Situation and Prospects of Nuclear Fusion as an Energy Source

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Chairman Governing Board Fusion for Energy

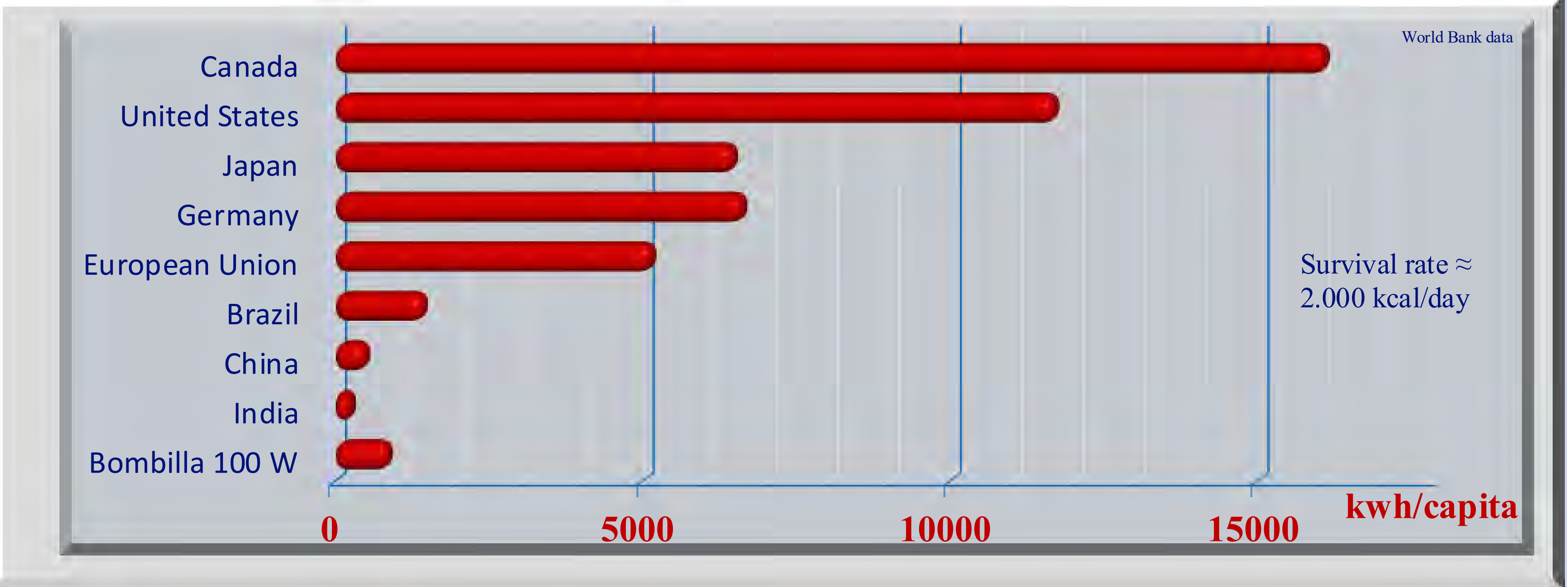
Institute of Nuclear Physics PAN
Krakow
16 October 2025

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat — Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

FUSION FOR ENERGY

Energy Consumption



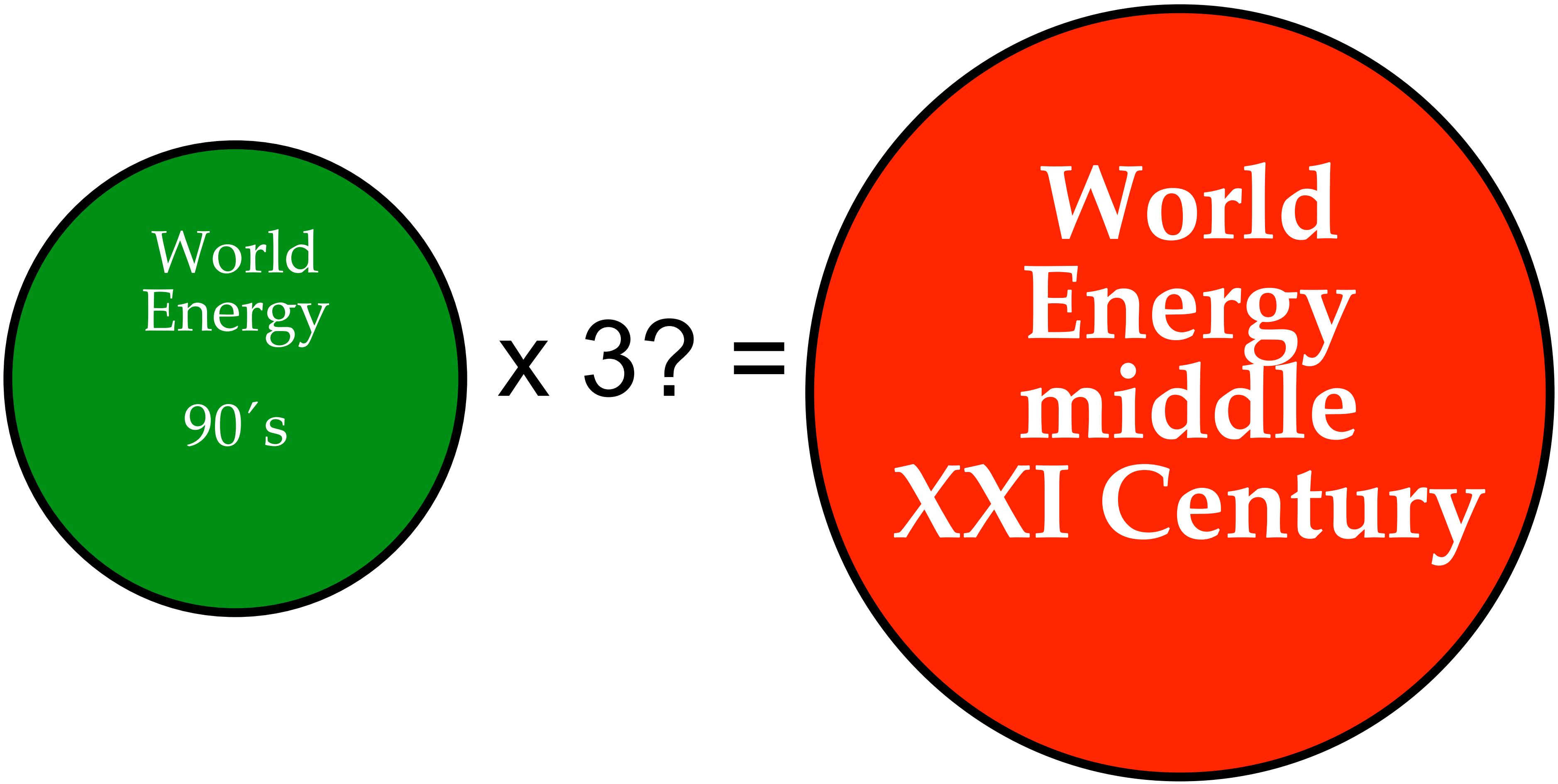
World average: 2000 kWh/person/year

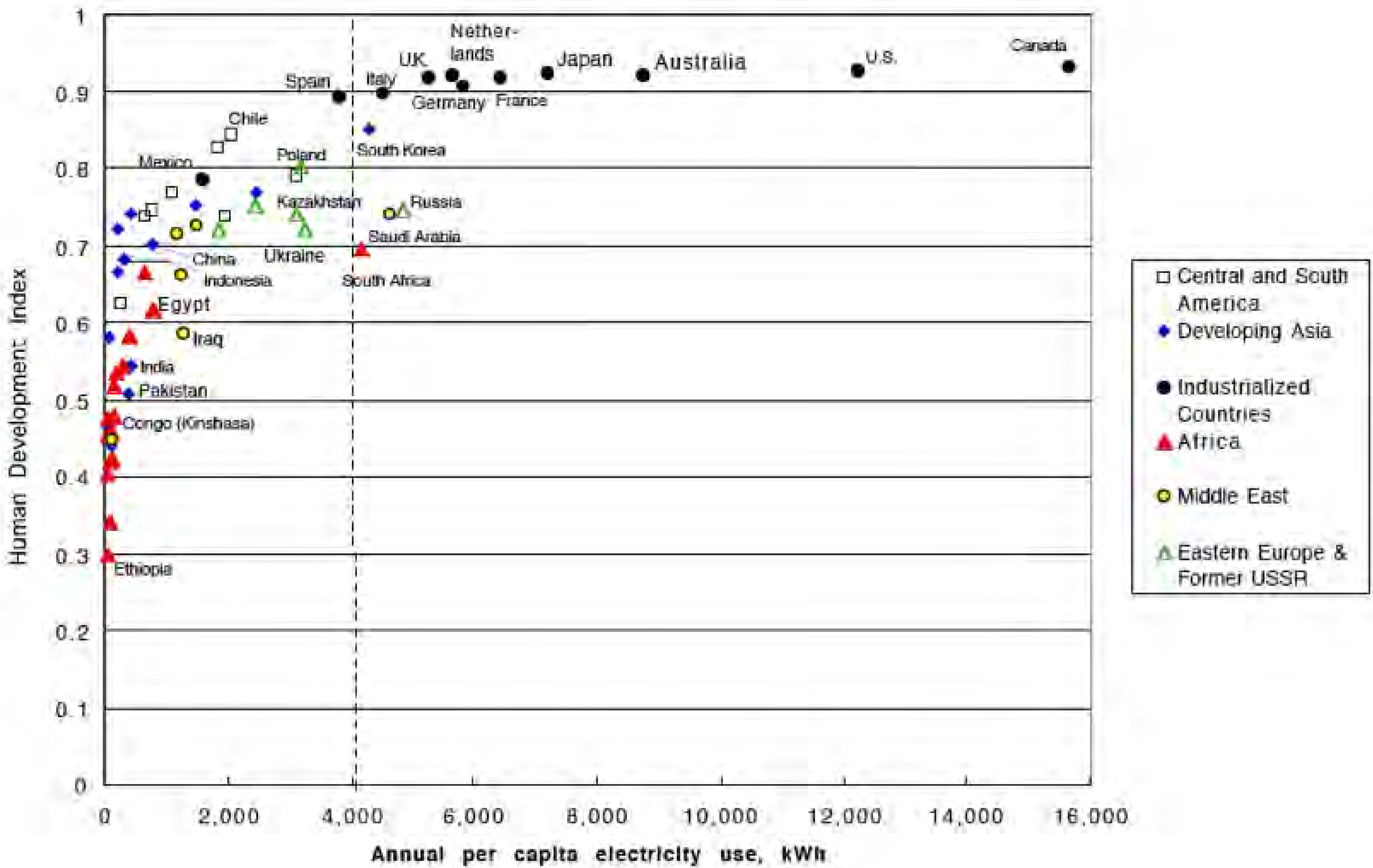
Total consumption (90´s):5.000 million x 2.000 = 10^4 TWh/y

Assume a future: Population doubles and less than 1/3 of American consumption allows a satisfactory quality of life

Total consumption (XXI):10.000 million x 3.000 = 3 x 10^4 TWh/y

Energy Consumption





Human Development Index
Annual per capita electricity use, kWh
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
Nether-lands
UK
Japan
Australia
U.S.
Canada
Spain
Italy
Germany
France
Chile
South Korea
Mexico
Poland
Kazakhstan
Russia
Saudi Arabia
China
Ukraine
Indonesia
South Africa
Egypt
Iraq
India
Pakistan
Congo (Kinshasa)
Ethiopia
Central and South America
Developing Asia
Industrialized Countries
Africa
Middle East
Eastern Europe & Former USSR

Energy Consumption

World
Energy
90´s

x 3? =

World
Energy
Middle
XXI Century

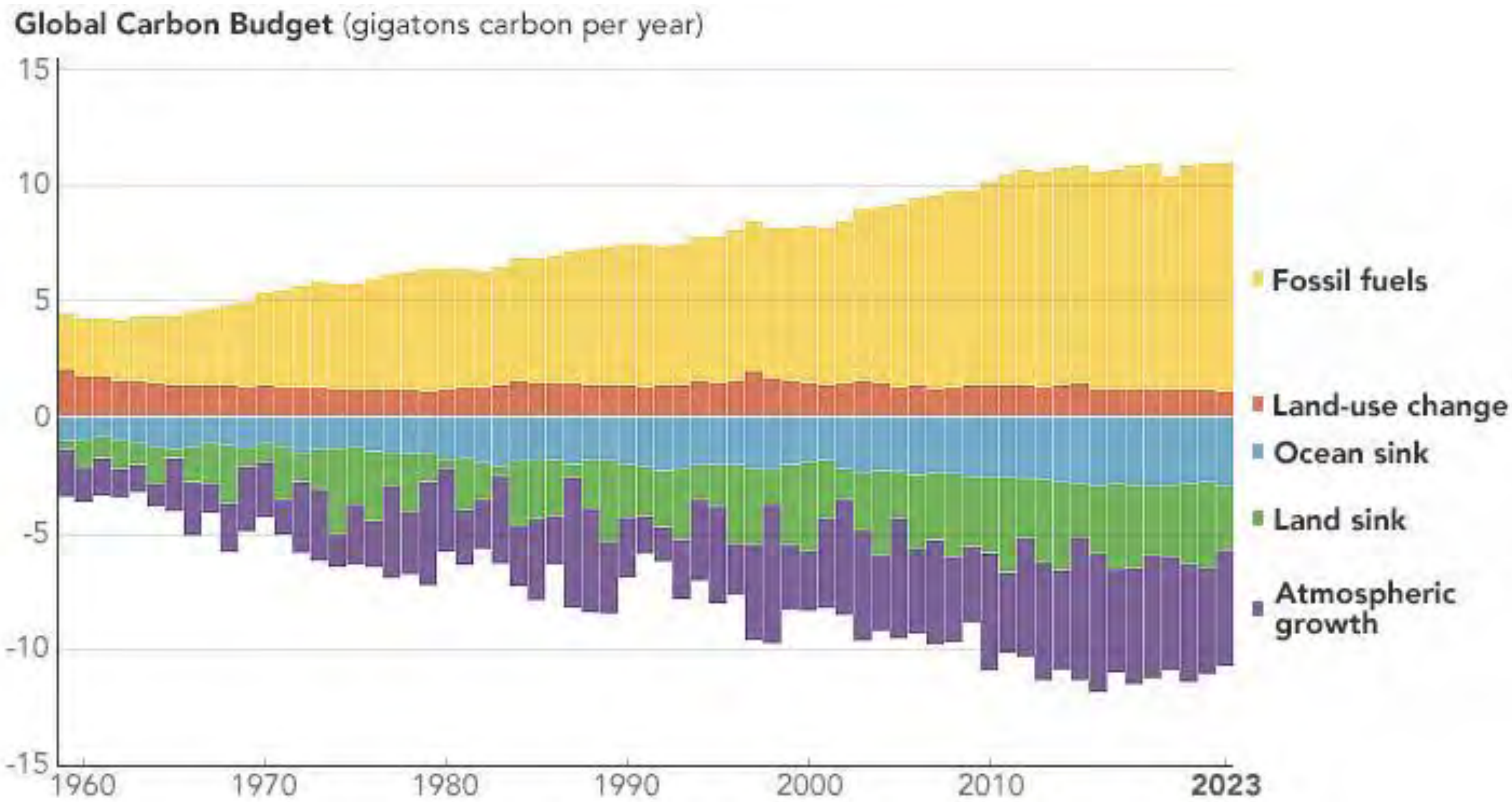
Oil	43 (32)%
Coal	22 (30)%
Gas	20 (24)%
Nuclear	8 (4)%
Hydro	5 (7)%
Other	2 (3)%

BP ENERGY OUTLOOK

New Energy mix →

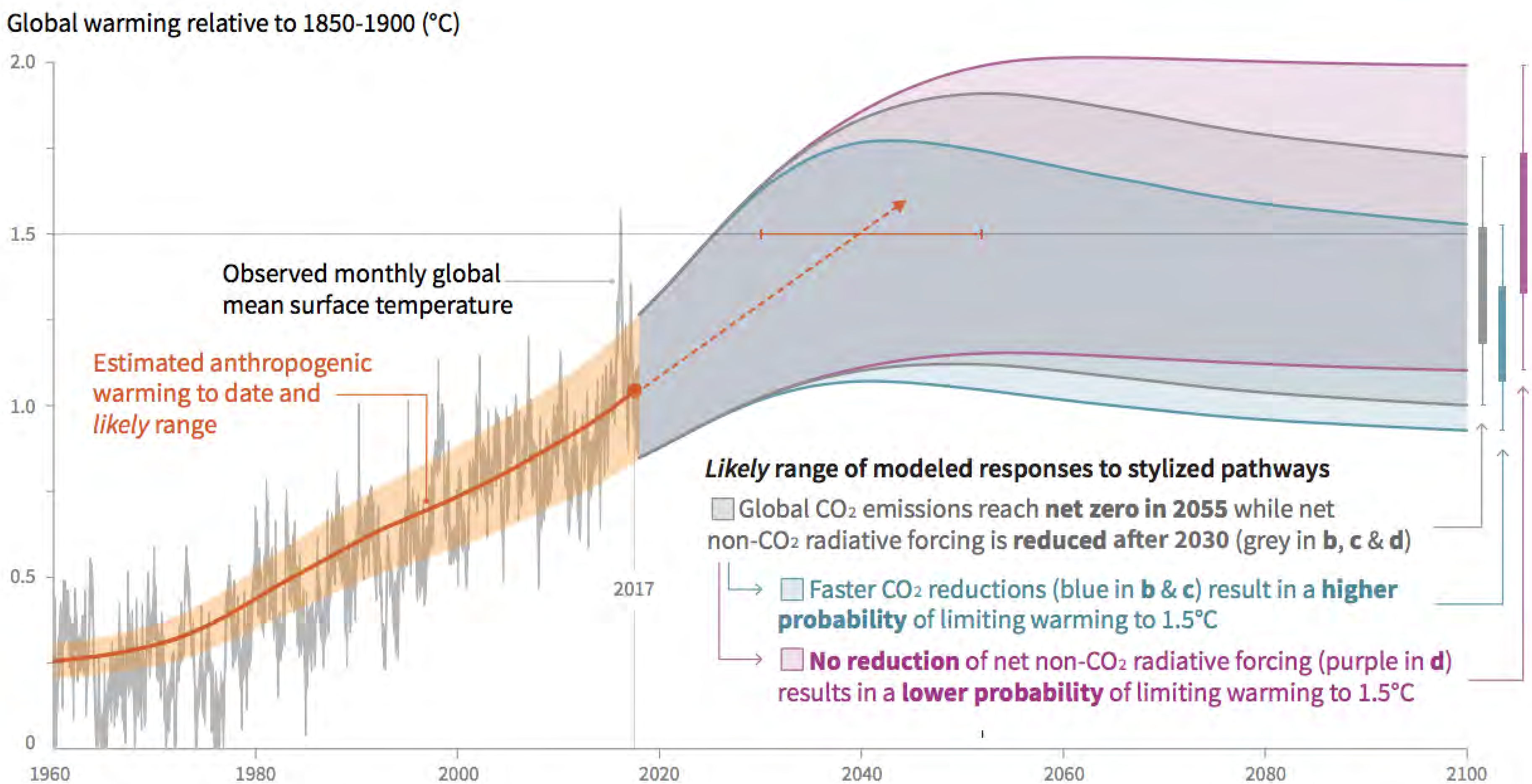
Resources Availability
Environmental consequences
Security of supply

Global Environmental Challenge
Emissions from Fossil Fuels Keeps Rising



Friedlingstein, P., et al. (2023) Global Carbon Budget 2023. Earth System Science Data, 15, 5301-5369

Reality - Projection

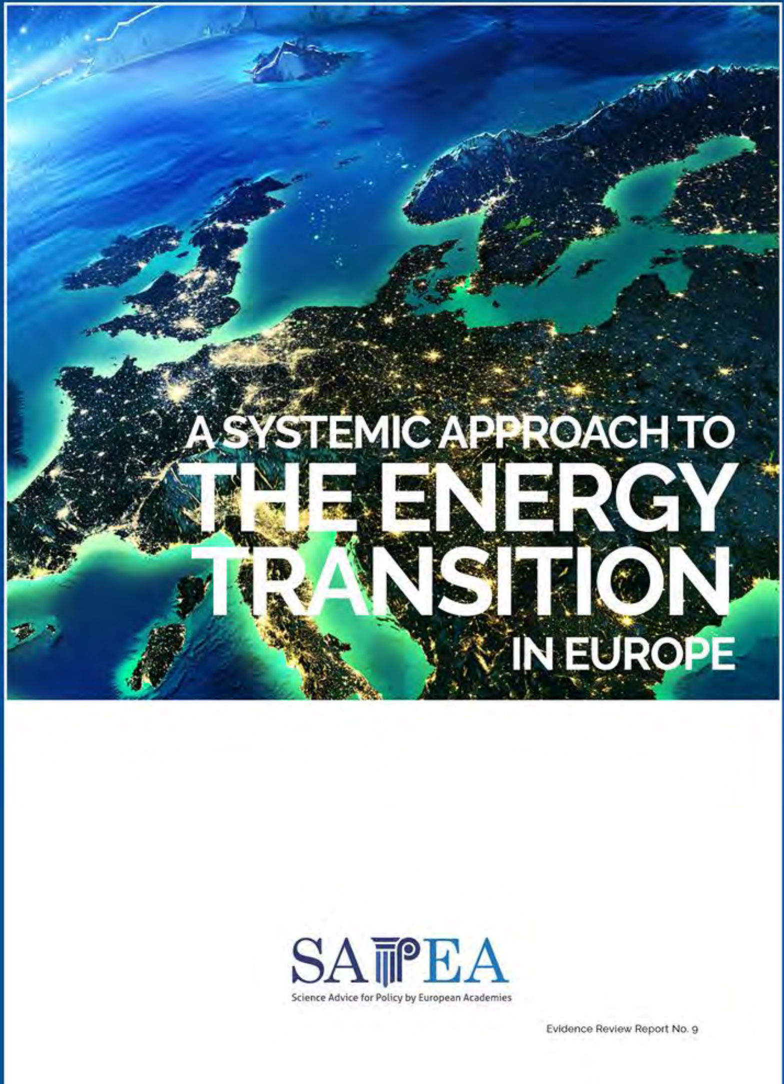


IPCC 2018

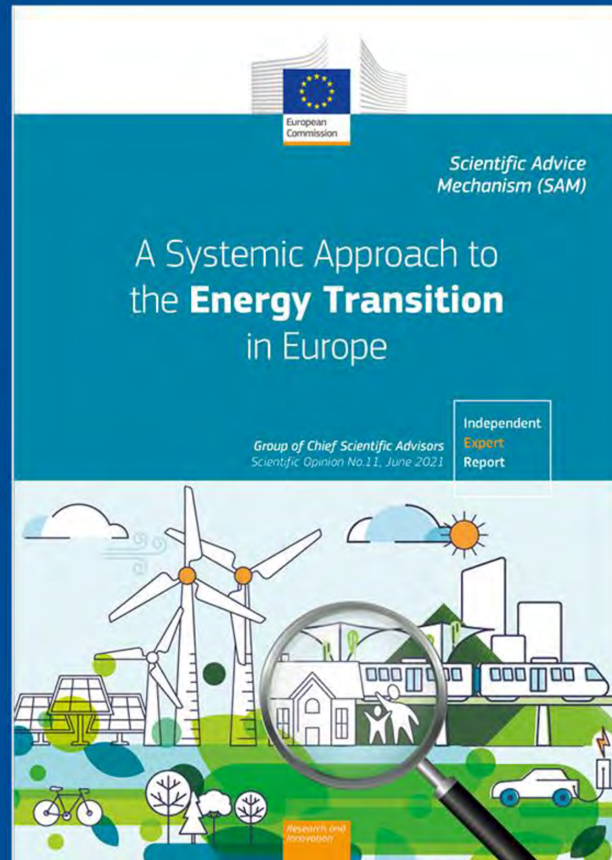
Energy Options

- Fossil
  - Coal
  - Gas
  - Oil
- Nuclear
  - Fission
  - Fusion ?
- Renewables
  - Hydro
  - Wind
  - Solar
  - Biomass
  - Other

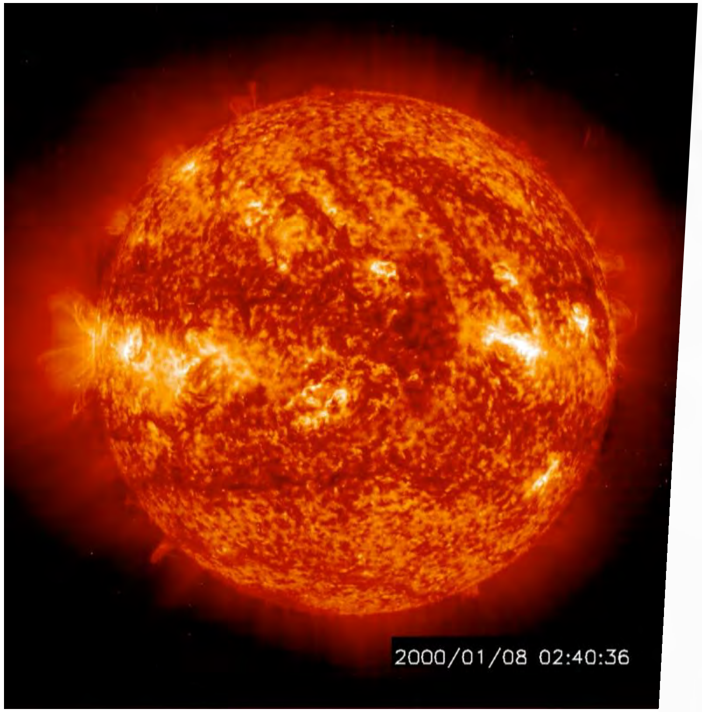
Note: The reduction in the global energy mix from 2009 to 2019 of fossil fuels has been a 0,1%
Source: REN21(Renewables Now)



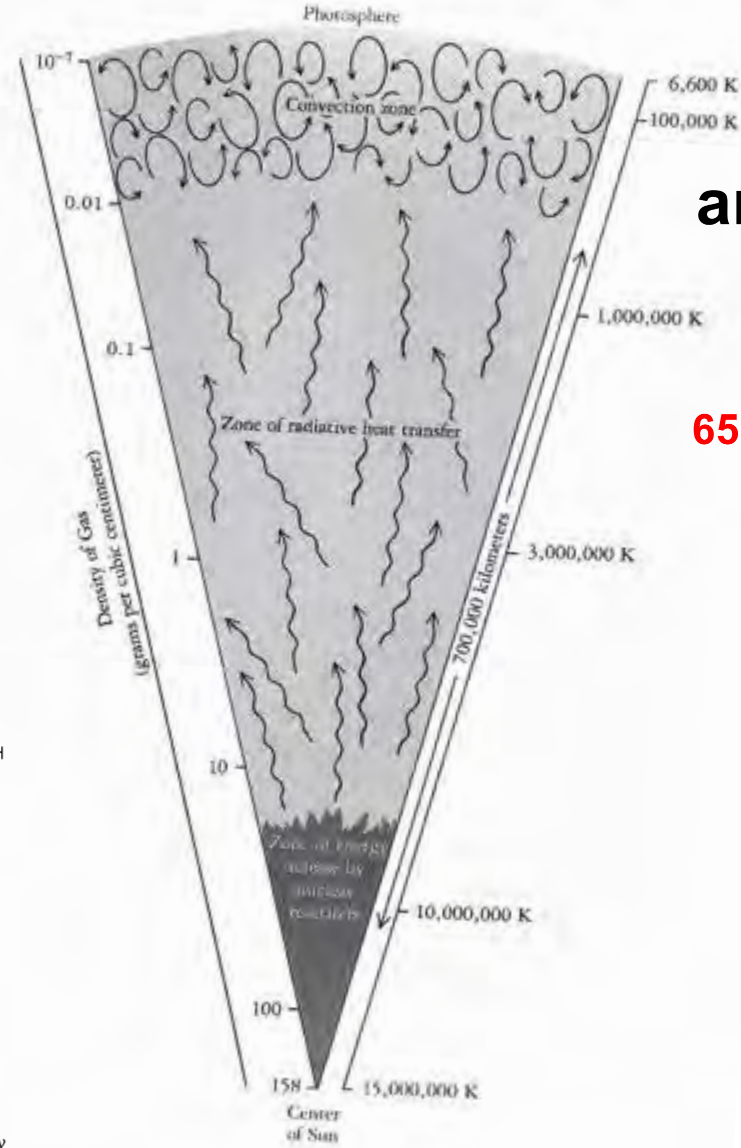
www.sapea.info/energy



Page 92:
"An additional challenge for an electricity system with high shares of VRE is to maintain grid stability in terms of frequency control. The dominant wind turbine type (variable speed) is interfaced through converters, as are all solar photovoltaic cells (PVs)s, and does not provide synchronous inertia. Hence, the transition to a system with high shares of VRE raises the risk of insufficient synchronous inertia needed to secure frequency quality and stability"



Our sun and Nuclear Fusion



650 Mt/s H_2 -> 645.5 Mt/s He

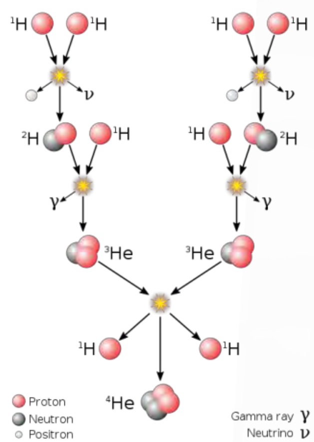
Mass loss:4.55 Mt/s

$E=mc^2$

Energy/s≈ 4×10^{26} w

Surface ≈ 60 Mw/m^2

Hans Bethe
Nobel Prize 1967



Mass ≈ 2×10^{30} Kg

$P_c \approx 265 \times 10^9$ atm

$D_c \approx 160.000\ kg/m^3$

$T_c \approx 15.000.000$ ºK

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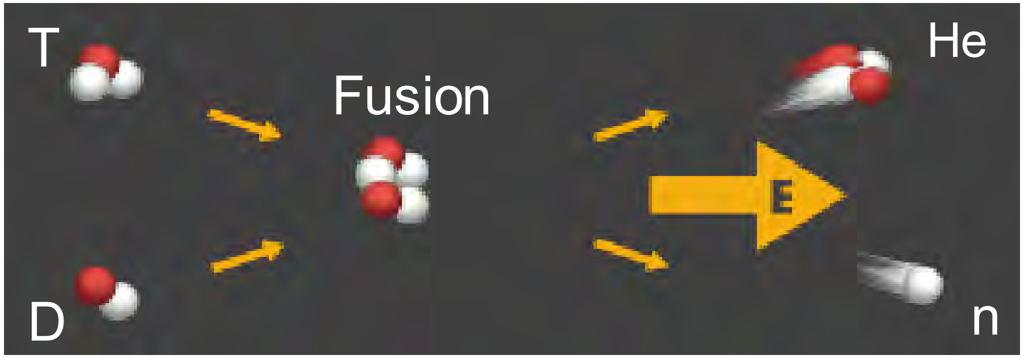
Fusion in our planet "... *is not the same as in the Sun* "

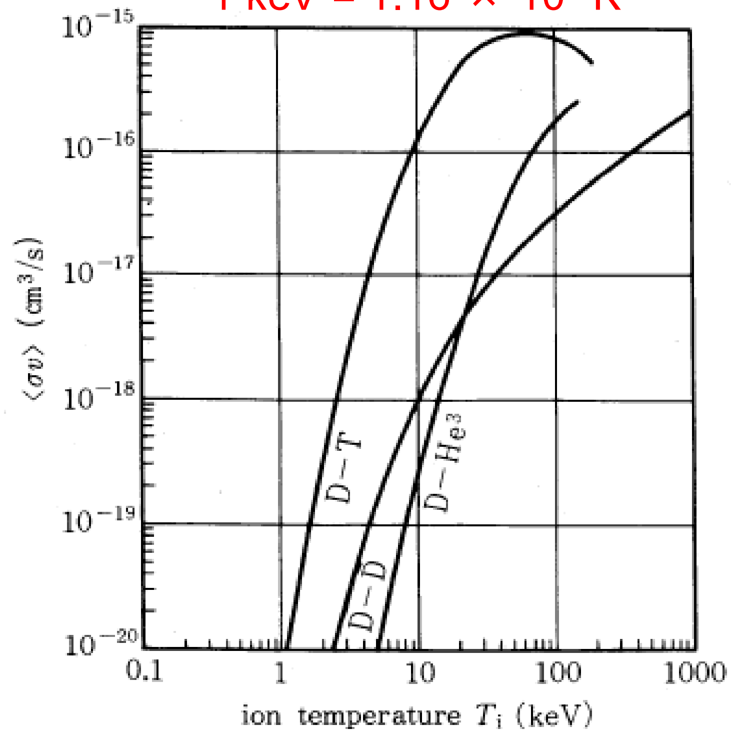


+ 20% Energy (3.5 MeV)

+ 80% Energy (14.1 MeV)

TRL 1-4 ……………………………….. TRL 4 - 9

1 keV = 1.16 × 10^7 K



- **Together with:**

$^1n + {}^6Li \Rightarrow {}^4He + {}^3T + 4.8\ MeV$

$^1n + {}^7Li \Rightarrow {}^3He + {}^3T + {}^1n - 2.5\ MeV$

to generate tritium

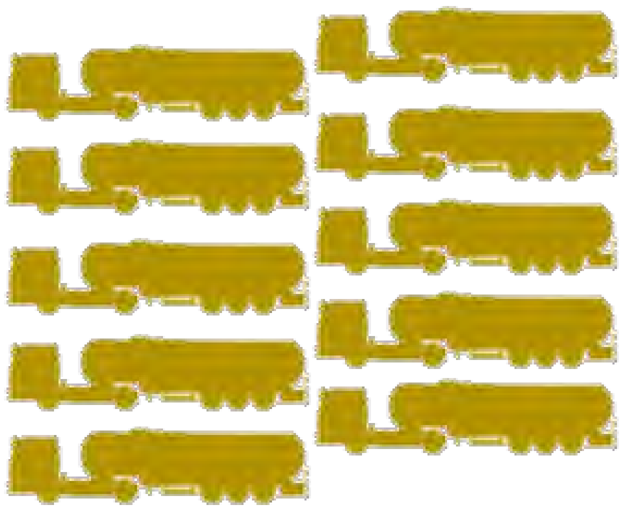
Why fusion could be an attractive energy source?

FUSION FOR ENERGY

280 liters of Earth crust
(50 g lithium)

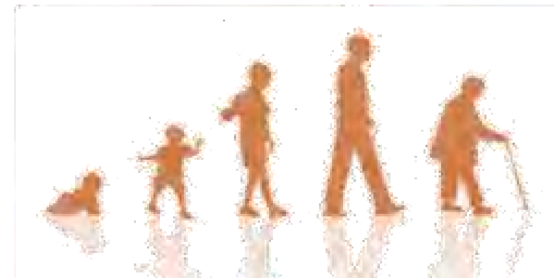
+ 400 liters of water
(12 g deuterium)

=



300 t of oil

=

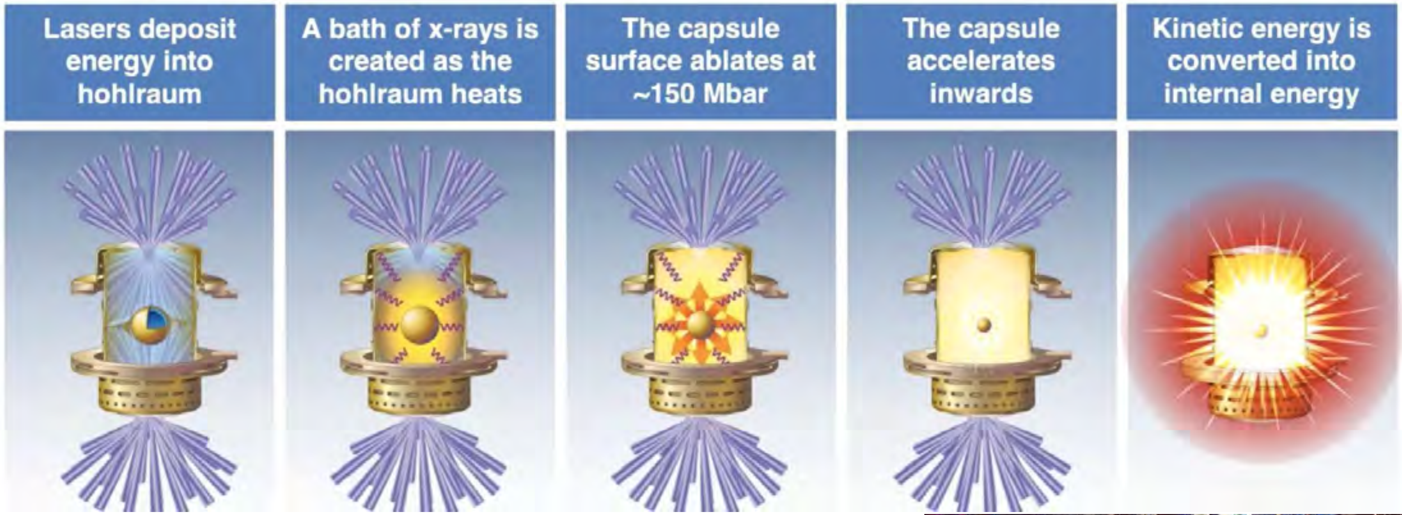


Total energy consumed by average EU citizen during whole life

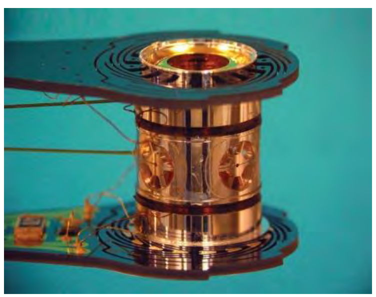
Lawrence Livermore National Laboratory

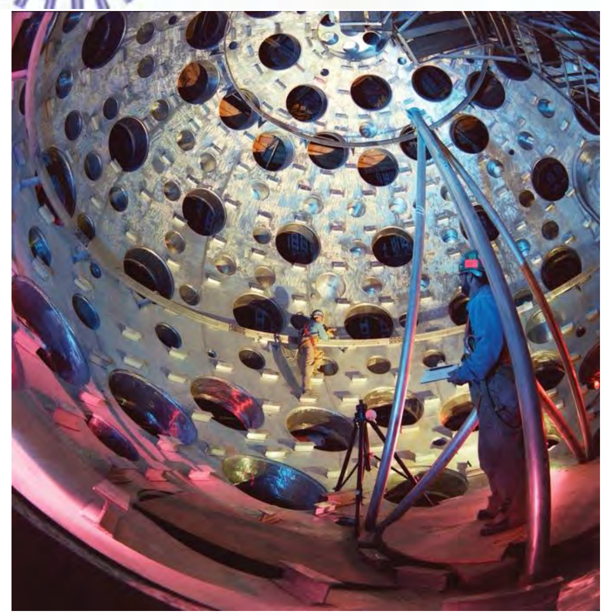
National Ignition Facility & Photon Science

Indirect drive inertial confinement fusion (ICF) uses x-rays to ablate and accelerate a capsule of fusion fuel to extreme velocity

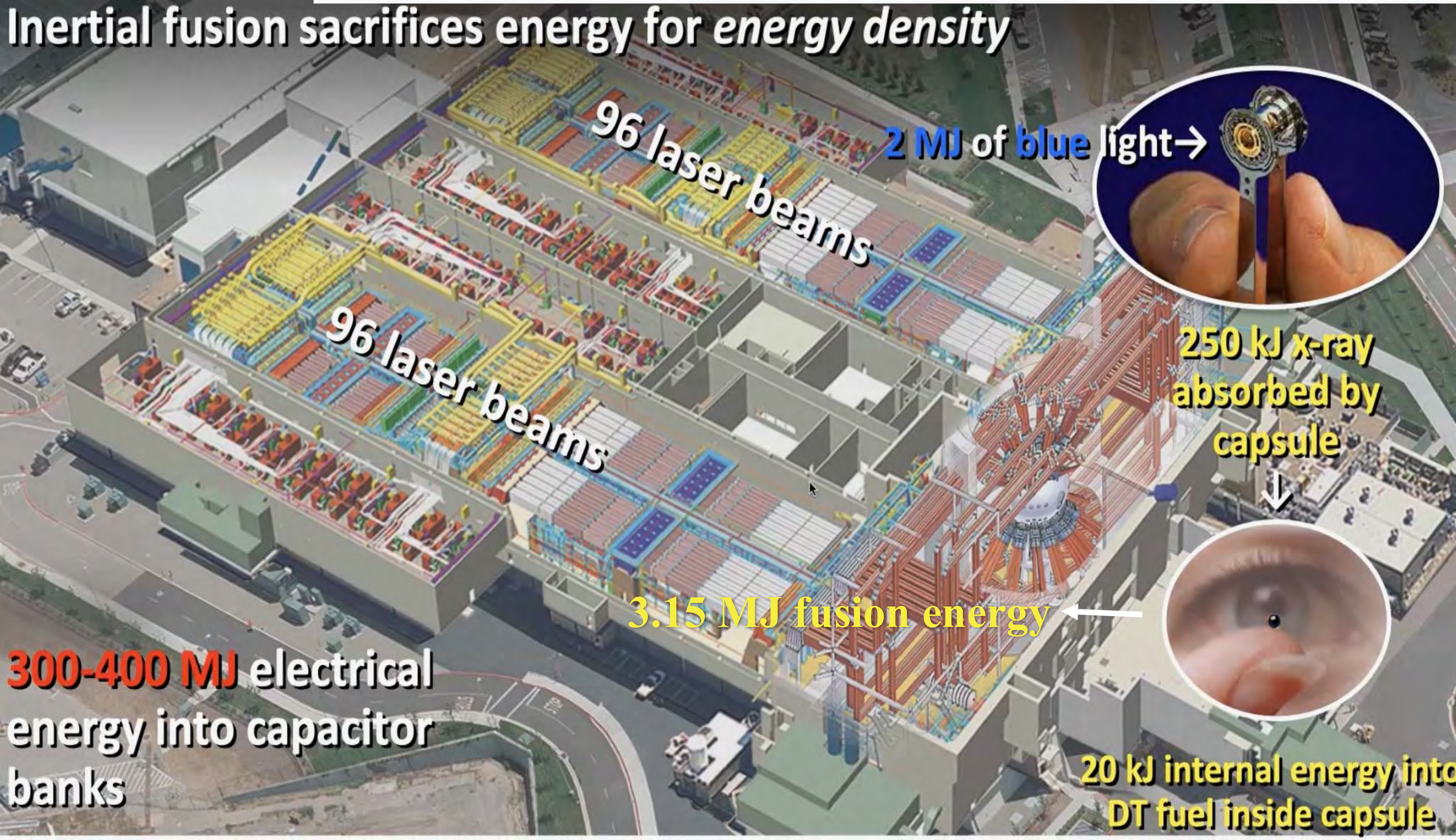


≈ 1 cm

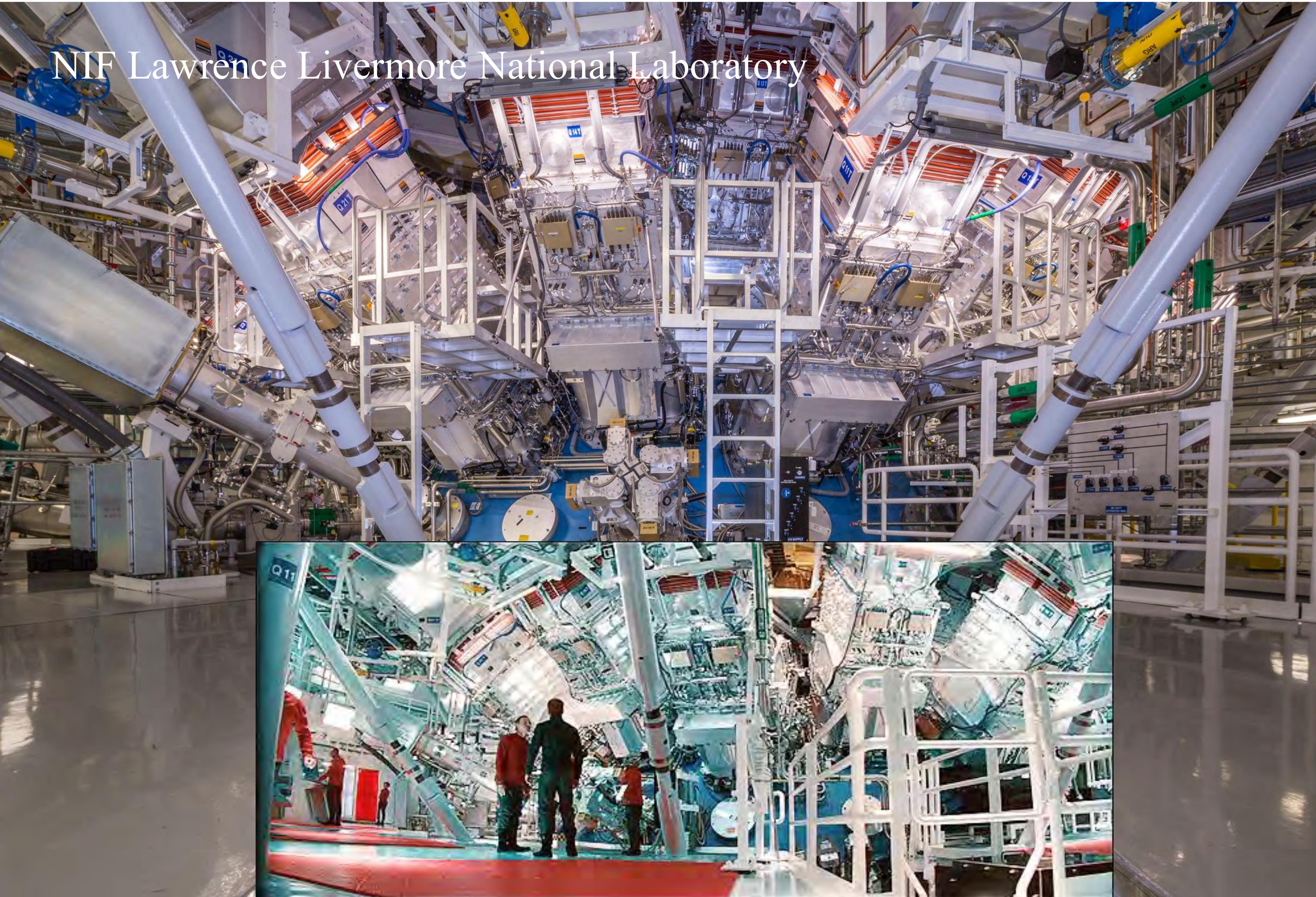


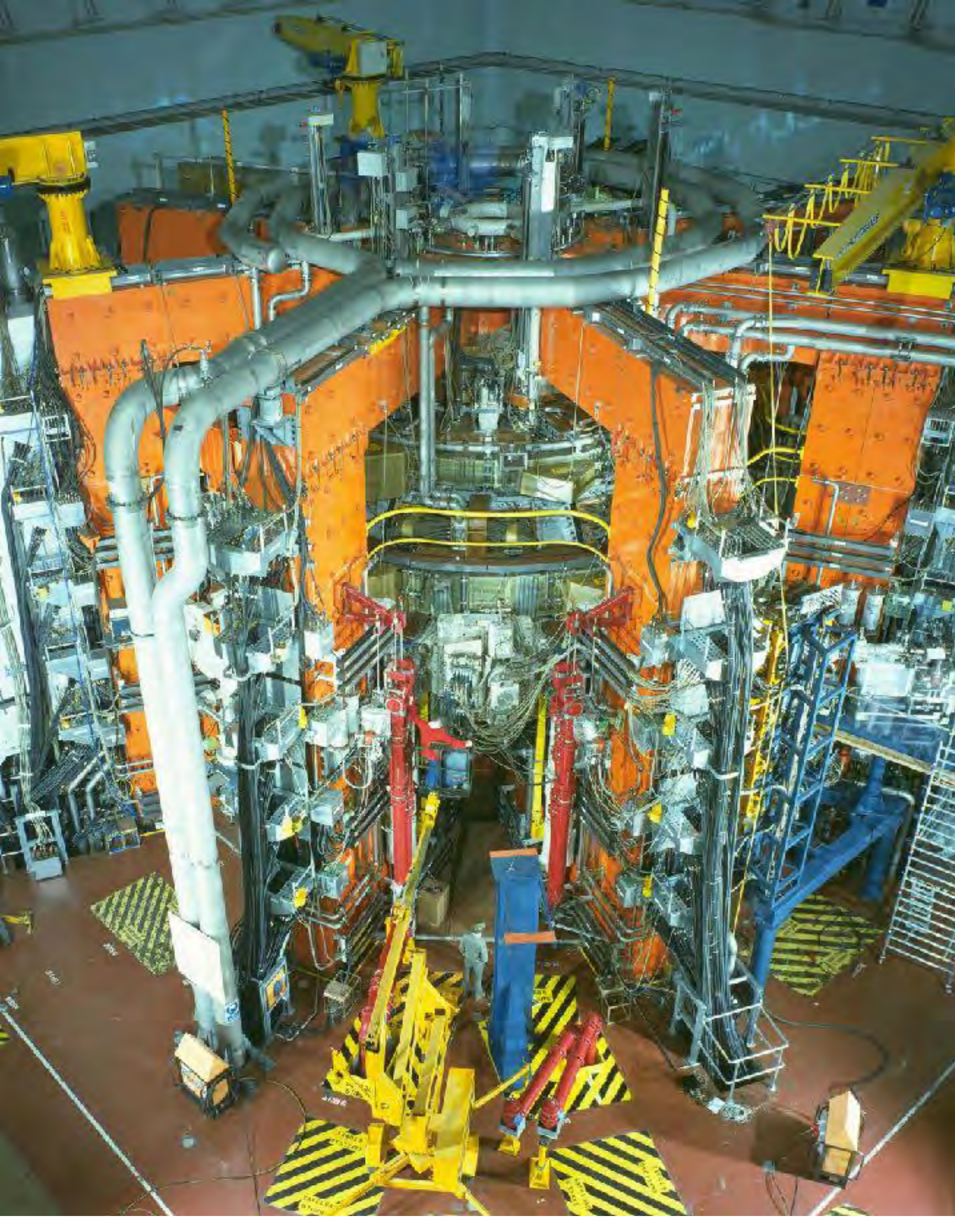


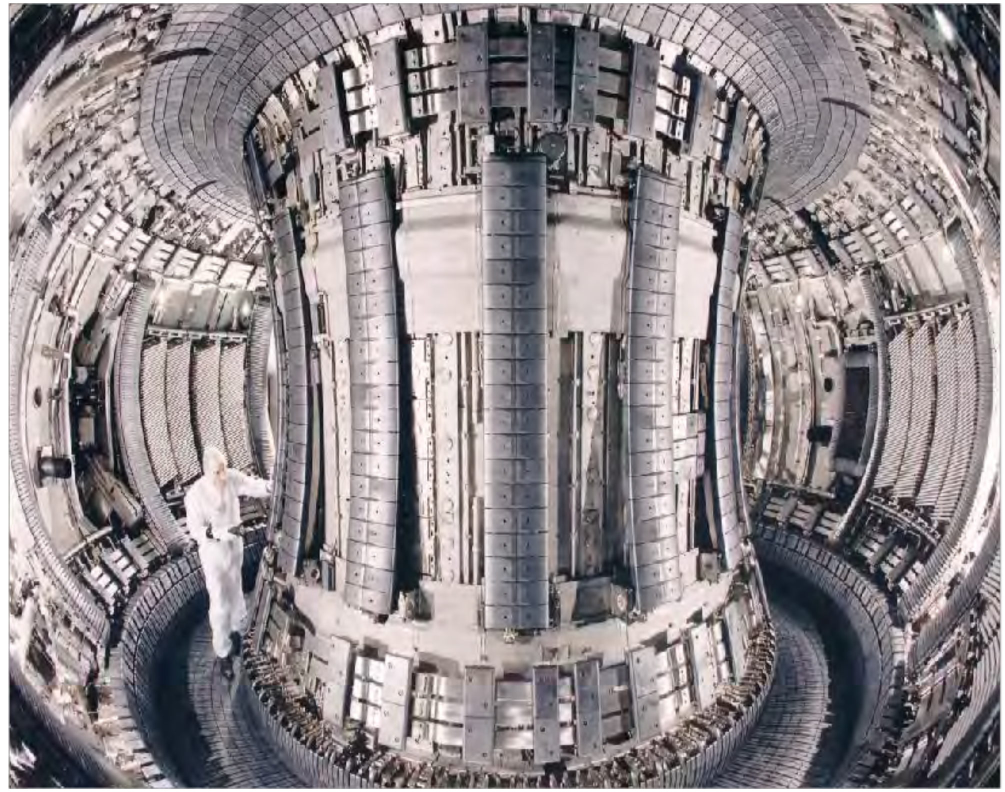
Inertial fusion sacrifices energy for *energy density*



NIF Lawrence Livermore National Laboratory

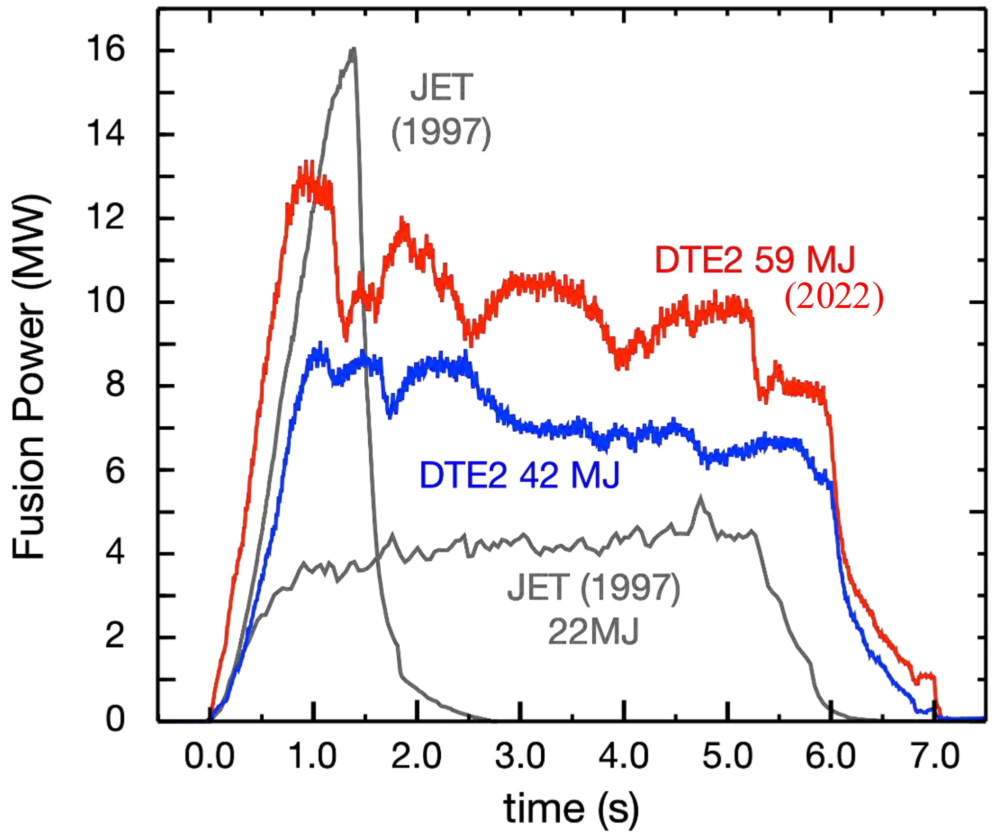






JET

World records



World record fusion energy in Joint European Torus (2022)

59 MJ of fusion energy generated

This is enough energy to bring about ~100 liters of water to boil

Used fuel:
100 µg of tritium &
70 µg of deuterium

Used fuel:
4 kg of coal

Images courtesy of Shutterstock

Plasma fusion performance

Temperature - T_i: *$1\text{-}2 \times 10^8$ K (10-20 keV)*
(~10 × temperature of Sun core)

Density - n_i: *1×10^{20} m^{-3}*
(~10^{-6} atmospheric density)

Energy confinement time τ_E: *a few seconds ($\propto$ current × radius^2)*
(plasma pulse duration ~1000s)

Fusion power amplification: $$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

⇒ World records: Q ≈ 1

⇒ ITER: Q ≥ 10

⇒ 'Controlled ignition': Q ≥ 30

The Way to Fusion Power – The ITER Story

The idea for ITER originated from the Geneva Superpower Summit on November 21,1985, when the Russian Premier Mikhail Gorbachev and the US-President Ronald Reagan proposed that an international Project be set up to develop fusion energy "as an essentially inexhaustible source of energy for the benefit of mankind".

"All the News That's Fit to Print"

The New York Times

Late Edition

Weather: Rain likely today, strong easterly winds; rain ending late tonight. Partly cloudy and warmer tomorrow. Temperatures: today 43-47, tonight 40-45; yesterday 38-62. Details, page C30.

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Text of the Joint U.S.-Soviet Statement: 'Greater Understanding Achieved'

Special to The New York Times

GENEVA, Nov. 21 — Following is the text of the joint Soviet-American statement at the end of the summit meeting today, as made public by the White House:

By mutual agreement, the President of the United States, Ronald Reagan, and the General Secretary of the Central, Committee of the Communist Party of the Soviet Union, Mikhail S. Gorbachev, met in Geneva Nov. 19-21. Attending the meeting on the U.S. side were Secretary of State George P. Shultz; chief of staff, Donald T. Regan; Assistant to the President, Robert C. McFarlane; Ambassador to the U.S.S.R., A
man; special adviser t
and the Secretary of S
Control, Paul H. Nitze;
retary of State of Eur
Rozanne L. Ridgway;
ant to the President fo
curity Affairs, Jack F

Attending on the So
member of the Politbu
tral Committee of
Minister of Foreign A
A. Shevardnadze; Firs
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Ambassador to the U
Anatoly F. Dobrynin; h
partment of Propagan
tral Committee of the C
sandr N. Yakovlev; he
partment of Internati
tion of the Central Con
C.P.S.U., Leonid M
assistant to the Genera
the Central Commi
C.P.S.U., Andrei M. A

These comprehensiv
covered the basic ques
Soviet relations and the
national situation. The
frank and useful. Serio
remain on a number of

While acknowledgin
ences in their syste
proaches to internat
some greater understa
side's view was achiev
leaders. They agreed a
to improve U.S.-Soviet
the international situati

In this connection the two sides have confirmed the importance of an ongoing dialogue, reflecting their strong desire to seek common ground on existing problems.

They agreed to meet again in the nearest future. The General Secretary accepted an invitation by the President of the United States to visit the United States of America, and the President of the United States accepted an invitation by the General Secretary of the Central Committee of the C.P.S.U. to visit the Soviet Union. Arrangements for the timing of the visits will be agreed upon through diplomatic channels.

In their meetings, agreement was reached on a number of specific

ple of 50 percent reductions in the nuclear arms of the U.S. and the U.S.S.R. appropriately applied, we well as the idea of an interim I.N.F. agreement.

During the negotiation of these agreements, effective measures for verification of compliance with obligations assumed will be agreed upon.

Risk Reduction Centers

The sides agreed to study the question at the expert level of centers to reduce nuclear risk taking into account the issues and developments in the Geneva negotiations. They took satisfaction in such recent steps in this direction as the modernization of

firmed that they are in favor of a general and complete prohibition of chemical weapons and the destruction of existing stockpiles of such weapons. They agreed to accelerate efforts to conclude an effective and verifiable international convention on this matter.

The two sides agreed to intensify bilateral discussions on the level of experts on all aspects of such a chemical weapons ban, including the question of verification. They agreed to initiate a dialogue on preventing the proliferation of chemical weapons.

Mutual Basic Force Reduction

ministries and departments in such fields as agriculture, housing and protection of the environment have been useful.

Recognizing that exchanges of views on regional issues on the expert level have proven useful, they agreed to continue such exchanges on a regular basis.

The sides intend to expand the programs of bilateral cultural, educational and scientific-technical exchanges, and also to develop trade and economic ties. The President of the United States and the General Secretary of the Central Committee of the C.P.S.U. attended the signing of the Agreement on Contacts and Exchanges in Scientific, Educational and Cultural Fields.

They agreed on the importance of resolving humanitarian cases in the spirit of cooperation.

They believe that there should be greater understanding among our peoples and that to this end they will encourage greater travel and people-to-people contact.

Northern Pacific Air Safety

The two leaders also noted with satisfaction that, in cooperation with the Government of Japan, the United States and the Soviet Union have agreed to a set of measures to promote safety on air routes in the North Pacific and have worked out steps to implement them.

Civil Aviation Consulates

They acknowledged that delegations from the United States and the Soviet Union have begun negotiations a[...] resumption of air services. The two [...] expressed their desire to reach a [...] beneficial agreement at an early [...] In this regard, an agreement was reach[...] on the simultaneous opening of co[...]sulates general in New York and Ki[...].

Environmental Protection

Both sides agreed to contribute [...] the preservation of the environme[...]

— a global task — through joint research and practical measures. In accordance with the existing U.S.-Soviet agreement in this area, consultations will be held next year in Moscow and Washington on specific programs of cooperation.

Exchange Initiatives

The two leaders agreed on the utility of broadening exchanges and contacts including some of their new forms in a number of scientific, educational, medical and sports fields (inter alia, cooperation in the development of educational exchanges and software for elementary and secondary school instruction; measures to promote Russian language studies in the United States and English language studies in the U.S.S.R.; the annual exchange of professors to conduct special courses in history, culture and economics at the relevant departments of Soviet and American institutions of higher education; mutual allocation of scholarships for the best students in the natural sciences, technology, social sciences and humanities for the period of an academic year; holding regular meets in various sports and increased television coverage of sports events). The two sides agreed to resume cooperation in combating cancer diseases.

The relevant agencies in each of the countries are being instructed to develop specific programs for these exchanges. The resulting programs will be re[...] by the [...] at their ne[...] meeting.

Fusion Research

The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentialy inexhaustible, for the benefit for all mankind.

Fusion Research

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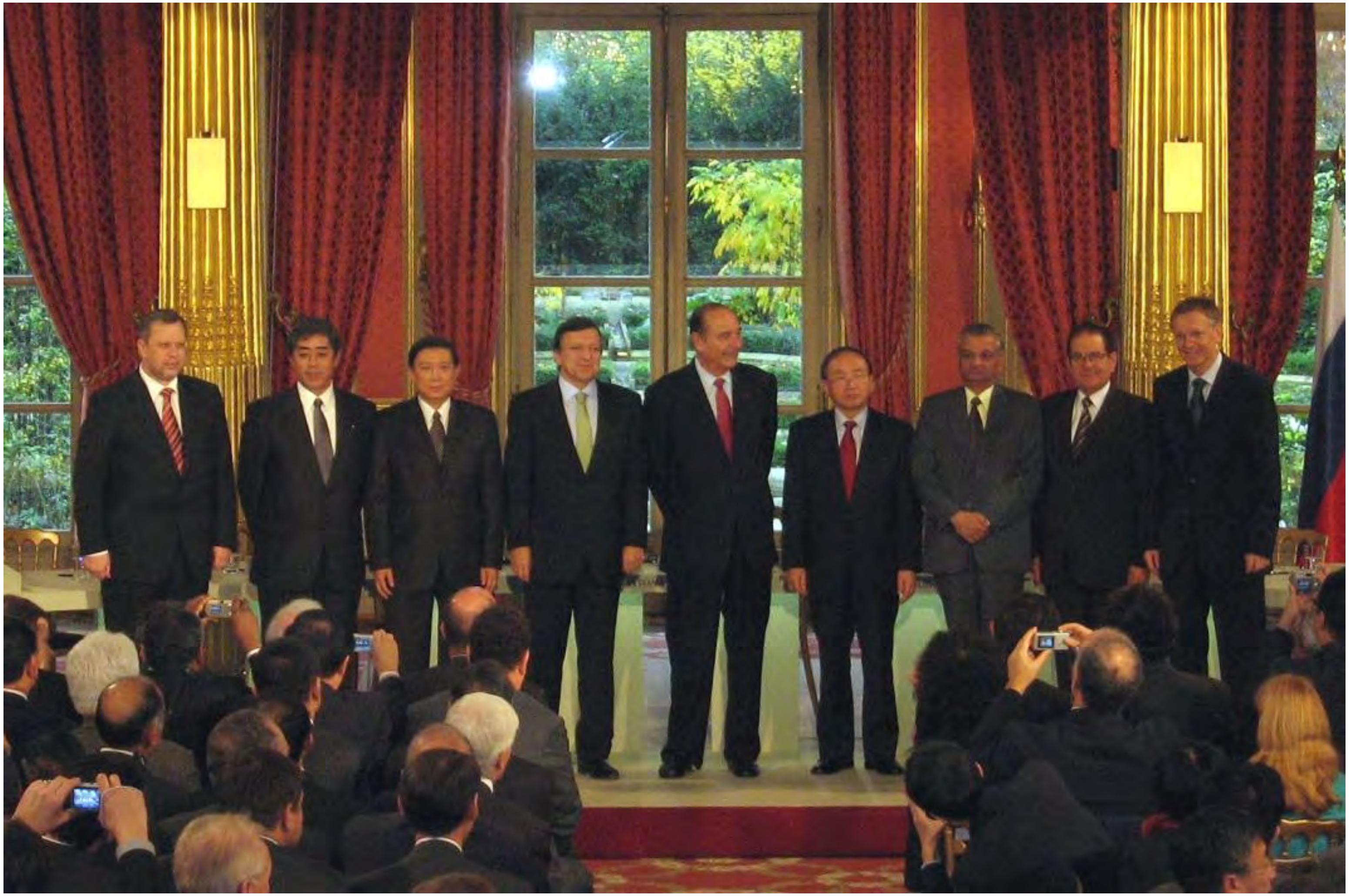
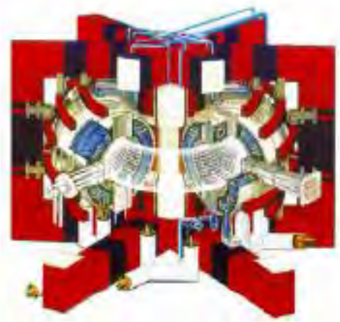
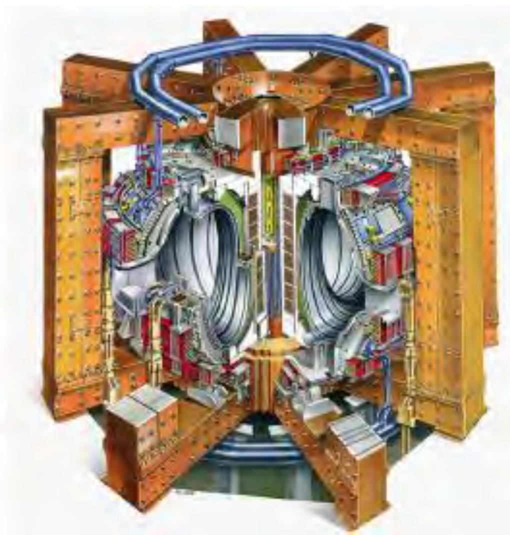
Collaboration is our greatest asset

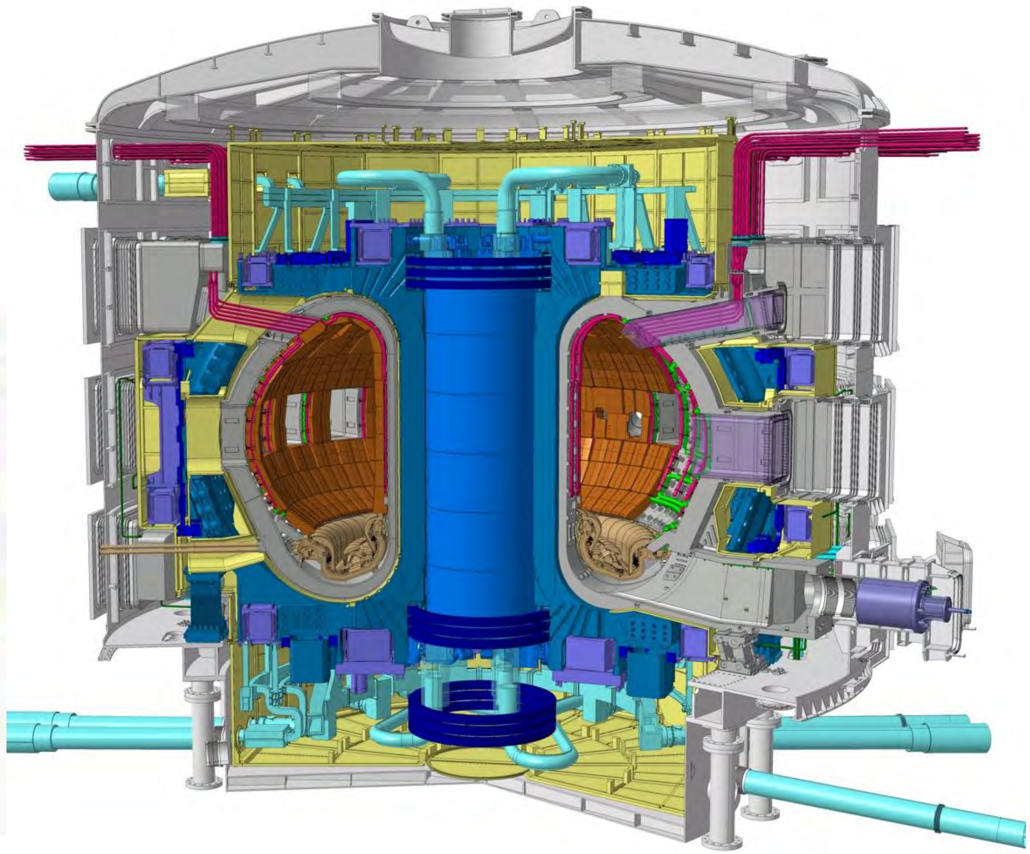


Ceremony ITER Agreement Signature, Elysee Palace, 21 November 2006

Next step







Tore Supra		JET		ITER	
V_{plasma}	25 m^3	V_{plasma}	80 m^3	V_{plasma}	830 m^3
P_{fusion}	~0	P_{fusion}	~16 MW, 2 s	P_{fusion}	~500 MW, ~400 s
T_{plasma}	~400 s	T_{plasma}	~30 s	T_{plasma}	~700 s

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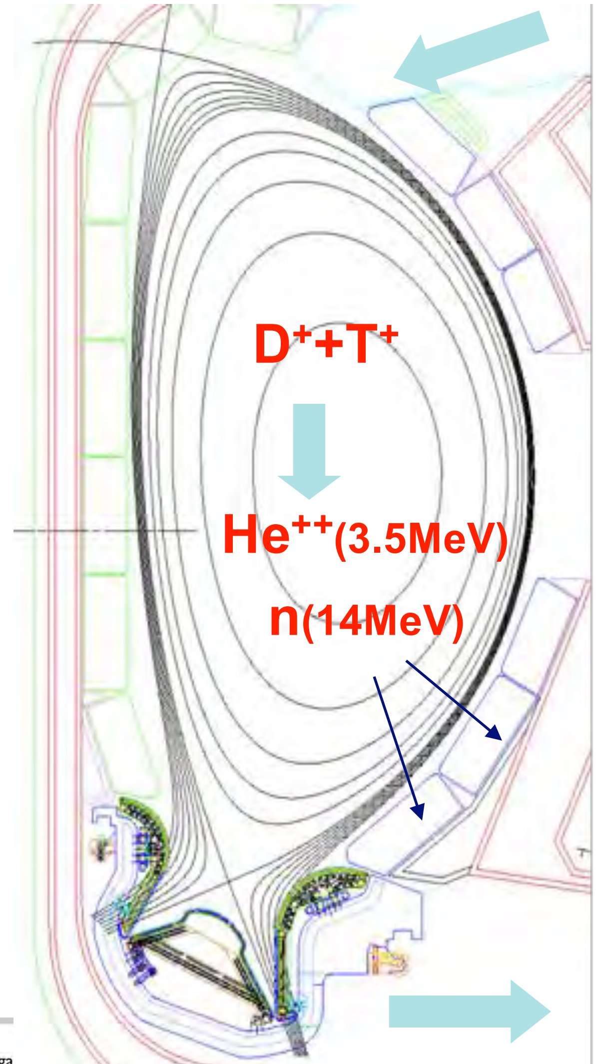
Fusion in ITER Plasma

Donut Shape Plasma

V:	$840 m^3$
R/a:	6.2m/2m
Vertical elongation:	1.85
Triangularity:	0.45

Density:	$10^{20} m^{-3}$
PeakTemperature:	17keV
Fusion Power:	500MW

Plasma Current :	15MA
Toroidal field:	5.3T



D_2, T_2 Fuel

Blanket: neutron absorber

Power Plant
Li-->T
High temperature

Divertor: particle and heat exhaust

He, D_2, T_2, impurities

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Site view today

FUSION FOR ENERGY

Site construction EUDA contribution

ITER is one of the most challenging energy research projects ever attempted

FUSION FOR ENERGY

23.000 tons

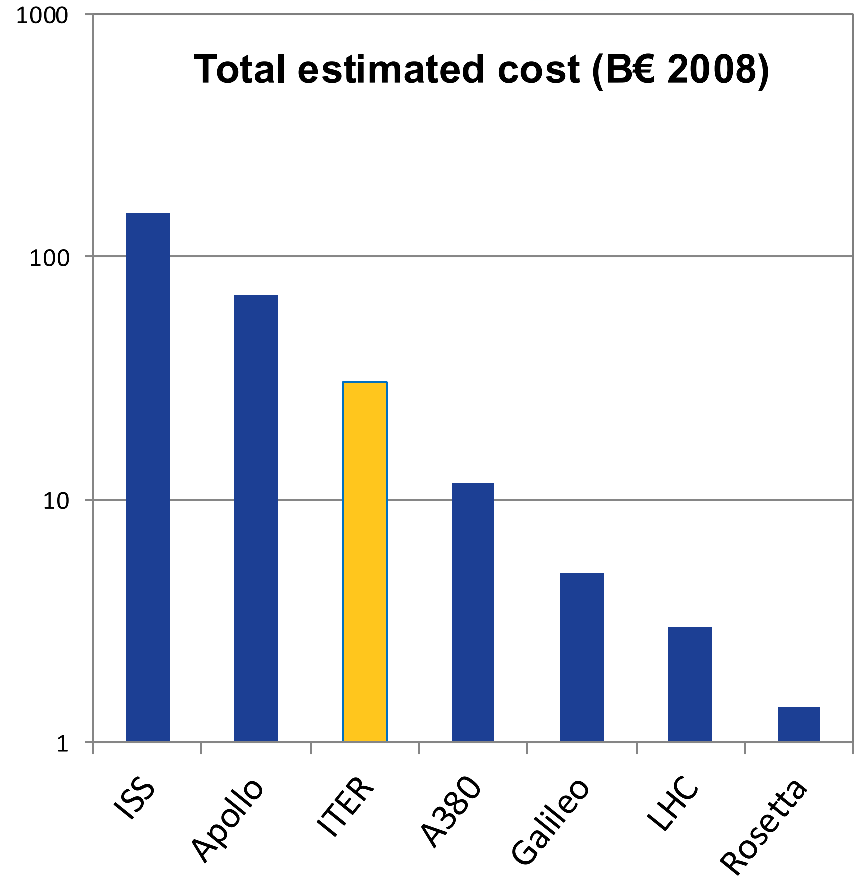
The **ITER Machine** will be 3 times the weight of the Eiffel Tower

10 million components

ITER: 10^7
Airbus 380: 10^6

400.000 tons

The **Tokamak Complex** will support the same weight as the Empire State Building



Fusion for Energy (F4E)

European Organisation for ITER & the Development of Fusion

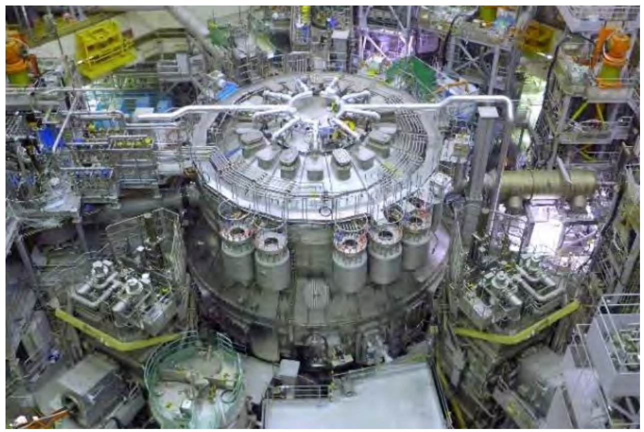
- **Fusion for Energy (F4E) is European organisation for the Development of Fusion with three missions:**
  - **European Domestic Agency for ITER**
  - **European Agency for Broader Approach**
  - **Prepare Programme for DEMO & IFMIF-DONES**
- Headquarters: Barcelona (Spain)
  Offices: Cadarache (France) & Garching (Munich)
- Staff: ~465 highly competent team of engineers and project managers with new organisation structure
- Budget: €5.6 billion 2021-2027
- Chair: Carlos Alejaldre
  Director: Marc Lachaise (since May 2023)

European Supply Chain has Delivered

FUSION FOR ENERGY



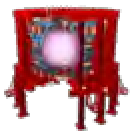



Europe Leading the Way

Pioneering the World's Most Advanced Fusion Facilities

FUSION FOR ENERGY



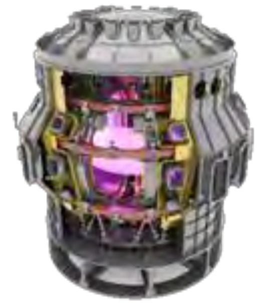
ASDEX
13m³
(1991 -)

WEST
15m³
(2016 -)

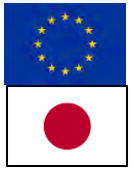
DTT
28m³

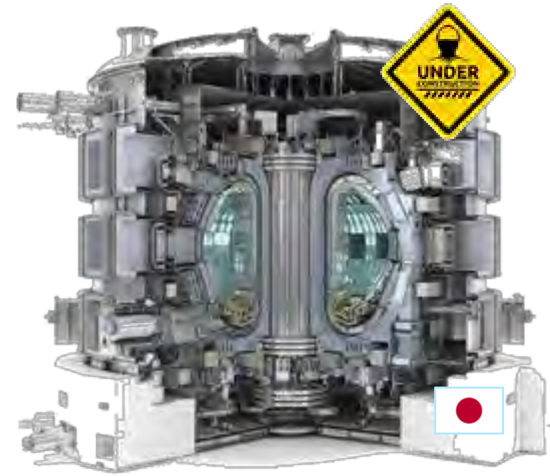
W7-X
30m³
(2015 -)

JET
100m³
(1983-2023)



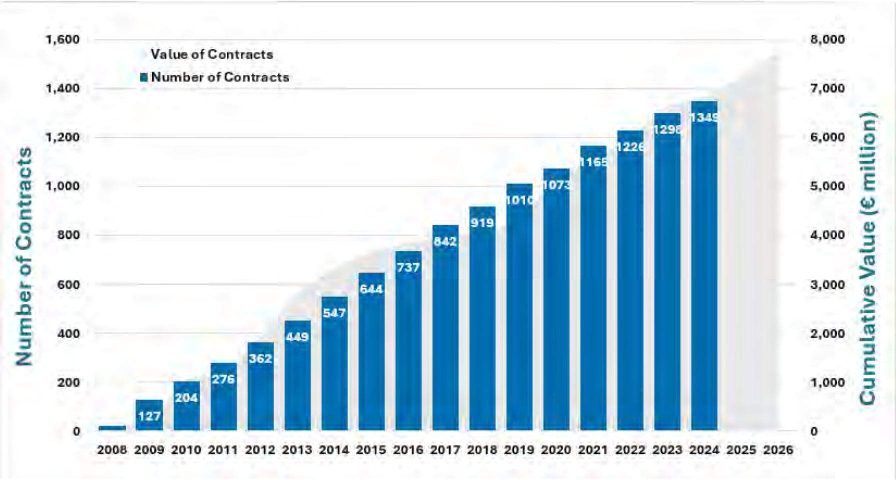
JT-60SA
135m³
(2023-)





ITER
840m³

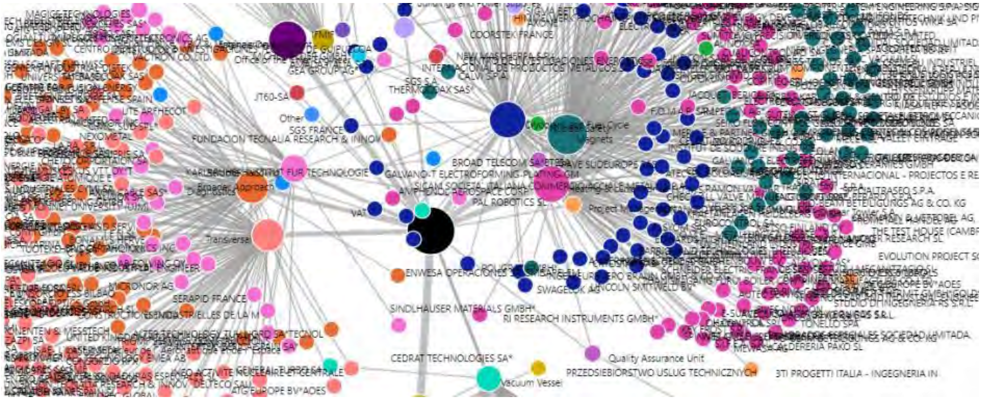
EU Supply Chain - over >2000 companies with €7bn investment to build ITER components



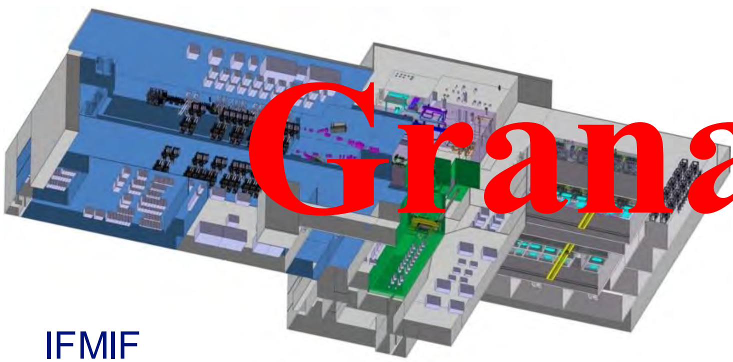
- Over €7bn of procurement
- >1200 contracts
- >2100 subcontractors
- >700 industries
- >75 research organisations

- 2350 Companies mapped
- 796 Main contractors
- 200+ Technologies mapped
- 23 EU Countries

… and growing

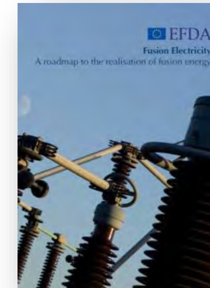


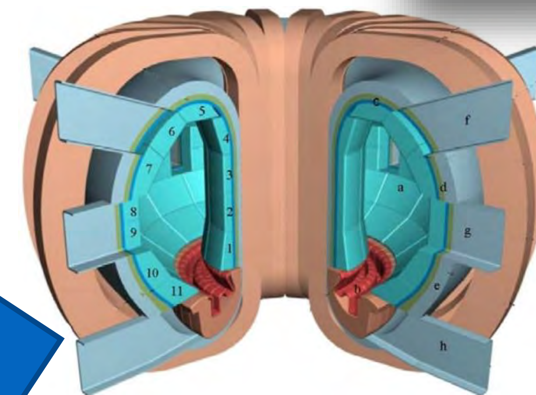
EUROPEAN ROADMAP TO NUCLEAR FUSION ENERGY



Granada

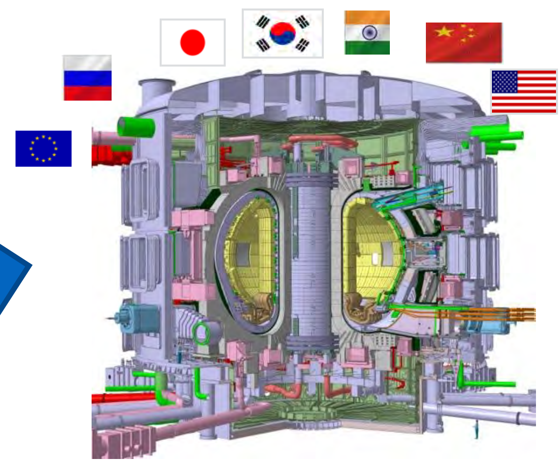
IFMIF
2 D+ beams, 40 MeV, 125 mA on a Li target





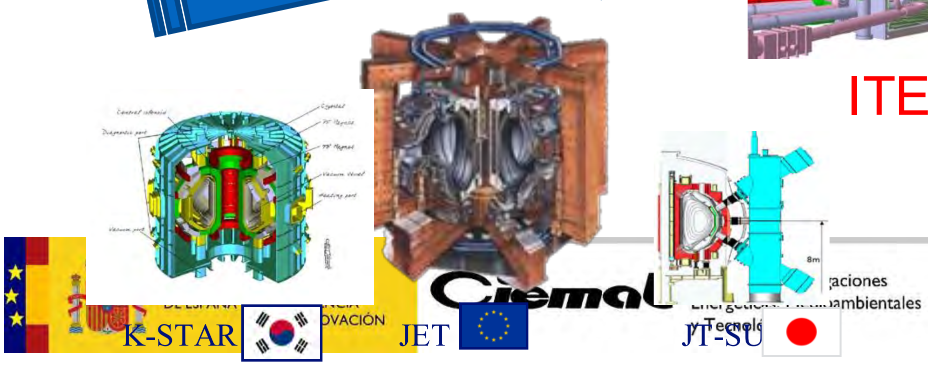
“DEMO” ≥ 500 MW_{el}

1 – 2 hours



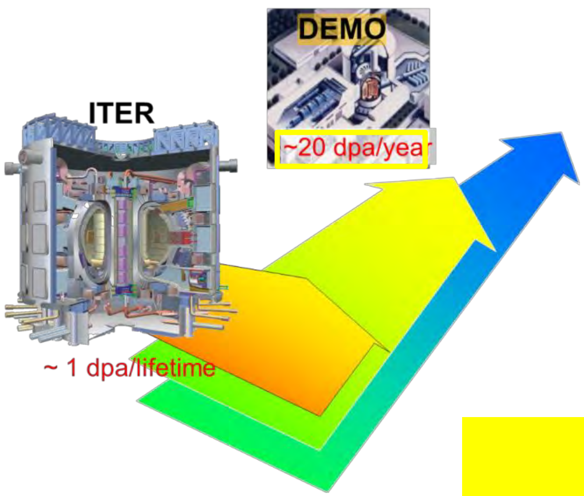
ITER – 500 MW_{th}

300– 500 secs



IFMIF- DONES

One of the main differences between ITER and DEMO is the radiation dose: at DEMO more than two orders of magnitude higher



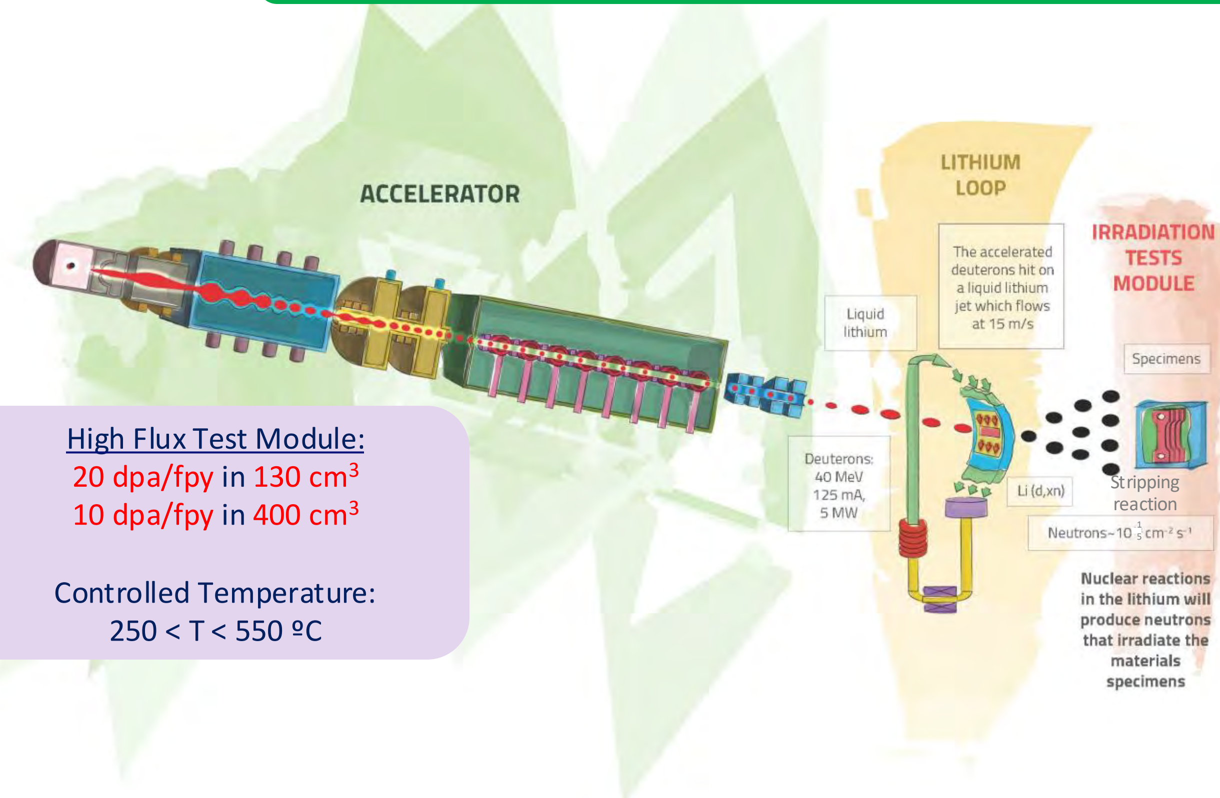
- Selection and qualification of candidate materials for fusion reactors
- Generation of engineering data for design, licensing and safe operation of DEMO up to end-of-life
- Completion, calibration and validation of databases (mainly generated from fission reactors research)
- Material testing and simulation carried out simultaneously to correlated fundamental understanding of radiation response of materials

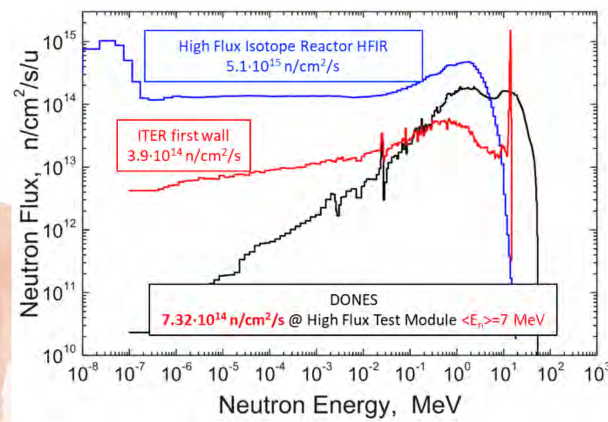
But also of interest in other scientific areas (nuclear physics, medical and industrial applications,…) due to its unique characteristics

Identified as high priority in the EU Fusion Roadmap
Included in the ESFRI Roadmap as a EU strategic facility

IFMIF-DONES

An accelerator based fusion-like neutron source to be used for the qualification of the materials to be used in the DEMO Reactor



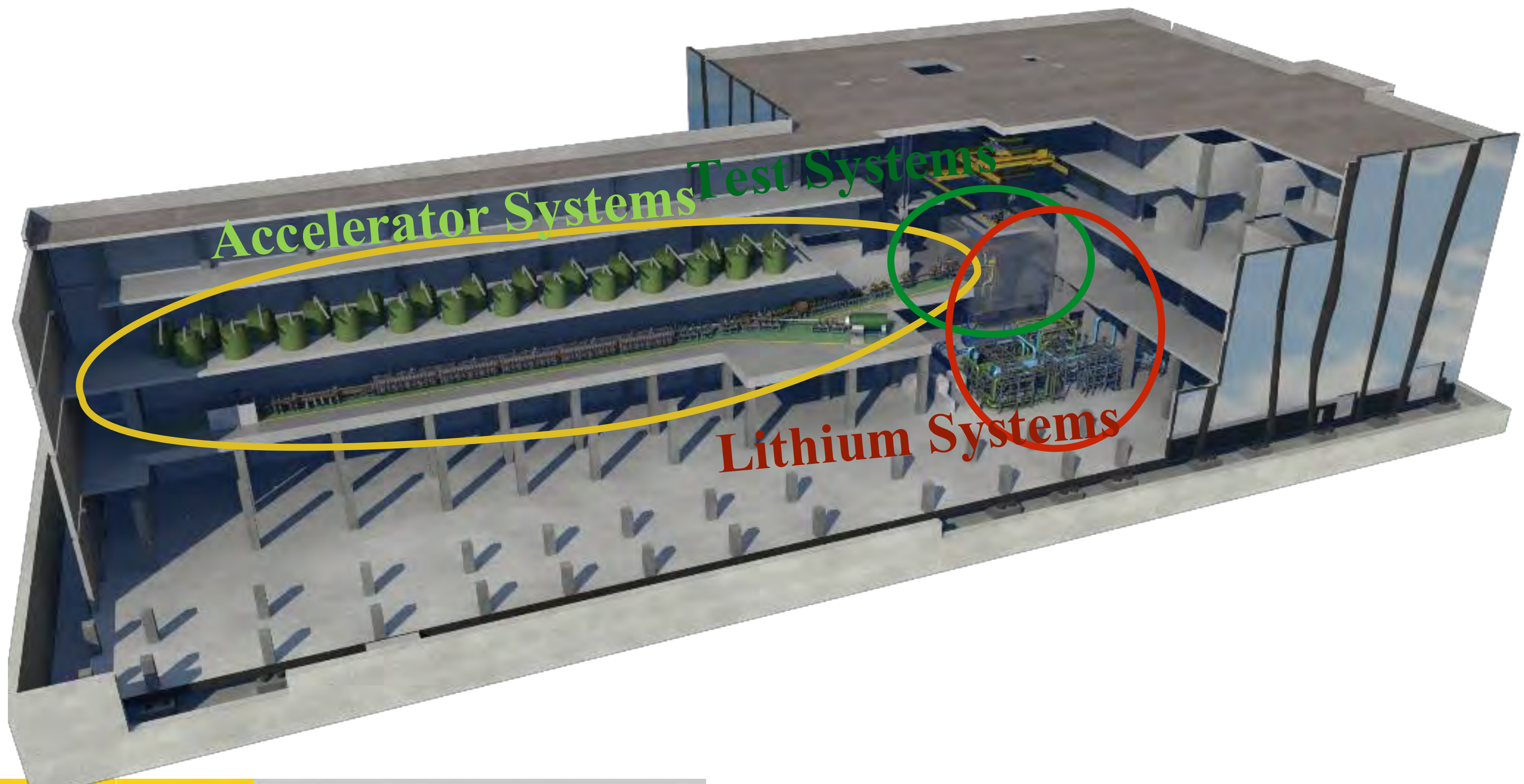


High Flux Test Module:
20 dpa/fpy in 130 cm^3
10 dpa/fpy in 400 cm^3

Controlled Temperature:
250 < T < 550 ºC

A neutron flux of ~ 10^{14} $n/cm^2/s$ is generated with a neutron spectrum up to 55 MeV energy

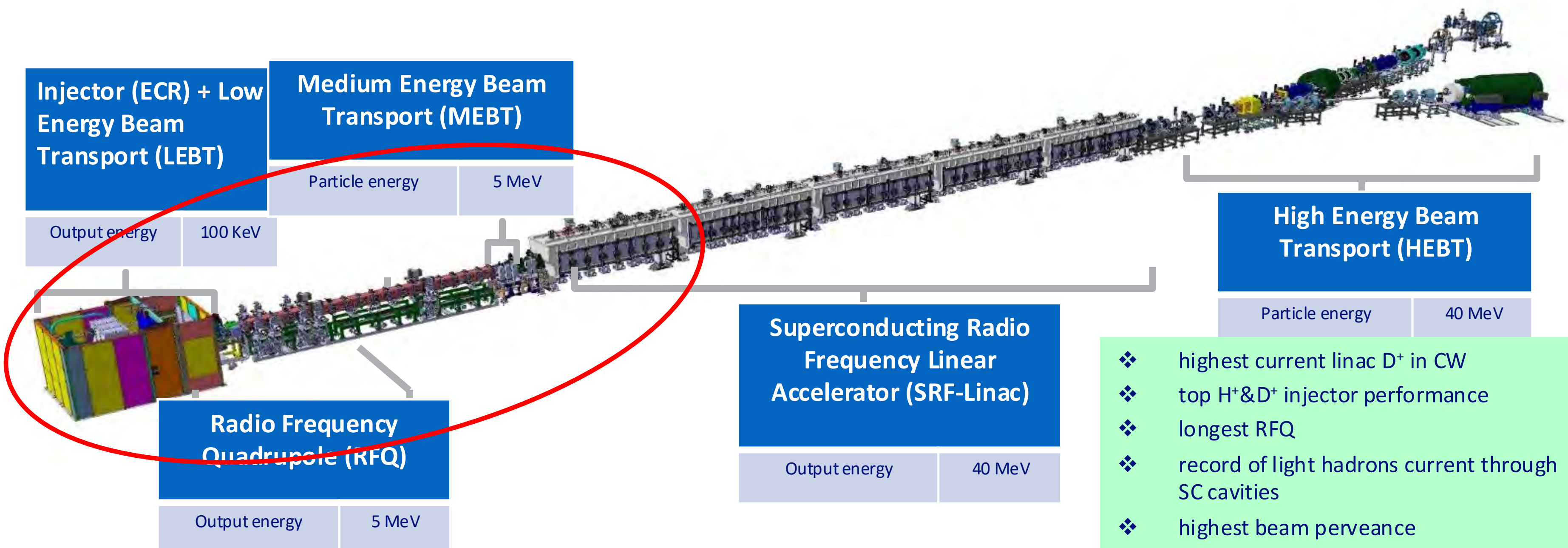
Overview of the Facility



Accelerator systems summary

175 MHz, 5MW, 125 mA, CW, high availability: One of the more powerful accelerators in the world

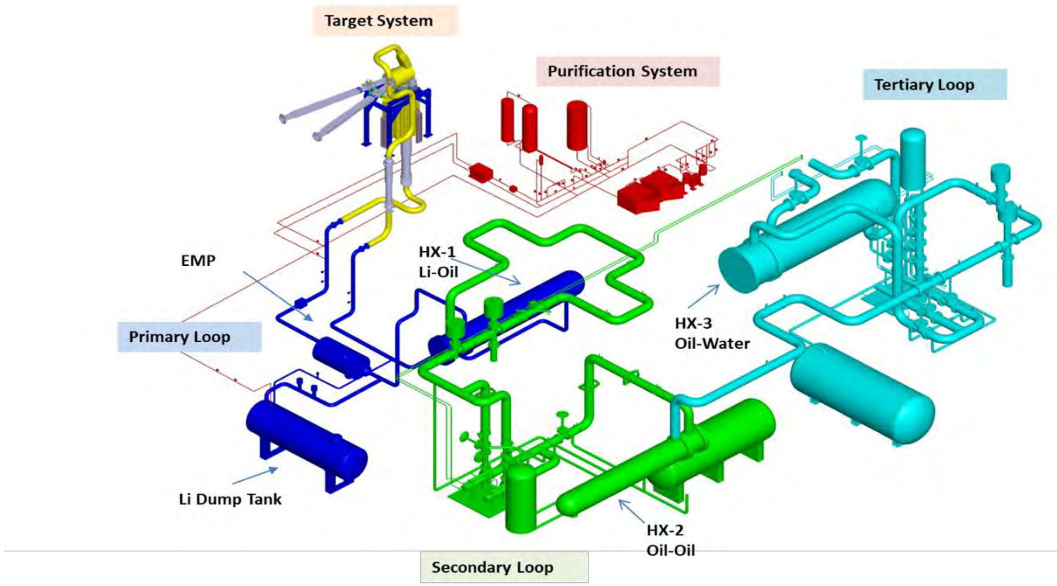
Waiting for validation results from IFMIF-EVEDA: LIPAc Prototype (Rokkasho)



- highest current linac D^+ in CW
- top H^+&D^+ injector performance
- longest RFQ
- record of light hadrons current through SC cavities
- highest beam perveance

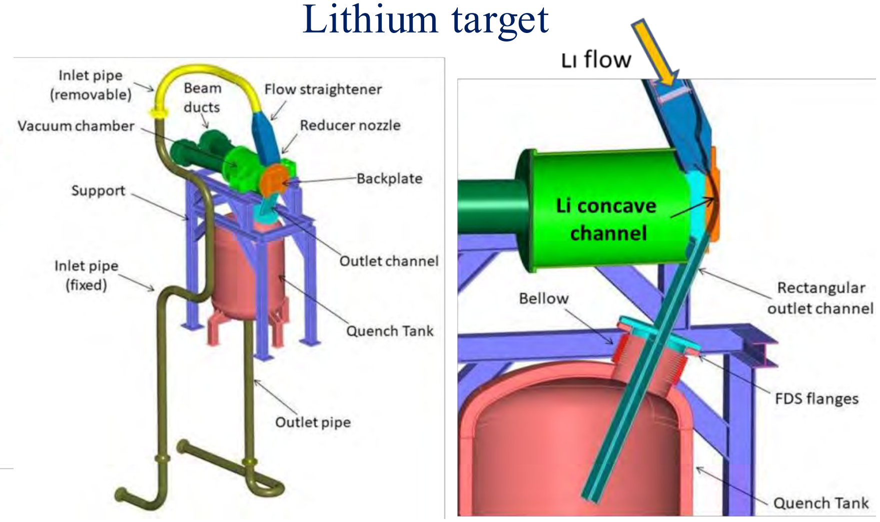
Lithium Systems

5 MW power handling, 15 m/s Li velocity, remote handling
Main requirements: Li flow stability and Li impurities control



Li volume ~14 m^3
Li flow rate ~100 l/s
Li temperature (cold side) ~300 °C

Lithium target



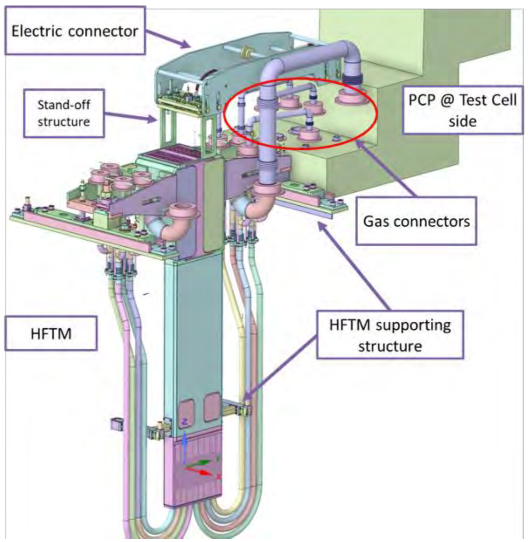
Jet thickness: 25±1 mm Li flow velocity: 15 m/s
Chamber pressure: 10^{-3} Pa Heat flux: 500 MW/m^2

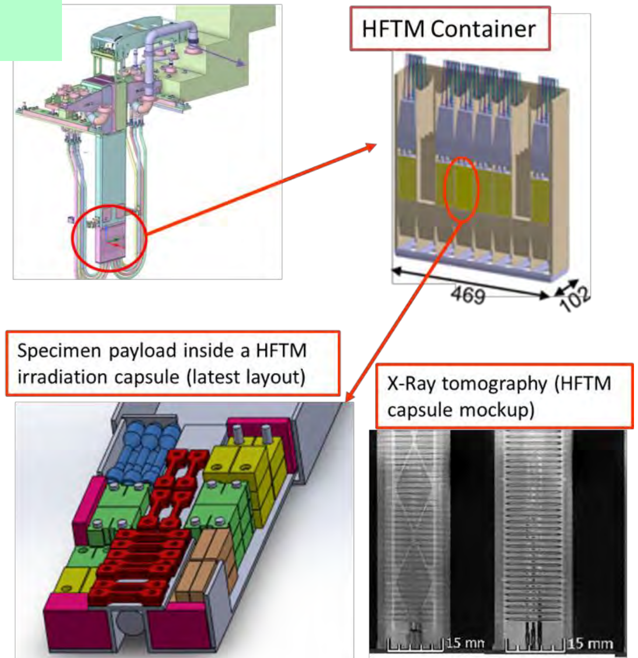
Test Systems

Main characteristics driven by the presence of neutrons and Li

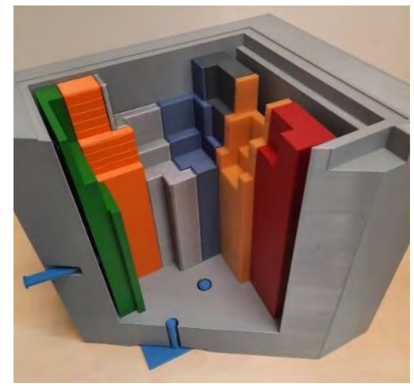
- **Internal components cooling by He**
- **Remote Maintenance required**

HFTM upper part





More than 850 specimens can be hold in the HFTM !!



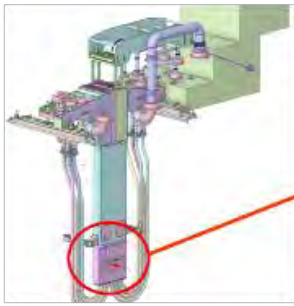
Test Cell Removable Shielding Blocks (Maintainability and minimizing neutron streaming)

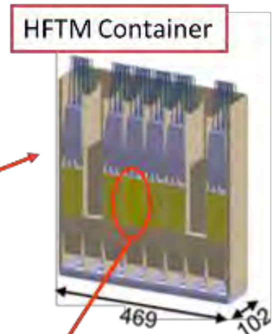
HFTM for materials qualification

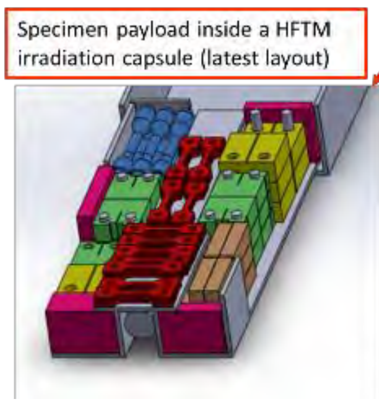
Present baseline design activities focuses on the High Flux Test Module (HFTM) for high-priority structural materials irradiation

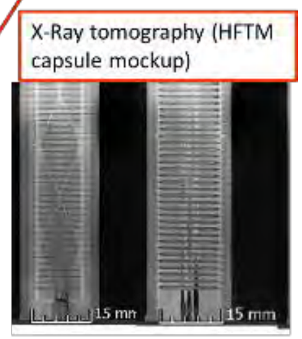
Objective: to irradiate a large volume of SSTT samples in the high flux region of DONES
First-to-be-installed irradiation experiment (critical path).

- Heating: Nuclear **2.3 W/g peak**, 17 kW tot., 1.5 kWe per capsule
- Cooled by **low pressure helium** gas (0.3MPa, 50°C), **Sodium** heat transfer filler
- Lifetime: 1year / 2.5 years (**53 dpa**).
Body made from **316LN** (acc. RCC-MRx)









Steel irradiation

- 13-35 dpa/fpy up to 300 cm³ (22-50 dpa/fpy with two accelerators)
- 10-15 appm He / dpa, 45-55 appm H / dpa.
- 250 – 550 °C, sodium immersed specimens

Copper irradiation (divertor heat sink)

- 5–30 dpa/fpy
- 6–8 appm He/dpa is (~DEMO), 48–50 appm(H)/dpa (~1.4x DEMO)
- >100°C, helium immersed specimens

Tungsten irradiation (armor)

- Up to 800°C, assisted by self-heating
- 8x20 cm³ (cylindrical HT capsules)
- 1–3 dpa/fpy in W
- 9–10 appm He / dpa, (2x of DEMO),
20–29 appm H / fpy, (3x of DEMO)

Adaptation for ODS-Steels and vanadium materials can be easily implemented

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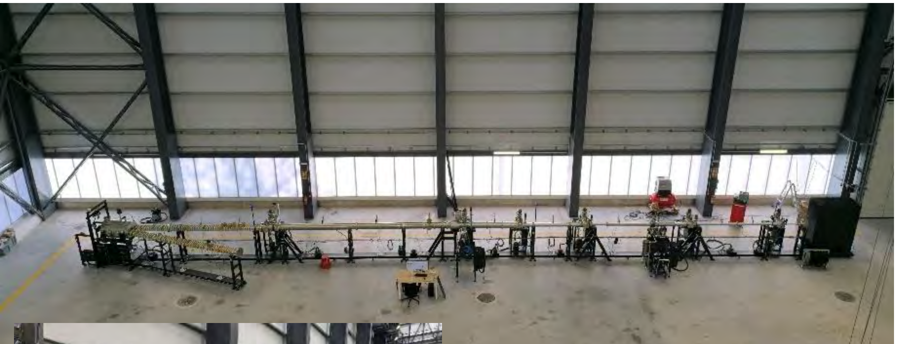
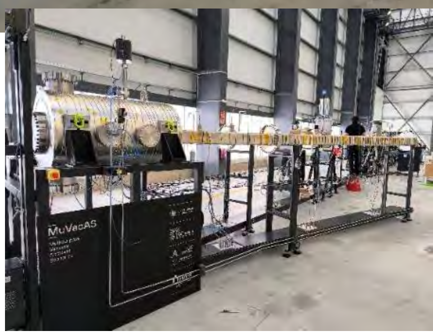
Experimental prototypes & tests



LITEC for developing lithium impurities trapping technologies



MuVACAS

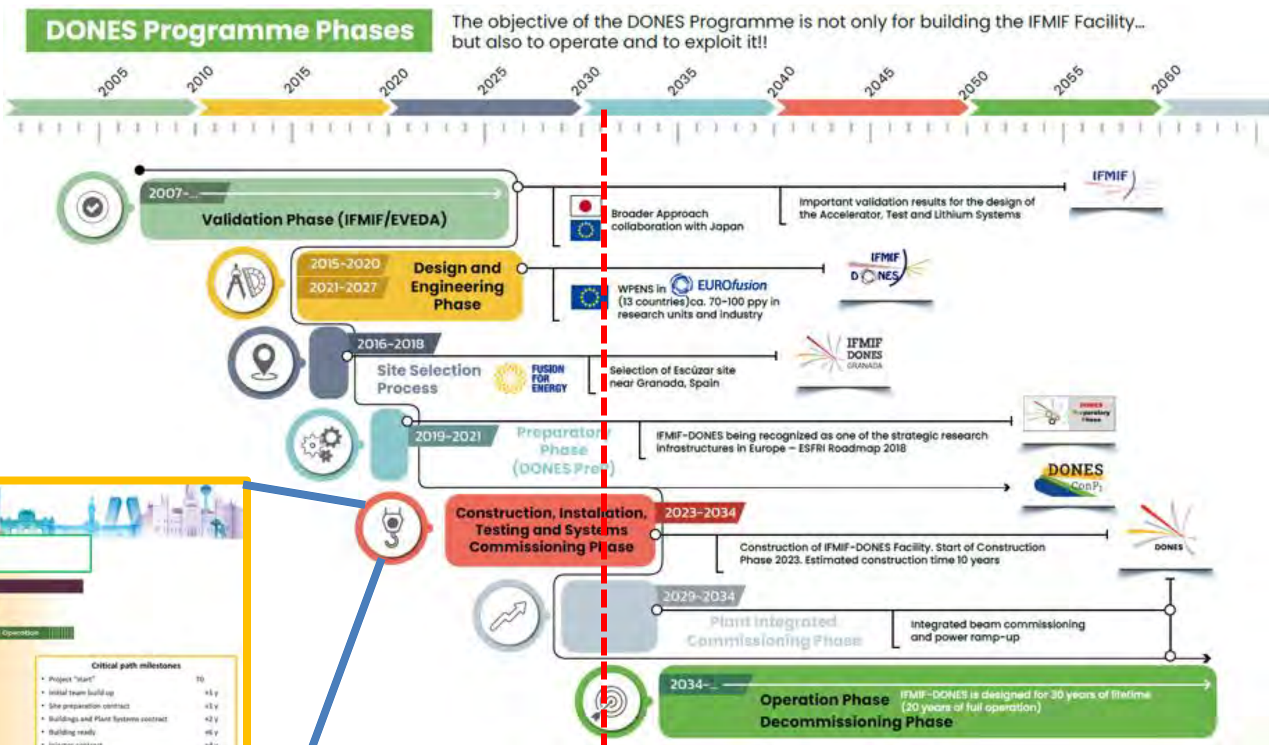
STUMM-PROTO

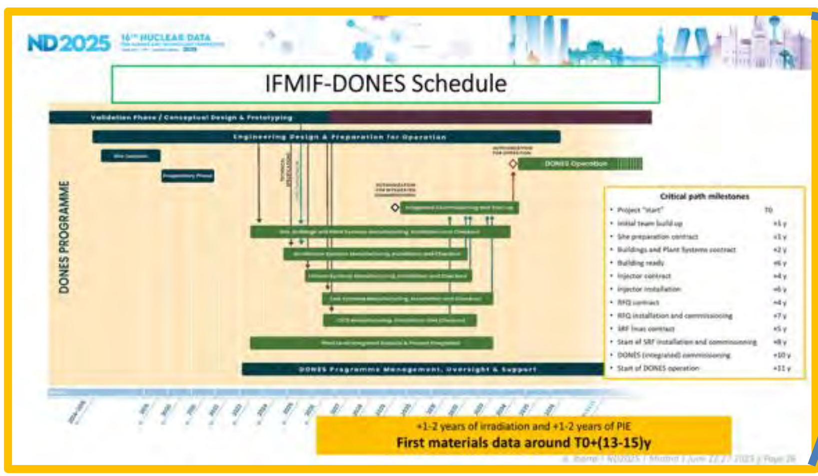
Quick Disconnecting System (QDS): To validate RH connection system at the target

Site Status

DONES

IFMIF-DONES ESPAÑA





DONES

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ESPAÑA

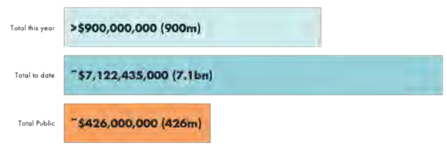
FUSION
INDUSTRY ASSOCIATION

The global fusion industry in 2024

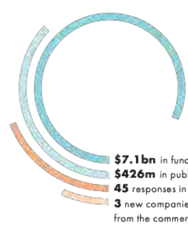
Fusion Companies Survey by the Fusion Industry Association

HIGHLIGHTS TO DATE

1. Total funding*



2. Change since 2023 survey



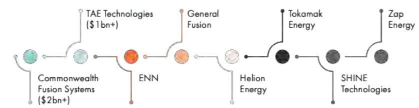
$7.1bn in funding, compared to **$6.2bn** at time of 2023 survey
$426m in public funding, compared to **$271m** in 2023
45 responses in 2024 vs **43** in 2023
3 new companies emerged and added to our survey, while one withdrew from the commercial industry.

* Some figures have been converted to dollars/rounded

3. Notable investments since 2023 survey*

* Several other large investments have not yet been publicly announced so are not included here

4. Companies with $200m investment or more

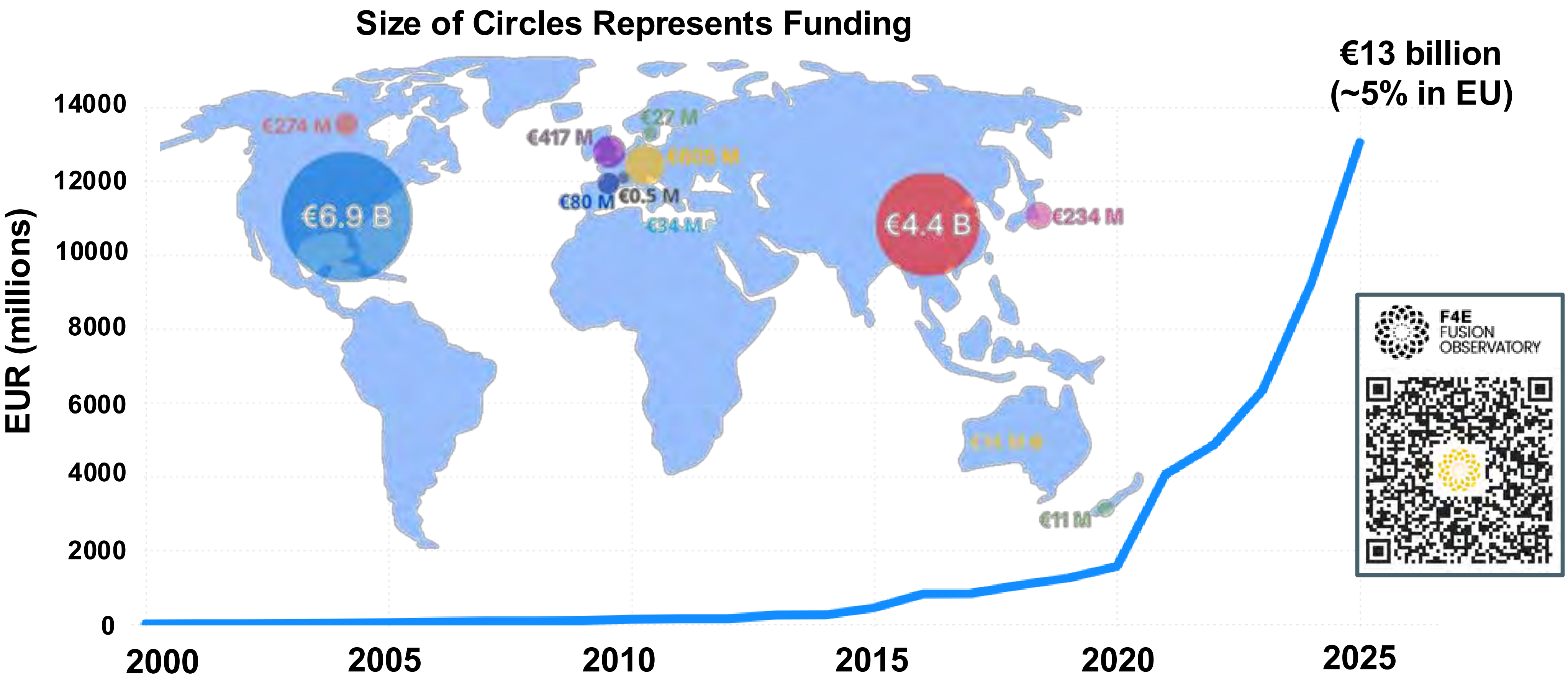


5. Location

By primary HQ

Private Fusion Investment in Booming

Can Europe Compete in the Fusion Start-up Era?



Private Fusion Investment Flows

US Fusion Ventures attracting EU investment

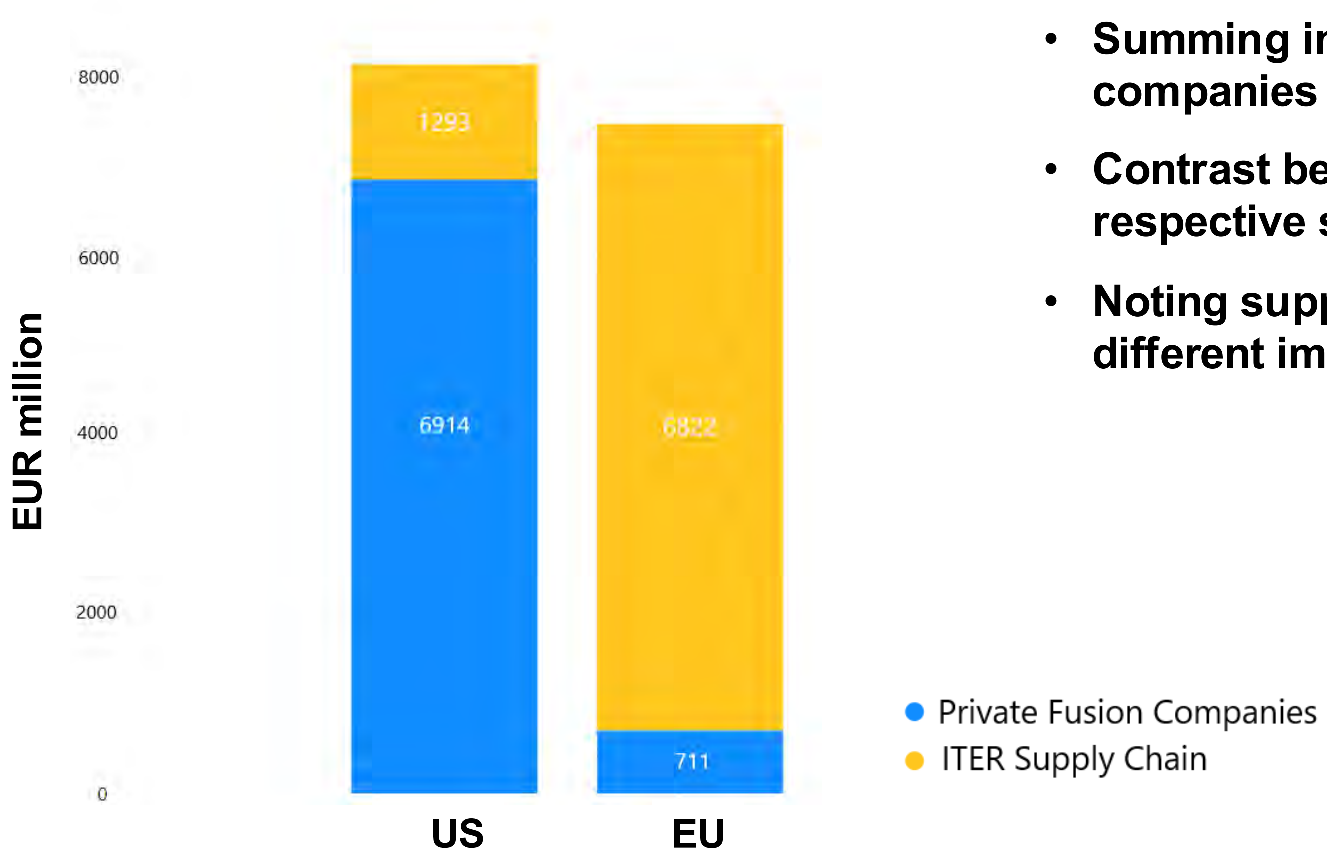
€160 million flows from EU to US fusion ventures

F4E FUSION OBSERVATORY

Total Investment Flows to Companies

EU's Strength Lies in its Supply Chain

FUSION FOR ENERGY



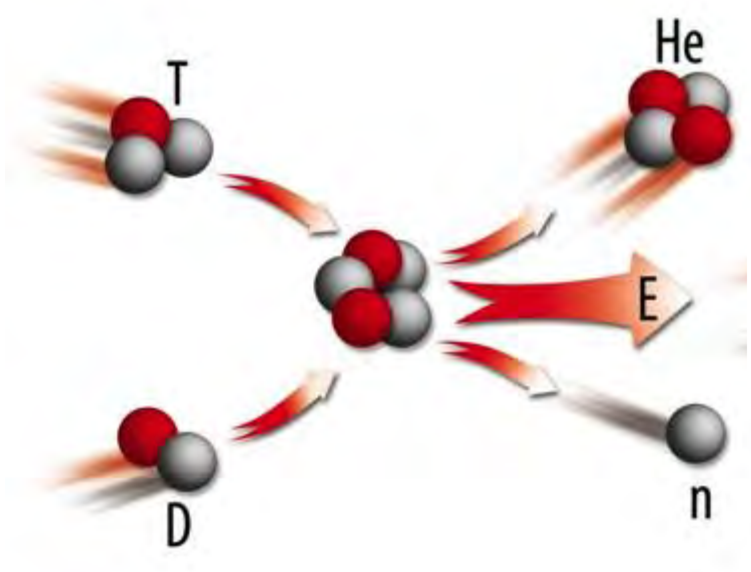
- **Summing investment in private fusion companies & ITER supply chain**
- **Contrast between USA & EU shows respective strengths**
- **Noting supply chain investment has different impact than fusion companies**

F4E FUSION OBSERVATORY

Is ITER a nuclear installation?

FUSION FOR ENERGY

The nuclear classification of ITER is due to:



- **Tritium inventory**

4 Kg (nuclear fuel for ITER)

- **Radioactive waste**

Very low (52%), low (39%) and medium activity/long life (9%)

41.688 Tons

(operation+dismantling)

The radioactive inventory classifies ITER in France as a

BASIC NUCLEAR INSTALLATION

ITER SAFETY FUNCTIONS

ITER has two safety functions:

- ➔ Confinement radioactive materials
- ➔ Limitation of radiation exposure

- There is no safety function associated to:
  - **Control of the fusion reactions.**
  - **Power dissipation (cooling systems)**

Safety Analysis

Internal Risks

- **Internal fire**,
- **Internal explosion**,
- Thermal deviations
- **Plasma transients**,
- Internal inundation,
- Missile effects,
- Whipping pipe,
- Mechanical risks,
- risques chimiques
- Magnetic and electromagnetic perturbations

External Risks

- **Seismic,**
- **Extreme climatic conditions, like hot weather, extreme cold, rain, snow, wind and lightening,**
- **External inundation,**
- **External fire ,**
- **Plane crash,**
- **Accidents associated to the industrial environment and transport routes, mainly external explosions,**
- **Accidents in a nearby installation at the site of CEA Cadarache.**

Design Basis Accidents

V1	In-vessel FW pipe leakage
X6	Heat exchanger leakage
X1	Loss of divertor heat sink
X2	Pump trip in divertor HTS
T1	Tritium process line leakage
L1	Loss of off-site power for 32 hours
	blackout for 1 h in Hot cell
V2	Multiple FW pipe break
	Multiple FW pipe break + 10 DV pipes break
V3	Loss of vacuum through one VV/cryostat penetration line (500 MW)
	Loss of vacuum through one VV/cryostat penetration line (700 MW)
X3	Pump seizure in divertor
X7	Heat exchanger tube rupture
X4	Large VV coolant pipe break (ACP mass is reduced 100 times: it is lower than in FW/BLK loop by factor 100)
	baking

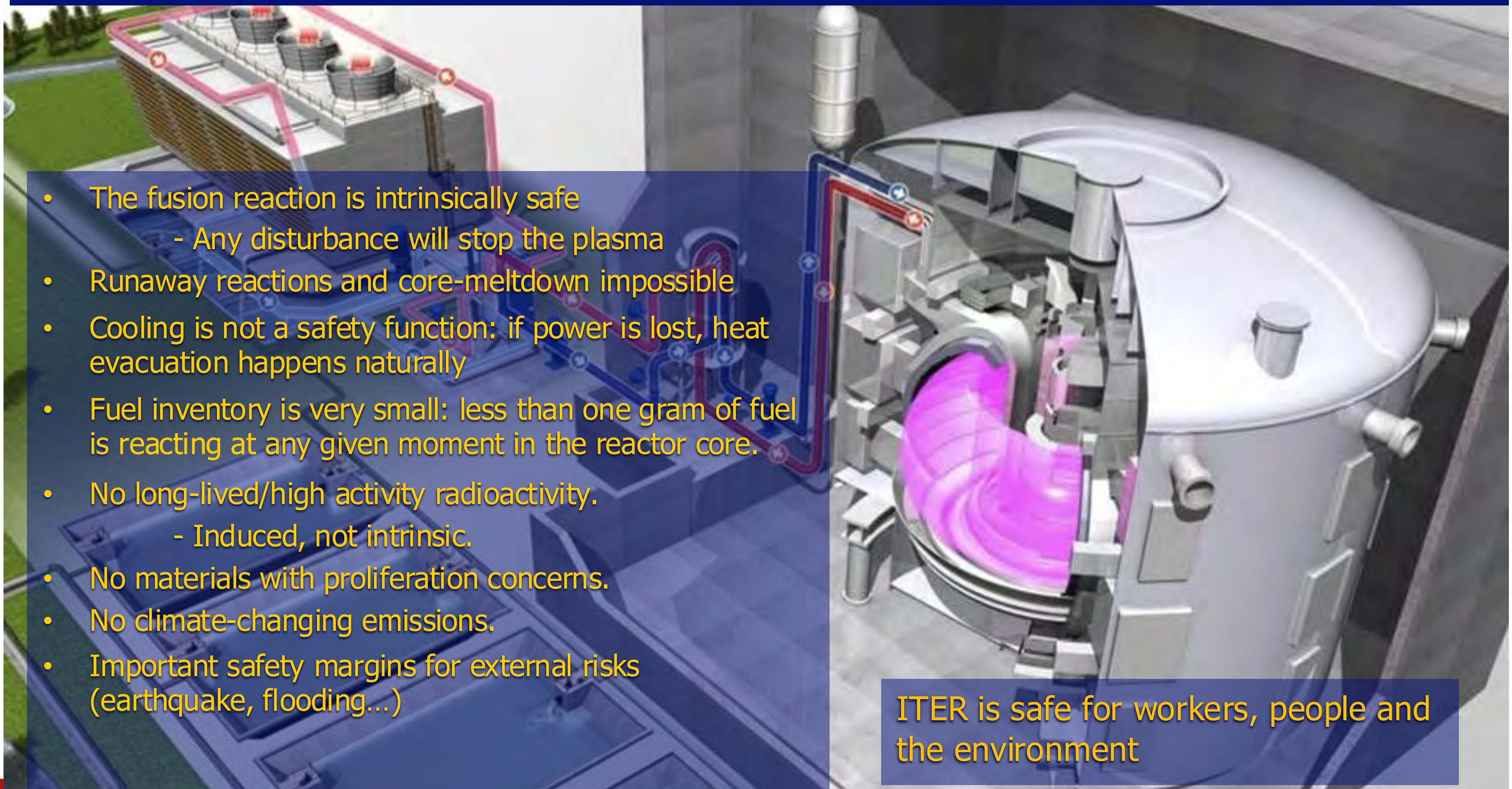
X5	Large DV ex-vessel coolant pipe break
	baking (controlled releases means through the stack and releases shall be multiplied by filtering factor)
X8	Coolant pipe break inside Port Cell (normal operation)
	baking, valves close
E1	Stuck divertor cassette and failure of cask
T2	Failure of transport hydride bed
T3	Isotope separation system failure
T4	Failure of fueling line
T5	Leak of tritiated water from WDS
M1	Toroidal field coil short
M2	Arc near confinement barrier
C1	Cryostat air ingress
C2	Cryostat water ingress
C3	Cryostat helium ingress
H1	Loss of confinement in hot cell

SAFETY ISSUES

- ANNUAL DOSE IN NORMAL CONDITIONS < 10 µSv at 200 m
  Long term < 3µSv
- MAXIMUM DOSE IN DESIGN BASIS ACCIDENT < 100 µSv at 200 m
  Long term < 17.6 µSv
- DUST EXPLOSION IN VACUUM VESSEL 332 µSv at 200 m
  BEYOND DESIGN ACCIDENT Long term < 200 µSv
- OTHER BEYOND BASIS ACCIDENTS ALSO SHOW LOW IMPACT AND NO "CLIFF EDGE" EFFECT:
  - ✓ Fire in tritium plant following failure of fire protection provisions: Maximum public dose 1.1 mSv (short term, 200m).
    Long term: 200 µSv
  - ✓ Worst event ("wet bypass"): max dose 4 mSv (short term, 200m),
    Long term: 130 µSv

How safe is ITER?

A Fukushima-like accident is impossible in ITER



- The fusion reaction is intrinsically safe
  - Any disturbance will stop the plasma
- Runaway reactions and core-meltdown impossible
- Cooling is not a safety function: if power is lost, heat evacuation happens naturally
- Fuel inventory is very small: less than one gram of fuel is reacting at any given moment in the reactor core.
- No long-lived/high activity radioactivity.
  - Induced, not intrinsic.
- No materials with proliferation concerns.
- No climate-changing emissions.
- Important safety margins for external risks (earthquake, flooding…)

ITER is safe for workers, people and the environment

nature energy

PUBLISHED: 31 OCT

Identification of safety ga demonstration reactors

Y. Wu[1]*, Z. Chen[1], L. Hu[1], M. Jin[1], Y. Li[1], J. Jiang[1], J. Y
D. Maisonnier[5], A. Kalashnikov[6], K. Tobita[7], D. Jack

To assist in the development of nuclear fusion as a viable co demonstration reactor (DEMO), which will build on the work o advanced nuclear energy systems, DEMO must satisfy several ronmental impact, high reactor availability, a closed fuel cycle still large scientific and technological safety gaps between the Here we review international fusion safety research and devel from ITER. We identify the main scientific and technological s sion energy, in particular Generation IV (Gen-IV) fission react for the design and operation of DEMO.

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Box 3 | Main gaps in ensuring the safety of DEMO.

Accidents

- Large gaps in component failure rate data needed for evaluating accident probabilities must be filled.
- Hydrogen/dust explosions need to be fully addressed to protect confinement barriers such as the vacuum vessel and building walls.
- Electromagnetic loads due to plasma disruptions need to be better understood.
- Decay heat removal may need to be developed as a safety function.
- Comprehensive consideration of design extension conditions and enhanced confinement is required to meet the 'no off-site emergency response' criterion.

Radioactive material for potential release

- Tritium operational release limits in ITER have never been verified, leaving this limit in DEMO unknown.
- R&D on the fraction of tritium burned in the plasma needs to be further enhanced to reduce the tritium inventory.

Occupational radiation exposure

- Remote handling technology required for maintenance operations must be developed and the design choices of DEMO must be optimized, to minimize occupational radiation exposure to workers.

Radioactive waste

- Low-activation materials must be ready for use in DEMO.
- Improved understanding of tritium retention in materials is needed, as is the development of detritiation systems (for example thermal furnace, fusion furnace).

Personal final comment

Plasma physics era has been essentially fulfilled (TRL 1-4?)

Nuclear Fusion Technology **Era** (TRL 4-9)

- Materials development and validation in a high flux neutron/particles environment
- Steady State
- Tritium fuel breeding and handling (inventory issues/accountancy)
- Heat exhaust/divertor
- Neutron & radiation shielding
- Remote handling/maintenance
- Nuclear safety integration/analysis/regulation
- Waste management/hot cell/tritiated waste
- Industry supply chain

From Stephen Hawking
"Brief Answers to the Big Questions", 2018

" Q: What world-changing idea, small or big, would you like to see implemented by humanity?

A: This is easy. I would like to see the development of fusion power to give an unlimited supply of clean energy! "

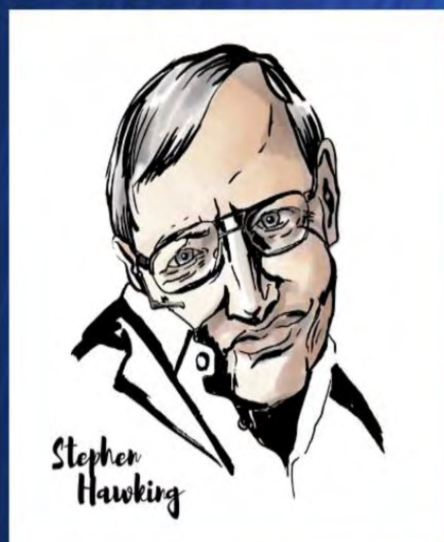

Image courtesy of Shutterstock