



## **explain energy stored per unit volume in a parallel plate capacitor** Class 12th Physics | Electrostatic Potential & Capacitance ↳ Super One Shot | By Ashu Sir - YouTube

The energy stored per unit volume in a parallel plate capacitor is given by the formula  $\frac{1}{2}\epsilon_0 E^2$ , where  $\epsilon_0$  is the permittivity of free space and  $E$  is the electric field between the plates.<sup>[1]</sup>

### **Energy Stored in a Capacitor**

When a capacitor is charged, it stores energy in the electric field created between the plates. The total energy stored ( $U$ ) in a capacitor can be written in three equivalent ways:

- $U = \frac{1}{2}CV^2$
- $U = \frac{1}{2}QV$
- $U = \frac{Q^2}{2C}$

Where:

- $C$  is capacitance,
- $V$  is potential difference,
- $Q$  is the charge.

For a parallel plate capacitor, the capacitance is  $C = \epsilon_0 \frac{A}{d}$  with area  $A$  and plate separation  $d$ .<sup>[1]</sup>

### **Derivation for Energy Per Unit Volume**

First, recall that the electric field between the plates is  $E = \frac{V}{d}$ . The volume between the plates is  $Ad$ , so energy per unit volume is:

$$\text{Energy per unit volume} = \frac{U}{Ad}$$

Substitute  $U = \frac{1}{2}CV^2$  and  $C = \epsilon_0 \frac{A}{d}$ :

$$U = \frac{1}{2} \left( \epsilon_0 \frac{A}{d} \right) V^2$$

$$\frac{U}{Ad} = \frac{1}{2}\epsilon_0 \frac{V^2}{d^2}$$

But since  $E = \frac{V}{d}$ , we get:

$$\frac{U}{Ad} = \frac{1}{2}\epsilon_0 E^2$$

## Physical Meaning

- This formula expresses that the energy is not just stored overall, but actually distributed in the electric field filling the space between the plates.
- The energy density increases with a stronger electric field.
- This result also applies generally to uniform electric fields in free space, not just to parallel plate capacitors.<sup>[1]</sup>

## Final Formula

$$\text{Energy stored per unit volume} = \frac{1}{2}\epsilon_0 E^2$$

Where  $\epsilon_0$  is approximately  $8.85 \times 10^{-12}$  F/m, and  $E$  is measured in volts per meter.<sup>[1]</sup>

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## from where $C = \epsilon_0 A/d$

The formula  $C = \epsilon_0 \frac{A}{d}$  for the capacitance of a parallel plate capacitor comes from the relationship between electric field, potential difference, and the definition of capacitance. When two large plates of area  $A$  are separated by a distance  $d$ , the capacitance is derived using these steps:

- The charge on each plate is  $Q$  and the plates have opposite signs.
- The electric field between the plates is  $E = \frac{\sigma}{\epsilon_0}$ , where  $\sigma = Q/A$ .
- The potential difference is  $V = Ed = \frac{Qd}{\epsilon_0 A}$ .
- Capacitance is defined as  $C = \frac{Q}{V}$ .
- Substituting,  $C = \frac{\epsilon_0 A}{d}$ .<sup>[3] [4] [5]</sup>

This formula assumes the plates are large and closely spaced, and the space between them is filled with air or vacuum.

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# Capacitance of Parallel Plate Capacitor With Dielectric Slab

When a **dielectric slab** is inserted between the plates of a parallel plate capacitor, the capacitance changes because the slab reduces the effective electric field (and potential difference) inside.

## Step-by-Step Derivation

### 1. Without Dielectric: Basic Capacitance

For plates of area  $A$  and separation  $d$ :

$$C_0 = \epsilon_0 \frac{A}{d}$$

where  $\epsilon_0$  is the permittivity of free space.

### 2. With Dielectric Slab (Thickness $t$ , Dielectric Constant $K$ )

- The region between plates is split into two:
  - **Region 1:** Air/vacuum of thickness  $d - t$
  - **Region 2:** Dielectric slab of thickness  $t$
- Electric field in region 1:  $E_0$ .
- Electric field inside dielectric (region 2):  $E = \frac{E_0}{K}$ , because dielectric reduces field by  $K$ .
- **Total potential difference between plates:**

$$V = E_0(d - t) + Et = E_0(d - t) + \frac{E_0}{K}t = E_0 \left[ (d - t) + \frac{t}{K} \right]$$

- Substitute  $E_0 = \frac{Q}{A\epsilon_0}$ :

$$V = \frac{Q}{A\epsilon_0} \left[ (d - t) + \frac{t}{K} \right]$$

- **Capacitance (definition):**  $C = \frac{Q}{V}$

$$C = \frac{Q}{\frac{Q}{A\epsilon_0} \left[ (d - t) + \frac{t}{K} \right]} = \frac{A\epsilon_0}{(d - t) + t/K}$$

### 3. Special Cases

- If the slab completely fills the space ( $t = d$ ):

$$C = \epsilon_0 \frac{A}{d} K = KC_0$$

## 4. Physical Meaning

- **Dielectric increases capacitance:** The slab allows the capacitor to store more charge for the same potential difference, thanks to its property  $K > 1$ .
- The more space the slab occupies, or the higher its dielectric constant, the higher the capacitance.

### Quick Summary:

- The capacitance increases when a dielectric slab is introduced.
- Final formula with slab of thickness  $t$ :

$$C = \frac{A\epsilon_0}{(d - t) + \frac{t}{K}}$$

- If the dielectric fills the entire gap ( $t = d$ ), then  $C = KC_0$ .

If you want a visual, or have a specific case (say, multiple slabs), let me know! Could you restate the final formula now, or tell me what changes if  $t = d$ ?

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## whats d-t

In the formula for a parallel plate capacitor with a dielectric slab,  $d - t$  refers to the thickness of the region between the plates that is *not* filled by the slab.<sup>[23]</sup> <sup>[24]</sup>

- $d$ : the total distance (separation) between the plates of the capacitor.
- $t$ : the thickness of the dielectric slab inserted between the plates, where  $t < d$ .

So,  $d - t$  gives the remaining distance between the plates that still has air (or vacuum), not the dielectric. For example, if the plates are 4 mm apart ( $d = 4$  mm) and the inserted slab is 3 mm thick ( $t = 3$  mm), then  $d - t = 1$  mm of the gap will be air and  $t = 3$  mm will be dielectric slab.<sup>[25]</sup>

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## from where the k came

The  $K$  in the formula is called the **dielectric constant** (also known as relative permittivity). It measures how much a material increases the capacitance of a capacitor compared to air or vacuum.<sup>[33]</sup> <sup>[34]</sup> <sup>[35]</sup>

- **Definition:**  $K = \frac{C_{\text{material}}}{C_{\text{vacuum}}}$ , where  $C_{\text{material}}$  is the capacitance with the dielectric slab, and  $C_{\text{vacuum}}$  is the capacitance with air or vacuum.
- Alternatively:  $K = \frac{\epsilon}{\epsilon_0}$ , where  $\epsilon$  is the permittivity of the dielectric, and  $\epsilon_0$  is the permittivity of free space.

- $\epsilon_0$  is always greater than or equal to 1 and is a **property of the material** used as the dielectric.

A dielectric constant greater than 1 means the material increases the capacitor's ability to store charge compared to air.<sup>[35]</sup> [33]

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## whats C<sub>0</sub> there in the end

In the context of the capacitor formulas,  $C_0$  stands for the capacitance of a parallel plate capacitor when there is **no dielectric** between the plates—meaning the space is filled only with air or vacuum.<sup>[43]</sup> [44] [45]

- Its formula is  $C_0 = \epsilon_0 \frac{A}{d}$ .
  - $\epsilon_0$ : permittivity of free space
  - A: area of each plate
  - d: distance between plates

When a dielectric is added, the capacitance increases, and  $C_0$  is used as the reference or "original" capacitance (without the dielectric) for comparison.<sup>[45]</sup> [43]

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