UNIVERSITÀ DEGLI STUDI DI TORINO

CINFAI SCUOLA ALTA FORMAZIONE

INFN TORINO

New Detectors for Beam Monitoring in Particle Therapy

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INFN Torino

Giornate di Studio sui Rivelatori - Scuola F. Bonaudi

February 10-14, 2020 Cogne

Outline

Physics for cancer

- Basic principles of Radiation Therapy
- Basic principles of Charged Particle Therapy

Instrumentation

- Accelerators
- Beam delivery system

Beam monitors

- Gas ionization chambers

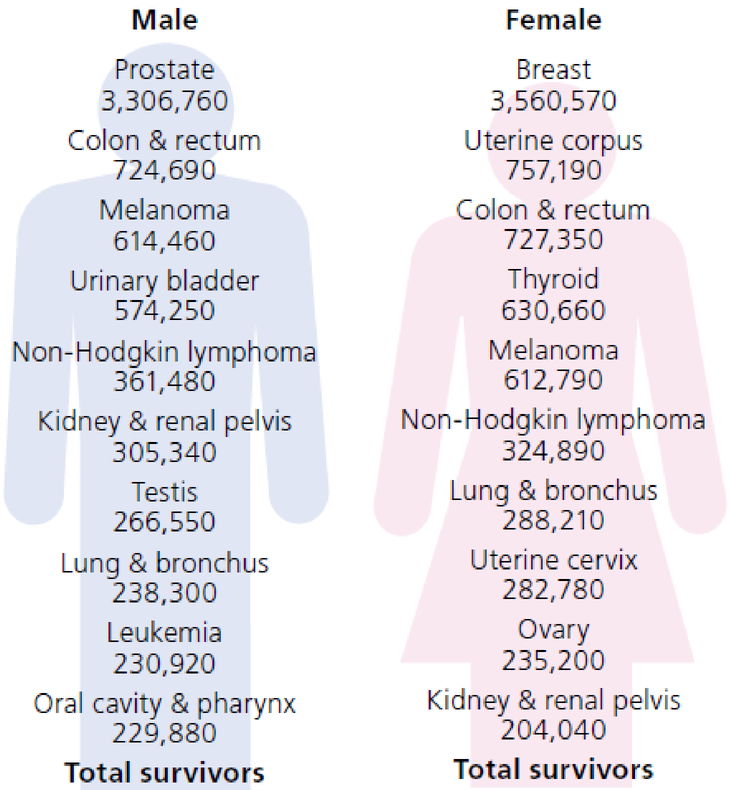
What's next?

The number of cancer survivors is increasing

Estimated US cancer survivors

~19 million new cancers/year

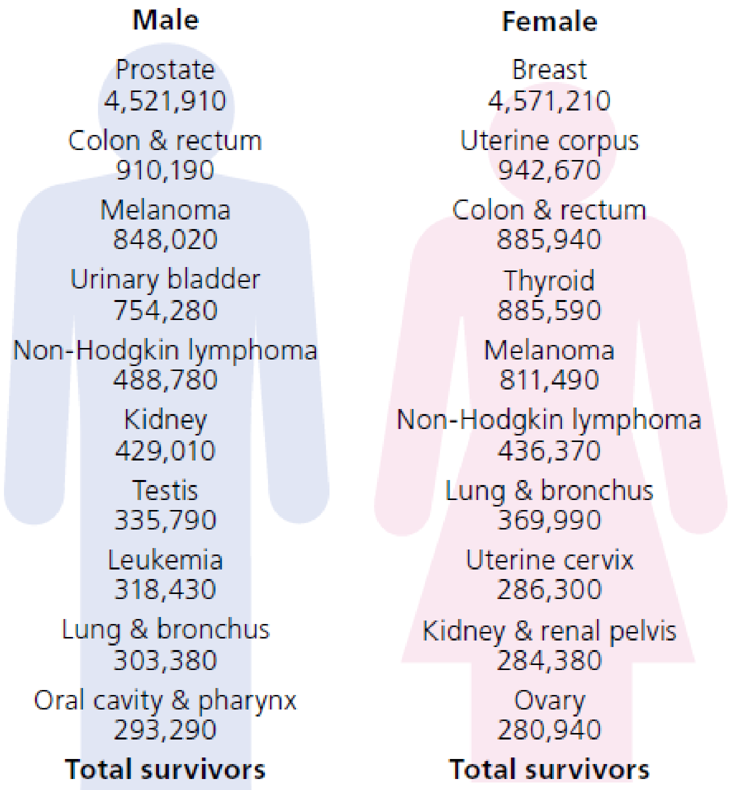
As of January **2016**



Male		Female	
Prostate	3,306,760	Breast	3,560,570
Colon & rectum	724,690	Uterine corpus	757,190
Melanoma	614,460	Colon & rectum	727,350
Urinary bladder	574,250	Thyroid	630,660
Non-Hodgkin lymphoma	361,480	Melanoma	612,790
Kidney & renal pelvis	305,340	Non-Hodgkin lymphoma	324,890
Testis	266,550	Lung & bronchus	288,210
Lung & bronchus	238,300	Uterine cervix	282,780
Leukemia	230,920	Ovary	235,200
Oral cavity & pharynx	229,880	Kidney & renal pelvis	204,040
Total survivors	**7,400,000**	**Total survivors**	**8,200,000**

As of January **2026**

~24 million new cancers/year



Male		Female	
Prostate	4,521,910	Breast	4,571,210
Colon & rectum	910,190	Uterine corpus	942,670
Melanoma	848,020	Colon & rectum	885,940
Urinary bladder	754,280	Thyroid	885,590
Non-Hodgkin lymphoma	488,780	Melanoma	811,490
Kidney	429,010	Non-Hodgkin lymphoma	436,370
Testis	335,790	Lung & bronchus	369,990
Leukemia	318,430	Uterine cervix	286,300
Lung & bronchus	303,380	Kidney & renal pelvis	284,380
Oral cavity & pharynx	293,290	Ovary	280,940
Total survivors	**10,000,000**	**Total survivors**	**10,300,000**

Total survivors 7,400,000 8,200,000 10,000,000 10,300,000

Reference [1]

+53% survivors in Italy

LA STAMPA

4 Febbraio 2020

Tumori: in 10 anni in Italia +53% di pazienti vivi dopo la diagnosi. Ma l'accesso a test e cure non è uguale per tutti

Fra i prossimi obiettivi della comunità scientifica l'abbattimento delle differenze regionali nel trattamento dei pazienti. Da AIOM appello alle Istituzioni perché venga seguito l'esempio delle Regioni più virtuose

Reference [2]

Clinical strategies for Cancer Treatment

- Surgery
- Chemotherapy
- Radiotherapy
- Immunotherapy
- Biological and targeted-therapy
- Combined and personalized therapy

Clinical strategies for Cancer Treatment

- Surgery
- Chemotherapy
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- Immunotherapy
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Radiation therapy after Marie Curie

BJC
British Journal of Cancer
www.nature.com/bjc

Check for updates

REVIEW ARTICLE

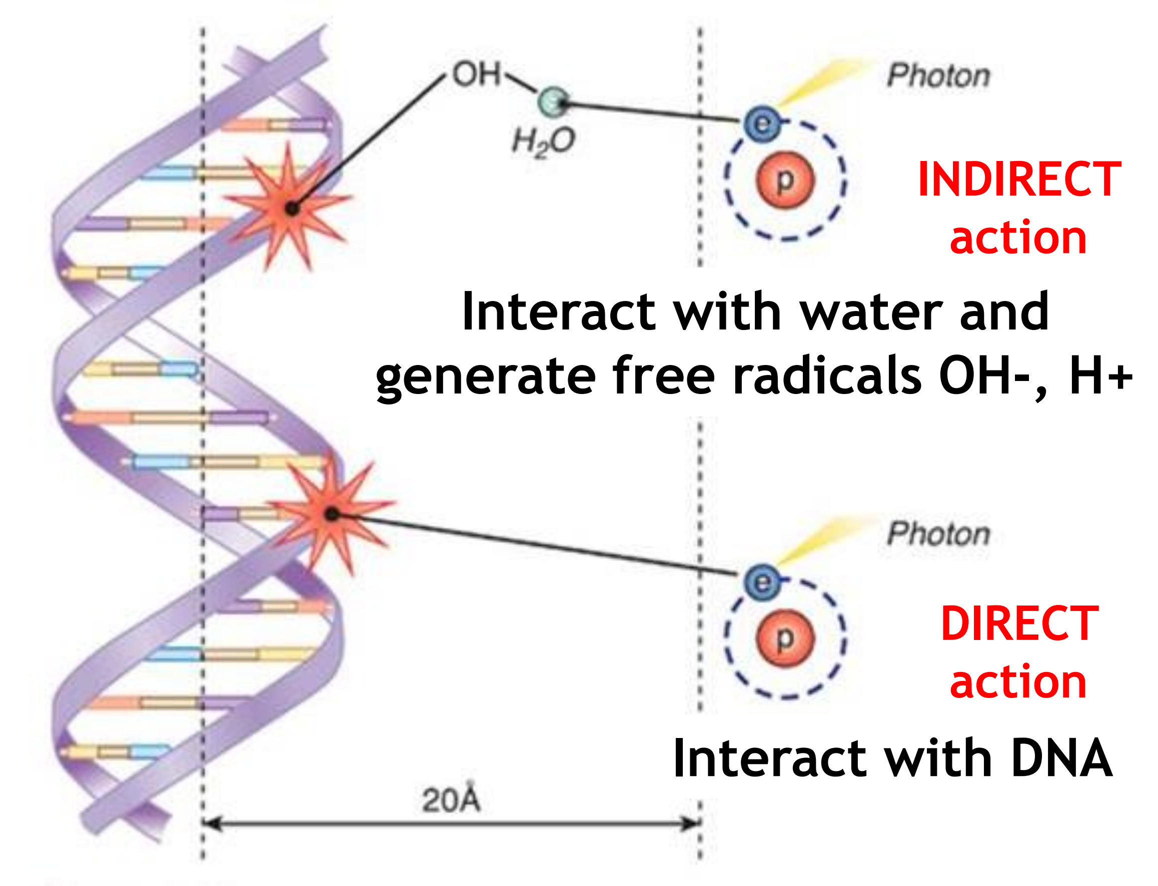
Practice-changing radiation therapy trials for the treatment of cancer: where are we 150 years after the birth of Marie Curie?

Mareike K. Thompson[1], Philip Poortmans[2], Anthony J. Chalmers[3], Corinne Faivre-Finn[4], Emma Hall[5], Robert A. Huddart[6], Yolande Lievens[7], David Sebag-Montefiore[8] and Charlotte E. Coles[9]

Reference [3]

Ionizing radiations damage and kill our cells

The target is the DNA



INDIRECT action

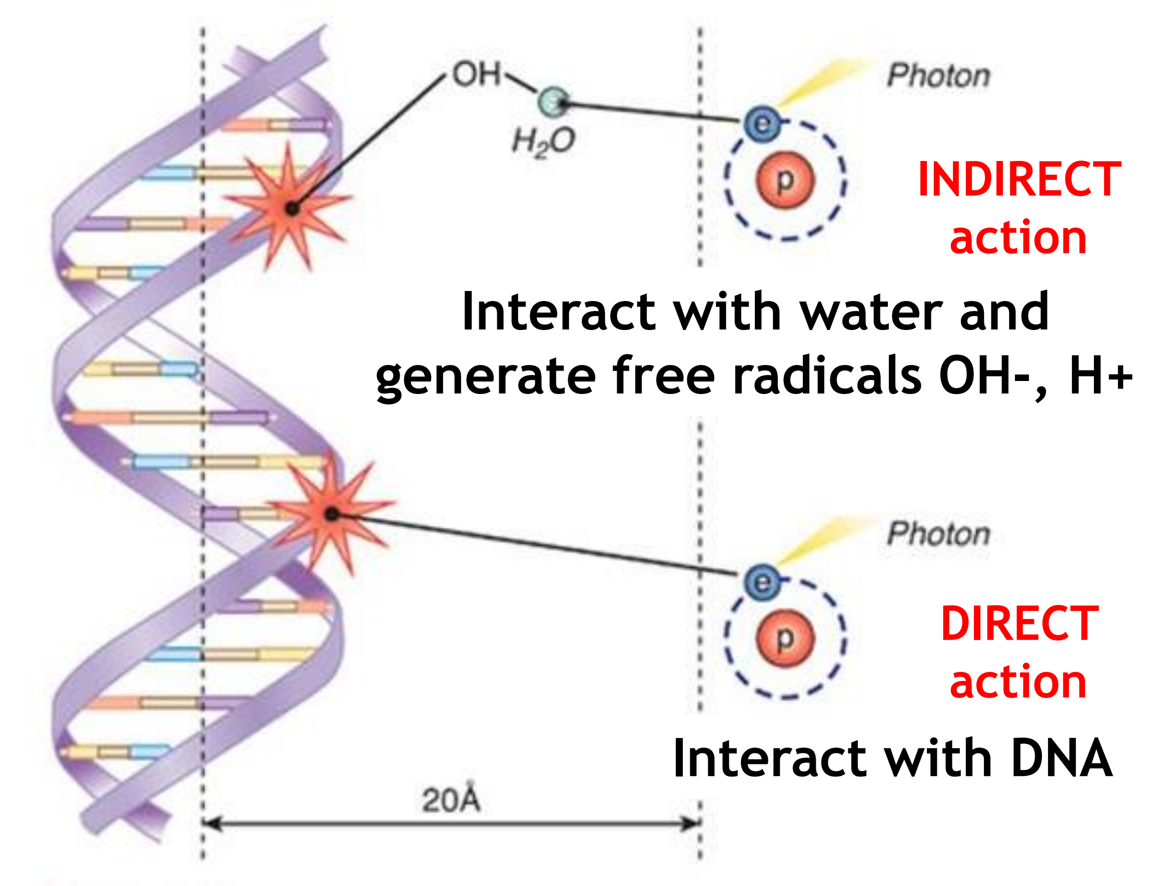
Interact with water and generate free radicals OH-, H+

DIRECT action

Interact with DNA

Ionizing radiations damage and kill our cells

The target is the DNA



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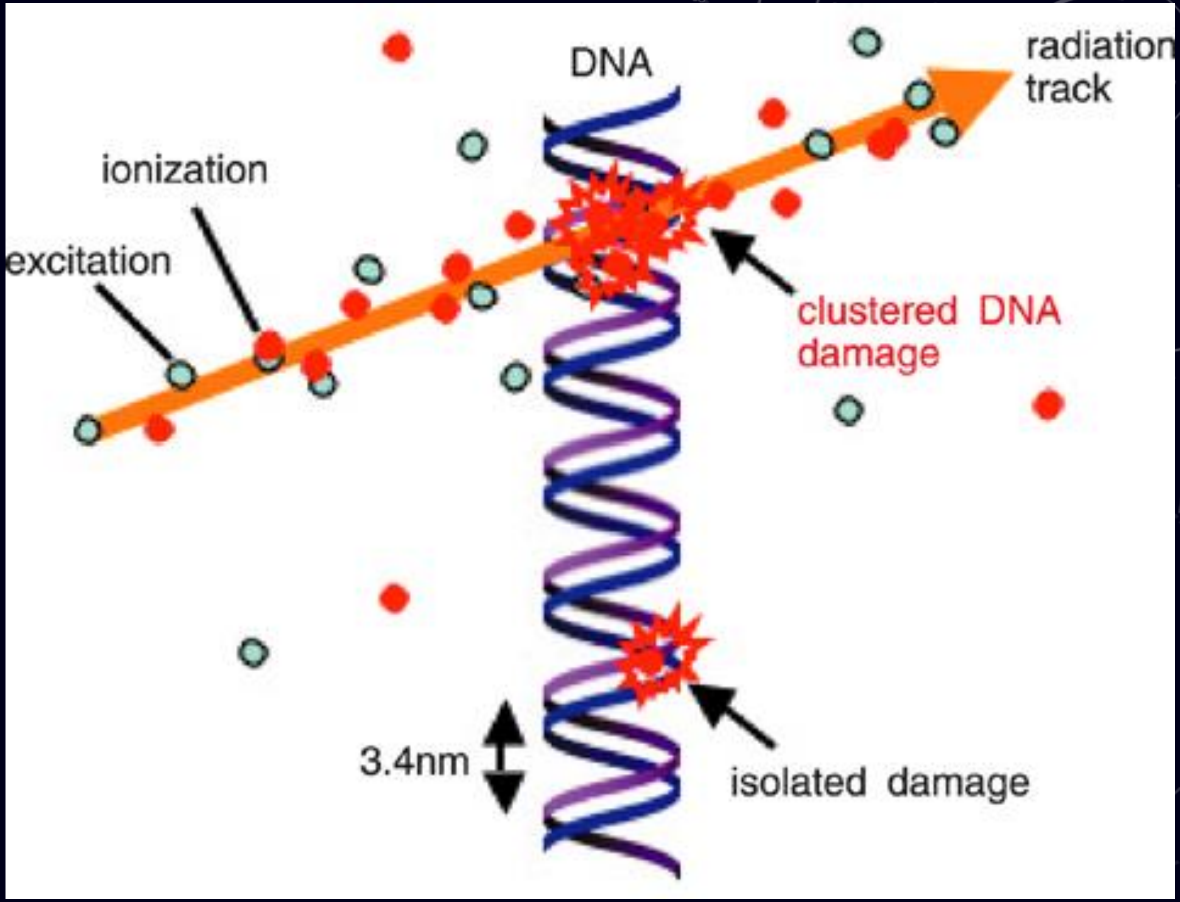
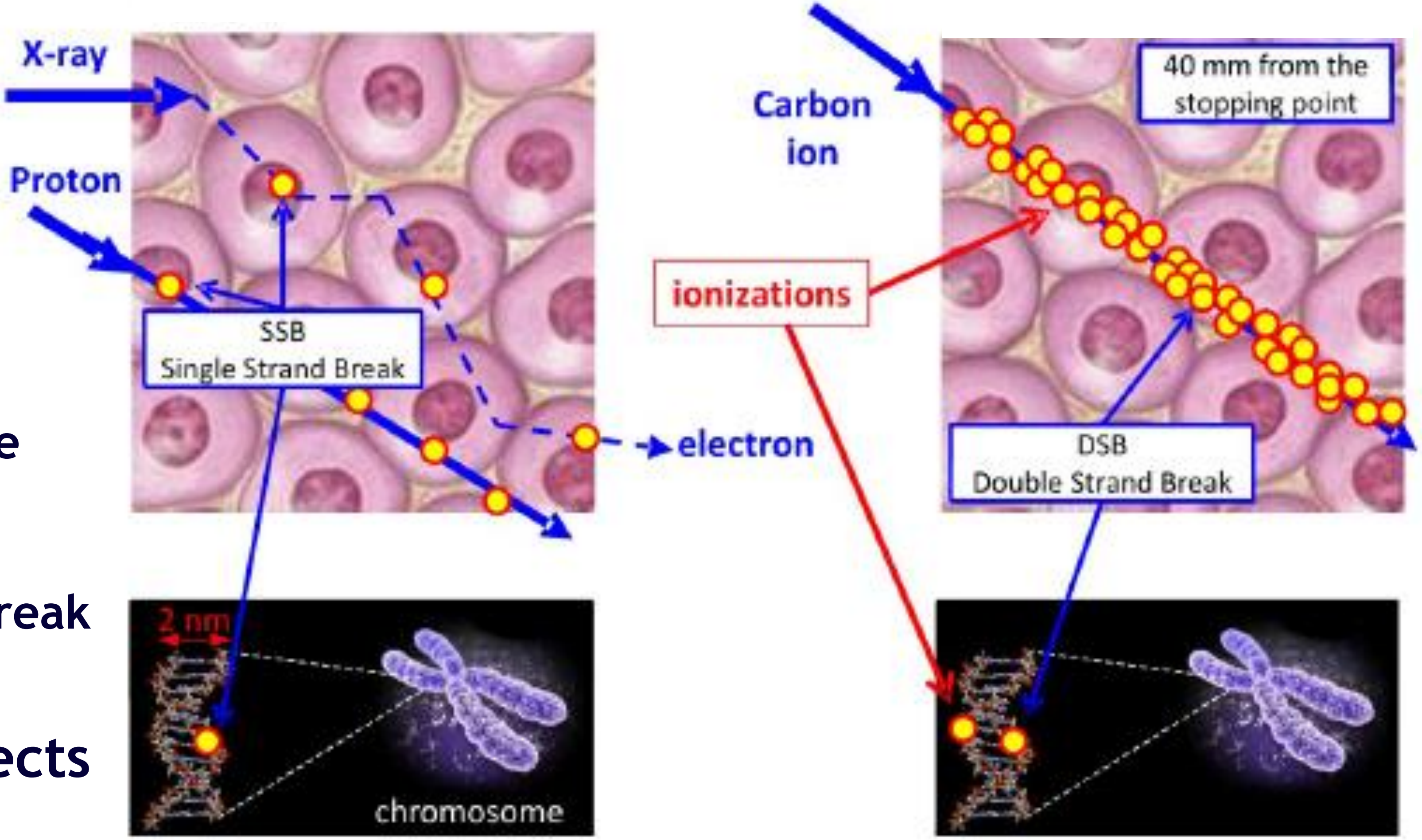


Single and Double Strand Breaks



Isolated damage

SSB
Single Strand Break

Sublethal effects

Clustered damage

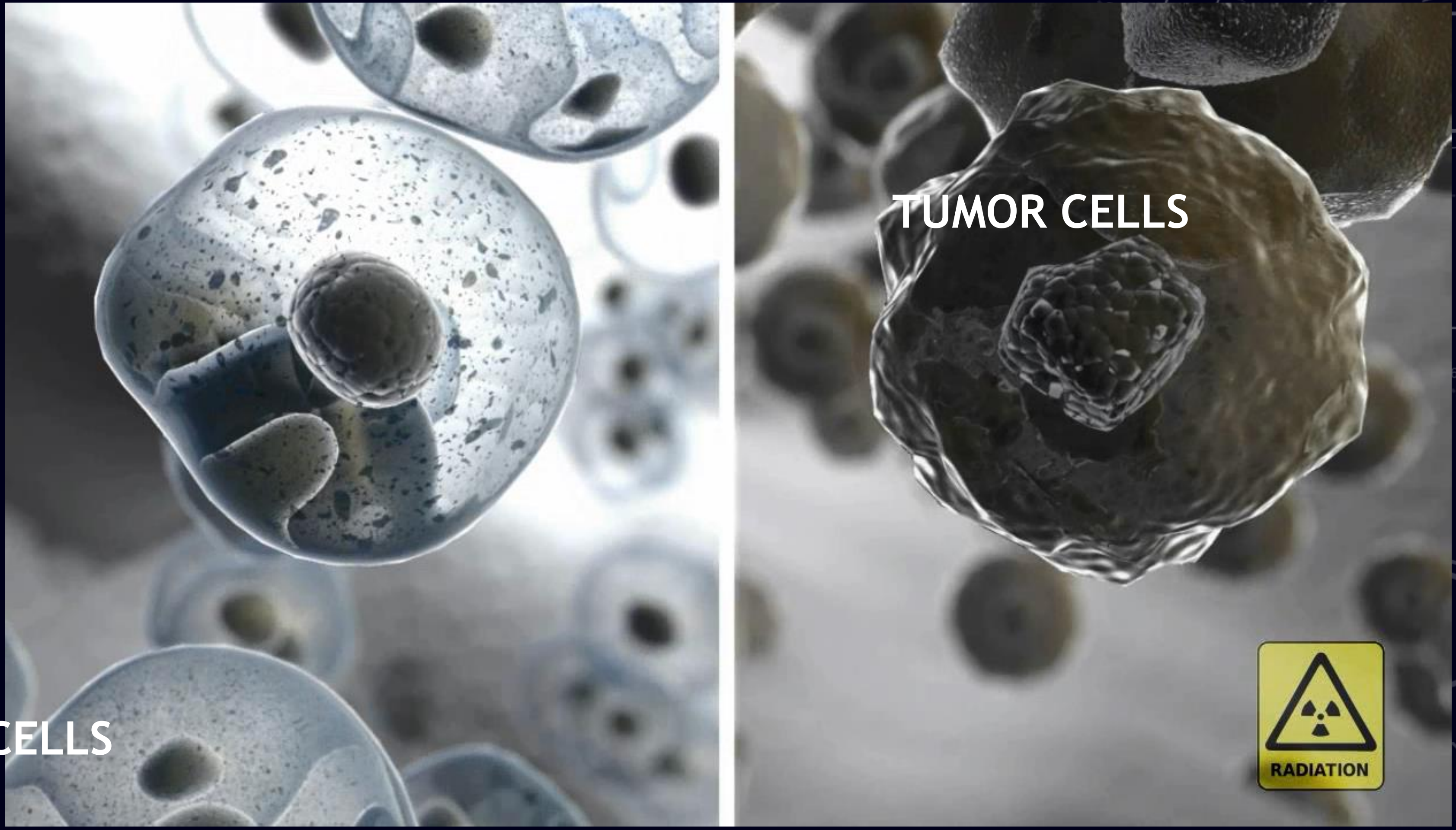
DSB
Double Strand Break

Lethal effects

Radiation therapy

Tumor cells are more sensitive to ionizing radiation than normal cells

→ Healthy cells repair themselves more easily



Ref 4

The killer amount of Energy

$$Dose = \frac{dE}{dm}\ [Gy\ = \mathrm{J/kg}]$$

The effects DEPEND ON DOSE

Typical killer dose 60-80 Gy

The effects DEPEND ON DOSE RATE

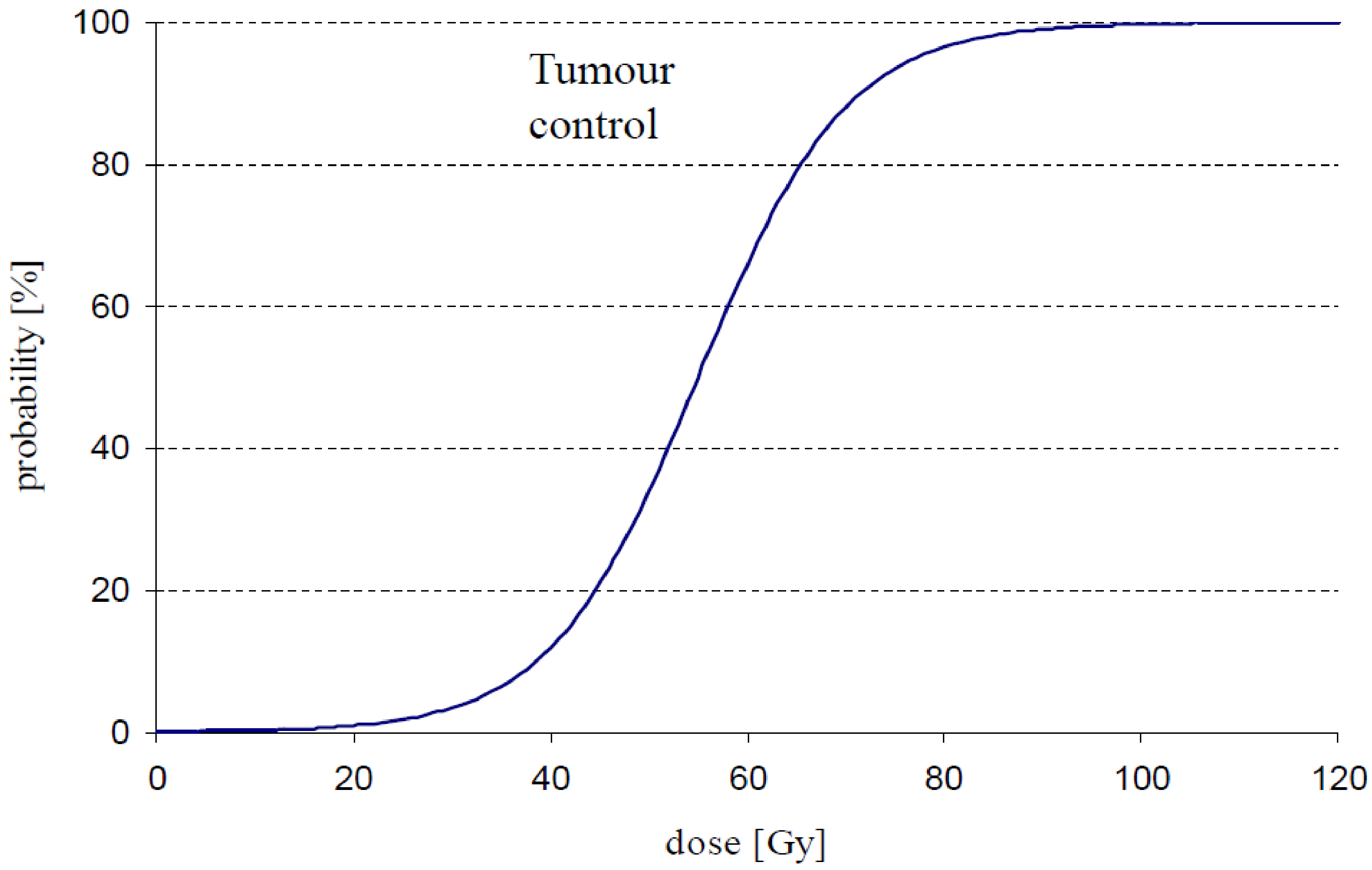
Delivered in 30-35 days → ~ 2 Gy/day

2 Gy delivered in 1-2 minute (averaged dose rate 2-1 Gy/min)

The effects DEPEND ON several other parameters like radiation type, tissue type, beam characteristics,…

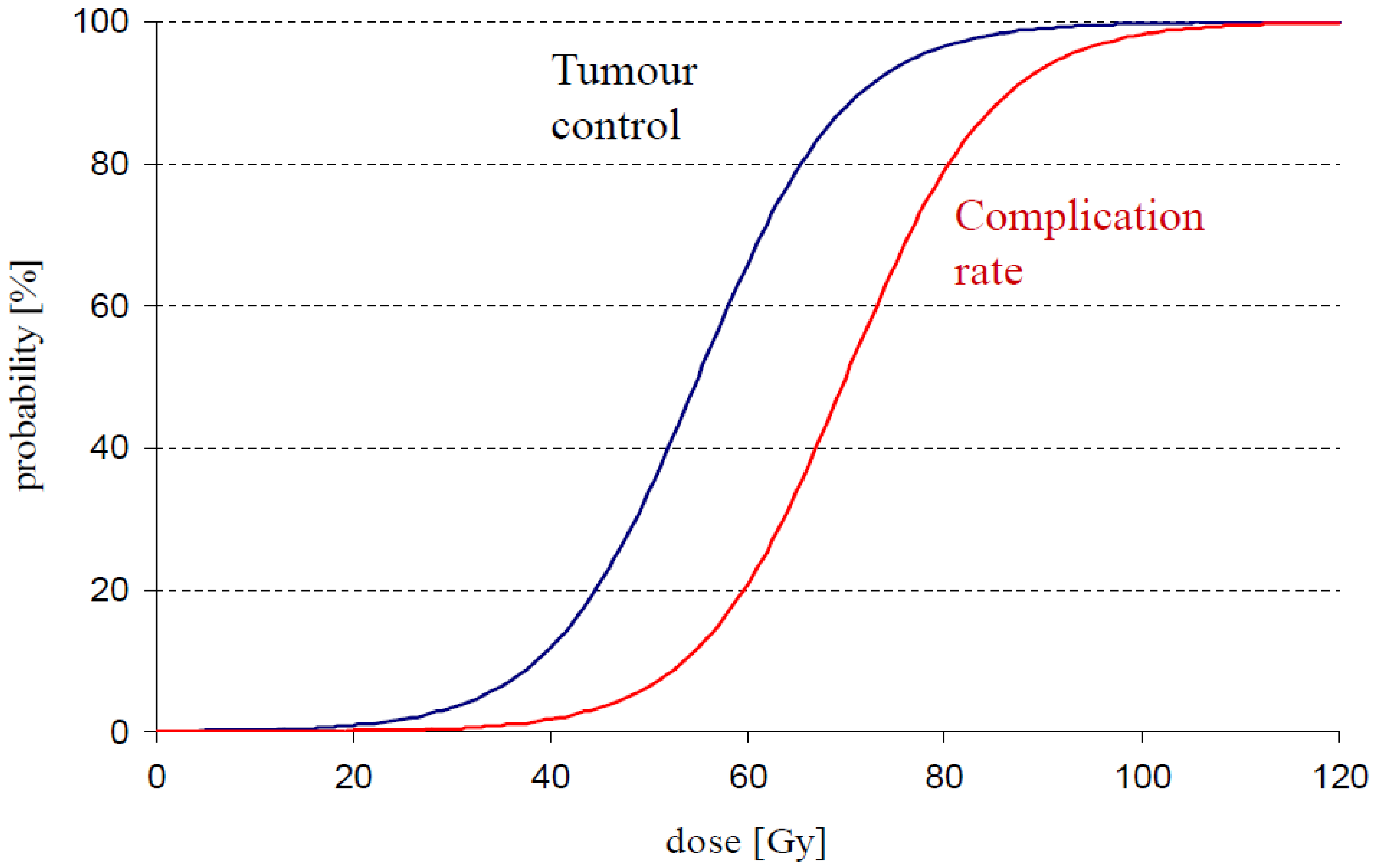
Tumor control vs dose

General principle to select the best dose

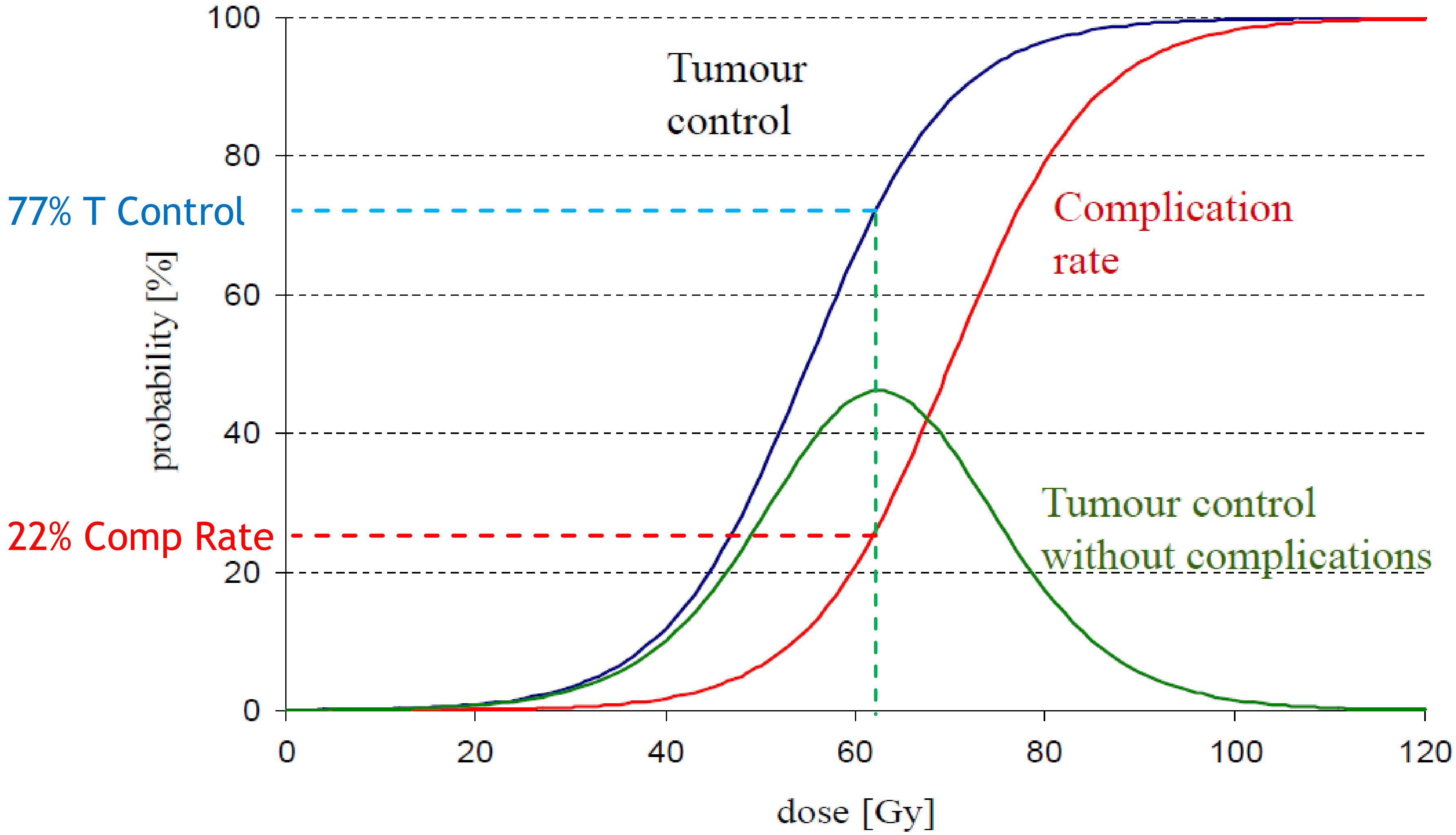


Complication rate vs dose

General principle to select the best dose that minimize the complication rate

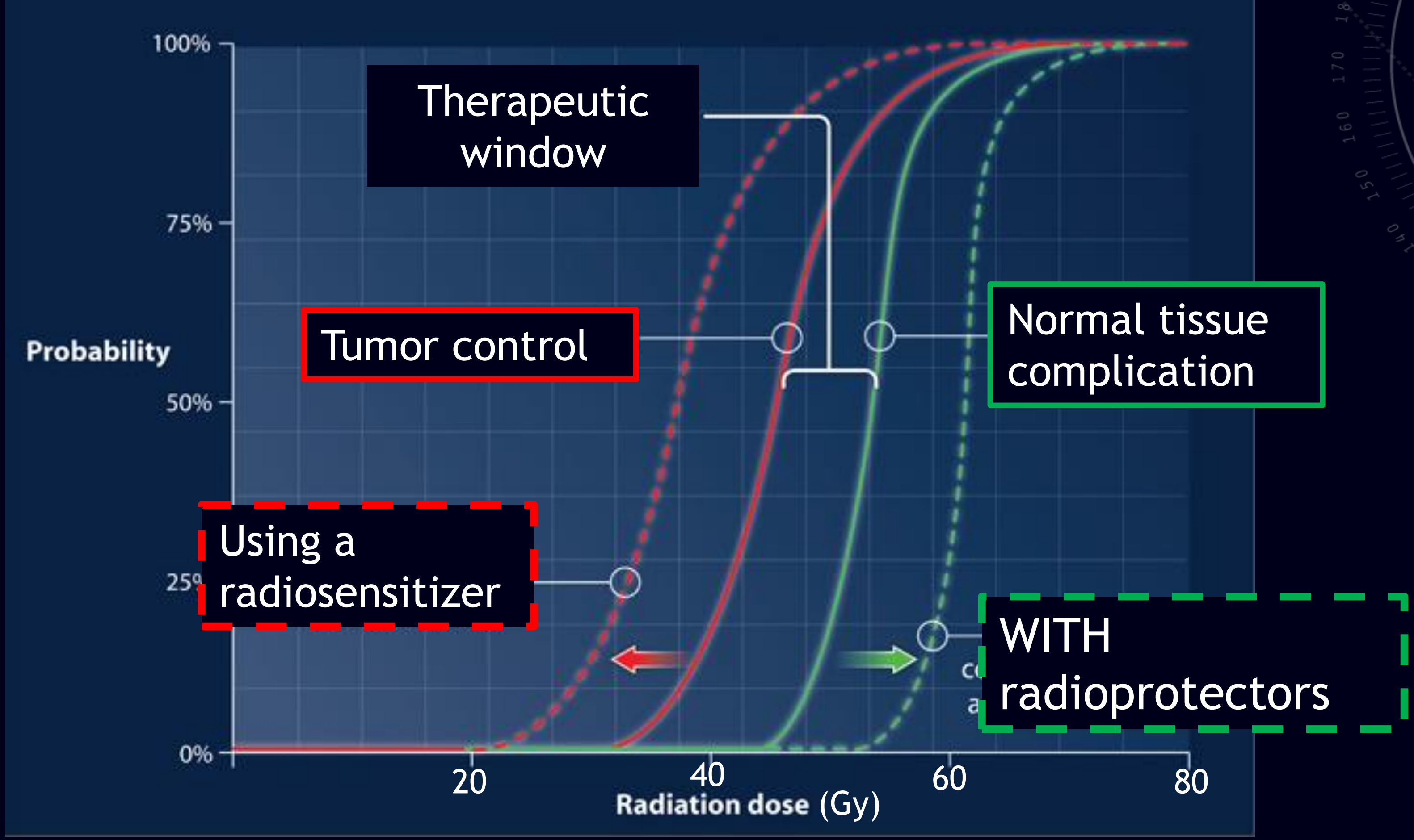


Clinical goal : tumor control without complications



Radiation oncology research and technological improvements

work to increase the therapeutic window



Therapeutic window

Tumor control

Normal tissue complication

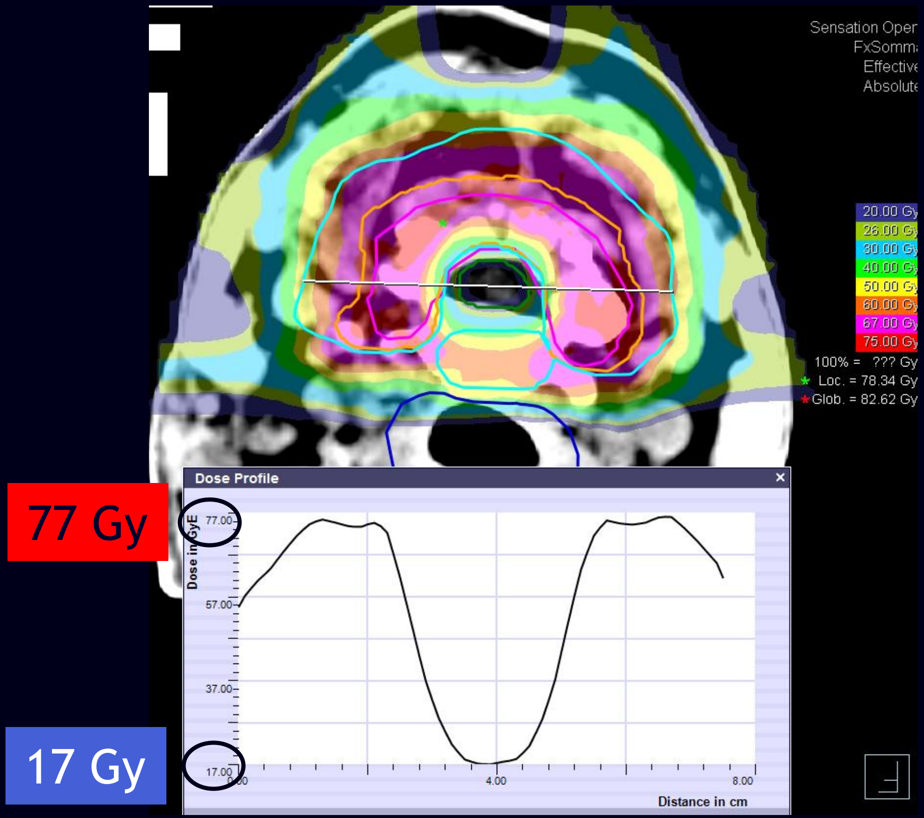
Using a radiosensitizer

WITH radioprotectors

Radiotherapy clinical goal

Kill efficiently the tumor cells while minimizing toxicity to normal tissues

Clinical goal



77 Gy

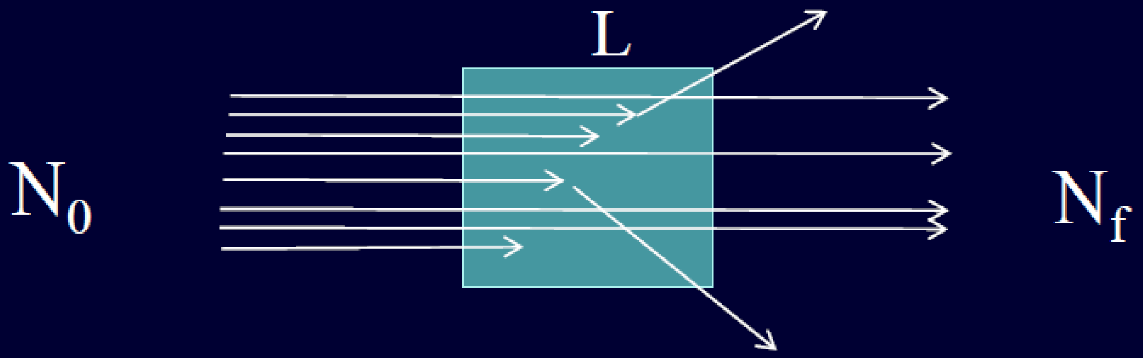
17 Gy

X-rays, protons and carbon ions

Interact differently with matter

Leading to different Depth Dose Distributions

Photon attenuation

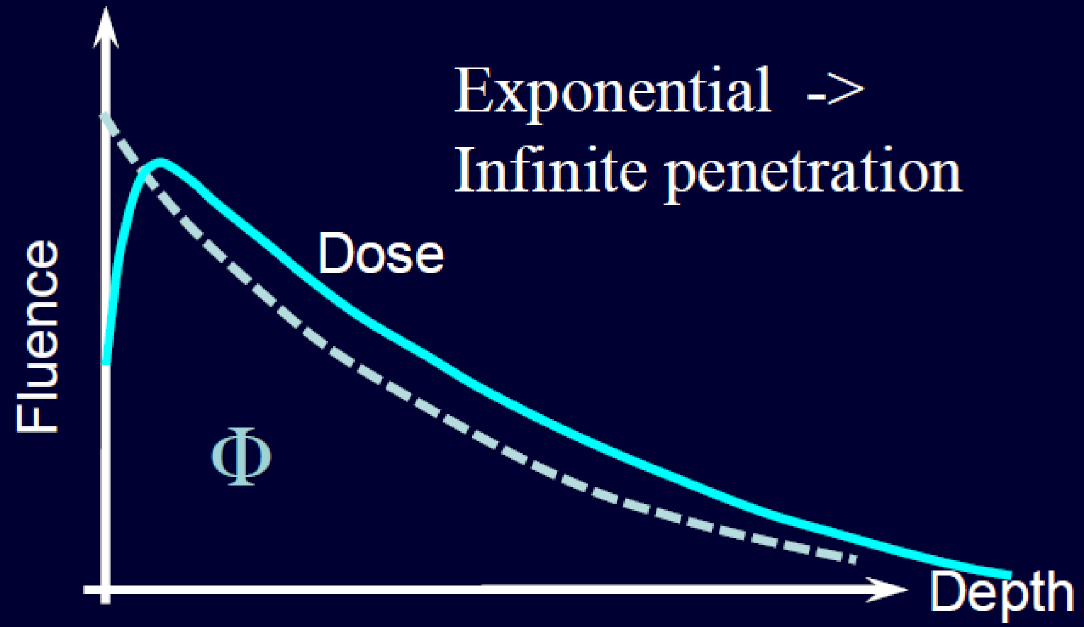


Number of photons decreases exponentially

$$N_f = N_0 \, e^{-\mu L}$$

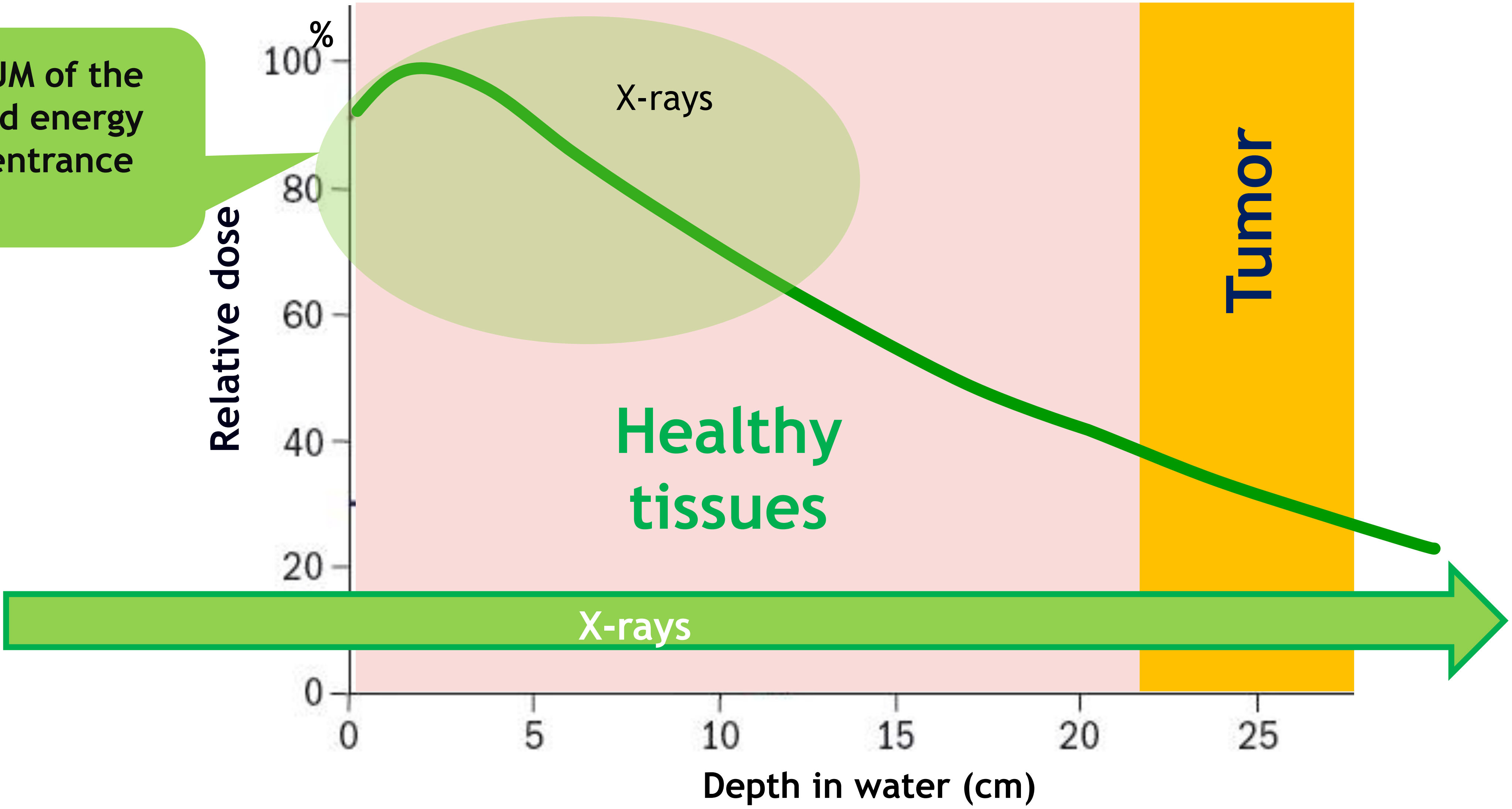
Fluence:

$$\Phi = N / A$$



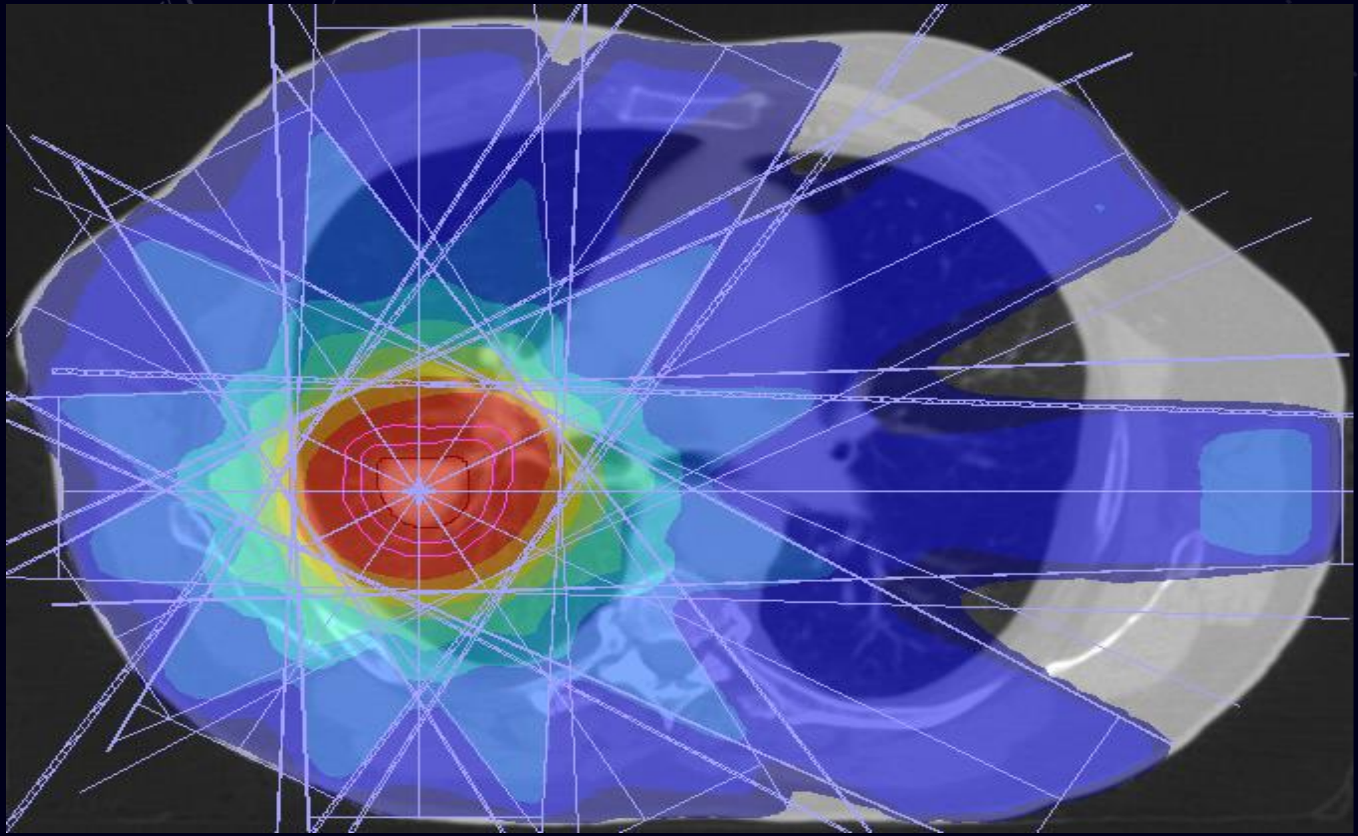
Exponential ->
Infinite penetration

X-rays Depth Dose Distributions



MAXIMUM of the released energy in the entrance region

X-rays come from several directions



To save healthy tissues, several beams coming from different directions around the patient are used. They are arranged to maximize their overlap into the region to be treated.

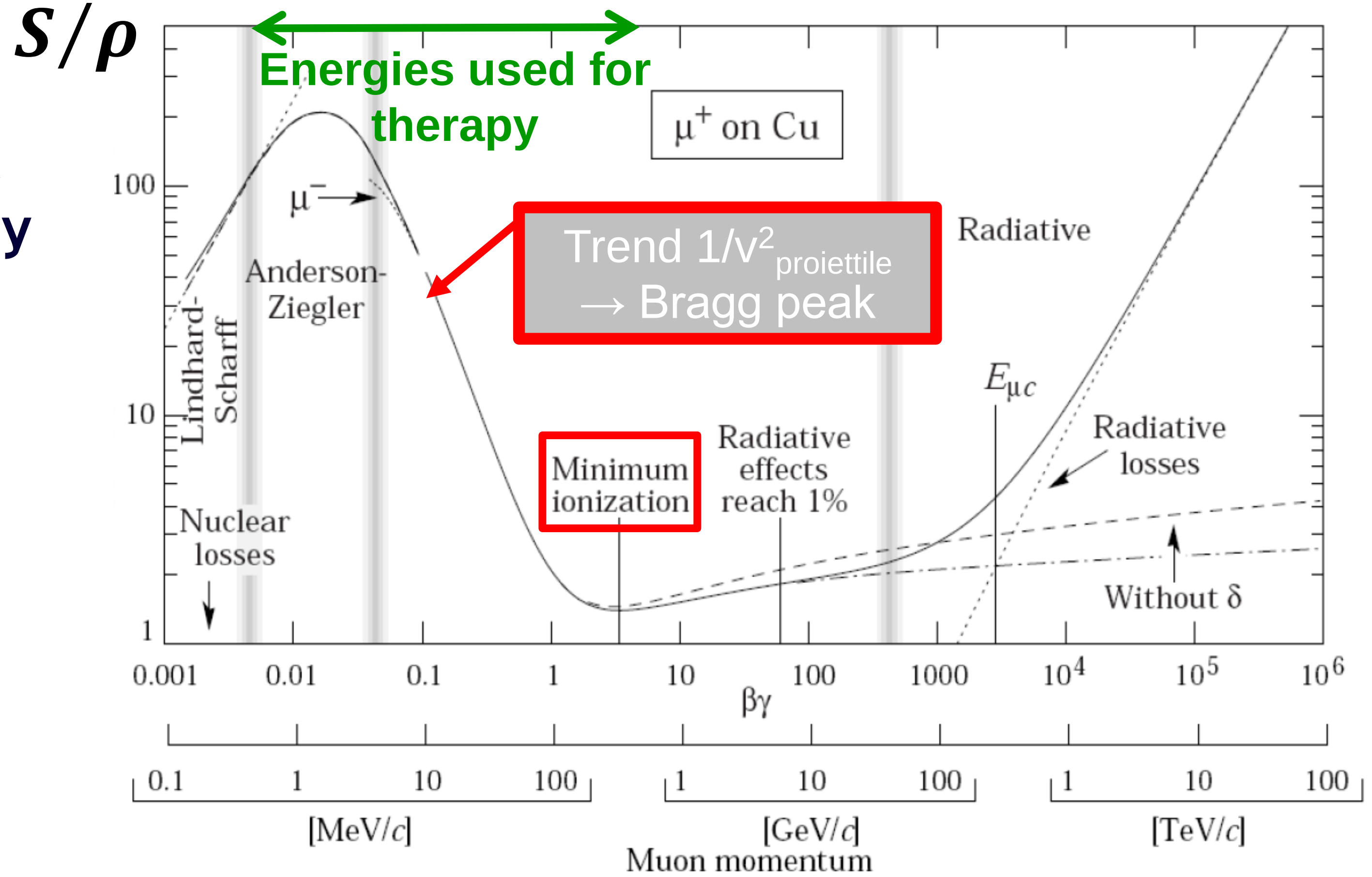
Charged particle Stopping power

Represents **the mean kinetic energy** Kp loss per distance travelled by charged particles traversing matter $(S = -dK_p/dx)$

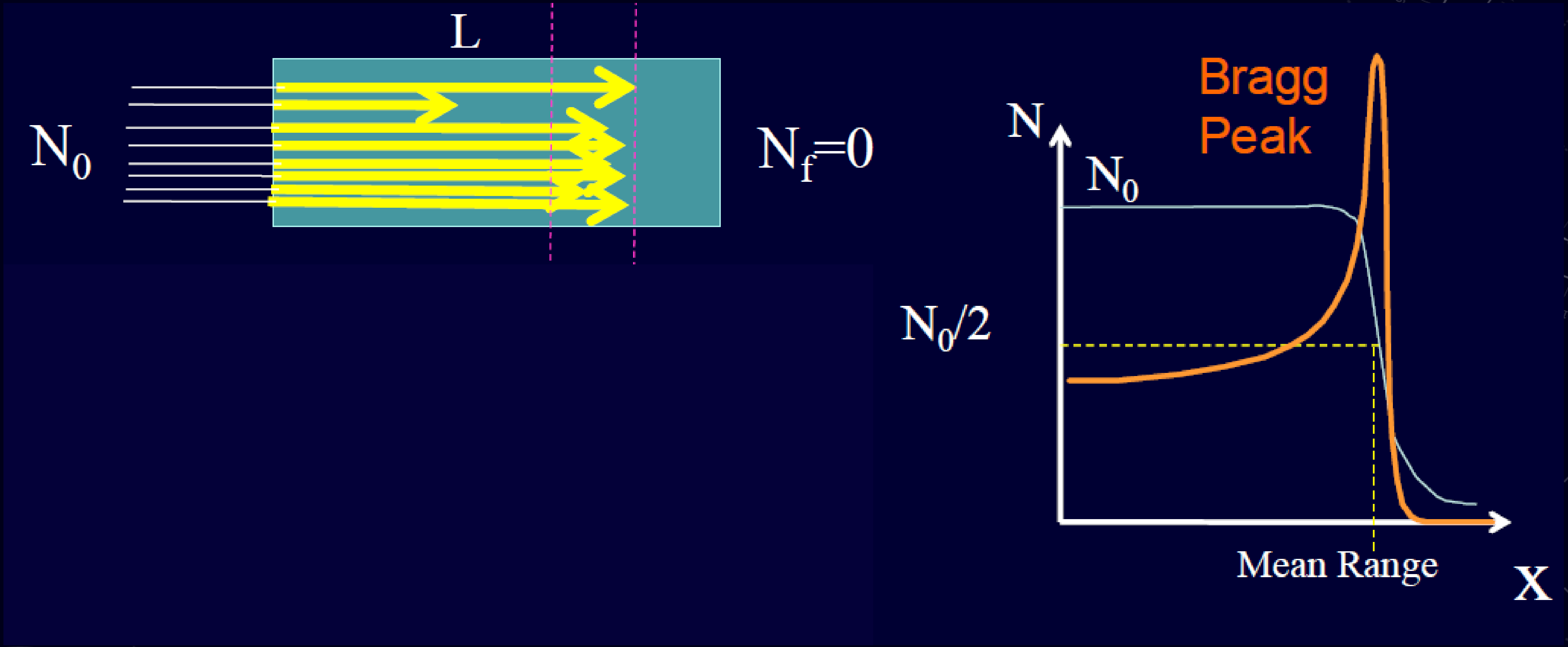
It is described by **di Bethe Bloch formula in the range of energies used for therapy**

$$S = C\,\rho\,\frac{Z}{A}\,\frac{Z_p^{\,2}}{v_p^{\,2}}\,\ln\left(\frac{2\,m_e\,v_p^{\,2}}{I}\right)$$

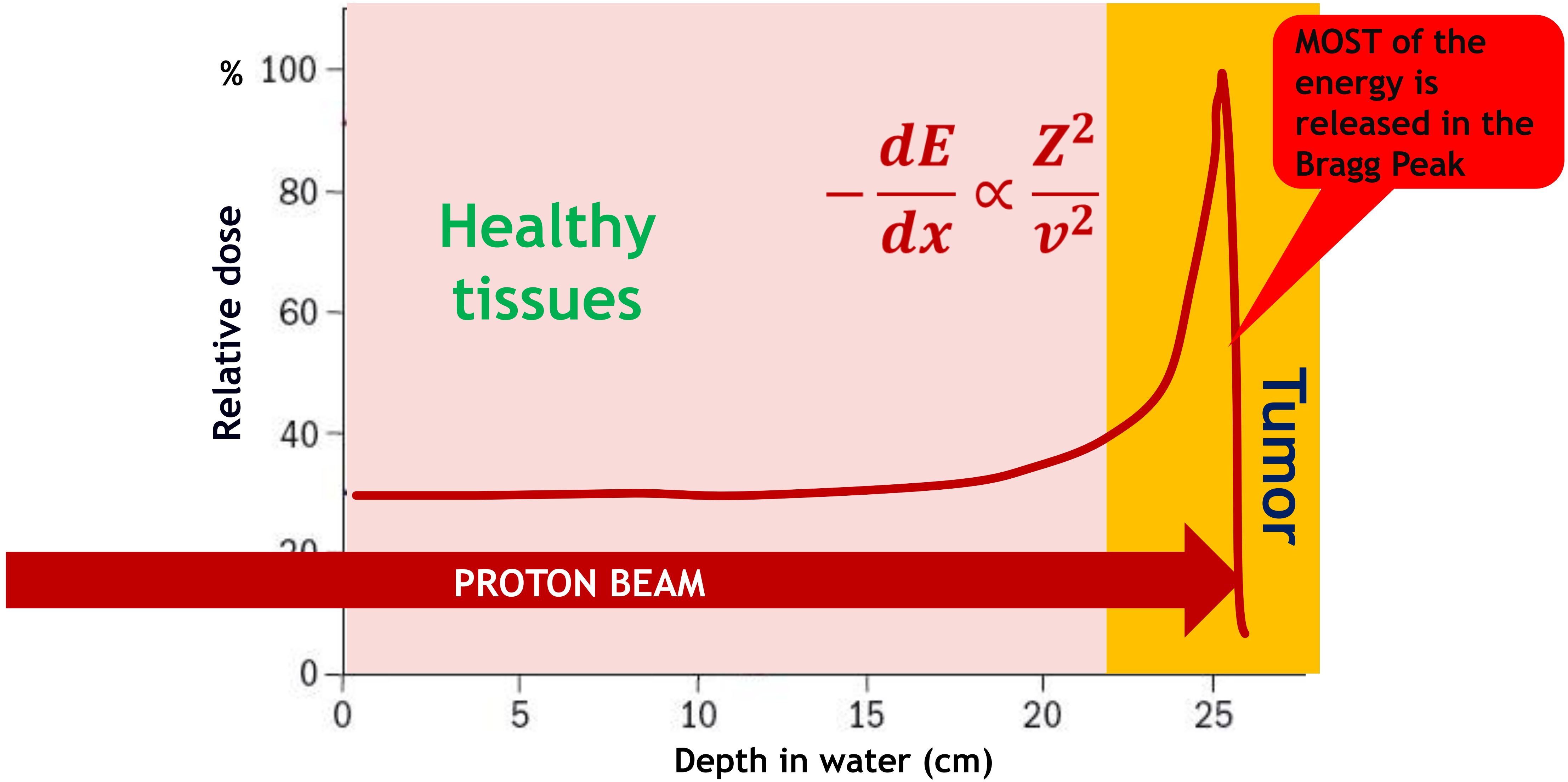
$$K_p = \frac{1}{2} m_p\, v_p^{\,2} \quad \Rightarrow \quad S \approx \frac{Z_p^2}{K_p}\ln(K_p)$$



Heavy charged particles do not attenuate



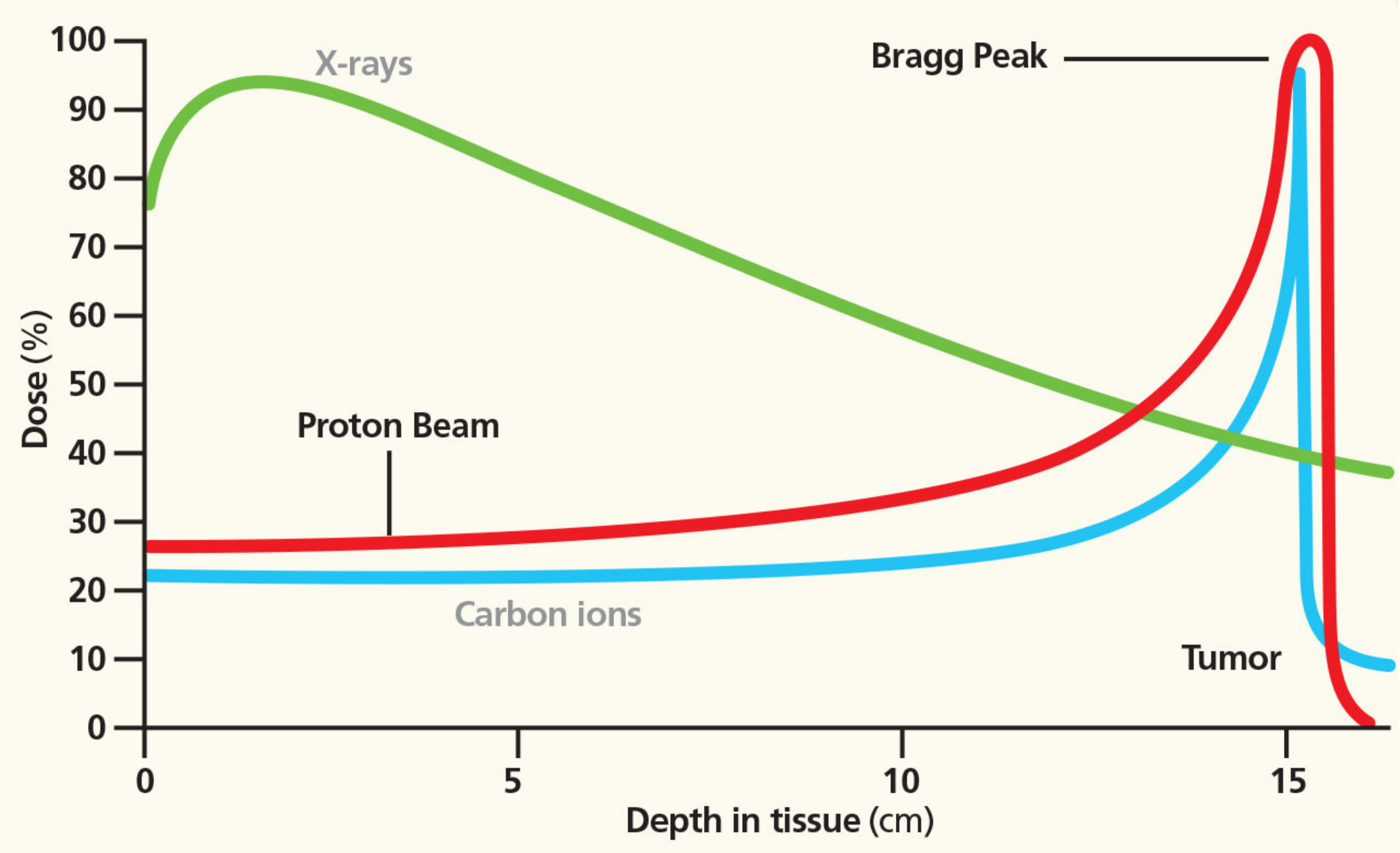
Protons and ions depth dose distribution



$$-\frac{dE}{dx} \propto \frac{Z^2}{v^2}$$

MOST of the energy is released in the Bragg Peak

Average dE/dx variation over a wide energy range



$$-\frac{dE}{dx} \propto \frac{Z^2}{v^2}$$

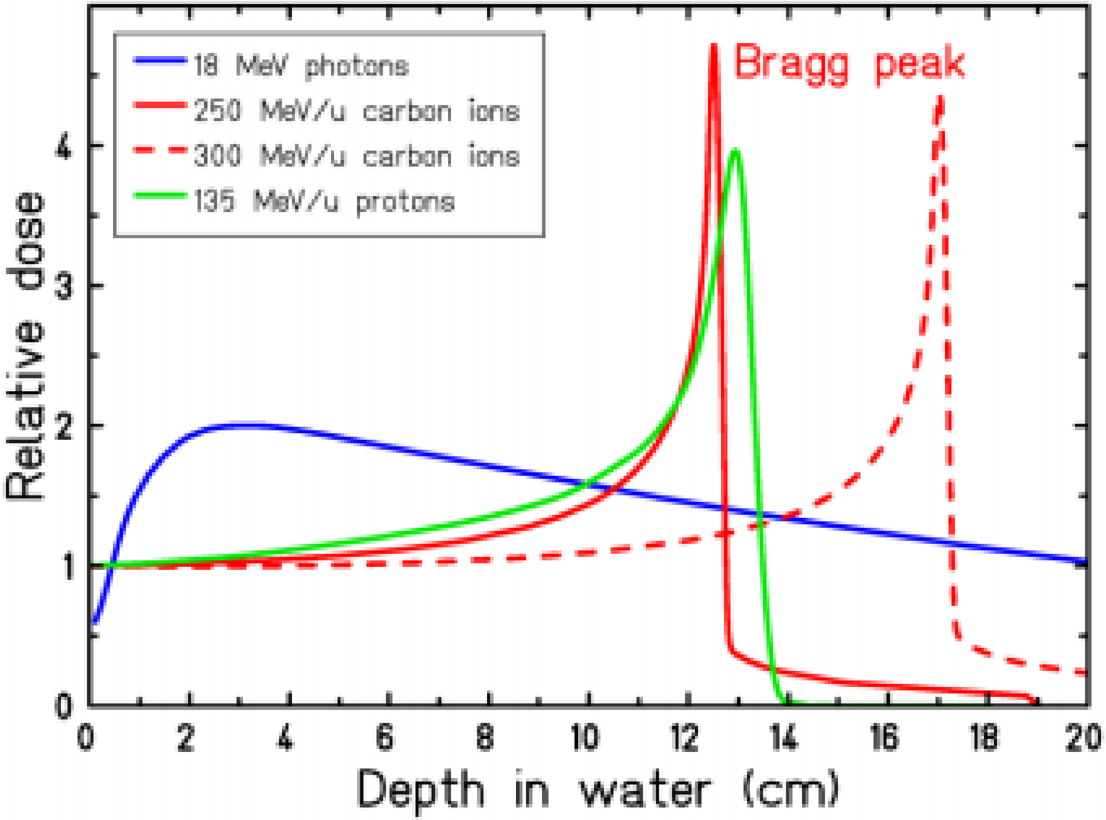
Carbon ions (Z=6)

^{12}C

- Narrow Bragg Peak
- Dose in the Peak tail due to fragmentation

Beam energy and range modulation

Spread Out Bragg Peak for dose modulation in depth



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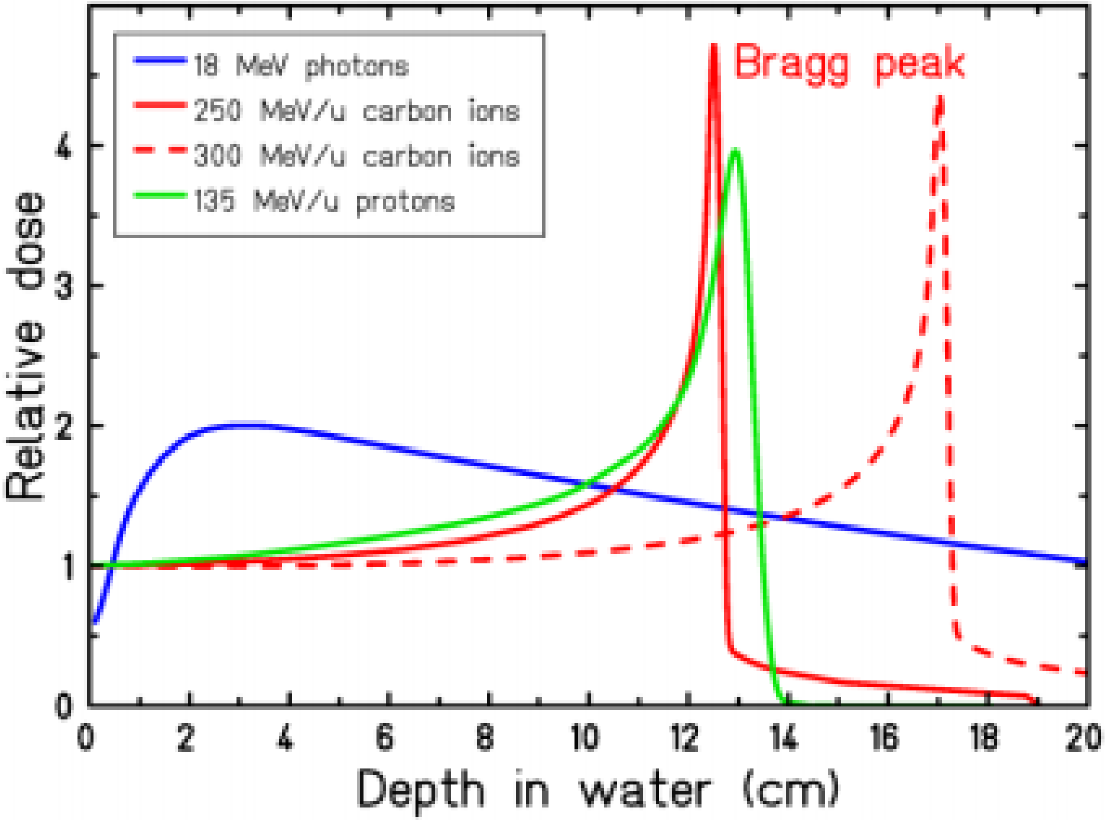
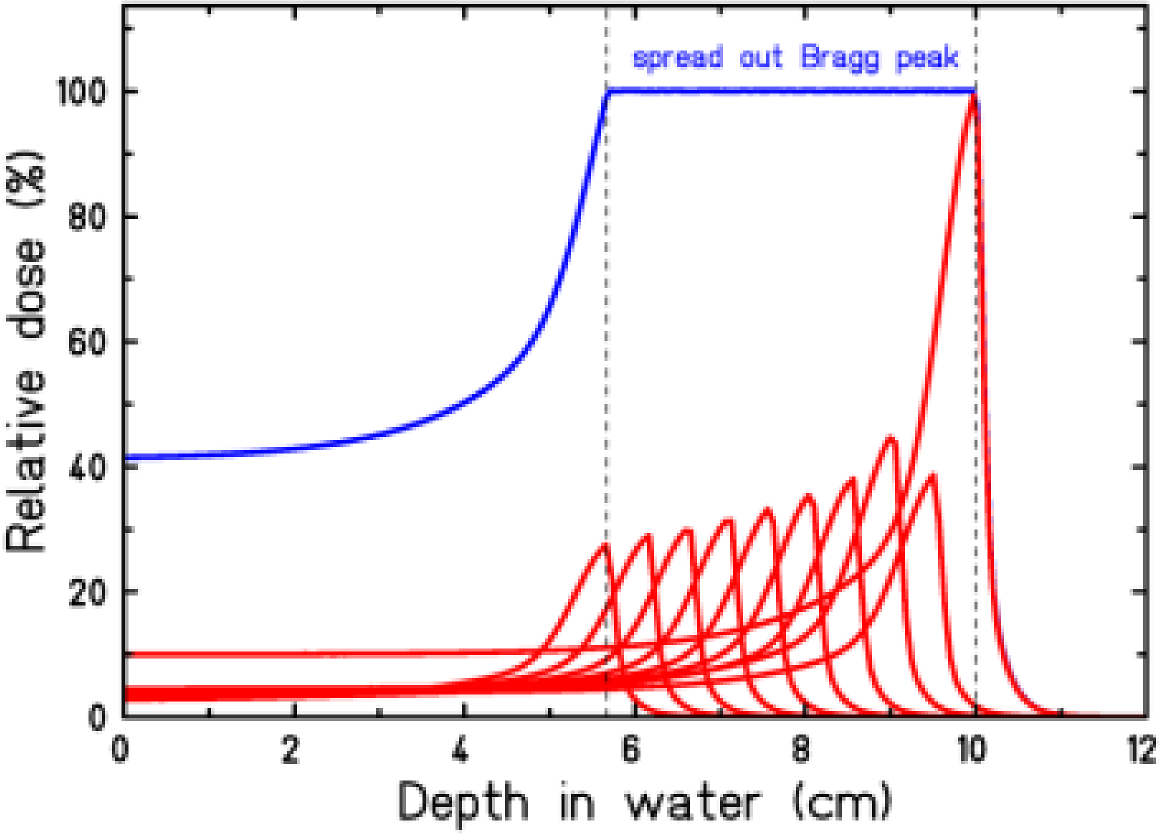


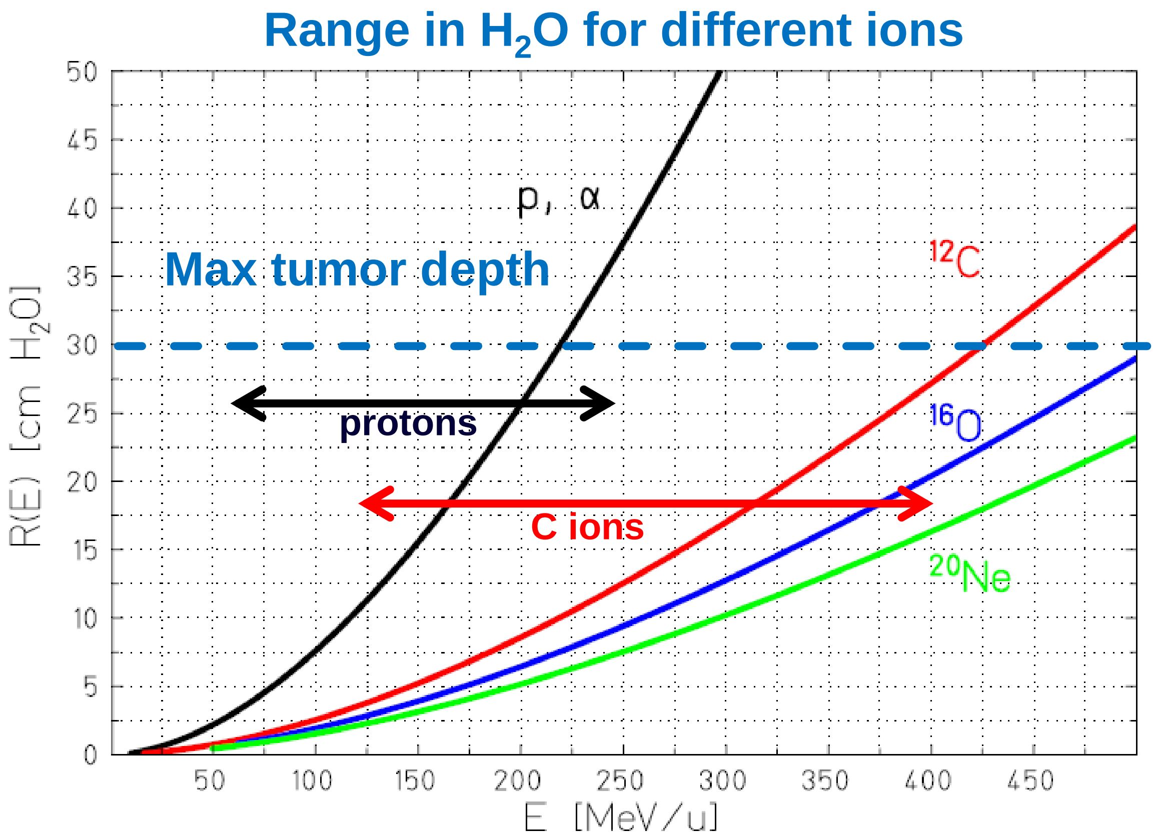


Range in water vs energy for different ions

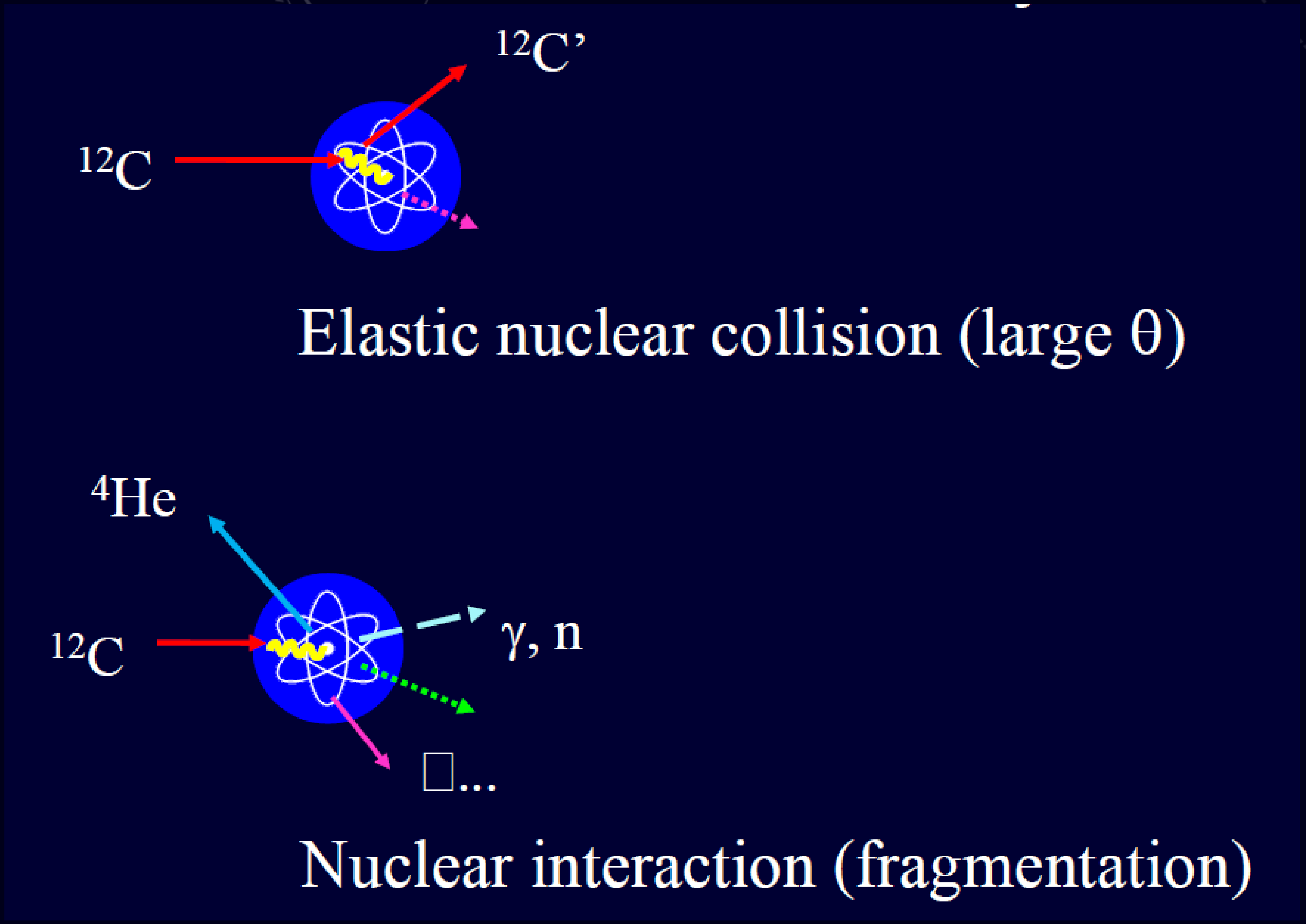
$$R = \int_{K_i}^{0} \frac{\mathrm{d}x}{\mathrm{d}K_p}\,\mathrm{d}K_p = \int_{0}^{K_i} \frac{1}{S}\,\mathrm{d}K_p$$

$$S \sim \frac{Z_p^{\,2}}{K_p} \qquad \Downarrow$$

$$R \sim \int_{0}^{K_i} \frac{K_p}{Z_p^{\,2}}\,\mathrm{d}K_p = \frac{K_p^{\,2}}{Z_p^{\,2}}$$



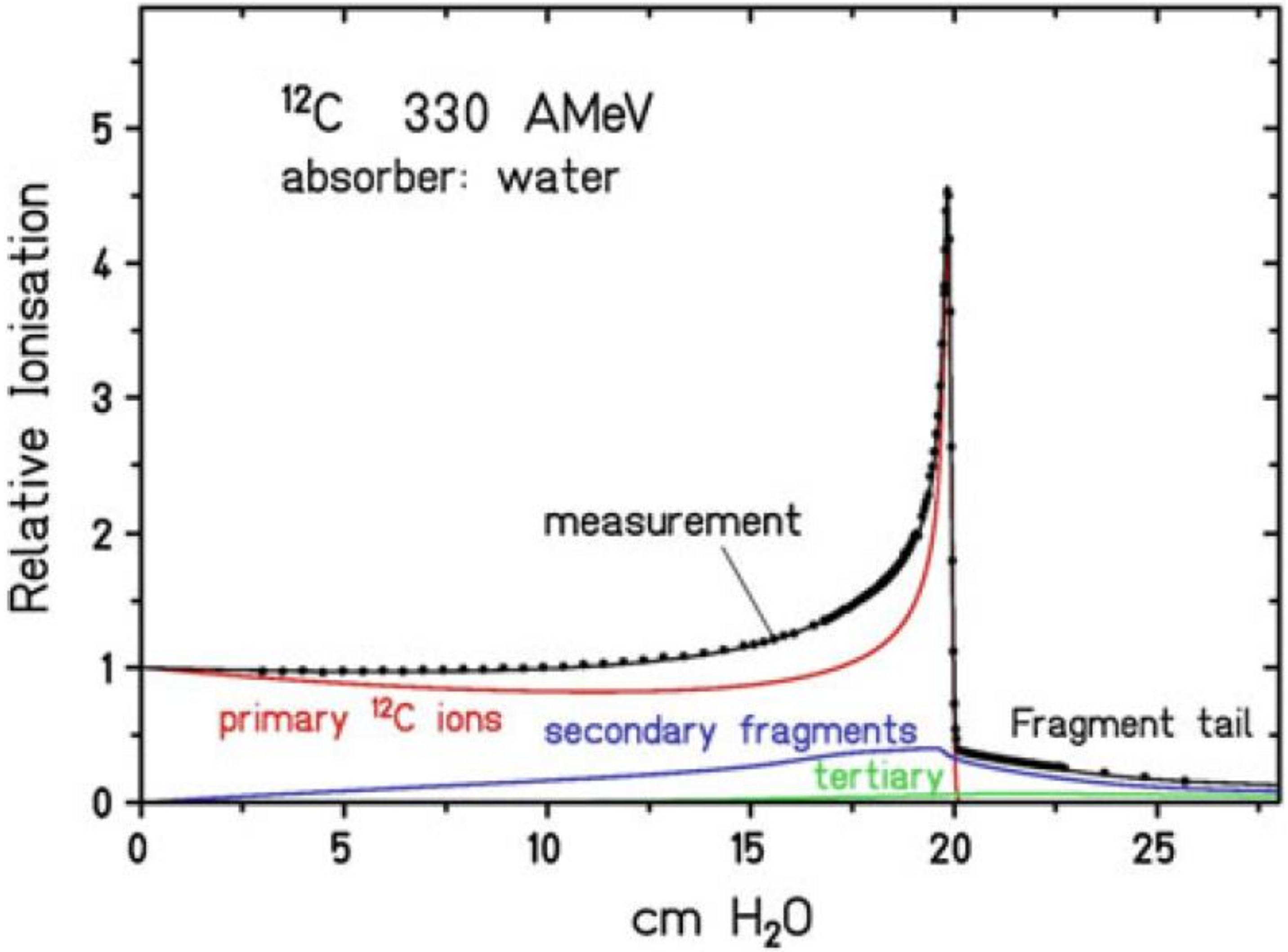
Nuclear interactions of heavy ions



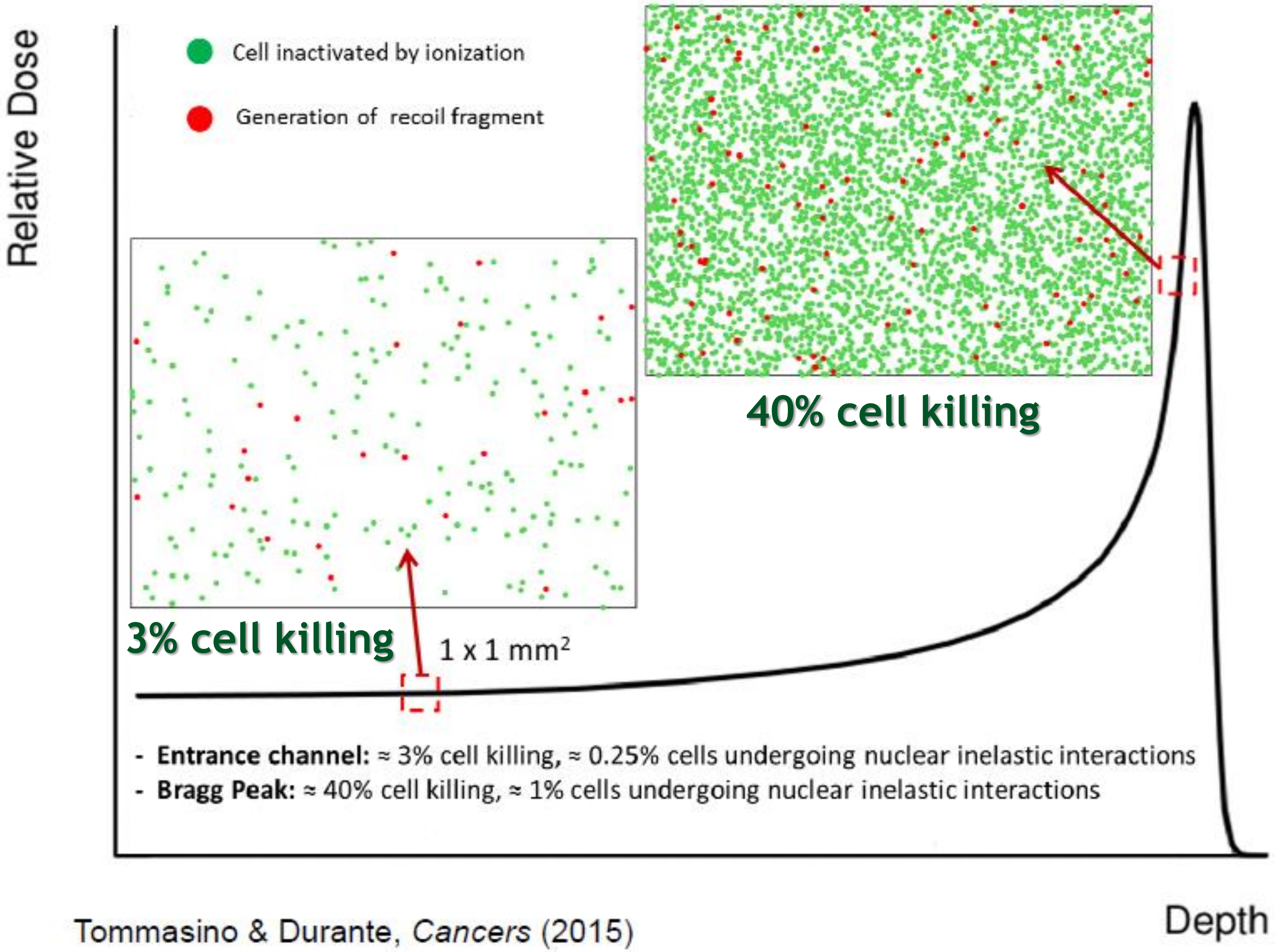
Elastic nuclear collision (large θ)

Nuclear interaction (fragmentation)

Dose from fragments with carbon ions



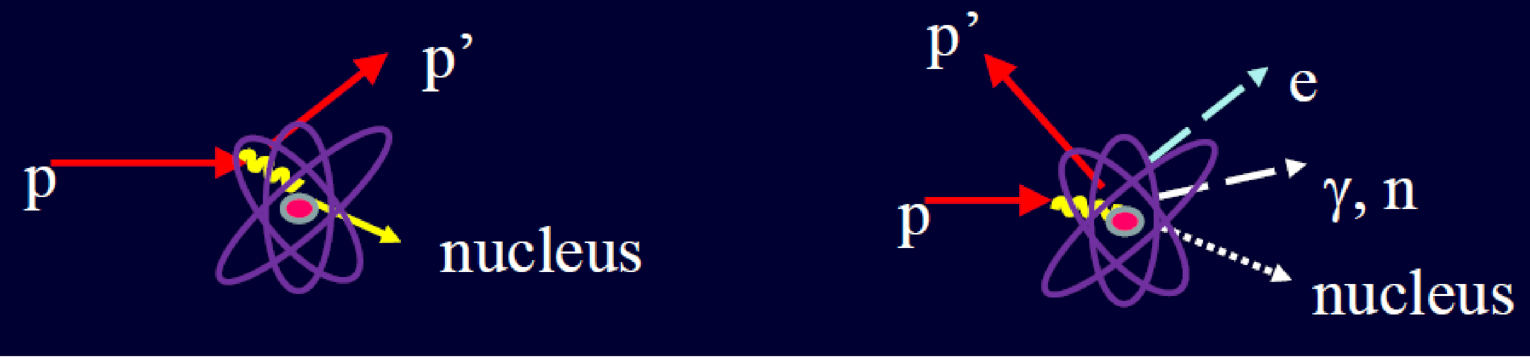
Impact of target fragmentation

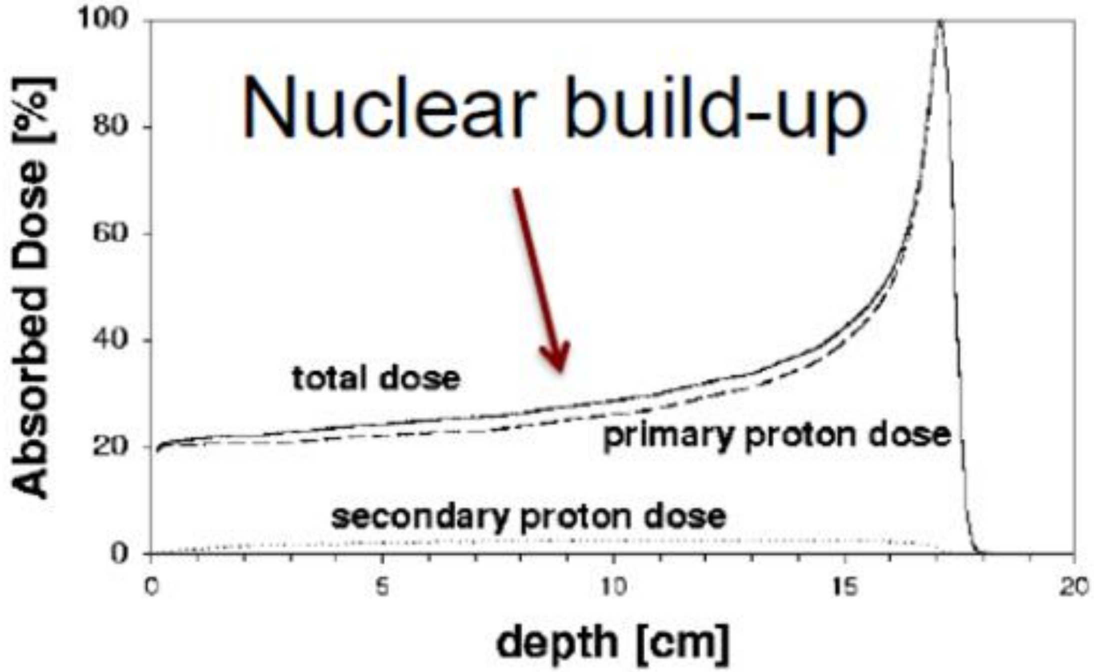


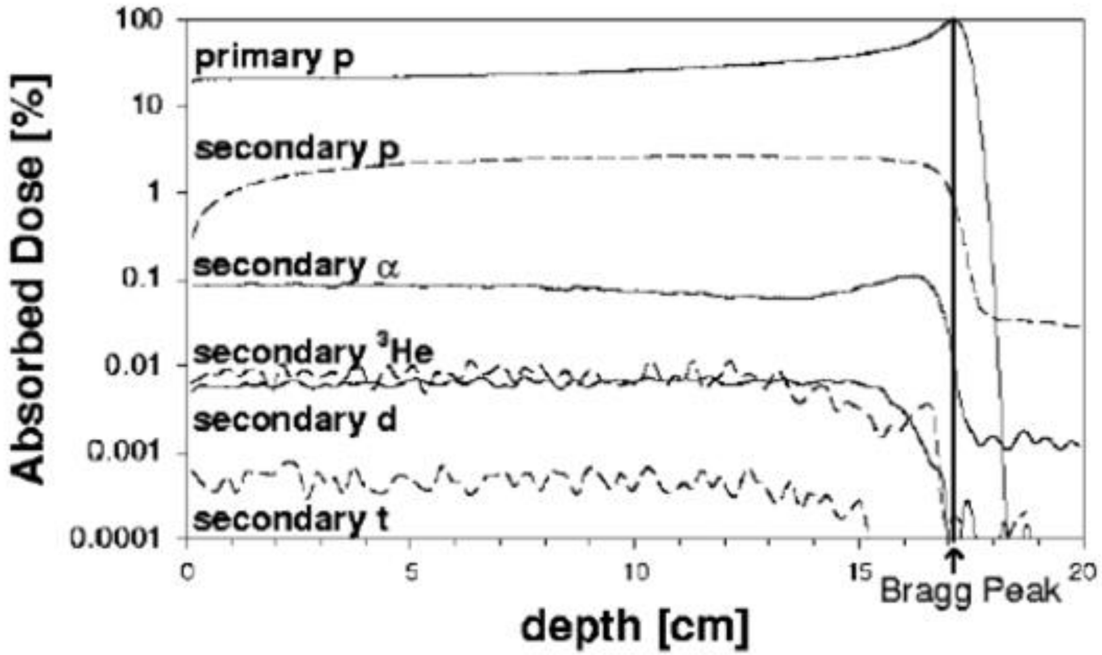
- **Entrance channel:** ≈ 3% cell killing, ≈ 0.25% cells undergoing nuclear inelastic interactions
- **Bragg Peak:** ≈ 40% cell killing, ≈ 1% cells undergoing nuclear inelastic interactions

Tommasino & Durante, *Cancers* (2015)

Nuclear interactions of protons

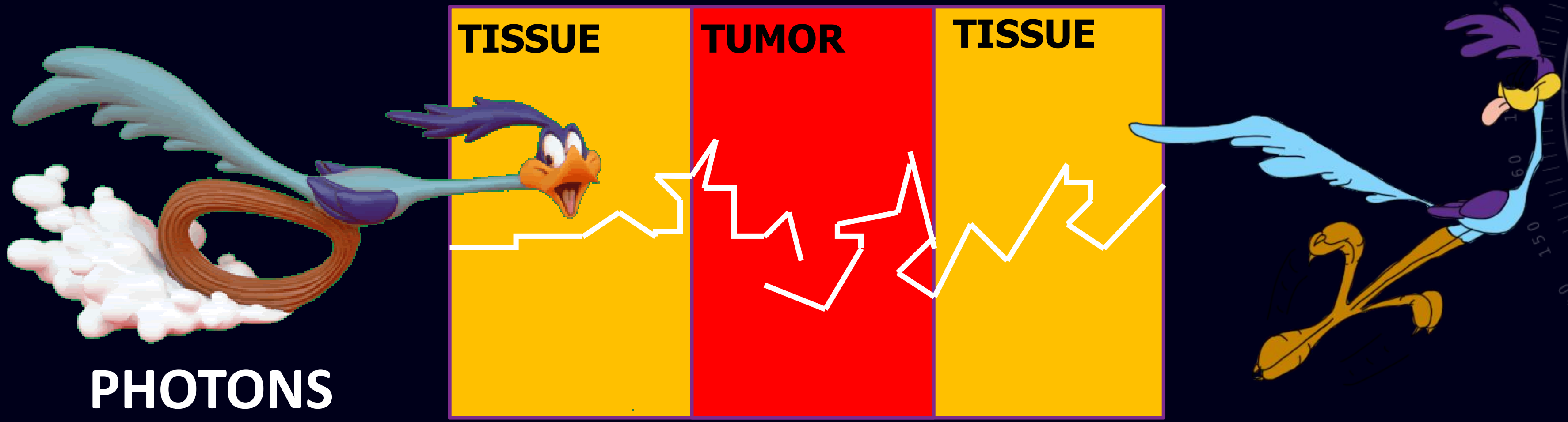






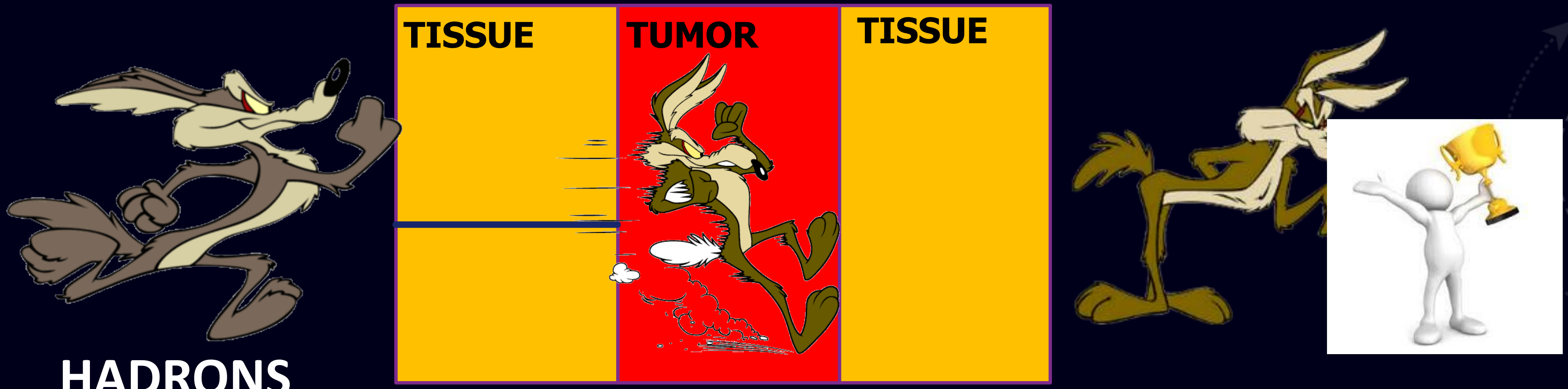
Summary

The physical strength of ions is…



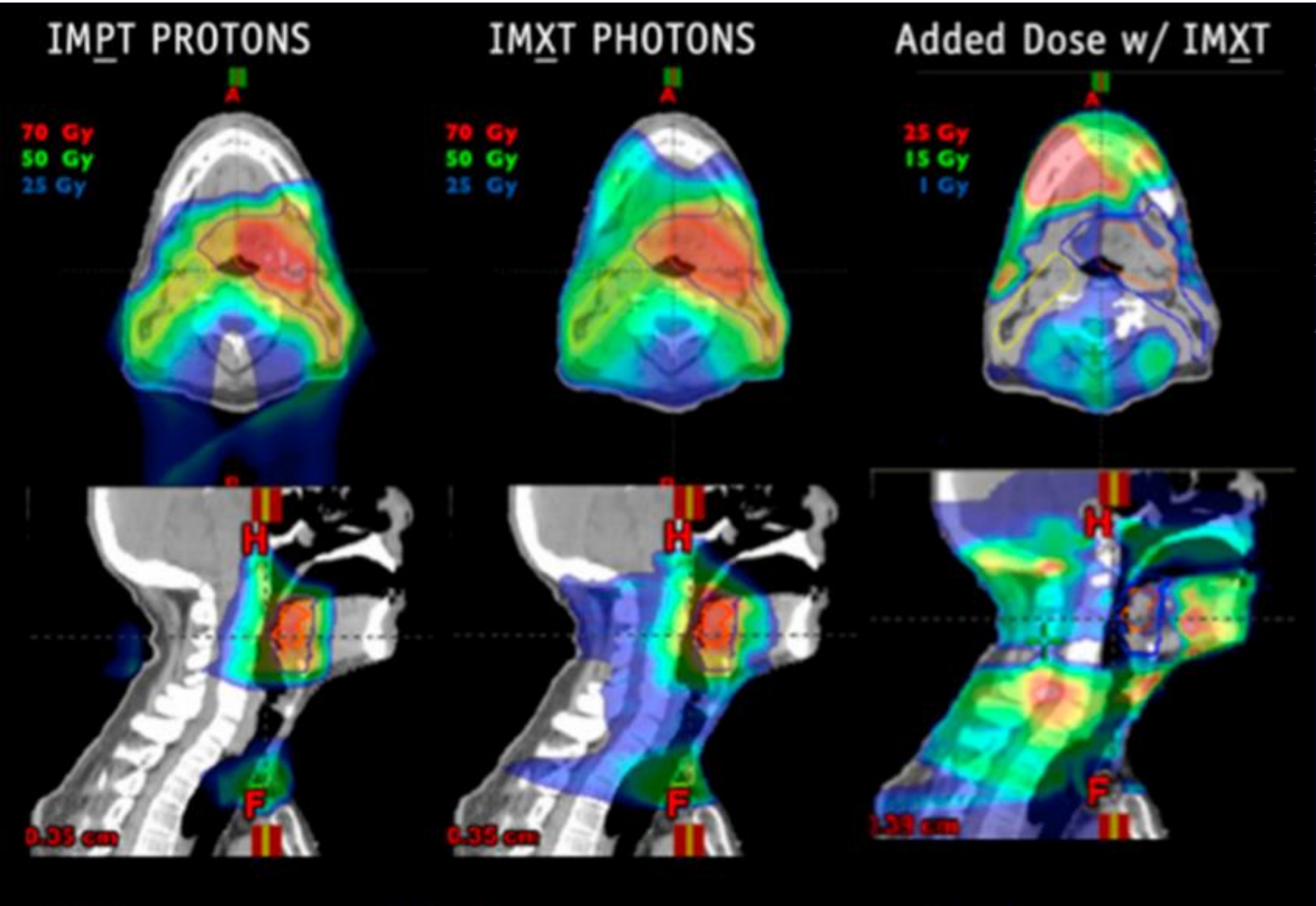
PHOTONS

…the ability to stop!!



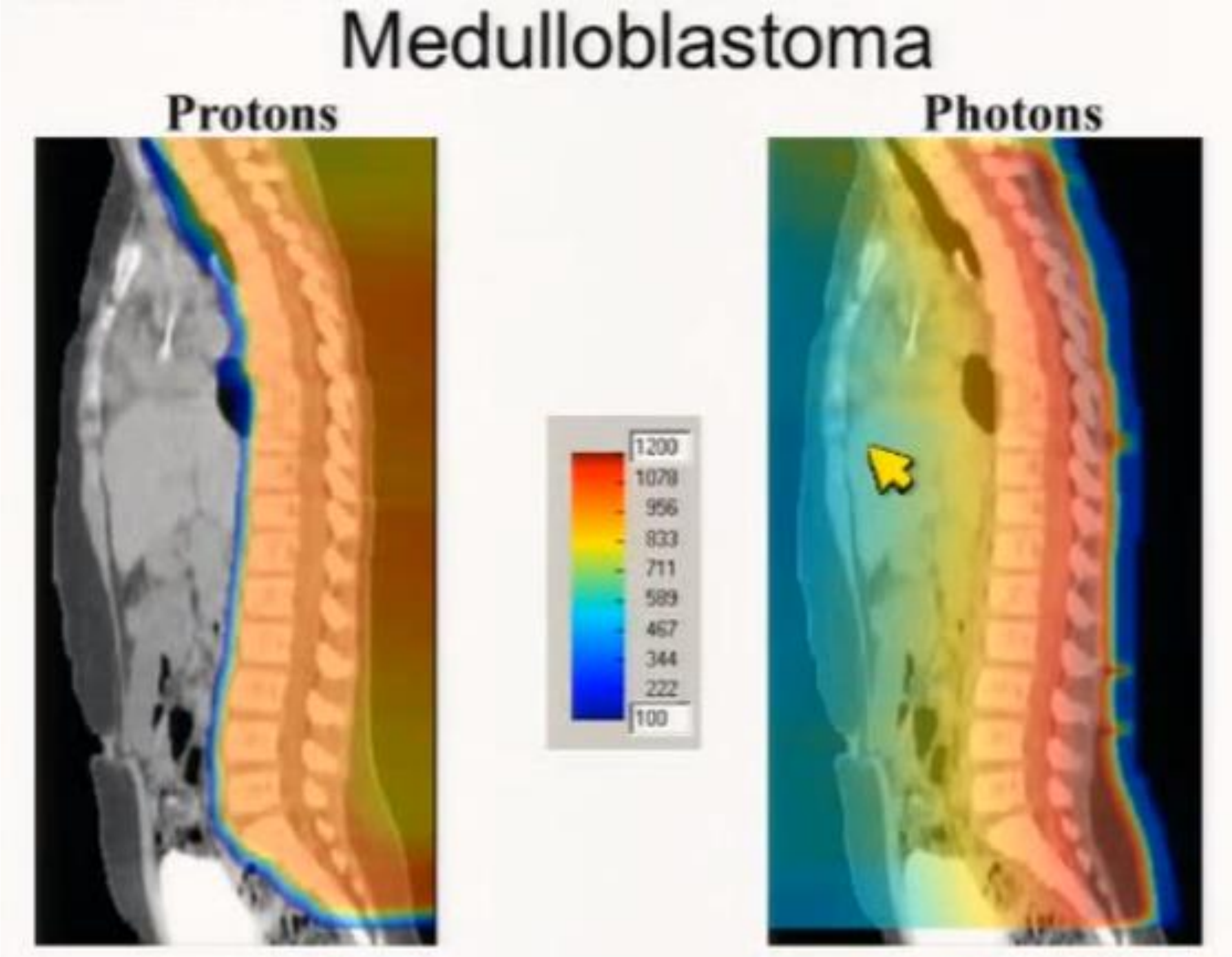
HADRONS

Protons vs photons for head&neck tumors

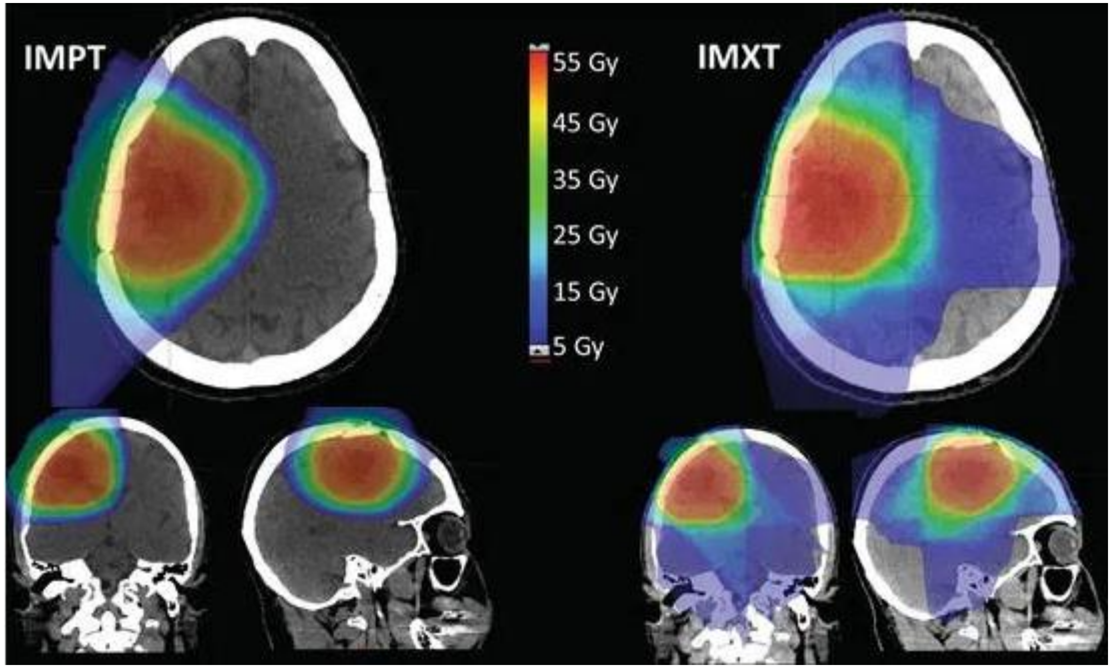


RED is high dose, GREEN is intermediate dose, BLUE is Lower dose

Protons vs photons for pediatric tumors



Pediatric brain tumors



X-rays, protons and carbon ions

Show different Linear Energy Transfer

Leading to different radiobiological effectiveness

The relative biological effectiveness - RBE

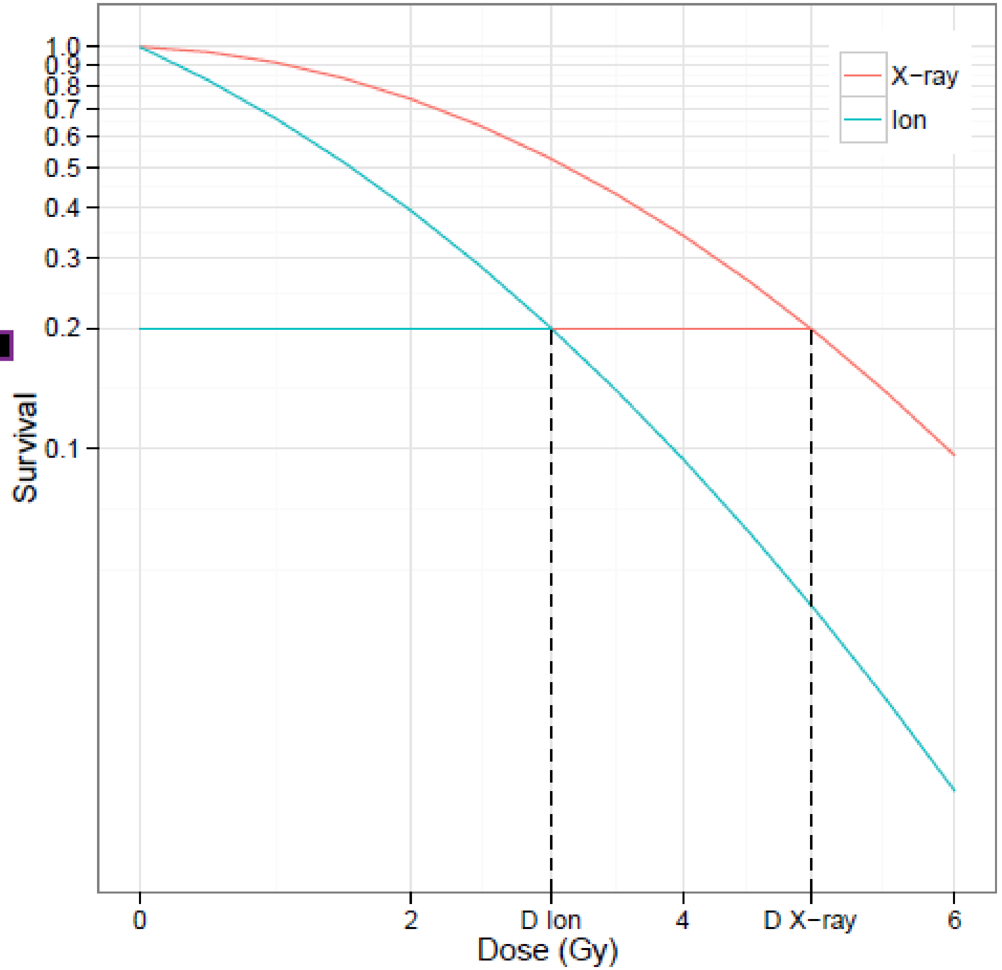
$$RBE_n = \left.\frac{D_X}{D_{\mathrm{Ion}}}\right|_{S_X = S_{\mathrm{Ion}} = n}$$

RBE is a function used to describe the biological effect of a radiation compared with X-rays effect

Survival curve and RBE

$$S(D) = \mathrm{e}^{-\alpha\, D - \beta\, D^2}$$

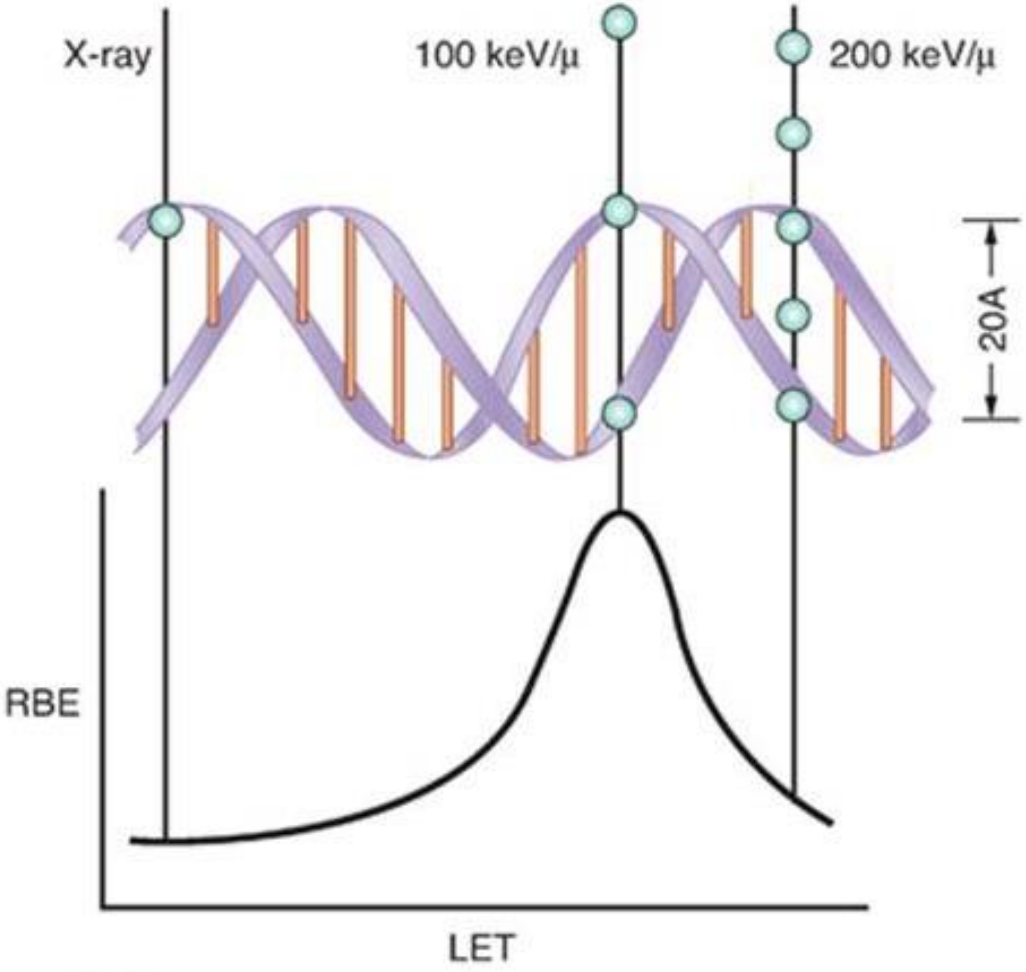
Same Biological Damage



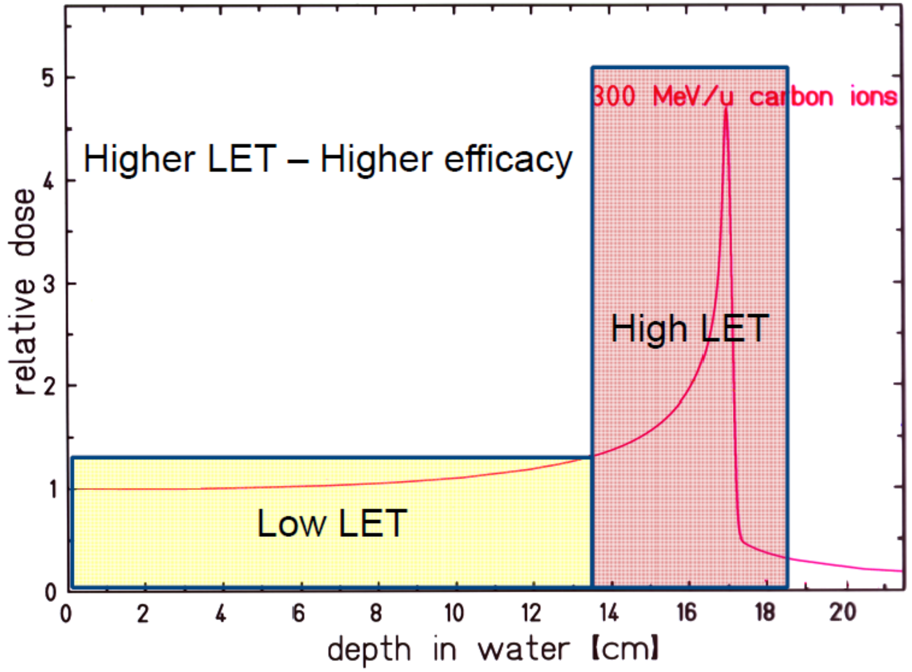
$$RBE_n = \left.\frac{D_X}{D_{\mathrm{Ion}}}\right|_{S_X = S_{\mathrm{Ion}} = n}$$

$$D_{\mathrm{bio}} = D \cdot RBE$$

Relative Biologic Effectiveness (RBE) depends on Linear Energy Transfer (LET)

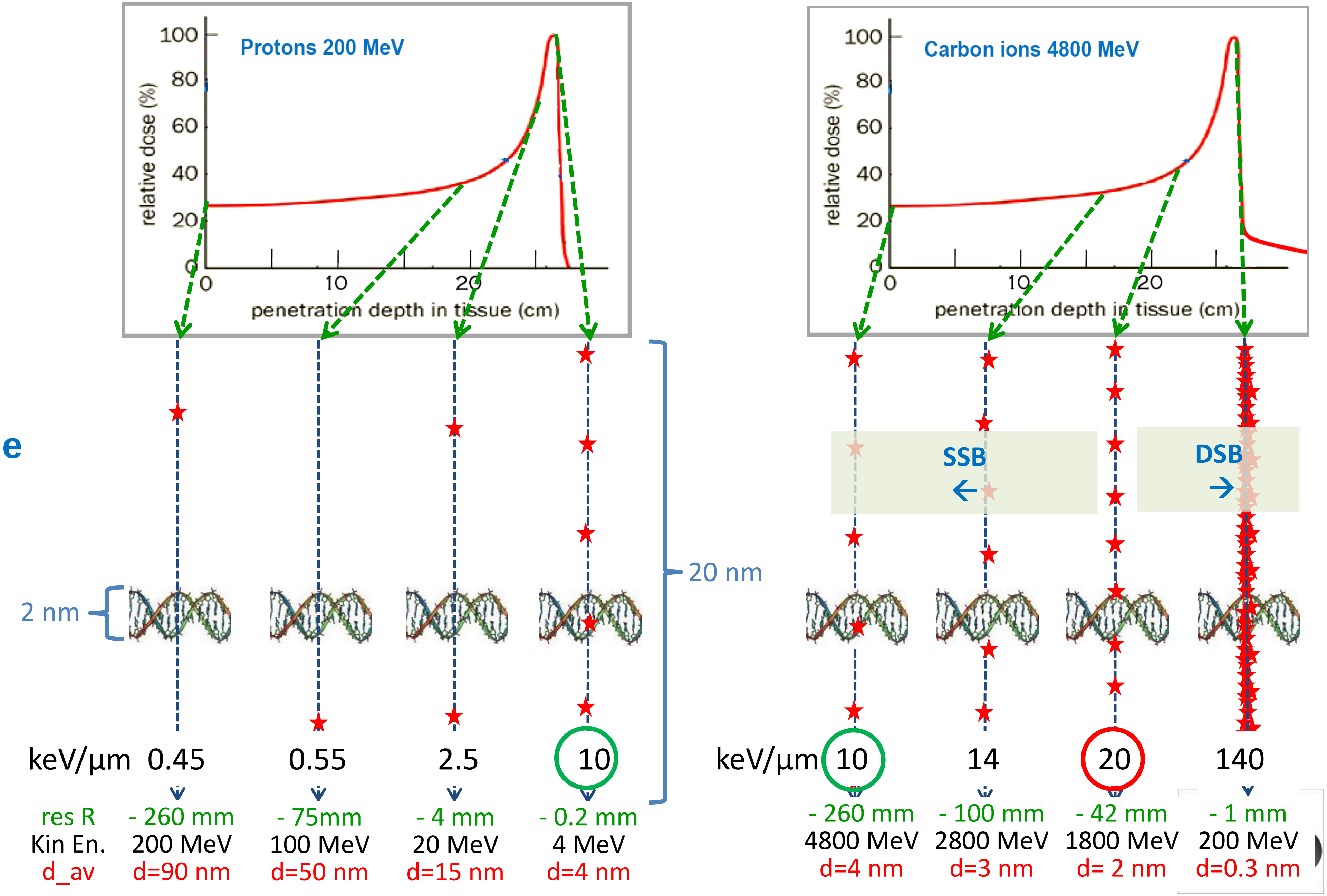


Carbon ions: high LET where needed



RBE

- **RBE for protons is costante (~ 1,1)**
- **RBE for carbon ions Change along the path with a maximum in the Bragg peak**



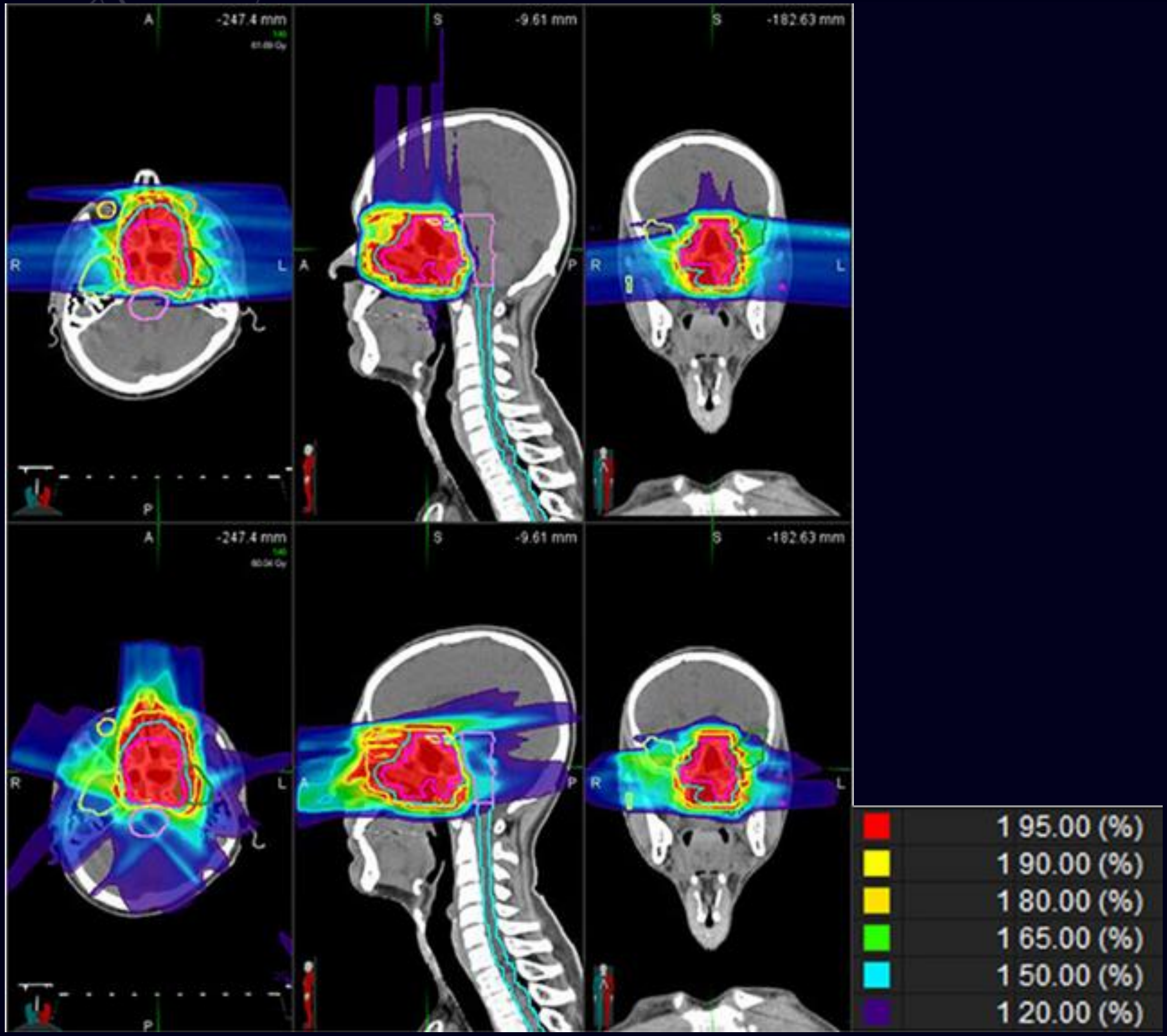
keV/µm	0.45	0.55	2.5	10
res R	- 260 mm	- 75mm	- 4 mm	- 0.2 mm
Kin En.	200 MeV	100 MeV	20 MeV	4 MeV
d_av	d=90 nm	d=50 nm	d=15 nm	d=4 nm

keV/µm	10	14	20	140
	- 260 mm	- 100 mm	- 42 mm	- 1 mm
	4800 MeV	2800 MeV	1800 MeV	200 MeV
	d=4 nm	d=3 nm	d= 2 nm	d=0.3 nm

Carbon ions vs X-rays

Carbon ions

X-rays



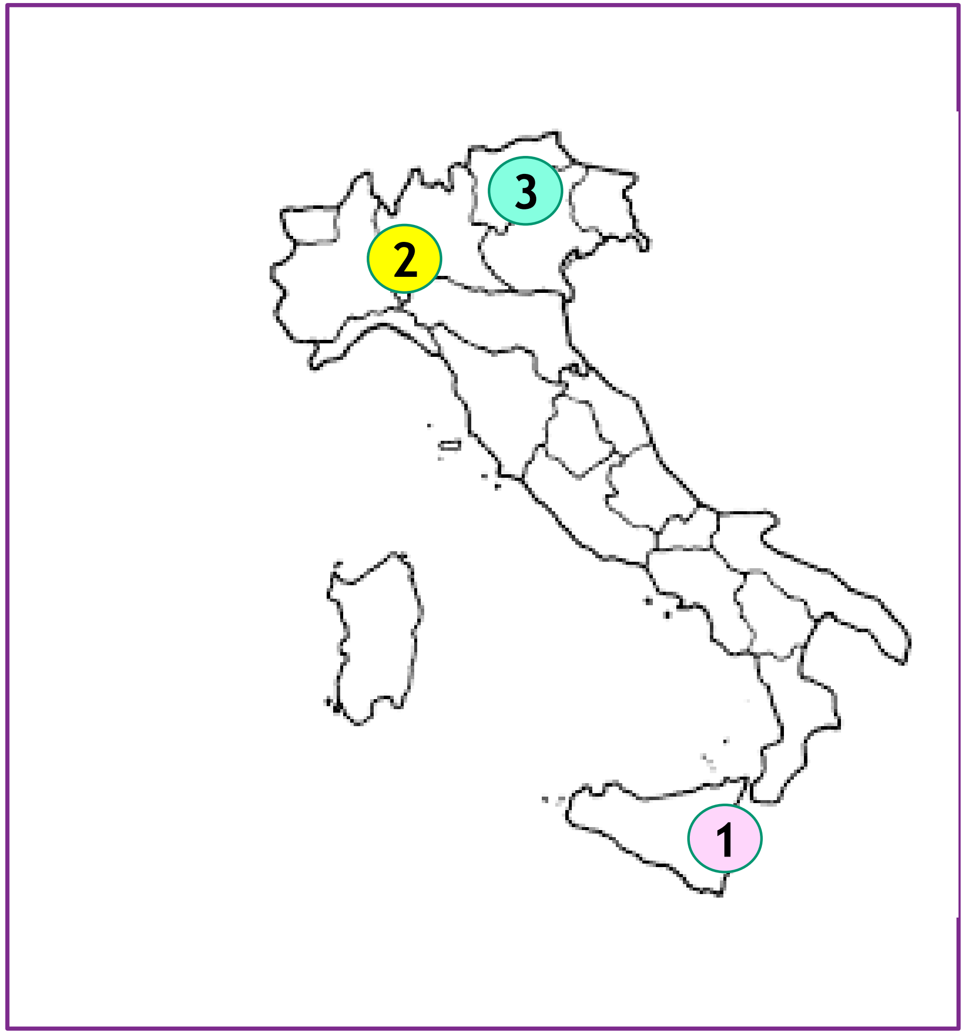
Centers worldwide and patients treated

January 2020

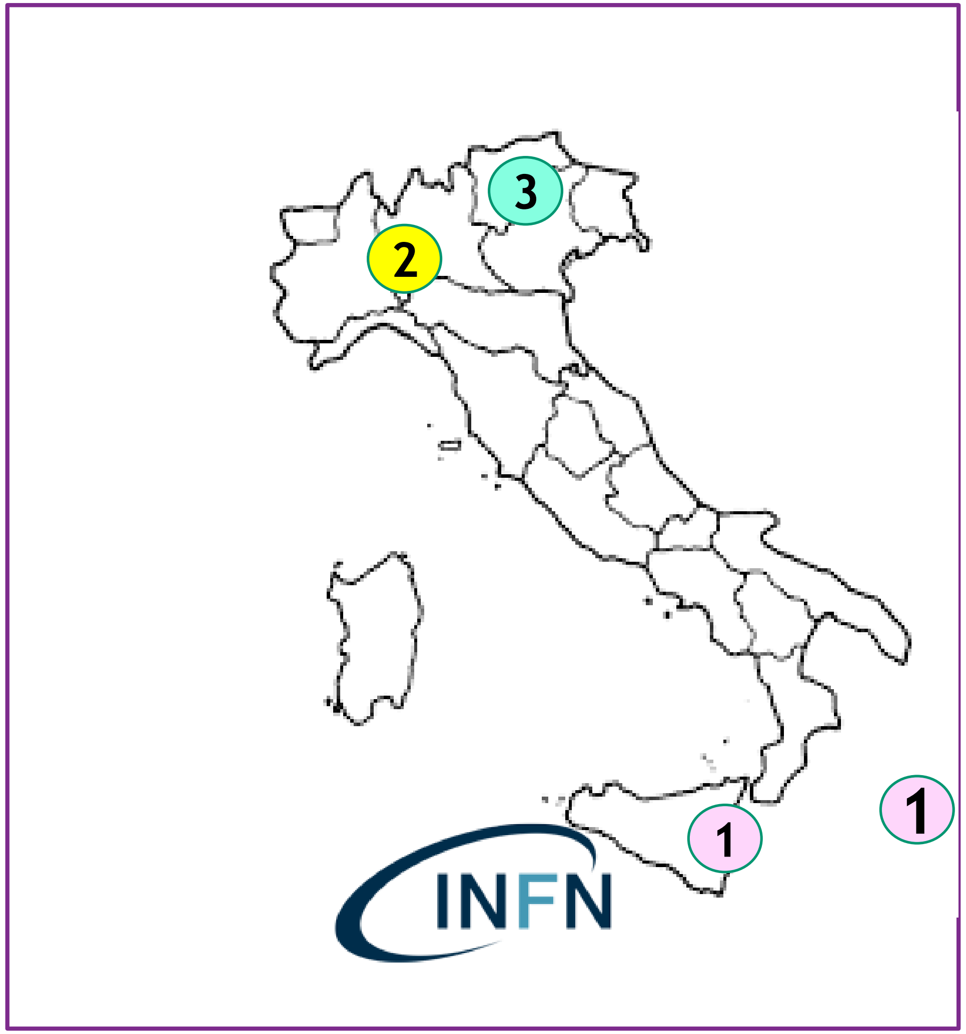
217400 30000

[Ref 5]

Italian particle therapy centers



Italian particle therapy centers



Beam line in the INFN Physics laboratory

CATANA - Catania
1st patient 2002
400 patients

CATANA in Catania

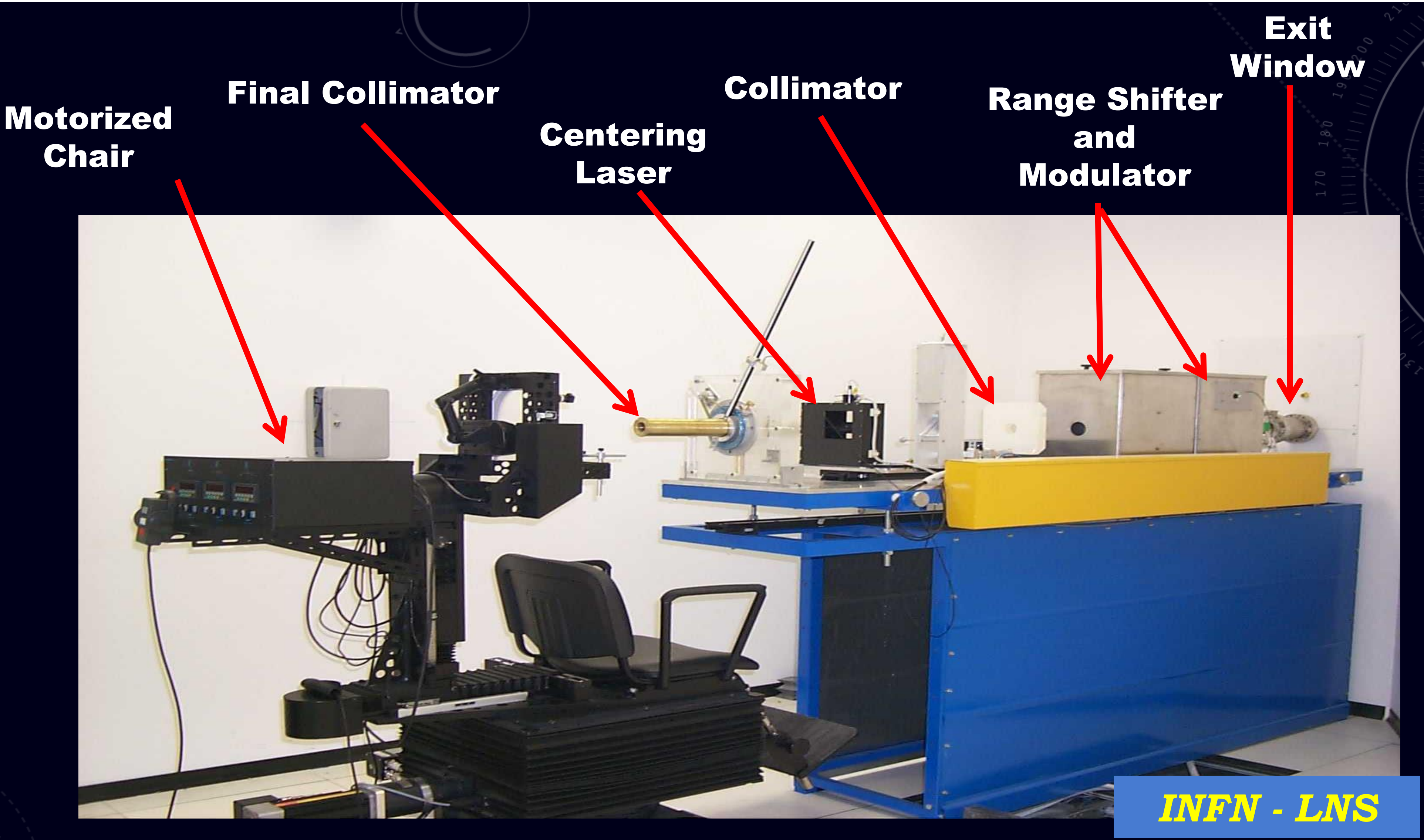
First center to treat with protons eye tumors

1st patient in 2002

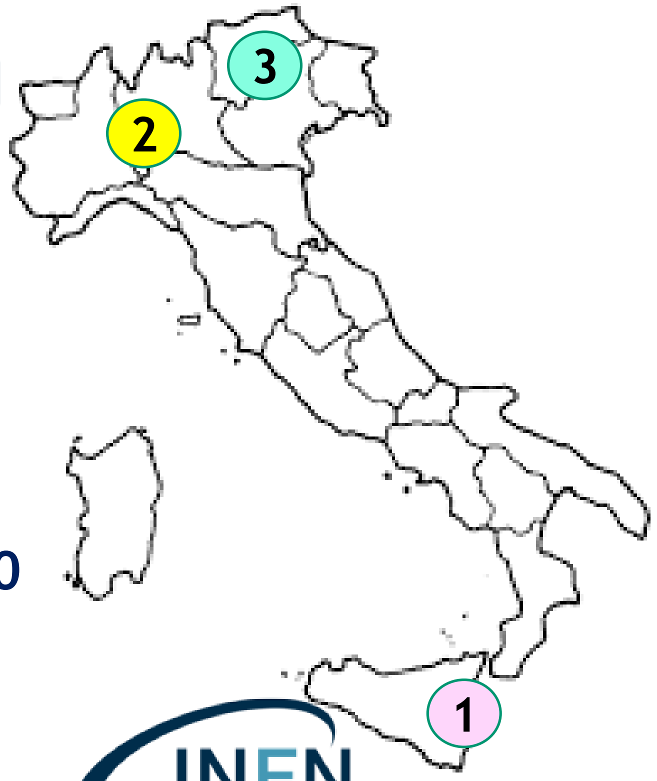
~200 treated patients

Centro di AdroTerapia e Applicazioni Nucleari Avanzate

CATANA BEAM LINE



Italian particle therapy centers



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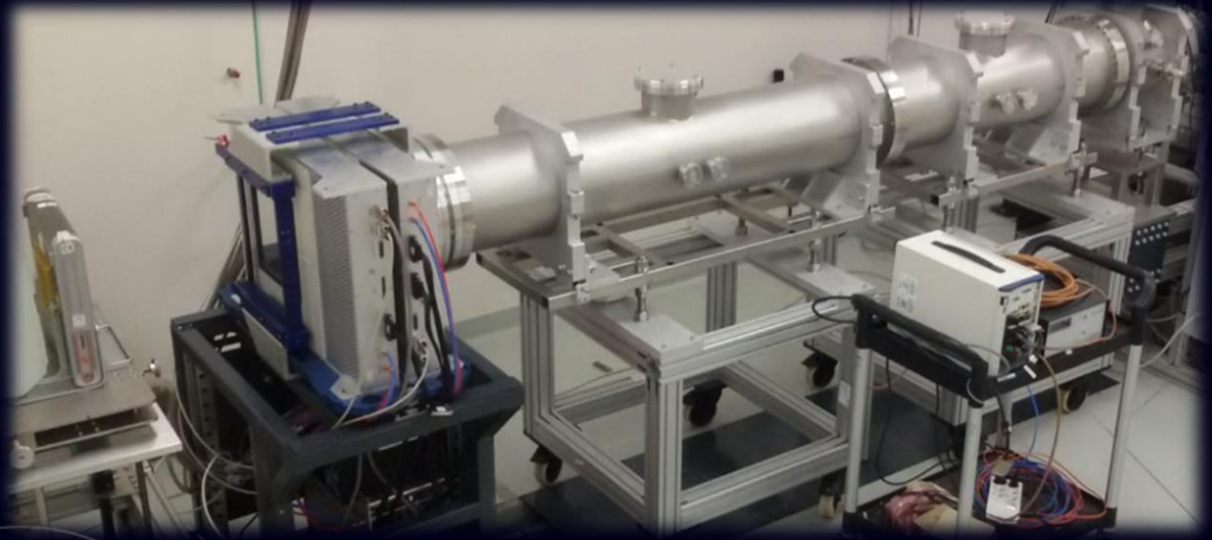
CNAO - Pavia
1st patient 2011
2500 patients 2019

Experimental beam line
End of commissioning 2020

Centro Nazionale di Adroterapia Oncologica - CNAO

One of the 6 facilities in the world with both Proton and carbon ions beams

- 1 experimental room under commissioning



3 treatment rooms

https://fondazionecnao.it/it/

1991 the idea → 2011 first patient

1991 : Ugo Amaldi (CERN) proposed a center for teletherapy with hadrons

First Italian center built for:

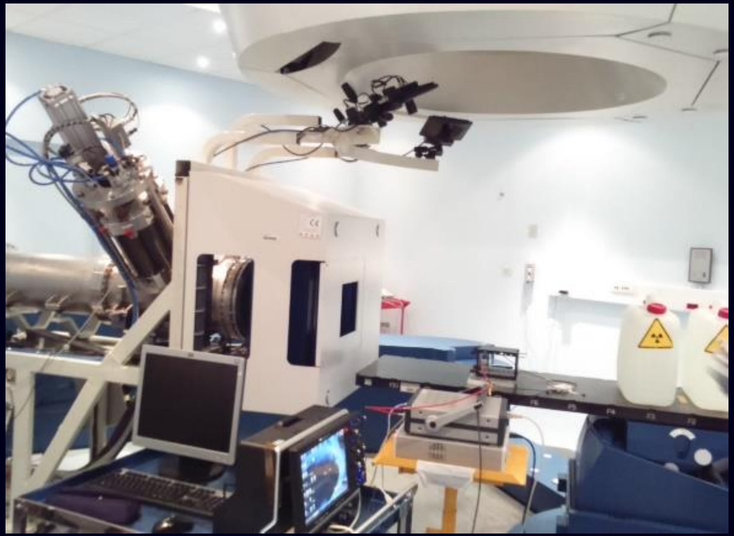
- Patients’ treatment with **carbon ions and protons**
- Clinical and radiobiological research

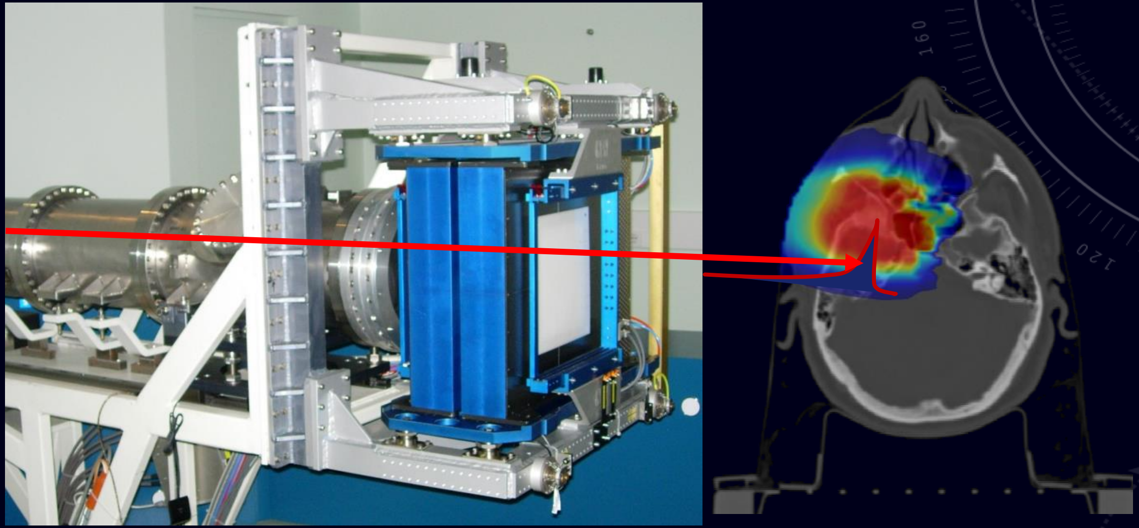
2011, September: beginning of the treatments with protons
2012, October: beginning of the treatments with carbon ions

CNAO experimental room

The CNAO nozzle

Developed by Fondazione CNAO, INFN and University of Torino

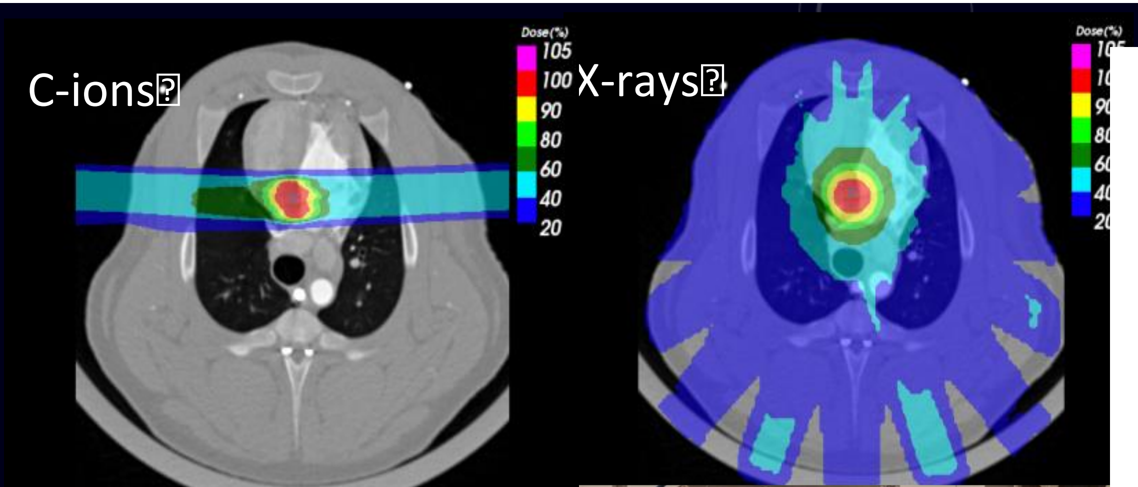


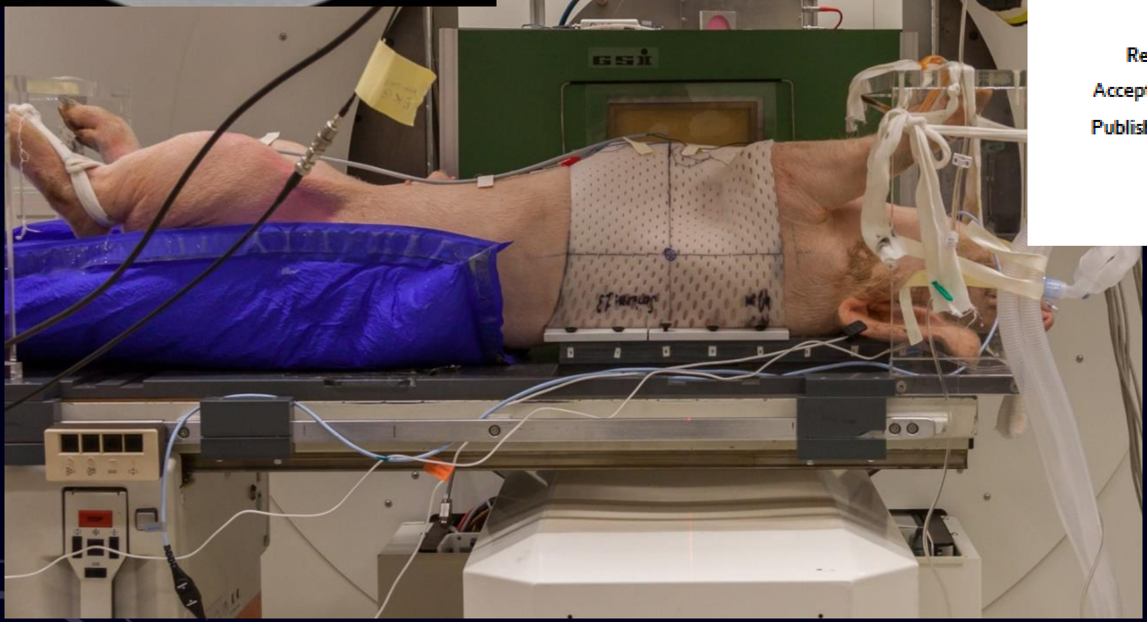


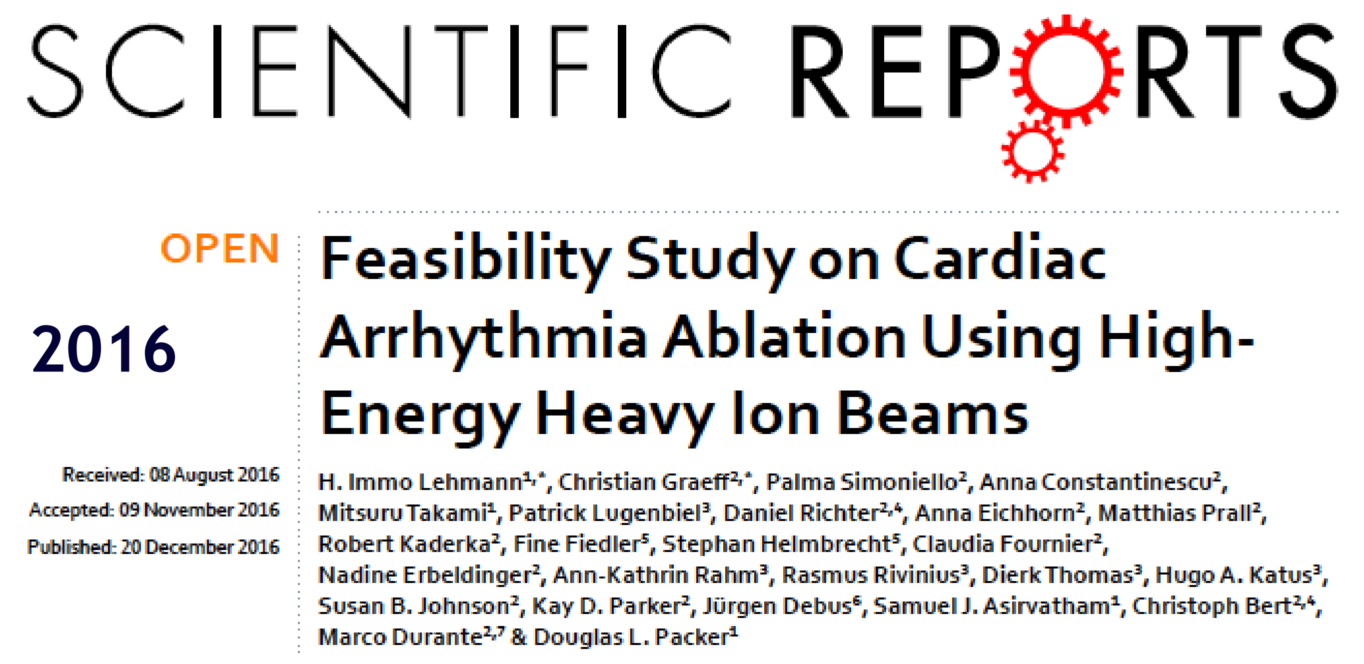
Reference [6]

CNAO Dose Delivery System: Particle detectors integrated with the synchrotron to guide and monitor the beam in real time

Particle therapy: beyond cancer







SCIENTIFIC REPORTS

OPEN

2016

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Published: 20 December 2016

Feasibility Study on Cardiac Arrhythmia Ablation Using High-Energy Heavy Ion Beams

H. Immo Lehmann[1,*], Christian Graeff[2,*], Palma Simoniello[2], Anna Constantinescu[2], Mitsuru Takami[1], Patrick Lugenbiel[3], Daniel Richter[2,4], Anna Eichhorn[2], Matthias Prall[2], Robert Kaderka[2], Fine Fiedler[5], Stephan Helmbrecht[5], Claudia Fournier[2], Nadine Erbeldinger[2], Ann-Kathrin Rahm[3], Rasmus Rivinius[3], Dierk Thomas[3], Hugo A. Katus[3], Susan B. Johnson[2], Kay D. Parker[2], Jürgen Debus[6], Samuel J. Asirvatham[1], Christoph Bert[2,4], Marco Durante[2,7] & Douglas L. Packer[1]

GSI

MAYO CLINIC

Courtesy of M. Durante

Not only cancer

January 22, 2020

CULTURE 22/01/2020 14:14 CET | **Aggiornato** 15 ore fa

Aritmia ventricolare trattata con un fascio di protoni, prima volta al mondo

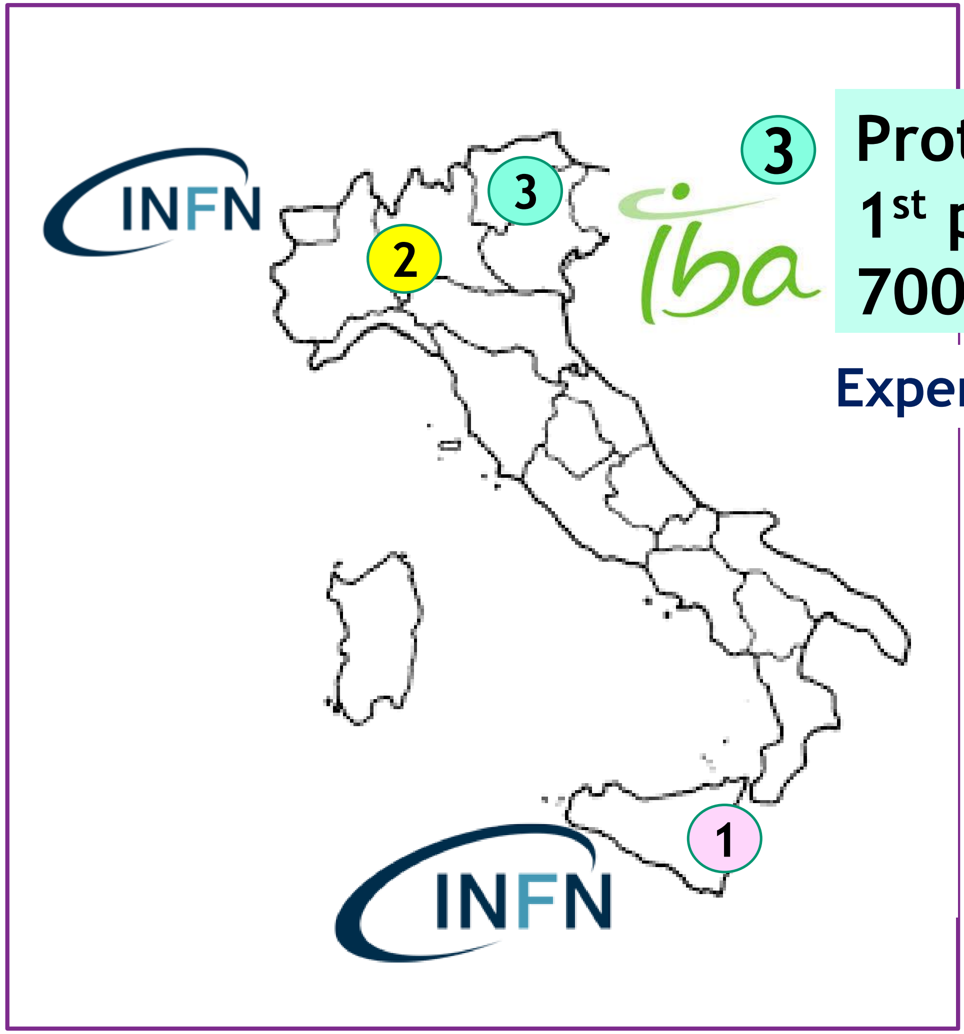
L'intervento, messo a punto in collaborazione con la Fondazione Irccs Policlinico San Matteo, è stato eseguito al Cnao di Pavia

ANSA

SCIEPRO/SCIENCE PHOTO LIBRARY VIA GETTY IMAGES

Illustration of a man's heart.

Italian particle therapy centers



3 **Proton Therapy Trento**
1st patient 2014
700 patients

Experimental beam line

PROTONTERAPIA TRENTO and TIFPA

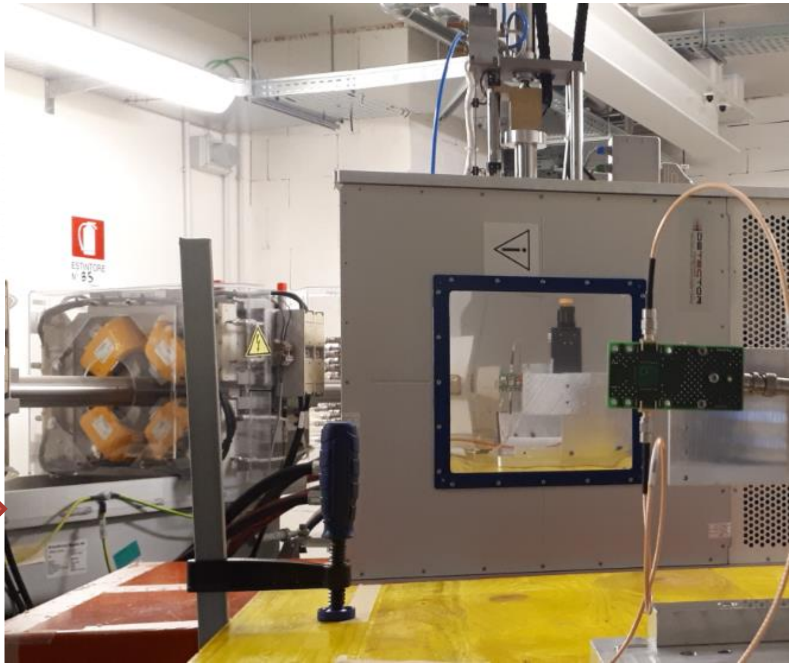
PROTONTERAPIA
TRENTO

https://protonterapia.provincia.tn.it/

TIFPA
Trento Institute for
Fundamental Physics
and Applications

Two treatment rooms with gantry

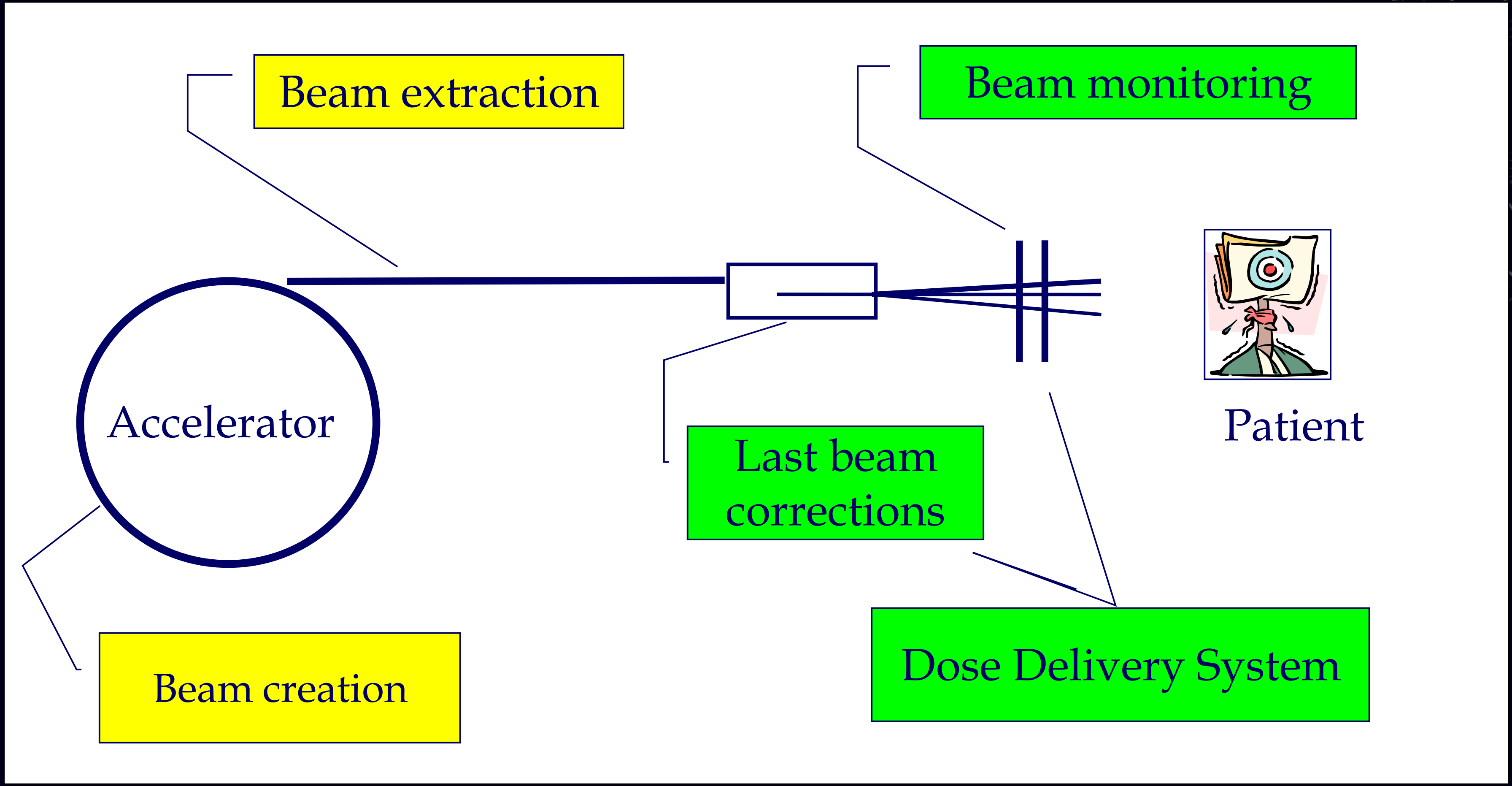
One experimental room for research



First treatments → end of 2014
1000 patients → end of 2019

Radiotherapy Instrumentation

Radiotherapy Instrumentation



Beam extraction

Beam monitoring

Accelerator

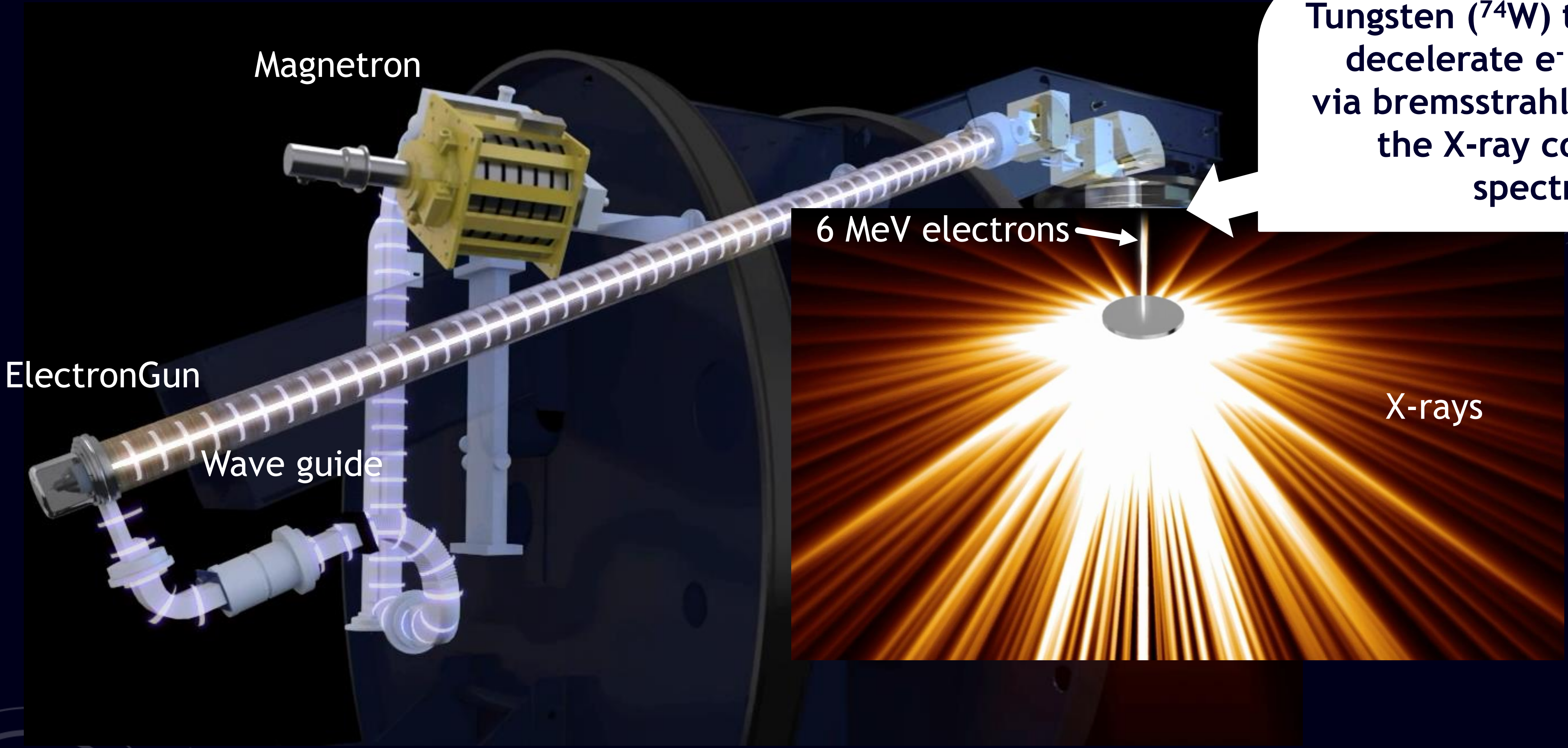
Patient

Last beam corrections

Beam creation

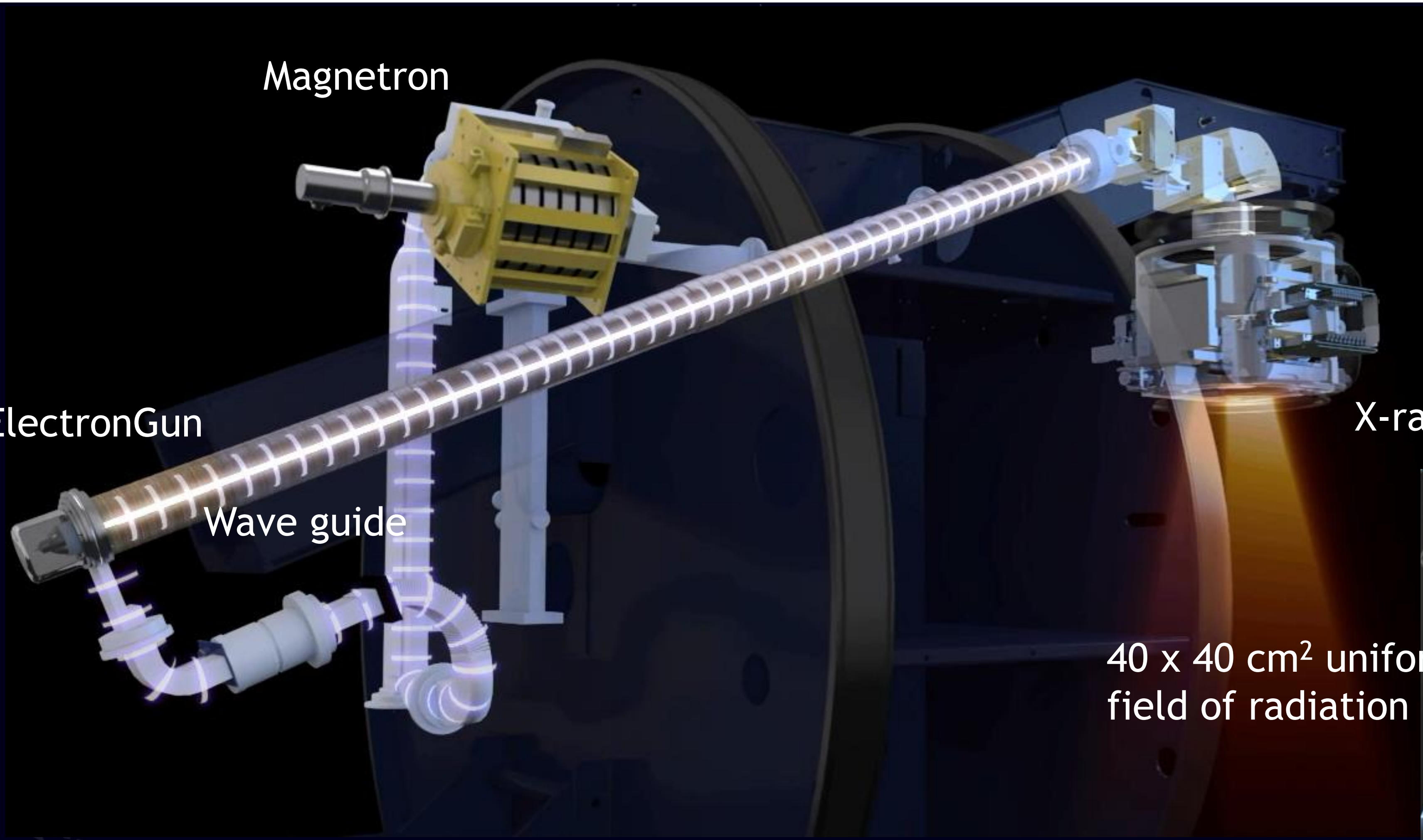
Dose Delivery System

LINAC for radiotherapy



Tungsten (^{74}W) target used to decelerate e^- to produce via bremsstrahlung radiation the X-ray continuous spectrum

LINAC for radiotherapy



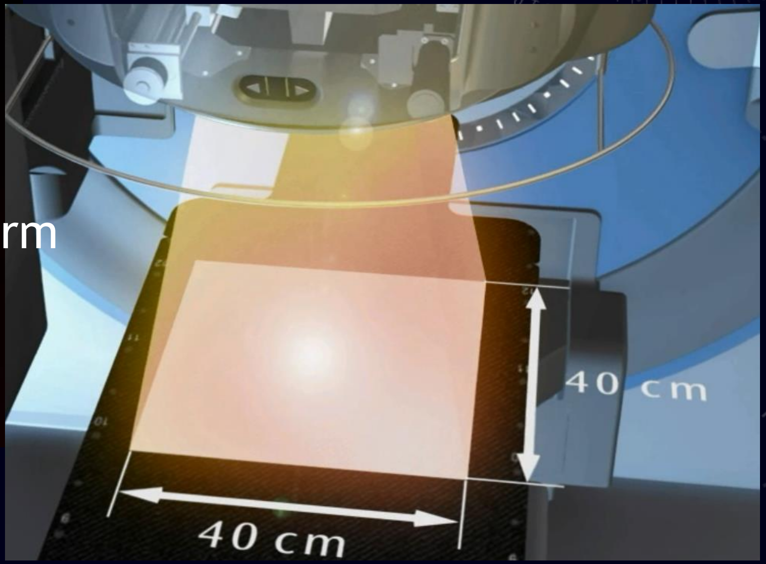
Magnetron

ElectronGun

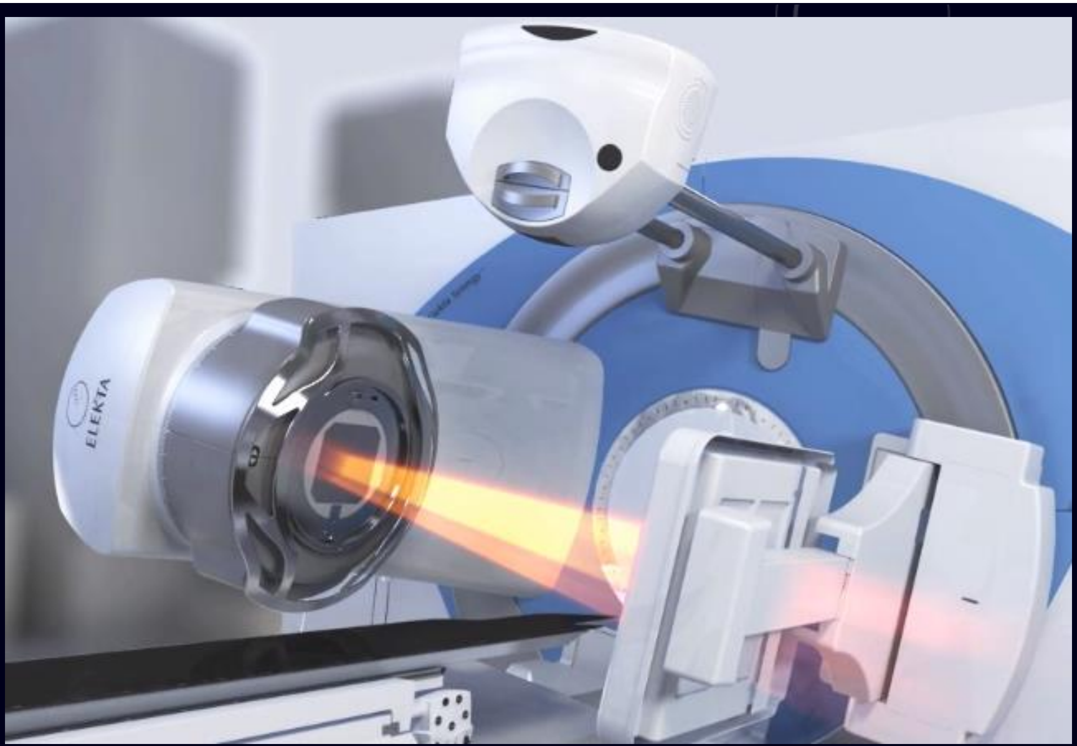
Wave guide

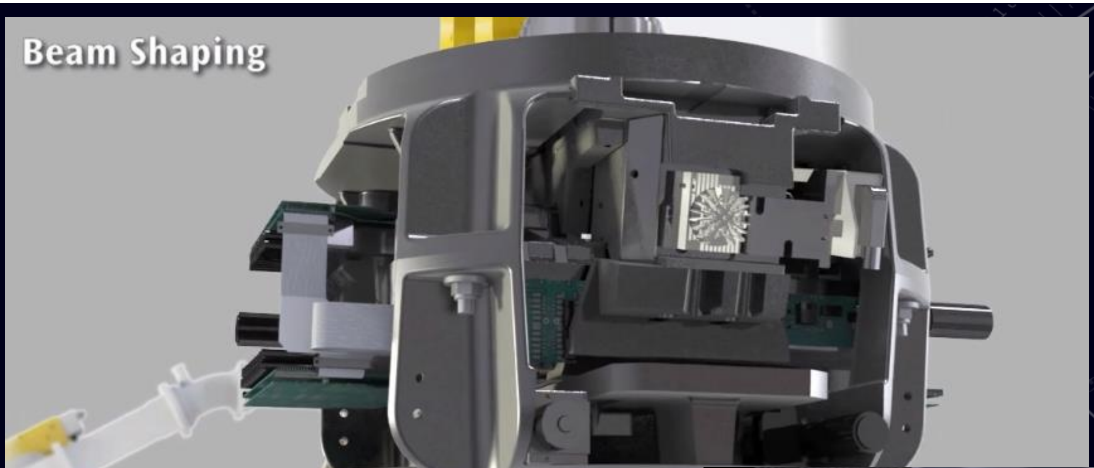
X-ray from 6 MV LINAC)

40 x 40 cm^2 uniform field of radiation

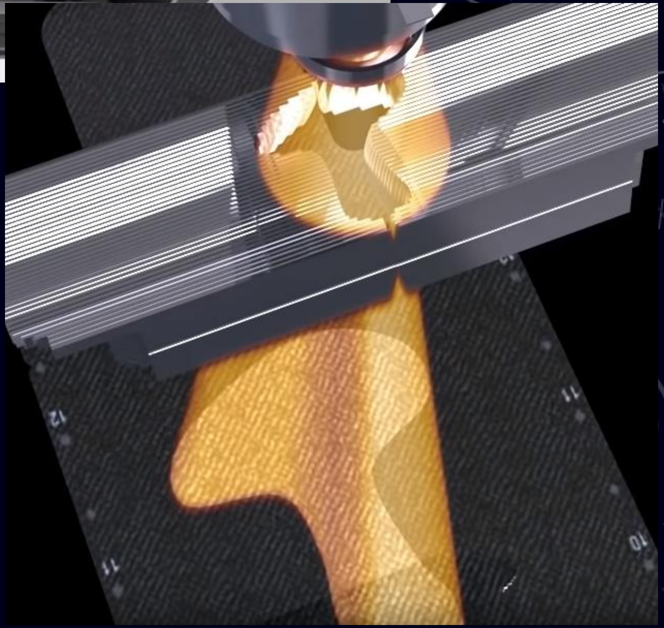


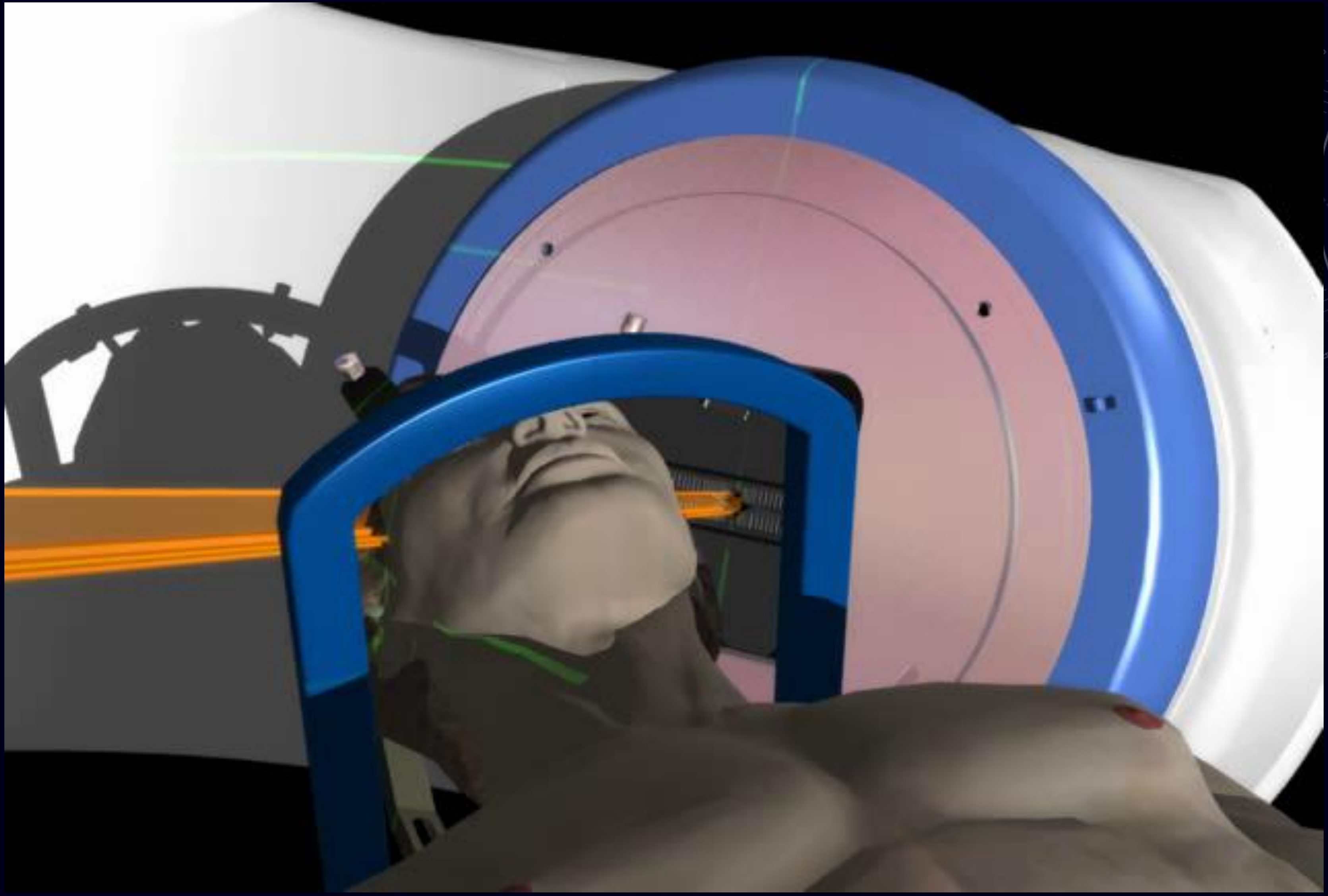
Dose Delivery to shape the X-ray beam





Dynamic multileaf collimator
to shape the beam
(up to 160 individual leaves)





Particle Therapy Instrumentation

The particle pencil beam must be **controlled** and **modified** just before the patient
→ **the Dose Delivery System includes the BEAM MONITORS**

Synchrotron
or
Cyclotron

Beam-line

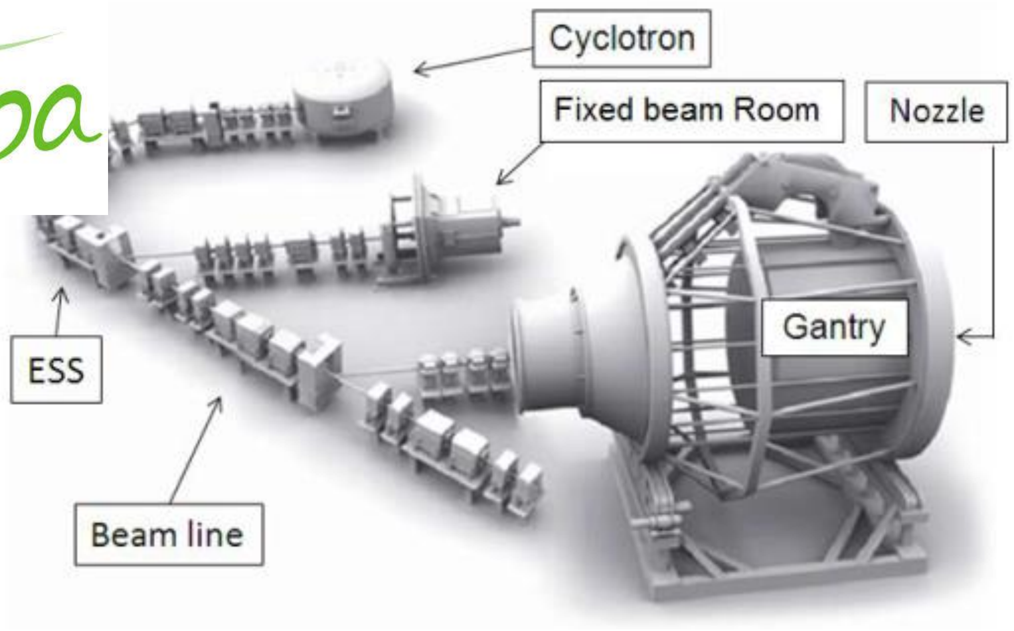
Magnets (dipoles and quadrupoles), vacuum chambers and beam diagnostic devices

Dose Delivery System

targets

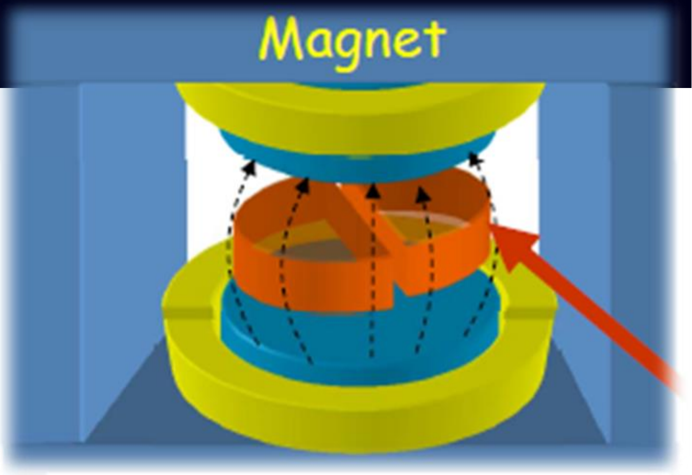

Patient

Cyclotron for proton therapy



ProteusOne and ProteusPlus turn-key proton therapy solutions from IBA (Belgium)

TIME STRUCTURE → CONTINUOUS BEAM

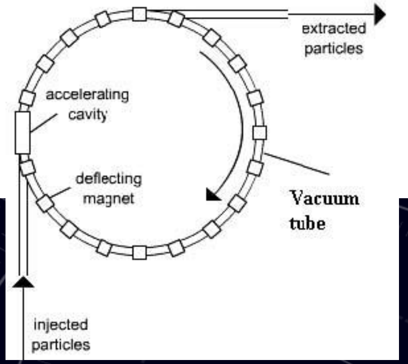


The cyclotron provides proton therapy reliably and at low cost (Main vendors on the market: IBA, Varian, Mevion, Hitachi).

Critical issues with cyclotrons:

1. Energy modulation (required to adjust the depth and scan the tumour) is obtained with degraders (sliding plates) that are slow and remain activated.
2. Large shielding

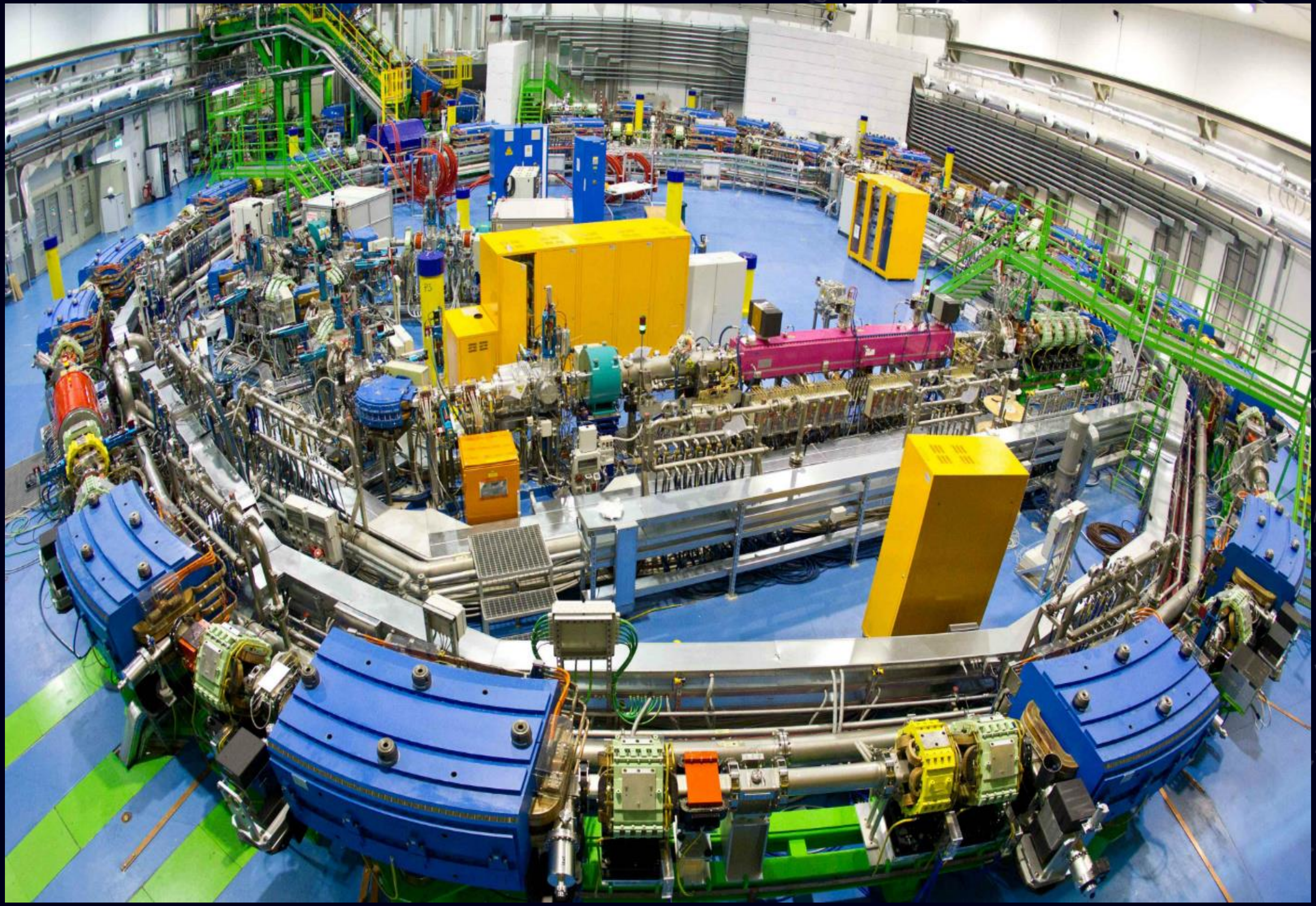
Synchrotron for heavy ion therapy



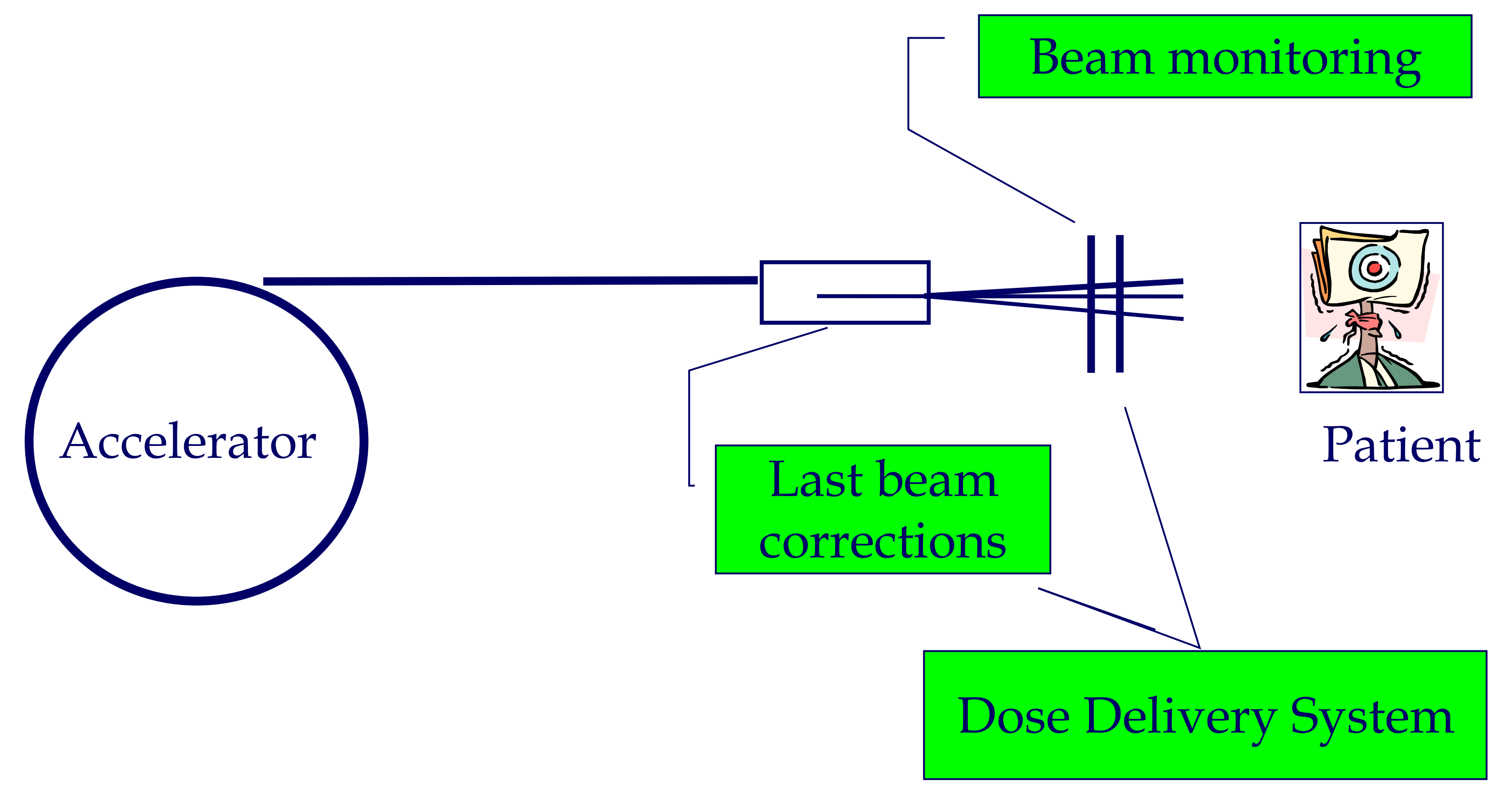
Accelerate different ion species
Modulate the beam energy

TIME STRUCTURE → beam delivered in spill
Duty cycle < 50 %

Very big (25 m Ø)
Complex
Expensive (construction and maintenance)



Radiotherapy instrumentation



Beam monitoring

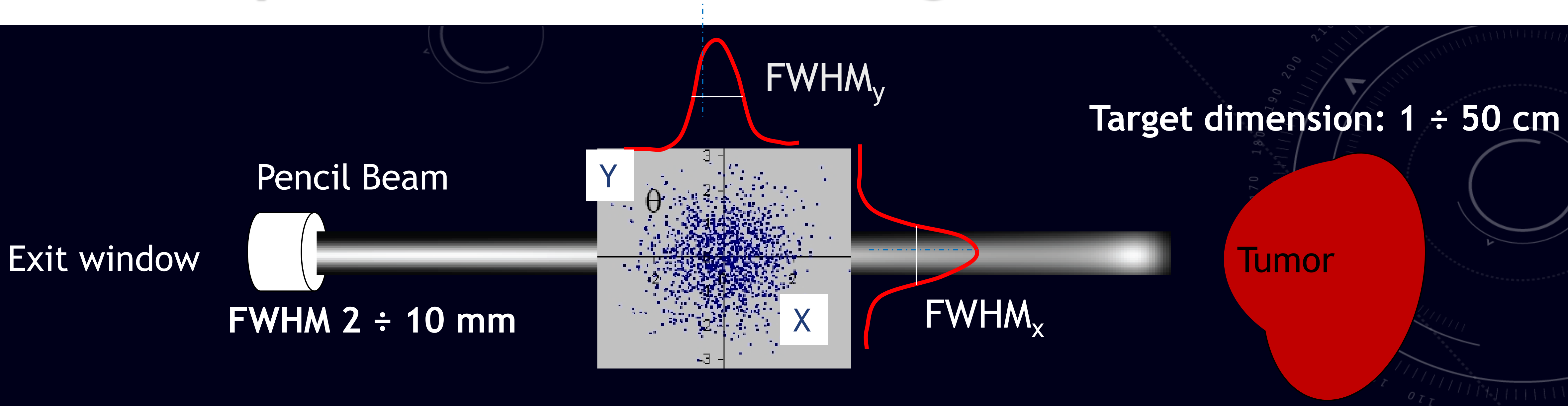
Accelerator

Patient

Last beam corrections

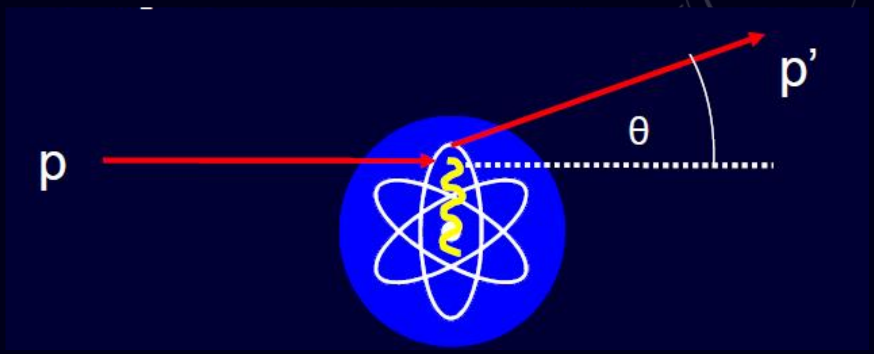
Dose Delivery System

Particle pencil beam and target characteristics

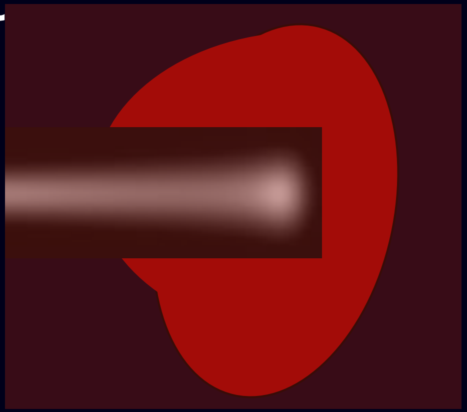


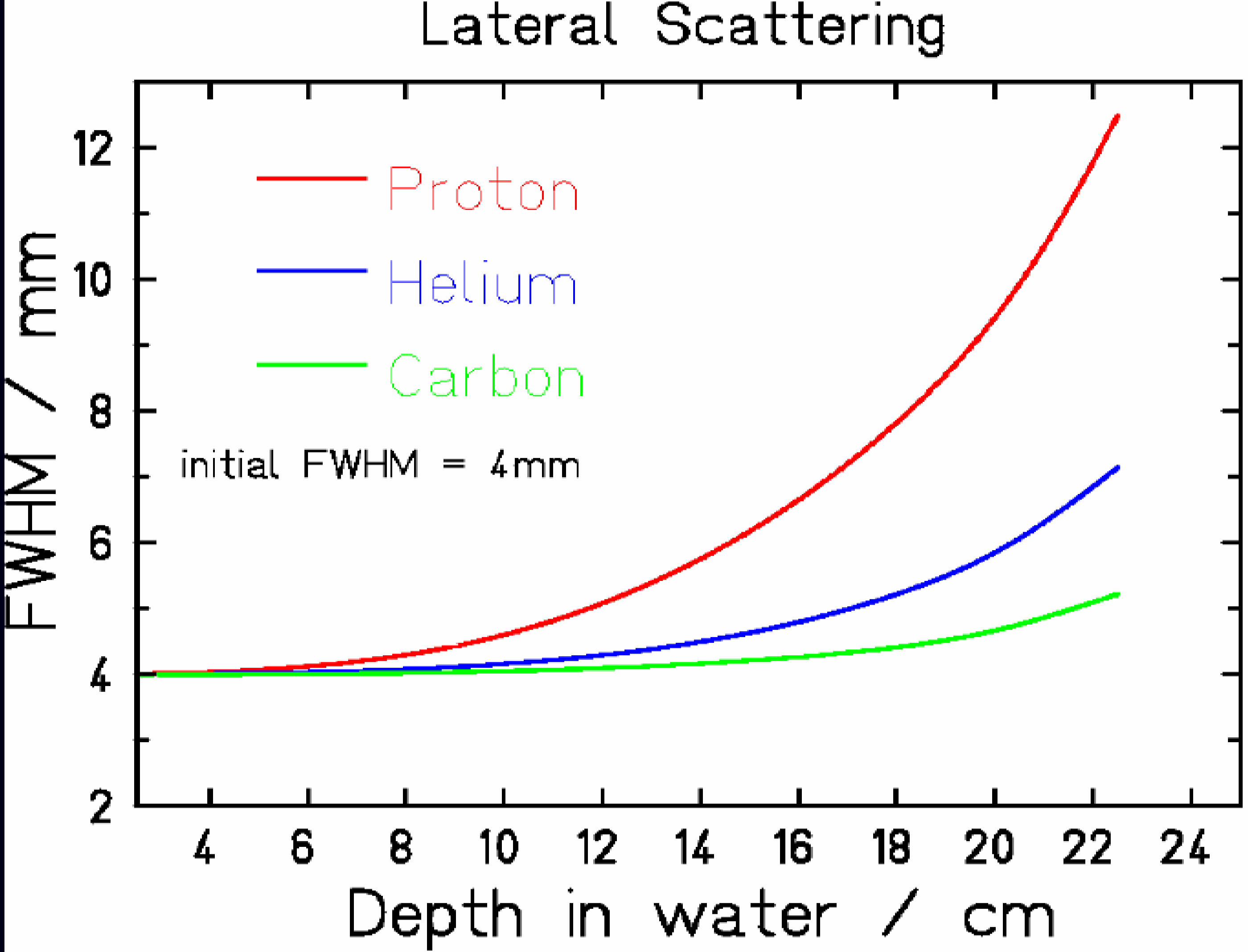
Beam range for protons/carbon ions	→	3÷30 cm
Beam energy range for protons/carbon ions	→	60÷250 MeV / 120÷400 MeV/u
Beam intensity for protons/carbon ions	→	$10^8 \div 10^{10}$ / $4\times10^7 \div 4\times10^8$ /sec
Spot size (FWHM in air at the isocenter) protons/carbon ions	→	7÷20 /4÷8 mm from highest to lowest energies
Field size (min/max) at the isocenter	→	20x20/40×40 cm^2

Effect of Multiple Coulomb Scattering

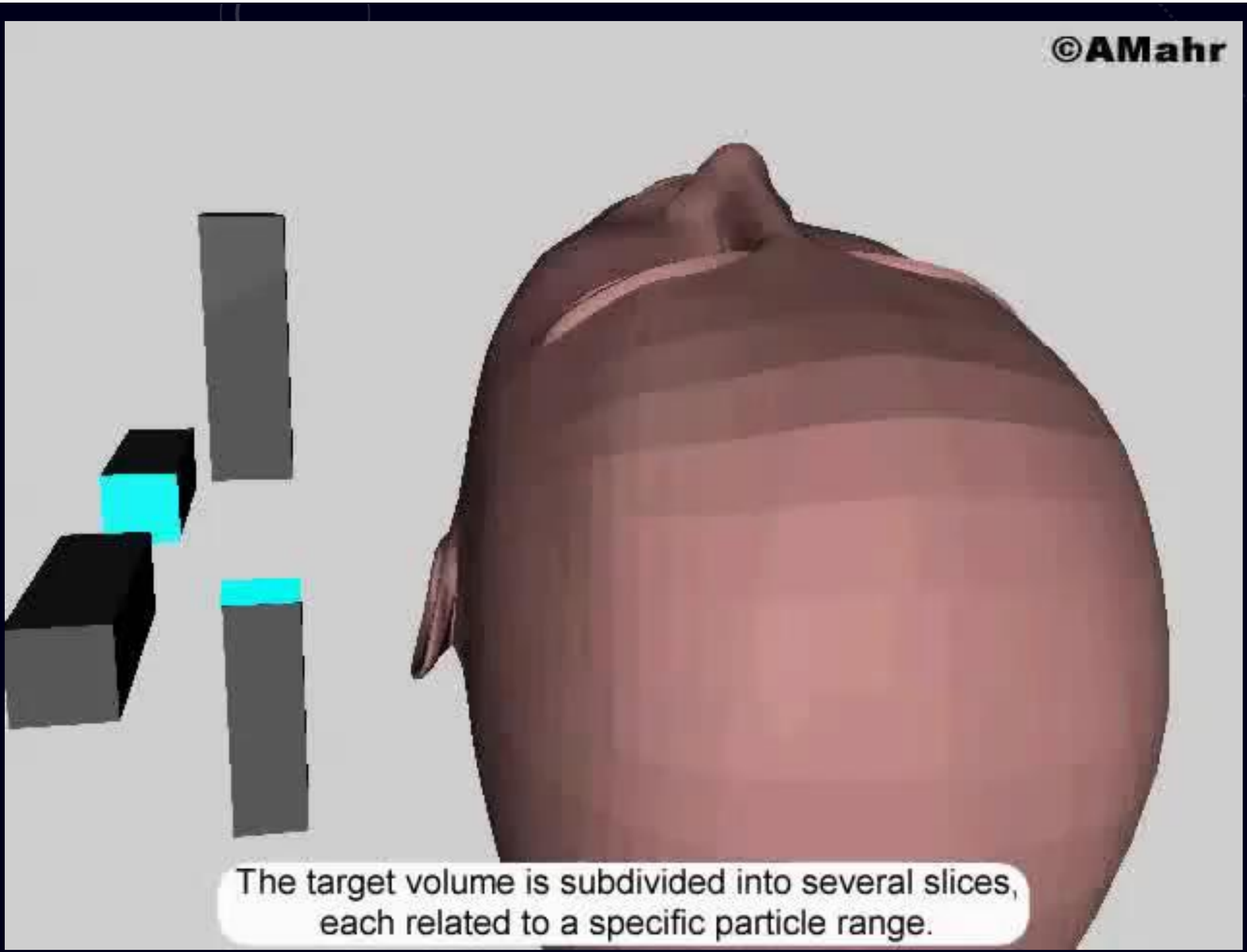


Scattering in air and in the body is not enough to cover the whole target



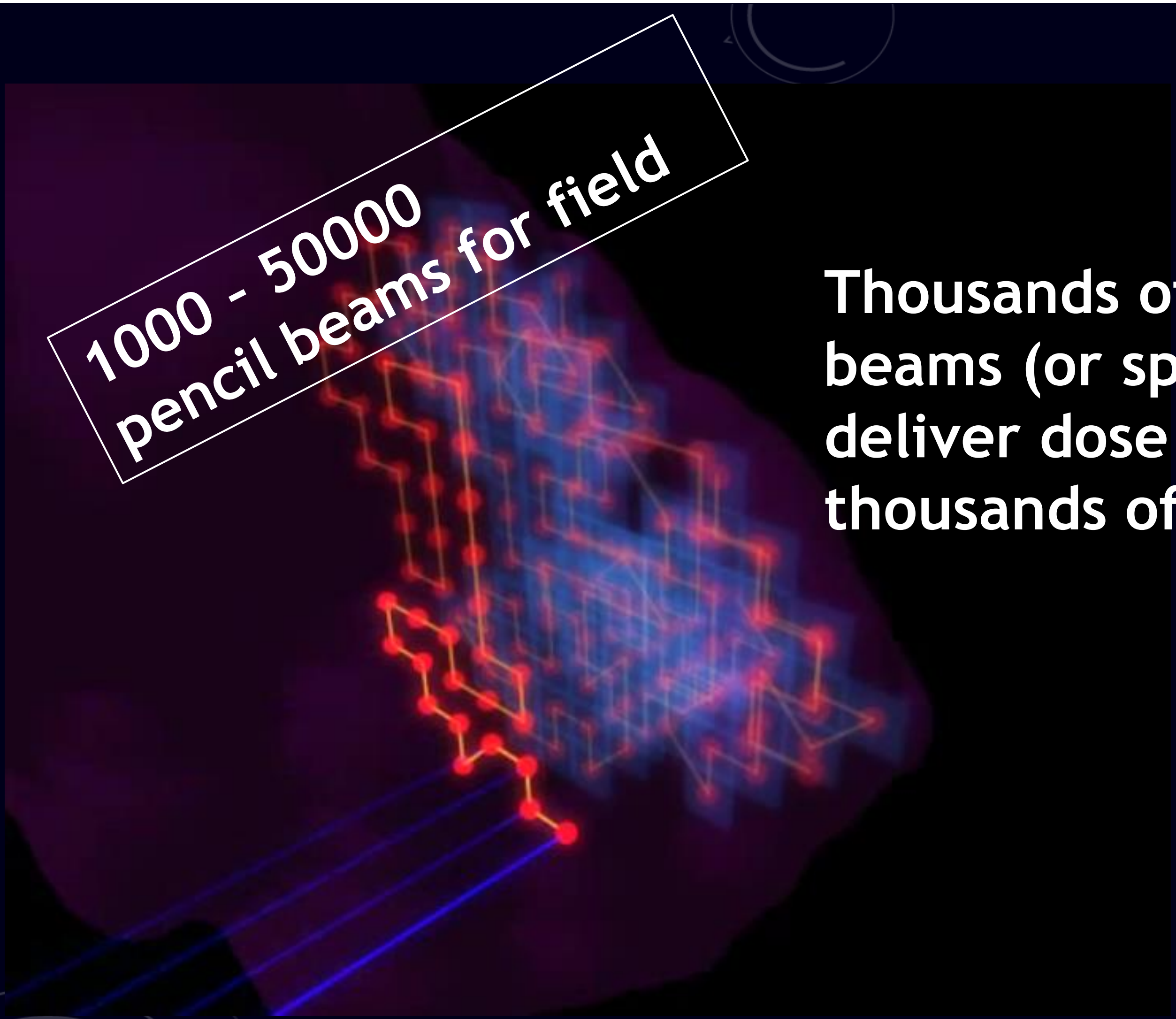


3D dose modulation with pencil beams

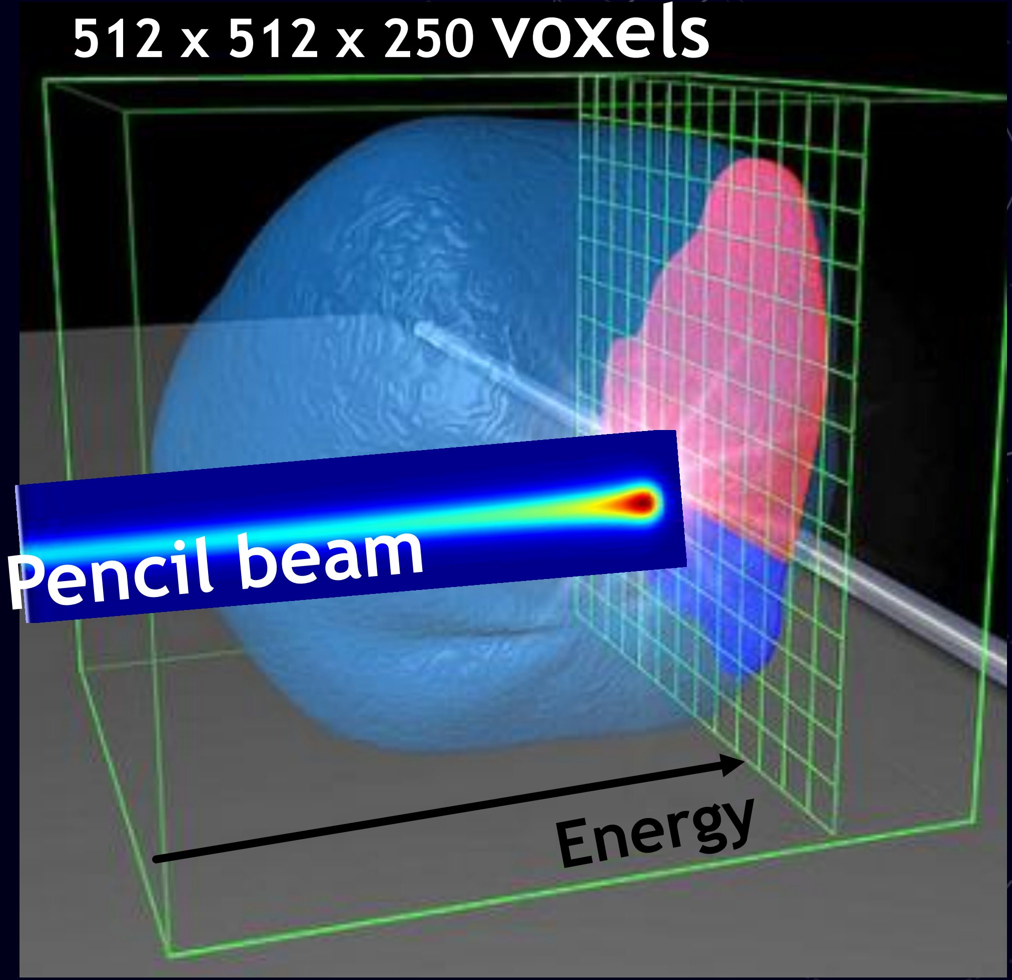


The target volume is subdivided into several slices, each related to a specific particle range.

3D dose modulation with pencil beams


1000 - 50000 pencil beams for field

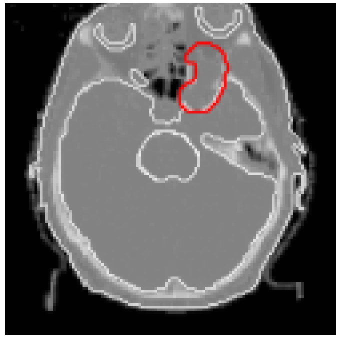
Thousands of pencil beams (or spots) deliver dose into thousands of voxels


512 x 512 x 250 **voxels**

Treatment Planning System

calculate the dose distributions delivered by particle beams

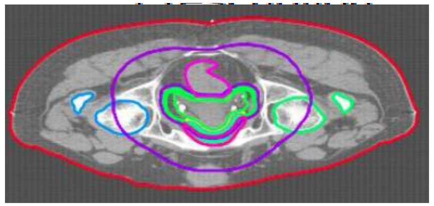
CT image : anatomical description



Irradiation set-up

(chosen beam line, number and direction of fields, beams energies, spot inter-distance. ...)

Prescription



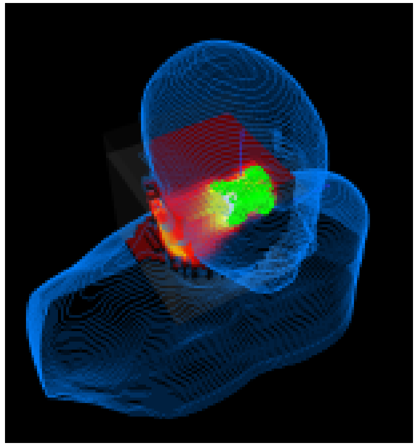
TPS

FORWARD COMPUTATION

INVERSE COMPUTATION

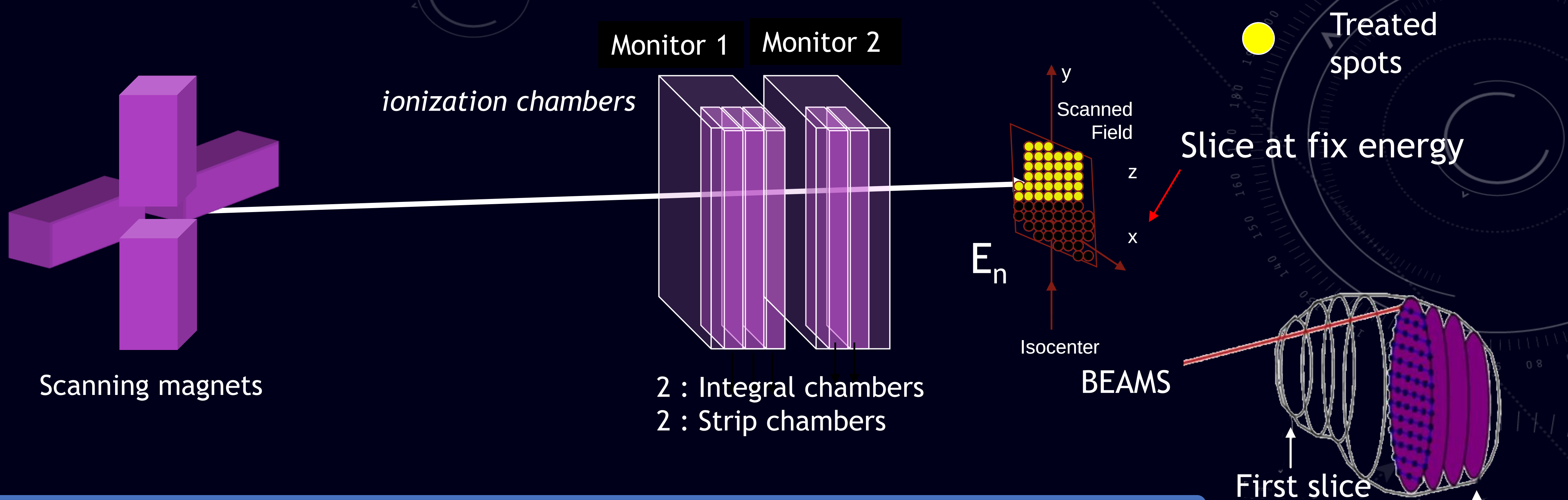
3D effects distributions

(dose, biological dose, LET, survival, ...)



OPTIMIZED SPOT FLUENCE

Modulated scanning technique driven by beam monitors



Monitor 1

Monitor 2

ionization chambers

Scanning magnets

2 : Integral chambers
2 : Strip chambers

y

Scanned Field

z

x

E_n

Isocenter

BEAMS

● Treated spots

Slice at fix energy

First slice
(min energy)

Last slice
(max energy)

- *Monitor on-line the beam (<u>fluence, position and dimension</u>)*
- Set the beam position spot by spot through the <u>scanning magnets power supplies</u>
- Correct on-line the beam position (feed-back operations)
- Stop the beam slice by slice or when something is wrong

[Ref 7]

Main tasks of beam monitors

To measure during treatment and before the patient …

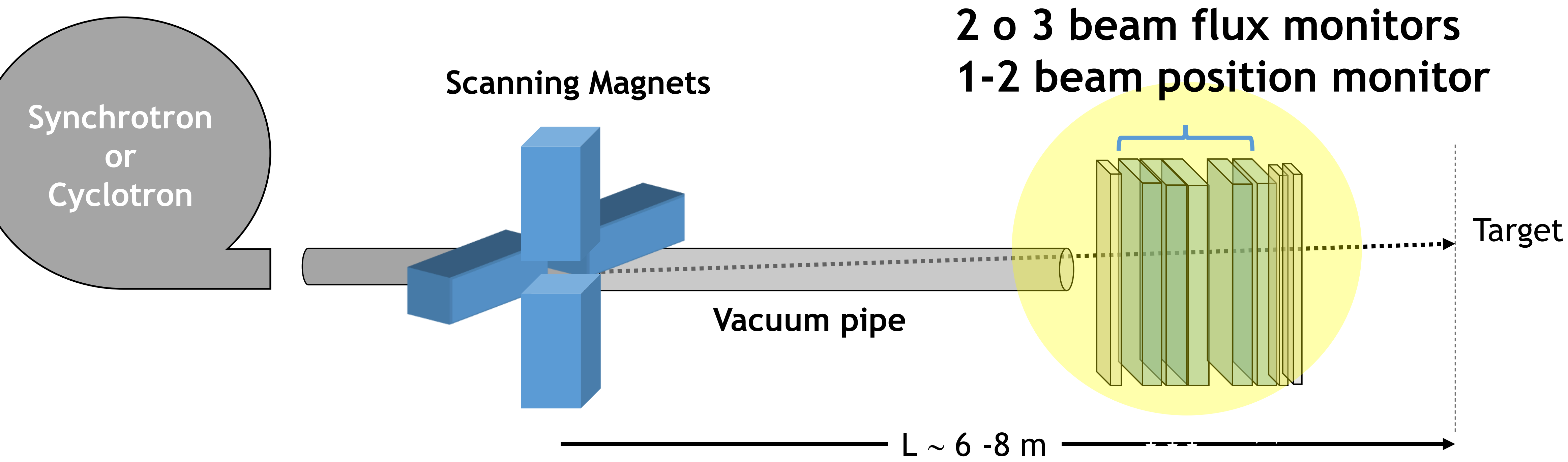
Beam flux and fluence (beam Intensity – dose rate)
→ **Accepted uncertainty 1-2 %**
Transversal Beam positions
→ **Accepted uncertainty 0.5 mm**
Transversal Beam shape (FWHMs - symmetry)
→ **Accepted uncertainty 1 mm**

Beam range or absolute energy
→ ***Accepted uncertainty 1 mm (0.5 - 1 MeV)***

Currently not online!!

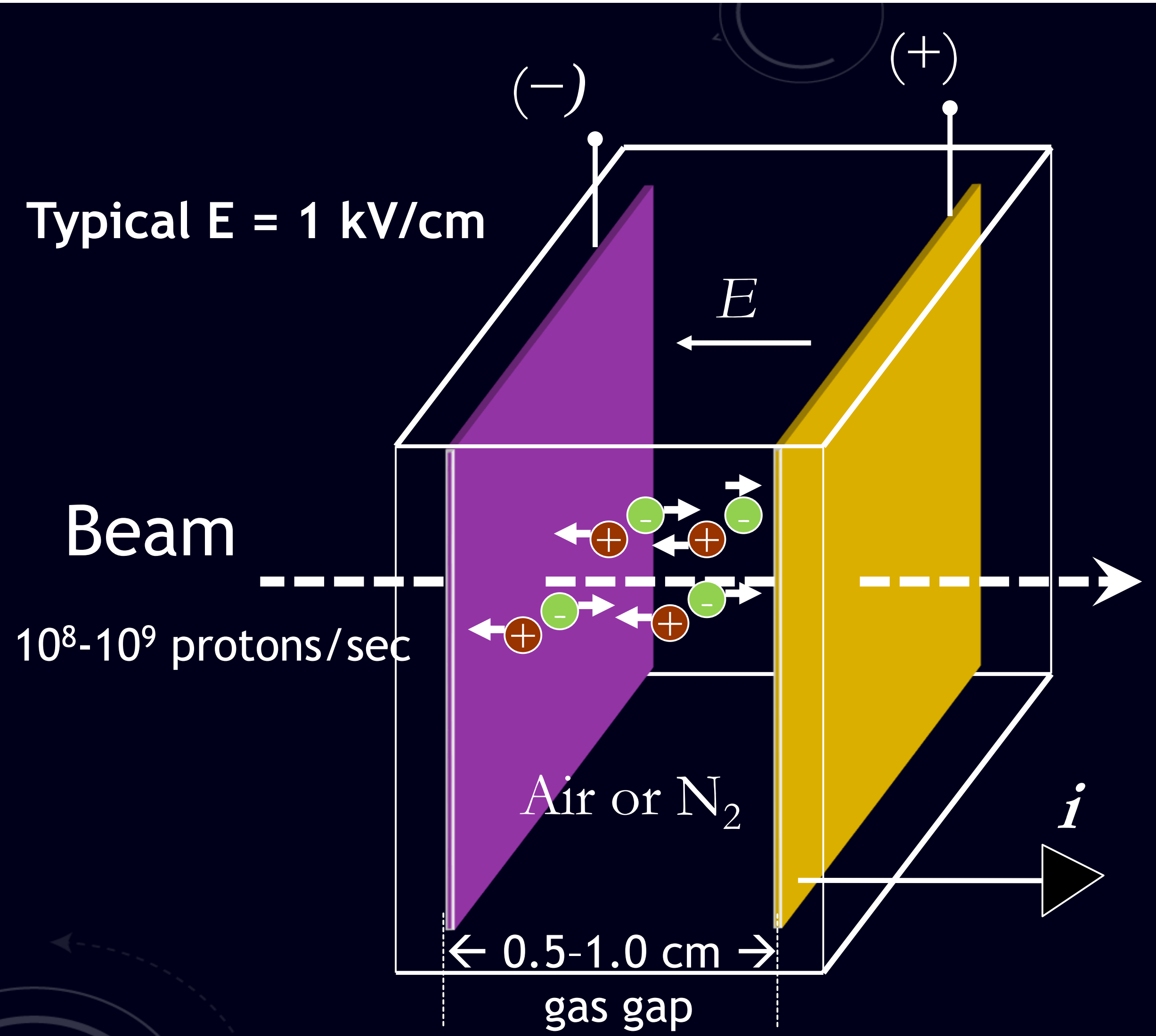
State of the art for beam monitoring

Worldwide the beam monitors are based on gas ionization chambers…

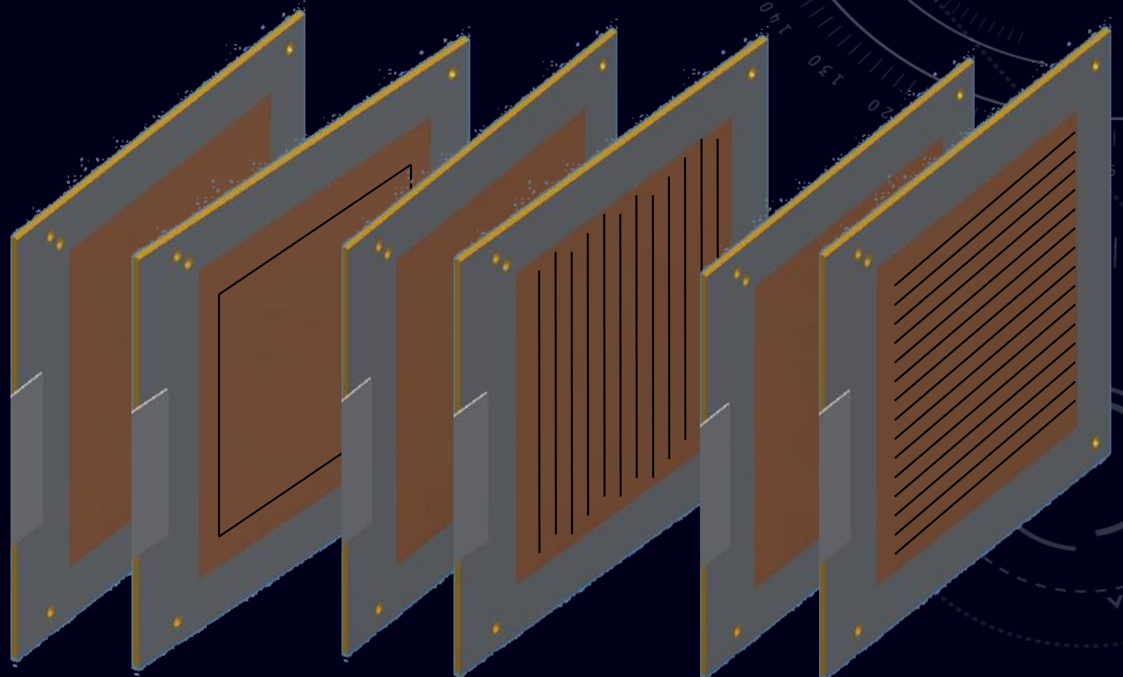


[Ref 8]

Beam monitors → Gas ionization chambers



Sequence of Parallel Plate ICs:
→ single large electrode for FLUX measurement
→ electrodes segmented in strips for BEAM POSITION measurement



Ionization chambers

IC measure a charge proportional to the number of particles sent to the patient

$$Q = \frac{S \cdot d \cdot e}{W} N$$

S = stopping power gas [keV/μm = MeV/mm]
d = distance between electrodes [mm]
e = elementary charge1,6·10^{-19} C
W= **mean energy to create a e- /ion pair**
(~ 30 eV = 3·10^{-5} MeV)

Collection time depends on the position of pair produced within the chamber

$$\boldsymbol{t_{-} \sim d/(\mu_{-} \cdot E) = 500\ \mathrm{ns} \quad (e^{-})}$$

$$\boldsymbol{t_{+} \sim d/(\mu_{+} \cdot E) = 400\ \mathrm{\mu s} \quad (ions)}$$

- Ion mobility in N_2

$\boldsymbol{\mu_{+} = 1,3\ \mathrm{cm^2 s^{-1} V^{-1}}}$

$\boldsymbol{\mu_{-} \approx 10^3\ \mathrm{cm^2 s^{-1} V^{-1}}}$ 1000 times faster!

→ Long collection times compared with the average time between two particles in clinical beams(1 ns)

Some numbers about IC

Assuming:

- Beam intensity $10^9 \; prot/s$

  (1 prot/ns)
- **E_p = 120 MeV**
- Gas N_2 in standard T e p
- $d = 0,5 \; cm, \; \Delta V = 500 \; V$

  $\rightarrow E = 1 \; \mathrm{kV/cm}$

From letterature:

- In N_2 $S = 7,0 \cdot 10^{-4} \frac{\mathrm{MeV}}{\mathrm{mm}}$

  $W = 3,5 \cdot 10^{-5} \; \mathrm{MeV}$
- Ion mobility $\mu_+ = 1,3 \; \mathrm{cm^2 s^{-1} V^{-1}}$
- e⁻ 1000 times faster!

  $\mu_- \approx 10^3 \; \mathrm{cm^2 s^{-1} V^{-1}}$

Energy loss by a proton through the chamber:

$S \cdot d = 3,5 \; keV$ → **negligible**

Number of pair e⁻ - ion

$$S \cdot d / W = 100$$

Collected charge very small!

$$100 \times 1,6 \cdot 10^{-19} C = \boxed{0,016 \; fC}$$

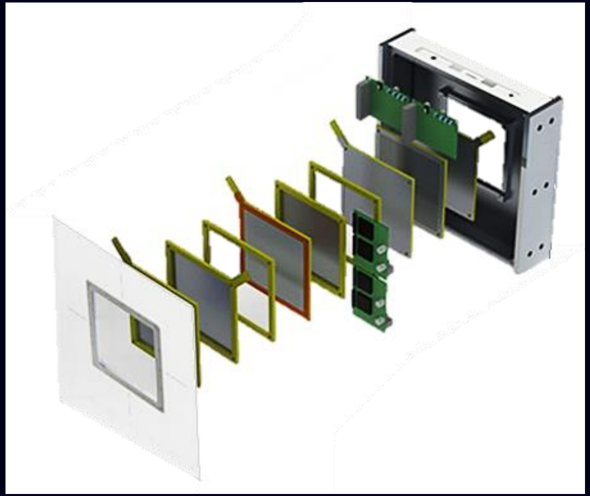
Collection time depends on the position of pair produced within the chamber

$$t_- \sim d/(\mu_- \cdot E) = 500 \; \mathrm{ns} \quad (e^-)$$

$$t_+ \sim d/(\mu_+ \cdot E) = \boxed{400 \; \mu\mathrm{s}} \quad (ioni)$$

→ **Long collection times compared with the average time between two particles in clinical beams (1 ns)**

From IC Monitor Units to Dose



Integrator $V_{out} \propto \int i(t)dt = Q$

ASIC

i (μA) →

Monitor counts →

Calibration

↓

N particles

↓

Dose Planning

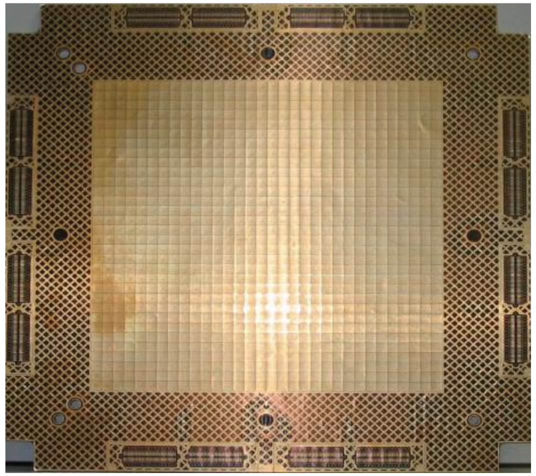
↓

Dose (Gy)

LOW SENSITIVITY

1 MU ~ 200 fC ~
- **7.2×10^3** protons (62 MeV)
- **1.9×10^4** protons (226 MeV)
- **341** carbon ions (115 MeV/u)
- **767** carbon ions (399 MeV/u)

IC with segmented anodes

Measured parameter	N.ro of ions →	beam position →	beam shape
Time between two readouts	1 µs →	100 µs →	200 µs
	Integral chamber	**STRIP**	**PIXEL**
	20x20 cm^2		
	1 channel	128 channels	1024 channels 32 x 32 pixels
Spatial resolution	None →	100 µm →	200 µm

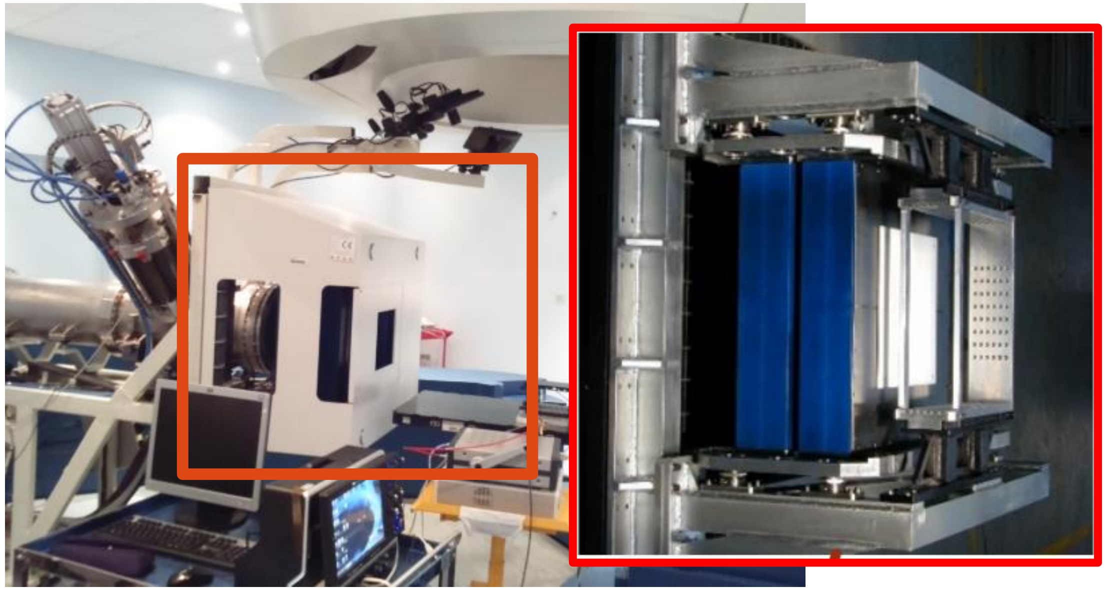
Advantages of gas ionization chambers

- Reliability & long term (years) stability
- Large (30x30 cm^2) sensitive area allowed
- Simple to use
- Deeply studied manufacture
- A few mm water equivalent thickness
- Radiation resistant

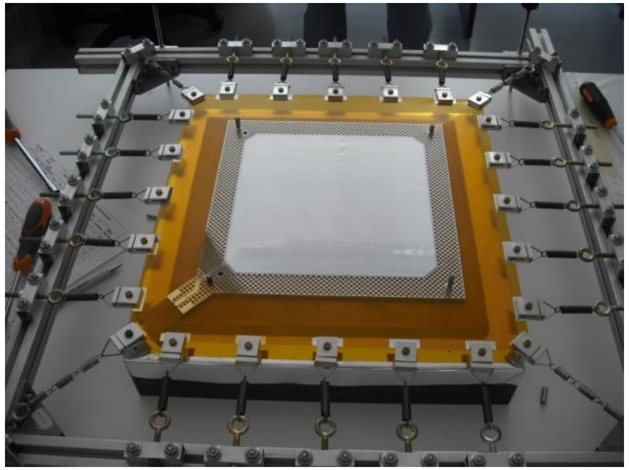
The best choice for current clinical requirements and existing accelerators

CNAO parallel plate ionization chambers

Thin electrodes “transparent” to the beam

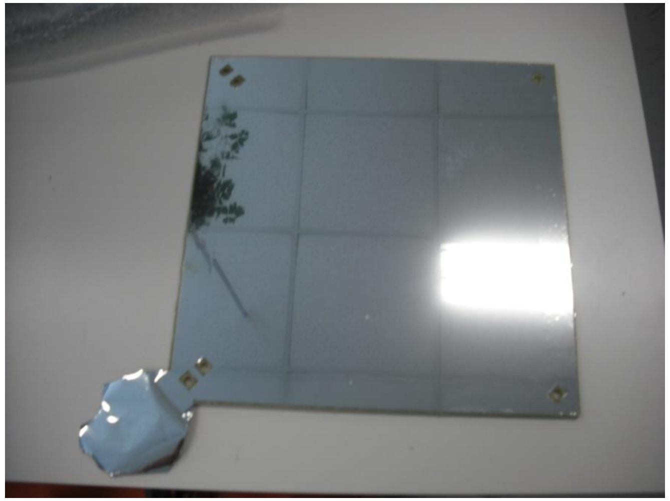


Anode



CNAO: chamber filled with N_2 → HV = 400 V
d = 0.5 cm

Cathode



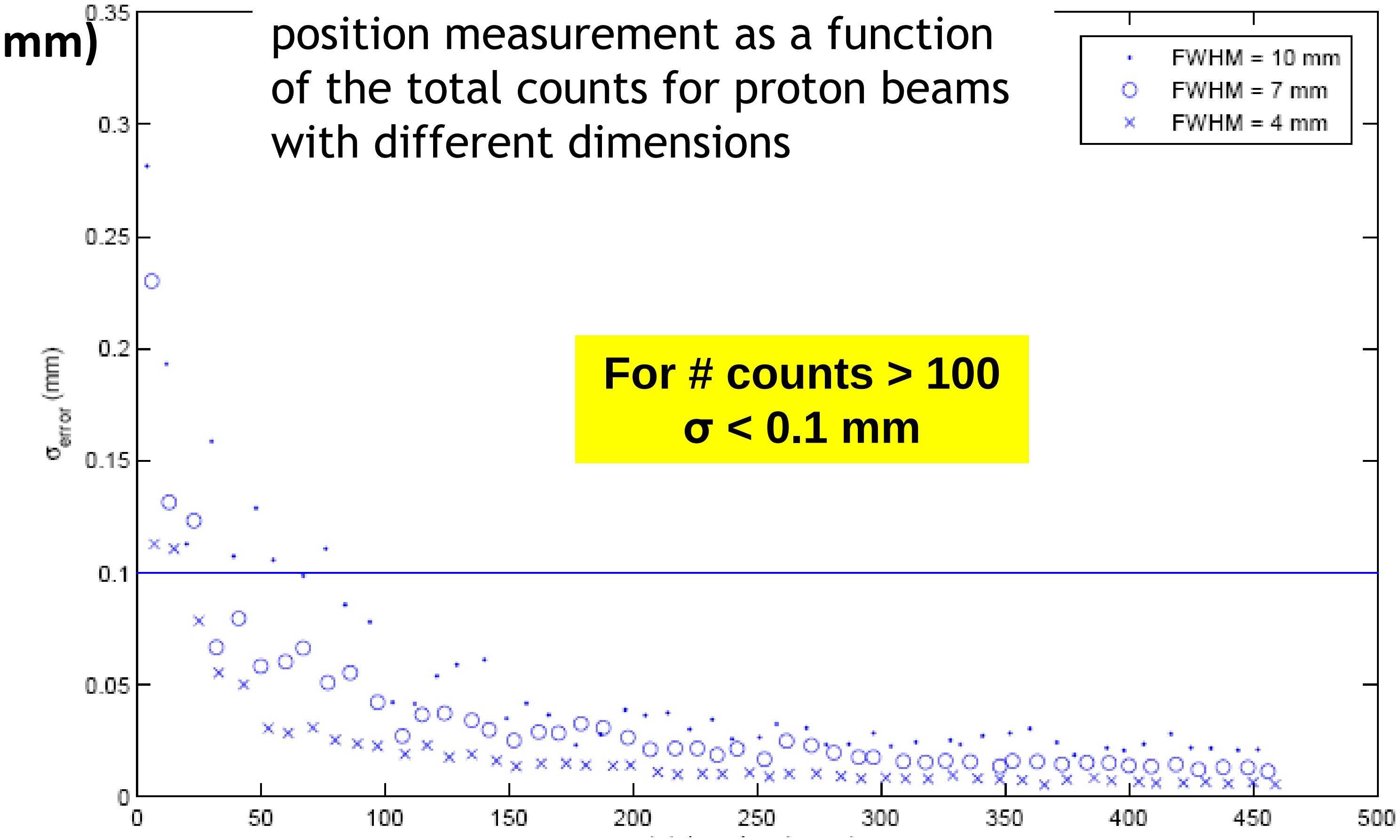
Position accuracy depends on readout counts

$$Error \propto \frac{1}{\sqrt{S_i}}$$

Minimum time to collect 100 counts: 100 μs
→ Beam intensity of 10^{10} protoni e $4*10^{8}$ carbon ions

100 counts = 20 pC

σ_{err} (mm)



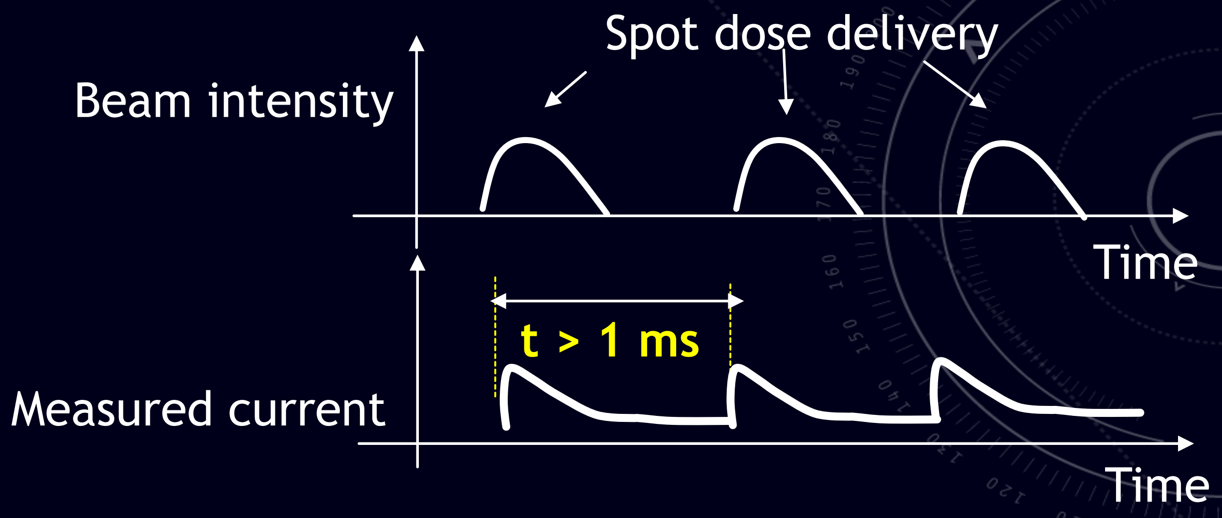
Standard deviation of the error on position measurement as a function of the total counts for proton beams with different dimensions

For # counts > 100
σ < 0.1 mm

Total readout counts per channel

CONSTRAINS of gas IC

- Slow collection time
  (400 µs for 0.5 cm gap)



CONSTRAINS of gas IC

- Slow collection time
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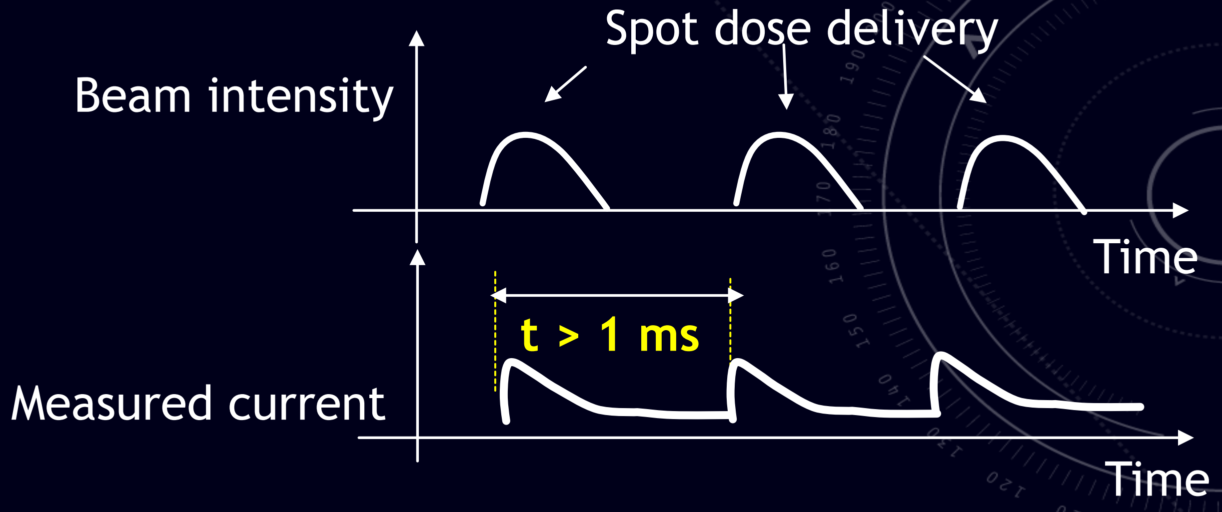

- Collected charge dependent on T, P, beam E
  → **Calibration needed**
- Low sensitivity (Q = 0.2-2 pC charge resolution)
  → **Threshold needed on the minimum number of particles per spot**
- **Charge recombination with high intensity and pulsed beams**

What’s next?

MUCH LOWER and MUCH HIGHER DOSE RATES
are required to deal with

- …………….
- New treatment modalities
- New accelerators
- New delivery techniques
- New dose fractionation
- ………….

Take home messages (I)

PHYSICS APPLIED TO MEDICINE INCLUDE SEVERAL TOPICS

Small research groups

⇩

Wide range of expertise

- RADIOBIOLOGY
- MEDICAL IMAGING
- PHYSICS OF ACCELERATORS
- PHYSICS OF BEAM DELIVERY
- RADIATION DETECTORS
- READOUT ELECTRONICS
- ALGORITHMS FOR DOSE CALCULATION

Take home messages (II)

CHARGED PARTICLE THERAPY IS NOW ACCEPTED AS BEING SELF-EVIDENT

WORLDWIDE THE BEAM MONITORS ARE GAS IONIZATION CHAMBERS

FOR NEW and IMPROVED TREATMENTS NEW RESEARCH AND TECHNOLOGIES are NEEDED

Take home messages (III)

WORLDWIDE THE CANCER SURVIVORS ARE INCREASING

PHYSICS APPLIED TO MEDICINE HAS CONTRIBUTED TO CANCER CURE SINCE THE DISCOVERY OF X-RAYS AND RADIOACTIVITY

UNIVERSITÀ DEGLI STUDI DI TORINO

CINFAI SCUOLA ALTA FORMAZIONE

INFN TORINO

Thanks for your attention!

Simona Giordanengo
INFN Torino

Giornate di Studio sui Rivelatori - Scuola F. Bonaudi

February 10-14, 2020 Cogne

References

[1] www.cancer.org/content/dam/cancer-org/research/cancer-facts-and-statistics/cancer-treatment-and-survivorship-facts-and-figures/cancer-treatment-and-survivorship-facts-and-figures-2016-2017.pdf

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