Medical Accelerators and Radiation Protection

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Outline

- Radiotherapy, general
  - Radiation oncology and its role
  - Radiobiology
  - Radiation effects
- Regulatory environment
- Radiotherapy
  - Accelerators
  - Beam delivery systems
- Radiation Protection
  - Protecting the Patient
  - Protecting the Personnel
  - Protecting the Public
- Physicists' role
  - Training and qualifications
  - Radiation Safety Officer / Health Physicist
- Facility design
  - Shielding
- Summary

Acknowledgements

- IAEA Radiation Protection of Patients
  - Excellent online, free material
  - Several slides from this presentation
- NRC 10 CFR 20: Standards of Protection Against Radiation
- NCRP-151
- State of California, Title 17
- Scripps Proton Therapy Center
  - Lei Dong, PhD

Radiotherapy

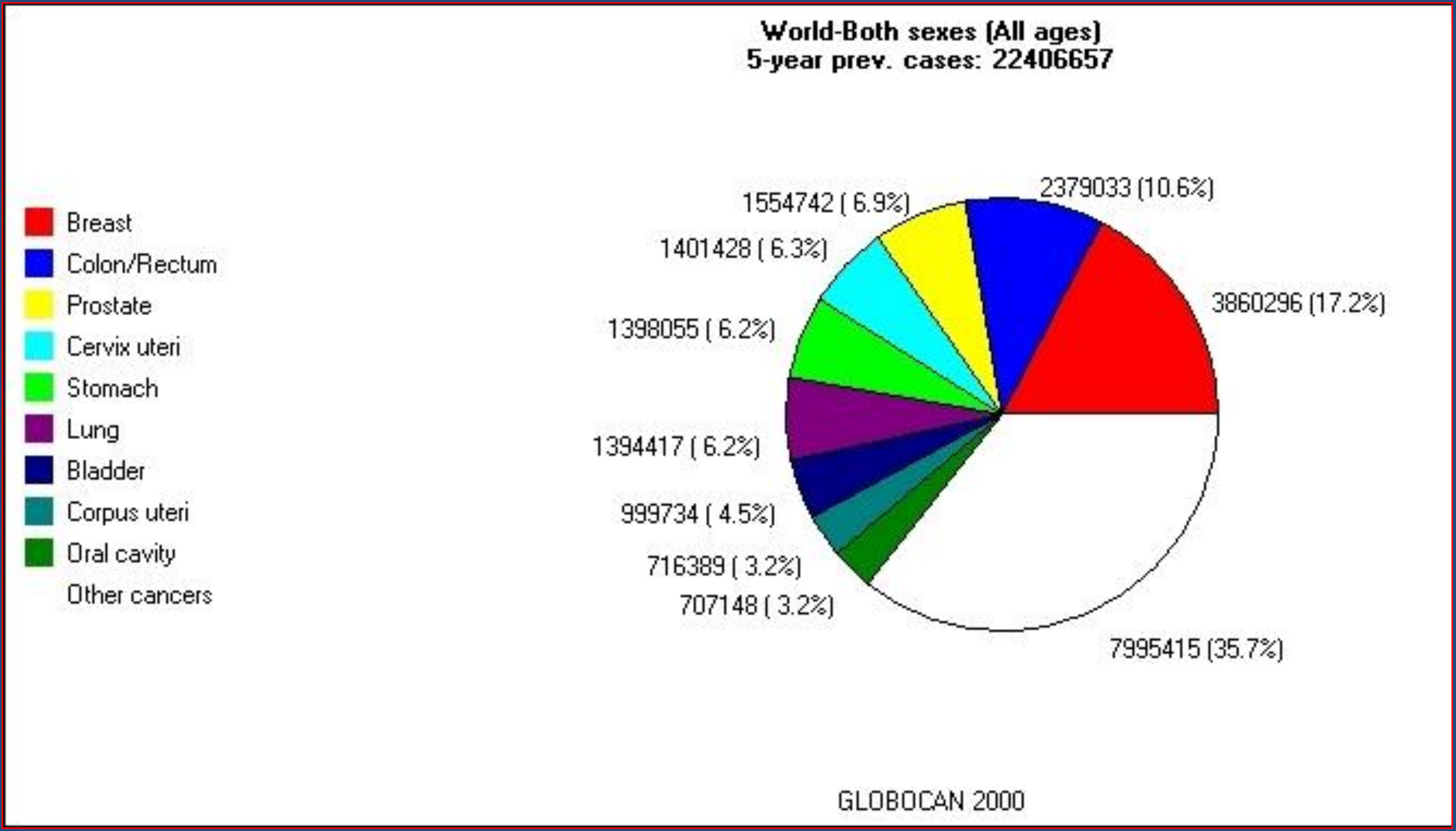
Principles

Radiotherapy

- One of the main treatment modalities for cancer (often in combination with chemotherapy and surgery)
- It is generally assumed that 50 to 60% of cancer patients will benefit from radiotherapy
- Minor role in other diseases

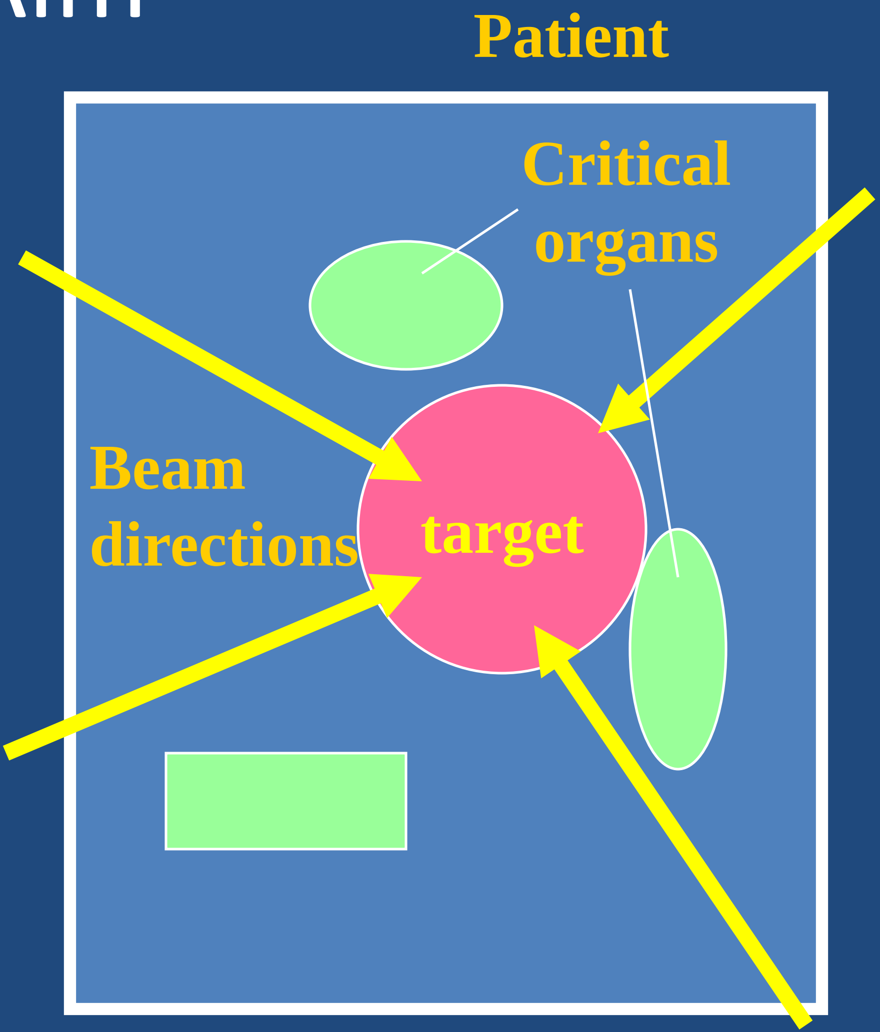
Siemens Oncology

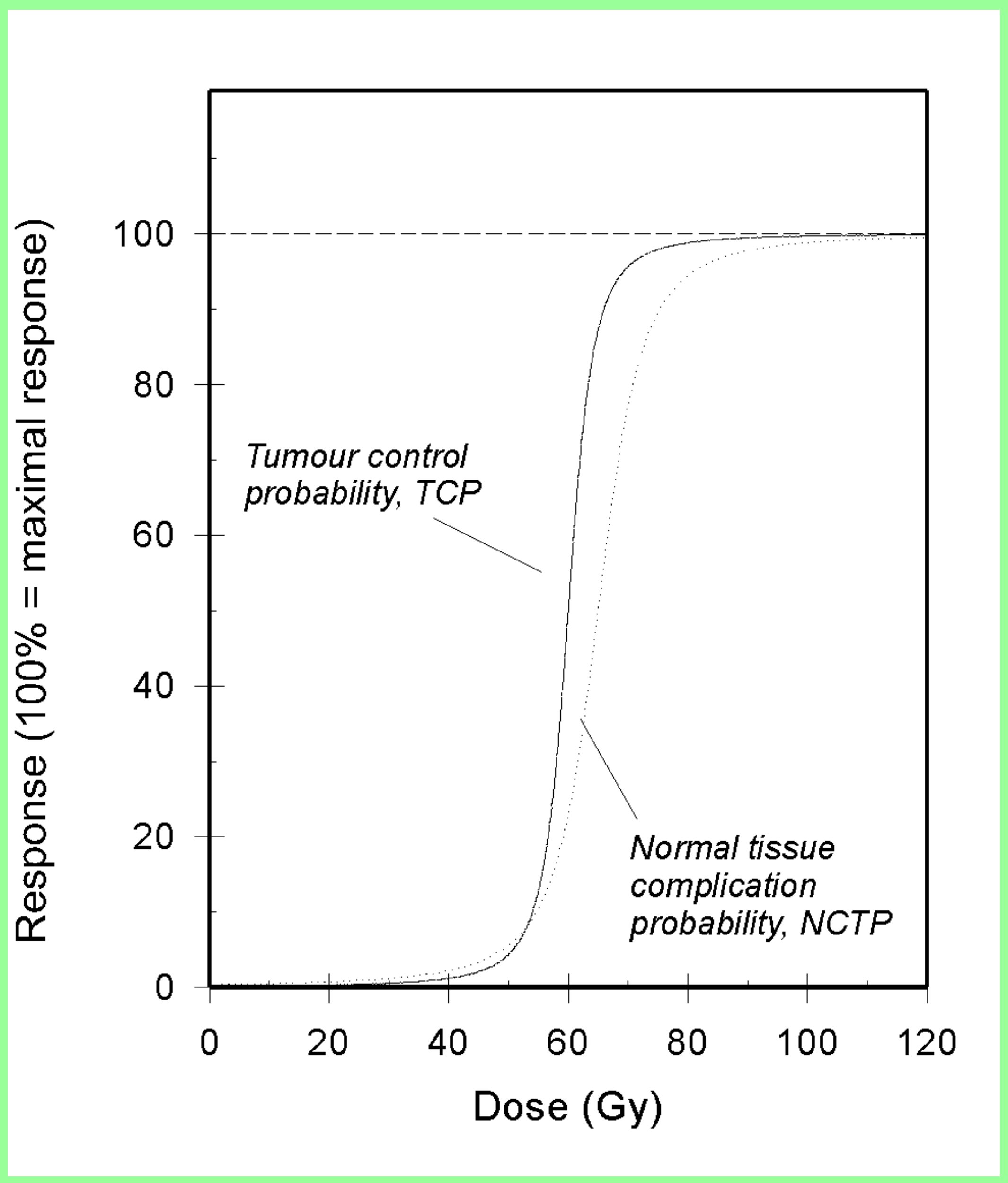
Cancer incidence (WHO)



Aim

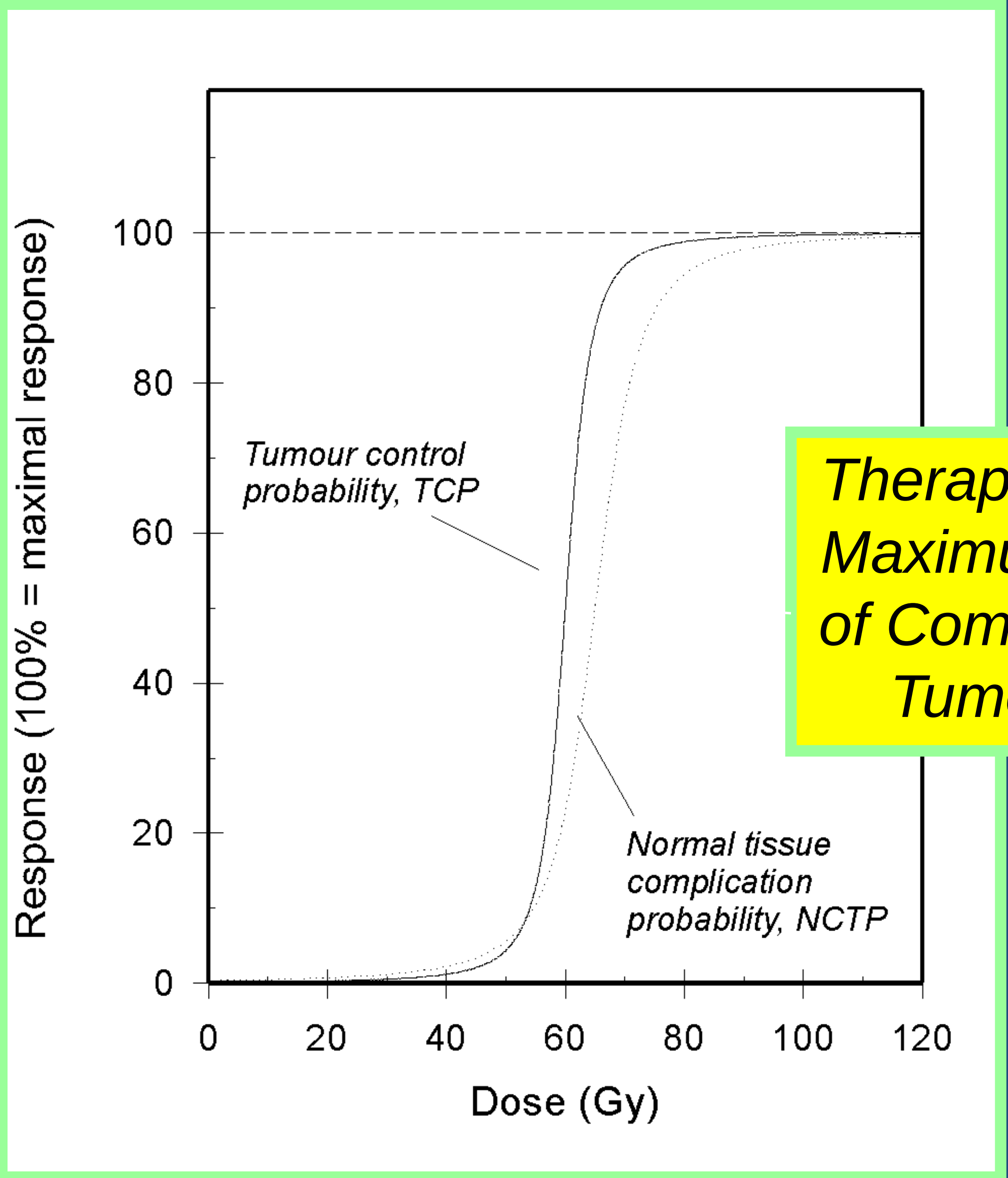
- To kill **ALL** viable cancer cells
- To deliver as much dose as possible to the target while minimising the dose to surrounding healthy tissues
- As opposed to chemotherapy





Dose response

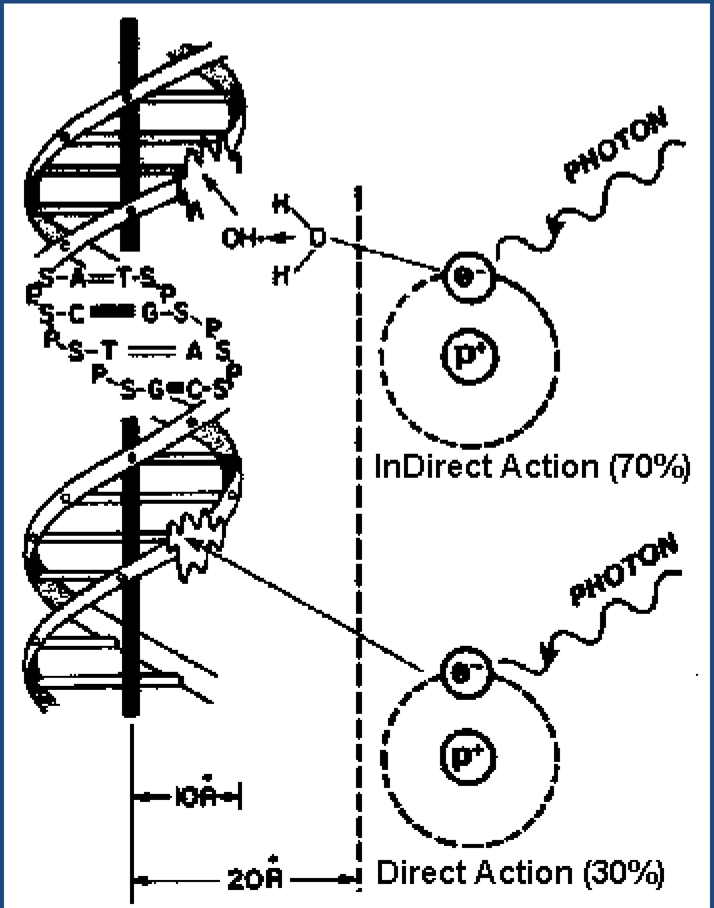
100% response means the tumour is cured with certainty (TCP) or unacceptable normal tissue damage (*e.g.* paralysis) is inevitable



Dose response

Therapeutic window: Maximum probability of Complication Free Tumour Control

Radiobiology

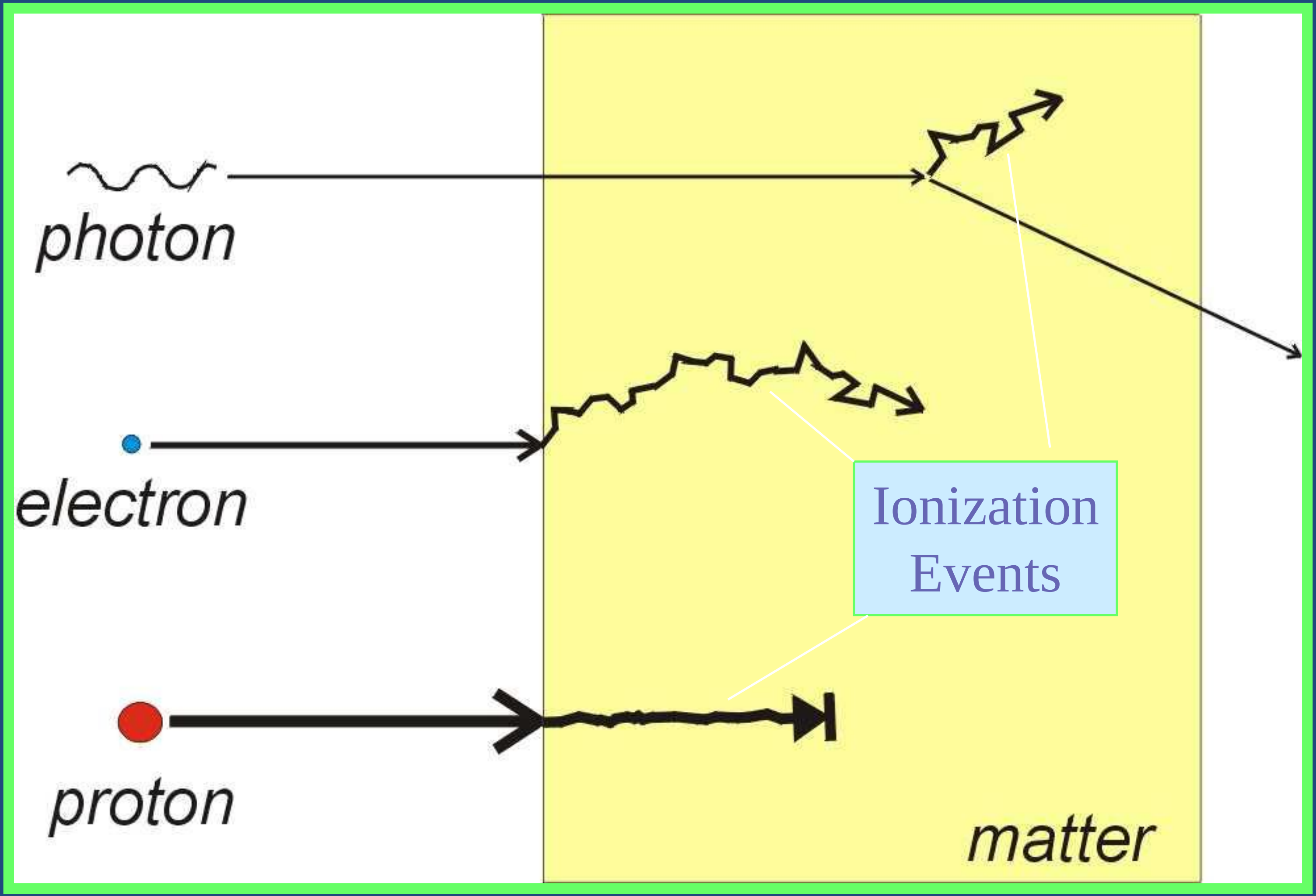


- Radiation damages DNA
  - Double strand break
- Cell is effectively "killed" or sterilyzed
- Different mechanisms
  - Indirectly ionizing
  - Directly ionizing

Types of Radiation

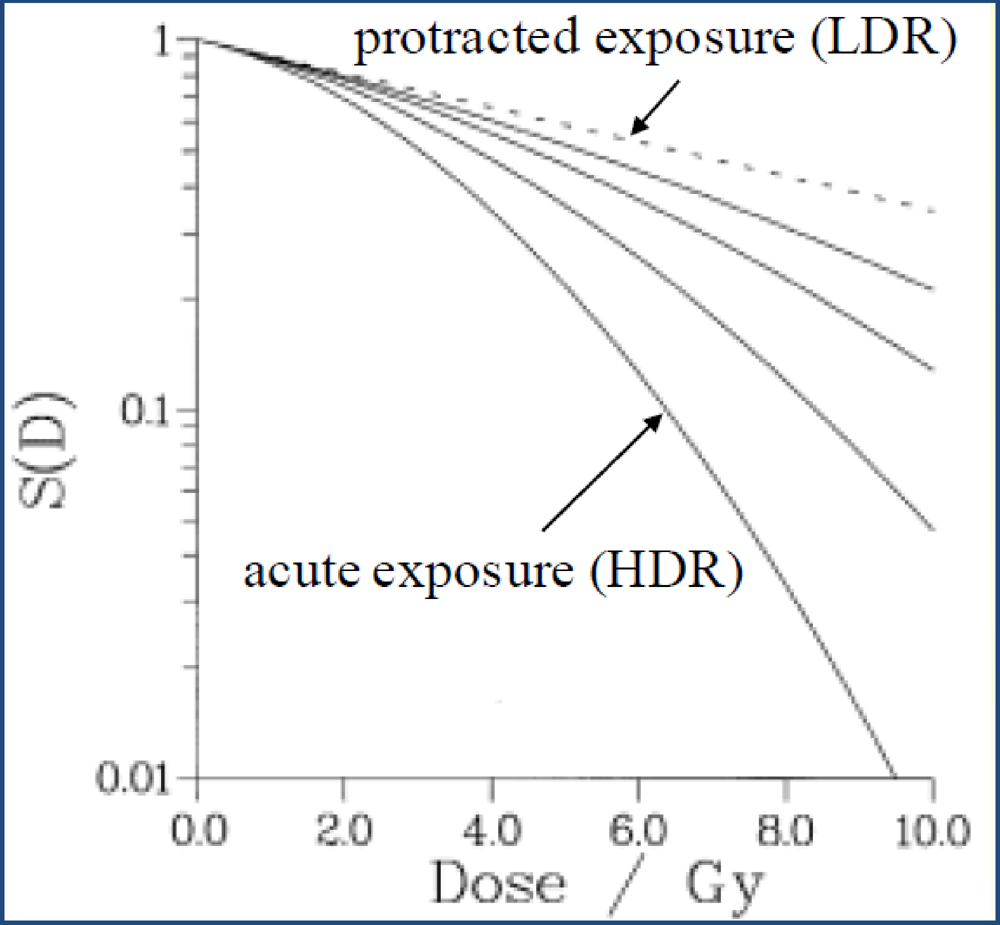
- Directly ionizing radiation - energy is deposited by the particle directly in matter (electrons, protons)
- Indirectly ionizing radiation - primary particle transfers energy to secondary particle which in turn causes ionization events (photons, neutrons)

Types of Radiation

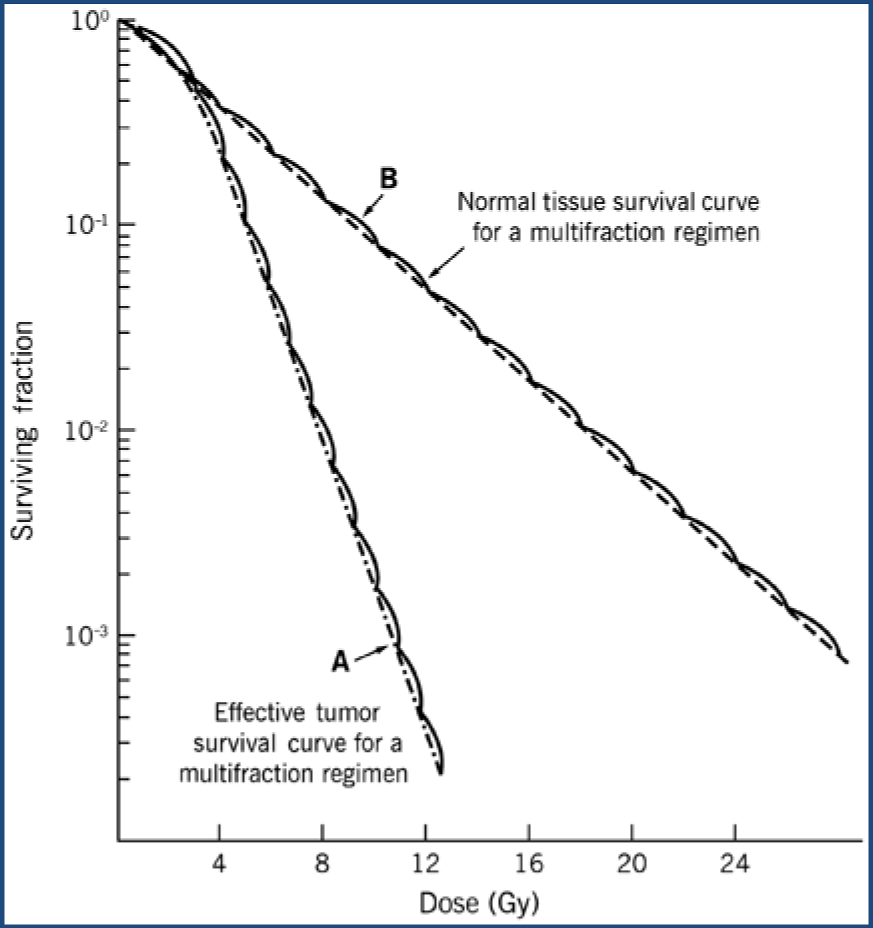


Acute vs. Protracted Exposure

- How quickly the dose is delivered matters
- In how many pieces the dose is delivered matters



Fractionated Radiotherapy



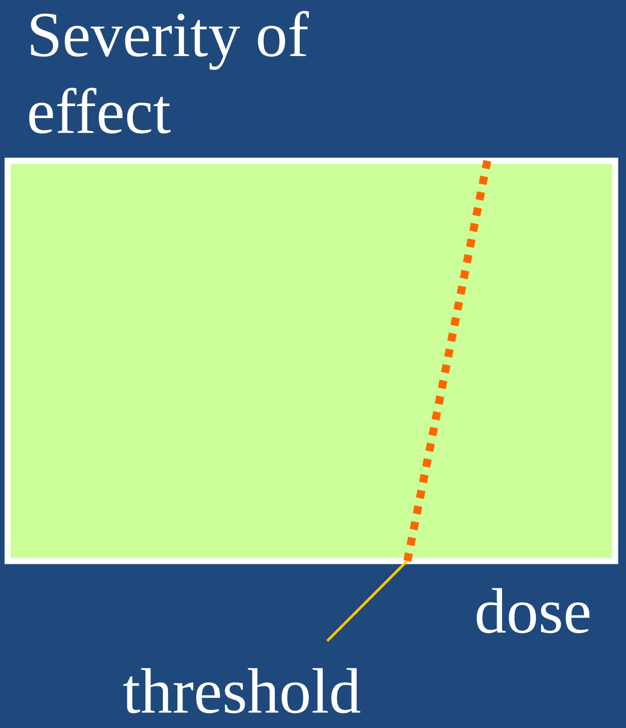
- Radiation damages tumors more readily than normal tissue
  - Normal tissue has mechanisms to repair and weather radiation damage
  - Tumors are not organized well for this
- Radiation therapy exploits this concept

Radiation Therapy is Ultimately About Biology

- What matters in the end is the biological effect!
  - Dose to the tumor determines probability of cure (or likelihood of palliation)
  - Dose to normal structures determines probability of side effects and complications
  - Dose to patient, staff and visitors determines risk of radiation detriment to these groups

Low dose: Stochastic effects	High dose: Deterministic effects

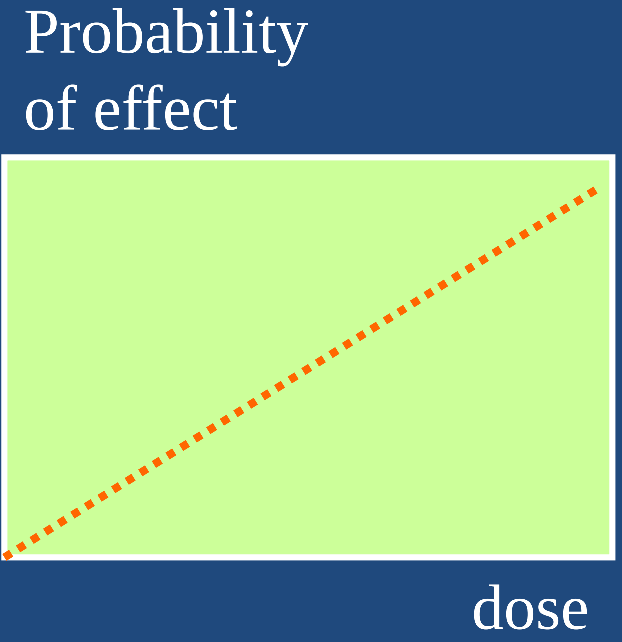
Deterministic effects



- Due to cell killing
- Have a dose threshold - typically several Gy
- Specific to particular tissues
- Severity of harm is dose dependent
- Example: skin arythema

Stochastic effects

- Due to cell changes (DNA) and proliferation towards a malignant disease
- Severity (example cancer) independent of the dose
- No dose threshold - applicable also to very small doses
- Probability of effect increases with dose
- Most severe: cancer



Radiotherapy

Regulatory Environment

What is an agreement state?

- The Nuclear Regulatory Commission
  - Governs all aspects of radiation management, from nuclear reactors to environmental contamination to medical devices

- As an agreement state, California “agrees” to manage the radiation hazards within the state for the federal government
  - They are required to meet the minimum standard set by the NRC, but are free to interpret and/or exceed that standard

Radioactive Materials vs Accelerator-produced Radiation

- Different forms of radiation are handled differently, from regulatory perspective
  - Radioactive materials : NRC or State
  - Accelerator radiation : State
  - PET Isotopes : NRC or State
  - Shipping radiation : DOT
- Different quantities are handled differently
- Different ability to disperse is handled differently

Regulatory Code

- The regulations are codified into the "California Code of Regulations"
- The Document:
  - Title 17: Public Health
    - Division 1: Department of Health Services
      - Chapter 5: Sanitation
        - » Subchapter 4.5: Radiation Technology
        - » Subchapter 4.6: Nuclear Medicine

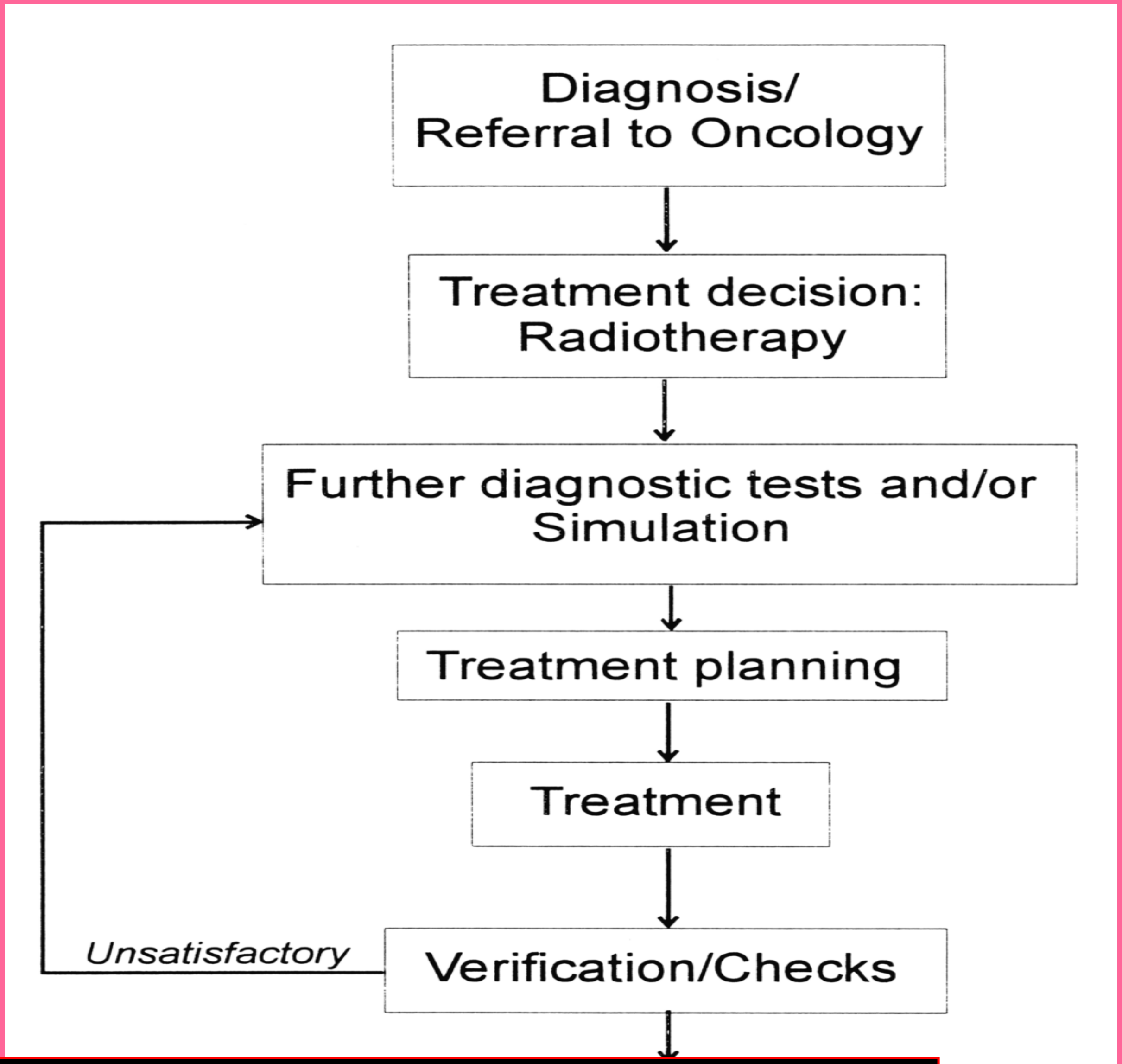
Radiation Safety Officer

- Specific title from the NRC
  - "…person within an organization responsible for the safe use of radiation and radioactive materials as well as regulatory compliance…"
- NRC/CA requires that a single RSO be established in writing to the state and that he/she meet several criteria
  - Education requirement
  - Training requirement

Radiotherapy

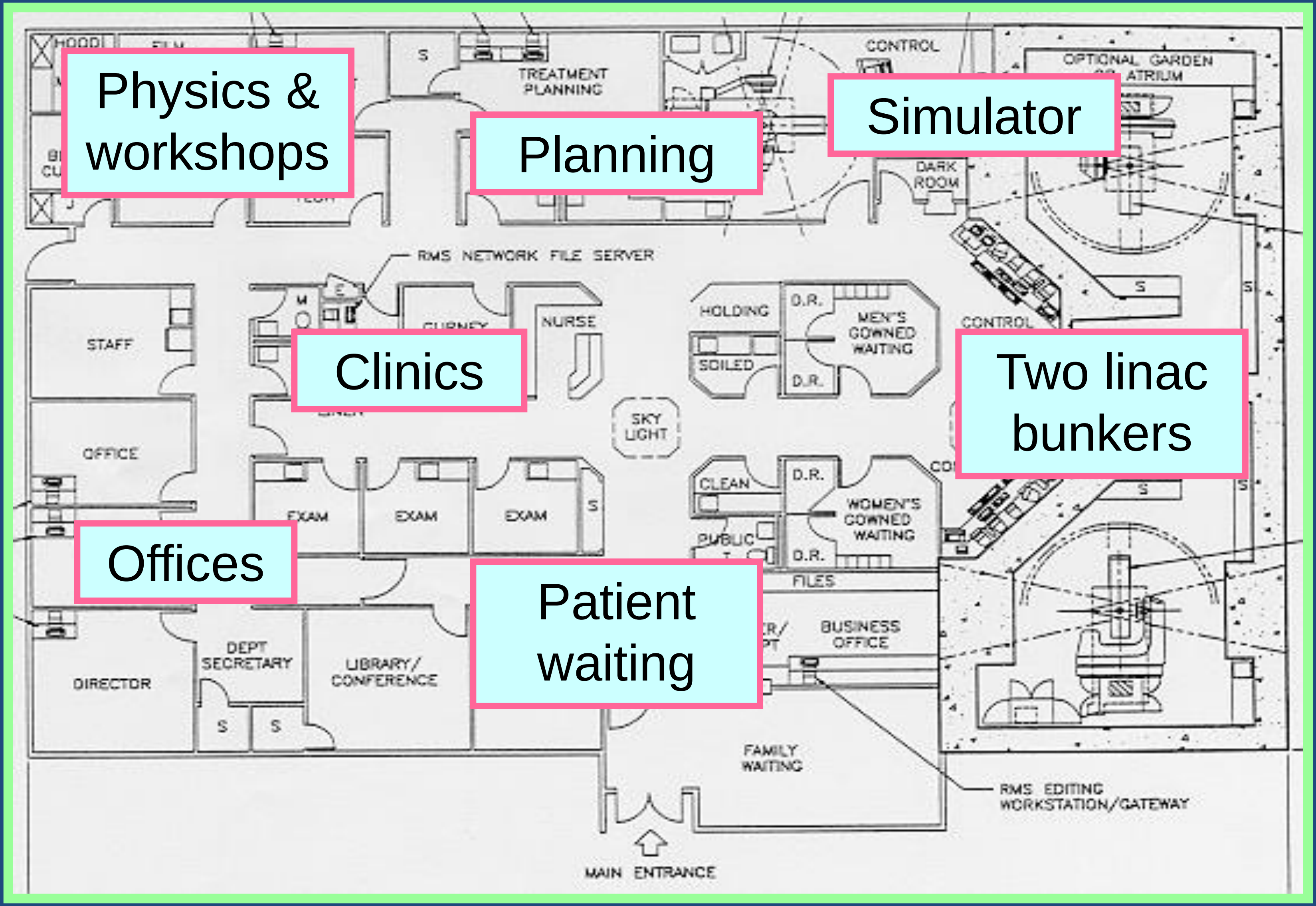
External Beam Radiotherapy

Patient Flow in Radio-therapy



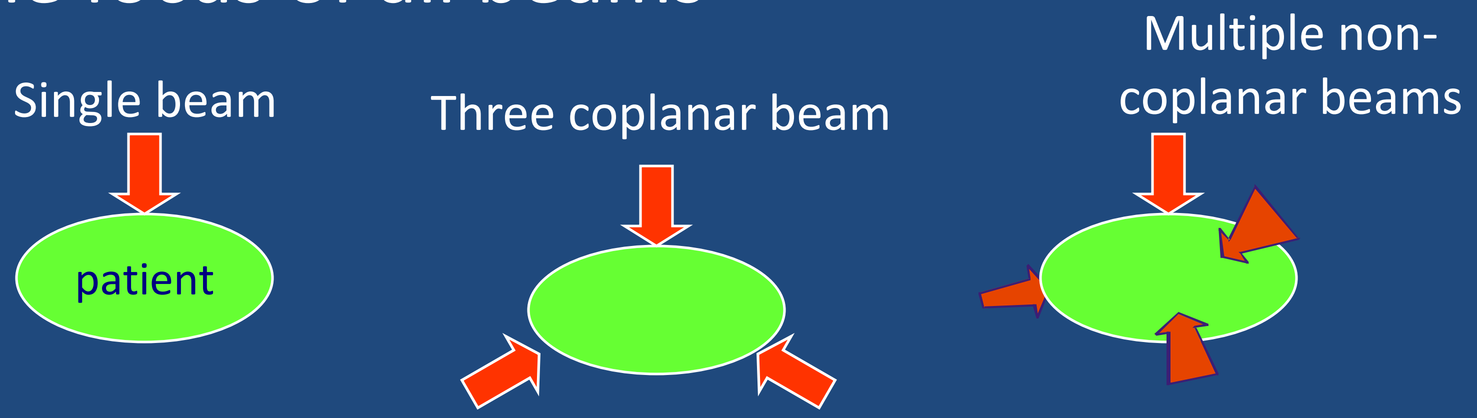
…not necessarily a straightforward process

Layout of a Department



External Beam Therapy (EBT)

- Non-invasive
- Target localization important and beam placement may be tricky
- Usually multiple beams to place target in the focus of all beams



EBT process: Use of radiation

Diagnosis

Acquisition of patient data
Simulator
CT scanner

Treatment plan

Creation of treatment and verification data
Simulation (virtual or real)

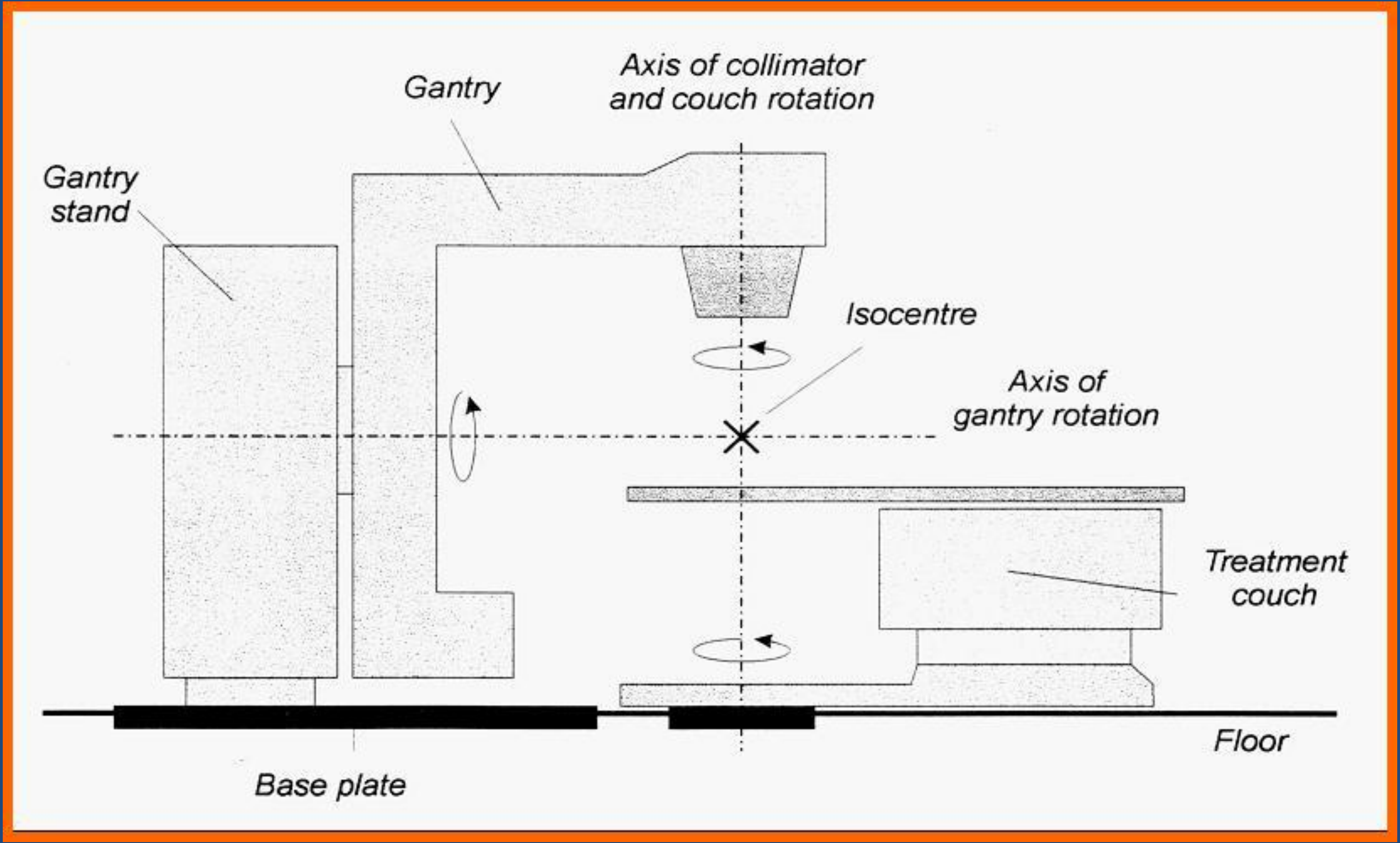
Treatment

Verification and follow up

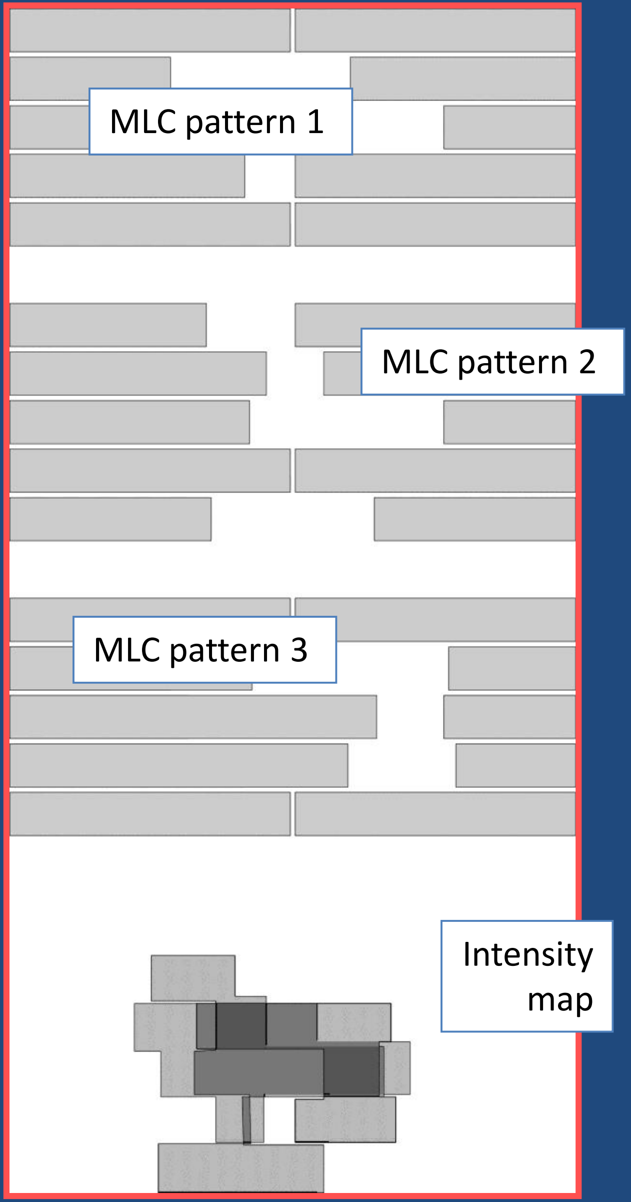
Megavoltage radiotherapy

- 60-Cobalt (energy 1.25MeV)
- Linear accelerators (4 to 25MVp)
- Skin sparing in photon beams
- Typical focus to skin distance 80 to 100cm
- Isocentrically mounted

Isocentric set-up



Intensity Modulation

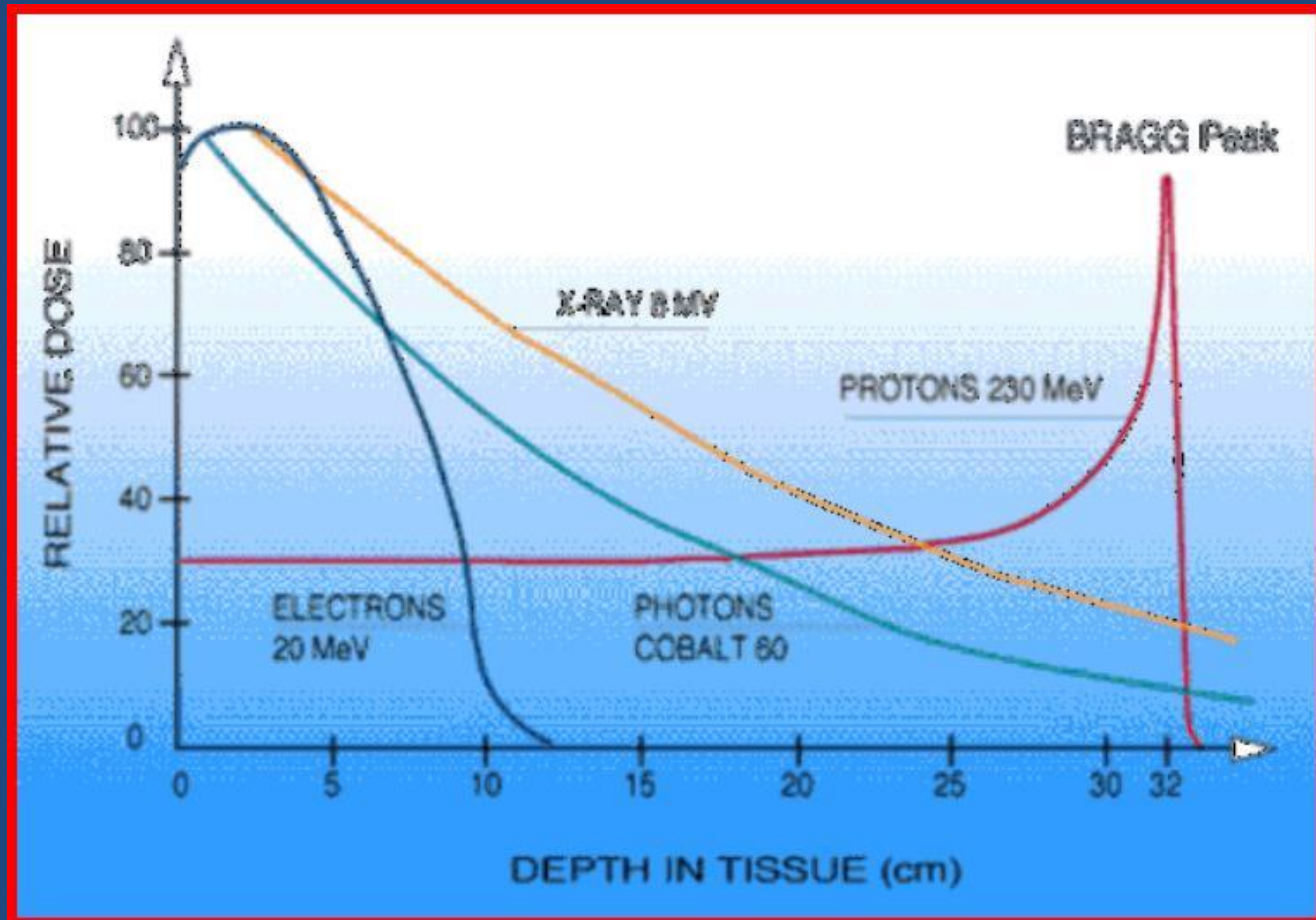


- Achieved using a Multi Leaf Collimator (MLC)
- The field shape can be altered
  - either step-by-step or
  - dynamically while dose is delivered

Other radiation types

- Neutrons
  - Complex radiobiology
  - Complex interactions
  - Potential advantages for hypoxic and radioresistant tumors
  - Not widely used
- Protons - probably the most promising other radiation type

Comparison to other radiation types



Radiotherapy

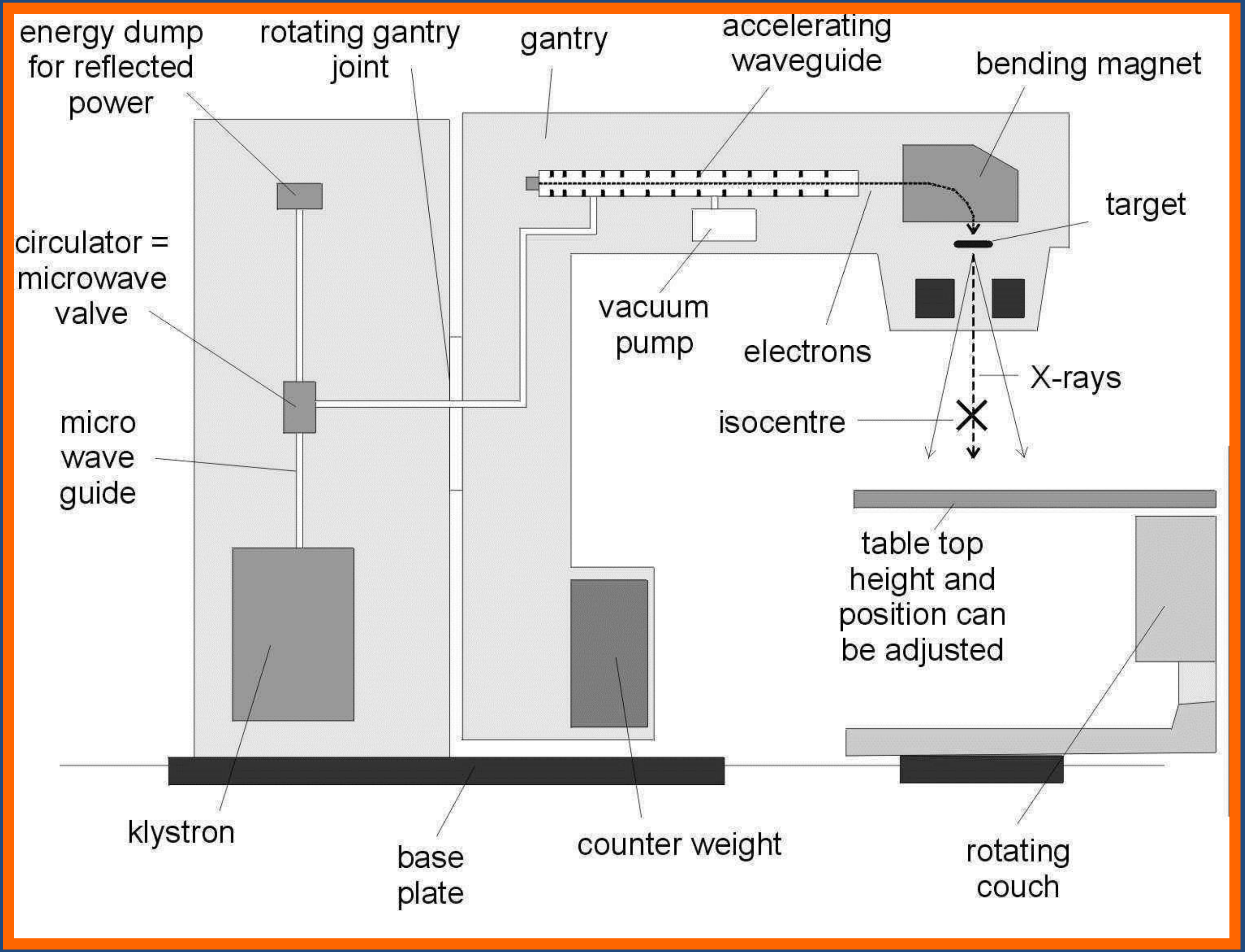
Accelerators

Medical Linear Accelerators

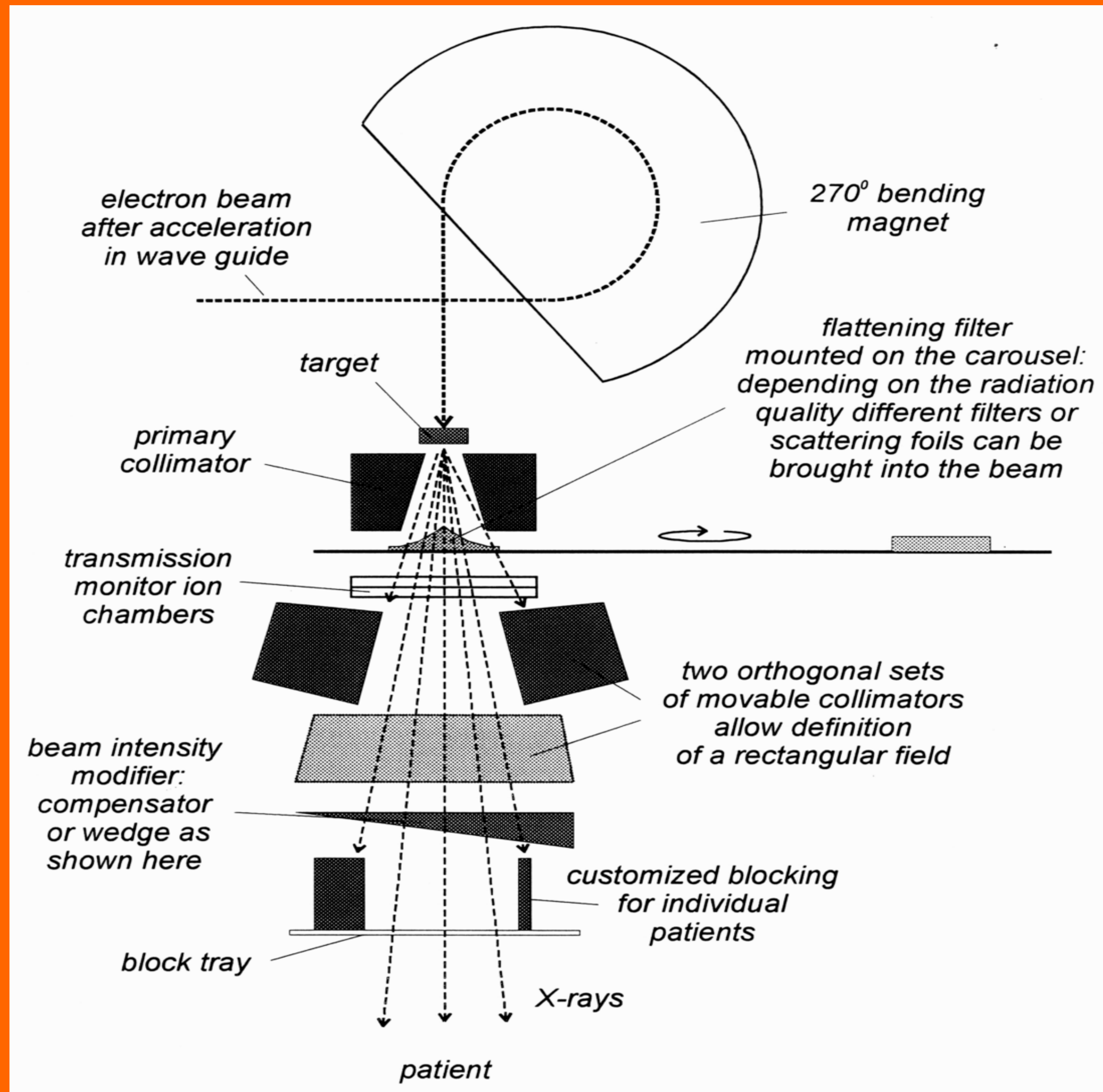
Courtesy Siemens

- Short: “linac”
- Most radiotherapy patients are treated using linacs
- Several manufacturers

Schematic drawing of a linac



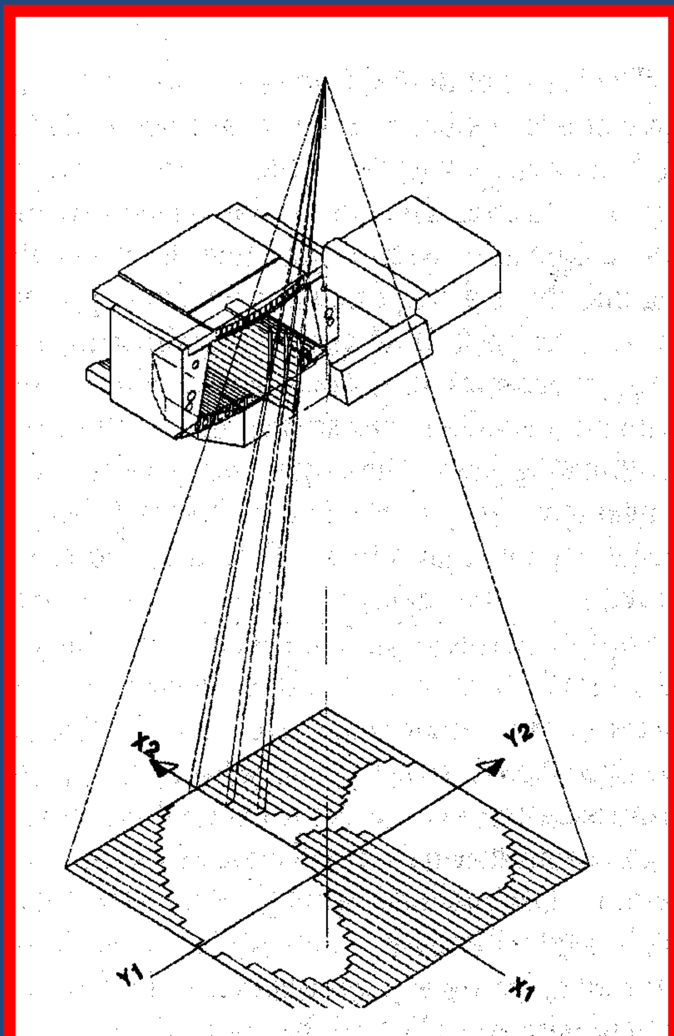
Treatment head

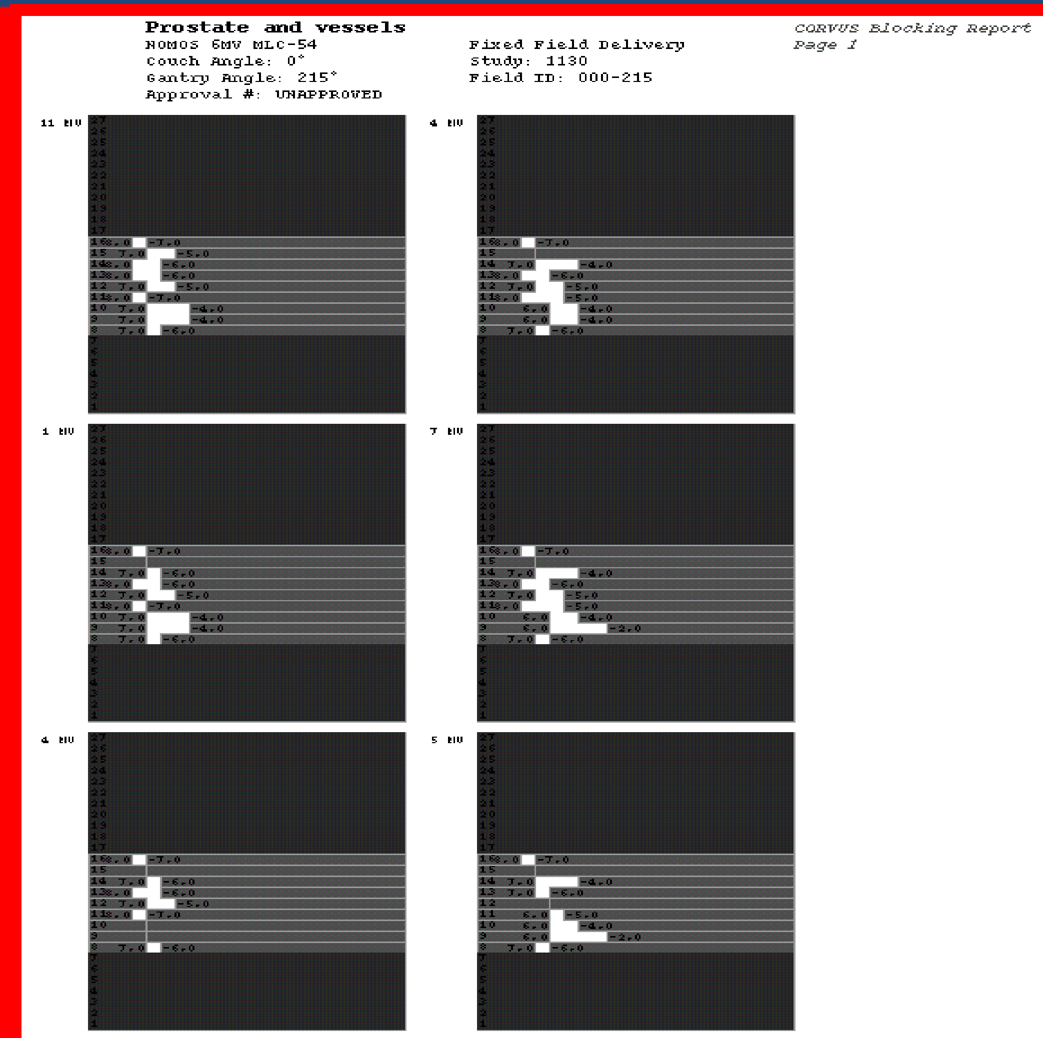


Multileaf Collimator (MLC)

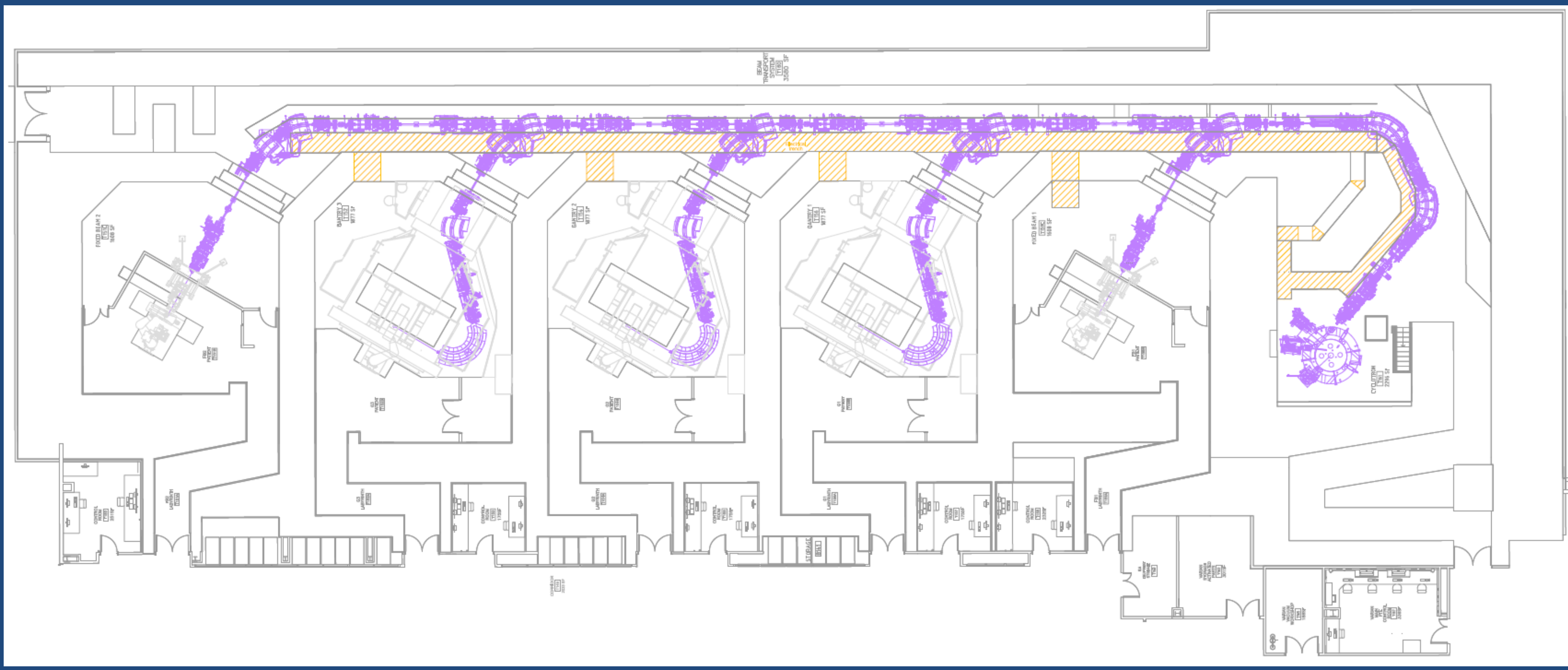
- Used to define any field shape for radiation beams
- Several variations to the theme:
  - different leaf widths (1cm to 0.4cm)
  - replaces collimators or additional to normal collimators

Multileaf Collimator (MLC)

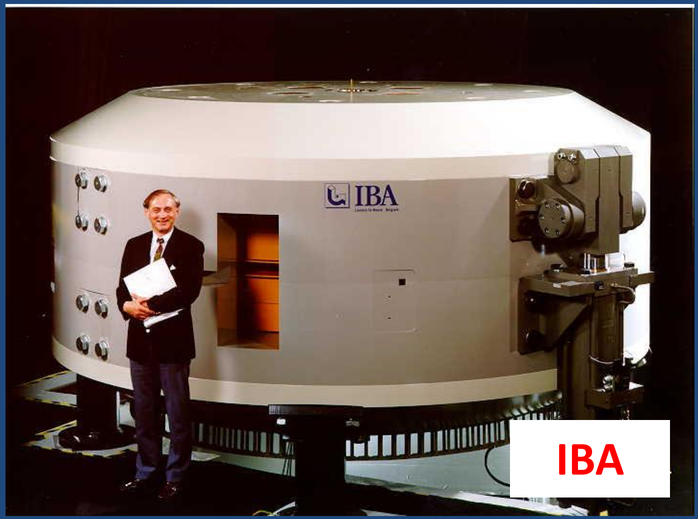


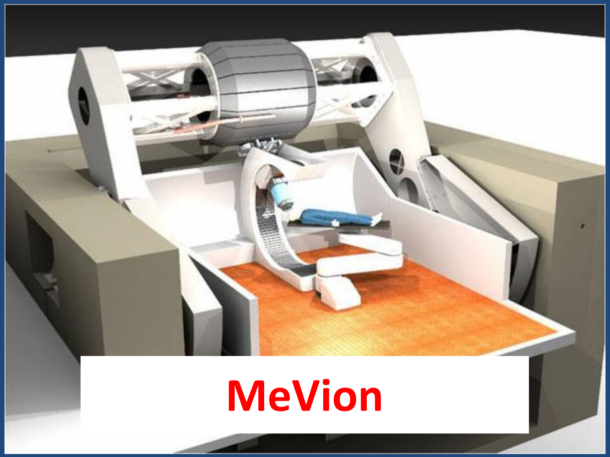


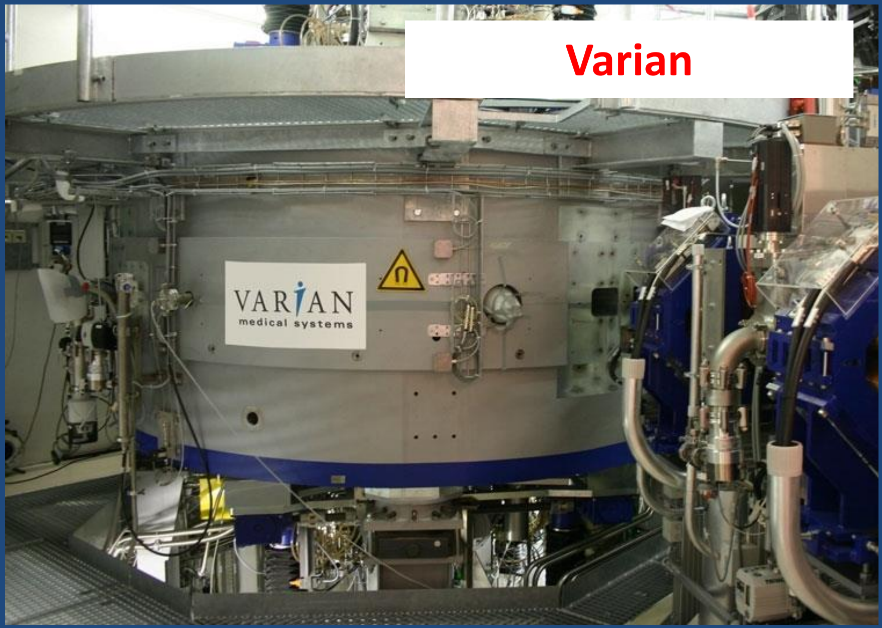
Proton Therapy Facility Overview



Accelerator - Cyclotron

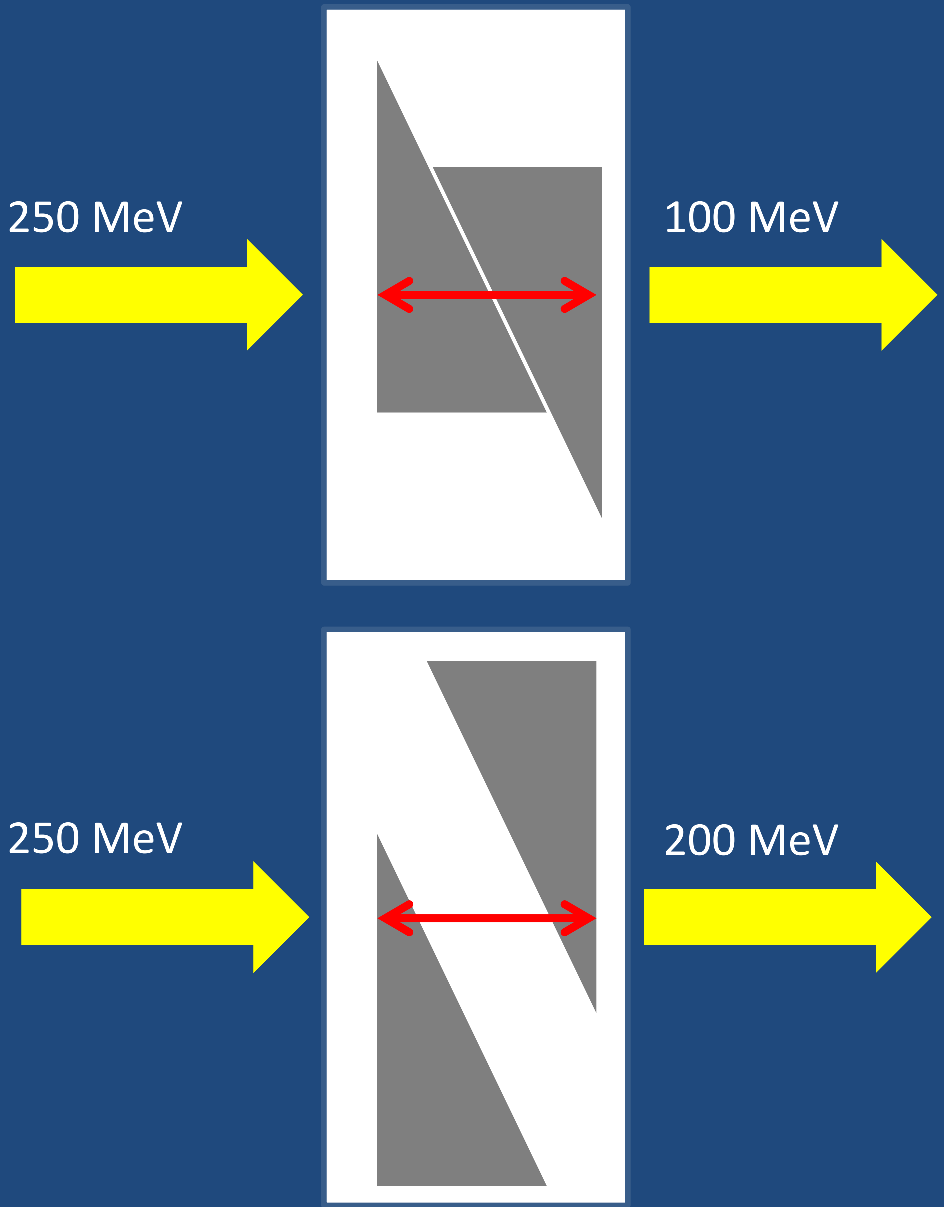






Cyclotron Proton Acceleration

Degrader



- Maximum energy of cyclotron into degrader
- Physical pathlength through degrader is static; water equivalent pathlength is variable
- Energy (i.e. range in water) loss is proportional to water equivalent pathlength of degrader material

Energy Selection Line

Divergence aperture

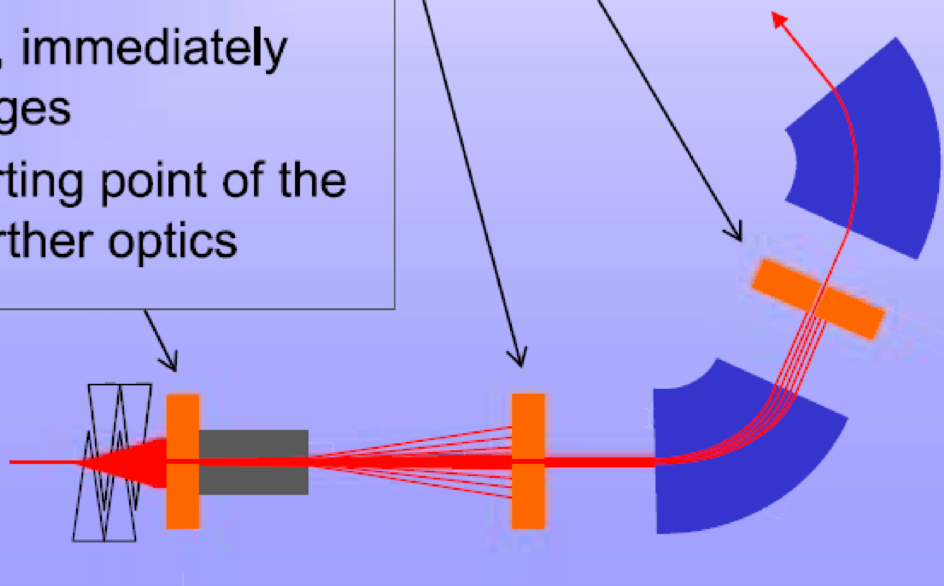
- Approx. 1 m behind the degrader
- Similar to the local aperture
- Defines the beam divergence (degree of scattering)

Energy slit

- In the center of the ESS achromat
- Two horizontally mo[illegible]ble copper blocks for setting the energy ***width***

Local aperture

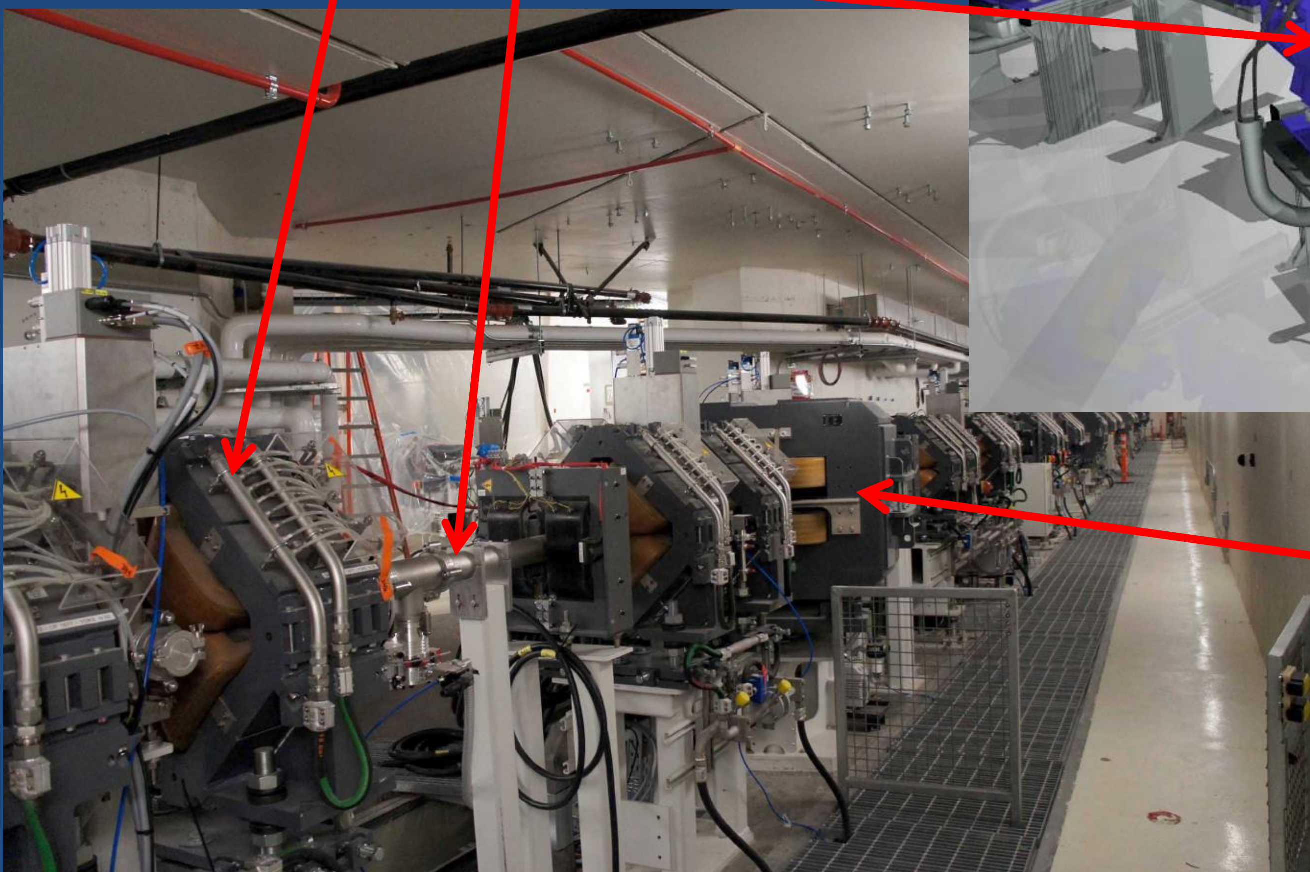
- In the degrader, immediately behind the wedges
- Defines the starting point of the beam for the further optics

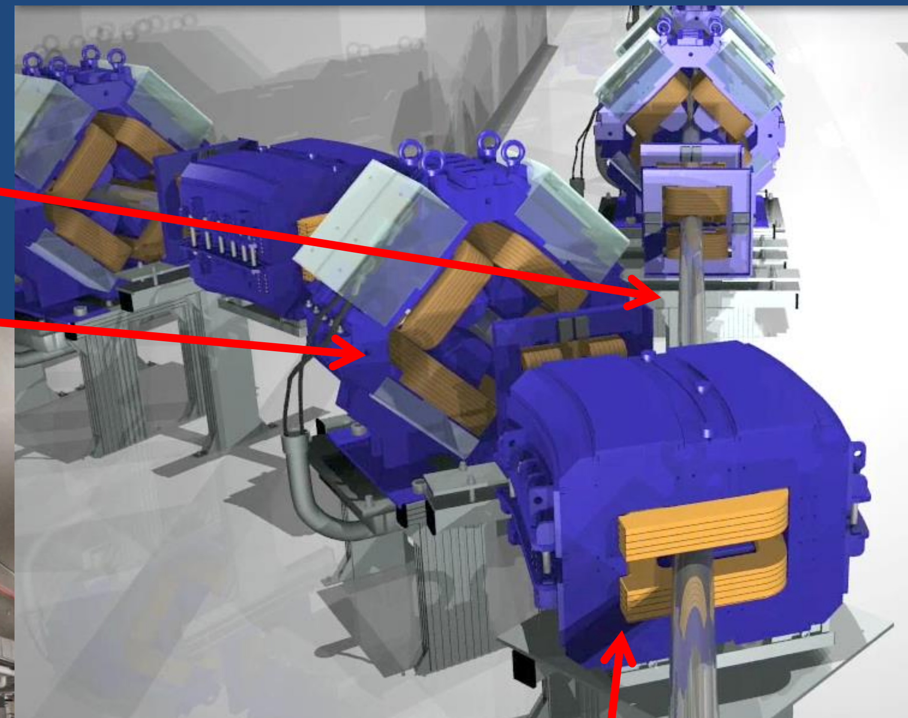


Beam Transport System

Vacuum Beam Pipe

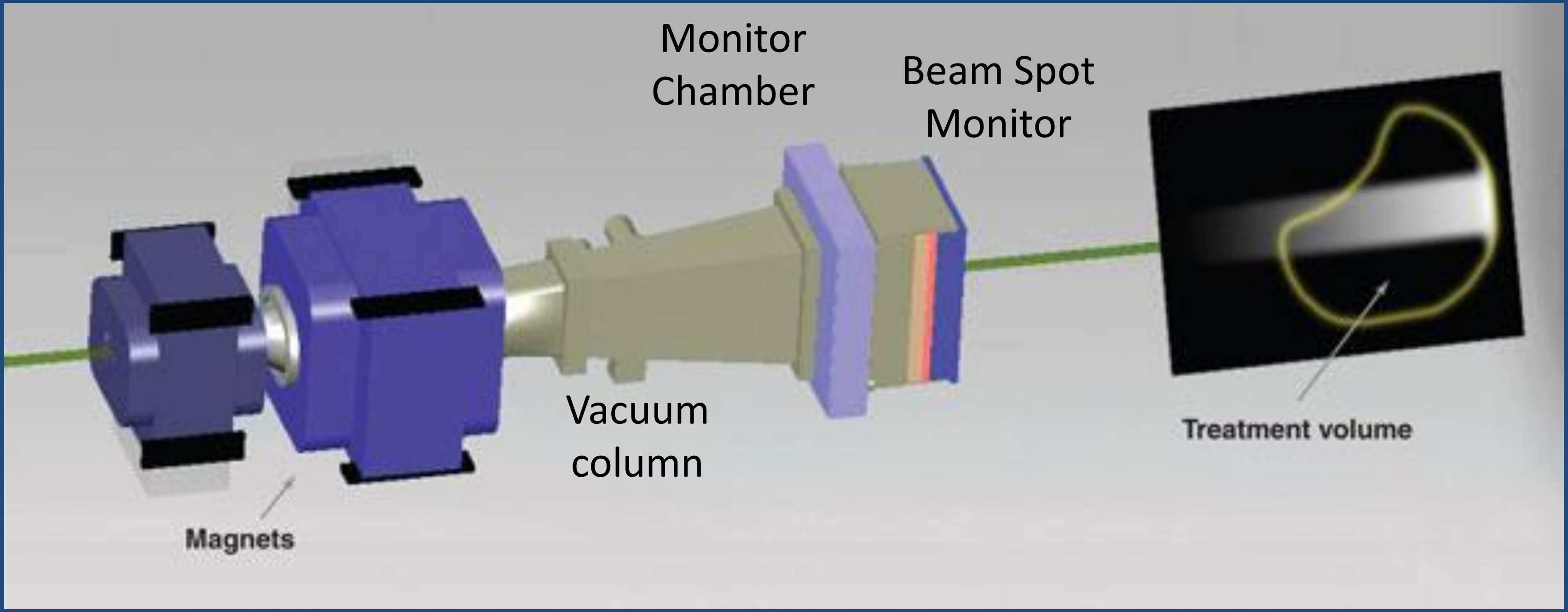
Quadrupole Focussing Magnet





Dipole Bending Magnet

Varian Nozzle

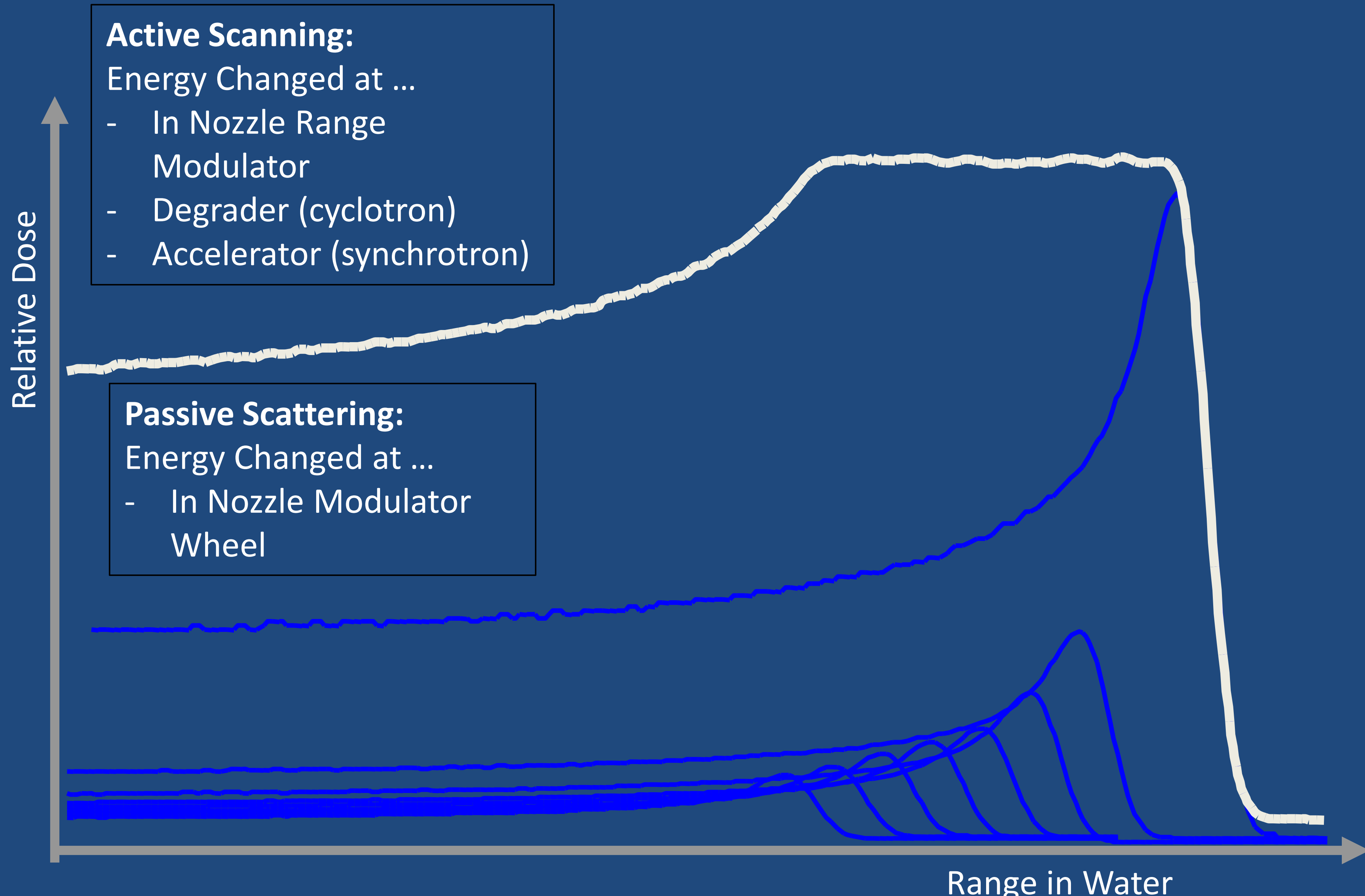


Radiotherapy

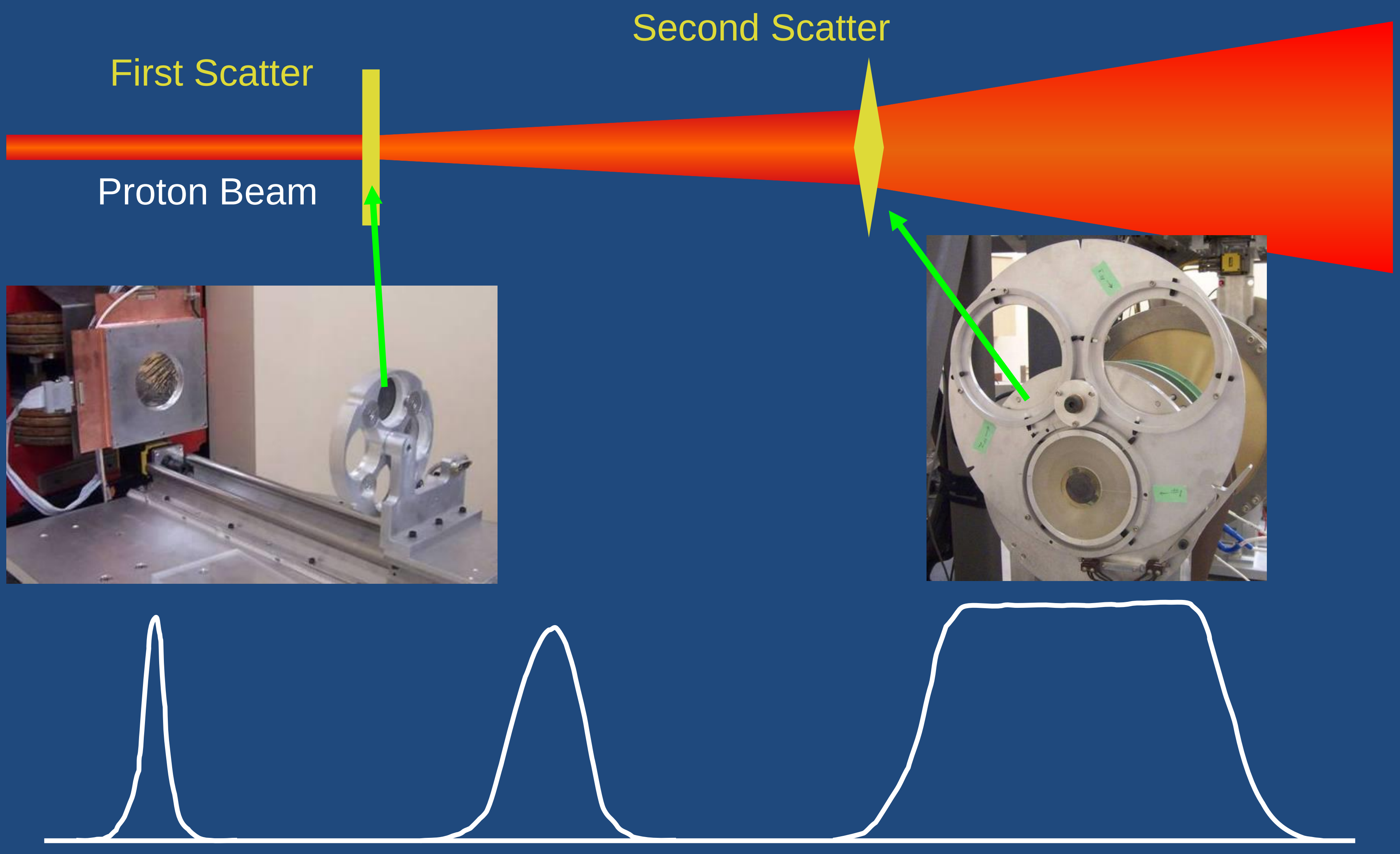
Proton Beam Delivery System

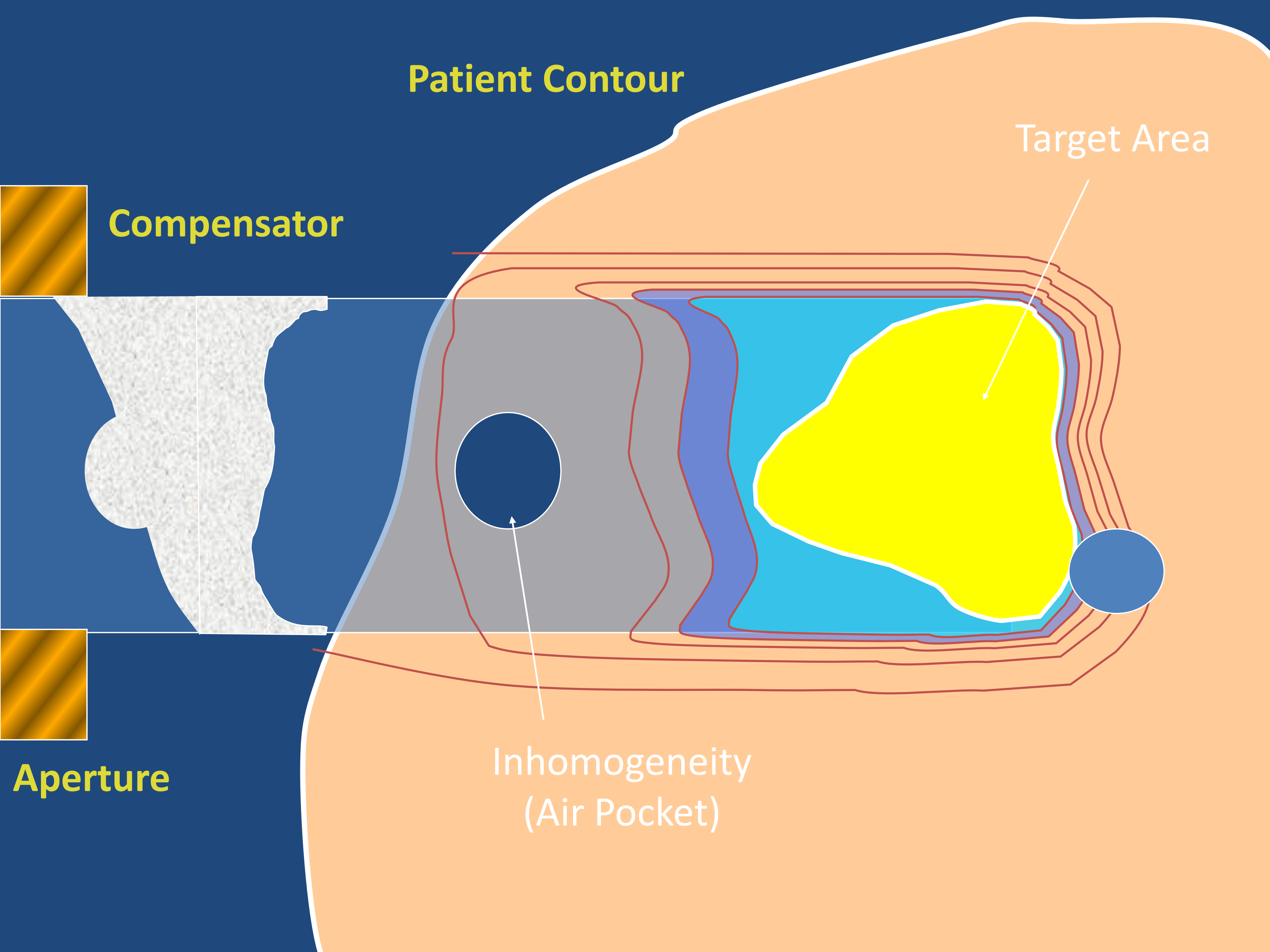
Range Modulation : SOBP

Concept shared across
Passive and Active Beam Delivery Techniques



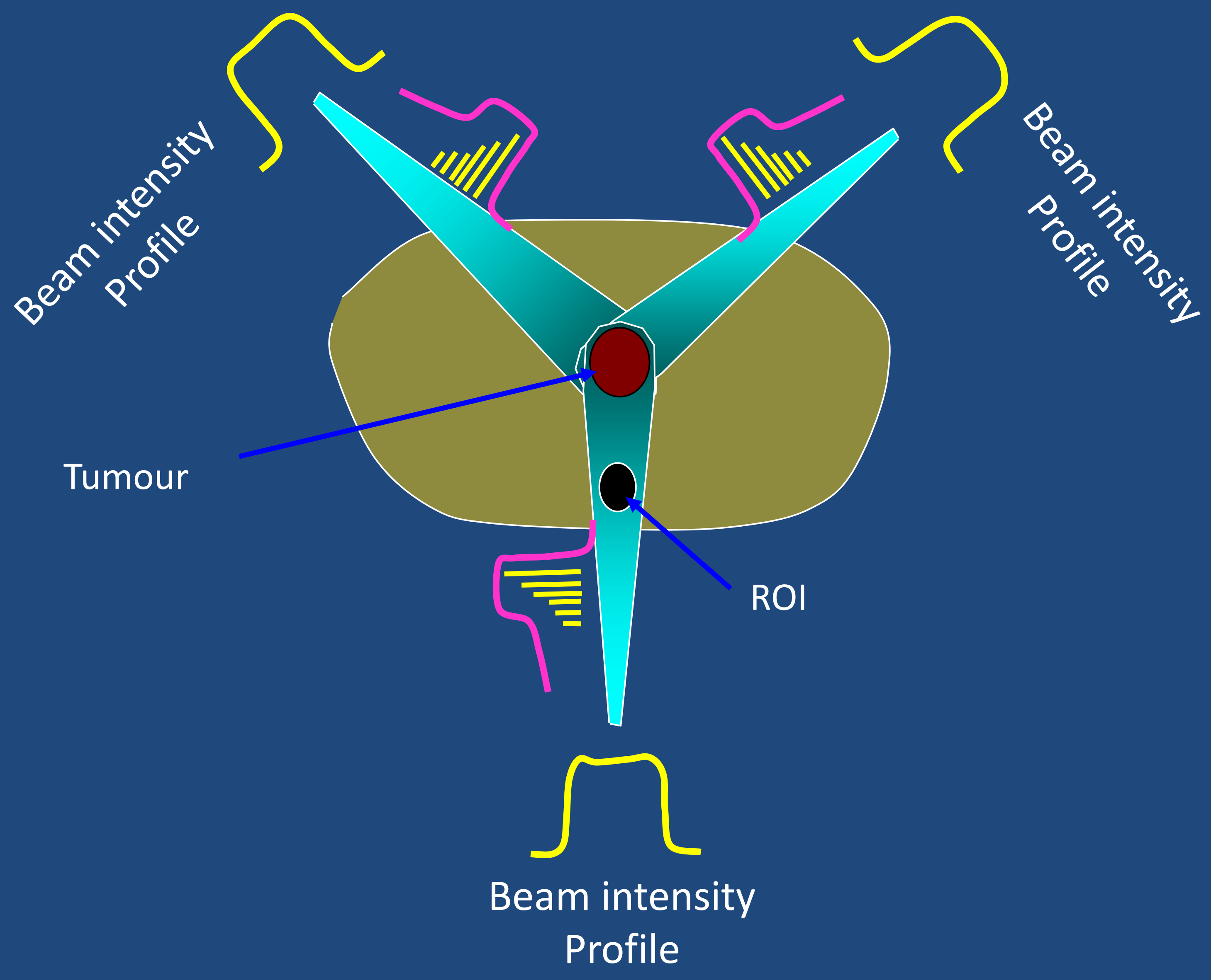
Passive Scattering



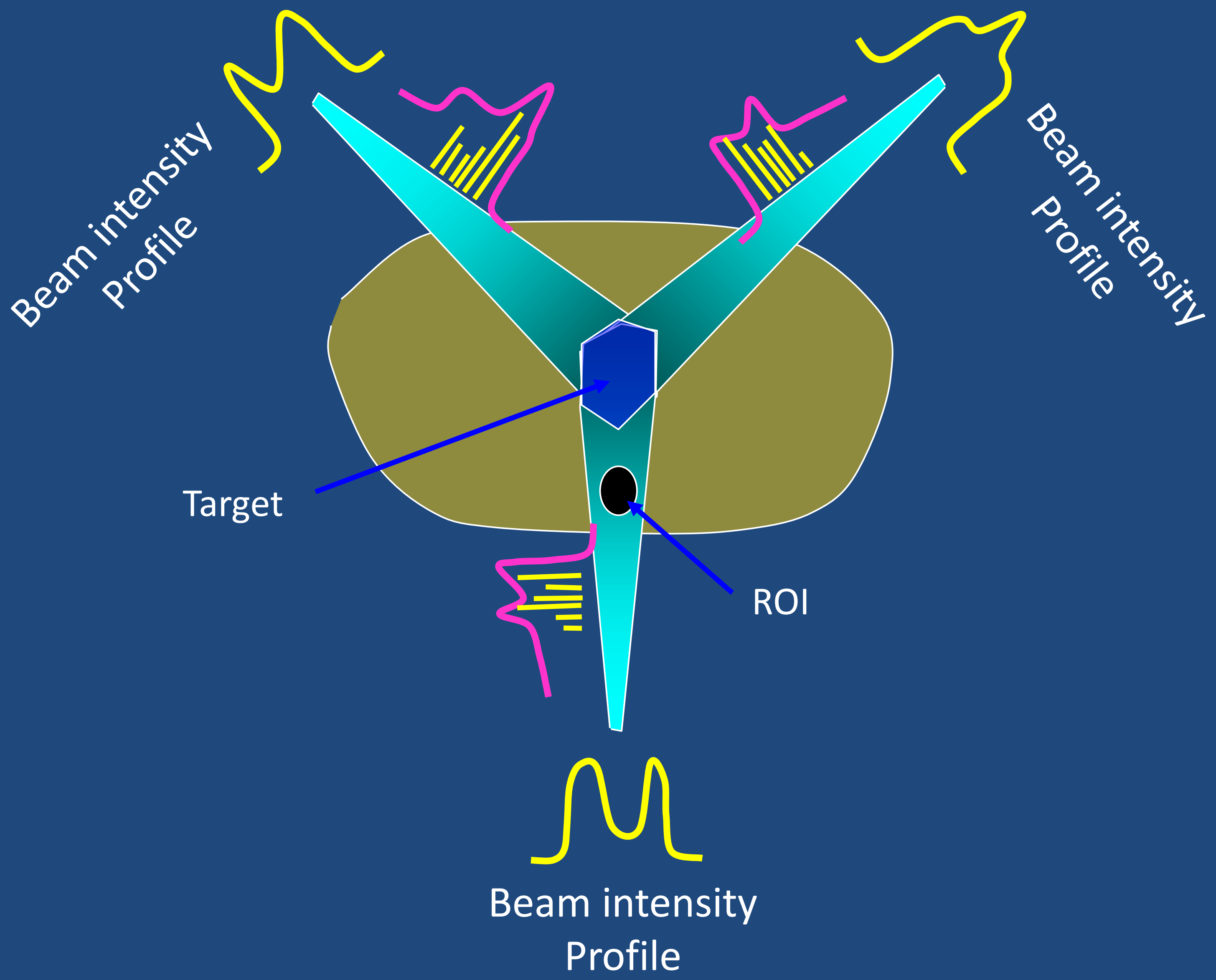

Patient Contour
Target Area
Compensator
Aperture
Inhomogeneity
(Air Pocket)

Pencil Beam Scanning (PBS)

Single Field Uniform Dose (SFUD)



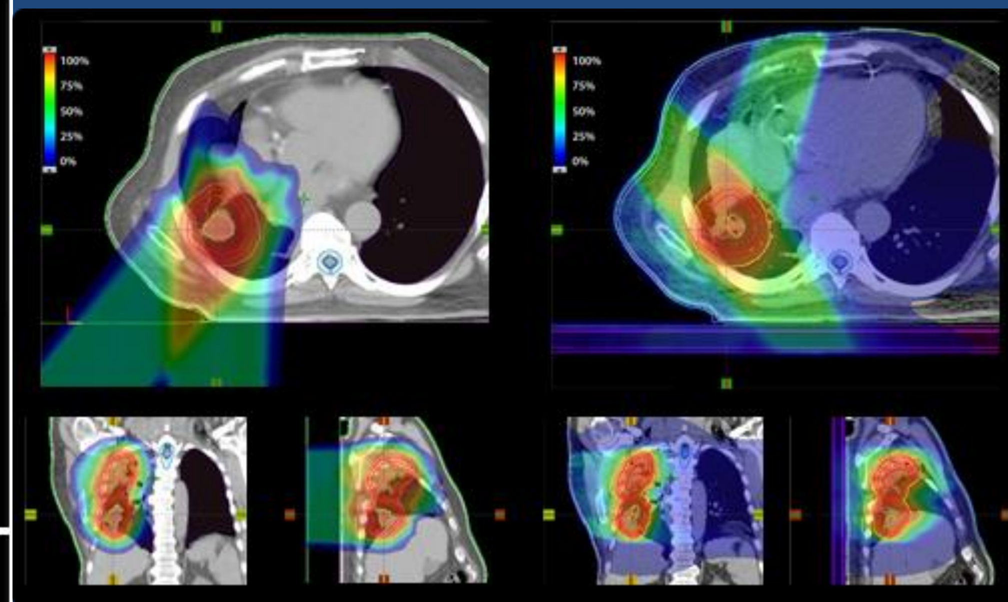
Intensity Modulated Proton Therapy (IMPT)



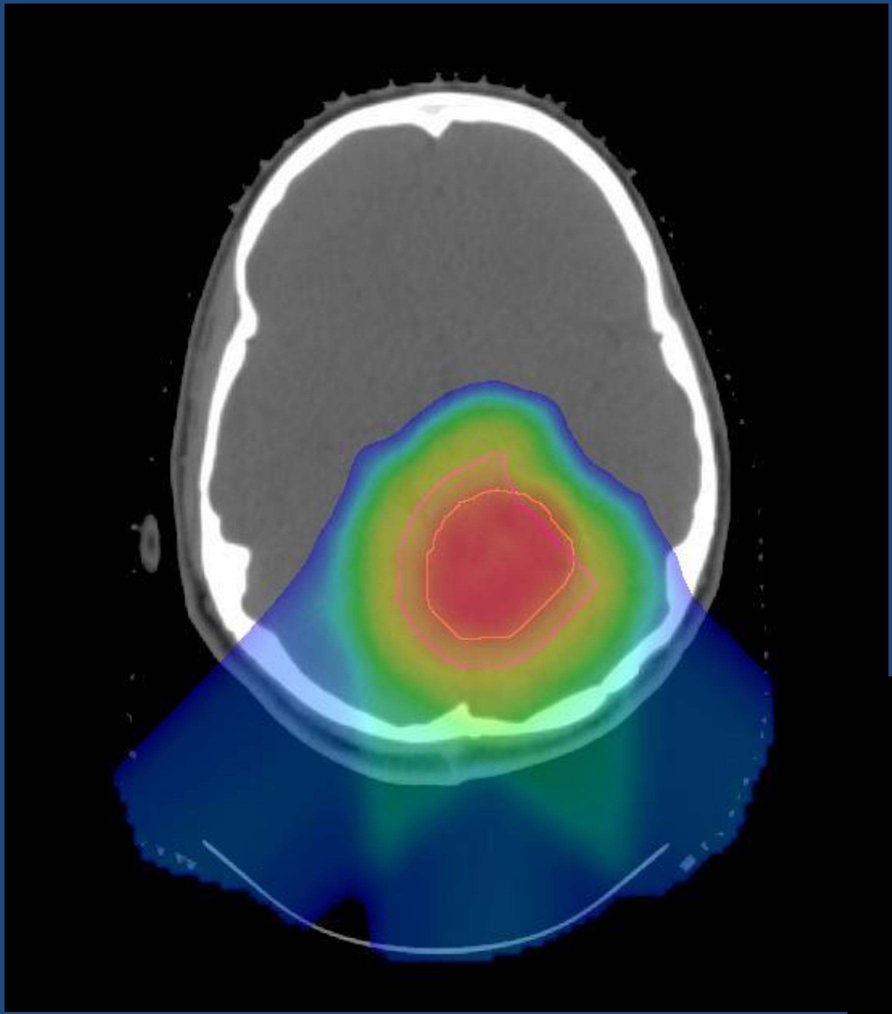
Clinical Examples

Clinical Examples of Proton vs Photon Therapy

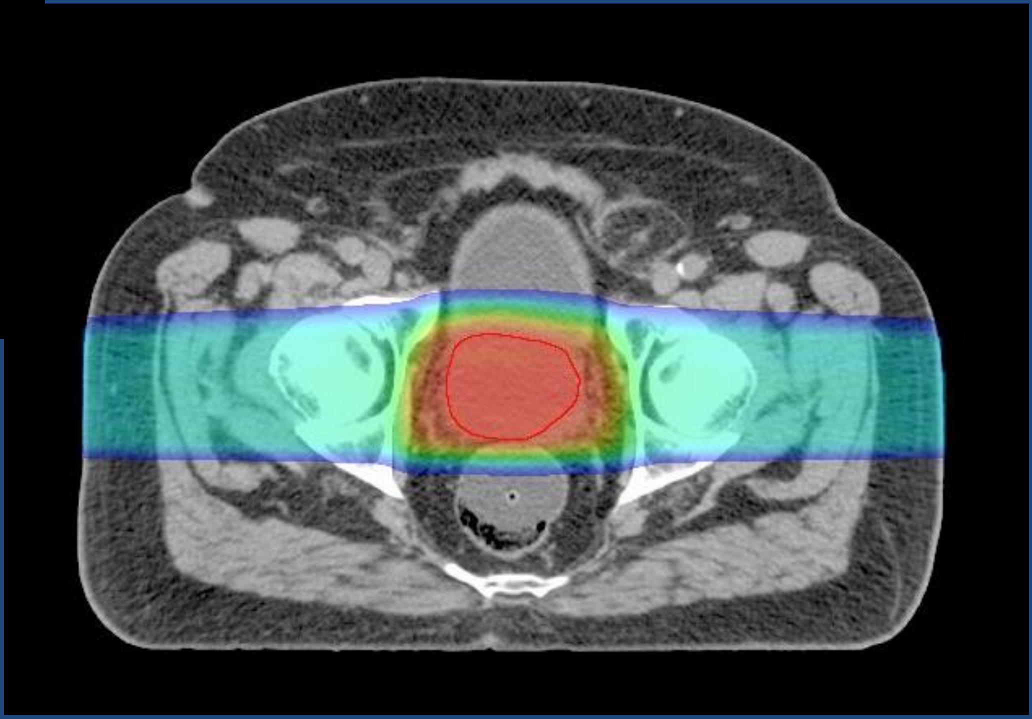
Craniospinal Irradiation



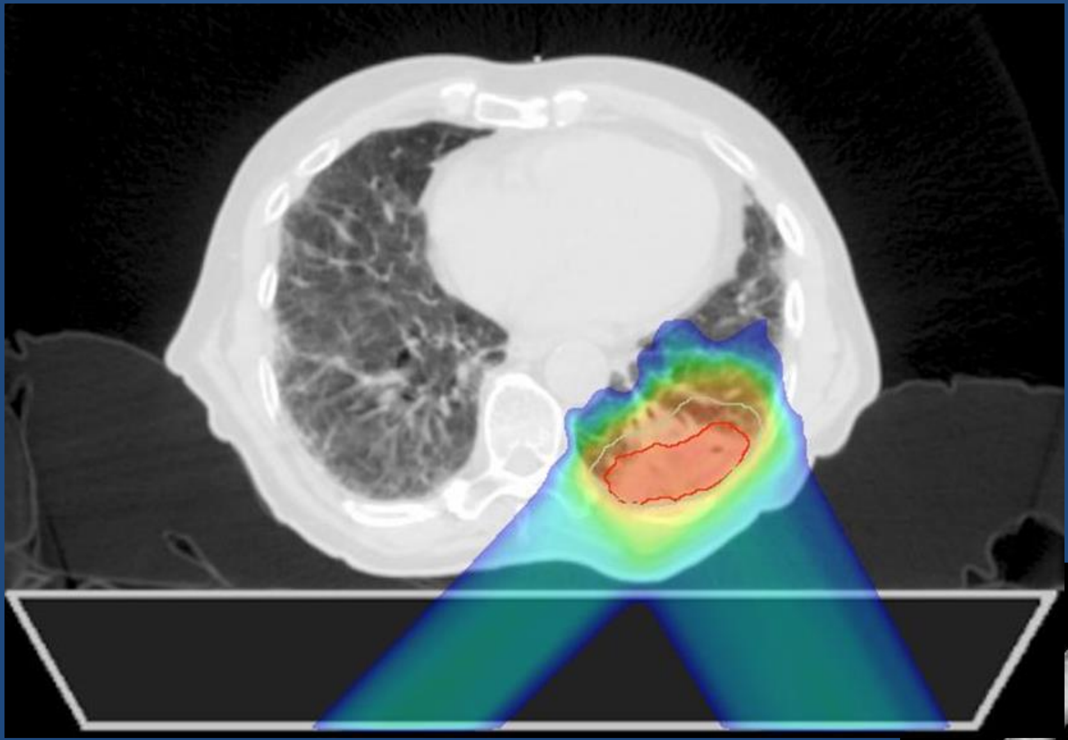
Posterior Lung Target Irradiation

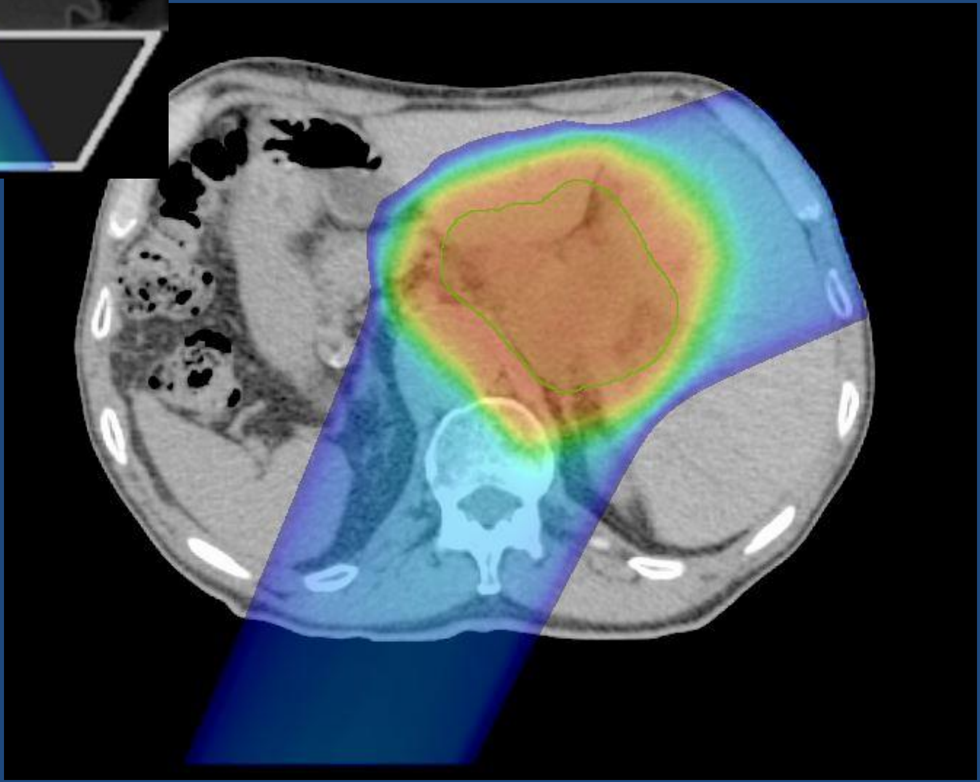


Clinical Examples of Proton Therapy



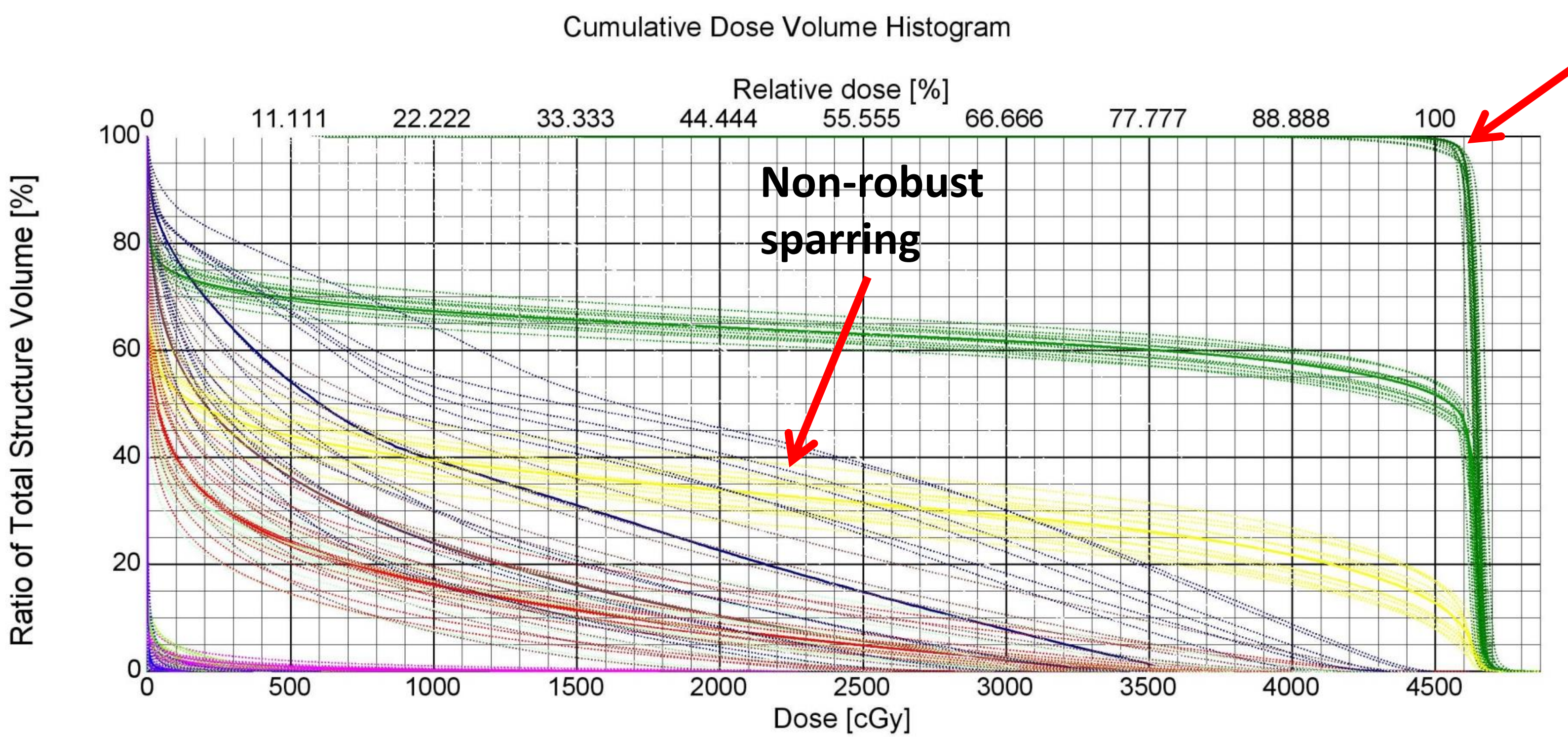
Clinical Examples of Proton Therapy





Scripps

Dose Volume Histogram: Example 1

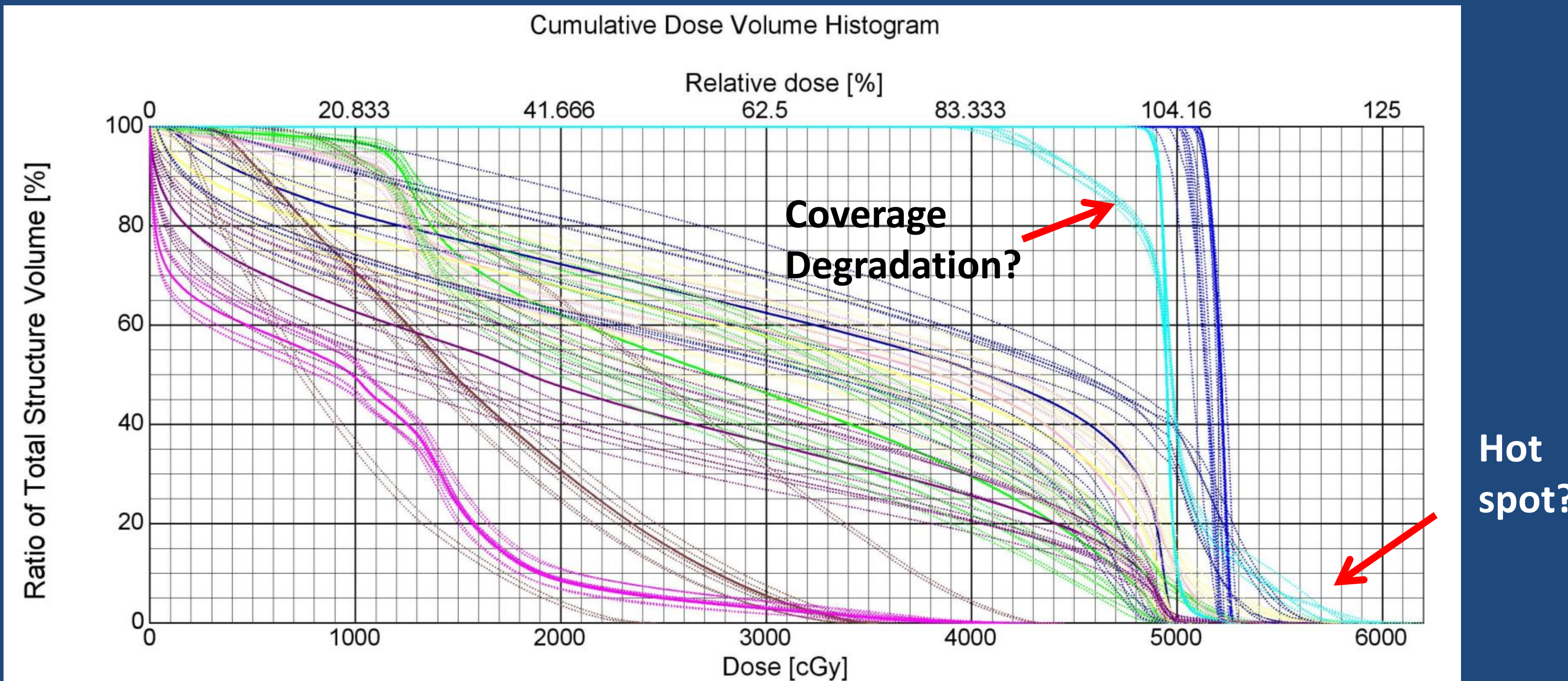


Robust Coverage

Range Uncertainty curves included!

Structure	Structure Status	Coverage [%/%]	Volume	Min Dose	Max Dose	Mean Dose	Modal Dose	Median Dose	Std Dev
Esophagus	Approved	100.0 / 100.3	13.5 cm³	0.0 cGy	3747.1 cGy	1052.6 cGy	0.3 cGy	603.0 cGy	1077.0 cGy
SpinalCord	Approved	100.0 / 100.4	20.4 cm³	0.0 cGy	435.0 cGy	7.4 cGy	0.3 cGy	0.3 cGy	33.7 cGy
Kidney_R	Approved	100.0 / 100.0	89.7 cm³	0.0 cGy	138.6 cGy	1.1 cGy	0.3 cGy	0.2 cGy	5.5 cGy
Kidney_L	Approved	100.0 / 100.0	127.0 cm³	0.0 cGy	0.4 cGy	0.2 cGy	0.0 cGy	0.2 cGy	0.1 cGy
Stomach	Approved	100.0 / 100.0	158.6 cm³	0.0 cGy	3704.5 cGy	623.7 cGy	0.3 cGy	199.1 cGy	842.5 cGy
Heart	Approved	100.0 / 100.0	512.2 cm³	0.0 cGy	3846.0 cGy	438.2 cGy	0.3 cGy	32.6 cGy	797.2 cGy
Bowel	Approved	100.0 / 100.0	560.8 cm³	0.0 cGy	3801.0 cGy	416.6 cGy	0.3 cGy	4.4 cGy	768.9 cGy
ITV_1	Approved	100.0 / 100.0	1035.6 cm³	4206.4 cGy	4797.5 cGy	4640.9 cGy	4648.5 cGy	4644.3 cGy	26.7 cGy

Dose Volume Histogram: Example 2



Range Uncertainty curves included!

Structure	Structure Status	Coverage [%/%]	Volume	Min Dose	Max Dose	Mean Dose	Modal Dose	Median Dose	Std Dev
DIL	Approved	100.0 / 100.5	0.9 cm³	5092.0 cGy	5270.4 cGy	5206.7 cGy	5230.4 cGy	5215.6 cGy	37.7 cGy
PenileBulb	Approved	100.0 / 100.1	2.1 cm³	236.2 cGy	3542.4 cGy	1576.8 cGy	422.4 cGy	1480.1 cGy	806.2 cGy
Sigmoid	Approved	100.0 / 100.0	35.6 cm³	66.9 cGy	5041.6 cGy	3301.5 cGy	4929.6 cGy	4066.4 cGy	1717.0 cGy
RectalWall_3mm	Approved	100.0 / 100.5	48.9 cm³	27.4 cGy	4972.5 cGy	3214.7 cGy	4910.4 cGy	3841.2 cGy	1573.8 cGy
Bladder	Approved	100.0 / 100.0	138.7 cm³	14.1 cGy	5075.2 cGy	3046.5 cGy	4944.0 cGy	3646.7 cGy	1781.0 cGy
Rectum	Approved	100.0 / 100.0	161.4 cm³	27.5 cGy	4972.5 cGy	2845.4 cGy	1257.6 cGy	2750.8 cGy	1370.2 cGy
CTV_48Gy	Approved	100.0 / 100.0	189.0 cm³	4761.0 cGy	5270.4 cGy	4955.8 cGy	4948.8 cGy	4949.0 cGy	47.0 cGy
FemoralHeads	Approved	100.0 / 99.6	307.7 cm³	0.0 cGy	4152.8 cGy	934.1 cGy	0.4 cGy	982.7 cGy	855.4 cGy

Radiation Protection at Medical Facility

Basic principles

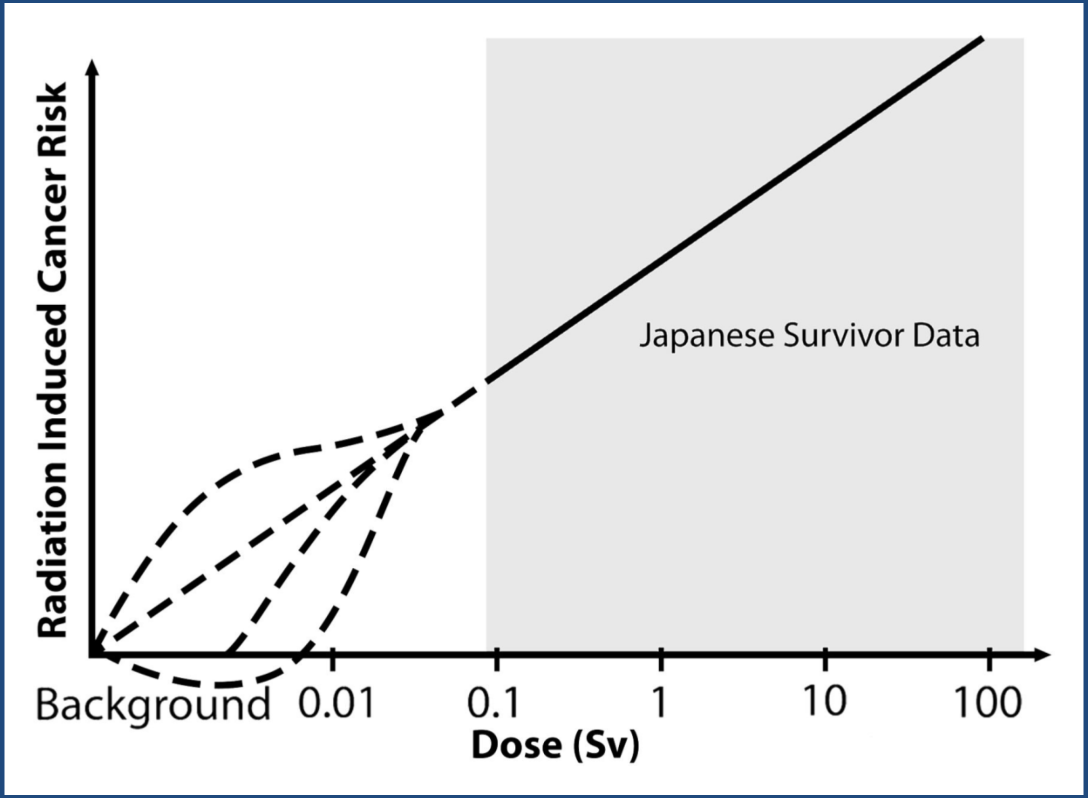
Optimization principle

As **L**ow **A**s **R**easonably **A**chievable

This means radiation exposure should be limited as much as possible keeping in mind the risk-benefit relation of radiation and its applications. For example, it is unreasonable to refuse an X Ray after a bone fracture because statistically this may shorten your life expectancy by one day. The benefits of the X Ray with its diagnostic value by far outweigh the risk associated with the radiation exposure.

ALARA

- ALARA : As Low As Reasonably Achievable
  - Where does this concept come from?



What are the main hazards at medical facility (especially proton center)?

- Primary beam
  - Protons
- Prompt secondary radiation
  - Neutrons, gammas, and many others
- Residual secondary radiation
  - Gammas

Primary Beam

- This is <u>proton</u> radiation produced by the cyclotron and transported to the treatment rooms during irradiation
- **Where**: cyclotron vault, beamline and treatment rooms
- **What**: high dose (0.5 Gy to 20 Gy)
- Interlocked, shielded and monitored
  - If it happens, it is both an acute and long-term risk and an event reportable to state
    - High risk, low frequency
  - E.g. late-night physicist irradiation

Prompt Secondary Radiation

- This is <u>neutron and gamma</u> radiation produced by the interaction of primary beam with other materials (e.g. the patient, phantoms, the nozzle housing, walls)
- **Where**: cyclotron vault, beamline and treatment rooms
- **What**: medium dose (typically 1-10% of primary beam depending biological effect)

Residual Secondary Radiation

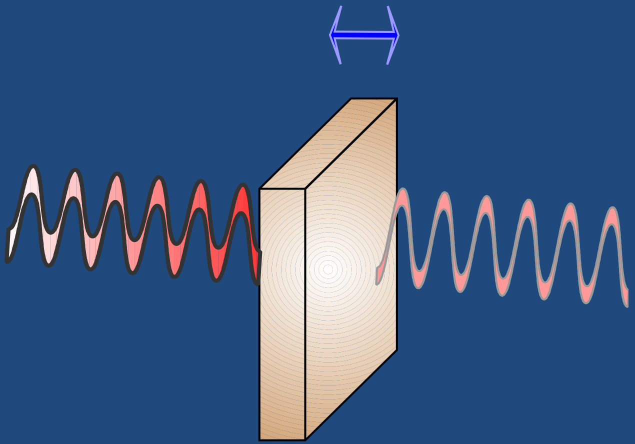
- This is <u>gamma</u> radiation produced by the decay of radioactive isotopes induced in materials by the interaction of primary beam (e.g. the nozzle, any beamline components, some phantoms)
- **Where**: cyclotron vault, beamline and treatment rooms
- **What**: low dose (depends on materials and time since irradiation)

Basic radiation protection strategies

- Hazard Reduction Methods:
  - Time

    Dose = Dose-rate x Time
  - Distance

    Dose-rate α 1/(distance)^2
  - Shielding



Who needs protection at a medical facility?

- The Patient
- The Staff
- The Public
  - This includes the patient, when he/she is not being treated

Protecting the Patient

Protecting the Patient

- Ensure accuracy of the delivery
  - Calibrating the beam delivery system
  - Commissioning (and modelling) the beam delivery system
  - Periodic quality assurance of machines
- Ensure safety of the delivery
  - Proper training and licensure
  - Interlocks, emergency stop, etc
- Establish clinical procedures in accordance with ALARA

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1. Absolute and relative dosimetry

- **Absolute dosimetry** is a technique that yields information directly on absorbed dose in Gy. This absolute dosimetric measurement is also referred to as calibration. All further measurements are then compared to this known dose under reference conditions. This means …
- **relative dosimetry** is performed. In general no conversion coefficients or correction factors are required in relative dosimetry since it is only the comparison of two dosimeter readings, one of them being in reference conditions.

Absolute dosimetry

- Required for every radiation quality once
- Determination of absorbed dose (in Gy) at one reference point in a phantom
- Well defined geometry (example for a linear accelerator: measurements in water, at 100cm FSD, 10x10cm^2 field size, depth 10cm
- Follows protocols
  - AAPM TG-51
  - IAEA TRS 398

Absolute dosimetry - Formulism

Dose = M,corr * k,q * N,dw

M,corr = M,raw * k,s * k,pol * k,tp * k,elec

M,corr = corrected measurement (nC)

M,raw = raw measurement (nC)

k,q = perturbation factor based on beam quality

N,dw = ADCL Co-60 calibration factor (Gy/nC)

k,s = ionic recombination factor

k,pol = polarity correction

k,tp = temperature and pressure correction

k,elec = electrometer correction

Relative dosimetry

- Relates dose under non-reference conditions to the dose under reference conditions
- Typically at least two measurements are required:
  - one in conditions where the dose shall be determined
  - one in conditions where the dose is known

Examples for relative dosimetry

- Characterization of a radiation beam
  - percentage depth dose, tissue maximum ratios or similar
  - profiles
- Determination of factors affecting output
  - field size factors, applicator factors
  - filter factors, wedge factors
  - patient specific factors (*e.g.* electron cut-out)

Scanning water phantom

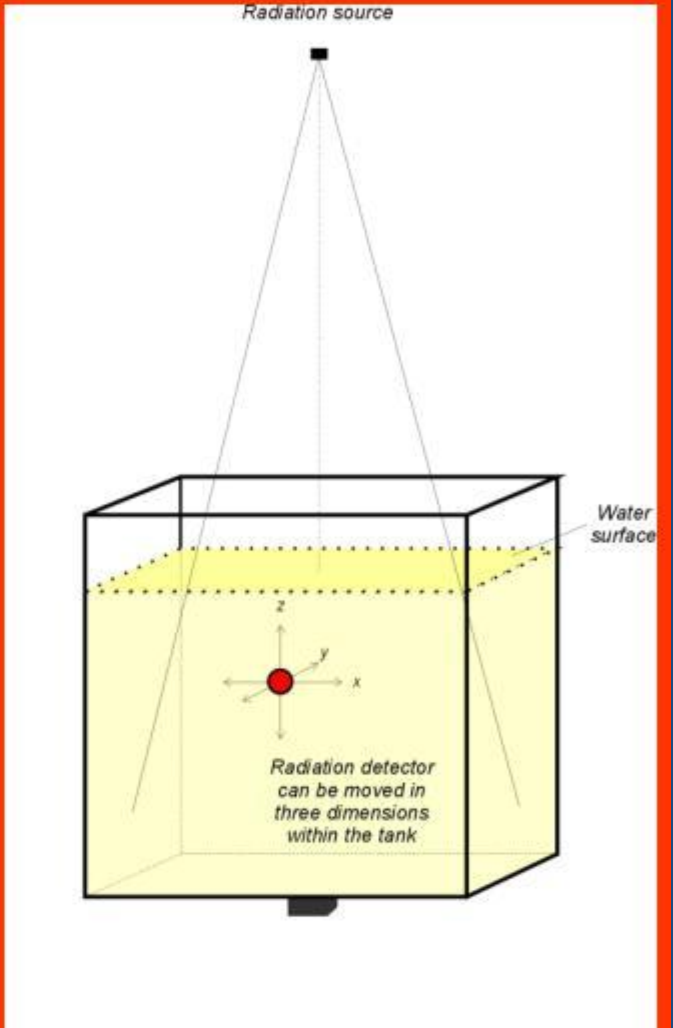


Figure 1: Schematic drawing of a water tank scanning system

Slab phantoms

Anthropomorphic phantom

Whole body phantom: ART

Cross section through a Farmer type chamber (from Metcalfe 1996)

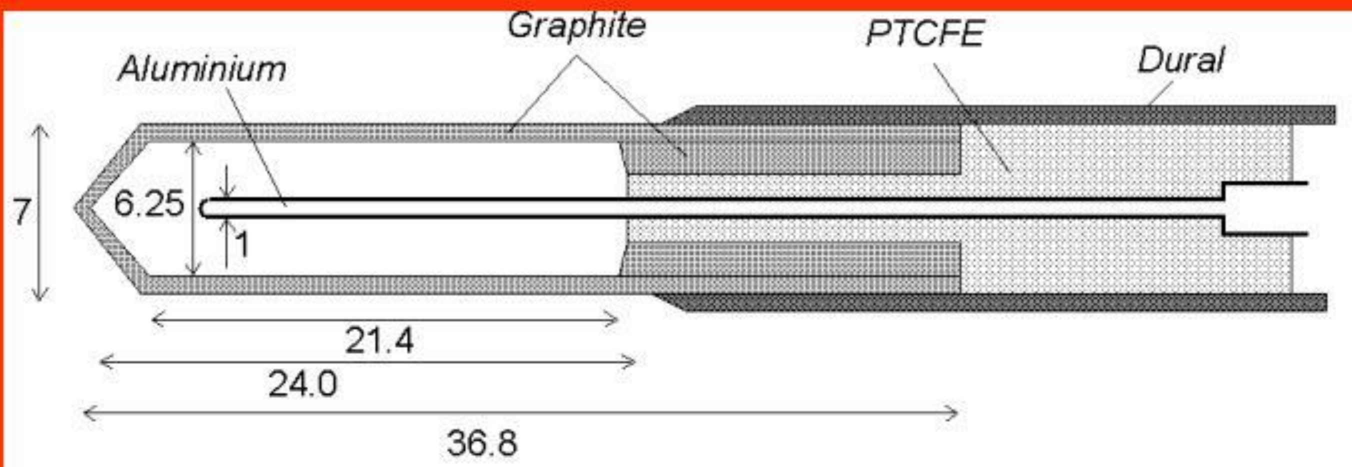


Figure 3.18: Cross section through a Farmer type ionization chamber; all measures in millimetre (redrawn from Aird and Farmer 1972)

Parallel plate chambers

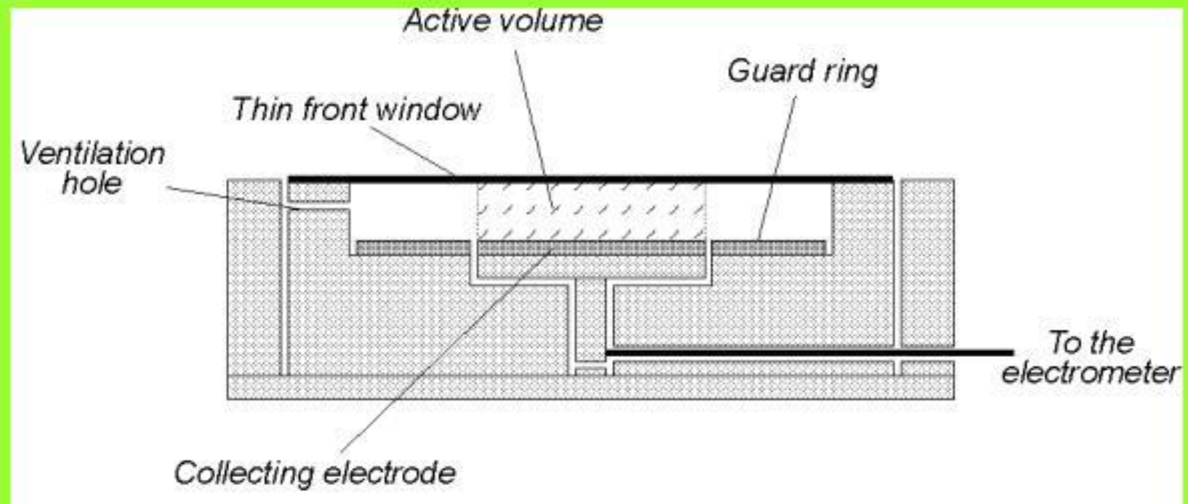
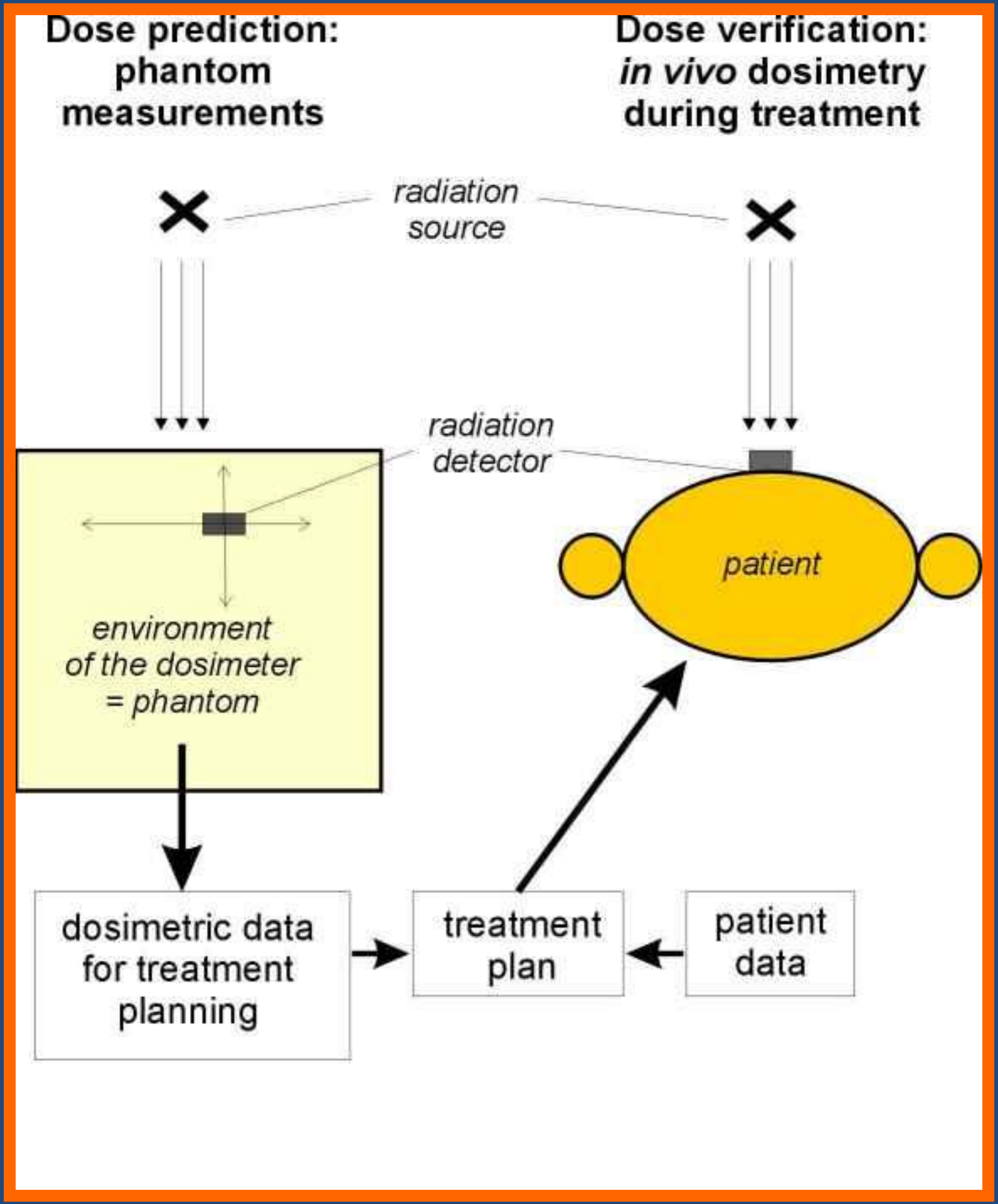


Figure 3.21: Schematic drawing of a plane parallel ionization chamber

From Metcalfe et al 1996

There are multiple objectives for dose measure-ments in radiotherapy practice



Protecting the Patient

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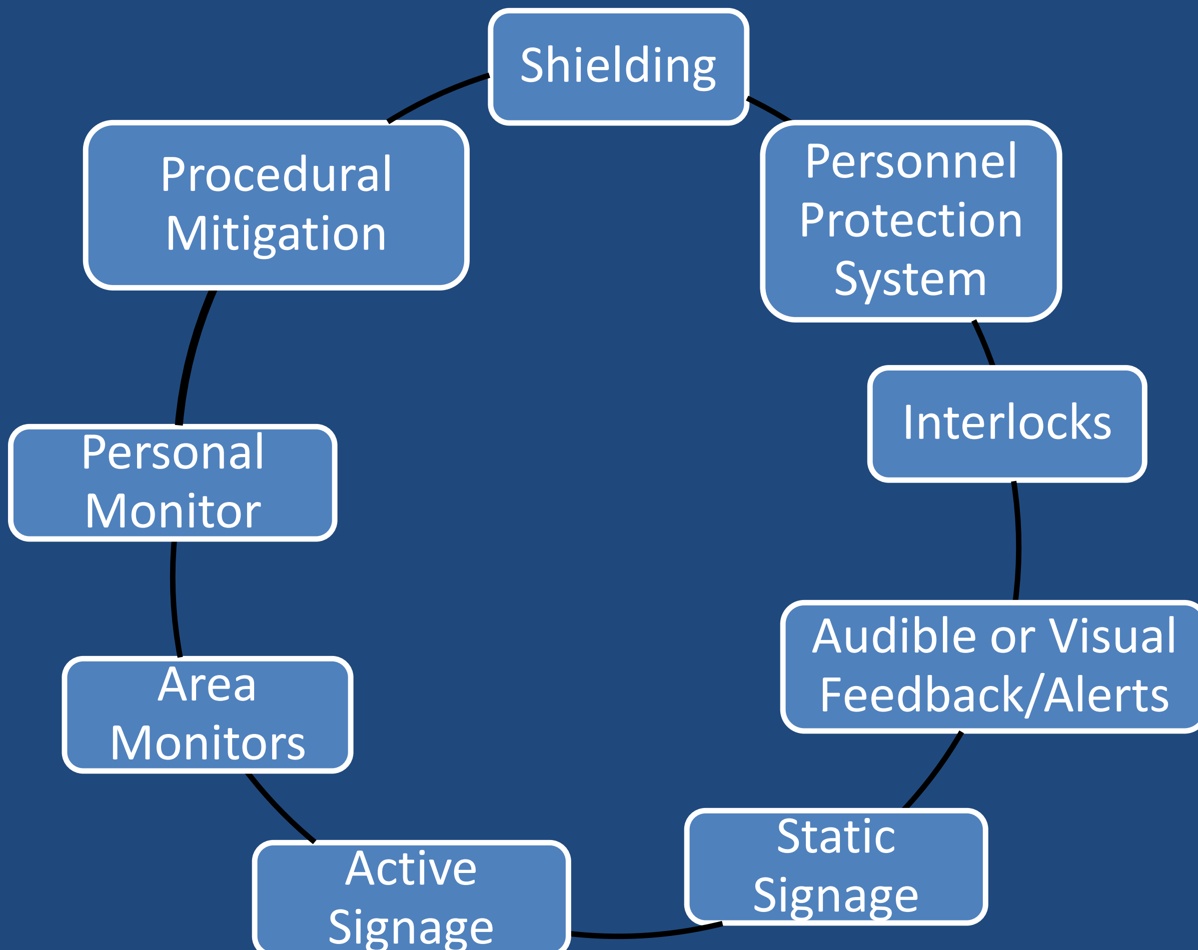
Training and Licensure

- Radiation Safety Training is an annual requirement by the State of California
- Physicians must hold the appropriate license to practice autonomously
- Radiation Therapists (typically Bachelor's degree) is a license individual with manadatory maintenance of license
- Medical Physicist is not required to be licensed or certified (!) in the State of California, but it is common practice to attain license
- Nurses and Dosimetrists (ie, treatment planning staff) may or may not be radiation workers, depending on the environment

Medical Physicist Credentials

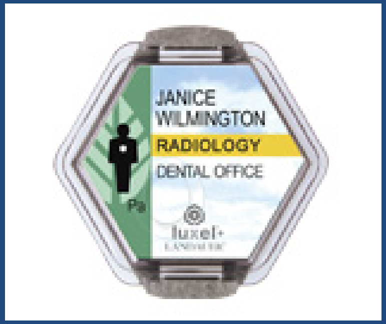
- Masters in Medical Physics from an accredited institution
  - PhD available from many institutions
- Following degree, an accredited residency in medical physics is required
- American Board of Radiology Certification
  - Three part national certification process
    - Part 1 : accredited degree and written physics exam
    - Part 2: pass Part 1, and 3 years of clinical experience, and written clinical physics exam
    - Part 3: pass Part 2, and oral exam by 5 board certified physicists
  - Maintenance of Certificate
    - Required certain continue education credits
    - Required three process improvement projects in ten year period
    - Required re-examination every 10 years

Mitigation of Radiation Risk Specifics



Radiation Risk Mitigation Specifics

- Monitoring
  - Area Monitors – audible and visual cue that radiation is in the treatment room
  - Personnel Monitors – measure radiation dose; routinely monitor occupational workers



Radiation Risk Mitigation Specifics

- Signage
  - Static – communicates radiation area; caution required
  - Active – relays information about room status; x-ray on, beam on, room clear, audio-visual, etc

Radiation Risk Mitigation Specifics

Interlocks and Monitors

- Dose Delivery
  - Primary, secondary and non-volatile dose monitors
  - Beam modulation monitor
    - For example, MLC monitors (photon), spot position monitor (proton)
- Room Secure Procedure
- Door Interlock

Protecting the Patient

- Ensure accuracy of the delivery
  - Calibrating the beam delivery system
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  - Proper training and licensure
  - Interlocks, emergency stop, etc
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Protecting the Staff

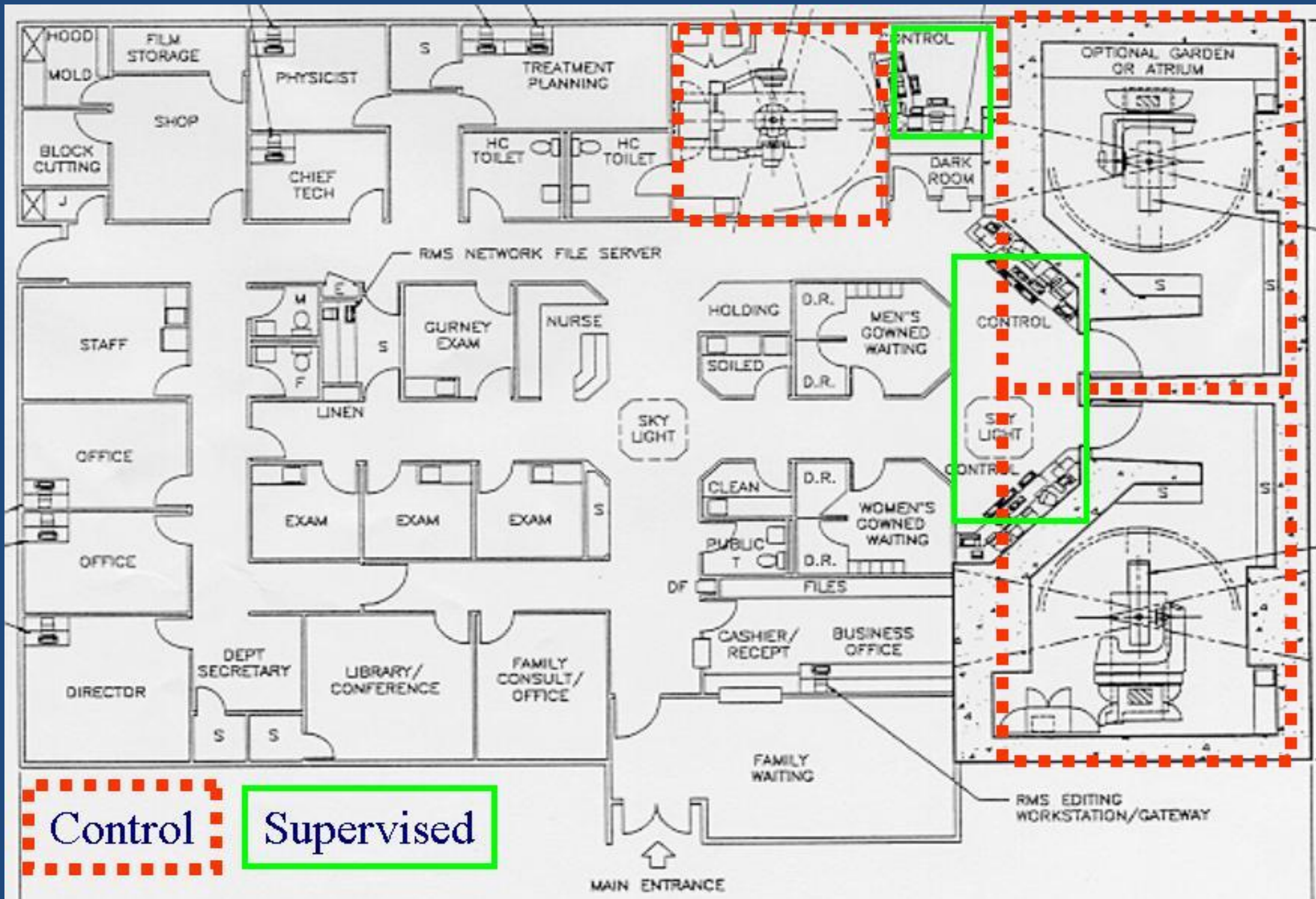
Protecting the Staff and Public

- Proper shielding
- Radiation exposure monitoring
- Mentioned previously
  - Ensure training and credentialing
  - Ensure safe operation of the machines
    - Emergency off, interlocks

Radiation Risk – Dose Limits

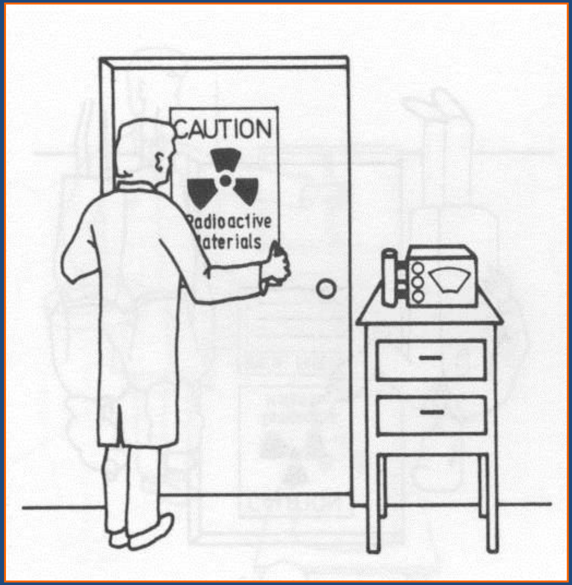
Description	Annual Dose Limit
Public	100 mrem
Occupational Worker	5000 mrem
Pregnant worker	500 mrem
Scripps Level I Threshold	625 mrem
Scripps Level II Threshold	1250 mrem

- State/NRC set limit at 10-100x less than the lowest known dose to cause any effect
- Typical hospital action levels are 10x less than that


HOOD
MOLD
FILM STORAGE
SHOP
BLOCK CUTTING
J
PHYSICIST
CHIEF TECH
S
TREATMENT PLANNING
HC TOILET
HC TOILET
CONTROL
DARK ROOM
OPTIONAL GARDEN OR ATRIUM
RMS NETWORK FILE SERVER
STAFF
M
F
S
LINEN
GURNEY EXAM
NURSE
HOLDING
SOILED
D.R.
MEN'S GOWNED WAITING
D.R.
CONTROL
S
S
SKY LIGHT
SKY LIGHT
CONTROL
OFFICE
OFFICE
EXAM
EXAM
EXAM
S
CLEAN
D.R.
WOMEN'S GOWNED WAITING
PUBLIC T
D.R.
S
S
DF
FILES
DEPT SECRETARY
LIBRARY/ CONFERENCE
FAMILY CONSULT/ OFFICE
CASHIER/ RECEPT
BUSINESS OFFICE
DIRECTOR
S
S
FAMILY WAITING
RMS EDITING WORKSTATION/GATEWAY
MAIN ENTRANCE
Control
Supervised

Controlled and supervised areas

- Access restrictions
- Require warning signs
- Monitoring of staff
- Interlocks where appropriate
- Written procedures



1. Shielding fundamentals

- Aim 1: to limit radiation exposure of staff, patients, visitors and the public to acceptable levels
- Aim 2: to optimize protection of patients, staff and the public
- Different considerations are required for:
  - superficial/orthovoltage X Ray units
  - Simulators, CT (dealt with in diagnostics course)
  - cobalt 60 units
  - linear accelerators
  - brachytherapy

Information required

- Equipment type
- Workload
- Target dose
- Use factor and direction of primary beam
- Distance to the area of interest
- Occupancy of area to be shielded
- Limit value in area to be shielded

Equipment type

- Type, manufacturer, serial number,…
- Source isotope, activity (date of calibration!), air KERMA, ...
- Radiation quality
- Dose rate
- Field size
- Extras: *e.g.* MLC, IMRT, EPID, ...

2. Assumptions for shielding calculations

- Radiation limit
- Workload
- Use factor
- Occupancy
- Distance
- Materials

Example for workload on linac

- Assume T = 2.5Gy at isocentre
- 50 patients treated per day on 250 working days per year

W = 50 x 250 x 2.5 = 31250 Gy per year

- allow for other uses such as physics, blood irradiation, …
- Total : 40000Gy per year at isocentre

IMRT and shielding

- In IMRT many more monitor units are delivered per field than in conventional radiotherapy.
  - The total target dose will still be the same - primary beam shielding will not be affected
  - However, the leakage radiation can be significantly increased (a factor of 10 is often assumed)

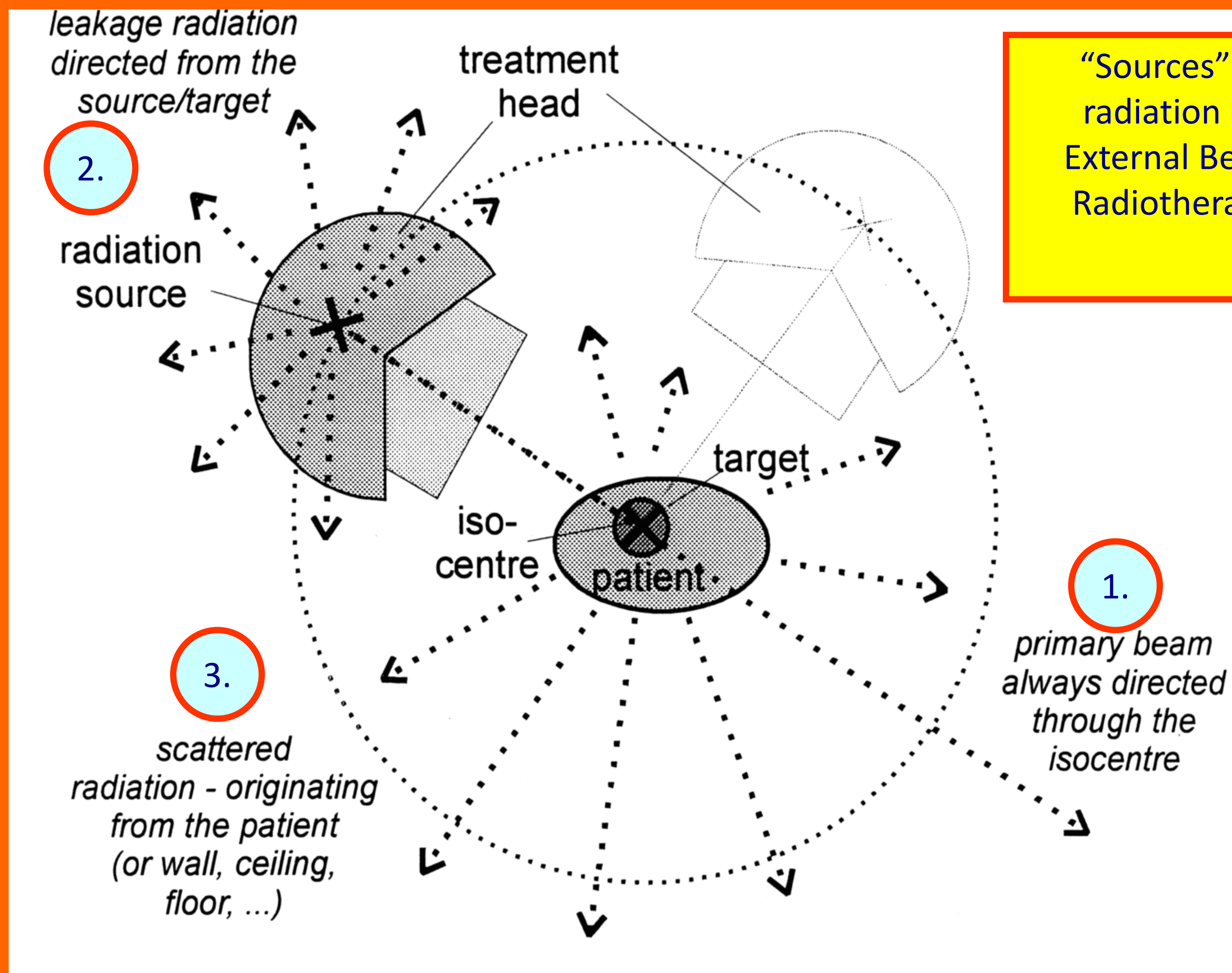
Use factor

- Fraction of time the ***primary*** beam is in a particular direction *i.e.* the chosen calculation point
- Must allow for realistic use
- For accelerators and cobalt 60 units usually the following is used:
- One conservative options:
    - 1 for gantry pointing down
    - 0.5 for gantry pointing up
    - 0.25 for lateral directions
- Another option:
    - 0.25 for each cardinal direction

Primary and secondary shielding

- Shielding must consider three source types of radiation:
  - primary (apply use factor)
  - scatter (no use factor - U = 1)
  - leakage (no use factor - U = 1)
- Brachytherapy does not apply a use factor (U = 1)

“Sources” of radiation in External Beam Radiotherapy



Secondary Sources in External Beam Radiotherapy

- Leakage:
  - dependent on design, typically limited to 0.1 to 0.2% of the primary beam
  - originates from target - not necessarily via the isocentre
- Scatter:
  - assumed to come from the patient
  - difficult to calculate - use largest field size for measurements
  - the lower the radiation energy, the more of a concern for photon beams

Occupancy of the area to be shielded

- Fraction of time a particular place is occupied by staff, patients or public
- Has to be conservative
- Ranges from 1 for all offices and work areas to 0.05 for toilets or 0.025 for unattended car parks
- Based on NCRP report 151

Occupancy (NCRP 151)

occupancy factor (T):

Location	Occupancy Factor (T)
Full occupancy areas (areas occupied full-time by an individual), *e.g.*, administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building	1
Adjacent treatment room, patient examination room adjacent to shielded vault	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors[b]	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

Neutron shielding

- Different concept from X Ray shielding
- Neutrons scatter more
- Attenuation (and scatter) depend VERY strongly on the neutron energy
- Best shielding materials contain hydrogen or boron (with high cross section for thermal neutrons)

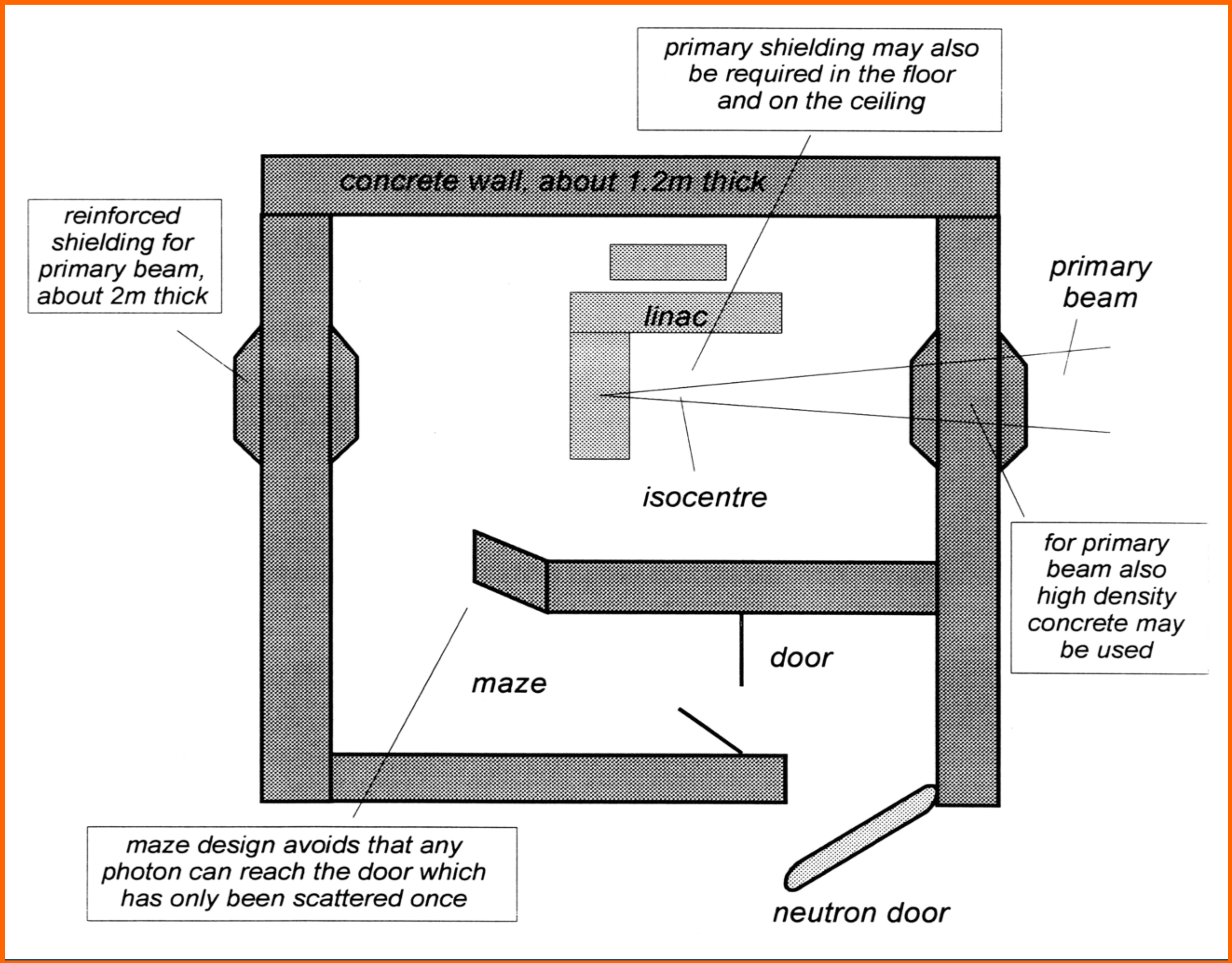
Features of neutron shielding

- Long maze - many ‘bounces’
- Neutron door - typically filled with borated paraffin
- … however, care is required as neutrons generate gammas which may require other materials for shielding again...

Activation

- Neutrons can activate materials in their beam
- High energy linacs are designed with materials with low activation cross section
- After high energy photon irradiation, beam modifiers such as wedges or compensators may become activated
- After prolonged use of high energy photons (*e.g.* for commissioning) it is advisable to let activation products decay prior to entering the room (>10min)

Schematic of a linac bunker



3. Basic shielding calculation

- Currently based on NCRP 57 and 151
- Assumptions used are conservative, so over-design is common
- Computer programs may be available, giving shielding in thickness of various materials

Shielding calculation

- Equipment type
- Workload W
- Target dose D
- Use factor U
- Distance d
- Occupancy of area to be shielded T
- Limit value in area to be shielded P

- *How can we calculate the required attenuation factor A (and therefore the barrier thickness B) by putting these parameters together?*

Example

- Waiting room adjacent to a linac bunker, distance 6m
- The linac has a workload of 40000Gy at isocentre per year
- FAD = 1m

Example for primary beam

- Equipment type = linac, FAD = 1m, 6MV
- W = 40000Gy/year
- (D = 2.5Gy)
- U = 0.25 (lateral approach)
- d = 6m
- T = 0.25 (waiting room)
- P = 0.001Gy/year (no additional constraint)

$A = WUT\,(d_{ref}/d)^2\,/\,P$

A = 69,444

Need nearly 5 orders of magnitude attenuation !

Shielding materials

- Lead
  - High physical density - small space requirements
  - High atomic number - good shielding for low energy X Rays
  - Relatively expensive
  - Difficult to work with

Shielding materials

- Iron/steel
  - Relatively high physical density - space requirements acceptable
  - Self supporting structure - easy to mount
  - Relatively expensive

Shielding materials

- Concrete
  - Cheap (when poured at the time of building construction)
  - Self supporting - easy to use
  - Relatively thick barriers required for megavoltage radiation
  - Variations in density may occur - needs checking

Tenth Value Layer Thicknesses (TVL) For Different Materials

TVL (cm) for different photon qualities (endpoint energy)							
Shielding material (density g/cm^3)	**500 kVp spectrum**	**4 MVp spectrum**	**4 MV mono-energetic**	**6 MVp spectrum**	**10 MVp spectrum**	**20 MVp spectrum**	**References**
Lead (11.3)	1.19	5.3	3.7	5.7	5.5 - 5.8	5.7	NCRP 2005 Cember 1992 Siemens 1994
Steel/Iron (7.8)		9.1	9.9	10	9.7 - 11	11	Cember 1992 Siemens 1994
Concrete (1.8-2.4)	11.7	29.2	35	37	38 - 41	46	NCRP 2005 Cember 1992 Siemens 1994
Ledite (approx 4)		14					Manufacture specifications

Note: Ledite is a mixture of lead shot in concrete available in bricks of various sizes. Ledite (and similar materials) are often used for shielding purposes as they combine a high physical density

Example for primary beam

- Equipment type = linac, FAD = 1m, 6MV
- W = 40000Gy/year
- D = 2.5Gy
- U = 0.25 (lateral approach)
- d = 6m
- T = 0.25 (waiting room)
- P = 0.001Gy/year (no additional constraint)

A = 69,444

Need to know the TVL (tenth value layer or thickness required to attenuate the beam by a factor of 10) of concrete in a 6MV beam

TVL = 30cm

Required barrier thickness:

B = 1.5m

Example for secondary barrier

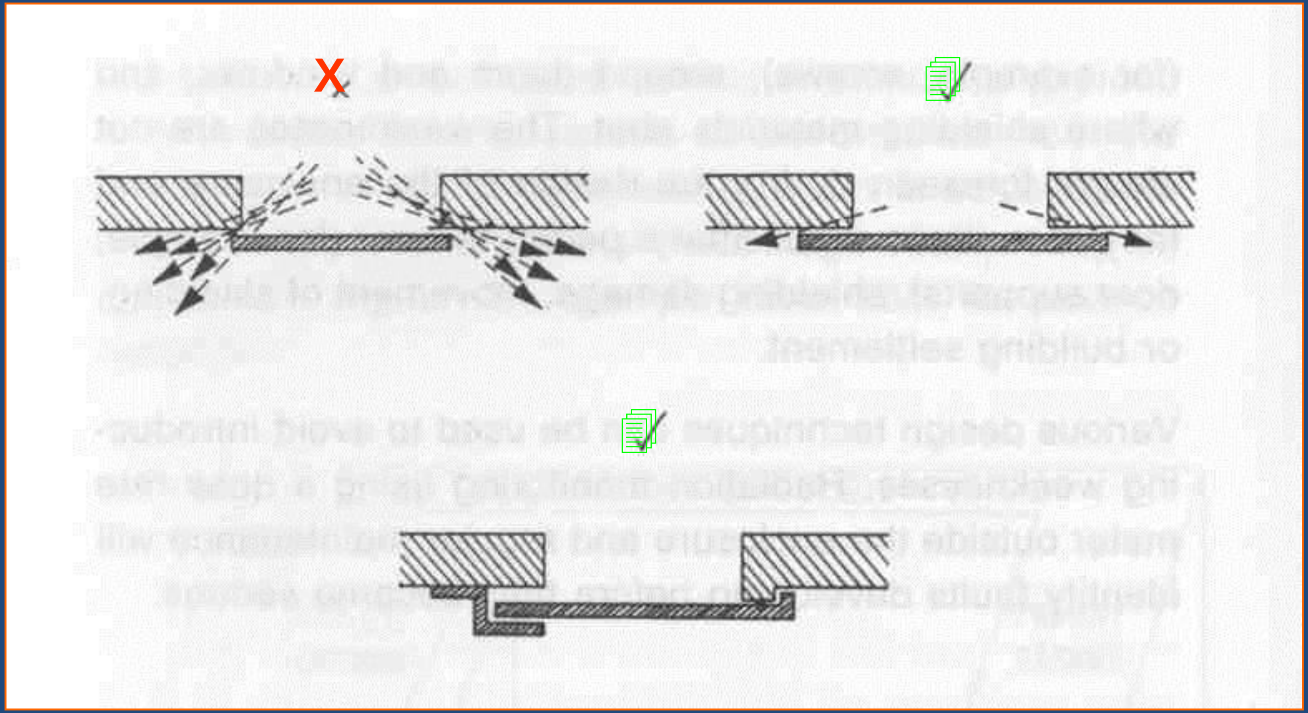
- Equipment type = 60-Co, FAD = 80cm
- W = 40000Gy/year
- (D = 2.5Gy)
- (U = 1)
- $d_{\text{to isocentre}}$ = 5.2m
- T = 1 (office above)
- P = 0.001Gy/year
- Dose constraint factor 0.3 (Cobalt unit is only one potential source)

$A = L\ WT\ (d_{ref}/d)^2\ /\ P$

L = "leakage and scatter factor" = 0.2%

A = ???

Doors



- Direct shielded door or not?
- Be aware of leakage radiation

Verification and surveys

- It is essential to verify the integrity of the shielding during building (inspections by the RSO) and after installation of the treatment unit (radiation surveys)
- Flaws may not be in the design - they could as well be in the execution
- Assumptions used in the design must be verified and regularly reviewed.

Radiation Survey *vs.* Monitoring

- Radiation survey is the test that the area is safe for use (in particular the commissioning)
- However, one also needs to make sure that all assumptions (*e.g.* workload) are correct and continue to be so. This process is called monitoring and involves long time radiation measurements.

Regular Area Monitoring

- Confirm the results of the radiation survey
- Radiation areas should be regularly checked in case the shielding integrity has changed
- This is especially important for rooms shielded with lead or steel sheet, as they may have moved and any joins opened up
- An area should be checked after any building works

IAEA Safety Report Series

IAEA Safety Report Series 17

- Only reported accidents
- Therefore likely bias towards countries with a reporting requirement and structure
- External beam and brachytherapy
- *Unsealed sources (covered in training on Nuclear Medicine)*

Accidental exposures in external beam RT can be grouped as follows:

- Equipment design
- Calibration of beams
- Maintenance
- Treatment planning and dose calculation
- Simulation
- Treatment set-up and delivery

Accidents in EBT

Category	No of cases	%
Equipment design	3	7
Calibration	14	30
Maintenance	3	7
Planning	13	28
Simulation	4	9
Set-up	9	20

Summary

- For medical facilities, it is critical to have the correct assumptions
  - Workload, type of modality, current and potential future use of abutting rooms, etc
- In the US, typically states regulate radiation protection
  - In addition to being familiar with the federal documents, you must consult the state for specifics
- NCRP-151 is key document for medical shielding
- Physicist is a key member of the radiation safety, as one of the few clinical personnel that has both the technical and clinical background to approach and reason through radiation safety risks and mitigations

Thank you