Medical Applications (of Particle Physics)

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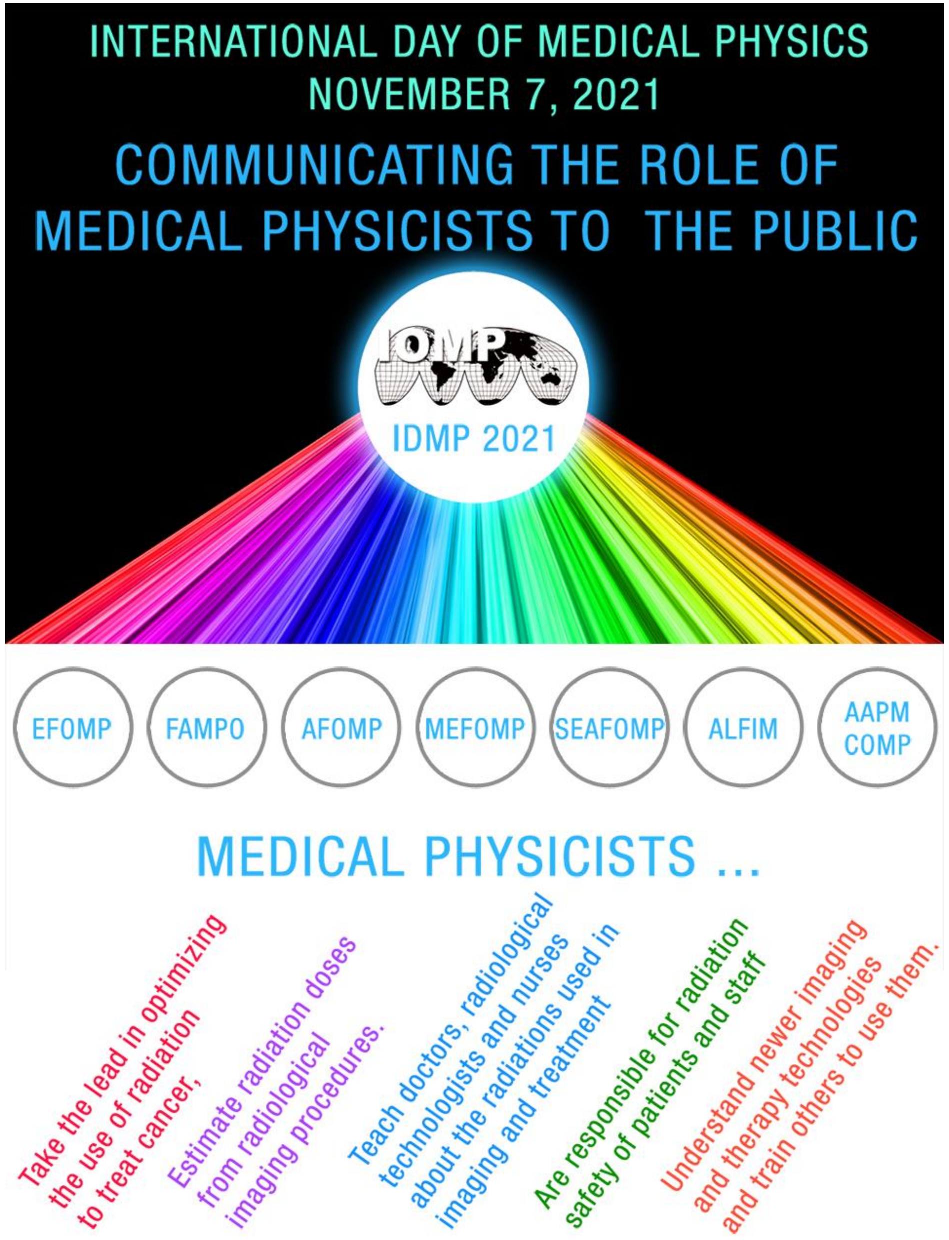
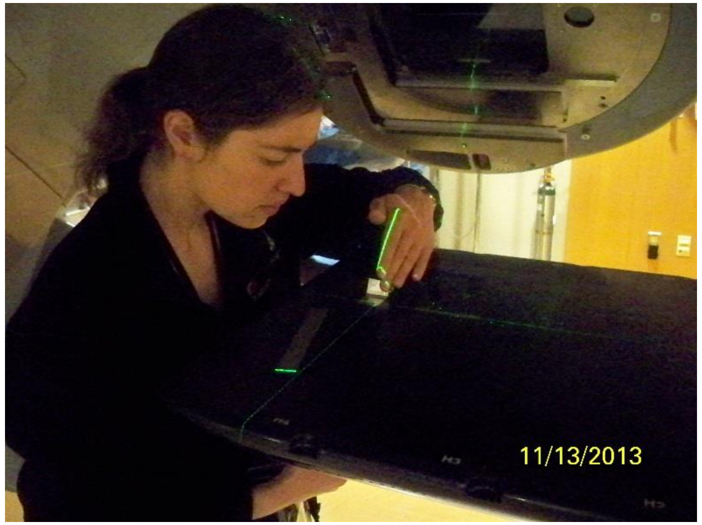
Learning objectives

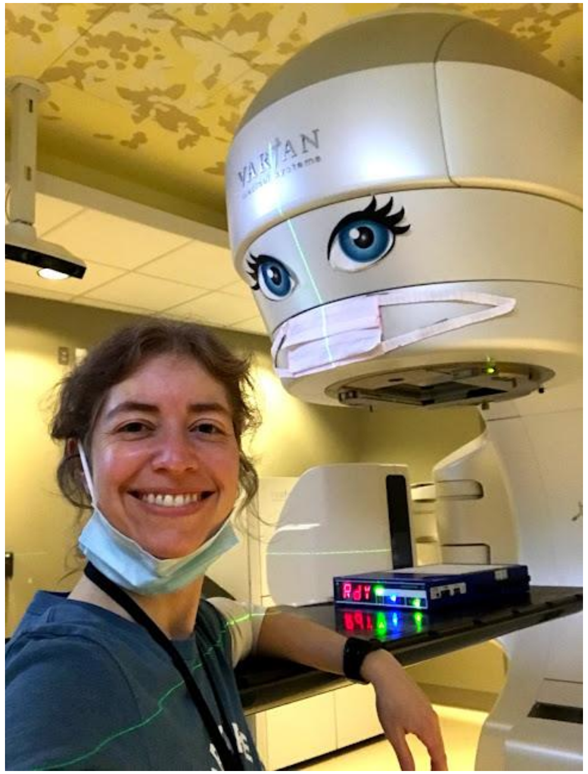
- By the end of this talk, you should be able to:
  - Give a brief history of radiation use in medicine
  - Describe some uses of radioisotopes and particle accelerators in medical imaging and cancer treatment
  - Know the 3 major specialties of medical physics: health, diagnostic, and therapy physics



My introduction

From the collision hall
…to the hospital



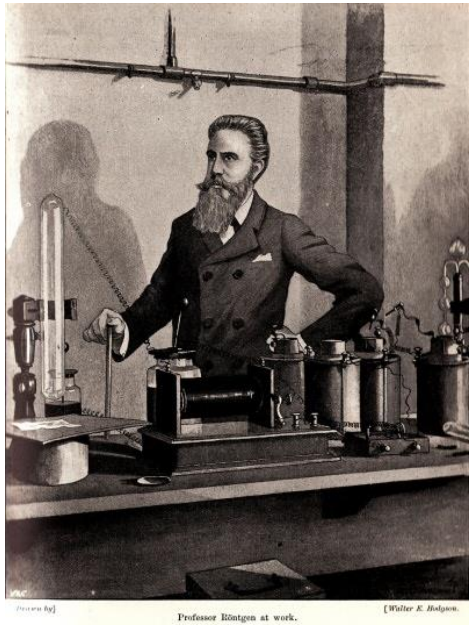


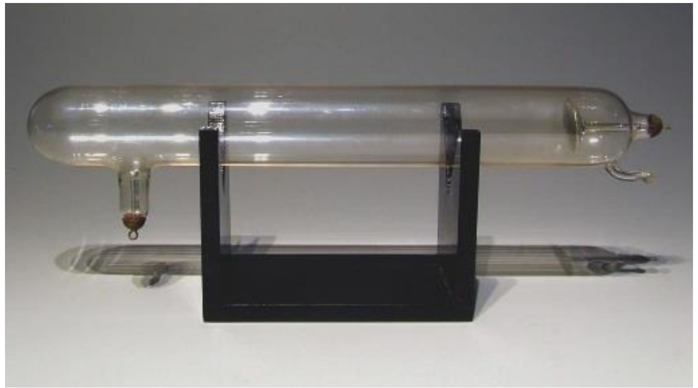
- High-energy physicist on CDF (2002-2010)
  - PhD with Johns Hopkins: B^{**0} meson and Σ_b baryon searches (2002-2007)
  - Postdoc with UW-Madison: high-mass Higgs → WW search (2007-2010)
- Therapy medical physics residency with Harvard (2010-2013)
  - Clinical Radiation Oncology medical physicist at MGH (2013-present)

A brief history of radiation in medicine

- It started with Roentgen's discovery of x-rays: Nov 8, 1895
  - Benefits of x-ray radiography immediately apparently (beginning of Radiology)
- Within a year, attempts were made to use x-rays to treat cancer (Rad Onc)
  - Initially had only very low energy x-rays, treatment limited to superficial lesions (skin, breast)

Wilhelm Conrad Roentgen (1845-1923). The first medical X-ray of the hand of Anna Roentgen, taken in 1895 by Wilhelm Conrad Roentgen (1845-1923).



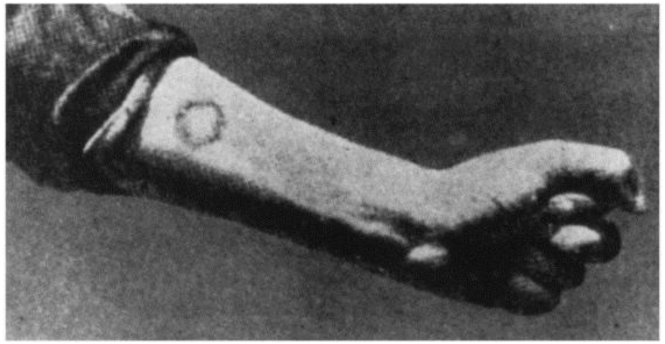


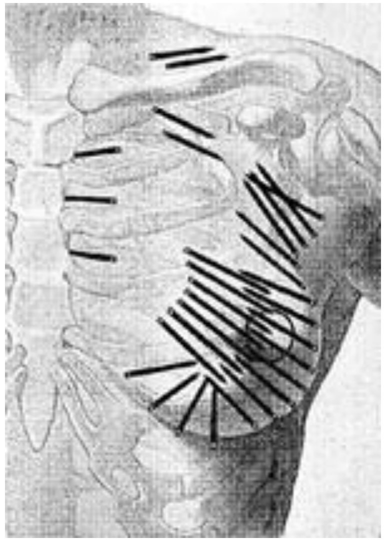
The Cathode Ray Tube site, www.crtsite.com, and the German Roentgen-Museum

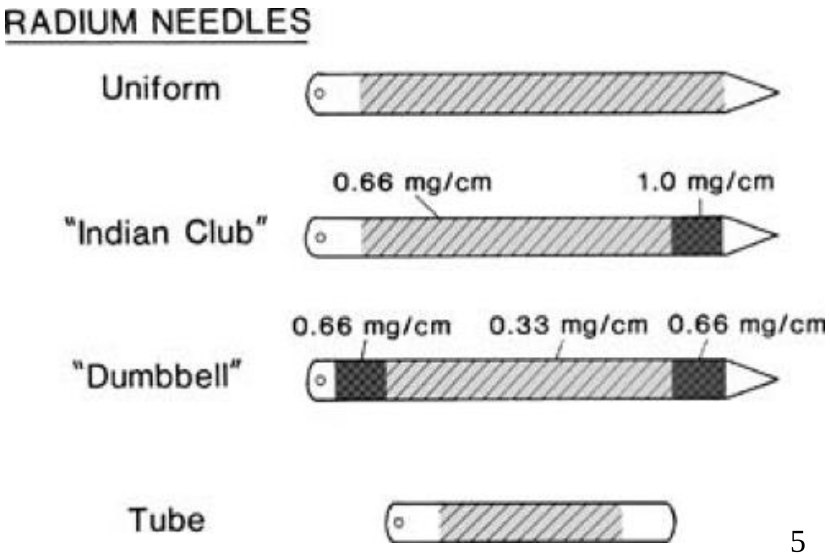
Discovery of radioactivity

Marie Curie is often referred to as the first medical physicist although the term didn’t exist during her time

- 1896: Becquerel discovered radioactivity
- Marie & Pierre Curie discovered Radium and isolated radioactive isotopes
  - 1901: Pierre Curie notes a burn from contact with Radium
  - Paved the way for Brachytherapy (short-distance therapy)
    - Placing radioactive sources on the skin, inside body cavities, or in needles placed in a tumor





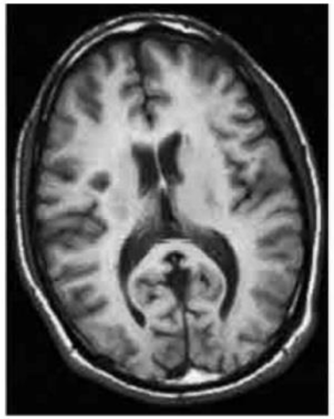


Physicists’ involvement in medicine

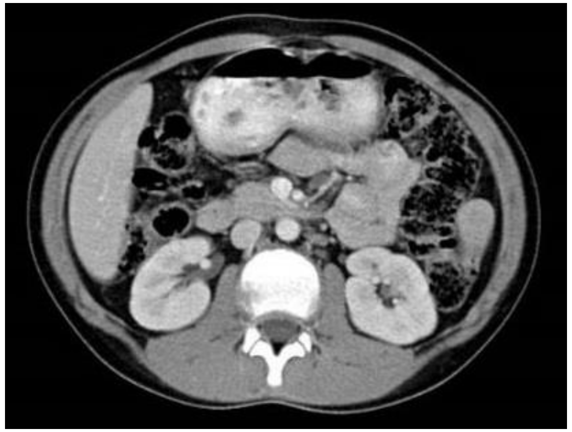
- By 1910, x-ray imaging and Radium radiotherapy well established
  - Physicists heavily involved in technology development
    - Coolidge developed more reliable x-ray tubes
    - Sievert standardized radiation measurement; early treatments relied on skin changes
- And finally, physicists also became involved with patient treatments
  - Hospitals in Britain formally appointed physicists around 1913
  - These physicists supported the development of equipment, radiation protection, calculation of radiation dose, and new treatment techniques
- Therapeutic Radiology was initially considered part of Radiology
  - Separate residency programs developed for Therapeutic Radiologists in the 1950s
  - By the 1980s, the specialty became known as Radiation Oncology

Progression of medical imaging

- Late 1930s: Manhattan project led to developments in nuclear physics technology & radioisotope production
  - Made into radiotracers for nuclear medicine imaging

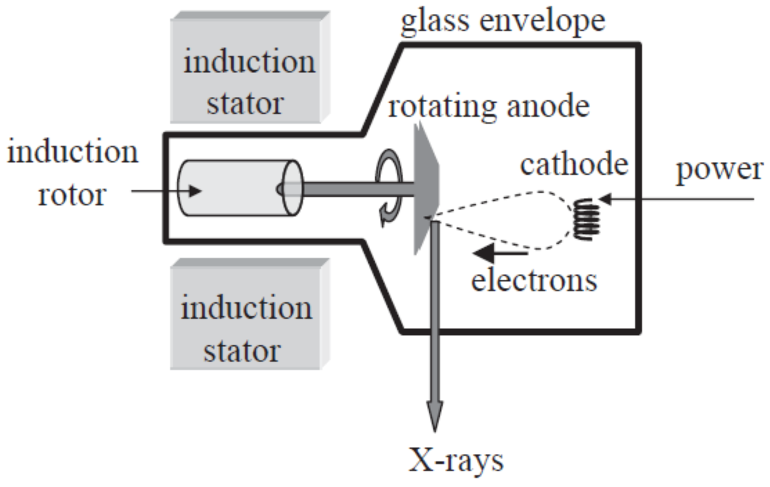


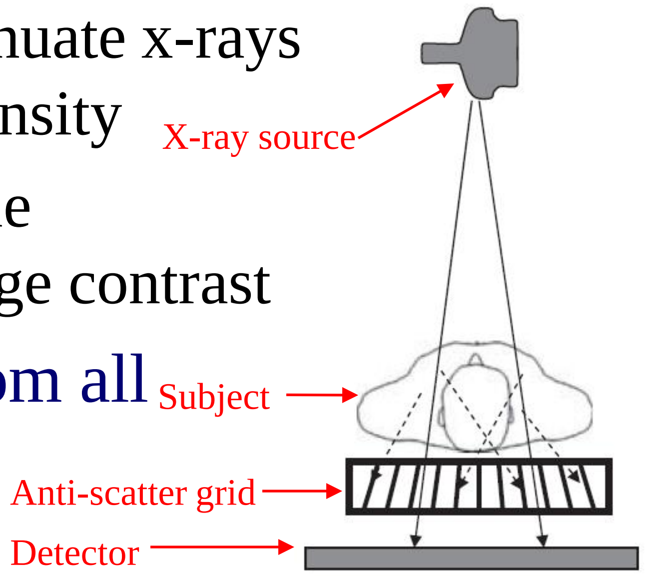
- Also late 1930s: ultrasound imaging introduced
- Rapid improvements in x-ray detectors, from single Geiger-Muller tube to arrays of detectors
  - Scintillators + PMTs → amorphous silicon + TFT arrays
- Late 1960s: development of Computed Tomography (CT)
- 1970s: Nuclear magnetic resonance imaging (MRI)
- Continue to improve resolution and contrast and reduce dose



X-ray imaging fundamentals

- X-ray imaging relies on detecting x-rays transmitted through an object
  - X-rays are scattered or attenuated by photoelectric or Compton interactions with atomic electrons
  - Objects of different thickness/density attenuate x-rays differently, leading to different image intensity
  - More sensitive detector detects more subtle differences in tissue, leading to better image contrast
- CT scanning is acquiring x-ray images from all directions to reconstruct a 3D image





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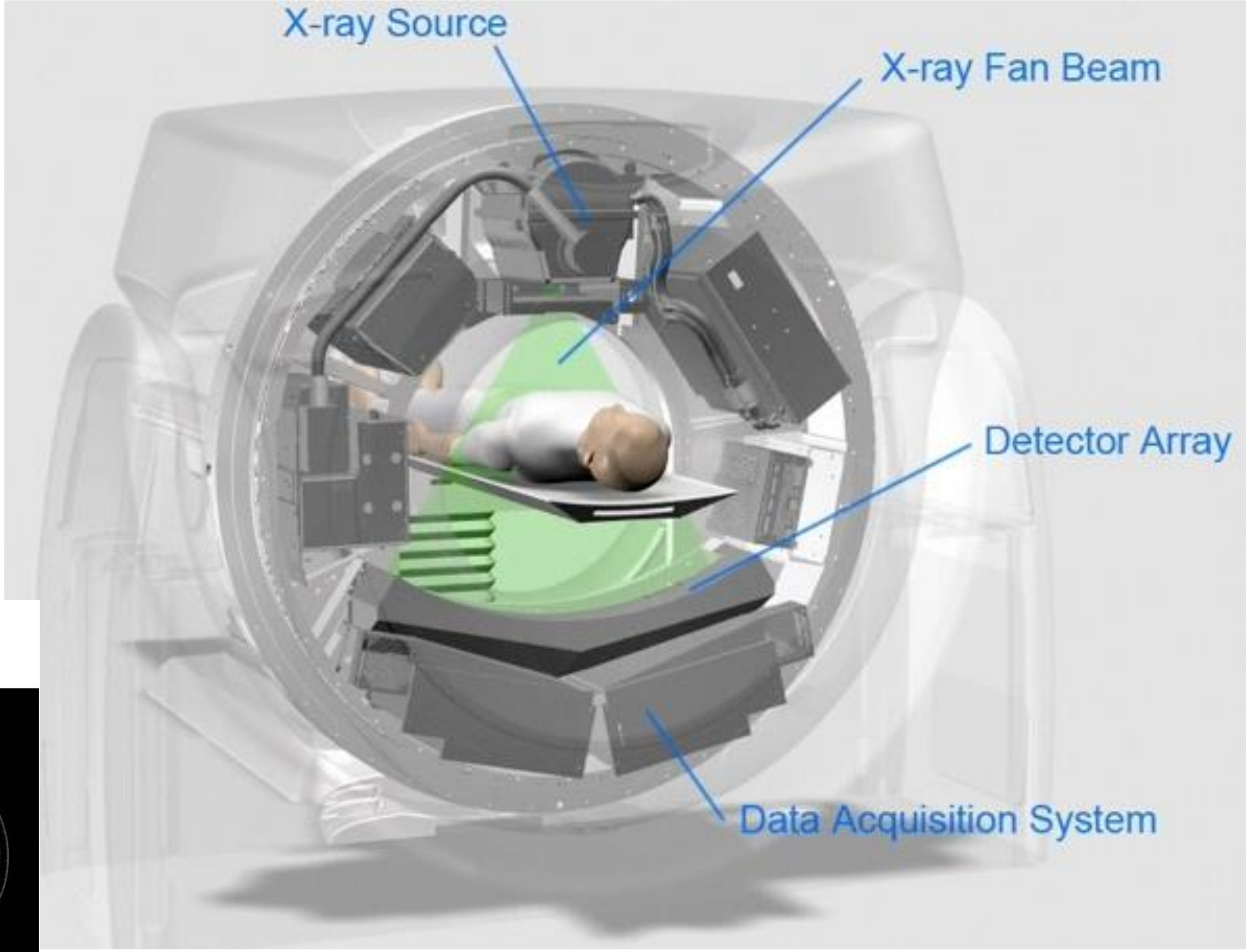
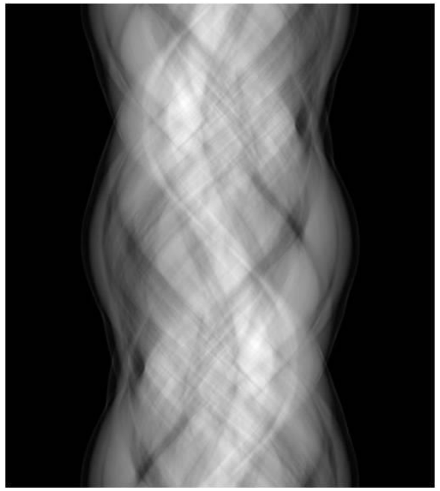
Introduction to Medical Imaging: Physics, Engineering and Clinical Applications, NB Smith & A Webb, Cambridge University Press

CT scan

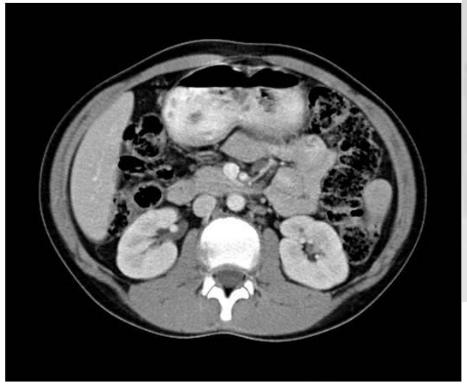
- Patient couch moves through continuously rotating x-ray gantry
- Requires a computer to reconstruct 3D image
  - Scattered photons create noise!



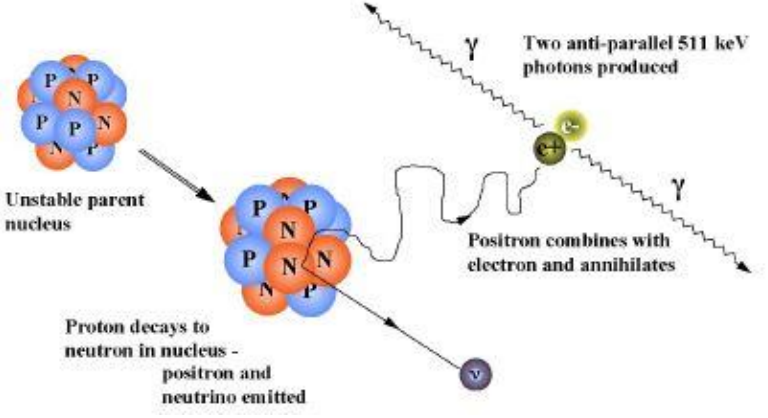
Sinogram



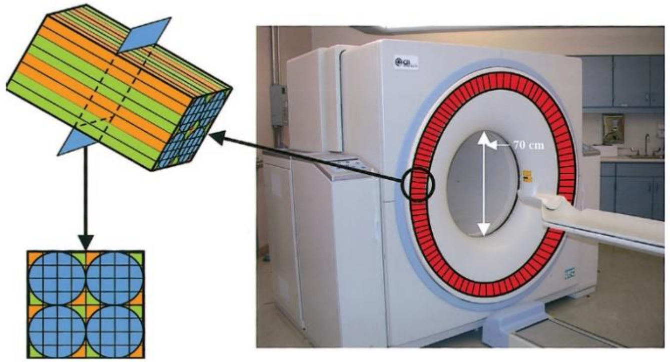
Reconstruct

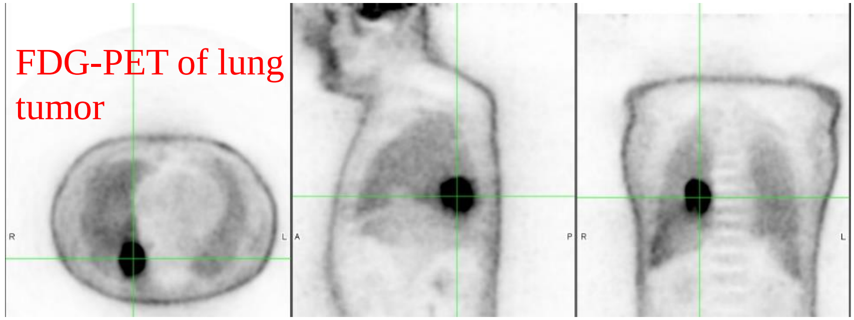


Nuclear medicine



- Radioactive isotopes are attached to tracer compounds that accumulate in a specific part of the body
  - Example: glucose will accumulate in tumors, so image with FDG = Fluorine-18 attached to glucose
- Images acquired using photons emitted by radioisotopes
  - Most isotopes are positron emitters, so the signal is back-to-back photons from positron annihilation
  - Will see more photons coming from areas where more radioisotope collected
  - PET = positron emission tomography
- Provides functional information rather than anatomic




FDG-PET of lung tumor

Production of radionuclides

- Radiochemistry discovery is searching for the best radionuclides and tracers to use for imaging particular diseases
- Nuclear medicine uses many short-lived radionuclides
  - Small facilities order them and have to be shipped
  - Large facilities produce as many as possible on-site
- MGH has a cyclotron for F-18 production
  - Can produce other isotopes as well
  - Also have a Technetium-99m generator
    - Used in >80% of nuclear medicine scans

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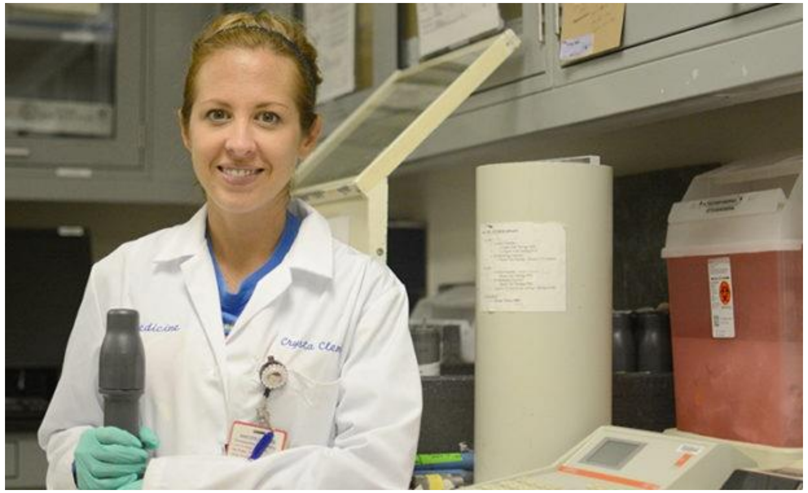
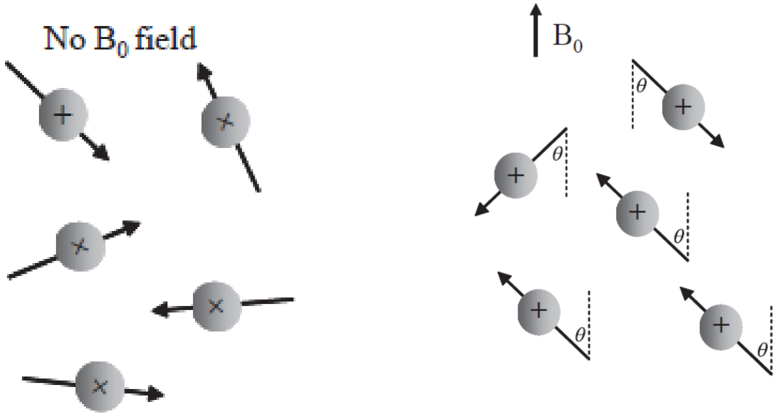
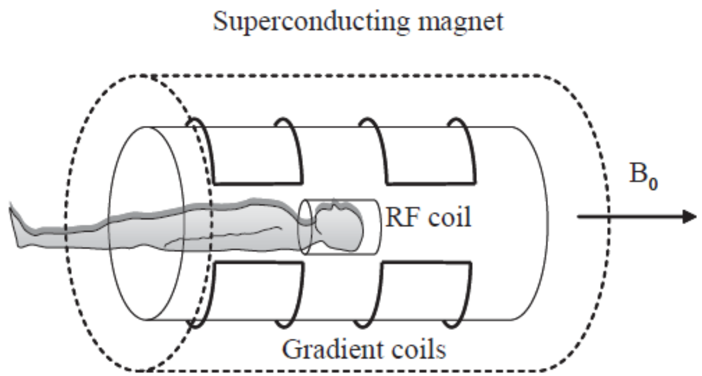
- Radiopharmacist draws up the appropriate doses as nuclear medicine procedure orders are placed

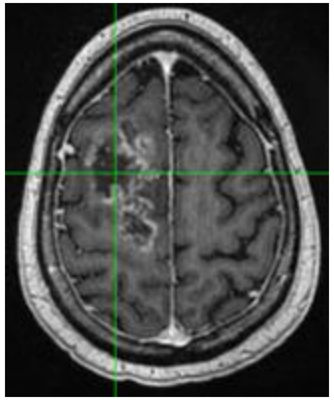


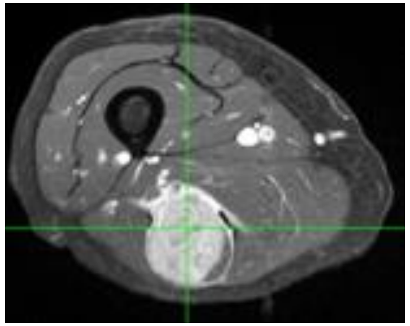
Magnetic Resonance Imaging

- Does not use ionizing radiation to form an image!
- Instead uses changing magnetic fields
  - Protons have a magnetic moment which can be manipulated with external magnetic fields
  - Changing magnetic fields causes nuclei to precess which creates measurable magnetization changes
  - Hydrogen density varies by tissue, so MRI “sees” different responses in tissues, creating image contrast
  - Best soft tissue imaging modality
- Physicists heavily involved in developing MRI and ongoing image improvements



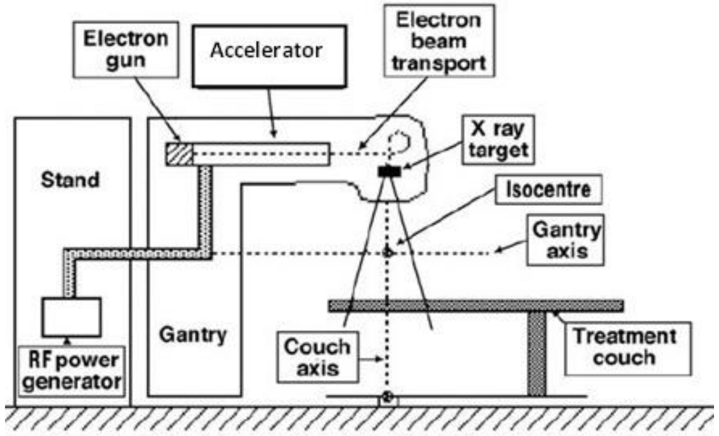






Development of Teletherapy

- Brachytherapy dominated for decades
  - Primary isotopes: ^{226}Ra, ^{137}Cs, ^{192}Ir
- Late 1940s: ^{60}Co used in teletherapy units (long-distance)
  - Gamma rays of 1.2 and 1.3 MeV; 5-year half-life
- 1950s: wartime efforts for radar led to development of electron linacs for delivery of megavoltage x-rays
  - Achieve higher energies and dose rates than available with radioisotopes, with fewer radiation safety concerns
  - Linacs developed with energies ranging from 4 to 30 MV
  - Proton accelerators proposed around this time (R. Wilson)

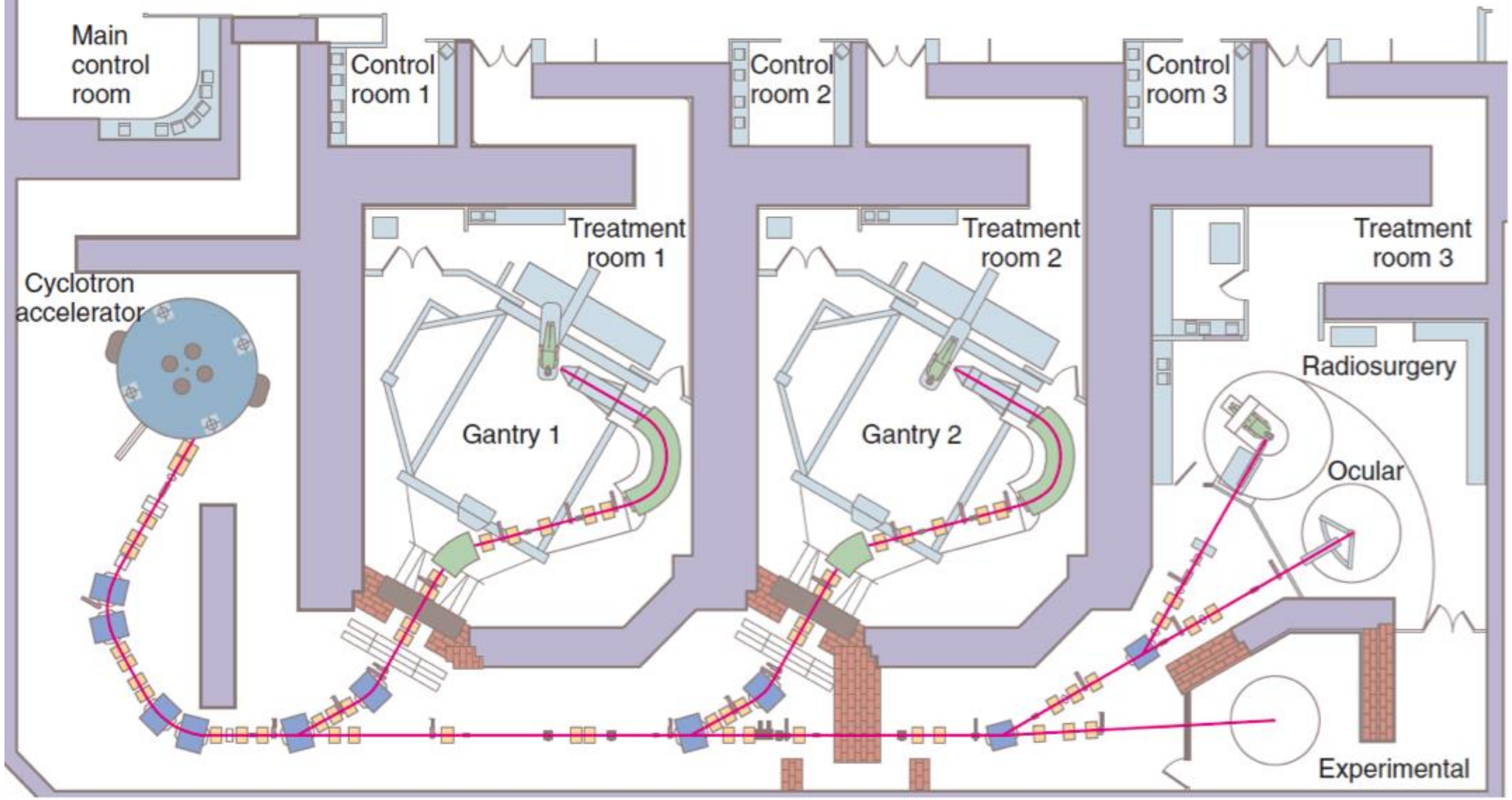


Modern medical linacs

- Commercial FDA-approved products with vendor support
  - Primarily two vendors: Elekta & Varian
  - Different designs, same functionality
- Linacs provide photon or electron beams
  - Photon energies: 6, 10, and 15 MV spectrum
  - Electron energies: 6 MeV up to 20 MeV
- Orthogonally mounted imaging x-ray tube and detector
- Linac and treatment couch rotate around a single axis point called the isocenter
  - Radiation beam directed towards patient from many possible angles
  - Makes it possible to target the radiation extremely accurately to the tumor!

Medical proton accelerators

- Initially used research accelerators and added a treatment gantry
  - MGH uses the former Harvard cyclotron to feed 2 gantry rooms and 2 fixed beam lines



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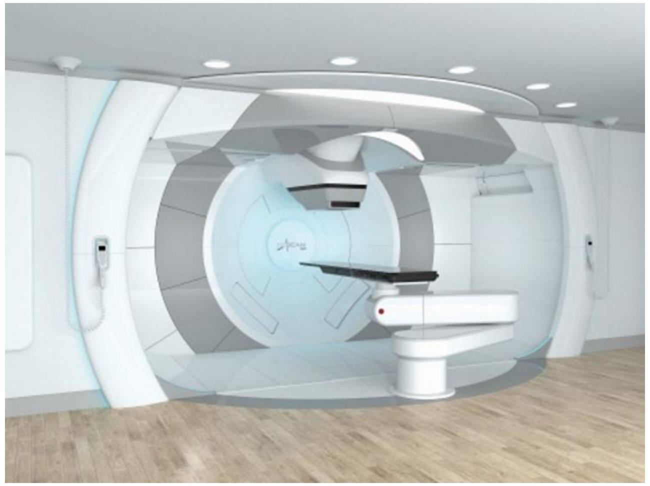
  - But this requires on-site engineering support, lots of space, and very expensive

Inside the treatment room at MGH

Outside the room (IBA)

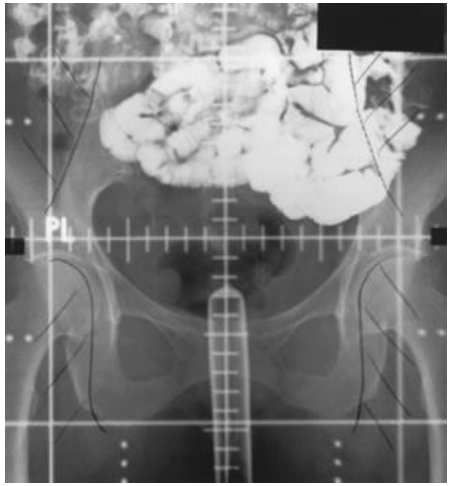
Medical proton accelerators

- Initially used research accelerators and added a treatment gantry
  - MGH uses the former Harvard cyclotron to feed 2 gantry rooms and 2 fixed beam lines
  - But this requires on-site engineering support, lots of space, and very expensive
- Now companies competing to make cost-effective single-room proton gantries
  - To keep the size reasonable, gantry only rotates ~200 degrees not 360

Targeted radiation therapy

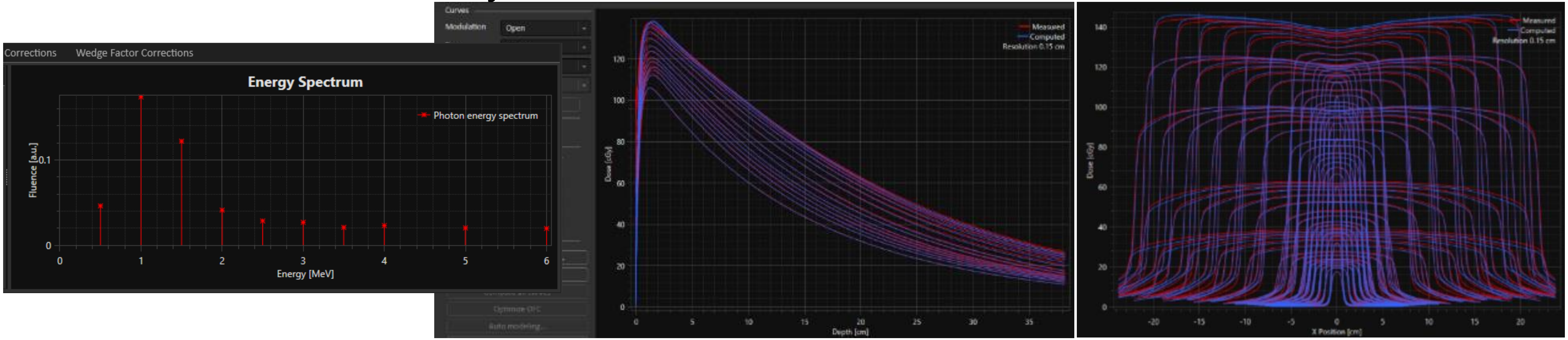
- First medical linacs delivered square fields of radiation
  - Used lead cutouts to block critical tissues from the radiation
- Technology advanced, and modern linacs have multi-leaf collimators (MLCs) that can create fields of any shape
  - MLCs can be programmed to move WHILE beam is on
  - This creates modulation of the radiation intensity to target dose at the tumor while sparing the healthy organs nearby
  - Requires specialized treatment planning software to calculate the ideal motion of these MLCs
- Also requires physics to verify the dose delivered!



How do we measure dose to patients?

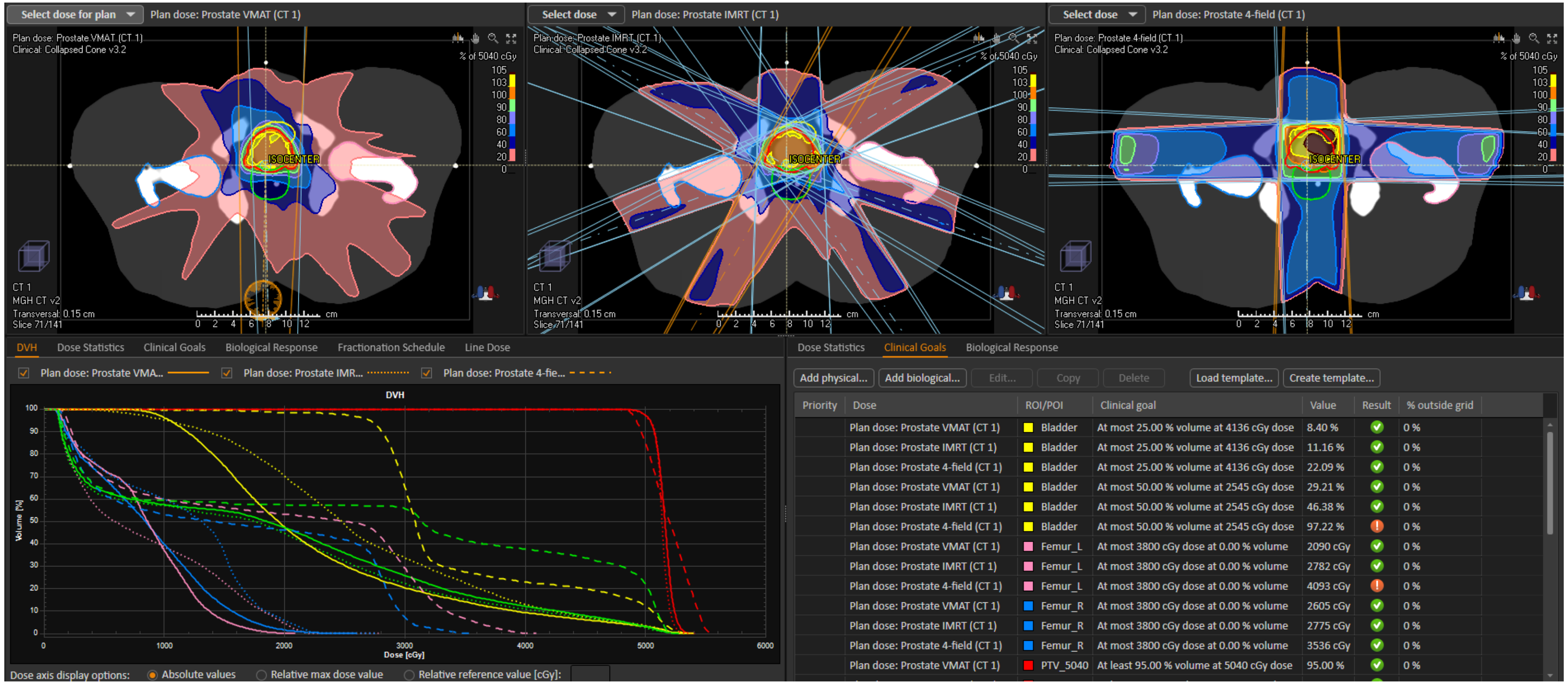
- Start with calibrated ionization chambers in water
  - Measure absolute dose, percent depth dose, and profiles
- Use that data to create a model of the photon beam from a specific machine in the treatment planning software
  - Software can now calculate dose for arbitrary field shapes
  - With electron density info, can calculate in non-water too

Iba-dosimetry.com



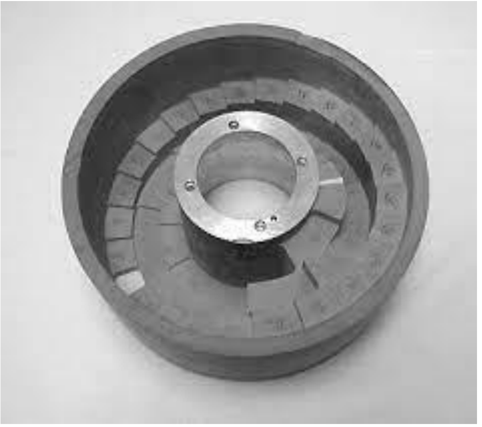
Photon treatment planning example

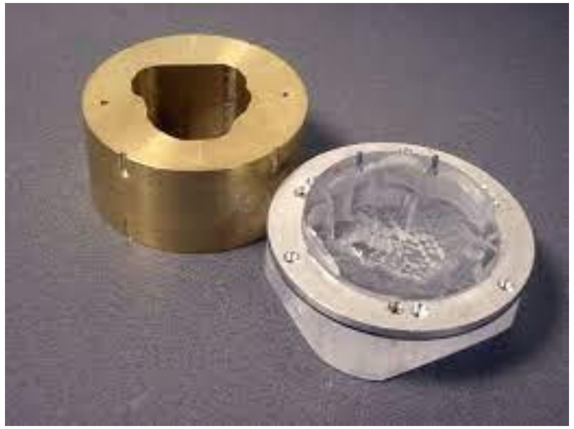
- Current state-of-the-art: gantry rotates continuously during treatment
  - Modulate gantry speed, dose rate, and MLC positions simultaneously
- Extremely conformal plans with low surface dose



Proton treatment planning

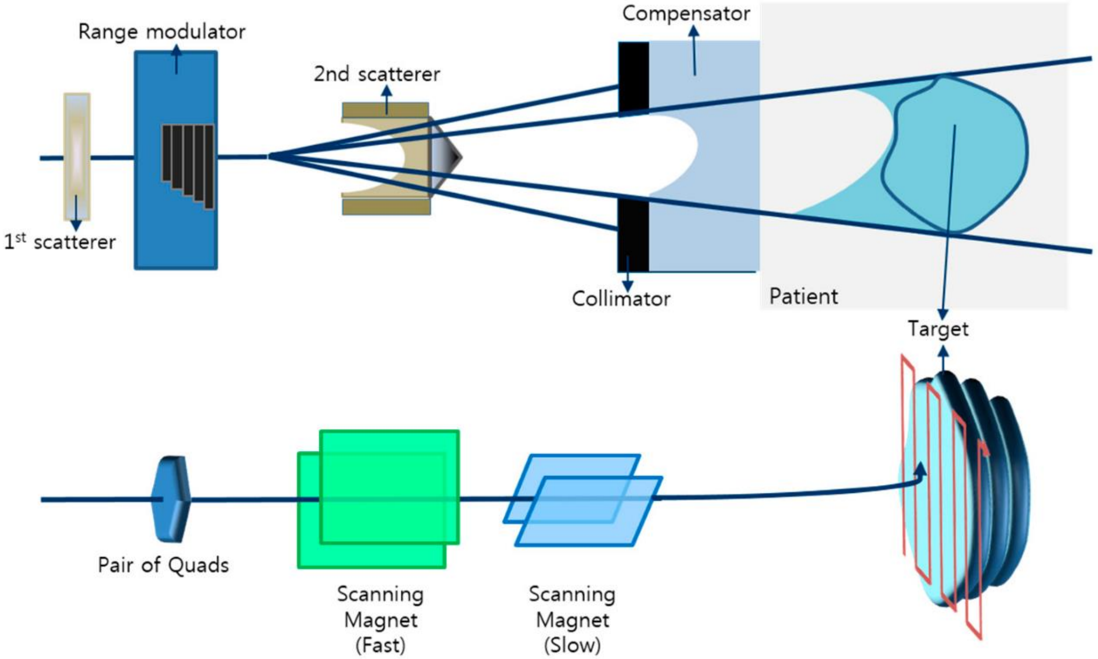
- Totally different physics from photons… need to control energy not intensity
  - Passive scatter: design patient-specific compensators to target tumor
  - Pencil beam scanning: energy switching allows scanning at different depths
- Proton dose distribution superior to photon, but increased cost limits use





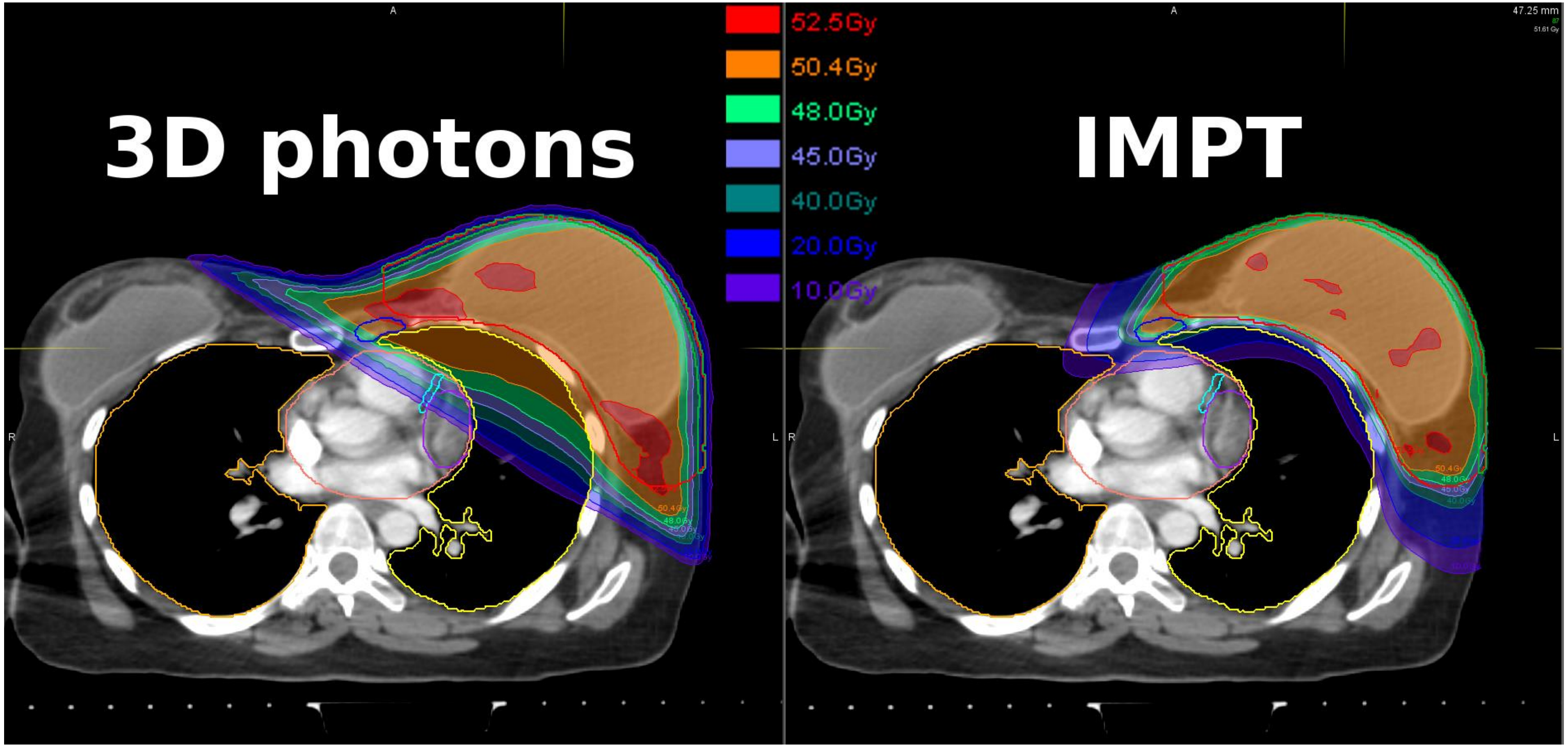
Range modulator, brass collimator, and plastic range compensator

Development of Optical Fiber Based Measurement System for the Verification of Entrance Dose Map in Pencil Beam Scanning Proton Beam. *Sensors* **2018**, *18*, 227



Protons vs Photons for breast cancer

- Protons can reduce dose to the heart, lungs, and contralateral breast



So… what is medical physics today?

- Medical physics covers all applications of physics to medicine
- Principally, medicine uses radiation for diagnosis or treatment
  - Medical physicists are required for quality assurance and safety at any facility offering imaging or radiation therapy
- 3 primary specialties:
  - Health physics (Radiation Safety) – primarily regulatory
    - Ensure radiation workers are not exposed during work
  - Diagnostic (Radiology) – many areas of crossover with therapy
    - Nuclear Medicine and MRI sometimes considered separate specialties
  - Therapy (Radiation Oncology) – by far the largest specialty
    - Primarily treating cancer patients

What does a medical physicist need to know?

- Each specialty has a dedicated curriculum, but in general:
  - Degree in physics (BS, MS, or PhD depending on career path)
  - Radiation protection and safety
  - Detailed understanding of particle interactions in matter
    - Photons, electrons, protons, neutrons, alpha particles, etc.
  - Operating principles of particle accelerators
  - Principles of medical imaging
  - Basic anatomy and radiation biology (how radiation affects biological systems)
- Medical physics graduate programs provide all the required coursework
  - Coming from a traditional physics program requires some additional coursework

Core curriculum for medical physicists

- Radiological Physics and Dosimetry
- Radiation Protection and Safety
- Fundamentals of Medical Imaging
- Radiobiology
- Anatomy and Physiology
- Radiation Therapy Physics

My career path

- Loved particle physics but saw few jobs available with Tevatron ending
  - Also, wanted to do work with more immediate impact on the world
  - Learned about medical physics through APS and former CDF colleagues
- Applied for both medical physics postdocs and residency programs
  - Lucky to get into the Harvard medical physics residency which provided all coursework and clinical training in 3-year program
- Since residency graduation in 2013,
  - Took a clinical position with MGH satellite and became an expert in planning
  - Completed board certification in 2014
  - Moved into clinical academic position at MGH main campus in 2015

HARVARD
Medical Physics Residency Program

MASSACHUSETTS GENERAL HOSPITAL
DEPARTMENT OF RADIATION ONCOLOGY

My life as a clinical academic therapy physicist

- Clinical: ~50% of an average week
  - Primary physicist on one linac, standard QA duties like new patient plan checks, lead physicist for photon planning
- Education: ~20%
  - Mentor residents in treatment planning, teach lectures
- Administration: ~20%
  - Committee and volunteer work inside MGH and for professional societies (APS, AAPM)
- Research: 10%?
  - No grant funding, no students or postdocs, so can only work on clinical development projects

What I like about medical physics

- Intellectually challenging
  - My primary role is problem-solver… ALL KINDS of problems
  - Clinical research, while not the same as basic research, presents interesting questions and can have an immediate impact
- Part of a team helping people receive care
  - At the end of every day, can really feel you made a difference to someone (even if they don't know it!)
- Being very hands-on
  - Working with the machines or patient data, making measurements, etc.
  - Working directly with people, communicating frequently

Summary

- There are a TON of medical applications of physics and accelerators
  - Radiation is used in both diagnosing and treating disease
  - Wide variety of radioisotopes and permanent radioactive sources in use
  - Also electronic/accelerator sources (kV x-rays, MV linacs, cyclotrons)
- Safe use of radiation requires physicists
  - Health physics for radiation safety, diagnostic physics for imaging, and therapy physics for treatment
  - Specific coursework beyond a general physics degree required for each specialty
- I never pictured myself working in a hospital as a physicist, but there's actually quite a few of us here!