Introduction to Medical Physics

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

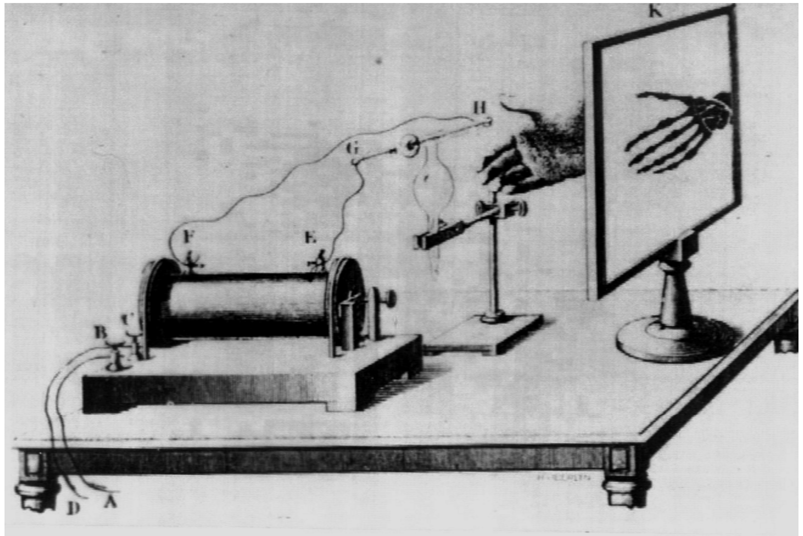
or, in other words

The application of physics techniques to the human health

Marco Silari, CERN

- 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



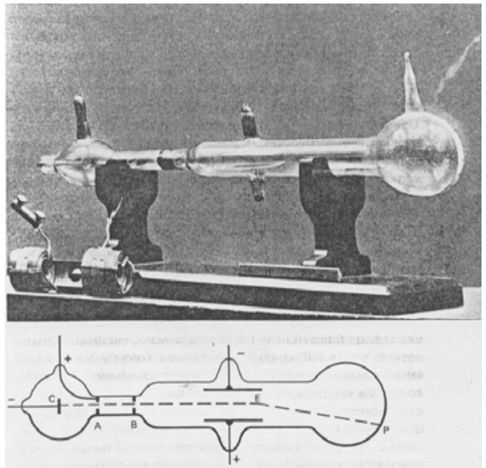
1895
discovery of X rays

Wilhelm Conrad Röntgen

J.J. Thompson

1897

“discovery” of the electron

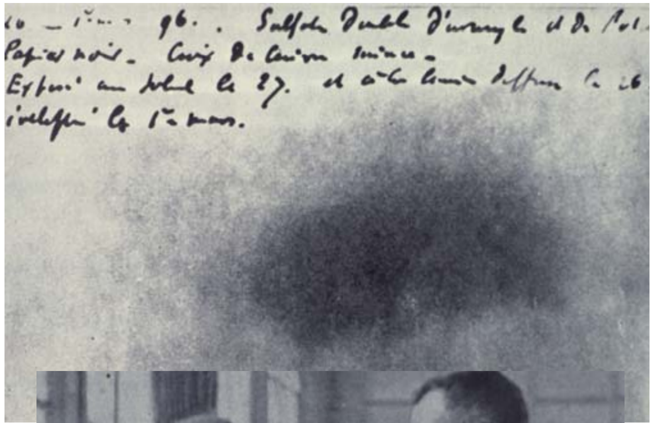


The beginnings of modern physics and of medical physics

Henri Becquerel
(1852-1908)

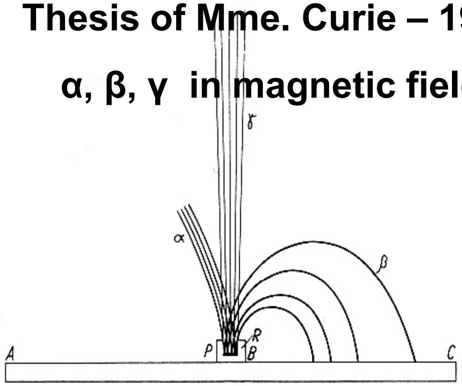
1896:

Discovery of natural radioactivity



Thesis of Mme. Curie – 1904

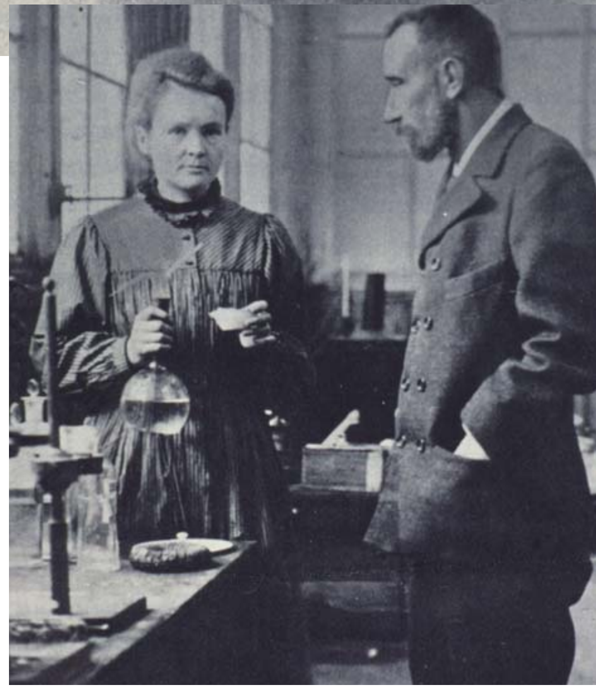
α, β, γ in magnetic field



Hundred years ago

1898

Discovery of polonium and radium

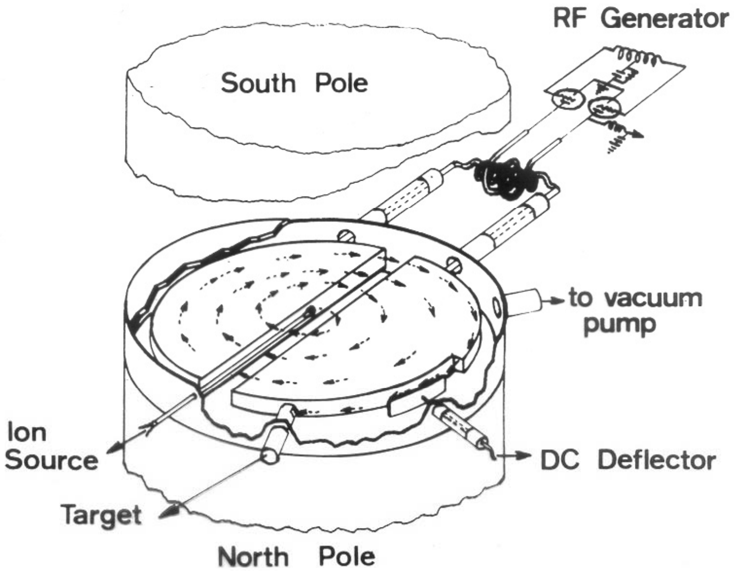


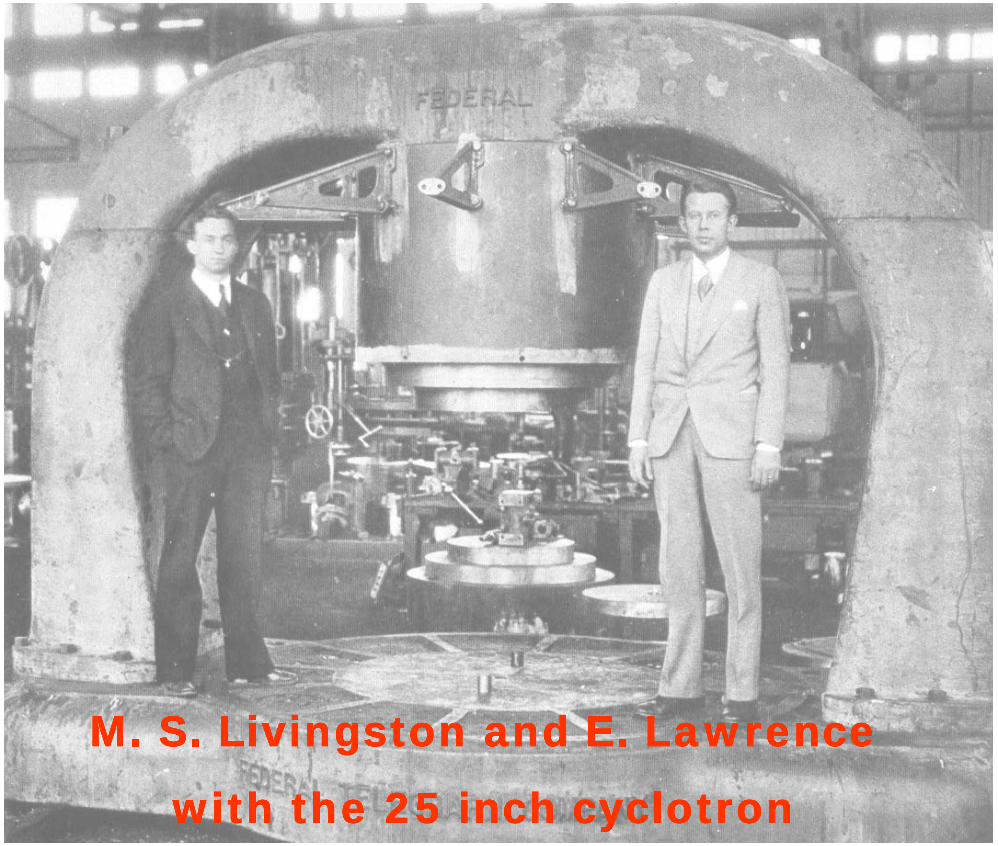
Marie Curie (1867 – 1934) **Pierre Curie (1859 – 1906)**

Tools for (medical) physics: the cyclotron

1930

Ernest Lawrence invents the cyclotron





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

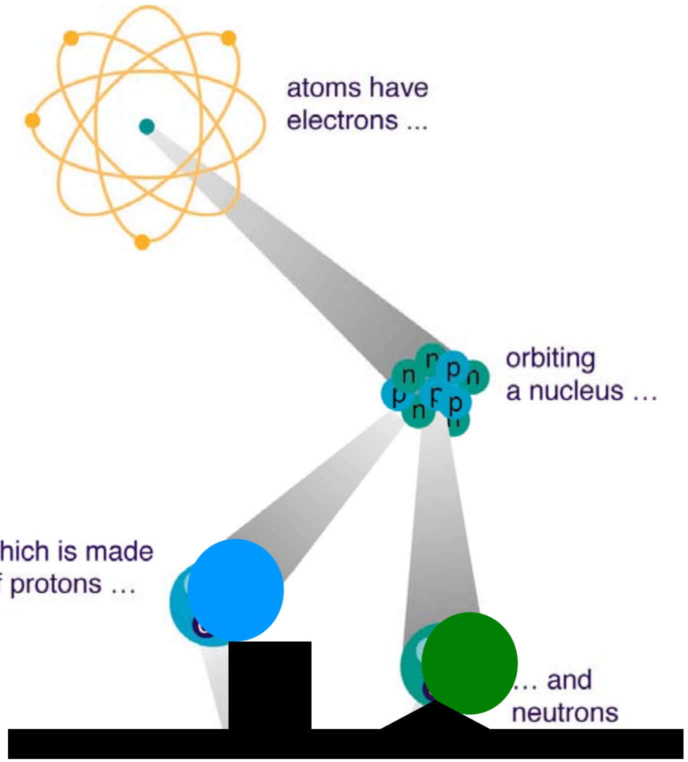
The beginnings of modern physics and of medical physics

James Chadwick

(1891 – 1974)

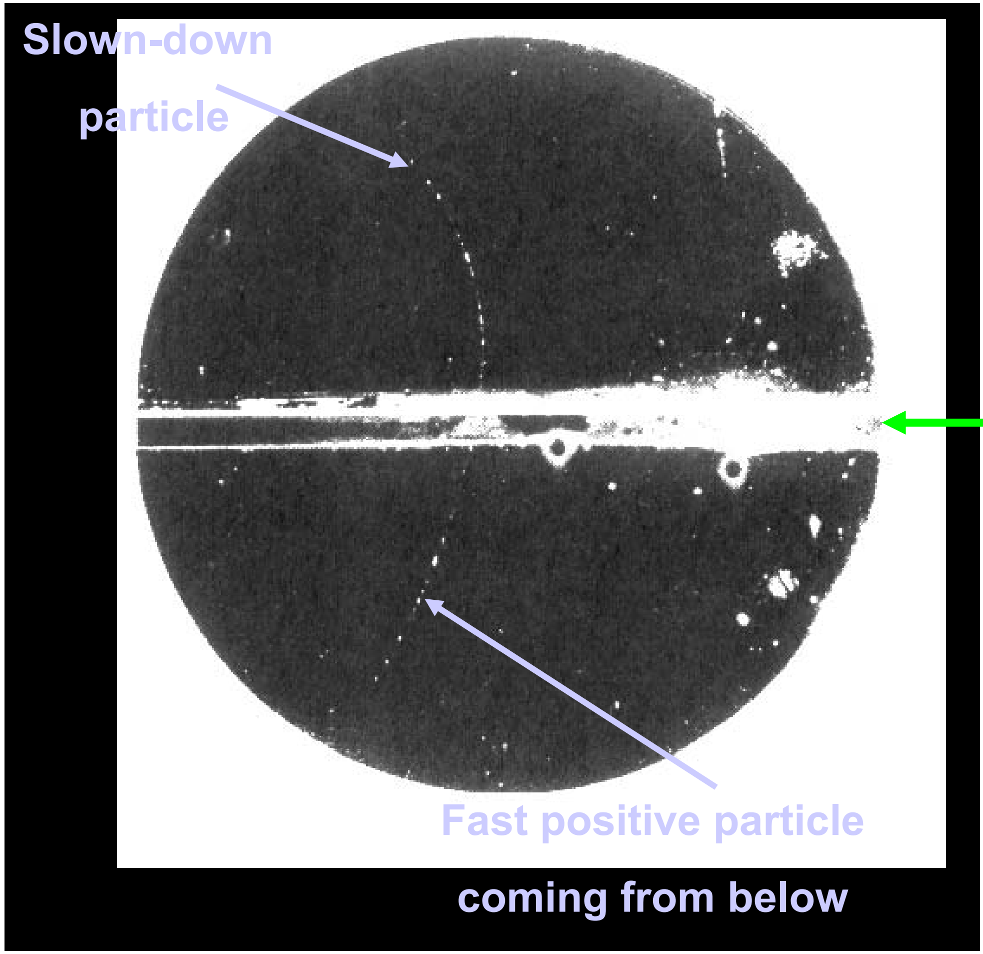
1932

Discovery of the neutron



1932 – C. D. Anderson

Discovery of the positron



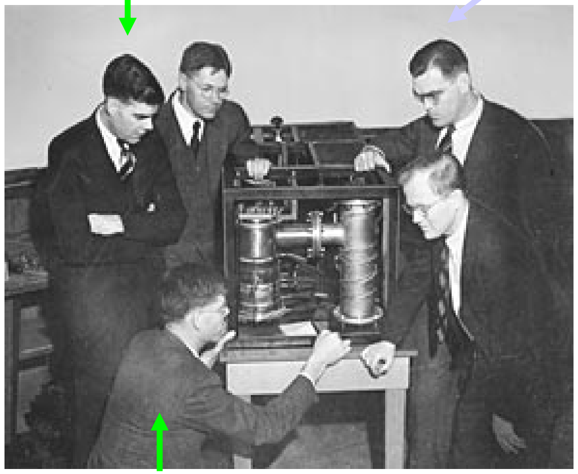
Layer of lead

Inserted in a cloud chamber

Tools for (medical) physics: the electron linac

Sigmur Varian

William W. Hansen



Russell Varian

1939

Invention of the klystron

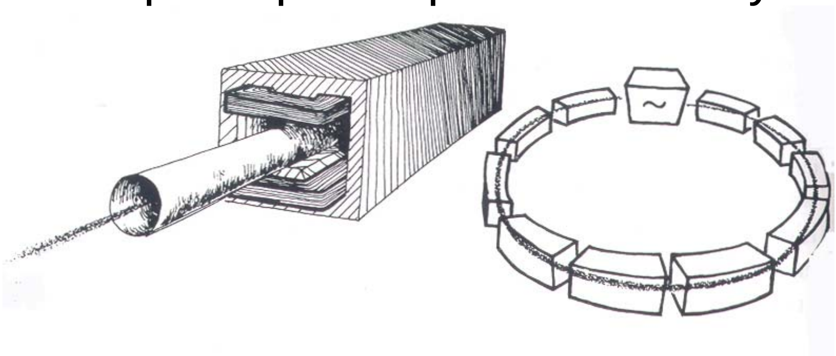
1947
first linac for electrons
4.5 MeV and 3 GHz

Tools for (medical) physics: the synchrotron

1945: E. McMillan and V.J.Veksler

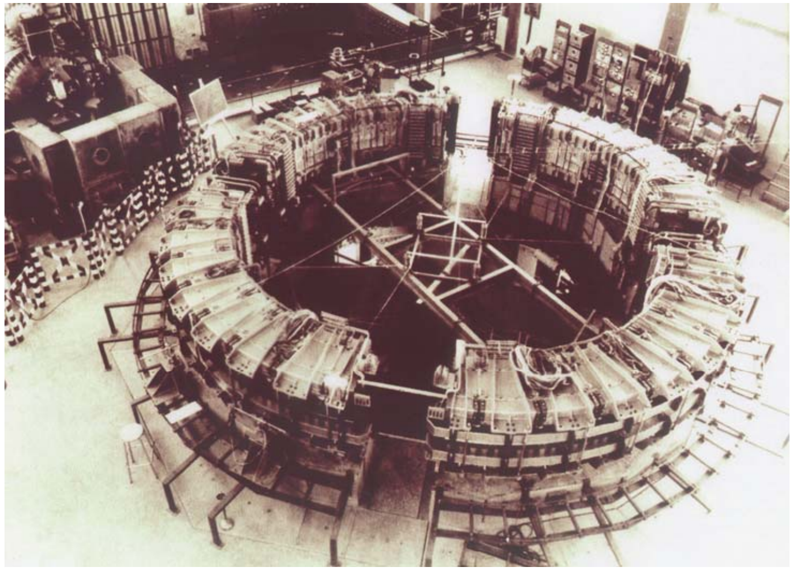
discover the

principle of phase stability



1 GeV electron synchrotron

Frascati - INFN - 1959

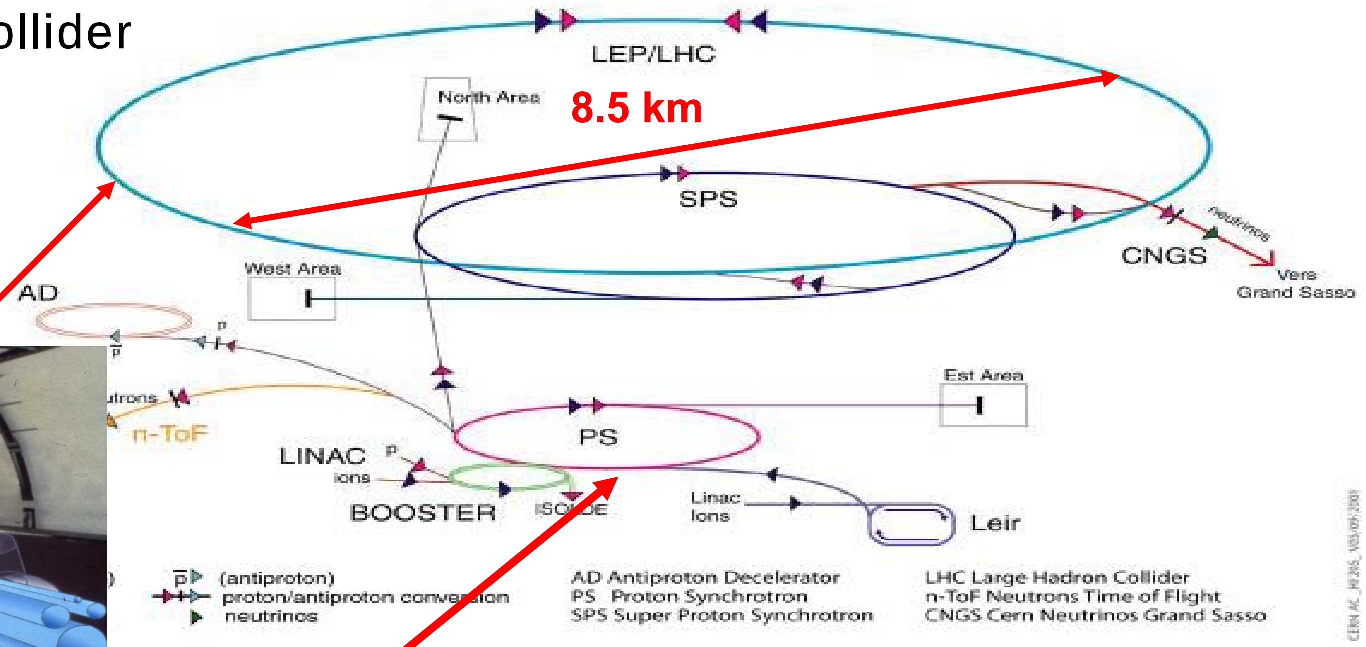


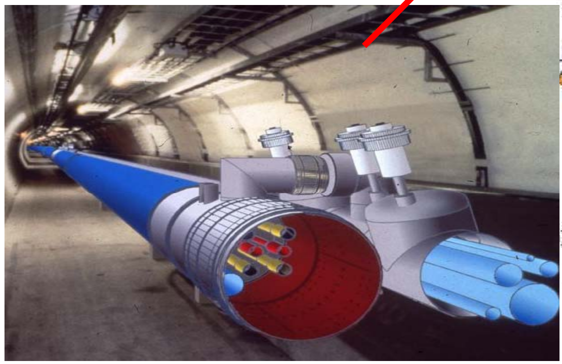
6 GeV proton synchrotron

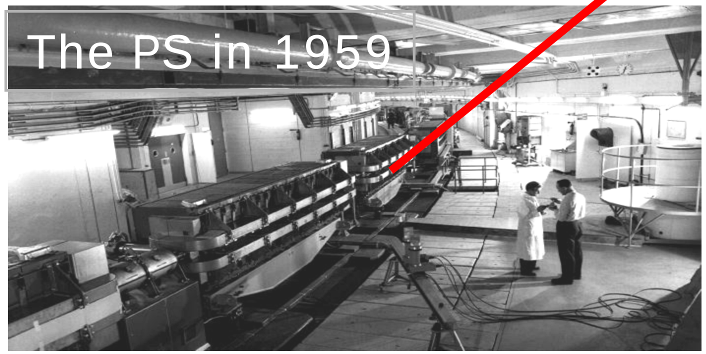
Bevatron - Berkeley - 1954

CERN accelerators

Large Hadron Collider
7 TeV + 7 TeV
Start in 2008





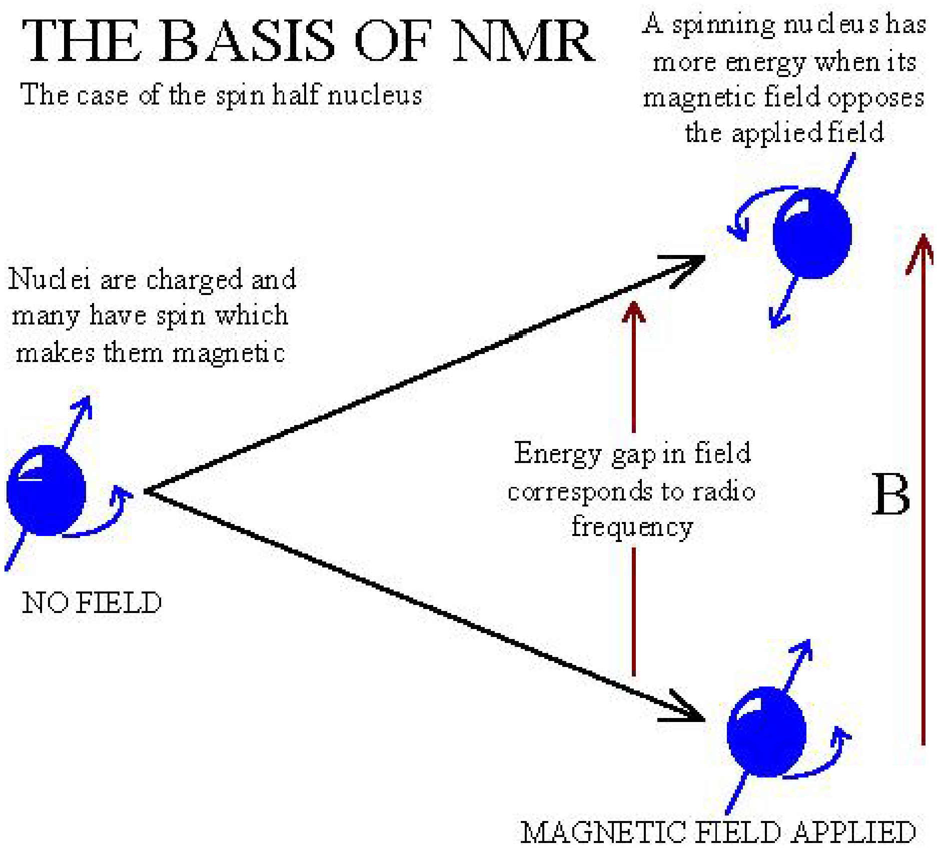

The PS in 1959

In 1952 the “strong-focusing” method

invented at BNL (USA)

was chosen for the CERN PS

Tools for (medical) physics: Nuclear Magnetic Resonance

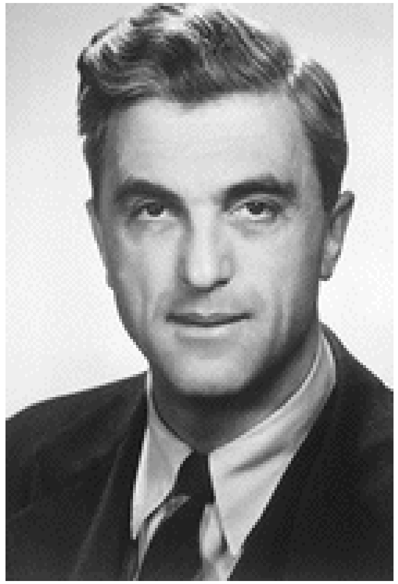


1938-1945

Felix Bloch and Edward Purcell

discover and study

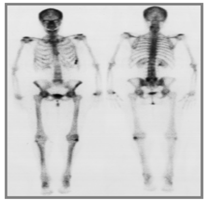
NMR



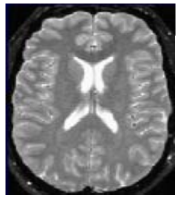
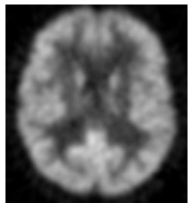
In 1954 Felix Bloch became

the first CERN Director General

Medical imaging

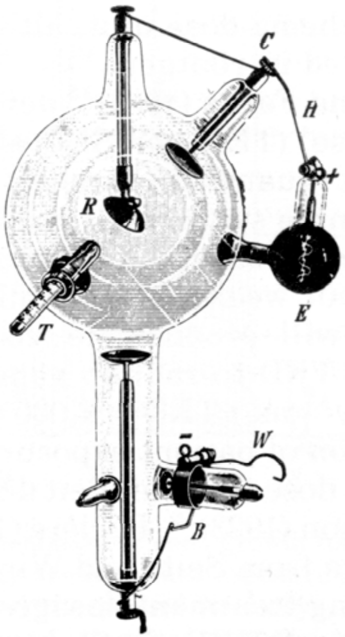
TECHNIQUE		YEAR	ENERGY	PHYSICAL PROPERTY	IMAGING
RADIOLOGY	X RAYS IMAGING	**1895**	X RAYS	ABSORPTION	
ECHOGRAPHY	ULTRASOUND IMAGING	1950	US	REFLECTION TRANSMISSION	
NUCLEAR MEDICINE	RADIOISOTOPE IMAGING	1950	γ RAYS	RADIATION EMISSION	

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

Röhren fremden Fabrikates.

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

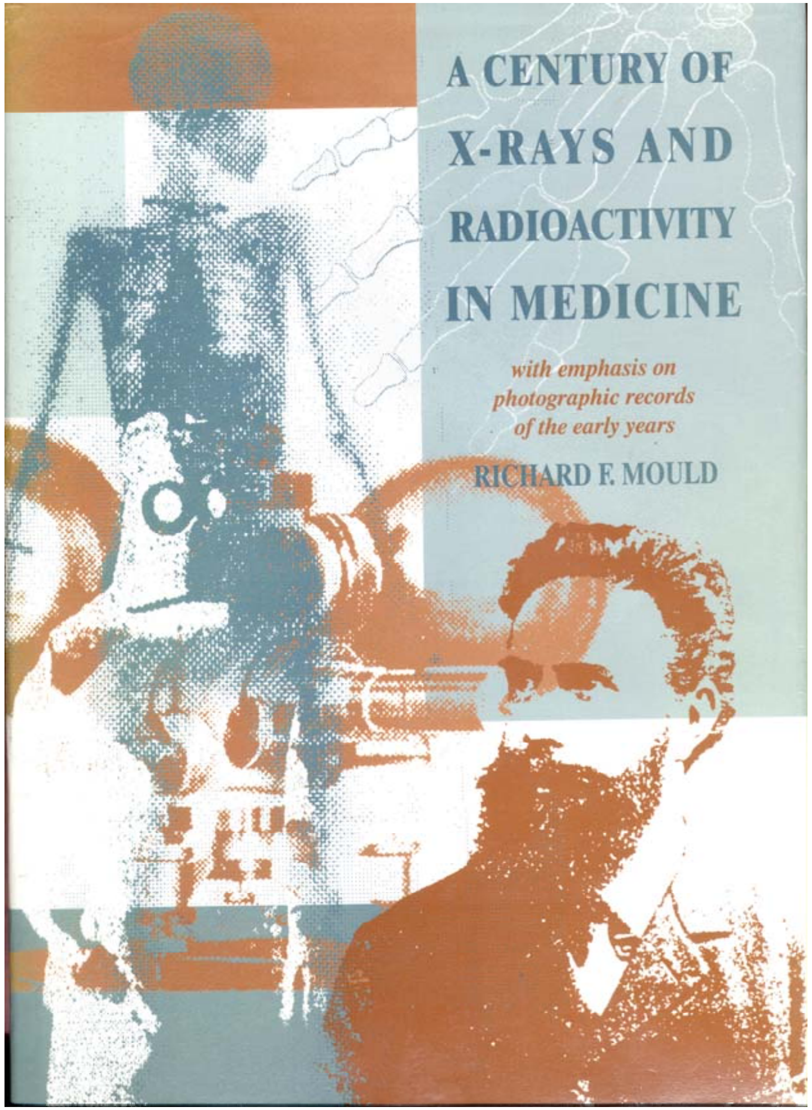


MONOPOL

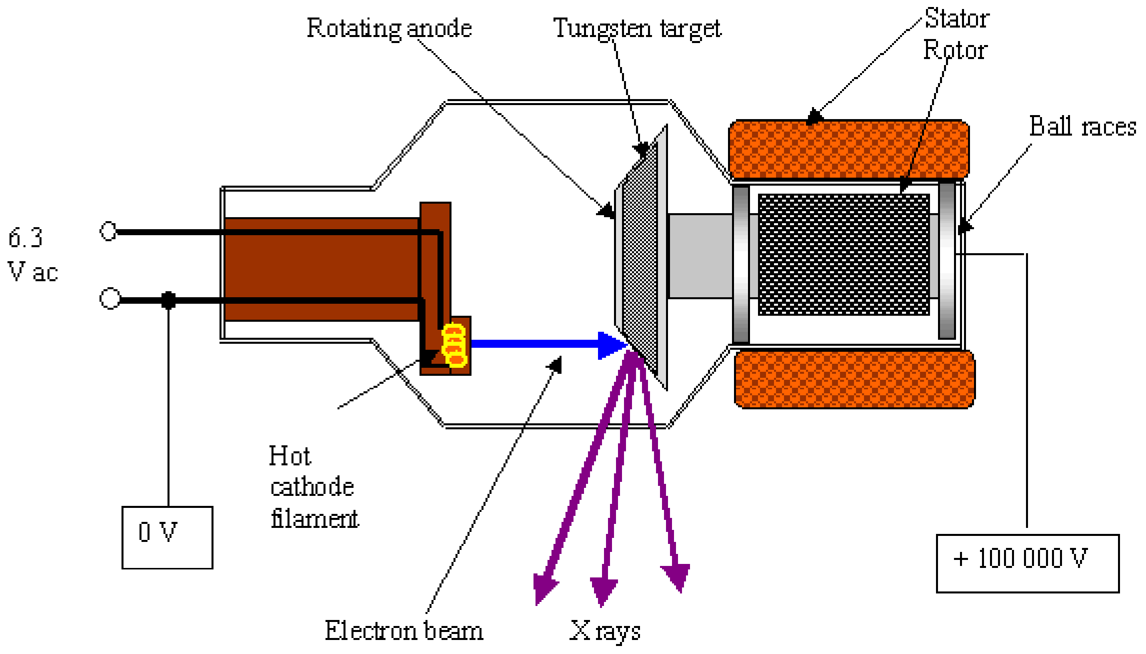
Schutzmarke.

Diese Röhre ist besonders für die Röntgen-Oberflächentherapie 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 Kohler's specification by 1914. (Courtesy: Siemens AG, Erlangen.)



Medical imaging: x-ray generator and image intensifier



X-ray tube

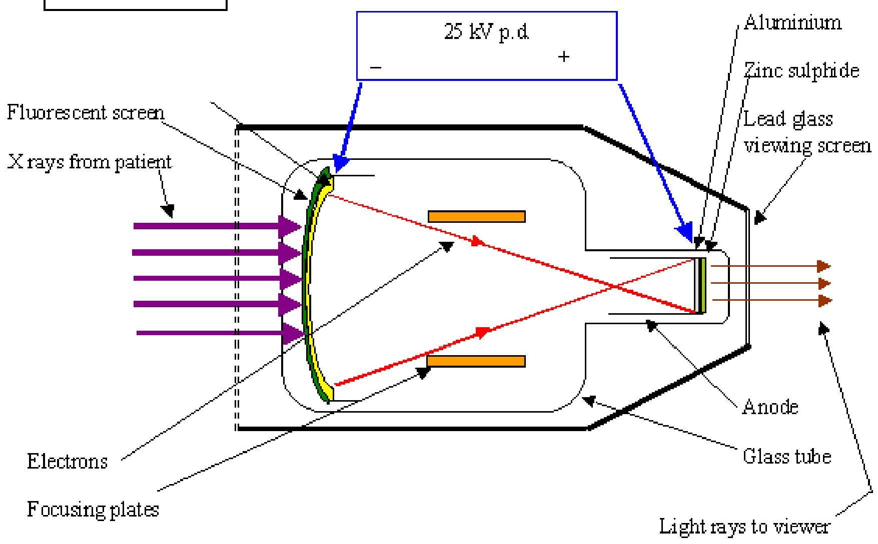


Image intensifier

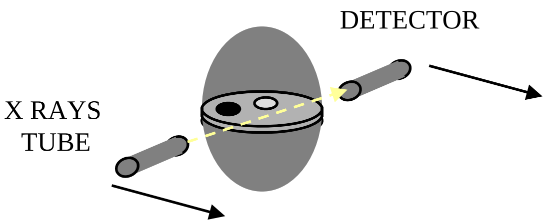
X-ray image versus CT scan

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).

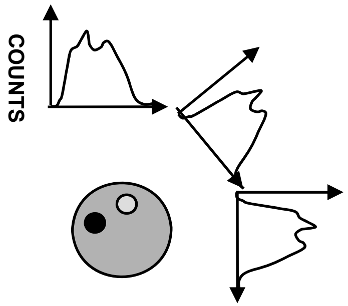
Shadows give an incomplete picture of an object's shape.

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.

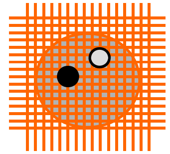
X-ray computerized tomography (CT)



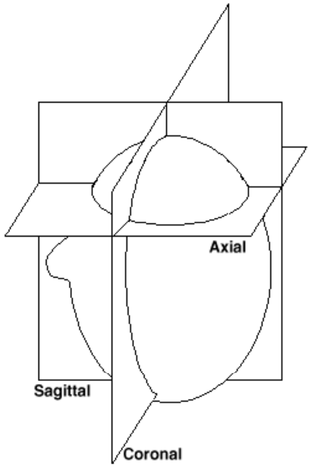
A – LINEAR SAMPLING



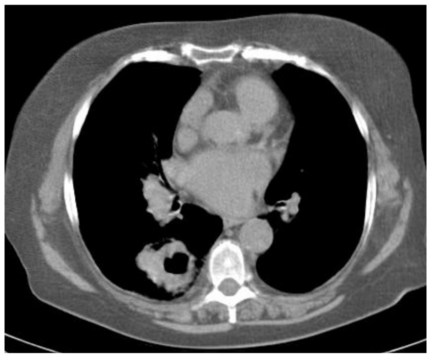
B – ANGULAR SAMPLING



C - RECONSTRUCTION

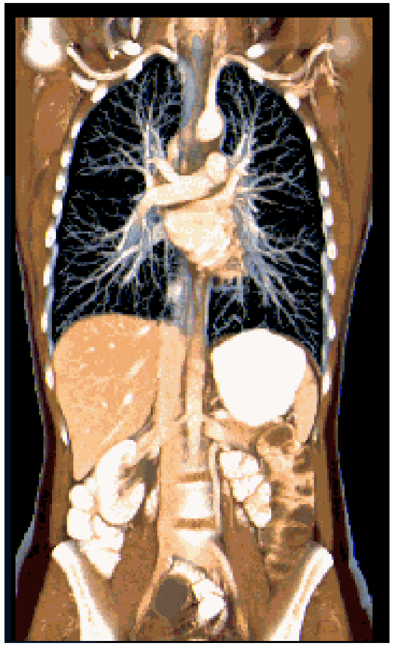


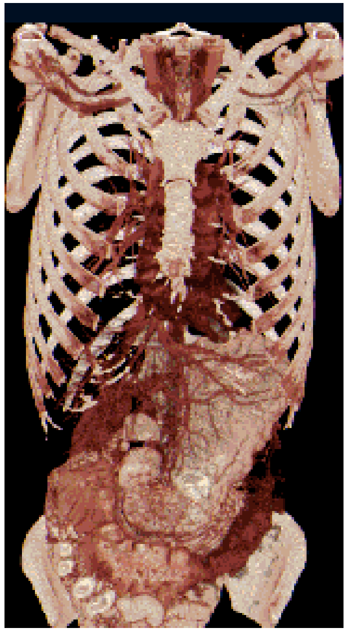
This is the basic idea of computer aided tomography. In a CAT scan machine, the X-ray beam moves all around the patient, scanning from hundreds of different angles. The computer takes all this information and puts together a **3-D image** of the body.



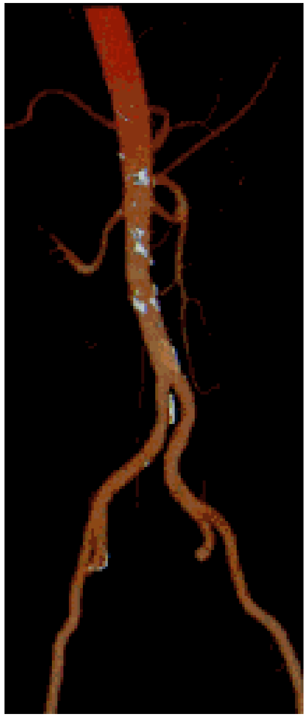
X RAYS
COMPUTERIZED TOMOGRAPHY

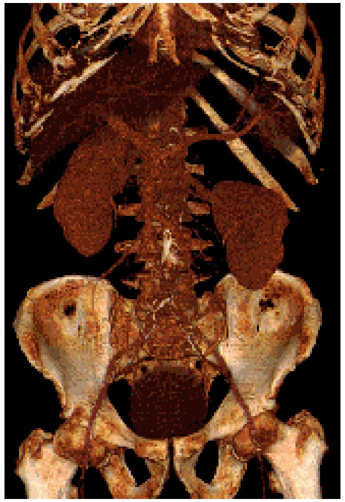
Volumetric CT

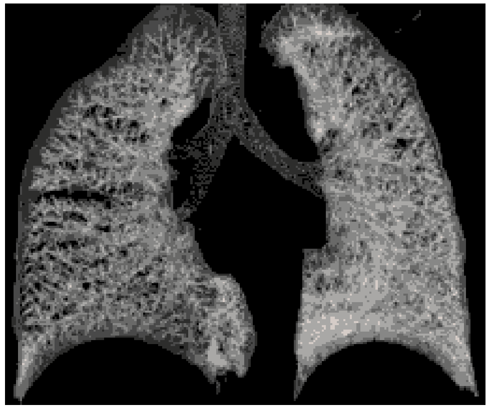




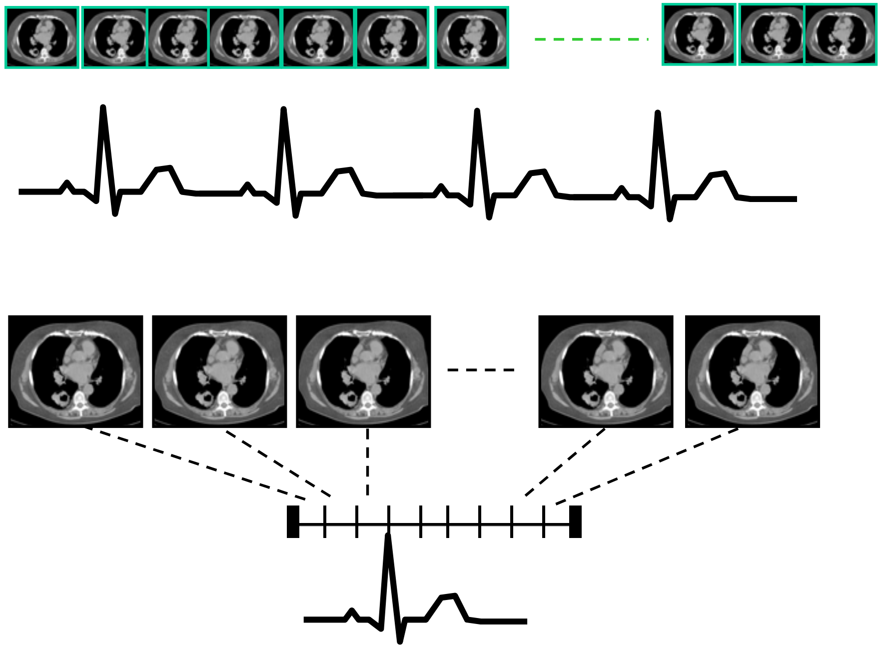
< 0,4 sec/rotation
Organ in a sec (17 cm/sec)
Whole body < 10 sec







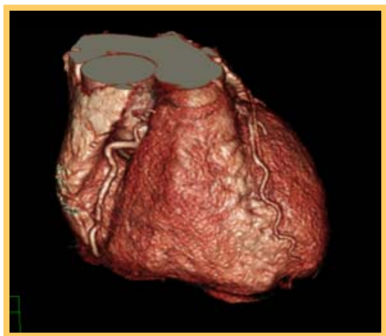
Cardiac CT



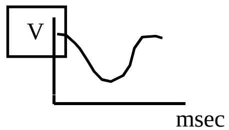
DYNAMIC CT ACQUISIION

ECG

PHASES OF A CARDIAC CYCLE



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

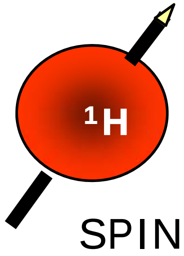


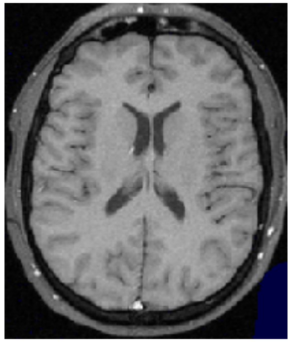
FUNCTIONAL PARAMETERS

VOLUME RENDERED IMAGE OF HEART AND VESSELS

Magnetic Resonance Imaging (MRI)

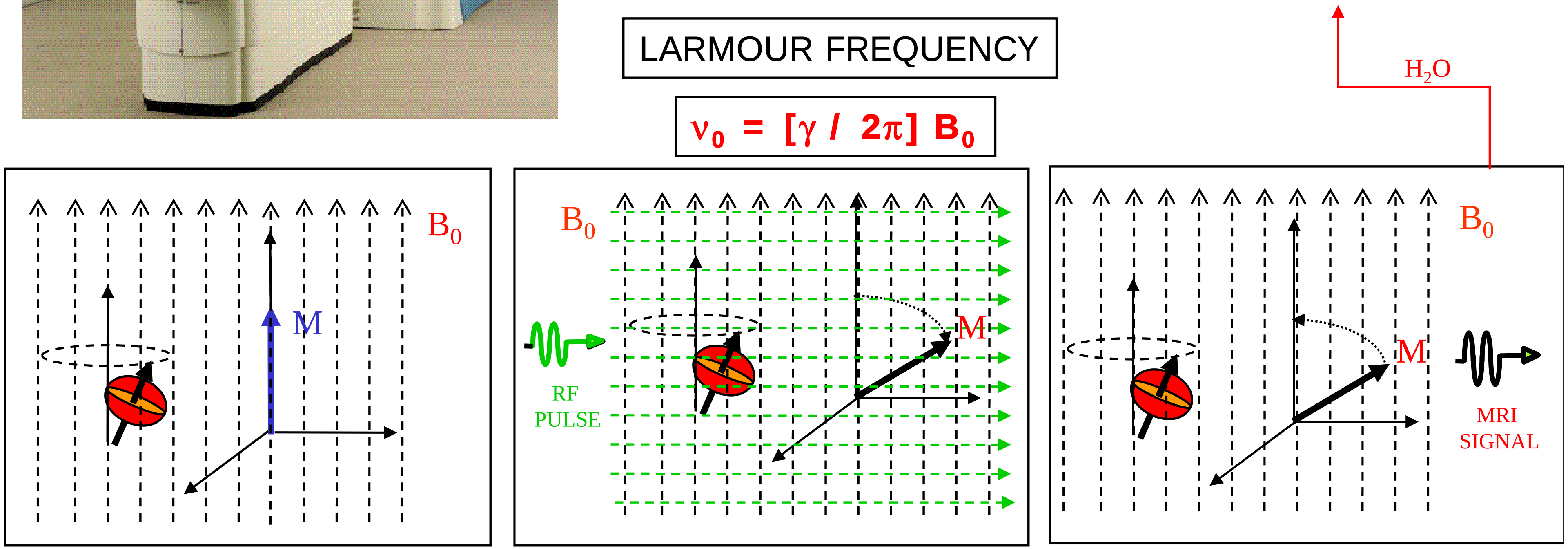
MAGNETIC FIELD: 1.5 – 3 Tesla





LARMOUR FREQUENCY

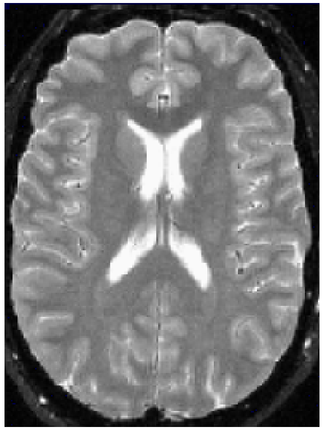
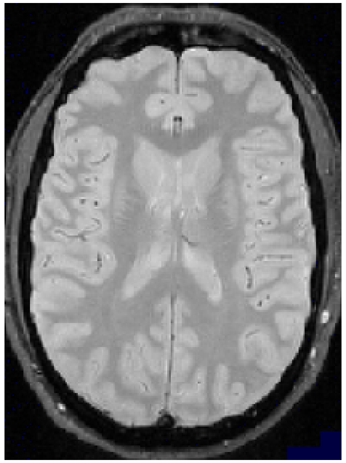
$\nu_0 = [\gamma / 2\pi] B_0$



EXCITATION

RELAXATION

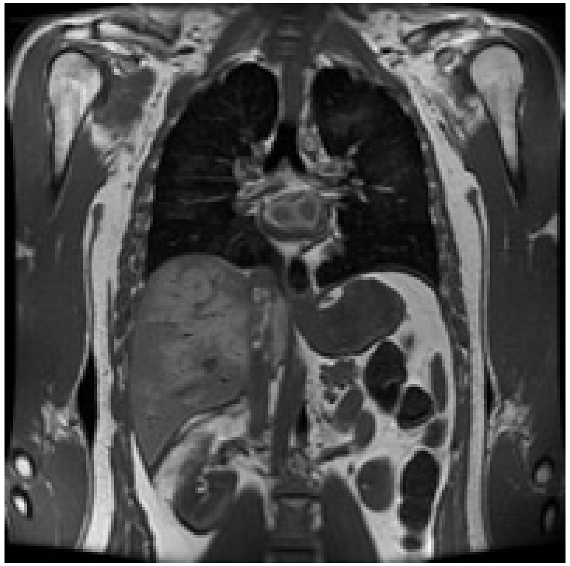
Magnetic Resonance Imaging (MRI): morphology

		
T1	T2	PD

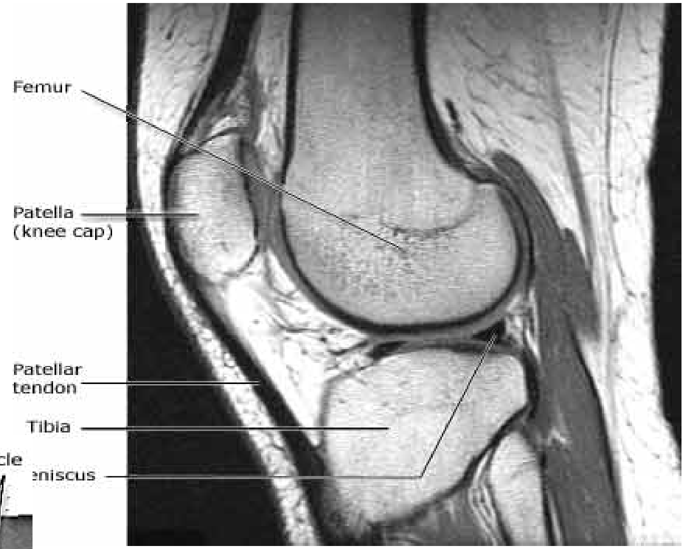
SCAN TIME to cover an entire organ:	~ min
SPATIAL RESOLUTION:	~ mm
CONTRAST RESOLUTION:	very high for soft tissues

Courtesy HSR MILANO

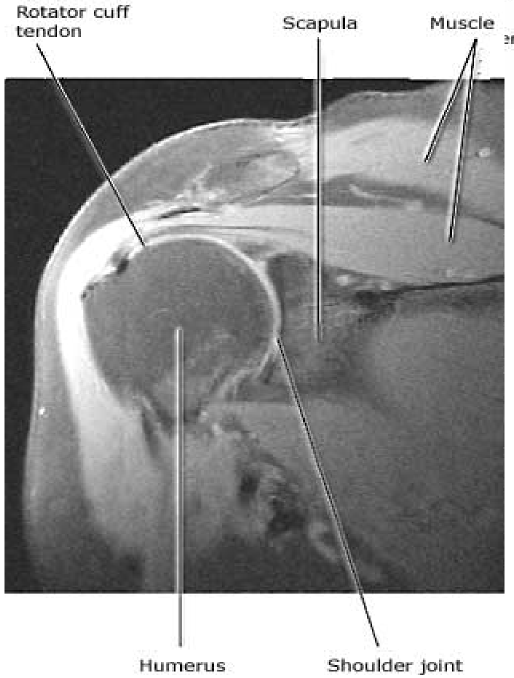
Magnetic Resonance Imaging (MRI): morphology



MRI of upper torso (courtesy NASA)

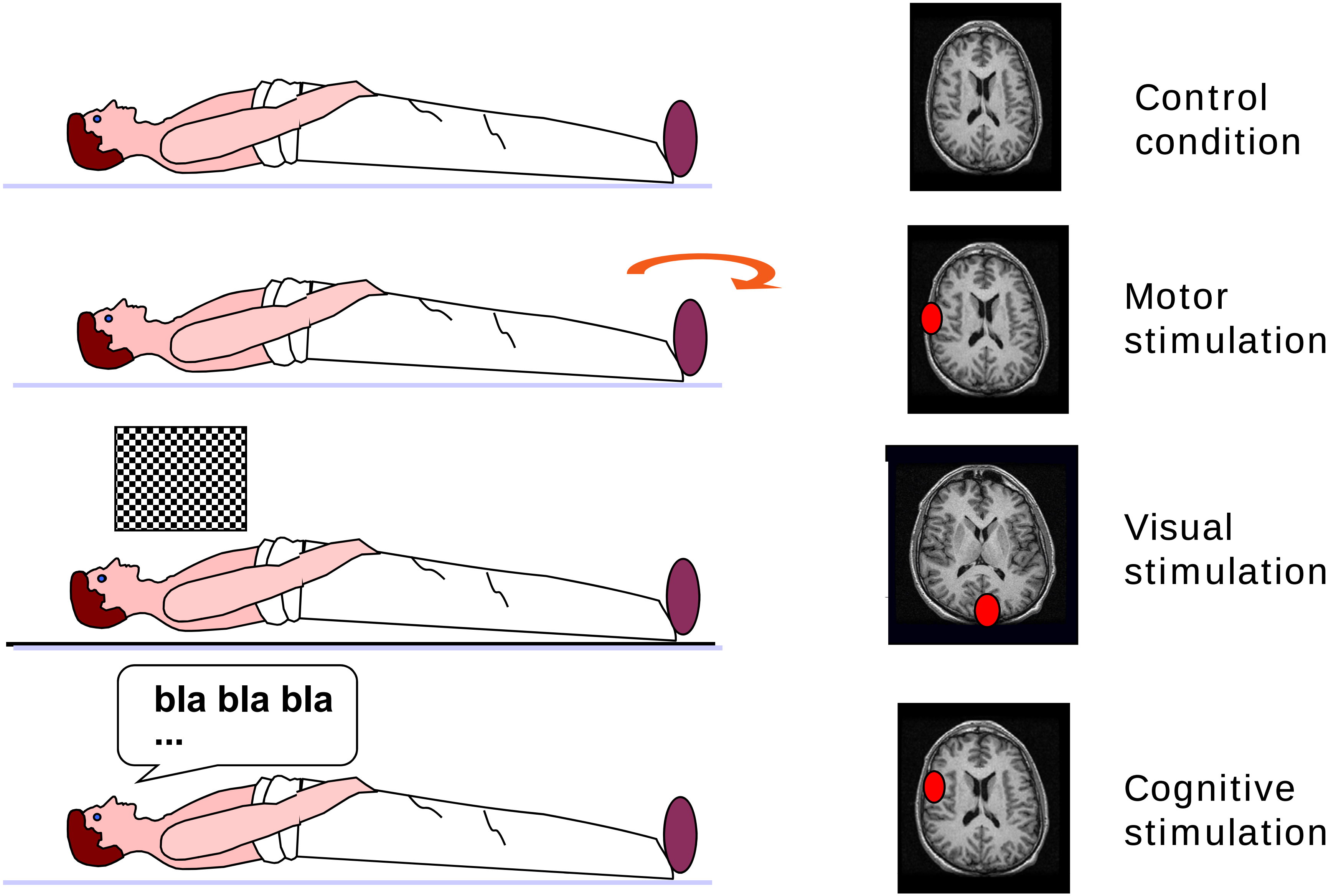


MRI of knee



MRI of shoulder

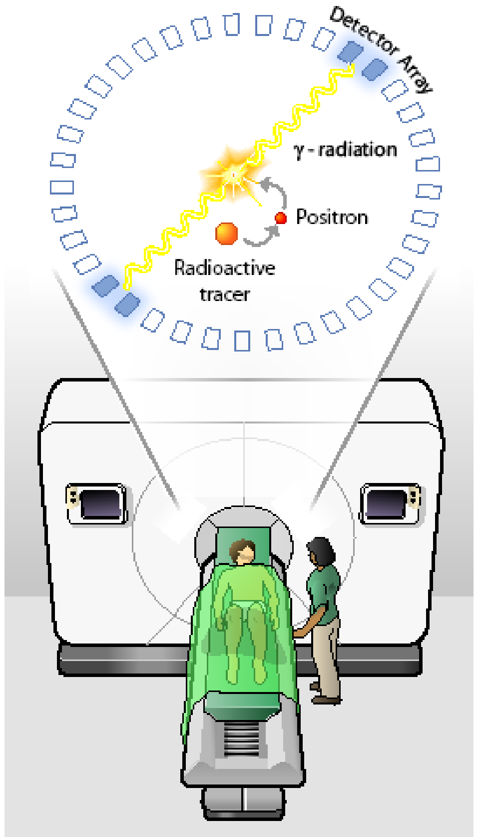
Magnetic Resonance Imaging (MRI): activation studies



Positron Emission Tomography (PET)

Cyclotron

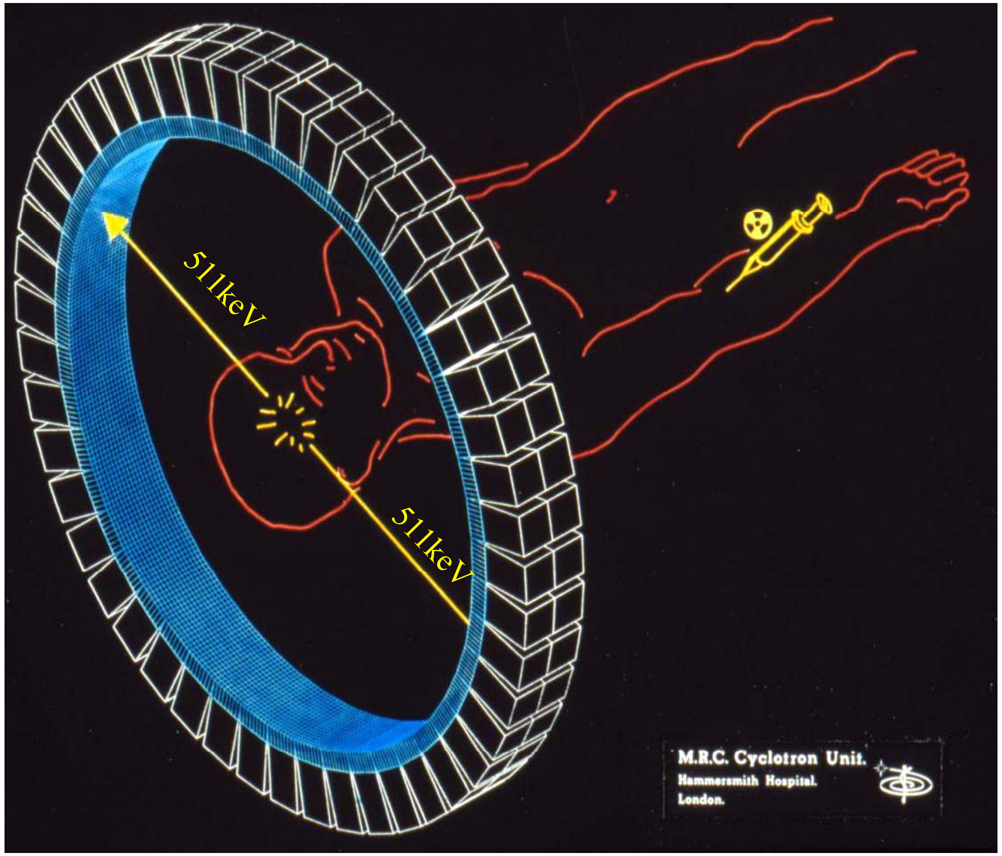
ISOTOPES	Half-Life	
11-C	20.4 min,	“natural”
13-N	10.0 min	“natural”
15-O	2.0 min	“natural”
18-F	109.8 min	“pseudo-natural”

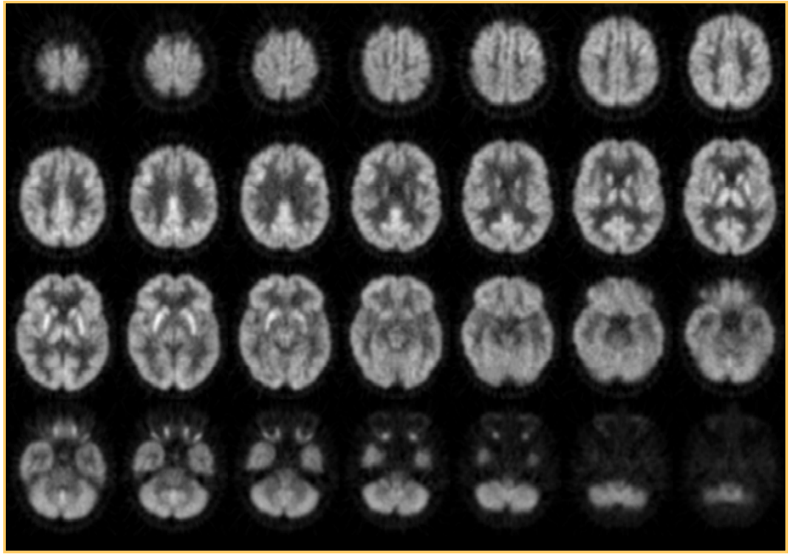


Radiochemistry

J. Long, “The Science Creative Quarterly”,scq.ubc.ca

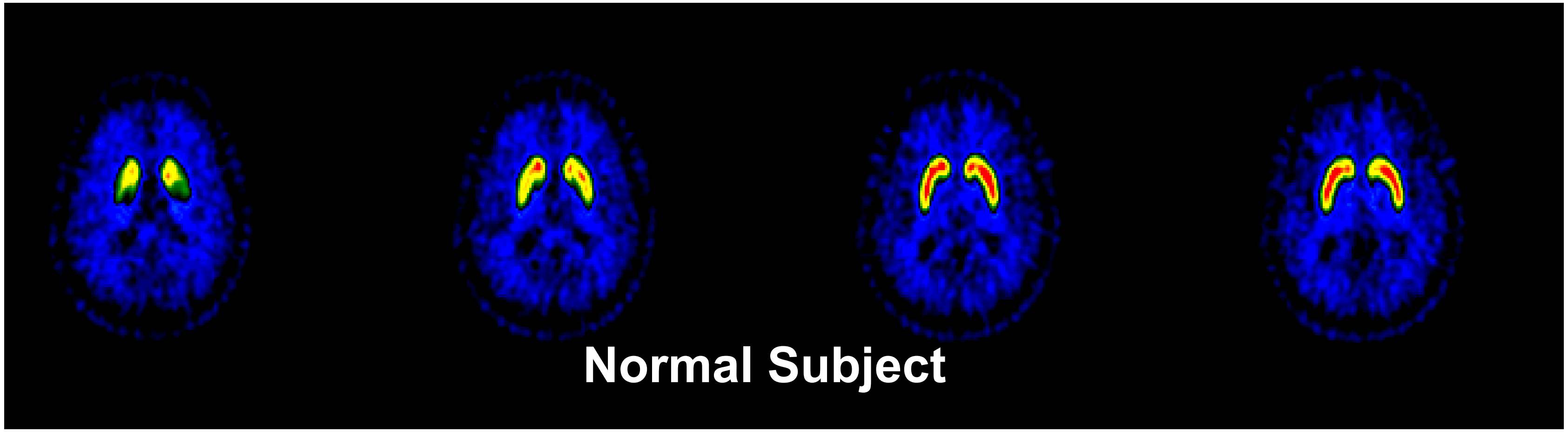
Positron Emission Tomography (PET)

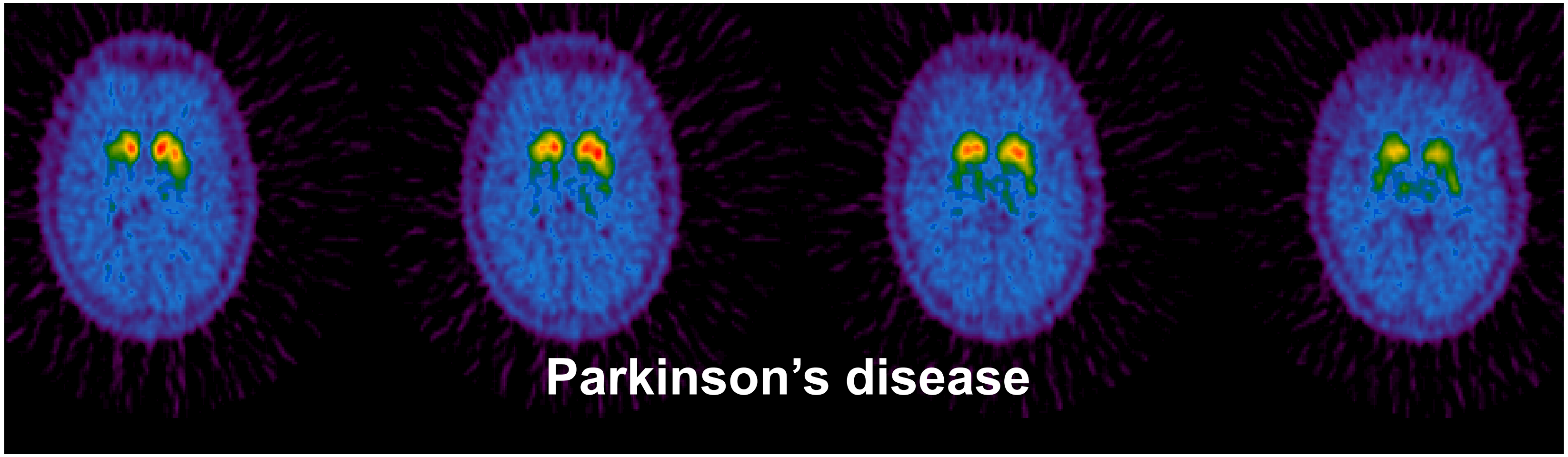




COVERAGE:
~ 15-20 cm
SPATIAL RESOLUTION:
~ 5 mm
SCAN TIME to cover an entire organ:
~ 5 min
CONTRAST RESOLUTION:
depends on the radiotracer

PET functional receptor imaging





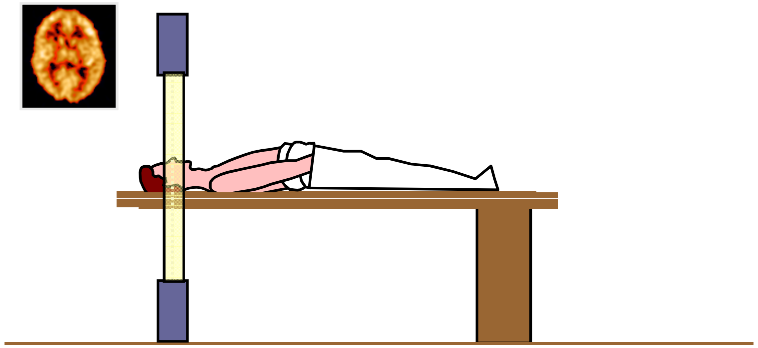
[^{11}C] FE-CIT

Courtesy HSR MILANO

HSR MILANO

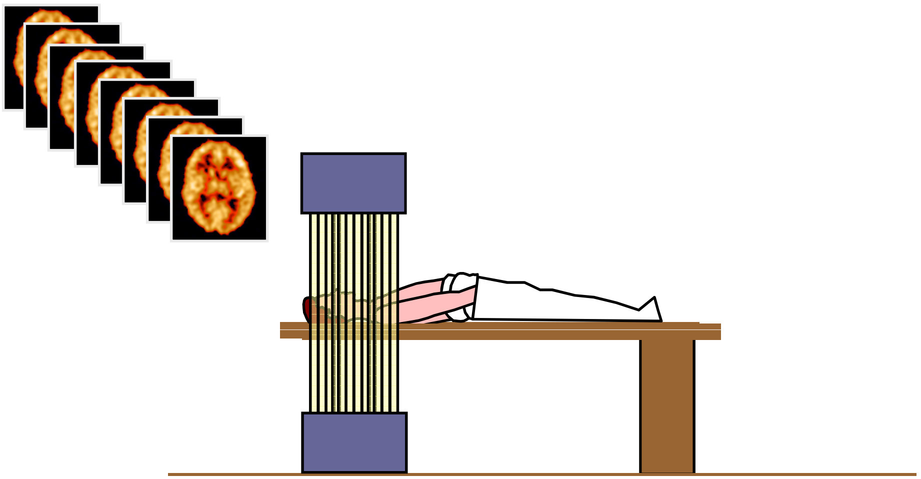
PET coverage and axial sampling

FIRST GENERATION PET



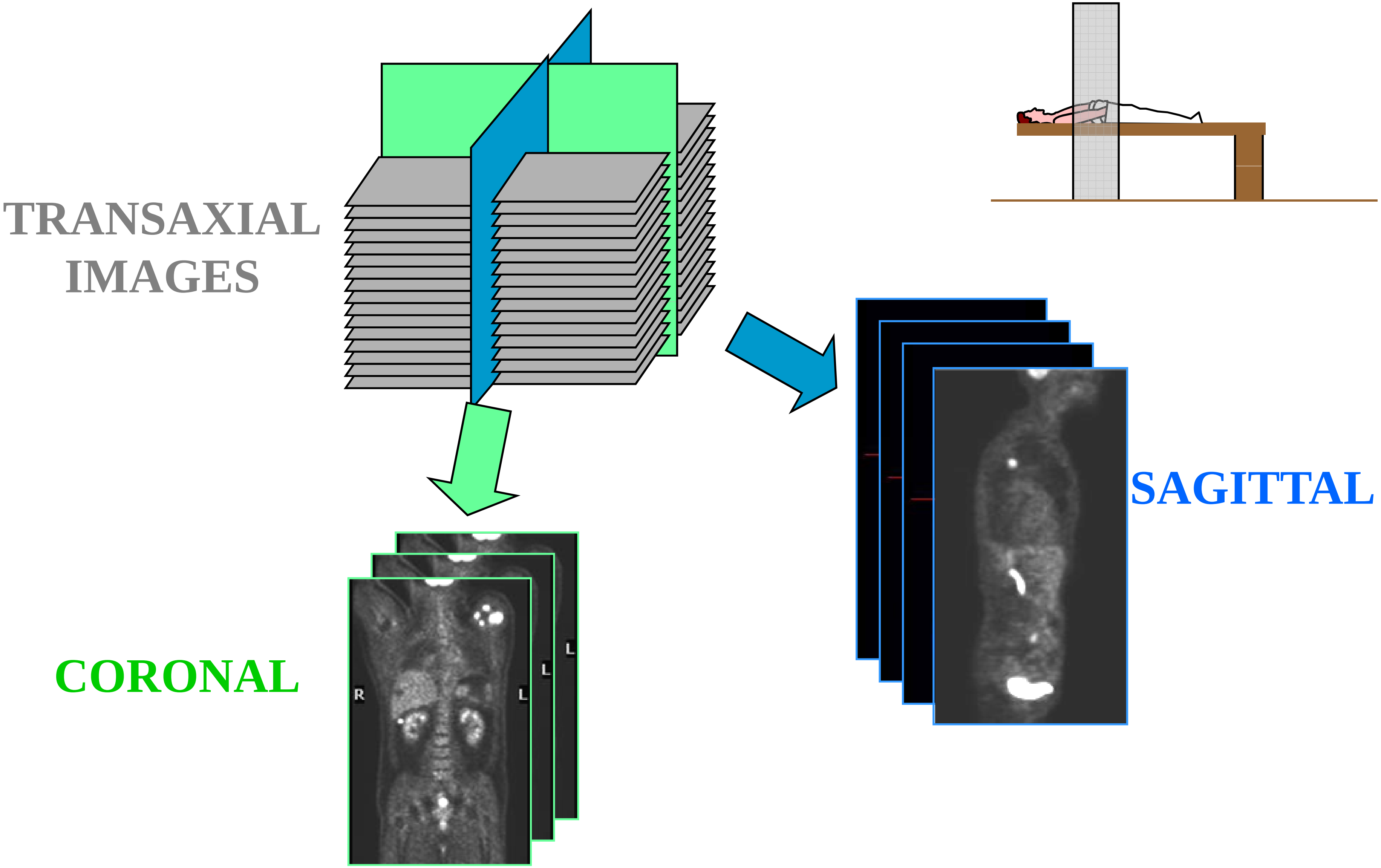
1 SLICE – 2 cm

CURRENT GENERATION PET

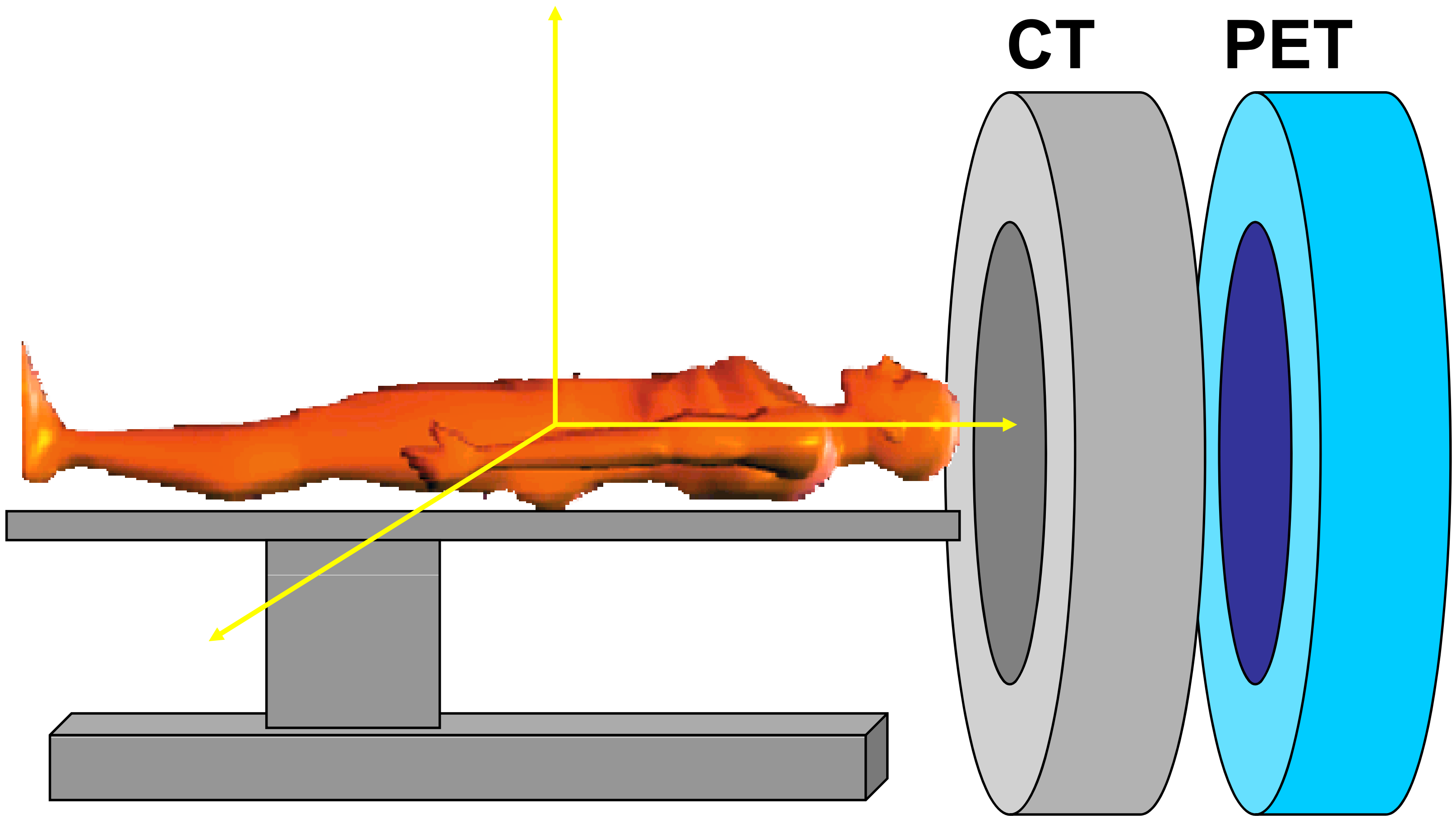


> 40 SLICES – 6 mm
Axial FOV: 15 –20 cm

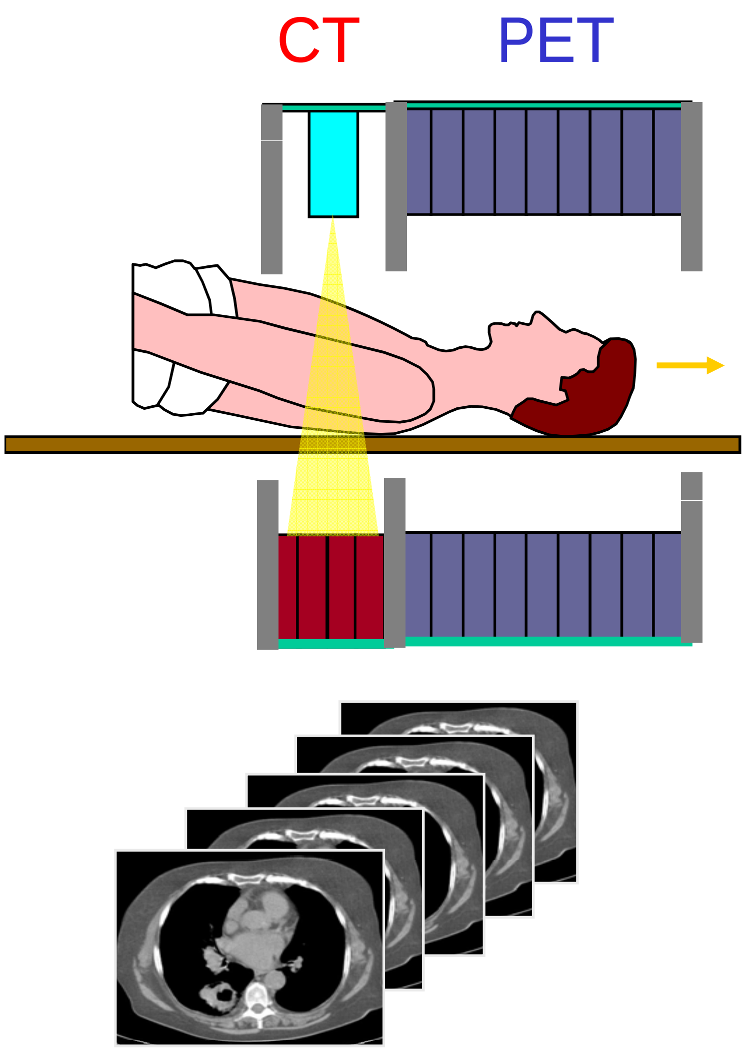
PET: total body studies



PET/CT scanner

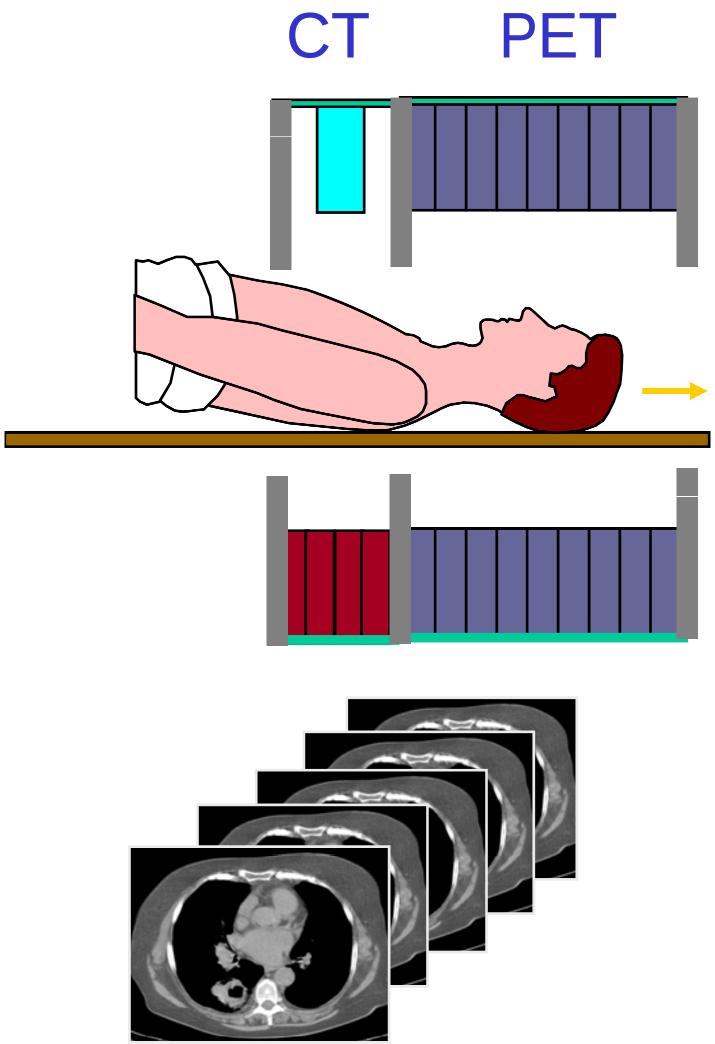


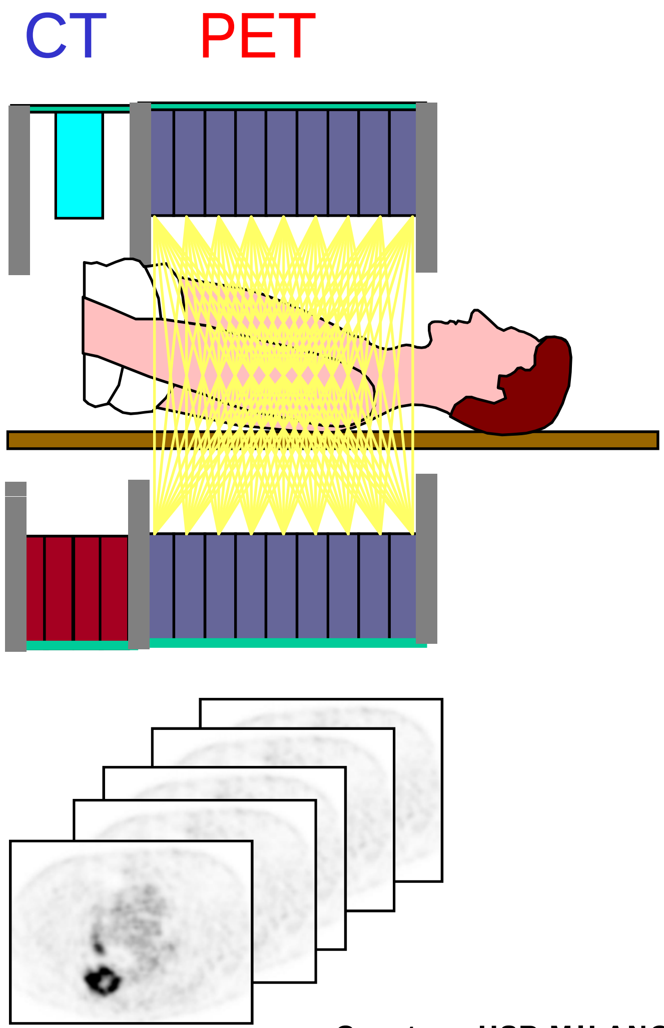
PET/CT scanner



Courtesy HSR MILANO

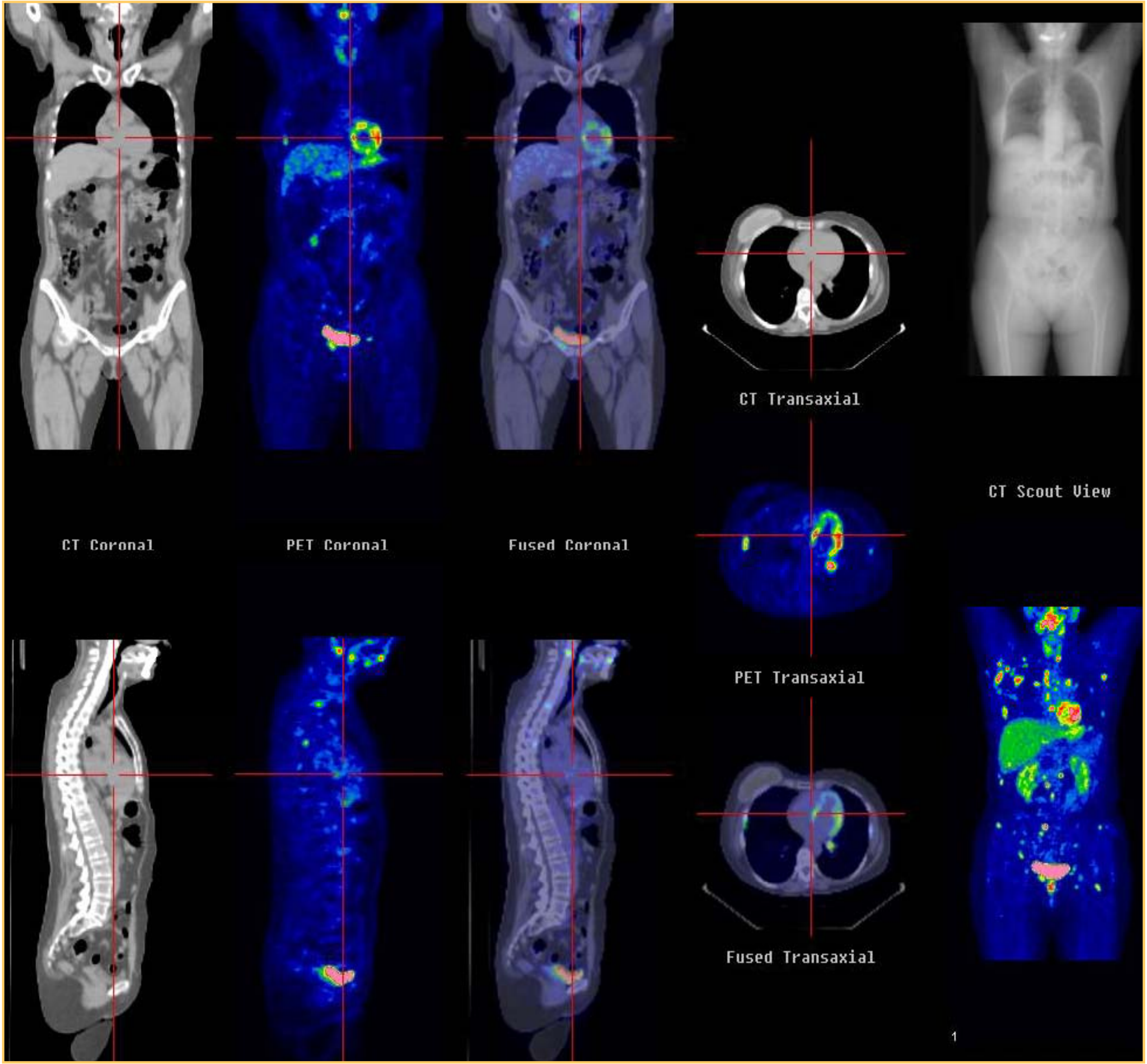
PET/CT scanner





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 >1GeV)	~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

(Medical radioisotope production, radiotherapy accelerators and research accelerators together: 9000)

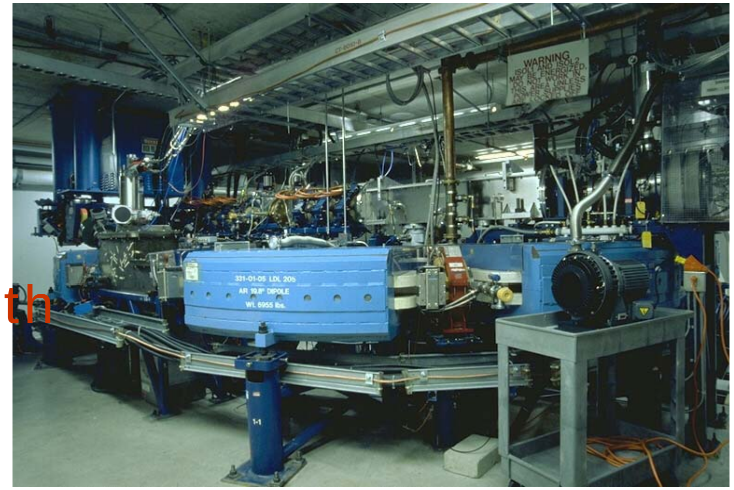
(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004

Three classes of medical accelerators

Electron linacs for conventional radiation therapy, including advanced modalities:

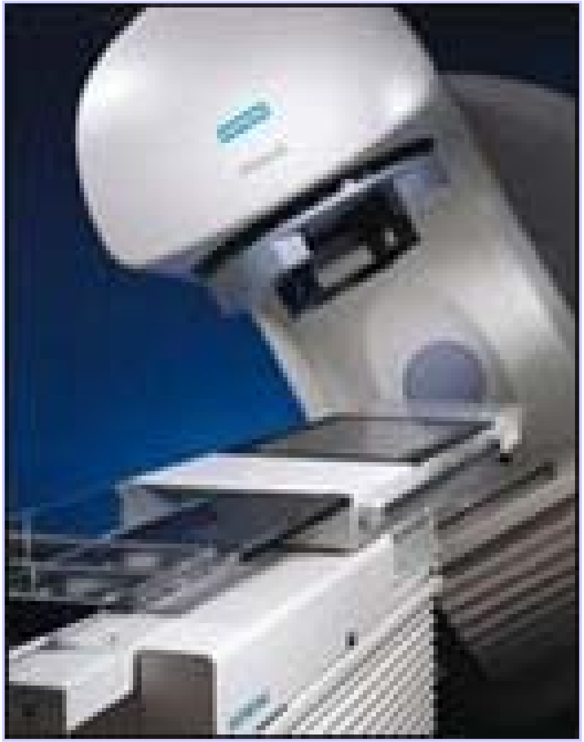
- Cyberknife
- IntraOperative RT (IORT)
- Intensity Modulated RT

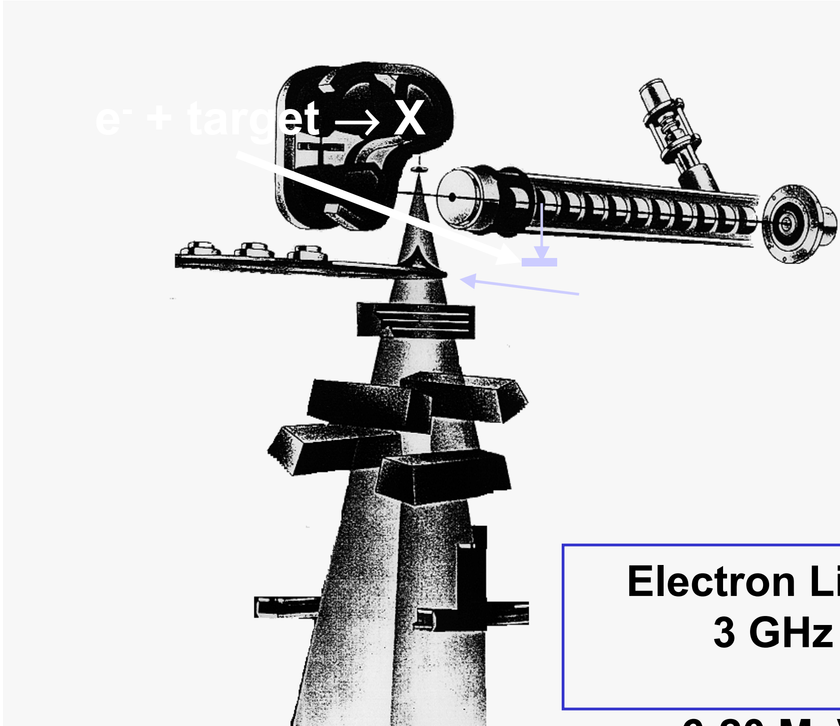
Low-energy cyclotrons for production of radionuclides for medical diagnostics



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

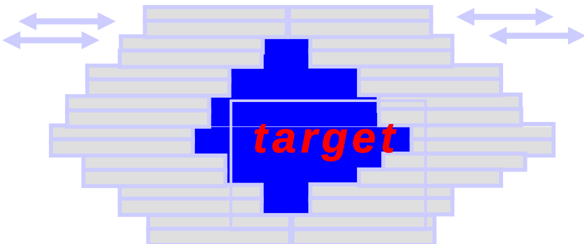
X-rays in radiation therapy: medical electron linacs



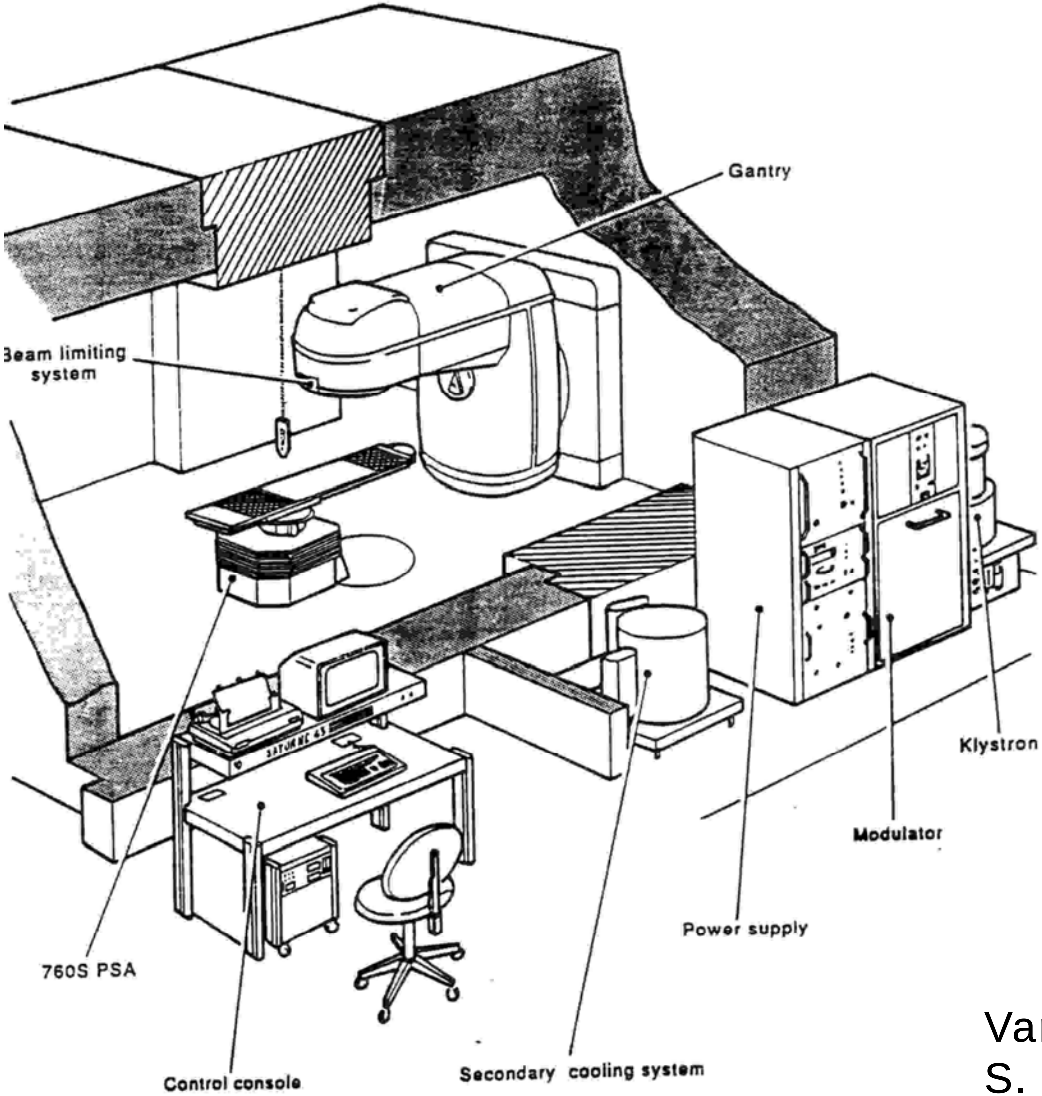


Electron Linac
3 GHz

6-20 MeV
[1000 x Röntgen]



Medical accelerators: electron linac



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

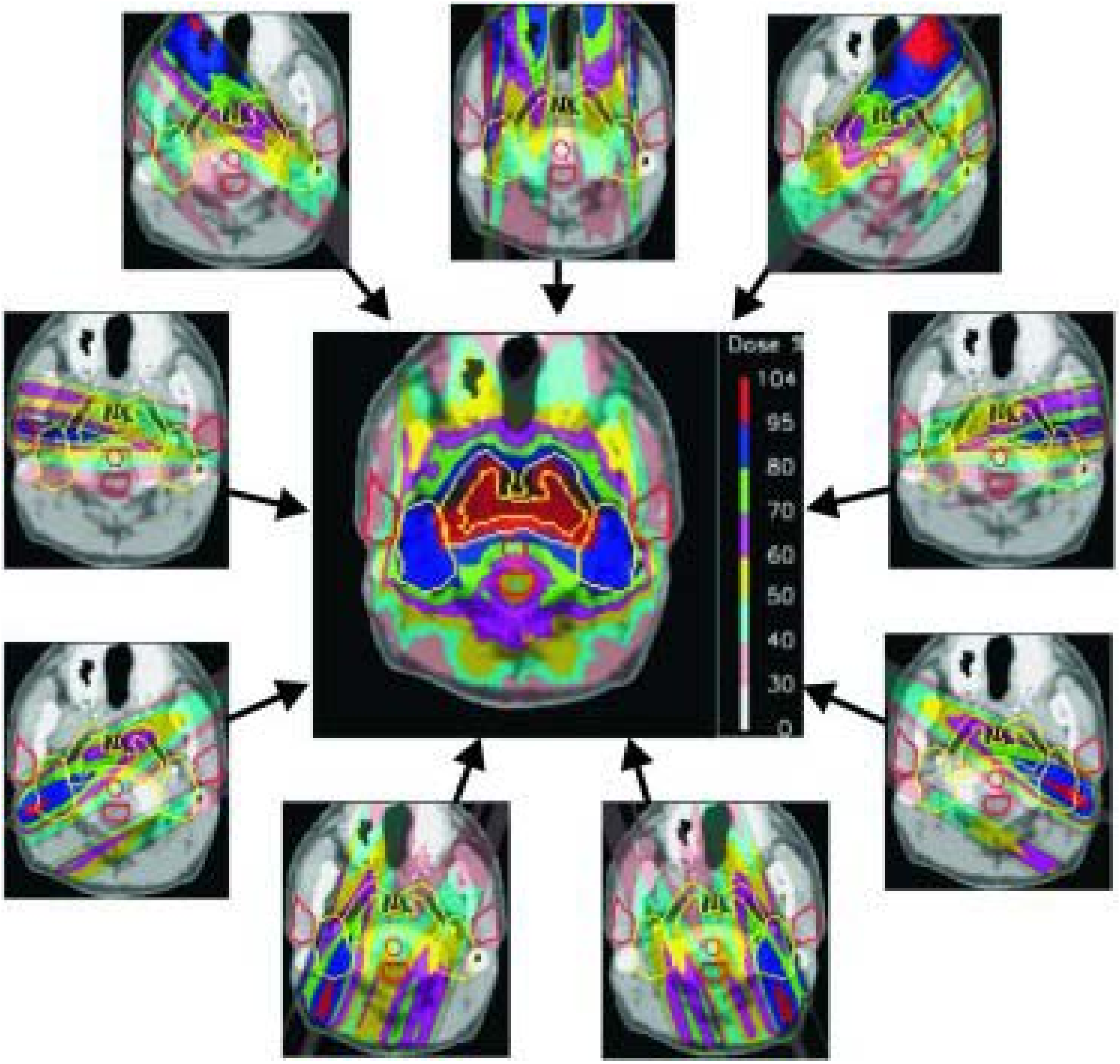
CyberKnife (CK) Robotic Surgery System

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

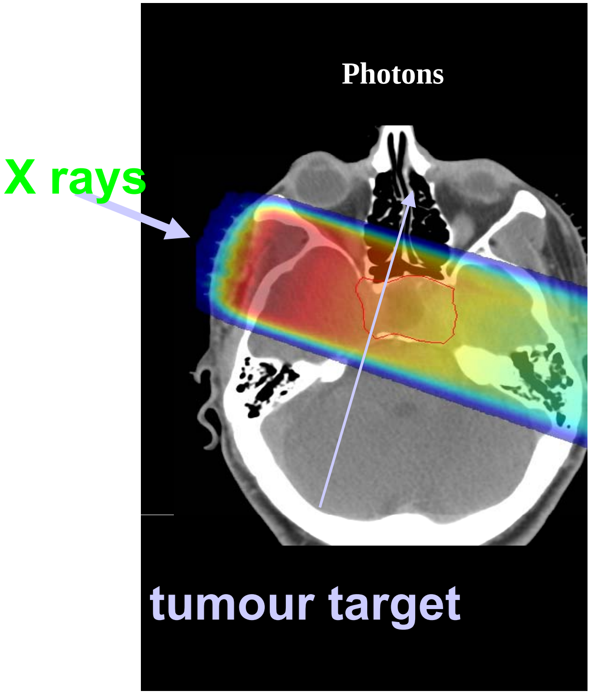
Intensity Modulated Radiation Therapy

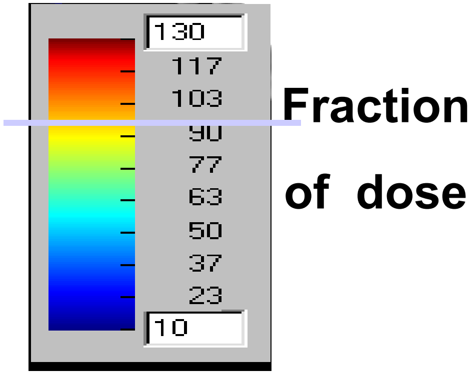


An example of intensity modulated treatment planning with photons. Through the addition of 9 fields it is possible to construct a highly conformal dose distribution with good dose sparing in the region of the brain stem (courtesy of T. Lomax, PSI).

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

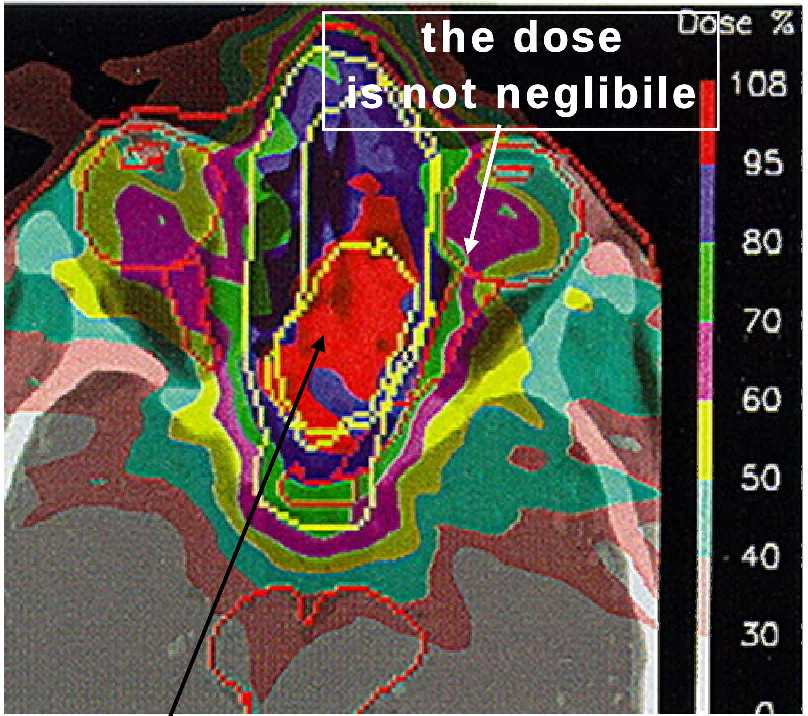
Yet X-rays have a comparatively poor energy deposition





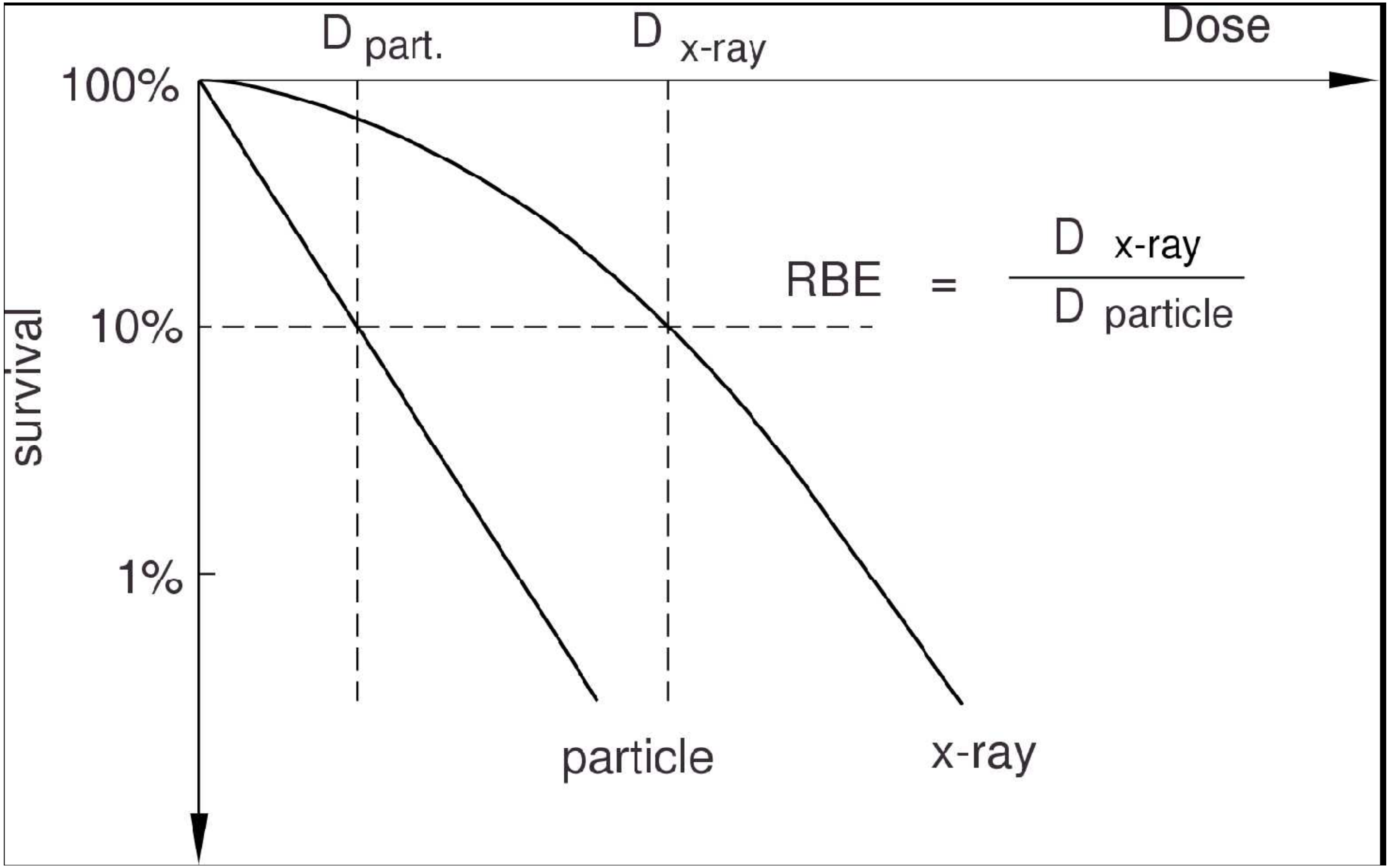
IMRT (Intensity Modulated Radiation Therapy)

with 9 crossing beams

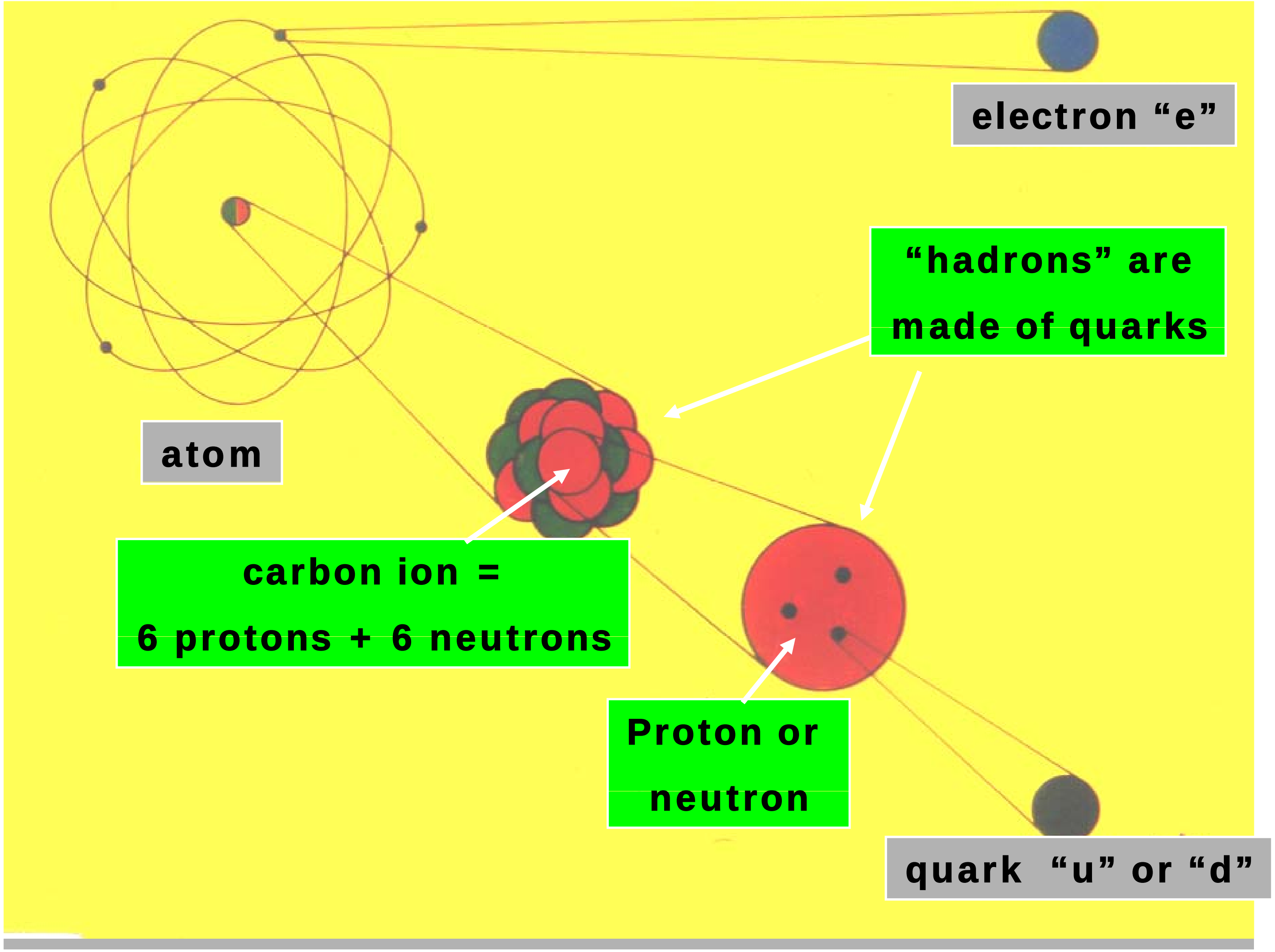


Tumour between the eyes

Radiobiological effectiveness (RBE)



Hadrontherapy: n, p and C-ion beams



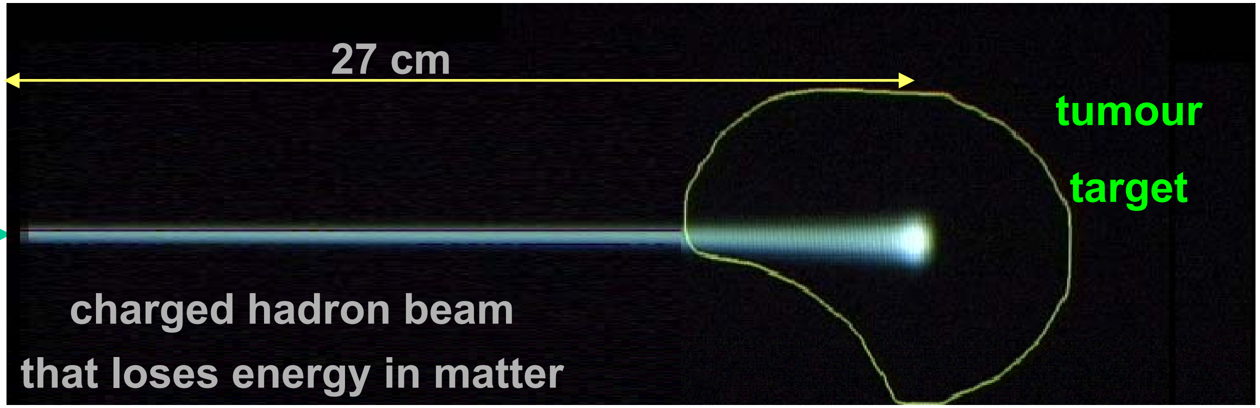
Hadrontherapy

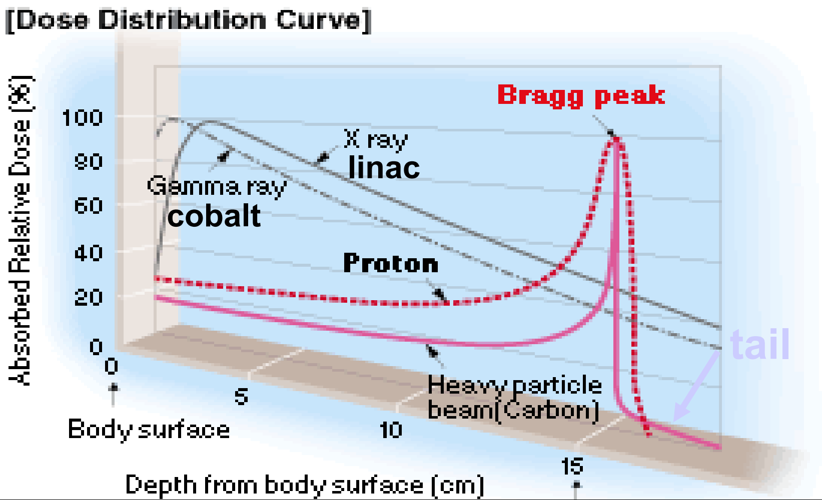
Charged hadrons have a much better energy deposition with respect to X-rays

200 MeV protons

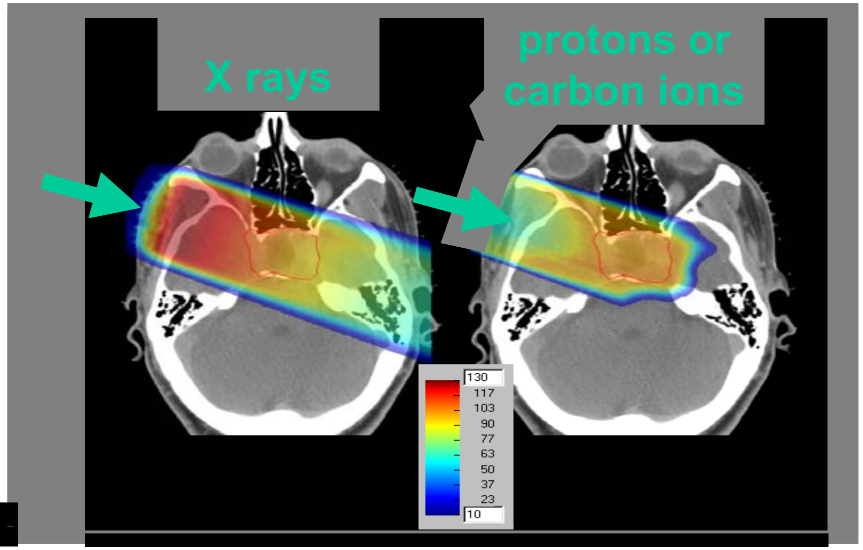
4800 MeV carbon ions

which control radioresistant tumours

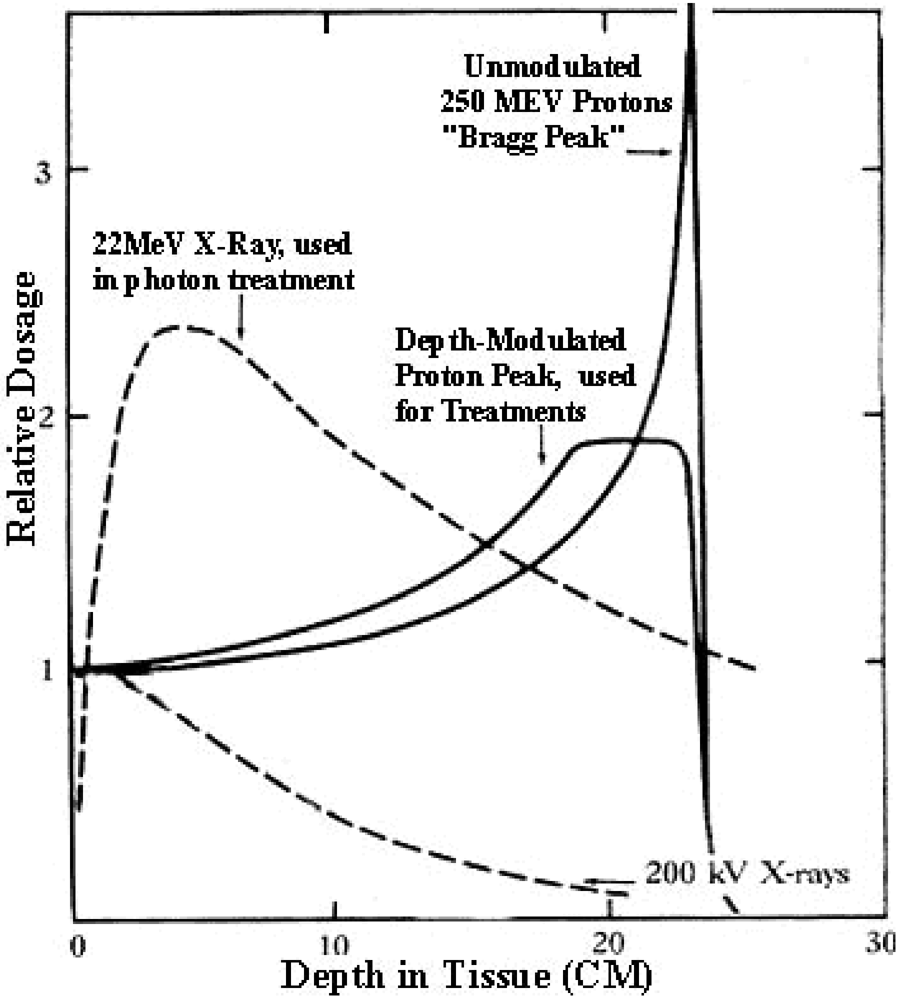


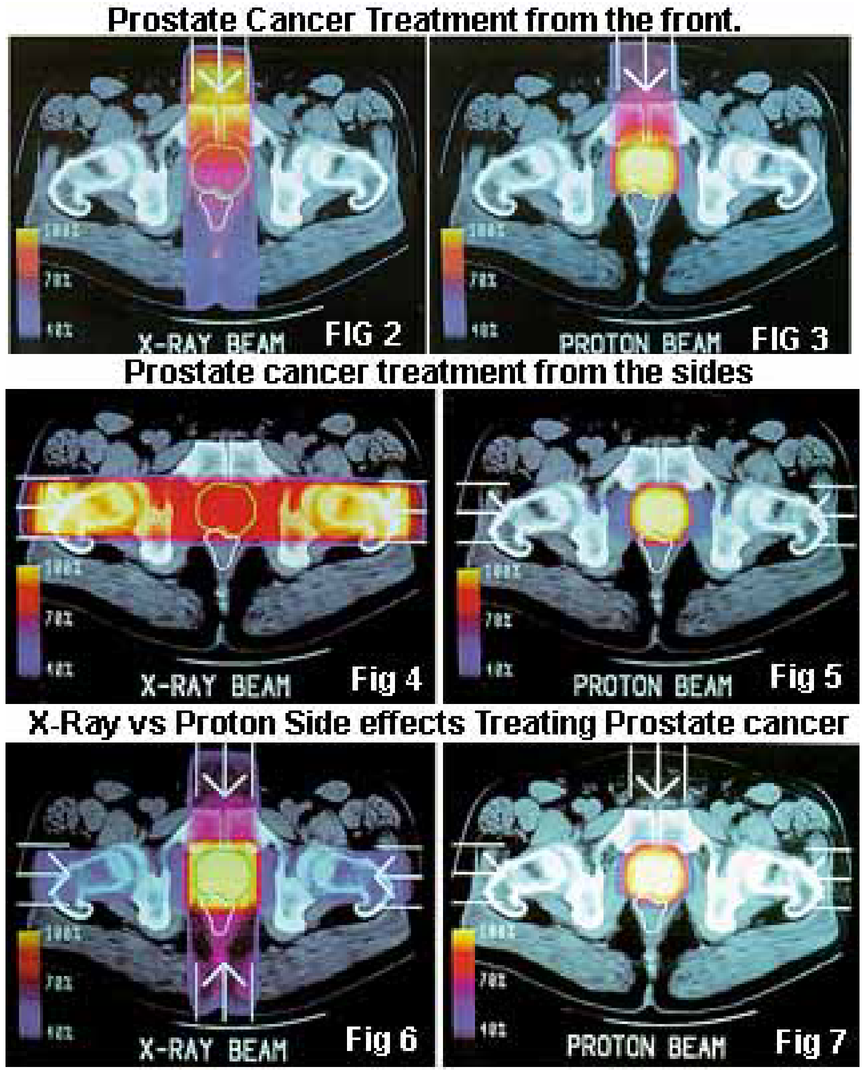


httt://global.mitsubishielectric.com/bu/particlebeam/index_b.html

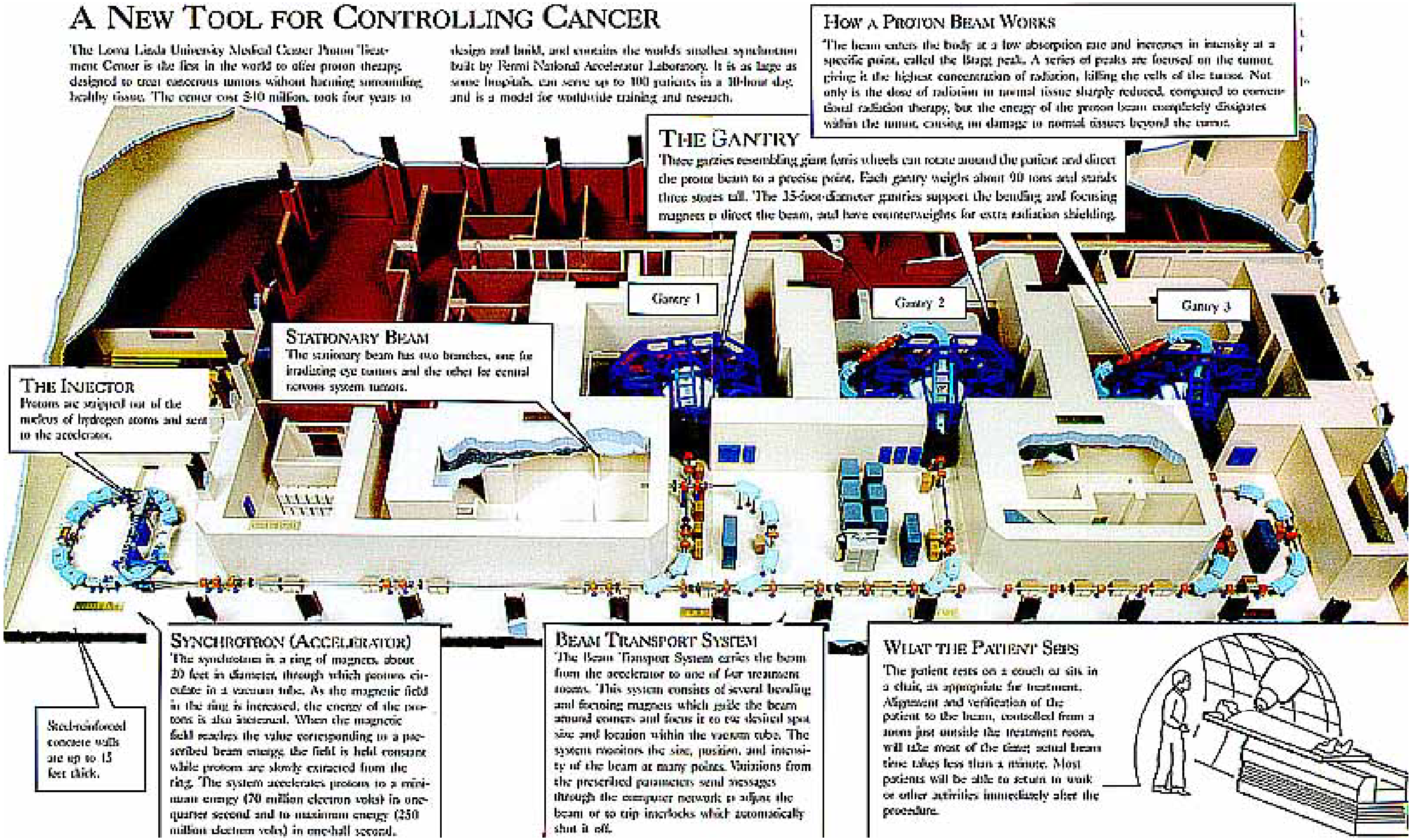


Proton radiation therapy

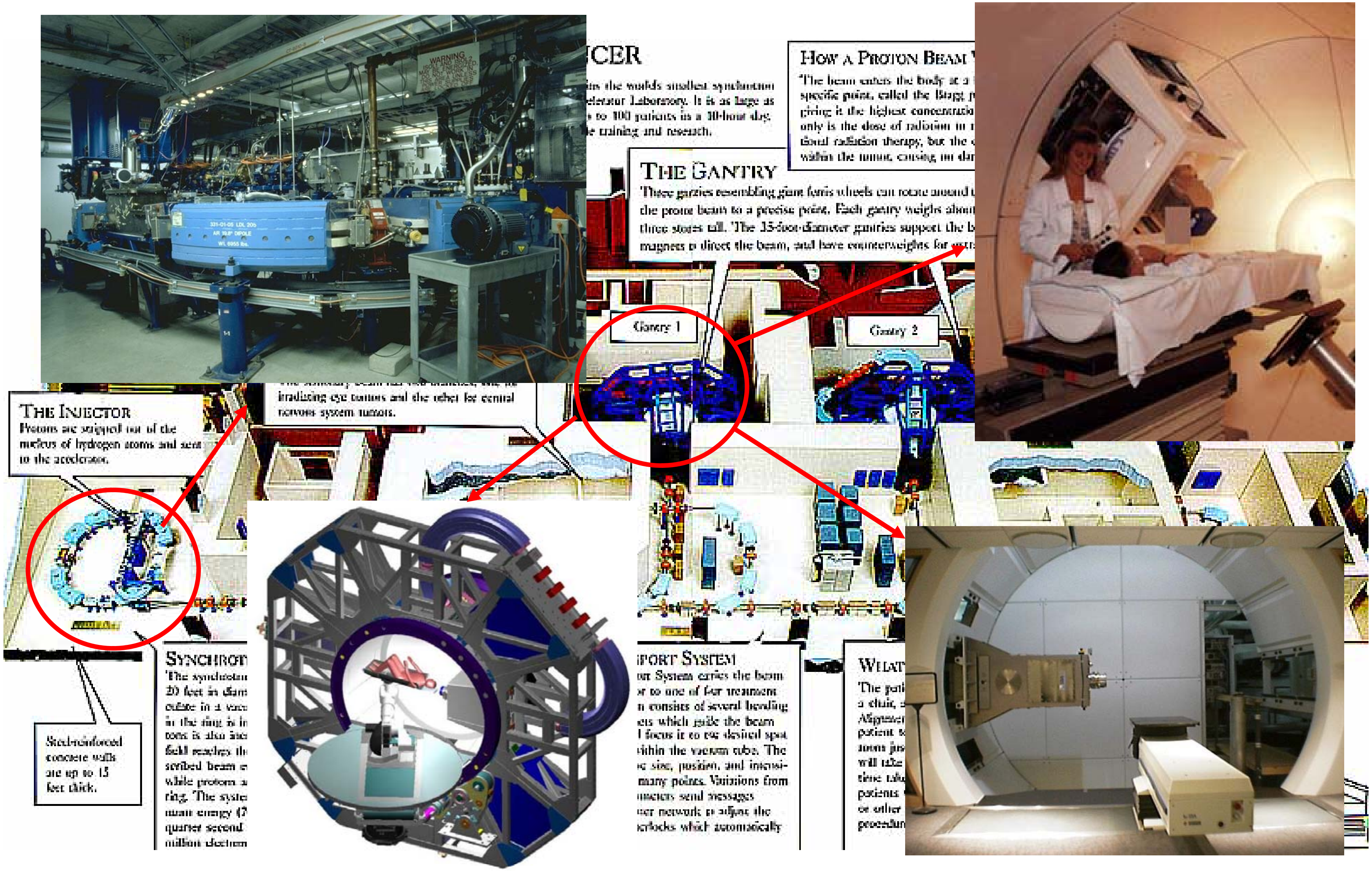




Loma Linda University Medical Center (LLUMC)



Loma Linda University Medical Center (LLUMC)



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.