LINEAR ACCELERATORS FOR RADIOTHERAPY

-

PART 2- SUB-SYSTEMS

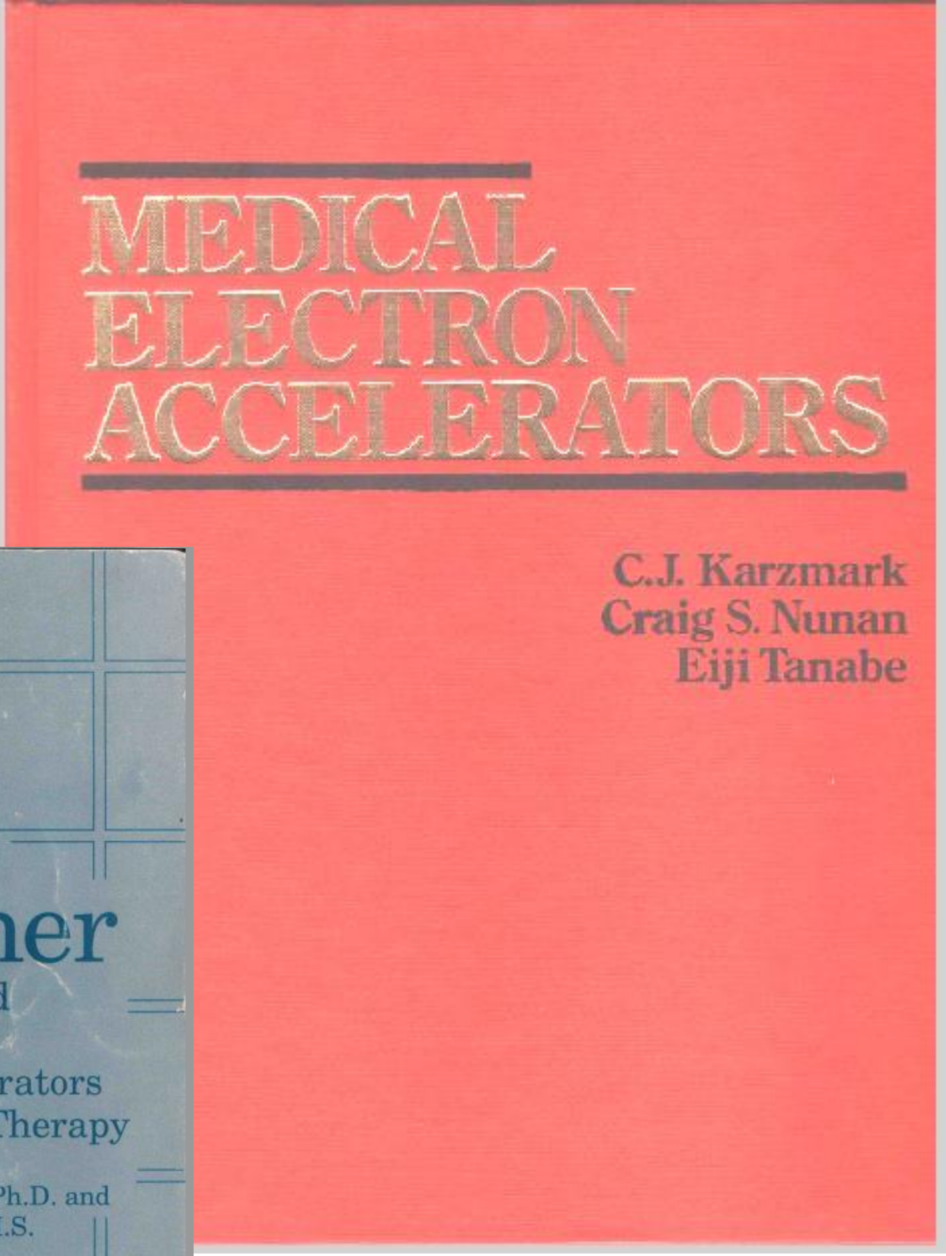
ICTP SCHOOL ON MEDICAL PHYSICS FOR RADIATION THERAPY
DOSIMETRY AND TREATMENT PLANNING FOR BASIC AND ADVANCED APPLICATIONS
March 27 – April 7, 2017
Miramare, Trieste, Italy

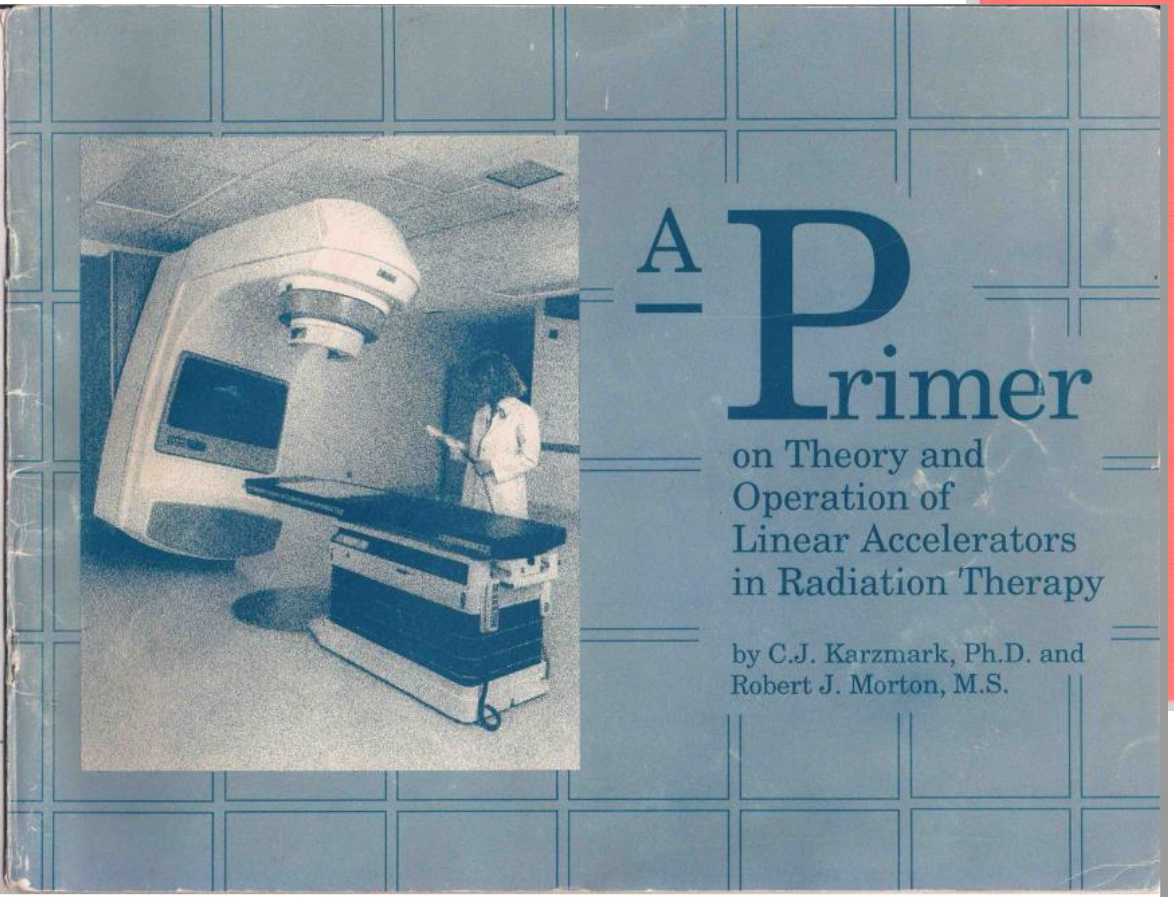
Yakov Pipman, D.Sc.

We all know about Linear Accelerators

What is Under the covers?

What is Under the covers?


MEDICAL
ELECTRON
ACCELERATORS
C.J. Karzmark
Craig S. Nunan
Eiji Tanabe


A Primer
on Theory and
Operation of
Linear Accelerators
in Radiation Therapy
by C.J. Karzmark, Ph.D. and
Robert J. Morton, M.S.

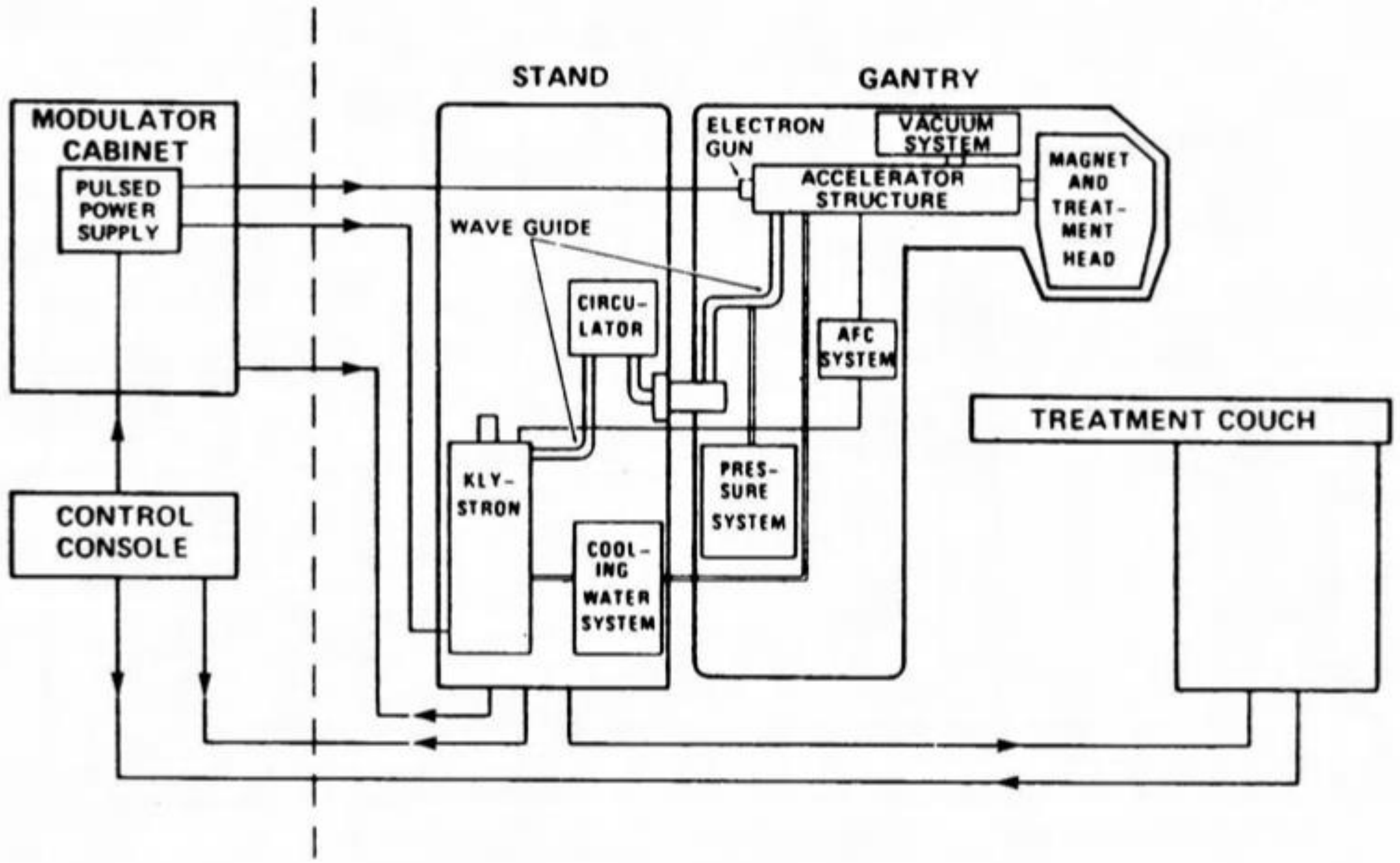


FIGURE 1-21 · Simplified block diagram of major parts of a medical linac.

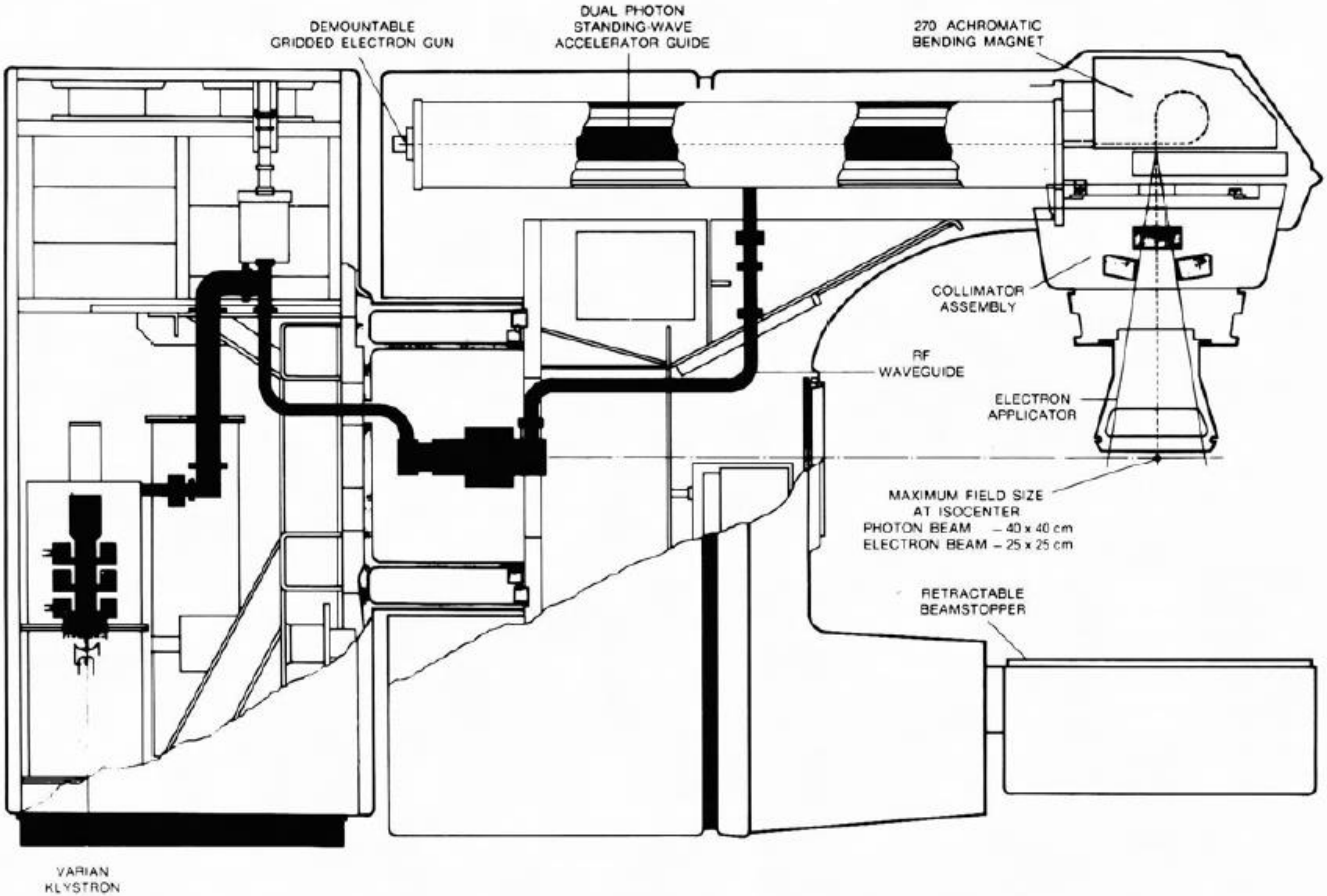


FIGURE 1-12 · Multimode linac with microwave energy switch and 270° doubly achromatic magnet—the Clinac 1800 (from Varian).

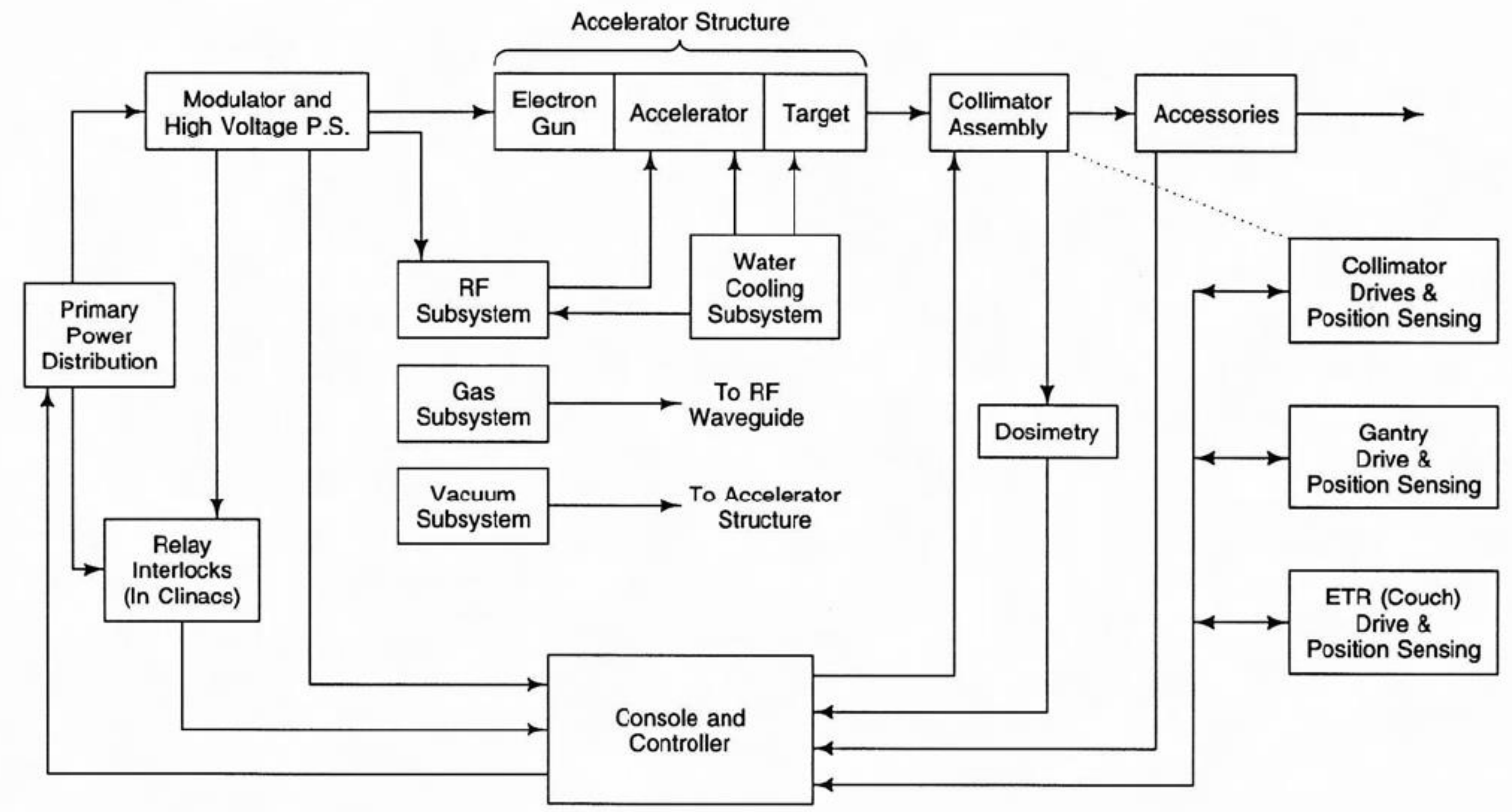
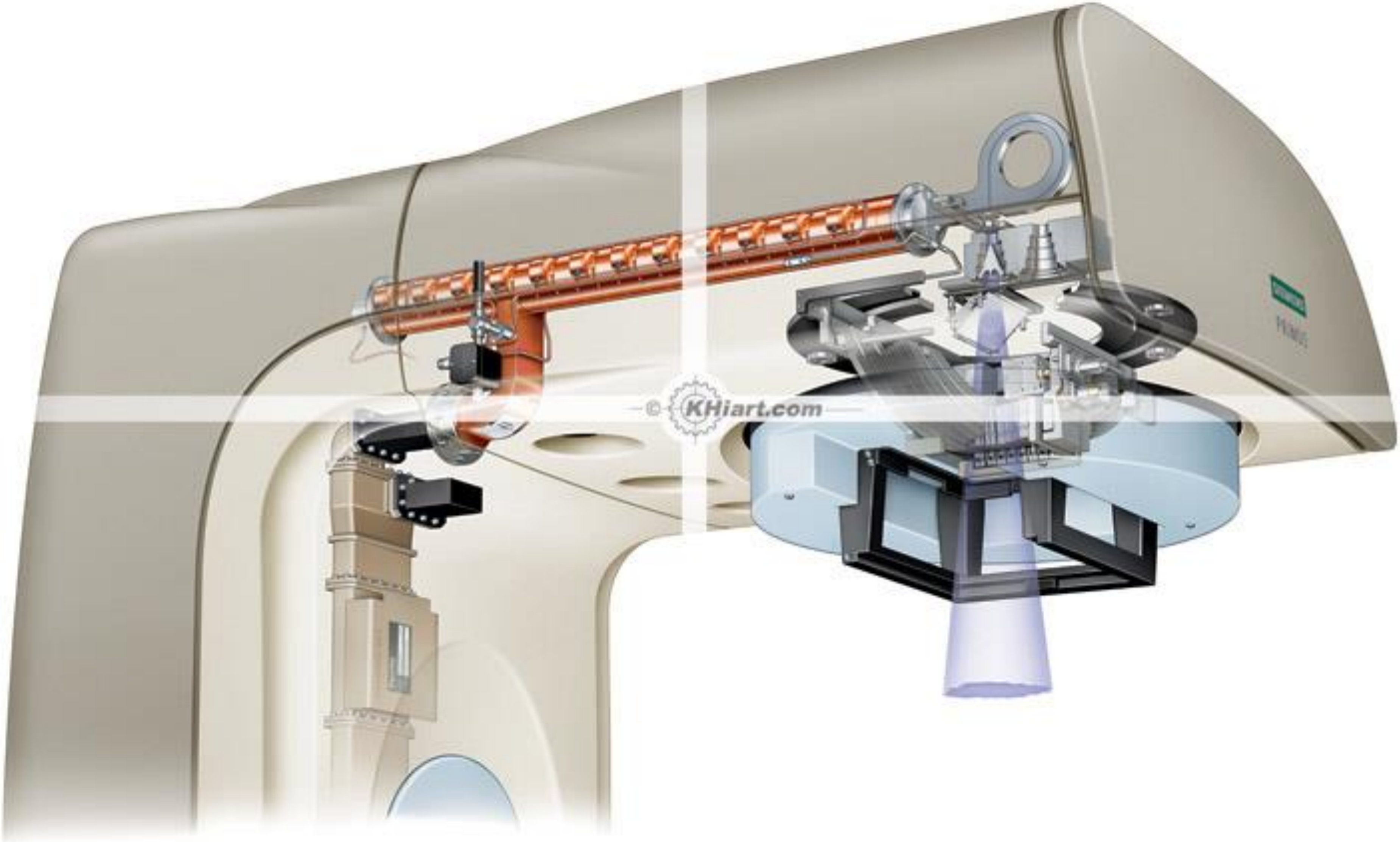


FIGURE 1-6 · Block diagram for low-energy machine.


ON
OFF

Ancillary systems

1. High Voltage – High Power
2. Resonant Cavity and beam transport
3. Vacuum
4. Beam steering
5. Mechanical - gantry
6. Mechanical - head
7. MLC
8. Cooling
9. Optics
10. Control console
11. External Laser system



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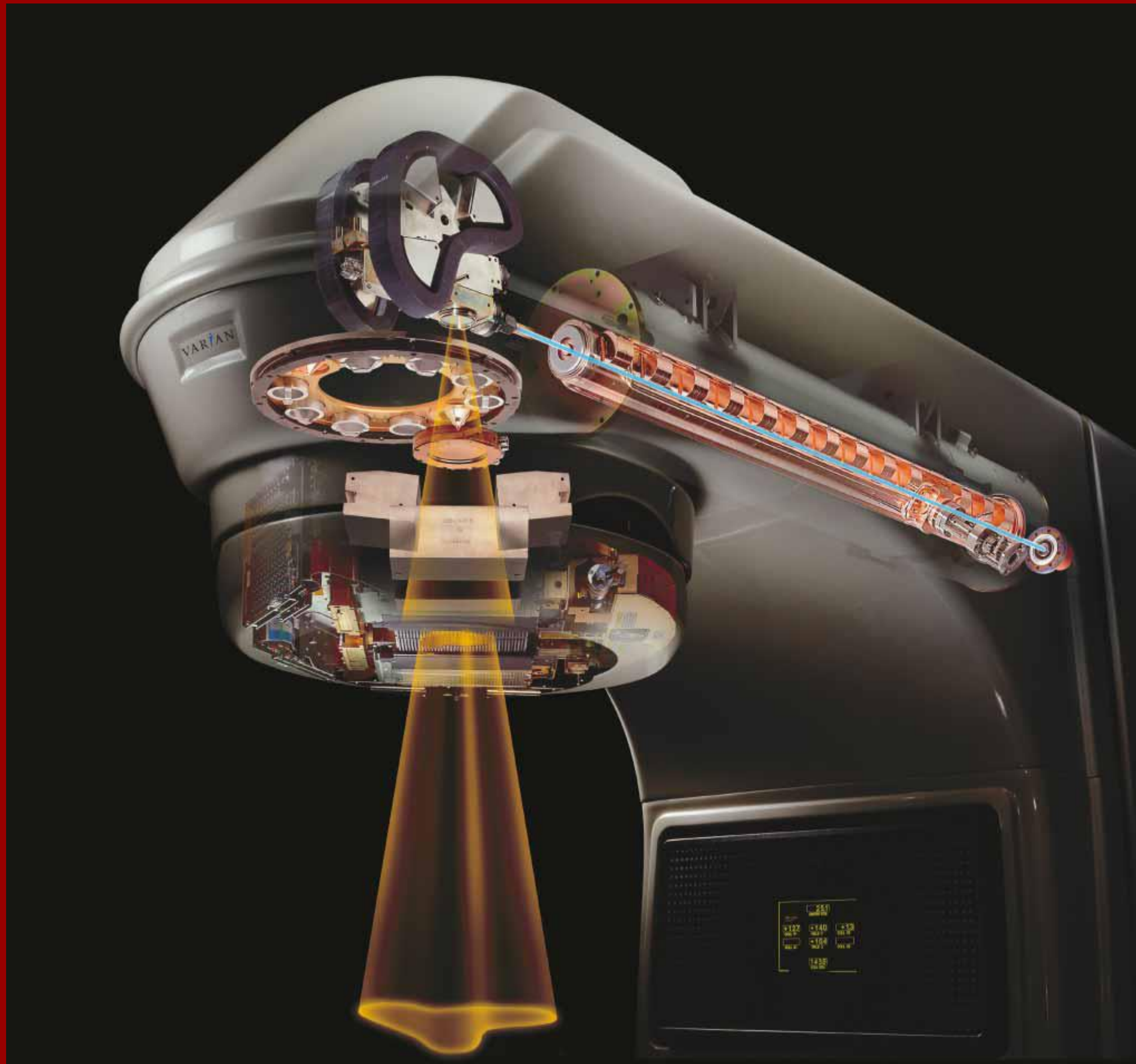
CLINAC


VARIAN

Control console – human interface

- **The "director" of the orchestra**

Radiation Therapy — Equipment and People

A linear accelerator control console showing all of the functions monitored during a treatment.

Control console - The “machinist” of the train

- The basic computer control system architecture of 3 major OEMs
- How mode selection and beam control are achieved
- How accelerator design dictates the computerization of linacs

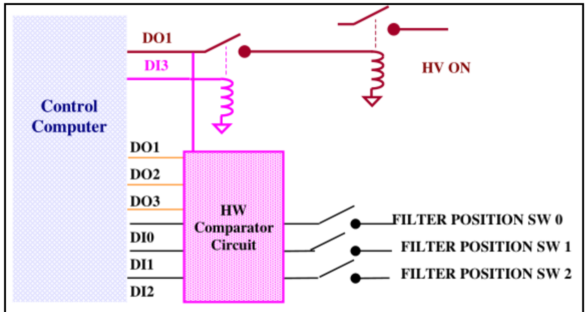
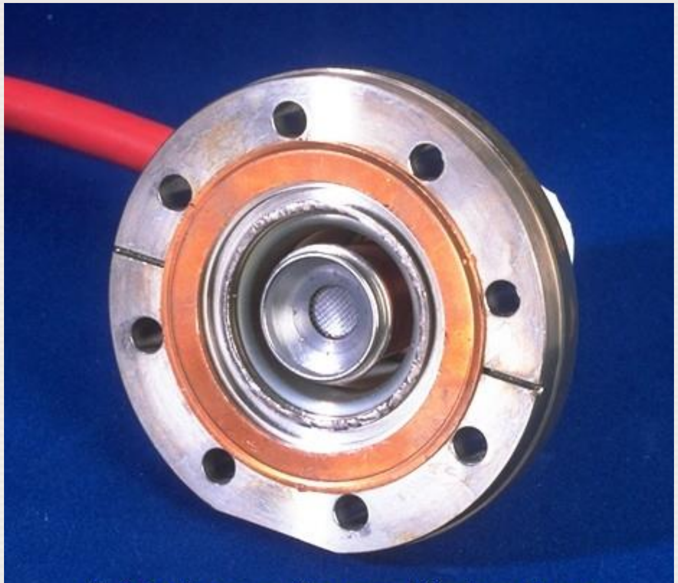


Figure 2: Computer control with hardware backup. The control computer enables or disables the HV ON line based on inputs from the Filter Position Switches. A hardware comparator also enables or disables the HV after comparing the expected data on DO 0 – DO2 with the filter switch data. In the event of software bug or switch failure, the HV could not be turned on with a filter out of position.

- How fundamental accelerator design impacts the design and implementation of IMRT.
- See: Handout for “The Theory and Operation of Computer-Controlled Medical linear Accelerators" MO-A-517A-01 Tim Waldron 7/15/02 (AAPM)

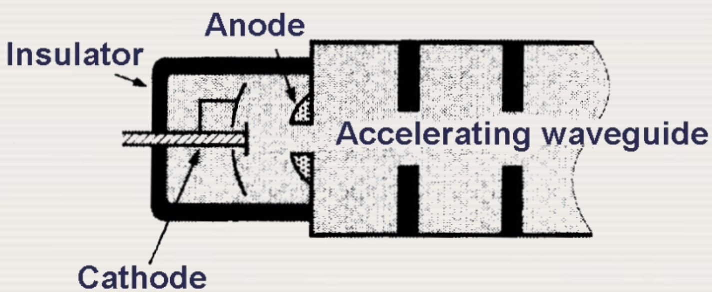
- The linac injection system is the source of electrons, a simple electrostatic accelerator referred to as the electron gun.
- Two types of electron gun are in use in medical linacs:
  - Diode type
  - Triode type
- Both electron gun types contain:
  - Heated filament cathode
  - Perforated grounded anode
  - Triode gun also incorporates a grid



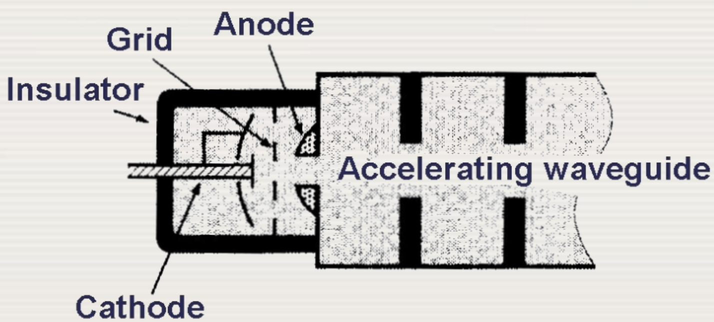
A triode gun from a Varian linac

- Two types of electron gun producing electrons in linac:

Diode type gun



Triode type gun



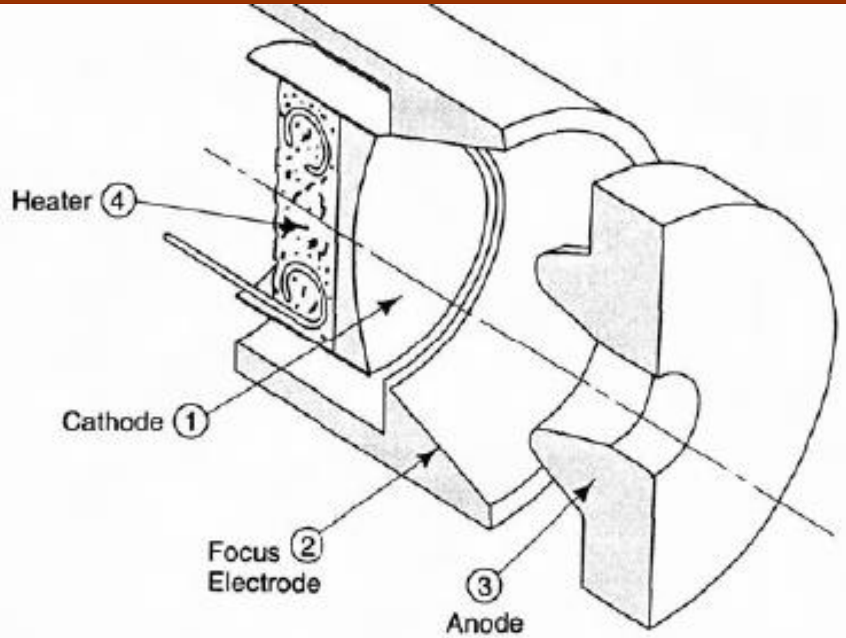


FIGURE 4-1 · Cross-sectional view of a diode electron gun.

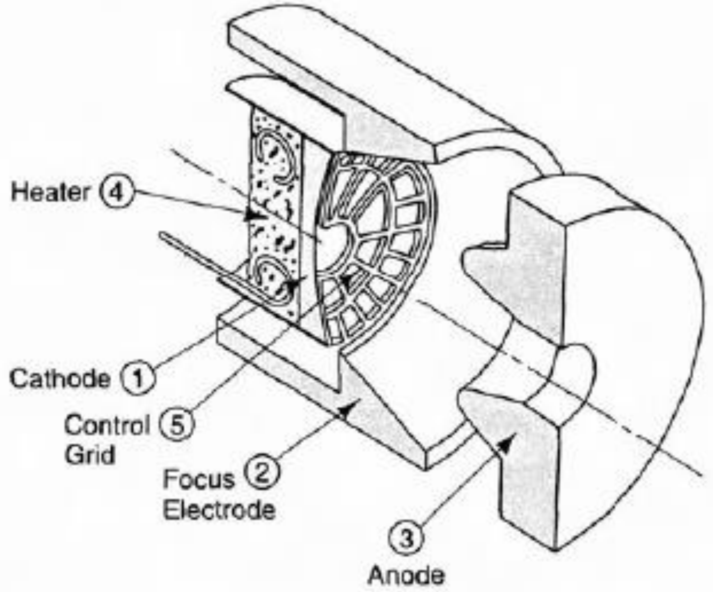
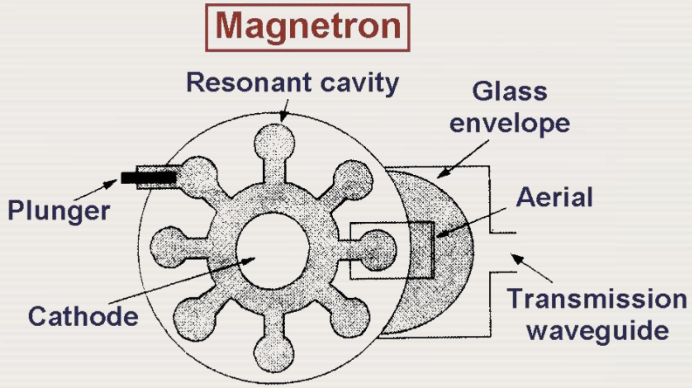
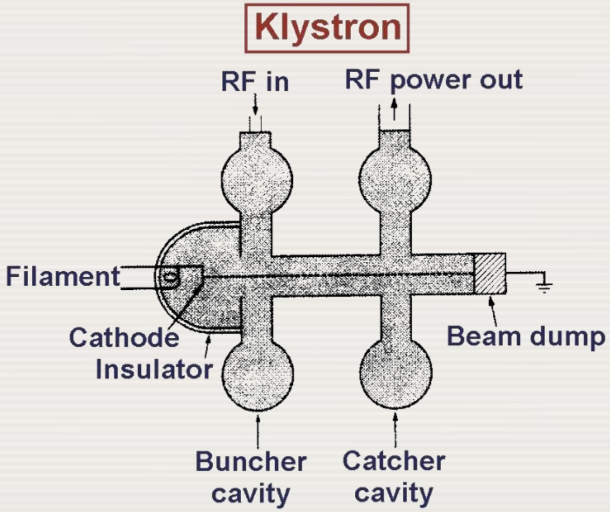


FIGURE 4-2 · Cross-sectional view of a triode electron gun with control grid.

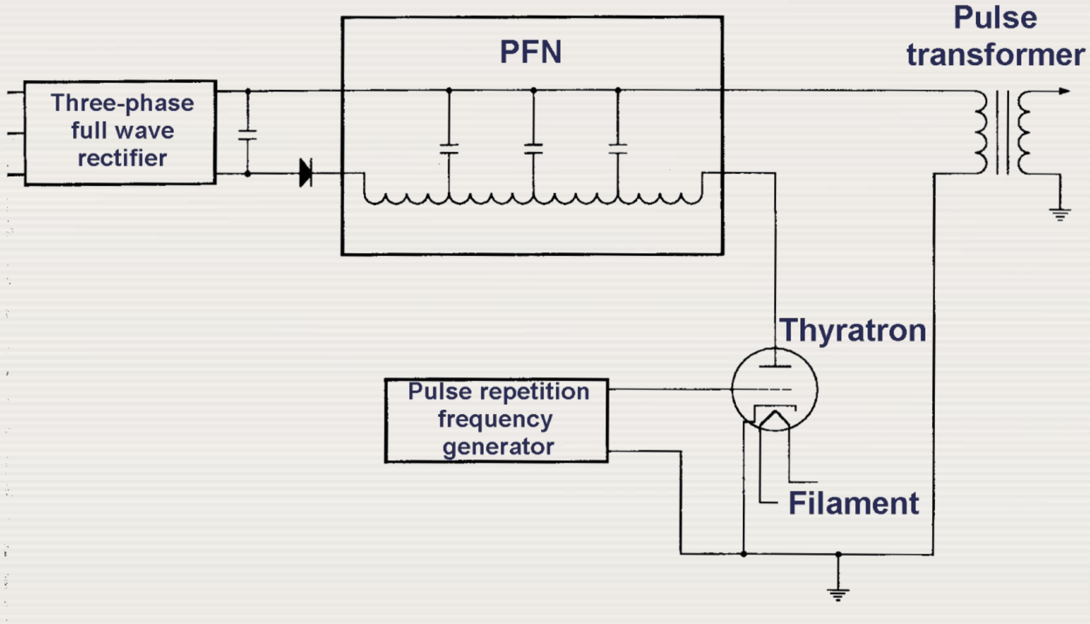
5.5.6 Radiofrequency power generation system

- The radiofrequency power generation system produces the microwave radiation used in the accelerating waveguide to accelerate electrons to the desired kinetic energy and consists of two major components:
  - RF power source (magnetron or klystron)
  - Pulsed modulator





- Pulsed modulator produces the high voltage (□100 kV), high current (□100 A), short duration (□1 μs) pulses required by the RF power source and the injection system.



High Voltage – High Power RF

The magnetron acts as a high power oscillator
A 12 cavity magnetron, where the magnetic field is applied perpendicular to the axis of the cavities
- **suitable for low energy accelerators (4, 6 MV)**
- **It is more unstable than klystron**
- **typically 2-3 MW peak power**
- **average lifetime ~ 1 yr, but can be extended by running it at a lower dose rate)**

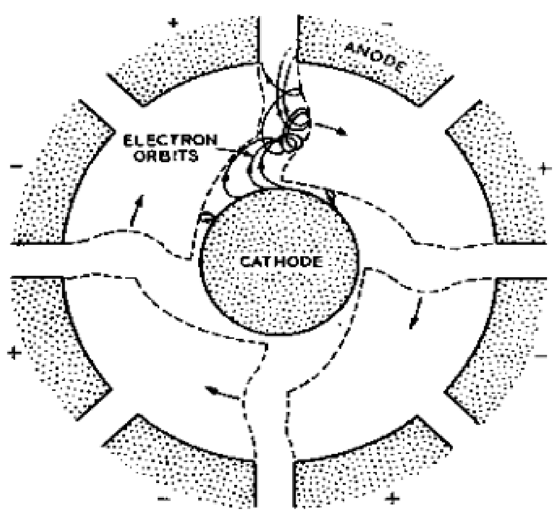
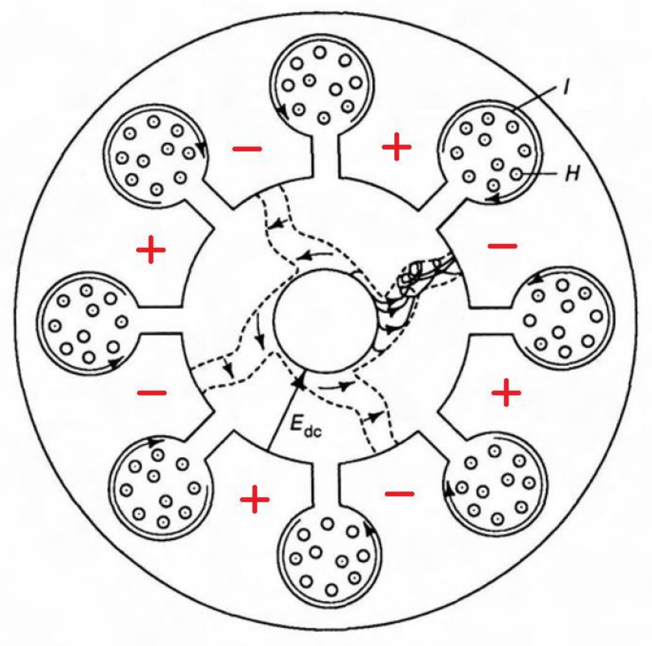


FIG. 326.—Space-charge distribution and electron paths in an 8-cavity magnetron, when oscillating.

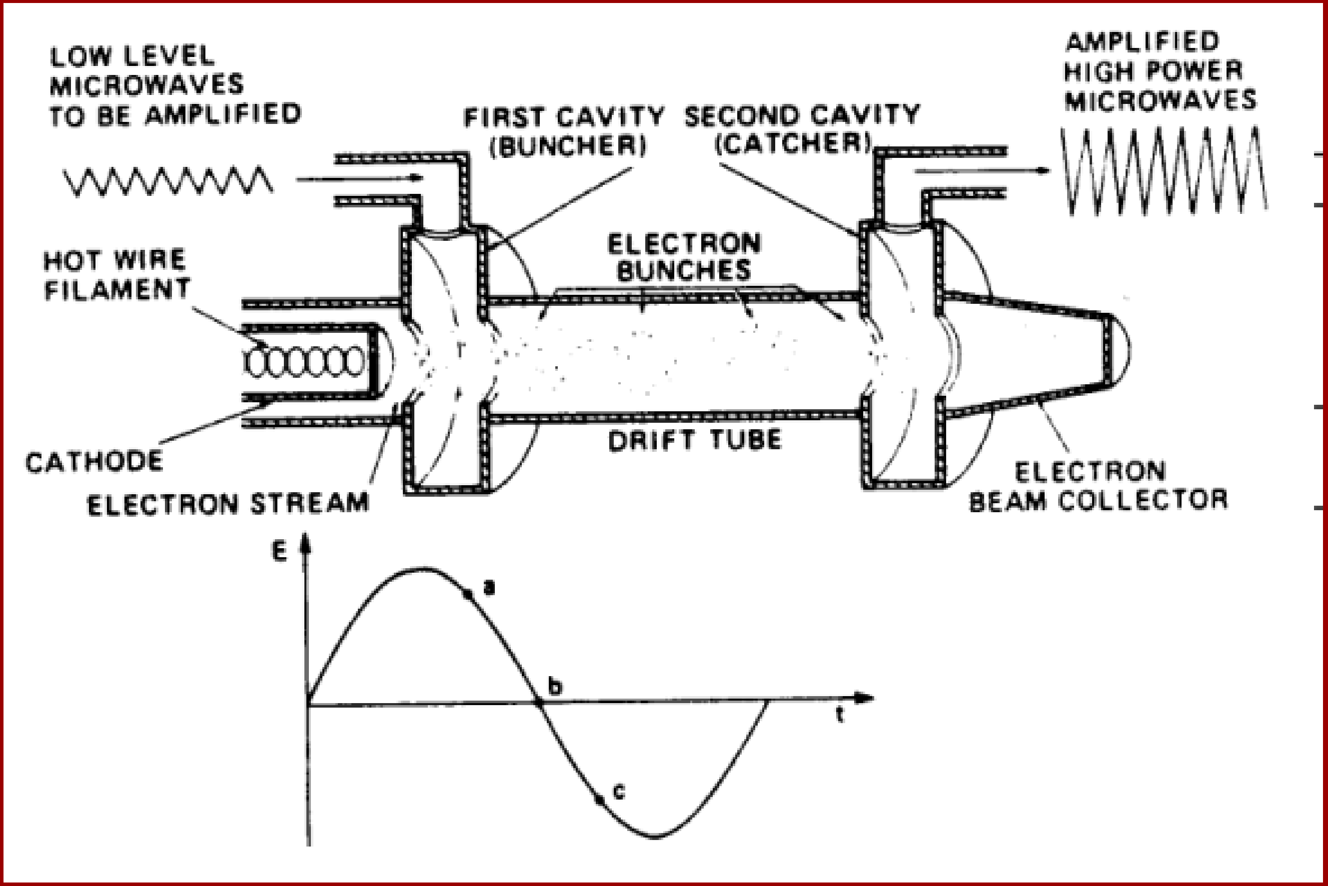


High Voltage – High Power RF

The Klystron acts as a power amplifier - suitable for high energy accelerators (> 10 MV)

- practical units generally have several stages, typically 20 MW peak power and 20 kW average power

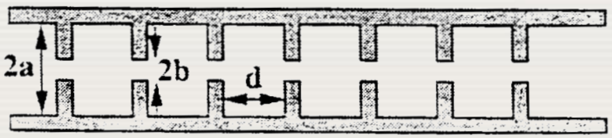
Requires the input of a very stable RF generator of several wats power



- Accelerating waveguide is obtained from a cylindrical uniform waveguide by adding a series of disks (irises) with circular holes at the centre, placed at equal distances along the tube to form a series of cavities.
  - The role of the disks (irises) is to slow the phase velocity of the RF wave to a velocity below the speed of light in vacuum to allow acceleration of electrons.
- The cavities serve two purposes:
  - To couple and distribute microwave power between cavities.
  - To provide a suitable electric field pattern for electron acceleration.

Uniform waveguide

Disk-loaded waveguide



- The accelerating waveguide is evacuated (10^{-6} tor) to allow free propagation of electrons.

Vacuum

All electron paths, as well as the klystron or magnetron, must be kept at high vacuum (10^{-7} torr level) (1 torr = 1 mmHg, 1 atm = 760 torr) to prevent electrical breakdown in the residual gas for the high electromagnetic fields used to accelerate electrons

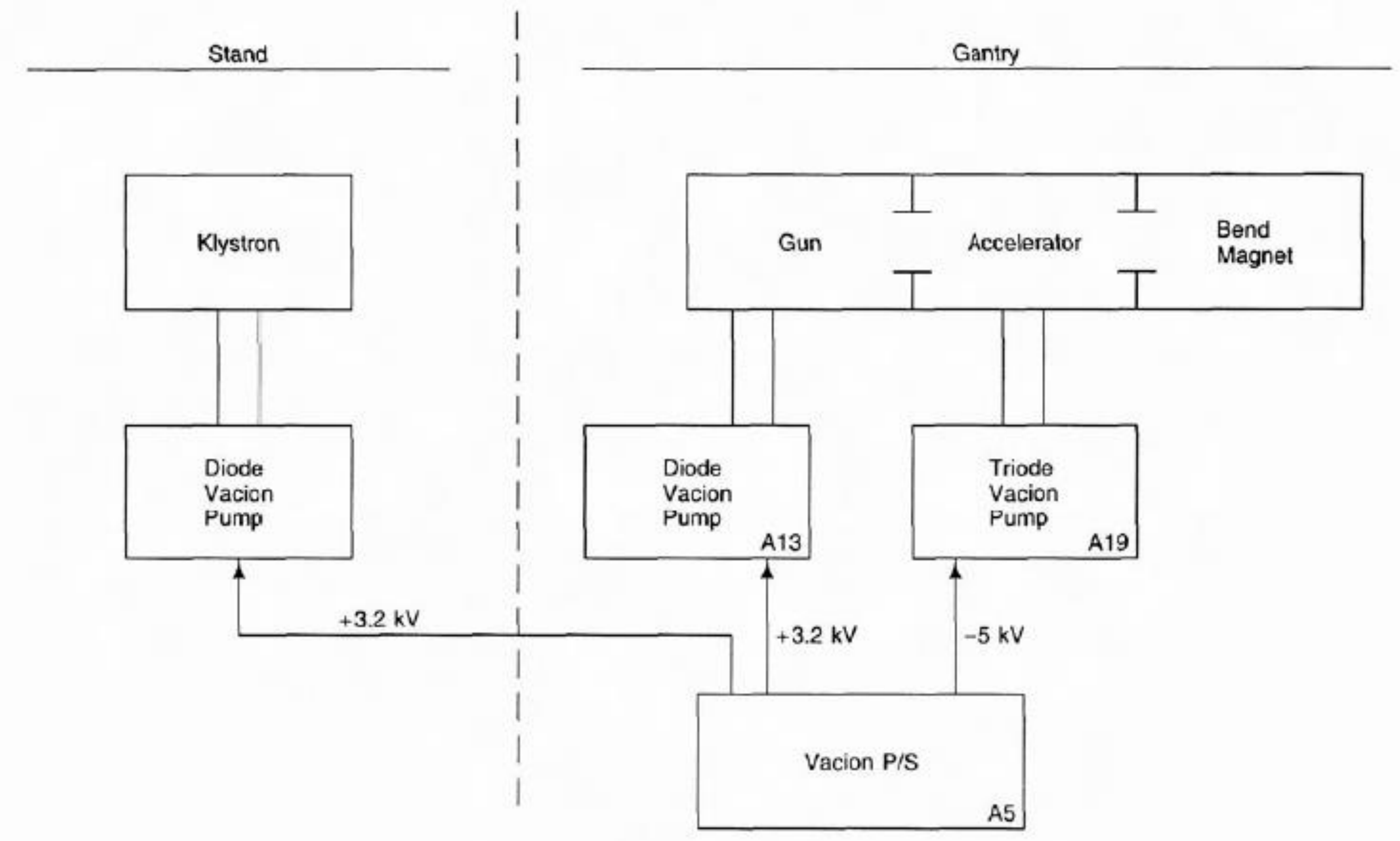


FIGURE 6-5 · Block diagram of vacuum system for Clinac 1800.

Vacuum

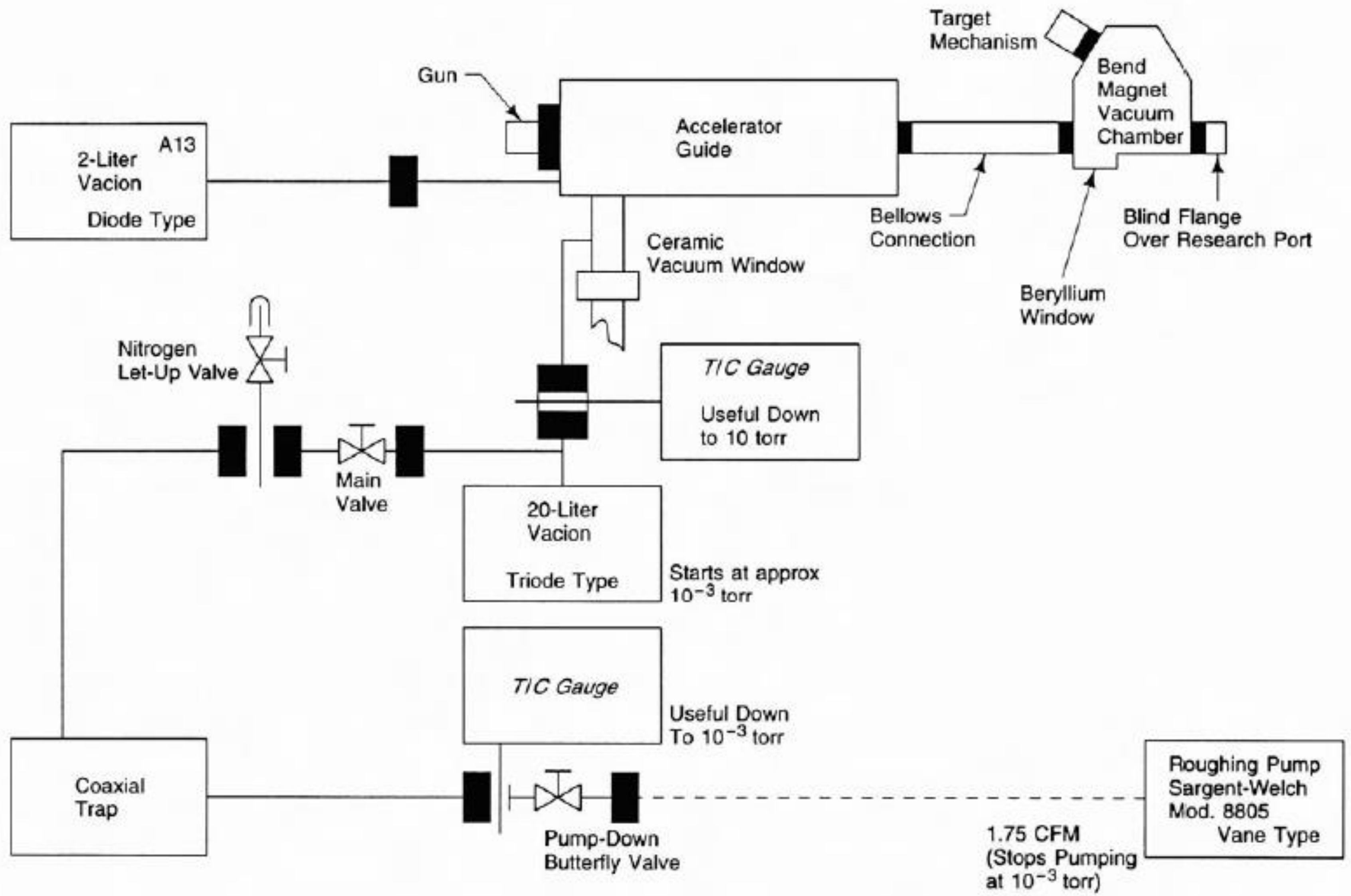
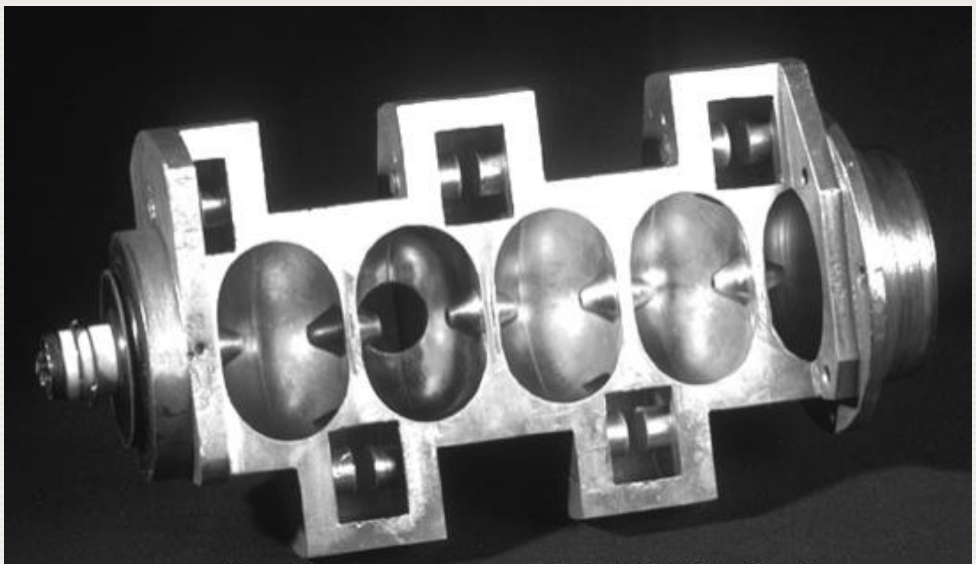


FIGURE 6-7 · Vacuum components in the gantry of a Clinac 1800.

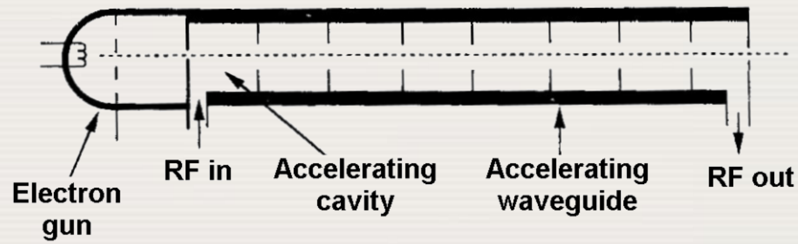
5.5.7 Accelerating waveguide

- Two types of accelerating waveguide are in use:
  - Traveling wave structure
  - Standing wave structure

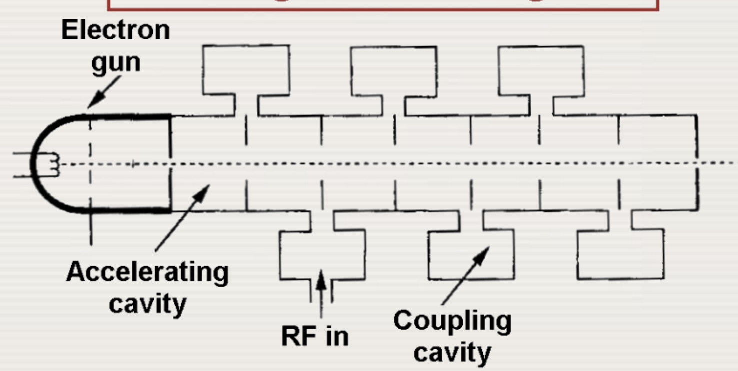


Standing wave waveguide (EMI Medical)

Travelling wave waveguide

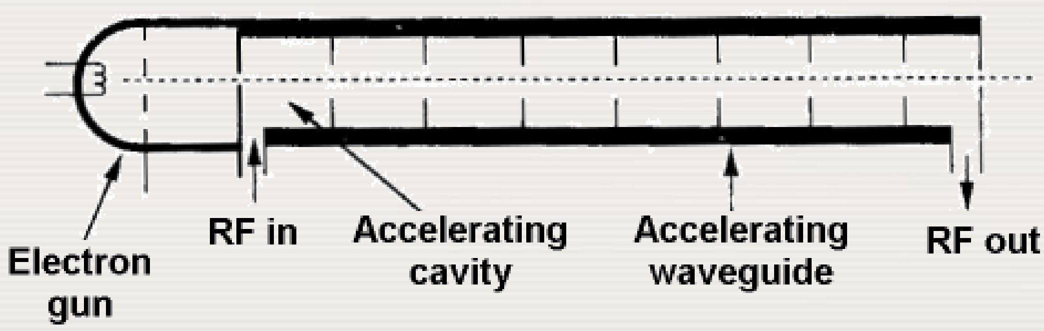


Standing wave waveguide



- In the travelling wave accelerating structure the microwaves enter on the gun side and propagate toward the high energy end of the waveguide.
- Only one in four cavities is at any given moment suitable for acceleration.

Travelling wave waveguide



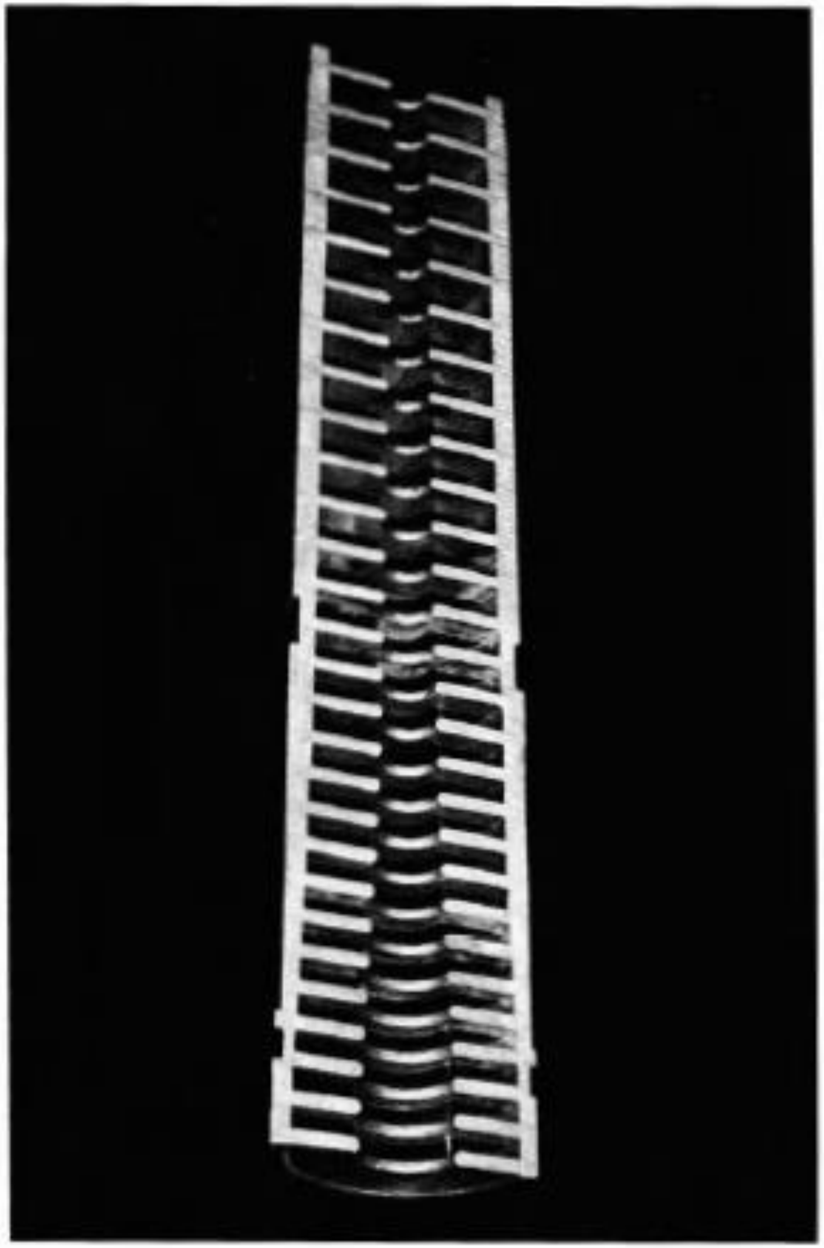
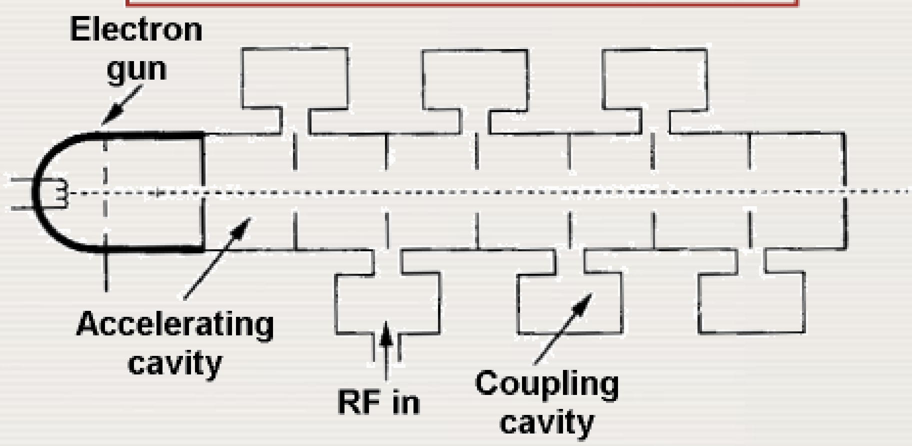


FIGURE 4-10 · Cutaway view of a TW accelerator structure with tapered buncher initial portion and constant gradient final portion.

- In the standing wave accelerating structure each end of the accelerating waveguide is terminated with a conducting disk to reflect the microwave power producing a standing wave in the waveguide.
- Every second cavity carries no electric field and thus produces no energy gain for the electron (coupling cavities).

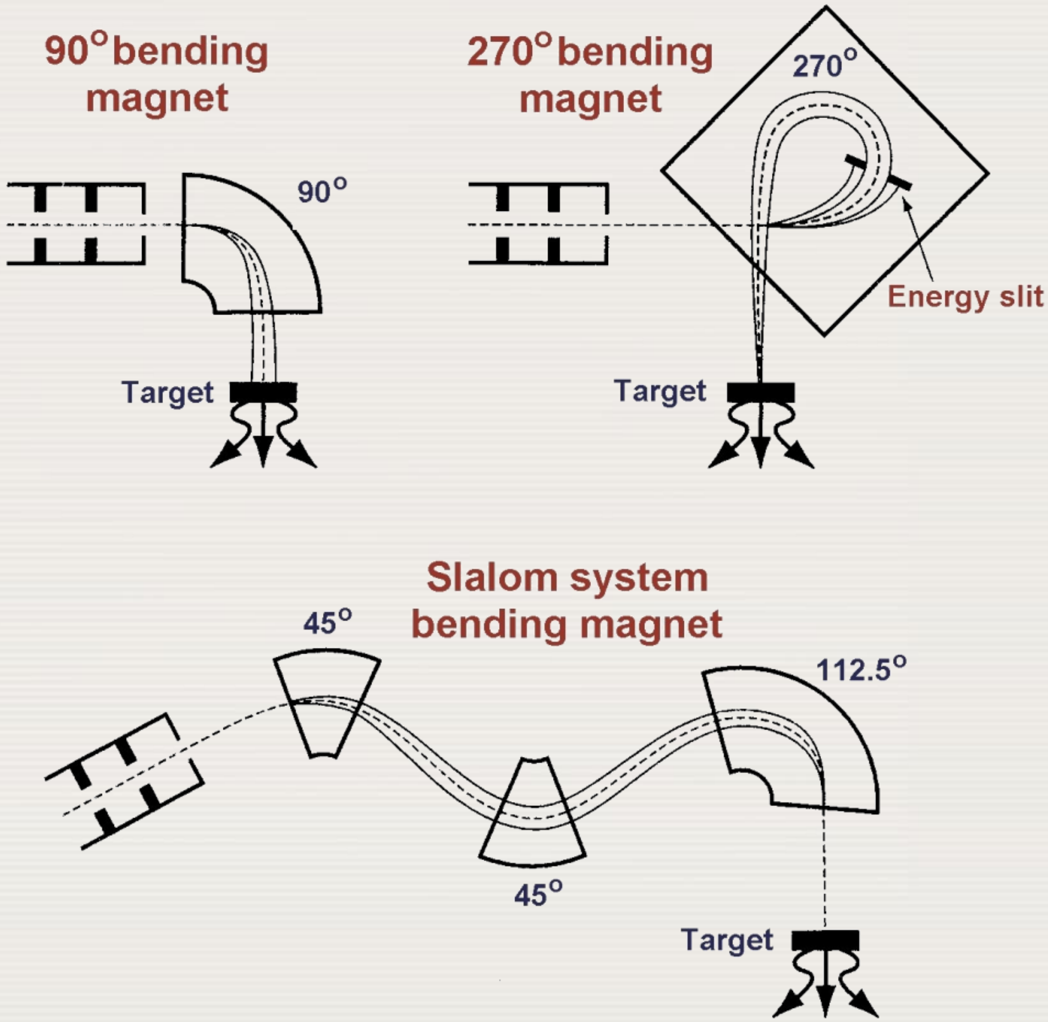
Standing wave waveguide



- In medium-energy and high-energy linacs an electron beam transport system is used to transport electrons from the accelerating waveguide to:
  - X-ray target in x-ray beam therapy
  - Beam exit window in electron beam therapy
- Beam transport system consists of:
  - Drift tubes
  - Bending magnets
  - Steering coils
  - Focusing coils
  - Energy slits

5.5 LINACS
5.5.10 Electron beam transport

- Three systems for electron beam bending:
  - 90º bending
  - 270º bending
  - 112.5º (slalom) bending



Beam Transport

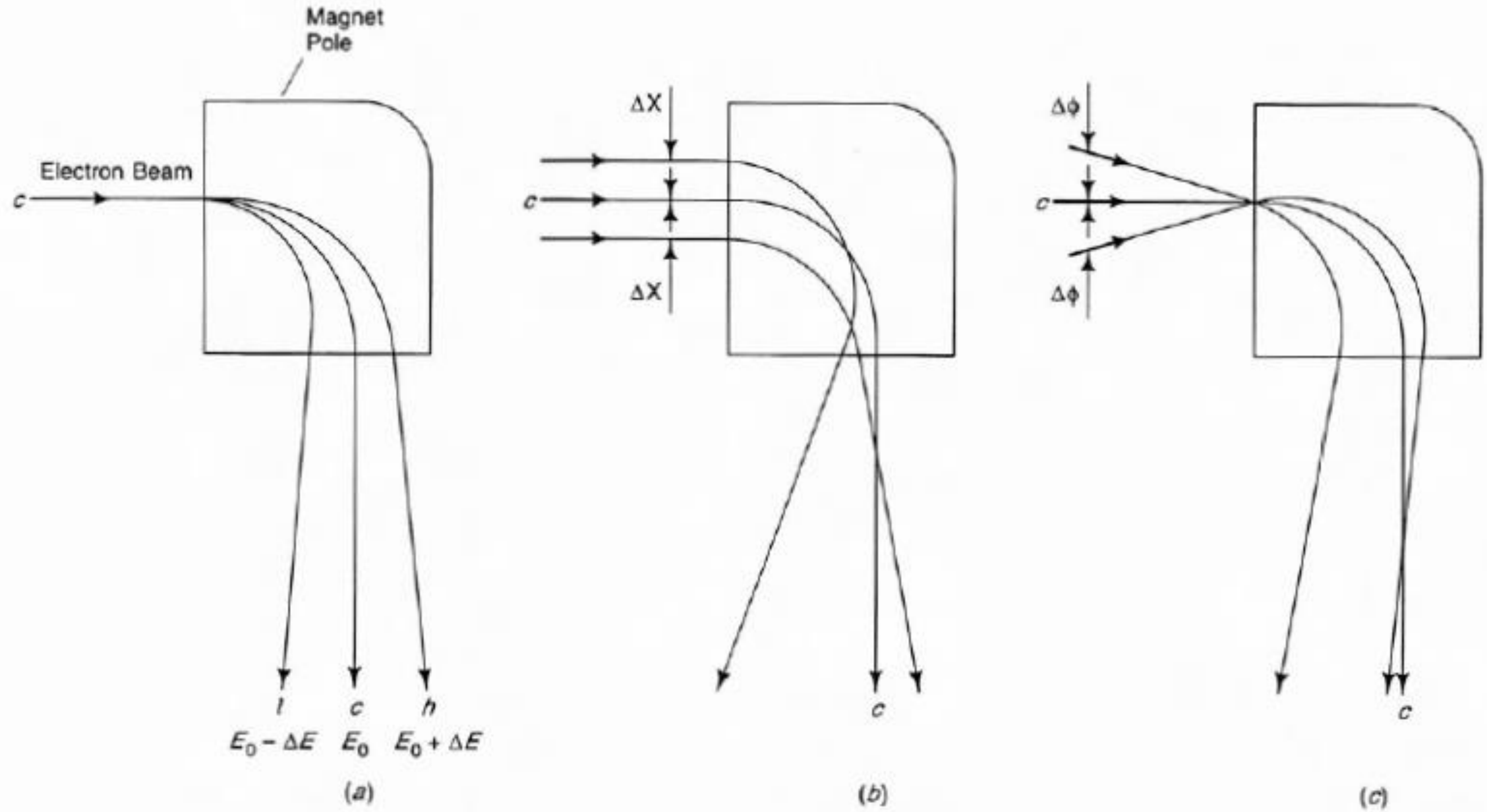


FIGURE 7-15 · Effect of 90° dipole magnet on exit beam having (a) energy spread, (b) radial displacement, and (c) radial divergence.

Steering effects on clinical beam

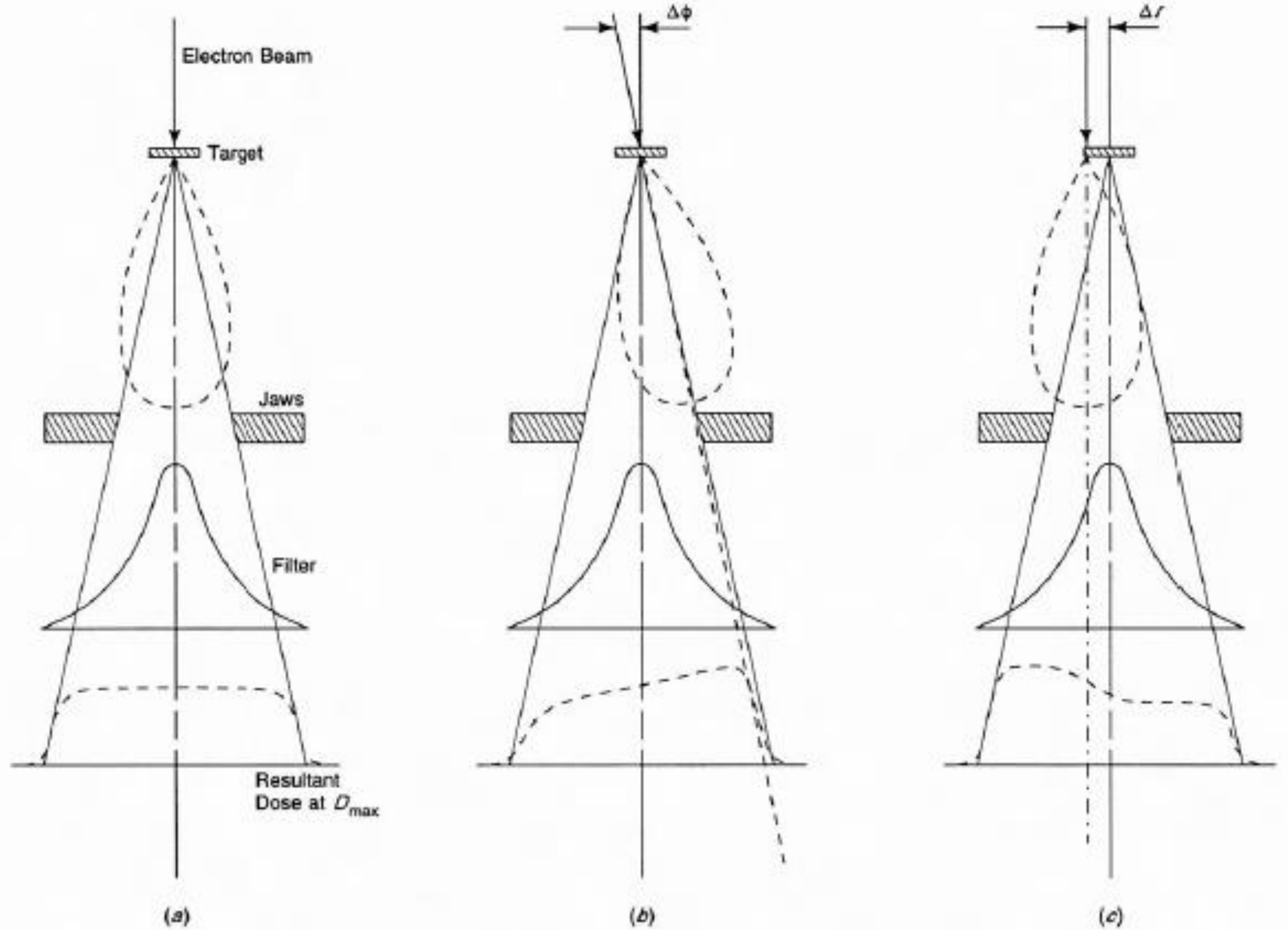


FIGURE 7-16 · Flattened x-ray field distributions. (*a*) Symmetrical, electron beam axial at x-ray target, (*b*) asymmetrical, electron beam tilted at x-ray target; and (*c*) asymmetrical, electron beam displaced at x-ray target.

Electron clinical beam

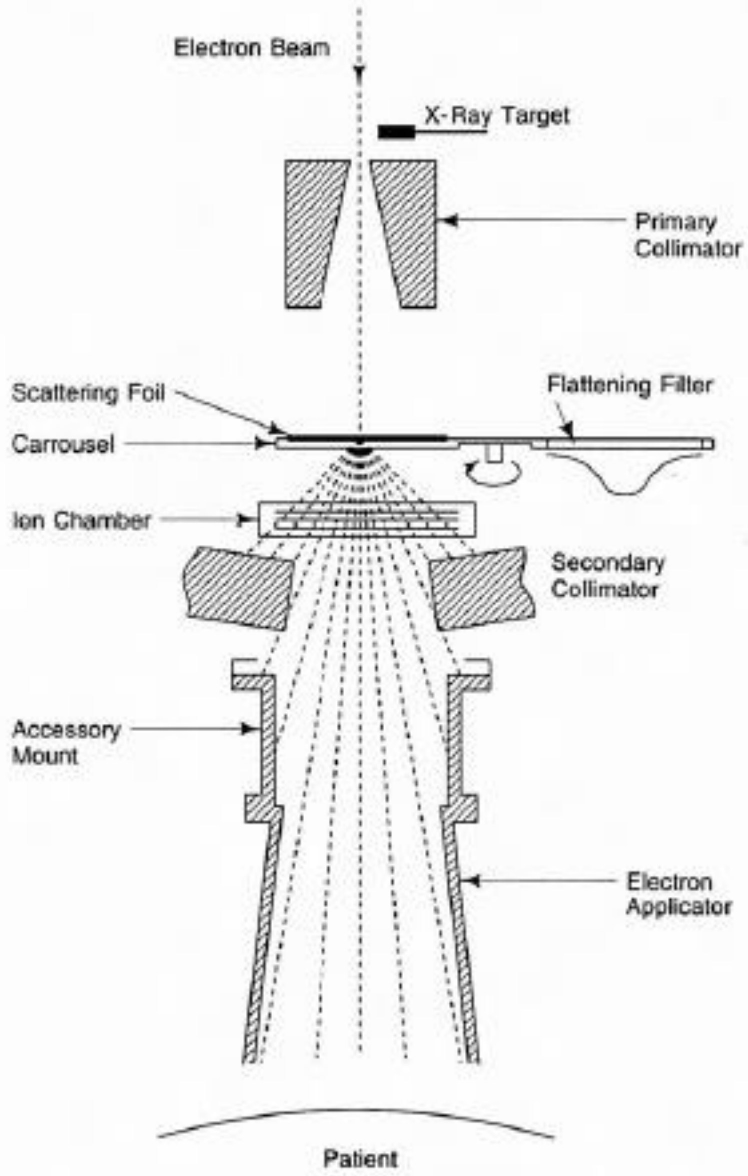


FIGURE 8-4 · **Beam subsystem for electron beam therapy. Cross section view including central axis of the beam.**

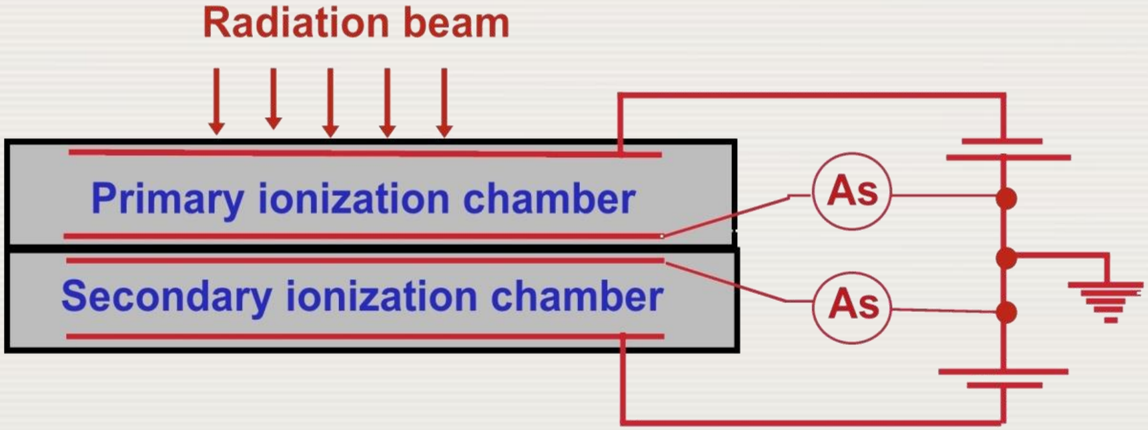
- To protect the patient, the standards for dose monitoring systems in clinical linacs are very stringent.

- The standards are defined for:

  - Type of radiation detector.
  - Display of monitor units.
  - Methods for beam termination.
  - Monitoring the dose rate.
  - Monitoring the beam flatness.
  - Monitoring beam energy.
  - Redundancy systems.

- **Transmission ionization chambers,** permanently embedded in the linac's x-ray and electron beams, are the most common dose monitors.

- They consist of two **separately sealed ionization chambers** with completely independent biasing power supplies and readout electrometers for increased patient safety.



Dose monitoring chamber

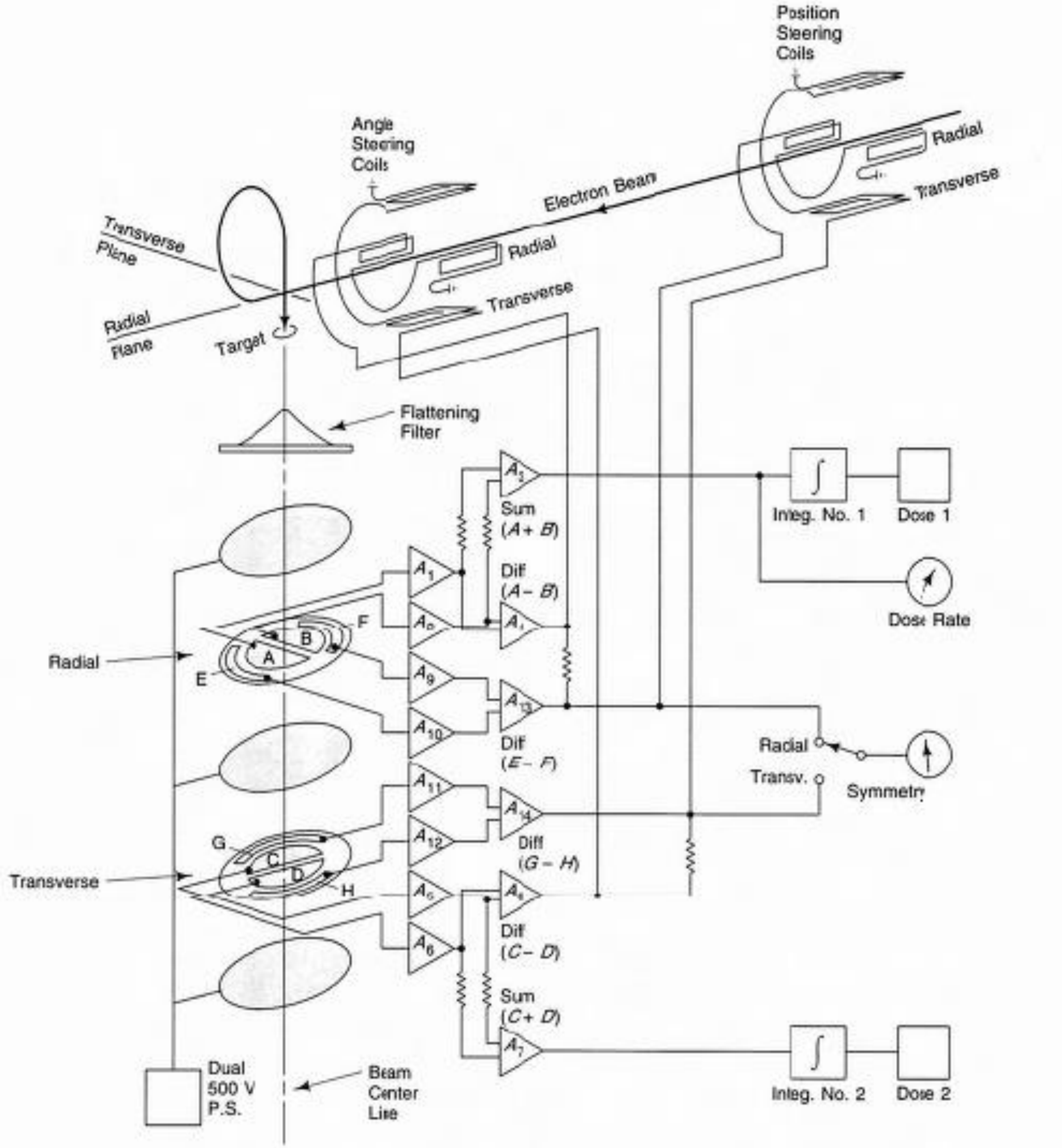


FIGURE 9-1 · Five-electrode ionization chamber with sinplified block diagram of dosimetry and beam steering system. The radial and transverse coordinate planes of the bending magnet orbit are identified in the upper left. The radial angle steering coils are actually located in the bending magnet, as shown in more detail in Figure 9-2.

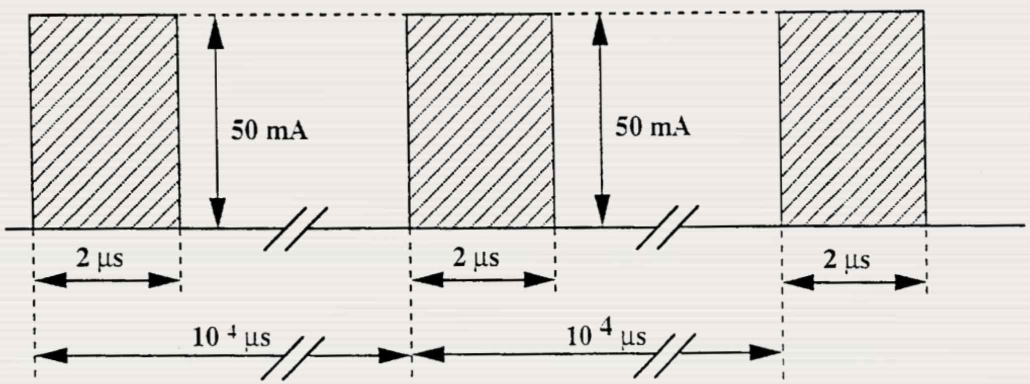
- Most linac transmission ionization chambers are **permanently sealed**, so that their response is not affected by ambient air temperature and pressure.
- The customary position for the transmission ionization chamber is between the flattening filter (for x-ray beams) or scattering foil (for electron beams) and the secondary collimator.

- The primary transmission ionization chamber measures the monitor units (MUs).
- Typically, the sensitivity of the primary chamber electrometer is adjusted in such a way that:
  - 1 MU corresponds to a dose of 1 cGy
  - delivered in a water phantom at the depth of dose maximum
  - on the central beam axis
  - for a 10x10 cm^2 field
  - at a source-surface distance (SSD) of 100 cm.

- Once the operator preset number of MUs has been reached, the primary ionization chamber circuitry:
  - Shuts the linac down.
  - Terminates the dose delivery to the patient.

- Before a new irradiation can be initiated:
  - MU display must be reset to zero.
  - Irradiation is not possible until a new selection of MUs and beam mode has been made.

- Typical **electron pulses** arriving on the x-ray target of a linac.



Typical values:

Pulse height: 50 mA
Pulse duration: 2 µs
Repetition rate: 100 pps
Period: 10^4 µs

- The target is insulated from ground, acts as a Faraday cup, and allows measurement of the electron charge striking the target.

Dose efficiencies

TABLE 9-1 · Linac operating parameters

X-rays[a]				Electrons[a]			
Energy, (MV)	Average beam current in µA	Filter trans. (%)	Dose Rate (cGy/m/1m)	Energy (MeV)	Average beam current in nA	Scatter Foil (mil)	Dose rate, (cGy/m/1m)
4	200	45	200[b]				
6	100	35	400[b]	6	100	3 Ta	500
10	70	30	500[c]	9	97	8 Pb + 7 Al button	500
15	50	25	500[c]	12	67		500
18	30	18	500[c]	16	42		500
25	20	10	500[c]	20	30		500

[a] $1 \mu A = 10^{-6}$ A. $= 10^{-3}$nA
[b] At 300 pps, 3.5-µs pulse.
[c] At 150 pps, 3.5-µs pulse.

Mechanical - gantry

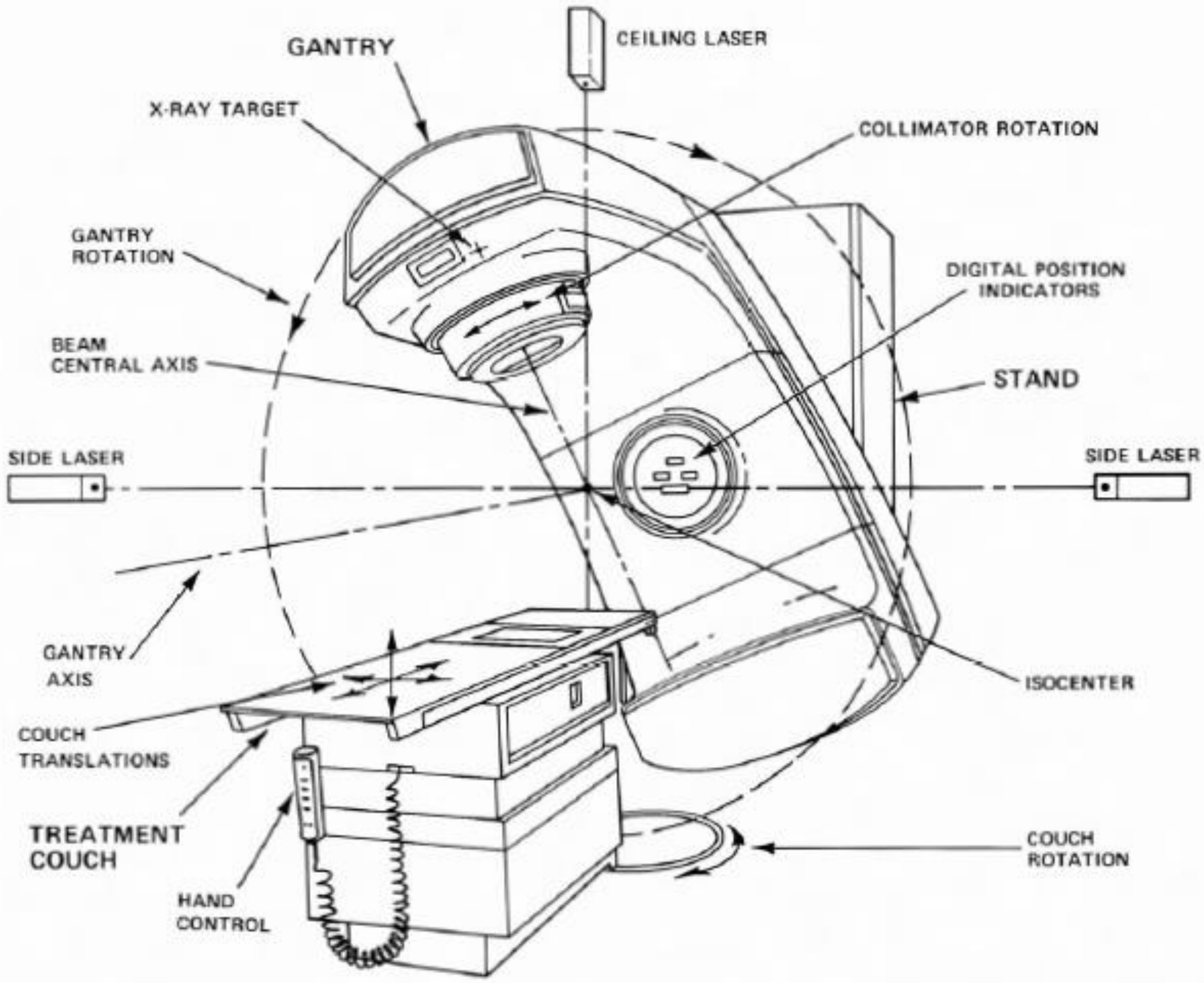


FIGURE 12-1 · Schematic view of a treatment unit emphasizing the geometric relationship of the linac and treatment couch motions. A pedestal type couch is illustrated.

Mechanical - head

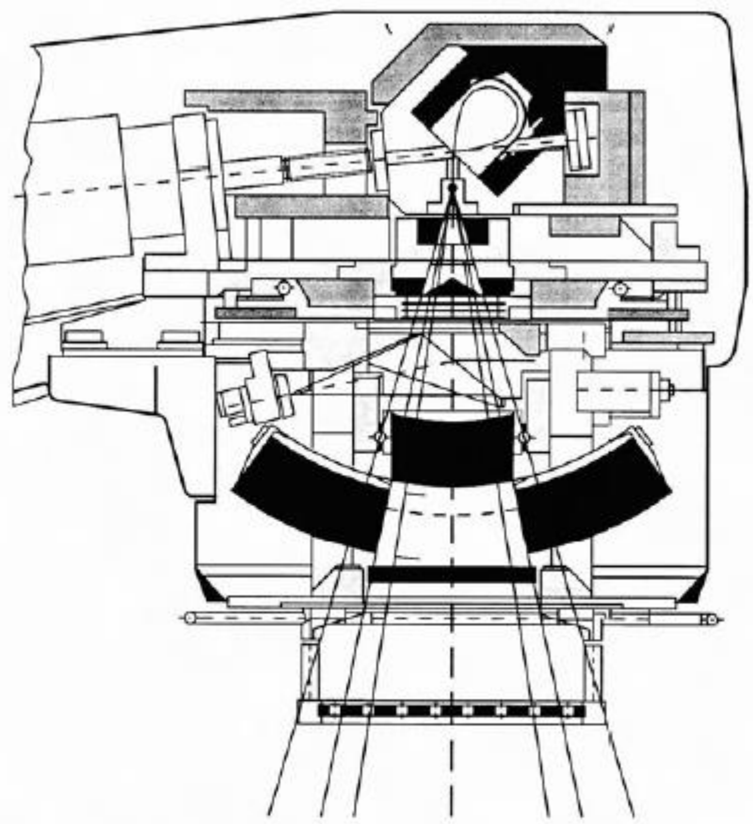


FIGURE 7-1 · Example of bend magnet cross section in radiation head, showing limited total space and typical space for individual items.

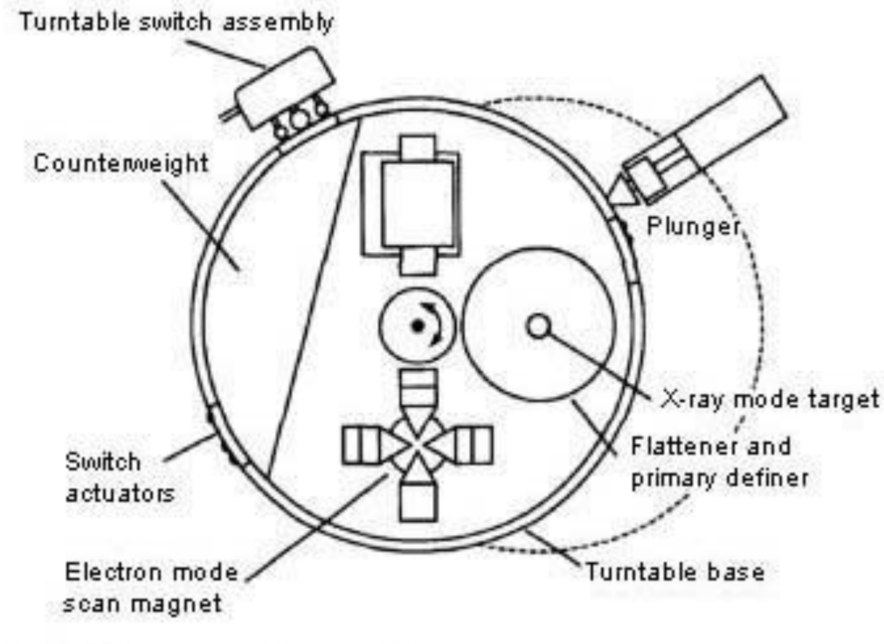
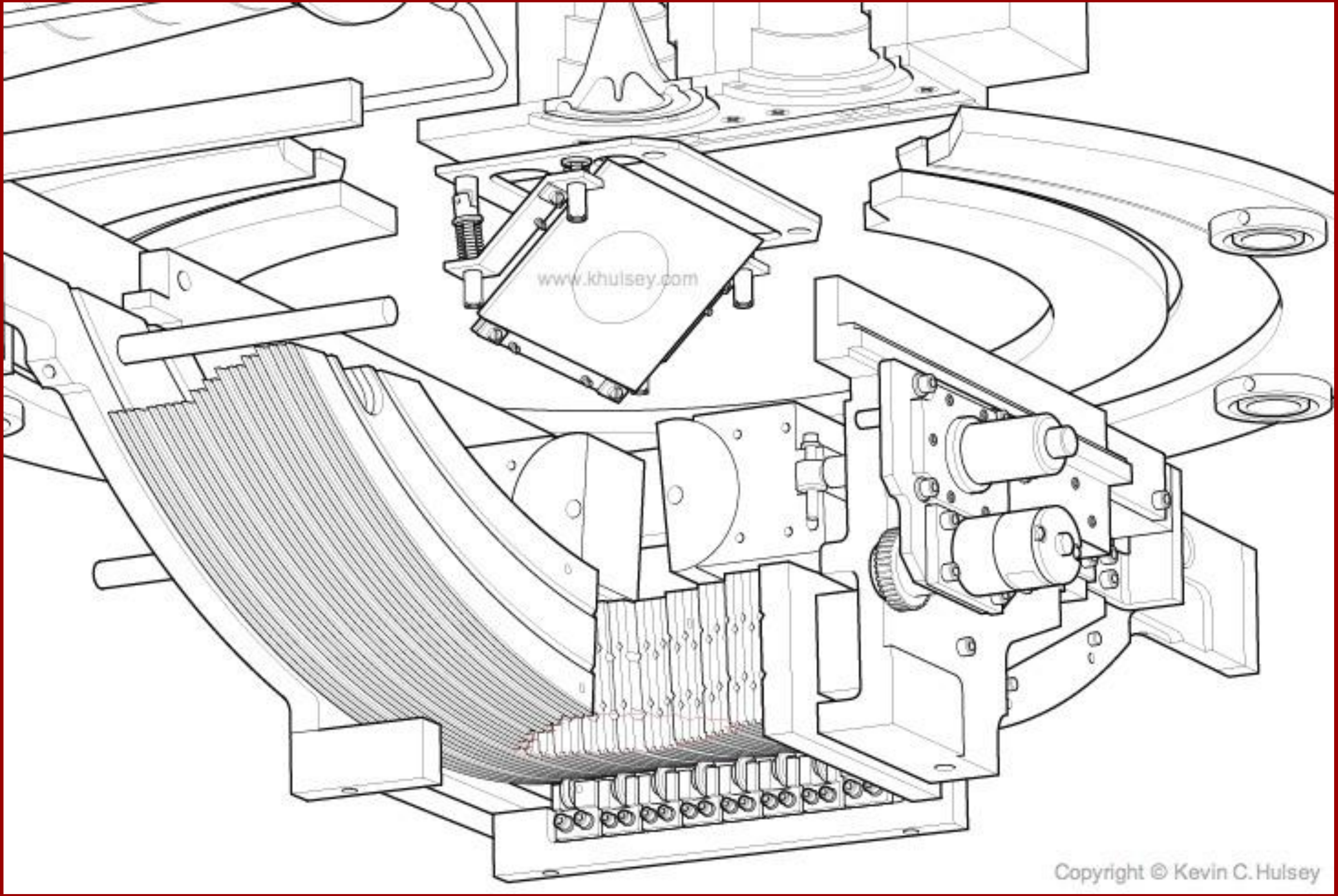
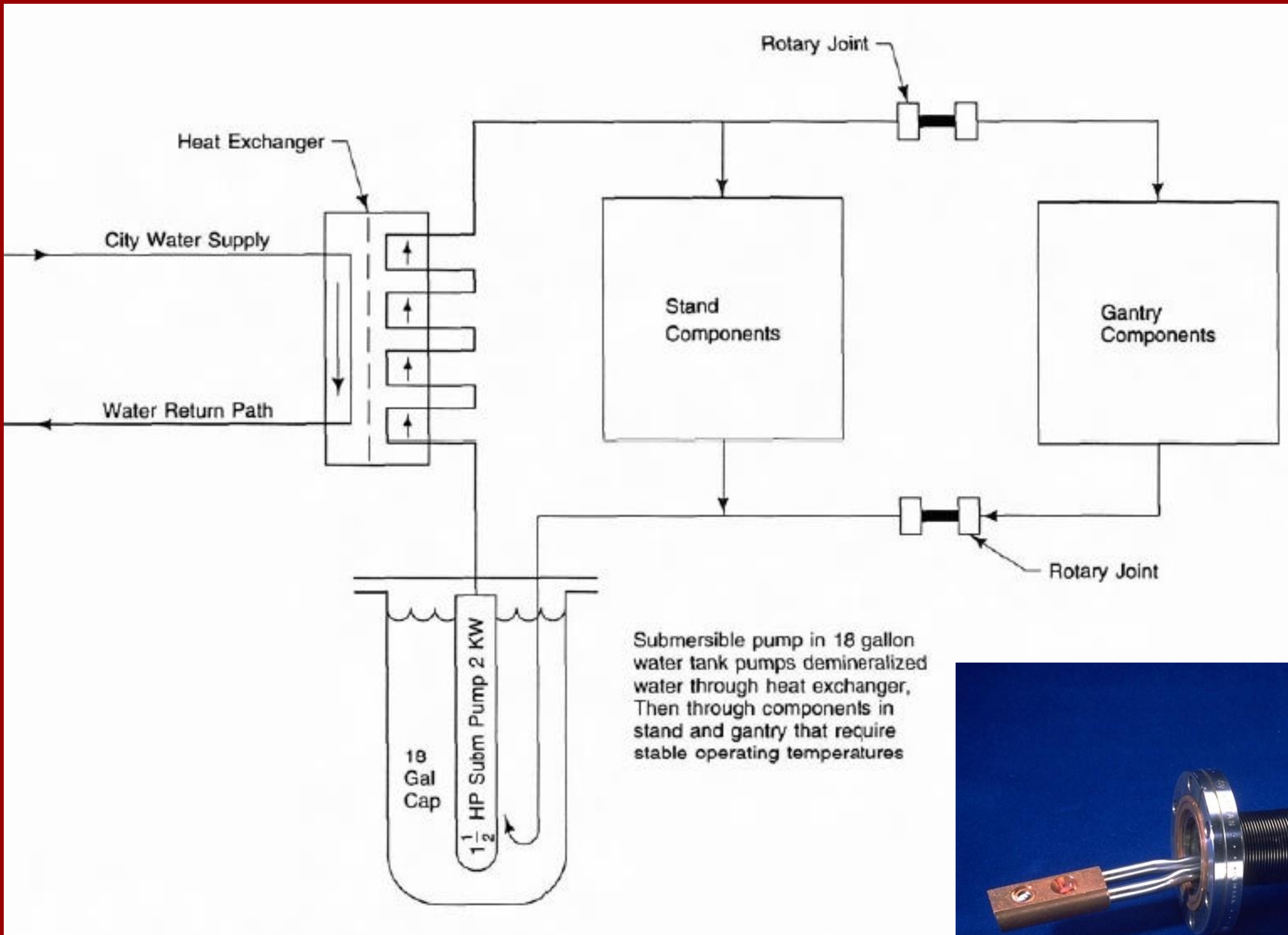


Figure B. Upper turntable assembly

MLC



Cooling



GURE 6-10 · Block diagram of basic water cooling system.

Movable x-ray target (Varian 10 MV linac)

Cooling – electricity costs vs water costs

Pneumatic system

Pressurized air drives mechanisms to:

move the target into place

operate the locking pin plungers on the carrousel,

operate the plungers on the shunt tee

to move the energy switch.

Air pressure is controlled by an air regulator (between 45 and 50 psig)

The air pressure to all the drive mechanisms is turned on and off by electrically operated air control solenoids.

Optics

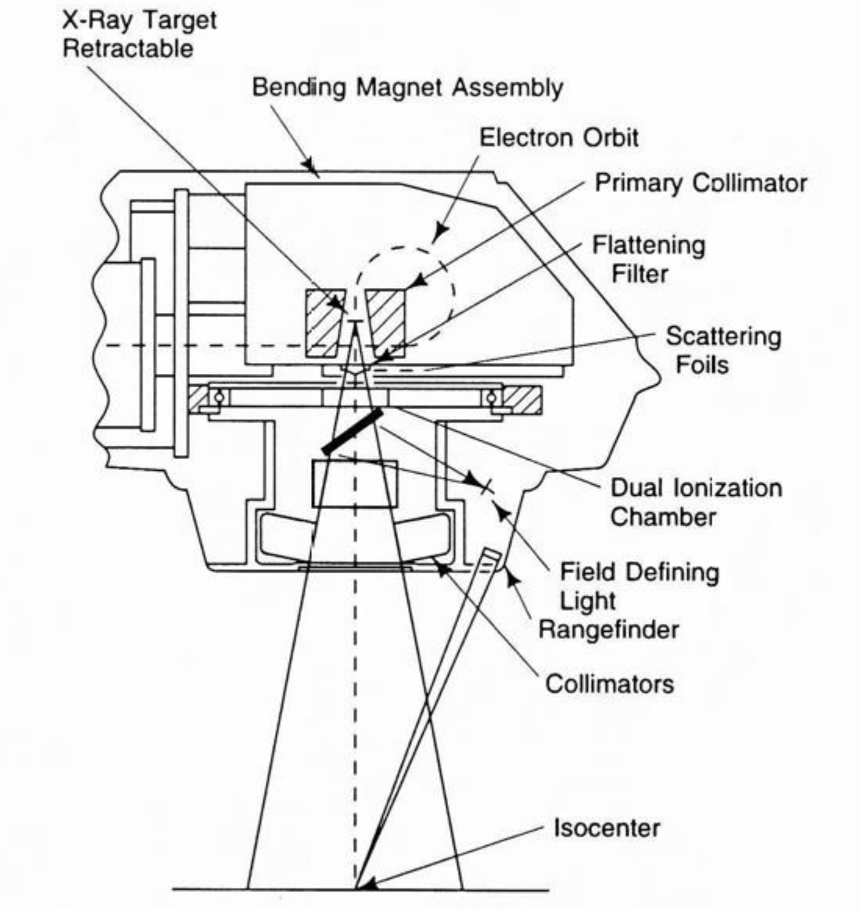


FIGURE 8-1 · Clinac 18 Treatment head. (Courtesy of Varian)

External Laser system

REVIEW ARTICLE

Advances in linear accelerator design for radiotherapy

C. J. Karzmark

Department of Radiology, Stanford University School of Medicine, Stanford, California 94305

(Received 17 March 1983; accepted for publication 1 December 1983)

The microwave-powered electron linear accelerator, or linac, is becoming the dominant radiotherapy treatment unit. Several technical advances, combined with attention to how patients are most effectively set up and treated, have led to continuing improvements in linac radiotherapy. This review describes: improvements in accelerator structures, widely variable energy linacs, microtrons, beam transport systems, and treatment head design.

References about subsystems of a linear accelerator

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

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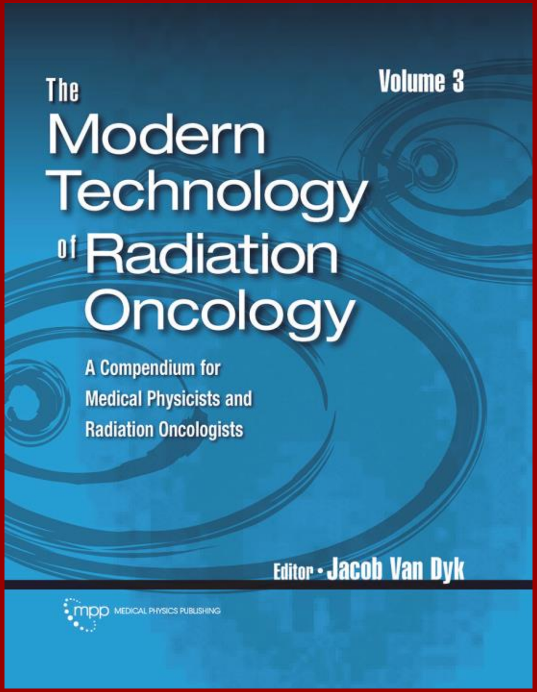

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Chapter 16 : "Radiation Oncology Medical Physics Resources for Working, Teaching, and Learning"

Jacob Van Dyk (Updated 5 July 2016)

https://www.medicalphysics.org/documents/vandykch16.pdf

Thank you!

Questions?

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