LINEAR ACCELERATORS FOR RADIOTHERAPY

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HOW DO THEY WORK?

ICTP SCHOOL ON MEDICAL PHYSICS FOR RADIATION THERAPY
DOSIMETRY AND TREATMENT PLANNING FOR BASIC AND ADVANCED APPLICATIONS
March 27 – April 7, 2017
Miramare, Trieste, Italy

Yakov Pipman, D.Sc.

Central element of Radiotherapy
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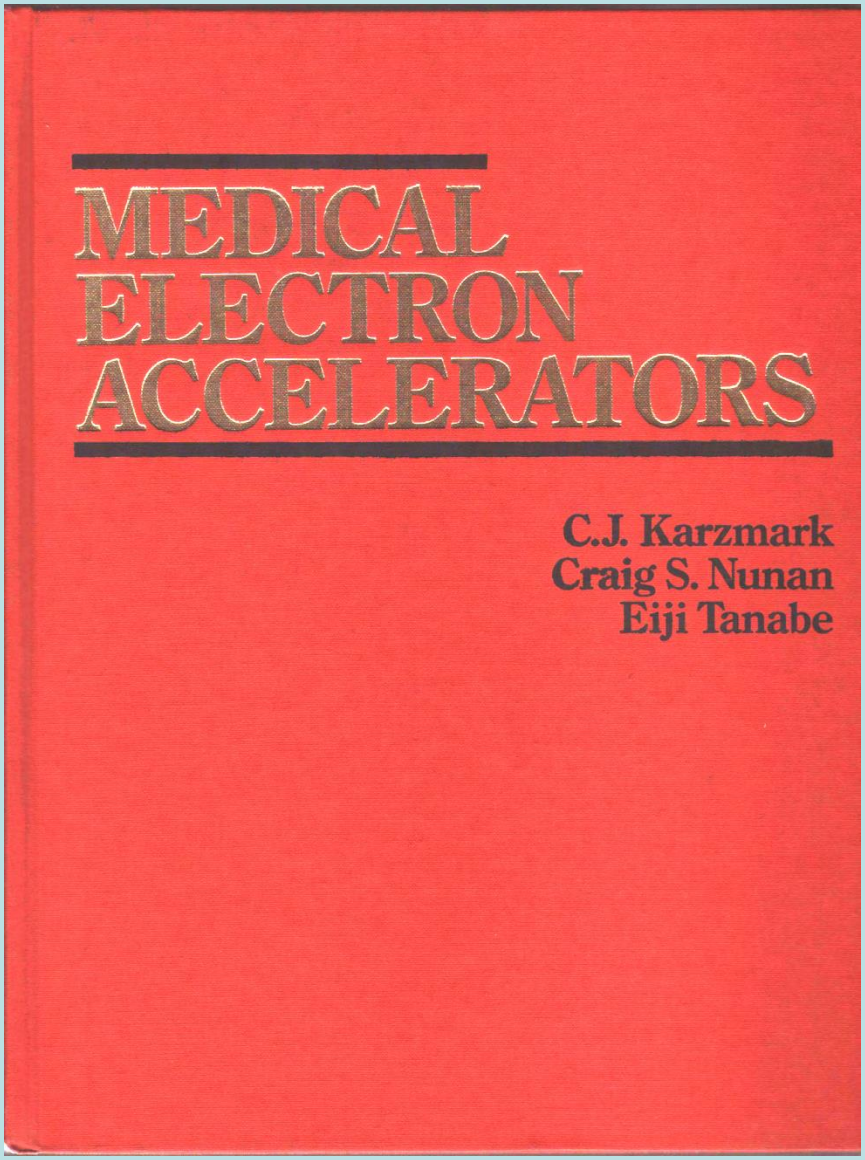
The linear accelerator



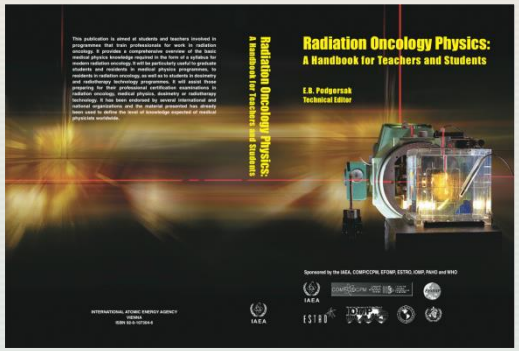
KARZMARK C.J., NUNAN C.S., TANABE E.,
Medical Electron Accelerators,
McGraw-Hill, New York (1993)

Chapter 5: Treatment Machines for External Beam Radiotherapy

Set of 126 slides based on the chapter authored by
E.B. Podgorsak
of the IAEA publication:
Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

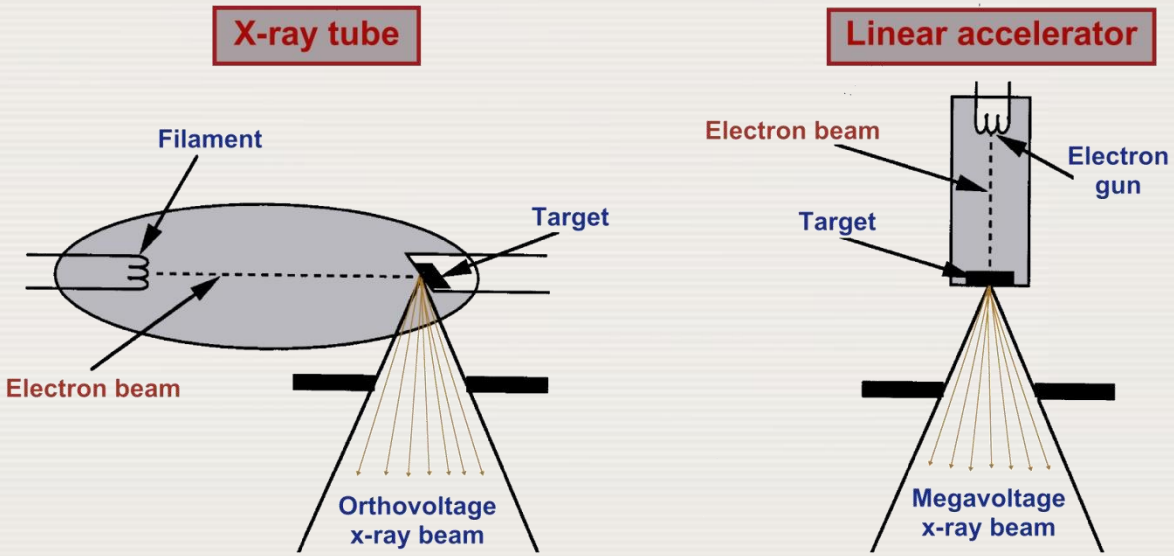
To familiarize the student with the basic principles of equipment used for external beam radiotherapy.



IAEA
International Atomic Energy Agency

Slide set prepared in 2006
by E.B. Podgorsak (Montreal, McGill University)
Comments to S. Vatnitsky:
dosimetry@iaea.org

- In the diagnostic energy range (10 - 150 kVp) most photons are produced at 90º from the direction of electrons striking the target (x-ray tube).
- In the megavoltage energy range (1 - 50 MV) most photons are produced in the direction of the electron beam striking the target (linac).



Tissue-phantom ratio $TPR_{20,10}$:

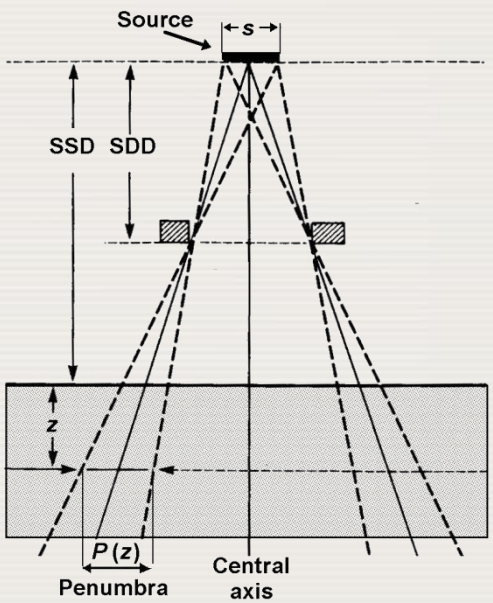
- $TPR_{20,10}$ is defined as the ratio of doses on the beam central axis at depths of z = 20 cm and z = 10 cm in water obtained at an SAD of 100 cm and a field size of 10x10 cm^2.
- $TPR_{20,10}$ is independent of electron contamination of the incident photon beam.
- $TPR_{20,10}$ is used as megavoltage beam quality specifier in the IAEA-TRS 398 dosimetry protocol.
- $TPR_{20,10}$ is related to measured $PDD_{20,10}$ as

$$TPR_{20,10} = 1.2661\, PDD_{20,10} - 0.0595$$

- Collimators of teletherapy machines provide square and rectangular radiation fields typically ranging from 5x5 to 35x35 cm^2 at 80 cm from the source.

- The geometric penumbra resulting from the finite source diameter, may be minimized by using:
  - Small source diameter
  - Penumbra trimmers as close as possible to the patient's skin (z = 0)

$$\frac{P(z)}{s} = \frac{(\mathrm{SSD} + z - \mathrm{SDD})}{\mathrm{SDD}}$$



5.5 LINACS

- Medical linacs are cyclic accelerators that accelerate electrons to kinetic energies from 4 to 25 MeV using microwave radiofrequency fields:
  - 10^3 MHz : L band
  - 2856 MHz: S band
  - 10^4 MHz: X band
- In a linac the electrons are accelerated following straight trajectories in special evacuated structures called accelerating waveguides.

5.5 LINACS

5.5.1 Linac generations

- During the past 40 years medical linacs have gone through five distinct generations, each one increasingly more sophisticated:

  (1) Low energy x rays (4-6 MV)
  (2) Medium energy x rays (10-15 MV) and electrons
  (3) High energy x rays (18-25 MV) and electrons
  (4) Computer controlled dual energy linac with electrons
  (5) Computer controlled dual energy linac with electrons combined with intensity modulation

5.5 LINACS

5.5.2 Safety of linac installations

- Safety of operation for the patient, operator, and the general public is of great concern because of the complexity of modern linacs.
- Three areas of safety are of interest
  - Mechanical
  - Electrical
  - Radiation
- Many national and international bodies are involved with issues related to linac safety.

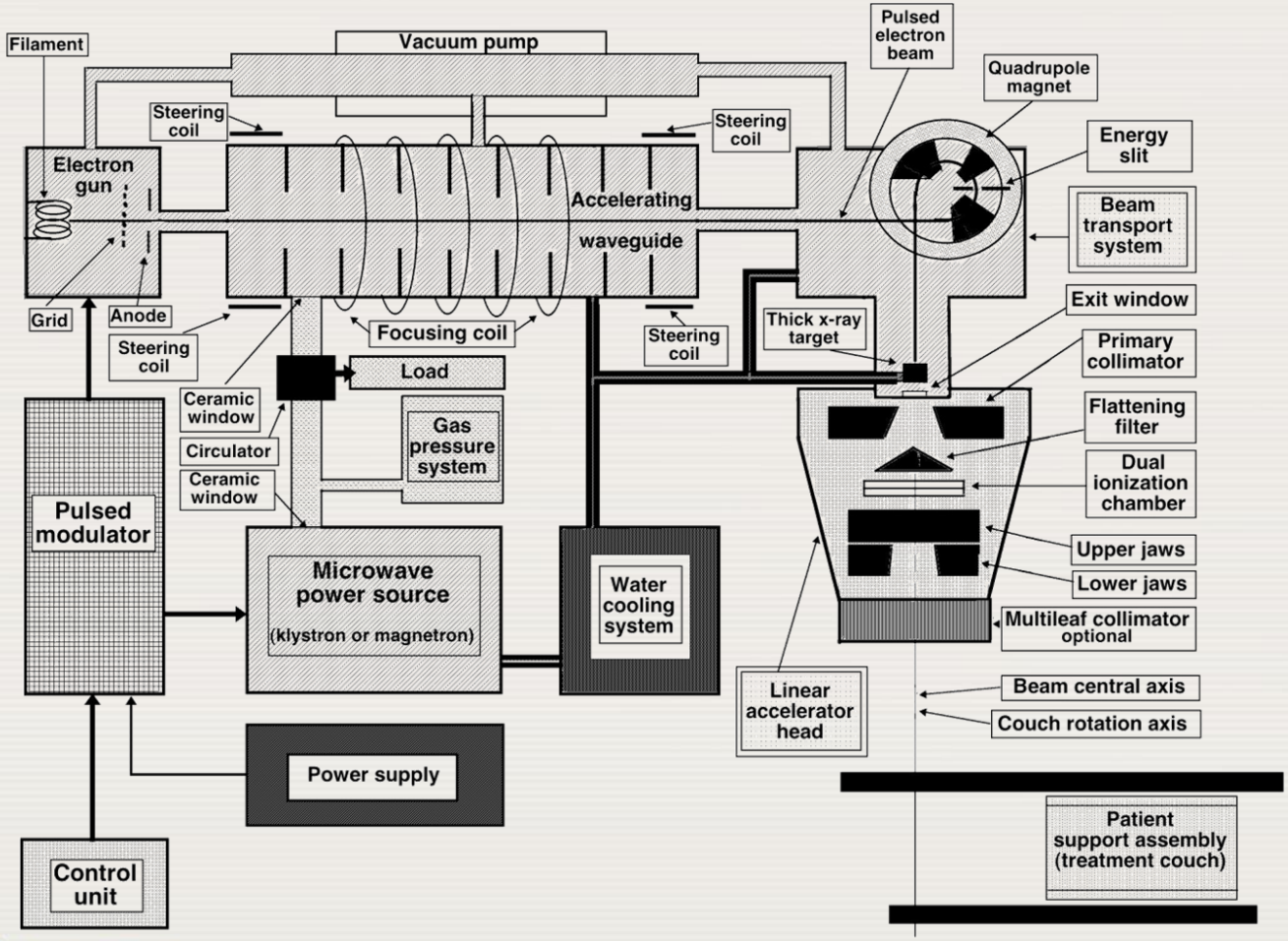
5.5.3 Components of modern linacs

- Linacs are usually mounted isocentrically and the operational systems are distributed over five major and distinct sections of the machine:
  - Gantry
  - Gantry stand and support
  - Modulator cabinet
  - Patient support assembly
  - Control console

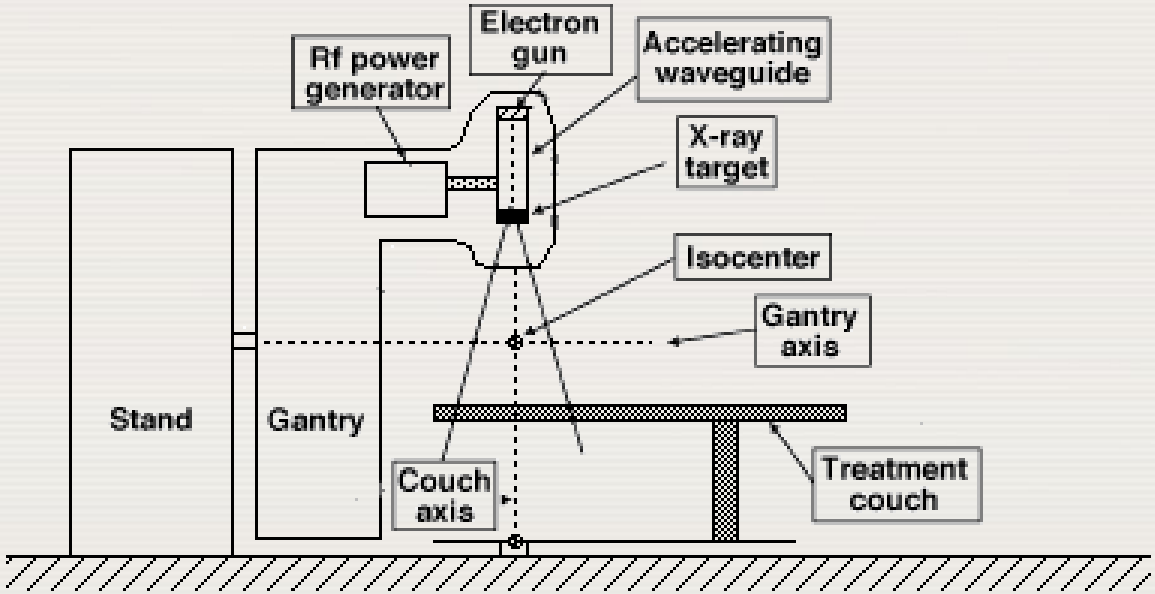
- The main beam forming components of a modern medical linac are usually grouped into six classes:

  (1) Injection system
  (2) Radiofrequency power generation system
  (3) Accelerating waveguide
  (4) Auxiliary system
  (5) Beam transport system
  (6) Beam collimation and monitoring system

- Schematic diagram of a modern fifth generation linac



- In the simplest and most practical configuration:
  - Electron source and the x-ray target form part of the accelerating waveguide and are aligned directly with the linac isocentre obviating the need for a beam transport system.
  - Since the target is embedded into the waveguide, this linac type cannot produce electron beams.

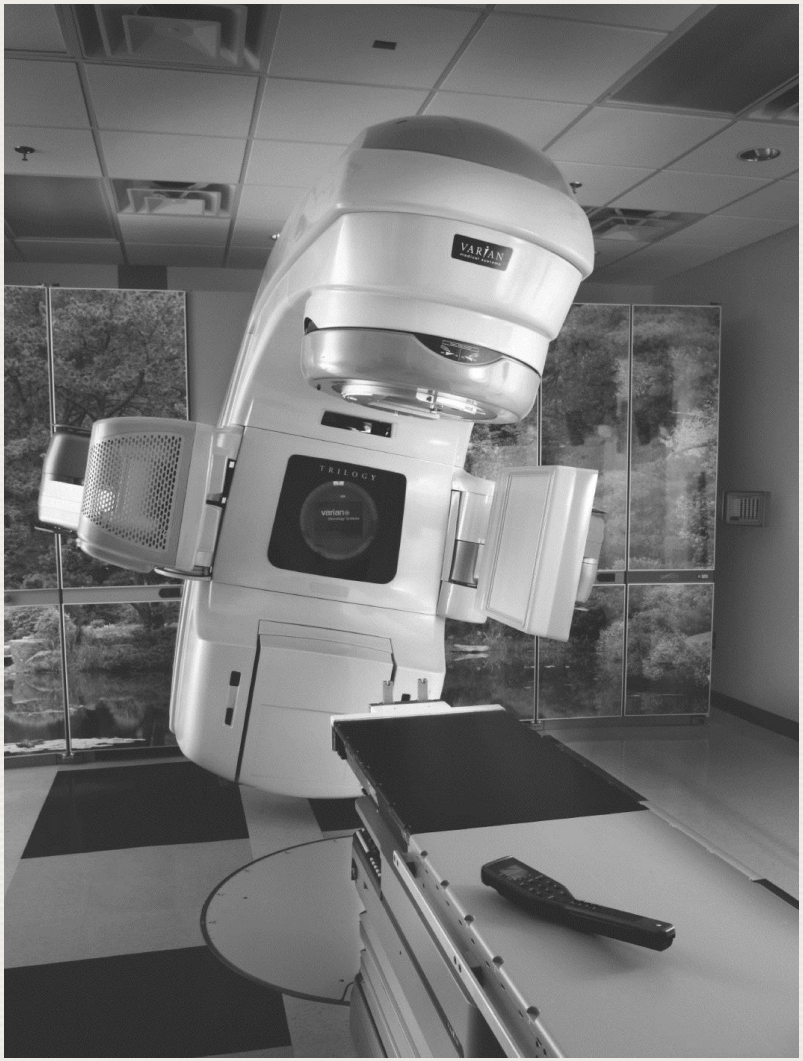


5.5.4 Linac generations

- Typical modern dual energy linac, incorporating imaging system and electronic portal imaging device (EPID), Elekta, Stockholm

- Typical modern dual energy linac, with on board imaging system and an electronic portal imaging device (EPID),

  Varian, Palo Alto, CA



5.5.7 Accelerating waveguide

- Waveguides are evacuated or gas filled metallic structures of rectangular or circular cross-section used in transmission of microwaves.
- Two types of waveguide are used in linacs:
  - Radiofrequency power transmission waveguides (gas filled) for transmission of the RF power from the power source to the accelerating waveguide.
  - Accelerating waveguides (evacuated to about 10^{-6} torr) for acceleration of electrons.

5.5 LINACS

5.5.8 Microwave power transmission

- The microwave power produced by the RF generator is carried to the accelerating waveguide through rectangular uniform waveguides usually pressurized with a dielectric gas (~~freon~~ or sulphur hexafluoride SF_6).
- Between the RF generator and the accelerating waveguide is a circulator (isolator) which transmits the RF power from the RF generator to the accelerating waveguide but does not transmit microwaves in the opposite direction.

5.5.11 Linac treatment head

- Electrons forming the electron pencil beam:
  - Originate in the electron gun.
  - Are accelerated in the accelerating waveguide to the desired kinetic energy.
  - Are brought through the beam transport system into the linac treatment head.
- The clinical x-ray beams or clinical electron beams are produced in the linac treatment head.

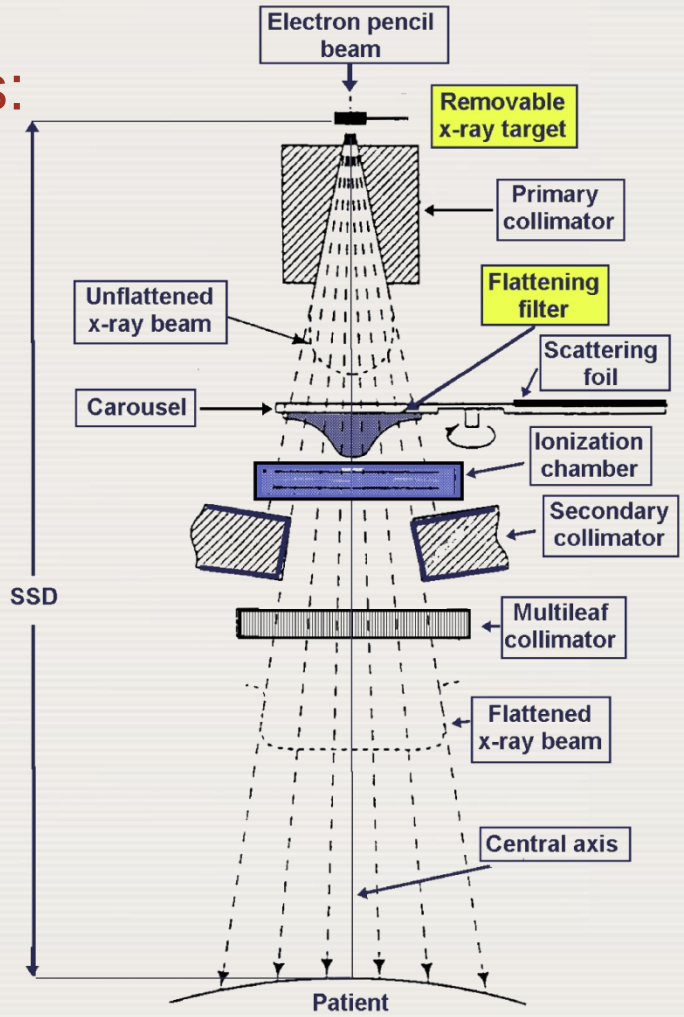
- Components of a modern linac treatment head:
  - Several retractable x-ray targets (one for each x-ray beam energy).
  - Flattening filters (one for each x-ray beam energy).
  - Scattering foils for production of clinical electron beams.
  - Primary collimator.
  - Adjustable secondary collimator with independent jaw motion.
  - Dual transmission ionization chamber.
  - Field defining light and range finder.
  - Retractable wedges.
  - Multileaf collimator (MLC).

- Clinical x-ray beams are produced with:
  - Appropriate x-ray target.
  - Appropriate flattening filter.
- Clinical electron beams are produced by:
  - Either scattering the pencil electron beam with an appropriate scattering foil.
  - Or deflecting and scanning the pencil beam magnetically to cover the field size required for electron treatment.
- The flattening filters and scattering foils are mounted on a rotating carousel or sliding drawer.

- Electrons:
  - Originate in the electron gun.
  - Are accelerated in the accelerating waveguide to the desired kinetic energy.
  - Are brought through the beam transport system into the linac treatment head.
- The clinical x-ray beams and clinical electron beams are produced in the linac treatment head.

- Megavoltage clinical x-ray beams:
  - Are produced in a linac x-ray target
  - Are flattened with a flattening filter.


Movable x-ray target (Varian 10 MV linac)

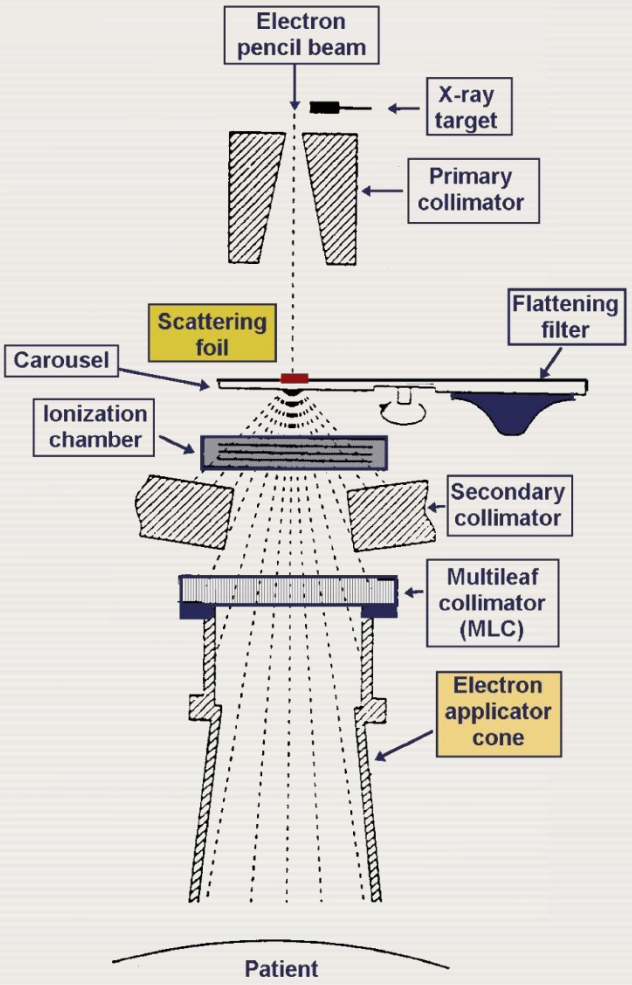


5.5.13 Beam collimation

- In modern linacs the x-ray beam collimation is achieved with three collimation devices:
  - Primary collimator.
  - Secondary adjustable beam defining collimator (independent jaws).
  - Multileaf collimator (MLC).
- The electron beam collimation is achieved with:
  - Primary collimator.
  - Secondary collimator.
  - Electron applicator (cone).
  - Multileaf collimator (under development).

5.5.14 Production of clinical electron beam

- To activate the electron mode the x-ray target and flattening filter are removed from the electron pencil beam.
- Two techniques for producing clinical electron beams from the pencil electron beam:
  - Pencil beam scattering with a scattering foil (thin foil of lead).
  - Pencil beam scanning with two computer controlled magnets.



5.7 SHIELDING CONSIDERATIONS

- Treatment rooms must comply:
  - Not only with structural building codes
  - But also with national and international regulations that deal with shielding requirements to render an installation safe from the radiation protection point of view.
- During the planning stage for a radiotherapy machine installation, a qualified medical physicist:
  - Determines the required thickness of primary and secondary barriers
  - Provides the information to the architect and structural engineer for incorporation into the architectural drawing for the treatment room.

5.8 COBALT-60 TELETHERAPY UNITS VERSUS LINACS

- In comparison with cobalt-60 teletherapy machines linacs have become very complex in design:
  - Because of the multimodality capabilities that have evolved and are available on most modern linacs (several x-ray energies and several electron energies).
  - Because of an increased use of computer logic and microprocessors in the control systems of linacs.
  - Because of added features, such as high dose rate modes, multileaf collimation, electron arc therapy, and the dynamic treatment option on the collimators (dynamic wedge), MLC leaves (IMRT), gantry or table while the beam is turned on.

References about accelerator technology

Linear Accelerators for Radiation Therapy, 2 nd edition. D. Greene and P. C. Williams: Bristol: Institute of Physics, 1997.

Treatment Machines For External Beam Radiotherapy, Chapter 5 in "Radiation Oncology Physics: A Handbook for Teachers and Students“ E.B. Podgorsak –download at http://www-pub.iaea.org/mtcd/publications/pdf/pub1196_web.pdf

Primer on Theory and Operation of Linear Accelerators, 2nd edition. C. J. Karzmark and R. Morton. Madison, WI: Medical Physics Publishing, 1998.

Medical Electron Accelerators. C. J. Karzmark, C. S. Nunan, and E. Tanabe. New York: McGraw-Hill Ryerson, 1993.

Reviews of Accelerator Science and Technology, vol. 2. Medical Applications of Accelerators. A. W. Chao and W. Chou. Hackensack, NJ: World Scientific, 2009.

Video illustrations about Linear Accelerator function

How a Linear Accelerator Works – HD - ELEKTA
https://www.youtube.com/watch?v=jSgnWfbEx1A

Elekta treatment unit https://www.youtube.com/watch?v=QsfQLyuAbLg

http://www.youtube.com/watch?v=hy9atKAqAf4 **(Part 1)**

https://www.youtube.com/watch?v=k27PZCUPeiE **(Part 2)**