Primary Beam Dose Dependence on Distance from Cargo and People Scanners

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PNNL-SA-61836
Work supported by the U.S. Department of Energy under
Contract No. DE-AC05-76RLO 1830

Paper MPM-B.4, Health Physics Society Annual Meeting
Pittsburgh, Pennsylvania, 14 July 2008

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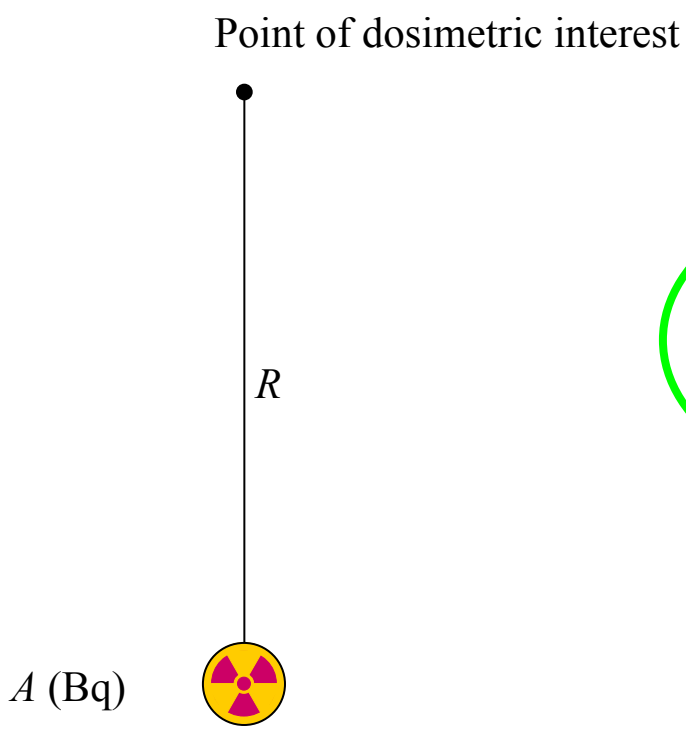
Introduction

- ANSI N43.16 is drafting a radiation safety standard for cargo and people scanners
- Sources
  - Radioactive Isotope Sources
    - ^{137}Cs, ^{60}Co
    - "Source strength" ΓA (Gy/s m^2)
  - Electrical sources
    - x-ray generator, accelerator
    - "Source strength" or output (Gy/s m^2)

Introduction -- 2

- Scanners present unique irradiation geometries
  - a 2-D fan-beam collimated point source that translates in 1 dimension
  - a stationary 2-D fan-beam collimated point source with cargo or people translating in 1 dimension
  - a 1-D “flying spot” (pencil beam) scanning in 2 dimensions
- How does the dose per scan depend on distance from the scanner?
- Is dose (or air kerma) $\propto$ 1/*distance* or 1/*distance*^{2}?

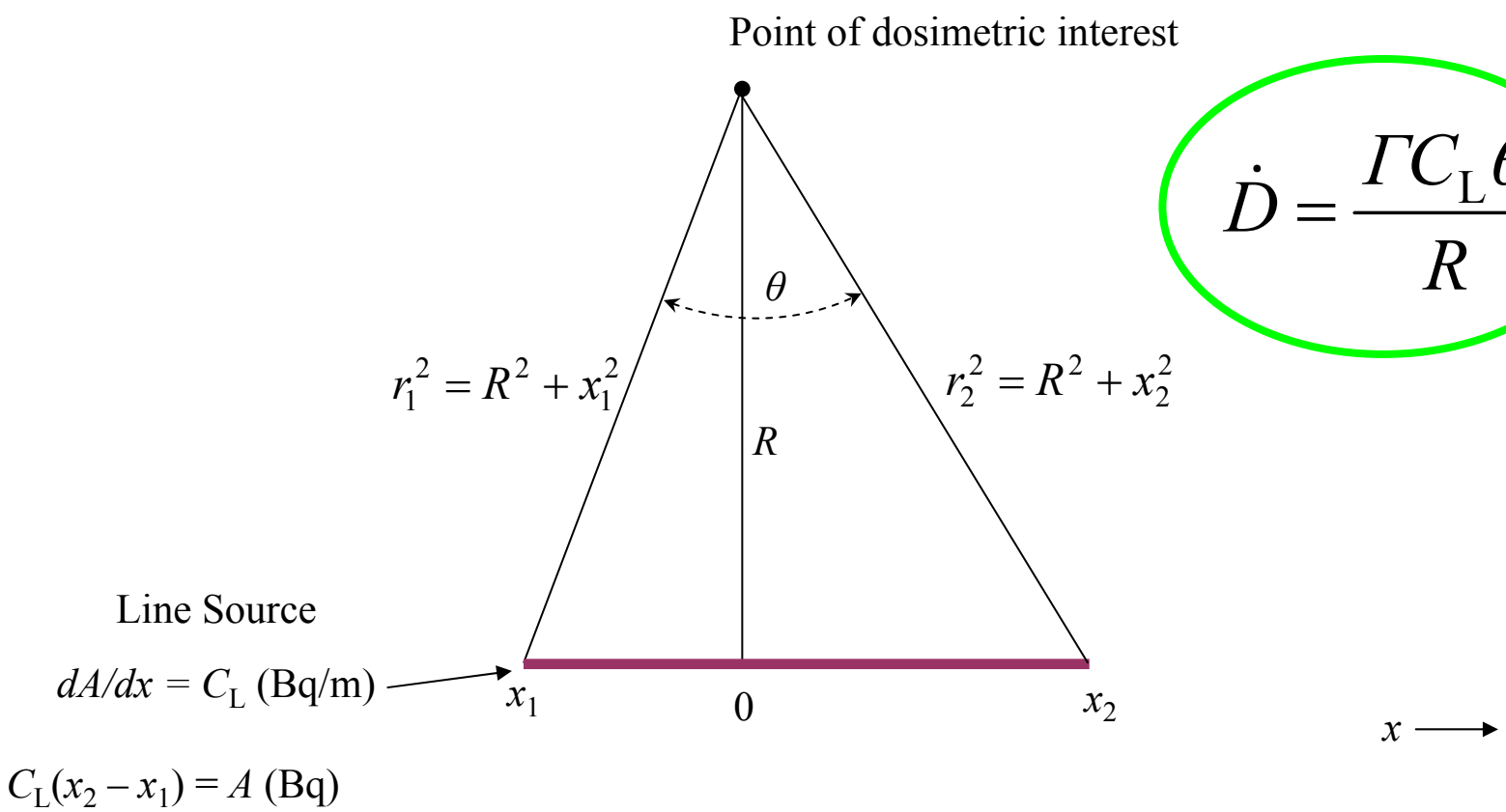
Stationary Point Source



$$\dot{D} = \frac{\Gamma A}{R^2}$$

Dose rate from a point source has "$1/R^2$" (inverse square) dependence on R.

Long Line Source

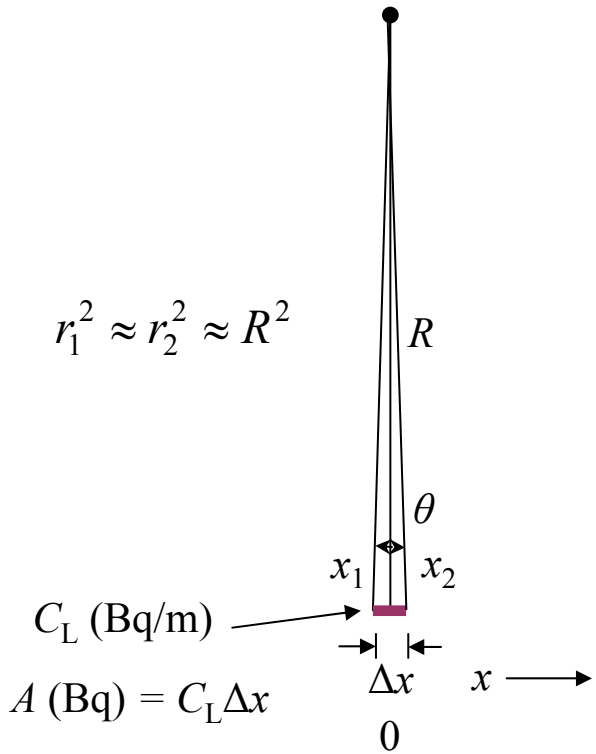


$$\dot{D} = \frac{\Gamma C_L \theta}{R}$$

Dose rate from a long line approaches "1/R" dependence for $(x_2 - x_1) >> R$.

see, e.g., Cember 3rd ed. p. 421

Short Line Source: Small Angle



$$\dot{D} \approx \frac{\Gamma A}{R^2}$$

Dose rate from a short ($\Delta x << R$) line has essentially the "$1/R^2$" (inverse square) dependence of a point source.

Line Source: Dose Rate and Dose

- Dose is linearly dependent on exposure time:

$$D = \frac{\Gamma C_{\mathrm{L}} \theta}{R} \Delta t$$

Unshielded Point Source Moving at Uniform Velocity

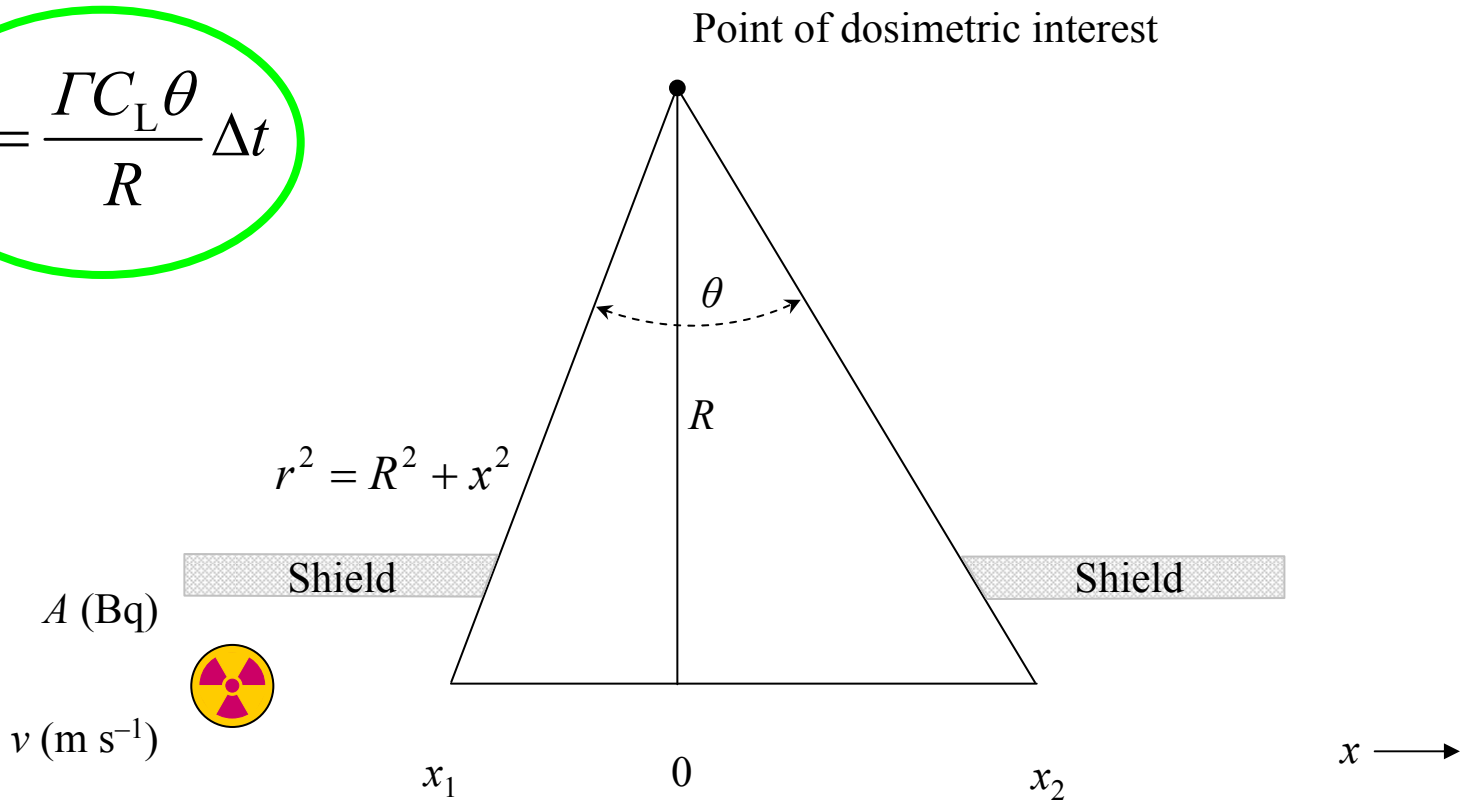
- Assume source is off, shuttered or completely shielded at each end of travel
- Start by considering time dependence of dose rate
- Finish by calculating dose

Unshielded Point Source Moving at Uniform Velocity

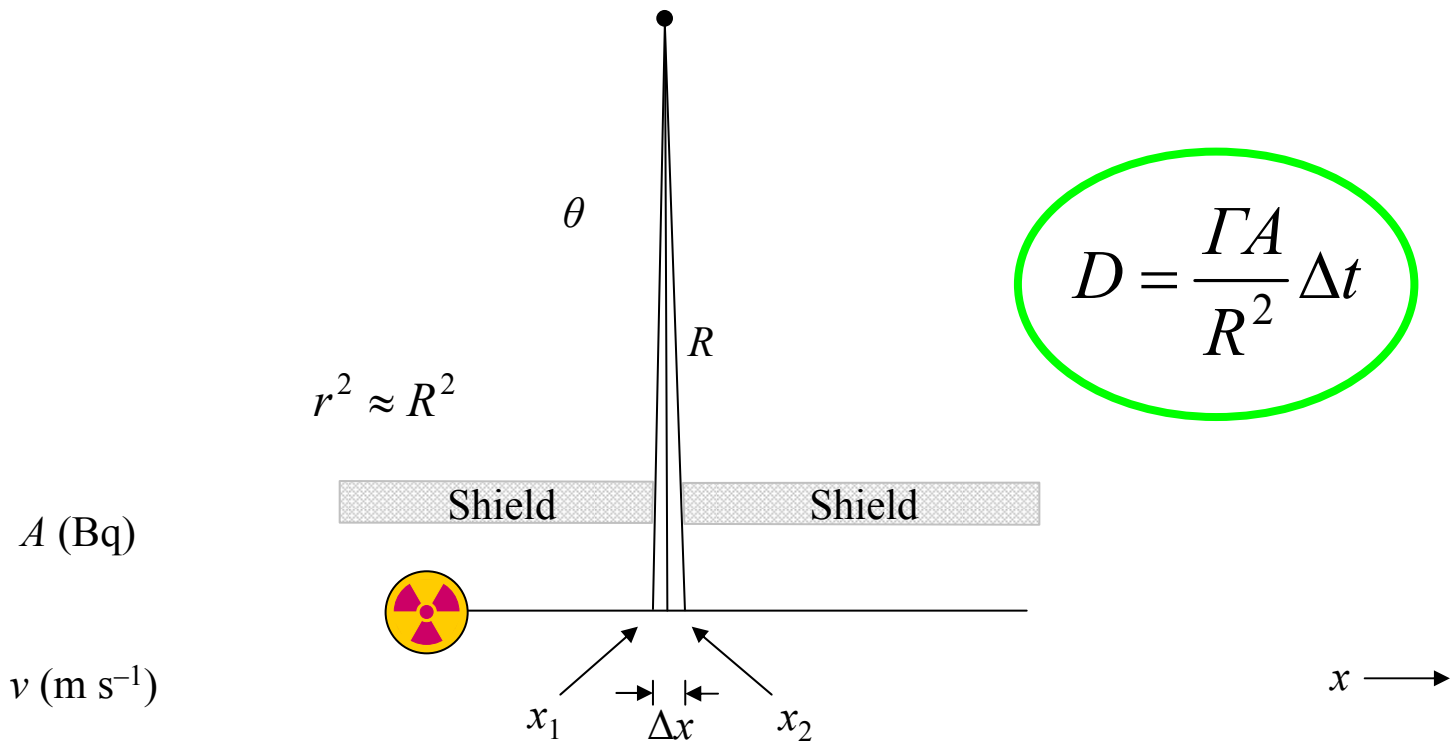
$$D = \frac{\Gamma A \theta}{vR} \text{ (Gy)}$$

- This is identical to the line source formula!

$$D = \frac{\Gamma C_{\mathrm{L}} \theta}{R} \Delta t$$



Dose from Moving Unshielded Point Source with Small Displacement



$$D = \frac{\Gamma A}{R^2}\Delta t$$

Dose rate from a short ($\Delta x << R$) movement has essentially the "$1/R^2$" (inverse square) dependence of a point source.

Narrowly-Collimated Point Source Moving at Uniform Velocity

Point of interest is only irradiated for a very short time.

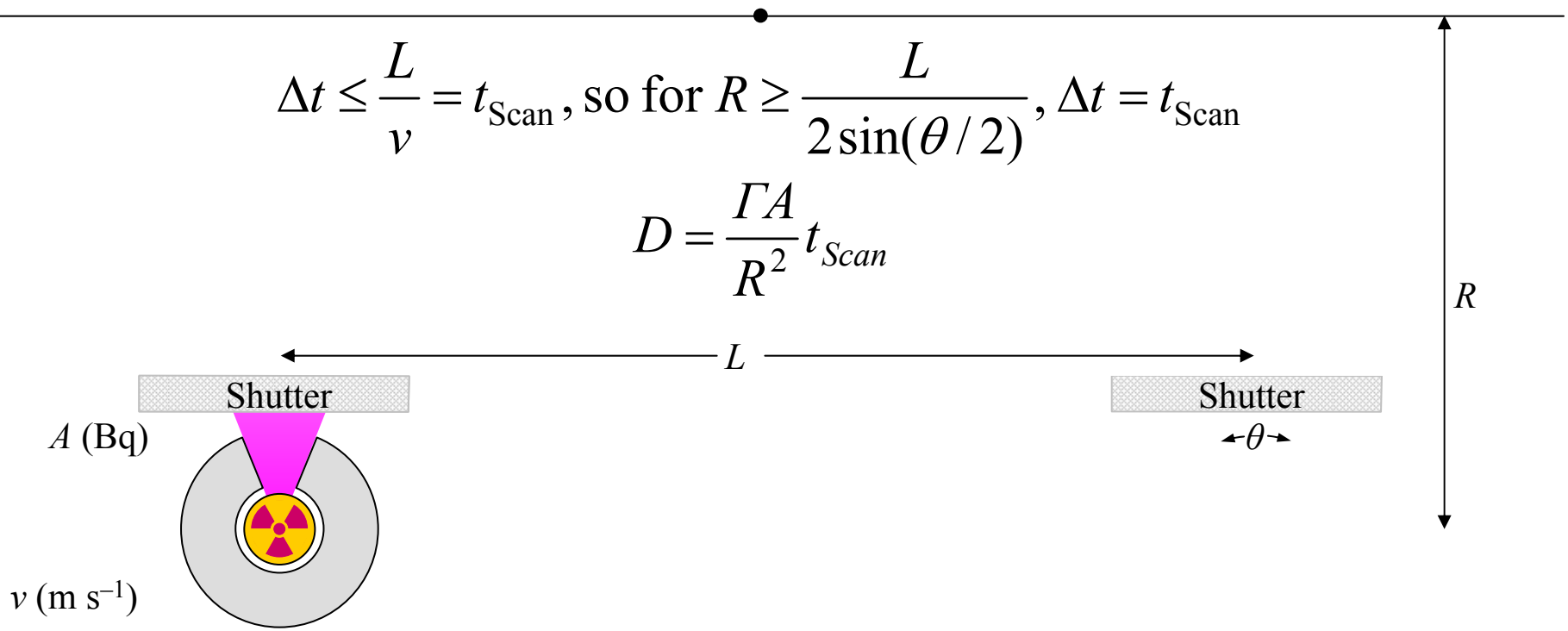
Collimated Point Source Moving at Uniform Velocity

$$\text{Point of interest irradiated for finite time } \Delta t = \frac{2R\sin(\theta/2)}{v}$$

$$D = \frac{\Gamma A}{R^2}\Delta t \approx \frac{\Gamma A \theta}{vR}$$

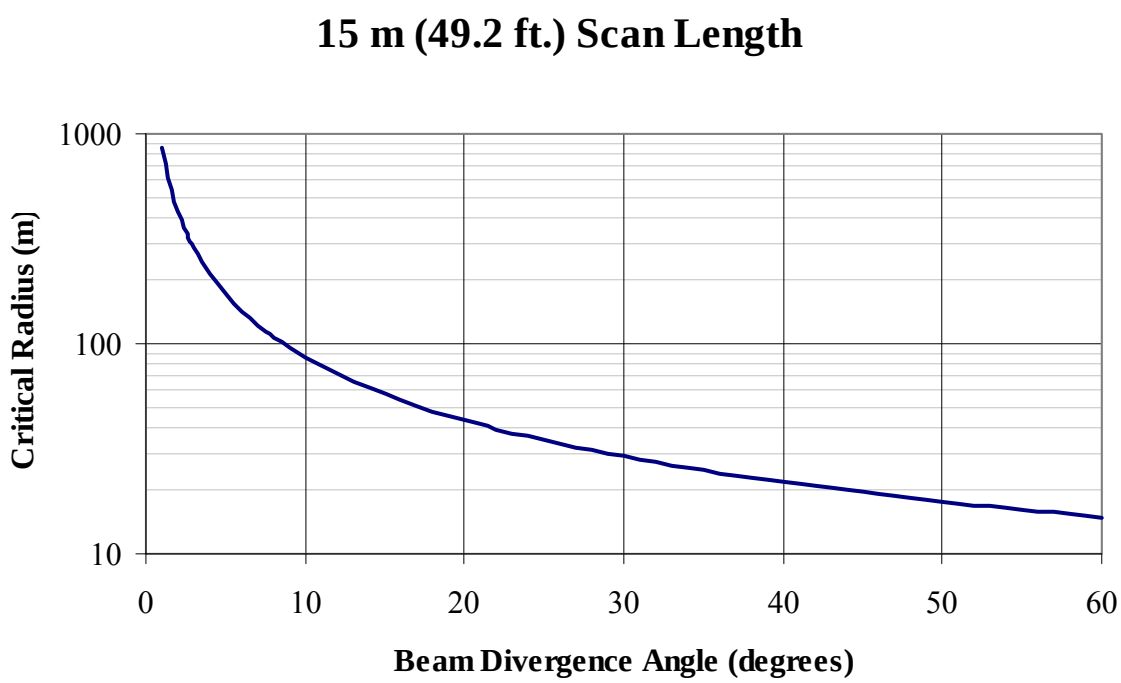
$$\Delta t \le \frac{L}{v} = t_{\text{Scan}}, \text{ so for } R \ge \frac{L}{2\sin(\theta/2)}, \Delta t = t_{\text{Scan}}$$

$$D = \frac{\Gamma A}{R^2} t_{Scan}$$

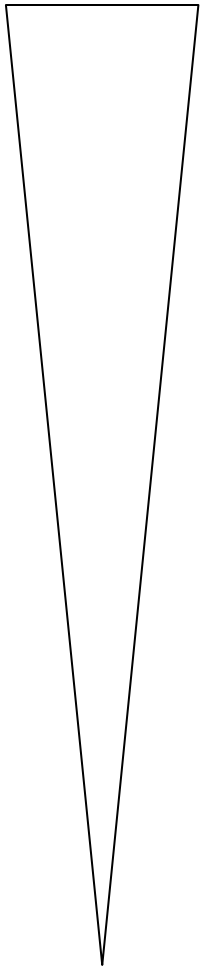


2 Regions: Near Field and Far Field

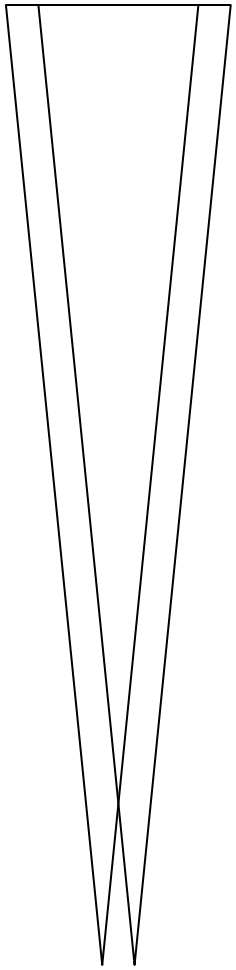
- There exists a critical radius $R_{crit} = L / (2\sin[\theta/2])$
- In the near field $(R < R_{crit})$, the dose rate drops as $1/R^2$, but the exposure time increases as $1/R$, giving a net $1/R$ distance dependence of the dose per scan
- In the far field $(R > R_{crit})$, the dose rate drops as $1/R^2$, and the exposure time is constant, giving a net $1/R^2$ distance dependence of the dose per scan



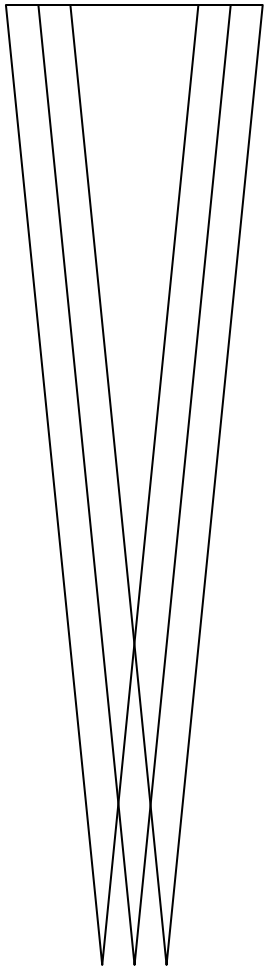
Overlap of Discrete Beams (e.g., “Pencil” Beams: 1 of 7



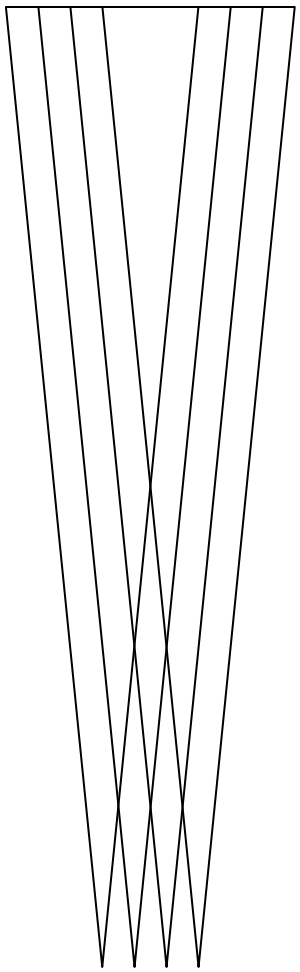
Overlap of Discrete Beams (e.g., “Pencil” Beams: 2 of 7



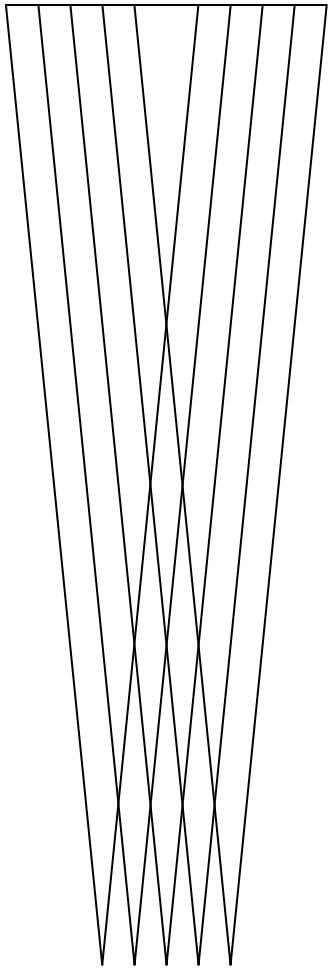
Overlap of Discrete Beams (e.g., “Pencil” Beams: 3 of 7



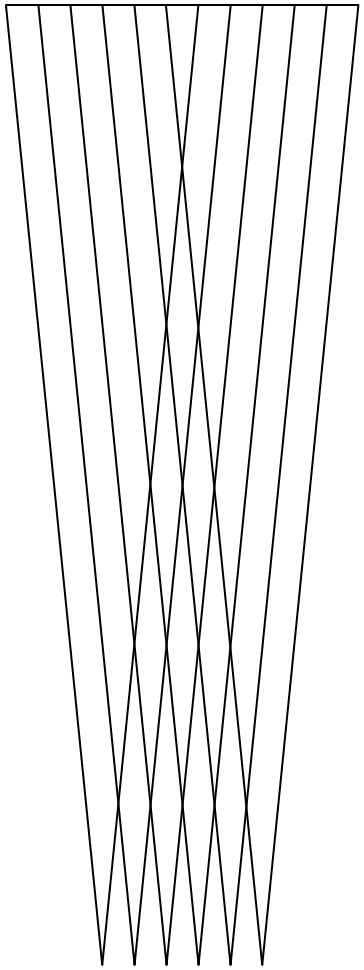
Overlap of Discrete Beams (e.g., “Pencil” Beams: 4 of 7



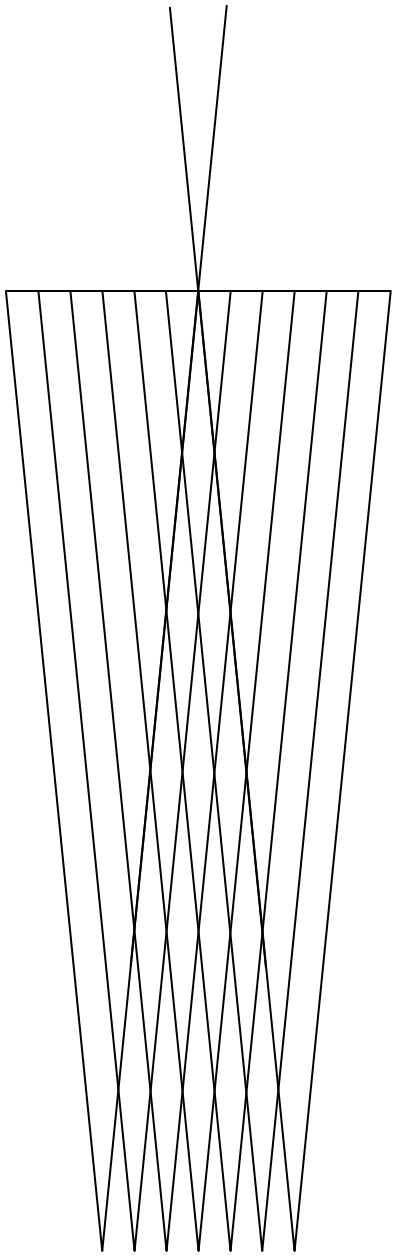
Overlap of Discrete Beams (e.g., “Pencil” Beams: 5 of 7



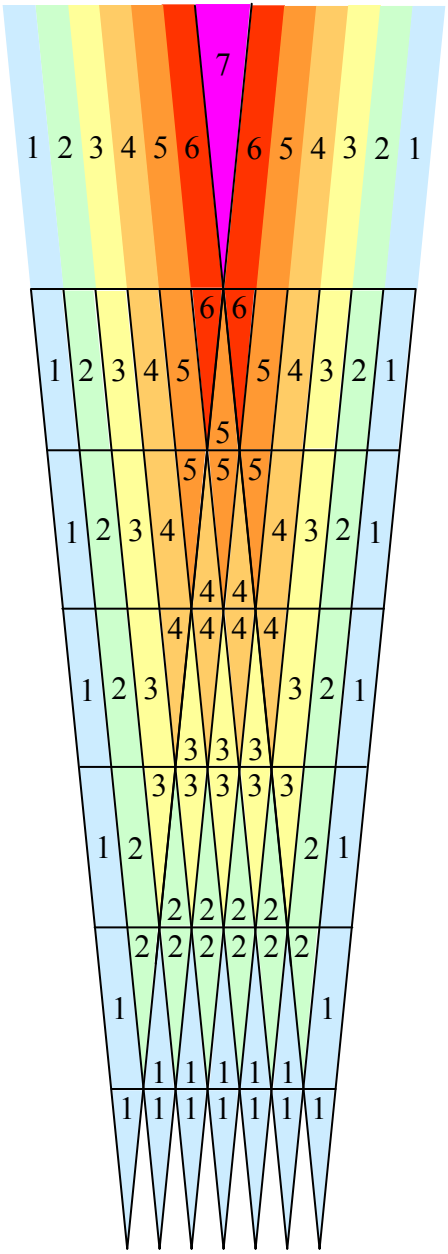
Overlap of Discrete Beams (e.g., “Pencil” Beams: 6 of 7



Overlap of Discrete Beams (e.g., “Pencil” Beams: 7 of 7

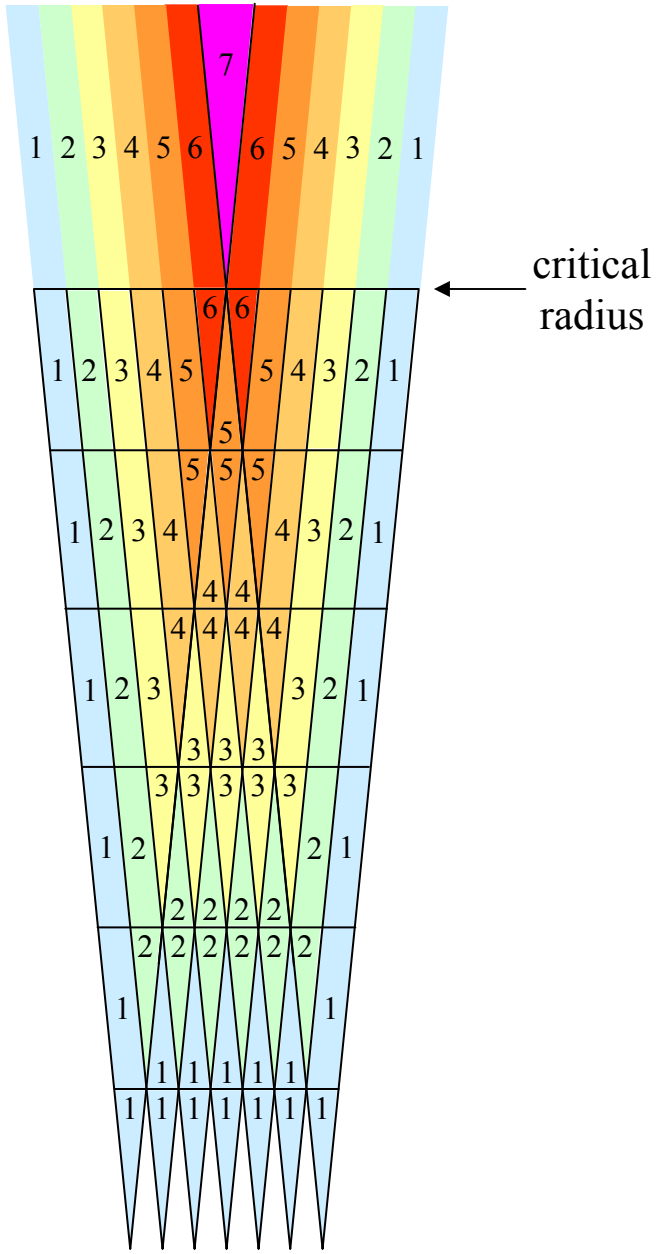


Overlap of Discrete Beams (e.g., “Pencil” Beams



Overlap of Discrete Beams (e.g., “Pencil” Beams)

- Number of times a voxel is irradiated increases “linearly” (actually, stepwise), with distance as *R*
- Intensity of single beam decreases smoothly as inverse square of distance
- Inside critical radius, dose per scan appears to decrease as 1/*R*
- Outside of critical radius, dose per scan decreases as $1/R^2$
  - For this example with 7 beams, every location in the “7” triangle and beyond is irradiated by all 7 beams
  - Fringe areas are irradiated by fewer beams



Identical Geometry

- Depending on the situation, θ can be either
  - the angle subtended by a line source as seen from a dosimetric point of interest, or
  - the collimation angle as seen from the source
- An unshielded point source* moving a small distance is identical to a collimated point source moving an unlimited distance

*That is off, shuttered, or shielded unless it is moving

Nuclear Transitions per Unit Length

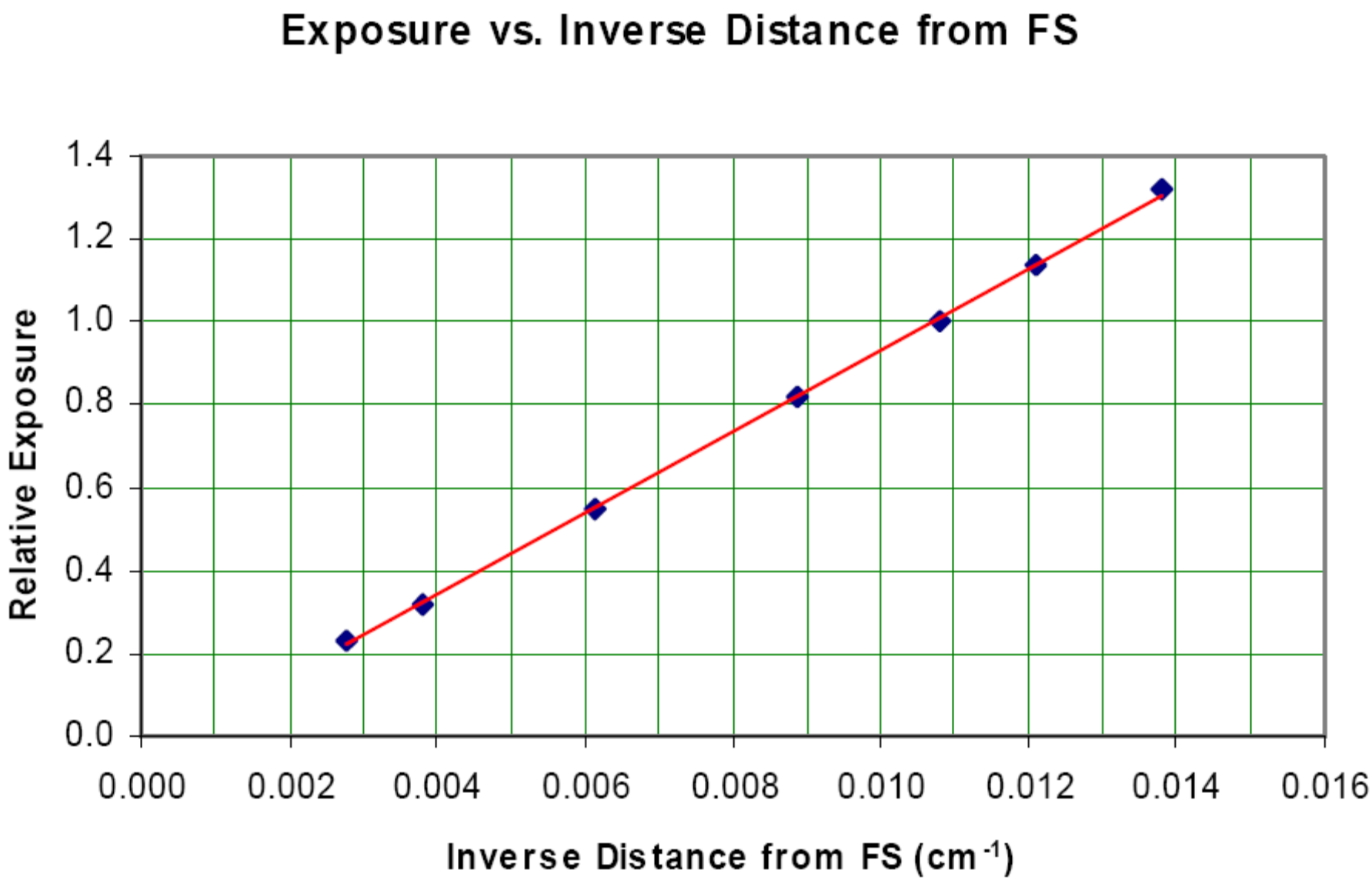
- Dose is proportional to
  - $C_L \Delta t$ in (Bq/m)(s) for a stationary line source
  - A/v in Bq/(m/s) for a moving point source
- Either set of units can be written (Bq·s)/m
- 1 Bq·s is a nuclear transition
- Thus, the number of *nuclear transitions* that occur *per unit length*
  - of a line source or
  - during the traversal of a point source

  is the unifying concept

$$\textit{Nuclear transitions per unit length} = C_L \Delta t = \frac{A}{v}$$

Universal Source Strength:
Air Kerma Rate at a Meter (Gy s^{-1} m^2)

- x-ray machine output
- $\Gamma C_L \Delta t$: uniform line source (e.g., pipe) with activity per unit length C_L exposed for time Δt
- $\Gamma A/v$: radionuclide source of activity A moving at velocity v


Exposure vs. Inverse Distance from FS
Relative Exposure
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
Inverse Distance from FS (cm-1)

Conclusions

- With the proper interpretation of θ,
  - Dose from a moving point source and dose from a stationary line source have identical formulas
  - Dose from a moving, collimated point source and dose from a moving, unshielded point source (that's shuttered when not moving) have identical formulas
  - The concept of *nuclear transitions per unit length* unifies the solutions
- For cargo and people scanners with highly collimated beams, dose varies
  - as the inverse of the distance from the source in the near field
  - as the inverse square of the distance from the source in the far field
- Assuming $1/R$ dependence at all distances is "conservative" in the sense of overestimating dose