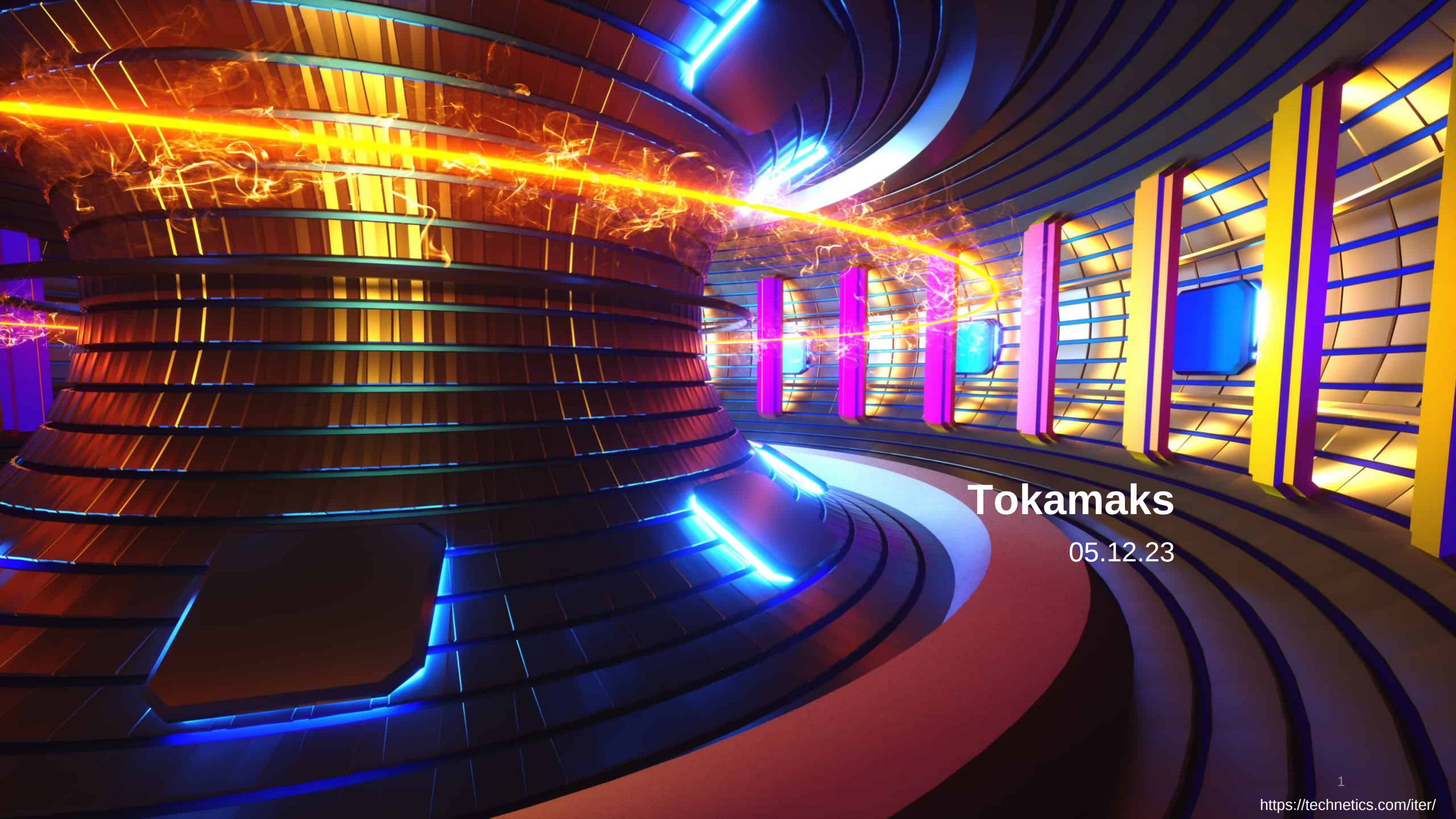


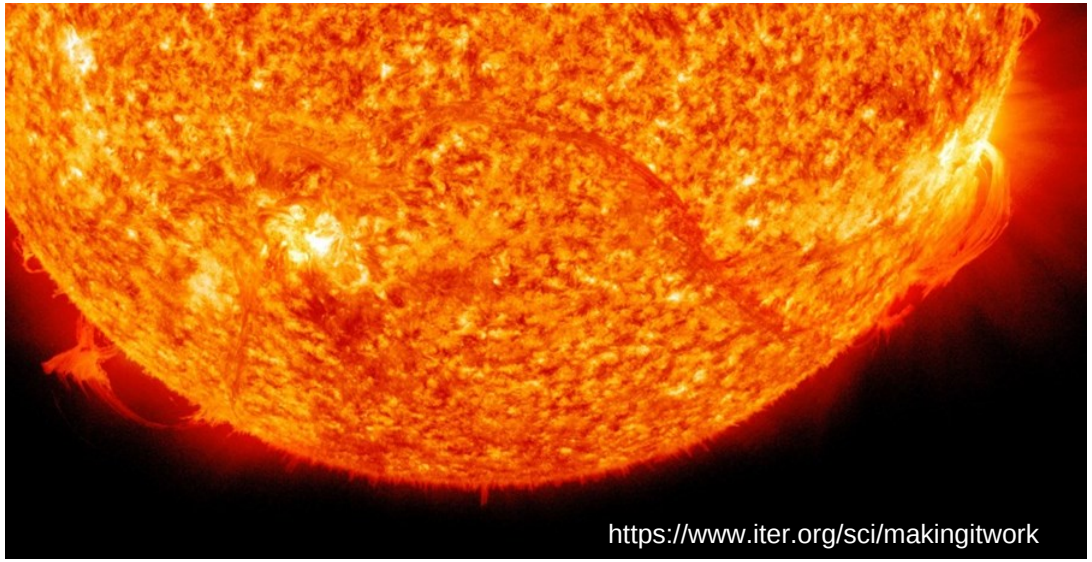
Tokamaks

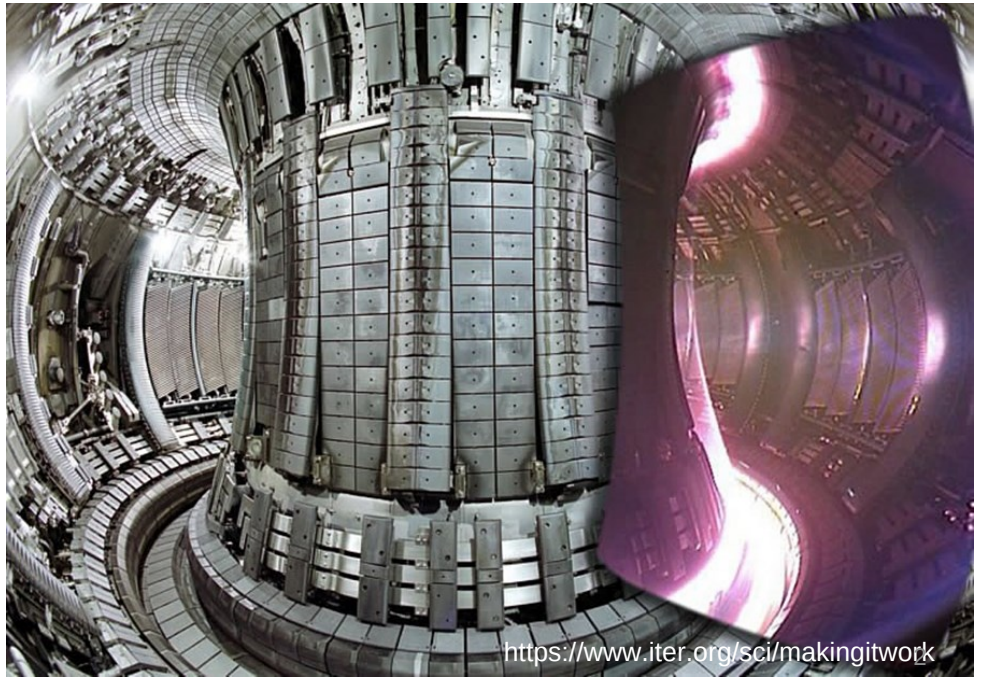
05.12.23

https://technetics.com/iter/

Why Tokamaks?

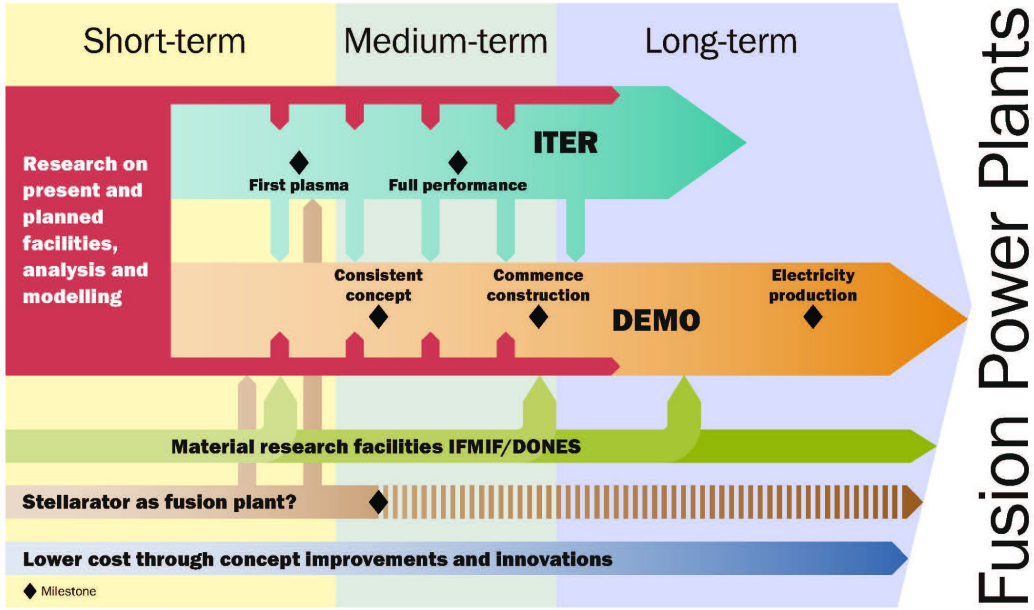
- Sun in a bottle
- Dos not need much computing power
- Most researched fusion concept





Outline

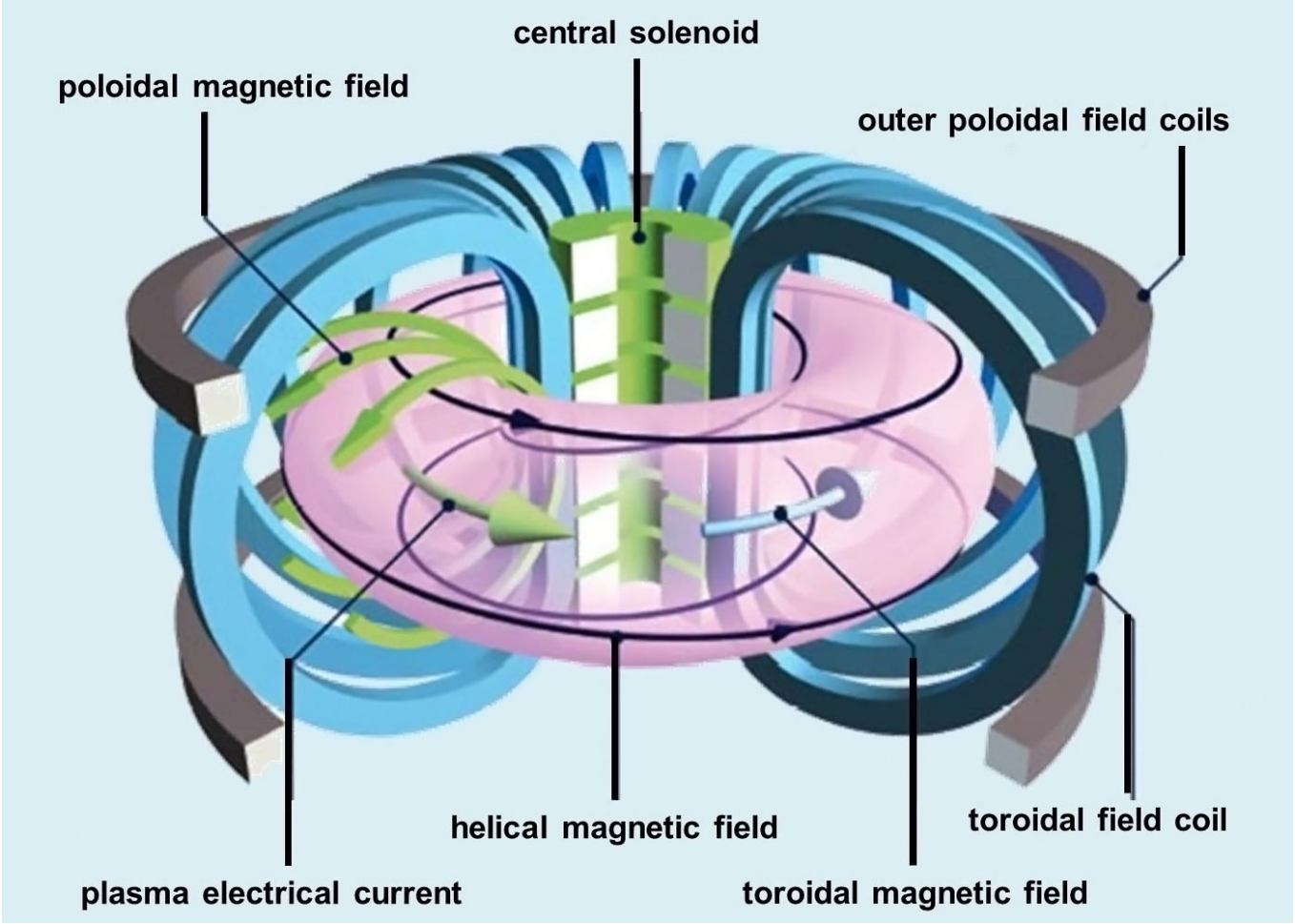
- Most important elements of a Tokamak
  - properties and applications of the different coils
  - Hoop-Force
- Historical overview
  - What does Tokamak mean?
  - Who invented it?
- Examples of tokamaks and their special features
  - ITER
  - SPARC



https://euro-fusion.org/wp-content/uploads/2022/10/Roadmap-illustrated.jpg

properties and applications of the different coils

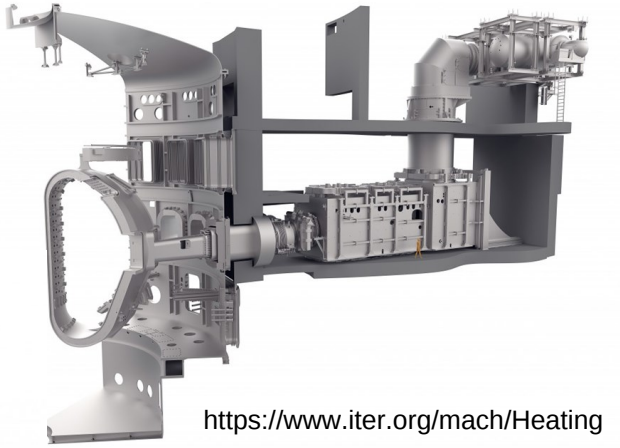
- Toroidal filed coil(TF):
  - Long way around the torus
  - Confinement
- Central solenoid(CS):
  - Short way around the torus
  - Current
  - Confinement
- Outer poloidal field coils(PF):
  - Outer polidal field
  - Shape and Position



https://scitechdaily.com/images/Tokamak-Components.jpg

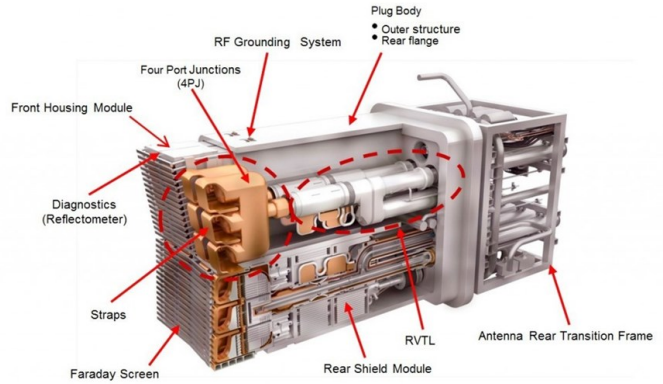
How to heat up to 150 million degrees Celsius?

- Neutral beam injection:
  - Uncharged high-energy particles (ca. 1MeV)
  - Energy transfer per collision



https://www.iter.org/mach/Heating

- Ion Cyclotron Heating(ICRH):
  - Electromagnetic radiation (ca. 40-55 MHz)
  - Energy transfer per ions in the plasma



https://www.iter.org/mach/Heating

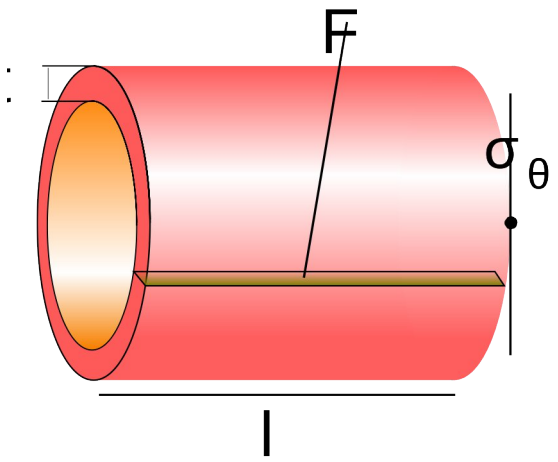
- Electron Cyclotron Heating(ECRH):
  - Electromagnetic radiation (ca. 170 GHz)
  - Electrons transfer energy to ions by collision
  - Minimize build-up of instabilities

https://www.iter.org/mach/Heating

Hoop-Stress

- Definition: Hoop stress is the force over area exerted cicumferentially in both directions on every particle in the cylinder wall.

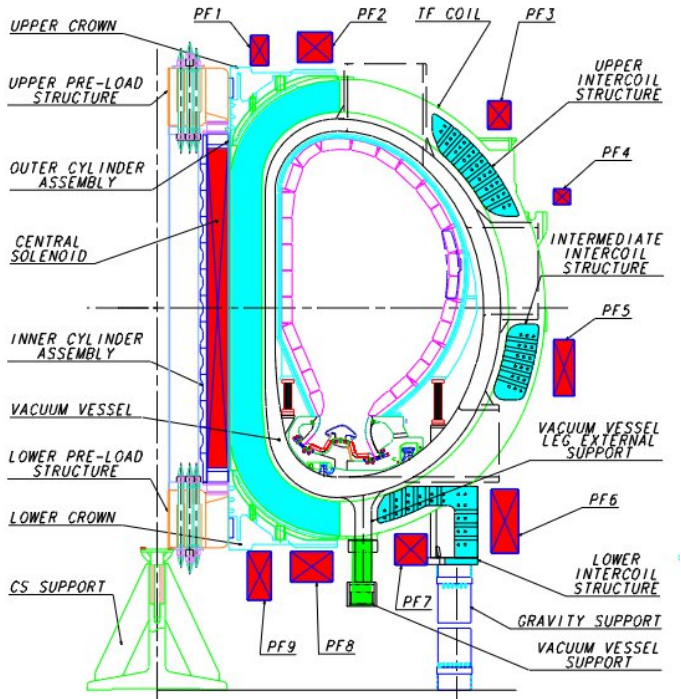
$$\sigma_\theta = \frac{F}{tl}$$



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

- Problem Tokamak (ITER):
  - Fatigue issue of the CS
  - 50.000 full-power pulses

- Solution:
  - Compressive hoop stress on CS
  - Operation close to fatigue limit TF

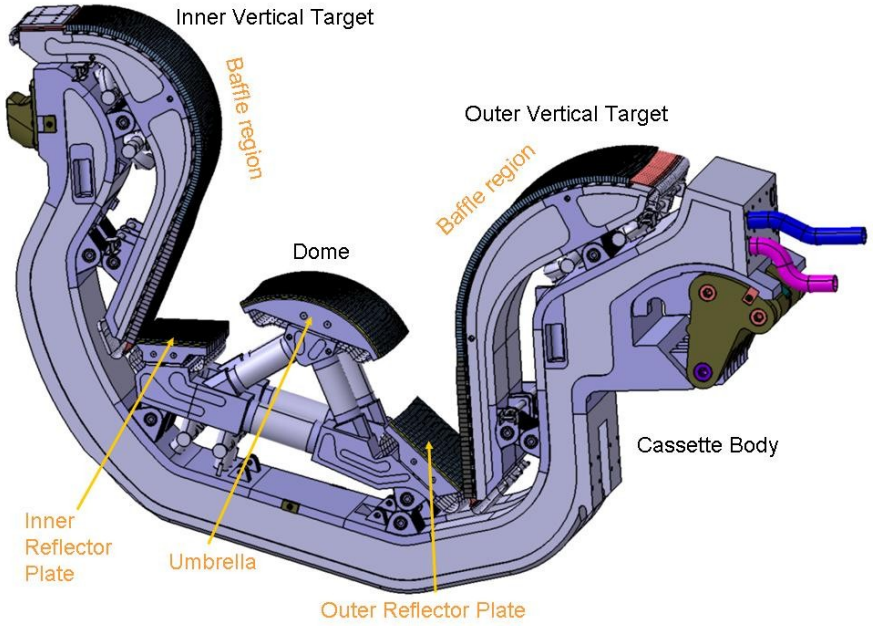


https://www-pub.iaea.org/MTCD/publications/PDF/csp_001c/pdf/iter_4.pdf

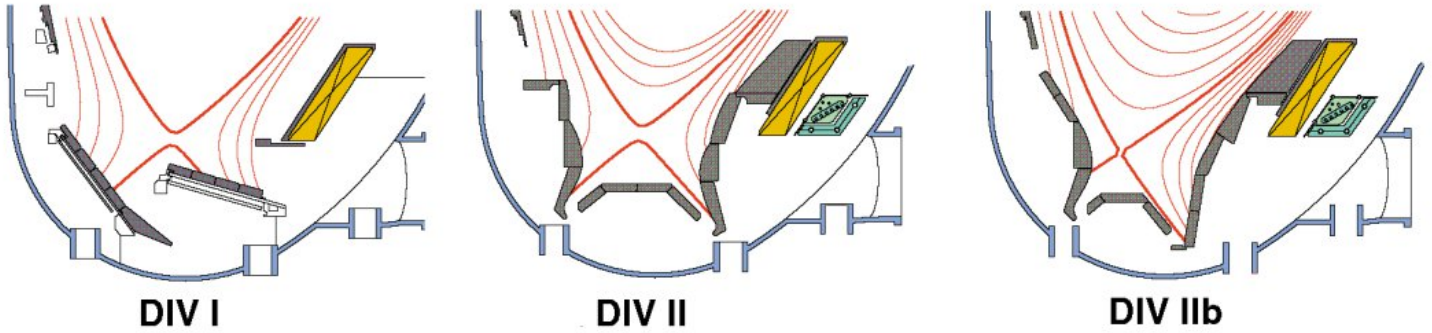
Divertor arrangement (ASDEX)

- Function:
  - Point of contact of the field lines
  - Removal of contaminants
  - Deflecting the field lines with a divertor field

- ASDEX (Upgrade):
  - H-Regime
  - Impurities distant from the center
  - arrangement



https://static.iter.org/all/newsline_1_120/img/61/divertor3.jpg._1024.jpg



https://www.ipp.mpg.de/47279/6_ipp_tokamaks.pdf

What does Tokamak mean?

- Etymology:
  - **то**роидальная **ка**мера с **ма**гнитными **к**атушками (***to****roidal'naya* ***ka****mera s* ***ma****gnitnymi* ***k****atushkami*)
  - **to**roidal **cha**mber with **ma**gnetic **c**oils
  - Tok -> Current

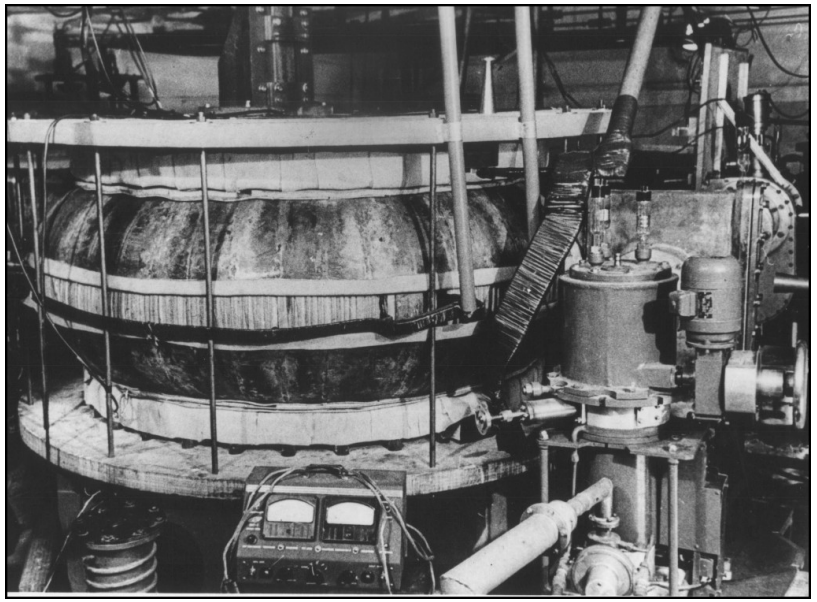
- Why did tokamak fever occur?

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

Early history (1955-1968)

https://de.wikipedia.org/wiki/Andrei_Dmitrijewitsch_Sacharow

https://de.wikipedia.org/wiki/Igor_Jewgenjewitsch_Tamm



https://www.iter.org/newsline/55/1194

History (1968-now)

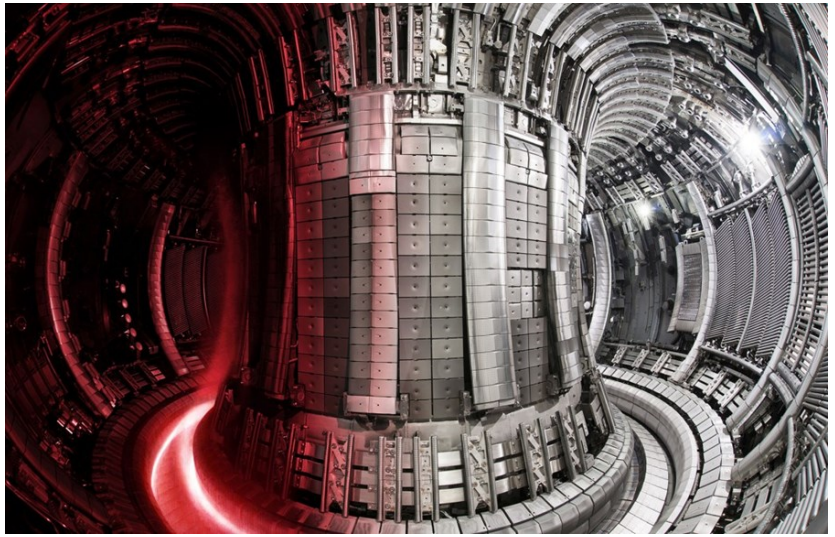
- (1968) T3: Plasma confinement of 10 milliseconds and a temperature of 10 Mio. K
- (1983) ASDEX: tested s divertor geometry for the first time
- (1991) JET: Deuterium-tritium plasma delivered 1,8 MW for two seconds
- (1994/95) TFTR: 10,7 MW of fusion power and Plasma temperature of 510 Mio. K
- (2020) KSTAR: Plasma confinement of 20s and a temperature of 100 Mio. K
- -> soon to com ITER (2035), SPARC (2025)

Examples of tokamaks

- JET:

Radius der Anlage (über alles):	7,5 Meter
Höhe (über alles):	11,5 Meter
Gewicht:	4000 Tonnen
Großer Plasmaradius:	2,93 Meter
Plasmahöhe:	4 Meter
Plasmabreite:	2,5 Meter
Plasmavolumen:	80 Kubikmeter
Plasmagewicht:	0,02 Gramm
Anzahl der Toroidalfeldspulen:	32
Spulenstrom:	max. 78 Kiloampere
Magnetfeld:	max. 4,0 Tesla
Plasmastrom	max. 5 Megaampere
Entladungsdauer:	max. 60 Sekunden
Heizleistung:	
- Neutralteilchenheizung	22 Megawatt
- Ionen-Zyklotronheizung:	15 Megawatt
- Lower-Hybrid-Stromtrieb	7 Megawatt

https://www.ipp.mpg.de/47279/6_ipp_tokamaks.pdf



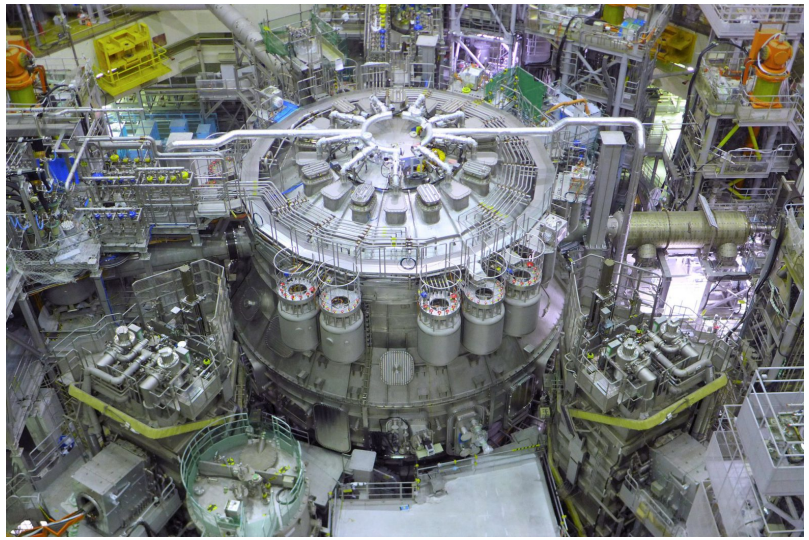
https://www.iter.org/newsline/-/3722

- JT-60SA:

Key facts & figures:

Plasma current: **5.5 MA**
Toroidal magnetic field: **2.25 Tesla**
Plasma major radius: **3 m**
Plasma minor radius: **<1.18 m**
Plasma volume: **130 m³**
Heating power: **40 MW (during 100 s)**
Weight: **2600 tonnes**
Size: **13,7 m diameter x 15,4 m height**

JT60_SA_Fact_Sheet_F4E_Copyright.pdf



https://fusionforenergy.europa.eu/news/first-tokamak-plasma-for-jt-60sa/

Examples of tokamaks

- ARC:

Design Parameter	Symbol	Value
Fusion power	P_f	525 MW
Total thermal power	P_{tot}	708 MW
Plant thermal efficiency	η_{elec}	0.40
Total electric power	P_e	283 MW
Net electric power	P_{net}	190 MW
LHCD coupled power	P_{LH}	25 MW
ICRF coupled power	P_{IC}	13.6 MW
Power multiplication factor	Q_e	3.0
Major radius	R_0	3.3 m
Plasma semi-minor radius	a	1.13 m
Plasma elongation	κ	1.84
Plasma volume	V_p	141 m^3
Toroidal magnetic field	B_0	9.2 T
Peak on-coil magnetic field	B_{max}	23 T
Plasma current	I_p	7.8 MA

https://library.psfc.mit.edu/catalog/reports/2010/15ja/15ja032/15ja032_full.pdf

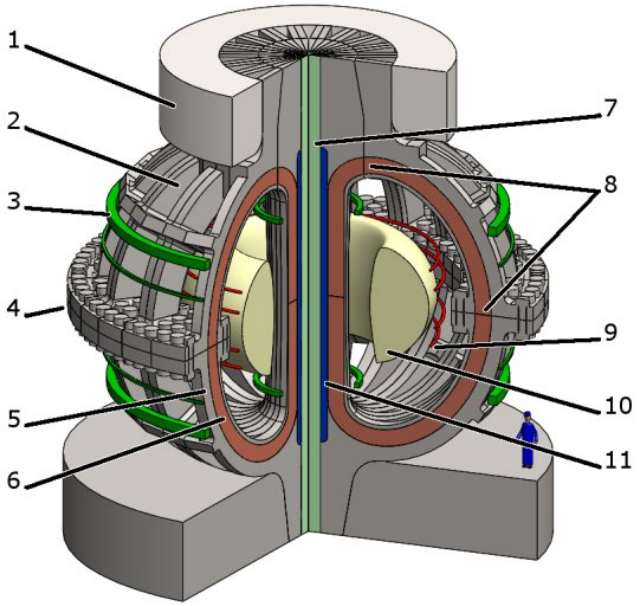
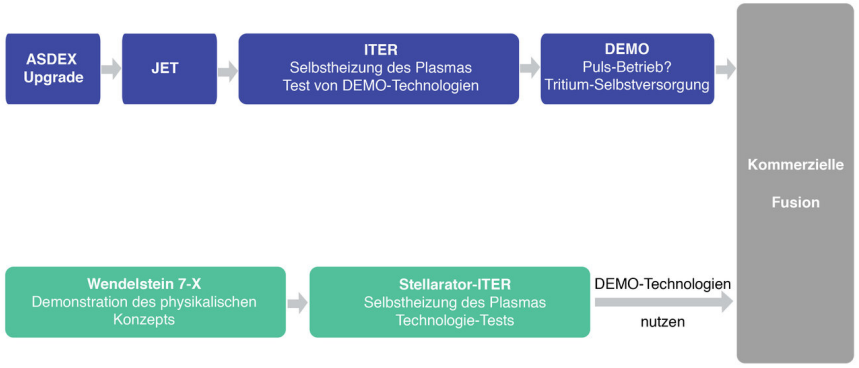


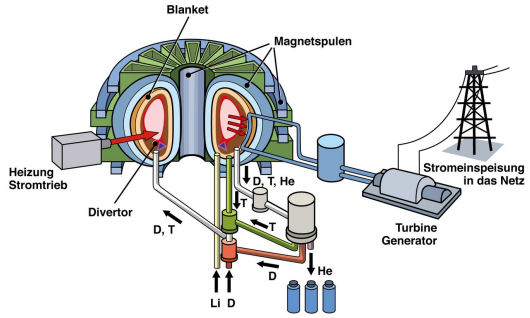
Figure 17: Schematic design of the coil systems, including: 1 – outward force support ring; 2 – top demountable leg of the TF coils; 3 – PF coils (in green); 4 – outer bolted joint between TF coil legs; 5 – bottom leg of the TF coils; 6 – TF coil winding pack; 7 – glass-filled epoxy reinforcement plug; 8 – TF electrical joints; 9 – AUX coils (in red); 10 – plasma; 11 – CS and bucking cylinder. The superconducting cables in the TF coils are shown in brown, within the steel support structure.

https://library.psfc.mit.edu/catalog/reports/2010/15ja/15ja032/15ja032_full.pdf

- DEMO:



https://www.ipp.mpg.de/9031/demo



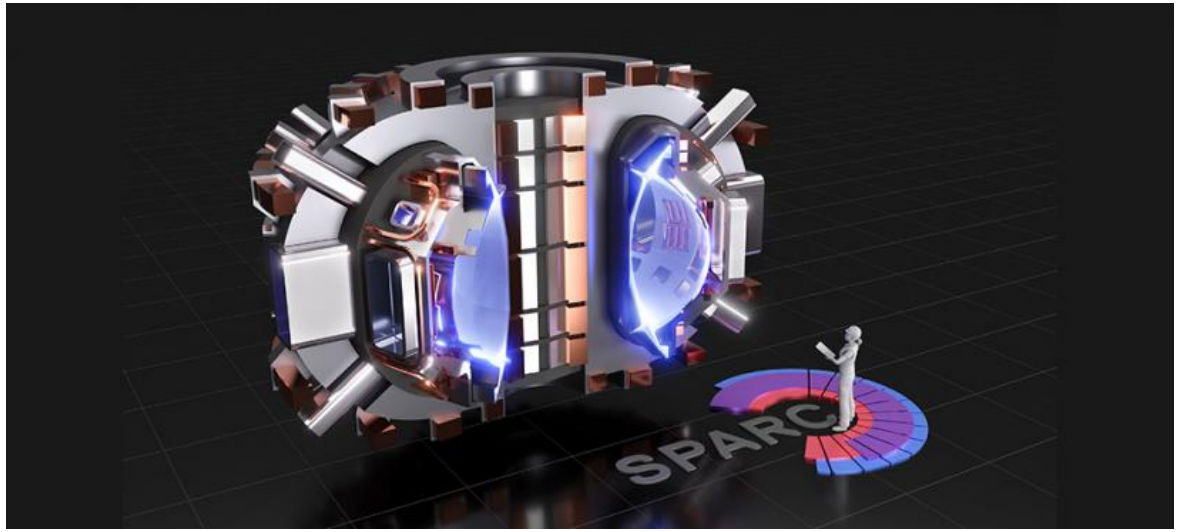
https://www.ipp.mpg.de/12215/aufbau

SPARC

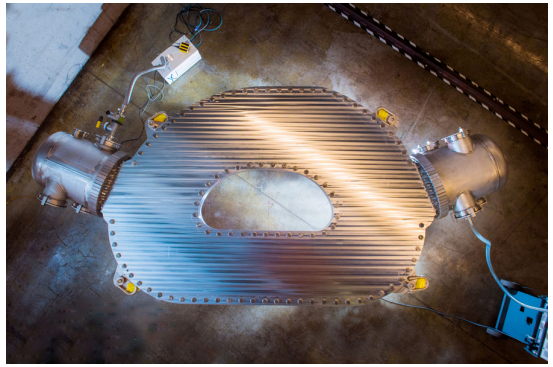
- Team:
  - MIT
  - Commonwealth Fusion Systems (CFS)

- Figures:
  - 50-100 MW of fusion power
  - Fusion gain Q > 10
  - Major radius 1,85m
  - Minor radius 0,57m

- Mission:
  - Brake-even fusion
  - Integrated engineering of HTS



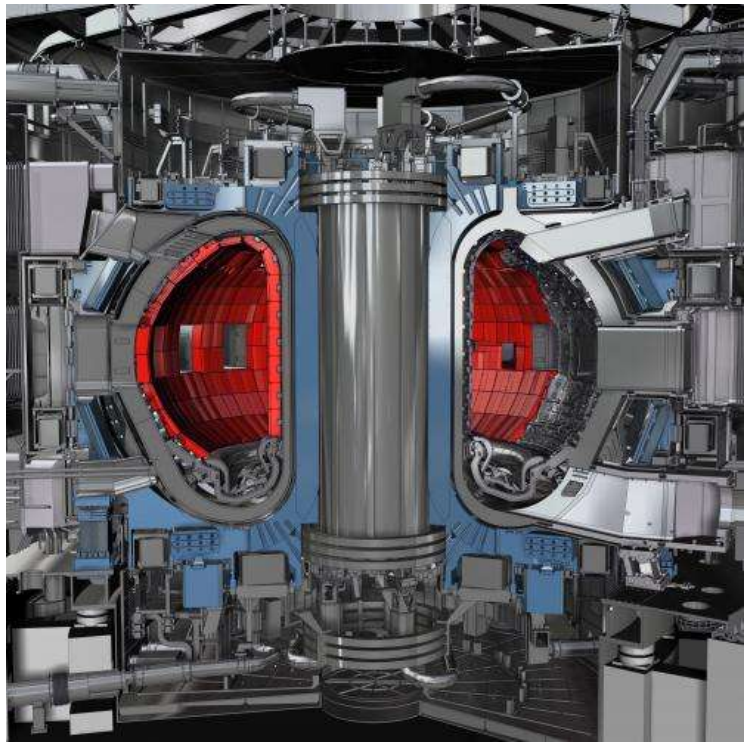
https://www.psfc.mit.edu/sparc



https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908

ITER

- Team:
  - EU,USA,Japan,South Korea
  - Russia, China, India
- Figures:
  - Fusion gain Q > 10
  - Q of min 5 for longer periods
- Mission:
  - prove that fusion reactions can produce significantly more energy than the energy supplied to initiate the reaction process

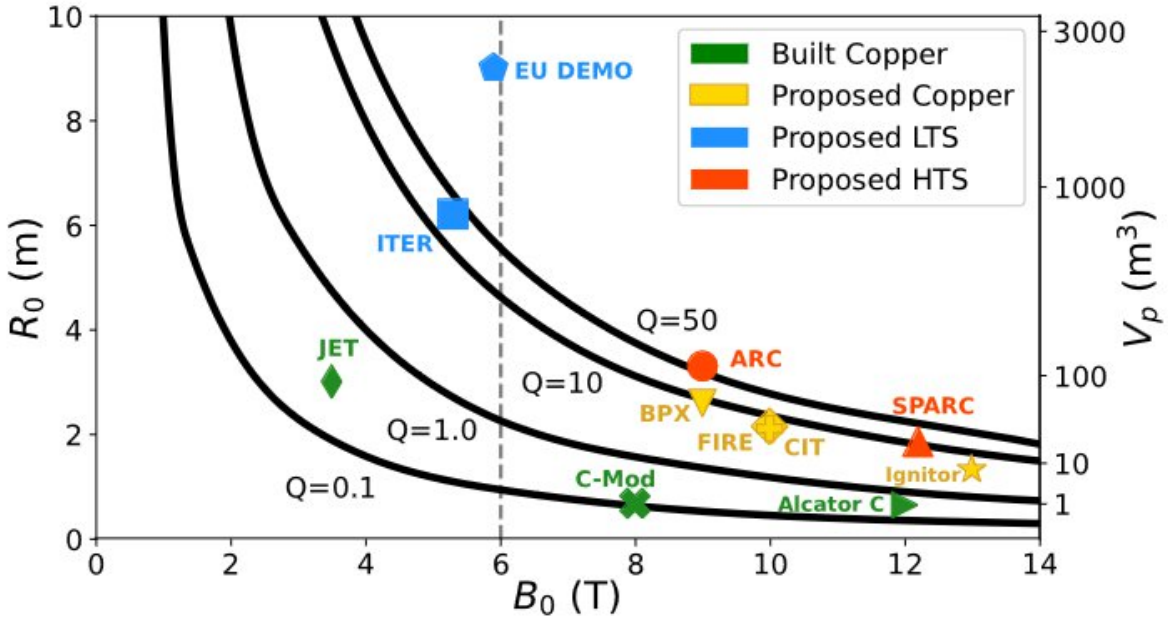


https://phys.org/news/2013-04-iter-blanket-technology.html

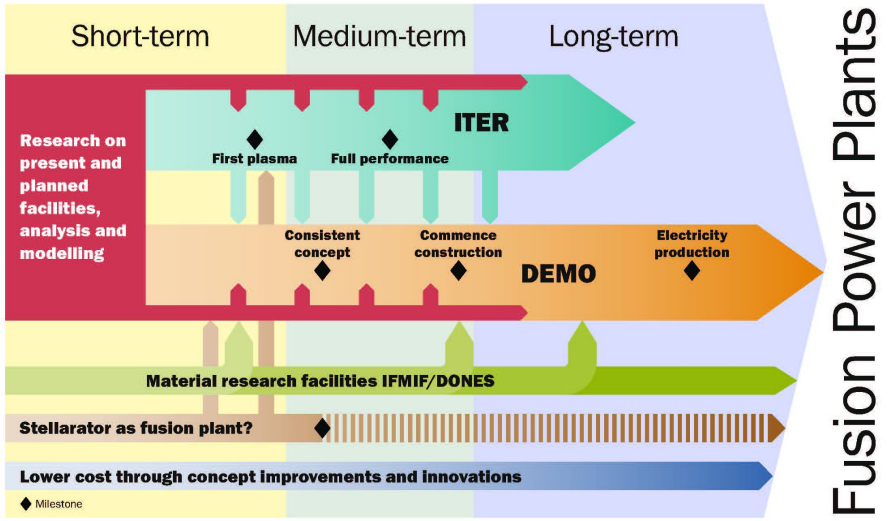
Gesamtradius (über alles):	15 Meter
Höhe (über alles):	30 Meter
Gewicht:	15000 Tonnen
Plasmaradius:	6,2 Meter
Plasmahöhe:	7,4 Meter
Plasmabreite:	4,0 Meter
Plasmavolumen:	837 Kubikmeter
Magnetfeld:	5,3 Tesla
Maximaler Plasmastrom:	15 Megaampere
Heizleistung und Stromtrieb:	73 Megawatt
Wandbelastung durch Neutronen:	0,57 Megawatt pro m^2
Fusionsleistung:	500 Megawatt
Brenndauer:	≥300 Sekunden

https://www.ipp.mpg.de/47279/6_ipp_tokamaks.pdf

Comparison



https://doi.org/10.1017/S0022377820001257 Published online by Cambridge University Press



https://euro-fusion.org/wp-content/uploads/2022/10/Roadmap-illustrated.jpg

Sources

- https://www.ipp.mpg.de/9778/tokamak
- https://link.springer.com/book/10.1007/978-3-662-55236-0
- https://pwl.home.ipp.mpg.de/tum/sig_skript_II.pdf
- https://www.ipp.mpg.de/47279/6_ipp_tokamaks.pdf
- https://www.ipp.mpg.de/44202/6_tokamak_theorie.pdf
- https://www.ipp.mpg.de/8602/jet
- https://fusionforenergy.europa.eu/news/jt-60sa-is-officially-the-most-powerful-tokamak/
- https://www.ipp.mpg.de/9031/demo
- https://library.psfc.mit.edu/catalog/reports/2010/15ja/15ja032/15ja032_full.pdf
- https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908