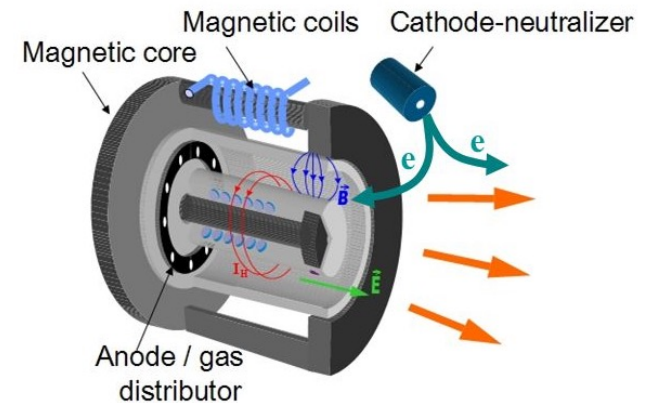
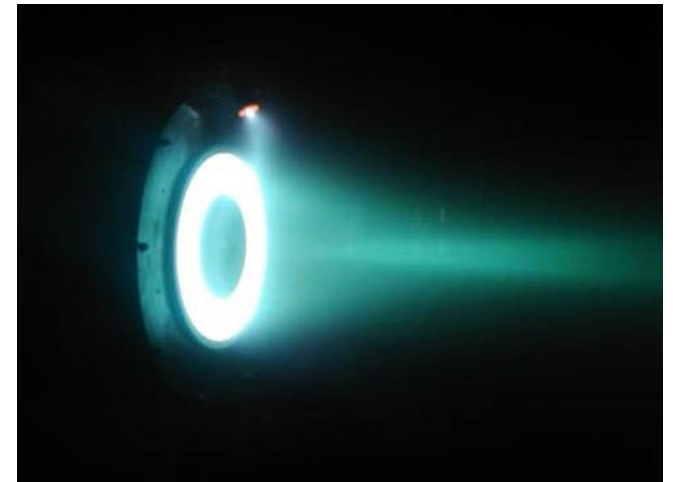


Short bio

- My interest in space travel led me to study Aerospace Engineering in Madrid (Spain) from 1999 to 2004
 - I worked on plasma thrusters in the research group of Eduardo Ahedo (EP2)
- In 2004, I started my graduate studies at MIT in rocket science, but I switched to fusion in 2006
 - Arturo convinced me!
- I got my PhD in 2009 and since then I have worked as a professor at MIT, Oxford and now Princeton
- I love to work on the theory of fusion plasmas because of its impact, its power to explain and predict unintuitive behavior of plasmas, and its elegance



HTX at PPPL



Introduction to Fusion Energy

Felix I. Parra

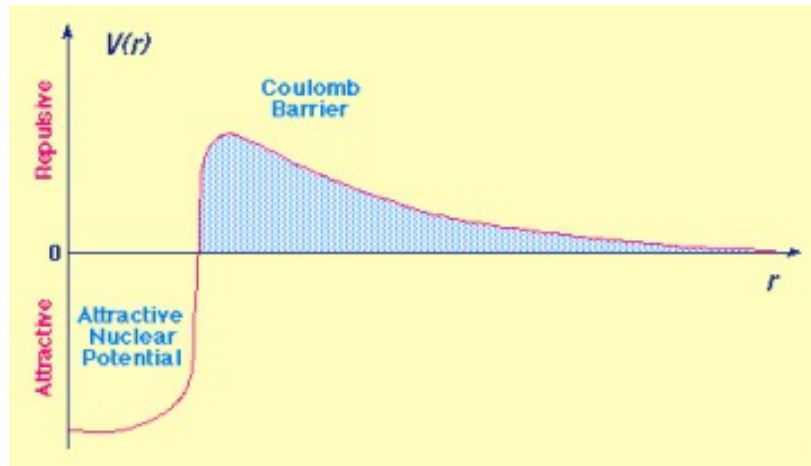
June 5, 2023

The promise of fusion energy

- Firm source of power
 - Independent of weather
- No CO₂ or greenhouse gasses
- It is an energy based on nuclear reactions, but
 - No high-level nuclear waste
 - No possibility of meltdown
- Fuel is abundant and available to all nations
 - Can be extracted from seawater
 - A GW fusion powerplant only needs a few kg of fuel per week – compared to the 100 tons of hydrocarbons needed to produce the same energy!

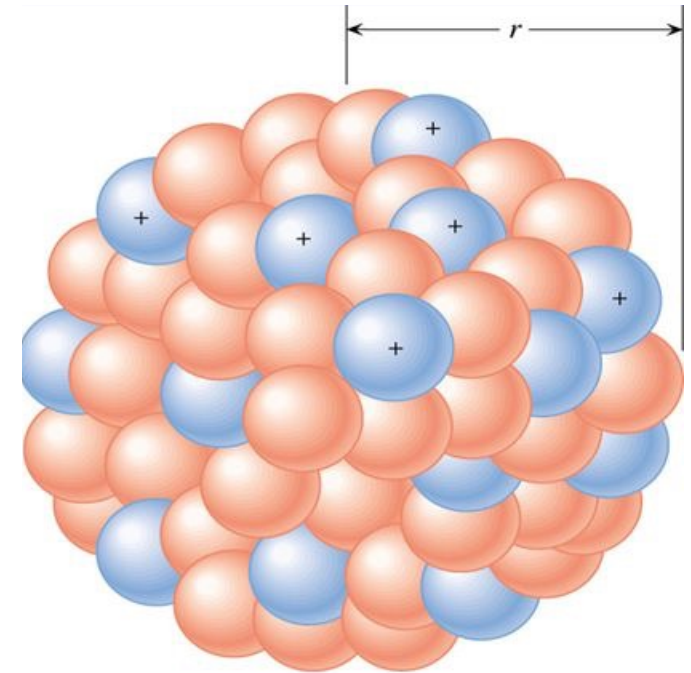
What is nuclear fusion energy?

Building a nucleus



- Binding energy per nucleon of a nucleus with N_p protons and N_n neutrons

$$\Delta E = \frac{[N_p m_p + N_n m_n - M]c^2}{N_p + N_n}$$

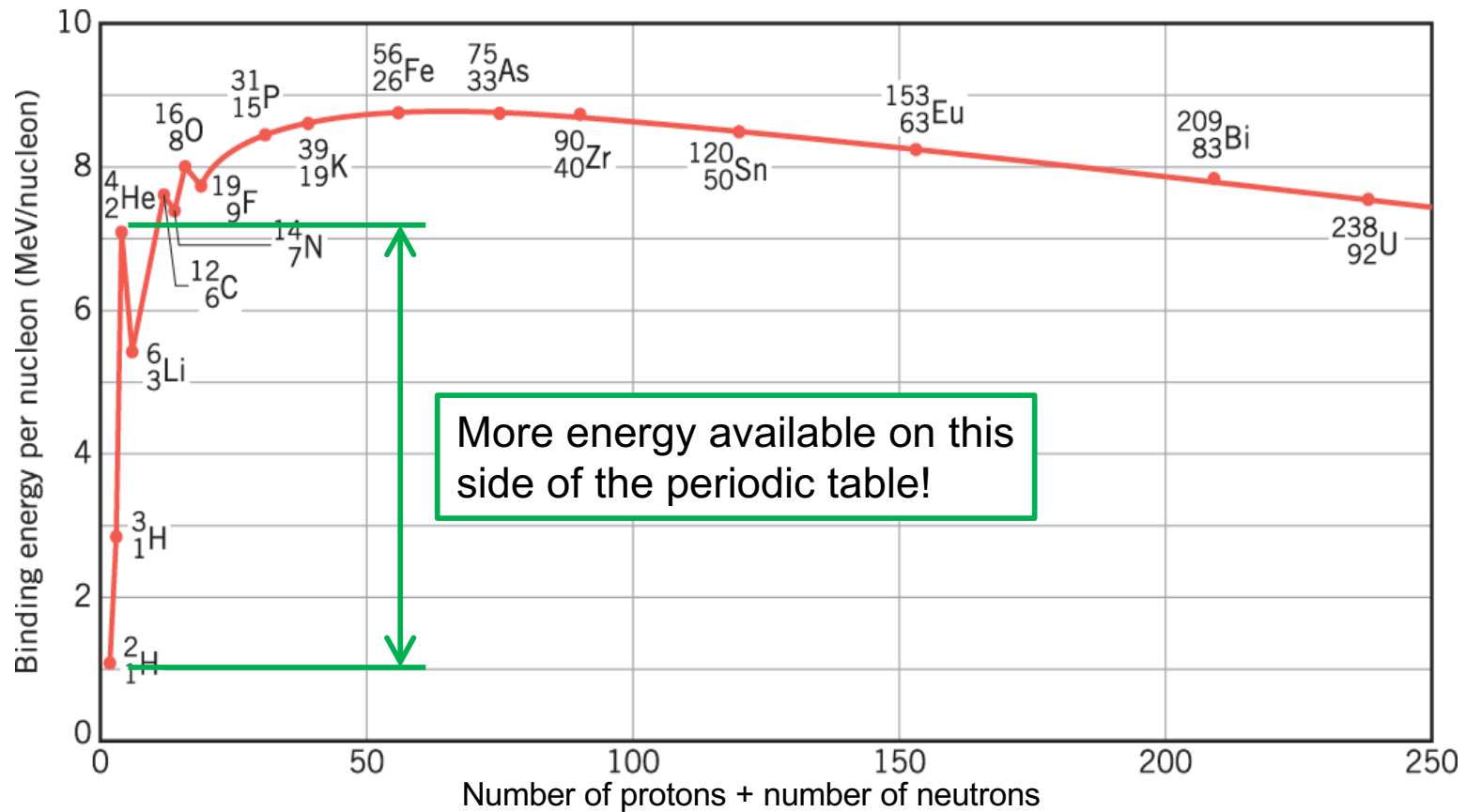


m_p = mass of the proton

m_n = mass of the neutron

M = mass of the nucleus

Nuclear binding energy per nucleon

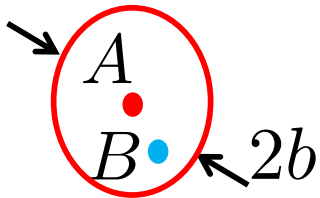


Fusion (and other) collisions

- Nuclei have a “size” = cross section σ

$$\sigma = \pi b^2$$

- b = range of interaction
- Mean free path λ : length that nucleus A travels without colliding with nucleus B



Collision

- Only one particle in the volume $\sigma\lambda$
- For n_B = number of nuclei B per unit volume,

$$n_B \sigma \lambda = 1 \Rightarrow \lambda = \frac{1}{n_B \sigma}$$

- Frequency of collisions of A with B :

- v = relative velocity between A and B

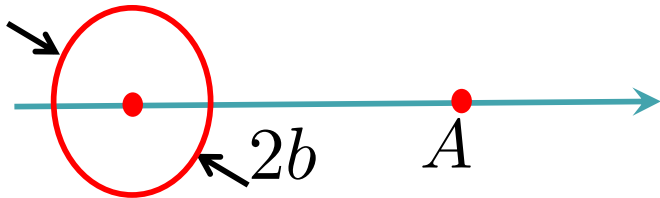
$$\nu_{AB} = \frac{v}{\lambda} = n_B \sigma v$$

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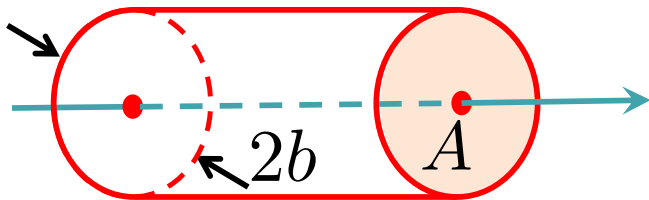
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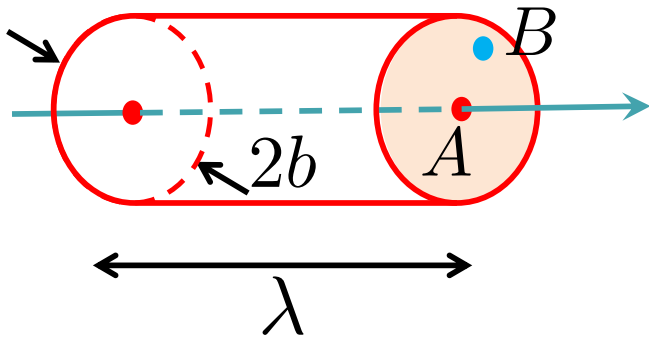
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Fusion (and other) collisions

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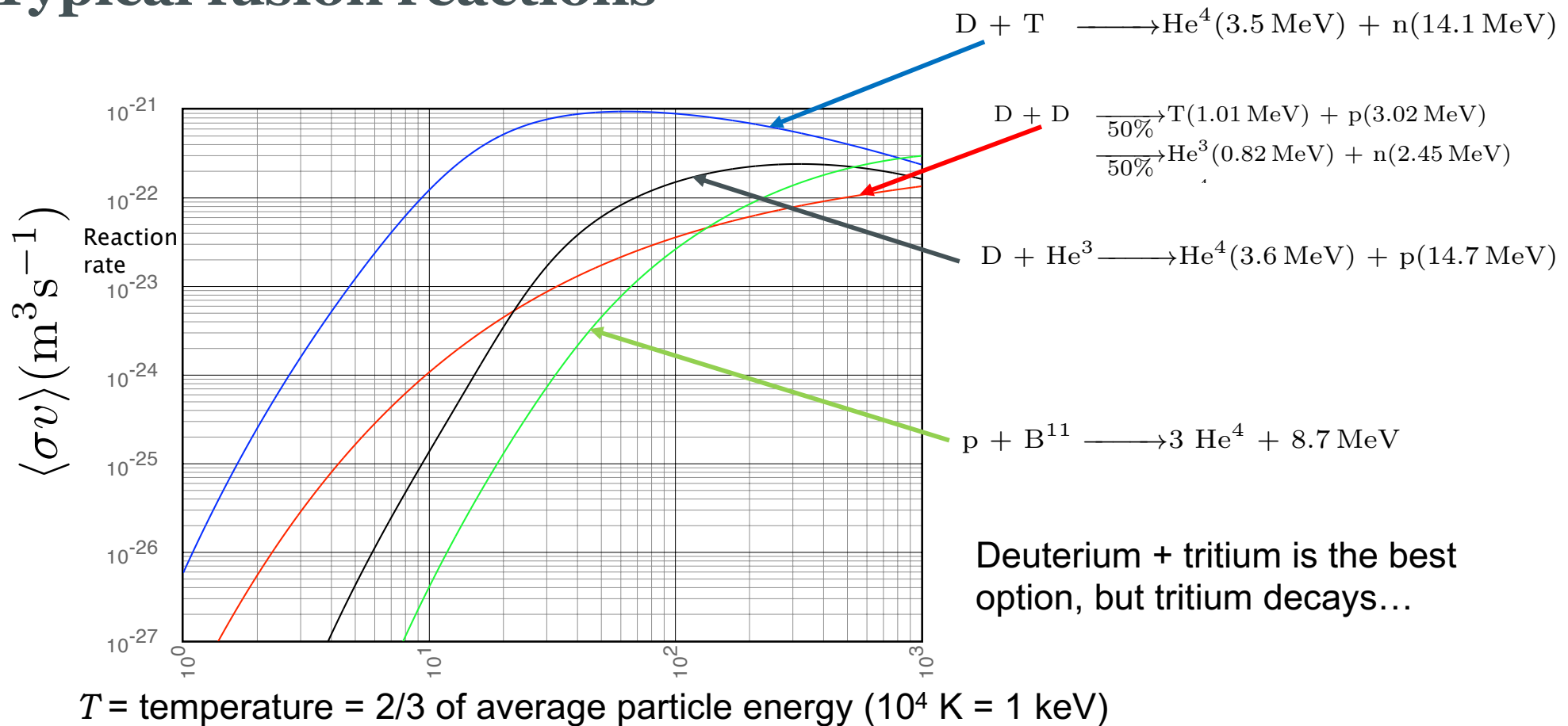
$$n_B \sigma \lambda = 1 \Rightarrow \lambda = \frac{1}{n_B \sigma}$$

- Frequency of collisions of A with B :

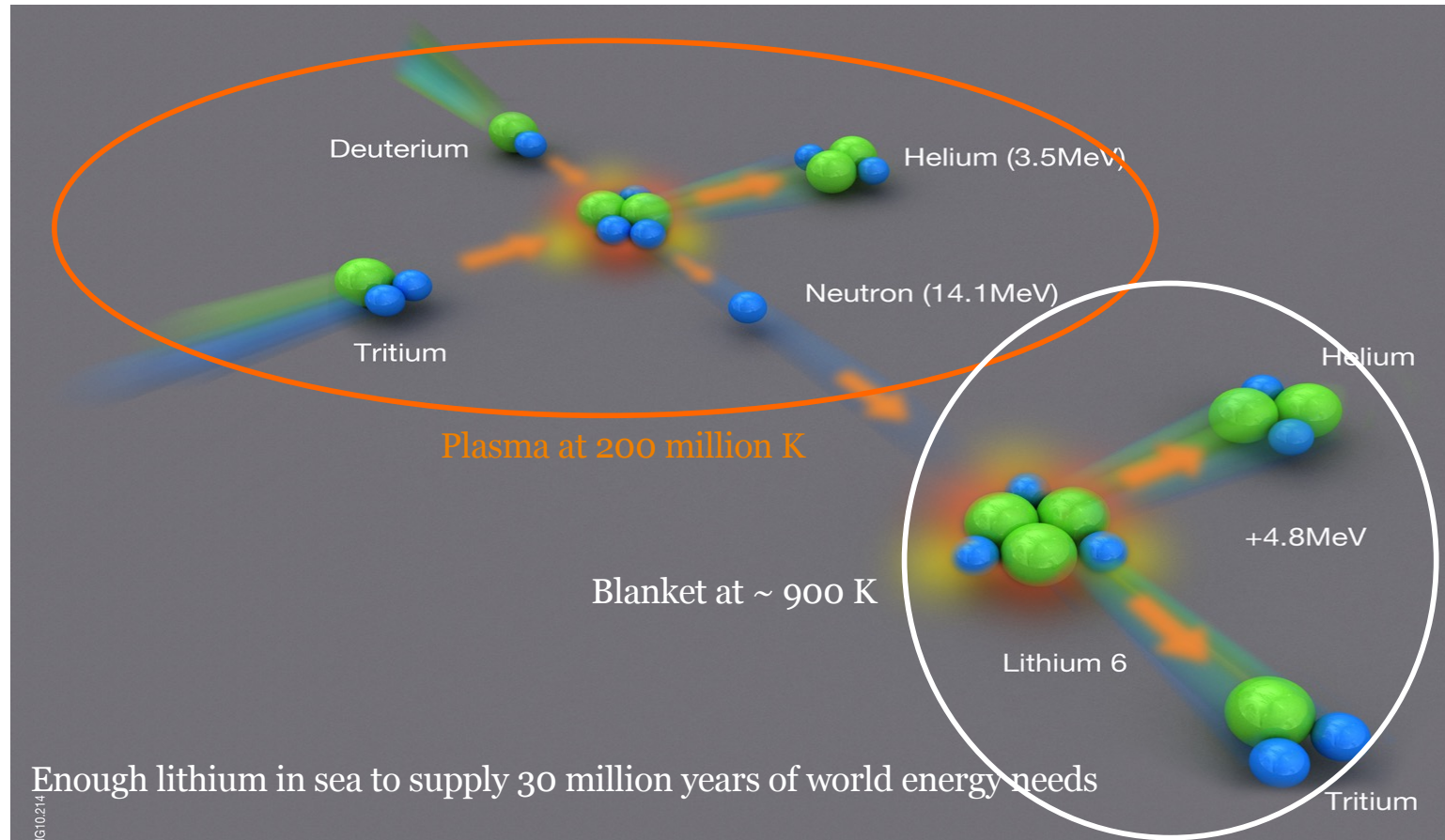
$$\nu_{AB} = \frac{v}{\lambda} = n_B \sigma v$$

- v = relative velocity between A and B

Typical fusion reactions



Deuterium-Tritium (D-T) fusion



We need plasmas for fusion

- Maximum reaction rate at $T \sim$ tens of keV = hundreds of million K
- Potential energy keeping nucleus and electron of hydrogen together = 12 eV $\ll T$
 $\Rightarrow$ in a fusion device positive nuclei and electrons are separated!
- **Plasma**: ionized gas composed of charge nuclei and electrons that satisfies local neutrality
 - Ionized gases of sufficient density and temperature are locally neutral: any charge immersed in the plasma will be rapidly neutralized by a large number of fast charged particles

Nuclear fusion reactions for energy

- **Break-even**: energy of He + neutron balances lost power

- Number of reactions per time and per unit volume: $n_D v_{DT} = n_D n_T \langle \sigma v \rangle = n_T v_{TD}$

$$n_D n_T \langle \sigma v \rangle (E_{\text{He}} + E_n) \geq \text{radiated power per unit volume} \\ + \text{other lost power per unit volume}$$

- Optimal: $n_D = n_T = n/2$, with n = total number of nuclei per unit volume
- Radiated power: produced by collisions between charged particles $\propto (\# \text{ particles})^2$

$$\text{radiated power per unit volume} = n^2 R(T)$$

- Other lost power: measured by figure of merit τ_E = energy confinement time

$$\text{other lost power per unit volume} = \frac{\text{energy per unit volume}}{\tau_E} = \frac{3nT}{\tau_E}$$

Lawson's criterion

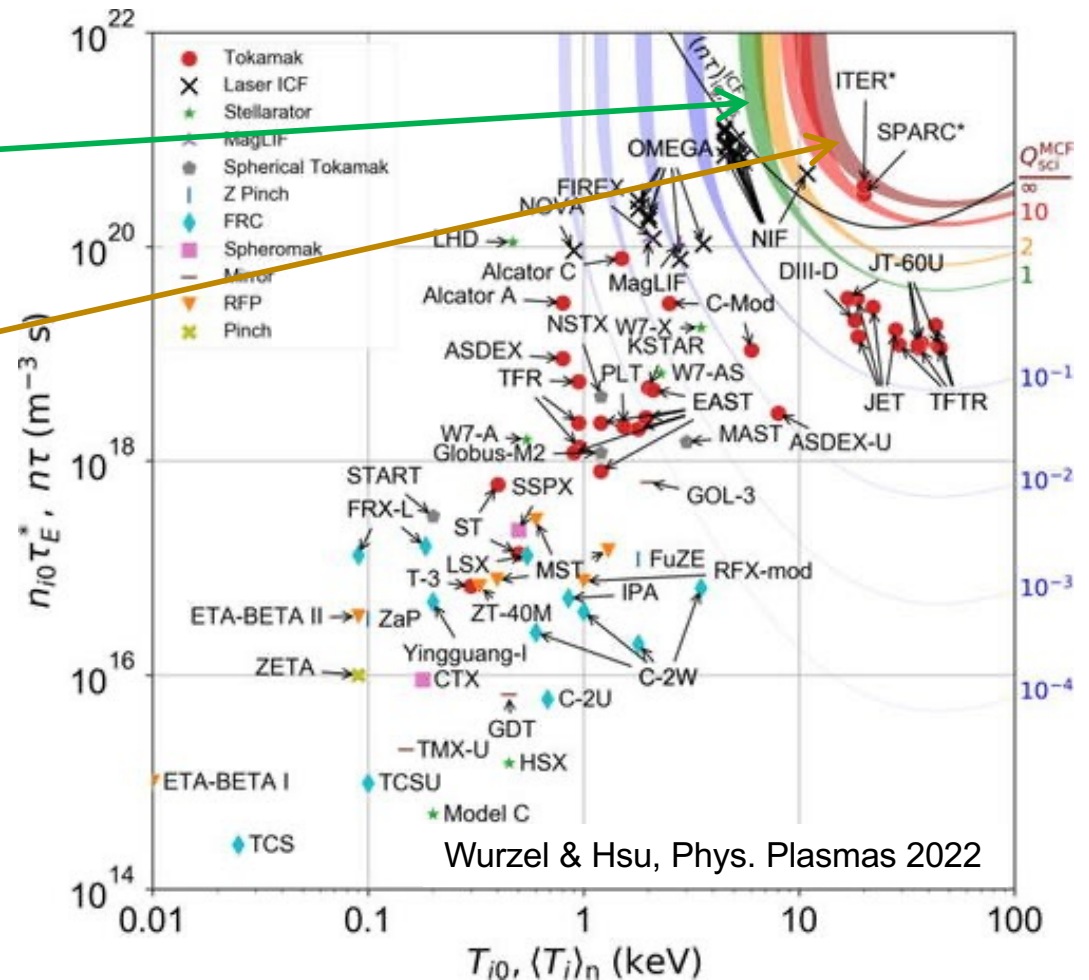
- **Break-even**

$$n\tau_E \geq \frac{3T}{\langle\sigma v\rangle(E_{\text{He}} + E_n)/4 - R}$$

- **Ignition:** energy of He balances energy losses, instead of energy of He + neutron

- Neutrons are not charged and are not easily confined

$$n\tau_E \geq \frac{3T}{\langle\sigma v\rangle E_{\text{He}}/4 - R}$$



Conditions for fusion

- Temperature: $T = 15 \text{ keV} = 150 \text{ million K}$
 - 10 times the temperature at the center of the sun!
 - Hottest place in solar system: JET, Oxfordshire, UK
- Density and energy confinement time: $n \tau_E = 10^{21} \text{ particles s/m}^3$
 - Magnetic confinement fusion
 - Density: $n = 10^{20} \text{ particles/m}^3$
 - A millionth of the atmospheric density
 - Energy confinement time: $\tau_E = 10 \text{ s}$
 - Inertial confinement fusion
 - Density: $n = 10^{31} \text{ particles/m}^3$
 - Denser than lead!
 - Energy confinement time: $\tau_E = 10^{-10} \text{ s}$

What is magnetic confinement fusion energy?

2D motion in a magnetic field

- We can use the fact that particles are charged to confine them
- Consider motion of charged particle perpendicular to a straight magnetic field
 - Circular motion: gyromotion or Larmor motion
 - Perpendicular force balance: magnetic force = centripetal acceleration

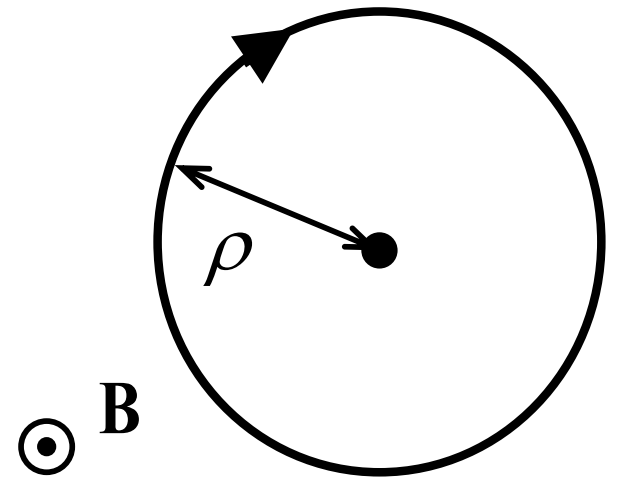
$$\frac{mv_{\perp}^2}{\rho} = qv_{\perp}B$$

- Gyroradius or Larmor radius

$$\rho = \frac{mv_{\perp}}{qB} = \frac{v_{\perp}}{\Omega}$$

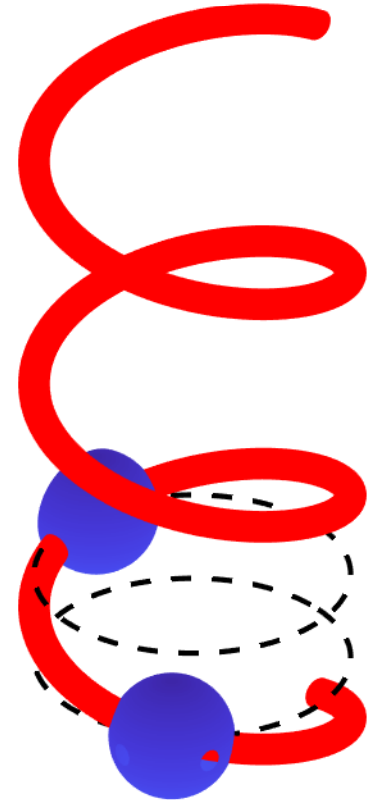
- Gyrofrequency or cyclotron frequency

$$\Omega = \frac{qB}{m}$$



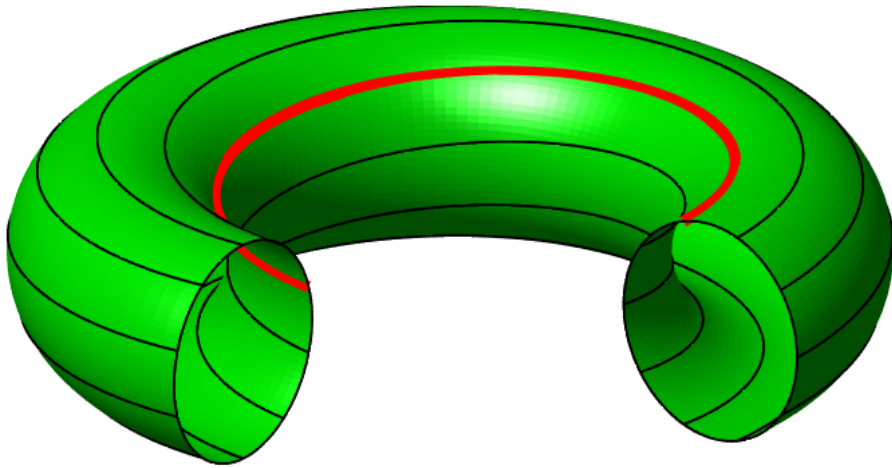
3D motion in a straight magnetic field

- No force parallel to magnetic field
⇒ constant parallel velocity $v_{\parallel}$
- Gyration + constant parallel velocity = helical motion
- Particle is confined in direction perpendicular to magnetic field but moves freely along magnetic field
- Magnetic confinement
 - Make gyroradius ρ small compared to machine by increasing B
 - Ensure magnetic field lines close on themselves



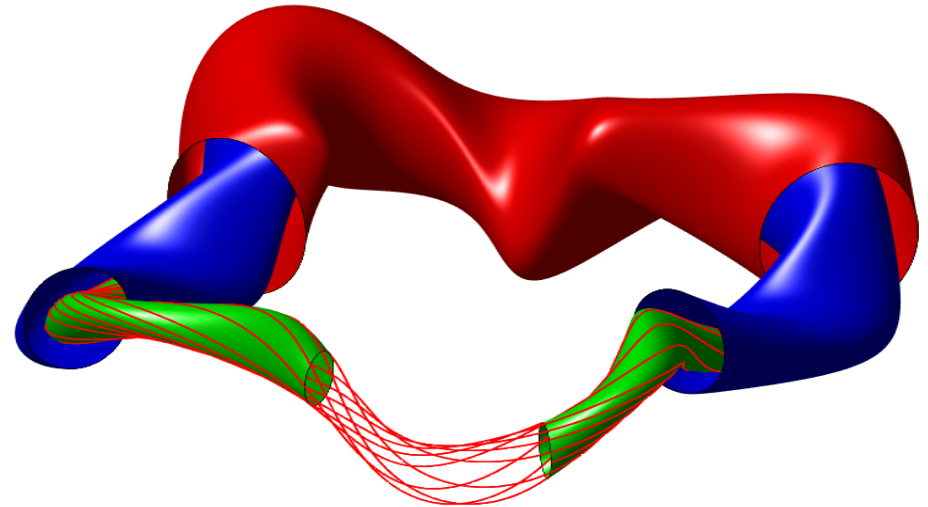
Tokamaks and stellarators

- You will learn that the best way to keep magnetic field lines from touching any walls and confine the plasma is to ensure that these lines trace surfaces



Tokamak (Russian acronym for "toroidal chamber with magnetic coils")

- Symmetric surfaces



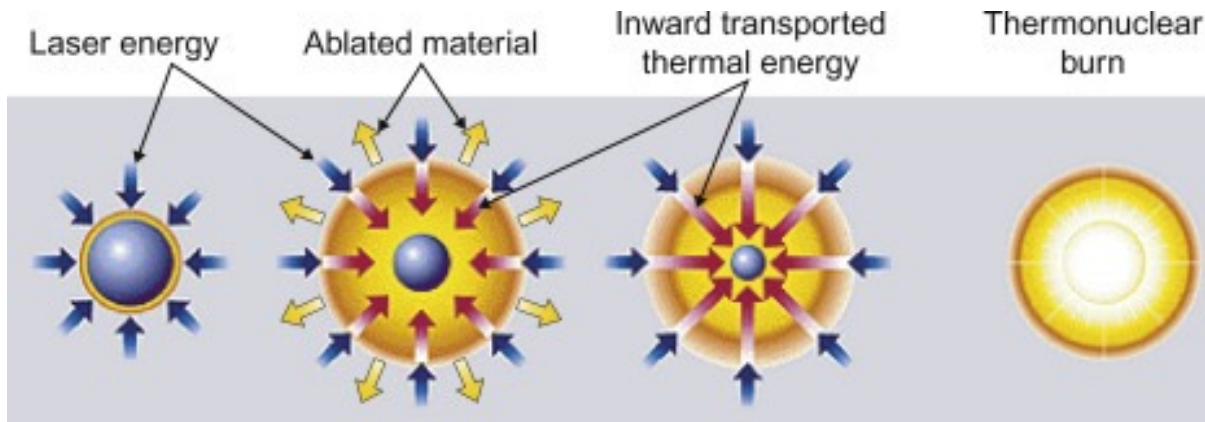
Stellarator

- Asymmetric surfaces

What is inertial confinement fusion energy?

Inertial confinement fusion

- Abandon the idea of a steady state burn and instead go with a series of explosions
 - This is how a car engine works: compress, explode the fuel, use the energy of the explosion and repeat
- Lasers and ablation are used to produce the compression

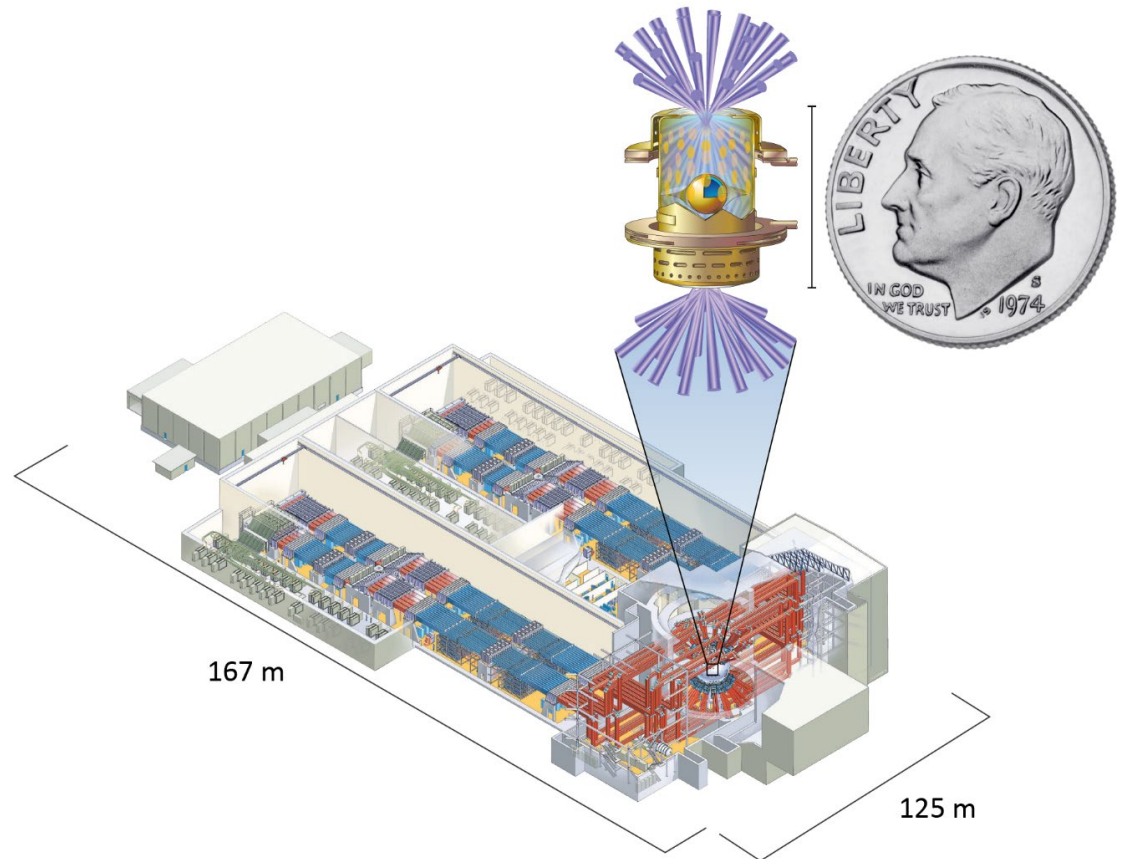


[McCracken & Stott,
Fusion, Elsevier, 2013]

- Energy confinement time = time of the implosion

The National Ignition Facility

- NIF is an Inertial Confinement Fusion facility at Lawrence Livermore National Laboratory
- World's most energetic laser (192 beams) delivers 500 TW of power for a few nanoseconds
- It recently made history (more on this later)



Sources: Lawrence Livermore National Laboratory (facility and hohlraum), BillionPhotos.com/stock.adobe.com (dime). | GAO-23-105813

There are other approaches to fusion, but there is no time to be exhaustive!

A bit of history

100 years of fusion. August 24th 1920 The British Association

- Arthur Stanley Eddington -- delivered the presidential address:
“The Internal Constitution of Stars”
- One of the many questions he addressed is:
Where does the energy radiated by the stars/sun come from?
- F. W. Aston had recently measured the masses of elements and shown: $M_{\text{hydrogen}} = 1.008$ and $M_{\text{helium}} = 4.0$
- Eddington proposed that the sun is transforming hydrogen into helium – thereby liberating “fusion energy”. It is. He went on to estimate the sun’s lifetime – surprisingly accurately (15 Billion years).



100 years of fusion. August 24th 1920 The British Association

- Arthur Stanley Eddington -- delivered the presidential address:

“The Internal Constitution of Stars”

- **“This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man (!) will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped”.**

Arthur Stanley Eddington 1920.



- Eddington proposed that the sun is transforming hydrogen into helium – thereby liberating “fusion energy”. It is. He went on to estimate the sun’s lifetime – surprisingly accurately (15 Billion years).

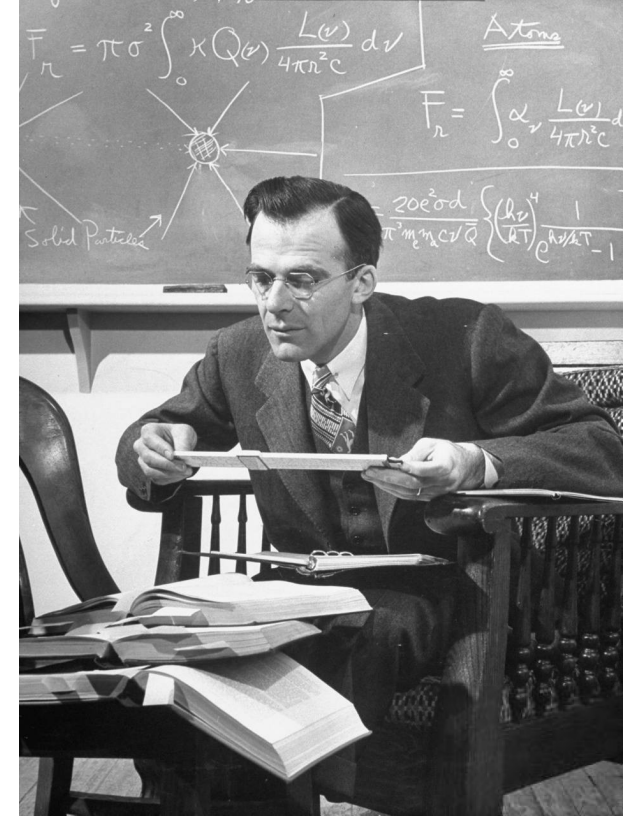
70 years ago: Argentina starts the fusion race

Ronald
Richter



Juan
Domingo
Perón

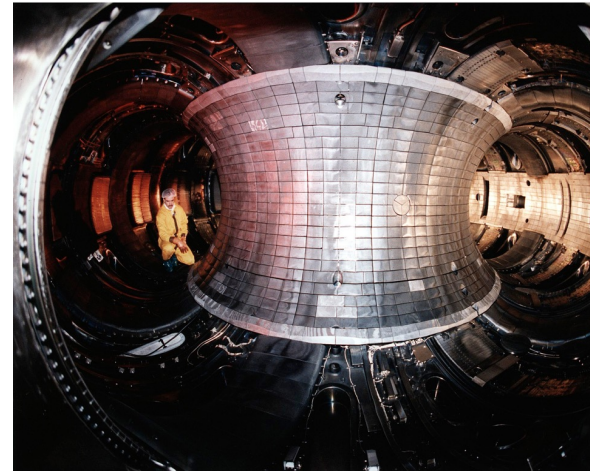
- March 24th 1951: Argentina claims (incorrectly) that scientist Ronald Richter has achieved fusion energy
- July 23rd 1951: Lyman Spitzer proposes (in secret) Project Matterhorn S to develop fusion energy for power production
- Princeton Plasma Physics Laboratory is born – but not named PPPL



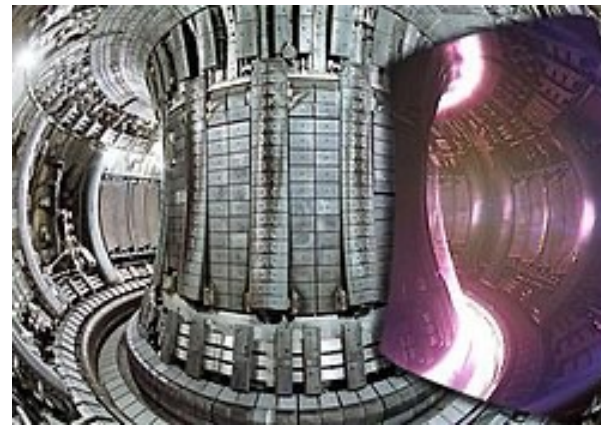
Lyman Spitzer 1948

The roaring 1990s

- The first two tokamaks that use nuclear fusion fuel (deuterium and tritium) are built
 - Tritium is not trivial to handle and requires special facilities
- In 1994, TFTR produced fusion energy that was 30% of the energy injected into it
- In 1997, JET produced fusion energy that was 67% of the energy injected into it
- TFTR was decommissioned in 1997, and JET is still operational
 - More on JET later



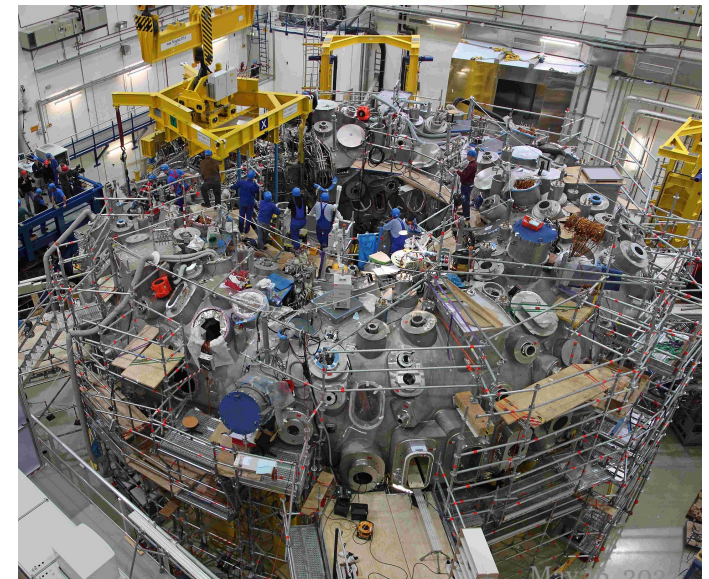
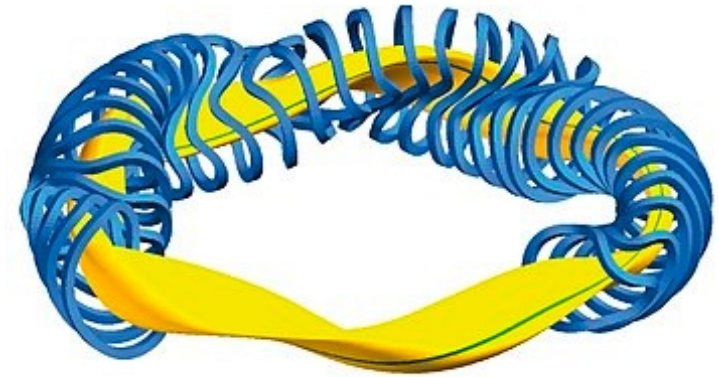
Tokamak
Fusion Test
Reactor
(TFTR), PPPL



Joint European
Torus (JET),
Culham, UK

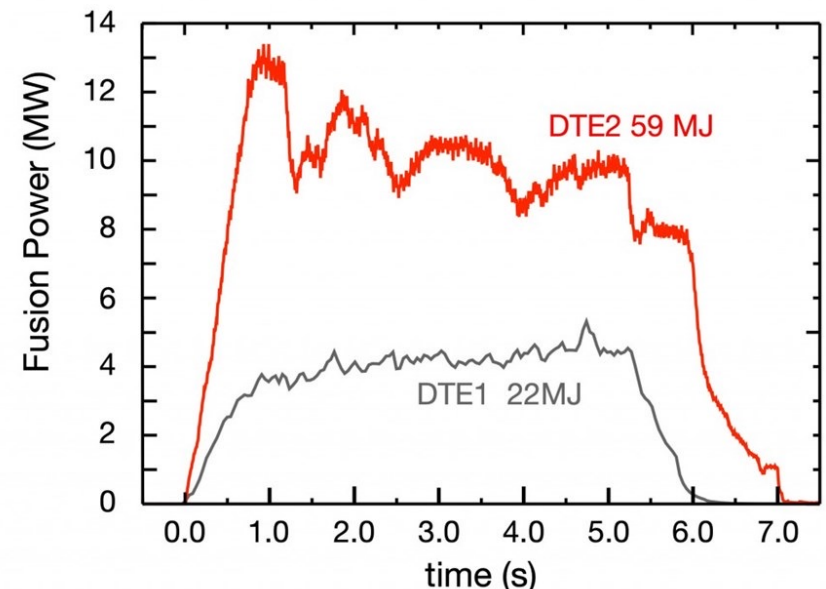
Stellarators start to catch up

- Stellarators, despite some obvious advantages over tokamaks, did not have comparable performance
- In 3D magnetic fields, there always exists a population of particles that will be unconfined
- A triumph of plasma theory: the position and strength of the magnets can be optimized to minimize this population of particles
- Wendelstein 7-X (Germany) is designed to reduce the losses due to these unconfined particles
- In 2015, Wendelstein 7-X starts operation
- In 2021, it is concluded that the optimization worked! [Beidler et al, Nature 2021]



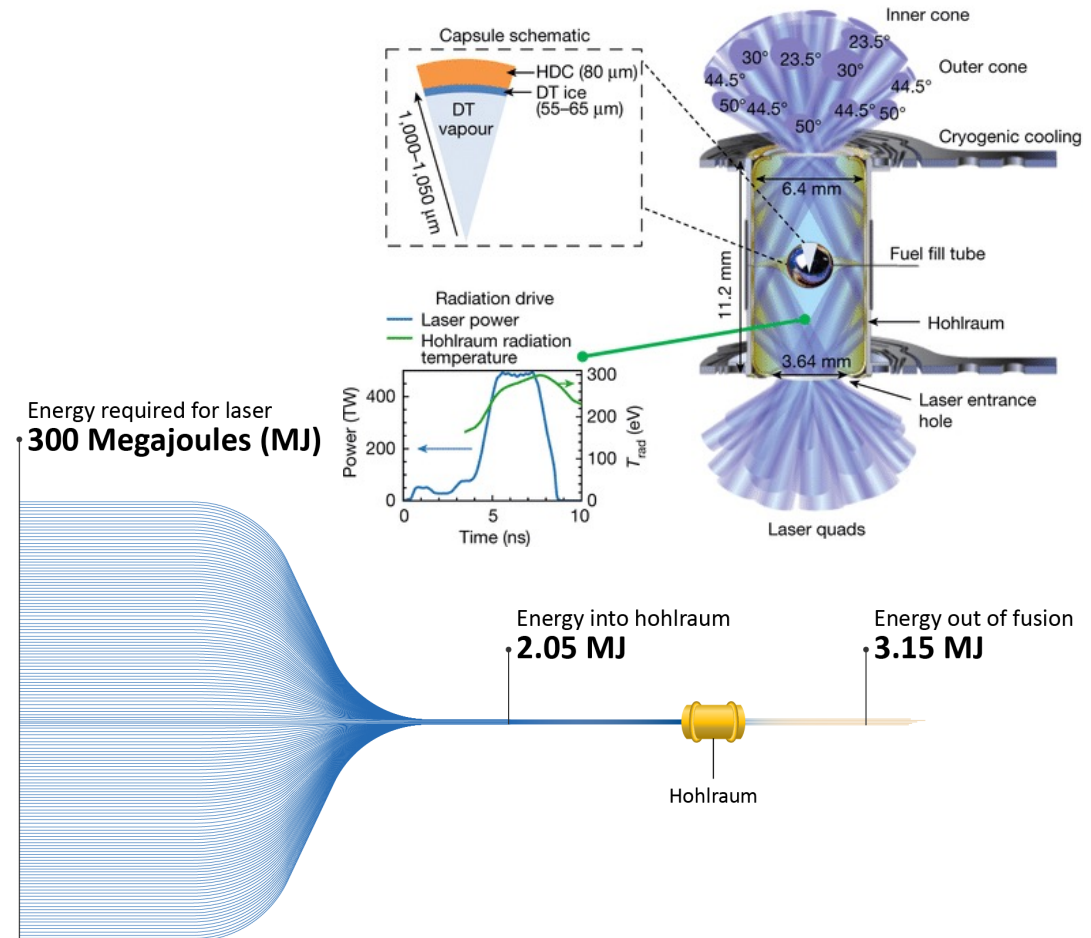
Record fusion power at JET

- In 2020, JET run with deuterium and tritium again
- The machine had to operate differently because of the new wall material: tungsten
- In 2021, JET announced that they had produced 59 MJ of fusion power in one shot, more than doubling their 1997 record of 22 MJ
 - 59 MJ = 16 kWh (an average US household used 29 kWh/day)



Breakthrough at NIF

- In 2022, the Department of Energy announced that NIF had achieved the first controlled fusion reaction that had produced more energy that had been injected into it
- 2.05 MJ of laser energy hit the target and 3.15 MJ of fusion energy was released, so the fusion energy was 54% more than the injected energy
- This is a great scientific achievement, but we still have more work to do!

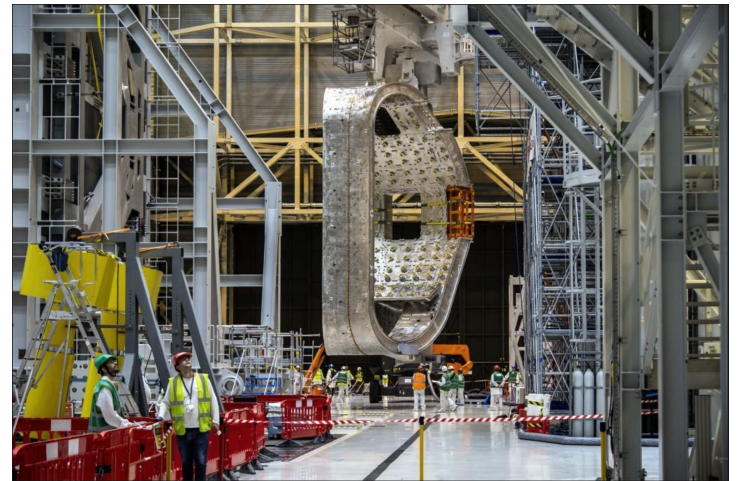
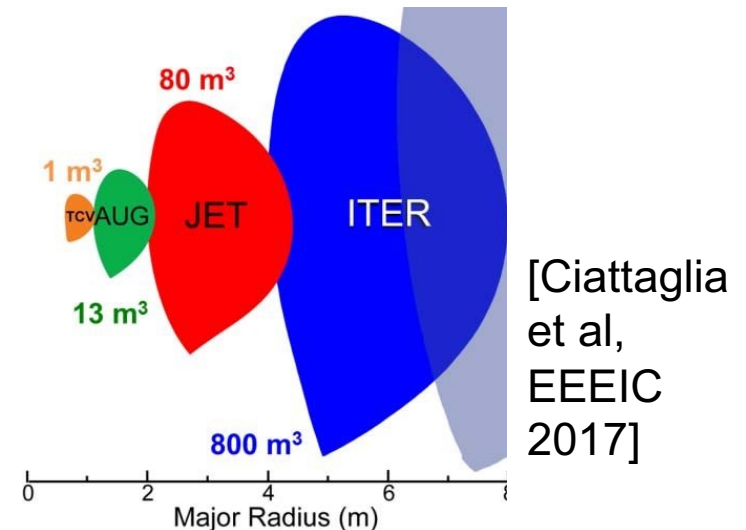


Source: GAO (presentation) Lawrence Livermore National Laboratory (information). | GAO-23-105813

Exciting times

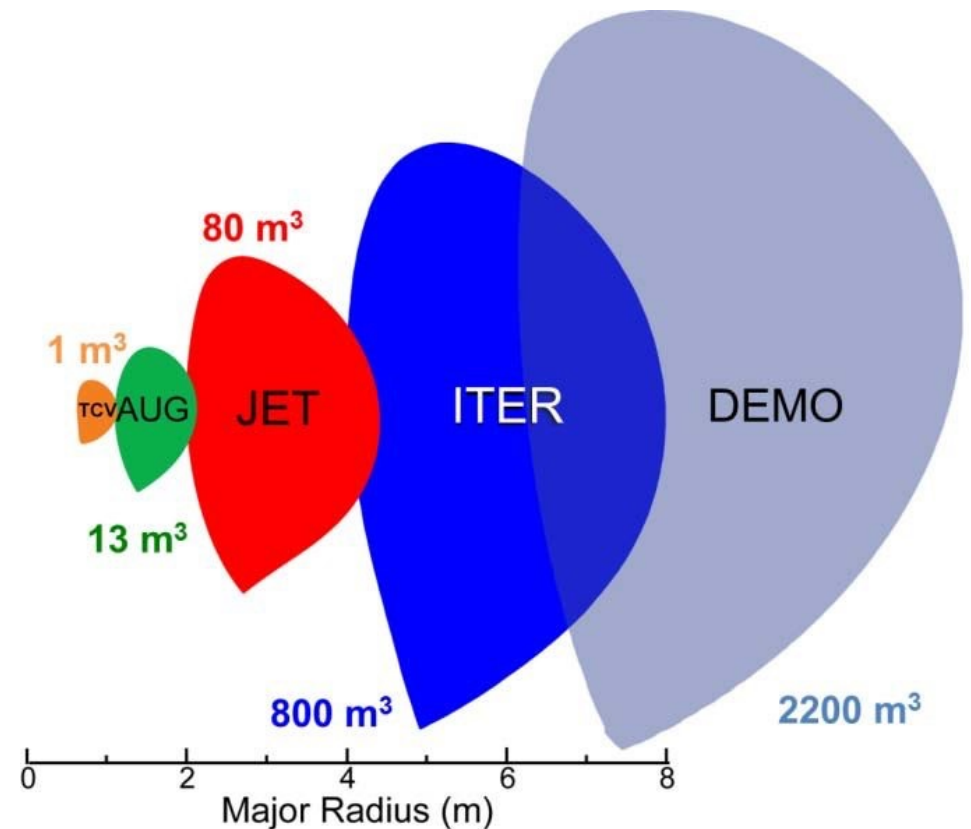
ITER

- ITER is a large tokamak designed to deliver fusion energy that is ten times the injected energy
 - ITER is an experiment, not a power plant
- It is an international project between the EU, China, India, Japan, Korea, Russia and the US
- The EU funds ~50%, and the rest is shared equally by the other partners
- Startup date is uncertain, but it is sure that ITER will not run with deuterium and tritium at least until 2035
 - Construction is 70% complete



What happens after ITER

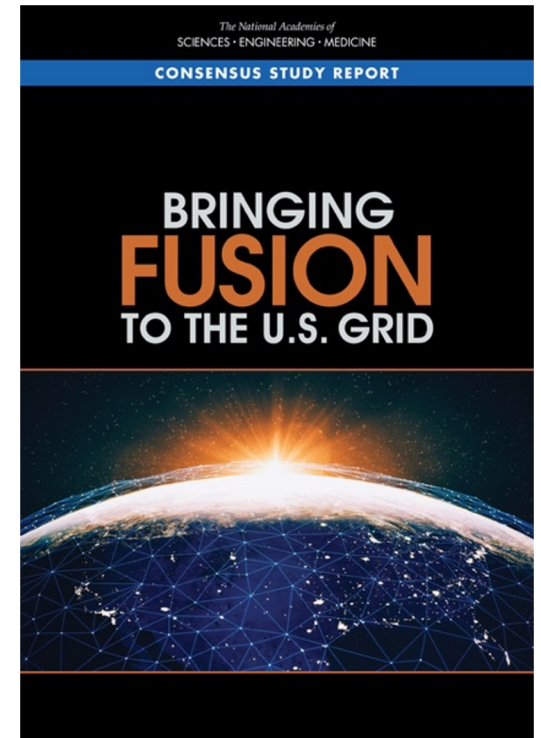
- The EU's fusion program (EUROfusion) considers ITER to be a step towards a demonstration reactor (EU-DEMO)
- EU-DEMO is similar to ITER but bigger because it takes a conservative approach, designing around the most proven technology and physics
- Other countries (Korea, Japan, China) are taking a similar approach
- The US is going a different way



[Ciattaglia et al, EEEIC 2017]

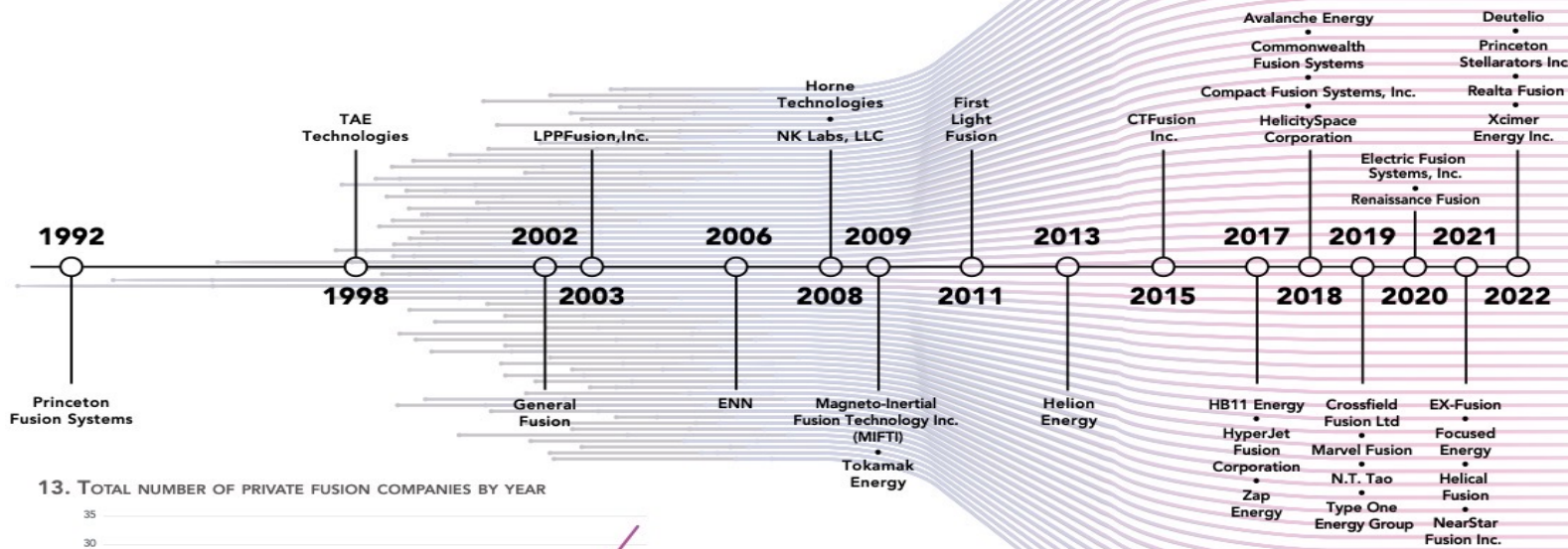
US Decadal Strategy to Accelerate Fusion to Commercialization

- *“The DOE will launch an agency-wide initiative, coordinating across program offices, to develop a decadal strategy to accelerate the viability of commercial fusion energy in partnership with the private sector. The 2021 National Academies of Sciences, Engineering, and Medicine (NASEM) report ‘Bringing Fusion to the U.S. Grid’ serves as a guiding document for the new initiative.” White House March 2022*
- *Bringing Fusion to the U.S. Grid: “the Department of Energy and the private sector should produce net electricity in a fusion plant in the United States in the 2035-2040 timeframe.”*

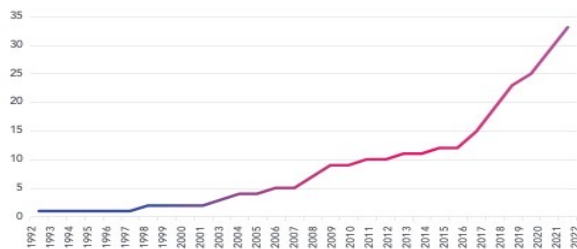


The private fusion industry is growing rapidly

12. FUSION COMPANIES FOUNDED IN THE LAST 30 YEARS



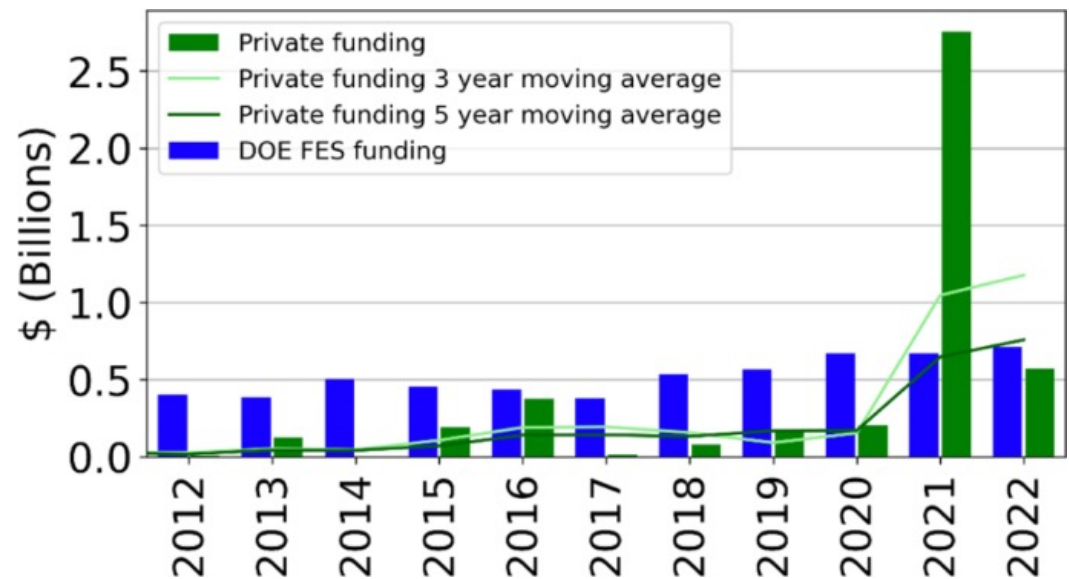
13. TOTAL NUMBER OF PRIVATE FUSION COMPANIES BY YEAR



Fusion Industry Association Report 2022

Private investment is now integral to the program

- Previously, all fusion research was publicly funded – now private funding is comparable
- Last week DoE announced the awardees of a new milestone-base fusion development program
 - Companies promise milestones and get reimbursed if they meet them
 - National laboratories such as PPPL are now subcontractors of these companies in addition to conducting basic research



[Hsu, JFE 2023]

What do we have to do to deliver fusion?

Physics to achieve break-even and ignition

Stability: too much pressure means plasma controls magnetic field instead of the magnetic field controlling the plasma

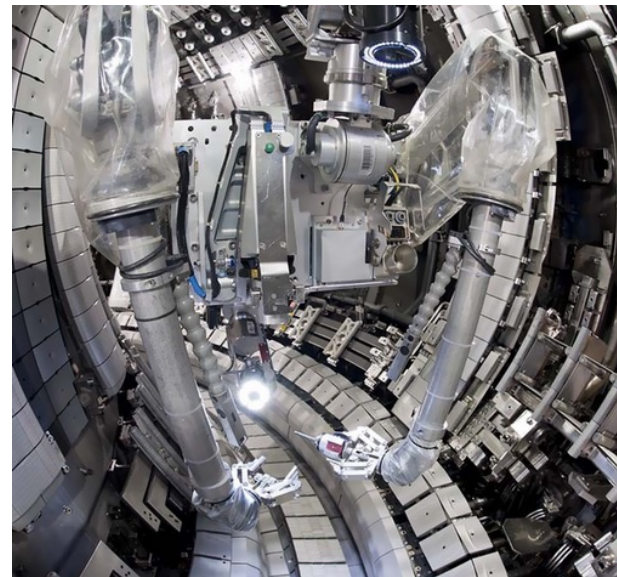
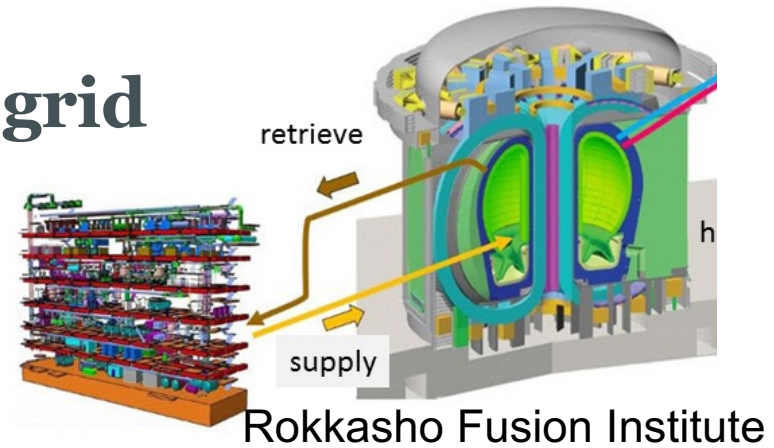
$$n\tau_E \geq \frac{3T}{\langle \sigma v \rangle (E_{\text{He}} + E_n)/4 - R} = f(T)$$

Confinement: most of the energy is lost through electromagnetic fluctuations known as turbulence

Heating: need to inject energy into very hot plasma using beams and electromagnetic waves

Technology to deliver power to the grid

- We need to breed tritium through lithium and this requires flowing lithium around the fusion power plant, in what is known as blankets
 - Hydrogen (and hence tritium) can penetrate materials easily, lodging in the holes of the lattice: we need a careful inventory of tritium
- We need materials that withstand tremendous heat fluxes and neutron damage
- Materials will become radioactive with half lives of the order of decades: repairs will require remote handling (robots!)
- We need strong electromagnets that are resilient and maintainable



[Sanchez, ESE 2014]

To conclude

- Fusion energy is in an exciting stage after decades of development
- There is still much work to do, and it takes all kinds:
 - Sophisticated theory
 - Massive computation
 - Complex experiments
 - Creative engineering
- I hope you enjoy this course and the research that you will be doing this summer