

good morning to all of you we were discussing ah magnetization in materials so let us recall that if you place a medium in a magnetic field that magnetic field induces magnetic dipoles or magnetizes the material and the magnetized material consists of a large number of tiny magnetic dipoles and these magnetic dipoles then generate their own magnetic field

so if you place a material in a magnetic field then the magnetic field gets altered and we are trying to discuss how do we incorporate this and calculate the magnetic field in the presence of material the problem is very similar to what we had done in electrostatics where we had looked at the problem of putting a dielectric inside an electric field

so when you place a dielectric inside an electric field the electric field polarizes the medium that means makes tiny electric dipoles in the medium and those tiny dipoles then generate their own electric fields and the total electric field that you observe is the sum of the electric field that you are applying and the electric field generated by the tiny dipoles in a very similar fashion when you place a medium in a magnetic field the the external magnetic field magnetizes the medium and magnetized medium generates its own magnetic field and the magnetic field that you measure or you observe is the sum total of the magnetic field that you have applied and the magnetic field generated by the magnetized medium

so we started to look at how do i represent a magnetized medium and how do i calculate what is the field generated by a magnetized medium

so let me recall that if you look if you take a

so we are looking at magnetization

so we have seen that if you take a a cylinder like this magnetized in this direction parallel to the axis then this magnetization that means its magnetized meaning that magnetization is magnetic dipole moment per unit volume that means you take a small tiny volume of the material that tiny volume is small compared to the size of the material but contains a larger number of atoms and that tiny volume will have a certain magnetic moment which is the sum of the magnetic moments of all the individual particles within that volume then that magnetic moment divided by the volume will give me the magnetic dipole moment per unit volume which is nothing but magnetization which is represented by capital m vector

so if you have a medium like this which is magnetized parallel to the axis we had seen that this is equivalent to having a surface current given by

so this is equivalent to a surface current per unit length of m now the direction of the surface current as i have drawn here is like this perpendicular magnetic field magnetization sorry and this magnetic the current per unit length is nothing but m

so if you take a length t here the total surface current on this surface would be n times t

so we had looked at this and found this magnetization

so now let me look at

so how do i in ah what is the effect of this kind of medium on an ampere's law

so we started looking at a solenoid

so let me look at again a solenoid which has ah which which is this is solenoid there is the medium here and i wind wires on this

so a wires wound on a medium and this wire is carrying current like this

so there are currents propagating like this each of the wire is carrying the same current just like a solenoid except that now this is a medium

so i have a current i flowing through the cur through the bias of the solenoid now what is the ah ampere's law ampere flow tells me $\int \mathbf{b} \cdot d\mathbf{l}$ is equal to μ_0 times current enclosed $\int \mathbf{b} \cdot d\mathbf{l}$ where b is the magnetic

field is equal to $\mu_0 n i$ enclosed now this

so when i have this medium and pass a current the current generates a magnetic field and that magnetic field will magnetize this medium and in this case the current produces a magnetic field which is pointing along the z axis and the magnetization will also be parallel to the z axis

so let me assume that the magnetization is something like this here

so if i look at this here

so i essentially have a medium which is magnetized in the vertical direction and the magnetic field produced by the external current is also in the vertical direction now i apply this ampere's law

so what i do is i take a loop of length l and integrate over this path

so i take a amperian loop crossing the solenoid and insert the material here and apply the ampere's law now what is the current enclosed please note that there are two components to current enclosed one is the current that i am passing through the wire which is i and the other is the current which is represented by the magnetization itself

so the magnetization is equivalent to a surface current

so on this within this loop i the current crossing consists of i enclosed consists of the current which i am passing through the wire and if the number of turns per unit length is n n is the number of turns per unit length number of turns per unit length then the current enclosed will have n times i times l there are $n l$ loops current crossing the path and each of them is as a current i and also i have magnetization

so magnetization is equivalent to a surface current passing in the same direction as this current and magnetization which is the current per unit length times l will be the current due to the magnetization

so i enclose now consists of two components one is the current actual current passing through the wire which is called the conduction current which is actually electrons are moving from one end to the other end passing through the wire the other is what is what is called the bound current that means current which is consisting of atoms circulating ah circulating electrons within each of the atoms in the material

so that current is represented by magnetization and

so the total current enclosed is given by $n i l$ plus $m l$

so mp ampere's law gives me $\oint \mathbf{B} \cdot d\mathbf{l}$ is equal to $\mu_0 (n i l + m l)$ so the current enclosed has conduction current plus the current due to magnetization which is represented by a surface current

so i am assuming here that the material gets uniformly magnetized and the uniform magnetization generates a surface current given by m times l within the length l now let me try to calculate this quantity $\int \mathbf{m} \cdot d\mathbf{l}$ over the same loop now remember outside the solenoid there is no magnetization because there is no medium

so on this part of the loop then integral will will give me zero on this part on these parts which are outside the solenoid again m is zero

so there is no contribution to the integral on these two parts which are lying within the medium m is perpendicular to $d\mathbf{l}$ because m is vertical and $d\mathbf{l}$ is at this in this in the perpendicular direction

so $m \cdot d\mathbf{l}$ contribution from here and from here becomes 0 and the only contribution comes from this part of the loop and along this length magnetization will be independent of position because of the symmetry of the problem

so this will be simply equal to m times l where m is the value of magnetization at this point times the length because there is no contribution to the integral from the remaining three parts of the of the closed circuit

so i can write this $\oint \mathbf{B} \cdot d\mathbf{l}$ as $\int \mathbf{B} \cdot d\mathbf{l}$

so let me divide by μ_0 both sides

so i get $\oint \mathbf{B} \cdot d\mathbf{l} / \mu_0 = \int \mathbf{J} \cdot d\mathbf{l} + \int \mathbf{J}_m \cdot d\mathbf{l}$

i have replaced \mathbf{B} by $\int \mathbf{J} \cdot d\mathbf{l}$

so let me take $\int \mathbf{J}_m \cdot d\mathbf{l}$ to the left hand side

so i will get the following $\oint \mathbf{B} \cdot d\mathbf{l} / \mu_0 - \int \mathbf{J}_m \cdot d\mathbf{l} = \int \mathbf{J} \cdot d\mathbf{l}$

ok what i have done essentially is taken $\int \mathbf{J}_m \cdot d\mathbf{l}$ to the left hand side

so $\oint \mathbf{B} \cdot d\mathbf{l} / \mu_0 - \int \mathbf{J}_m \cdot d\mathbf{l}$ will be equal to $\int \mathbf{J} \cdot d\mathbf{l}$ now as in the last lecture i introduced a new vector called \mathbf{H} vector which is $\mathbf{B} / \mu_0 - \mathbf{J}_m$ this is the defining equation for a vector \mathbf{H} remember in electrostatics i had introduced a vector called \mathbf{D} vector displacement vector which was related to the electric field and the polarization $\epsilon_0 \mathbf{E} + \mathbf{P}$ is equal to \mathbf{D} similarly i introduce a new vector called \mathbf{H} vector which is $\mathbf{B} / \mu_0 - \mathbf{J}_m$

so this equation simply gives me $\oint \mathbf{H} \cdot d\mathbf{l} = \int \mathbf{J} \cdot d\mathbf{l}$ and what is $\int \mathbf{J} \cdot d\mathbf{l}$

$\int \mathbf{J} \cdot d\mathbf{l}$ is nothing but the free current passing through this loop the current which i am passing through the wire the conduction current which is passing which is called the free current the conduction current passing through the loop is the only one which is crossing this

so the right hand side is simply equal to I_{enc} where I_{enc} is equal to free current enclosed by the loop

so i get a new form of ampere's law $\oint \mathbf{H} \cdot d\mathbf{l} = I_{enc}$

enclosed this is again ampere's law which is valid in the presence of material now the advantage of this equation if this kind of an equation is that on the right hand side i only have free currents which are existing that means the current which i am passing through the wires and all the properties of the medium material are contained in the defining equation for \mathbf{H} which is magnetization essentially

so \mathbf{H} is equal to $\mathbf{B} / \mu_0 - \mathbf{J}_m$ the properties of the medium are contained in \mathbf{m} and

so \mathbf{H} contains the properties of the medium and the free charge enclosed is on the right hand side three currents enclosed now this equation is similar to the modification of gauss's law which we discussed in terms of displacement vector i showed you at that time that the modified form of gauss's law is very helpful in the presence of material especially when there are symmetries similarly this equation this form of ampere's law is very useful especially in the presence of symmetries because if i can i need to know only the free currents in this circuit and if i have use symmetry to take \mathbf{H} out of this integral then i will be able to calculate \mathbf{H} vector and from \mathbf{H} vector i should be able to calculate all other quantities like magnetic field magnetization and

so on and

so forth

so this is a very very useful form of ampere's law now i must mention here although i have derived this equation for the case of a solenoid wire bound on a material this equation is a very general law it is valid in general and is a modified form of ampere's law which contains \mathbf{H} vector instead of \mathbf{B} vector and \mathbf{H} vector definition is $\mathbf{B} / \mu_0 - \mathbf{J}_m$ this is the definition of \mathbf{H} vector now for a large class of materials for a large class of materials the magnetization is proportional to the \mathbf{H} factor for a large class of materials the magnetization is proportional to \mathbf{H} and χ_m is the proportionality constant which is called the magnetic susceptibility remember we had introduced the electric susceptibility in electrostatics similarly we have a magnetic susceptibility in magnetostatics which is the proportionality constant between \mathbf{m} and \mathbf{H} now this is for the last class of materials that \mathbf{m} is proportional to \mathbf{H}

and such media are also called as linear media because m is proportional to h the relationship between m and h is linear they are also called linear media and this is a linear relationship and this is the last loss of materials which are which belongs to this one of the example is diamagnetic materials now diamagnetic materials have a χ_m which is less than zero and paramagnetic materials which has χ_m greater than zero and in both these materials the value of χ_m is much much less than one in both diamagnetic and paramagnetic materials this value of susceptibility is very very small compared to one now there is a third class of materials ferromagnetic in which the magnetization is not proportional to h i will come to a discussion of ferromagnetic materials a little later and also the diamagnetic and paramagnetic materials themselves but right now i want to emphasize that for media for a major class of media which are diamagnetic or paramagnetic materials the magnetization is proportional to the h vector and the relationship is written as m is equal to χ_m times h

so if i use this equation for m in this equation

so i want to use m is equal to $\chi_m h$ in this equation

so i will get the following equation

so i had this equation let me rewrite h is equal to i have defining equation v by μ_0 minus m

so this tells me b is equal to μ_0 into h plus m and i am replacing m by χ_m times h

so b becomes μ_0 into $1 + \chi_m$ into h and this is written usually as μ times h where μ is equal to μ_0 into $1 + \chi_m$ now what is μ_0 we have introduced long time back μ_0 is the permeability of free space and μ is called the permeability of the medium

so the medium properties are represented in μ the magnetic properties of the medium are represented by μ the magnetic permeability of the medium it is similar to the dielectric constant and the directive permeability of the medium that we had introduced in electrostatics similarly we have μ_0 as the permeability of free space μ is the permeability the medium which is given by μ_0 into $1 + k_m$

so it depends on the susceptibility and as i mentioned before since for dia and paramagnetic materials χ_m is much much less than one

so for diamagnetic and paramagnetic materials χ_m is much much less than one so μ_0 is approximately equal to μ sorry μ is equal to approximately μ_0 and actually for diamagnetic χ_m is less than zero this implies μ is less than μ_0 and for paramagnetic χ_m is greater than zero this implies μ is greater than μ_0 approximately equal to μ_0 but slightly greater than μ_0 for paramagnetic slightly less than μ_0 for diamagnetic because diamagnetic have χ_m as negative

so the value of μ is slightly less than μ_0 for diamagnetic μ is slightly more than μ_0 for paramagnetic materials

so we have defined a permeable permeability μ we can also define a relative permeability k_m is equal to μ by μ_0 which is equal to $1 + \chi_m$ these are this is the relative permeability of medium just like relative permittivity which was called the dielectric constant in the in electrostatics here we have a relative permeability which is μ by μ_0 and for paramagnetic and diamagnetic materials this relative permeability is very close to one ah we will discuss ferromagnetic materials slightly later in more details and also diamagnetic and paramagnetic and you will appreciate that in ferromagnetic materials the permeability definition itself is to be discussed little carefully

so what we see is that there are when you place a medium in a magnetic field external magnetic field that external magnetic field magnetizes the medium the

magnetized medium then generates its magnetic field and the total magnetic field gets altered because of magnetization now let me give you some a table of typical values of χ_m for diamagnetic and paramagnetic materials

so χ_m for dia and paramagnetic some examples to give you an idea of the values here

so let me look at a table for diamagnetic

so bismuth minus sixteen point four into ten to the minus five

so this is χ_m copper is minus zero point nine eight ten to the minus five diamond minus two point two ten to the minus five gold minus three point five ten to the minus five silver minus two point four ten to minus five water minus point nine ten to the minus five

so as you can see here the susceptibility is very very small and

so μ is approximately μ_0 and all the susceptibility values are negative these are diamagnetic material examples and i will give you some examples for paramagnetic materials aluminium

so this is χ_m here two point one ten to the power minus five platinum twenty six ten to the minus five magnesium one point two ten to the minus five tungsten six point eight ten to the minus five uranium forty ten to the minus five oxygen one ninety ten to the minus eight gadolinium forty eight ten to the minus two

so these are again some examples of paramagnetic materials and you can see here typically the susceptibility values are much smaller than one and

so for both diamagnetic and paramagnetic materials the value of permeability is very close to permeability for free space and in most calculations ah of electromagnetics people will assume that μ is equal to μ_0 typically in these materials ah in diamagnetic paramagnetic materials in ferromagnetic materials the story is very different and i will we will when we discuss properties of material specifically we will be able to appreciate the ah large difference in the permeability between ferromagnetic and ah diamagnetic paramagnetic materials ferromagnetic materials of course all of you know these are iron etcetera which are ah which are which form permanent magnets and they have a very strong magnetic field even in the absence of magnetization in the even in the absence of an external magnetic field

so we will discuss the three diamagnetic paramagnetic and ferromagnetic materials in little more detail after we discuss an example

so i want to consider one example of using the modified form of ampere's law to show you that it is possible to calculate the magnetic field the magnetization etcetera in a problem in which there is ah material within the in the system

so the example which i want to look at is the following i have a cylinder a dielectric cylinder here and i am passing current in a solenoid

so this is the wires of the solenoid i am going to assume that the system is infinitely long

so this is the wire which is carrying the current

so let me draw a side view

so this will be the cylinder here

so the side view will look something like this

so i have the material here current is coming out from on this side through the wires and the current is going back into the page on the other side

so current is coming up from here going in here and this is the material

so now in the earlier example i had assumed that the material was filling the entire solenoid now what happens if the material does not fill the entire solenoid but the material is only part of the solenoid

so as i have drawn here i have a solenoid which has a winding and again let me assume n is the number of turns per unit length and i is the current to the wire

so i want to calculate the magnetic field inside the material

so this is the material here

so this material has χ_m a susceptibility k_m magnetic system Δi_m and outside it is free space

so here it is one and outside it is sorry χ_m is zero everywhere else except in the medium

so μ is μ_0 here μ is μ_0 here μ is μ_0 into one plus k_m here μ is equal to μ_0 μ_0 outside

so i want to calculate what is the magnetic field inside and outside this medium in the solenoid the first thing that we notice is that the moment i pass the current the magnetic field generated by the current in the solenoid is in this direction

so this is the z direction

so magnetic field will be in this direction everywhere inside the solenoid of course outside the solenoid there is no magnet there is no magnetic field as we have seen before for an infinitely long solenoid the magnetic field outside is zero

so magnetic field generated inside now this magnetic field is going to magnetize this medium and with the magnetization in this direction

so the magnetic field generated by the current carrying conductor magnetizes the medium which then has a magnetization in the vertical direction and this magnetization as we have seen is equivalent to current passing through the surface of this of this material now i want to use this modified form of ampere's law $\oint \mathbf{H} \cdot d\mathbf{l} = i_{\text{free enclosed}}$ that is the ampere's law which i want to use to calculate \mathbf{H} vector everywhere because this equation is in terms of \mathbf{H} vector i will calculate \mathbf{H} vector everywhere and from its vector i will be able to calculate the \mathbf{B} vector

so now let me draw this figure again

so this is the inside material and my current carrying conductor is here now i want to take a loop like this for calculating this integral this is my integral $\oint \mathbf{H} \cdot d\mathbf{l} = i_{\text{free enclosed}}$ now to do this i need to take a loop

so first let me take two loops one is this loop and now that is loose loop c one c two and remember the \mathbf{B} field is like this \mathbf{M} field is like this and \mathbf{H} field will also be like this

so \mathbf{H} is \mathbf{B} by μ_0 \mathbf{H} is equal to minus \mathbf{M} and \mathbf{B} is equal to μ_0 into one plus k_m

so this equation we have derived earlier these two equations we had obtained earlier you know the equations \mathbf{p} is equal to μ_0 into one plus k_m into \mathbf{h} and \mathbf{h} is \mathbf{B} by μ_0 minus \mathbf{M}

so this is what i have written again now for path c one

so of course there is a magnetic field here also this is the magnetic field everywhere is within the solenoid

so in this path this path does not enter the medium i know the magnetic field to be along the z direction

so this is this is the z direction here upward direction z direction the magnetic field is parallel to z axis there is no magnetic field outside

so integral over path this path is zero integral over this path is zero because magnetic field is perpendicular to this path in fact there is no contribution from the here and here because there is no magnetic field but over this path of this part of the path which lies inside the solenoid \mathbf{B} vector is perpendicular to $d\mathbf{l}$ vector

so there is no contribution from here \mathbf{H} vector is also perpendicular to the path

so there is no contribution of the integral from here and here

so if \mathbf{H} is the \mathbf{H} field here

so this equation this integral tells me $\oint \mathbf{h} \cdot d\mathbf{l}$ if l is this length is equal to now what is the current enclosed n number of

so there are current wires crossing this

so this is n times i times l the number of loops crossing this path is n times l because n is the number of turns per unit length

so n times length is the number of loops crossing this spot each part each of these path carries a current i

so the total current process passing is ni

so $\oint \mathbf{h} \cdot d\mathbf{l}$ is equal to ni and in vector form $\oint \mathbf{h} \cdot d\mathbf{l}$ is equal to $n i k \text{ cap}$

so this is \mathbf{ah}

so this is the magnetic this is the \mathbf{h} vector \mathbf{ah} in the region between this this region

so let me call \mathbf{uh}

so the region between the wires of the solenoid and the medium this is the edge vector

so that gives me the \mathbf{x} vector here

so what i find is if this is the \mathbf{at} in this region in this region \mathbf{h} is equal to because this path has actually in this region

so i am calculating \mathbf{h} vector in this region now let me calculate for path c two now look here for path c two again i apply the same law there is no expected outside

so there is no contribution from here and from these two parts of the path for these two parts of the path \mathbf{h} vector which is along z direction is perpendicular to real vector

so there is no contribution from these two paths either

so only contribution is coming from this part

so if \mathbf{h} is the \mathbf{h} vector here i will find \mathbf{h} is equal

so if i call \mathbf{h} as

so like let me call it \mathbf{h}' here

so if \mathbf{x}' is the \mathbf{h} vector within the medium

so for path two i apply the same equation $\oint \mathbf{x}' \cdot d\mathbf{l}$ is equal to i free enclosed

so i will get \mathbf{x}' into l is equal to what is the total current enclosed now please remember in the right hand side of this equation i only have the free current the conduction current the current that i am passing through the wire this path contains bound currents but bound currents do not enter on the right hand side here the right hand side only contains the free currents

so i have to only bother about the free currents on the right hand side the bound currents are already contained in the edge vector because bound currents are contained in \mathbf{m} vector which is actually contained as a part of its factor

so free current is the one which i am which i have to bother about for the right hand side and the free current passing through the length l again if this length l is the same as before which is equal to $n i l$

so this is equal to $n i l$ which implies \mathbf{h}' is equal to ni and \mathbf{s}' vector is equal to $n i k$ which is also equal to \mathbf{h} vector \mathbf{x}' vector is nik \mathbf{x}' is nik

so what is happening is

so if this is the material here these are the bias of the solenoid here \mathbf{h} is equal to nik here \mathbf{h} is the same

so \mathbf{h} is the same throughout the region of the solenoid within the solenoid and of course \mathbf{h} is zero outside

so \mathbf{h} vector is equal to nik everywhere \mathbf{ah} within this

so \mathbf{h} vector here here everywhere is the same within the solenoid outside the solenoid \mathbf{h} vector is zero

so without knowing anything about the property of medium without knowing

anything about the surface currents bound currents etcetera i have been able to calculate \mathbf{x} vector now this has been made possible because i knew that by symmetry arguments \mathbf{b} vector is vertical \mathbf{m} vector is vertical \mathbf{h} vector is vertical and \mathbf{b} is zero outside \mathbf{m} is zero outside \mathbf{h} zero outside etcetera

so all these arguments which i had used to get the magnetic field of a solenoid based on symmetry arguments are still valid and that has helped me to do this integration on the left hand side in spite of the fact that i did not know exactly the value of h and that has helped me to find out the h vector within the solenoid and outside the solenoid for this problem

so h vector is the same whether you are within the medium here within this medium or outside the medium as long as you are within the solenoid h vector is the same now i know the relationship between \mathbf{x} vector and \mathbf{b} vector \mathbf{b} is equal to $\mu_0 \mathbf{h}$ into one plus χ_m into h

so the medium which i am putting inside i am assuming to be linear to be related to \mathbf{h} to have an equation \mathbf{m} is equal to $\chi_m \mathbf{h}$ which i had introduced

so \mathbf{b} is equal to $\mu_0 \mathbf{h}$ into $\chi_m \mathbf{h}$

so let me i need to calculate now what i need to calculate is the magnetic field here here and of course the magnetic field outside is zero \mathbf{b} is outside zero

so i need to calculate what is the \mathbf{b} vector within the material of the solenoid within the material here and within between the material and the wires of the solenoid

so let me draw again

so this is the medium here the wires

so let me call this region one and this is region two

so in region one χ_m zero because there is no medium this region one also included include this part this is the same reason because remember this is the material and the wires are going like this ok

so this is this entire thing outside this cylinder is actually the within the solenoid is given one

so \mathbf{b} is equal to $\mu_0 \mathbf{h}$ which is equal to $\mu_0 n \mathbf{i}$

so magnetic field in this region is $\mu_0 n \mathbf{i}$ and please recall the discussion in solenoid it is the same as if there was no medium inside for this problem because of symmetry it

so happens that the magnetic field here \mathbf{b} vector here is the same as as if there was no material here now why why is this happening in spite of the fact that there is a material inside the reason is the following please remember the material is magnetized because of the magnetic field the magnetization of this material is like this this magnetization is equal to surface currents like this this surface current is equivalent to a solenoid which is this solenoid and that solenoid has no magnetic field outside let me give you the argument again how is it that the magnetic field in this region region one happens to be the same as the magnetic field in the absence of the material this is

so because of the following argument when i pass a current through the solenoid that current magnetizes the material that magnetization of the material is along the z axis this magnetization leads to \mathbf{h} is effectively equal to surface current on the surface of this material which is going like this current this surface current is equivalent to a solenoid of this dimension and this dimension of solenoid does not produce a magnetic field outside its dimension and

so the magnetic field here is primarily generated only by these currents and not by this current and

so the magnetic field here is the same as if there was no material now what about region two region two \mathbf{b} is equal to $\mu_0 \mathbf{h}$ into one plus χ_m into h which is equal to $\mu_0 \mathbf{h}$ into one plus $\chi_m \mathbf{h}$ is $n \mathbf{i}$ times and this is also equal

to μ times n_i

so all that has happened is magnetization inside has changed the magnetic field within the medium to μ times $n_i k$ the magnetic field outside is $\mu_0 n_i k$

so magnetic field inside the material is different from the magnetic field outside and it depends on this difference between μ and μ_0 of course for paramagnetic and diamagnetic μ is very close to μ_0

so the magnetic field inside the material and outside the material are almost equal to each other but they are slightly different now its also interesting to note that for diamagnetic materials χ_m is negative which means that μ is less than μ_0 which means the magnetic field inside the material is slightly less than the magnetic field outside because μ is less than μ_0 χ_m is negative

so the magnetic field inside the material for the diamagnetic material here is slightly less than the magnetic field outside for paramagnetic materials χ_m is positive μ is bigger than μ_0

so magnetic field inside the material is slightly more than the magnetic field outside

so the presence of the material modifies the magnetic fields in different parts and in this problem which has a lot of symmetry we have been able to use the modified form of ampere's law to calculate the magnetic field everywhere in fact we can also calculate the magnetization of this medium magnetization we remember is χ_m into h which is equal to $\chi_m n_i k$

so we have got the magnetization here now you see here for diamagnetic χ_m is negative

so let me draw the figure here again

so if i had a diamagnetic core that means if this medium was diamagnetic magnetization is like this for a paramagnetic m is like this b and h are like this both cases b and h are along the z direction in this case magnetization is opposite and

so this remember now that this downward magnetization is actually equivalent to current in the reverse direction and that current actually produces the magnetic field which is opposite to the directional magnetic field produced by the current carrying conductors in a diamagnetic materials magnetization is downward this downward magnetization generates a magnetic field in this downward direction because of this bound current and that is opposite to the directional magnetic field produced by the current carrying conductor and

so the magnetic field inside the material is slightly less than the magnetic field outside in paramagnetic materials the magnetization has the same direction and hence produces the magnetic field in the same direction as the coil and hence it adds to the magnetic field of the coil and the magnetic field inside the paramagnetic material is slightly more than the magnetic field outside and that is the reason why we find that the magnetic field inside a the diameter material is likely reduced the magnetic field inside the paramagnetic material is slightly increased compared to the the airspace

so let me draw a figure

so let me draw the cross section it looks like this

so this is the material and suppose this is the this is the coil

so this is the coil here and this is the material here

so let me draw a couple of figures suppose i want to do draw h versus position

so h is zero outside zero outside and h is the same everywhere h is the same inside the dielectric inside the magnetic material outside the magnetic material within the solenoid it is the same h is constant everywhere and if i want to plot b and if i assume it is paramagnetic b is μ_0 outside b is slightly increased inside compared to outside

so b inside is slightly more than the b outside in a paramagnetic in a diamagnetic b inside will be slightly less than the outside for a diamagnetic for a paramagnetic material it is like this

so what i have been able to show to a very simple example is that i have been able to use the modified form of ampere's law to find out what is the magnetic field inside a solenoid which has a a core within the mid solenoid our discussion has assumed that the core has a linear susceptibility i will come to the problem of what happens if the core is made of ferromagnetic materials when we discuss ferromagnetism little more detail and that will indicate to me what is the difference between putting a parametric or diamagnetic material inside and a ferromagnetic material inside

so this form of ampere's law which we have been able to write down is a very very useful form of ampere's law this form of of ampere's law is very useful and that can help us to this form is very useful form of ampere's law and this form can help us to solve a large number of problems and i in in using this formula all i need to know is the free current that is passing through the circuit which is what i am passing through the conductors and the bound currents etcetera which are caused by magnetization are contained in the definition of \mathbf{h} vector and if there is symmetry in my problem then it is possible to solve the left hand side also and finally calculate the magnetic field \mathbf{h} vector magnetization and

so on

so the modified form of ampere's law is very useful

so what we have done till now is looked at the introduced magnetization as dipole moment per unit volume showed magnetization leads to a surface current uniform magnetization leads to surface current and that surface current then produces a magnetic field and the total magnetic field is a sum of the magnetic field that you have generated externally and the magnetic field generated by magnetization magnetization of the medium

so now i want to discuss the different types of materials different types of media which have magnetic properties

so as i mentioned before there are three primary class of magnetic materials diamagnetic paramagnetic and ferromagnetic diamagnetic paramagnetic and ferromagnetic are three types of media which have magnetic properties which which which have different magnetic properties and of course there are some other materials which you will not discuss in the course here

so first i want to discuss something about diamagnetic properties paramagnetism and finally ferromagnetism now what are these dimensional materials you see atoms first of all the any any matrix consists of a large number of atoms and each atom consists of protons neutrons and electrons these electrons are essentially forming orbits around the around the nucleus and when electrons have a an orbit around the nucleus as we discussed some time before this orbital motion gives me a magnetic moment to the electron motion and that is called the orbital magnetic moment

so electrons in my classical picture i will assume that the electrons are spinning but rotating around the nucleus but ah one has to use quantum mechanics to describe the properties

so i see that the orbital motion or orbital motion of the electrons around the nucleus produces an orbital magnetic moment as i mentioned before electrons also have a spin

so which is a inherent property of the electron just like mass and charge and that spin also has an associated magnetic moment

so these electrons have both orbital magnetic moments and spin magnetic moments and the atom consists of a large number of electrons and

so to calculate the total magnetic moment of the atom i need to add vectorially the magnetic moments of orbital motion and the spin magnetic moments to get the total magnetic moment now it is possible in many atoms that when you add all the magnetic moments of all the constituent electrons you find that they all cancel each other off

so with the result that the atom does not possess any intrinsic magnetic moment recall our discussion electrostatics where i had an atom with a nucleus positively charged nucleus and an electron cloud the centers of the negative and positive charges if they match at the center the electric dipole moment of this is zero

so the atom does not possess an electric dipole moment similarly here i have atoms in which the magnetic moment is determined by the orbital motion and the spin of the electrons and the the atoms have electrons in such a fashion that when you add up the orbital magnetic moments and spin magnetic moments of all the electrons what you find is it has no net magnetic moment

so if you have this material the atoms are all part of material here and the atoms ah do not have an intrinsic magnetic moment

so there is no magnetic field associated with this material now the moment i place this material in a magnetic field the magnetic field now induces the magnetization in the medium now we will discuss a very important law when we discuss next topic of electromagnetic induction that there is a law called lenz's law and because of lenz's law what we find is the magnetization magnetic dipole moment of these atoms is directed in the direction opposite to the applied magnetic field

so if i apply magnetic field vertically up the magnetic dipole moments of the atoms which this induces this the external magnetic field induces magnetic moments of atoms and those induced magnetic moments are pointing downwards and this is obtained by lenz's law and this magnetic moment now points in the direction opposite the magnetic field

so this happens in materials which are called diamagnetic materials

so diamagnetic materials consist of atoms which have no intrinsic magnetic dipole moment and when you place this in a external magnetic field each atom becomes a small dipole magnetic dipole and these dipoles are all oriented oppositely directed to the applied magnetic field and when you remove this magnetic field external magnetic field the atoms again lose their dipole moments and they all become again without any multiple moments at all

so the magnetization generated in these materials depends on the external magnetic field

so ah let me write here the atoms no intrinsic dipole moment of constituent atoms dipoles are induced by the external magnetic field induced dipoles directed opposite to external applied magnetic field and the magnetization disappears when the external field is removed now it is this reason that the dipole moments are pointing in the direction opposite to the magnetic field that the susceptibility is negative and it is interesting that these these diamagnetic materials are pushed from regions of high field to smaller b in an homogeneous field that is if you place a diamagnetic material in a magnetic field in in non uniform magnetic field they are pushed away from the magnetic field instead of being attracted they are pushed away and thats a very classic diomagnetic material and the this diamagnetism is present actually in all materials and is independent of temperature

so this is one class of materials which we have discussed today what i will do in the next class is to discuss the second class of materials called paramagnetic materials and some other properties and then we will look at little more detail of ferromagnetic materials and their properties and how they are

able to generate such strong magnetic fields thank you you

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