How to measure dose?
- Demystifying TG21

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Background

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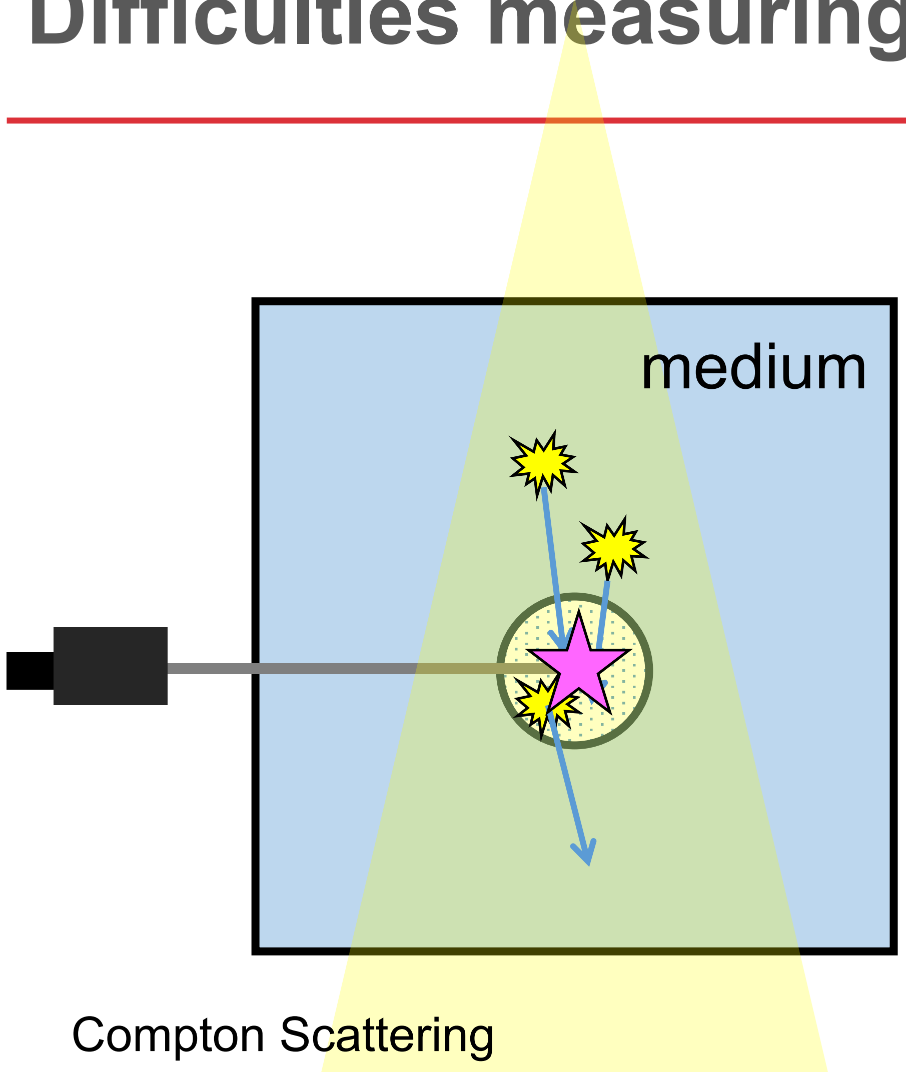
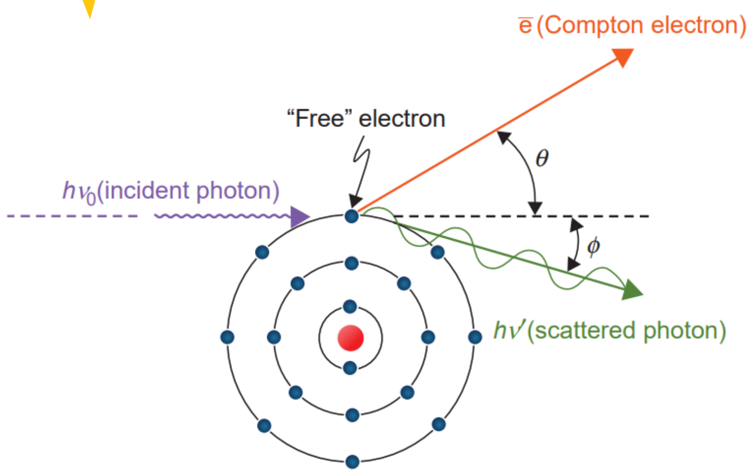
- TG-51
  - Reading to dose: Calibration factor $N_{d,w}$
  - Standard to user beam: Beam quality factor k_Q
- TG-21

Difficulties measuring the dose



Compton Scattering $\propto \rho_e$



Compton Scattering
Rayleigh Scattering
Photoelectric interaction
Pair/Triplet Production

Dose is not directly measurable …

The physical picture of stopping power

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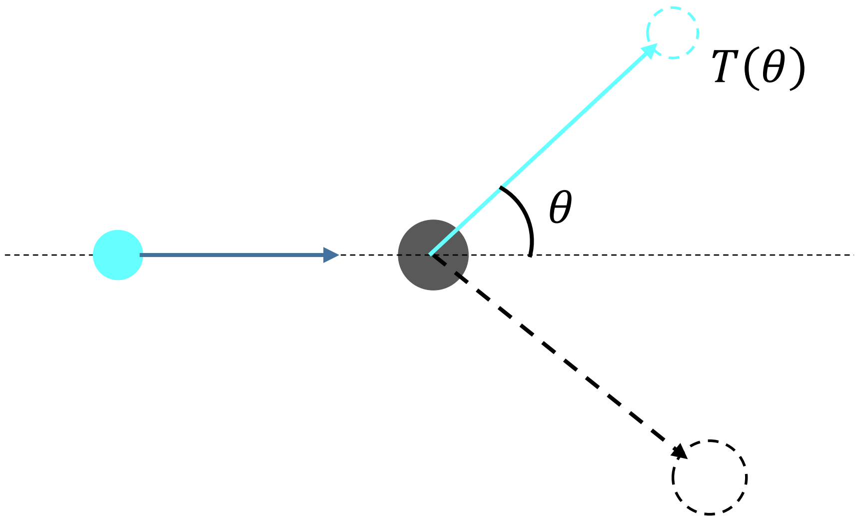
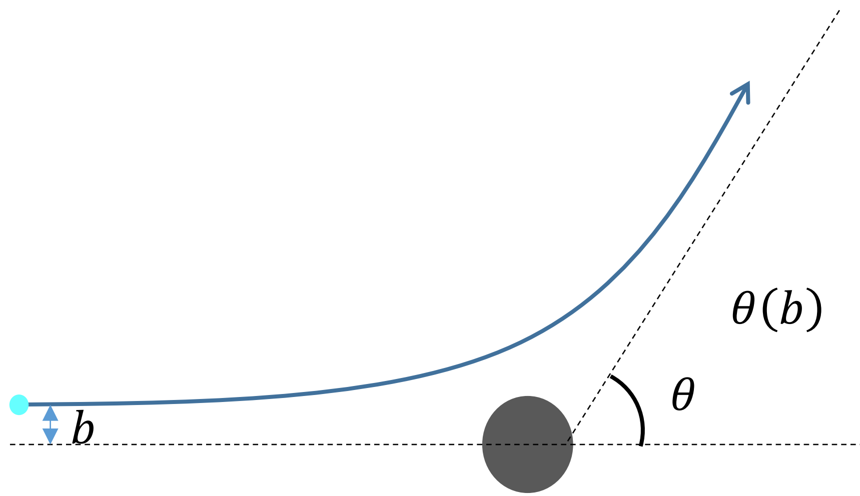
Two-body Collision



Angular Energy Transfer
(Energy)

Coulomb Scattering



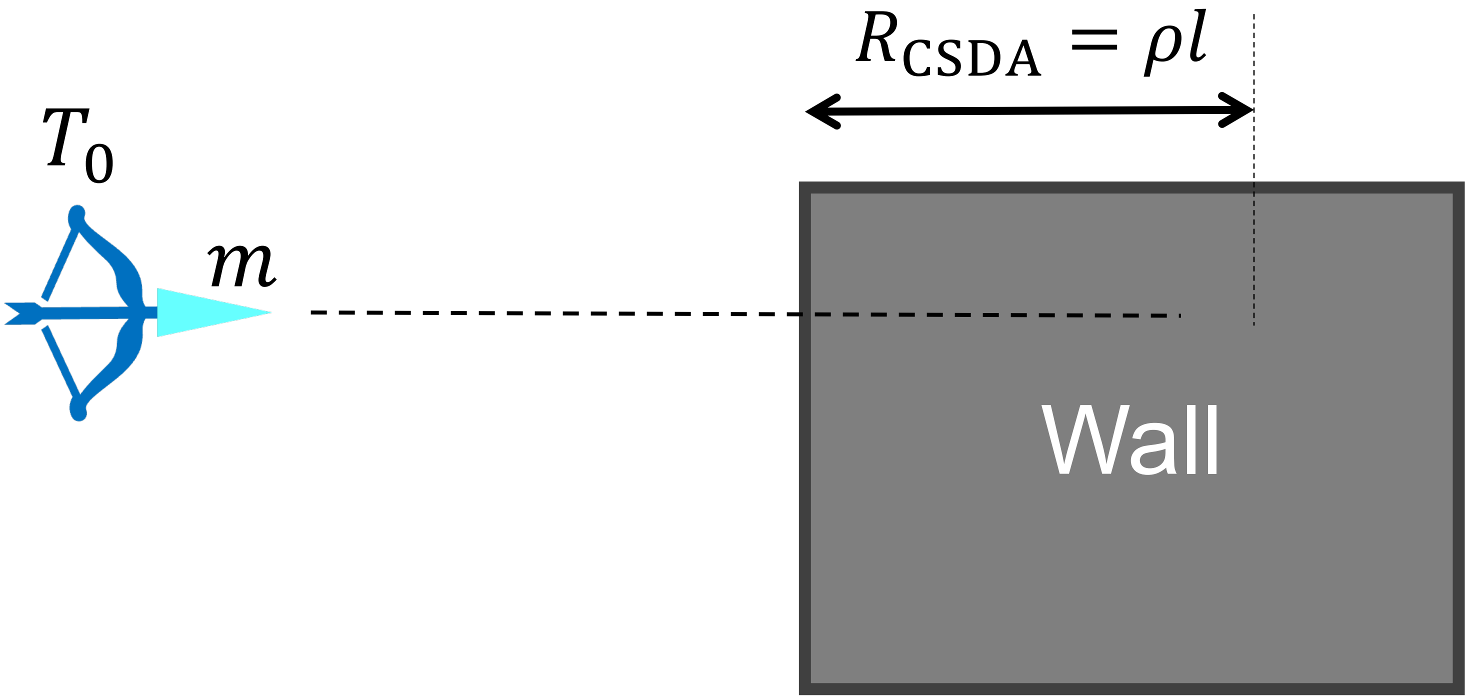
Angular Cross Section
(Probability)

Total Energy Transferred

$$E_{tr} = \int T(\theta)\, \mathrm{d}b(\theta)$$

What is stopping power?

- For charged particle interaction



How photon beam deposits dose?

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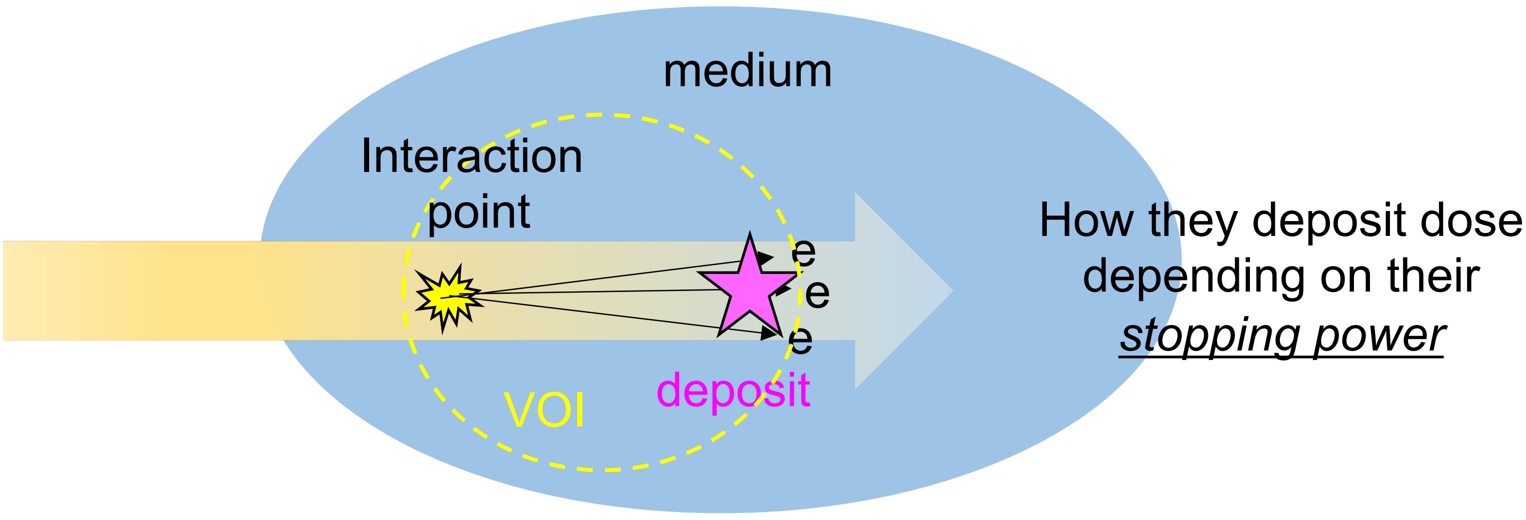
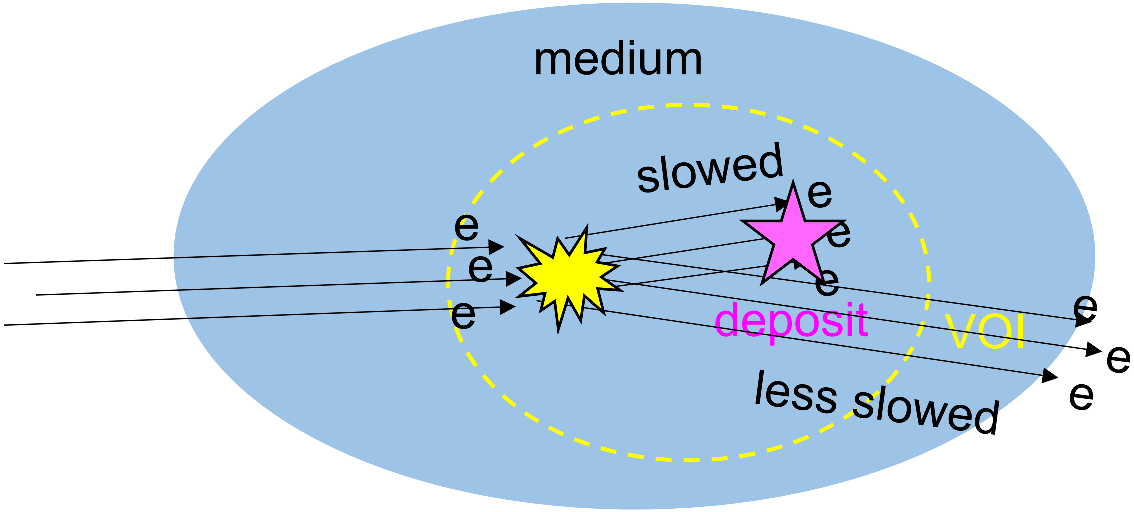
- From photon perspective:
  - The photon fluence attenuates.
  - Photon energies are transferred to electrons.
  - The secondary electrons deposit energy → dose.
    - Secondary electron spectrum remain similar.



How electron beam deposits dose?

- From electron perspective
  - Electrons continuously slow down ($E\downarrow$)
    - Secondary electrons spectrum varies with depth.
  - Considering energy transfer lower than a threshold (Δ) $\rightarrow$ "restricted"
    - Energy deposit locally.



☆Dose equivalency

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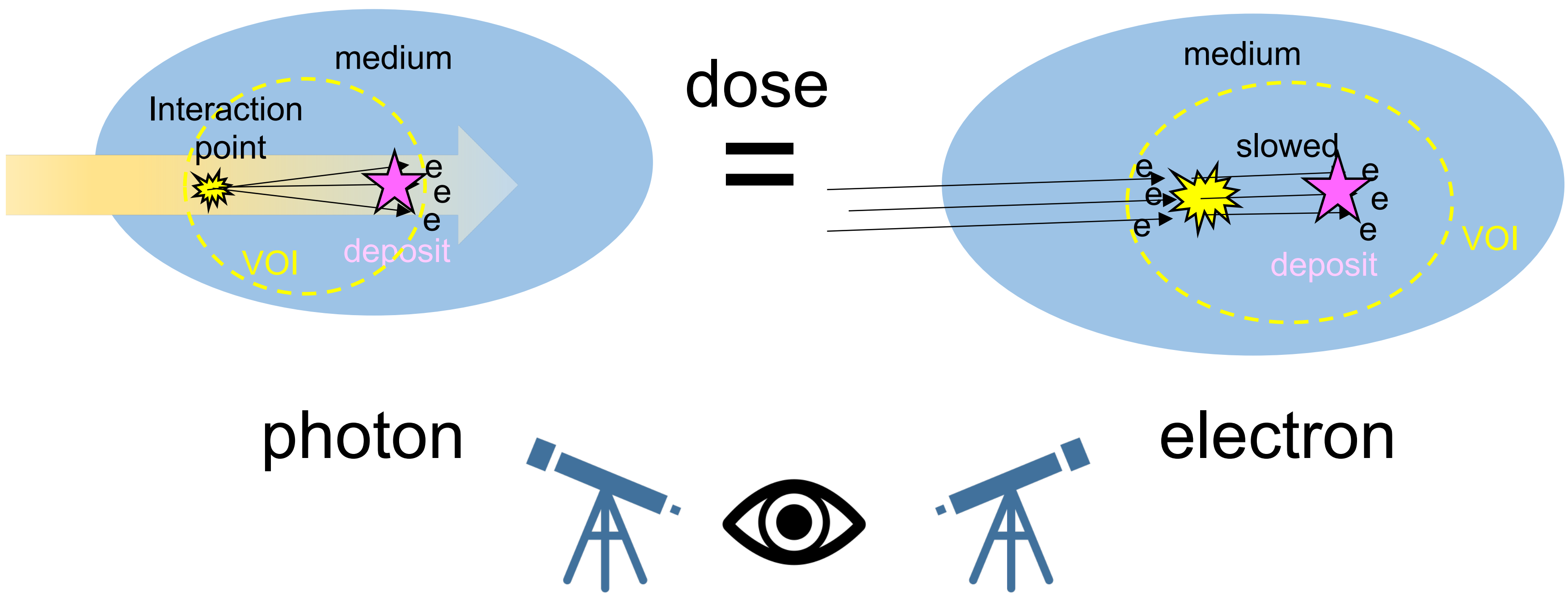
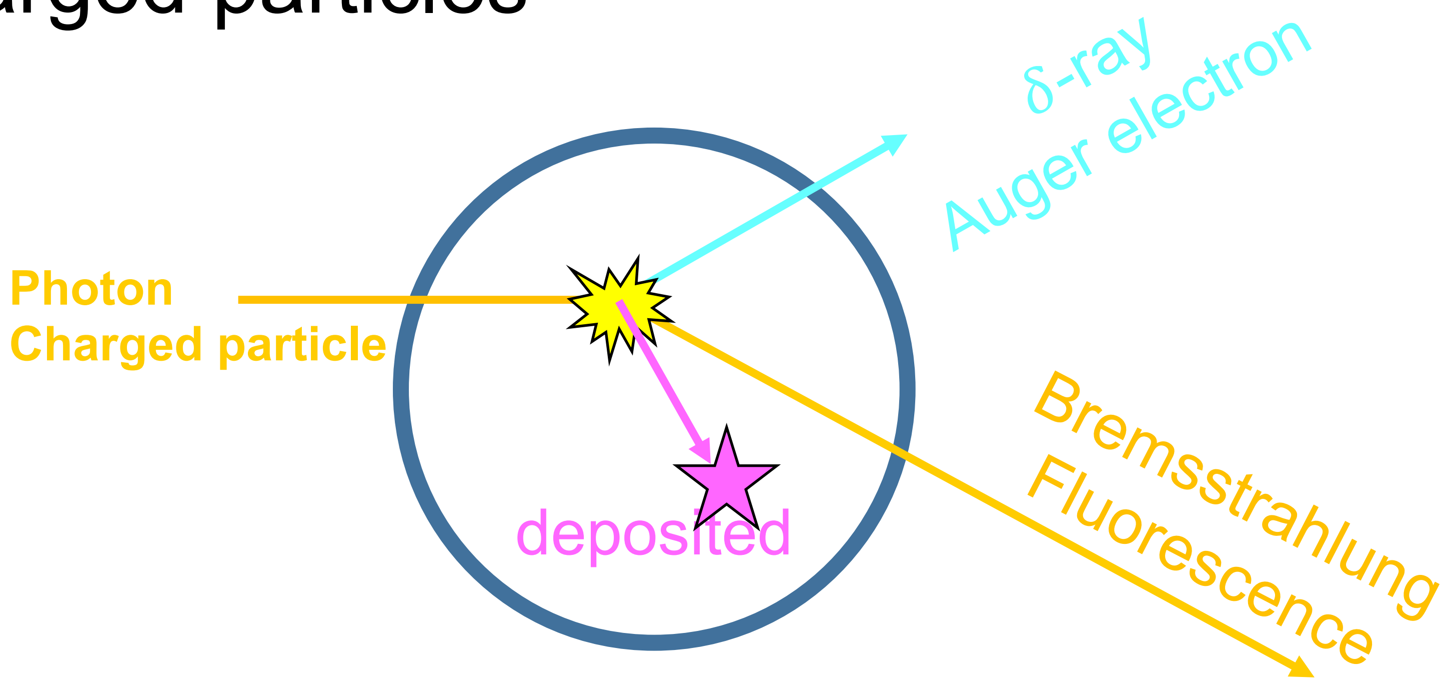


What is dose?

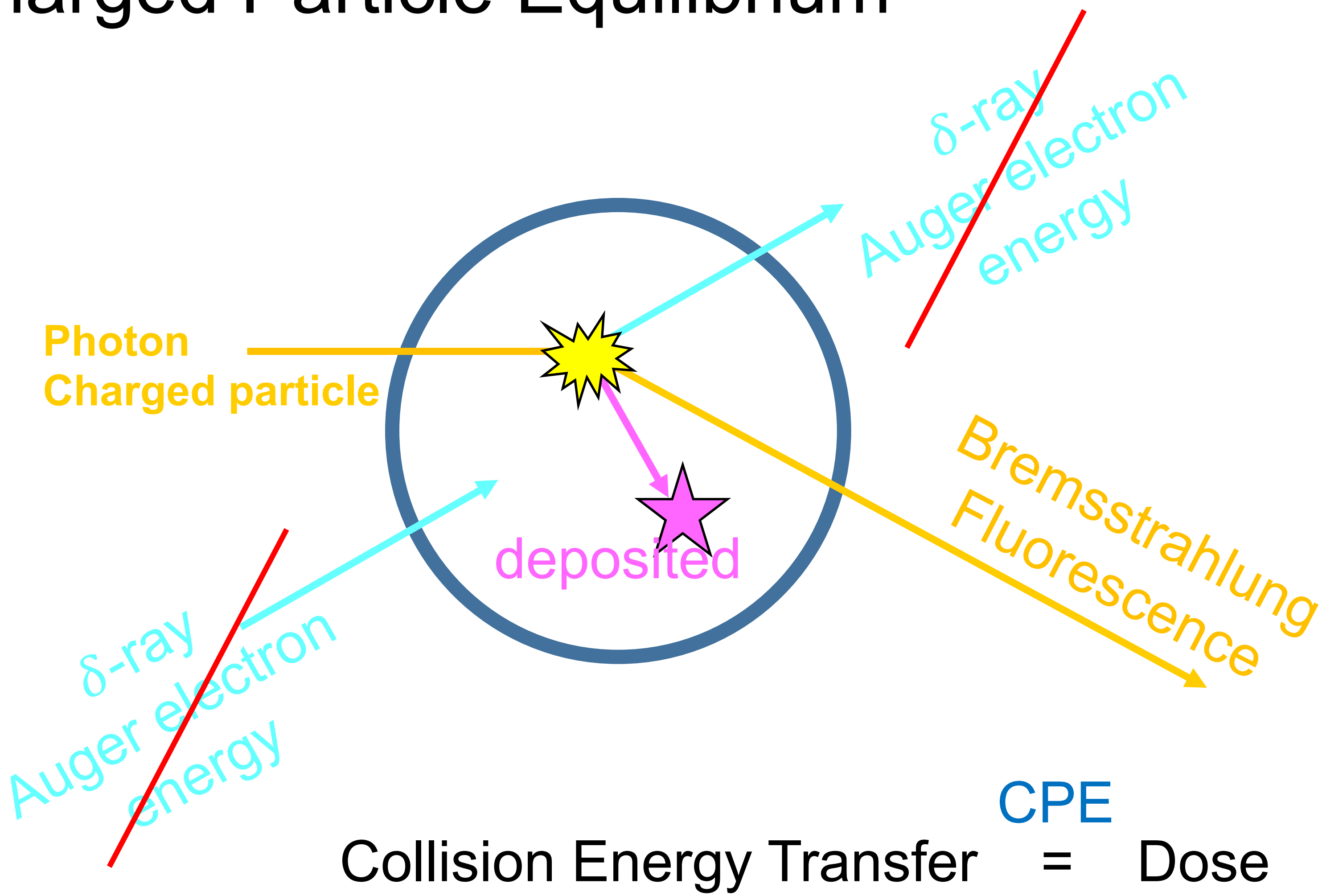
- Energy Transfer among radiation and charged particles



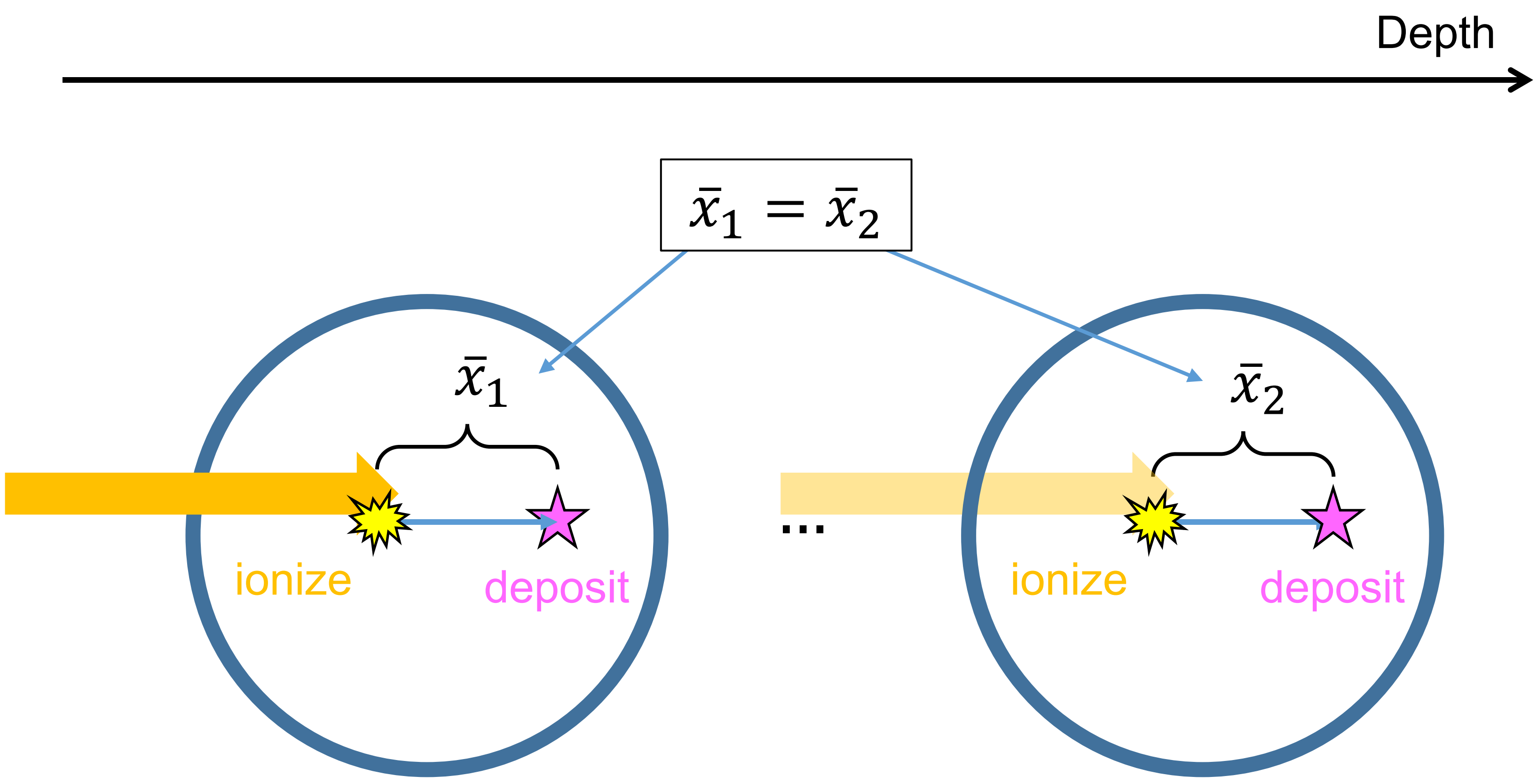
$$\text{Energy transfer } (K) \neq \text{Dose}$$

Ideal scenario to measure dose

- Charged Particle Equilibrium

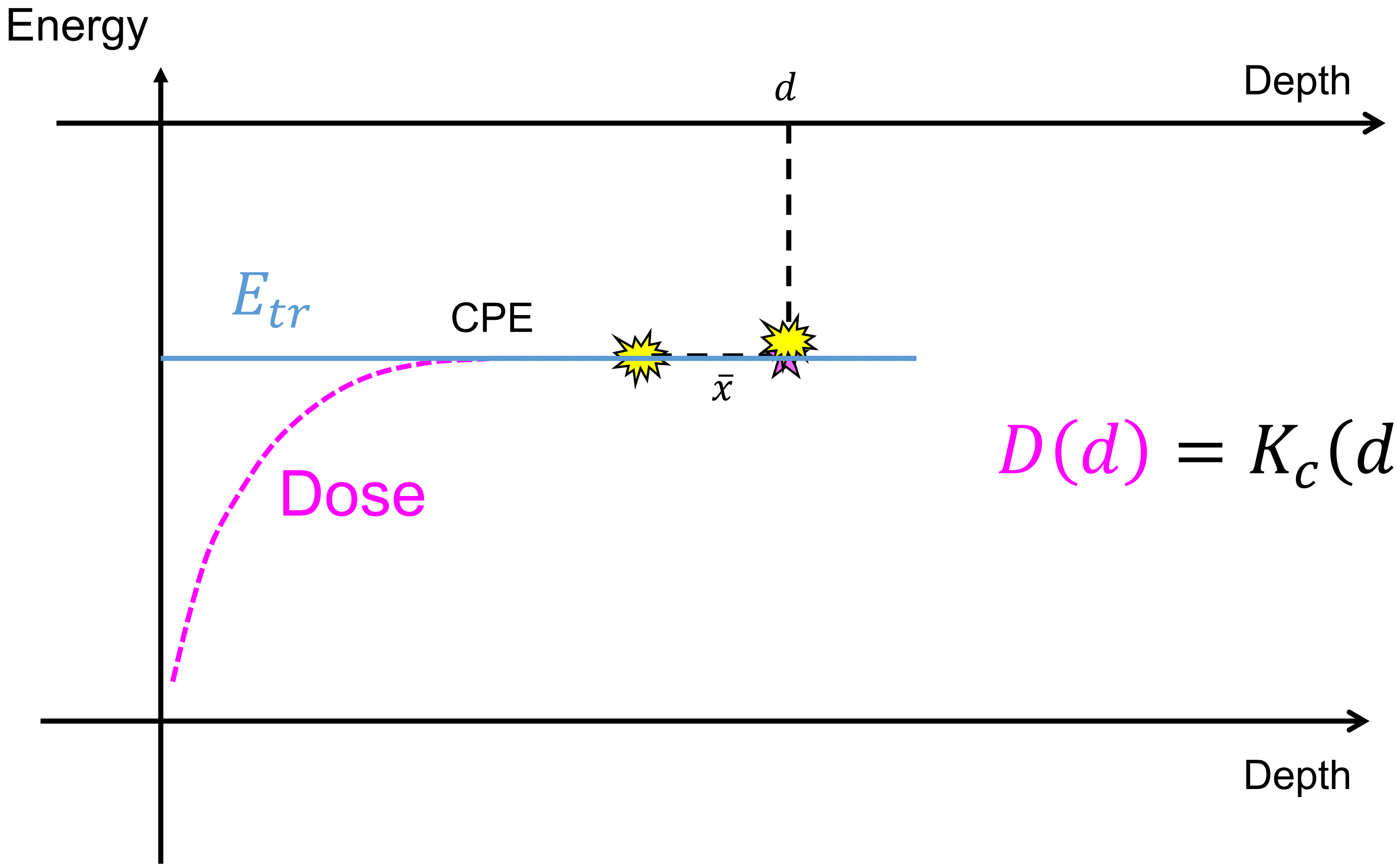


Transient CPE



same photon-energy → same secondary electron spectrum

CPE



$$D(d) = K_c(d)$$

TCPE curve

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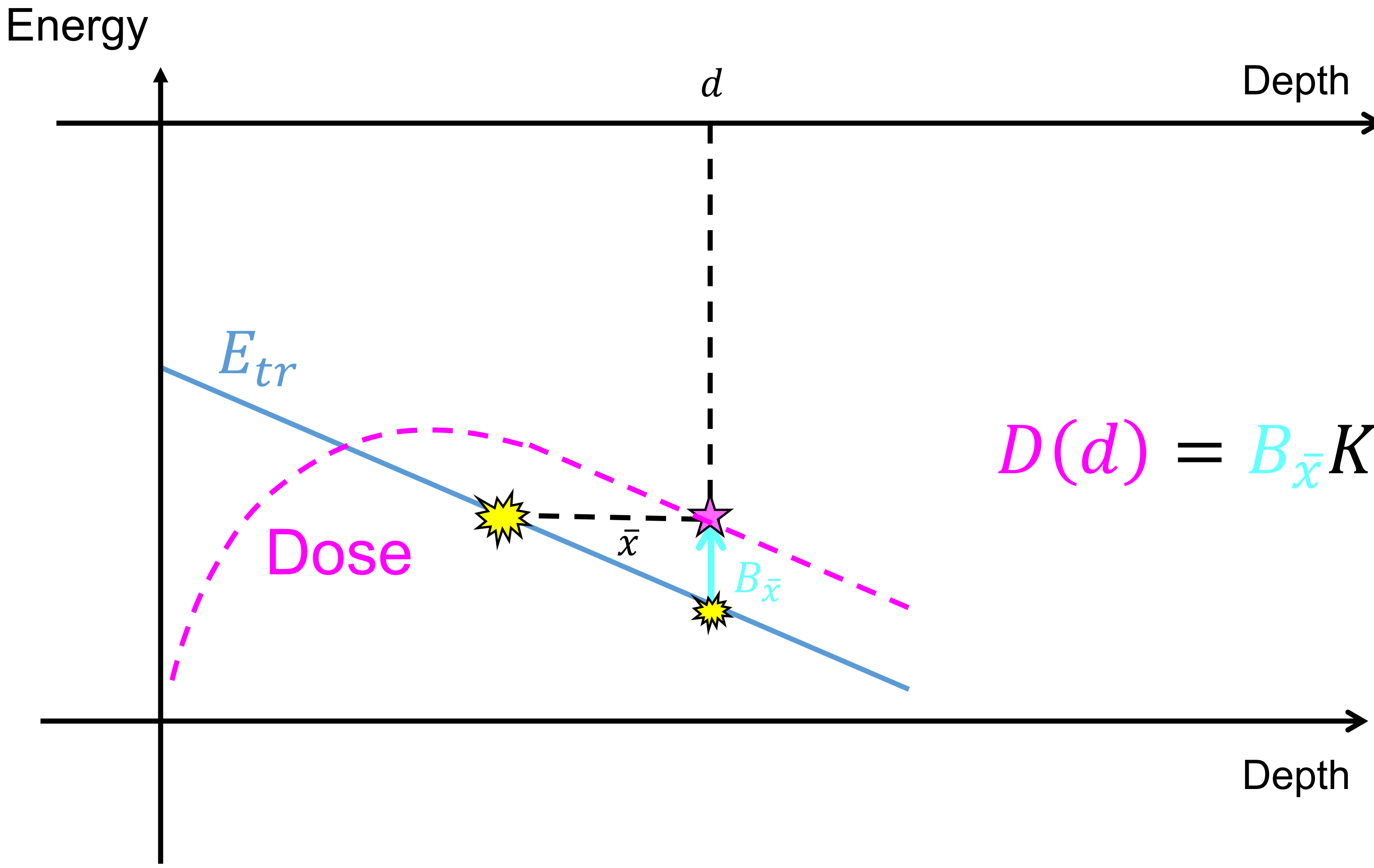
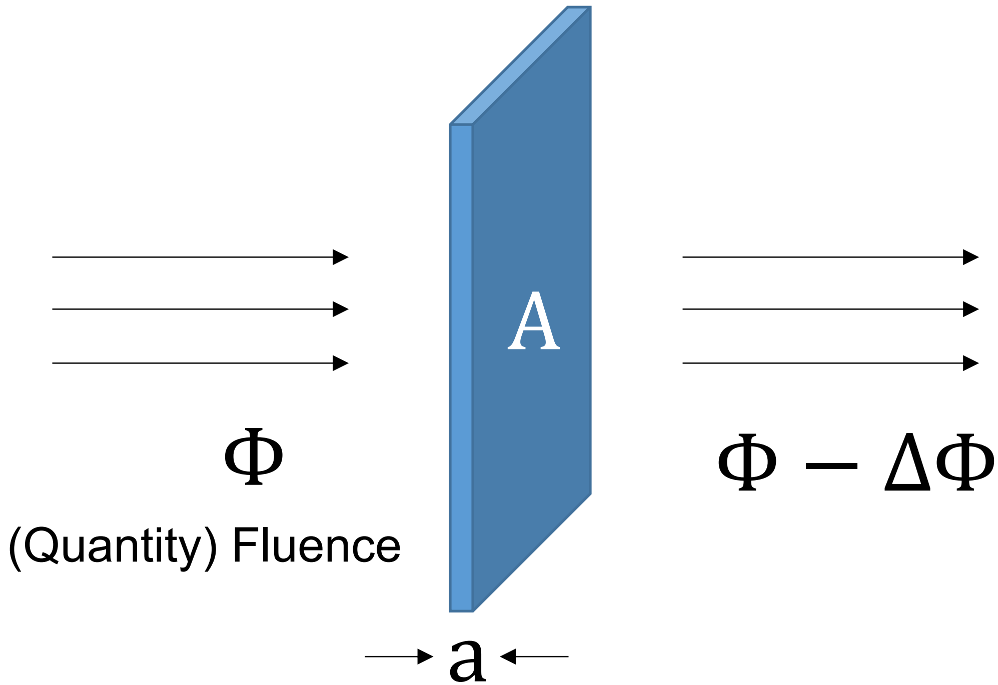


$$D(d) = B_{\bar{x}} K_c(d)$$

Principle of dose measurement



$$D \xleftarrow{\text{TCPE}}$$

K_c

$$\text{KERMA} = \frac{E_{tr}^{c}}{m}$$

$$= E\Phi(E)\left(\frac{\mu_{ab}(E)}{\rho}\right)$$

Energy Fluence

Principle of dose measurement

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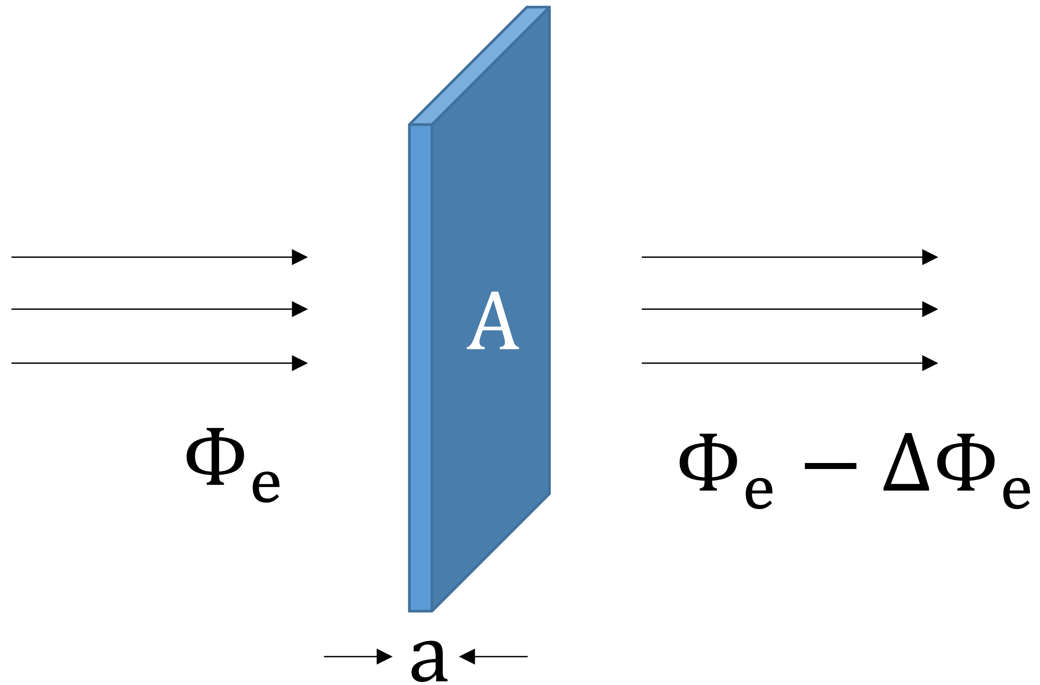
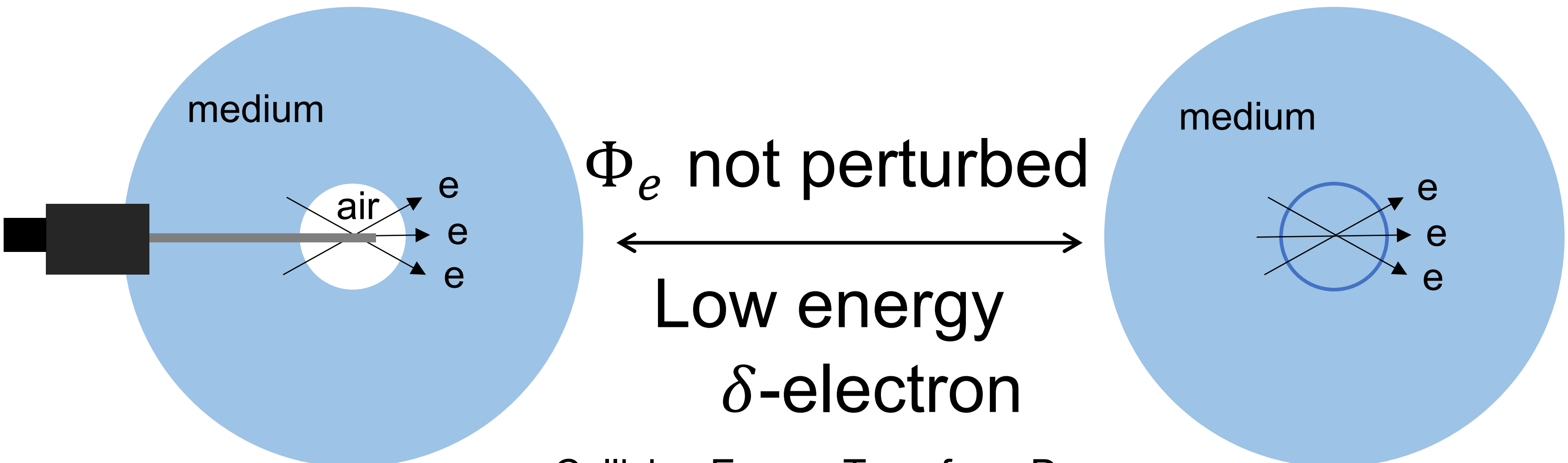


$$D \xleftarrow{\text{local}} \text{CEMA} = \frac{E_{tr}^{c}}{m}$$

$$= \Phi_{\text{e}}(\text{E}) \left(\frac{S_{col}(E)}{\rho}\right)$$

Quantity Fluence

Bragg-Gray Cavity Theory (Small Cavity)



Collision Energy Transfer = Dose

$$D_{\mathrm{air}}(E) \longrightarrow D_{\mathrm{med}}(E)$$

$$= \Phi_e(E)\left(\frac{S}{\rho}\right)_{\mathrm{air}}(E) \qquad = \Phi_e(E)\left(\frac{S}{\rho}\right)_{\mathrm{med}}(E)$$

Bragg-Gray Cavity Theory (Small Cavity)

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$$D_{\mathrm{air}} = \int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\mathrm{air}}(E) \qquad D_{\mathrm{med}} = \int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\mathrm{med}}(E)$$

$$\frac{D_{\mathrm{med}}}{D_{\mathrm{air}}} = \frac{\int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\mathrm{med}}(E)}{\int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\mathrm{air}}(E)}$$

Bragg-Gray Cavity Theory (Small Cavity)

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$$D_{\text{air}} = \int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{air}} (E) \qquad D_{\text{med}} = \int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{med}} (E)$$

$$\frac{D_{\text{med}}}{D_{\text{air}}} = \frac{\dfrac{\int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{med}} (E)}{\int \mathrm{d}E\ \Phi_e(E)}}{\dfrac{\int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{air}} (E)}{\int \mathrm{d}E\ \Phi_e(E)}}$$

Normalized by $\Phi_e(E)$

Bragg-Gray Cavity Theory (Small Cavity)

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$$D_{\text{air}} = \int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{air}} (E) \qquad D_{\text{med}} = \int \mathrm{d}E\ \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{med}} (E)$$

bar means "average" effect

$$\frac{D_{\text{med}}}{D_{\text{air}}} = \frac{\left(\frac{\overline{S}}{\rho}\right)_{\text{med}}}{\left(\frac{\overline{S}}{\rho}\right)_{\text{air}}}$$

Normalized by $\Phi_e(E)$

Bragg-Gray Cavity Theory (Small Cavity)

$$D_{\text{air}} = \int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{air}}(E) \qquad D_{\text{med}} = \int \mathrm{d}E \; \Phi_e(E) \left(\frac{S}{\rho}\right)_{\text{med}}(E)$$

$$\frac{D_{\text{med}}}{D_{\text{air}}} = \left(\frac{\overline{S}}{\rho}\right)_{\text{air}}^{\text{med}}$$

Normalized by $\Phi_e(E)$

Bragg-Gray Cavity Theory (Small Cavity)

$$\frac{B K_{\text{med}}}{B K_{\text{air}}} \xleftarrow{\text{TCPE}} \frac{K_{\text{med}}}{K_{\text{air}}} = \left(\frac{\overline{\mu}}{\rho}\right)_{\text{air}}^{\text{med}}$$

same build-up $B_{\bar{x}}$

Normalized by $\Psi(E)$

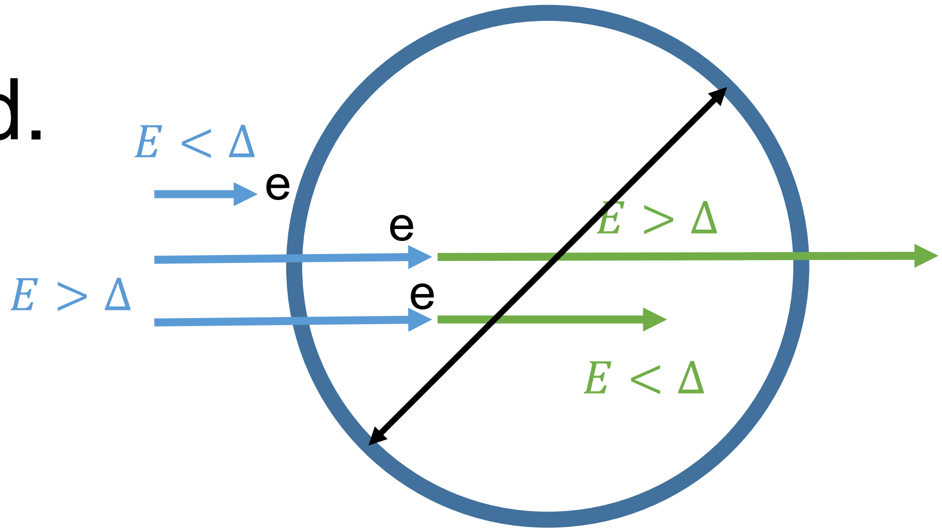
Bragg-Gray Cavity Theory (Small Cavity)

$$\frac{D_{\text{med}}}{D_{\text{air}}} \xleftarrow{\text{TCPE}} \frac{K_{\text{med}}}{K_{\text{air}}} = \left(\frac{\overline{\mu}}{\rho}\right)_{\text{air}}^{\text{med}}$$

Normalized by $\Psi(E)$

Spencer-Attix correction

- Δ: chamber size related.
- Only electron energy > Δ can enter the cavity.
- Only of energy < Δ deposits energy in the volume, becoming "dose".



$$D_{\text{cavity}} = \int_{\Delta}^{E_{\max}} dE\,\Phi(E) \left(\frac{S}{\rho}\right)_{\Delta}(E)$$

Measuring dose in free air

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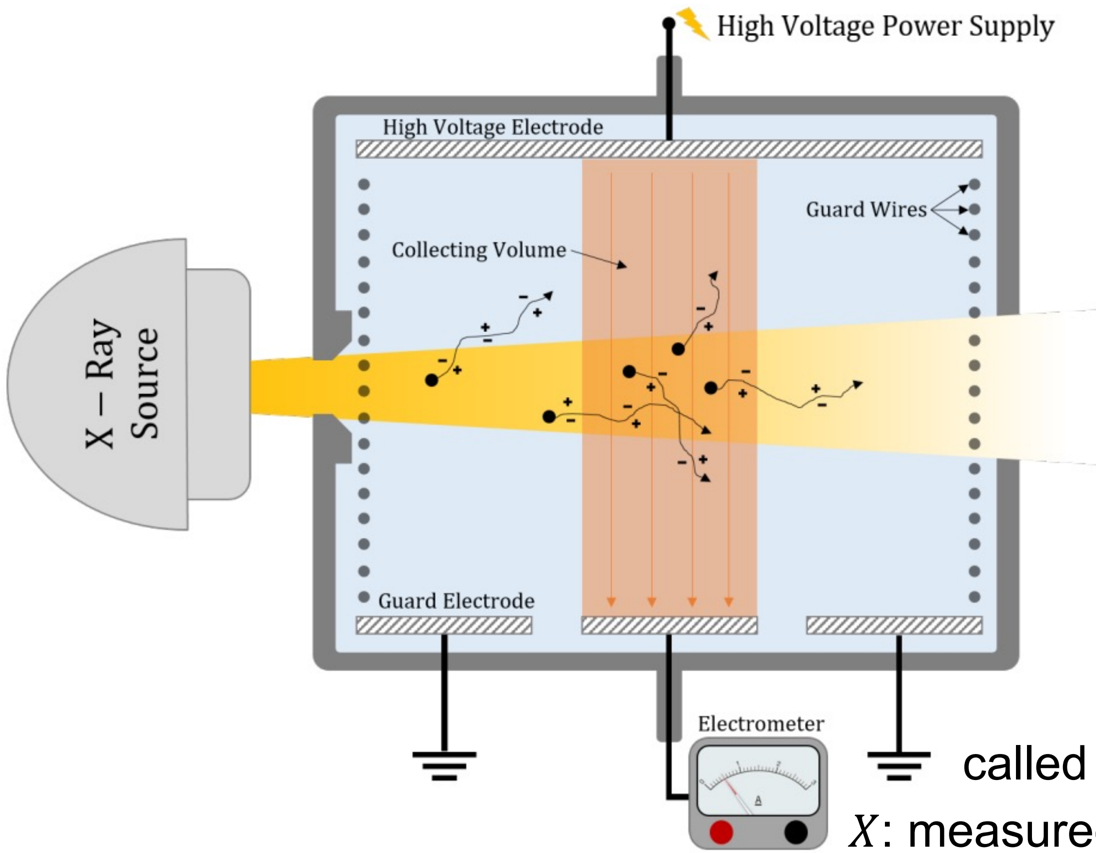

called "exposure" $\propto E_{tr}$

X: measured charges collected

$$K_{c_{\text{air}}} = \left(\frac{X}{e}\right) \overline{W} = X\left(\frac{\overline{W}}{e}\right)_{\text{air}}$$

energy needed per ion pair

Measuring dose in free air

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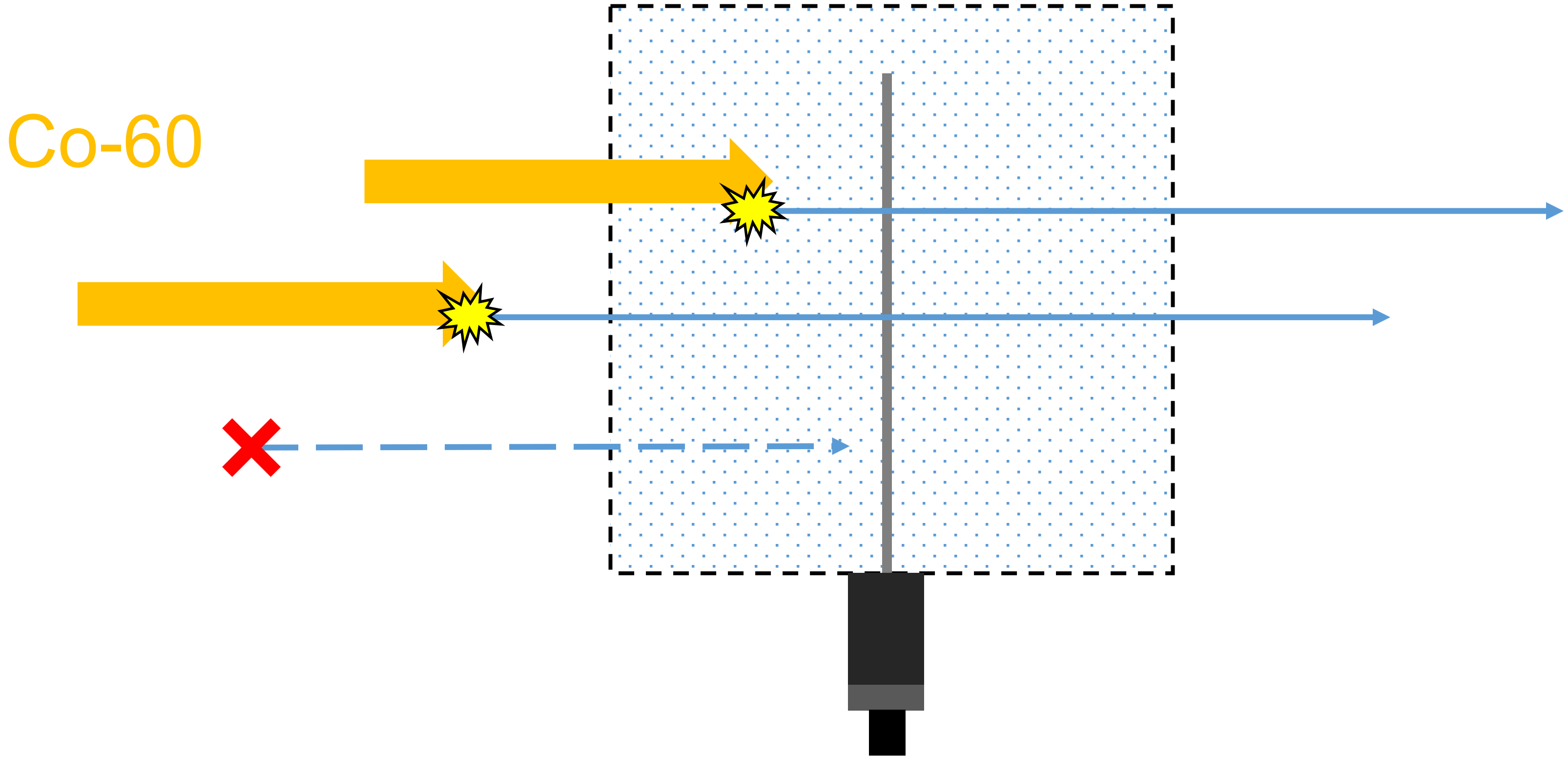
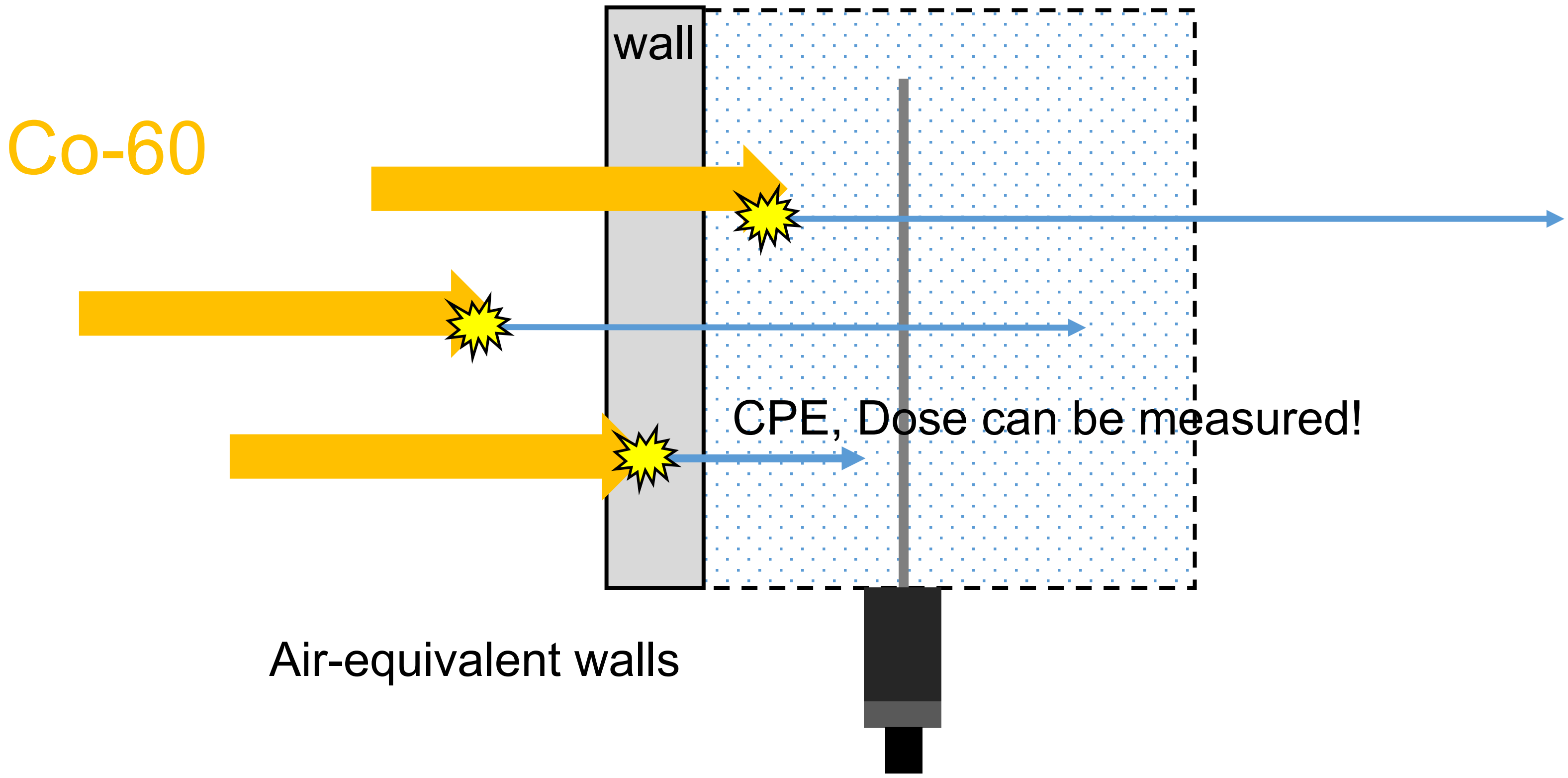
No CPE!

Dose cannot be measured!



Free-air chamber (sagittal)

Measuring dose in free air



Measuring dose via a chamber

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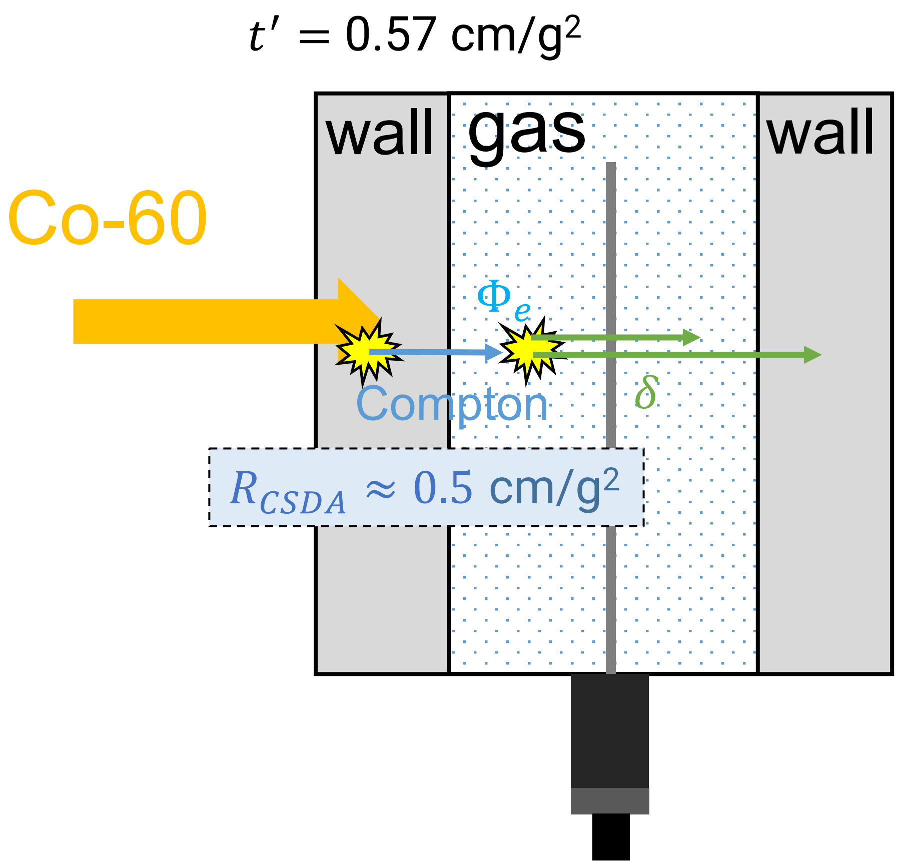

Ion chamber (sagittal)

Electron Perspective

$$D_{\text{gas}} = \Phi_e \left(\frac{\overline{S}}{\rho}\right)_{\text{gas}}$$

restricted by Δ

Measuring dose via a chamber

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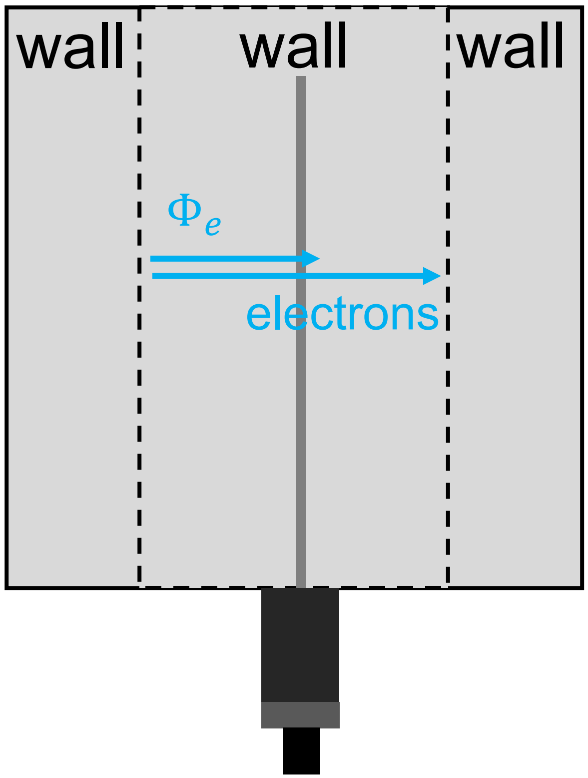
Electron Perspective



Ion chamber (sagittal)

$$D_{\text{wall}} = \Phi_e \left(\frac{\overline{S}}{\rho}\right)_{\text{wall}}$$

restricted by Δ

Measuring dose via a chamber

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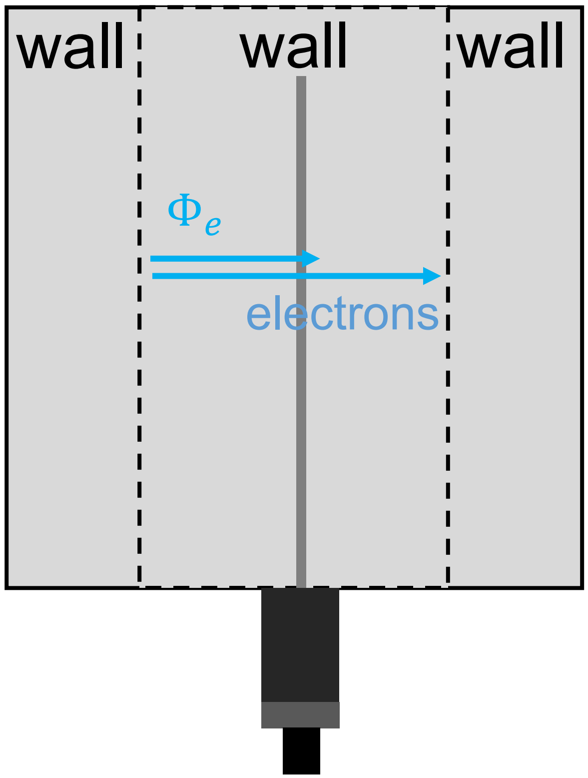
Electron Perspective



Ion chamber (sagittal)

$$D_{\text{wall}} = D_{\text{gas}} \left(\frac{\bar{S}}{\rho}\right)_{\text{gas}}^{\text{wall}}$$

Measuring dose via a chamber

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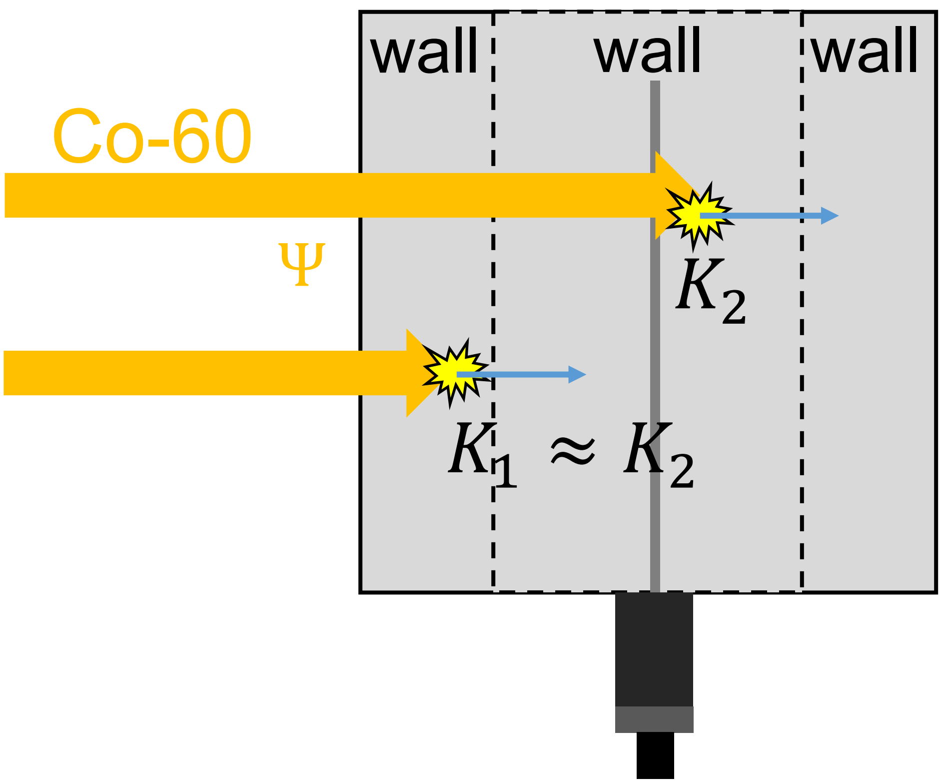
Energy

Photon Perspective



Ion chamber (sagittal)

Constant w/o attenuation

$$K_{c_{\text{wall}}} = \Psi \left(\frac{\overline{\mu_{ab}}}{\rho} \right)_{\text{wall}}$$

$$D_{\text{wall}} = B_{\bar{x}} K_{c_{\text{wall}}}$$

Upstream Interaction

Measuring dose in a chamber

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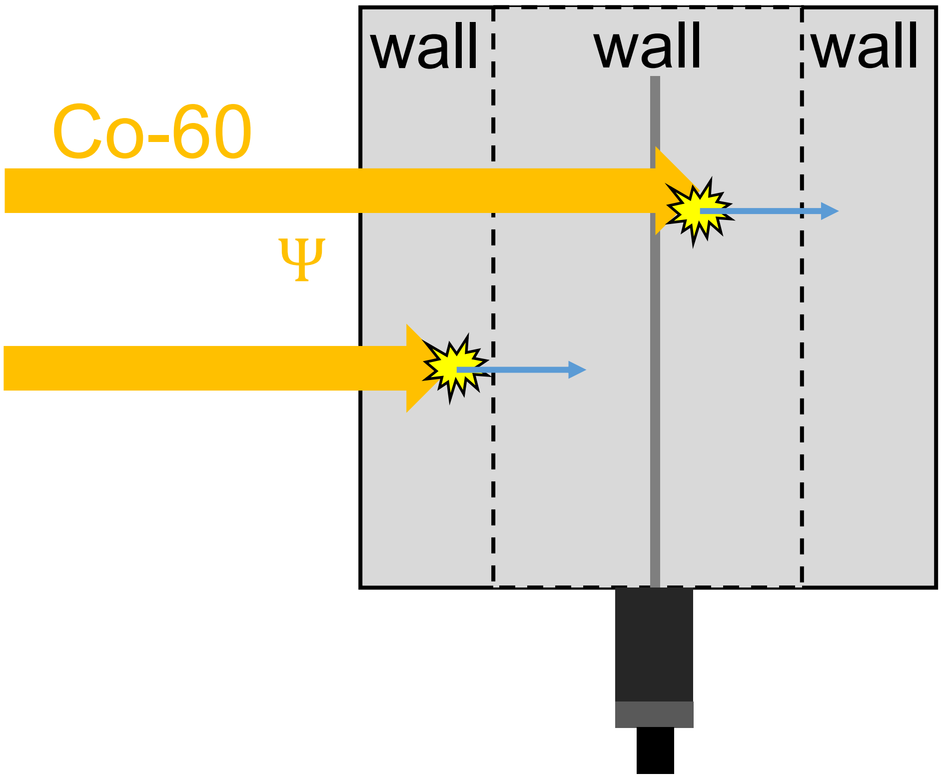
Photon Perspective



Ion chamber (sagittal)

$$K_{c_{\text{wall}}} = \Psi \left(\frac{\overline{\mu_{ab}}}{\rho} \right)_{\text{wall}}$$

$$D_{\text{wall}} = A_{\text{wall}} B_{\bar{x}} K_{c_{\text{wall}}}$$

Attenuation

Measuring dose in a chamber

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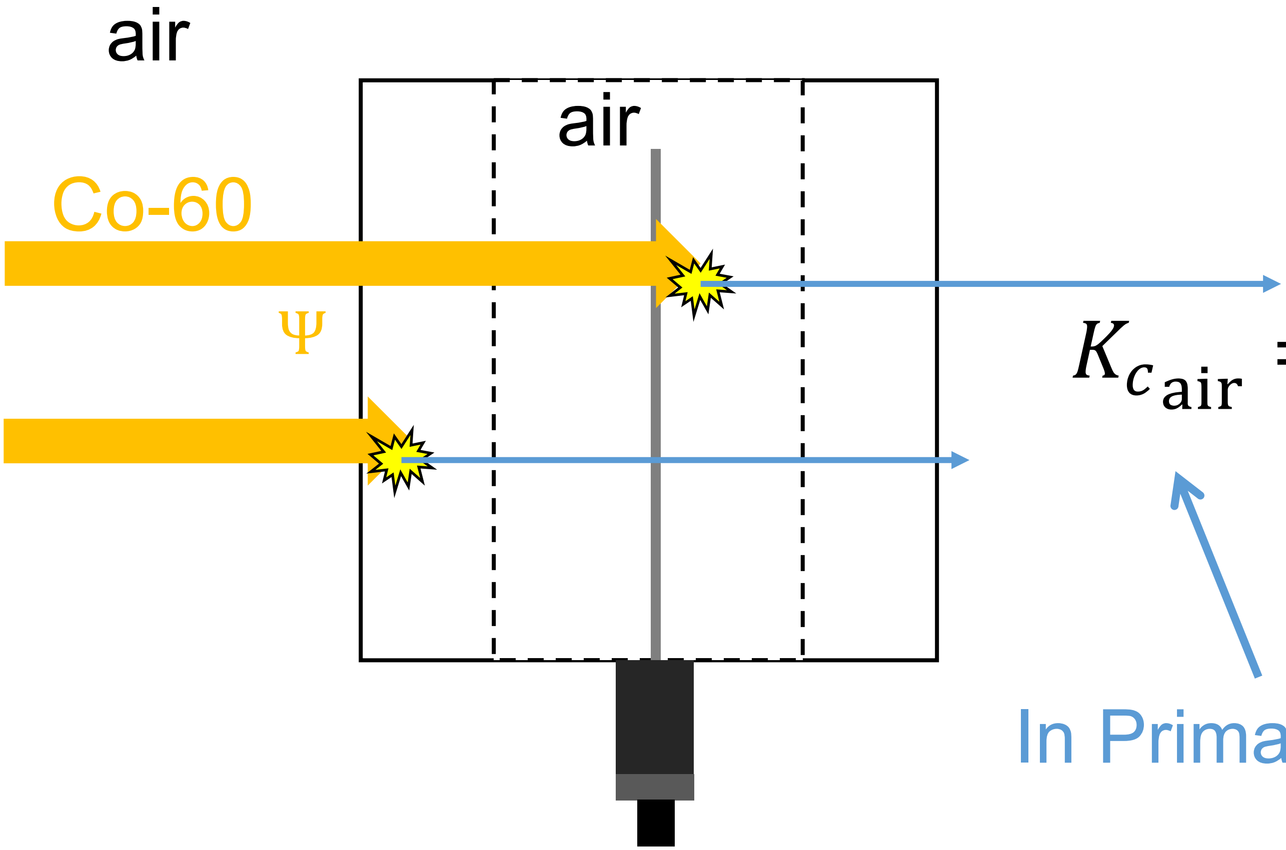

$$K_{c_{\text{air}}} = \Psi \left(\overline{\frac{\mu_{ab}}{\rho}} \right)_{\text{med}}$$

In Primary Lab

Ion chamber (sagittal) ≈free-air chamber

Measuring dose via a chamber

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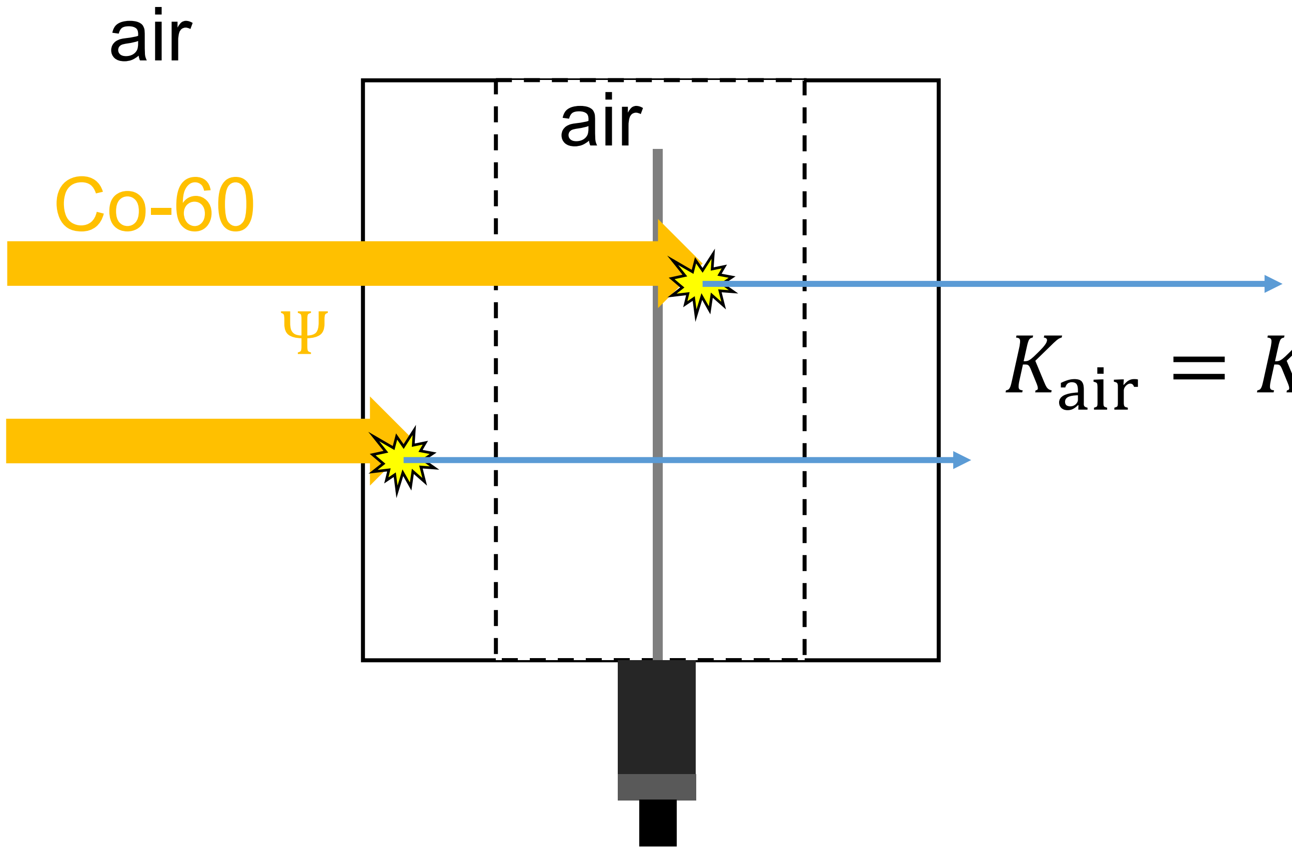
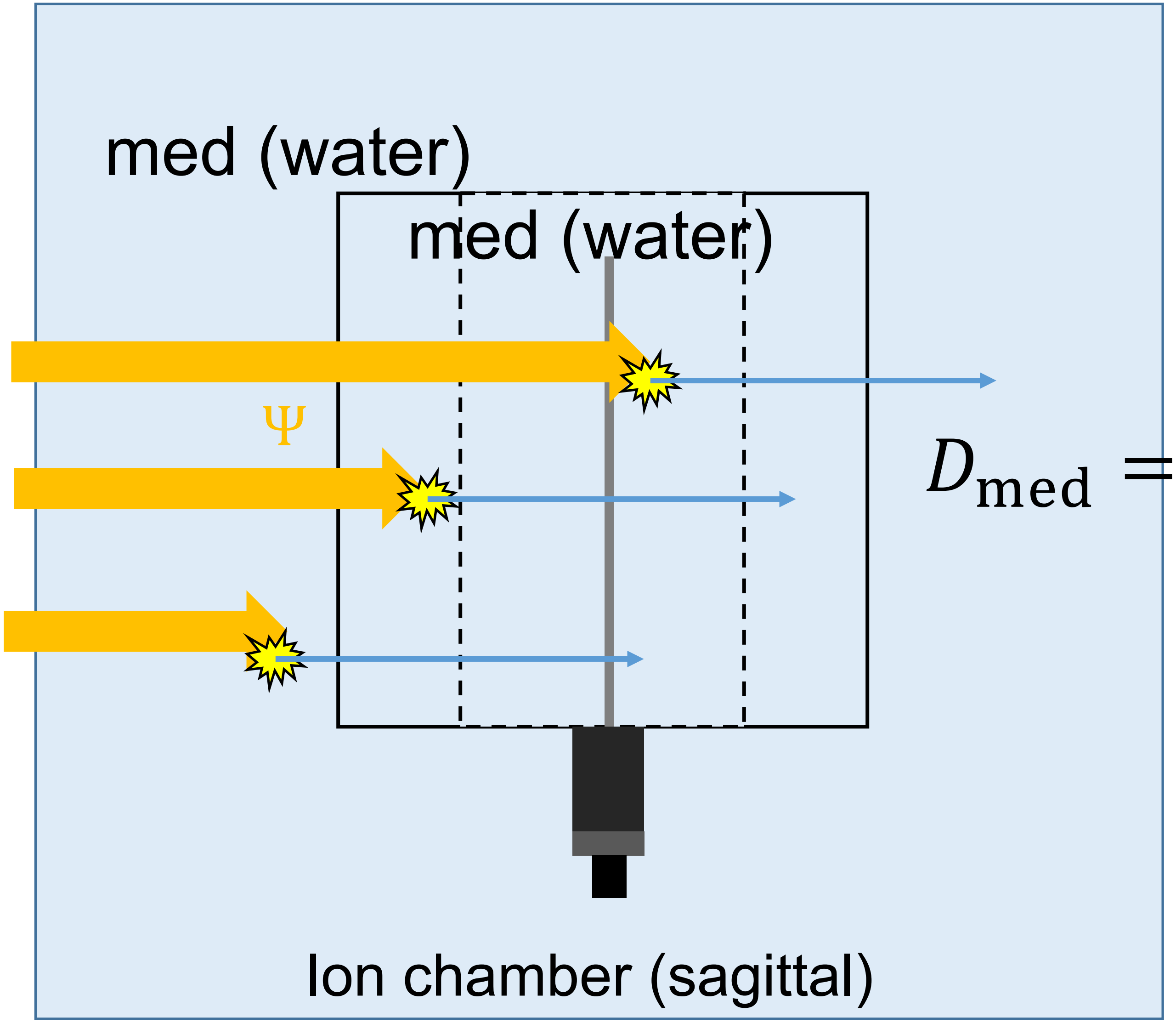


Ion chamber (sagittal)

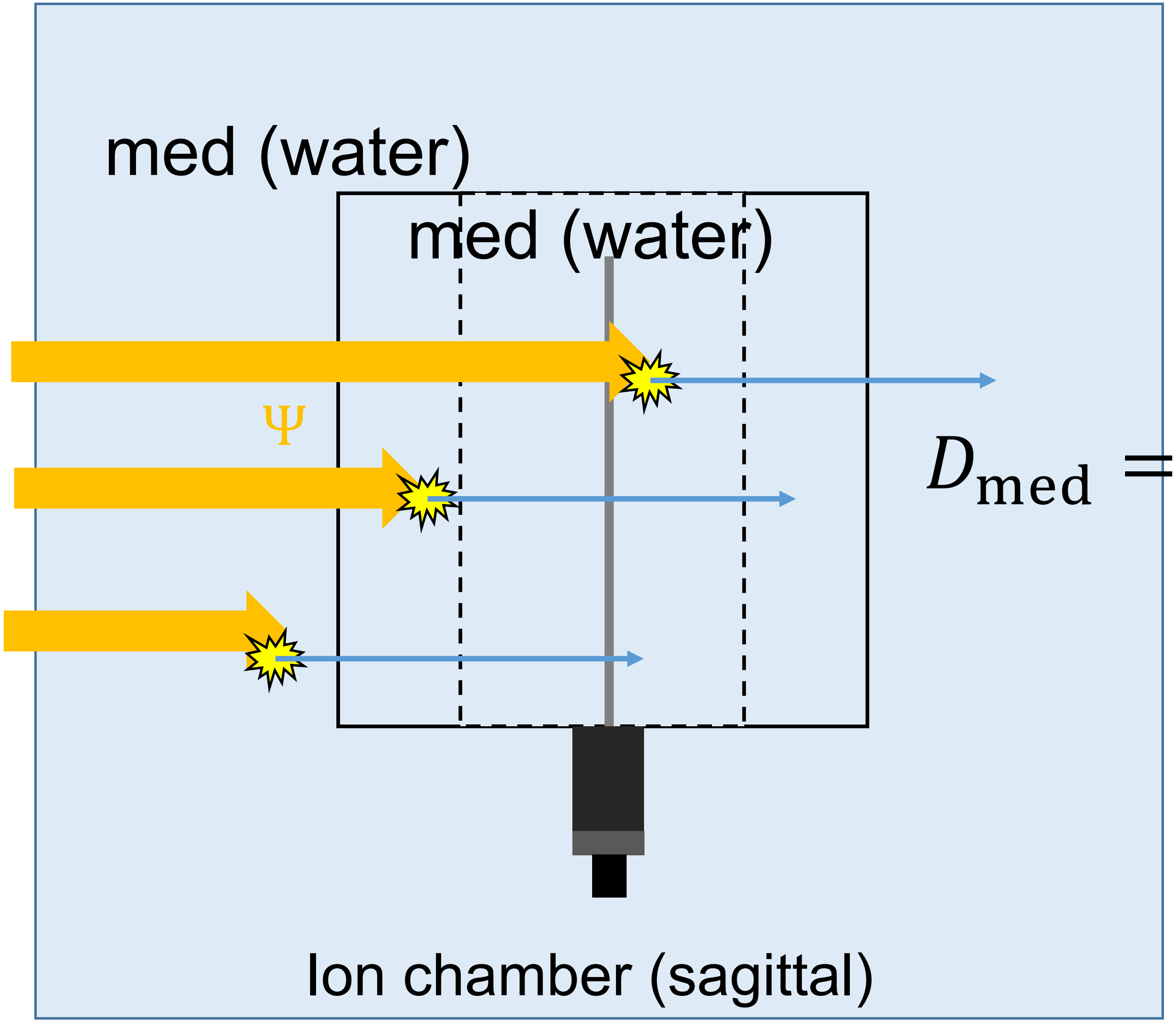
$$K_{\text{air}} = K_{\text{wall}} \left(\overline{\frac{\mu_{ab}}{\rho}} \right)_{\text{wall}}^{\text{air}}$$

Measuring dose via a chamber



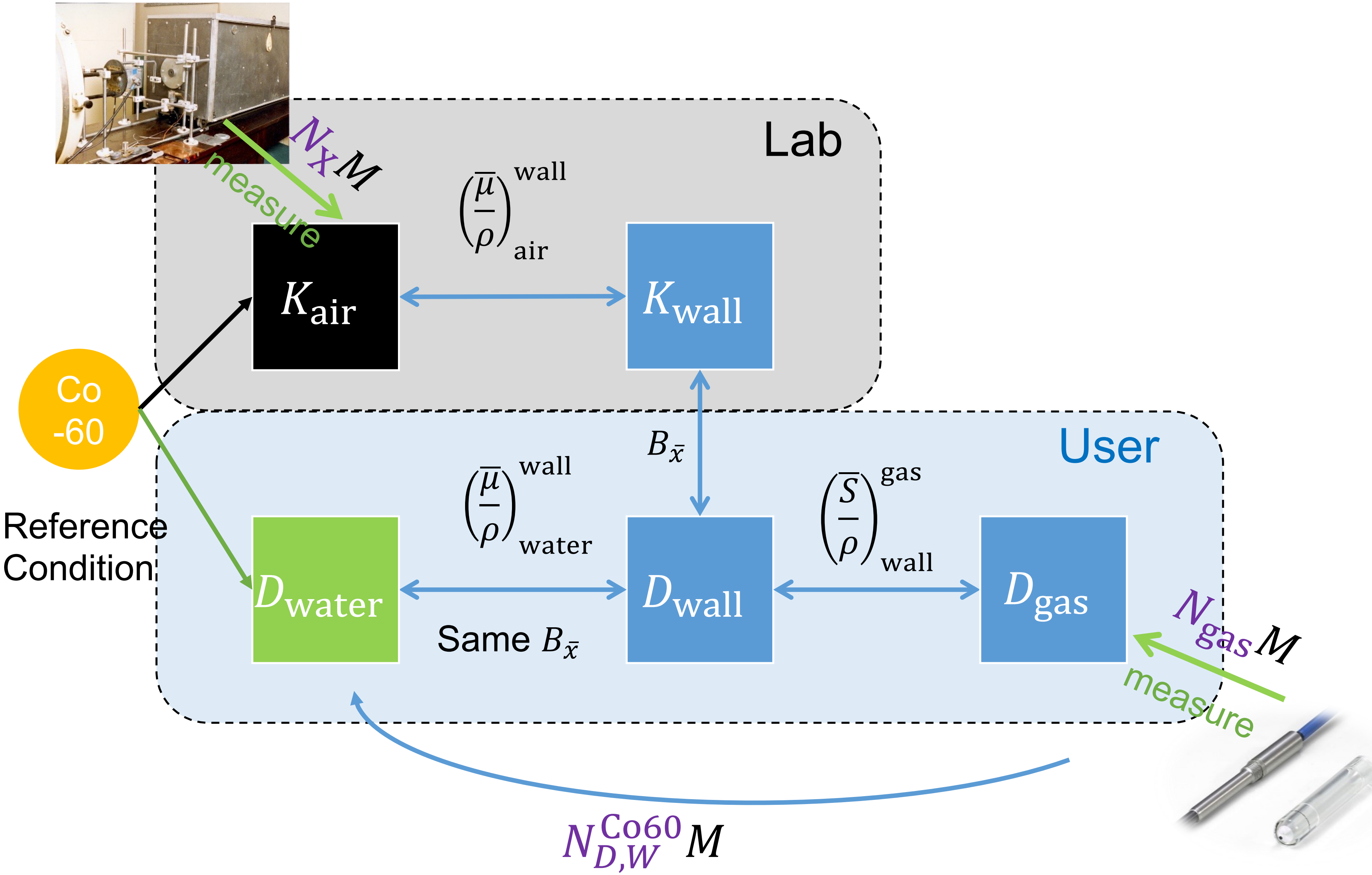
$$D_{\mathrm{med}} = B_{\bar{x}} \Psi \left(\frac{\overline{\mu_{ab}}}{\rho} \right)_{\mathrm{med}}$$

Measuring dose via a chamber



$$D_{\mathrm{med}} = D_{\mathrm{wall}} \left(\frac{\overline{\mu_{ab}}}{\rho}\right)_{\mathrm{wall}}^{\mathrm{med}}$$

Summary of dose measurement



TG-21: Secondary Lab

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recombination attenuation build-up

$$N_{\text{gas}} = N_X \frac{\left(\frac{\overline{W}}{e}\right)_{\text{air}} A_{ion} A_{\text{wall}} B_{\text{wall}}}{\left(\frac{\overline{\mu}}{\rho}\right)_{\text{wall}}^{\text{air}} \left(\frac{\overline{S}}{\rho}\right)_{\text{gas}}^{\text{wall}}}$$

photon perspective

electron perspective

TG-21: User

recombination

Chamber replacing medium

$$N_{\text{gas}} = N_{D,w}^{\text{Co60}} \frac{\left(\frac{\overline{W}}{e}\right)_{\text{air}} A_{ion} A_{\text{repl}}}{\left(\frac{\overline{\mu}}{\rho}\right)_{\text{wall}}^{\text{water}} \left(\frac{\overline{S}}{\rho}\right)_{\text{gas}}^{\text{water}}}$$

Given energy spectrum

photon perspective

electron perspective

User beam

$$N_{D,w}^{Q} = N_{D,w}^{\text{Co60}} k_Q$$

Summary

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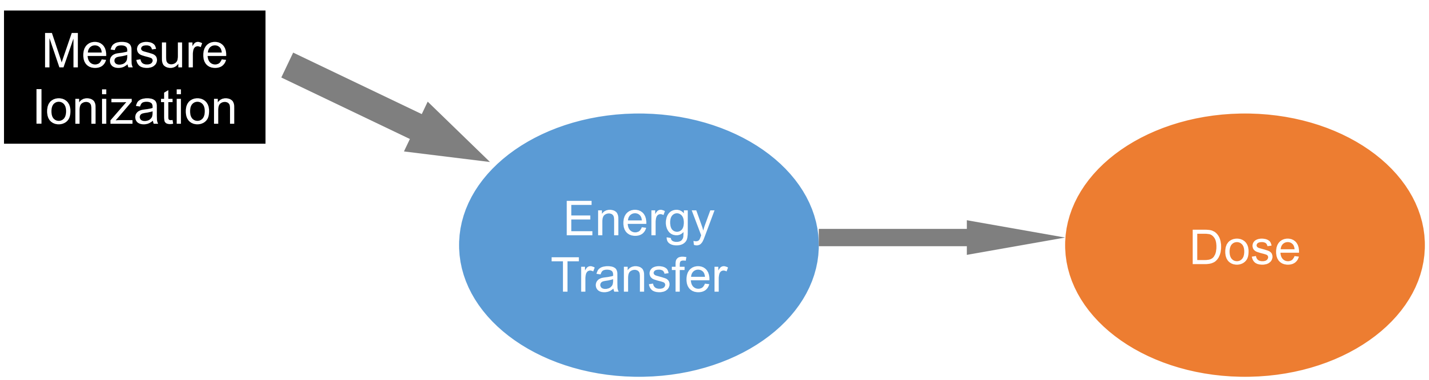
- We demystified TG-21 by understanding the process of energy transfer among radiation and charged particles and the process of dose deposition.
- We utilized cavity theory to measure dose through an ion chamber in the real world.



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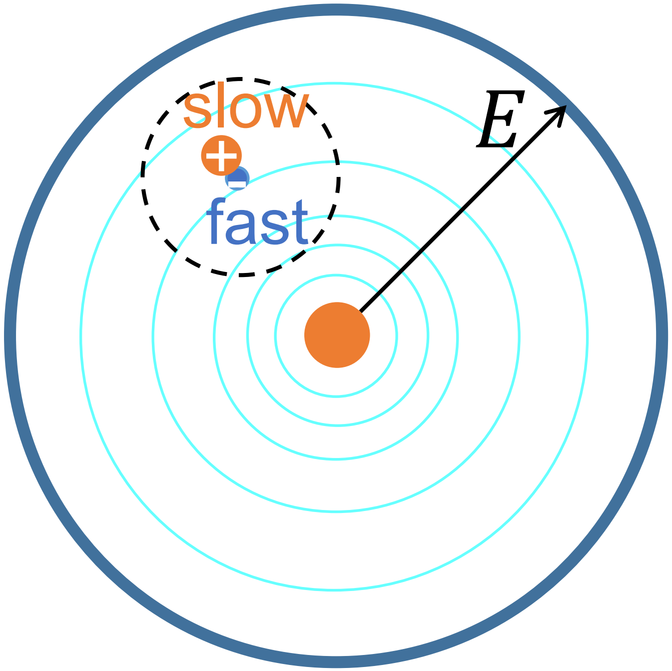
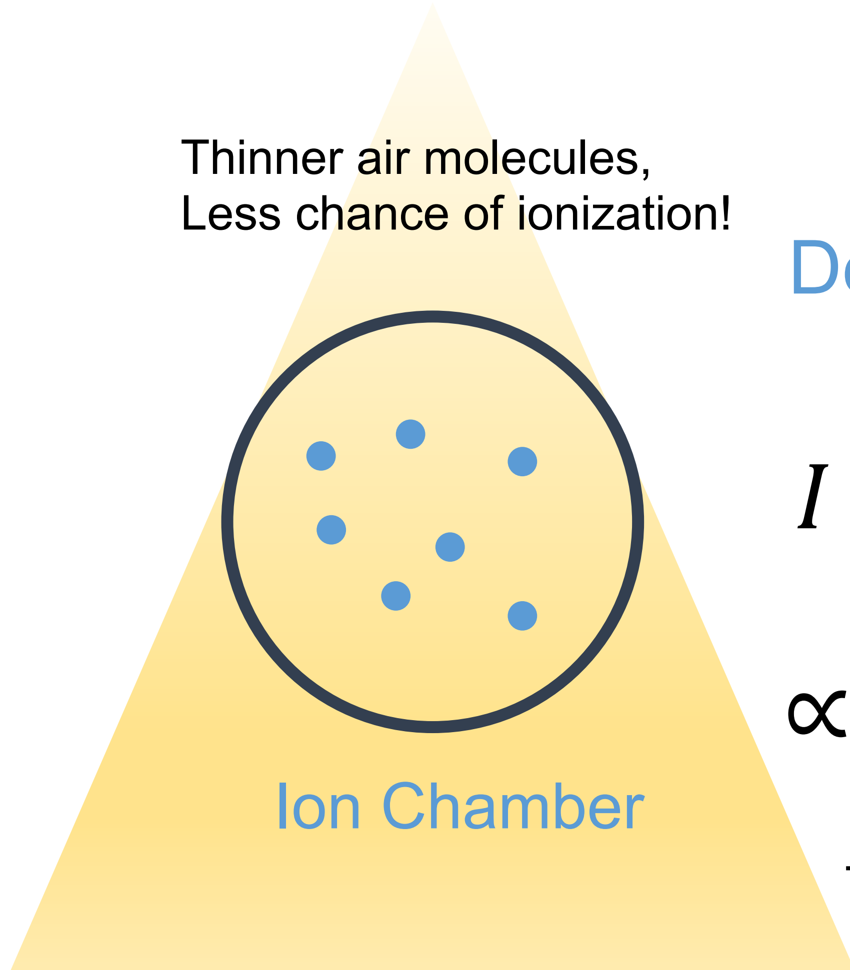
Rotation Mentor: Xiao Wang

Cylindrical chamber: what's good?



What is P_{TP} ?



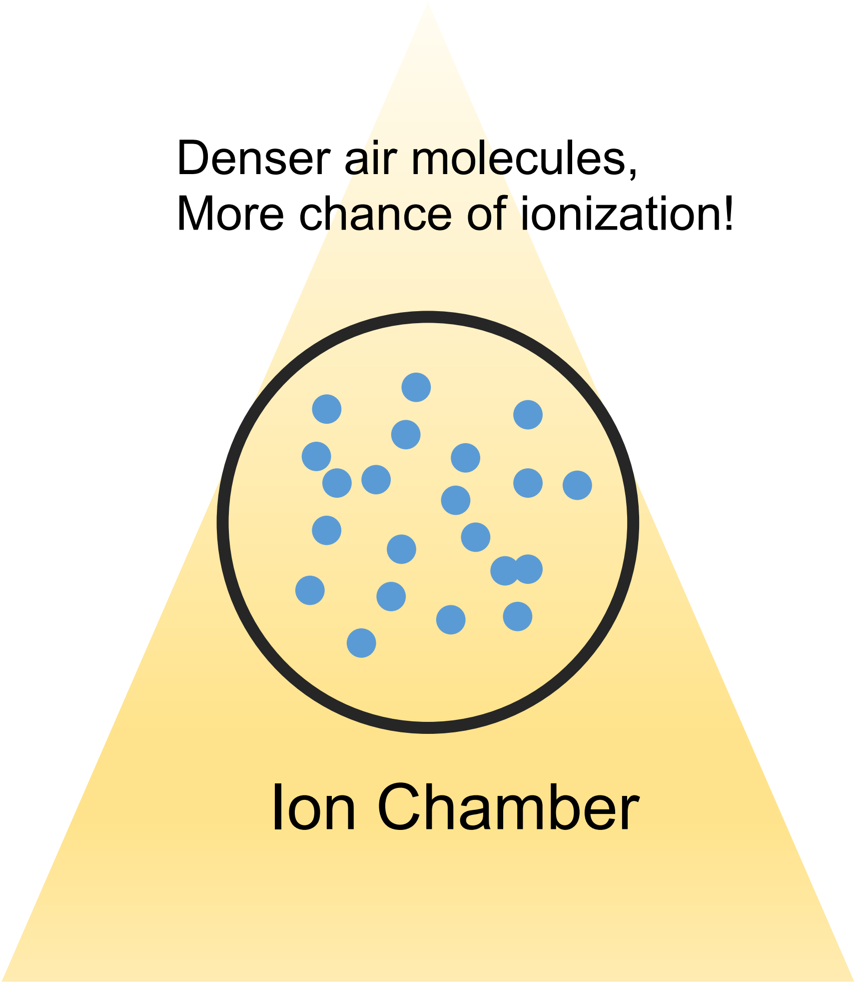
Density of Quantity

$$I \propto \rho = \frac{N}{V}$$

$$\propto \frac{nN_A}{V} \propto n$$

The amount of substance

What is P_{TP} ?



$$I \propto n$$

What is P_{TP} ?

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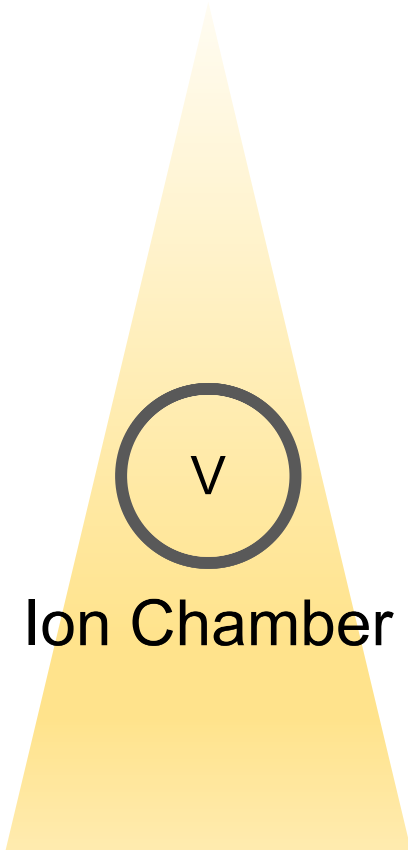
- Ideal gas equation



$$PV = nRT$$

$$n \propto \frac{P}{T} \propto I$$

Air Density

Ionization

What is P_{pol} (polarity effect)?

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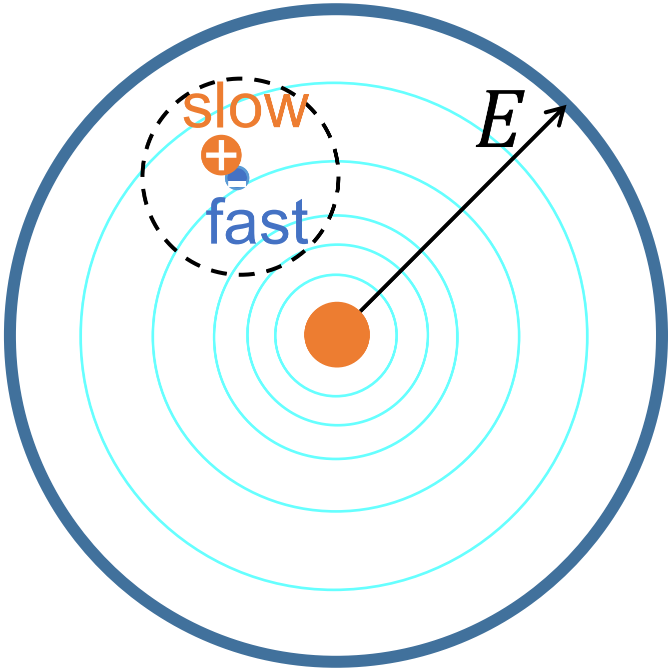
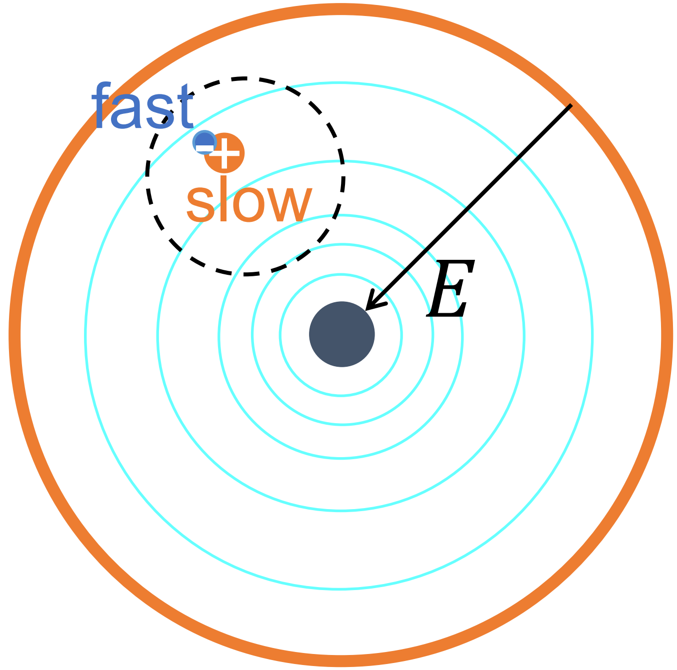
+300 V -300 V

$$P_{ion} = \frac{M_+ - M_-}{2M_+}$$

What is P_{pol} (polarity effect)?

- For a cylindrical chamber





Recombination↑
charge collection time↑
(dead time↑)

Cause (I): the design

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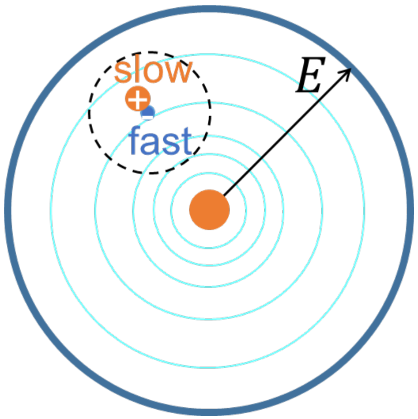
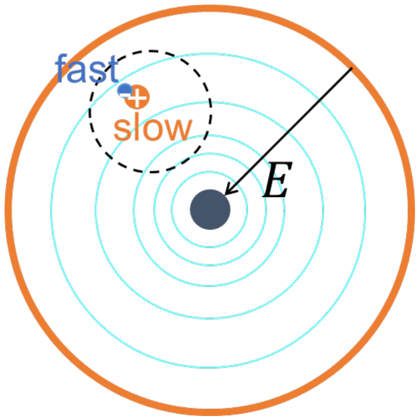
- We are supposed to collect 100 nC.



98 nC



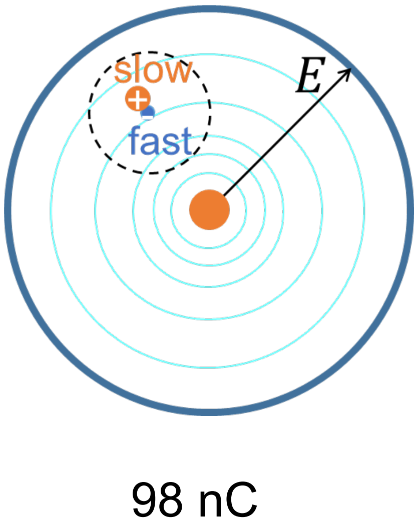
-95 nC

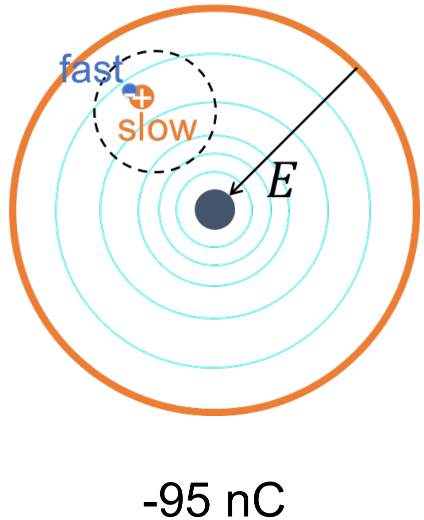
$$M_{corr} = M_{raw}\left(\frac{M_+ - M_-}{2M_+}\right) = 98\times\frac{98+95}{2\times 98} = 98\times 0.985$$

$$= 96.5\, nC$$, even worse!!

Cause (I): the design

- We are supposed to collect 100 nC.





$$M_{corr} = M_{raw}\left(\frac{M_+ - M_-}{2M_+}\right) = 98\times\frac{98+95}{2\times 98} = 98\times 0.985$$

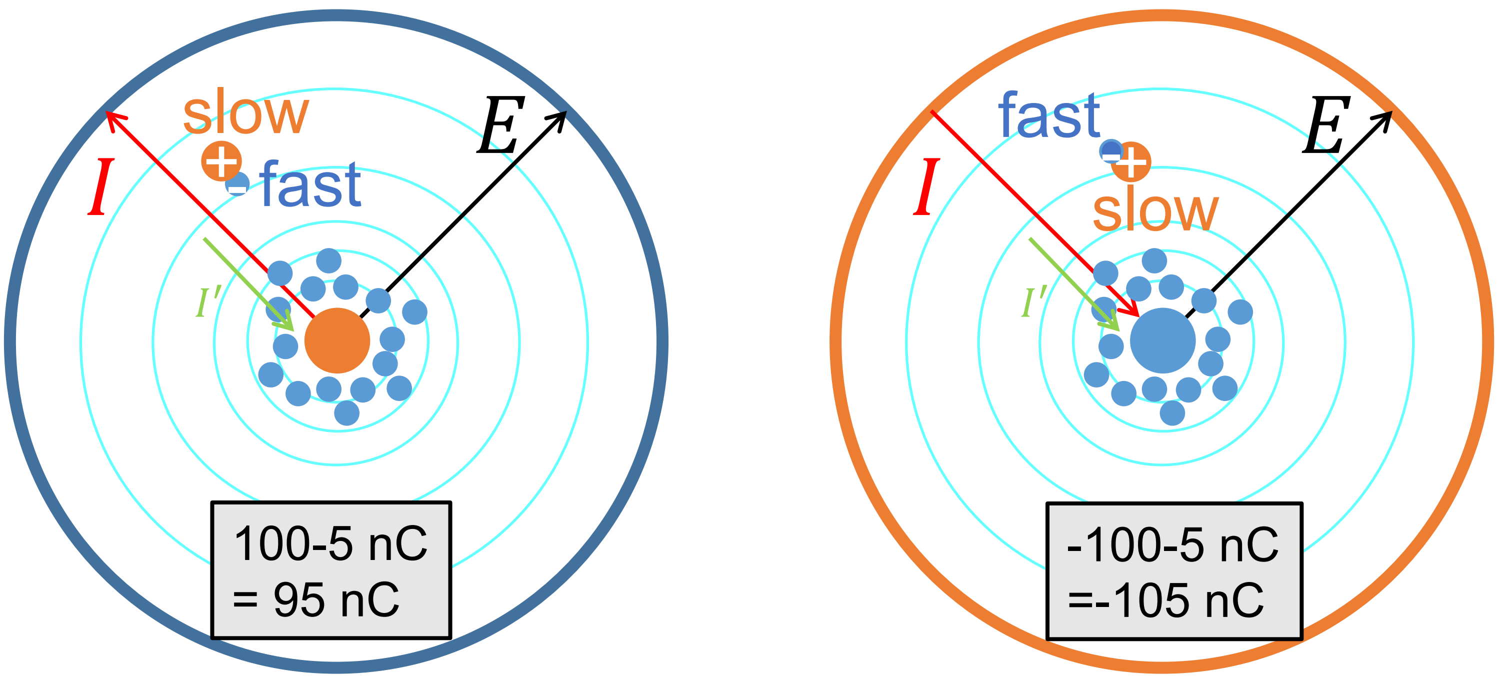
$$= 96.5\, nC$$, even worse!!

Cause (I): the design

- TG-51 is not trying to correct polarity effect related to the chamber design.

Cause (II): Electron Contamination

- We are supposed to collect 100 nC.



$$M_{corr} = M_{raw}\left(\frac{M_+ - M_-}{2M_+}\right) = 95\times\frac{95+105}{2\times 95}$$

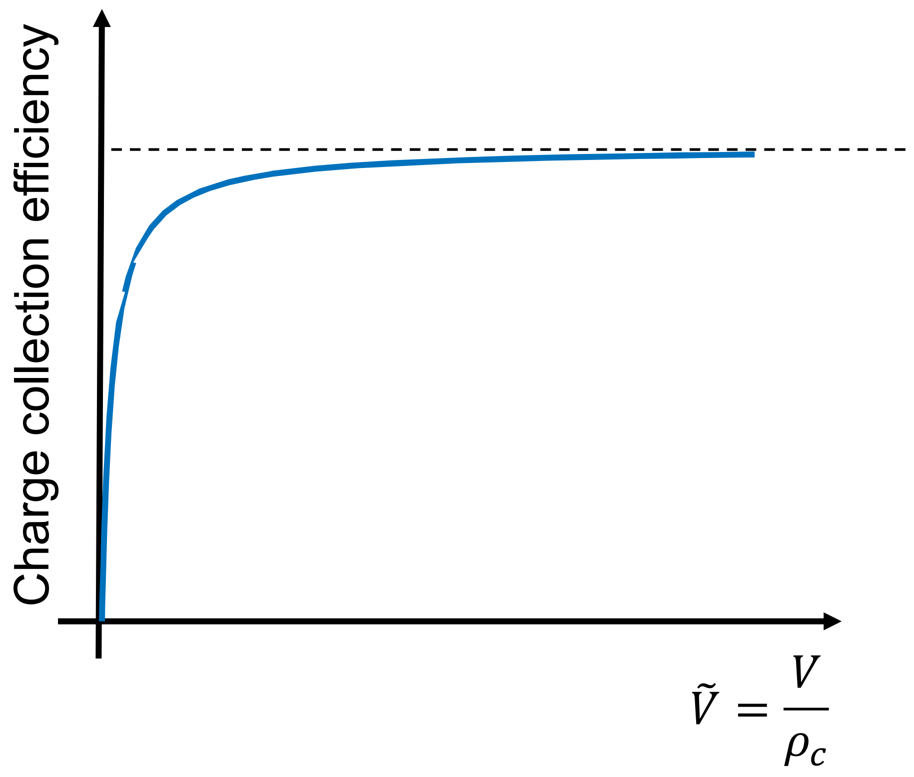
$= 100\ nC$, perfect!!

Cause (II): Electron Contamination

- TG-51 corrects polarity effect related to any type of electric current contamination of <u>a fixed direction.</u>

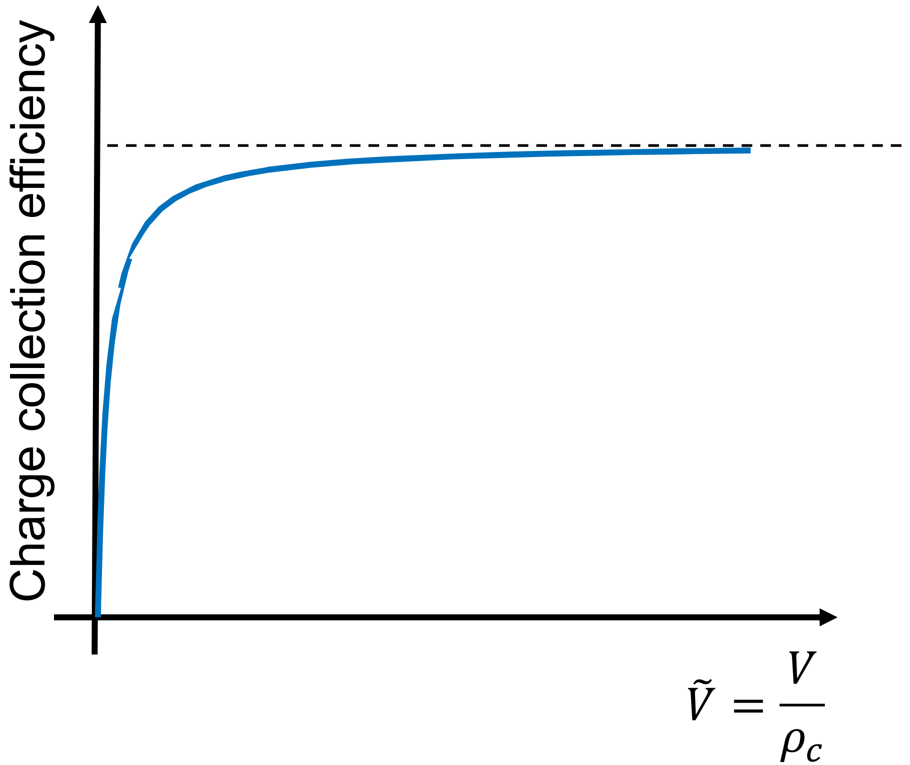
What is P_{ion} (recombination)?

- In principle, how to correct $\boldsymbol{P_{ion}}$?
  - Measure the collected charge at each voltage and then extrapolate to the limit.



What is P_{ion} (recombination)?

- In principle, how to correct $\boldsymbol{P_{ion}}$?
  - Measure the collected charge at each voltage and then extrapolate to the limit.



Theoretical model of P_{ion}.

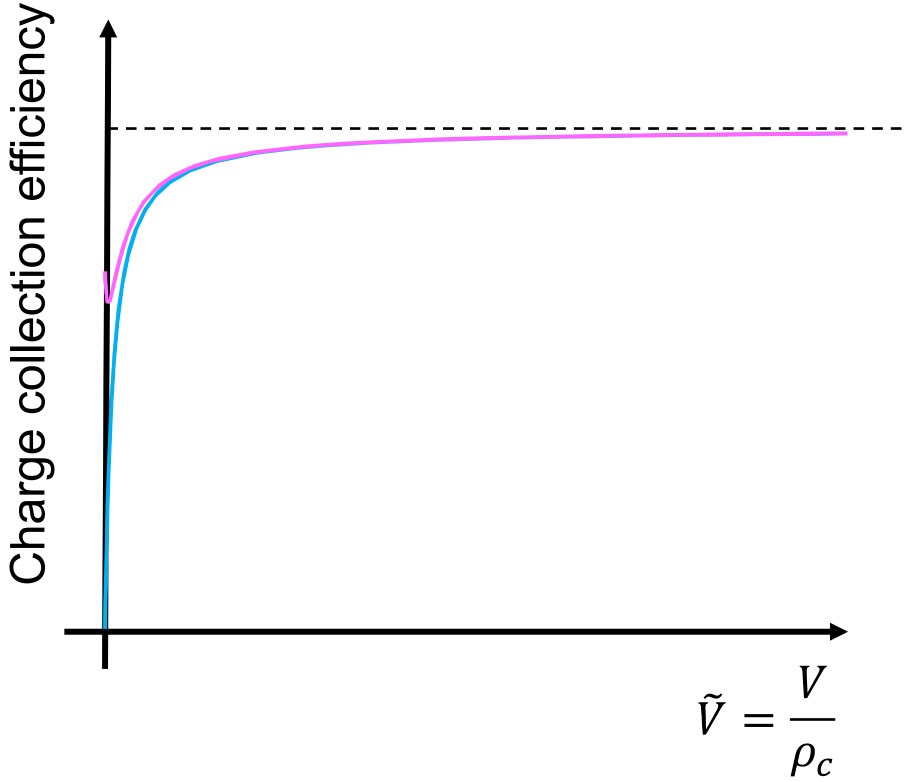
RUTGERS

$$p = \tilde{V} \ln\left(1 + \frac{1}{1+\tilde{V}}\right)$$

$$p = \tilde{V}\left(\frac{1}{1+\tilde{V}}\right) + \frac{3}{4}\left(\frac{1}{1+\tilde{V}}\right)^2 + \cdots$$

Pulsed Beam

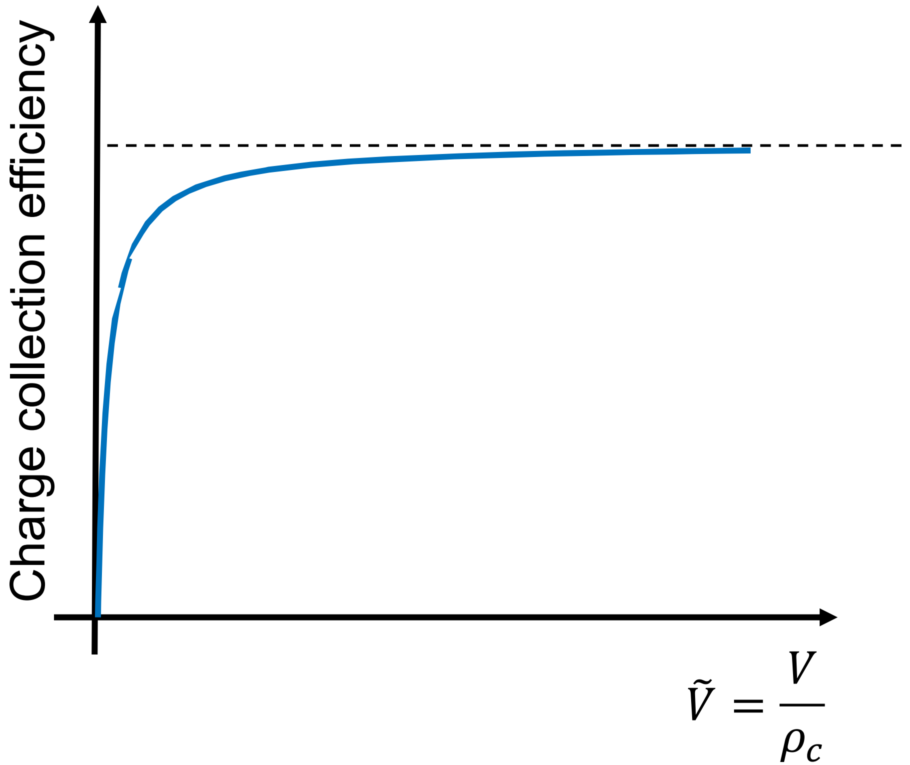
Pulsed-swept Beam



Theoretical model of P_{ion}.

$$p = \frac{\tilde{V}}{1 + \tilde{V}}$$

Charge collection efficiency



How TG-51 correct P_{ion}.

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- Charge collection efficiency:

$$p = \frac{\tilde{V}(\rho)}{1 + \tilde{V}(\rho)}$$

- The so-called "two-voltage" technique:

$$M_H = Cp_H = \frac{\tilde{V}_H(\rho)}{1 + \tilde{V}_H(\rho)} \qquad M_L = Cp_L = \frac{\tilde{V}_L(\rho)}{1 + \tilde{V}_L(\rho)}$$

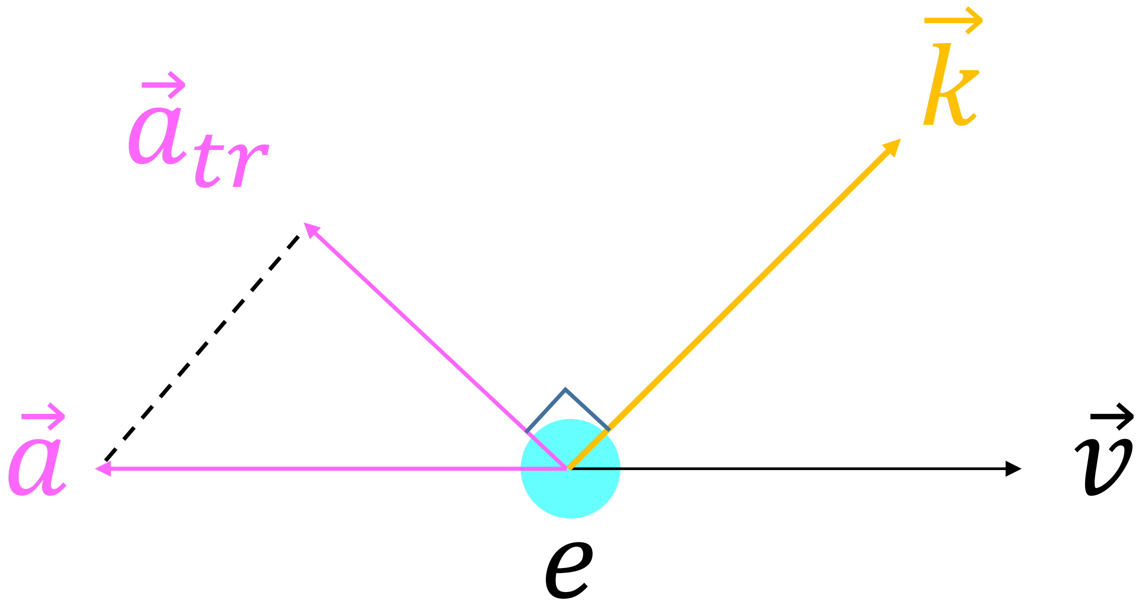
Solve for p_H

How TG-51 correct P_{ion}.

$$p_H = \frac{1 - \frac{V_H}{V_L}}{\frac{M_H}{M_L} - \frac{V_H}{V_L}}$$

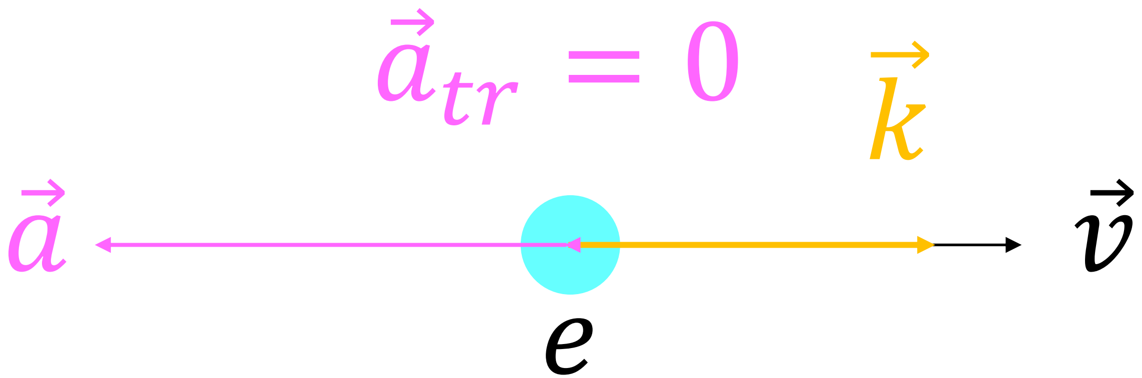
Solve for $\boldsymbol{p_H}$

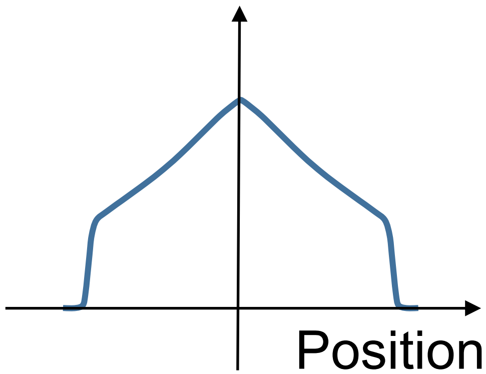
The physical picture of radiation stopping power



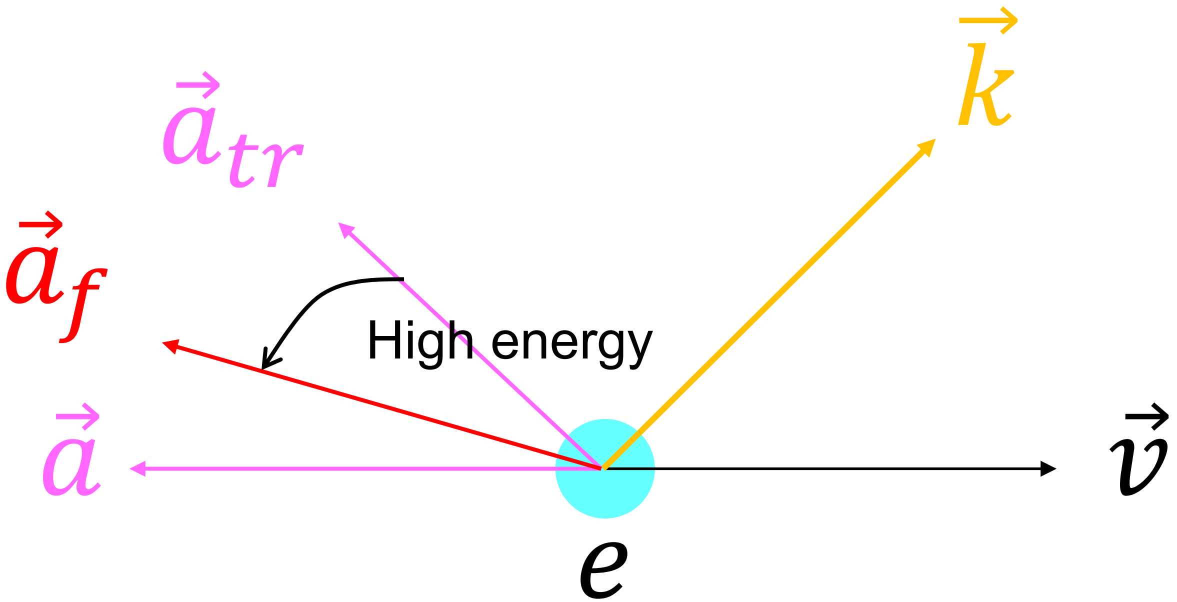
The physical picture of radiation stopping power

RUTGERS

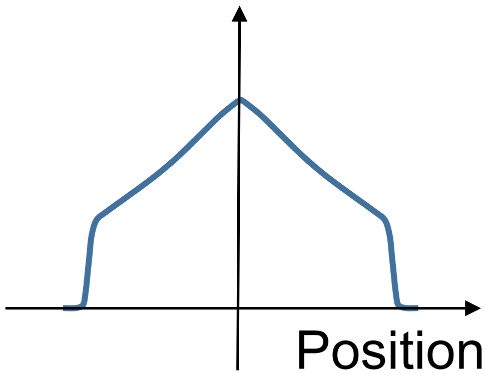




The physical picture of radiation stopping power

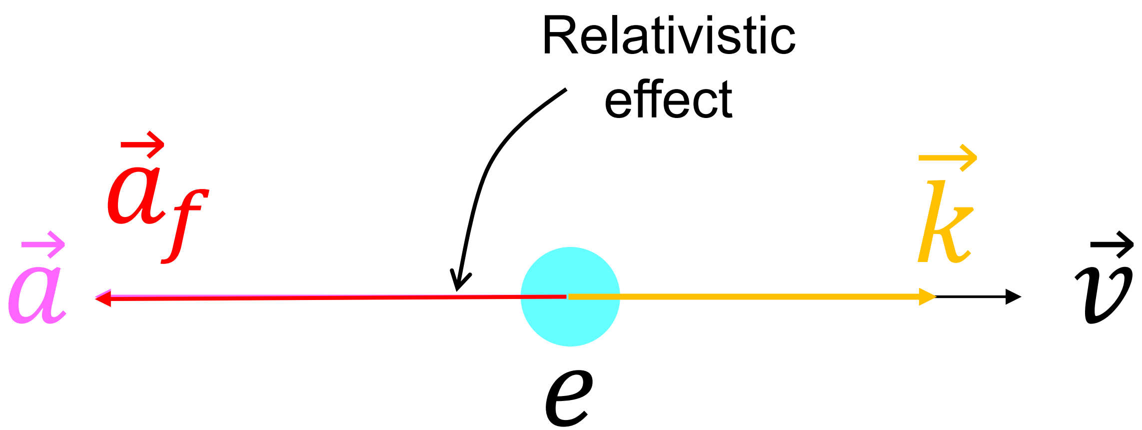


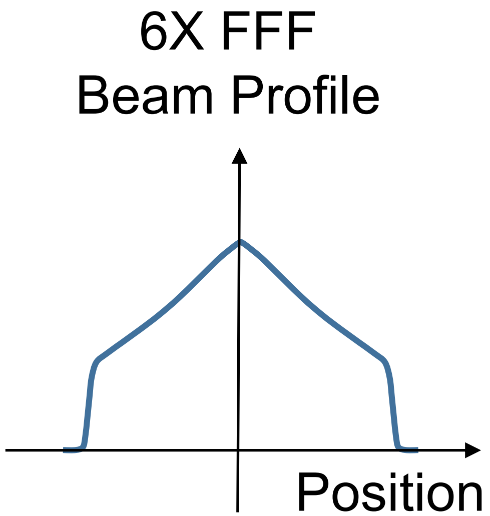
6X FFF
Beam Profile



The physical picture of radiation stopping power

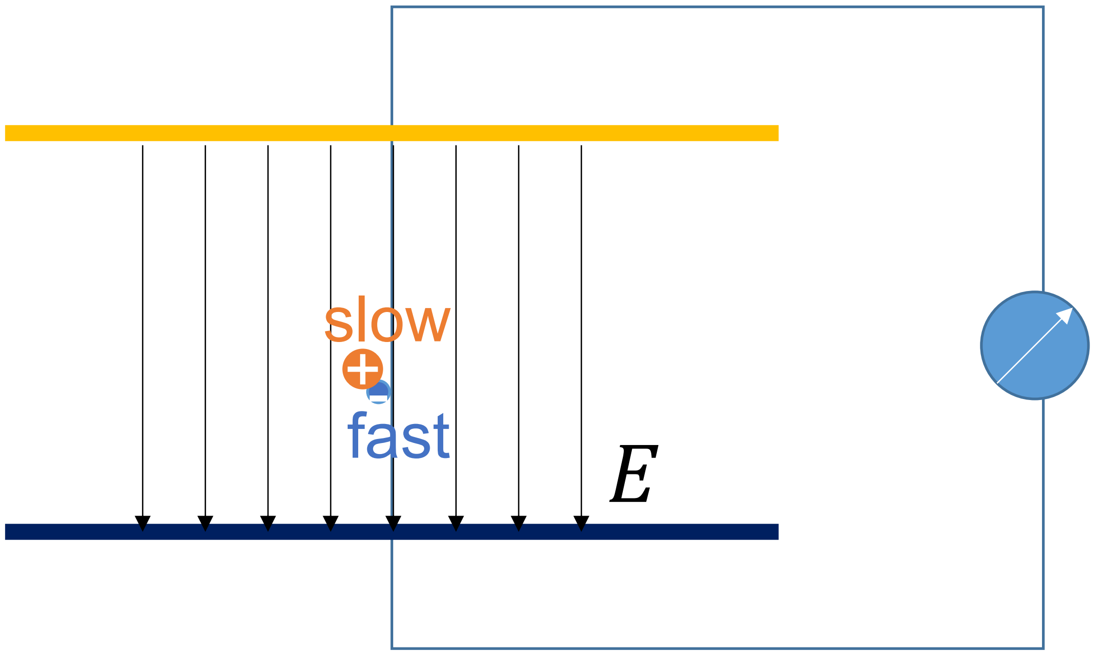
RUTGERS





Electrometer reading corrections

RUTGERS



1e collected

Regardless of the ionization location

$$M = M_{\mathrm{raw}} P_{ion} P_{pol} P_{TP}$$