laboratoire d'optique appliquée

Medical Applications with Laser Plasma Accelerators

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2nd Annual EUCARD meeting, PARIS, May 10-13 (2011)

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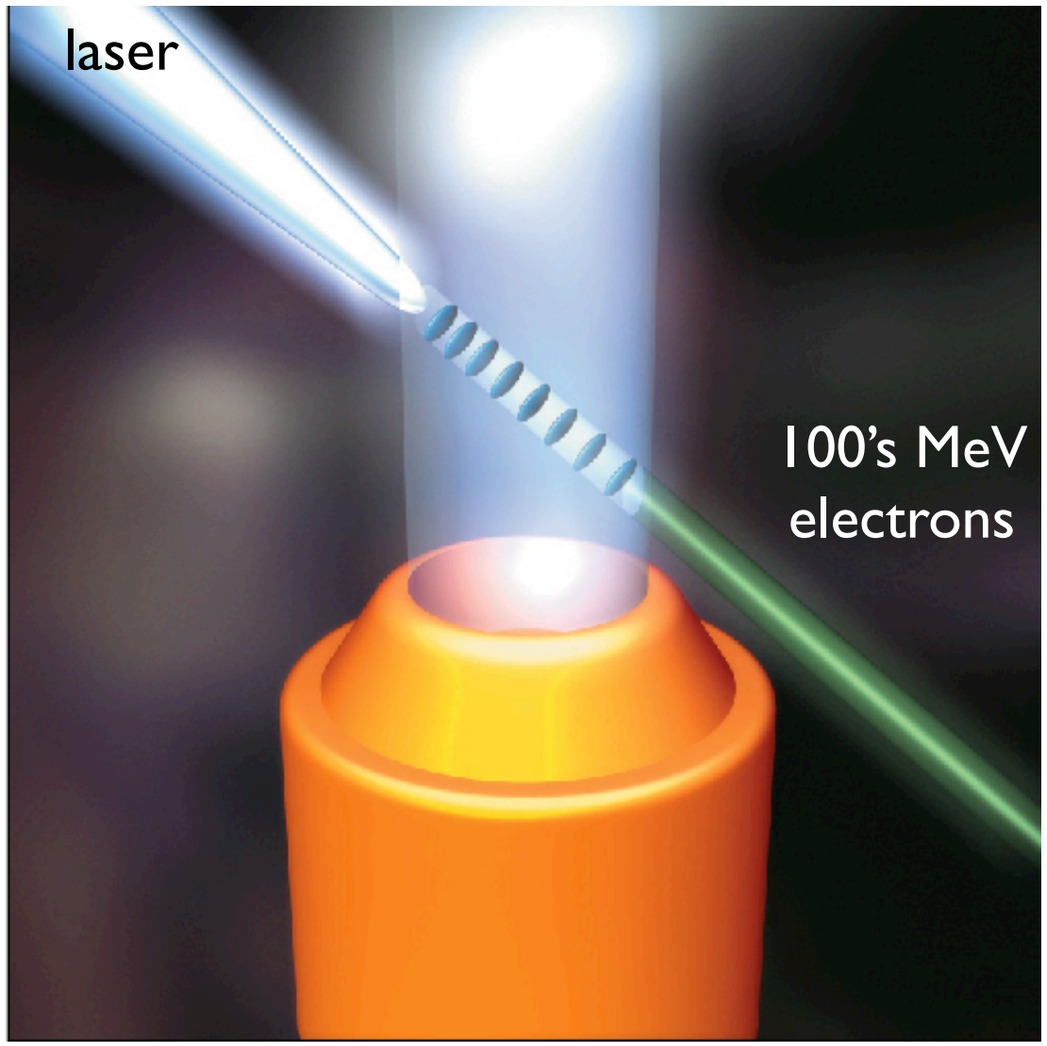
Thanks to :

Compactness of Laser Plasma Accelerators

EuCARD

1 mm



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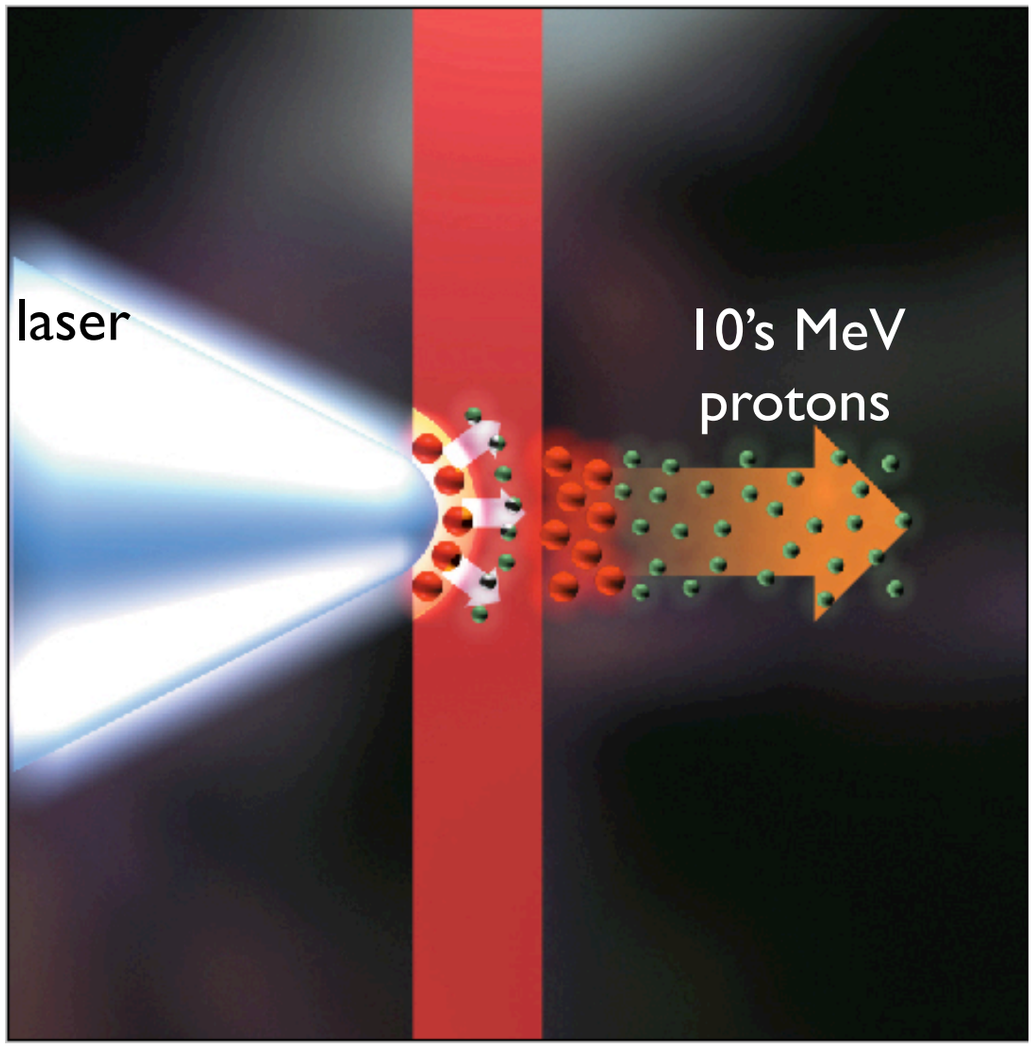


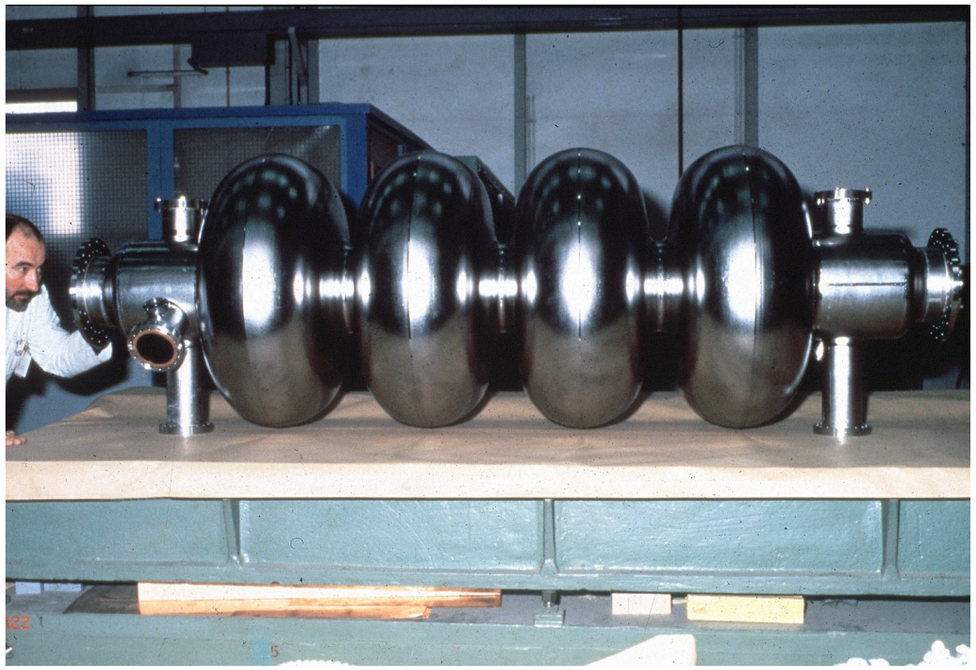
V. Malka et al., Science **298**, 1596 (2002)
V. Malka et al., Nat. Phys **4** (2008)

loa

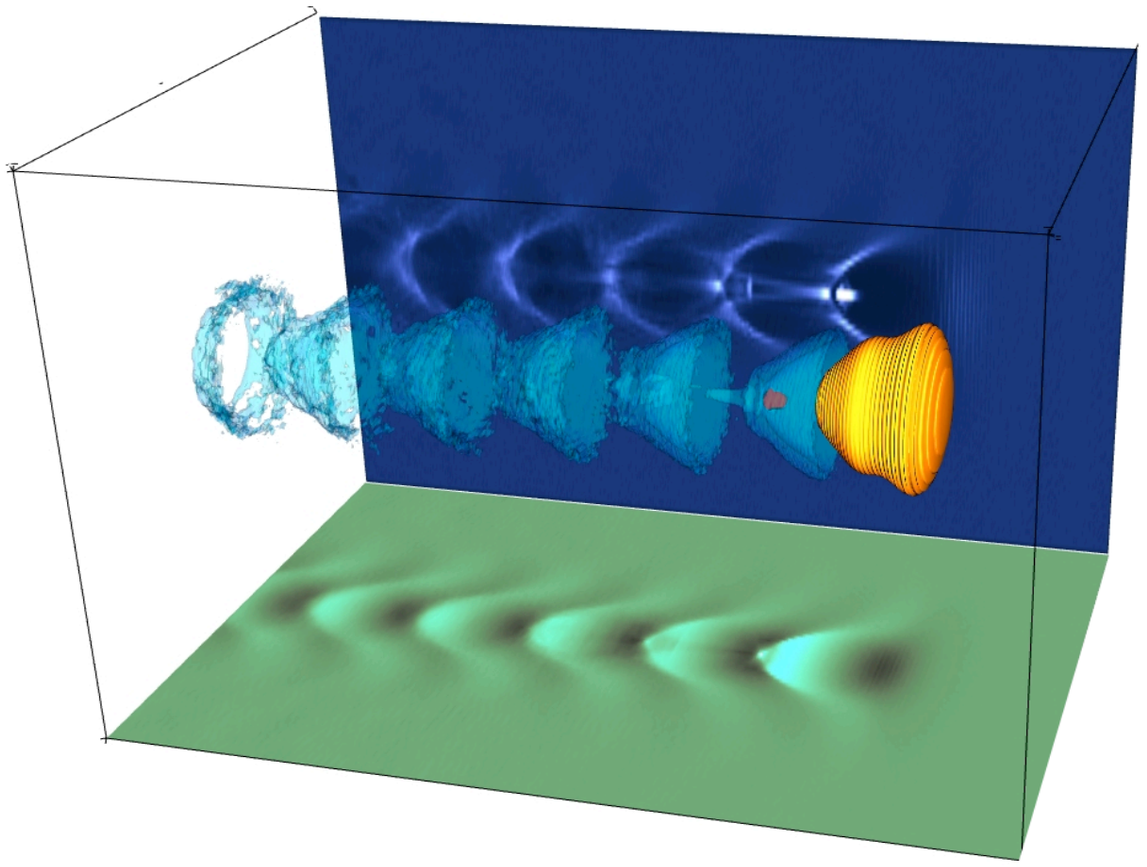
2nd Annual EUCARD meeting, PARIS, May 10-13 (2011)

Compactness of Laser Plasma Accelerators

RF Cavity



Plasma Cavity



Electric field < 100 MV/m

Electric field > 100 GV/m

V. Malka et al., Science **298**, 1596 (2002)

Properties of e-beam produced by LPA

Good beam quality & Monoenergetic dE/E down to 1 % √

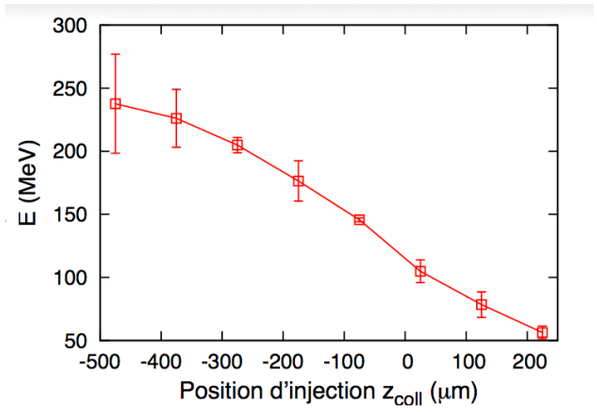
Beam is very stable √

Energy is tunable: 20-300 MeV √

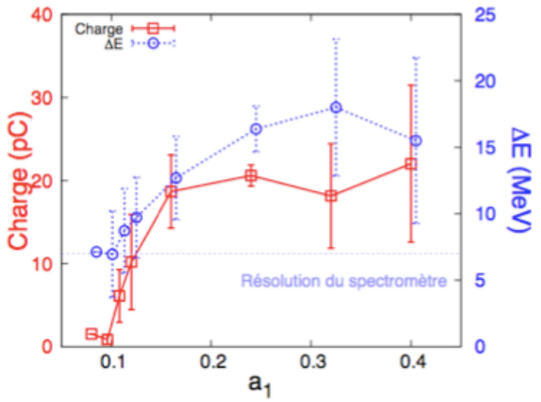
Charge is tunable: 1 to tens of pC √

Energy spread is tunable: 1 to 10 % √

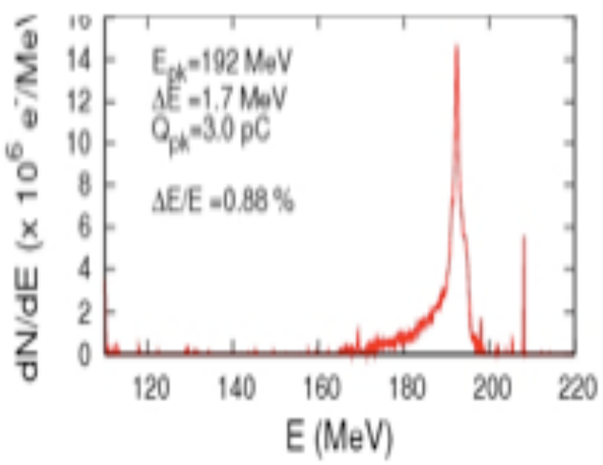
Ultra short e-bunch : 1,5 fs rms √



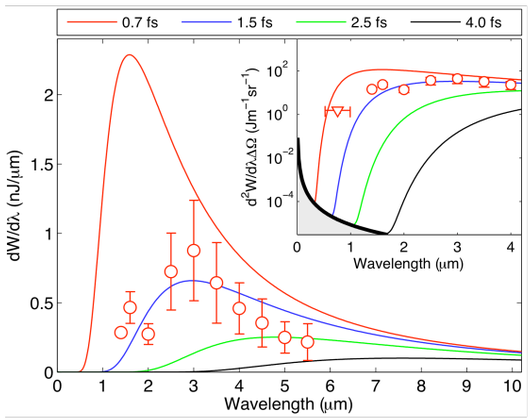
J. Faure *et al.*, Nature **444**, 737 (2006)



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

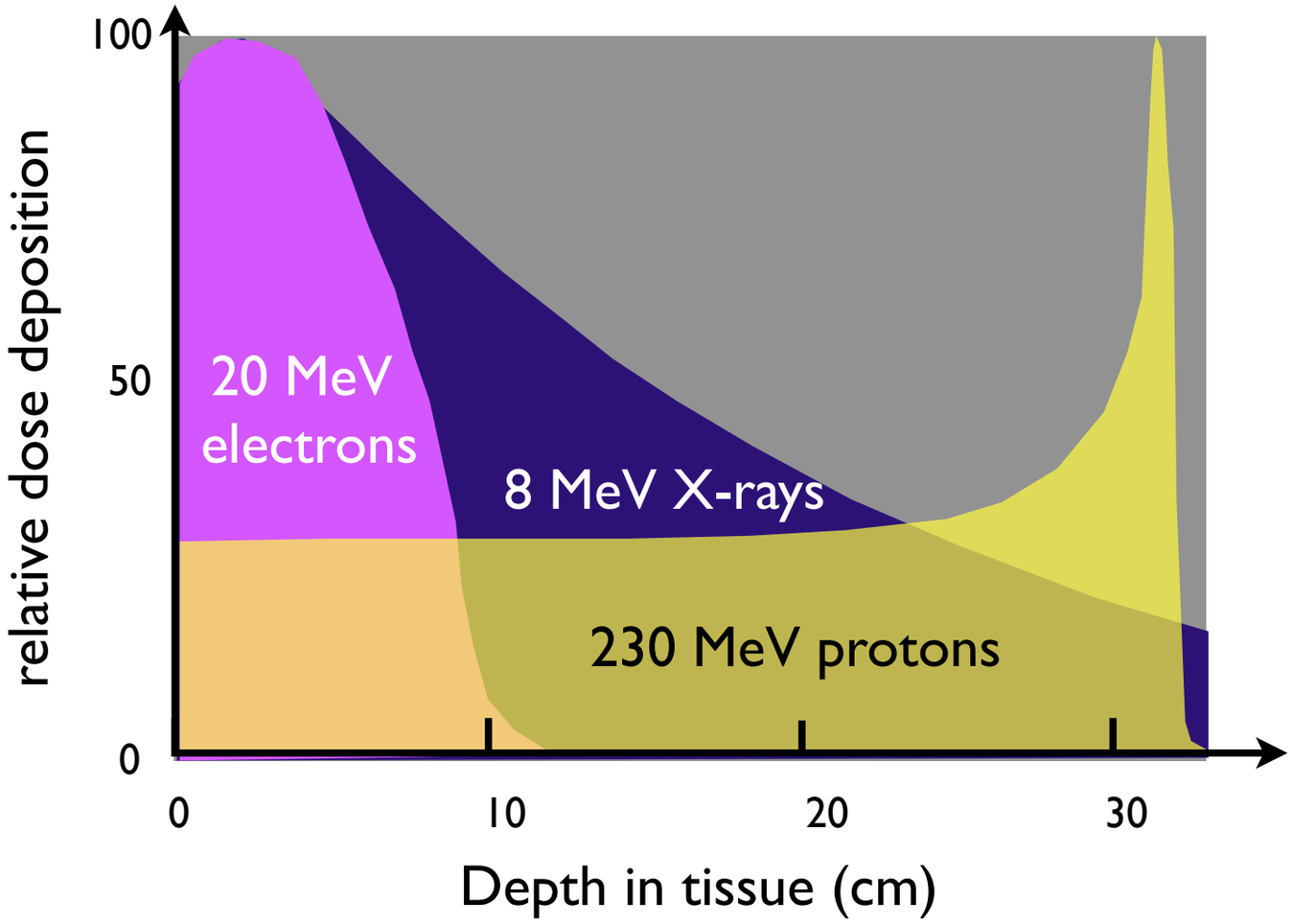


C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)



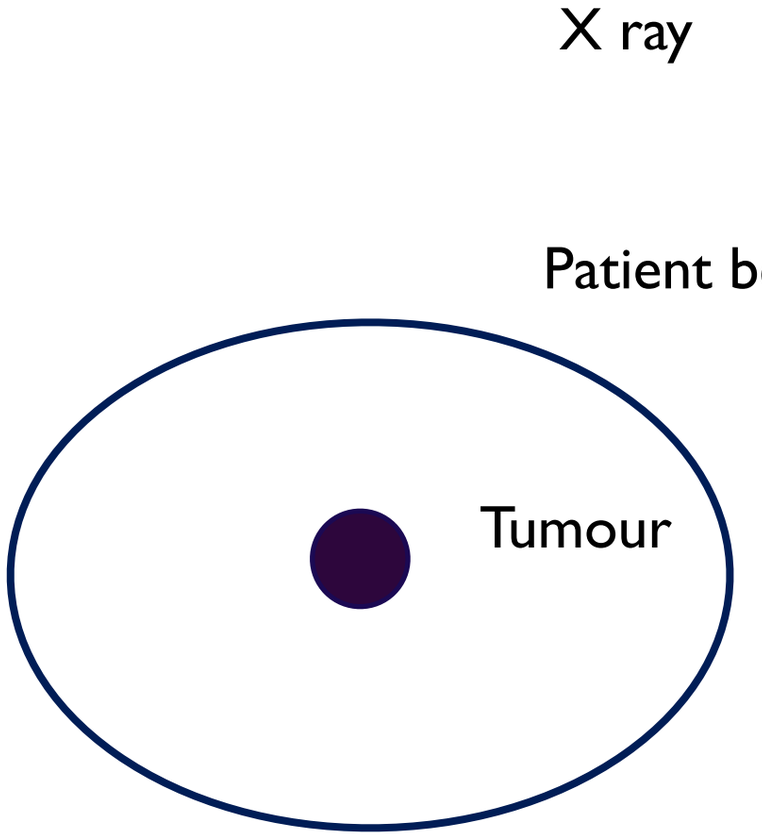
O. Lundh *et al.*, Nature Physics, March 2011

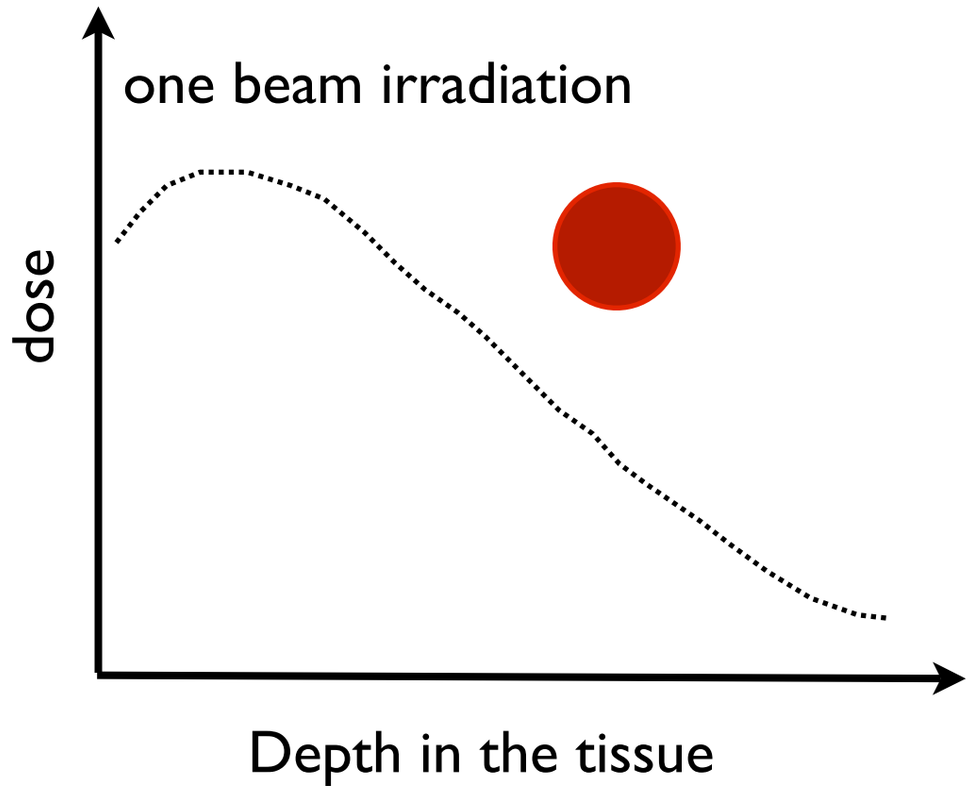
Medical applications : cancer treatment



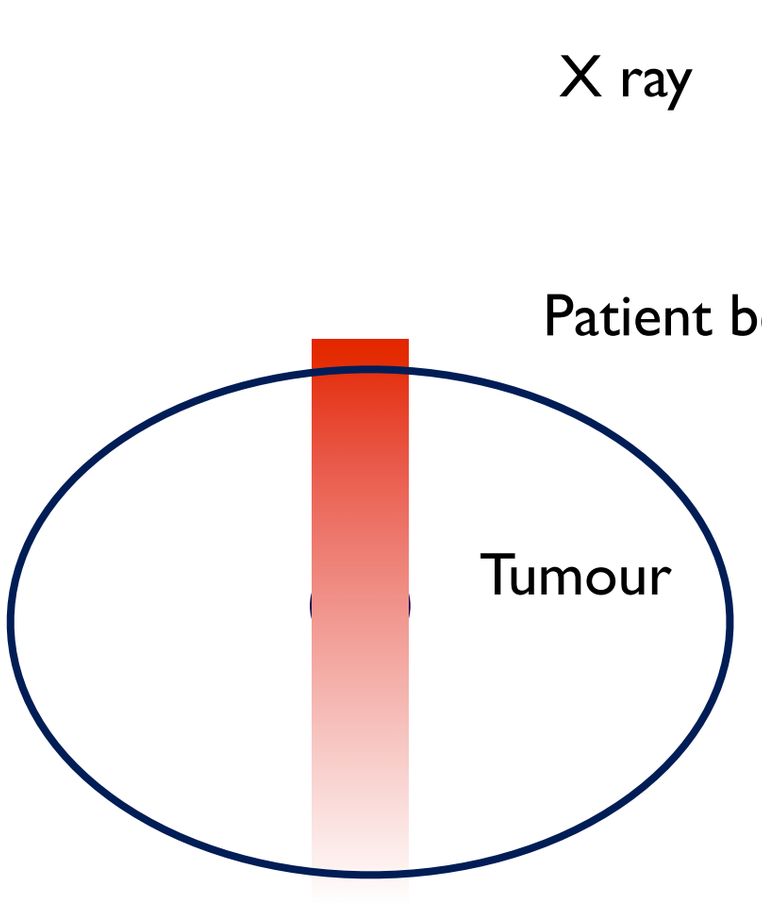
95% of radiotherapy is done with X ray

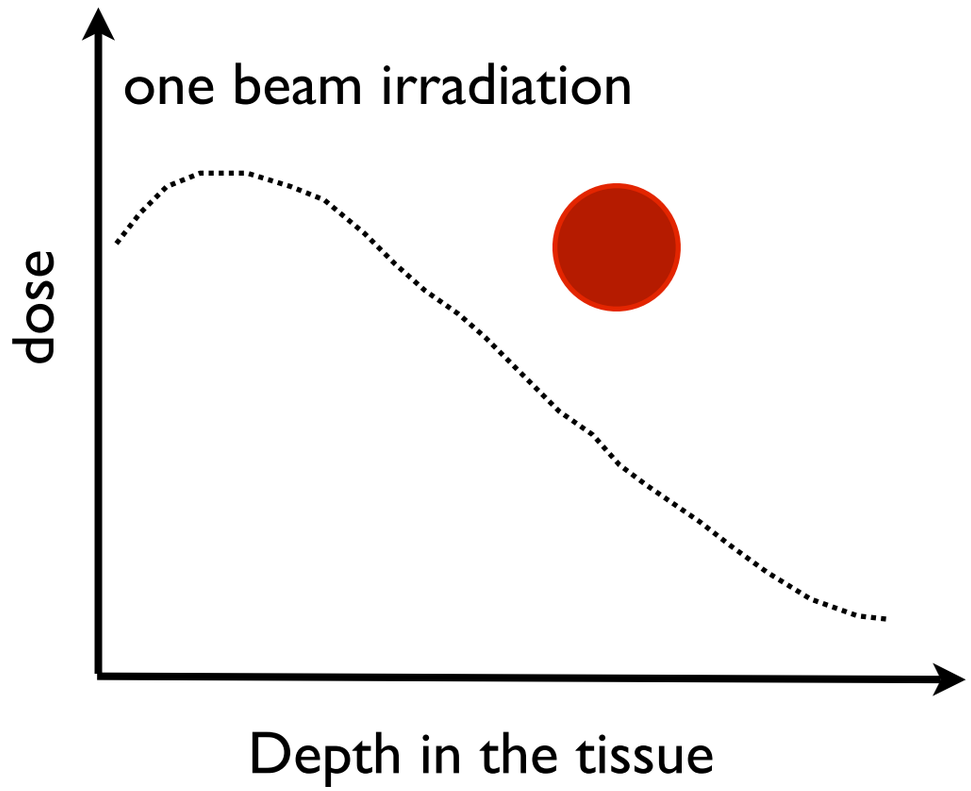
Radiotherapy : principle



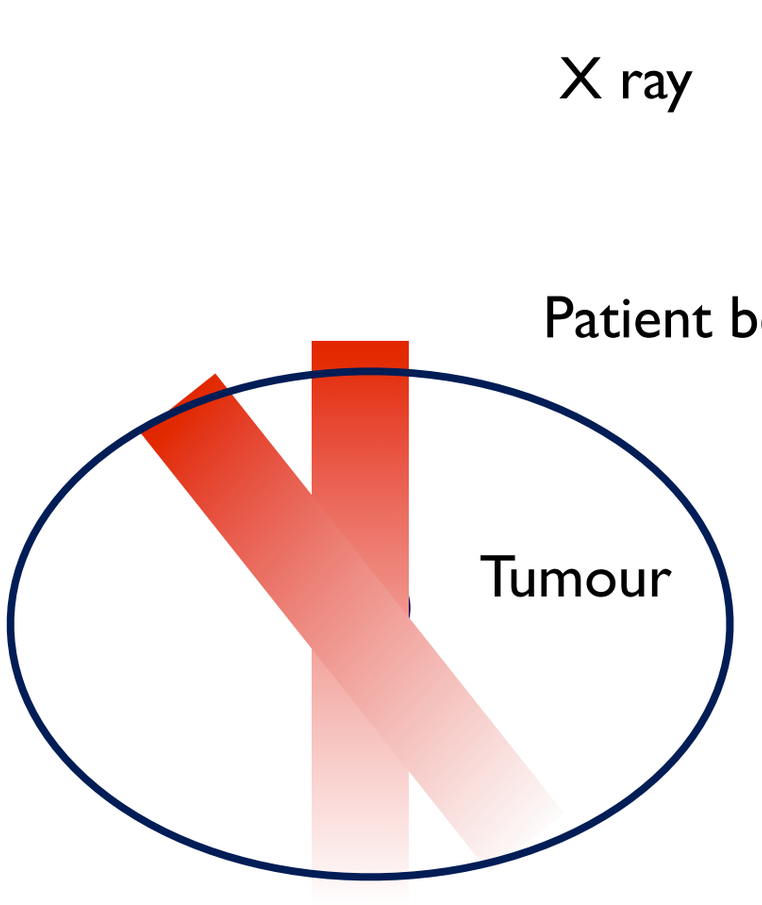


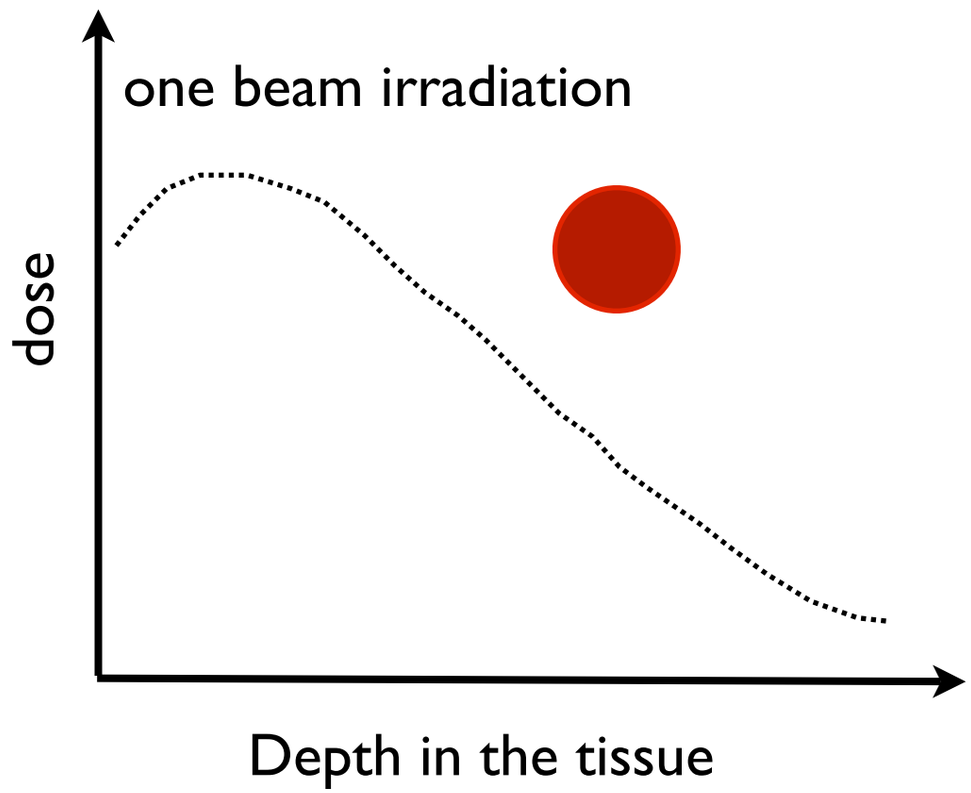
Radiotherapy : principle



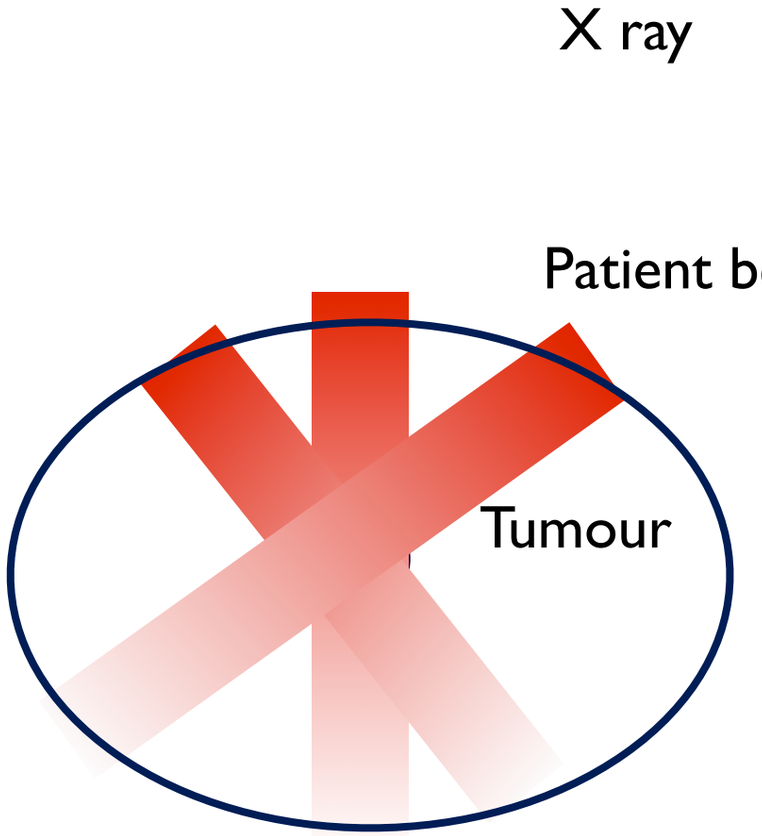


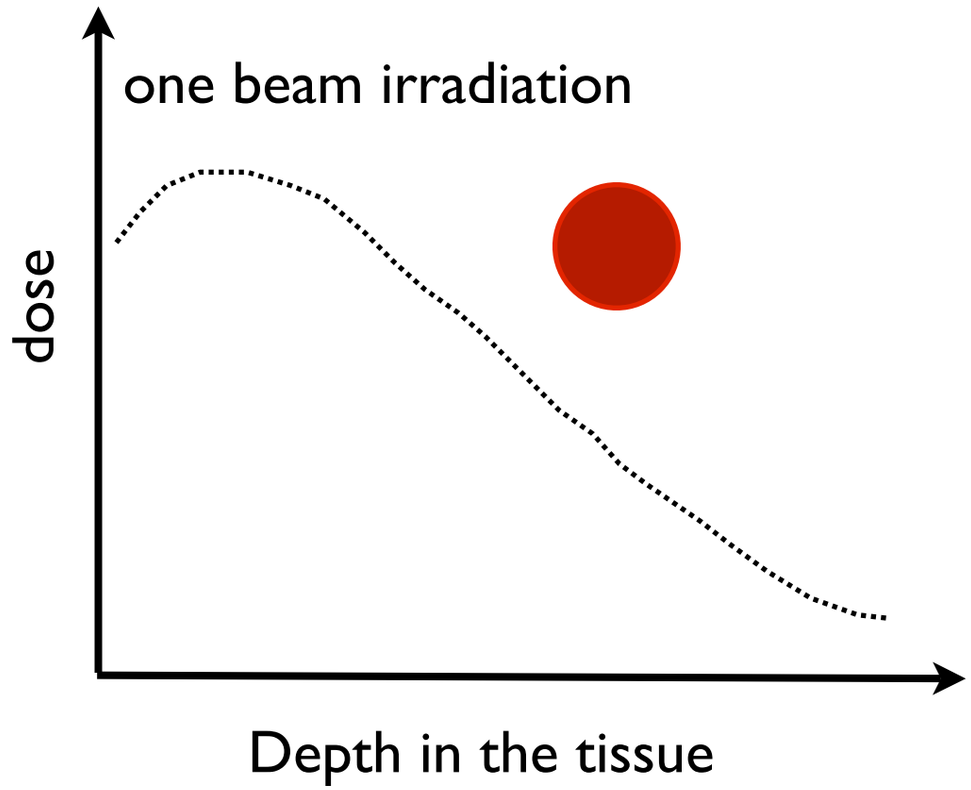
Radiotherapy : principle



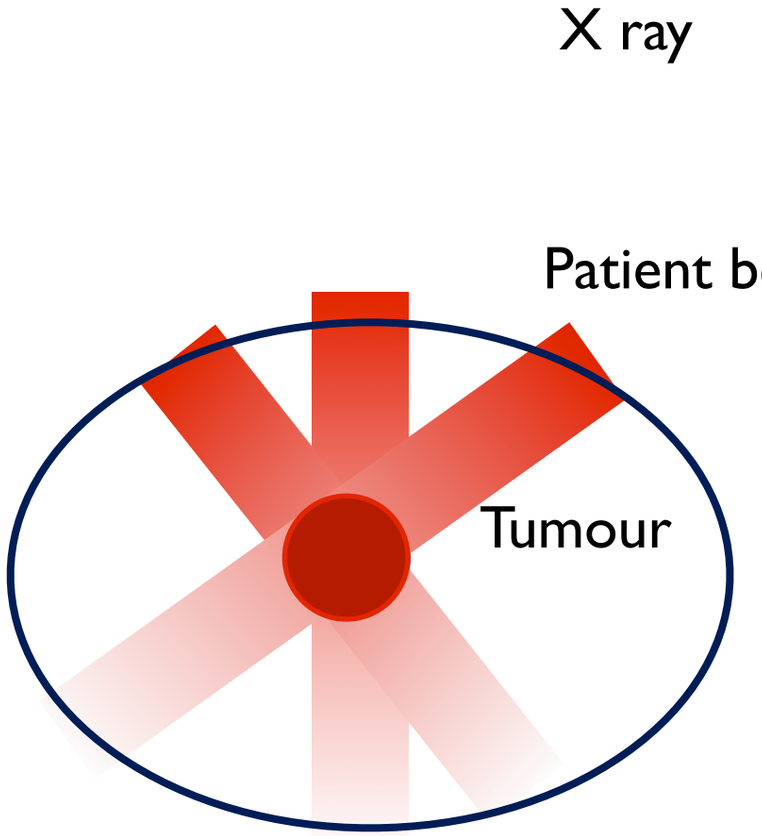


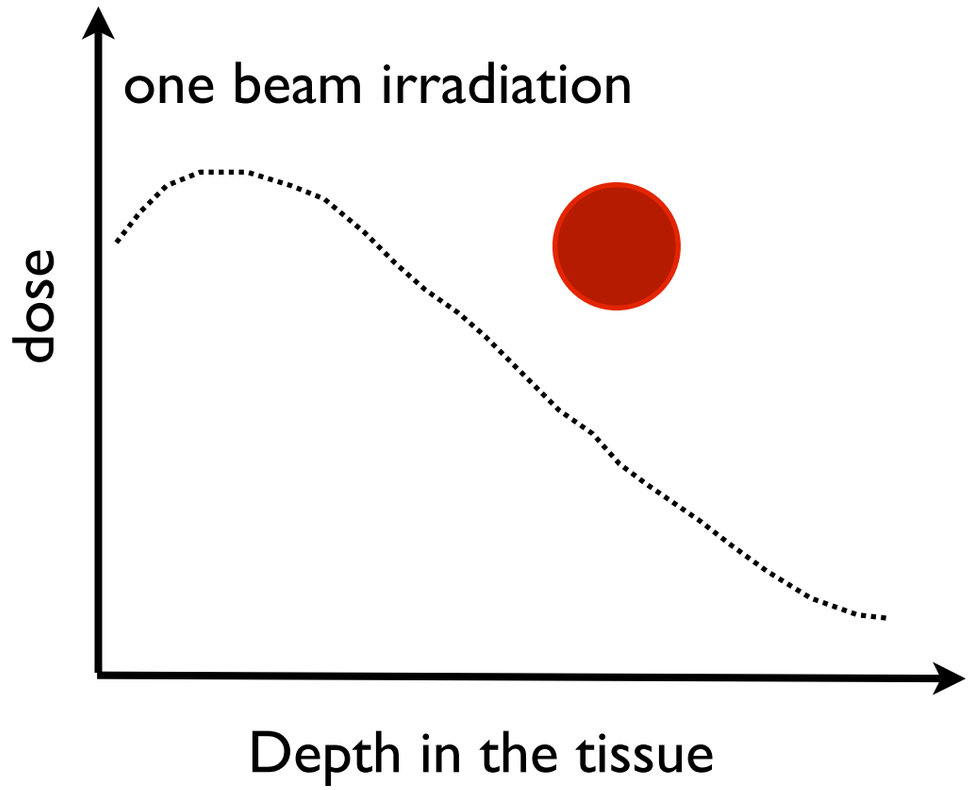
Radiotherapy : principle



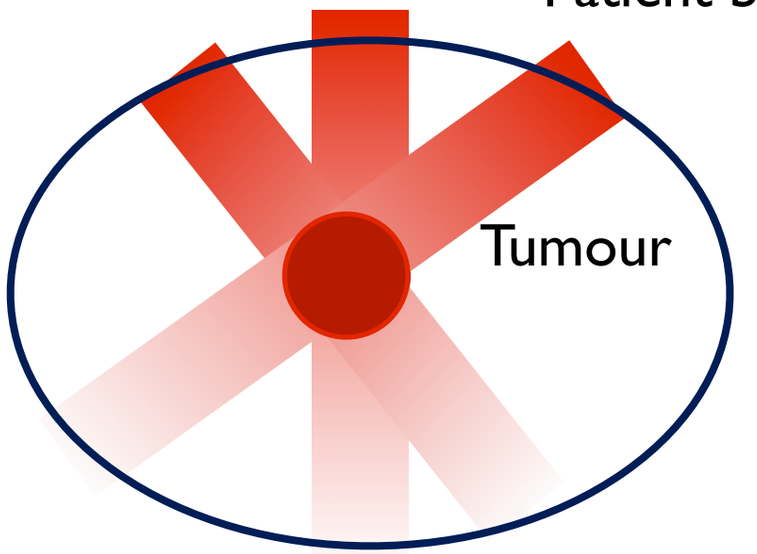


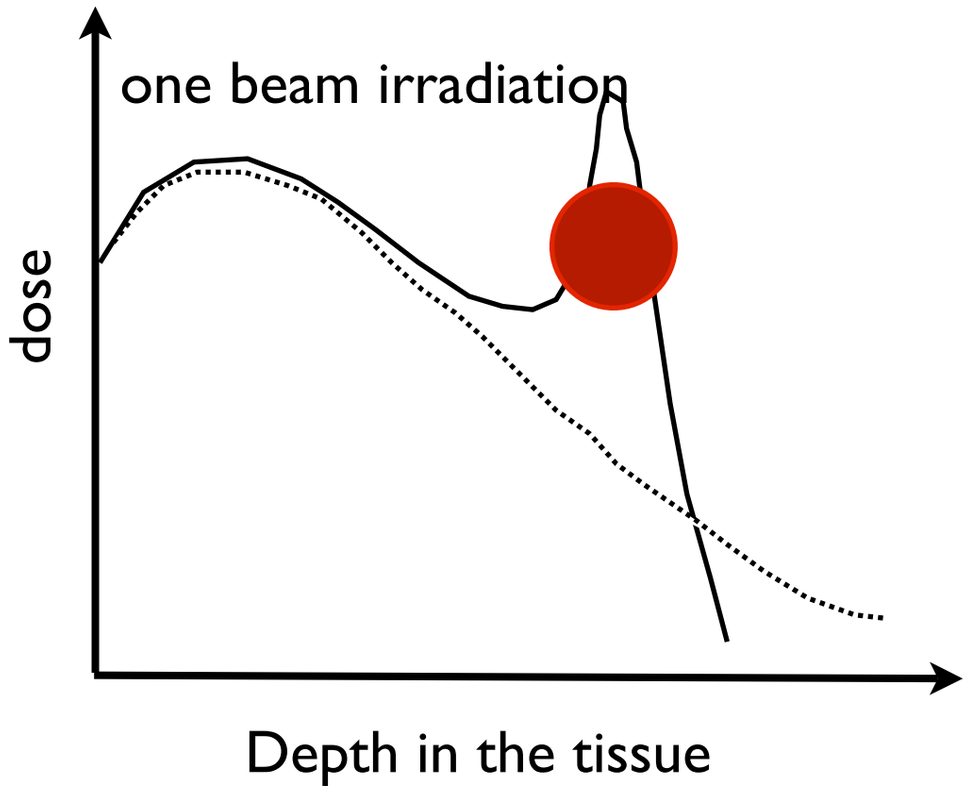
Radiotherapy : principle



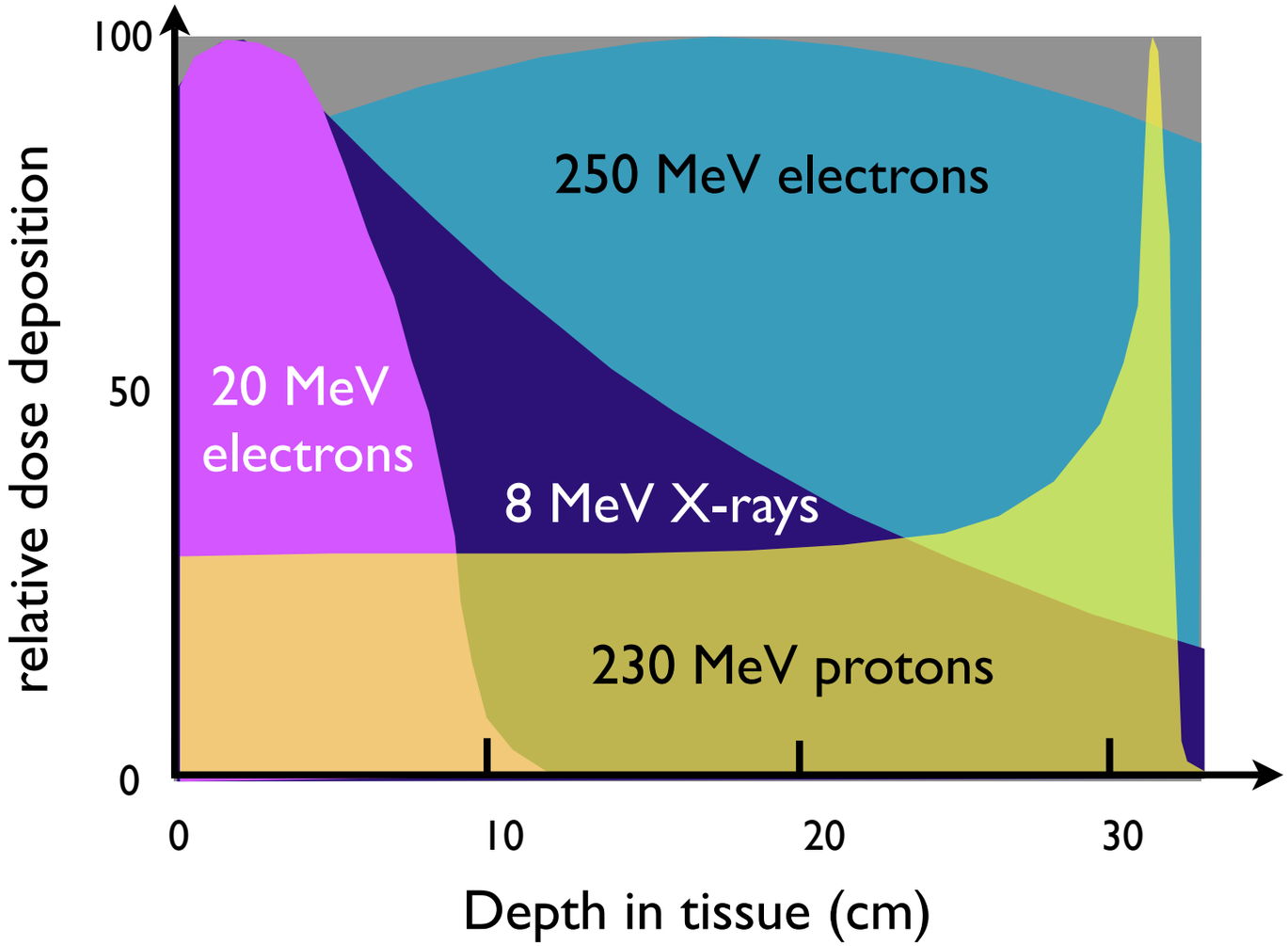


Radiotherapy : principle



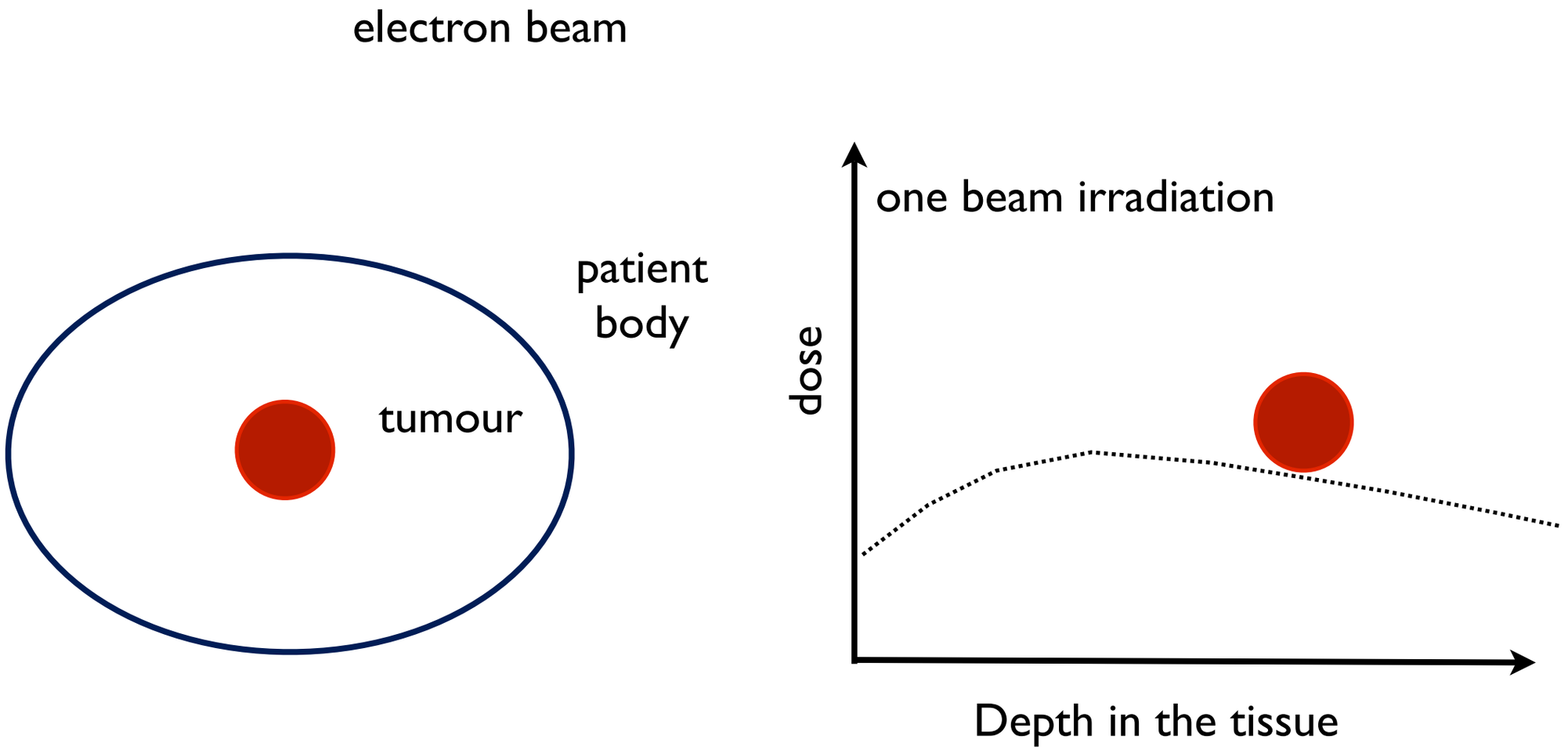


Medical applications : cancer treatment

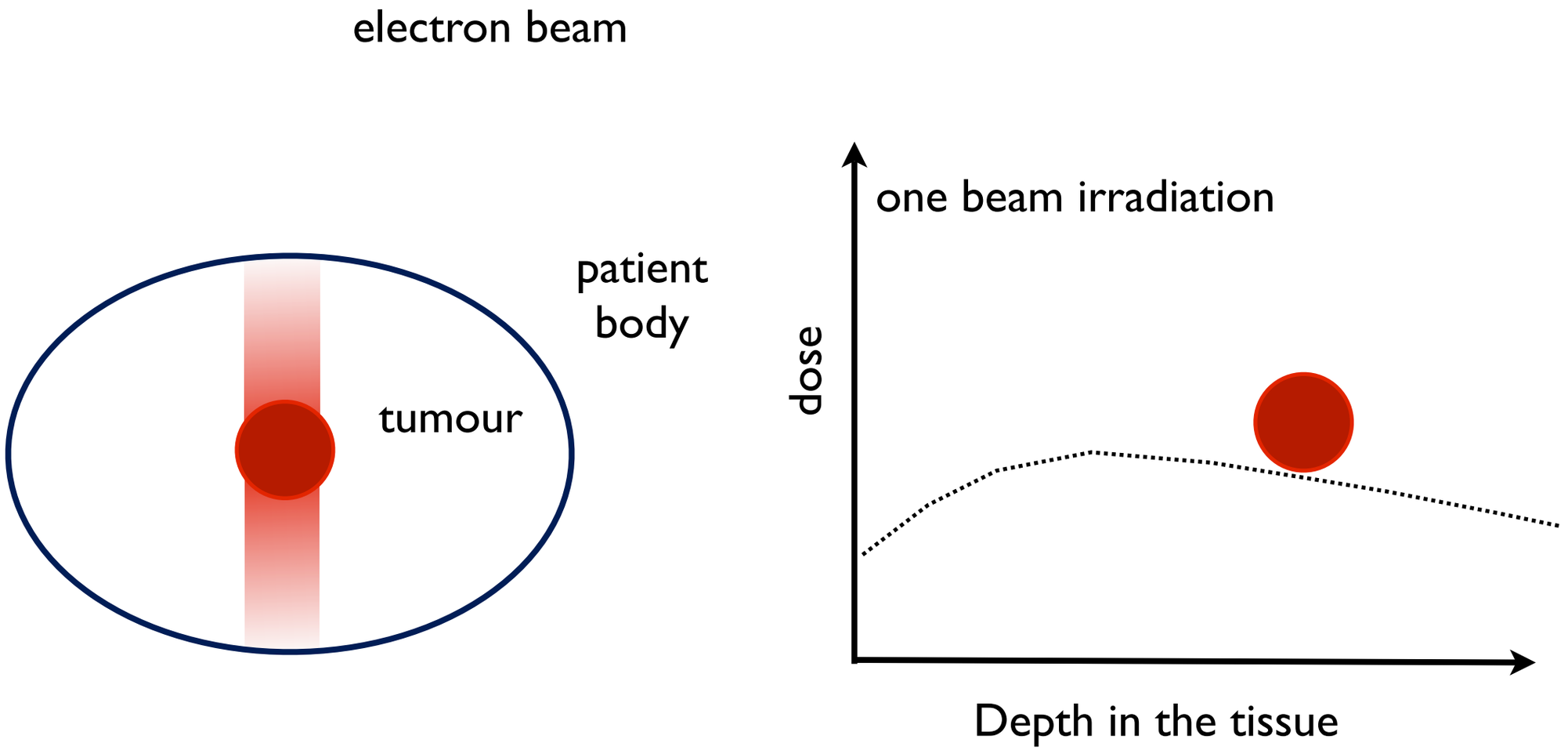


VHE electron depose the dose deep in the body

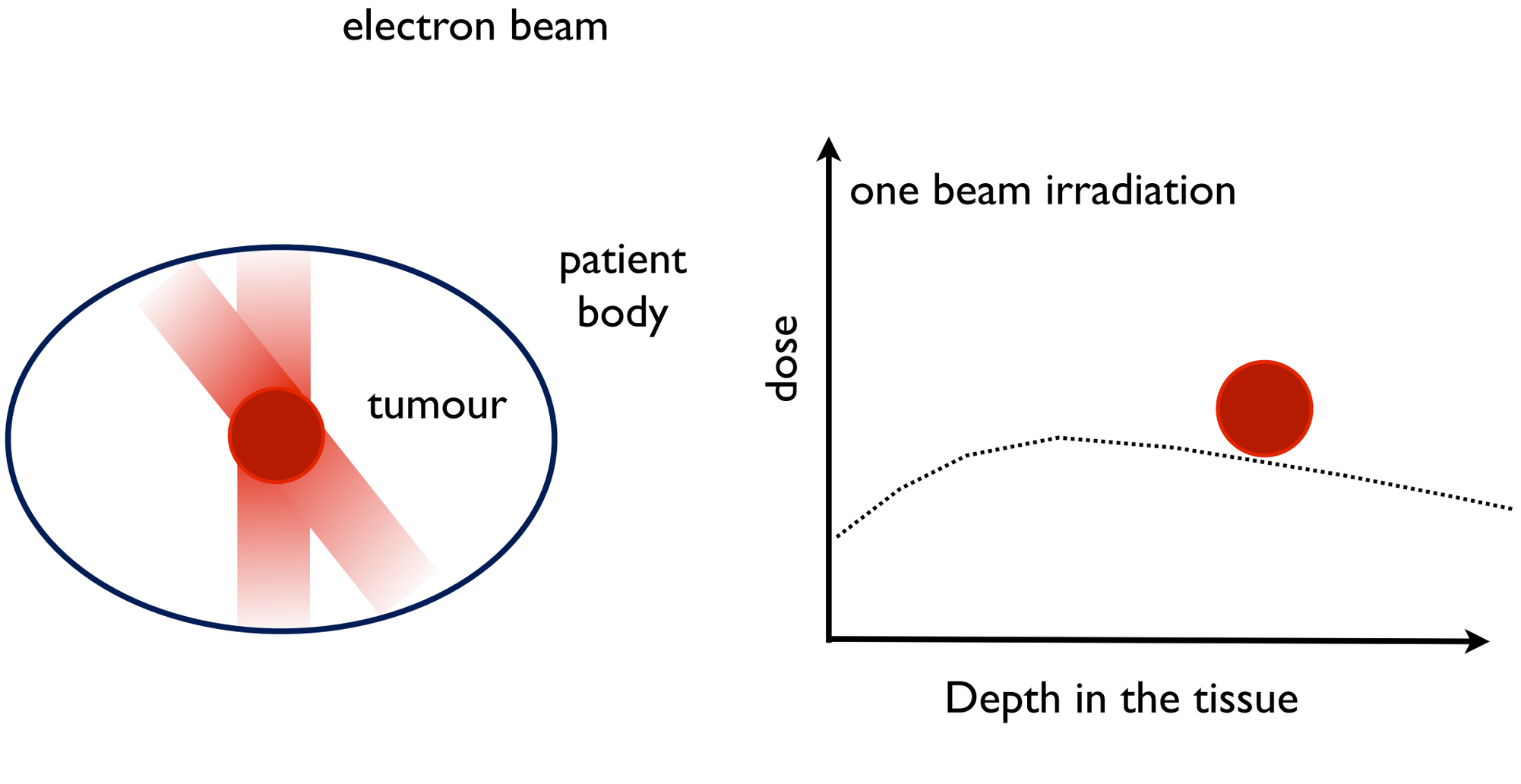
Medical applications : cancer treatment



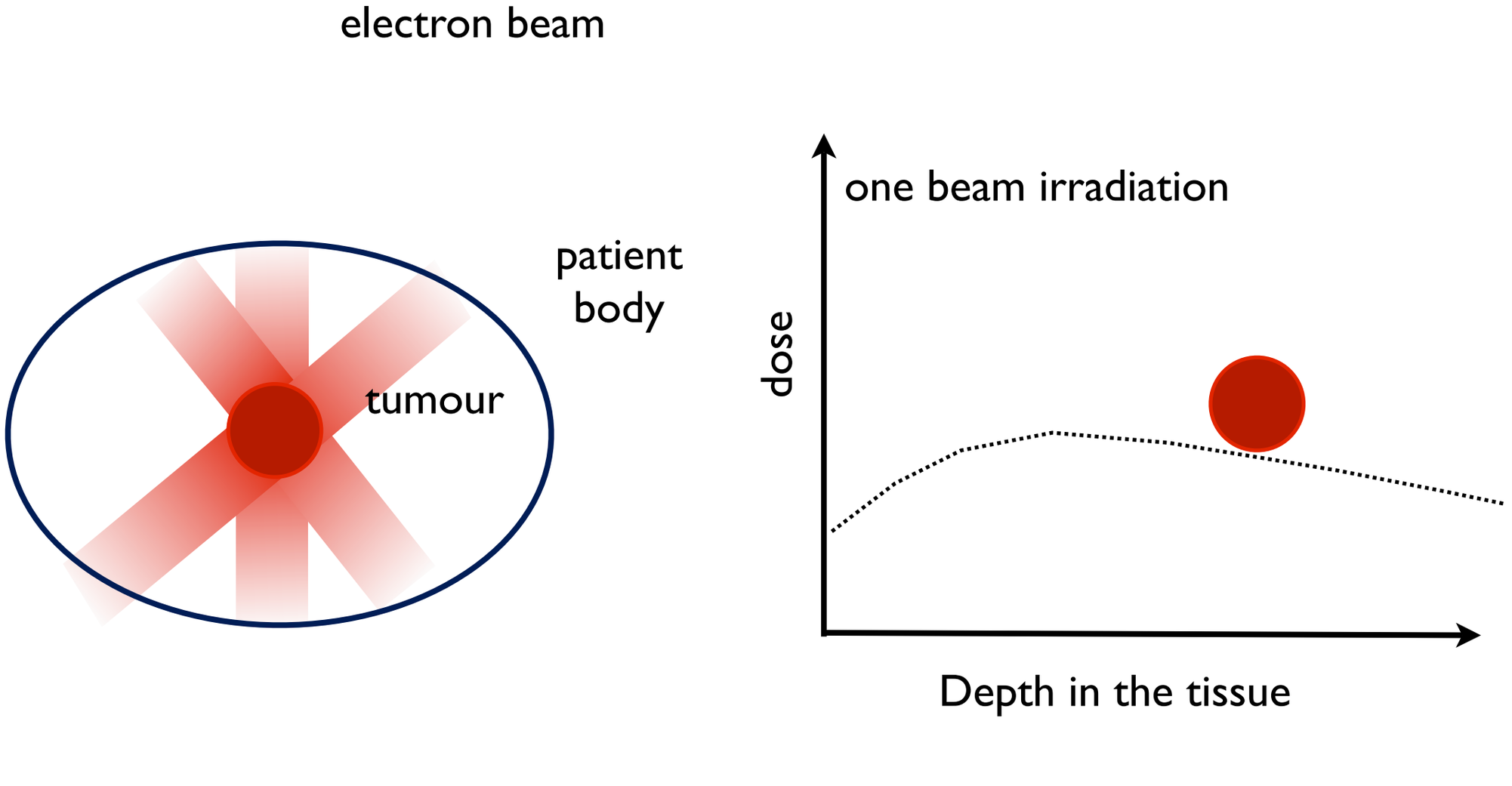
Medical applications : cancer treatment



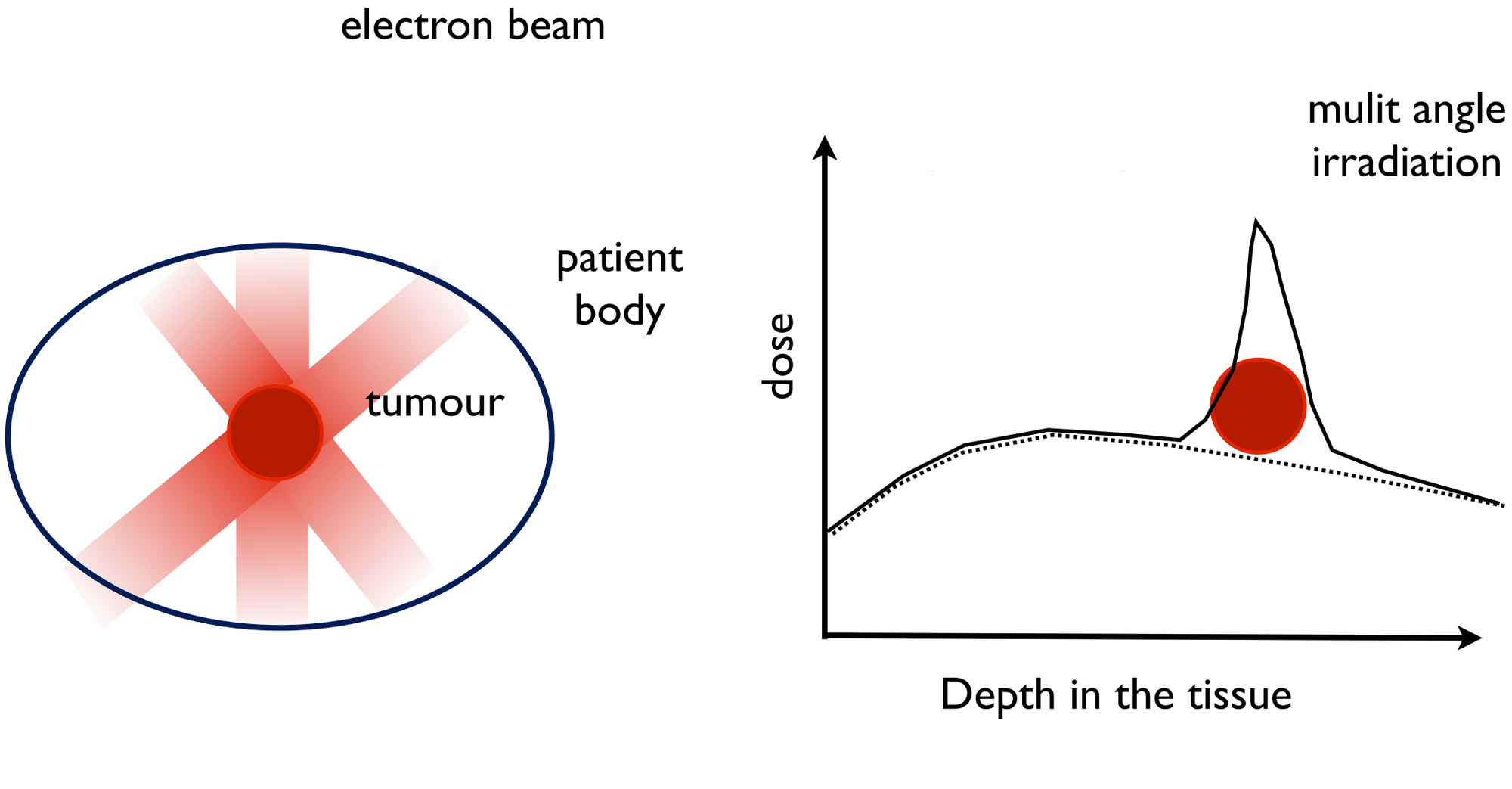
Medical applications : cancer treatment



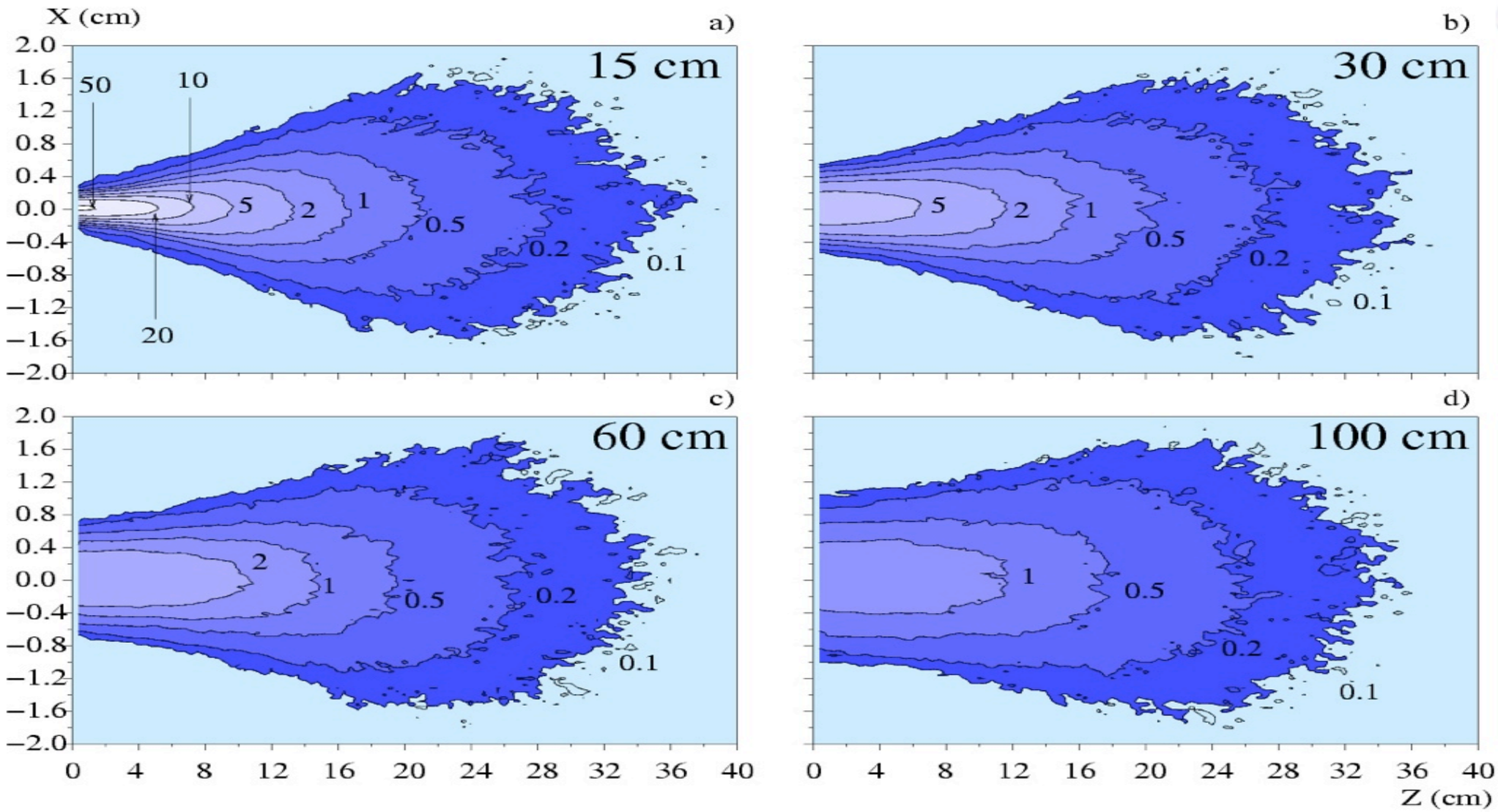
Medical applications : cancer treatment



Medical applications : cancer treatment



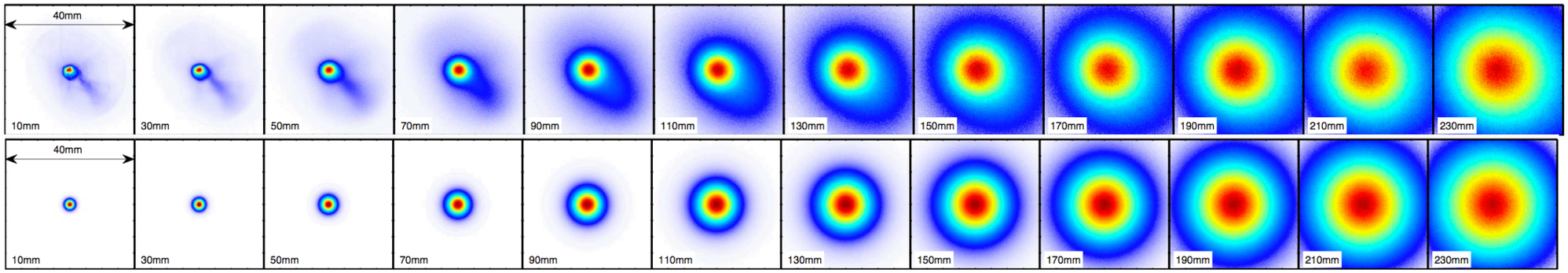
Medical applications : isodose calculation

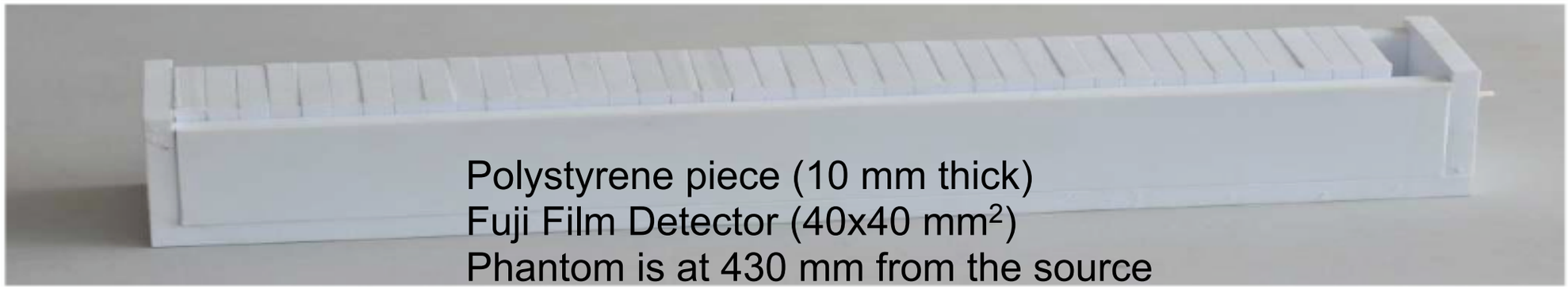


isodose curve : 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50 Gy/nC.
distance of the source a:15 cm, b:30 cm, c:60 cm, d:100 cm

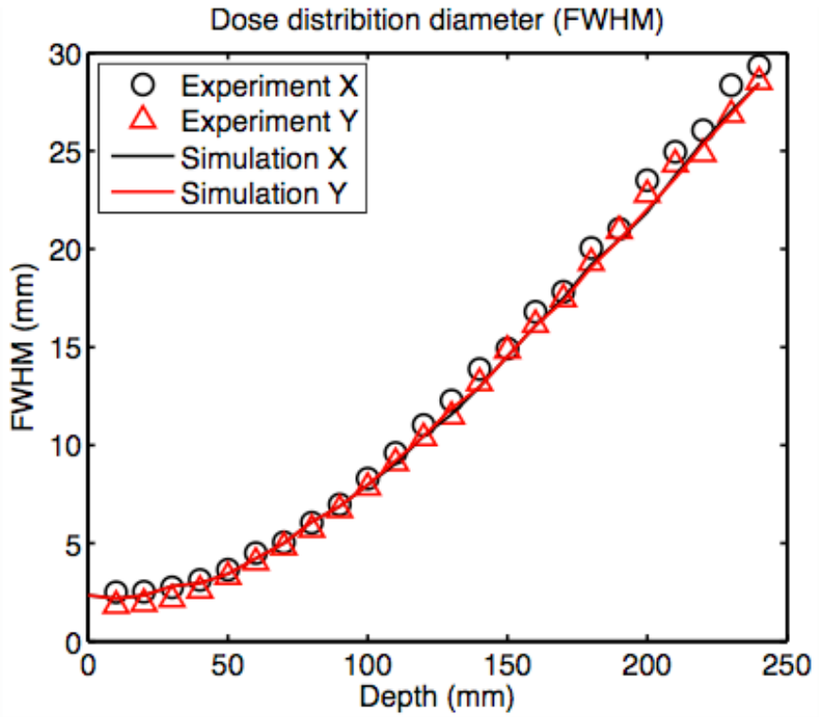
Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006), in coll. with DKFZ

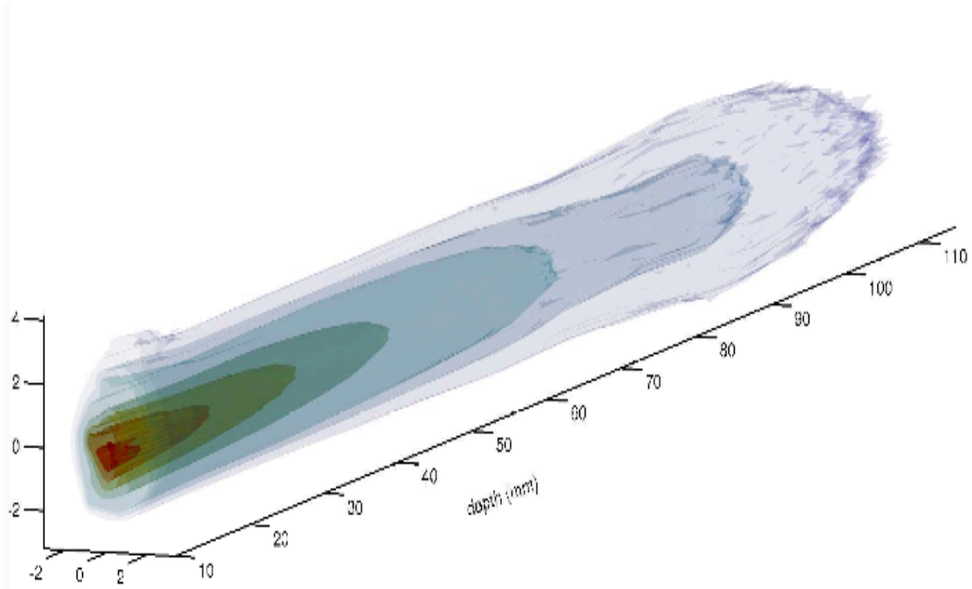
Some examples of applications : radiotherapy





E_{pic}=120 MeV
ΔE=20 MeV
Q_{pic}=30pC
Θ=4.5mrad
D_{max}=1Gy/tir

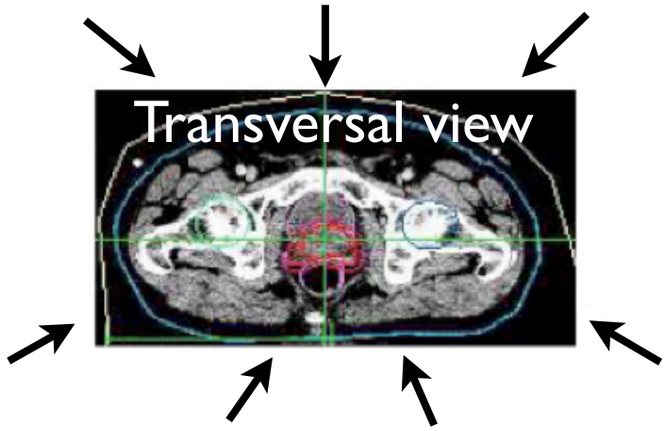


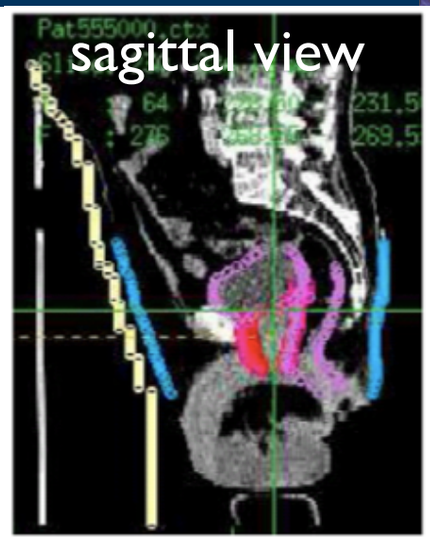


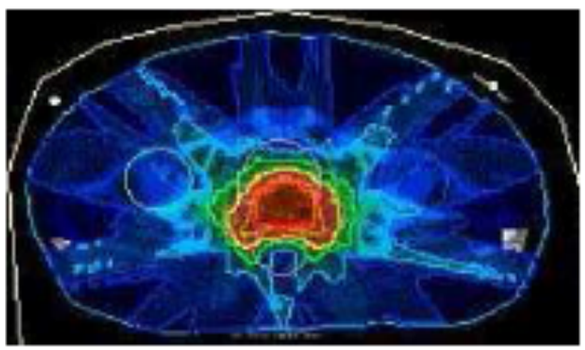
O. Lundh et al., to be submitted, in collaboration with W. De Neve group from University Hospital of GENT

Cancer treatment improvements : real case of prostate

irradiation at 7 angles

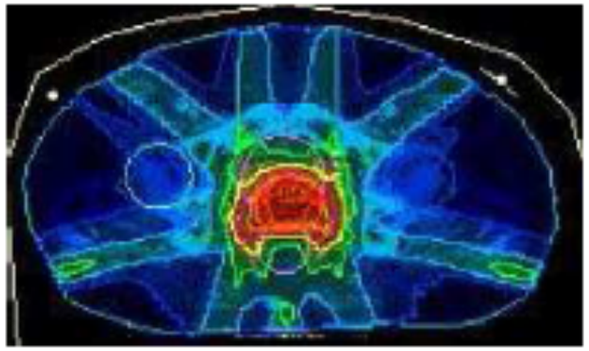






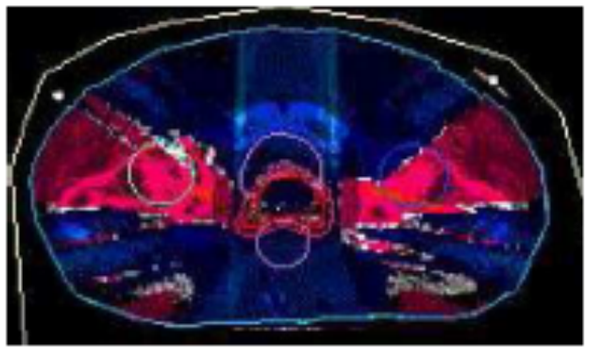
(a)

250 MeV electrons



(b)

X rays IMRT



(c)

Difference

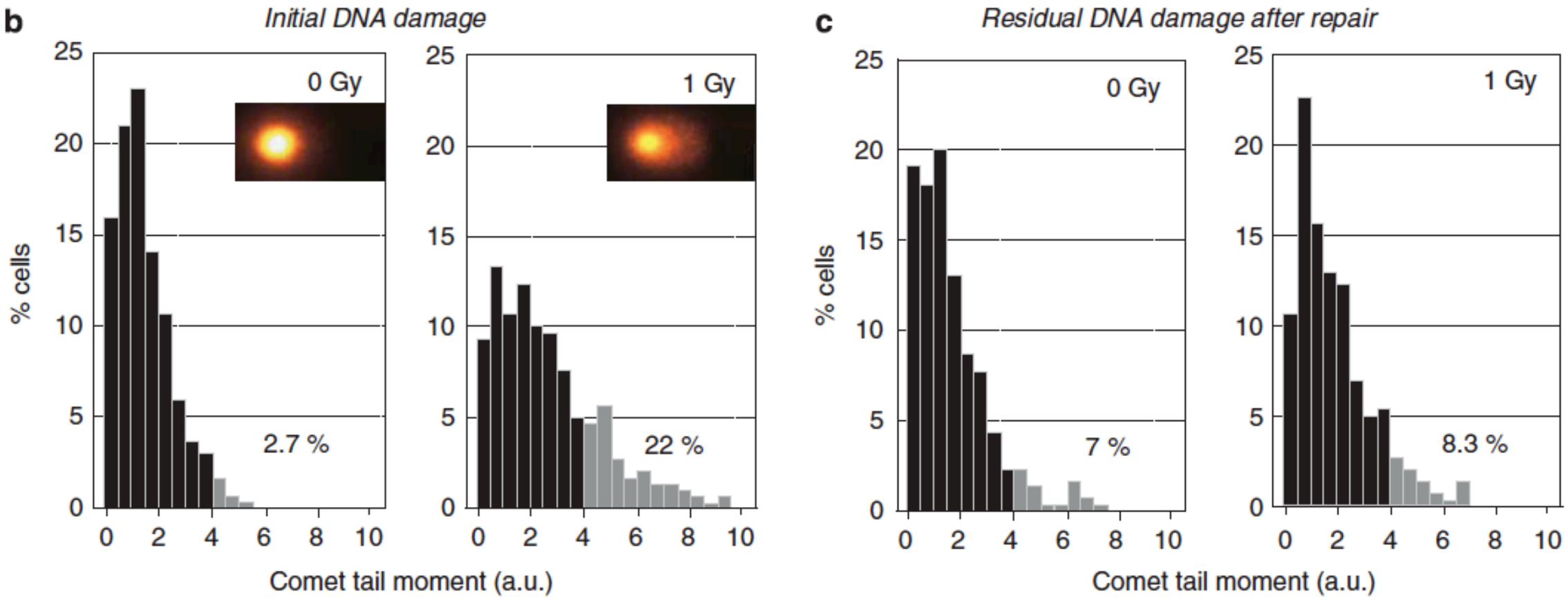
Y. Glinec, et al., Med. Phys. **33**, (1) 155-162 (2006)

T. Fuchs, et al. Phys. Med. Biol. **54**, 3315-3328 (2009)
En coll. Avec DKFZ

Laser-accelerated electrons can provide a better dose sparing of critical structures (up to 19%) at a similar target coverage compared to photons.

Radiobiological effects with dose rate of 10^{13} Grays/s

Induction of DNA damage in skin carcinoma cells irradiated at a very high dose rate by a single ultrashort bunch of high-energy electrons (100 fs pulse duration, mean energy of 95 MeV), the pellet containing about 5.10^5 human skin carcinoma cells. Single shot (1.02±0.13 Gy, dose rate 10^{13} Gy/s).



(b, c) Time-dependent evaluation of DNA damage using the alkaline comet assay for sham-irradiated (0 Gy) and irradiated carcinoma cells (1 Gy) immediately after the femtosecond irradiation (b) and after 1 h of repair time at 371C (c). A significant difference between the distributions of 0 and 1 Gy samples was found for initial damage.

O. Rigaud *et al.* Cell Death and Disease 1e**73**, (2010)

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Conclusions

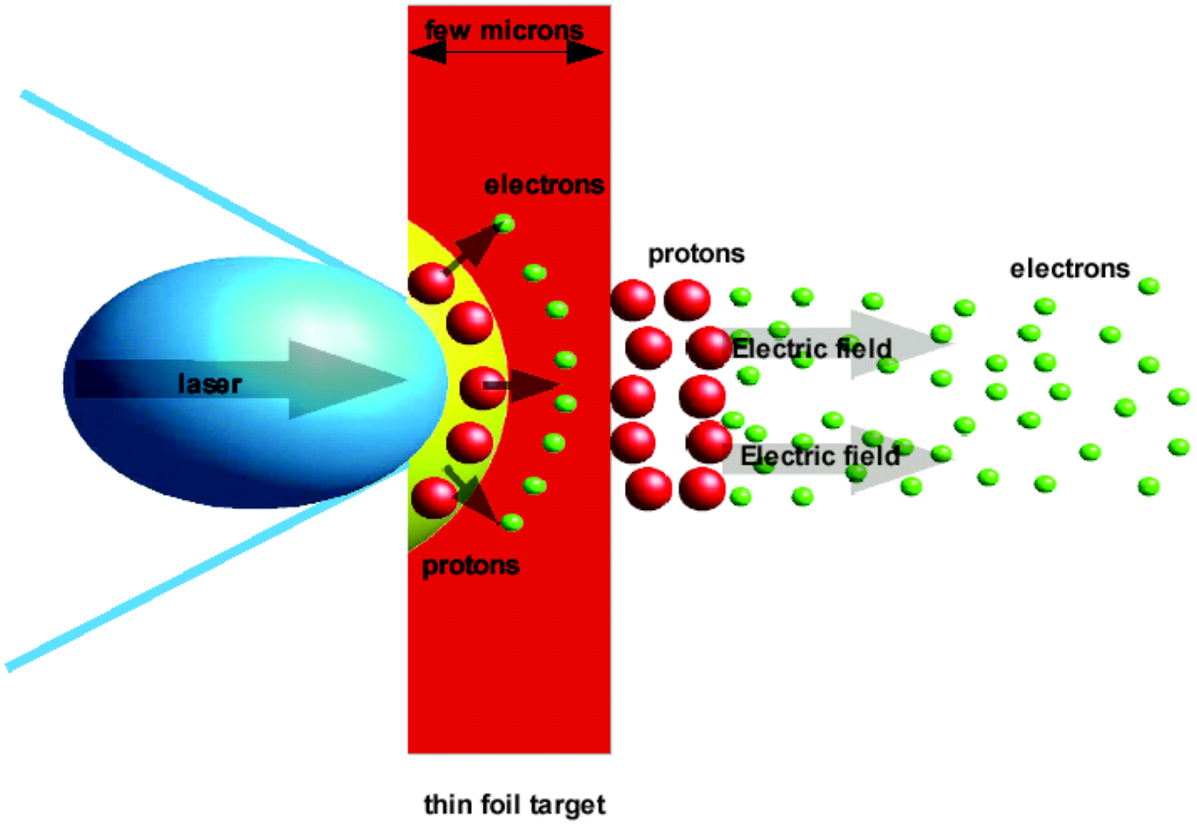
Accelerators point of view : Two laser beams allow the control of many e-beam parameters

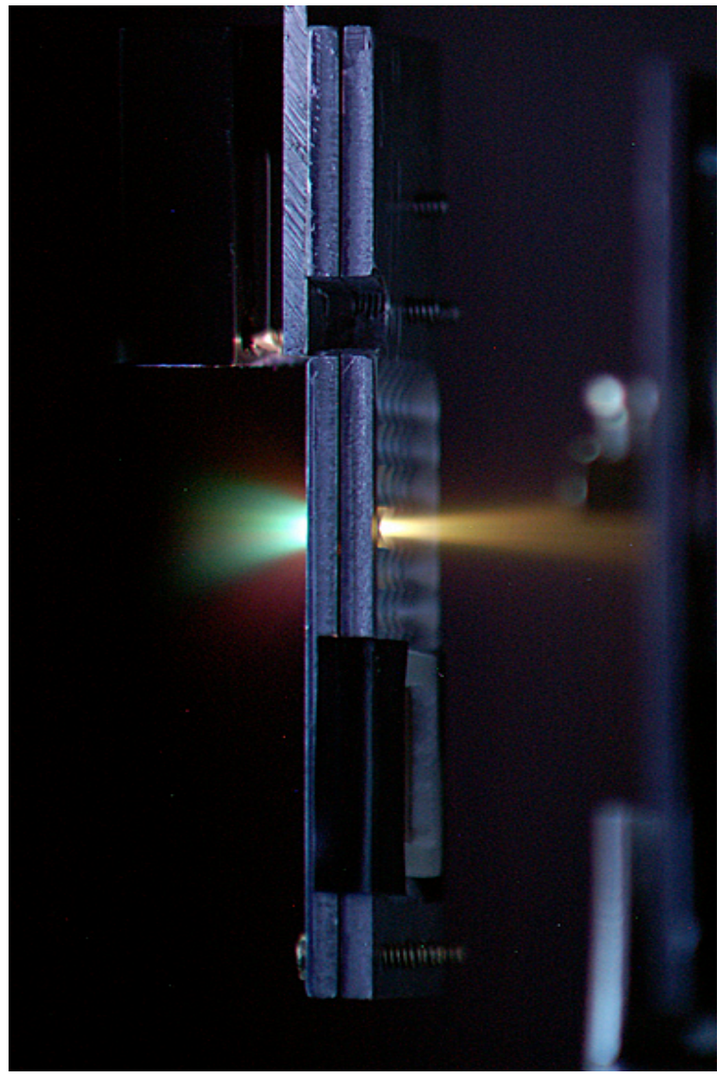
- Good beam quality & Monoenergetic dE/E down to 1 % √
- Beam is very stable √
- Energy is tunable: 20-300 MeV √
- Charge is tunable: 1 to tens of pC √
- Energy spread is tunable: 1 to 10 % √
- Ultra short e-bunch : 1,5 fs rms √

Physics point of view : many new aspects of the interaction have been revealed :

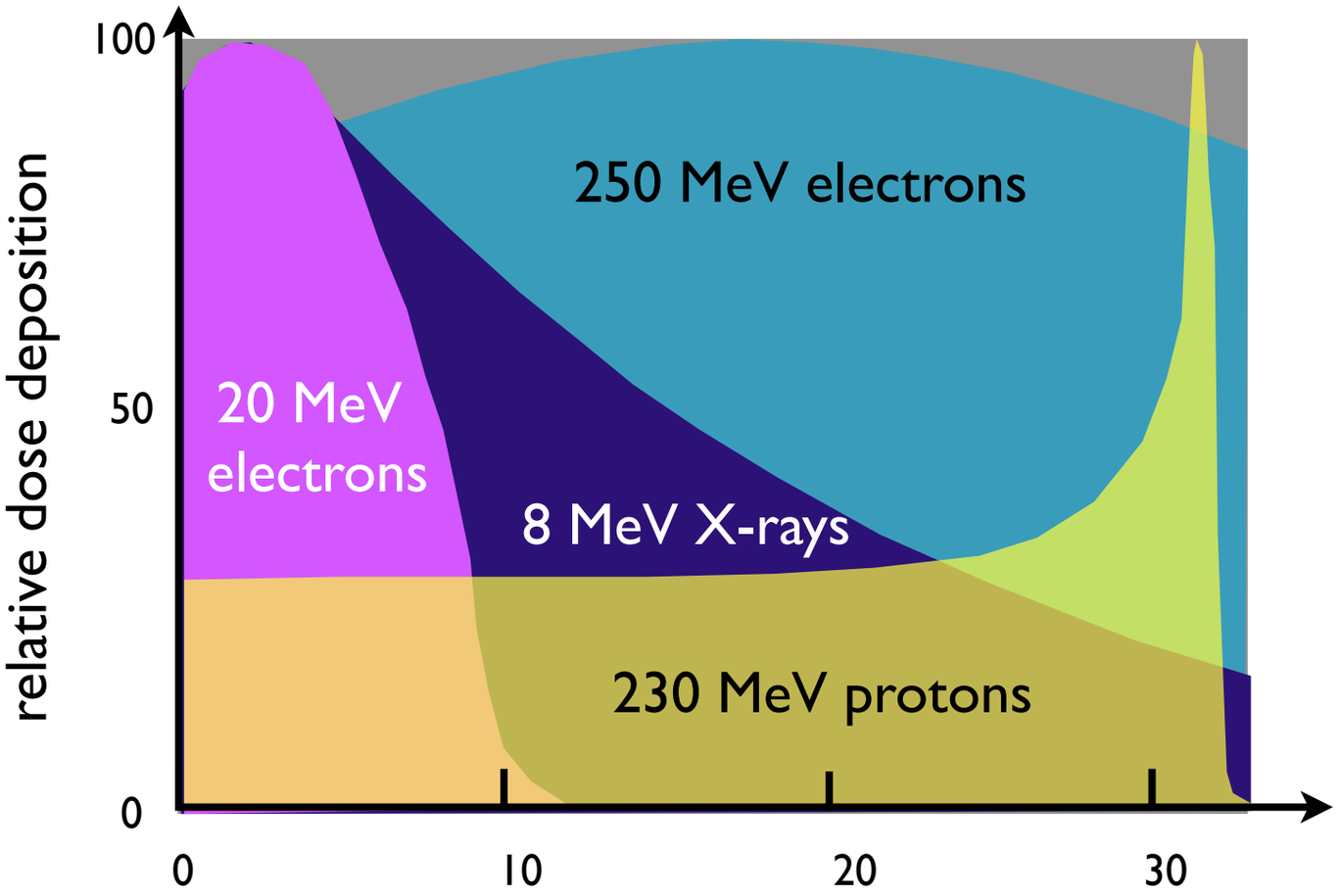
- Heating processes with crossed polarized lasers √
- Inhibited plasma waves effect √
- Beam loading effect : optimum charge of 20pC √

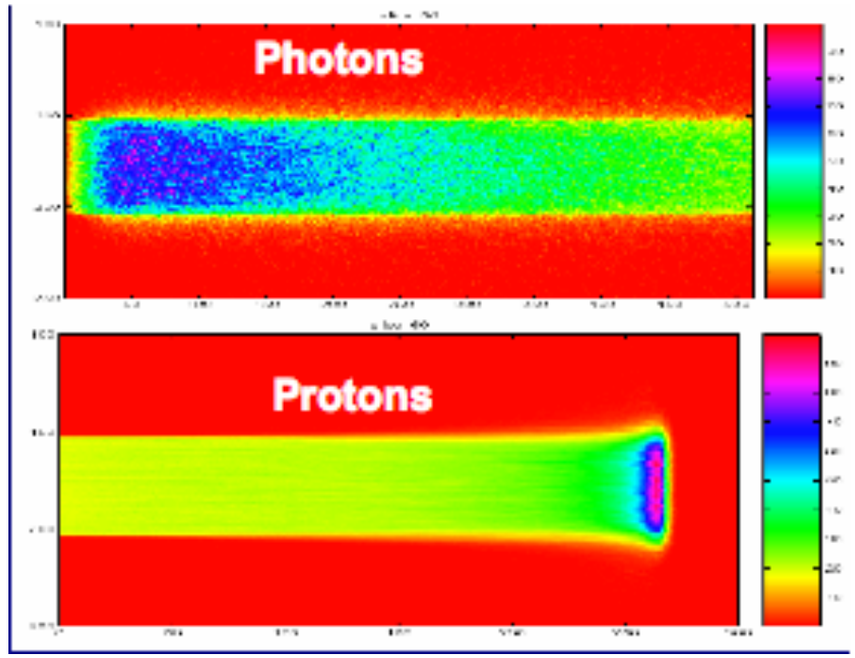
Accélération de protons : principe

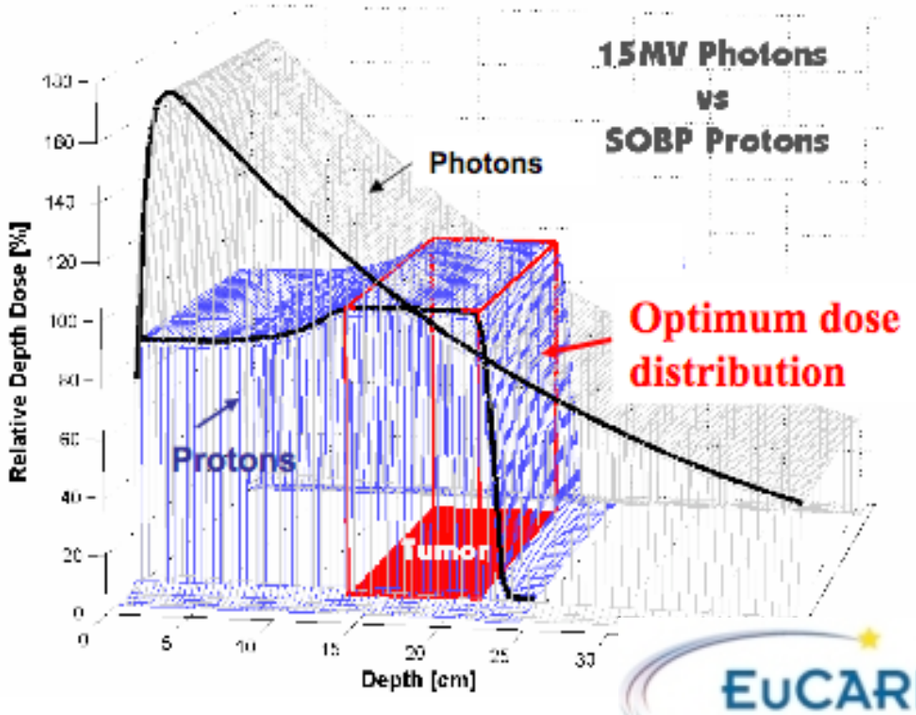




Protons provide superior dose distributions



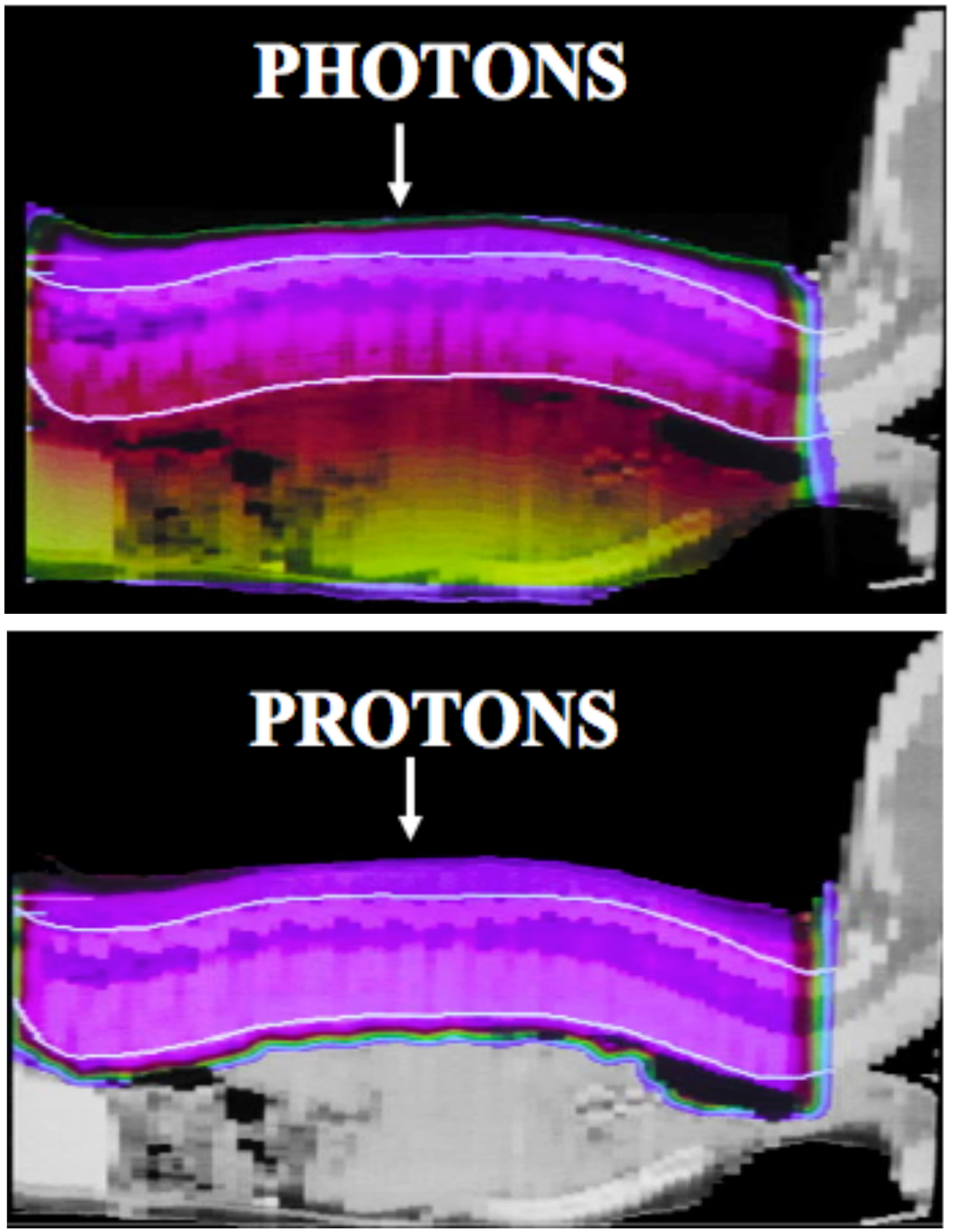


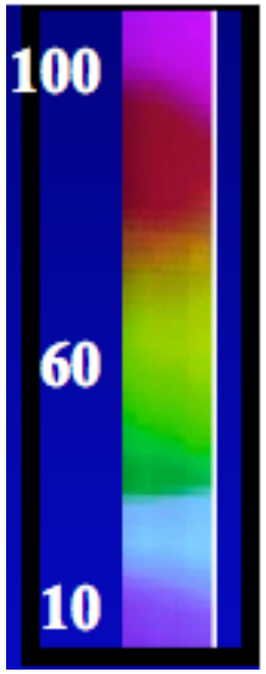


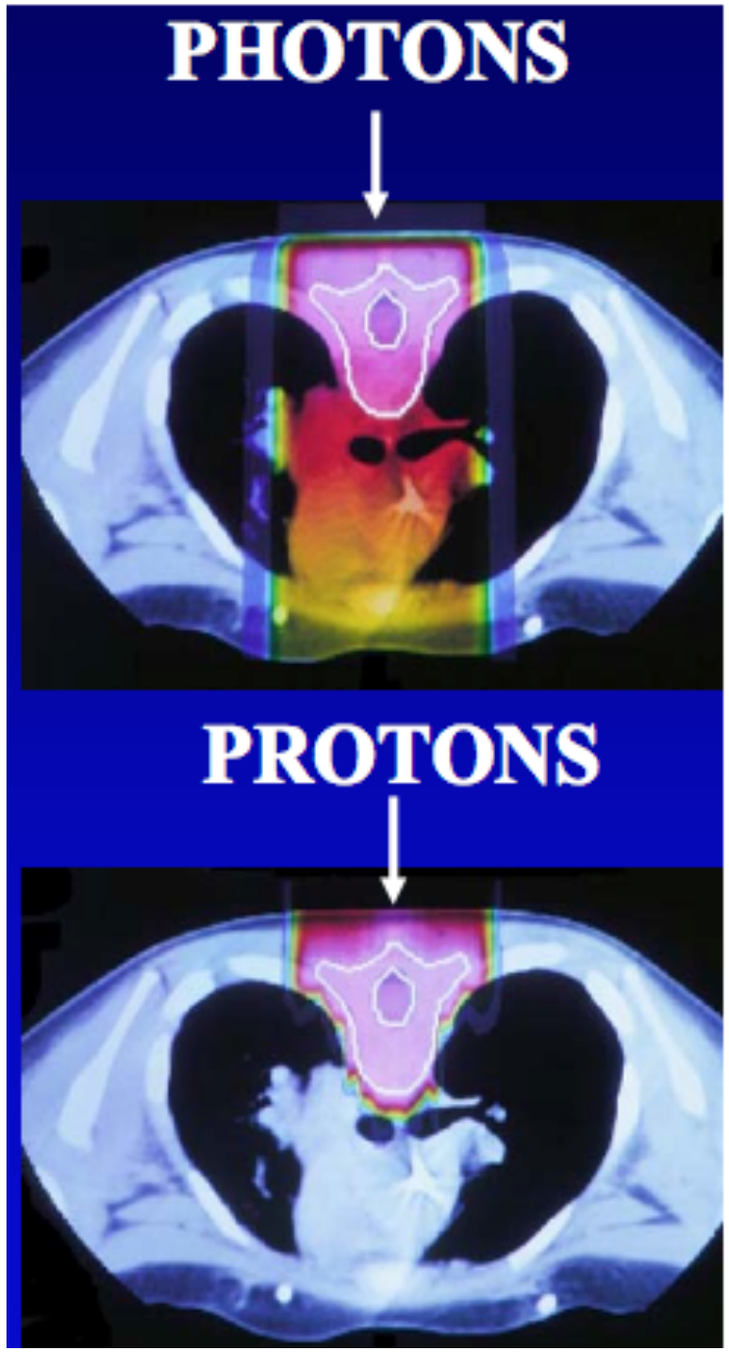
-The « optimum » dose distribution delivers 100% dose to the tumour target and not to critical normal tissues.
-Proton beams deliver dose distribution that are more optimum than those from photon beams
-This should result in improved clinical outcomes when proton beams are used.

Protons provide superior dose distributions

Medulloblastoma







courtesy of Prof. A. Smith

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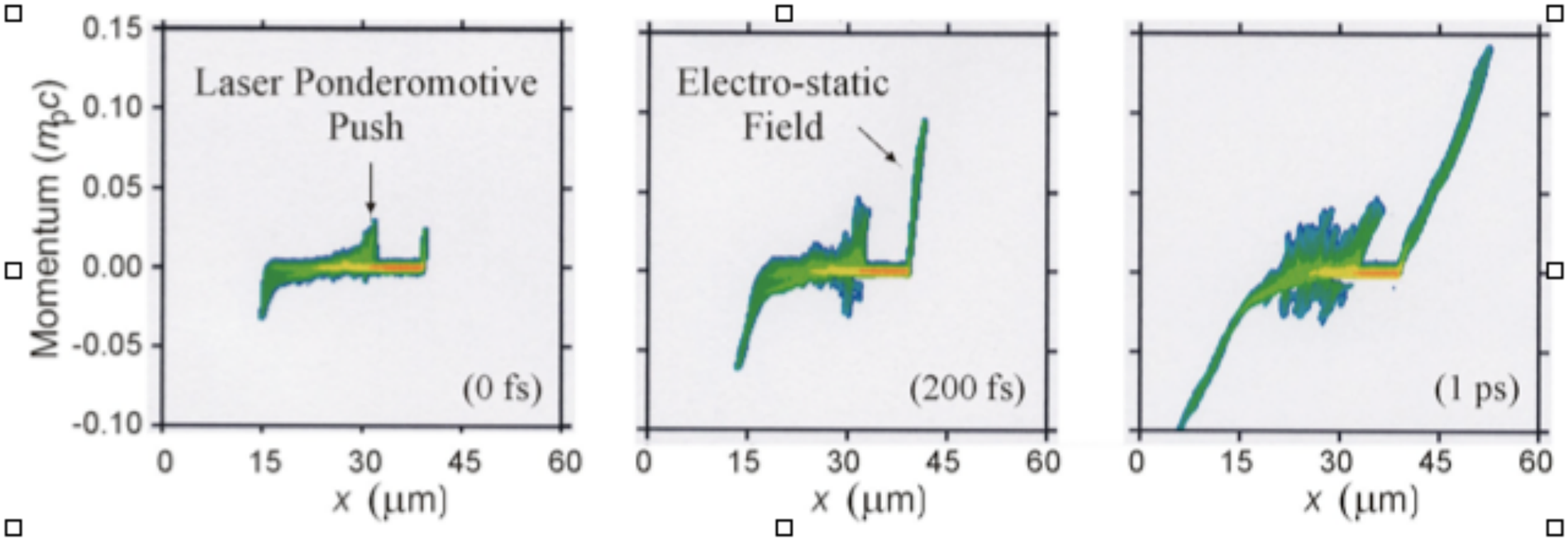
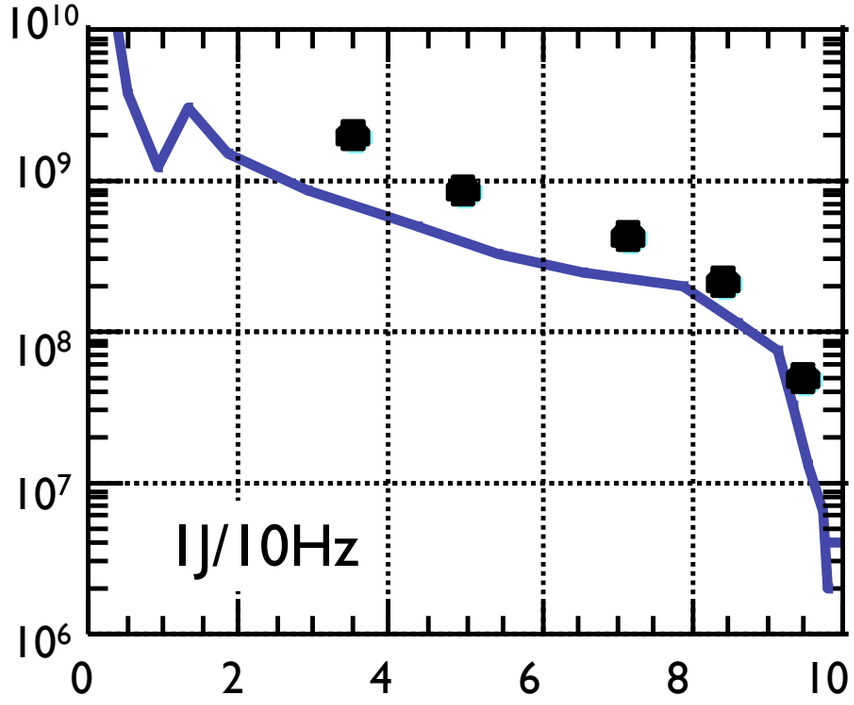
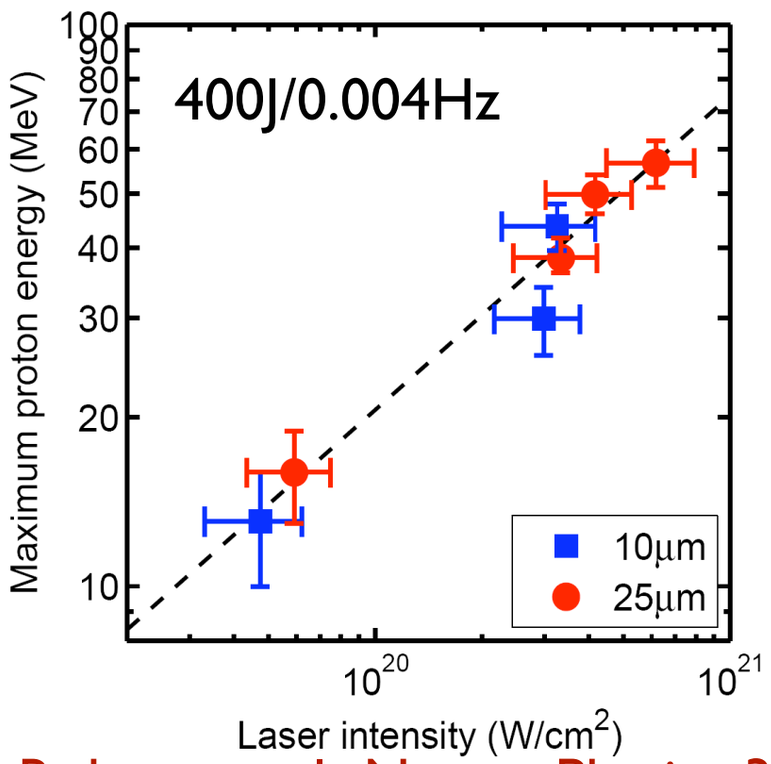
Three ion beams are produced





V. Malka et al., Appl. Phys. Lett. 83, 15(2003), Med. Phys. 31, 6(2004)



Robson et al., Nature Physics 3 (2007)

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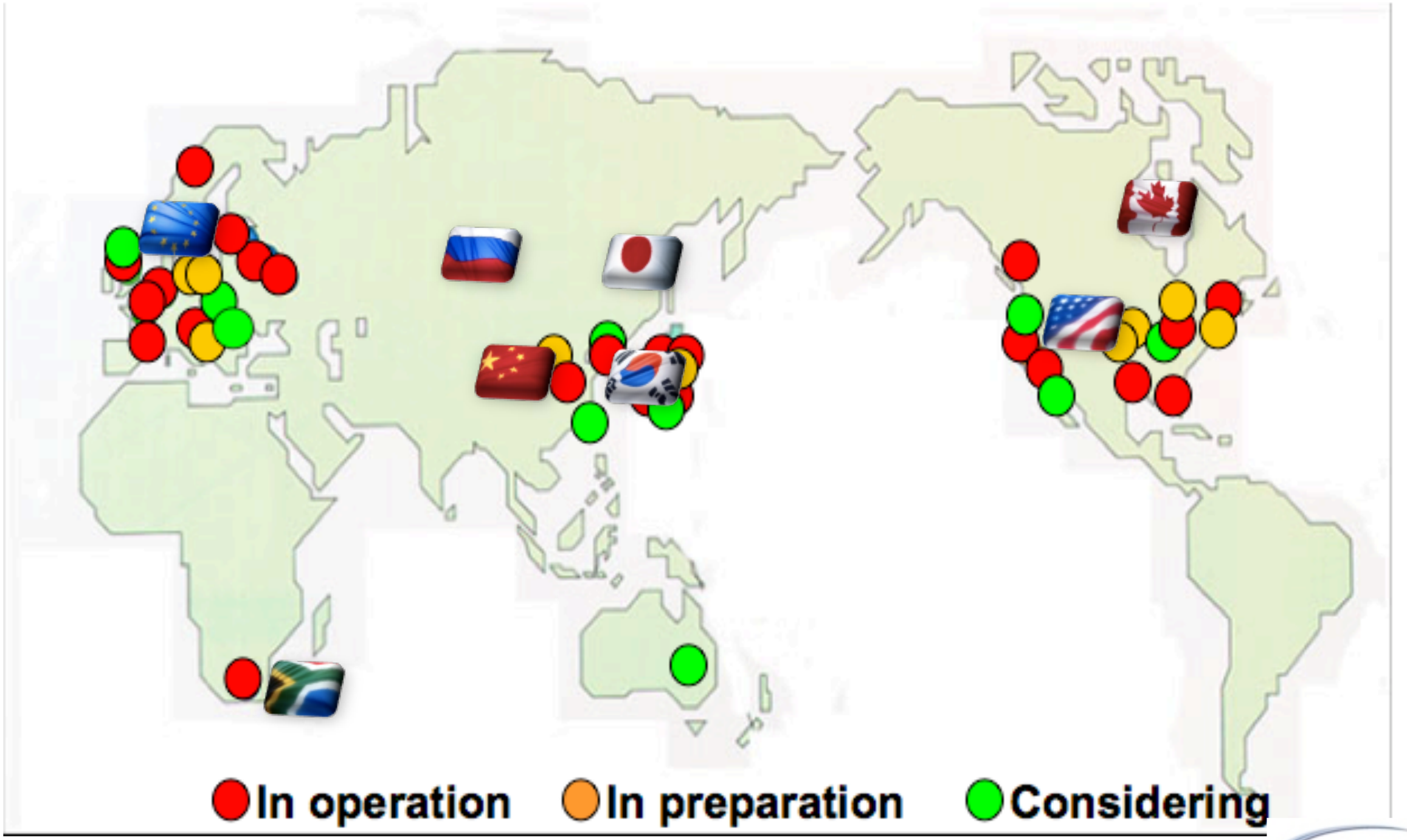
Protontherapy Facilities in the World (20 proton, 3 Carbon)



Protontherapy Facilities in the World (20 proton, 3 Carbon)

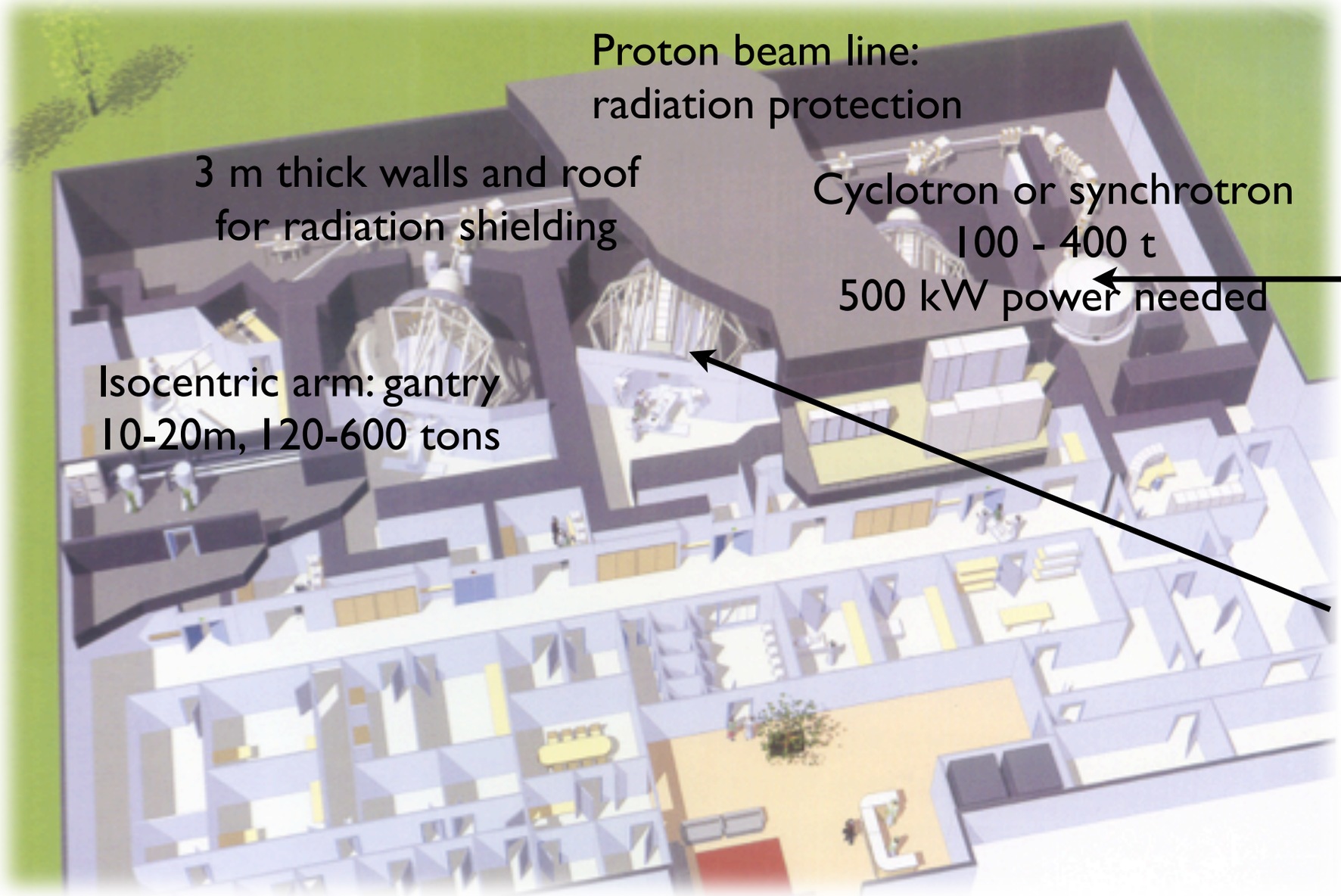
Very selective prescription because of the cost and of the weight of the infrastructure.
Determined by the need of having an high balistic precision.

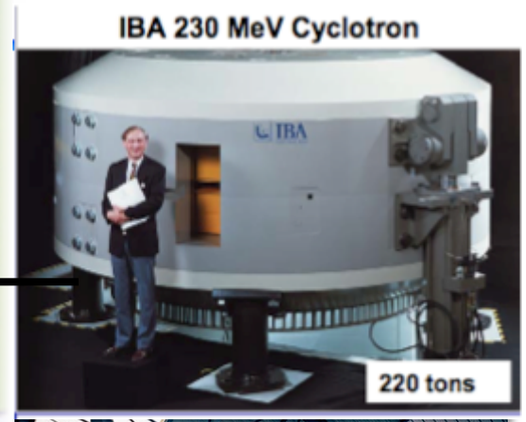
Medical impact	Tumour localisation	Nb of patient per year	Total
Major prescriptions	Eyes tumours	400 / 450	
	Neuro-oncology and Rachis	2.000 / 2.500	
	Childs and adolescent	300 / 500	
	Sarcomes retro-peritony	80 / 100	**2.800 / 3.550**
other possible prescriptions	ORL	500 / 1.000	
	Lungs (poumons)	3.000 / 4.000	
	other cancers	1.000 / 1.500	**4.500 / 6.500**
Potential prescriptions	Some prostate cancers	2.500 / 3.000	
	Re-irradiations	500 / 1.000	**3.000 / 4.000**

recent publication: protontherapy should be beneficial for 15% of patients wich requires radiotherapy treatment (i.e. 27.000 patients per year in France)
Capacity of protontherapy in France : 600 patients per year (800 en 2011).

Protontherapy : basic numbers

10 millions more people affected each year
6 millions are treated by conventional radiotherapy
9% of them could be treated by proton therapy: only 0.1% actually are
Beams have still a very low impact on overall tumor therapy
About 500 more proton therapy centers required to satisfy the need





Accelerators used in protontherapy

Hitachi 250 MeV synchrotron

IBA 230 MeV Cyclotron

Varian/ACCEL Superconducting Cyclotron

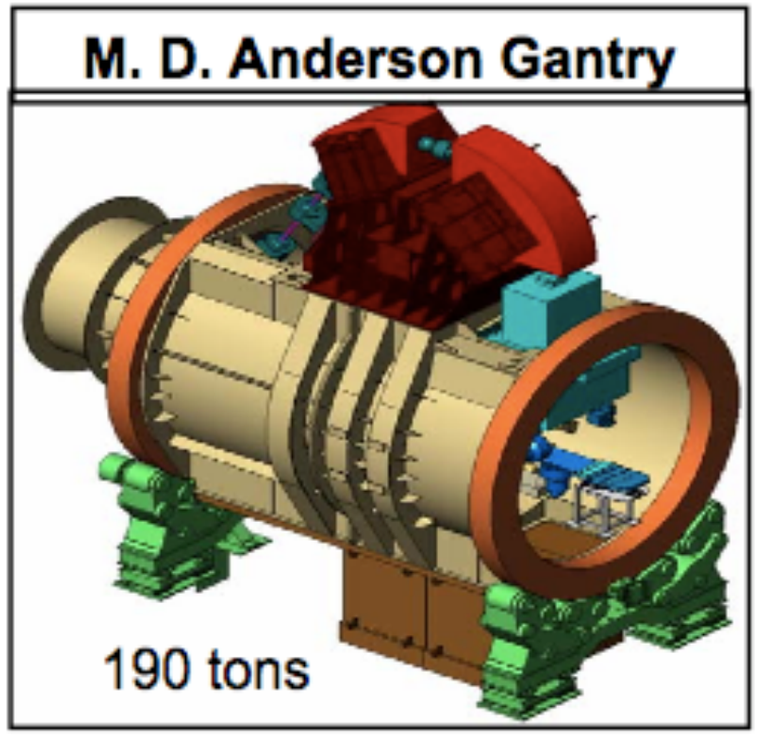
Still River Superconducting Synchrocyclotron

Specification :

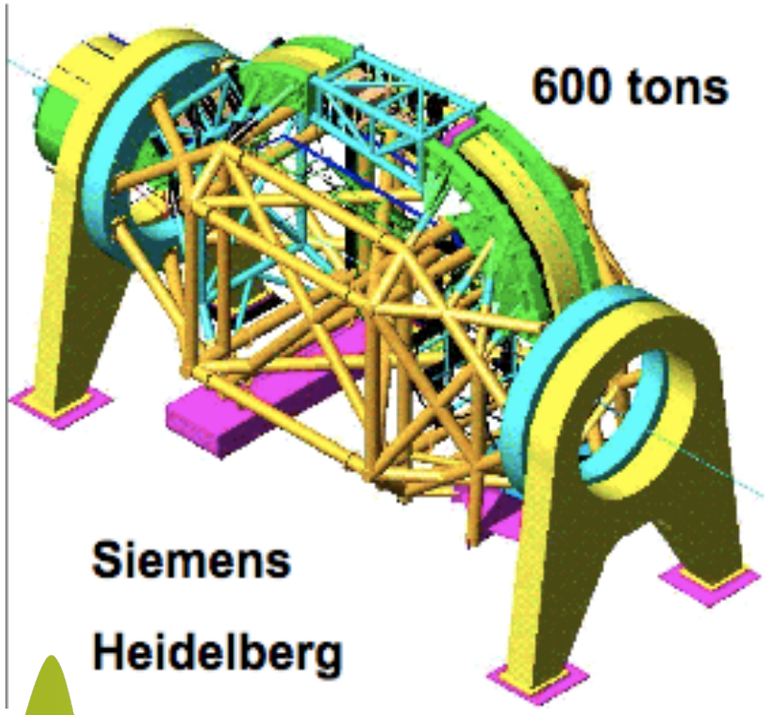
- Diameter : 3,4 m
- Weight : 60 tons
- « Self » radioprotection
- Courant max : 500 nA (3. 10^{12} $p.s^{-1}$)
- Output Energy : 250 MeV
- Extraction efficiency : 80%
- Emittance : few p-mm.mrad
- 95 % reliability (garanty by the compagny)
- 6 compagnies in the world

Cost ~10 M€

Accelerators used in protontherapy

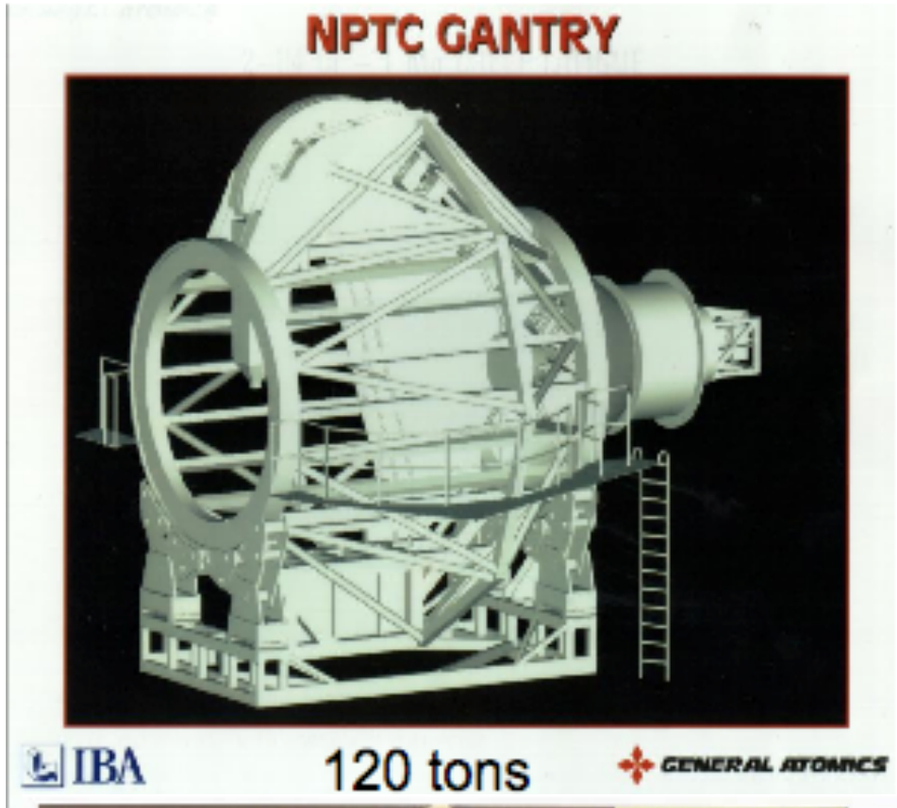


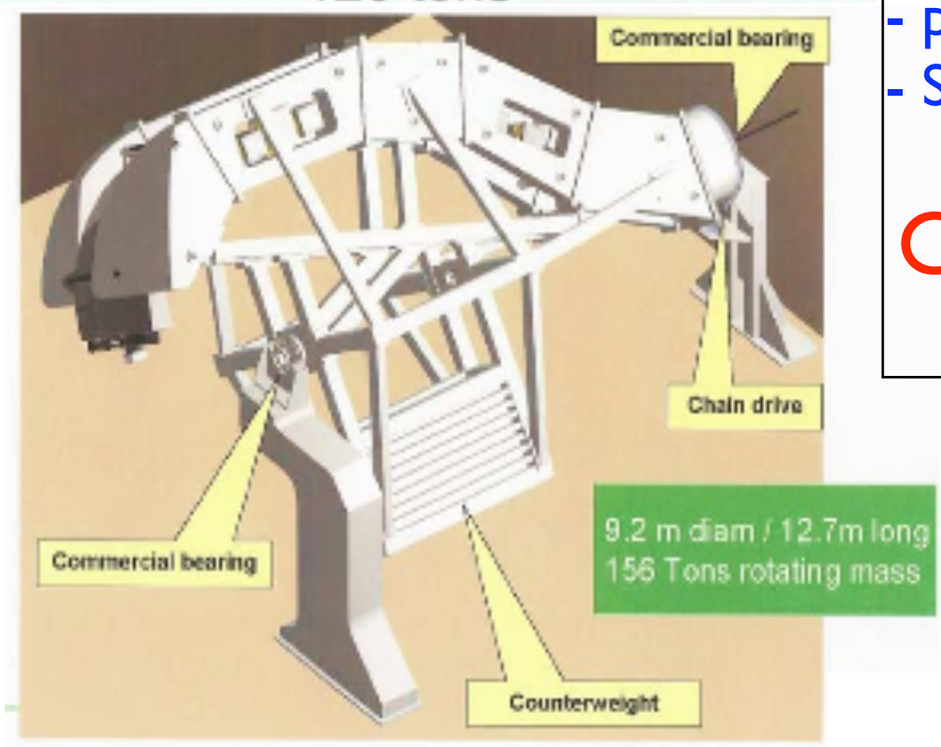
Hitachi



Siemens

Heidelberg



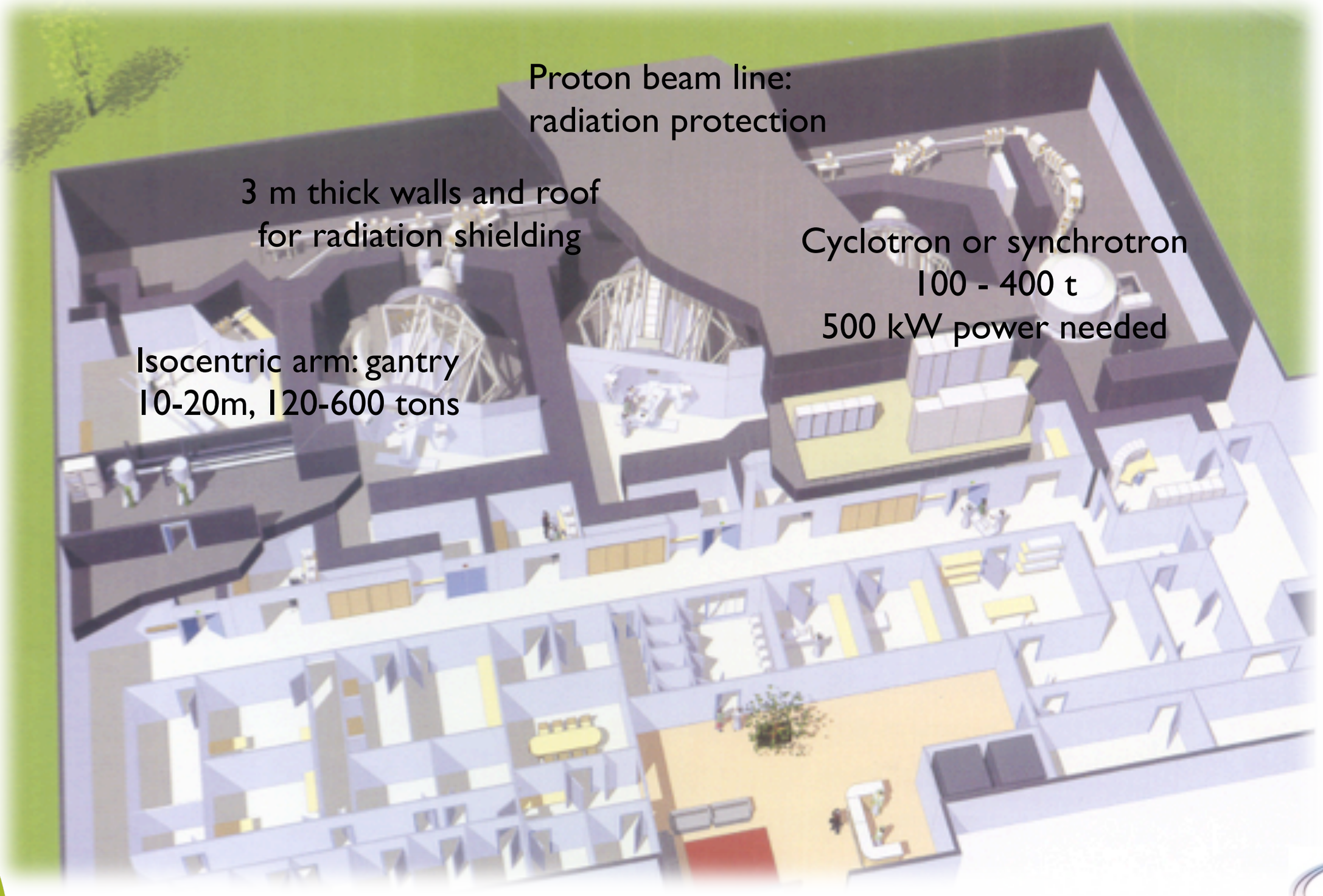


Specification :

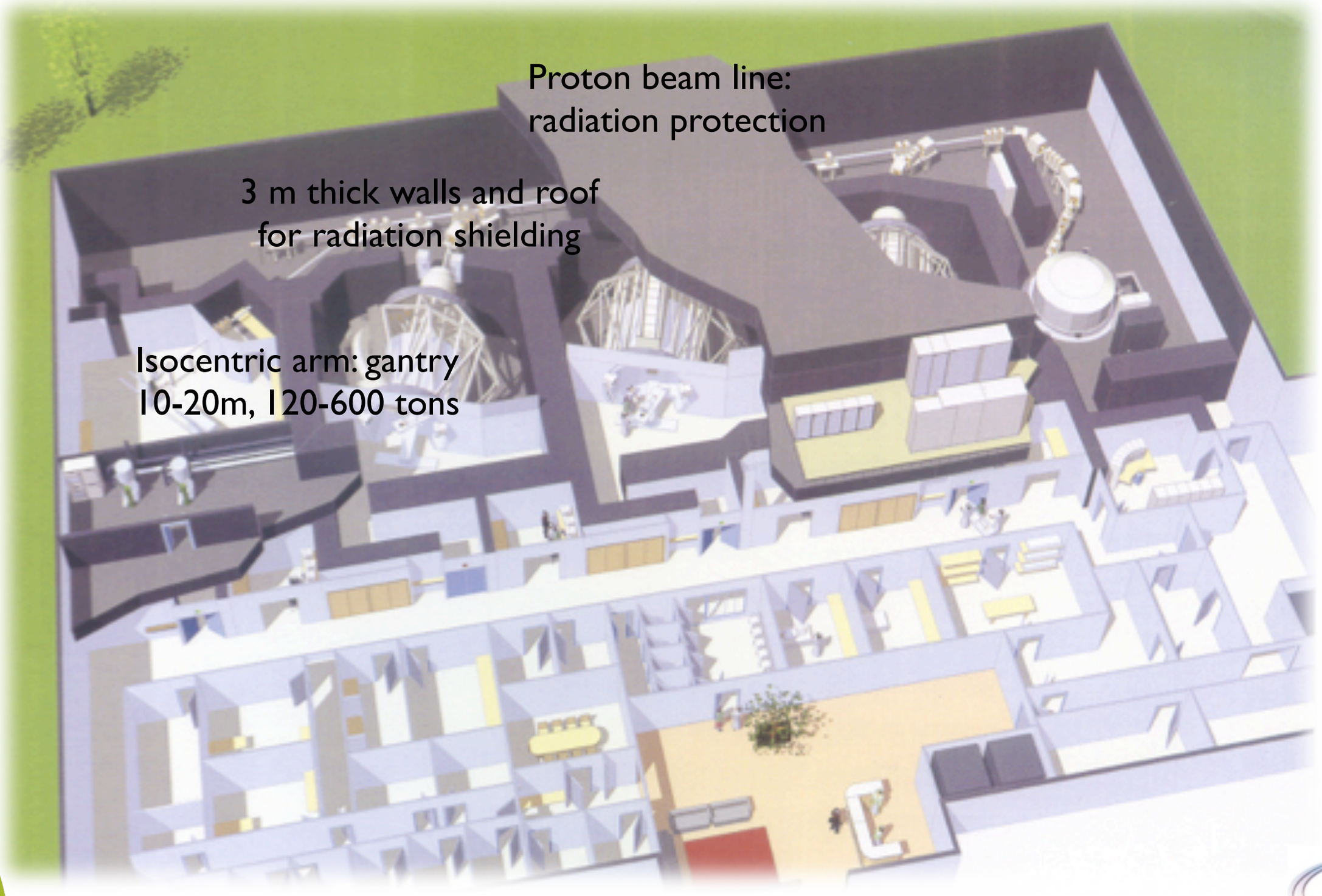
- Diameter : 3,4 m
- Weight : 120-600 tons
- precision : mm
- Size: 12-20m

Cost ~10-20 M€

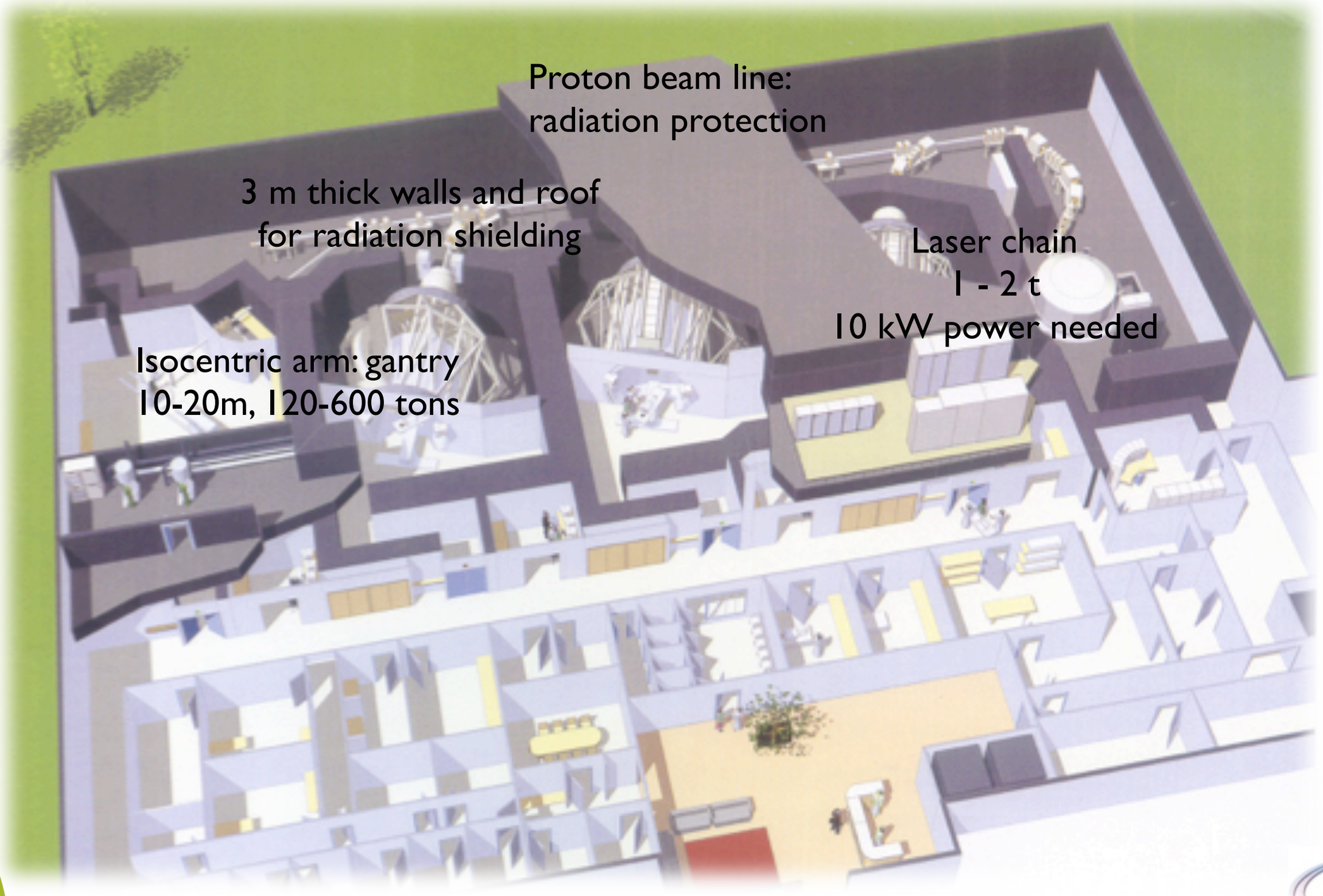
Protontherapy : basic numbers



Protontherapy : basic numbers



Protontherapy : basic numbers



Protontherapy : basic numbers

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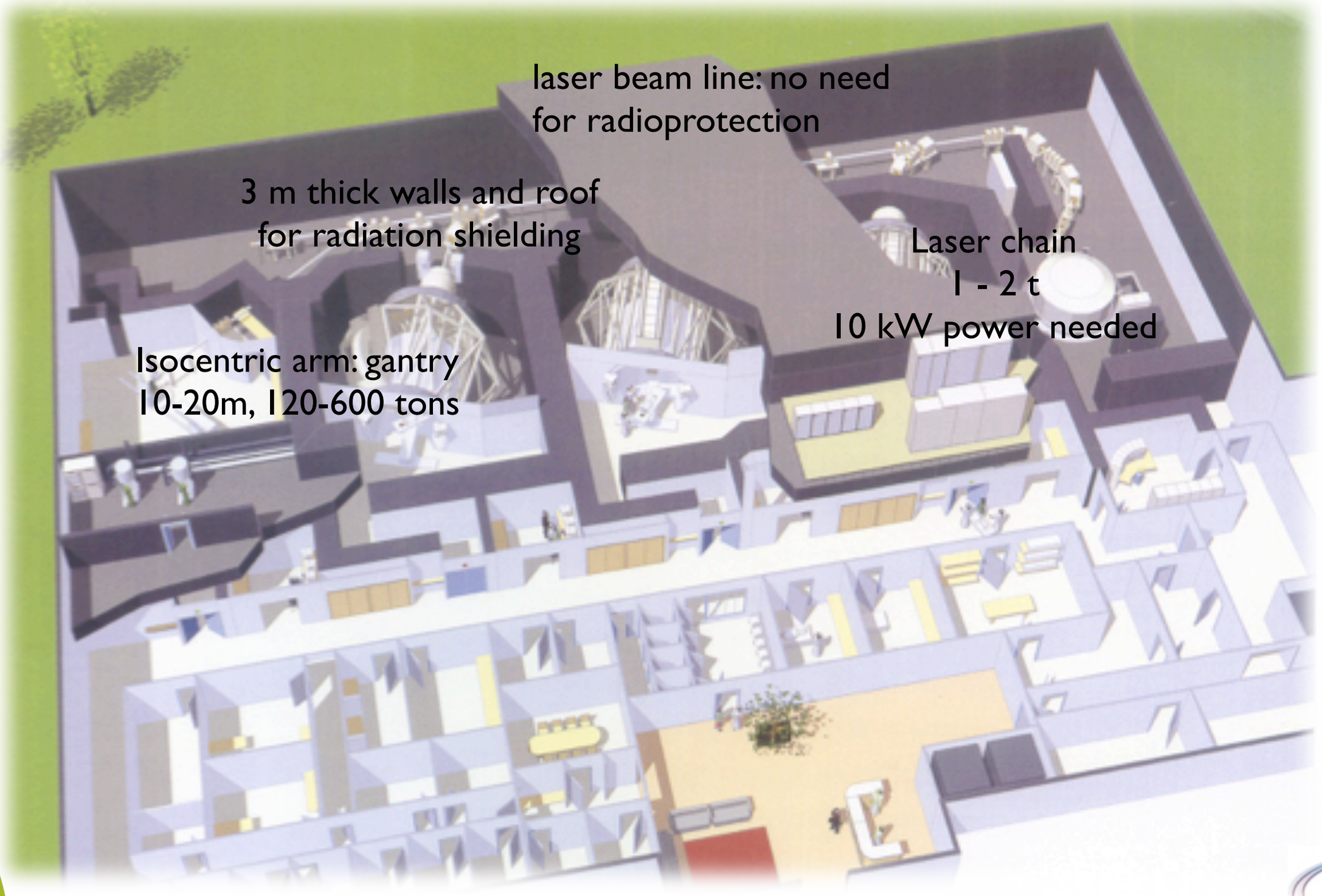
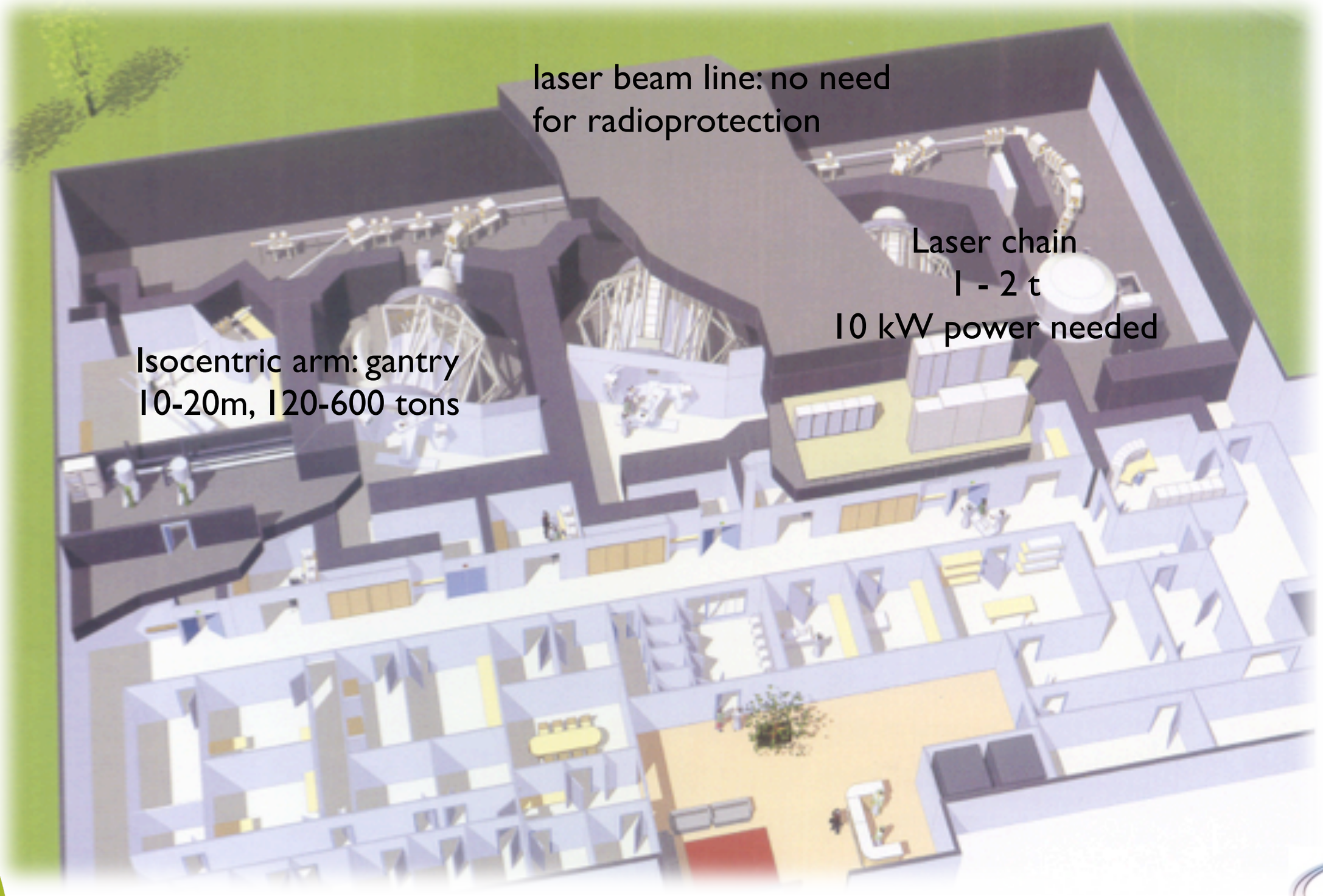
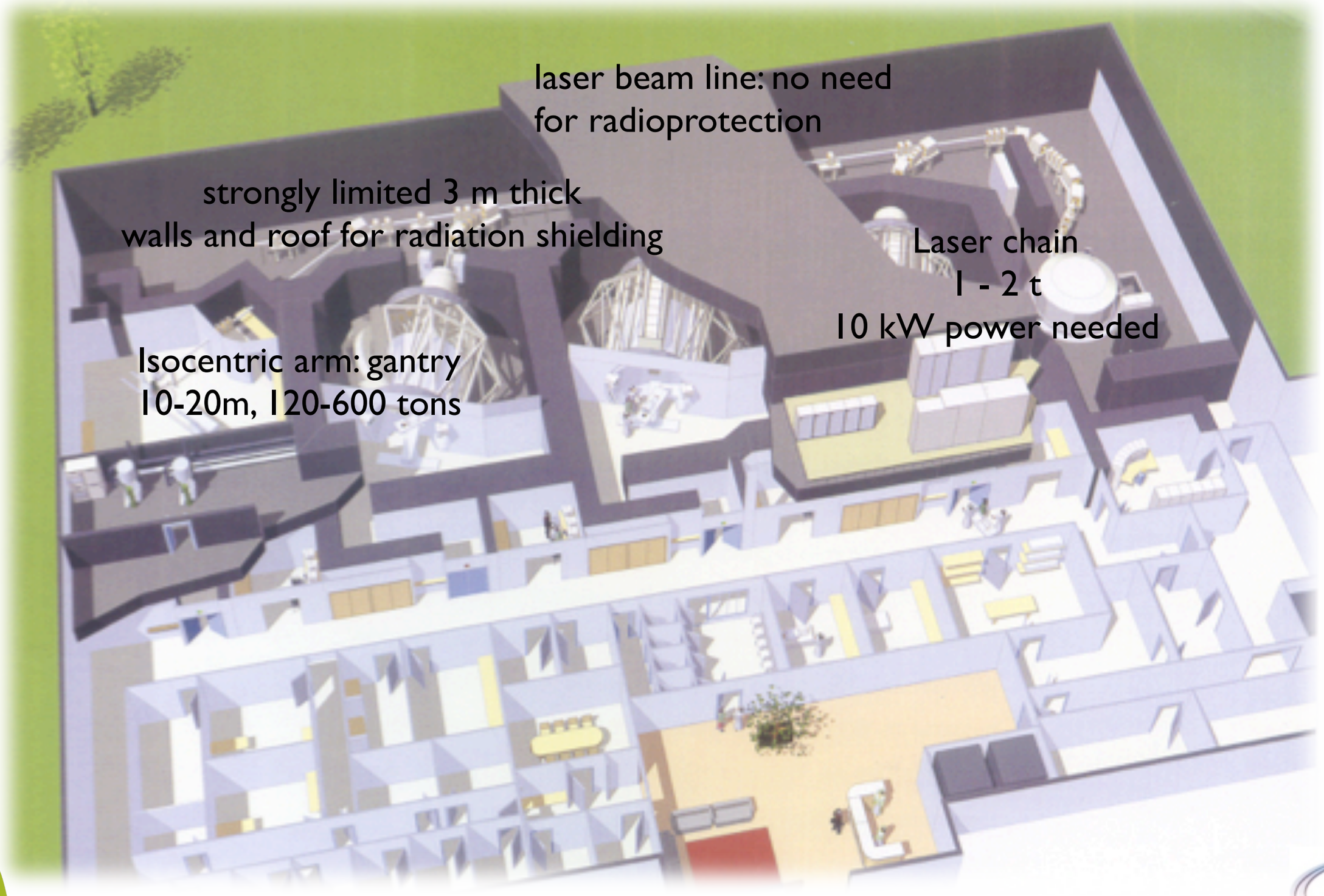


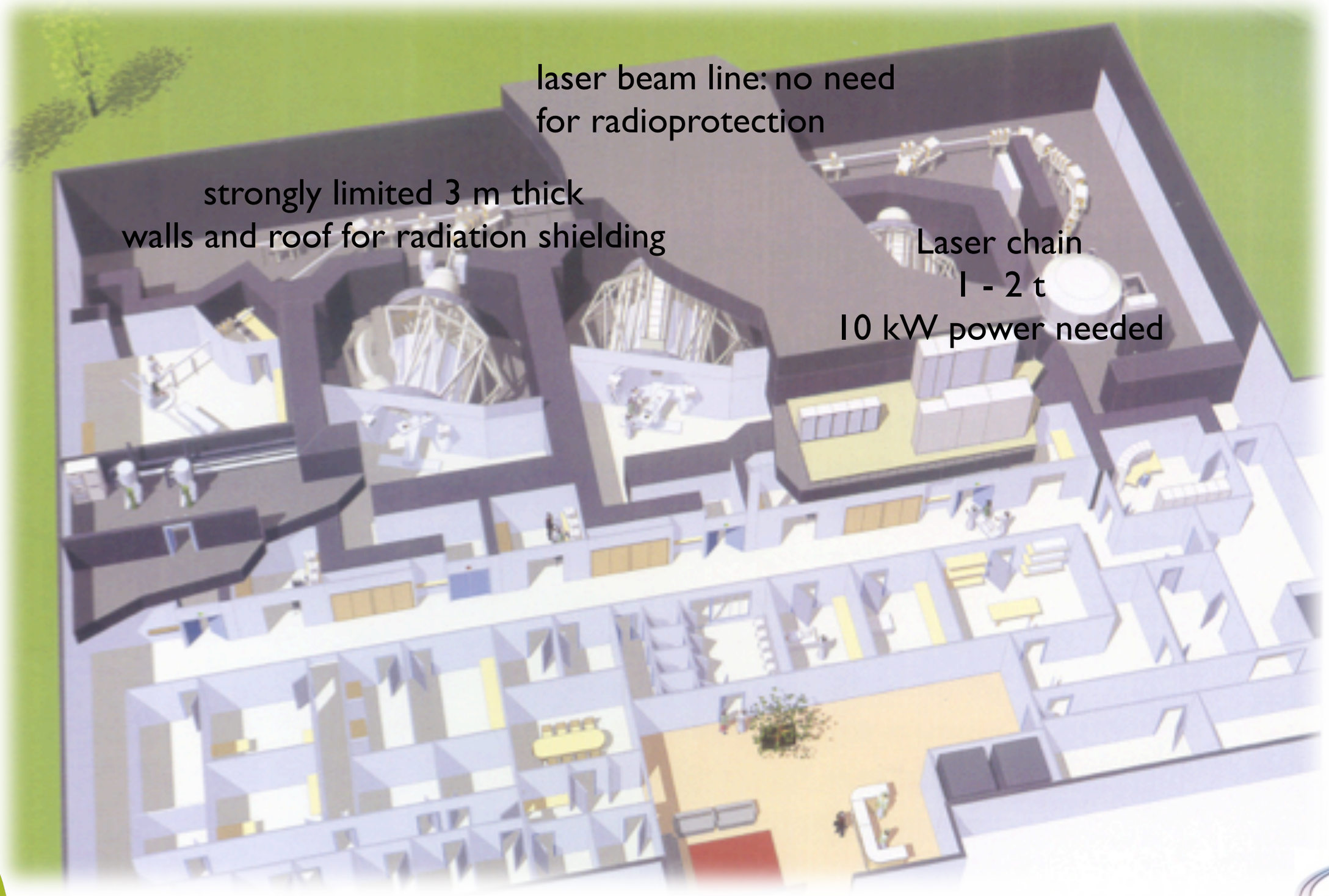
Protontherapy : basic numbers



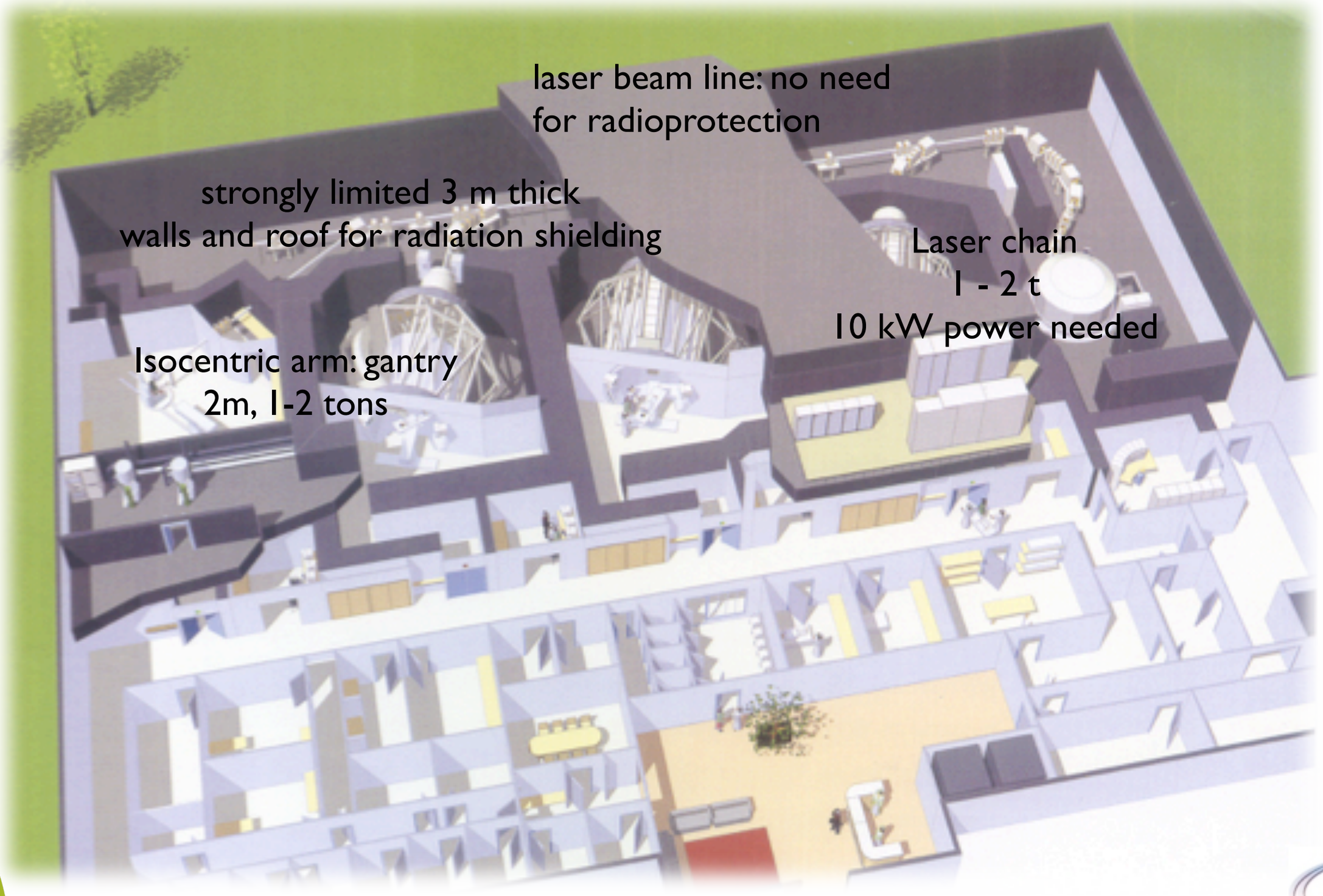
Protontherapy : basic numbers



Protontherapy : basic numbers



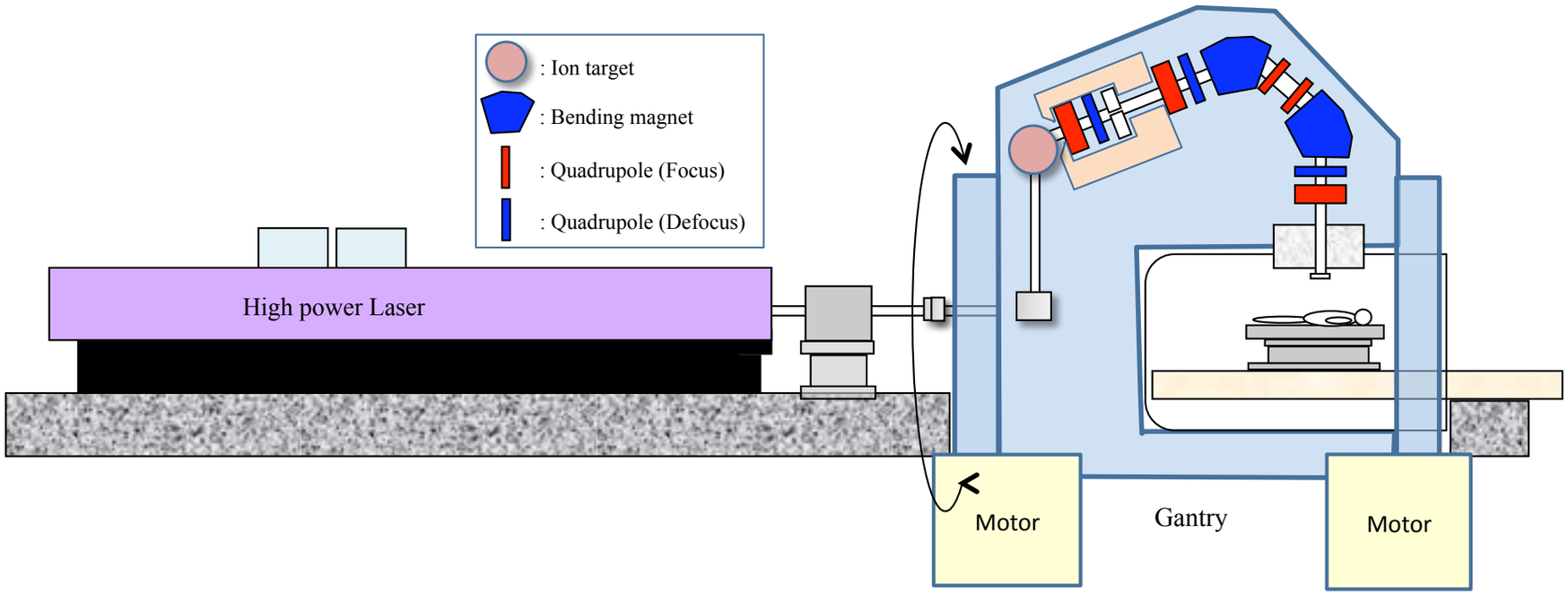
Protontherapy : basic numbers

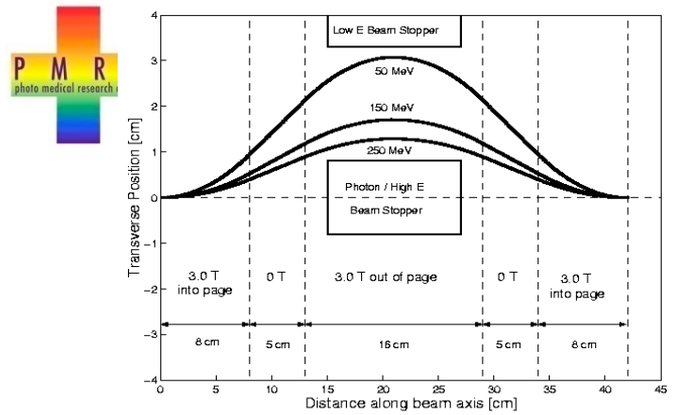


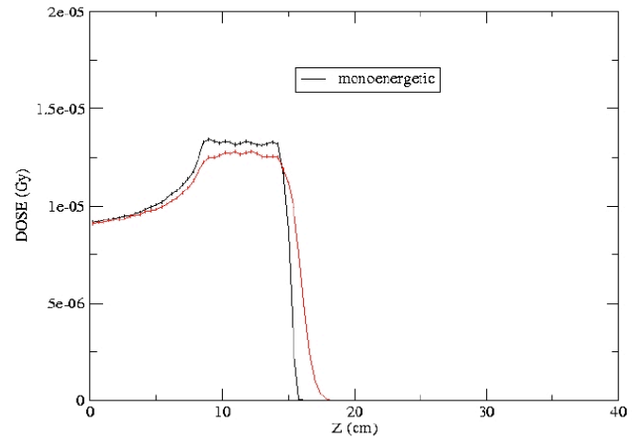
Protontherapy Facilities in the World (20 proton, 3 Carbon)

振興調整費

Design Concept : 55 MeV Laser-Driven Proton Beam (80 MeV Cutoff) Embedded into a Gantry * (Double Bend Achromat)







In this example transmission to the application is about 1.2 % . Therefore 10^7 protons per pulse at the patient requires ~ nC bunch charge at source ; so the net laser-to- delivered proton conversion efficiency for 'relevant' or delivered protons in this design is smaller (< 10^{-4}) at the application end. Generation of proton spectra with reduced divergence and energy spread can significantly improve transmission. An ILDIAS goal - improve the net laser-to- delivered proton efficiency.

** courtesy of H. Sakaki, PMRC*

The SAPHIR consortium

SAPHIR: Source Accélérée de Protons par laser de Haute Intensité pour la Radiothérapie
(Accelerated Proton Source by Ultra Intense Laser for Protontherapy)

Economical Challenges

Reduction of the investment and operating costs
Reduction of the overall size of the equipments
Reduction of radioprotection constraints
Optimization of dose deposition

Technical challenges

Getting more than 65 MeV pour eye treatment and 150-200 MeV for others.
Proton energy spectrum fully controlled
Stability and reproducibility
Applied dose

Total budget (consolidated) : 20 M€

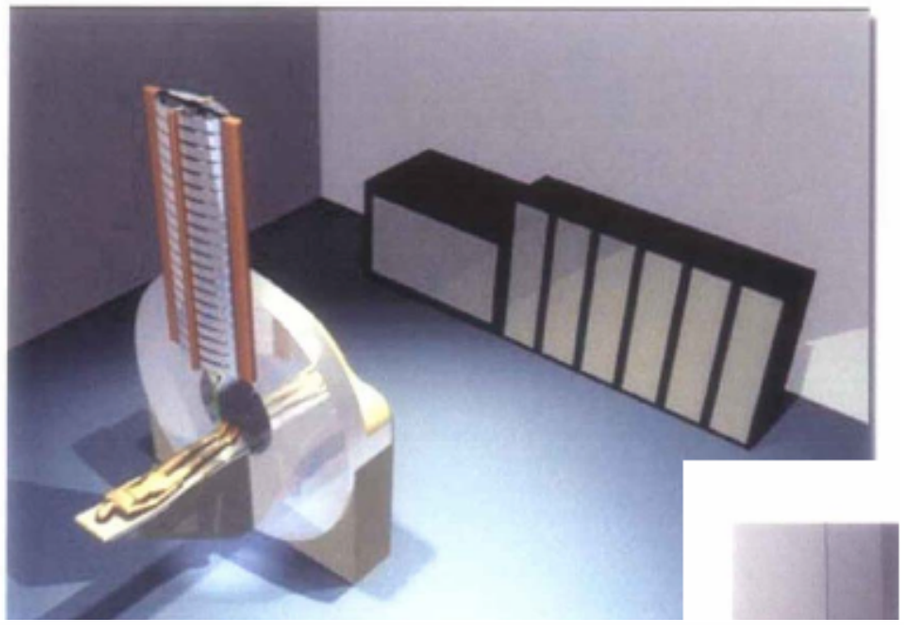
Financial support
OSEO: 6.25 M€
Region Ile de France: 1 M€

7 Partners

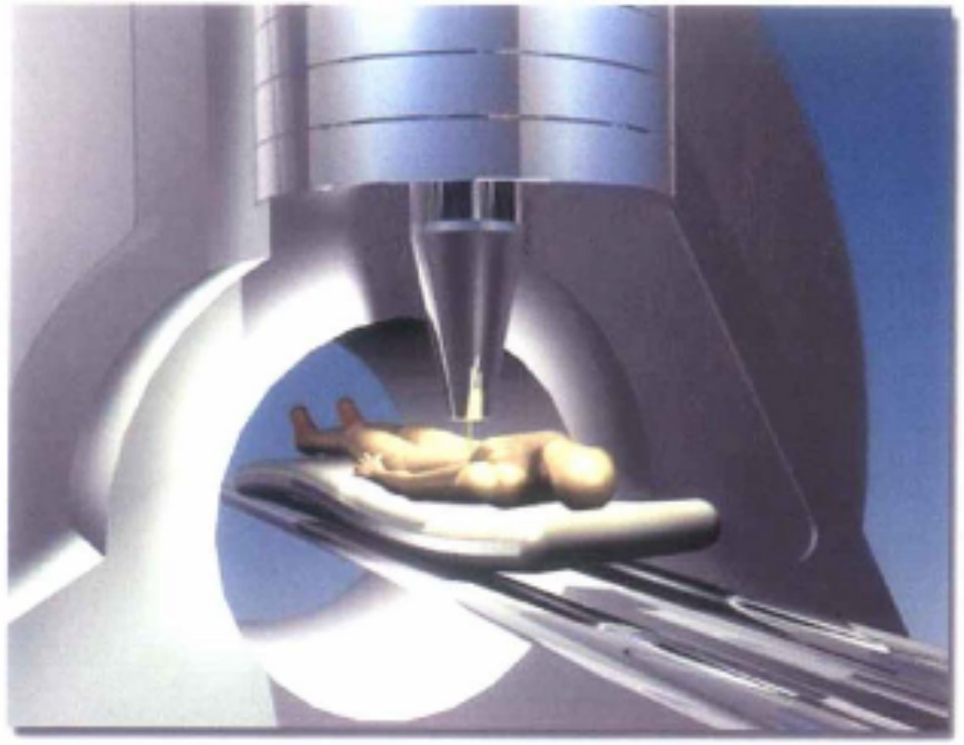
Amplitude TECHNOLOGIES
institutCurie Centre de Protonthérapie d'Orsay
DOSIsoft
Imagine Optic
UNIVERSITÉ PARIS-SUD 11
IRAMIS
Institut de cancérologie GUSTAVE ROUSSY VILLEJUIF - www.igr.fr
EuCARD

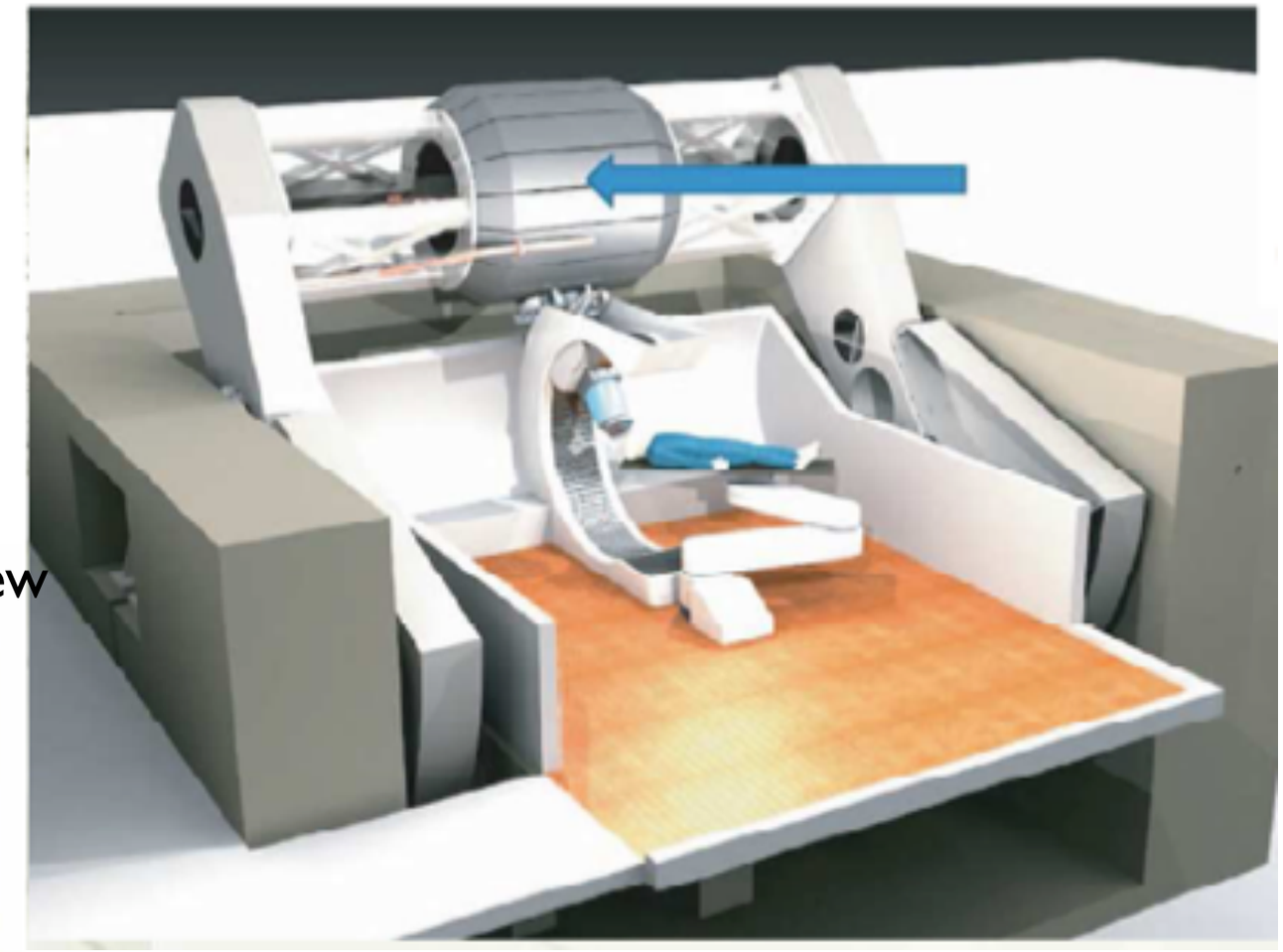
2nd Annual EUCARD meeting, PARIS, May 10-13 (2011)

Protontherapy Facilities in the World (20 proton, 3 Carbon)



Dielectric Wall Accelerators : artistic view





Monarch 250
Synchrocyclotron cryogenic (9T, 20 t.)

Conclusion and Perspectives

- Stability has been improved by improving the laser contrast
  30 % enhanced proton peak energy by preforming the plasma
- They produce quasi monoenergetic beam (structured target or RPA see)
- Peak energy still moderated : 19MeV with 10 Hz laser, 70 MeV with PW large scale laser : 70 MeV with 300 J, ps laser
- Number of proton per second can be a problem ?
- Target fabrication and alignment at high repetition rate ? In progress (LIBRA)
- Biological response with high current dose? In progress (FZD, see Kraft et al., NJP special issue 2010)
- Electron LPA satisfies mostly all the requirements
- Proton LPA is still very challenging
- New technics are coming (and are wellcome!)

V. Malka et al., Nature Physics **4**, June 2008