good morning to all of you ah we will continue with our discussions on magnetostatics remember in the last class we had discussed about magnetic fields produced by various current configurations and towards the end we started looking at magnetic field produced by a very important element which is called the solenoid

so let me recall a solenoid consists of a an object a circular usually it is a circular geometry and you have a wire which is wound very closely around the cylindrical structure and which carries the current through the through the coil

so if you if i draw the arrows

so the current may be flowing like this the same current flows through the entire all the wires of the solenoid and as we as we have already seen each current canning coil in this will produce its own magnetic field the total magnetic field produced by this solenoid will be the sum of the magnetic field produced by all the current elements of the solenoid

so we started looking at using ampere's law to obtain the magnetic field produced by such a solenoid

so we will consider an infinitely long closely bound solenoid closely wound implies that the loops are circular in shape but the the loop is almost like in a plane its actually like a helix it goes like this but if they are very closely bound i can consider each circle to be like a circular loop of wire and ah the i can neglect the rate the dependence of current on the horizontal direction and

so the current flows through this through this loops and producing magnetic field

so we use first symmetry arguments to show that magnetic field cannot have any dependence on this this coordinate that means it has to be the same at this point at this point at this point inside the solenoid outside the solenoid everywhere for the same position there is no change in magnetic field as you move parallel to the axis of the solenoid also if the windings are very close then there can be no dependence on the angle of the

so if i if i draw the solenoid like this here and the the coils are carrying current like this here then there can be no dependence on this coordinate and there can be no dependence on this coordinate that is as you go around the solenoid the magnetic field must remain the same if the winding is very close ah that's not true if the winding is not very closely spaced coils but in in general situation i will assume that the coil is very closely bound which means that the magnetic field is independent of this coordinate magnetic field is independent of this coordinate and

so magnetic field can only depend on the distance from the axis of the solenoid which i call r that is the only dependence on the magnetic field now what about the components of the magnetic field

so magnetic field will have components which are one component can be along this direction one component will be along this direction and one component will be along the azimuthal direction

so if i look from the top this is my solenoid

so there could be a component like this there could be a component like this and there could be component in this direction now we have used gauss's law for magnetic fields and showed that this component has to be zero p r has to be zero we used ampere's law using a an amperian loop circling the solenoid and showed that this component is also zero the only component that will survive is a component which is along the axis of the solenoid the only component that survives is along the axis of the solenoid

so if i call the axis of the solenoid at z axis the only magnetic field component that survives is the b z component the z component of the magnetic field is at z axis is the axis of the solenoid and

so the only component that survives is b z

so through symmetry arguments and through using gauss's law for magnetic fields and through using ampere's law for magnetic fields we have been able to deduce some very general characteristics of the solenoid and that file we find finally that can there can be only one component of magnetic field which is b z z is the axis of the solenoid symmetry axis of the solenoid and that can only depend on the radial coordinate the distance from the axis of the solenoid now using this we try to calculate what how does the magnetic field vary with distance

so we will now calculate what is the magnetic field produced by the solenoid

so for that let me draw the solenoid here

so i have the solenoid here the current elements are coming up here

so i going down into the page and the current is coming up towards me on the left side

so the current is flowing like this and this is my z axis now what we have shown is that the magnetic field is can only have a z component magnetic field can only have a z component and it can depend only on r this distance it cannot have a dependence on z it cannot have a dependence on this angle it can only depend on r

so now i want to use ampere's law to find out the magnetic field inside and outside the solenoid

so what we do is following i take a a ah an amperian loop

so this is let me draw the the coil here

so these are the current carrying conductors current coming out towards me here on the left side and going into the page on the right side ok

so this is z axis

so i take a loop here outside outside the solenoid

so let me call this a b c d

so this is my amperian loop

so according to appears law

so let me call this distance ah this distance r one and this distance r two

so current ampere's law integral b dot d l is equal to mu naught i n closed

so if i take an amperian loop and integrate over the that closed loop then integral v dot d l must be equal to mu naught i enclosed for this loop a b c d current enclosed is zero

so this must be equal to zero

so what i get is a to b b dot d plus b to c b dot d l plus c to d v dot d l plus d to a b dot d l must be zero this integration a to b b to c c to d t to a that's a complete ah close integral now as we have already seen that b can only have a z component that is a component along this direction this is my z axis here

so if you look at the path b c d l vector is like this b vector is perpendicular to b c

so b dot d l must be zero along this path

so this is zero similarly in the path d to a the d l element is along this direction and b vector is perpendicular to this direction

so b dot l is zero from d to a

so the only two integrals which survive are a to b and c to d now also note that when i integrate from a to b i am not changing the distance from the axis i am only changing the position of z and we have already seen that the magnetic field is independent of my position along the z axis

so the magnetic field must be the same from a to b and similarly from c to d

so what i get is essentially ah integral a to b p dot d l plus integral c to d b dot d l is equal to zero and this still tells me b at r one into integral a to b d l ah plus b at r two integral c to d d l has become zero that means b at r

one integral a to b d l must be equal to b of r two integral d to c d l
so i will i have changed the direction of integration
so a to b and d to c integration are over the same length
so this implies b at r one is equal to b at r
so what it implies is the magnetic field is independent of the distance of this point from the axis of the solenoid
so magnetic field here is the same amounting field here now if i let r2 to infinity then the magnetic field must go to zero as i go at infinite distance from the solenoid
so for r two tending to infinity p of r two tends to zero and because this equation is independent of r one and r two b must be equal to zero for points outside the solenoid please note here i have shown through the ampere's law that the magnetic field at this distance r one must be equal to magnetic field at a distance r two that means magnetic field must be independent of the distance from the axis because r1 and r2 are arbitrary i am not chosen any space as long as both r1 and r2 lie outside the solenoid magnetic field at r1 and magnetic field are towards equal
so magnetic field must be independent of the distance from the axis outside the solenoid and in the limit r two tend to infinity i know that the magnetic field will tend to zero and
so magnetic field must be zero everywhere outside the solenoid magnetic equivalent is zero everywhere outside the solenoid now i must still calculate the magnetic field inside the solenoid
so for that what i do is the following i take ah again the same solenoid here the current element the current is coming towards me on the left side currently is going inwards on the right side now i take a loop which lies partly inside and partly outside a b c d now let me assume that this length is l now lets see the ah again i want to use this integral p dot d l is equal to mu zero i enclosed now we define a quantity for the solenoid the number of turns per unit length that means when i when i wind a solenoid i have a lot of windings and i take a unit length and measure the number of windings and that tells me how many windings are there in the solenoid
so if you know the number of turns per unit length and if you know the length of the solenoid you can find out how many is the total number of turns in the solenoid
so this is a quantity which i will need
so number of turns per unit length
so in a length l the number of turns will be in this the number of turns here will be n times l and each turn carries a current i
so total current enclosed by the loop is equal to n l i each loop carries a current i and there are n l loops within this
so this path encloses n l loops
so the total current enclosed is n l i and
so i get the ampere's law tells me the integral v dot d l be equal to mu zero n i into l now let me look at this path
so i need to calculate the left hand side to get the magnetic field i must be able to integrate and get the left hand side
so for this let me look at it now this integra integration is from a b c d now as before the integral along b c and a d will vanish because magnetic field has only a z component and my integration path is perpendicular to z axis i also know that magnetic field outside is zero
so the integration over c to d will also vanish and the only integral that will survive is from a to b and because magnetic field is independent of the position along a to b i will simply get this integral will become b times integral d l

from a to b is equal to mu naught n i into l now integral d l from a to b is nothing but this length a to b which is l

so b times l is equal to mu naught and i into l this implies b is equal to mu naught ni and i can write the magnetic field vector as mu naught n i into k cap where ah let me draw the solenoid again

so this is my z axis and the coils are any current like this these are the coils closely bound solenoid coils and the current is flowing like this

so interesting to see that the magnetic field has no dependence on r within the solenoid it is equal to mu naught ni point along the z direction and completely uniform

so magnetic field within the solenoid at any point is the same but please remember we have calculated this magnetic field for an infinitely long closely bound solenoid it depends on the permit permeability free space the number of turns per unit length and the current passing through the wires the same current is passing through all wires and

so it creates a uniform magnetic field within the solenoid

so this is equivalent to a capacitor parallel plate capacitor in electrostatics where if you have a parallel plate capacitor we remember we know that the electric field between the plates of the capacitor is uniform and if you have a large area capacitor then towards the center the magnetic the electric field is uniform similarly here if you had a very very long solenoid towards the center the solenoid will behave as if it was infinitely long and your magnetic field will be uniform and parallel to the z axis

so that is a very interesting relationship we have got from using ampere's law and some symmetry arguments and remember here we did not have to do any integration any complex integration ah which will be involved in using biofiber law ah but of course this has been done for an infinitely long solenoid if your finite length solenoid things change

so let me ah calculate ah it is possible to calculate the magnetic field along the axis of a finite length solenoid using bios effort law and let us do that and i want to show you that at the edge of the solenoid the magnetic field is half of this mag this number that you have got got here

so will let me look at a finite ah a solenoid now

so ah let me draw the solenoid here ah this is the cross section

so the current is coming towards me here going in to my z axis

so as you can see the current is flowing like this and the magnetic field will be towards z axis here

so here i will calculate the magnetic field at this point at the end of the solenoid of a solenoid which has a certain finite length

so let me call the length of the solenoid is capital l and i will leave it here to calculate the magnetic field inside the solenoid i will put a problem a little later ok

so i want to use the bio savart law to calculate the magnetic field along the axis of a solenoid now i will use this following expression that we had obtained before that remember we had obtained this formula

so if i had a a circular loop of wire carrying a current i the magnetic field along the axis b vector is equal to mu naught i by two if radius of the wire is r and if there are n turns i will get mu naught i into n into r square by r square plus z square raised to one three by two a cap where this distance is the point at a distance z from the axis from the center of the circular loop of wire the the loop the loop there are n loops here very closely bound n loops which each wire is carrying current i and i am calculating the magnetic field along the axis of this loop

so i can use this formula because actually a solenoid consists of a large

number of loops placed at different distances
 so for example at this point these slopes will produce that magnetic field this loop will produce another magnetic field this two will produce another magnetic field but on the axis all the magnetic fields produced by all the current elements are parallel and along the z axis
 so it is very easy for us to do an integration because i just need to do an addition of the magnetic fields
 so for this what i do is the following i consider a small element of the solenoid between z and z plus d z i consider an infinite decimal length of the solenoid lying between z and z plus dz and
 so the number of turns will be number of turns per unit length into dz
 so here ah n is the number of transfer unit length
 so in the length d z then number of turns will be d z ah n times d z and this distance is z
 so i am calculating the magnetic field at this point
 so magnetic field at this point will be
 so let me call this db will be equal to mu naught i into n dz number of turns divided by two into if the radius of the solenoid is a i will have a square by a square plus z square raised to the power 3 by 2 k cap
 so what i have done is i have used this formula this is the formula for the magnetic field produced at a distance z from the axis of a closely bound loop of n turns of radius r and here my number of turns for this solenoid of length dz is actually n times dz
 so i have replaced the number of turns here by n times dz and i have replaced r by the radius of the solenoid
 so the total magnetic field v will be equal to mu naught n i by two a square into integral d z by a square plus z square three by two and k cap k cap as a constant and remember now integration over z from z is equal to z i am calculating the magnetic field at the edge of the solenoid of a certain length l
 so integral goes from zero to l now this is a straight forward integration all i have to do is to replace z equal to a tan theta
 so d z is equal to a secant square theta d theta a square plus z square will be equal to a square sequence square theta
 so this integral d z by a square plus z square s per 3 by 2 will be equal to integral a secant square theta d theta by a cube second cube theta and
 so this is nothing but secant square theta cancels out one by second theta is cos theta
 so i get this is equal to one by a square integral cos theta d theta which is nothing but one by a square sin theta between two limits of integration
 so the limits of integration here i must calculate
 so the limits were from z is equal to zero to l
 so z is equal to zero corresponds to theta is equal to zero and z is equal to l corresponds to theta is equal to tan inverse l by a z is equal to zero the limit the lower limit of integration corresponds to theta equal to zero and z is equal to l corresponds to tan inverse l by a
 so this is nothing but one by a square sine of tan inverse l
 so i can substitute this value of the integral in this equation and get the magnetic field b as mu naught n i by two a square into one by a square sine of tan inverse l by which is equal to into k cap mu naught and i by two sine of tan inverse
 so thats the magnetic field at the edge of the solenoid on the axis which were precisely obtained from using ampere bioservo law now if length is very large compared to radius then l by a becomes very large and tan inverse of a large quantity is pi by two tan inverse infinity is pi by two

so tan inverse of a very large quantity is close to pi by two and sin pi by two is close to one

so i get b at z is equal to zero is approximately mu naught n i

so if i had a a solenoid like this very long solenoid then at this point b is mu naught n i by two and deep inside its solenoid is very very long ah then deep inside theor the magnetic field will be you know

so the edge of the solenoid this is on the axis for an infinitely long solenoid the magnetic field is uniform right across

so let me draw a figure which will show you an approximate picture of the magnetic field lines of a finite solenoid

so here is the solenoid

so let me draw the current carrying loops like this

so this is all current closely bound ah solenoid finite length

so if i were to draw the magnetic field lines they will look something like this

so the magnetic field and you have some fields coming out like this and

so the fields coming out like this

so that is a typical field within a solenoid

so this line will go like this here

so as you can see here the magnetic field lines are essentially pointing along the axis of the solenoid almost and being uniform within the solenoid

so what we have seen is ah for a ah to calculate the magnetic field using biosaver law we could do it on the axis of the solenoid of axis it becomes quite complicated at the same time we could use ampere's law for an infinitely long closely bound solenoid and get the magnetic field inside and

so most typical solenoids ah can be approximated as ah reasonably long solenoids and the magnetic field that you have got as mu naught and i by two mu naught ni is a reasonably accurate value

so let me take an example

so let me take a solenoid of length twenty centimeters radius a 3 centimeters and number of turns is equal to five hundred

so total number of turns this is total number of turns

so and current five amperes

so the number of turns per unit length which is equal to 500 by 20 which is equal to 25 per centimeter and b is equal to mu naught ni which is equal to 4 pi 10 to the minus 7 into twenty five hundred turns per meter multiplied by five amperes which is which is about point zero one six tesla

so this is close to the center because the fine the length is 20 centimeters much bigger than the radius three centimeters

so close to the center the magnetic field will be point one zero one six tesla or sixteen milli tesla while at the edge of the solenoid it will be about half of this value and outside it will keep on decreasing as you move away

so that gives you typical figure ah an expression for the magnetic field and gives you a number numerical value of the kinds of magnetic fields we can obtain by passing current through this solenoid coil now i want to take another example which is called a toroid

so a solenoid is a straight device a toroid is another device in which i have a current carrying loop which is which is bound along the cylindrical this thing which is closing on itself and is called a toroid and there are closely bound finding turns turns here

so current enters from here and leaves out from here

so that is a toroid if you if the radius becomes very very large the radius of the torrent becomes very large it's almost a straight it's only becomes towards an infinitely long solenoid now we can again use symmetry arguments to show that

the only component of magnetic field that will survive is the component along this direction

so that means only this component of magnetic field will survive

so here magnetic field can only be in this direction magnitude failure can only be in this direction if at all

so there are other components like this component and the radial component just vanish and once i have this i can actually use ampere's law to calculate the magnetic field within and outside the toroid

so if i take for example a loop

so let me draw the toroid in one plane here that's the plane and

so let me take

so this is my toroid

so there are coils coming towards me there are current current conductors here on the outside of this structure and on the inside of the structure ok

so let me take a path which looks like this and one part another path and a third part

so this call this is i call path one path two per three three parts now you can see that for path one integral b dot d l must be zero because path one does not enclose any current carrying conductor and if the magnetic field has only this component and my integration is along this direction this must be equal to nothing but b times if there is radius is r one b times two pi r one is equal to zero which implies b is equal to zero because magnetic field has only this component and is independent of the position along this ax this circle i can take i i'll get b dot d l is equal to b dot this this distance and i can take b out of integral and i get an integral like this and

so magnetic field inside no matter where you are inside that is in this region in this complete region within the steroid coils here magnetic field is zero similarly in path two integral b dot d l is equal to now look here there are coils which are with currents enclosed

so let me assume the current is coming out towards me here and current is going here

so you can see here that the the number of turns here and the number of turns are exactly equal

so the net current and all the coils are carrying the same current

so net current enclosed by path two must be zero there are equal number of current carrying conductions which are going coming towards me as mean as going inside

so the net current passing enclosed by this loop is zero and again because i can integrate this and get ah b times two pi r two is equal to zero dot two is this radius i get b is equal to zero

so inside and outside the solid toroid the magnetic field is zero i can integrate for the path two which is inside the solid for the path three which is inside the solenoid integral b dot d l mu naught i enclosed which is equal to mu naught times now if the total number of turns is n subscript t i will get n substitute t into i where n subscript t is the total number of turns in the toroid and again as before because b has only this component and if the radius of this path is r i will get b times oh

so there is a small dependence of magnetic field on the distance from the axis of the toroid from this point center of the toroid but if the diameter of the toroid is small compared to the this radius then the variation in small r is very negligible in this distance and this is almost a constant magnetic field within this also note that if capital r if the radius if this radius becomes larger and larger then within the solenoid my my this distance is negligible compared to capital r and this will tend to n t by two pi r is the number of

turns per unit length two pi r is the circumference of the circle here and n t is the total number of turns and this reduces to the magnetic field of an infinitely long solenoid as it indeed should if the thyroid becomes of infinitely large radii

so these examples have shown us the ah application of ampere's law to calculate magnetic fields in some important situations and as we have seen whenever there is a symmetry in the system i can use symmetry arguments to estimate the dependence of magnetic field on position and the and whether which components a magnetic field will survive

so there are two two points here one is b vector dependence on the three coordinates and which components of b vector survive in the given configuration now the structure is does not have symmetry or is a finite length etcetera it becomes much more complicated then i would have to use an actual integration using biosevered law to calculate the magnetic field as a function of position

so mps law is very useful in many situations and in many situations we can get an approximate value for the magnetic field using ampere's law now having discussed how to generate magnetic fields and how magnetic fields how to calculate magnetic field generated by current carrying conductors in different configurations like a straight current carrying conductor a circular loop of wire a solenoid a toroid etcetera now i want to move to another very very important aspect which is ah motion of charged particles in magnetic field

so how does suppose i have a region containing a magnetic field and if i have a charge inside the magnetic field moving at a certain speed what is the path taken by the charge ah what is the direction of motion etcetera now let us recall ah we had shown that the the magnetic force on a charged particle is q v cross b

so let me draw the figure again here

so this is the magnetic field direction and this is the v direction and the charge is a positive charge q the force forces in this direction

so we have to use the right handed screw rule to calculate the direction of the force if the charge is positive the force is in the direction of v cross b if the charge is negative the force in the direction of minus v cross b

so here with the charge the positive charge particle the force is along this direction and please remember the force is always perpendicular to both the velocity and the magnetic field very different from the case for a electrostatic field where the force was in the direction either towards along the direction of electric field or opposite to the natural electric field

so if you have a charge moving in a region which has both electric and magnetic fields the total force will consist of the electrostatic force plus the force due to the magnetic field

so that's the more general relation for force acting on a charge if the charge is at rest of course then the only force is electrostatic force

so even if there is a magnetic field within the region if the charge is at rest it has no magnetic force if there is no electric field there is the only force that acts is the magnetic force which is q v cross p

so suppose i take a a region containing its uniform magnetic field and ah and have a charge which is moving in that magnetic field the force because of the magnetic field is always perpendicular to the velocity

so the force cannot change the speed of the particle because the force is always perpendicular to the velocity vector the force cannot change the speed of the particle it will accelerate the particle but not change its speed please remember acceleration is a vector and it depends on the rate of change of velocity with time and that can they can be acceleration without changing speed thats what will happen here and

so if you have is if you have a magnetic field let me say for example in this region which is going to into the page here uniform magnetic field going into the page

so if i have a particle which is a positive particle which moves like this

so the force will be v cross b

so v cross b downwards

so the force will be upwards

so it will change the direction of motion of the particle like this and every time the force will go like this

so the particle will execute a circular motion the force is always perpendicular to the velocity vector

so the third particle is moving like this here the force is like this here the forces like this here the forces like this

so i have a region of uniform magnetic field and i launch a particle inside the region with a uniform with a positive charge and the magnetic force will make it curved and move in a circular path and the force which will act on this will be f is equal to q v into b v and b are perpendicular

so the force is q v b and let me put the magnitude here the force direction depends on the magnitude of the force is simply magnitude of

so this force will make the particle move in a circular path and this force is towards the center of the circular path and

so this is the centripetal force is equal to we know that centripetal force is m v square by r r is the radius of the path

so this force centripetal force is provided by the magnetic field

so i must have m v square by r is equal to mod q into v into b which gives me radius as m b by u times

so thats the radius of the charge particle which is ah circulating around this uniform magnetic field

so uniform magnetic field b will make a particle go along a circular path whose radius is given by mv by q by q into b and of course it depends on this ratio mass by charge or charge by mass of the particle and the velocity

so slower particles will have smaller adif curvatures faster particles will have larger radius of curvature now from this expression for r i can calculate the angular velocity of the particle which is omega is equal to v by r which is nothing but mod q b by m

so v is r is mb by qb

so i substituted that and i get omega frequency is this and i can define ah the

so number of revolutions

so the particle keeps on rotating the circular path like this and the number of revolutions per unit time will be f which is equal to omega by two pi which is equal to mod q b by two pi

so this frequency of revolution

so the particle the particle will go along circular path

so this magnetic field is

so it keeps circling trading along the path of radius r the angular velocity is q b by m and the frequency of revolution is simply given by mod q into b by two pi m and this frequency is called the cyclotron frequency will come to this later ah cyclotron frequency please note that this frequency is independent of the radius of motion of the particle it only depends on the magnetic field and the ratio of q to m charge to mass ratio and the magnetic field and independent of the radius of revolution and this fact we will use in understanding the operation of an article of particle accelerator

so there are number of accelerators which are used to accelerate particles and we will study ah an accelerator called cyclotron which is used to accelerate

charged particles and that uses this fundamental property of this motion in a magnetic field which states that the frequency that is number of revolutions per second of this particle is independent of the radius of of the of the path that the particle is following and it only depends on the ratio of q to m and the magnetic field of course now there are a number of applications which these forces magnetic and electric forces find

so i'll just discuss one or two interesting applications and one one or two ah aspects which have led to discoveries earlier ah the first one is thompson's experiment now let me look at a region which contains an electric field and a magnetic field

so let me say that i have a positive charge plate here negatively charged plate here

so the electric field is pointing downward and let me assume that i have there is a magnetic field in this region a uniform magnetic field pointing downward

so there is a region of space in which i have an electric field produced by a parallel plate capacitor uniform electric field pointing downwards and a magnetic field produced by some arrangement in which magnetic field is pointing downwards now let me look at what happens if i launch a charged particle from here

so let me assume that the particle has is positively charged

so what will what will be the effect of the electric field the electric field will try to push it down because this is a positive charge particle will be attracted towards the negative charge plates here and try to move down at the same time the magnetic field because it is now propagating for practical magnetic field it will have its force and you can see here that v cross b the velocity is like this and b is downward

so v cross b is upwards

so magnetic field magnetic force will be upwards

so this will be the q v b and downward will be q a

so this particle will have a force q e downwards because of electric field and q v be upwards because of the magnetic field if the particle at a negative charge the electric force will be upwards and the magnetic force will be downwards

so in this configuration across electric and magnetic fields there are two forces acting on the particle there is an electric force which is trying to push the charge towards one of the electrodes depending on the charge sign of the charge is either if the charge is positive this charge is being pushed down by electric field and pushed up by the magnetic field and

so what will happen is suppose the velocity of the charge particle is such that q e is equal to q v b that is v is equal to e by b if the velocity of the particle the electrostatic field and the magnetic field satisfy this relationship b is equal to e by b then the charged particle will go undeflected straight because then it has no net force acting on it the electric force is exactly balanced by the magnetic force

so i can use this very interesting concept to do to select particles for example for of a certain velocity from a collection of particles

so if i have charged particles with the certain velocity coming i can use this to select particles of a known velocity i can use this to as thompson did he did an experiment to measure the charge to mass ratio of of an electron and i will discuss the next class and a very interesting instrument which is based on this which is called the mass spectrometer which is also used as a principle to to to to look at different isotopes in a in element configuration etcetera and then we will use this to calculate to look at some particle accelerators primarily a cyclotron

so let me leave a problem to you here

so consider a solenoid or finite length z axis

so calculate using biosaver law and plot a schematic of variation of b with position along the axis

so calculate to take an arbitrary point ah calculate the total magnetic field at that point along the axis because of all the coils and we had actually done only only at the edge but i will leave it as a problem is very simple extension of that prop of the example you can calculate and i will urge you to plot the magnetic field along the axis of the solenoid thank you you