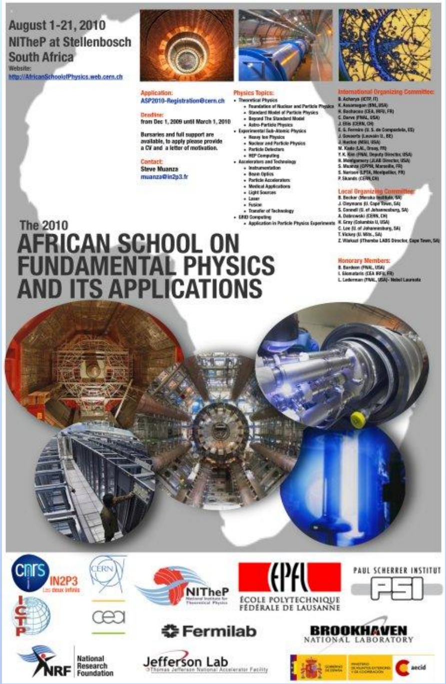
African School of Physics 2010


August 1-21, 2010
NITheP at Stellenbosch
South Africa
Website:
http://AfricanSchoolofPhysics.web.cern.ch

Application:
ASP2010-Registration@cern.ch

Deadline:
from Dec 1, 2009 until March 1, 2010

Bursaries and full support are available, to apply please provide a CV and a letter of motivation.

Contact:
Steve Muanza
muanza@in2p3.fr

Physics Topics:
- Theoretical Physics
  - Foundation of Nuclear and Particle Physics
  - Standard Model of Particle Physics
  - Beyond The Standard Model
  - Astro-Particle Physics
- Experimental Sub-Atomic Physics
  - Heavy Ion Physics
  - Nuclear and Particle Physics
  - Particle Detectors
  - HEP Computing
- Accelerators and Technology
  - Instrumentation
  - Beam Optics
  - Particle Accelerators
  - Medical Applications
  - Light Sources
  - Laser
  - Fusion
  - Transfer of Technology
- GRID Computing
  - Application in Particle Physics Experiments

International Organizing Committee:

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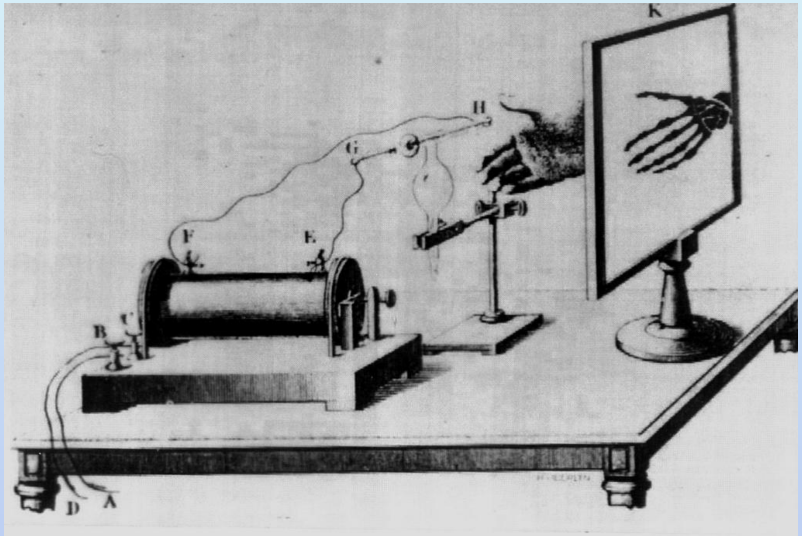
The 2010
AFRICAN SCHOOL ON FUNDAMENTAL PHYSICS AND ITS APPLICATIONS

Introduction to medical accelerators

Marco Silari
CERN, Geneva, Switzerland

The beginnings of modern physics and of medical physics

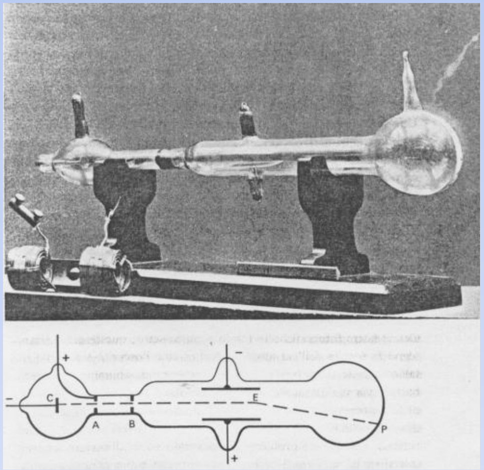


1895
discovery of X rays

Wilhelm Conrad Röntgen

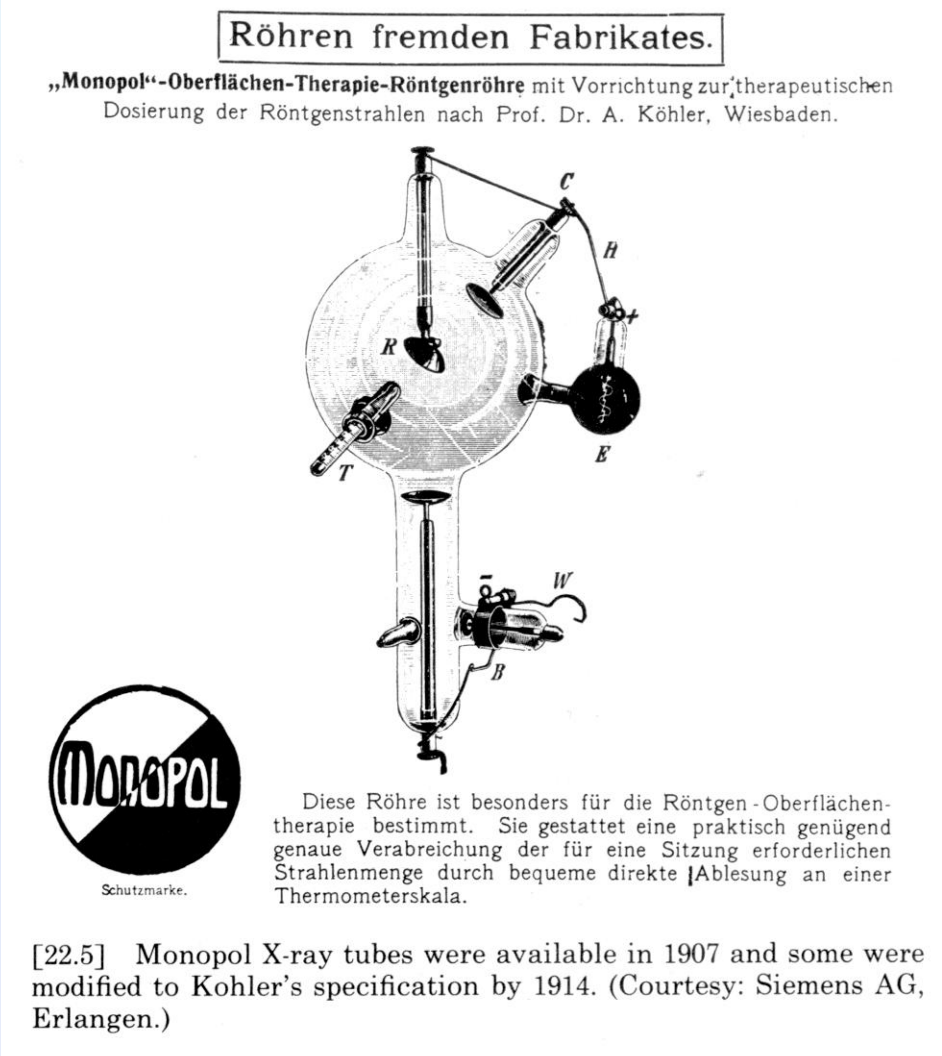
J.J. Thompson

1897
"discovery" of the electron



Courtesy Prof. Ugo Amaldi

(An accelerator for) Medical imaging

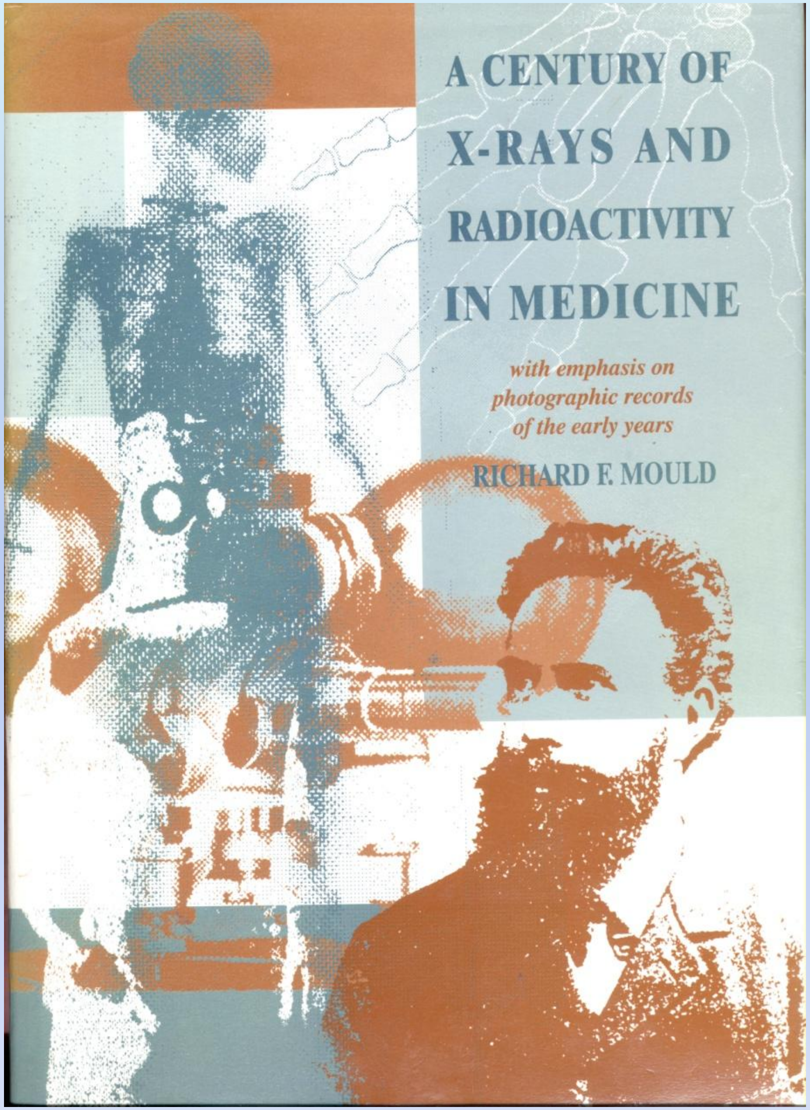


Röhren fremden Fabrikates.

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

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.)



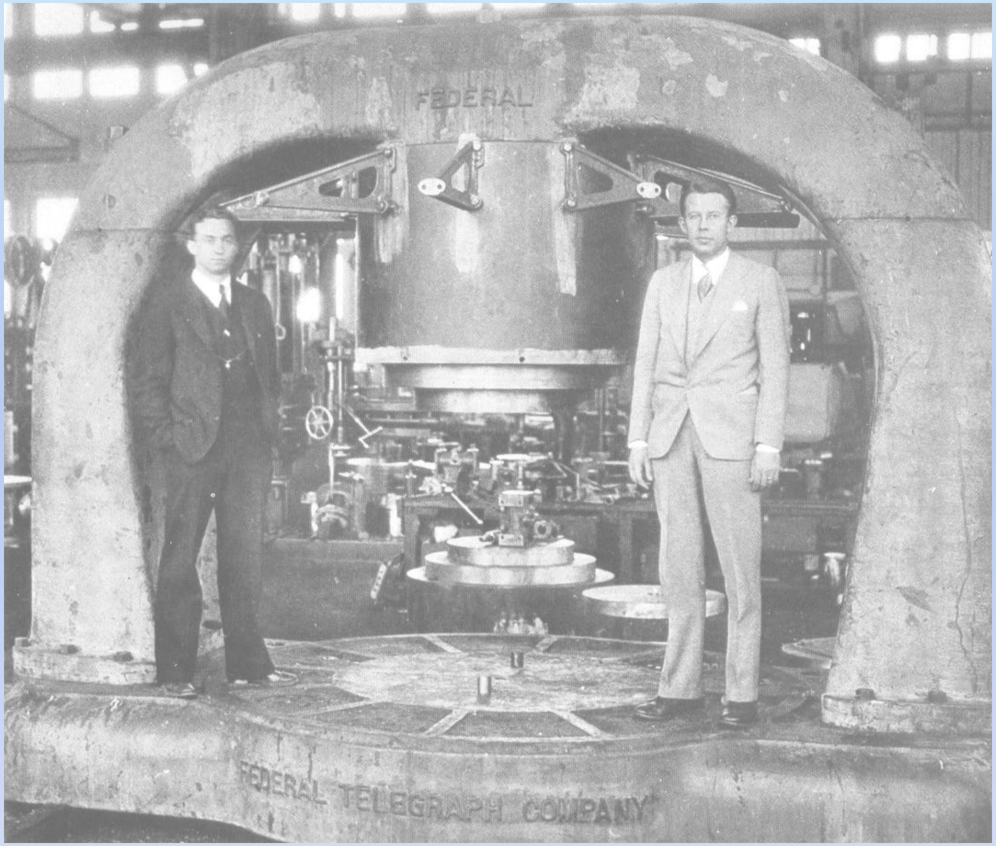
A CENTURY OF X-RAYS AND RADIOACTIVITY IN MEDICINE

with emphasis on photographic records of the early years

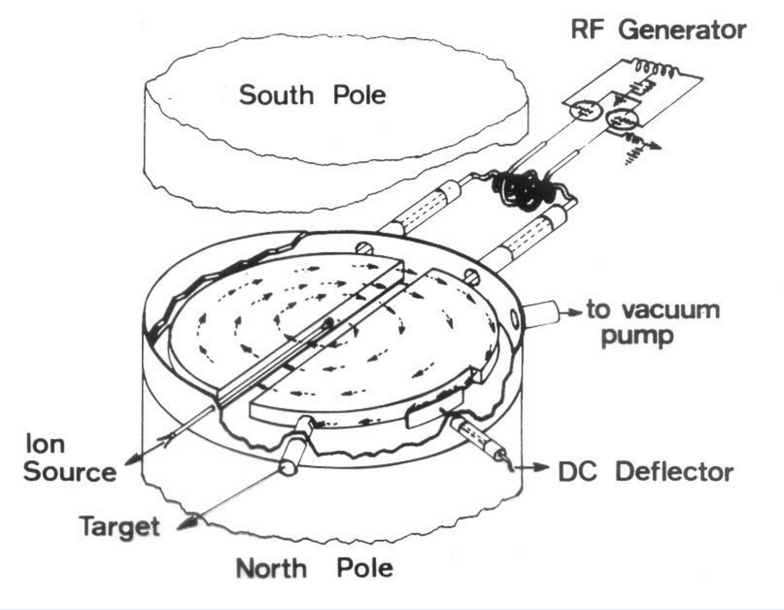
RICHARD F. MOULD

Tools for (medical) physics: the cyclotron

1930
Ernest Lawrence invents the cyclotron



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



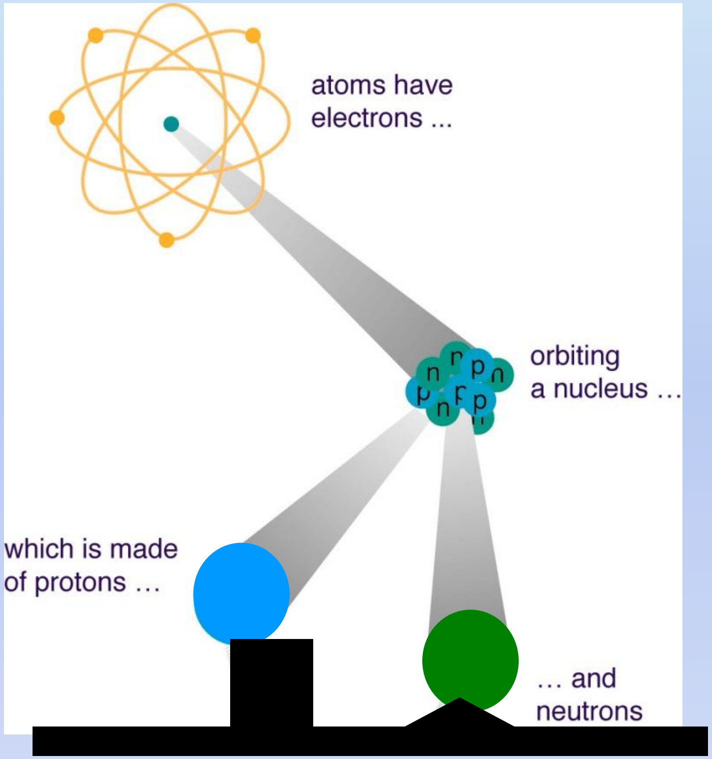
Courtesy Prof. Ugo Amaldi

The beginnings of modern physics and of medical physics

James Chadwick
(1891 – 1974)

1932

Discovery of the neutron



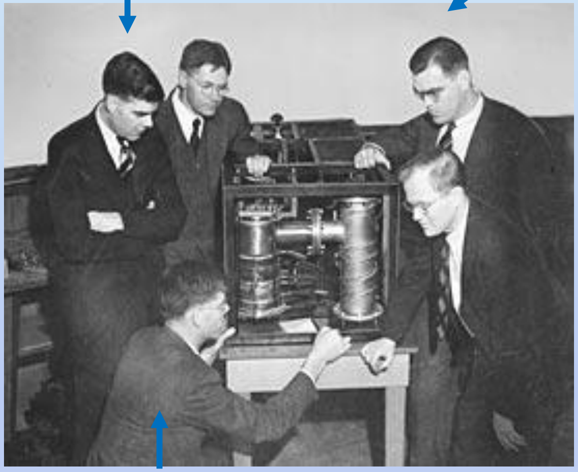
Cyclotron + neutrons = first attempt of radiation therapy with fast neutrons at LBL (R. Stone and J. Lawrence, 1938)

Courtesy Prof. Ugo Amaldi

Tools for (medical) physics: the electron linac

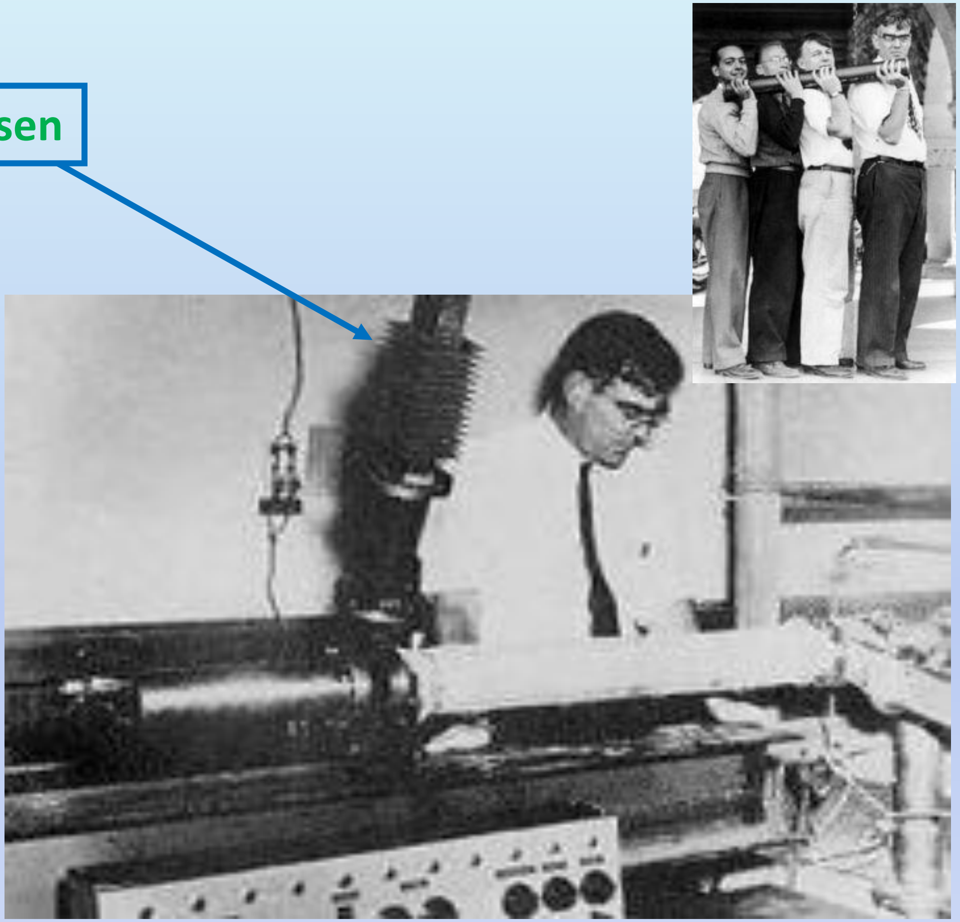
Sigmur Varian

William W. Hansen



Russell Varian

1939
Invention of the klystron



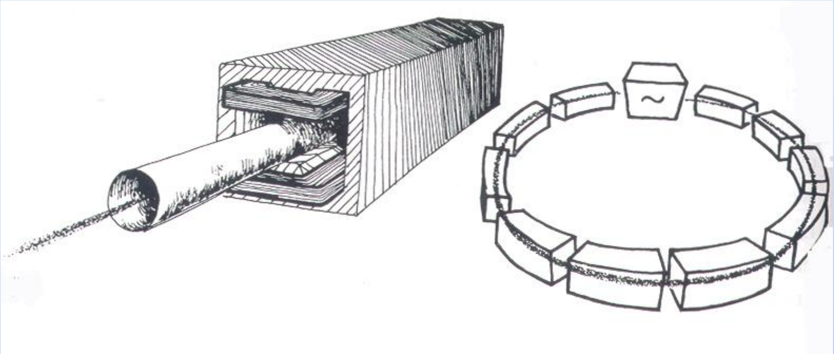
1947
first linac for electrons
4.5 MeV and 3 GHz

Courtesy Prof. Ugo Amaldi

Tools for (medical) physics: the synchrotron

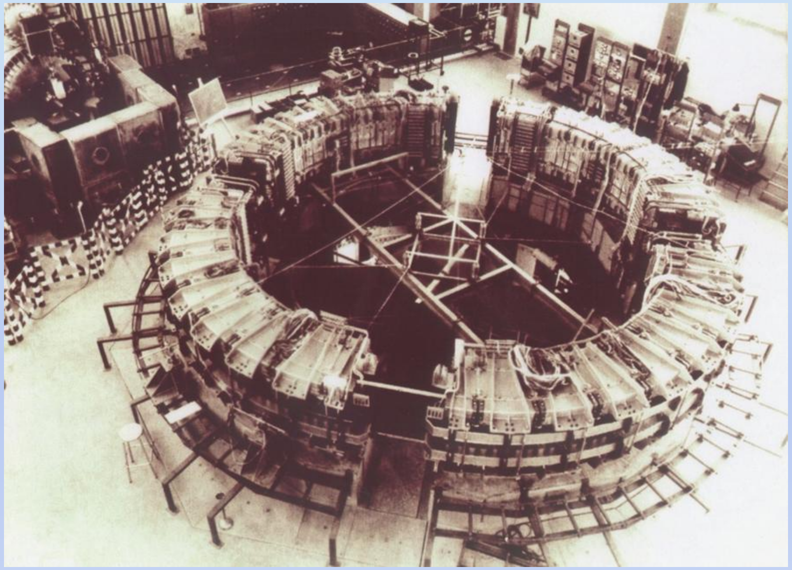
1945: E. McMillan and V.J. Veksler

discover the principle of phase stability



1 GeV electron synchrotron

Frascati - INFN - 1959



6 GeV proton synchrotron

Bevatron - Berkeley - 1954

Courtesy Prof. Ugo Amaldi

Accelerators operational in the world

Three main applications:

1) Scientific research
2) Medical applications
3) Industrial uses

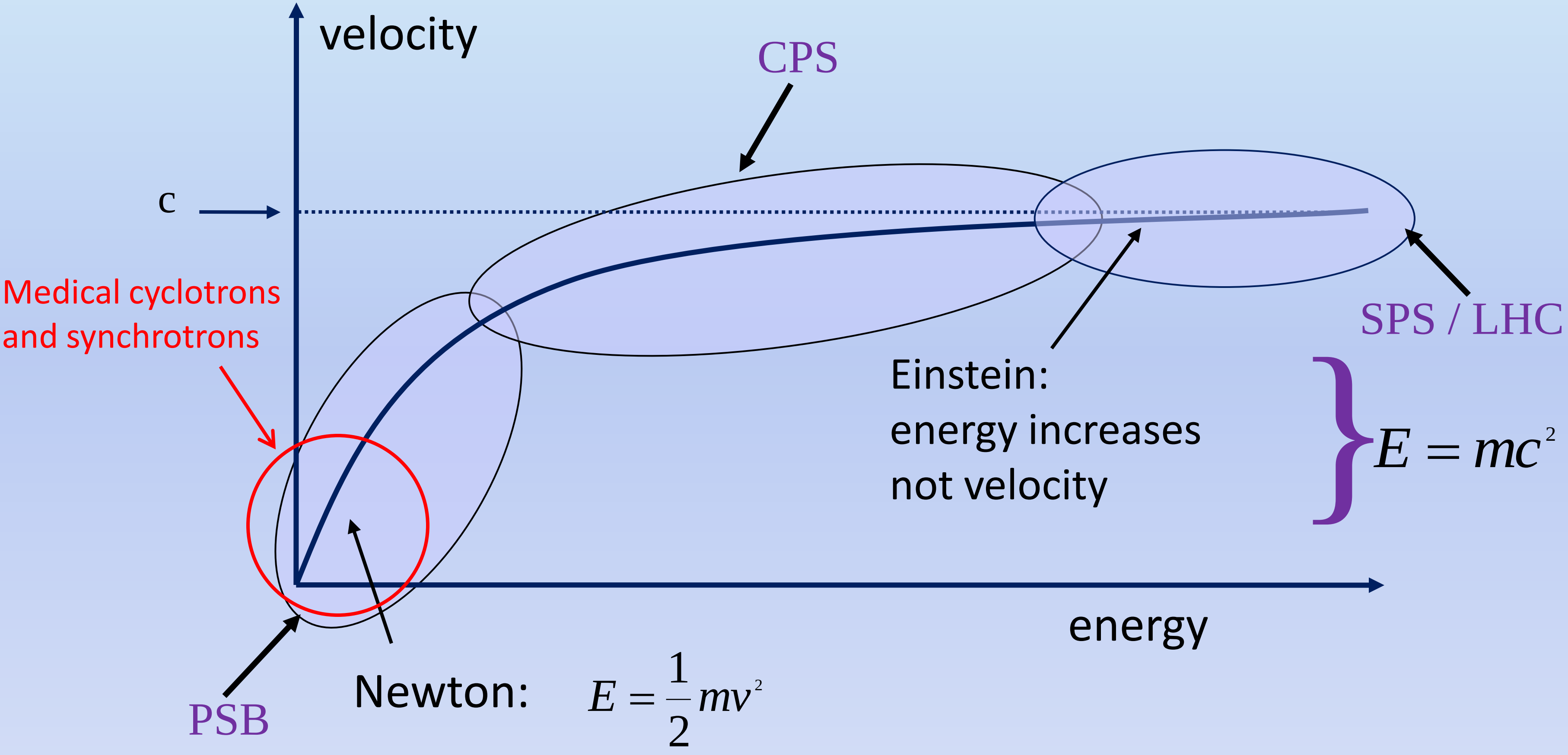
CATEGORY OF ACCELERATORS	NUMBER IN USE (*)
High-energy accelerators (E >1 GeV)	~ 120
Synchrotron radiation sources	> 100
Medical radioisotope production	~ ~~200~~ ~ 1000
Accelerators for radiation therapy	> 7500
Research accelerators including biomedical research	~ 1000
Industrial processing and research	~ 1500
Ion implanters, surface modification	> 7000
TOTAL	➢17500 ~ 18000

10,000

Adapted from "Maciszewski, W. and Scharf, W., *Particle accelerators for radiotherapy, Present status and future*, Physica Medica XX, 137-145 (2004)"

Relativity

CERN accelerators



Medical cyclotrons and synchrotrons

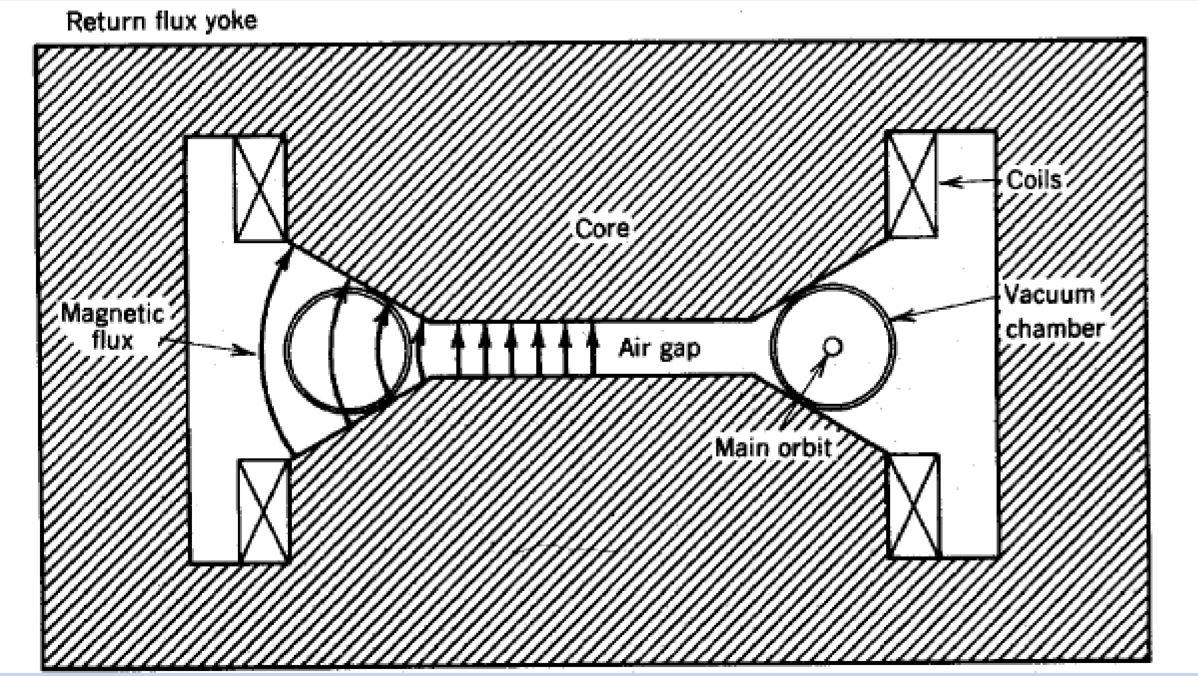
Einstein:
energy increases
not velocity

$$E = mc^2$$

Newton: $E = \frac{1}{2} mv^2$

The betatron

Schematic diagram of betatron with air gap



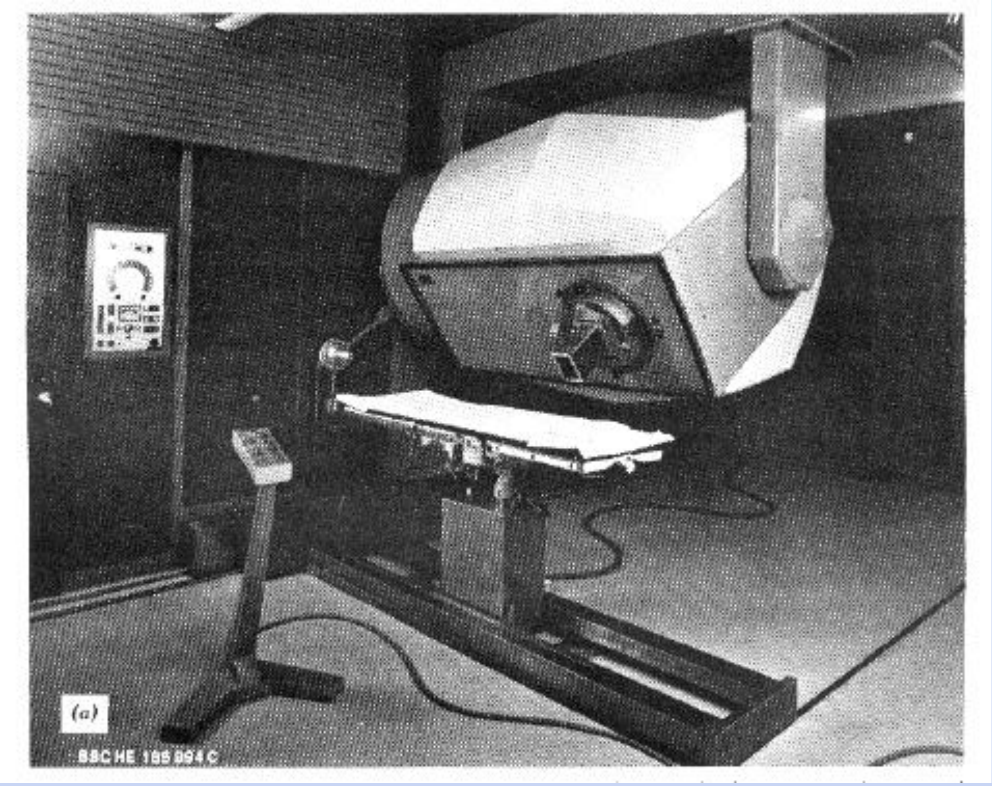
$$B(R) = \frac{1}{2}\overline{B}(R)$$

$B(R)$ = field at the orbit

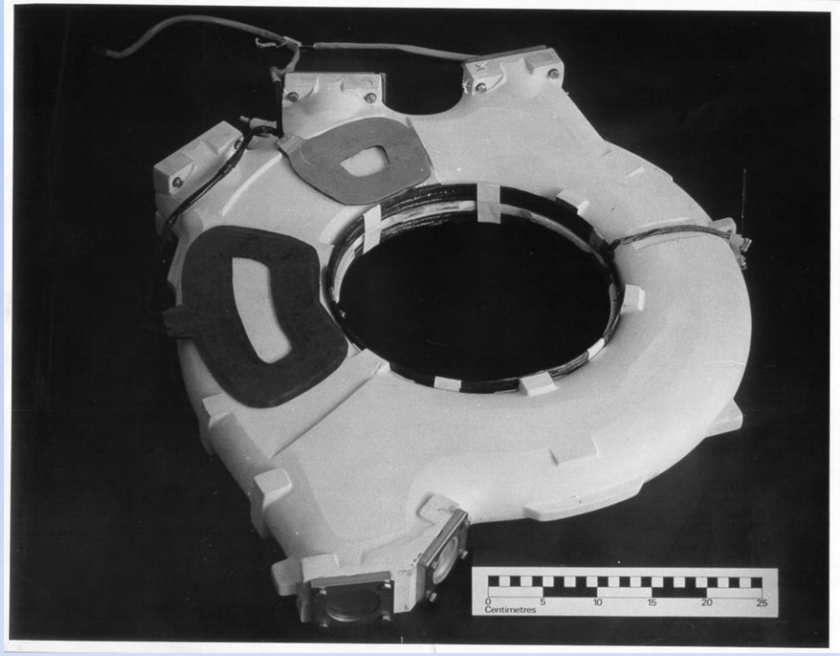
$\overline{B}(R)$ = average flux density through the orbit

- **Magnetic field produced by pulsed coils**
- **The magnetic flux inside the radius of the vacuum chamber changes with time**
- **Increasing flux generates an azimuthal electric field which accelerates electrons in the chamber**

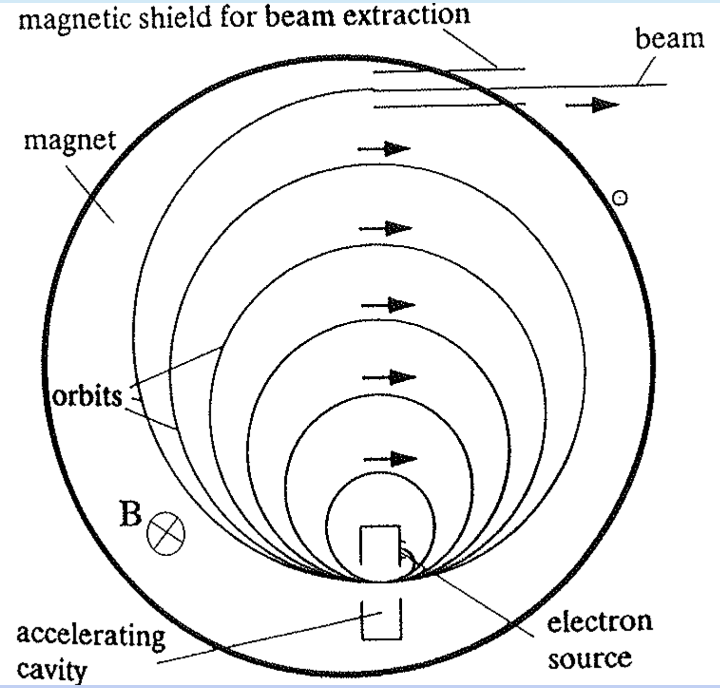
The betatron



An old 45 MeV betatron for radiation therapy



The microtron



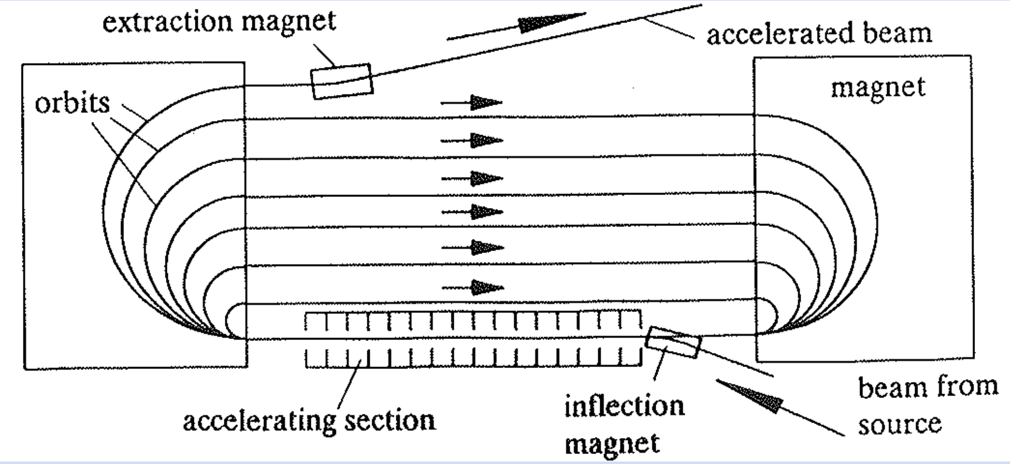
An “electron cyclotron”

- **Uniform magnetic field**
- **Fixed-frequency RF system**
- **Well-separated orbits**

Bending radius $\frac{1}{r} = \frac{eB}{cp} = \frac{eB}{mc^2\gamma\beta}$

Revolution time $\tau = \frac{2\pi r}{v} = \frac{2\pi mc}{e}\frac{\gamma}{B}$

Racetrack microtron



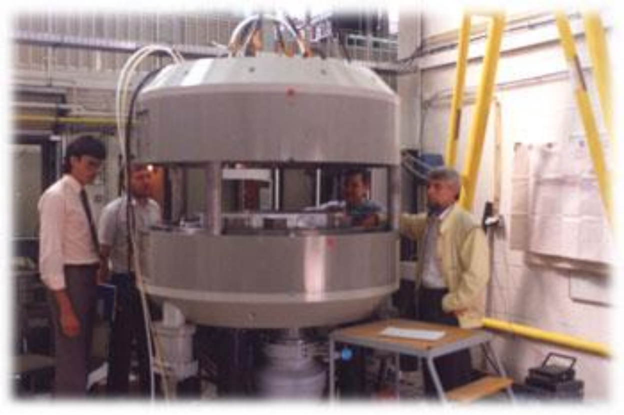
- Isocronism only if $\gamma \approx 1$
- If $\gamma > 1$, $\Delta\tau$ per turn = $\Delta\gamma$
- To have isochronism it must be $\Delta\tau$ per turn = $h\tau_{RF}$
- Required energy gain per passage
  - for electrons $\Delta E_e = 511$ keV
  - for protons $\Delta E_p = 938$ MeV

Magnet weight ≈ $(\text{energy})^3$

Three classes of modern medical accelerators

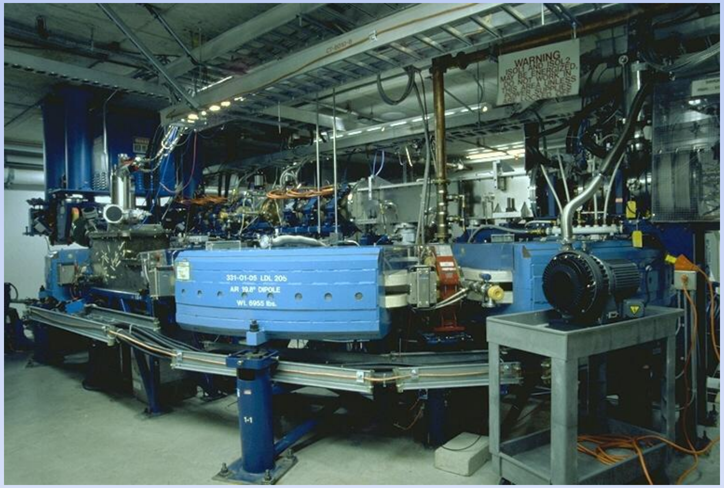
Electron linacs for conventional radiation therapy, including advanced modalities:

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



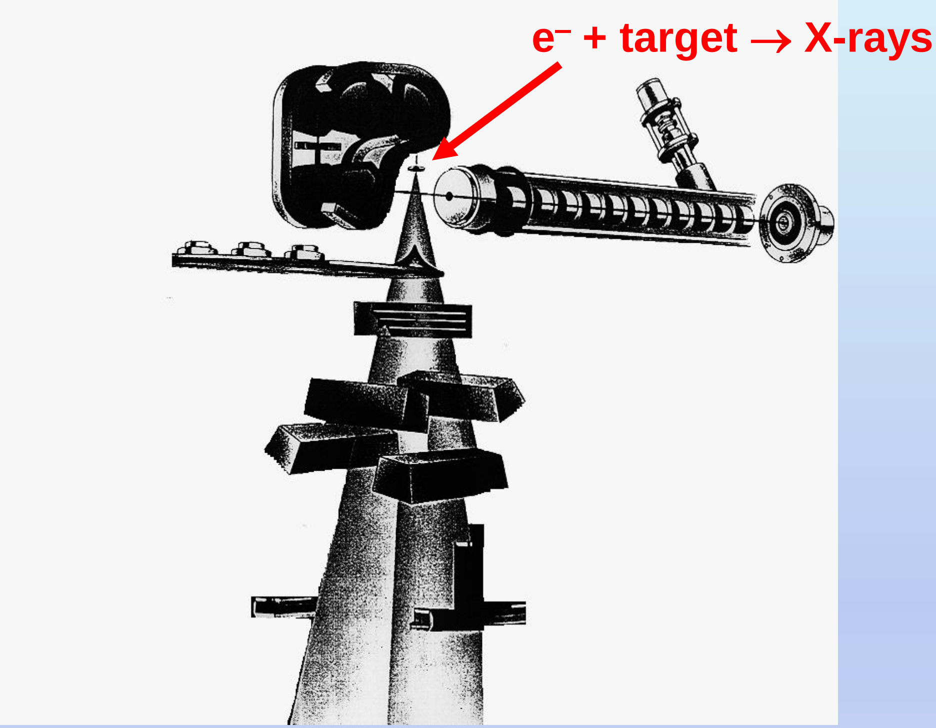
Low-energy cyclotrons for production of radionuclides for medical diagnostics

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

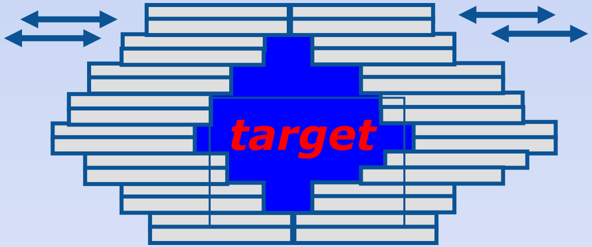


Medical linear electron accelerator

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



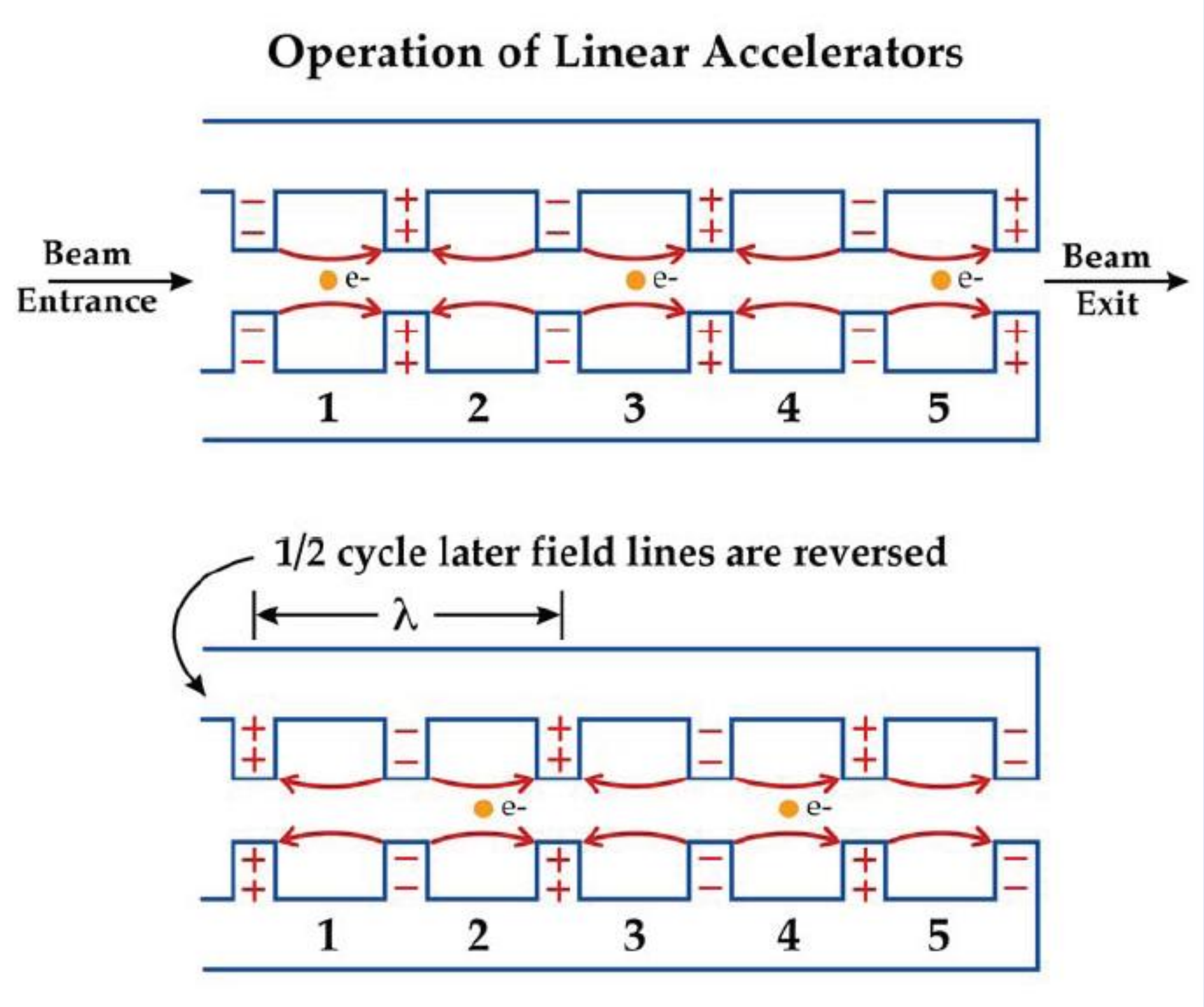
e⁻ + target → X-rays



Multi-leaf collimator

3 GHz frequency

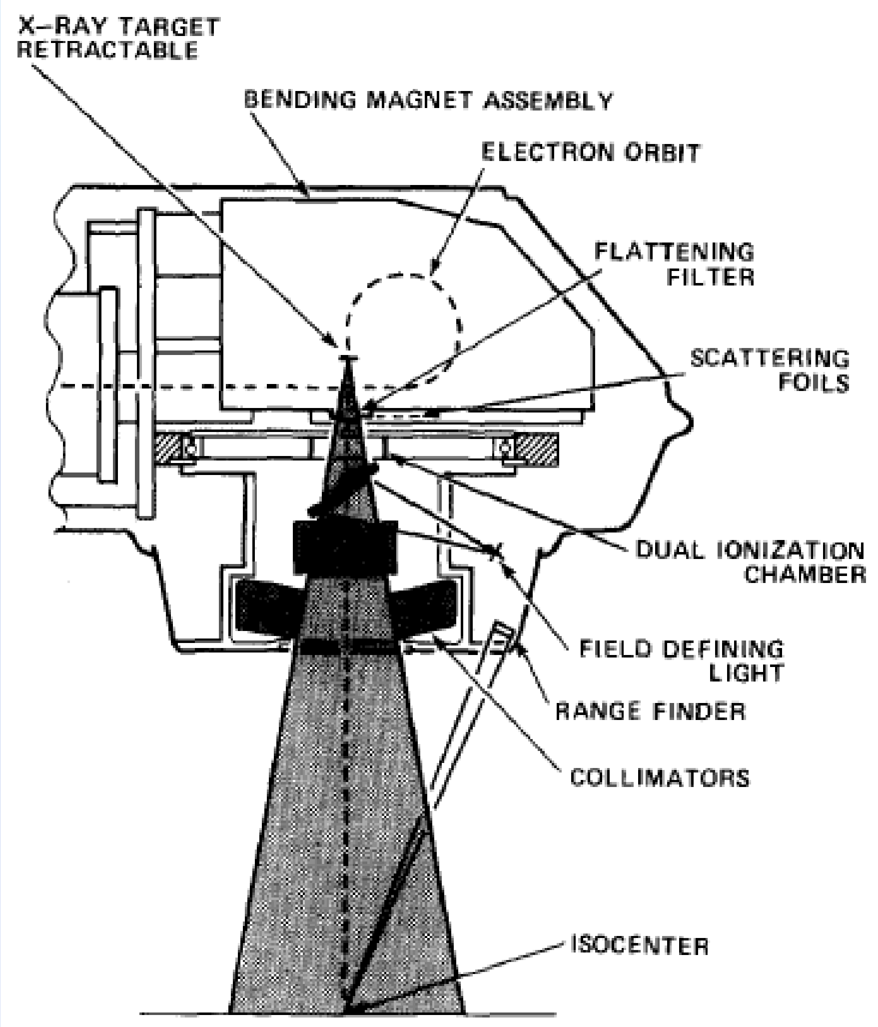
Electron acceleration in a wave guide



Particles initially in cell 1 arrive in cell 2 to get further accelerating kick. Frequency must match particles velocity and cell periodicity = ½ λ:

$$f = \frac{v}{\lambda}$$

Schematic drawing of a typical therapy head for a medical electron accelerator



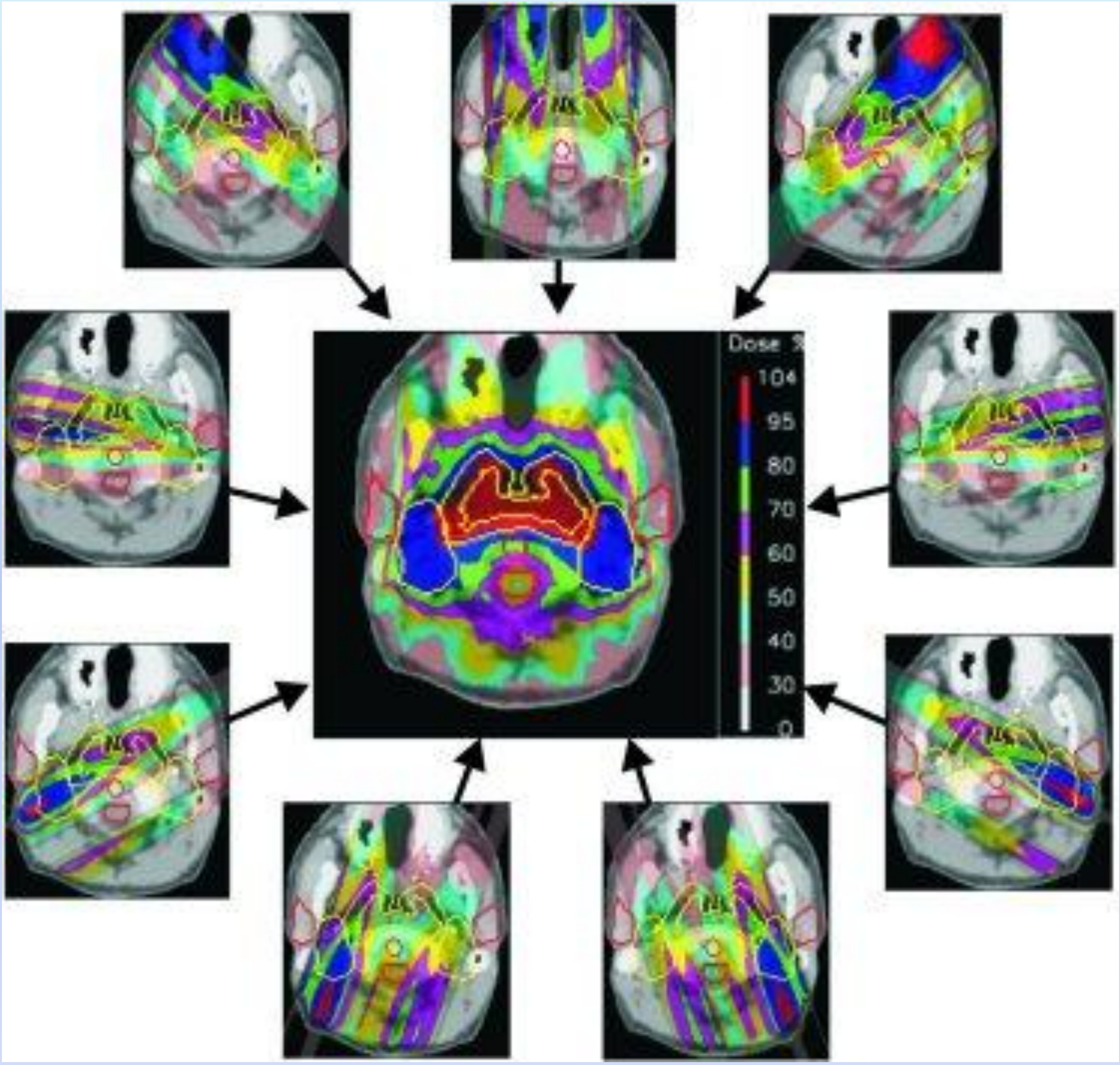
CyberKnife (CK) Robotic Surgery System

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 (IMRT)

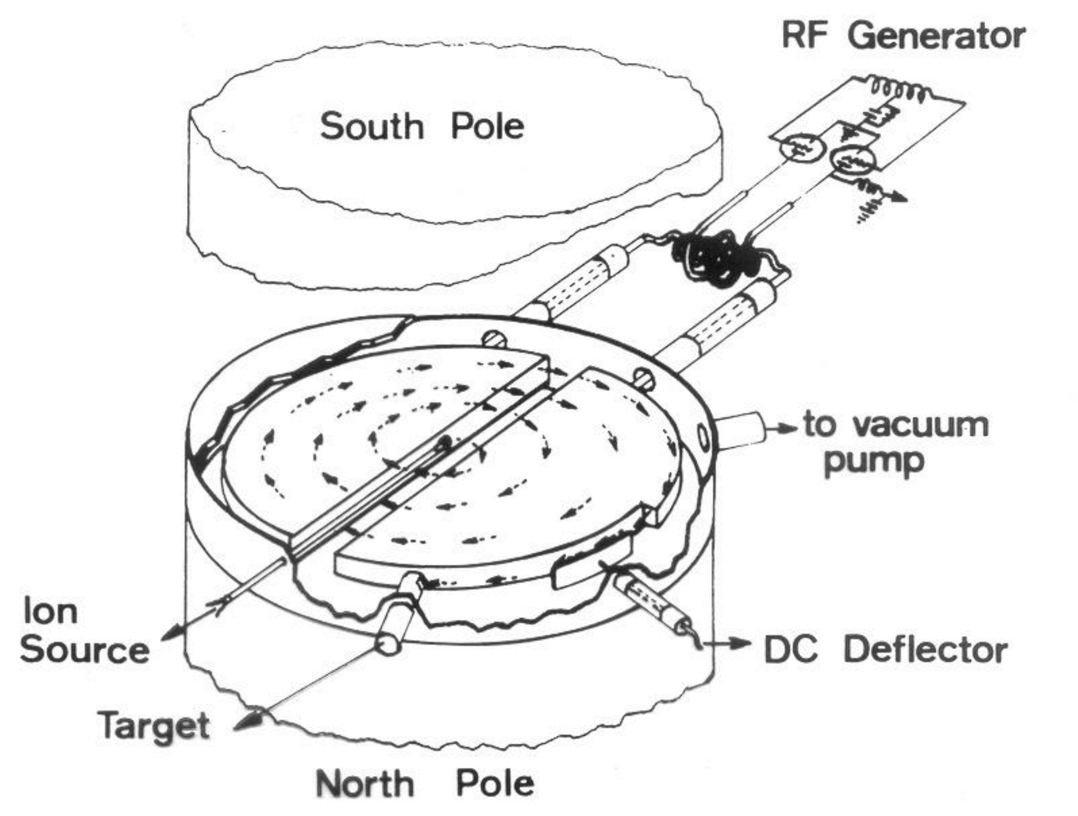


An example of intensity modulated treatment planning with photons. Through the addition of 9 fields it is possible to construct a highly conformal dose distribution with good dose sparing in the region of the brain stem (courtesy of T. Lomax, PSI).

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

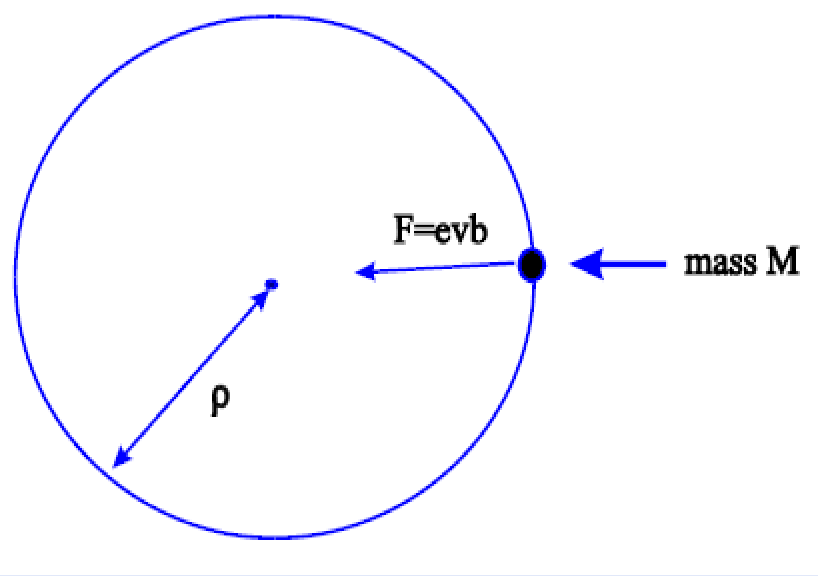
Yet X-rays have a comparatively poor energy deposition as compared to protons and carbon ions

The cyclotron



Scanditronix MC40

Motion of a particle in a dipole magnetic field (the field is in/out of the plane of this slide)



$$F = \frac{mv^2}{\rho},$$ where ρ = radius of curvature of the path

$$F = evB = \frac{mv^2}{\rho}$$

(p = momentum = mv)

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

Bρ = 33.356·p [kG·m] = 3.3356·p [T·m] (if p is in GeV/c)

Bρ is called "magnetic rigidity" of the particle and is an index of how difficult is to bend the motion of a charged particle by a magnetic field

The cyclotron

$F = q(\mathbf{E} = \mathbf{v} \times \mathbf{B})$

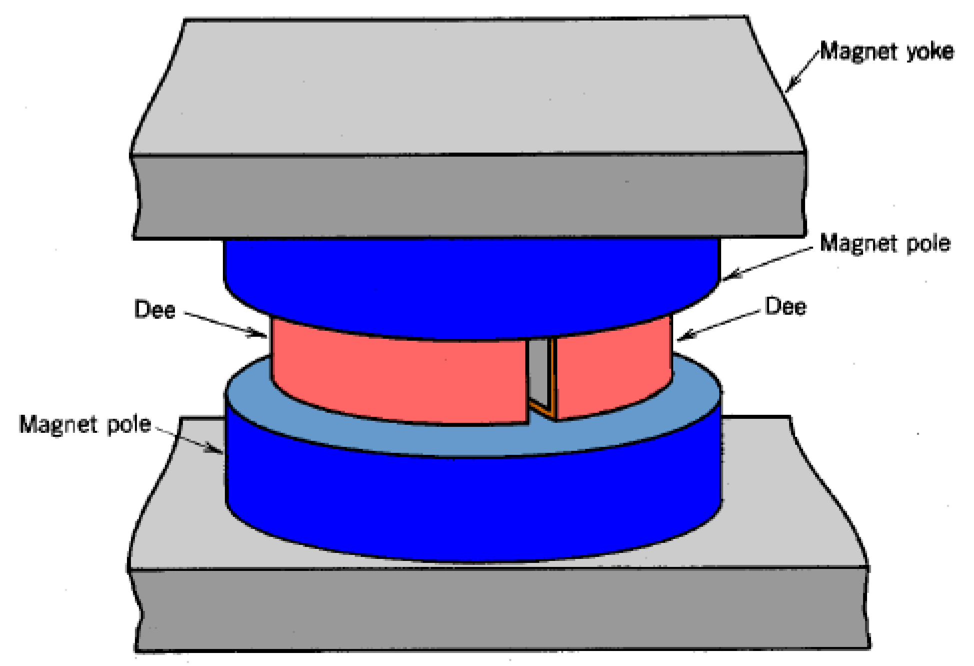
$mv^2 / \rho = qvB$

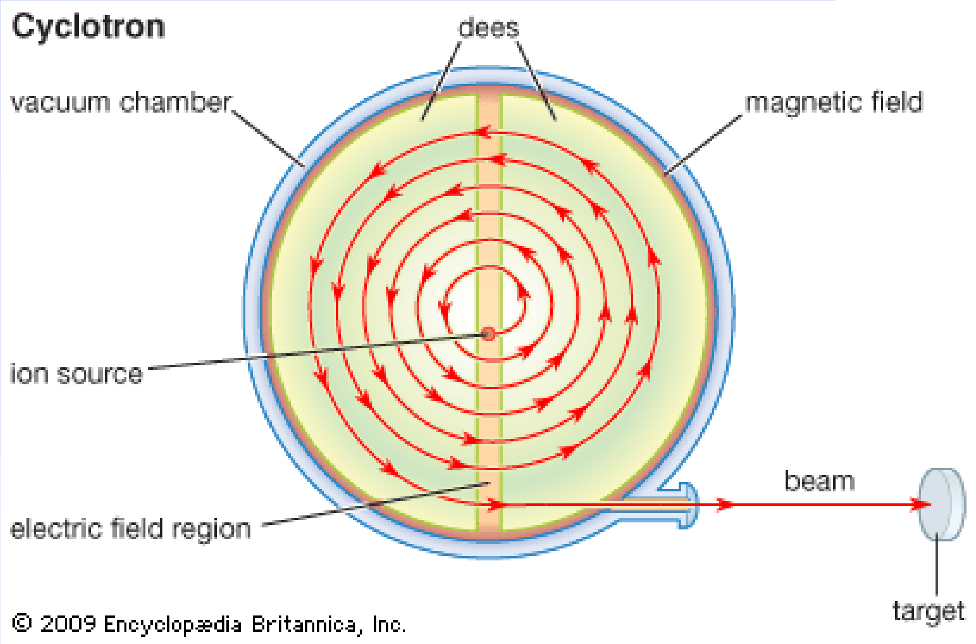
Rev. frequency $f = qB/2\pi m$

Rev. period $\tau = 1/f$ is independent of v

Resonant acceleration with $f_{RF} = h \cdot f$

⇒ Isochronism





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Maximum energy/nucleon:

$T/A = k\,(B\rho)^2\,(Z/A)^2$

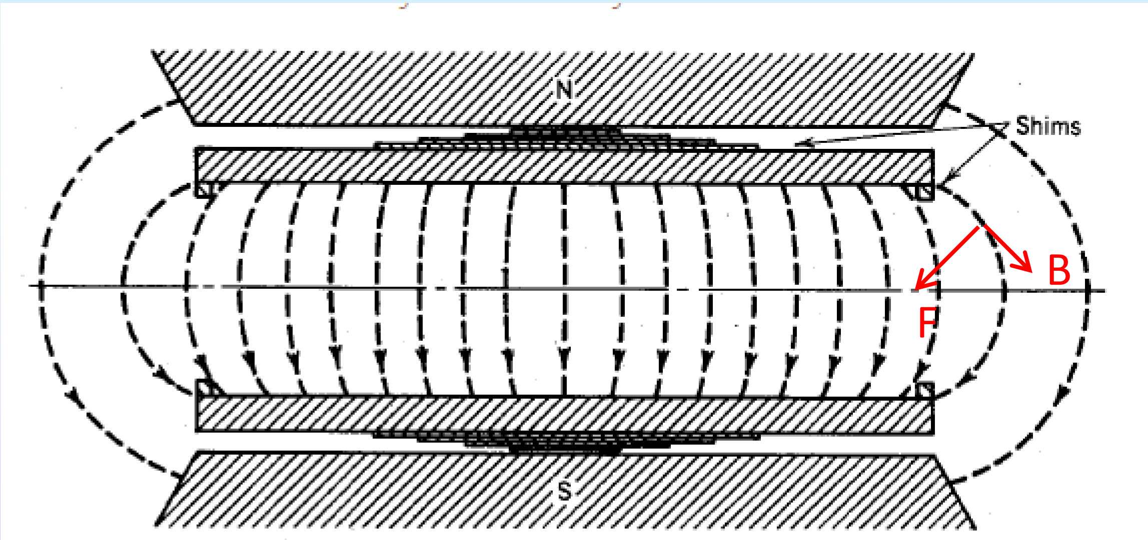
with $k = e^2 / 2m_p$

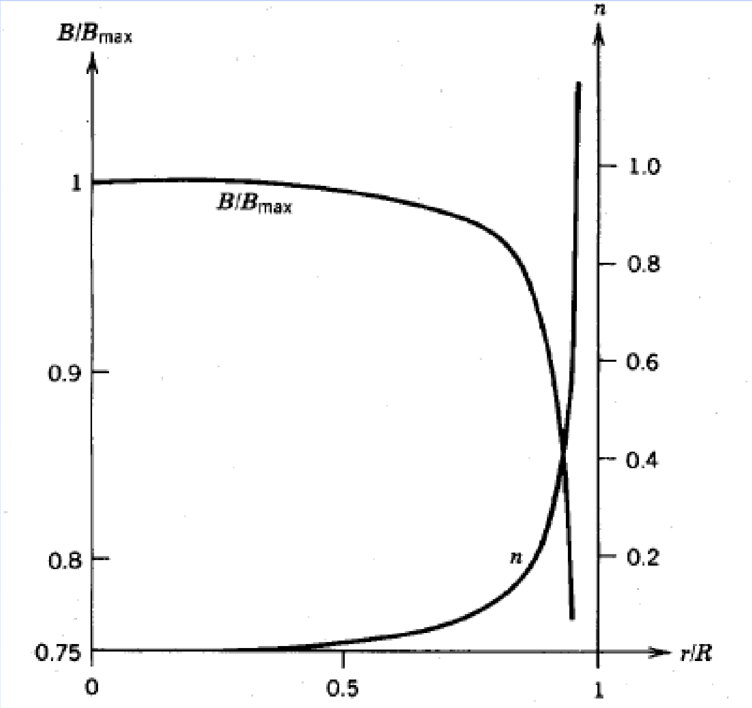
$K = k\,(B\rho)^2$ is called "bending limit"

$K = 48\,(B\rho)^2$ (MeV)

if B is in teslas and m in metres

The classical (non relativistic) cyclotron





Magnetic fields of uniform-field cyclotron: (top) Sectional view of cyclotron magnetic poles showing shims for optimizing field distribution. (left) Radial variation of vertical field magnitude and field index.

- Weak focusing
- Decrease of rev. frequency f with r
- Loss of isochronism

➢ Two solutions to achieve higher energies:

  - synchrocyclotron
  - AVF cyclotron

The AVF (isochronous) cyclotron

AVF = azimuthally varying field

B(r,θ) = <B(r)> + Mod(r, θ)

- RF constant
- <B> rises with radius r to compensate for the relativistic increase of the particle mass

f = q<B>/2πmγ

Vertical focusing achieved by the azimuthal variation of B

A further component of the axial focusing force is obtained by giving the sectors a spiral shape

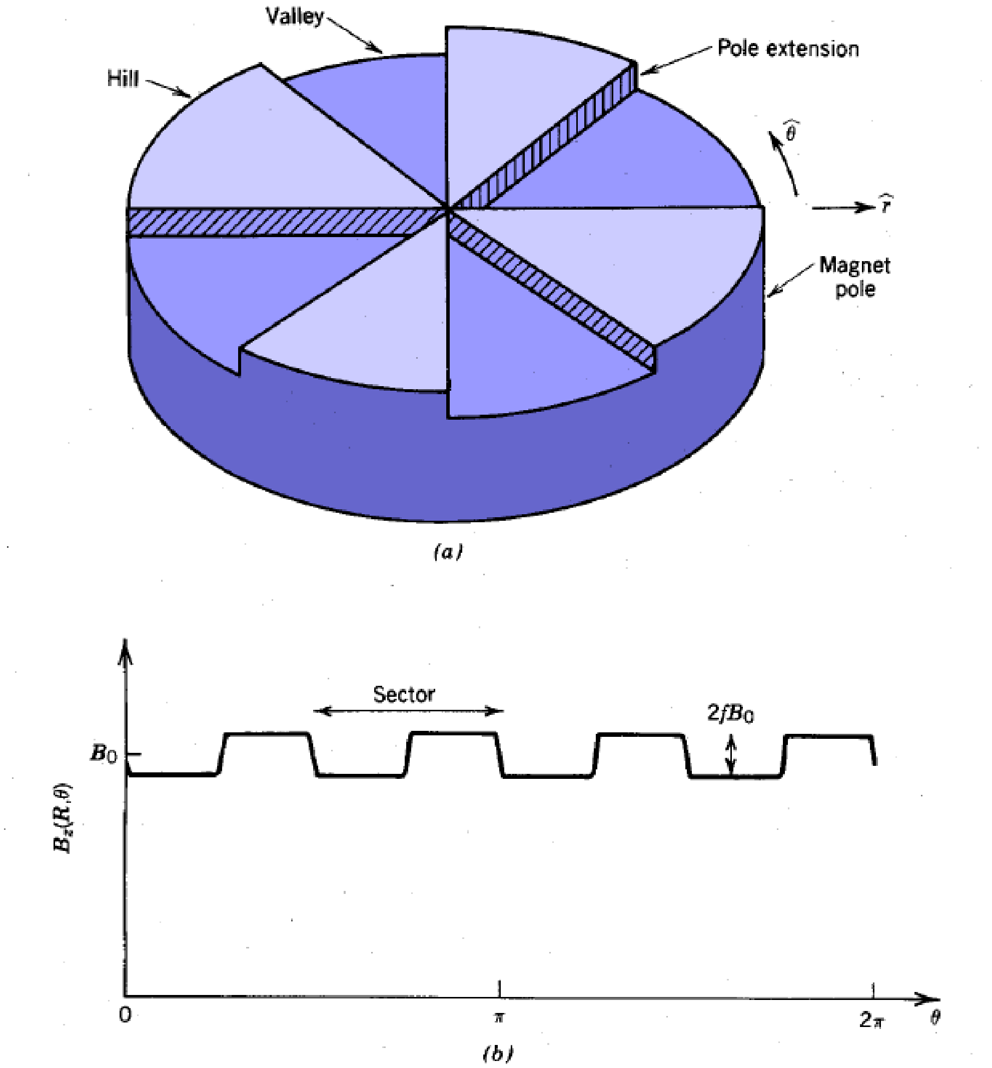
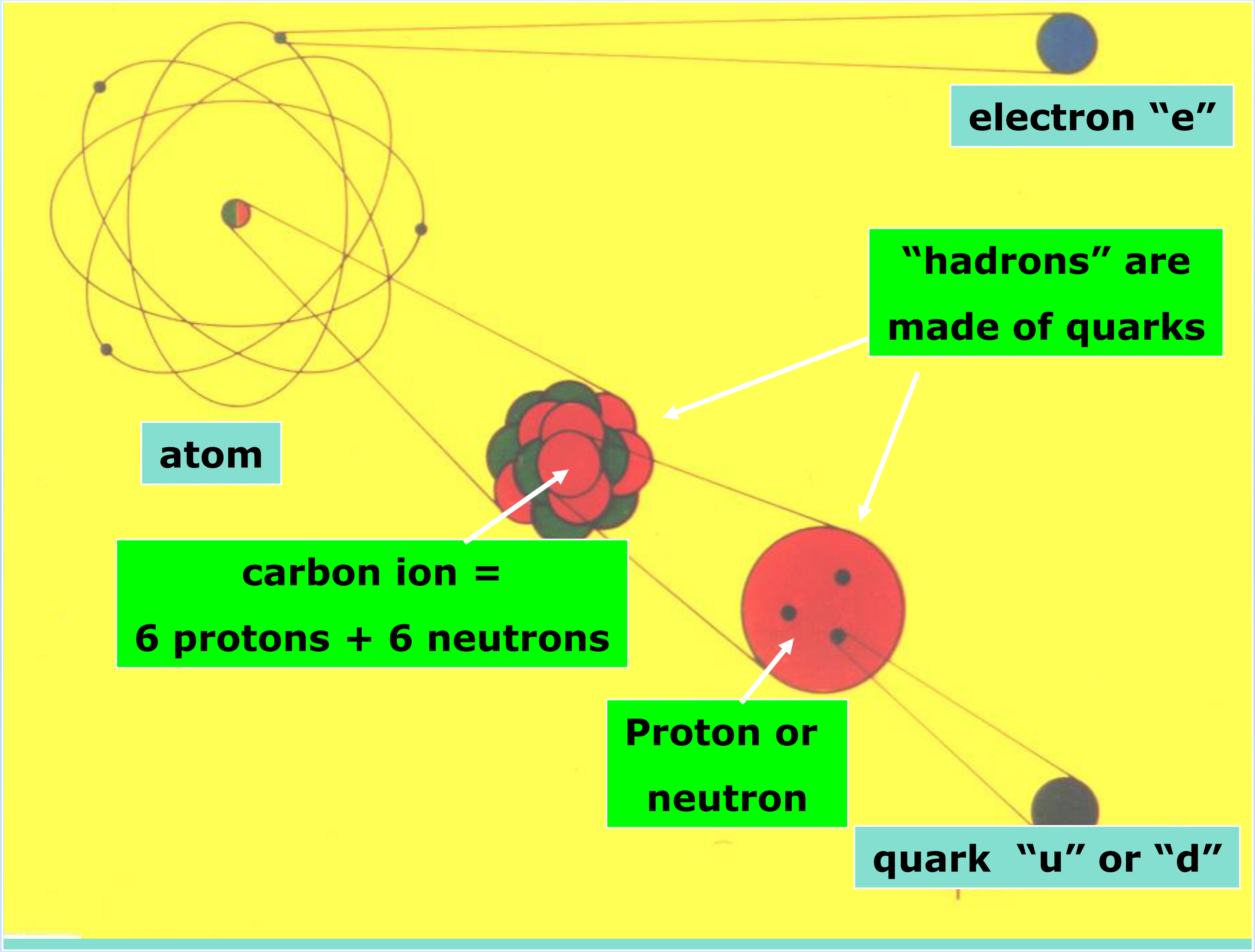


Figure 15.6 Magnetic fields in AVF cyclotron. (*a*) Magnet pole of AVF cyclotron, no spiral angle. (*b*) Vertical field amplitude as function of azimuth at constant radius.

Hadrontherapy: n, p and C-ion beams



electron "e"

"hadrons" are made of quarks

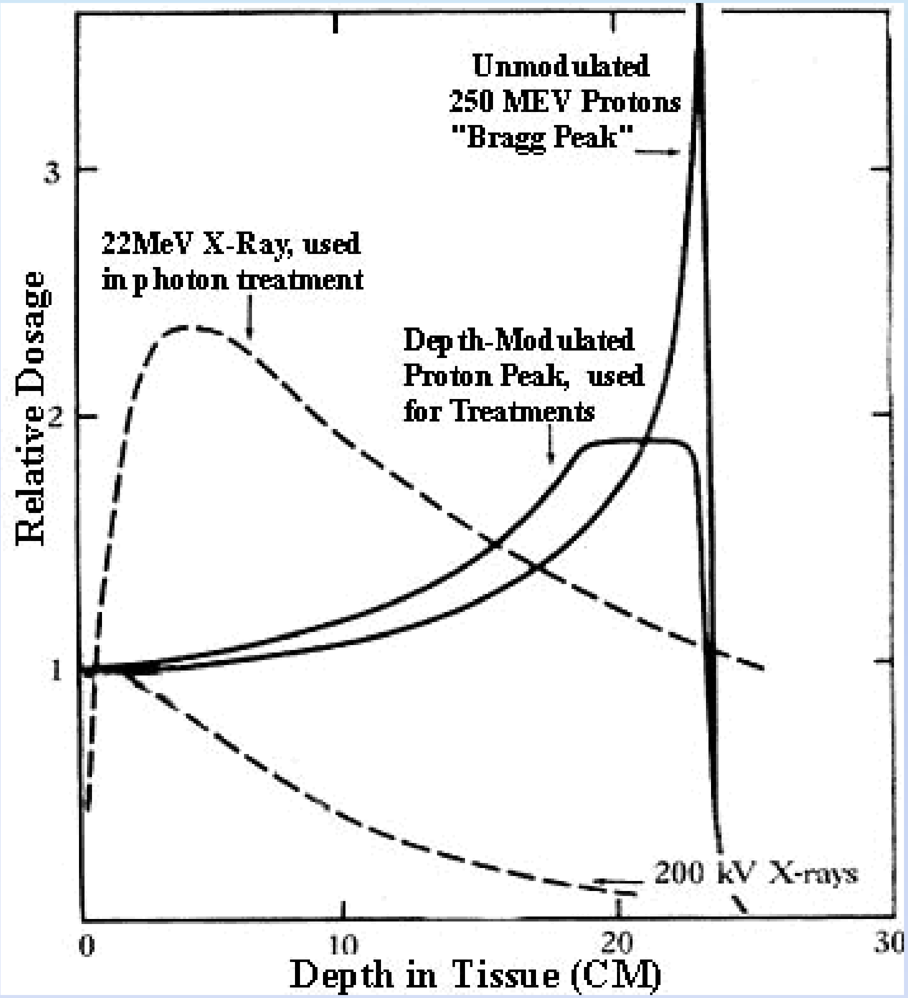
atom

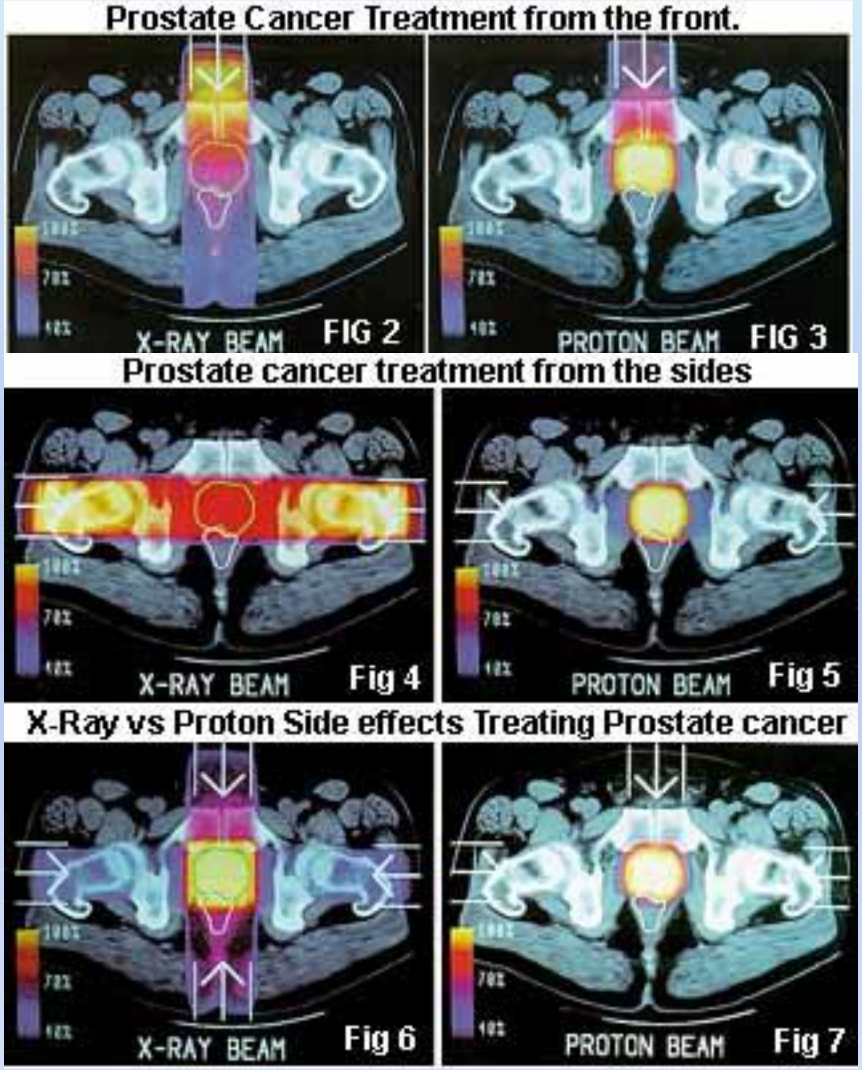
carbon ion = 6 protons + 6 neutrons

Proton or neutron

quark "u" or "d"

Proton radiation therapy





Clinical results

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 %	

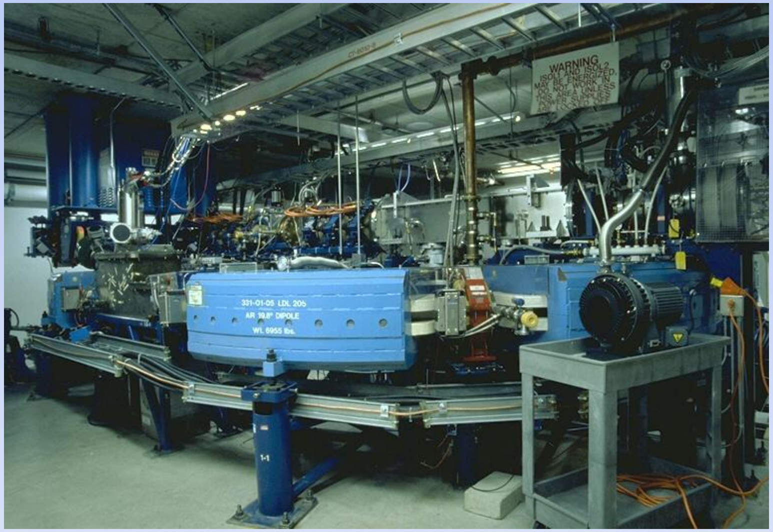
Table by G. Kraft 2007
Results of C ions

Cyclotrons and synchrotrons for proton therapy


IBA

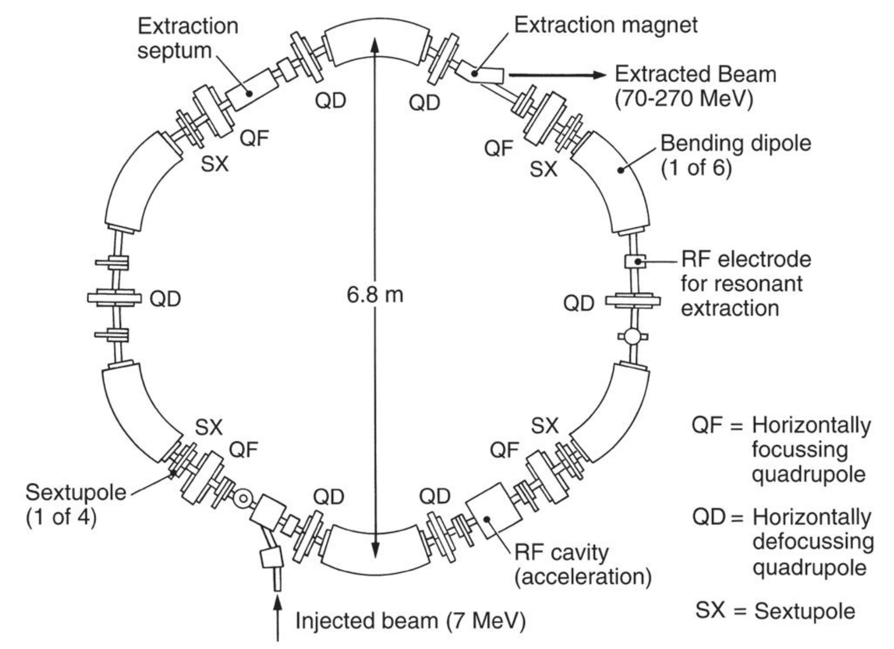

Accel-Varian


Hitachi

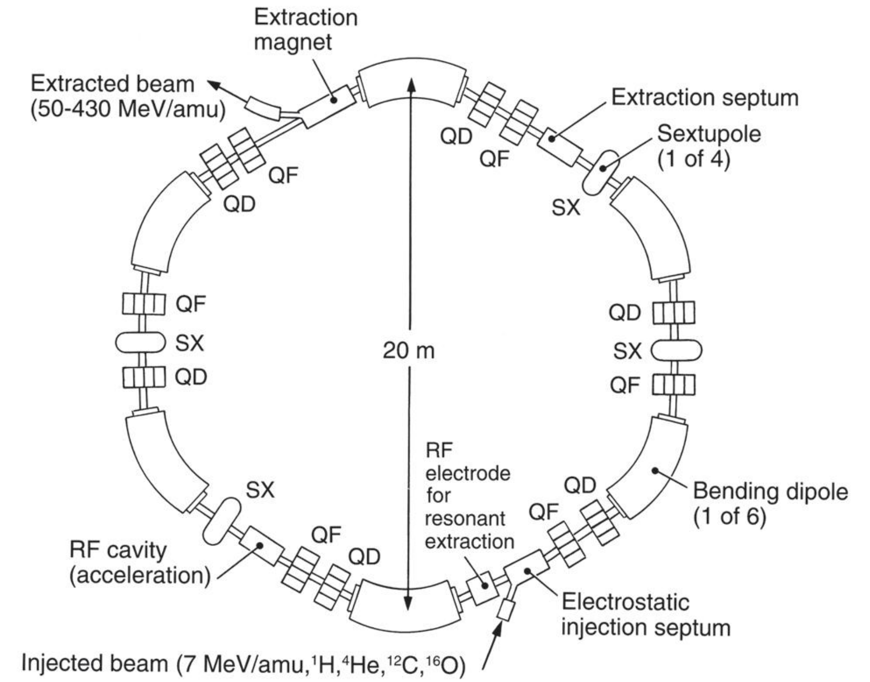

Loma Linda (built by FNAL)

Proton versus carbon-ion synchrotrons

Hitachi proton synchrotron

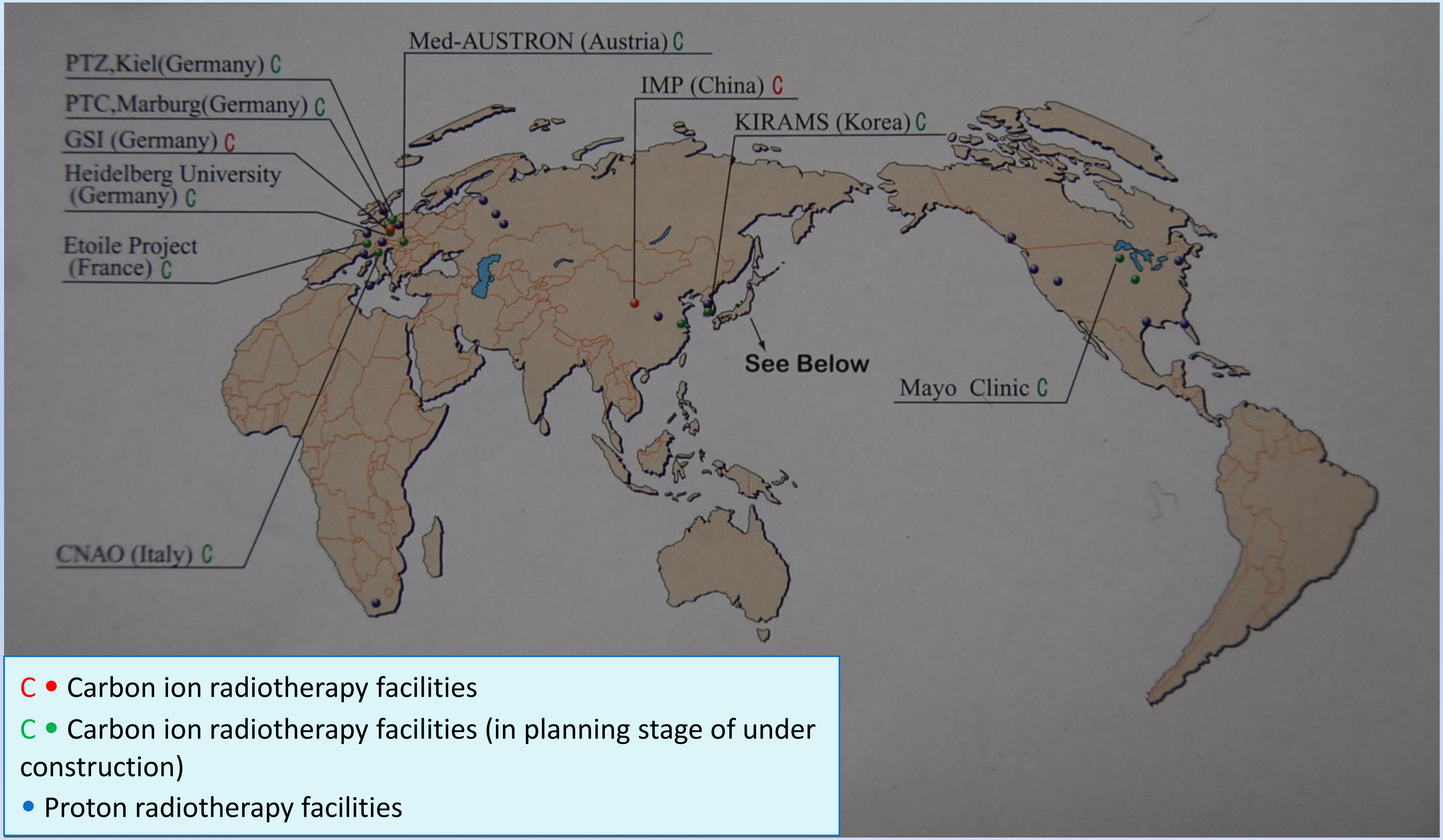


Siemens ion synchrotron



G. Coutrakon, Accelerators for Heavy-charged-particle Radiation Therapy, *Technology in Cancer Research & Treatment, Volume 6, Number 4 Supplement, August 2007*

Hadron-therapy in the world



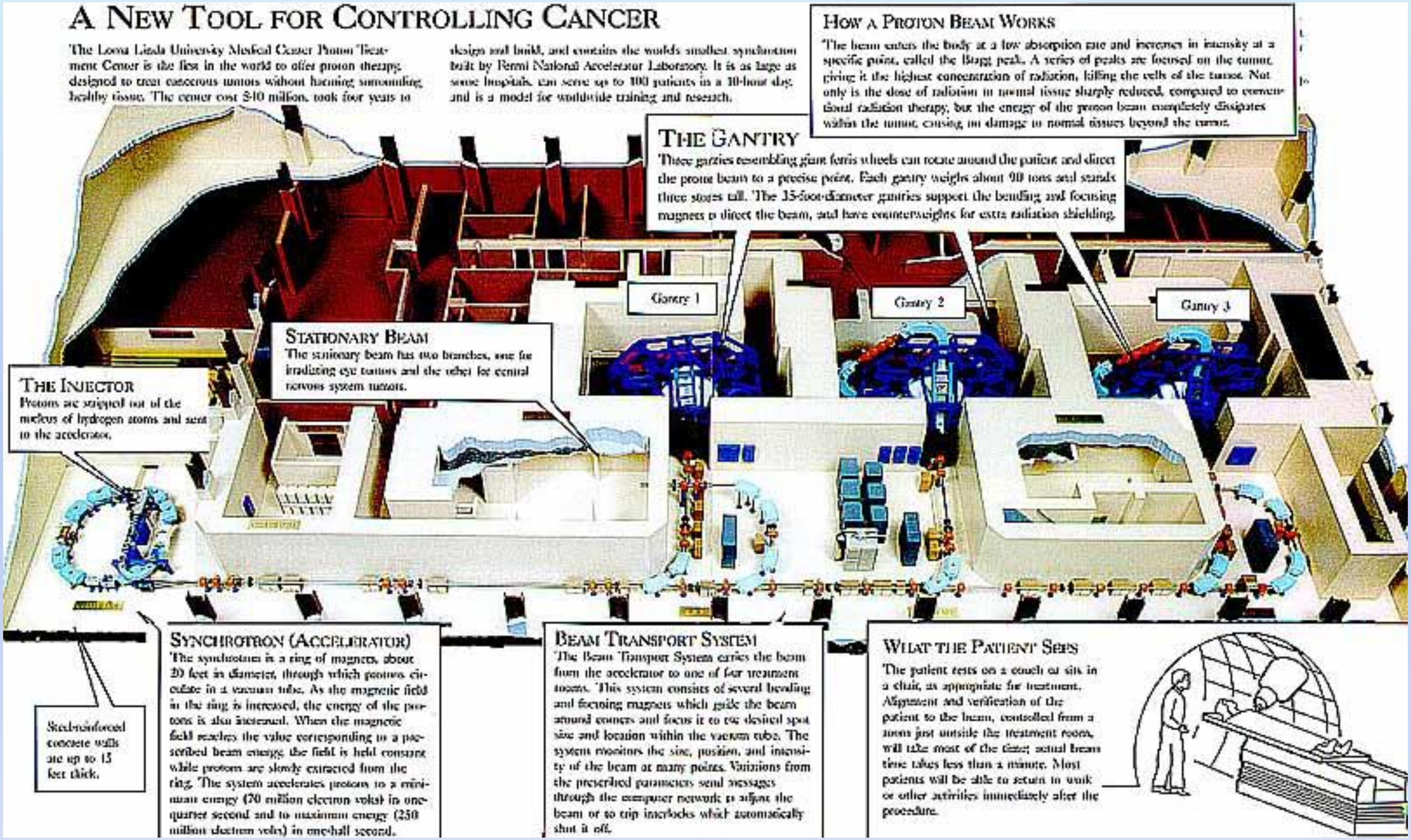
C ● Carbon ion radiotherapy facilities

C ● Carbon ion radiotherapy facilities (in planning stage of under construction)

● Proton radiotherapy facilities

Courtesy NIRS

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 $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.

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.

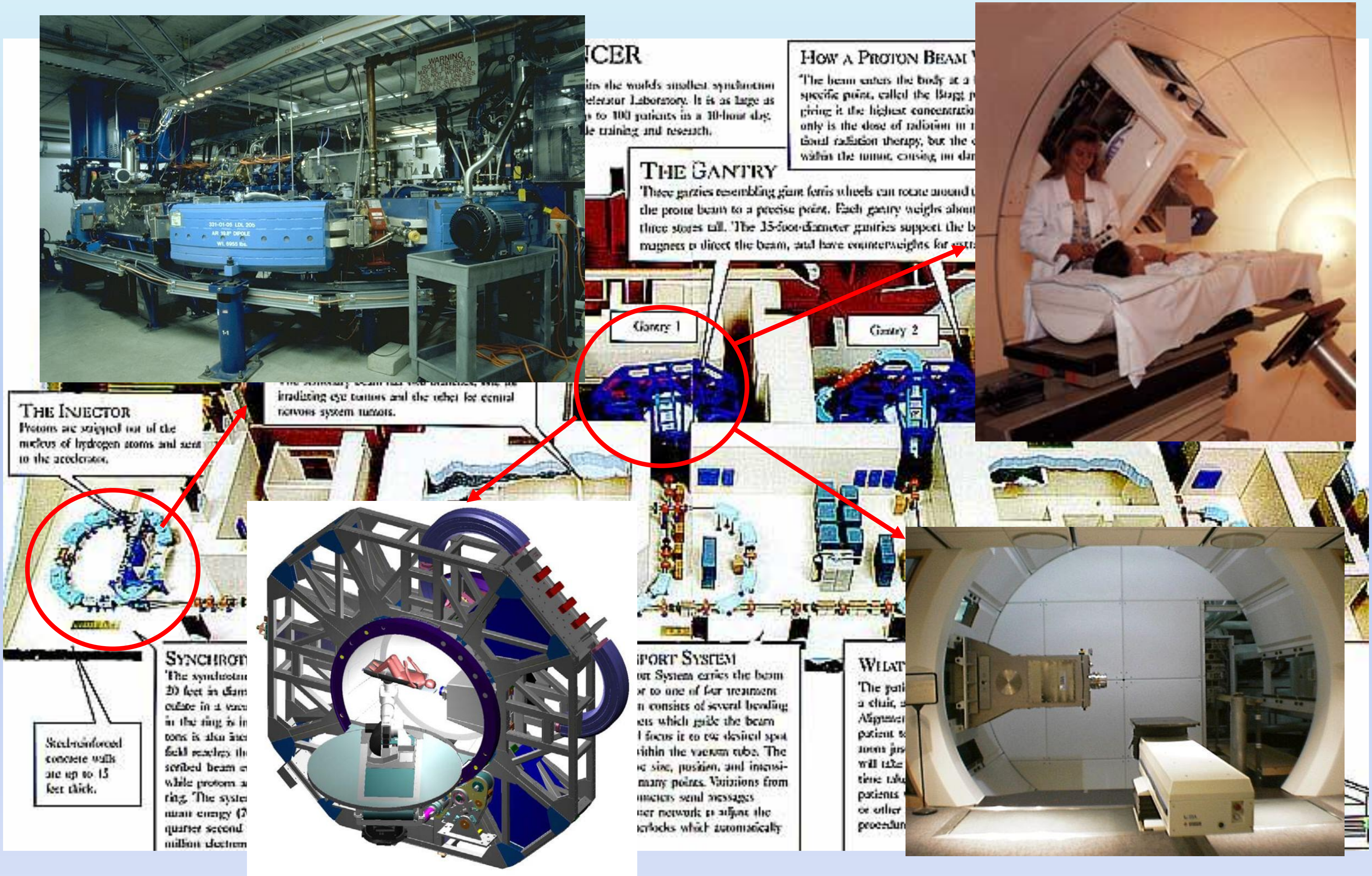
BEAM TRANSPORT SYSTEM

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)



NCER

ins the worlds smallest synchrotron
celerator Laboratory. It is as large as
s to 100 patients in a 10-hour day.
le training and research.

HOW A PROTON BEAM

The beam enters the body at a
specific point, called the Bragg p
giving it the highest concentratio
only is the dose of radiation in t
tional radiation therapy, but the
within the tumor, causing no dar

THE GANTRY

Three gantries resembling giant ferris wheels can rotate around
the proton beam to a precise point. Each gantry weighs about
three stories tall. The 35-foot-diameter gantries support the b
magnets to direct the beam, and have counterweights for extr

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.

SYNCHROT

The synchrotron
20 feet in diam
culate in a vacu
in the ring is in
tons is also inc
field reaches th
scribed beam e
while protons a
ring. The syste
mum energy (2
quarter second
million electron

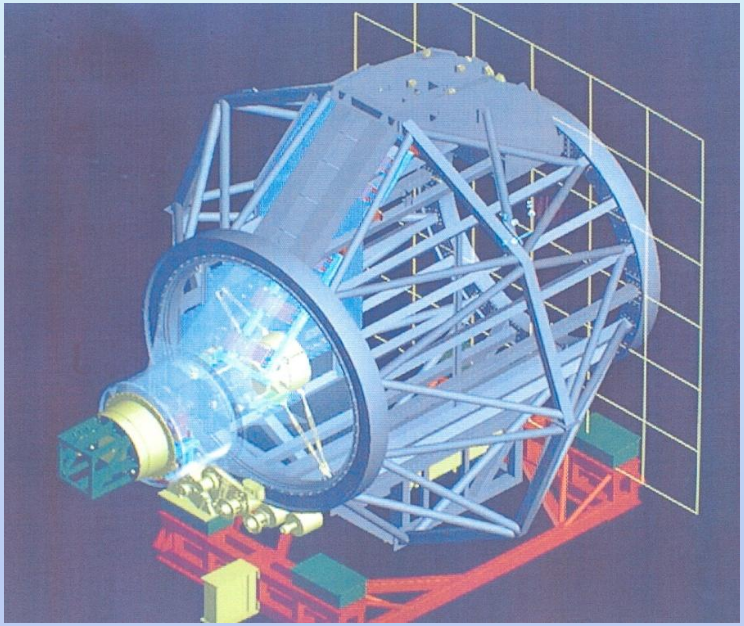
SPORT SYSTEM

ort System carries the beam
or to one of four treatment
n consists of several bending
ets which guide the beam
l focus it to the desired spot
within the vacuum tube. The
e size, position, and intensi-
many points. Variations from
meters send messages
ter network to adjust the
erlocks which automatically

WHAT

The pati
a chair,
Alignmen
patient s
tions jus
will take
time tak
patients
or other
procedur

A PT facility is not just the accelerator…



The IBA proton gantry

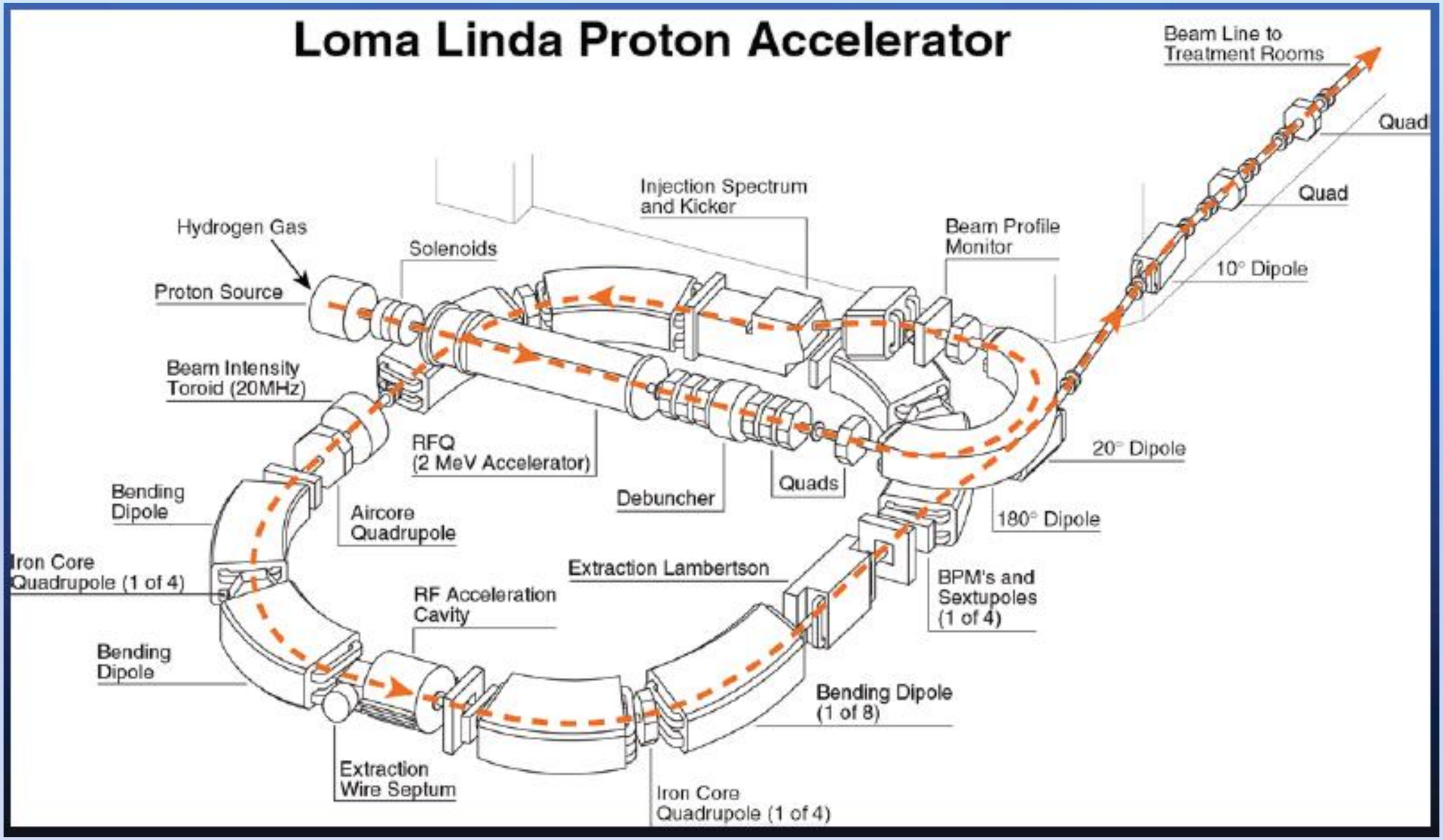
A gantry is a massive structure that allows directing the beam to the tumour from any direction. It carries

- the final section of the beam line
- the beam spreading ‘nozzle’
- the proton ‘snout’ which carries the aperture and range compensator

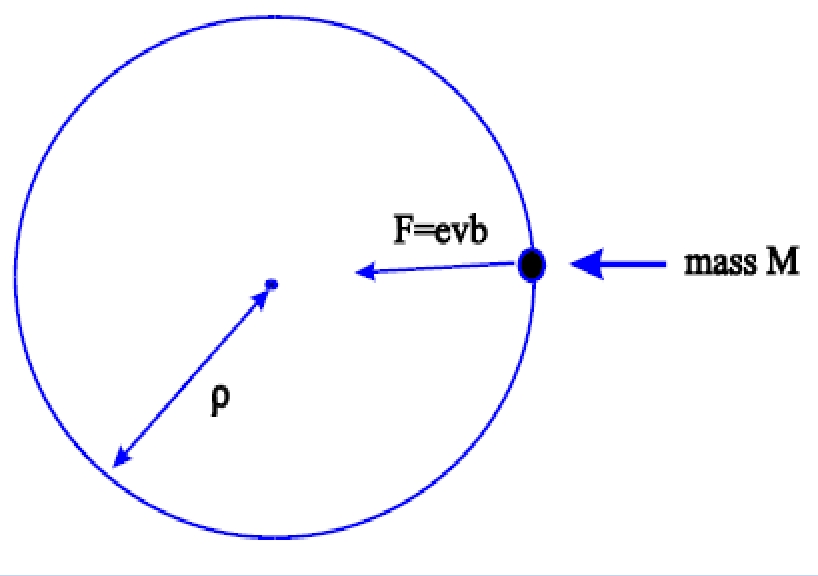
What it looks like to the patient: gantry room at the Midwest Proton Radiotherapy Institute (MPRI) (modified IBA gantry)

Adapted from B. Gottschalk

The LLUMC proton synchrotron



We have already seen the motion of a particle in a dipole magnetic field…



$$F = \frac{mv^2}{\rho},$$ where ρ = radius of curvature of the path

$$F = evB = \frac{mv^2}{\rho}$$

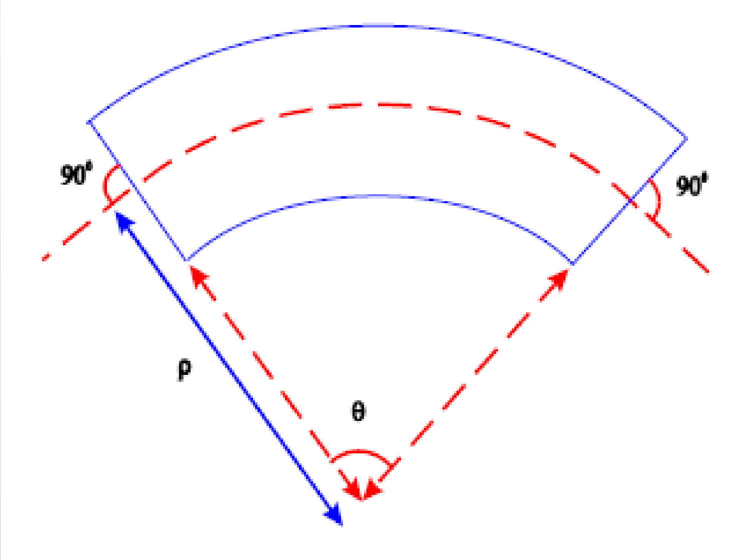
(p = momentum = mv)

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

Bρ = 33.356·p [kG·m] = 3.3356·p [T·m] (if p is in GeV/c)

Bρ is called "magnetic rigidity" of the particle and is an index of how difficult is to bend the motion of a charged particle by a magnetic field

Trajectory of particles in a dipole field



Trajectory of a particle in a bending magnet

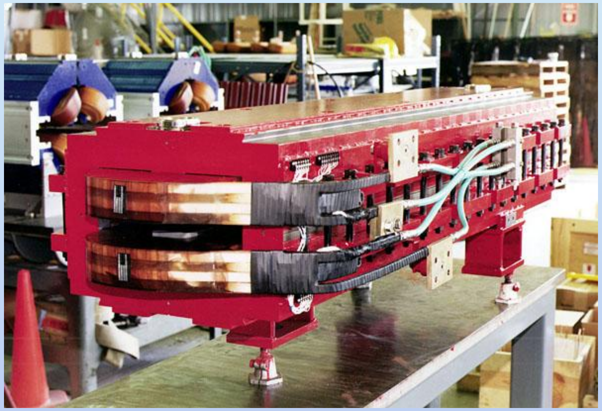
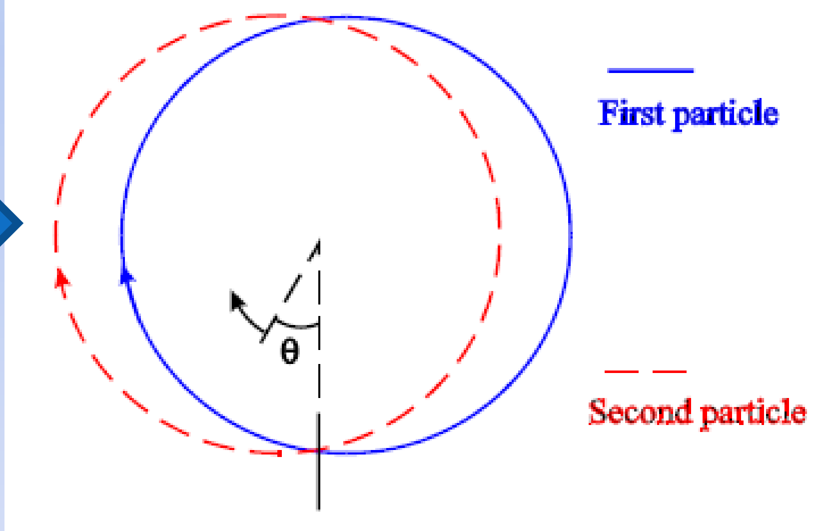


Photo: courtesy ANL

Unfortunately an accelerator contains more than one particle!

Number of circulating particles in a synchrotron is typically in the order of 10^{10} - 10^{12} and more

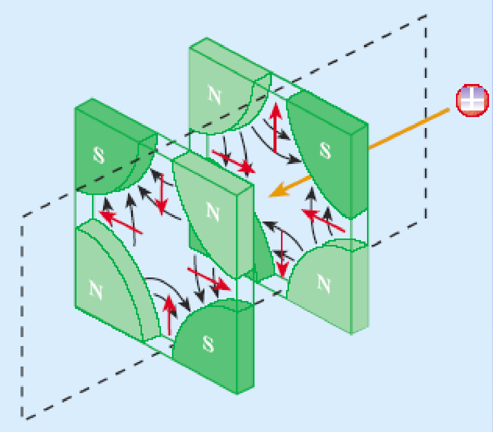


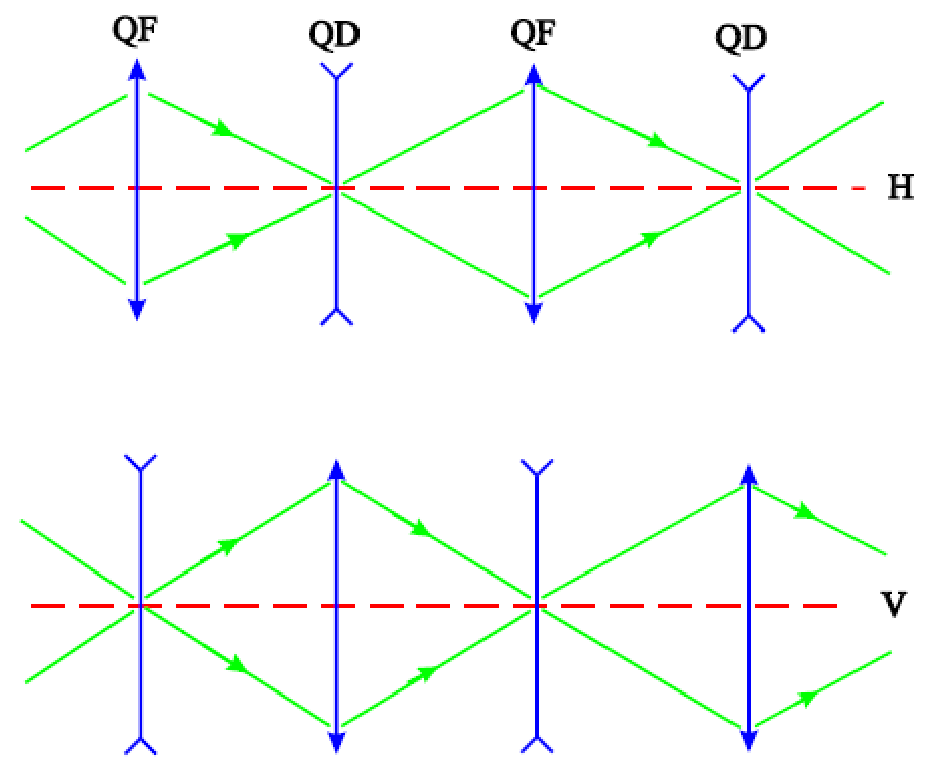
Two particles in a dipole field, with same momentum but different initial angles

Quadrupoles as thin lenses

Light rays passing through a series of focusing and defocusing lenses

The lenses, which are concave in one plane, are convex in the other

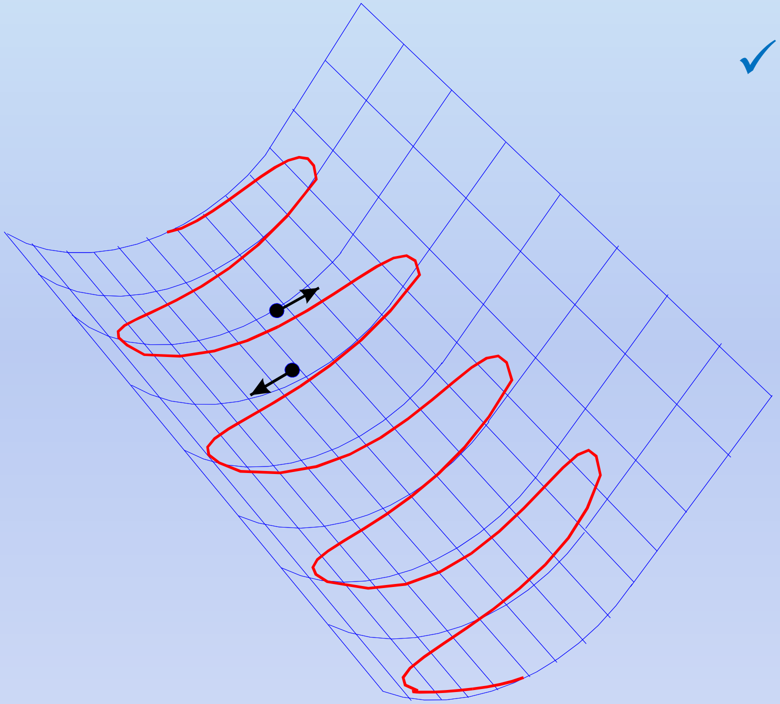




In both cases the concave lenses will have little effect as the light passes very close to their centre, and the net result is that the light rays are focused in both planes

The mechanical equivalent

- ✓ The gutter below illustrates how the particles in a synchrotron behave due to the quadrupolar fields.



- ✓ Whenever a particle beam diverges too far away from the central orbit the quadrupoles focus them back towards the central orbit.

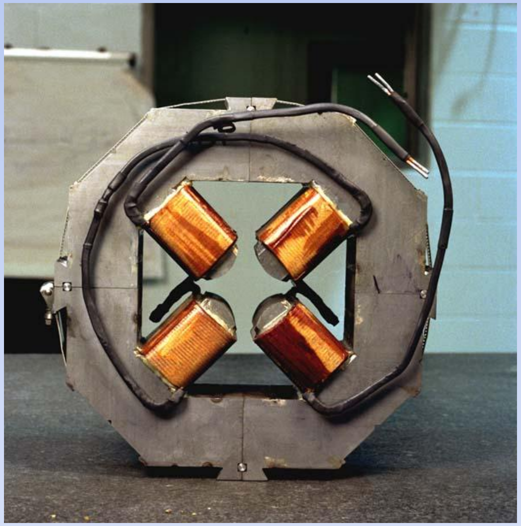


Photo courtesy Fermilab Visual Media Services

Hadron-therapy in Europe

O in operation
◊ in construction
Δ planned

Yellow = p only
Orange = p and C

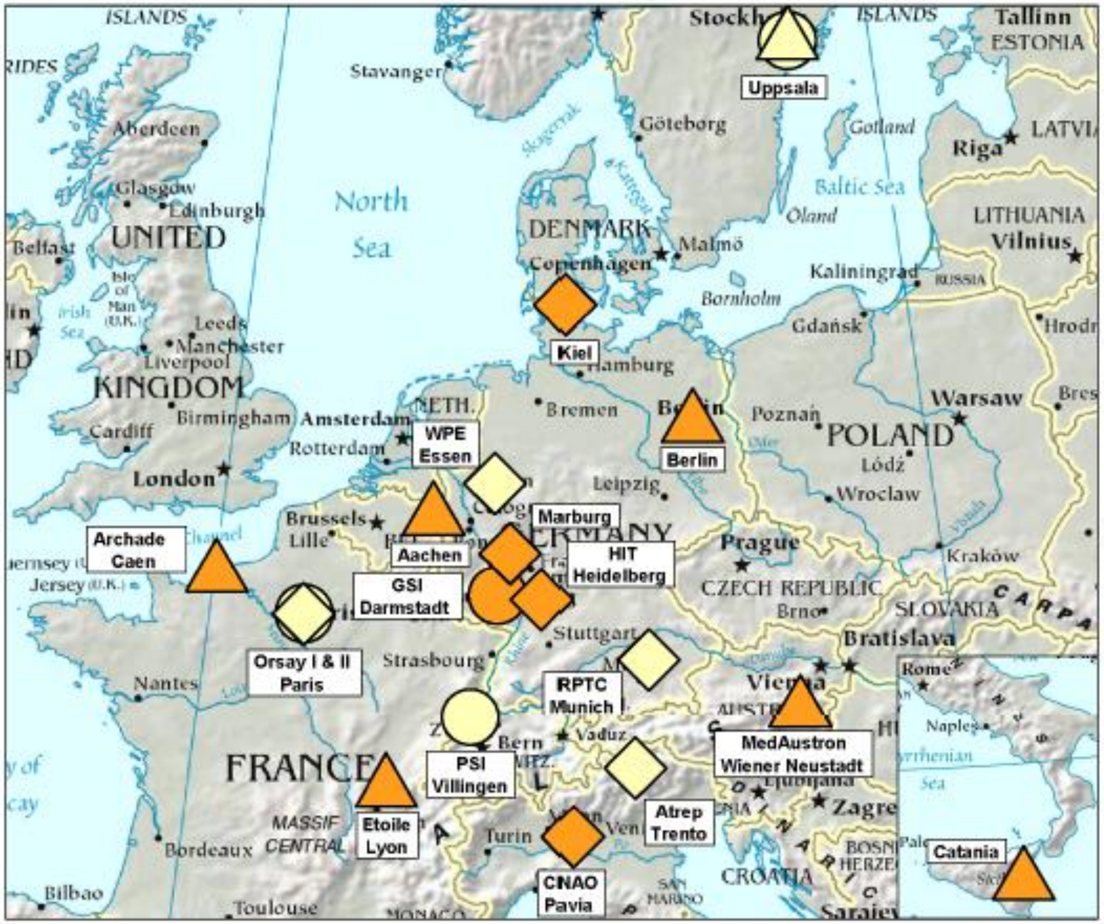
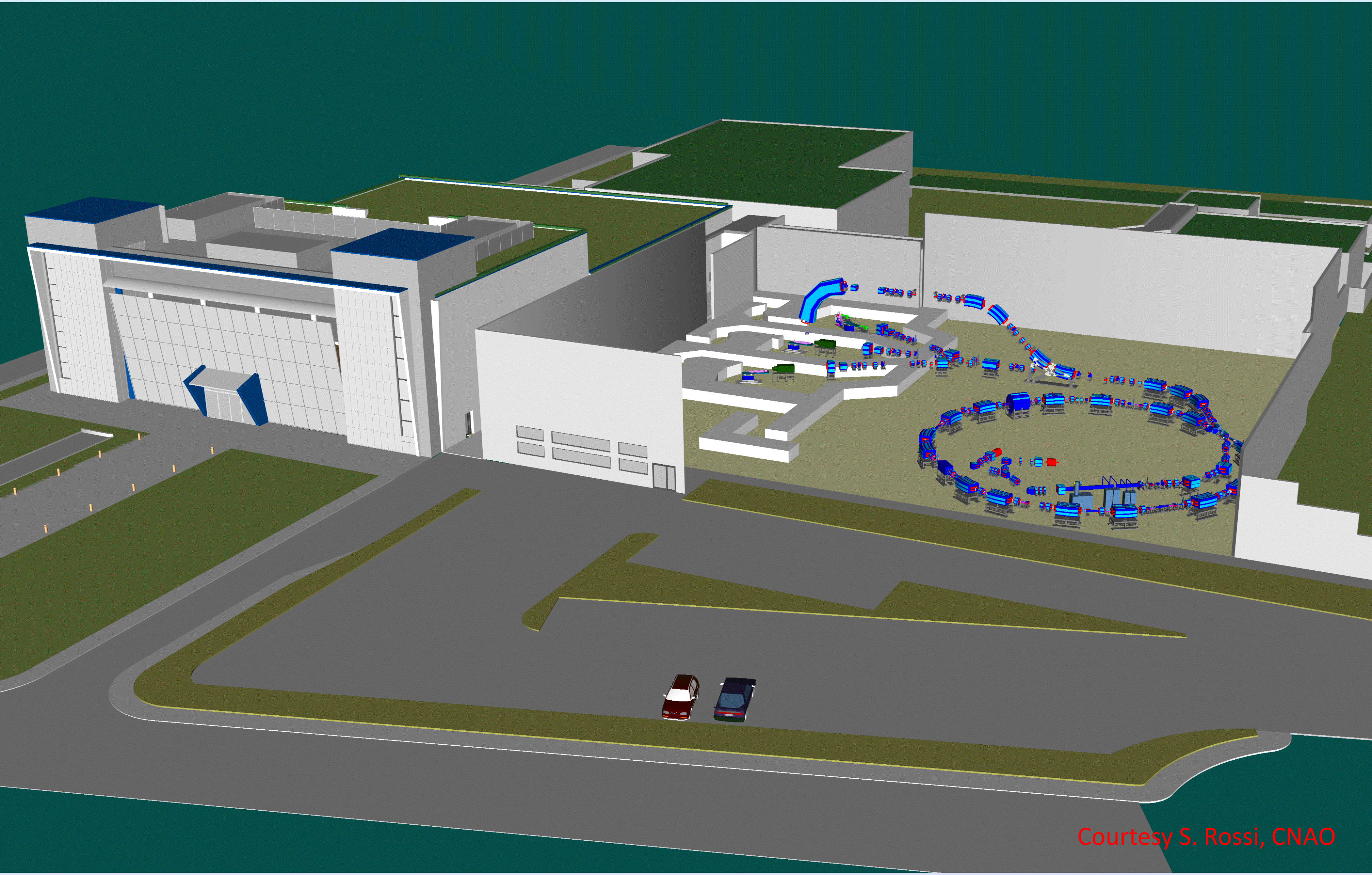


FIGURE 1. Map of Europe showing the present status of the ion beam therapy. The status of different projects is given by the symbols: in operation ○; under construction ◇; planned △.
The type of the facilities is indicated by the colors: yellow – proton only; orange – Carbon and protons.

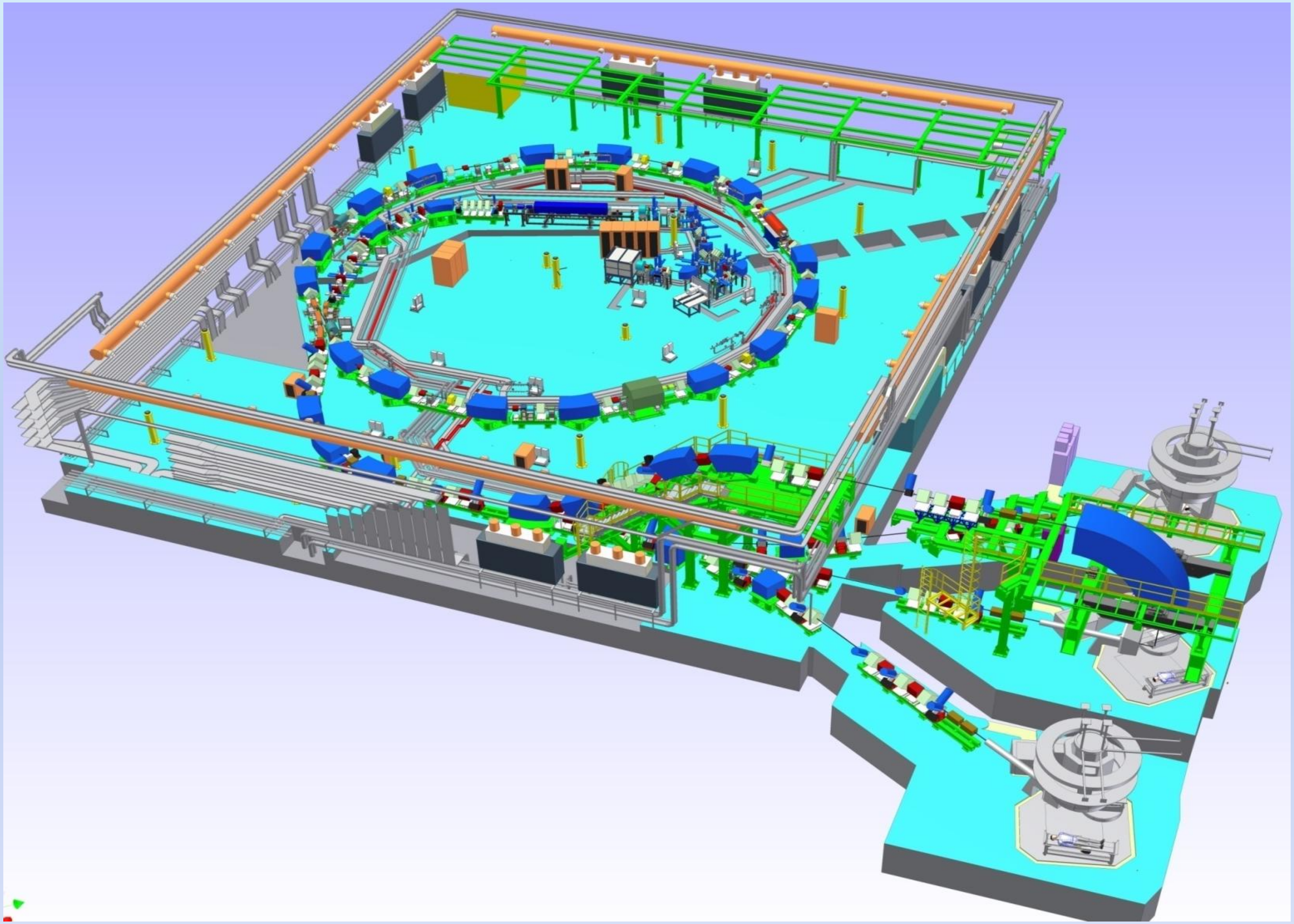
G. Kraft, Proc. of CAARI 2008, AIP, p. 429

National Centre for Oncological hadrontherapy (CNAO) in Pavia

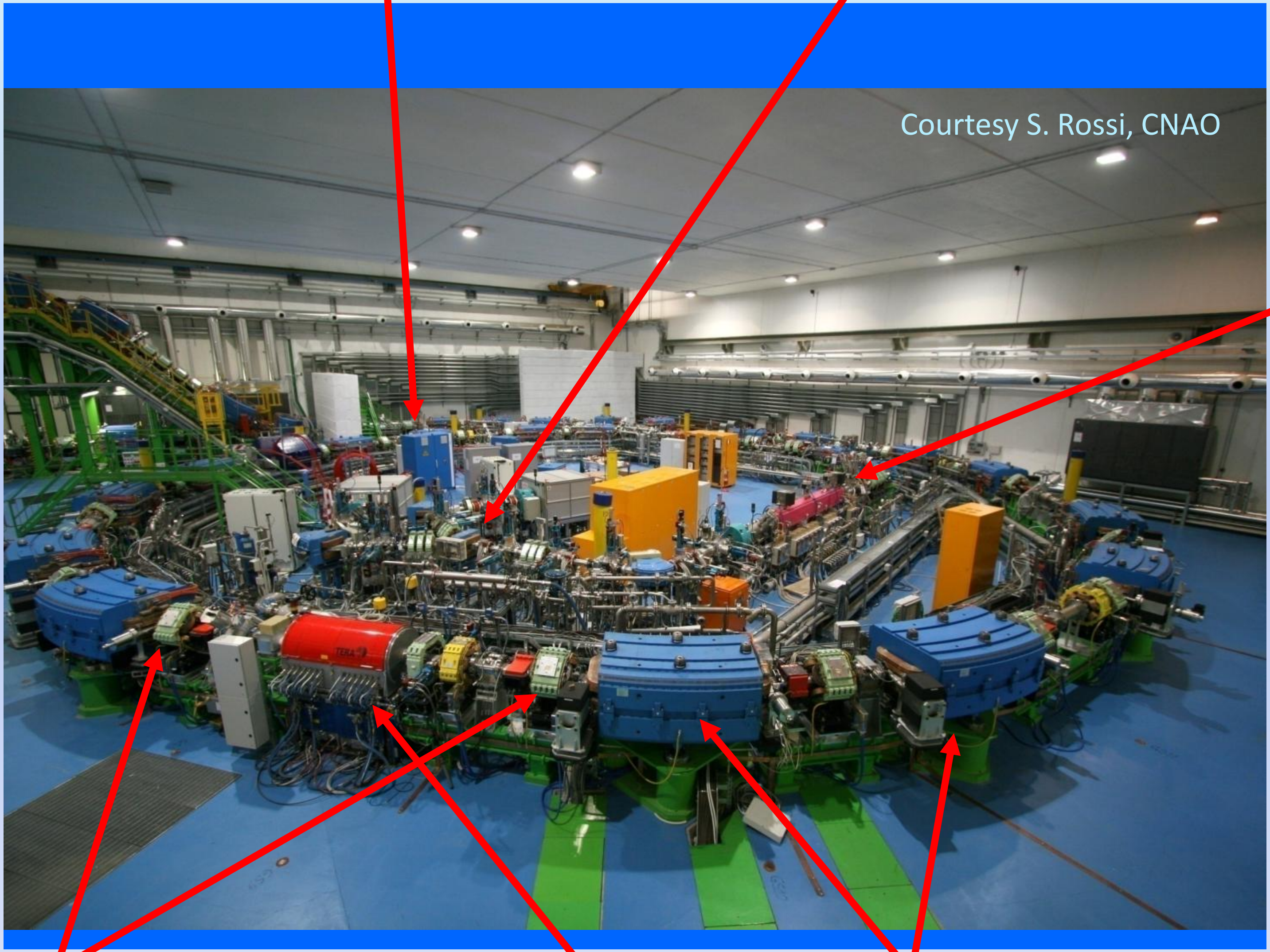


Courtesy S. Rossi, CNAO

National Centre for Oncological hadrontherapy (CNAO) in Pavia



The CNAO synchrotron



Courtesy S. Rossi, CNAO

Ion sources

LEBT components

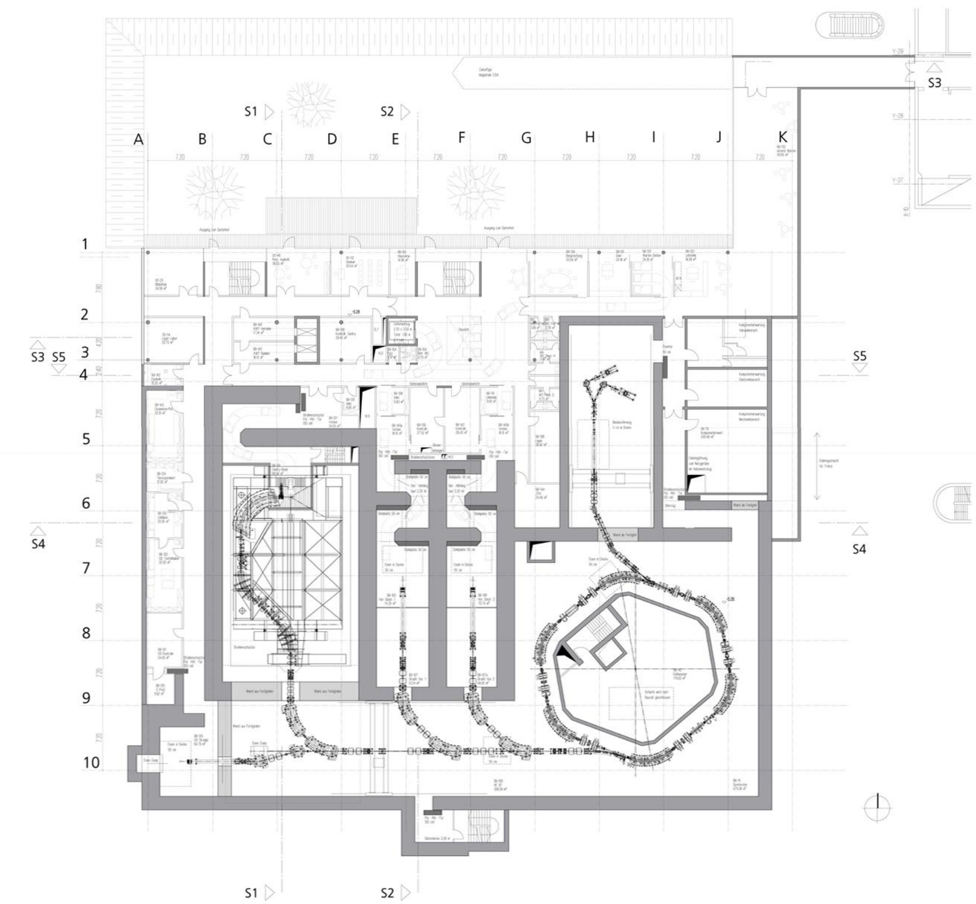
Injector linac

Quadrupole magnets

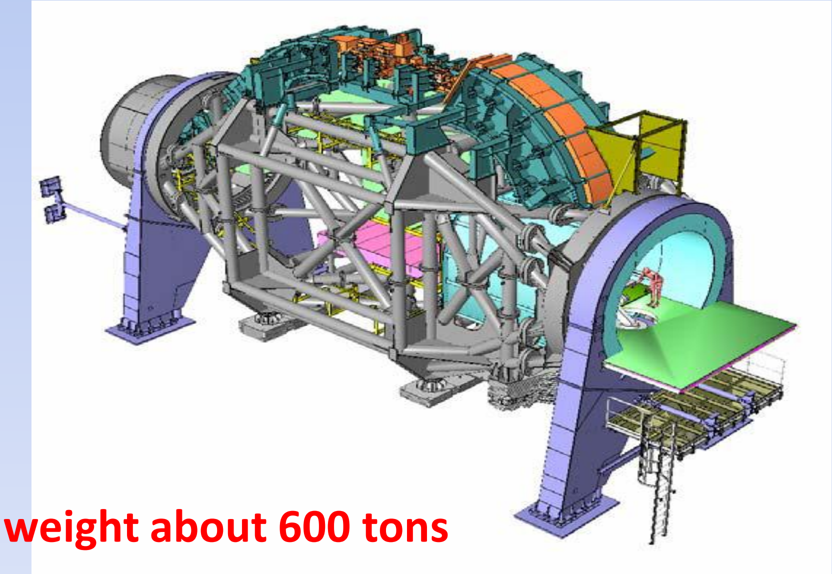
RF cavity

Dipole magnets

Heavy Ion Therapy Unit at the University of Heidelberg clinics



Courtesy HIT

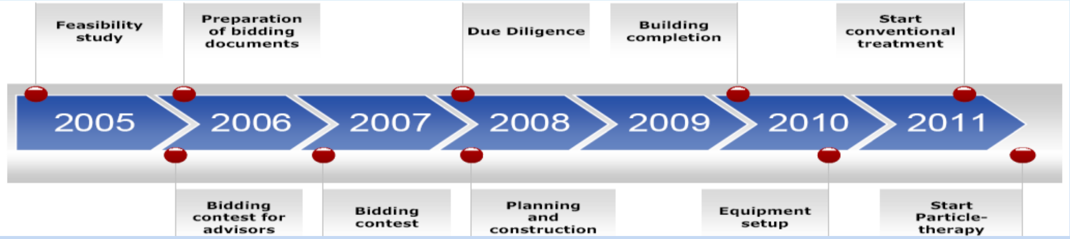


The HIT heavy ion gantry, weight about 600 tons

North European Radio-oncological Centre in Kiev

NRoCK

North European Radiooncological Center Kiel



Feasibility study

Preparation of bidding documents

Due Diligence

Building completion

Start conventional treatment

2005 2006 2007 2008 2009 2010 2011

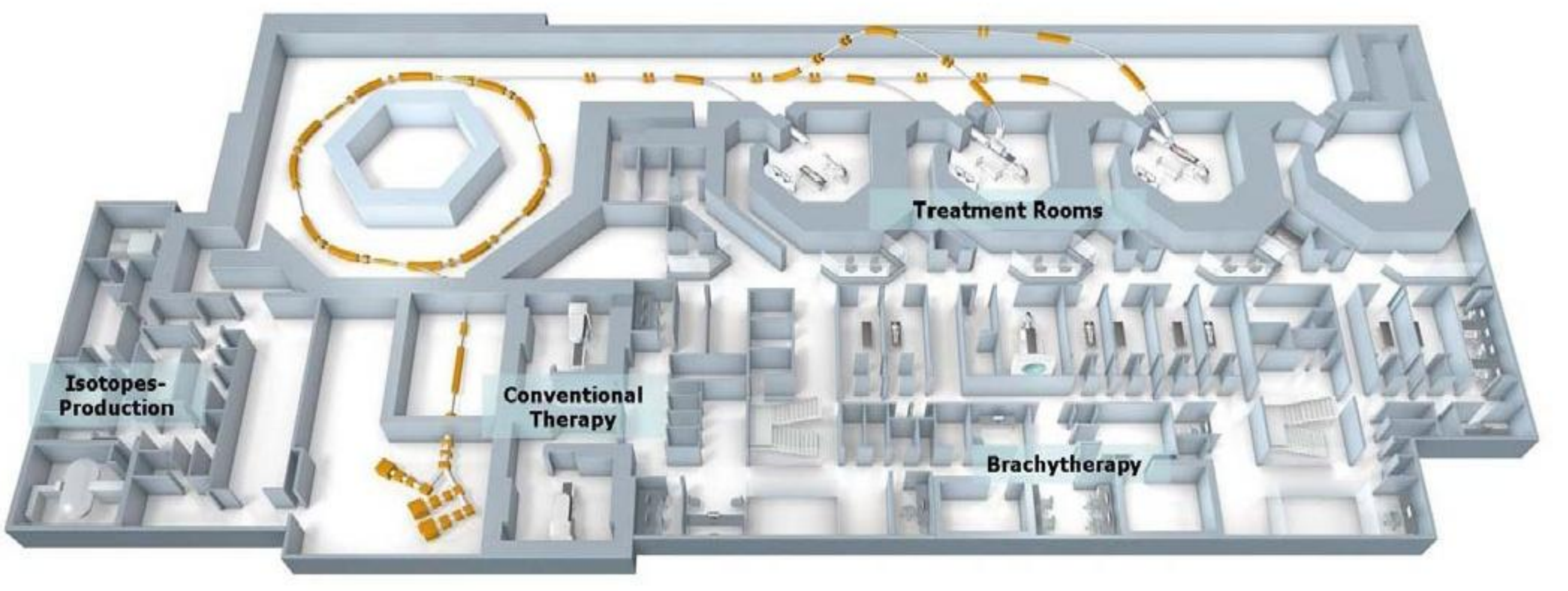
Bidding contest for advisors

Bidding contest

Planning and construction

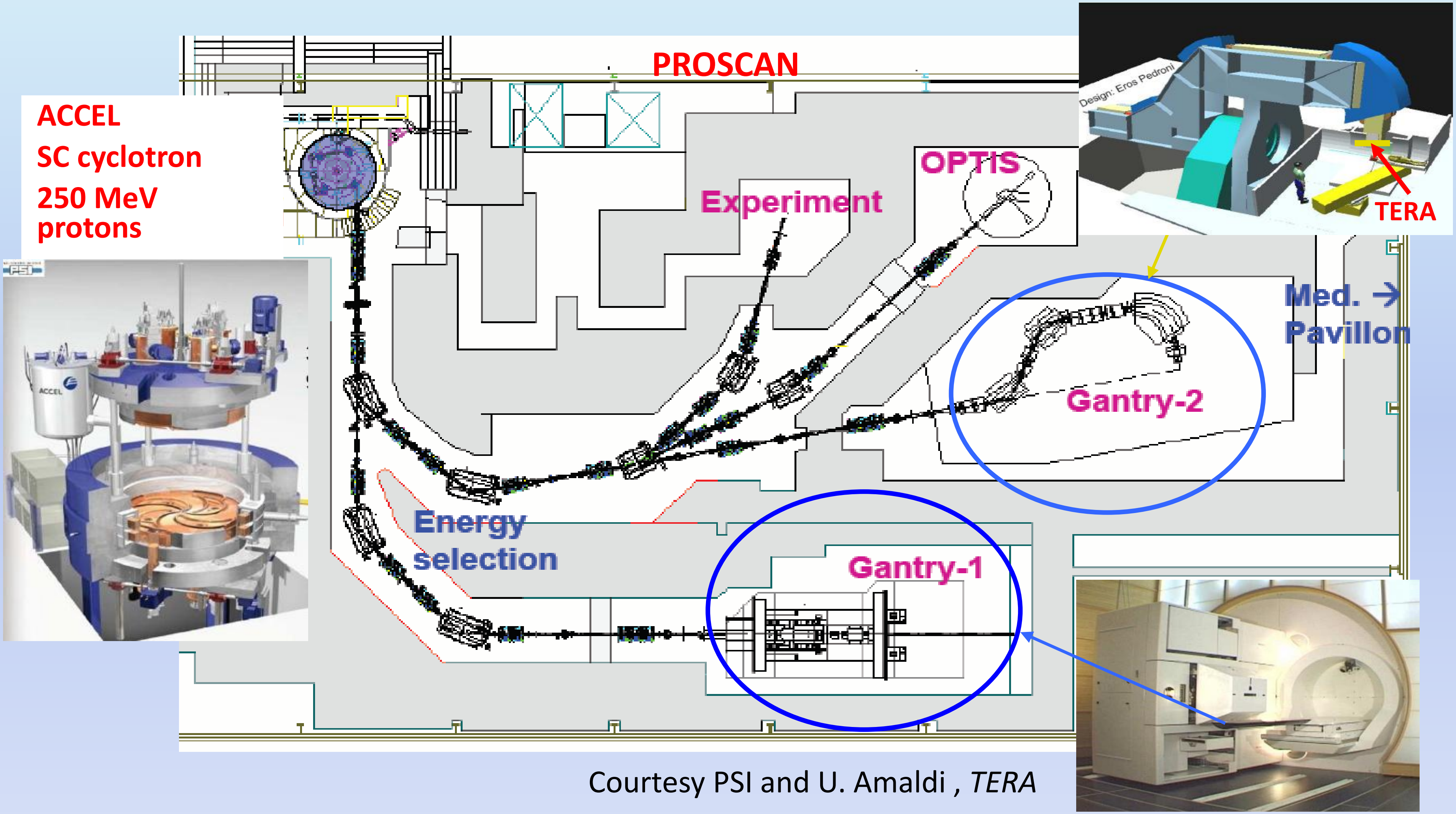
Equipment setup

Start Particle-therapy



PROSCAN at PSI, Switzerland

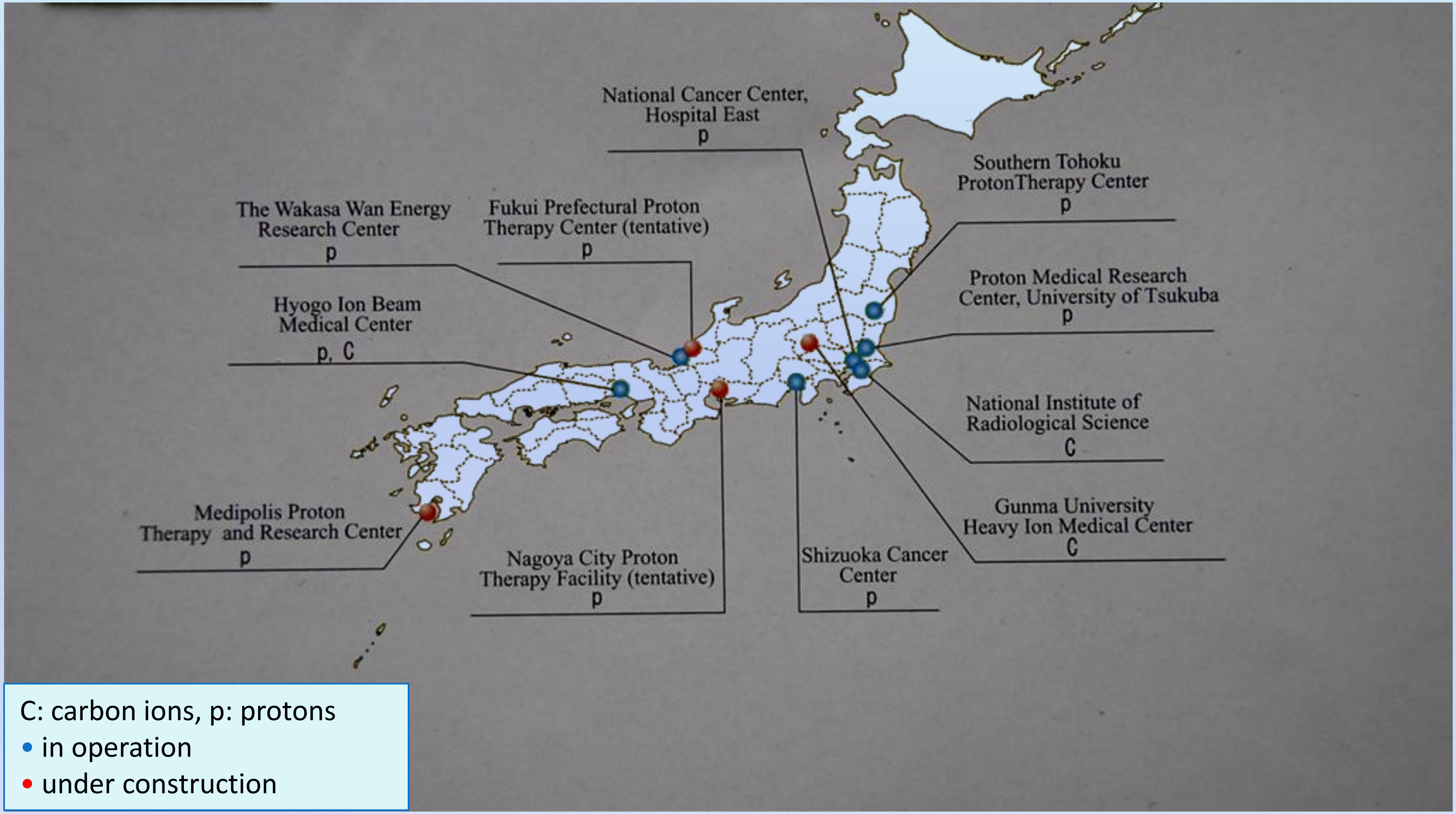
ACCEL
SC cyclotron
250 MeV protons



Courtesy PSI and U. Amaldi , *TERA*

J.M. Schippers et al., NIM BB 261 (2007) 773–776

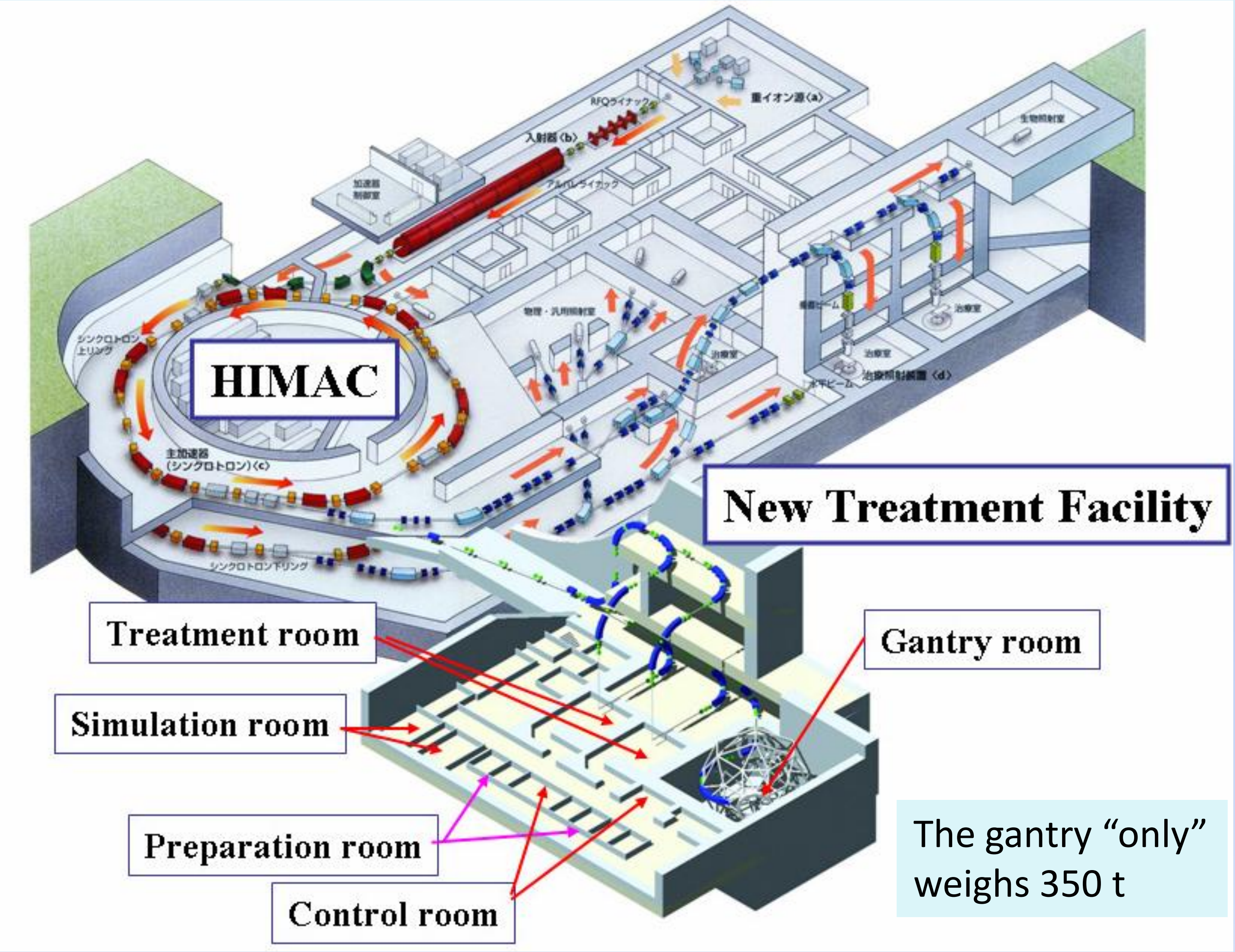
Hadron-therapy in Japan



C: carbon ions, p: protons
● in operation
● under construction

Courtesy NIRS

HIMAC in Chiba

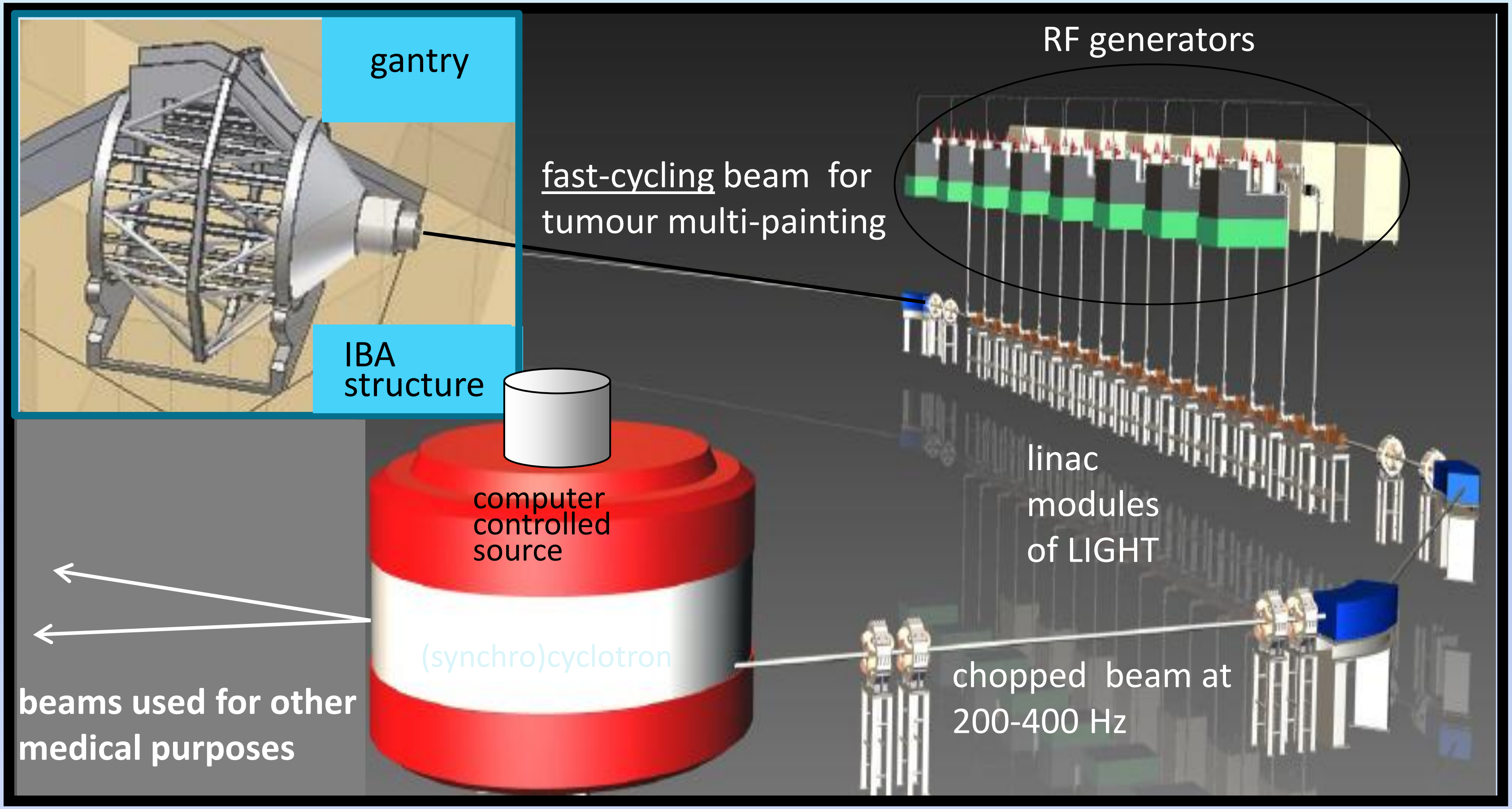


The gantry “only” weighs 350 t

K. Noda et al., Recent progress on HIMAC for carbon therapy, Proc. of PAC09

Some new concepts

TERA Cyclinac=cyclotron+linac for Image Guided Hadron-therapy



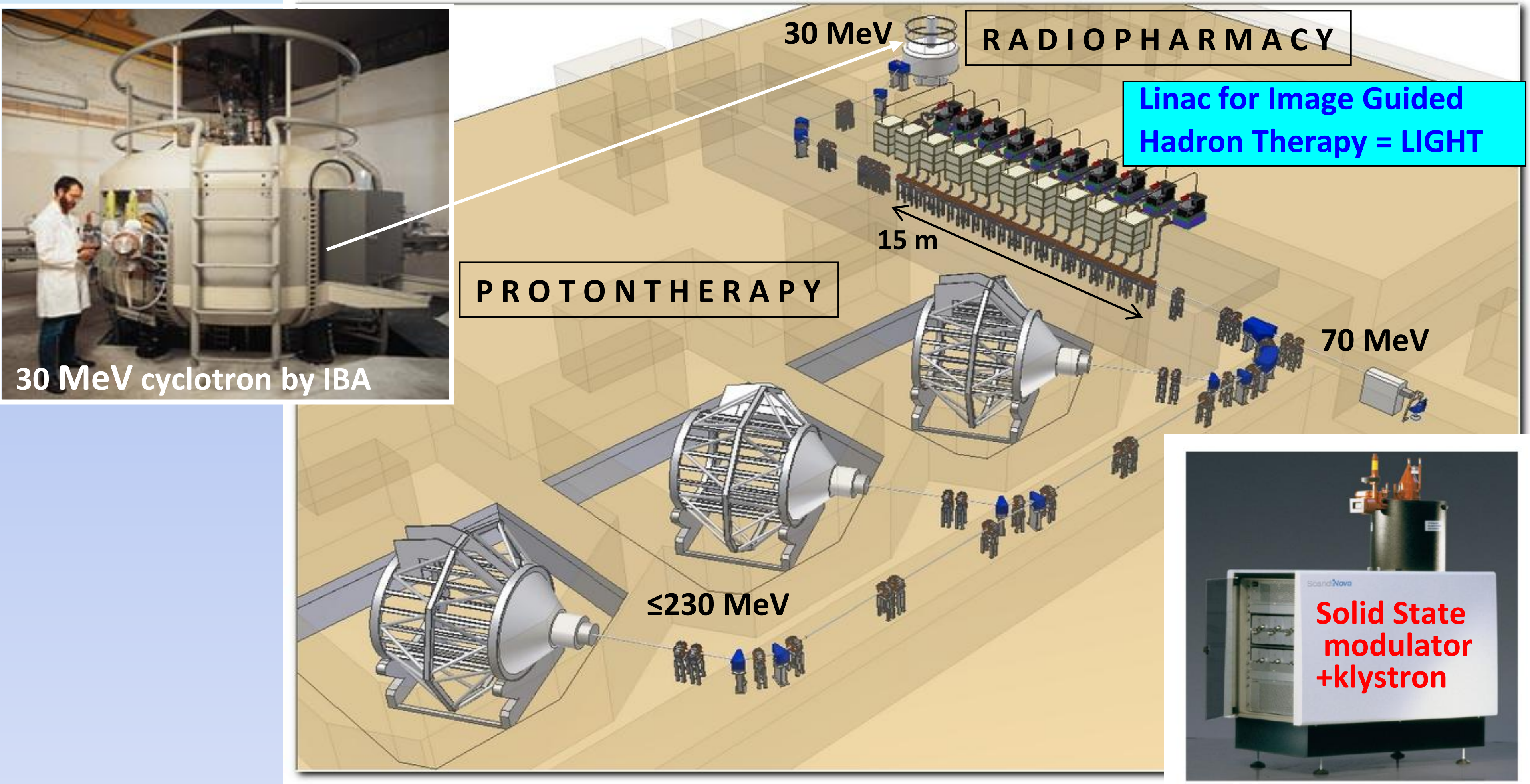
The energy is adjusted in 2 ms in the full range by changing the power pulses sent to the 16-22 accelerating modules
The charge in the next spot is adjusted every 2 ms with the computer controlled source

Courtesy U. Amaldi, *TERA*

IDRA = Institute for Diagnostics and Radiotherapy

A proton cyclinac

Courtesy U. Amaldi, *TERA*

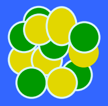


A.D.A.M. SA, Application of Detectors and Accelerators to Medicine, a CERN spin-off company will build LIGHT, and has an agreement with IBA for the delivery of the rest and the overall control

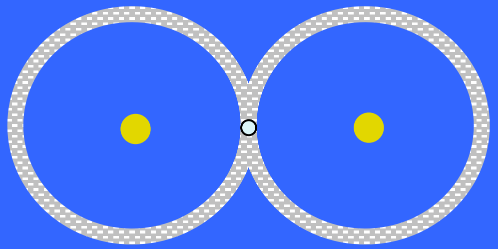
The 250-300 MeV SC cyclotron designed by LNS, Italy

SCENT = Superconducting Cyclotron for Exotic Nuclei and Therapy

The superconducting cyclotron accelerates particles with **Q/A = ½**



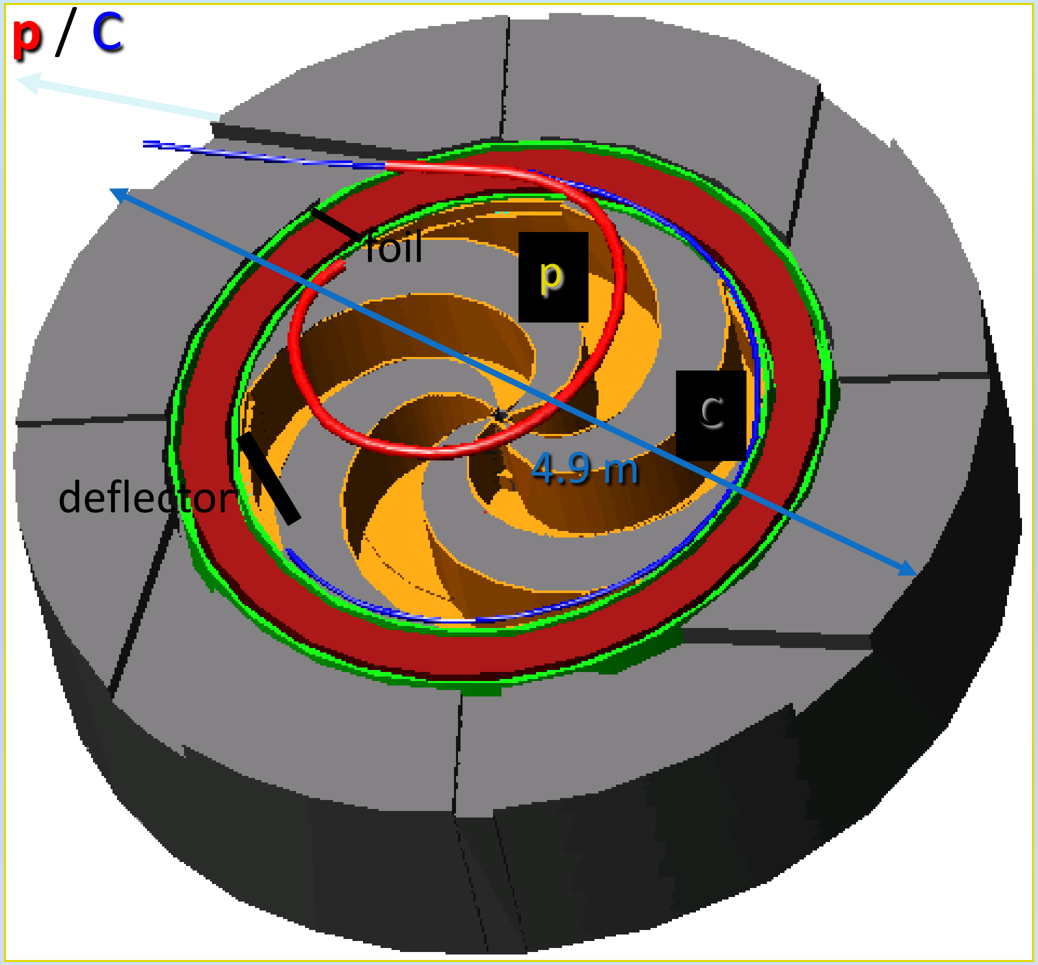
$^{12}C^{6+}$ $6p^+ + 6n$



H_2^+ $2p^+ + 1e^-$

Output energies:

protons	250 MeV
carbon ions	3000-3600 MeV



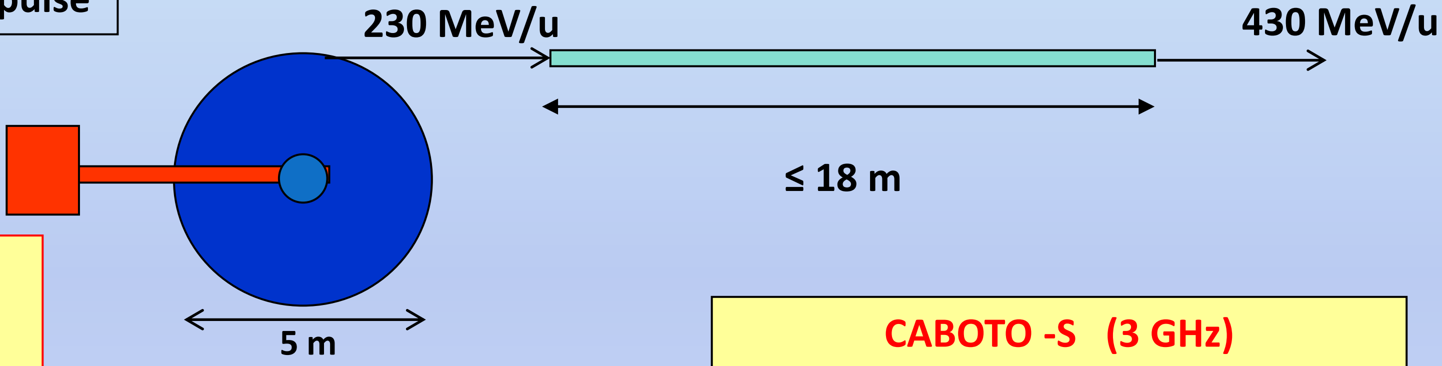
L. Calabretta et al, NIM A 562 (2006) 1009 -1012

CABOTO = Carbon Booster for Therapy in Oncology

TERA Foundation, Italy

SC EBIS source by
DREBIT – Dresden
300 Hz – 10^8 C/pulse

400 MV – 3-9 GHz linac
≤ 1.5 μs pulses



Two sources:

$^{12}C^{6+}$ H_2^+

SC Synchrocyclotron
230 MeV/u
H_2^+ and C^{+6}
@ 300 Hz

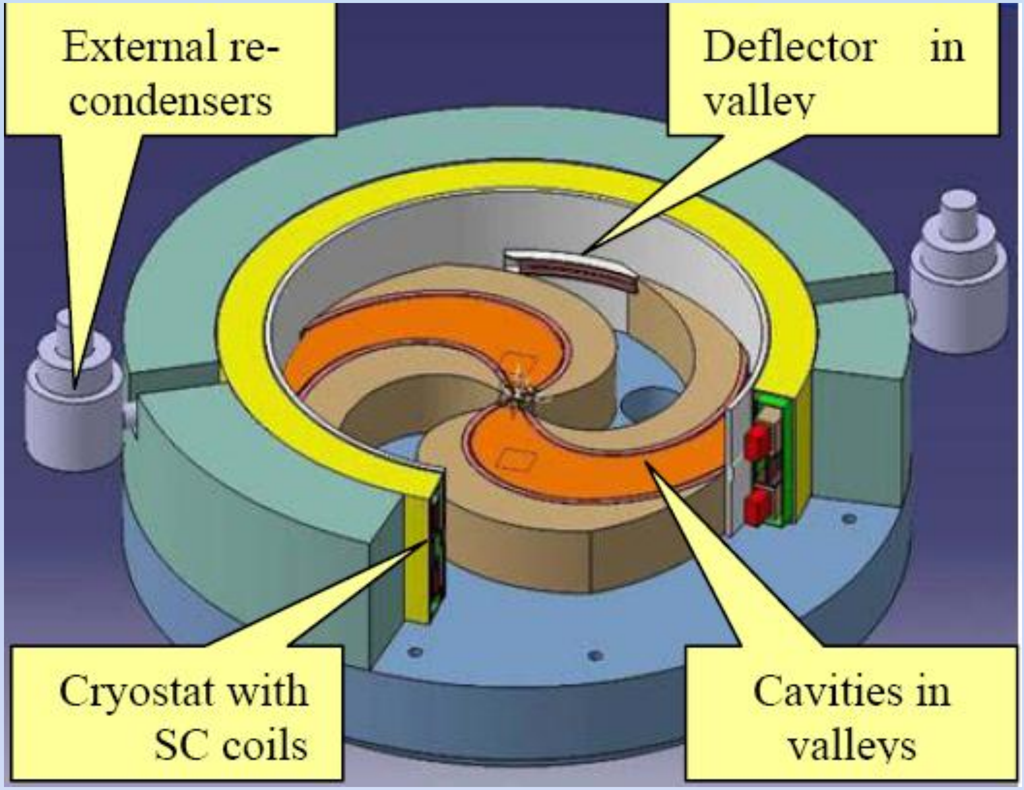
CABOTO -S   (3 GHz)
CABOTO -C   (6 GHz)
CABOTO -X   (9 GHz)
design projects

Collaboration: EPFL and CERN - CLIC

Courtesy U. Amaldi, *TERA*

IBA 400 MeV/u carbon-ion cyclotron

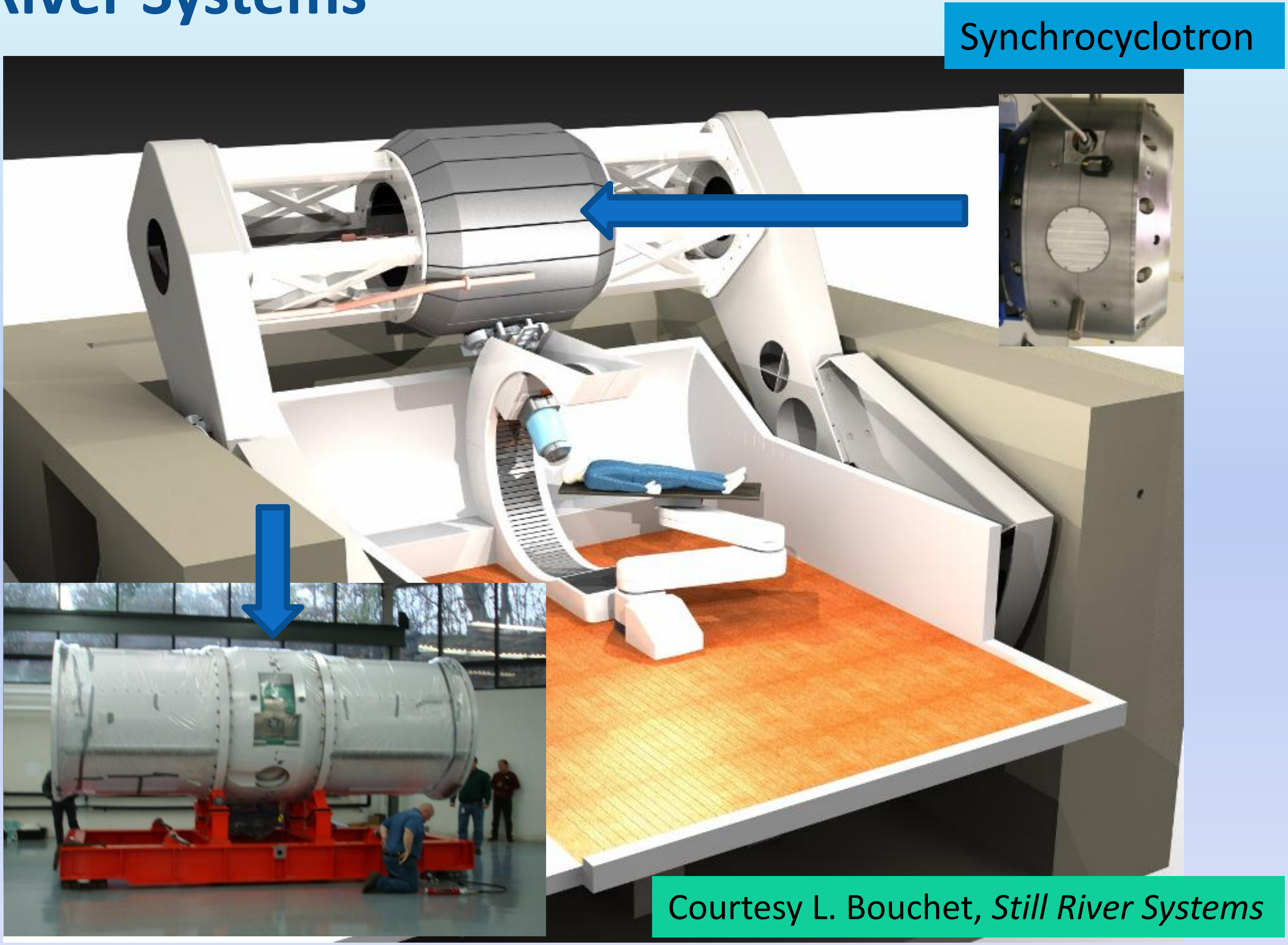
“Archade” (at Ganil in Caen, France) is based on the new IBA 400 MeV/u superconducting cyclotron



Courtesy Y. Jongen, *IBA*

- **Maximum energy: 400 MeV/u, adjustable externally by ESS**
- **Superconducting magnet. Hill field 4.5 T**
- **Cooling by helium loop, with 4 external recondensers**

Still River Systems

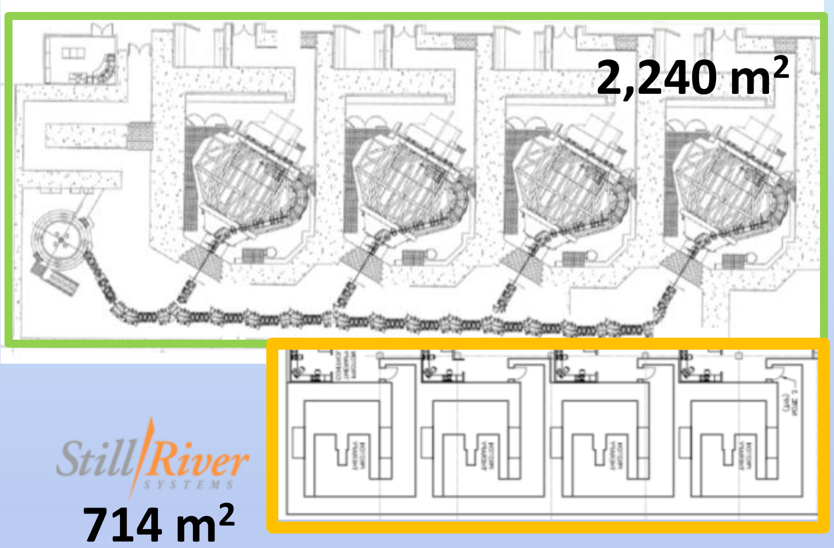


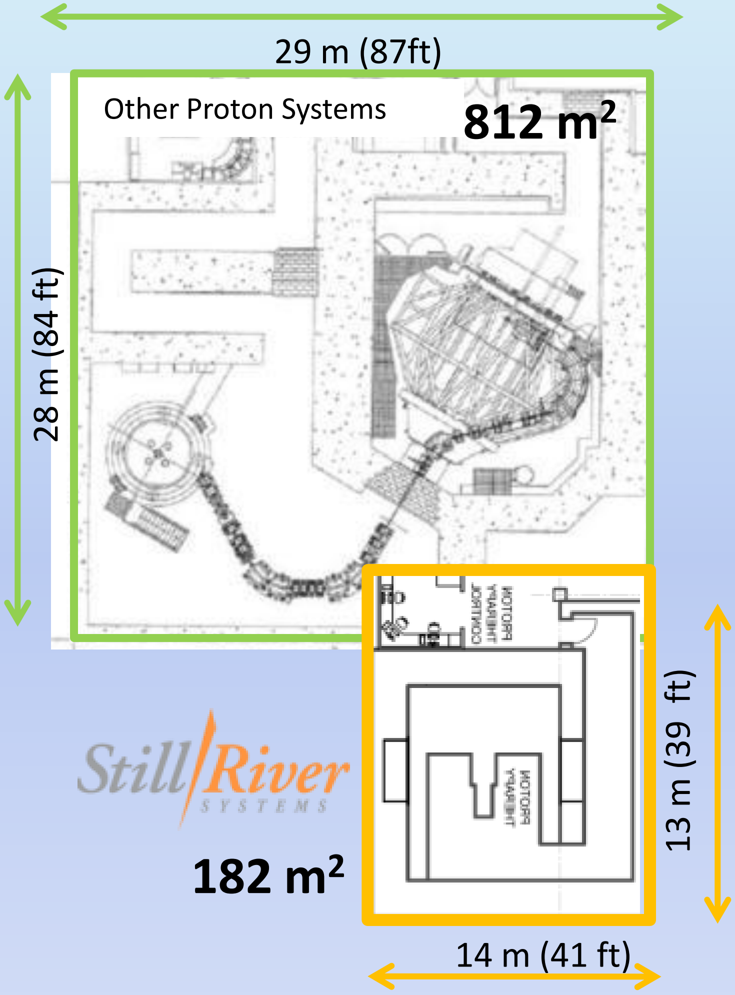
Courtesy L. Bouchet, *Still River Systems*

Still River Systems

Synchrocyclotron @ 10 Tesla
Proton energy: 250 MeV
Ion source tested up to 1,000 nA
Cooling is through cryo-compressors (NO liquid Helium)
Low maintenance requirements – quarterly only
Time structure: similar to linear accelerator with gating and scanning capabilities

Multi-room versus single-room facilities





Advantages of single-room facility:

- ✓ **Modularity**
- ✓ **Reliability / back-up**
- ✓ **PT treatment available at more hospitals**
- ✓ **(Hopefully) cost**

Courtesy L. Bouchet, *Still River Systems*

Some textbooks

C.K. Karzmark, Advances in linear accelerator design for radiotherapy, Medical Physics 11, 105- 128 (1984)

S. Humphries, Principles of charged particle acceleration, John Wiley and Sons

H. Wiedemann, Particle accelerator physics, Springer- Werlag

S. Baird, Accelerators for pedestrians, CERN AB-note-2007-014

PTCOG: Particle Therapy Co-Operative Group
http://ptcog.web.psi.ch/