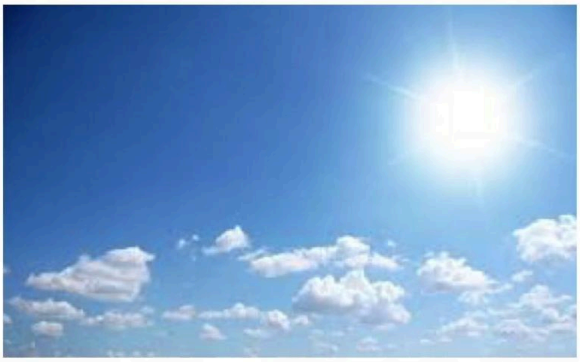
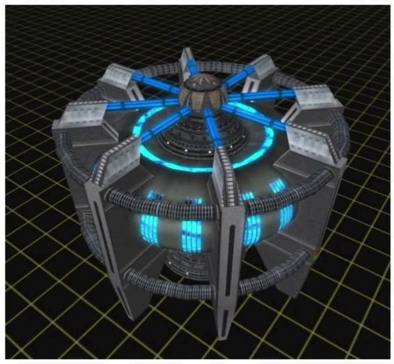


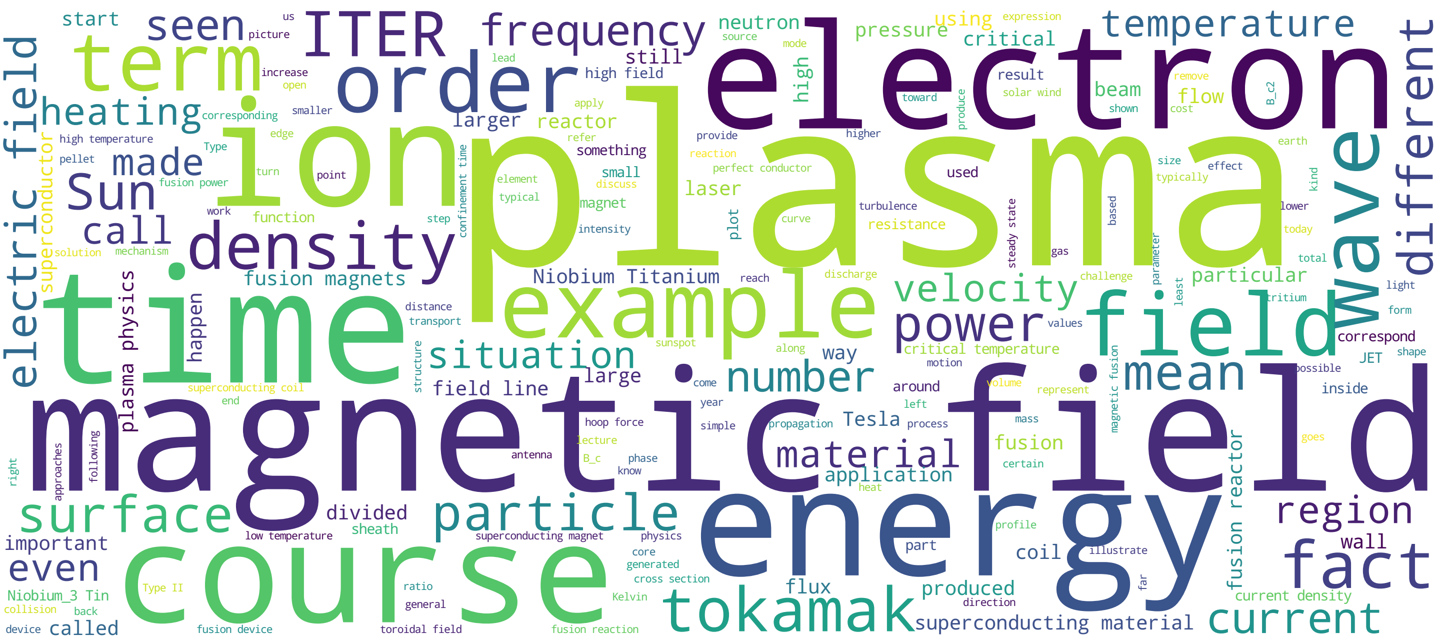


Applied superconductivity for fusion

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 6g

Ambrogio Fasoli – *based on input from Pierluigi Bruzzone*



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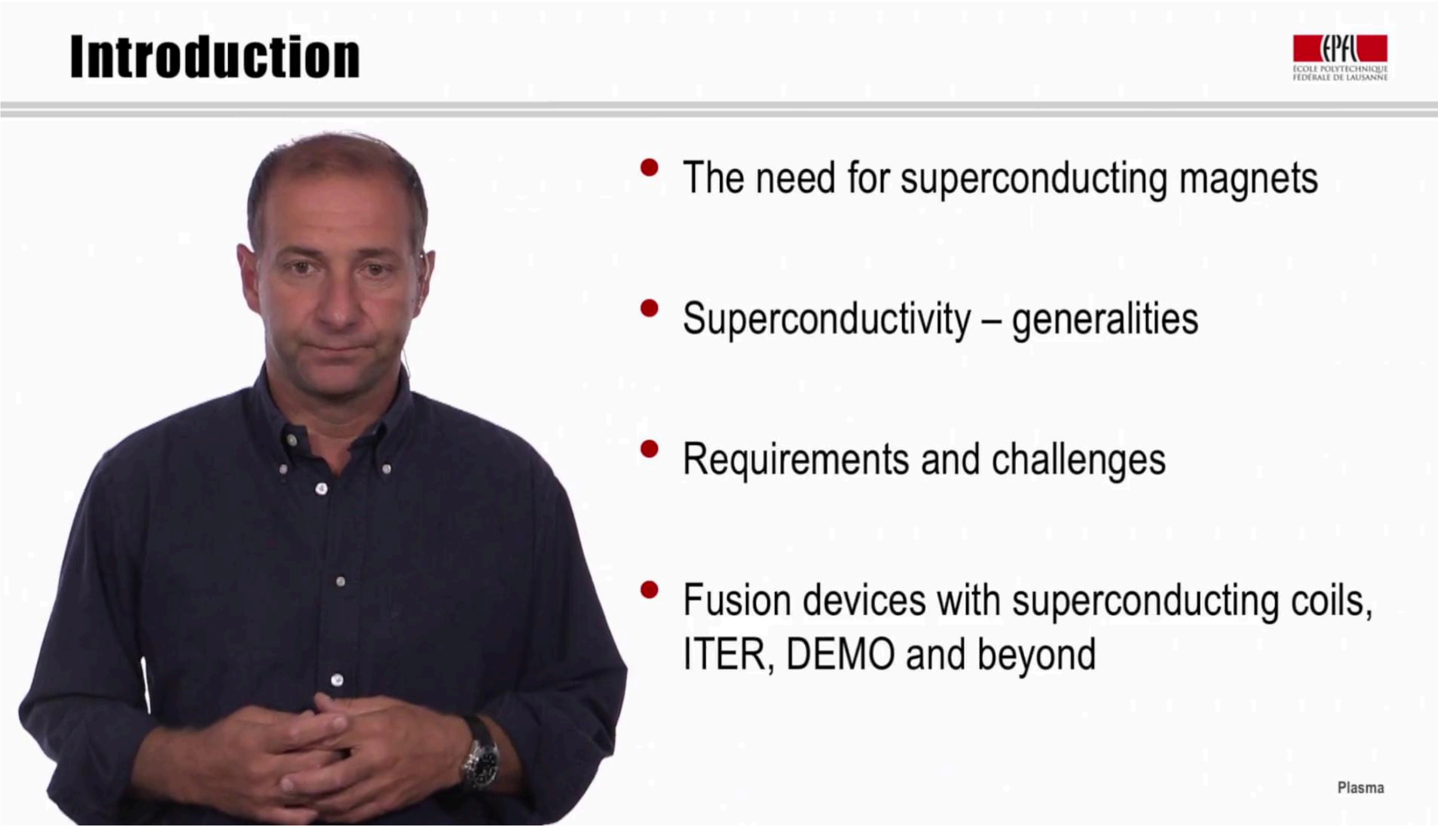


Welcome to the course on plasma physics and applications. In today's module, we'll address issues related to applied superconductivity for fusion. This is not a topic of plasma physics itself, but it is the main enabling technology for fusion energy, that is, for one of the main applications of plasma physics. We'll look at the need for superconducting magnets for magnetic fusion, and some few general points on superconductivity, and the requirements and challenges that employing superconductors for fusion imply. And we'll look at some examples of fusion devices that use superconducting coils today. And more importantly, ITER, DEMO, and the steps beyond that, that is, the final fusion reactor.

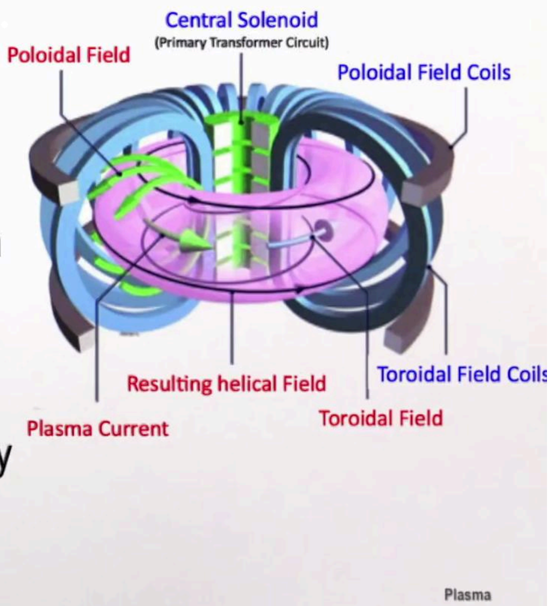
Notes

Summary

0m 05s

The need for superconducting magnets

- Plasma confinement needs high magnetic fields over large volumes
  - Increasing B is key for performance of magnetic fusion reactors
  - $n\tau_E T$ scales with B^{α}, where $\alpha \geq 2$, depending on assumptions
- Copper coils can generate large fields, but not in steady-state
  - Current density in steady-state ≤10 A/mm^2
- For steady-state, superconductors are necessary
  - Current density in steady-state ≤1000 A/mm^2
  - Low dissipation in the coils, low recirculating power

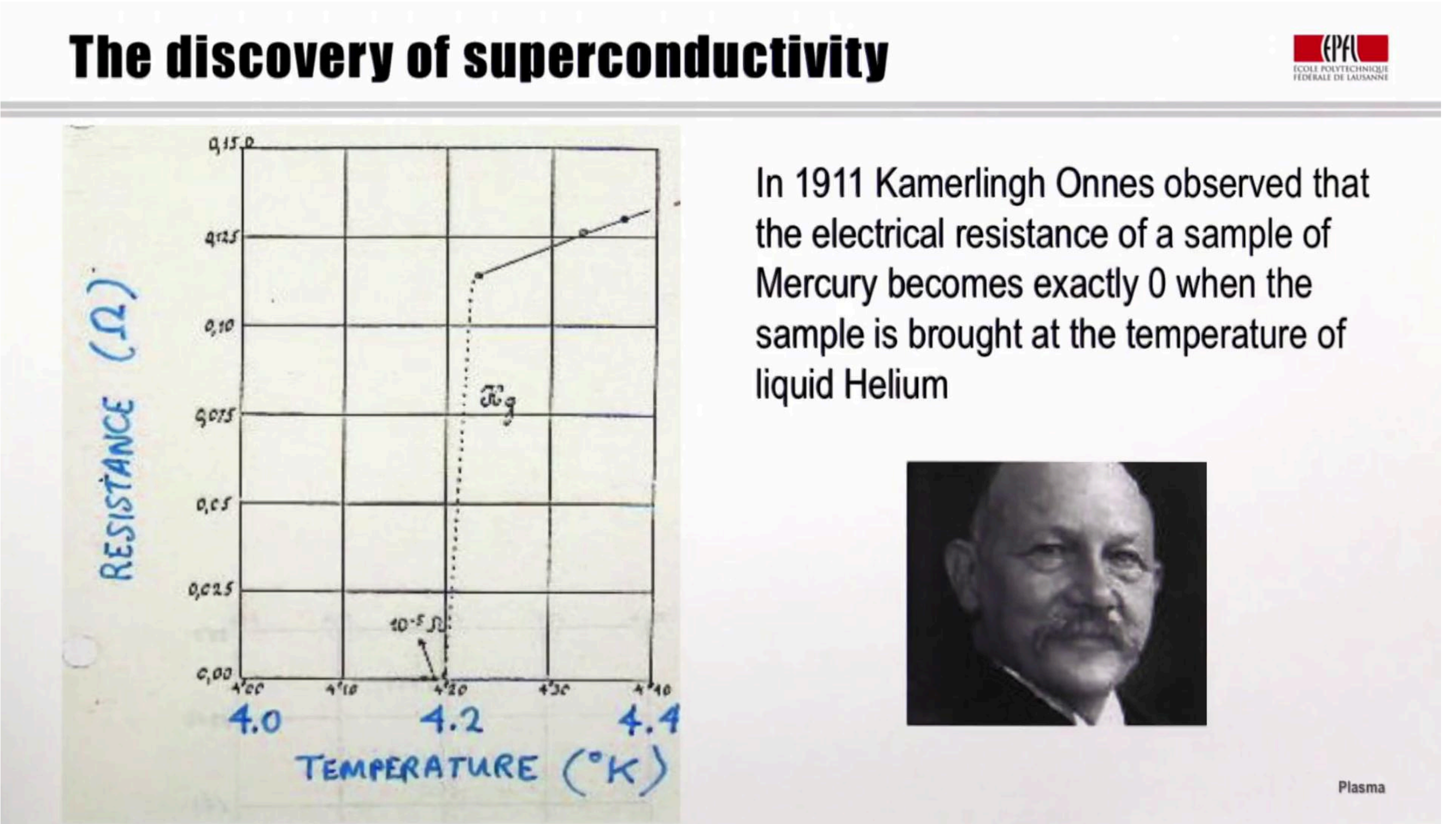


We have seen that plasma confinement needs high magnetic fields over large volumes, that is, the volume in which the plasma is embedded. Increasing the intensity of the field is key for the performance of magnetic fusion reactors. In fact, the so-called triple product, which I'll remind you, is the product of the density of the plasma times the energy confinement time times the temperature, scales with the power of B. And that power, depending on the assumptions, is in general, larger than two. Copper coils can generate large fields, but not in steady-state, because the current density in steady-state is limited to something like about 10 Ampere per square millimetres. For steady-state, we need superconductors. Superconductors can carry current densities of the order of 1,000 Amperes per square millimetre. And also, of course, they imply very low dissipation in the coils, and therefore, for reactor, a very important factor, a low recirculating power.

Notes

Summary

0m 53s

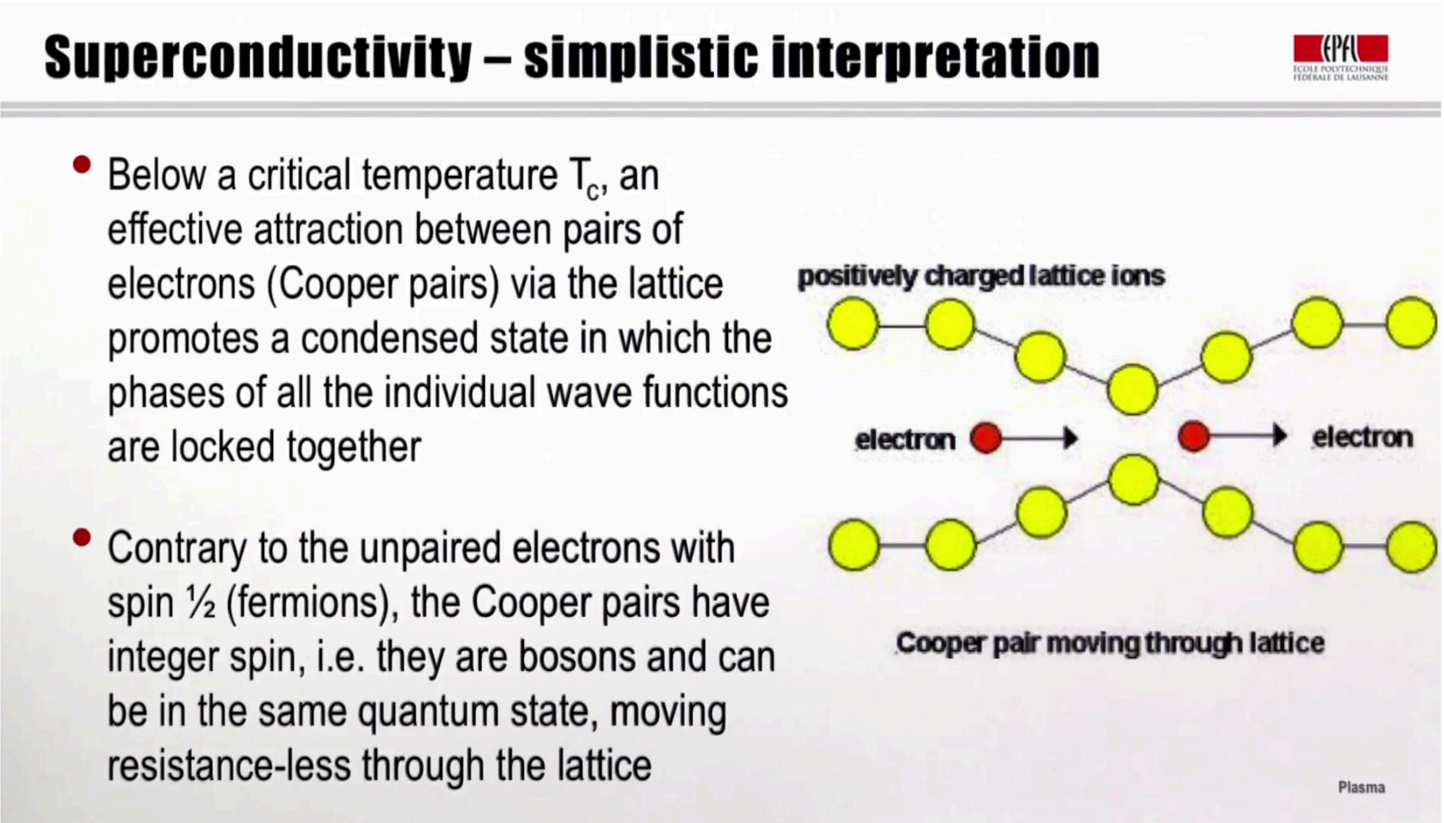


Superconductivity was discovered in 1911 by Kamerlingh Onnes, who observed that the electrical resistance of a sample of Mercury became not just small, but exactly zero when the sample was brought at the temperature of liquid helium. So this is the original plot that he produced. You see that below 4.2 degrees Kelvin, the resistance is identically equal to zero. So that opened the field of superconductivity.

Notes

Summary

1m 58s

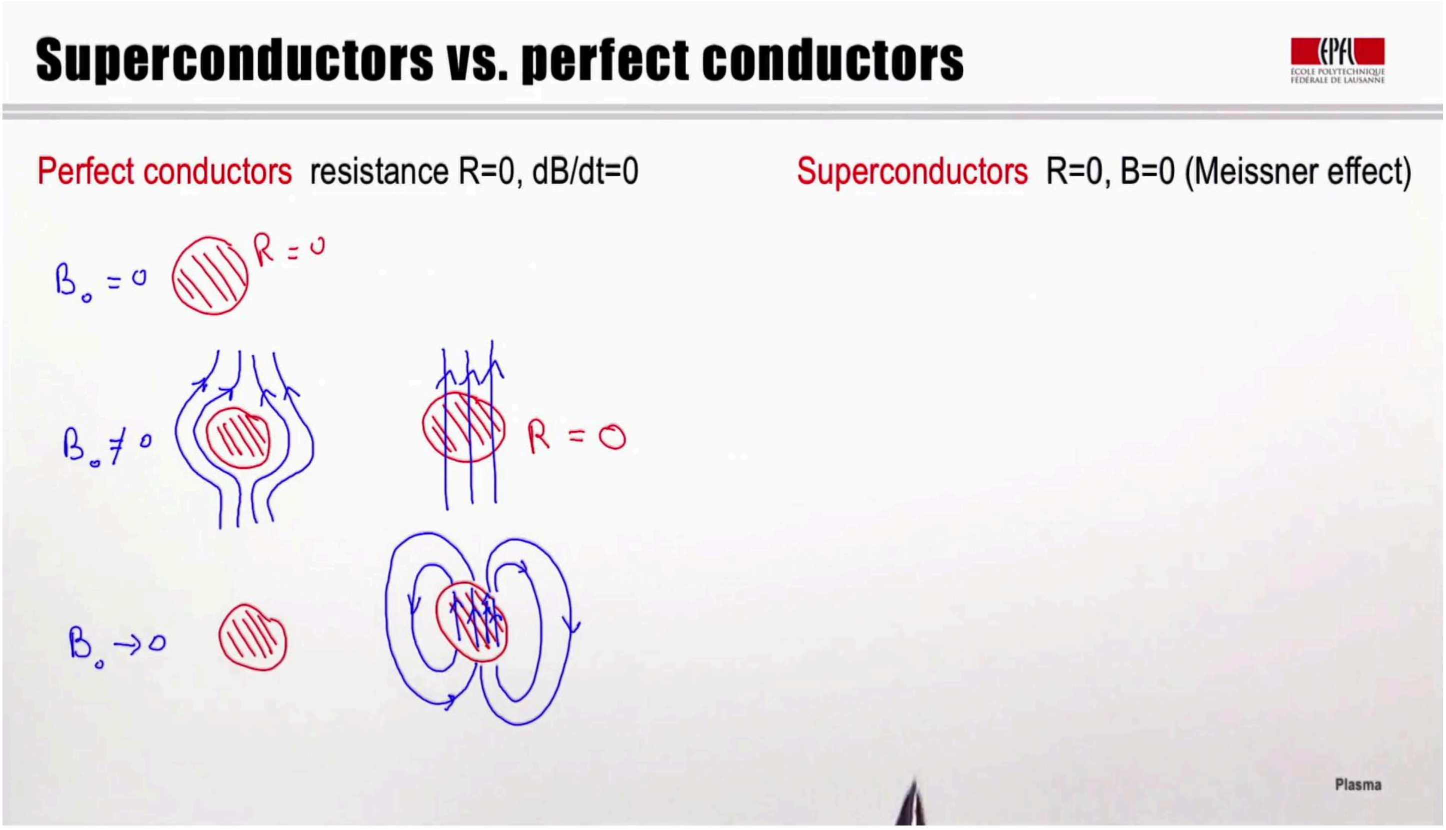


We have no pretension in this course to explain the physics behind superconductivity, but let's just give a very simplistic interpretation of what happens in the microscopic scale. Below a critical temperature, which I refer to as T_c, there's an effective attraction between pairs of electrons, which we call Cooper pairs. And that attraction happens through the lattice, and promotes a condensed state in which the phases of all the wave functions are locked together. So contrary to the unpaired, or let's say, normal electrons, which have a spin one-half, the fermions, the Cooper pairs have integer spin. That means they are bosons. And therefore, they can be in the same quantum state and move resistance-less through the lattice as indicated in the cartoon on the right.

Notes

Summary

2m 30s

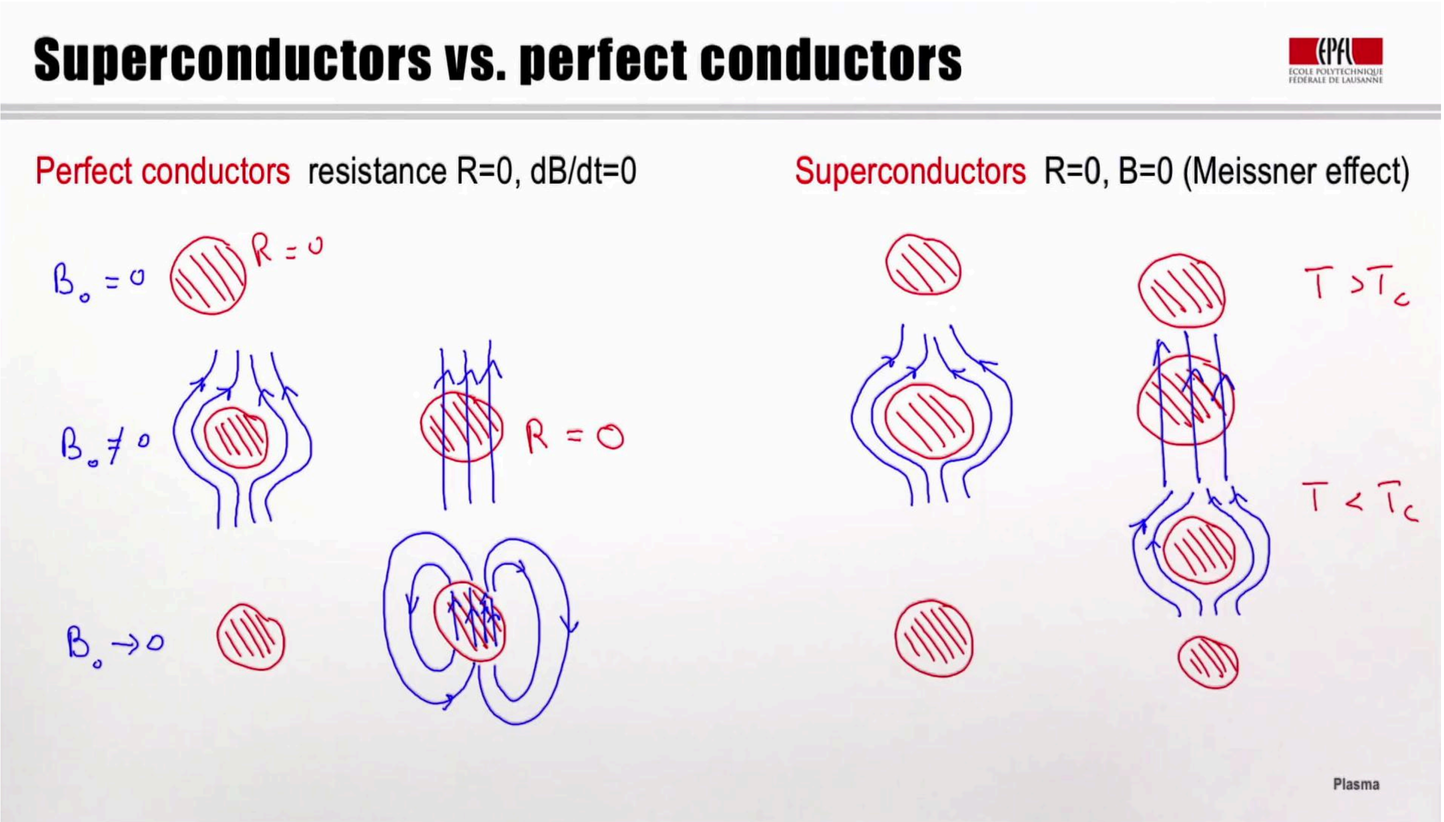


Let us briefly discuss the differences between superconductors and perfect conductors. By a perfect conductor, we mean a sample that has zero resistance. Therefore, that prevents variations of the magnetic field with time, or variation with flex through it. So take the sample here. No resistance. Say we start from a situation in which we have no applied field. And then we do apply a field. But the zero resistance on the sample prevents the field lines from entering into it. So the field lines, we have a shape of this kind. And we have to go around the sample. Now we remove the field, and the sample will stay simply in its state of zero resistance, of no field inside. Now, if we start from a situation in which the sample is immersed in a field, and it's resistance is made to zero. And then we remove the field. What happens is that the field has to try and stay the same inside the sample to preserve the flux, and therefore you will have a shape of this kind. So if we make a sample a perfect conductor in the presence of an externally-applied magnetic field, it would try, and it will keep its own field inside. In case of a superconductor, the situation is somewhat different.

Notes

Summary

3m 17s

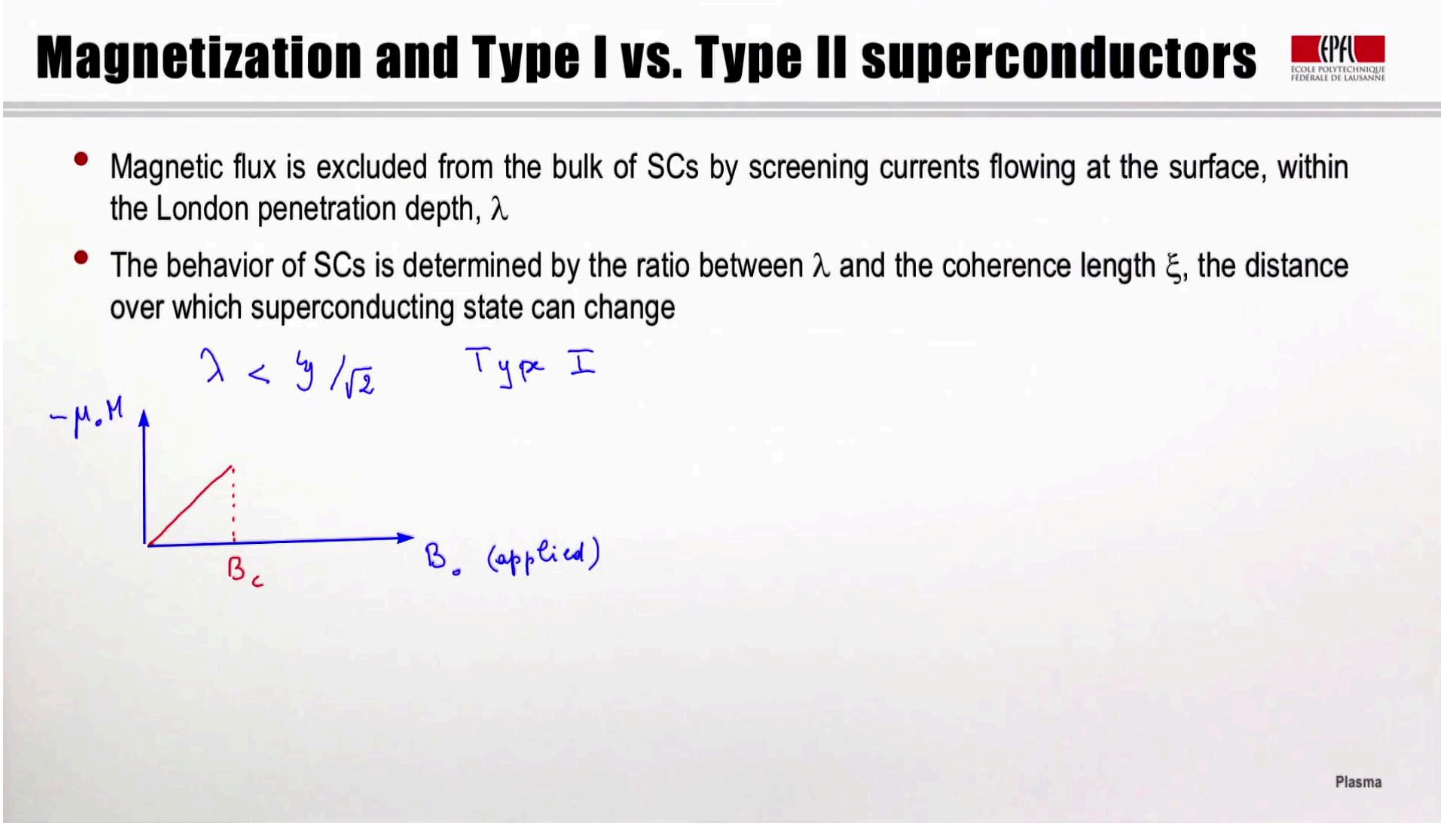


Let's start from the first sequence, so no field to begin with. Then we apply a field, and in this case, it's similar, identical to what happens in the perfect conductor. That is, the field goes around the superconducting sample, and it cannot penetrate inside. Then we remove the field again, and we are left with a superconducting sample that has no field inside. So the first case in which we apply a field to a sample and remove it is identical to that of a perfect conductor. What is different is when we apply a magnetic field to a sample that can become superconductor, say, we have a sample that can be superconductor, but it is not superconductor because we are at higher temperature than the critical temperature, which a transition occurs. We apply a field to that. Then we lower the temperature, so the sample becomes superconducting. The field is expelled from the sample. That's different from what we had in the case of a perfect conductor because the sample does not preserve its state of magnetic field inside, but it expels the field. If we then remove the field, as in the last step in the previous case, the field is still zero inside the superconductor. So we have positively expelled the field from the area of the superconducting material. That's the so-called Meissner effect.

Notes

Summary

4m 52s



We can now look at the magnetization and the distinction between Type I and Type II superconductors. What happens is that the magnetic flux is excluded from the bulk of the superconducting materials by screening currents that flow at the surface of the material. And that happens within a certain penetration depth, which we call the London penetration depth, or Lambda. And the behaviour of the superconducting material is determined by the ratio between this penetration depth Lambda, and the coherence length Xi, which is the distance over which typically the superconducting state can change. So let's see the two different cases defining Type I and Type II superconductivity. In the first case, we have that the penetration depth is smaller than Xi, or more precise, smaller than Xi over square root of 2. That's the Type I case. If in this situation, represent the applied field on the horizontal axis, and the magnetization times M_0 and times minus 1, so it is minus Mu_0 M on the vertical axis. We have a behaviour of the following kind. We have a perfect compensation of the external field up to a certain value of the field itself, which we call the critical field B_c.

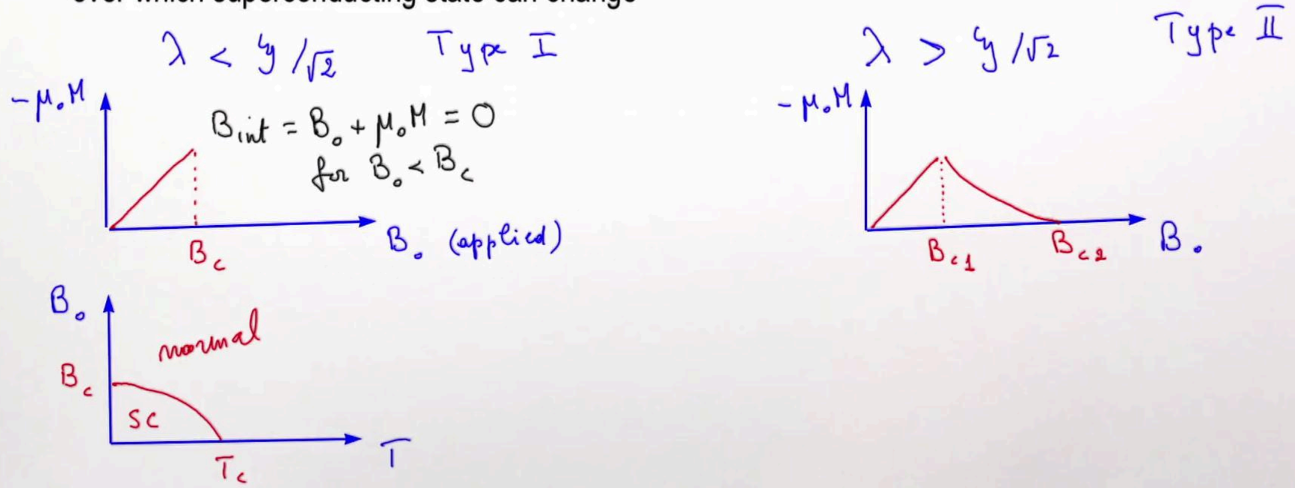
Notes

Summary

6m 28s

Magnetization and Type I vs. Type II superconductors

- Magnetic flux is excluded from the bulk of SCs by screening currents flowing at the surface, within the London penetration depth, λ
- The behavior of SCs is determined by the ratio between λ and the coherence length ξ, the distance over which superconducting state can change



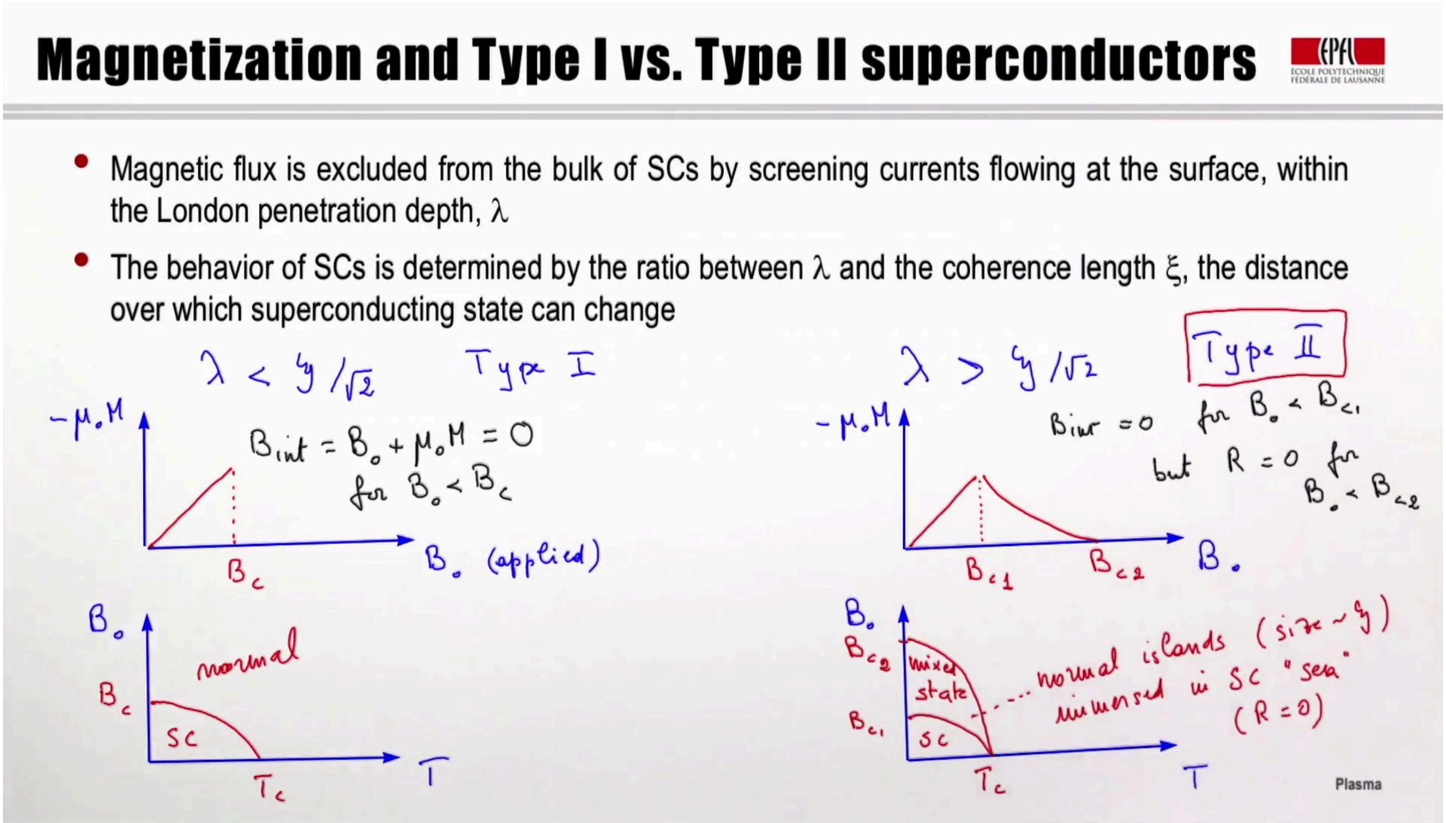
Plasma

This means that the internal field, which is equal to B_0 plus Mu_0 M is identical, equal to zero, for values of the externally-applied field, that's smaller than the critical value B_c. We can represent the situation also on a different representation, which is field versus temperature. We have a curve that defines a state of superconductivity below a certain value of the temperature, which is a critical temperature T_c, and the certain value of the field, which is the critical value B_c. That's a superconducting state. Outside, we have, we could call a normal behaviour. The opposite situation occurs when Lambda is larger than Xi over square root of 2, and that's what we call the Type II superconductivity. If I represent the same kind of plot for this situation, I have the following. Here is still the applied magnetic field. Here is still the magnetization times minus Mu_0. And the behaviour is the same for the first part of the curve, so that means I compensate completely the field that I apply outside with the magnetization inside. But that's only true to a certain critical value B_c1, which is generally relatively small, and after that, the curve goes down, reaching zero at a certain second critical value B_c2.

Notes

Summary

8m 10s

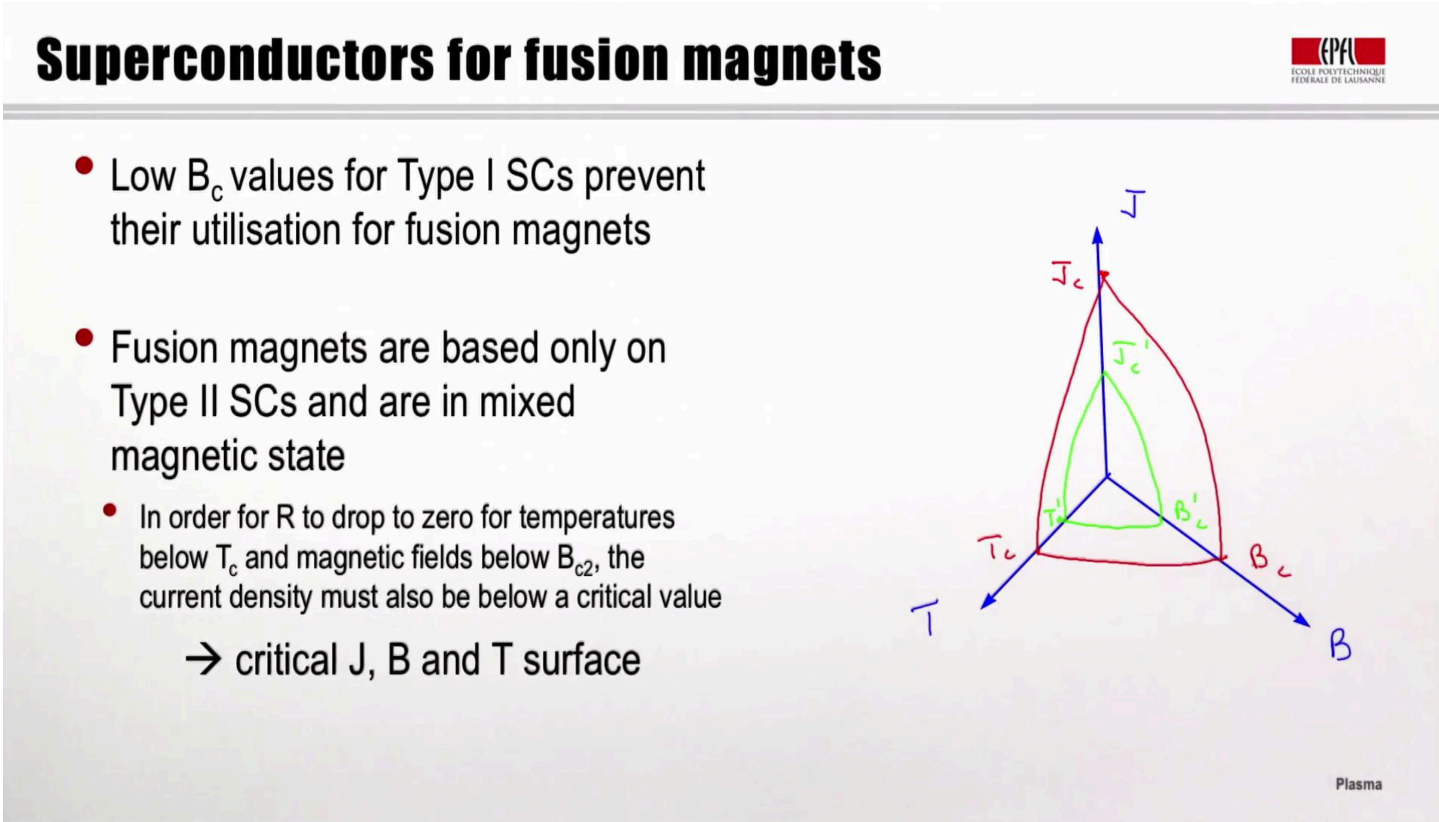


The internal field is zero, only for B_0 smaller than B_c1. But the resistance keeps being zero for values above B_c1 up to B_c2, so for B_0 smaller than B_c2. In the B_0 versus T representation, what we have is first, a region up to T_c and up to B_c1, which is pure superconducting region, as we had in Type I. But then, we have a second region, which is defined by B_c2 in terms of magnetic field intensity, and still, by T_c in terms of temperature, which is what we call a mixed state in which you have normal islands whose size is typically Xi that are immersed in a sea of a superconducting material with zero resistance. So that defines the Type II superconductivity.

Notes

Summary

10m 23s

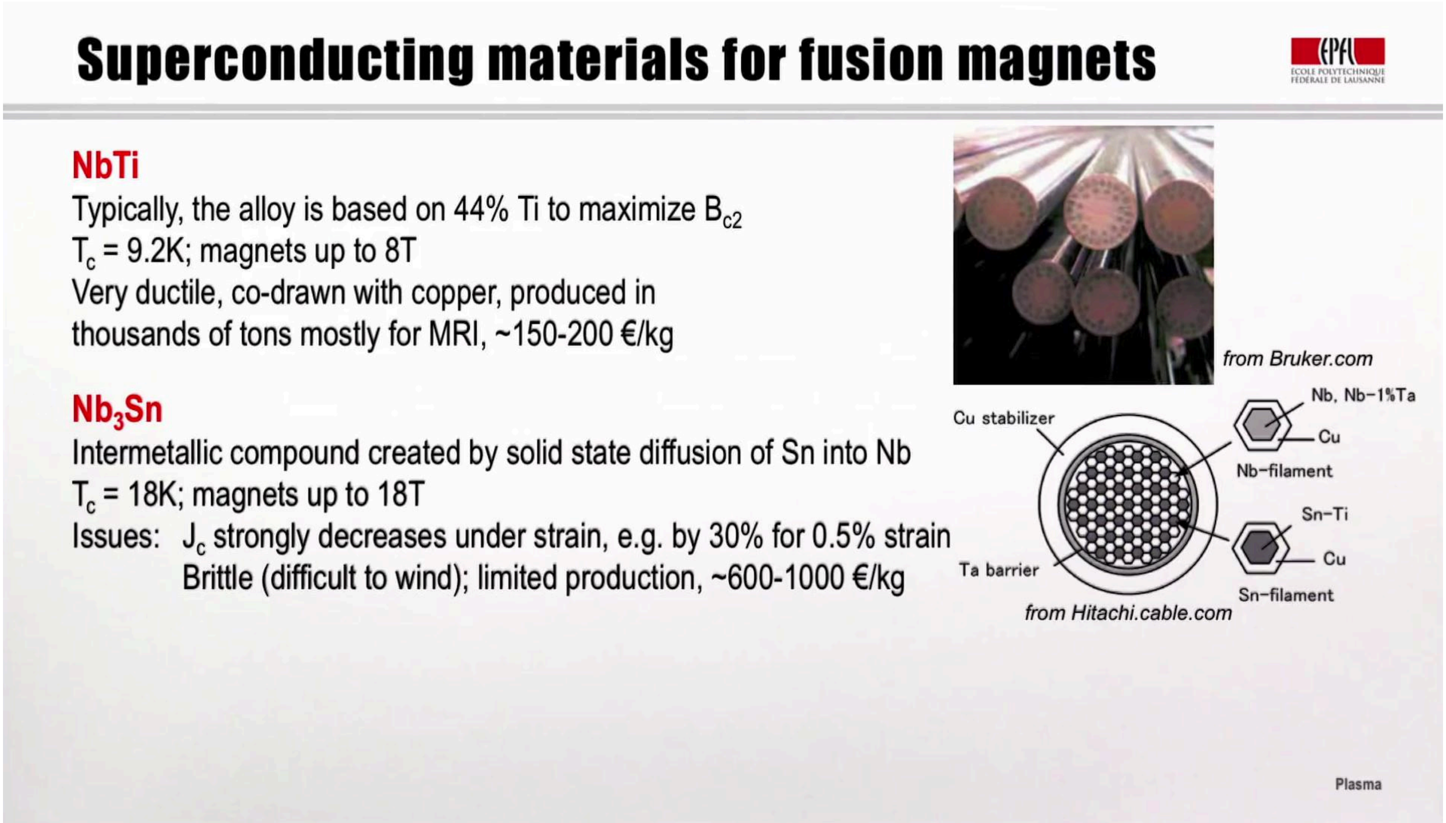


Let's now start thinking about using these superconductors for fusion. And the first important point to make is that the values of B_c for Type I superconductors are far too small to prevent their utilisation for fusion magnets. So fusion magnets in practice, are based only on Type II superconductors, And therefore, are in a mixed magnetic state as we have briefly discussed. And in order for the resistance to drop to zero for temperatures below the critical value and for magnetic fields below B_c2, we have another limiter to comply with, and that's the current density. The current density must also be below a critical value. So that means we have a defining surface in the J, B and T graph that limits the property of superconductors. Let's illustrate that in a plot. Here, we have a B in this axis, temperature in the other axis and the current density in the vertical axis. Superconductivity is defined within the surface of a given shape that's limited by the corresponding critical values. So this will be B_c, this will be T_C, and then we have also a critical value for the current density that we typically call J_c. Different materials have slightly different shapes and limitations for this curve. So for example, we can draw a material that has a smaller critical surface, that would be in green here, with its own, say, B_c prime, it's own J_c prime, and it's on T_c prime.

Notes

Summary

11m 47s



We're now ready to discuss superconducting materials that in practice, can be used for fusion magnets. As we say, they're all of Type II. The first one I can mention is Niobium Titanium, which is typically an alloy that's based on something like 44 percent of Titanium in order to maximise the value of the critical field B_c2. Its critical temperature is 9.2 Kelvin. And the magnets that we can build out of this material can go up to eight Tesla. It's a very ductile material that's produced by being co-drawn with copper. And it's produced in large quantities mostly for medical application in MRIs. Its cost is therefore, not that high. It's about €150 to €200 per kilogramme. Second kind of material that we can use is Niobium_3 Tin, which is an intermetallic compound that's created by solid-state diffusion of Tin into Niobium. It has a critical temperature of 18 Kelvin. And the magnets we can make out of it can go up to 18 Tesla, which is of course, very interesting for fusion applications. However, there are a few issues. The critical value of the current density strongly decreases under strain. For example, 0.5 percent of strain is sufficient to decrease that by 30 percent, and that's not a good piece of news for fusion.

Notes

Summary

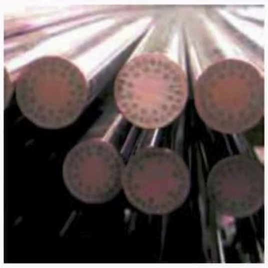
13m 45s

Superconducting materials for fusion magnets

EPFL ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

NbTi

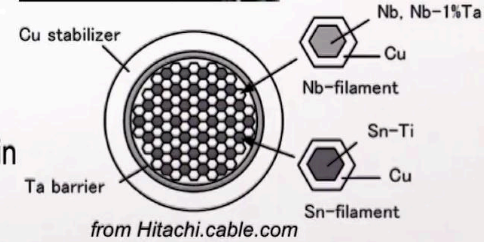
Typically, the alloy is based on 44% Ti to maximize B_{c2}
T_c = 9.2K; magnets up to 8T
Very ductile, co-drawn with copper, produced in thousands of tons mostly for MRI, ~150-200 €/kg



from Bruker.com

Nb_3Sn

Intermetallic compound created by solid state diffusion of Sn into Nb
T_c = 18K; magnets up to 18T
Issues: J_c strongly decreases under strain, e.g. by 30% for 0.5% strain
Brittle (difficult to wind); limited production, ~600-1000 €/kg



from Hitachi.cable.com

Plasma

It's a very brittle material, so it's difficult to wind into coils, and has quite a limited production, which amounts to a relatively large cost of the order €600 to €1,000 per kilogramme.

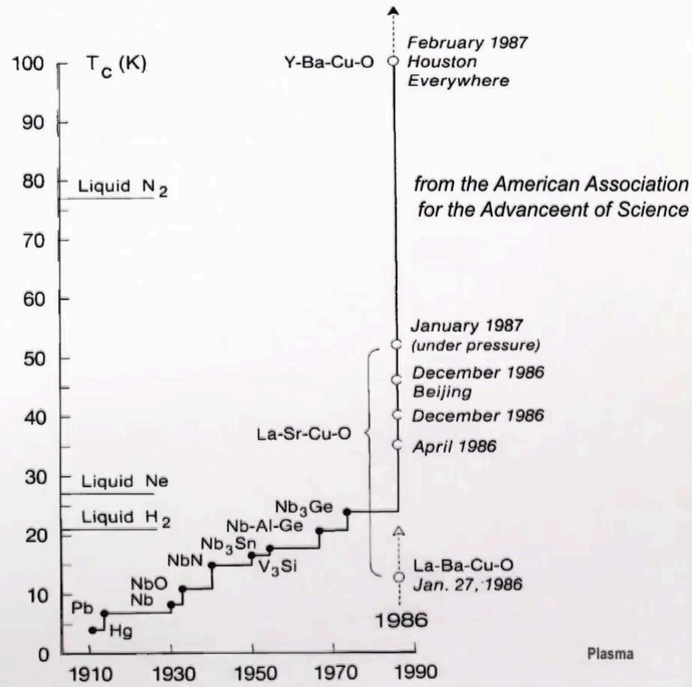
Notes

Summary

15m 14s

High temperature superconductivity

- In 1986 Bednorz and Müller discovered superconductivity at 30K
- Two classes of HTS materials are potentially suitable for fusion magnets
  - Bismuth strontium calcium copper oxide compounds (Bi2212, Bi2223)
  - Rare earth barium oxide compounds (ReBCO)
- The main potential advantage of HTS for fusion is the possibility of operating at magnetic fields higher than 20T

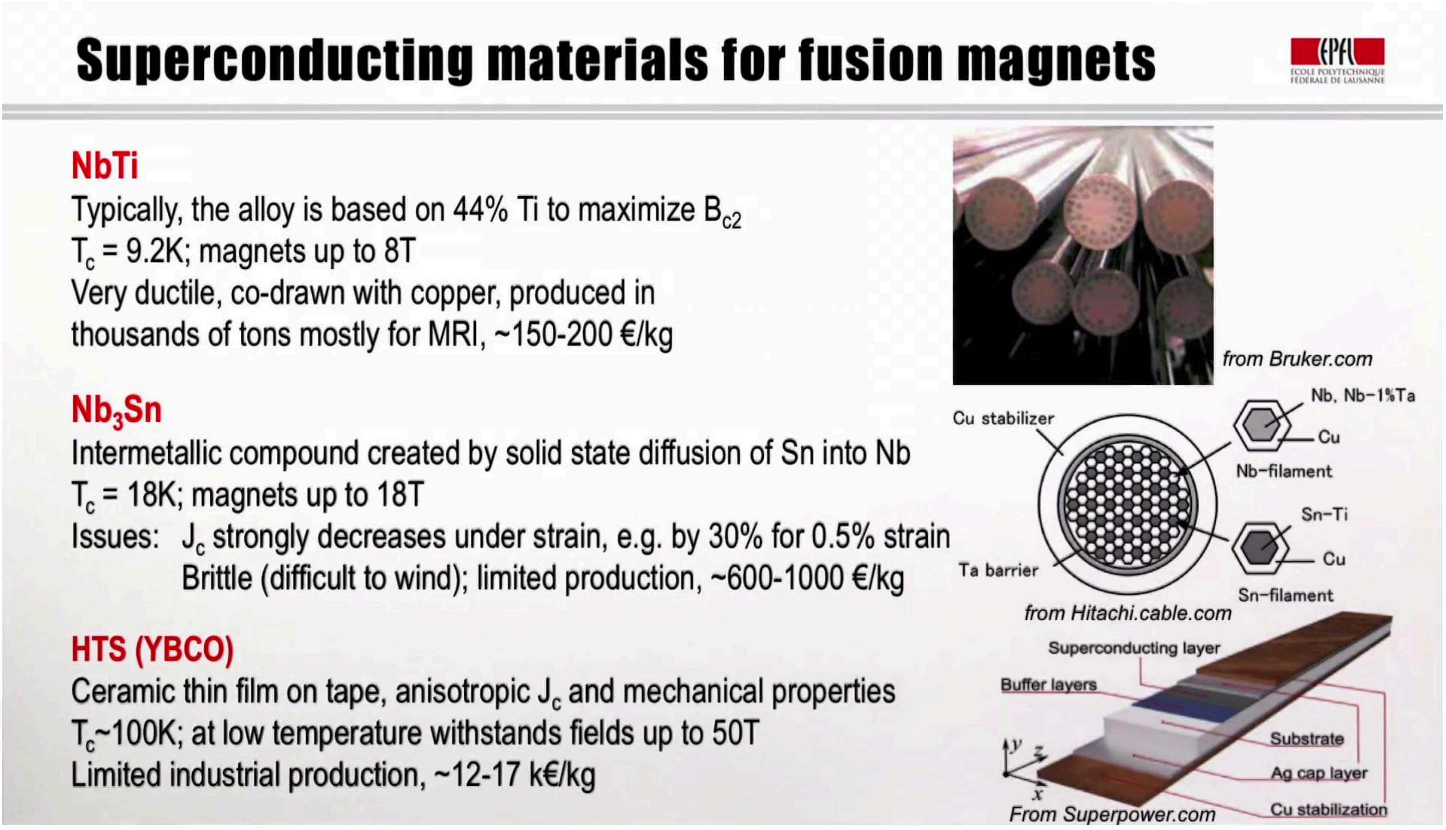


And before completing the family of possible superconductors that are used for fusion, I mentioned the discovery of high-temperature superconductivity, which can open up new avenues. The discovery was done by Bednorz and Müller in 1986, in fact, in Switzerland, who discovered that you can have superconductivity at 30 degrees Kelvin. You can see on the plot on the right here, the critical temperatures for the different materials, as they have evolved throughout the years with a big jump when the high-temperature superconductivity was discovered. And therefore, you can see almost a vertical development here in the first year, or first couple of years. Nowadays, we have two classes of HTS materials that can be suitable for producing fusion magnets. First class is that made of the Bismuth Strontium Calcium Copper Oxide compounds, or Bi2212, or Bi2223. Second class is made of rare earth Barium Oxide compounds, which refer to generally as ReBCO. The main potential advantage of HTS for fusion is not so much the high value of the critical temperature, but it's the possibility of operating magnetic fields that are very high, higher than 20 Tesla.

Notes

Summary

15m 28s

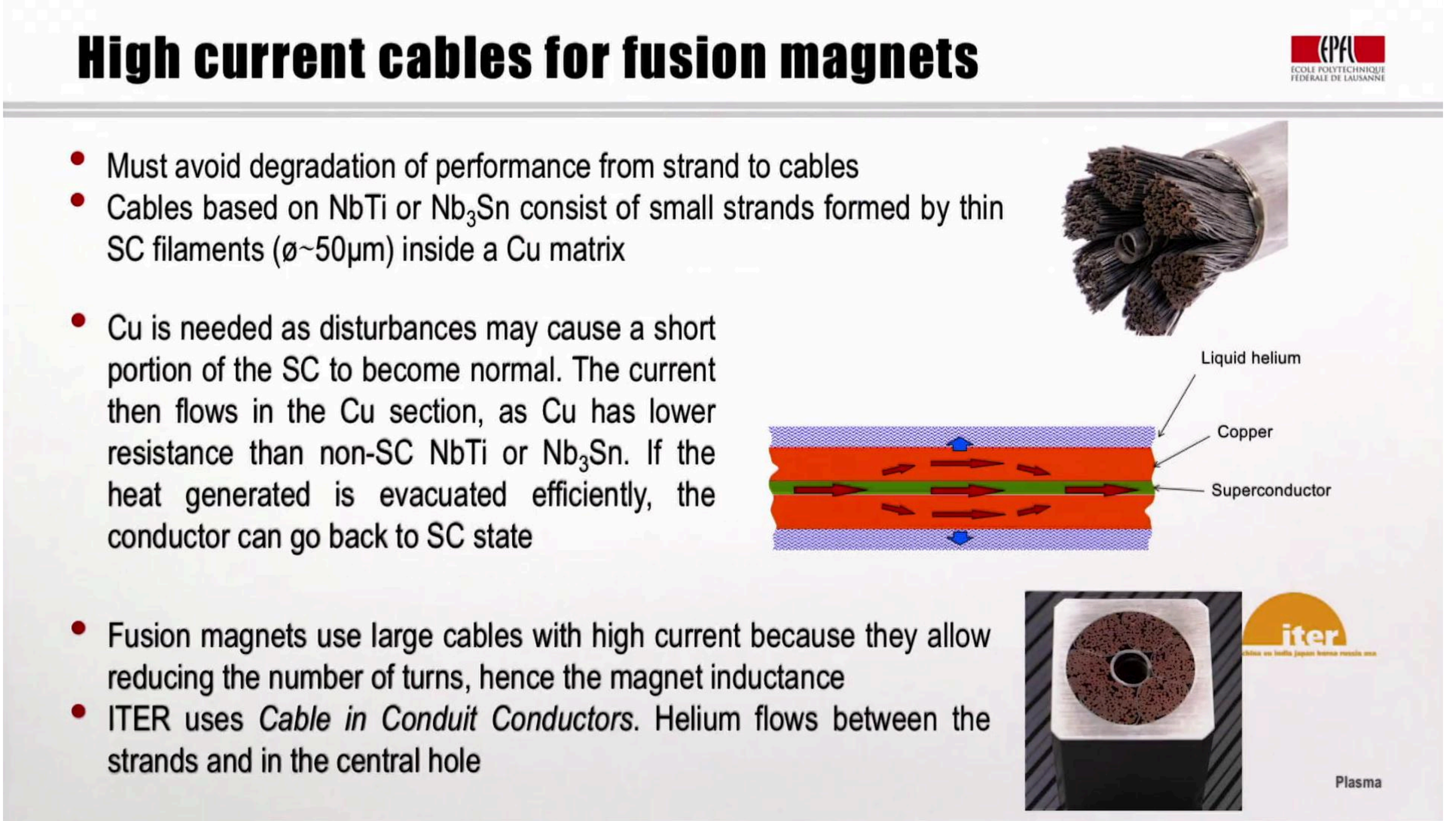


So now adding to the list we have made before, we have the new class HTS, for example, Yttrium BCO, which are in the form of ceramic thin films that are on tape, which unfortunately bring anisotropic properties in terms of mechanical aspects, but also in terms of current density. So the design has to take this into account. The critical temperature is very high, 100 degrees Kelvin, but we have to go to low temperature in order to explore the potential in high fields. And if we do go to low temperatures, this conductor can withstand fields up to 50 Tesla. It's a new technology with so far very limited industrial production, and therefore, very high cost, which is of the order of €12,000 to €17,000 per kilogramme.

Notes

Summary

16m 53s



Now looking at the cables for fusion magnets, we have to go from strand to cable, and possibly avoiding the degradation of performance as we make that transition. The cables that we use today are mostly made of either Niobium Titanium or Niobium_3 Tin. And they consist of small strands that are formed, in turn, by very thin filaments of superconducting material, as thin as about 50 microns in diameter. And they are embedded in a Copper matrix. Why Copper? Copper is needed as the disturbances can occur, and can cause a short portion of the superconducting material to become normal, that is, non-superconducting. In this sketch, this is illustrated here. So the current would flow in a superconducting material. But if there's a portion of it that's no longer superconducting, the current will flow in the Copper section. And that's because the Copper section will have a lower resistance than the non-superconducting version of Niobium_3 Tin or Niobium Titanium. Now, if we're good enough with the heat extraction, if the heat that's generated by this resistive path is evacuated efficiently, then the conductor can go back to superconducting state, and therefore, we can have sort of a in-situ cure for this local disturbance.

Notes

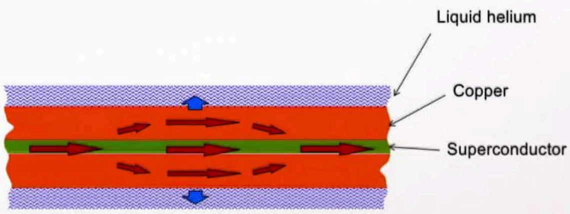
Summary

17m 43s

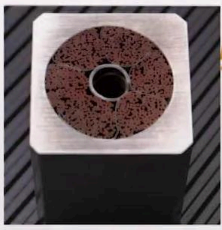
High current cables for fusion magnets

- Must avoid degradation of performance from strand to cables
- Cables based on NbTi or Nb_3Sn consist of small strands formed by thin SC filaments (ø~50µm) inside a Cu matrix

- Cu is needed as disturbances may cause a short portion of the SC to become normal. The current then flows in the Cu section, as Cu has lower resistance than non-SC NbTi or Nb_3Sn. If the heat generated is evacuated efficiently, the conductor can go back to SC state



- Fusion magnets use large cables with high current because they allow reducing the number of turns, hence the magnet inductance
- ITER uses *Cable in Conduit Conductors*. Helium flows between the strands and in the central hole



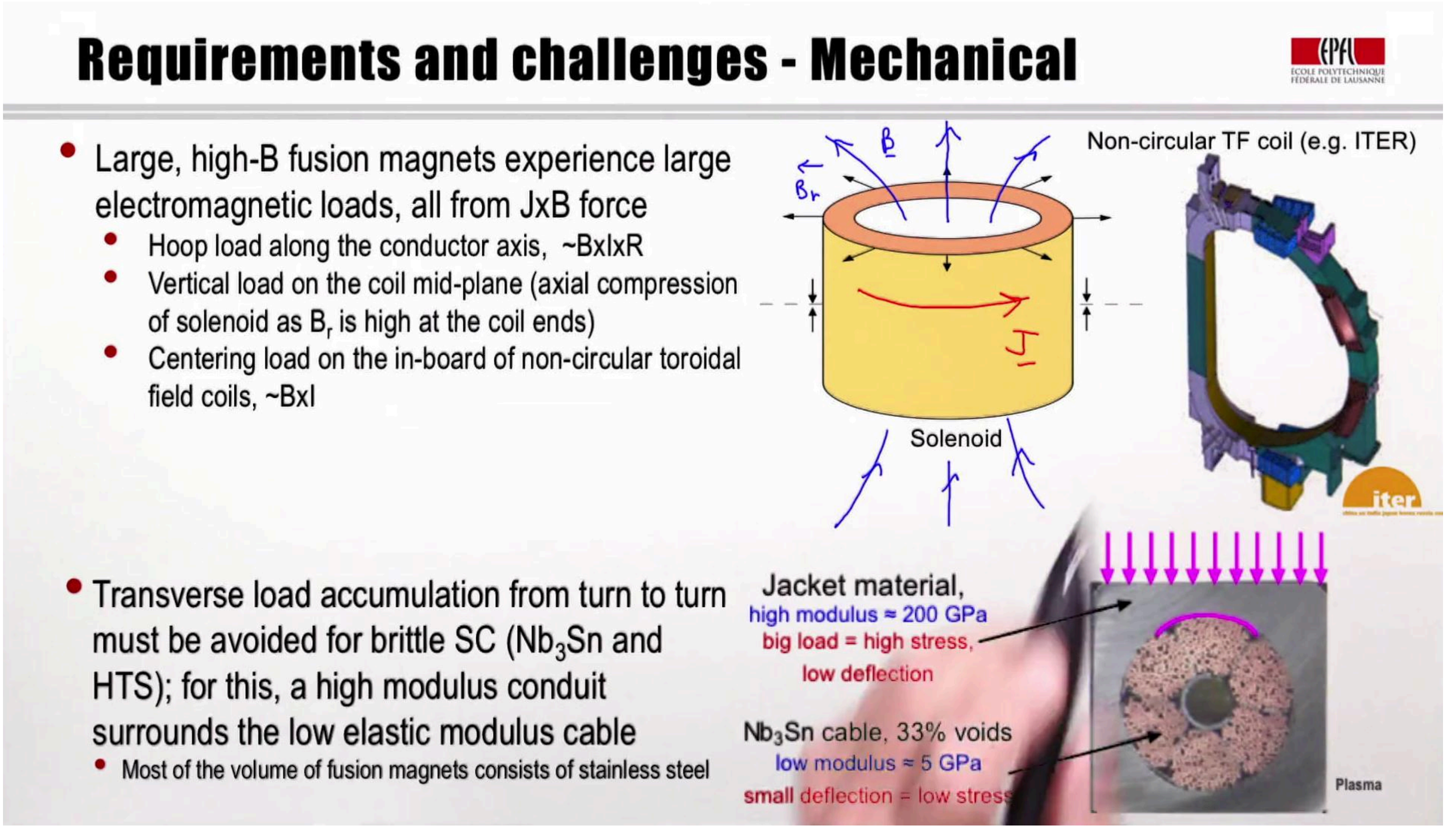
Plasma

And that's why we have Copper around. In practice, in fusion magnets, we always use very large cables that carry large current, not just large current densities, because this allows us to reduce the number of turns, hence, the magnetic inductance. ITER, for example, uses a concept called Cable in Conduit, in which Helium flows both in between the strands in the voids that are left by the strands, and in the central hole in the conductor. As we see immediately, the conduit around, which is made of stainless steel, is there for mechanical stability.

Notes

Summary

19m 05s

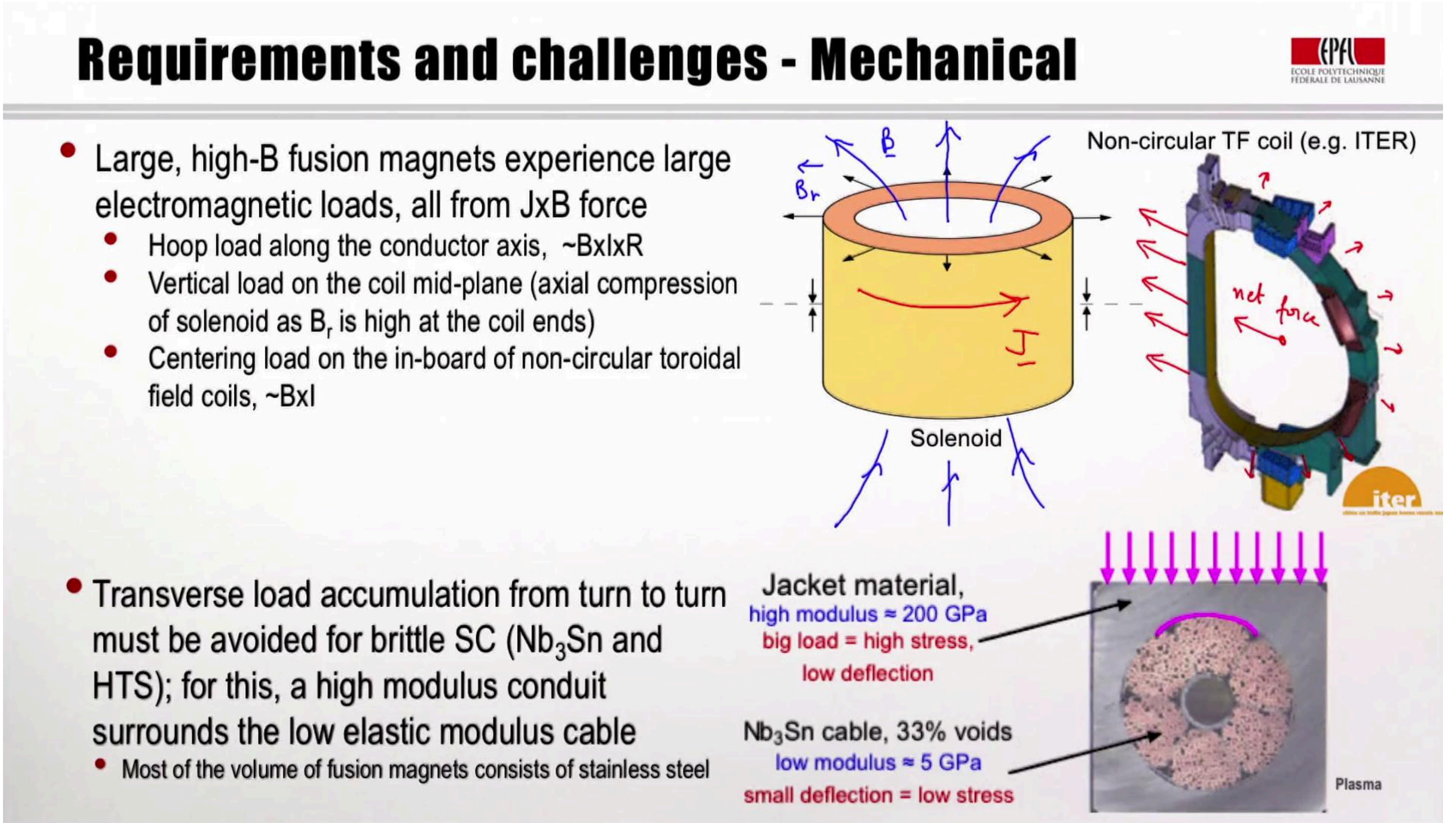


So let's discuss the requirements and challenges that making magnets out of superconducting material entail. First of all, in terms of mechanical properties. The large fusion magnets that we're building are immersed in very high fields, and therefore, experience very large electromagnetic loads, essentially all issued fundamentally from the JxB force. First of all, there's a force that we refer to as the hoop force or hoop load, along the conductor axis. So suppose the magnetic field is produced by a current that goes in this direction. The magnetic field will therefore, be in the vertical direction here, and coming up the solenoid this way, So the hoop force tends to open up the coil, and that's proportional to the field intensity to the current, and to the radius of curvature. We also have a radial component for the field here at the two ends of the solenoid, which produces an axial compression of the solenoid in the middle, which is a vertical load, if you'd like, in this drawing. If you look at the actual toroidal field coil, for example, that of ITER, that's not circular. So why is that important?

Notes

Summary

19m 44s



That is important because if I look at the hoop force which I can represent as these vectors here, that's not going to be symmetric between the in-board and the out-board. In-board being practically vertical, the hoop force would be very large. The out-board being much more curved, so a smaller radius of curvature, will have a smaller hoop force. So there will be a net force that will pull the magnet towards the in-board side. That force will be proportional to the field and the current that flows in the coil. One thing that has to be avoided is the transverse load accumulation from turn to turn. In particular, that would be very critical for brittle superconducting materials such as Niobium_3 Tin and the HTS materials that we have in mind for future applications. So that's why we have this conduit around the superconducting cable made of high modulus material, typically stainless steel, because the cable itself will have a low elastic modulus, and therefore will be deformed too much by the accumulation of this stress. In fact, as a consequence, most of the volume of the fusion magnets actually consists of a stainless steel.

Notes

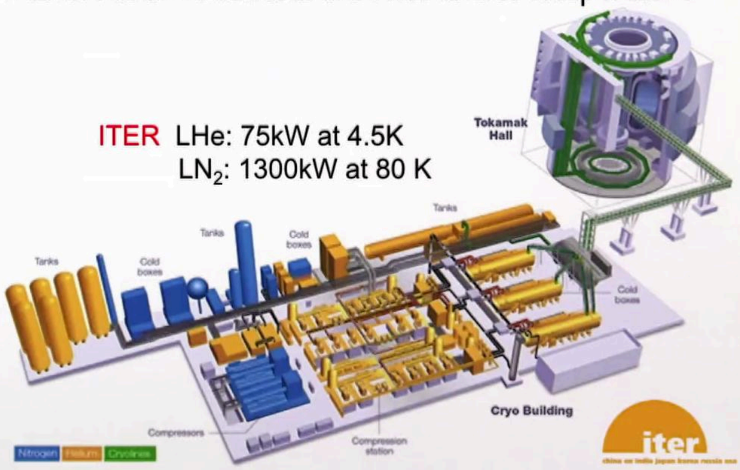
Summary

21m 24s

Requirements and challenges - Thermal

- The large mass of the SC magnets is kept cold in a cryostat by large He refrigerators, which use a few tens MW electric power to remove heat loads of several tens kW at low temperature
- Main heat loads
  - Nuclear radiation on the TF coils
  - Ohmic heating of the conductor joints
  - Heat conduction (feeders and gravity support)
  - AC losses in the coils
  - Pumping losses for He circulation
  - Heat radiation from room temperature

ITER LHe: 75kW at 4.5K
LN_2: 1300kW at 80 K



- The variation of the operating temperature must be kept within a margin of ~1-2 K
- Note that HTS also need to be cooled below ~10-20 K to withstand high fields

Plasma

Let's look at the thermal requirements and challenges. The large mass of the superconducting magnets must be kept very cold in a cryostat that uses very large Helium refrigerators. Typically, we use a few tens of megawatts of electrical power to remove heat loads over several tens of kilowatts at low temperature. This is an example of the cryo-building or the cryostat system in ITER, which has a cooling power of 75 kilowatts at 4.5 Kelvin for the Helium circuit and 1.3 megawatts at 80 Kelvin for the liquid nitrogen circuit. Liquid nitrogen is in blue here, the helium is in orange, and the cryo lines that go to the cryostat and then the tokamak are in green. What are the main heat loads? We have the nuclear radiation on the TF coils that's generated by the neutrons that are fissioned by the fusion reactions in the core of the plasma. We have some Ohmic heating at the conductor joints, which are not perfect conductors. Heat conduction through the feeders and gravity supports. AC losses in the coils. And we have pumping losses for the circulation of the Helium in the system. And finally, we have some heat radiation from the room temperature component.

Notes

Summary

22m 54s

Requirements and challenges - Thermal

- The large mass of the SC magnets is kept cold in a cryostat by large He refrigerators, which use a few tens MW electric power to remove heat loads of several tens kW at low temperature
- Main heat loads
  - Nuclear radiation on the TF coils
  - Ohmic heating of the conductor joints
  - Heat conduction (feeders and gravity support)
  - AC losses in the coils
  - Pumping losses for He circulation
  - Heat radiation from room temperature

ITER LHe: 75kW at 4.5K
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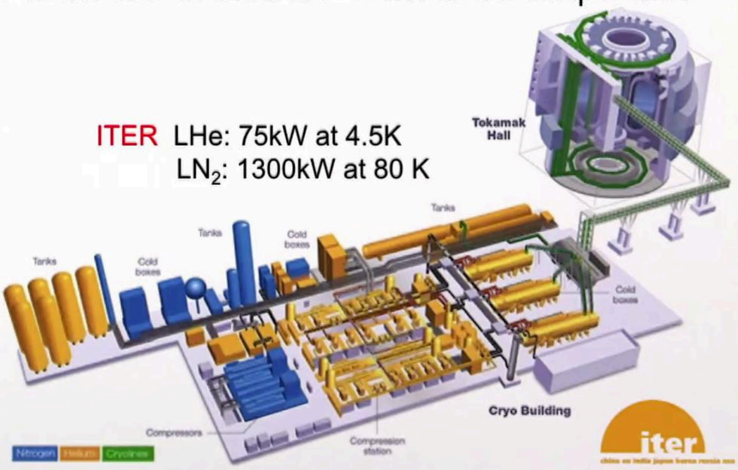


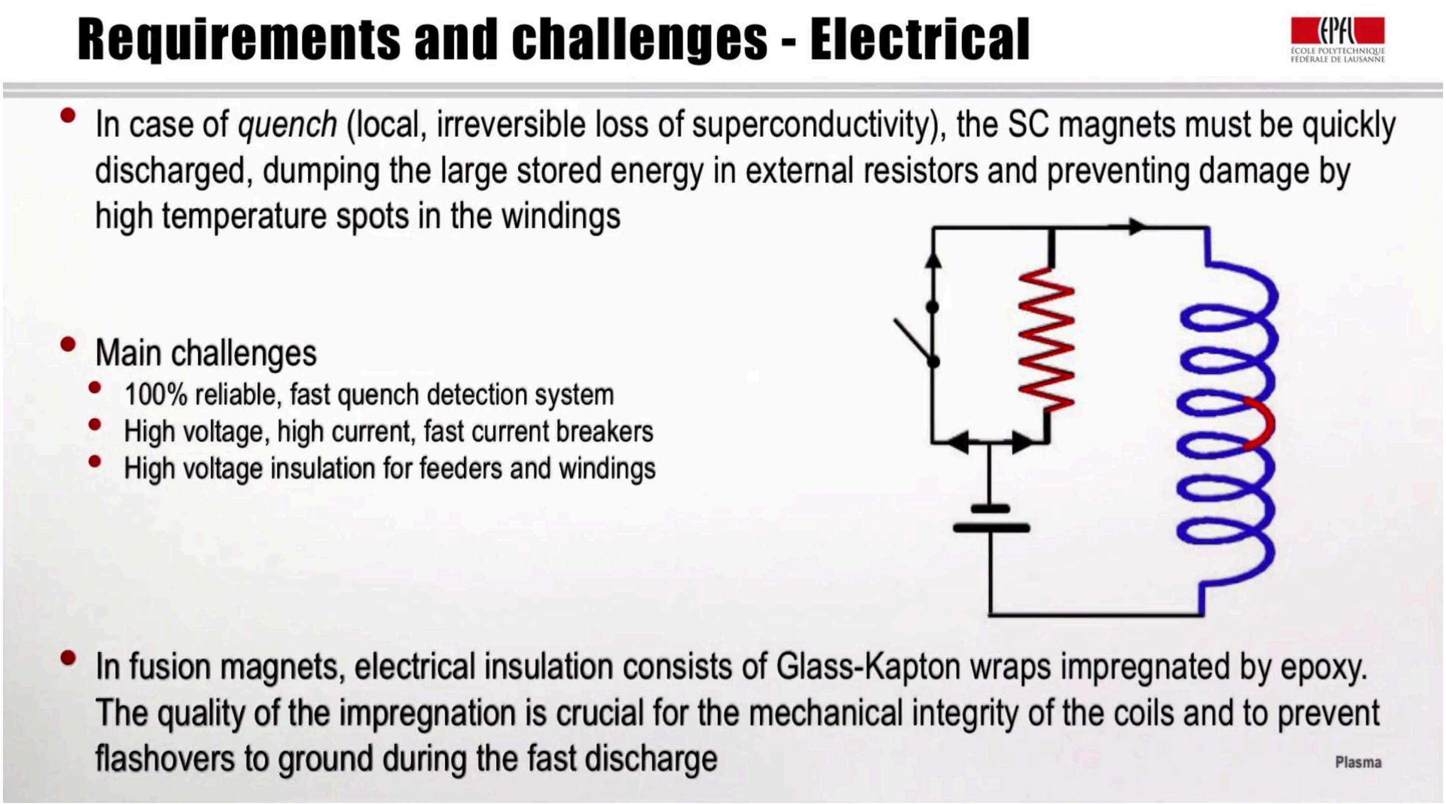
- The variation of the operating temperature must be kept within a margin of ~1-2 K
- Note that HTS also need to be cooled below ~10-20 K to withstand high fields

We noticed that the variation of the operating temperature must be kept within the margin of one, maximum two, degrees Kelvin. We also note that even for high temperatures for conductors, we need to be cooled below 10K to 20K to withstand high fields and to have good current densities.

Notes

Summary

24m 18s



Challenges are also posed by the electrical aspects of the magnets. In particular, in case of quench, which is the term we use to define a local irreversible loss of superconductivity, we must discharge the superconducting magnets very quickly and dump the large stored energy that's in them, in external resistors, therefore, preventing the damage by high temperature spots in the windings. So what are the challenges of doing that? We have to have a 100 percent reliable, fast quench detection system. We have to have fast current breakers that can withstand high voltage and high currents. So this is the breaker that would open the circuit if we have a quench. So a portion of the superconductor that is no longer superconducting, we have to have the current that go through and is dissipated by this resistor, so we have to open that breaker very quickly. And of course, we have to have high voltage insulation for both the feeders and the windings. In fusion magnets, the electrical insulation consists of Glass-Kapton wraps that are impregnated by epoxy. This may sound like a relatively easy detail, but in fact, the quality of the impregnation is very crucial for the mechanical integrity of the coils, and it's very important to prevent electrical discharges or flashovers to ground during the phase of the fast discharge of the coil itself.

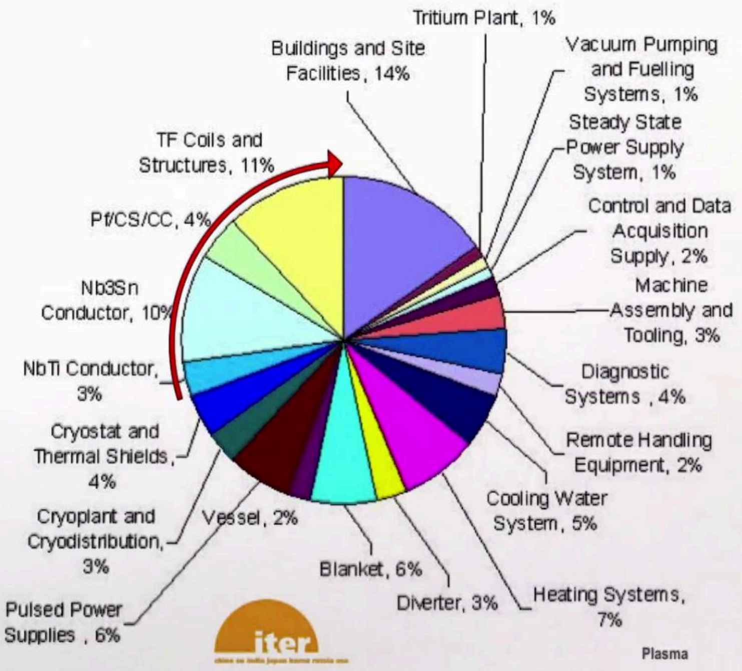
Notes

Summary

24m 41s

Requirements and challenges - Economical

- Cost of SC material: ~100-1000 times that of Cu
- SC magnets make up a substantial fraction of the capital cost for a large fusion device, ≈ 30% for ITER
- Cost effective design and manufacture of SC magnets are crucial issues

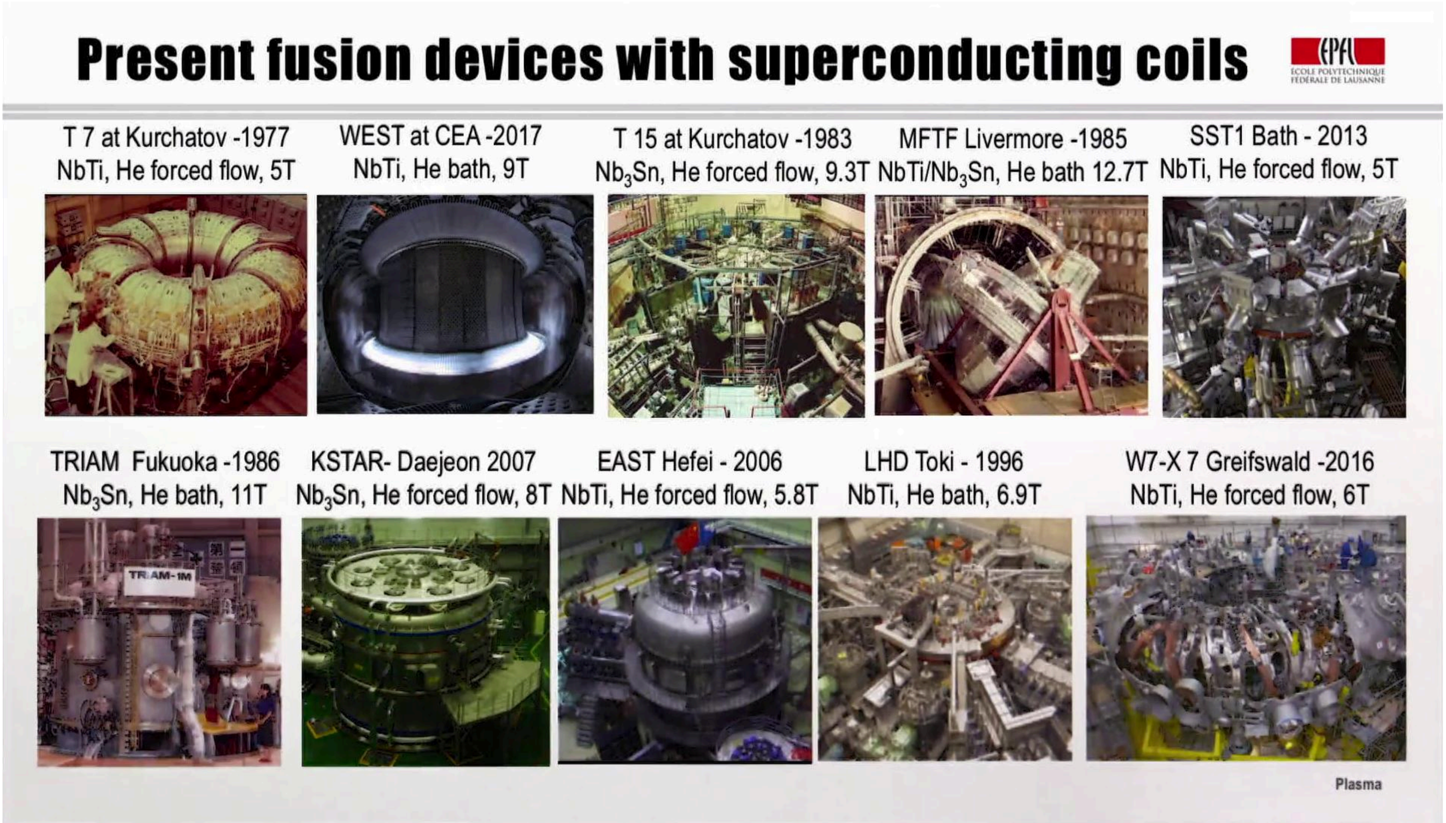


Last but not least, there are economical challenges for the coils. The cost of the materials that we use for superconducting coils is about 100 to 1,000 times that of Copper. As a consequence, the superconducting magnets make up a very substantial fraction of the total cost for a large fusion device. For example, in this pie from ITER, you can see the different aspects and the different components that are represented in terms of the fraction of total cost. And the conductors for the superconducting magnets are here, Niobium Tin, Niobium Titanium, and the other elements for the coil structures, for example, are all here, amounting in total to about 30% percent of the capital cost. So that means that cost-effective design and manufacture for these magnets are absolute crucial issues.

Notes

Summary

26m 12s

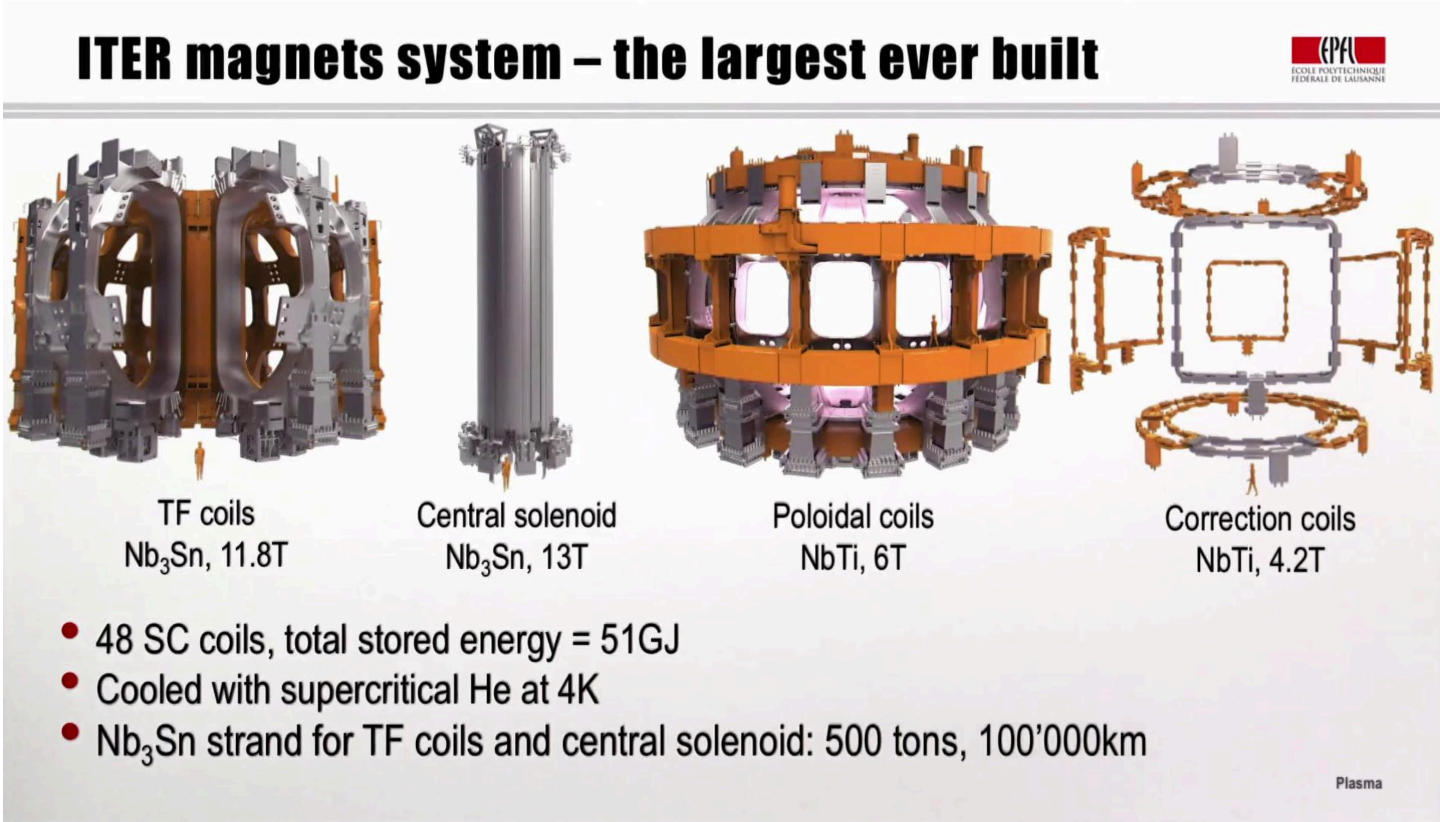


Just to show pictorially, that we're already using several fusion devices that employ superconducting coils, here are the pictures of some of them, starting from the one built in 1977 at Kurchatov in Russia, goes up to 5 Tesla with Niobium Titanium coils. We have the most recent WEST facility at CEA. It's a new version of a Tore Supra, in France, that employs also Niobium Titanium, going up to nine Tesla. And several other examples in the East, the KSTAR in Korea, EAST in China. And the superconducting stellarator here that goes up to six Tesla, also using Niobium Titanium, and the forced flow for Helium.

Notes

Summary

27m 05s

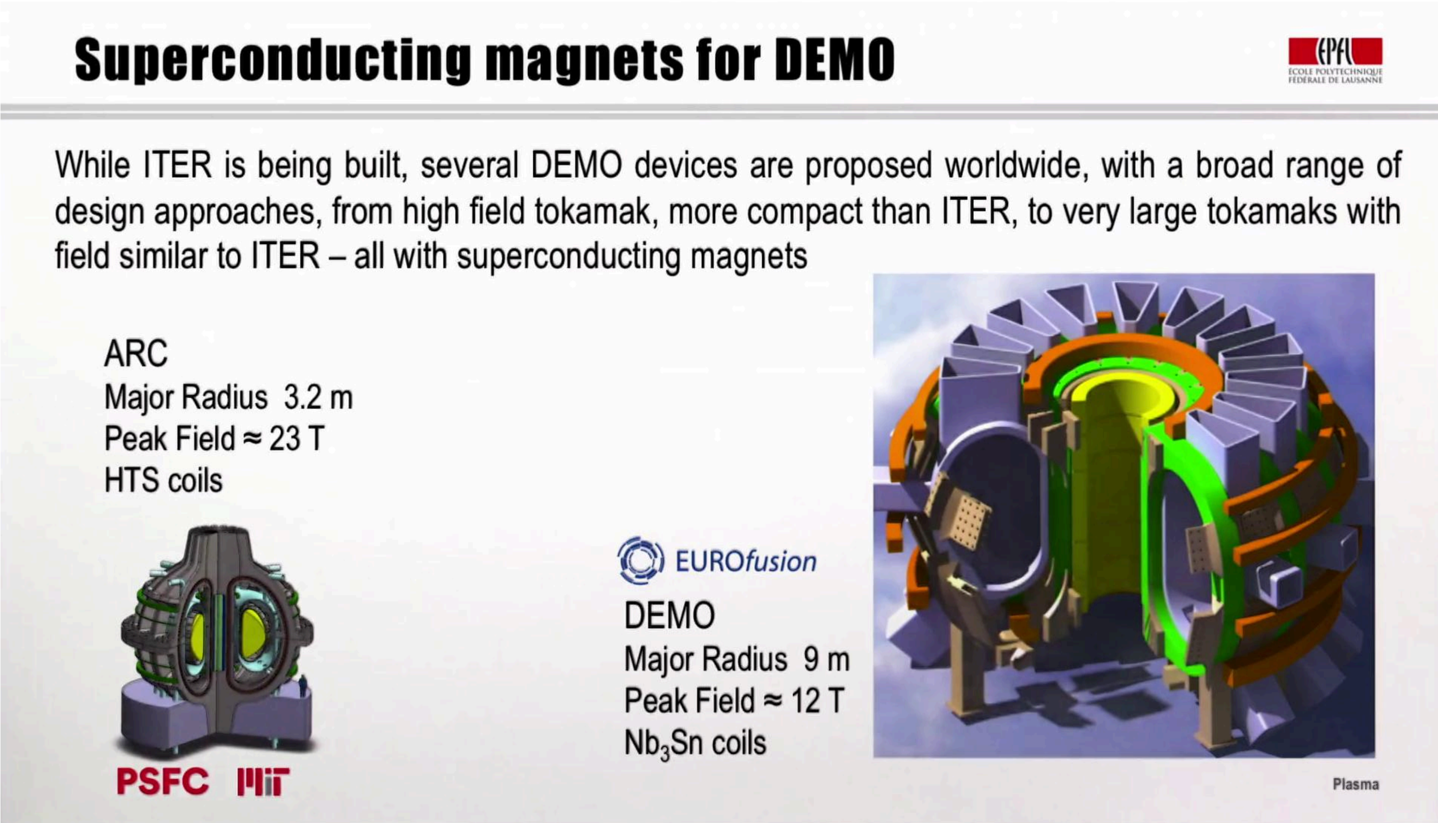


Now let's look at what's being built for ITER. In fact, that's the largest magnet system ever built. We see different components here. The TF coils, the toroidal field coils, made of Niobium_3 Tin, going up to 11.8 Tesla. The central solenoid for driving the Ohmic current into the plasma, also Niobium_3 Tin, up to 13 Tesla. The poloidal coils, which don't require such a high field, and therefore, can be made of Niobium Titanium. As the correction coils, which only need to go up to 4.2 Tesla, also made of Niobium Titanium. In total, we have 48 superconducting coils amounting, when they operate, to a total stored energy of more than 50 gigajoule, which is a gigantic number. They're all cooled with supercritical helium at four Kelvin. And just to give you an idea of the challenge, this is the largest single procurement for a Niobium_3 Tin superconducting material. And the strand for the TF coils and the central solenoid together correspond to a weight of about 500 tonnes and to a length of about 100,000 kilometres.

Notes

Summary

27m 58s

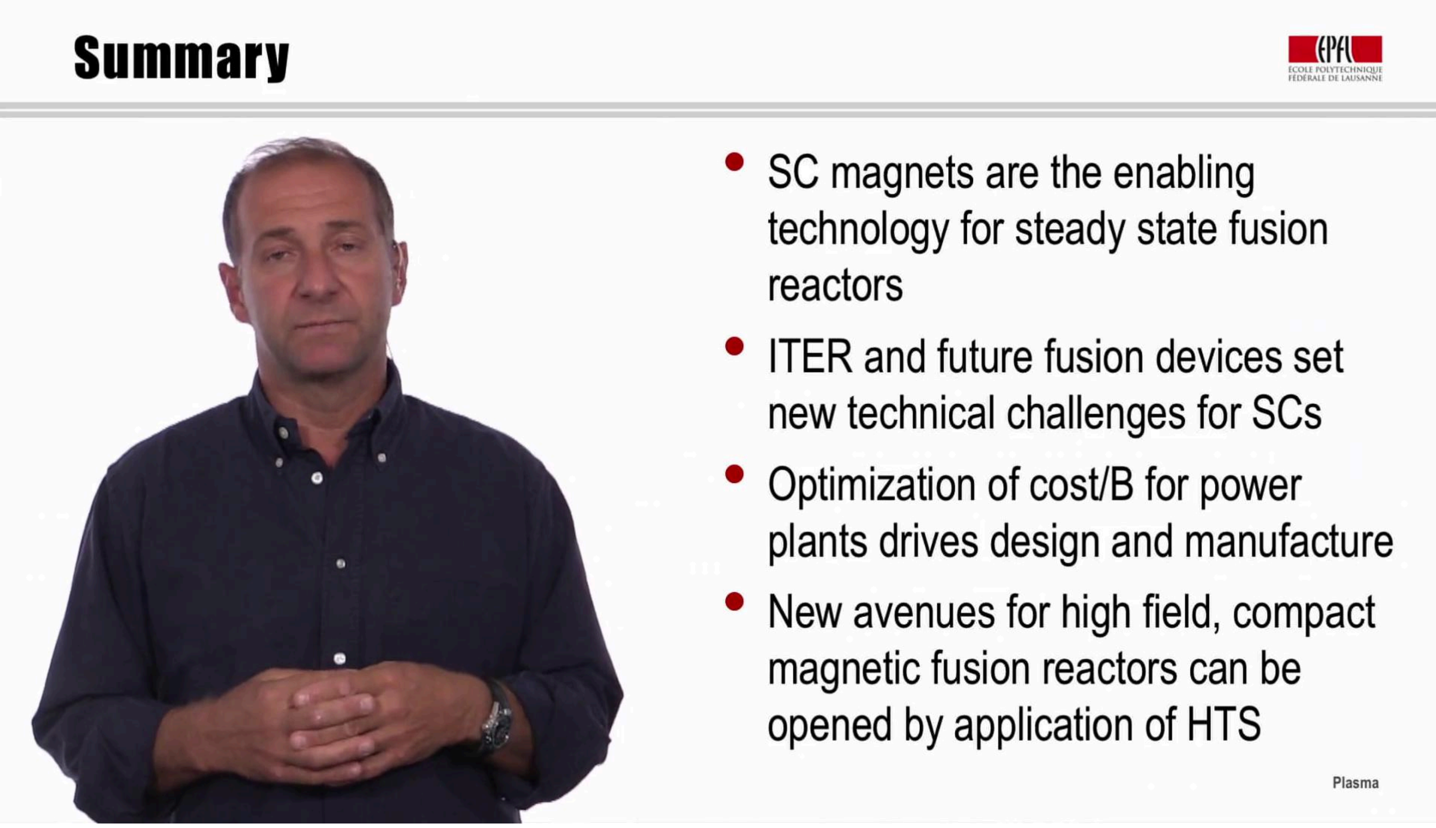


As we have discussed in other lectures, ITER will demonstrate that fusion can be done scientifically and technologically on Earth. But we need one other step to demonstrate that we can also have an economical development of fusion energy, and that's referred to as DEMO. And while ITER is being built, several DEMO devices or approaches, are proposed throughout the world. There's a broad range of approaches, in fact, from very high field tokamak, which is much more compact than ITER, to tokamaks that are somewhat slightly larger version of ITER. Here, on the left, you see an example of the high-field compact proposals. This is the ARC proposal from MIT in US. And that employs high-temperature superconducting coils with a peak field up to 23 Tesla. So you can see the size is relatively small compared to the other proposal that I illustrate here, which is the European DEMO proposal, nine metres of major radius as opposed to three, and the peak field of 12 Tesla. This is using low-temperature Niobium_3 Tin superconducting coils. All of these proposals around the world, all of the possible ideas and approaches for the step after ITER use superconducting magnets.

Notes

Summary

29m 15s



In summary, we have seen that superconducting magnets are a main element of enabling technology for fusion reactor developments. ITER and all the fusion devices we have in mind set new technical challenges that are very demanding for superconductors. A main element for the development of a power plant based on a magnetic fusion concept is the optimization of the cost-to-performance ratio of the magnets, that is, the cost divided by the magnetic field intensity that can be produced over the large volume. And that's a main driver for design and manufacture of the magnets, and of the reactor. New avenues for high-field compact magnetic fusion reactors can be opened by the application of high-temperature superconductivity.

Notes

Summary

30m 34s