
Introduction to Medical Physics

A branch of applied physics concerning
the application of physics to medicine

or, in other words

The application of physics techniques to the human health

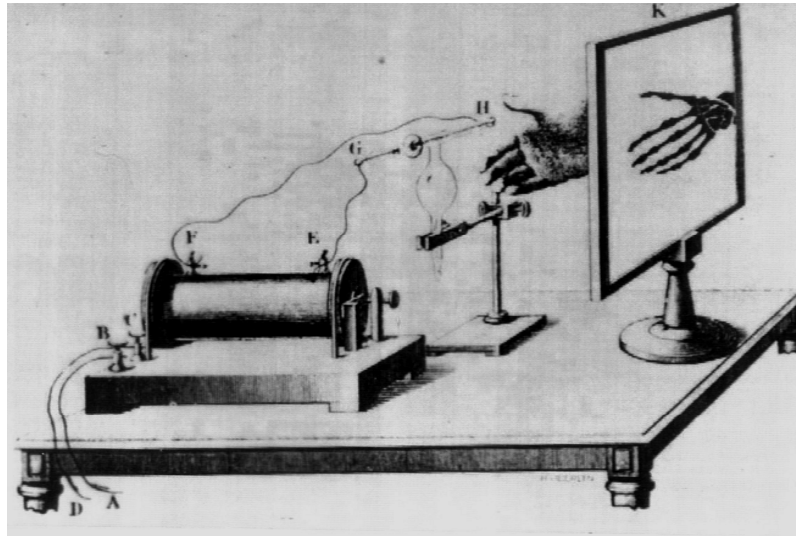
Marco Silari, CERN



Introduction to Medical Physics

- Physics discoveries
- Tools for physics applied to medicine
- Medical imaging
- Magnetic Resonance Imaging (MRI)
- CT
- PET and PET/CT
- Conventional radiation therapy
- Hadron therapy

The beginnings of modern physics and of medical physics



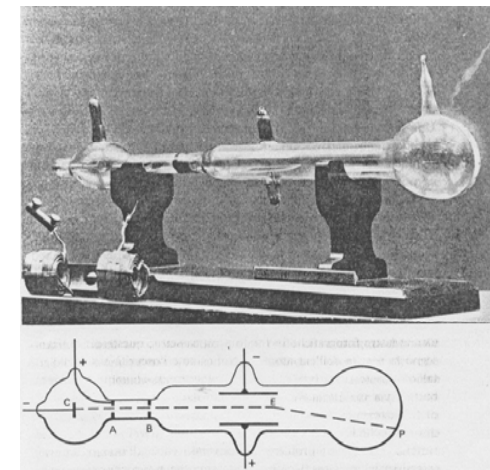
1895
discovery of X rays

Wilhelm Conrad
Röntgen



J.J. Thompson

1897
"discovery" of the
electron



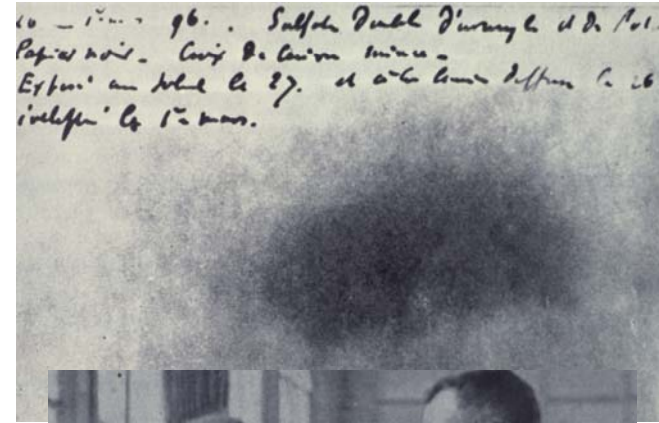
The beginnings of modern physics and of medical physics



Henri Becquerel
(1852-1908)

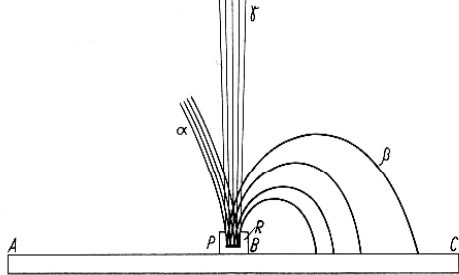
1896:

Discovery of natural
radioactivity



Thesis of Mme. Curie – 1904

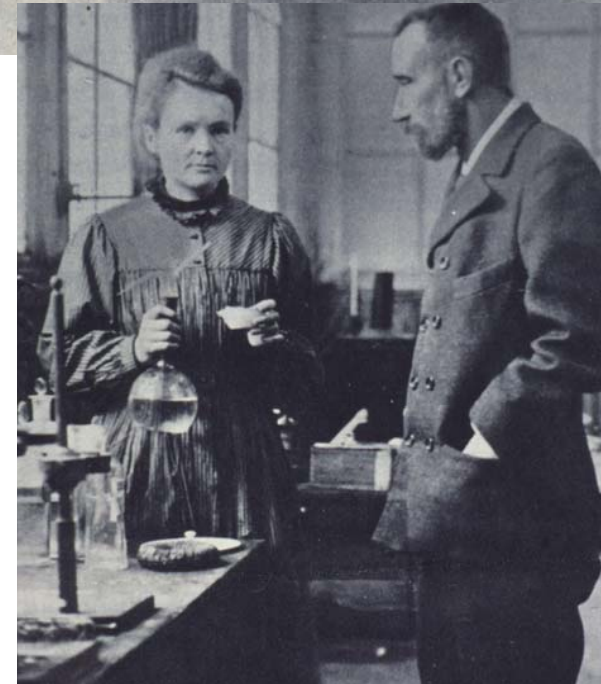
α , β , γ in magnetic field



Hundred years ago

1898

Discovery of polonium
and radium



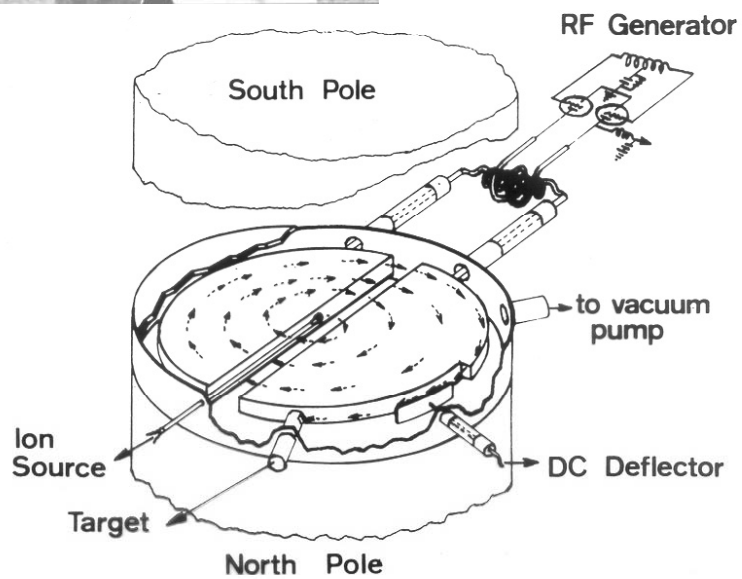
Marie Curie Pierre Curie
(1867 – 1934) (1859 – 1906)

Tools for (medical) physics: the cyclotron



1930

Ernest Lawrence invents the cyclotron



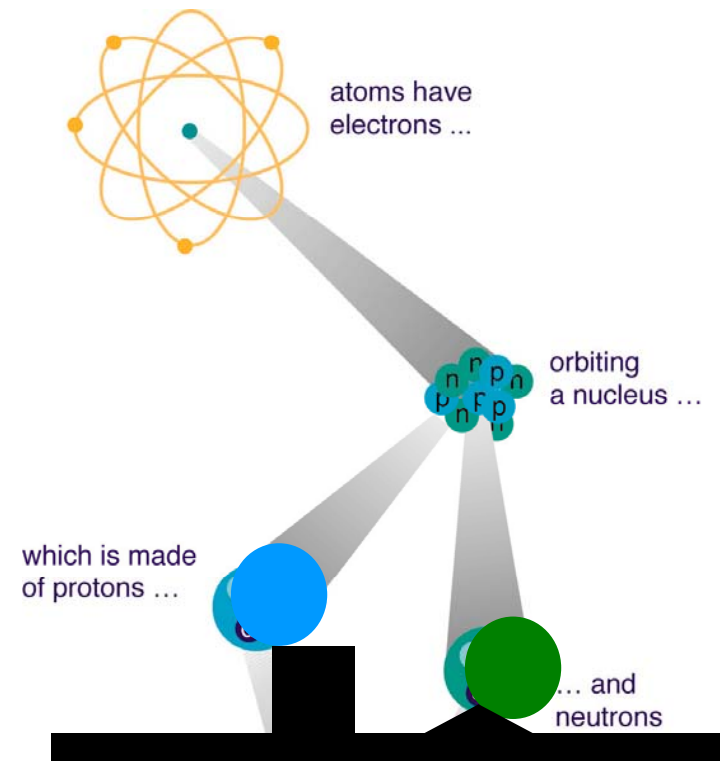
**M. S. Livingston and E. Lawrence
with the 25 inch cyclotron**

The beginnings of modern physics and of medical physics



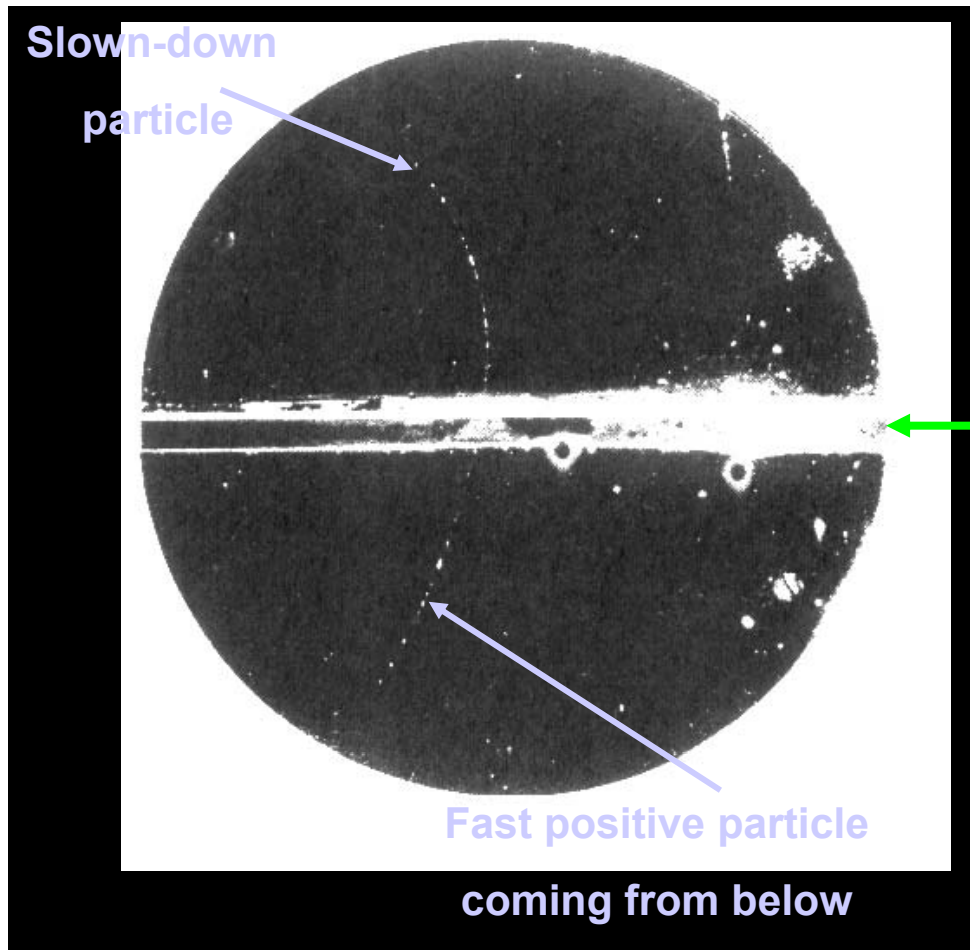
James Chadwick
(1891 – 1974)

1932
Discovery of the neutron



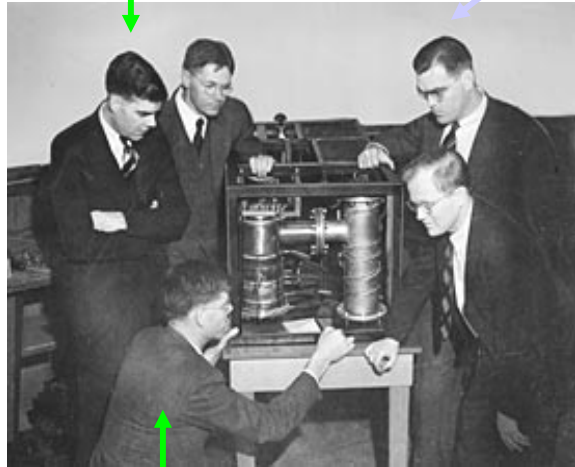
The beginnings of modern physics and of medical physics

1932 – C. D. Anderson
Discovery of the positron



Tools for (medical) physics: the electron linac

Sigmur Varian

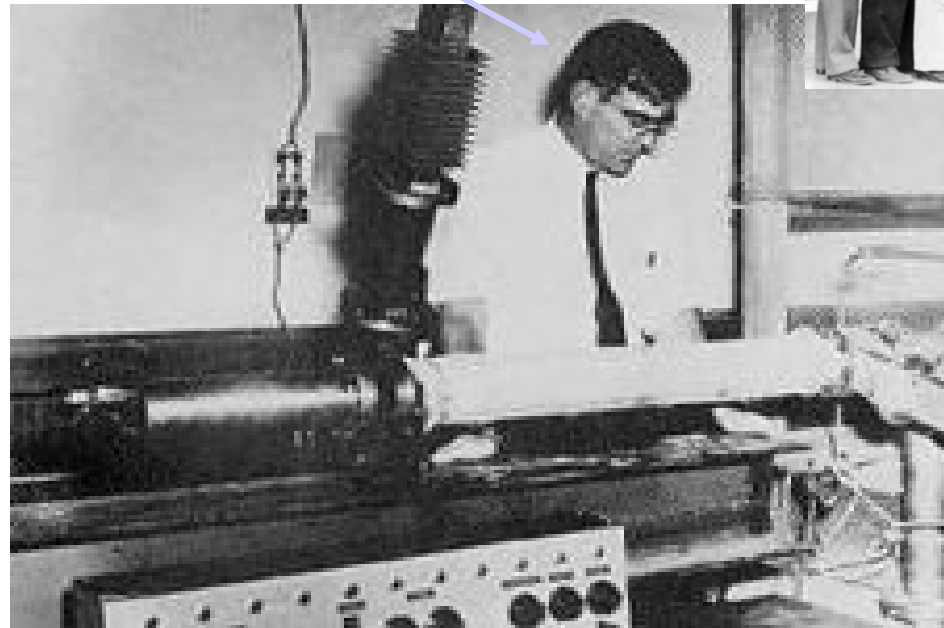


Russell Varian

1939

Invention of the klystron

William W. Hansen



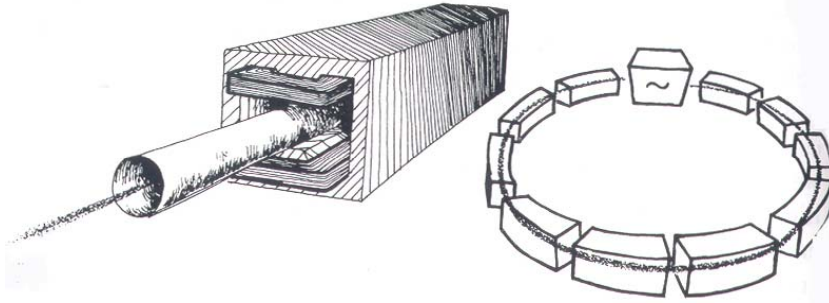
1947
first linac for electrons
4.5 MeV and 3 GHz



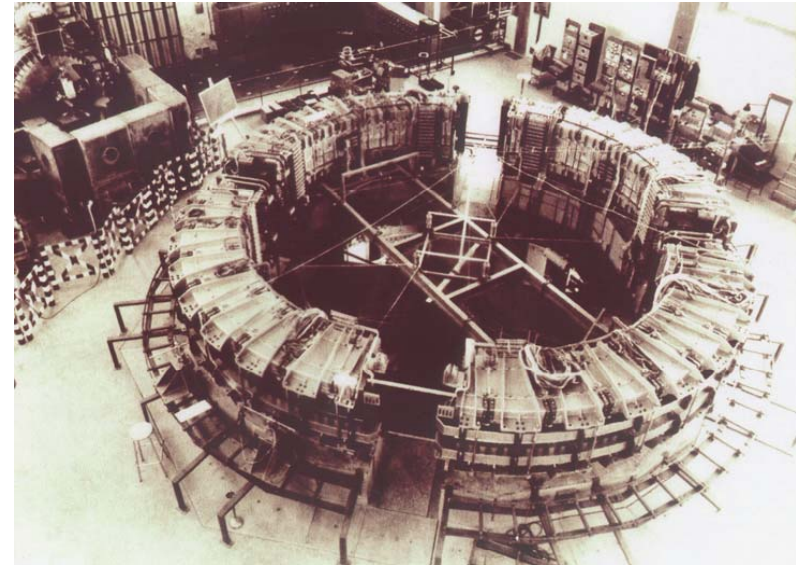
Tools for (medical) physics: the synchrotron

1945: E. McMillan and V.J.Veksler

discover the
principle of phase stability



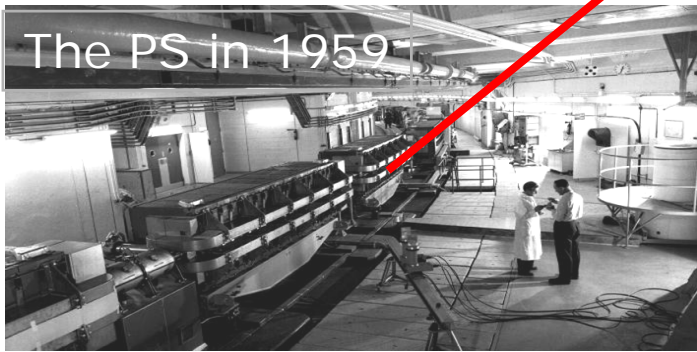
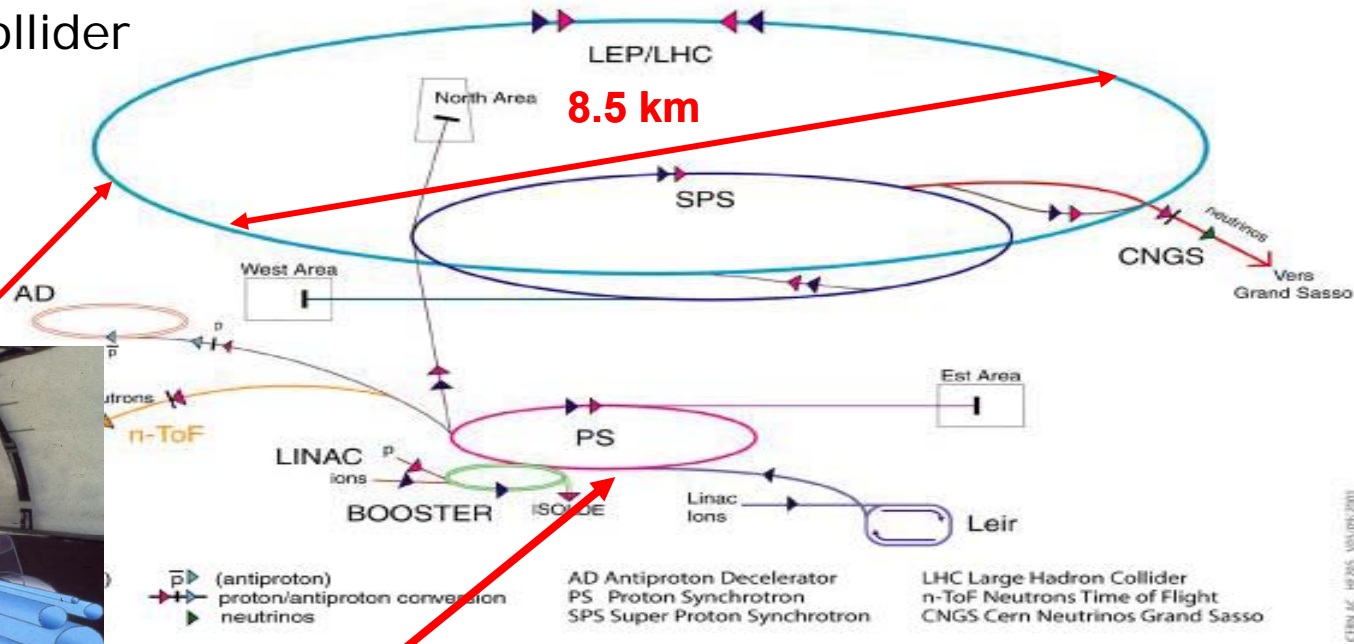
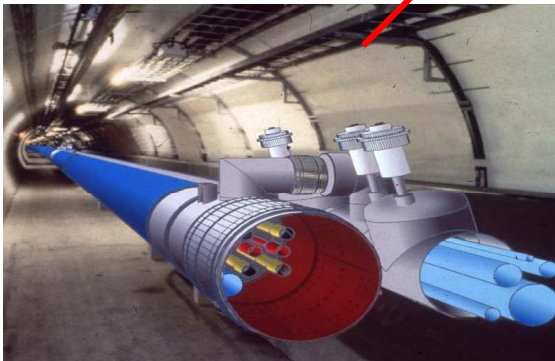
1 GeV electron synchrotron
Frascati - INFN - 1959



6 GeV proton synchrotron
Bevatron - Berkeley - 1954

CERN accelerators

Large Hadron Collider
7 TeV + 7 TeV
Start in 2008



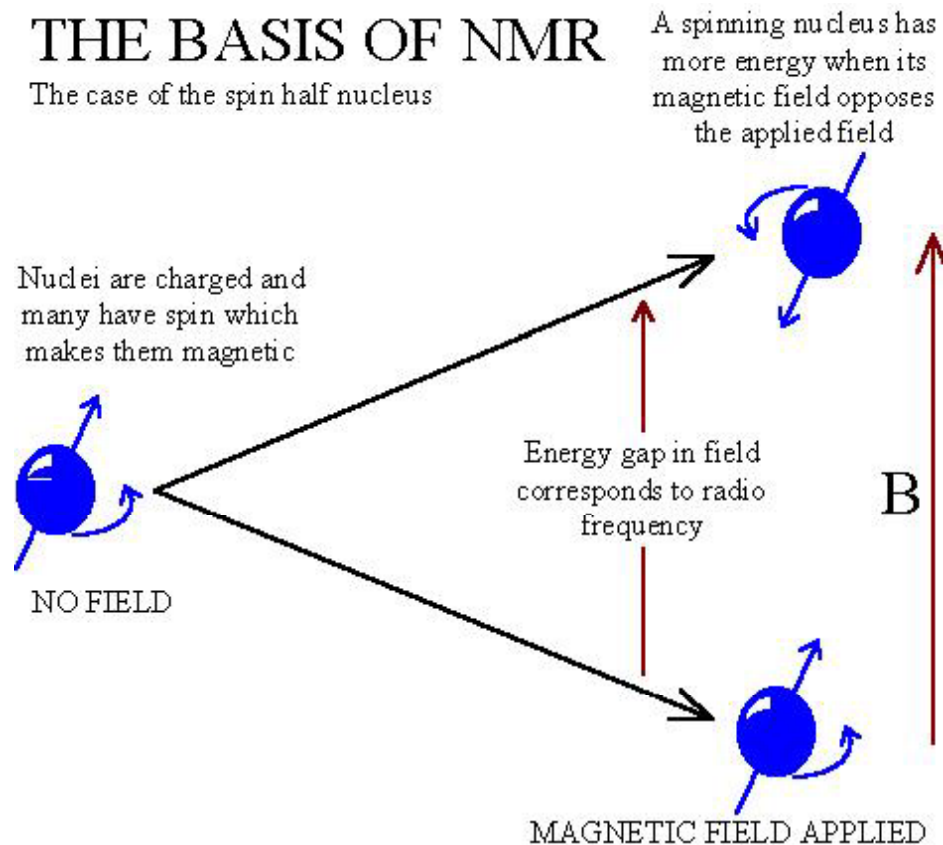
In 1952 the "strong-focusing" method
invented at BNL (USA)
was chosen for the CERN PS



Tools for (medical) physics: Nuclear Magnetic Resonance

THE BASIS OF NMR

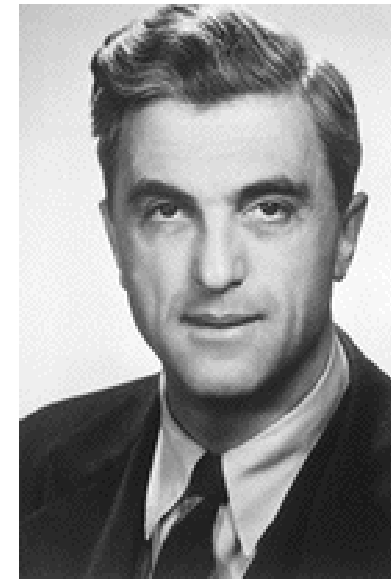
The case of the spin half nucleus



1938-1945



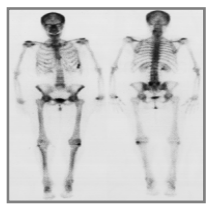
Felix Bloch and Edward Purcell
discover and study

NMR


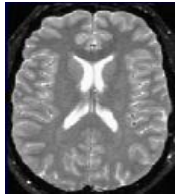
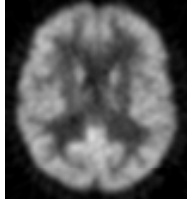


In 1954 Felix Bloch became
the first CERN Director General

Medical imaging

TECHNIQUE		YEAR	ENERGY	PHYSICAL PROPERTY	IMAGING
RADIOLOGY	X RAYS IMAGING	1895	X RAYS	ABSORPTION	
ECHOGRAPHY	ULTRASOUND IMAGING	1950	US	REFLECTION TRANSMISSION	
NUCLEAR MEDICINE	RADIOISOTOPE IMAGING	1950	γ RAYS	RADIATION EMISSION	

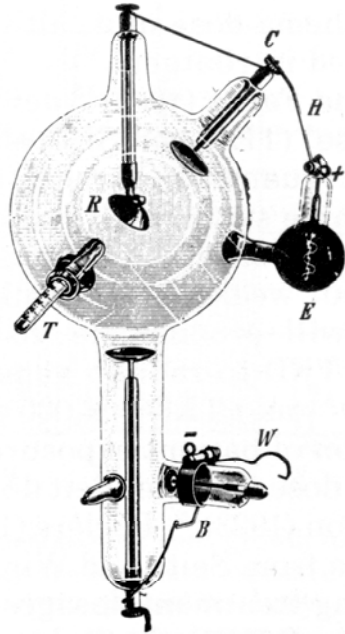
Medical imaging

TECHNIQUE		YEAR	ENERGY	PHYSICAL PROPERTY	IMAGING	
X RAYS COMPUTERIZED TOMOGRAPHY	CT	1971	X RAYS	ABSORPTION		MORPHOLOGY
MAGNETIC RESONANCE IMAGING	MRI	1980	RADIO WAVES	MAGNETIC RESONANCE		MORPHOLOGY /FUNCTION
POSITRON EMISSION TOMOGRAPHY	PET	1973	γ RAYS	RADIATION EMISSION		FUNCTION

Medical imaging

Röhren fremden Fabrikates.

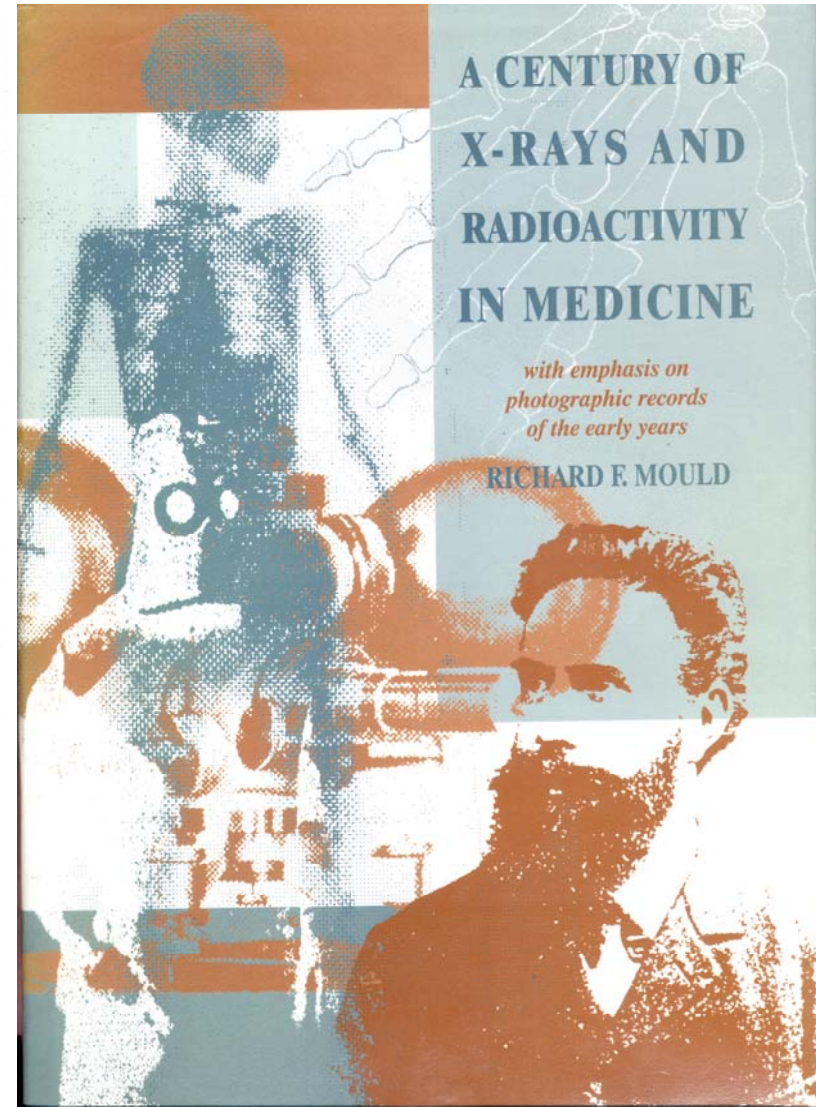
„Monopol“-Oberflächen-Therapie-Röntgenröhre mit Vorrichtung zur therapeutischen Dosierung der Röntgenstrahlen nach Prof. Dr. A. Köhler, Wiesbaden.



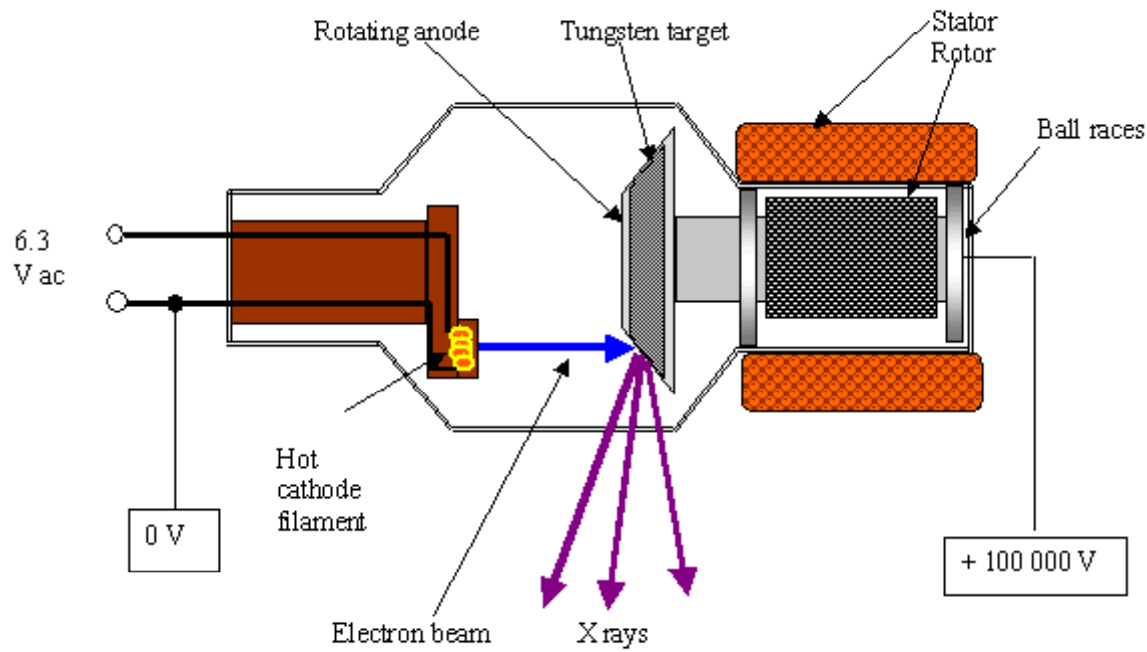
Schutzmarke.

Diese Röhre ist besonders für die Röntgen-Oberflächen-therapie bestimmt. Sie gestattet eine praktisch genügend genaue Verabreichung der für eine Sitzung erforderlichen Strahlenmenge durch bequeme direkte Ablesung an einer Thermometerskala.

[22.5] Monopol X-ray tubes were available in 1907 and some were modified to Köhler's specification by 1914. (Courtesy: Siemens AG, Erlangen.)

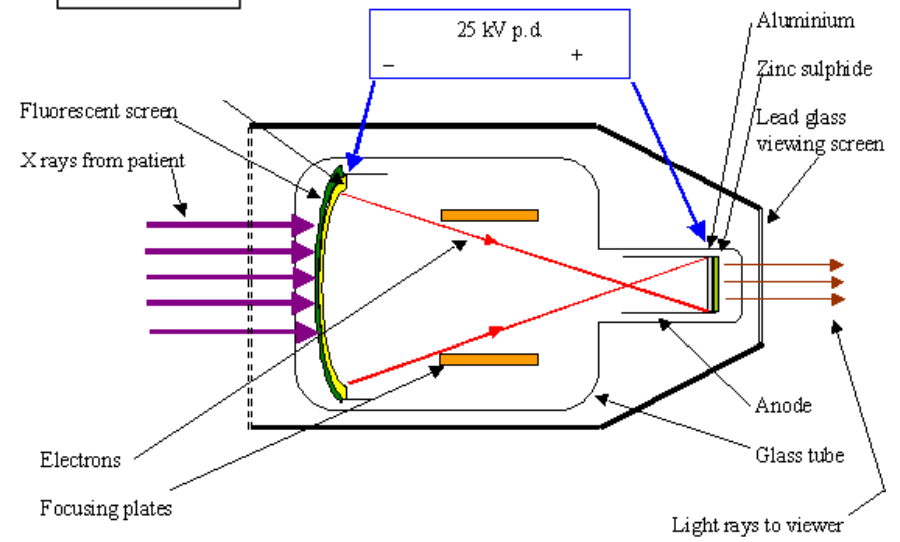


Medical imaging: x-ray generator and image intensifier



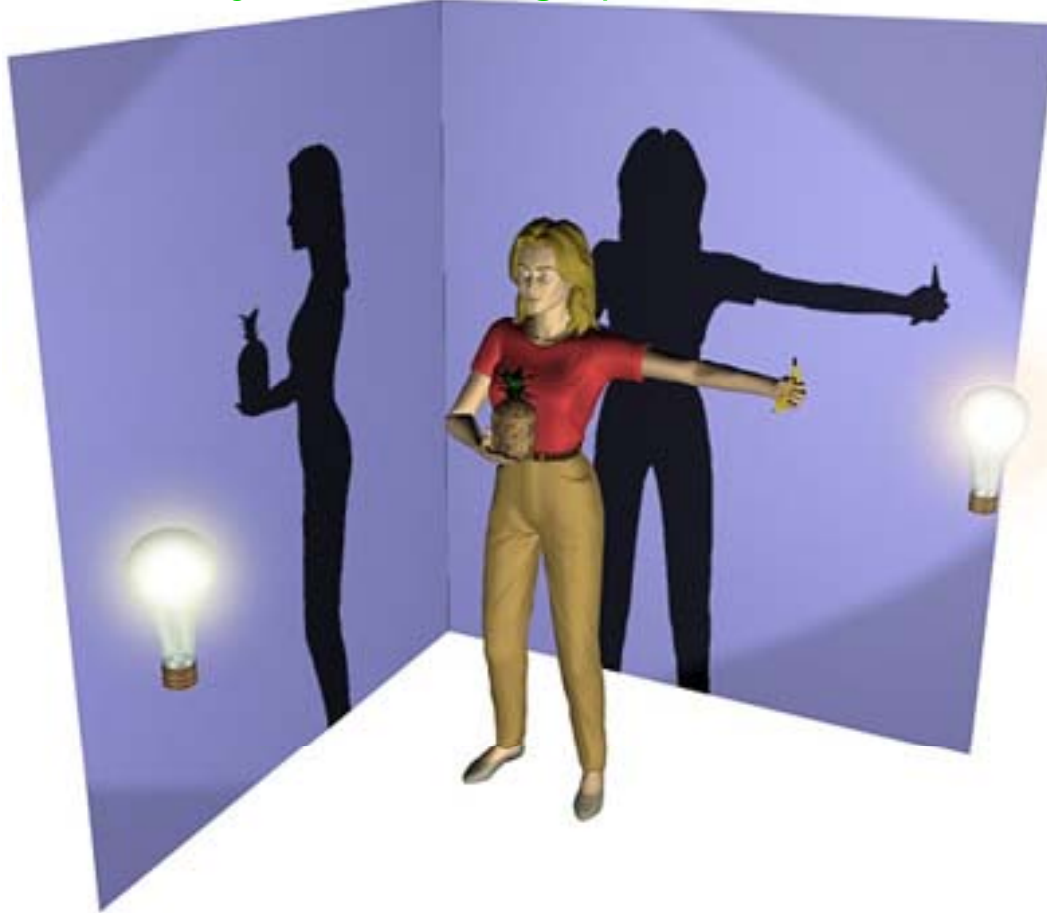
X-ray tube

Image intensifier



X-ray image versus CT scan

A conventional X-ray image is basically a **shadow**: you shine a “light” on one side of the body, and a piece of film on the other side registers the silhouette of the bones (to be more precise, **organs and tissues of different densities show up differently on the radiographic film**).

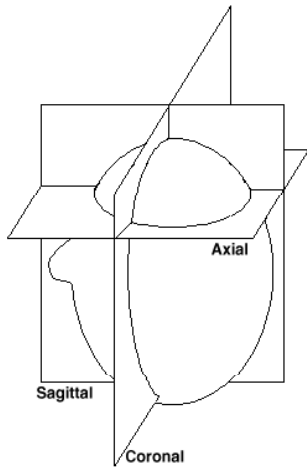
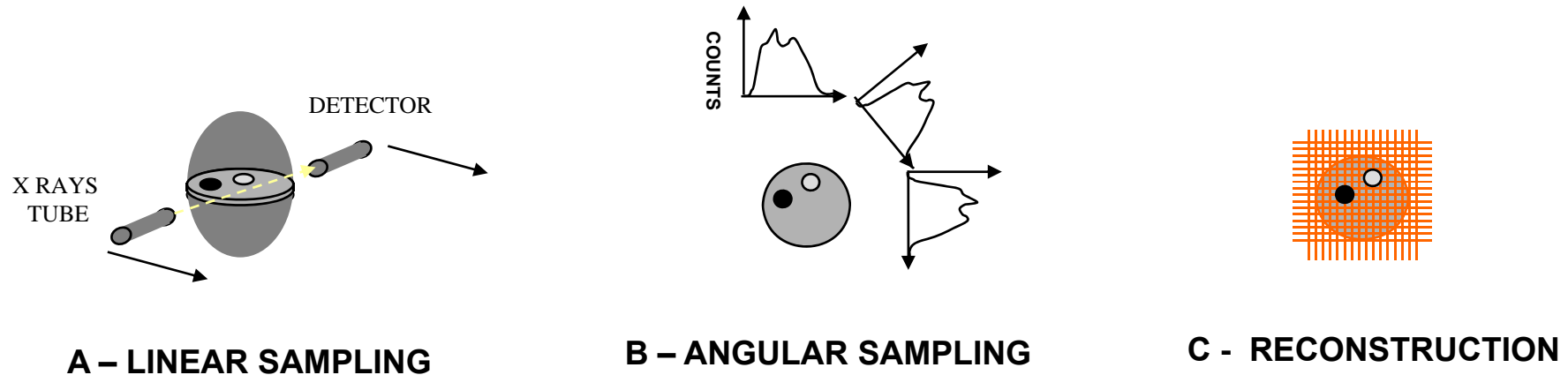


Shadows give an incomplete picture of an object's shape.

Look at the wall, not at the person. If there's a lamp in front of the person, you see the silhouette holding the banana, but not the pineapple as the shadow of the torso blocks the pineapple. If the lamp is to the left, you see the outline of the pineapple, but not the banana.

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X-ray computerized tomography (CT)

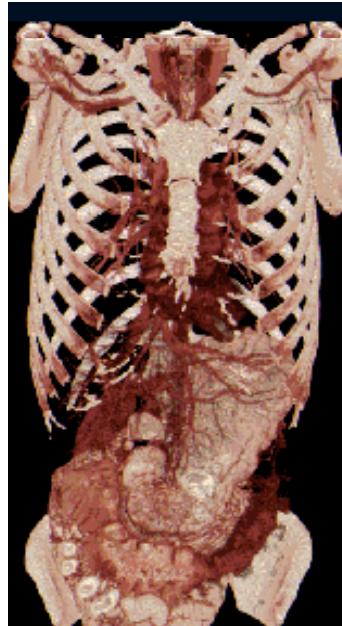
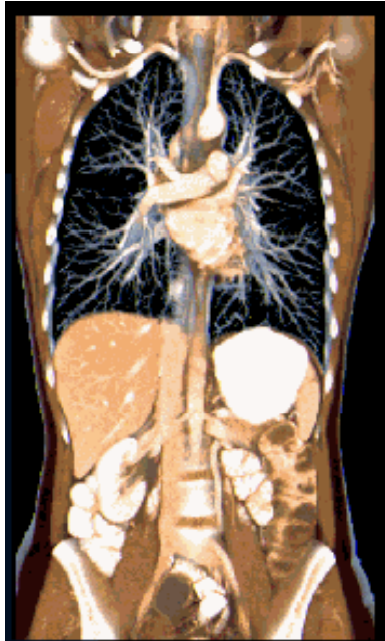


This is the basic idea of computer aided tomography. In a CAT scan machine, the X-ray beam moves all around the patient, scanning from hundreds of different angles. The computer takes all this information and puts together a **3-D image** of the body.

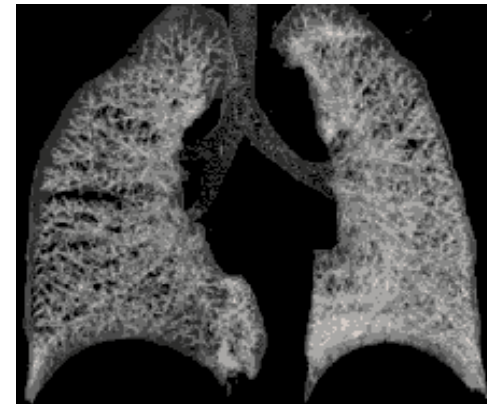
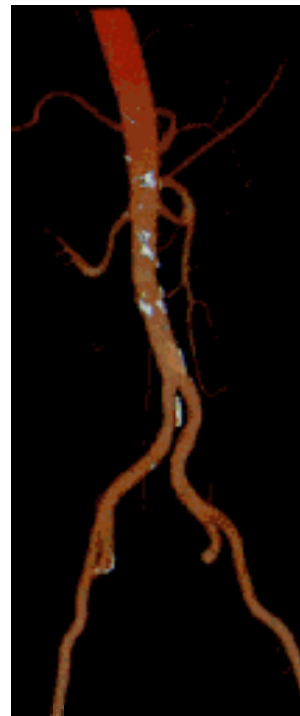


**X RAYS
COMPUTERIZED TOMOGRAPHY**

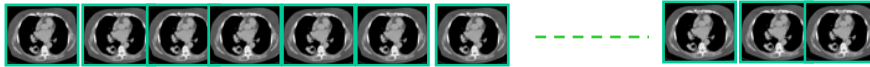
Volumetric CT



< 0,4 sec/rotation
Organ in a sec (17 cm/sec)
Whole body < 10 sec



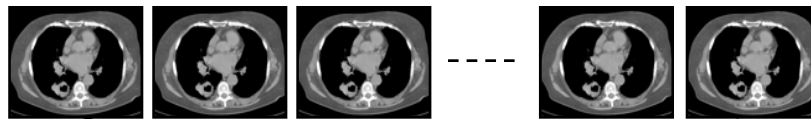
Cardiac CT



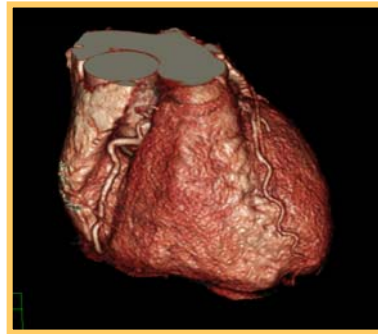
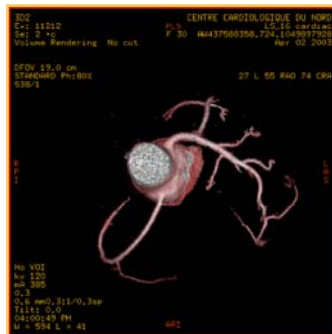
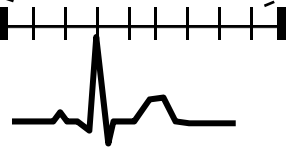
DYNAMIC CT ACQUISITION



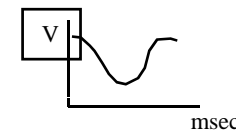
ECG



PHASES OF A CARDIAC CYCLE



- EJECTION FRACTION
- CARDIAC OUTPUT
- REGIONAL WALL MOTION
- ..



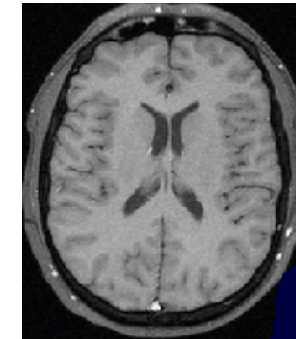
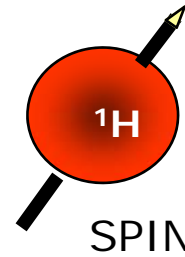
FUNCTIONAL PARAMETERS

VOLUME RENDERED IMAGE OF HEART AND VESSELS

Magnetic Resonance Imaging (MRI)

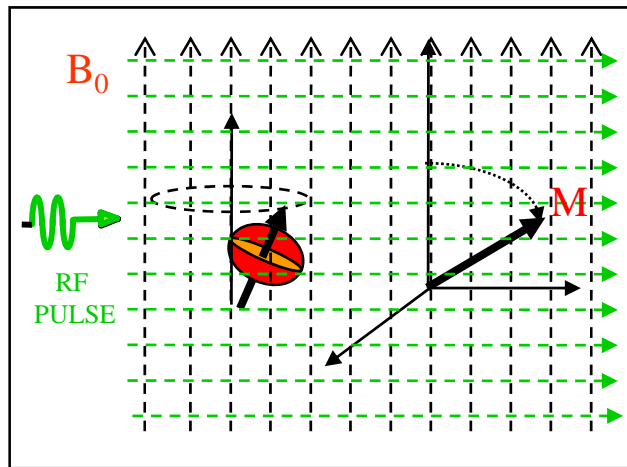
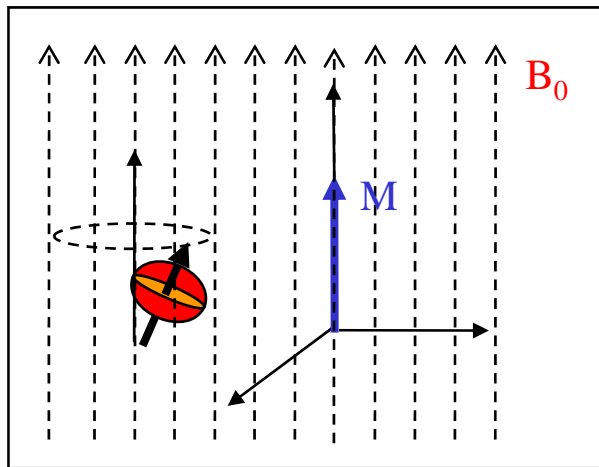
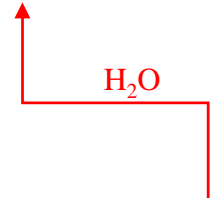


MAGNETIC FIELD: 1.5 – 3 Tesla

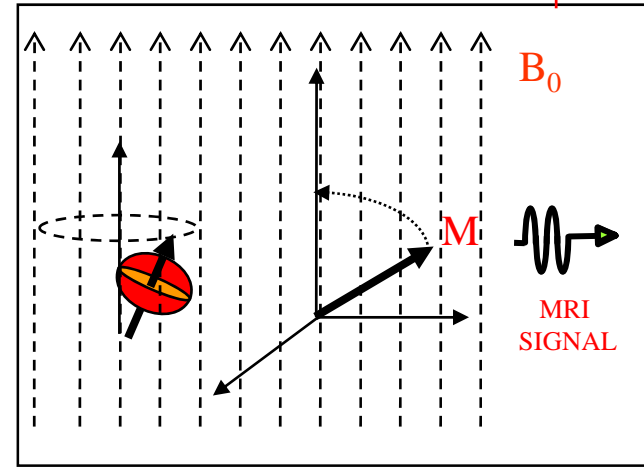


LARMOUR FREQUENCY

$$\nu_0 = [\gamma / 2\pi] B_0$$



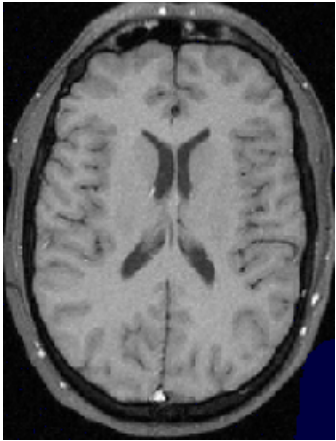
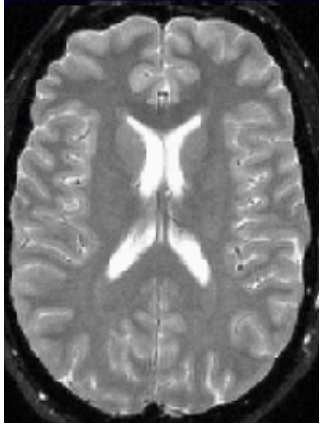
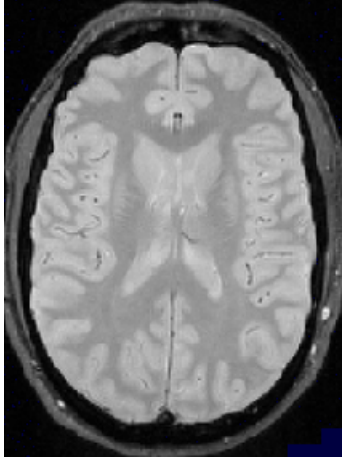
EXCITATION



RELAXATION



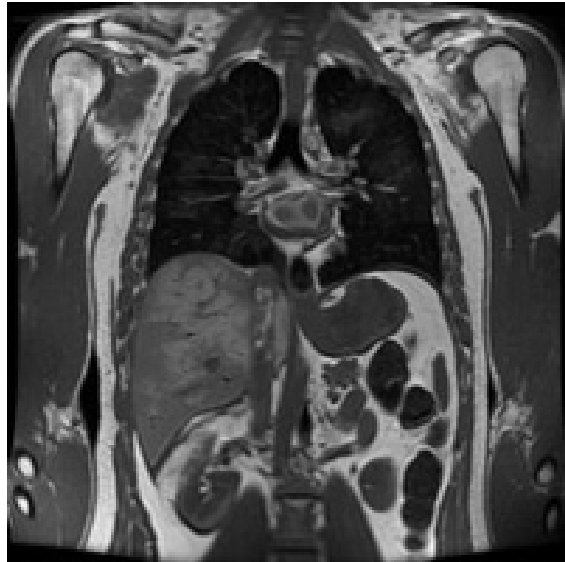
Magnetic Resonance Imaging (MRI): morphology

		
T1	T2	PD

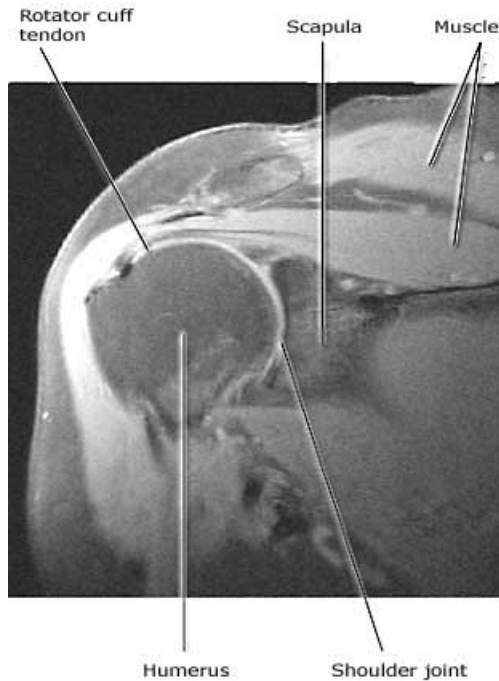
SCAN TIME to cover an entire organ:	~ min
SPATIAL RESOLUTION:	~ mm
CONTRAST RESOLUTION:	very high for soft tissues

Courtesy HSR MILANO

Magnetic Resonance Imaging (MRI): morphology



MRI of upper torso
(courtesy NASA)

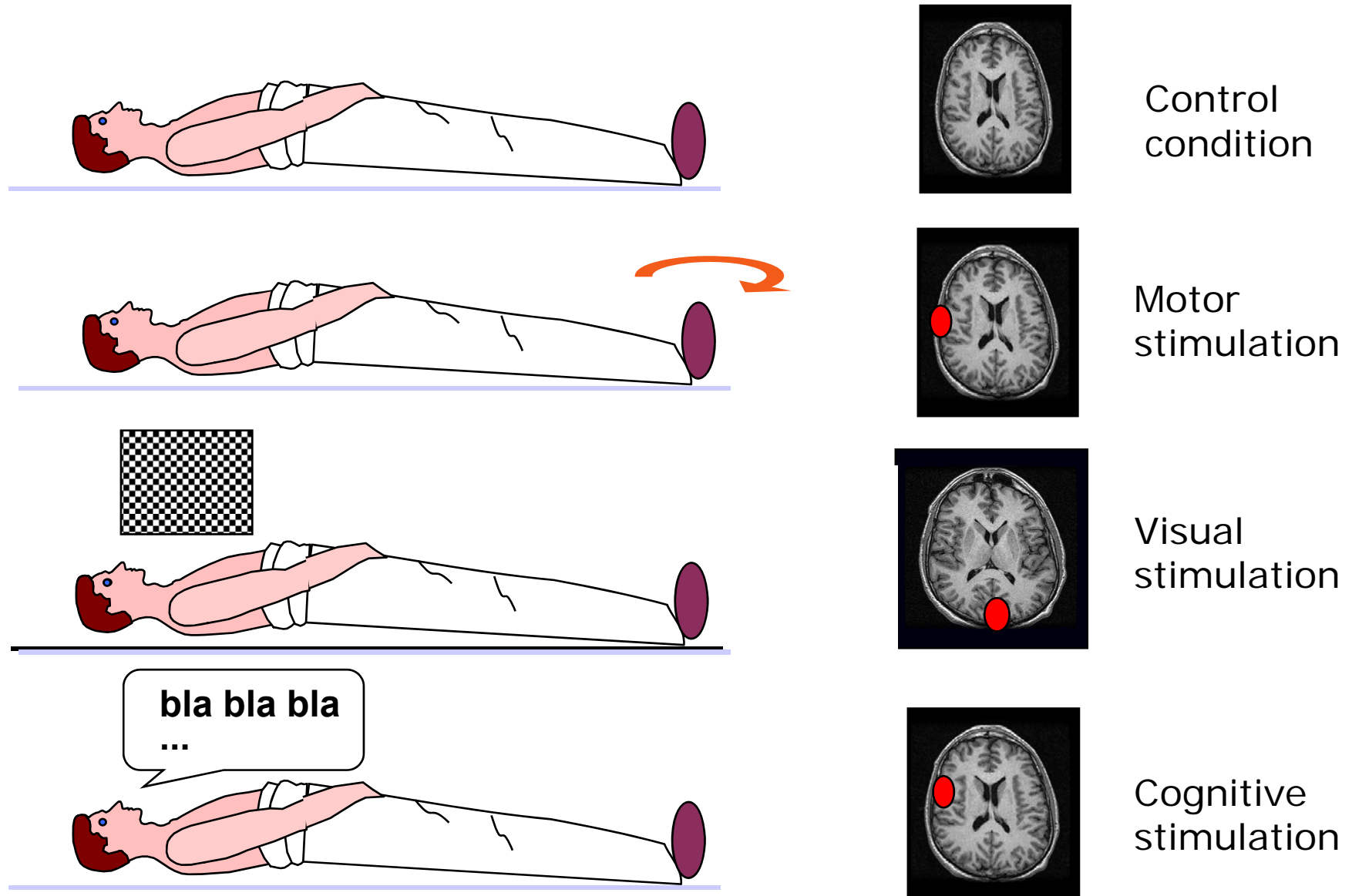


MRI of shoulder

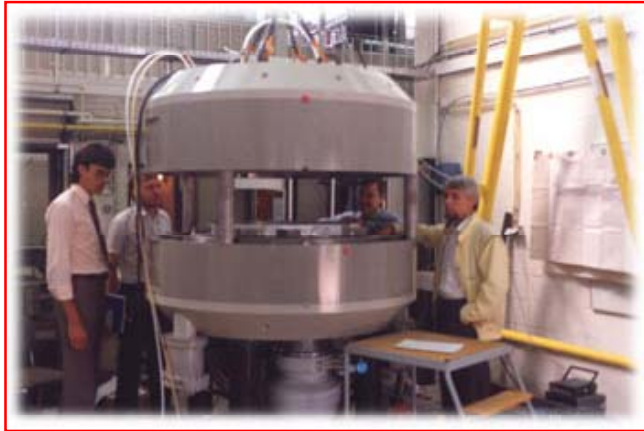


MRI of knee

Magnetic Resonance Imaging (MRI): activation studies



Positron Emission Tomography (PET)

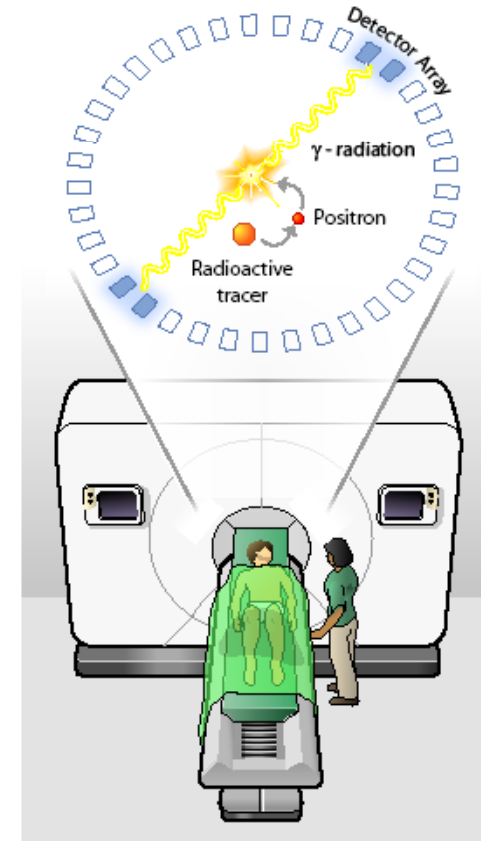


Cyclotron

ISOTOPES	Half-Life	
11-C	20.4 min,	"natural"
13-N	10.0 min	"natural"
15-O	2.0 min	"natural"
18-F	109.8 min	"pseudo-natural"

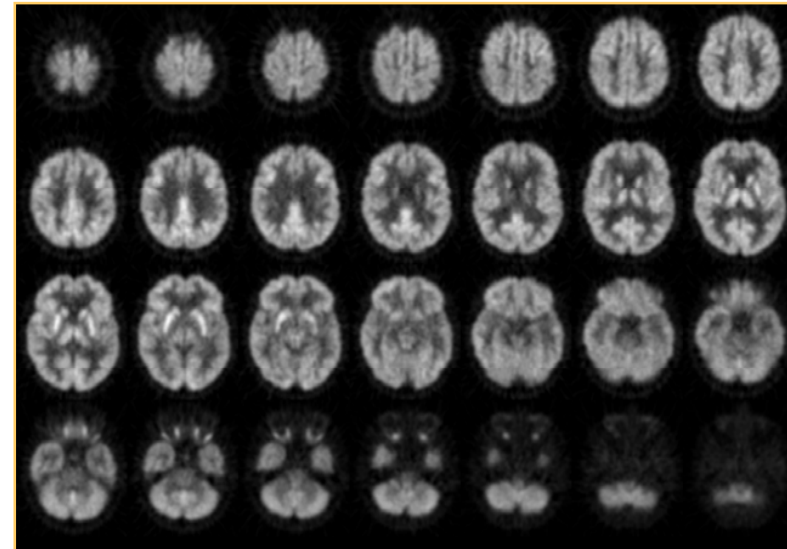
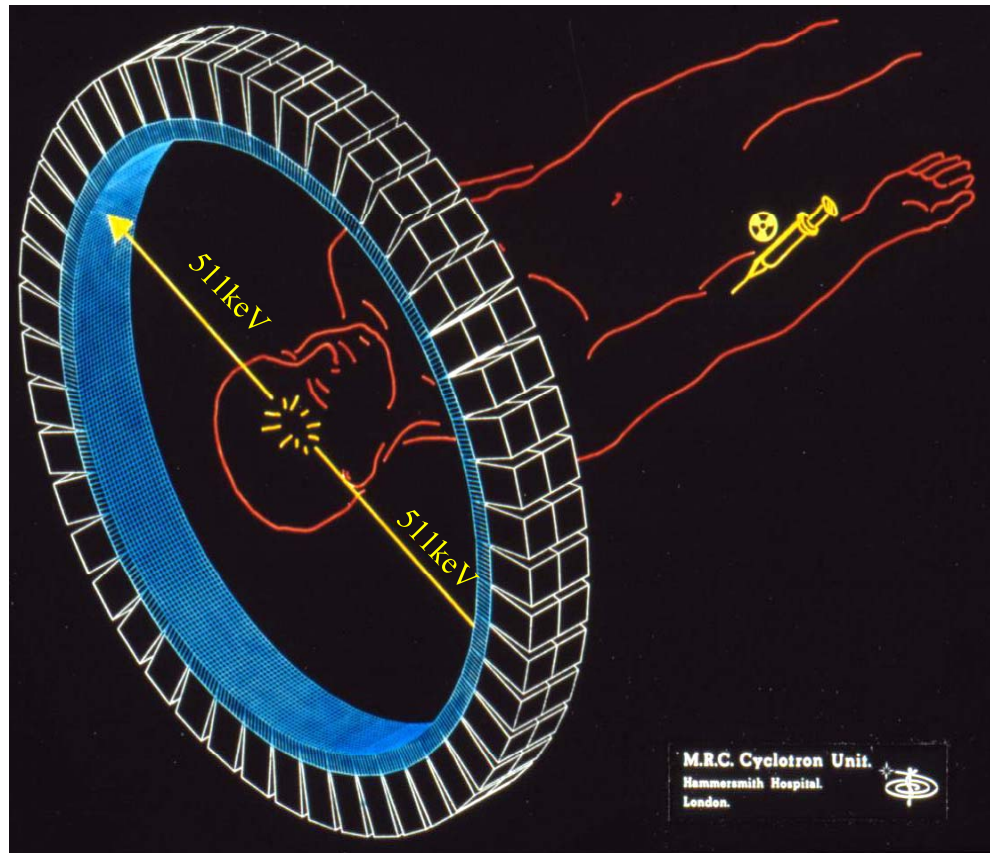


Radiochemistry



J. Long, "The Science Creative Quarterly", scq.ubc.ca

Positron Emission Tomography (PET)



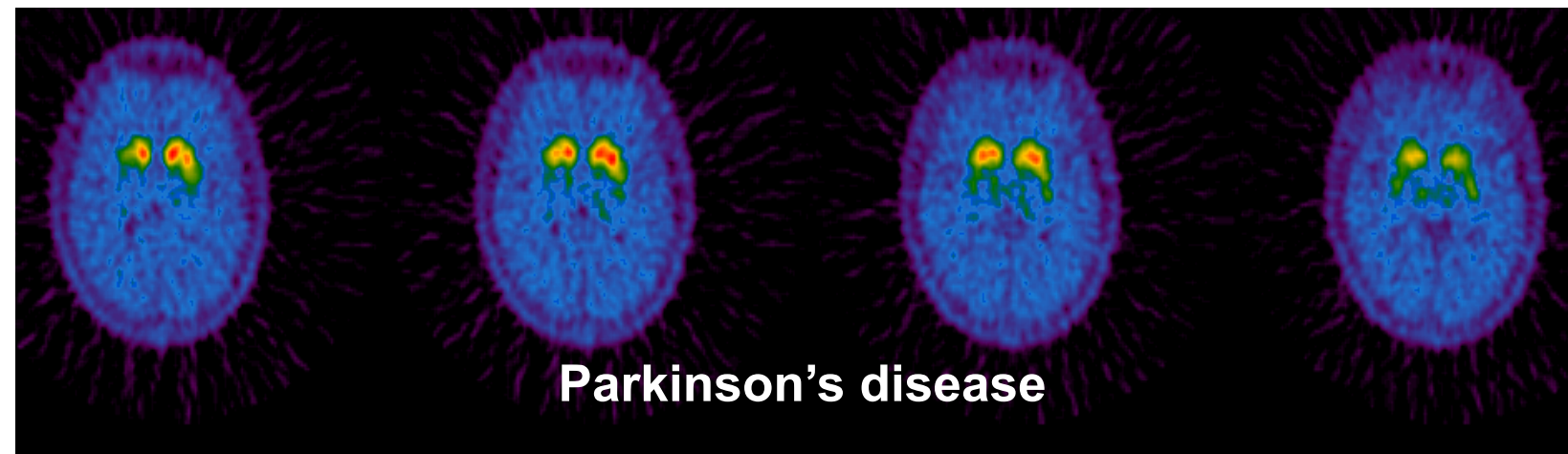
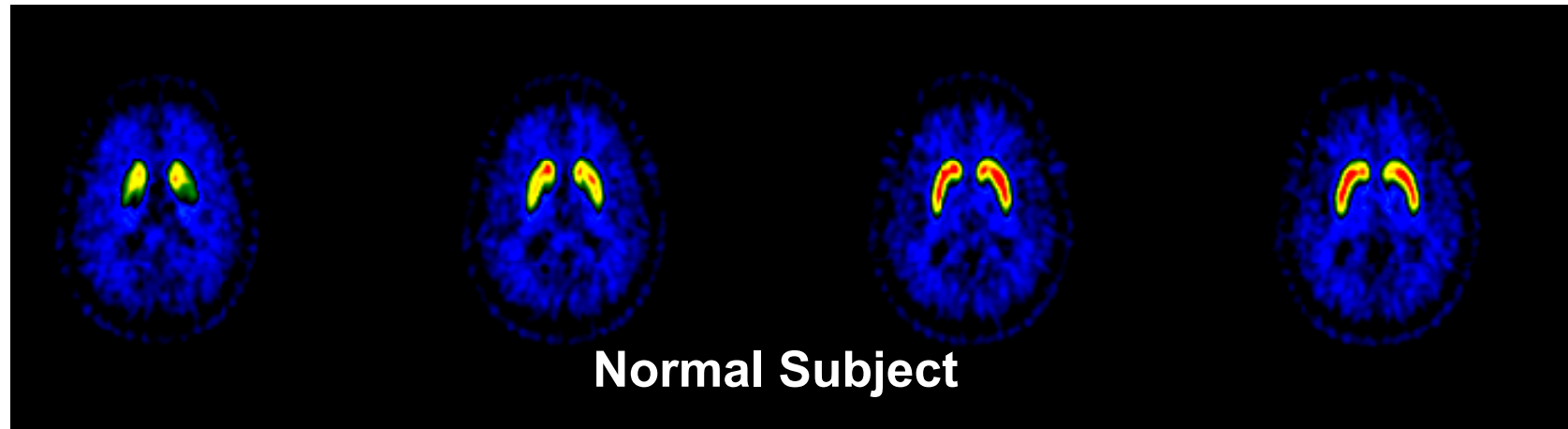
COVERAGE:
~ 15-20 cm

SPATIAL RESOLUTION:
~ 5 mm

SCAN TIME to cover an entire organ:
~ 5 min

CONTRAST RESOLUTION:
depends on the radiotracer

PET functional receptor imaging

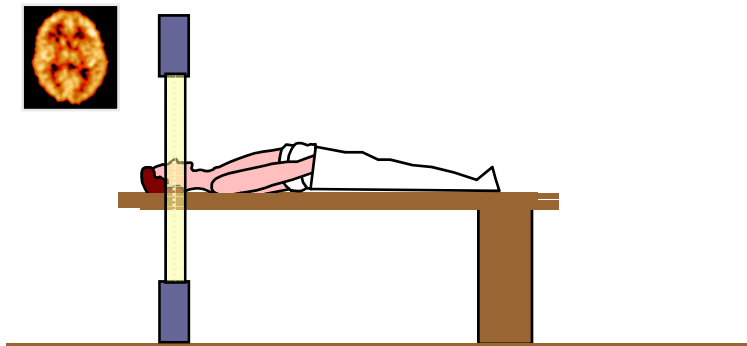


$[^{11}\text{C}]$ FE-CIT

Courtesy HSR MILANO

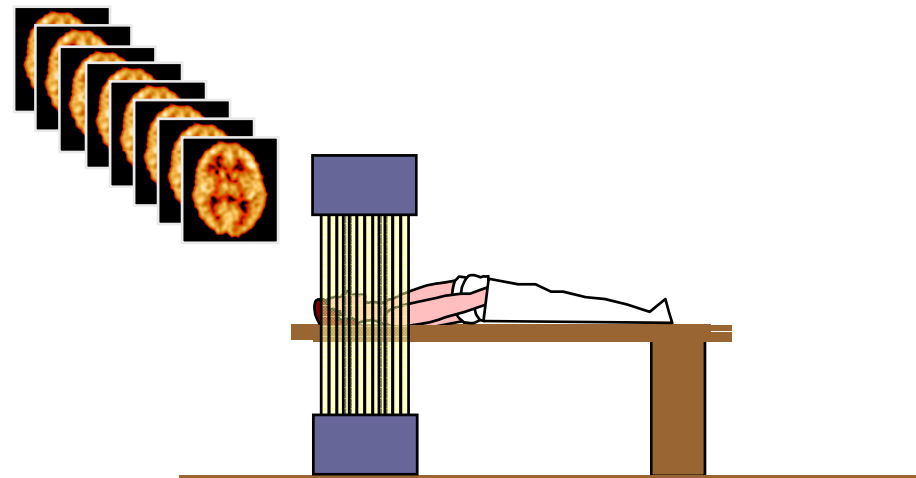
PET coverage and axial sampling

FIRST GENERATION PET



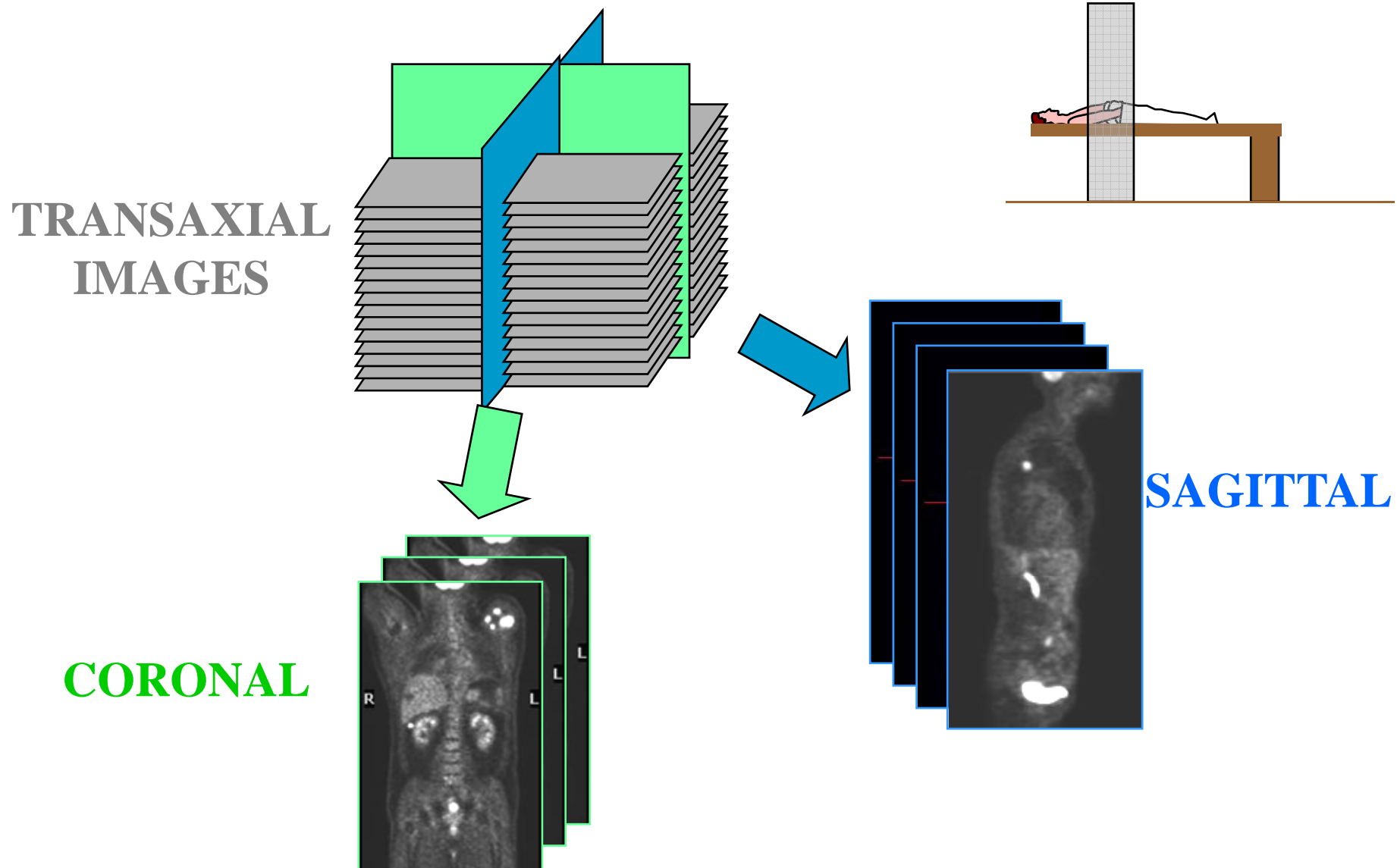
1 SLICE – 2 cm

CURRENT GENERATION PET

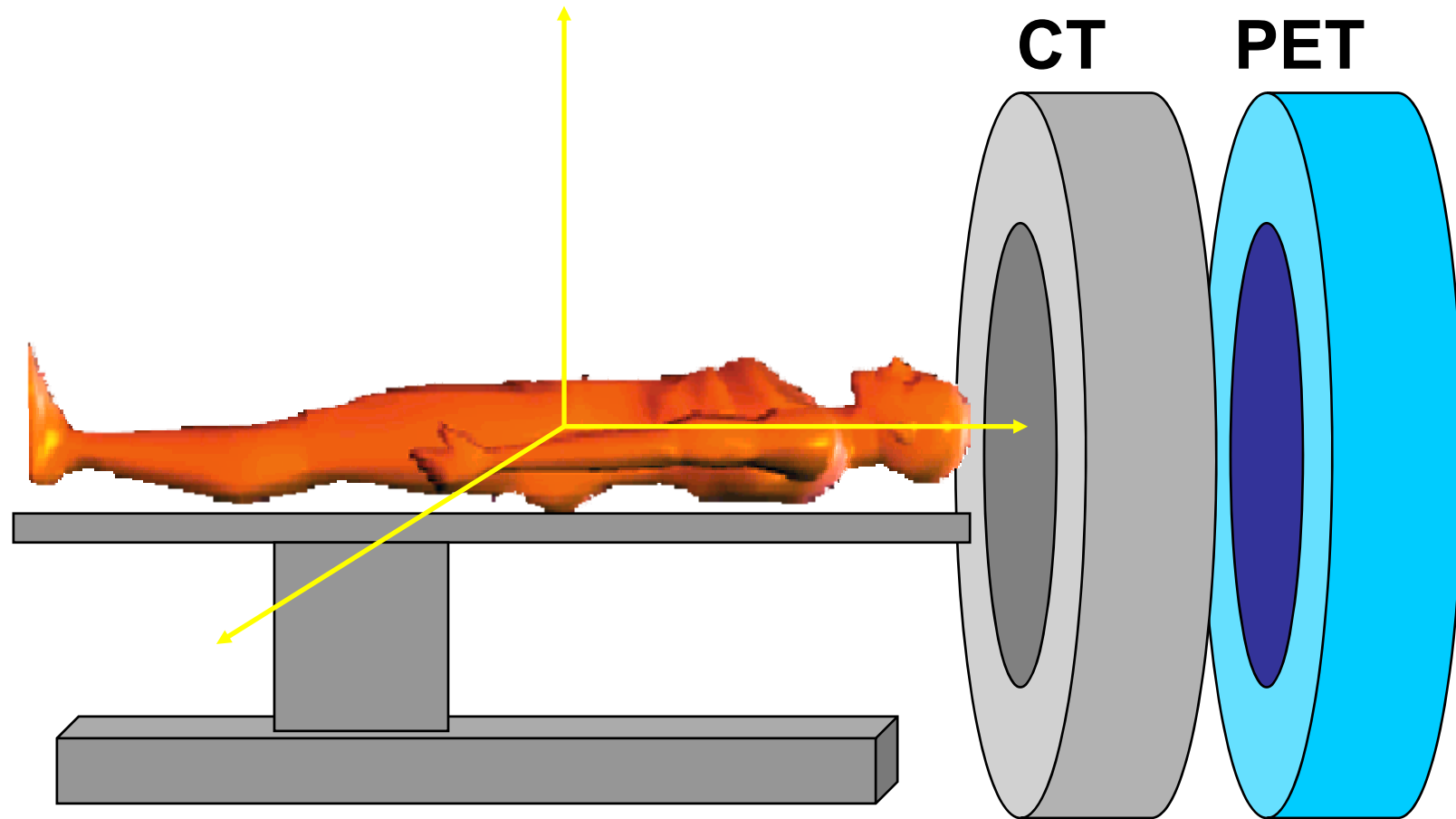


> 40 SLICES – 6 mm
Axial FOV: 15 –20 cm

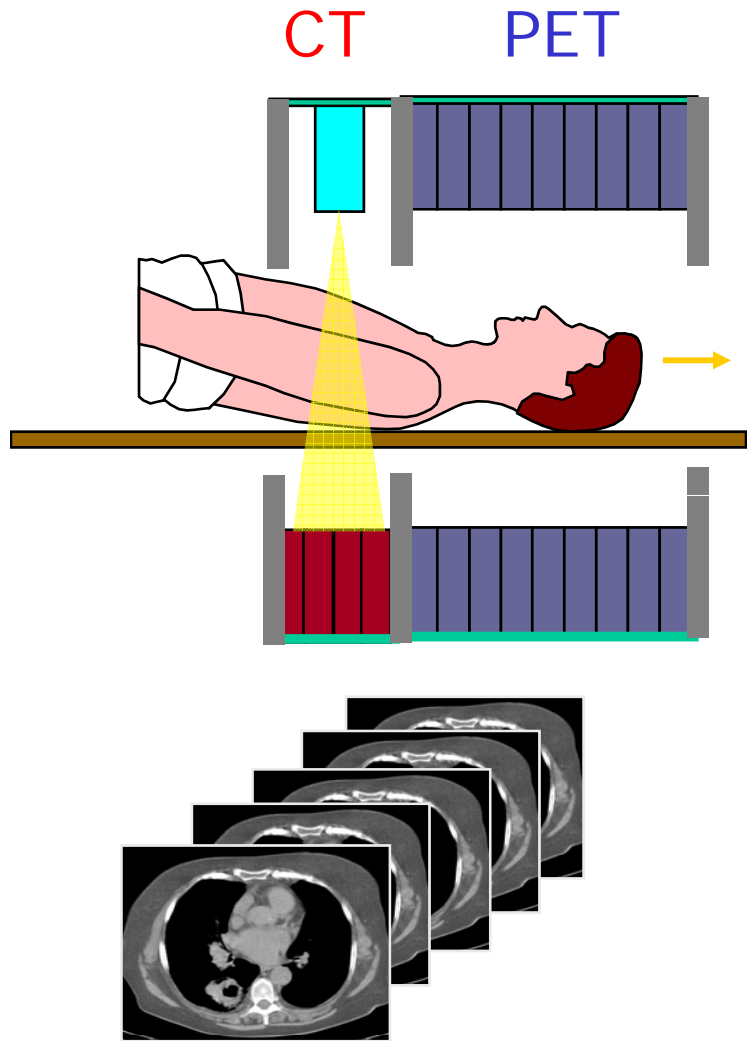
PET: total body studies



PET/CT scanner

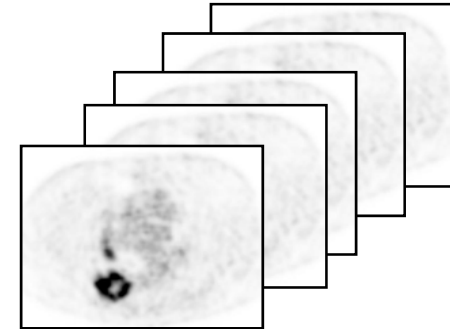
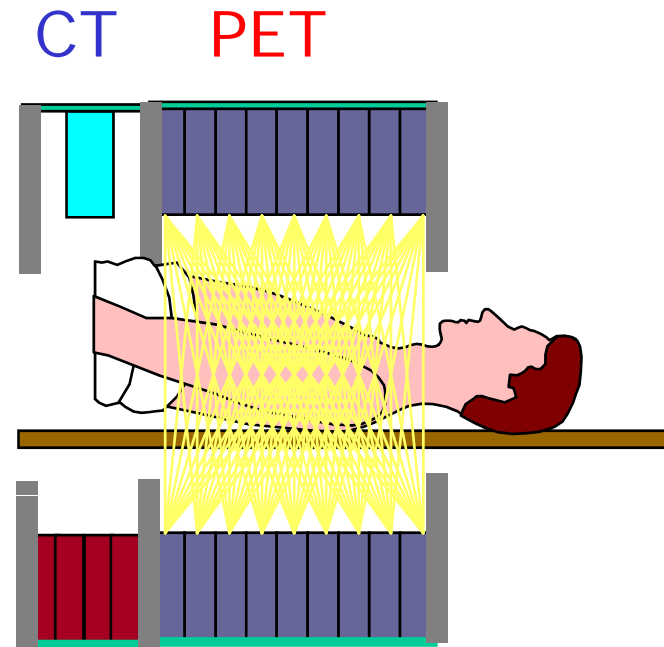
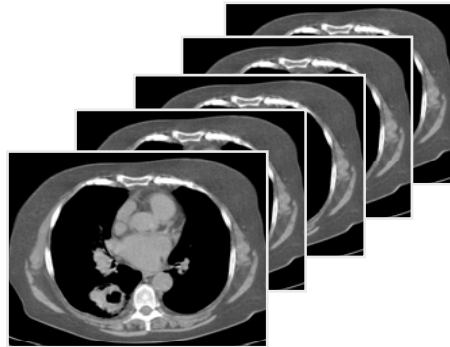
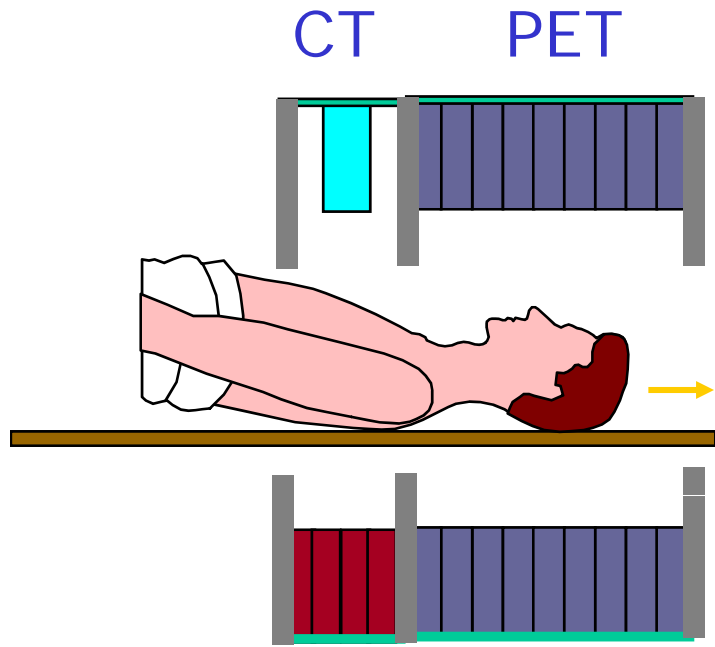


PET/CT scanner



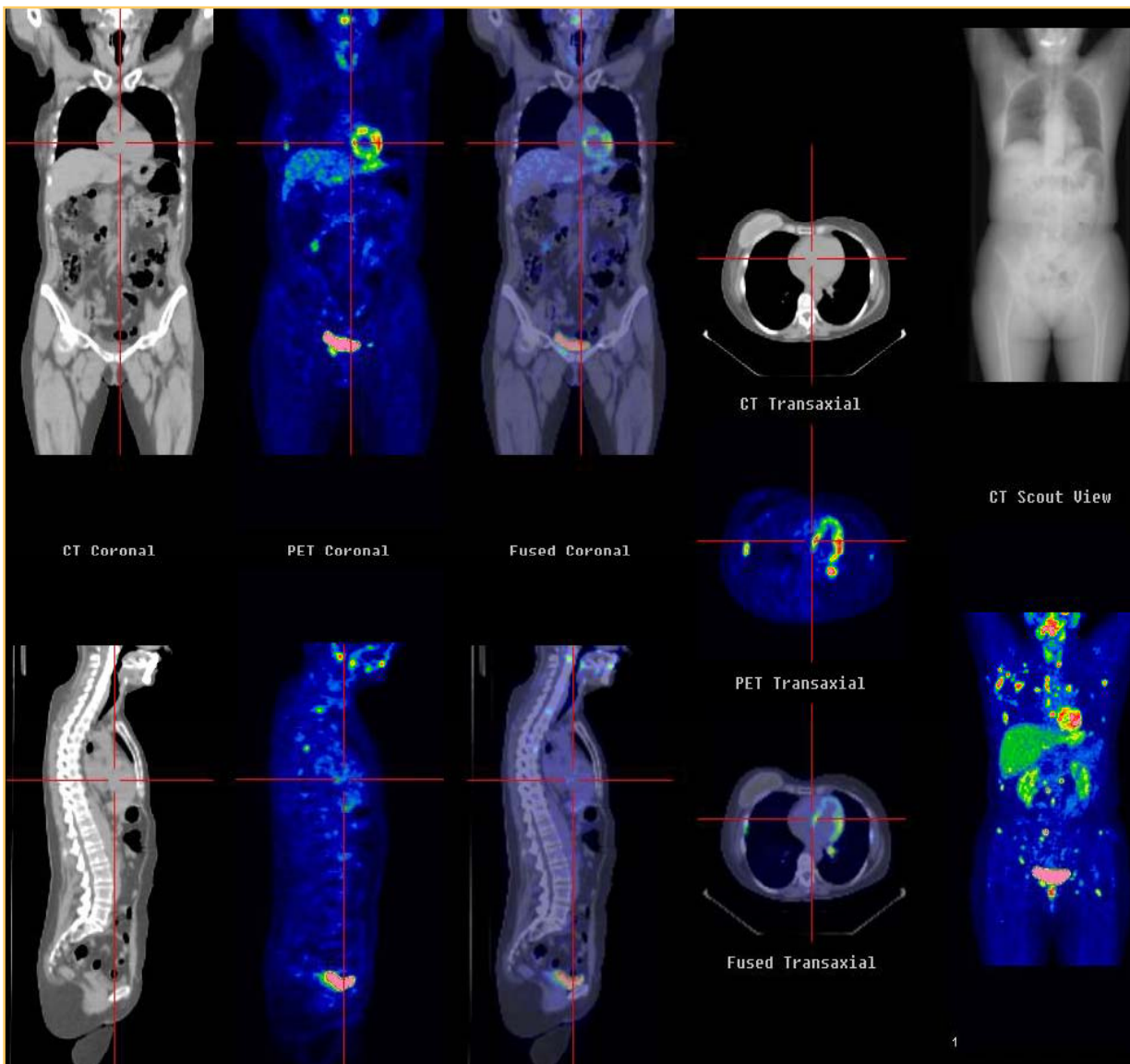
Courtesy HSR MILANO

PET/CT scanner



Courtesy HSR MILANO

^{18}F -FDG PET/CT



Courtesy HSR MILANO

Summary of accelerators running in the world

CATEGORY OF ACCELERATORS	NUMBER IN USE (*)
High Energy acc. ($E > 1\text{GeV}$)	~120
Synchrotron radiation sources	>100
Medical radioisotope production	~200
Radiotherapy accelerators	> 7500
Research acc. included biomedical research	~1000
Industrial processing and research	~1500
Ion implanters, surface modification	>7000
TOTAL	> 17500
(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004	

Three classes of medical accelerators

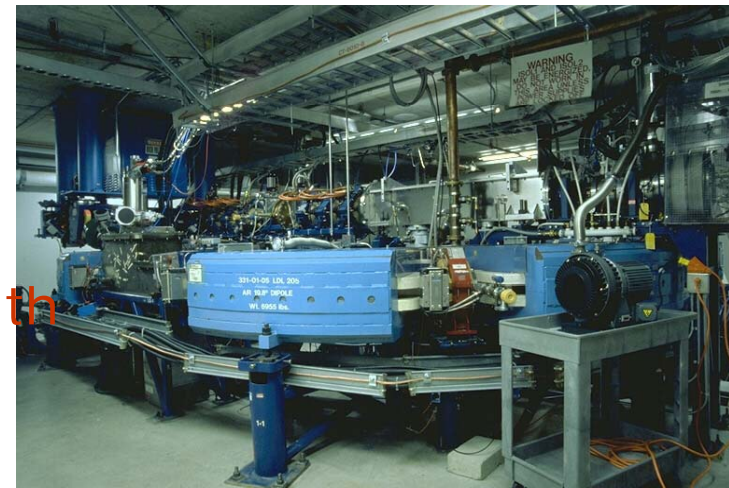
Electron linacs for conventional radiation therapy, including advanced modalities:

- Cyberknife
- IntraOperative RT (IORT)
- Intensity Modulated RT

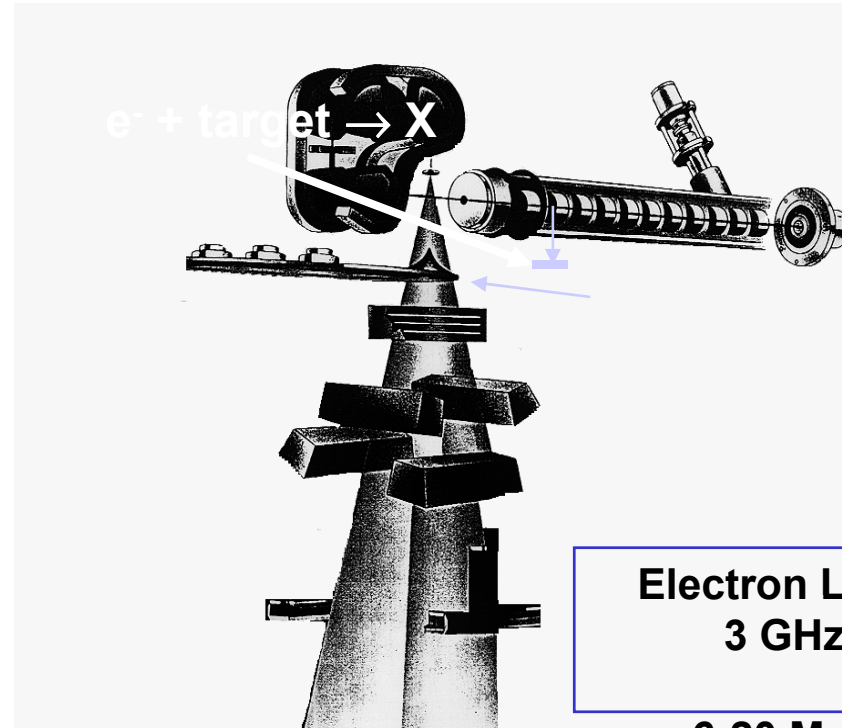


Low-energy cyclotrons for production of radionuclides for medical diagnostics

Medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u ^{12}C -ions)

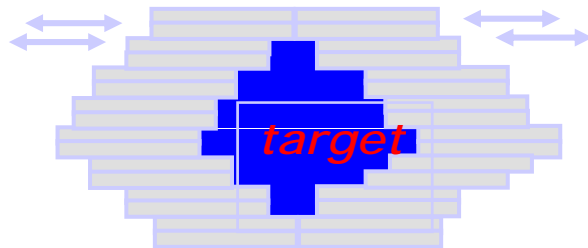


X-rays in radiation therapy: medical electron linacs

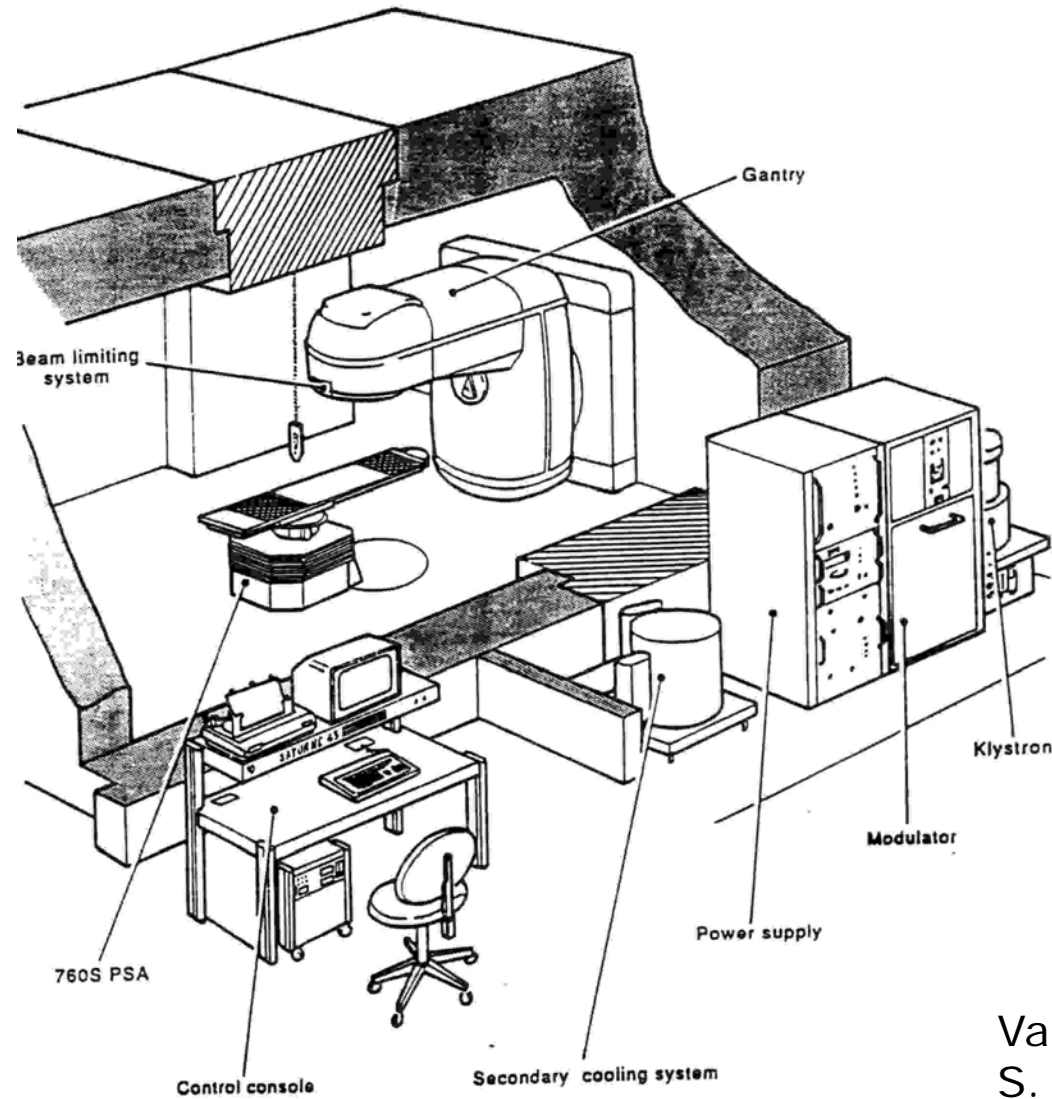


**Electron Linac
3 GHz**

**6-20 MeV
[1000 x Röntgen]**



Medical accelerators: electron linac



Varian Clinac 1800 installed in the S. Anna Hospital in Como (Italy)

CyberKnife (CK) Robotic Surgery System

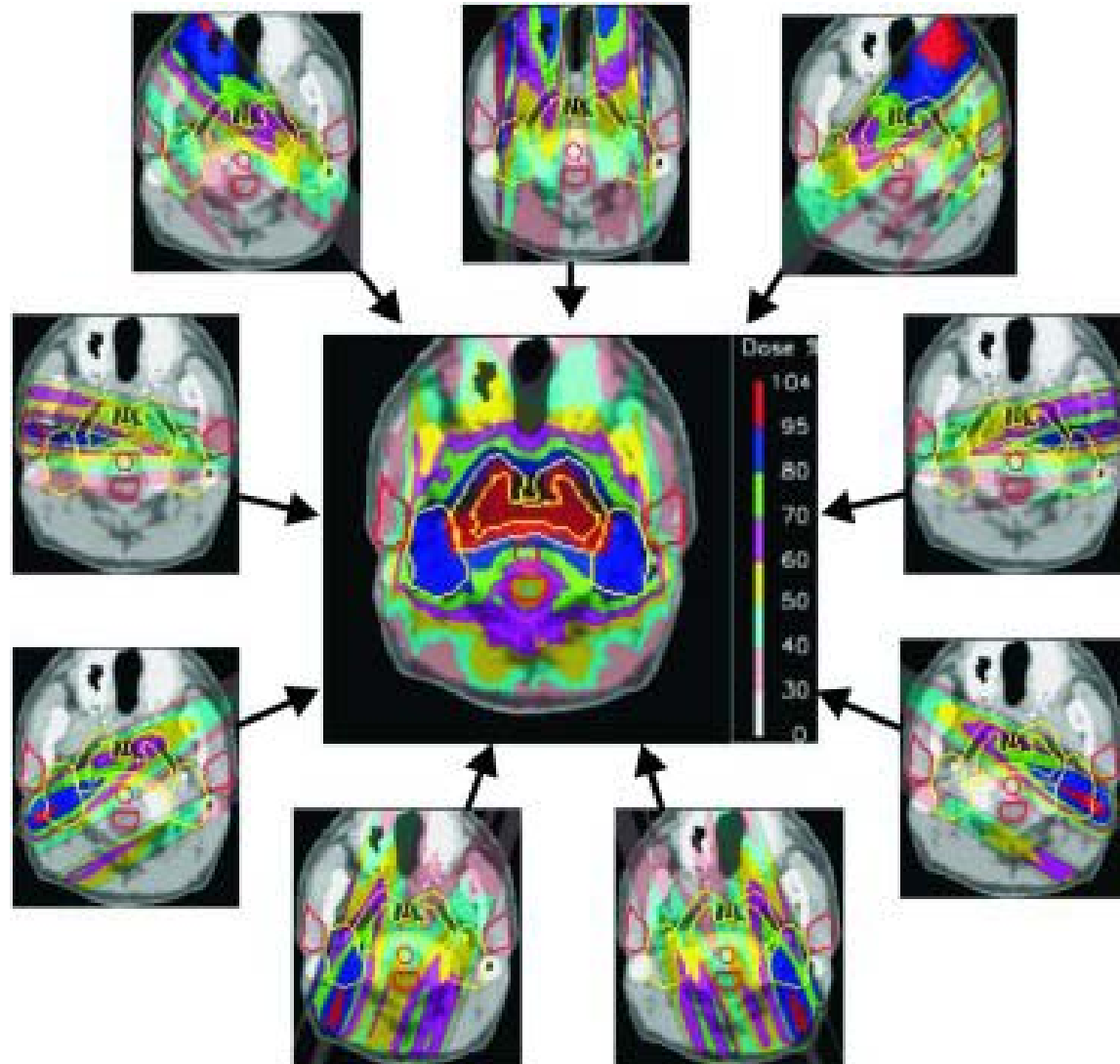
6 MV Linac mounted on a robotic arm



- No flattening filter
- Uses circular cones of diameter 0.5 to 6 cm
- Non-Isocentric
- Average dose delivered per session is 12.5 Gy
- 6 sessions/day
- Dose rate @ 80 cm = 400 cGy/min

<http://www accuray.com/Products/Cyberknife/index.aspx>

Intensity Modulated Radiation Therapy

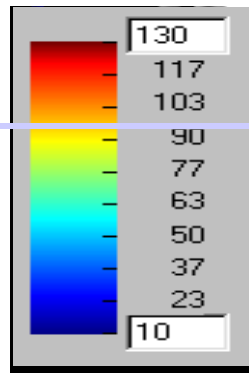
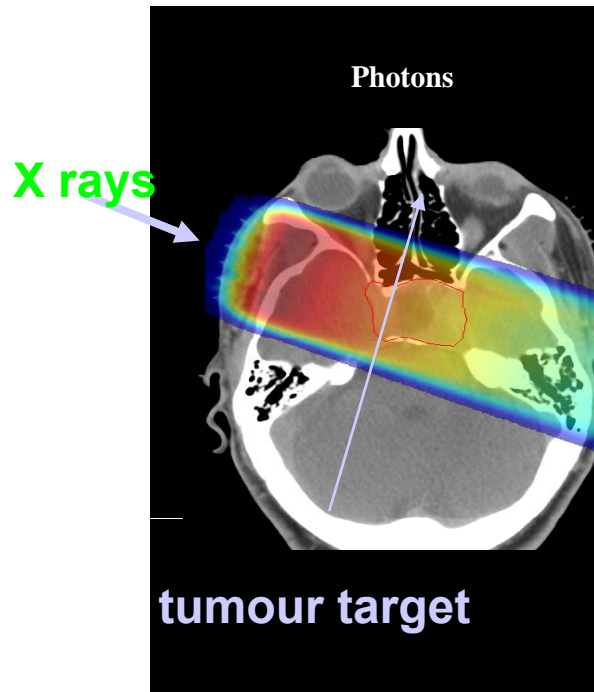


An example of intensity modulated treatment planning with photons. Through the addition of 9 fields it is possible to construct a highly conformal dose distribution with good dose sparing in the region of the brain stem (courtesy of T. Lomax, PSI).

E. Pedroni, Europhysics News (2000) Vol. 31 No. 6

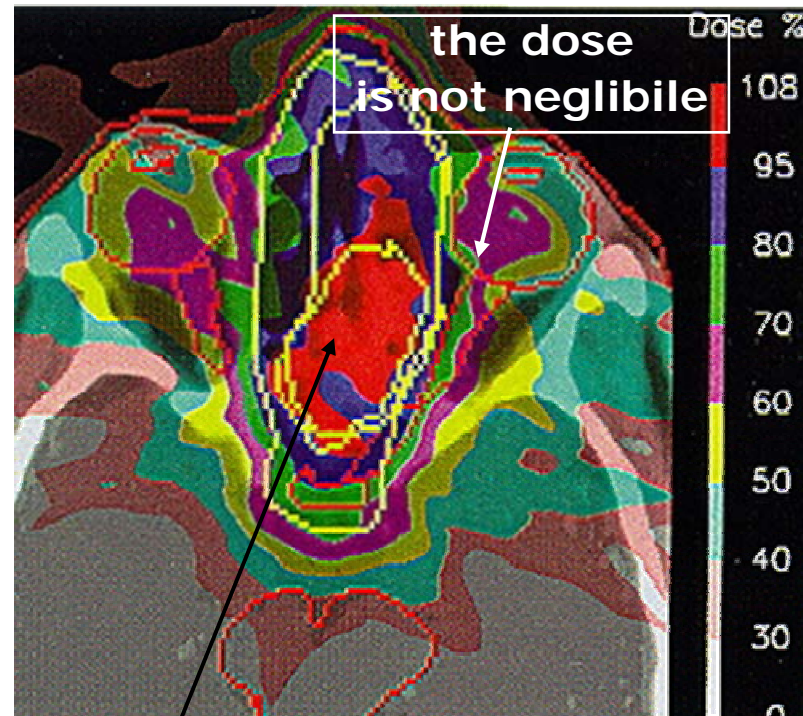
Intensity Modulated Radiation Therapy

Yet X-rays have a comparatively poor energy deposition



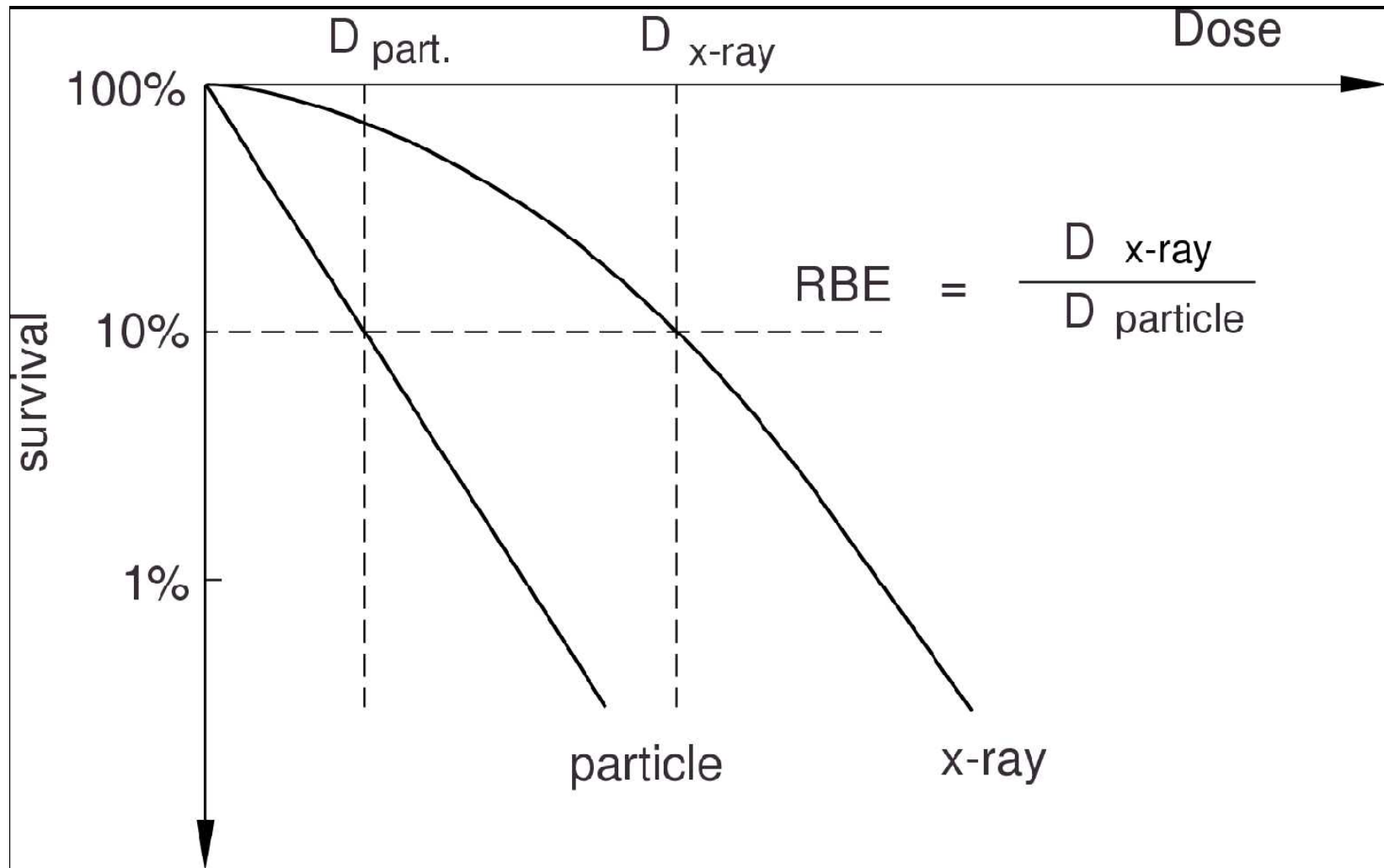
Fraction of dose

IMRT (Intensity Modulated Radiation Therapy) with 9 crossing beams

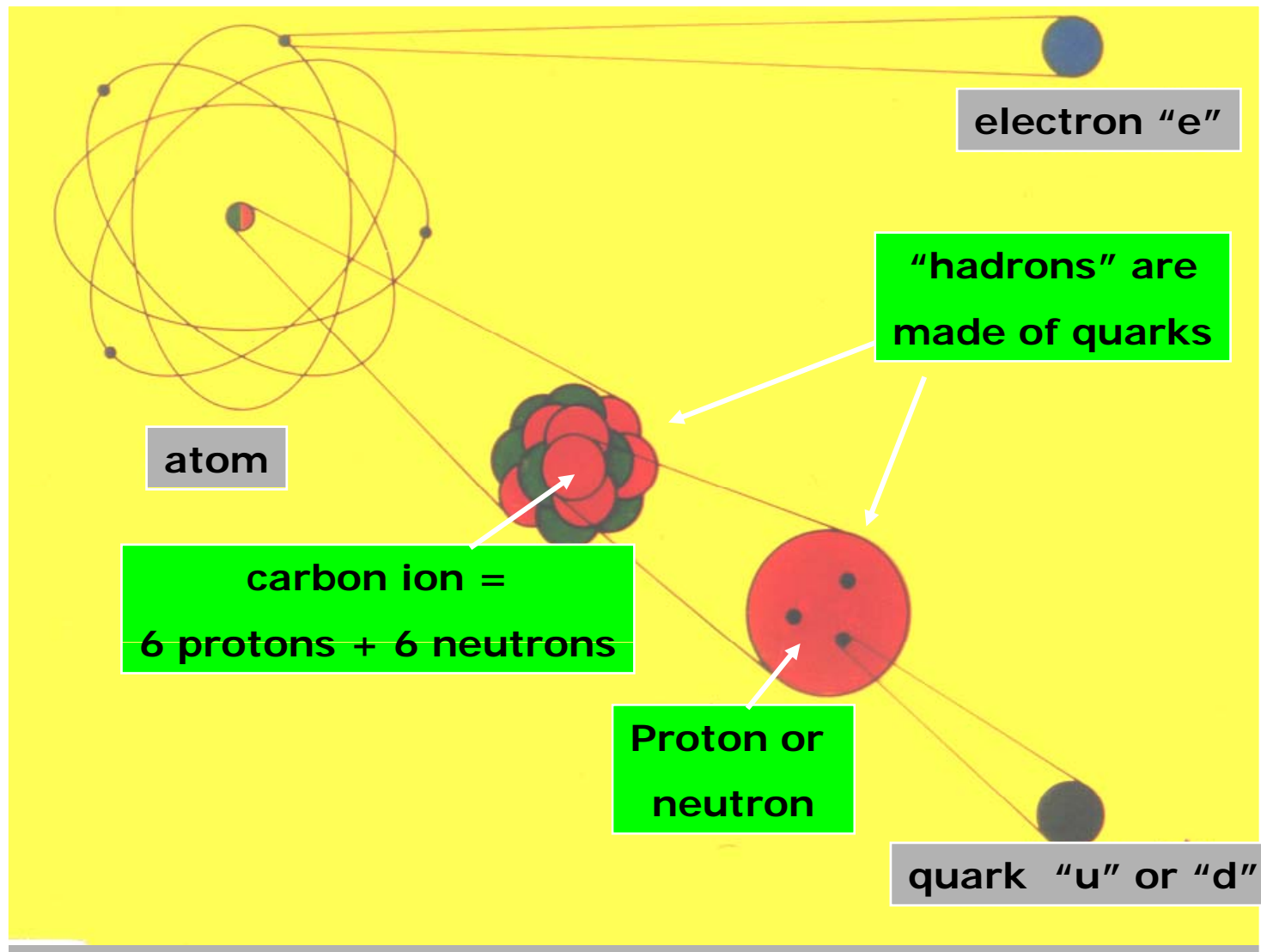


Tumour between the eyes

Radiobiological effectiveness (RBE)

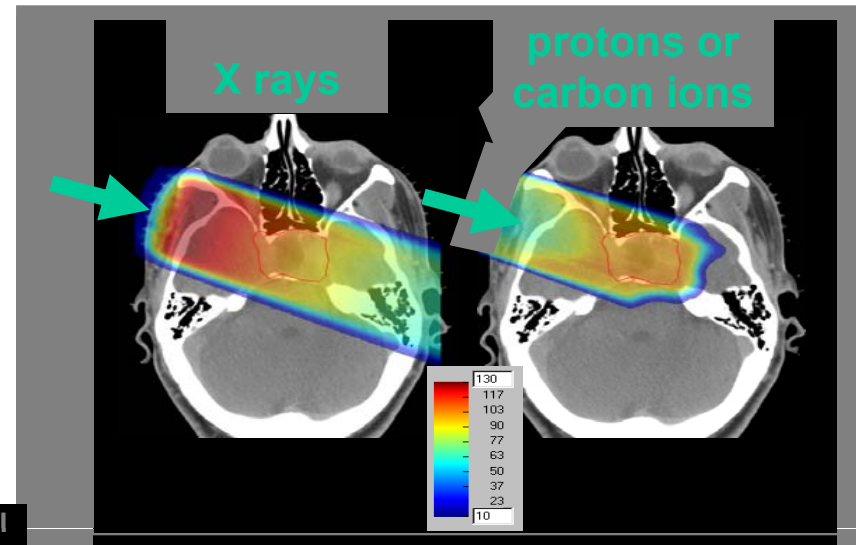
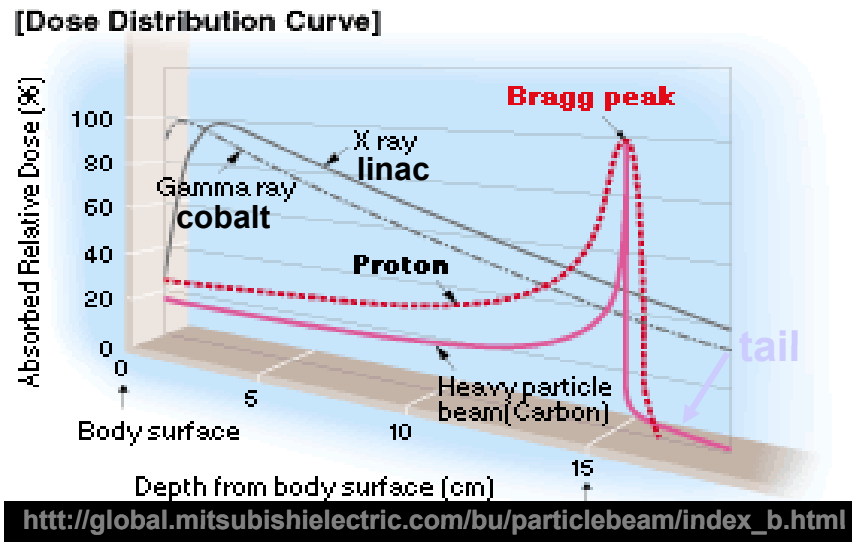
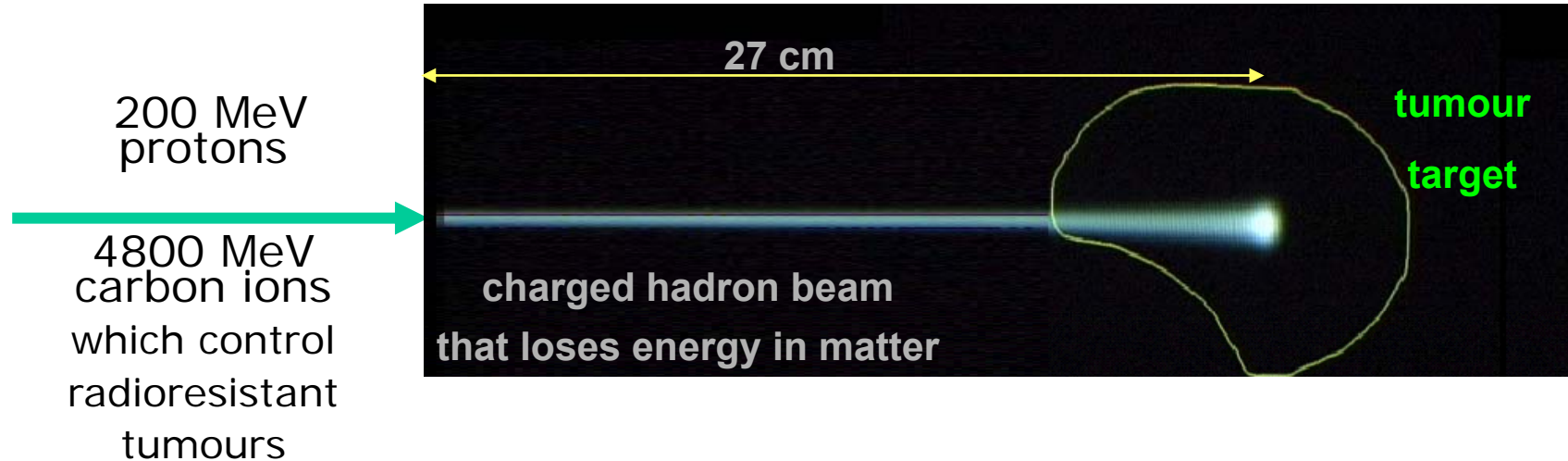


Hadrontherapy: n, p and C-ion beams

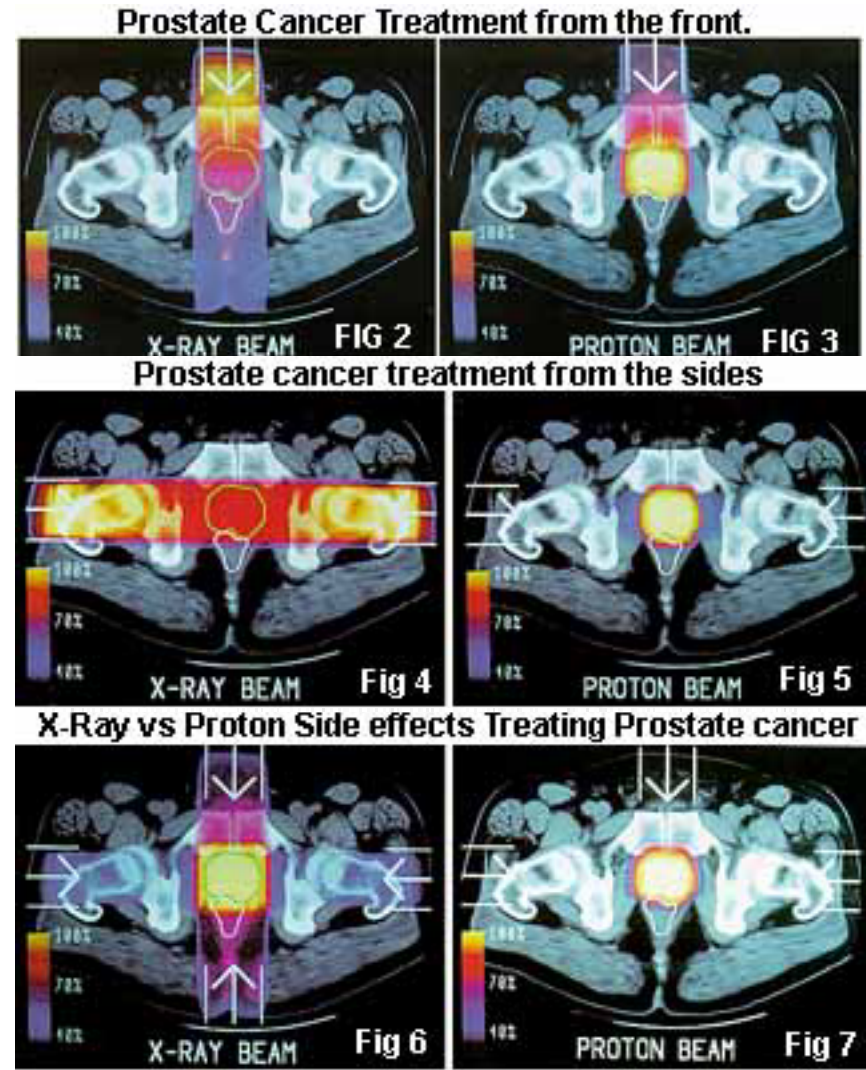
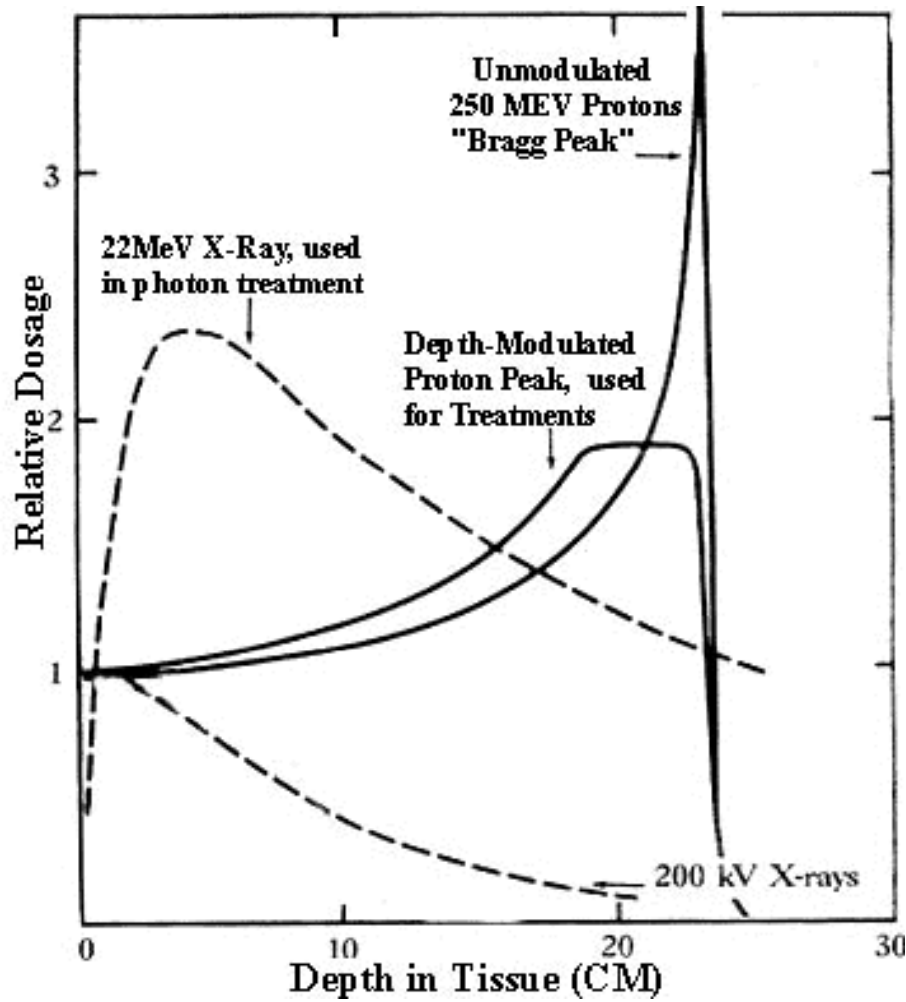


Hadrontherapy

Charged hadrons have a much better energy deposition with respect to X-rays



Proton radiation therapy



Loma Linda University Medical Center (LLUMC)

A NEW TOOL FOR CONTROLLING CANCER

The Loma Linda University Medical Center Proton Treatment Center is the first in the world to offer proton therapy, designed to treat cancerous tumors without harming surrounding healthy tissue. The center cost \$10 million, took four years to

design and build, and contains the world's smallest synchrotron built by Fermi National Accelerator Laboratory. It is as large as some hospitals, can serve up to 100 patients in a 10-hour day, and is a model for worldwide training and research.

HOW A PROTON BEAM WORKS

The beam enters the body at a low absorption rate and increases in intensity at a specific point, called the Bragg peak. A series of peaks are focused on the tumor, giving it the highest concentration of radiation, killing the cells of the tumor. Not only is the dose of radiation in normal tissue sharply reduced, compared to conventional radiation therapy, but the energy of the proton beam completely dissipates within the tumor, causing no damage to normal tissues beyond the tumor.

THE GANTRY

Three ganties resembling giant ferris wheels can rotate around the patient and direct the proton beam to a precise point. Each gantry weighs about 90 tons and stands three stories tall. The 15-foot-diameter ganties support the bending and focusing magnets to direct the beam, and have counterweights for extra radiation shielding.

STATIONARY BEAM

The stationary beam has two branches, one for irradiating eye tumors and the other for central nervous system tumors.

THE INJECTOR

Protons are stripped out of the nucleus of hydrogen atoms and sent to the accelerators.

SYNCHROTRON (ACCELERATOR)

The synchrotron is a ring of magnets, about 20 feet in diameter, through which protons circulate in a vacuum tube. As the magnetic field in the ring is increased, the energy of the protons is also increased. When the magnetic field reaches the value corresponding to a prescribed beam energy, the field is held constant while protons are slowly extracted from the ring. The system accelerates protons to a minimum energy (20 million electron volts) in one-quarter second and to maximum energy (250 million electron volts) in one-half second.

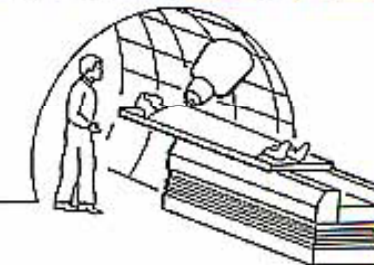
Steel-reinforced concrete walls are up to 15 feet thick.

BEAM TRANSPORT SYSTEM

The Beam Transport System carries the beam from the accelerator to one of four treatment rooms. This system consists of several bending and focusing magnets which guide the beam around corners and focus it to the desired spot size and location within the vacuum tube. The system monitors the size, position, and intensity of the beam at many points. Variations from the prescribed parameters send messages through the computer network to adjust the beam or to trip interlocks which automatically shut it off.

WHAT THE PATIENT SEES

The patient rests on a couch or sits in a chair, as appropriate for treatment. Alignment and verification of the patient to the beam, controlled from a room just outside the treatment room, will take most of the time; actual beam time takes less than a minute. Most patients will be able to return to work or other activities immediately after the procedure.



Loma Linda University Medical Center (LLUMC)

CER
 This is the world's smallest synchrotron...
 Laboratory. It is as large as...
 to 100 patients in a 10-hour day...
 for training and research.

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PORT SYSTEM
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 to focus it to the desired spot...
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 computer network to adjust the...
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WHAT
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 or other...
 procedur...



Acknowledgements

I am indebted to Ugo Amaldi (TERA Foundation and University of Milano Bicocca, Italy) and Maria Carla Gilardi (University of Milano Bicocca, Italy) for providing me with many of the slides that I have shown you today.

I also wish to thank David Bartlett (formerly Health Protection Agency, UK) for pointing me to the very interesting book shown on slide 14.