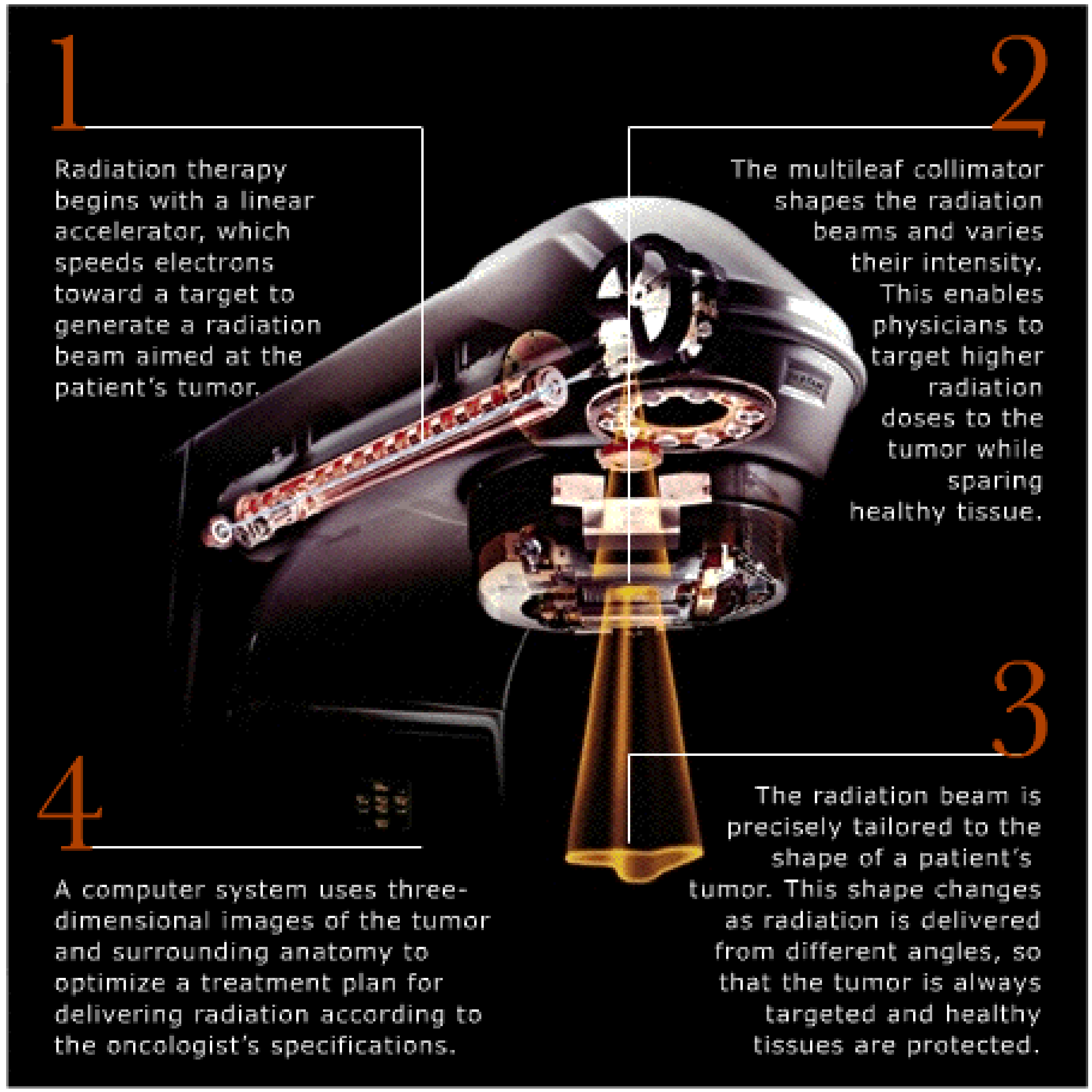
- Introduction: an historical review — I
- Applications in medical diagnostics — II
- Particle accelerators for medicine — III
- Applications in conventional radiation therapy — IV
- Hadrontherapy, the frontier of cancer radiation therapy — V
  - Proton-therapy
  - Carbon ion therapy
  - Neutrons in cancer therapy

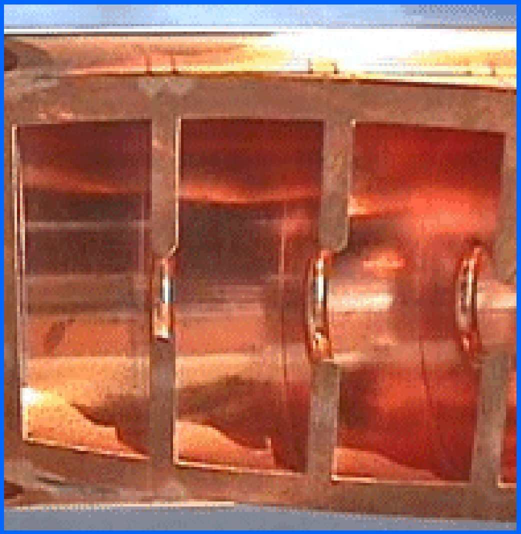
Electron linacs for radiation therapy

An electron linac mounted on a rotating gantry

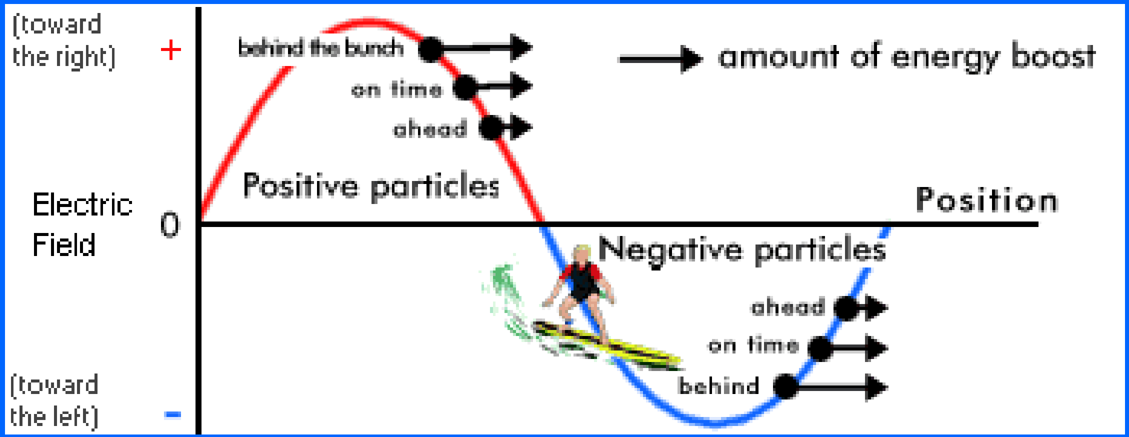
How a Linac Works

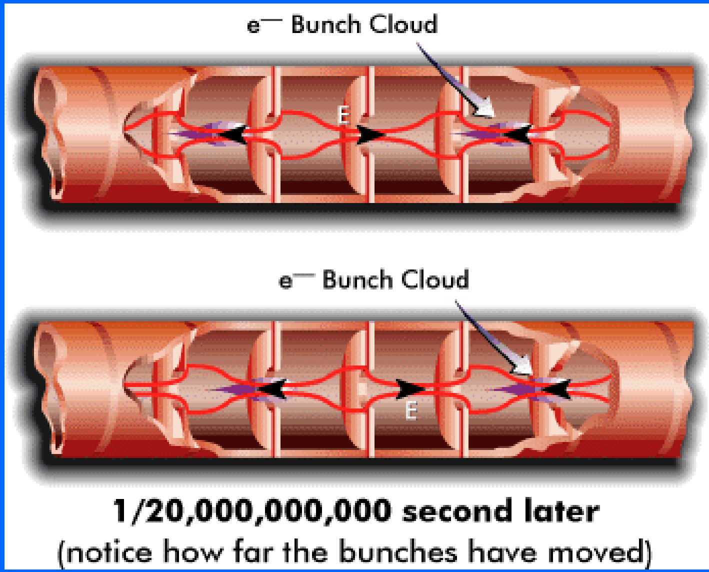


- 3 GHz cavities



- Traveling wave principle (electrons are already relativistic at 500 keV)





- Gradient about 10 MeV / m

Klystrons

- Klystrons (sometimes magnetrons) are used to produce the 3 GHz radiofrequency power that is brought to the cavities by a wave guide.

In a klystron:

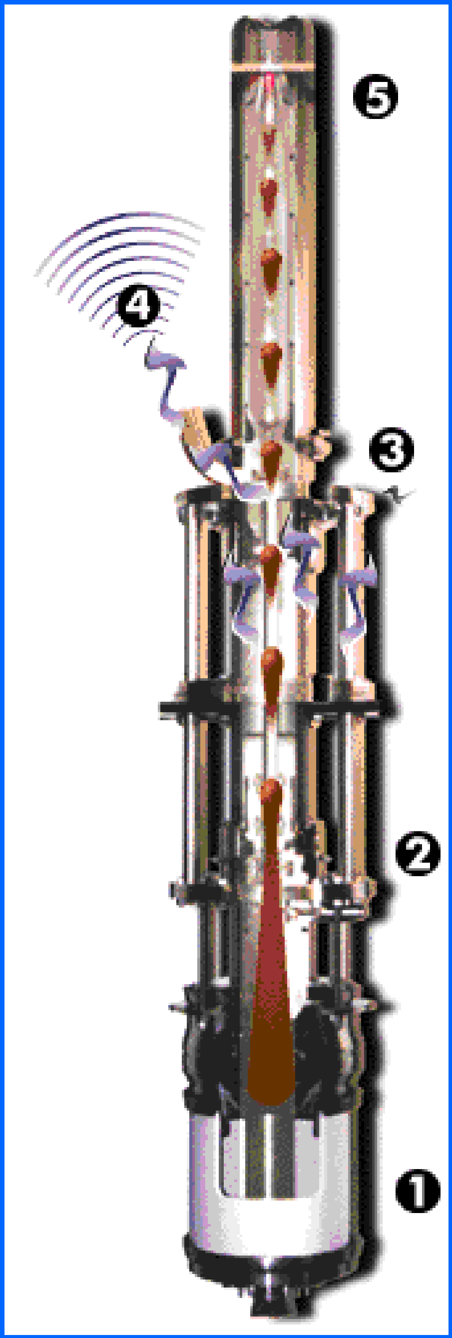
•The electron gun ❶ produces a flow of electrons.

•The bunching cavities ❷ regulate the speed of the electrons so that they arrive in bunches at the output cavity.

•The bunches of electrons excite microwaves in the output cavity ❸ of the klystron.

•The microwaves flow into the waveguide ❹ , which transports them to the accelerator.

•The electrons are absorbed in the beam stop. ❺



Proton and ion accelerators

Production of isotopes	Hadrontherapy
Cyclotrons	Cyclotrons
(linacs)	Synchrotrons
	(linacs?)

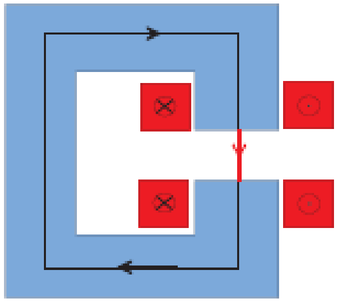
Main components

Components:

- **Ion sources**
- **Injection devices**
- **Vacuum chamber and vacuum pumps**
- **Radio-frequency acceleration cavities and radio-frequency generators**
- **Magnets**
  - **Bending dipoles**
  - **Focusing quadrupoles (sextupoles)**
- **Extraction devices**
- **Beam transport lines**

Magnets

1D Field Calculation for a Conventional Dipole



$$\oint \vec{H} \cdot d\vec{s} = \int_A \vec{J} \cdot d\vec{A}$$

$$H_{\mathrm{iron}}\, s_{\mathrm{iron}} + H_{\mathrm{gap}}\, s_{\mathrm{gap}} = \frac{1}{\mu_0 \mu_r} B_{\mathrm{iron}}\, s_{\mathrm{iron}} + \frac{1}{\mu_0} B_{\mathrm{gap}}\, s_{\mathrm{gap}} = N\, I$$

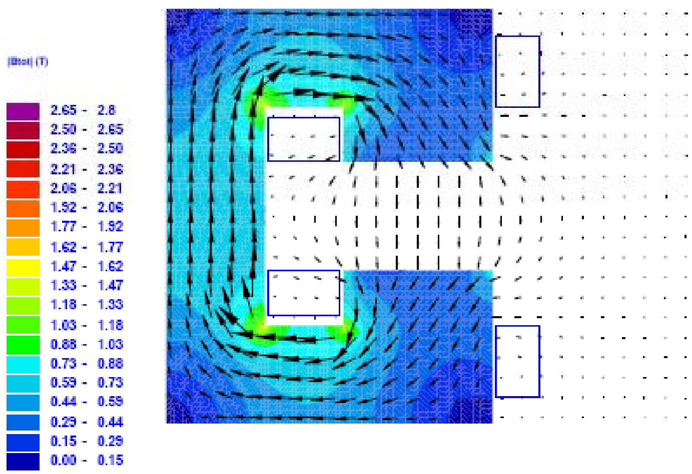
$$\mu_r \gg 1 \qquad B_{\mathrm{gap}} = \frac{\mu_0 N\, I}{s_{\mathrm{gap}}}$$

Warning 1: Check that the magnetic circuit contains no flux concentration which increases the magnetic flux density above 1 T, as in this case fringe fields can no longer be neglected.

“C” and “H” bending dipoles

Magnet Metamorphosis

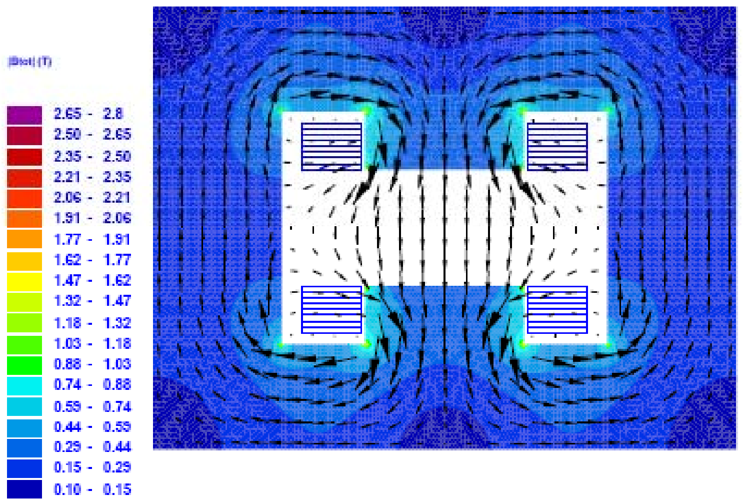
(C- Core, LEP Dipole)



$N \cdot I = 4480$ A $\quad B_1 = 0.13$ T $\quad B_s = 0.042$ T $\quad$ Fill.fac. 0.27

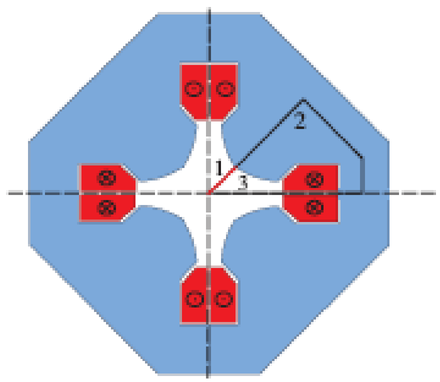
Magnet Metamorphosis

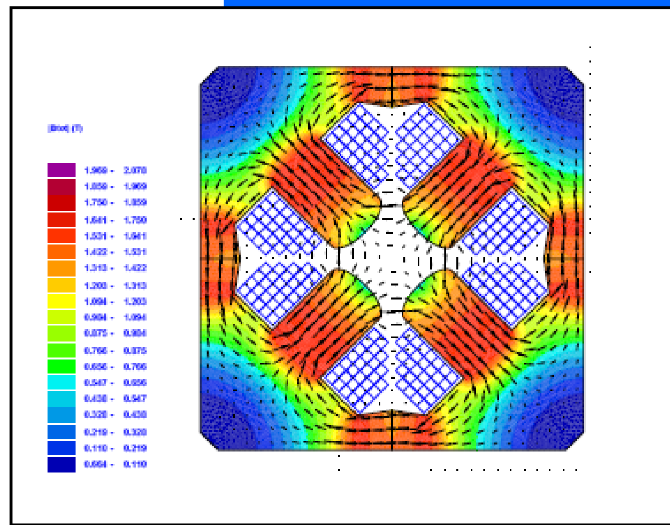
(H-Magnet)



$N \cdot I = 24000$ A $\quad B_1 = 0.3$ T $\quad B_s = 0.065$ T $\quad$ Fill.fac. 0.98

1D Field Calculation for a Conventional Quadrupole





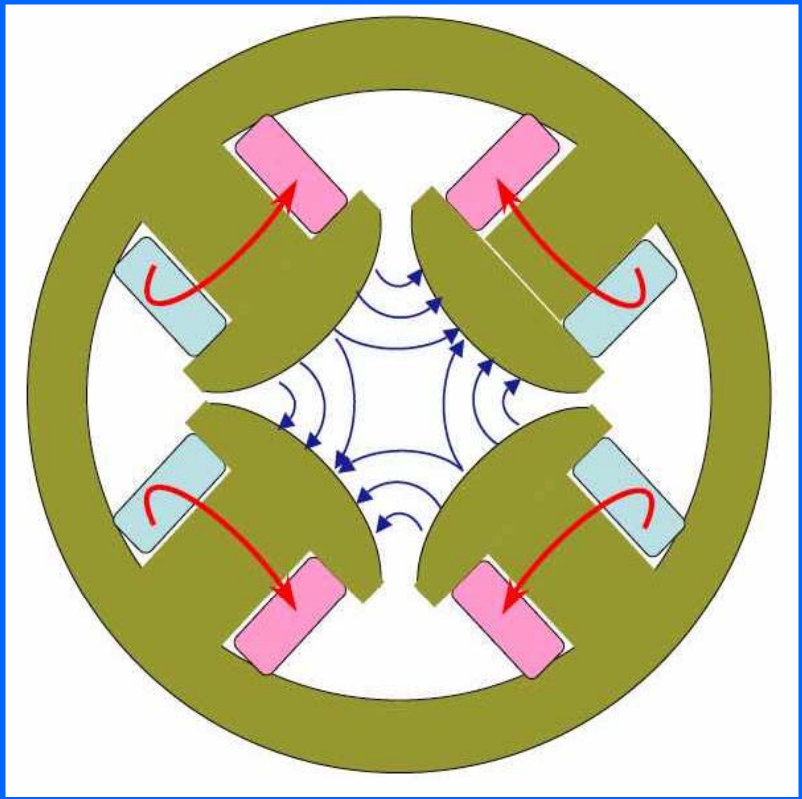
$$\oint \vec{H} \cdot d\vec{s} = \int_1 \vec{H}_1 \cdot d\vec{s} + \int_2 \vec{H}_2 \cdot d\vec{s} + \int_3 \vec{H}_3 \cdot d\vec{s} = N\,I$$

$$B_x = gy \qquad B_y = gx \qquad \Rightarrow \qquad H = \frac{g}{\mu_0}\sqrt{x^2 + y^2} = \frac{g}{\mu_0} r$$

$$\int_0^{r_0} H dr = \frac{g}{\mu_0}\int_0^{r_0} r dr = \frac{g}{\mu_0}\frac{r_0^2}{2} = N\,I \qquad \Rightarrow \qquad g = \frac{2\mu_0 NI}{r_0^2}$$

Quadrupoles

- Used for focusing the beams
- The quadrupole poles are hyperbolic
  - constant magnetic field gradient
  - focusing “lens“ in *x* and defocusing in *y*, or vice versa.



$$B_y = B_0 \frac{x}{a}, \quad B_x = B_0 \frac{y}{a}$$

$$\ddot{x} + \frac{q v_s B_0}{\gamma m a} x = 0$$

Focusing

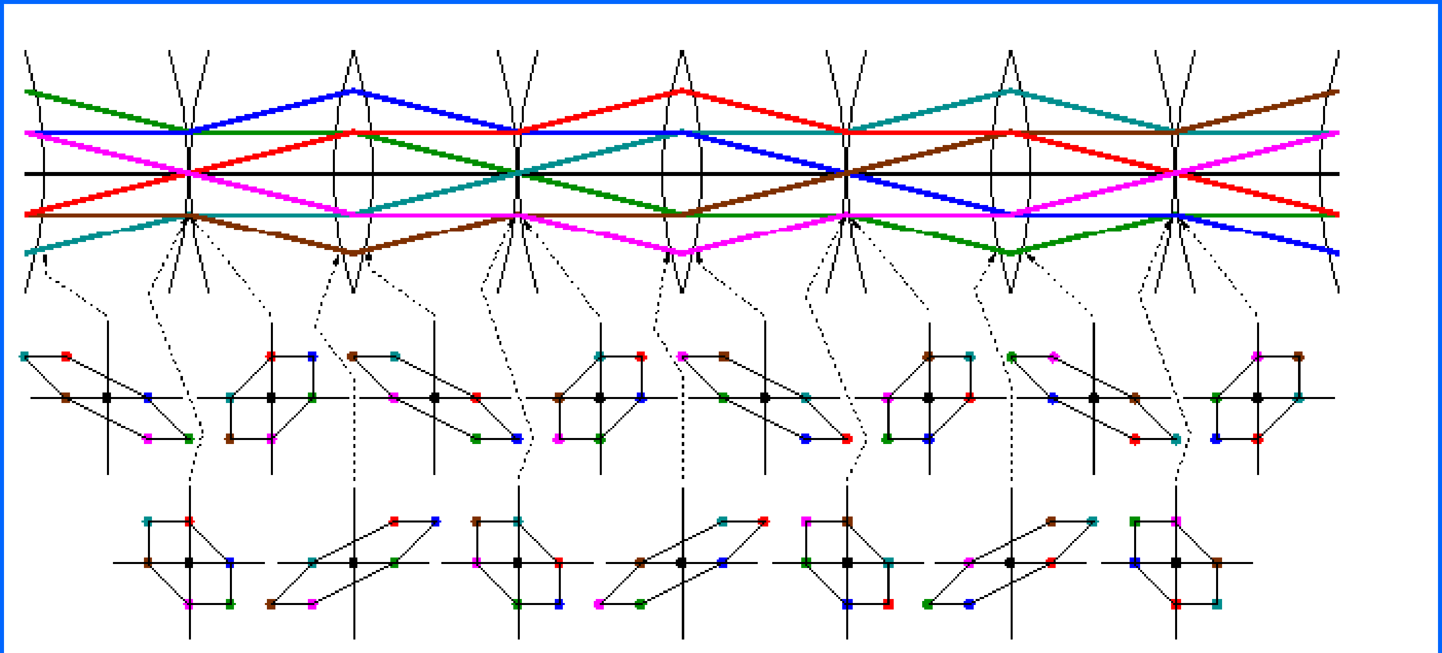
$$\ddot{y} - \frac{q v_s B_0}{\gamma m a} y = 0$$

Defocusing

Strong focusing

- Quadrupoles are used in “multiplets” → the global effect is focusing!

- Example : in a doublet “lenses“ alternate in sign, and x and y are opposite. Focusing and defocusing alternate in the two planes.



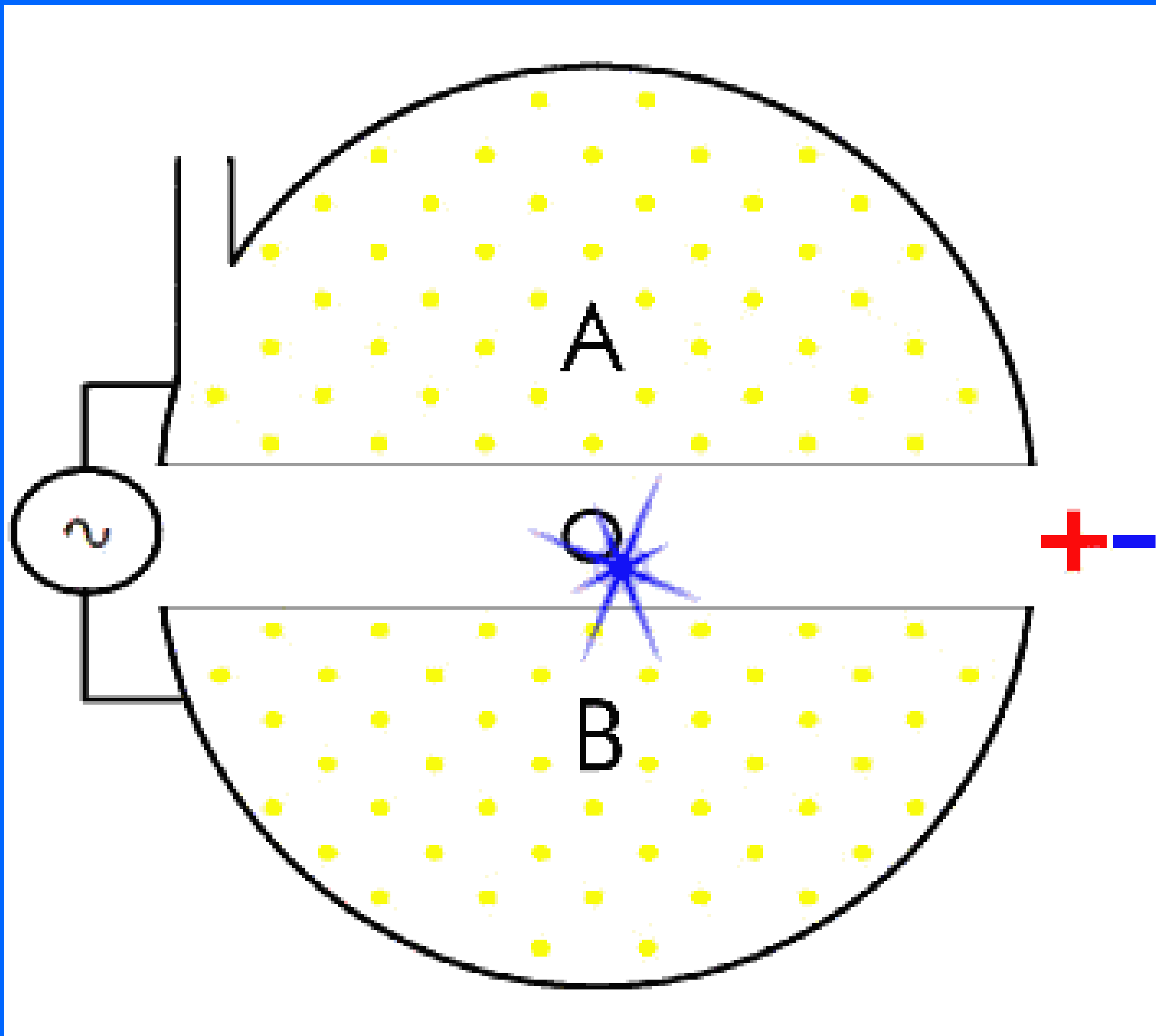
x, x’

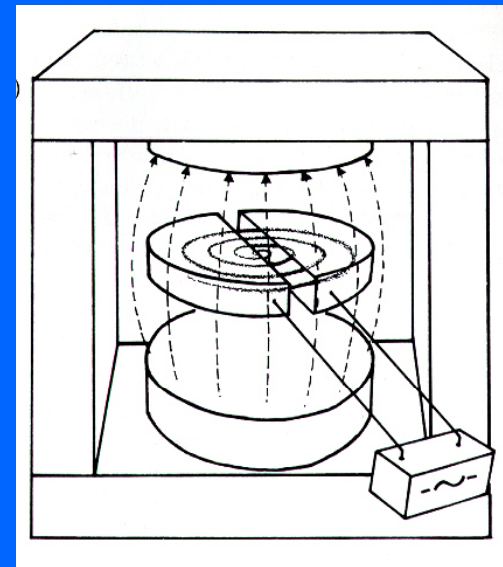
Emittance plane

(x plane only!)

- The key point is that the beam is smaller in the defocusing lenses than in the focusing lenses.

Cyclotrons for the production of radio-isotopes





Cyclotron frequency

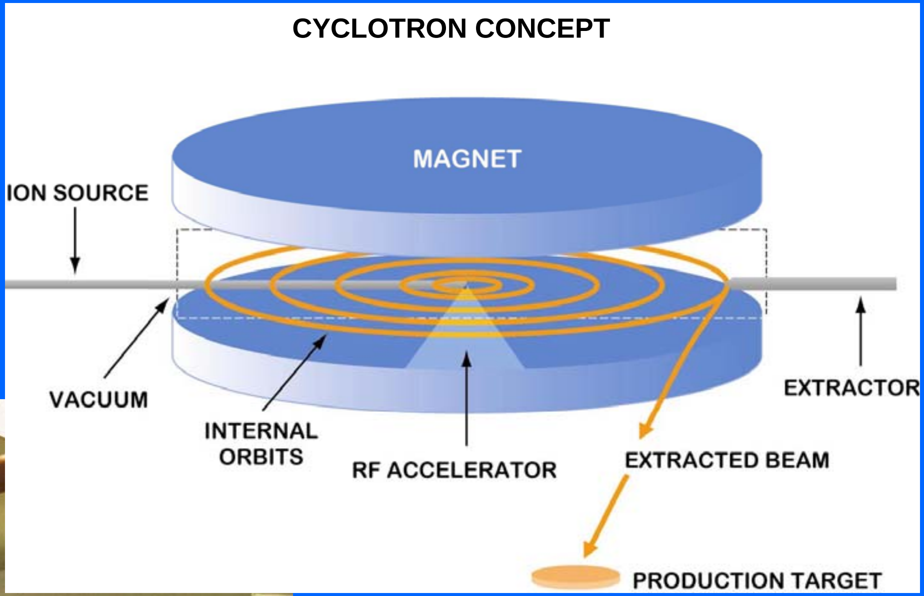
- $\nu = qB / 2\pi m$
- **Independent from the speed!**
- **For protons:**
- ν = B [T] x 15.28 MHz/T

Main requirements for the production of radioisotopes

- **High currents : 10 μA to 2 mA**
- **Energies:**
  - **10-20 MeV protons for PET isotopes (18-F)**
  - **30 MeV for industrial production of isotopes for SPECT**
  - **70 MeV or more and multi-particle (deuterons, alphas, ions) mainly for research**

Example: the TR30 cyclotron

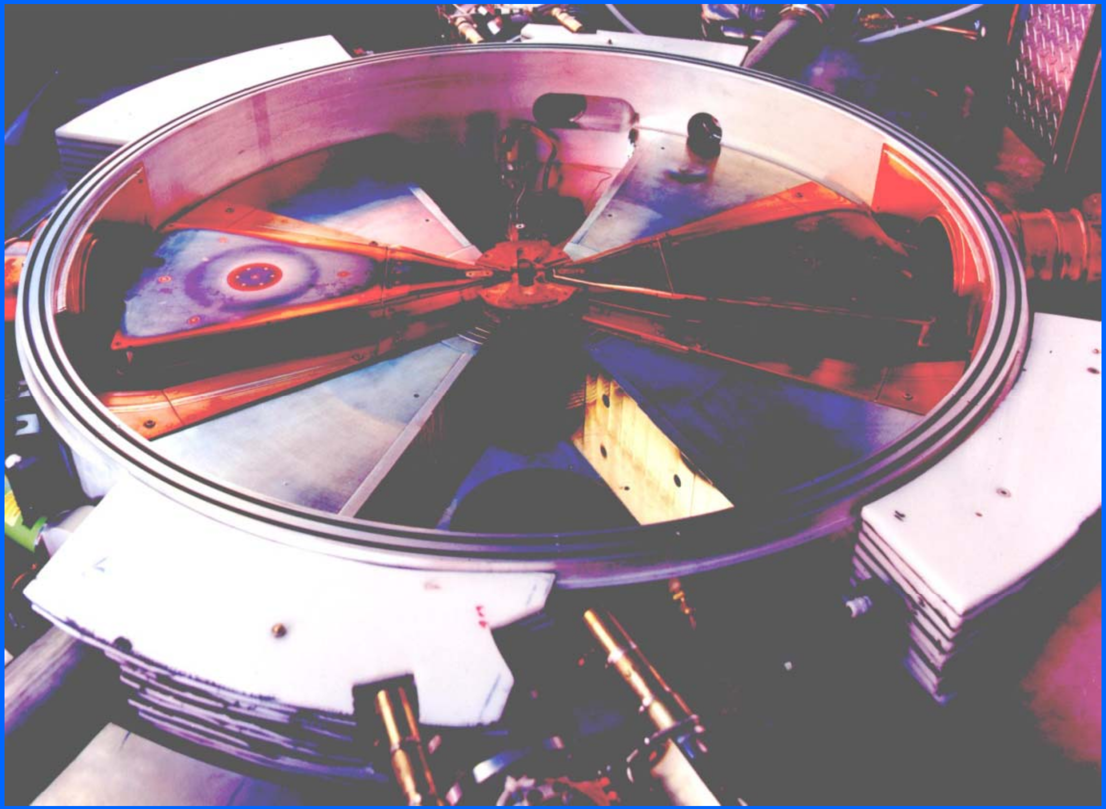
- 30 MeV, up to 1.5 mA proton beams
- Magnetic field (average) 1.2 T
- Cyclotron frequency : 18.33 MHz



Courtesy ACSI

Vancouver, Canada

Inside the cyclotron



- Two 45 degrees "dees"
- RF frequency 73 MHz (4th harmonic)
- RF field 50 kV
- 4 accelerations per turn: 50 keV x 4 = 200 keV/turn
- 150 turns to reach 30 MeV

Extraction

- H^- ions are accelerated (not protons)
- Extraction through stripping foil (efficiency about 100%)

Magnetic field

- Not constant!
  - "Hills": 1.9 T
  - "Valleys": 0.5 T
  - Trajectories are not circular!

The world's largest cyclotron

TRIUMF laboratory, Vancouver Canada

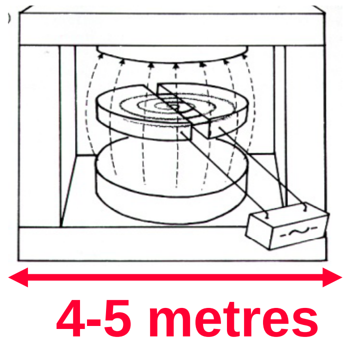
- **500 MeV protons (they start to be relativistic… see the shape of the "dees")**
- **up to 50 μA (25 kW power only on the beam!)**
- **18 m diameter, 4000 tons**

Accelerators for hadrontherapy

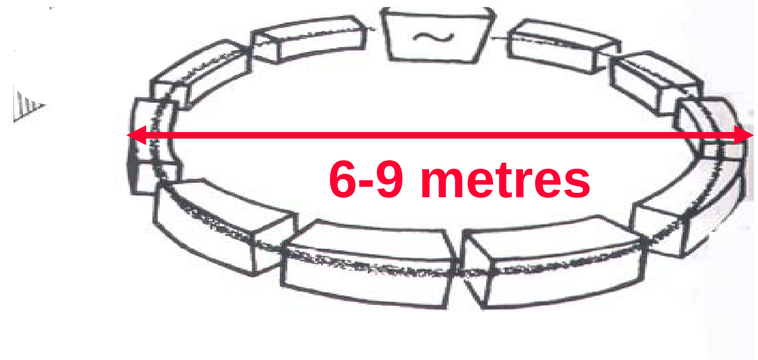
The accelerators used today in hadrontherapy

Teletherapy with protons (~ 200 MeV)

CYCLOTRONS (Normal or SC)

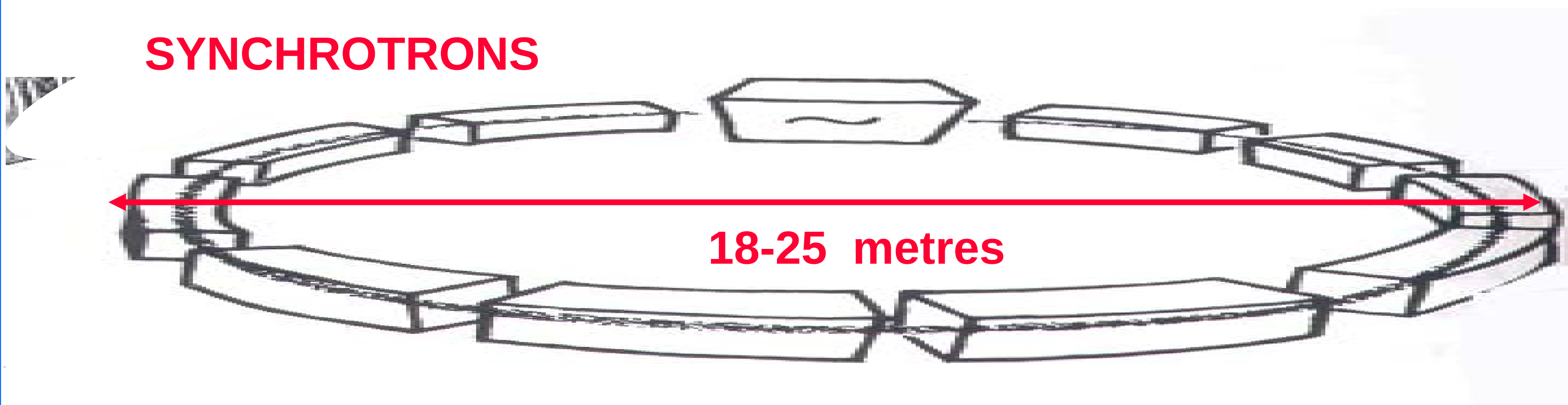


SYNCHROTRONS



Teletherapy with carbon ions (~ 4800 MeV)

SYNCHROTRONS



Why?

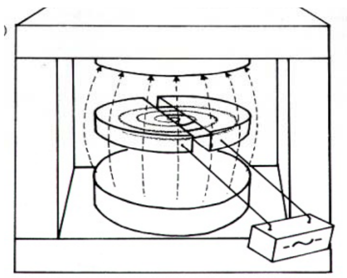
- Beam rigidity : is the product of the magnetic field B and the radius of curvature ρ for a charged particle in that magnetic field
- With some kinematics …

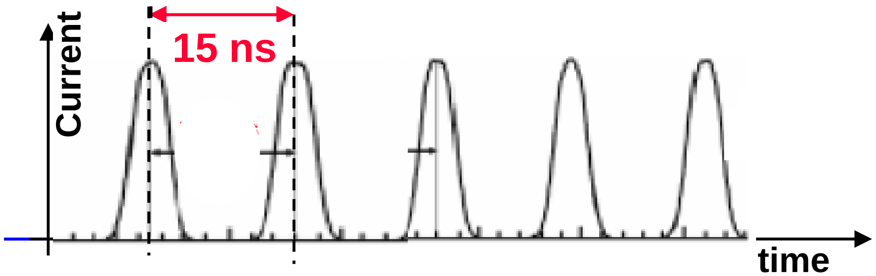
$$B \cdot \rho = \frac{\sqrt{2mc^2 E}}{q \cdot e \cdot c}$$

- For 200 MeV protons : 2.1 T·m
- For 4800 MeV carbon ions : 5.8 T·m
- For the same B the radius of curvature is three times larger for carbon ions!

The time structures of the beams are very different

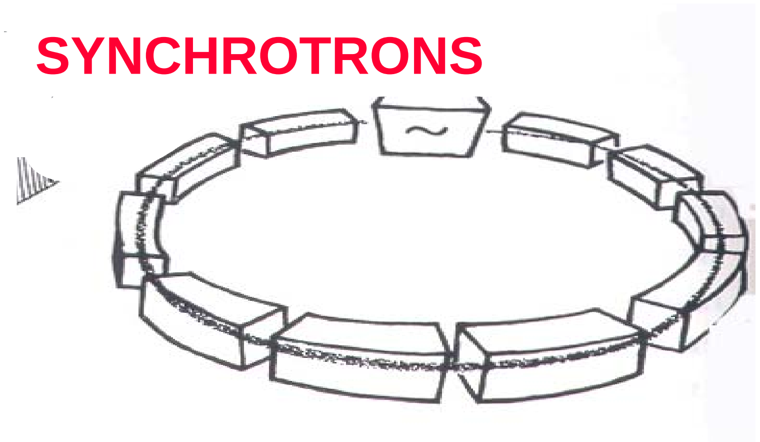
CYCLOTRONS (*) (Normal or SC)

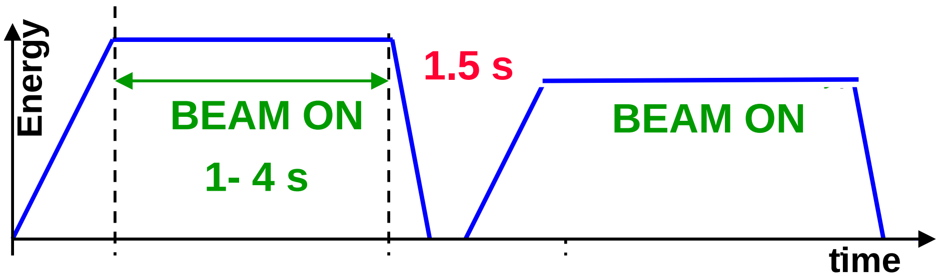




A pulsed beam of fixed energy is always present

SYNCHROTRONS

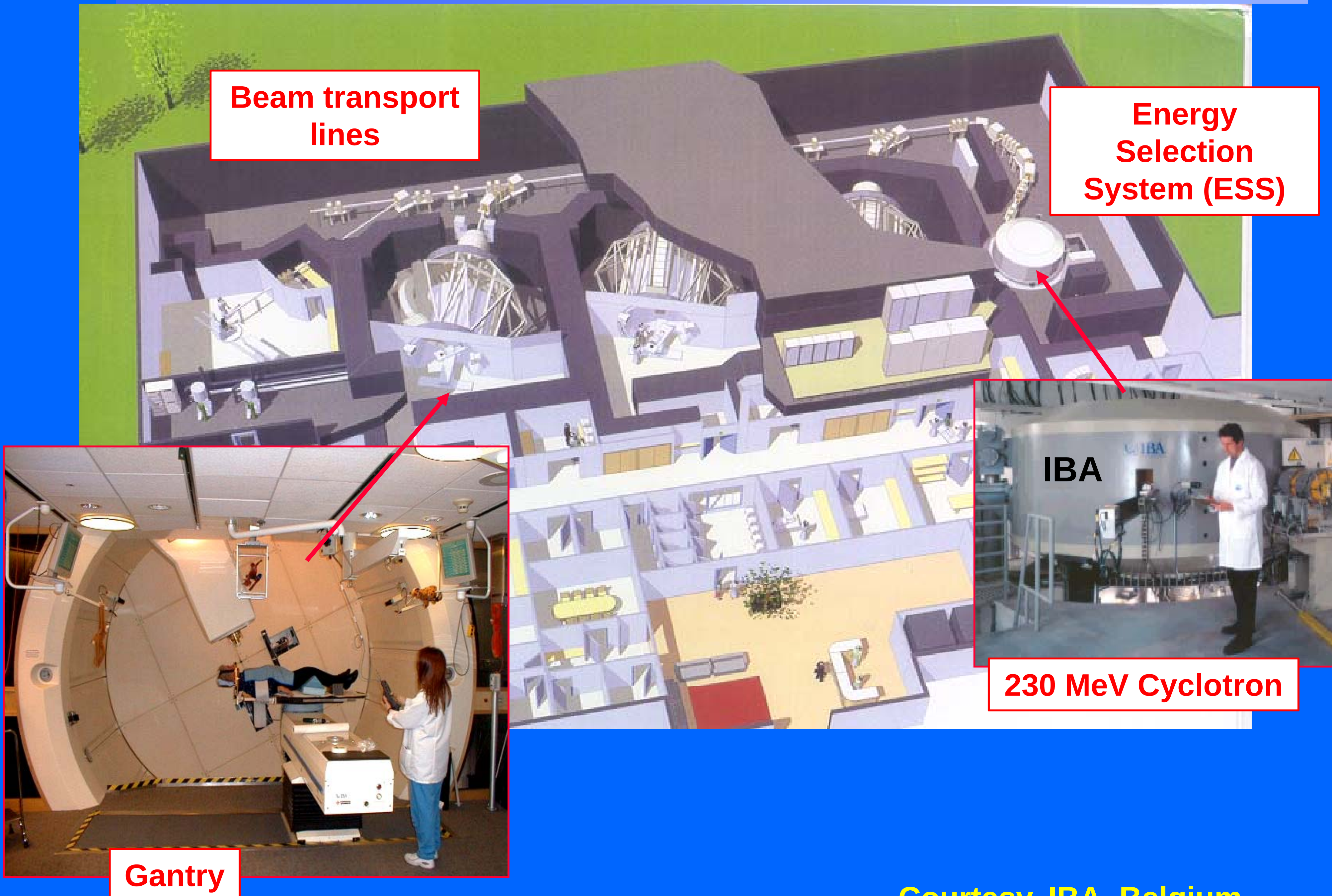




A cycling beam of variable energy has ~1 second gaps

(*) A synchrocyclotrons cycles at hundreds Hertz

Cyclotron solution for protons by IBA - Belgium

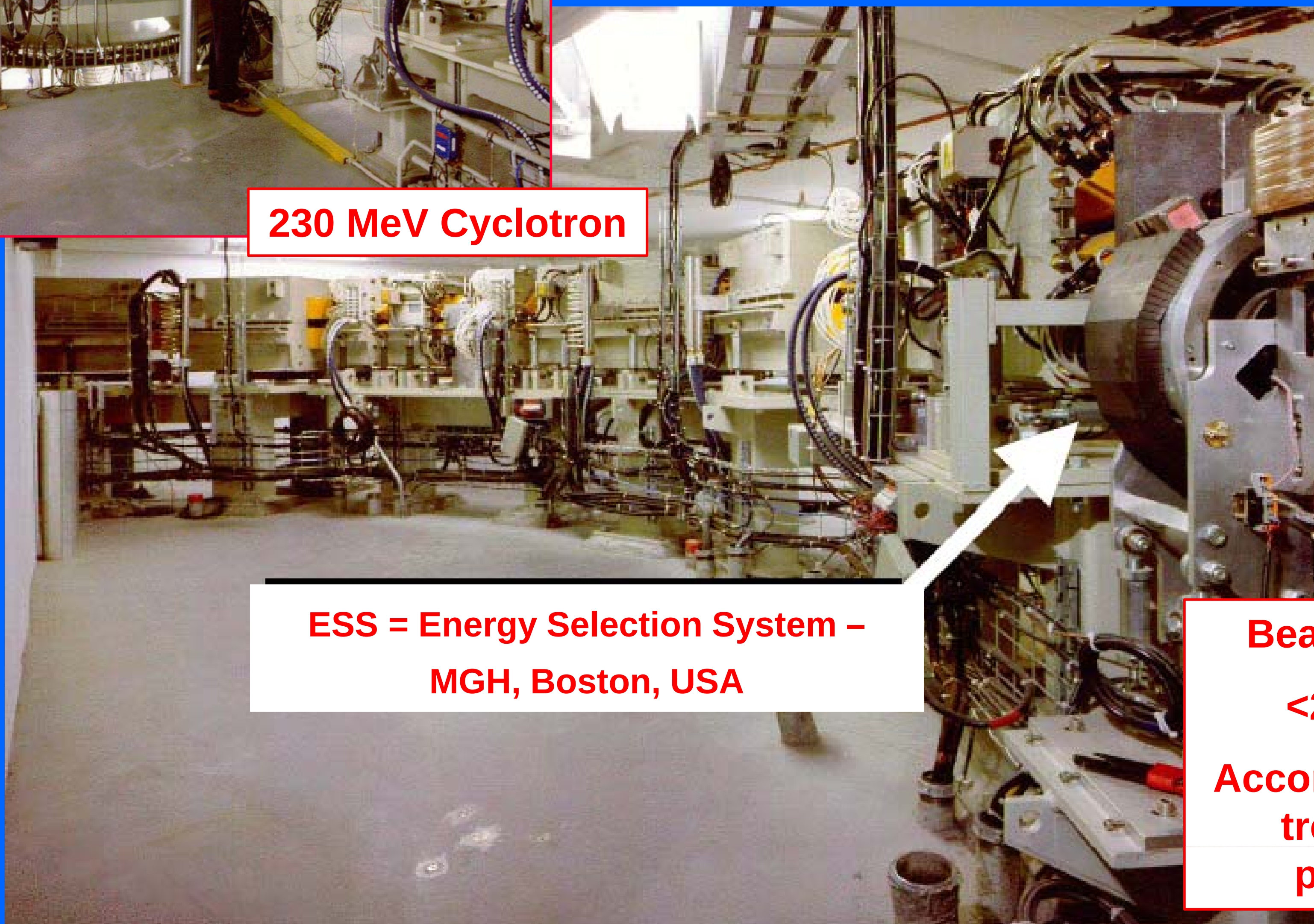


Courtesy, IBA, Belgium

A cyclotron needs a long ESS

Courtesy, IBA, Belgium

230 MeV Cyclotron



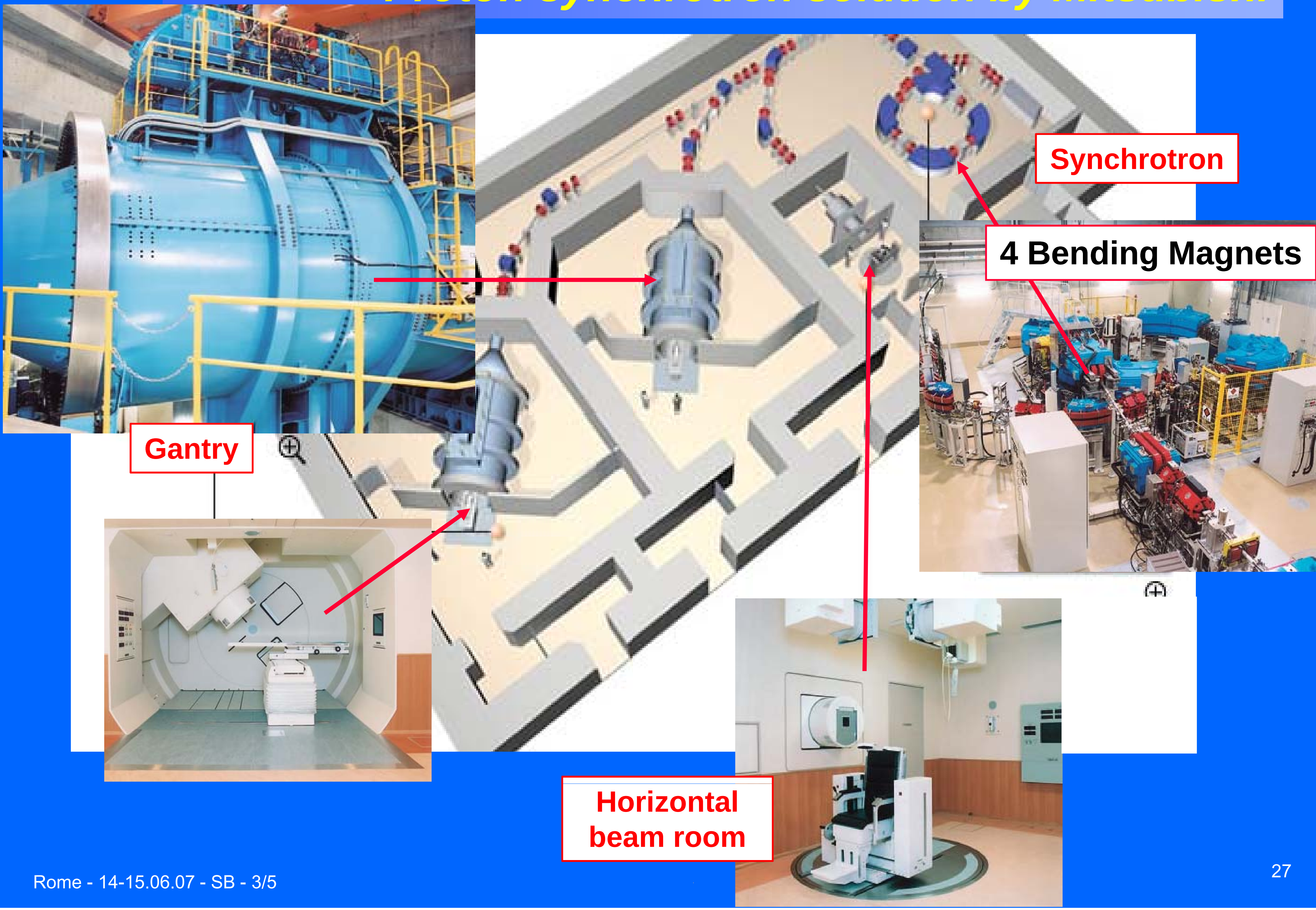
ESS = Energy Selection System – MGH, Boston, USA

Beam energy

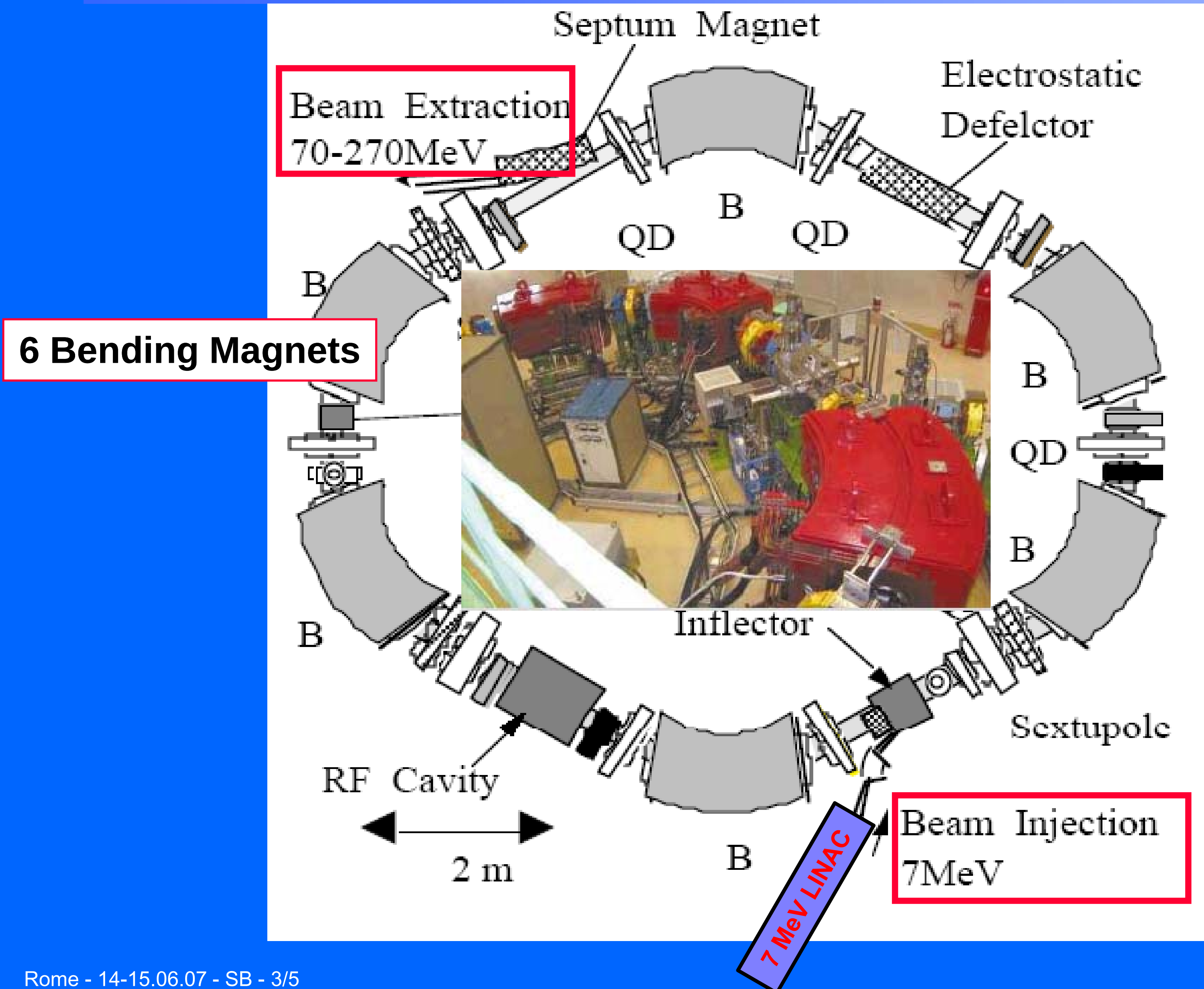
<230 MeV

According to the treatment panning

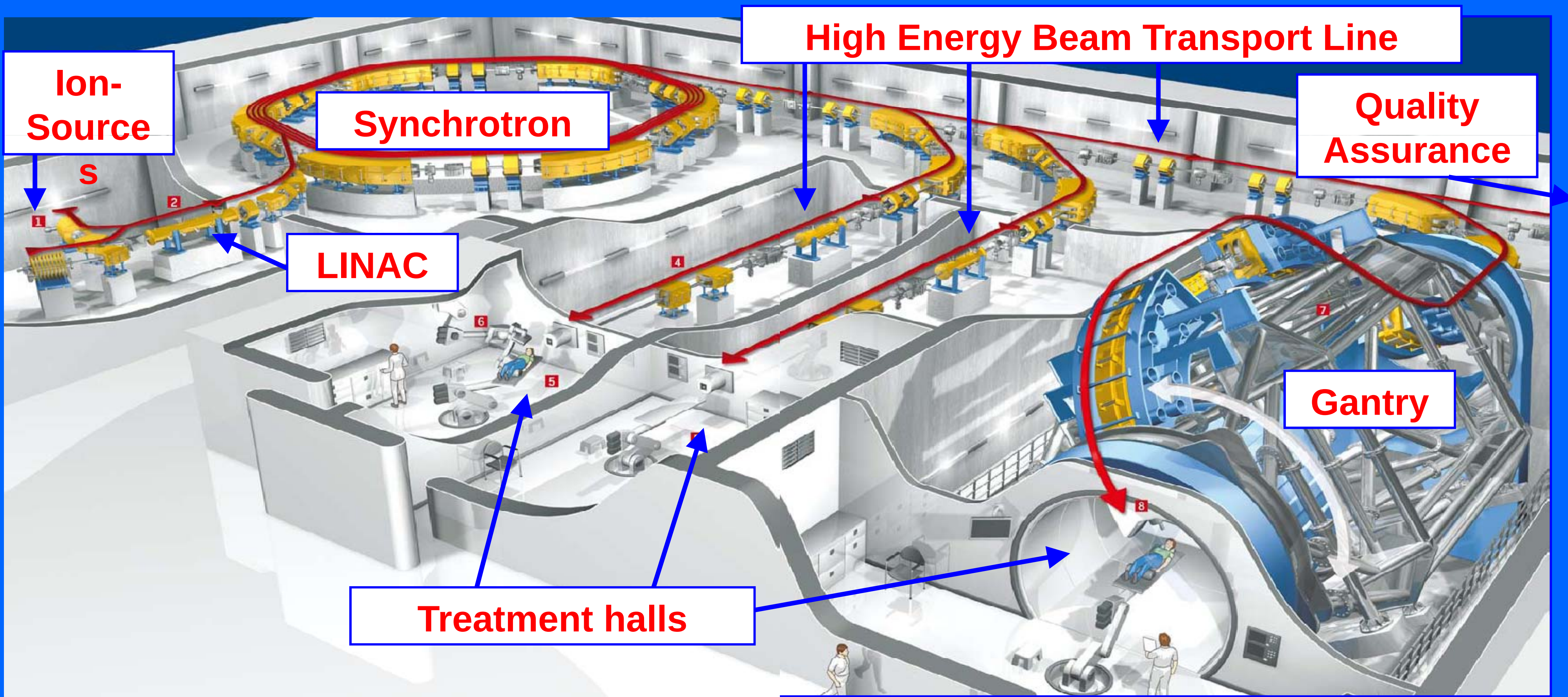
Proton synchrotron solution by Mitsubishi



Hitachi synchrotron: M.D. Anderson center in Houston

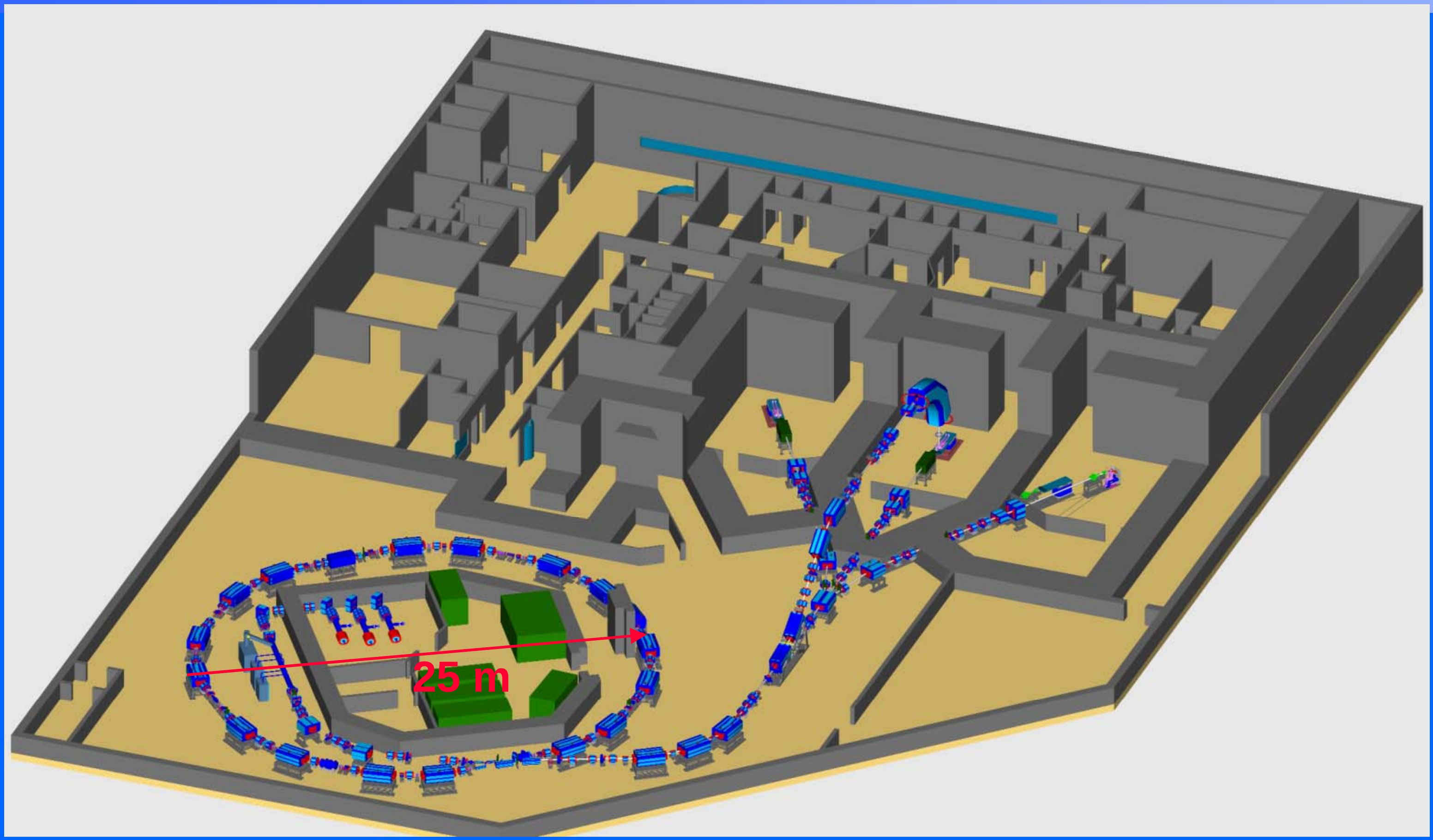


Synchrotron solution for protons and carbon ions



- **HIT project in Heidelberg (Germany)**
- **24 m diameter synchrotron**
- **Carbon ion gantry : 600 tons, 24 m diameter**

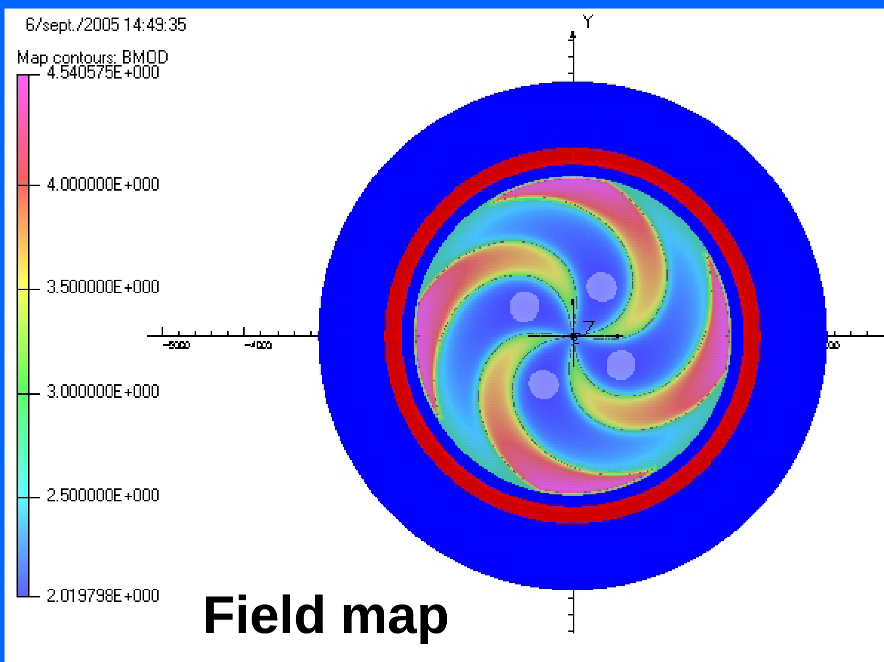
The synchrotron of the CNAO under construction in Pavia, Italy

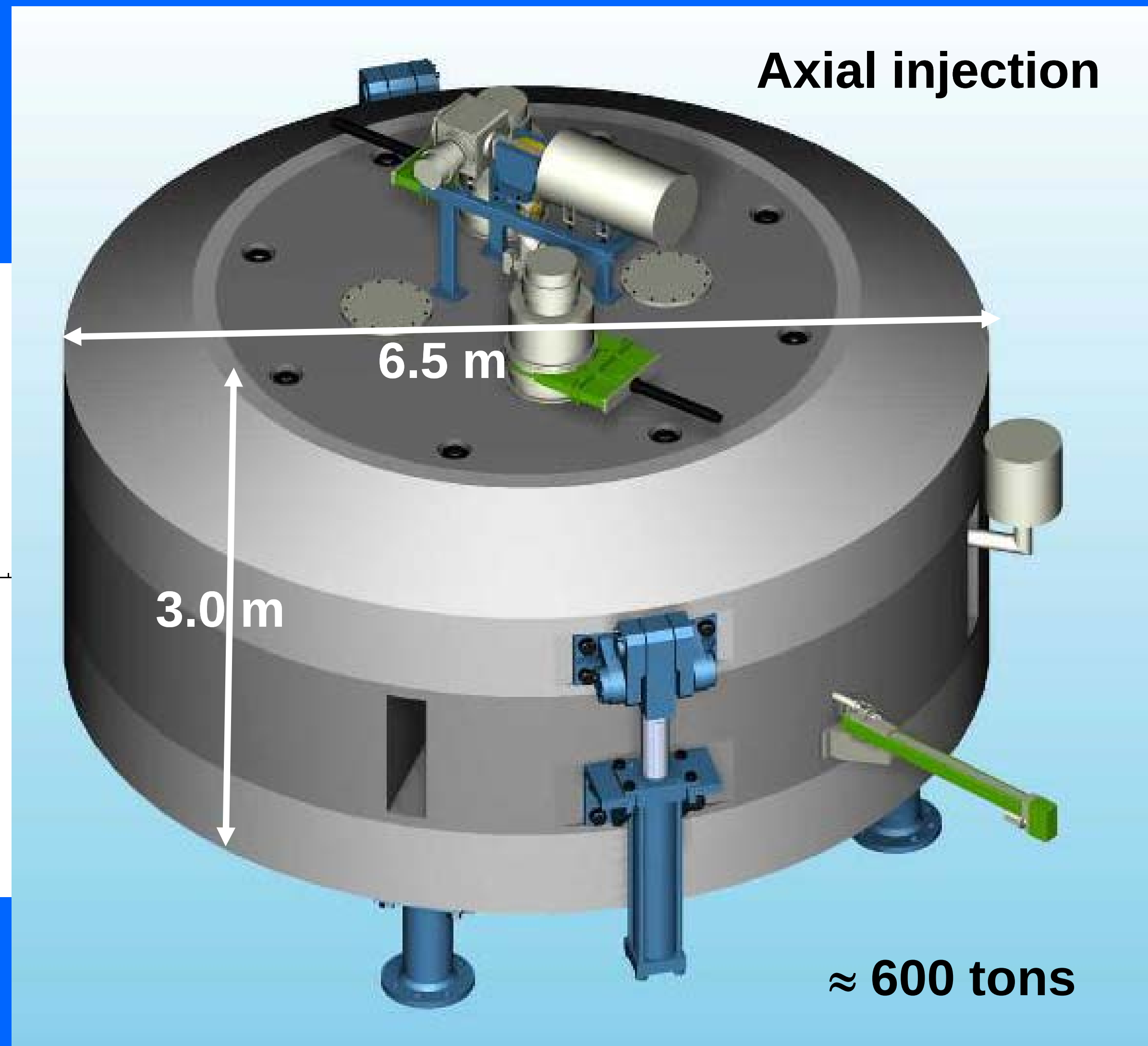


- **Centro Nazionale di Adroterapia Oncologica**
- **25 m diameter synchrotron based on the PIMMS study (CERN, TERA, et al.)**
- **Protons and carbon ions**
- **4 fixed beams, 3 treatment rooms**

Two projects for the future of hadrontherapy

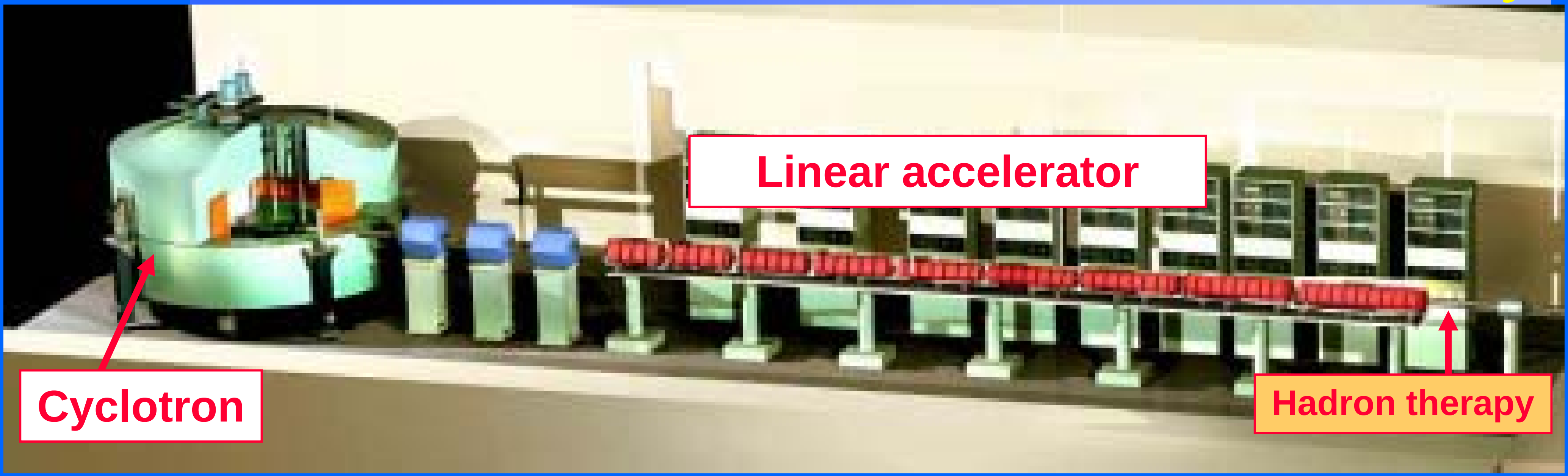
IBA: the new 400 MeV/u SC cyclotron





- **Still in a R&D phase**
- **Proton and carbon ion therapy**
- **Other ions can be accelerated (Li, Be)**

The CYCLINAC: a project of the TERA Foundation, Italy

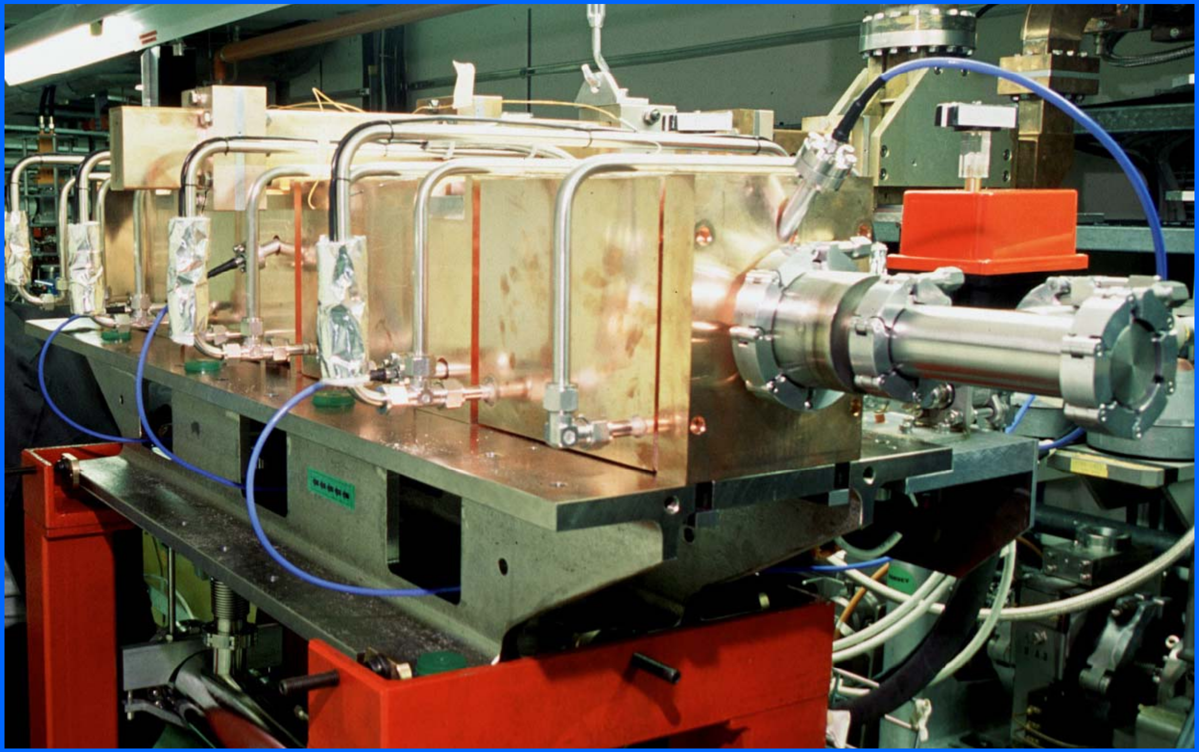


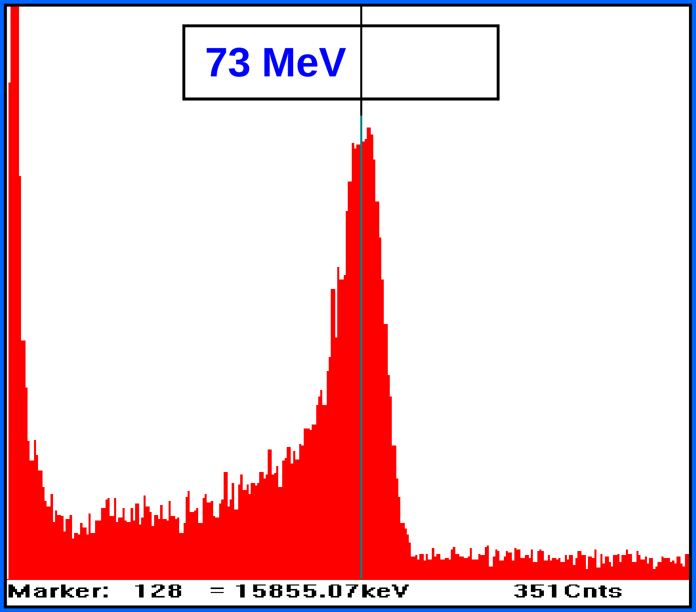
- **CYCLINAC = CYClotron + LINAC**
- **Commercial cyclotron for the production of radioisotopes**
- **Linac to boost the beam energy for hadron-therapy**

Two main functions

DIAGNOSTICS + THERAPY

Prototype of LIBO (3 GHz LInac BOoster)





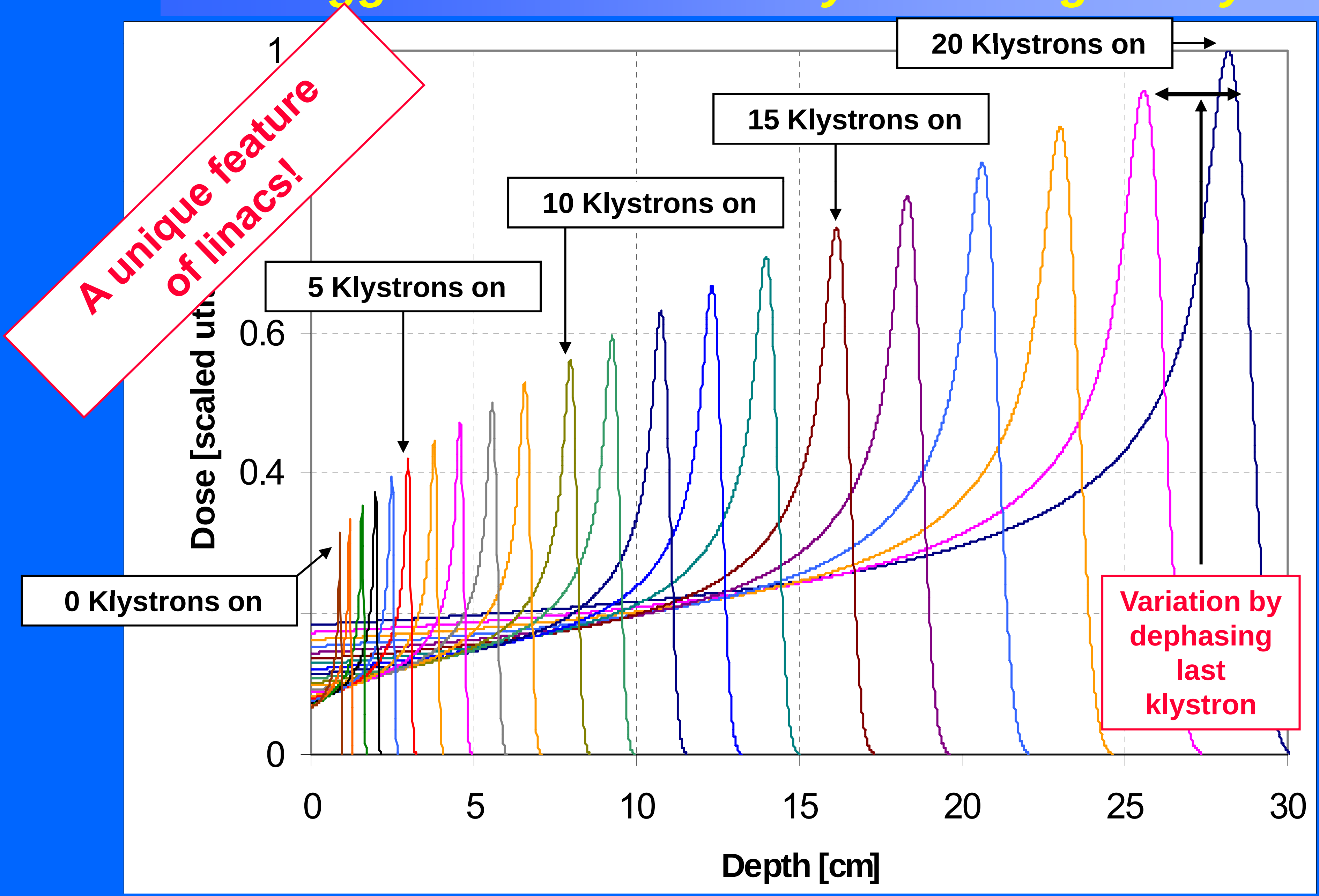
Collaboration INFN-CERN-TERA 1999-2002

Module tested at LNS of INFN, Catania

NIM A 521 (2004) 512

Accelerated beam from the 60 MeV cyclotron of LNS

Bragg curves obtained by switching off klystrons



End of part III