Medical Applications of Modern Physics

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Medical Physics

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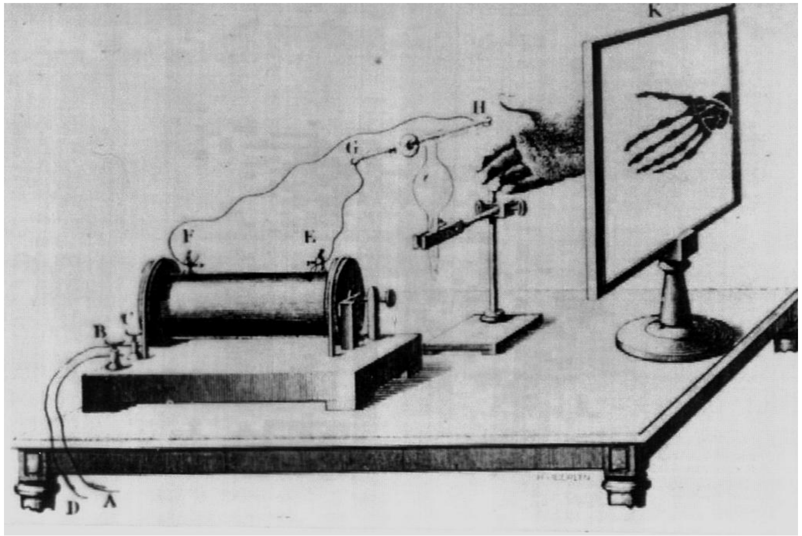
A branch of applied physics concerning the application of physics to medicine

or, in other words

The application of physics techniques to the human health

- Physics discoveries
- Tools for physics applied to medicine
- Medical imaging
- CT
- PET and PET/CT
- Conventional radiation therapy
- Hadron therapy

The beginnings of modern physics and of medical physics



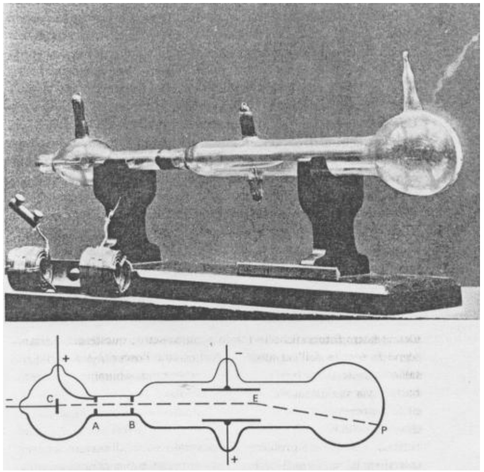
1895
discovery of X rays

Wilhelm Conrad Röntgen

J.J. Thompson

1897

"discovery" of the electron

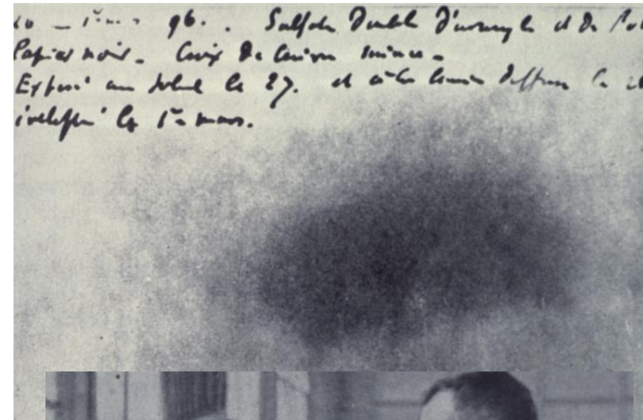


The beginnings of modern physics and of medical physics

Henri Becquerel
(1852-1908)

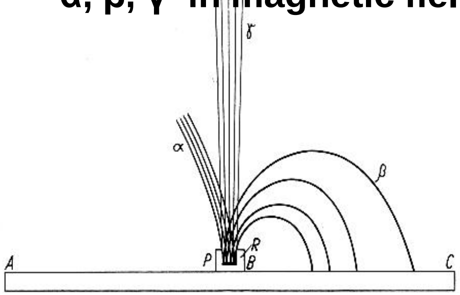
1896:

Discovery of natural radioactivity



Thesis of Mme. Curie – 1904

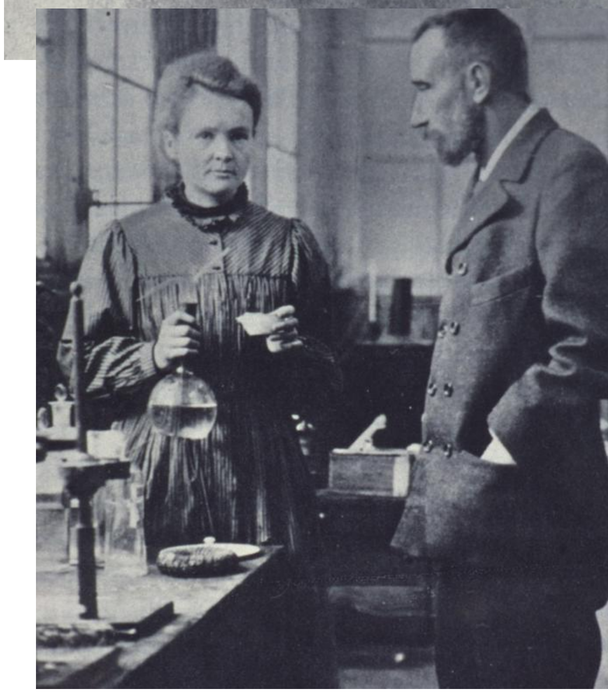
α, β, γ in magnetic field



Hundred years ago

1898

Discovery of polonium and radium

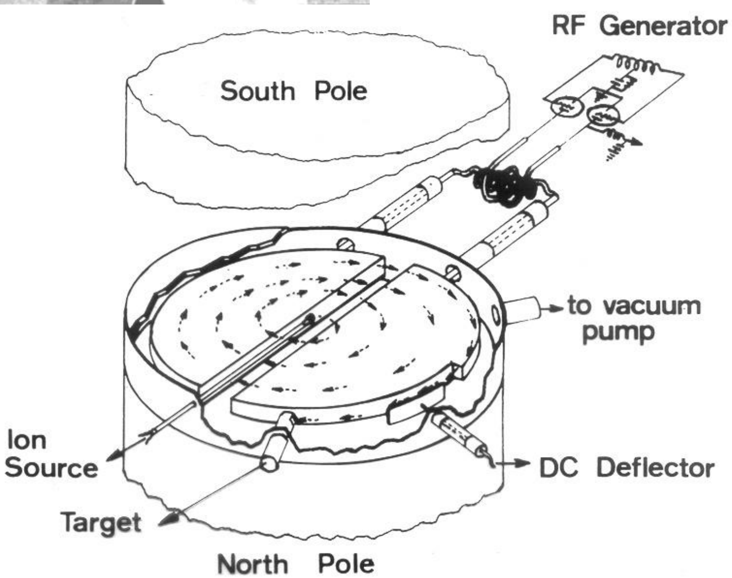


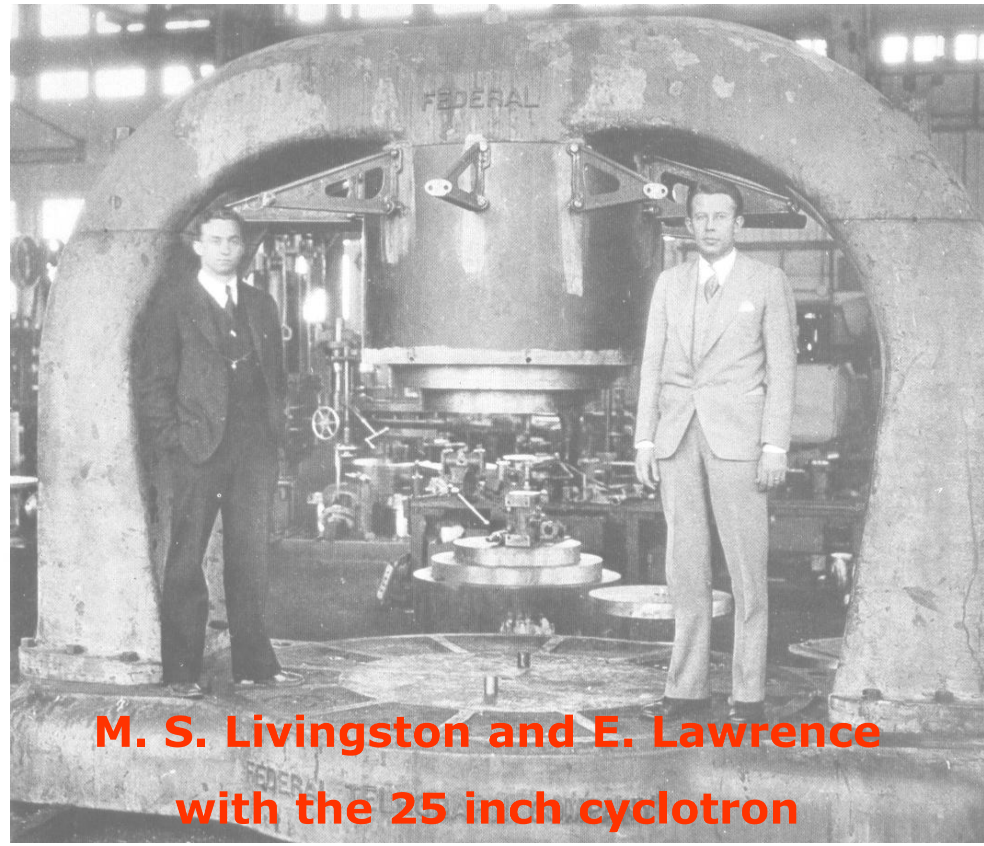
Marie Curie (1867 – 1934) **Pierre Curie (1859 – 1906)**

Tools for (medical) physics: the cyclotron

1930

Ernest Lawrence invents the cyclotron



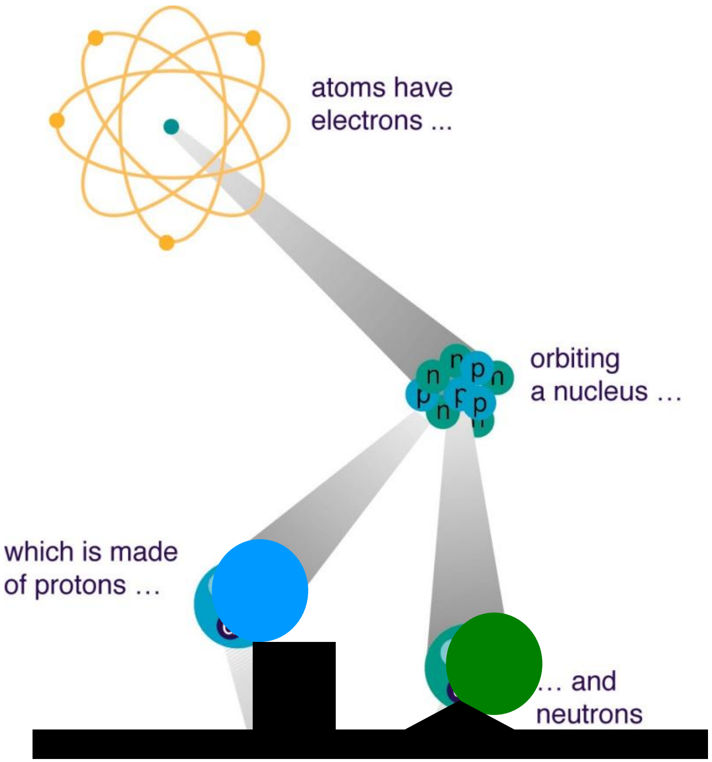


James Chadwick

(1891 – 1974)

1932

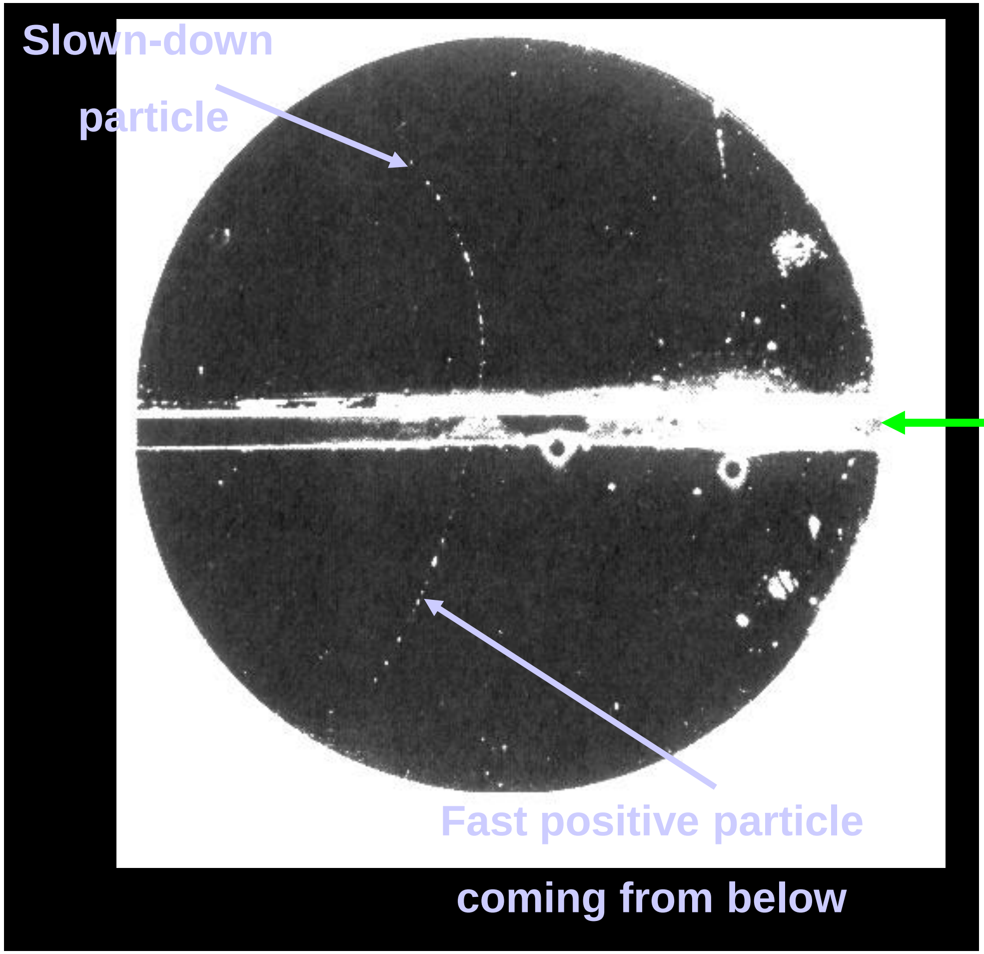
Discovery of the neutron



The beginnings of modern physics and of medical physics

1932 – C. D. Anderson

Discovery of the positron



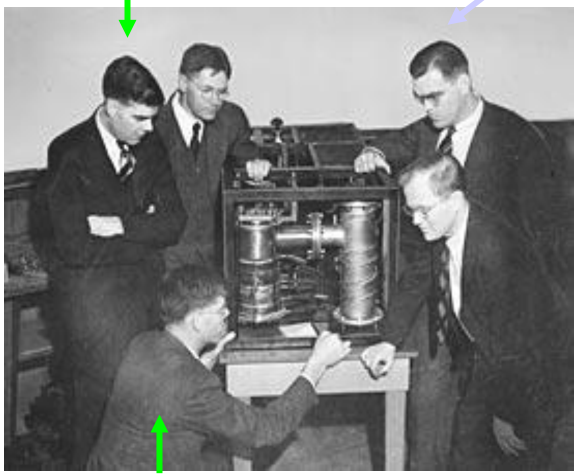
Layer of lead

Inserted in a cloud chamber

Tools for (medical) physics: the electron linac

Sigmur Varian

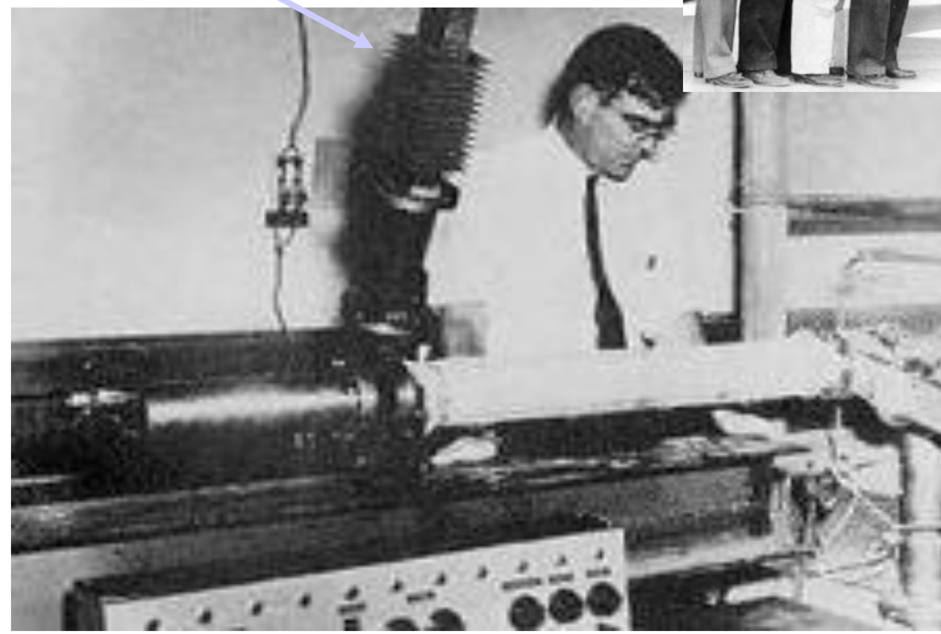
William W. Hansen



Russell Varian

1939

Invention of the klystron



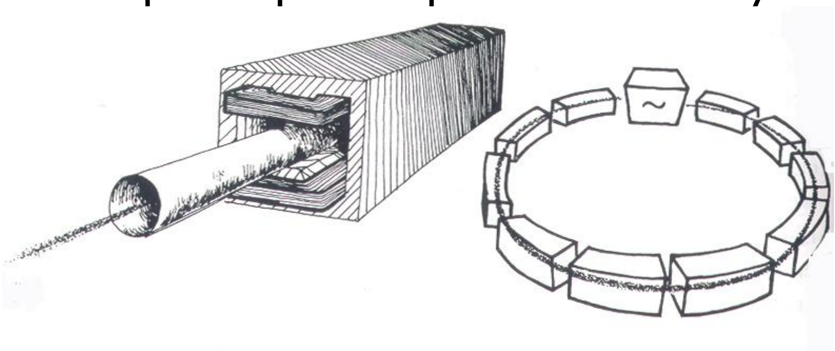
1947
first linac for electrons
4.5 MeV and 3 GHz

Tools for (medical) physics: the synchrotron

1945: E. McMillan and V.J.Veksler

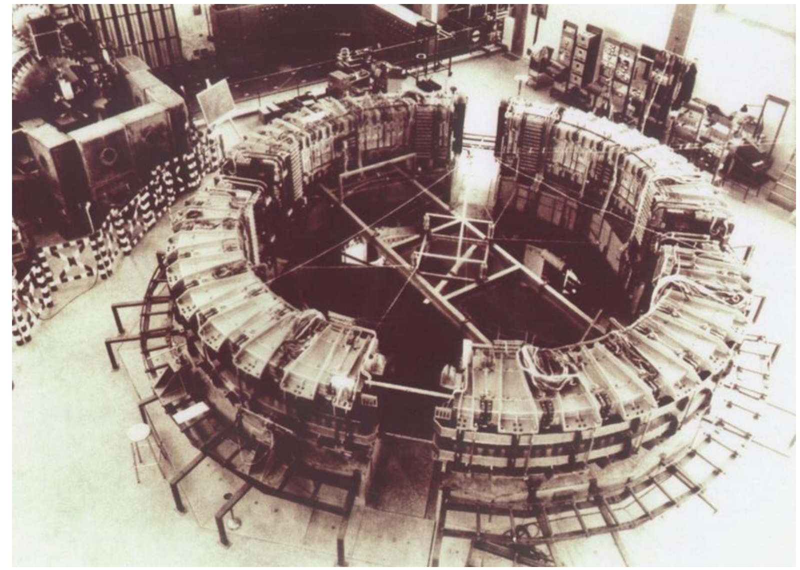
discover the

principle of phase stability



1 GeV electron synchrotron

Frascati - INFN - 1959

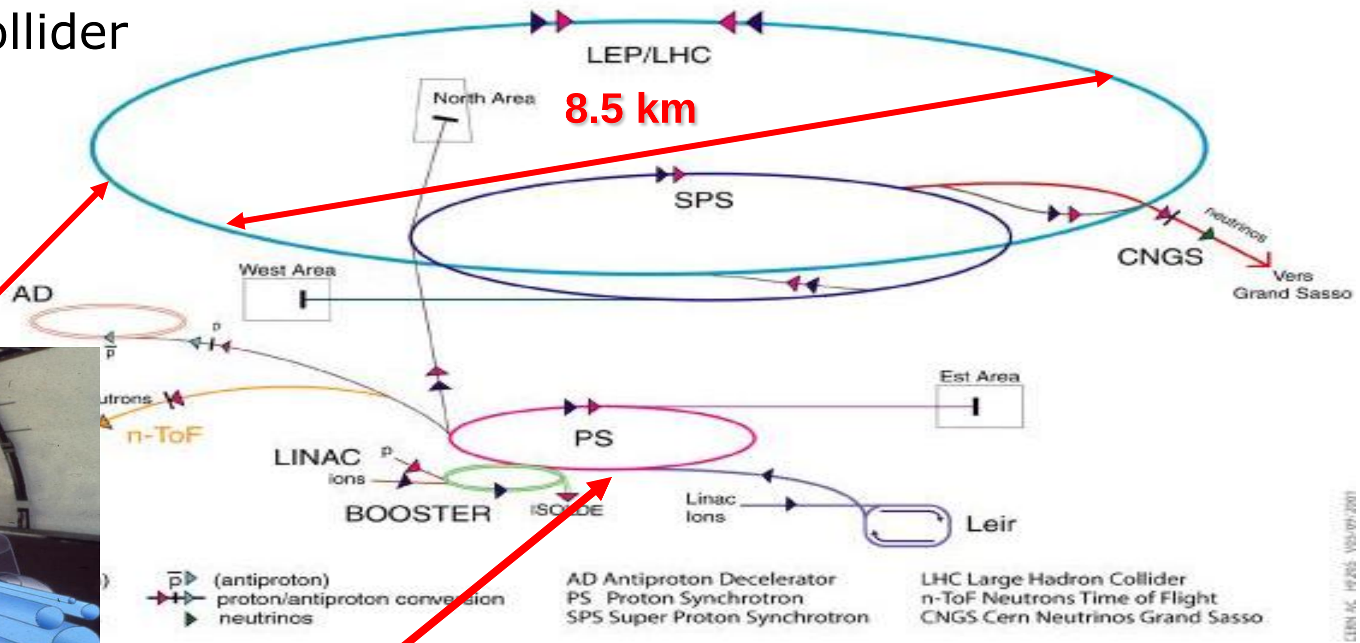


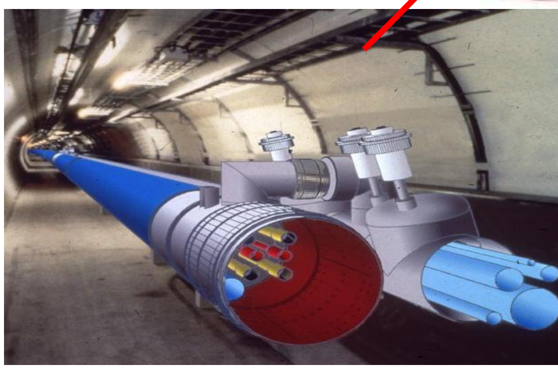
6 GeV proton synchrotron

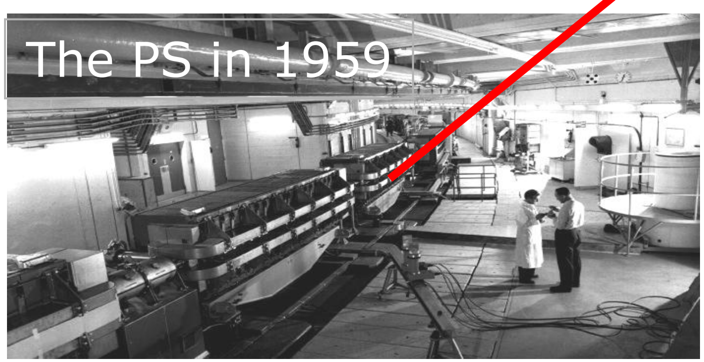
Bevatron - Berkeley - 1954

CERN accelerators

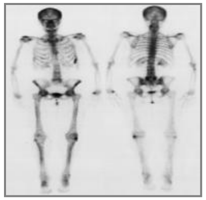
Large Hadron Collider
7 TeV + 7 TeV
Start in 2008



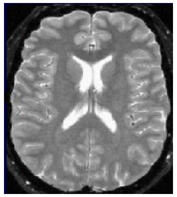
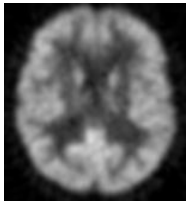



The PS in 1959

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

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	

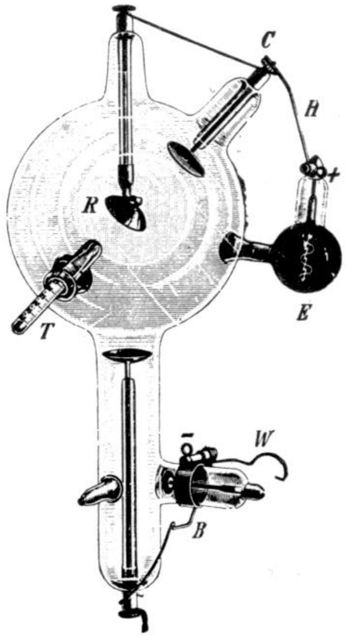
Medical imaging

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.

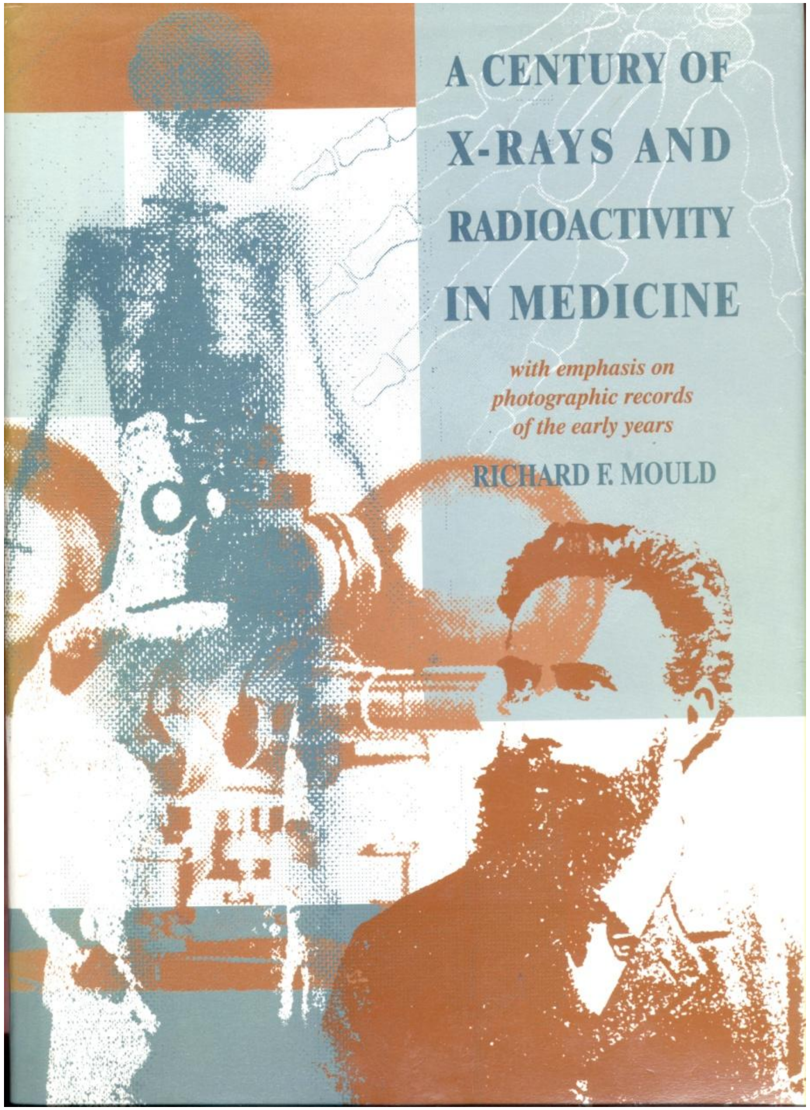


MONOPOL

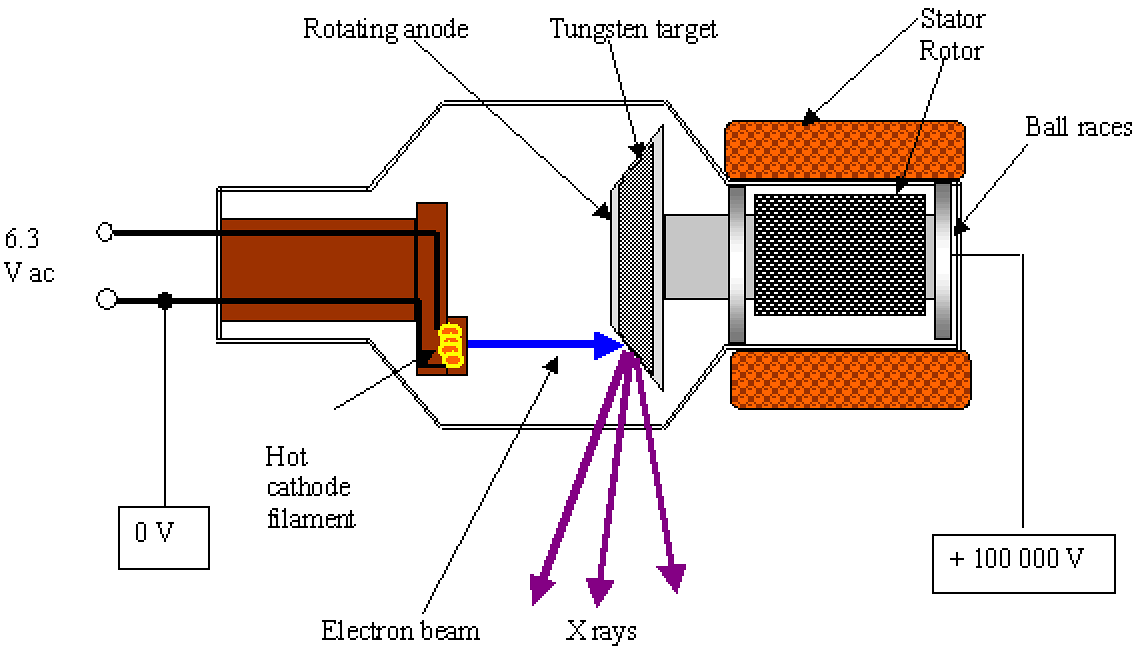
Schutzmarke.

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 Kohler's specification by 1914. (Courtesy: Siemens AG, Erlangen.)



Medical imaging: x-ray generator and image intensifier



X-ray tube

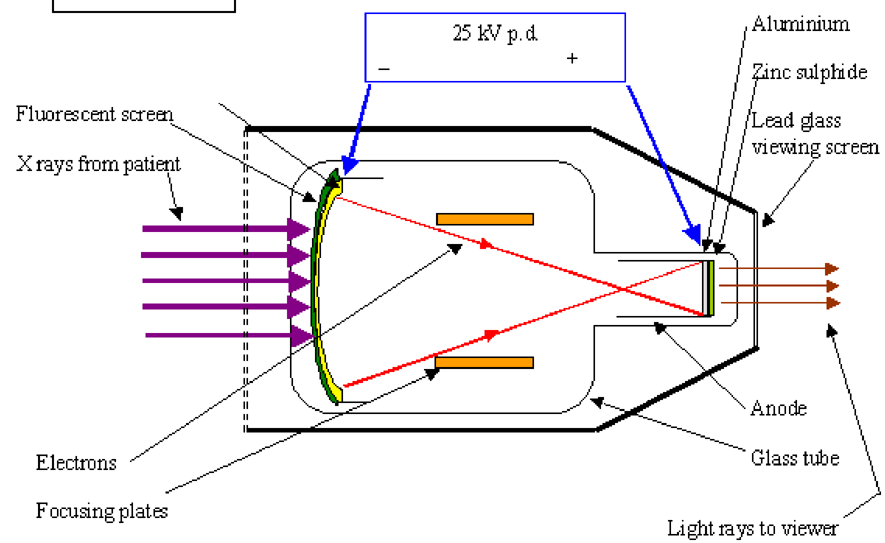
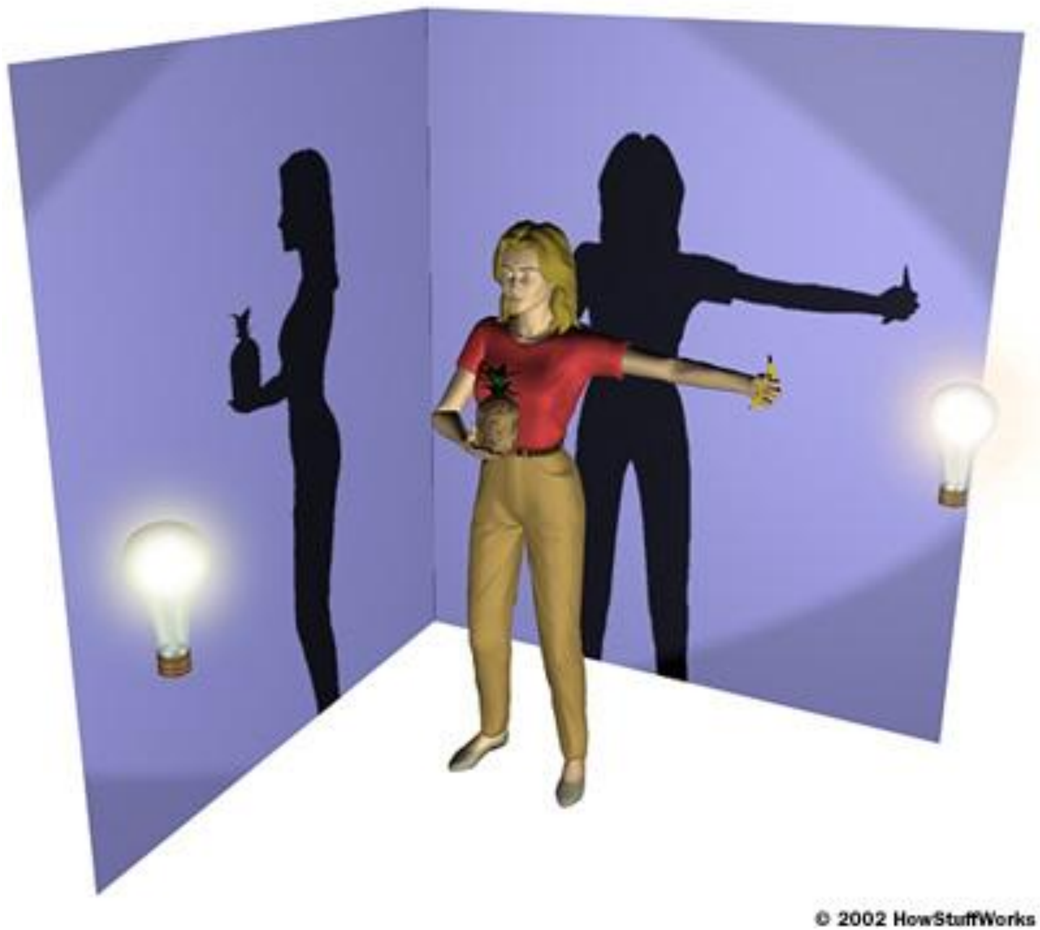


Image intensifier

X-ray image versus CT scan

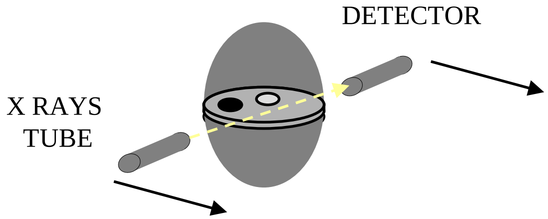
A conventional X-ray image is basically a shadow: you shine a “light” on one side of the body, and a piece of film on the other side registers the silhouette of the bones (to be more precise, organs and tissues of different densities show up differently on the radiographic film).



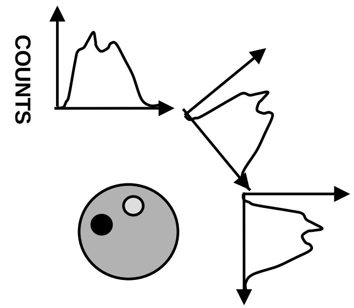
Shadows give an incomplete picture of an object's shape.

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.

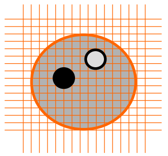
X-ray computerized tomography (CT)



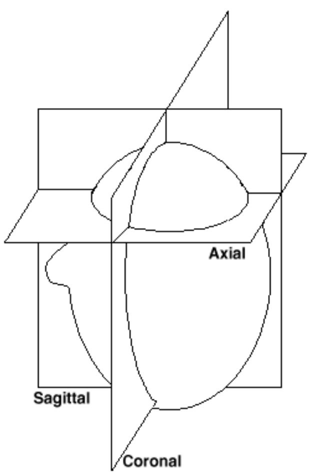
A – LINEAR SAMPLING



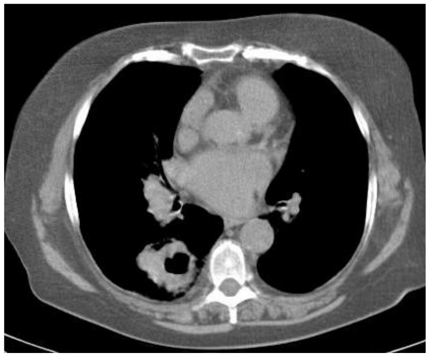
B – ANGULAR SAMPLING



C - RECONSTRUCTION



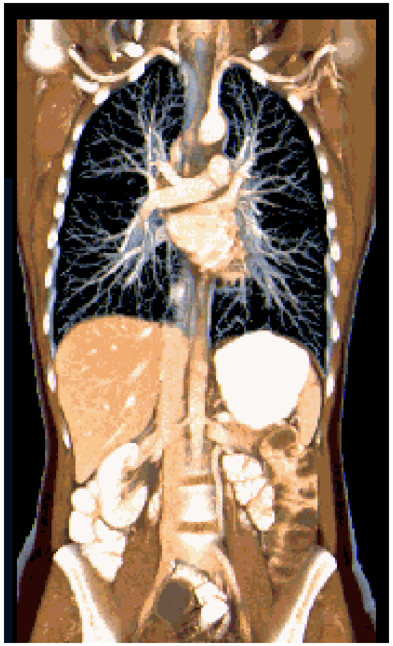
This is the basic idea of computer aided tomography. In a CAT scan machine, the X-ray beam moves all around the patient, scanning from hundreds of different angles. The computer takes all this information and puts together a **3-D image** of the body.

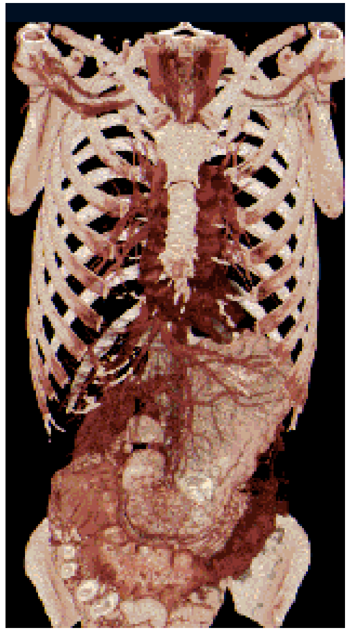


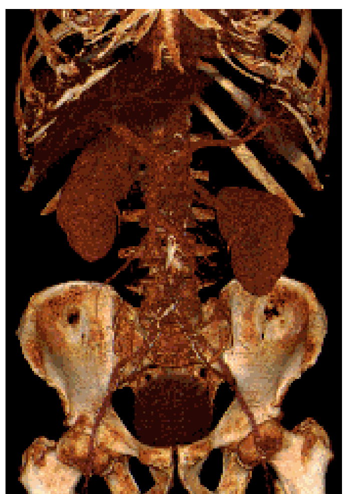
X RAYS
COMPUTERIZED TOMOGRAPHY

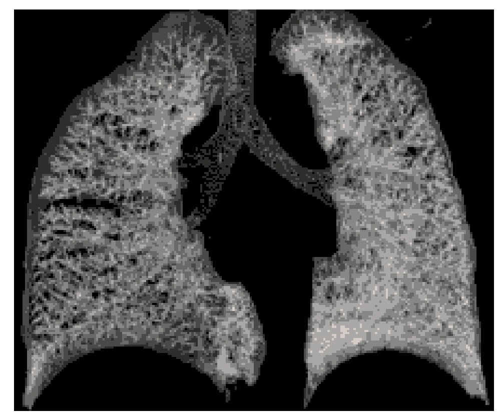
Volumetric CT

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

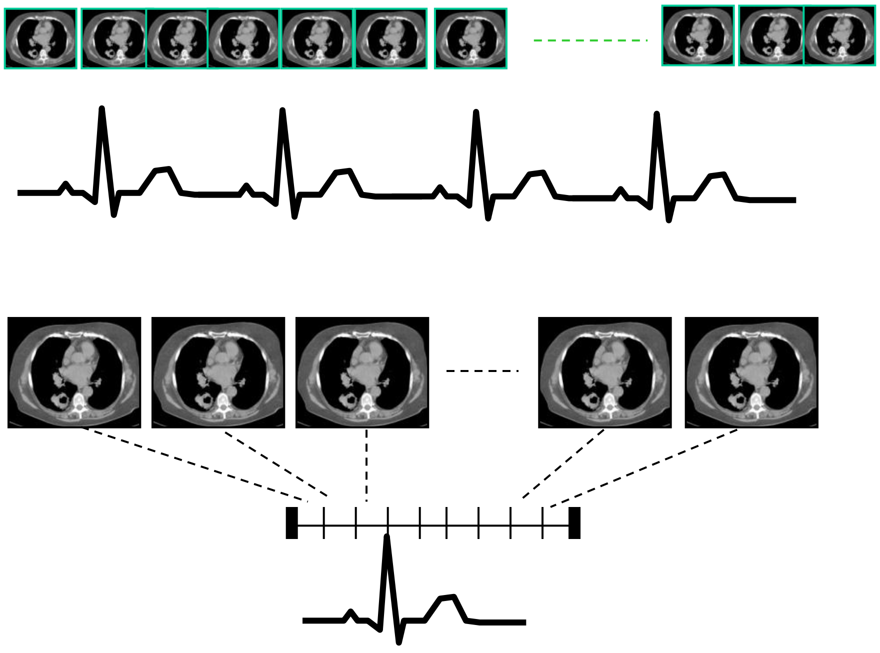








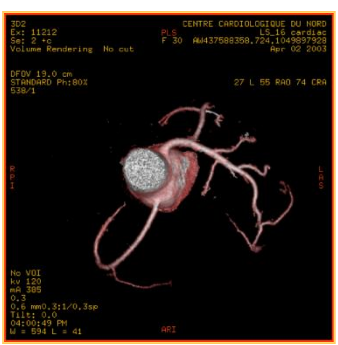
Cardiac CT

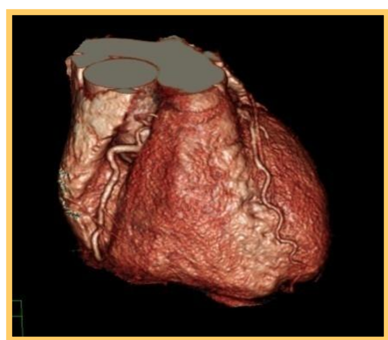


DYNAMIC CT ACQUISIION

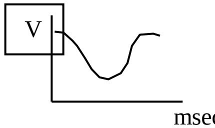
ECG

PHASES OF A CARDIAC CYCLE





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



FUNCTIONAL PARAMETERS

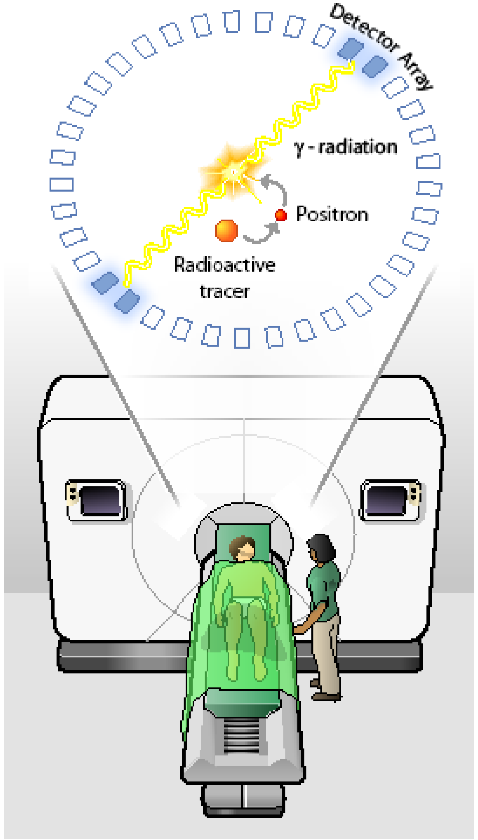
VOLUME RENDERED IMAGE OF HEART AND VESSELS

Positron Emission Tomography (PET)

Cyclotron

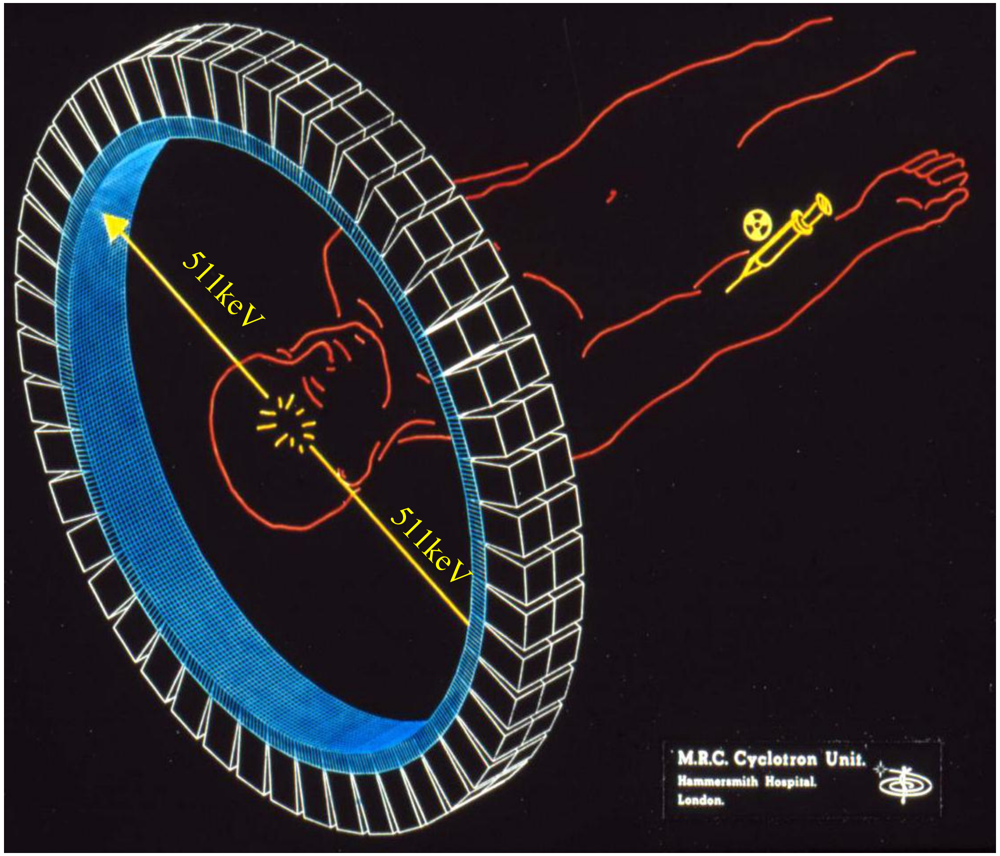
ISOTOPES	Half-Life	
11-C	20.4 min,	"natural"
13-N	10.0 min	"natural"
15-O	2.0 min	"natural"
18-F	109.8 min	"pseudo-natural"

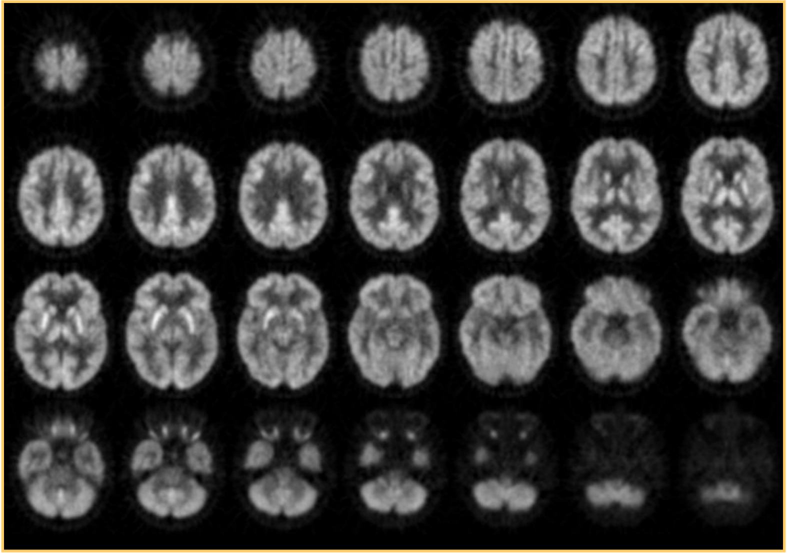
Radiochemistry



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

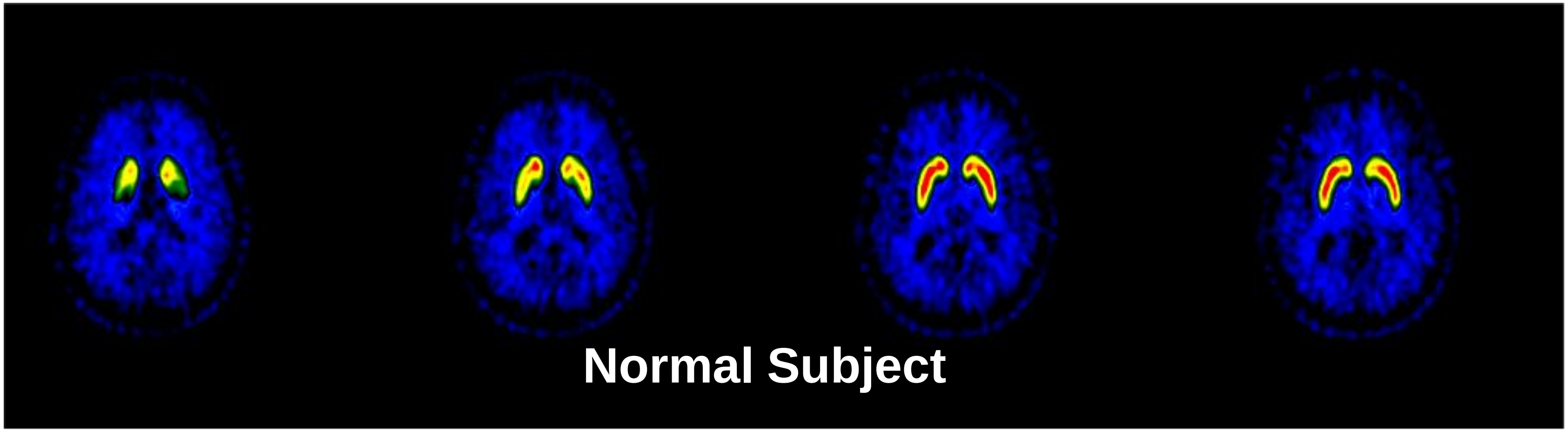
Positron Emission Tomography (PET)

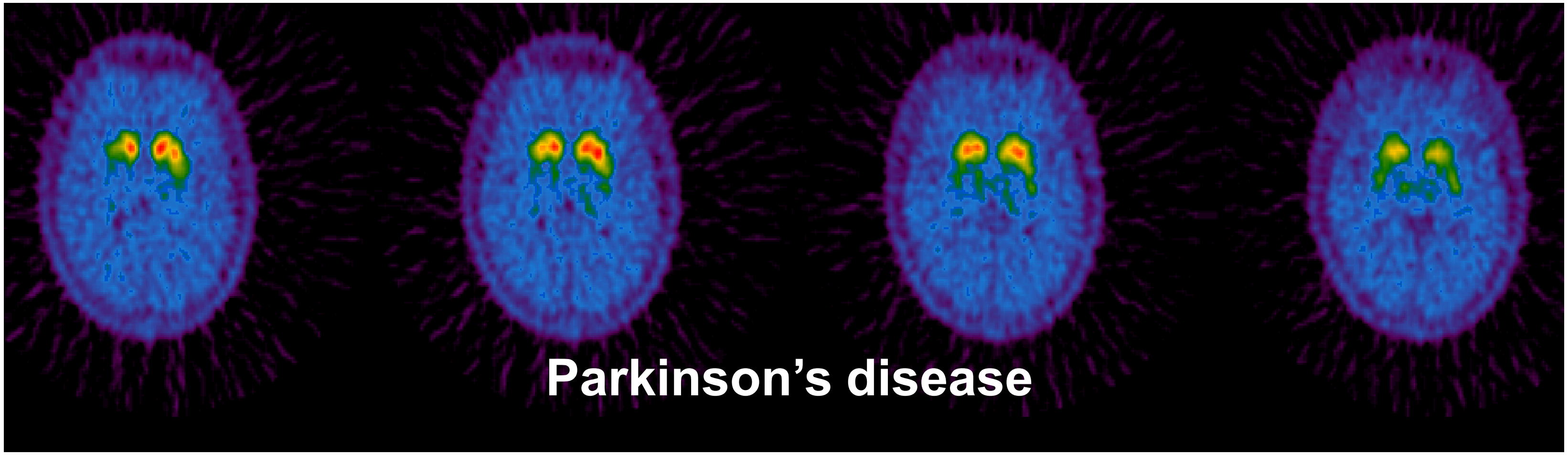




COVERAGE:
~ 15-20 cm
SPATIAL RESOLUTION:
~ 5 mm
SCAN TIME to cover an entire organ:
~ 5 min
CONTRAST RESOLUTION:
depends on the radiotracer

PET functional receptor imaging



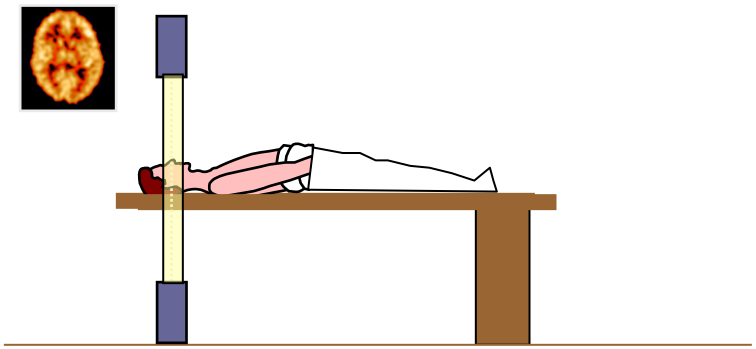


$[^{11}C]$ FE-CIT

Courtesy HSR MILANO

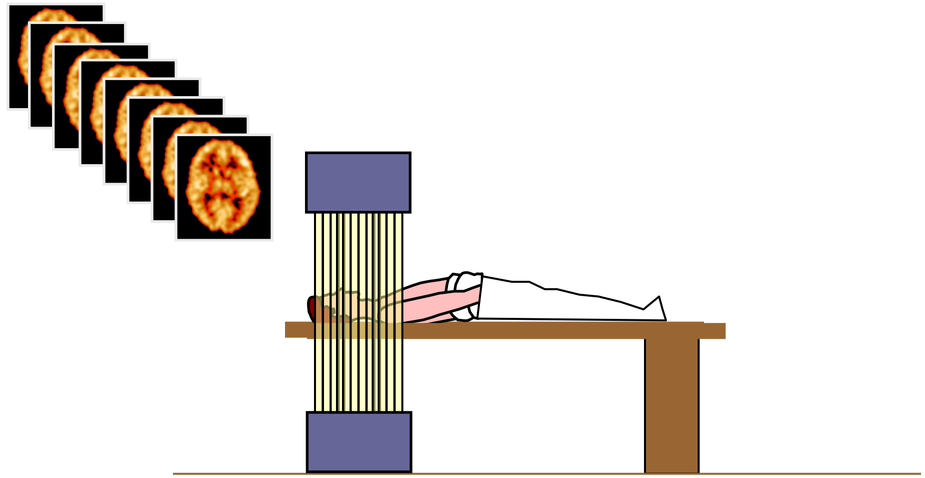
PET coverage and axial sampling

FIRST GENERATION PET



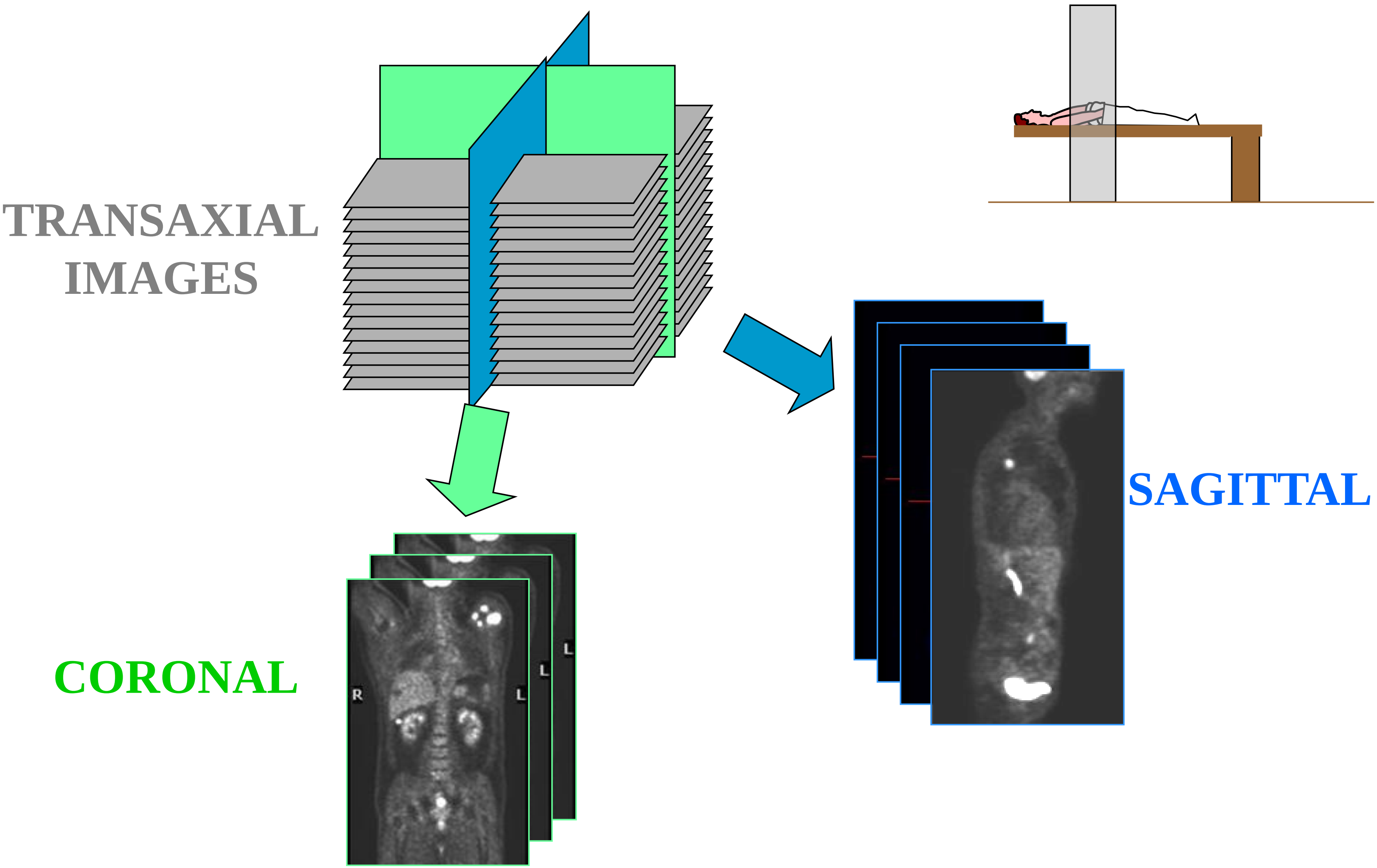
1 SLICE – 2 cm

CURRENT GENERATION PET

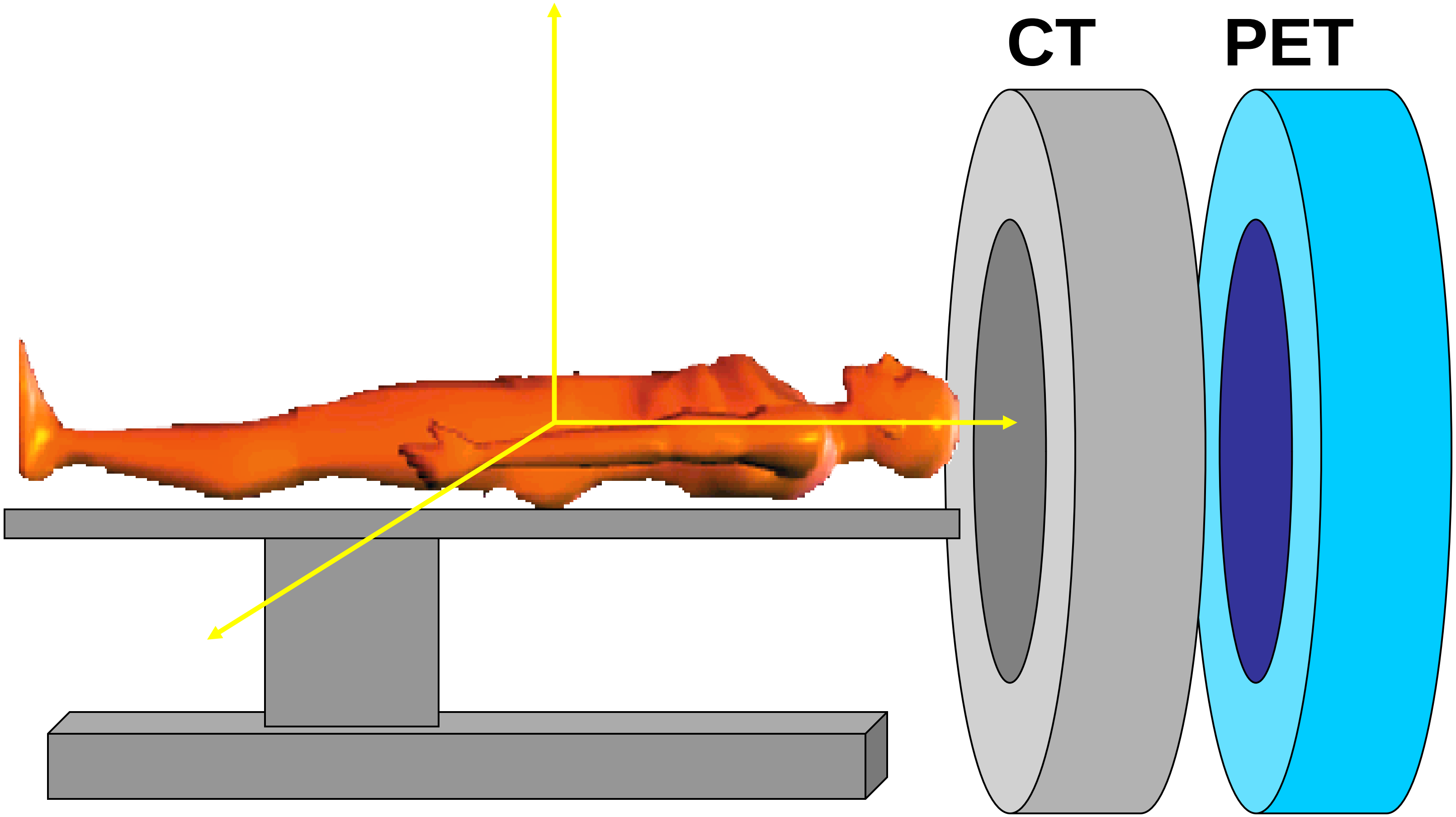


> 40 SLICES – 6 mm
Axial FOV: 15 –20 cm

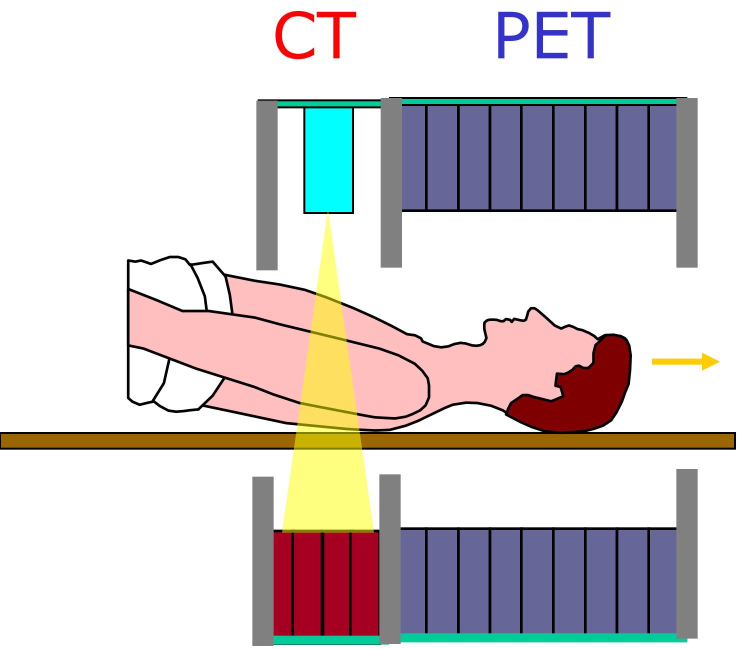
PET: total body studies

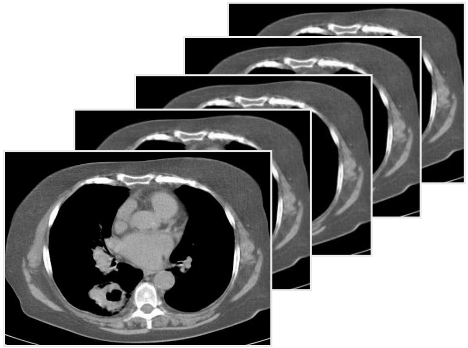


PET/CT scanner



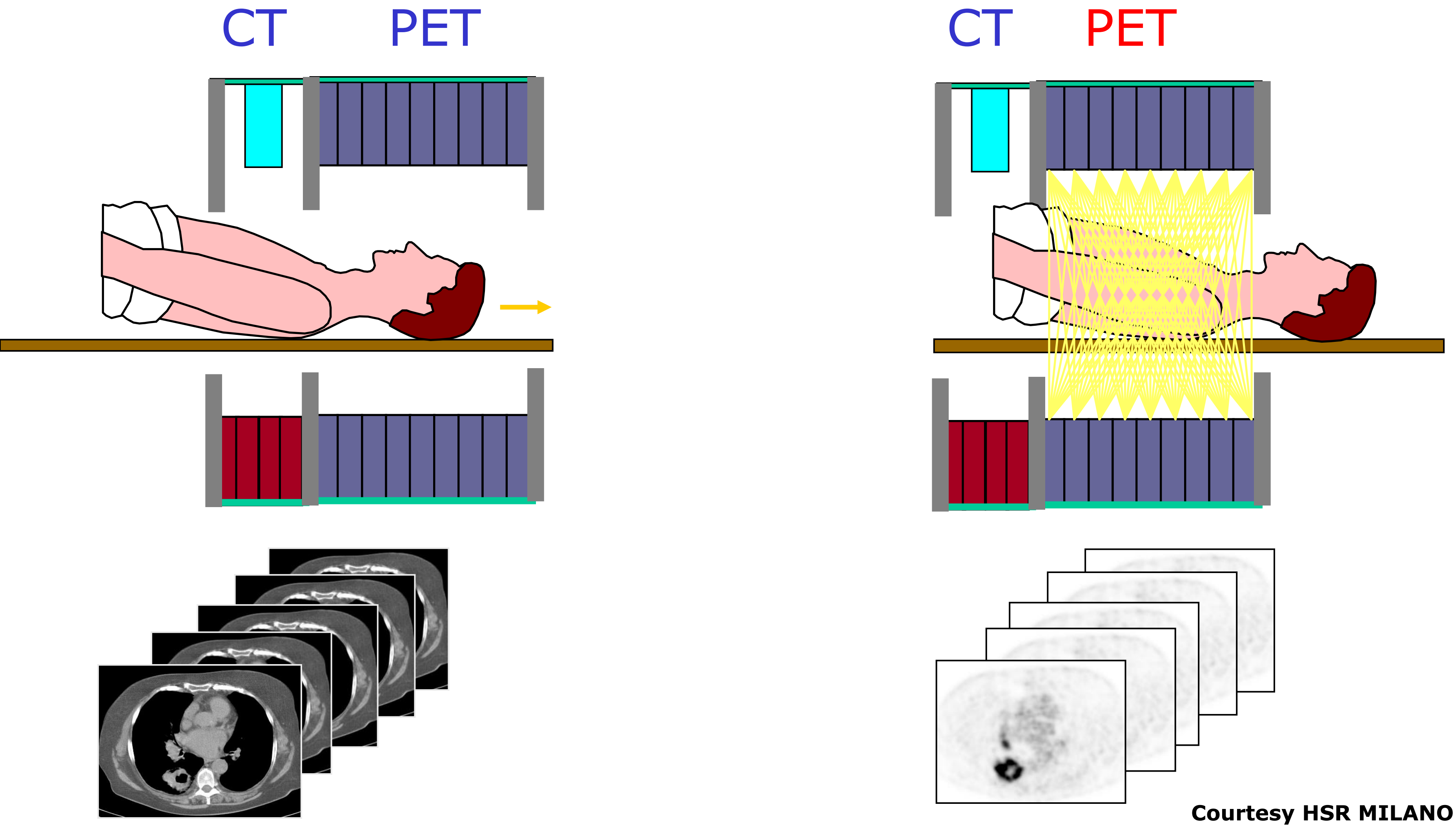
PET/CT scanner





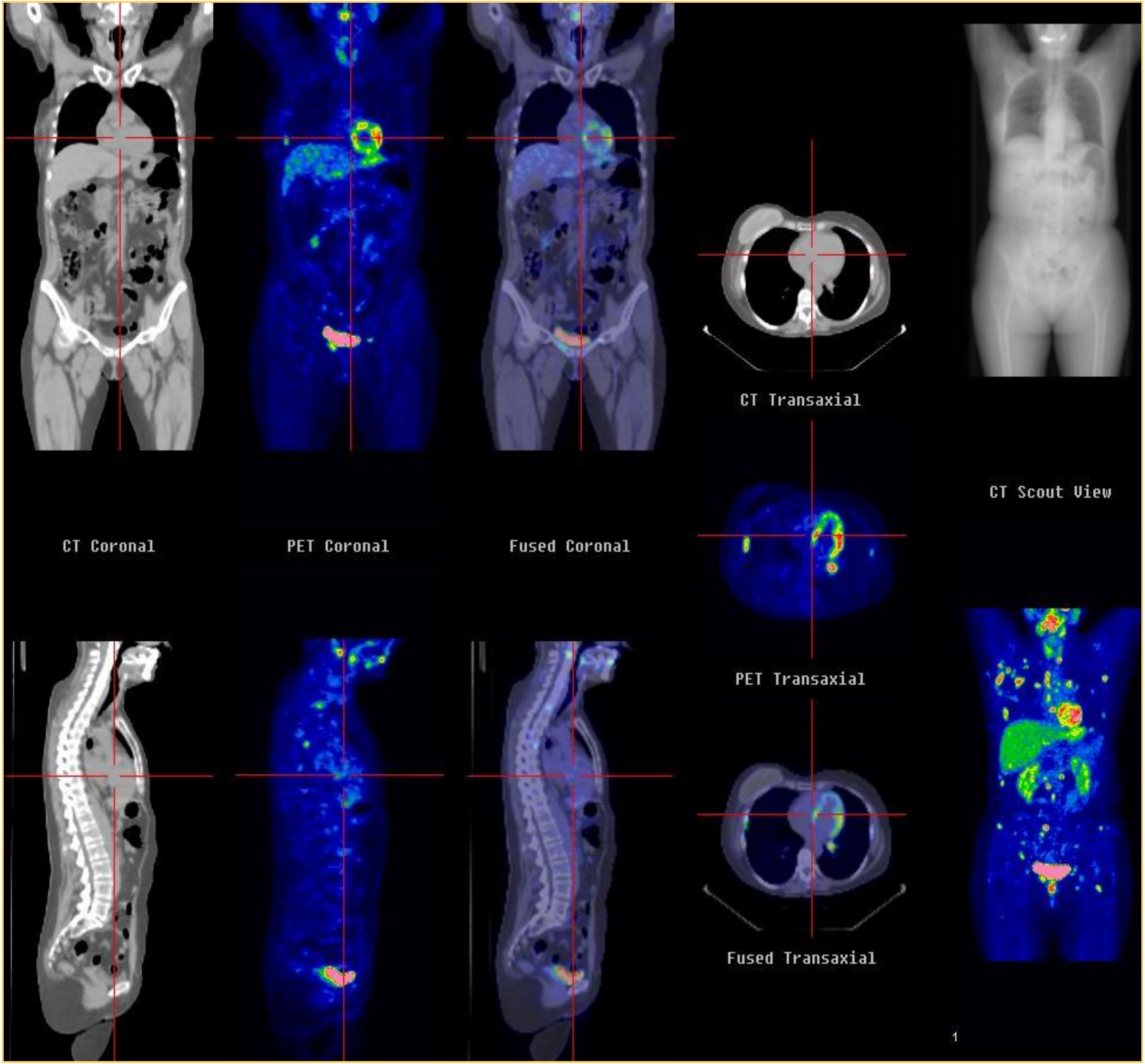
Courtesy HSR MILANO

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 GeV)	~120	
Synchrotron radiation sources	>100	
Medical radioisotope production	~1000	}
Radiotherapy accelerators	> 7500	} 10000
Research acc. included biomedical research	~1000	}
Industrial processing and research	~1500	
Ion implanters, surface modification	>7000	
TOTAL	> 18000	

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

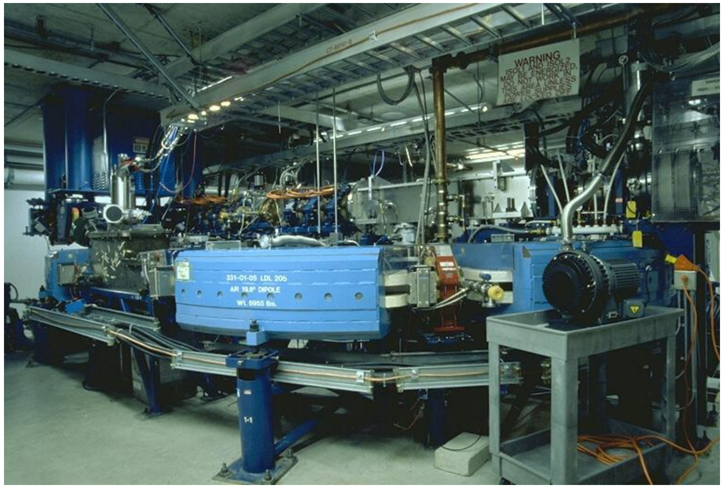
Three classes of medical accelerators

Electron linacs for conventional radiation therapy, including advanced modalities:

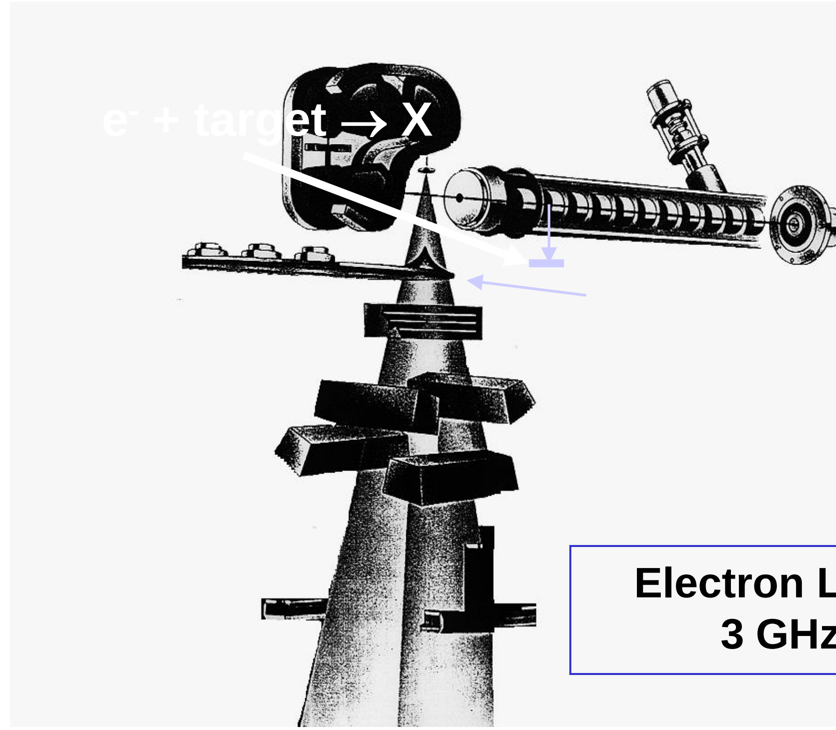
- Cyberknife
- IntraOperative RT (IORT)
- Intensity Modulated RT

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



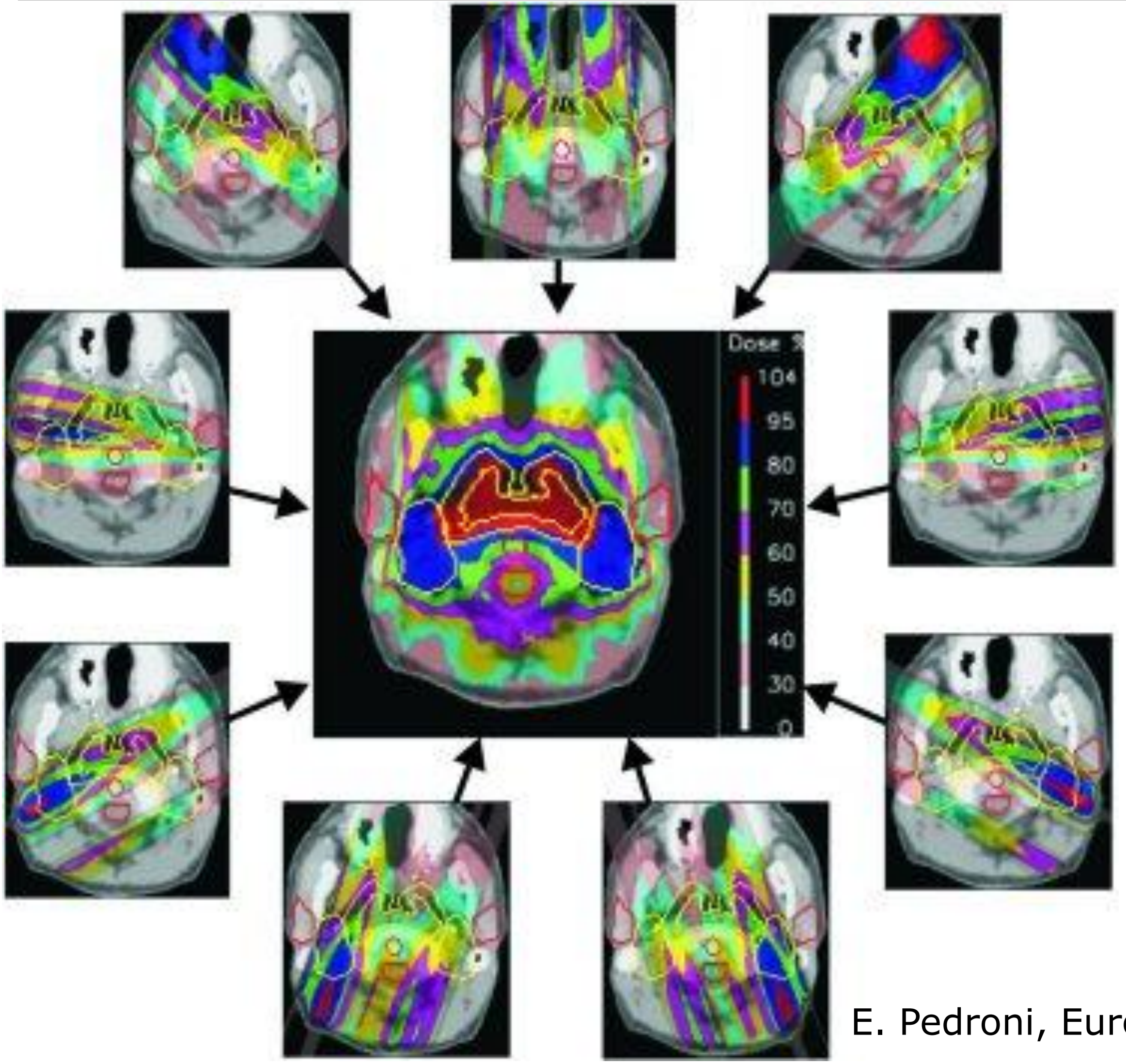
Electron Linac
3 GHz

6 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

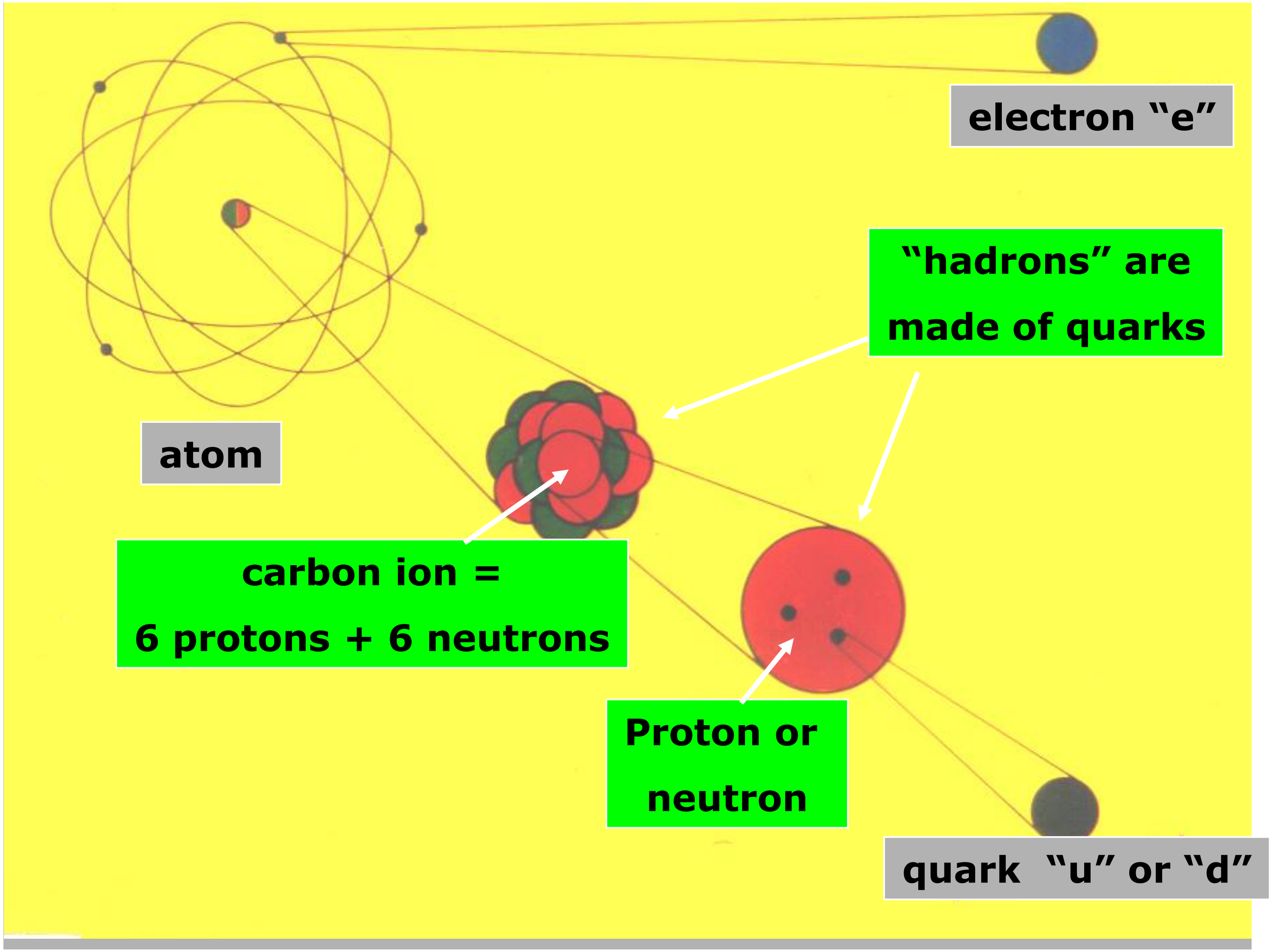


An example of intensity modulated treatment planning with photons. Through the addition of 9 fields it is possible to construct a highly conformal dose distribution with good dose sparing in the region of the brain stem (courtesy of T. Lomax, PSI).

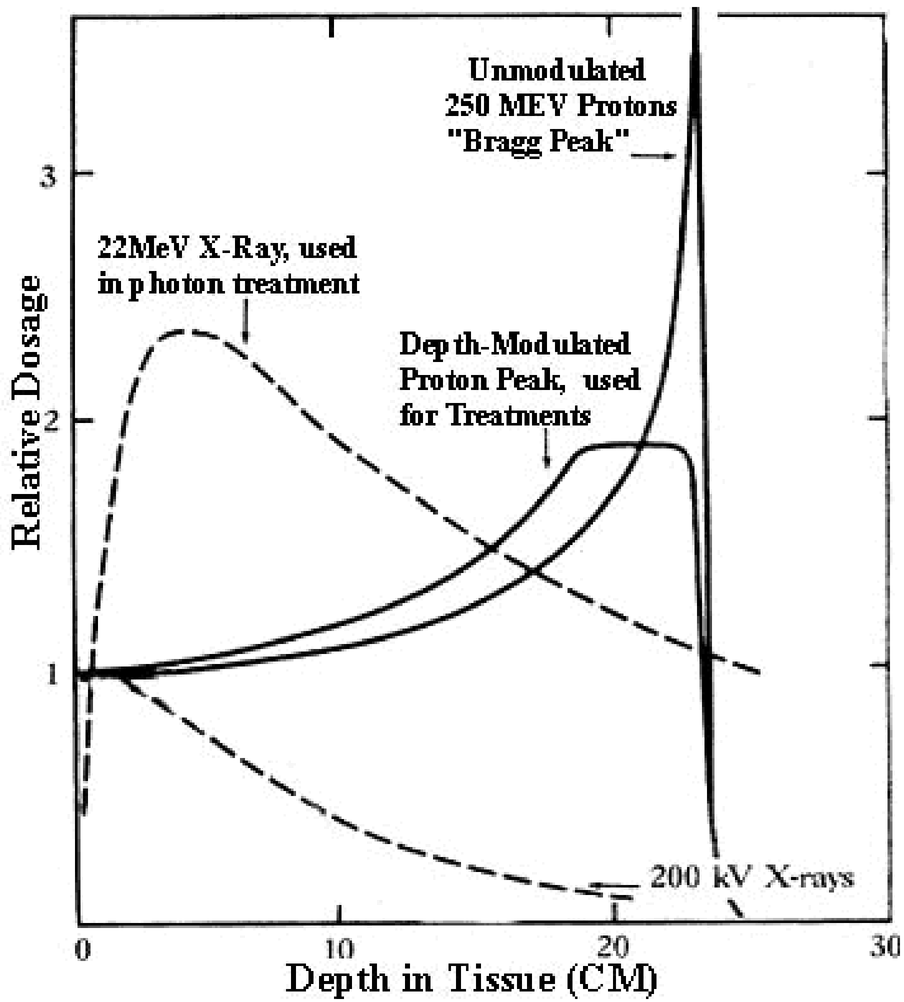
E. Pedroni, Europhysics News (2000) Vol. 31 No. 6

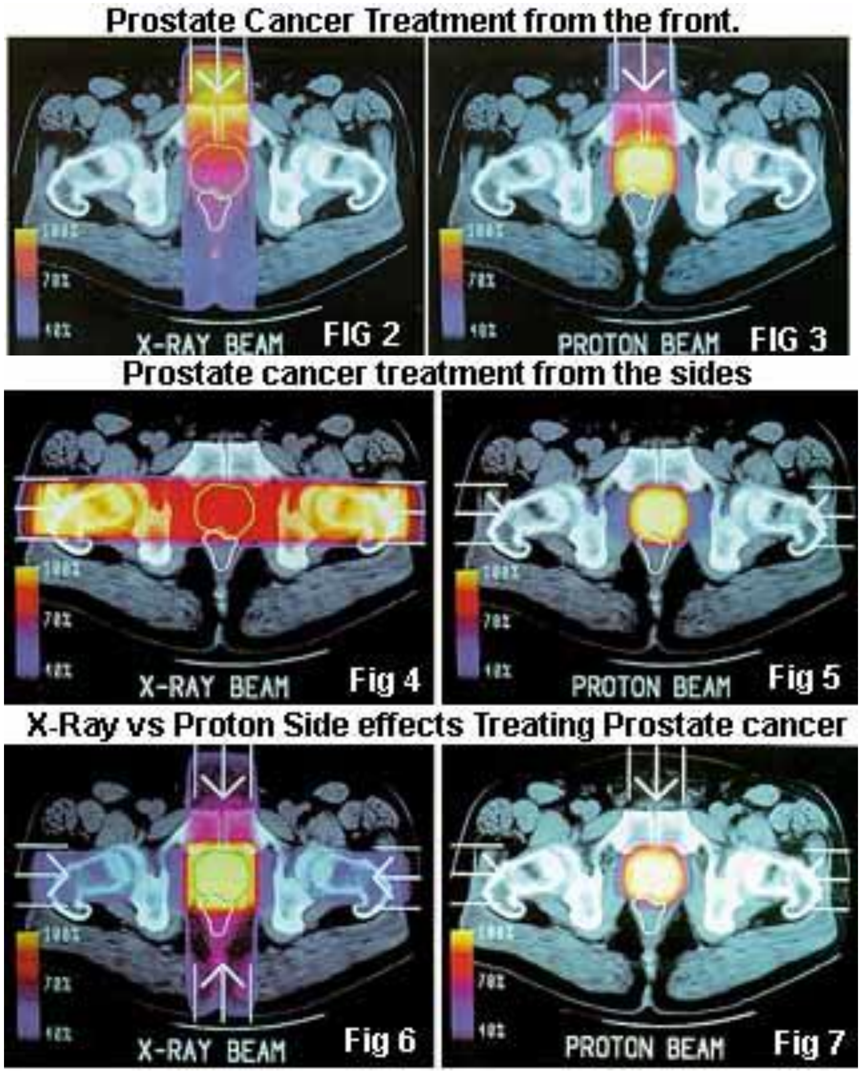
Yet X-rays have a comparatively poor energy deposition as compared to protons and carbon ions

Hadrontherapy: n, p and C-ion beams

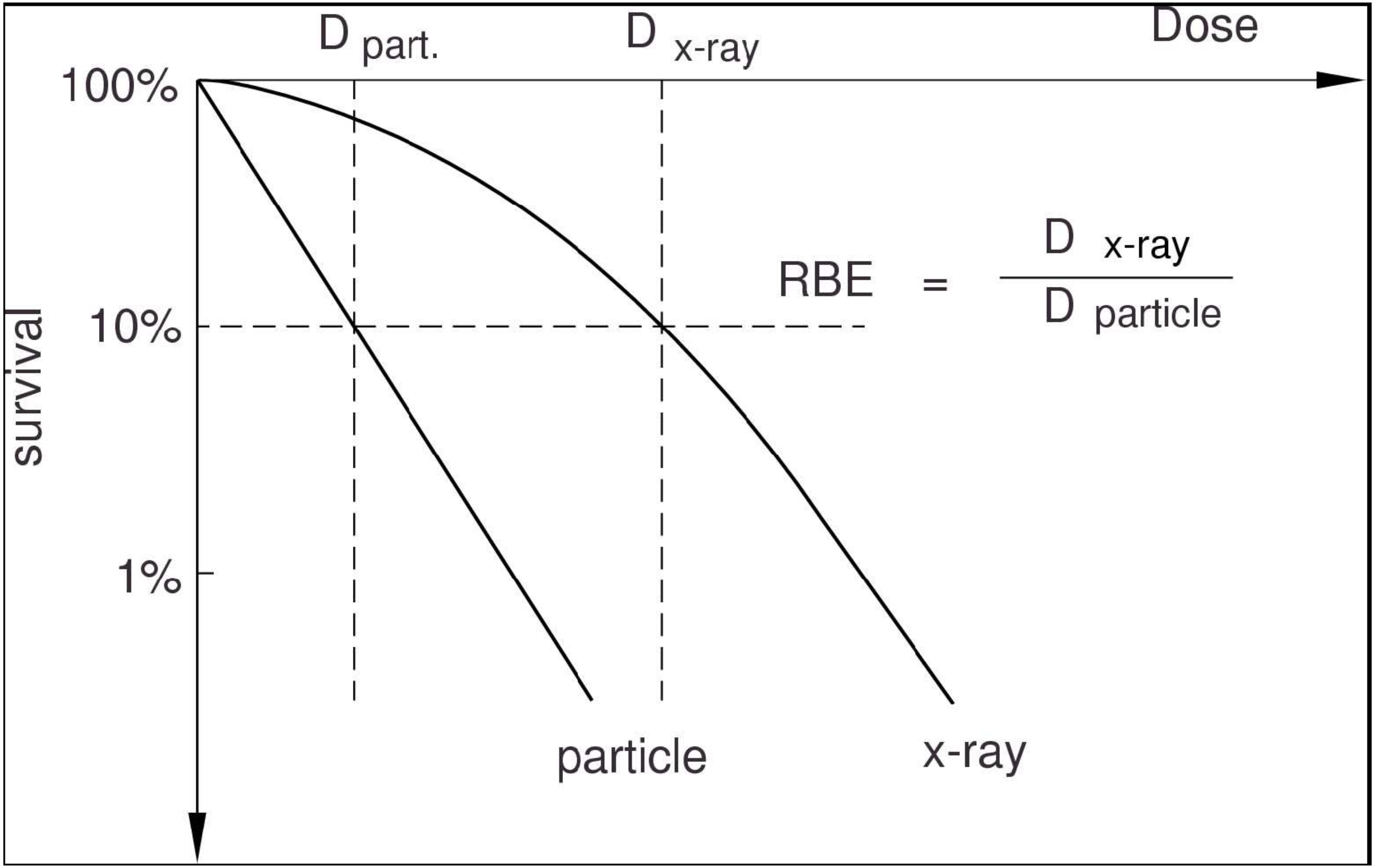


Proton radiation therapy





Radiobiological effectiveness (RBE)



G. Kraft, 2007 - Results for C ions

Indication	End point	Results photons	Results carbon HIMAC-NIRS	Results carbon GSI
Chordoma	local control rate	30 – 50 %	65 %	70 %
Chondrosarcoma	local control rate	33 %	88 %	89 %
Nasopharynx carcinoma	5 year survival	40 -50 %	63 %	
Glioblastoma	av. survival time	12 months	16 months	
Choroid melanoma	local control rate	95 %	96 % (*)	
Paranasal sinuses tumours	local control rate	21 %	63 %	
Pancreatic carcinoma	av. survival time	6.5 months	7.8 months	
Liver tumours	5 year survival	23 %	100 %	
Salivary gland tumours	local control rate	24-28 %	61 %	77 %
Soft-tissue carcinoma	5 year survival	31 – 75 %	52 -83 %	

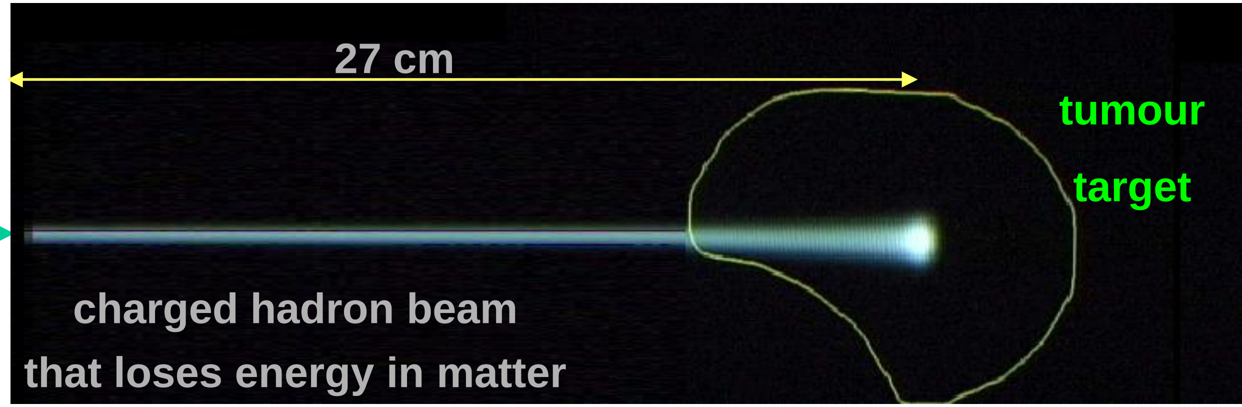
Hadrontherapy

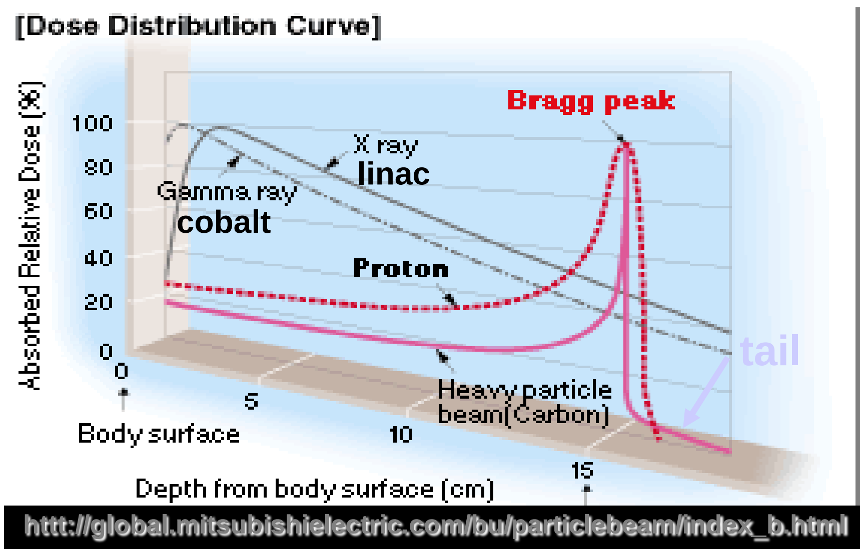
Charged hadrons have a much better energy deposition with respect to X-rays

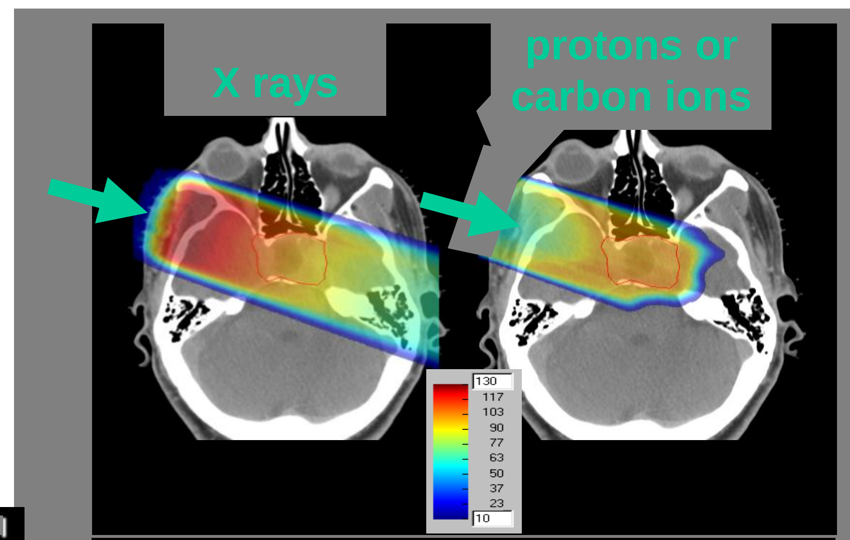
200 MeV protons

4800 MeV carbon ions

which control radioresistant tumours





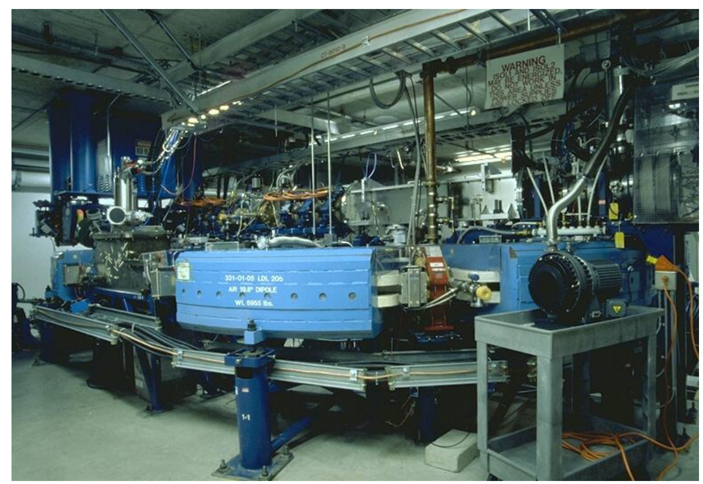


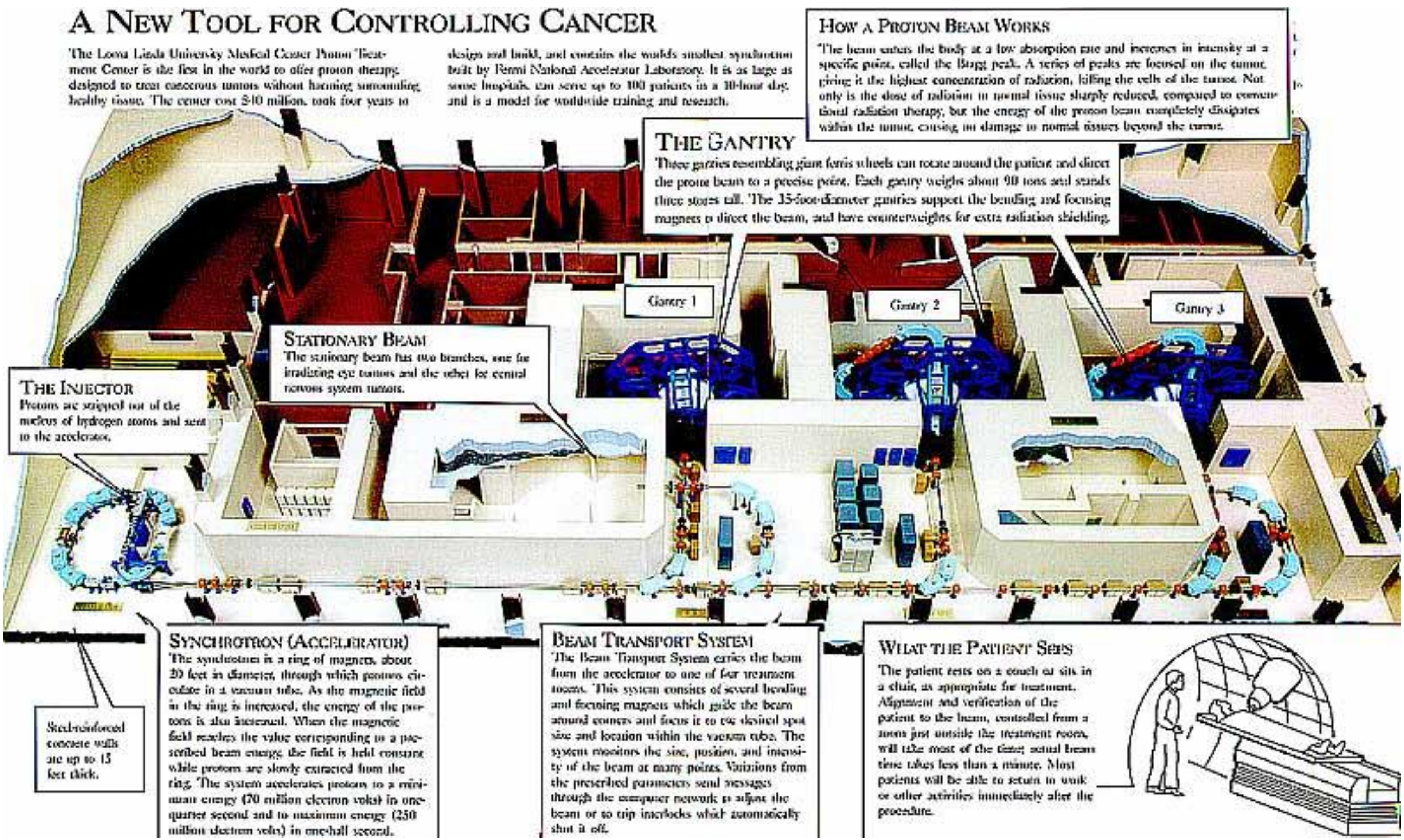
Proton radiation therapy


IBA

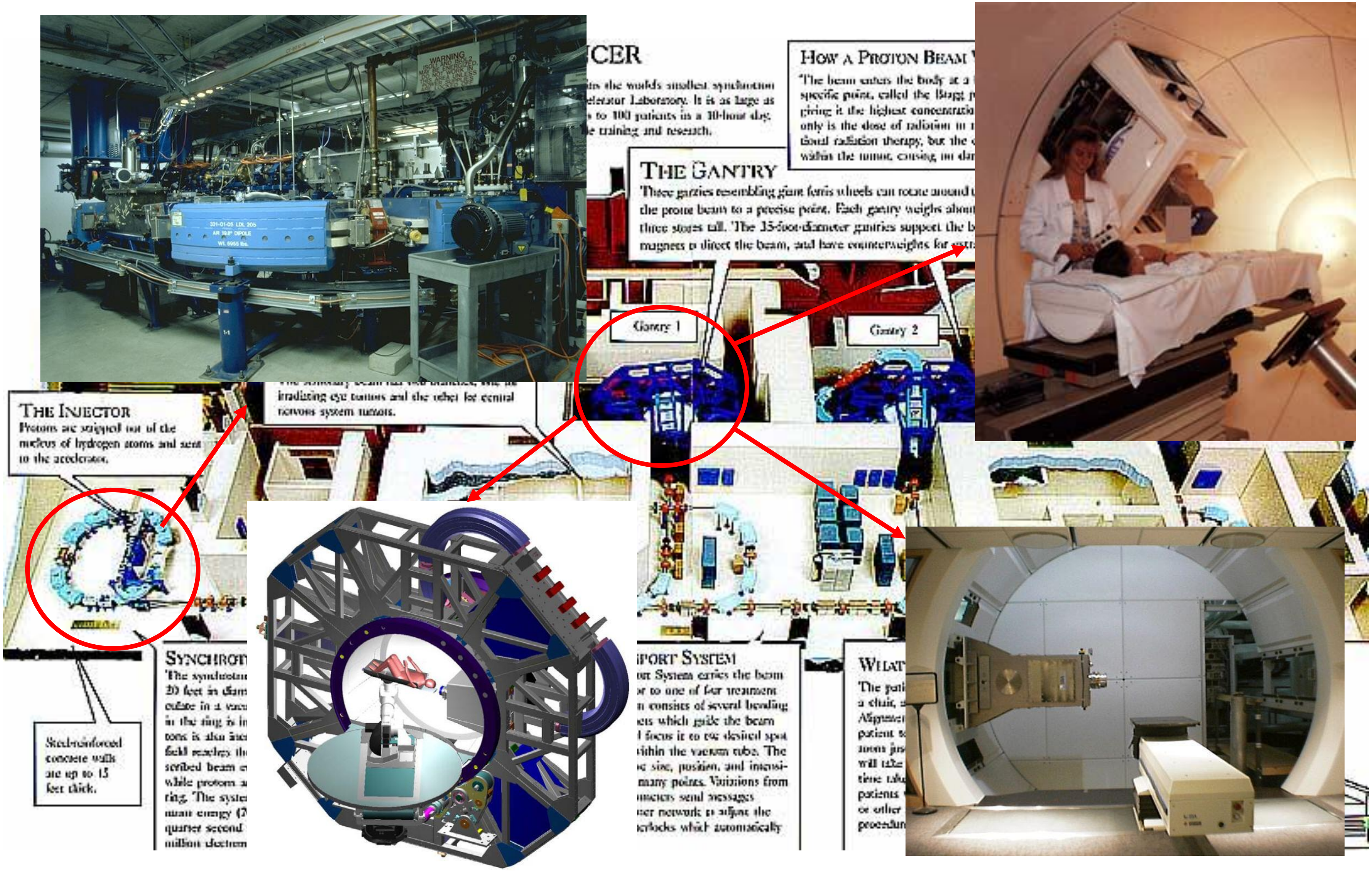

Accel-Varian


Hitachi


Loma Linda (built by FNAL)


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 $40 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 to 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 gantries 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 35-foot-diameter gantries support the bending and focusing magnets to direct the beam, and have counterweights for extra radiation shielding.
Gantry 1
Gantry 2
Gantry 3
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 accelerator.
Steel-reinforced concrete walls are up to 15 feet thick.
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 (70 million electron volts) in one-quarter second and to maximum energy (250 million electron volts) in one-half second.
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)



Hadron-therapy in Europe

O in operation
in construction
Δ planned

Yellow = p only
Orange = p and C

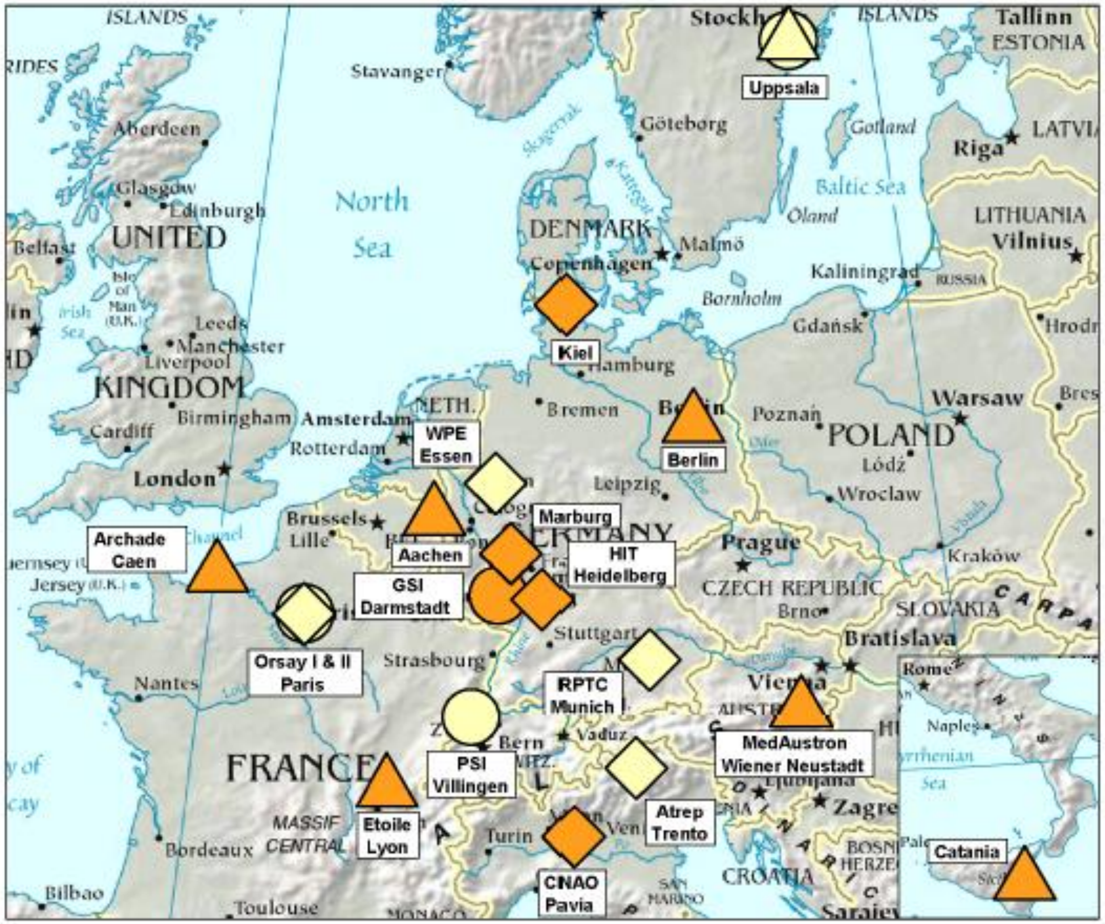
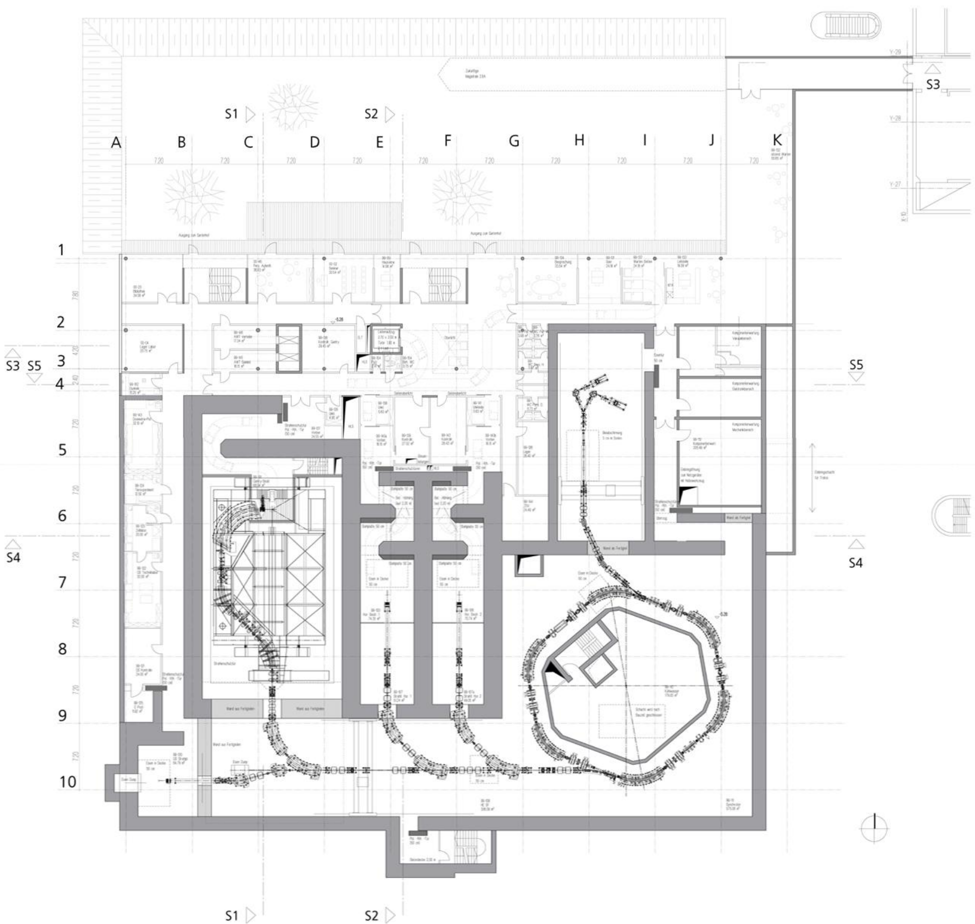


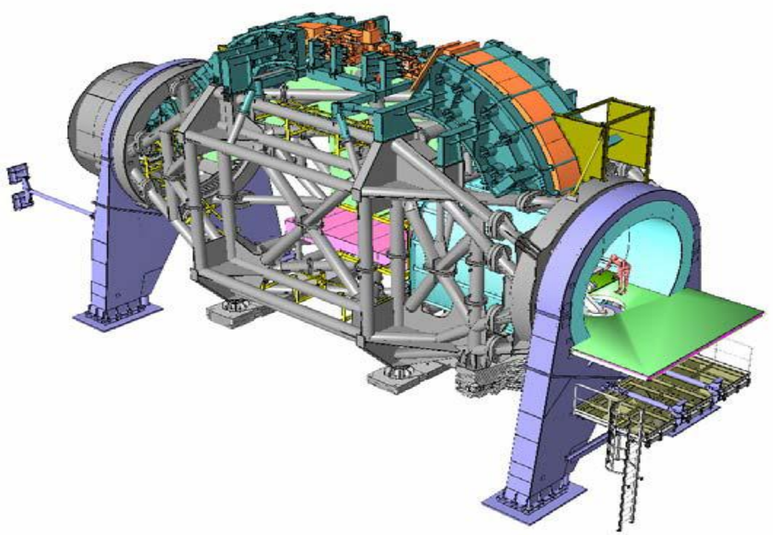
FIGURE 1. Map of Europe showing the present status of the ion beam therapy. The status of different projects is given by the symbols: in operation ◯; under construction ◇; planned △
The type of the facilities is indicated by the colors: yellow – proton only; orange – Carbon and protons.

G. Kraft, Proc. of CAARI 2008, AIP, p. 429

Heavy Ion Therapy Unit at the University of Heidelberg clinics

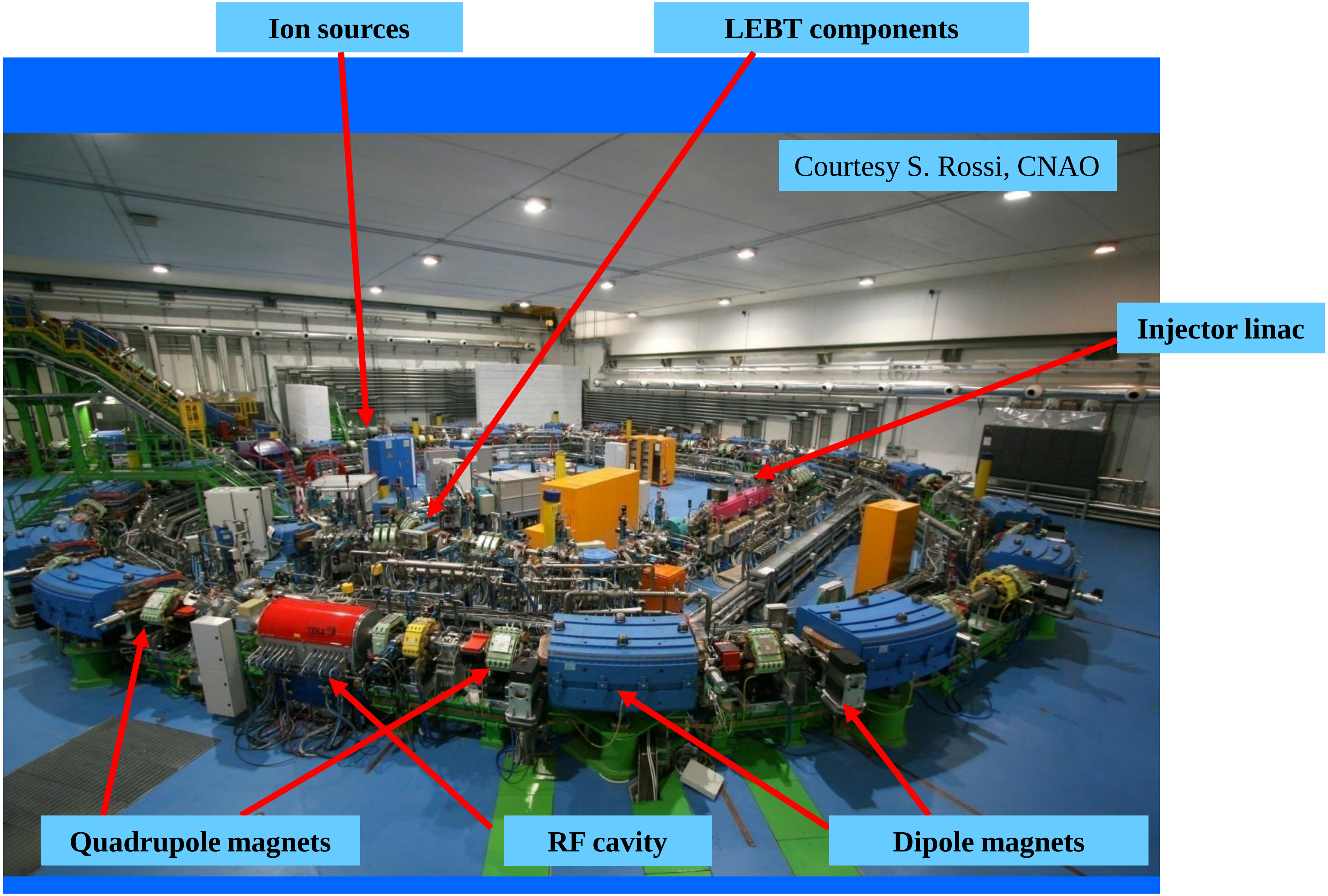


Courtesy HIT



The HIT heavy ion gantry, weight about 600 tons

National Centre for Oncological Hadrontherapy, CNAO, Italy



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.