Sebastian Klüter
Heidelberg University Hospital, Germany

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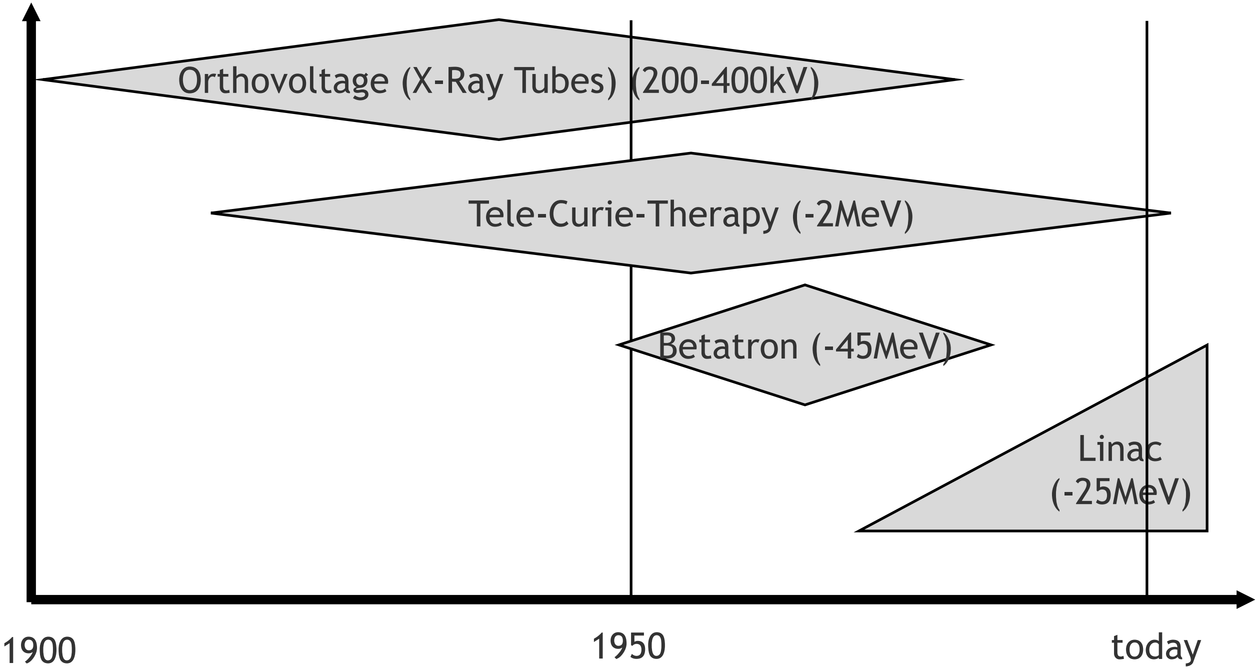
Treatment machines for photon radiotherapy

HIRO
Heidelberg Institute for Radiation Oncology
National Center for Radiation Research in Oncology Heidelberg
supported by:
German Cancer Research Center (DKFZ)
Heidelberg University Hospital
Heidelberg Ion-Beam Therapy Center (HIT)
Medical Faculty Heidelberg

DKTK German Cancer Consortium

Timeline: machines used for photon radiotherapy



X-Rays: used therapeutically very soon after discovery

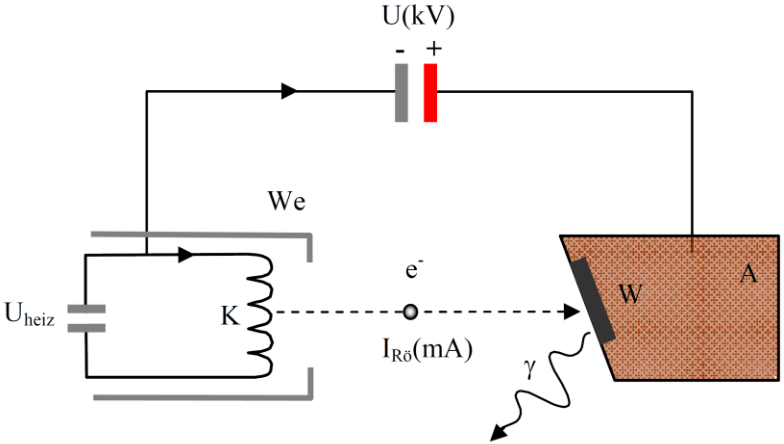
Leopold Freund, Vienna 1896

Treatment of a hairy naevus of a five-year old girl with fractionated X-ray therapy over two weeks

Before therapy

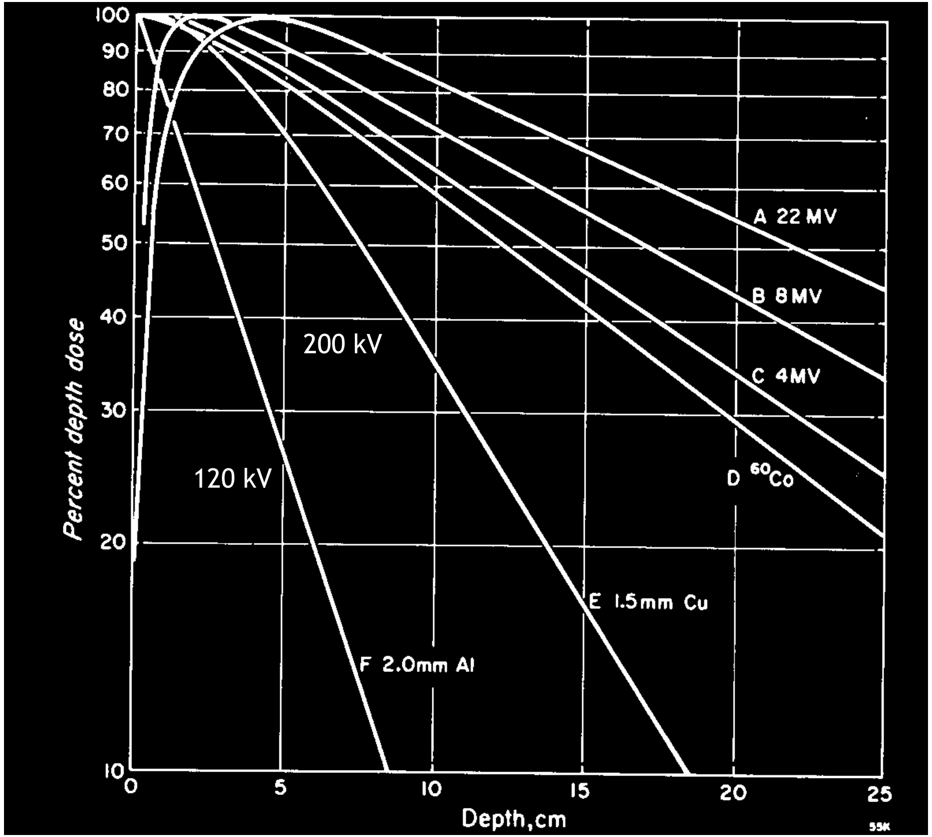
60 years later

X-Ray tube:

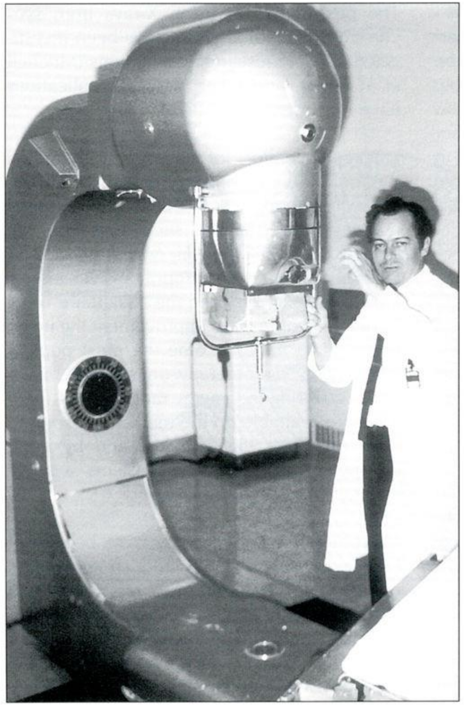


Source: Medizinische Universität Wien

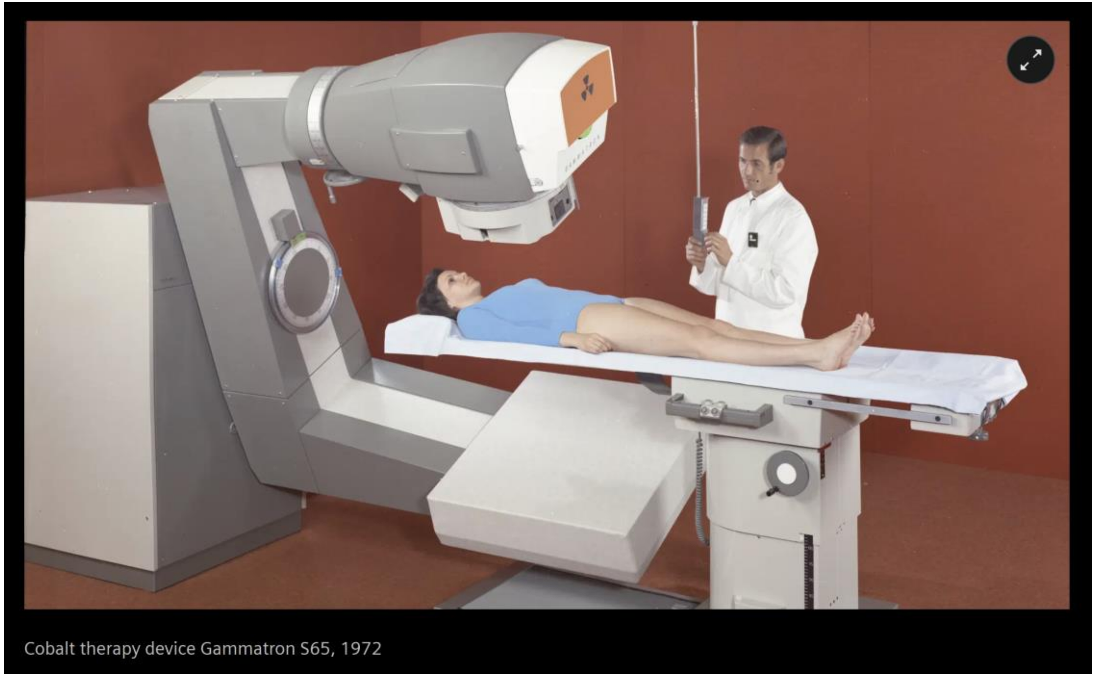
But: High photon energy is needed for RT of deep tumors



External beam therapy with ^{60}Co



Cobalt-60 Teletherapy machine
(around 1950)



www.medmuseum.siemens-healthineers.com

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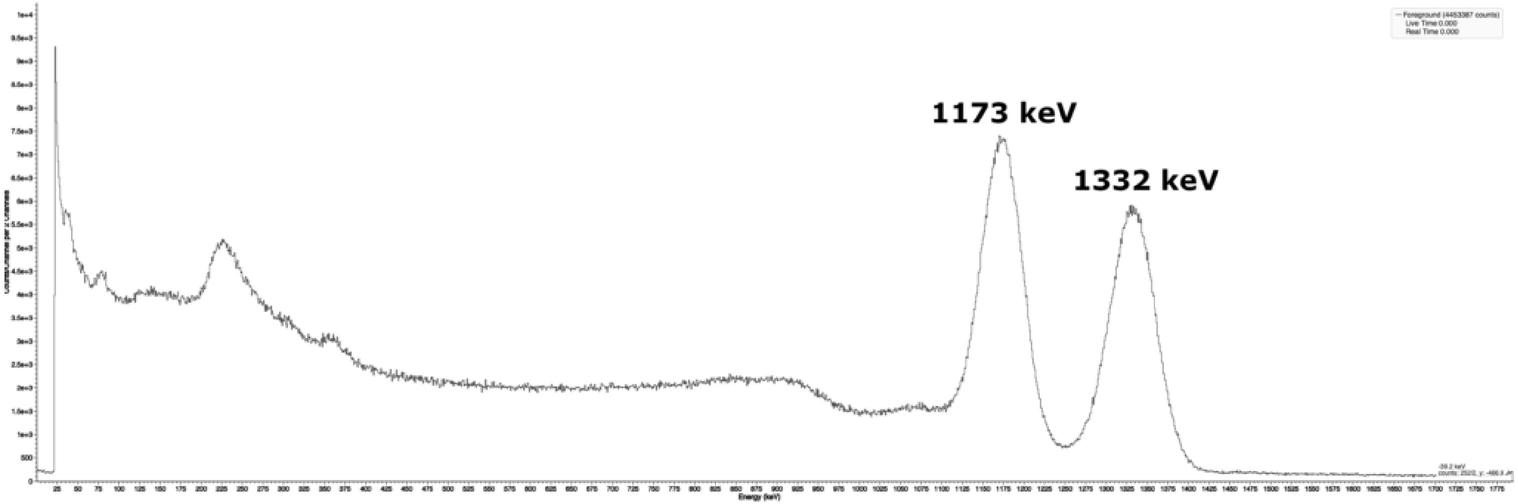
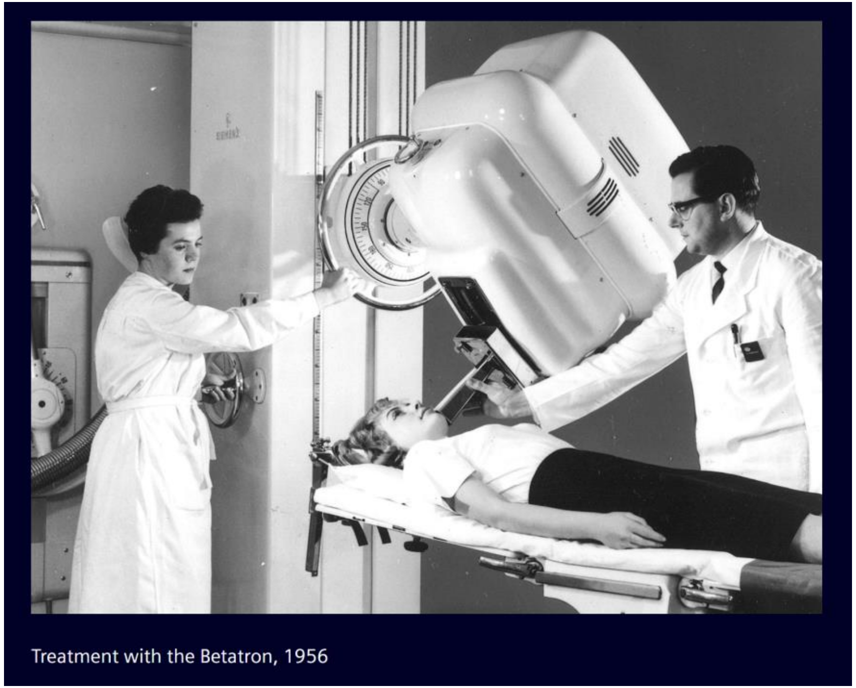
Energy spectrum of ^{60}Cobalt



https://allradioactive.com/cobalt-60/

Also: radioactive material (storage, disposition, accidents)

Betatron: photon energies up to 45 MeV

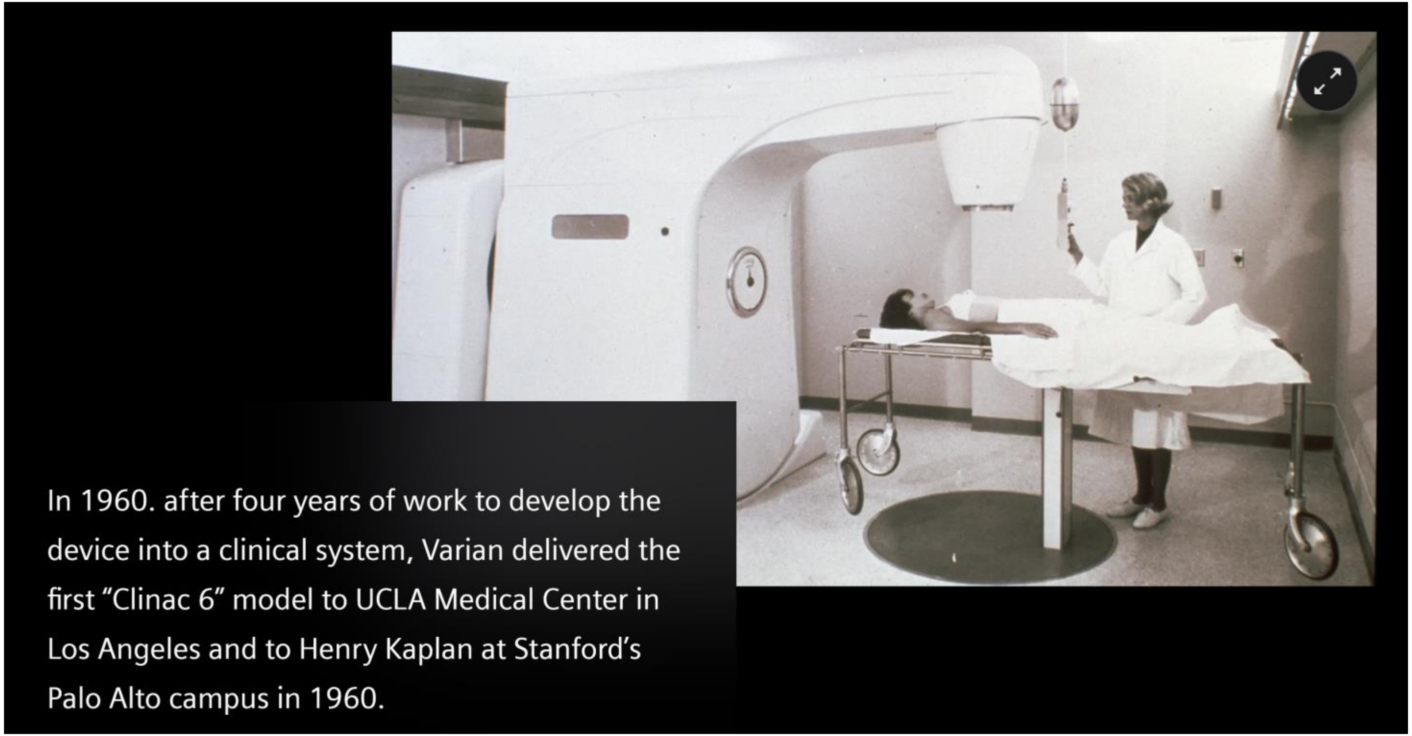


Treatment with the Betatron, 1956

https://www.siemens.com › history › medical-technology

https://en.wikipedia.org/wiki/Betatron
Photograph by Suzie Sheehy, CC BY-SA 4.0

Fist medical linacs



www.medmuseum.siemens-healthineers.com

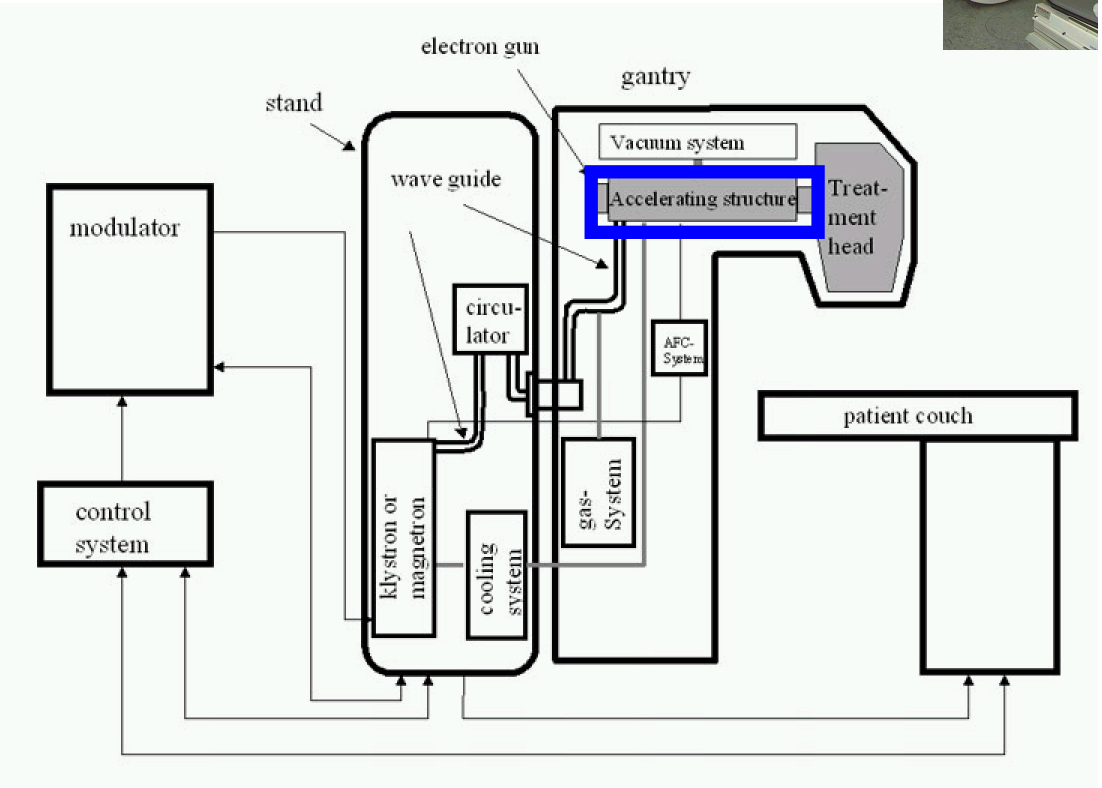
Modern Linear Accelerators

“C-Arm” Linac

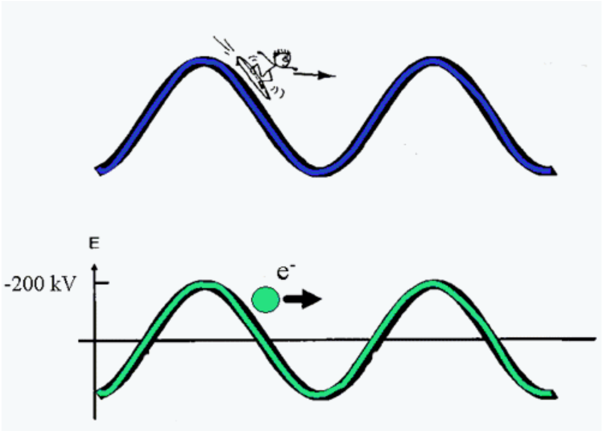
Can operate in electron and photon mode

Energy: around 6-21 MeV

Modern Linear Accelerators



Electrons are accelerated by an electromagnetic wave



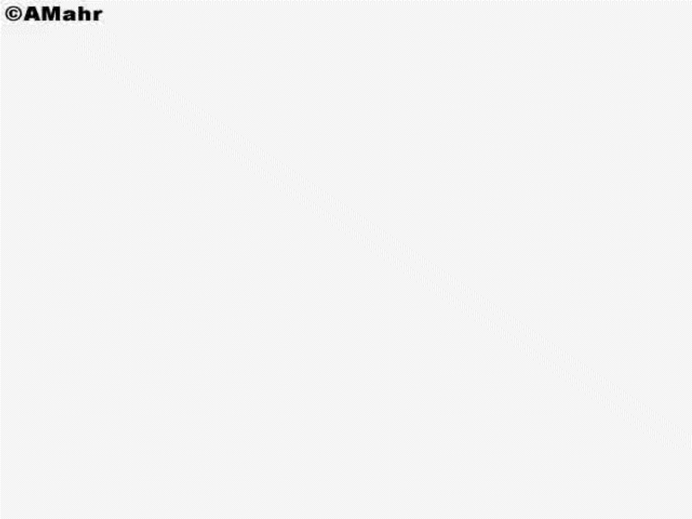
Medical photon Linacs usually operate in the S-Band

f = 3 GHz ←→ λ = 10 cm

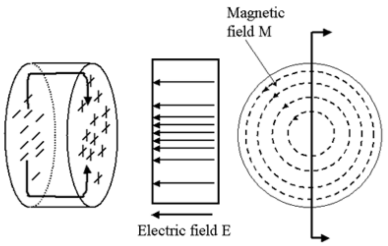
Acceleration tube

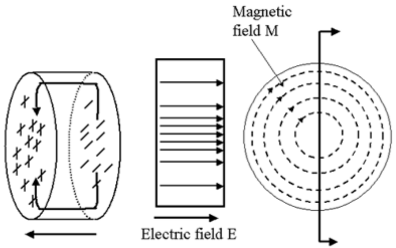
Electrons are accelerated in cavity resonators

Acceleration tube = connection of a lot of those cavities



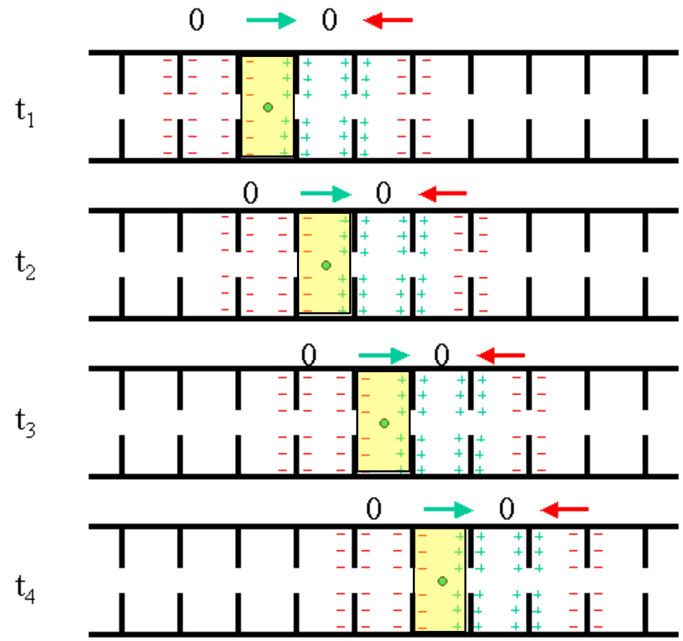
In resonance, the charge distribution in the tube changes with the frequency of the RF wave

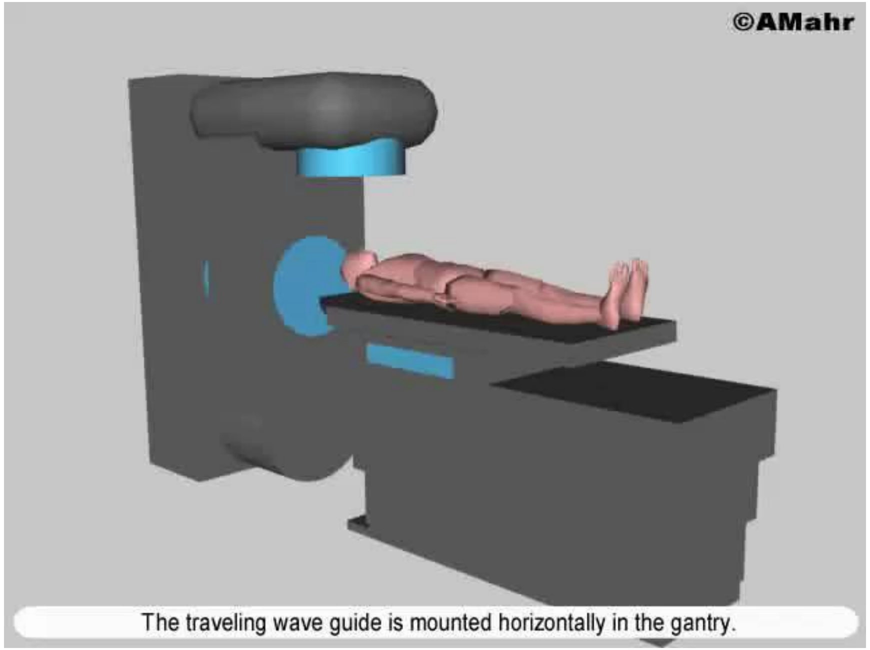




Schlegel und Mahr 2007, 3D Conformal Radiation Therapy, Springer Verlag

Travelling wave linear accelerator



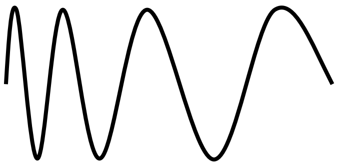


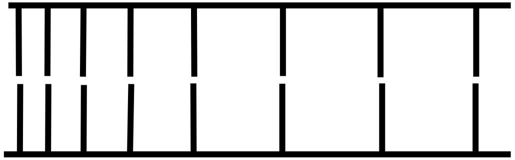
Schlegel und Mahr 2007, 3D Conformal Radiation Therapy, Springer Verlag

Travelling wave linear accelerator

Electrons must always be in phase with the accelerating wave

→ Design of the tube needs to be adjusted to the speed of the electrons





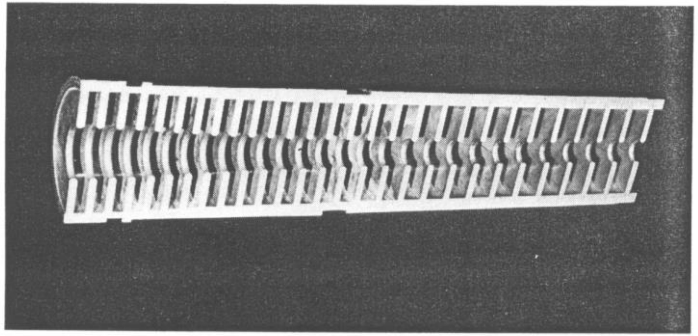
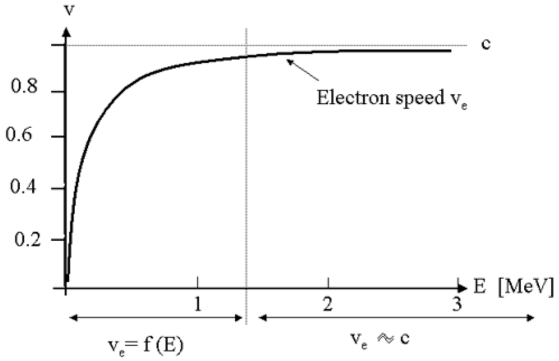


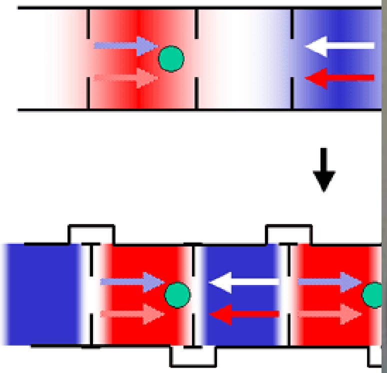
FIG. 2. Cutaway traveling wave accelerator structure; the buncher section is on the left and the uniform section is on the right.

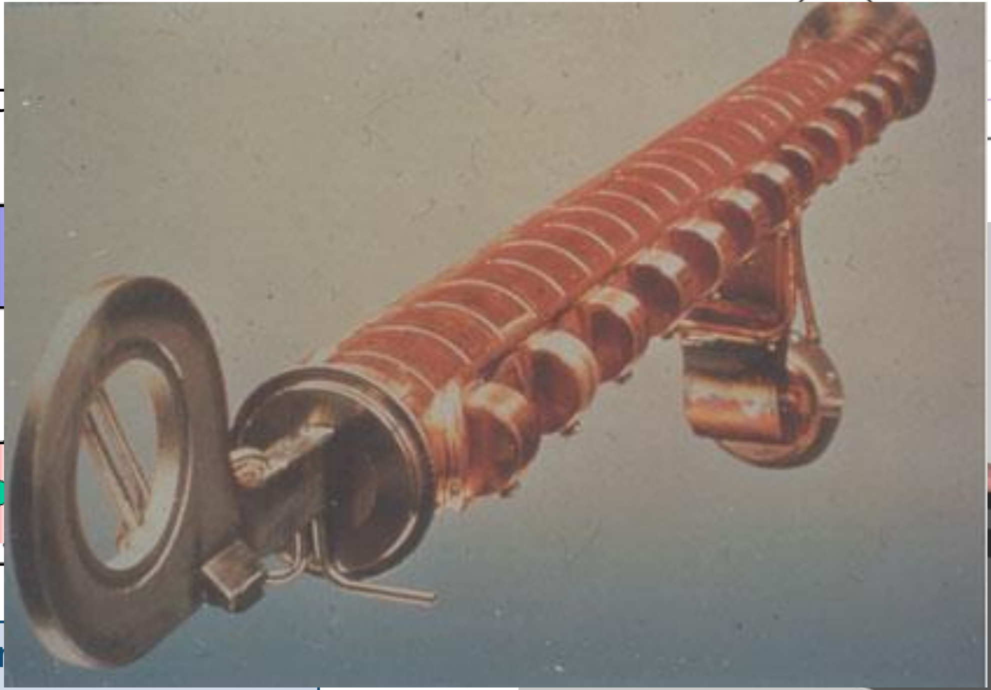


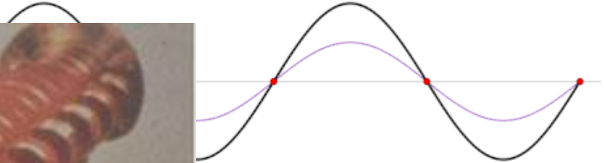
E_{kin}	v / c	m / m_0
15 keV	0,24	1,03
100 keV	0,6	1,25
1 MeV	0,941	2,96
10 MeV	0,999	22,4
100 MeV	0,999987	196,7

Standing Wave Linac

Accelerating wave is
and interferes with t







Zero-field elements r
→ side-coupled structure
Length is cut to almost 1/2!

Schlegel und Mahr 2007, 3D Conformal Radiation Therapy, Springer Verlag

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Modern linacs for radiotherapy

Varian True Beam

Standing wave Linac,
electron and photon mode,
Different energies

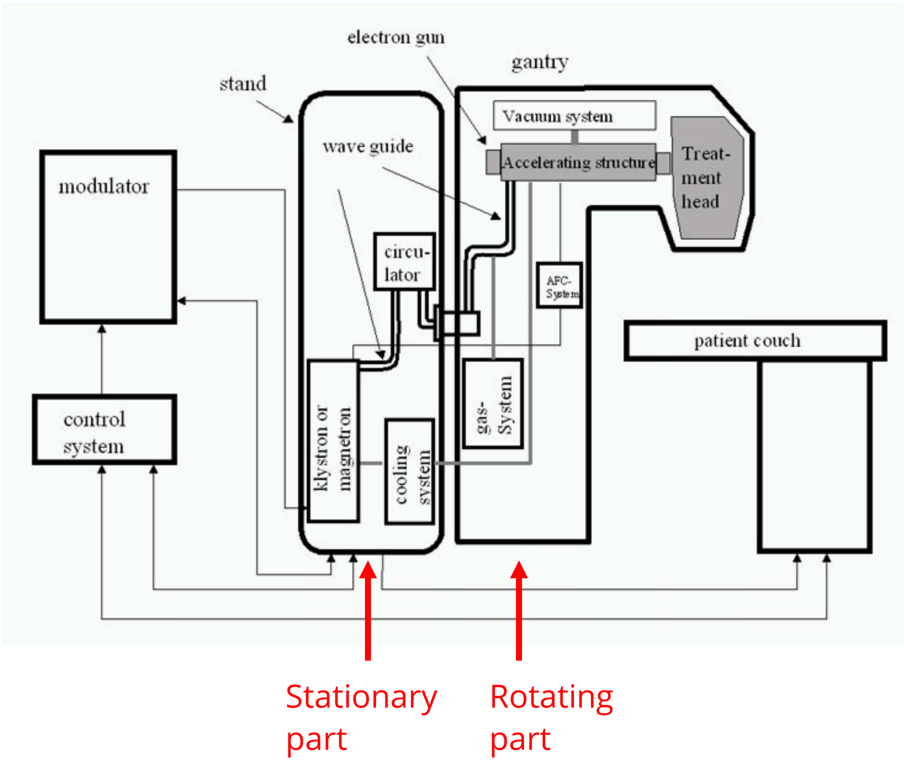
Elekta VersaHD / Evo

Travelling wave Linac,
electron and photon mode,
Different energies

Modern linacs for radiotherapy

Varian True Beam

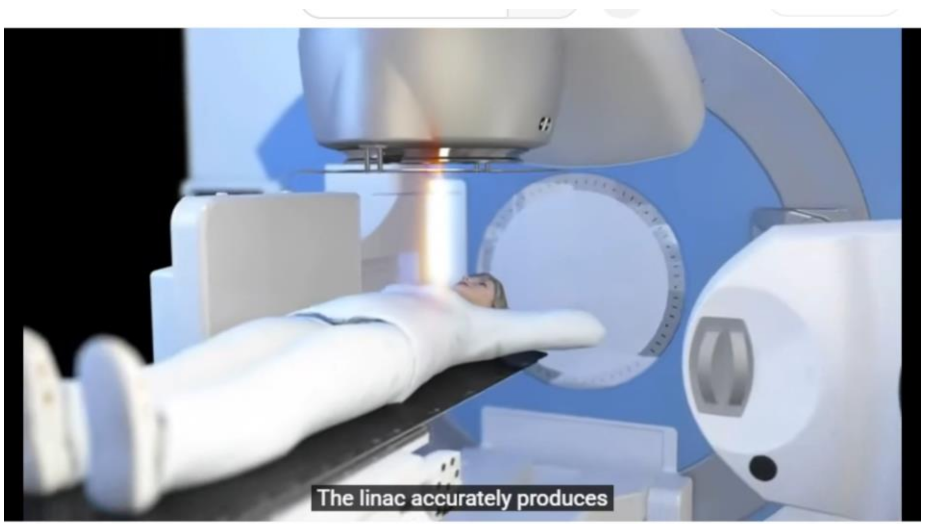
Standing wave Linac,
electron and photon mode,
Different energies



Modern linacs for radiotherapy

Elekta VersaHD / Evo

Travelling wave Linac,
electron and photon mode,
Different energies



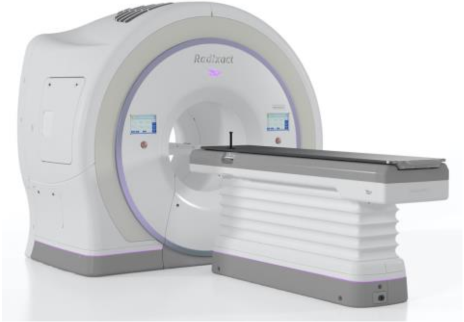
https://www.youtube.com/watch?v=jSgnWfbEx1A

Modern linacs for photon radiotherapy

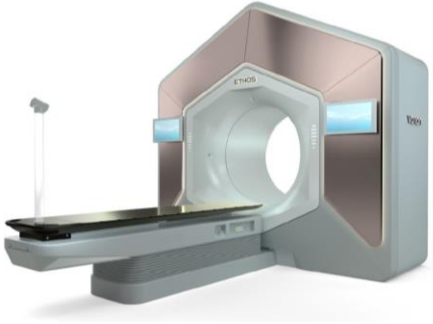
Accuray Cyberknife

9 GHz (X-Band)

Accuray Radixact Tomotherapy



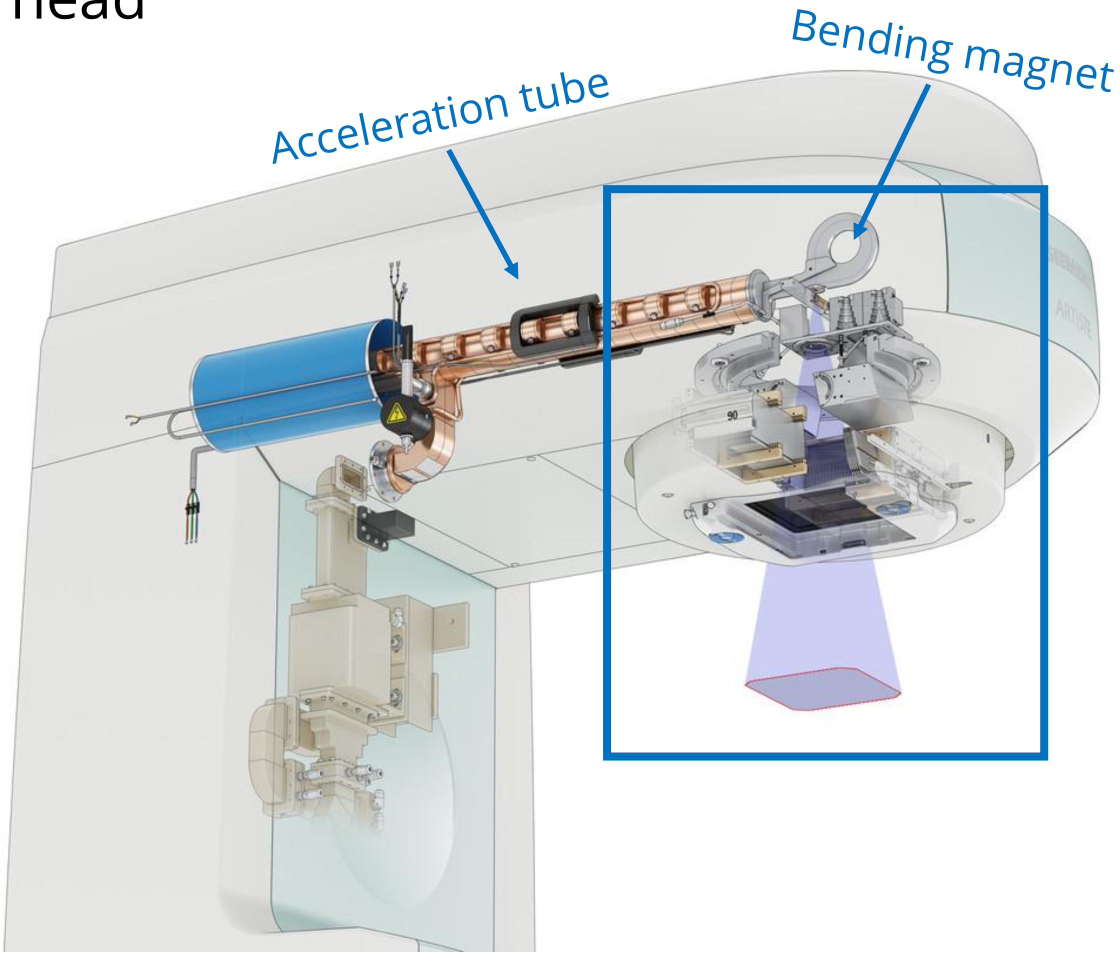
Varian Halcyon / ETHOS



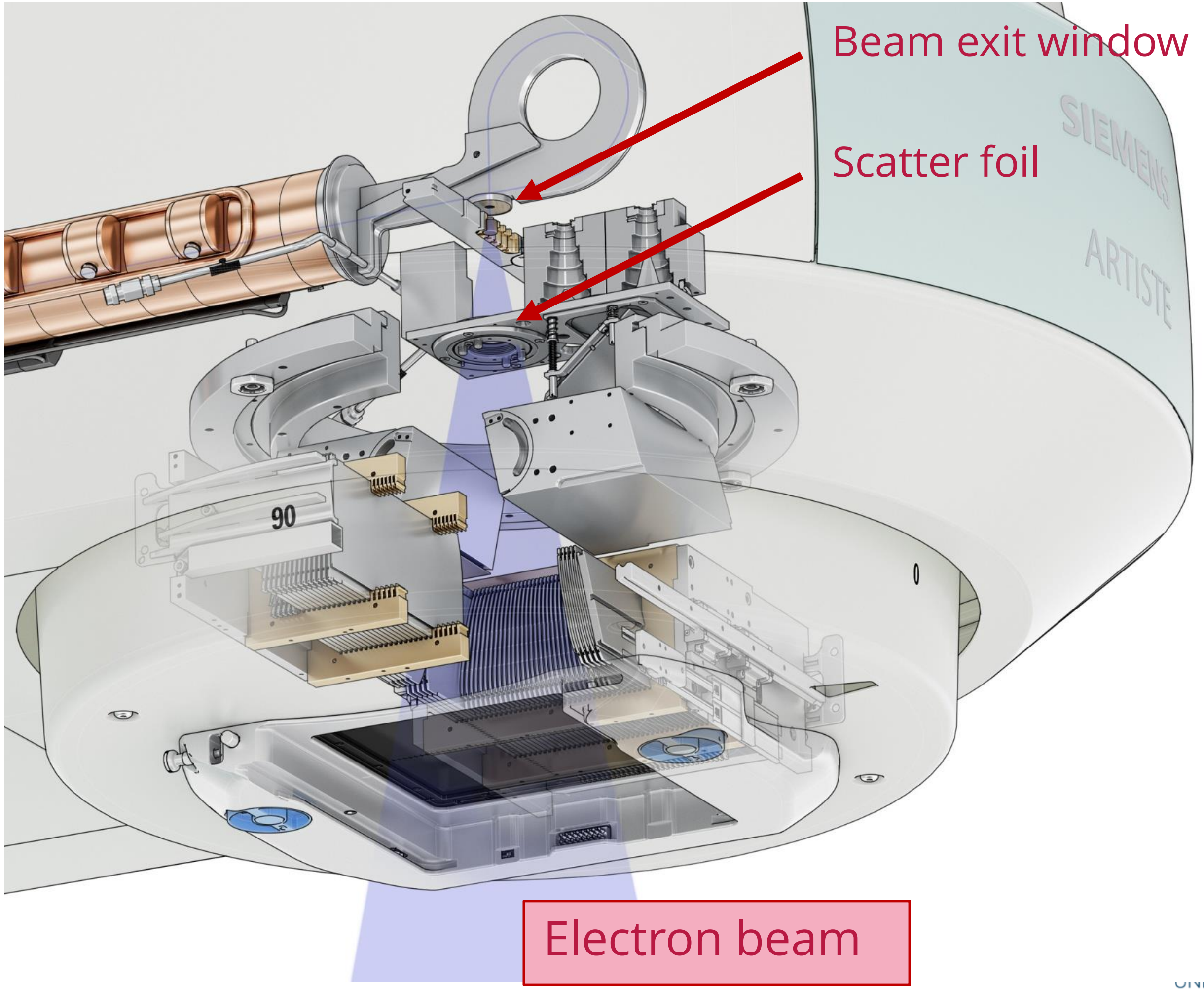
MR-Linacs (Elekta / Viewray)

All have in common: Standing Wave Linac, 6 MV FFF beam only

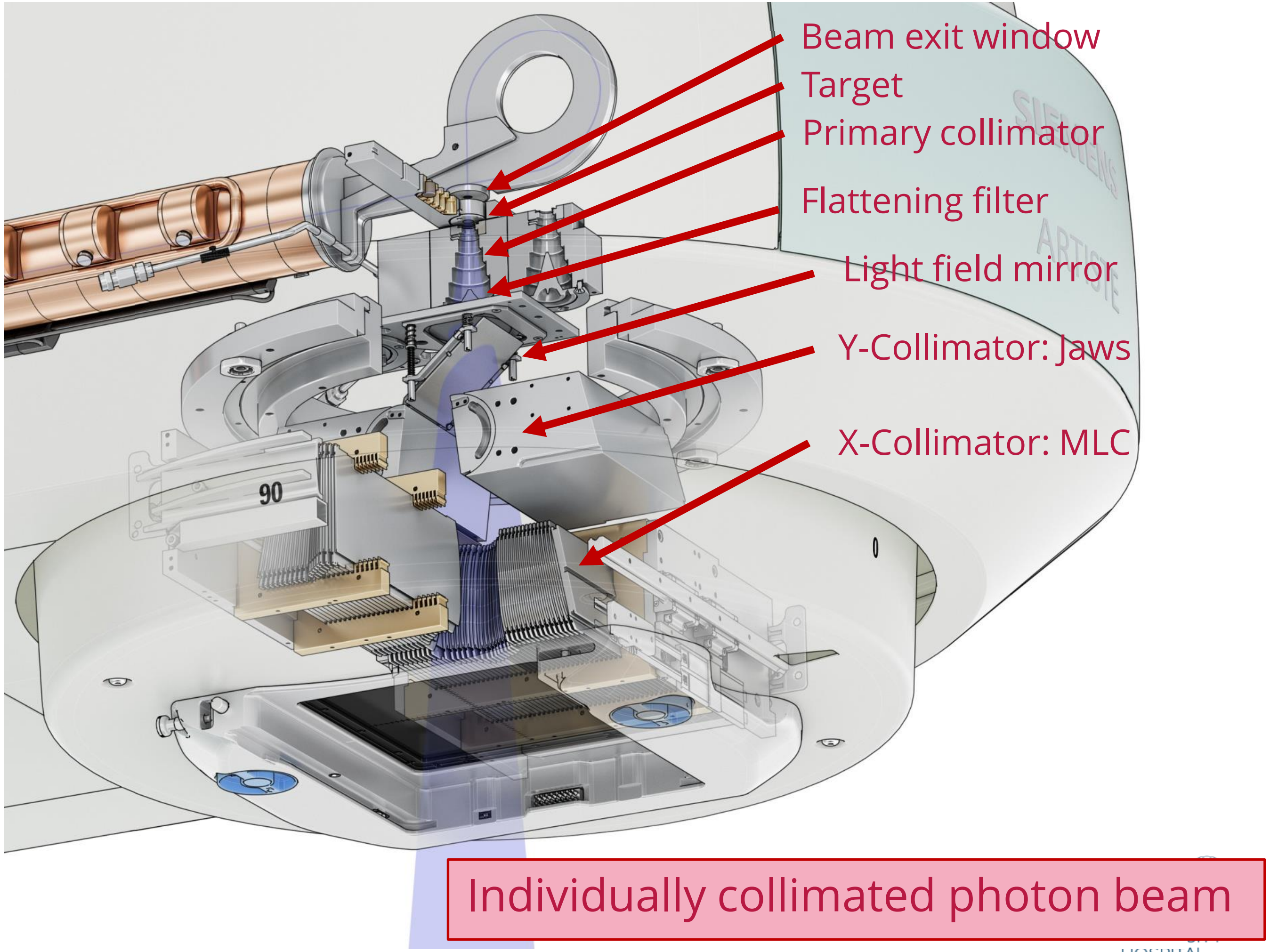
Treatment head



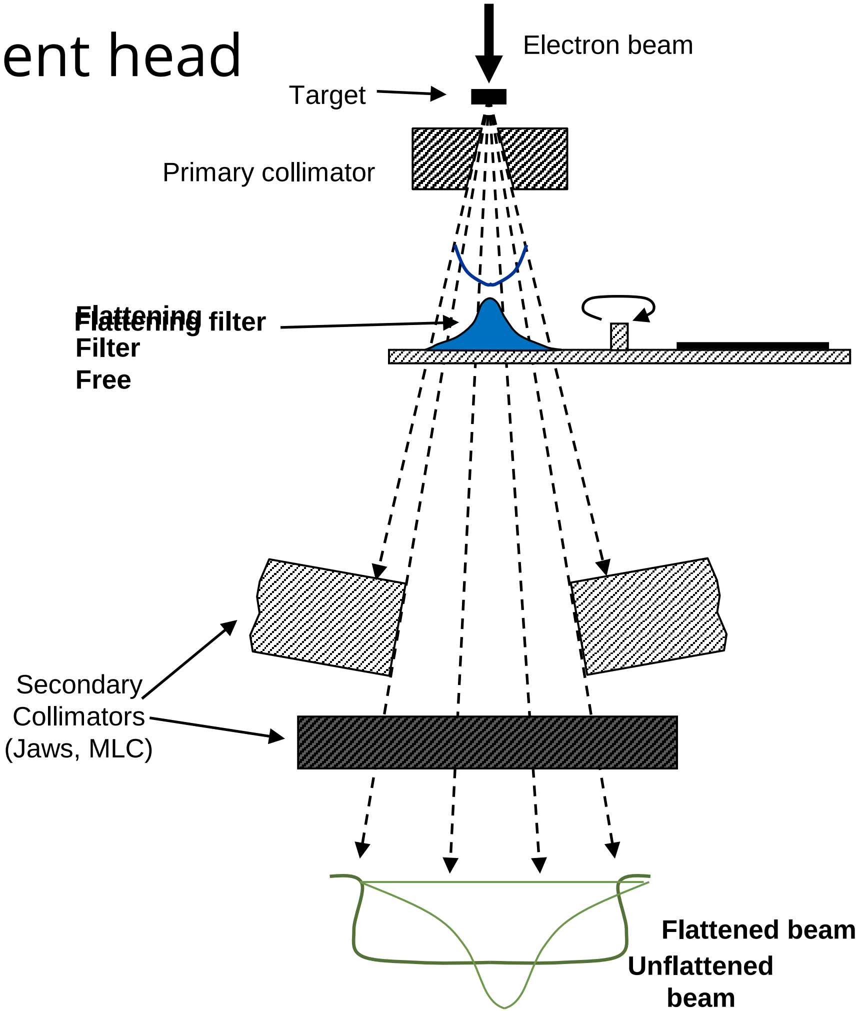
Treatment head

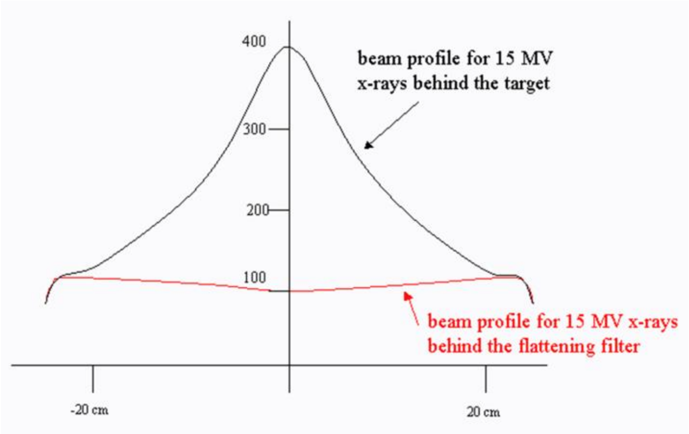


Treatment head



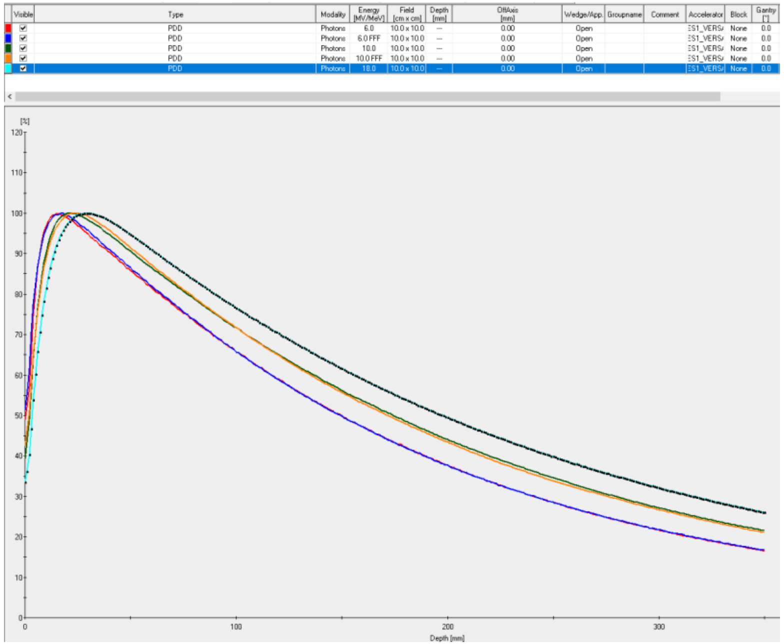
Treatment head

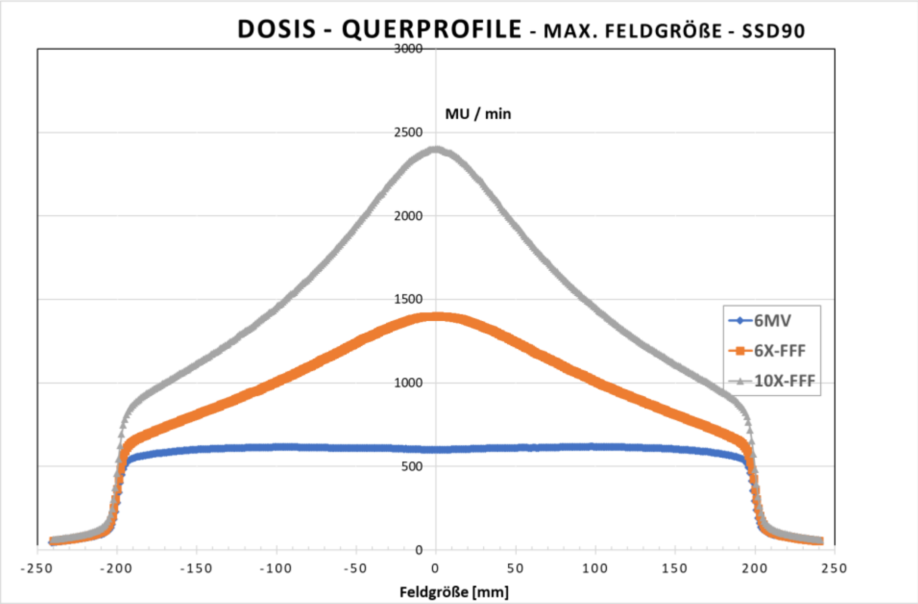




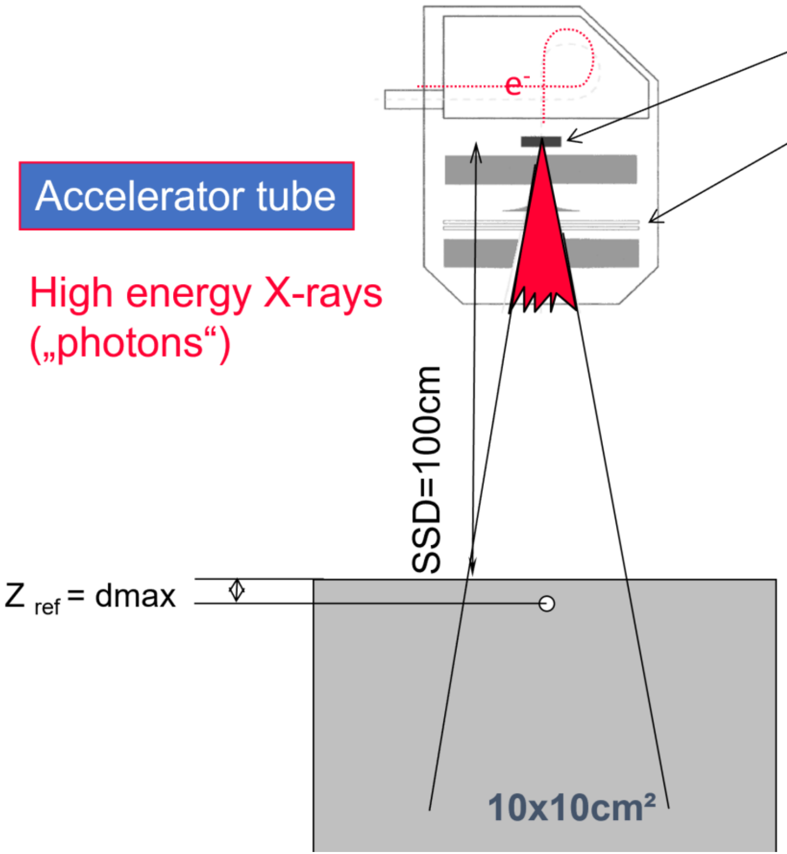
Flat and un-flat beams for different photon energies

6X, 6XFFF, 10X, 10XFFF, 18X   FG: 10x10cm² SSD:100cm





Linac dose calibration

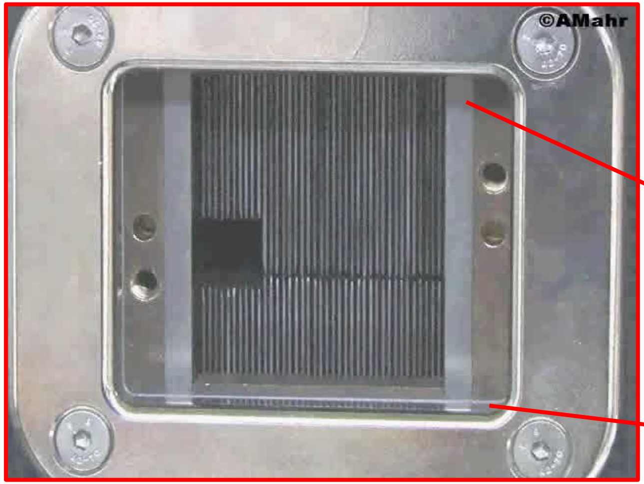


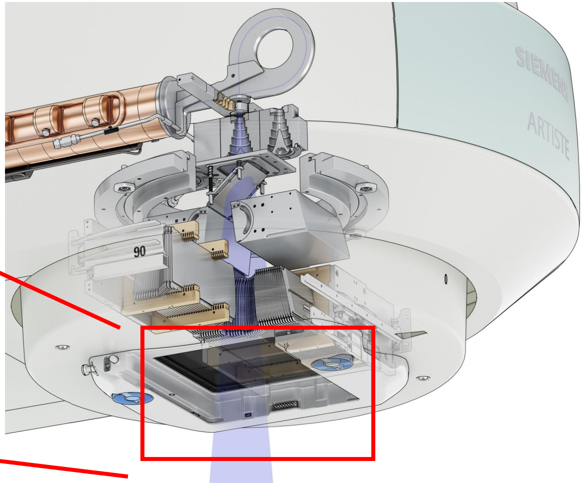
- Linac delivers bunches of photons,
- Linac is calibrated, so that the chamber measures 1 cGy per delivered 1 Mu at the following conditions

SCD (source chamber distance): SSD+dmax
SSD (source surface distance): 100 cm
field size: 10x10cm², depth : d_{max}
MU – Monitor Unit

1cGy / MU
0.01Gy / MU

Beam shaping: Multi-Leaf Collimator (MLC)

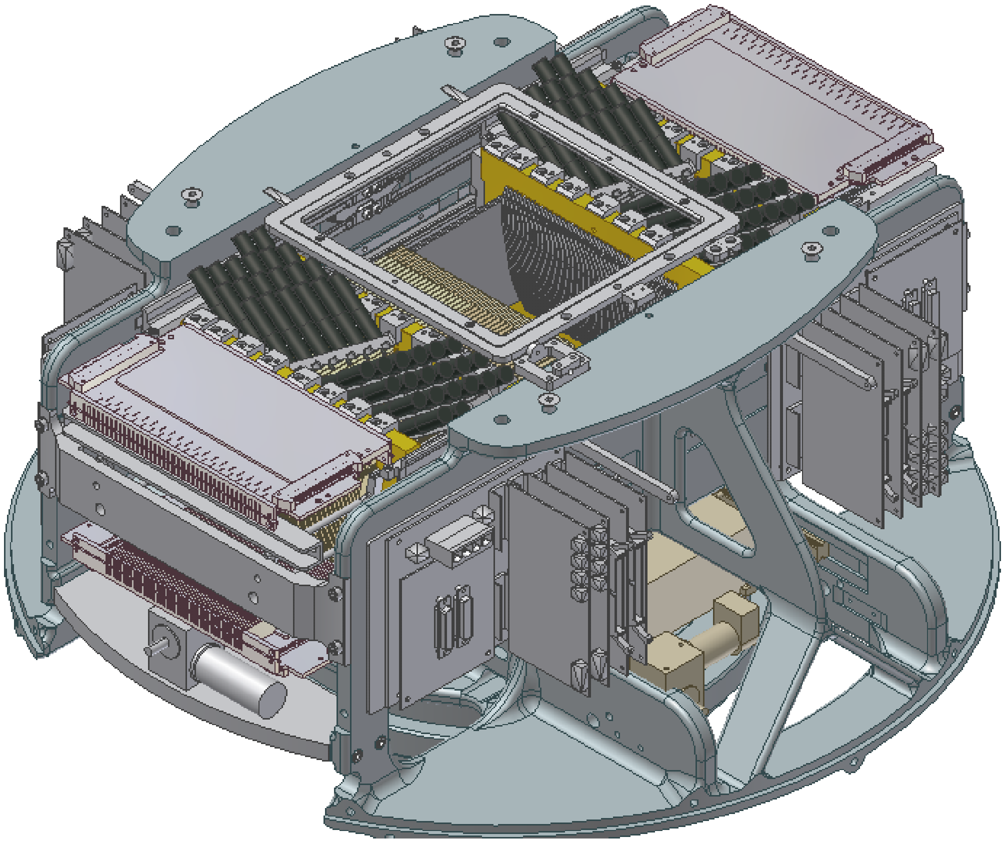




Tungsten leaves, motorized, each individually positioned

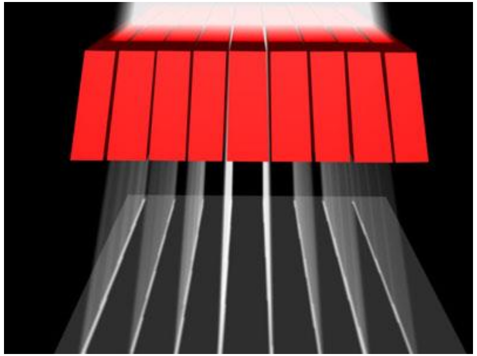
Height: high enough to attenuate the beam to < 0.5 %

Beam shaping: Multi-Leaf Collimator (MLC)



MLC transmission and leakage

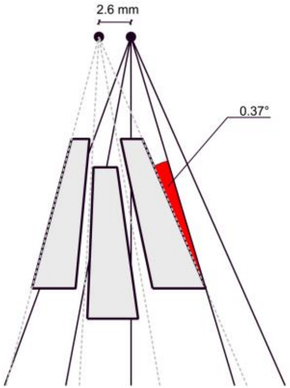
Dependent on the leaf design:

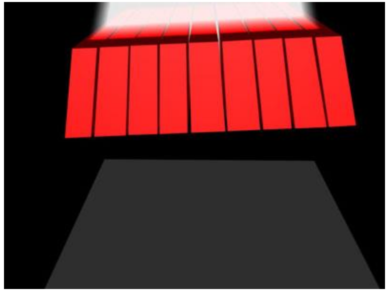


Here: single focus,

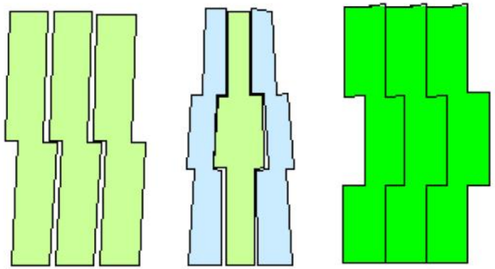
Leaf sides aligned with the source, in order to get sharp penumbra

Interleaf leakage





Leaf tilt can reduce interleaf leakae

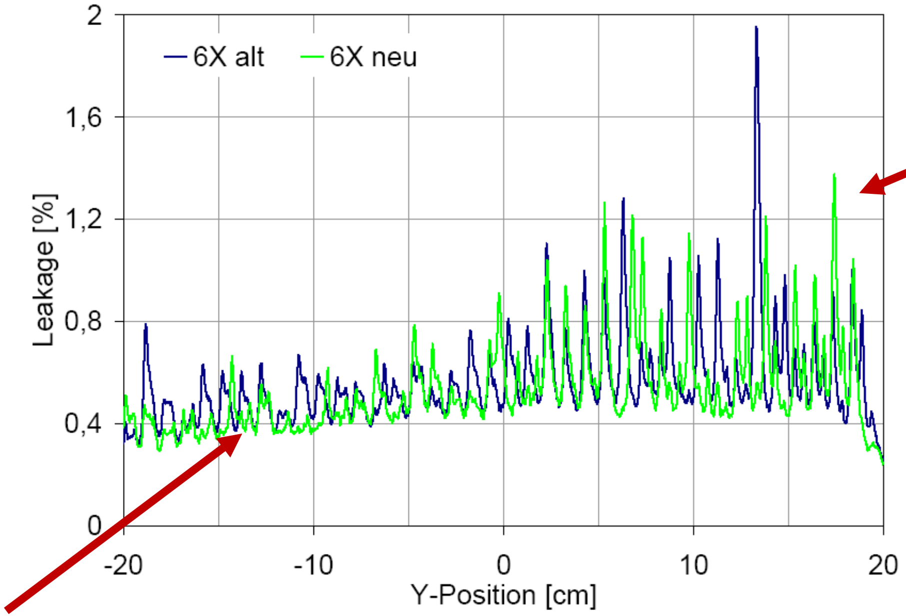


Alternative:

Tongue-and-Groove Design

MLC transmission and leakage

Measurement in a water tank:

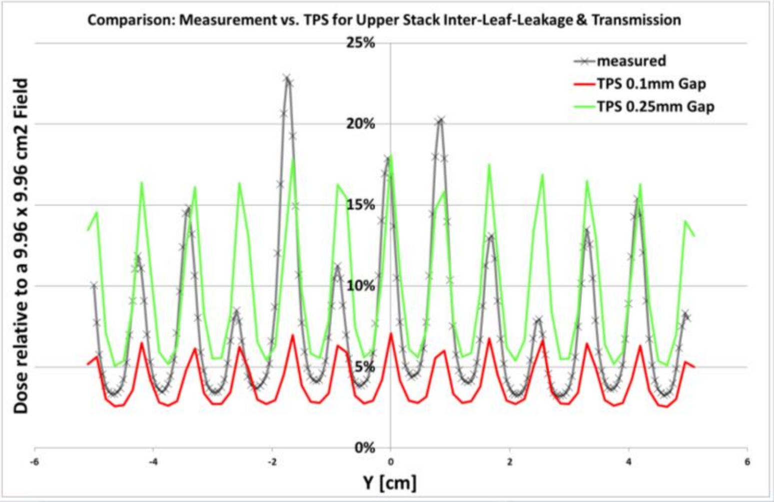


Leakage peaks at the position of the gaps between two leaf sides

Underground: Transmission through the leaves

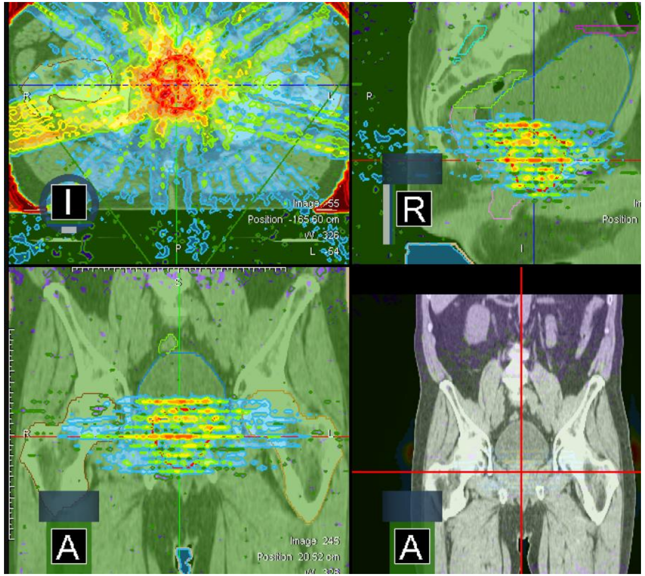
MLC leakage: not only a design question

Example: commissioning of our MR-Linac



- → Gap width is a parameter of the Monte Carlo Simulation and can be adjusted
- → Gap Width of 0.25mm yielded best agreement, but vendor hat set 0.1mm

Has non-negligible impact on patient dose



2% dose difference for a Prostate IMRT Plan

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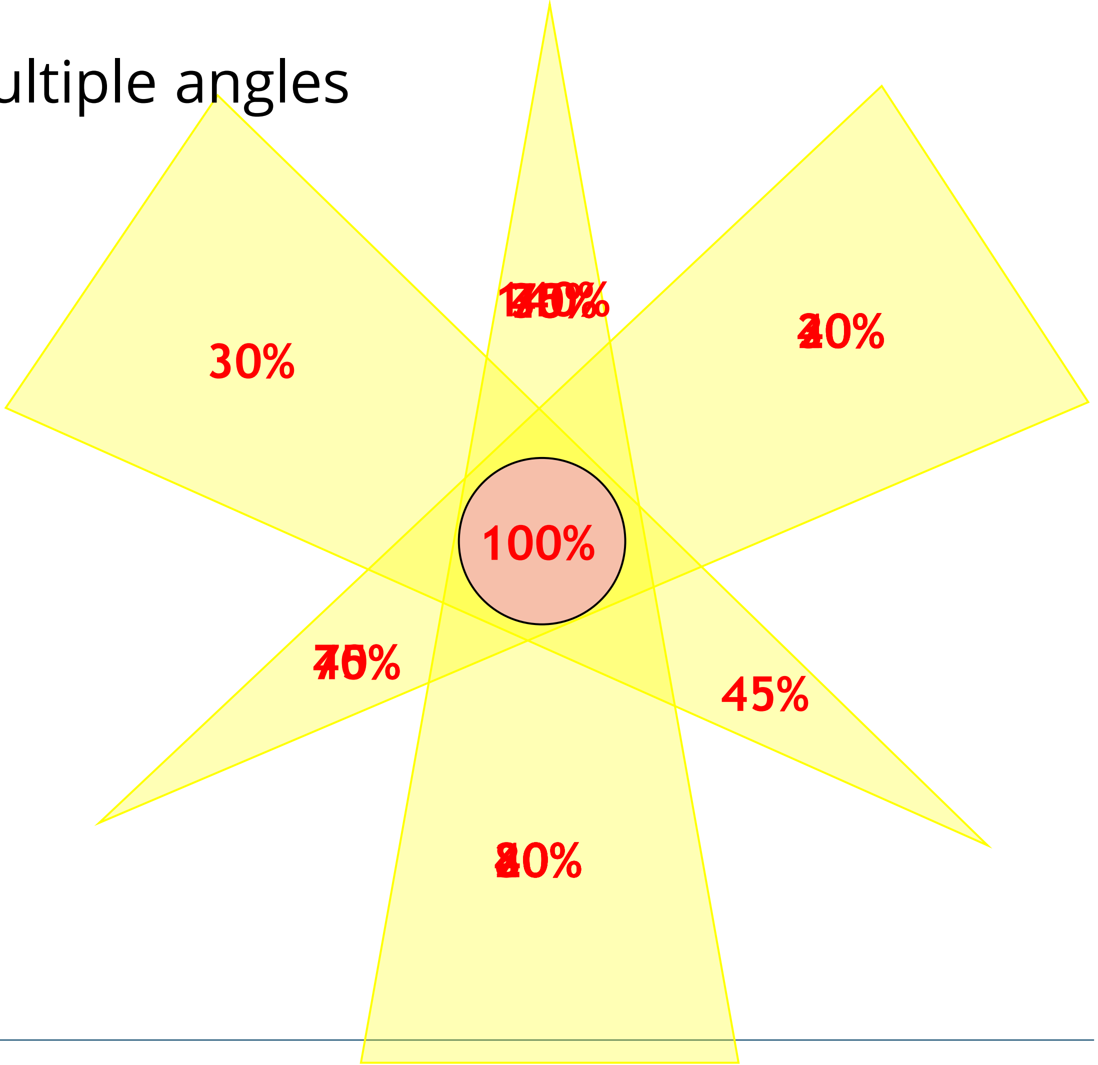
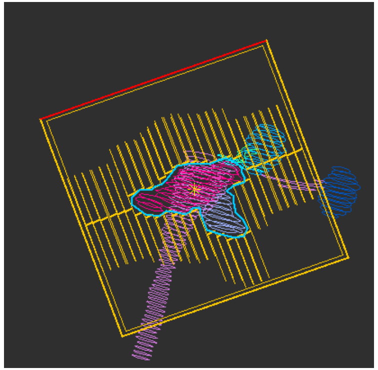
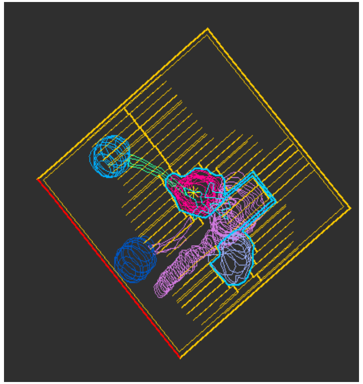
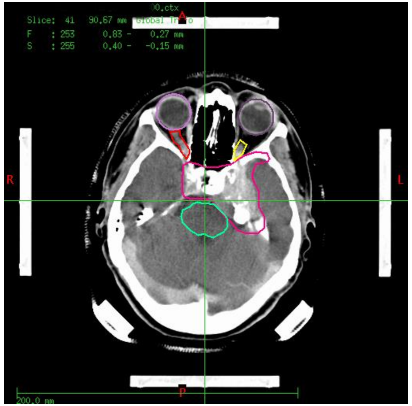
Photon RT needs multiple angles

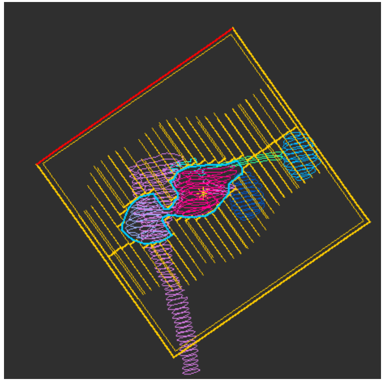


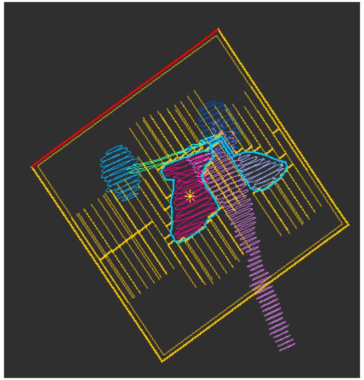
3D conformal radiation therapy











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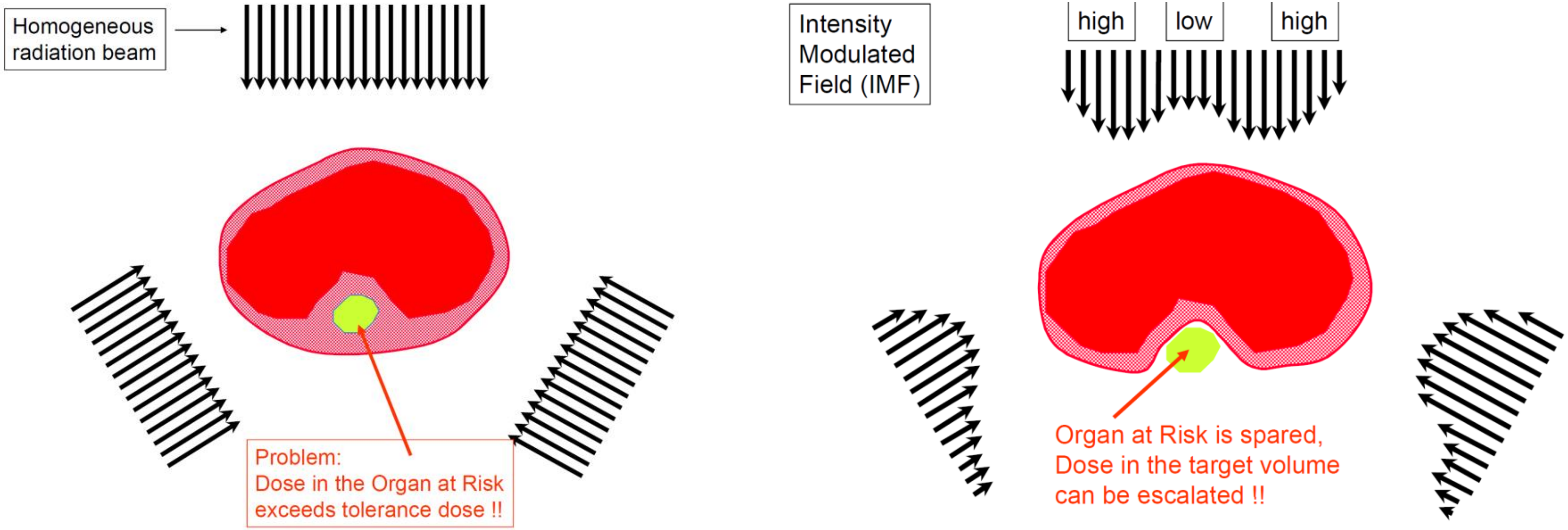
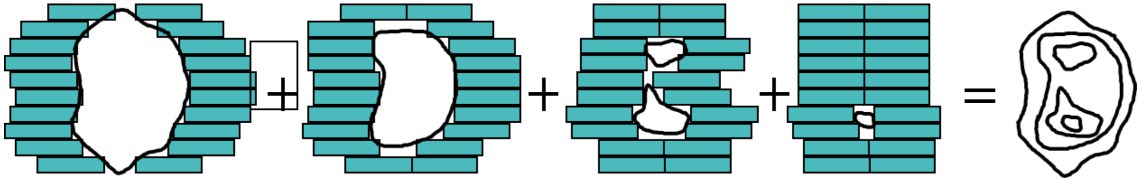
Intensity Modulated Radiation Therapy: IMRT



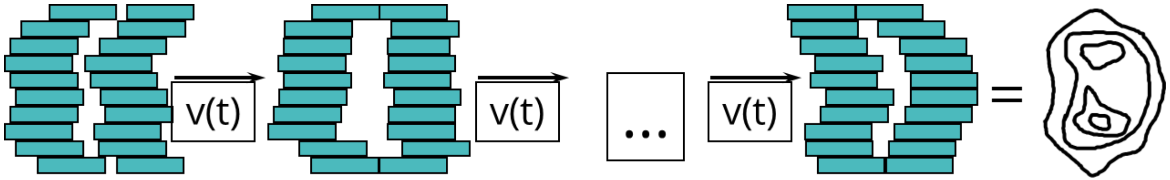
Leaf Sequencing for IMRT

Static MLC

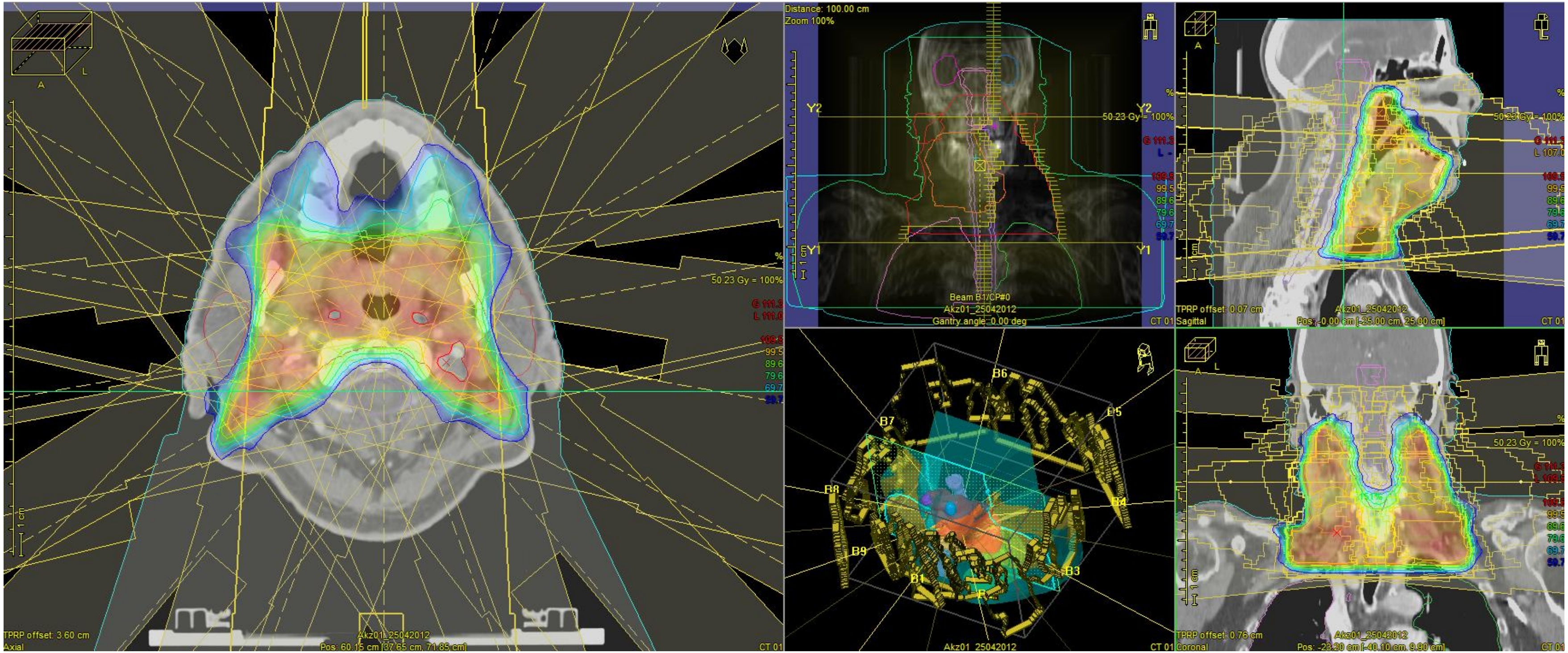


Number of discrete levels:

Dynamic MLC



Step and shoot IMRT



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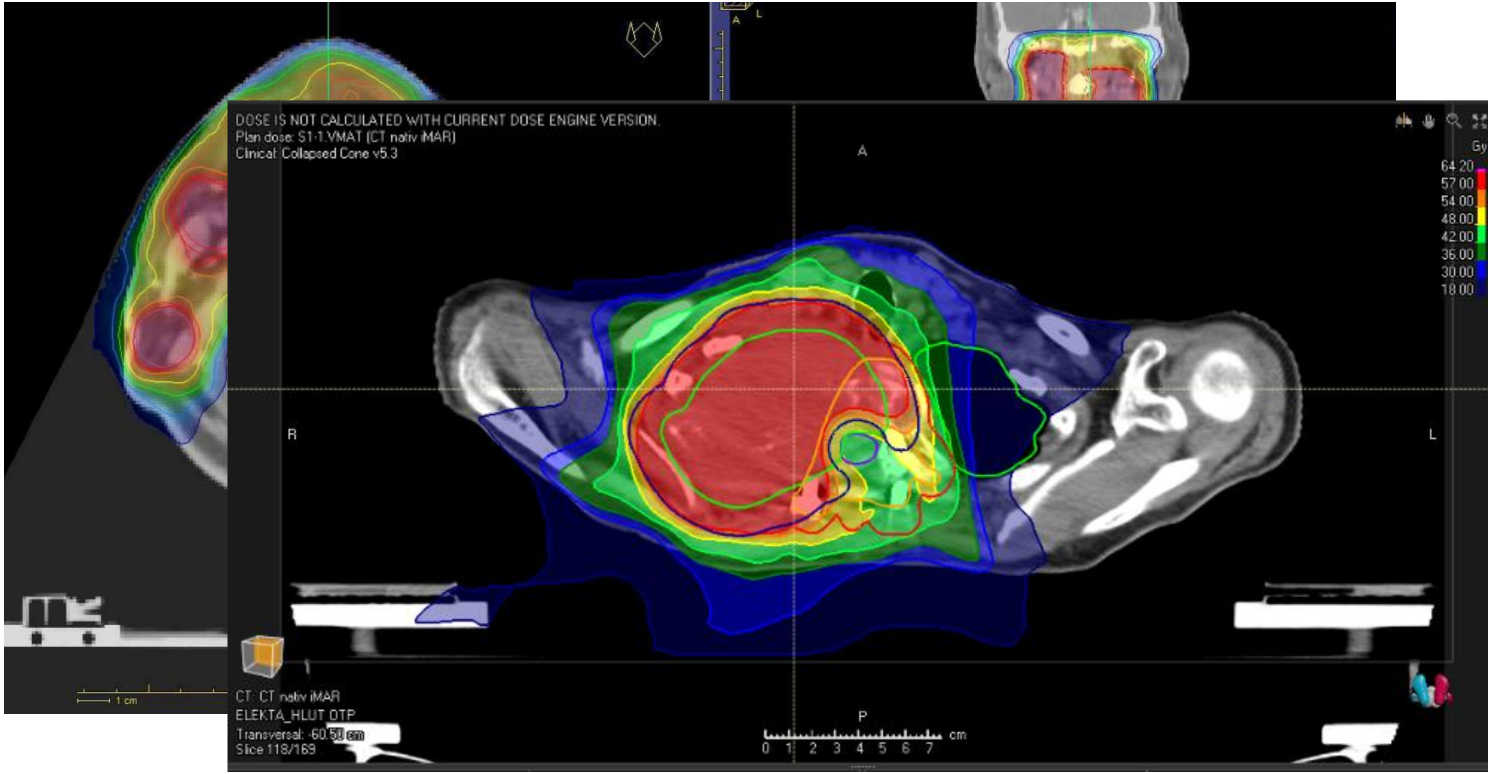
Volumetric Modulated Arc Therapy (VMAT)

Characteristics:

- Not as many degrees of freedom for modulation, but usually enough
- Low dose is spread around full arc
- In some cases, more than one arc is necessary

https://www.youtube.com/watch?v=3pMdzBMaN-c

VMAT examples



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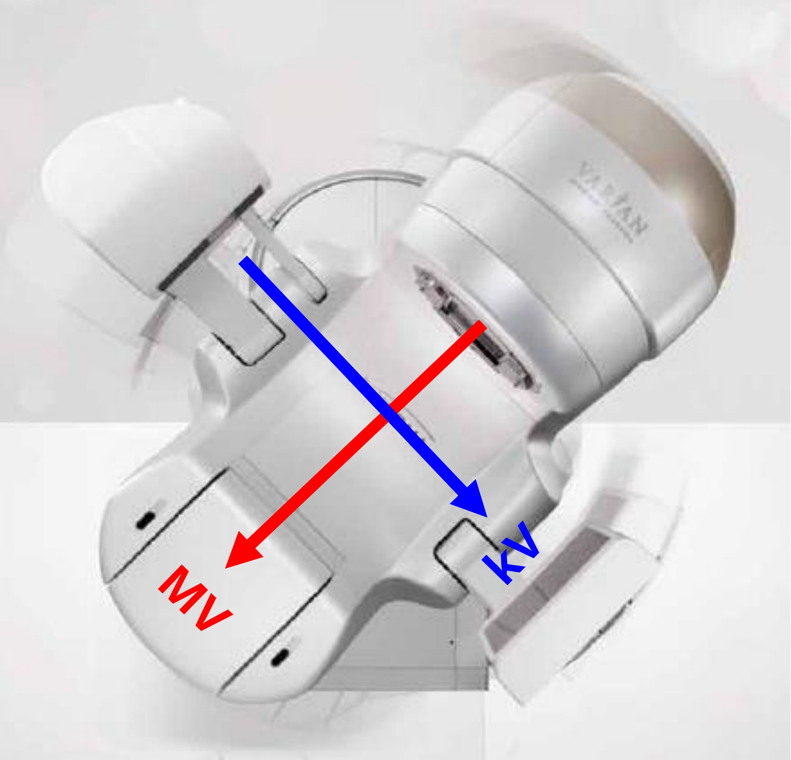
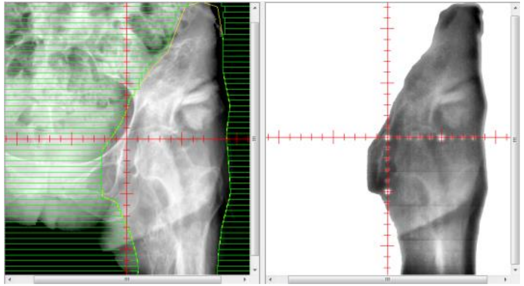
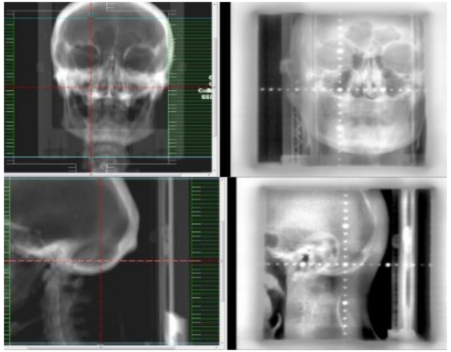
Integrated imaging

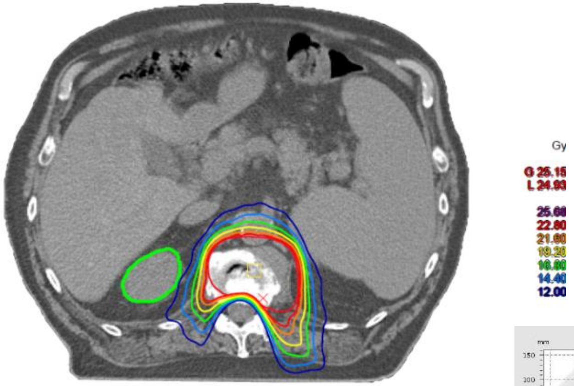


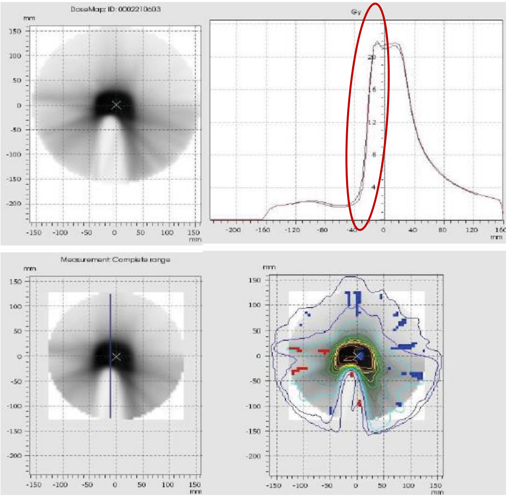


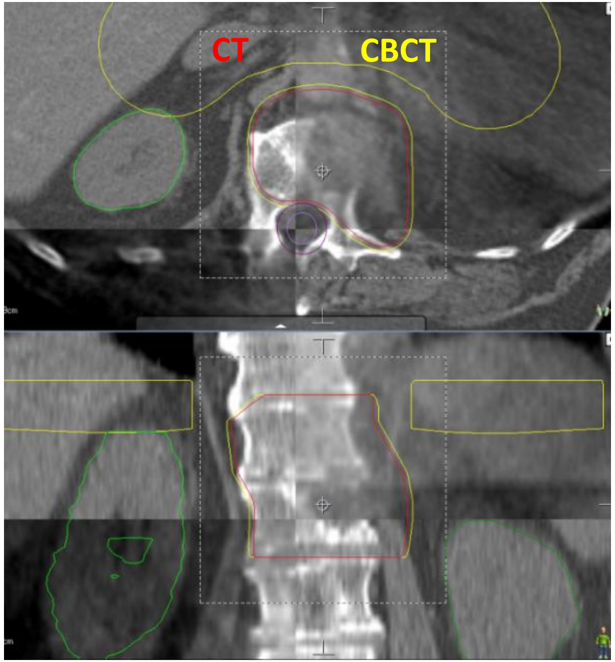


- 2D kV imaging
- 2D MV imaging
- 3D CBCT
- 4D CBCT

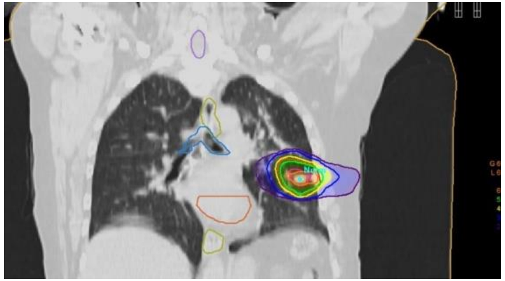
Clinical use of integrated imaging

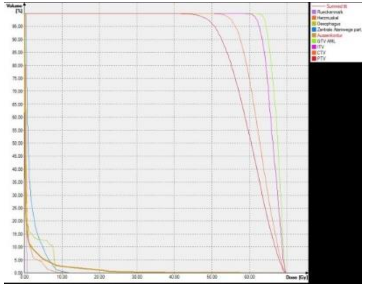




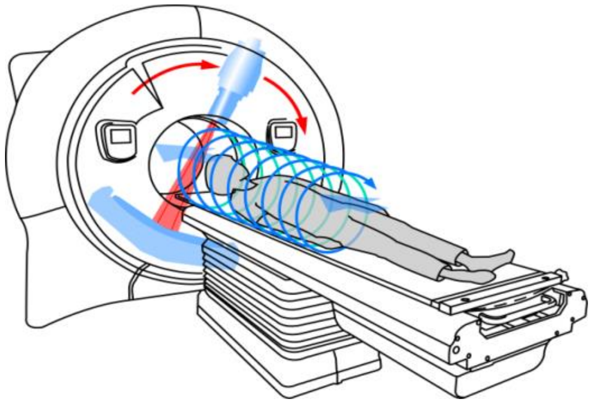


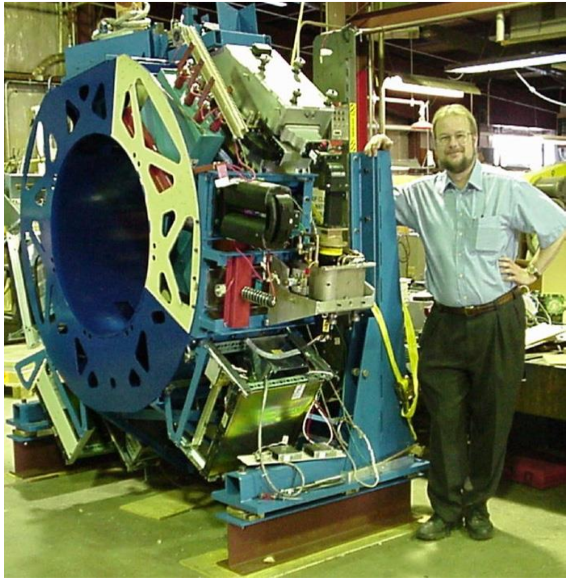
Clinical use of integrated imaging: 4D-CBCT





Tomotherapy

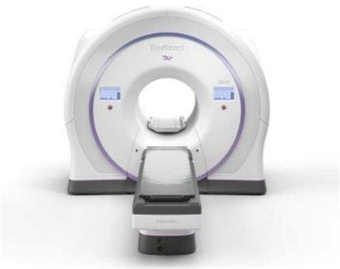




Rock Mackie with his first clinical prototype in 2000

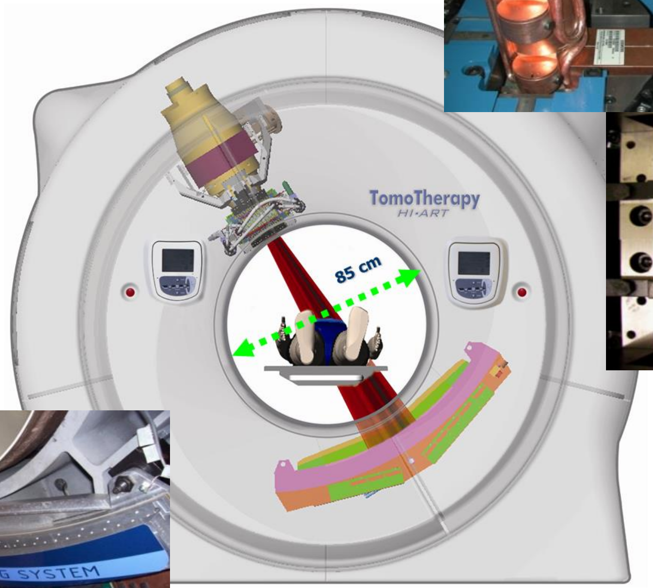
Hi-Art II
UHD: 2006

Tomo HDA
UHD: 2011



Radixact
UHD: Nov. 2025

Tomotherapy



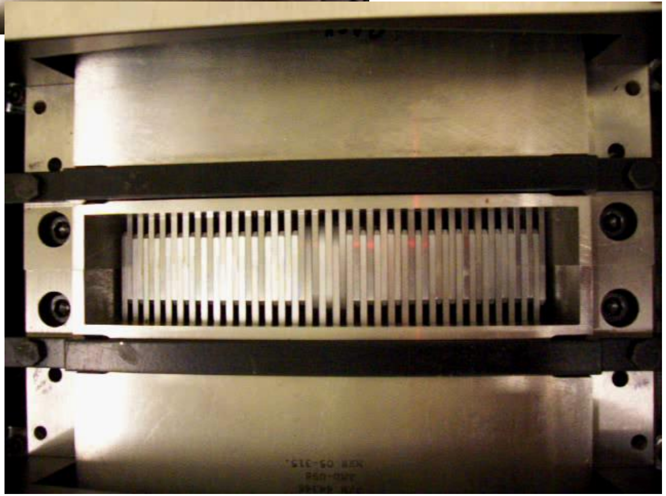
6 MV FFF
8,5 Gy/min

Binary MLC (opens and closes with compressed air within ~15 ms)

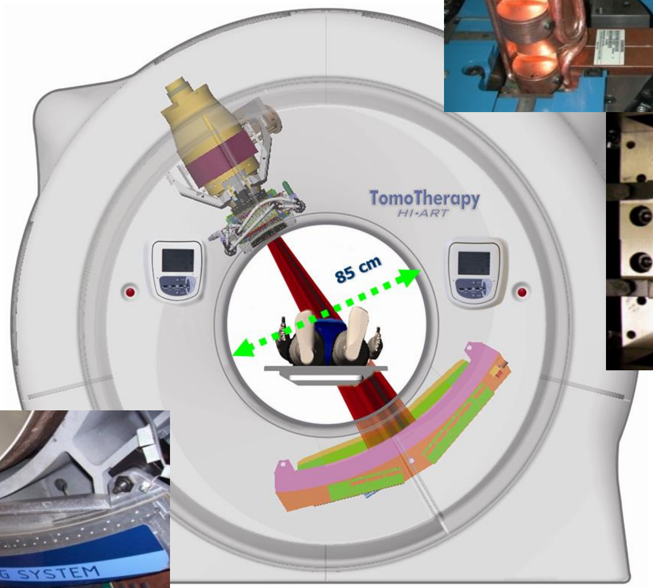
CT detector for helical imaging (3.5 MV)

Tomotherapy

6 MV FFF
8,5 Gy/min



Binary MLC (opens and closes with compressed air within ~15 ms)



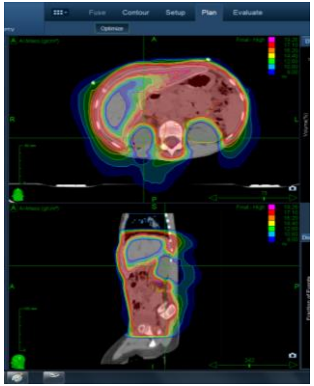
CT detector for helical imaging (3.5 MV)

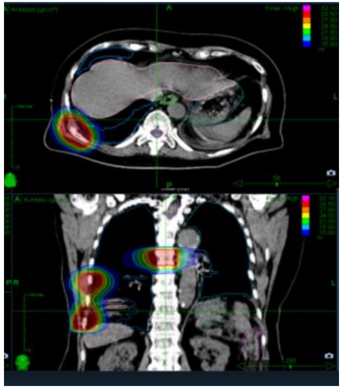
Advantages of tomotherapy

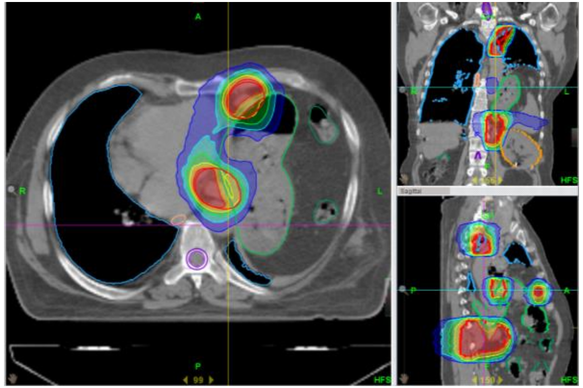
Very easy treatment of long volumes,

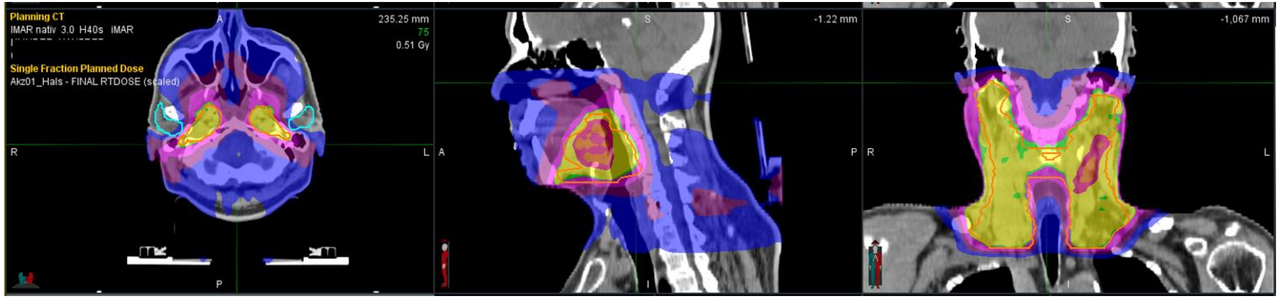
Very high modulation possible (complex cases)

„dose painting“

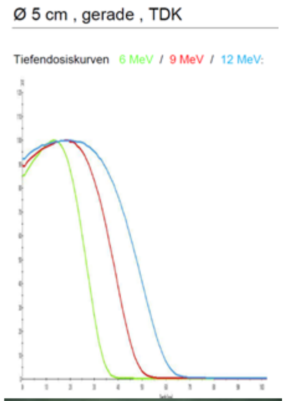


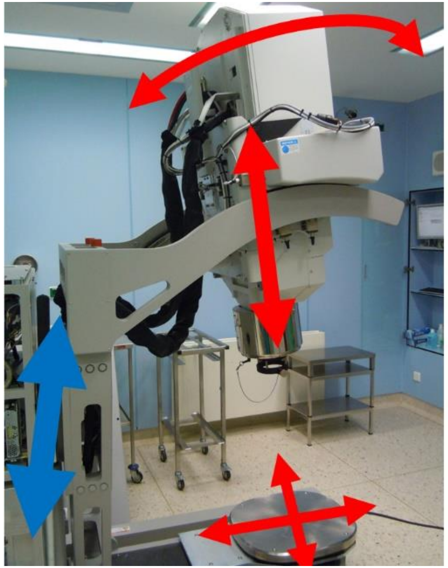






Mobile electron linac for intraoperative RT





The End