PHY 554
Fundamentals of Accelerator Physics
Lectures 25-26
Scientific and Societal Applications of Accelerators

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http://case.physics.stonybrook.edu/index.php/PHY554_fall_2016

Your presentations:

presentation 20-25 mins, 5 mins Q&A

- **December 7, Wednesday, 5:30 pm, P122**
  - Xiangdong Li, *Electron cooling*
  - Irina Petrushina, *SRF system for Coherent Electron Cooler*
  - Jun Ma, *Coherent electron cooling*
  - Kentaro Mihara, *Space charge effects*
  - Sukho Kongtawong, *Low emittance design for a light source*
- **December 15, Thursday, 9:00 am, P122**
  - Kai Shih, *Beam-beam effects*
  - Kelsey Buggelli, *Polarize electron "Gatling" gun*
  - Mael Flament, *Electron beam welding and machining*
  - Dhananjay Ravikumar, *Cryogenics in accelerators*

Societal Applications of Accelerators

- **Semiconductors:** The semi-conductor industry relies on accelerator technology to implant ions in silicon chips, making them more effective in consumer electronic products such as computers, smart phones and MP3 players.
- **Clean air and water:** Studies show that blasts of electrons from a particle accelerator are an effective way to clean up dirty water, sewage sludge and polluted gases from smokestacks.
- **Cancer therapy:** When it comes to treating certain kinds of cancer, the best tool may be a particle beam. Hospitals use particle accelerator technology to treat thousands of patients per year, with fewer side effects than traditional treatments.
- **Medical diagnostics:** Accelerators are needed to produce a range of radioisotopes for medical diagnostics and treatments that are routinely applied at hospitals worldwide in millions of procedures annually.
- **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
- **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- **Nuclear energy:** Particle accelerators have the potential to treat nuclear waste and enable the use of an alternative fuel, thorium, for the production of nuclear energy.

http://www.acceleratorsamerica.org/resources/applications/index.html

Scientific Applications

- **High energy and Nuclear Physics** – colliders
- **Neutron sciences** – neutron spallation sources
- **Photon Sciences** – light sources
  - **Pharmaceutical research:** Powerful X-ray beams from synchrotron light sources allow scientists to analyze protein structures quickly and accurately, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS.
  - **DNA research:** Synchrotron light sources allowed scientists to analyze and define how the ribosome translates DNA information into life, earning them the 2009 Nobel Prize in Chemistry. Their research could lead to the development of new antibiotics.
- ……….

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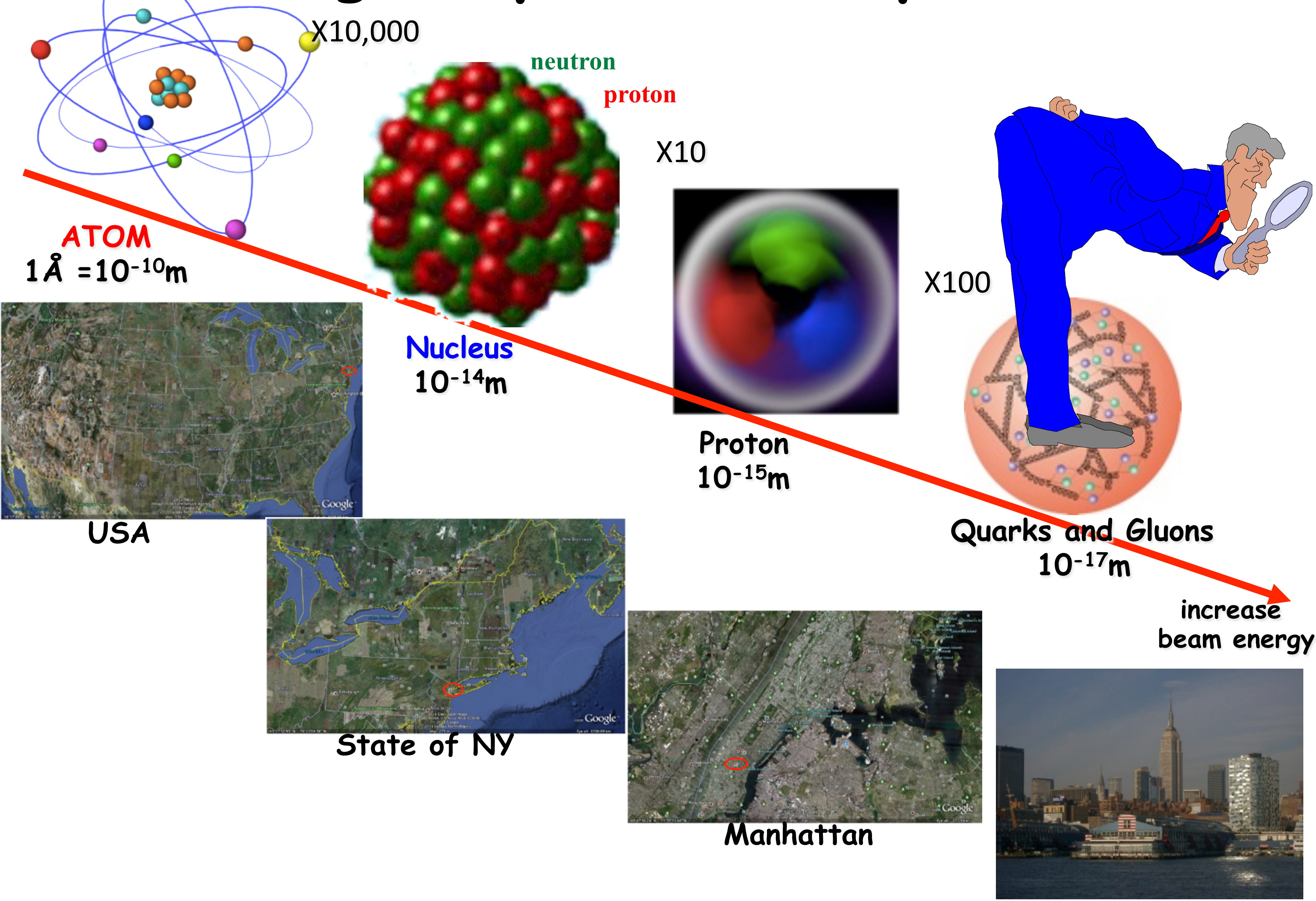
Why we need Colliders?

Looking deeper and deeper inside!



High Energy and Nuclear Physics

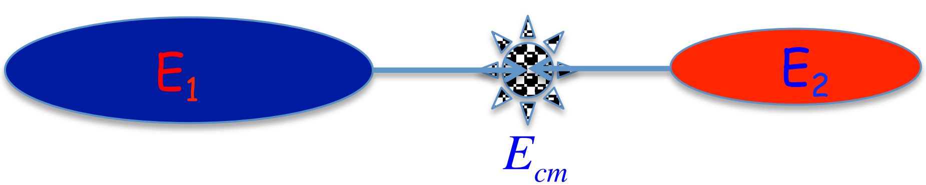
- Colliders – world's most powerful microscopes
- Hence, they allow to look into the matter on smaller and smaller scale, and, sometimes, discover new states of mater or new particles

$$\delta x \cdot \delta p \geq \hbar \qquad \delta p \leq \frac{E_{cm}}{c}; \quad \delta x \geq c\frac{\hbar}{E_{cm}}$$

or for new particles

$$M_{part} \leq \frac{E_{cm}}{c^2}$$

- For ultra-relativistic particles the c.m. energy is a simply twice the geometrical average of the colliding particles



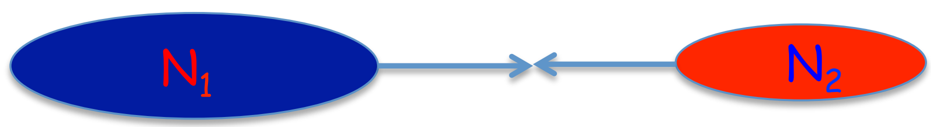
$$E_{cm} \cong 2\sqrt{E_1 E_2}$$

Collider	E_1, GeV	E_2, GeV	E_{cm}, GeV
RHIC	250 p	250 p	500.0
eRHIC	250 p	21.2 e-	145.6
LHC	6500 p	6500 p	13,000.0
B-factory	3.5 e-	10.58 e+	12.2
Fixed target	E_1, GeV	E_2, GeV	E_{cm}, GeV
CEBAF	6 e-	0.938 p	4.7
	12 e-	0.938 p	6.7
	6 e-	0.00051 e-	0.1
	12 e-	0.00051 e-	0.2

Productivity of colliders

- It is called LUMINOSITY

$$L = f_c \frac{N_1 N_2}{A} \cong f_c \frac{N_1 N_2}{2\pi \sqrt{\beta_{x1}\varepsilon_{x1} + \beta_{x2}\varepsilon_{x2}} \sqrt{\beta_{y1}\varepsilon_{y1} + \beta_{y2}\varepsilon_{y2}}}$$



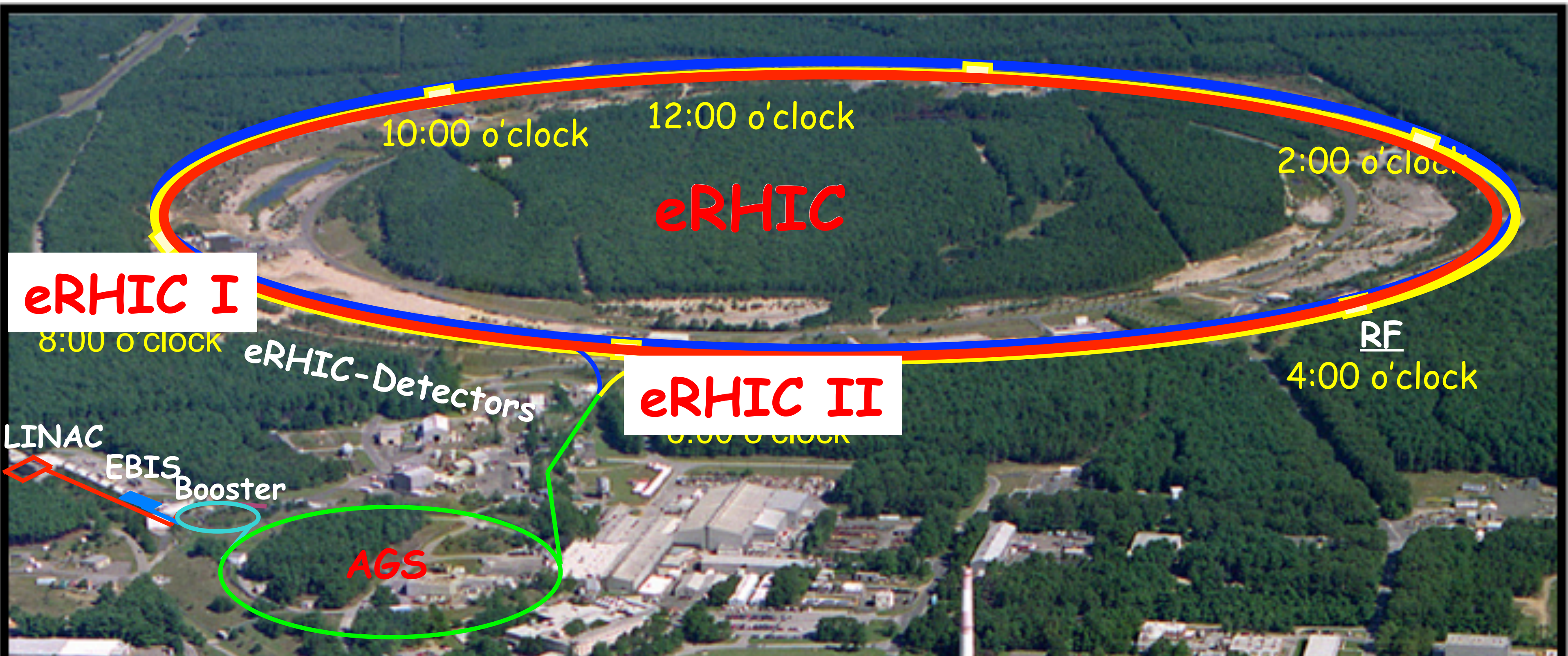
If an event A->B has a cross-section $\sigma_{A\to B}$ (for example generating HIGGS particle), then the speed of producing them is simply given by the Product of the cross-session and the luminosity

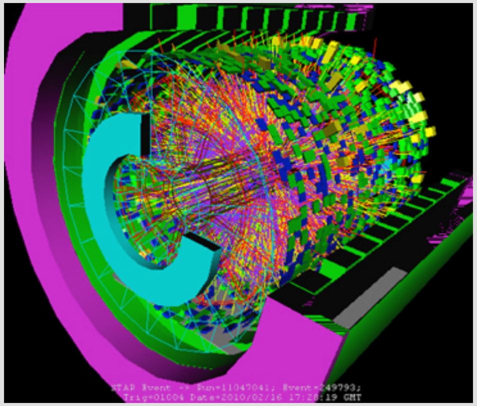
$$\dot{N}_{A\to B} = \sigma_{A\to B} \cdot L$$

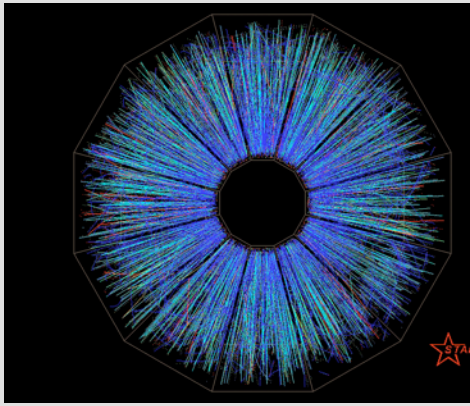
Luminosity is measured in $cm^{-2}sec^{-1}$

Collider	L
RHIC	10^{32}
eRHIC	10^{33} - 10^{34}
LHC	10^{34}
B-factory	10^{34}
Fixed target	L
CEBAF	10^{35}

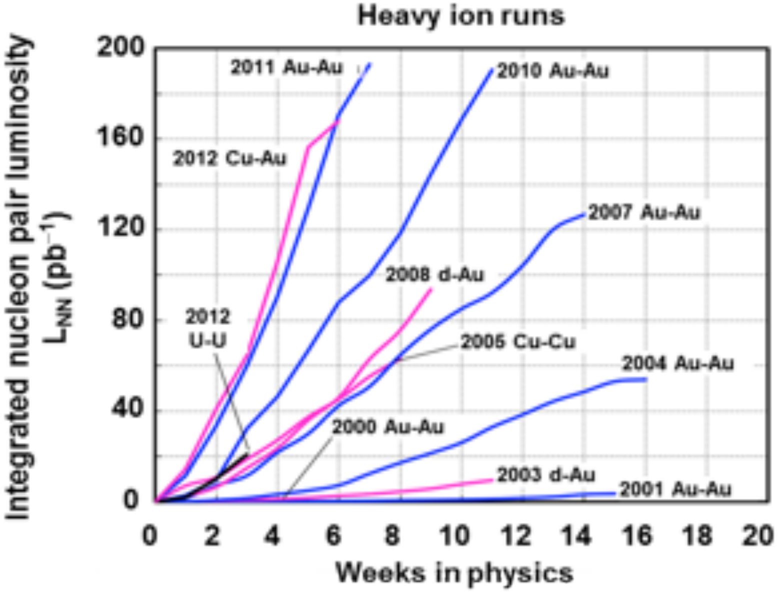
From RHIC to eRHIC

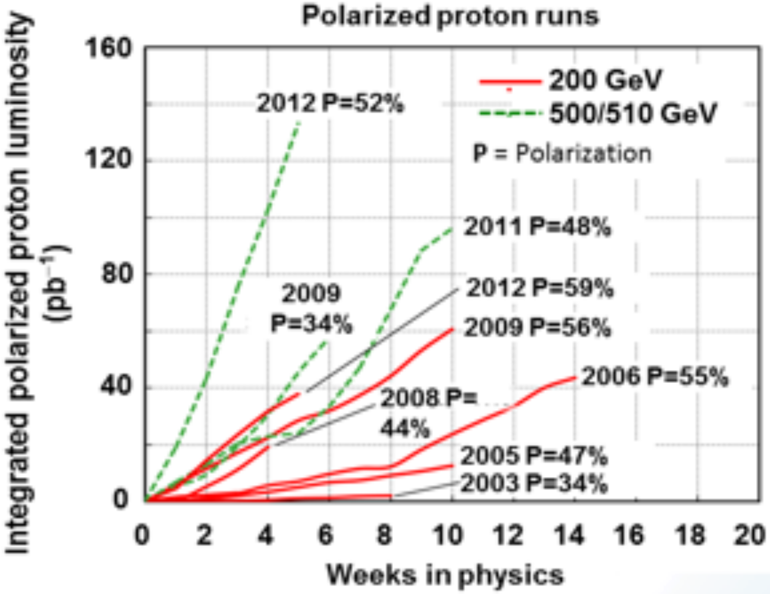






Dramatic Improvements in Performance & Versatility





Collision partners	Beam energies (GeV/nucleon)	Peak pp-equivalent luminosities achieved to date, scaled to 100 GeV/n[b)]
Used to date		
Au+Au	3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 31, 65, 100	195×10^{30} cm^{-2}s^{-1}
d+Au[a)]	100	100×10^{30} cm^{-2}s^{-1}
Cu+Cu	11, 31, 100	80×10^{30} cm^{-2}s^{-1}
p↑+p↑ (polarized)	11, 31, 100, 205, 250, 255	165×10^{30} cm^{-2}s^{-1} at 255 GeV
Cu+Au[a)]	100	230×10^{30} cm^{-2}s^{-1}
U+U	96	60×10^{30} cm^{-2}s^{-1}
Considered for future		
Au+Au	2.5, 7.5	
p+Au	100	
p↑+ ^{3}He↑ [a)]	166	

2 new colliding beam species / combinations in 2012

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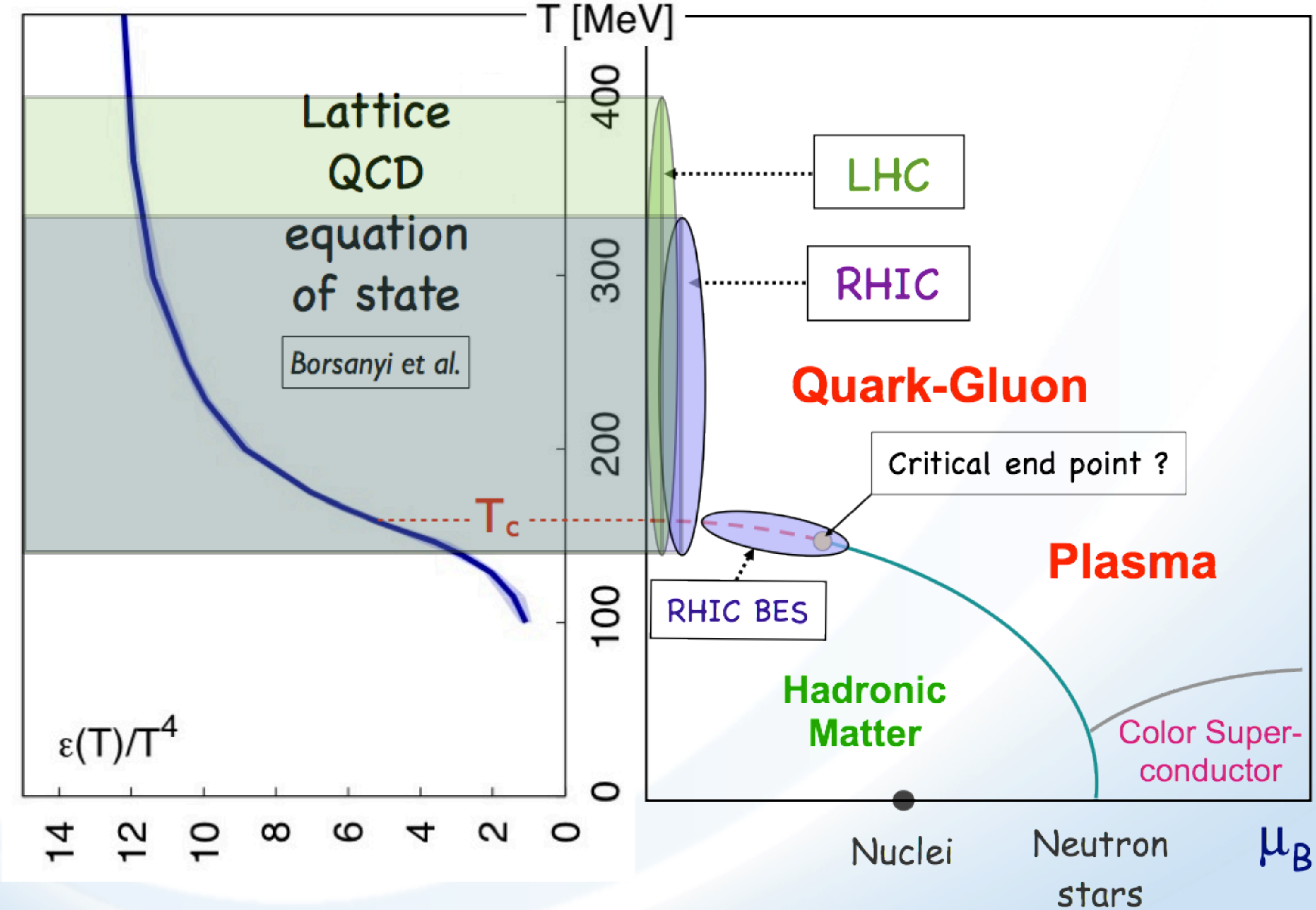
QCD Phase Diagram



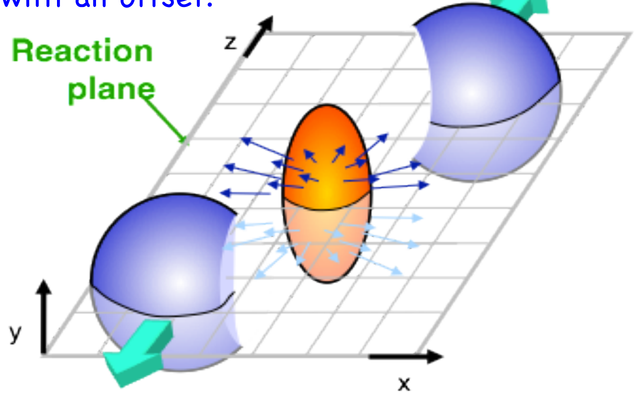
Anisotropic flow: The Perfect Liquid

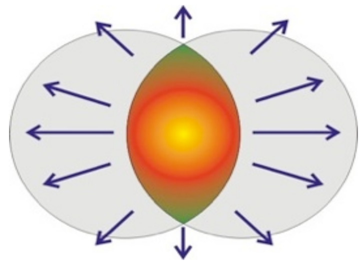
η/s = 0

η/s = 1/4π

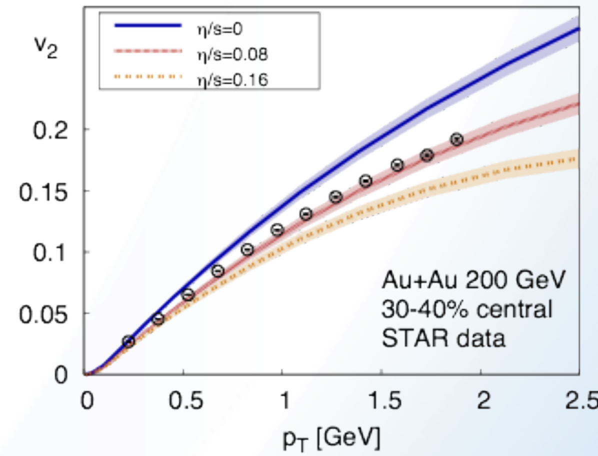
η/s = 2/4π

- two nuclei collide rarely head-on, but mostly with an offset:





only matter in the overlap area gets compressed and heated

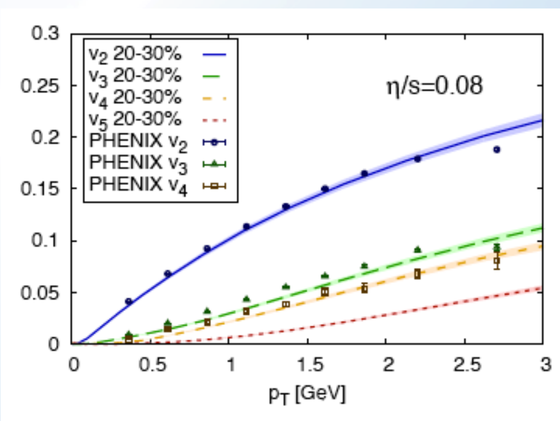


η/s → 1/4π

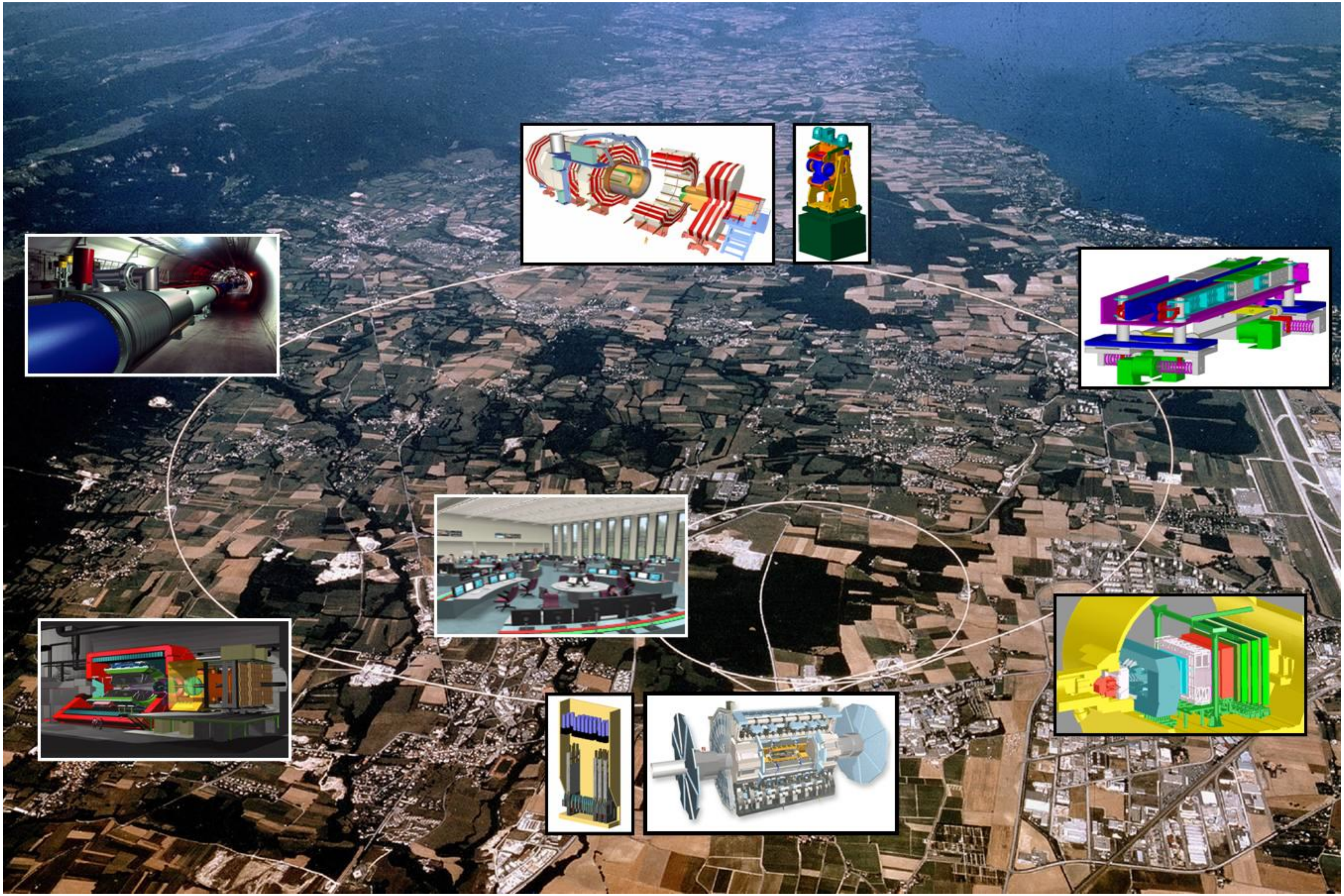
$$2\pi \frac{dN}{d\phi} = N_0\left(1 + 2\sum_n \mathrm{v}_n(p_T,\eta)\cos n\left(\phi - \psi_n(p_T,\eta)\right)\right)$$

anisotropic flow coefficients

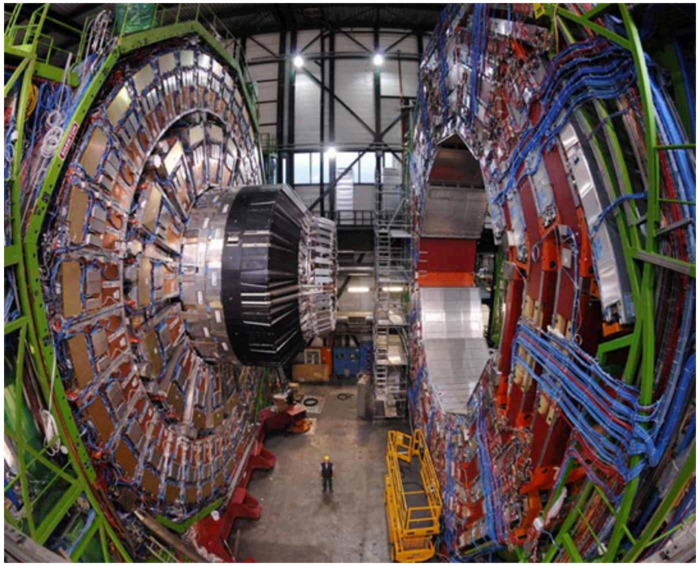
event plane angle

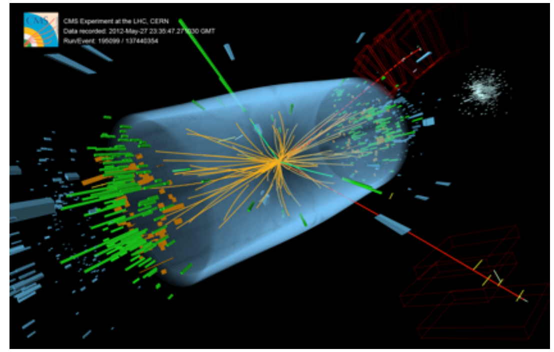


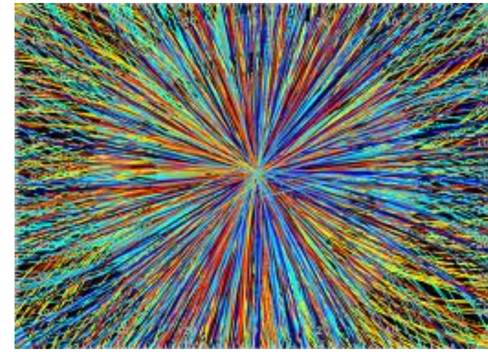
LHC – energy frontier

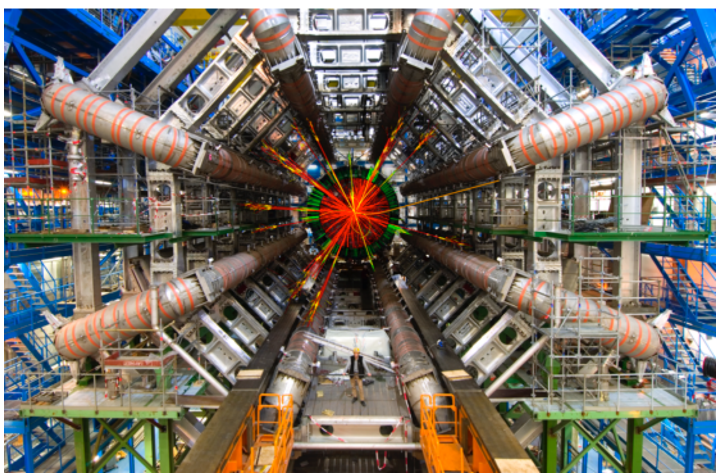


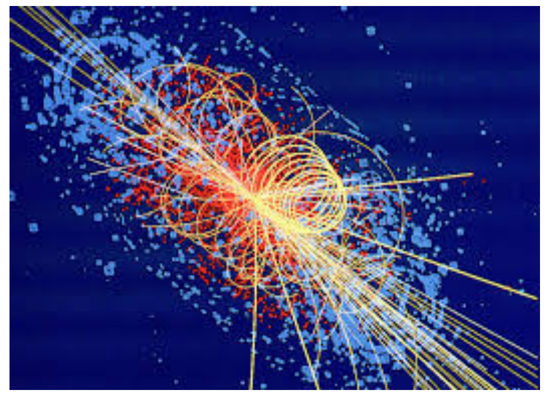
LHC – energy frontier

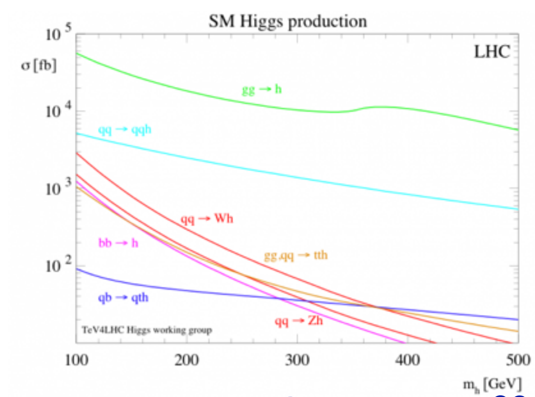


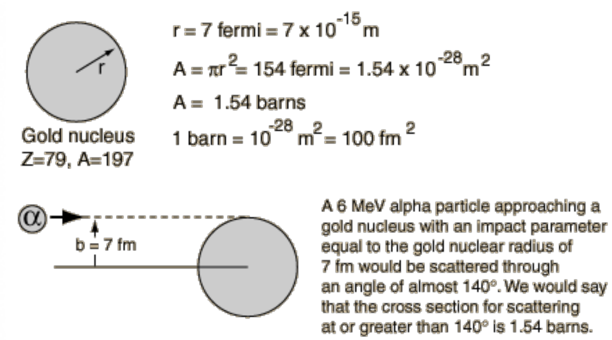






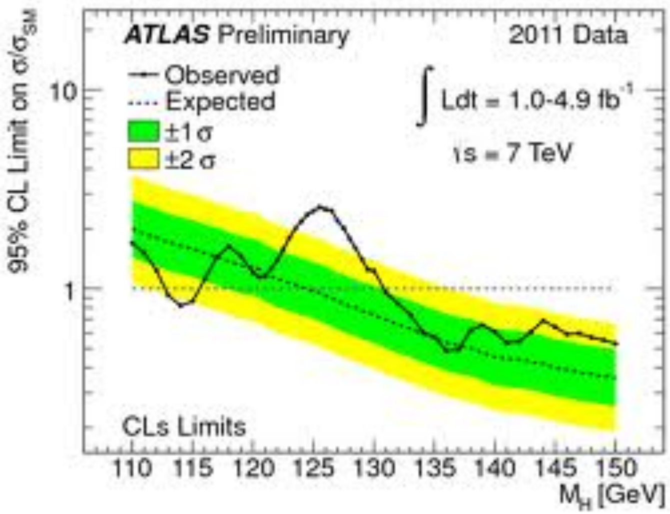


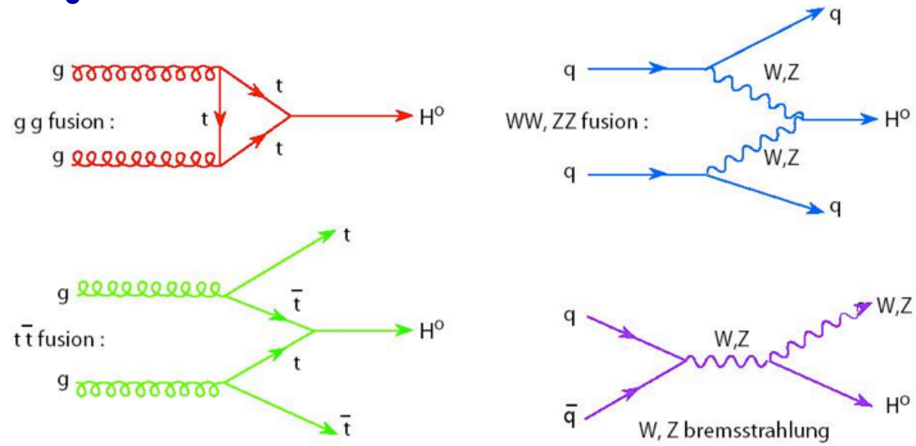




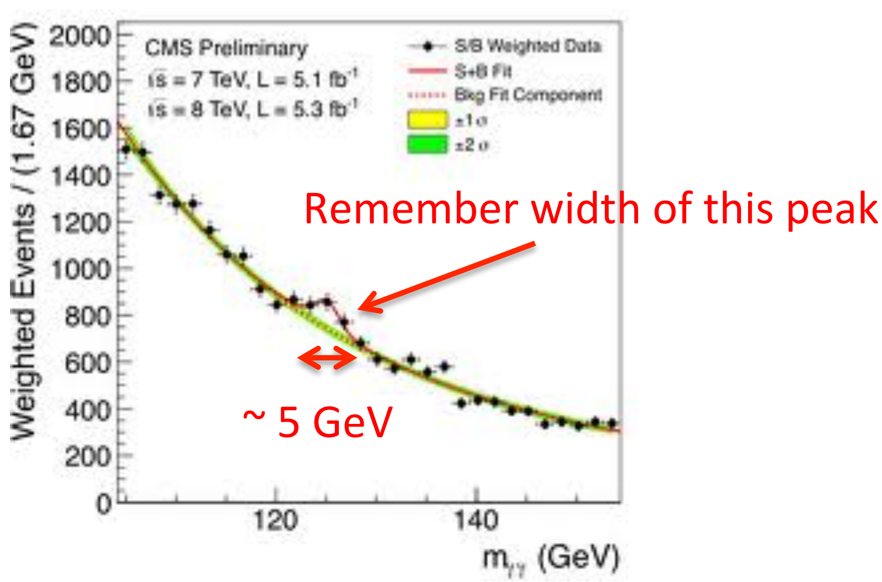
1 Barn=10^{-28} cm^2, 1 fb=10^{-43} cm^2

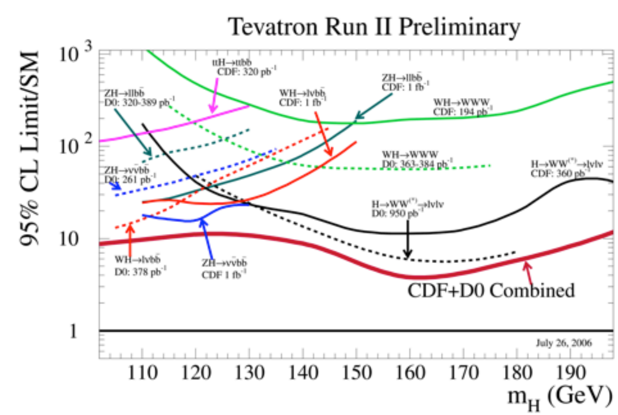
Higgs at LHC: blip in cross-section





Tevatron at FERMILAB has necessary energy reach but did not had enough luminosity to find Higgs – it only had “hints”

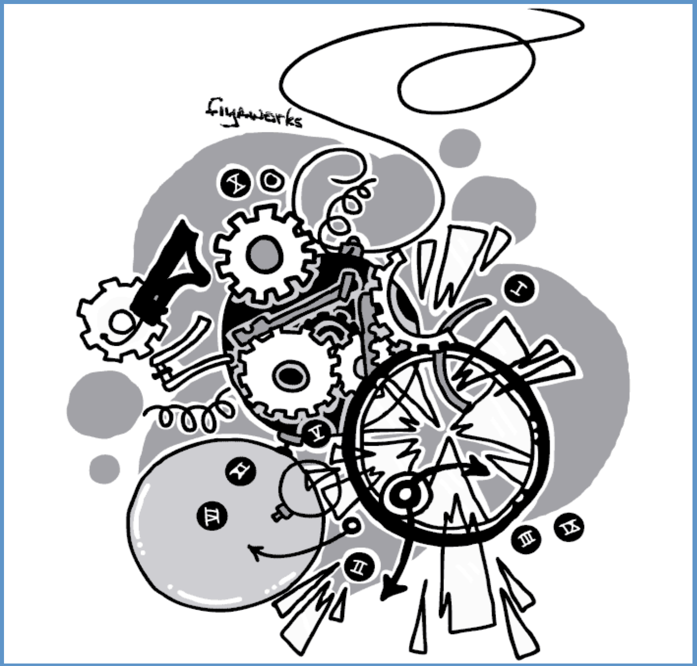




Why leptons and not hadrons?

Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

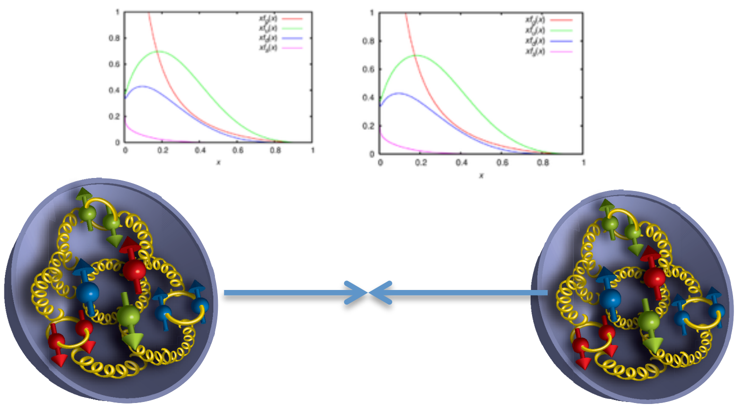
R. Feynman



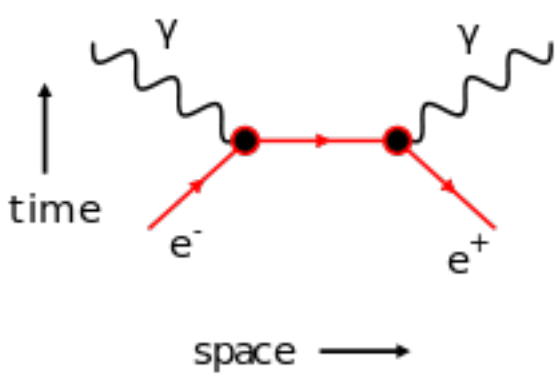
Courtesy of Mathew Lamont

Why e^+e^- or e^-h colliders?

To the best of our knowledge electrons and positions (or muons) do not have internal structure



Colliding hadron is as colliding two caps of quark-gluon soup (+ sea quarks): energies and polarization are varying and initial state is unknown



Pure initial state (energy of annihilated electron-positron pair)

Very precise knowledge of the energy and polarization

B-factories

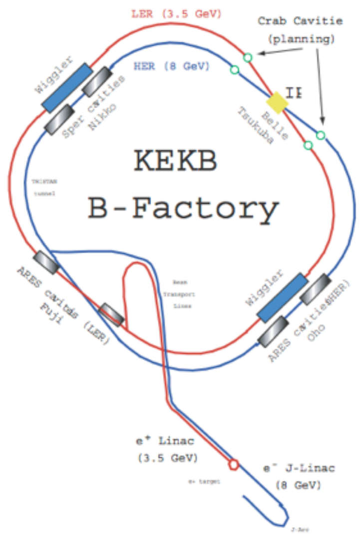
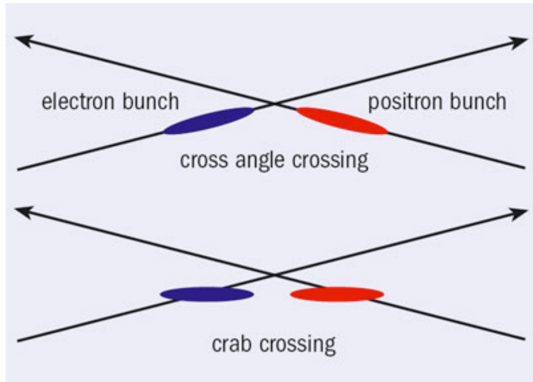
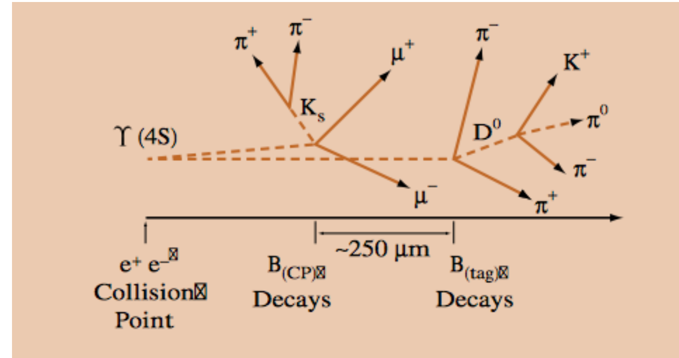


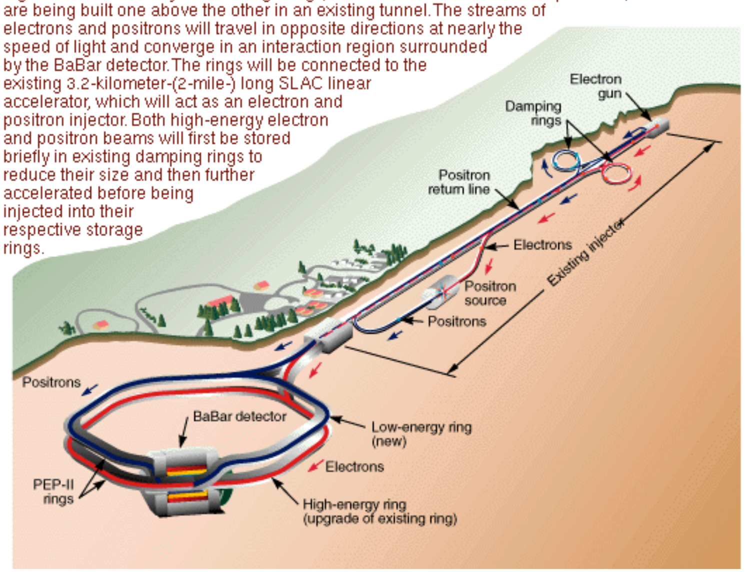
Figure 1: A schematic view of the KEKB.

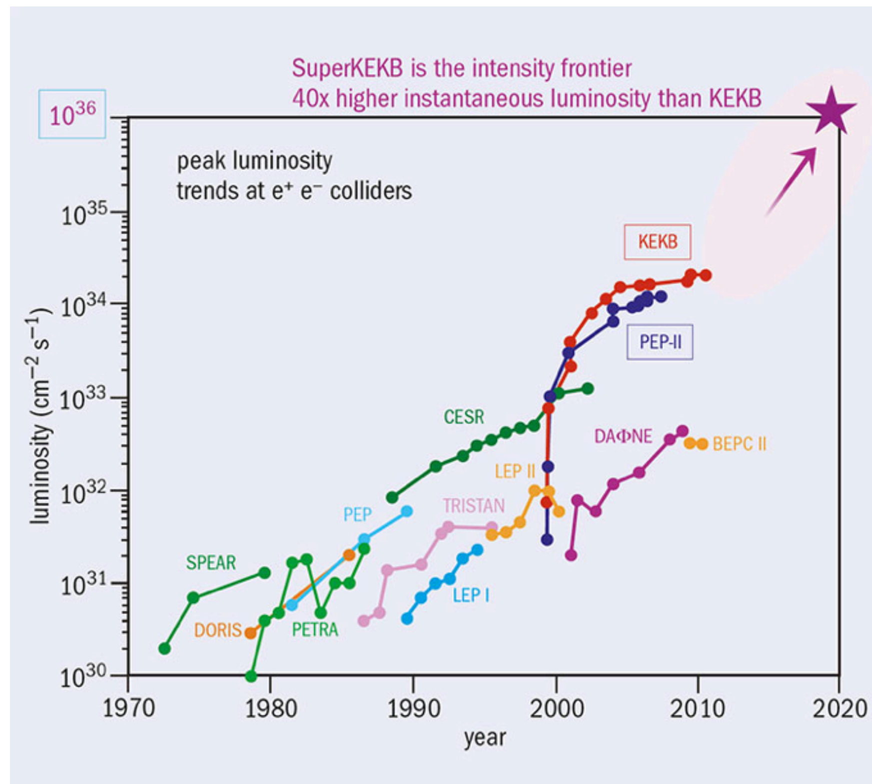




A typical "golden event" at an asymmetric B factory. The first B meson decays into a J/ψ (which immediately decays to $\mu^+\mu^-$) and a K_S, while the second B yields a clear tag.

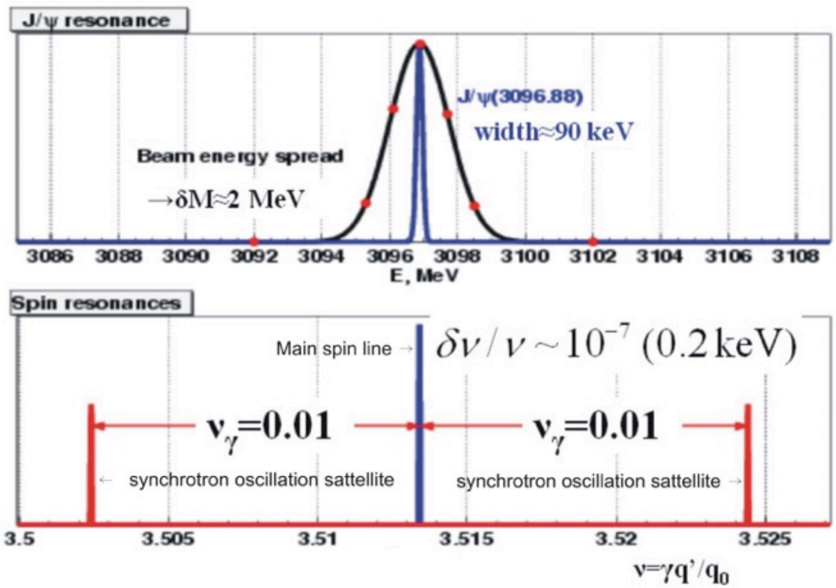
Figure 2. The B-Factory's two storage rings, one for electrons and one for positrons, are being built one above the other in an existing tunnel. The streams of electrons and positrons will travel in opposite directions at nearly the speed of light and converge in an interaction region surrounded by the BaBar detector. The rings will be connected to the existing 3.2-kilometer-(2-mile-) long SLAC linear accelerator, which will act as an electron and positron injector. Both high-energy electron and positron beams will first be stored briefly in existing damping rings to reduce their size and then further accelerated before being injected into their respective storage rings.

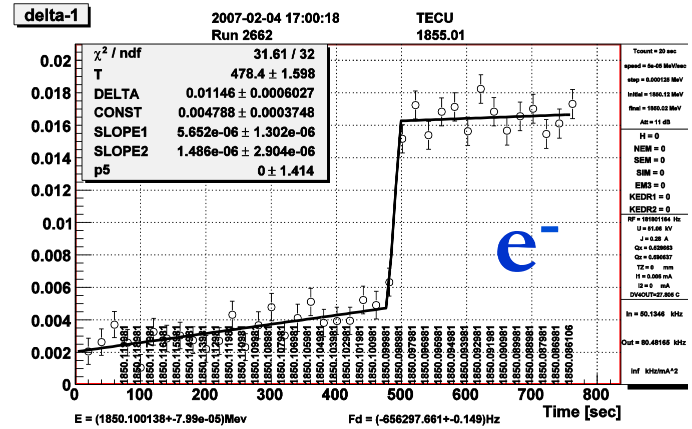


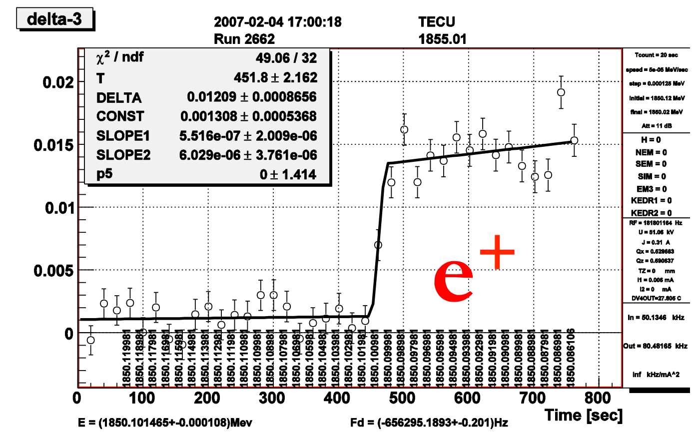


Resonance depolarization method

BEAM ENERGY SPREAD AND SPIN SPECTRA at VEPP-4M







In homogeneous magnetic field a width of the spin spectra is $\sim 10^{-9}$!
In real storage ring it is $\sim 10^{-7}$ due to betatron oscillations and nonlinearity of magnetic field and noise in magnet system

E_p - E_e =(1.32±0.14) keV: 0.4 p.p.m. energy accuracy

Compare this with 1% scale resolution in p-p collisions

Largest e^+e^- collider - LEP

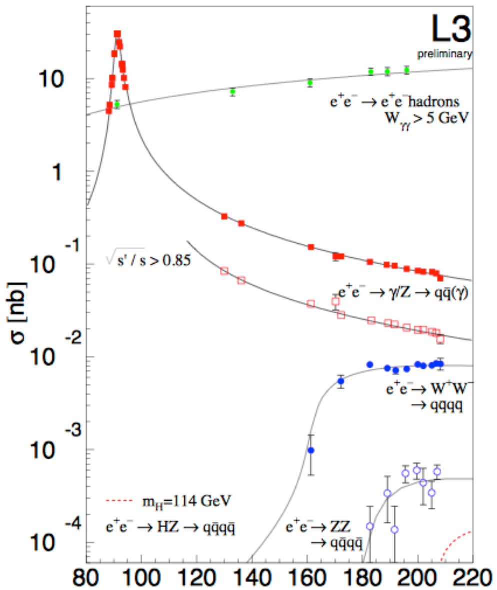
PR04.00 23.06.00

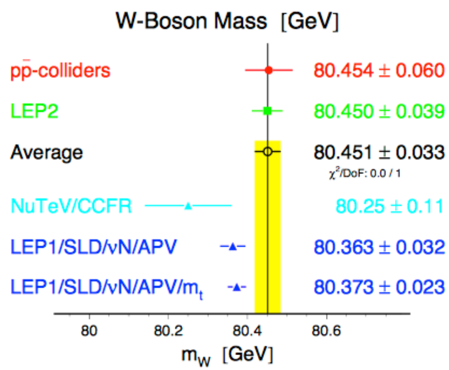
The LEP machine at CERN is the largest particle collider in the world. In a ring 27 km in circumference, buried about 100 m underground, bunches of electrons and positrons race round in opposite directions...

Last sprint for LEP

The Director General, Prof. Luciano Maiani, began his report with the performance of the Laboratory's flagship accelerator, the Large Electron-Positron collider, LEP, during its final year. LEP is achieving its highest energy collisions ever with beams of over 104 GeV, well exceeding its design energy and giving experiments a final chance of discovering the still-elusive Higgs particles before the end of it's experimental programme in September. Thanks to precision data from LEP and elsewhere, scientists already know that Higgs particles, if they exist, must be within range of LEP's successor, the LHC.

LEP – W & Z factory





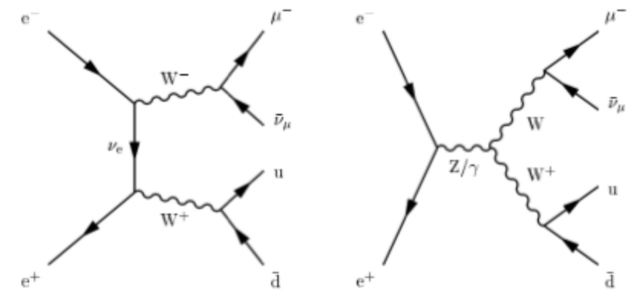


Figure 16. CC03 diagrams for W^+W^- production with subsequent decay into $u\bar{d}$ and $\mu\bar{\nu}_\mu$.

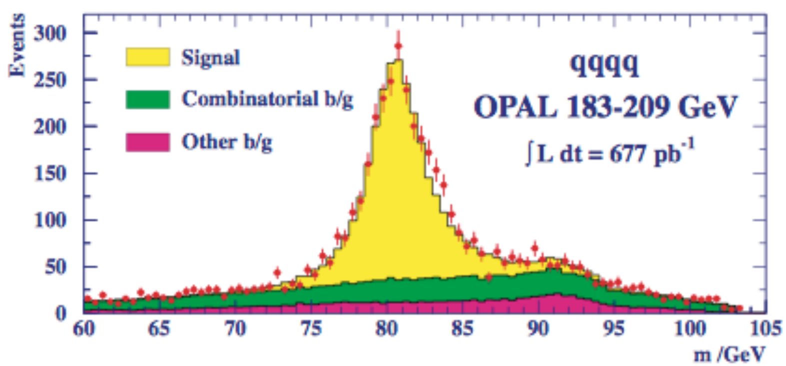


Figure 19. Reconstructed W mass distribution for all OPAL $W^+W^- \to q\bar{q}q\bar{q}$ data from $\sqrt{s} = 183$ to 209 GeV. The histogram shows the SM expectation for $M_W = 80.42$ GeV.

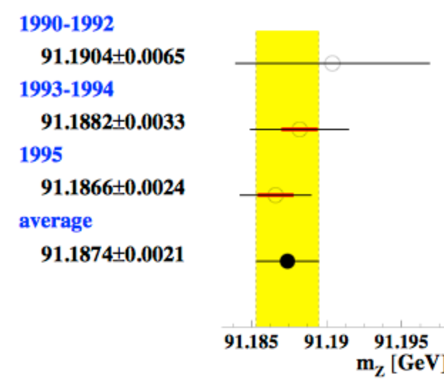


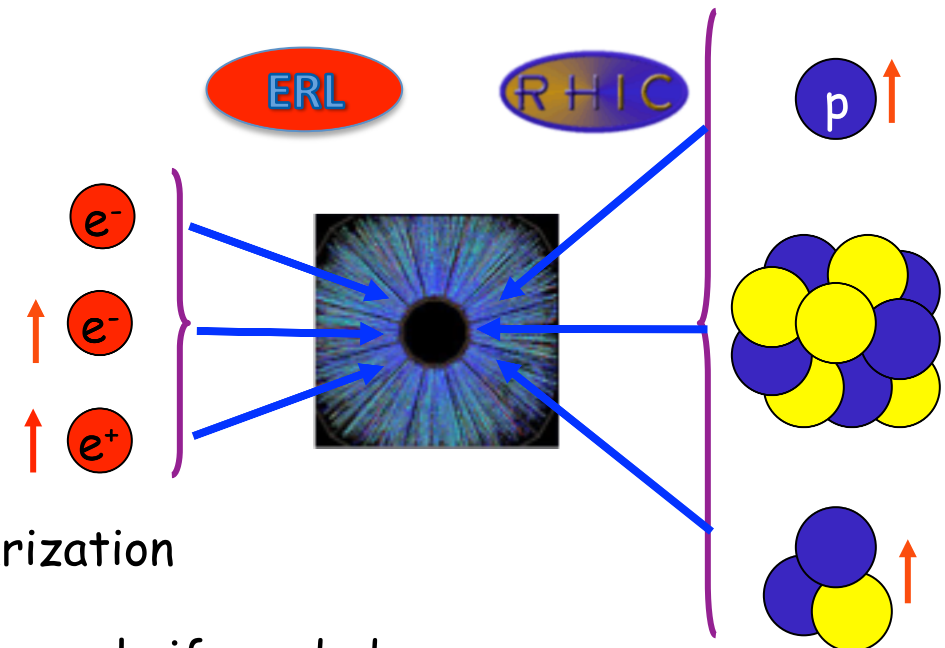
Figure 5. m_Z combined by EWWG for the different periods of data taking.

$$m_W = 80.450 \pm 0.026(stat.) \pm 0.030(syst.) GeV.$$

$$m_Z = 91.1874 \pm 0.0021\ GeV.$$

eRHIC: QCD Facility at BNL

Un-polarized and polarized leptons 10-20 (30) GeV



Polarized protons 50-250 GeV

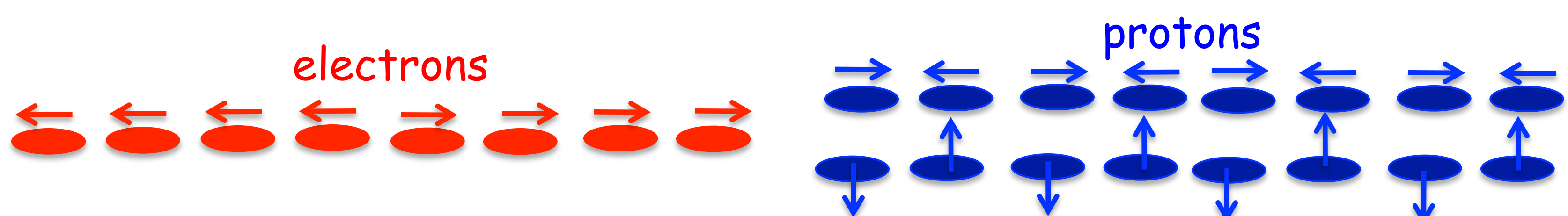
Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u

Polarized light ions
He^3 166 GeV/u

80% e^- beam polarization

Polarized positrons only if needed

Center mass energy range: $\sqrt{s}$=30-140 (175) GeV;
Luminosity ~ 10^{33}-10^{34} cm^{-2} sec^{-1}



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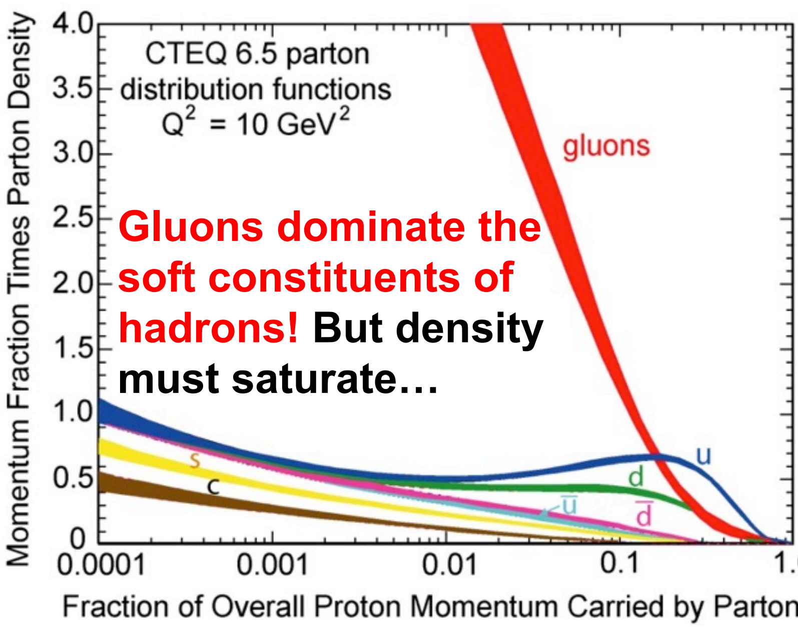
Office of Nuclear Physics

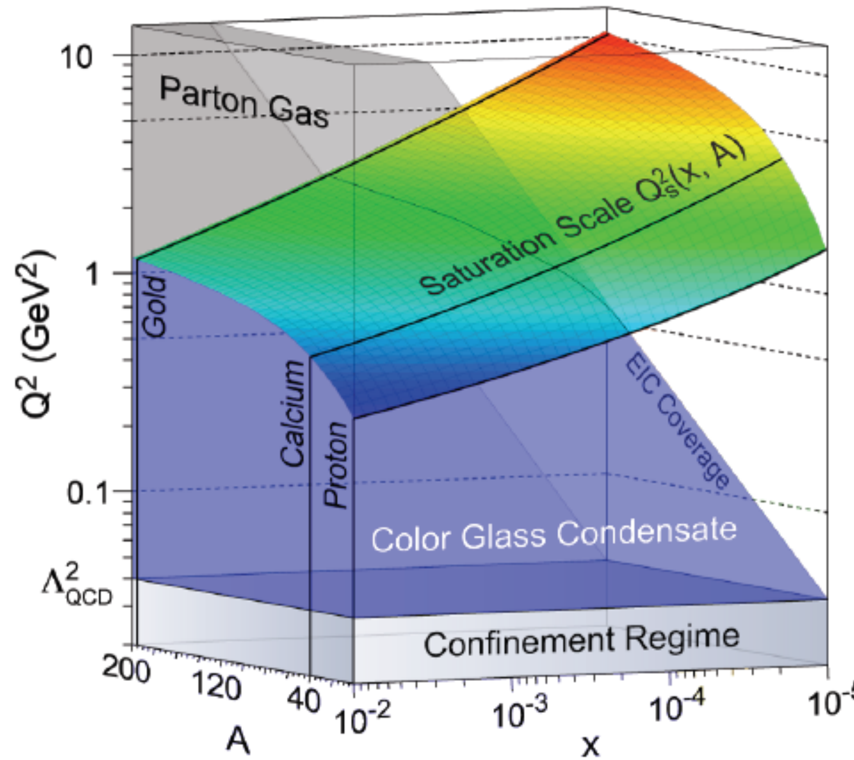
EIC Science: Gluon-Dominated Cold Matter in e+A

Search for supersymmetry @ LHC, ILC (?): ***seeking to unify matter and forces***

Electron-Ion Collider: ***reveal that Nature blurs the distinction***

Deep inelastic scattering @ HERA ?





EIC probes *weak* coupling regime of very high gluon density, where gauge boson occupancy >> 1. *All ordinary matter has at its heart an intense, semi-classical force field* -- can we demonstrate its universal behavior? Track the transition from dilute parton gas to CGC? "See" confinement reflected in soft-gluon spatial distributions inside nuclei?

Industrial Applications

- ✓ Ion Implantation
- ✓ Electron beam materials processing
- ✓ Electron beam irradiators
- ✓ Radioisotope production
- ✓ Ion Beam Analysis
- ✓ High Energy X-ray Inspection
- ✓ Neutron generators
- ✓ Synchrotron radiation
- ✓ ……..

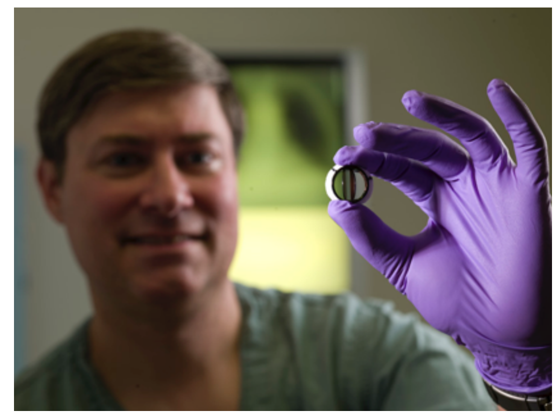
Industrial Accelerators

- **DC Voltage**
  - Van de Graaff – Use a charge carrying belt or "chain". Energies range from 1 to 15 MeV at currents from a few nA to a few mA.
  - Dynamitron & Cockcroft Walton generator – Basically voltage multiplier circuits at energies to up to 5 MeV and currents up to 100 mA.
  - Inductive Core Transformer (ICT) – A transformer charging circuit with energies to 3 MeV at currents to 50 mA.
- **RF Linacs**
  - Electron linacs – standing wave cavities from 0.8 to 9 GHz. Energies from 1 to 16 MeV at beam power to 50 kW.
  - Ion linacs – all use RFQs at 100 to 600 MHz. Energies from 1 to 70 MeV at beam currents up to mA.
- **Circular**
  - Cyclotrons – ion energies from 10 to 70 MeV at beam currents to several mA.
  - Betatrons – electron energies to 15 MeV at few kW beam power.
  - Rhodotron – electron energies from 5 to 10 MeV at beam power up to 700 kW.
  - Synchrotron – electron energies up to 3 GeV and ion energies up to 300 MeV/amu.

Materials modification

Electron beams make shrink wrap tougher and better for storing food and protecting other products, such as board games, CDs and DVDs

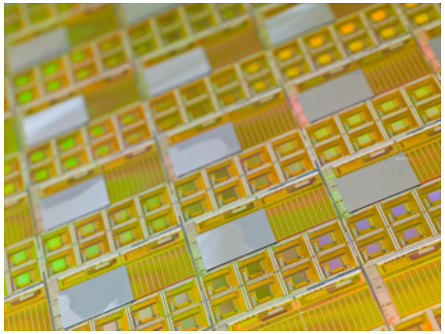
The auto industry uses particle accelerators to treat the material for radial tires, eliminating the use of solvents that pollute the environment.



There is a hope to improve the safety of artificial heart valves by forming them from material bombarded by ions

Ion implantation

The semiconductor industry relies on accelerator technology to implant ions in silicon chips.



Semiconductors

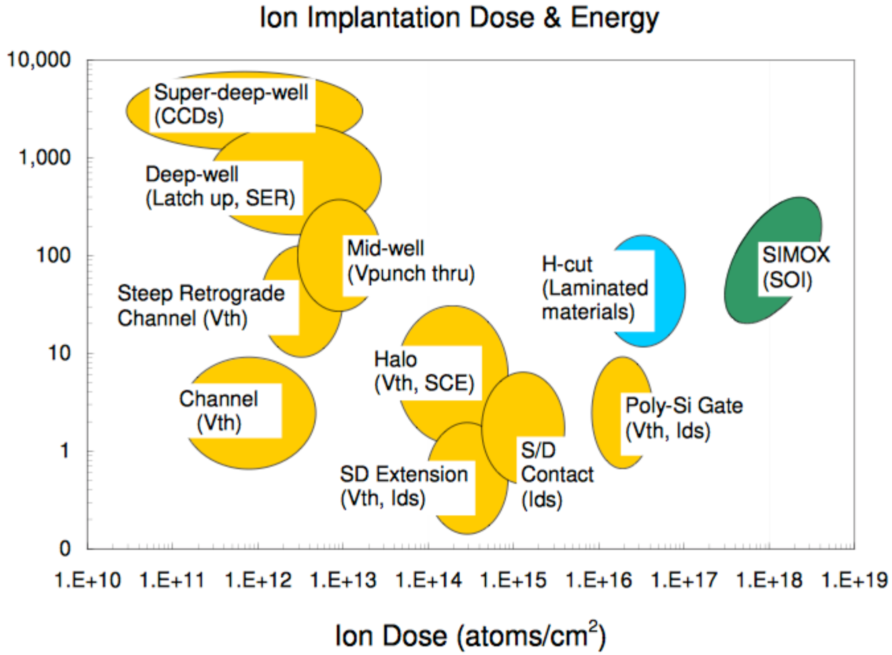
- CMOS fabrication
- SIMOX
- Cleaving silicon
- MEMS

Metals

- Harden cutting tools
- Artificial human joints

Ceramics & glasses

- Harden surfaces
- Modify optics



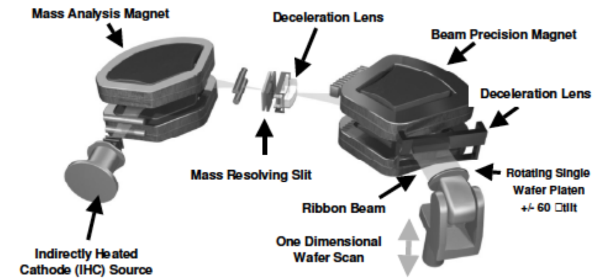
All digital electronics now dependent on ion implantation.

Ion implantation

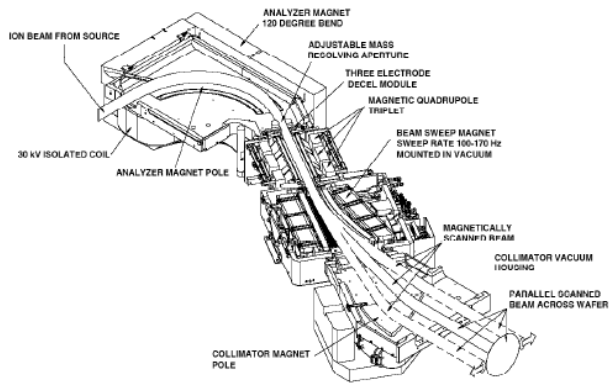
Ion Implantation Accelerators

Accelerator classifications

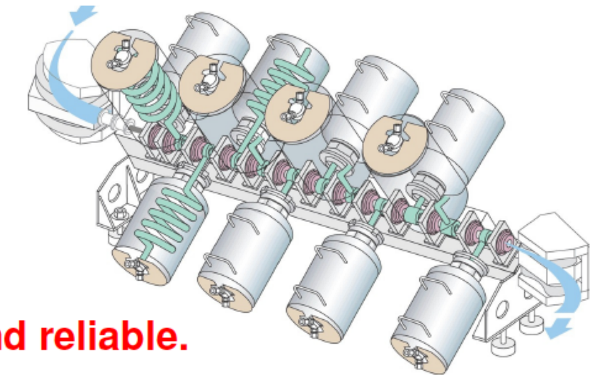
- **Low energy/ high current**
  - “High current implanters”
  - Ion energies from few hundred eV to tens of keV.
  - Variable energy, single gap with currents to 50 mA.



- **Medium energy/ medium current**
  - Original ion implanter
  - Variable energies of 50 to 300 keV range
  - Currents in the 0.01 to 2 mA range.
  - Usually multi-gap direct voltage units using voltage-multiplier HV power supply.



- **High energy/ low current**
  - Variable energy from 1 to 10 MeV
  - Beam currents to hundreds of microamperes.
  - Can be linacs or tandem charge-exchange columns
  - Both use high-charge-states for upper energy range.



These systems have become highly specialized and reliable.

Material Processing/Modifications

- Electron beam processing involves irradiation (treatment) of products using a high-energy electron beam
- Electron beam processing is used in industry primarily for three product modifications:
  - Crosslinking of polymer-based products to improve mechanical, thermal, chemical and other properties
  - Material degradation often used in the recycling of materials
  - Sterilization of medical and pharmaceutical goods, foods and other products

Material Processing/Modifications

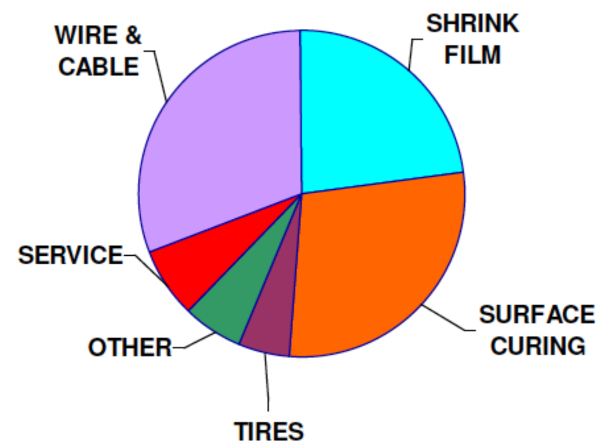
Electron Beam Irradiators

- Cross linking of materials (largest application)
- Sterilization of single-use disposable medical products – surgical gowns, surgical gloves, syringes, and sutures (growing applications)
- Food and waste irradiation (largest potential applications)

Cross linking applications

Product	Applications
Cross-linked polyethylene(PE) and PVC	Heat and chemical-resistant wire insulation; pipes for heating systems
Cross-linked foam polyethylene	Insulation, packing and flotation material
Cross-linked rubber sheet	High quality automobile tires
Cross-linked polyurethane	Cable insulation
Cross-linked nylon	Heat and chemical resistant auto parts
Heat resistant SiC fibers	Metal and ceramic composites
Vulcanized rubber latex	Surgical gloves and finger cots
Cross-linked hydrogel	Wound dressings
Acrylic acid grafted PE film	Battery separators
Grafted polyethylene fiber	Deodorants
Curing of paints and inks	Surface coating and printing

Cross linking by industry



Total of $50 billion per year

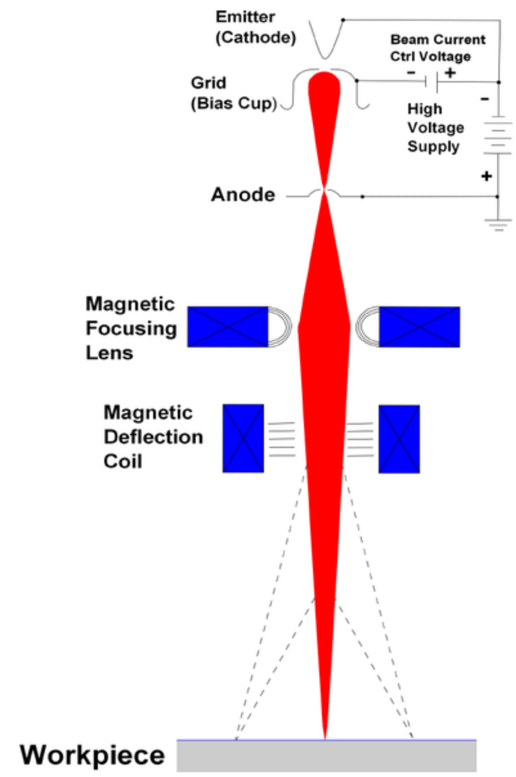
Material Processing/Modifications

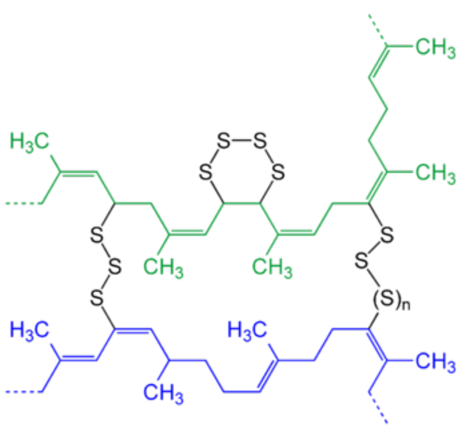
Electron Beam Irradiation Accelerators

- 100 to 300 keV — Single gap, self-shielded sheet beam systems without beam scanning. Beam currents from 10 to 2000 mA; treat 1 to 3 m wide material. Used for curing thin film coatings and cross-linking laminates and single strand wire.
- 450 to 1000 keV — Larger dc systems with scanned beams and self-shielding. Beam currents from 25 to 250 mA; treat 0.5 to 2 meter wide material. Mainly used for cross-linking, curing and polymerization processes in the tire, rubber and plastics industry.
- 1 to 5 MeV — Scanned beam dc systems capable of 25 to 200 kW beam power; scanned beam width up to ~2 meters. Used for cross-linking and polymerization of thicker materials, and for sterilization of medical products.
- 5 to 10 MeV — High energy scanned beam systems capable of 25 to 700 kW beam power. Used for medical product sterilization and cross-linking and polymerization of even thicker materials. They are also used as x-ray generators for food irradiation, waste water remediation, and gemstone color enhancement for topaz and diamonds.

Crosslinking

- A cross-link is a bond that links one polymer chain to another.
- Cross-linking is used in both synthetic polymer chemistry and in the biological sciences.
- Although the term is used to refer to the "linking of polymer chains" for both sciences, the extent of crosslinking and specificities of the crosslinking agents vary. Of course, with all science, there are overlaps, and the following delineations are a starting point to understanding the subtleties.
- **When cross links are added to long rubber molecules, the flexibility decreases, the hardness increases and the melting point increases as well.**

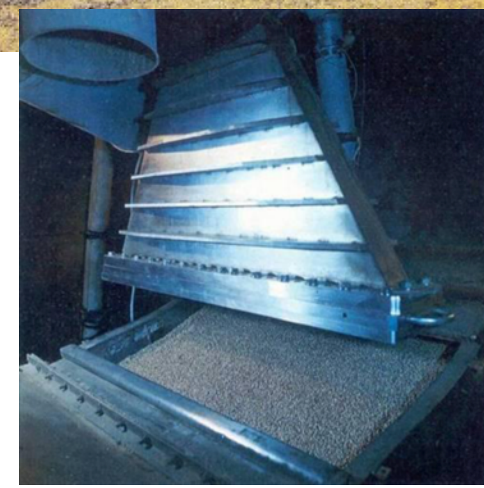




Vulcanization is an example of cross-linking. Schematic presentation of two "polymer chains" (blue and green) cross-linked after the vulcanization of natural rubber with sulfur (n = 0, 1, 2, 3 …).

Micro-biological sterilization

- ✓ Electron beam processing has the ability to break the chains of DNA in living organisms, such as bacteria, resulting in microbial death and rendering the space they inhabit sterile.
- ✓ E-beam processing has been used for the sterilization of medical products and aseptic packaging materials for foods as well as disinfestation, the elimination of live insects from grain, tobacco, and other unprocessed bulk crops.
- ✓ Sterilization with electrons has significant advantages over other methods of sterilization currently in use. The process is quick, reliable, and compatible with most materials, and does not require any quarantine following the processing.



Granary weevil

Granary weevil (*Sitophilus granarius*): An adult lays up to 450 eggs singly in holes chewed in cereal grains. Each egg hatches into a white, legless larva, which eats the grain from the inside. The larva pupates within the grain and the adult then chews its way out. The exit holes are characteristic signs of weevil damage. The life cycle takes about one month under summer conditions and adults may survive for a further eight months. The granary weevil is a small dark brown-black beetle about 4mm long with a characteristic rostrum (snout) protruding from its head. It has biting mouth parts at the front of the rostrum and two club-like antennae.

Sterilization of products

Pest & Pathogen Control:

Example: Half of grain produced on the Earth is infested by bugs: they have to be stopped, or grain is gone…

Electron Beam processing as a disinfestation method replaces antiquated environmentally unfriendly methods such as fumigation and chemical dipping.

A significant area for this technology is the herb and spice industry. These commodities are valued for their distinctive flavors, aromas and colors. They can be processed by this technology to reduce bacterial contamination without compromise to their sensory properties.

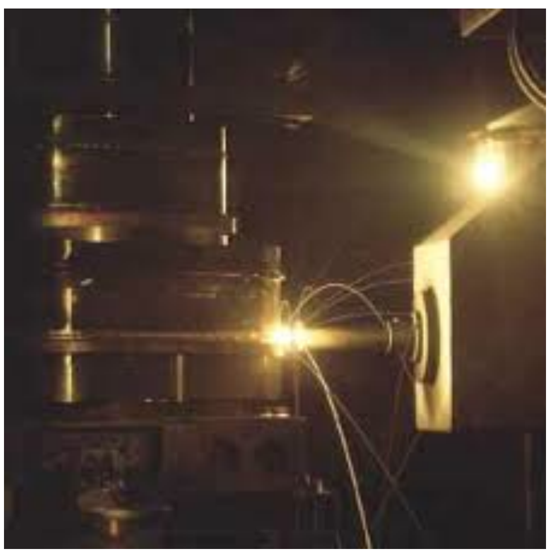
Fruits, vegetables, grains and other food items can be processed by Electron Beam to control fruit flies and other insects that use these commodities as a host for propagation.

Suitable as a quarantine measure, several countries rely on this technology to treat food commodities prior to exporting

Sterilization of *other, less testy,* products

technology of the livestock enterprises waste decontamination with the help of electron beam

What else?



Dec. 15 Presentation

Mael Flament, *Electron beam welding and machining*

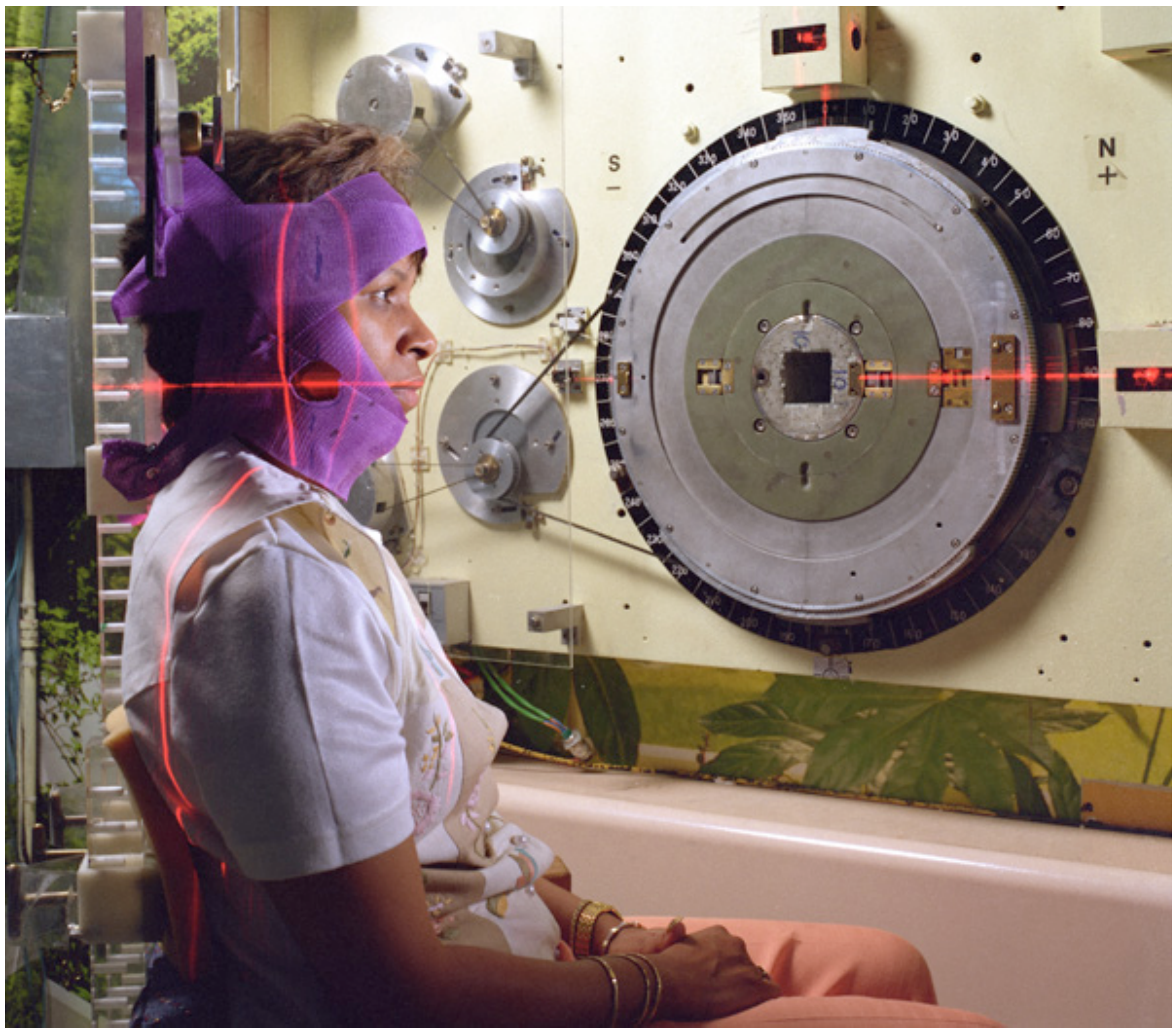
Key advantages

- Using electron beam with energies below 10 MeV (e.g. below giant nuclear resonance!) does not leave residual radioactivity
- To a large degree, it is just a use of electrical power to eliminated the intruders
- Hence, such treatment does not changes chemical structure of the irradiated products while effectively killing leaving bugs or bacteria
- Replacing dangerous (killer!) chemicals with is environmentally neutral treatment

Medical Applications

- ✓ In contrast with other applications, medical applications of any technology is most humane and broadly accepted by society.
- ✓ Some of accelerator applications in medicine – like radiation therapy – are well known.
- ✓ Many are know only to experts.
- ✓ Here is a short (and incomplete) list of accelerator applications in medicine :
    - ✓ Hadron radiation therapy
    - ✓ Gamma-ray (Photon) radiation therapy
    - ✓ X-ray tubes
    - ✓ Sterilization of material & equipment
    - ✓ Isotopes
    - ✓ Angiography
    - ✓ Neutron capture therapy
    - ✓ Genome project
    - ✓ Reconstruction of protein structures
    - ✓ Developing new drugs and new materials

γ-Ray Radiation Therapy



X-ray tubes are well known

History of medical applications of accelerators

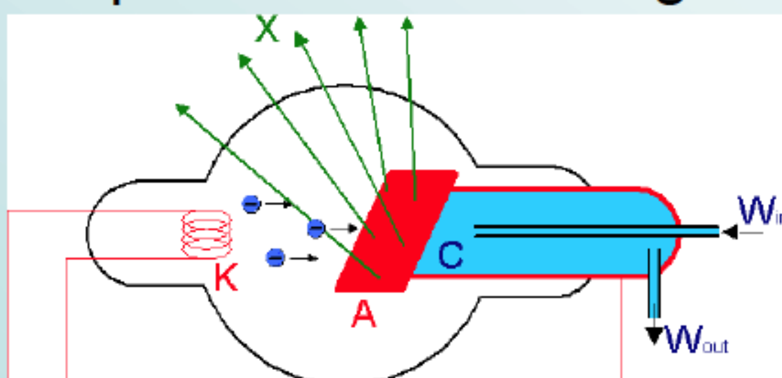
1895 *Wilhelm Conrad Röntgen* (1845 – 1923) discovers the X-rays on 8th November at the University in Würzburg

1896 On 23rd January Röntgen announced his discovery and demonstrated the new kind of radiation by a photograph of the hand of his colleague *Albert von Kolliker*

1897 First treatments of tissue with X-rays by *Leopold Freund* at University in Vienna

1901 Physics Nobel prize for W.C. Röntgen

Schematics of an X-ray tube – an “electrostatic accelerator”



X-ray tubes and beyond

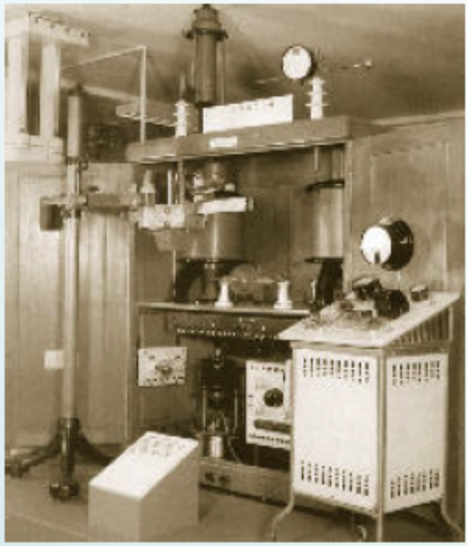
History of medical applications of accelerators

1899 First X-ray treatment of carcinoma in Sweden by *Stenbeck* and *Sjögren*

1906 Vinzenz Czerny founded the “Institute for Experimental Cancer research” in Heidelberg – the first of its kind

1913/4 Invention of part- and full-rotation radiation instrumentation

1920´s Industrially manufactured X-ray apparatus; example from Reiniger-Gebbert & Schall AG (later: Siemens), Erlangen; 1922) with a high-voltage of 150 kV – without shielding!



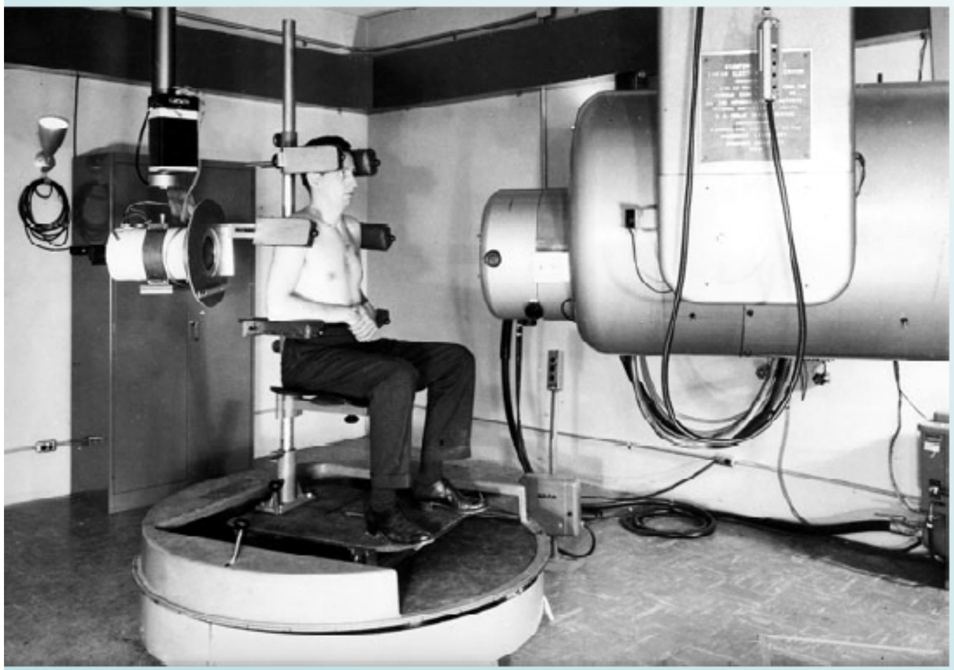
1930 First linear accelerator principle invented by *Rolf Wideroe*

1949 *Newberry* developed first linear accele-rator for therapy in England

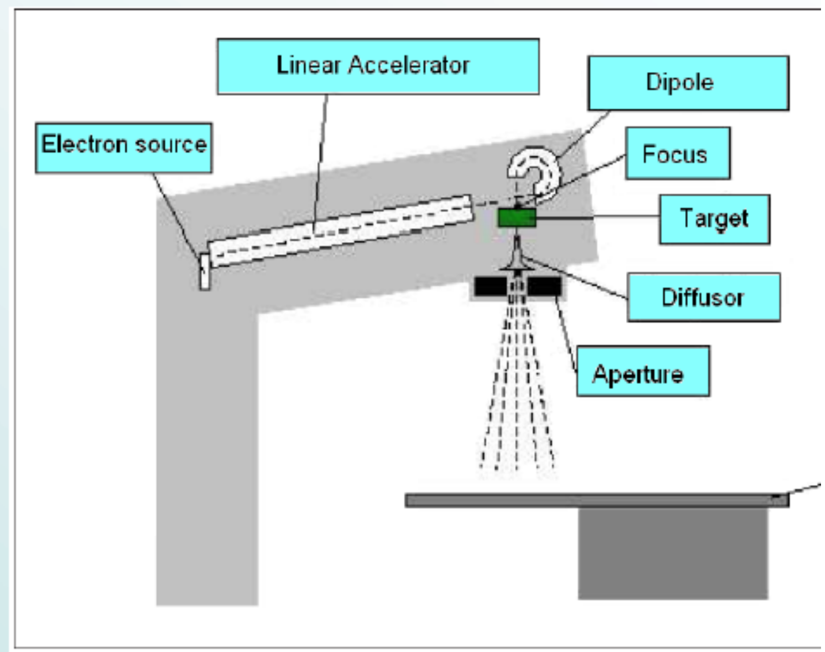
X-ray tubes and beyond

History of medical applications of accelerators

1950´s and later	Development of compact linear accelerators by Varian, Siemens, GE, Philipps and others with energies up to around 25 MeV (and above)



radiotherapy (Stanford linac)



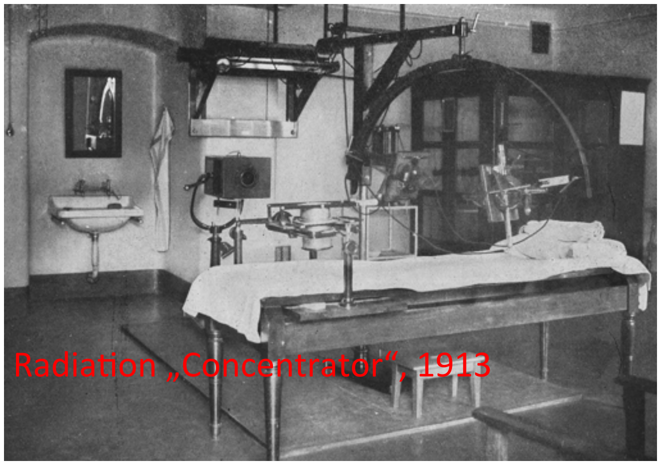
modern linac for therapy

Linac-based γ-Ray Radiation Therapy

Started in 1956 and since then treated about 50 million patients

In developed countries there is 5-10 medical linacs per 1 million inhabitants

It simply means that there are thousands of such accelerator!



Radiation „Concentrator", 1913

Linac by AccSys Technology

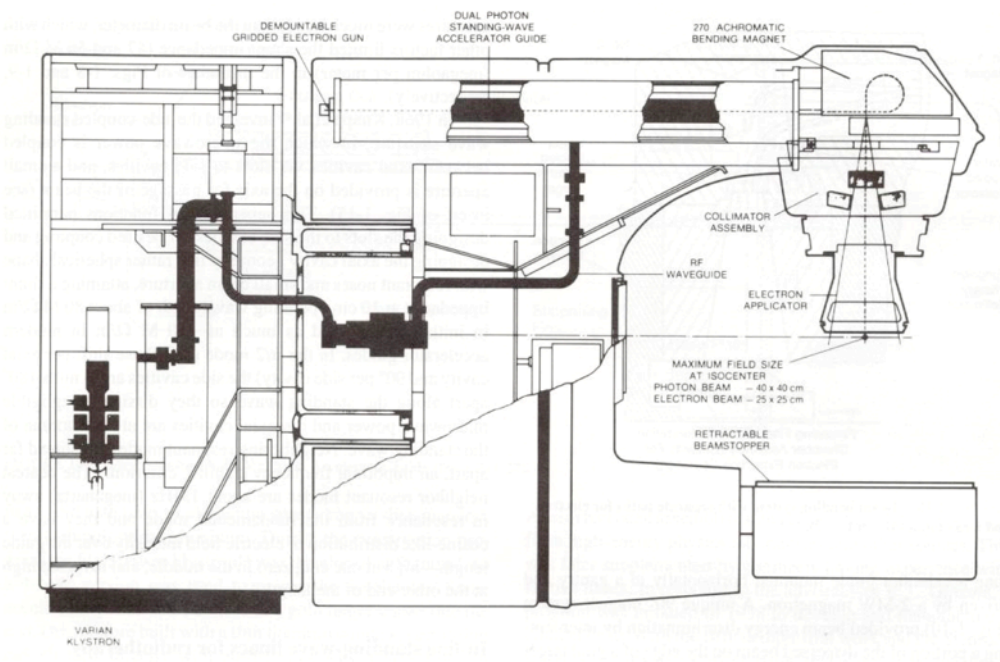
Table 1
Number of Radiotherapy units in France, on 1 January 1995 [1]

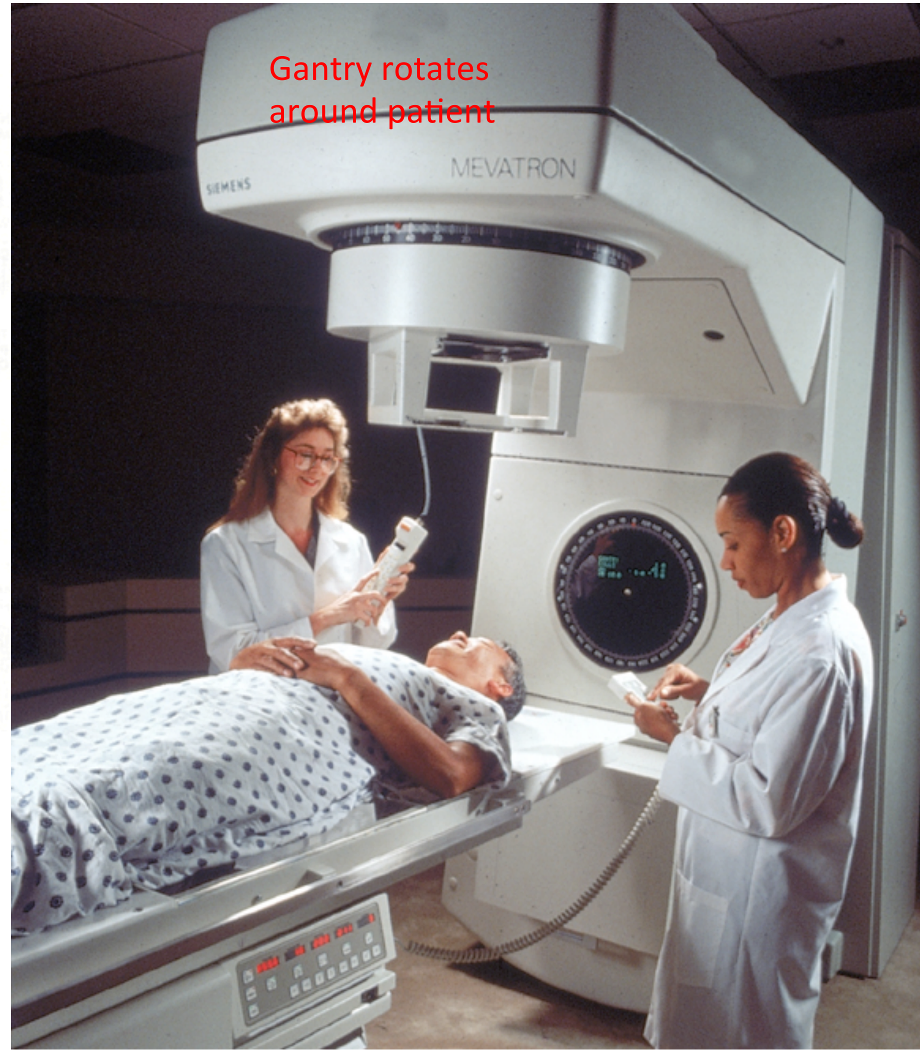
A. ELECTRON LINEAR ACCELERATORS					
	GE-CGR MeV		Other Companies		Total *
4-6 MV	Orion 5	19	Siemens (Mevatron)	3	36
			Philips (SL 75/5)	9	(+5)
			Clinac 600 C		
10 MV	Neptune 10	26			29
	Saturne 1M	3			(-1)
15 MV	Saturne 15	5	Siemens (Mevatron MD)	8	51
	Saturme 1	9	Philips (SL 18)	6	(+17)
	Saturne 41	23			
20 MV	Saturne 20	8	Philips (SL 75/20)	3	31
	Saturne 11	9	Clinac 2100C	6	(-17)
	Saturne 42	5			
25-40 MV	Sagittaire 32 MV	7			15
	Sagittaire 40 MV	3			(-2)
	Saturne 25 MV	5			
20-25 MV	Saturne 111	4			4
25 MV	Saturne 43	37	Philips (SL 75/25)	9	56
			Siemens (Mevetron KD2)	10	(+12)
Total Linear Accelerators		163		59	222
					(+14)
B. OTHER TYPES OF RADIATION THERAPY UNITS					
Cobalt Units			133 (-11)		
Betatron			1		
Hadron Therapy					
Cyclotron: neutron therapy (Orléans)			1		
Cyclotron: neutron + protontherapy (Nice)			1		
Synchrotron: protontherapy (Saclay)			1		

* The differences since 01.01.1994 are given (+) or (-)

Linear accelerators are manufactured by several vendors

γ-Ray Radiation Therapy
The systems can be rather compact

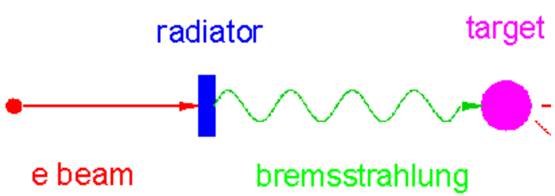


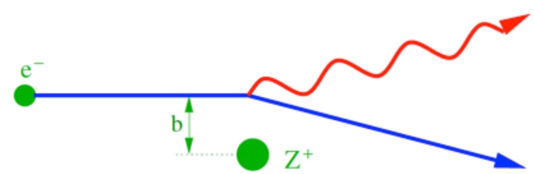


Varian Clinac 1800
Medical linear accelerator

γ-Rays Production

Medical linacs use monoenergetic electron beams between 4 and 25 MeV. Electron beam collides with a a high-density (such as tungsten) target generating via process called Bremsstrahlung (from *bremsen* "to brake" and *Strahlung* "radiation”, http://en.wikipedia.org/wiki/Bremsstrahlung) hard-X-rays and γ-Rays with energy spectrum up to the electron beam energy





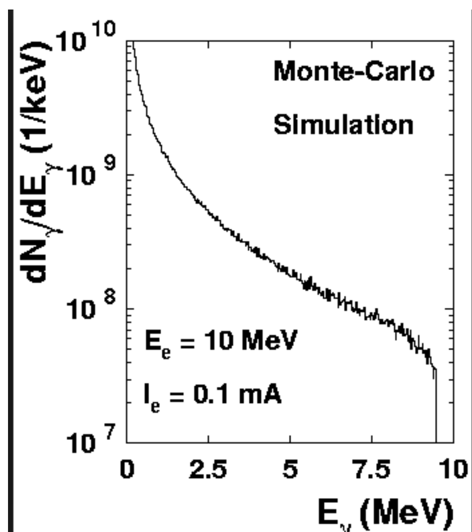
$$\frac{d\sigma}{dk\,d\Omega} = \frac{2\alpha^2 e^2}{\pi k m^4}\left\{\left[\frac{2\epsilon-2}{(1+u^2)^2}+\frac{12u^2(1-\epsilon)}{(1+u^2)^4}\right]Z(Z+1) + \left[\frac{2-2\epsilon-\epsilon^2}{(1+u^2)^2}-\frac{4u^2(1-\epsilon)}{(1+u^2)^4}\right]\left[X-2Z^2 f_c((\alpha Z)^2)\right]\right\}$$

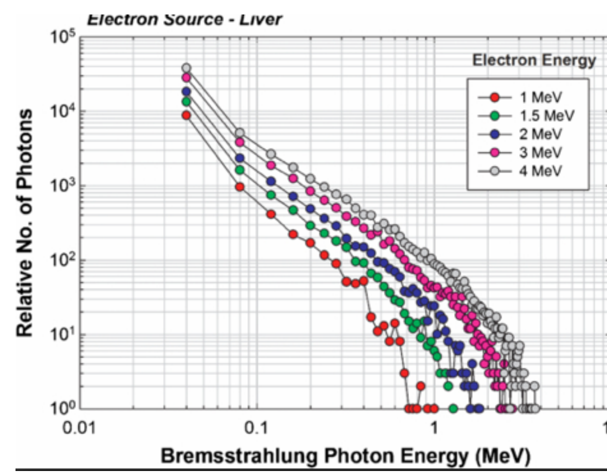
$$u = \frac{E\theta}{m}$$

$$X = \int_{t_{min}}^{m^2(1+u^2)^2}\left[G_Z^{el}(t)+G_Z^{in}(t)\right]\frac{t-t_{min}}{t^2}\,dt$$

$G_Z^{el,in}(t)$ atomic form factors

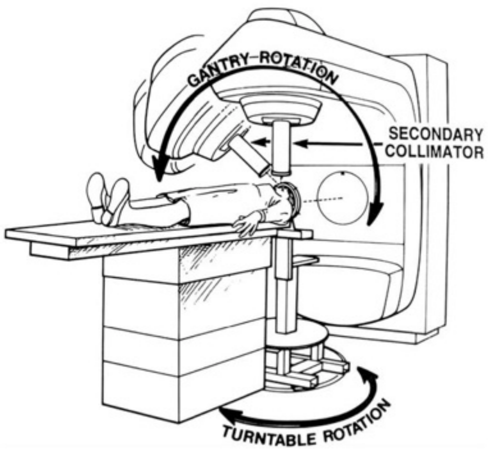
$$t_{min} = \left[\frac{km^2(1+u^2)}{2E(E-k)}\right]^2 = \left[\frac{\epsilon m^2(1+u^2)}{2E(1-\epsilon)}\right]^2$$

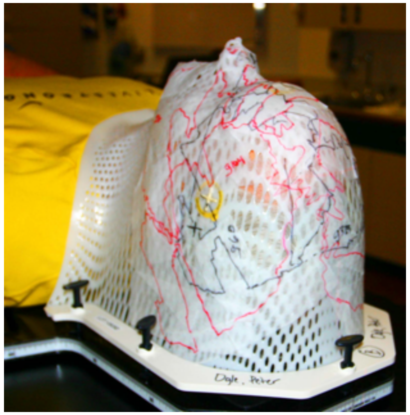


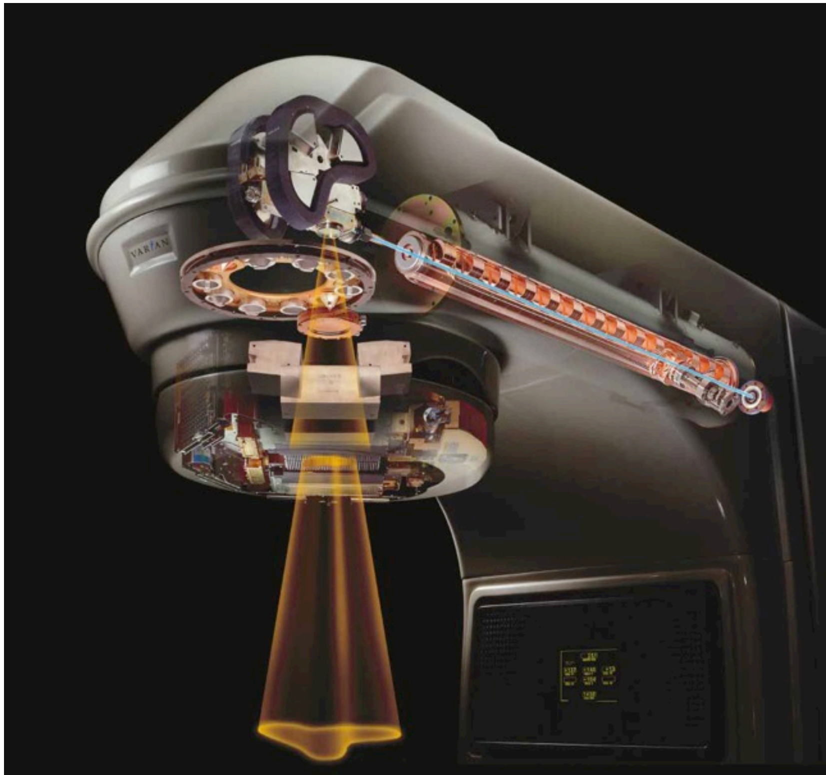


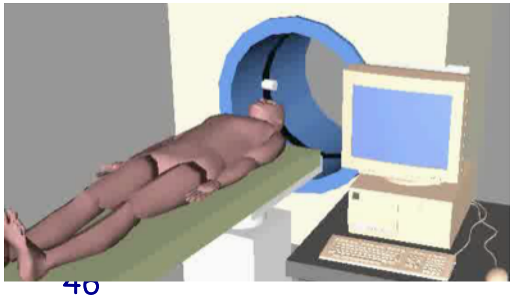
γ-Ray Radiation Therapy

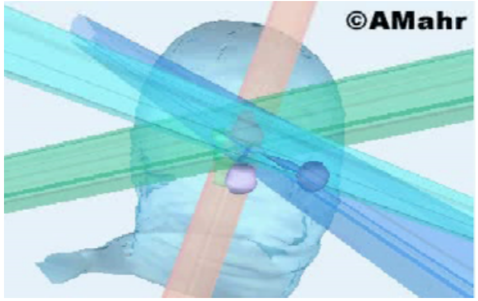
- The gamma-rays beam is further filtered to remove soft photons, collimated, shaped to fit specific task
- The beam is then delivered at multiple angles to minimize the radiation exposure of the surrounding tissue and to deliver the necessary dose of the radiation to a tumor
- It is all computer controlled from the patient model
- This is a BIG business…









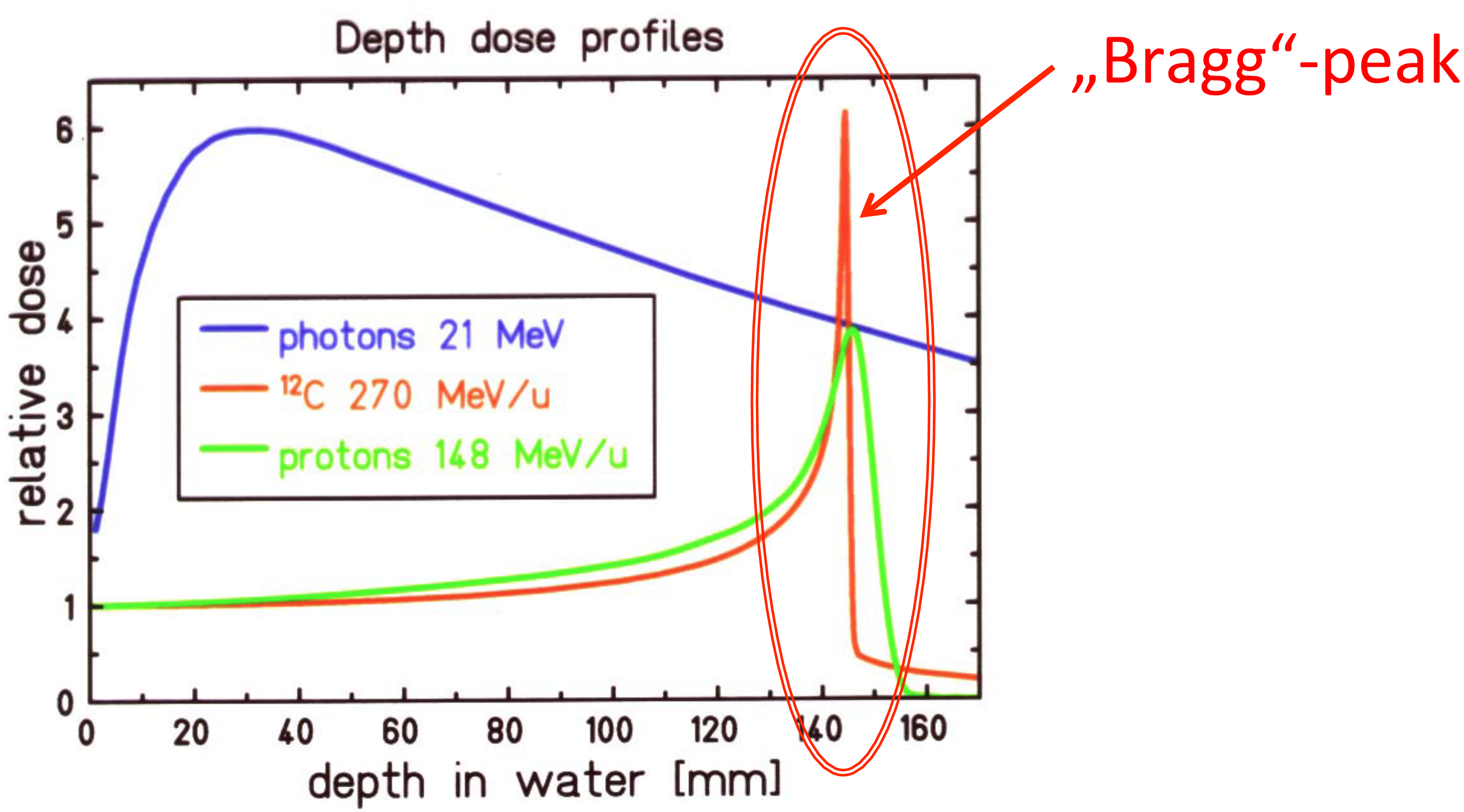


Hadron radiation therapy

- Comparing with γ-ray radiation therapy it is more effective, but also much more expensive
- Instead of room it occupies a building with the hadron beam source located in well-shielded accelerator hall
- There are fewer hadron (proton or ion) therapy centers

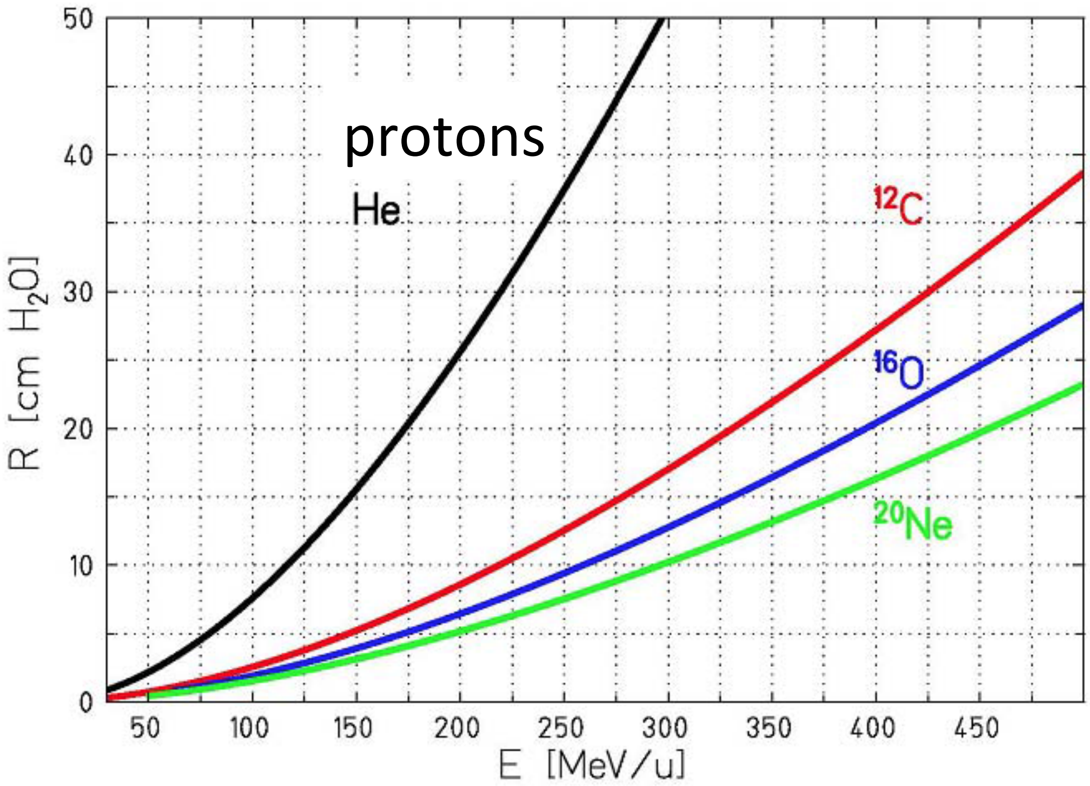
Why Hadron radiation therapy?

- Hadron Beams Slow Down And Stop depositing the energy at the very end of the pass
- While γ-rays deposit the energy evenly through the tissue
- Thus with hadron it is possible to concentrate the exposure where it is needed and reduce damage to the surrounding healthy tissue by 4-6 fold
- In medicine it can be difference between life and death

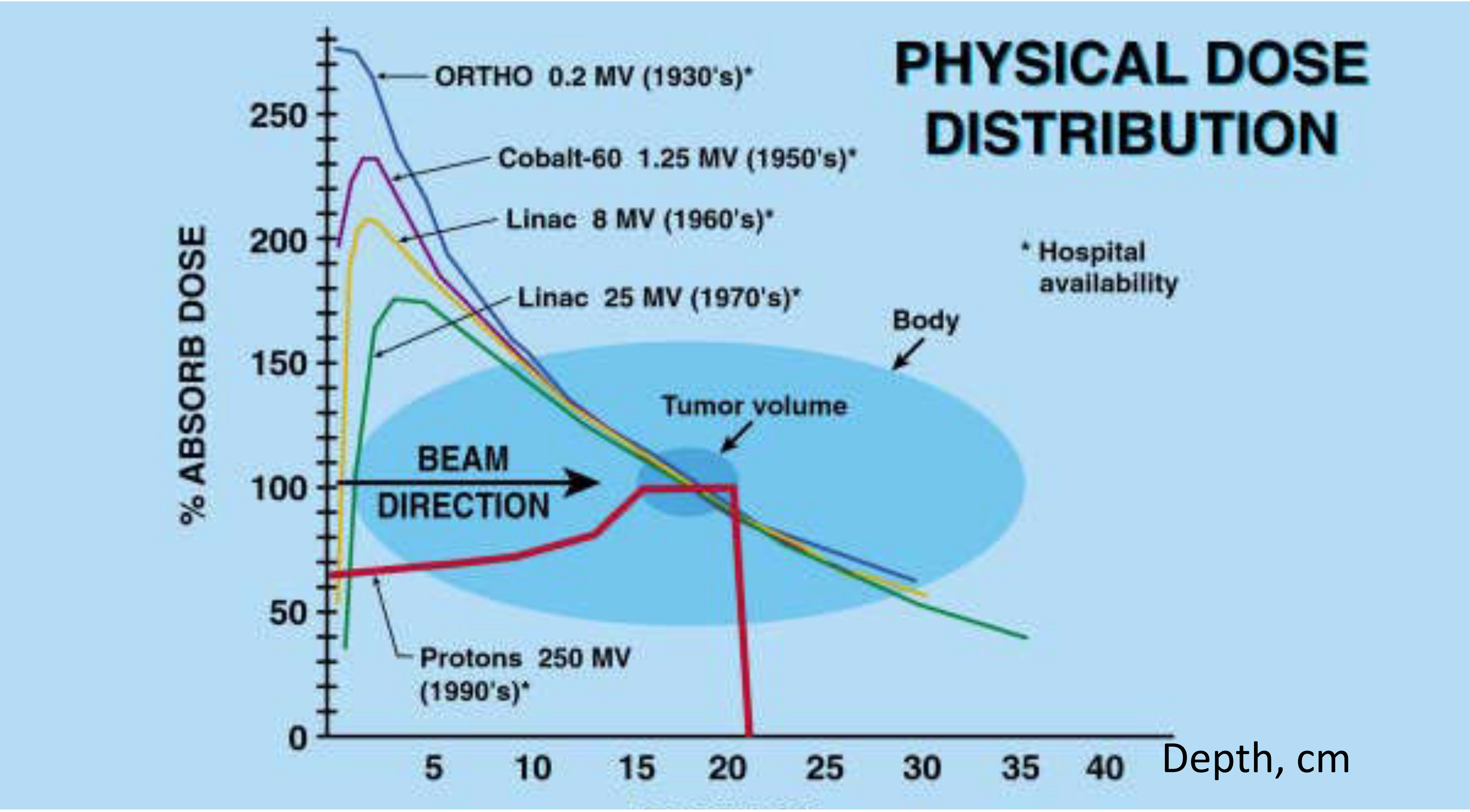


Hadron radiation therapy
It's simply the physics!

Depth range of the beam penetration in water should be ~30 cm. It defines the energy of the accelerator: p ~ 220 MeV, C ions ~ 430 MeV/u

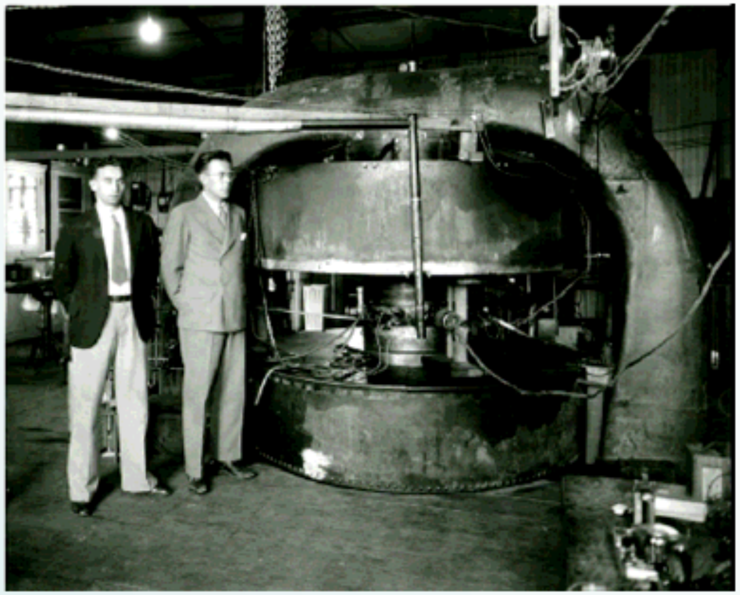


Hadron radiation therapy
It's simply the physics!



History of Hadron radiation therapy

History of medical applications of accelerators

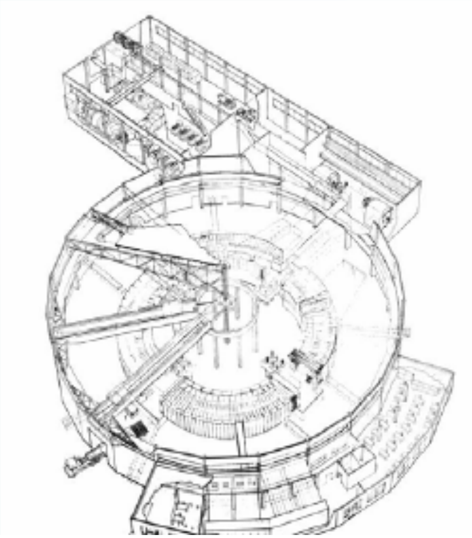


1929 Invention of cyclotron by *Ernest Lawrence*

1930´s Experimental neutron therapy

1946 R. R. Wilson proposed proton & ion therapy

1950's Proton therapy, LBL Berkeley (184” cyclotron)



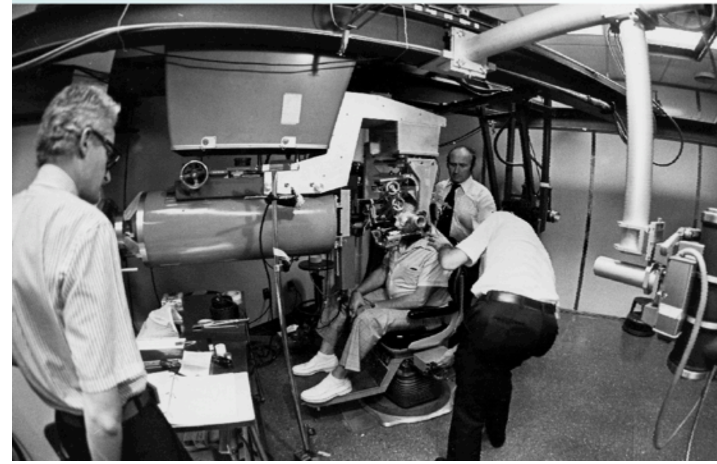
1945 *Edwin Mattison McMillan* at University of California and *Vladimir Iosifovich Veksler* (Soviet Union) invented the synchrotron principle

1975 Begin of carbon therapy in Bevalac synchrotron (Berkeley)

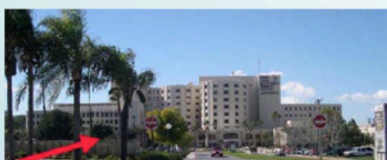
History of Hadron radiation therapy

Harvard Cyclotron:
Patient Treatments 1974-2002

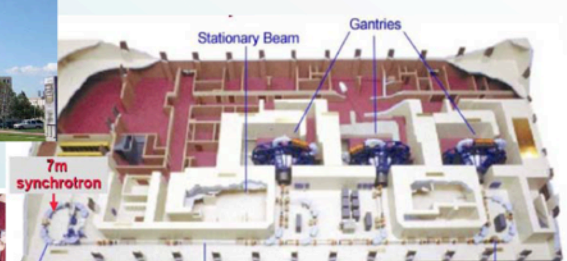
Treatment Of Occular Melanoma
At The Harvard Cyclotron

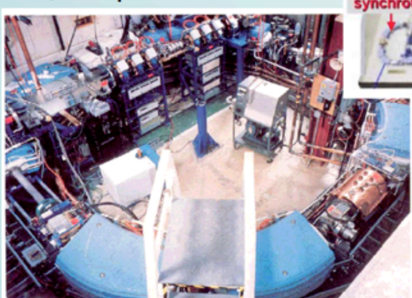


First Hospital Based Particle Therapy Facility – Loma Linda/USA



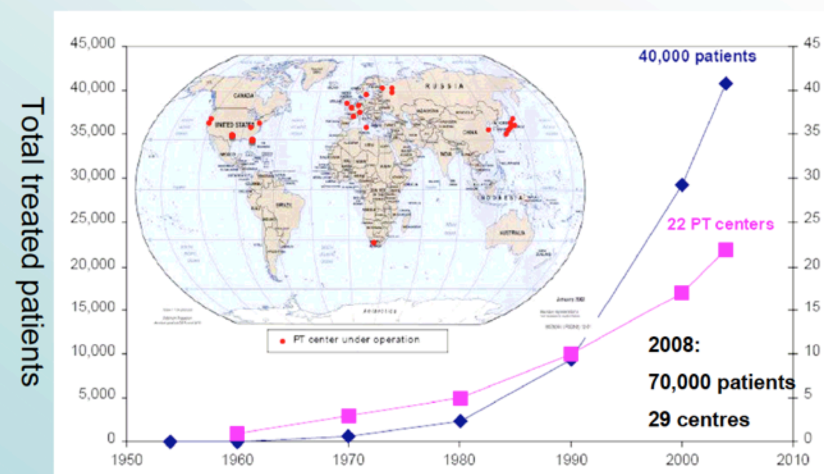
13,500 patients treated





1st hospital based proton therapy centre (since 1990) using a synchrotron – designed and commissioned by Fermilab
2005: 160 sessions/day

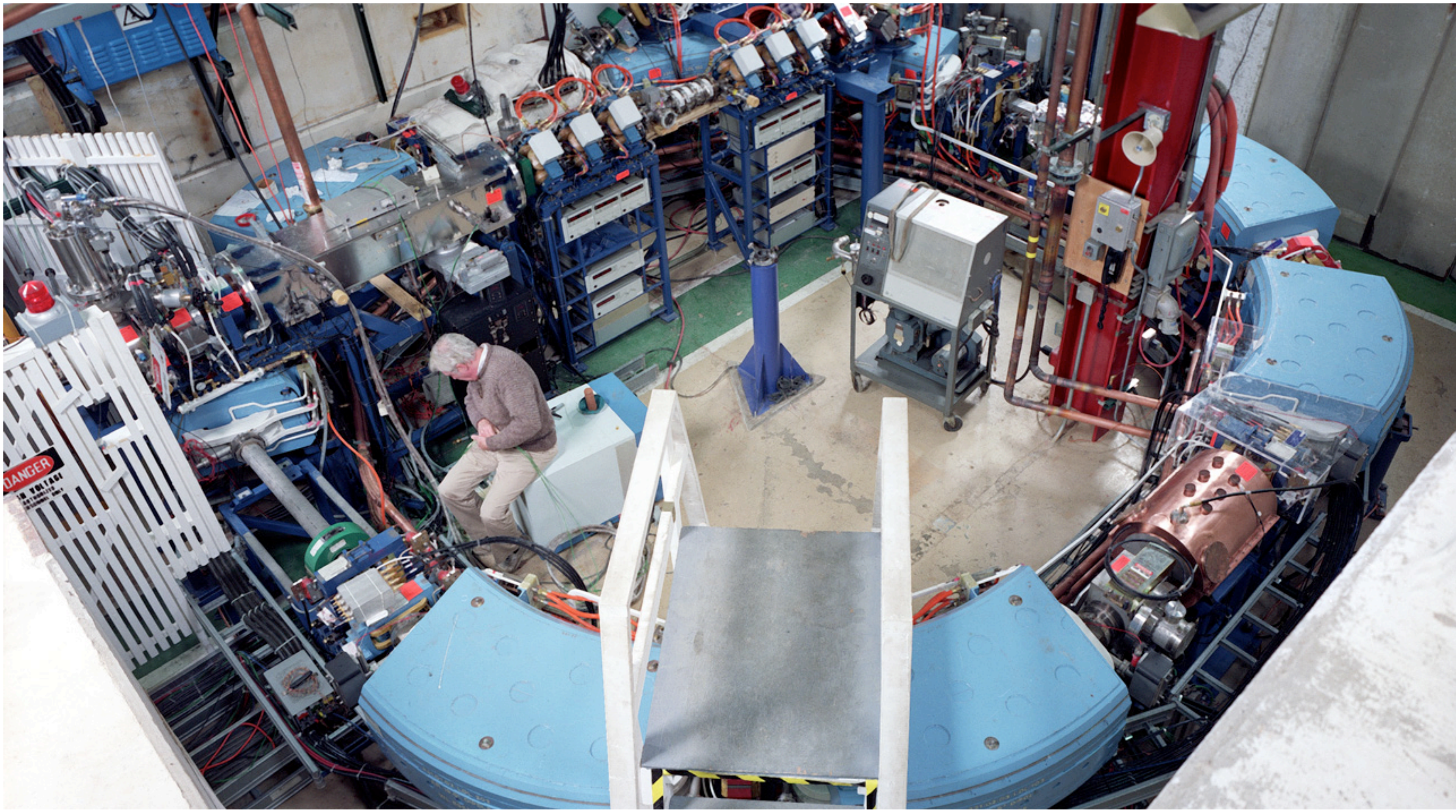
Particle Therapy Facilities - worldwide



PT centres: a rapidly growing market

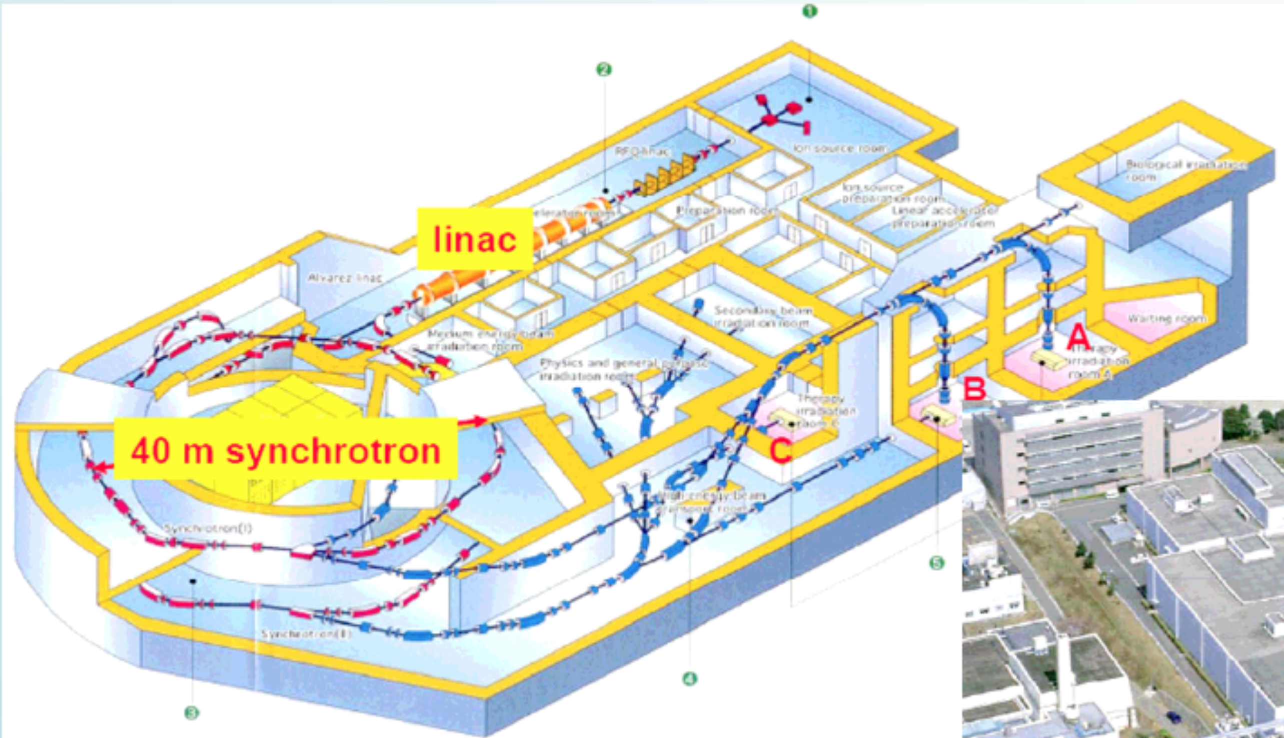
Accelerator Parts

Proton Therapy Synchrotron at Fermilab



Hadron therapy centers

Particle Therapy Facilities – HIMAC/Japan



The Heavy Ion Medical Accelerator of NIRS (since 1994)

Two identical 800 MeV/u synchrotrons for ions up to Argon; mainly Carbon is used

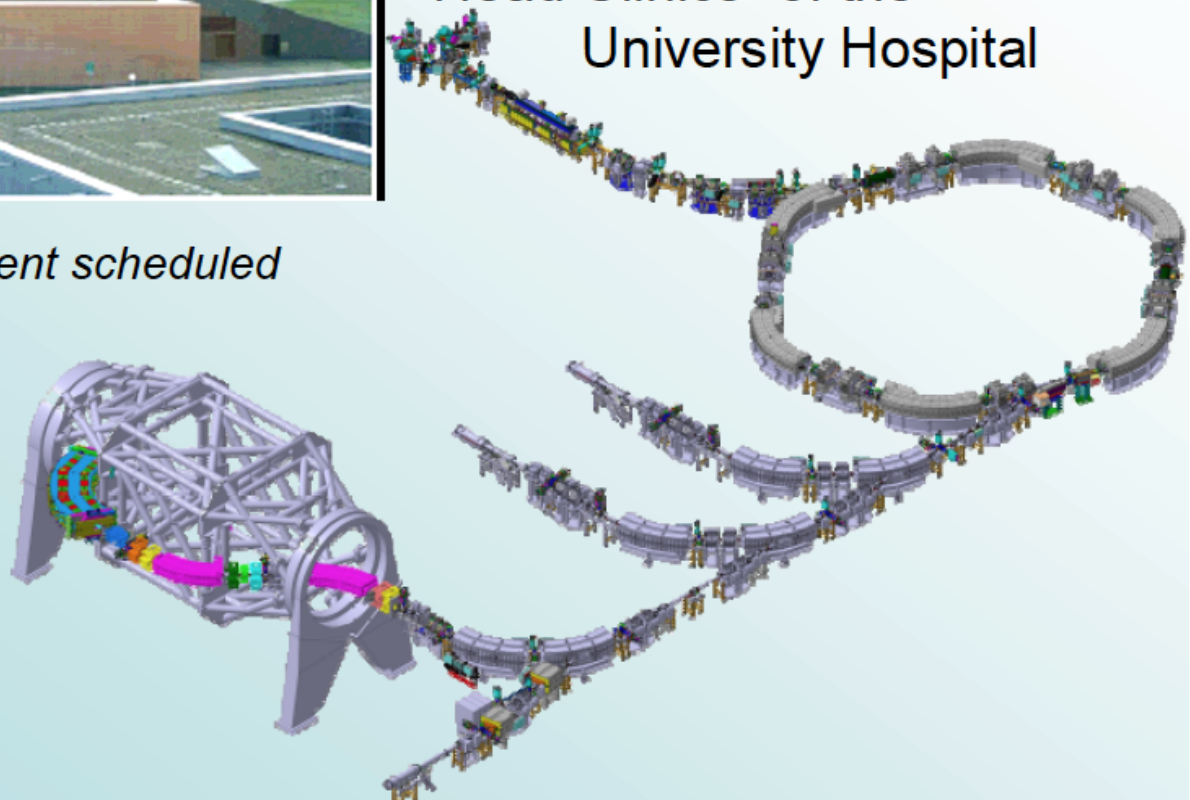
4,500 patients treated

Hadron therapy centers

Particle Therapy Facilities – HIT/Heidelberg

Compact building (60 x 70 m², 3 levels), directly linked to the "Head Clinics" of the University Hospital

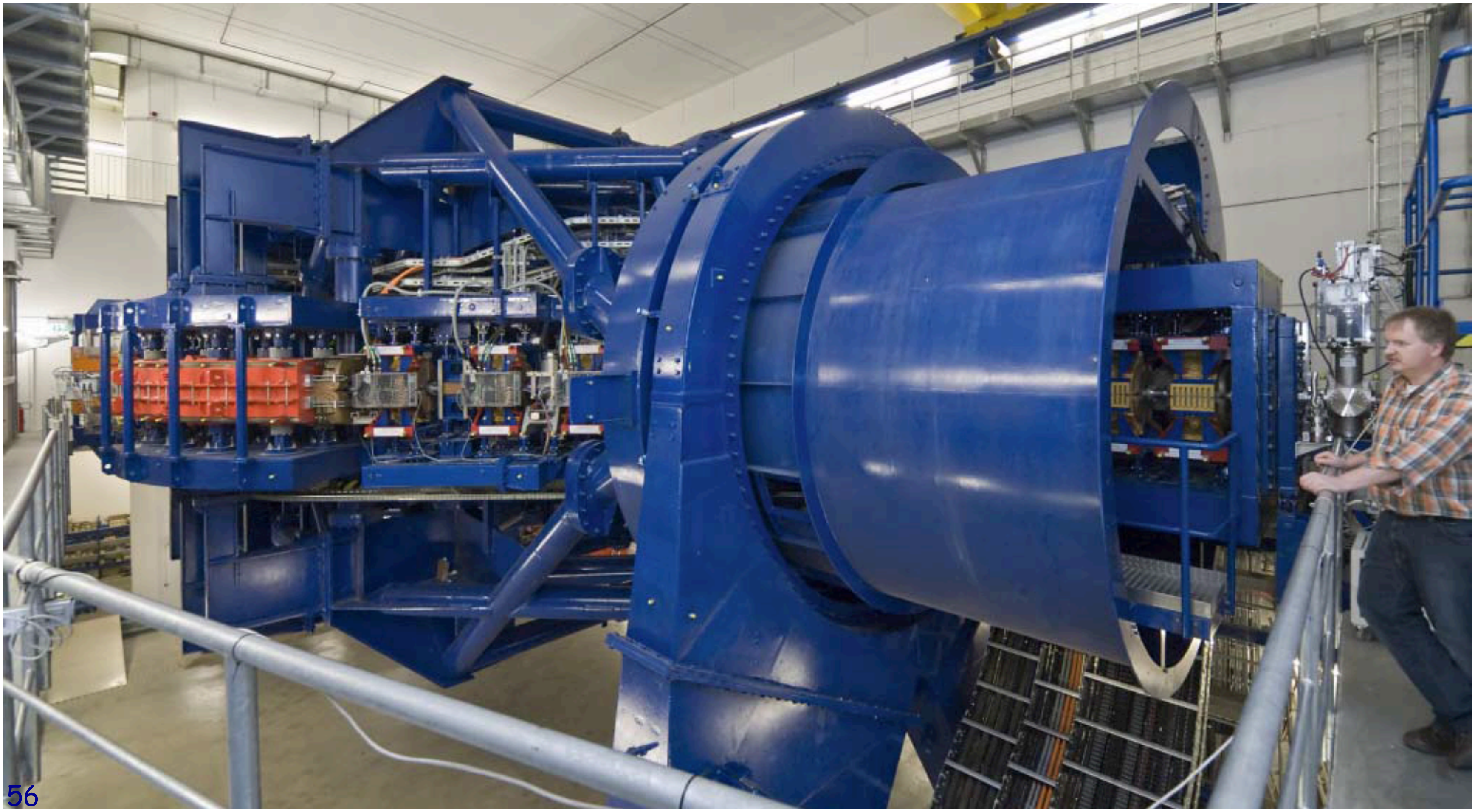
Start of patient treatment scheduled in 2 weeks



Accelerator Parts

Therapy Facility HIT/Heidelberg

World's first isocentric ion gantry –including a scanning system: Ø = 13m, 25m long, 600 tons, 0.5 mm max. deformation



Accelerator Parts

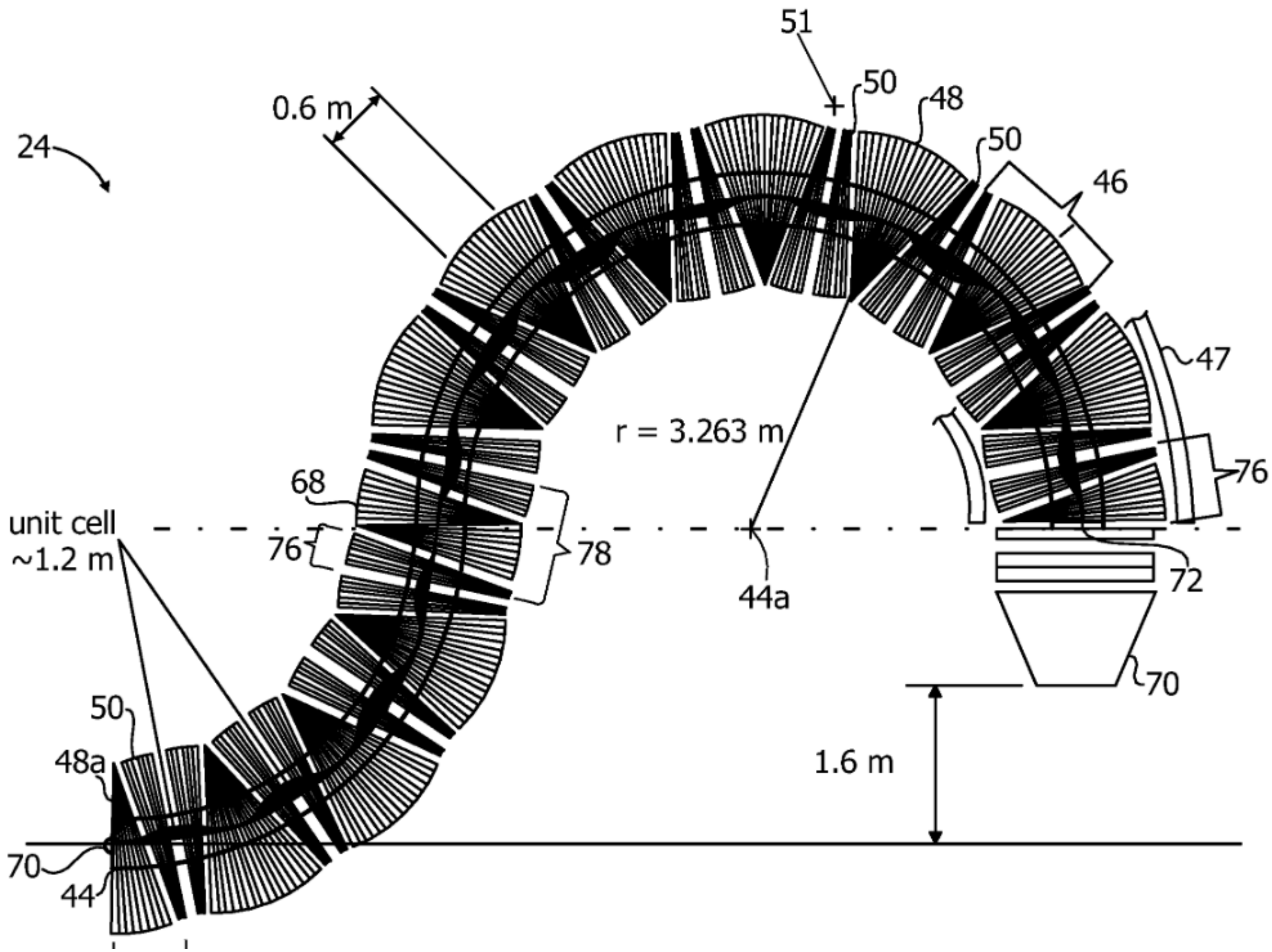
Gantries: goal is to propagate an focus hadron beam with variable energies

Accelerator Parts

Gantries: monsters in modern accelerators

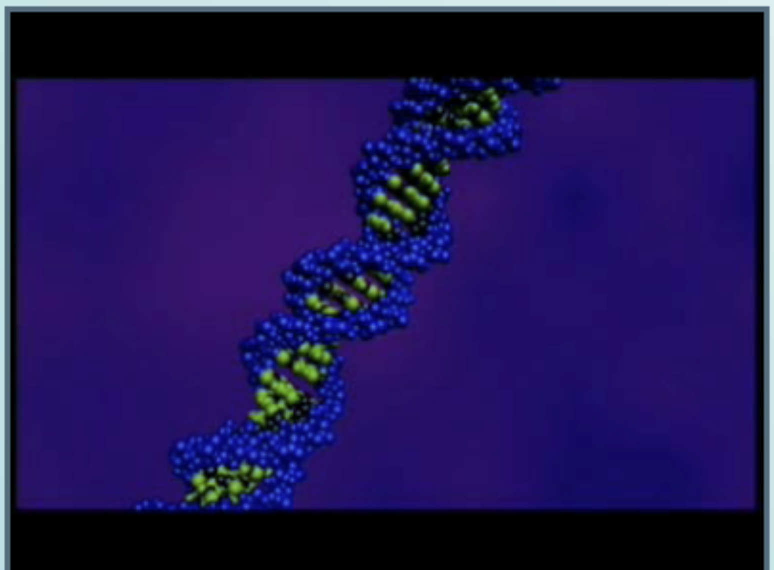
Accelerator Parts

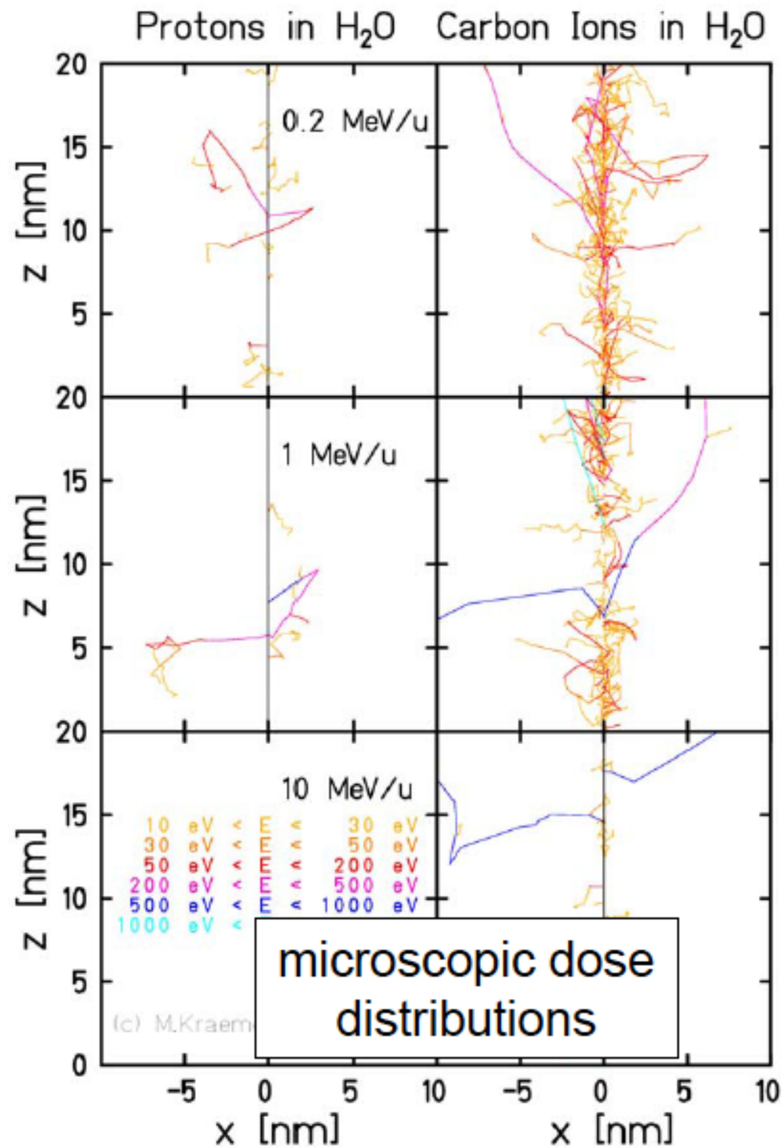
New ideas: compact FFAG gantry (© D. Trbojevic, BNL)



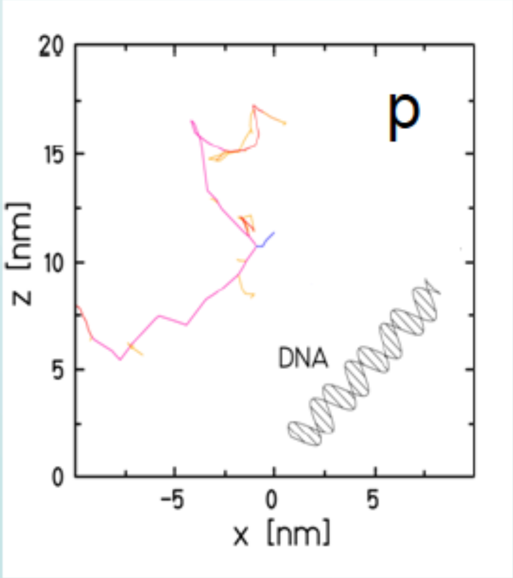
Physics and Biology of radiation therapy

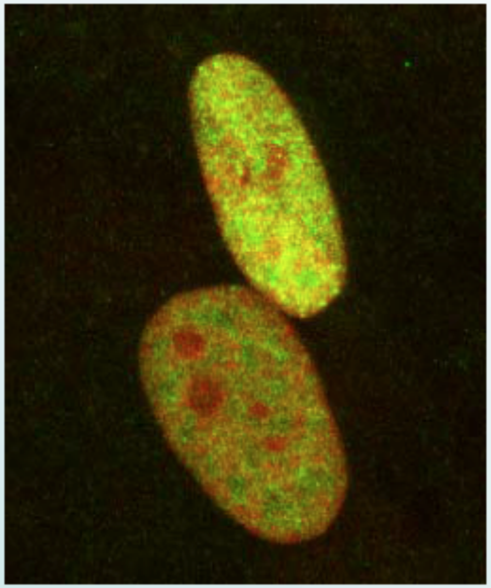
Basic effect of radiation on cells: energy loss in matter leads to defects in the DNA – double strand breaks of the DNA kills the cell. Tumor cells have less repair capabilities than normal cells.





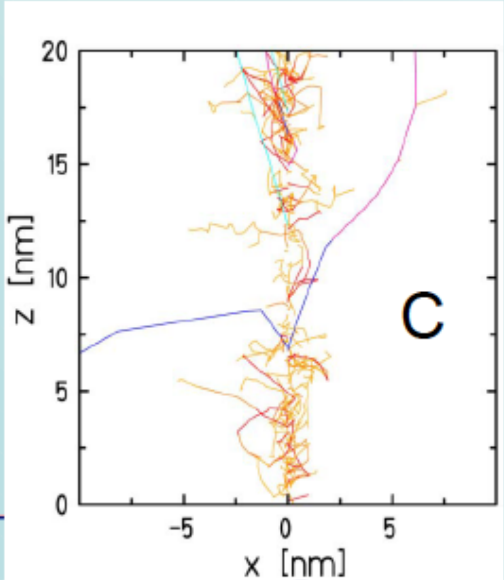
Physics and Biology of radiation therapy

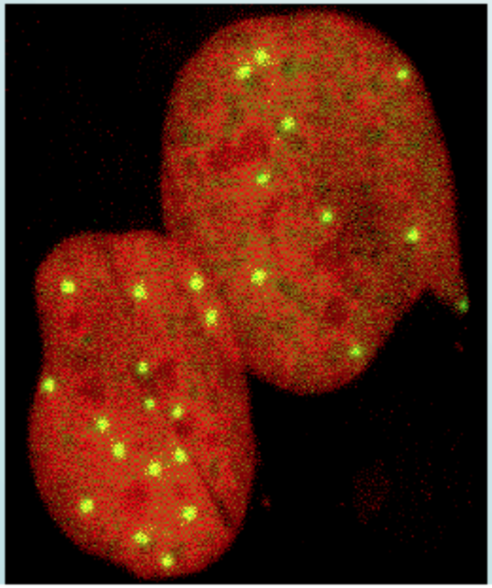




Low LET

Homogeneous deposition of dose





High LET

Local deposition of high doses

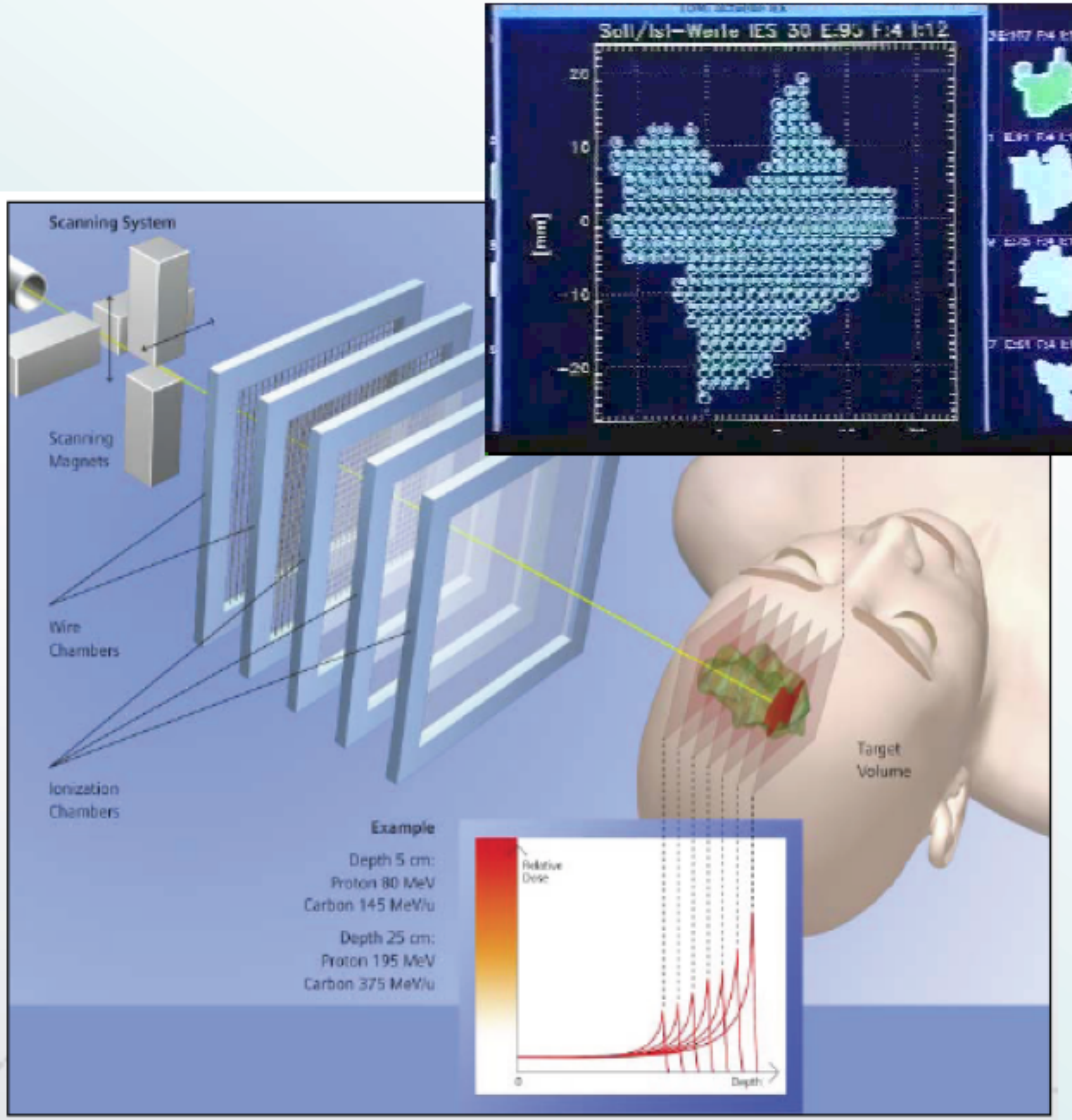
LET: Linear energy transfer

Optimized Treatment By Beam Scanning

Development in the 90ies:
Scanning techniques

a) Protons (Pedroni PSI): spot scanning gantry (1D magnetic pencil beam scanning) plus passive range stacking (digital range shifter)

b) Ions (Haberer et al.): raster scanning (2D magnetic pencil beam scanning) plus active range stacking (spot size, intensity) in the accelerator

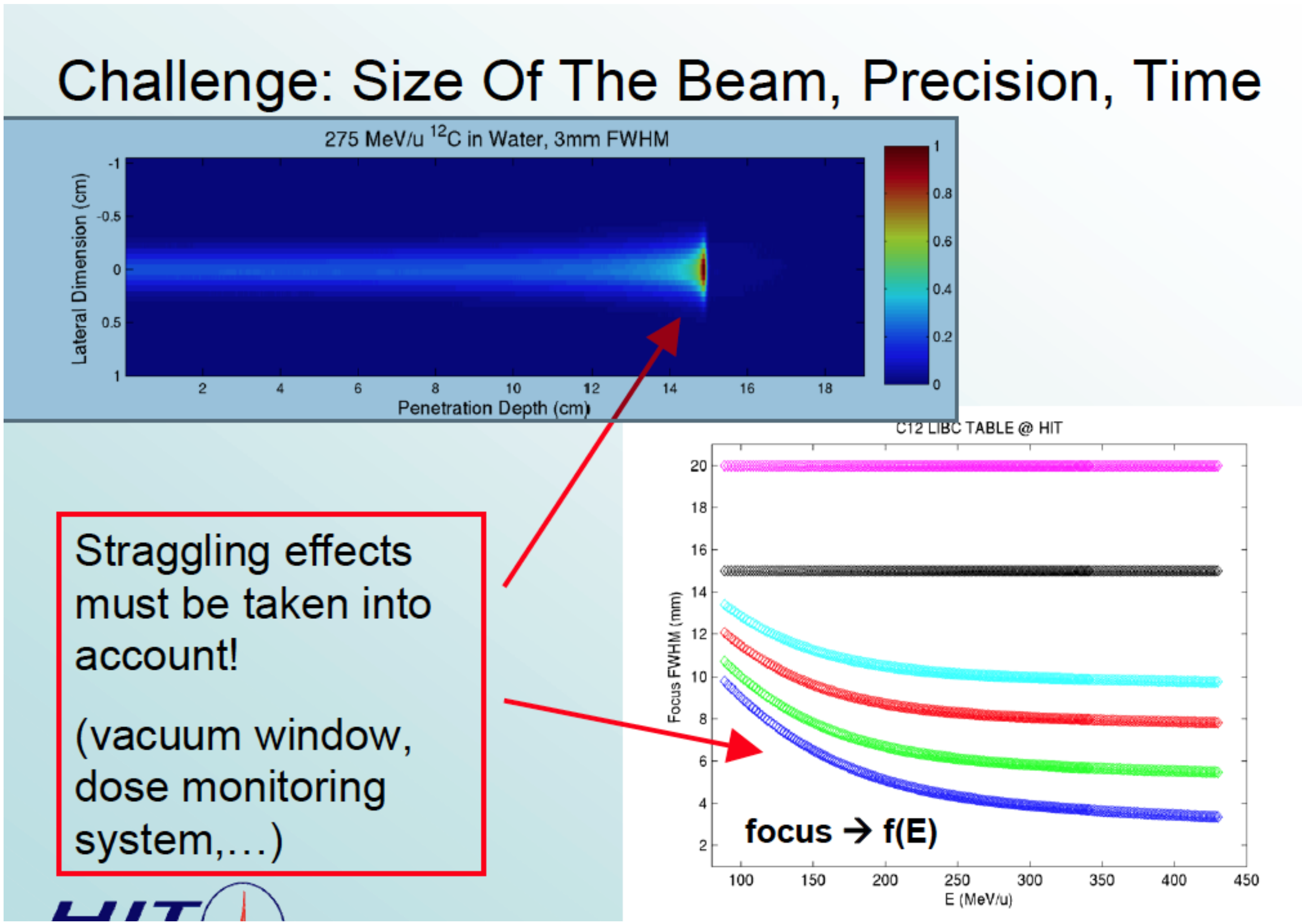


Intensity-Controlled Rasterscan Technique, Haberer et al., GSI, NIM A,1993

HIT
Heidelberger Ionenstrahl-Therapiezentrum

Optimization of the treatment

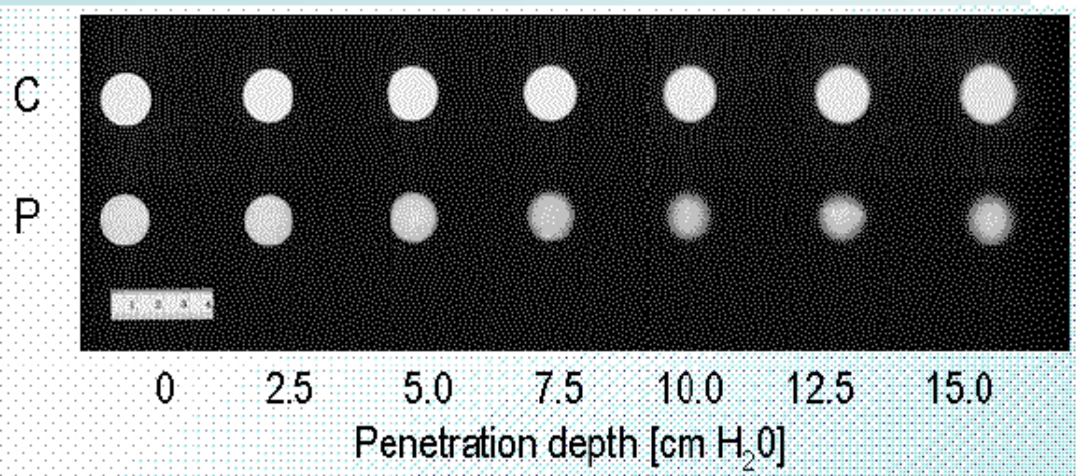
- ✓ Modern trend is to have exposures from multiple directions with multiple energies
- ✓ Hence, accelerator should provide a well controlled intensity shots of the beam with programed energy – not a trivial fit for a hadron accelerator

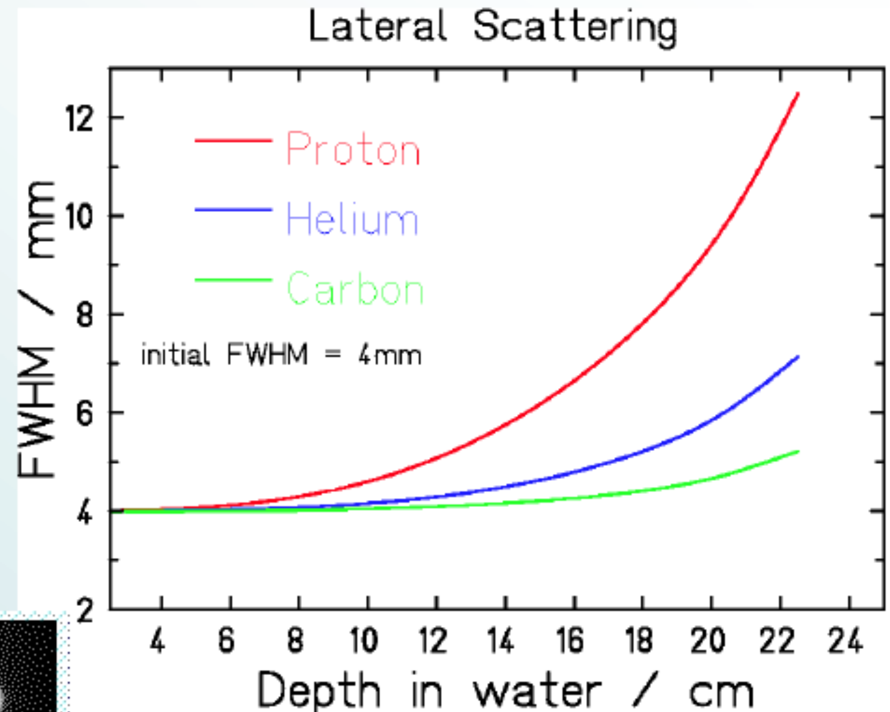


Optimization of the treatment

Beam Size

Higher local precision with carbon for deep-seated tumour treatment





What is a good medical isotope?

- For applications in medicine, nature and "man-made" physics approaches provide many different radionuclides to choose from.
- The choice of radionuclide is critical for achieving successful diagnostic imaging and cancer treatment outcomes.
- Objectives:

1) Diagnostic nuclear medicine: high quality images of activity in the patient, with low patient radiation dose
2) Therapeutic nuclear medicine: high amount of energy imparted to the target tissue (to destroy cancer cells) relative to critical normal organs and tissues (to prevent radiation damage and side-effects)

Medical isotope shortages

Officials Scramble for Solutions to Global Isotope Shortages

As global demand continues to grow for the medical isotope necessary for imaging procedures, most of the reactors used to produce technetium-99m (Tc-99m) will be permanently decommissioned within six years. A task force set up last year in the EU to consider solutions to isotope shortages released its first report this month to the European Commission. The report suggests convening stake-holders to discuss alternative diagnostic and therapeutic procedures.

Reactor shutdown causes another isotope shortage

Updated Fri. Dec. 12 2008 7:08 PM ET
CTV.ca News Staff

A temporary shutdown at the Chalk River, Ont. nuclear reactor is causing a shortage of medical isotopes, forcing Canadian doctors to scramble to cancel and rearrange appointments with their patients.

The isotope shortage is expected to last until the middle of next week, CTV News has learned.

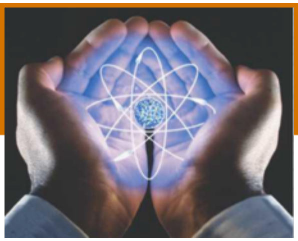
The shortage is expected to affect Ontario, Quebec, parts of the Maritimes, the northern United States and perhaps even Mexico.

Atomic Energy of Canada Ltd., responsible for the Chalk River nuclear facility, told CTV News that the shutdown was "normal" on Thursday night, but on Friday said the shutdown was "longer than expected."

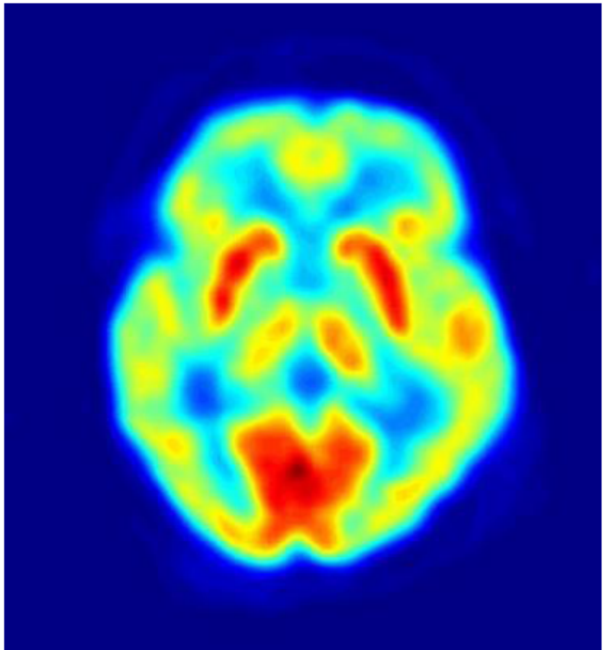
Radiopharmaceuticals
- Positron Emitters
- Beta/gamma Emitters
- Alpha Emitters

Medical Devices
- Sealed Sources
- Microsphere Applications
- Nanosphere Applications

Positron emitters



- Cancer Metabolism and Functional Imaging
  - F-18-fluorodeoxyglucose (FDG) glucose analog, measures hexokinase activity (glucose metabolism), phosphorylated by hexokinase to F-18-FDG-6-PO_4, elevated in tumor cells, chemically trapped in cells
  - F-18-amino acids (phenylalanine, tyrosine) image metastatic lesions
  - F-18-fluorothymidine measures thymidine kinase activity (DNA synthesis)
  - F-18-flouromisonidazol (FMISO) images tumor hypoxia
  - F-18-estradiol breast tumor detection

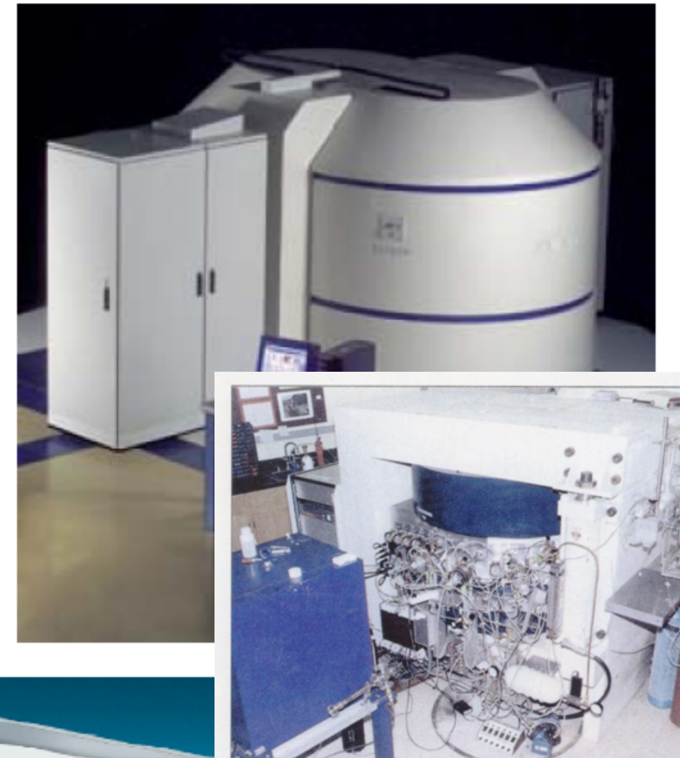


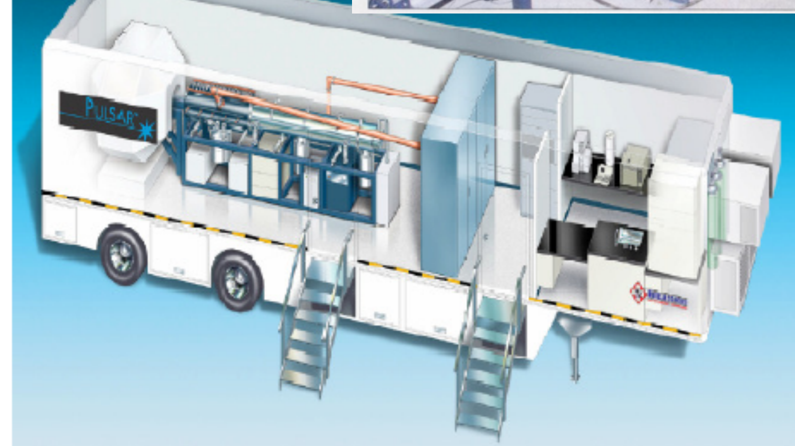
Radioisotope Production

- **Applications** (>50 routine radioisotopes)
  - Industrial – Gauging & calibration
  - Medical – Diagnostics & treatment
    - SPECT
    - PET
    - Brachytherapy

- **Cyclotrons & Linacs** – both protons & deuterons
  - PET – self shielded systems from 7 to 18 MeV with current < 200 μA)
  - SPECT – energies from 22 to 70 MeV with currents up to 2 mA

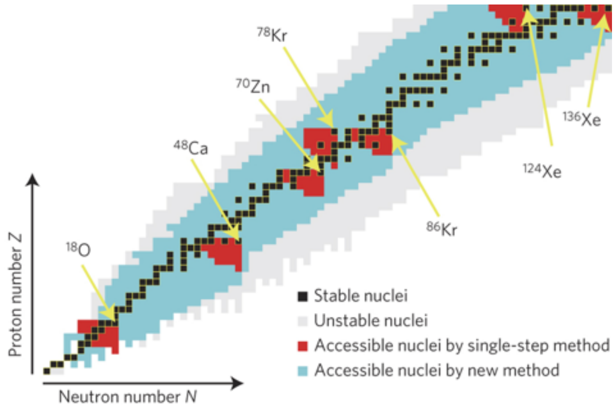
- **Vendors**
  - GE Healthcare (Sweden)
  - Siemens Medical Systems (USA)
  - Ion Beam Applications SA (Belgium)
  - Advanced Cyclotron Systems (Canada)
  - Sumitomo Heavy Industries (Japan)
  - Samyoung Unitech Co. (Korea)
  - Thales GERAC (France)
  - AccSys Technology, Inc. (USA)

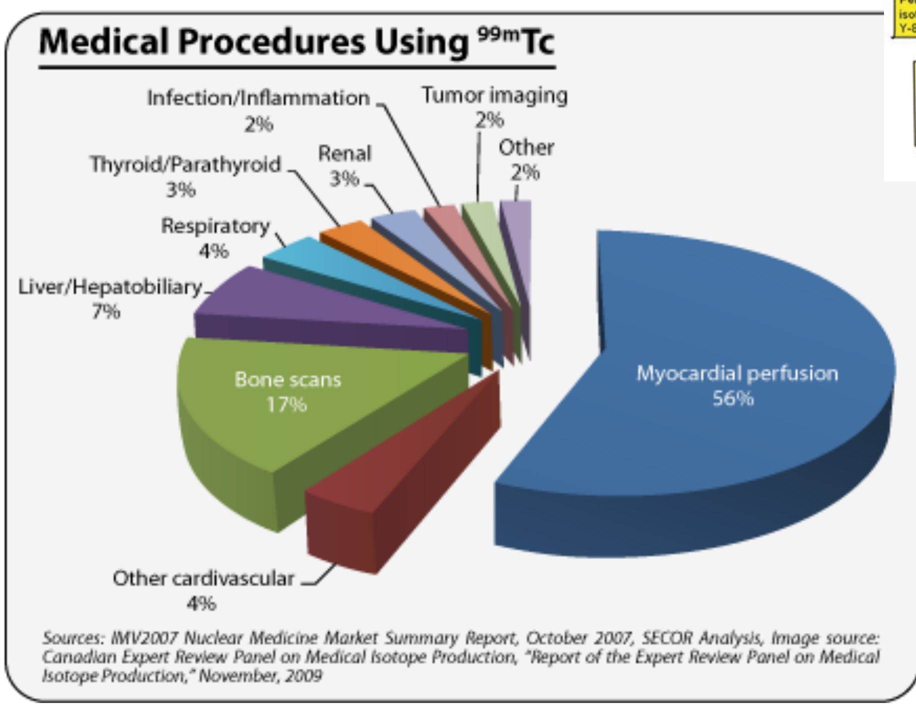


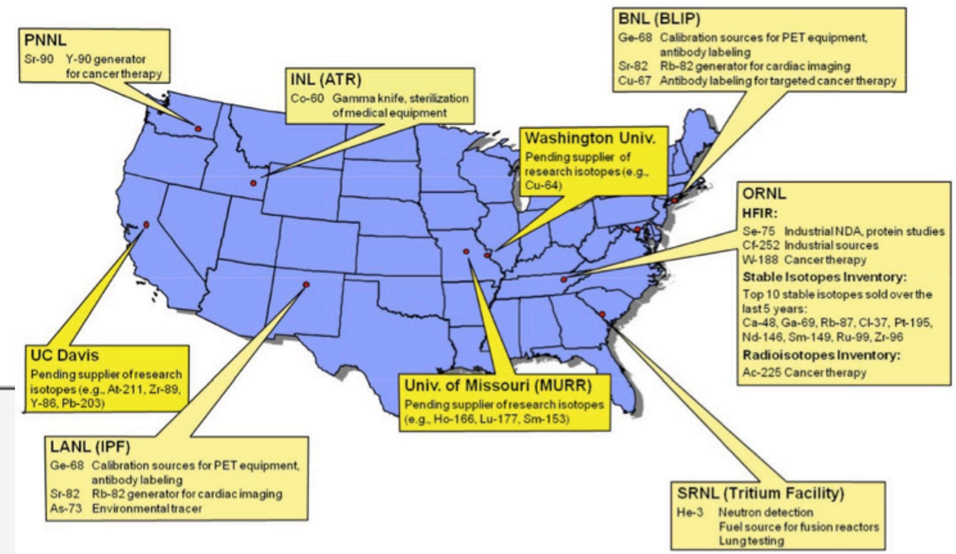


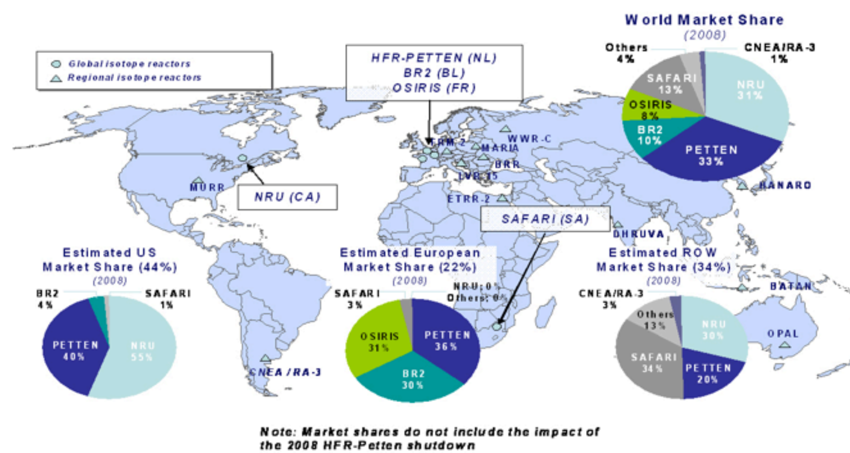
Large growth in compact accelerators for PET.

Radio isotope production

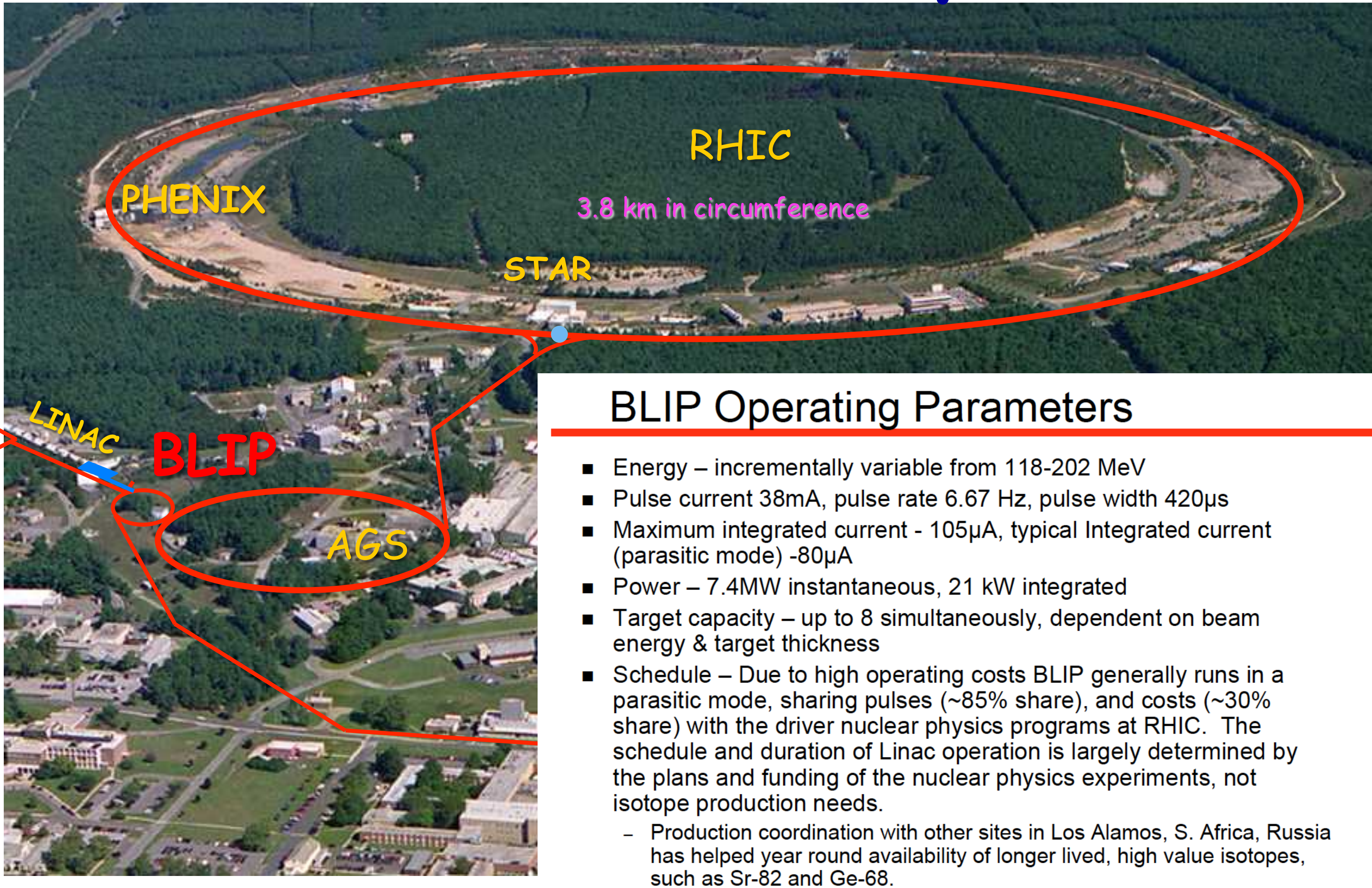








eRHIC: QCD Facility at BNL



BLIP Operating Parameters

- Energy – incrementally variable from 118-202 MeV
- Pulse current 38mA, pulse rate 6.67 Hz, pulse width 420μs
- Maximum integrated current - 105μA, typical Integrated current (parasitic mode) -80μA
- Power – 7.4MW instantaneous, 21 kW integrated
- Target capacity – up to 8 simultaneously, dependent on beam energy & target thickness
- Schedule – Due to high operating costs BLIP generally runs in a parasitic mode, sharing pulses (~85% share), and costs (~30% share) with the driver nuclear physics programs at RHIC. The schedule and duration of Linac operation is largely determined by the plans and funding of the nuclear physics experiments, not isotope production needs.
  - Production coordination with other sites in Los Alamos, S. Africa, Russia has helped year round availability of longer lived, high value isotopes, such as Sr-82 and Ge-68.

Summary

- We only touched upon a variety of practical/ societal applications of accelerators
- Accelerators play and will continue playing an important role in technological progress of the humanity – both through direct economical impact and spin-off from the knowledge obtained using accelerators or technology developed for them
- Advances in accelerator technology, especially tend towards a compact accelerators, are closely watched by industrialist
- BTW, this is why finding industrial position for accelerator physicists and engineers is a relatively easy fit…

End of lectures

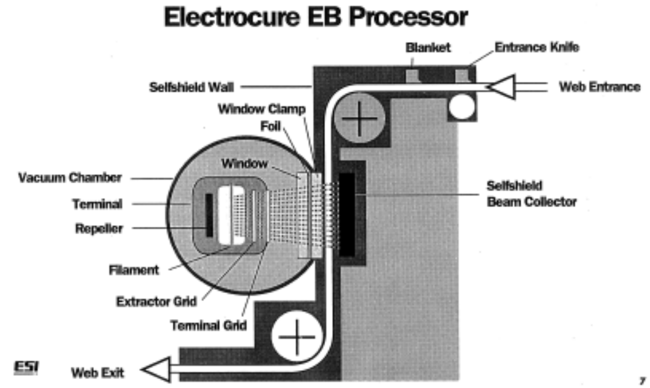
Instead of conclusions

- You learned quite a bit about the accelerators, accelerator science and accelerator applications
- We hope that you would use this knowledge in your future studies and research

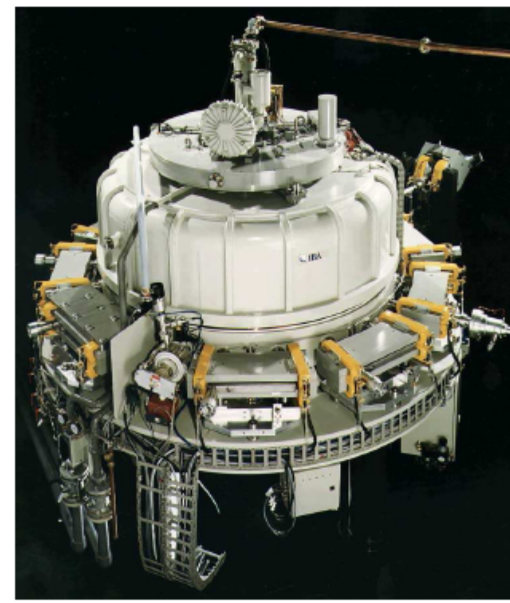
Back-ups

Electron Beam Irradiation Accelerator Vendors

- **Low energy sheet beams**
  - Energy Sciences, Inc. (USA)
  - IBA (Belgium)
  - Electron Crosslinking AB (Sweden)
  - Advanced Electron Beams (USA)
  - Wasik Associates (USA)
  - Nissin High Voltage Corp. (Japan)
  - PCT Prod. & Mfg., LLC, formerly RPC Industries (USA)



- **High energy systems**
  - IBA (Belgium), which owns RDI in the USA
  - Nissin High Voltage Corporation (Japan)
  - Denki Kogyo Co, Ltd. (Japan)
  - IHI Corporation (Japan)
  - Vivirad (France)
  - Mevex (Canada)
  - L-3 Communications Pulsed Sciences Division (USA)
  - Budker Institute of Nuclear Physics (BINP) – Russia
    - EB TECH Co., Ltd. (Korea) – BINP collaboration
    - Center for Advanced Technology (India) – BINP collaboration



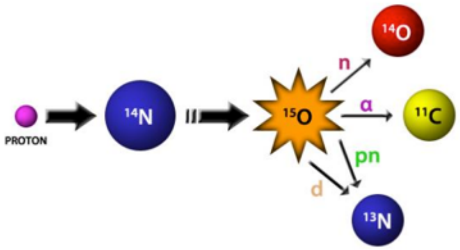
Crosslinking: rubber

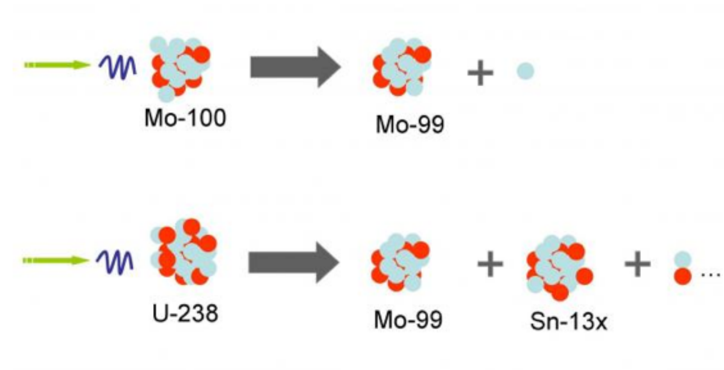
- Crosslinking is the core chemical process of linking the plastic rubber molecules into a three-dimensional network structure with elastic properties, namely the finished rubber. The choice of crosslinking agent, the desired crosslinking density and the reactivity of the crosslinking system used have a decisive influence on the material properties. As a result, there may be substantial changes in their stress values, tensile strength, hardness, elasticity, gas permeability, high-temperature or swelling resistance during the crosslinking reaction.

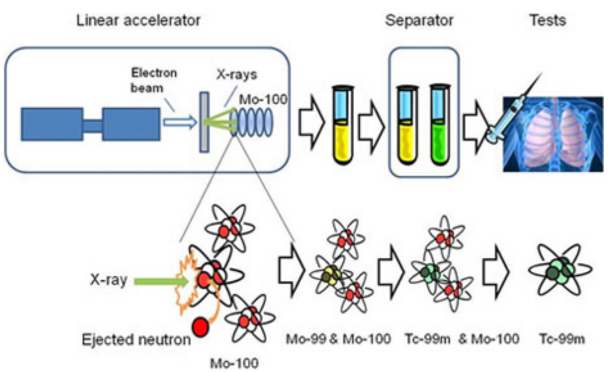
- The most well-known crosslinking agent is elemental sulfur, which is used in conjunction with zinc oxide, stearic acid and compounds known as vulcanization accelerators. In addition, sulphur-free systems are used as well, such as p-quinone dioxime together with oxidizing agents, peroxides with crosslinking coagents, diamino compounds, resins or metal oxides.

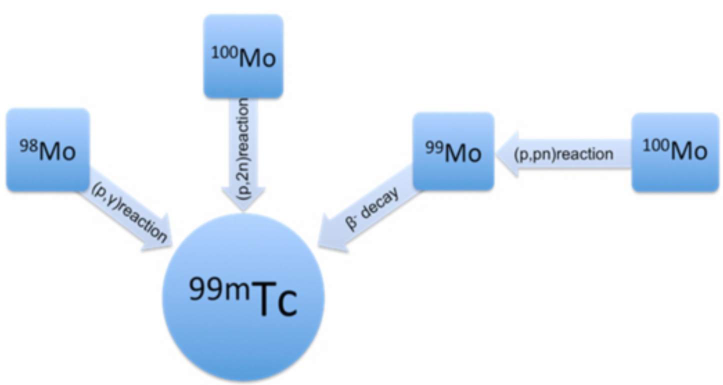
- The choice of crosslinking systems is determined on the one hand by the chemical characteristics of the polymer. For instance, rubbers containing diene groups, such as NR, IR, SBR, BR or EPDM, can be crosslinked with numerous versions of the classical sulphur system. However, similar attempts with EVA, AEM or FKM would be doomed to failure.

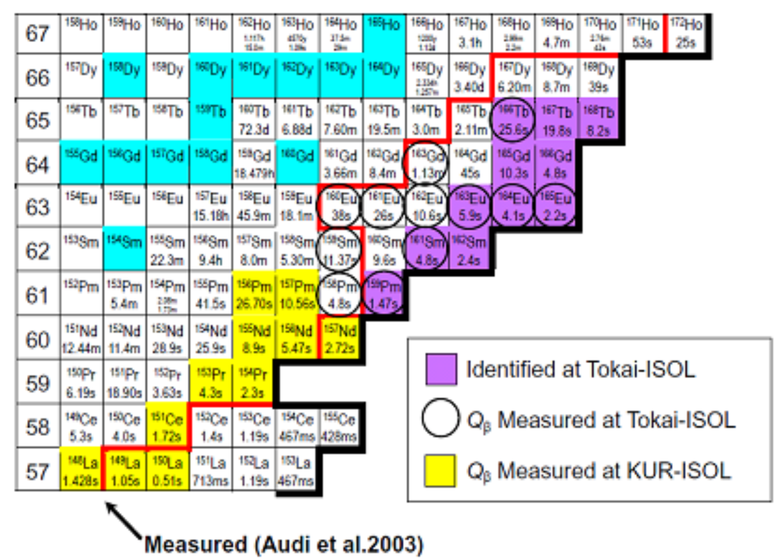
Radioisotope production



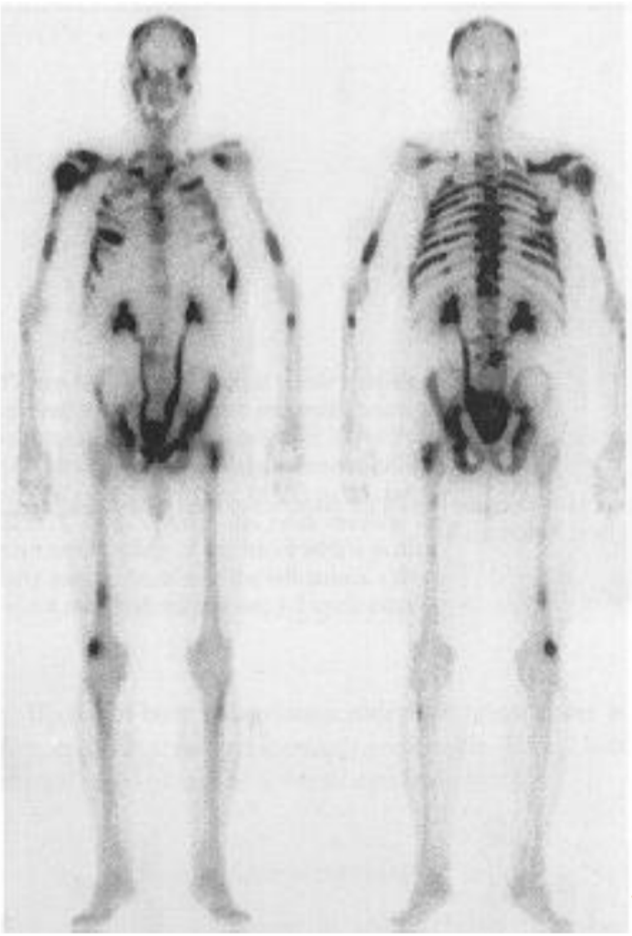








Bone pain agents



P-32-orthophosphate
Sr-89 chloride (Metastron)
Sm-153-EDTMP phosphonate (Quadramet)
Ho-166-EDTMP phosphonate
Sn-117m(stannic 4+)-DTPA
Lu-177 DOTMP/EDTMP
Re-188-hydroxyethylidene diphosphonate (HEDP)
Re-186, -188-HEDP hydroxyethylidene diphosphonate
Re-188 dimercaptosuccinic acid
I-131-α-amino(4-hydroxybenzylidene)-disphosphonate
Y-90-chloride
Ra-223-chloride (AlphaRadin)

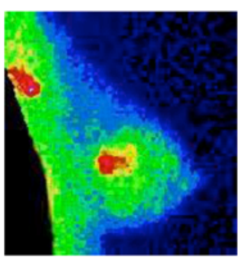
FDA product categories

Drugs	Biologics	Devices
^{89}Sr-chloride	^{90}Y-peptide	^{90}Y-microspheres
^{131}I-sodium iodide	^{131}I-antibody	^{125}I-seeds
^{99m}Tc sestamibi		^{137}Cs-intracavitary brachytherapy

Radiopharmaceuticals in nuclear medicine

Standard photon-emitter clinical imaging agents

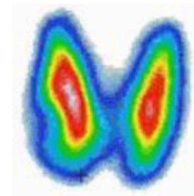
- Tc-99m (about 35 common diagnostic radiopharmaceuticals)
- I-131 sodium iodide
- In-111, I-123, Tl-201, Ga-67, Xe-133



Tc-99m-sestamibi scan shows breast tumor

Therapy agents

- Thyroid disease (benign and malignant)
  - Iodine-131 sodium iodide, oral
  - Targets thyroid (hormone-secreting) tissues, salivary glands, cancer metastases



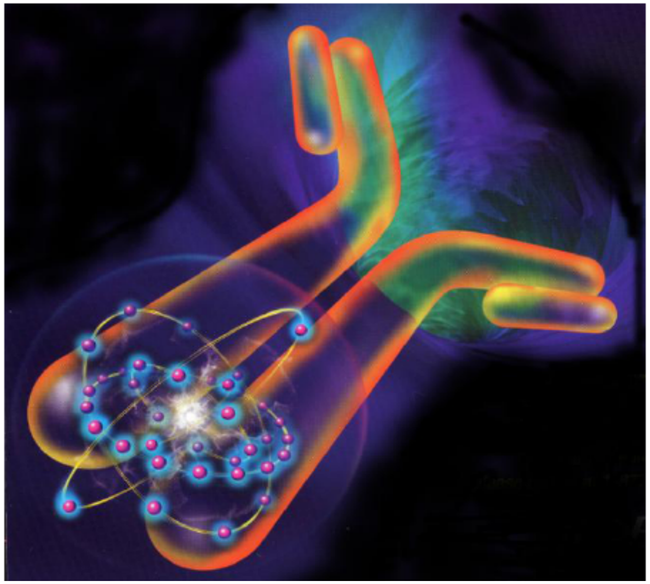
I-131 scan of normal thyroid

Therapy agents

- Myeloproliferative diseases (bone marrow)
  - P-32 sodium phosphate (targets trabecular bone surfaces)
  - P-32 orthophosphate for polycythemia vera
  - Ho-166-DOTMP plus melphalan for multiple myeloma
- Malignant ascites (intraperitoneal cavity)
  - P-32 chromic phosphate colloid
  - Y-90 silicate, colloidal suspensions
  - Y-90-labeled anti-ovarian-cell antibodies
    - Targets cell-surface antigens
    - Problem achieving sufficiently high, uniform radiation doses

Radiolabeled antibodies, antibody constructs, engineered antibodies, diabodies, hormones, peptides

Hodgkin's disease	Y-90-antiferritin, Y-90 mAb
Acute leukemia	I-131-mAb, Bi-213 mAb
Colorectal cancer	Y-90-mAb, I-131-mAb
Brain glioma, astrocytoma	At-211-anti-tenascin Ab
Melanoma	Pb-212/Bi-212 peptide
Many others	(Cu-67, Lu-177, Bi-213, Ac-225, At-211, Bi-212)

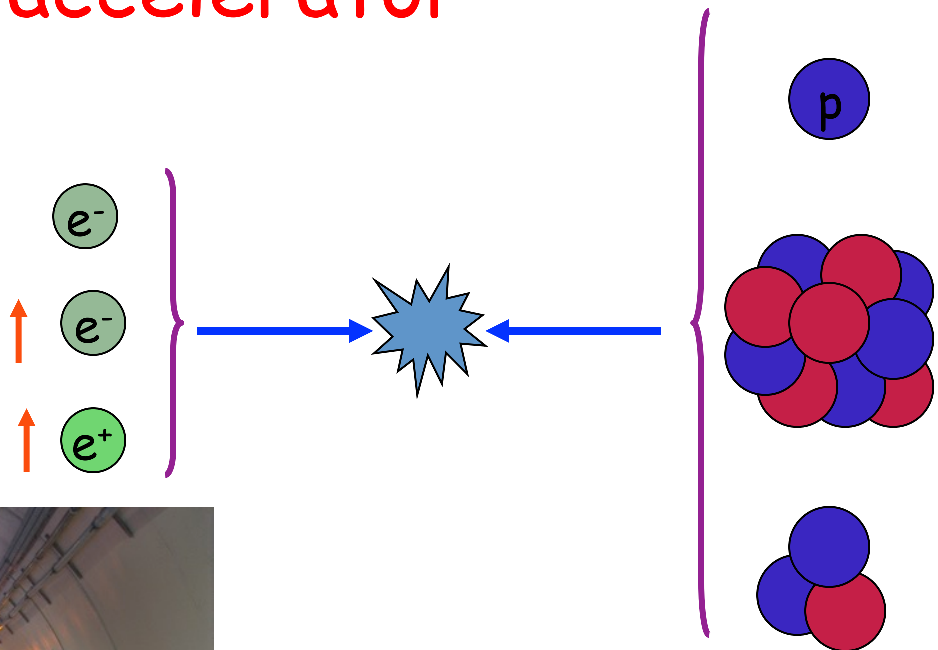


Pacific Northwest
NATIONAL LABORATORY

LHeC Scope

Electron accelerator

Unpolarized and polarized leptons 60-140 GeV



LHC

Protons up to 7 TeV

Heavy ions 3 TeV/u

Other ions?

Center mass energy range: 0.5- 2 TeV

Ion Beam Analysis

- **Techniques**
  - Rutherford Back Scattering (RBS)
  - Elastic Recoil Detection Analysis (ERDA)
  - Nuclear Reaction Analysis (NRA)
  - Particle Induced X-ray Emission (PIXE)
  - Particle Induced Gamma ray Emission (PIGE)
  - Nuclear Resonance Reaction Analysis (NRRA)
  - Resonant Scattering Analysis (RSA)
  - Charged Particle Activation Analysis (CPAA)
  - **Accelerator Mass Spectrometry (AMS)**

Applications

- Semiconductor quality
- Environmental monitoring
- Geological studies
- Oceanography studies
- Biomedical science

- **Vendors**
  - National Electrostatic Corp. (USA)
  - High Voltage Engineering Europa (Netherlands)

High Energy X-Ray Inspection

- Accelerators
  - Medical system “spin-offs”
  - Electron linacs & betatrons – 1 to 16 MeV
- Applications
  - Radiography of large castings
  - Examination of rocket motors and munitions
  - Port examination of containers & semi-trailers
- Major vendors
  - Varian Medical Security & Inspection Products (USA)
  - Nuctech (China)
- Smaller vendors
  - L & W Research (USA)
  - HESCO (USA)
  - EuroMeV (France)
  - MEVEX (Canada)
  - JME Ltd. (UK)

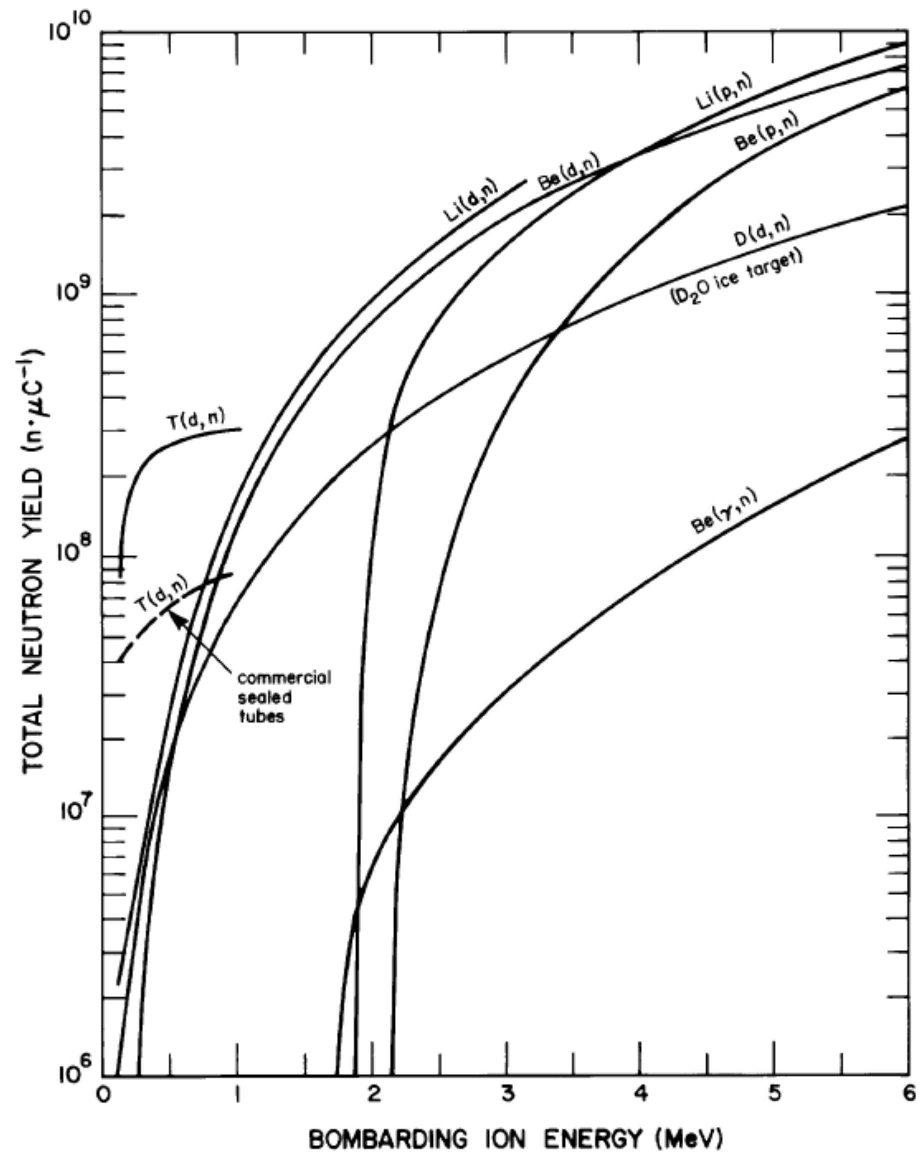
Neutron Generators

Applications

- Cancer therapy, including BNCT
- NDE, including security checking
- Material analysis

Vendors

- Principal vendors for sealed tubes:
  - Thermo Scientific (USA)
  - Adelphi Technology, Inc (USA)
  - EADS Sodern (France) and
  - All-Russia Research Institute of Automatics-VNIIA (Russia)
- Large US producers for oil well logging:
  - Halliburton Co.,
  - Schlumberger Well Services
  - Baker Atlas
- Accelerator-based generator vendors:
  - AccSys Technology, Inc. – p and d linacs
  - IBA – Dynamitron
  - Sumitomo Heavy Industries – cyclotrons
  - NEC and HVEE – electrostatic accelerators



Synchrotron Radiation

- **Application fields:**
  - Semiconductor industry – includes lithography, studies of material interfaces and other production issues.
  - Chemical industry – studies of properties such as stress or texture of various materials produced and the chemical reactions themselves.
  - Biomedical field – includes protein crystallography, imaging molecular structures and molecular dynamics studies in tissue cells.

- **Vendors:**
  - Oxford Instruments Accelerator Technology Group (UK) – several superconducting systems for semiconductor lithography
  - Danfysik (Denmark) – normal conducting systems in Canada and Australia
  - Sumitomo Heavy Industries (Japan) – compact normal conducting systems

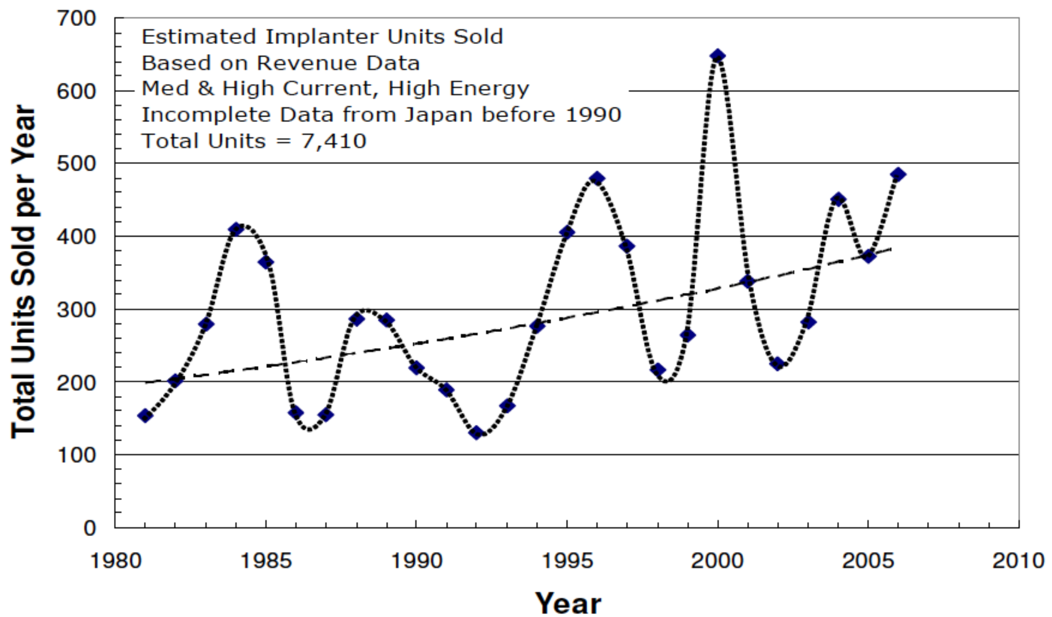
It is a BIG business

Industrial Accelerator Business

Application	Total (2007)	Systems sold/yr	Sales/yr ($M)	System price ($M)
Ion Implantation	~9500	500	1,400	1.5 – 5.0
Electron beam modifications	~4500	100	150	0.5 – 2.5
Electron beam & X-ray irradiators	~2000	75	130	0.2 – 8.0
Ion beam analysis (including AMS)	~200	25	30	0.4 – 1.5
Radioisotope production (including PET)	~550	50	70	1.0 – 30
High energy x-ray inspection	~650	100	70	0.3 – 2.0
Neutron generators (including sealed tubes)	~1000	50	30	0.1 – 3.0
Total	18,400	900	1780	

It is a BIG business

Ion Implantation Accelerator Sales



Major Vendors

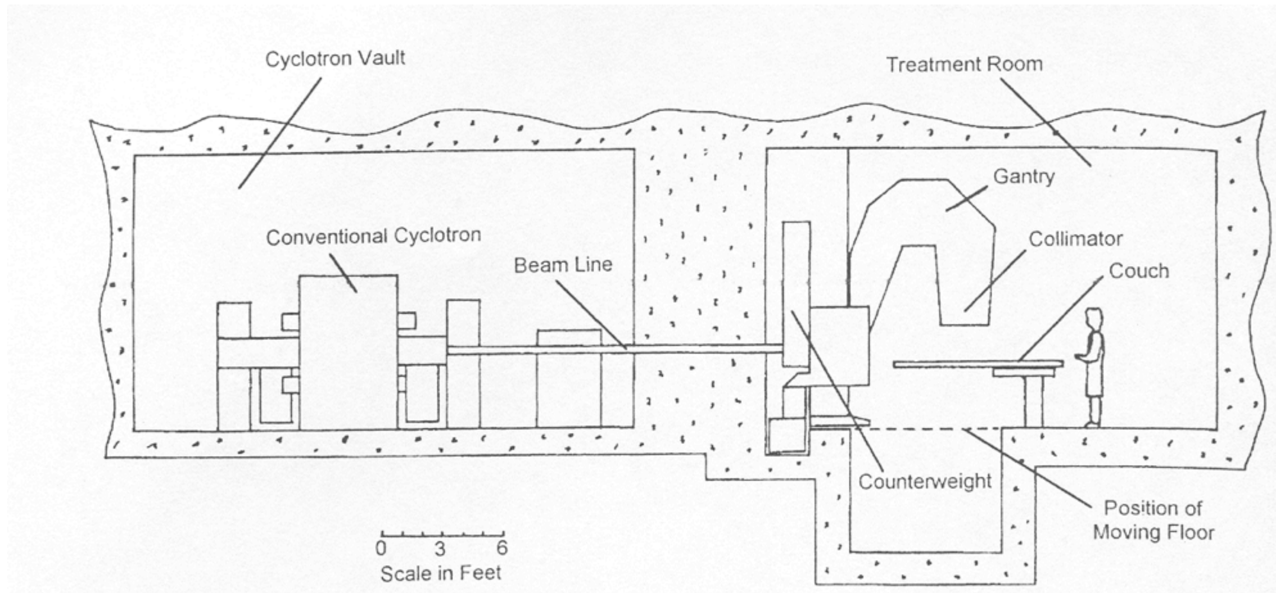
- Varian Semiconductor Equipment (USA)
- Axcelis Technology (USA) & SEN Corp., a joint venture in Japan with Sumitomo
- Nissin Ion Equipment Company (Japan)
- Applied Materials – left the business in 2007

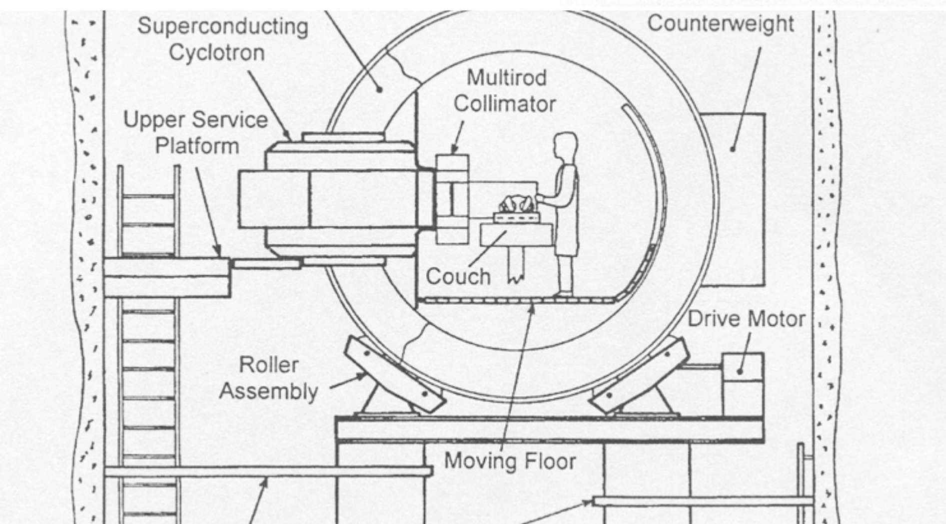
Misc. vendors

- Ulvac Technologies & IHI Corp (Japan)
- China Electronics Technology Group (China)
- Ibis Technology (USA)
- Advanced Ion Beam Technology (USA)
- HVEE B.V. (Netherlands)
- National Electrostatic Corporation (USA)
- Danfysik (Denmark)

Accelerator Parts

Cyclotrons in Hospitals in Detroit and Seattle





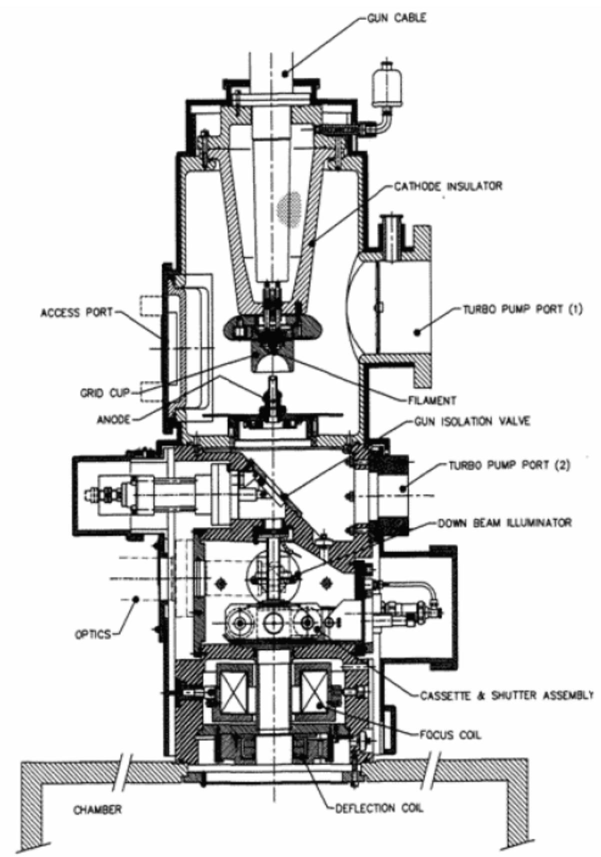
Material Processing/Modifications

Electron Beam Materials Processing

- Application of electron guns dating to 1905
  - Critical to automotive production
  - Refractory metals
  - Dissimilar metals
  - Precision cutting and drilling
- Beam energy from 60 to 200 keV
- Beam power from 6 to 200 kW

- **Major Vendors**
  - Sciaky, Inc. (USA)
  - All Welding Group AG (PTR Group and Steigerwald Strahltechnik) (Germany)
  - Cambridge Vacuum Engineering (UK)
  - Bodycote Techmeta (France)

- **Smaller vendors**
  - Pro-beam (Germany)
  - Orion (Russia)
  - Mirero (Korea)
  - Omegatron (Japan)
  - NEC Corporation (Japan)
  - Mitsubishi Electric Corporation (Japan)

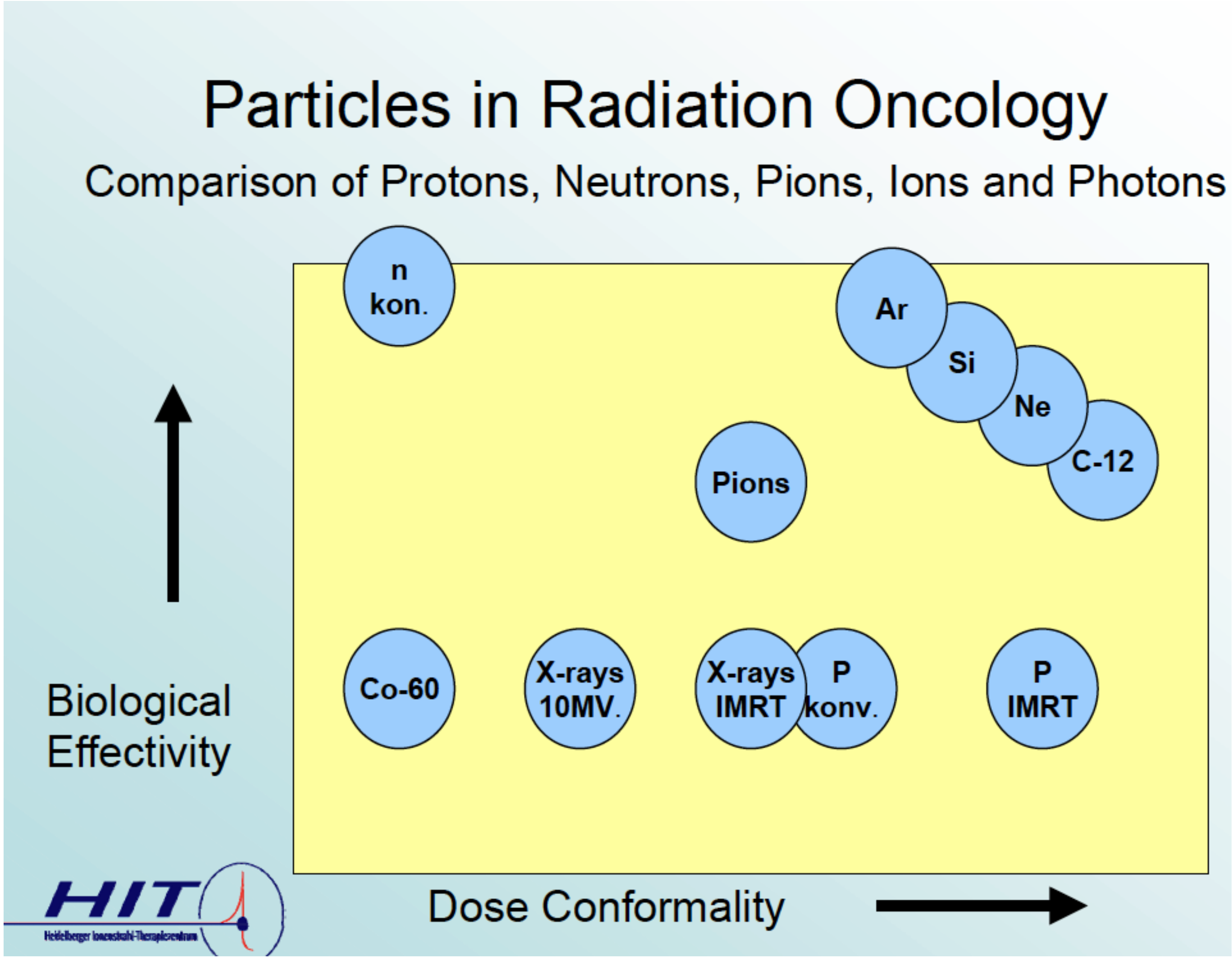


A mature business with large growth now in developing countries

Particle Therapy Facilities – HIT/Heidelberg

HIT concept and layout is based on experience from GSI; 448 patients were treated with carbon beams from 1997 – 2008 using raster scanning technique

Radiation therapy

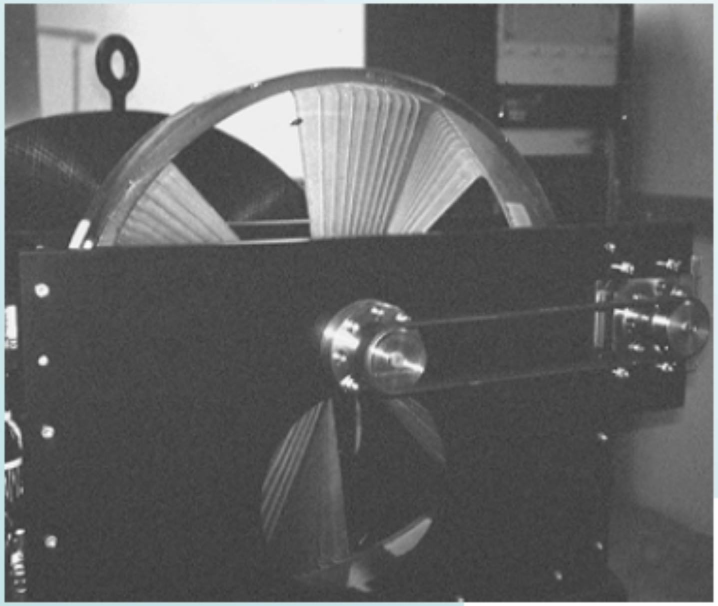


We do it at BNL....

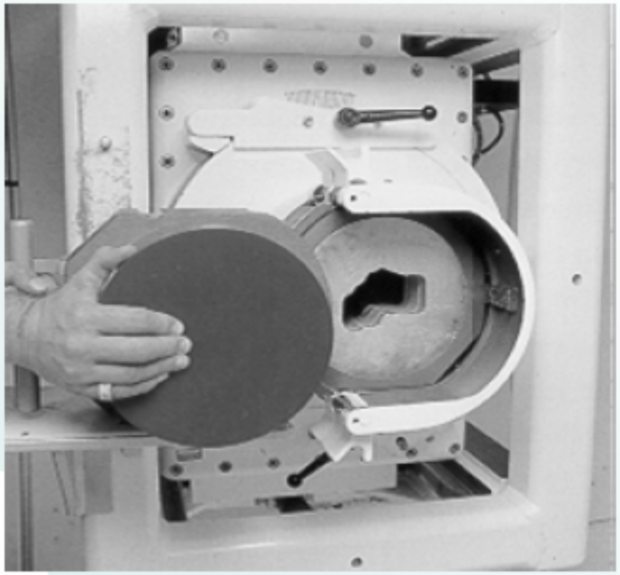
- Isotope Production and Distribution at BLIP
  - **Distribution for sale; process & target development to improve quality & yield.**
  - **Sr-82/Rb-82 for human heart scans with PET**
  - **Ge-68 for calibration of PET devices**
  - **Zn-65 tracer for metabolic or environmental studies**
- Radioisotope R&D
  - **Sn-117m, Cu-67, for cancer therapy applications**
  - **Y-86 for cancer imaging**
- Radiation damage studies
  - **target and magnet materials for future high power accelerators, collaboration with BNL Physics & ES&T Departments**
  - **high temperature superconductors for FRIB, collaboration with BNL Magnet Division and ES&T Department**
- Training
  - **Support (space, equipment, faculty) for DOE funded Nuclear Chemistry Summer School, a 6 week undergraduate course in nuclear and radiochemistry**

Optimization of the treatment

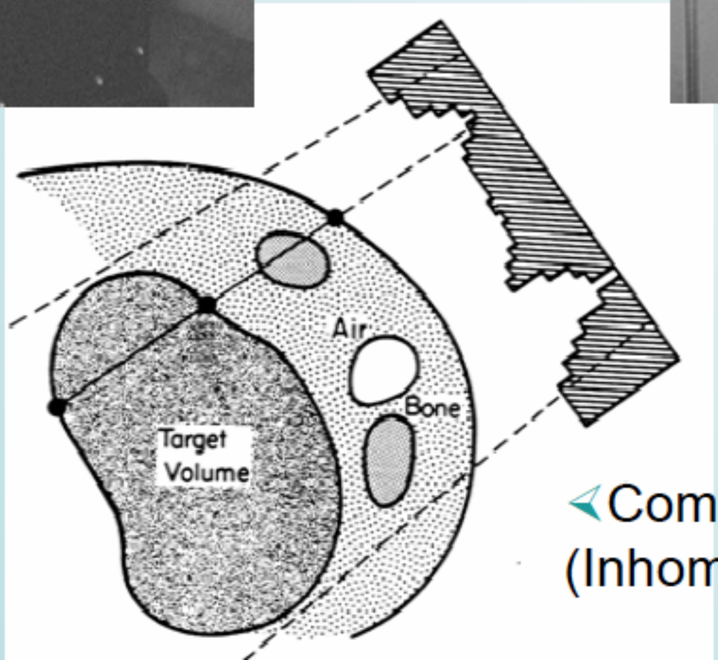
Conforming the Beam to the Target: Scattering Method



Modulator (Thickness)



Collimator (Shape)



Compensator (Inhomogeneities)

Accelerator Parts

Gantries: monsters in modern accelerators

The HIT facility. Source: Photo Gallery of the HIT.