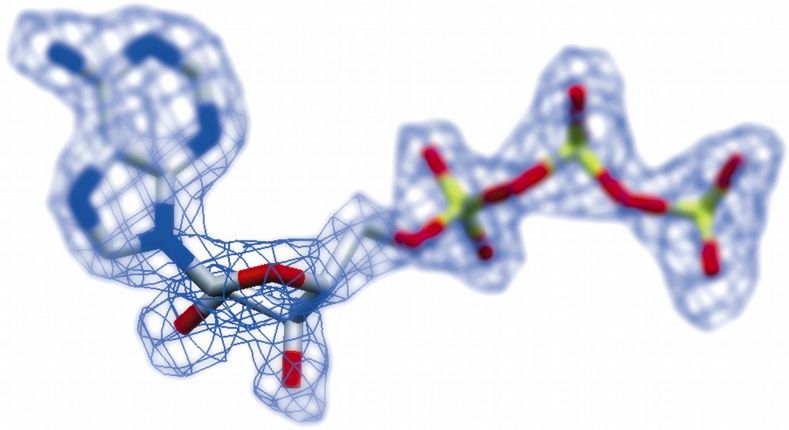


Biomedical Research at an SLS



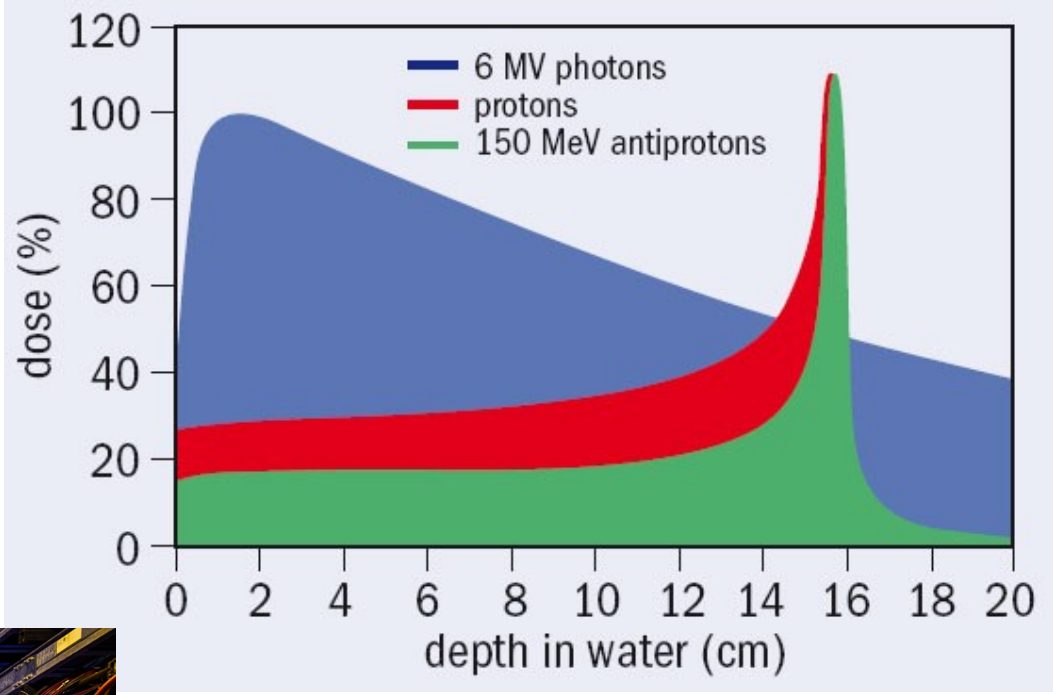


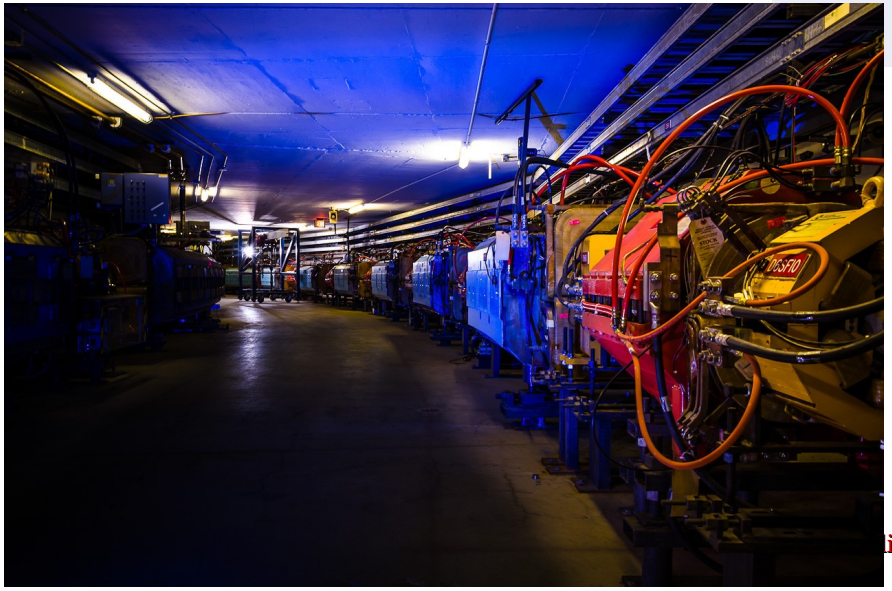




Some Future Research Avenues

Antihadrotherapy Research is being performed at CERN to use antiprotons instead of protons for cancer therapy since they lose energy even more sharply.





This is the Antiproton Decelerator (AD) at CERN. We use these antiprotons for antihydrogen trapping research as well as for ACE – Antiproton Cancer Experiment

Robert Wilson and Fermilab

Pastore: Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?

Wilson: No, sir; I do not believe so.

Pastore: Nothing at all?

Wilson: Nothing at all.

Pastore: It has no value in that respect?

Wilson: It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things. It has nothing to do with the military, I am sorry.

Pastore: Don't be sorry for it.

Wilson: I am not, but I cannot in honesty say it has any such application.

Pastore: Is there anything here that projects us in a position of being competitive with the Russians, with regard to this race?

Wilson: Only from a long-range point of view, of a developing technology. Otherwise, it has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country, except to make it worth defending.