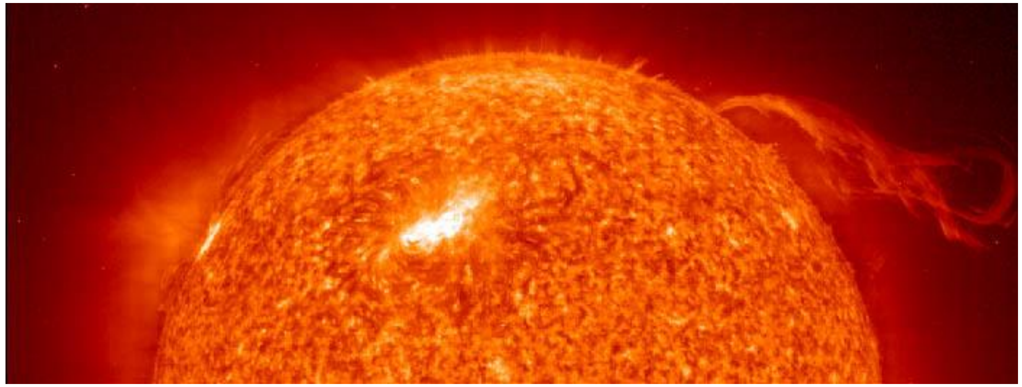
EUROfusion

FinnFusion



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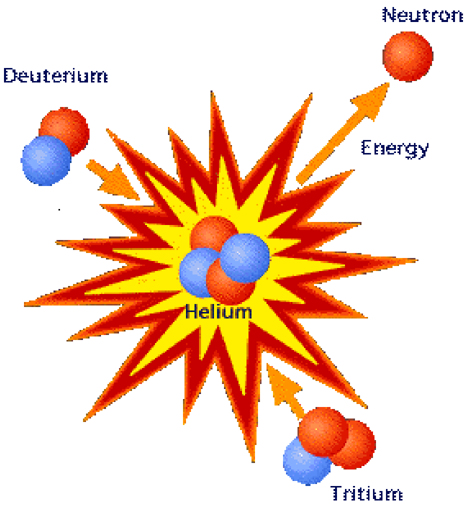
Aim for nuclear fusion as an energy source

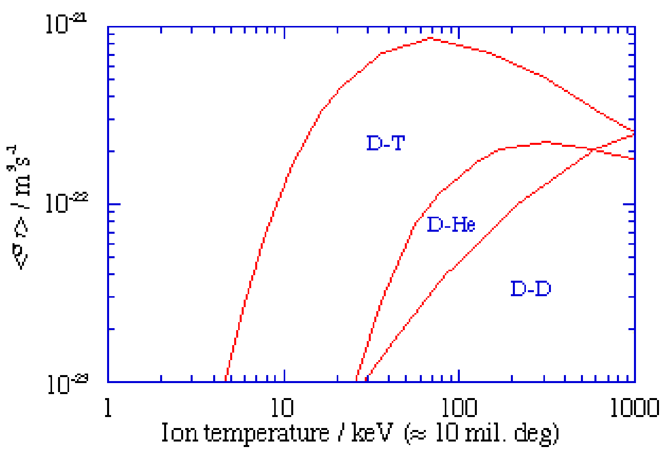
- Nuclear fusion works well in several known cases
- In nature:
  - The sun and all stars
- Made by man:
  - Nuclear physics enabled by ion accelerators
  - Thermonuclear weapons
- However, getting it to work in a controlled energy-producing manner on Earth is a challenge
- Many many approached have and are being tried
  - Z-pinch, National Ignition Facility, ~~“cold fusion”~~
  - The one approach closest to energy production is fusion produced in tokamaks, and hence we focus on that

Which reaction to use for fusion?

- The fusion reaction easiest to achieve is
  - D + T -> He^4 + n + energy 17 699 keV
- This is not the same as in the sun, but produces about the same amount of energy
- The energy production is:
  - 70 keV in (max probability)
  - 17600 keV out
    - Energy production by a factor of 250!
  - 17600 keV is 4 million times more than energy release in the *chemical* reaction D + T = DT molecule



Reaction cross sections

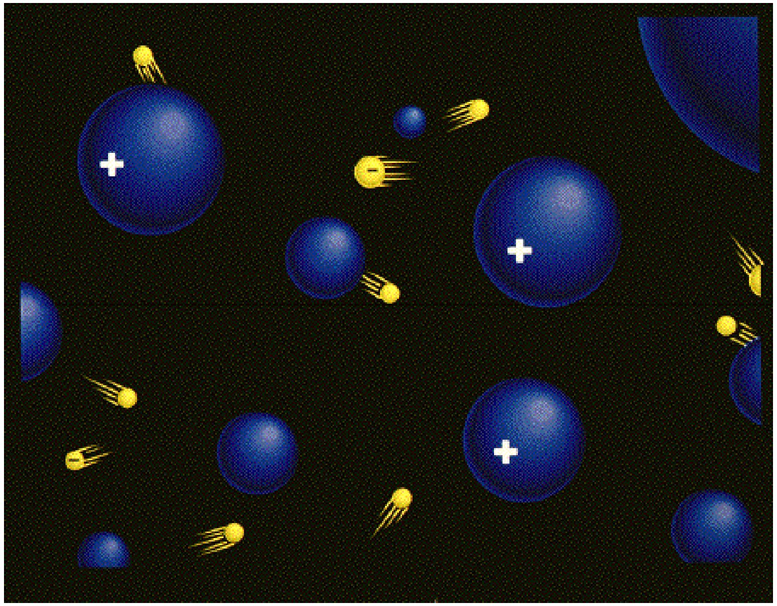


Why is it fusion energy production worth aiming for?

- Fusion produces very large amounts of energy
- The fuel would last for very long:
  - D essentially forever (1/2000 water molecules contain D)
  - T can be obtained from Li, which exists in ample amounts in the earths core
- It is safe
  - Any disruption in the operation stops the reactions within seconds
- Now harmful greenhouse gases produced
- No long-lived radioactive waste
  - The reaction product He is completely harmless

Need for high temperatures and a plasma

- The basic problem with nuclear fusion is that for it to occur with any appreciable probability, one needs extremely high temperatures (10 - 100 millions ^{o}C)
  - This is because the positively charged nuclei repel each other with the Coulomb electric force, and to overcome the repulsion one needs very high kinetic energies, corresponding to very high temperature
- At these temperatures, matter only exists in the form of a plasma



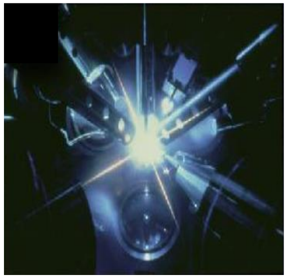
More specific requirements for fusion: the triple product

- The nuclei must have a high enough **temperature**
- The nuclei must have a high enough **density**
- The must stay at this high density a long enough time, known as the "**confinement time**"
- The product **temperature x density x confinement time** determines the fusion efficiency
- In the sun, there is a combination of high density (pressure) and an extremely long (billions of years) confinement time
  - Temperature about 10 – 15 million ^{o}C
- In controlled fusion on earth, the confinement time existing in the sun cannot be achieved
  - Hence one instead needs an even higher temperature than in the sun, around 100 million ^{o}C !

How to confine the plasma?

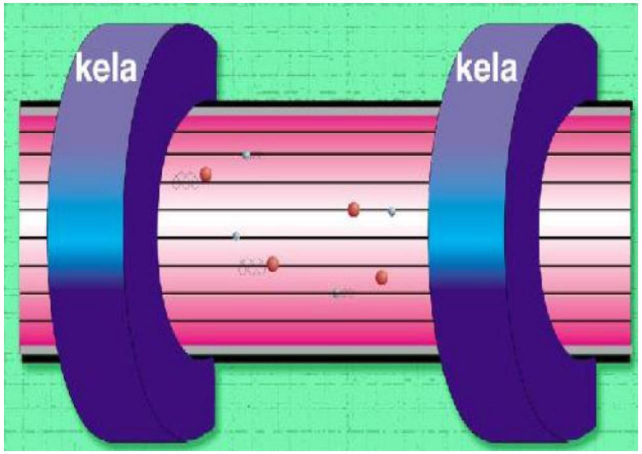
- To achieve controlled nuclear fusion for energy production, one needs to find a way to get a large triple product **temperature x density x confinement time. How??**
- The solution of the sun: Huge mass => huge gravity
  - Works well, but completely impossible on earth

- Magnetic confinement
  - Strong magnetic fields control the movement of the plasma particles and keeps them inside a ‘magnetic bottle’
- Inertial
  - An intensive energy ray, such as a laser, is used to compress hydrogen momentaneously to achieve an extremely high pressure and temperature, leading to fusion power before the system blows apart
  - Might work, but far from energy production



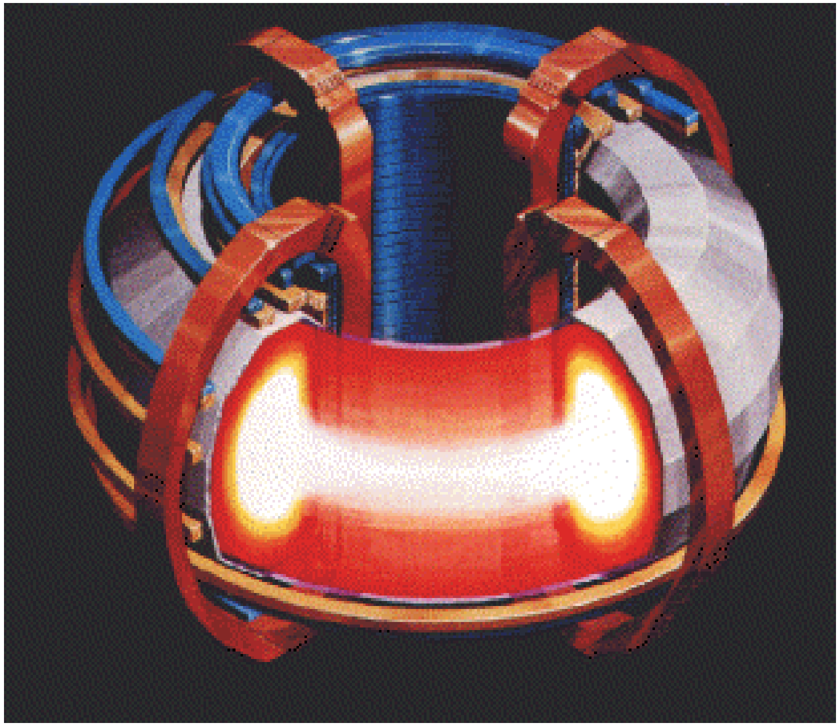
Magnetic confinement

- Magnetic confinement has been studied by far the most
- The idea is to use very strong electric and magnetic fields to keep the plasma confined
- Ordinary coils wrapped in a ring can be used to confine a plasma in a cylinder
  - Relatively small energy loss perpendicular to the plasma



- But at the ends of the cylinder, one gets huge energy or plasma losses
- How to solve this problem?

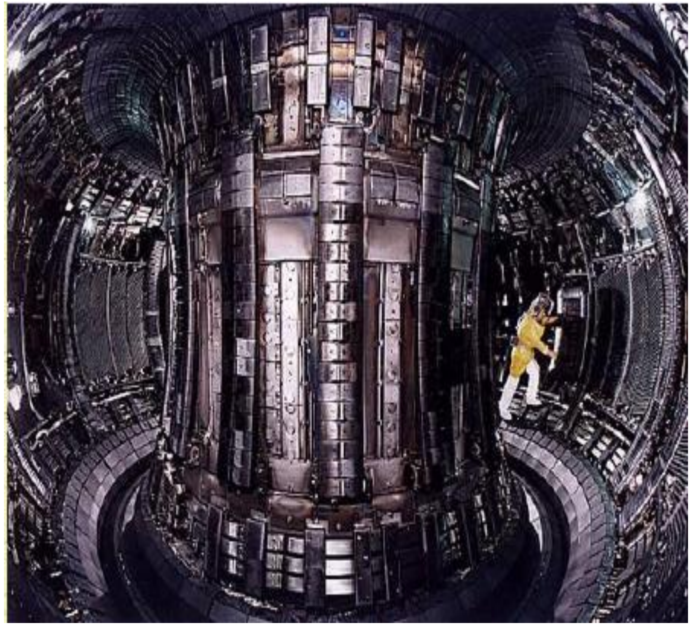
Fusion in a Tokamak

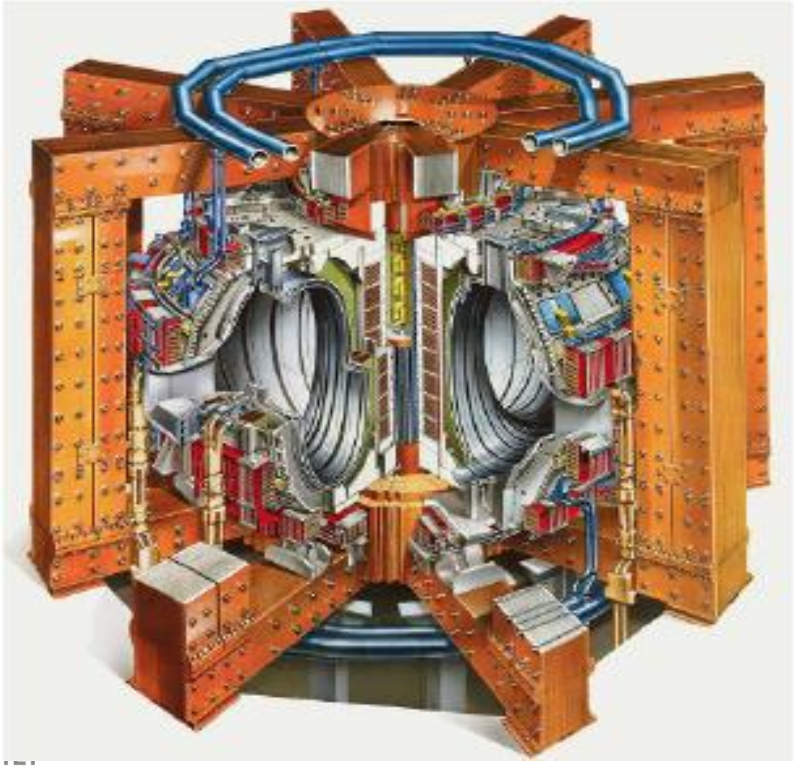


- **Solution:** bend the cylinder around to form a ***torus***
- Now there are no ends => no energy loss at ends!
- This is the basic idea of **tokamak**
  - Tokamak is abbreviation from russian words "**то**роидальная **ка**мера с **ма**гнитными **к**атушками" [toroidal'naya kamera s magnitnymi katushkami meaning toroidal chamber with magnetic coils]
- Two sets of coils used:
  - The red "toroidal" coils produce a cylindrical magnetic field
  - The blue "poloidal" coils are used to shape and control the plasma
- The gray walls are used to confine the hydrogen gas before the plasma is ignited
- The plasma is extremely hot (white) in the middle and colder (red) on the outer side of the torus.

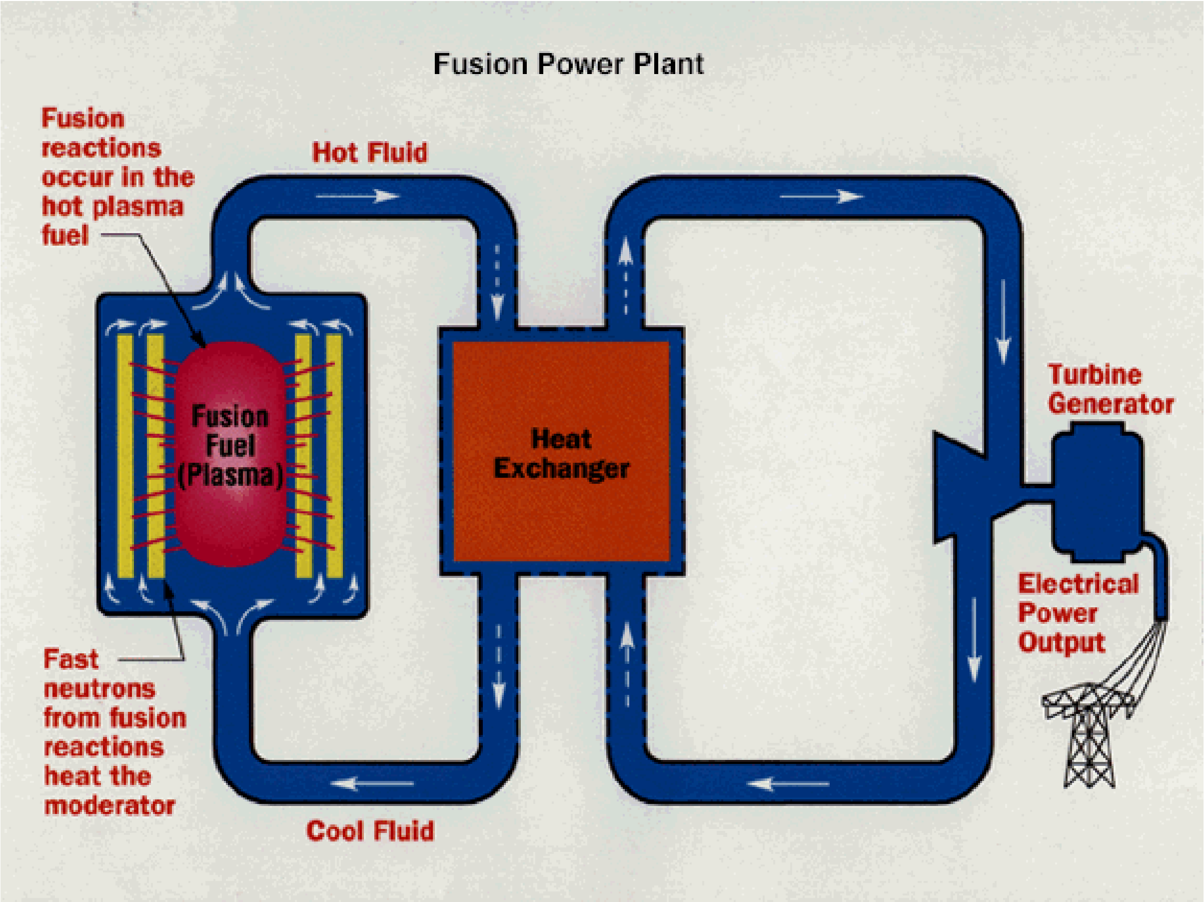
A real tokamak

- The largest tokamak now existing, JET in the UK





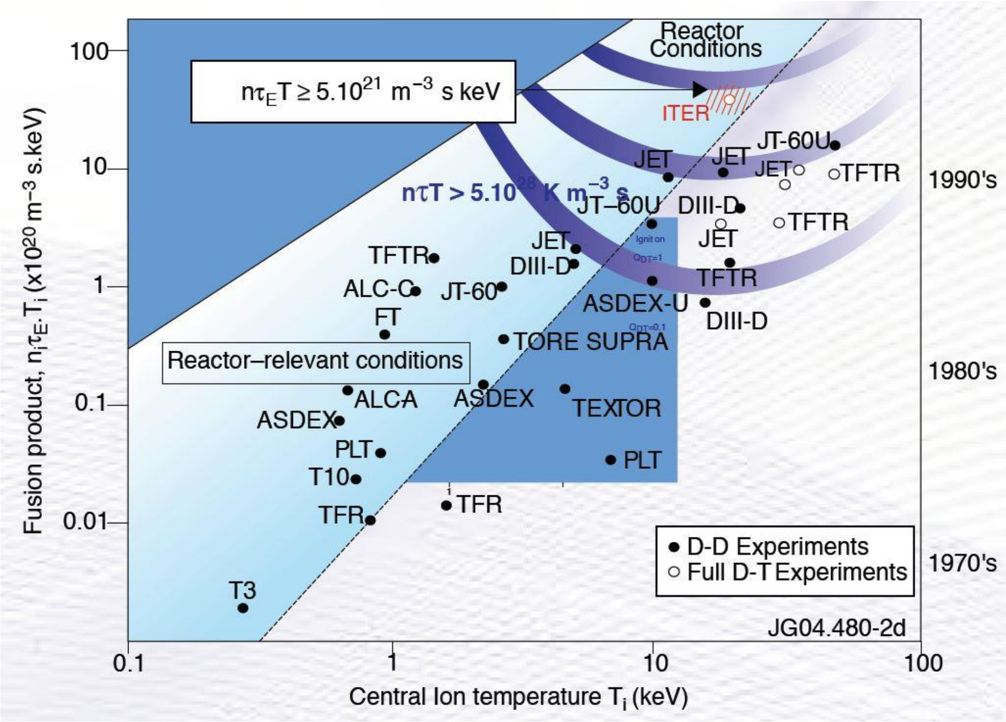
What would a fusion power plant look like – how to get energy out?



As a conventional heat power plant

How far are we from this?

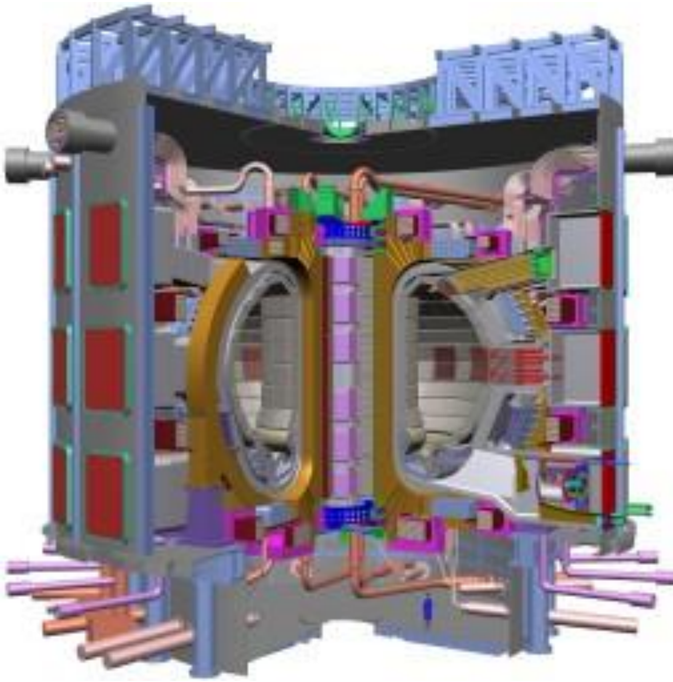
- Tokamak-like fusion has achieved huge advances
  - In the 1970's, one could get out 1 W by 1 MW heating
  - JET has avchieved 16 MW out by 20 MW heating: almost breakeven
- The next big tokamak ITER is almost power-plant size



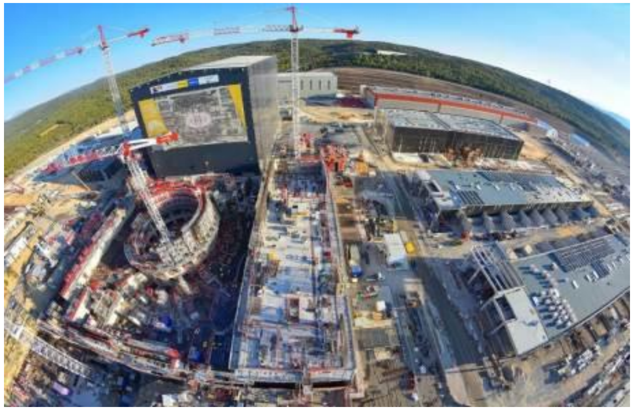
[Picture from: J. Mlynar, "Focus On: JET," European Centre of Fusion Research, EFD-R(07)01, March 2007]

ITER

- The next big fusion machine is ITER, currently under construction in Cadarache in south France
  - About 50 km from Marseille
- Under construction by a new, completely international consortium
  - Europe, Japan, USA, Russia, China, Korea, India
- Building now well under way
  - Dec 2017 announced to be 50% complete
- After ITER, next machine should be demonstration power plant DEMO



ITER construction site Oct 2017

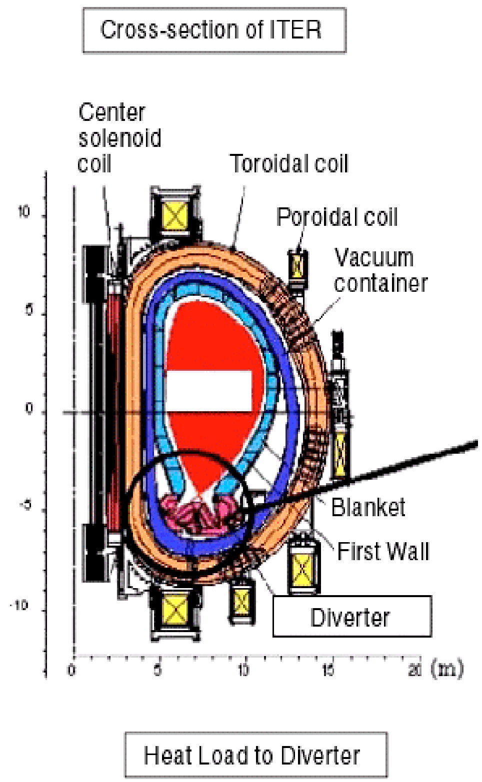


Challenges for ITER and DEMO

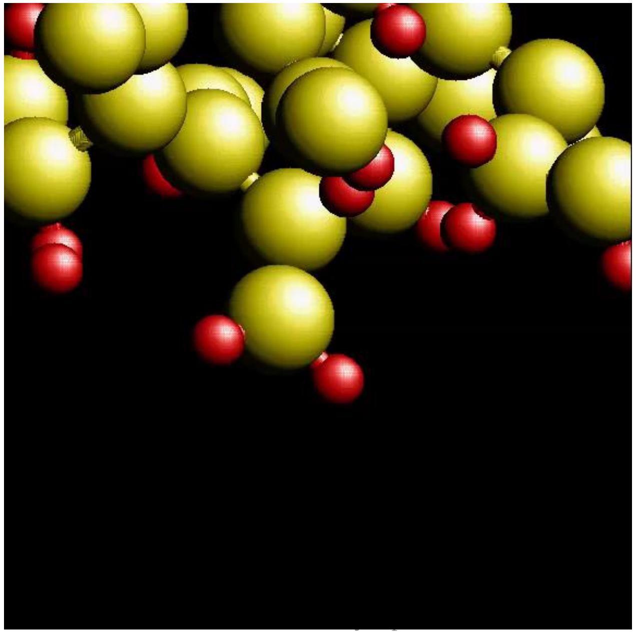
- The plasma physics is fairly well under control, and it is almost guaranteed that ITER will produce energy by a factor of 10-20
  - DEMO should produce by a factor of 50, suitable for commercial energy production
- What are then the remaining challenges?
- **Construction** of such a big machine
  - Major engineering design challenge: ~ 20 m height self-supporting walls that maintain vacuum, just to mention one challenge
  - Cooling challenge: 100 million K in plasma, about 2 m away superconducting magnets at 4 K
- **Tritium breeding:**
  - The world only has enough T to run 1 reactor => reactors need to be built so they can make their own T from Li
- **Materials!**
  - Hot plasma sputters atoms from walls
  - Neutrons affect the structural materials and degrade their mechanical properties

Materials challenge example

- One of the main challenges for both ITER and DEMO is the erosion of molecules from the plasma-facing materials
- We are studying this with atom-level simulations to give 'materials feedback' to the plasma physics and estimate material durability
  - In 1999-2002 we explained why carbon-based materials erode in reactors, and showed that this cannot be avoided. This eventually lead to the ITER design only having metals in the first wall



Erosion of CD_3 from C (yellow) fusion reactor wall by incoming D ion (red)



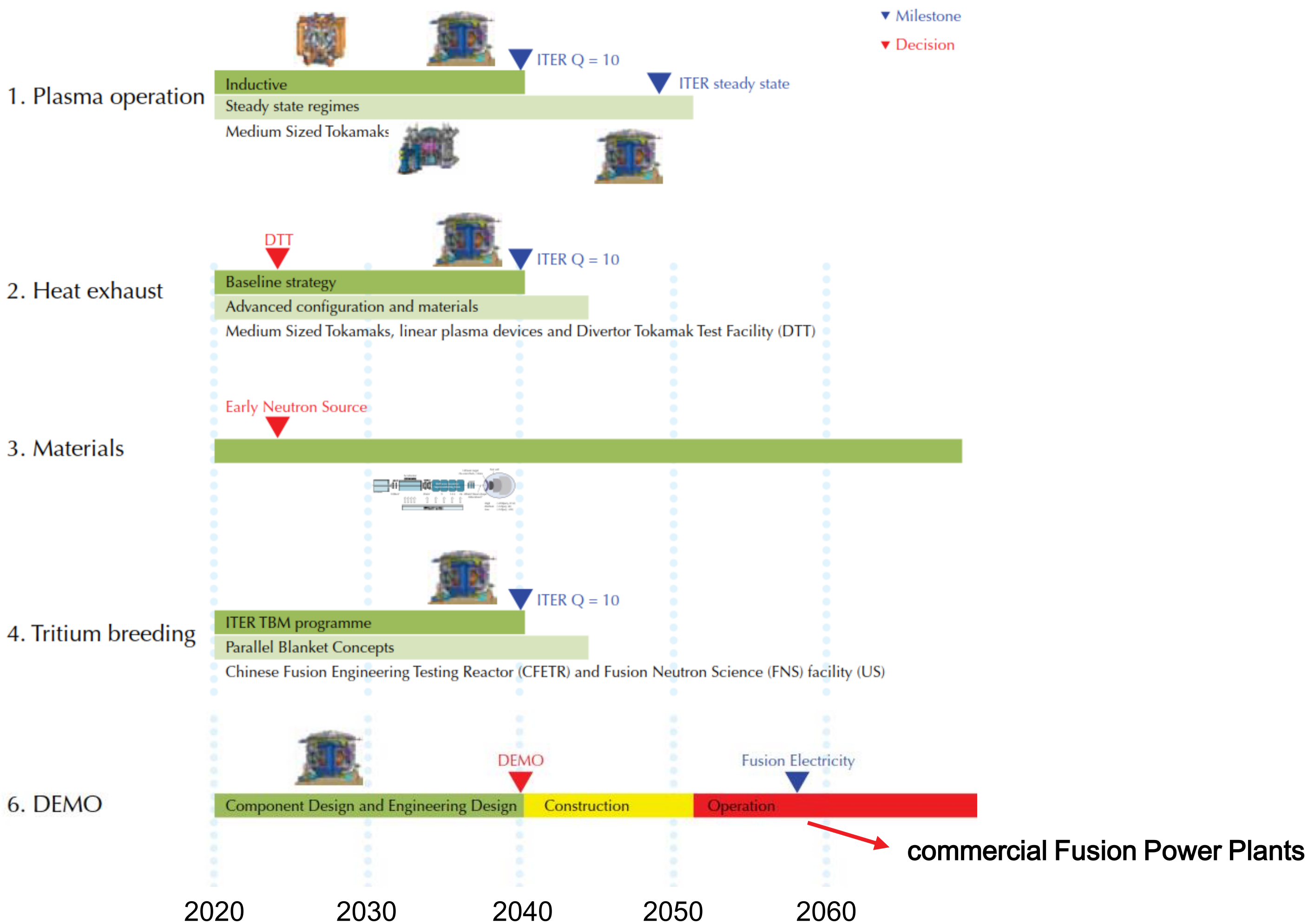
Roadmap to fusion energy

- The EU (EUROFusion) is making systematic planning to reach fusion electricity production by 2055.
- Effort summarized in “**Fusion Electricity:** A roadmap to the realisation of fusion energy”
- 2012 version (update 2018 just being finalized):

https://www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/Roadmap.pdf

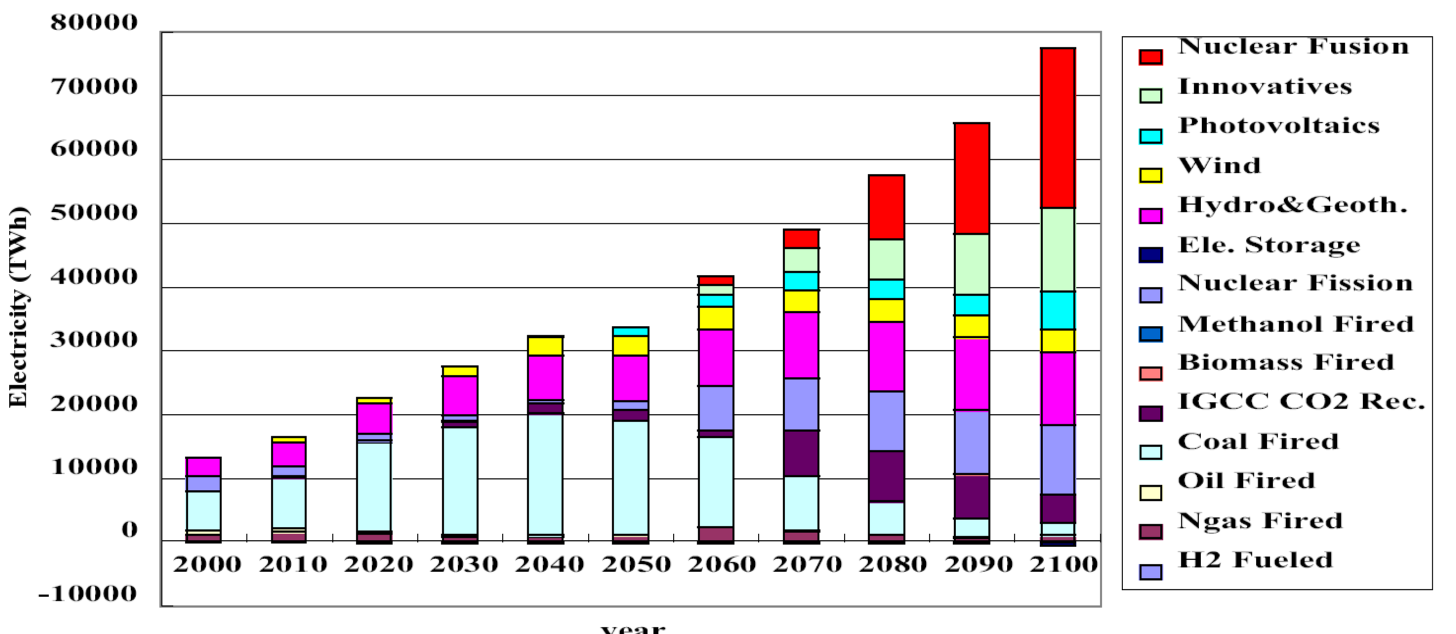
Roadmap to fusion energy

- Key points (simplified from 2012 version but with new timeline)



Role of fusion in world energy production

- If ITER and DEMO are successful, fusion could become a significant part of world energy production from the 2060's on
  - Energy production works already now with long time scales
    - Compare with regular fission power plant Olkiluoto 3 now built in Finland: designed to be operational until 2070's.



[Source: http://www-jt60.naka.jaea.go.jp/english/html/presen01/18th_WEC_kikuchi.pdf]

Conclusions

- Nuclear fusion is one of the extremely few energy forms that could provide huge amounts of energy for millions of years to go without any significant environmental problems
- The ITER machine now under construction will provide a working knowledge of how to control a plasma for large-scale energy production
  - Construction of ITER is also a major engineering challenge and test case
- The next stage DEMO could pave the way for fusion energy production from the 2050's on
- Major materials challenges remain for long-term, commercially viable fusion power plant operation
  - But these are being solved right now!