Fluid Dynamics for Astrophysics
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Lecture - 60
Non-ideal MHD: Introduction to magnetic reconnection

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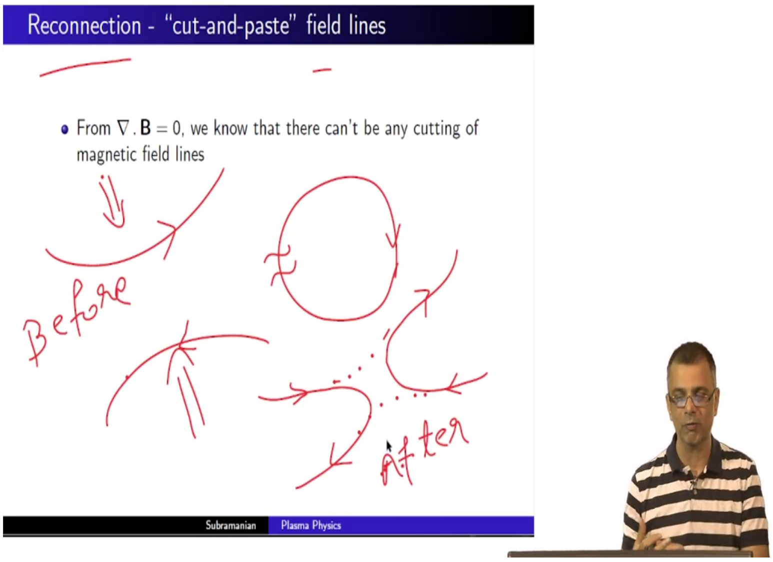

Yes hi, so we are back and from now on we are going to be addressing very important aspect in magnetized fluids and namely that of Reconnection. This is a phenomenon that is really outside the purview of Ideal Magneto Hydrodynamics ok.

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So, what I mean to say here is that phenomenon of reconnection which is essentially cut-n-paste of field lines magnetic field lines ok. This is a Non ideal MHD this falls within the purview of non ideal MHD, in other words everything that we have discussed so far by way of ideal MHD.

It breaks down for this particular phenomenon ok. So, you might ask why I thought we were discussing ideal MHD and I the whole point I thought was you know ideal MHD is good for certain things and so you know what is the point? Well I just want you to keep this in mind for the time being and I will tell you exactly how it violates ideal MHD.

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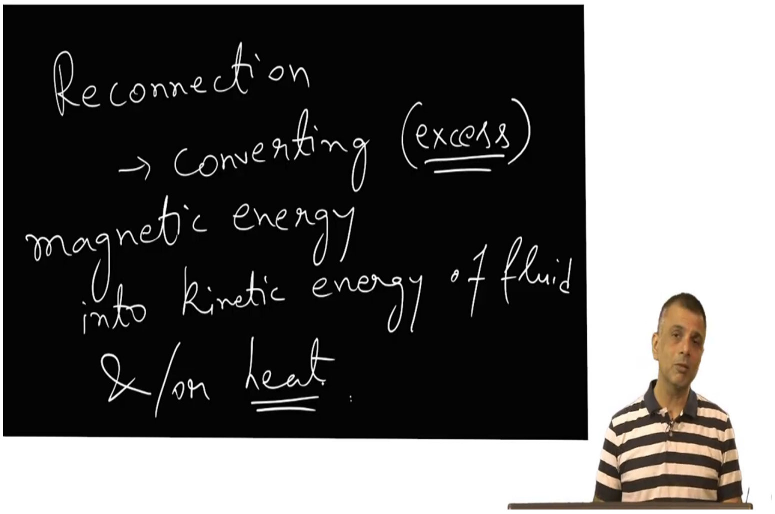

But the thing is reconnection is very important phenomenon from the point of view of converting magnetic energy converting I might even say excess magnetic energy ok I will explain what I mean by excess in a minute ok. Converting magnetic energy into say kinetic energy of the fluid kinetic in other words bulk motion of the fluid, kinetic energy of fluid and or heat, heating the plasma making the plasma hotter than it is hotter than it originally was ok.

Now this is this in many ways this is the real reason it is so important in or rather reconnection is invoked so often in astrophysics ok. In an astrophysics one often struggles to explain the heating of plasma, the plasma that you observe is too hot is often hotter than it ought to be ok. So, in other words you always are searching for an energy source ok, one is heating the plasma who is responsible for heating the plasma and so on so forth.

Now, magnetic field lines many times are stressed, in other words they are you remember when we talked about a potential field configuration when we when we said you know B can be written as a minus grad phi kind of thing phi is a scalar potential ok and then you have provided a certain boundary condition and then you solve Laplace's equation to find a, find the magnetic field. So, this would be a potential configuration right which by definition is a lowest energy configuration.

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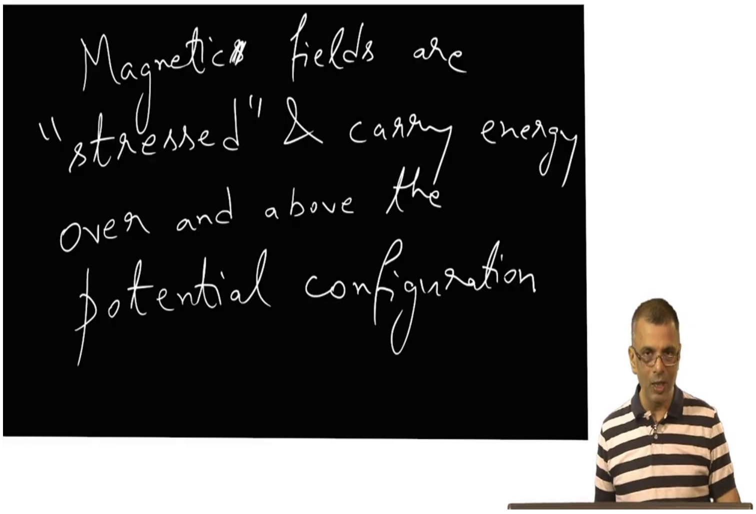

But in many case it is reasonable to suspect that magnetic fields are stressed or they are twisted and turned ok and carry energy over and above the potential configuration for any given situation ok. Now, we know that everything in nature generally likes to have you know whatever there is relaxed to the potential configuration.

If I place a pencil on the edge of this table it tends to fall off ok. Why ok it falls out that is one thing that is because it is attracted by gravity, but it falls off so as to attain the lowest possible potential energy ok. So, it always nature always tends to minimize energy and the potential configuration in this case is the lowest possible energy state.

So, but in many cases this reason to believe in many astrophysical situations it is reason there is reason to believe that the magnetic energy the magnetic fields are stressed or a twisted and because of plasma motions and things like that. We will you know a come to more specific details of this later on, but at the moment I just want to motivate the idea why we are talking about reconnection at also. I just want a briefly motivated before delving into the details ok.

So, the thing is in many astrophysical situations it is reasonable to expect that magnetic fields are quote unquote stressed and they carry energy over and above the lowest energy configuration which is the potential configuration.

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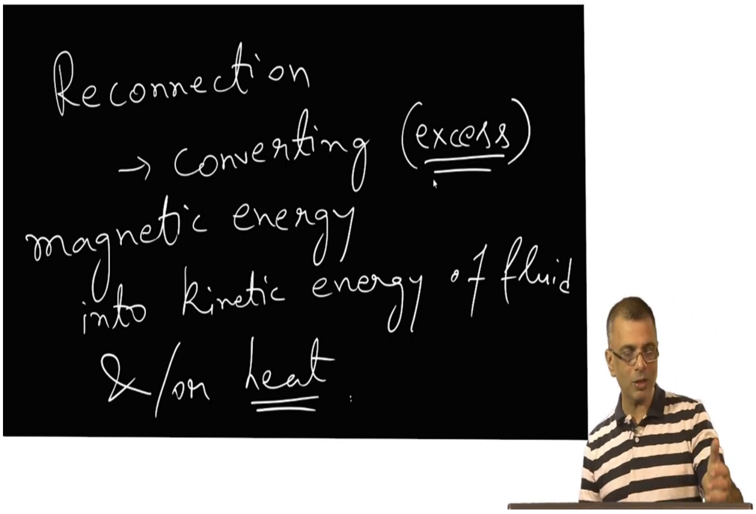

And the reconnection phenomenon enables these stressed fields the stressed B field configuration ok to relax. In other words come down to the potential configuration and of course in doing so you know the I mean so the stress configuration has more energy in the potential configuration is a lowest possible energy. So, there is an energy differential. So, this excess energy so that is what I mean by saying this ok this excess magnetic energy ok.

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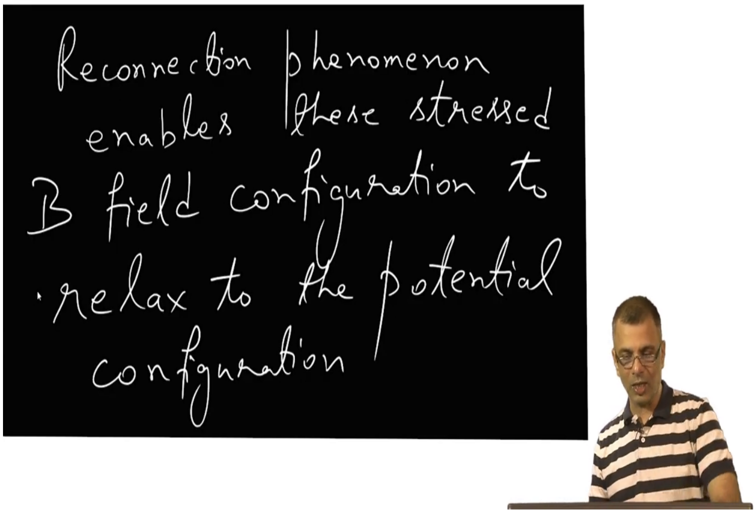

The reconnection enables this change enables the stressed feels to relax to a lower energy configuration and the excess energy is converted partly in to kinetic energy of the fluid, in other words it is converted into accelerating the bulk fluid and or heating the fluid. And so this is a way of heating the fluid or the plasma I really should say yeah. So, heating the plasma ok and so this is a way of explaining reconnection essentially is invoked as not exactly an energy source, but via media for the energy source.

The ultimate energy source is the magnetic field configuration. But how can you extract energy from magnetic fields configuration via this process called reconnection. So, now with that little you know introduction let us now turn our attention to try to consider what reconnection really is ok what is this.

Now you see from divergence of B equal 0 which is sacrosanct you cannot you know you cannot violate that we this essentially says that magnetic fields are always closed loops ok. You cannot cut lines like this not possible ok they are always closed loop ok.

But reconnection the whole point of reconnection is there is cutting and pasting. In other words if there is a we will see this if there are 2 magnetic fields lines that approach like this, of course this closes back and this closes back you know in other words it is not as if this is just isolated this is this closes back somewhere far away and this also closes back very far away ok. If these 2 magnetic field lines approach each other for whatever reason ok it may be the fluid the I mean as you know an ideal MHD.

And I will tell you I told you this is a non ideal MHD effect yes. But ideal MHD is still valid in the bulk it is only exactly where the reconnection is happening that the assumptions of ideal MHD have broken down, I we will elaborate on that on all this in a minute ok.

But so consider 2 oppositely field directed field lines like so which are approaching each other, why are they approaching each other because the bulk fluid is telling them to do so ok. This would be the arrow of the bulk fluid flow they can be one can handle such situations where there are these oppositely directed flows.

And because the bulk fluid is here is flowing this way and bulk fluid here flowing this way and the magnetic fields are frozen into the fluid in the bulk in the large scale fluid the magnetic fields are still frozen in ideal MHD still holds ok. The magnetic fields have to obey whatever the fluid flow is telling them to.

So, they approach each other and they approach each other very very close by and so this would be a before situation. And so what would happen afterwards is that this guy this portion reconnects to this portion and this portion reconnects to this portion leading to a situation which looks like this.

This was what was before and this is what is after ok, this would be before and this would be after ok. In other words what happen was this used to be like this and this used to be like this. But now these fields have reconnected in other words this field line has connected with this field line and this field line is connected with this field line to change the configuration ok. So, this was what it look like before and this is what it looks like afterwards ok.

There is a very common cartoon to illustrate the phenomenon of reconnection, but bare in mind this is really very simplistic this is showing something in just 2 dimensions in in reality reconnection is a 3 dimensional phenomenon and with all those caveats let us proceed ahead.

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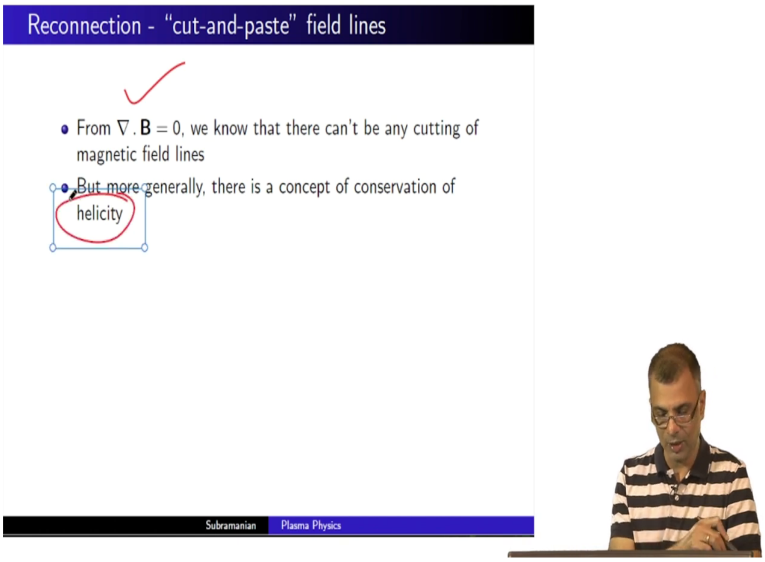

There are several reasons reconnection is not allowed in ideal MHD, number 1 it violates divergence of B 0, number 2 there is we remark this earlier in ideal MHD just like there is conservation of flux there is also a conservation of a related quantity called helicity ok.

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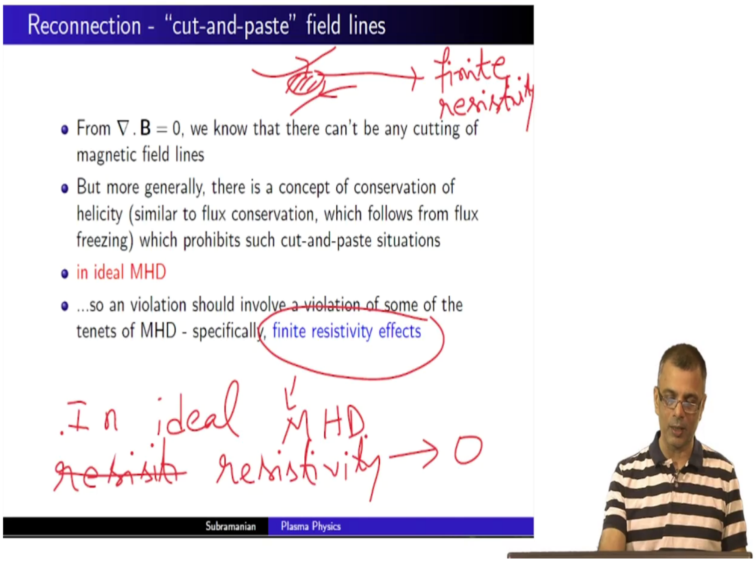

And the conservation of helicity is yeah. So, it similar to flux conservation which follows from flux freezing, but conservation of helicity is not the same as flux conservation it is slightly different. But at any rate conservation of helicity explicitly forbids cutting and pasting of field lines ok yeah.

So, it prohibit such cut and paste situations like we saw. In ideal MHD the ideal MHD tenets are reallly valid only in the bulk fluid and in small areas where the reconnections actually happening the laws of ideal MHD can be violated ok, because of finite resistivity effects because kinetic effects come into pictures so on and so forth.

We will discuss all these. And so this cutting and pasting can be allowed alright. If reconnection is violating ideal MHD you know it should it should involve a violation of some of the tenets of MHD which is specifically it in many times one invokes finite resistivity effects.

You know in ideal MHD, in ideal MHD resistivity tends to 0 right, so strictly speaking it is 0 or conductivity is infinite. That is how? However if you involve finite resistivity effects at least in very local situations like where you have you know these 2 field lines coming very close together, at least in in this diffusion region out here if you invoke finite resistivity. Then you can get away by saying, you can get away by saying that ideal MHD is kind of violated around here.

Whereas, very far away it is still ideal MHD and ideal MHD is not violated ok. So, just wanted to give you a flavor right. So, specifically finite resistivity effects are often. So, which of these ideal MHD is tenets is violated well, this one can often be violated finite resistivity effects ok.

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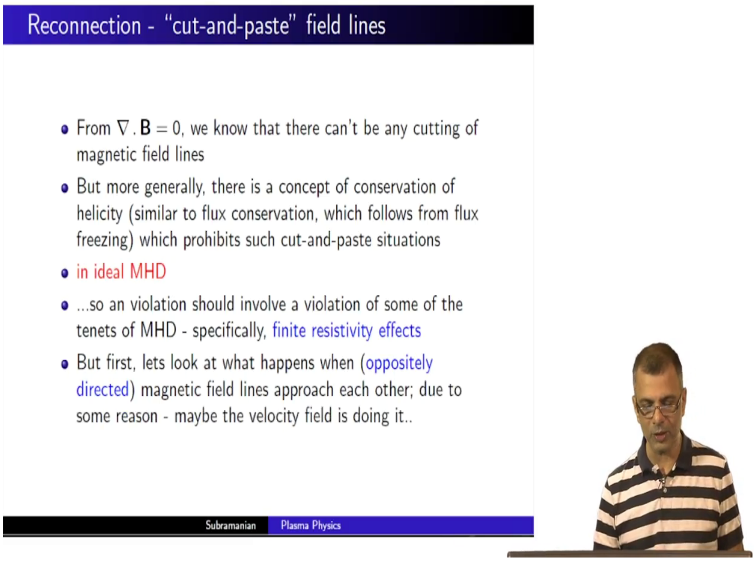

Now so, but first let us look at what happens when oppositely directed magnetic fields you know approach each other right. So, due to some reason maybe the velocity field is doing it like we said right.

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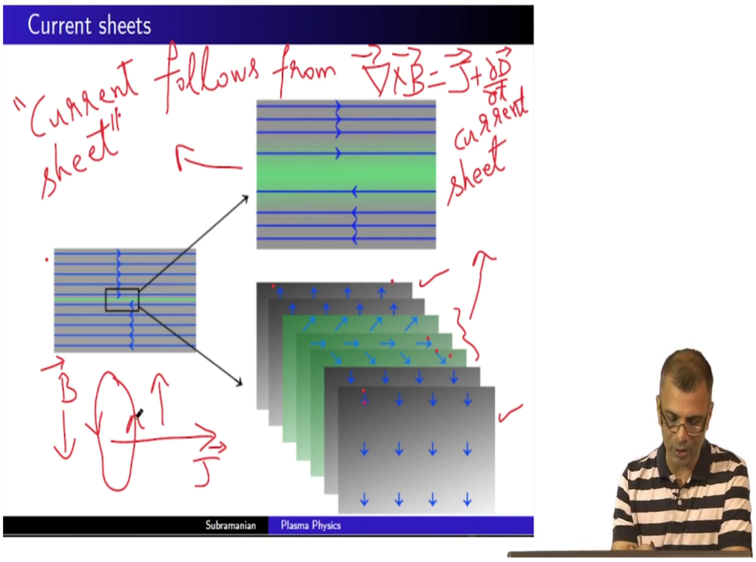

So, what happens what happens is you see this is a cartoon of oppositely directed field lines this you know the blue lines of the magnetic feed lines and so they are directed this way out here and this way out here. And of course, they close back the, close back in infinity somewhere in the close back at infinity that is not a problem but they are approaching each other. Now, let us blow up and something is happening where this green thing is there.

This is what is called current sheet ok we will you know examine this in a bit of detail lets blow this up. The small thing is blown up like this ok and you see. So, this is essentially where current sheet is formed is formed ok. Why would be need a current sheet we will discuss this in a minute.

Another way of blowing this up even more is to say that so essentially this picture is turned by 90 degrees out here. So, you see it is not as if there is an abrupt change there is an abrupt change in the magnetic field direction between here and here ok. If you look at the plane if you cut this plane you know perpendicular to the plane of the screen it starts looking like this ok.

So, the magnetic fields were originally pointing this way and finally after everything is over the magnetic fields are pointing the other way.

Opposite where you see this is opposite from that ok. That is evident but exactly how does this transition happen between here and here, the transition happens rather gradually ok. Between here and here there is a slide change in magnetic field direction and here the change in the magnetic field direction is a little more evident.

And here the magnetic field becomes almost horizontal and here it starts rotating a little more. Until by the time you come here the magnetic field has completely flipped it is 180 degrees out of phase from what it was here ok. And this entire thing this entire region is called the current sheet.

Why we call it this funny name current sheet I will tell you in a minute. So, you say this thing of current sheet this simply follows from Amperes law ok, there is something about this green region which is which lies in between regions of oppositely directed magnetic fields right.

So, which makes it look like a current sheet ok. So, the way I would think is easiest to understand is consider the right hand rule where you have you know a current loop sorry a magnetic field loop giving rise to a current this would be J and this would be B, this is the magnetic field loop and this is the current ok.

Now, you say on either side either the j might not be pointing this way it might be pointing this way, either way it is the right hand rule ok. But the main thing that is the that is not so important, the main thing to notice is that if you project this loop on the screen the magnetic field is in this direction here and it is in this direction here. So, on either side of the current ok and on either side of the current the magnetic fields are pointing in opposite direction and that is exactly what is going on here.

If you need the magnetic field to change directions ok simply for my Amperes law there is no way out there has to be a current in between ok and how exactly is that current directed. Well in this case the simplest way is to look at this diagram and in this case the current is directed either into the plane of the screen.

Or out of the plane of the screen depending upon how the right hand rule goes. At any rate this green region contains currents that are whose direction is perpendicular to the plane of the screen ok. So, that is why it that the fact that there is a current sheet follows simply from Amperes law ok follows from ok plus displace in current if you will ok that is not so important. You might say that you do not want to have a physical current here you want to have a displacement current here that is fine ok.

It can be this kind of current and it can be this kind of current either way there is a current ok and that the direction of that current is perpendicular to the plane of the paper that is it. You can either understand it this way or you can understand it in this elementary way either way ok.

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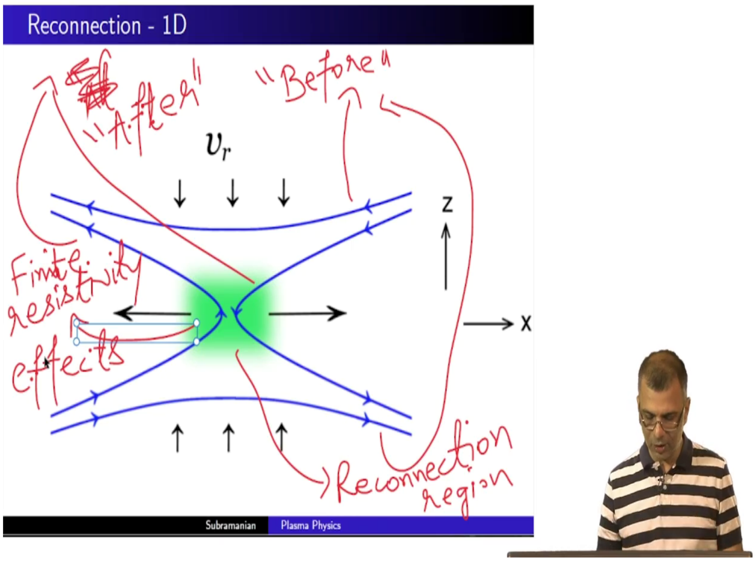

So, let us now look at a 1D picture of a reconnection. So, this is exactly what we had drawn earlier. So, this is the before picture ok, so this is a so for some reason oppositely directed magnetic fields are approaching each other they are frozen into the fluid and the fluid is making these two magnetic fields lines approach each other ok.

And after they approach each other what happens is this guy chooses to reconnect with this guy to form this kind of loop and this guy chooses to reconnect with this guy to form this kind of a loop. So therefore, this and this are an after kind of thing after afterward well after reconnection right. So, this and this an after thing and this and this are a before thing ok right. So, and what a and this this green region is the, is a region where the reconnection actually happens.

So, this is you would call the reconnection region, this is where the current sheet is formed and all those interesting things happen. And afterwards what happens because this reconnection happens there like magnetic fields are still like rubber bands remember they tend to snap, they tend to snap apart in this direction like this like this and like that they tend to snap apart in they actually drive flows these a called reconnection outflows; so very interesting ok.

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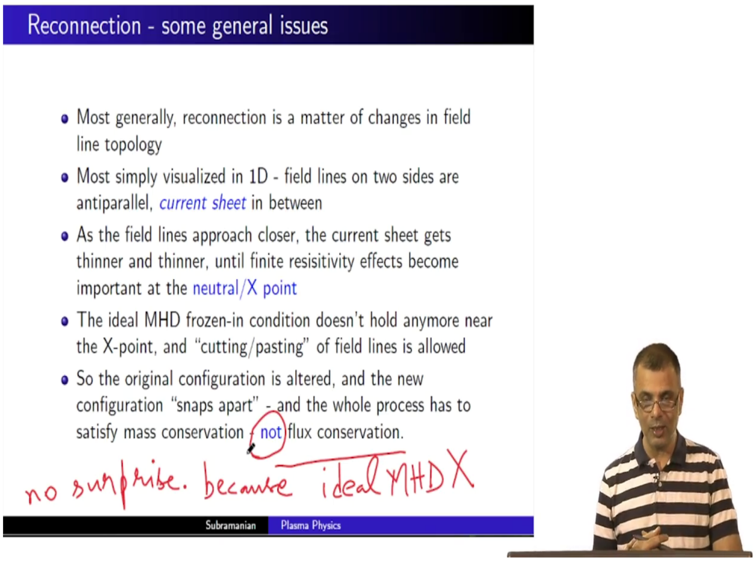

So, and so before we delve into the specifics of reconnection it is useful to sort of lay down some general issues we have already discussed this, but it is good to look at it in another way. Most generally reconnection is a matter of changes in field line topology this is one example.

But you know and like we said like I said in the beginning this is just a 2 dimensional you know cartoon and in even in 2 dimensions the situation can be much more complex and you know in reality this thing actually happens in 3 dimensions lie we live in 3 dimensions obviously.

So, in 3 dimensions what happens is reconnection is that it is best to understand reconnection as that process which allows changes in field line topology ok right. It is more simply visualized in 1D of course, like this it is most simply visualized in 1D with you know field lines and it is actually 2 dimensions way really.

And so the field lines in the 2 sides are antiparallel and there is a current sheet in between this thing that we talked about, either here or here right this is a current sheet in between. And as the field lines approach closer we have said we have said this the current sheet gets thinner and thinner on to finite resistivity effects become important at the quote unquote neutral or x point and that is what this is. So, here in the reconnection region finite resistivity effects.

Finite resistivity effects become important ok, just in this small region ok the current sheet becomes thinner and thinner and thinner and it is in this region that finite resistivity effects become important ok.

And that is called this also in the reconnection region is also often called the neutral point of the x point, for obvious reasons you see the field line configuration kind of looks like an x ok. You can also think of it is a neutral point because right here right in the center the magnetic field is technically 0 ok.

This complete annulations of magnetic fields so is also called a neutral point ok now. So, we said finite resistivity effects become important in that thin region. So, what about it? Well because finite resistivity is not allowed in MHD ok, in MHD technically you know resistivity tends to 0 right.

So therefore, as a result the ideal as the ideal MHD frozen in condition does not hold any more, you remember the frozen in condition the fact that magnetic fields are completely frozen in to the fluid tells the magnetic fields what to do and so on so forth. This is a consequence this is the direct consequence this followed from E plus V cross B over C equal

0 you remember. So, that is how we derive the Alfven flux freezing theorem will come back to that in a minute ok.

But all of that a relied on rather heavily on the fact that the resistivity was technically equal to 0. Now if that is no longer so ok the ideal MHD frozen in condition does not hold any more only in that local region only in the in that green region ok at the near the x point and cutting and pasting of field lines is allowed like this kind of thing.

There this kind of, this kind of cutting and pasting is allowed ok and that is what so. So the original configurations altered and the new configuration kind of snaps apart ok and the whole process of course has to satisfy mass conservation. In other words the amount of mass that is flowing in to this neutral x point has to equal the amount of mass that is leaving ok. So, that is one thing this mass conservation is still followed; however, very importantly magnetic flux is no longer conserved very important.

Now this is kind of a shocking statement what do you mean I thought flux conservation was a secret thing, flux is always conserved yes that is correct but that is only in no that is only in ideal MHD ok. This is really no surprise because ideal MHD is violated, ideal MHD is violated at the neutral point at the x point, therefore flux conservation is no longer flux can be annulated flux can be swallowed up ok. Who swallows that what happens to the magnetic energy well this is exactly what we said earlier ok.

Magnetic energy is technically converted into other forms of energy such as the kinetic energy of the fluid and it is also converted into heat and so on so forth ok. So, this is the whole point of reconnection we involve reconnection we invoke all this fancy non ideal effects and everything to somehow to serve as a (Refer Time: 27:13) as a via media to convert magnetic energy into other forms of energy such as bulk kinetic energy yeah bulk kinetic energy of the fluid of fluid motion.

Like a half rho u squared kind of energy. But also thermal energy to heat up the plasma hot plasma radiates and that radiation is what is observed. So, most of the time when we observe the radiation it seems like you know suppose it s a thermal black body radiation you estimate the temperature from the peak you know from the peak wavelength of the radiation and you say well this seems a little hotter than one would expect ok. So, there is something going on there is some kind of heating process going on.

If not global at least local at least there is at least some local heating going on ok. What is first of all what is energy reservoir that is supplying the heat well most likely magnetic energy. In other words there is some way that magnetic fields are being stressed and twisted and turned.

And so that they carry they you know carry with them more energy than the lowest possible energy state. So, that is one thing. But more importantly ok so you pump some energy into the magnetic field fine. But how you going to convert that into heat energy well here you go reconnection is such a (Refer Time: 28:31) that allows conversion of magnetic energy into heat energy. You are now allowing for finite resistivity and therefore you can think of a Ohm’s law kind of thing and Joule heating sort of thing.

Just like an I square R that you are familiar with. You now have a, you have a non zero or a finite R ok. So, we will stop here for the time being and we will continue with more details about reconnection.

Thank you.