Practice Course in Plasma

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Institute of Space and Plasma Sciences, National Cheng Kung University

2021 spring semester

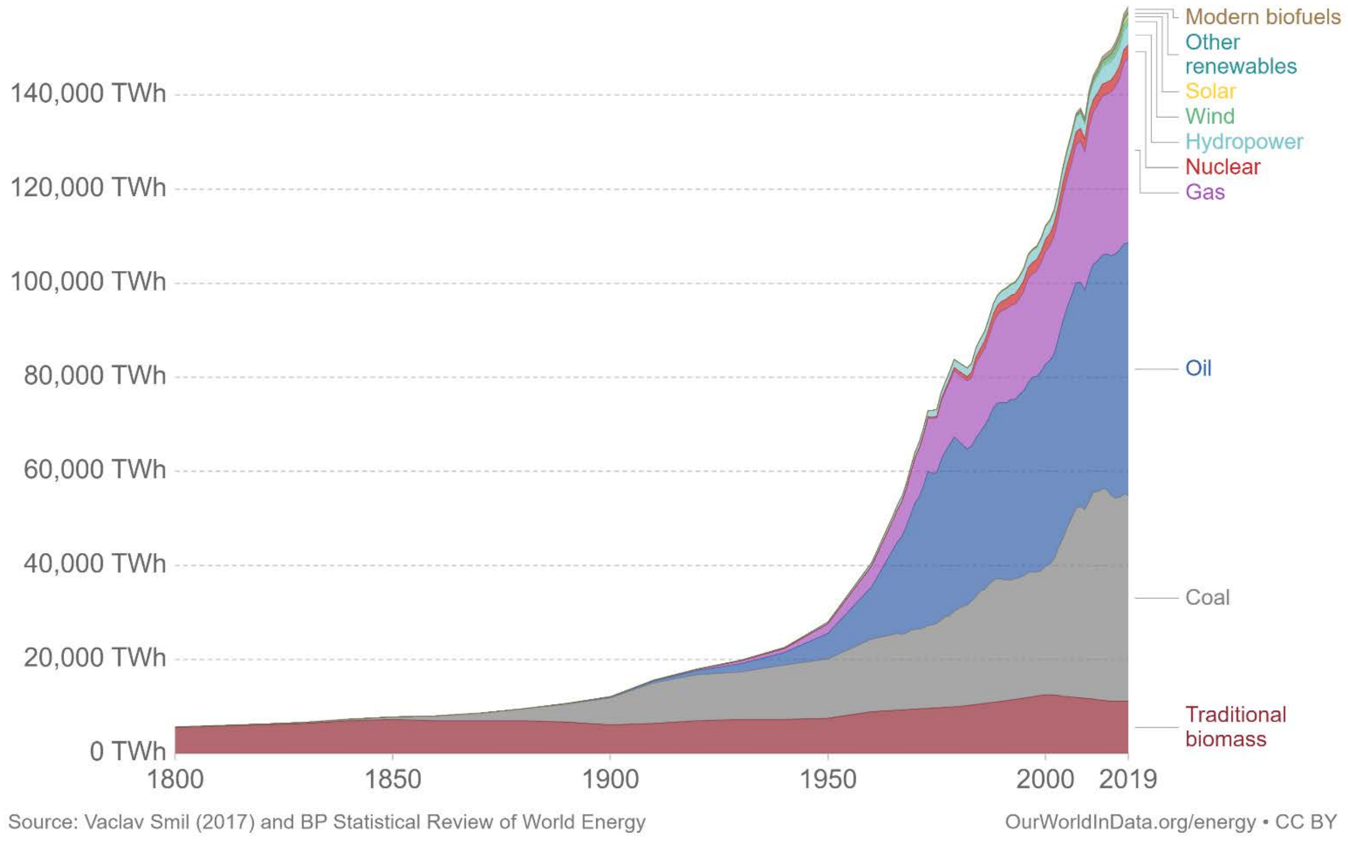
Thursday 9:10-12:00

Material: http://capst.ncku.edu.tw/PGS/index.php/teaching/

Lecture 1

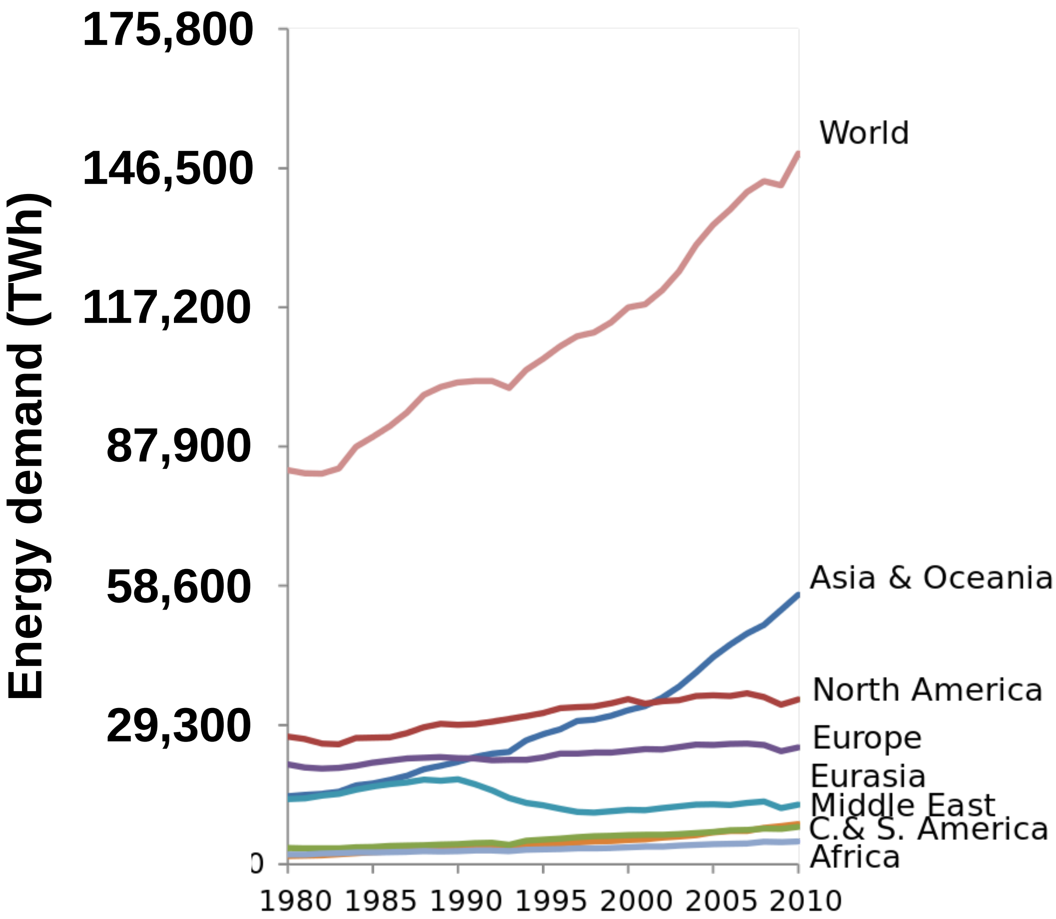
Global direct primary energy consumption

Global direct primary energy consumption



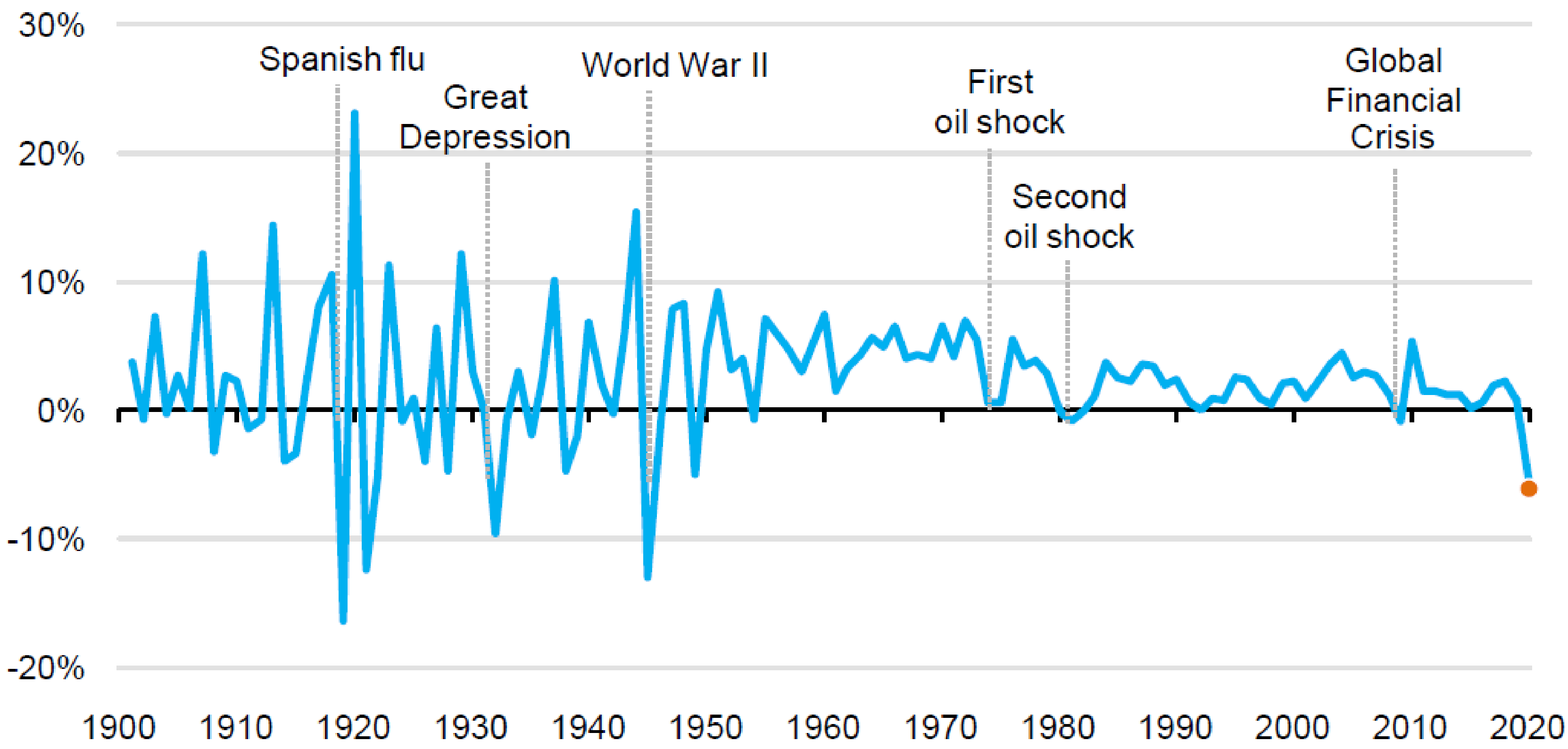
https://ourworldindata.org/grapher/global-primary-energy?time=earliest..latest

Annual Energy Demand by Region



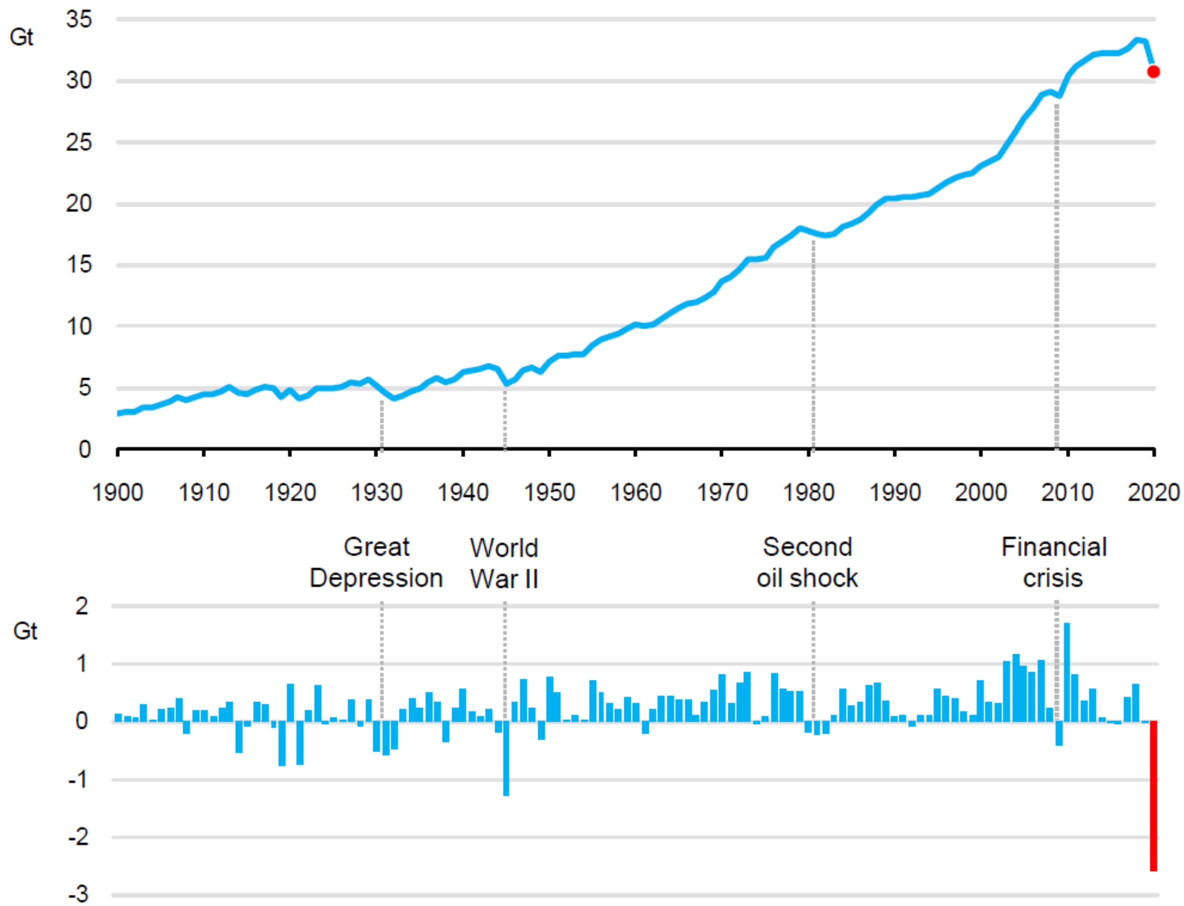
https://en.wikipedia.org/wiki/World_energy_consumption#cite_note-21

Rate of change in global primary energy demand



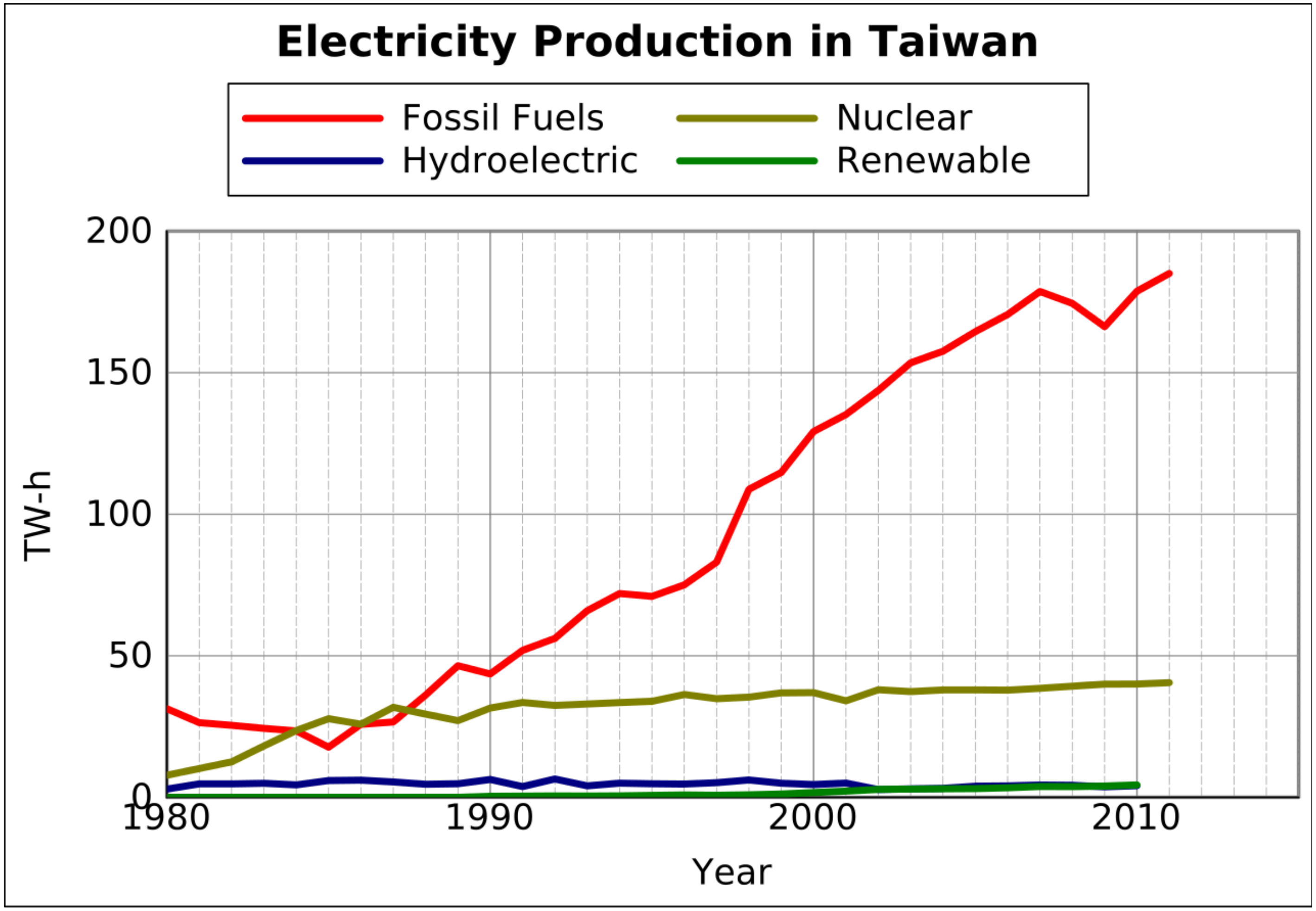
Global Energy Review 2020 by International Energy Agency (IEA)

Global energy-related CO_2 emissions



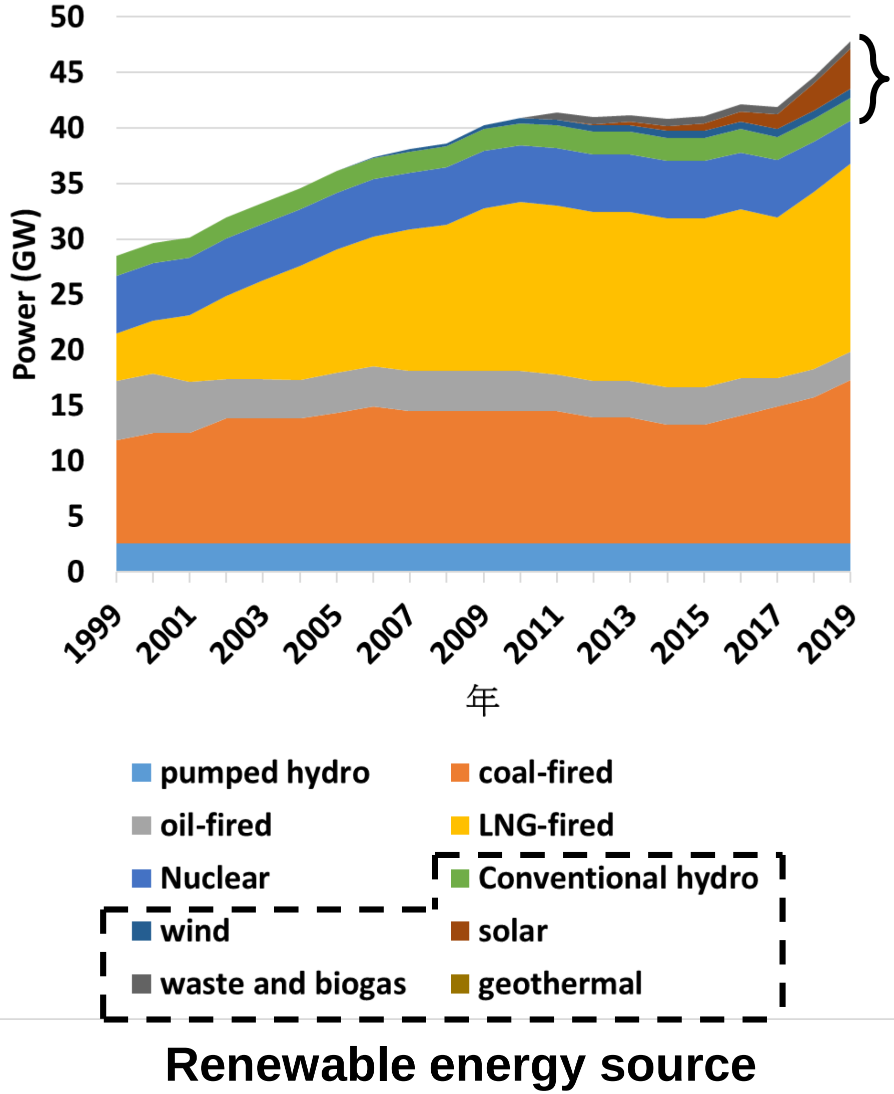
Global Energy Review 2020 by International Energy Agency (IEA)

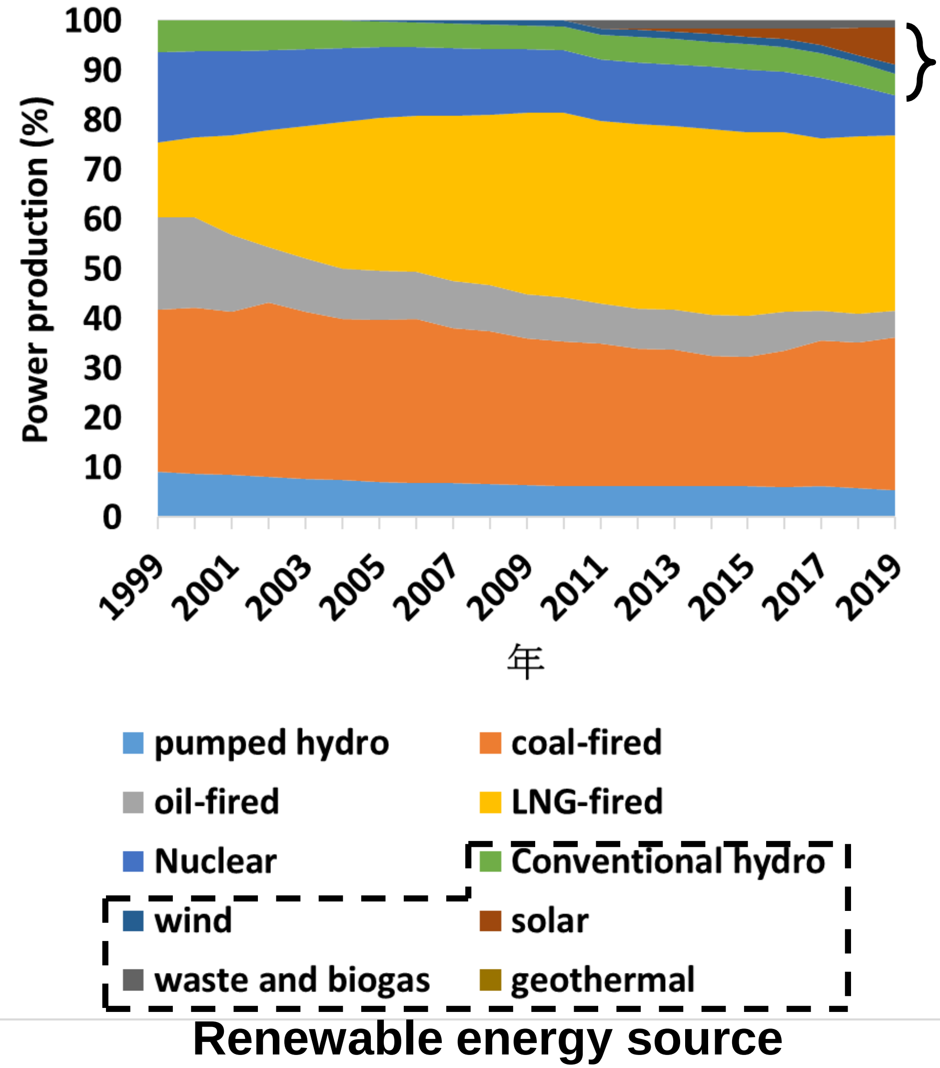
Electricity production in Taiwan



https://zh.wikipedia.org/wiki/%E5%8F%B0%E7%81%A3%E9%9B%BB%E5%8A%9B%E7%94%A2%E6%A5%AD#cite_note-energymonthly-10

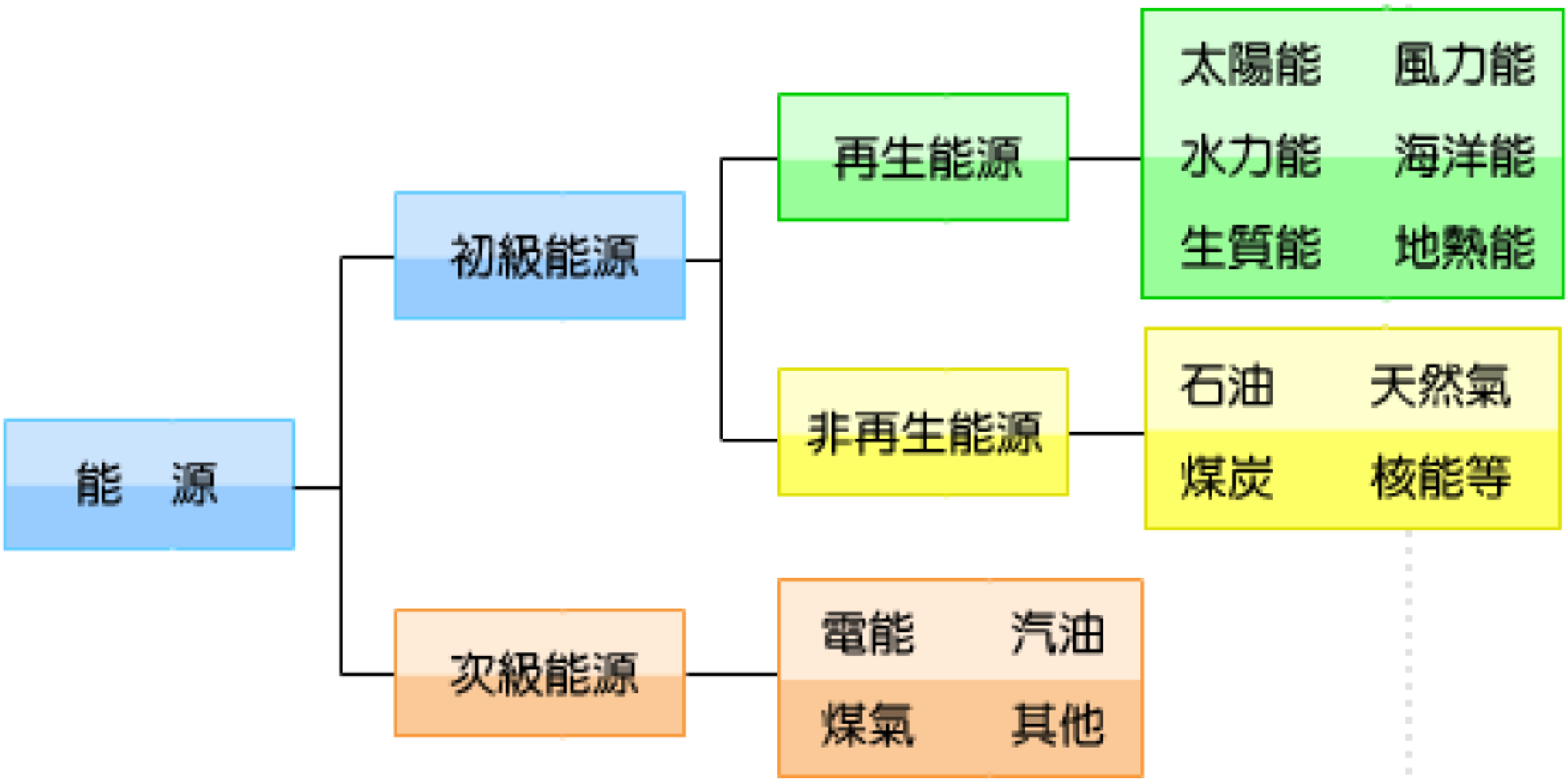
歷年台電系統發電廠裝置容量





經濟部能源局

Energy source can be categorized by being processed or not



Energy densities of different energy sources

Source	Energy density (J/m^3)
Solar	1.5×10^{-6}
Geothermal	0.05
Wind @ 5 m/s	7
Tidal water	0.5~50
Oil	4.5×10^{10}
Gasoline	10^{10}
Natural gas	4×10^{7}
Nuclear Fission (5% ^{235}U + 95% ^{238}U)	1.5×10^{18} (8×10^{13} J/kg)
Nuclear Fusion (50% D + 50% T)	(5.4×10^{14} J/kg)
Fat (food)	3×10^{7}
Human	1000

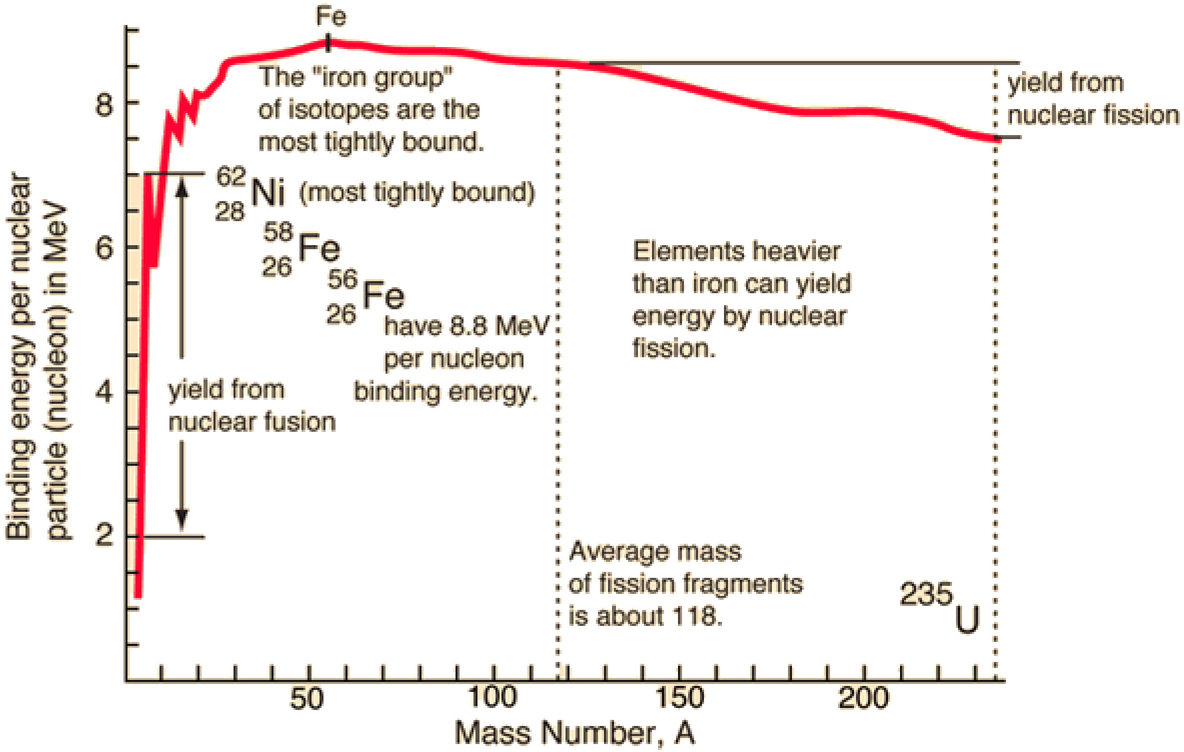
B. E. Layton, Int. J. Green Energy, 5, 438, 2008

Power density is low for solar panel and wind turbine

- **Solar panel: ~175 W/m^2.**
- **Wind Turbine: 5~10 MW per generator with blade diameter of 100 m. Assume each generator occupies 100x100 m^2 => 1000 W/m^2.**
- **Area needed to generate 40,000 MW:**
  - **Solar panel: 460 km^2 , half day only.**
  - **Wind turbine: 80 km^2, half season only.**
- **Area in Taiwan: 36,000 km^2 .**
- **Area in Tainan: 2,192 km^2 .**

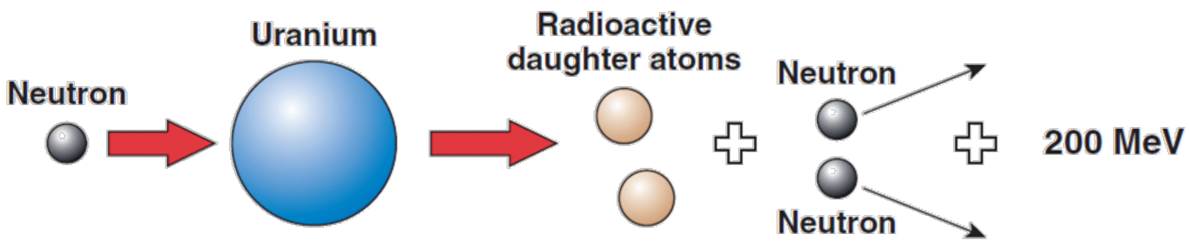
B. E. Layton, Int. J. Green Energy, 5, 438, 2008

The "iron group" of isotopes are the most tightly bound

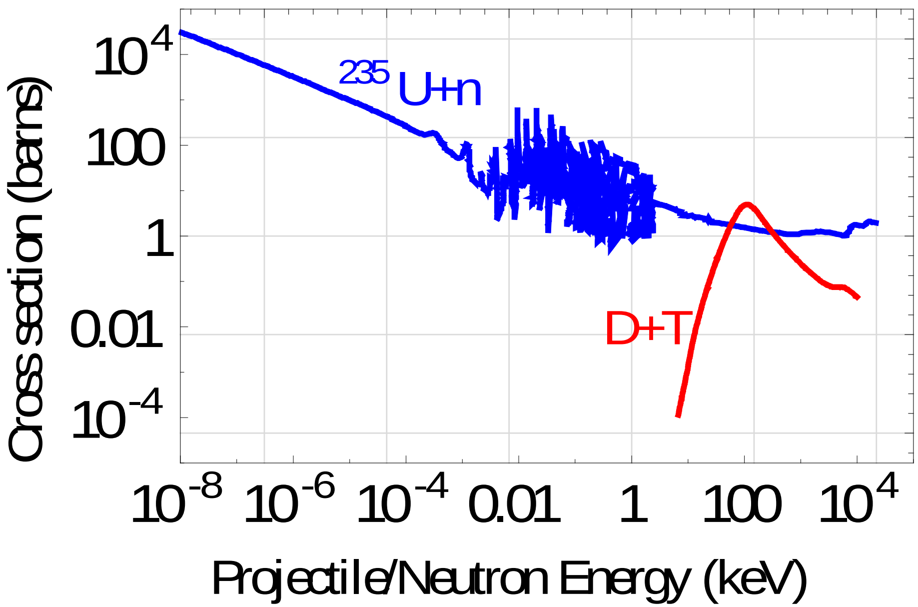


http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

Chain reaction can happen in U^{235} fission reaction



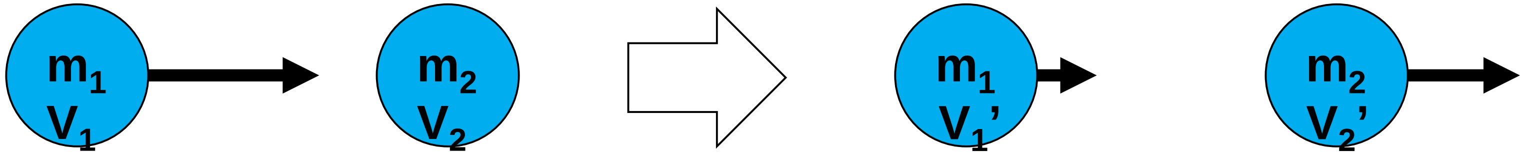
$$n +_{92}^{235} U \rightarrow_{92}^{236} U \rightarrow_{56}^{144} Ba +_{36}^{89} Kr + 3n + 177\ \mathrm{MeV}$$



- **Power plant fuel:**
  5 % ^{235}U + 95 % ^{238}U

https://en.wikipedia.org/wiki/Uranium-235
Talk given by Matthew Bunn, IGA-232: Controlling the World's Most Dangerous Weapons, Harvard Kennedy School, 2013

Neutron moderator is needed to slow down the fast neutron



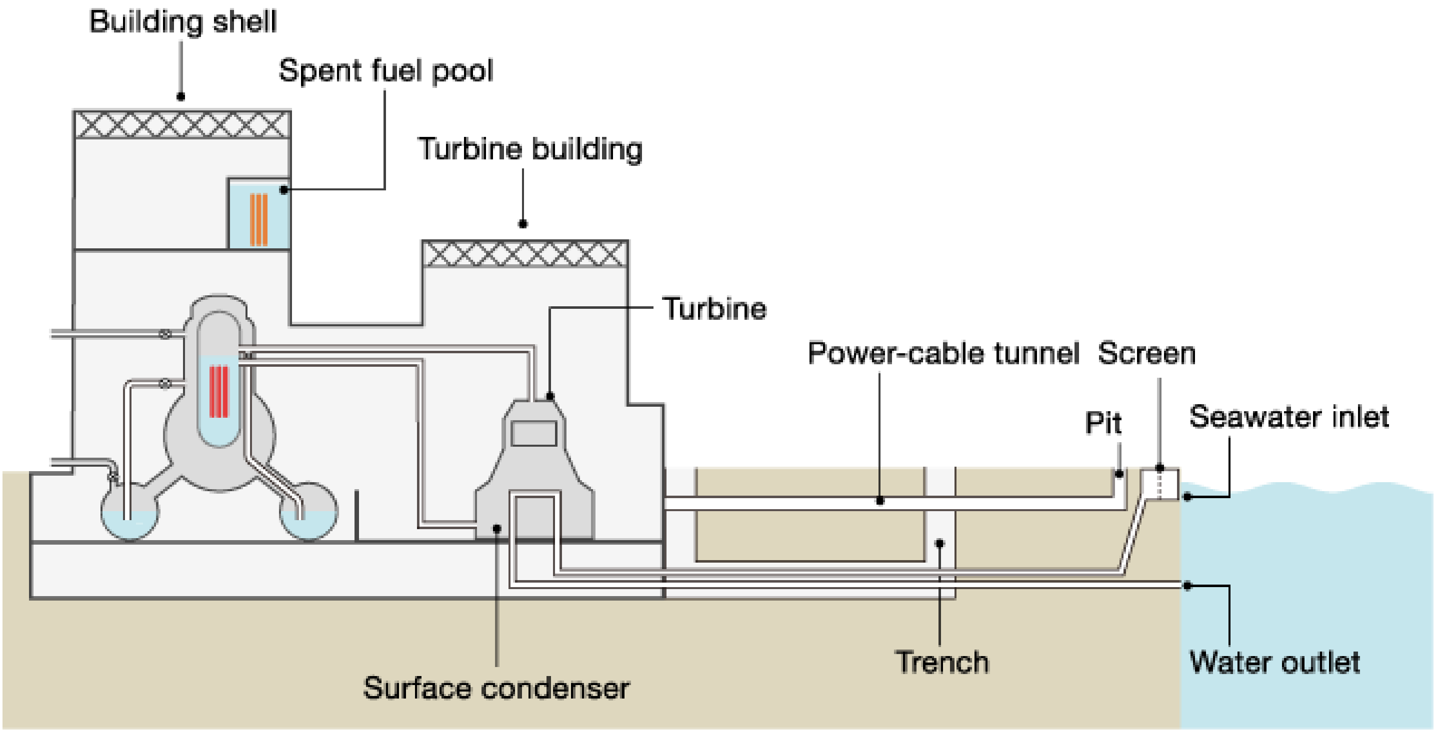
	H	D	Be	C	O	U
M(amu)	1	2	9	12	16	238
Energy decrement	1	0.7261	0.2078	0.1589	0.1209	0.0084
#/ collisions (2M eV $\rightarrow$ 1 eV)	18 (H_2O)	25 (D_2O)	86	114	150	2172

- **Neutrons are absorbed by H_20 since they stop after colliding with hydrogens.**

- **The moderating efficiency is nearly 80 times higher for heavy water than for light water.**

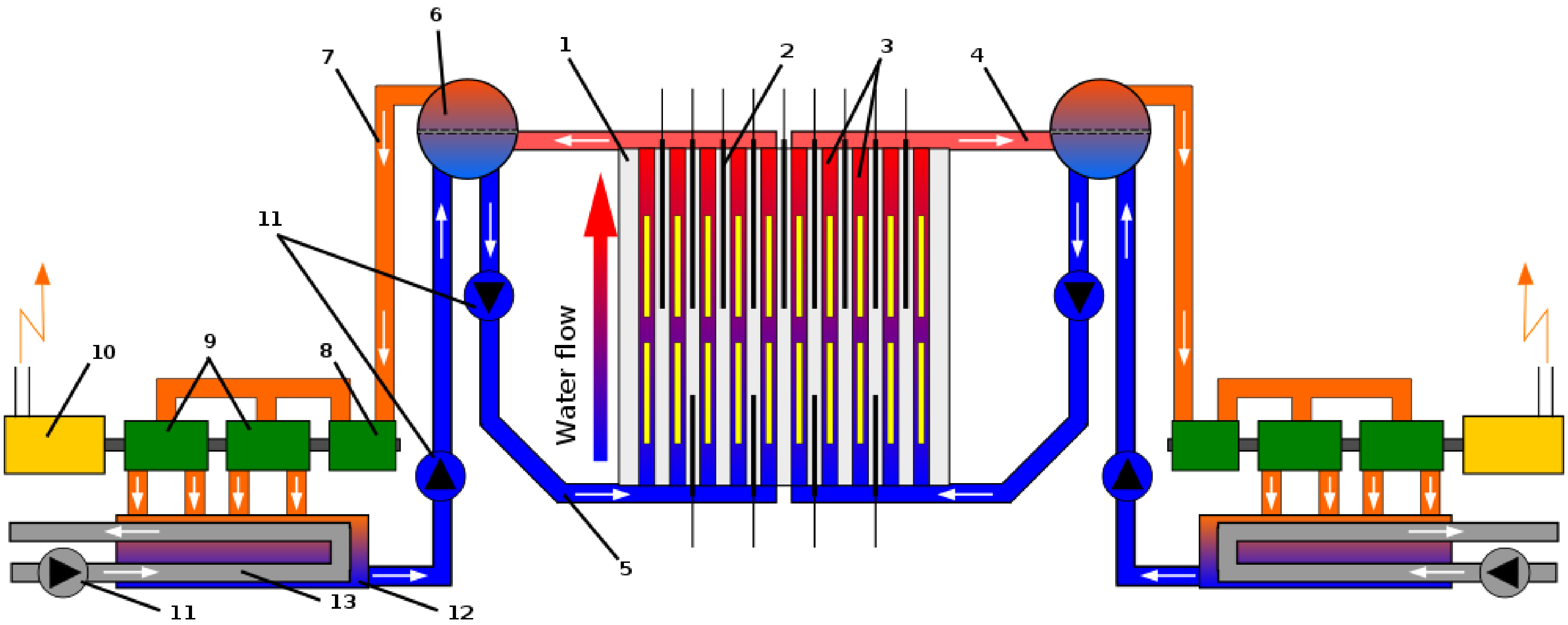
https://en.wikipedia.org/wiki/Neutron_moderator

The Fukushima Daiichi nuclear power plants



https://www.miraikan.jst.go.jp/sp/case311e/home/pics/npp2/index.html

The Chernobyl fission power plant (Reaktor Bolshoy Moshchnosti Kanalniy, RBMK)

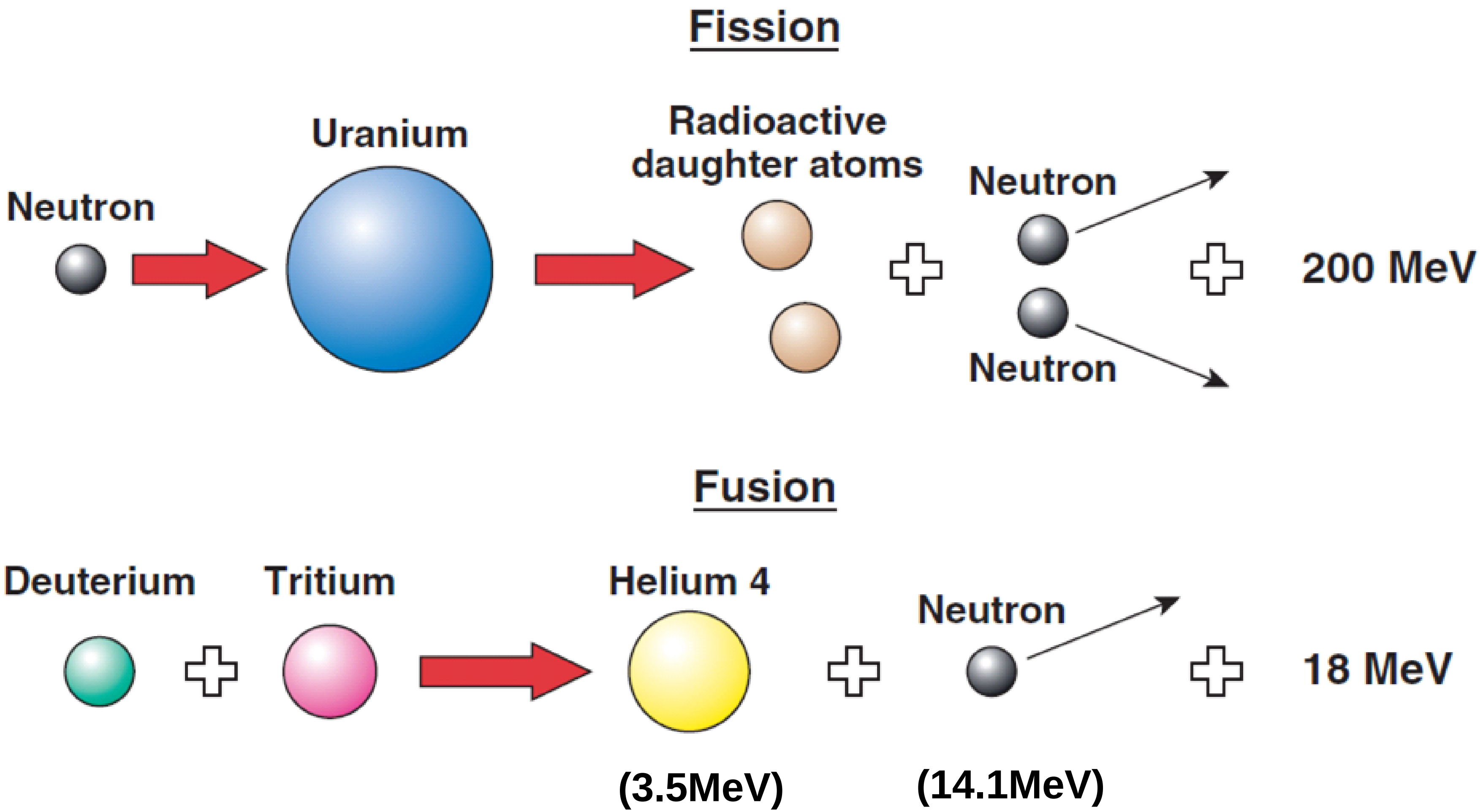


Legend :

1. Graphite moderated reactor core
2. Control rods
3. Pressure channels with fuel rods
4. Water/steam mixture
5. Water
6. Water/steam separator
7. Steam inlet
8. High-pressure steam turbine
9. Low-pressure steam turbine
10. Generator
11. Pump
12. Steam condenser
13. Cooling water (from river, sea, etc.)

https://www.wikiwand.com/en/RBMK

Nuclear fusion and fission release energy through energetic neutrons



Nuclear fusion provides more energy per atomic mass unit (amu) than nuclear fission

Fusion of $^2H + ^3H$: $$\frac{Q}{A} = \frac{17.6\ MeV}{(3+2)\ amu} = 3.5\ \frac{MeV}{amu}$$

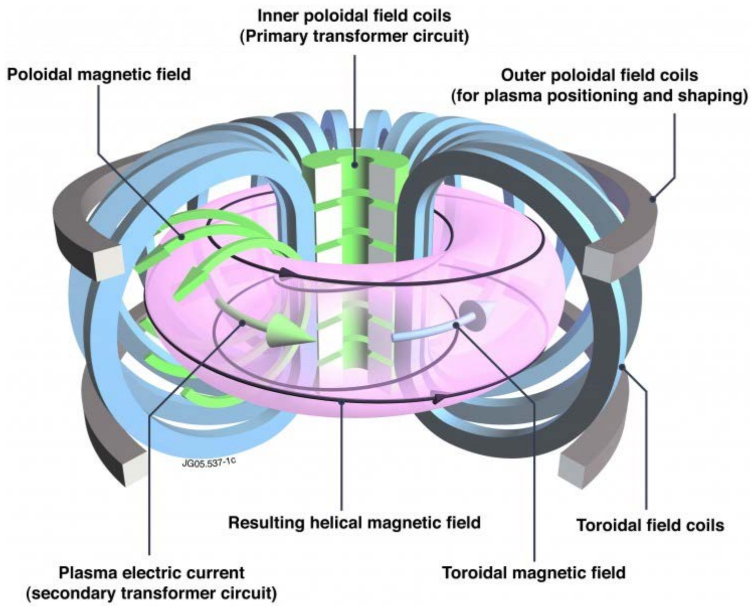
Fission of ^{235}U: $$\frac{Q}{A} = \frac{200\ MeV}{236\ amu} = 0.85\ \frac{MeV}{amu}$$

Source	Energy density
Nuclear Fusion (50% D + 50% T)	**5.4 x 10^{14} J/kg**
Nuclear Fission (5% ^{235}U + 95% ^{238}U)	**1.5 x 10^{18} J/m^3** **8 x 10^{13} J/kg**

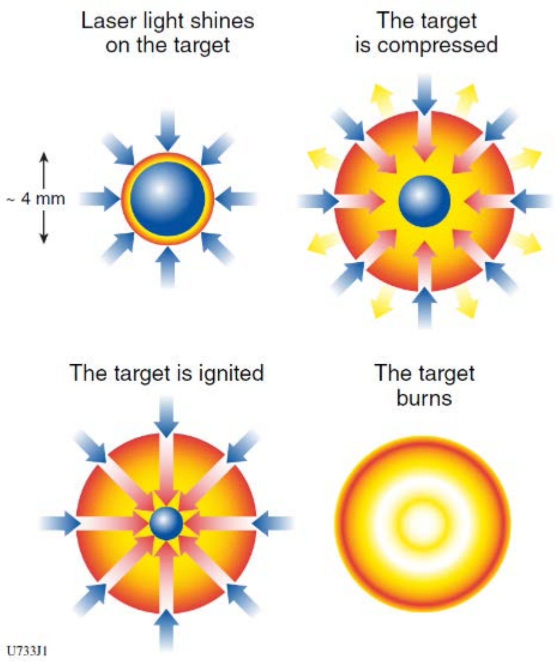
	Half-life (years)
U235	**7.04x10^8**
U238	**4.47x10^9**
…	
Tritium	**12.3**

Nuclear fusion as an energy source is being developed

- **Magnetic confinement fusion (MCF)**

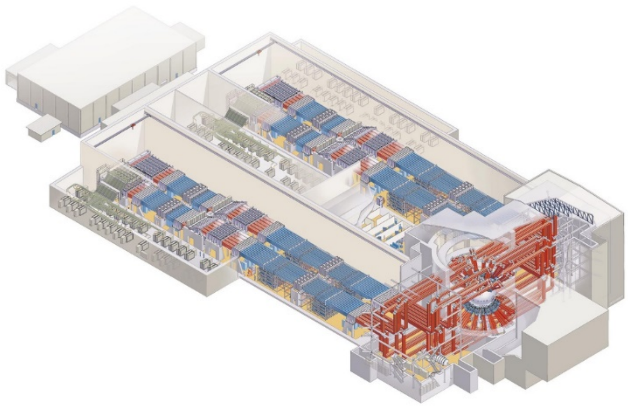


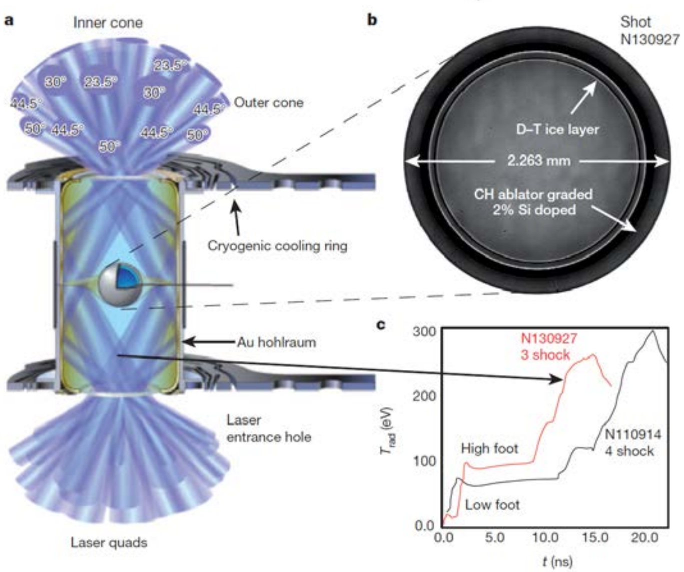
- **Inertial confinement fusion (ICF)**

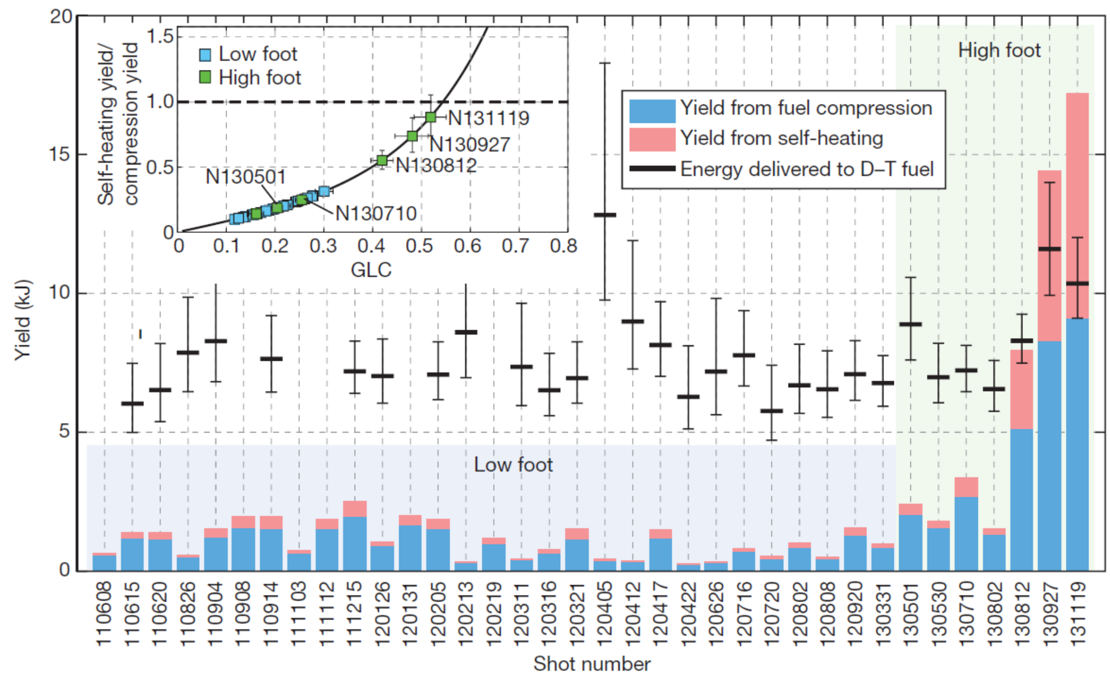


https://www.euro-fusion.org/2011/09/tokamak-principle-2/
Inertial confinement fusion: an introduction, Laboratory for Laser Energetics, University of Rochester

Nature letter “Fuel gain exceeding unity in an inertially confined fusion implosion”





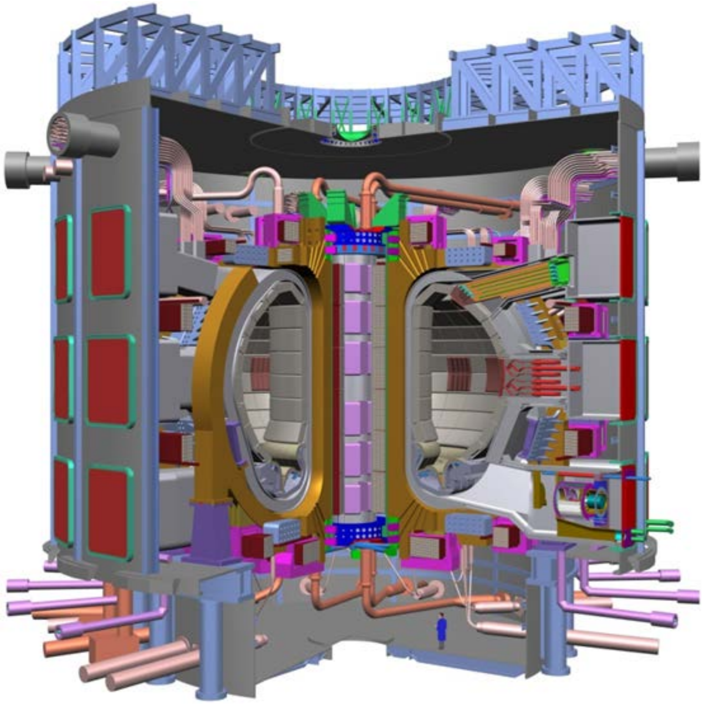


- **Fuel gain exceeding unity was demonstrated for the first time.**

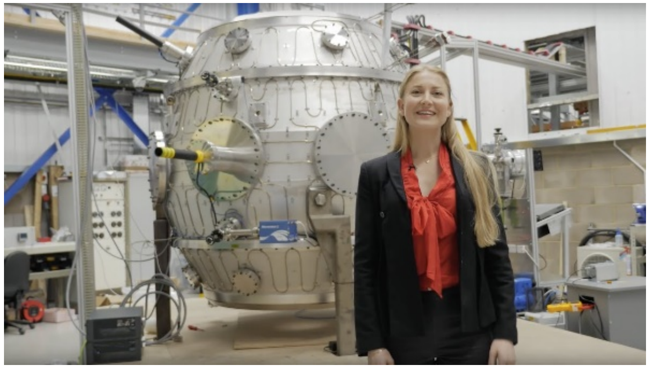
Nature 506, p343, 2014

Many groups aim to achieve ignition in the near future

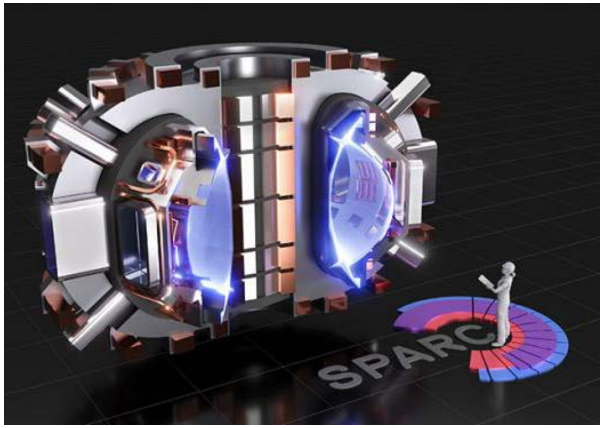
- **ITER – 2025 First Plasma**
  2035 D-T Exps
  2050 DEMO



- **Tokamak energy, UK**
  - **2025 Gain**
  - **2030 to power grid**



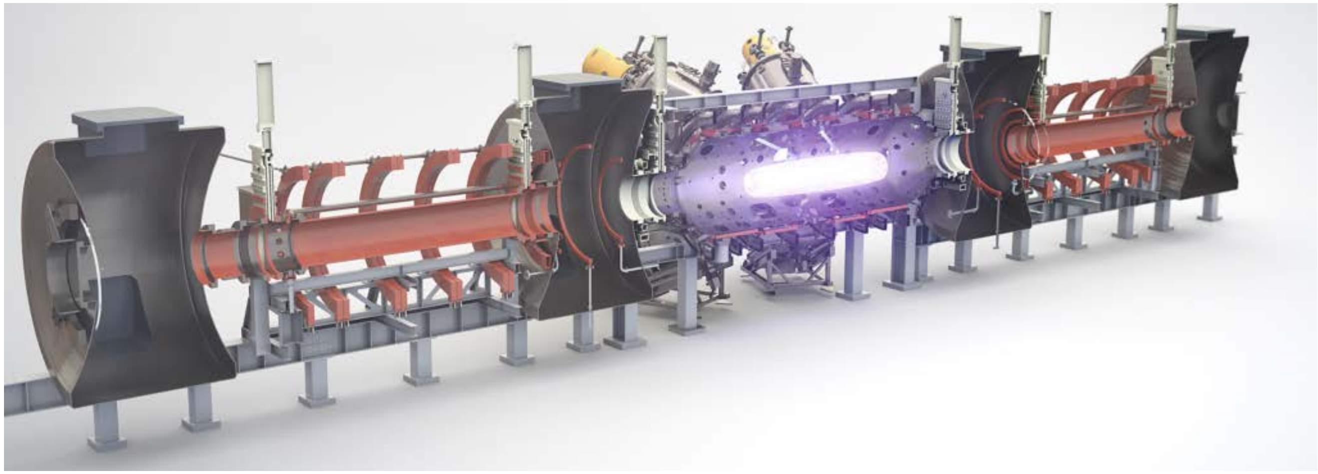
- **Commonwealth Fusion Systems, USA – 2025 Gain**



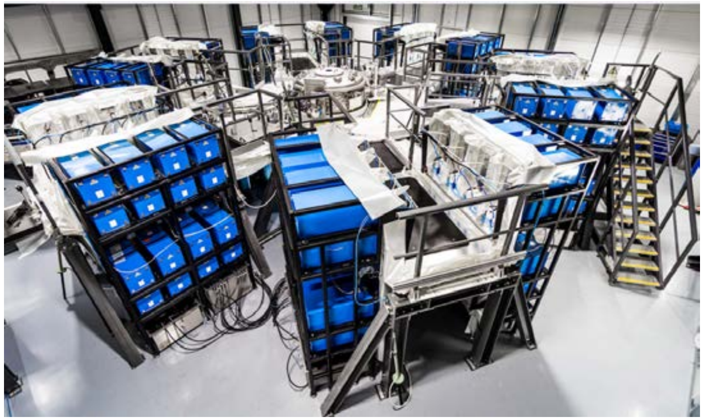
https://www.iter.org
https://www.tokamakenergy.co.uk/
https://www.psfc.mit.edu/sparc

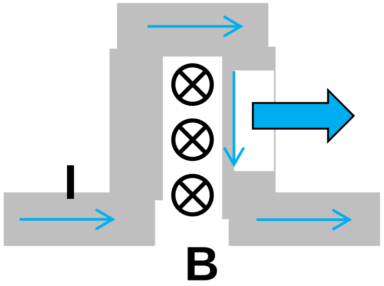
There are more ideas

- **Tri-alpha energy, USA – 2025 Gain?** $^{1}P + ^{11}B \rightarrow 3\ ^{4}He$



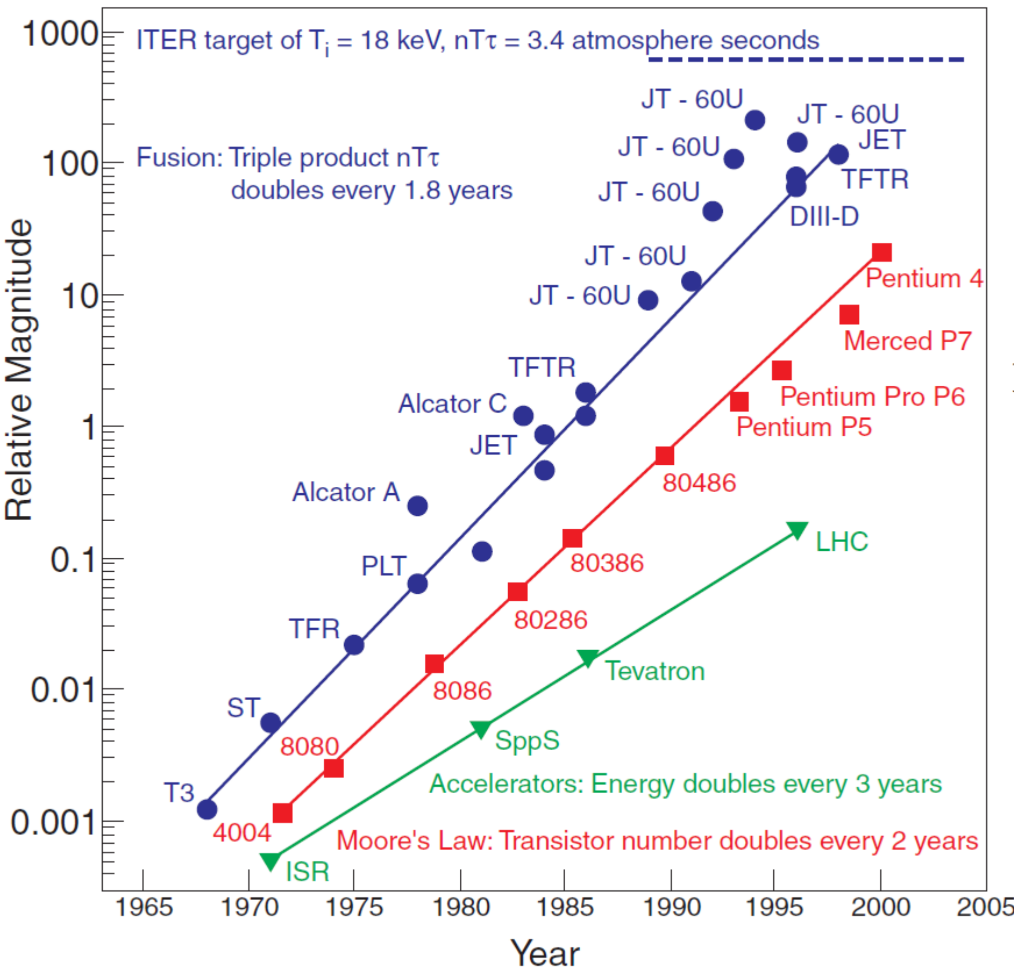
- **First Light Fusion Ltd, UK – 2024 Gain**

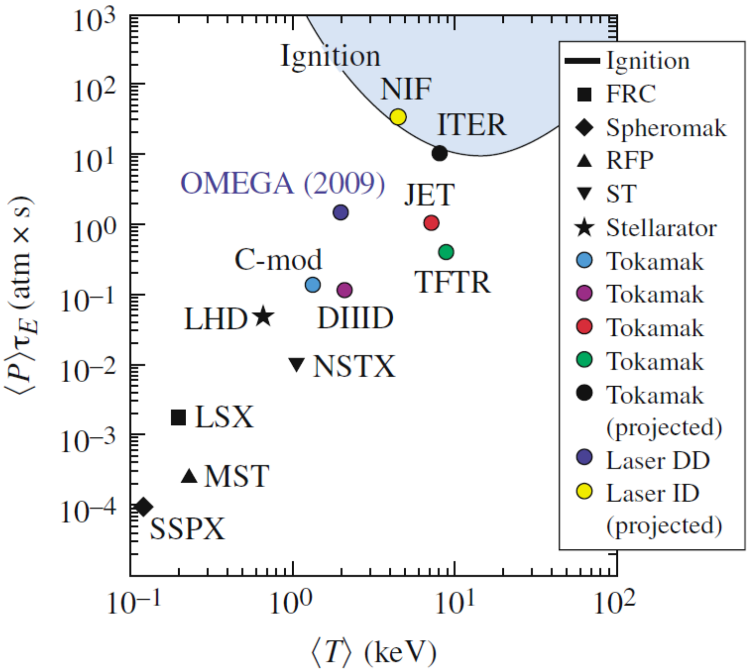




https://tae.com/
https://firstlightfusion.com/

The performance of a fusion plasma has doubled every 1.8 years like the Moore's law

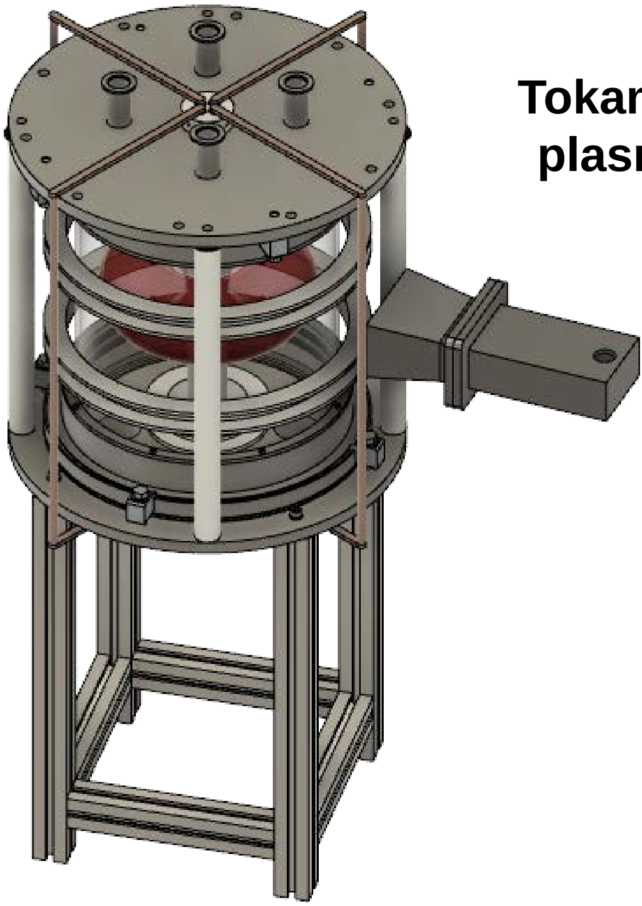


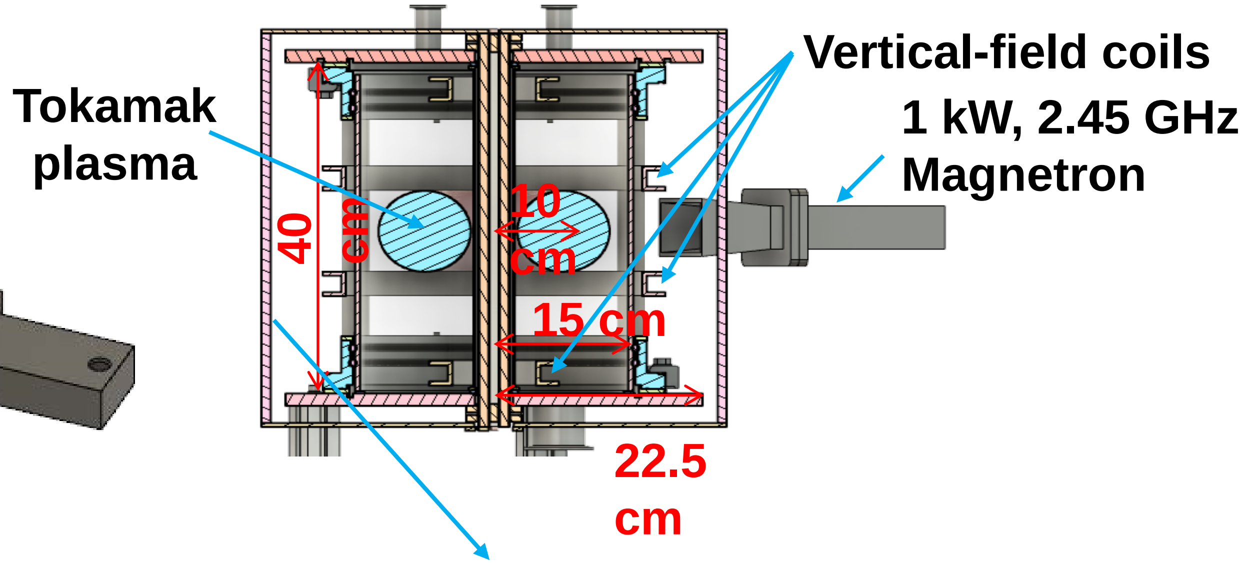


- **Nuclear fusion is coming in the near future.**

A. J. Webster, Phys. Educ. **38**, 135 (2003)
R. Betti, etc., Phys. Plasmas, **17**, 058102 (2010)

We are going to build a spherical tokamak in this class





4 toroidal-field coil connected in series. Two turns in each coil. 2.5 kA pulsed-current.
B=876 G @ 4.6 cm will be used for ECR heating.

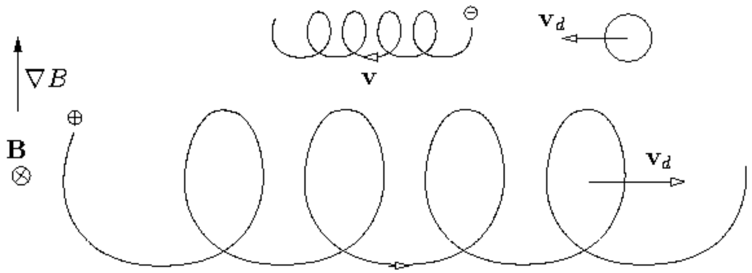
- Gas: Ar, 10^{-2} Torr.
- Initial plasma: generated by RF.
- Microwave pulse width: 8 ms.
- Magnetic field pulse width: 1 ms.

Main components of the spherical tokamak is being built by my students

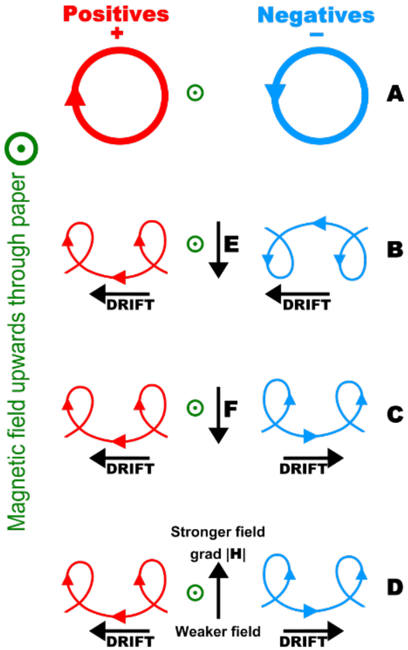
- **Components built by my students:**
  - **Vacuum Chamber.**
  - **Toroidal field coil.**
  - **Microwave heating.**
  - **RF generated plasma.**
- **The missing part of the system:**
  - **Poloidal field generated by the plasma current.**

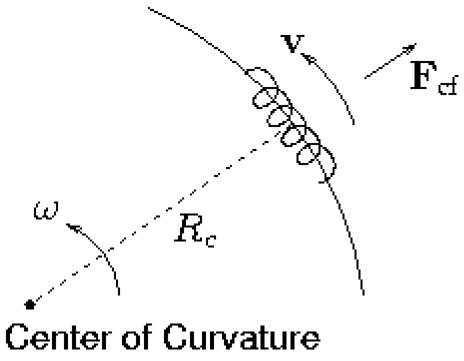
Plasma current will be generated by the Grad-B drift and the Curvature drift current

- **Grad-B drift**



- **Curvature drift**

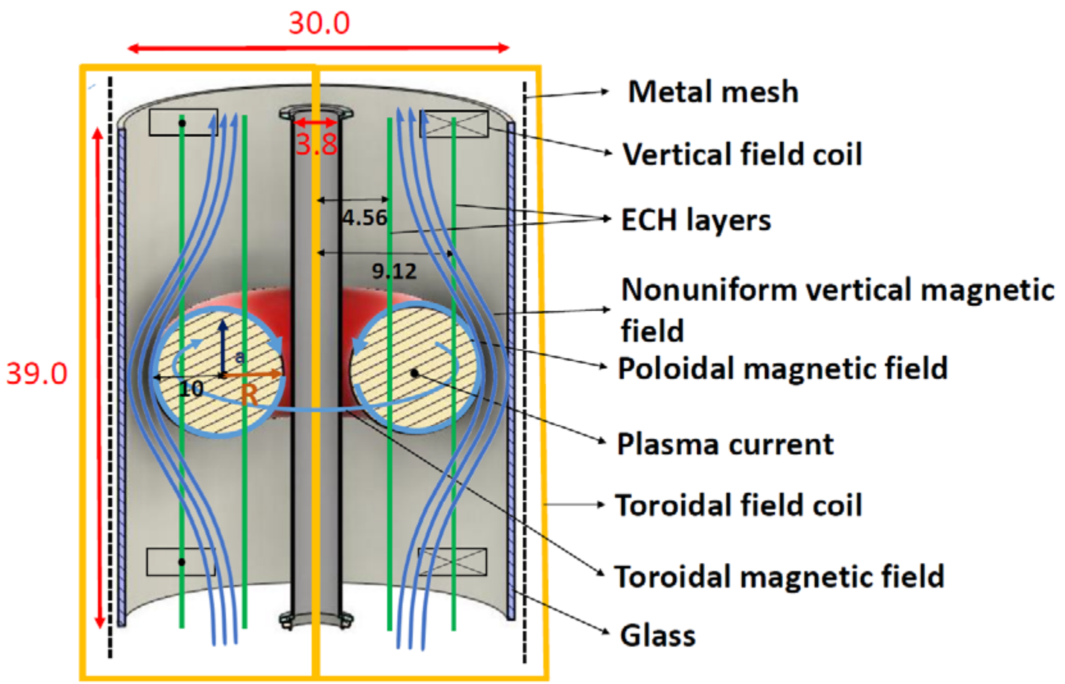




https://en.wikipedia.org/wiki/Guiding_center
http://silas.psfc.mit.edu/introplasma/chap2.html

Three components of the spherical tokamak will be built in class

- **Components built in class:**
  - **Vertical field coil (VF coil).**
  - **Pulse forming network for driving VF coil.**
  - **Rogowski coil for measuring plasma current.**
  - **(Triple probe for measuring Plasma characteristics.)**



Class schedule

Week	Progress Description
1	2/25 簡介、分組、課程執行介紹
2	3/ 4 慣性控制核融合
3	3/11 磁場控制核融合
4	3/18 真空系統
5	3/25 電漿源
6	4/ 1 校慶(放假)
7	4/ 8 電漿加熱技術
8	4/ 15 脈衝功率系統
9	4/ 22 電漿量測

Week	Progress Description
10	4/ 29 小組討論
11	5/ 6 各組口頭報告設計
12	5/ 13 托克馬克各次系統實作
13	5/ 20 托克馬克各次系統實作
14	5/ 27 各組口頭報告進度
15	6/ 3 托克馬克各次系統實作
16	6/10 托克馬克各次系統實作
17	6/17 托克馬克實作
18	6/24 各組口頭報告實驗成果

Grading

- 4 people in each team
- Grade by team (75 % of the final score)
  - Design presentation (15 %, i.e., 11.25 % of the final score)
  - Progress presentation (15 %, i.e., 11.25 % of the final score)
  - Final presentation (20 %, i.e., 15 % of the final score)
  - Experimental results (20 %, i.e., 15 % of the final score)
  - Final report (30 %, i.e., 22.5 % of the final score)
- Grade by person in each team (25 % of the final score)
  - Contribution of each person needs to be provided in each presentation and report.
  - The percentage of the contribution will be added to the final score.
  - Ex1: Contribution of 25 % of design presentation => 25x15% will be added to the final score.