Outline

1. Introduction: a historical overview
2. Modern medical diagnostics
3. Particle accelerators for medicine
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
    - The problem of organ motion
    - Innovative gantries
    - The role of imaging
    - Single room facilities
    - Innovative accelerators

The future of hadrontherapy

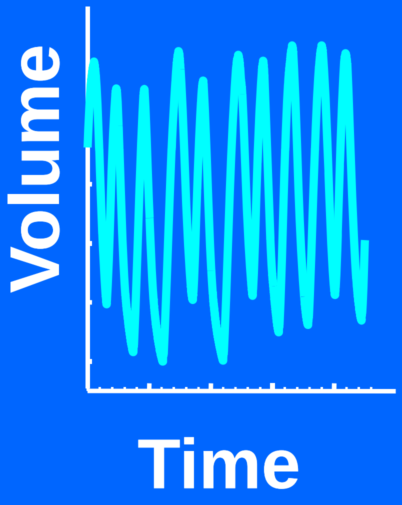
Two main driving forces:

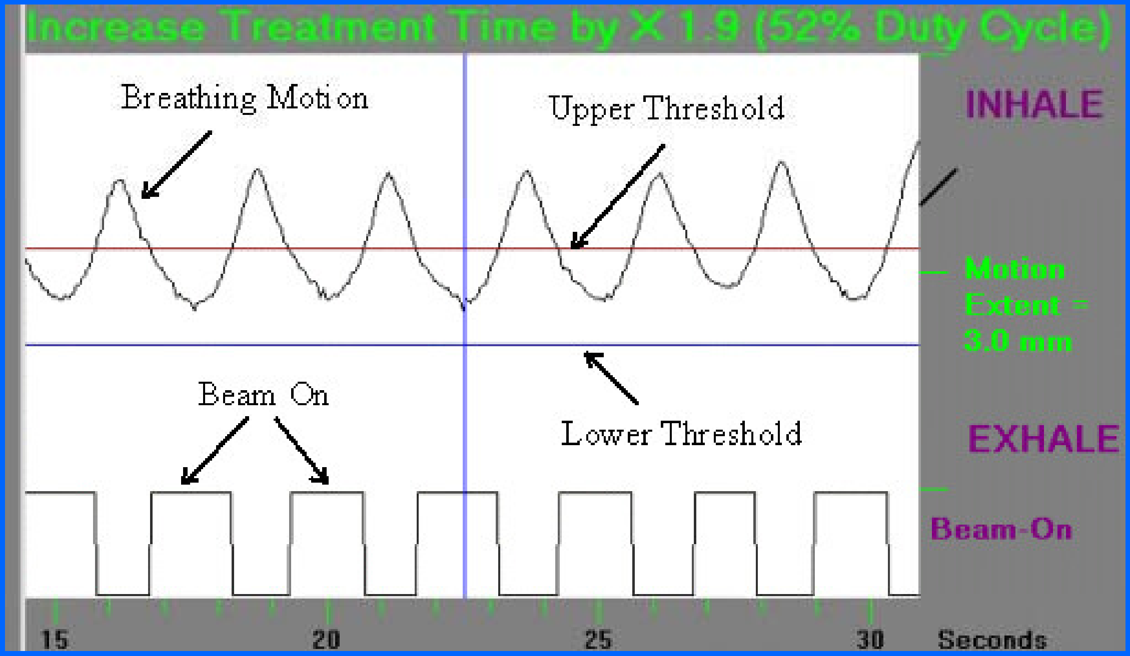
- **Improve the local control reducing secondary effects**

- **Reduce costs, size and complexity**

What happens if an organ moves during irradiation?

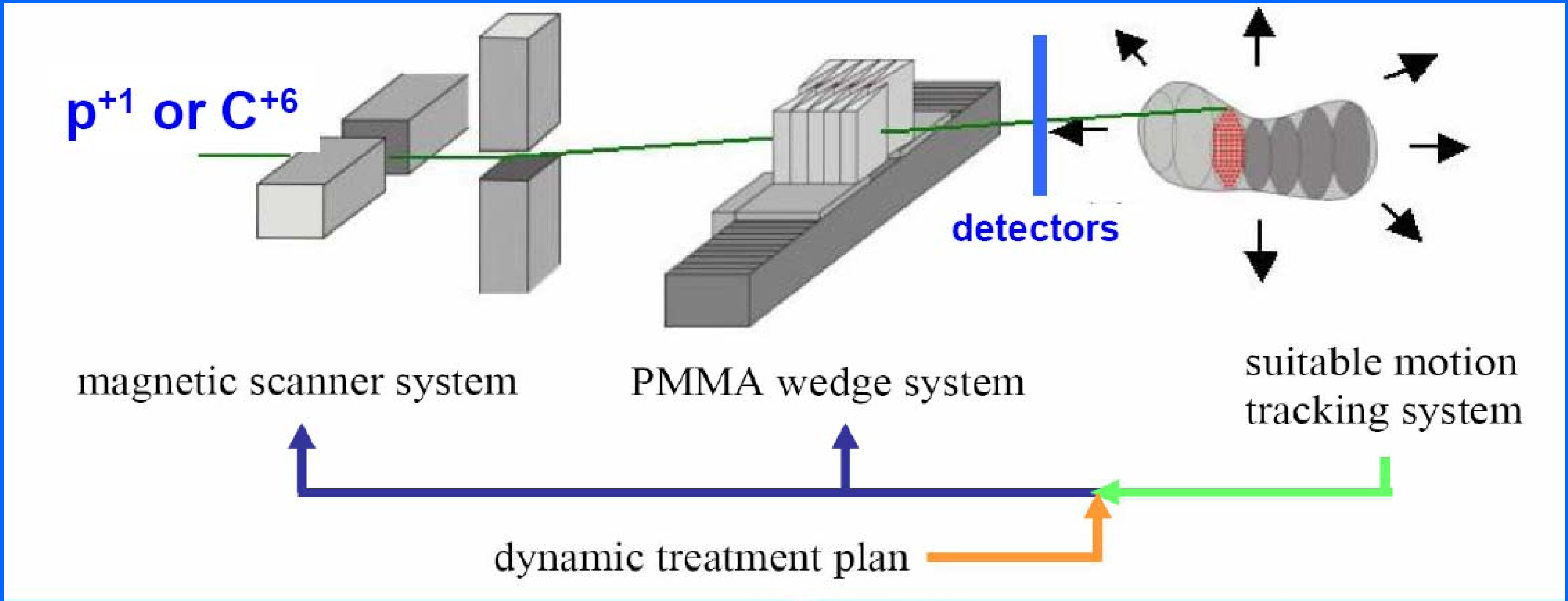
Organ motion (present): respiratory gating





- The beam reaches the patient only when the “gate” is ON
- Synchrotrons: synchronization of the respiration of the patient with the cycle of the accelerator
- Technique already in use in Japan (Tsukuba)

Moving organs (future): organ tracking

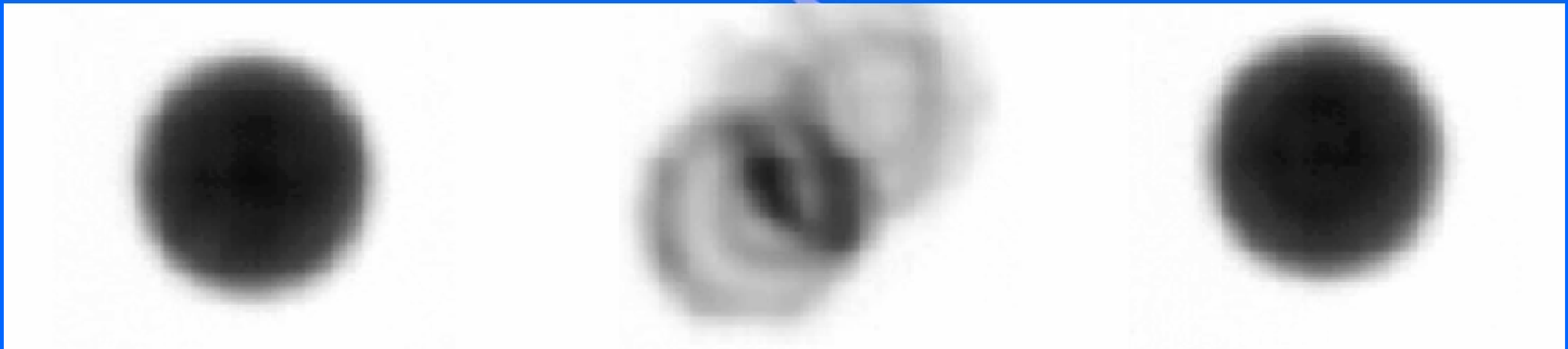


magnetic scanner system

PMMA wedge system

suitable motion
tracking system

dynamic treatment plan



static

moving,
non-compensated

moving,
compensated

Sven O. Grözinger, GSI Darmstadt

Multi-painting

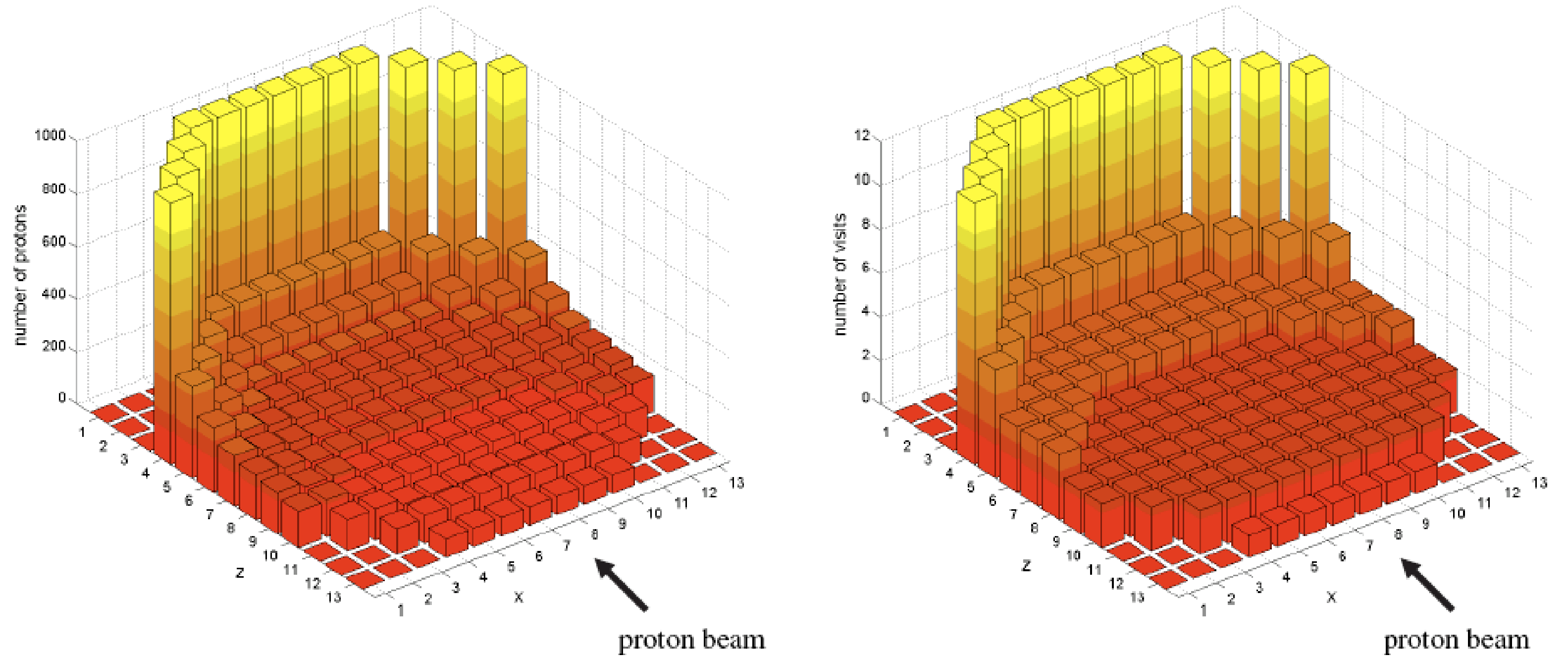


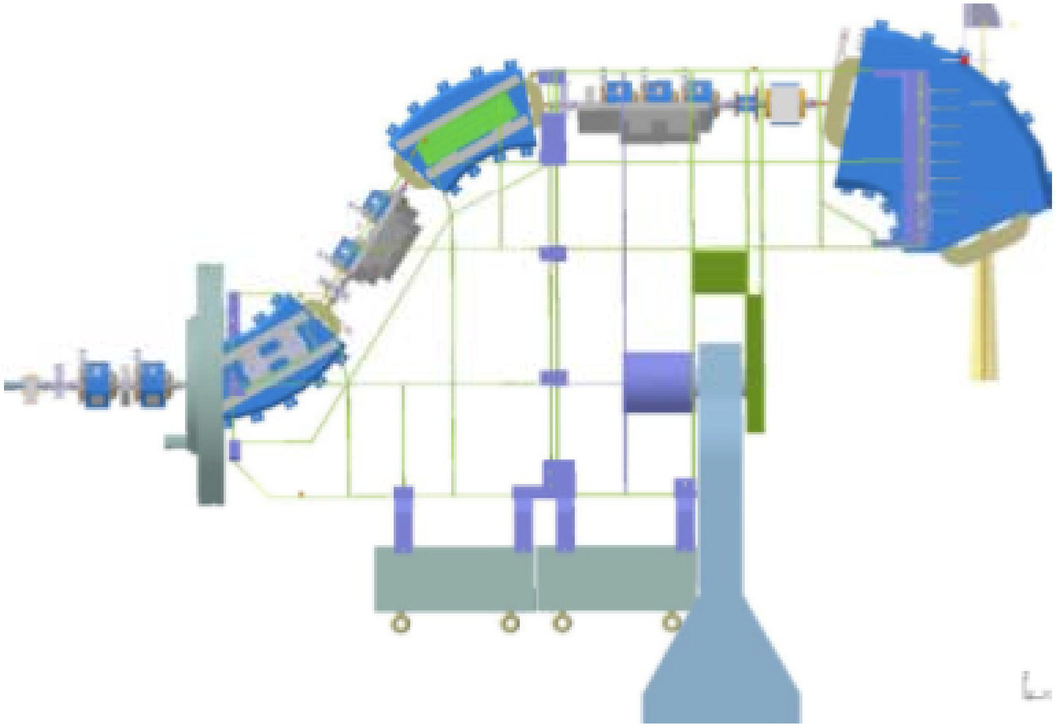
Fig. 12. Number of protons (in arbitrary units) delivered in each voxel of the central transversal slice needed to obtain a ±1.25% uniform dose distribution to a 6.2-cm-radius spherical volume (1 L) centered at a 20 cm depth in water (left); number of "visits" needed to obtain a flat equivalent dose distribution with the condition with the condition that any missing visit dose not change the total local dose by more than 3% (right). The coordinates z and x are given as a number of voxels; z is the longitudinal and x the transversal coordinate [58].

- **In radiation therapy, a ±2.5% uniform dose has to be delivered to the tumor target**
- **If the dose is given in n successive "paintings" of the tumour volume, possible fluctuations due to a missed or over dosed voxel are reduced as $n^{1/2}$**
- **A fast cycling accelerator helps to keep the treatment time low!**
- **The figure refers to the case of a cyclinac**

Innovative gantries

The Gantry 2 at PSI

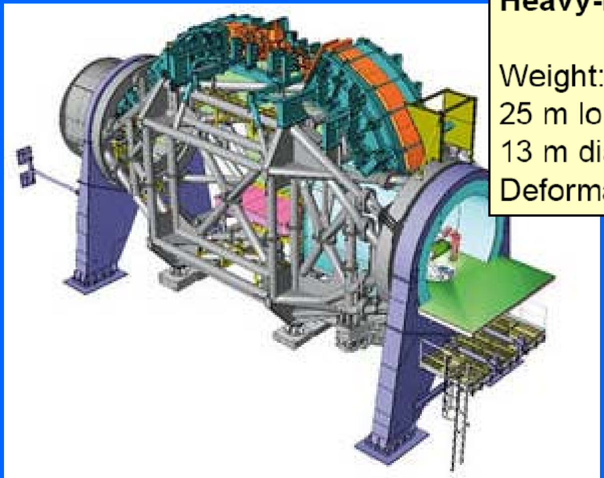
- **A tool for developing advanced beam scanning techniques**
  - Iso-centric layout (~ 4 m radius)
  - Double magnetic scanning (parallel) – started upstream of the last 90° bend
  - Dynamic beam energy variations with the beam (gantry beam line with laminated magnets)



- **New characteristic**
  - The new PSI gantry rotates only on one side by -30° to 185°
  - Flexibility of beam delivery achieved by rotating the patient table in the horizontal plane
  - Analogy with longitude and latitude in world-geography

Courtesy E. Pedroni, PSI

Gantries for carbon ions?

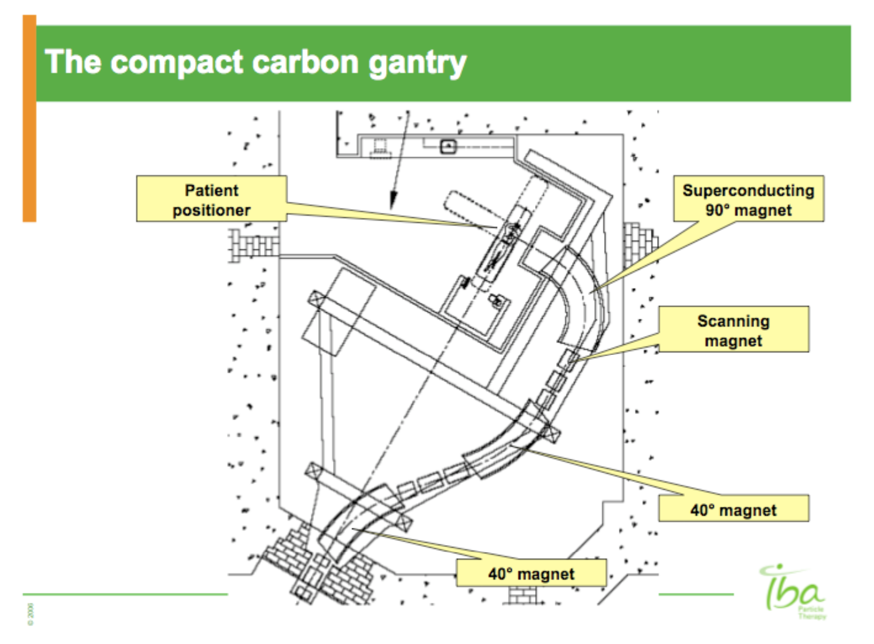


Heavy-ion Gantry

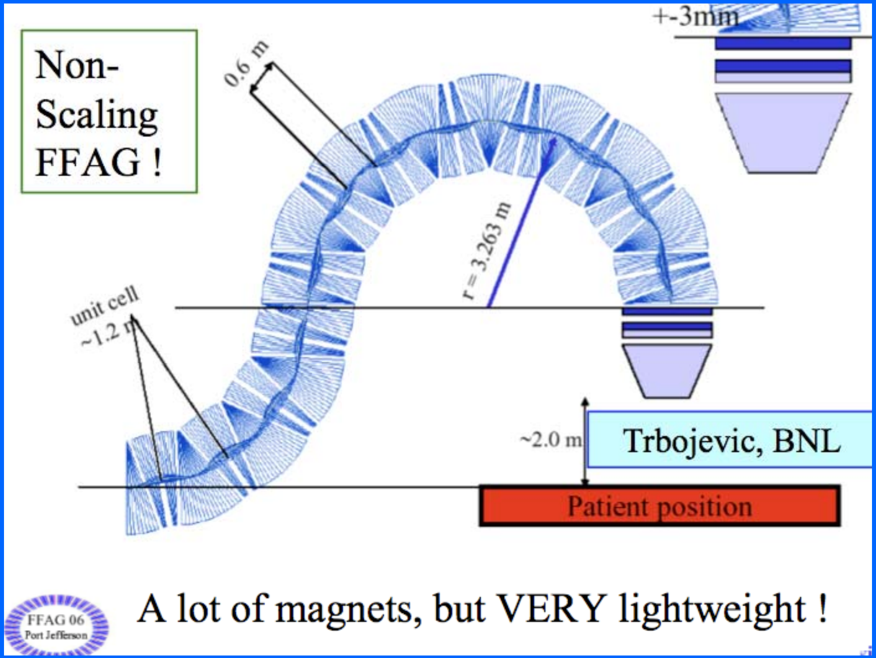
Weight: 600 t
25 m long
13 m diameter
Deformation < 0.5 mm

The gantry installed at HIT is the only one ever built!

Solutions for the future?



The compact carbon gantry



Non-Scaling FFAG !

A lot of magnets, but VERY lightweight !

The role of imaging

PET can help for planning in radiation therapy

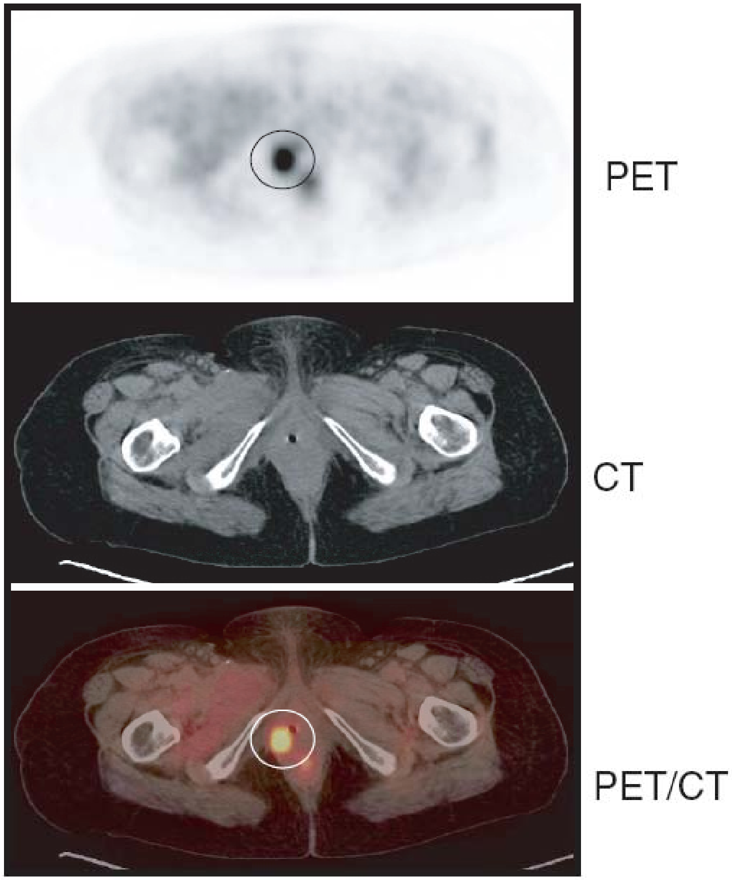
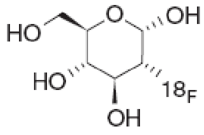
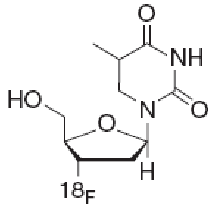
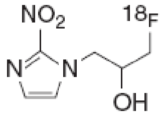
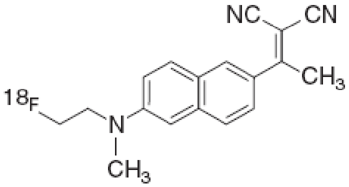


Figure 1 PET, CT, and PET/CT images of a patient with cervical cancer, undetected except on the PET images. (The circles highlight the focal area of FDG uptake, indicative in this case of cervical cancer, on the PET image and the PET/CT overlay image, but no abnormality is seen on the standard CT image.)

Radio labeled tag	Molecular structure	Physiological parameter	Example of clinical use
^{18}F FDG		Glucose utilization	Possible malignancy
^{18}F FLT		Cell proliferation	Possible malignancy
^{18}F MISO		Cell proliferation	Determining radiation exposure
^{18}F FDDNP		Amyloid plaque binding agent	Alzheimer's disease marker

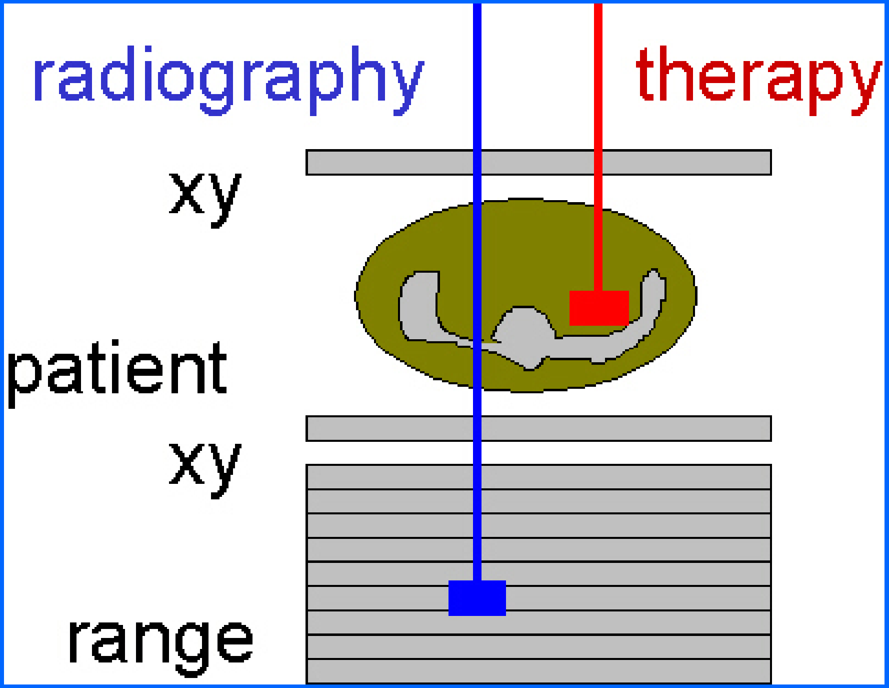
R. Nutt et al., CLINICAL PHARMACOLOGY & THERAPEUTICS,

Vol. 81 Num. 6, Pag. 792, June 2007

A research topic: proton radiography

- CT gives information on the density of electrons (Hounsfield numbers)
- CT is commonly used in diagnostics
- CT is commonly used in conventional radiation therapy to calculate the treatment planning
  - X and MeV gamma rays interact with the electrons
- CT is used also in proton and ion therapy to calculate the treatment planning but…
  - Protons and ions interact with matter through dE/dx -> density ρ, Z
  - Compton effect is proportional to Z but not the photoelectric effect !
  - Corrections are applied

Proton radiography and proton CT



Radiography with X-rays

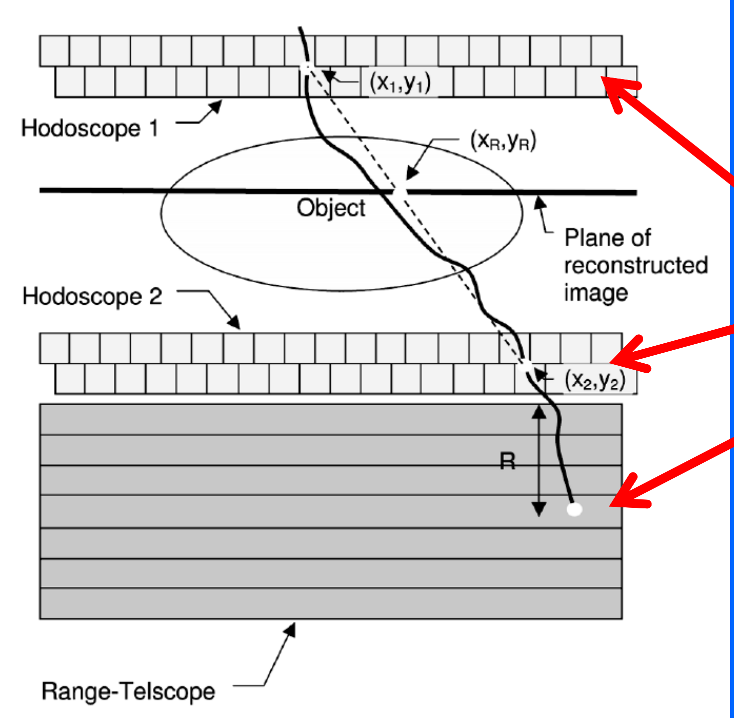
- **“Counts” the number of photons**

(attenuation coefficient)

Proton radiography

- **Protons with enough energy to penetrate the body**
- **Residual range mesurement**

Proton radiography



Scintillating fibers

E. Pedroni et al., PSI

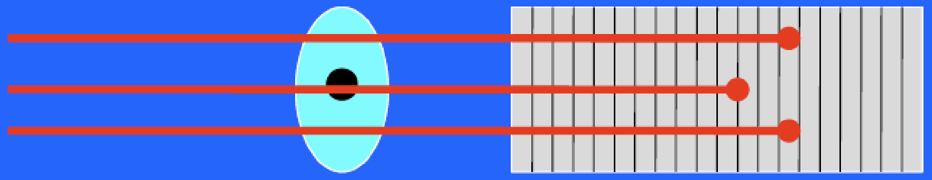
Advantages

- **No need for corrections like for X-ray CT**
- **Less dose to the patient (every proton brings information!)**

Disadvantages

- **Need of large accelerators usually used also for therapy (timing problem)**
- **For now it is a research issue (PSI)**

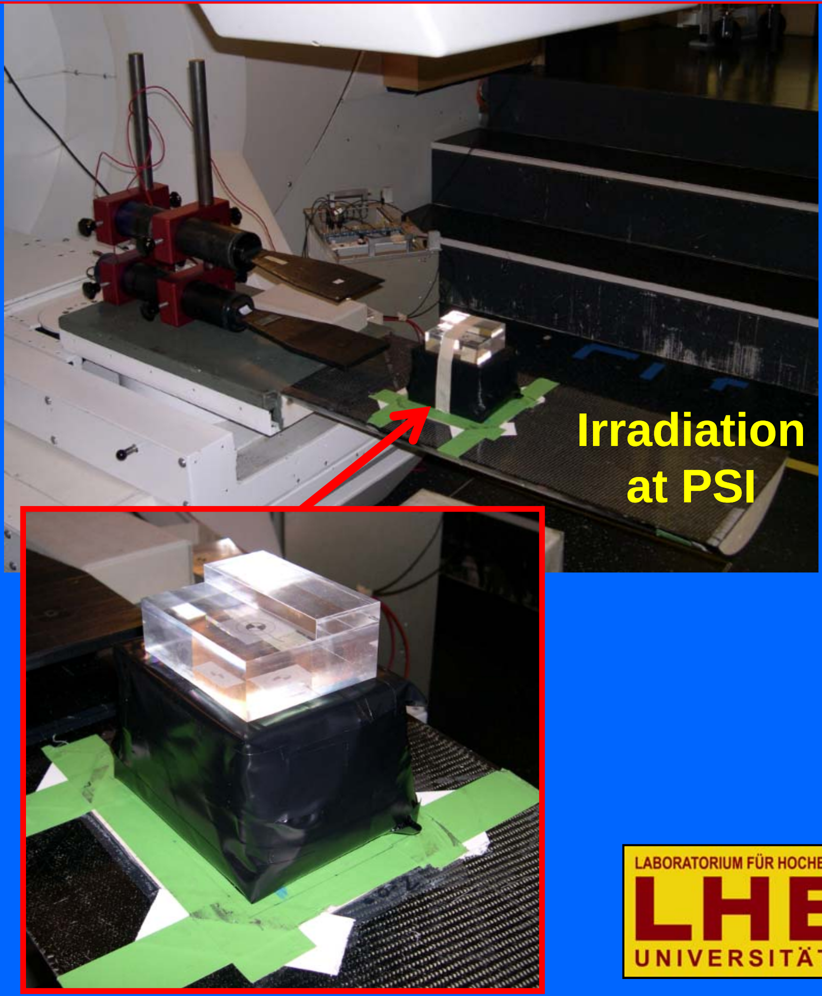
Proton radiography with nuclear emulsions



Proton beam

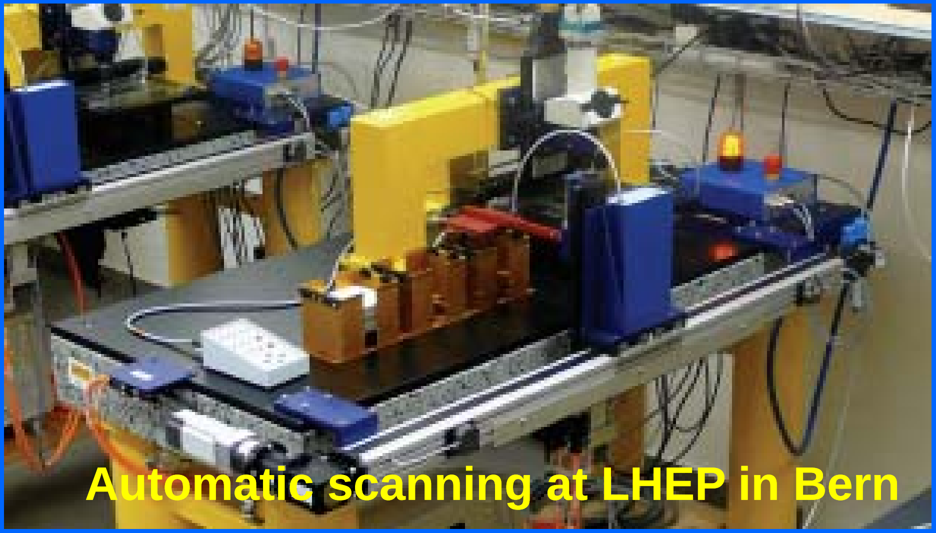
Object

“Brick” made of nuclear emulsions and plastic absorbers

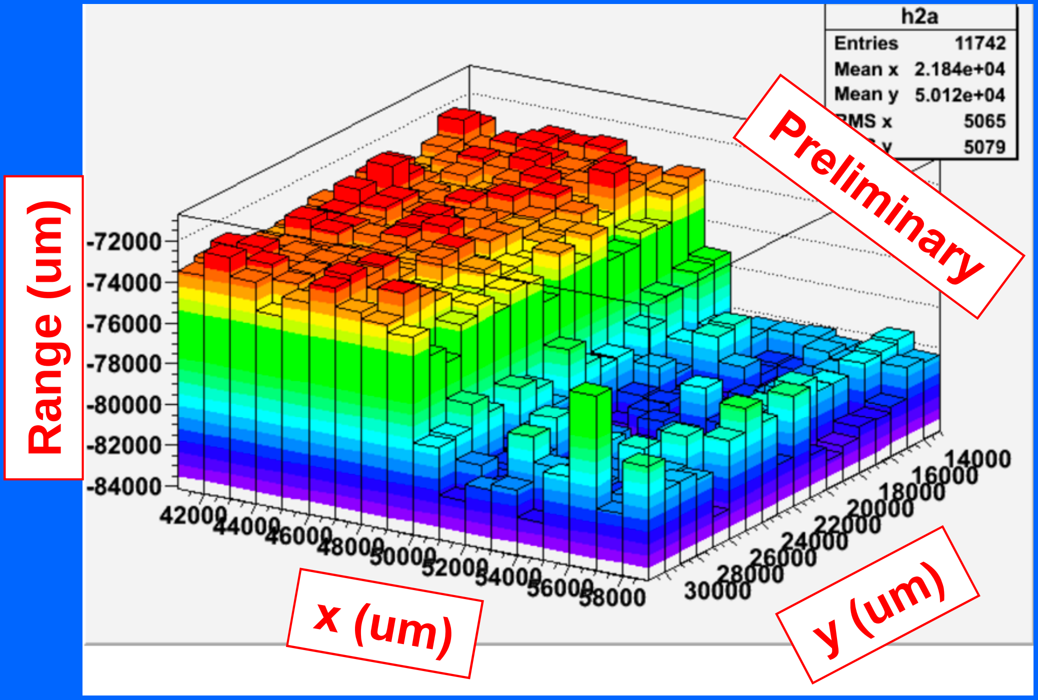


Irradiation at PSI

LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN



Automatic scanning at LHEP in Bern



S. Braccini et al, submitted to JINST, 2010.

Single room facilities

How many treatment rooms are needed?

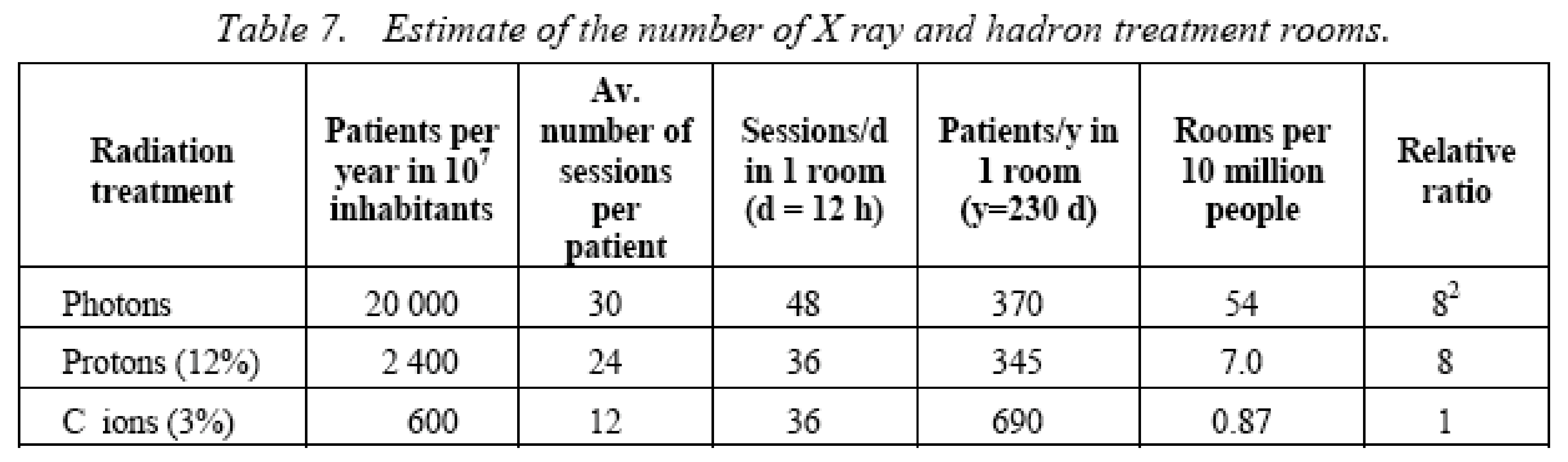


Table 7. Estimate of the number of X ray and hadron treatment rooms.

Radiation treatment	Patients per year in 10^7 inhabitants	Av. number of sessions per patient	Sessions/d in 1 room (d = 12 h)	Patients/y in 1 room (y=230 d)	Rooms per 10 million people	Relative ratio
Photons	20 000	30	48	370	54	8^2
Protons (12%)	2 400	24	36	345	7.0	8
C ions (3%)	600	12	36	690	0.87	1

Single room facilities for proton therapy?

- **250 MeV, 15 tons synchrocyclotron mounted on its gantry**
- **10 T superconducting magnet !**
- **First full system almost constructed**
- **Final acceleration test still to be performed**
- **FDA clearance pending**

Courtesy Still River Systems

Innovative accelerators

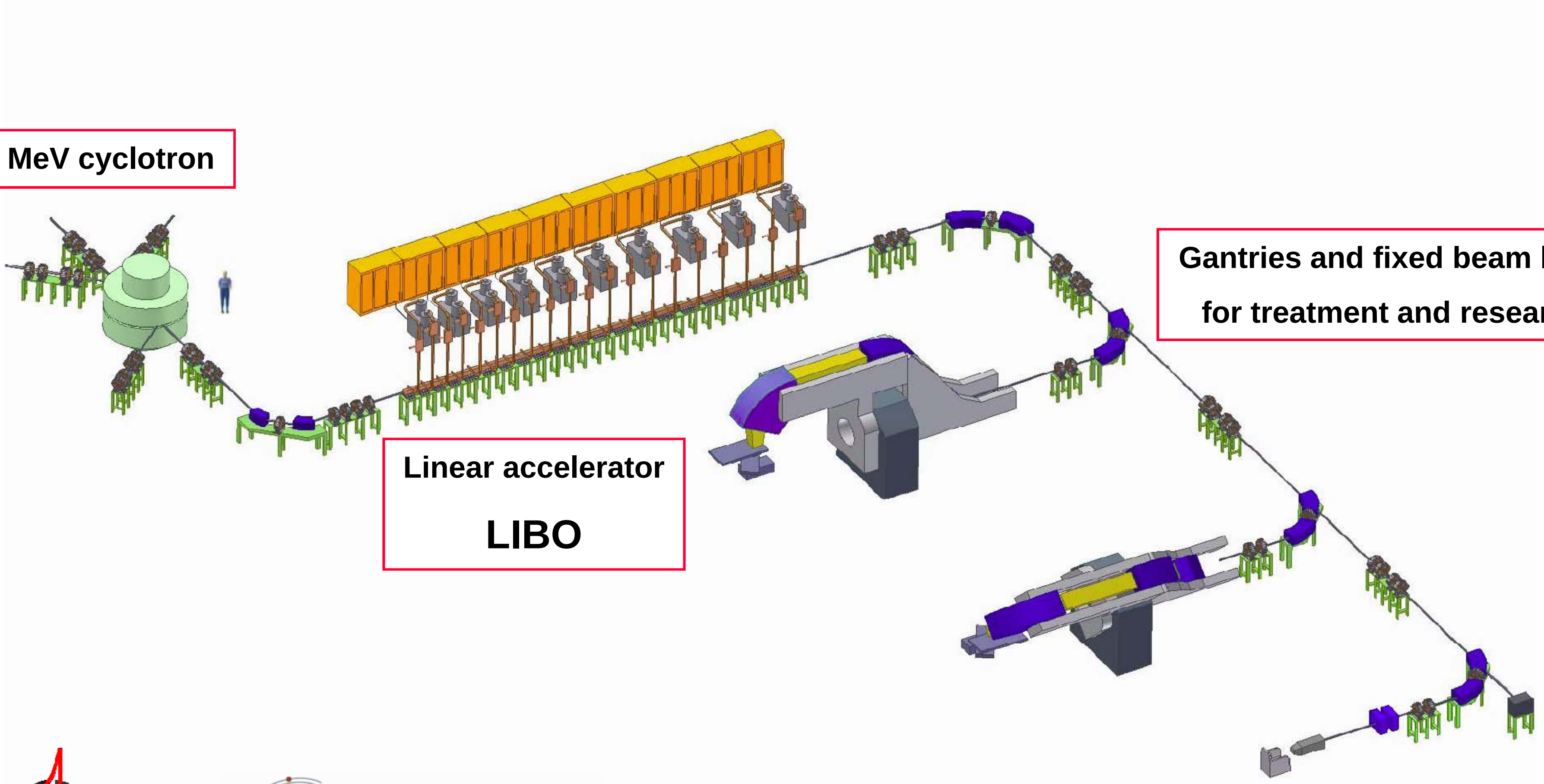
Cyclotrons and synchrotrons (Present)

- **Proton therapy: 4-5 m diameter cyclotrons and 6-8 m diameter synchrotrons**
- **Carbon ions: 20-25 meter diameter synchrotrons**

Linacs for hadronterapy?

IDRA

Institute for Diagnostics and RAdiotherapy



30 MeV cyclotron

Linear accelerator

LIBO

Gantries and fixed beam lines

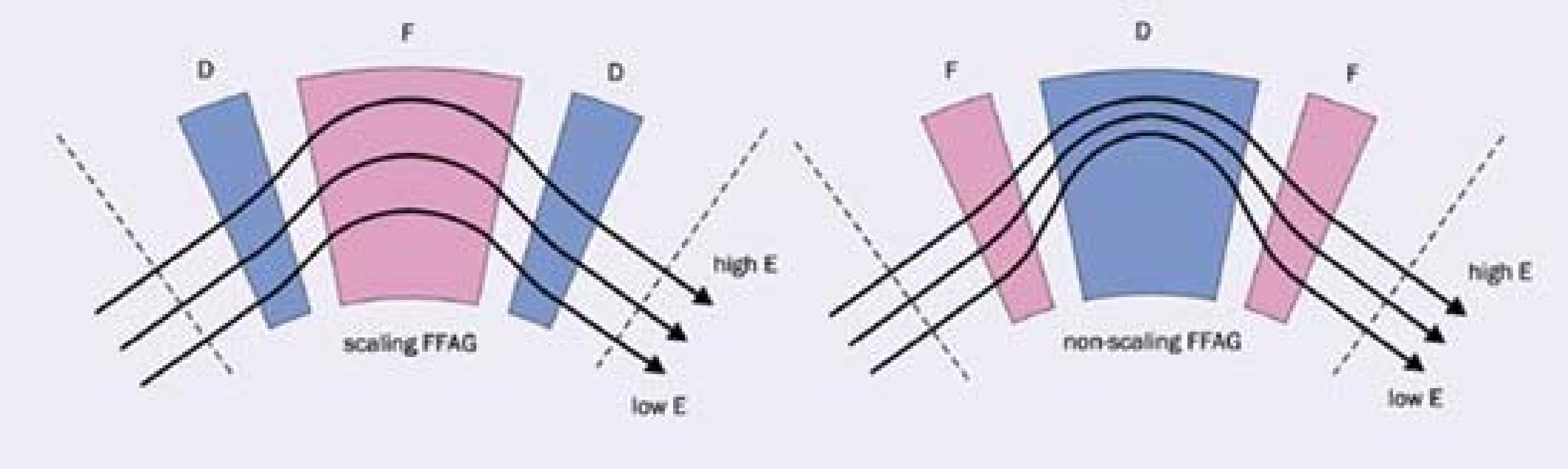
for treatment and research

TERA → ADAM Applications of Detectors and Accelerators to Medicine

Courtesy U. Amaldi

FFAGs?

- Fixed Field Accelerating Gradient Accelerator (FFAG)
  - Fixed magnetic field
  - Large aperture beam pipe to allow different energy beams
  - Composed by many magnets organized in triplets
  - Potential advantages for hadronterapy: variable energy, fast cycling
  - The extraction and the transport of the beam to the patient is challenging
  - Possibility of high currents



FFAG for protons

Fig. 7. The first proton therapy radial sector 150 MeV S-FFAG, built and commissioned at KEK in 2003.

FFAG for carbon ions?

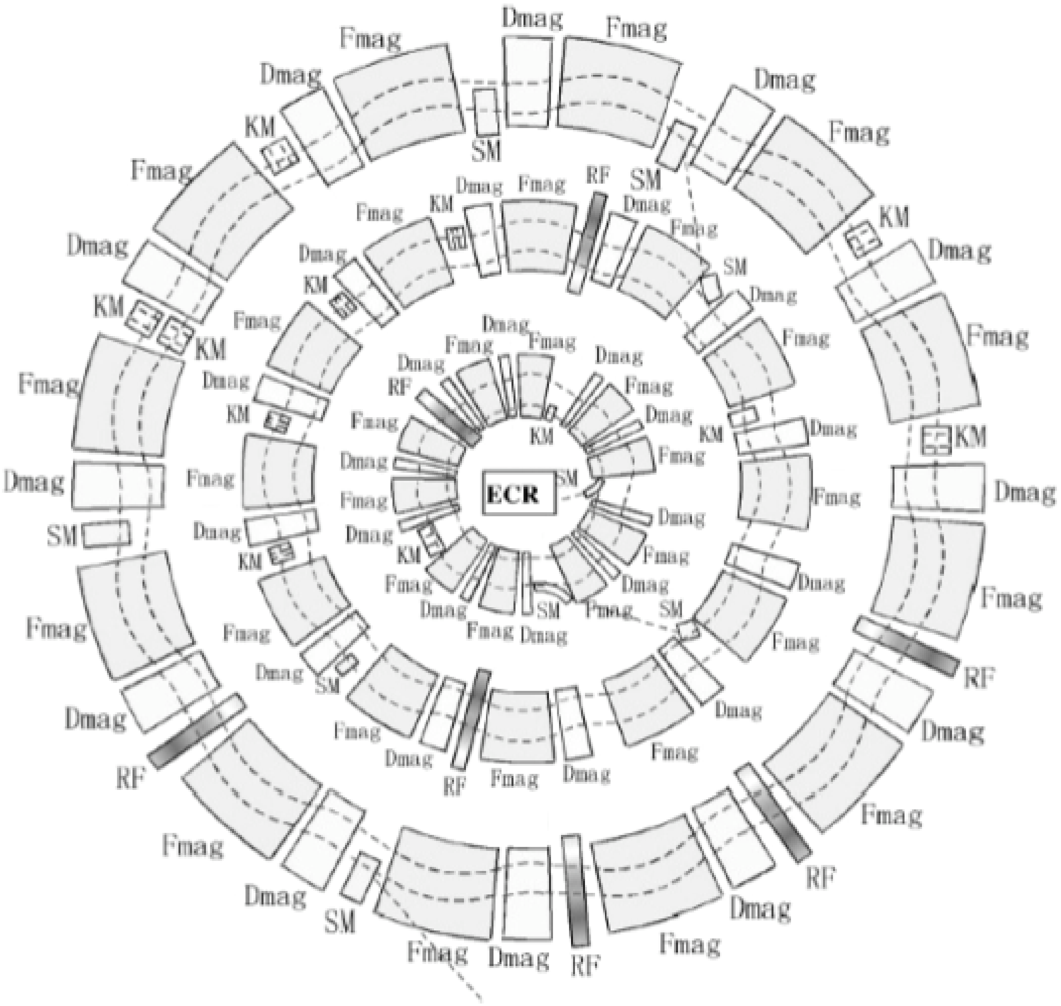
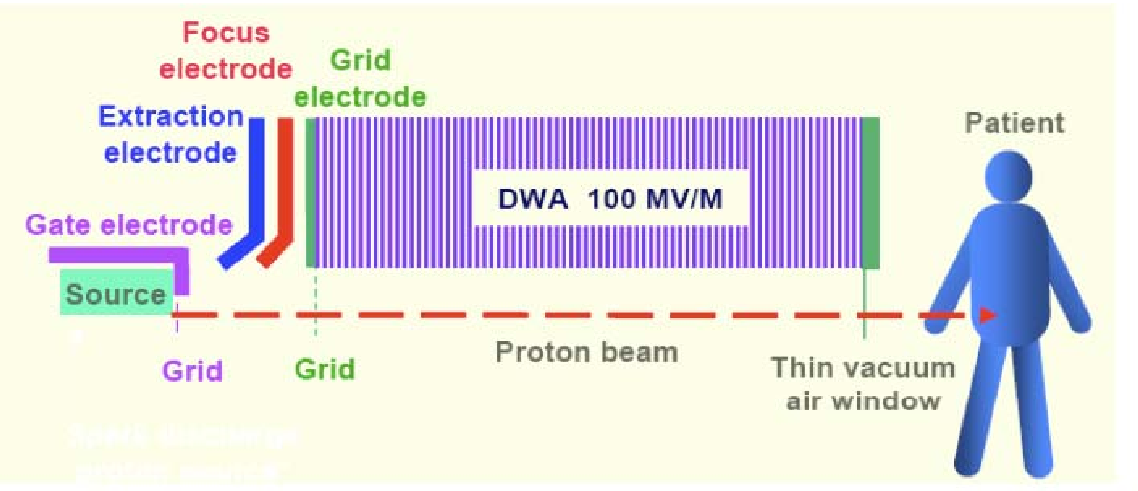


Fig. 13. A new design for $^{12}C^{6+}$ and proton, new radial sector S-FFAG accelerators for the Chiba facility in Japan. Cavities (RF), septum (SM), and kicker magnets (KM) are shown in each ring.

- 3 FFAG rings in succession:
  - First: from 40 keV/u (from ECR ion source) to 6 MeV/u
  - Second 6–100 MeV/u
  - Third 100-400 Mev/u
- Very complex project proposed for Chiba
- A synchrotron was chosen instead.

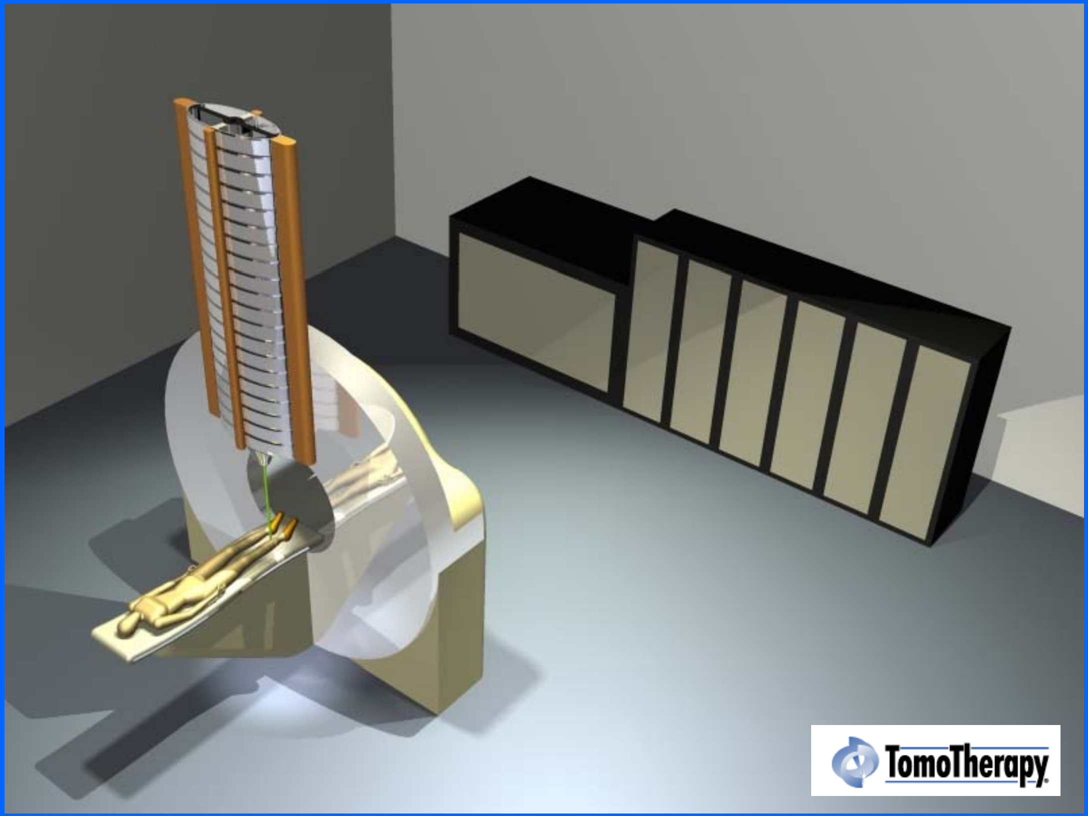
D. Trbojevic, RAST2, 2009.

New technologies for accelerating particles?

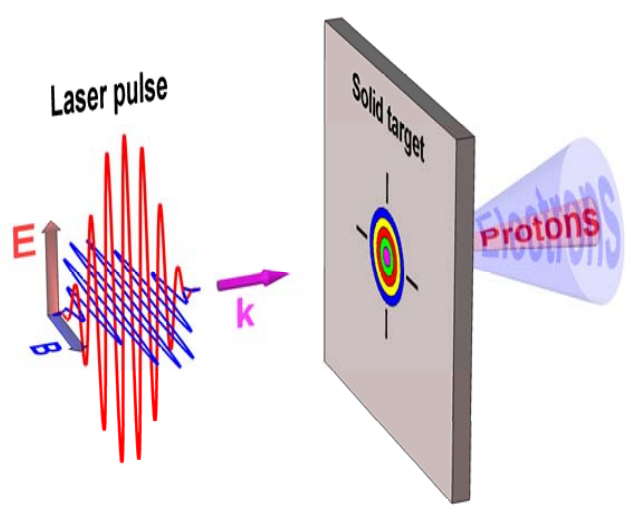


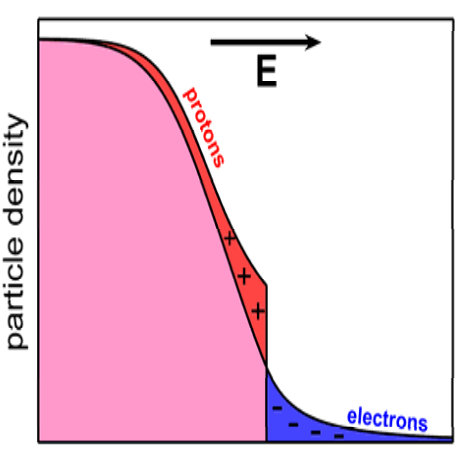
- **Dielectric Wall Accelarator (DWA)**
- **Very intense pulsed electric fields made possible by the use of special innovative dielectric materials (Blumlein)**
- **Very high accelerating gradients 100 MV/m can be obtained**

- **About 2 m long accelerator mounted on a gantry**
- **Single room solution for proton therapy**
- **Project initiated by LLNL (USA)**
- **Partnership agreement with TomoTherapy Inc.**
- **Prototype under development**



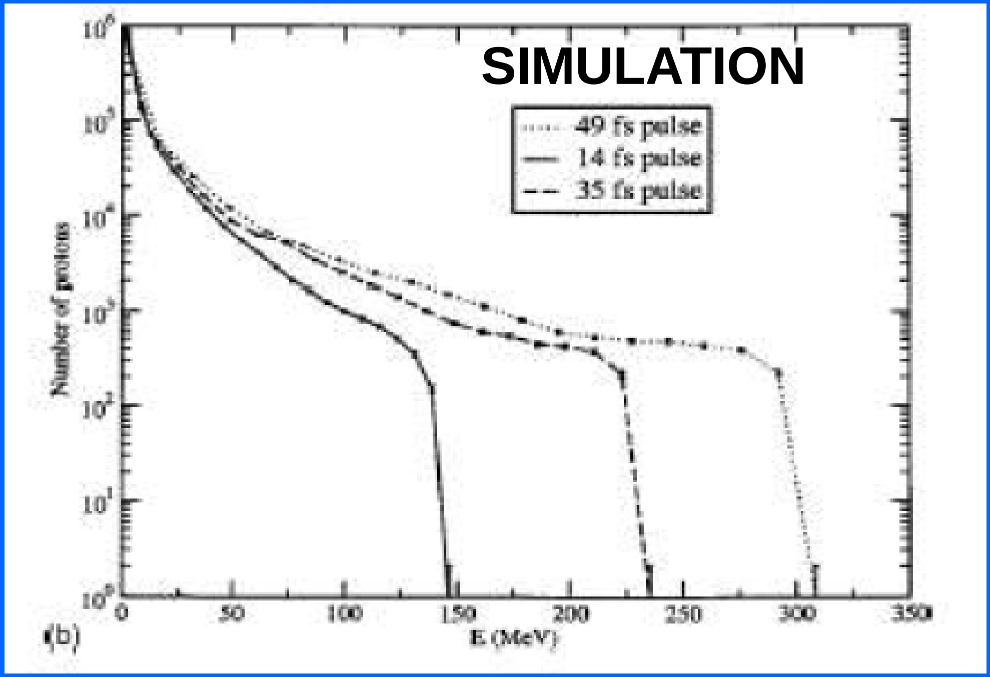
The long term future: laser – plasma accelerators?



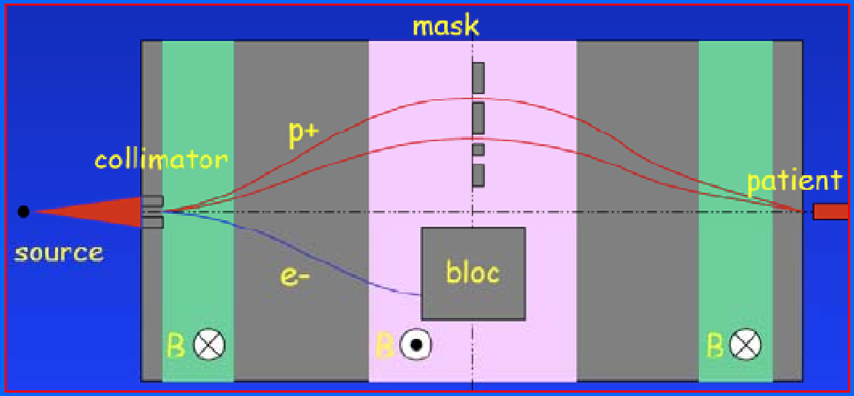


The mechanism

- ~ 10^{13} protons measured
- Max. proton energy: 58 MeV at LLNL (USA)

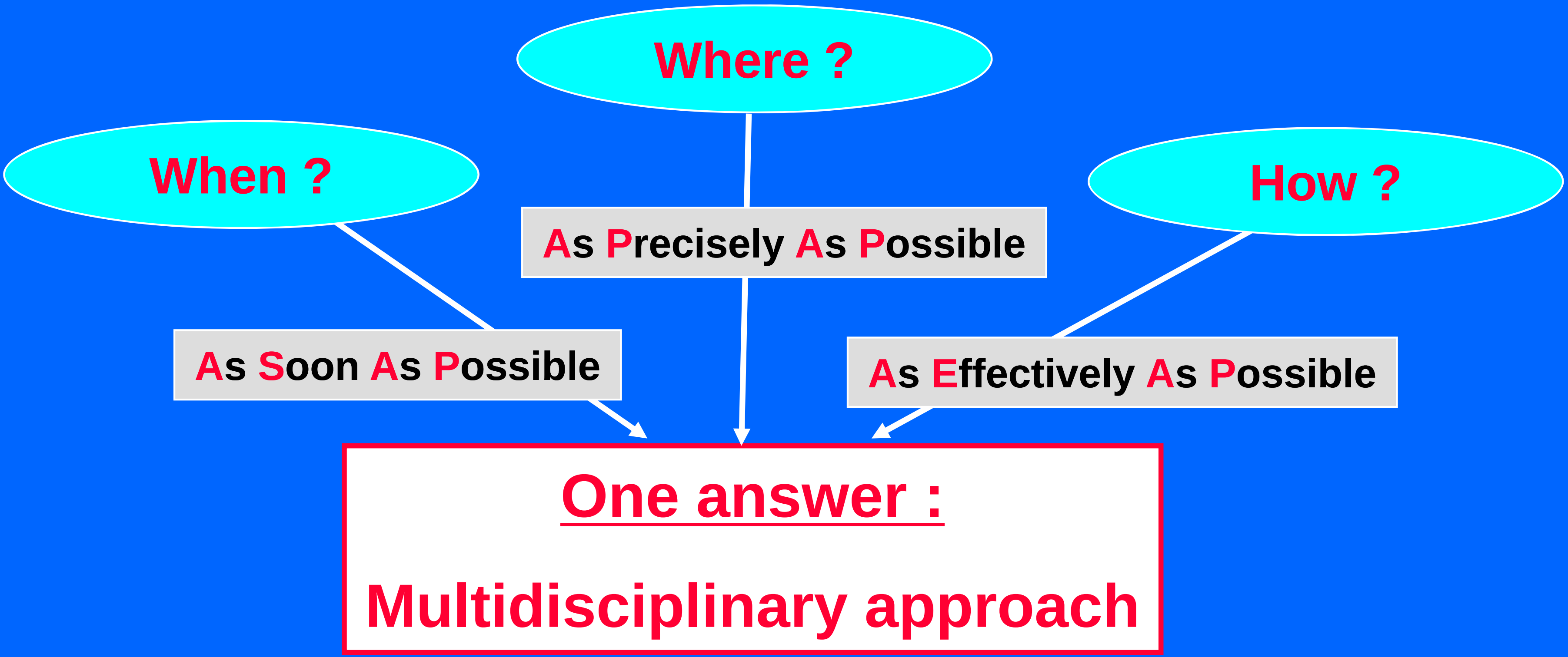


- Laser: 50 fs, 50 J (Petawatt!)
- I = 10^{21} W/cm^2
- >10^{11} protons up to 300 MeV
- Continuous energy, the dose distribution system is difficult!



The challenge of medical sciences

Three fundamental questions to detect and cure the disease:



Where ?

When ?

How ?

As Precisely As Possible

As Soon As Possible

As Effectively As Possible

<u>One answer :</u>

Multidisciplinary approach

Some examples :

- **Non-invasive screening (molecular markers, imaging, …)**
- **High precision diagnostics (MRI, TC, PET, SPECT, …)**
- **High precision non-invasive therapy (hadrontherapy, …)**

Conclusions and Outlook

- **Since the beginning of particle physics, more than one-hundred years go…**

Particle physics offers medicine and biology very powerful tools and techniques to study, detect and attack the disease

To fully exploit this large potentiality, all these sciences must work together!

Physics is beautiful and useful!

(Ugo Amaldi)

References

Selected textbooks:

- Accelerators: CERN Accelerator School (CAS), Cyclotrons, linacs and their applications, CERN-96-02 (http://cas.web.cern.ch/cas/Proceedings.html).
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- Hadrontherapy: H. M. Kooy and T. F. Delaney, Proton and Charged Particle Radiotherapy, Lippincott Williams & Wilkins, 2007.

Review papers:

- U. Amaldi and S. Braccini, Present and Future of Hadrontherapy, in Superstrong Fields in Plasmas, D. Batani et al. editors, American Institute of Physics, 2006, p. 248.
- U. Amaldi, S. Braccini and P. Puggioni, High Frequency Linacs for Hadrontherapy, in Reviews of Accelerator Science and Technology, vol. II (RAST2), World Scientific, 2009, 111-131.
- S. Braccini, Scientific and Technological Development of Hadrontherapy, World Scientific, ISSN 2010-0868 and arXiv:1001.0860.
- U. Amaldi, S. Braccini et al., Accelerators for hadrontherapy: from Lawrence cyclotrons to linacs, to be published by Nuclear Inst. and Methods in Physics Research A, 2010.

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End of part VIII