# Basics of Light Ion Treatments: Depth Dose and Range

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# Objectives

1. Describe the underlying physical processes that shape the depth dose curves for different particles.

2. Describe various parameters associated with range.

3. Provide a survey of the sources of uncertainties in range within the patient and the magnitude of each.

# Assumptions

- This presentation assumes the audience is familiar with:
  - » ionization and stopping powers
  - » multiple Coulombic scattering
  - » bremstrahlung
  - » nuclear reactions
- The purpose of the presentation is to give the audience a "feel" for the magnitudes of the effects and how they influence light ion treatments.

# Rationale for Light Ion Treatments

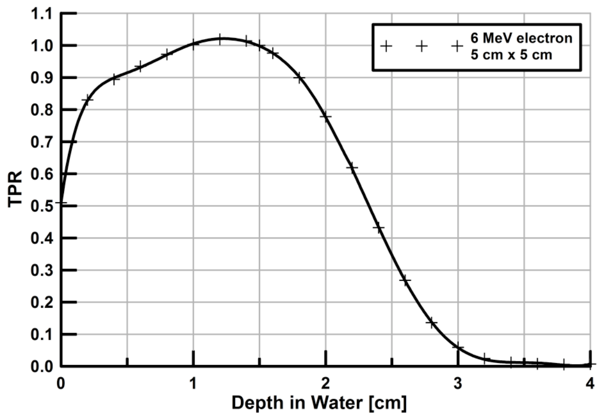
1. The dose delivered to non-target tissues relative to the dose delivered to target tissues is lower than for other radiation beams due to the depth dose distribution.

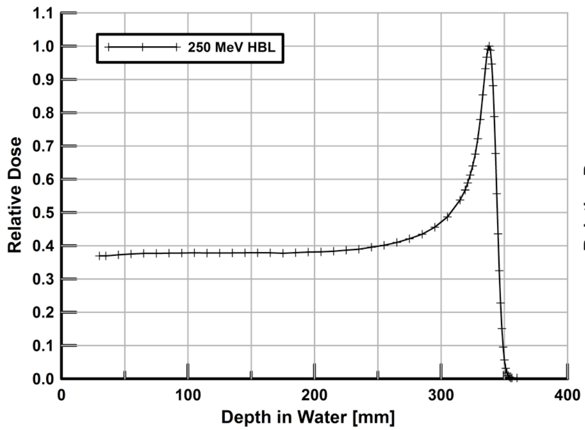
2. The lateral and distal dose gradients are higher than for other radiation beams enabling better splitting of the target and normal tissues.

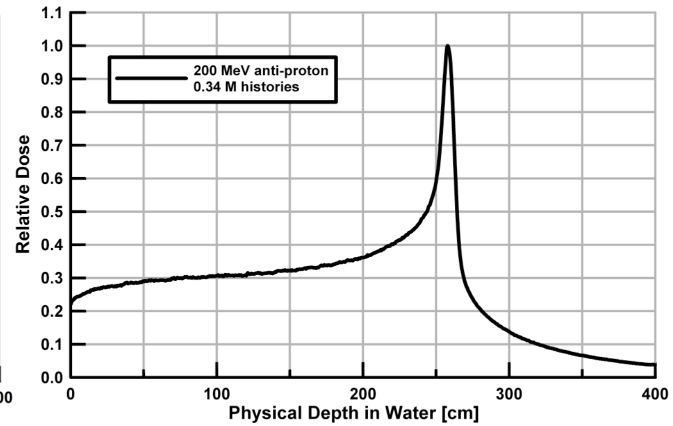
3. For ions heavier than helium, a differential RBE with depth results in a higher effective dose in target tissues compared to surrounding normal tissues.

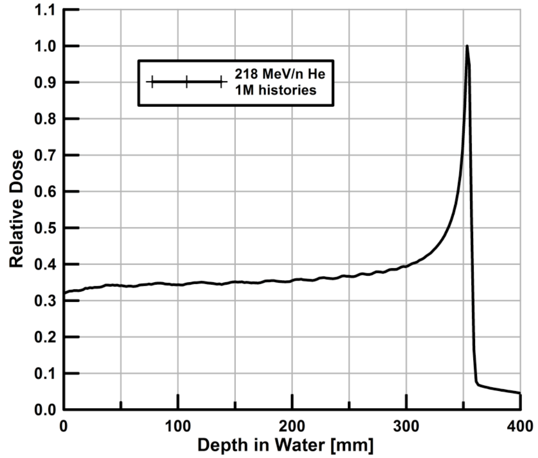
# Depth Dose Distributions - Non-modulated

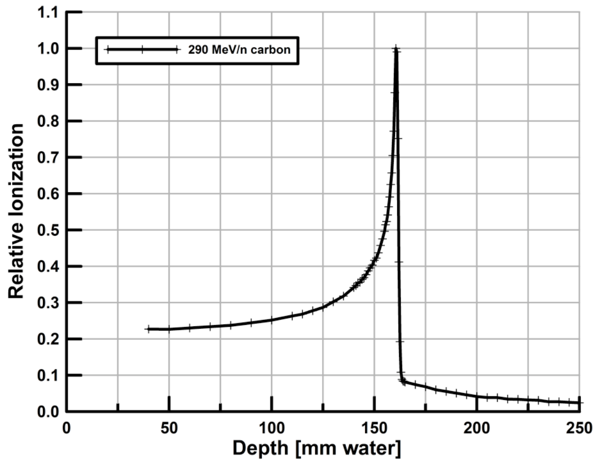
[all distributions normalized to maximum dose]

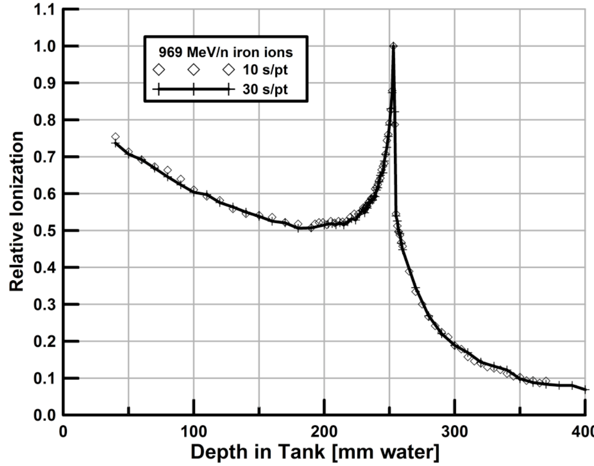
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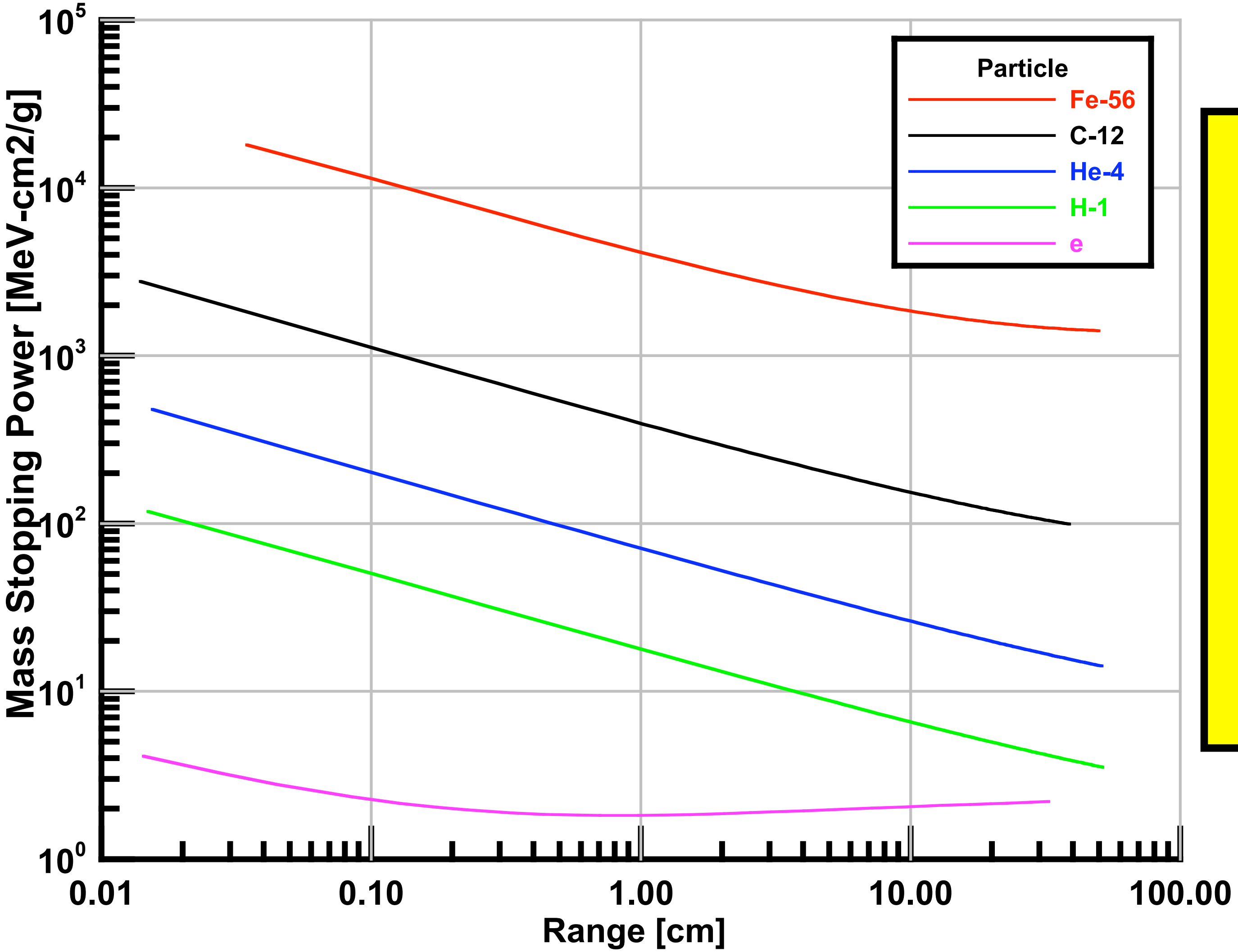
# Processes that Determine the Shape of the Depth Dose Distribution

| Particle | e | H-1 | anti-H | He-4 | C-12 | Fe-56 |
|---|---|---|---|---|---|---|
| increasing stopping power with decreasing energy | + | +++ | +++ | +++ | +++ | +++ |
| increasing obliqu ity fluence buildup | +++ | o | o | o | o | o |
| straggling from stochastic energy losses | + | + | + | + | + | + |
| straggling from multiple scattering paths | +++ | ++ | ++ | + | + | + |
| straggling from multiple heterogeneity paths | + | ++ | ++ | +++ | +++ | +++ |
| bremstrahlung | + | o | o | o | o | o |
| nozzle scatter | ++ | + | + | + | + | + |
| nuclear attenuation | o | + | + | + | + | ++ |
| buildup from secondary particles | ++ | + | + | + | ++ | +++ |
| tail from secondary part icles | o | + | +++ | + | ++ | +++ |

# Electronic Stopping Power Versus Energy and Particle



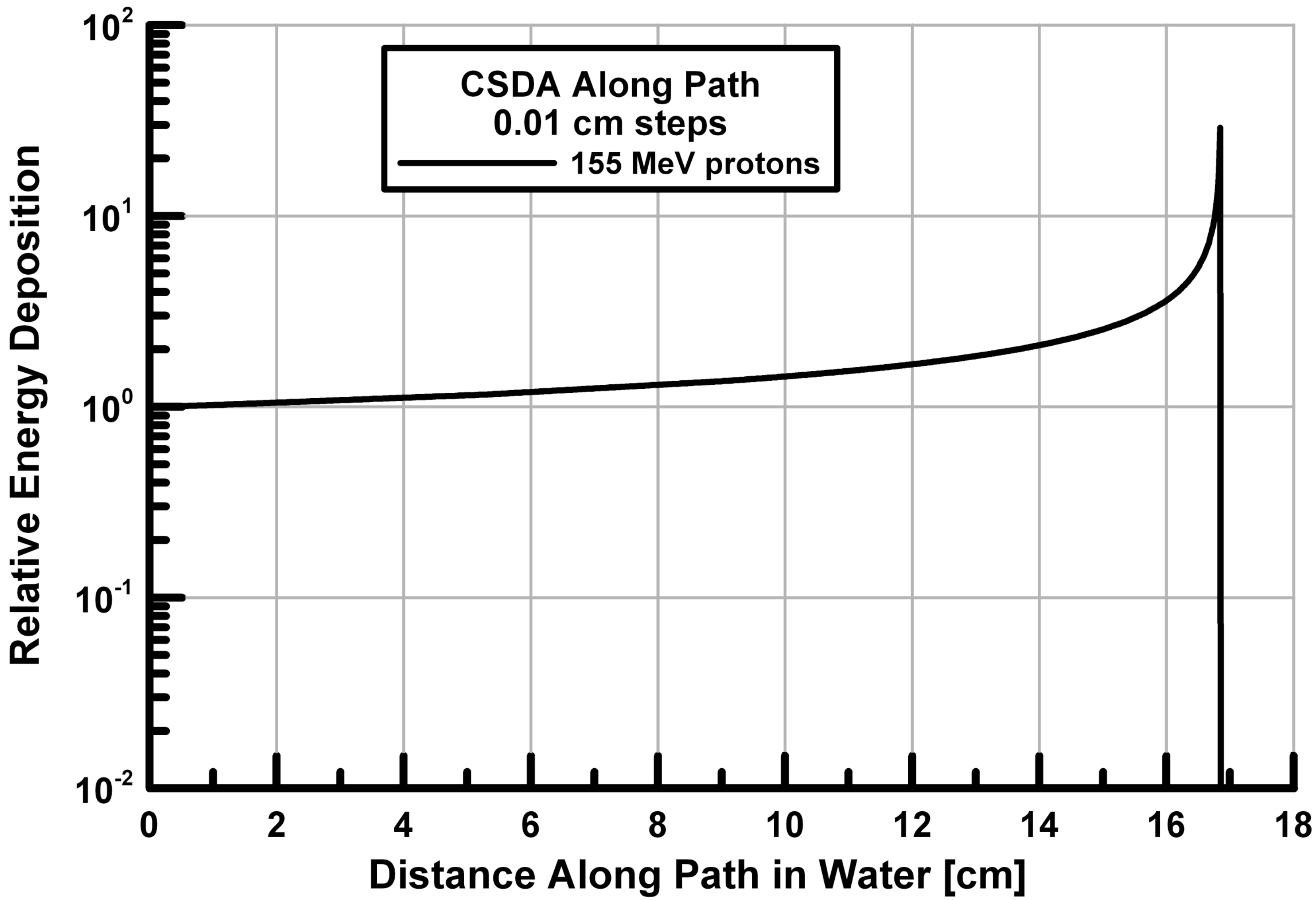

rule of thumb -

Stopping power of highest energy (clinically used) proton beam is twice that of electrons; i.e. 4 MeV/cm instead of 2 MeV/cm.

# Speed of Particles

| | electron | | | proton | | | carbon | | |
|---|---|---|---|---|---|---|---|---|---|
| Range [cm] | energy [MeV/cm] | speed [v/c] | S [MeV/cm] | energy [MeV/cm] | speed [v/c] | S [MeV/cm] | energy [MeV/cm] | speed [v/c] | S [MeV/cm] |
| 0.1 | 0.34 | 0.80 | 2.09 | 8.83 | 0.14 | 49.7 | 196 | 0.18 | 1119 |
| 0.3 | 0.74 | 0.91 | 1.92 | 16.3 | 0.18 | 30.5 | 364 | 0.25 | 677 |
| 1.0 | 2.04 | 0.98 | 1.82 | 31.8 | 0.25 | 17.8 | 711 | 0.34 | 395 |
| 3.0 | 5.90 | 1.00 | 1.90 | 58.6 | 0.34 | 10.9 | 1314 | 0.44 | 247 |
| 10.0 | 21.8 | 1.00 | 2.05 | 115.1 | 0.45 | 6.56 | 2621 | 0.58 | 154 |
| 30.0 | 88.8 | 1.00 | 2.19 | 216.6 | 0.58 | 4.24 | 5092 | 0.73 | 107 |

# Proton Depth Dose Curve - Ionization Loss Only Along Path

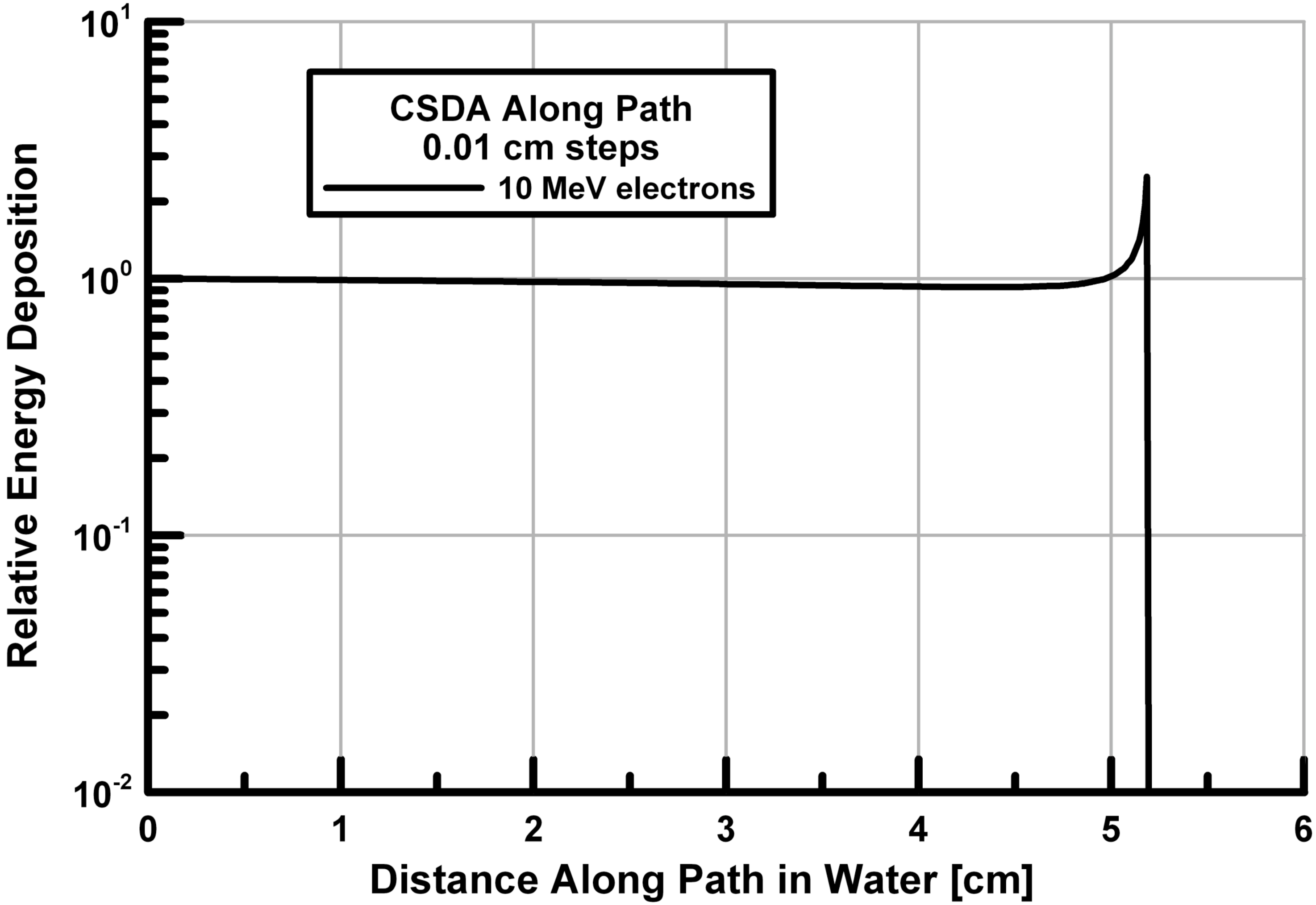



max S / ent S ≈ 185:1

CSDA peak/entrance ≈ 29:1

measured peak/entrance ≈ 4:1

# Electron Depth Dose Curve - Ionization Loss Only Along Path

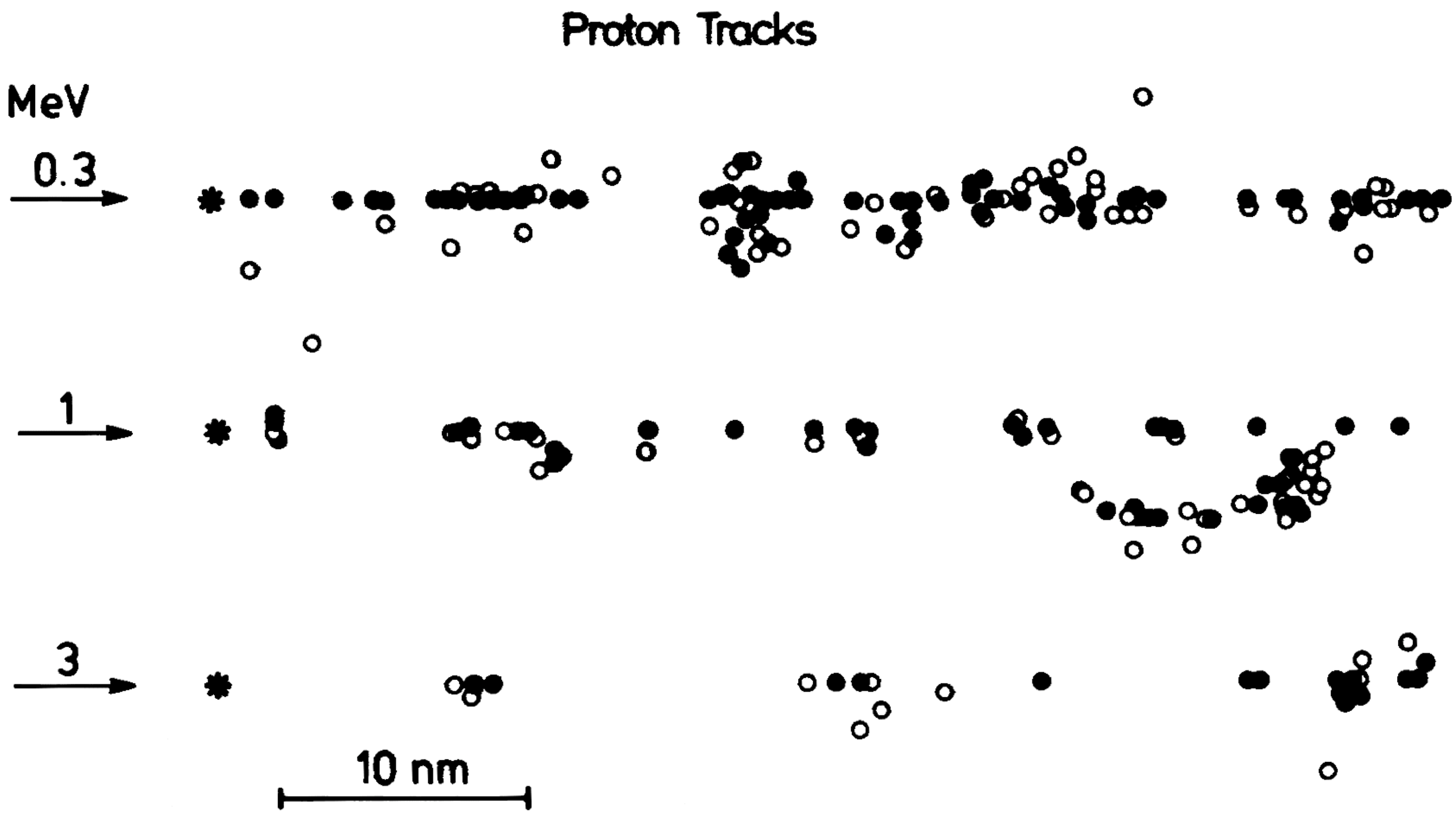



max S / ent S ≈ 27:1

CSDA peak/entrance ≈ 2.5:1

measured peak/entrance ≈ 1.1:1

# Straggling from Stochastic Energy Losses



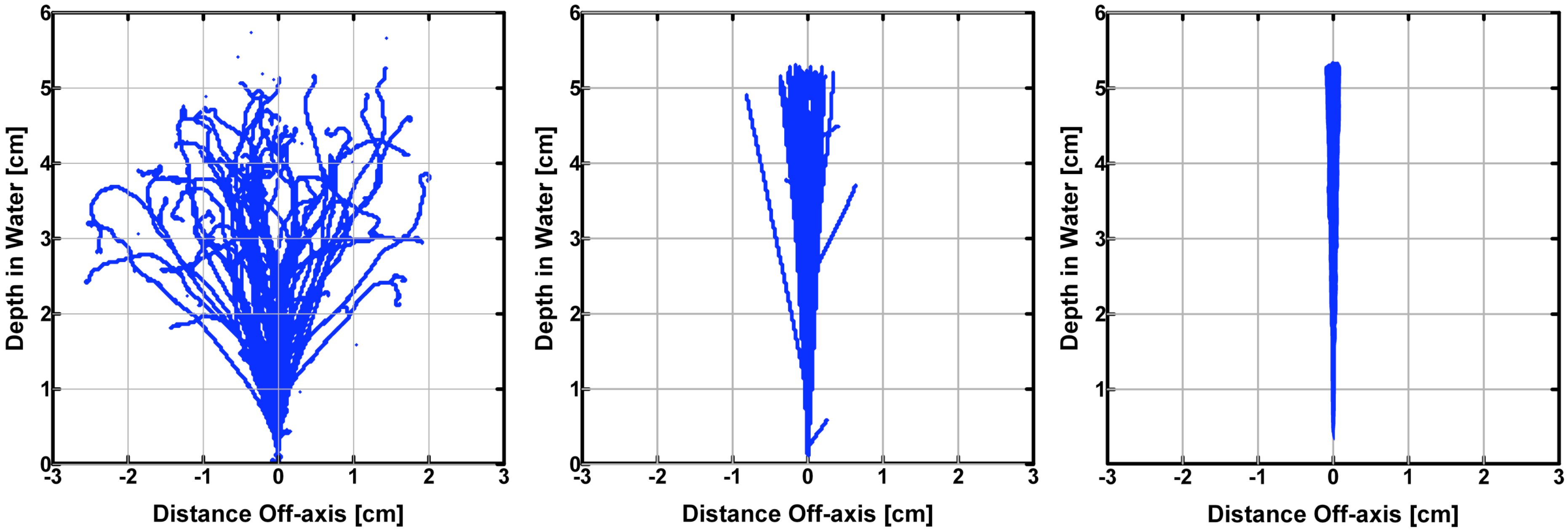

ICRU 36 / Paretzke 1980

# Straggling from Multiple Particle Paths

10 MeV electrons
50 histories

80 MeV protons
50 histories

150 MeV/n carbon ions
500 histories




MCNPX simulations

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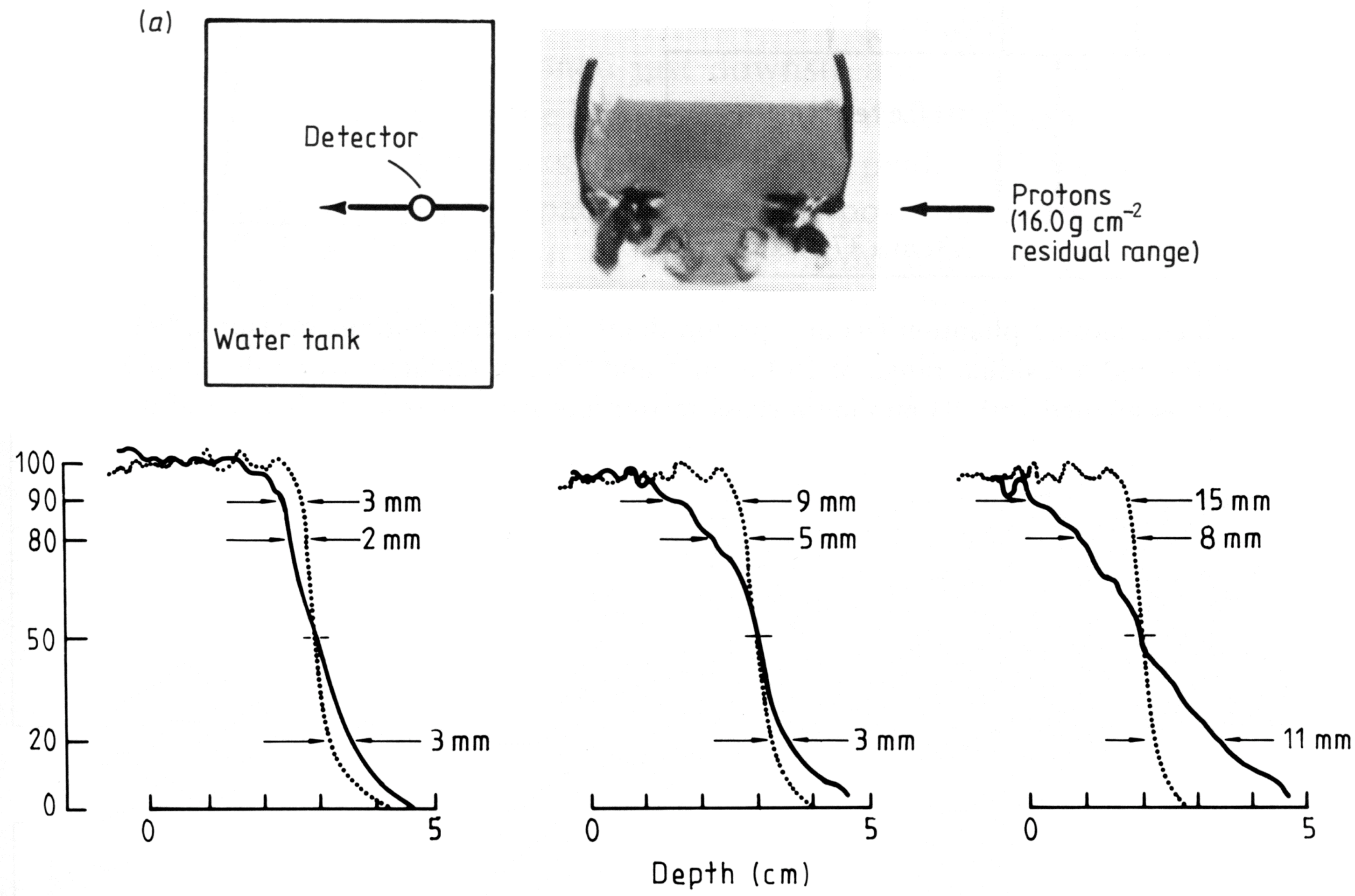
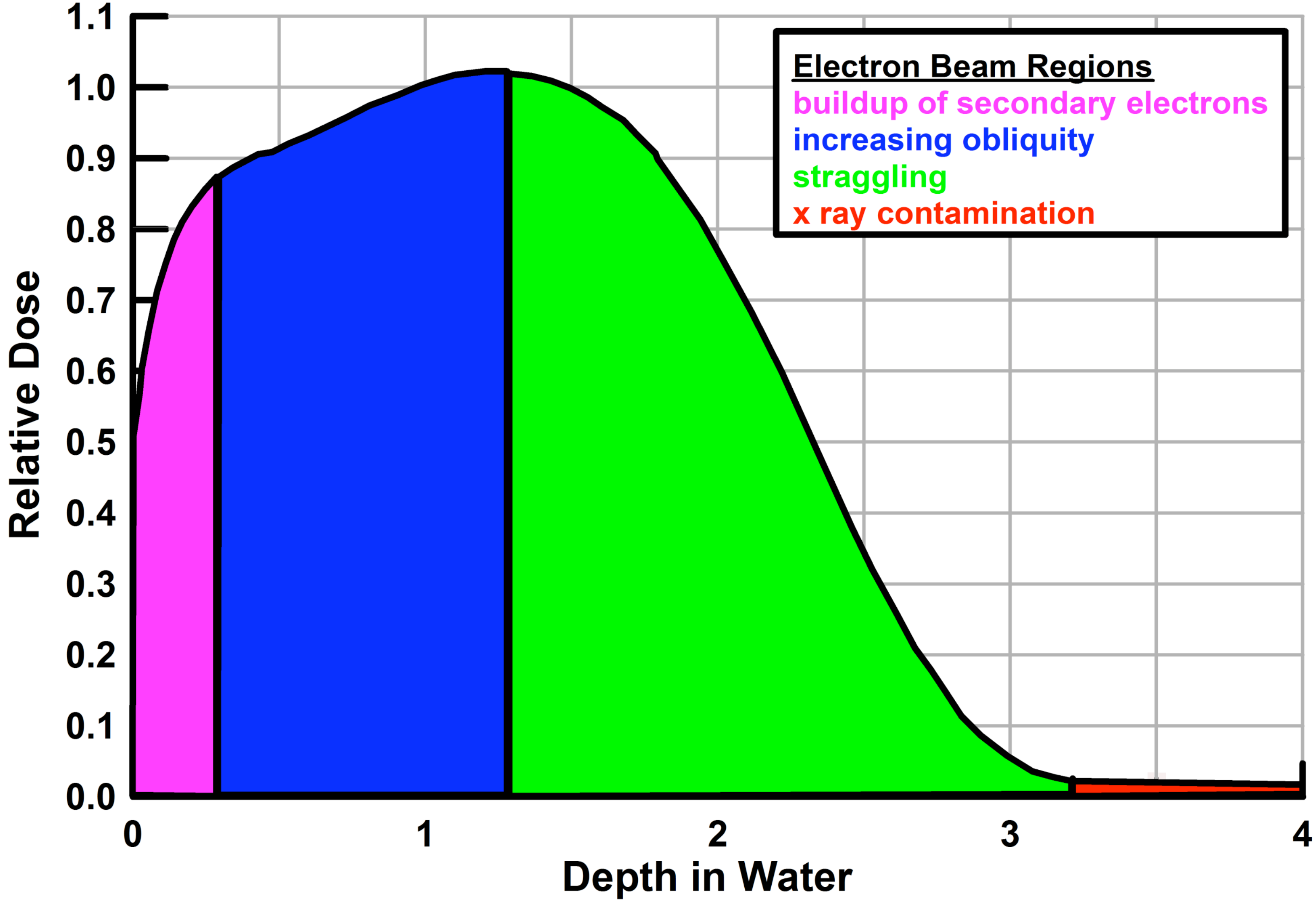
# Straggling from Multiple Paths Through Heterogeneities




Urie et al. 1983

# Electron Depth Dose Curve - Multiple Processes

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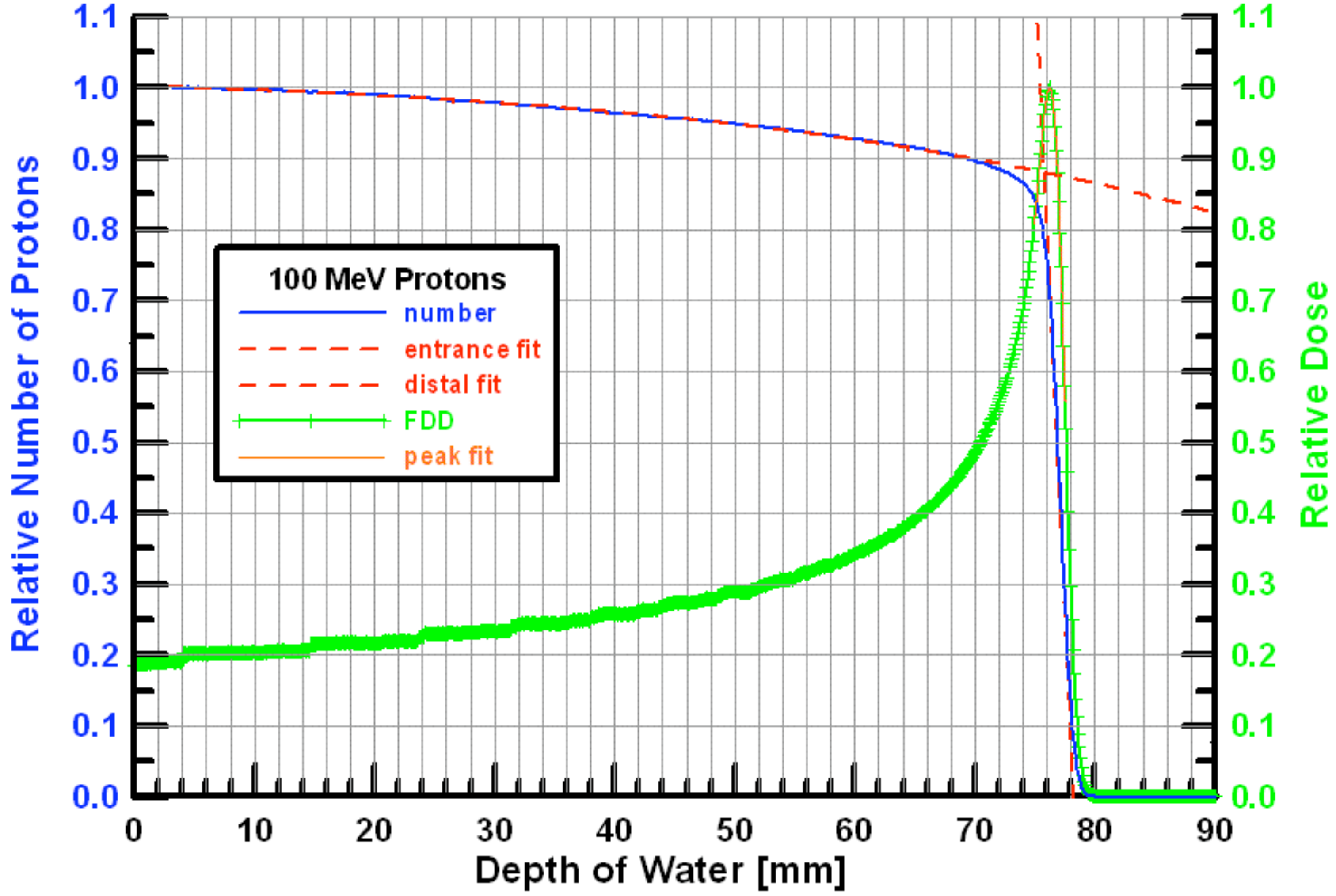
# Depth Number Distribution / Depth Dose Distribution

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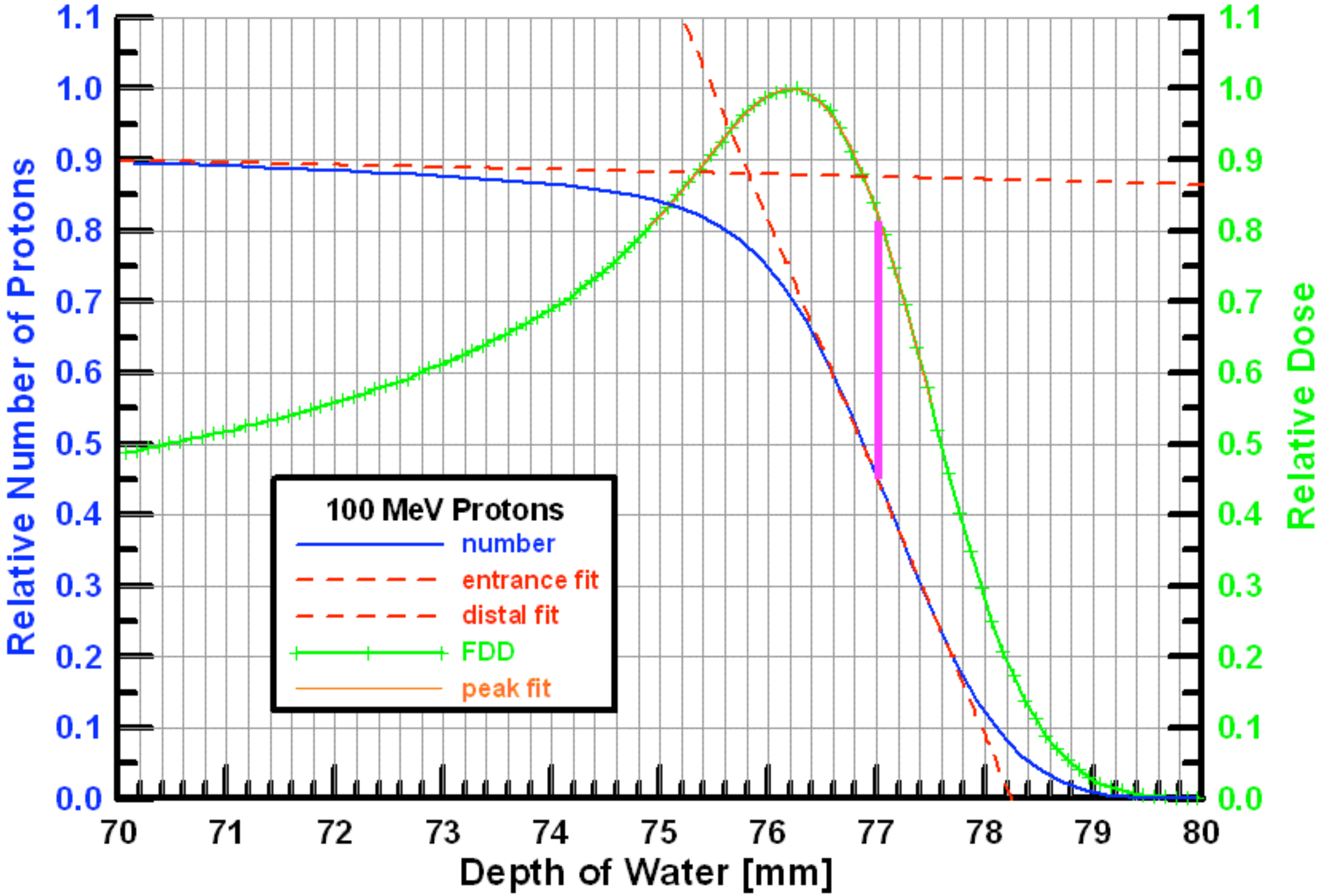
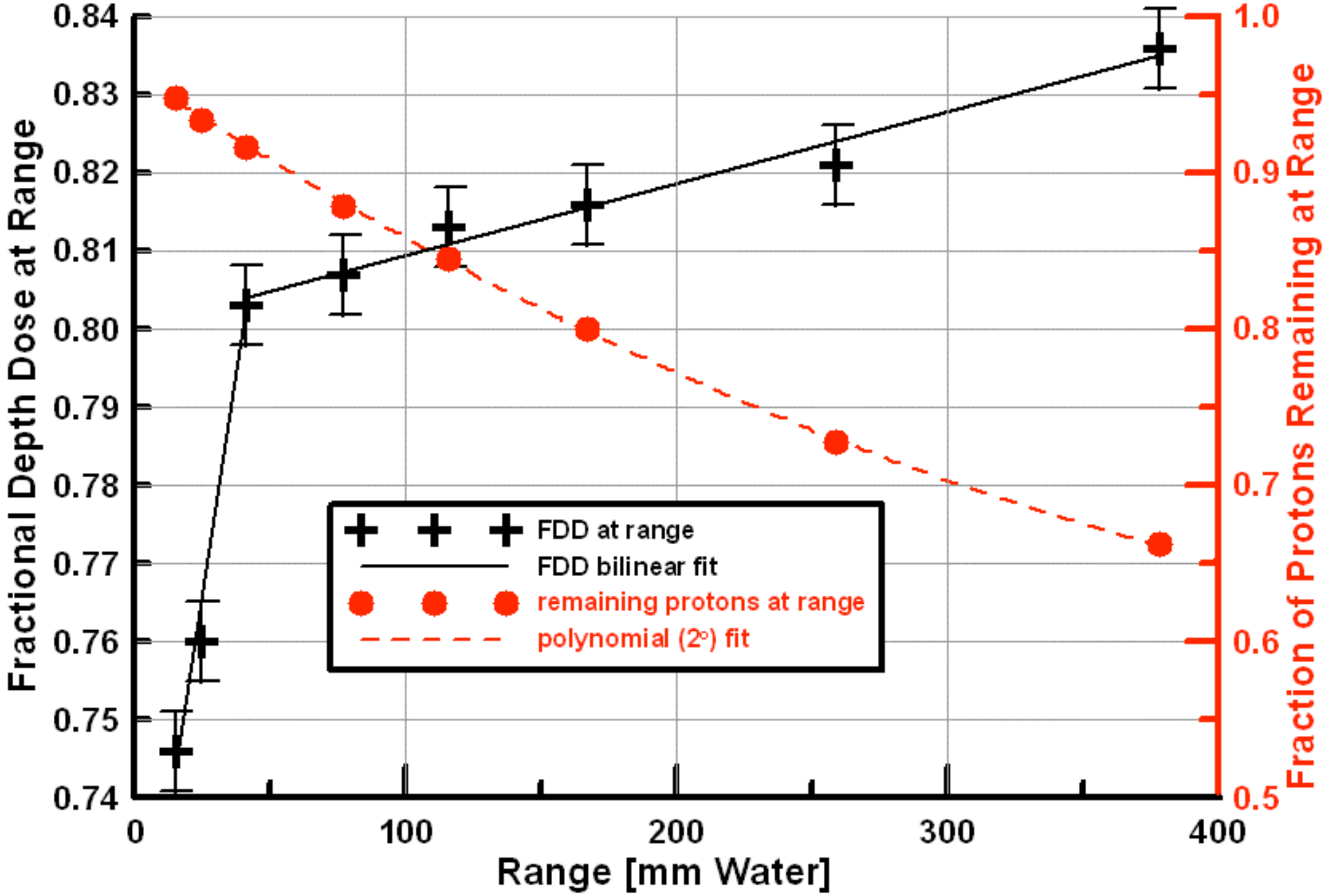
# End of Range / Peak Region Magnified



# Range of Protons in Non-modulated Beam
# Number of Protons Lost




rule of thumb -

for every cm of depth, ≈ 1% of protons undergo nuclear reaction

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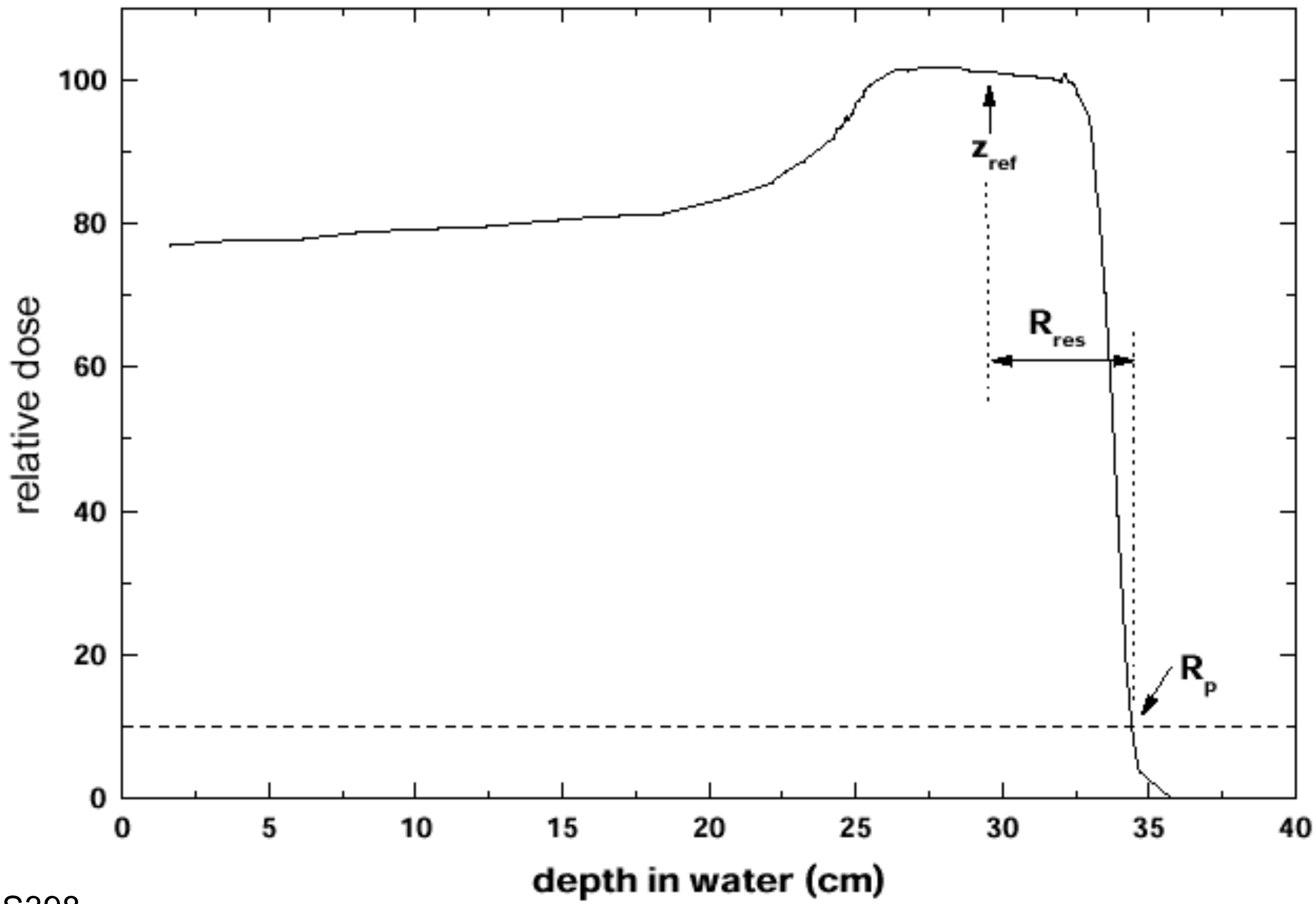
# Residual Range for Dosimetric Purposes - Modulated or Non-modulated




IAEA TRS398

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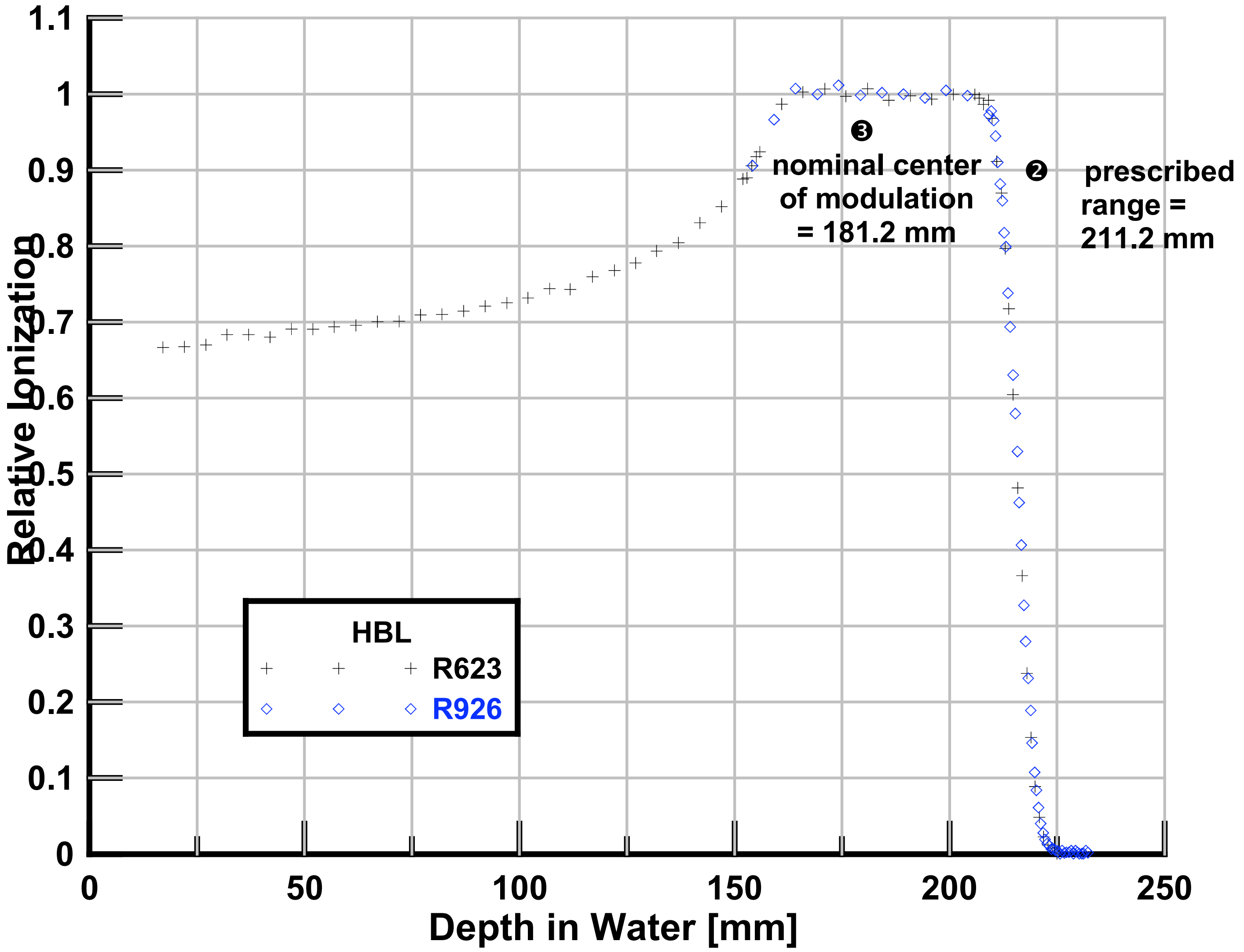
# Prescribed Range of Modulated Beam



# Uncertainties in Measuring Standard Range in Water

| | |
|---|---|
| • water tank window | ± 0.008 mm |
| • parallel plate chamber waterproof lid | ± 0.036 mm |
| • parallel plate chamber front wall | ± 0.044 mm |
| • setting of reference depth with spacer | ± 0.3 mm |
| • calibration of water tank scanning mechanism | ± 0.23 mm |
| • backlash in water tank scanning mechanism | ± 0.3 mm |
| • rigidity and tilt of ion chamber mount on scanning mechanism | ± 0.3 mm |
| • total range uncertainty | ± 0.571 mm |

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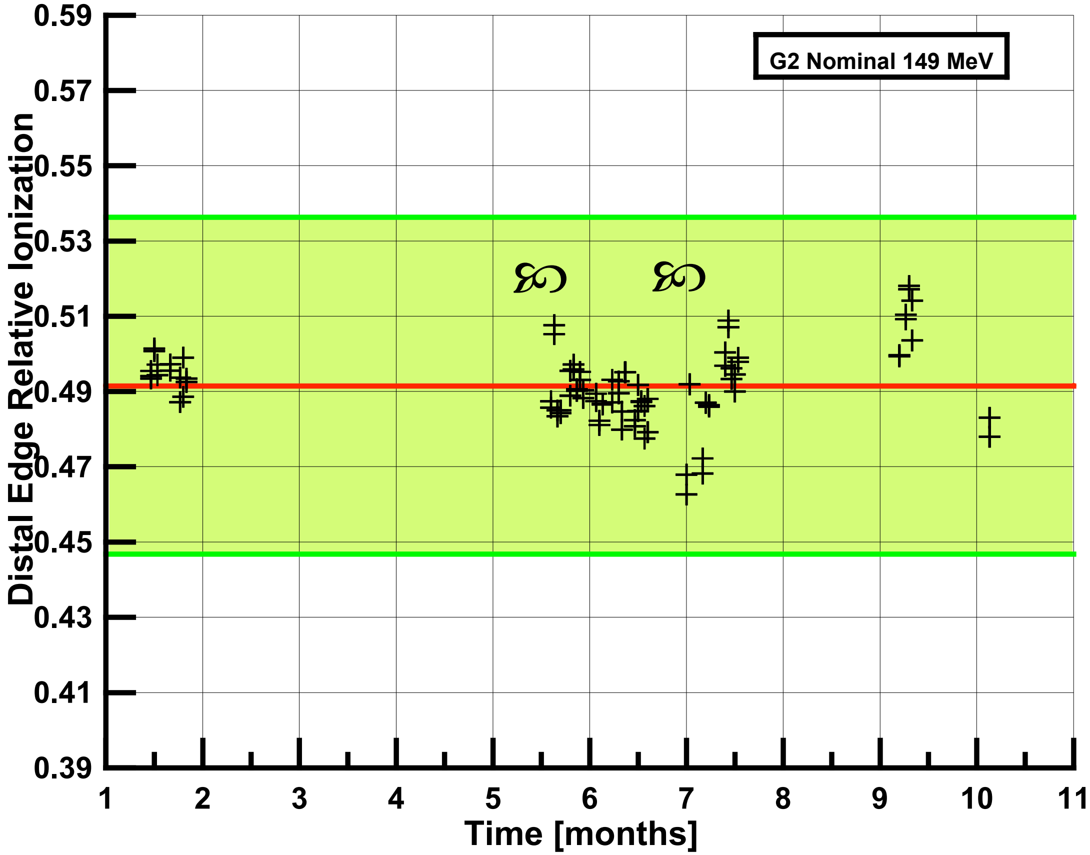
# Uncertainties in Delivering Correct Energy or Range Each Treatment




- accelerator beam energy
- variable rangeshifters
- scattering foils

- total of ± 0.1 to ± 1.0 mm depending upon method used by accelerator for verification

# Uncertainties in Stopping Powers

- range in water
  - » ICRU 49 (1993) versus Janni (1982)
    ≈ 4 mm different at 250 MeV (≈1%)
  - » several studies have shown the I-value is closer to the 81.77 eV used by Janni than the 75.0 eV used by ICRU 49

- Relative Linear Stopping Power for protons
  - » Moyers et al. (1992): tissue substitutes and ancillary equipment - calculated/literature versus measured 0.4 - 3.0%
  - » Schneider et al. (1996): tissues -
    calculated/literature versus measured 1.6%
  - » small energy dependence (ignored in most TPSs)
    ≤ ±1% for z<13 between 30 and 250 MeV

# Uncertainties in CT Numbers

| cause | uncertainty | mitigation |
|---|---|---|
| scanner calibration for standard conditions | ± 0.3% day -to-day | patient specific scaling |
| kVp, filter, and FOV selection | ± 2.0% PMMA, PC<br>> ± 2.0% bone | use only calibrated conditions |
| volume scanned | ± 2.5% | patient specific scalin g |
| position in scan | ± 1.5% water<br>> ± 3.0 % bone | portal / region specific scaling |
| alignment devices* artifacts | variable | substitution |
| implant artifacts | up to 80% | MVXCT or substitution |
| contrast agents (not present during tx ) | 8% | second CT or substitution |
| metal implants | KV - > max #<br>MV - volume dependent | z ≤ 22 - MVXCT<br>z > 22 - substitution |

*tabletops, fixation frames, biteblocks, fiducial screws, etc.

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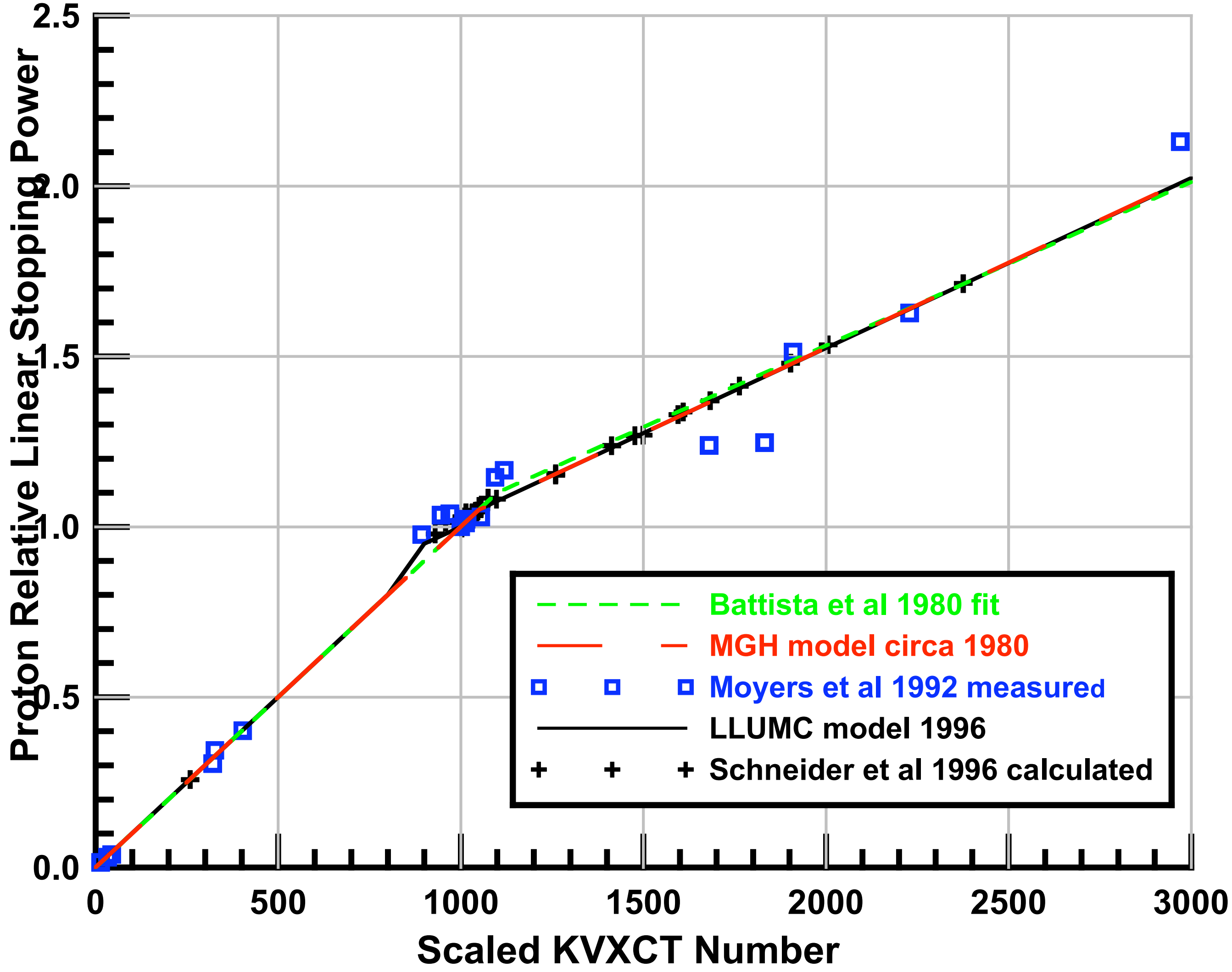
# Uncertainties in Converting CT # to RLSP

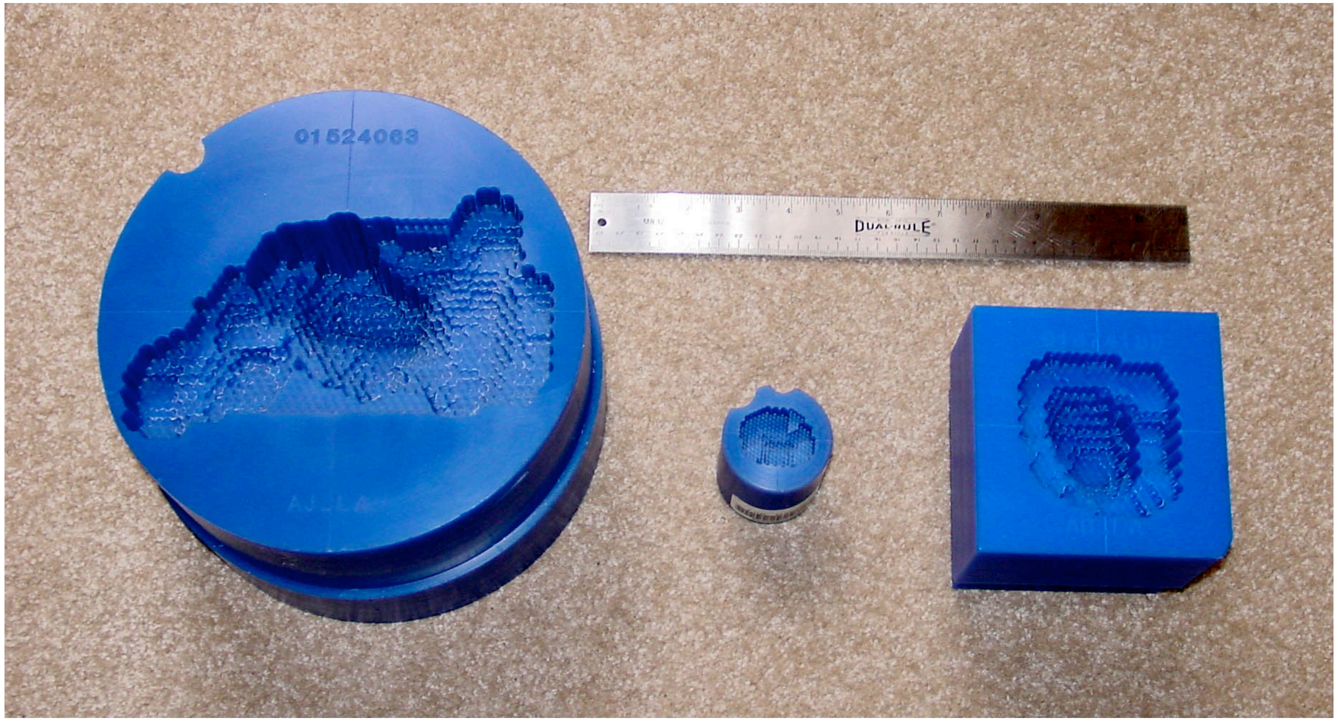



for std. tissues, CT # to RLSP ≤ 1.5%

for some other materials, CT # to RLSP >> 1.5%

# Uncertainties in Bolus Water Equivalent Thickness

| | |
|---|---|
| ● bolus material density (with lot sampling) | ± 0.5% → 0.4 mm |
| ● bolus manufacturing | ± 0.3 mm |
| ● bolus voids (with CT sampling) and/or contamination | ± 0.5 mm |
| » will not be everywhere | |
| ● total bolus: $((0.4 + 0.3)^2 + 0.5^2)^{0.5}$ | ± 0.9 mm |

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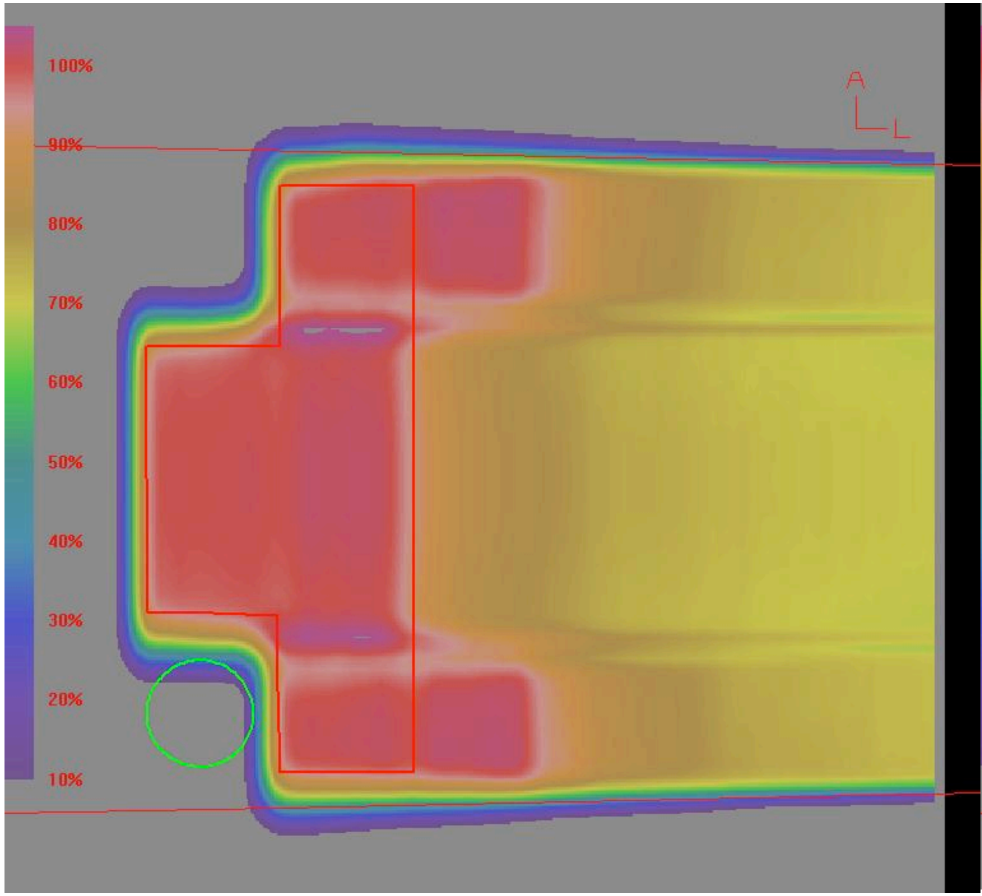
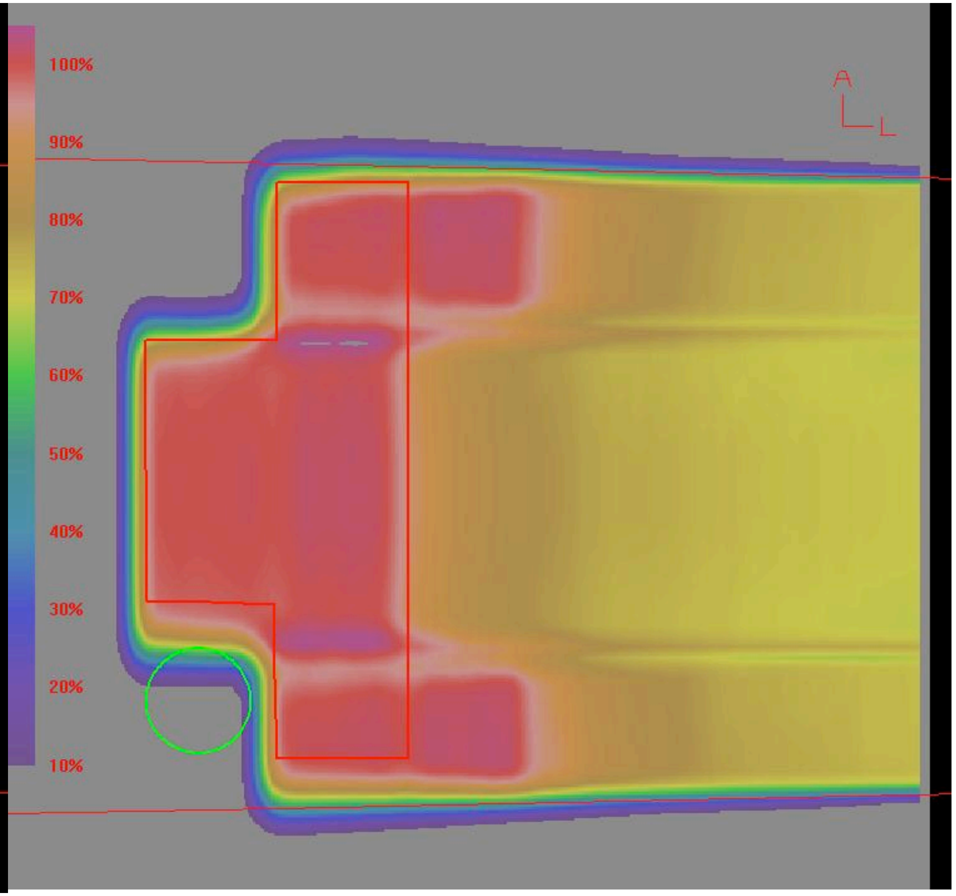
# Bolus Position with Respect to Patient

## (Lateral Set-up Uncertainty Effect on Range)




nominal patient/bolus alignment




3 mm patient/bolus miss-alignment

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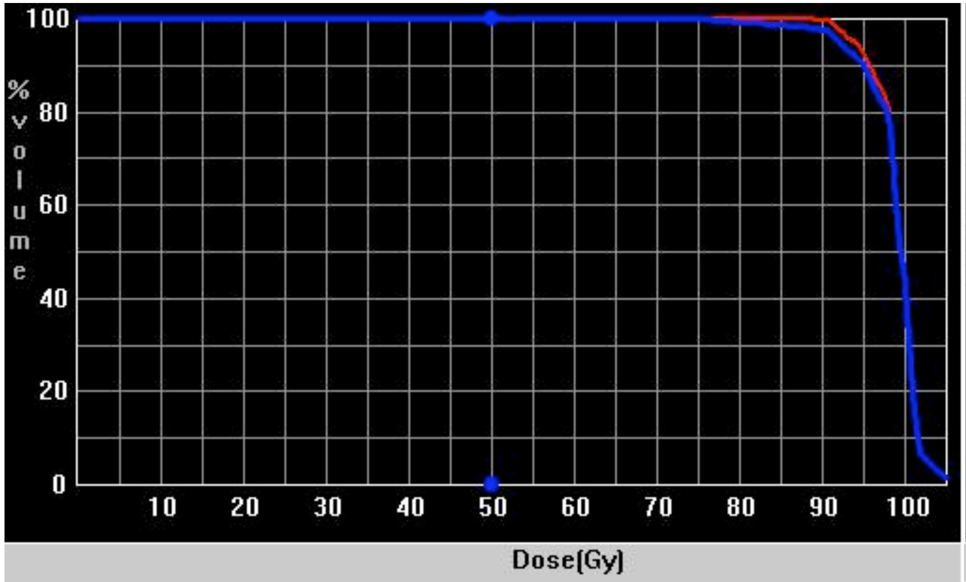
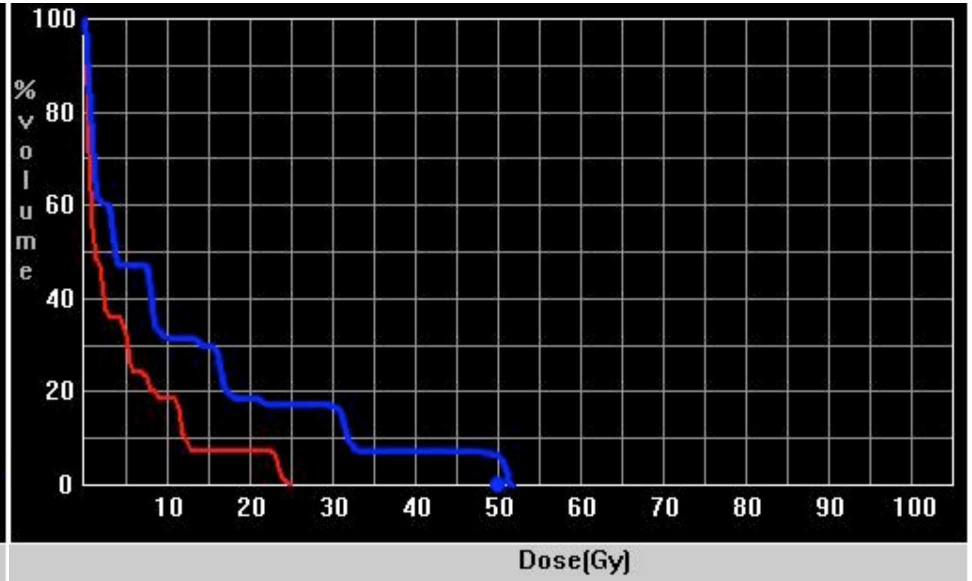
# Bolus Position with Respect to Patient
## (Lateral Set-up Uncertainty Effect on Range)




target DVH




normal tissue DVH

# Summary of Typical Penetration Uncertainties

| | |
|---|---|
| standard energy (or range) | ± 0.6 mm |
| energy (or range) reproducibility | ± 1.0 mm |
| bolus WET | ± 0.9 mm |
| alignment devices* | ± 1.0 mm |
| CT# accuracy (after scaling) | ± 2.5% |
| RLSP of tissues and devices | ± 1.6% |
| energy dependence of RLSP | ± 1.0% |
| CT# to RLSP (soft tissues only) | ± 1.5% |
| bolus position relative to patient | variable |
| heterogeneity straggling | variable |
| patient motion | variable |

Range Uncert.
2 mm

CT Uncert.
3.5%

Planning
bolus expansion
multiple angles

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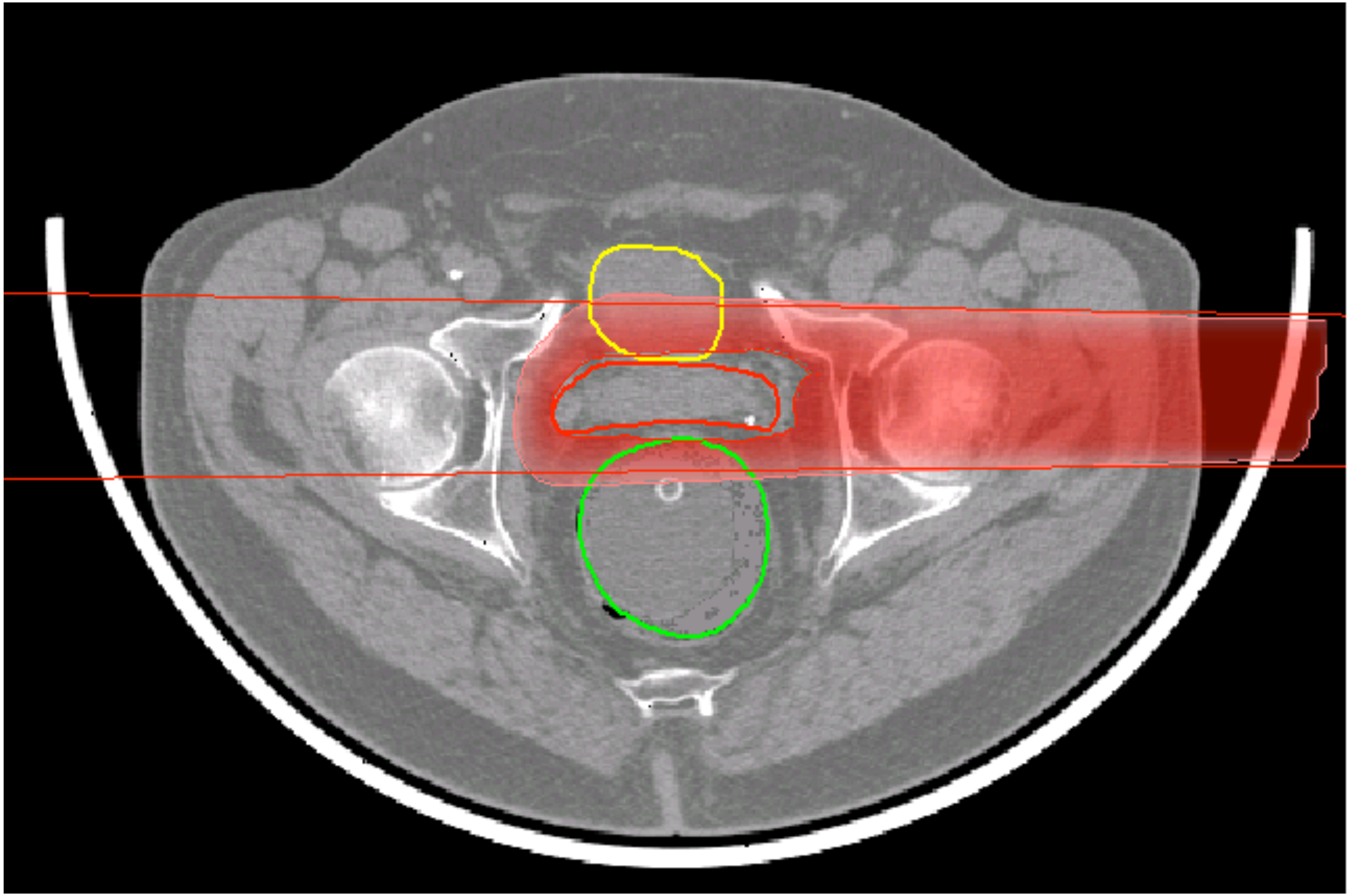
# Desired Distribution

[90% - 10% dose shown in red]



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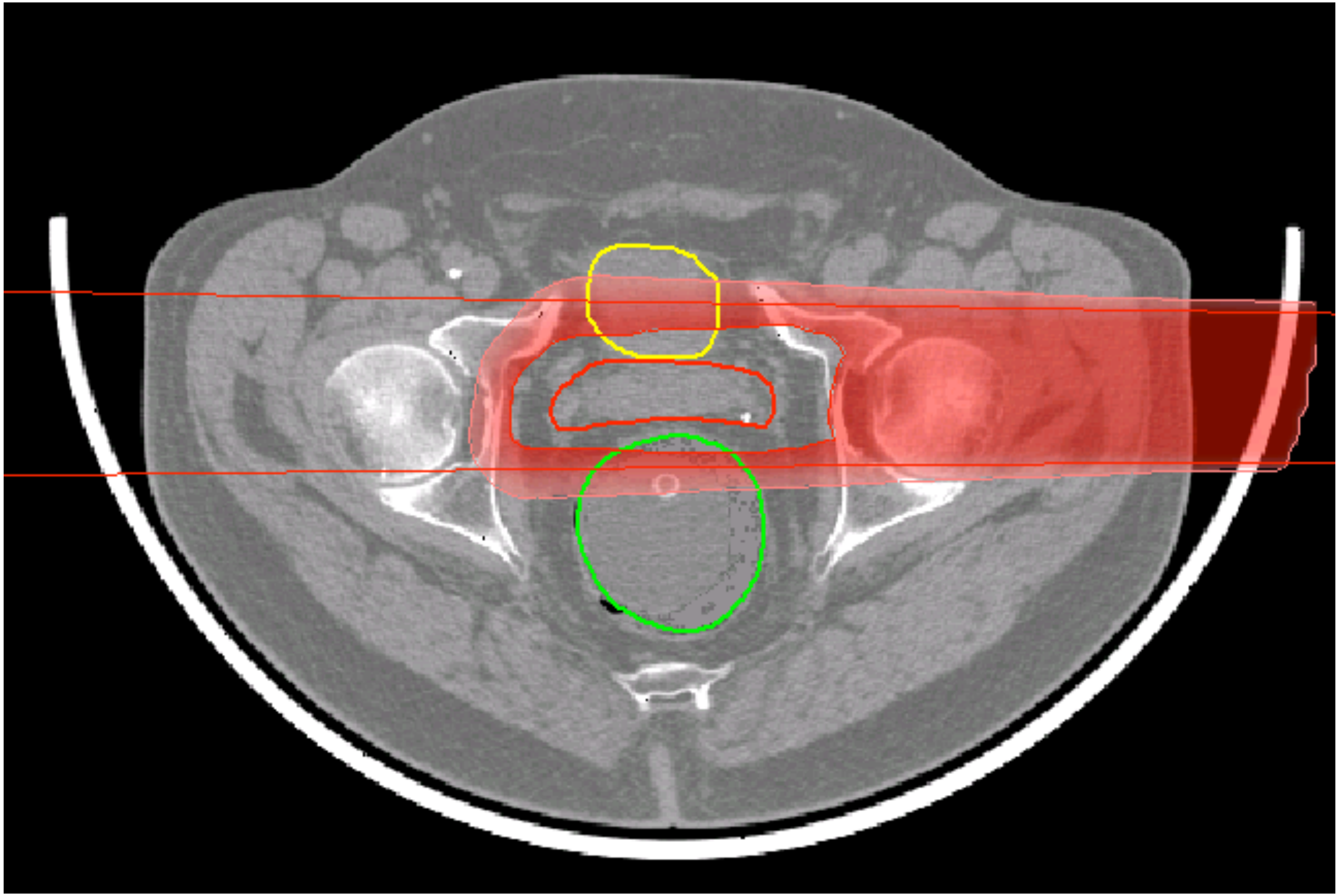
# Planned Nominal Distribution

[90% - 10% dose shown in red]



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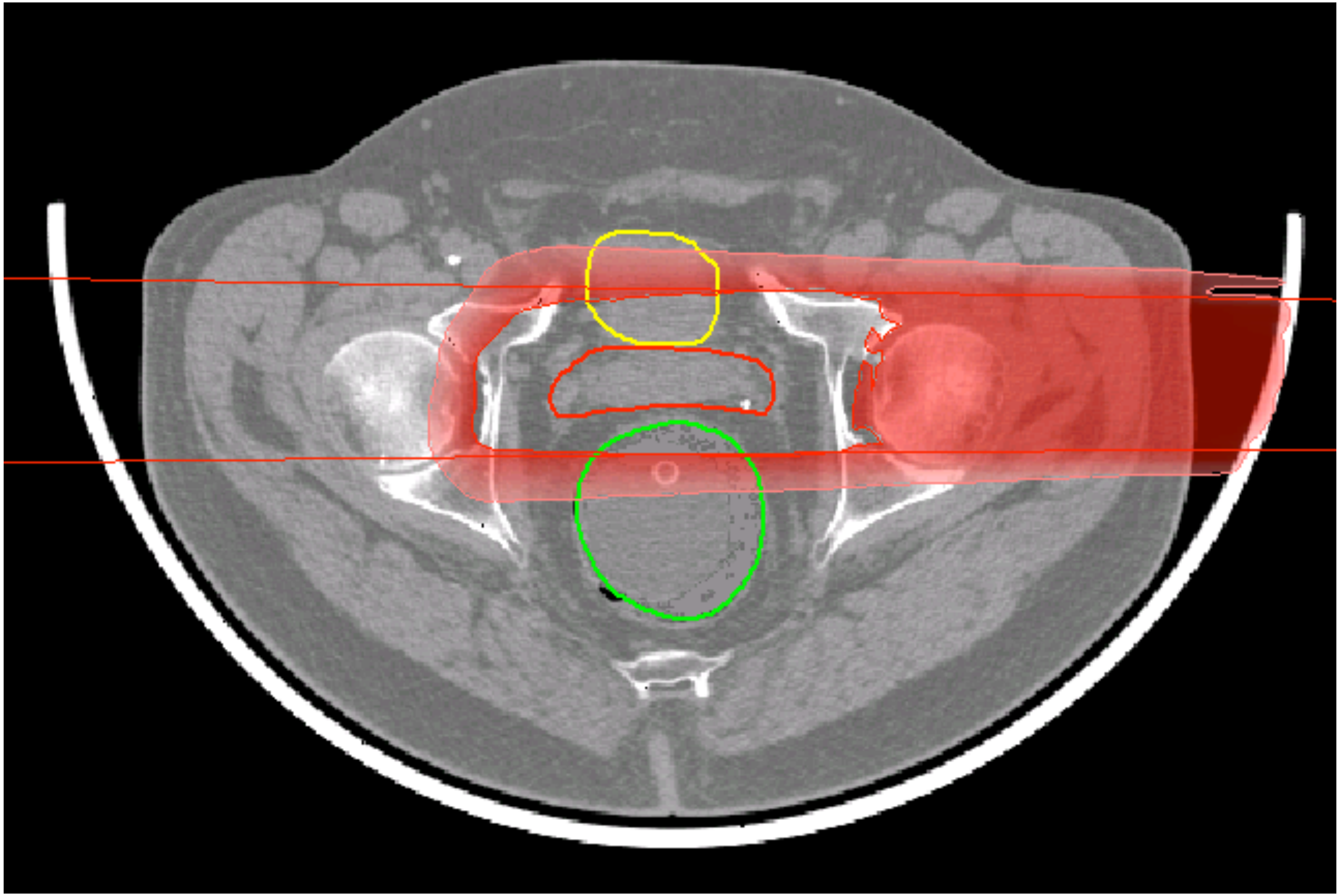
# Might Get These Doses at These Locations

[90% - 10% dose shown in red]



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# Summary

- The shape of light ion beam depth dose distributions is determined by multiple processes.
- The term range can have different meanings.
- The depth of penetration of a light ion beam in a patient is uncertain due to several factors. Allowances must be made to account for these factors.