Outline

1. Introduction: a historical overview
2. Modern medical diagnostics
3. Particle accelerators for medicine
    - Electron linacs
    - RF generators
    - Beam transport
    - Ion accelerators for radioisotope production and hadrontherapy
4. Conventional radiation therapy
5. Basic principles of hadrontherpy
6. Present and future of hadrontherapy
7. A tour in a hadrontherapy centre
8. Specific topics in hadrontherapy

Accelerators are fundamental in modern medicine

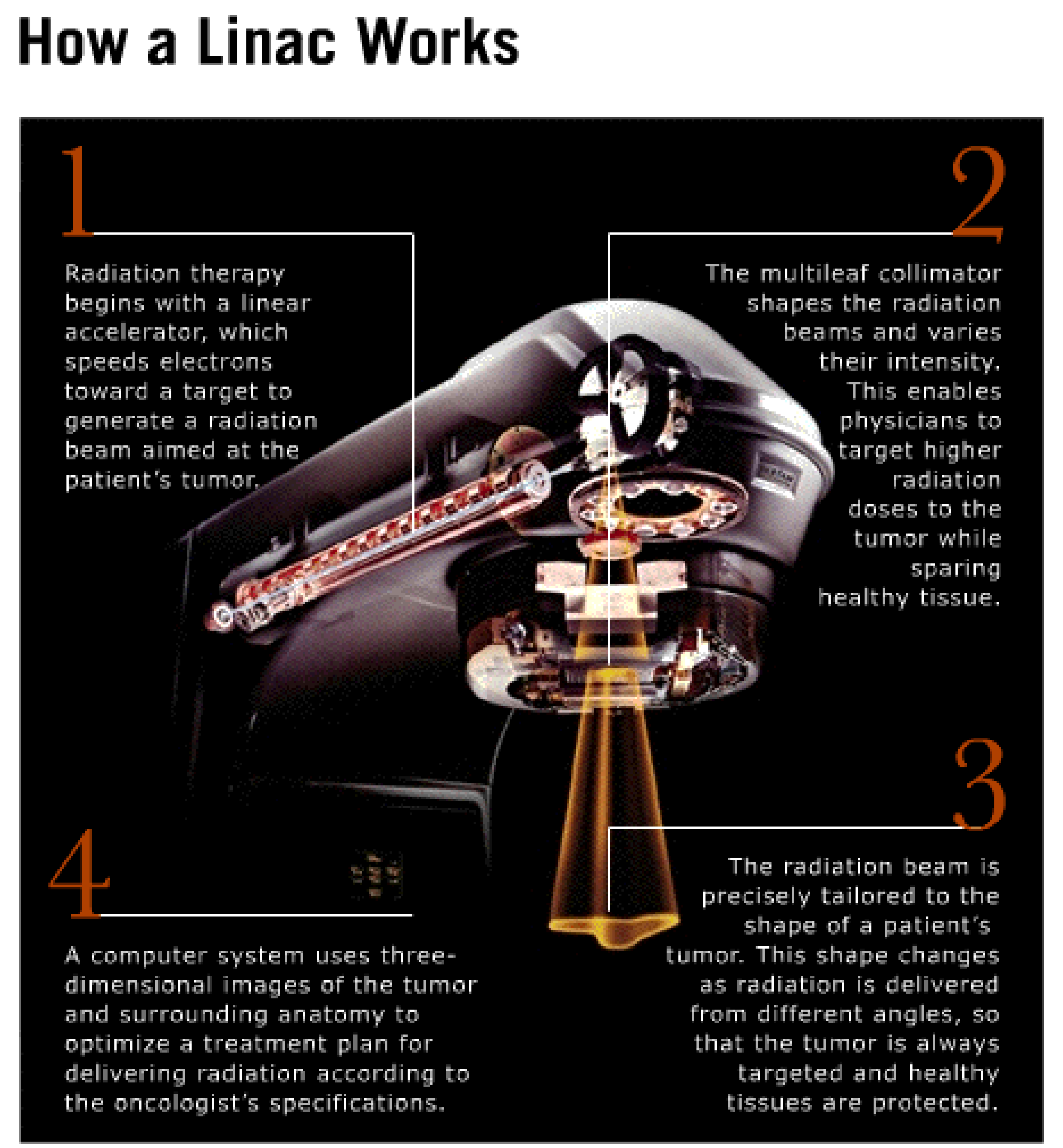
CATEGORY OF ACCELERATORS	NUMBER IN USE (*)	
High Energy acc. (E >1GeV)	~120	
Synchrotron radiation sources	>100	
Medical radioisotope production	~200	9000
Radiotherapy accelerators	> 7500	
Research acc. included biomedical research	~1000	
Acc. for industrial processing and research	~1500	
Ion implanters, surface modification	>7000	
TOTAL	> 17500	

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

- **About half are used for bio-medical applications**

Electron linacs for radiation therapy

An electron linac mounted on a rotating gantry



How a Linac Works

1

Radiation therapy begins with a linear accelerator, which speeds electrons toward a target to generate a radiation beam aimed at the patient's tumor.

2

The multileaf collimator shapes the radiation beams and varies their intensity. This enables physicians to target higher radiation doses to the tumor while sparing healthy tissue.

3

The radiation beam is precisely tailored to the shape of a patient's tumor. This shape changes as radiation is delivered from different angles, so that the tumor is always targeted and healthy tissues are protected.

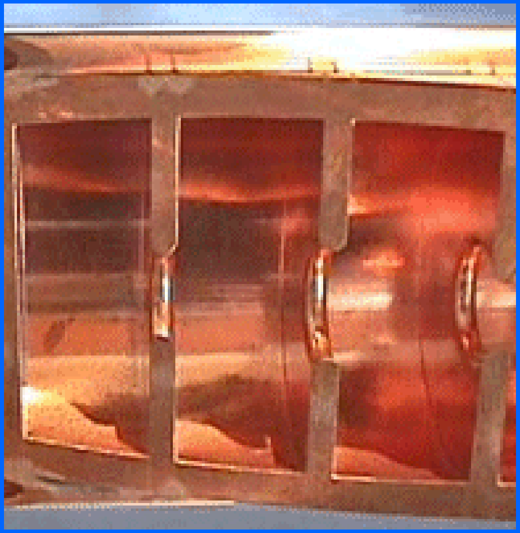
4

A computer system uses three-dimensional images of the tumor and surrounding anatomy to optimize a treatment plan for delivering radiation according to the oncologist's specifications.

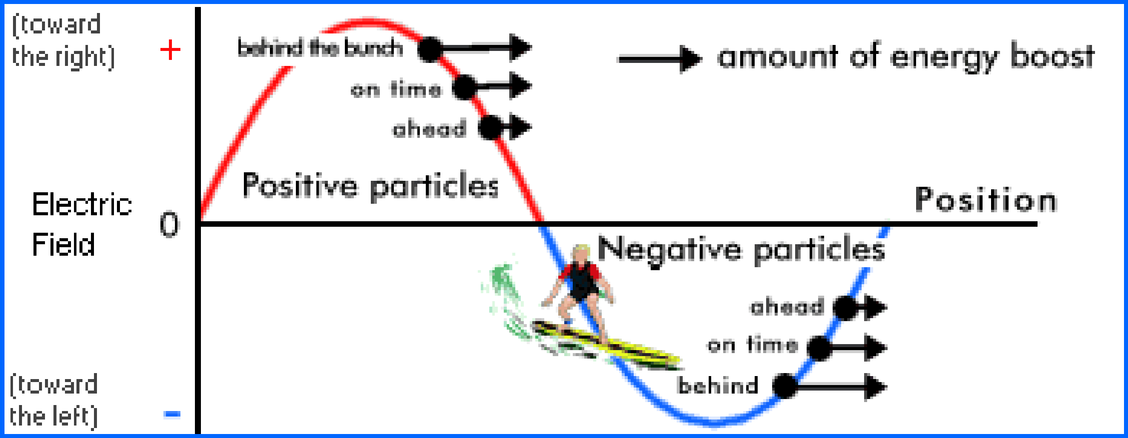
Characteristics

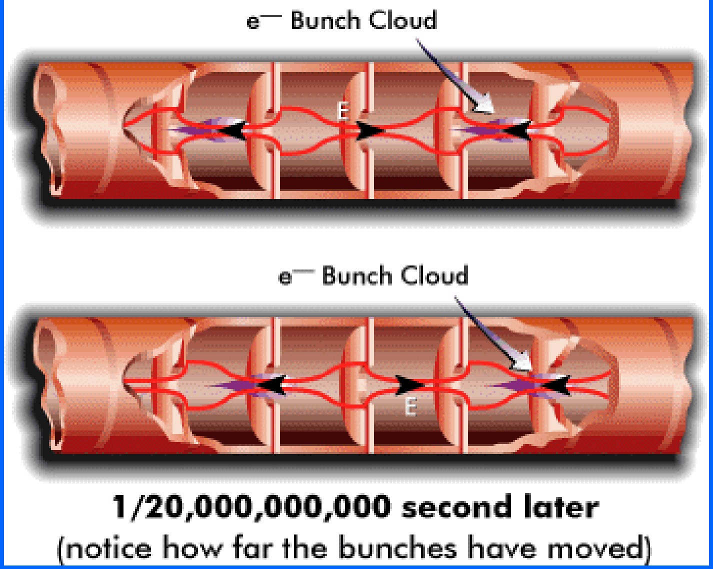
- 3 GHz cavities

1 inch = 2.54 cm



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





1/20,000,000,000 second later
(notice how far the bunches have moved)

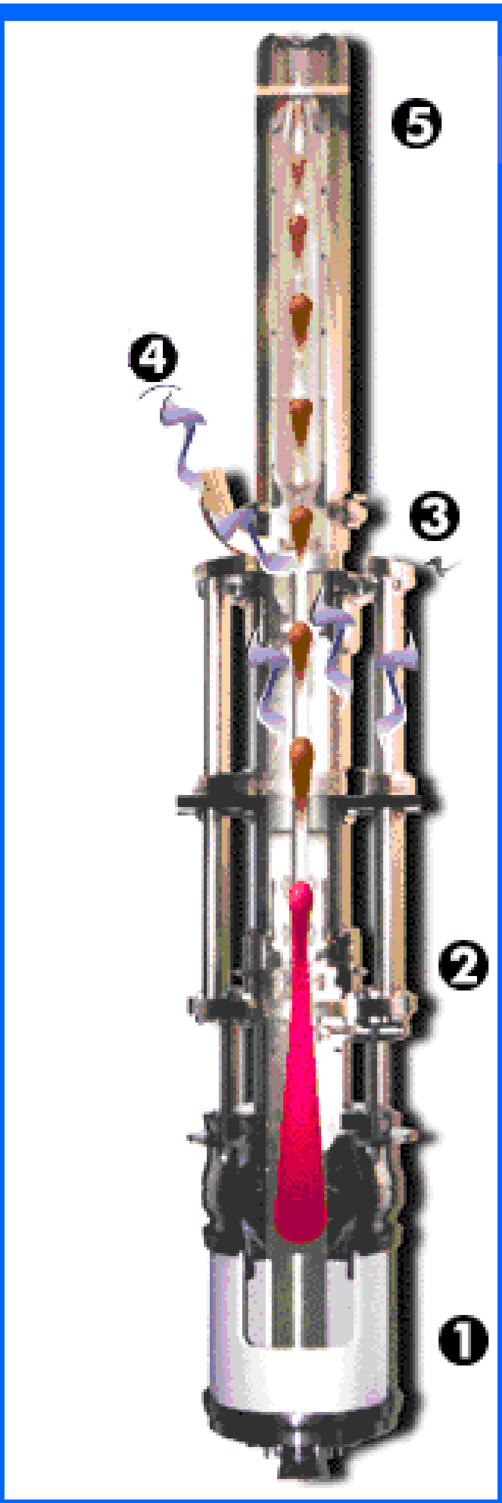
- Gradient about 10 MeV / m

Radio Frequency (RF) generators

Klystrons

- Invented in 1939 by Russel “the inventor” and Sigurd “the pilot” Varian (interesting book: “The inventor and the pilot”)
- It is fundamental for radar applications
- It is a sort of “inverted accelerator”

Klystrons



- Klystrons are used to produce the 3 GHz radiofrequency power that is brought to the cavities by a wave guide.
- Very high voltage: 100-200 kV (X-ray hazard!)
- “High Q” cavities
- Transverse focusing with a solenoid
- Peak power of the order of 1- 5 MW or more

In a klystron:

•The electron gun ❶ produces a flow of electrons.

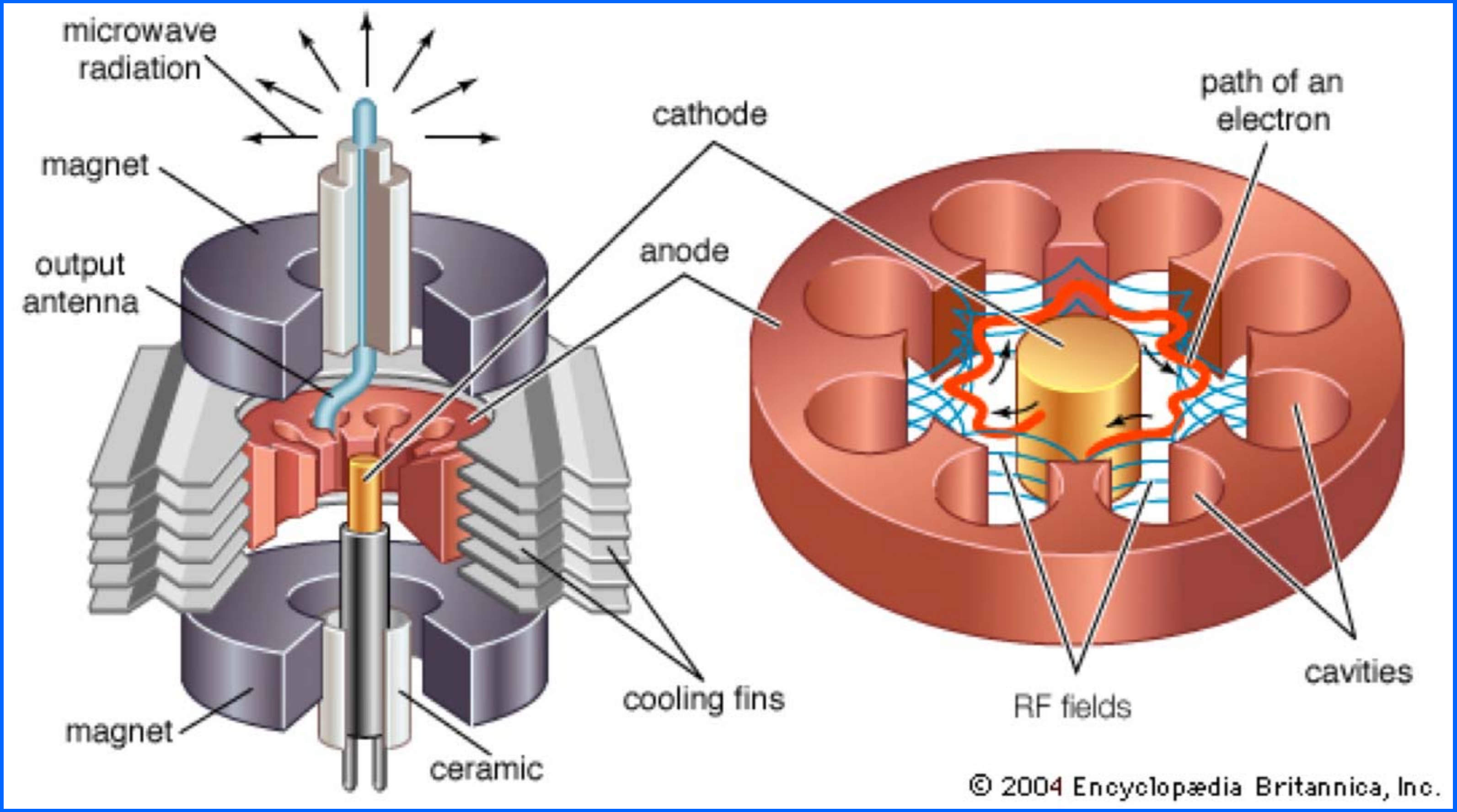
•The bunching cavities ❷ regulate the speed of the electrons so that they arrive in bunches at the output cavity.

•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.

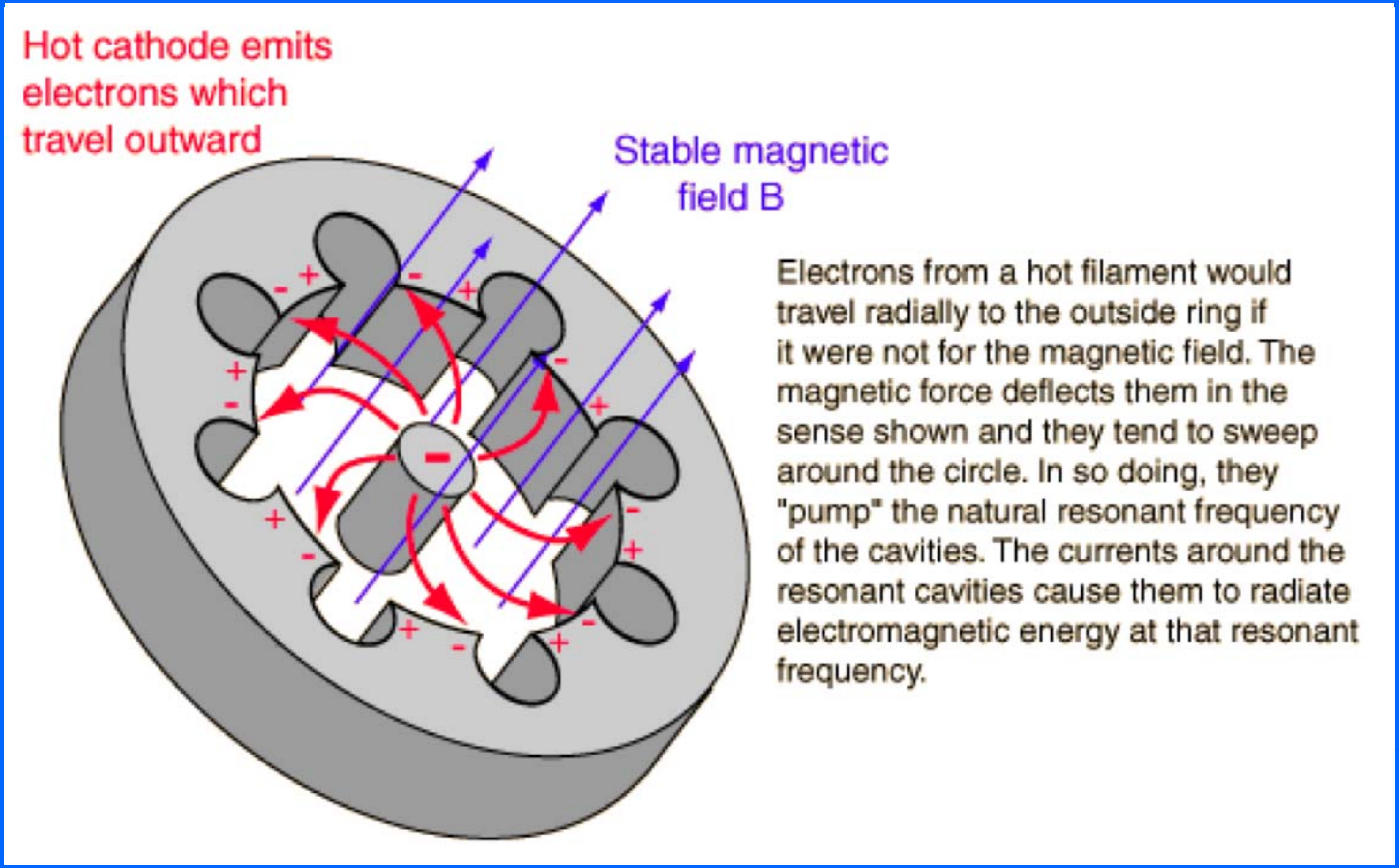
•The electrons are absorbed in the beam stop. ❺

Magnetrons



- Every microwave oven is equipped with a magnetron!
- Operating frequency : 2450 MHz

Magnetrons



Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.

- A. W. Hull first investigated the behavior of magnetrons in 1921

Klystrons and magnetrons for accelerators

	Klystrons	**Magnetrons**
Cost	Higher	Lower
Complexity	Higher	Lower
Phase drive	Yes	No (auto oscillating)
Control of the phase with many units	Yes	No (studies underway)

Modulators

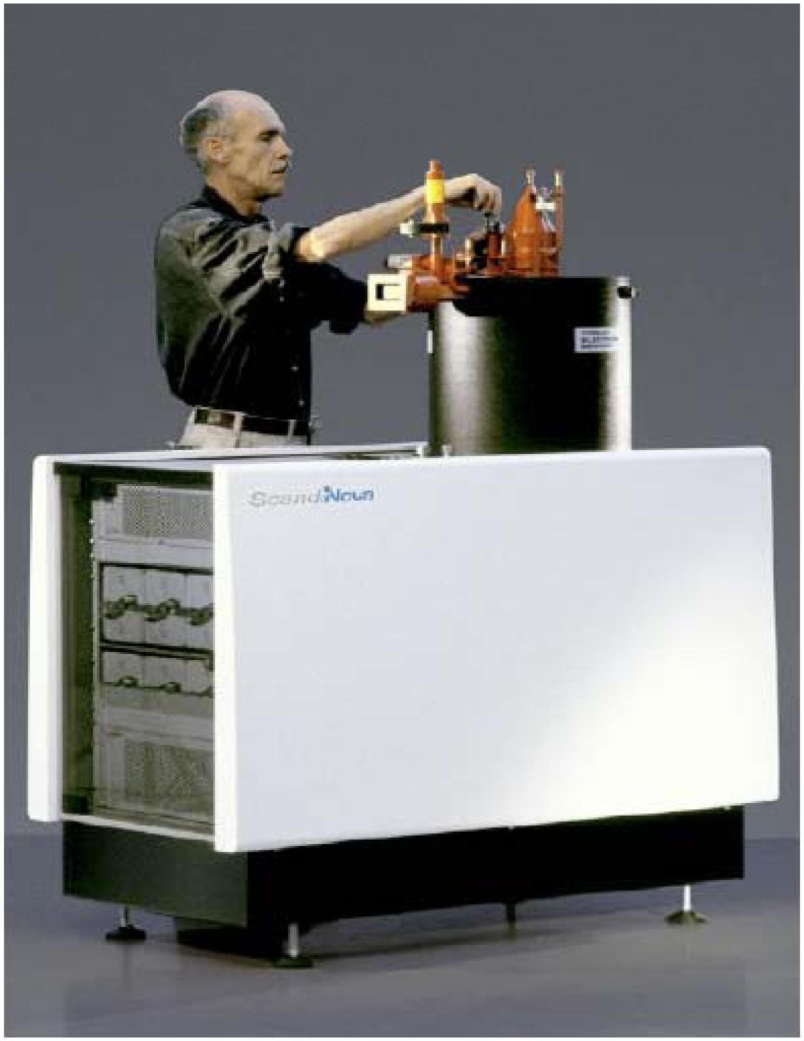
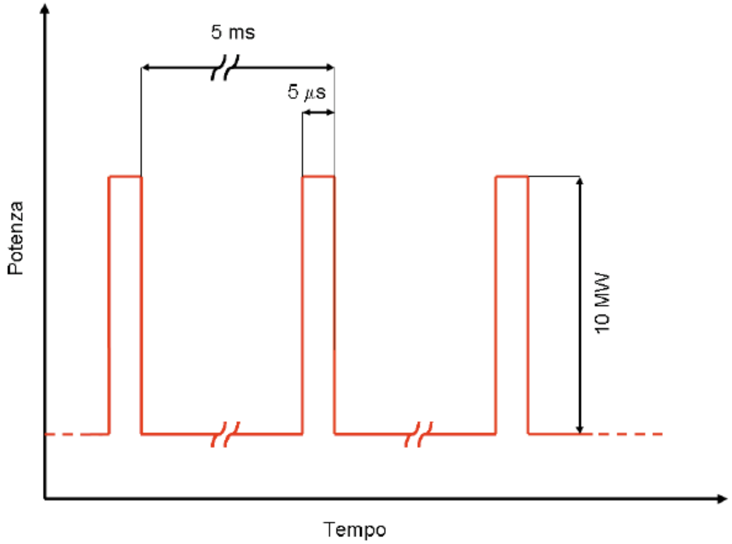


Fig. 10. The 7.5 MW klystron is powered by a solid state modulator commercialized by Scandinova Systems AB (Uppsala). LIBO employs 10 modulator/klystron sytems.

- Modulators are used to provide the pulsed power to klystrons
- Basic principle: energy is stored on a set of capacitors which are discharged using a “thyratron” (gas) or a solid state switch.



Proton and ion accelerators

Main uses and types

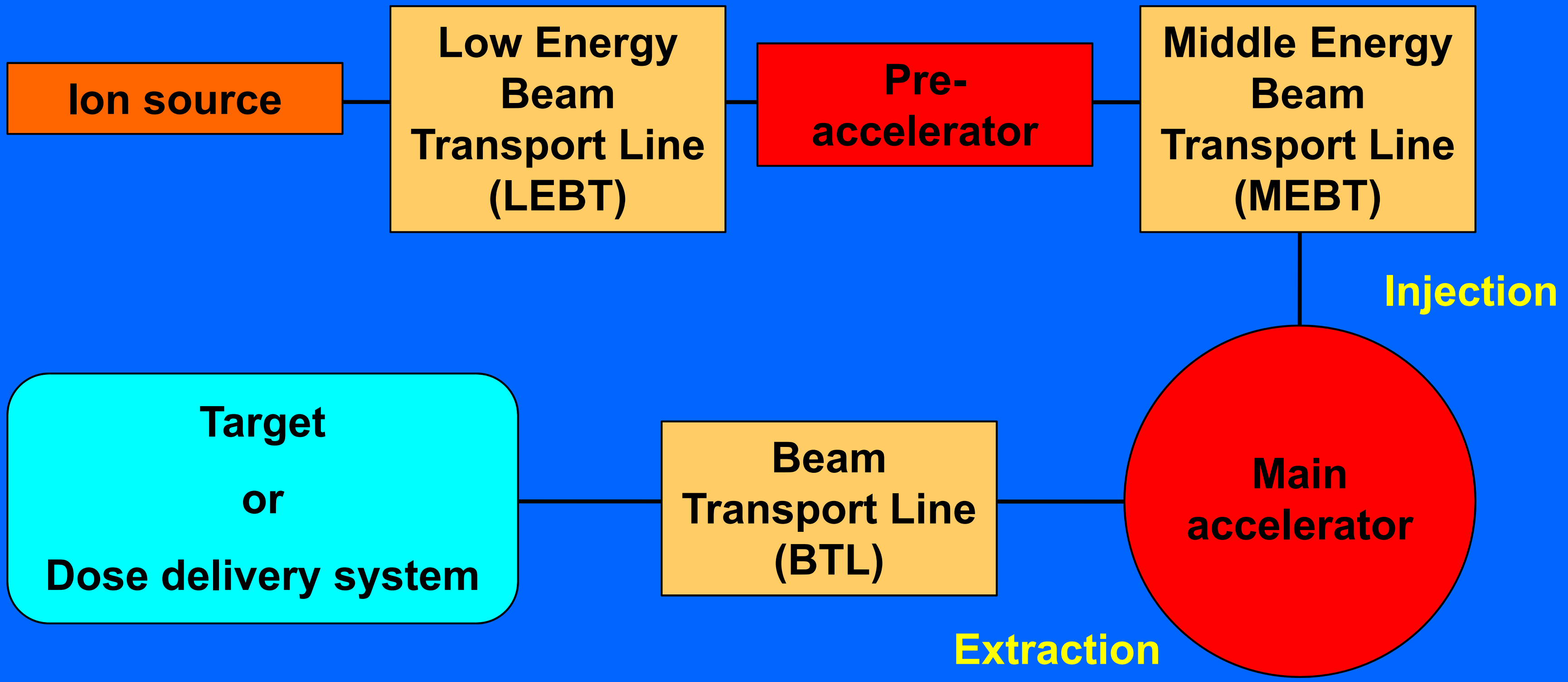
Production of isotopes	**Hadrontherapy**
Cyclotrons	Cyclotrons
(linacs)	Synchrocyclotrons
	Synchrotrons
	(linacs?)
	(FFAGs?)

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
- Targets or dose delivery systems

General scheme



Ion source

Low Energy Beam Transport Line (LEBT)

Pre-accelerator

Middle Energy Beam Transport Line (MEBT)

Injection

Main accelerator

Extraction

Beam Transport Line (BTL)

Target

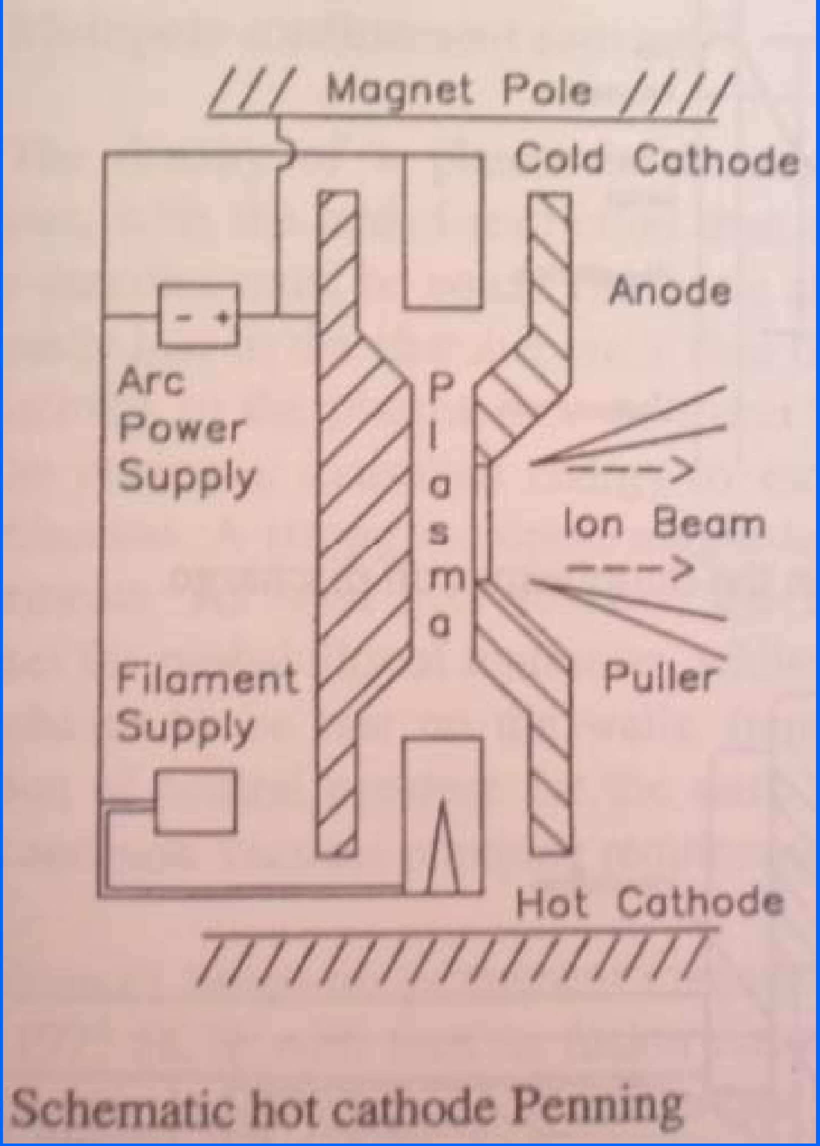
or

Dose delivery system

- This scheme applies to accelerator complexes (ex. synchrotrons)
- For simpler machines some of these components are not present

Ion sources

A typical Penning source

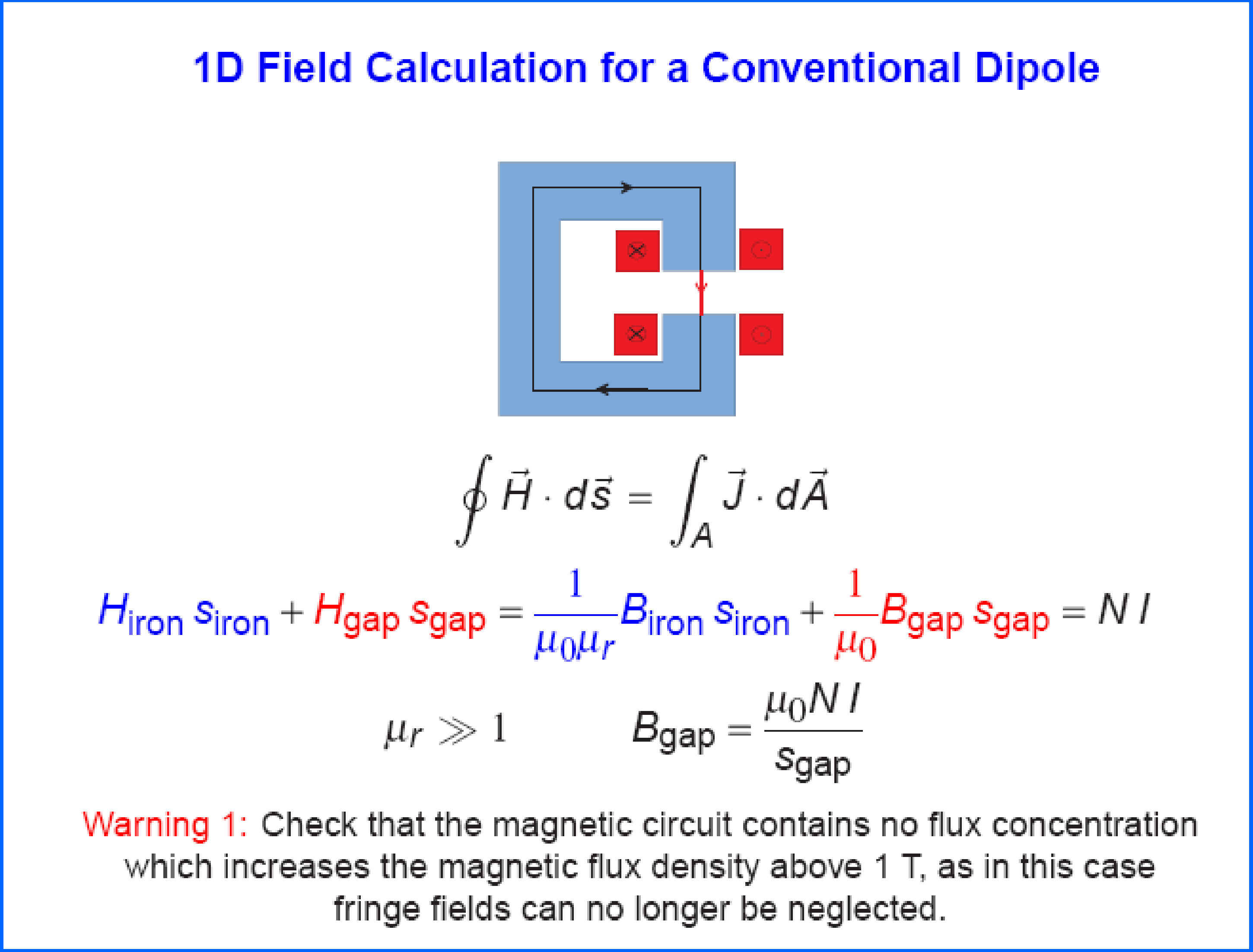


Schematic hot cathode Penning

- Cylindrical anode immersed in an axial magnetic field
- Electron emitter (cathode)
- Ignition of gas (ex. Hydrogen)
- A discharge (Penning discharge) is created
- The electron travel in cycloidal paths, thus increasing the probability to ionize the gas by collision
- A plasma is formed
- Ions (ex. Protons or H-) are extracted with an electric field
- In cyclotrons the source can be internal and the magnetic field of the cyclotron is used
- The cathodes and the chimney need regular maintenance (ex. every 500 h of functioning)

Magnets and beam transport lines

Bending dipoles



1D Field Calculation for a Conventional Dipole

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

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

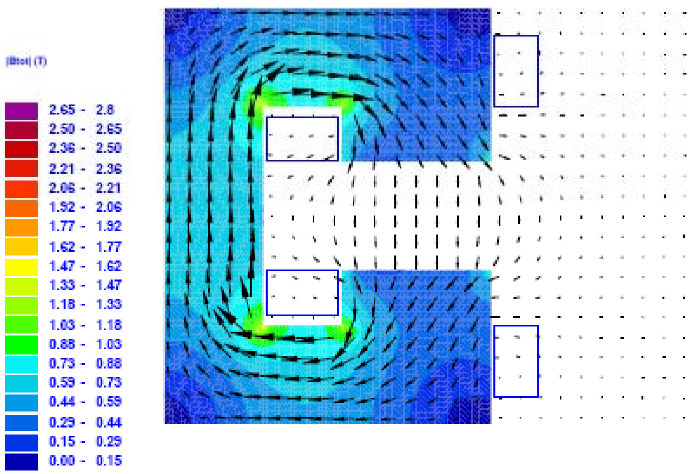
$$\mu_r \gg 1 \qquad B_{\text{gap}} = \frac{\mu_0 N\, I}{s_{\text{gap}}}$$

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

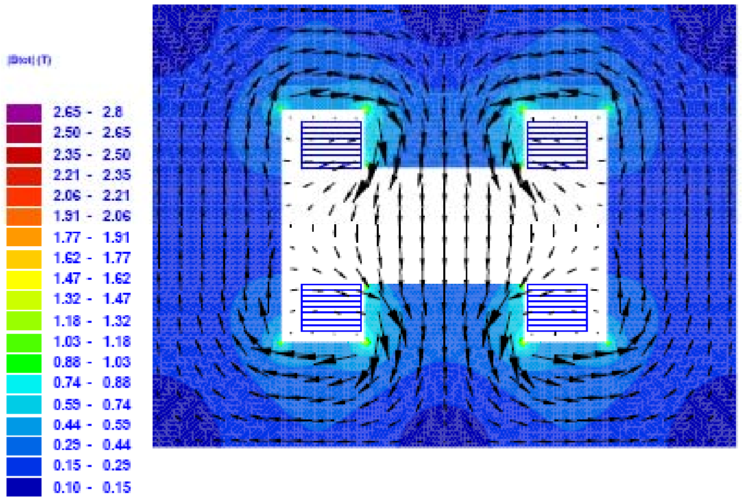
(C- Core, LEP Dipole)



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

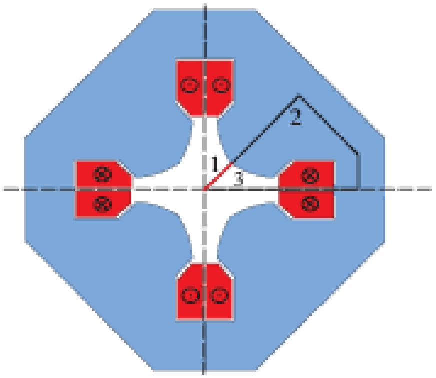
Magnet Metamorphosis

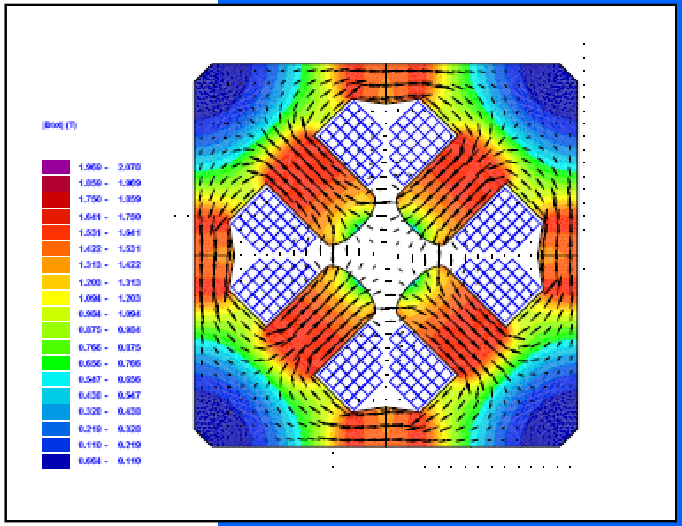
(H-Magnet)



$N \cdot I = 24000$ A $B_1 = 0.3$ T $B_S = 0.065$ T 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.

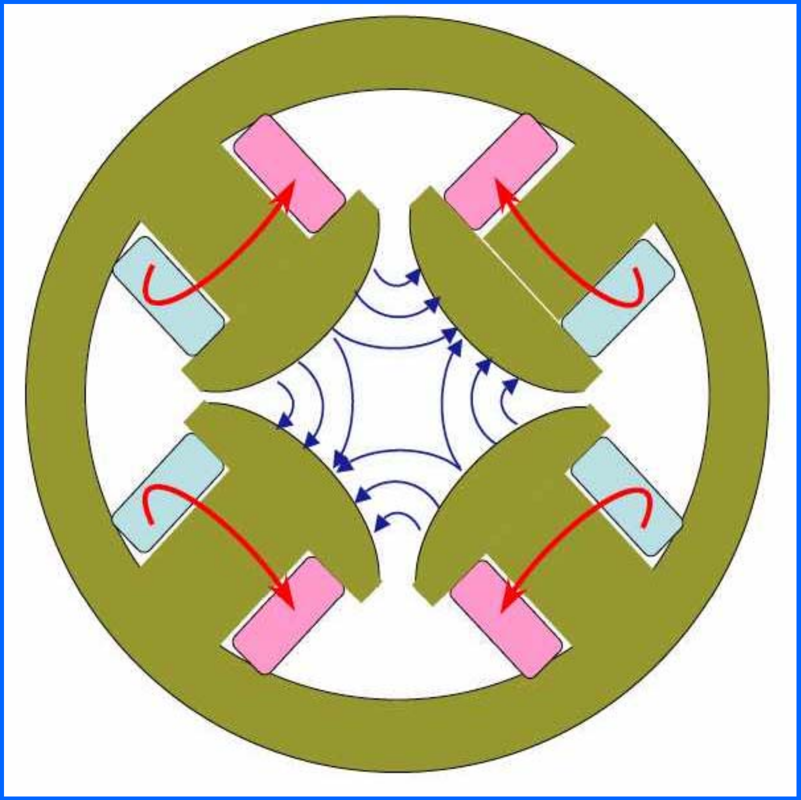
$$B_y = B_0\frac{x}{a}, \quad B_x = B_0\frac{y}{a}$$

$$\ddot{x} + \frac{qv_sB_0}{\gamma ma}x = 0$$

Focusing

$$\ddot{y} - \frac{qv_sB_0}{\gamma ma}y = 0$$

Defocusing

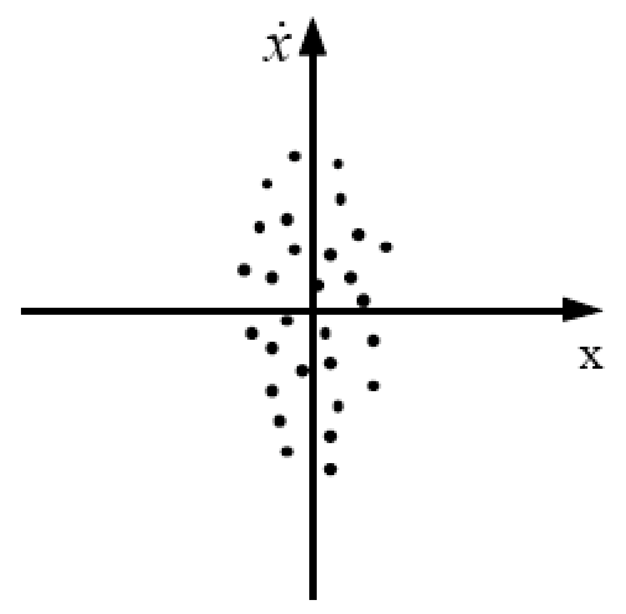


Important beam parameters

- The beam is usually represented in the phase space (x, x‘) (y, y‘) for the transverse coordinates (x’ and y’ are usually measured in mrad being v_x/v and v_y/v, respectively)

- Along the beam direction, z gives the position of the particles and β=v/c gives the velocity

- The beam is usually assumed to be gaussian

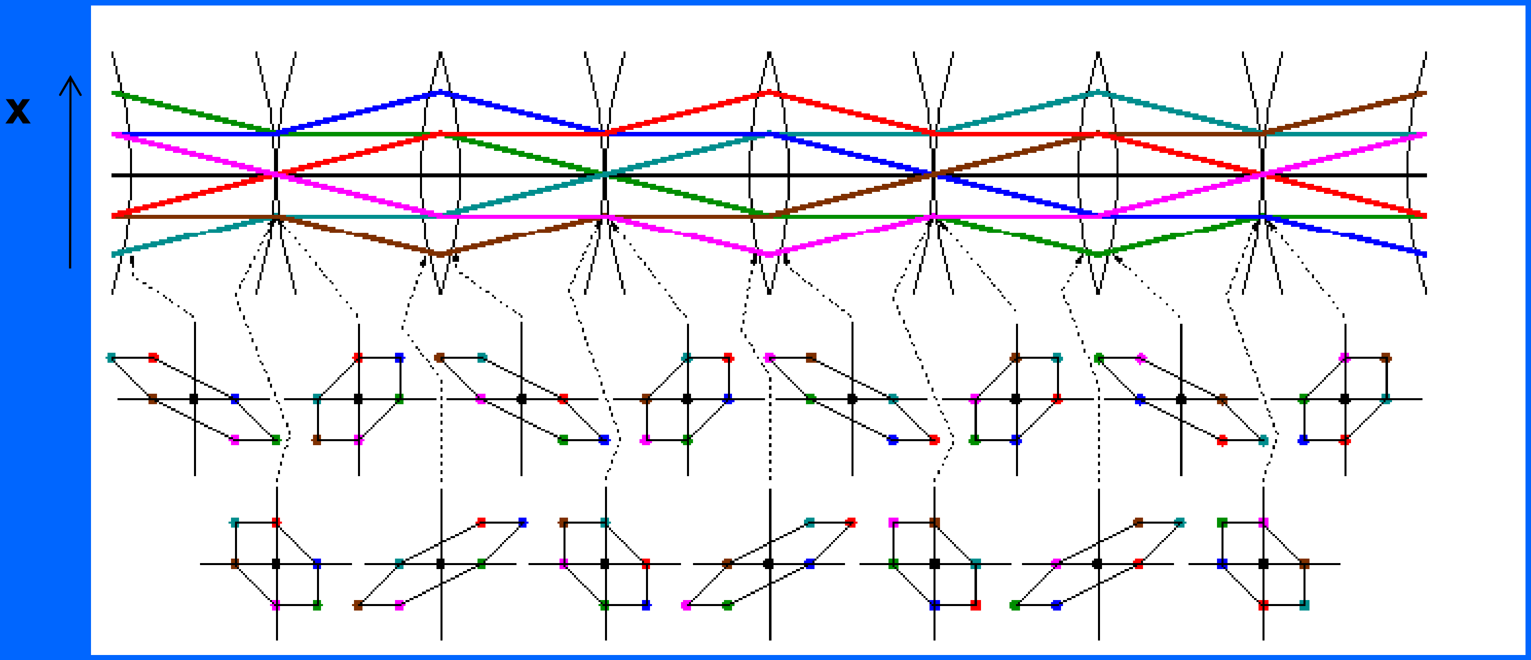


- The beam emittance is given by the 2 or 3 σ truncated area of the gaussian
- It is usually expressed in [mm mrad] or [π mm mrad]
- It is a good figure to evaluate the quality of a beam

Strong focusing

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

- Example : FODO (focusing & defocusing) lattice in one plane. The global effect on the emittance is focusing.



x, x’

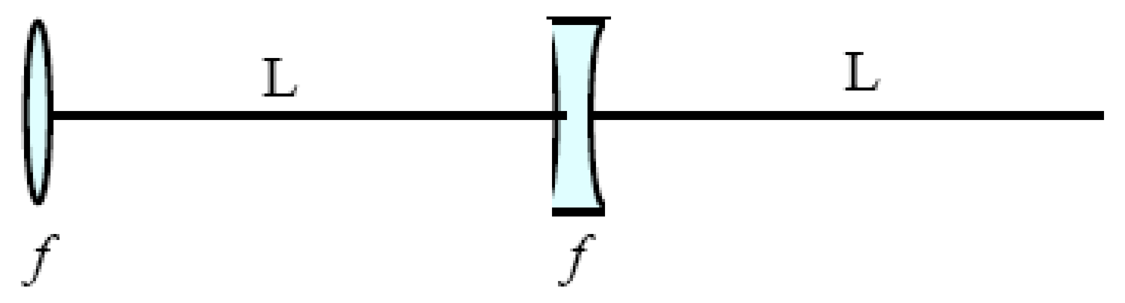
Emittance plane

(x plane only!)

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

Matrix formalism

- The effect of quadrupoles can be approximated as the effect of thin lenses in optics



- The matrix formalism (operators) can be used
- Example: Focusing, drift, defocusing, drift

$$M_H = M_O M_D M_O M_F = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ 1/f & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$$

Exercise: a Beam Transport Line (BTL)

A typical low β accelerator: the Radio Frequency Quadrupole (RFQ) accelerator

The RFQ

- Question: how can we accelerate 30 keV protons (β=0.03) from an ion source to a few MeV (ex. 2 MeV β=0.07) ?
- A very much used solution is the RFQ based on electric quadrupoles arranged in a special geometry

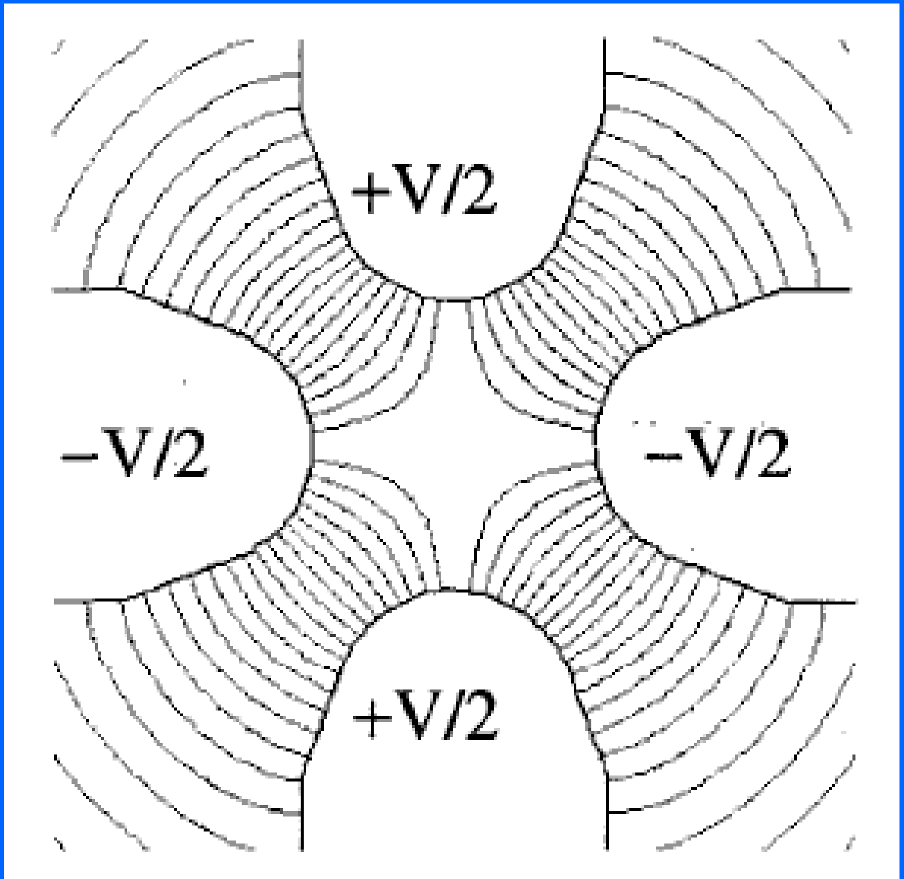
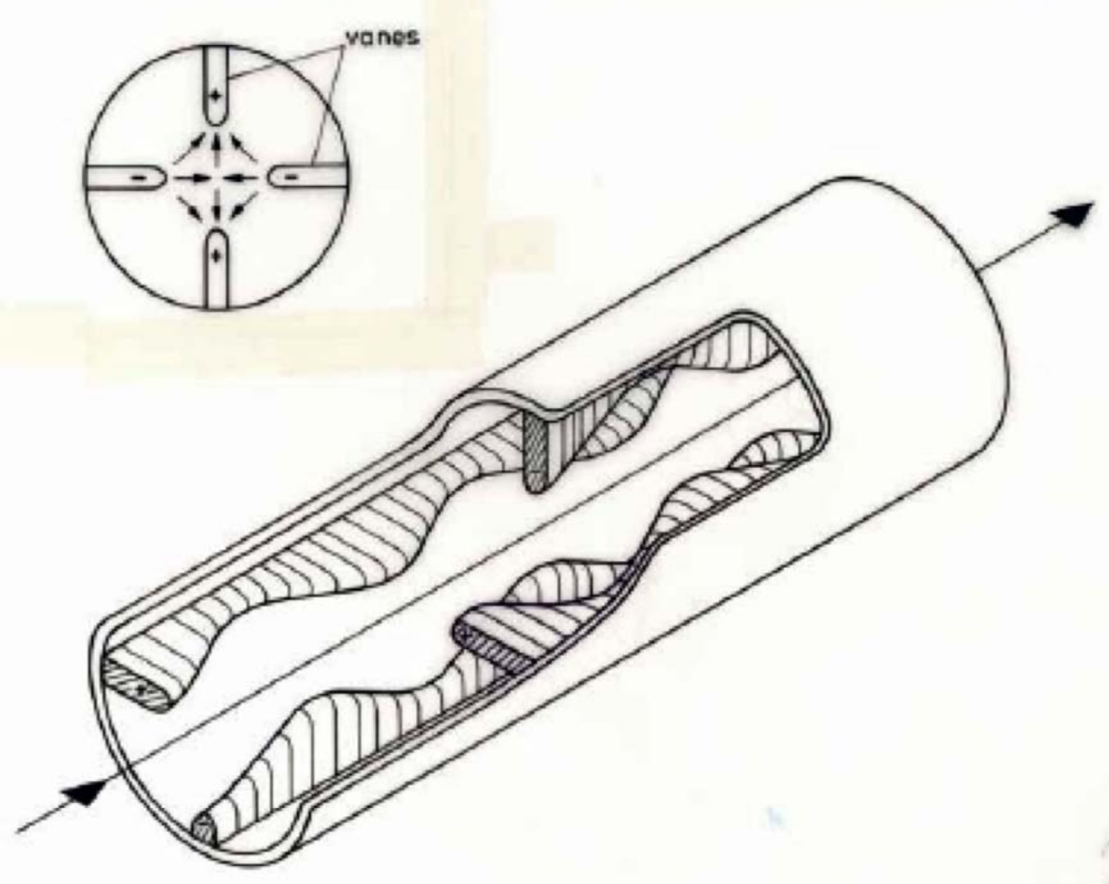
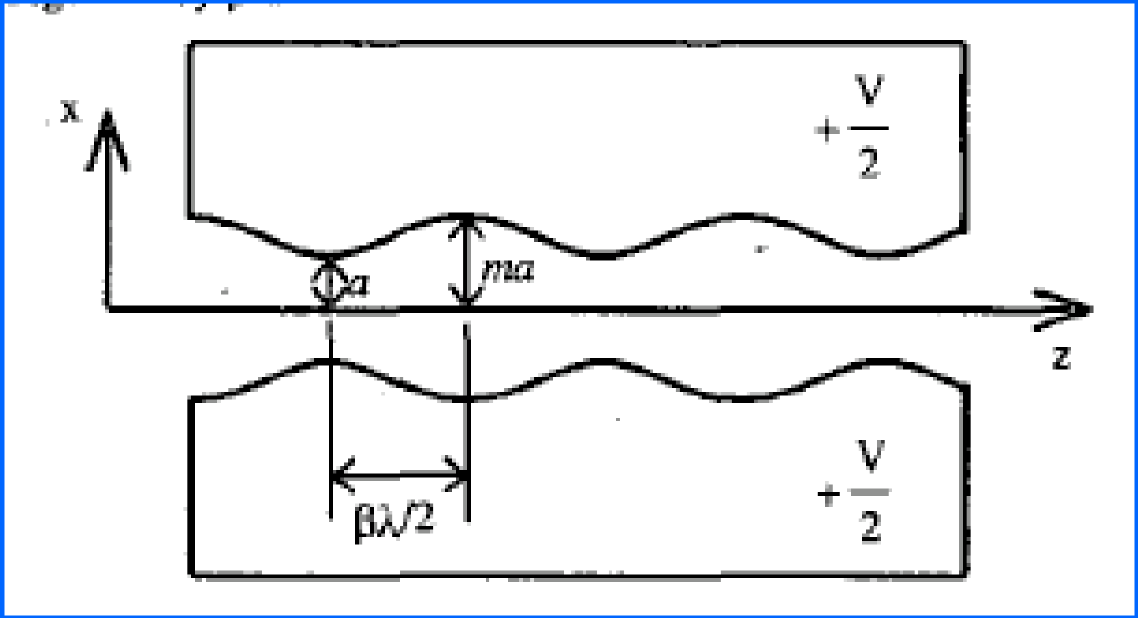


Figure 1: Electric field lines in a RFQ.



The RFQ



- Three functions:
    - Acceleration
    - Focusing
    - Bunching
- λ=cT is fixed and determined by the RF frequency (period T)
- βλ/2 determines the size of an half cell
- The mechanical structure is such to follow the evolution of β
- The cells increase in length
- Example: frequency 425 MHz
    - E= 30 keV -> βλ/2 = 1.05 cm
    - E= 2 MeV -> βλ/2 = 2.45 cm

One RFQ was used in L3 for BGO calibration

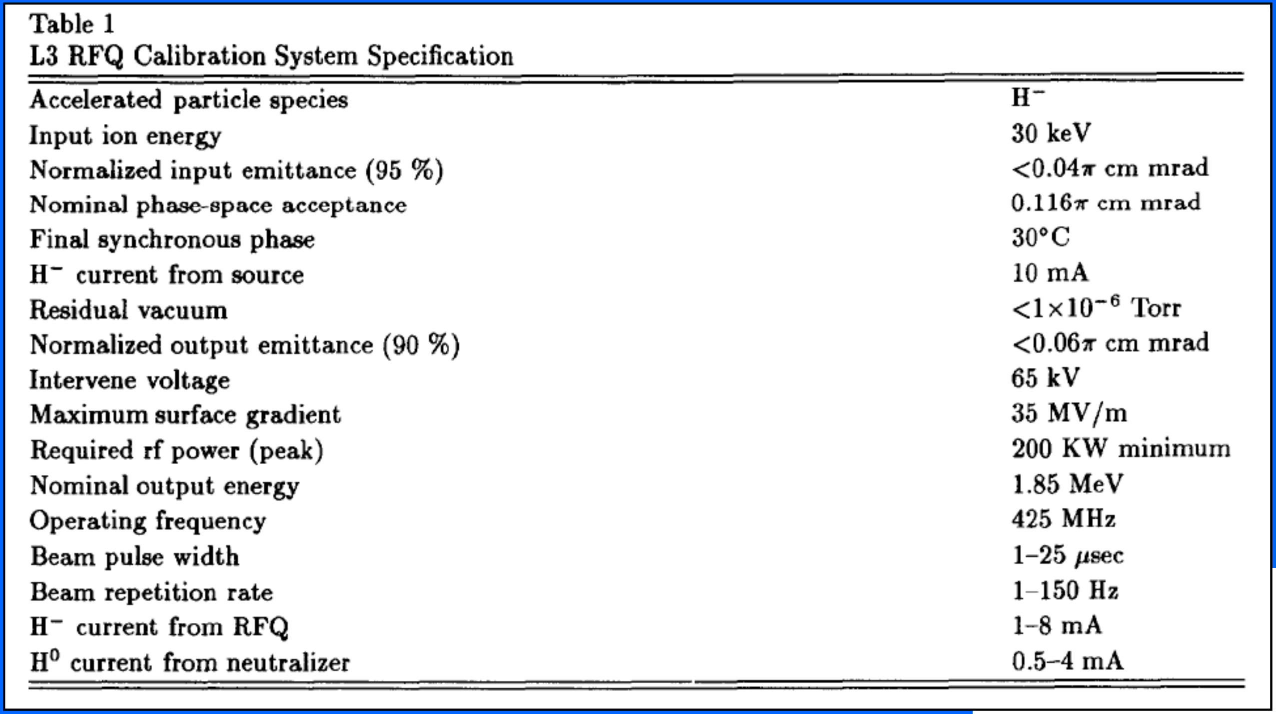
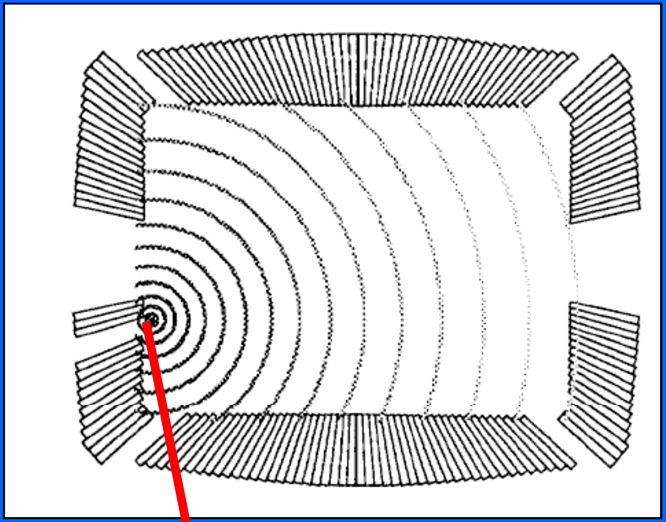
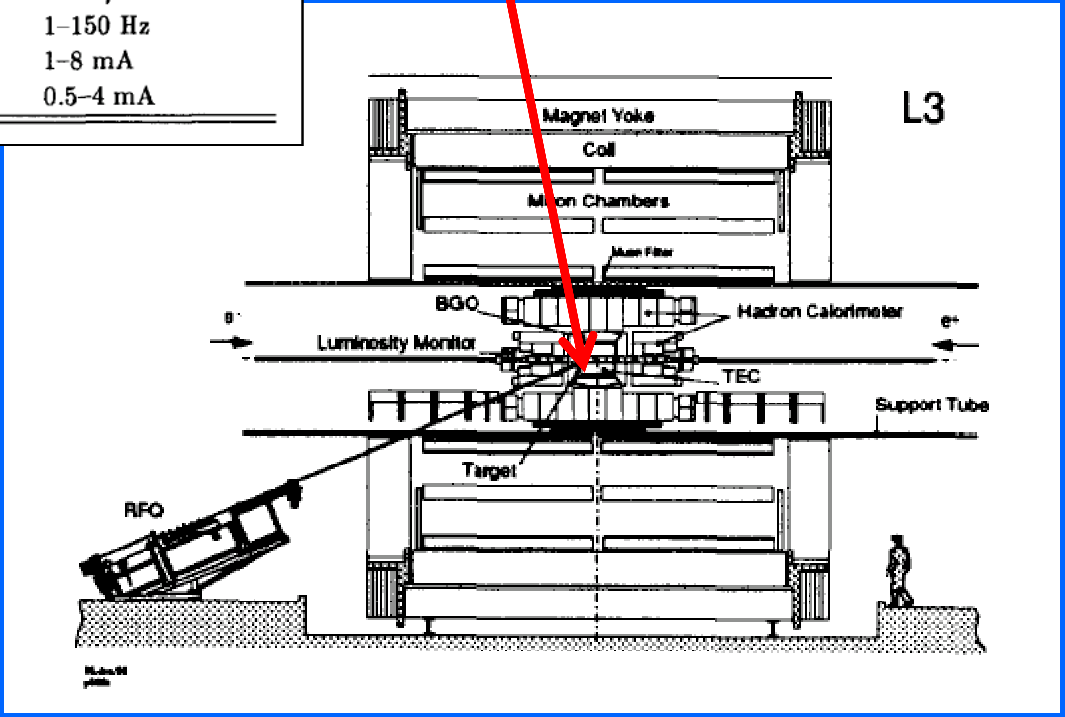


Table 1
L3 RFQ Calibration System Specification

Accelerated particle species	H^-
Input ion energy	30 keV
Normalized input emittance (95 %)	$<0.04\pi$ cm mrad
Nominal phase-space acceptance	0.116π cm mrad
Final synchronous phase	30°C
H^- current from source	10 mA
Residual vacuum	$<1\times10^{-6}$ Torr
Normalized output emittance (90 %)	$<0.06\pi$ cm mrad
Intervene voltage	65 kV
Maximum surface gradient	35 MV/m
Required rf power (peak)	200 KW minimum
Nominal output energy	1.85 MeV
Operating frequency	425 MHz
Beam pulse width	1–25 μsec
Beam repetition rate	1–150 Hz
H^- current from RFQ	1–8 mA
H^0 current from neutralizer	0.5–4 mA



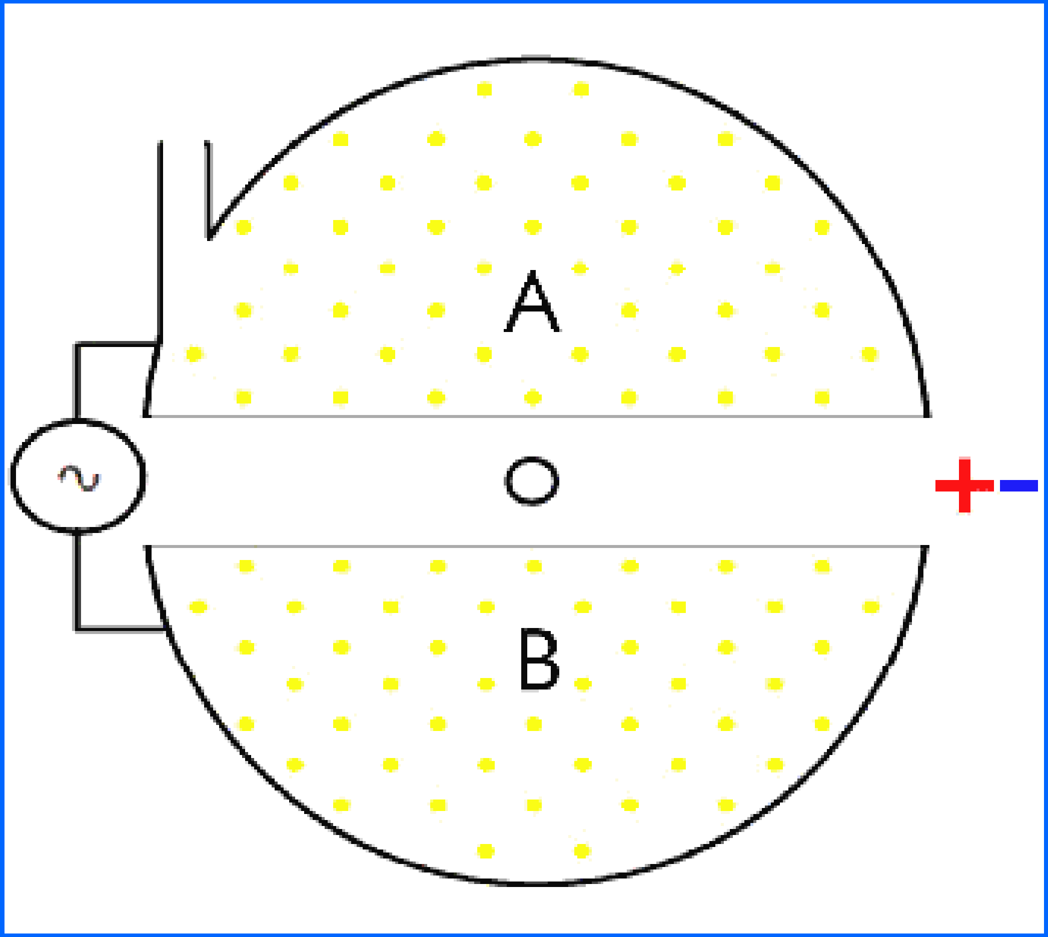


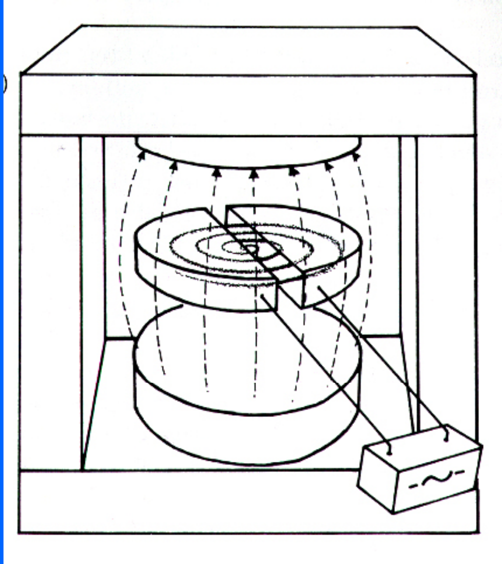
Principle: 17.6 MeV photons from the reaction

$$p + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{8}_{4}\mathrm{Be} + \gamma$$

Cyclotrons for the production of radio-isotopes

The cyclotron





Cyclotron frequency

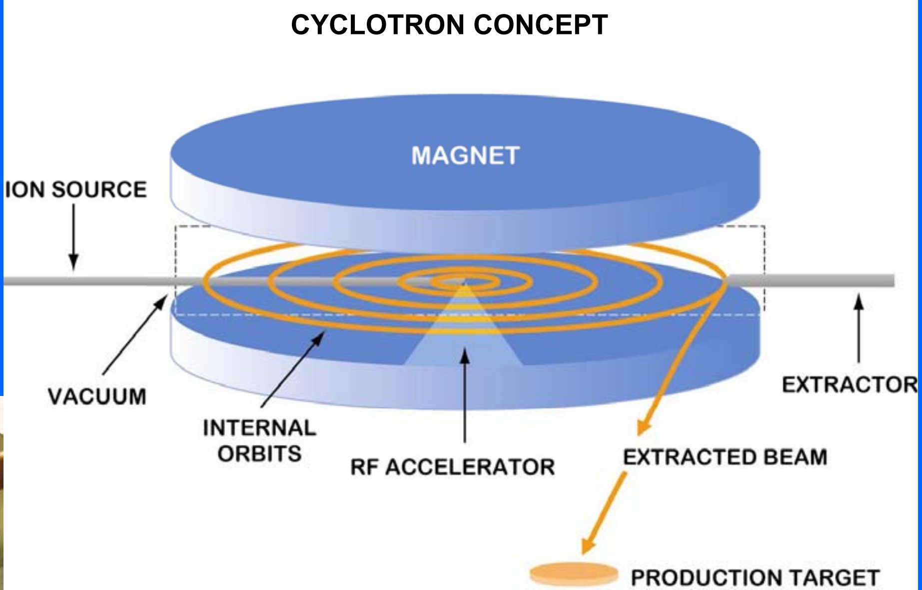
- $\nu = qB / 2\pi m$
- Independent from the speed!
- For protons:
- ν = B [T] x 15.28 MHz/T

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

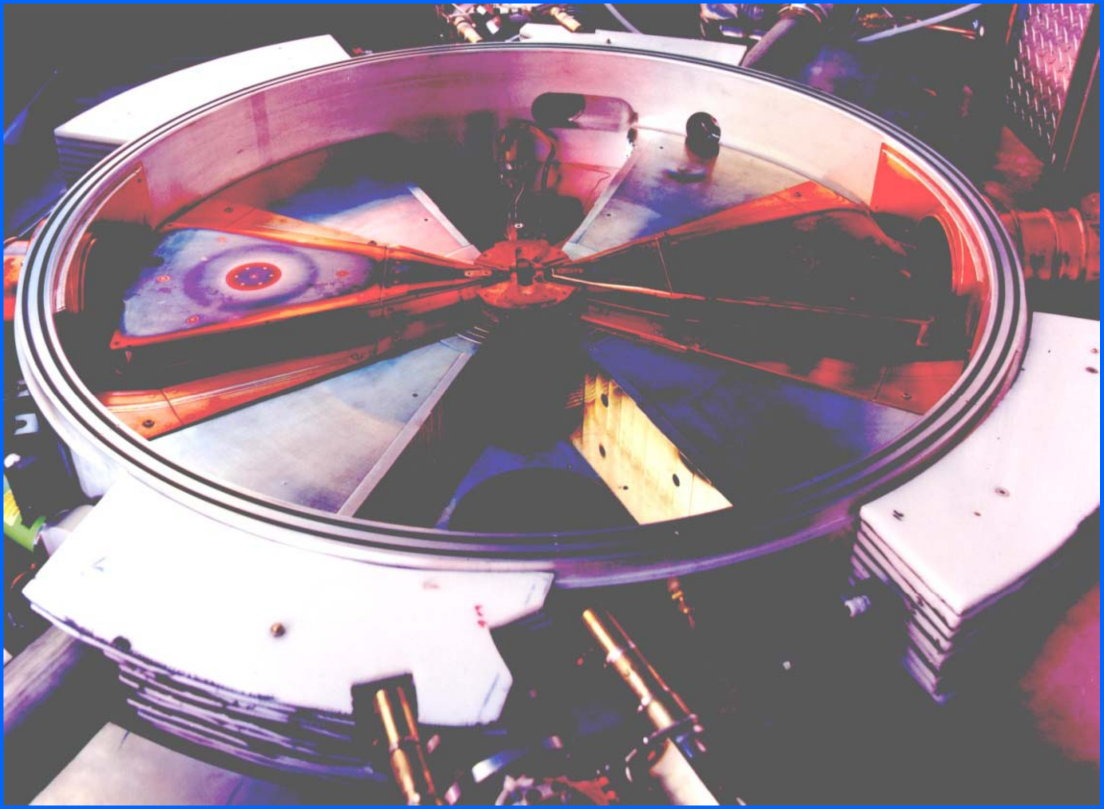
- 30 MeV, up to 1.5 mA proton beams
- Magnetic field (average) 1.2 T
- Cyclotron frequency : 18.33 MHz



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!

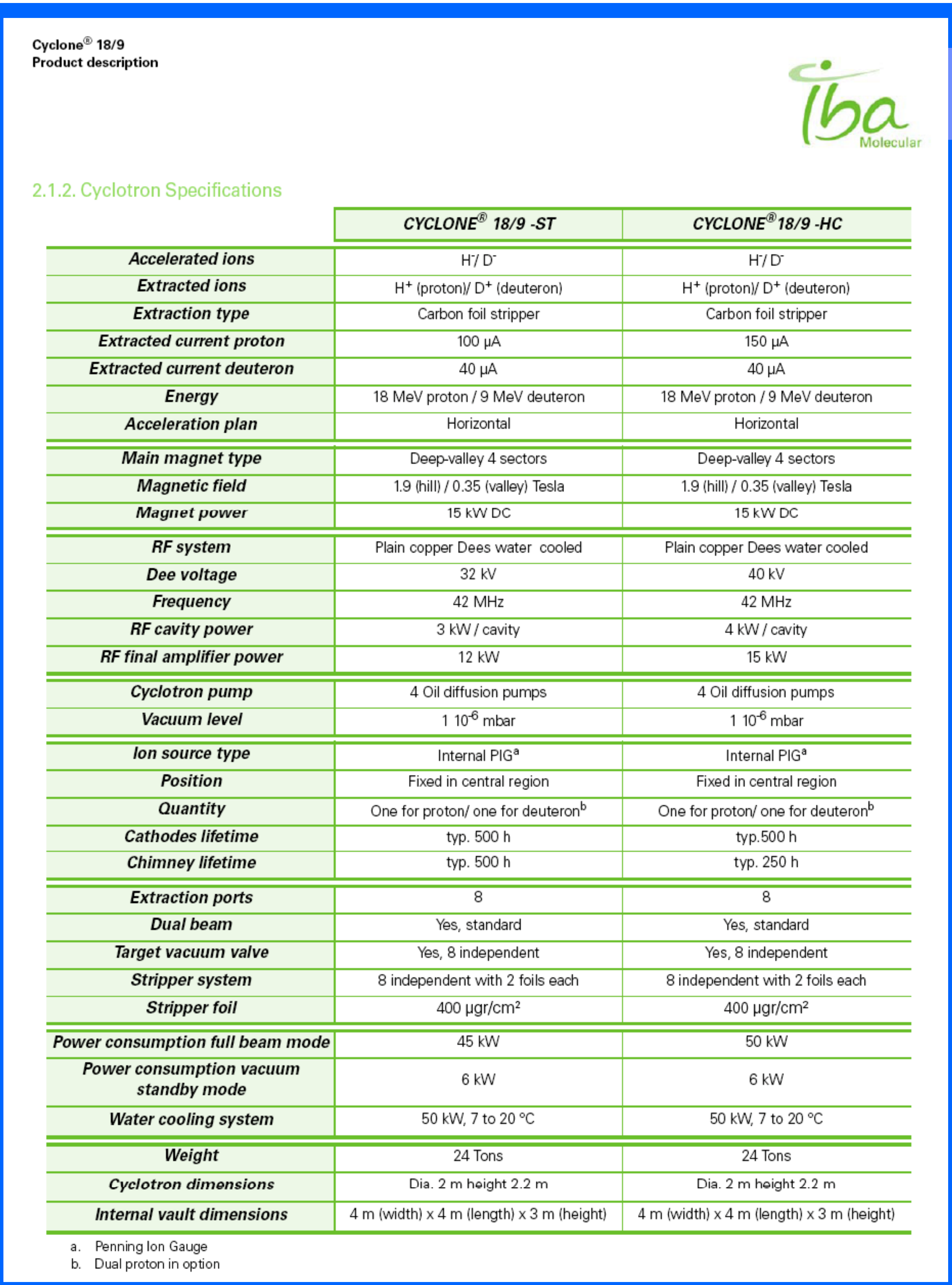
Exercise: a cyclotron working in 4th harmonic

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

The "Bern" cyclotron



Cyclone® 18/9
Product description

2.1.2. Cyclotron Specifications

	CYCLONE® 18/9 -ST	CYCLONE® 18/9 -HC
Accelerated ions	H^-/ D^-	H^-/ D^-
Extracted ions	H^+ (proton)/ D^+ (deuteron)	H^+ (proton)/ D^+ (deuteron)
Extraction type	Carbon foil stripper	Carbon foil stripper
Extracted current proton	100 µA	150 µA
Extracted current deuteron	40 µA	40 µA
Energy	18 MeV proton / 9 MeV deuteron	18 MeV proton / 9 MeV deuteron
Acceleration plan	Horizontal	Horizontal
Main magnet type	Deep-valley 4 sectors	Deep-valley 4 sectors
Magnetic field	1.9 (hill) / 0.35 (valley) Tesla	1.9 (hill) / 0.35 (valley) Tesla
Magnet power	15 kW DC	15 kW DC
RF system	Plain copper Dees water cooled	Plain copper Dees water cooled
Dee voltage	32 kV	40 kV
Frequency	42 MHz	42 MHz
RF cavity power	3 kW / cavity	4 kW / cavity
RF final amplifier power	12 kW	15 kW
Cyclotron pump	4 Oil diffusion pumps	4 Oil diffusion pumps
Vacuum level	1 10^{-6} mbar	1 10^{-6} mbar
Ion source type	Internal PIG[a]	Internal PIG[a]
Position	Fixed in central region	Fixed in central region
Quantity	One for proton/ one for deuteron[b]	One for proton/ one for deuteron[b]
Cathodes lifetime	typ. 500 h	typ.500 h
Chimney lifetime	typ. 500 h	typ. 250 h
Extraction ports	8	8
Dual beam	Yes, standard	Yes, standard
Target vacuum valve	Yes, 8 independent	Yes, 8 independent
Stripper system	8 independent with 2 foils each	8 independent with 2 foils each
Stripper foil	400 µgr/cm²	400 µgr/cm²
Power consumption full beam mode	45 kW	50 kW
Power consumption vacuum standby mode	6 kW	6 kW
Water cooling system	50 kW, 7 to 20 °C	50 kW, 7 to 20 °C
Weight	24 Tons	24 Tons
Cyclotron dimensions	Dia. 2 m height 2.2 m	Dia. 2 m height 2.2 m
Internal vault dimensions	4 m (width) x 4 m (length) x 3 m (height)	4 m (width) x 4 m (length) x 3 m (height)

a. Penning Ion Gauge
b. Dual proton in option

Fig. 1: CYCLONE® 18/9

Fig. 2: CYCLONE® 18/9 median plane showing the Dees and 4-sector poles

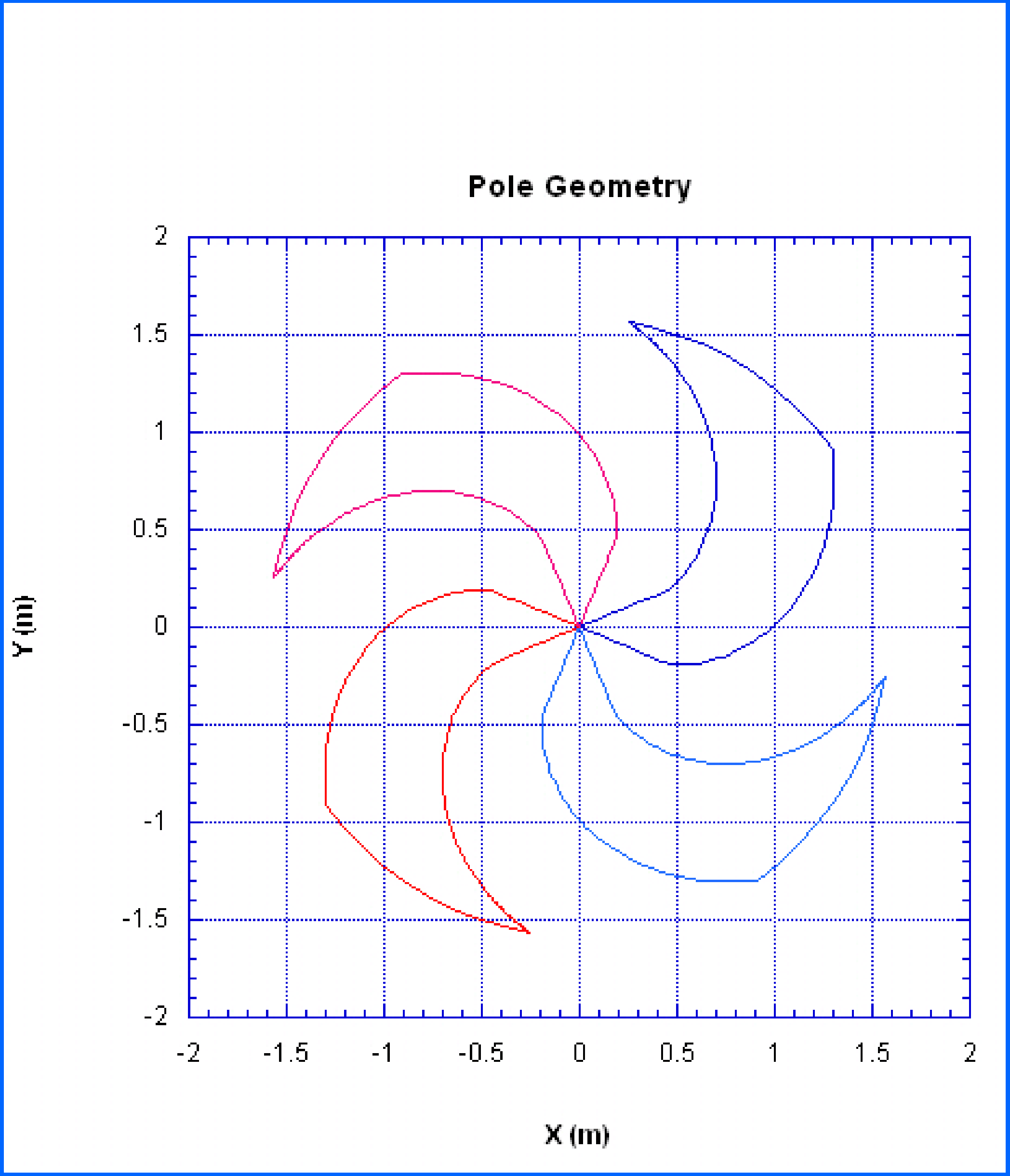
The synchrocyclotron

Relativistic ions

- What happens when ions become relativistic?
- Is the basic relation $\nu = qB / 2\pi m$ still valid?

- Yes, but m becomes the relativistic mass ($m_0\gamma$) and increases with energy

- Three possibilities:
  - Change pole geometry
  - Increase B towards the edge
  - Change the frequency during acceleration (synchrocyclotrons)



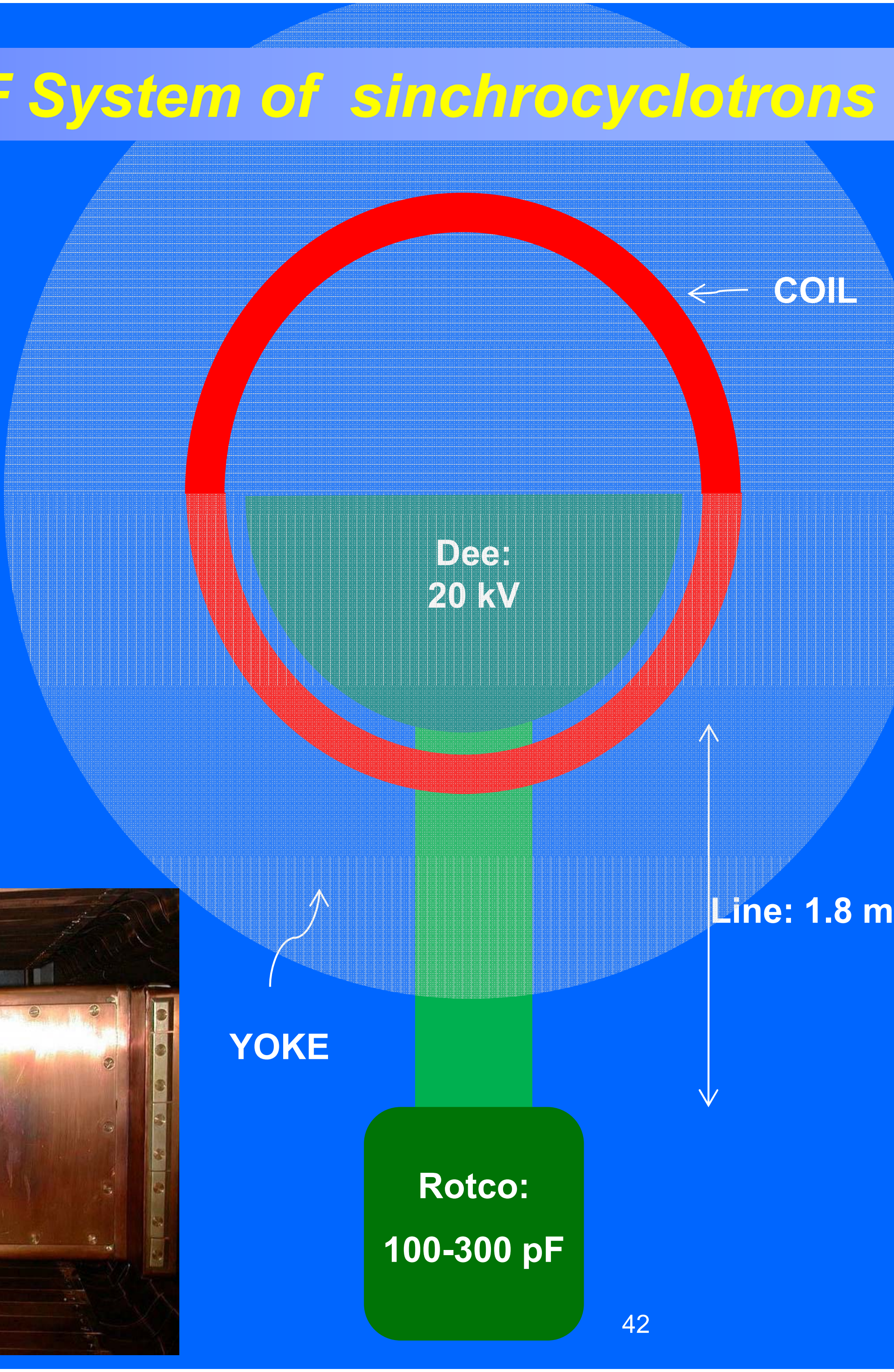
The RF System of sinchrocyclotrons

→ System composed of:

a) **rotating variable capacitor**
b) coaxial rectangular transmission line
c) 180° Dee

→ RF **Frequency Modulation** range: 20 %

→ Power consumption : **12 kW (mean)** / 59 kW (peak)



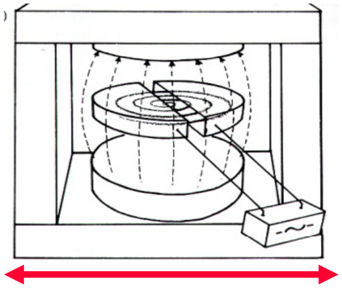
The rotating capacitor at Orsay Synchrocyclotron

Accelerators for hadrontherapy

The accelerators used today in hadrontherapy

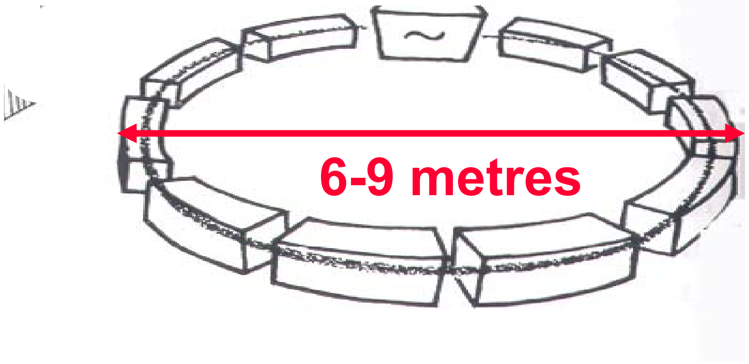
Teletherapy with protons (~ 200 MeV)

CYCLOTRONS (Normal or SC)



4-5 metres

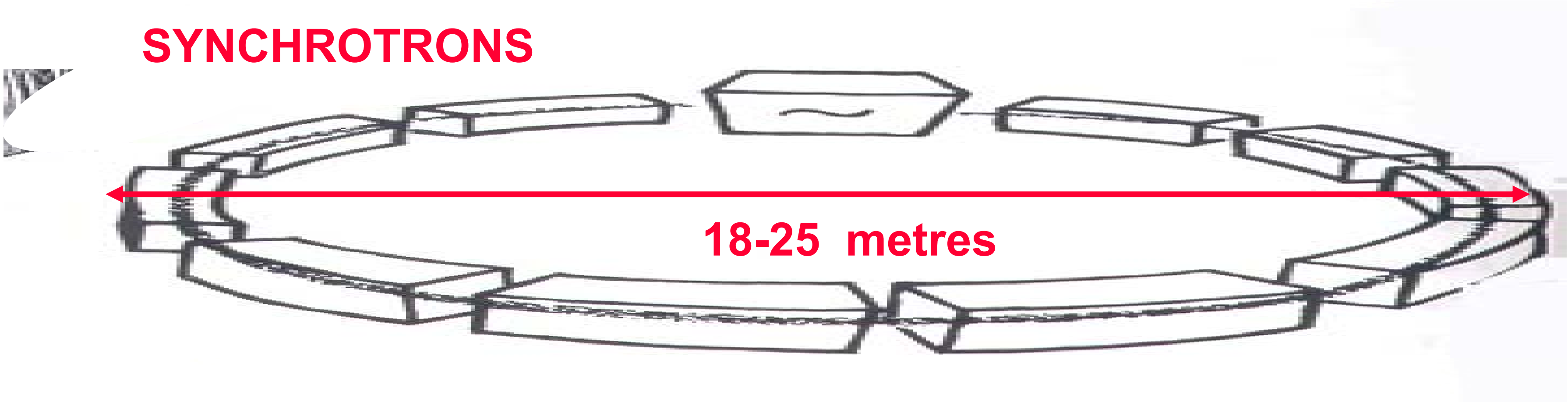
SYNCHROTRONS



6-9 metres

Teletherapy with carbon ions (~ 4800 MeV)

SYNCHROTRONS



18-25 metres

Exercise: beam rigidity

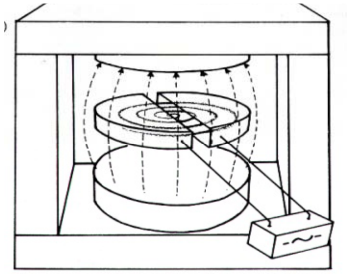
- Why are accelerators for hardontherapy so large?
- Beam rigidity : is the product of the magnetic field B and the radius of curvature ρ for a charged particle in that magnetic field
- With some kinematics …

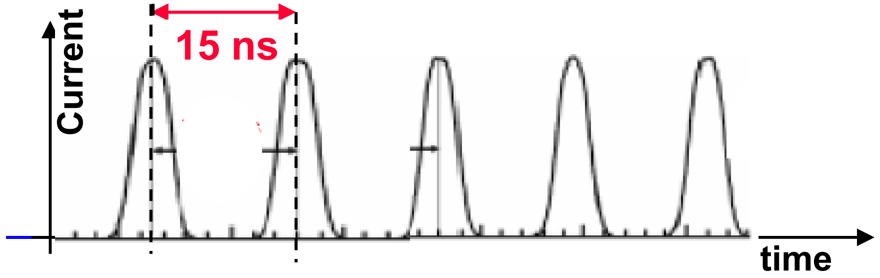
$$B\cdot\rho=\frac{\sqrt{2mc^2E}}{q\cdot e\cdot c}$$

- 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

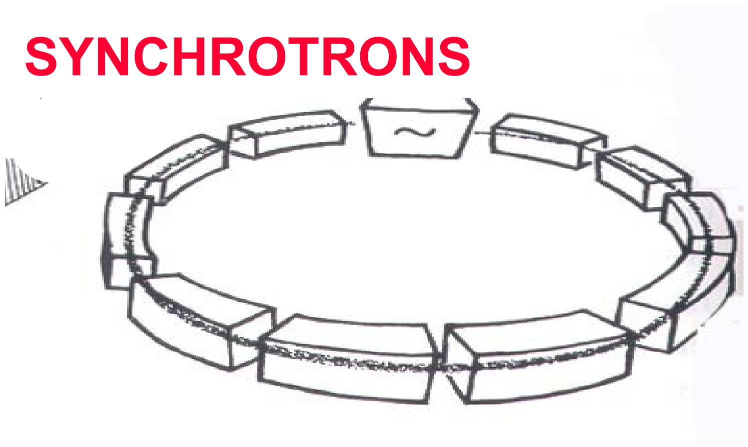
CYCLOTRONS (*) (Normal or SC)

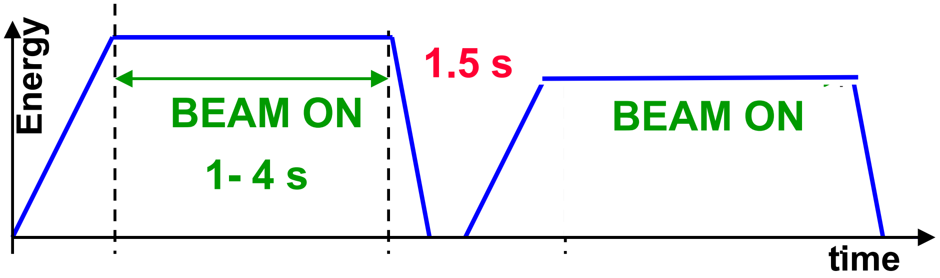




A pulsed beam of fixed energy is always present

SYNCHROTRONS

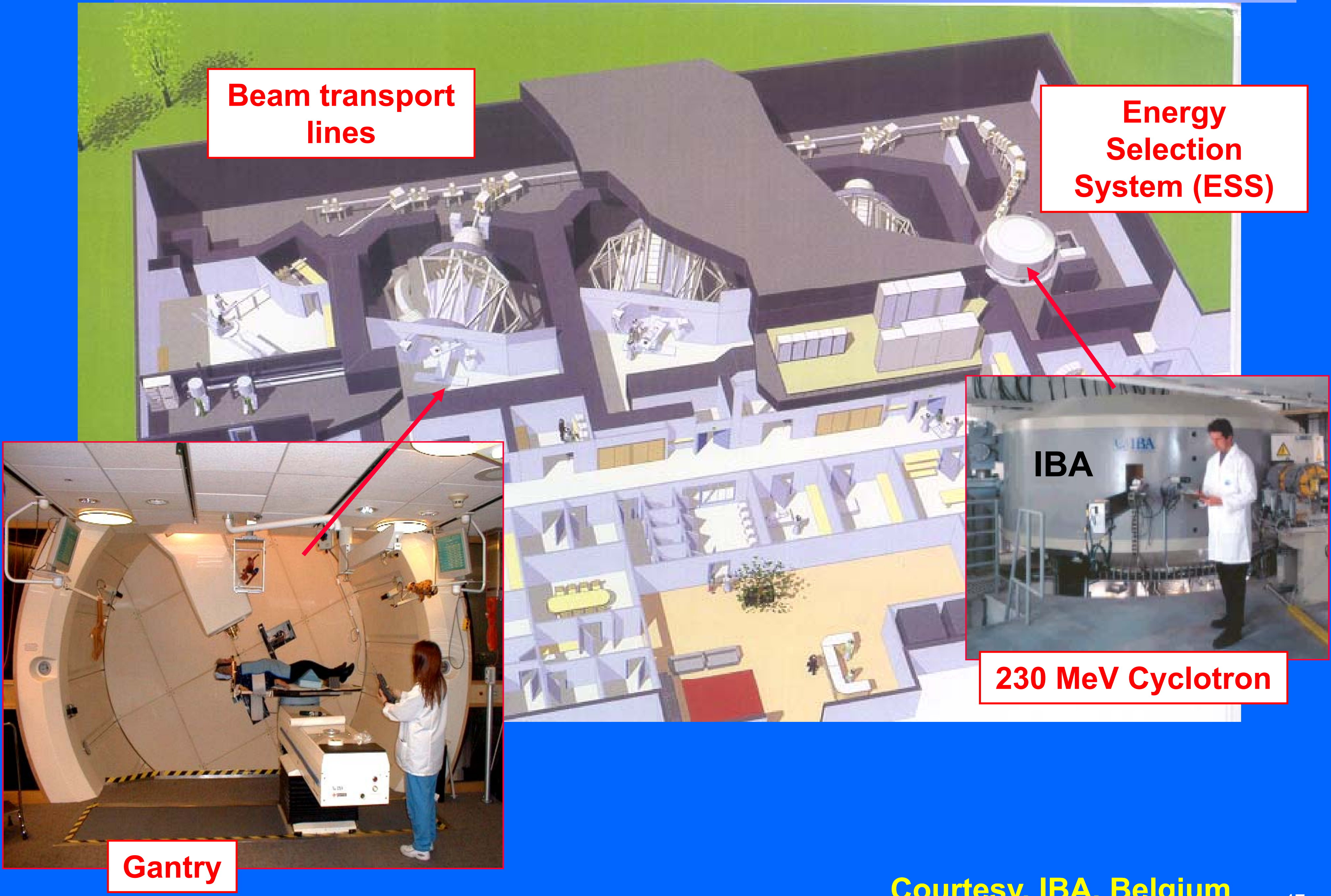




A cycling beam of variable energy has ~1 second gaps

(*) A synchrocyclotrons cycles at hundreds Hertz

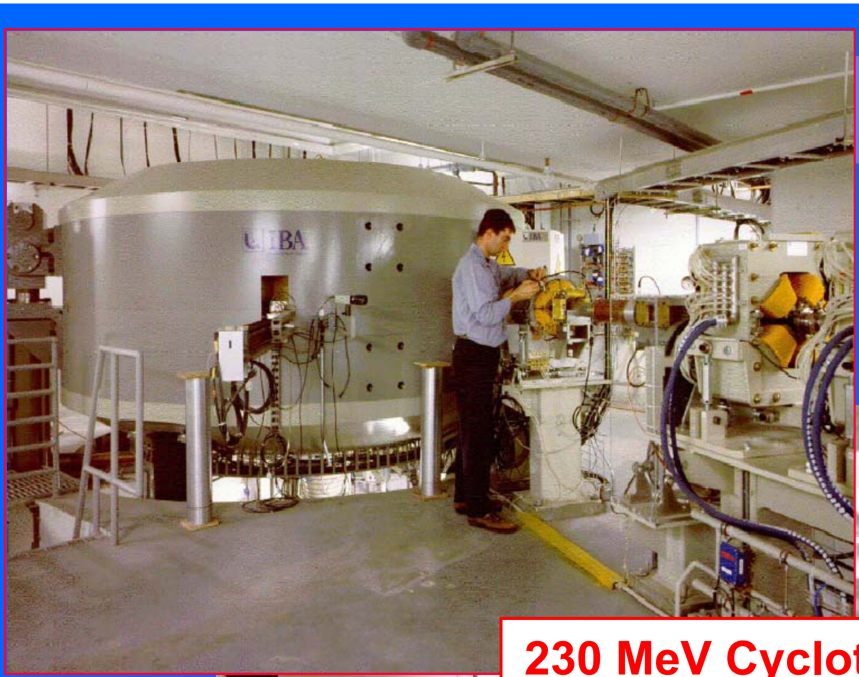
Cyclotron solution for protons by IBA - Belgium



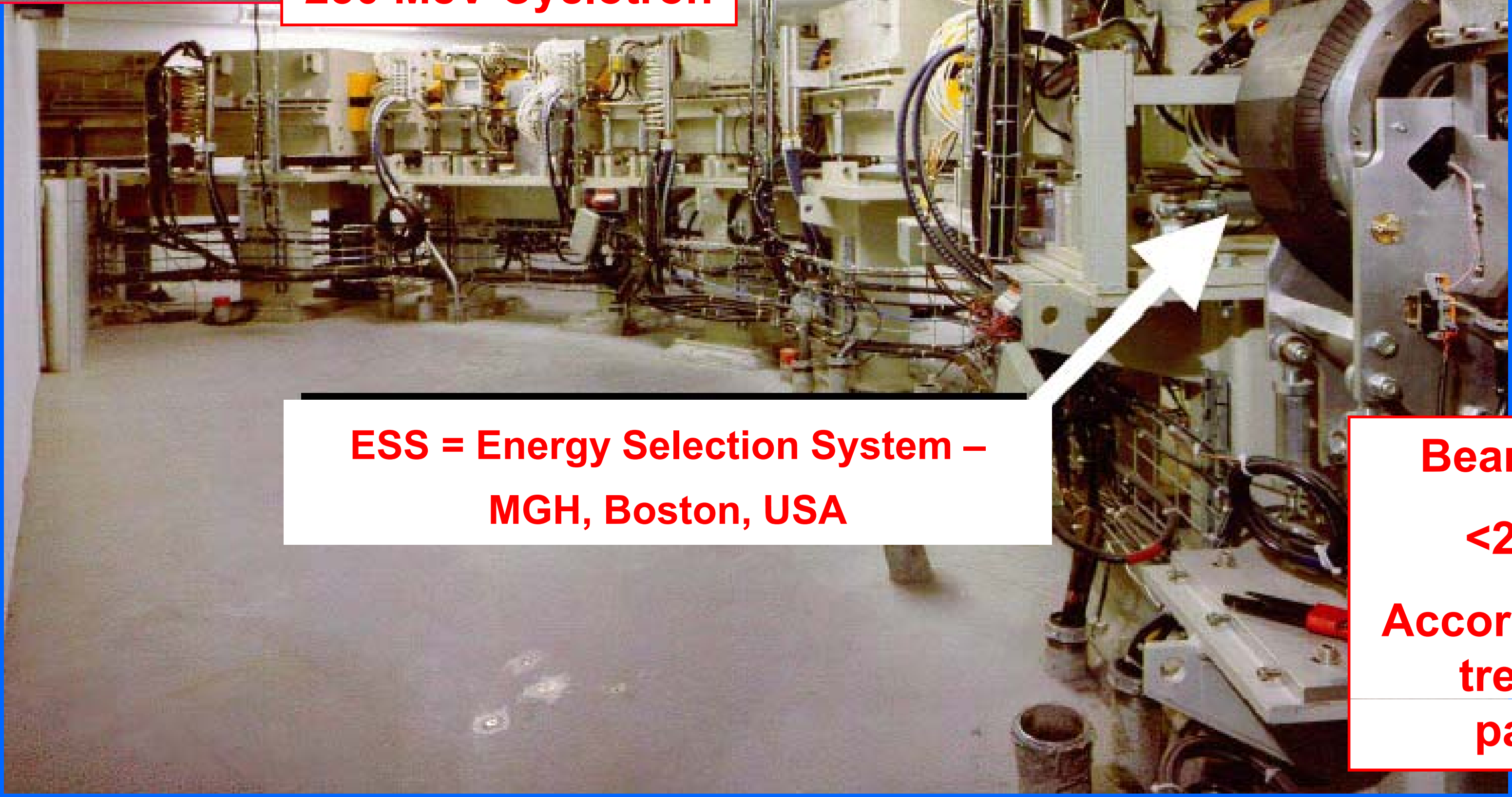
Courtesy, IBA, Belgium

A cyclotron needs a long ESS

Courtesy, IBA, Belgium



230 MeV Cyclotron



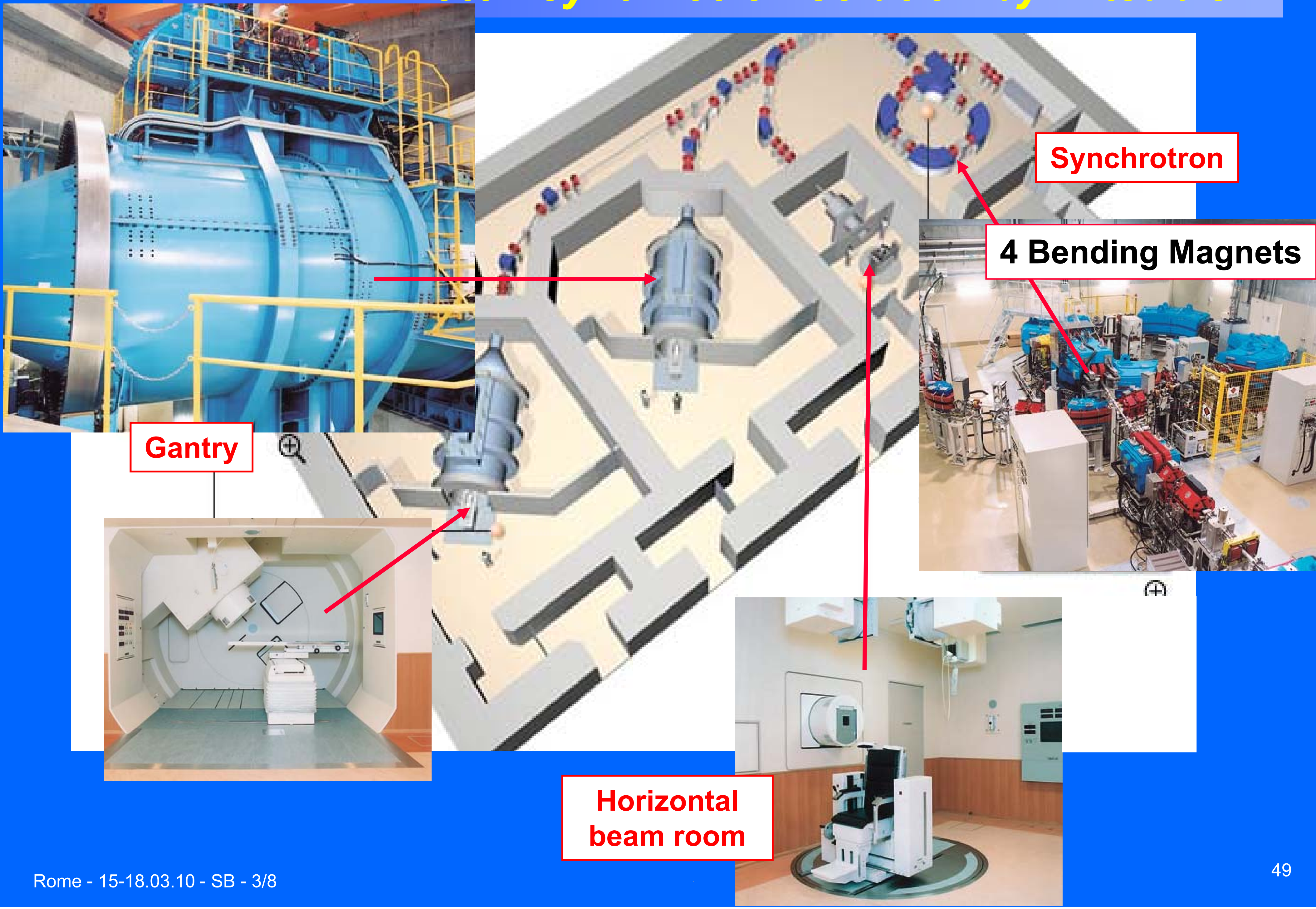
ESS = Energy Selection System – MGH, Boston, USA

Beam energy

<230 MeV

According to the treatment panning

Proton synchrotron solution by Mitsubishi



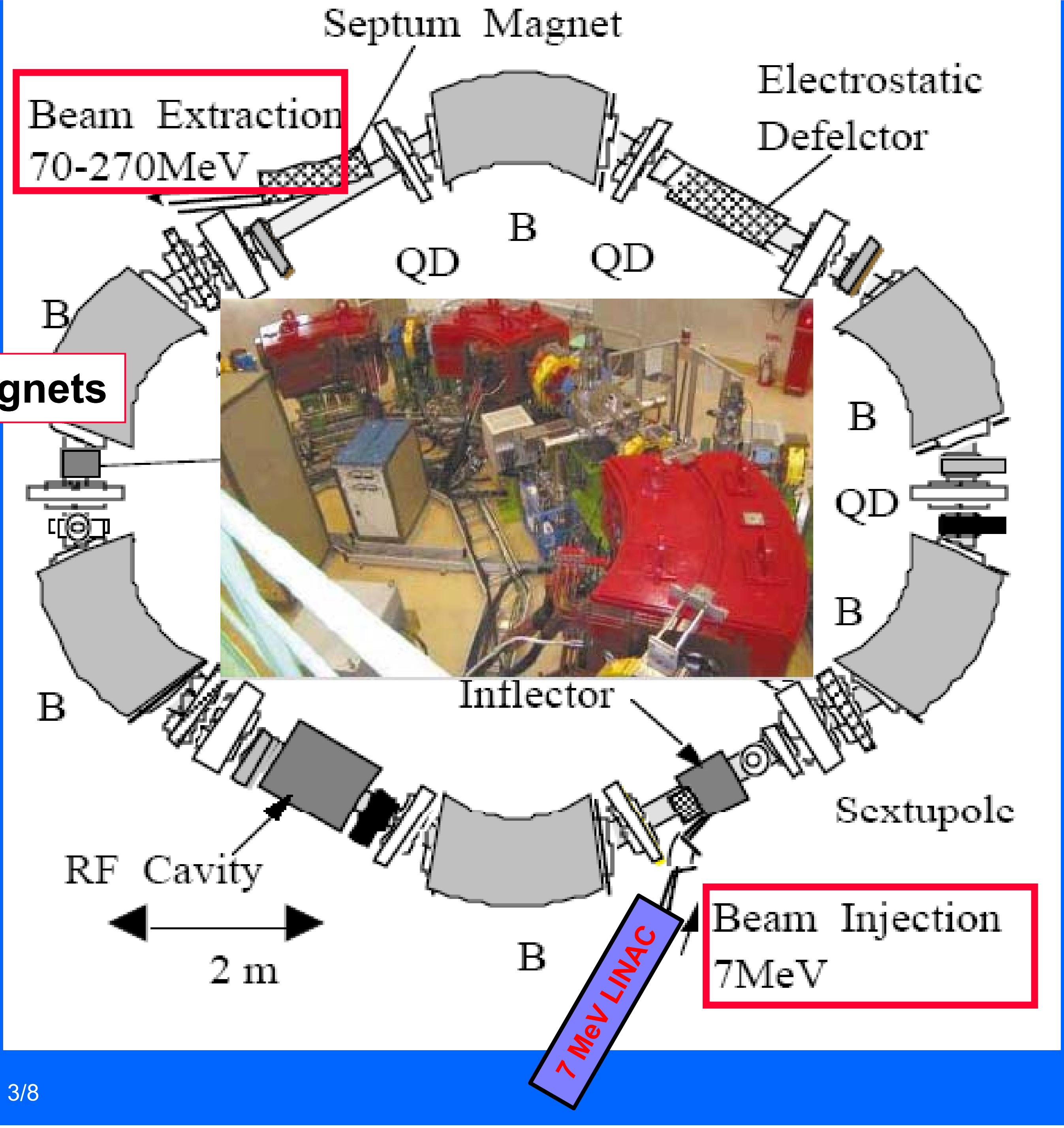
Synchrotron

4 Bending Magnets

Gantry

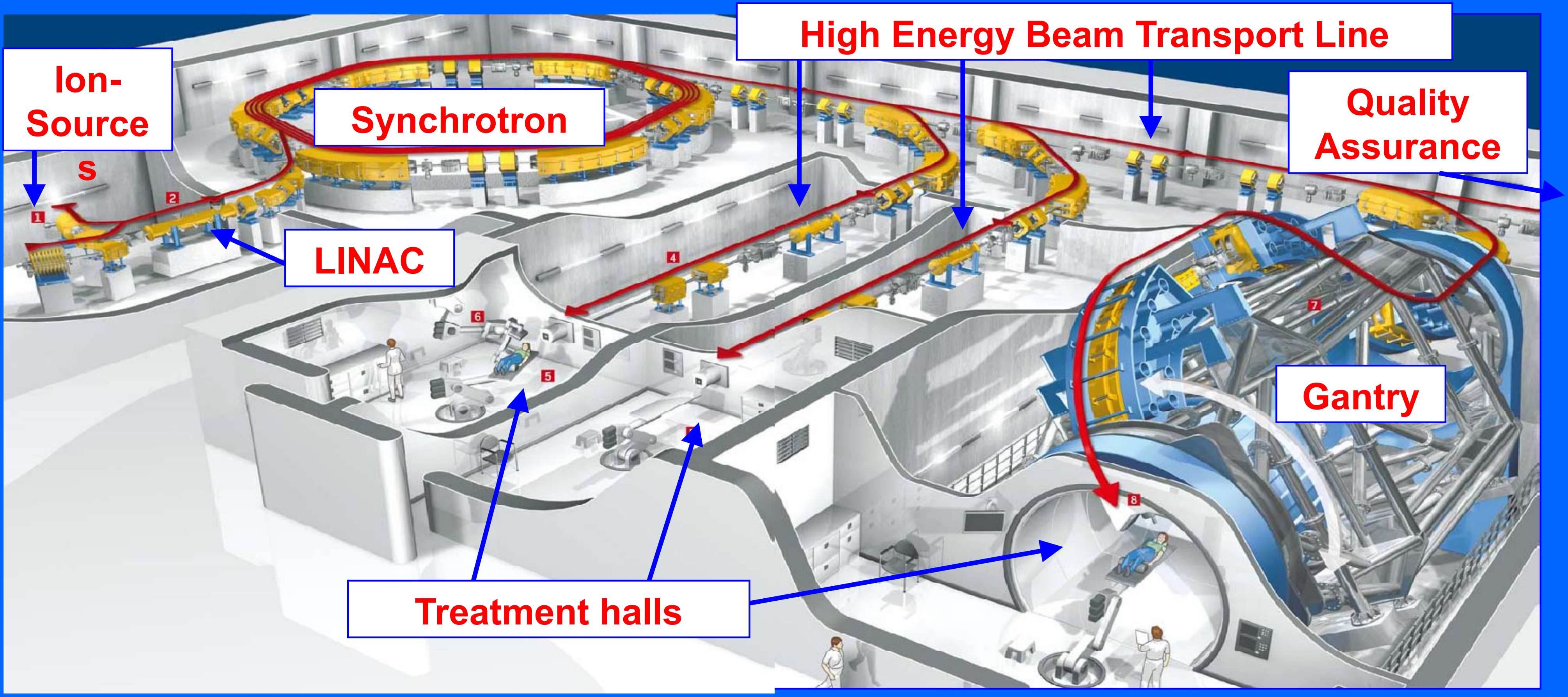
Horizontal beam room

Hitachi synchrotron: M.D. Anderson center in Houston



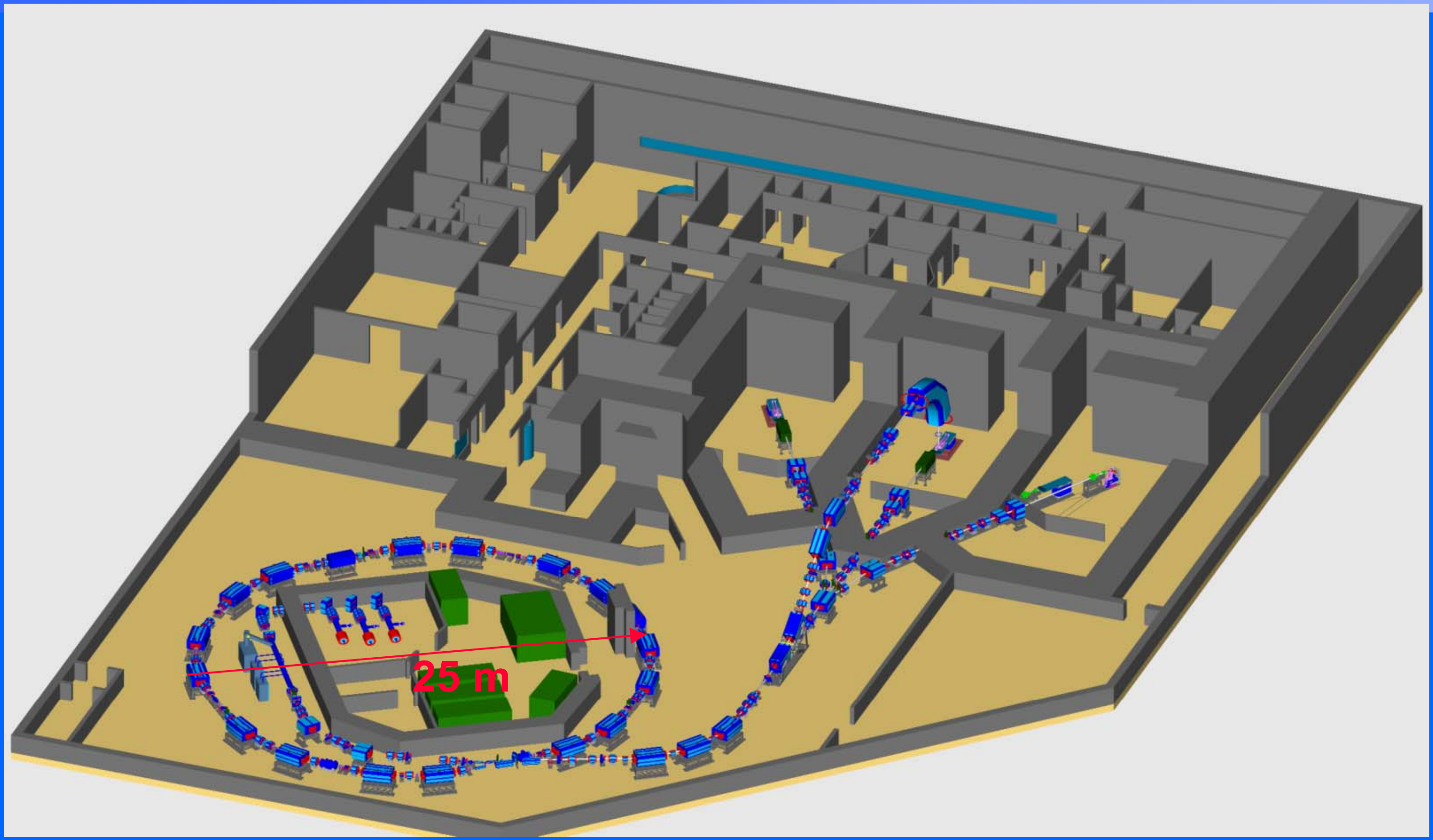
6 Bending Magnets

Synchrotron solution for protons and carbon ions



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

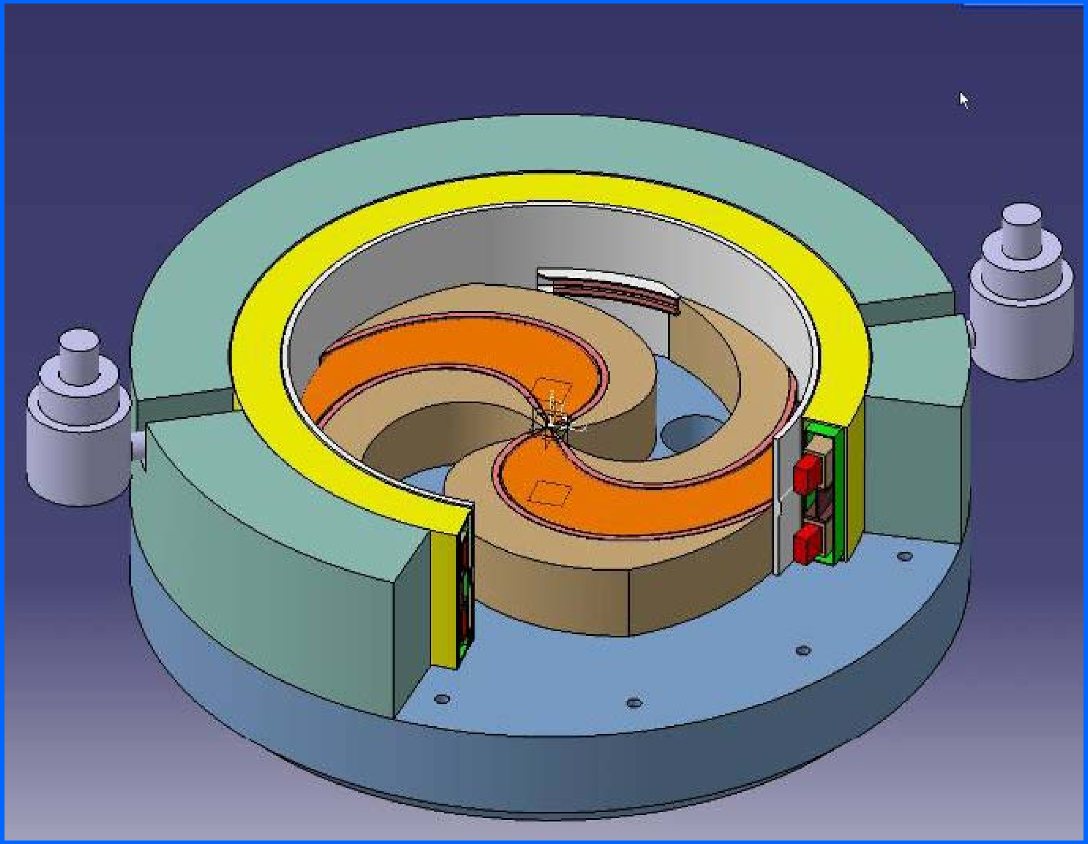
The synchrotron of the CNAO under construction in Pavia, Italy



- **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

A SC cyclotron for carbon ion therapy

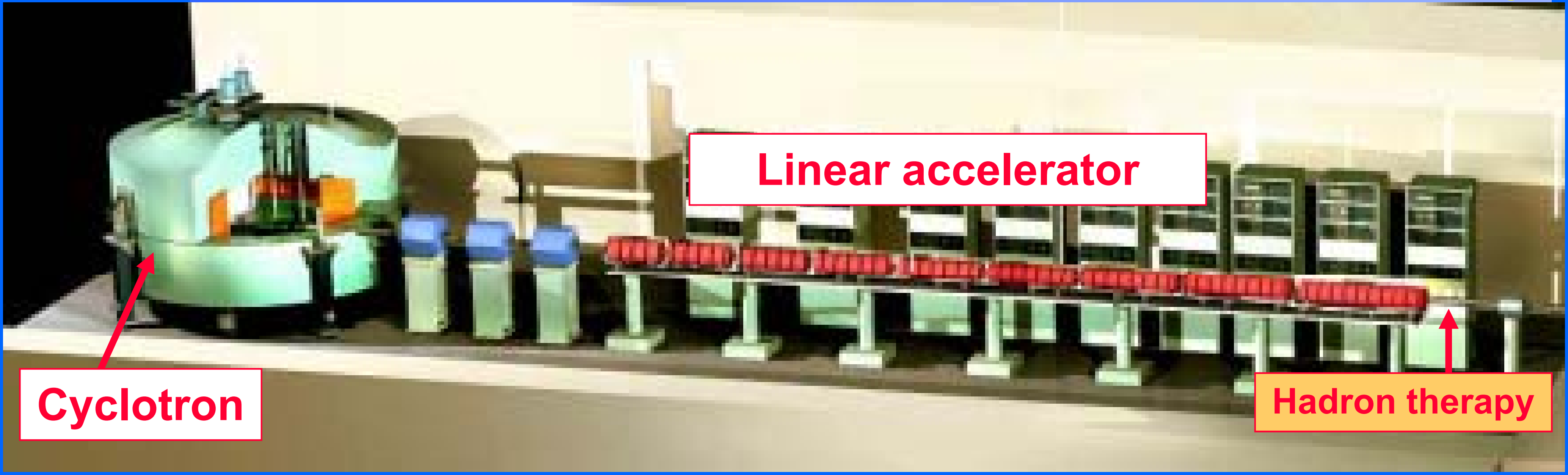


- Superconducting isochronous cyclotron, accelerating Q/M = 1/2 ions to 400 MeV/U (H2 +, Alphas, Li6 3+, B10 5+, C12 6+, N14 7+, 016 8+, Ne20 10+)
- Diameter 6.3 meters
- Design by IBA (Belgium)
- The first prototype will be realized in Caen by the Archade consortium

iba

Archade
ADVANCED RESOURCE CENTRE FOR HADRONTHERAPY IN EUROPE

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**

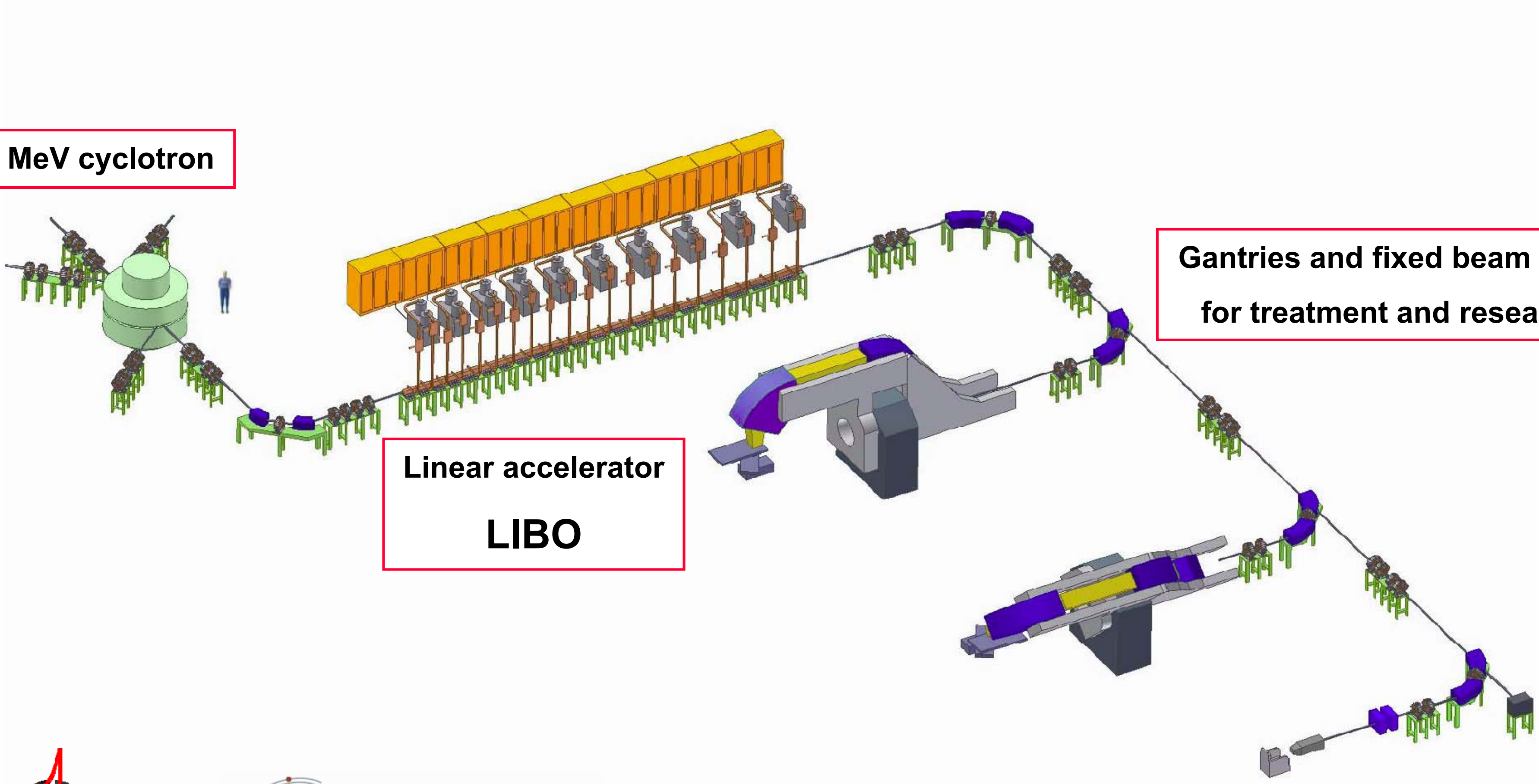
Two main functions

DIAGNOSTICS + THERAPY

Linacs for hadronterapy?

IDRA

Institute for Diagnostics and RAdiotherapy



30 MeV cyclotron

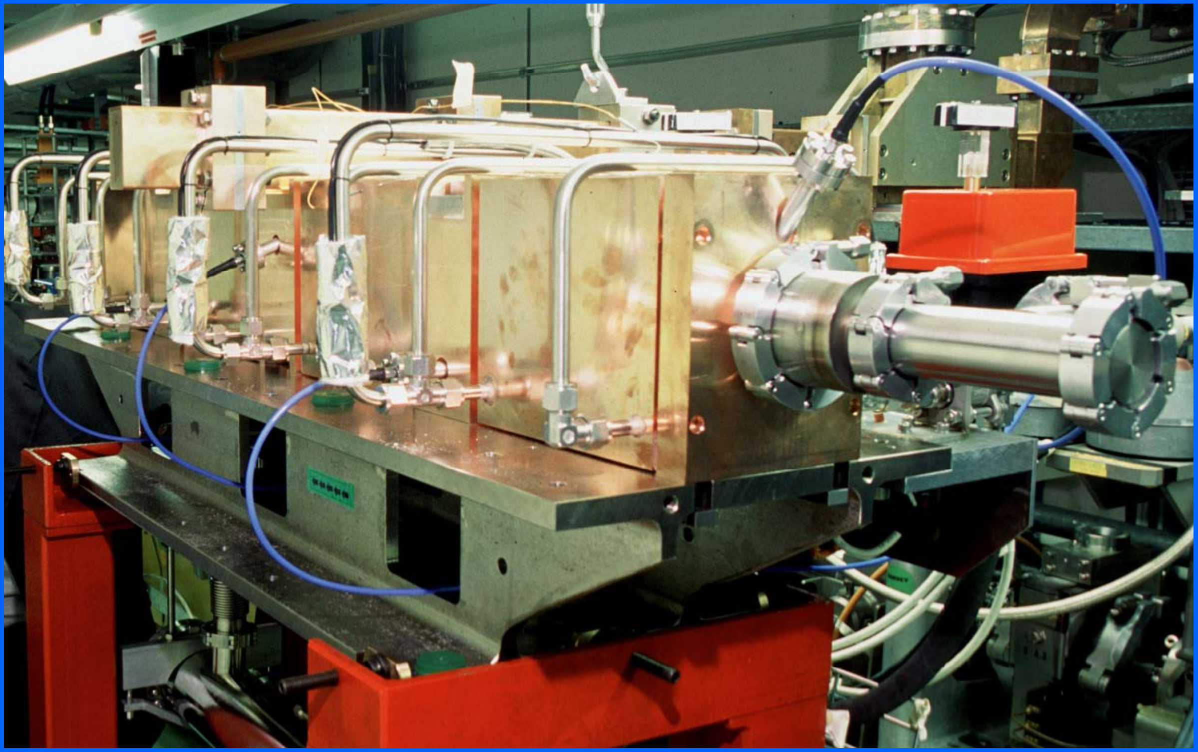
Linear accelerator

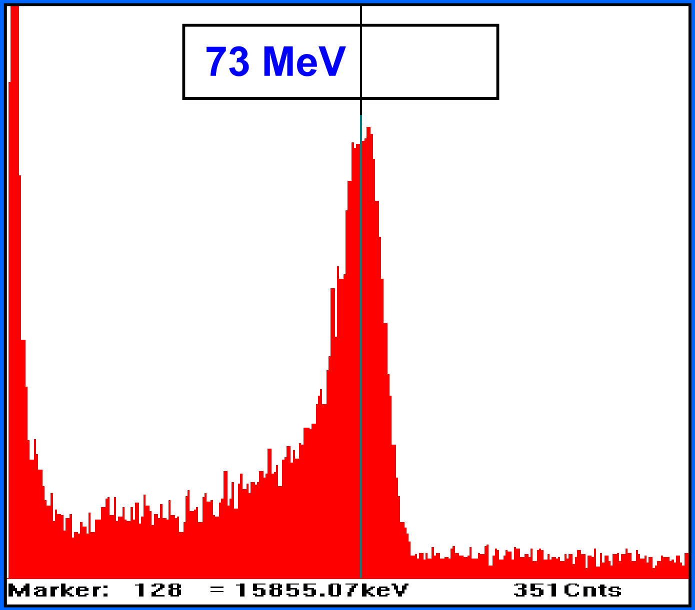
LIBO

Gantries and fixed beam lines for treatment and research

Courtesy U. Amaldi

Prototype of LIBO (3 GHz LInac BOoster)





Accelerated beam from the 60 MeV cyclotron of LNS

Collaboration INFN-CERN-TERA 1999-2002

Module tested at LNS of INFN, Catania

U. Amaldi et al, NIM A 521 (2004) 512

LIBO is a Side Coupled Linac (SCL)

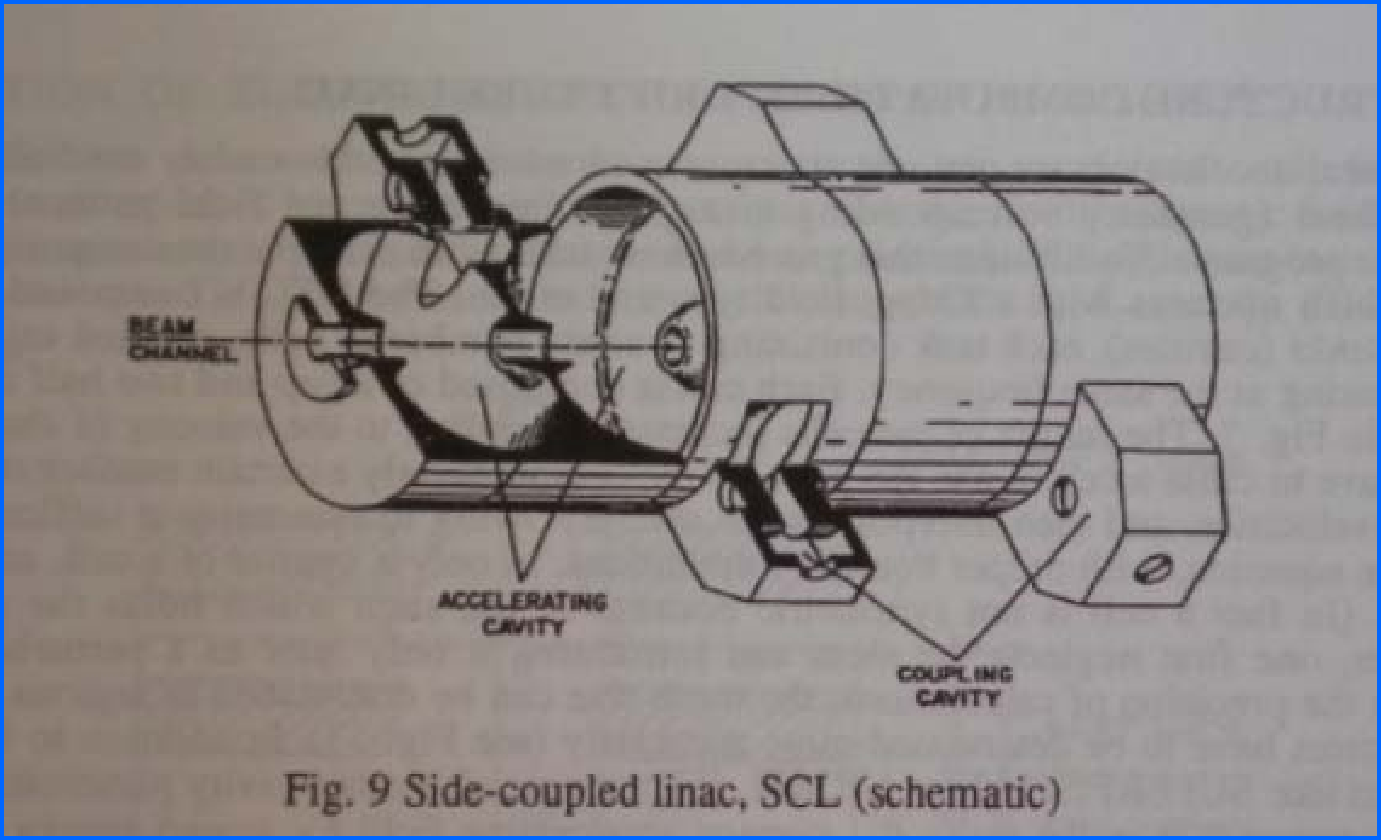


Fig. 9 Side-coupled linac, SCL (schematic)

- **Convenient at β>0.3 (about 50 MeV for protons)**
- **Accelerating + coupling cells (biperiodic structure)**
- **The field vector Ez is in phase opposition in adjacent cells**
- **Modular structure, with longer modules for higher β**

The cells and the bridge coupler of LIBO

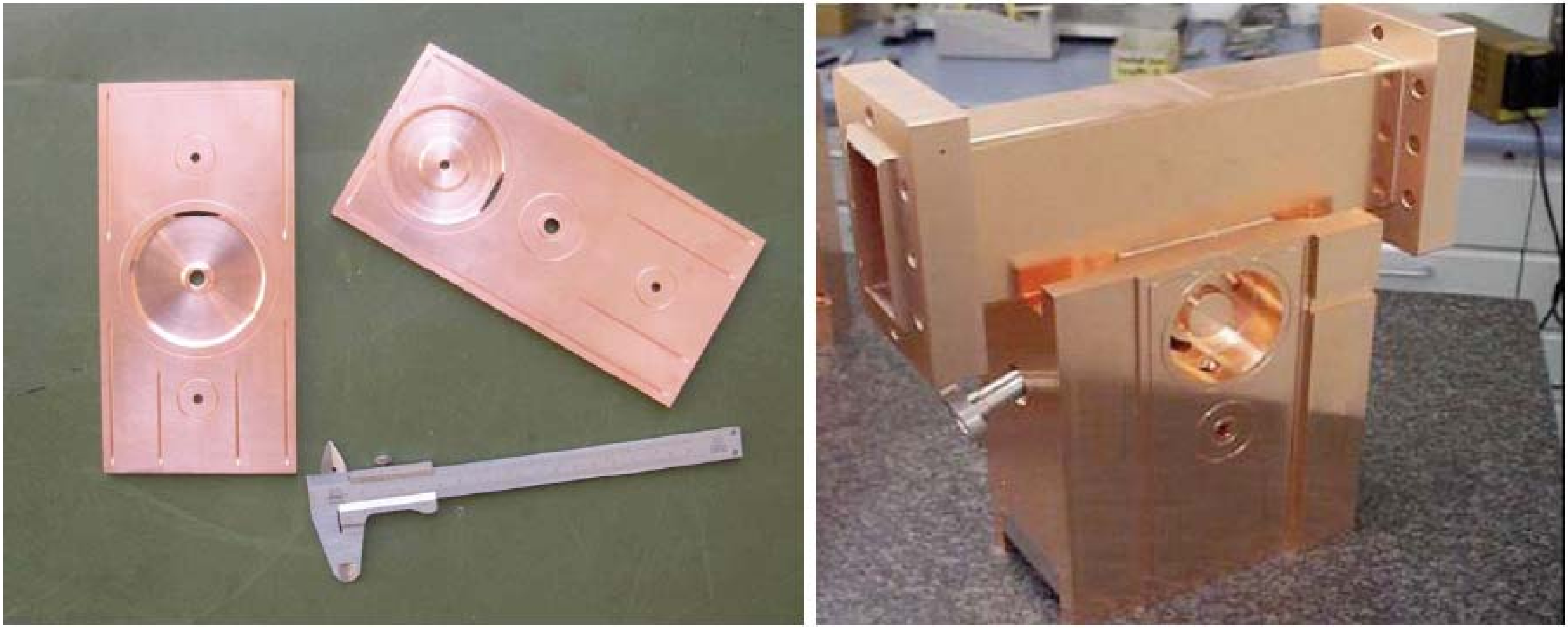


Figure 6. *Two half-cells (left figure) and the bridge coupler of the 50 cm long module - made of two tanks- which accelerates protons from 30 MeV to 35 MeV (right figure).*

A smaller "dual" accelerator

SCENT

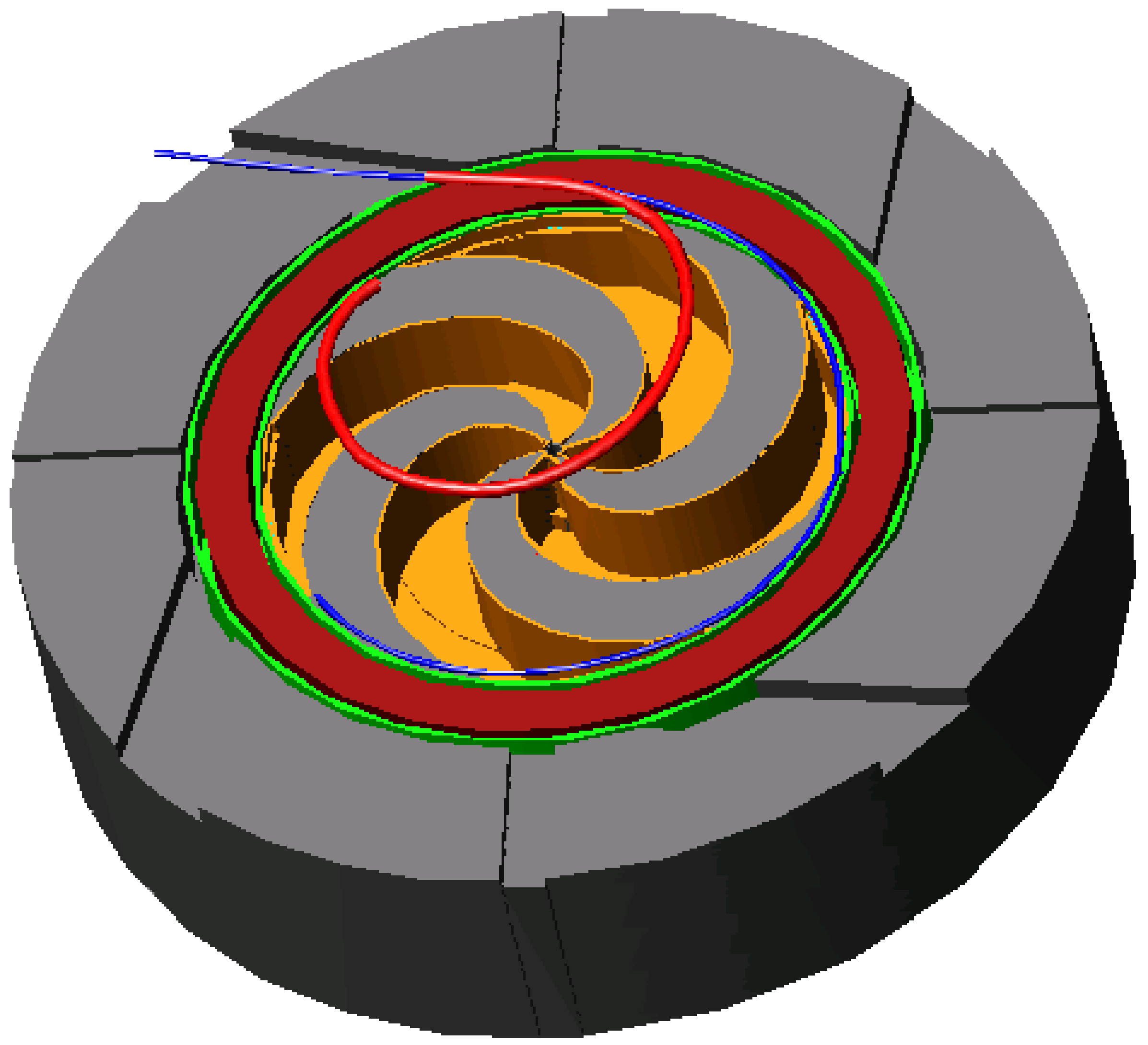
300 MeV/u SC cyclotron

- ***H_2^+ molecules***

  300 MeV proton beam for deep seated cancer treatment

- ***300 MeV/u fully stripped C ions***

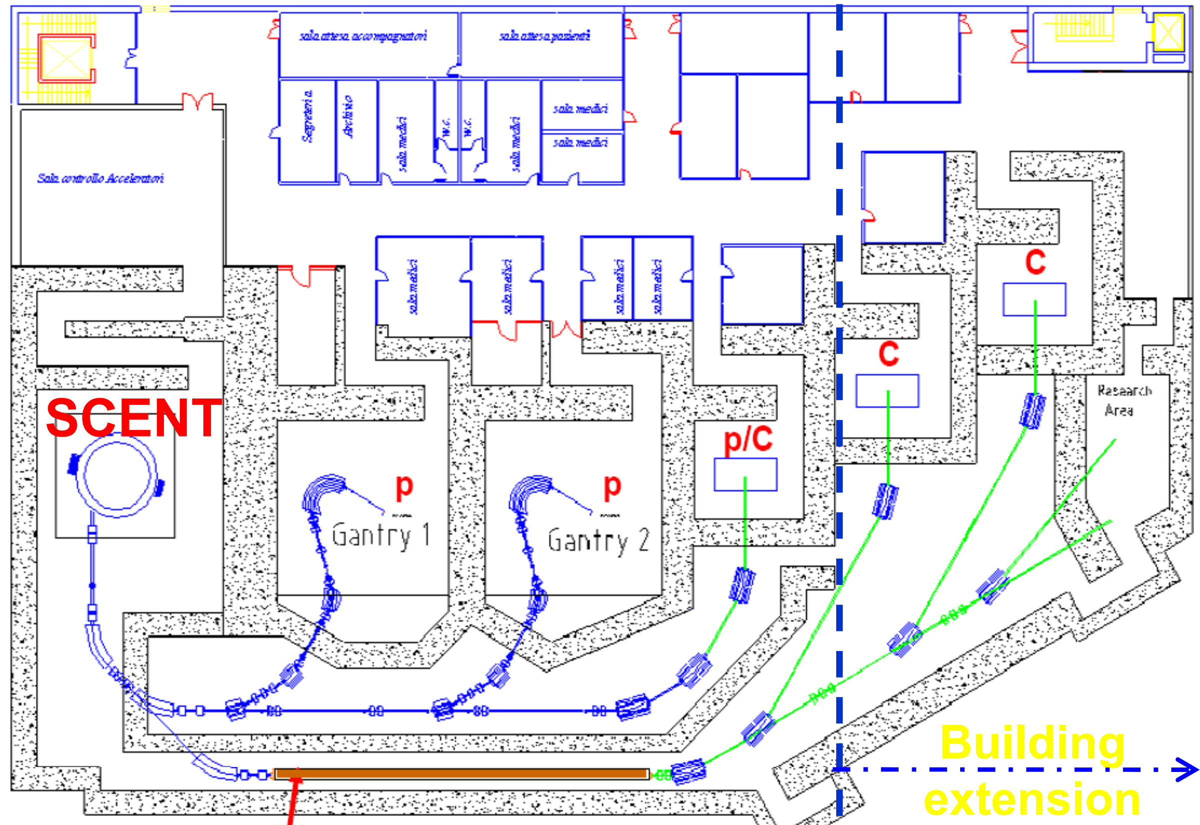
  maximum penetration of 16 cm in water

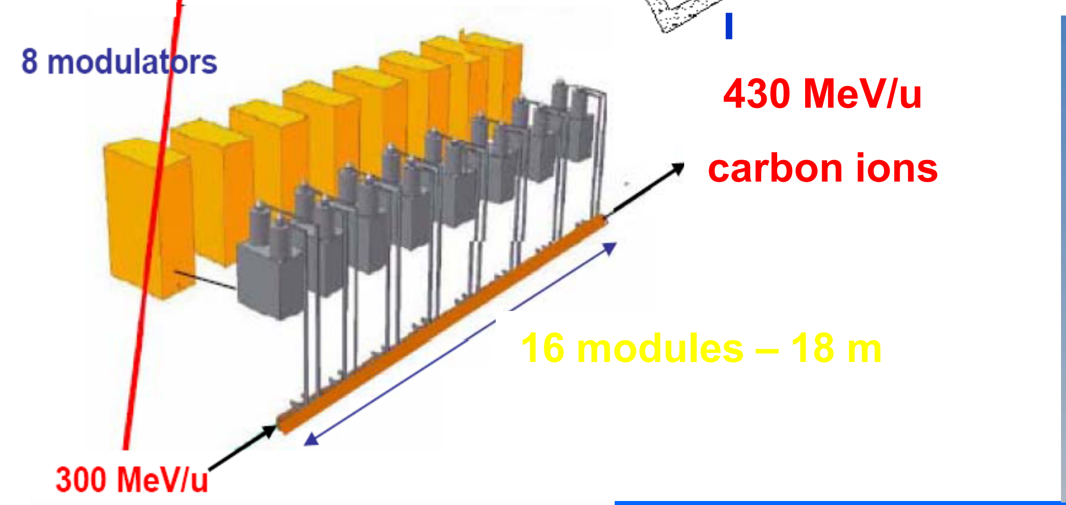


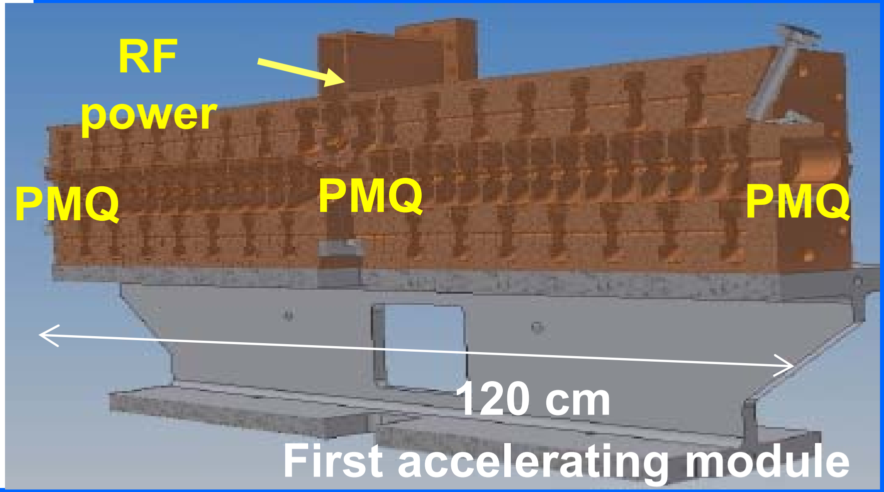
Project of INFN LNS / IBA

SCENT + CABOTO

CArbon BOoster for Therapy in Oncology at 3 GHz



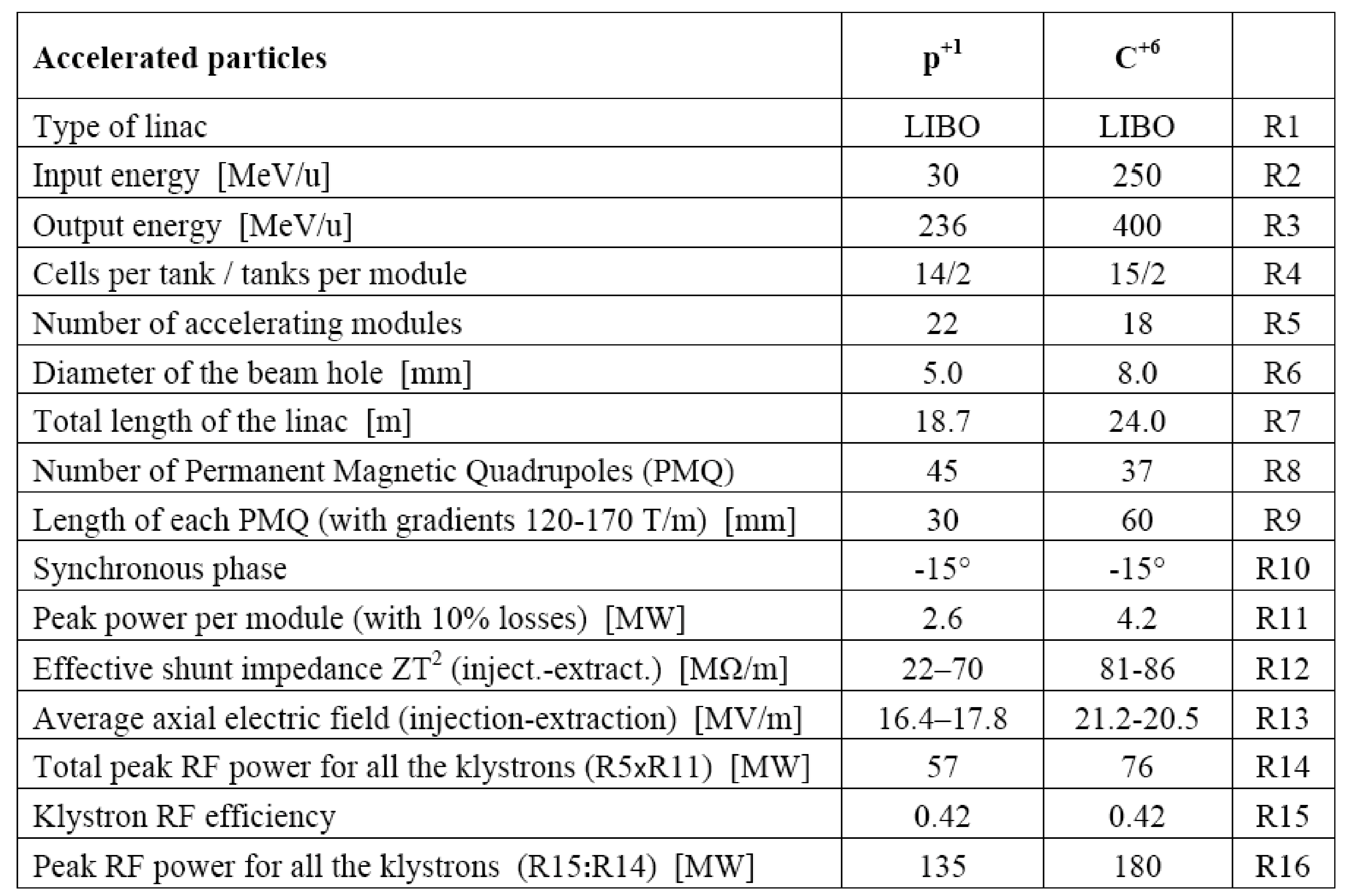




First accelerating module

Courtesy U. Amaldi

Main parameters of the proton and carbon linacs

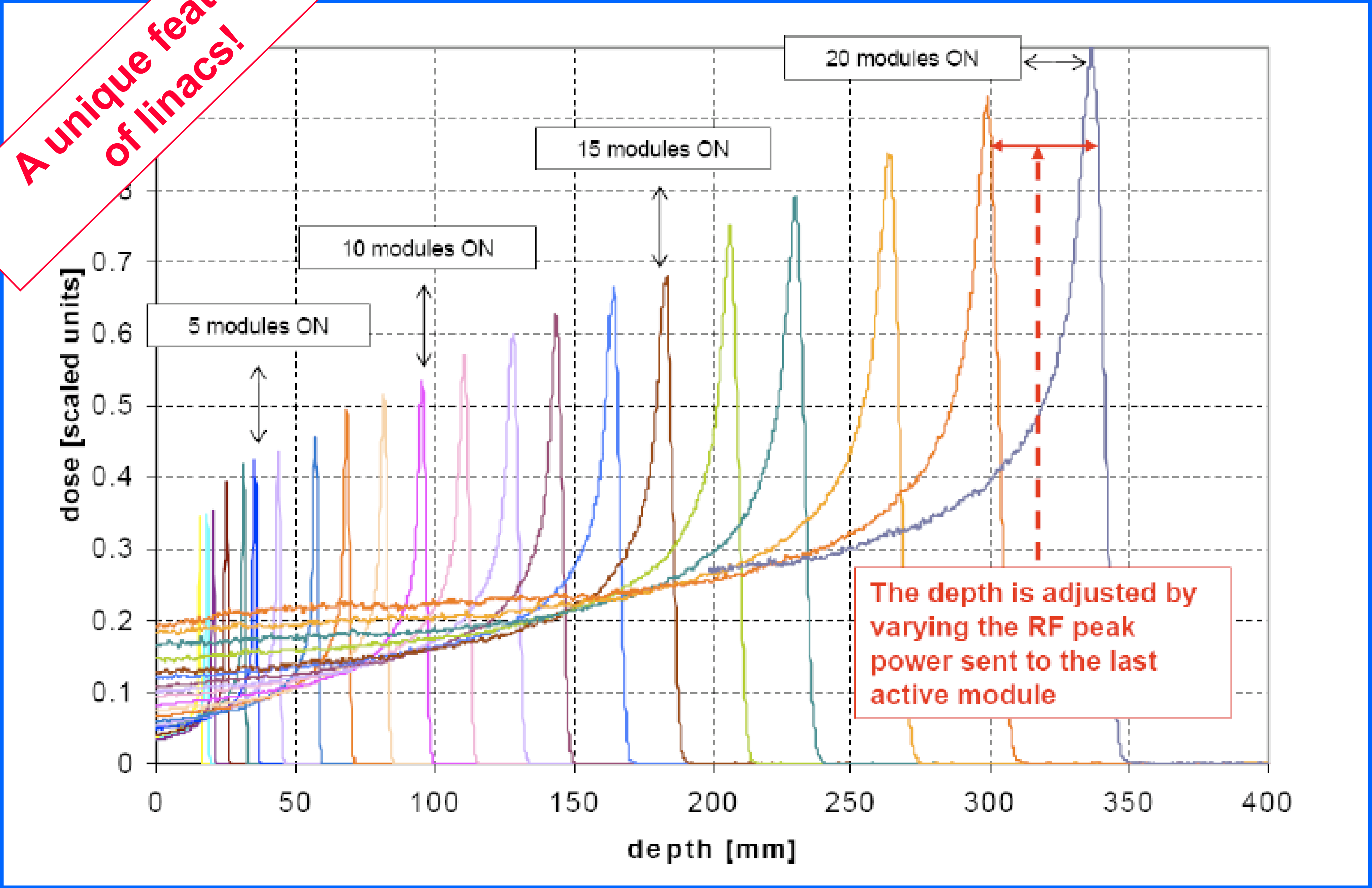


Accelerated particles	p^{+1}	C^{+6}	
Type of linac	LIBO	LIBO	R1
Input energy [MeV/u]	30	250	R2
Output energy [MeV/u]	236	400	R3
Cells per tank / tanks per module	14/2	15/2	R4
Number of accelerating modules	22	18	R5
Diameter of the beam hole [mm]	5.0	8.0	R6
Total length of the linac [m]	18.7	24.0	R7
Number of Permanent Magnetic Quadrupoles (PMQ)	45	37	R8
Length of each PMQ (with gradients 120-170 T/m) [mm]	30	60	R9
Synchronous phase	-15°	-15°	R10
Peak power per module (with 10% losses) [MW]	2.6	4.2	R11
Effective shunt impedance ZT^2 (inject.-extract.) [MΩ/m]	22–70	81-86	R12
Average axial electric field (injection-extraction) [MV/m]	16.4–17.8	21.2-20.5	R13
Total peak RF power for all the klystrons (R5xR11) [MW]	57	76	R14
Klystron RF efficiency	0.42	0.42	R15
Peak RF power for all the klystrons (R15:R14) [MW]	135	180	R16

U. Amaldi et al, CYCLINACS: FAST-CYCLING ACCELERATORS FOR HADRONTHERAPY, arXiv:0902.3533

The energy can be continuously varied

A unique feature of linacs!



The depth is adjusted by varying the RF peak power sent to the last active module

A comparison with respect to energy variation

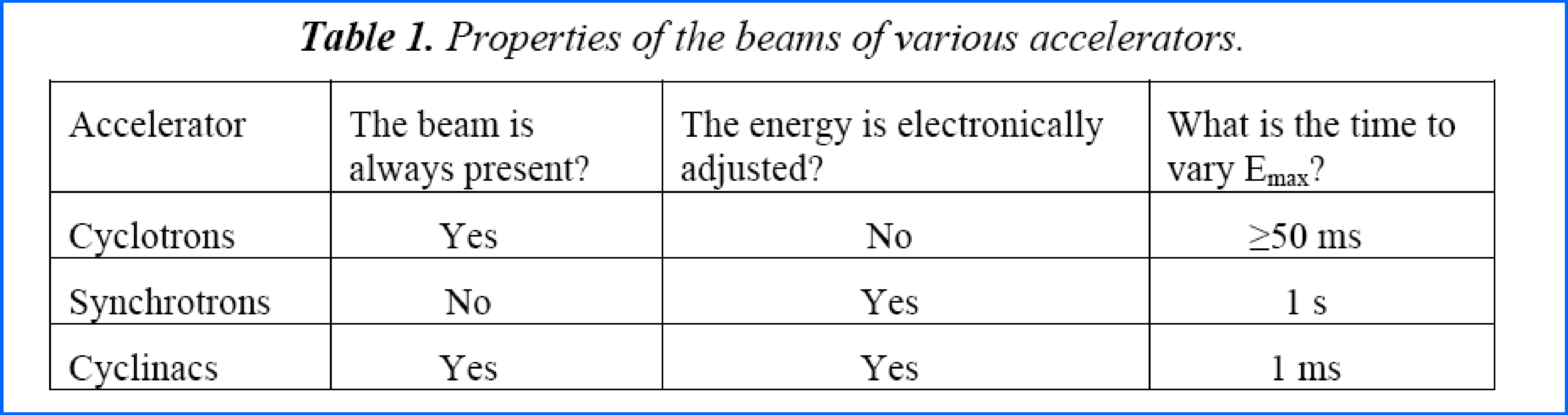


Table 1. Properties of the beams of various accelerators.

Accelerator	The beam is always present?	The energy is electronically adjusted?	What is the time to vary E_{max}?
Cyclotrons	Yes	No	$\geq$50 ms
Synchrotrons	No	Yes	1 s
Cyclinacs	Yes	Yes	1 ms

- **Very important in hadrontherapy to treat moving targets!**

End of part III