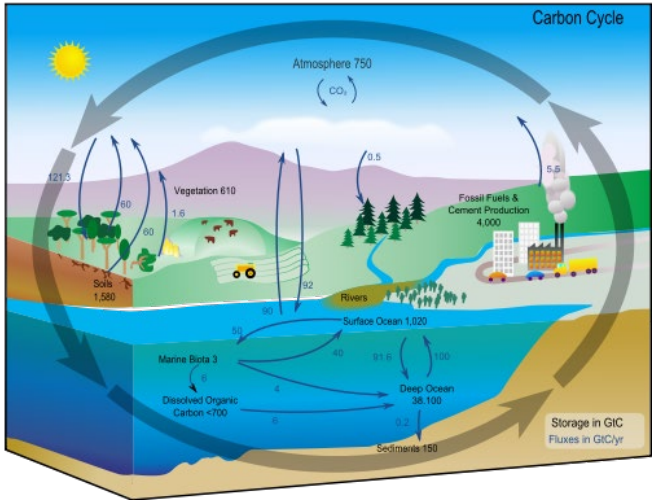
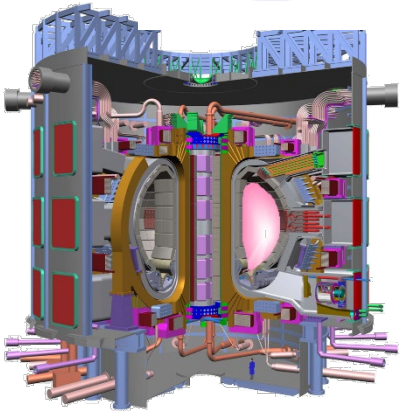
Fusion energy and its future

Aart W. Kleyn





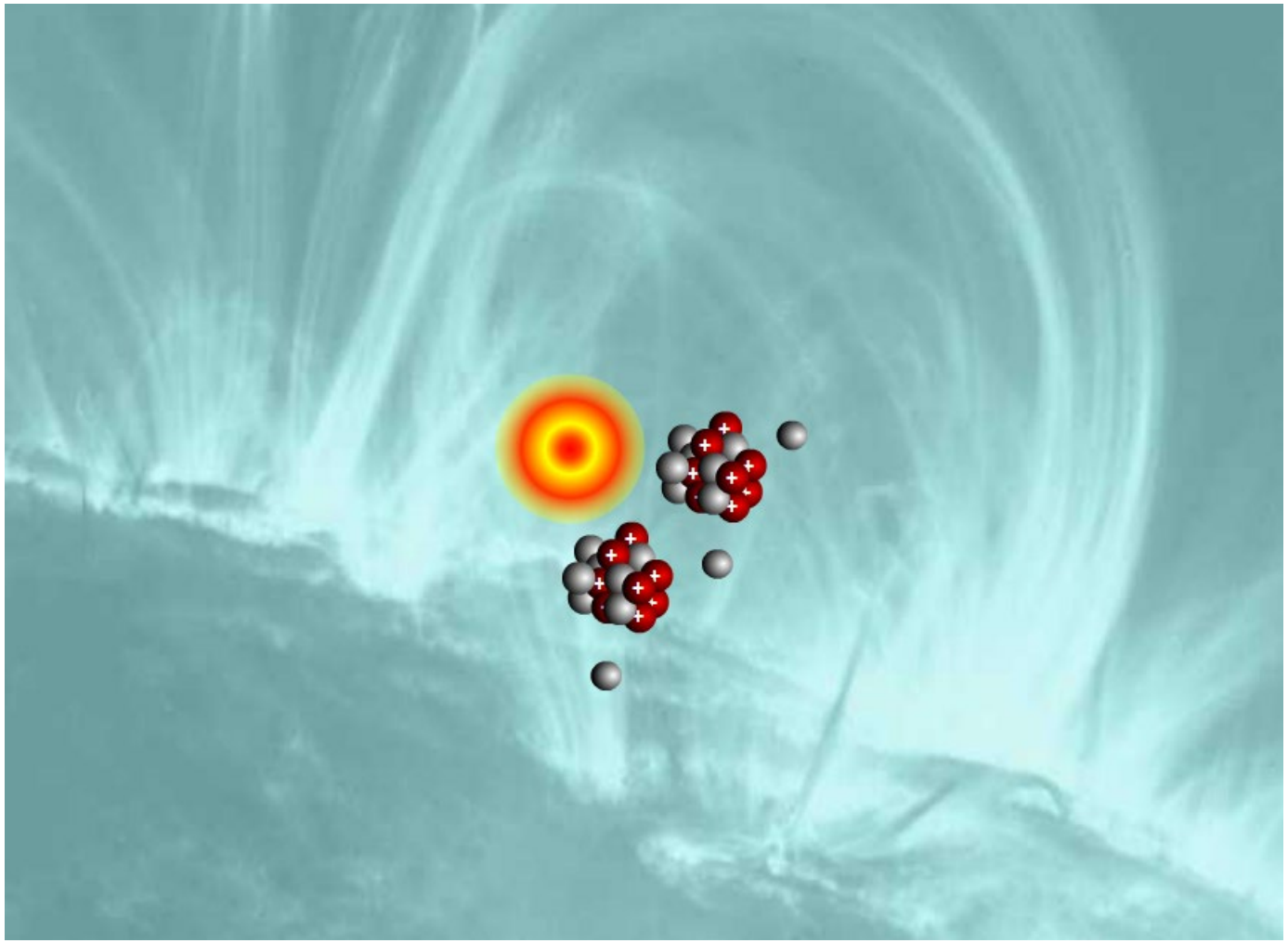
CIDS: Center of Interface Dynamics for Sustainability, Chengdu Sichuan, China
Leiden Institute of Chemistry, Leiden University, NL
Van 't Hoff Institute for Molecular Sciences, University of Amsterdam, NL a.w.kleijn@contact.uva.nl
Dutch Institute for Fundamental Energy Research (DIFFER), Eindhoven, The Netherlands



Energie conversie in electriciteit

- Kolen verbranden: vervuilend, fossiele CO_2 emissie
- Biomassa verbranden: vervuilend, hernieuwbare CO_2 emissie
- Aardgas verbranden: schoon, fossiele CO_2 emissie, efficient
- Waterkracht: verandert omgeving, geen CO_2 emissie, efficient, probleem met langdurige droogte
- Kernenergie, schoon, geen CO_2 emissie, publieke acceptatie, nucleair afval, proliferatie
- Wind molen: verandert omgeving, geen CO_2 emissie, efficient, probleem met windstilte
- Zonne-energie (PV): verandert omgeving, geen CO_2 emissie, efficient, probleem met duisternis
- Een goed opslag medium voor electriciteit is er niet
- Kernfusie, schoon, compact, geen CO_2 emissie, onbewezen technologie

Nuclear fission: n + $^{235}U \rightarrow 3n$ + fragments



No neutrons: no reaction, no heat
With neutrons: chain reaction (Corona R=3), need neutron stopper for control
Fragments formed: further decay producing waste and heat


Confined supply of oil and gas
CO_2 emission and climate change
Fusion Energy:
let's build a sun on earth

Nuclear fusion: the first 100 years

1920
Sir Arthur Edington proposes that stars release energy by fusing hydrogen into helium.

1934
Physicists at the University of Cambridge achieve human-caused nuclear fusion for the first time by bombarding heavy hydrogen with deuterons, discovering tritium and helium-3 in the process.

1950
Andrei Sakharov and Igor Tamm propose the tokamak, a device using magnets to contain plasma.

1960
Computer calculations indicate that inertial confinement fusion is a practical possibility. The world's first laser — built this same year — looks like it could be the right tool to implement the idea.

1958
First controlled thermonuclear fusion achieved with the Scylla I pinch device at Los Alamos National Laboratory in the US.

1958
The first tokamak begins operation at the Kurchatov Institute in Moscow.

1974
A private company, KMS Fusion, achieves the world's first laser-induced fusion.

1975
The Princeton Large Torus tokamak sets temperature records above what is needed for commercially viable fusion.

1982
Researchers in Germany discover that heating plasma above a certain threshold doubles the time it can be confined. Reaching this high-confinement threshold becomes the basis for most future tokamak operations.

2021
JET nearly triples its 1997 record, producing 59 MJ of energy over five seconds.

1997
JET produces 21.7 megajoules (MJ) of energy from a fusion reaction, a world record that will hold until 2021.

1983
The Joint European Torus (JET) begins operation at the Culham Centre for Fusion Energy in Oxfordshire as the largest magnetic confinement plasma experiment.

2022
Lawrence Livermore National Laboratory, using IFC laser technology, produces more energy from fusion than the energy delivered by the laser producing it.

OUR INDUSTRIAL LIFE

the fuel for fusion

sufficient for the yearly electricity consumption of a family

75 mg Deuterium

225 mg Lithium

to be found in

2 liter water and

250 g earth/stone

energy content:

48 000 million Joule

corresponding

1 000 liter oil





Waste from fusion power plants

Fusion does not produce greenhouse gases

The only gas produced by the fusion process itself is helium. This is a harmless and inert gas already present in the earth's atmosphere. A 1000 MW fusion power plant would only produce about 250 kilograms of helium each year, whereas a comparable coal-fired power plant produces about seven million tons of carbon dioxide every year. The operation of a fusion power plant does not produce greenhouse gasses.

China opens one of those every week!!

Waste from a 1000 MW power plant per year

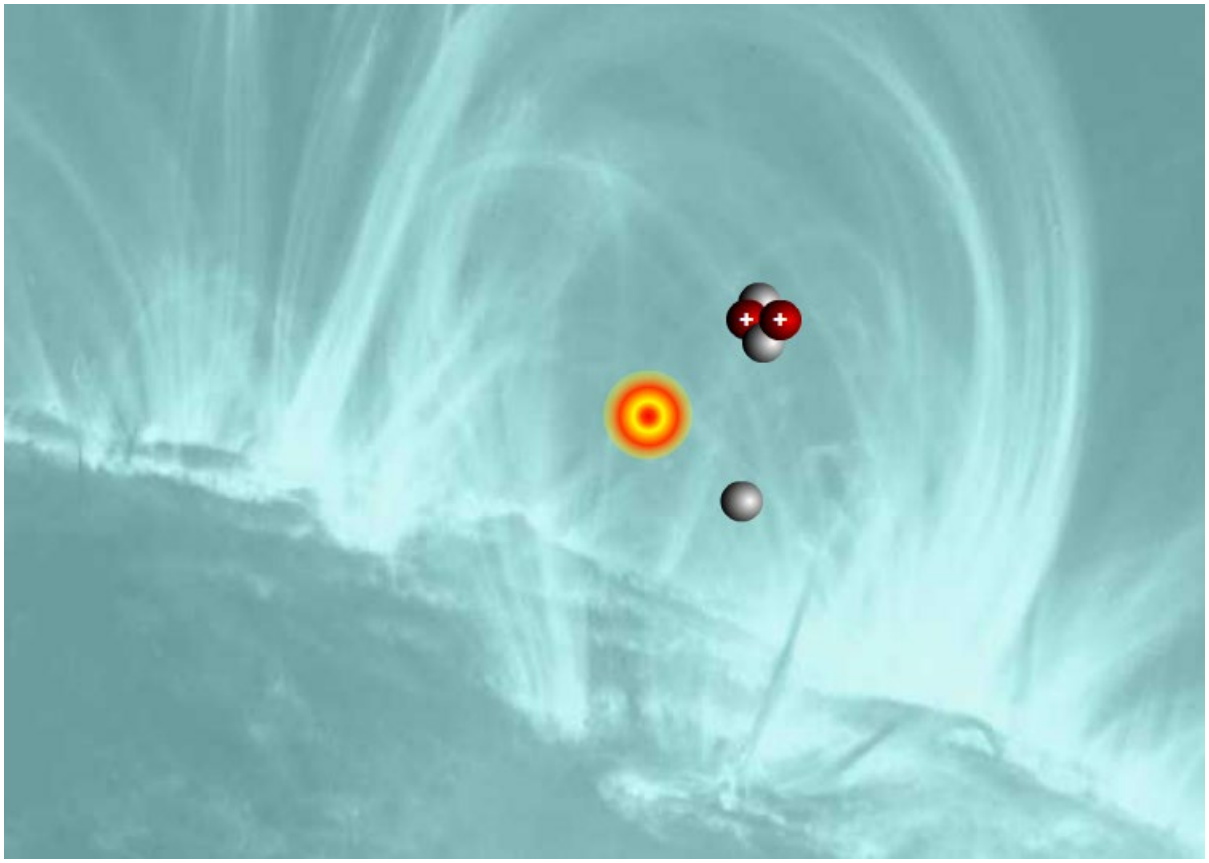
Coal	7.200.000 tons CO_2 5.800 tons SO_2
Gas	3.600.000 tons CO_2
Fission	32 tons of spent fuel
Fusion	250 kilograms of helium

This cd-rom was partly financed by the European Commission

EFDA • European Fusion Development Agreement

email • info@efda.org

Nuclear fusion: $^2D + ^3T \rightarrow n + ^4He$



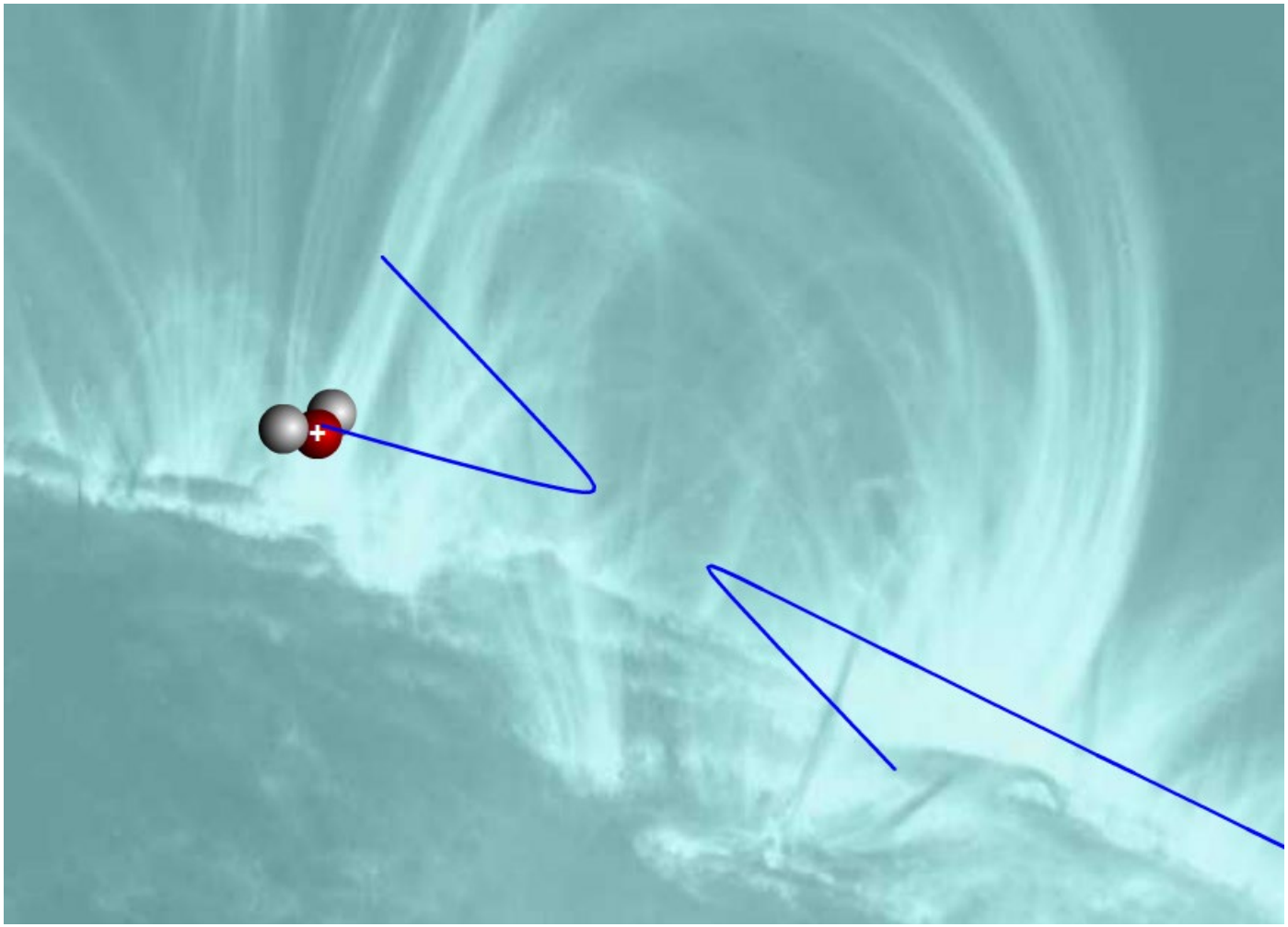
No chain reaction: no runaway danger

Total reaction: $^2D + ^6Li \rightarrow 2\ ^4He + 22.4$ MeV.

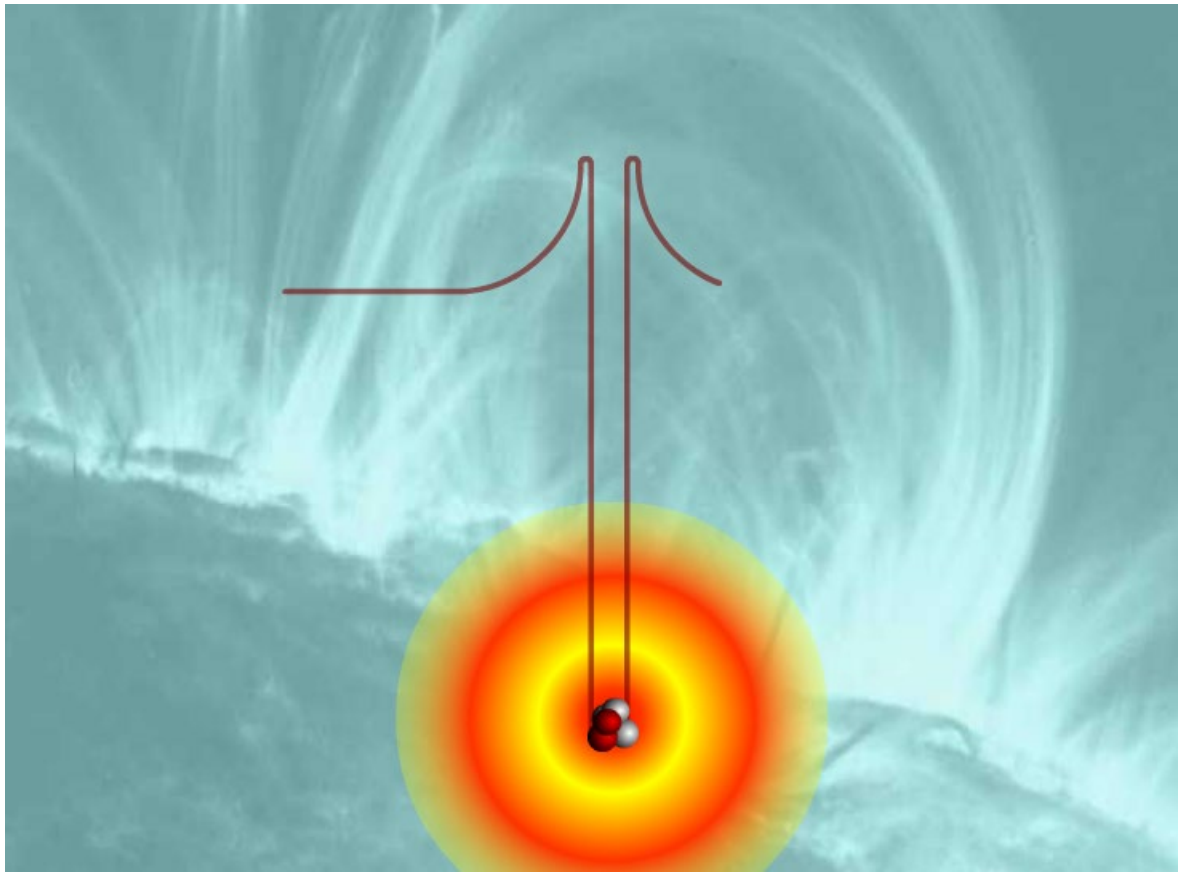
Compare: $2\ CO + O_2 \rightarrow 2\ CO_2 + 10$ eV

Why don't we have it ???

Coulomb repulsion between the reacting ions

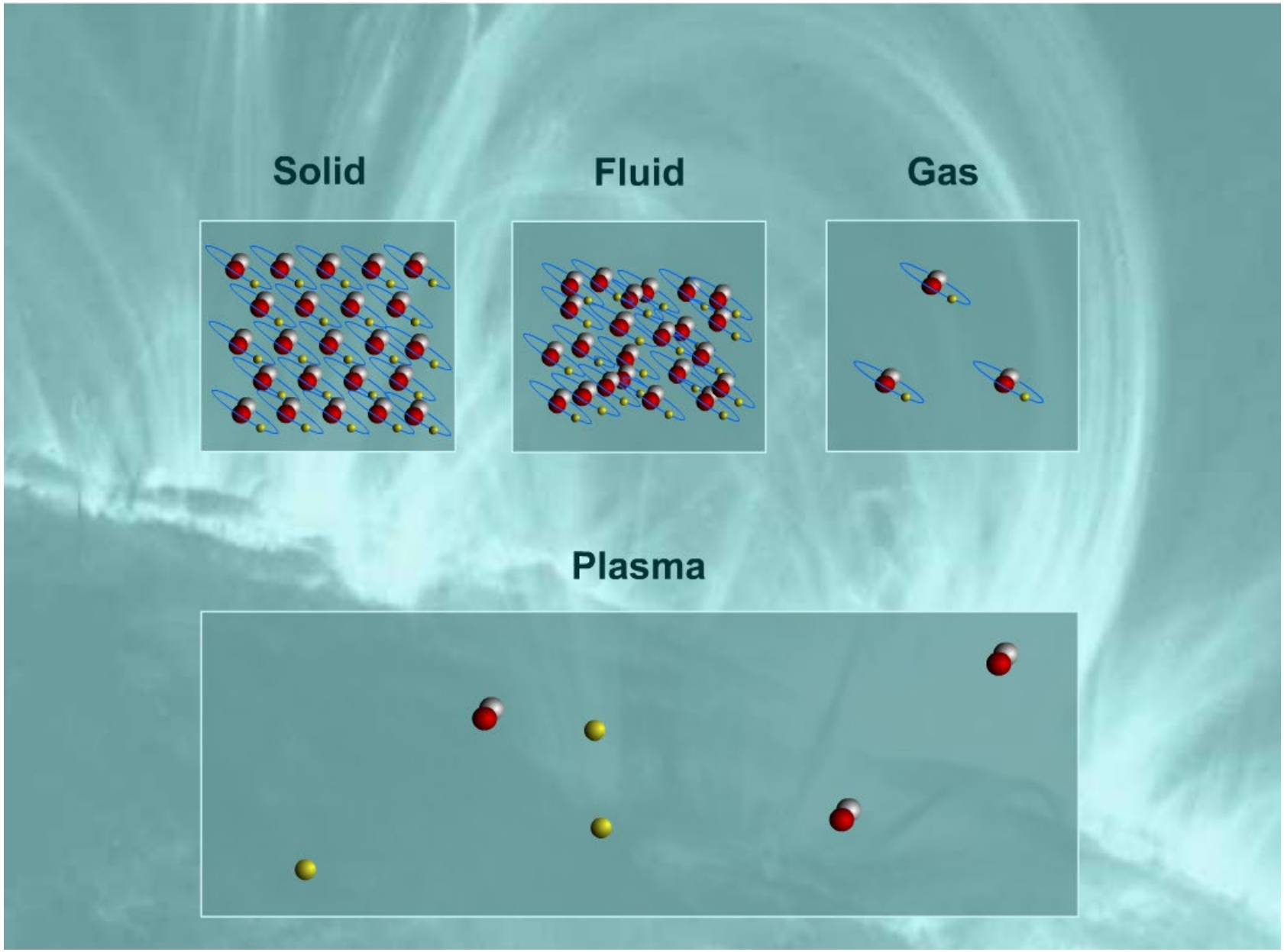


Coulomb barrier and nuclear attraction

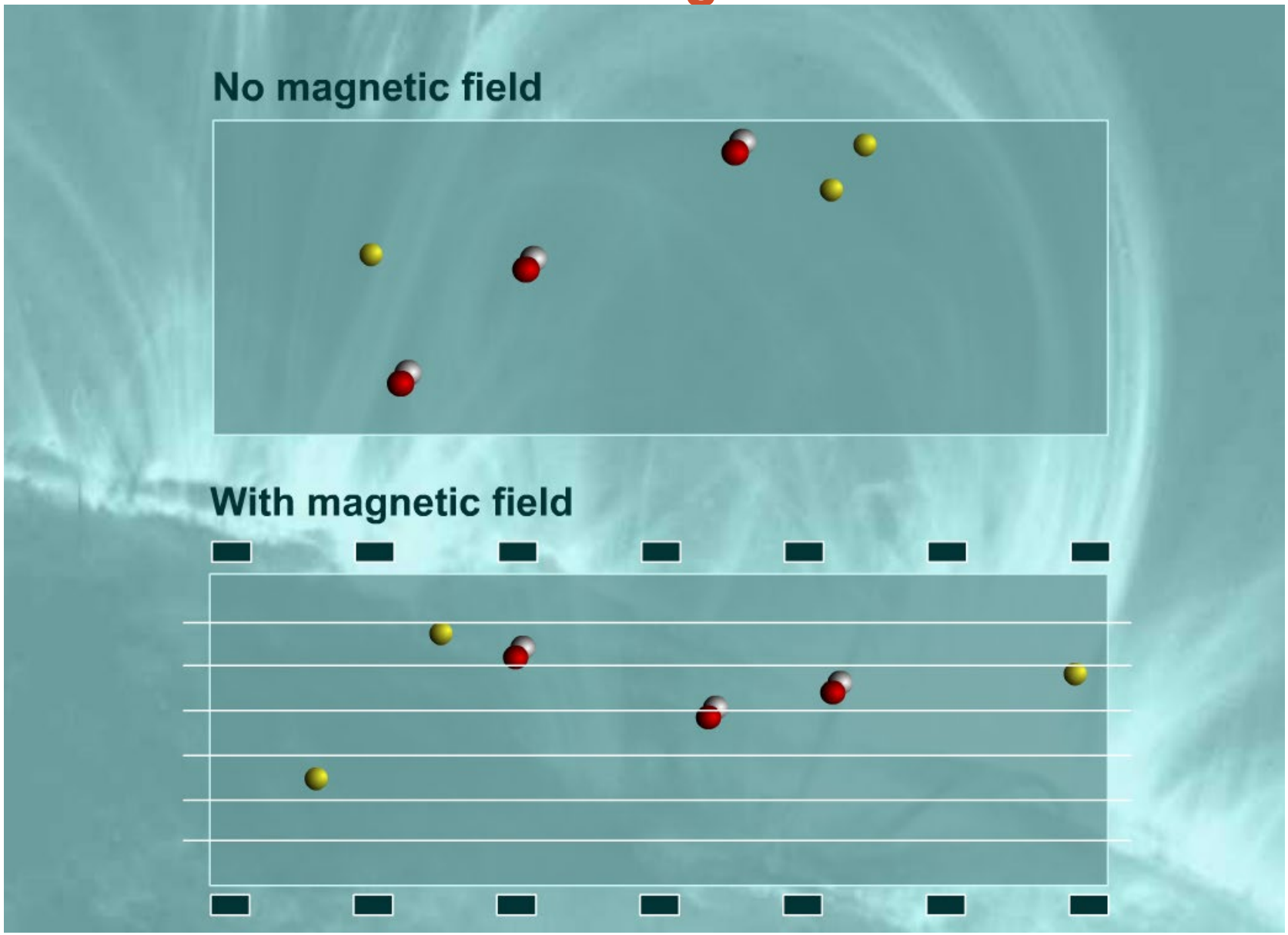


Overcoming the barrier requires 20.000 eV (> 200 000 000 ^{o}K)

States of matter

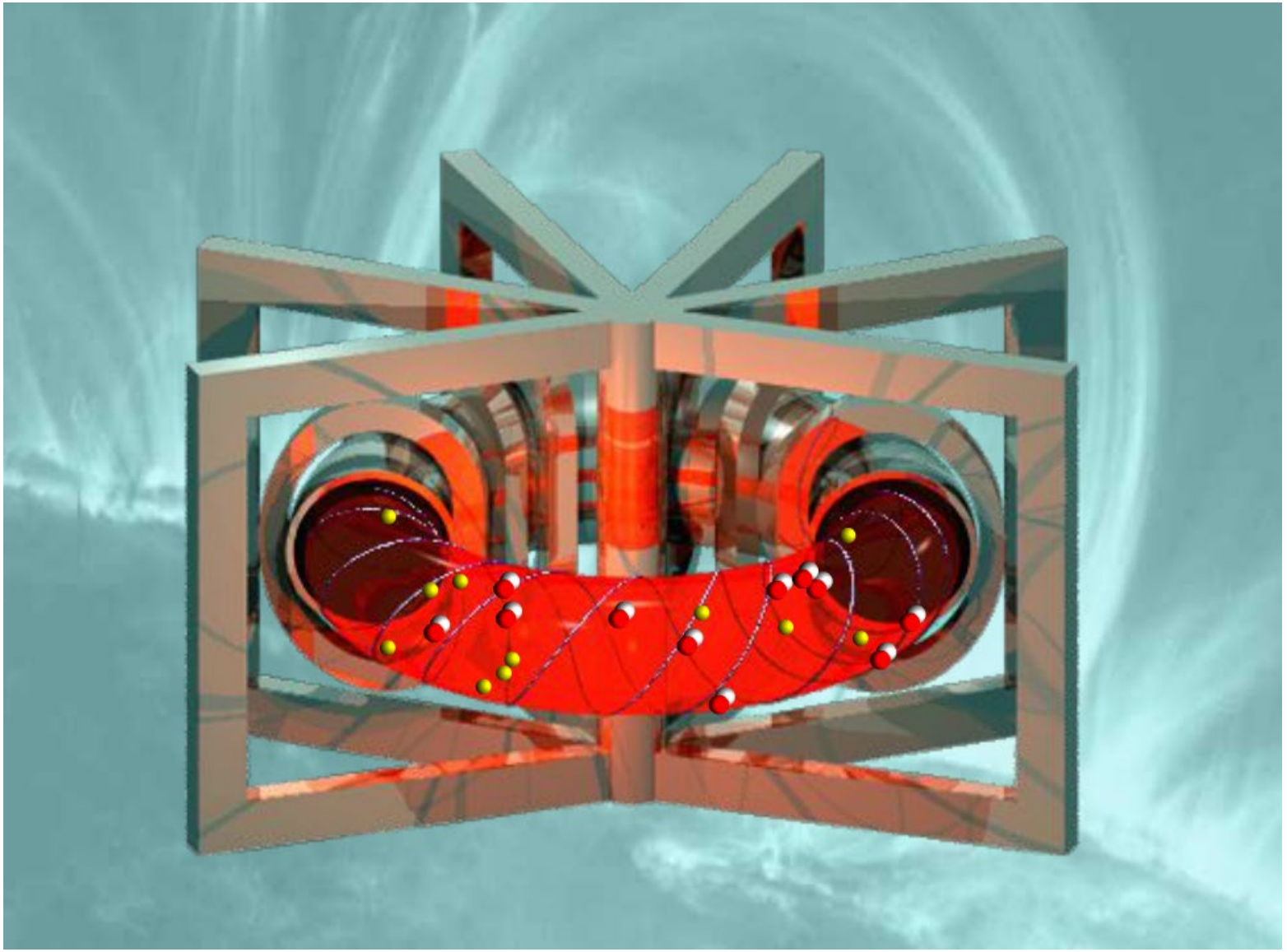


Plasma confinement in a magnetic field allows boundless heating



The sun on earth: the Tokamak

In de ban van de ring



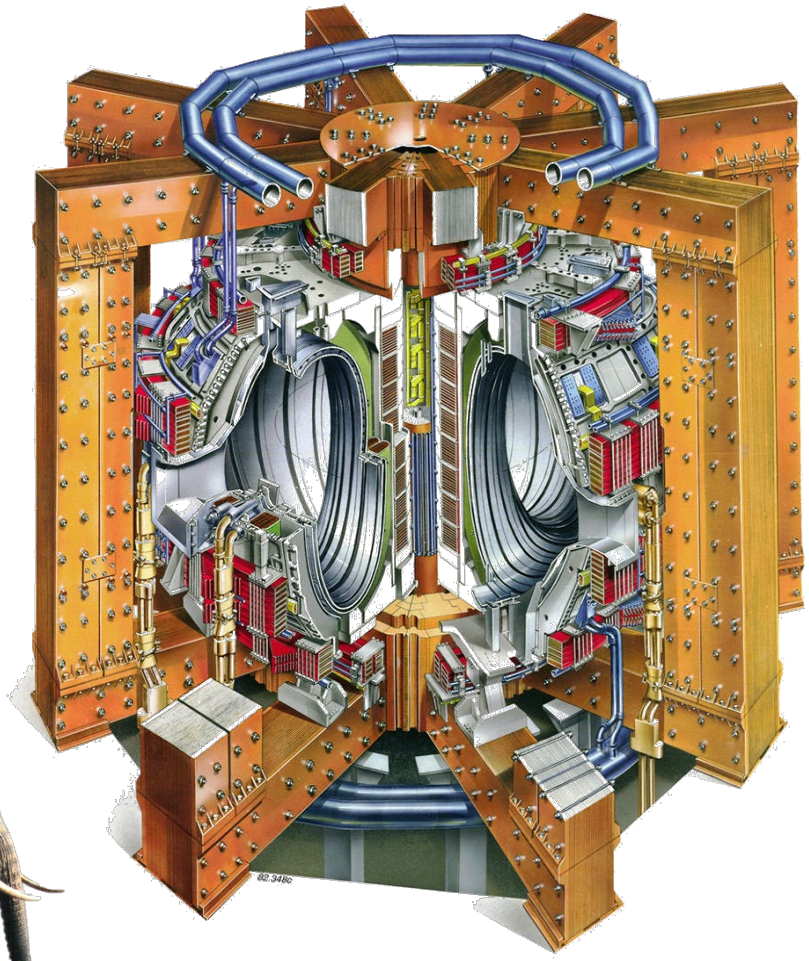
Progress in Fusion:

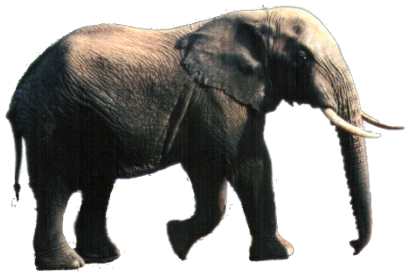
JET

16MWth output,
25MW input

energy multiplication
0.6x

Realized in 1991, on schedule





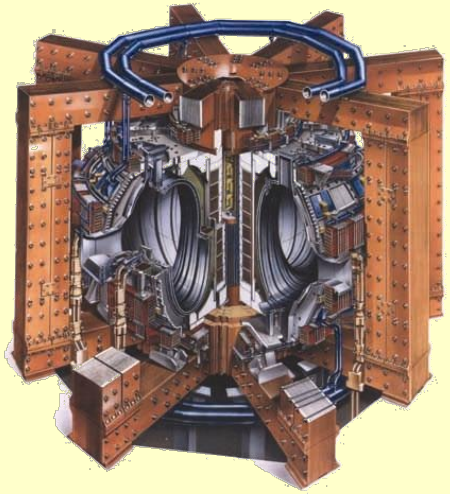

DE PRETTO-ESCHER WYSS
ITALIA
VISITOR
VISITOR
VISITOR
UKAEA

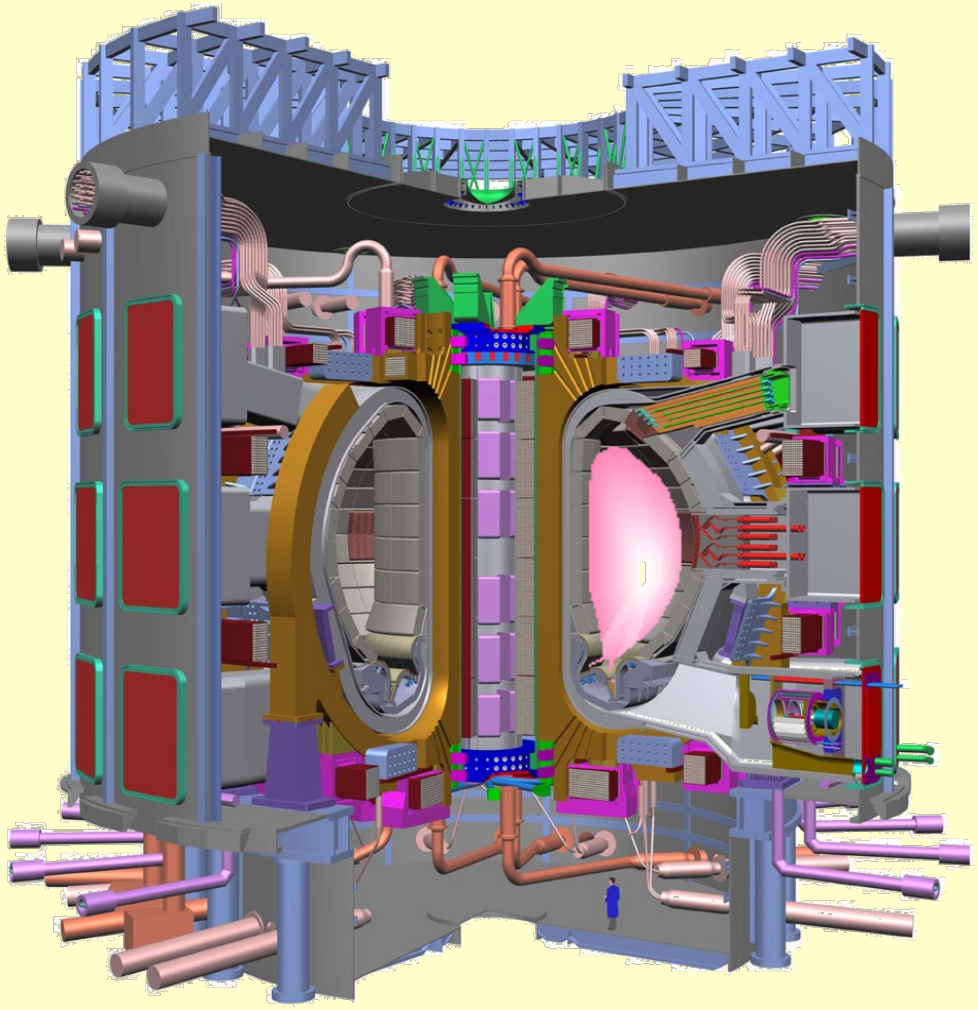
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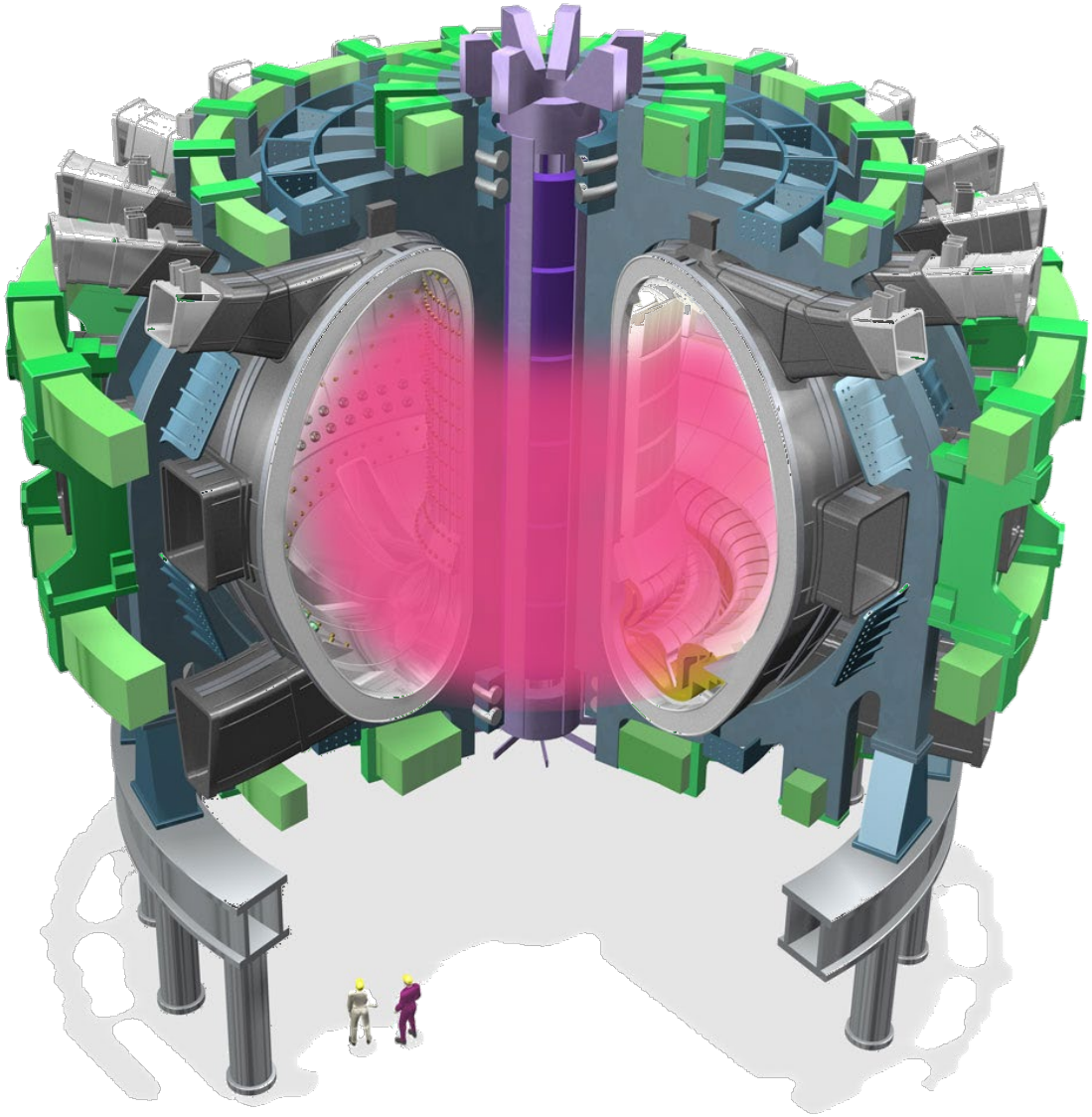
ITER

JET



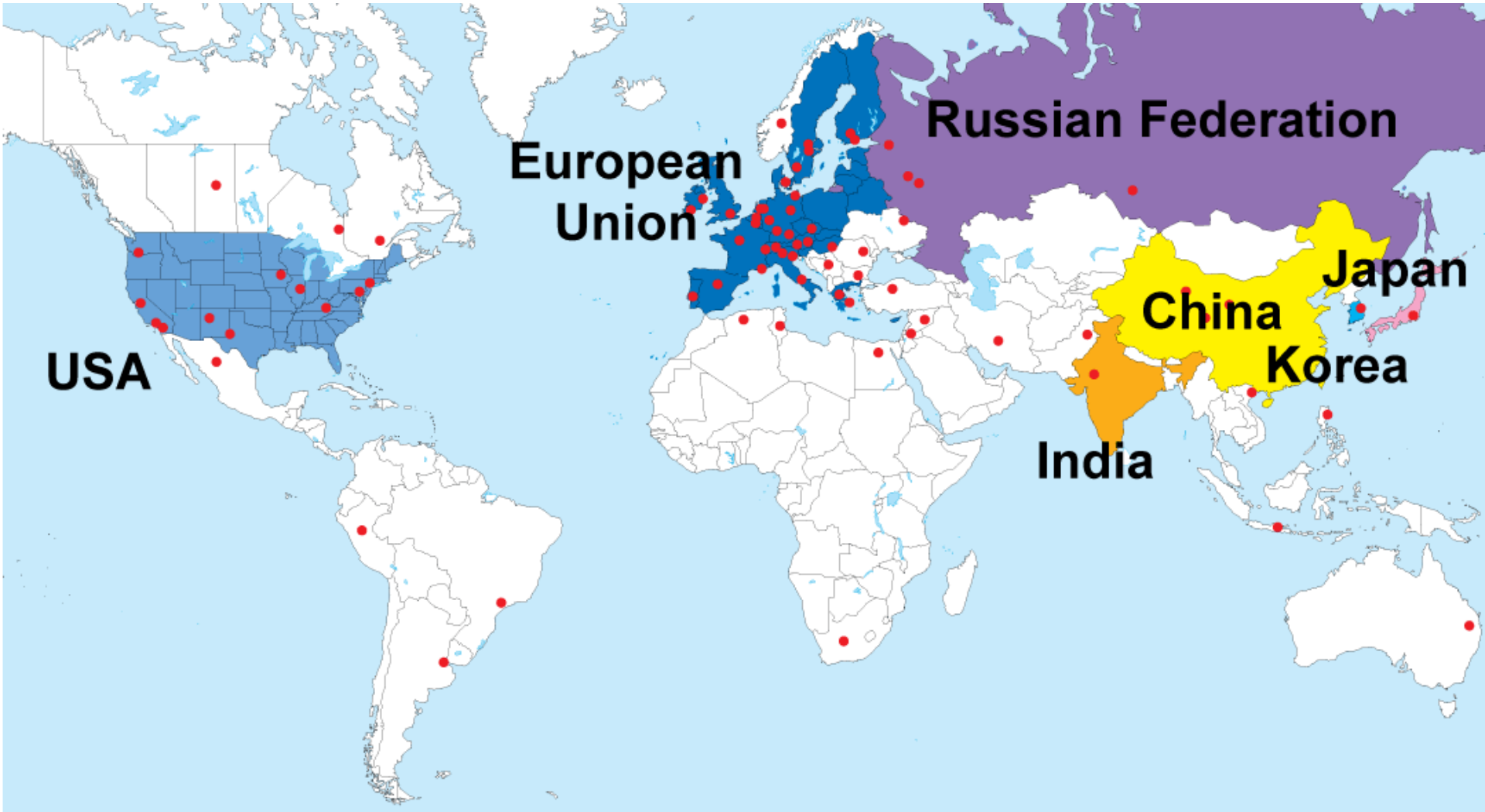


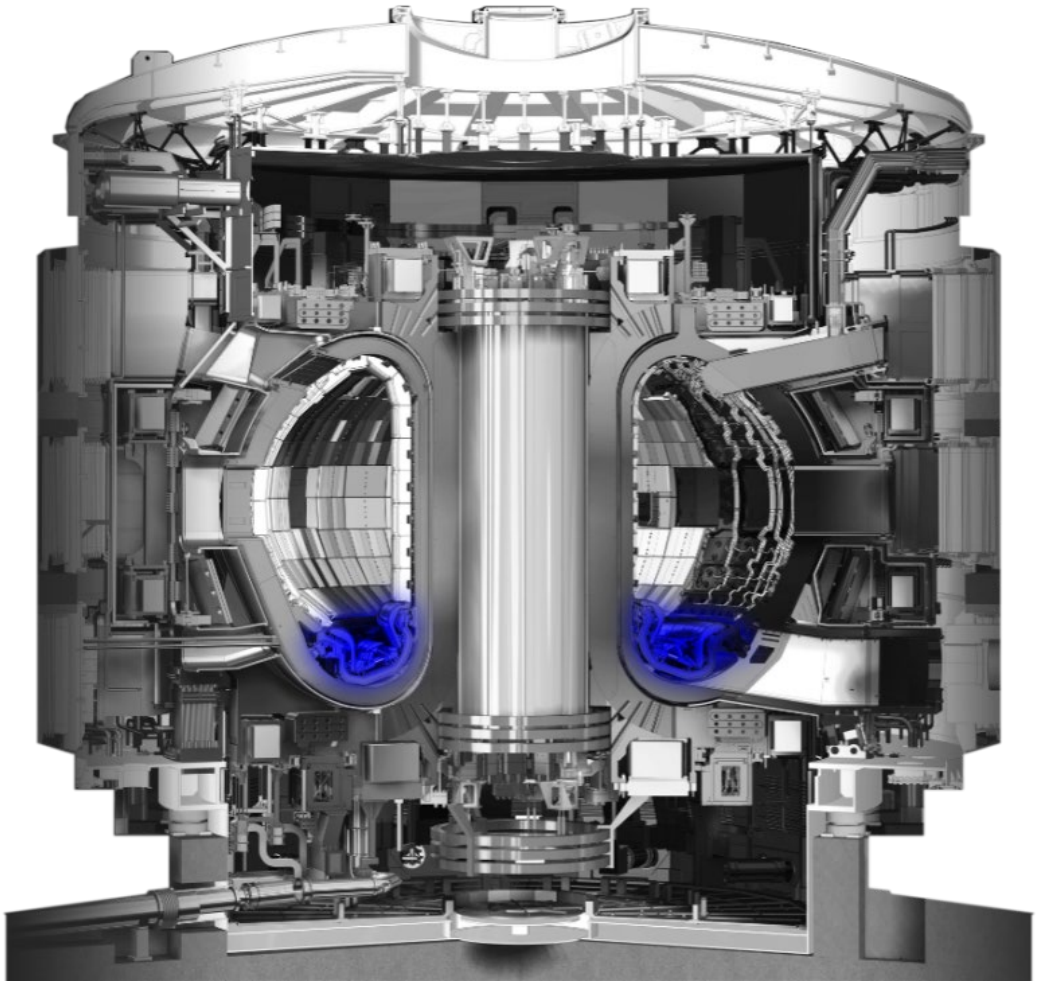
ITER



ITER is an international collaboration

www.ITER.org





ITER: extremely complex, behind schedule, very expensive

ITER: facts and pictures www.iter.org



Central magnet sustains twice the thrust of space shuttle launch



Weight 4 times the Eiffel tower







Fusie is klaar als het echt nodig is (Russische aartsvader)



ITER by Cadarache, bij Aix-en-Provence (ITER.org)

Alternatives for ITER:

Problems of ITER are the size, the huge magnets and the international dimenson

A number of private fusion startups have also sprung up in the last couple years. Reducing the size is a joint denominator.

The Fusion Industry Association estimates that private fusion firms have raised $7.1 billion in total investment as of July 2024, with nearly a billion of that coming in over the last year.[4]

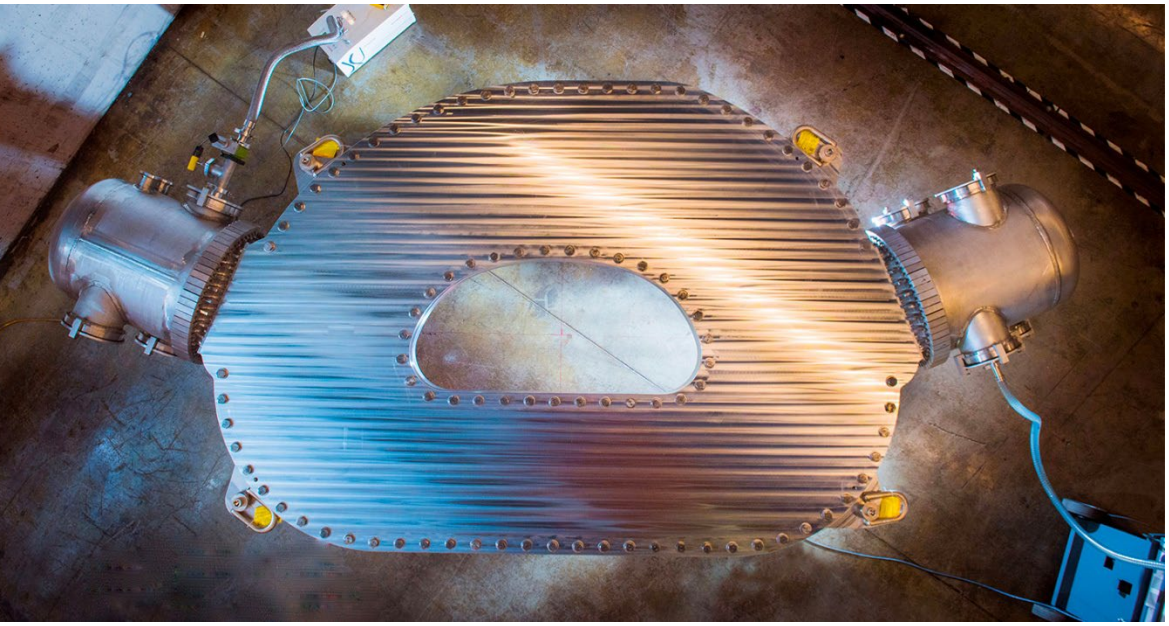
- Commonwealth Fusion Systems, which came out of MIT, has raised more funding than any other start-up: $2 billion since its founding in 2018. It has developed the world's most powerful high-temperature superconducting magnets, which it will use to build a tokamak named SPARC.[5] It recently announced plans to build the world's first grid-scale commercial fusion power plant in Virginia.[6]
- Pacific Fusion is using a novel technology called "pulsed magnetic fusion," which uses magnetic pulses instead of lasers to inertially contain plasma.

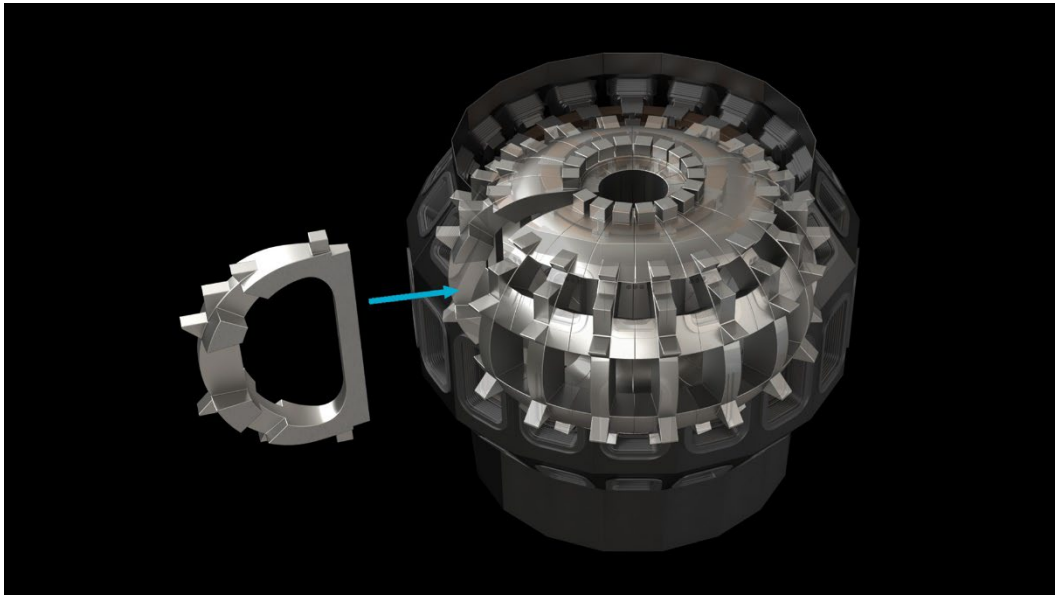
- A number of other startups are reviving older fusion technologies. Zap Energy is building a pinch device, Type One Energy and Thea Energy are building stellarators, and Realta Fusion is building magnetic mirror devices. The ENN Group, one of China's largest private companies, is working on tokamak variations called "compact toroid" magnetic confinement devices.
- Several companies are developing innovative new twists on traditional fusion devices. OpenStar is creating a reverse tokamak: instead of surrounding plasma with magnets, it levitates a magnet within the plasma itself. Helion uses a unique combination of magnetic confinement and IFC to generate electricity directly from helium fusion. General Fusion plans to use magnets to contain plasma while it compresses it with steam-driven pistons.

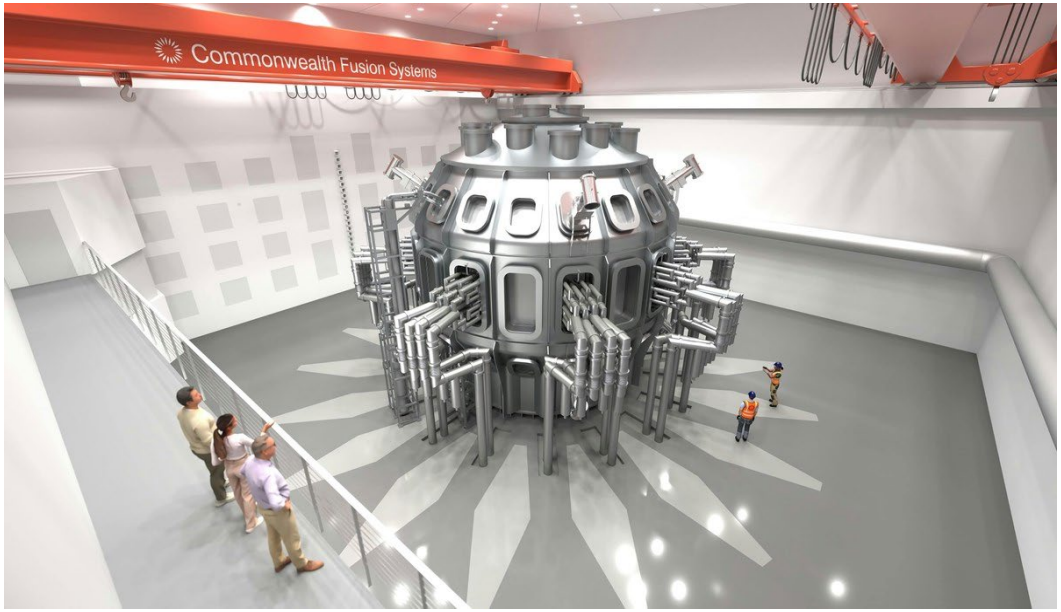
Despite the optimism of these fusion start-ups that they will start producing fusion in the 2030s, the considered consensus of energy scientists seems to be that technological advancements have made fusion much more likely, but that it won't be ready for widespread power generation until at least after 2050 or 2060.[7]

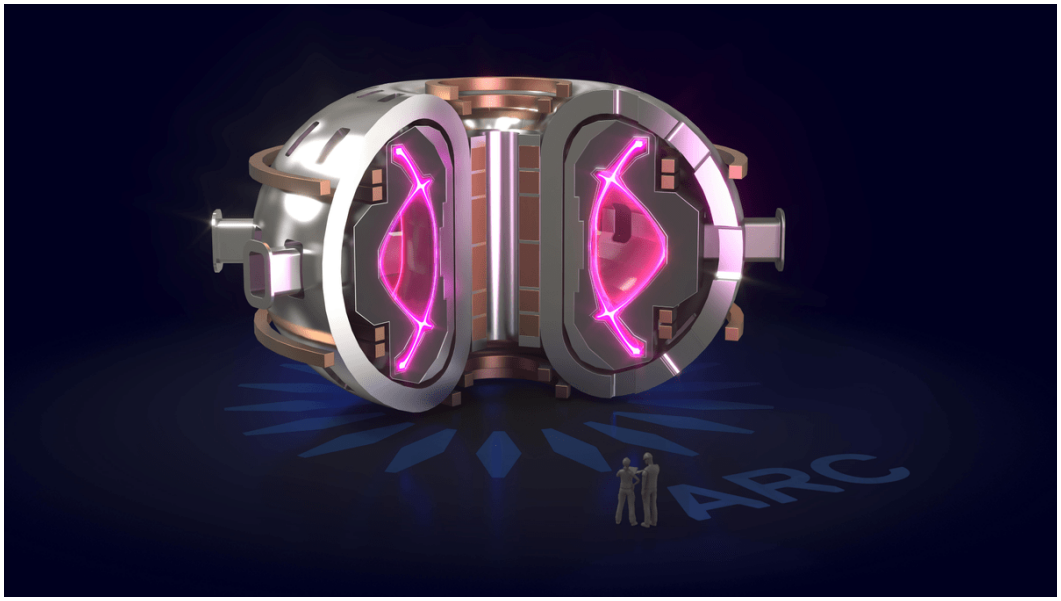
OpenStar CEO Ratu Mataira remains clear-eyed but optimistic, telling CNN, "Not all of the fusion companies will be successful. OpenStar might be one of those, but we as a society will learn faster."

CFS: High TC superconductors in fusion









Alternatives for ITER: CFS systems

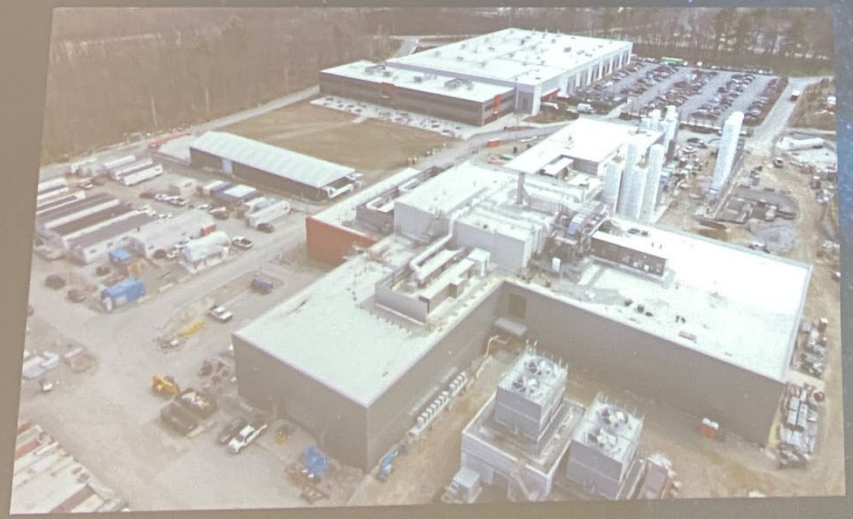
SPARC

ARC

Commonwealth Fusion Systems

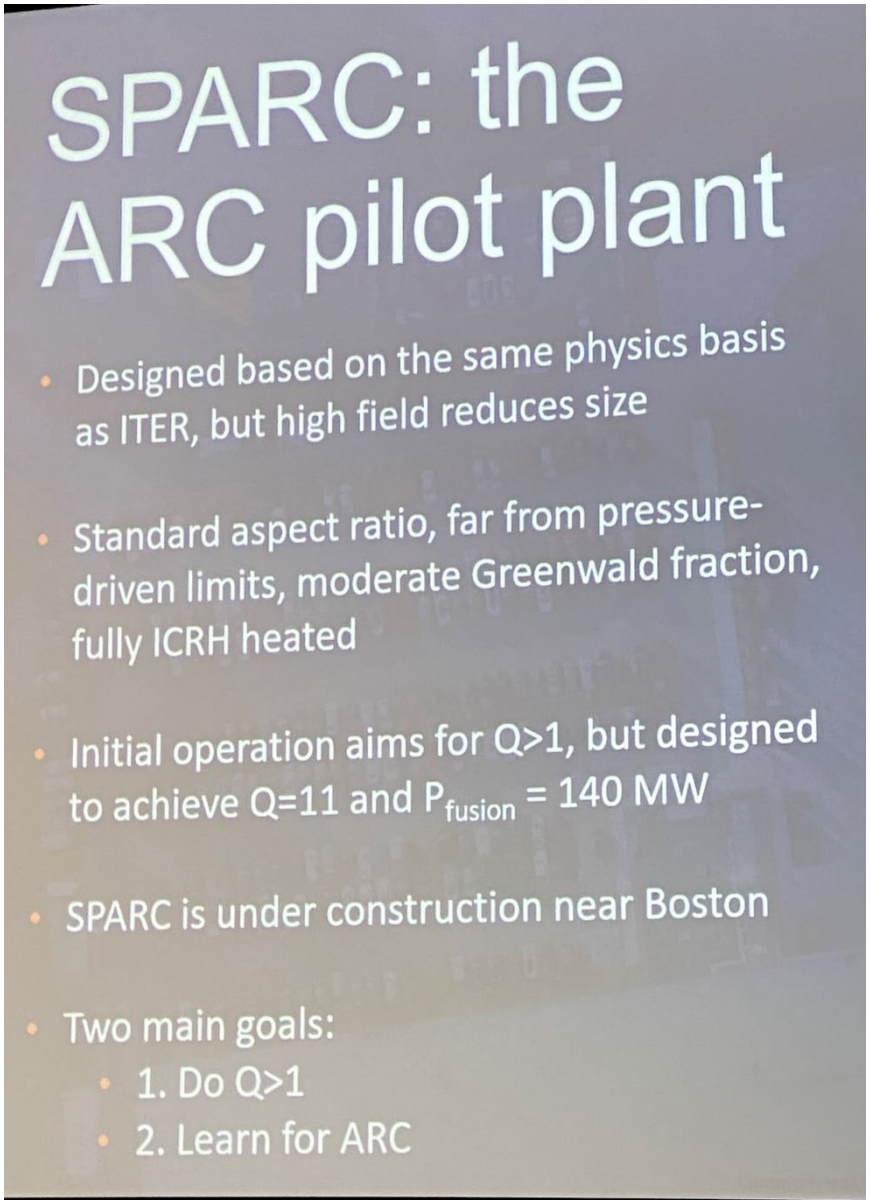
CFS is on a path to deliver commercial fusion energy

- CFS was founded in 2018, spun out of MIT with the goal of commercializing fusion energy to combat climate change
- CFS has raised more than $2 billion from venture capital investors
- There are now more than 1000 employees in the diverse, high caliber team
- We work with university, national lab, and other partners around the world





The target for SPARC



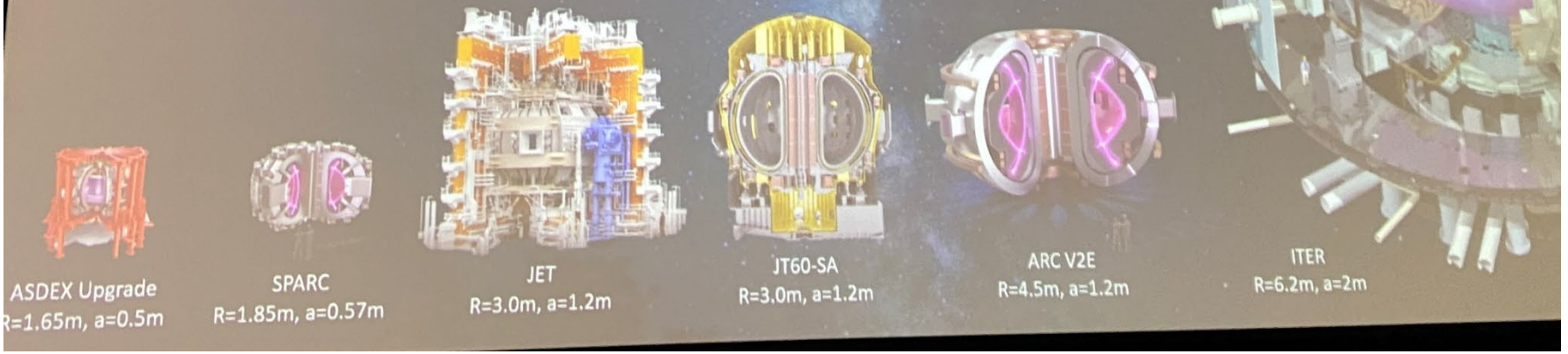
The target for a commercial power plant



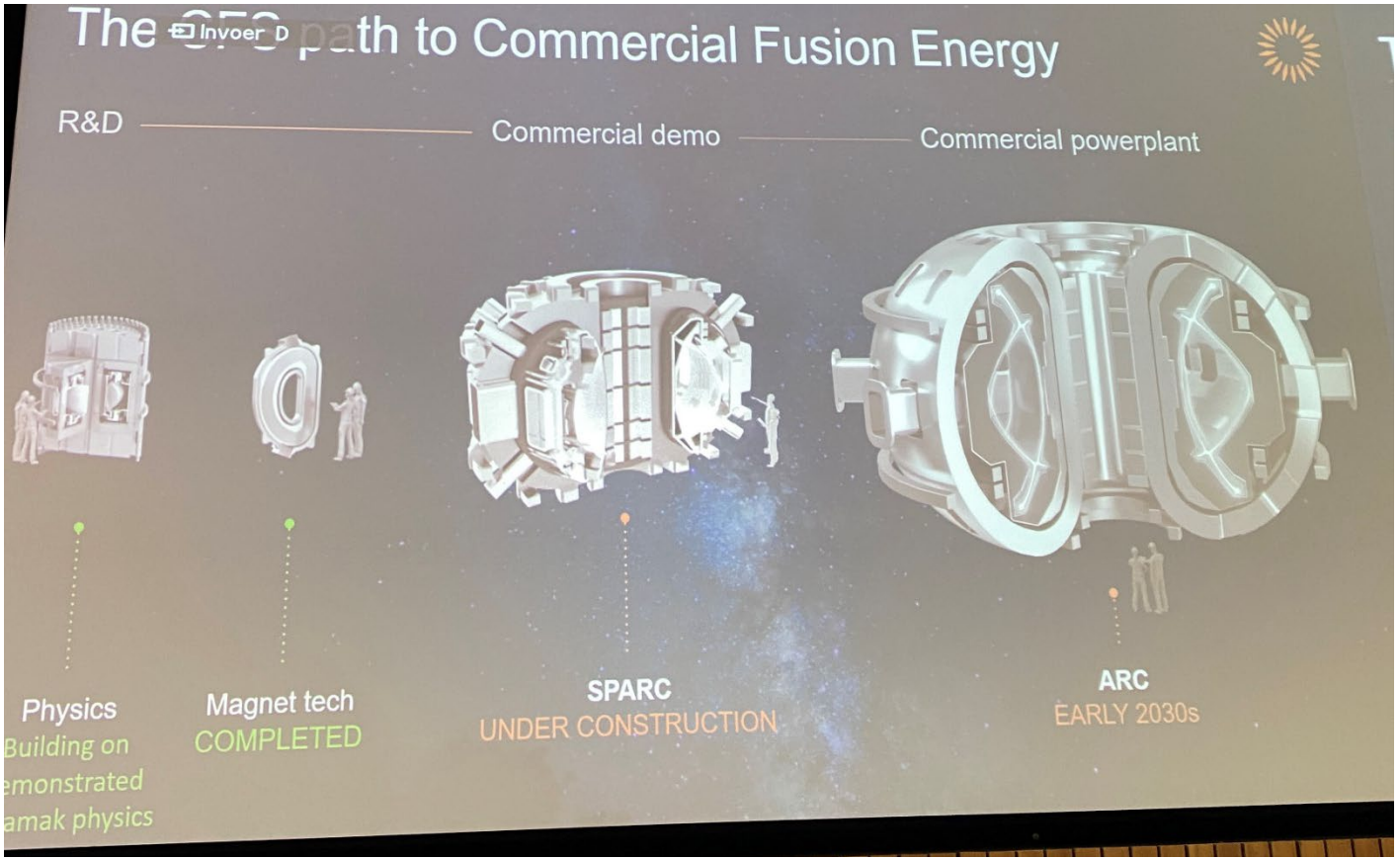
The spectrum of tokamaks

ARC V2E in the context of other tokamaks

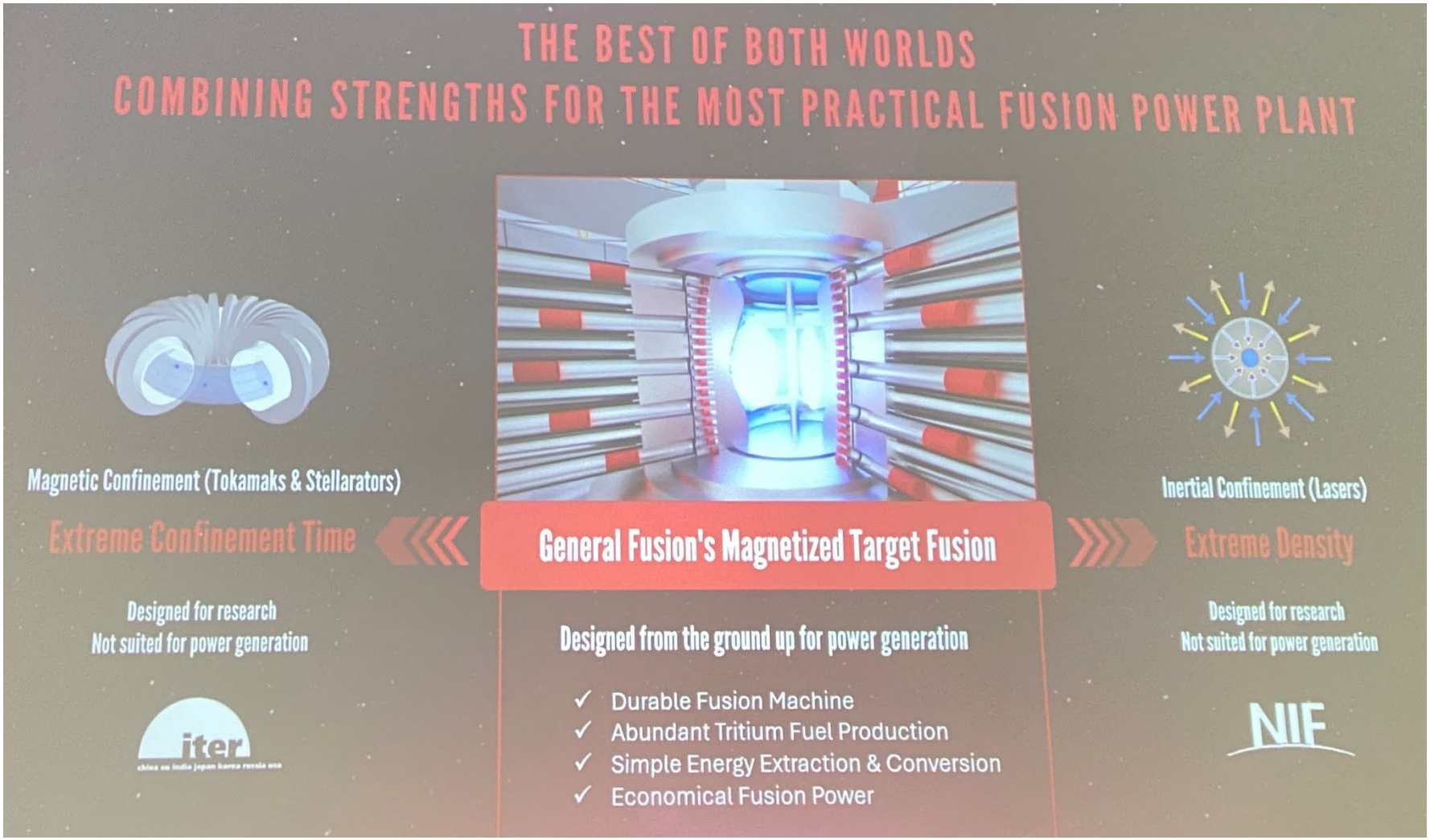
- With a major radius of 4.5m, the current iteration of ARC is roughly 2.5 times larger than SPARC in linear size (1.85m) and is slightly larger than the existing JET and JT60-SA tokamaks
- Due to different aspect ratios, the plasma cross sections in ARC and JT60-SA are very similar, with a minor radius of ~1.2m and an edge elongation of ~1.8
- ARC remains much smaller than ITER, which has a major radius of 6.2m and more than 4x the plasma volume of ARC



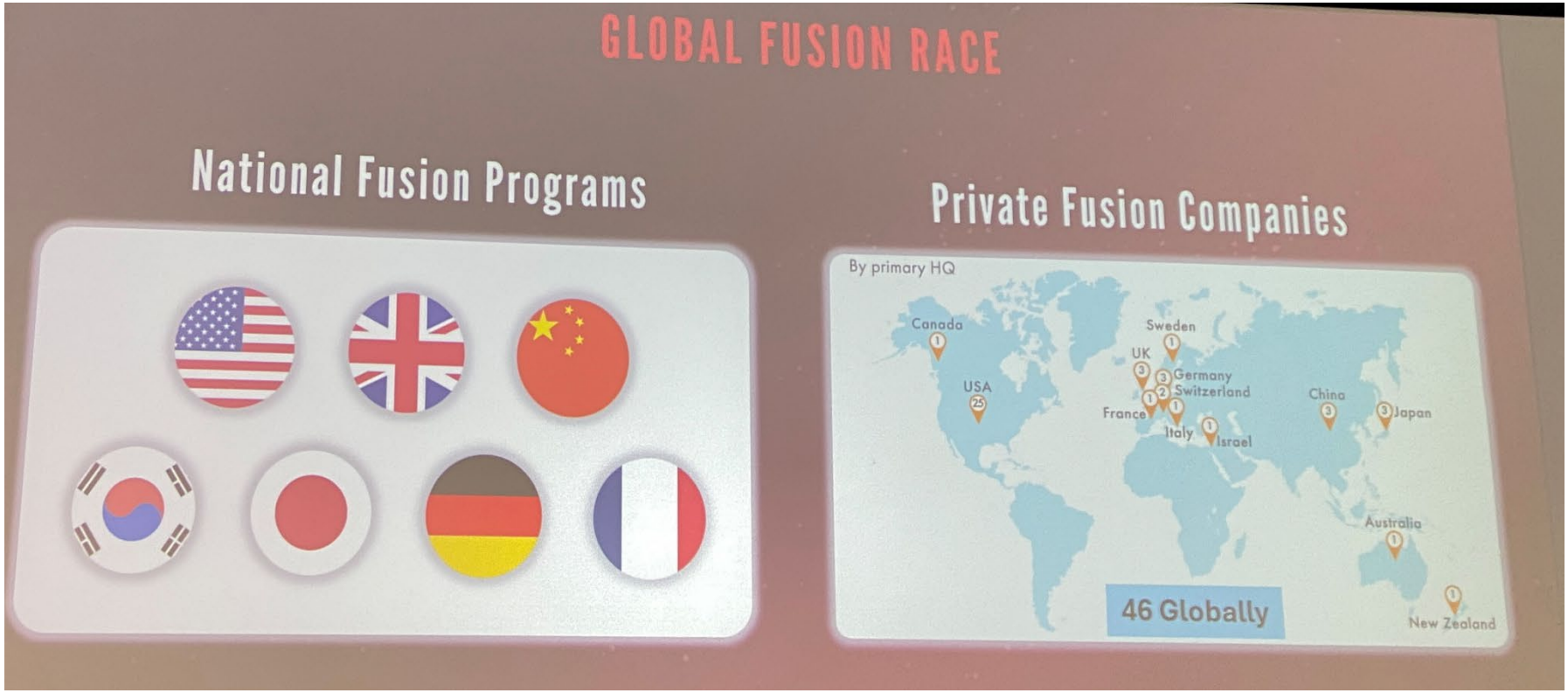
The CFS roadmap



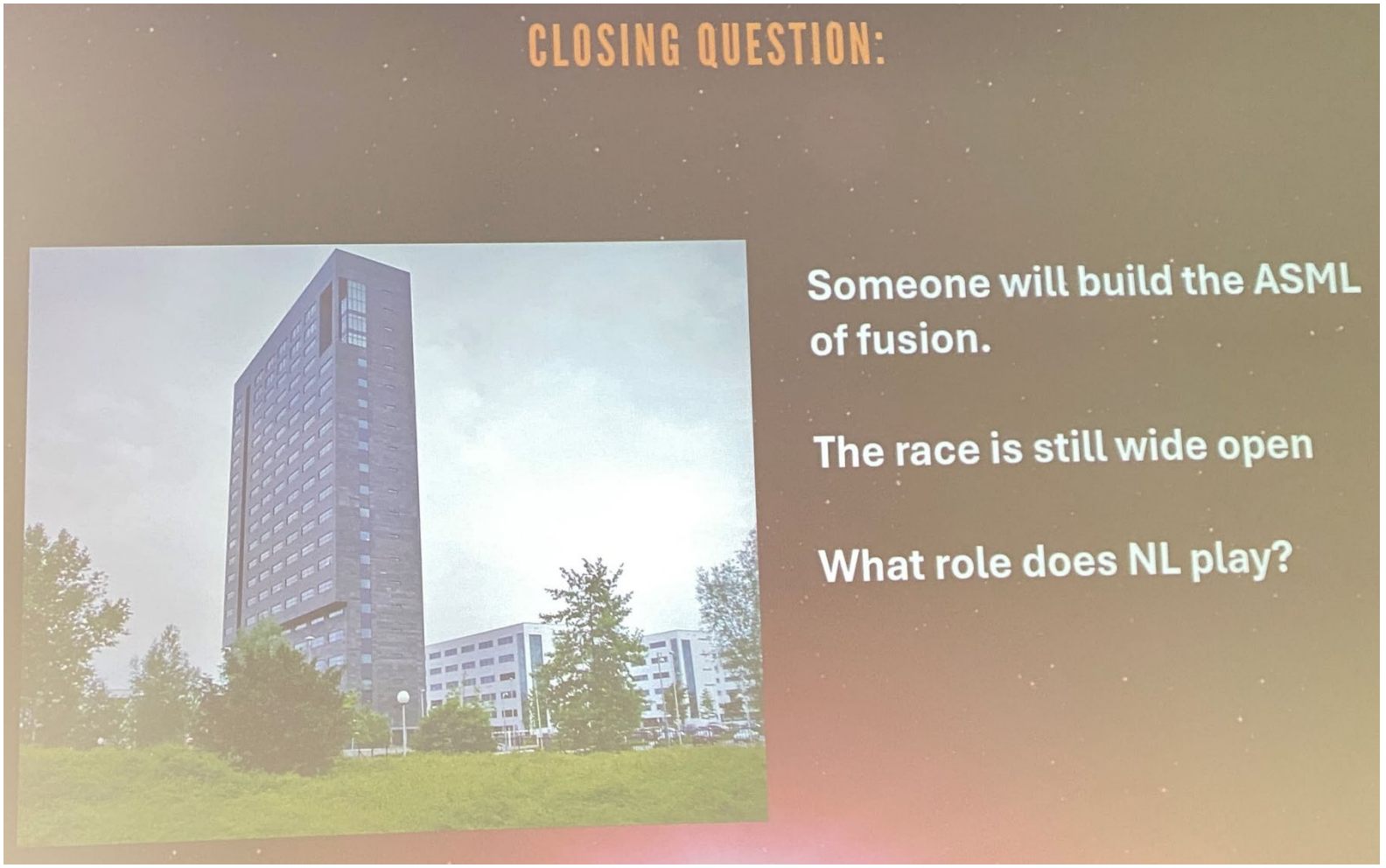
Canadian alternative for tokamaks



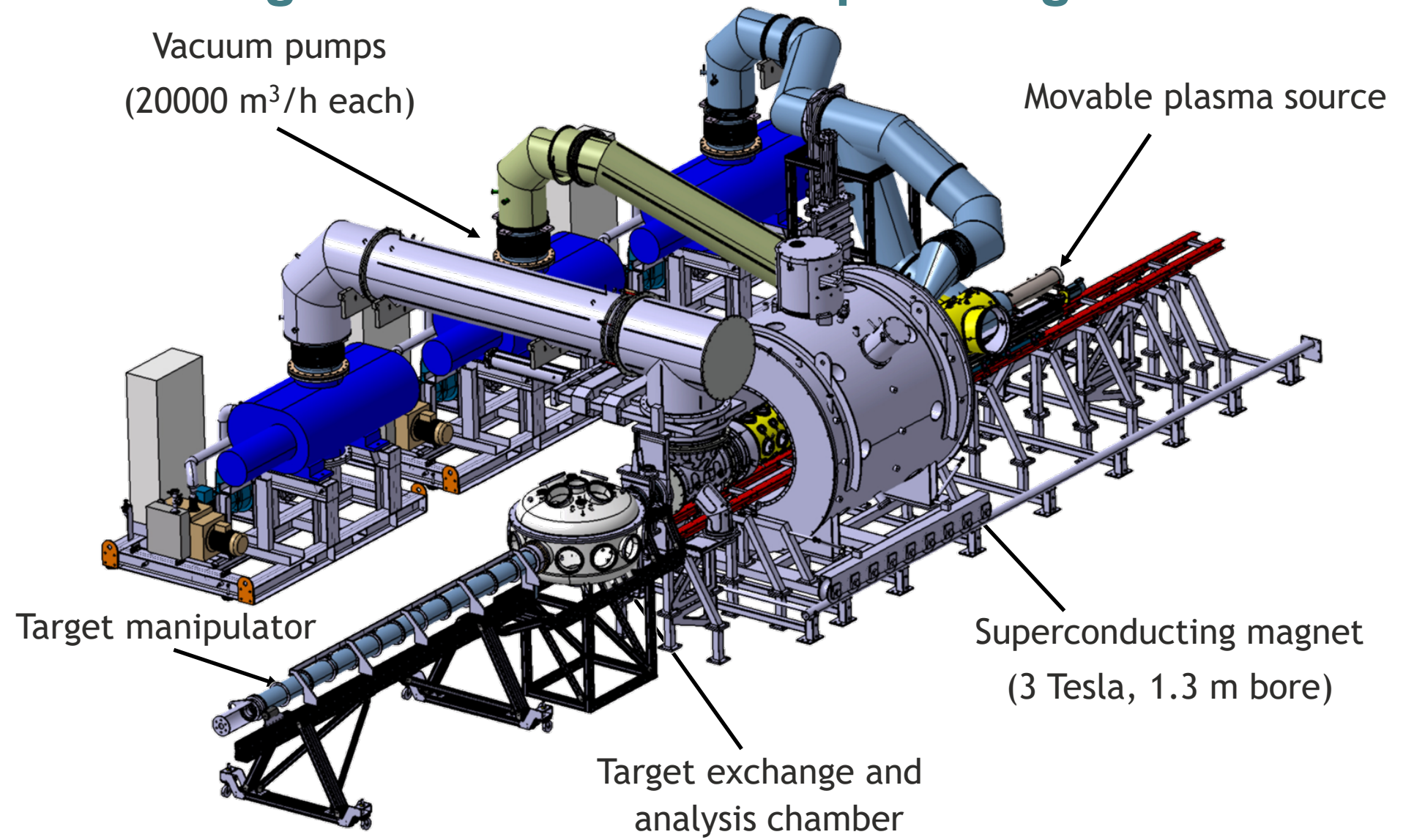
The international spectrum

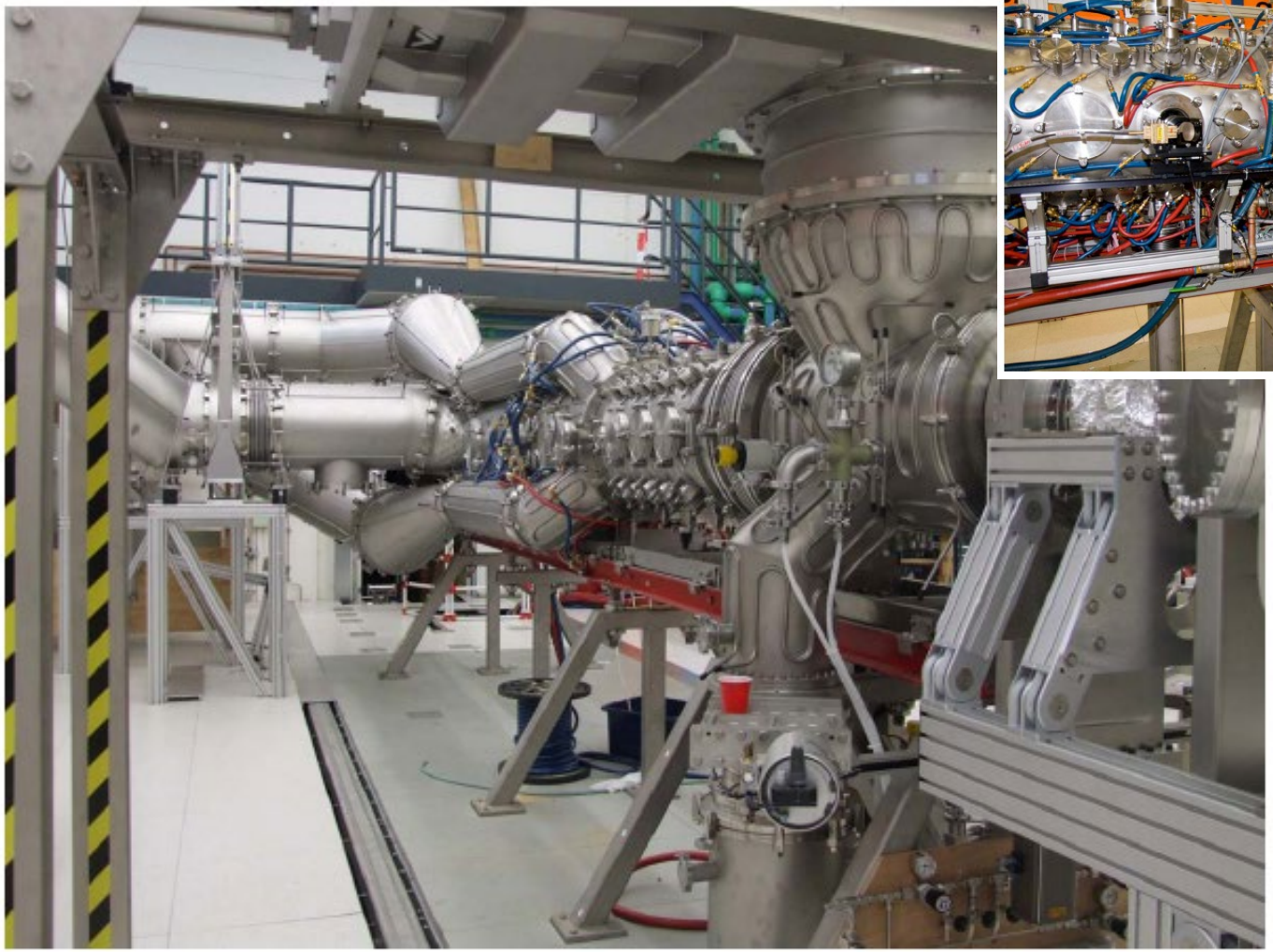


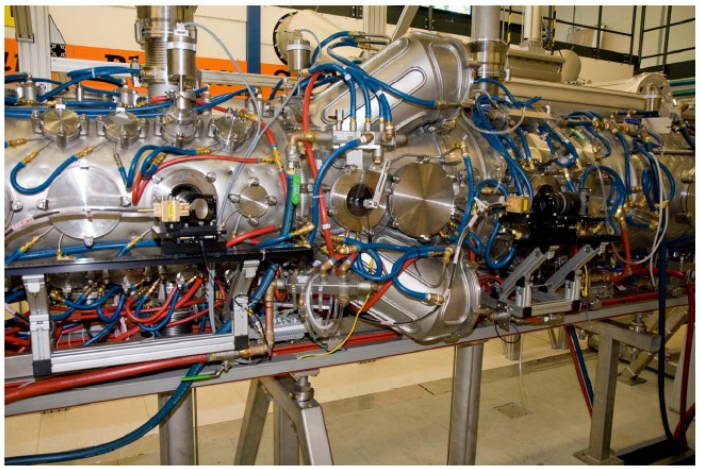
Who will win the race?



Magnum-PSI: new linear plasma generator







Conclusion:

- If the current very fast developments continue, fusion should at least be in the energy scenarios within a decade
- Fusion can be a preferred follow-up to fission
- Fusion can contribute to solving the waste problem of fission
- There is no proliferation issue for fusion
- Fusion does not produce long term radioactive waste.

Components of a fusion plant

