Medical accelerators

Dr. Lutz Müller, Director ICC

Welcome to Nuremberg

…a short lecture on local dialect

…just read it loud…

Ulcer des hot me fie an reason air-guides cost on fill air-bat – supper lot

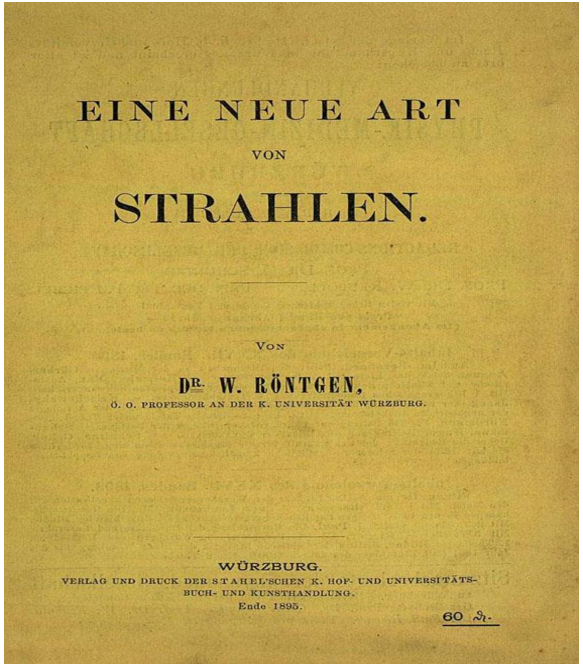
~prepared with ambition and a lot of work, my god ! (well, but I like it :-)

Way an mention blows a zoo a blade sin I felt – des buggy fie net

~ unbelievable how funny things can come to one’s mind

C.W. Röntgen

Würzburg 1895 (just +100 kM from here)



EINE NEUE ART

VON

STRAHLEN.

VON

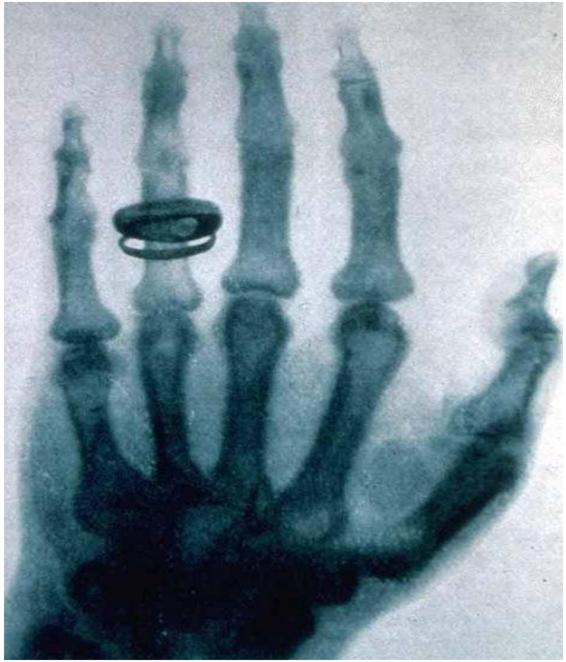
DR. W. RÖNTGEN,

Ö. O. PROFESSOR AN DER K. UNIVERSITÄT WÜRZBURG.

WÜRZBURG.

VERLAG UND DRUCK DER STAHEL'SCHEN K. HOF- UND UNIVERSITÄTS-
BUCH- UND KUNSTHANDLUNG.
Ende 1895.

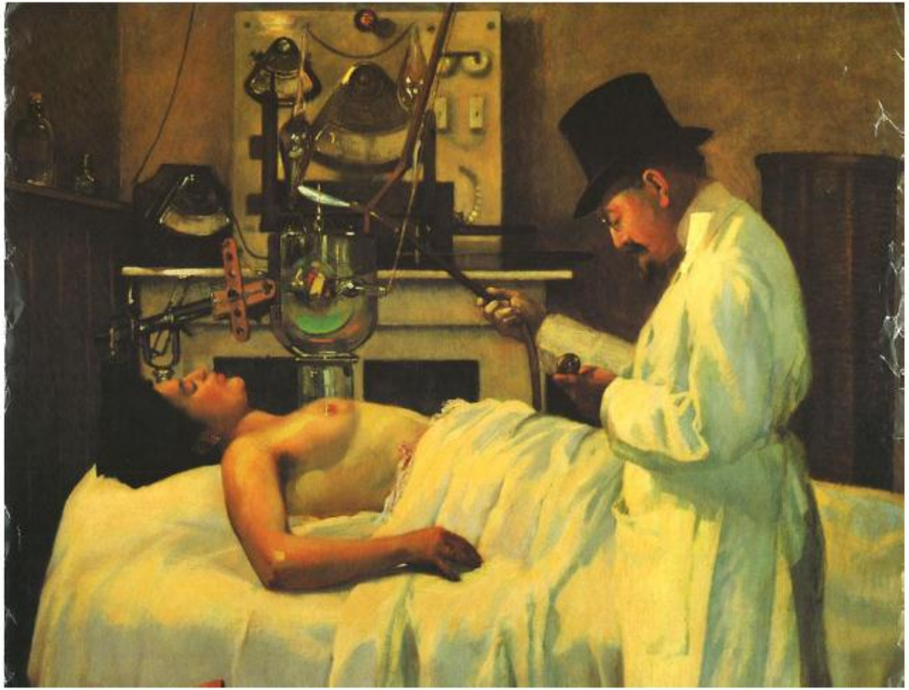
60 ₰.



Early Breast Therapy (Chicotot 1897)

…in the Good ol' Times of Positivism

n.b. only 2 years after the discovery of x-rays!



In this self-portrait, Chicotot holds in his right hand a gas burner for regulating the high voltage current through the bulb and controlling the exposure time (30 minutes in 1897, but 10 seconds by 1899).

Leopold Freund, Vienna 1897

70 years after Treatment

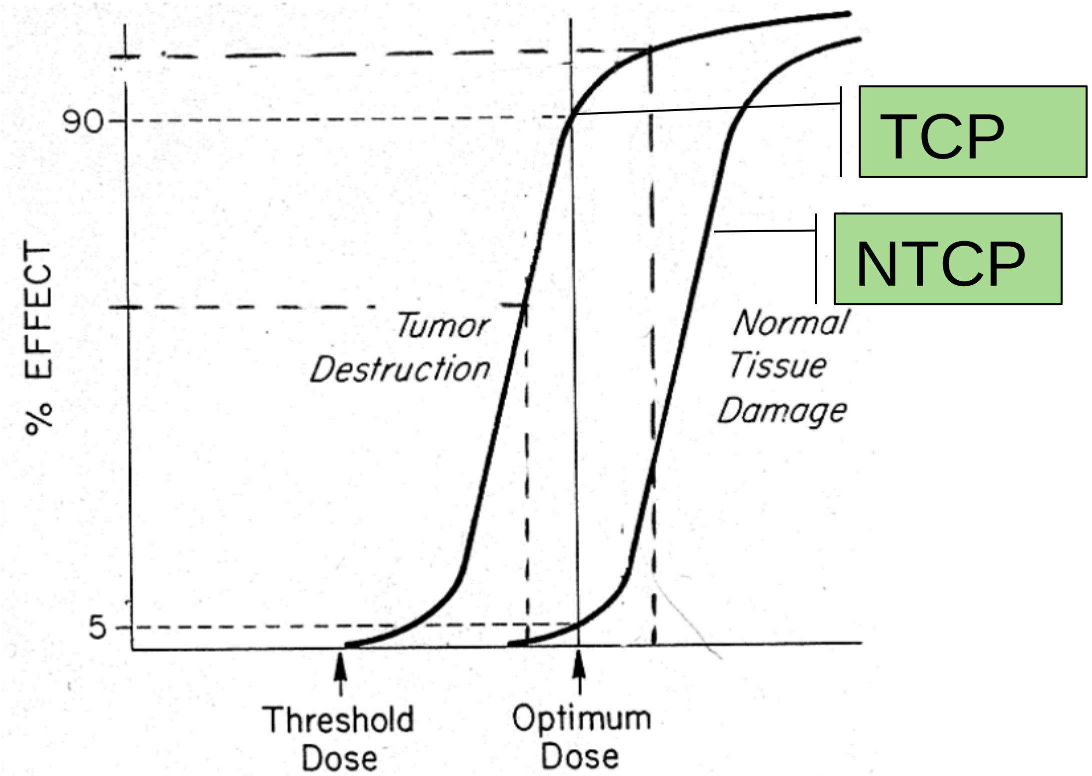
5 yo Girl with Naevus Pigmentosus Piliferus

Radiotherapy can treat 30% cancers while Chemo/Biotherapy 2% - But considered as the "sticking plaster" of oncology"

S. Webb

The Principle of Radiation Therapy

…just in a Nutshell…



Projectiles for RT

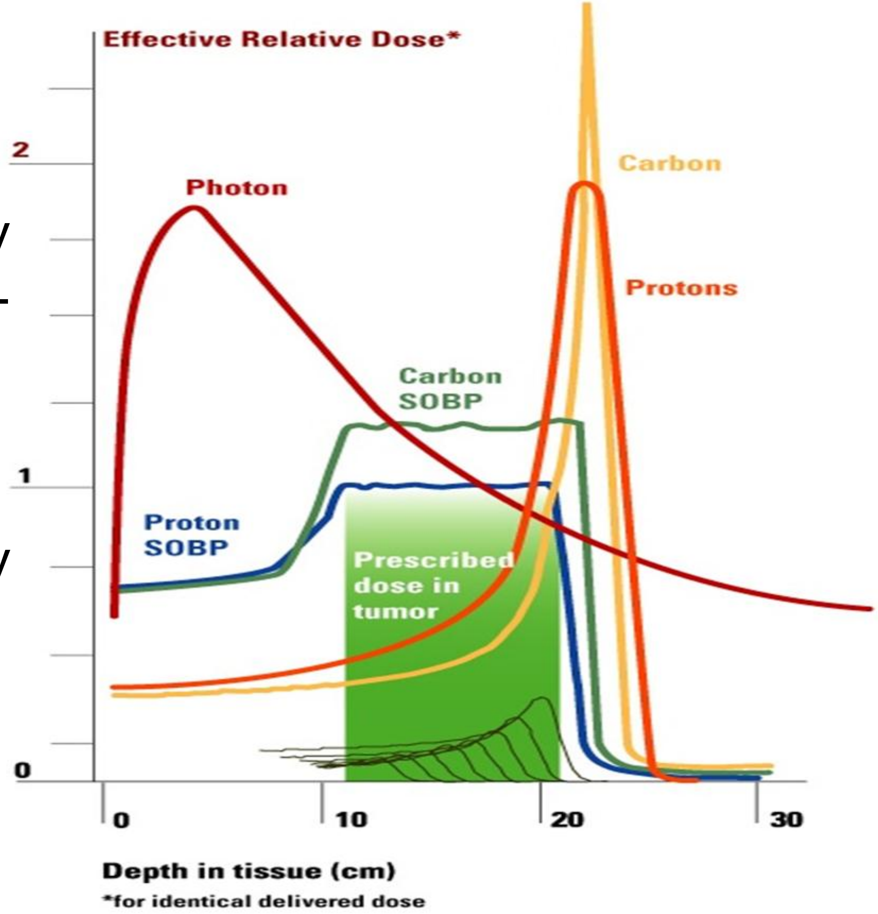
Photons vs. Charged Particles

Photons: indirectly ionizing, few primary interactions, dose deposition by secondary electrons

*build-up region, **D_{max}** and falloff (electron equilibrium)*

Protons: directly ionizing, many primary interactions

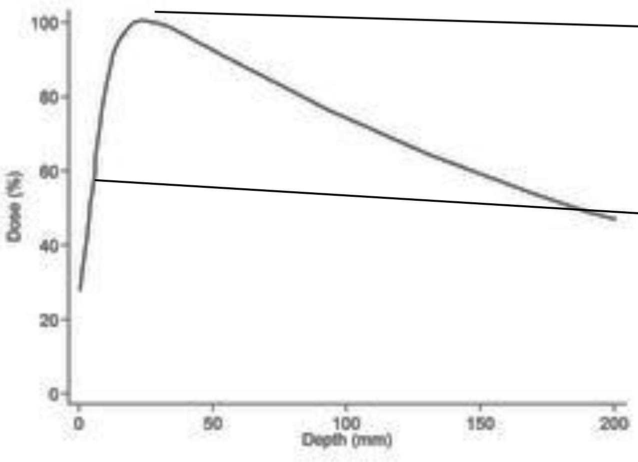
*Low proximal dose deposition, **Bragg-Peak** , sharp distal fall-off*
More pronounced for heavier ions like ^{12}C



Photon Depth Dose Curves

Build-up effect

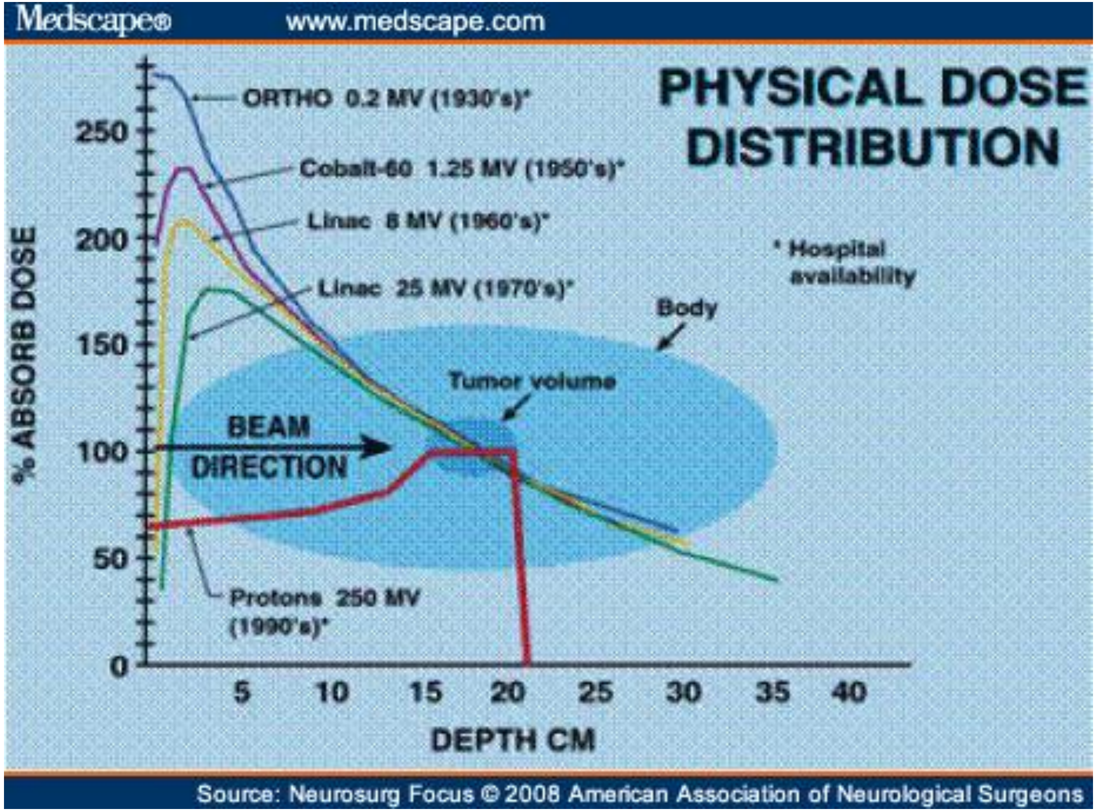
Depth-dose distribution of photons



Dose Maximum in some cm depth

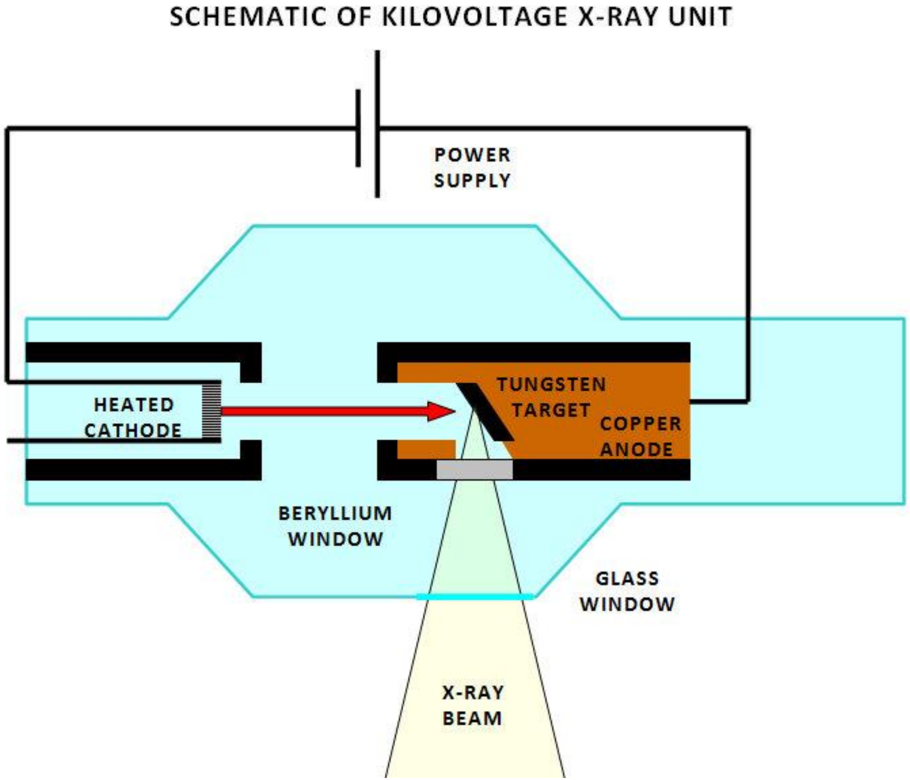
Lower Dose to Skin

X-ray dose deposition



X-ray tube

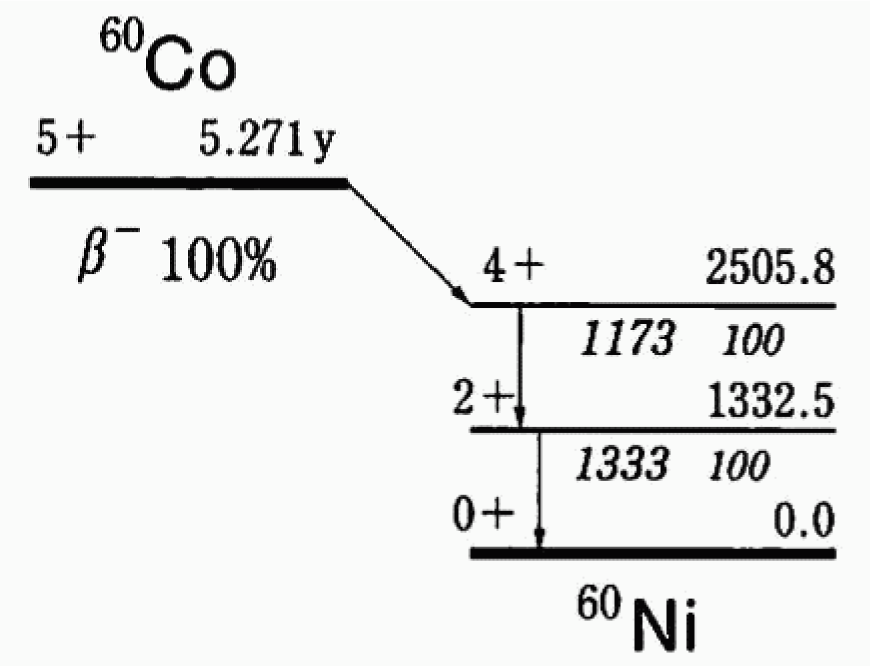
Up to some 100s of kV



How to raise the acceleration voltage ?

Alternative: Radioactive Source

Modern Cobalt unit (ICC)



A failed attempt….

1928: Curt Urban, Arno Brasch, and Fritz Lange successfully achieved 15 MV by harnessing lightning in the Italian Alps !

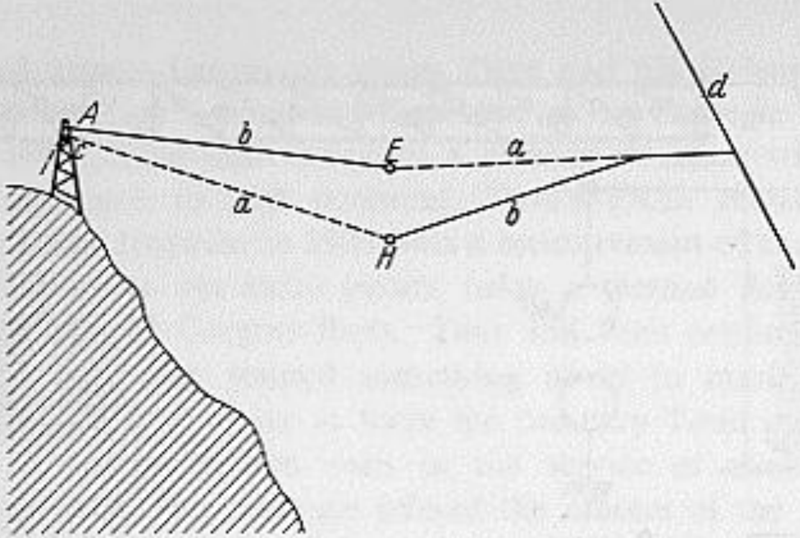


FIG. 2.1 Brasch and Lange's lightning catcher. E and H are the spheres between which the discharge occurs; AE, the antenna; a,a, insulators; b,b, conductors; d, a grounded wire. Brasch and Lange, *Zs. f. Phys.*, *70* (1931), 17.

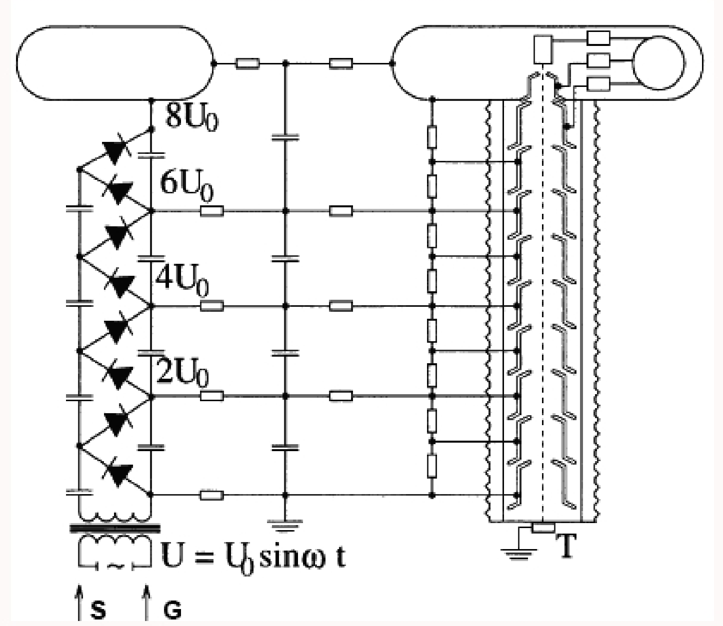
15 MV,
but….

- The two who survived the experiment went on to design an accelerator tube capable of withstanding that voltage.

Cockroft-Walton (Voltage Multiplier)

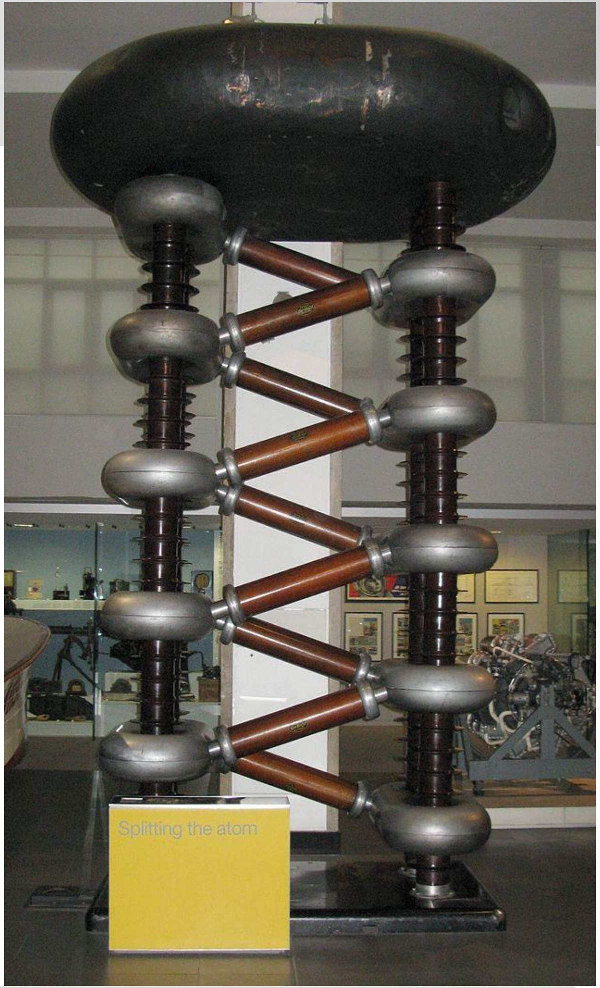
1st accelerator-induced nuclear reaction (1930)

$$^{7}\mathrm{Li} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + 17{,}35\ \mathrm{MeV}$$



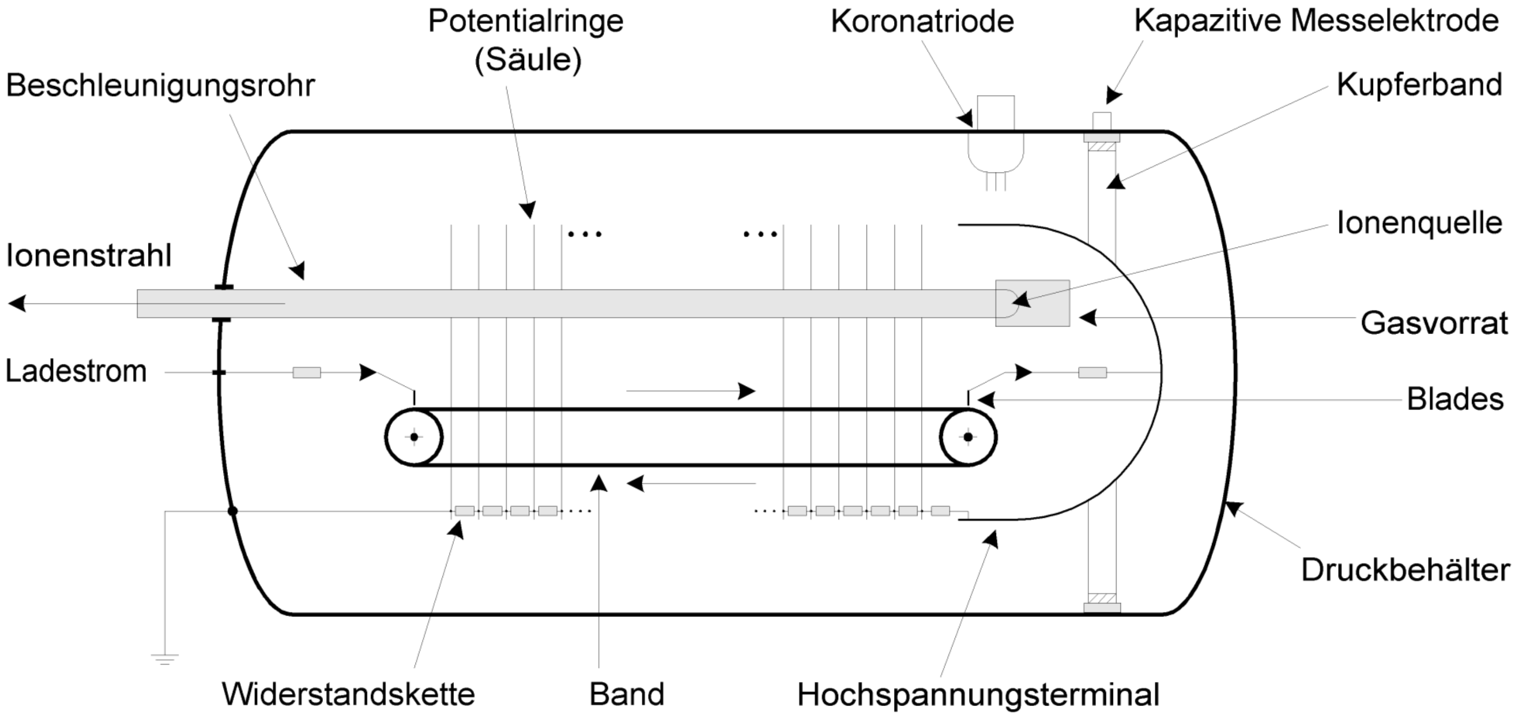
S Schubsäule
G Glättungssäule
T Target

Strahlrohr mit Widerstandskette und Beschleunigungselektroden



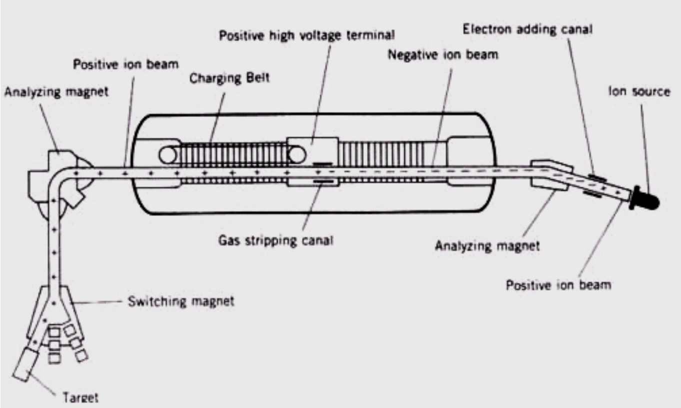
Van-de-Graaf Accelerator

Mechanical Charge transport



Tandem Accelerator (up to ~ 20 MV)

Weizmann Institute of Science, Israel

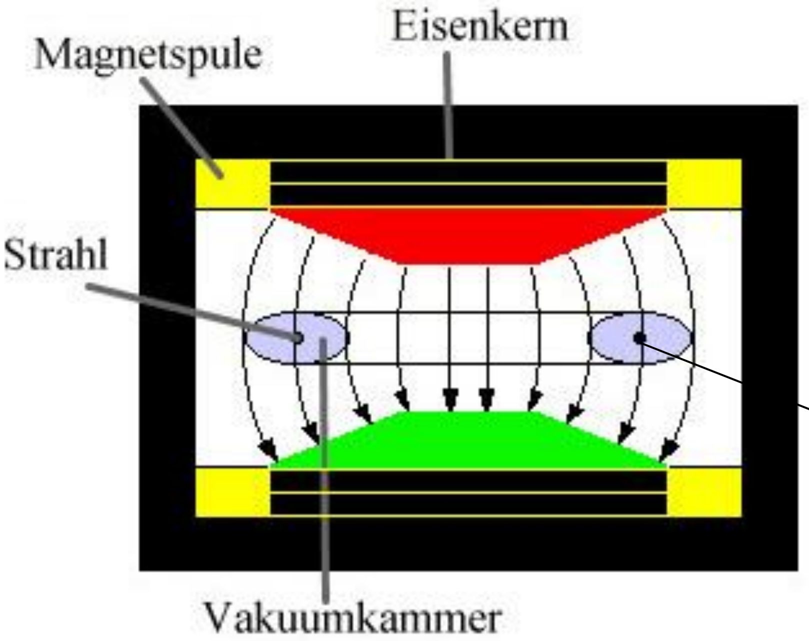


Largest static field accelerators, but not appropriate for electrons

Workhorses of Nuclear Structure Physics! (1970s)

The Betatron

…a kind of Transformer….



$$\oint_{\partial A} \vec{E} \cdot d\vec{s} + \left(\iint_A \frac{\partial \vec{B}}{\partial t} \cdot d\vec{A} \right) = 0$$

Electron beam is the 'secundary coil'

1st Betatron in Germany

Göttingen 1951

DER SPIEGEL 32/1951

FORSCHUNG

ATOM-MEDIZIN

Der Krebs wird beschossen

Einmal in der Woche werden in Göttingen Krebskranke aus den Kliniken in das Physikalische Institut an der Bunsenstraße gebracht. Anderthalb bis zwei Minuten lang müssen sie sich neben die Elektronenschleuder, einen mannshohen Bestrahlungsapparat aus einem Gewirr von Eisenteilen, Rohrleitungen, Drähten und Schaltern setzen. Die Aerzte stehen mit der Stoppuhr in der Hand daneben. Die Bestrahlungsdauer muß auf Sekunden genau eingehalten werden. Die Patienten sitzen da und merken nichts. Wenn sie aufstehen dürfen, warten sie noch immer, daß etwas geschehen soll.

Erst in den nächsten Tagen und Wochen geschieht etwas. Die Krebsgeschwulst wird „erosiv", rötet sich, verliert ihre äußeren Schutzschichten und bildet sich dann zurück. Nach vier bis zwölf Wochen ist in den meisten Fällen nur noch eine Narbe vorhanden.

Prof. Bode hat den Verlauf der Heilung auf vielen Photos festgehalten. In seiner Schreibtischschublade liegen die Porträtaufaufnahmen runzliger Altfrauengesichter und verhärmter Greise. Sie tragen, für jeden sichtbar, die Zeichen, die noch vor wenigen Jahrzehnten ein Todesurteil bedeuteten: Kirschkern-, walnuß- oder gar bananengroße Krebsgeschwülste im Nasenwinkel, an der Wange, an der Lippe oder in der Nähe des Auges.

Die Patienten sitzen da ...
Strahlenbiologe **Martius**

winden hatten", erzählte Professor M im April 1951 seinen Kollegen. Satire müßte einen traurigen Anfang haben.

Als die Amerikaner in den letzten Apriltagen 1945 in Erlangen einrücken, finden sie im Laboratorium der Siemens-Reini-

eine salomonische Lösung: Die Betatrone können fertiggestellt werden, aber es wird vorerst streng untersagt, mit ihnen zu arbeiten.

Das inzwischen erschienene Kontrollratsgesetz Nr. 25 läßt Atomexperimente für medizinische Zwecke zu, wenn eine Sondergenehmigung der Militärregierung vorliegt. Aber wieder gibt es ein Dilemma: Ehe mit dem neuen Gerät Krebsgeschwülste beschossen werden können, sind viele physikalische Messungen nötig. Ist das nun vorbereitende Atom-Medizin oder verbotene Atom-Physik?

Der britische Forschungsoffizier von Göttingen deutet in dieser unsicheren Lage an, daß er dem Betatron keinen „militärischen" Wert zusprechen könne. In Göt-

len. Das muß genau bekannt sein, ehe zum erstenmal auf der Welt ein Mensch mit schnellen Elektronen beschossen werden kann.

Betatron

1st Generation of Medical Accelerators

LINAC concept

Wideröe 1929

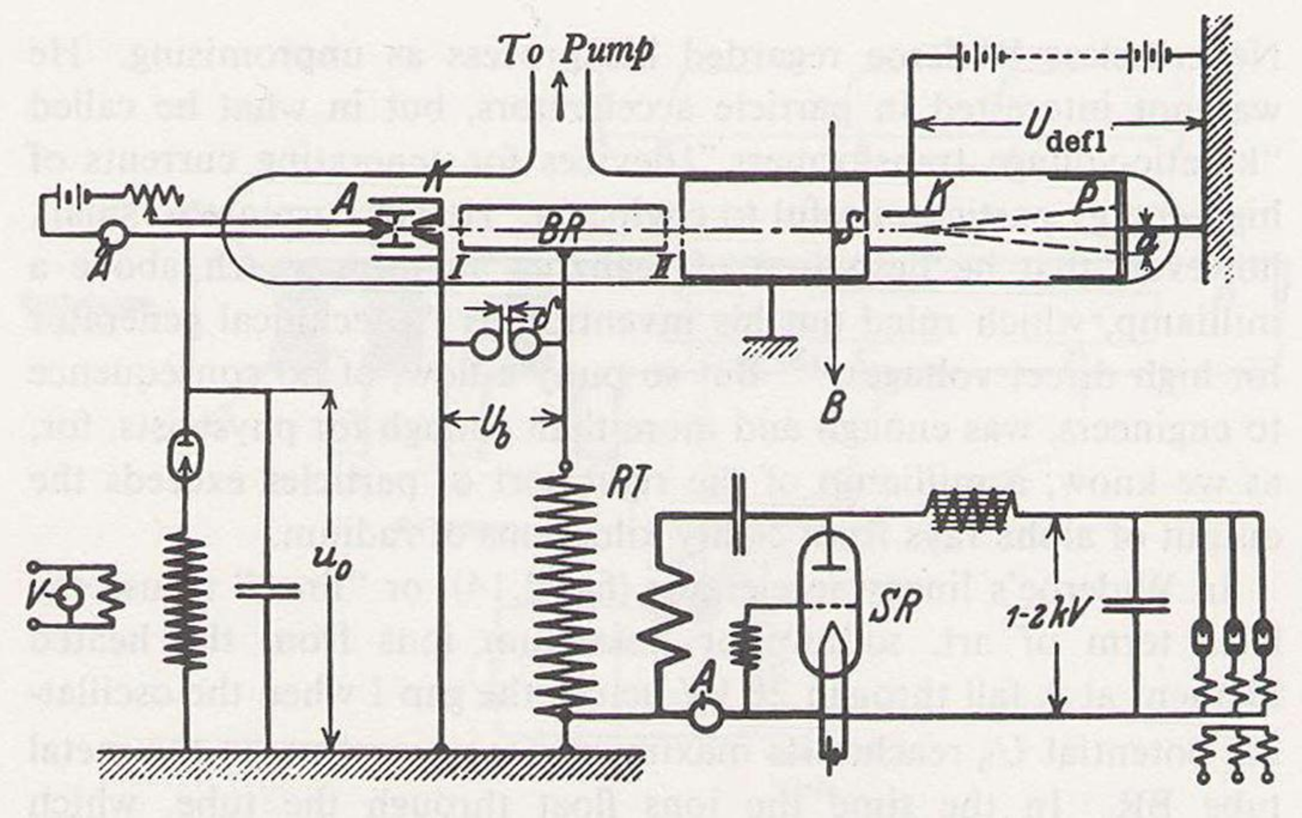
R. Wideröe proposed an accelerator by using an alternating voltage across many alternating “gaps.”

It was not without a myriad of problems

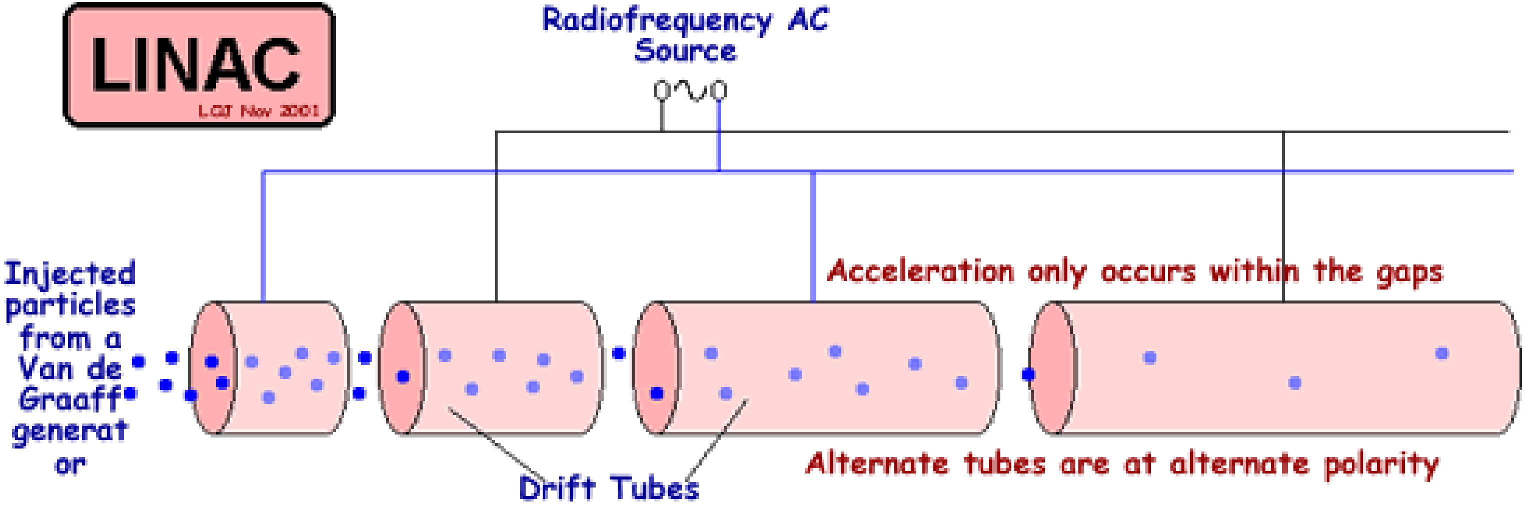
- Focusing of beam
- Vacuum leaks
- Oscillating high voltages

His professor refused any further work because it was “sure to fail.”

Wideröe still published his idea in *Archiv für Elektrotechnik*

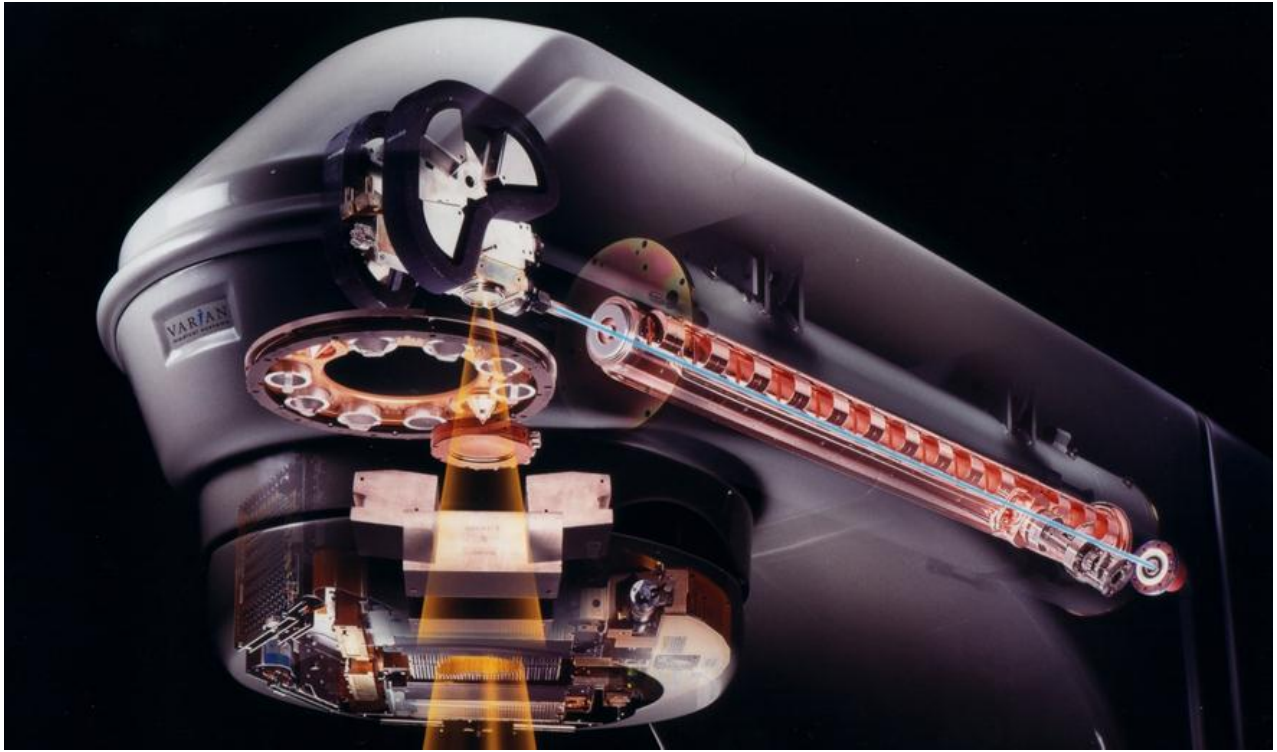


LINAC with drift tubes (Varian)



Varian LINAC

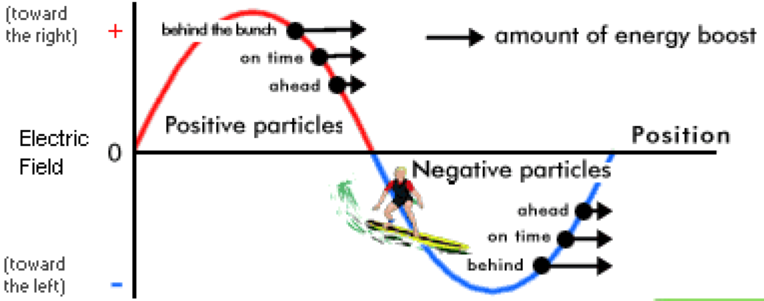
Drift Tubes

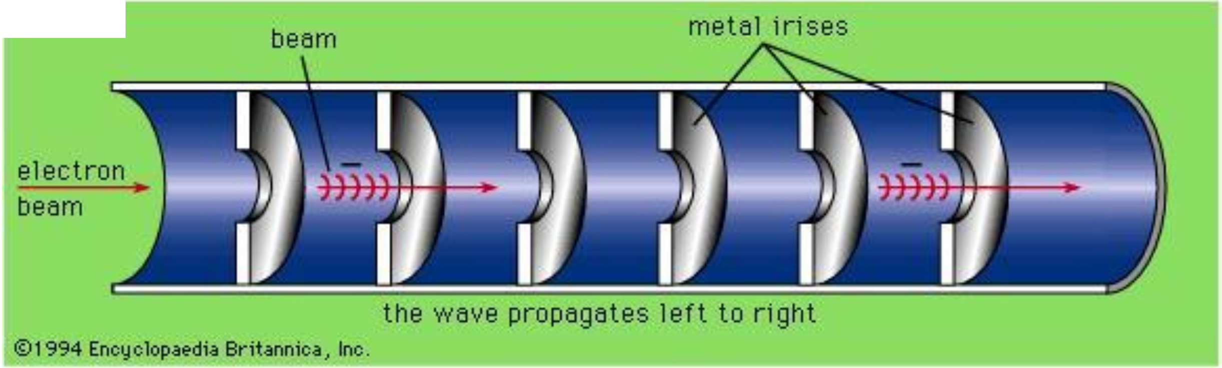


Alternative: Travelling Wave

…but phase speed must be < c

Travelling Wave LINAC





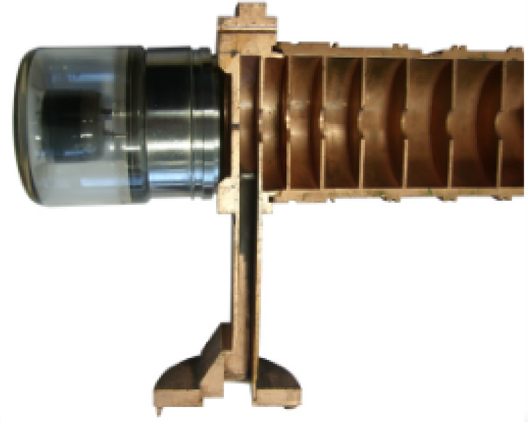
Phase speed of wave must be < C !

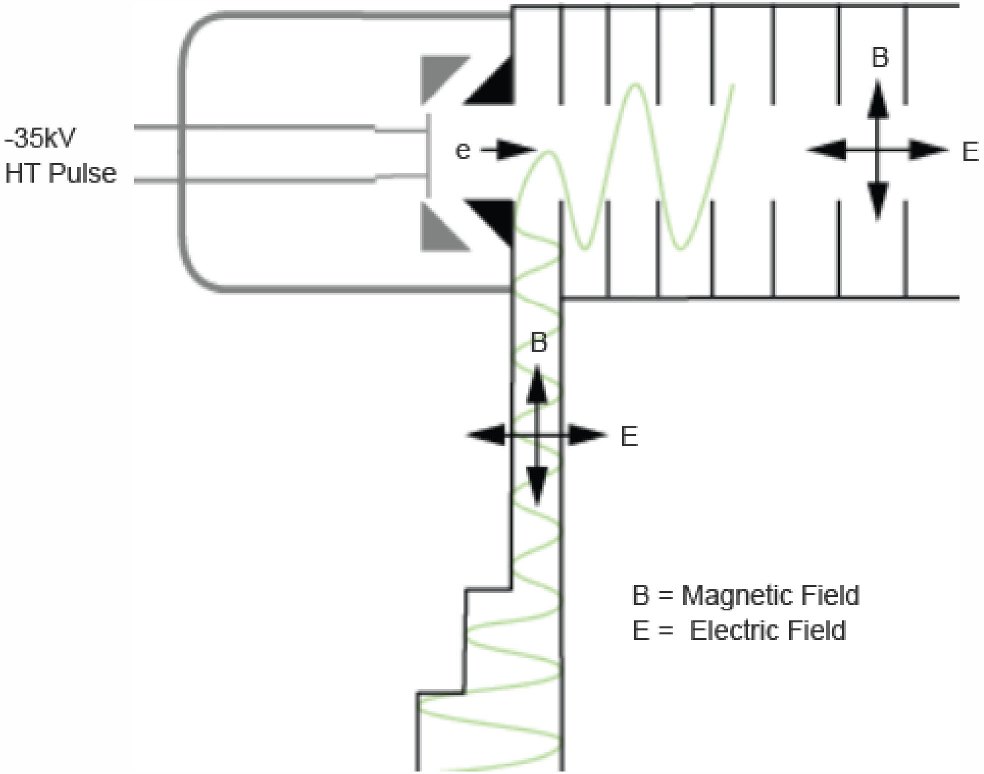
Input Mode Transformer

The RF from the magnetron travels at a velocity that is too high to synchronize with the electrons from the gun.

The purpose of the input mode transformer is to slow down the RF to 0.4 c (c = speed of light 299,792,458 metres per second - thats fast!!) to match the velocity of the electrons from the gun.

It also changes the field mode of the RF wave in the rectangular waveguide from transverse electric (TE) to transverse magnetic (TM) for acceleration of the electrons from the gun.





Electron Acceleration

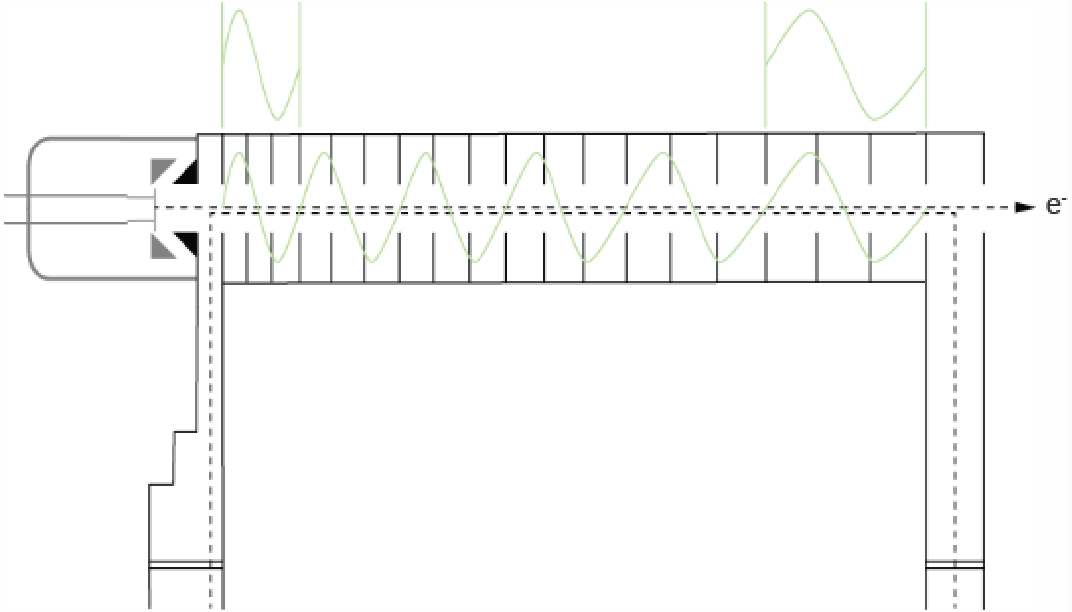
The heart of the system is the accelerating waveguide, which increases the velocity of the electrons from their injection energy to their final energy. Electrons injected from the electron gun gain energy from the RF travelling down (travelling wave) the accelerating waveguide.

Electrons entering the waveguide need to enter at the correct phase of the RF wave to be accelerated. A bunch of electrons is formed and continue to be accelerated.

Applying the formula:

- Velocity = frequency x wavelength

The frequency of the RF is fixed but the wavelength is changed by cell geometry therefore increasing wave velocity. The bunches of electrons will therefore accelerate with the RF wave to approximately 0.998 c at the output of the waveguide.



Waveguide (ELEKTA)

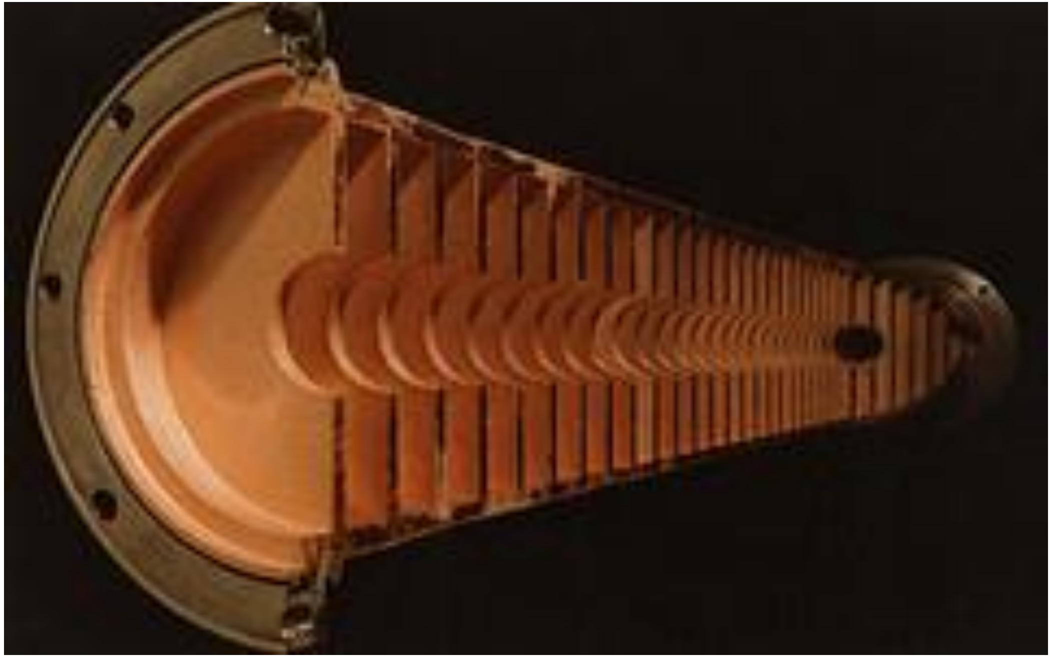
The accelerating waveguide is formed by two cylindrical waveguide sections that are joined at the center. The first section of the accelerating waveguide is known as the injector (or buncher) section and the other is known as the relativistic section.

Spacing and geometry of the iris plates in the waveguide changes along its length allowing the RF and electrons to accelerate.

To provide electrical isolation in the accelerating waveguide a vacuum is maintained by two ion pumps one at each end of the waveguide.

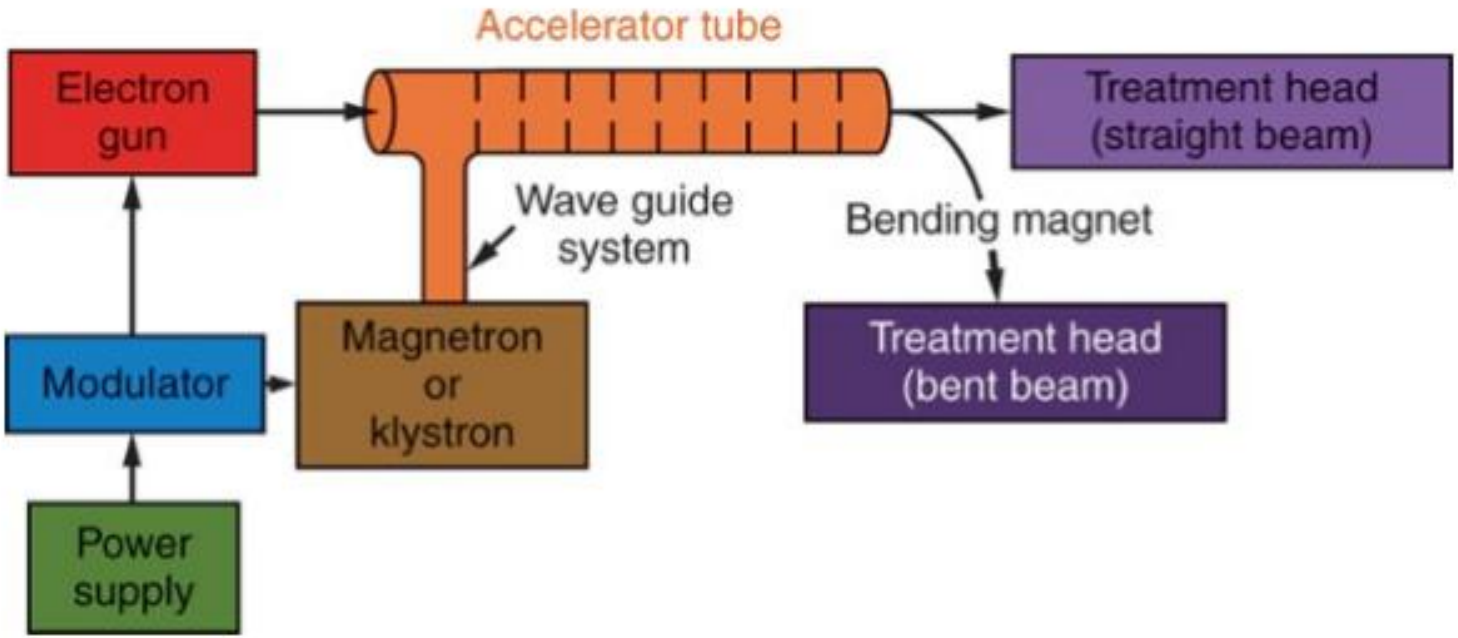
Waveguide of ELEKTA LINAC

Travelling Wave Tube



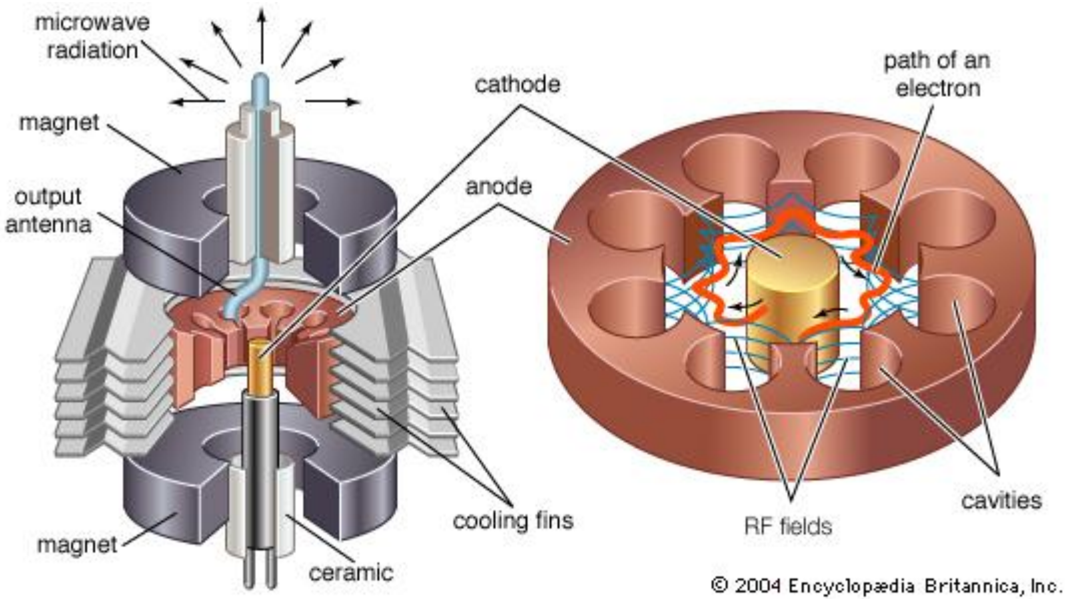
Varian LINAC

LINAC Block Diagram



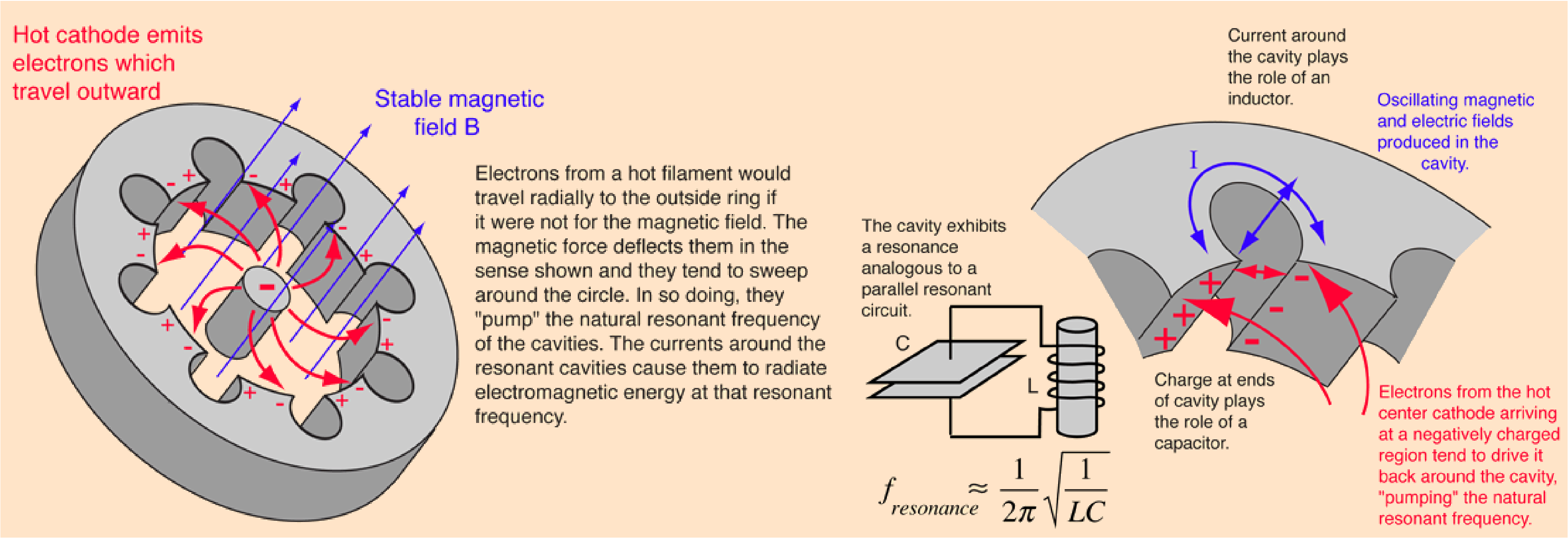
How to create the RF

Magnetron



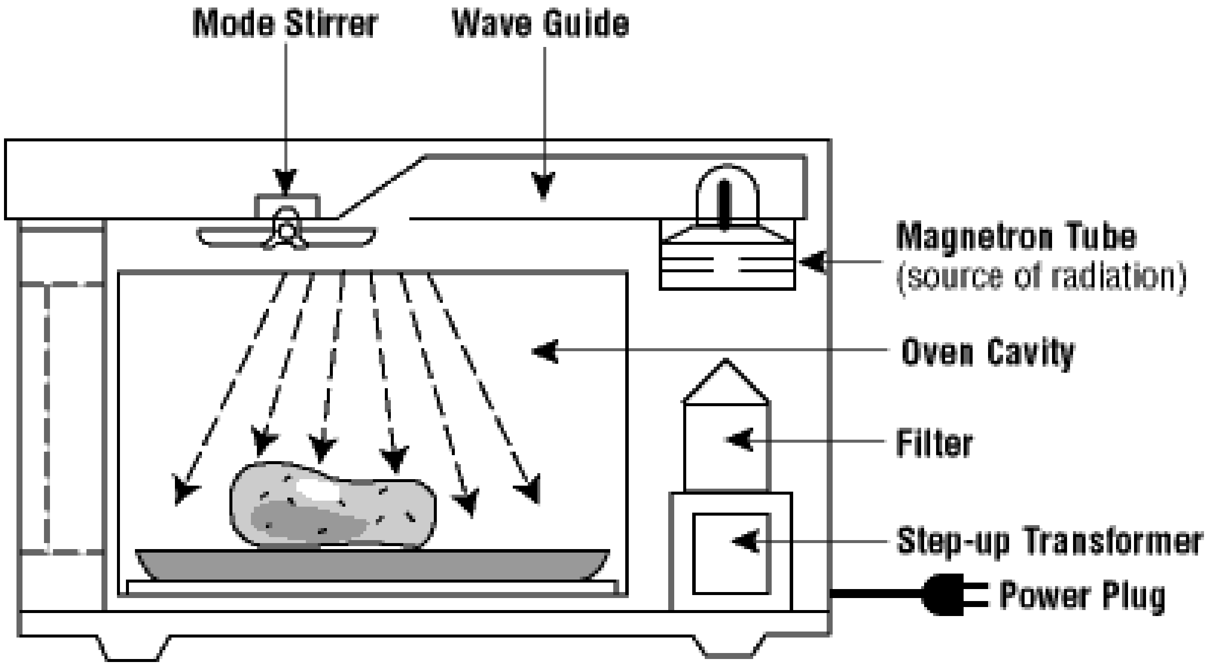
Magnetron

RF generation in resonant cavities



…you have a Magnetron in your kitchen…

Cheap and powerful microwave source



Magnetron

The magnetron consists of a cylindrical cathode, heated by a filament, surrounded by a resonant cavity anode structure. This is mounted inside the magnetron magnet which is an electromagnetic coil.

Filament Heating

The magnetron filament voltage is controlled by software to maintain the cathode temperature to supply a constant number of electrons.

RF Generation

The previously generated high voltage pulse is applied to the magnetron cathode. This negative pulse emits electrons from the cathode towards the anode. Due to the electro magnetic field from the magnetron magnet, the electrons are forced to follow a curved path between the cathode and the anode. The passage of the electrons past the cavities causes a build up of RF.

Roll over the image to discover more.

Alternative: Klystron

…invented by broth. Varian…

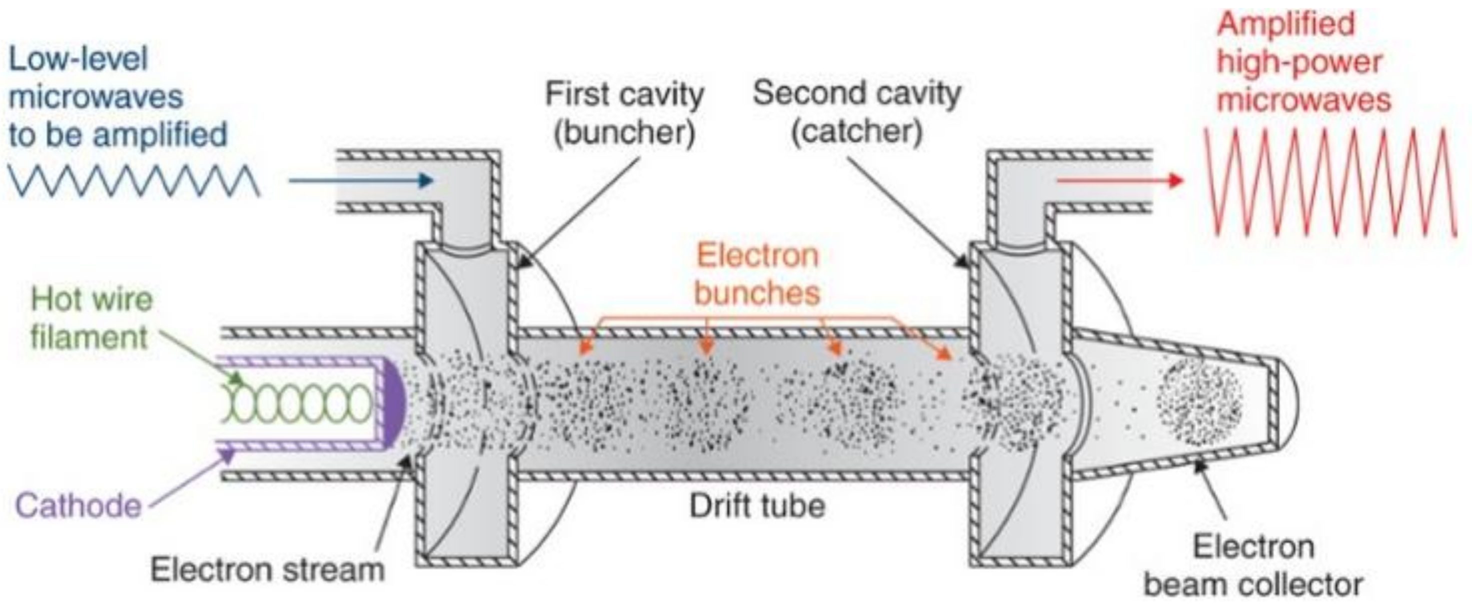


Figure 4.8 Cross-sectional drawing of a two-cavity klystron. (From Karzmark CJ, Morton RJ. *A Primer*...

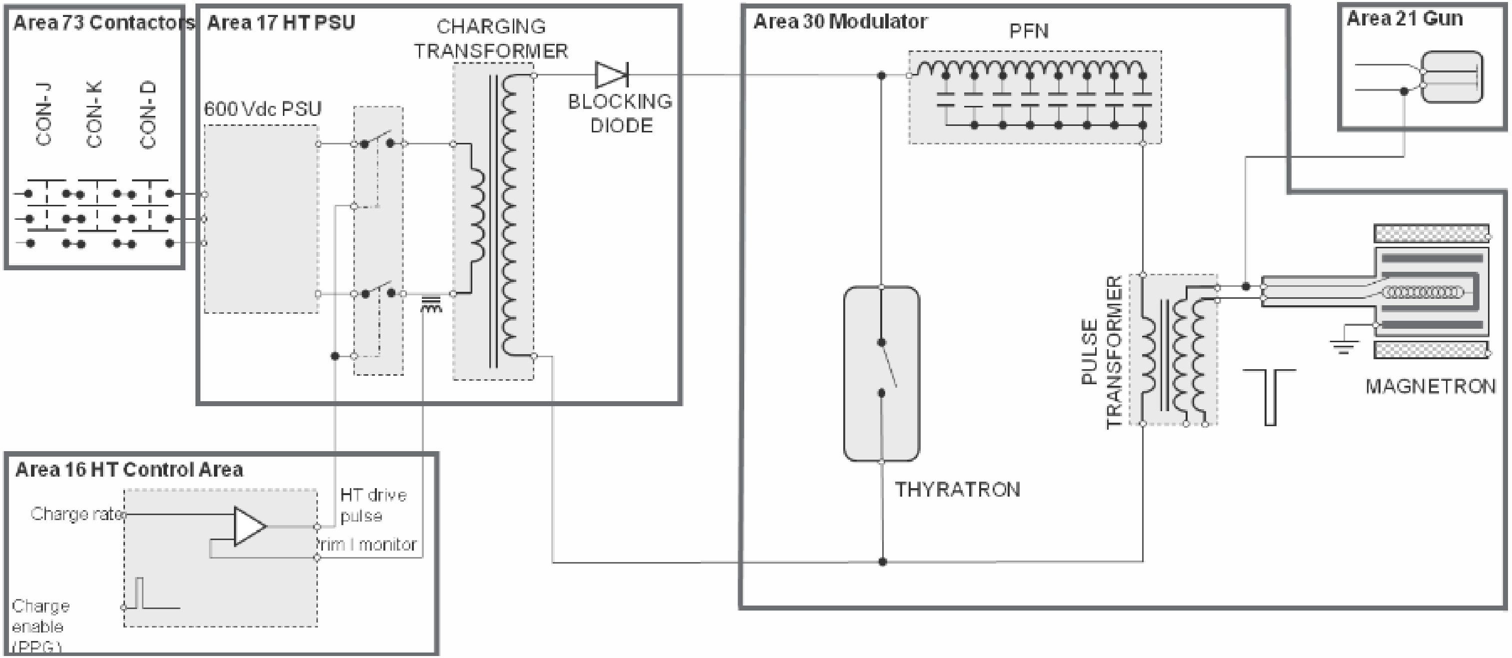
The Klystron is a microvave amplifier, needs low-power Rf input

Beam Generation (ELEKTA)

Beam Generation

ELEKTA

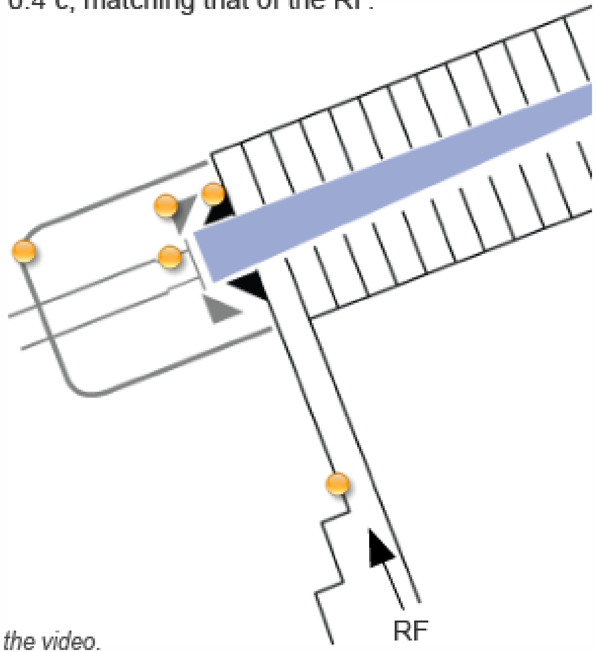
To begin we will discover how the high voltage pulse is generated. The HT PSU in combination with the Modulator develops the pulse. Safety - critical interlocks must be met prior to enabling the pulses. Examples of the interlocks are: room doors, beam loaded and confirmed, and the pressing of the start key on the function keypad.

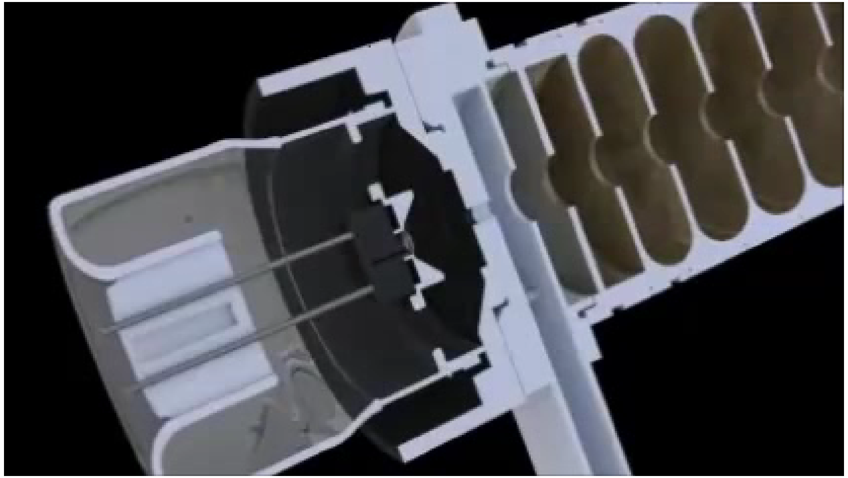


Electron Gun

Before looking at the acceleration process, we need a supply of electrons.

The electron gun is the source of electrons for the electron beam. The filament is heated generating electrons through thermionic emission. The high voltage pulse generated from the modulator is applied between the filament (cathode) and anode producing a strong focussing field and liberating the electrons from the gun. The field guides the electrons into the accelerating waveguide at a velocity of approximately 0.4 c, matching that of the RF.





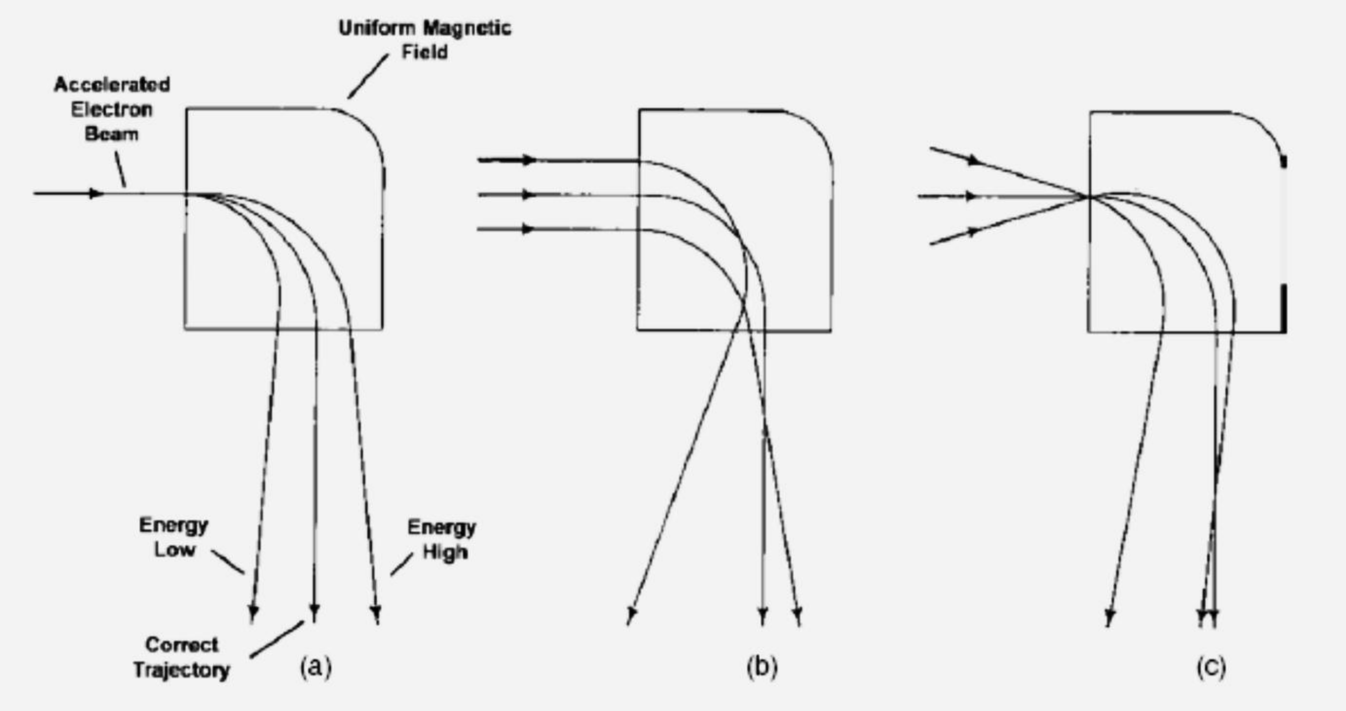
*Click **Play** to see the video.*

The RF is generated by a magnetron and is guided into a circular accelerating waveguide where it is used to accelerate the electrons supplied from the electron gun.

At the end of the accelerating waveguide the remaining RF power is dissipated in an RF Load. Since the remaining RF is not re-circulated, the system is described as non feedback and is capable of up to 18 MeV or 15 MV.

Chromatic aberration

And other aberrations

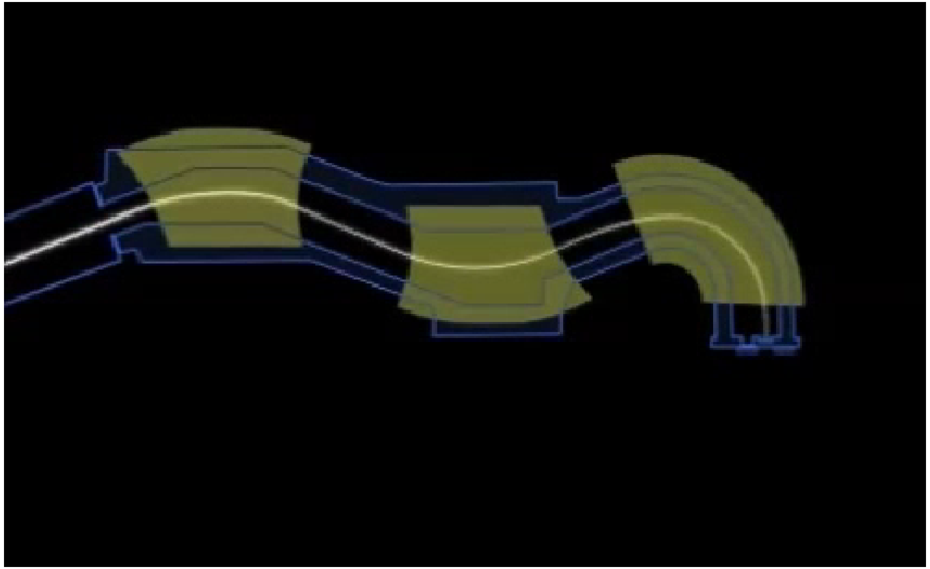


Achromatic Deflection (ELEKTA)

From the bellows, the electron beam is transported through the beam bending system comprising an achromatic triple magnet array in an evacuated flight tube.

The magnet array (slalom) provides double focusing of the electron beam. Under its influence, the beam is deflected through 112° (from 22° above horizontal to 90° below).

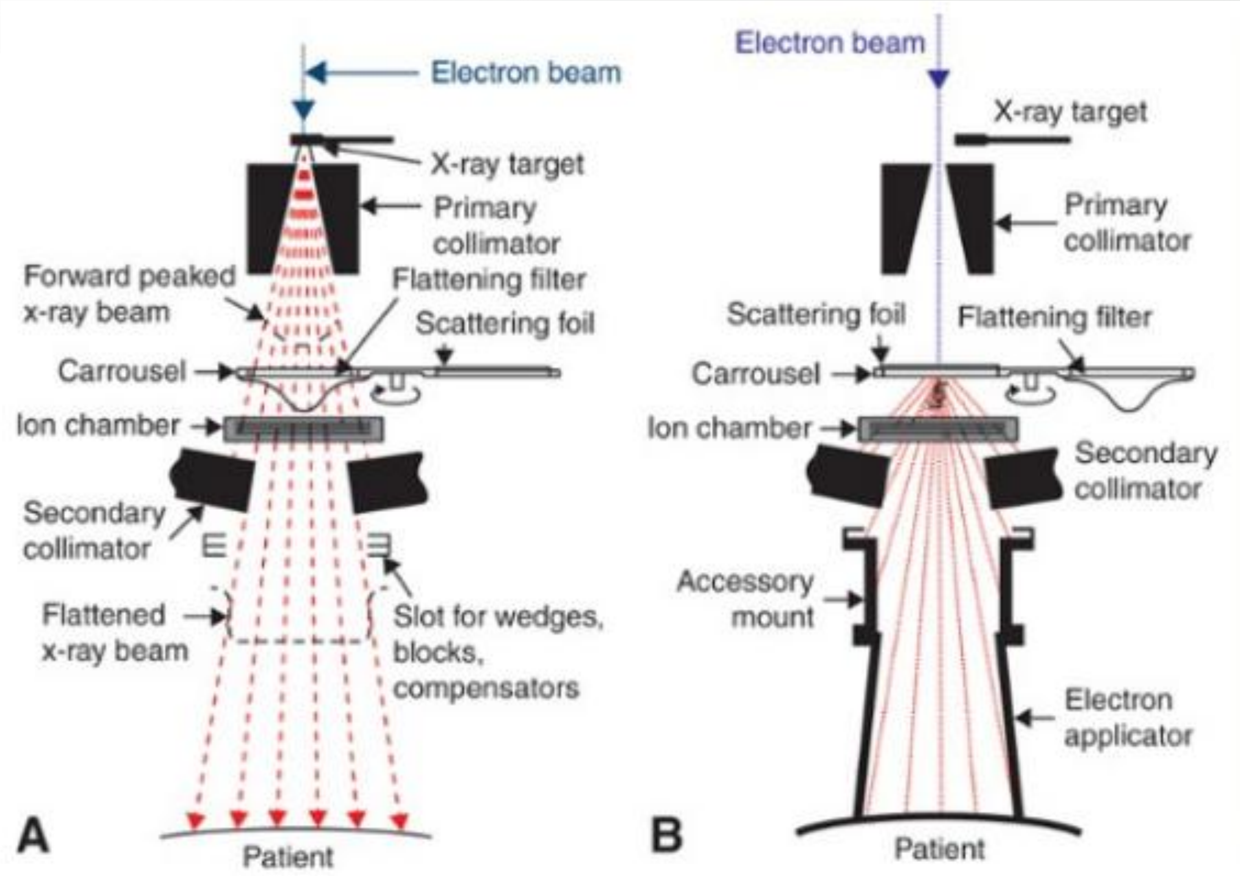
This is illustrated in the video.



*Click the **Play** button to watch the video.*

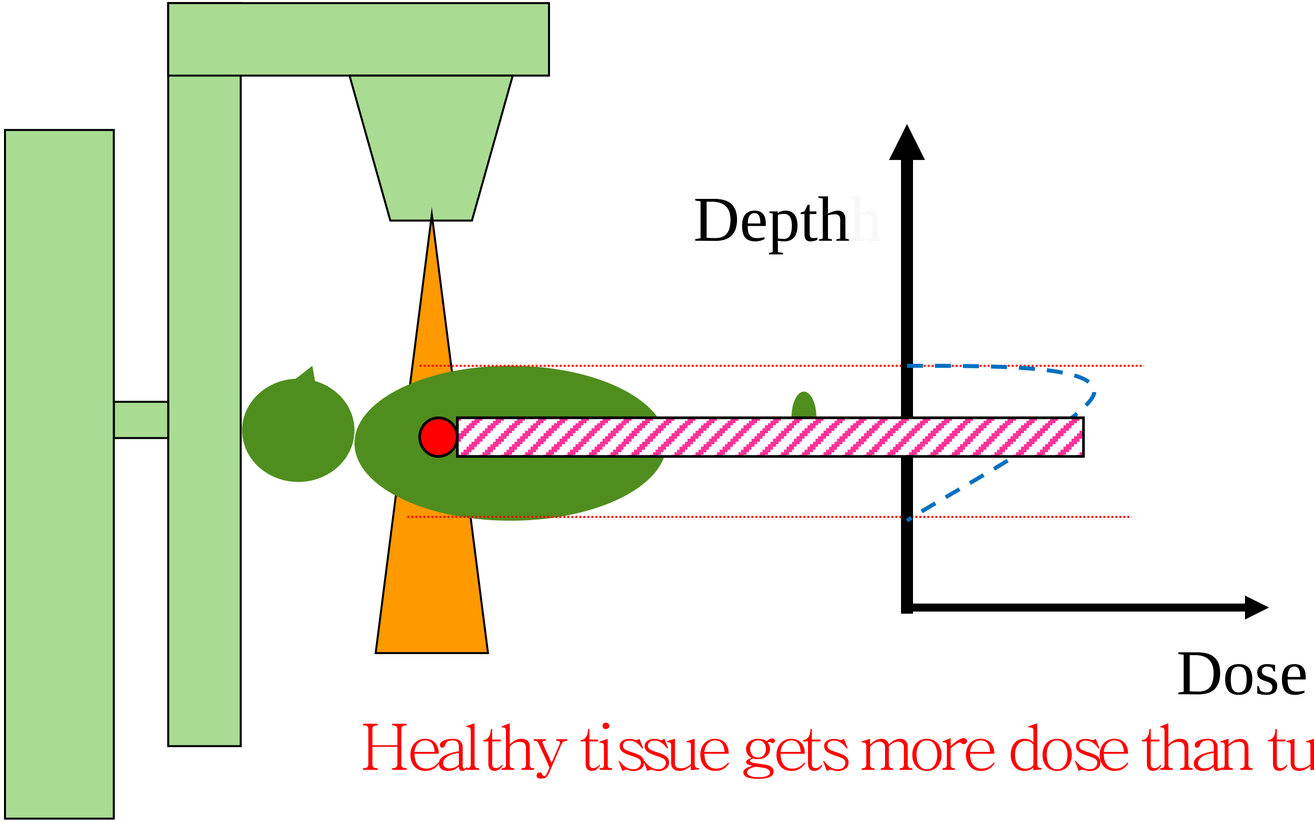
LINAC head

Photon mode



electron mode

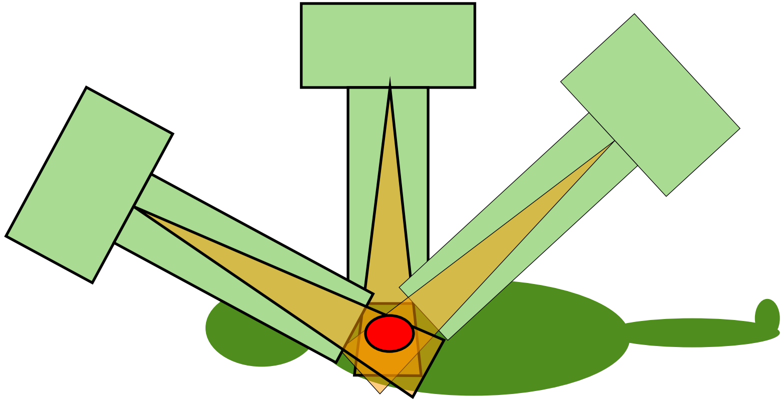
Depth-Dose Profile for PHOTON (γ) radiation



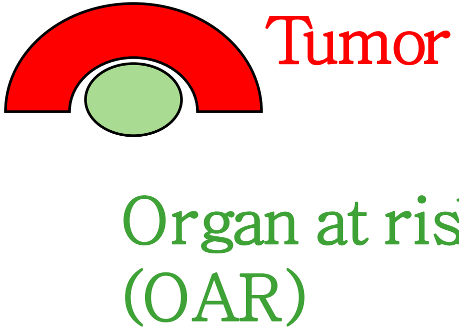
Healthy tissue gets more dose than tumor !

Solution: Isocentric Gantry

Field superposition: …a lot to a little, a little to a lot

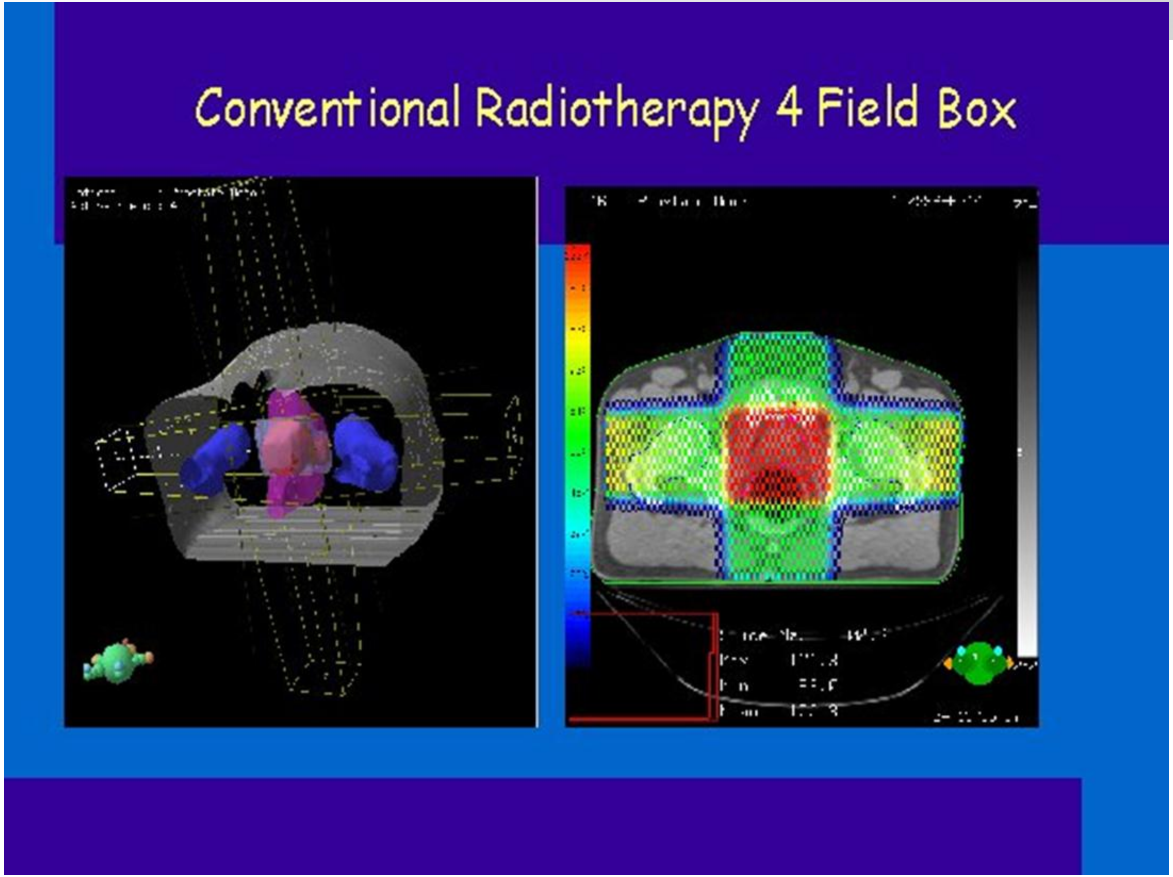


But: could one achieve a better conformity of dose distribution, specially for such cases:

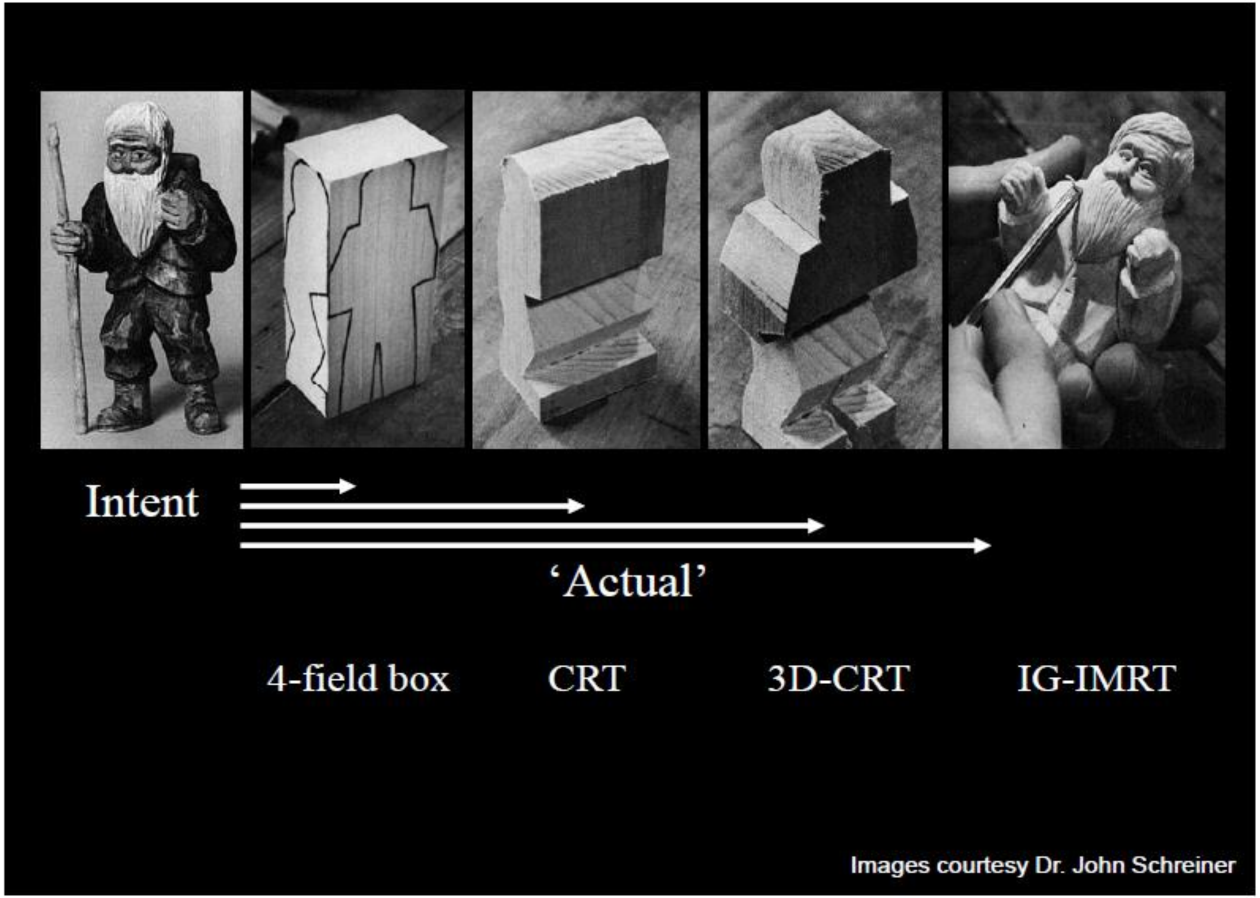


Isocentric Gantry: rotation around tumor
Superposition of rectangular fields
Dose maximum in the tumor region !

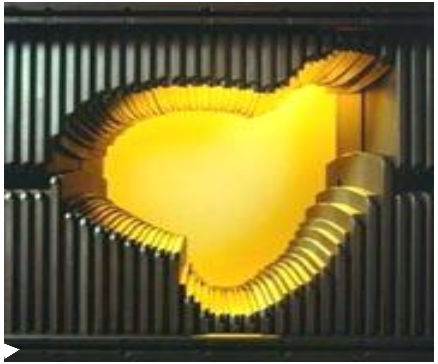
4 Field Box

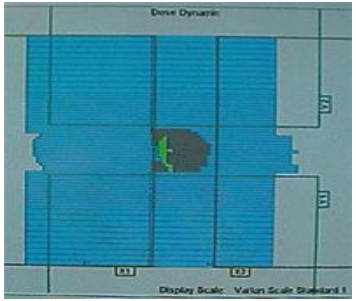


Development of conformity in RT



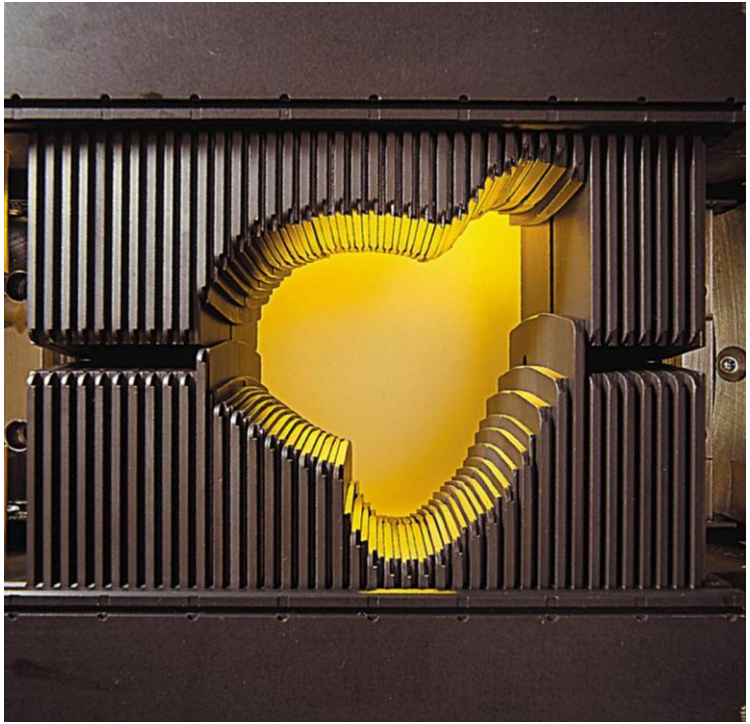
Multileaf Collimator in LINAC





3D conformal Therapy

Adapt collimator opening to tumor shape



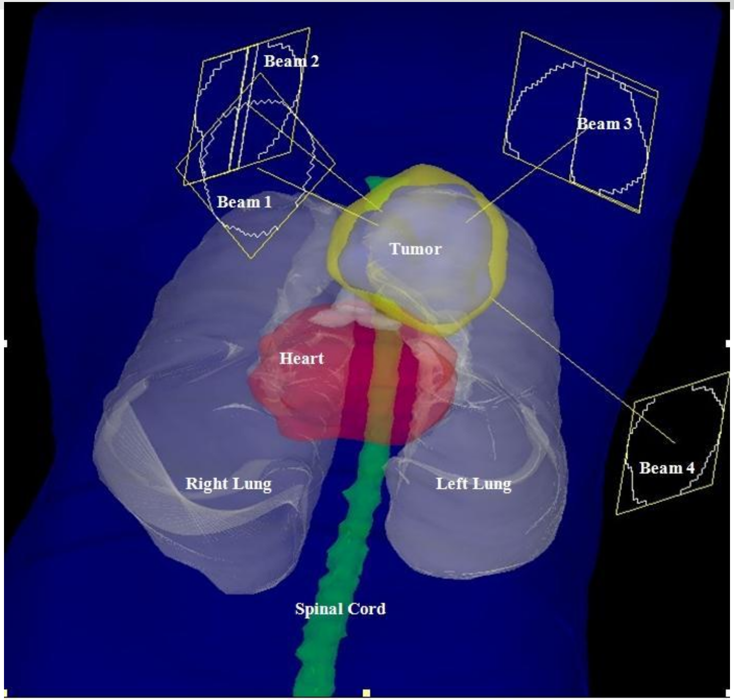
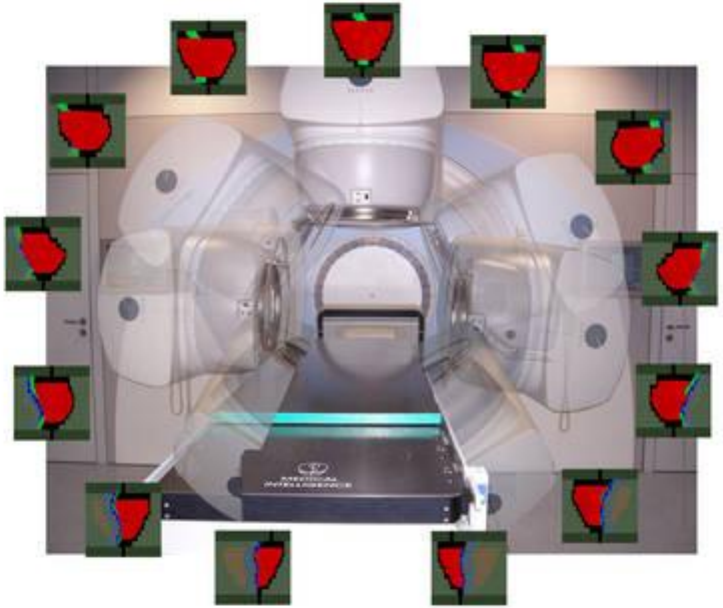
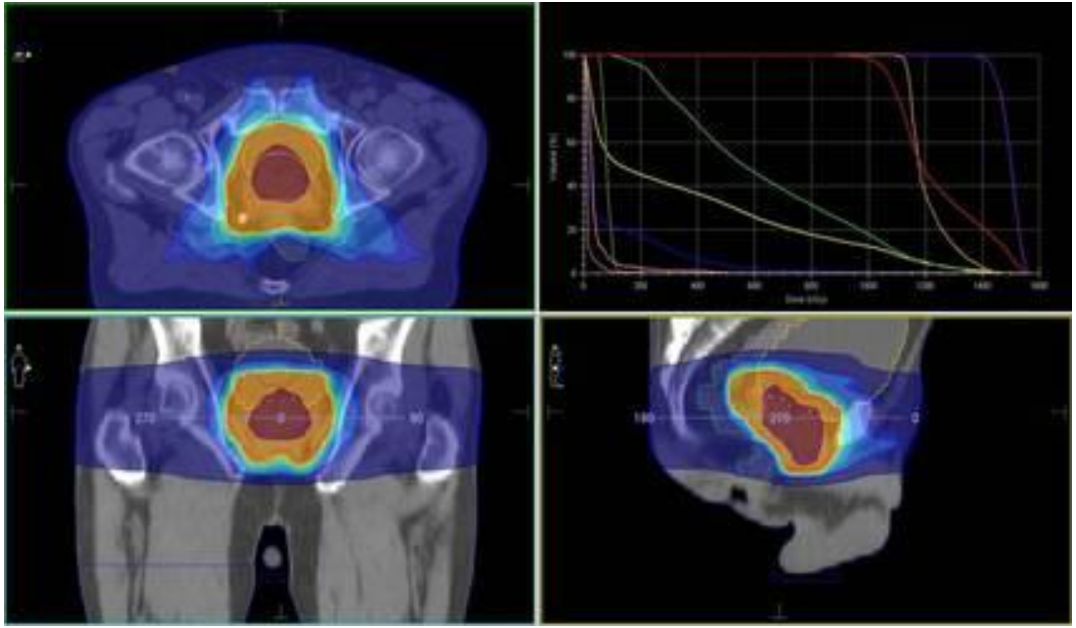
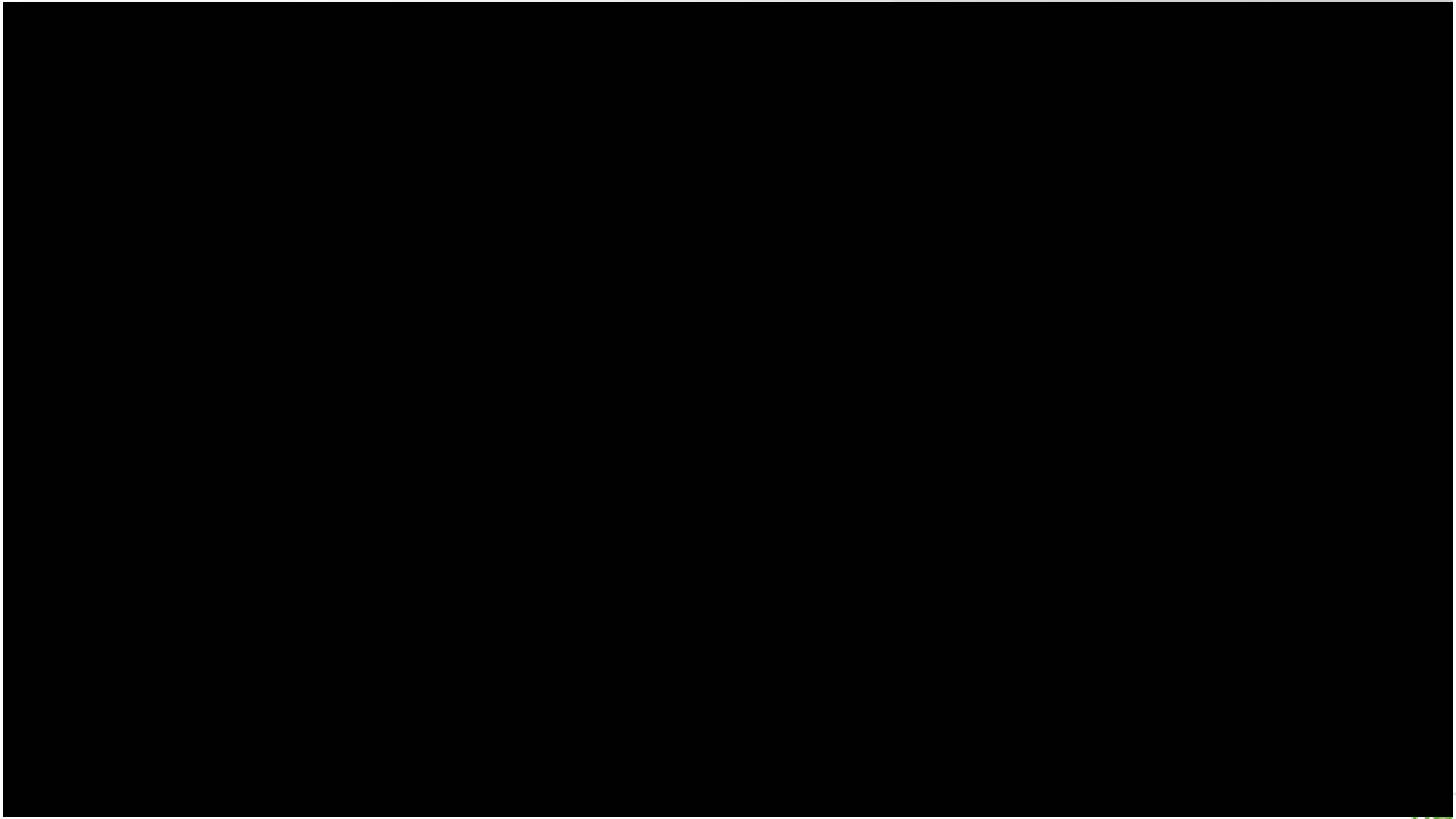


Figure 1. 3D conformal radiation treatment planning. Multiple fields of radiation are shaped to treat a lung tumor. The use of multiple beams (Beams 1-4) also allows normal tissues such as the heart, spinal cord and normal lung to be spared from high radiation doses.

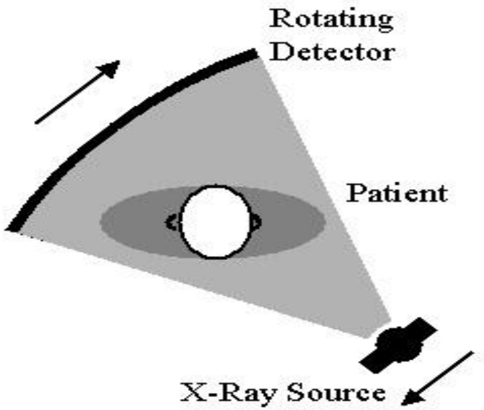
Conformal Arc

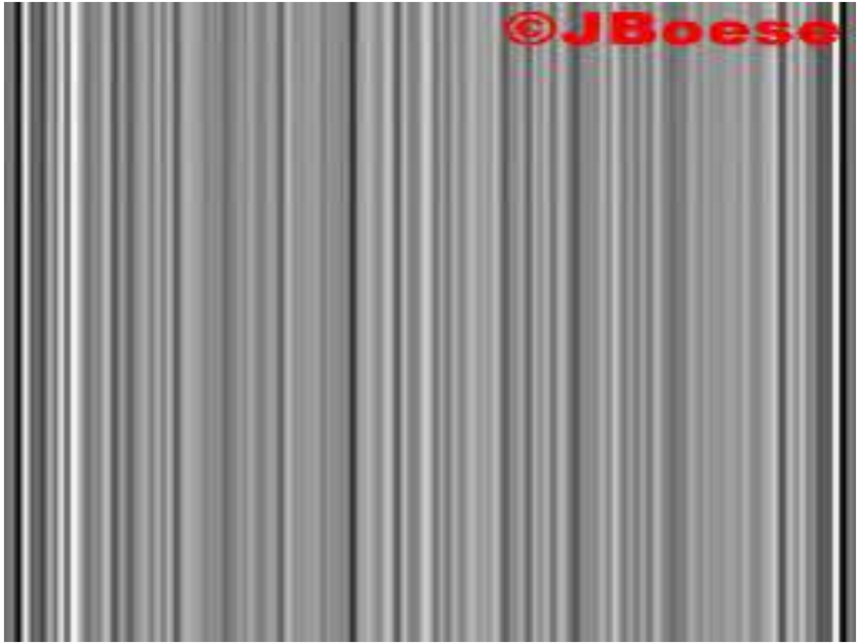




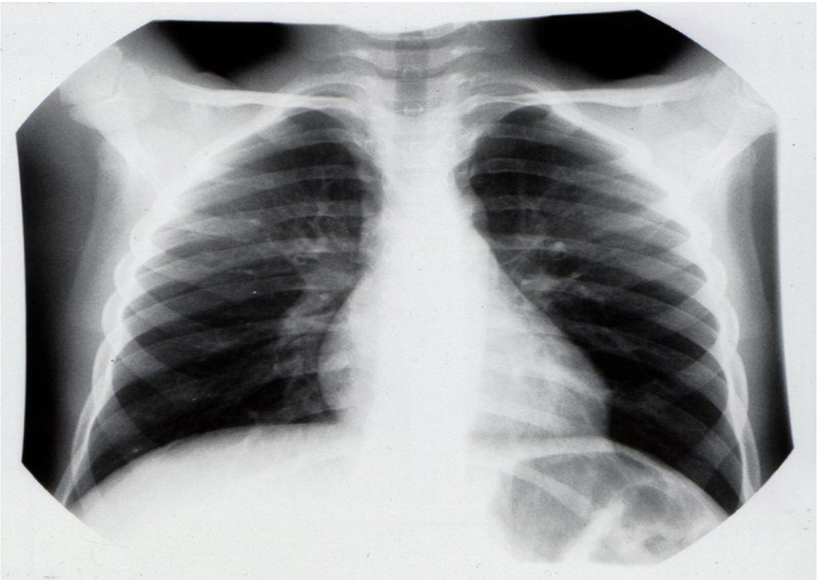


Computed Tomography (CT)





Thorax- conv. X-ray vs. CT



Conventional x-ray

Coronal section from multi-slice CT

IMRT and CT

CT:

take pictures (=modulated intesity) under many angles

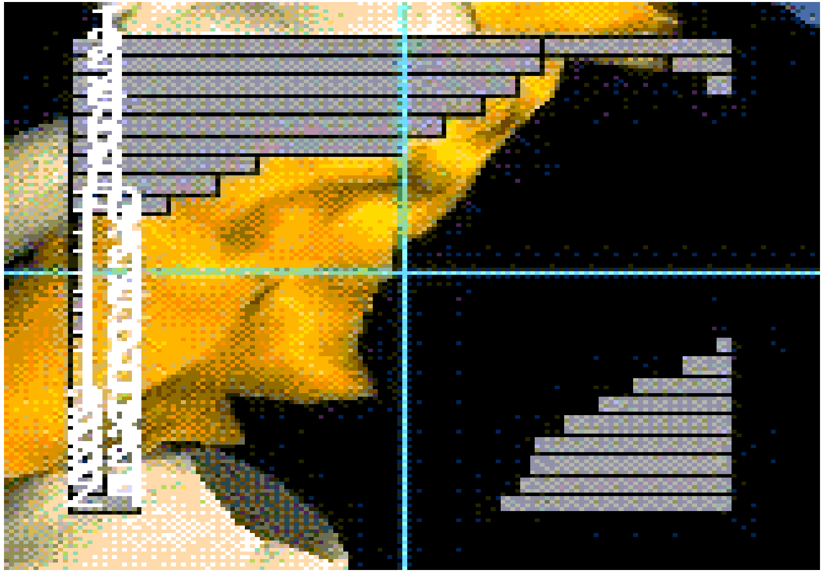
Reconstruct 3-D density distribution

IMRT:

Irradiate with modulated intensity pattern from many angles

create 3-D dose distribution

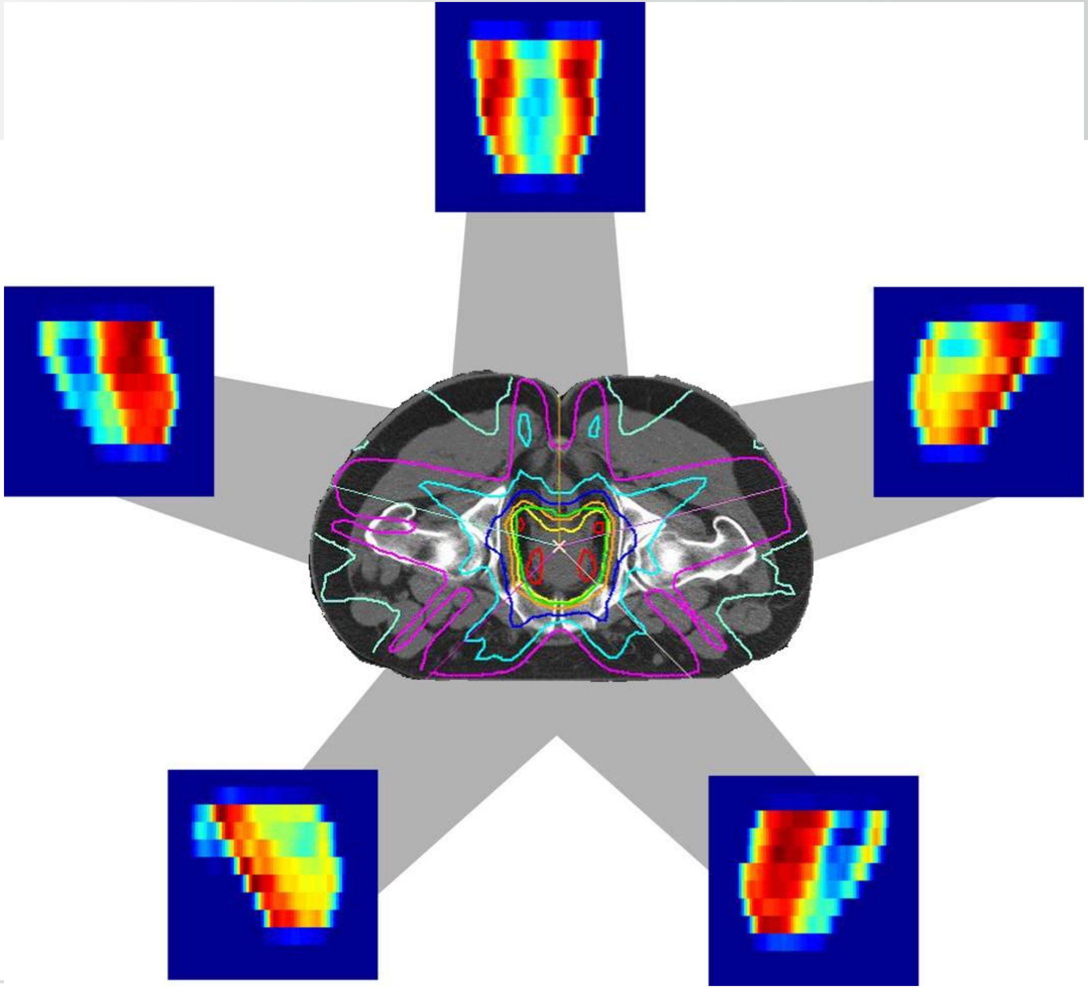
IMRT



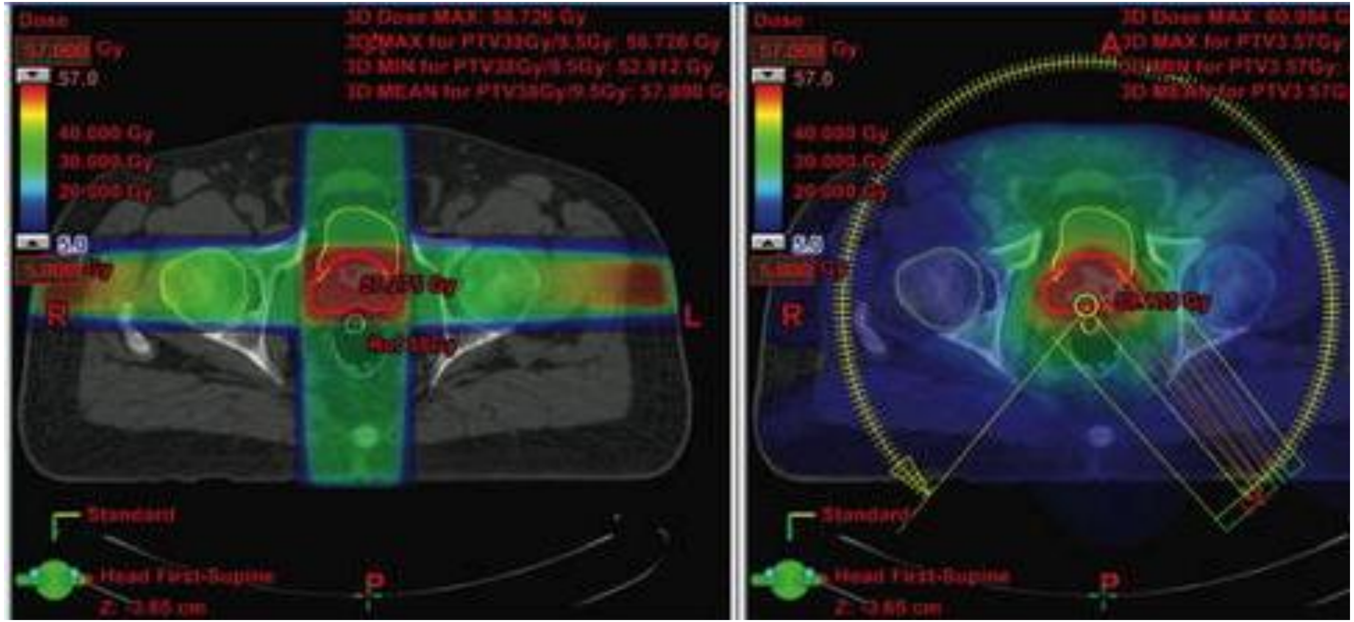
•*As the treatment head arcs, "leaves open and close to control the amount of radiation given in each "beam's eye view."*

•*This creates the ability to tightly sculpt dose.*

IMRT

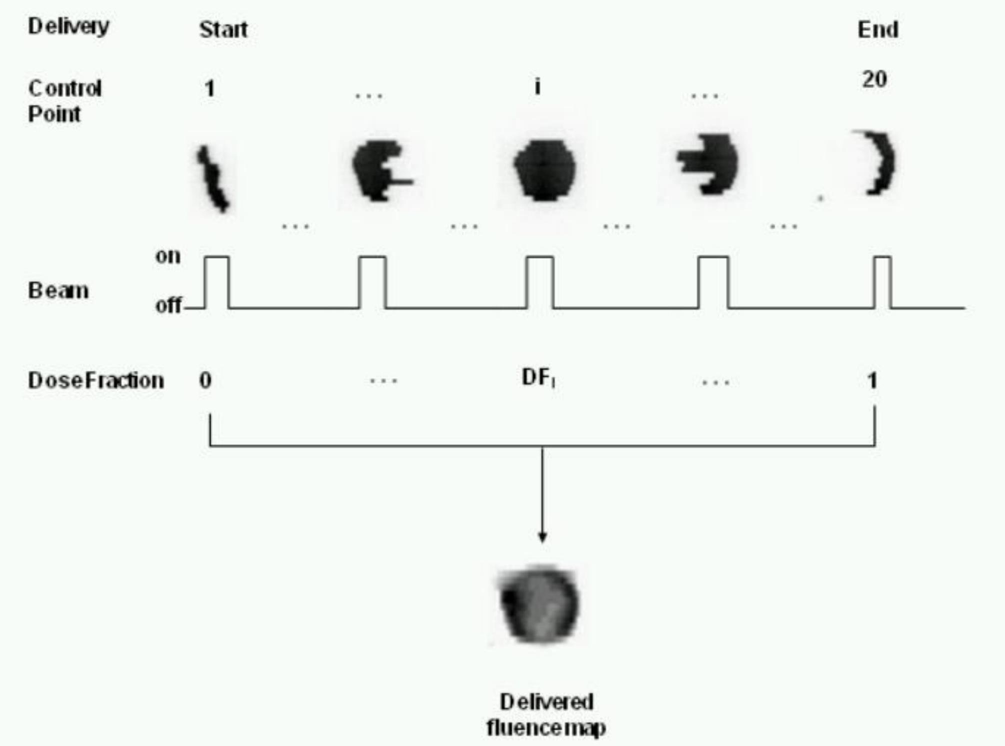


3D CRT vs. Conformal arc



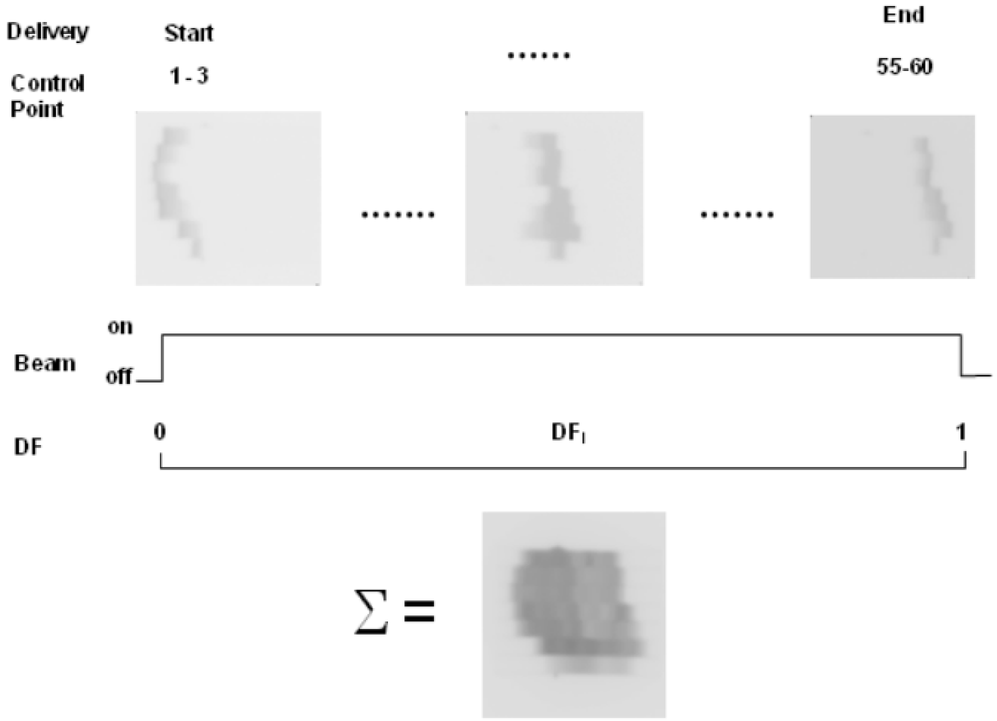
Step-and-shoot delivery of IMRT

Static segments form a field



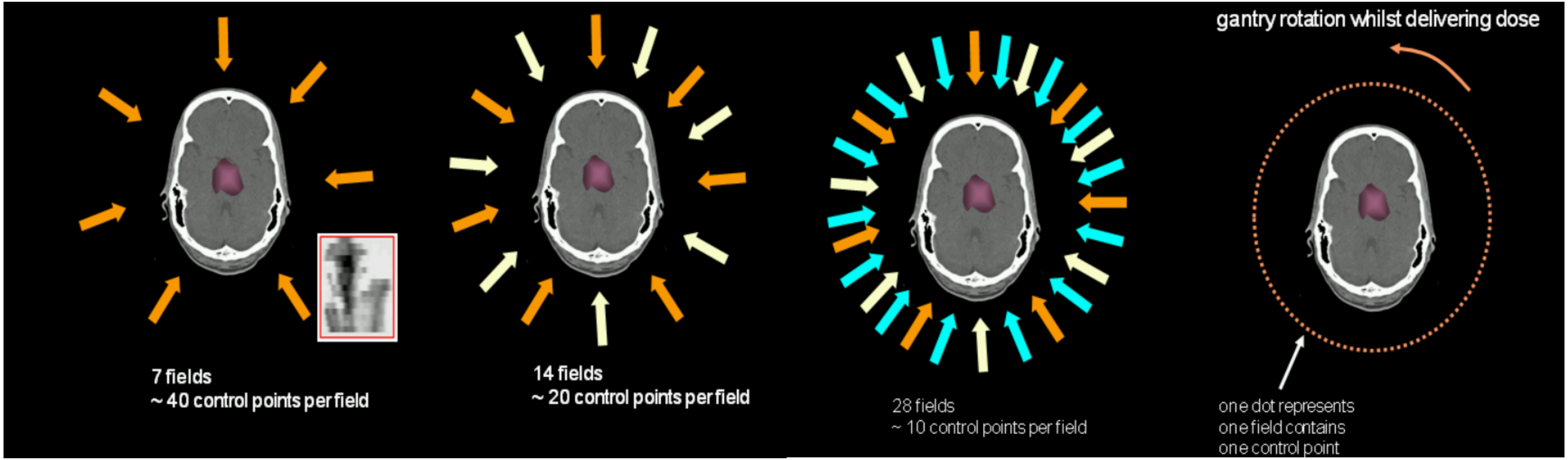
Sliding Window delivery

Dynamic collimator motion during field delivery



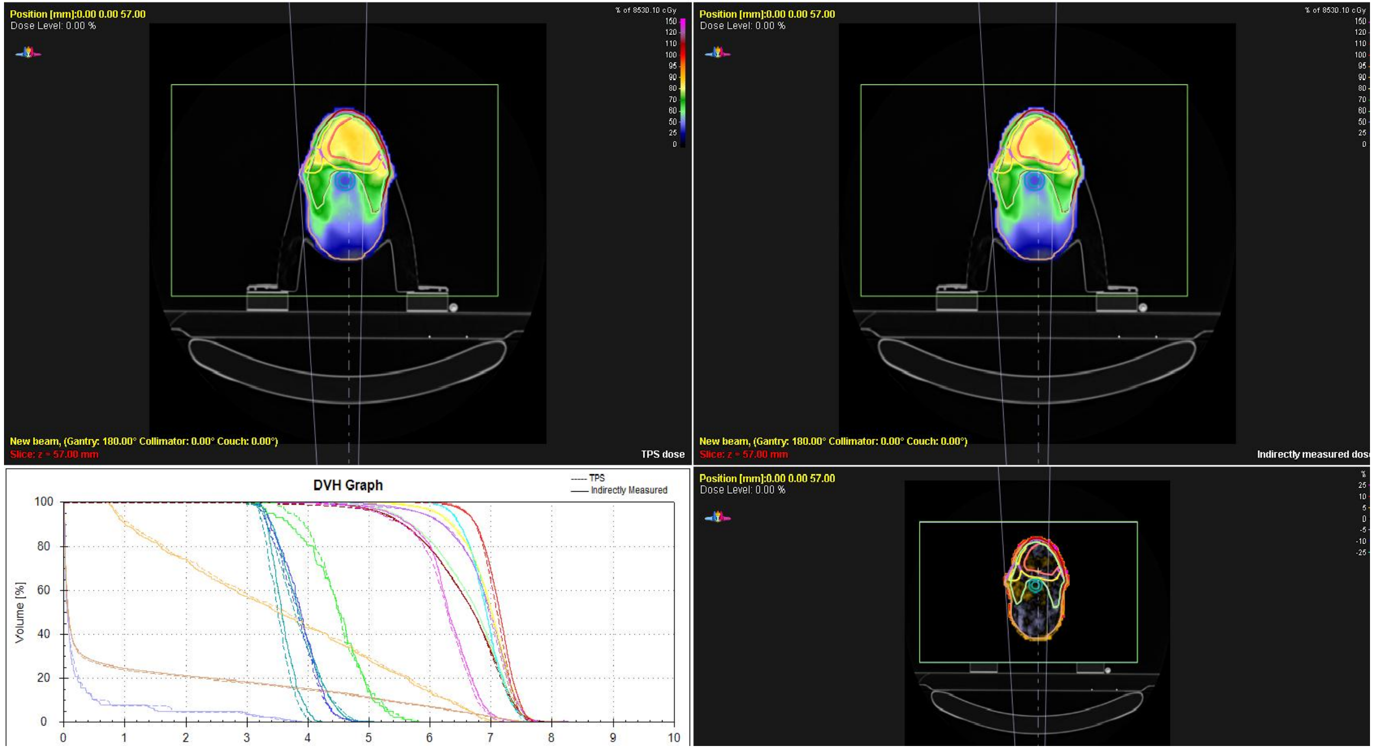
VMAT delivery

Volumetric Modulated Arc



Vmat H&N Plan

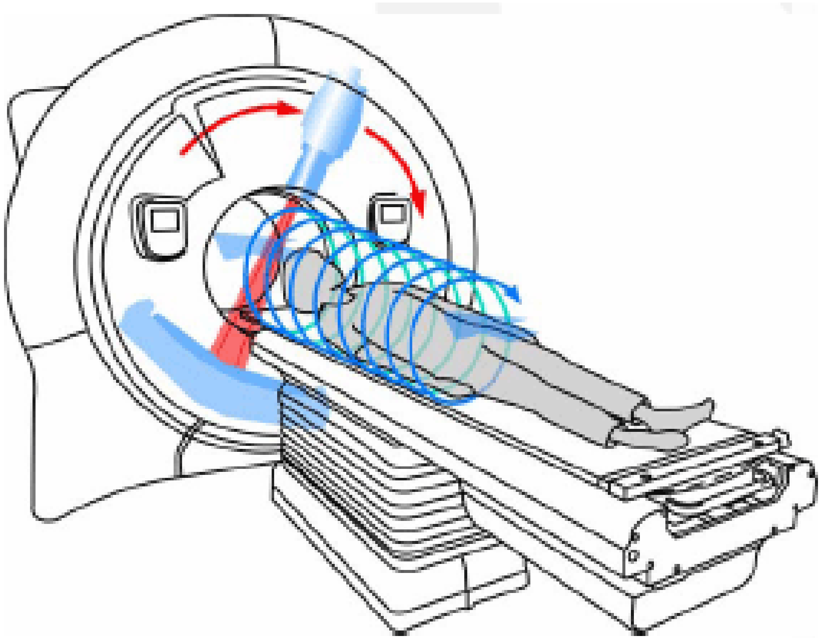
MONACO plan vs. COMPASS measurement

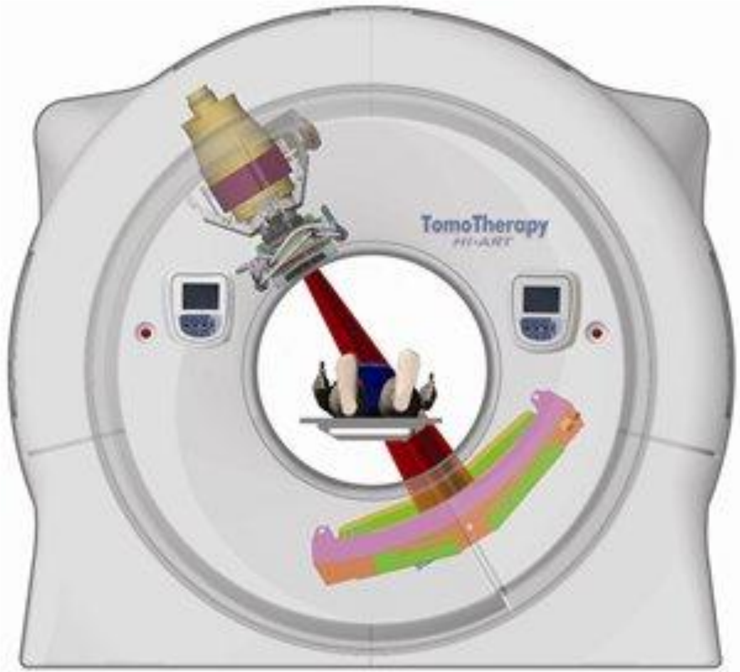


RapidArc Treatment

Tomotherapy

Helical delivery

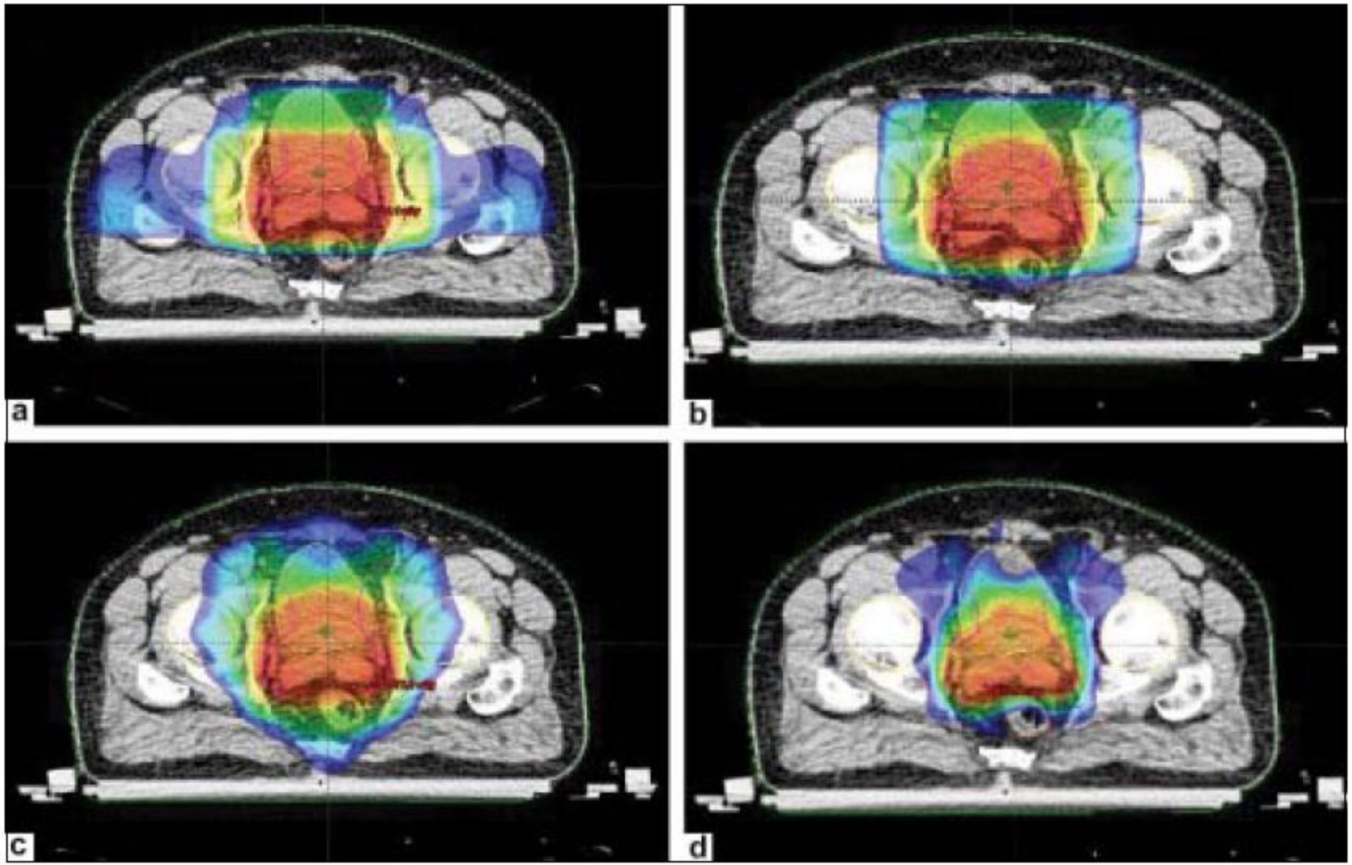




Anpassung des Dosisprofils

CONV + CONV

CONV + 3D CRT



IMRT + IMRT

S boost + IMRT

Figure 2: Dose above 45 Gy: (a) CONV + CONV, (b) CONV + 3DCRT, (c) IMRT + IMRT, and (d) SIBIMRT

Portal Imaging (EPID)

iViewGT

iViewGT is an electronic portal imaging device. It consists of an imaging panel opposite the beam limiting device. The x-rays produced by the treatment machine fall on a scintillator within the panel which gives off light with respect to the radiation, the light being detected by an array of photodiodes.

The images produced can be used for routine quality assurance, e.g. by providing a record of treatment, to check patient movement during treatment, to check organ movement such as that which occurs in the lung and to check the accuracy of the clinical set-up

iViewGT can also be used for routine MLC and Beam Modulator calibration.

iViewGT hardware comprises:

- Imaging panel containing a scintillator plate, amorphous silicon photodiode array and electronics for reading out image information
- Retractable panel arm with lateral and longitudinal movements
- Dedicated PC containing image acquisition hardware and software and image database

Cone-Beam CT imaging

Elekta Synergy XVI

An Elekta Synergy® machine is a digital accelerator with the addition of a diagnostic X-ray tube and imaging panel mounted at 90° to the MV beam direction. The diagnostic system is referred to as XVI or X-ray Volume Imaging.

The XVI system can take planar images, movie sequences and can reconstruct a set of images taken whilst the gantry is being rotated into a 3D volume view. This type of reconstruction is known as a cone beam CT as it is created from an open (cone shaped) X-ray field.

XVI hardware comprises:

- Imaging panel containing a scintillator plate, amorphous silicon photodiode array and electronics for reading out image information. The panel is not the same as iViewGT
- X-ray tube
- kV Generator providing x-ray tube control.
- Retractable panel arm with lateral and longitudinal movements.
- Dedicated PC containing image acquisition hardware and software and image database

Image Guidance

Projectiles for RT

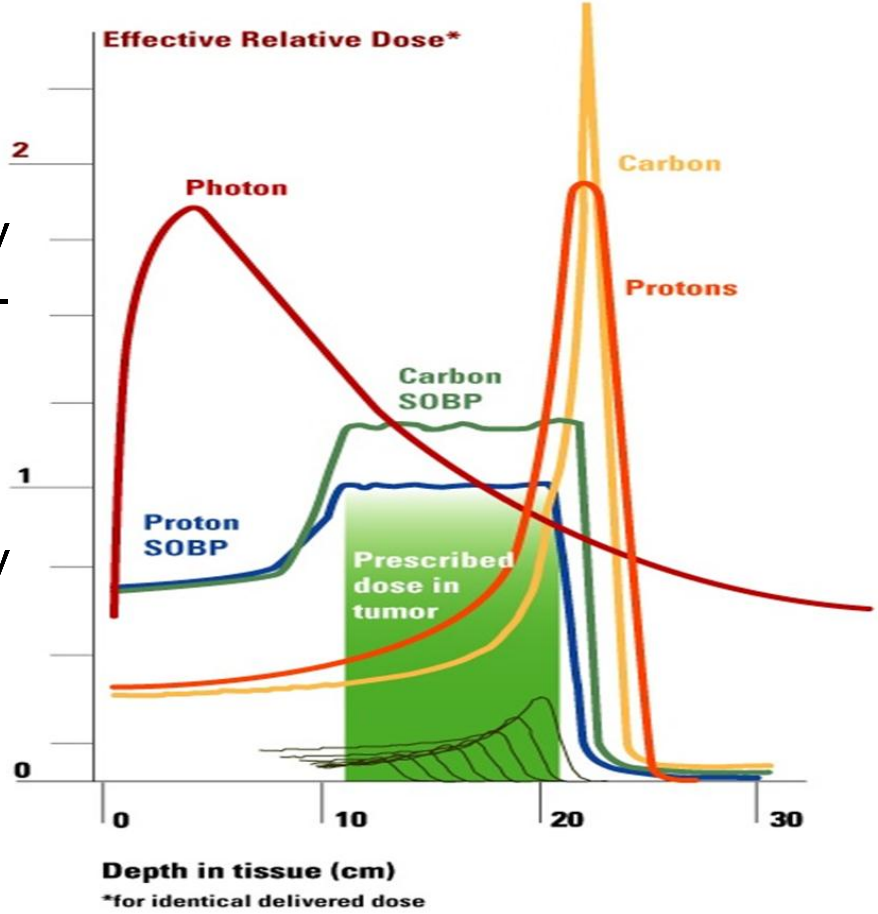
Photons vs. Charged Particles

Photons: indirectly ionizing, few primary interactions, dose deposition by secondary electrons

build-up region, D_{max} and falloff (electron equilibrium)

Protons: directly ionizing, many primary interactions

*Low proximal dose deposition, **Bragg-Peak** , sharp distal fall-off*
More pronounced for heavier ions like ^{12}C



The other way…round!

E.O. Lawrence 1929

In April 1929, UC Berkley's youngest Physics professor happened across *Archiv fur Elektrotechnik*.

Not able to read German he just looked at the diagrams and pictures of the journal.

Immediately after seeing Wideröes schematic, Lawrence fully comprehended it's implications. He was excited !

PLATE 1.4 Lawrence as a young associate professor. University Archives, TBL.

Cyclotron concept

Conceptual Cyclotron Design

Ernest Lawrence proposed a modification to Wideroe's double gap linac: bend the tubes and apply a magnetic field to bend the ion's path.

Cyclotron concept

“R cancels R”

Ernest quickly jotted down the following:

$F_r = mv^2/r$ and

$F_B = qvB$

thus:

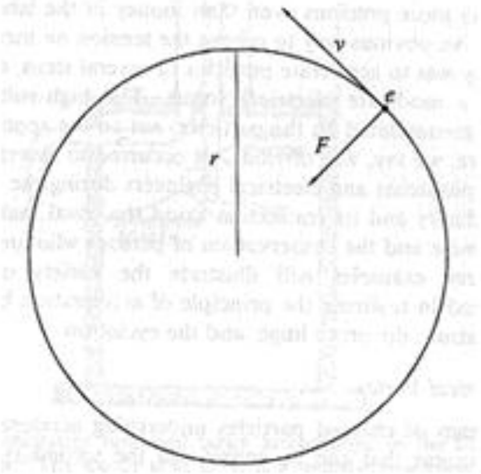
$r = mv/qB$

$\omega = 2\pi f = v/r$

substitute:

$f = qB/2\pi m$

R cancels R !



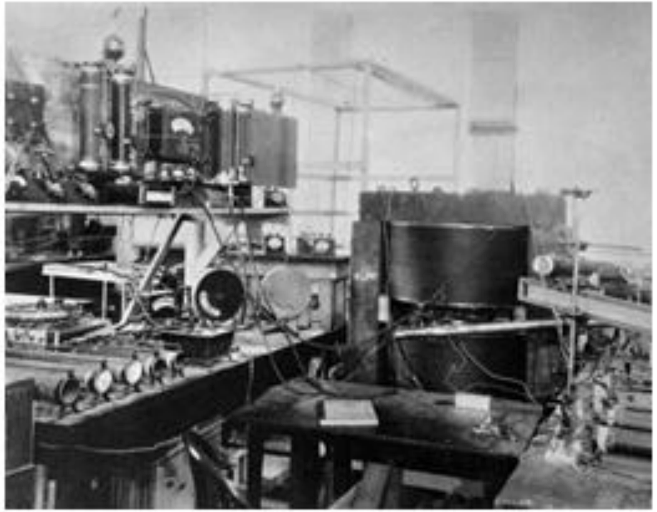
1st Cyclotron….1.1 MeV Protons!

The 11 inch 1.1 MeV

January 1932

Telegram to Lawrence:

"Dr. Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add 'Whoopee'!"



Limitation of Cyclotron

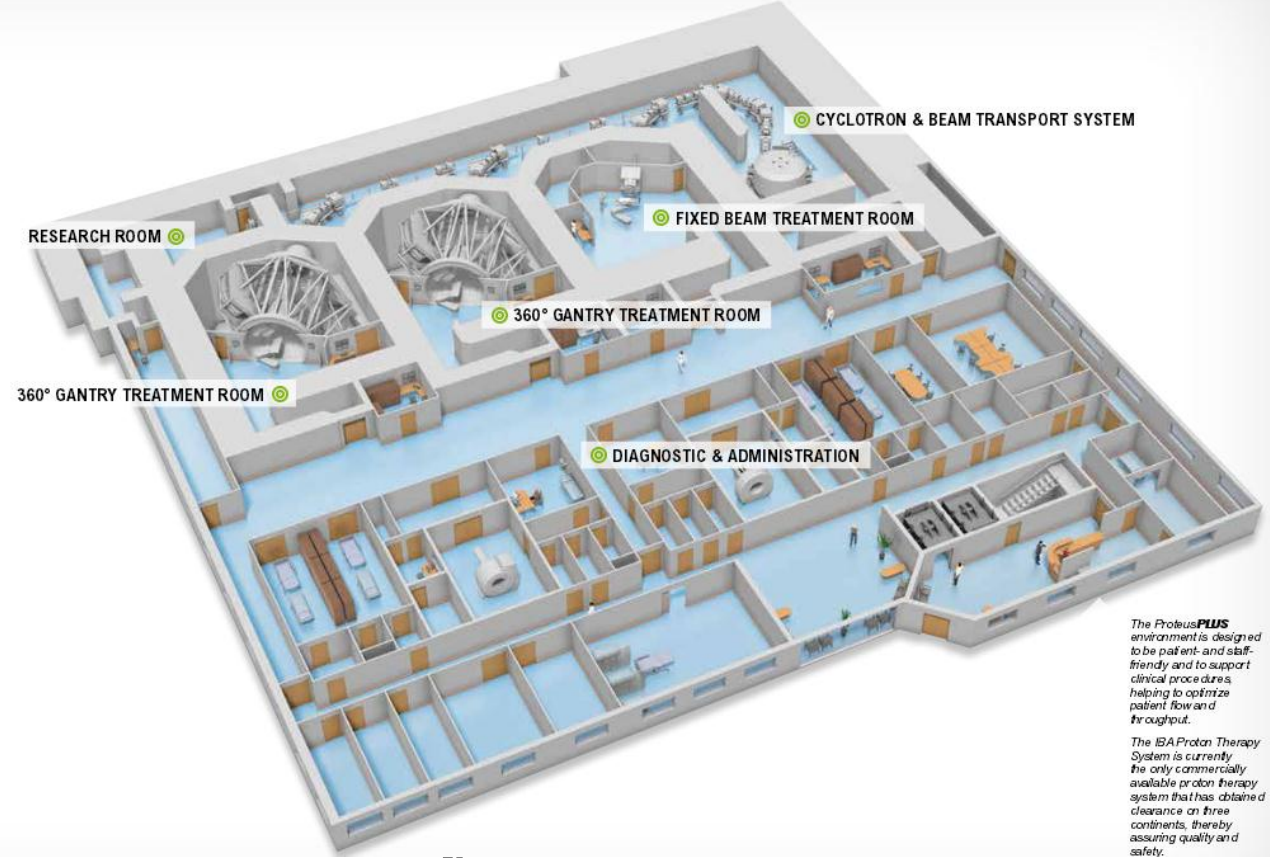
Relativistic mass increase

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \frac{m_0}{\sqrt{1 - \beta^2}} = \gamma m_0$$

Isochroneous Cyclotron $B = \gamma B_0$

Synchrocyclotron $f = \frac{f_0}{\gamma} = f_0 \sqrt{1 - \beta^2}$

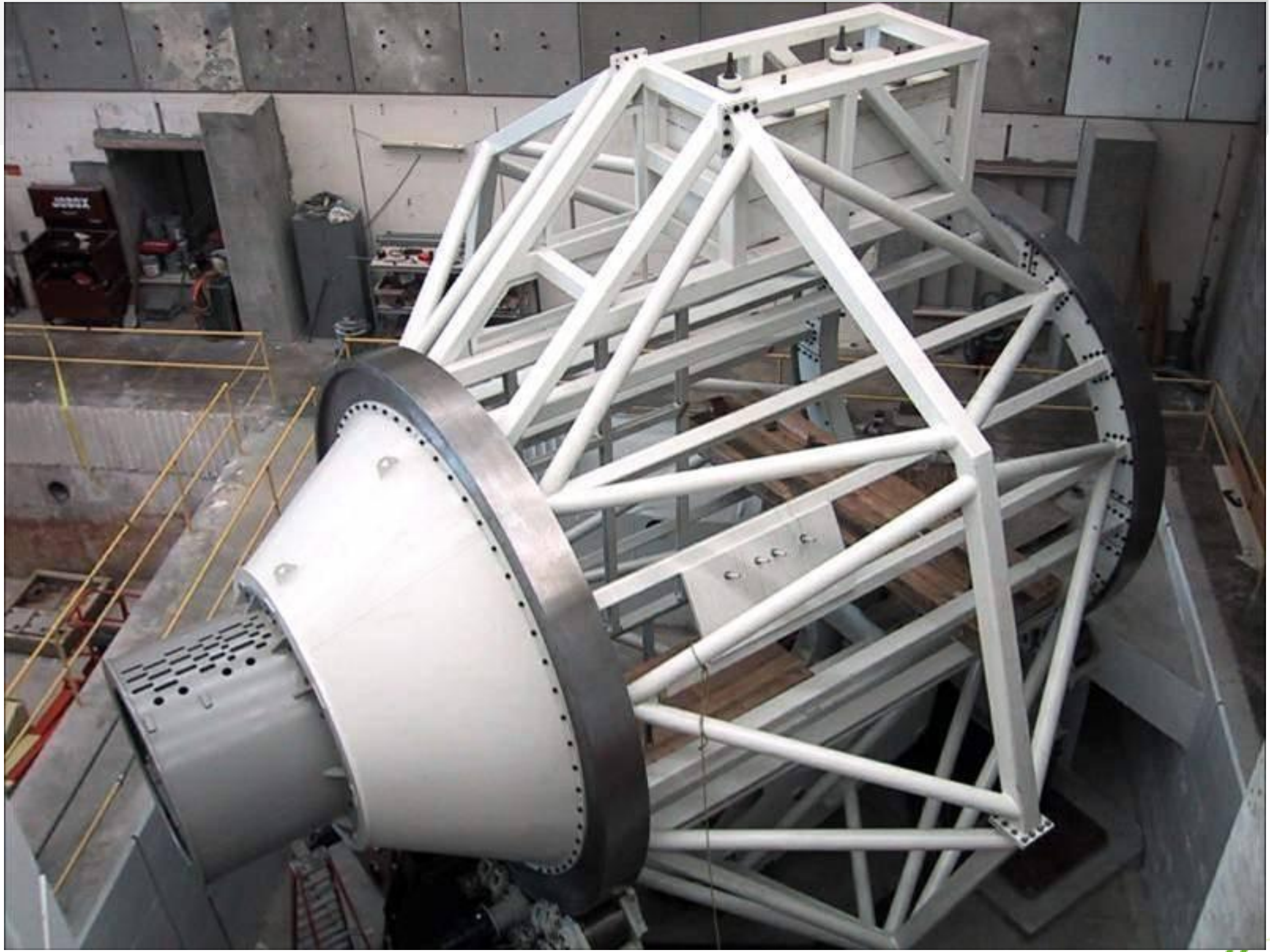
Proteus Plus – Isochronous Cyclotron



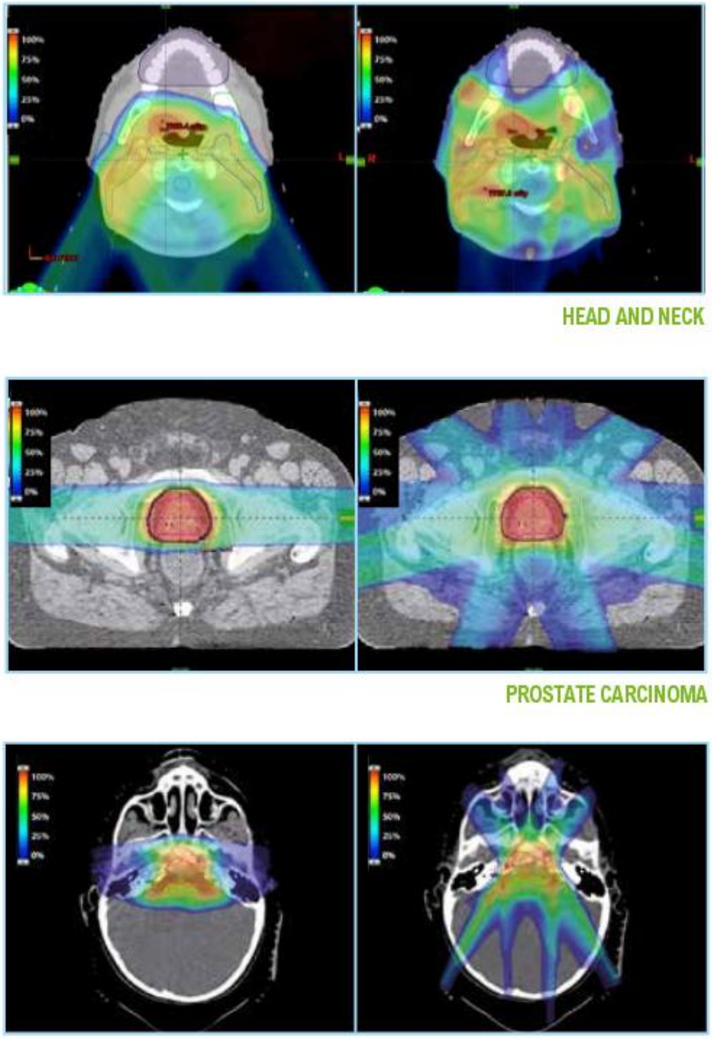
The ProteusPLUS environment is designed to be patient- and staff-friendly and to support clinical procedures, helping to optimize patient flow and throughput.

The IBA Proton Therapy System is currently the only commercially available proton therapy system that has obtained clearance on three continents, thereby assuring quality and safety.

Gantry



Protons vs. IMRT



Images with the courtesy of Stefan Both, Ph D. PEDIATRIC CHORDOMA

Proteus One

Superconducting Synchrocyclotron

S2C2

Main features and parameters

Subsystems:

- Magnetic Circuit
- Superconducting coil
- RF System
- Ion Source+Central Region
- Extraction System
- Extracted beam line

Pencil Beam Scanning