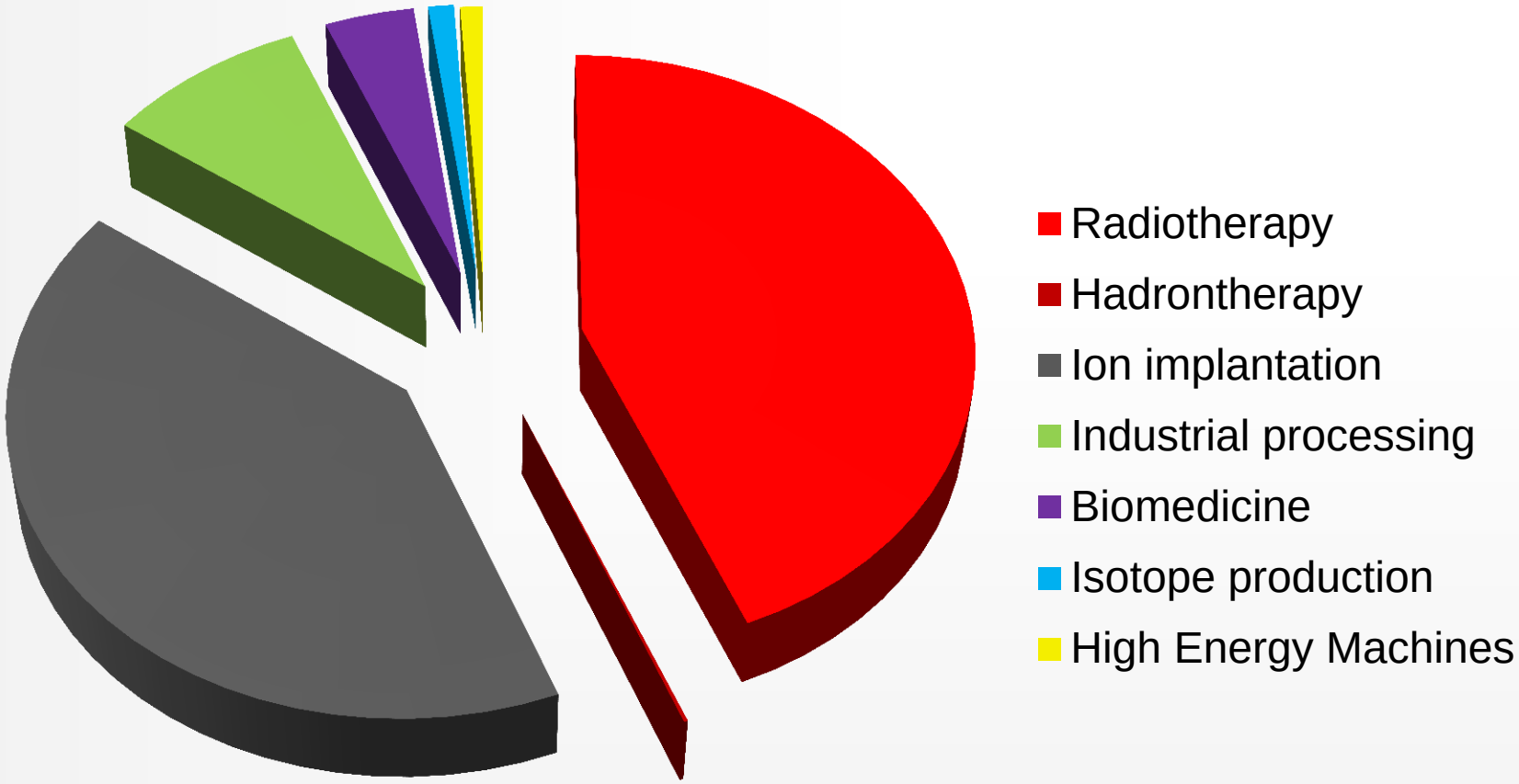
Medical applications

Caterina Biscari

Alba-CELLS

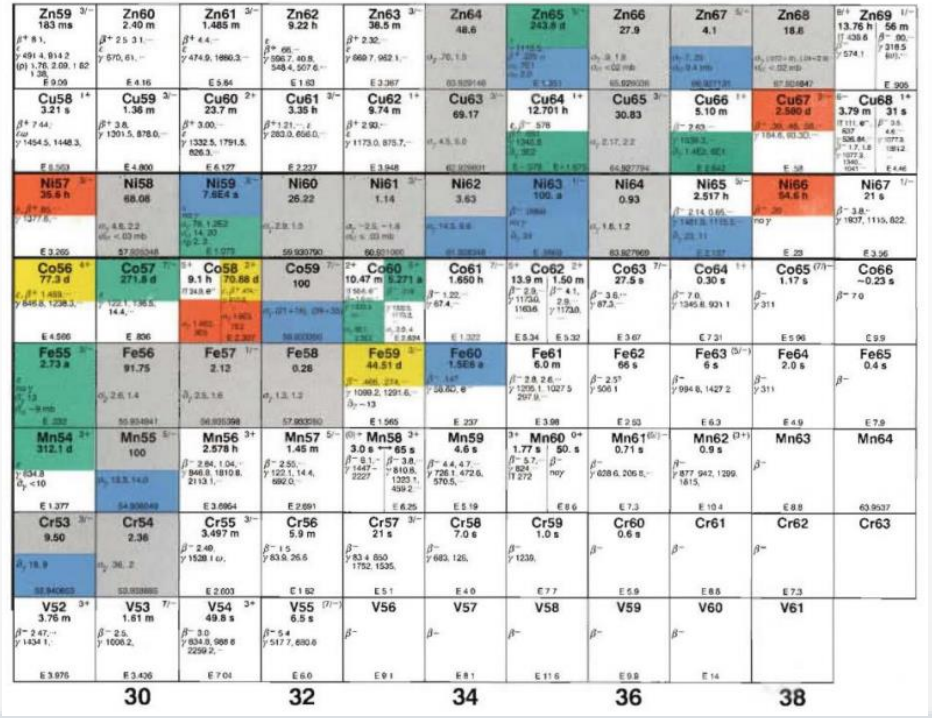
~30000 accelerators in the world



Isotope production

- Isotope production for medical diagnoses purposes - First isotopes produced by Lawrence in his cyclotron in 1934
- Since then both nuclear reactors and accelerators produce isotopes for an ever increasing demand
- Accelerators are used to bombard production targets with beams of charged nuclei impinging on targets to produce a wide range range of isotopes

The range of particle energies and intensities vary between facilities -- 10 - 100 MeV for commercial cyclotrons dedicated for isotope production, with higher energies available at some research accelerators



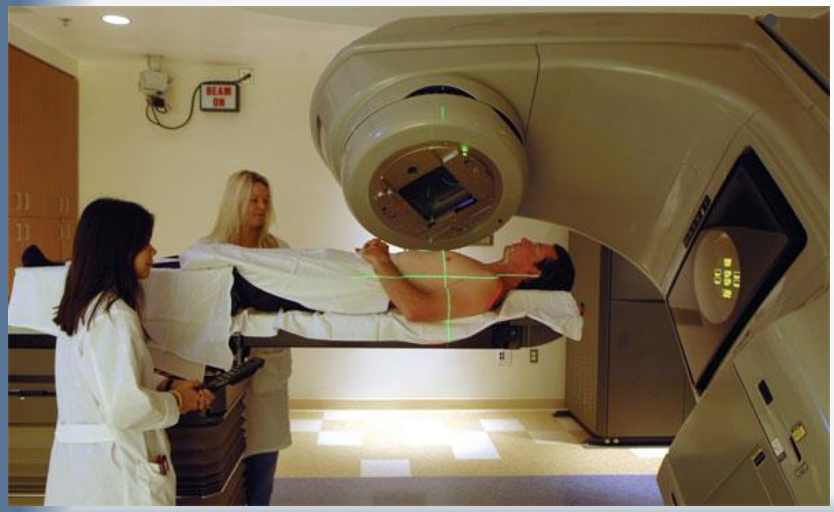
See for example:
http://www.isotopes.gov/outreach/reports/Medical_Isotope_Production_Use.pdf

Cancer therapy: X-rays

- 1937: first X-rays irradiation from van de Graaff electrostatic machine
- 1956 : first patient treated with radiotherapy at Stanford – eye tumor
- Since then 40 millions patients have been treated
- Today 50% of cancer patients are X-ray treated (70% in industrialised countries), either alone or in combination with other techniques.
- Electron Linacs (4 – 22 MeV) produce e- to be shot on a metallic target and produce X-rays

Courtesy of Department of Radiation Oncology

The first patient to receive radiation therapy from the medical linear accelerator at Stanford was a 2-year-old boy.

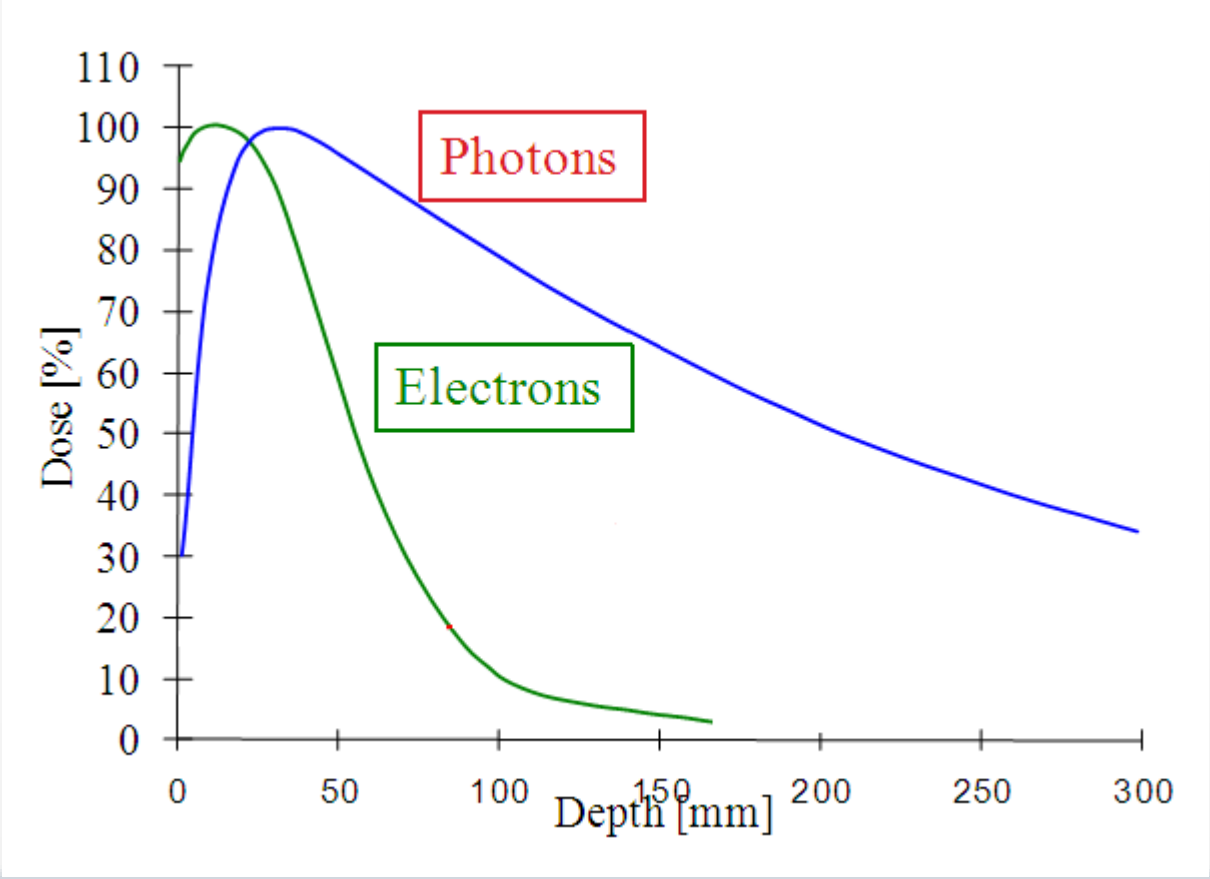


Commercially produced

- Thousands of compact and fully reliable Linacs are daily treating patients
- Control of radiation dose and radiation fields decrease collateral effects
- IMRT = intensity modulated radiation therapy

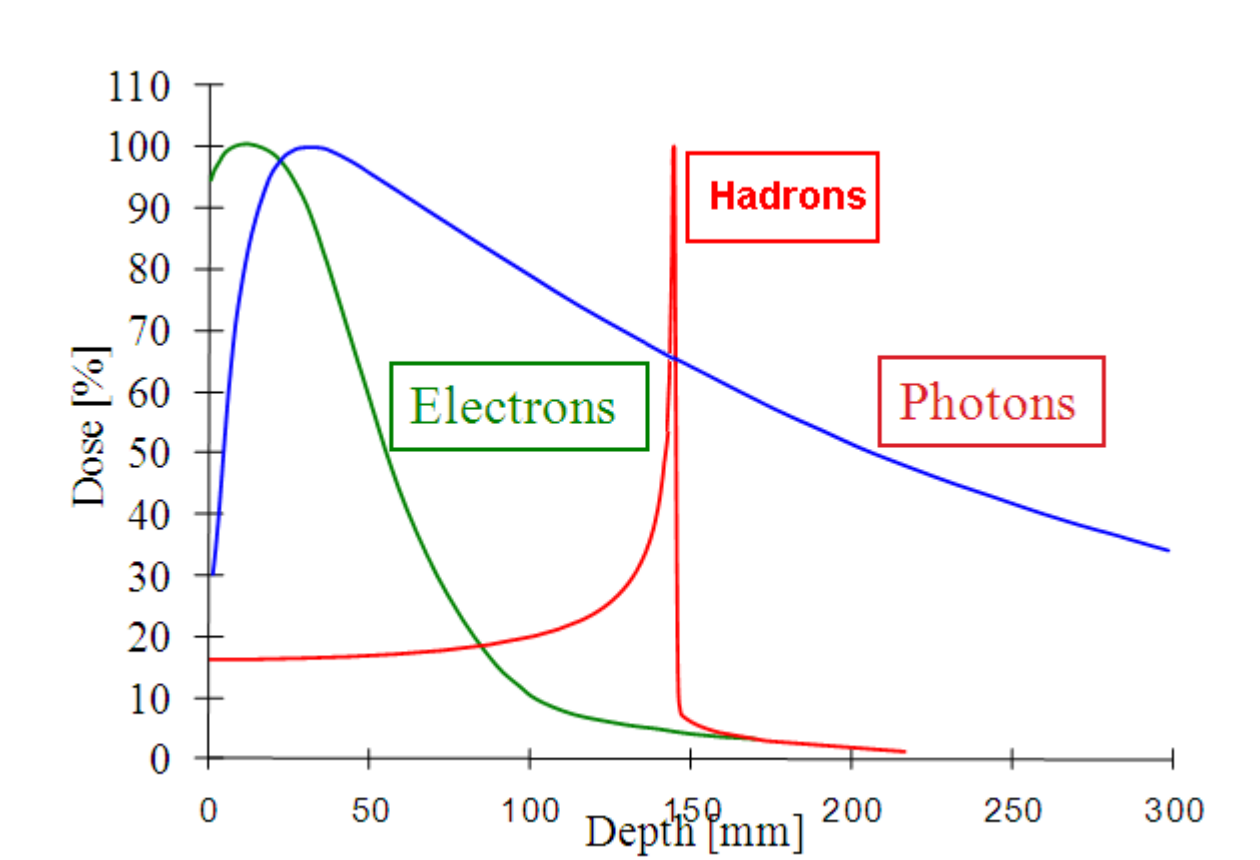
Radiotherapy

Radiotherapy uses electrons and photons to kill cancer cells damaging the DNA.
These particles loose energy at beam entrance and then exponentially.
The depth-dose deposition characteristics cause damage also to healthy tissues
Computer-aided treatment plans (IMRT) allows to reduce this counterpart



Radiotherapy and hadrontherapy

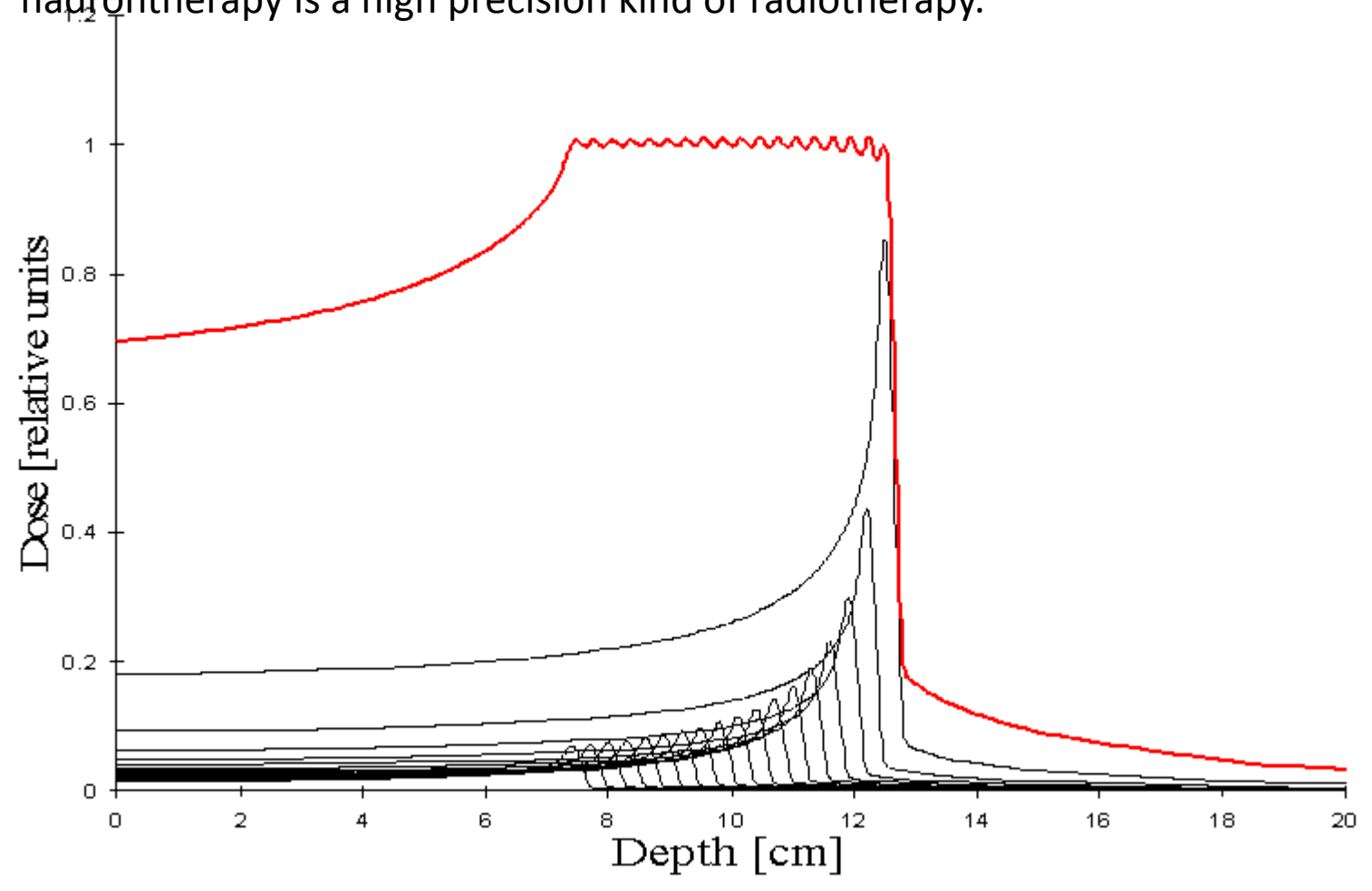
Hadrontherapy uses hadrons (protons and ions)
Particles at high energy deposit relatively little energy as they enter an absorbing material but tend to deposit extremely large amounts of energy in a very narrow peak, the Bragg peak, as they reach the end of their range: Very localized depth-dose deposition



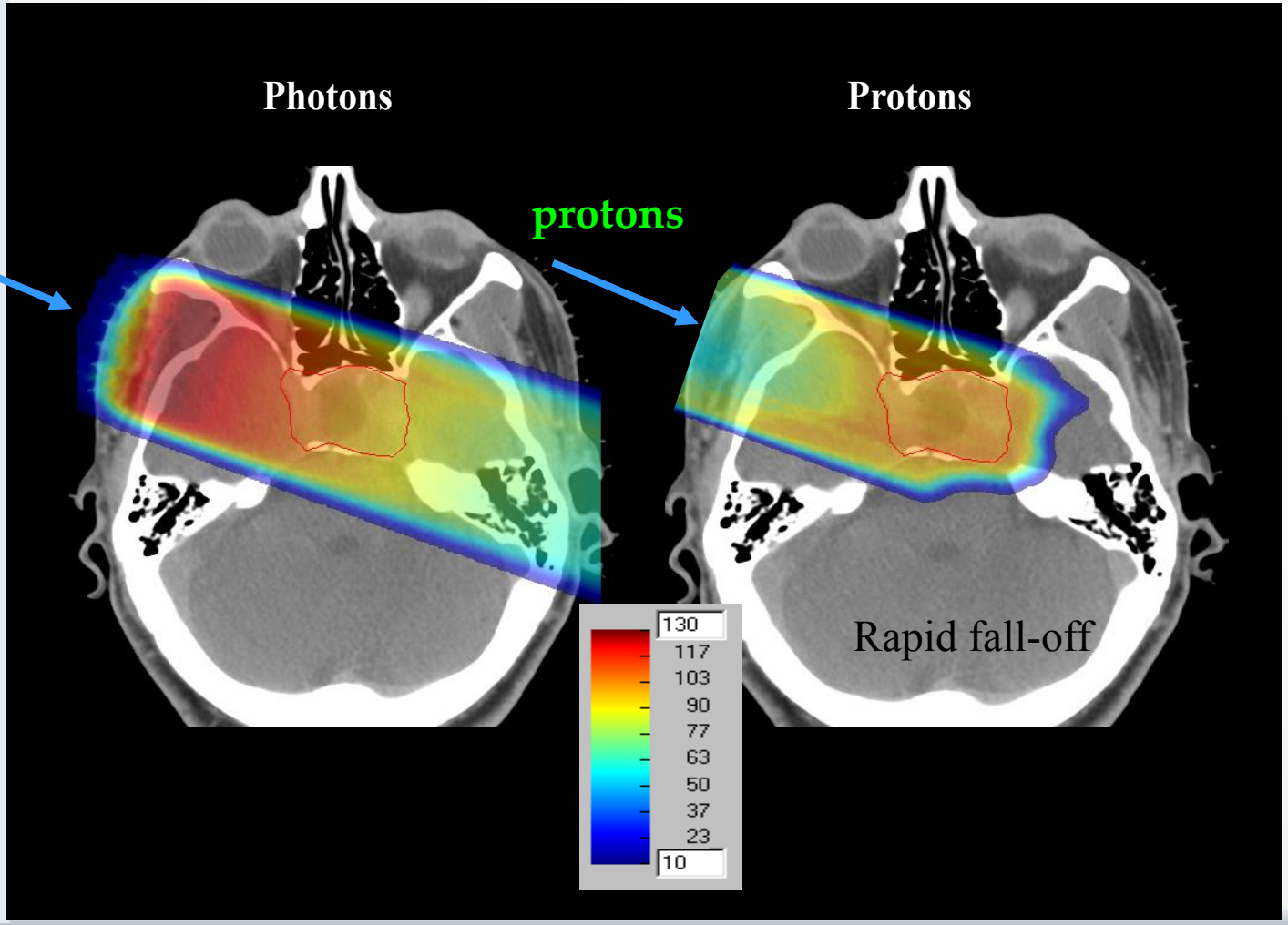
The depth and magnitude of the Bragg peak is determined by the mass and charge, as well as the particle initial energy

Hadrontherapy: Spread Out Bragg Peak

It is possible to localize longitudinally the irradiation only on the tumor target: hadrontherapy is a high precision kind of radiotherapy.

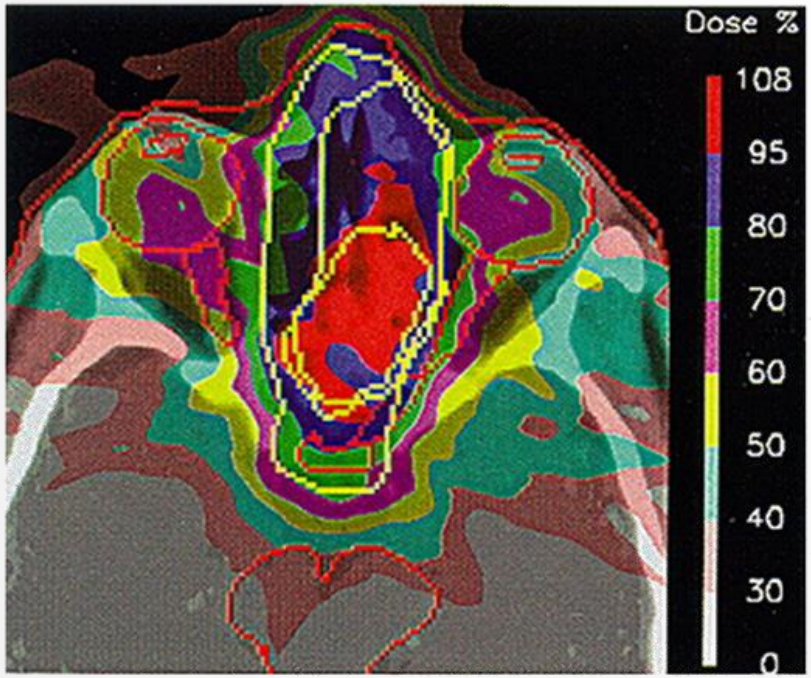


Macroscopic advantage of hadrons

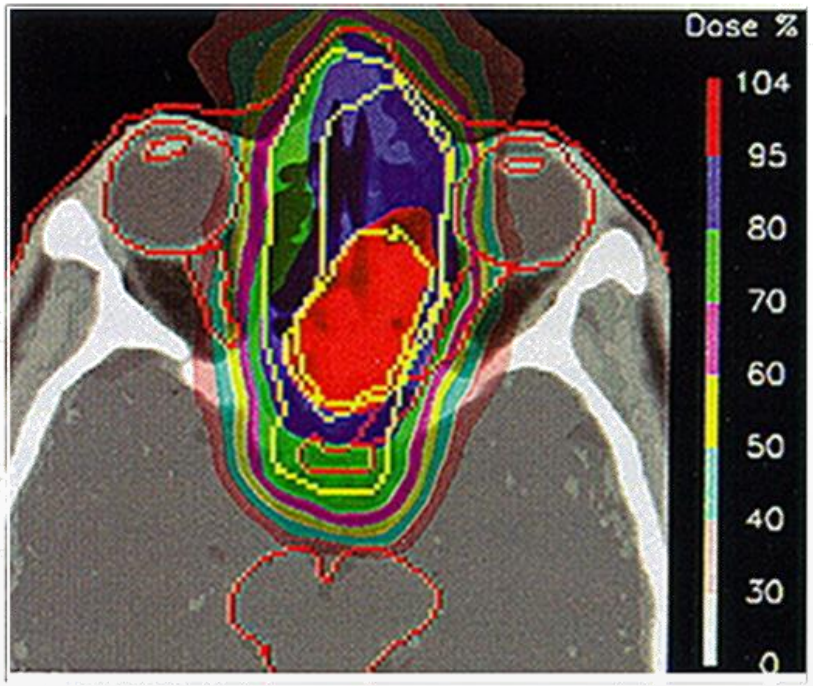


Better dose distribution

9 X beams



1 proton beam



tumor between eyes

Cell survival

$SF = \exp[-(\alpha D+\beta D^2)]$

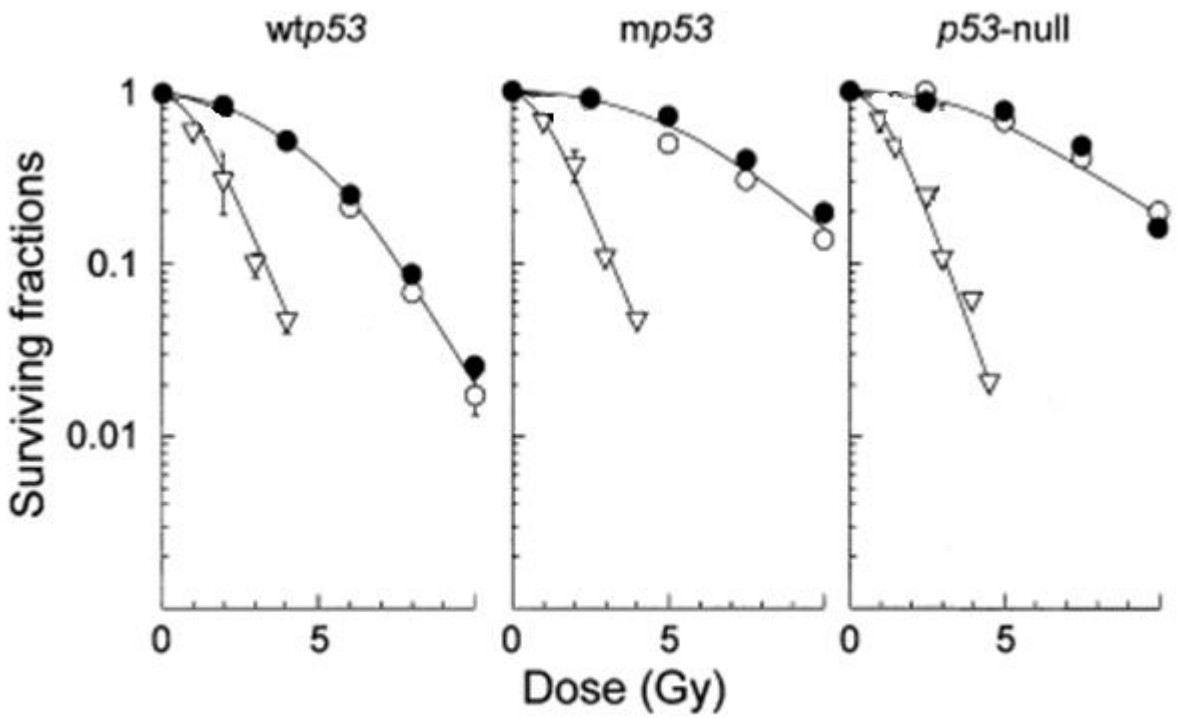
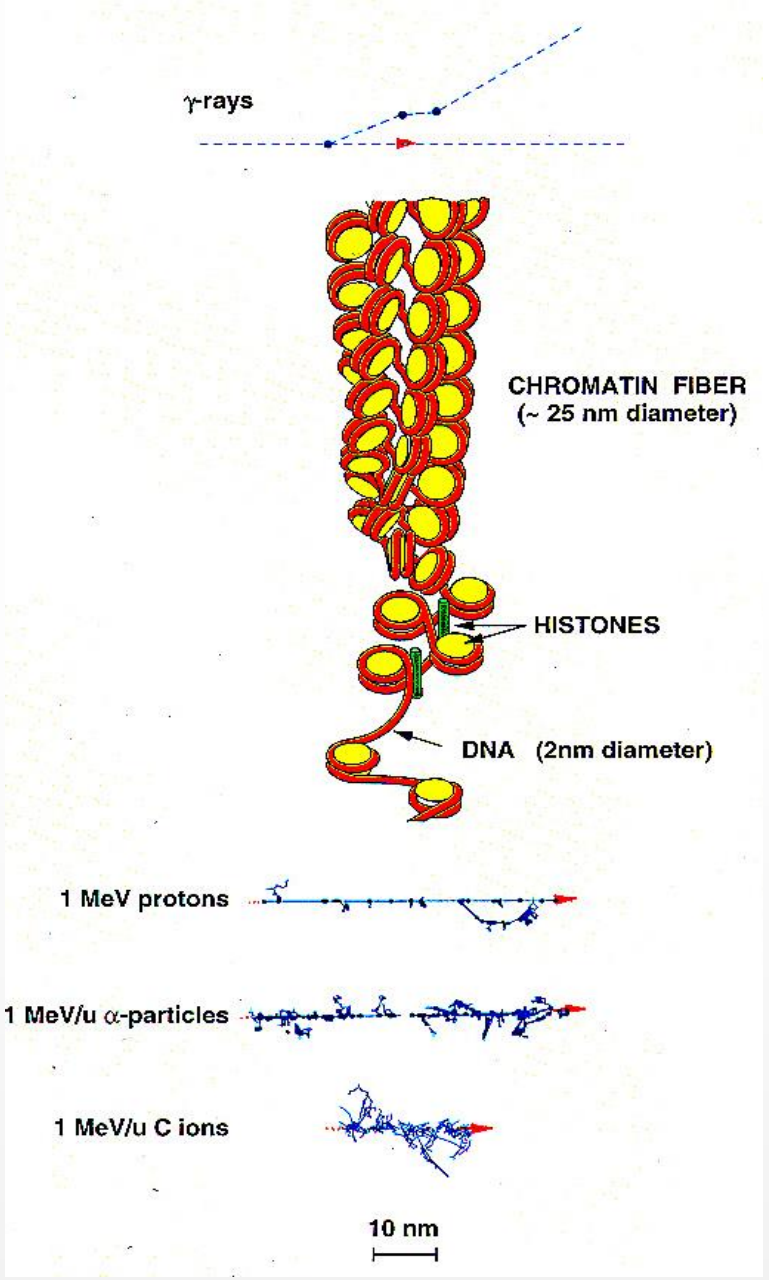


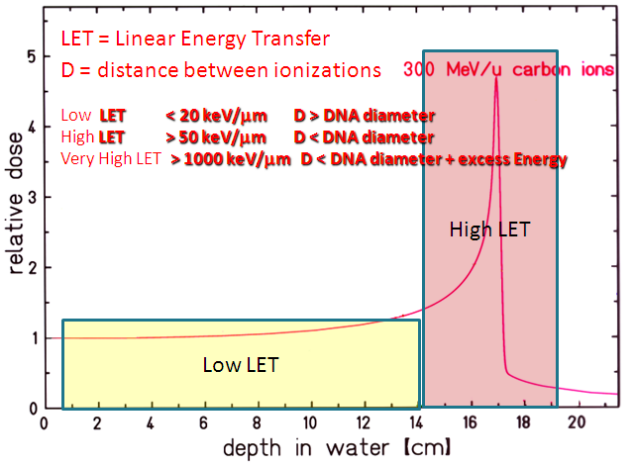
Fig. 2. Survival curves of cells exposed to X-rays (○ and ●) and 100 KeV/μm (▽) carbon beams.

- Ionization breaks chemical bonds
- Free radicals creation (mainly hydroxyl radical, OH^-, and superoxide, O_2^- . Poison for the cell!)
- The target is DNA, ionization distribution is relevant

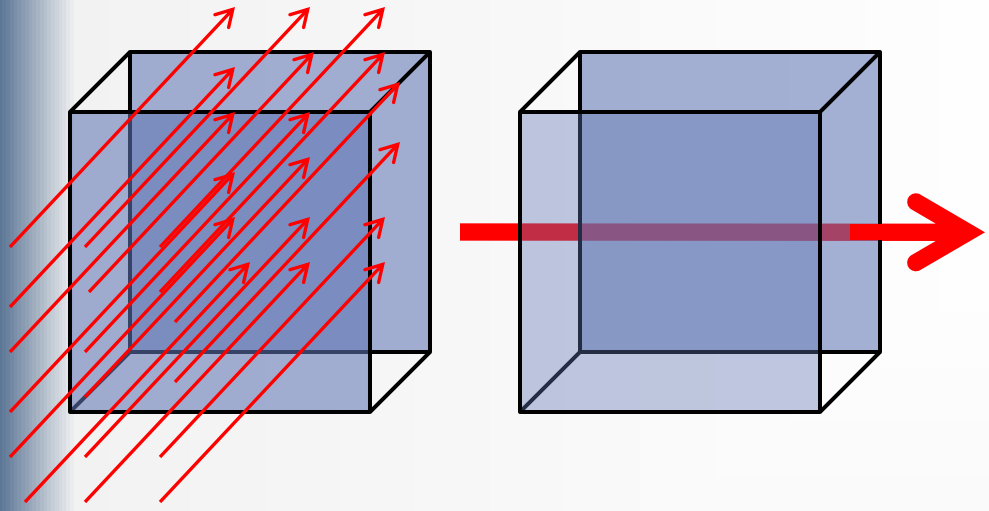


LET Linear Energy Transfer

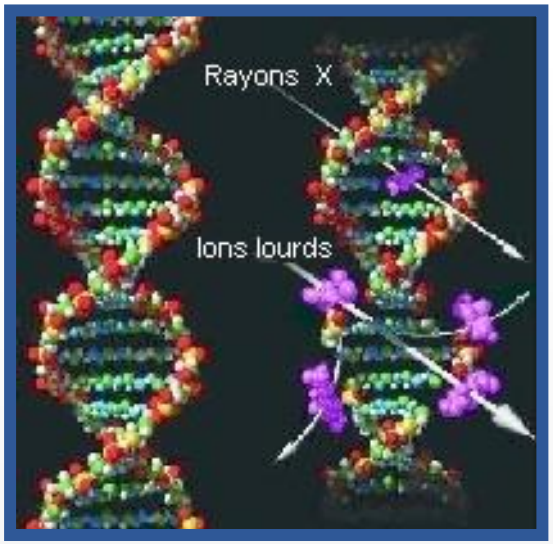
Hadrontherapy biological basis



Carbon ions have higher *LET* than protons



Low LET High LET



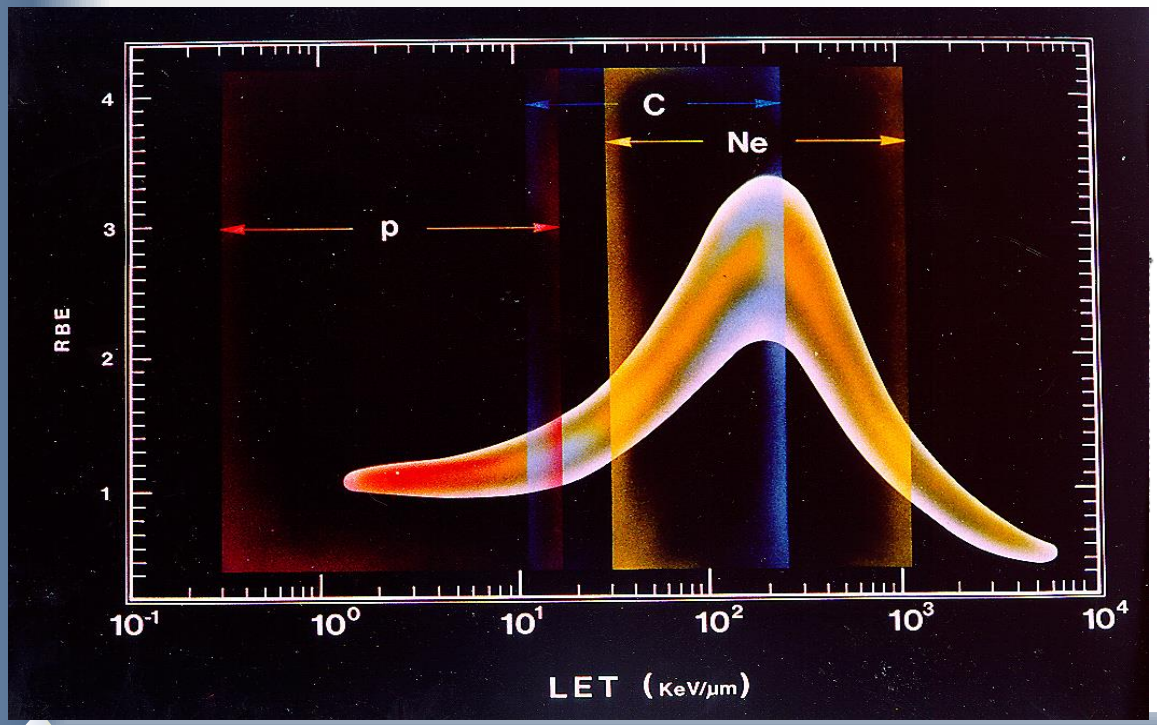
Energy deposition in matter

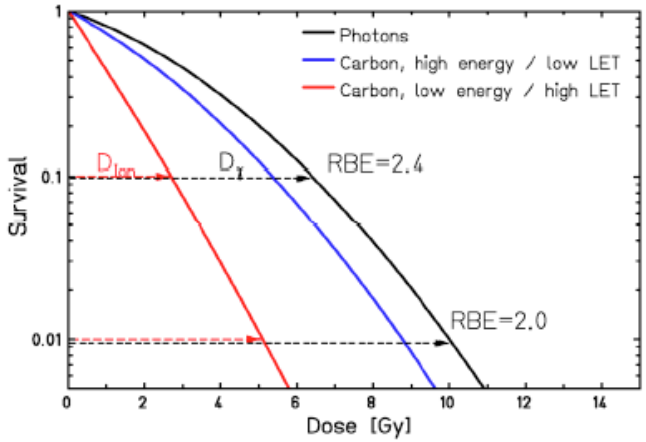
D = distance between ionizations

Low LET	**< 20 keV/mm**	**D > DNA diameter**
High LET	**> 50 keV/mm**	**D < DNA diameter**
Very High LET	**> 1000 keV/mm**	**D < DNA diameter + excess Energy**

RBE : *relative biological effectiveness*

Qualitatively the energy deposited by carbon ions is more efficient, in terms of cell destruction, than the energy deposited by protons.
The higher efficiency in killing cells is expressed by the *RBE, which* is the ratio between the photon and the ion doses which are necessary for producing the same biological effect.
Carbon RBE > 3 in the Bragg peak region
>= 1 in the entry channel.





The survival curve for the target cells for late injury is "curvier" than that for acute effects

RBE varies with particle type and energy, dose, dose per fraction, degree of oxygenation, cell or tissue type, biological end point, etc

Protons

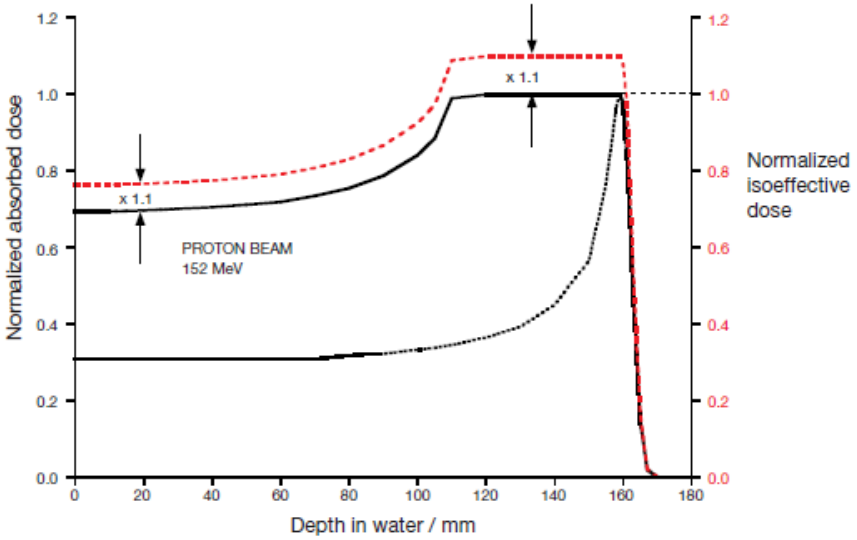


FIG. 1.1. Variation in depth of the absorbed dose of a monoenergetic (dotted line) and a spread out clinical (solid line) proton beam of 152 MeV and the corresponding weighted dose for radiation quality (RQ) (red dotted line, right ordinate). The RQ weighted dose (or RBE weighted dose) is obtained assuming a weighting factor $W_{RQ} = 1.1$ at all depths, protons being delivered with the same fractionation conditions as photons (courtesy P. Andreo).

Carbon Ions

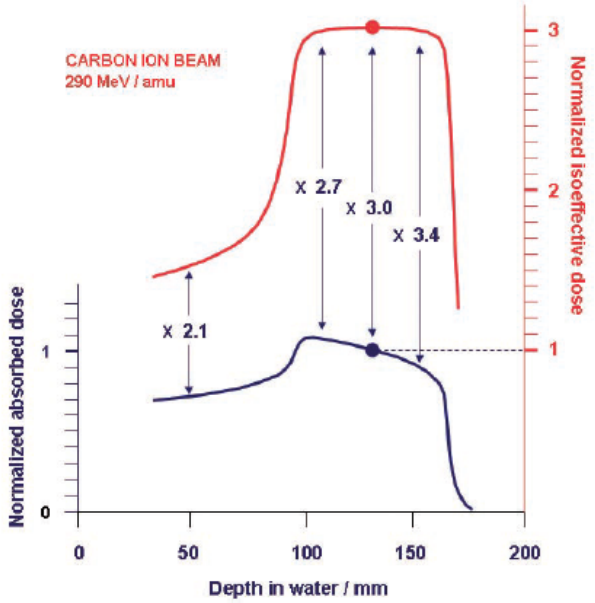


FIG. 1.2. Comparison of the absorbed dose and isoeffective dose variations with depth in a carbon ion beam. Carbon ion irradiation of a PTV located between 100 and 160 mm in depth using a 290 MeV/amu beam. The presentation is similar to Fig. 1.1. However, the RBE of a carbon beam significantly increases with depth. Therefore, in order to obtain a uniform 'isoeffective dose' (plateau) across the SOBP, the absorbed dose needs to be adapted (modulated) and decrease with depth. The weighting factors used to derive the isoeffective dose at different depths are indicated in the figure [1.12] (for more details, see Annex IV).

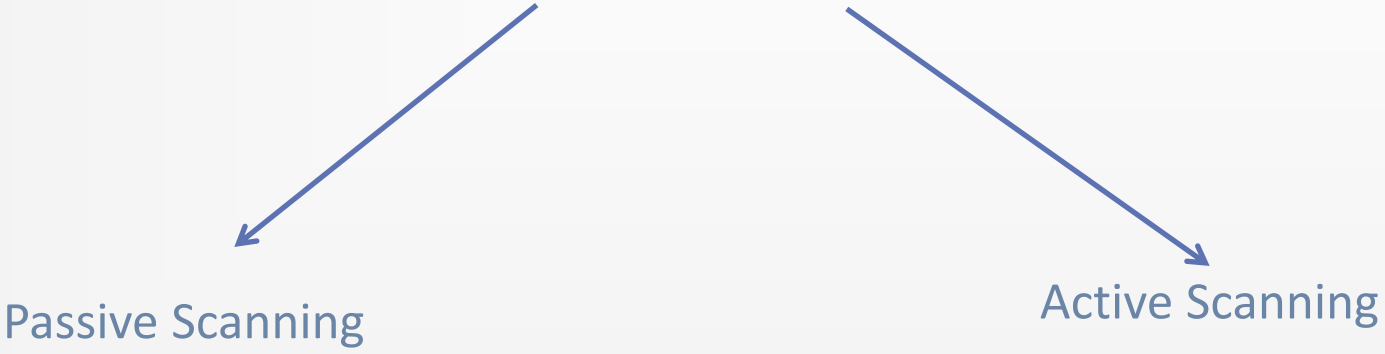
Accelerator design criteria

The kind of the accelerator depends mainly on:

- The species to be accelerated

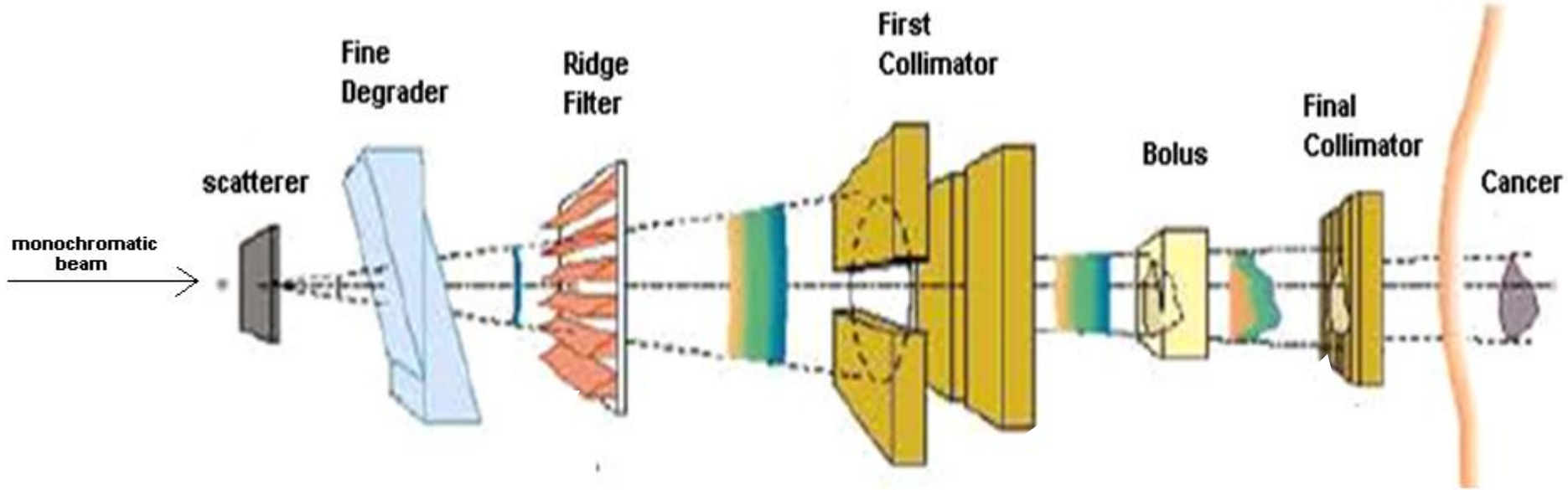
particle	Penetration range	Energy range	Brho range
Proton	30-300 mm	60-250 MeV/u	1.16-2.31 Tm
Carbon	30-300 mm	120-400 MeV/u	3.18-6.34 Tm

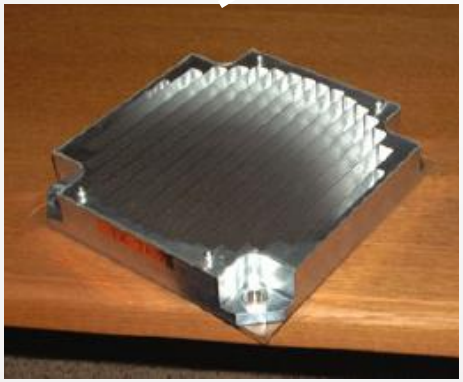
- The radiation shaping and delivery method



Passive Scanning

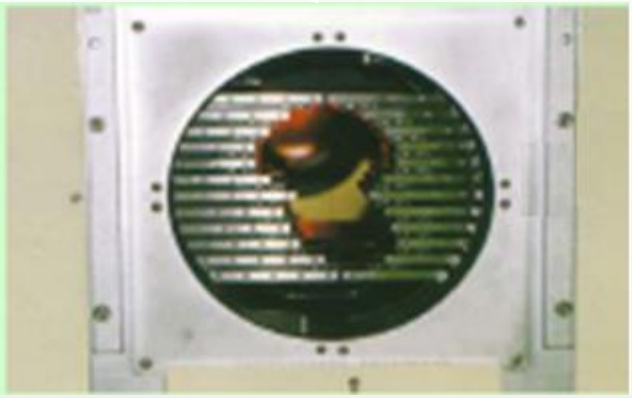
Passive scanning is based on putting several absorbers before the patient to change longitudinal and transverse characteristics





Ridge filter

Bolus



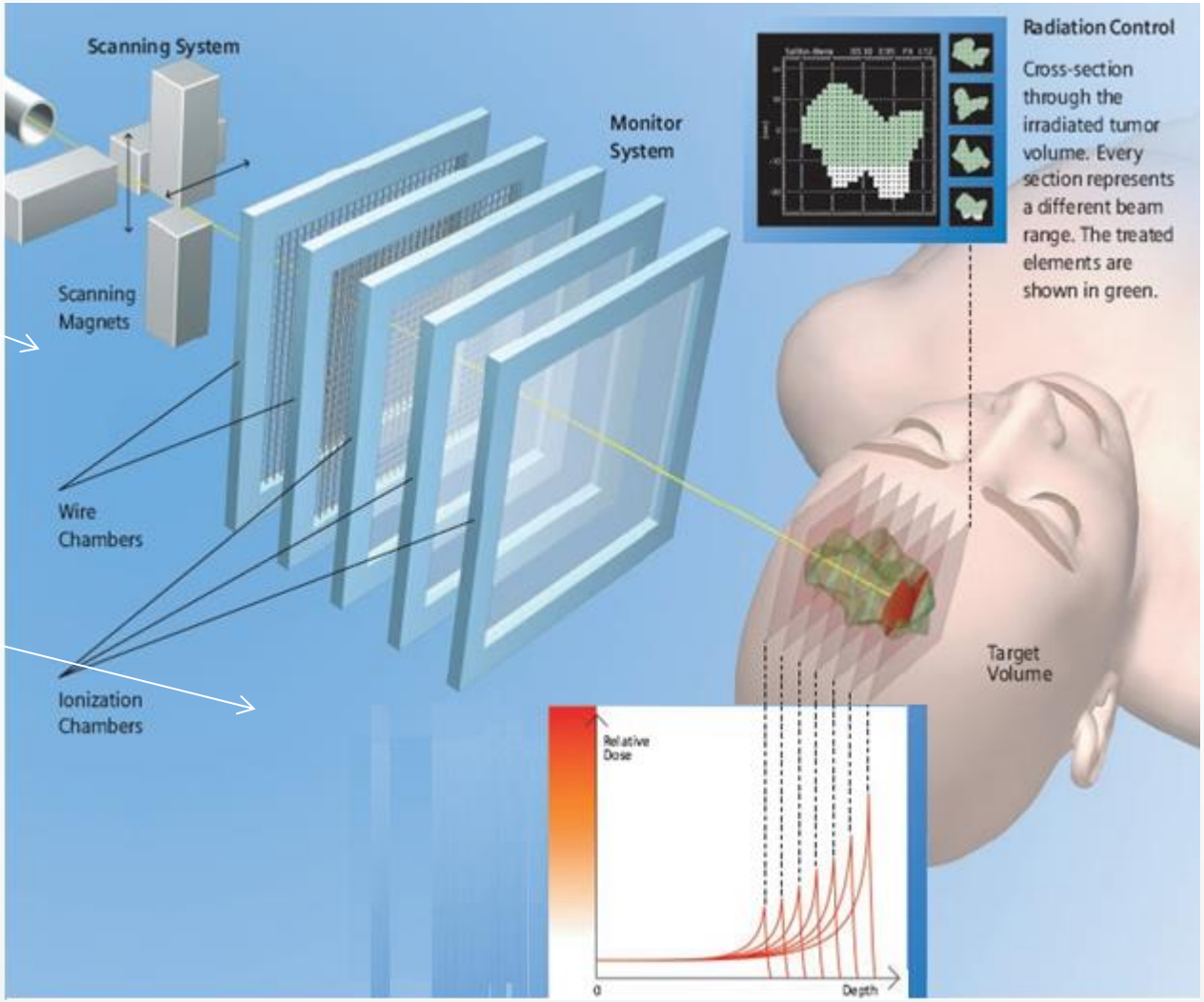
Multi-leaf final collimator

Active Scanning

Fast magnets paint the tumour transversally
Each voxel is irradiated during ~ 5 msec

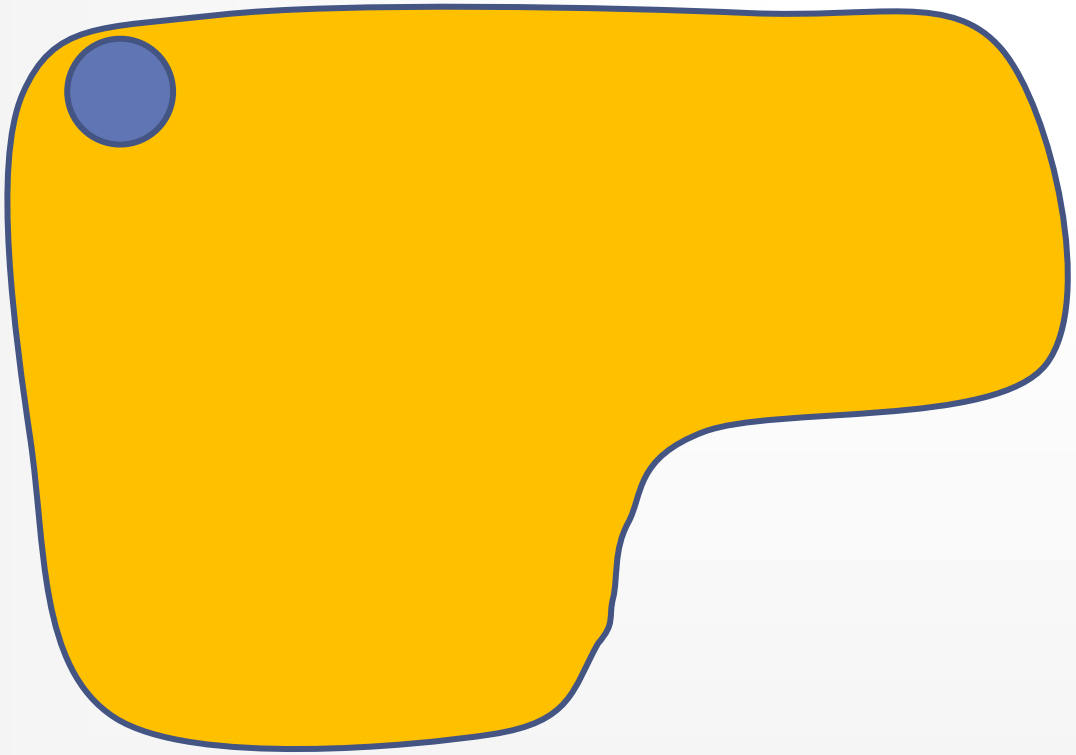
A nozzle system controls the delivered dose

Several Bragg peaks from the accelerator paint the tumour longitudinally



First use in Japan (1980) and then regularly used at GSI, PSI, HIT, CNAO

Scanning beam



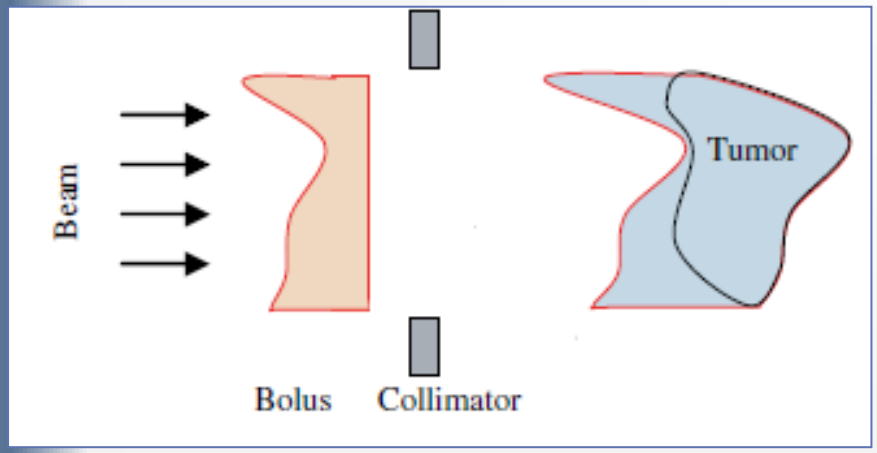
Active vs Passive

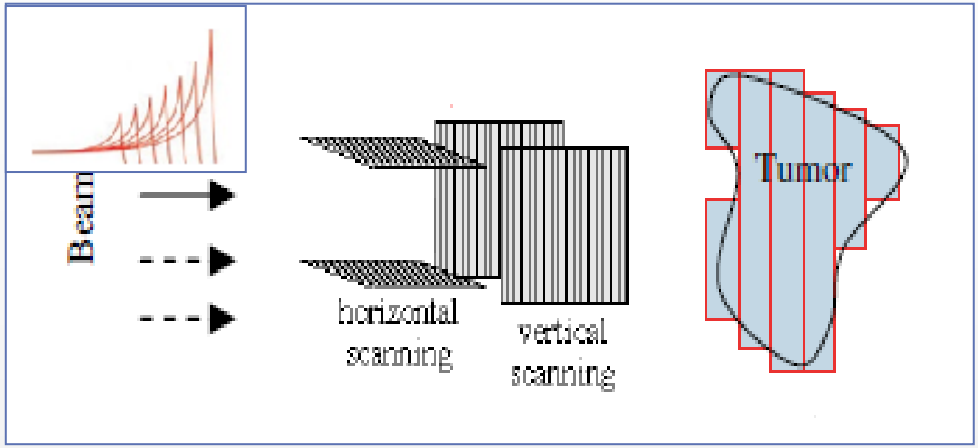
Passive system needs patient-specific hardware: Bolus, Multileaf collimator

There are errors on dose irradiation:

- Bolus conforms the most distal surface
- Absorbers → Nuclear Fragmentation → Tailing of Bragg Peak
- Heavy ions need thicker absorbers → greater energy and currents from the accelerator.

Active system needs a more challenging control of beam characterizations and of the scanning magnets but **allows a more precise dose irradiation of the tumor target**



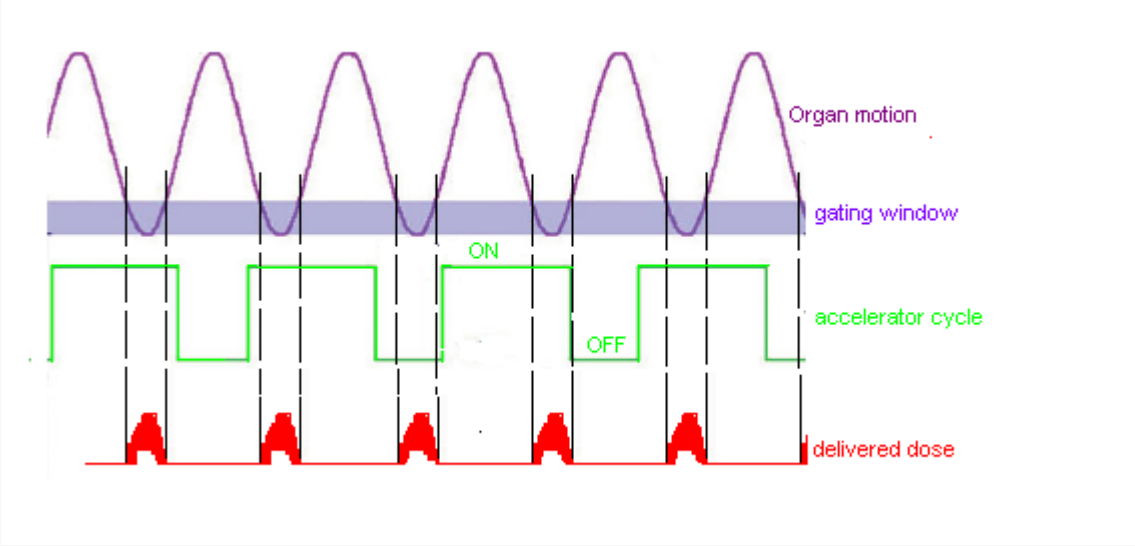


Moving organs

Active system is critical in the case of moving organs. R&D is in progress worldwide about several techniques: Gating, repainting, beam tracking

Repainting consists in underdosing the tumour and increasing the treatment sessions

Gaiting consists in irradiating only at a specific position of the organ



Beam Tracking is an adjustment in real-time of treatment plan considering the 4D organ motion signal.

Types of accelerators

Three accelerators can provide clinical beam: LINAC, Cyclotrons, Synchrotrons. The energy and the species of hadrontherapy make LINAC up to now not very practical and feasible

Nowadays Hadrontherapy centers are Cyclotrons and Synchrotrons

Cyclotrons	Synchrotrons
Compact (4 m diameter)	More complicated
cheaper	More expensive
DC beam	Pulsed beam
High current (hundreds nA)	Lower currents (tens nA)

BUT…

Types of accelerators

…BUT

Cyclotrons are easy for protons; only one CHALLENGING PROPOSAL exists for carbon
Cyclotron compactness is partially offset by the place required by the medical structure
Passive scanning is needed with cyclotrons because the energy from accelerator is fixed

while

Synchrotrons can accelerate protons and carbons.
A synchrotron designed for 300mm C6+ can accelerate 1<=Z<=6 and O up to 19 cm.
Synchrotron can perform active scanning.

Nowadays the best technological layout for a hadrontherapy center is a

Carbon Synchrotron equipped with active scanning.

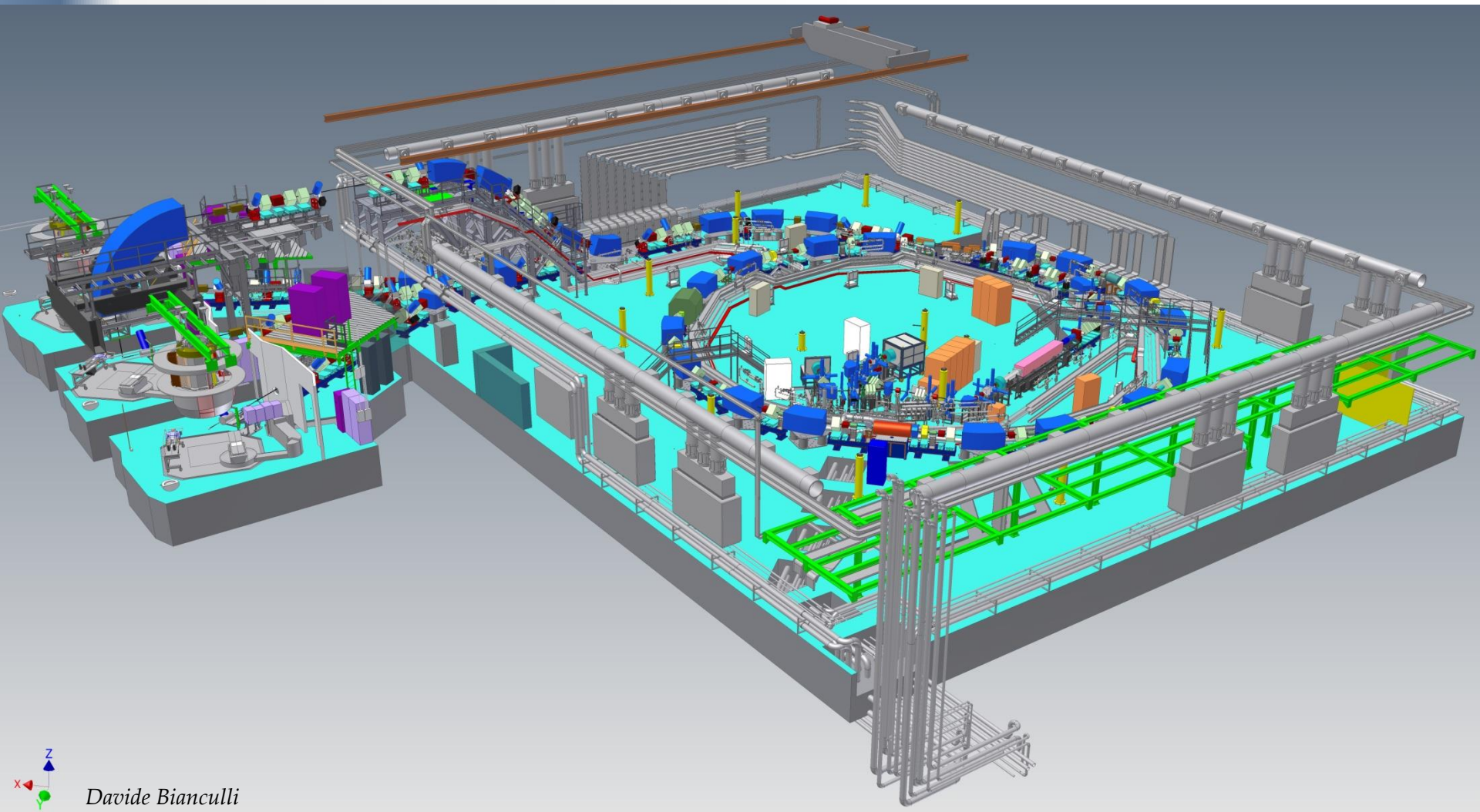
A carbon synchrotron facility is made up of:

1. A low energy injector
2. A ring
3. The extraction lines

CNAO, Pavia

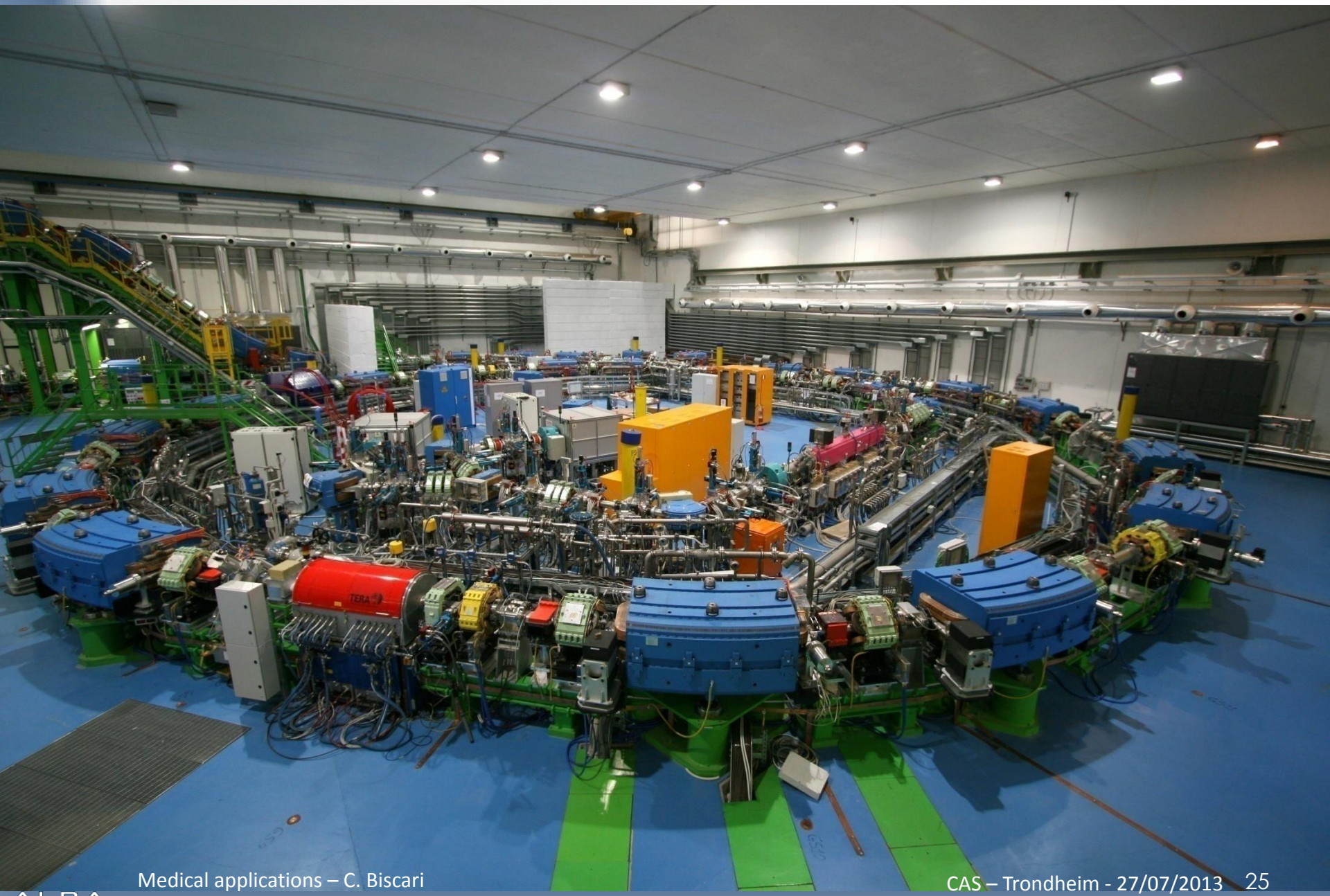
ITALY

CNAO - Accelerator and Treatement Rooms

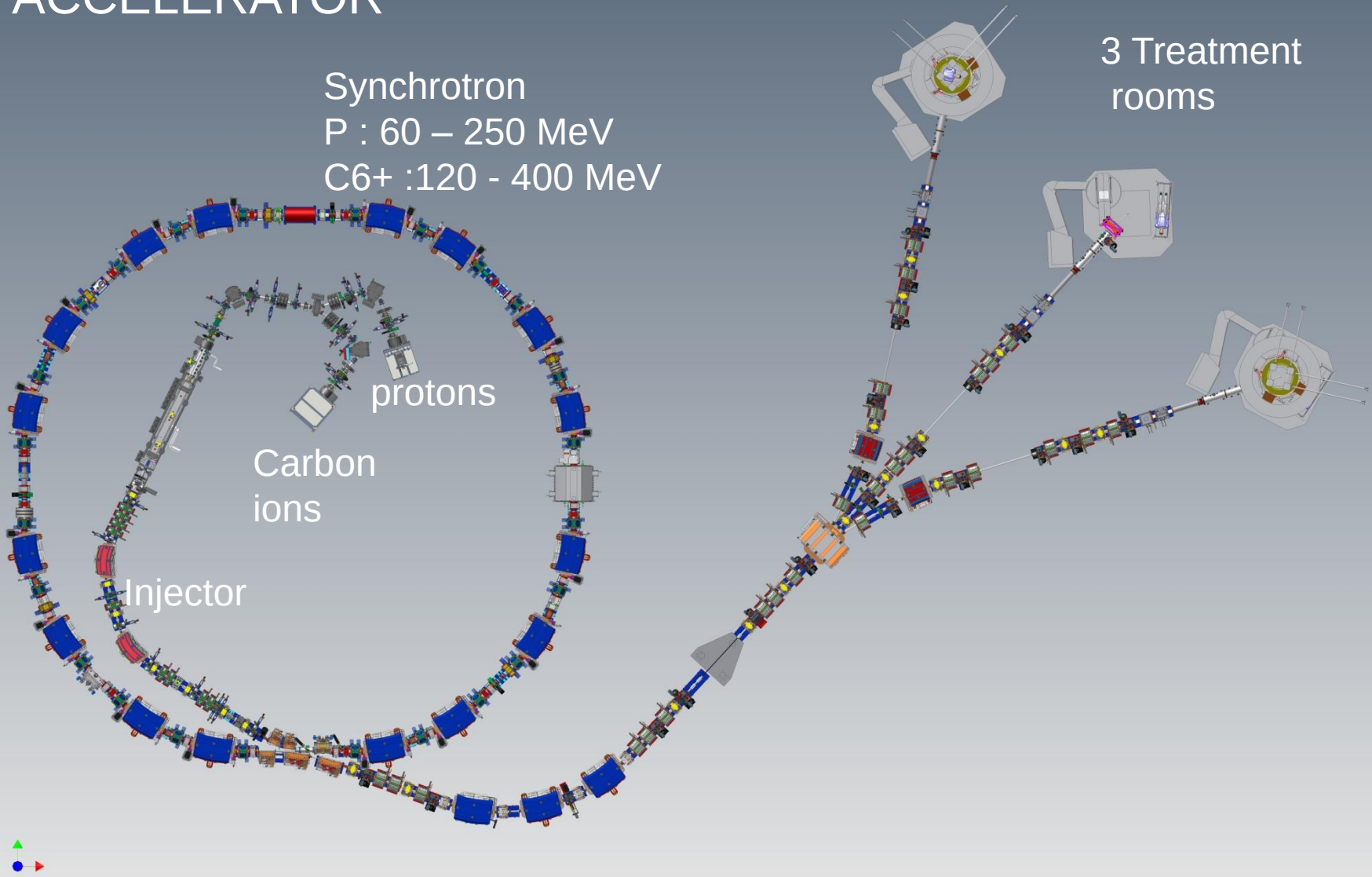


Davide Bianculli

Synchrotron hall

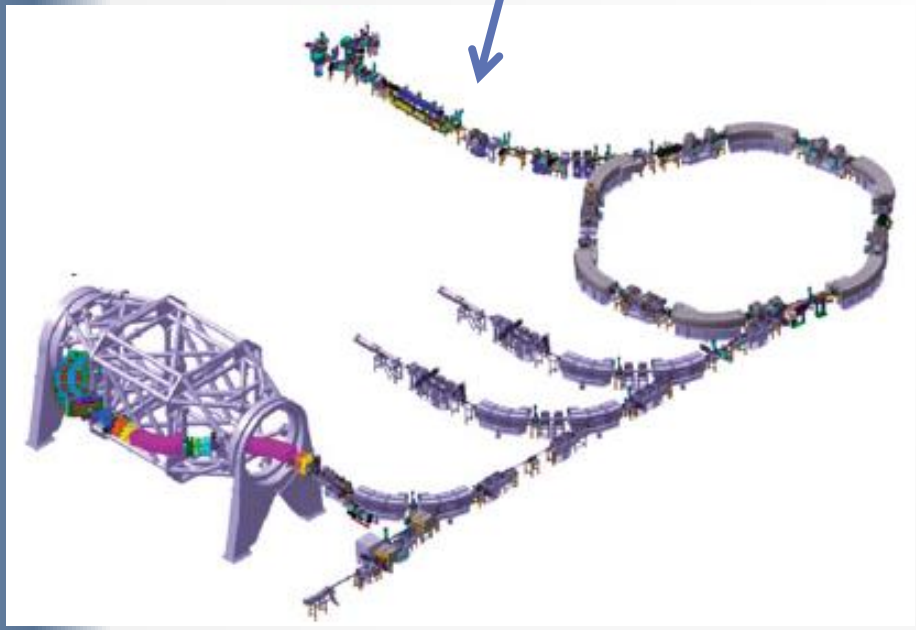


ACCELERATOR

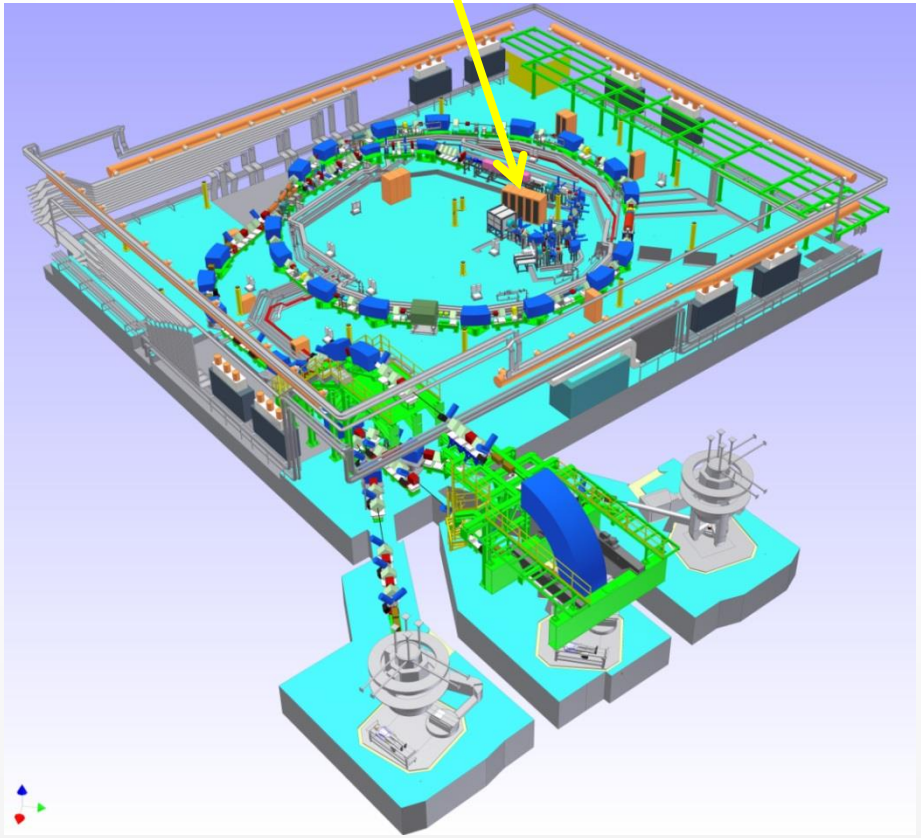


Synchrotron facility layout: Injector

The injector is placed outside the ring for easier maintenance or inside to save space

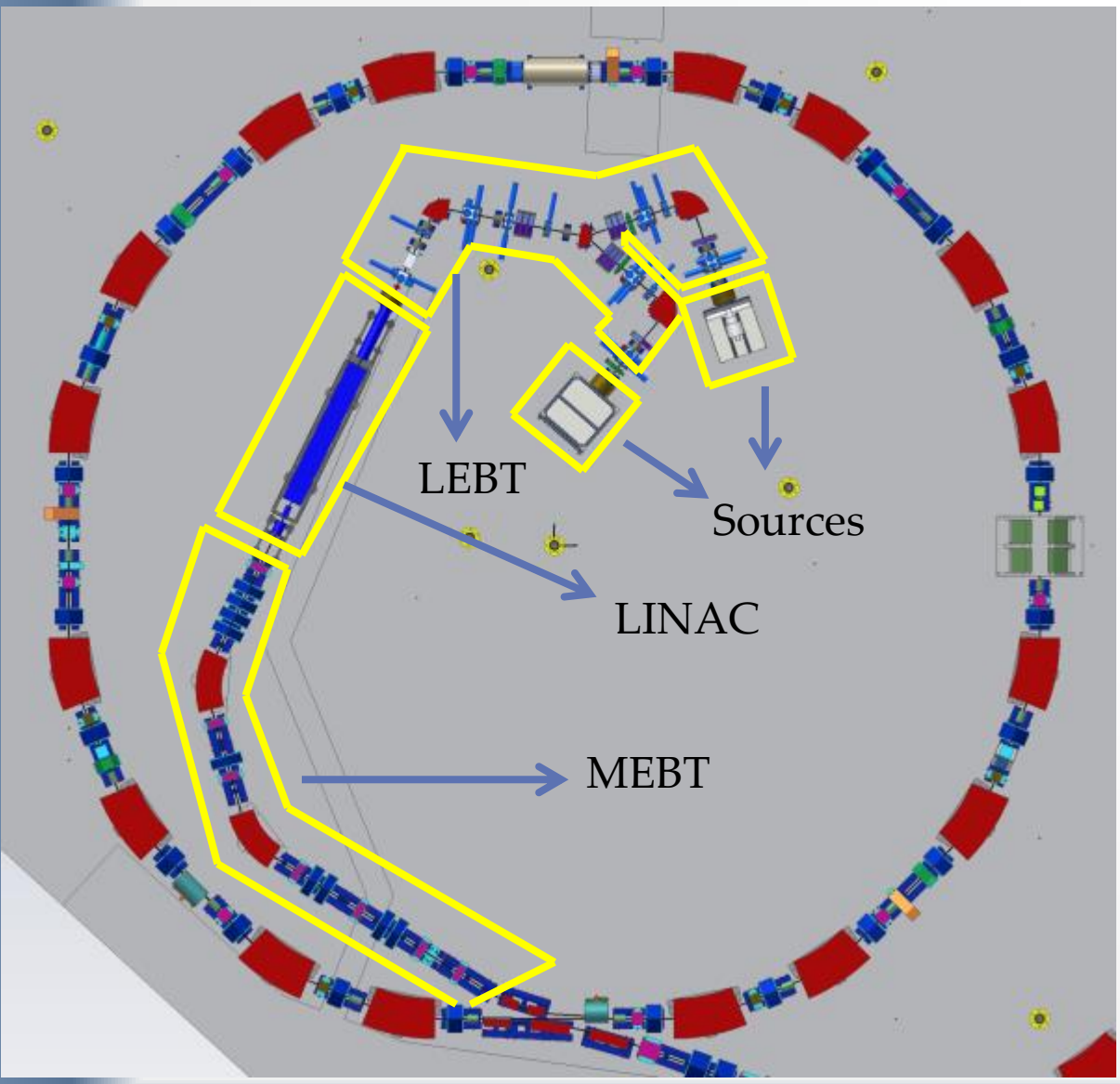


HIT (Heidelberg, Germany)



CNAO (Pavia, Italy)

Synchrotron facility layout: Injector

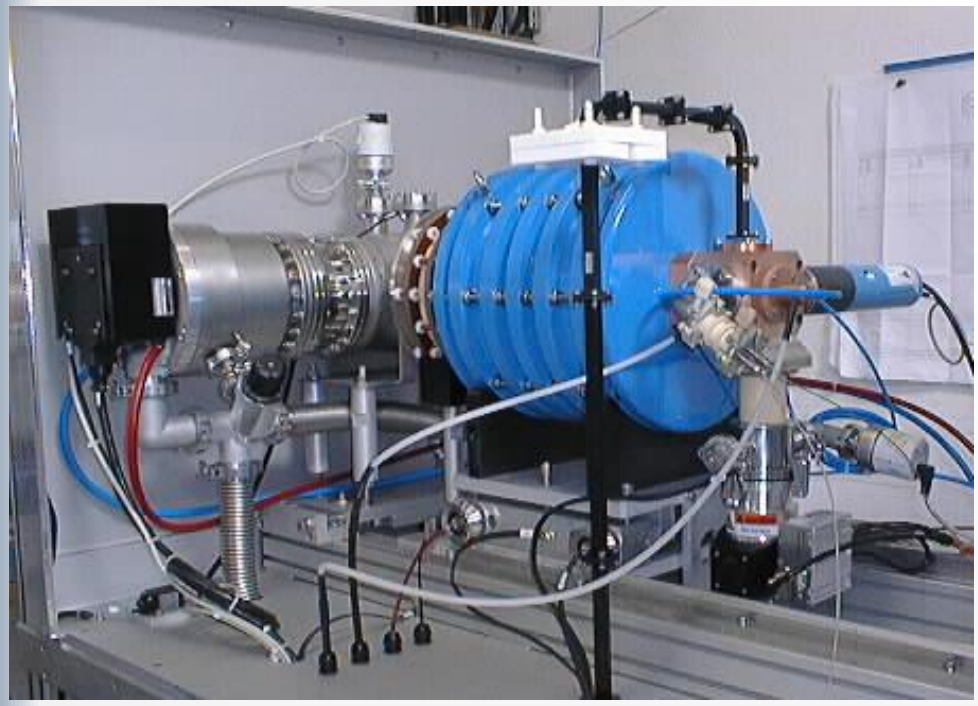


An injector is made up of:

1. Two or three sources
2. A LEBT (Low Energy Beam Transfer line)
3. A low energy Linac
4. A MEBT (Medium Energy Beam Transfer line)

ION SOURCE

The type of ions sources are PIG, EBIS but, above all, ECR (Electron Cyclotron Resonance) Ion Sources
At CNAO 2 ECRs: Both can deliver H3+, C4+ and other species



- Double wall, water cooled plasma chamber, 7 mm diameter aperture for beam extraction.
- Permanent magnets system providing the axial and radial confinement (axial field from 0.4 to 1.2 T, radial field 1.1 T)
- Copper made “magic cube” for microwave injection system = waveguide to coaxial converter with a tuner to minimize the reflected power.
- RF window for the junction between the magic cube at high vacuum and the waveguide at atmospheric pressure.
- A gas injection system.
- A DC bias system to add electrons to the plasma and decrease the plasma potential.
- An RF generator of about 400 W at 14.5 GHz (the effective power used in operation is below 300W).
- Flexible frequency variable travelling wave tubes amplifiers (TWTA) .

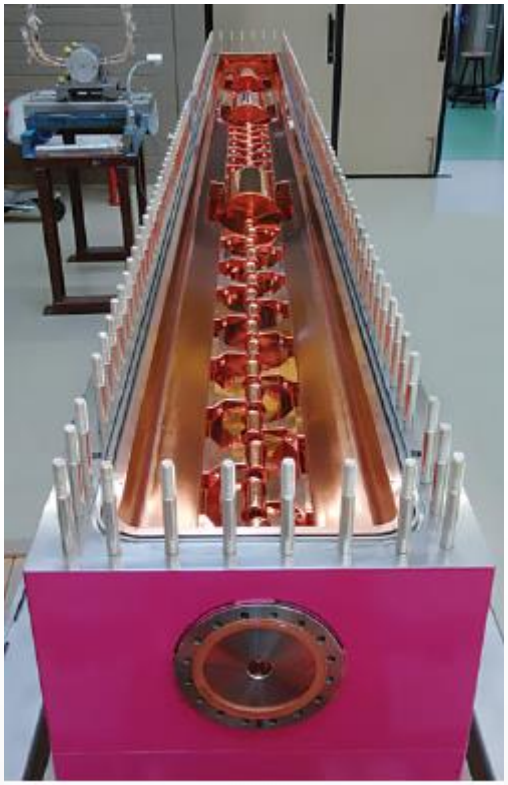
Built by Pantecknic on INFN-LNS Design
Gas are ionized by RF power at electron cyclotron resonance frequency (10-18 GHz)
The magnetic trap for the electrons is obtained with a solenoid and an exapolar magnet

Linac

RFQ+IH

RFQ

IH



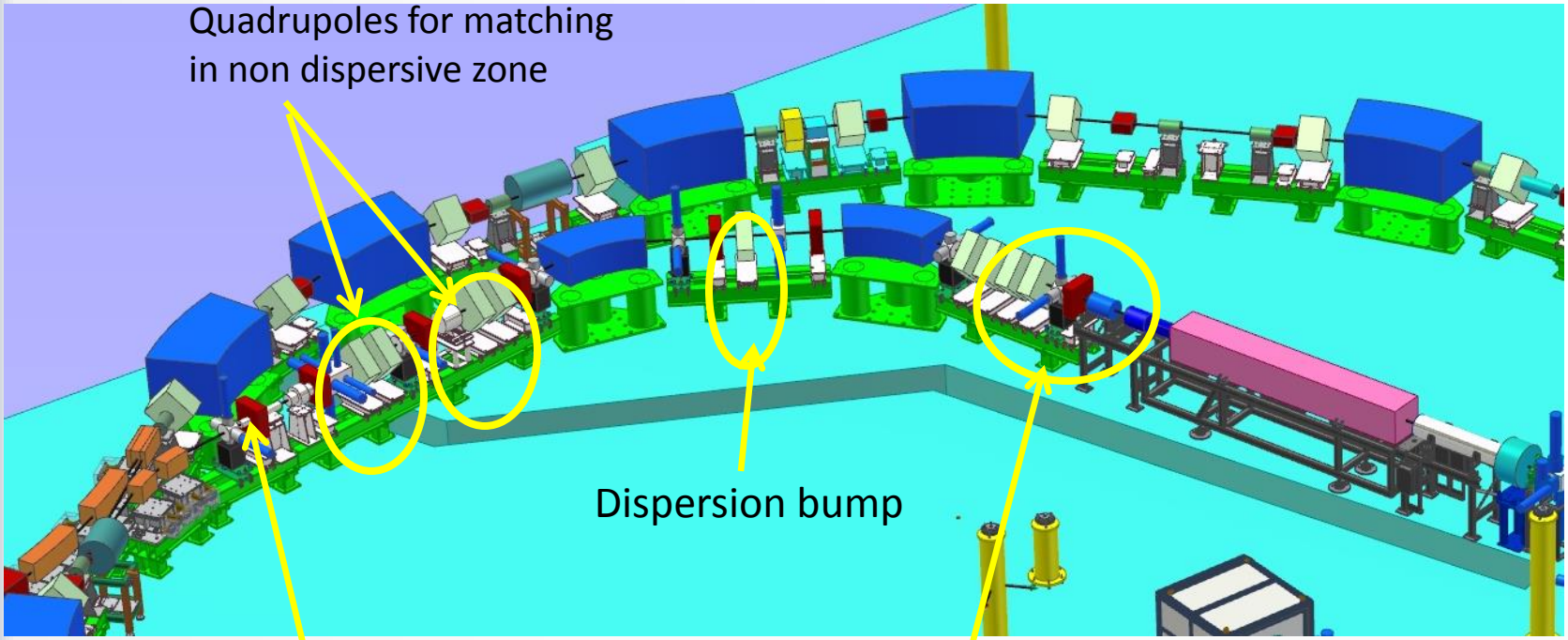
Four-rod like type
Energy range = 8 – 400 keV/u
Electrode length = 1.35 m,
Electrode voltage = 70 kV
RF power loss (pulse): about 100 kW
Low duty cycle: around 0.1%

RFQ
0.008-0.4 MeV/u H^{3+}
0.008-0.4 MeV/u C^{4+}

IH
0.4-7 MeV/u H^{3+}
0.4-7 MeV/u C^{4+}

3 Integrated magnetic triplet lenses	
56 Accelerating gaps	
Energy range	0.4 – 7 MeV/u
Tank length	3.77 m
Inner tank height	0.34 m
Inner tank width	0.26 m
Drift tube aperture diam.	12 – 16 mm
RF power loss (pulse)	≈ 1 MW
Averaged eff. volt. gain	5.3 MV/m

MEBT



Debuncher to minimize the injected beam momentum spread

Stripping foil

Positions:	10
Foil material:	Carbon
Foil thickness:	100-200 µg/cm²
Foil diameter:	15 mm
Beam diameter:	5 mm
Position accuracy:	±0,5 mm

Beams for treatments

Same Bρ

$$H_3^+ \rightarrow H^+$$
$$C^{4+} \rightarrow C^{6+}$$

Ring: Slow Extraction

Dose homogeneity : ± 2.5% → a single turn extraction (<1 μsec) not possible

↓

Unstable but controlled beam betatron oscillations: the motion amplitude grows until an electrostatic septum allows the extraction of the particle.

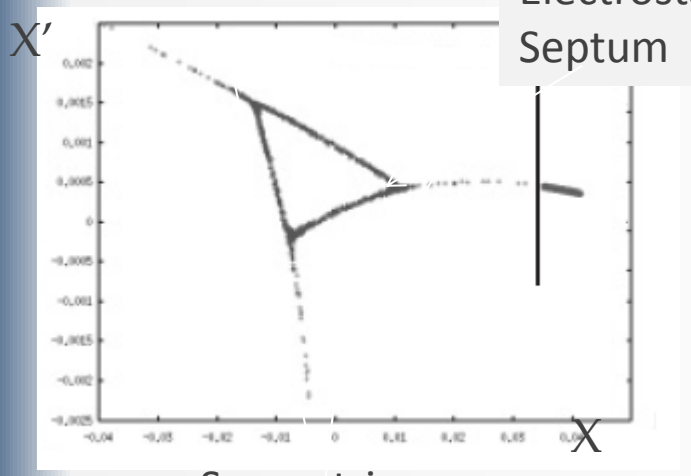
↓

Extraction mechanism strongly influences the ring design
Optical layout must guarantee a machine tune near to an unstable value during the extraction.
The part of the beam with the resonance tune is extracted.
In the present facilities the unstable tune is chosen N/3. A sextupolar field feeds the resonance:

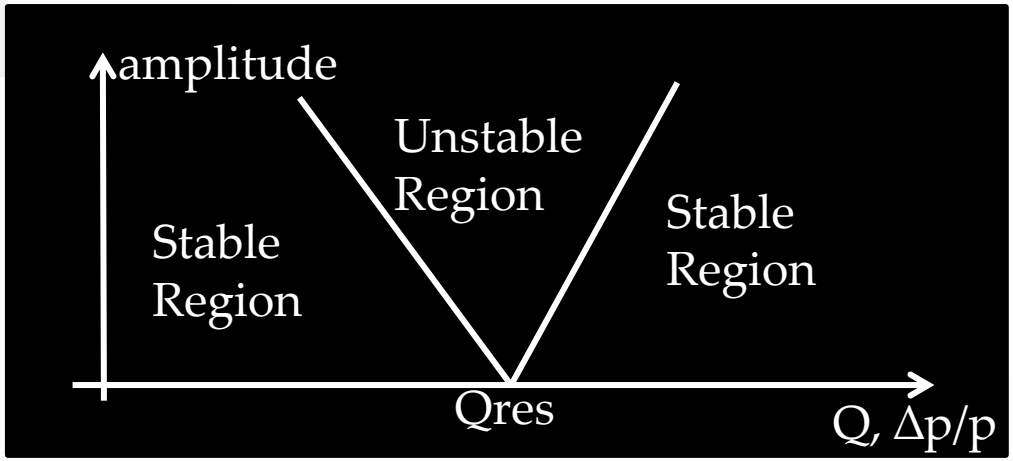
THIRD ORDER RESONANCE SLOW EXTRACTION MECHANISM

Ring: Slow Extraction

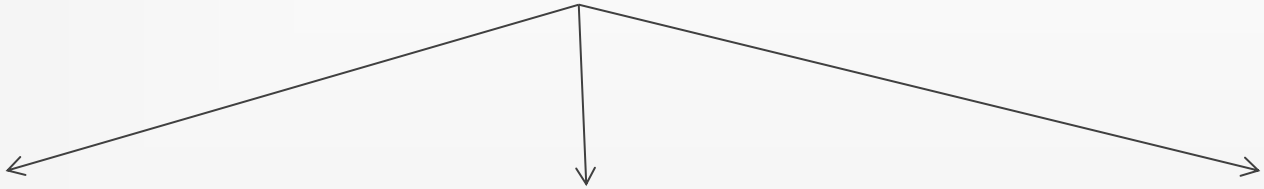
Horizontal Phase Space
at the resonant tune



Steinbach diagram



Beam can be driven to the resonance condition by three methods:



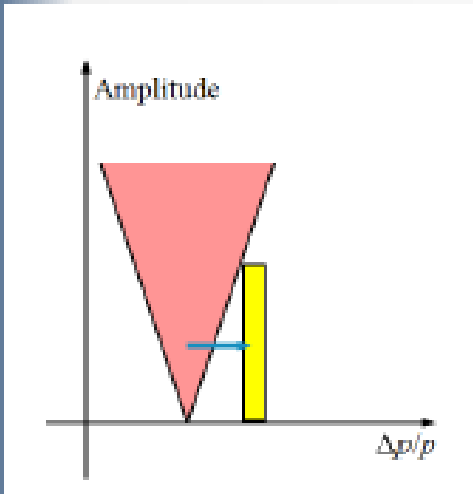
amplitude
selection

amplitude-momentum
selection

RFKO
RF Knock-out

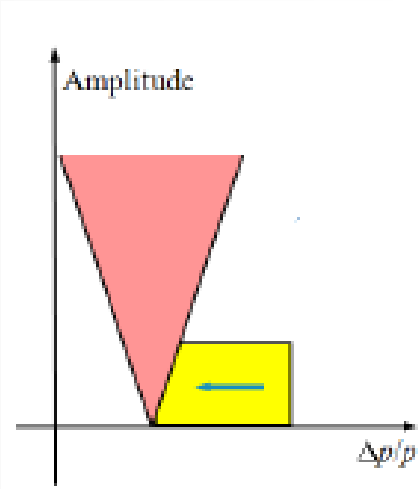
Ring: Slow Extraction

amplitude selection



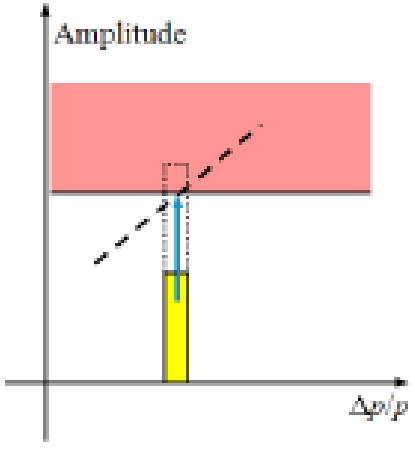
- Not constant optics
- Narrow dp/p
- Not constant position, size, energy of extracted beam
- No more used

amplitude-momentum selection



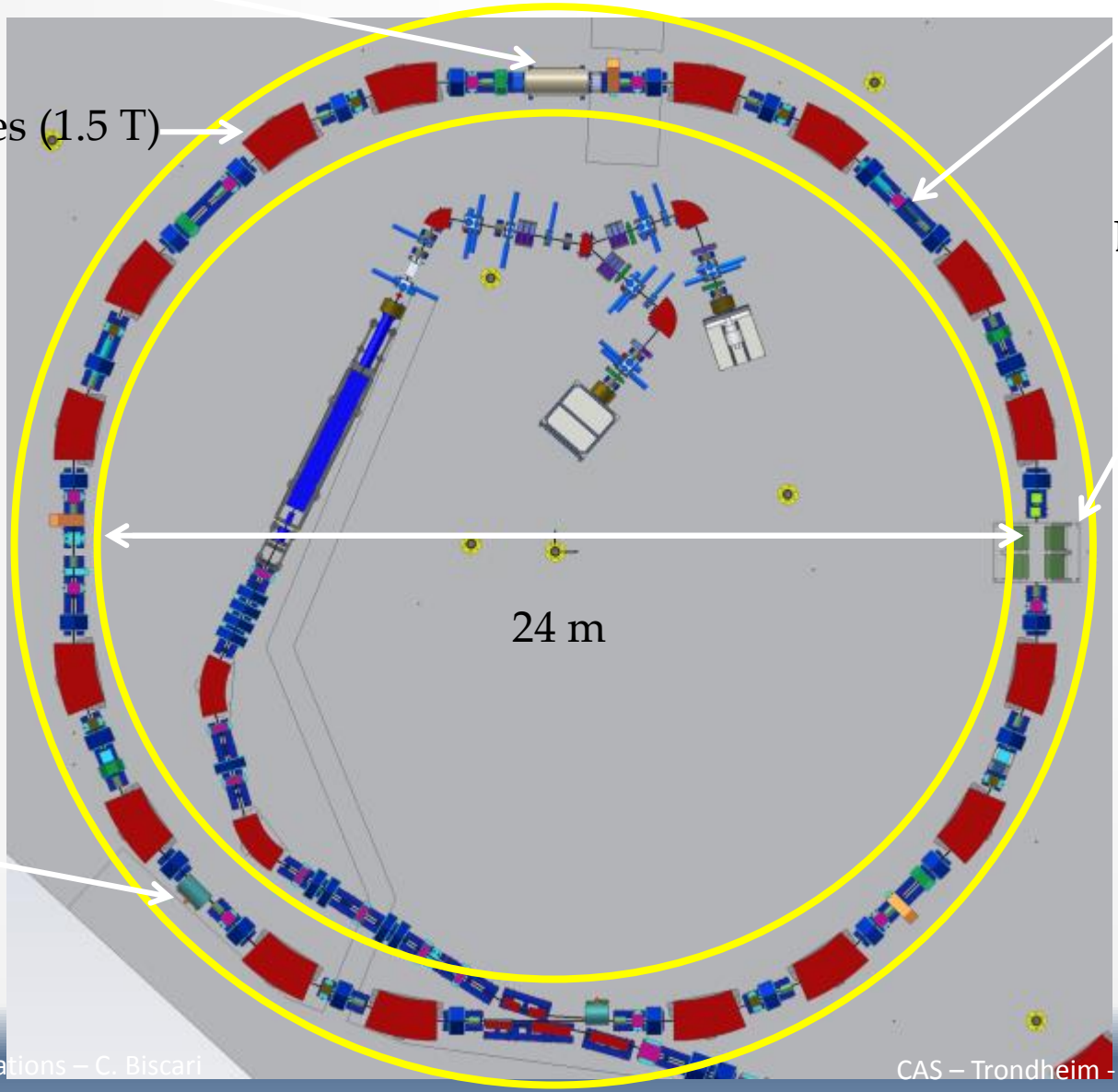
- Constant optics
- Large beam dp/p
- Constant position, size, energy of extracted beam
- Use of a betatron core

RFKO



- Constant optics
- Constant position, size, energy of extracted beam
- Use of a transverse RF exciter

Synchrotron facility layout: Ring



Ring : RF cavity

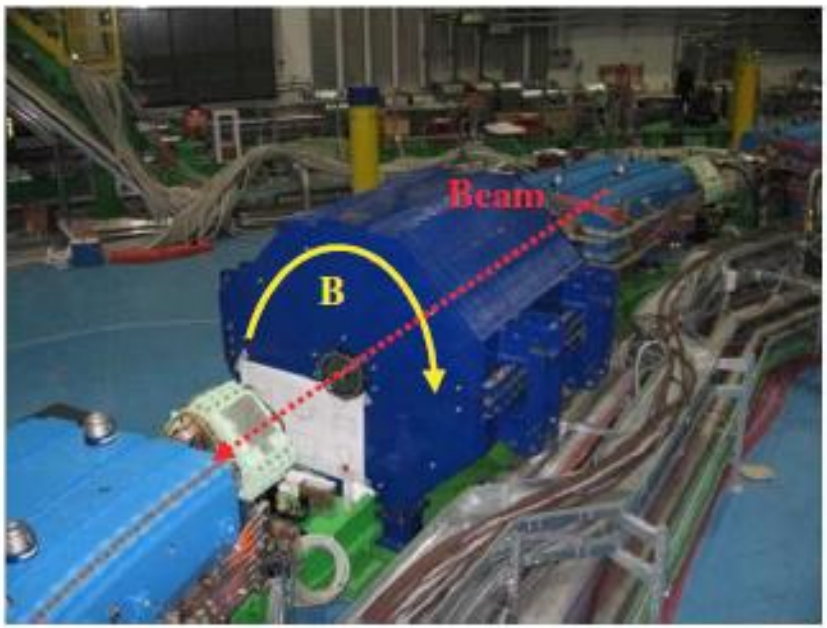
Acceleration is performed with a single RF cavity at harmonic 1 or 2 based on the principle of ferrite-loaded cavities and with tetrode or solid state technology for the amplifier. Nowadays ferrite often is replaced by amorphous alloy to reduce cavity length

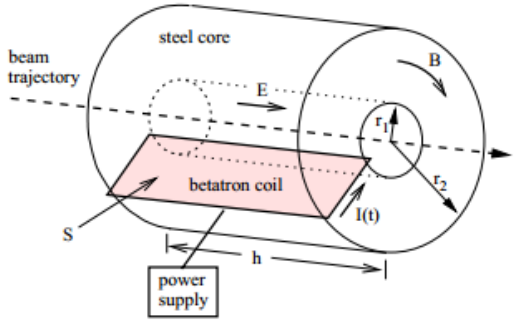
Vitrovac amorphous alloy Fe-Co

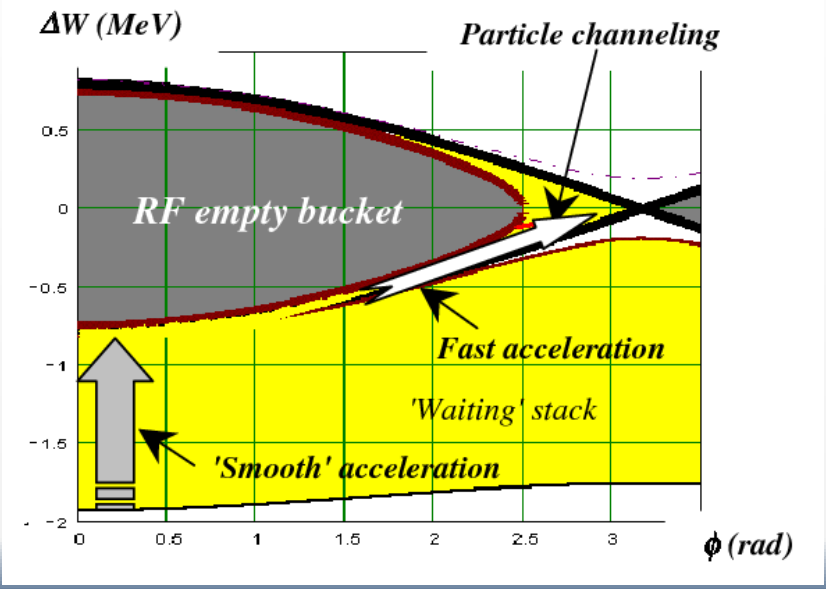
Frequency Range	0.4 MHz-3 MHz
Voltage Range	50 V-10000 V
Vitrovac current	0-10 A
Cavity length	1.3 m
Q	1-5
Rshunt	900-500 ohm

Ring: Betatron Core

High inductance device: the only active element during extraction. All the other elements, and thus also the lattice functions, are kept static, the RF voltage is switched off. Therefore, the energy of the extracted beam is kept constant, no RF structure can appear in the spill and sources of ripples are minimised.







To reduce ripple spill RF cavity is used with the technique of empty bucket channelling

Extraction lines

The beam quality at all the energies (stable position, possibility to have round beams with more dimensions, RT control of the dose) constraints on magnetic lattices, power supplies, magnets, control system, Nozzle.

Irradiation from different directions is mandatory. It can be realized:

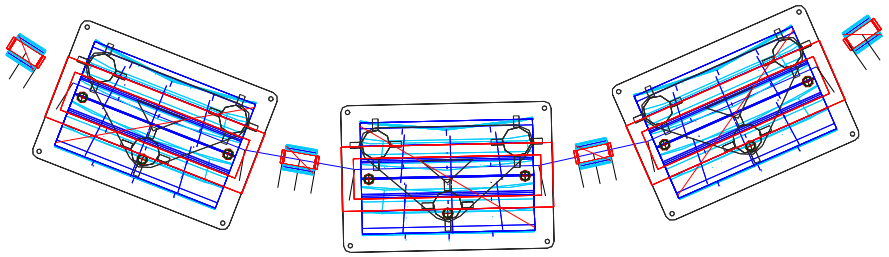
1. Displacing the patient
2. Several lines in the same room
3. Gantry

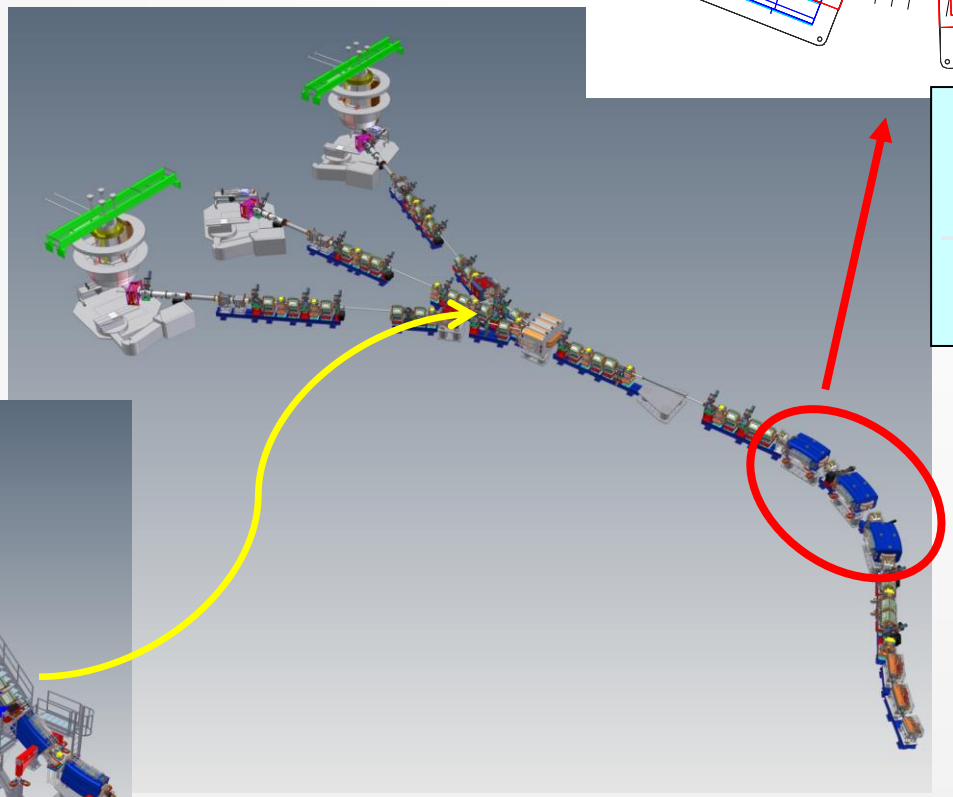
Nowadays gantries for protons are present in most facilities.
A gantry for carbon is more challenging!
To date only HIT is equipped with a carbon ions gantry
(600 tons at 13 m against the standard 100 tons at 10 m)

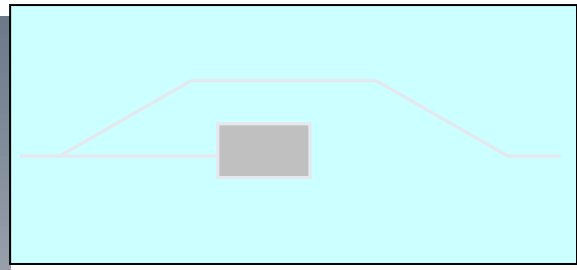
First heavy ions gantry at Heidelberg

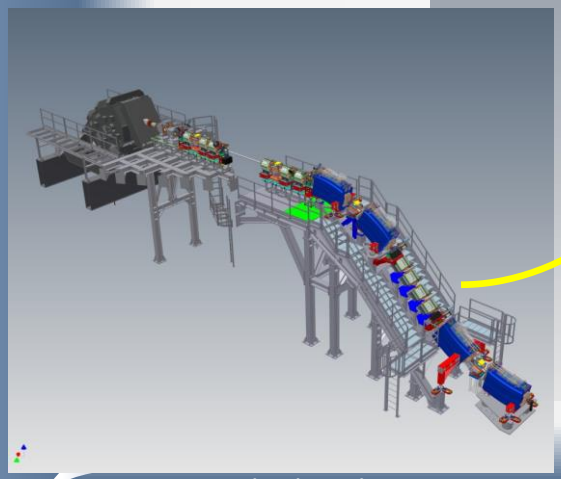
CNAO Extraction lines

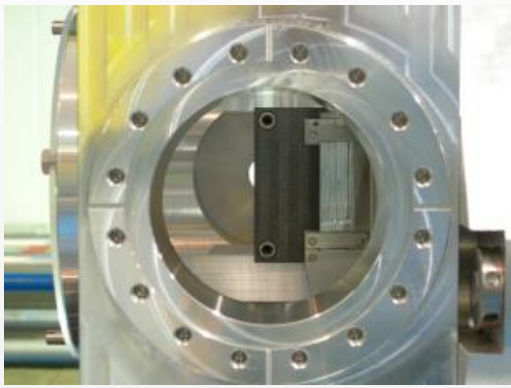
CNAO lines: 3 treatment rooms: 2 with horizontal line and 1 with horizontal and vertical one. The beginning of the line has 4 fast magnets (100 microsec) to dump the beam for patient security.











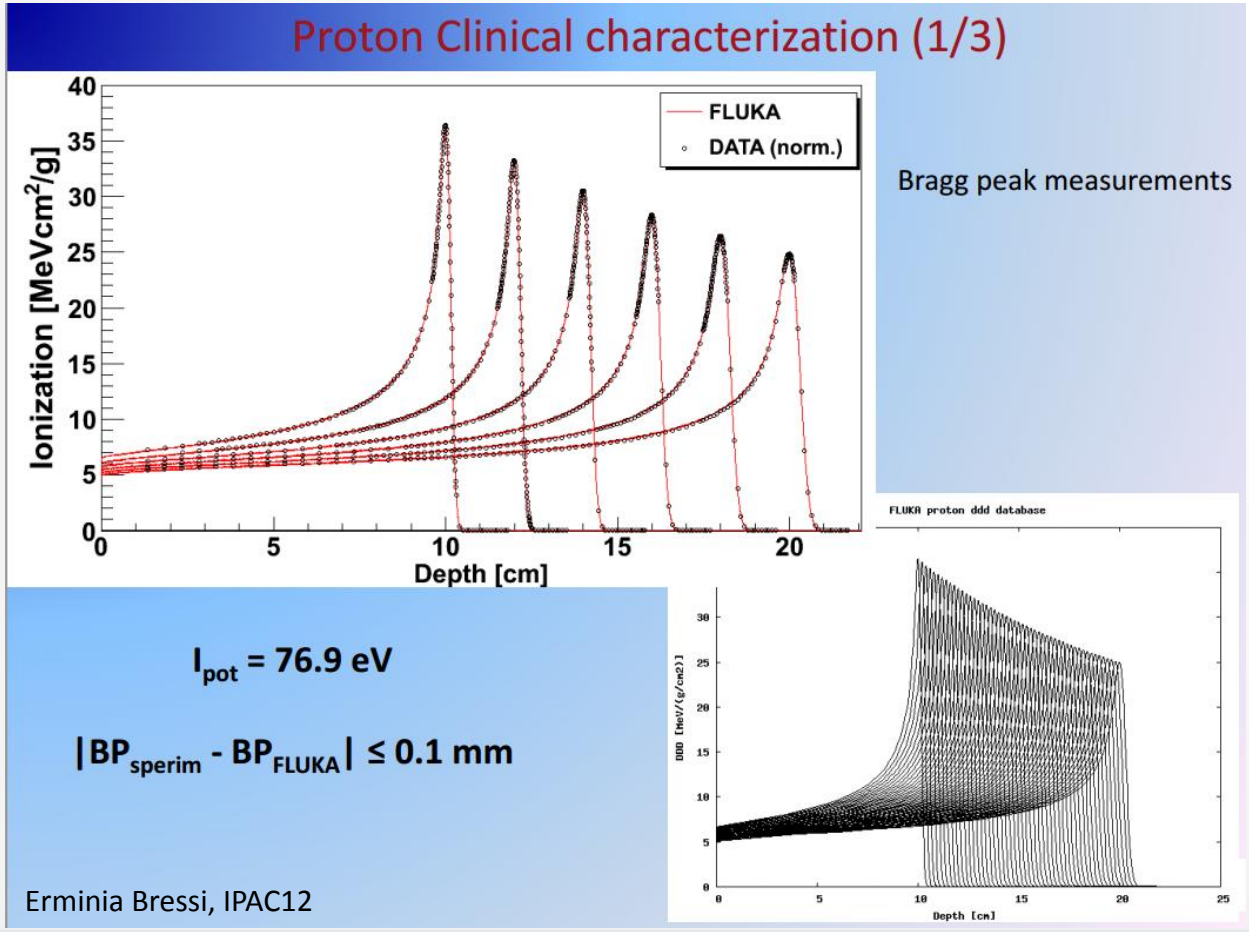
Orders of magnitude

Dose uniformity required: ± 2.5%

Treatment session duration:	**30 min**
Irradiation duration:	**3 min**
Slice thickness:	**2 – 4 mm**
Spot size:	**4 - 10 mm**
Position precision:	**0.1 mm**
Energy precision:	**10^{-4}**
Spot duration:	**5 - 10 ms**
Beam current:	**0.1 - 1 nA**
Measurement time:	**< 100 ms**

Energy precision: 10^{-4}

Energy measured with Bragg peak on water, feedback on position at BPM in high dispersion region – Precision much better than accelerator based measurements



CNAO Design Parameters I

Protons (10^{10}/spill)				
	LEBT (*)	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	**7-250**	**60-250**
Imax [A]	1.3×10^{-3}	0.7×10^{-3}	5×10^{-3}	7×10^{-9}
Imin [A]	1.3×10^{-3}	70×10^{-6}	0.12×10^{-3}	17×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	45	1.9	0.67-4.2	0.67-1.43(V)
$\varepsilon_{90,geo}$ [π mm mrad]	180	9.4	3.34-21.2	3.34-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.013 (0.026)	0.38	0.38-2.43	0.38-2.43
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.2)‰	±(1.2-3.4)‰	±(0.4-0.6)‰

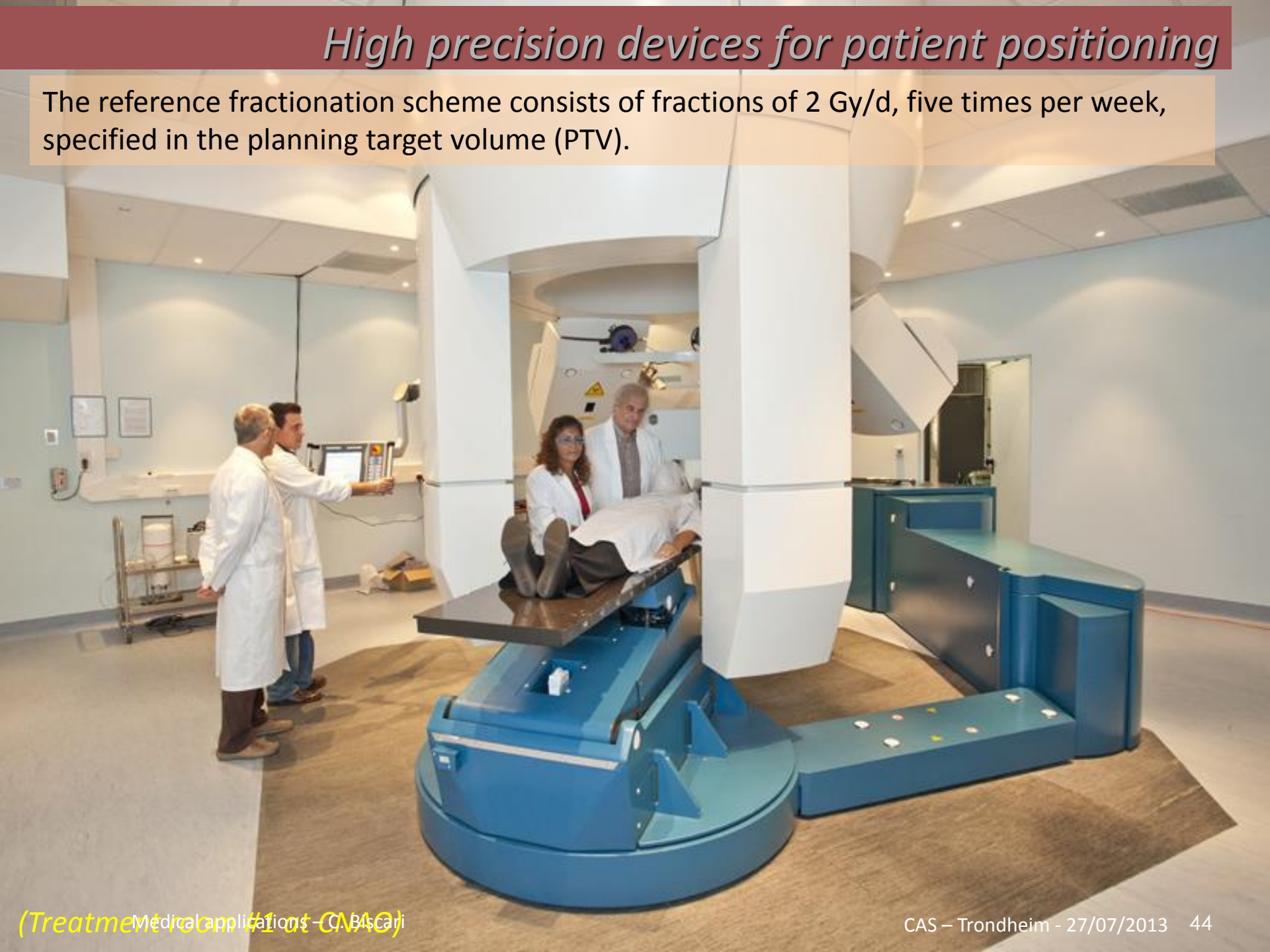
* (H_2^+, H_3^+)

CNAO Design Parameters II

Carbon ($4 \cdot 10^8$ C/spill)				
	LEBT (C^{4+})	MEBT	SYNC	HEBT
Energy [MeV/u]	0.008	7	7-400	**120-400**
Imax [A]	0.15×10^{-3}	0.15×10^{-3}	1.5×10^{-3}	2×10^{-9}
Imin [A]	0.15×10^{-3}	15×10^{-6}	28×10^{-6}	4×10^{-12}
$\varepsilon_{rms,geo}$ [π mm mrad]	45	1.9	0.73-6.1	0.73-1.43(V)
$\varepsilon_{90,geo}$ [π mm mrad]	180	9.4	3.66-30.4	3.66-7.14 (V) 5.0 (H)
Magnetic rigidity [T m]	0.039	0.76	0.76-6.34	3.25-6.34
$(\Delta p/p)_{tot}$	±1.0‰	±(1.2-2.0)‰	±(1.2-2.9)‰	±(0.4-0.6)‰

High precision devices for patient positioning

The reference fractionation scheme consists of fractions of 2 Gy/d, five times per week, specified in the planning target volume (PTV).



(Treatment room #1 at CNAO)

3D Real-time IR Optical Tracking (OTS)

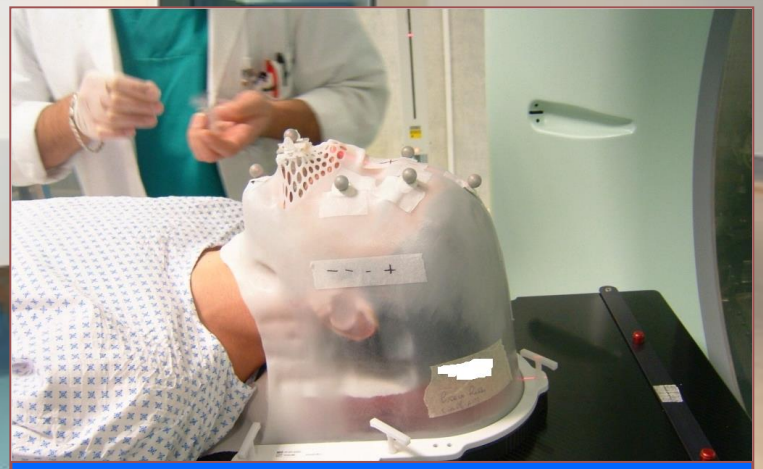
- Real time reconstruction of spherical markers and surfaces
- Sub-millimeter accuracy : peak 3D errors <0.5 mm
- 3D data flow @70 Hz

X-ray Patient Verification System (PVS)

- 2 X-ray tubes (deployable) , 2 flat panels (deployable)
- Supporting structure rotation: ±180°
- Rotation and deployment accuracy: ± 0.15mm, ± 0.1°

Patient Positioning System (PPS)

- Automatic couch or chair docking
- Absolute accuracy: ≈ 0.3 mm

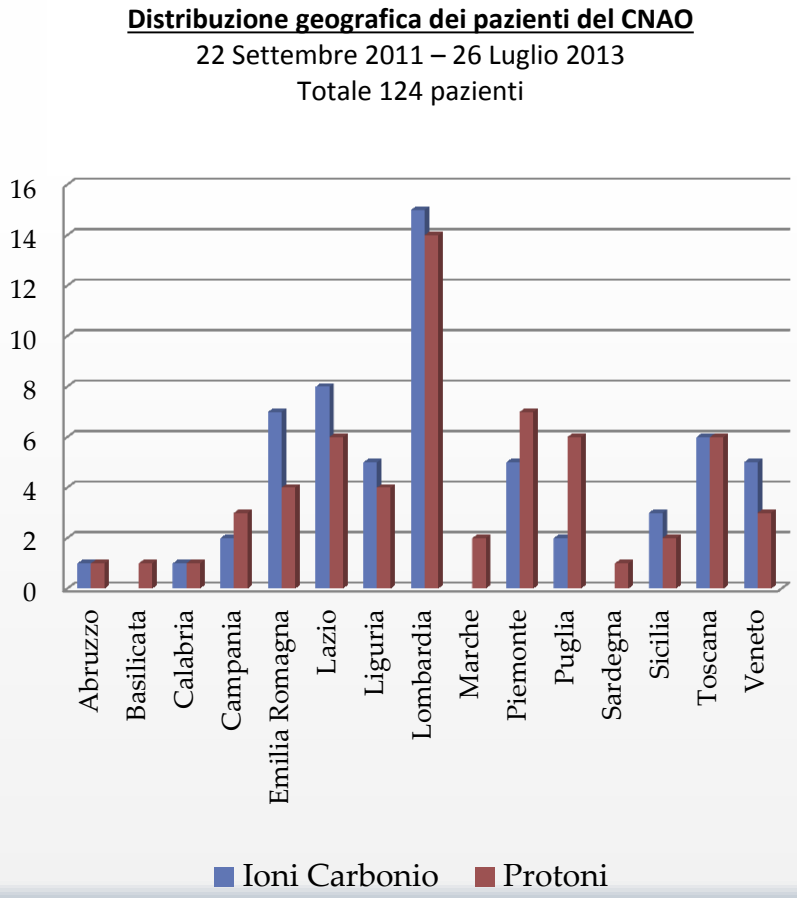


Markers, low density fixation materials

CNAO medical activity

1st patient protons: September 2011
1st patient Carbon Ions: September 2012
Three treatment rooms operational
62 Patients treated with protons
62 treated with Carbon ions

Cranium chordome and chondrosarcoma
Sacral chordome and chondrosarcoma
Intracranial meningioma
Salivary glands carcinoma
Trunk sarcoma
Prostate carcinoma
Aero-digestive mucosae melanoma



Hadrontherapy first proposed by R. Wilson in 1946

R.R. Wilson, "Foreword to the Second International Symposium on Hadrontherapy," in Advances in Hadrontherapy, (U. Amaldi, B. Larsson, Y. Lemoigne, Y., Eds.), Excerpta Medica, Elsevier, International Congress Series **1144**: ix-xiii (1997).

Radiological Use of Fast Protons

ROBERT R. WILSON
Research Laboratory of Physics, Harvard University
Cambridge, Massachusetts

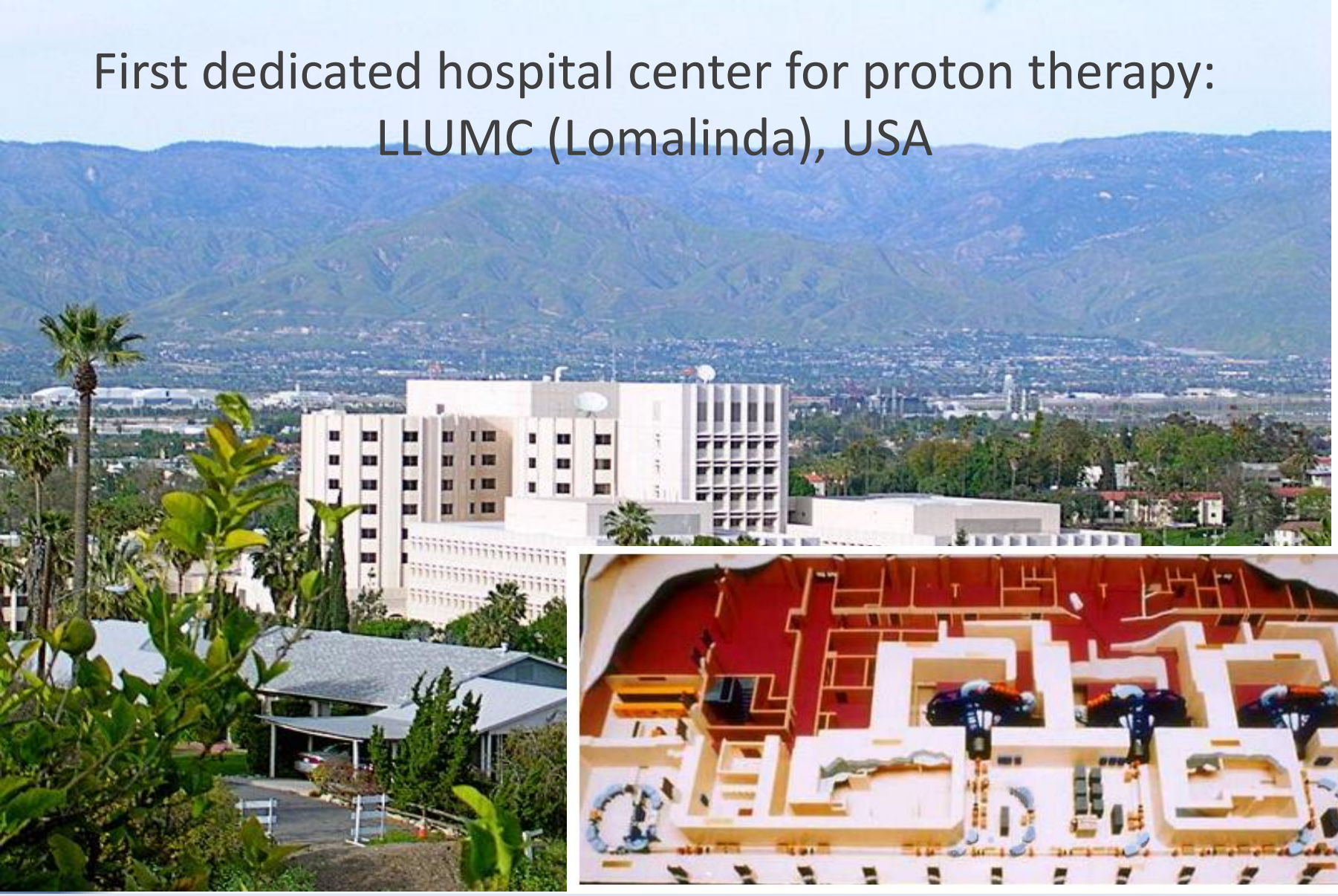
EXCEPT FOR electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in the part, been due to the very short ation in tissue of protons, deu particles from prese -energy mach how per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate interiorly a strictly localized region

Radiology 47: 487-491, 1946

In 1954: 30 patients treated with protons at LBL (Lawrence Berkeley Laboratory)
In the next years other treatments in other research centers were performed (Uppsala, Harvard, Dubna, St.Petersburg, Moscow, PSI, Chiba, Tsukuba)
In 1990 the first dedicated hospital facility has started treatments at Loma Linda (LLUMC)

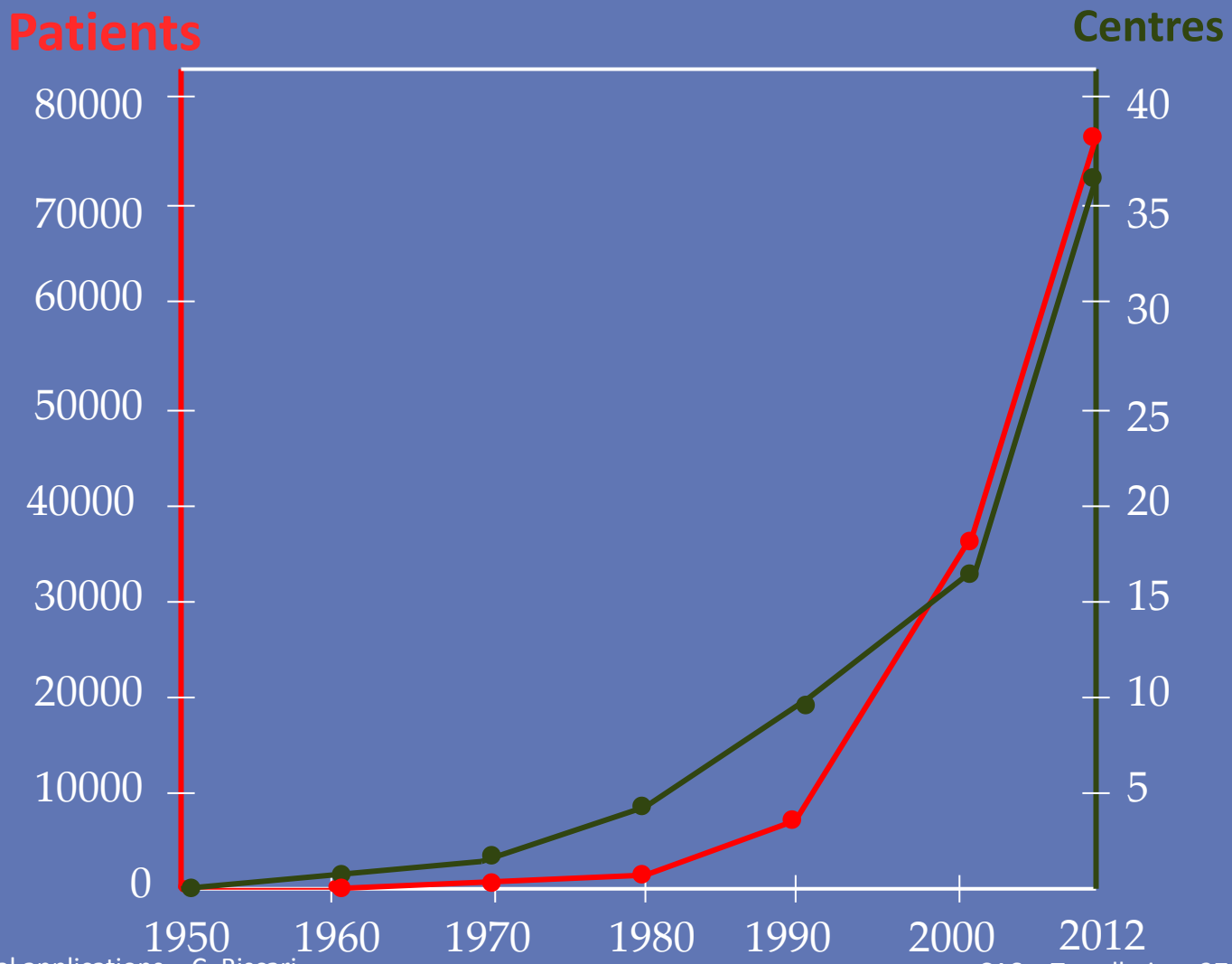
First dedicated hospital center for proton therapy: LLUMC (Lomalinda), USA



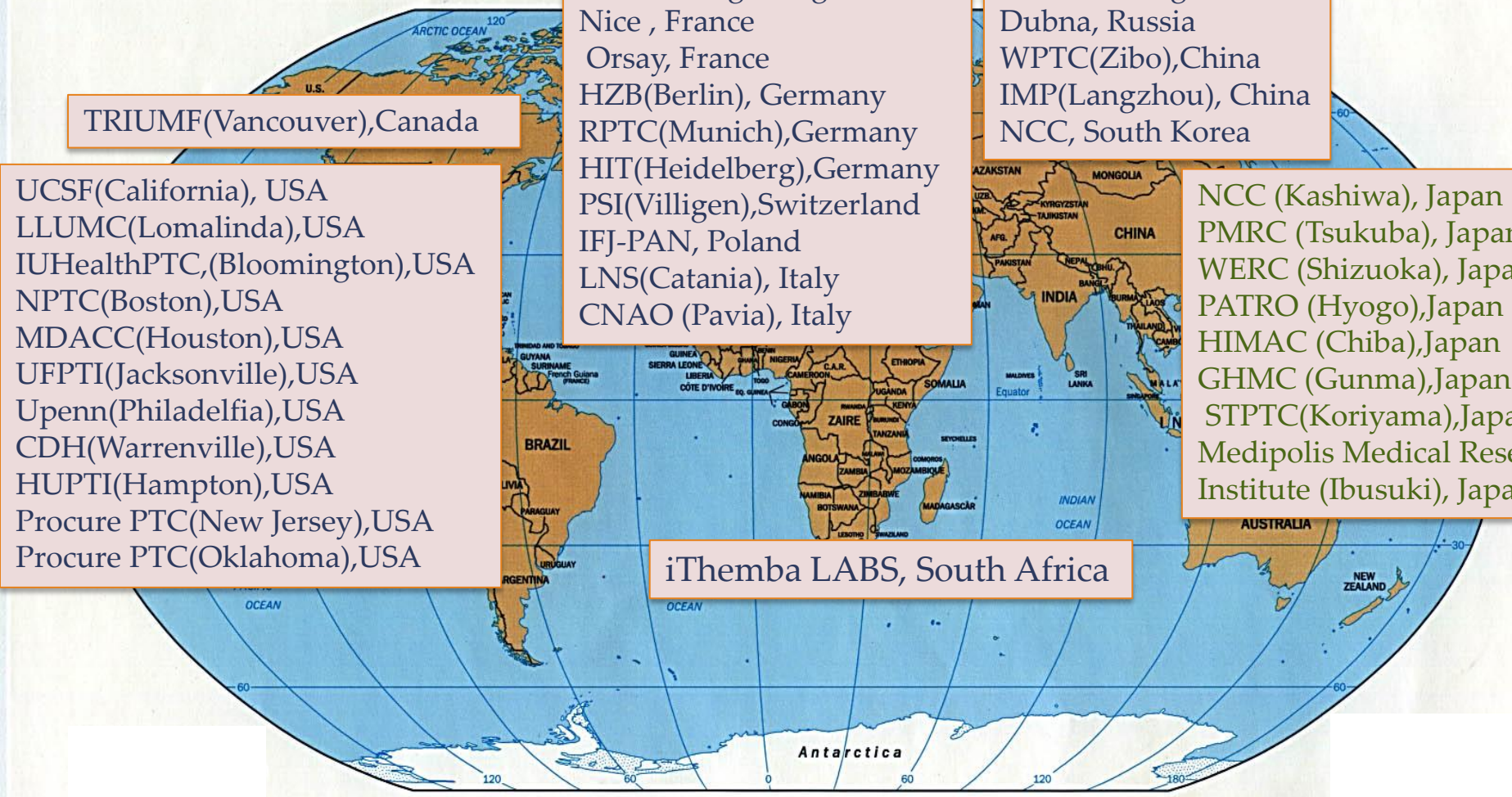
Proton synchrotron (70-250 MeV) equipped with a fixed beam room with two beam lines, three rotating gantries and a research room with three beam lines.
To date over 15000 patients have been treated.

Hadrontherapy history: Rapid Growth

doubled in last decade



Hadrontherapy in the world



TRIUMF(Vancouver),Canada

UCSF(California), USA
LLUMC(Lomalinda),USA
IUHealthPTC,(Bloomington),USA
NPTC(Boston),USA
MDACC(Houston),USA
UFPTI(Jacksonville),USA
Upenn(Philadelfia),USA
CDH(Warrenville),USA
HUPTI(Hampton),USA
Procure PTC(New Jersey),USA
Procure PTC(Oklahoma),USA

Uppsala , Sweden
Clatterbridge, England
Nice , France
Orsay, France
HZB(Berlin), Germany
RPTC(Munich),Germany
HIT(Heidelberg),Germany
PSI(Villigen),Switzerland
IFJ-PAN, Poland
LNS(Catania), Italy
CNAO (Pavia), Italy

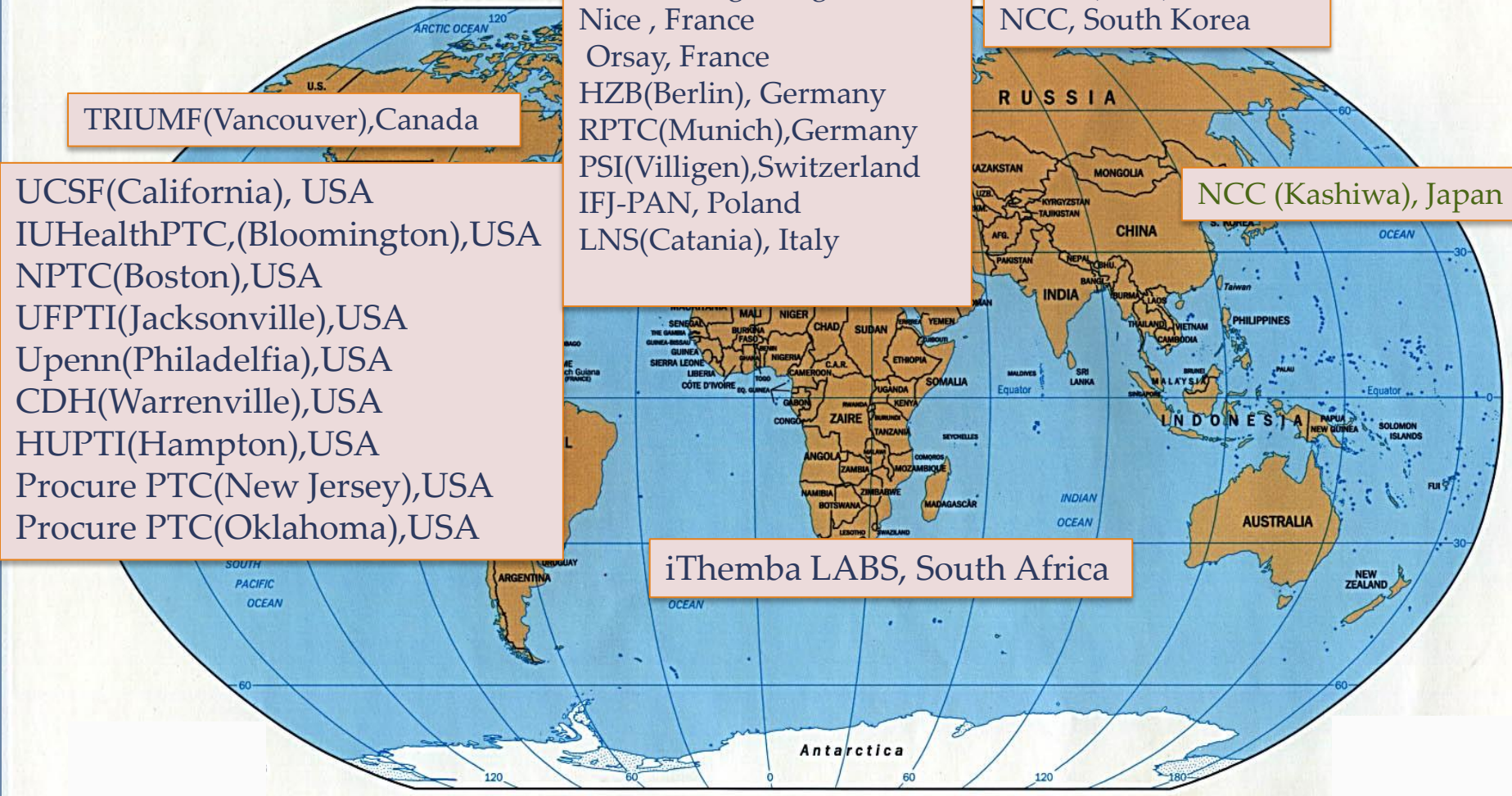
ITEP(Moscow), Russia
St. Petersburg, Russia
Dubna, Russia
WPTC(Zibo),China
IMP(Langzhou), China
NCC, South Korea

NCC (Kashiwa), Japan
PMRC (Tsukuba), Japan
WERC (Shizuoka), Japan
PATRO (Hyogo),Japan
HIMAC (Chiba),Japan
GHMC (Gunma),Japan
STPTC(Koriyama),Japan
Medipolis Medical Research Institute (Ibusuki), Japan

iThemba LABS, South Africa

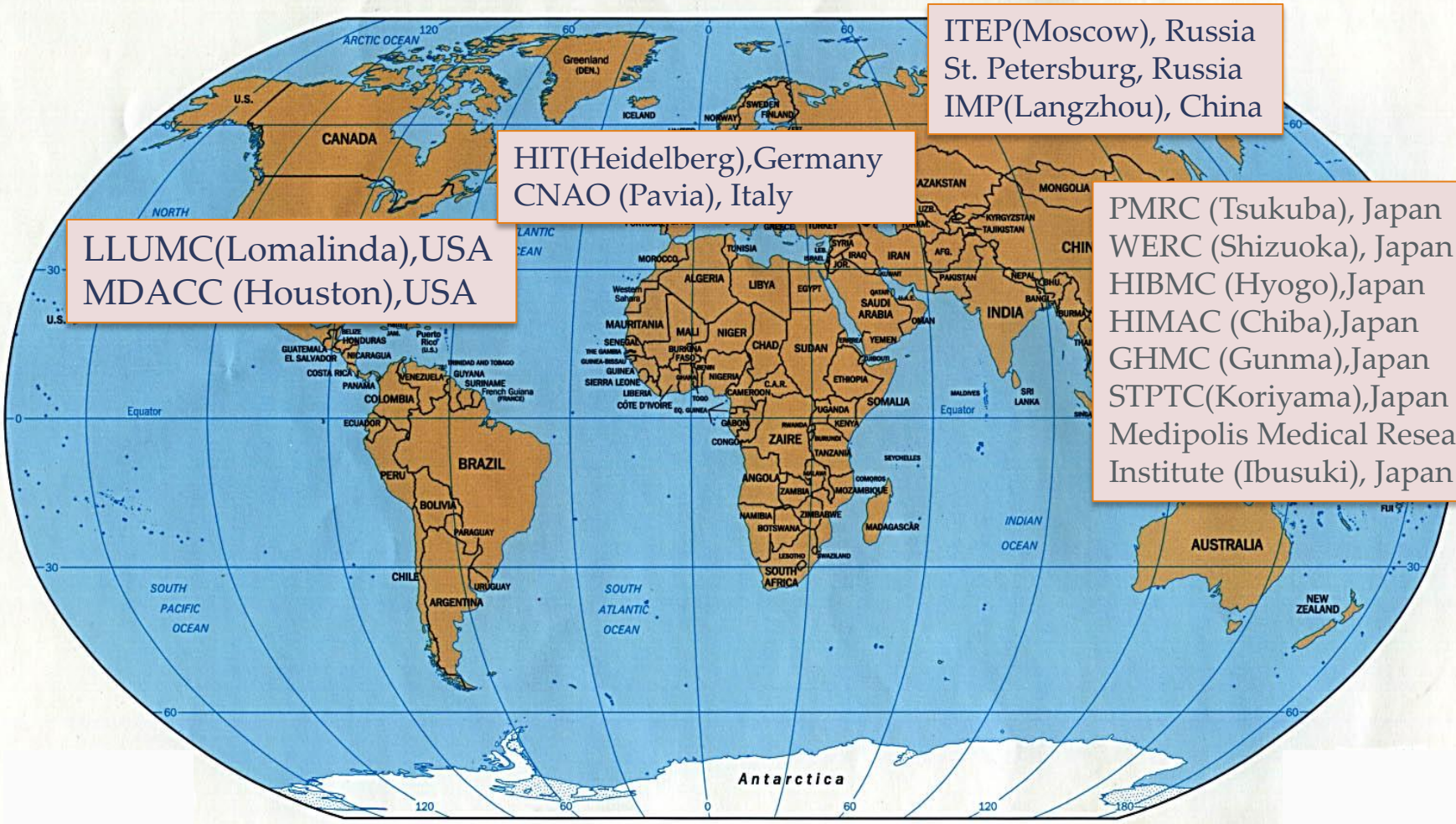
~ 80000 patients (8000 with Carbon ions)

Hadrontherapy in the world: Cyclotrons



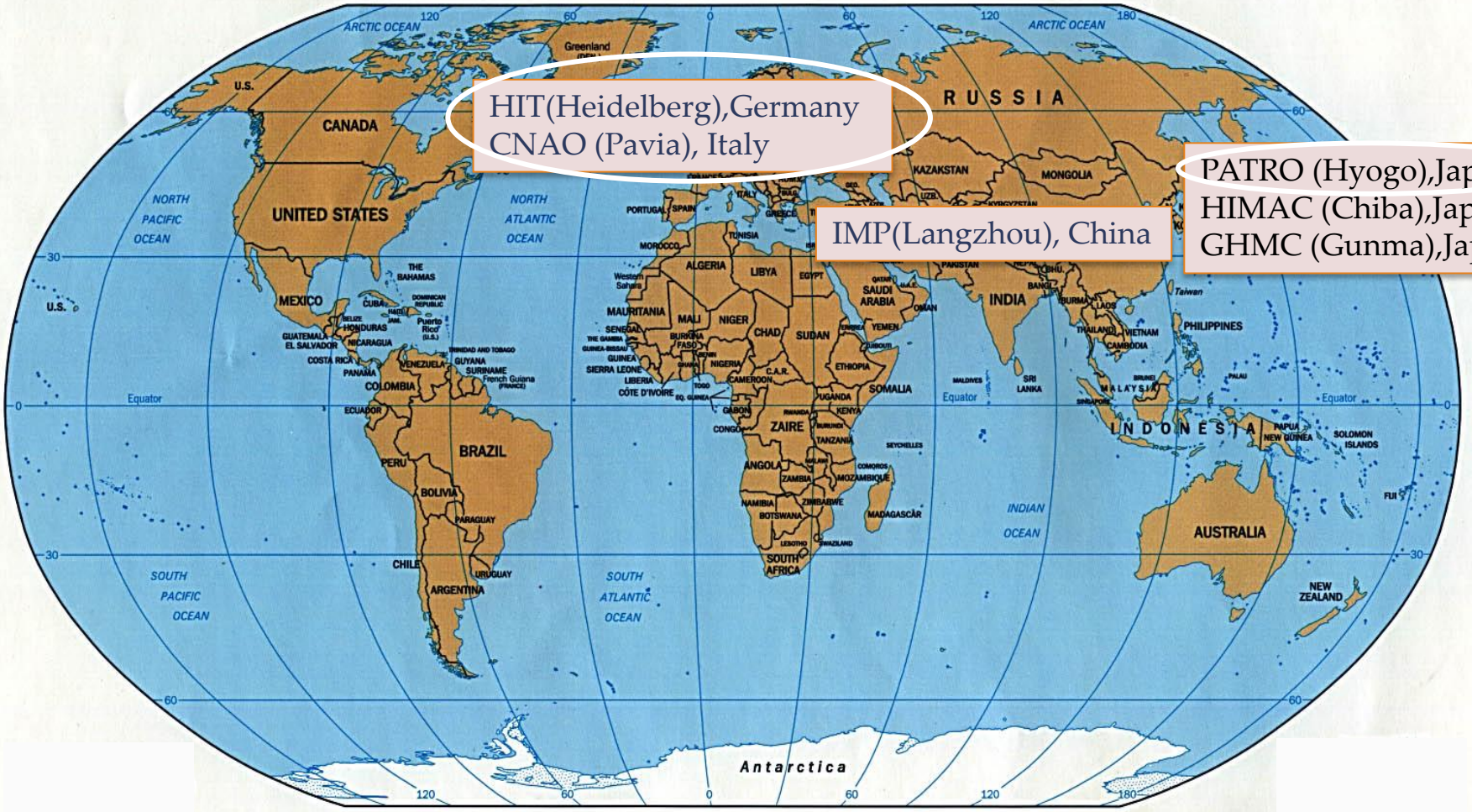
24 cyclotron facilites

Hadrontherapy in the world: Synchrotrons



14 synchrotron facilities

Hadrontherapy in the world: Carbon Synchrotrons



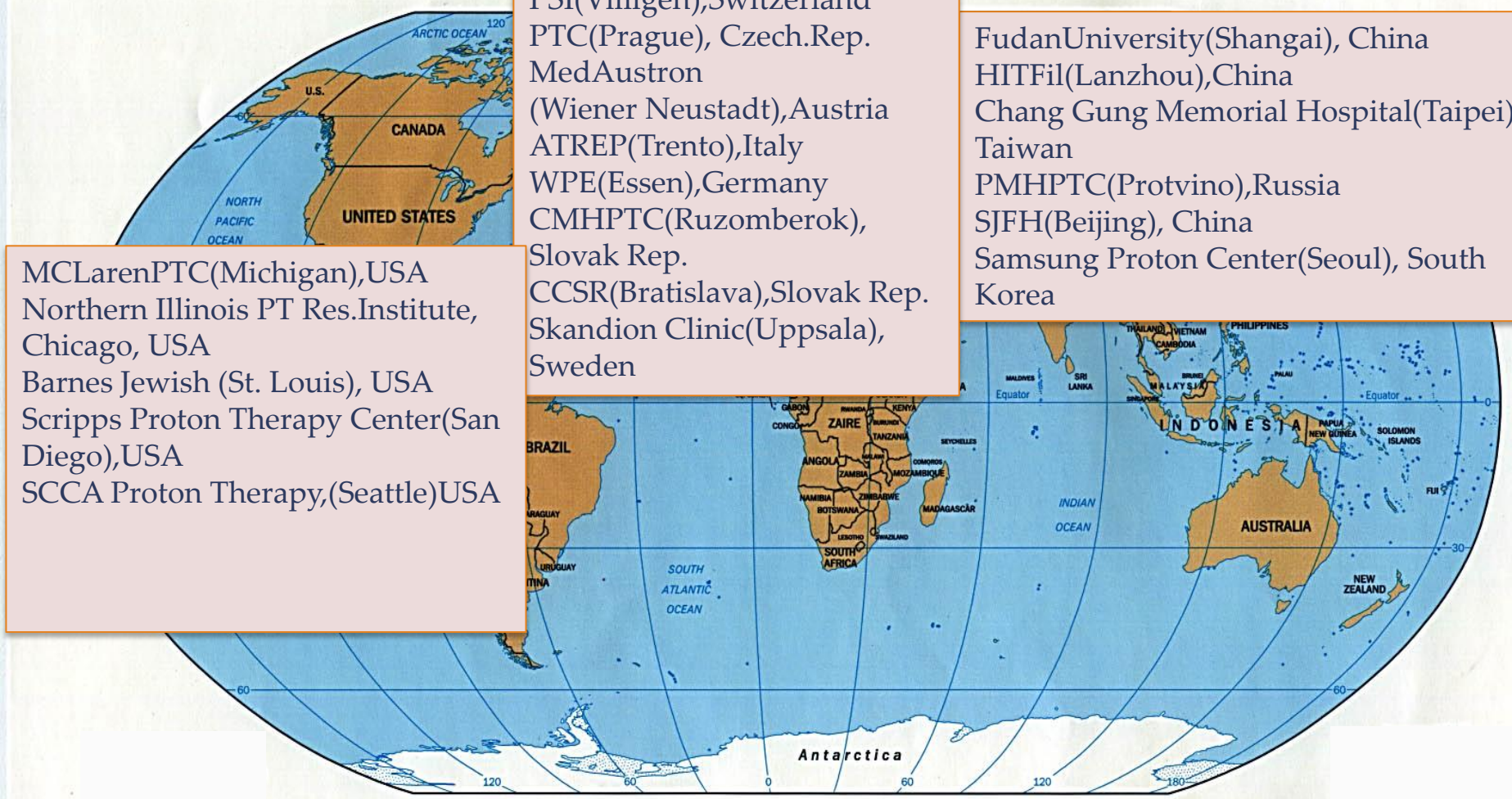
6 carbon synchrotron facilities:
only HIT, CNAO and PATRO produce both clinical protons and carbon ions

Hadrontherapy in the world: New facilities (under construction or ready to start)

PSI(Villigen),Switzerland
PTC(Prague), Czech.Rep.
MedAustron
(Wiener Neustadt),Austria
ATREP(Trento),Italy
WPE(Essen),Germany
CMHPTC(Ruzomberok),
Slovak Rep.
CCSR(Bratislava),Slovak Rep.
Skandion Clinic(Uppsala),
Sweden

FudanUniversity(Shangai), China
HITFil(Lanzhou),China
Chang Gung Memorial Hospital(Taipei),
Taiwan
PMHPTC(Protvino),Russia
SJFH(Beijing), China
Samsung Proton Center(Seoul), South
Korea

MCLarenPTC(Michigan),USA
Northern Illinois PT Res.Institute,
Chicago, USA
Barnes Jewish (St. Louis), USA
Scripps Proton Therapy Center(San
Diego),USA
SCCA Proton Therapy,(Seattle)USA



USA, Europe, Asia: 12 proton cyclotrons; 2 proton-carbon synchrotrons;

2 proton synchrotrons; 1 carbon synchrotron; 1 proton synchro-cyclotron

Hadrontherapy business

The idea of hadrontherapy facilities has passed from the research field to the business field with several commercial firms:
IBA, Hitachi, Mitsubishi, Sumitomo, Varian, Still River, Optivus, Siemens

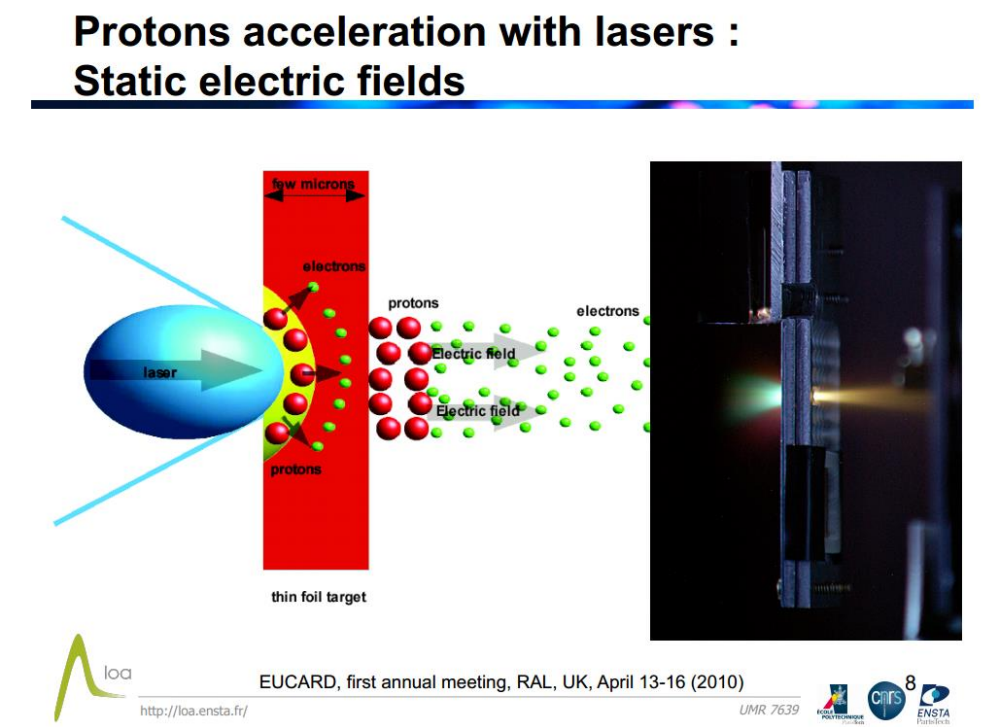
… Hadron therapy is the epitome of a multidisciplinary and transnational venture: its full development requires the competences of physicists, physicians, radiobiologists, engineers and IT experts, as well as collaboration between research and industrial partners.

The translational aspects are extremely relevant because the communities involved are traditionally separate and they have to learn to speak the same "language". Ions that are considered "light" by physicists, such as carbon, are "heavy" for radiobiologists – and this is just one of many examples (from Cern Courier, Nov 23, 2011)

Hadrontherapy future

Worldwide R&D for more compact and/or advanced accelerators:

- FFAG: Fixed Field alternating Gradient: in the middle between a cyclotron and a synchrotron. DC beam with fast energy change! The radius change slightly because B changes with the radius. A fast energy change could be a good solution in treating moving organs



- LIBO: Linac Booster Linac @ 3 GHz, 27MV/m for protons from 30 MeV to 250 MeV exploiting the standard 30 MeV cyclotrons for radioisotopes as injector.
- Laser Plasma acceleration: heavy ions acceleration by high power lasers
- DWA: dielectric wall induction linac: new dielectrics 100 MV/m (instead of 10) 250 MeV proton linac 3 m long

Ackwoledgements

- To all CNAO Team, with whom I shared three years of work during the commissioning of the facility, to Marco Pullia and Erminia Bressi, for all the information and fruitful discussions, and specially to Luciano Falbo, from whom I have borrowed most of the slides (talk at HIAT2012, Chicago, http://www.phy.anl.gov/hiat12/Proceedings/papers/proceed.pdf, p. 156)