

Medical application of proton accelerators

Lars Hjorth Præstegaard
Aarhus University Hospital



Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

Outline

- Production of medical radionuclides by proton cyclotrons
- Proton therapy (radiotherapy with protons):
 - Rationale for proton therapy
 - Accelerators for proton therapy
 - Treatment delivery of proton therapy
 - Challenges in proton therapy
 - The future of proton therapy



Production of medical radionuclides



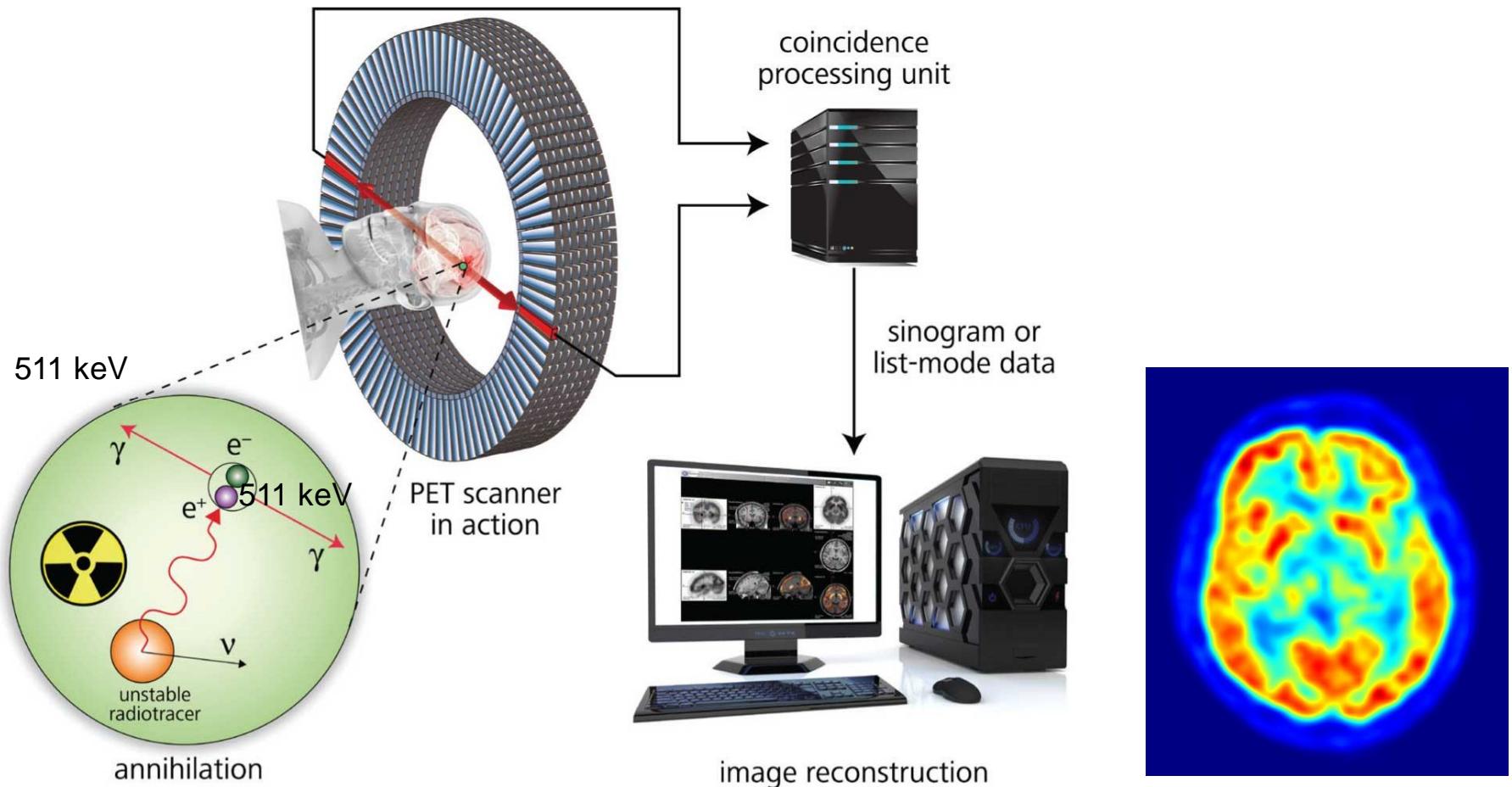
Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

Positron emission tomography (PET)

Proton cyclotron \Rightarrow Radionuclides with β^+ decay channel \Rightarrow **Positrons**

Main application: **PET scanner**

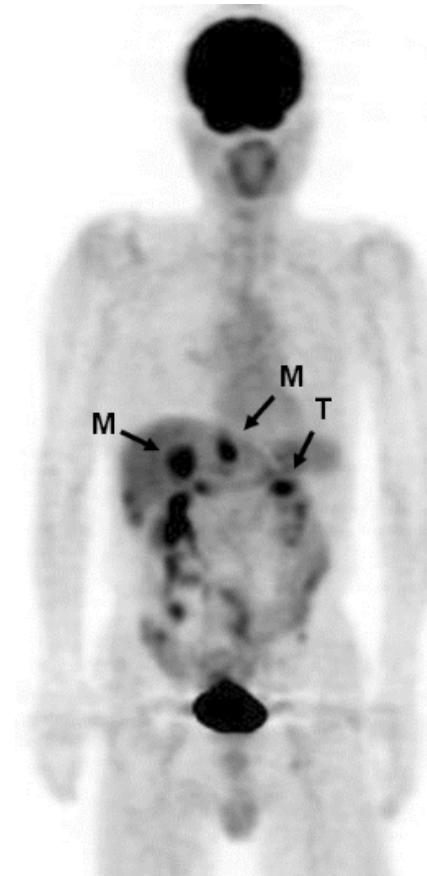


PET imaging with FDG tracer

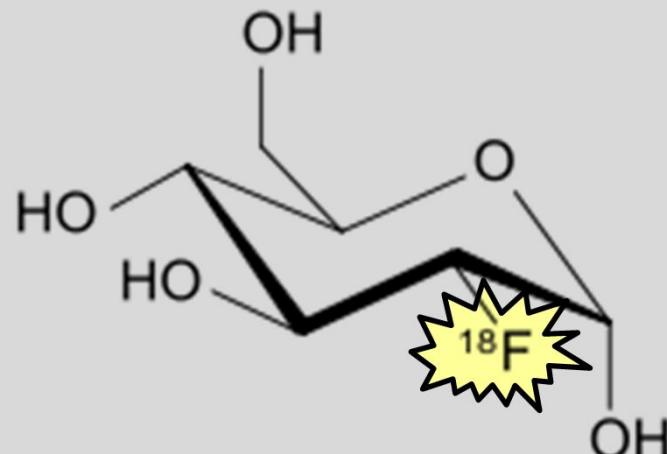
PET tracer:

- Distribution of radionuclide should be linked to a biological process
- PET tracer = Radionuclide inserted into a biological molecule

FDG-PET scan of cancer patient :



FDG tracer (similar to glucose):



Cancer tracer

T: Tumour
M: Liver metastases

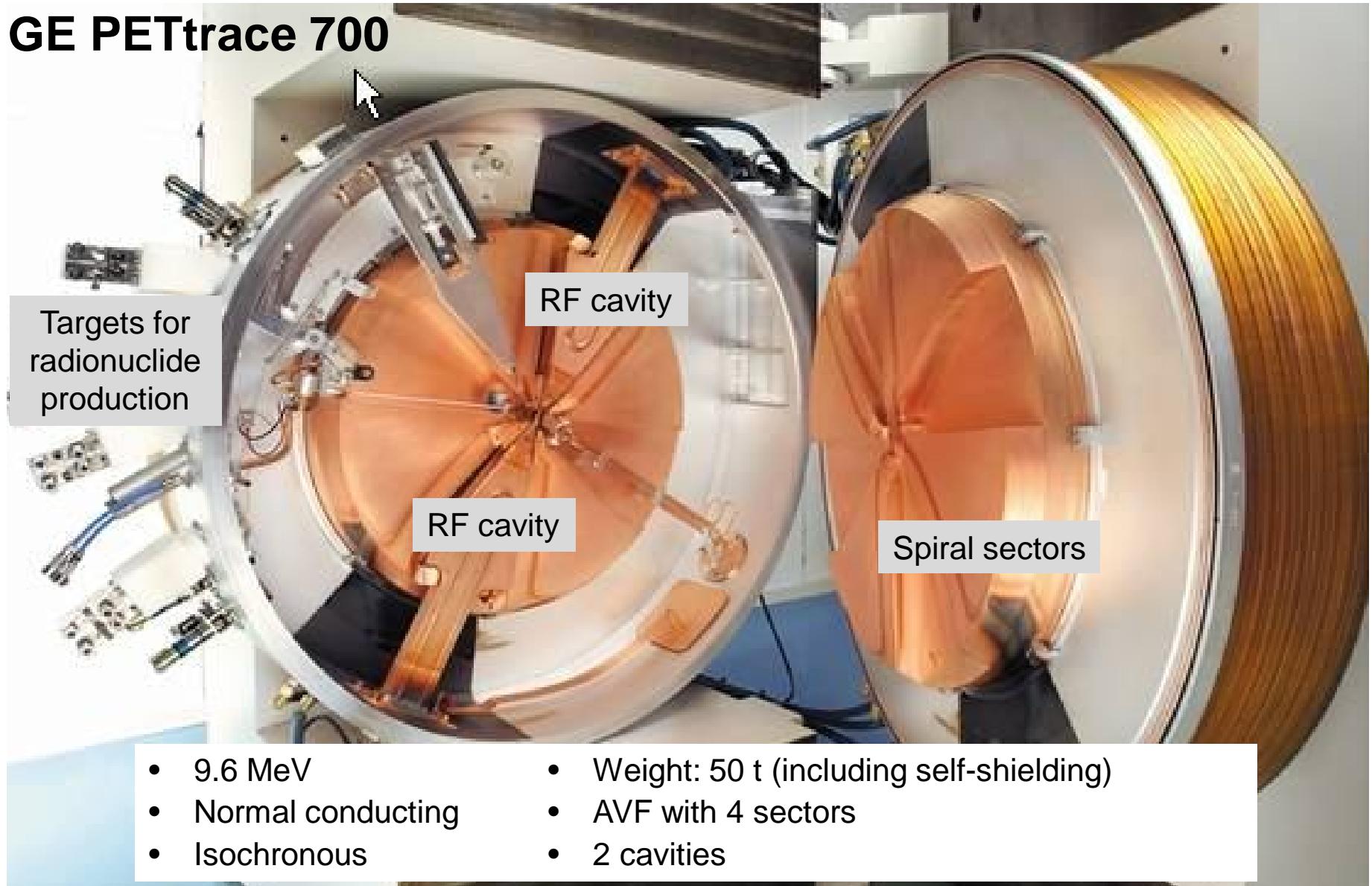


Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Compact low-energy proton cyclotron

GE PETtrace 700



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Cyclotron-produced radionuclides

Nuclide (half-life)	Production reactions	Common beam energies (MeV)	Diagnostic uses
^{11}C (20.4 m)	$^{14}\text{N}(\text{p}, \alpha)^{11}\text{C}$	14	Dopamine binding (brain) Heart metabolism Amino acid metabolism (cancer detection)
^{13}N (10.0 m)	$^{16}\text{O}(\text{p}, \alpha)^{13}\text{N}$ $^{13}\text{C}(\text{p}, \text{n})^{13}\text{N}$	20 8	Heart blood flow Protein Synthesis
^{15}O (2.0 m)	$^{14}\text{N}(\text{d}, \text{n})^{15}\text{O}$ $^{15}\text{N}(\text{p}, \text{n})^{15}\text{O}$ $^{16}\text{O}(\text{p}, \text{pn})^{15}\text{O}$	8 8 29	Brain blood flow Oxygen metabolism Blood volume
^{18}F (109.8 m)	$^{18}\text{O}(\text{p}, \text{n})^{18}\text{F}$ $^{20}\text{Ne}(\text{d}, \alpha)^{18}\text{F}$	14 14	Glucose metabolism (all tissues) Dopamine synthesis (brain)



Rationale for proton therapy

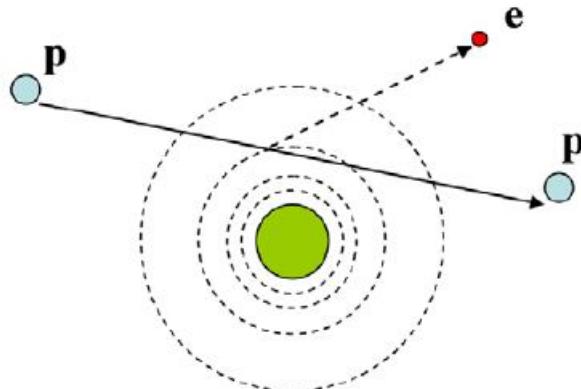


Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

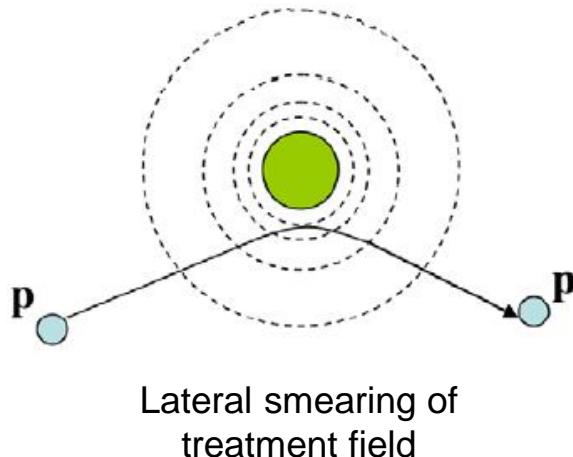
Interactions of a proton with matter

1. Inelastic Coulomb interaction with atomic electrons

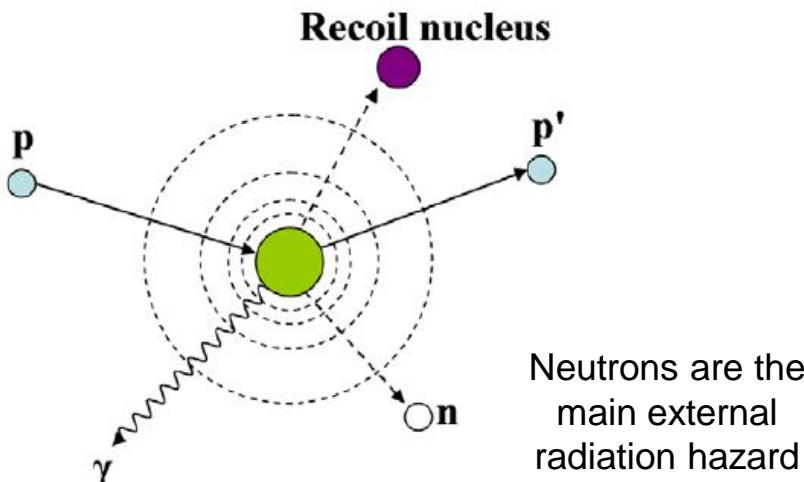


- Dominating interaction
- Ionization (=dose) \Rightarrow **Killing of cancer cells**
- Small energy loss per interaction \Rightarrow **Continuous slowing down of proton** \Rightarrow **Well-defined range**
- Range secondary electrons < 1mm \Rightarrow **Dose is absorbed locally**
- No significant deflection of protons ($m_p = 1832 \cdot m_e$)

2. Elastic coulomb scattering with nucleus



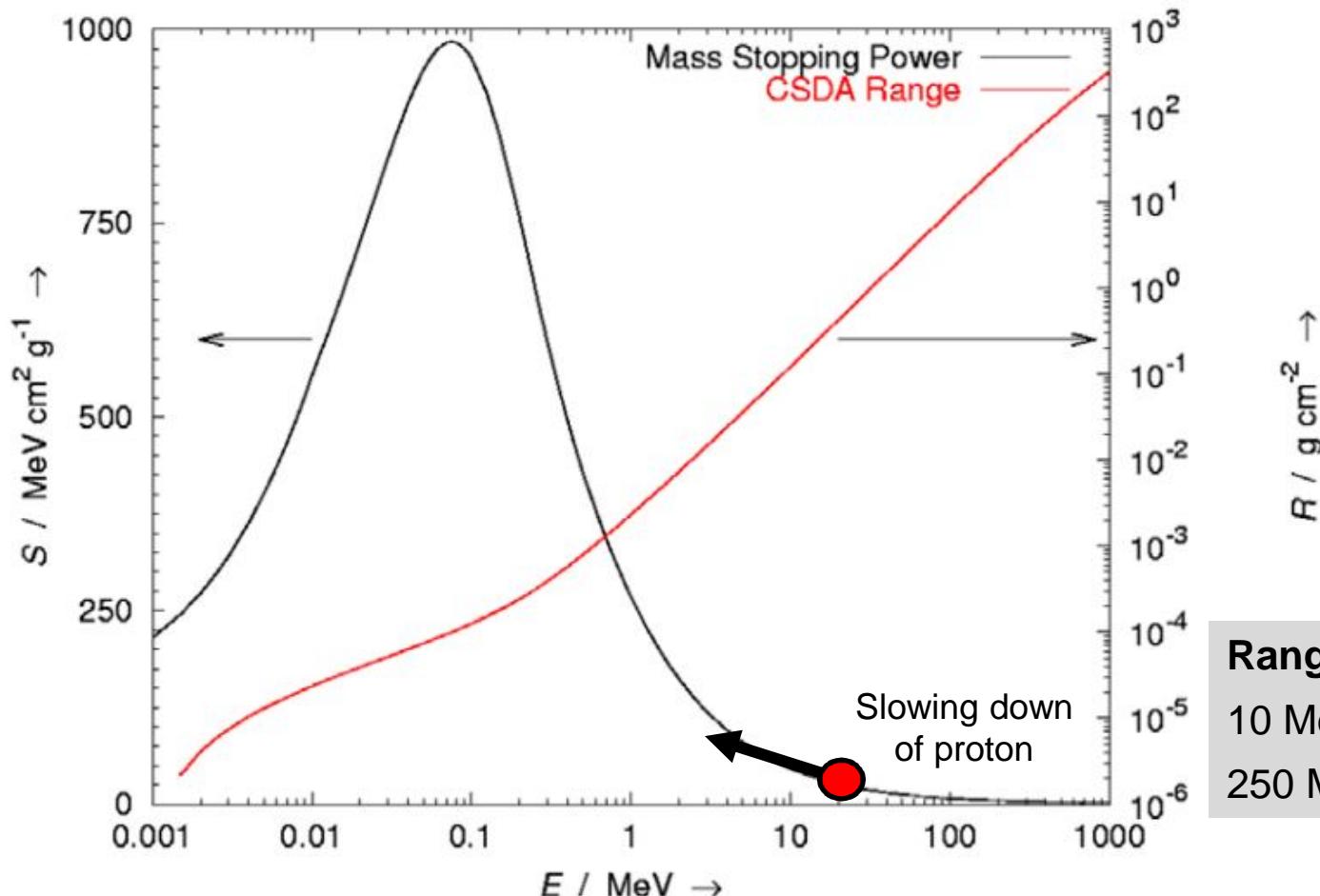
3. Non-elastic nuclear interaction



Proton stopping power

Stopping power: Energy loss per unit length

Stopping power and range of protons in water:



Range of protons in water:
10 MeV: 1.2 mm
250 MeV: 37.9 cm

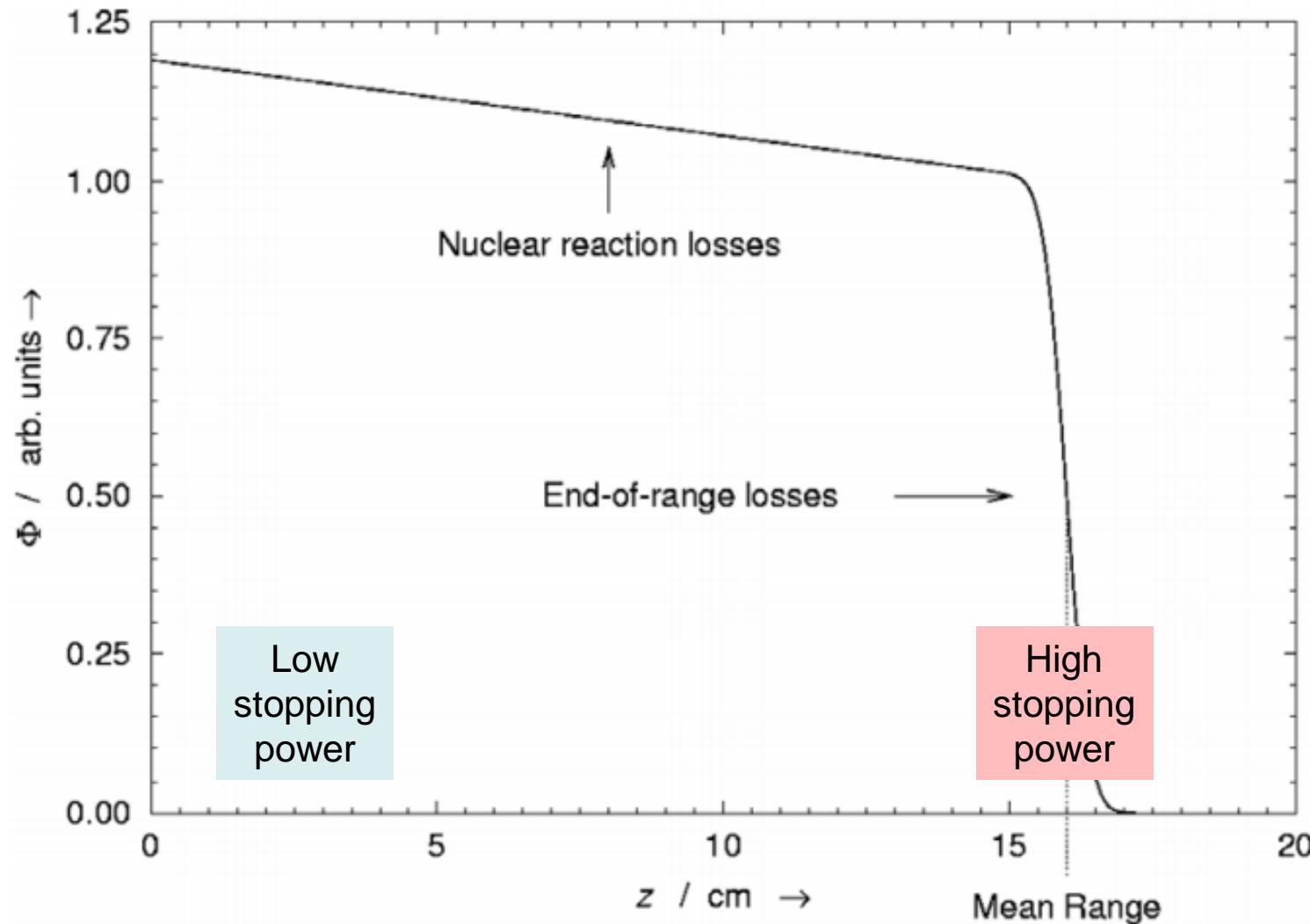


Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Proton fluence versus depth

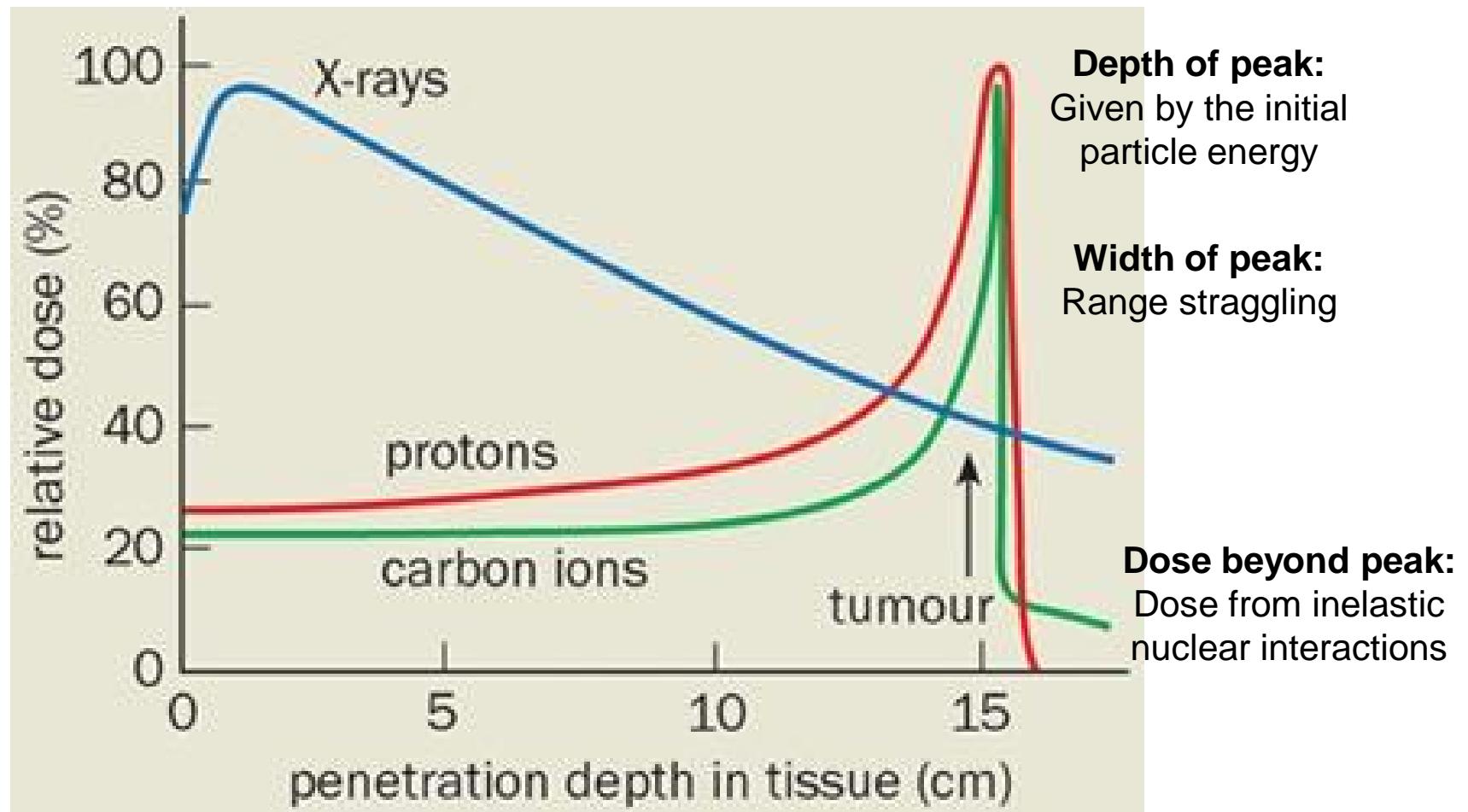
Proton fluence of 152 MeV protons:



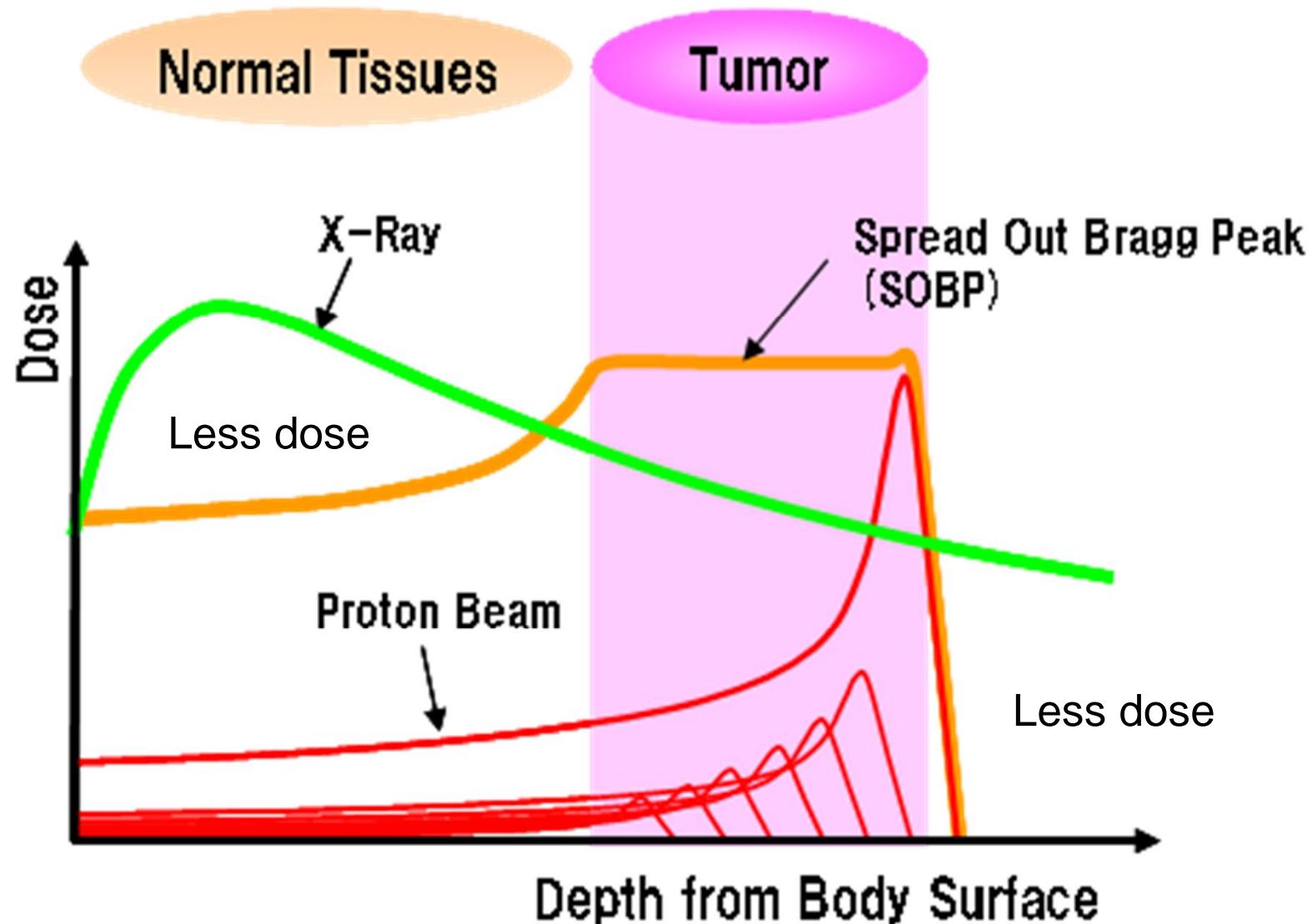
Dose versus depth: The Bragg peak

Dose deposition = proton fluence · stopping power = **Bragg peak**

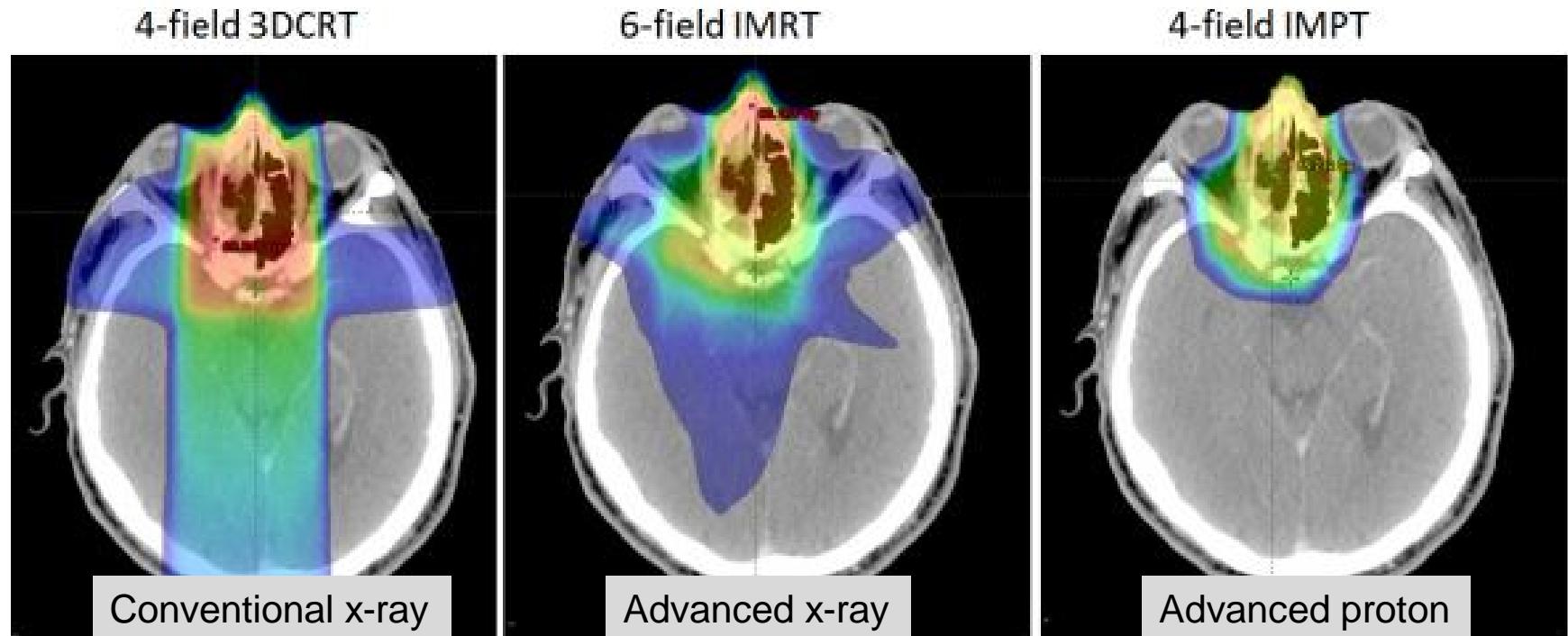
⇒ **Most dose** is deposited at the **final range** of the charged particle



Spread-out Bragg peak



Dose distribution of proton treatment



Proton therapy: Less dose to healthy tissue

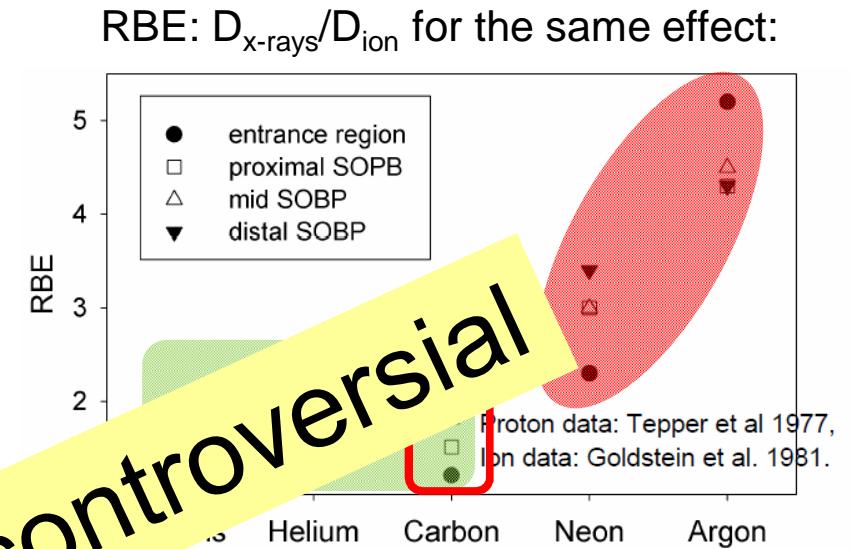
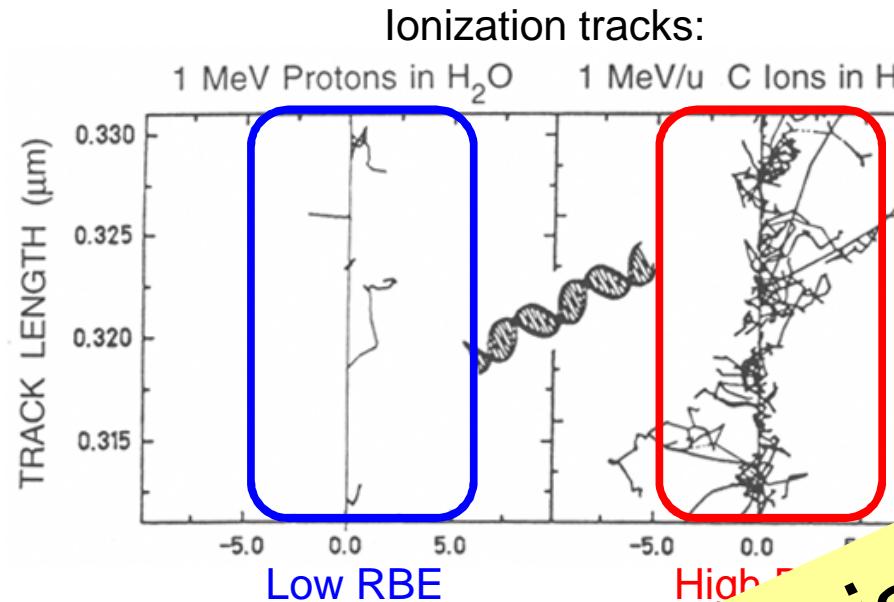


- 1. Less complications** (same dose)
- 2. Better tumor control** (higher dose, same complications)

~10 % of RT patients
can significantly
benefit from proton
therapy



Treatment with ions heavier than the proton



Main properties of ion therapy

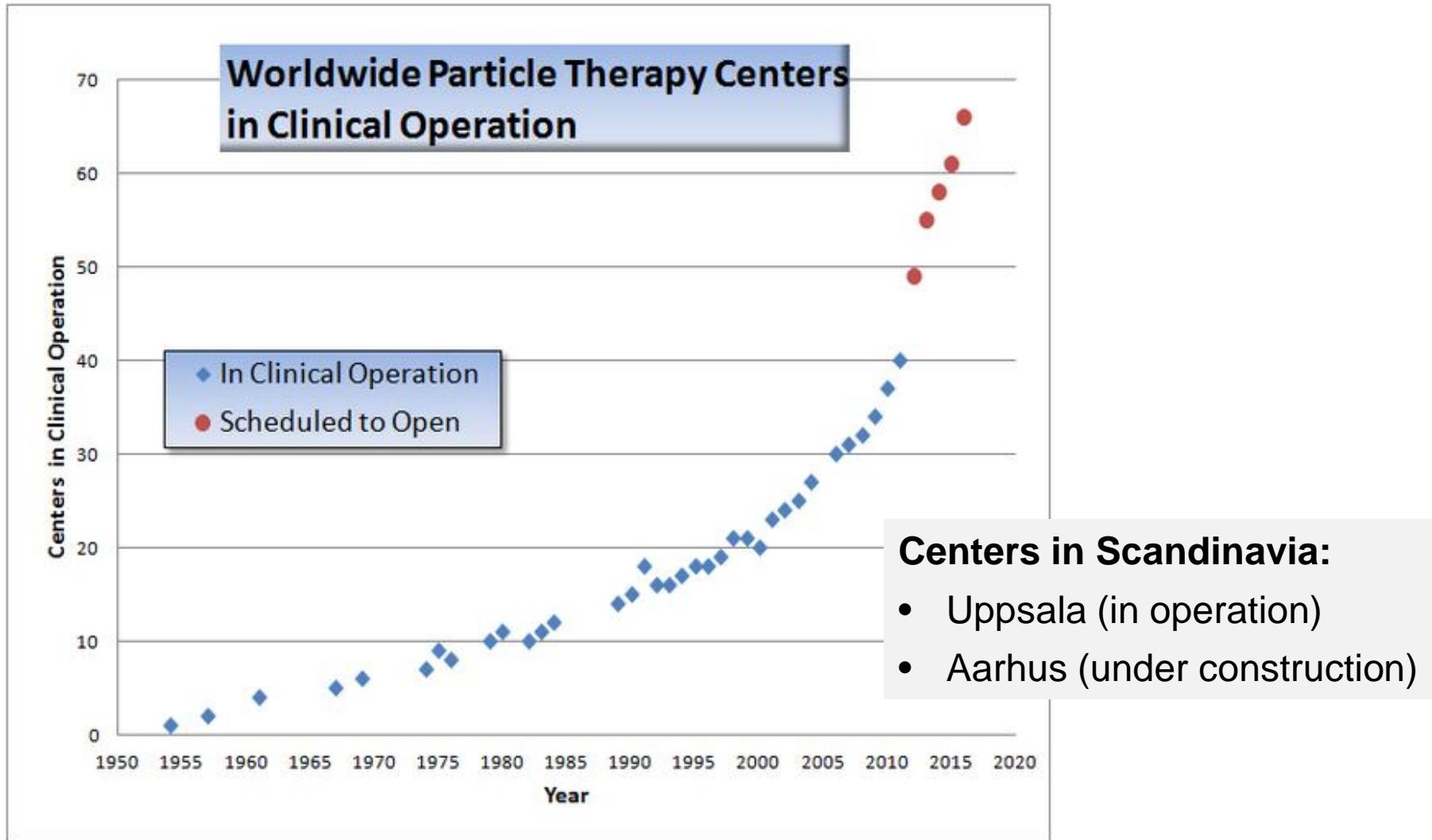
- Higher RBE \Rightarrow Less dose to healthy tissue
- Reduced Coulomb scattering \Rightarrow “Sharper” treatment field
- High RBE \Rightarrow Reduced repair benefit of healthy tissue



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Rapid increase of hadron therapy



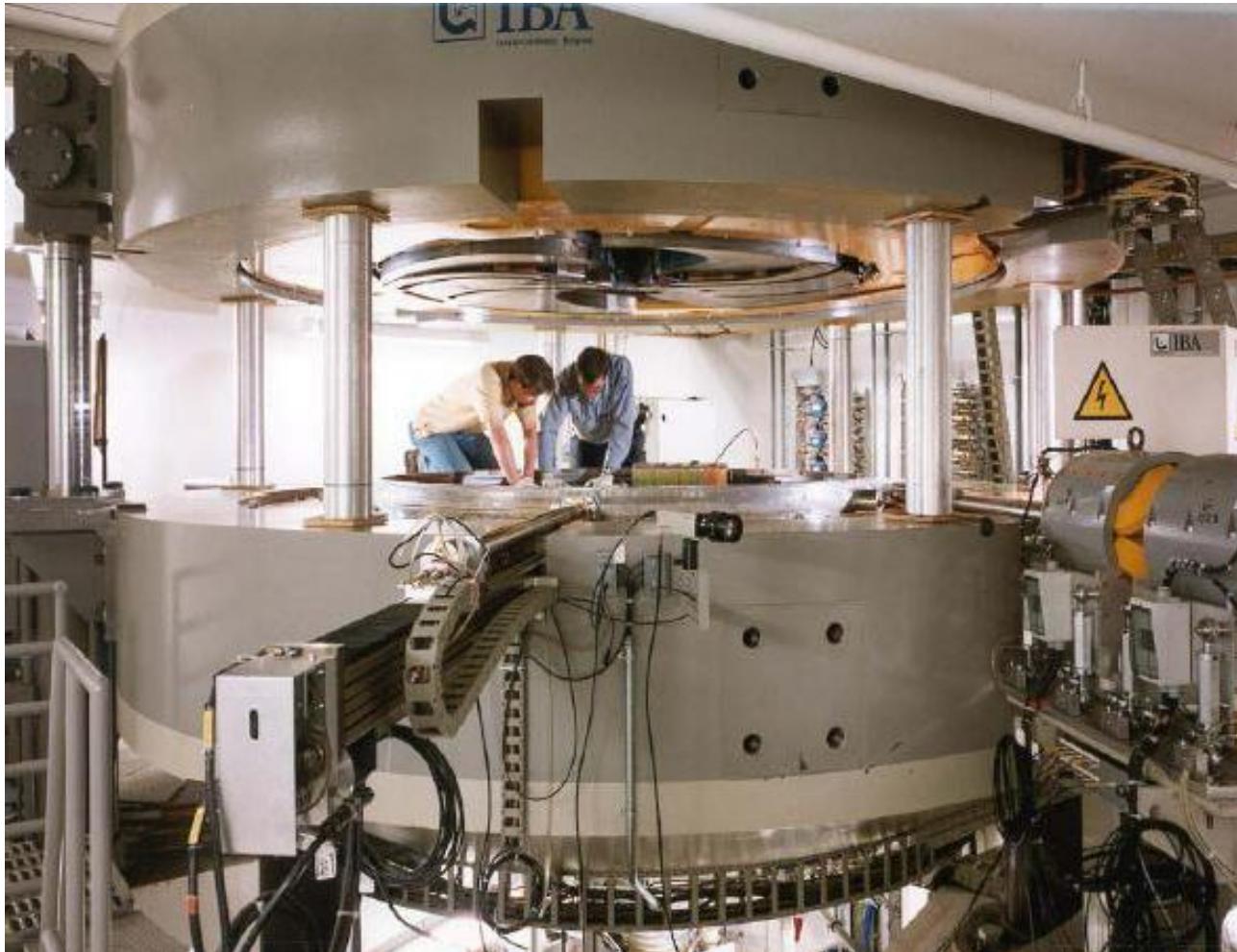
Accelerators for proton therapy



Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

IBA 230-MeV proton cyclotron



- 230 MeV (fixed)
- Normal conducting
- Isochronous
- Weight: 220 t
- Diameter: 4.3 m
- Field: 1.74-2.2 T
- AVF with 4 sectors
- 2 cavities
- 300 nA CW



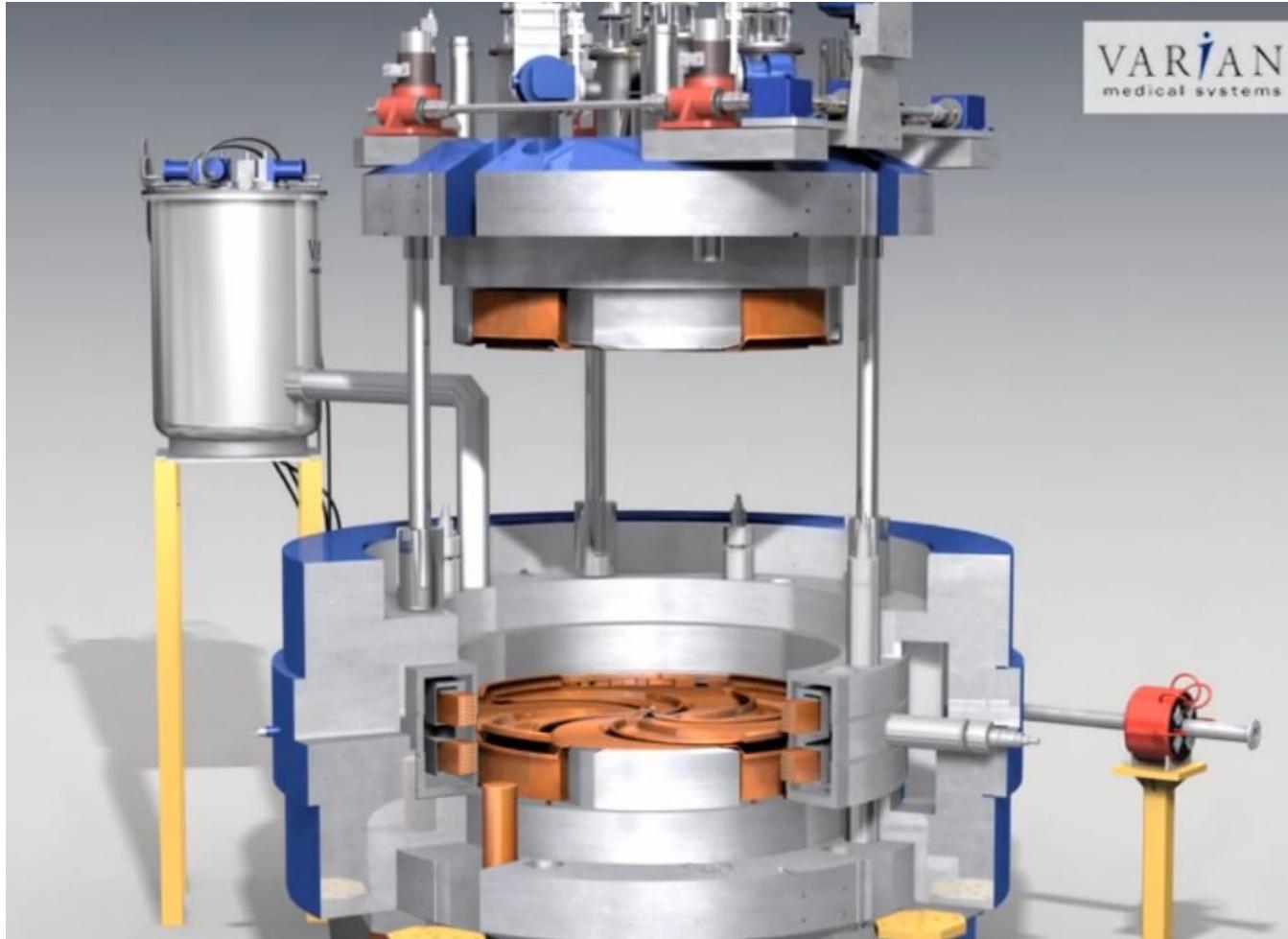
IBA proton cyclotron: Vertical focusing



Energy of the accelerated protons, MeV	235
Average magnetic field, T at the centre	1.70
at the extraction radius	2.15
Extraction radius, m	1.08
Magnetic field at the extraction radius, T in the hill	3.09
in the valley	0.98
Gap of the magnetic system, cm in the hill	9.6-0.9
in the valley	60
Number of sectors	4
Coil current x number of turns, kA	525
Power of the magnet coil, kW	190
Weight of the magnet, tons	210
Number of dees	2
Accelerating voltage, kV at the centre	55
at the extraction radius	150



Varian 230-MeV proton cyclotron



- 250 MeV (fixed)
- Superconducting
- Isochronous
- Weight: 90 t
- Diameter: 3.1 m
- Field: 2.4-4.8 T
- AVF with 4 sectors
- 4 cavities
- 800 nA CW



Mevion 250-MeV proton synchro-cyclotron



- 250 MeV (fixed)
- Superconducting
- Non-isochronous
- Weight: 20 t
- Diameter: 1.8 m
- Field: ~9 T
- Magnet pole: Cylinder symmetric
- Beam current: 30 nA (pulsed)

Very high magnetic field (>5 T)

- ⇒ Significantly reduced azimuthal field variation
- ⇒ **Insufficient ver. focusing** for isochronous acc.

Synchro-cyclotron:

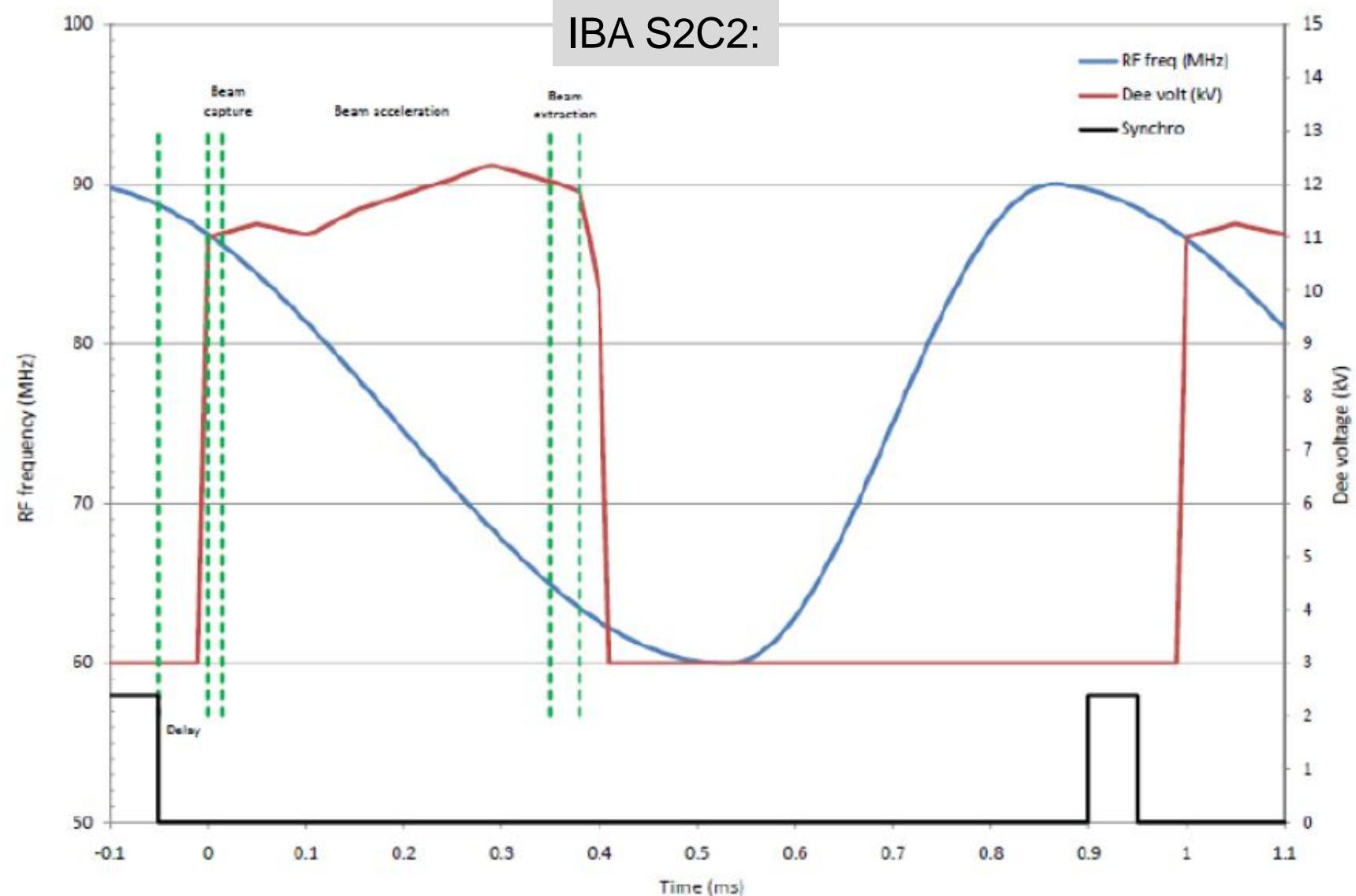
1. $B \downarrow$ versus r (vertical focusing)
 2. Relativistic ions: $m(r)$ increases versus r
- ⇒ Revolution frequency \downarrow versus radius



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Synchro-cyclotron: Acceleration cycle



Hitachi 230-MeV proton synchrotron



- 70 MeV-230 MeV
- Normal conducting
- Size: 5.1 m x 5.1 m + linac
- Beam current: ~1 nA CW



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Treatment delivery of proton therapy



Aarhus University Hospital
ÅRHUS SYGEHUS

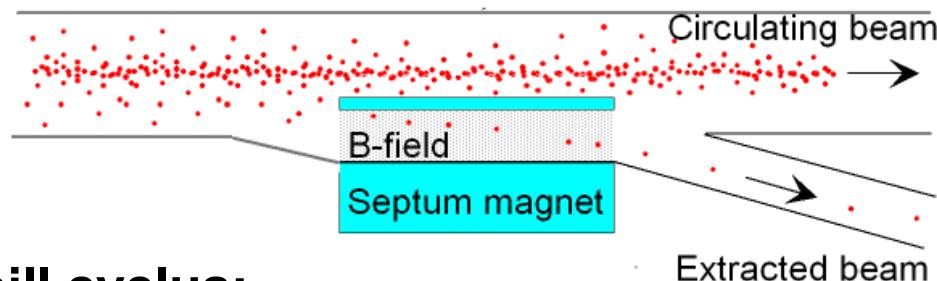
regionmidtjylland **midt**

Synchrotron: Slow extraction

Proton therapy \Rightarrow Need for CW beam

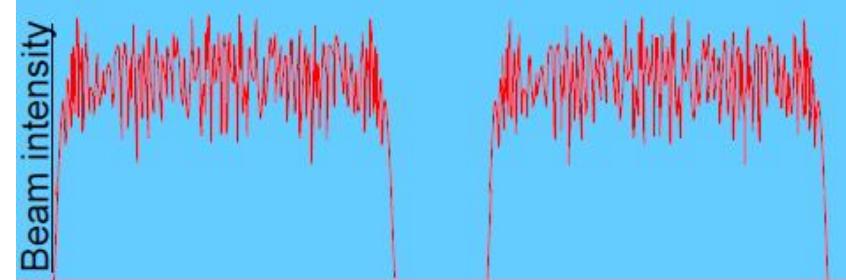
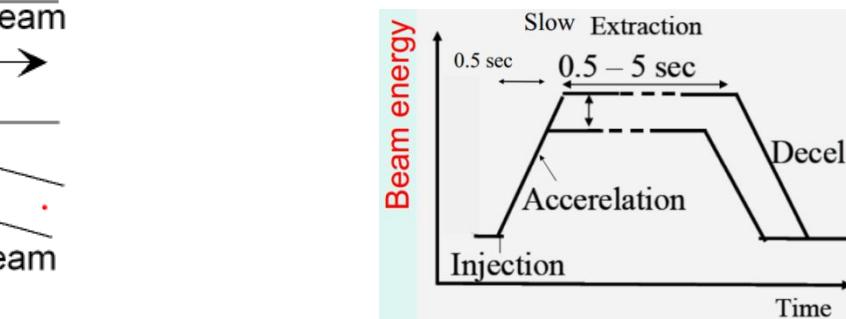
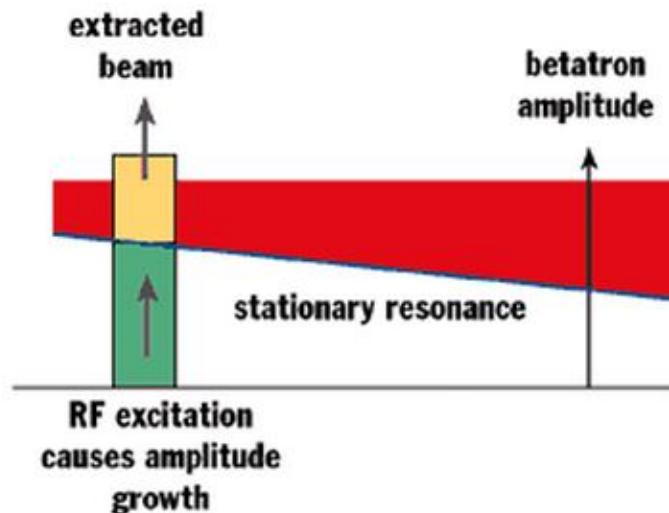
Slow extraction:

- Betatron tune close to resonance \Rightarrow Reduced area of transverse separatrix
- Transverse RF excitation of the beam
 \Rightarrow Particles excited outside separatrix
 \Rightarrow Particles spiral outside extraction septum



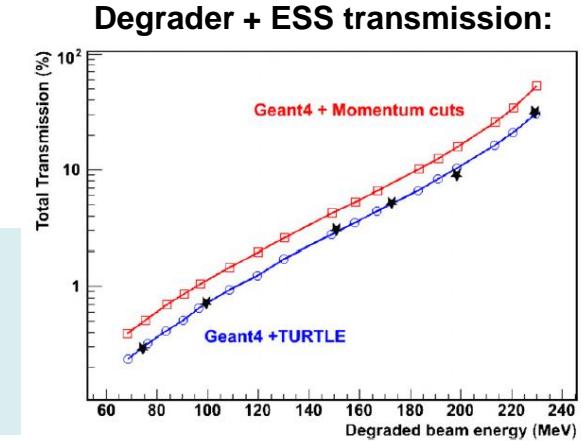
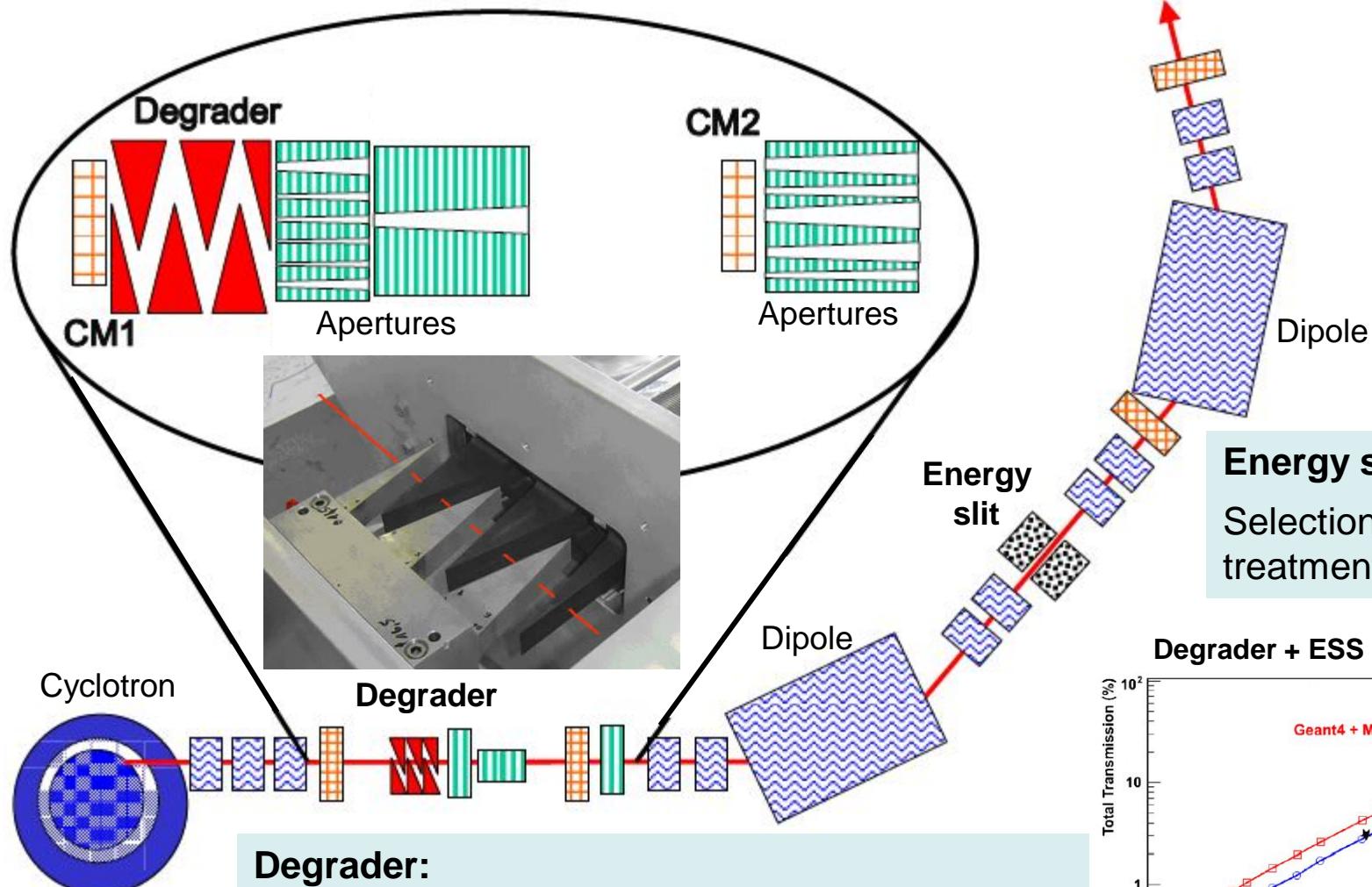
Spill cyclus:

1. Fill ring with $\sim 10^9$ protons
2. Accelerate ($\sim 0.5\text{-}1$ s)
3. Slow extraction during $1\text{-}10$ s
4. Decelerate ($\sim 0.5\text{-}1$ s)



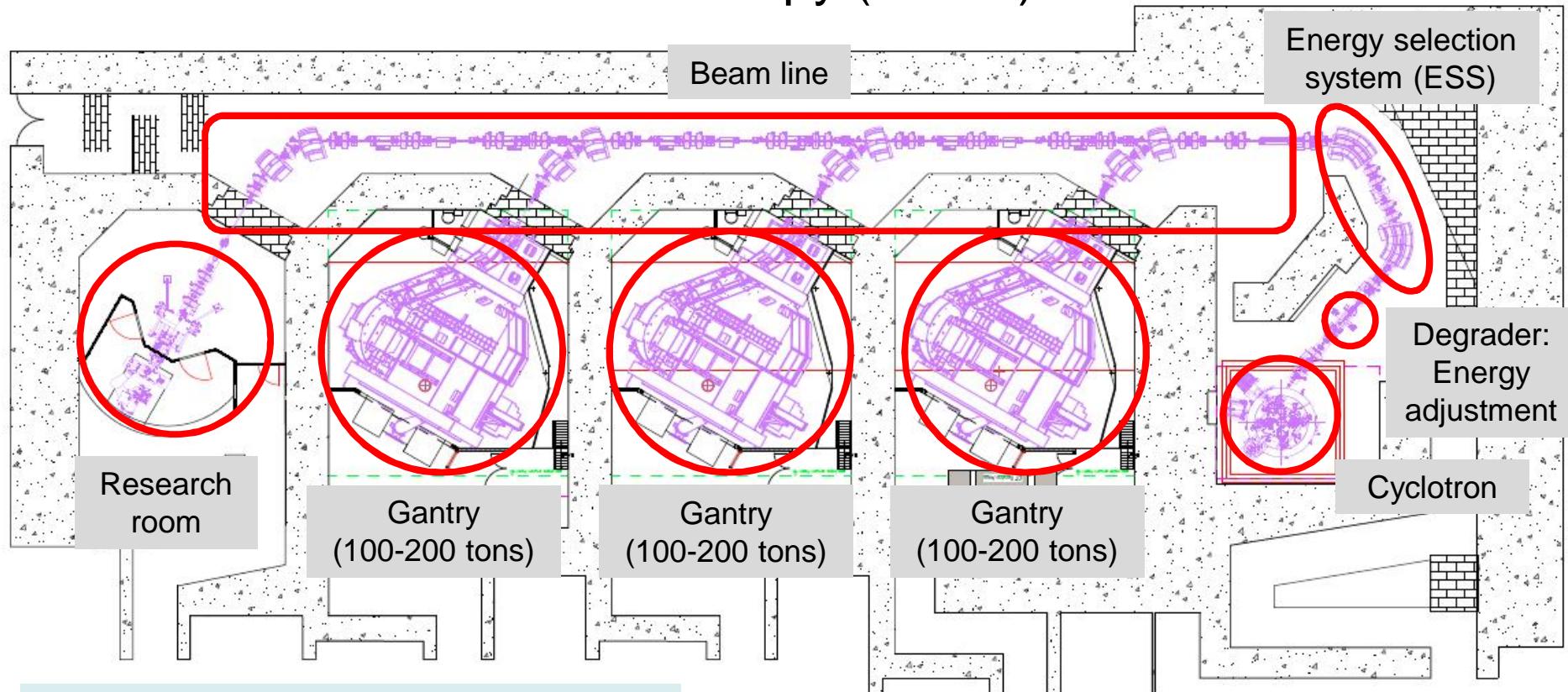
Cyclotron: Energy degradation

Courtesy by PSI



Multi-room proton therapy facility

Danish Center for Proton Therapy (DCPT):



Time line:

- March 2015: Equipment contract
- July 2017: Installation of equipment
- October 2018: First patient

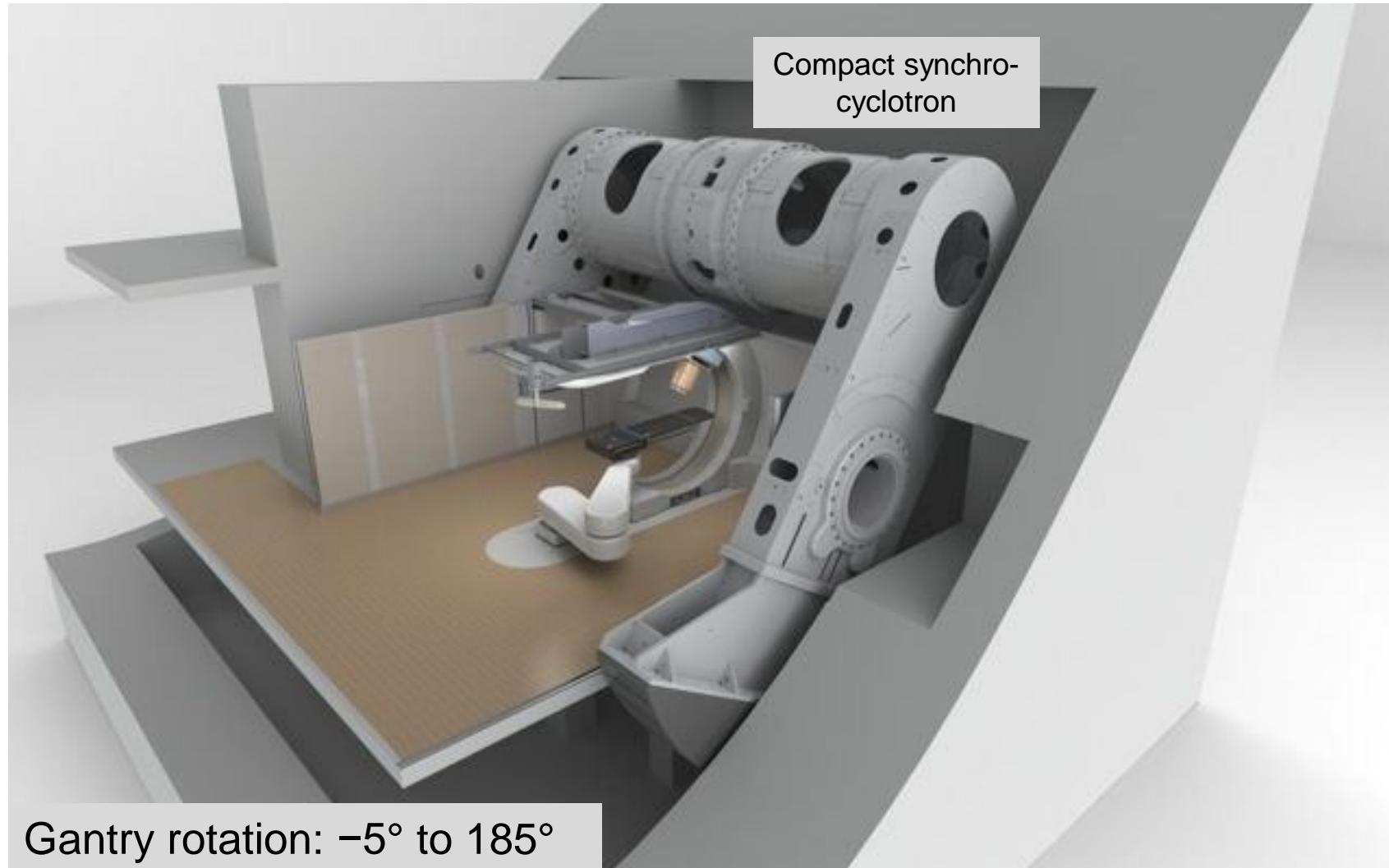


Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Single-room proton therapy facility

Mevion single-room solution:



Aarhus University Hospital, Århus Sygehus

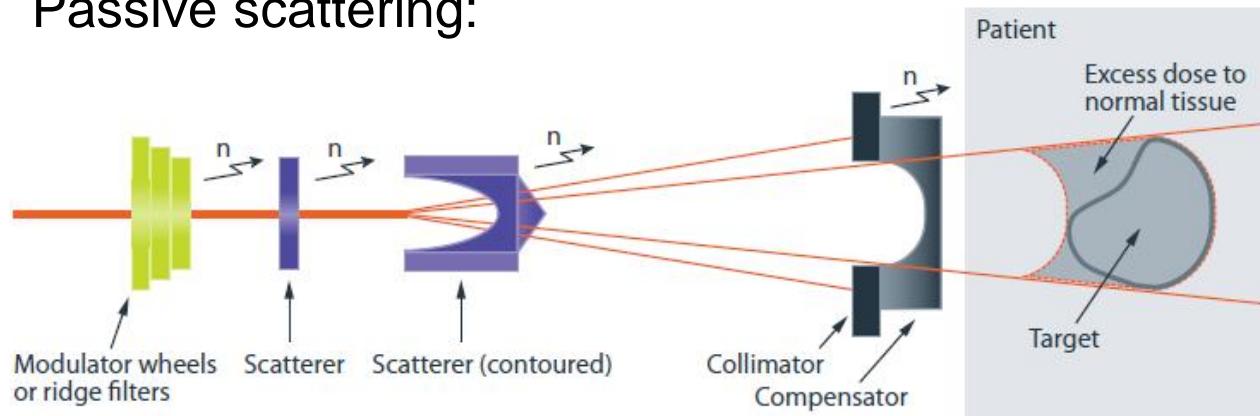
regionmidtjylland **midt**

Dose deposition in the patient

Dose distribution of raw pencil beam:

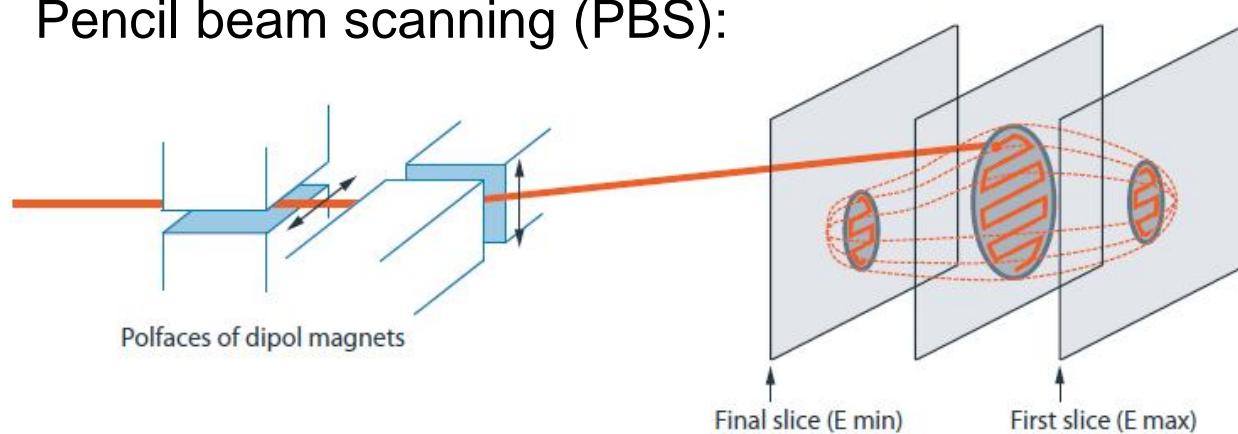


Passive scattering:



- Simple
- Straight forward treatment of moving organs
- Excess dose to normal tissue
- Significant neutron dose
- Patient-specific collimators and compensators

Pencil beam scanning (PBS):



- No requirement of patient-specific collimators and compensators
- Interplay effect for moving organs



Gantry

Varian gantry in Munich



Proton gantry:

Weight: 100-200 t

Diameter: ~10 m

Speed: 360°/min

Treatment center accuracy: < 1 mm

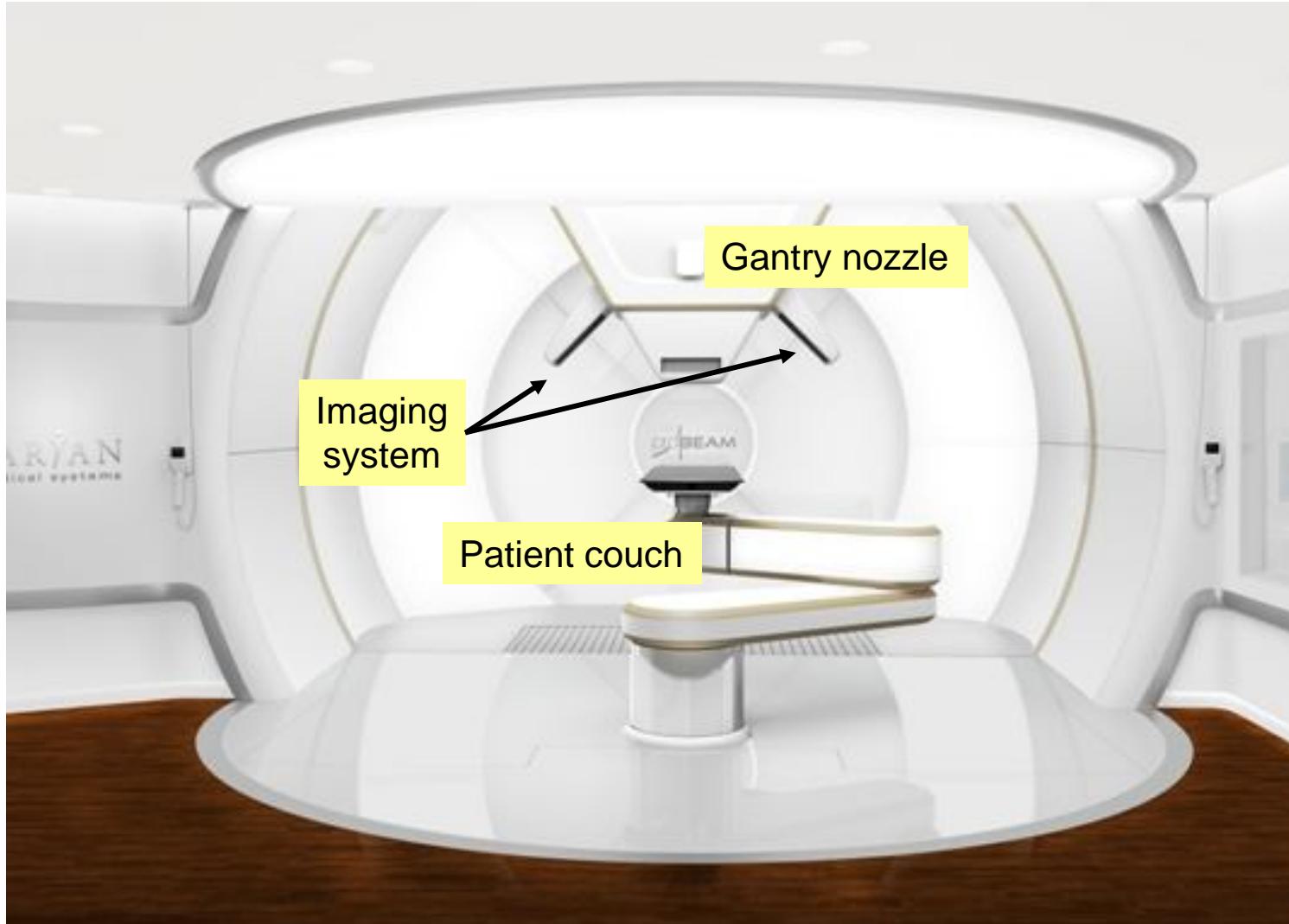


Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Treatment room

Varian ProBeam:



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Proton therapy vender videos

IBA proton therapy

<https://www.youtube.com/watch?v=MS590Xtq9M4>

Varian proton therapy

<https://www.youtube.com/watch?v=LGVRIMWr-8c>

Mevion proton therapy

<https://www.youtube.com/watch?v=NU2kua1o6i8>



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**

Challenges in proton therapy

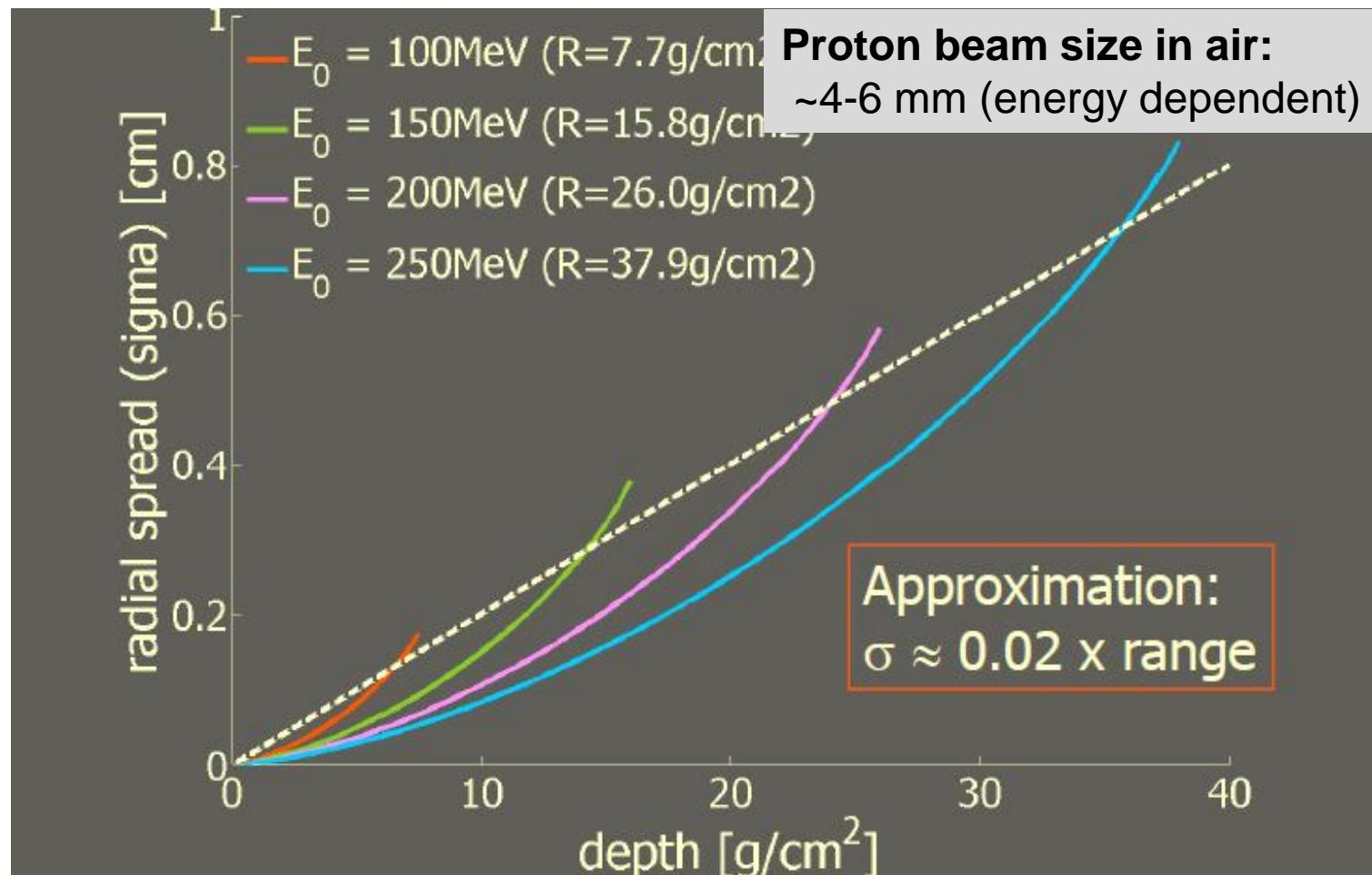


Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

Lateral proton scattering in the patient

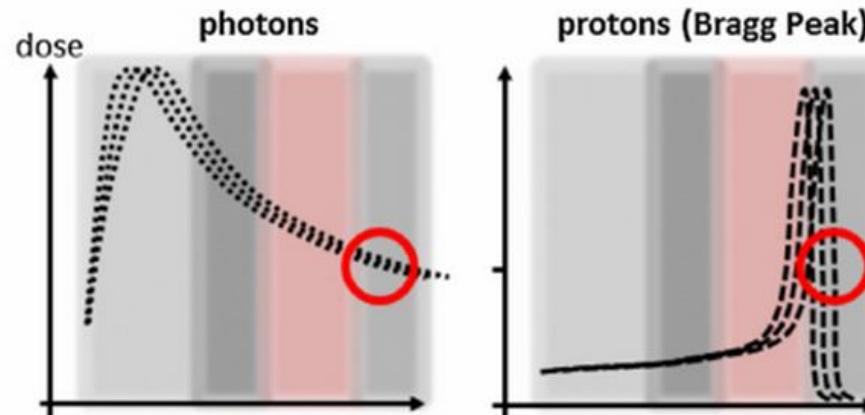
Lateral scattering of protons in water:



- ⇒ Significant increase of beam size due to scattering in water
- ⇒ Larger field penumbra than for x-ray treatment at large depths

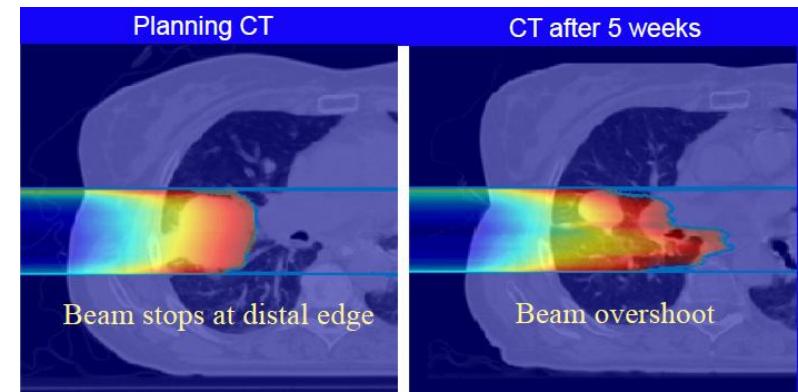


High sensitivity range uncertainties



Causes of range uncertainty:

- CT number to stopping power conversion (200 mm depth: uncertainty of ~6 mm)
- Tumor shrinkage
- Organ motion during treatment (respiration, rectum gas, bladder filling etc.)



Consequence: Large treatment margin required :=(



The future of proton therapy

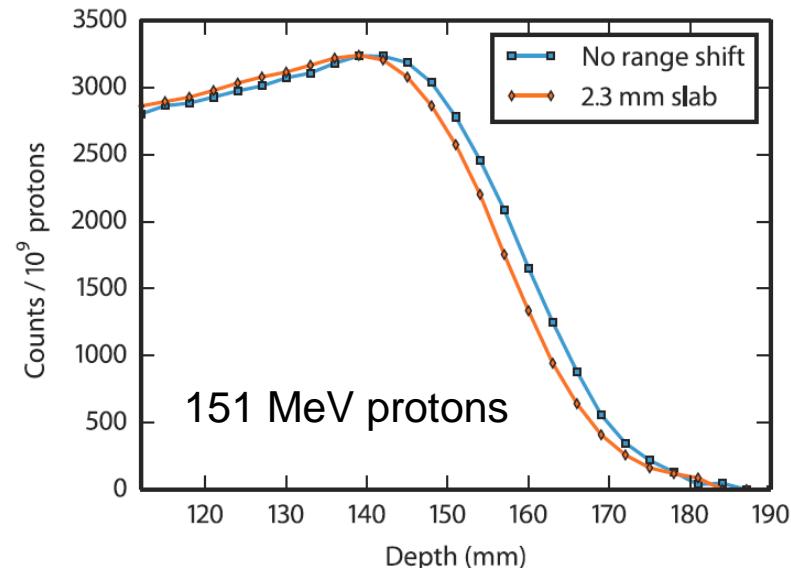
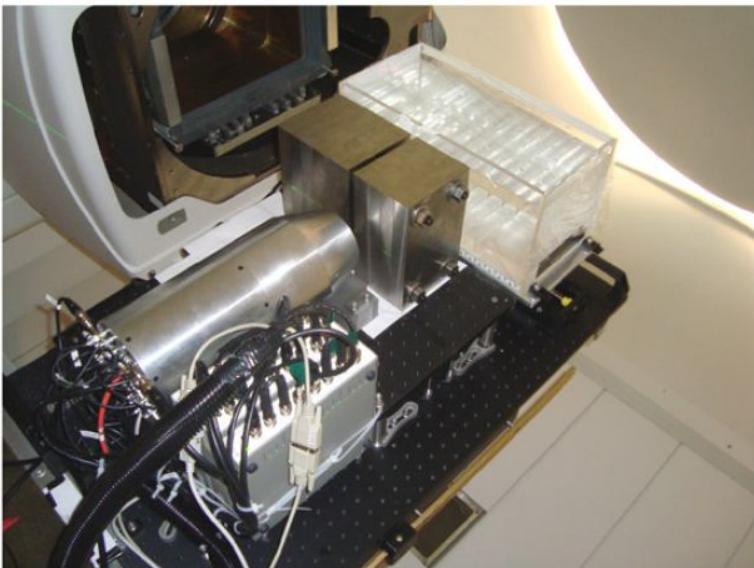


Aarhus University Hospital
ÅRHUS SYGEHUS

regionmidtjylland **midt**

Range verification

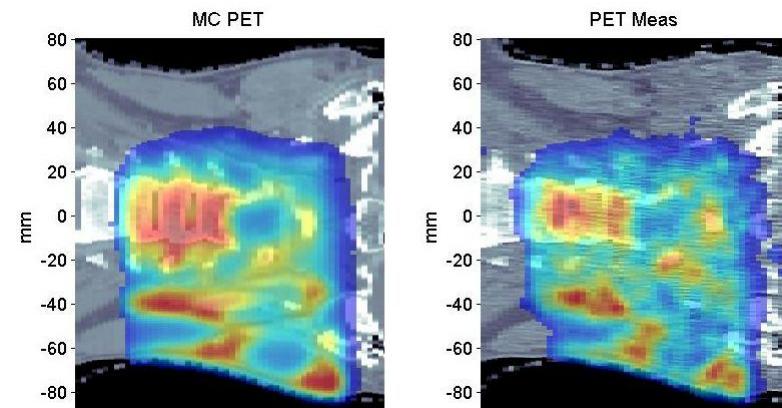
Prompt gamma:



PET:

Radionuclide	Half live (min)	Nuclear reaction channels
^{15}O	2.037	$^{16}\text{O}(\text{p},\text{pn})^{15}\text{O}$ /16.79
^{11}C	20.385	$^{12}\text{C}(\text{p},\text{pn})^{11}\text{C}$ /20.61, $^{14}\text{N}(\text{p},2\text{p}2\text{n})^{11}\text{C}$ /3.22,
^{13}N	9.965	$^{16}\text{O}(\text{p},3\text{p}3\text{n})^{11}\text{C}$ /59.64 $^{16}\text{O}(\text{p},2\text{p}2\text{n})^{13}\text{N}$ /5.66,
^{30}P	2.498	$^{31}\text{P}(\text{p},\text{pn})^{30}\text{P}$ /19.7
^{38}K	7.636	$^{40}\text{Ca}(\text{p},2\text{p}2\text{n})^{38}\text{K}$ /21.2

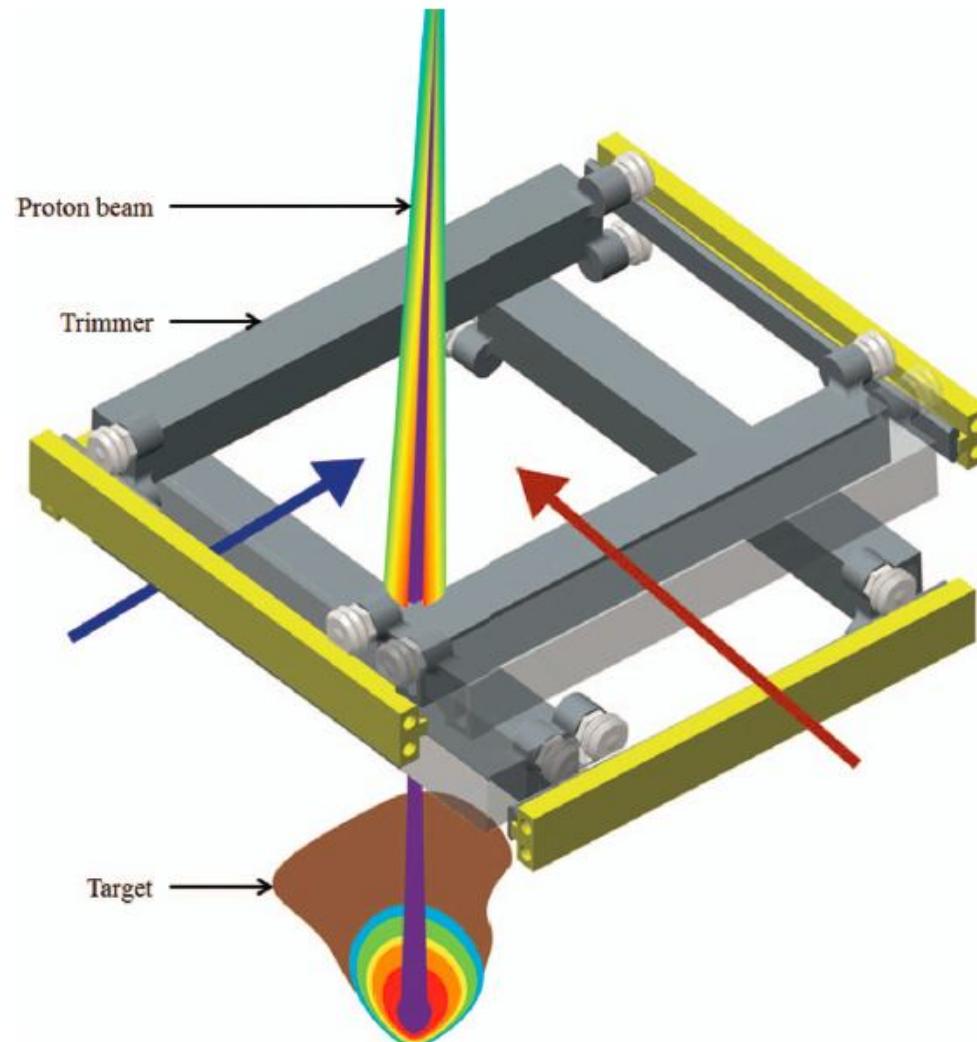
Challenge of PET radionuclide washout:



Aarhus University Hospital, Århus Sygehus

regionmidtjylland midt

Dynamic sharpening of field penumbra



⇒ Smaller in-air penumbra

Med. Phys. 41 (9), September 2014



Aarhus University Hospital, Århus Sygehus

regionmidtjylland **midt**