PHYS 3446 – Lecture #11

Wednesday, Oct. 12, 2016
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- Energy Deposition in Media
  - Charged Particle Detection
  - Ionization Process
  - Photon Energy Loss

Reminder: Assignments

1. Reading assignment: CH 4.3; CH5
2. End of the chapter problems: 3.2
3. Derive the following equations:
   - Eq. 4.8 starting from conservation of energy
   - Eq. 4.11 both the formula

- Due for these homework problems is next Monday, Oct. 16.

Forces in Nature

- We have learned the discovery of two additional forces
  - Gravitational force: formulated through Newton's laws
  - Electro-magnetic force: formulated through Maxwell's equations
  - Strong nuclear force: Discovered through studies of nuclei and their structure
  - Weak force: Discovered and postulated through nuclear β-decay

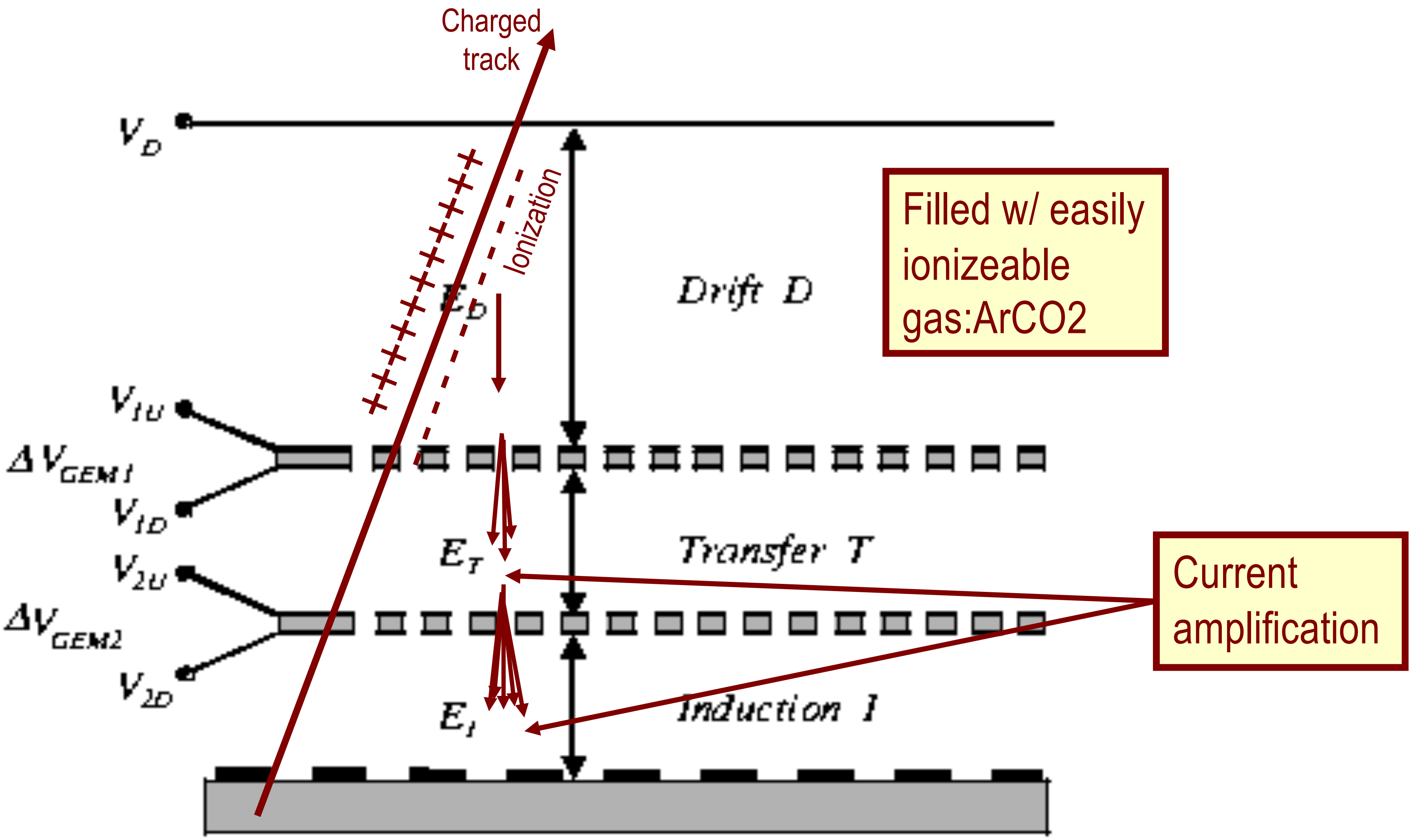
Forewords

- Physics is an experimental science
  - Understand nature through experiments
- In nuclear and particle physics, experiments are performed through scattering of particles
- In order for a particle to be detected:
  - Must leave a trace of its presence ➔ deposit energy

Forewords

- The most ideal detector should
  - Detect particle without affecting them
- Realistic detectors
  - Use electromagnetic interactions of particles with matter
    - Ionization of matter by energetic, charged particles
    - Ionization electrons can then be accelerated within an electric field to produce detectable electric current
  - Sometime catastrophic nuclear collisions but rare
  - Particles like neutrinos which do not interact through EM and have low cross sections, need special methods to handle

How does a charged particle get detected?



C. GEMs

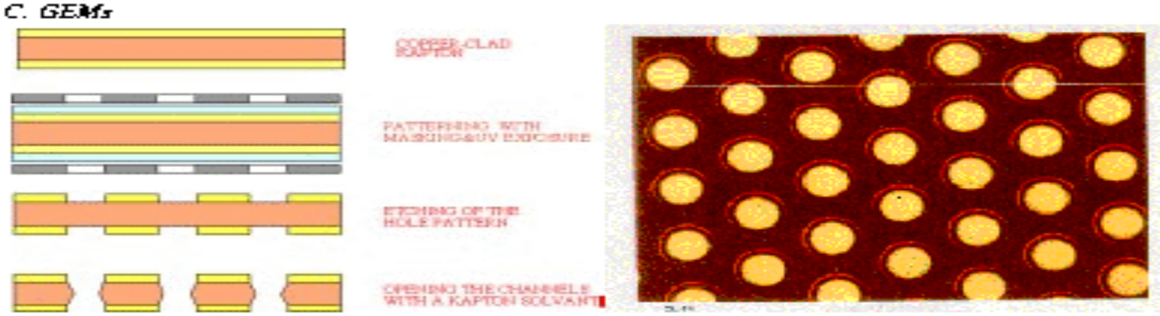
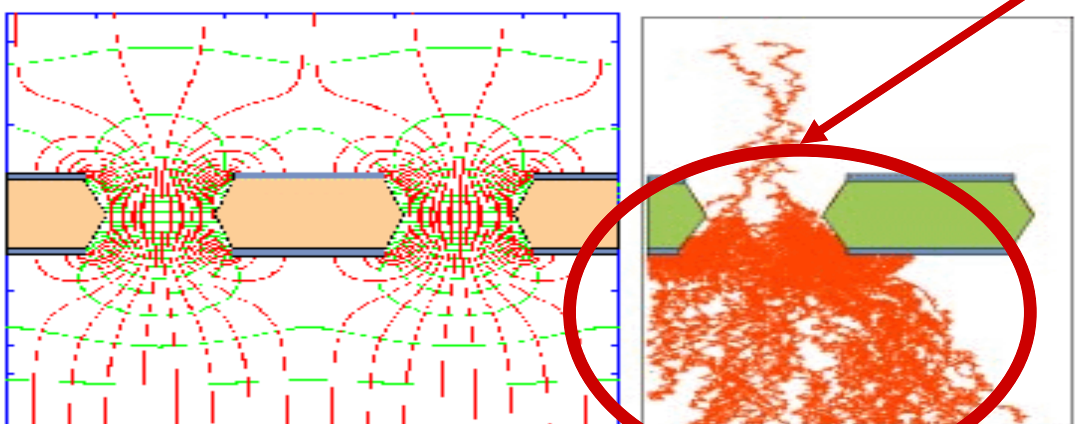


Fig. 14 (a) Chemical etching Process of a GEM (b) A GEM foil

A new concept of gas amplification was introduced in 1996 by Sauli: the Gas Electron multiplier (GEM) [27] manufactured by using standard printed circuit wet etching techniques' schematically shown in Fig. 14(a). Comprising a thin (~50 μm) Kapton foil, double sided clad with Copper, holes are perforated through (fig. 15b). The two surfaces are maintained at a potential gradient, thus providing the necessary field for electron amplification, as shown in Fig. 15(a), and an avalanche of electrons as in Fig. 15(b).

Large amplification



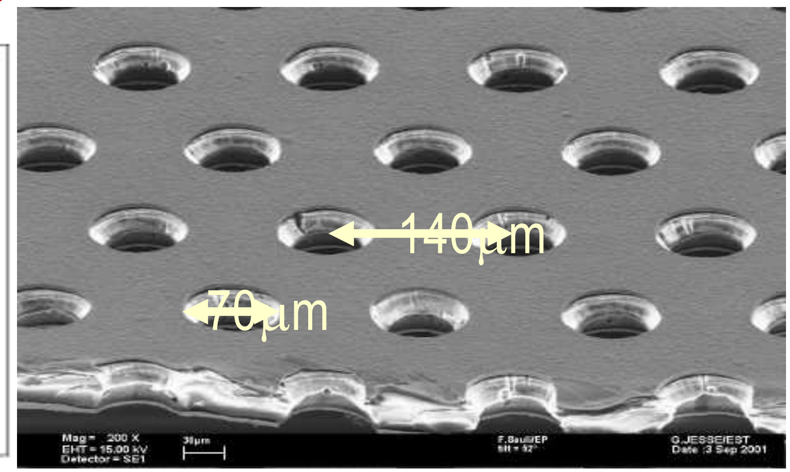
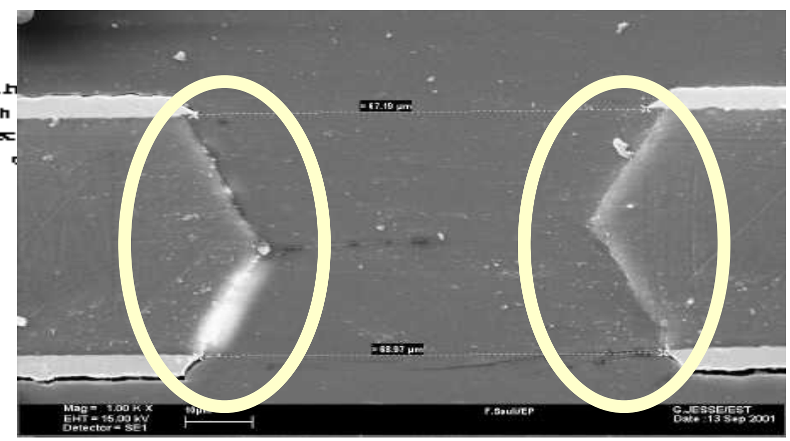


Fig. 15(a) Electric Field and (b) an avalanche across a GEM channel



Coupled with a drift electrode above and a readout electrode below, it acts as a highly perfor[…] micropattern detector. The essential and advantageous feature of this detector is that amplification [...] detection are decoupled, and the readout is at zero potential. Permitting charge transfer to a sec[...] amplification device, this opens up the possibility of using a GEM in tandem with an MSGC o[...] second GEM.

CERN-open-2000-344, A. Sharma

Charged Particle Detection

- What do you think is the primary interaction when a charged particle is traversing through a medium?
  - EM interactions with the atomic electrons in the medium
- If the energy of the charged particle is sufficiently high
  - It deposits its energy (or loses its energy in the matter) by ionizing the atoms in the path **electrons**
  - Or by exciting atoms or molecules to their excited states **photons**
  - What are the differences between the above two methods?
    - The outcomes are either electrons or photons
- If the charged particle is massive, its interactions with atomic electrons will not affect the particles trajectory
- Sometimes, the particle undergoes a more catastrophic nuclear collisions

Ionization Process

- Ionization properties can be described by the stopping power variable, S(T)
  - Definition: amount of kinetic energy lost by any incident particle per unit length of the path traversed in the medium
  - Referred as ionization energy loss or energy loss

$$S(T) = -\frac{dT}{dx} = n_{ion}\bar{I}$$

Why negative sign?

The particle's energy decreases.

- T: Kinetic energy of the incident particle
- n_{ion}: Number of electron-ion pair formed per unit path length
- $\bar{I}$: The average energy needed to ionize an atom in the medium; for large atomic numbers ~10Z eV.

Ionization Process

- What do you think the stopping power of the given medium depends on?
  - Energy of the incident particle
    - Depends very little for relativistic particles
  - Electric charge of the incident particle
- Since ionization is an EM process, easily calculable
  - Bethe-Bloch formula for relativistic particle

$$S(T) = \frac{4\pi (ze)^2 e^2 nZ}{m\beta^2 c^2}\left[\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right) - \beta^2\right]$$

  - z: Incident particle atomic number
  - Z: medium atomic number
  - n: number of atoms in unit volume ($=\rho A_0/A$)
  - m: mass of the incident particle

Ionization Process

- In natural α-decay, the formula becomes

$$S(T) = \frac{4\pi (ze)^2 e^2 nZ}{m\beta^2 c^2}\left[\ln\left(\frac{2mc^2\cancelto{1}{\gamma^2}\beta^2}{\bar{I}}\right) - \cancelto{\sim 0}{\beta^2}\right] \approx \frac{4\pi (ze)^2 e^2 nZ}{m\beta^2 c^2}\ln\left(\frac{2mc^2\beta^2}{\bar{I}}\right)$$

  - Due to its low kinetic energy (a few MeV) and large mass, relativistic corrections can be ignored
- For energetic particles in accelerator experiments or beta emissions, the relativistic corrections are substantial
- Bethe-Bloch formula can be used in many media for various incident particles over a wide range of energies

Ionization Process

- Why does the interaction with atomic electrons dominate the energy loss of the incident particle?
  - Interactions with heavy nucleus causes large change of direction of the momentum but little momentum transfer
    - Does not necessarily require large loss of kinetic energy
  - While momentum transfer to electrons would require large kinetic energy loss
    - Typical momentum transfer to electrons is 0.1MeV/c and requires 10KeV of kinetic energy loss
    - The same amount of momentum transfer to a gold nucleus would require less than 0.1eV of energy loss
- Thus Bethe-Bloch formula is inversely proportional to the mass of the particle

$$S(T)=\frac{4\pi(ze)^2e^2nZ}{m\beta^2c^2}\left[\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right)-\beta^2\right]$$

Ionization Process

- At low particle velocities, ionization loss is sensitive to particle energy. How do you see this?

$$S(T)=\frac{4\pi(ze)^2e^2nZ}{m\beta^2c^2}\left[\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right)-\beta^2\right]$$

  - Stopping power decreases as v increases!!

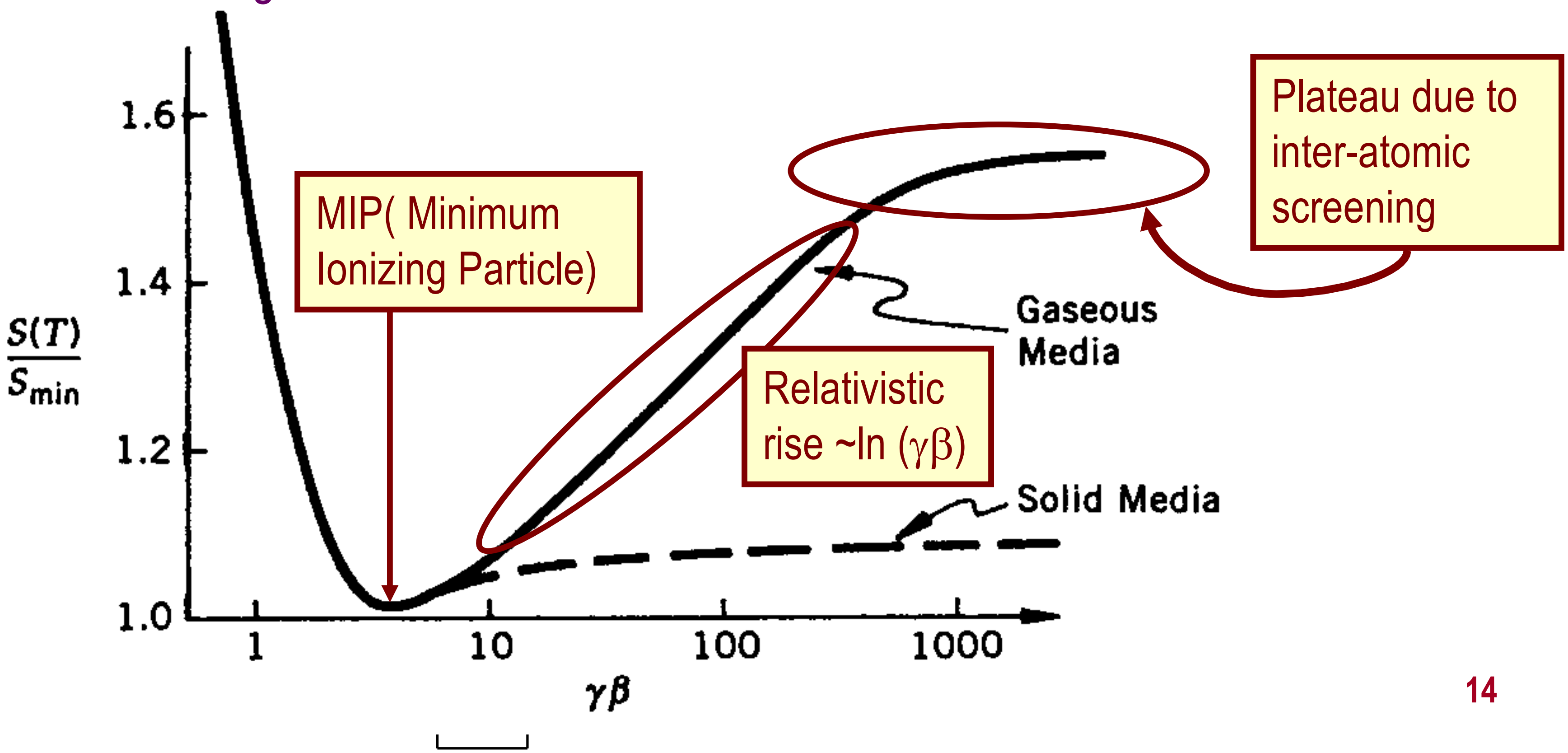
- This shows that the particles of different rest mass (M) but the same momentum (p) can be distinguished due to their different energy loss rate

$$S(T)\propto\frac{1}{v^2}=\frac{1}{(\beta c)^2}=\frac{M^2\gamma^2}{(M\gamma\beta c)^2}=\frac{M^2\gamma^2}{p^2}$$

- At low velocities (γ~1), particles can be distinguished

Properties of Ionization Process

- The stopping power decreases with increasing particle velocity independent of incident particle mass
  - Minimum occurs when $\gamma\beta$~3
    - Particle is minimum ionizing when v~0.96c
    - For massive particles the minimum occurs at higher momenta
  - This is followed by a ln($\gamma\beta$) relativistic rise by Beth-Bloch formula
  - Energy loss plateaus at high $\gamma\beta$ due to long range inter-atomic screening effect which is ignored in Beth-Bloch



Ionization Process

- At very high energies
  - Relativistic rise becomes an energy independent constant rate
  - Cannot be used to distinguish particle-types purely using ionization
  - Except for gaseous media, the stopping power at high energies can be approximated by the value at $\gamma\beta \sim 3$.
- At low energies, the stopping power expectation becomes unphysical
  - Ionization loss is very small when the velocity is very small
  - Detailed atomic structure becomes important

Ranges of Ionization Process

- Once the stopping power is known, we can compute the expected **range** of any particle in the medium
  - The distance an incident particle can travel in a medium before its kinetic energy runs out

$$R = \int_0^R dx = \int_T^0 \frac{dx}{dT} dT = \int_0^T \frac{dT}{S(T)}$$

- At low E, two particles with the same KE but different masses can have very different ranges
  - This is why α and β radiations have quite different requirements to stop

Units of Energy Loss and Range

- What would be the sensible unit for energy loss?
  - MeV/cm
  - Equivalent thickness of g/cm^2: MeV/(g/cm^2)
- Range is expressed in
  - cm or g/cm^2
- Minimum value of S(T) for z=1 at $\gamma\beta$=3 is

$$S(T)_{\min} \approx -\frac{4\pi e^4 A_0 \left(\rho Z/A\right)}{m\beta^2 c^2}\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right) \approx 5.2\times 10^{-7}\left(13.7-\ln Z\right)\rho Z/A \text{ erg/cm}$$

- Using <Z>=20 we can approximate

$$S(T)_{\min} \approx 3.5\frac{Z}{A}\text{ MeV/}\left(\text{g/cm}^2\right)$$

Straggling, Multiple Scattering and Statistical process

- Phenomenological calculations can describe average behavior but large fluctuations are observed in an event-by-event bases
  - This is due to the statistical nature of the scattering process
    - Finite dispersion of energy deposit or scattering angular distributions is measured
- Statistical effect of angular deviation experienced in Rutherford scattering off atomic electrons in the medium
  - Consecutive collisions add up in a random fashion and provide net deflection of any incident particles from its original path
  - Called "Multiple Coulomb Scattering" ➔ Increases as a function of path length

$$\theta_{rms} \approx \frac{20MeV}{\beta pc} z \sqrt{\frac{L}{X_0}}$$

    - z: charge of the incident particle, L: material thickness, X_0: the radiation length of the medium

Ex: Multiple Scattering Angles

- Compare the multiple scattering angles of 5MeV proton to 5MeV electron through 1cm of Ar gas whose radiation length is 105m at atmospheric pressure and 0°C.
- For proton which is non-relativistic

$$p_p = \sqrt{2M_pT_p} = \sqrt{2\cdot 1000\,MeV/c^2\cdot 5\,MeV} \approx 100\,MeV/c$$

$$v_p = \sqrt{2T_p/M_p} = \sqrt{2\cdot 5\,MeV/1000\,MeV/c^2} \approx 0.1c$$

$$\theta_{rms} \approx \frac{20MeV}{\beta pc} z\sqrt{\frac{L}{X_0}} = \frac{20}{0.1\cdot 100}\cdot 1\cdot\sqrt{\frac{0.01}{105}} \approx 0.02rad \approx 20mrad$$

- For the electron which is relativistic

$$p_e = \frac{E}{c} = \frac{T+m_ec^2}{c} \approx 5.5\,MeV/c \qquad \beta \sim 1$$

$$\theta_{rms} \approx \frac{20MeV}{\beta pc} z\sqrt{\frac{L}{X_0}} = \frac{20}{1\cdot 5.5}\cdot 1\cdot\sqrt{\frac{0.01}{105}} \approx 0.04rad \approx 40mrad$$