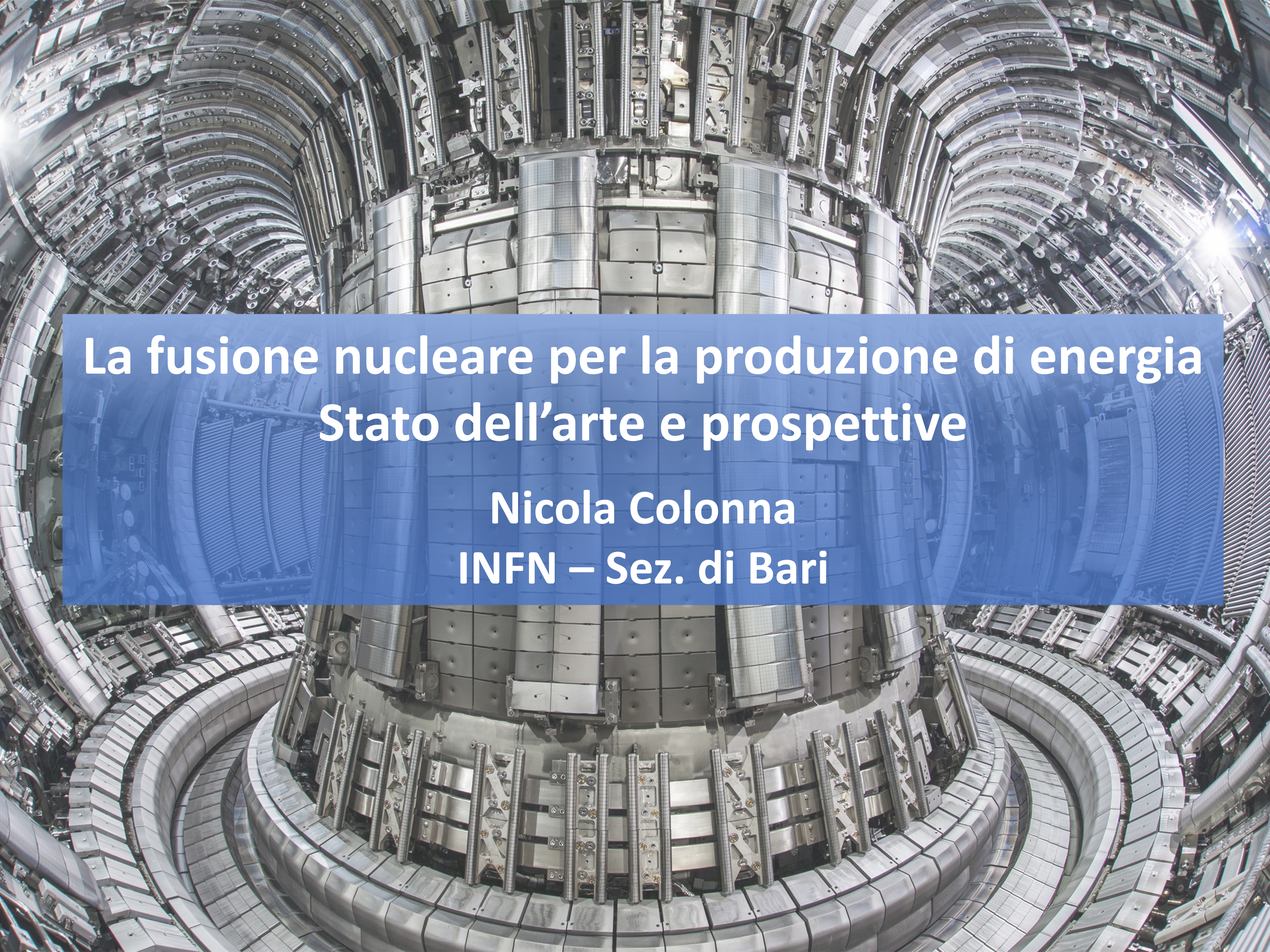
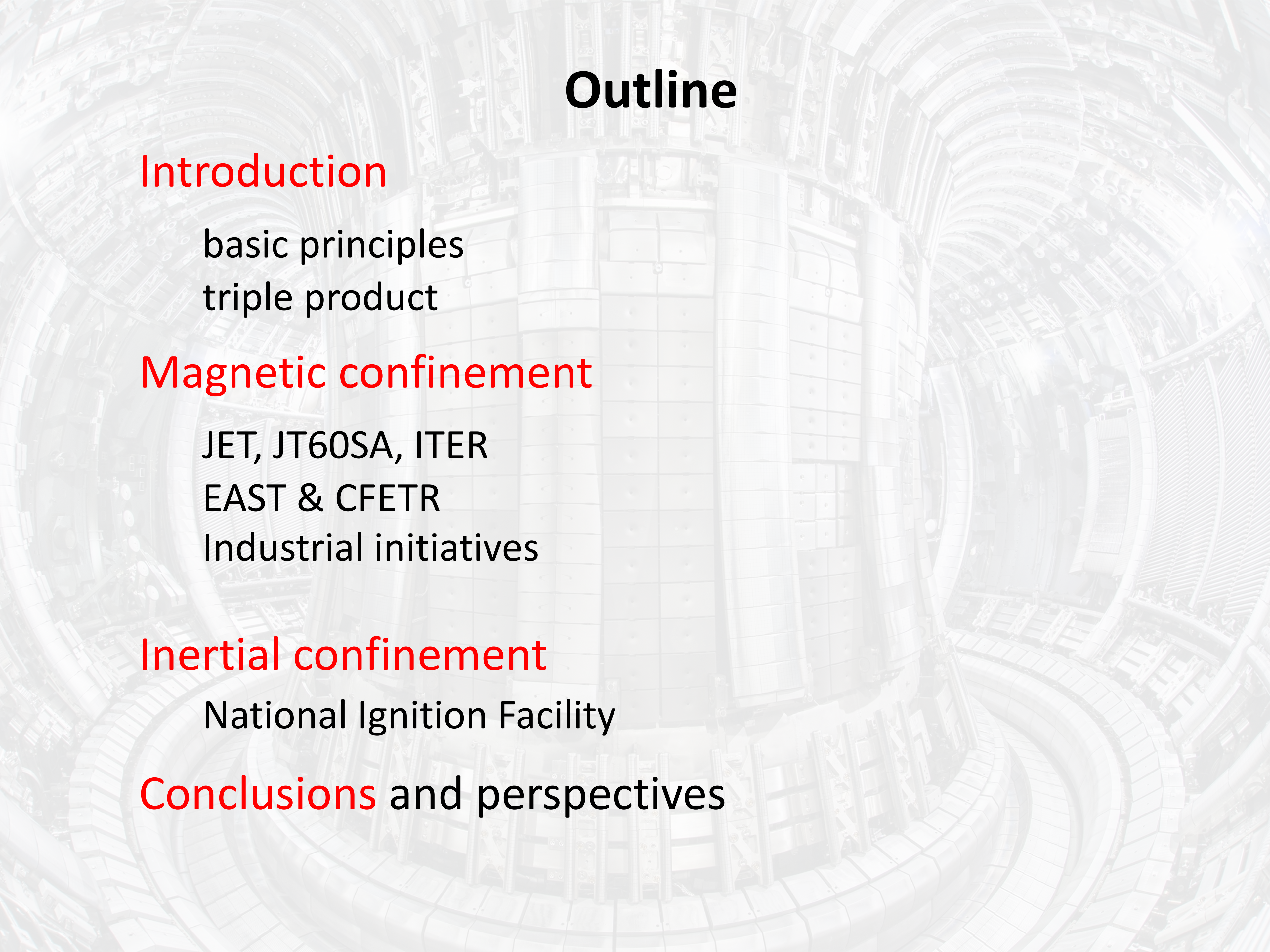


La fusione nucleare per la produzione di energia
Stato dell’arte e prospettive

Nicola Colonna
INFN – Sez. di Bari

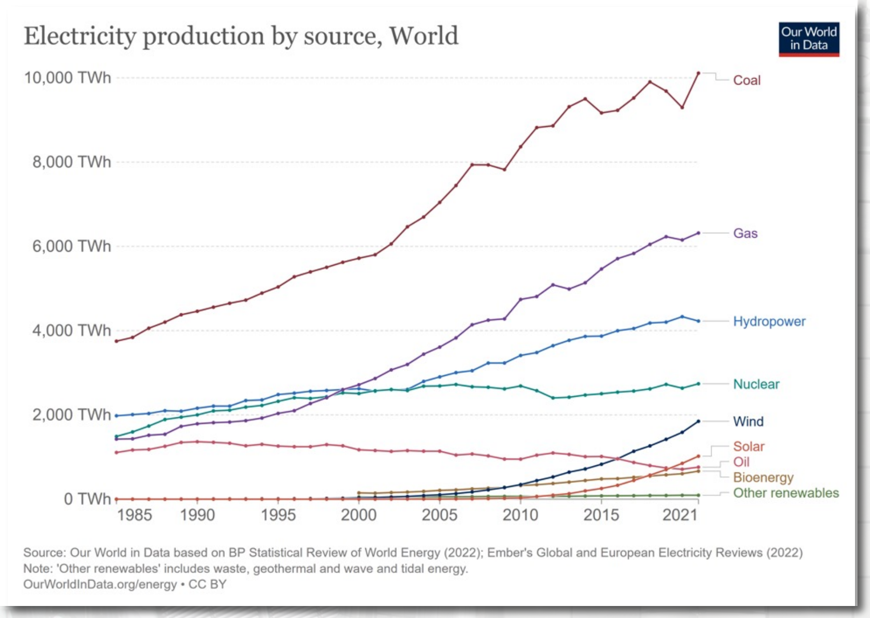


Outline

- Introduction
  - basic principles
  - triple product
- Magnetic confinement
  - JET, JT60SA, ITER
  - EAST & CFETR
  - Industrial initiatives
- Inertial confinement
  - National Ignition Facility
- Conclusions and perspectives

The energy consumption and production

Hannah Ritchie, Max Roser and Pablo Rosado (2022) - "Energy". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/energy' [Online Resource]


Electricity production by source, World

Source: Our World in Data based on BP Statistical Review of World Energy (2022); Ember's Global and European Electricity Reviews (2022)
Note: 'Other renewables' includes waste, geothermal and wave and tidal energy.
OurWorldInData.org/energy • CC BY

The energy consumption in the world is steadily increasing (almost linearly), almost doubling in 40 years.

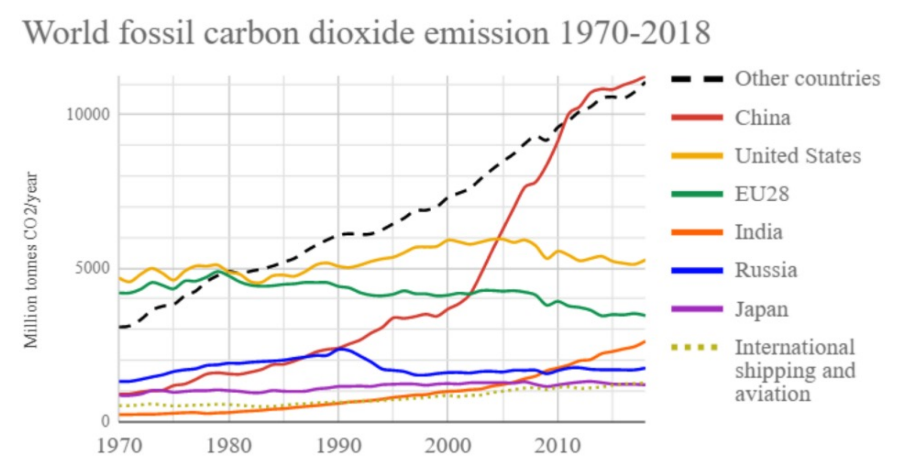
Fossile fuels still provide about 80% of the energy request.

Renewable sources are growing, but still largely insufficient.

All predictions indicate that the energy demand is going to continue growing in the next decades.

Nuclear power has a low public acceptance (mostly because of probability of accidents and waste disposal).

Renewable sources have problems of availability and low power intensity (land occupancy).


World fossil carbon dioxide emission 1970-2018

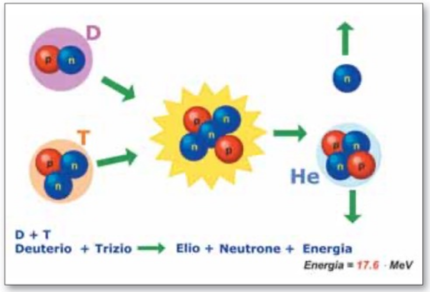
Need to find alternative energy sources.

Nuclear fusion

FUEL: *abundant and available everywhere in the world*

Deuterium: from sea water, enough for million of years

Tritium – Very little quantity in Nature, but it can be produced in the reactor (n+Li). Litihium reservoirs in mines sufficient for thousands of years, millions of years if extracted from the oceans.



SAFETY: *no risks of severe accidents*

No possibility of uncontrolled reactions, the necessary conditions for sustained reactions are always under human control.

ENVIRONMENTAL POLLUTION: *low greenhouse gas and radioactivity*

Low emission of CO_2 and other greenhouse gases (mostly in the construction phase).

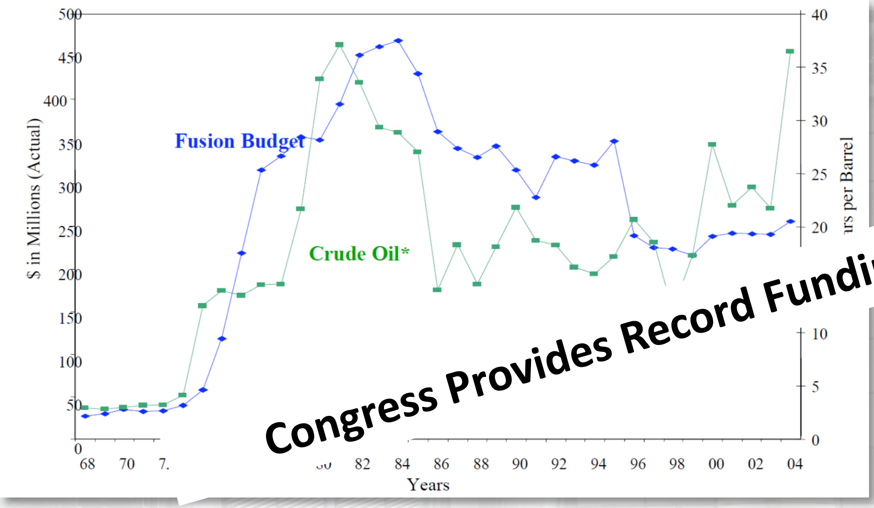
In normal operating conditions, radioactivity outside the reactor is <1% of the natural radioactivity level. In case of severe accident, no long-term radiotoxicity (actinides in fission reactors).

NUCLEAR WASTE & DECOMMISSIONING: *No long-term radioactive waste*

Tritium has a half-life of 12.5 years

Activation products (structural material) have short half-life, after 100 year from the stop, 80% of the materials are clean and can be recycled.

Fusion research



Congress Provides Record Funding for Fusion Energy in 2023

Interest in fusion ener is directly correlated to r fossile fuel sourc

ever, it requires a large effort, budget and time.

Last year record budget in the US of 2.8 B$ (accelerate commercial fusion energy)

Development of nuclear fusion reactors for energy production requires scientific and technologic advances in a variety of fields:

- Nuclear physics
- Plasma Physics
- Magneto Hydro Dynamics (MHD)
- Material Science
- Superconductive Magnet technology
- Particle accelerators
- Etc…

Fuel and reactivity

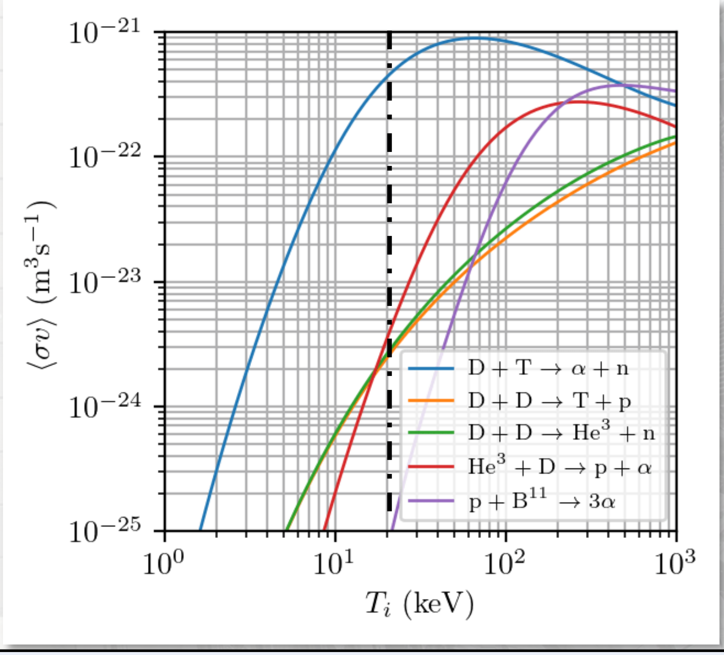
The power density produced in a reactor with a plasma of ion density n is given by:

$$P_{fus} = \frac{1}{4} E_R n^2 \langle \sigma v \rangle \quad W/m^3$$

$<\sigma v>$ is the velocity averaged cross section (VACS): $< \sigma v > = \int f(v)\, \sigma(v)\, v\, dv$

$< \sigma v >$ also called "reactivity“
(power per unit plasma density)

Reaction	E_R (MeV)
$D+D \rightarrow {}^3He + n$	3.28
$D+D \rightarrow {}^3H + p$	4.04
$D+T \rightarrow {}^4He + n$	17.6
${}^3He+{}^3He \rightarrow {}^4He + 2p$	12.86
$p+{}^{11}B \rightarrow 3\ {}^4He$	8.7

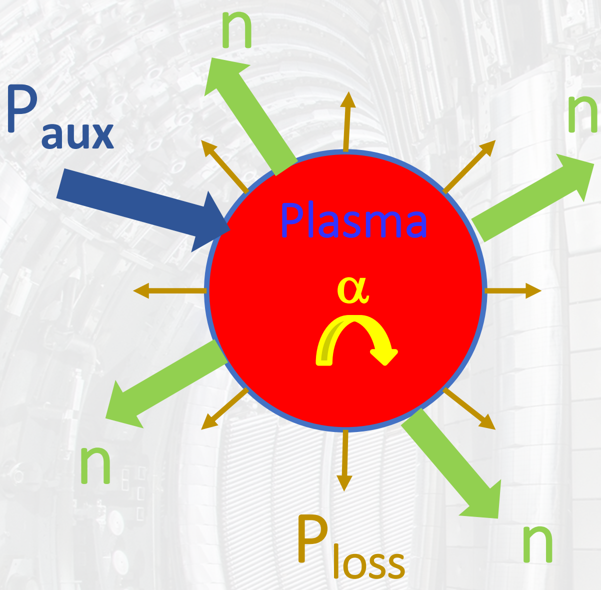


The most convenient reaction is D-T (advantages by far superior to disadvantages):

PROS: highest Q-value, high VACS at low temperature (20 keV or 230 million degrees), produces neutrons that transport energy outside the plasma (+tritrium breeding).

CONS: neutron damage to structural elements.

The energy gain



P_{aux} = external power

α-particles do not escape the plasma. Their energy (20% of the total fusion energy) contribute to plasma heating.

Neutrons carry away 80% of fusion power, and this power can be converted in electricity.

$$Q = \frac{P_{fus}}{P_{aux}} = \frac{P_{fus}}{P_{loss} - P_{\alpha}} = \frac{{}^{1}\!/_{4}\, E_r n^2 < \sigma v >}{W_{pl}/\tau_E - P_{\alpha}}$$

τ_e is the energy confinement time (time for the plasma to loose its thermal energy) once all heat sources are turned off. It is related to the isolation effectiveness.

Ignition condition: $P_{loss} = P_{\alpha}$

The gain depends on:

n	plasma density
T	plasma temperature
τ_E	energy confinement time

An idea of the gain of a reactor is provided by the so-called **“triple product”** $n\tau_E T$.

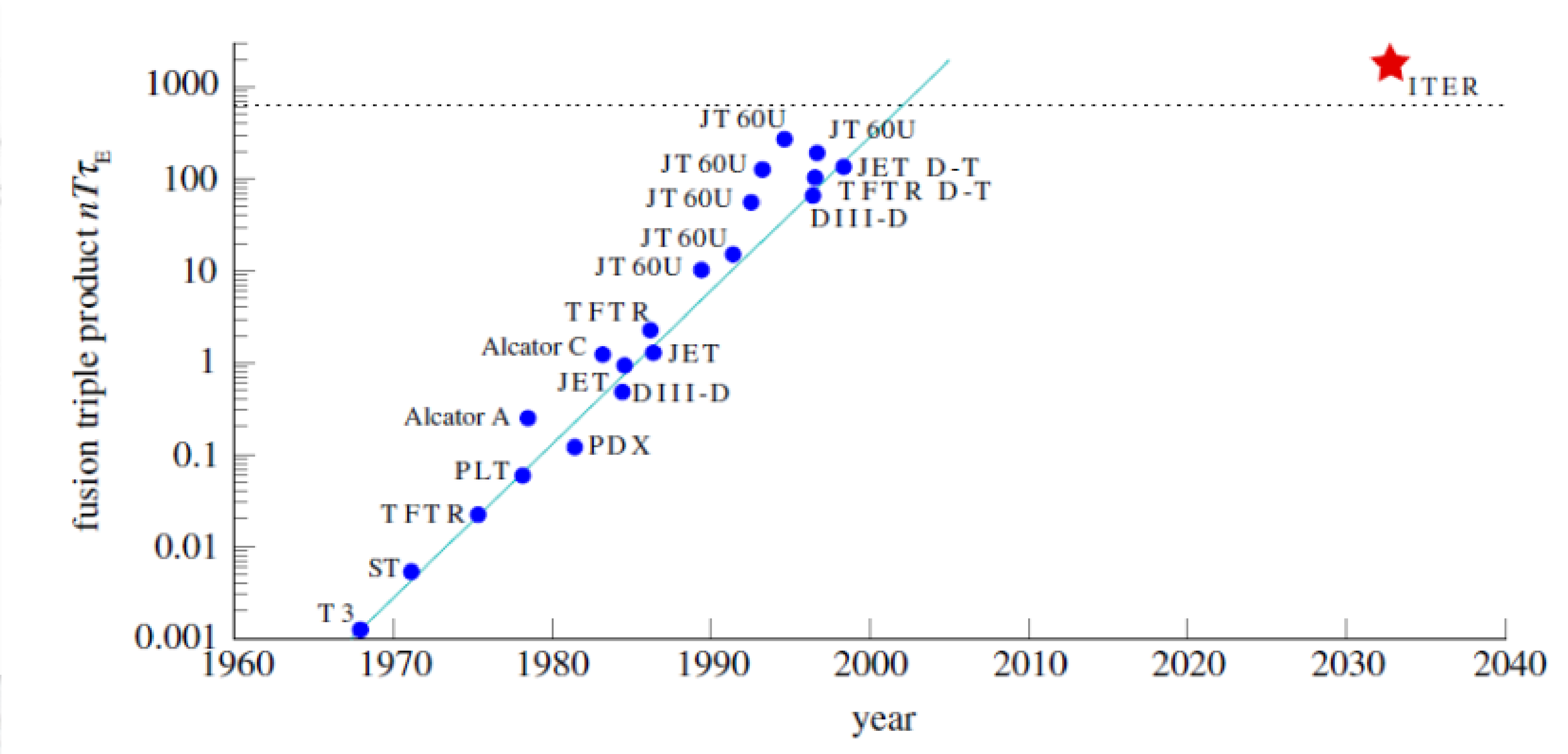
Lawson criterion

A combination of calculations and experience indicates that the condition for a net gain (Q≥3) is:

$$nT\tau_e \geq 3 \cdot 10^{21}\ [m^{-3}\ s\ keV]$$

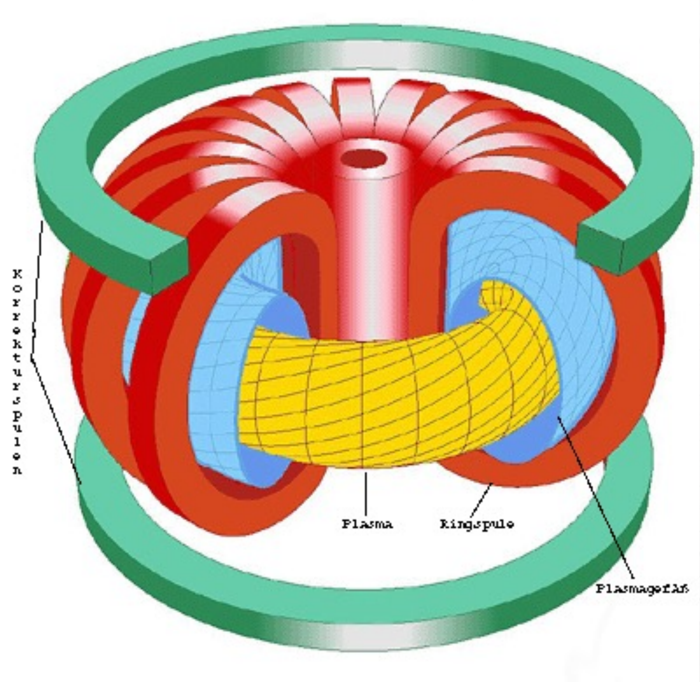
Known as "Lawson criterion" for energy production with nuclear fusion. Holy Grail of fusion energy production.

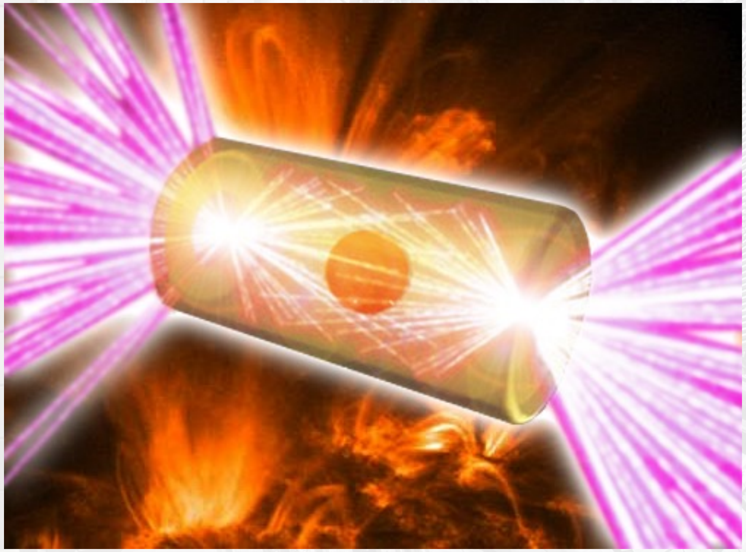
PS: nT = P plasma pressure



How to make controlled nuclear fusion

Two different methods for confining plasma





Magnetic confinement

$n \approx 10^{20}\ \mathrm{m}^{-3}$ $T \approx 15$ keV $\tau_E \approx 3$ s

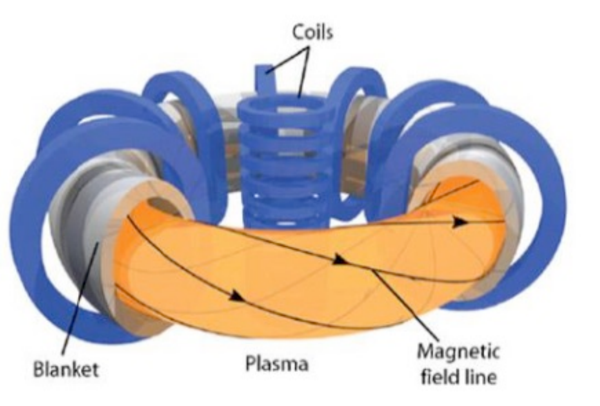
Inertial confinement

$n \approx 10^{30}\ \mathrm{m}^{-3}$ $T \approx 30$ keV $\tau_E \approx 10^{-10}$ s

The Tokamak (1958)

TOKAMAK comes from the Russian "**TO**roidal **KA**mara **MA**gnit **K**atushka", i.e. **toroidal chamber with magnetic coils**.

Need two major magnetic fields: Toroidal (along the plasma) and poloidal (around the plasma).



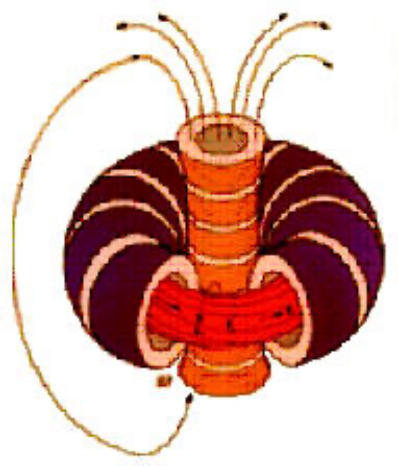
In a tokamak the **toroidal magnetic field is** generated by coils. **Not uniform**. This causes **drifts and forces** that **push the plasma** radially **outwards**.

Necessary also a **poloidal magnetic field**. Generated by a **toroidal plasma current** induced by a **time-dependent magnetic field** (central solenoid).

Combination of a **toroidal and poloidal** magnetic fields generates **helical magnetic field** (averages out the drifts).

Use of solenoid **("inductive" mode**) leads to **pulsed operation** (several seconds or minutes).

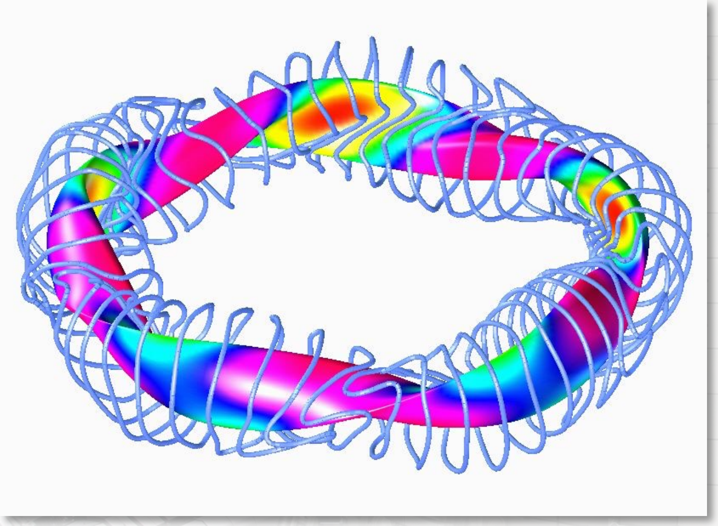
Traditional tokamaks are intrinsically pulsed machines, not suitable for power reactors.



The stellarator

A **steady-state operation** (needed for power reactors) requires **non-inductive** generation of plasma current for poloidal magnetic field and plasma heating.

Could be achieved with RF-induced or self-induced “bootstrap” current, now being investigated (one of the goals of new machines, like JT-60SA, ITER, EAST, CFETR, etc…).



An alternative solution for steady-state operation is the STELLARATOR

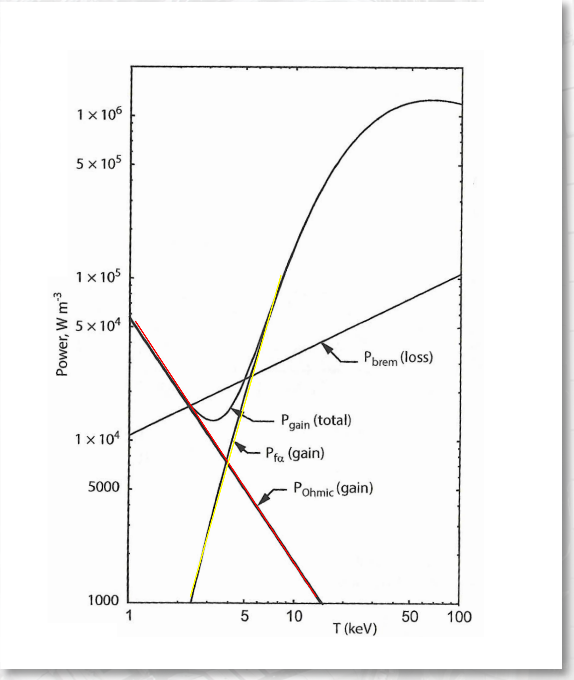
Helical magnetic field can also be generated by one set of coils only, with a particular shape.

Design require complicated calculations, now possible with powerful computers.

The most advanced one is W7-X (Germany)

Plasma heating

Plasma heating systems are needed to bring the plasma to the temperature needed to start fusion reactions and compensate for power losses when $P_\alpha < P_{loss}$.



The plasma current density *J*, combined with the plasma resistivity η leads to heating by Joule effect **(ohmic heating)**:

$$P_\Omega \sim \eta J^2$$

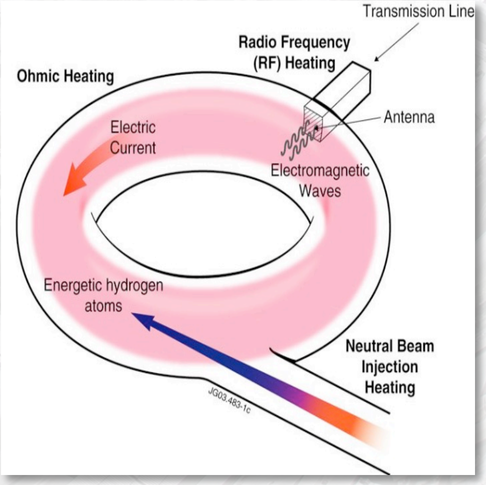
Initially $P_\Omega >> P_{loss}$ => plasma temperature increases. However;

- η decreases with temperature ($T^{-3/2}$) and J cannot be increased, as it can generate instabilities => P_Ω decrease with T.
- P_{loss} increase with temperature (as $T^{1/2}$).

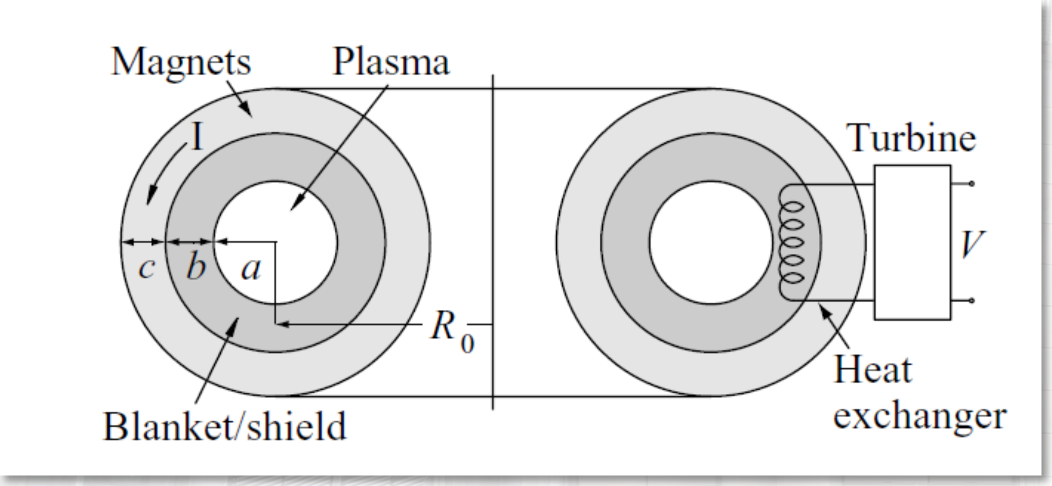
$P_{loss} > P_\Omega$ at $T \approx 3.5$ keV, lower than needed to start fusion.

Auxiliary heating systems are needed to “bridge the gap” between ohmic eating and fusion ignition (or to keep stady-state operation):

- Injection of high-power Radiofrequency wave (RF heating)
- Injection of neutral beams at high energy (Neutral beam injection, NBI). **Not always necessary**.



The main elements of a fusion reactor



General structure:

- Plasma
- Blanket
- Vacuum vessel
- Magnets

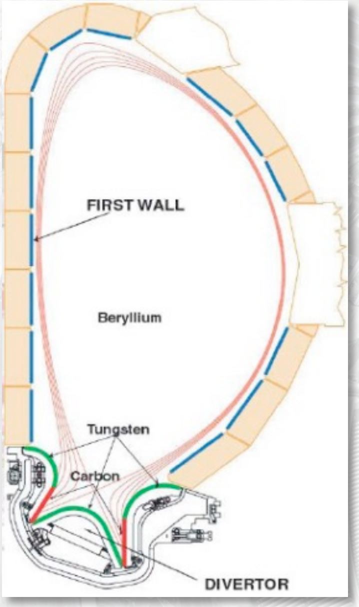
The role of the blanket:

1) face directly the plasma (first wall), has to withstand the enormous heat and particle flux (MW/m^2) without melting **(Be, Cu or stainless steel)**. Subject to neutron damage !!
2) Absorb 14 MeV neutrons and transform energy in heat (heat exchanger for steam generation)
3) Shield the coils from all type of radiations (including heat)
4) Perform Tritium breeding

1 GW$_e$ fusion power plant needs **55.6 kg** per full power year (CANDU reactors produce about 130 g per year ~25 kg in stock). It has to be produced in the reactor by n+Li reactions:

$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8\ MeV$ $n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.5\ MeV$

The divertor



Particles escaping the plasma are directed by the magnetic field on an element at the bottom or top (or both) of the tokamak.

Huge heat and particle load, requires highly resistant material, both to temperature and radiation.

A crucial element of any a tokamak.

Made of Tungsten, highest melting point of all metals (3400 ºC), and radiation-resistant.

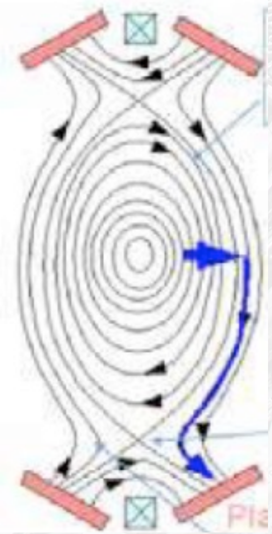
May not be able to withstand the heat load of for future power reactors (DEMO).

Need to investigate other solutions.

DTT
Divertor Tokamak Test facility
Project Proposal

The Divertor Tokamak Test (DTT, Frascati), will study different material, geometrical and magnetic configurations of the divertor.

A double-null configuration reduces considerably divertor problems.



Increasing the triple product

Lawson criterion

$$nT\tau_E \geq 3 \cdot 10^{21}\ [m^{-3}\ s\ keV]$$

In principle, higher gain can be obtained by increasing all three factors in the triple product. However:

T cannot be increased much because <σv> decreases and energy losses increase; an optimal value is T=15 keV.

To increase *n* (i.e. the plasma pressure) requires increasing the magnetic pressure, but B is limited by the superconducting technology.

Option left: increase the **energy confinement time τ_E**

$$\underbrace{nT}_{\frac{B^2}{2\mu_0}}\tau_E \propto R^{1.3} B^3$$

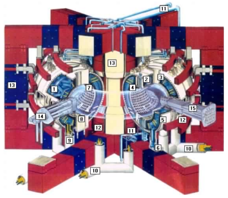
scaling rule

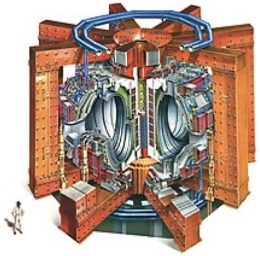
$$\tau_E = 0.048\, M^{0.5}\, I_p^{0.85} \mathbf{R^{1.2}}\, a^{0.3}\, k^{0.5}\, n^{0.1}\, B^{0.2}\, P^{-0.5}$$

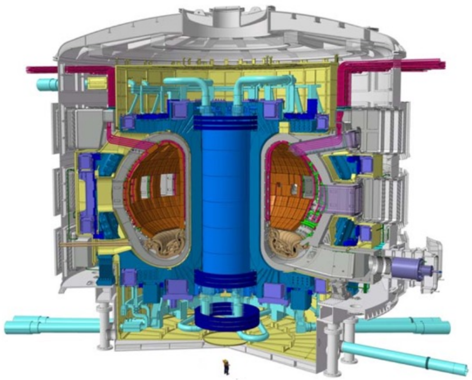
M	average isotopic mass number
I_p	plasma current (MA)
R	tokamak major radius (m)
a	plasma radius (m)
k	elongation (h/a)
n	central line density (10^{20} m^{-3})
B	magnetic field (T)
P	heating power (MW)

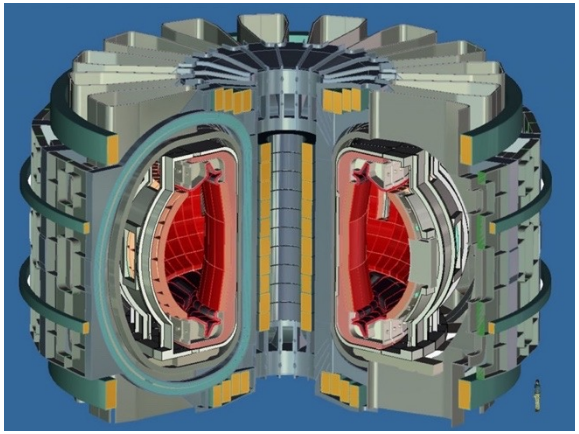
The most important dependence of τ_E is on the major radius R, i.e. the reactor size.

Size comparison







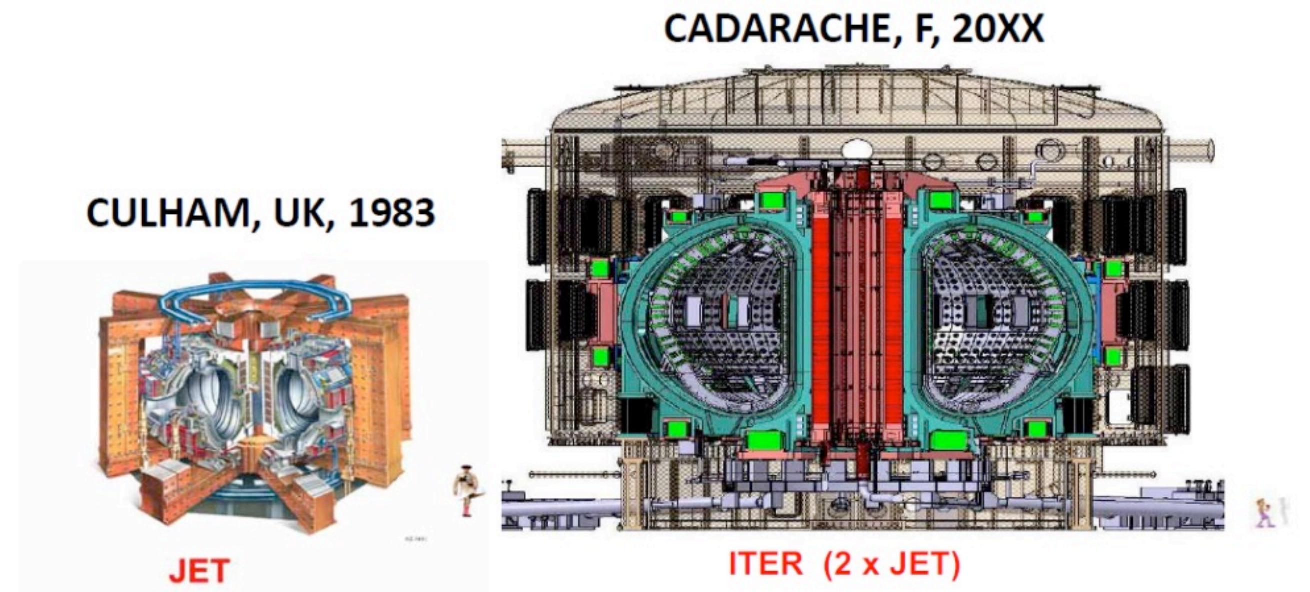


Tore Supra	JET	ITER	DEMO
1988	1983	>2025	>2050
$Q<<1$	$Q \approx 0.6$	$Q \approx 10$	$Q \approx 25$
$R_0 = 2.5$ m	$R_0 = 3$ m	$R_0 = 6.2$ m	$R_0 = 7\text{-}10$ m
$\tau_E = 0.3$ s	$\tau_E = 1.2$ s	$\tau_E = 3.7$ s	$\tau_E = ?$
$V_p = 25$ m^3	$V_p = 80$ m^3	$V_p = 800$ m^3	$V_p = 1000\text{-}3500$ m^3
$P_{th} \approx 0$ MW	$P_{th} \approx 16$ MW	$P_{th} \approx 500$ MW	$P_{th} \approx 2000\text{-}4000$ MW

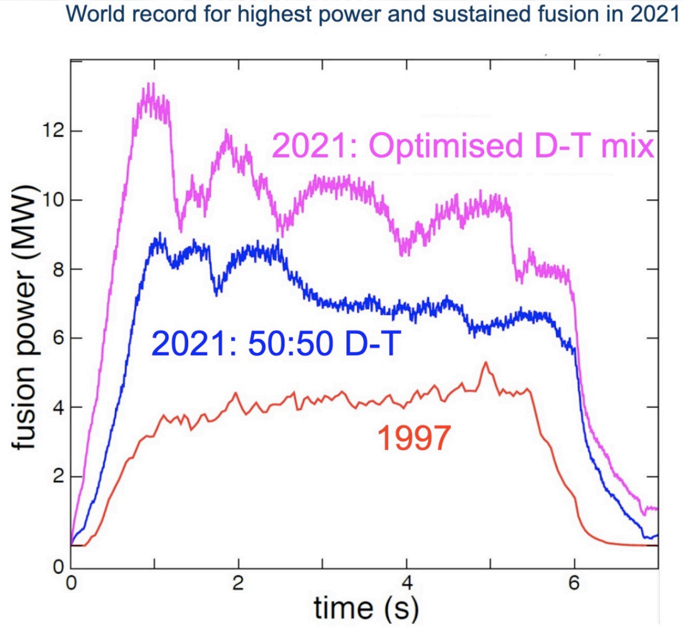
ITER: first reactor that will prove Q>1 (but no electricity production)
DEMO: first prototype that will generate electricity

Question: considering their size (and hence costs), will such reactors ever be competitive?

ITER parameters

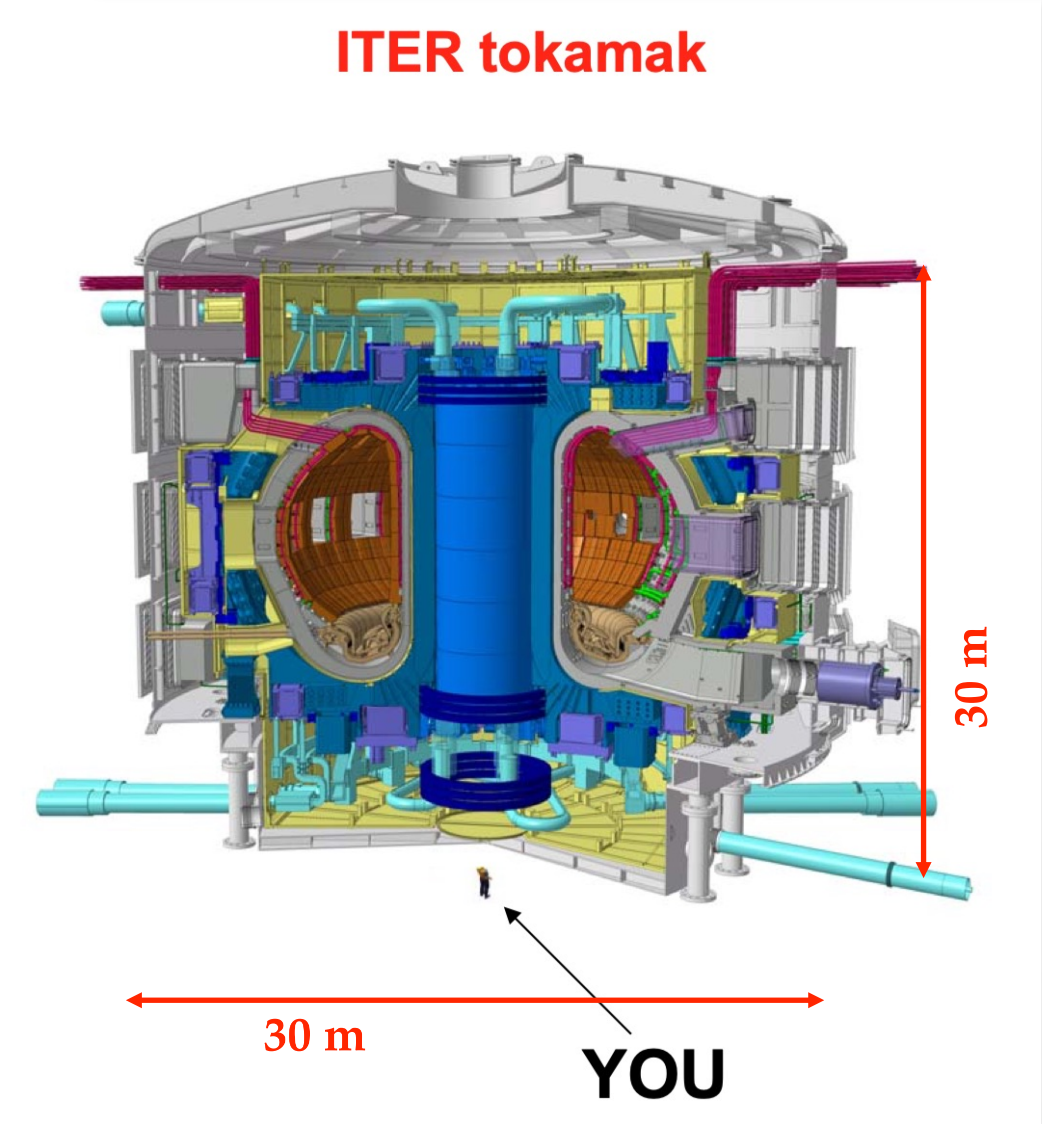


Biggest fusion reactor ever built, twice the size of JET (the largest tokamak currently active) in linear dimension (8 times in volume).


World record for highest power and sustained fusion in 2021

	JET	ITER
Major radius (m)	2.96	6.2
Minor radius (m)	1.25	2.
Plasma volume (m^3)	100	837
Magnetic field (T)	3.8	5.3
Plasma current (MA)	7	15
Plasma density ($\times 10^{20}$ m^{-3})	0.8	0.9
Temperature (keV)	14	11.2
Confinement time (s)	1.2	3.7

ITER
International Thermonuclear Experimental Reactor



The biggest project on nuclear fusion.

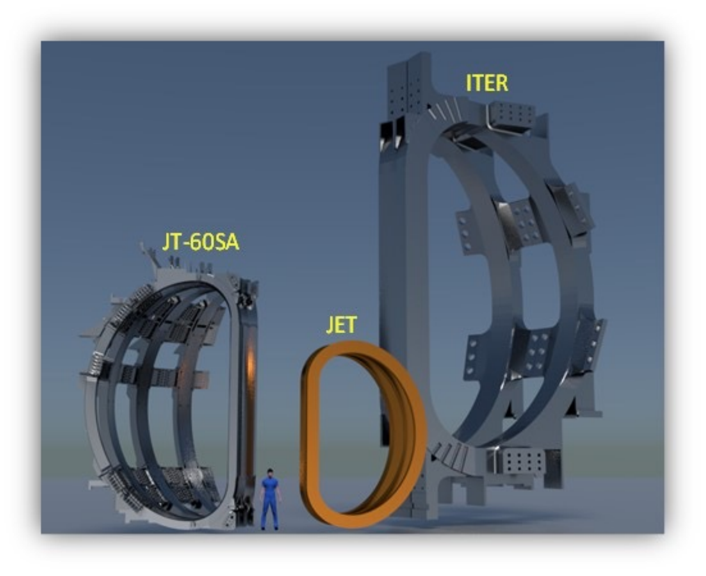
Largest tokamak ever built. Goals:

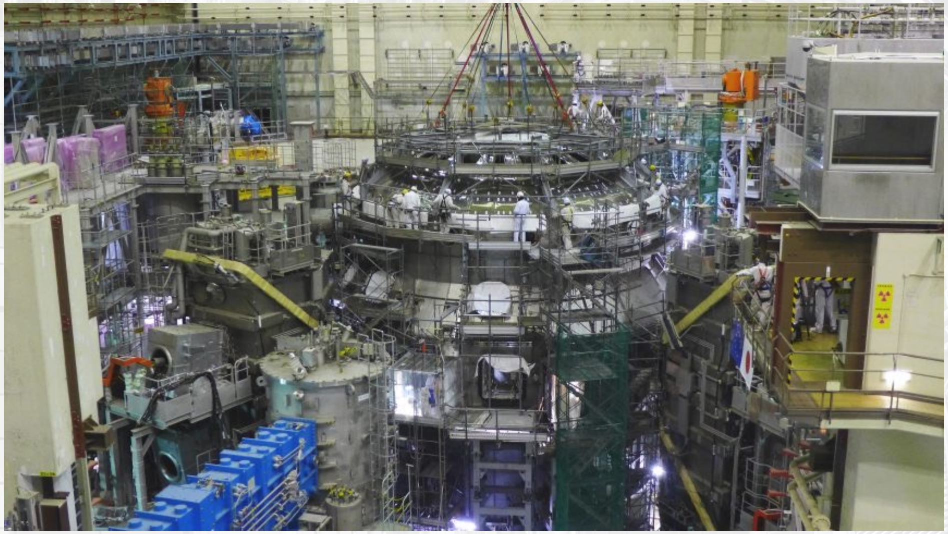
- Reach Q≈10 (**10 times** the power used to heat the plasma).
- Pulse duration of ~10 minutes (JET record is 5 s), producing 500 MW.
- Demonstrate steady-state operation («Advanced Tokamak» up to 1 h)
- Develop and validate new fusion technologies (tritium breading

ITER will not produce electricity, but will pave the way to a future reactor for energy production (DEMO).

The "record" machine (including delay)

JT-60SA (Naka, Japan)





- Currently the most powerful tokamak, based on an International agreement ("Broader Approach") between Japan and EU.
- Another step forward, ancillary to ITER (plasma volume 1/6 of ITER).
- Address key physics issues on plasma behavior (initially only H, than D).
- It will not use D-T fuel (avoid activation), but if it did it would reach break-even point
- Pulse length: 100 s (ITER > 400 s).

Explore the non-inductive steady-state operation (more relevant for power reactors) and high beta plasma regimes.

The Chinese fusion program

Two **major centers**: Academy of Science Institute for Plasma Physics (**ASIPP, Hefei**) and Southwestern Institute of Physics (**SWIP,** Chengdu)

Currently in operation 3 tokamaks with different programs: **EAST**, HL-2M and J-TEXT

Future reactor: Chinese Fusion Engineering Testing Reactor (**CFETR**) (ready by 2030).

J. Zheng et al., The Innovation 3 (2022), 100269

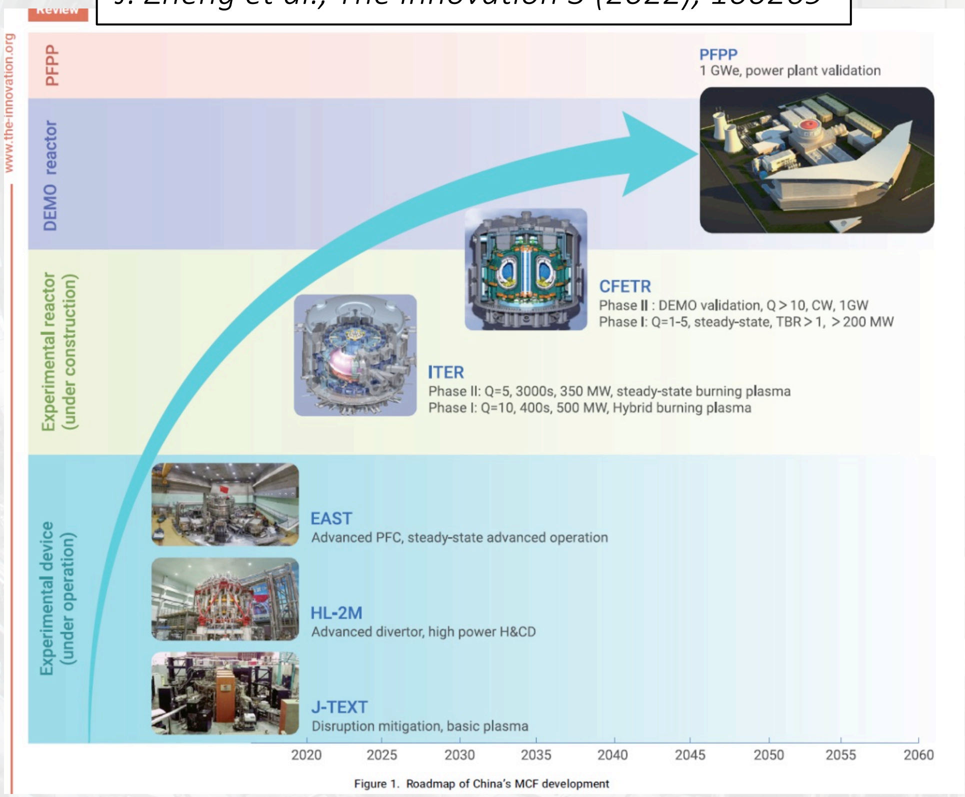


Figure 1. Roadmap of China's MCF development

EAST (ASIPP, 2006):

- first **full superconducting** tokamak
- R=**1.9 m,** I_p=1 MA, two divertors and NBIs
- Test **long-pulse** (400 s) and **steady-state** operation (1000 s) with non-inductive current.
- Milestones: reached **1056 s (6 keV)** on Dec. 2021 & **403 s (11 keV)** on April 2023.

CFETR:

- Similar goals of DEMO
- R=**7.2 m**, 14 MA, 1 GW power
- **Engineering design completed**
- R&D for critical components ongoing

High temperature superconducting magnets

$$n\tau_e T \propto R^{1.3} B^3$$

The triple product increases with the reactor dimension and/or with the magnetic field:

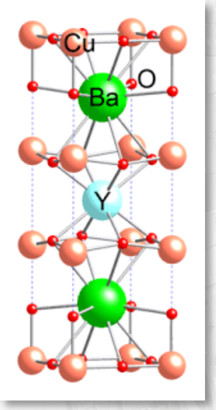
- higher field -> higher pressure
- same gain with smaller reactors

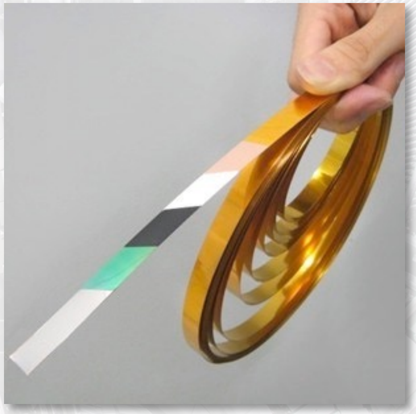
Traditional and low temperature superconductors have a limitation on the maximum magnetic field (~ 13 T)

Breakthrough: high temperature (77 K) superconductors can be used to produce higher magnetic fields (HTS magnets).

ReBCO (Rare-earth Barium Cupper Oxide)

High temperature magnets built with REBCO tapes, allow to reach 20 T.





Large experience at MIT-PSFC (Plasma Science and Fusion Center) on high-magnetic field, high-pressure tokamaks.

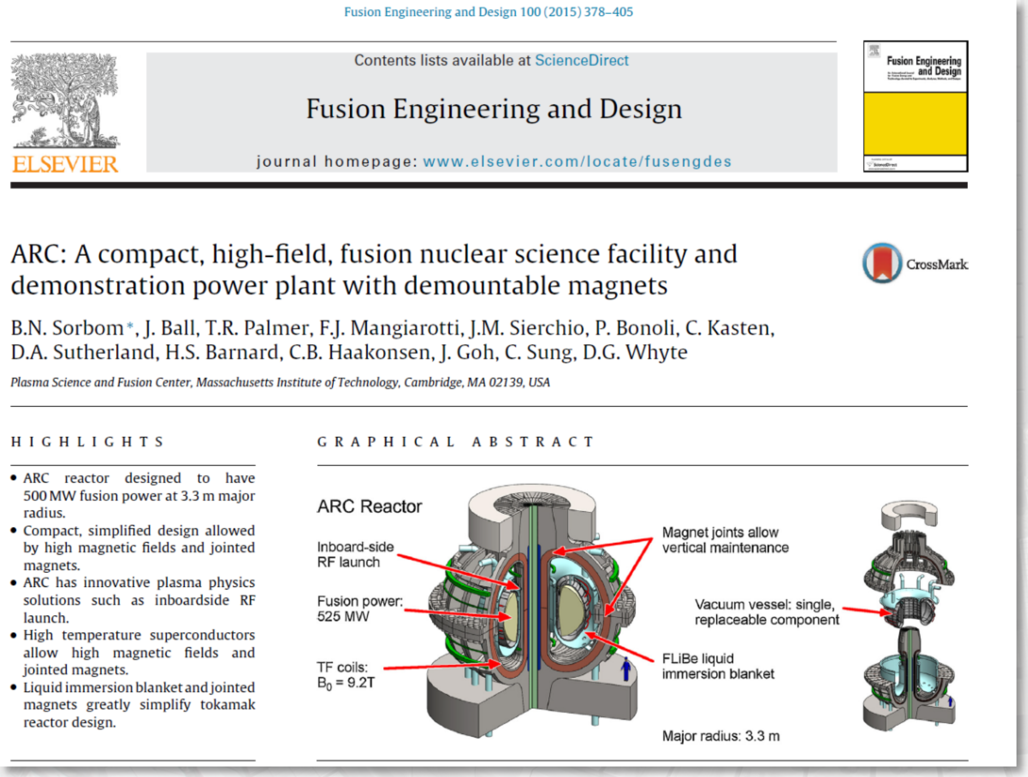
ALCATOR C-mod operated at MIT between 1996 and 2016 unique in the world.

ARC (**A**ffordable, **R**obust, **C**ompact)
Commonwealth Fusion Systems

Born as a student-led project following a class on reactor design at MIT, published in 2015

MIT Start-up: Commonwealth Fusion System (CFS) https://cfs.energy

Could become the first ever fusion reactor to produce electricity … in 2035 !!



Fusion Engineering and Design 100 (2015) 378–405

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journal homepage: www.elsevier.com/locate/fusengdes

ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets

B.N. Sorbom*, J. Ball, T.R. Palmer, F.J. Mangiarotti, J.M. Sierchio, P. Bonoli, C. Kasten, D.A. Sutherland, H.S. Barnard, C.B. Haakonsen, J. Goh, C. Sung, D.G. Whyte

Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

HIGHLIGHTS

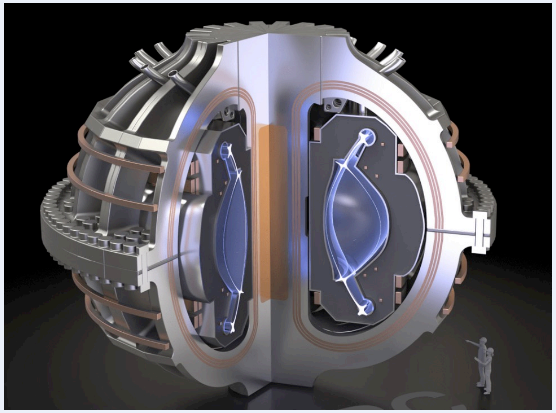
- ARC reactor designed to have 500 MW fusion power at 3.3 m major radius.
- Compact, simplified design allowed by high magnetic fields and jointed magnets.
- ARC has innovative plasma physics solutions such as inboardside RF launch.
- High temperature superconductors allow high magnetic fields and jointed magnets.
- Liquid immersion blanket and jointed magnets greatly simplify tokamak reactor design.

GRAPHICAL ABSTRACT

Main features

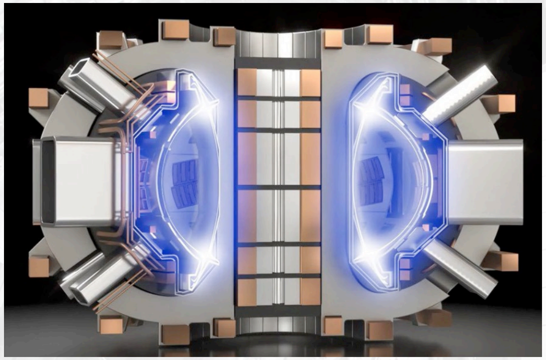
- High Magnetic Field (up to
- Fully non-inductiv
- Two divert
- C ular (demountable)
- beam injection
- iquid blanket and T breeder (FLiBe)

Reasonable cost



https://cfs.energy/technology

A preliminary step: SPARC (CFS)

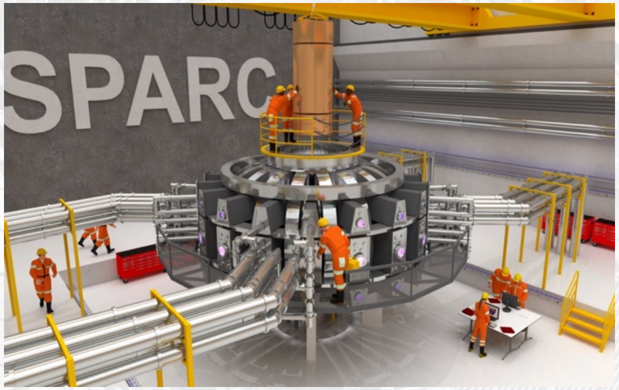


http://cfs.energy/technology

First fusion reactor based on the High Temperature Superconducting (HTS) magnets.

Q > 2 (could be as high as 11)

Strong Physics basis (MIT school)



Ken Filar, PSFC Research Affiliate

CFS now established in Devens (near Boston), the site is under construction (fusion campus).

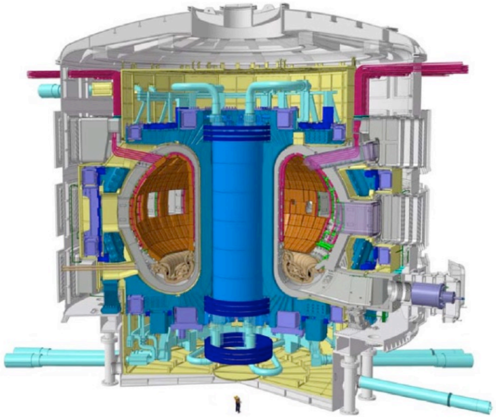
First magnet already built and tested (successful).

Predicted to be **completed by 2025**.

ENI is participating in the project, and has recently signed a **strategic framework agreement**.

The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology (http://cfs.energy/technology)

Size comparison



ITER

>2025

R_0 = 6.2 m

V_p = 800 m^3

Q ≈ 10

P_{th} ≈ 500 MW

SPARC

~ 2025

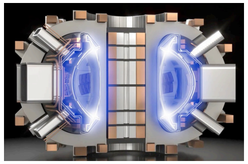
R_0 = 1.9 m

V_p = 20 m^3

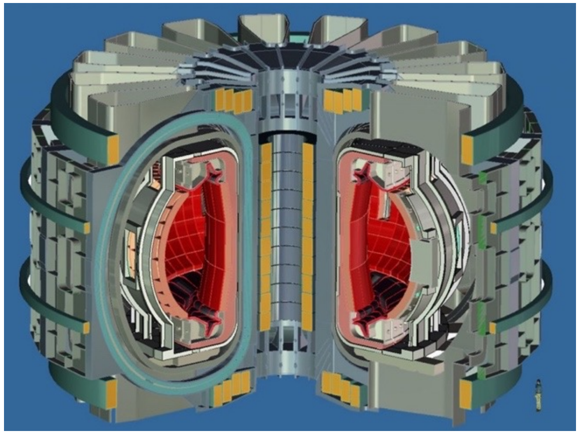
Q > 2

P_{th} ≈ 140 MW

P. Rodriguez-Fern.
Nucl. Fusion **62**
(2022) 042003



Electricity production



DEMO

>2050

R_0 = 7-10 m

V_p = 1000-3500 m^3

Q ≈ 25

P_{th} ≈ 2000-4000 MW

ARC

~ 2035

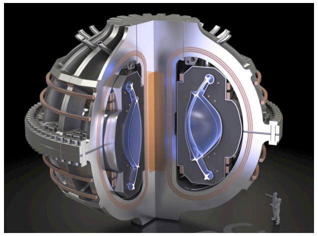
R_0 = 3.3 m

V_p = 140 m^3

Q ≈ 3

P_{th} ≈ 700 MW

B.N. Sorbom
Fus. Eng. Des. 100
(2015) 378



Fusion Startups

Currently 41 startups in the world. Ranking based on growth, innovation, …

1. **CFS (Comm. Fus. Sys.)**
Cambridge (**US**)
Funded: 2018
Funding: **2.1 B$**

HTS

2. **Helion**
Redmond (**US**)
Funded: 2013
Funding: **550 M$**

D+^{3}He
FRC

3. **General Fusion**
Burnaby (**Canada**)
Funded: 2002
Funding: **437 M$**

MTF

4. **Tokamak Energy**
Abingdon (**UK**)
Funded: 2009
Funding: **87 M$**

HTS

5. **TAE**
Lake Forest (**US**)
Funded: 1998
Funding: **1.2 B$**

p+^{11}B
FRC

6. **Marvel**
Munich (**Germany**)
Funded: 2019
Funding: **67 M$**

7. **Phoenix**
Madison (**US**)
Funded: 2005
Funding: **29 M$**

8. **First Light Fusion**
Oxford (**UK**)
Funded: 2011
Funding: **105 M$**

Fusion company in Europe

GAUSS FUSION
Hanau (**Germany**)
Funded: 2022
Funding: **?? M$**

HTS

Goal: bringing the **first European GWe fusion power plant** (Gauss GIGA fusion power plant) online **by 2045**.

Based on the stellarator concept.

Public-private partnership (PPP) with national and **European** institutions

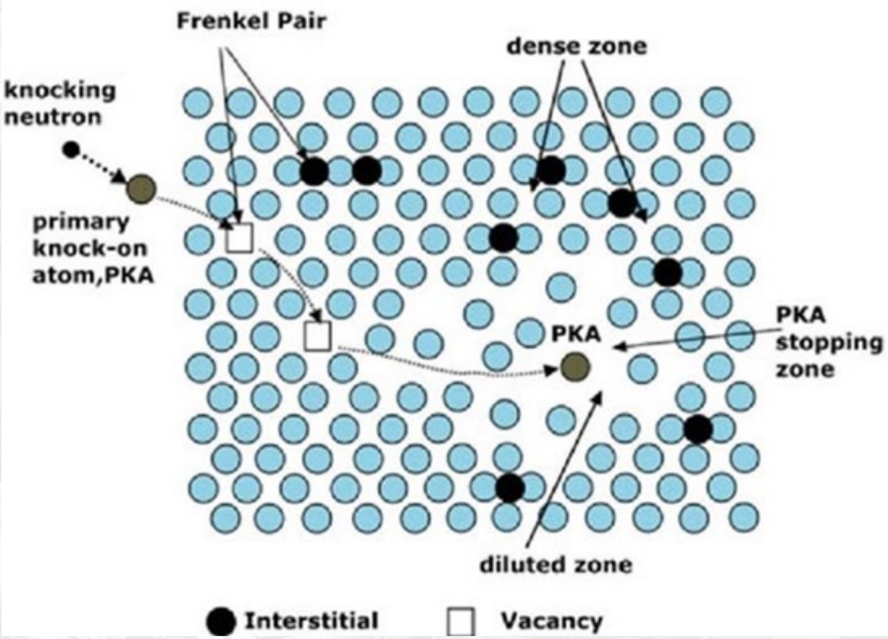
Founding companies from Germany, France, Italy and Spain (with expertise in fusion technology).
Cooperation with European research institutes:

- Max Planck Institute for Plasma Physics (IPP)
- CERN
- Karlsruhe Institute of Technology (KIT)
- ENEA

Since Sept. 2023 Stefano Buono and Siegfried Russwurm in Gauss Fusion Supervisory Board.

Neutron damage

$$\mathbf{D} + \mathbf{T} \longrightarrow {}^{4}\mathbf{He}\ (3.5\text{MeV}) + \mathbf{n}\ (14.1\text{MeV})$$



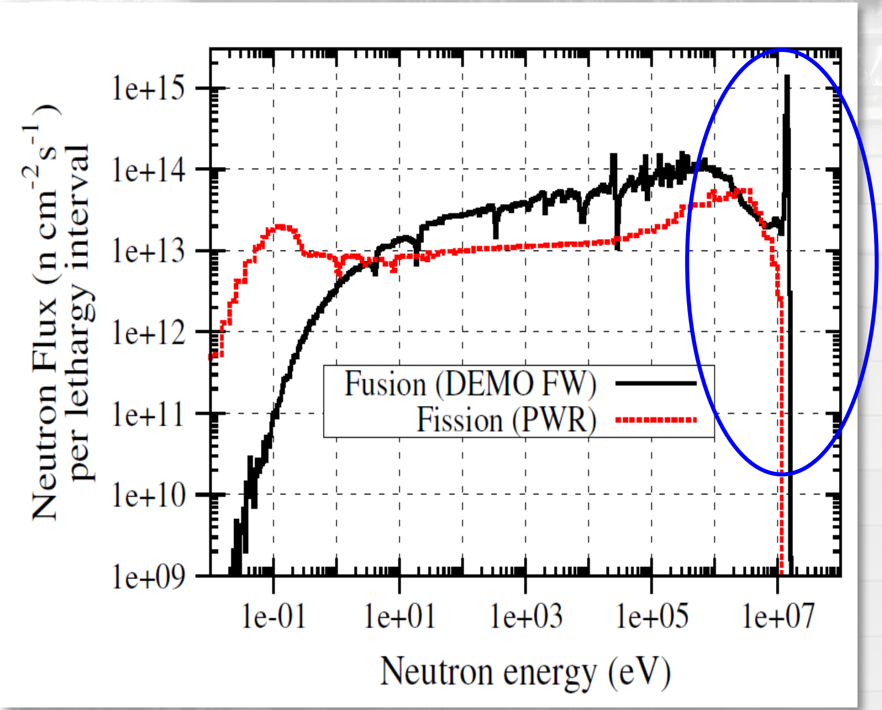
The huge neutron flux produced in a D-T fusion reactor can produce damage in the structural materials (blanket), severely limiting their lifetime.

Neutrons reactions with materials:

- elastic scattering, causing atom displacement (lattice defects)
- capture reaction, that could lead to transmutation (change chemical composition)
- Emission of p, d, t and α, leading to gas formation.

Neutron damage causes **deformation, embrittlement, bubble formation, loss of conductivity**, and in general degradation of thermo-mechanical properties. Problem for all future fusion reactors.

Gas production



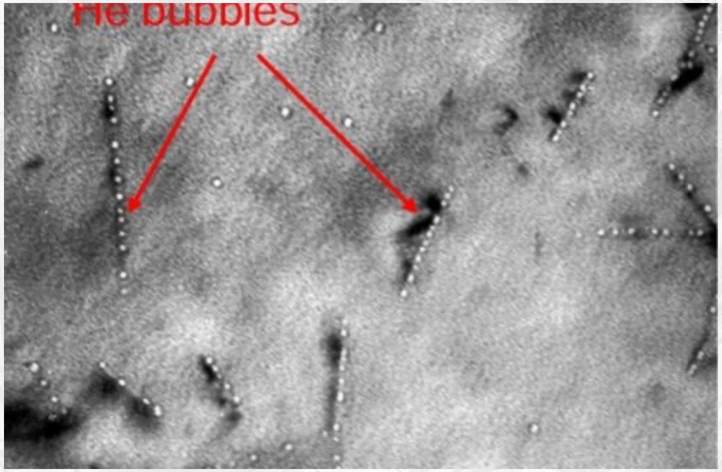
Fusion neutron spectrum has a peak at 14 MeV, not present in fission.

Much higher gas production (x10-100) in fusion structural materials relative to fission (threshold (n,cp) reactions).

The experience on neutron damage in fission reactors not directy applicable to fusion reactors. Need data !

Experimentally: **Irradiate material** and measure the effect (destructive or non-destructive analysis).
Need **high flux neutron facilities: (IFMIF/DONES, D-T generator, e-linac …)**

Simulations: **Transport neutrons** and ions through the material lattice (Molecular Dynamics)
Need **computers**, **models** and **neutron data**.



The principle of inertial fusion

Inertial fusion based on the idea that fusion can be achieved by compressing a sphere of D and T (gas or ice) to extremely high density and high temperature.

For the method and timing, it resembles a micro nuclear explosion.

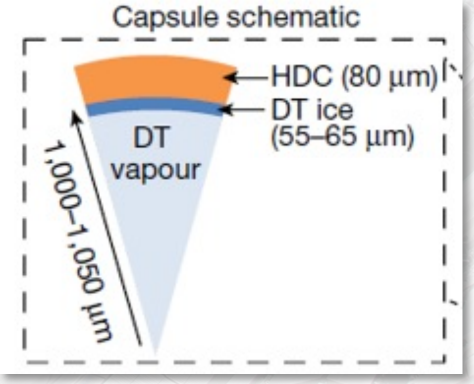
Very small confinement time since it is impossible to confine the energy after the “explosion”.

Triple product in IF

$n \approx 10^{30}\ \mathrm{m^{-3}}$ $T \approx 30\ \mathrm{keV}$ $\tau_E \approx 10^{-10}\ \mathrm{s}$

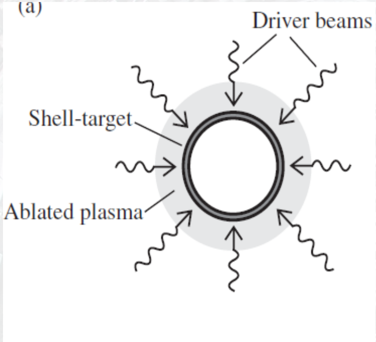
The energy needed for compression and heating can be provided by radiation, in particular Laser beams.

The fuel is a small hollow sphere of D-T ice with D-T gas inside, surrounded by a shell of high density Carbon, call ablator.



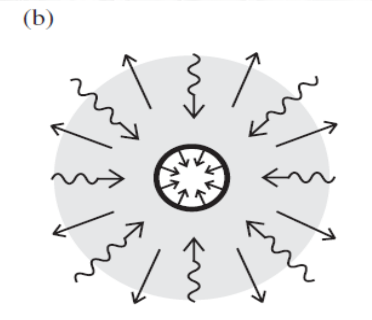
The four phases of inertial fusion

ABLATION



A **radiation hits** the **“ablator” shell** (HDC), ionizing it and forming a hot plasma.

IMPLOSION

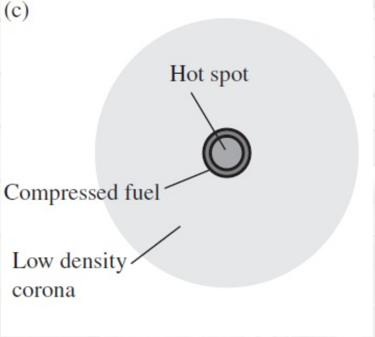


The **ablator “explodes” outwards,** causing a “rocket-like” **implosion of the DT fuel**, compressing it to **Mbar pressure**.

$v_{imp} \approx$ **350/400 km/s**

Takes nanoseconds

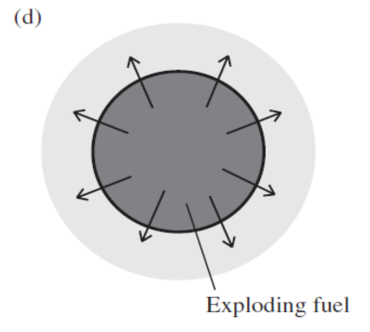
STAGNATION



The **kinetic energy** of the implosion is transformed in internal energy. Pressure raises to 100 Gbars, T>5 keV.

A **hot spot** is produced, and **fusion reaction starts.**

EXPLOSION

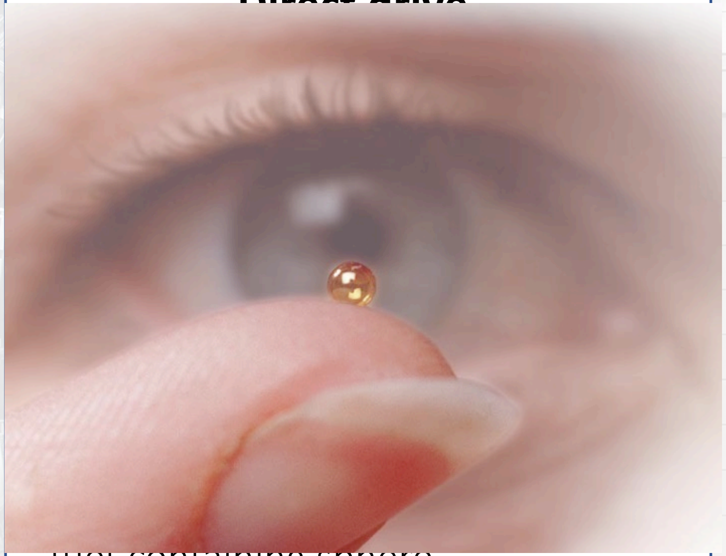


α-particles from fusion **heat** up the remaining fuel, causing the fuel to explode.

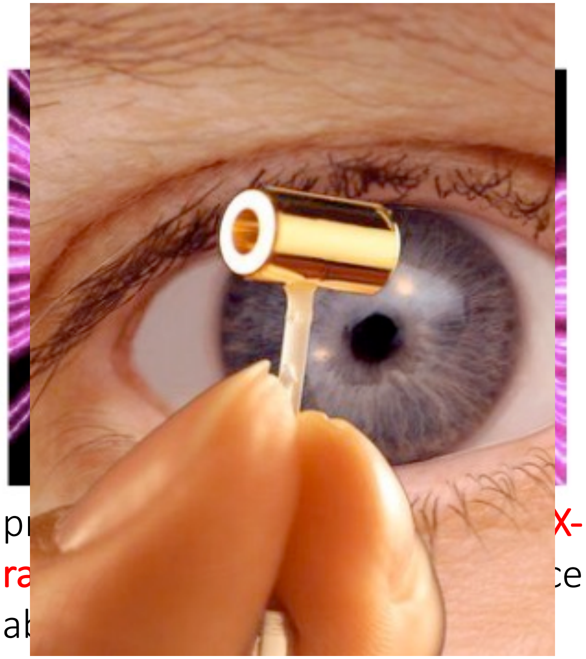
The fuel compression and heating

Two ways to obtain inertial confinement

Direct drive



fuel-containing sphere



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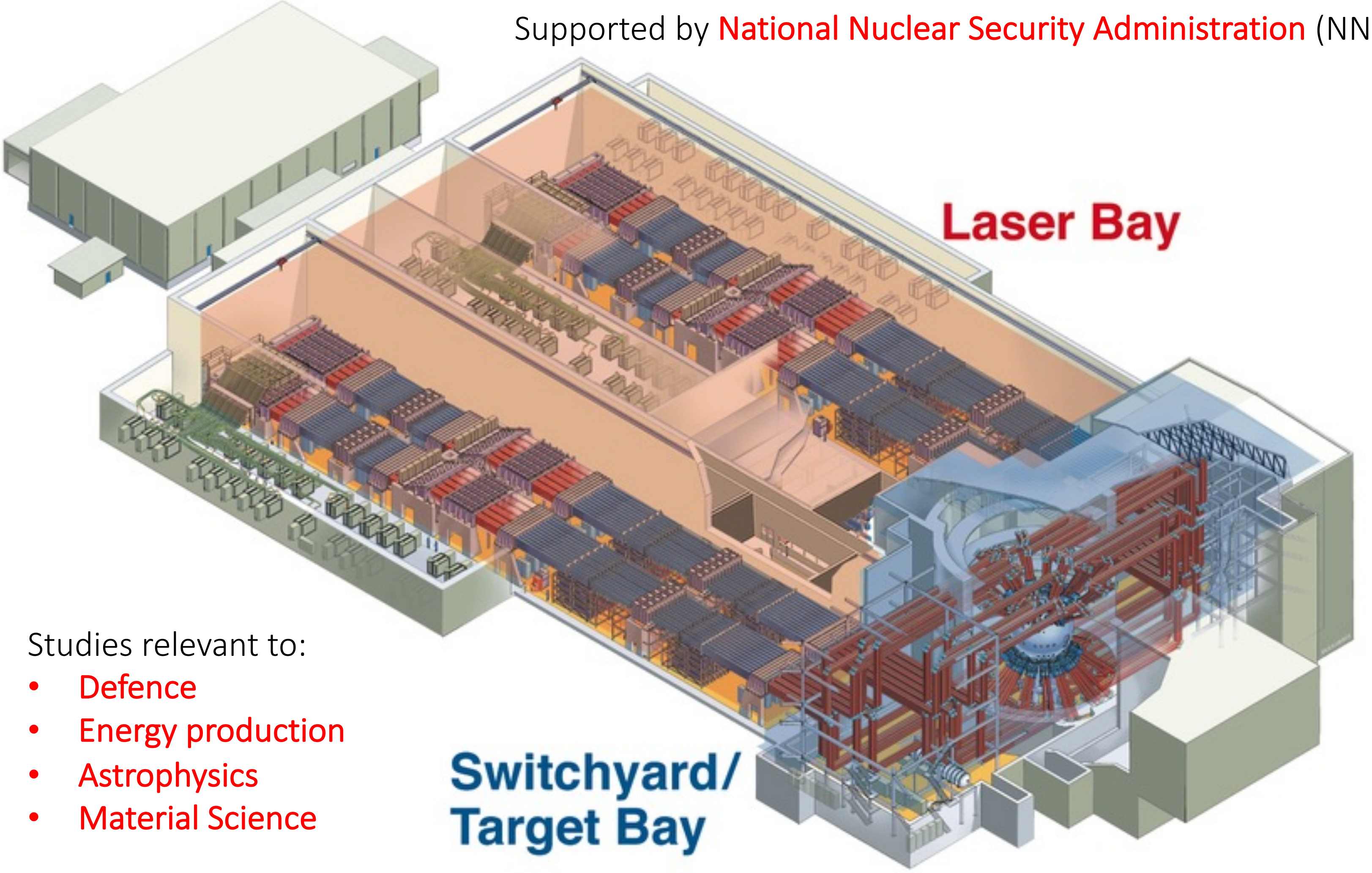
The preferred method is now the indirect one:

- lasers hit the inner wall of a cylindrical “pellet” (called hohlraum) with the fuel sphere inside.
- pellet made of high-Z material and has two apertures at the bases (for laser beams).

Two projects: MegaJoule in France, and NIF in USA.

National Ignition Facility (NIF)
Lawrence Livermore National Laboratory (USA)

Supported by National Nuclear Security Administration (NNSA)



Studies relevant to:

- Defence
- Energy production
- Astrophysics
- Material Science

The lasers

Laser hall (three football fields long)

Laser beams enter a vacuum chamber of 10 m diameter.

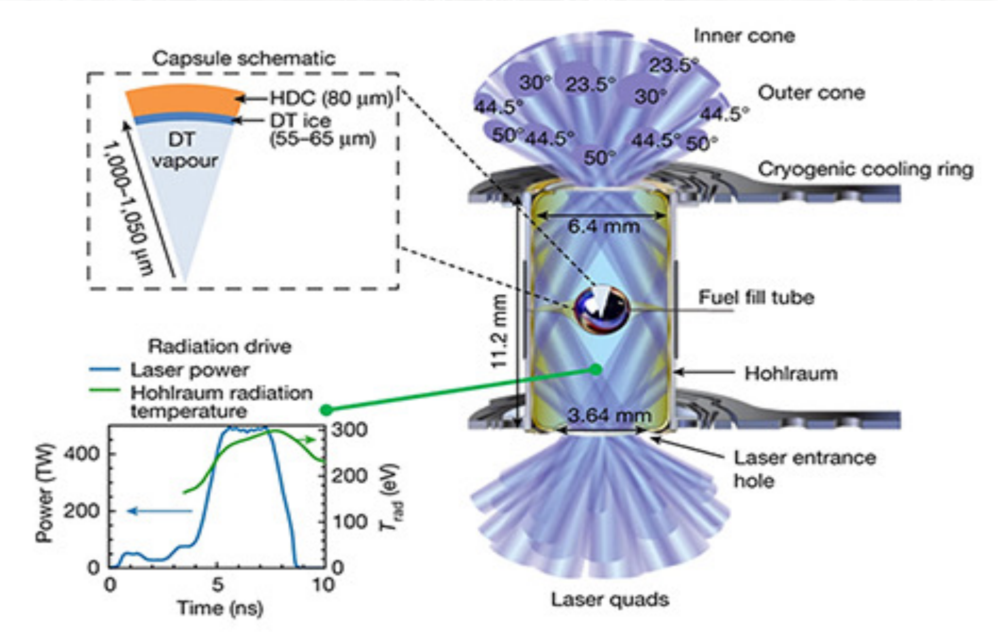
They converge on the fuel, at the center of the chamber.

Based on 192 laser beams
Frequency-tripled Nd glass
Laser power: 500 TW
Duration of the pulse: 5 ns
Energy to produce laser beams: 300 MJ
Energy on target: > 2 MJ

To produce laser beams need 100 times their energy. Very inefficient process !

Challenges: produce high-power laser beams, high purity D-T capsules (spherical, with radius deviation of parts per million or less), and optimal hohlraum.

The target

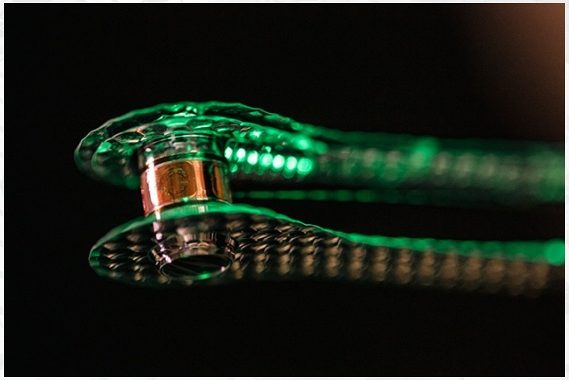


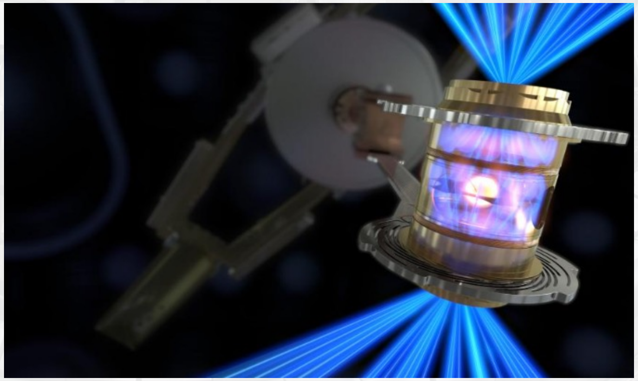
Diameter of the capsule: 2 mm
Mass of D-T fuel: 200 µg
(1 mg D-T = 85 kg TNT)

The laser beams hit the internal walls of the hohlraum.

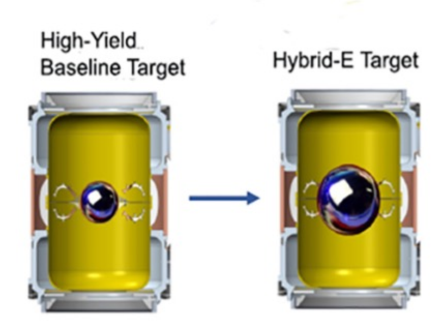
An X-ray thermal bath at T≈300 eV is formed.

The X-ray absorbed by the HDC shell cause ablation, implotion, hot spot formation and fusion reaction.



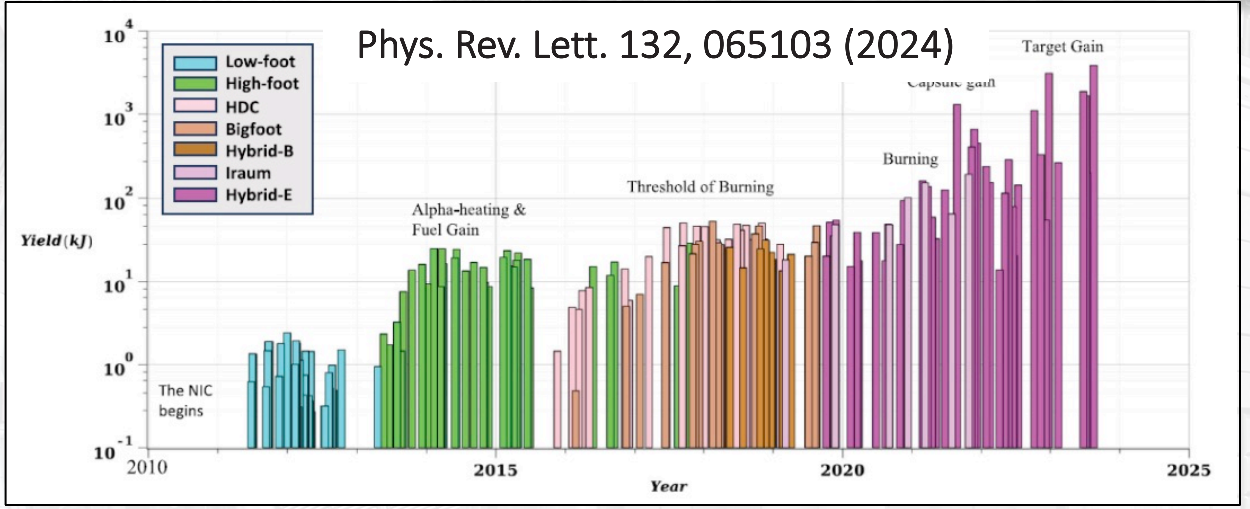


Improved configuration



The results

PRL 132, Feb. 2024 (102, 103, 104)


Phys. Rev. Lett. 132, 065103 (2024)

Clear evolution in energy yield, obtained by improving:

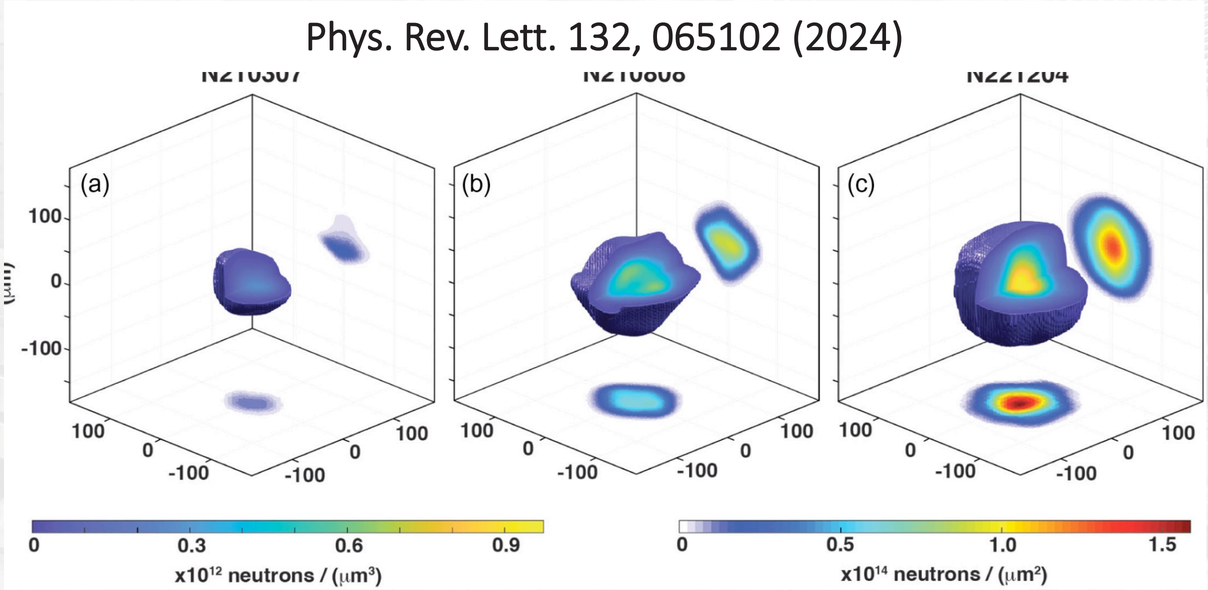
- laser time-structure,
- HDC shell thickness
- target purity
- ....

On Dec. 5th, 2022 produced more energy (3,1 MJ) than delivered to the target (2 MJ).

Burned 4% of D-T fuel.

Corresponding "gain" Q=1.5

Q=0.01 when considering energy spent to produce laser beams.


Phys. Rev. Lett. 132, 065102 (2024)

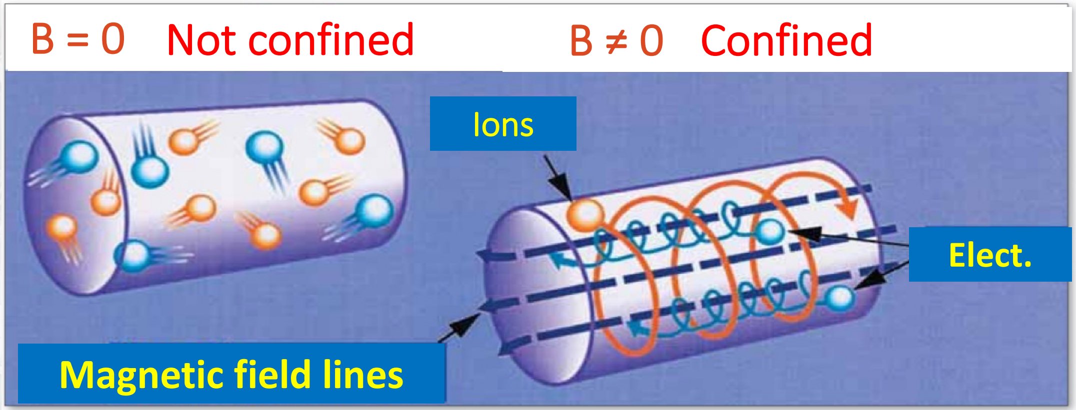
Summary and conclusions

- Nuclear fusion: a clean and renewable source in future energy mix could help replacing fossile fuels in the long term (not much hope for short-medium term).
- Magnetic confinement based on low-temperature superconductors still require R&D (ITER and DEMO). Not ready by 2050. Too big and costly to be competitive.
- Inertial fusion much less convenient at present and also requires several decades before first power reactor (if any).
- High-temperature superconductors are an important breakthrough, that could potentially lead to commercial reactors in the medium term (<2050).
- Several private companies rushing for the first commercial power fusion reactor (different options for magnetic confinement).
- CFS is currently the most advanced: high-field reactors (HTS magnets): SPARC to demonstrate Q>2 by 2025, ARC first prototype of compact reactor for electricity production by 2035.
- In Europe Tokamak Energy (spherical) and GAUSS Fusion (stellarator).
- The next decade will be crucial for the future of fusion energy.

WORK IN PROGRESS

Thank you for your attention and … stay tuned !

Magnetic confinement



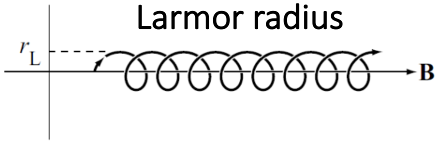
Plasma: globally neutral, locally ionized.

Electrons and ions in a magnetic field are subject to Lorentz force.

Helical trajectory around the field lines.

Confined in the transverse direction (i.e. perpendicular to B).

Larmor radius



$$m\frac{d\boldsymbol{v}}{dt} = q\boldsymbol{v}\times\boldsymbol{B}$$

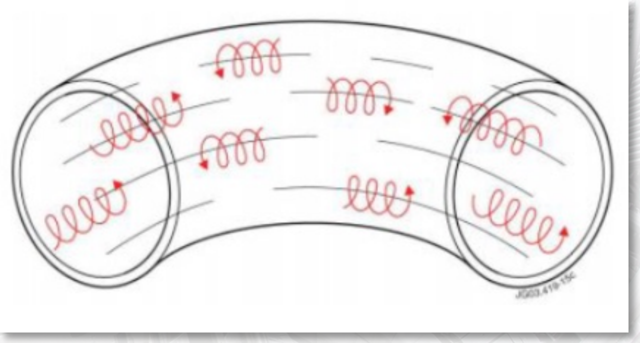
$$\boldsymbol{r_L} = \frac{\boldsymbol{v}}{\boldsymbol{\omega}} = \frac{\sqrt{\boldsymbol{2mKT}}}{\boldsymbol{qB}}$$

$$\boldsymbol{\omega} = \frac{\boldsymbol{qB}}{\boldsymbol{m}}$$

for B=5 T and KT = 15 keV →

$$r_{Le} = 8.3\times10^{-5}\ \mathrm{m}$$
$$r_{Li} = 5.\times10^{-3}\ \mathrm{m}$$

$$\omega_{ce} = 8.8\times10^{11}\ \mathrm{s}^{-1}$$
$$\omega_{ci} = 2.4\times10^{8}\ \mathrm{s}^{-1}$$



In a linear configuration (cylinder) no confinement in the longitudinal direction (attempts using the so-called mirror effect (large field gradient along the axis. Very inefficient).

The problem is solved by “closing” the cylinder on itself, in the so-called “toroidal” configuration (with a toroidal magnetic field).

Magneto Hydro Dynamics (MHD)

The field that studies the macroscopic behavior of the plasma in a magnetic field is Magneto Hydro Dynamics (MHD): combines the laws of hydrodynamics with those of electromagnetism to describe plasma stability and instability.

Momentum equation

$$\rho \frac{d\boldsymbol{v}}{dt} = \boldsymbol{J}\times\boldsymbol{B} - \nabla p$$

Stability

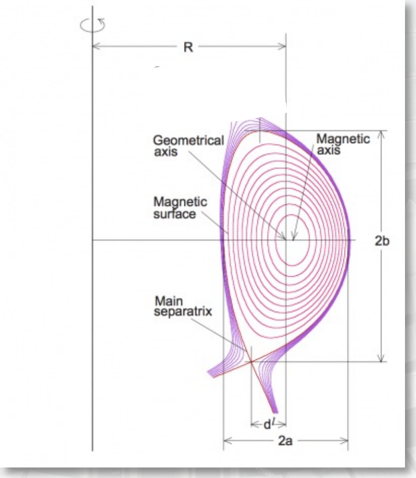
$$\nabla p = \boldsymbol{J}\times\boldsymbol{B} \Longrightarrow \nabla p = -\nabla \frac{B^2}{2\mu_0} + \dots .$$

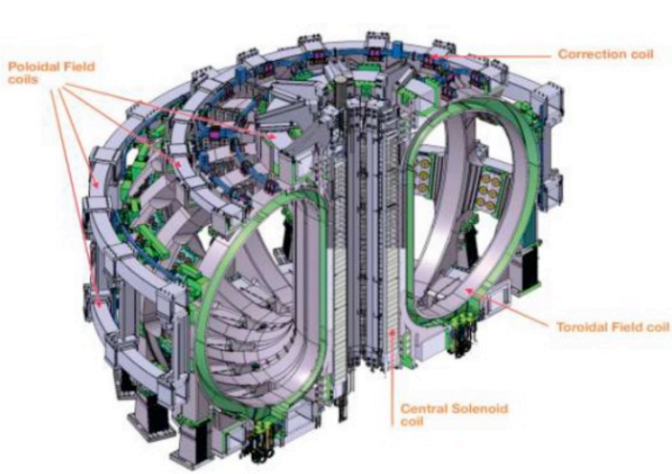
magnetic pressure

A general MHD solution for stability leads to a plasma elongated and triangular (optimizes toroidal force balance).

Toroidal coils are D-shaped.

Additional poloidal field coils (horizontal rings) are needed for position and shape control.





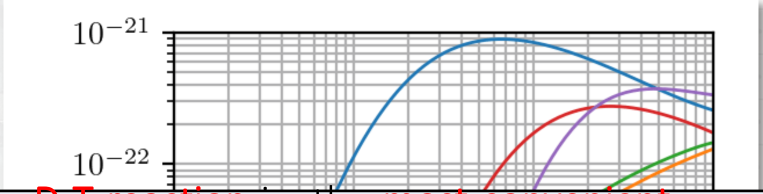
Reaction rate and power density

The power density produced in a reactor with a plasma of ion density n is given by:

$$P_{fus} = \frac{1}{4} E_R n^2 \langle \sigma v \rangle \quad W/m^3$$

<σv> is the velocity averaged cross section (VACS): convolution of the velocity-dependent cross section with the velocity distribution (Maxwellian distribution, function of temperature T):

$$< \sigma v > = \int f(v)\, \sigma(v)\, v\, dv \qquad f(v) = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} v^2 e^{-mv^2/2\mathrm{kT}}$$



Reaction	E_R (MeV)
D+D -> ^{3}He + n	3.28

The **D-T reaction** is the **most convenient** one. High VACS already around **20 keV** (230 million degrees !!).

Problems: needs **Tritium breeding + neutron damage** to structural elements.

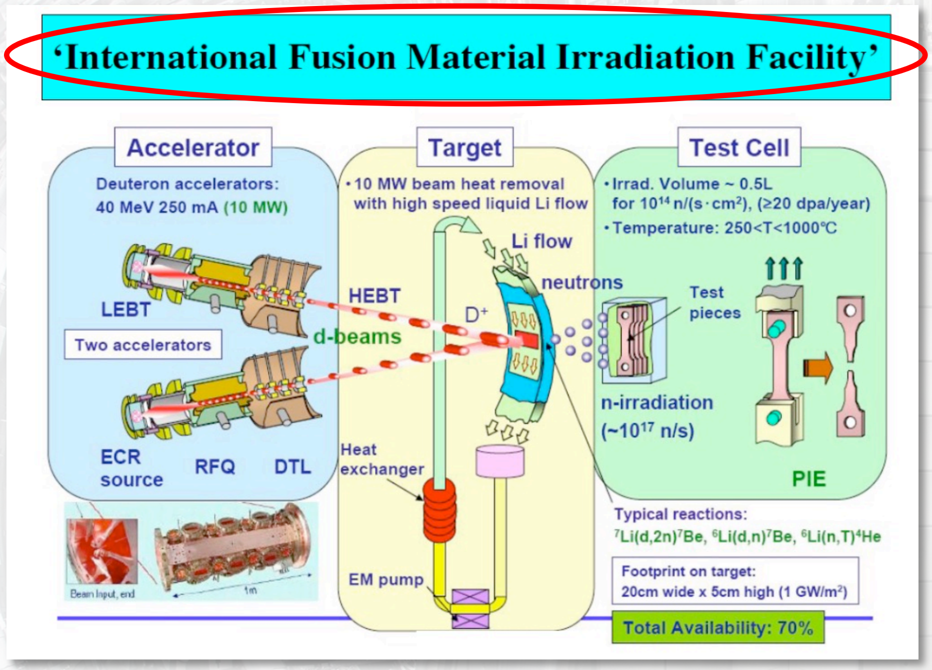
The advantages of the D-T reaction are by far superior than the disadvantages.

The **most convenient reaction** is **D-T**:

- **highest Q-value**
- **Cross section** peaks at lower energy and with **larger value**
- **Produces neutrons** that can transport energy outside the plasma

the VACS.
w on kT).

The IFMIF/DONES project



‘International Fusion Material Irradiation Facility’

Accelerator

Deuteron accelerators: 40 MeV 250 mA (10 MW)

Target

- 10 MW beam heat removal with high speed liquid Li flow

Test Cell

- Irrad. Volume ~ 0.5L for 10^{14} n/(s·cm^2), (≥20 dpa/year)
- Temperature: 250<T<1000℃

Typical reactions: $^7Li(d,2n)^7Be$, $^6Li(d,n)^7Be$, $^6Li(n,T)^4He$

Footprint on target: 20cm wide x 5cm high (1 GW/m^2)

Total Availability: 70%

Neutron irradiation facility for fusion materials (ancillary project, in preparation of future high-power reactors).

Irradiate material with neutron beams of extremely high flux for “accelerated” radiation damage (obtain in a few years the same damage predicted in fusion reactors after decades of operation).

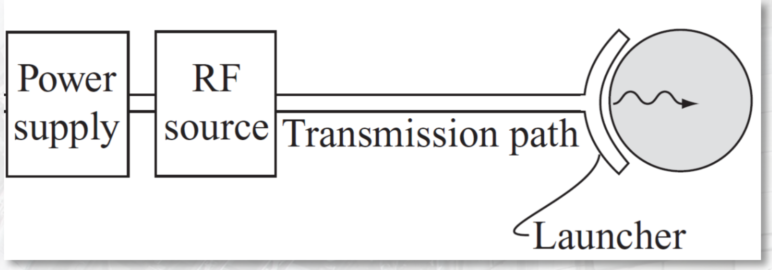
Neutron spectrum similar to fusion reactors.

Made of three parts:

- Accelerator (40 MeV, 250 mA) - INFN contribution
- a neutron-production target
- irradiation or test cell

Originally assigned to Japan, now being built in Granada (Spain): DONES (Demo Oriented NEutron Source)

Radiofrequency heating and Neutral Beam Injection



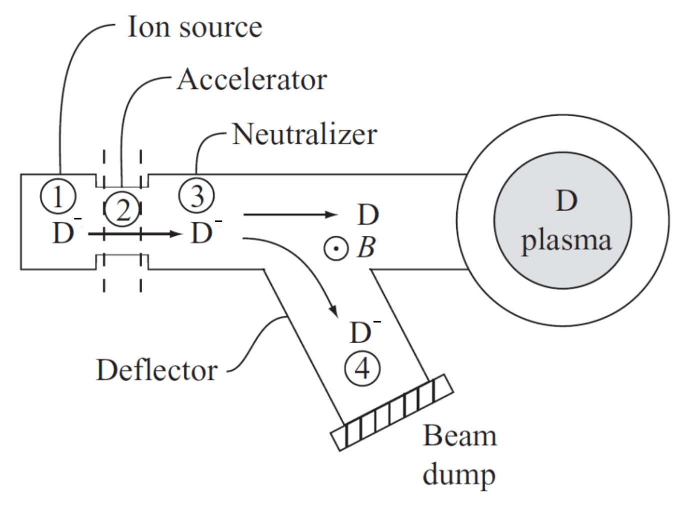
An electromagnetic wave of frequency similar to (i.e. resonant with) the cyclotron frequency of the particle can transfer energy to the particle: **ECRH** (Electron Cyclotron Resonance Heating) and **ICRH** (for ions).

$$\boldsymbol{\omega = \frac{qB}{m}}$$

$$\xrightarrow{B = 5\ T}$$

$$f_e = \omega_e/2\pi = 140\ GHz$$
$$f_i = \omega_i/2\pi = 38\ MHz$$

Additional RF with intermediate frequency of a few GHz is also used (Lower Hybrid Heating)



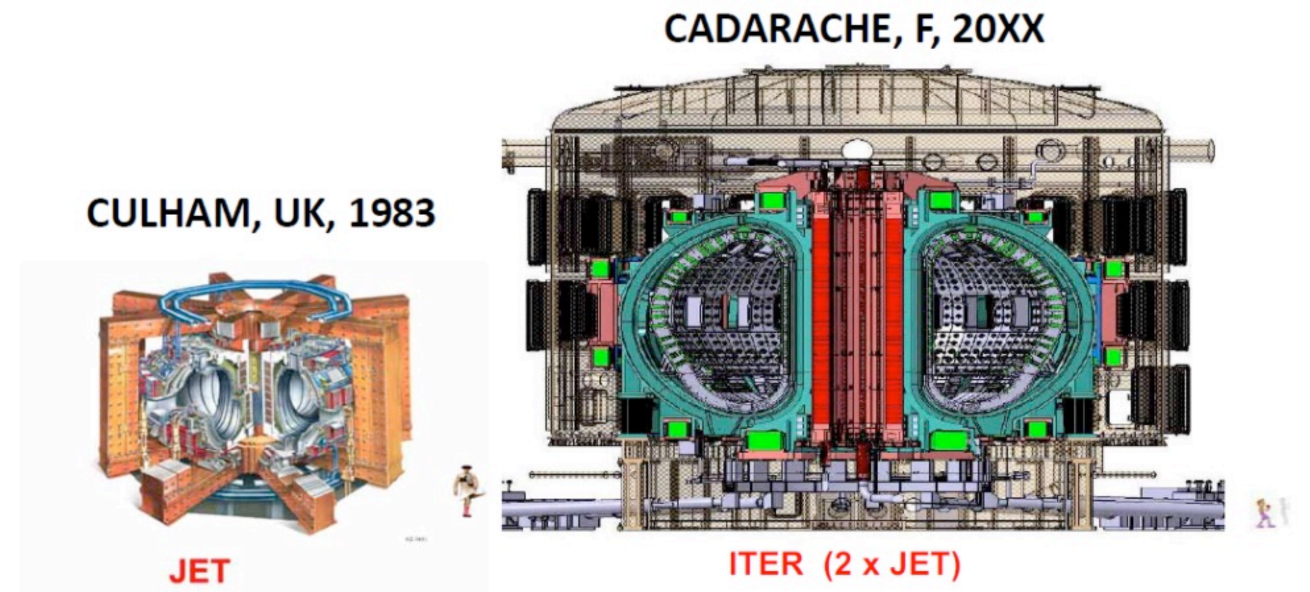
"Neutral" deuterium beam at MeV energy and high current (tens of Amperes) injected into the plasma (the beam KE is transferred to internal energy of the plasma).

Neutral beams are produced by means of:

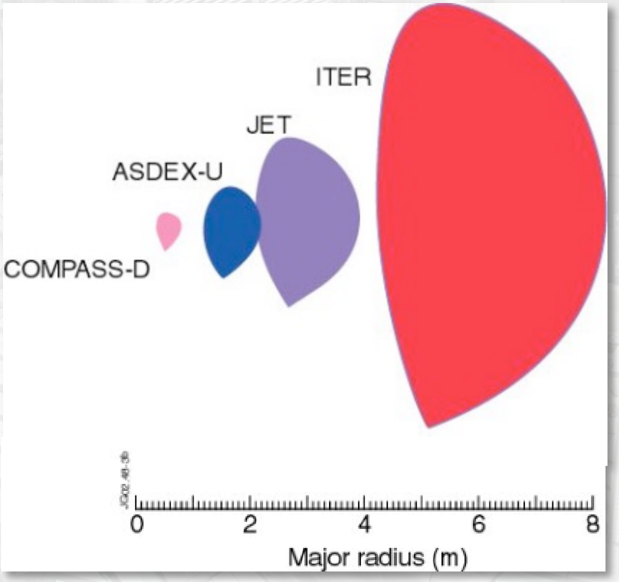
- negative ion source and extraction region (D^- at 100 keV energy and 40 A current)
- Acceleration stage: high voltage grids
- Neutralizer: gas cells in which charge exchange occurs.

Problem: the neutralization efficiency is only 60%. The remaining 40% of the ion beam has to be deflected and collected onto a dump (possibly by electric field). Space charge effects near dump.

ITER parameters



Biggest fusion reactor ever built, twice the size of JET (the largest tokamak currently active) in linear dimension (8 times in volume).



	JET	ITER
Major radius (m)	2.96	6.2
Minor radius (m)	1.25	2.
Plasma volume (m^3)	100	837
Magnetic field (T)	3.8	5.3
Plasma current (MA)	7	15
Plasma density ($\times 10^{20}$ m^{-3})	0.8	0.9
Temperature (keV)	14	11.2
Confinement time (s)	1.2	3.7

World record for highest power and sustained fusion in 2021