Radiotherapy Instrumentation Session

Particle Beam Instrumentation

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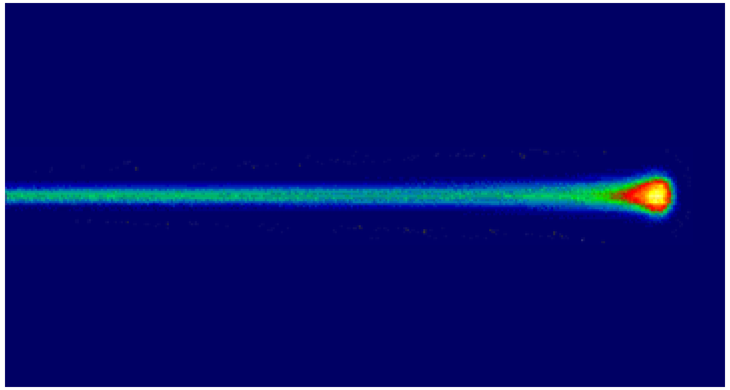
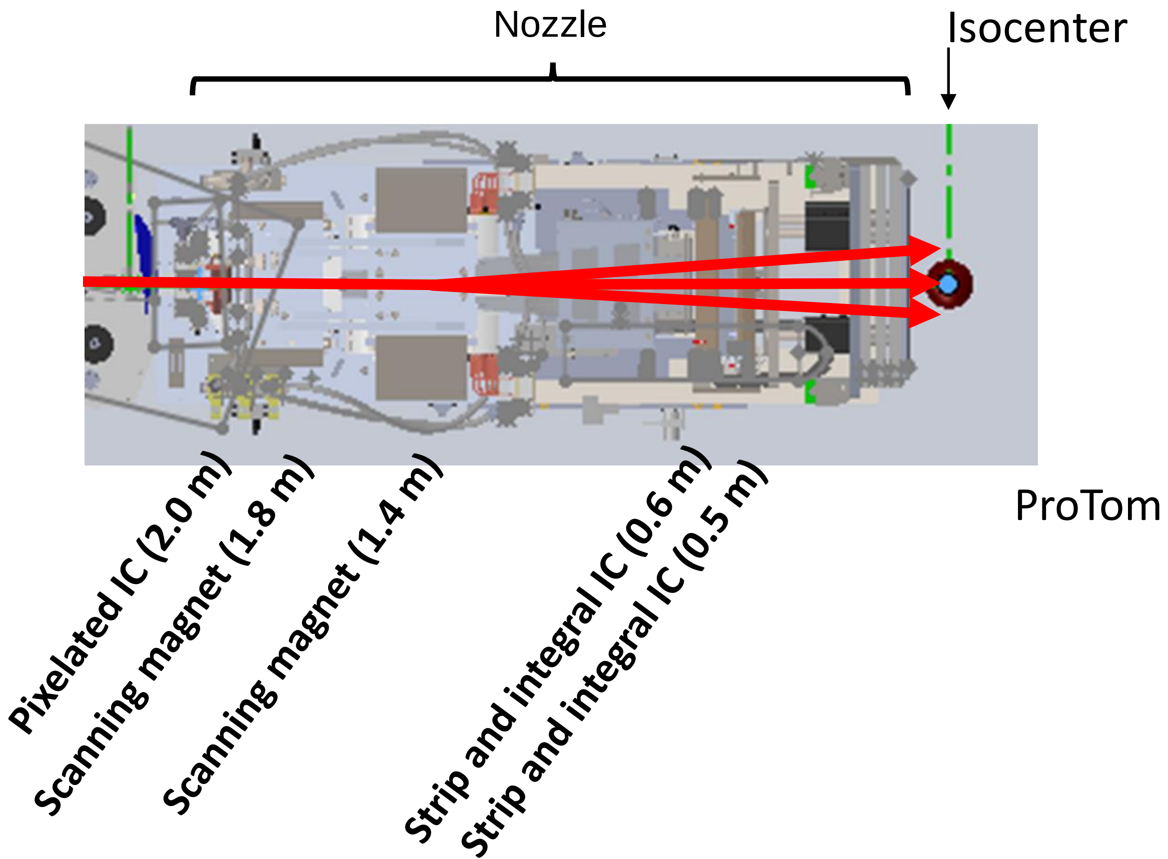
Conflict of interest: None

Particle Beam Instrumentation for Radiotherapy

- Topics:
  - Dosimetry devices
  - Beamline instruments
  - Discussion of instrumentation for “hot” topics
- Description of a pencil beam scanning nozzle

A proton pencil beam in water





Absorbed dose to water

Description:

- Approximately 60% of the human body is water
- Prescribed doses and current empirical knowledge is based on absorbed dose to water
- Water phantoms are relatively simple and convenient devices
  - Motorized phantoms can move a detector in 1, 2 or 3 dimensions
- State of the art: IC-based TRS-398, 2006 protocol
  - Air-filled ionization chamber (IC) in a water phantom in the path of the beam
  - $D_{w,Q} = M k_{TP} k_{elec} k_{pol} k_s N_{D,w}^{60_{Co}} k_{Q,60_{Co}}$
  - Overall uncertainty 2.5%
    - Largest contributions are $N_{D,w}^{60_{Co}}$ (1.4%) and $k_{Q,60_{Co}}$(1.7%)

Examples:

PTW

IBA Dosimetry

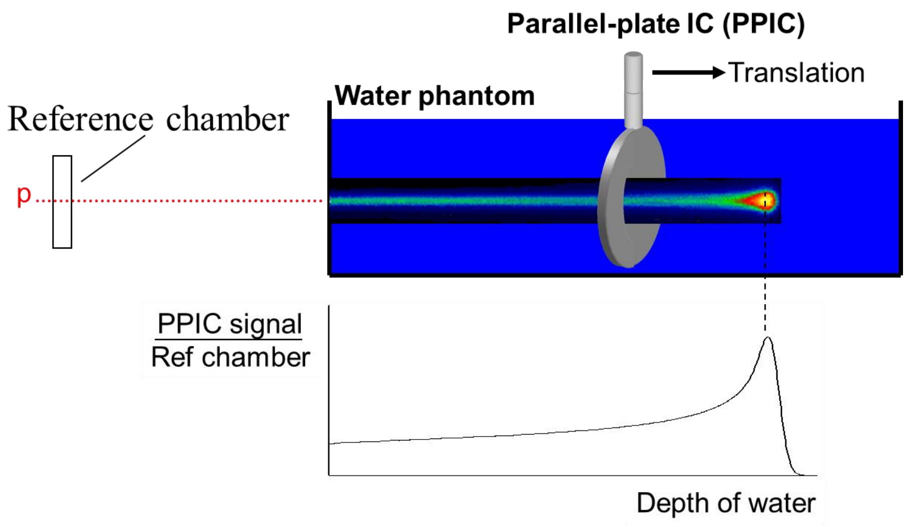
Comments:

- IC damage/recalibration
- Uncertainty is a fairly large piece of the overall radiotherapy error budget ~5%
- Questions about use in scanned beams
- Calorimeters directly measure absorbed dose to water with smaller uncertainty but are not common and are difficult to use

Depth-dose measurements

Description:

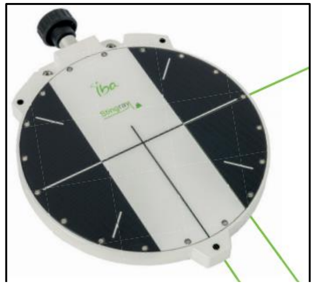
- Measure PPIC/Ref chamber signal vs. depth



- Technically "depth-ionization" measurements
- The energy-dependence of the water/air stopping power ratio is usually small, even for carbon ions (≤ 1%)

Examples:

PTW Markus chamber, 0.5 cm diameter



IBA Dosimetry Stingray, 12 cm diameter

PTW

Comments:

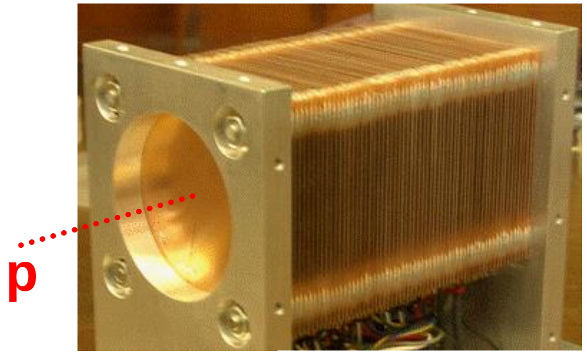
- Depth is a very challenging measurement
  - Preference to have motorized stages with encoders
- Recombination may change with depth
- Suitability of other detectors e.g., film, silicon, diamond, and scintillators usually compared to ionization chambers

Multi-IC devices: longitudinal

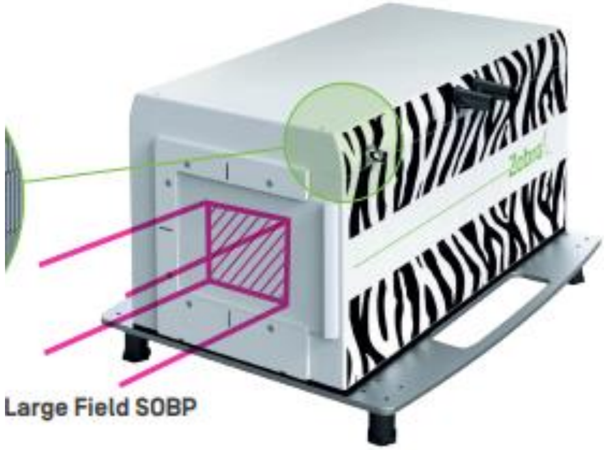
Description:

- Multi-Layer Ionization Chamber (MLIC)
- Multiple parallel-plate IC separated in the longitudinal direction (depth)
- For instantaneous depth-dose measurements

Examples:



Gottschalk, 2008



IBA Dosimetry

Comments:

- Calibration done by the user using their water phantom
- Fast consistency checks

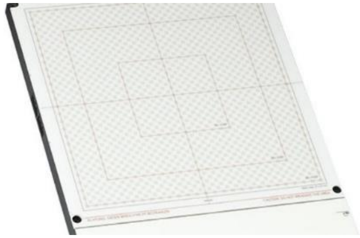
Multi-IC devices: planar

Description:

- 2D array of ionization chambers
- Largely for lateral profile measurements
- Can be scanned in depth

Examples:

IBA MatriXX PT/ONE
1020 ionization chambers



PTW Octavius
1405 ionization chambers

Pyramid, PX3, 120 pixels,
3.8 mm pitch

IBA Digiphant,
1D scanner with MatriXX

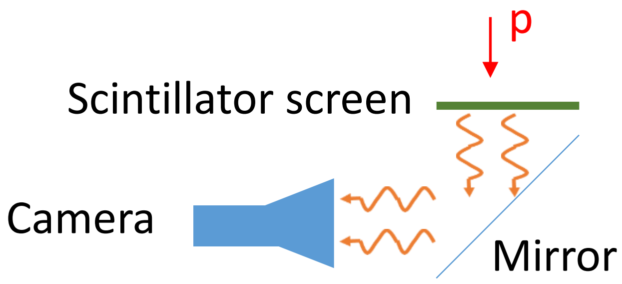
Comments:

- These are very versatile, dependable and sensitive devices
- Need larger area array 30 x 40 cm, to sample entire beam with one acquisition
- Need finer pixel pitch either in the center or separate device to measure beam size and position
- Depth is a very challenging measurement

High-resolution lateral measurements

Description:

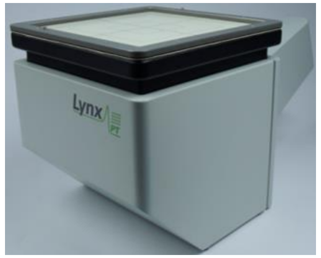
- High resolution measurements are needed when beam size, sigma $\lesssim$ IC array pixel pitch
- Measure sigma, position, virtual SAD
- Devices are available with <0.5 mm resolution
- Scintillator screen and camera



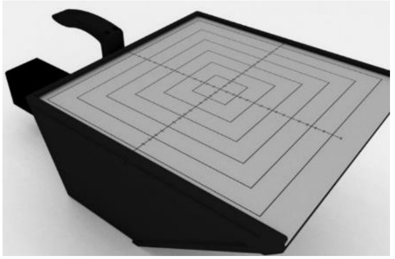
- Also, film + scanner, diode array (e.g. Magic Plate), diamond detector array, flat panel, GEM

Examples:

Lexitek
Scintillator screen
and camera



IBA dosimetry
Scintillator screen
and camera



Logos
Scintillator screen
and camera

Ashland Gafchromic
EBT3 film

Comments:

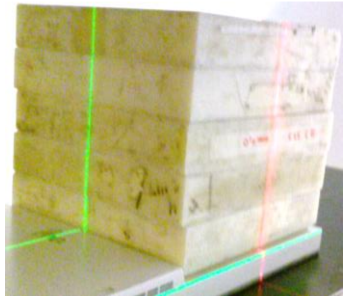
- Some of these detectors have LET dependence
  - Keep the detector in the entrance region when measuring position and sigma
  - Useful for QA (fast consistency check)
- Lexitek has a scintillator screen with small LET dependence

3D measurements

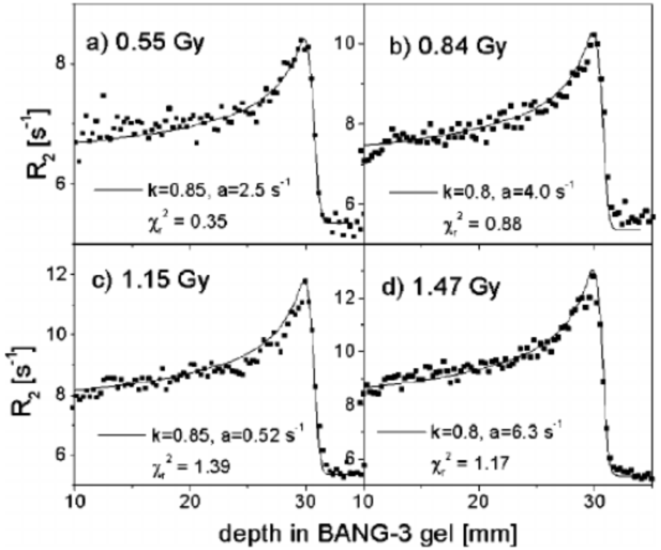
Description:

- Film stacks
  - IROC uses 2 orthogonal planes
- Bang Gel
  - Irradiate Gel
  - Use MRI or optical CT to read out
- 3D array of ion chambers
  - Layers of strip and parallel plate chambers interleaved with plastic slabs

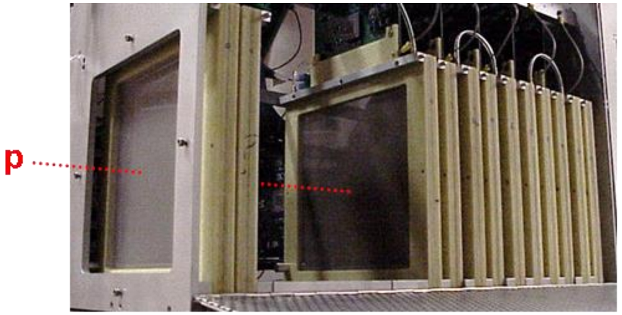
Examples:



Alternating plastic phantom and film



BANG-3
J. Heufelder, 2002



Magic Cube
R. Cirio, 2004

Comments:

- None of the 3D measurements have really taken off in the community. This could be due to:
  - Complicated
  - Needs user calibration vs. ion chamber
  - LET dependence
  - Ease of use

Origin alignment

Description:

- Check alignment of the imaging origin with the nozzle axis
- BB, Film and scanner
- Align BB with imaging system, shoot BB with beam, examine film behind it

Examples:

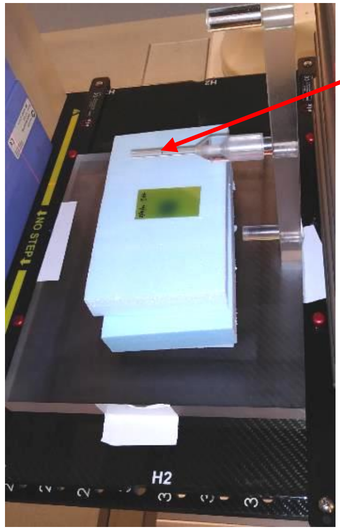
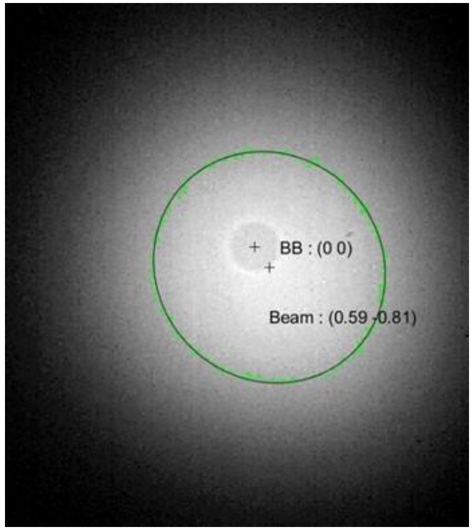


Image and irradiate

Scan

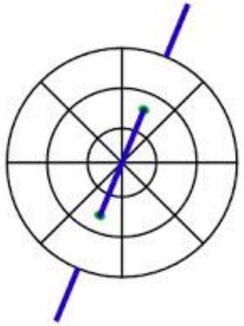


Analyze

Comments:

- Very intuitive
- Slow

- Scintillator screen and camera
    - Puck at the end of cone is aligned by imaging
    - Scintillator captures the trajectory of the beam



Logos. Conical scintillator screen and camera

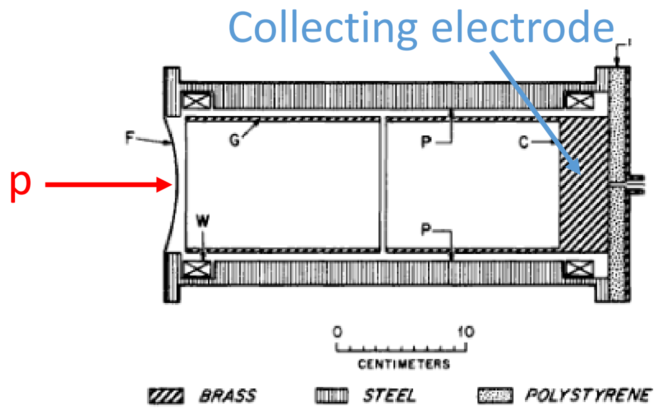
- Much faster
- Currently needs user calibration vs. film

Faraday cup

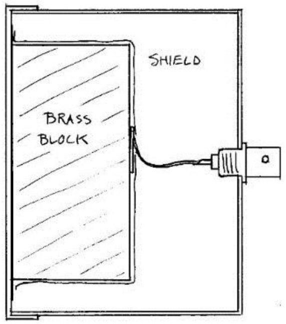
Description:

- Collect the charge or current of the beam itself with a beam stop
- Traditional Faraday cup
  - Magnetic field and vacuum to manage secondary electrons
- HCL Faraday cup
  - Brass beam stop wrapped in Kapton and surrounded by conductive sheet

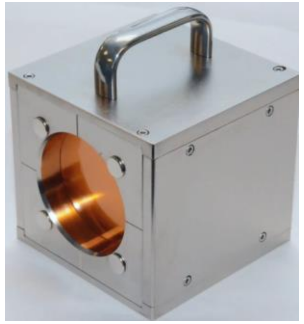
Examples:



Traditional Faraday cup, Verhey, 1979



Gottschalk, 2008



Pyramid Faraday cup and Multi-layer Faraday cup

Comments:

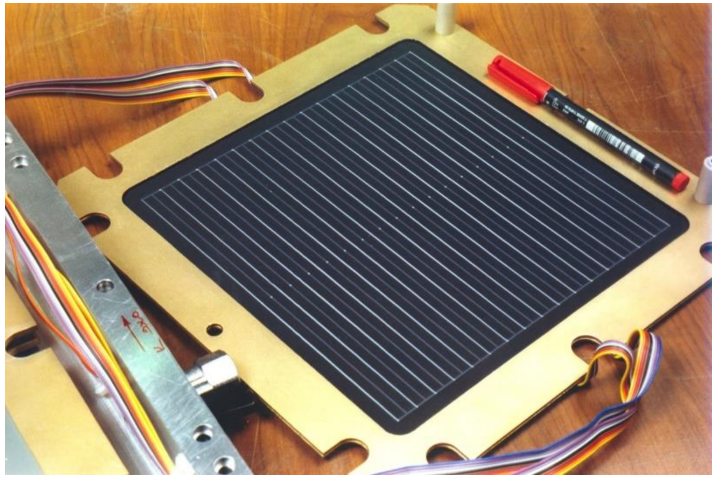
- Useful to check recombination in other devices
- Challenging with collimator/aperture scatter
- Challenging with C-ion beams due to nuclear interactions
- Traditional Faraday cup accuracy better than 1% with narrow proton beams
- HCL device response vs. traditional ~3% for protons with E> 50 MeV but much easier to use
- Gp vs. MU. Gp makes more sense for scanning nozzles because MU is not related to dose anymore

More comments on dosimetry

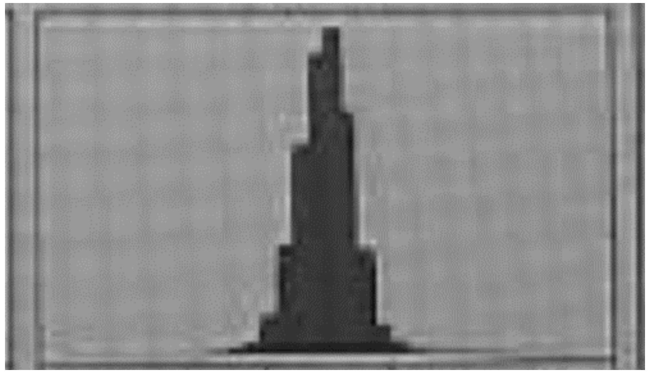
- Most instrumentation is built for photon therapy and adapted for particle therapy
  - Diodes vs. ion chamber
  - Pixel placement for a photon beam
  - Synchronizing acquisition with irradiation
- Avoid requiring the end user to calibrate the device
  - Fast consistency checks can be the exception
- Efficiency
  - Combining acquisitions, e.g. detector arrays
  - Rapid analysis
  - Lighter/smaller
  - Workflow
  - Cost
- Detector geometry
  - Thinner, smaller pixel spacing, wider area
- Accuracy
- Robustness
- Log file analysis to eliminate some measurements

Particle therapy machine instrumentation

- Wide area (integral) chambers for MU (or Gp), which monitor the number of protons during a treatment
  - The primary chamber stops the beam at a target MU
  - **Extra MU** delivered or collected after target is reached
- Segmented IC, strip IC, multi-wire IC, or scintillator screens are used for monitors in the beam line



Gottschalk, 2008



- Magnetic field probes check beam line magnets and nozzle scanning magnets
  - Can feedback to power supply to correct for hysteresis
  - Types
    - Hall probes, e.g. Pyramid Technical Consultants, Group 3
    - NMR

More comments on machine instrumentation

- Thin devices (for those devices in the path of the beam)
  - Preference to have devices constantly monitor the beam rather than retractable
- Compact geometric size
  - Sometimes we don’t have enough instrumentation due to available space, e.g. two sets of BPMs just before the gantry to align the beam with the axis
- Faster instrumentation and/or suitable for higher beam currents
  - Faster irradiation time
  - Improve task schedule frequency to check the beam more often
- Reliability
- Devices that provide feedback to control the beam in real time, e.g. beam position and sigma, rather than just interlock

“Hot” topics

- Prompt gamma
  - Detecting the depth of treatment by prompt gamma rays
- Proton radiography
  - Detecting residual range and position of transmitted protons
- FLASH
  - Very high dose rates ~100 Gy/sec
  - Synchrocylotrons at higher beam currents
- PET
- MRI protons
  - Dosimetry in a magnetic field
- Arc therapy
  - Cylindrical array of ion chambers
- Microdosimetry and biological response
  - Structure of dose deposition at the size of a cell (and DNA), lineal energy measurements
  - Dose in tissue or LET effects
- In-vivo dosimetry
  - Size, read-out, workflow, accuracy, patient comfort, access to target, and voltage concerns
  - Clinics should do more to check the actual dose in the patient e.g. TLD, diodes

Summary

- Ionization chambers are the most widely used instrument
  - 1D and 2D arrays are available
  - 3D, wide field, and high resolution still WIP
- Other instruments discussed
  - Scintillator screen + camera
  - Film
  - Faraday cup
  - Calorimeter
  - Magnetic field probes