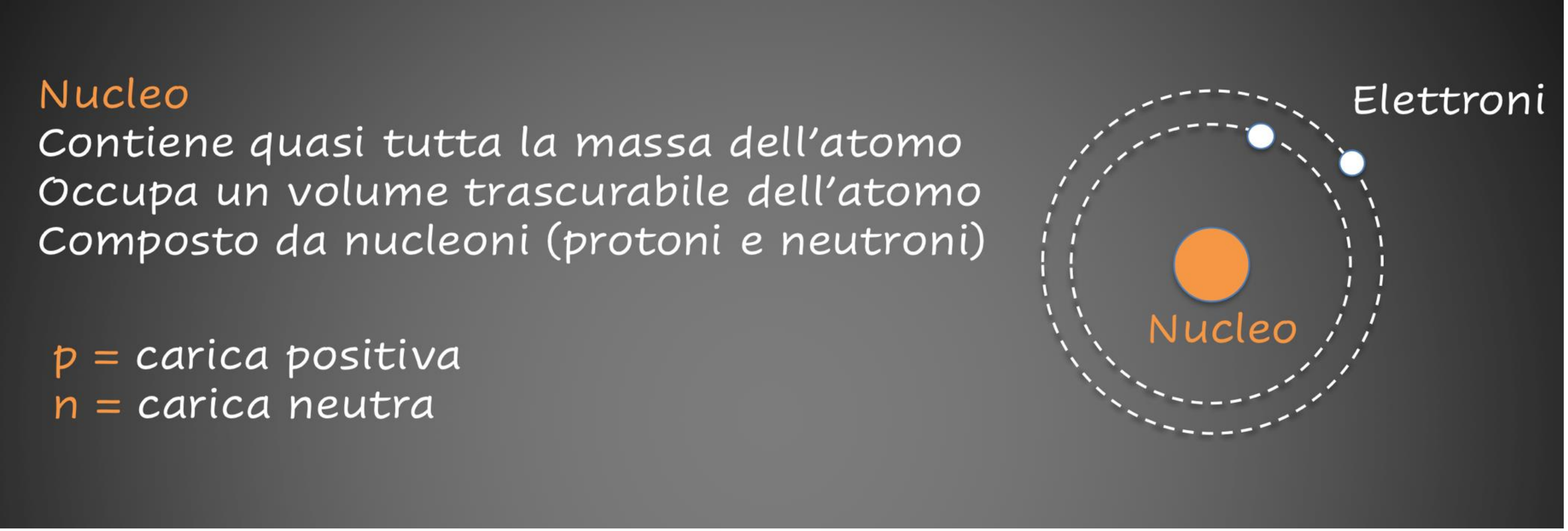
A che punto siamo?

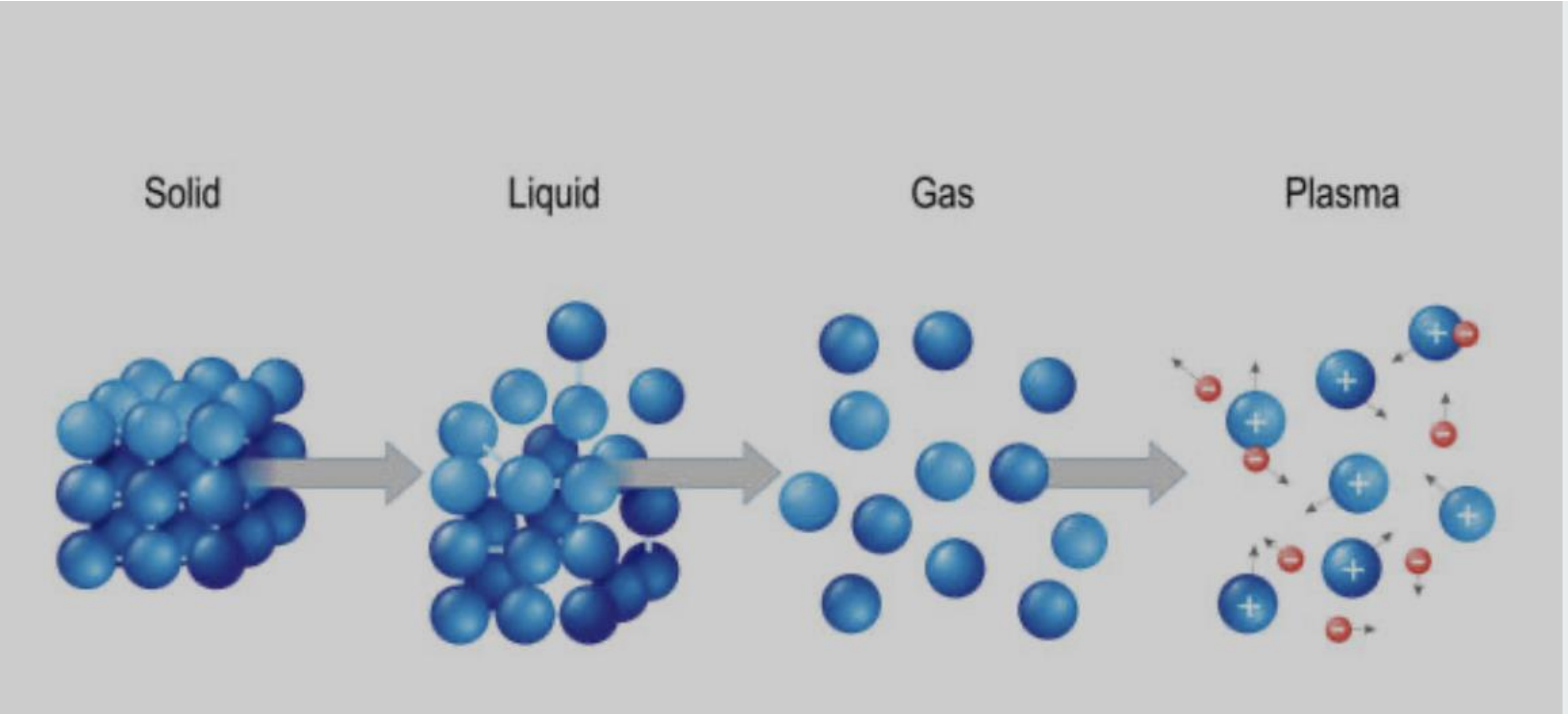
Perché?

- Fra le affermazioni più ricorrenti primeggia quella secondo la quale la fusione magnetica sarebbe prossima a rendersi disponibile per applicazioni commerciali.
- Sorge pertanto la curiosità di ragionare realmente, con un approccio scientifico e non commerciale, su a che punto sia il percorso verso il reattore, sia a confinamento magnetico che inerziale

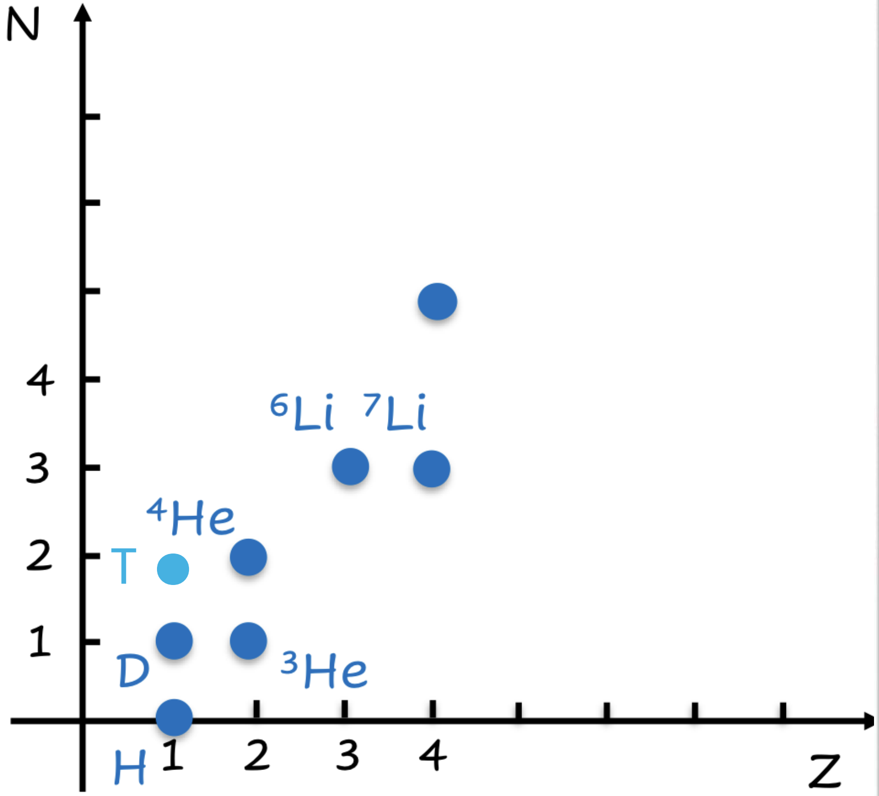
- La fusione è tutto ☺
- I dispositivi per lo studio della fusione
- Le road map eurofusion 2012 e 2018
- La road map DOE 10/2025
- La road map cinese
- Lo slancio verso la fusione
- Indicatori di prestazioni (il fattore Q)
- I risultati ottenuti (Jet campagne D-T)
- La road map Inerziale
- I risultati ottenuti

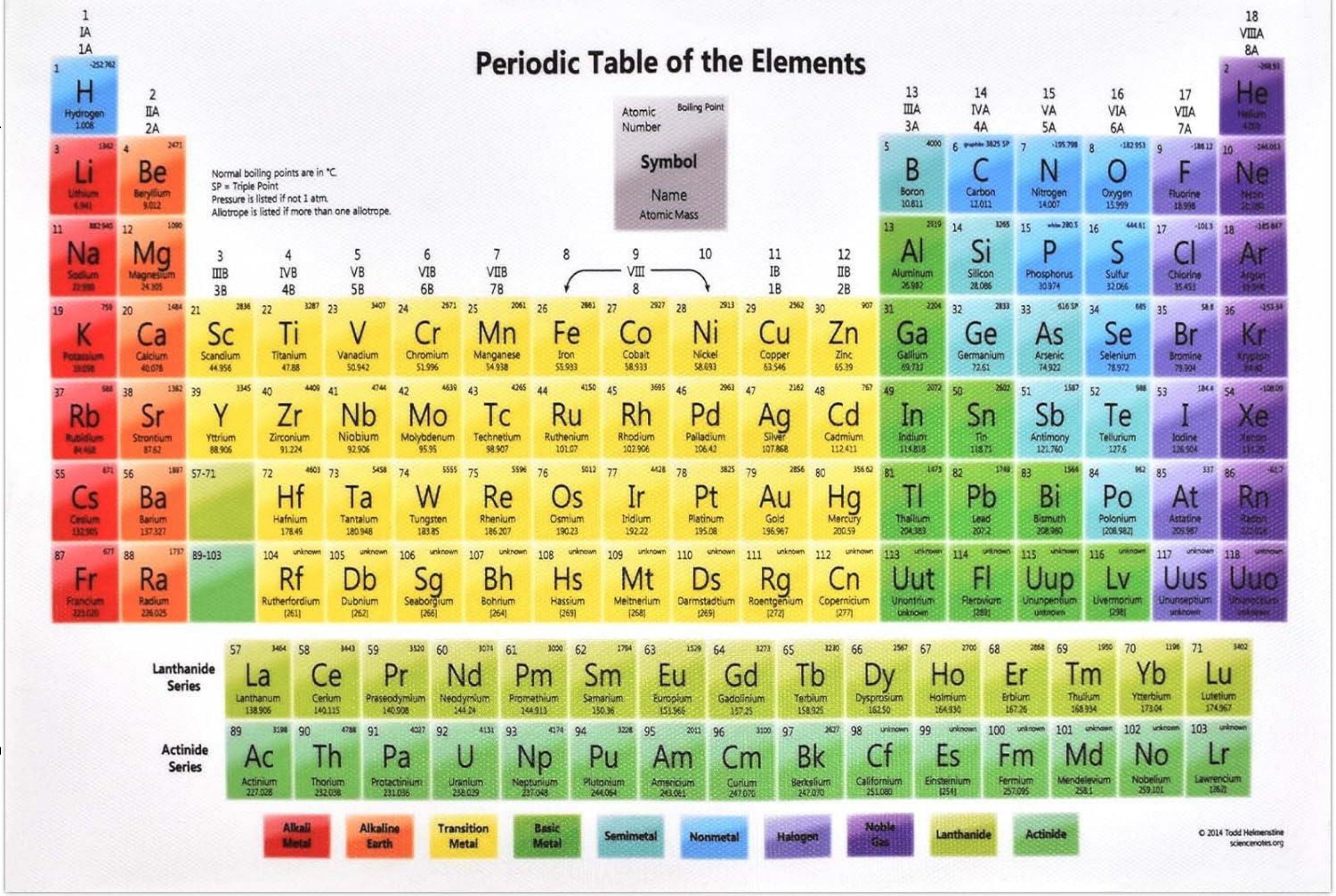


Lo stato della materia

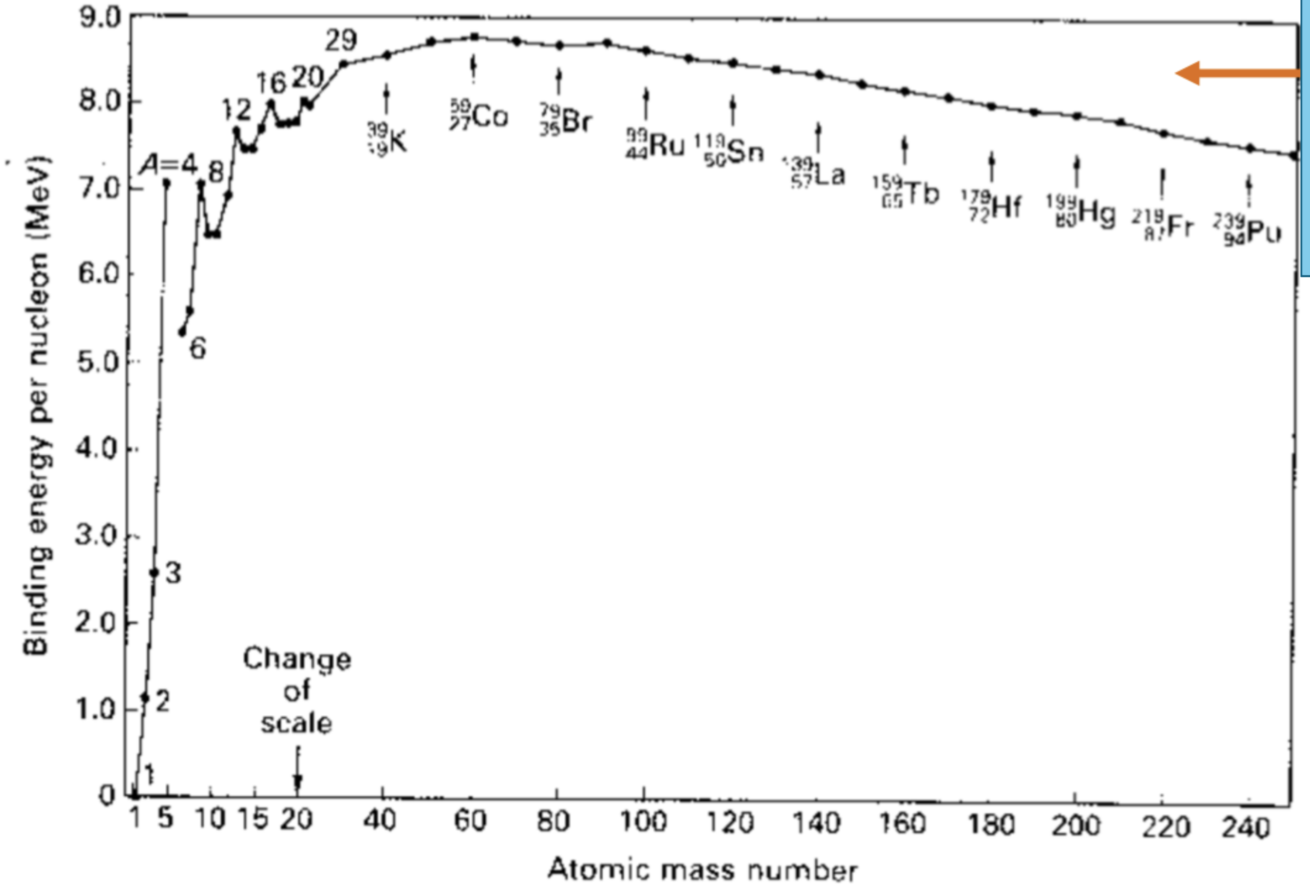


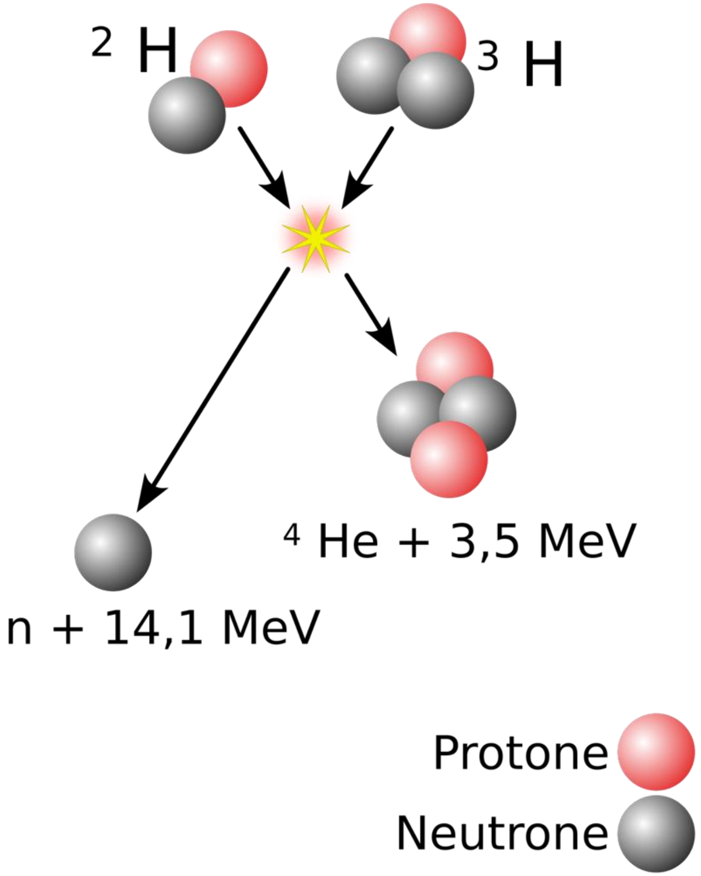
Gli elementi chimici si distinguono per il numero atomico



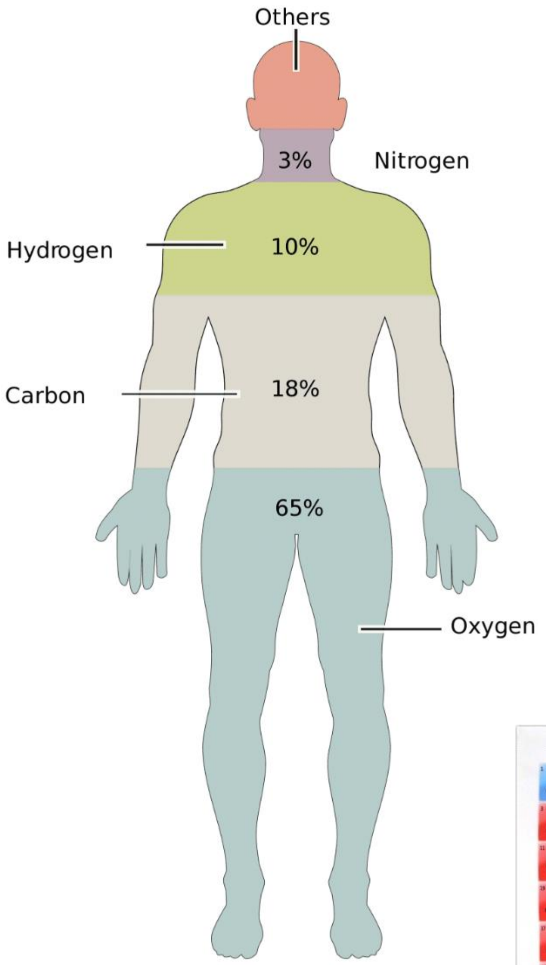


Fornendo energia i nuclei leggeri tendono ad aggregarsi (fusione), nuclei pesanti tendono a separarsi (fissione) entrambi i processi sono esoenergetici





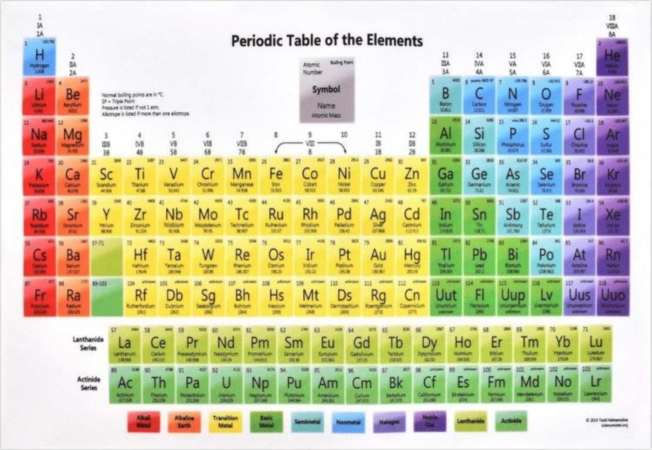
La fusione è l’origine di tutto

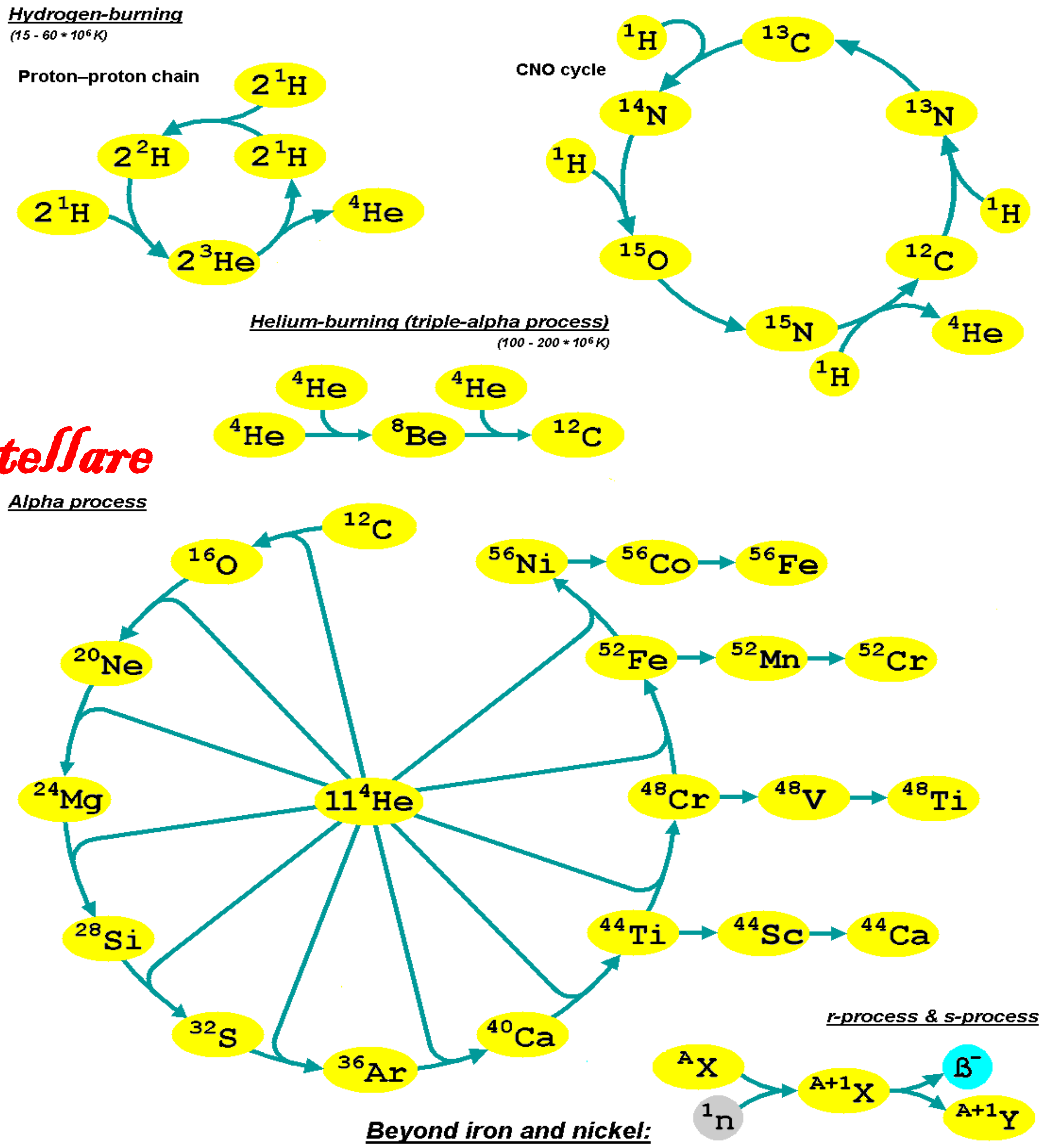


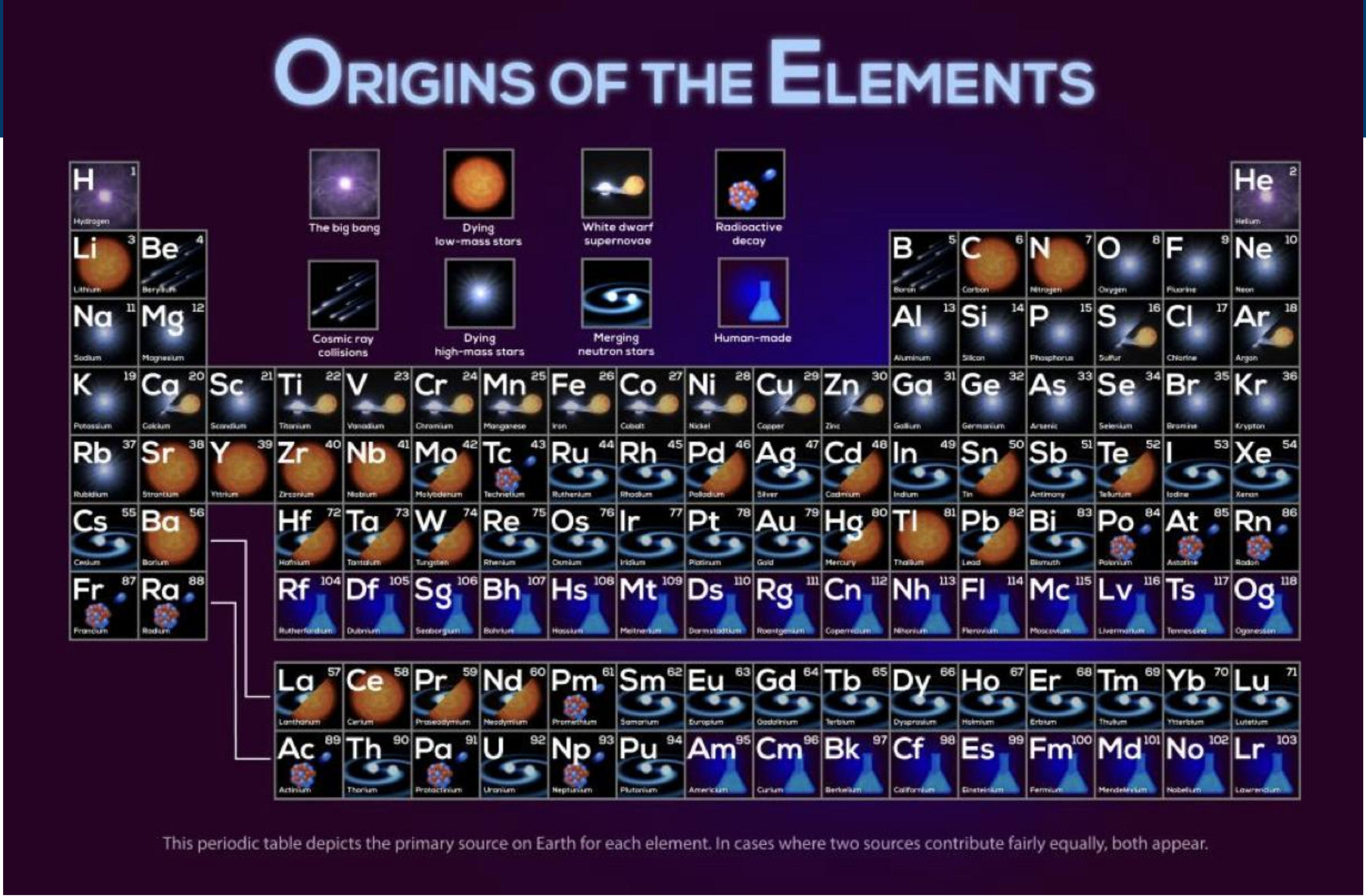
Nucleosintesi

primordiale

evoluzione stellare






ORIGINS OF THE ELEMENTS
The big bang
Dying low-mass stars
White dwarf supernovae
Radioactive decay
Cosmic ray collisions
Dying high-mass stars
Merging neutron stars
Human-made
H 1
He 2
Li 3 Be 4 B 5 C 6 N 7 O 8 F 9 Ne 10
Na 11 Mg 12 Al 13 Si 14 P 15 S 16 Cl 17 Ar 18
K 19 Ca 20 Sc 21 Ti 22 V 23 Cr 24 Mn 25 Fe 26 Co 27 Ni 28 Cu 29 Zn 30 Ga 31 Ge 32 As 33 Se 34 Br 35 Kr 36
Rb 37 Sr 38 Y 39 Zr 40 Nb 41 Mo 42 Tc 43 Ru 44 Rh 45 Pd 46 Ag 47 Cd 48 In 49 Sn 50 Sb 51 Te 52 I 53 Xe 54
Cs 55 Ba 56 Hf 72 Ta 73 W 74 Re 75 Os 76 Ir 77 Pt 78 Au 79 Hg 80 Tl 81 Pb 82 Bi 83 Po 84 At 85 Rn 86
Fr 87 Ra 88 Rf 104 Df 105 Sg 106 Bh 107 Hs 108 Mt 109 Ds 110 Rg 111 Cn 112 Nh 113 Fl 114 Mc 115 Lv 116 Ts 117 Og 118
La 57 Ce 58 Pr 59 Nd 60 Pm 61 Sm 62 Eu 63 Gd 64 Tb 65 Dy 66 Ho 67 Er 68 Tm 69 Yb 70 Lu 71
Ac 89 Th 90 Pa 91 U 92 Np 93 Pu 94 Am 95 Cm 96 Bk 97 Cf 98 Es 99 Fm 100 Md 101 No 102 Lr 103
This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

La sola energia di cui disponiamo è quella generata da reazioni nucleari

- Tutti gli elementi chimici sono frutto di reazioni nucleari
- Il vero motore dell'universo è l'energia nucleare

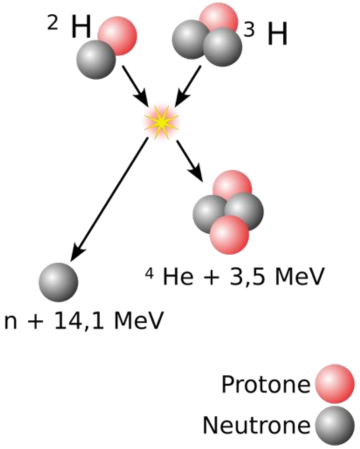
di **Fusione** o di **Fissione**

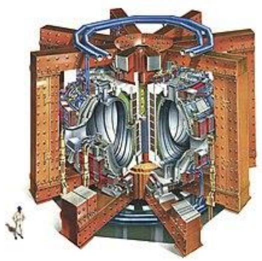
- **Solare** reazioni di fusione
- **Idroelettrica** (evaporazione)
- **Eolica** (differenze di pressione atmosferica, onde)
- **Combustibili fossili**, **biomasse** (fotosintesi)
- **Geotermica**
- **Fissione**

Riusciremo a produrla direttamente?

Pertanto cerchiamo di generare sulla terra le condizioni per le quali gli elementi possano fondere

Macchine a confinamento magnetico





JET

1983

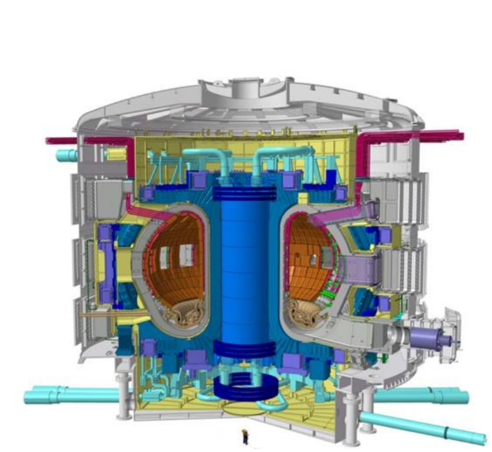
$Q \approx 0.3$

$R_0 = 3$ m

$\tau_E = 1.2$ s

$V_p = 80$ m^3

$P_{th} \approx 16$ MW$_{th}$



ITER

>2035

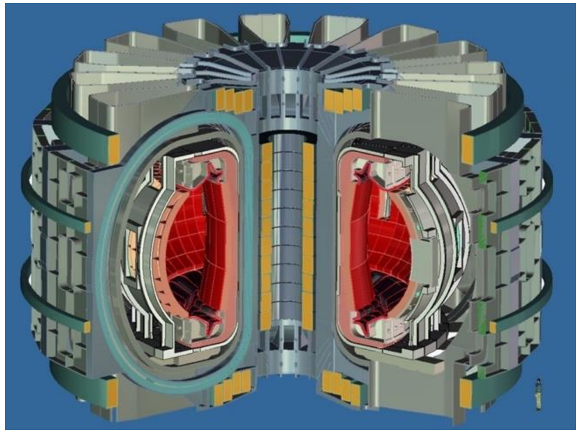
$Q \approx 10$ nel 2044

$R_0 = 6.2$ m

$\tau_E = 3.7$ s

$V_p = 800$ m^3

$P_{th} \approx 500$ MW$_{th}$



DEMO

>20??

$Q \approx 25$

$R_0 = 7\text{-}10$ m

$\tau_{E >}$ 4 s

$V_p = 2500$ m^3

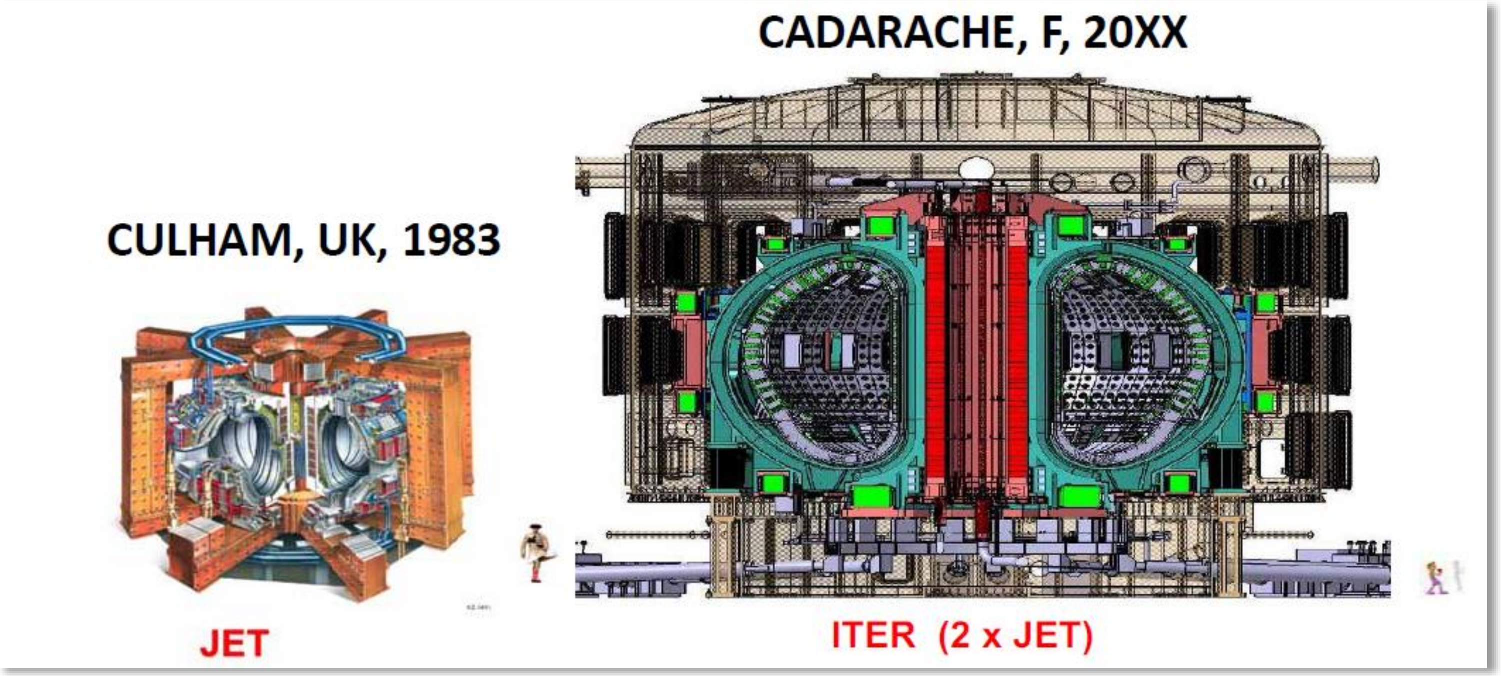
$P_{th} \approx 1650$MWth

350 MWe

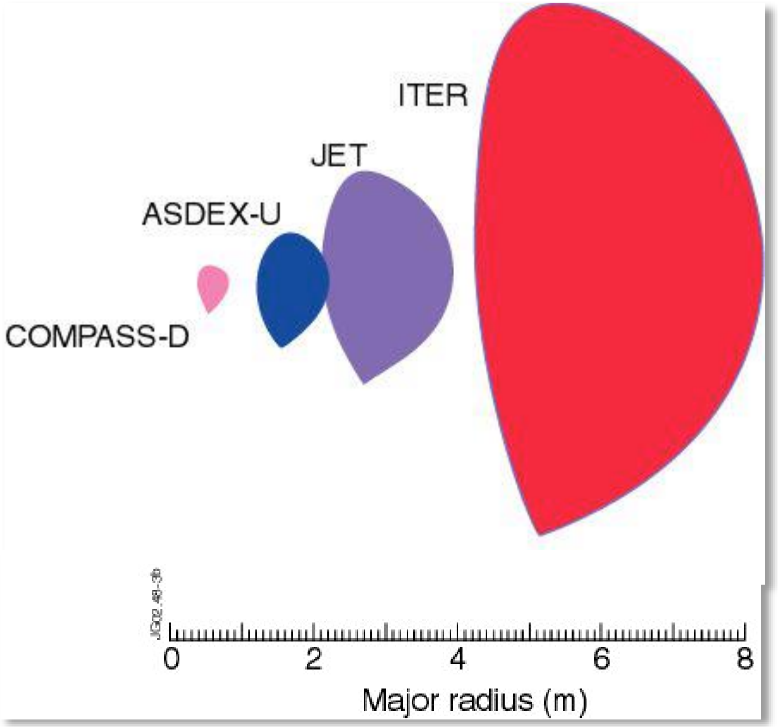
ITER: first reactor that will **prove Q>1** (but no electricity production)
DEMO: first prototype that will **generate electricity**

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

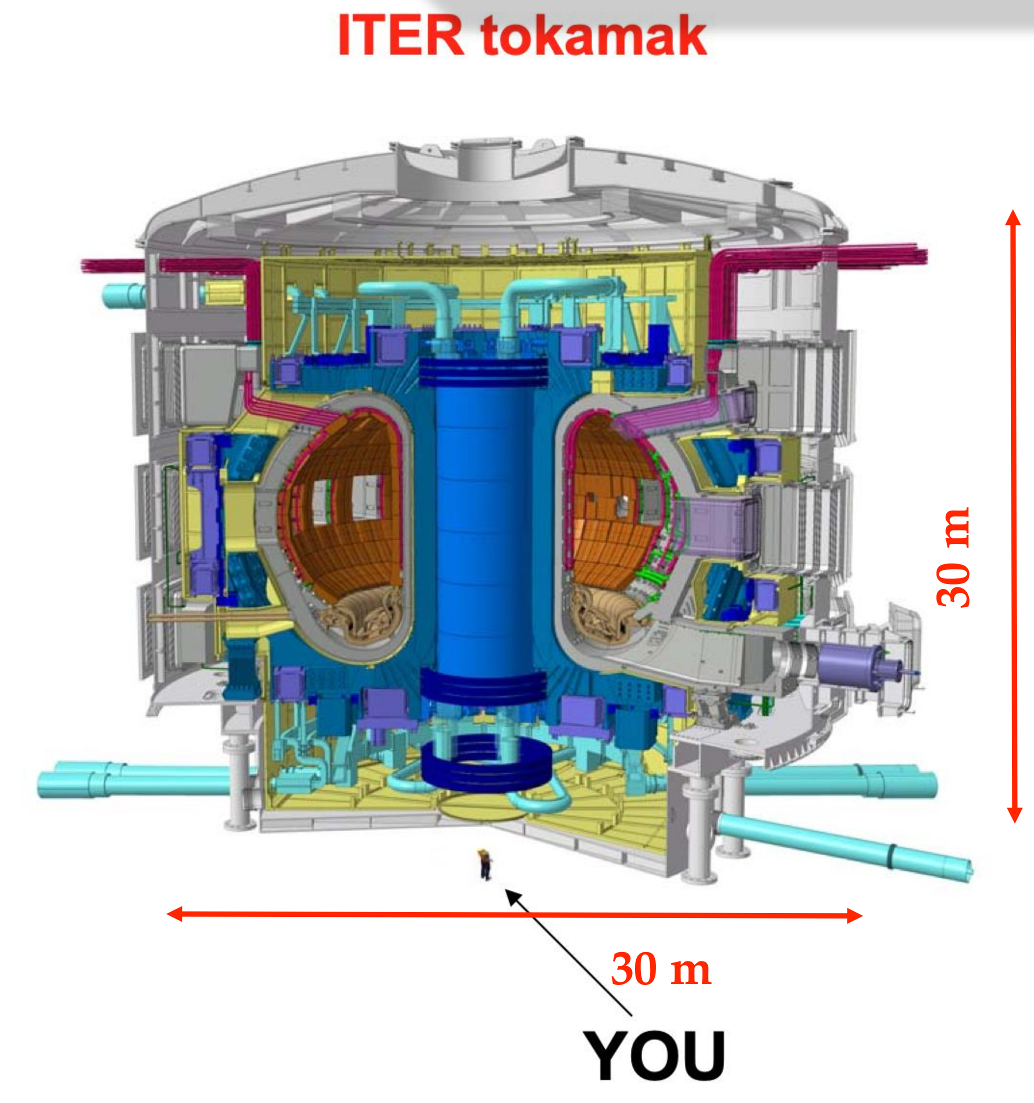
ITER parameters



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



ITER
International Thermonuclear Experimental Reactor



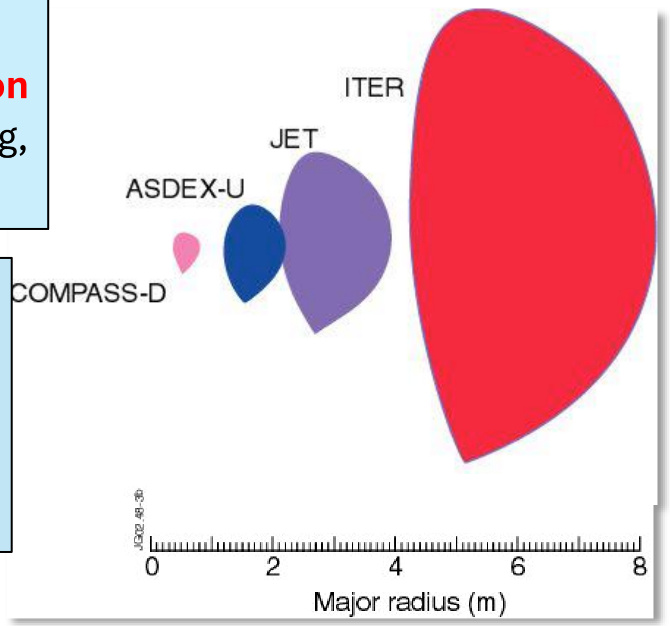
The **biggest** project on nuclear fusion.

Largest tokamak ever built, its goals are:

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

Currently been built in **Cadarache** (France), should be completed by 2035.

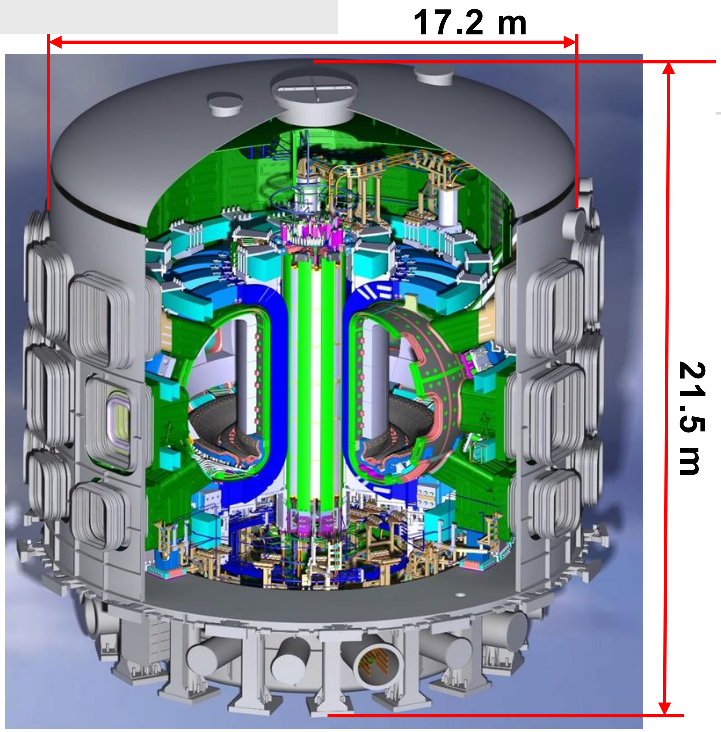
ITER will **not produce electricity**, but will pave the way to a future reactor for energy production (**DEMO**).

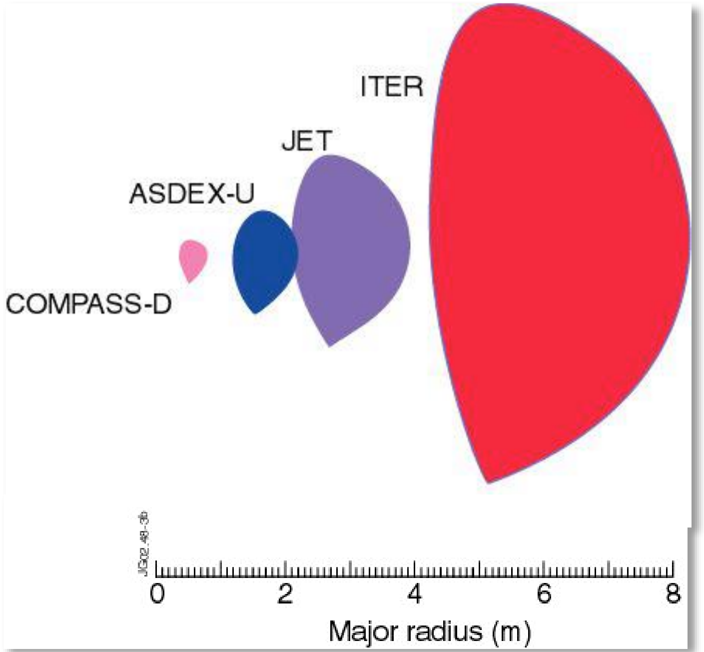


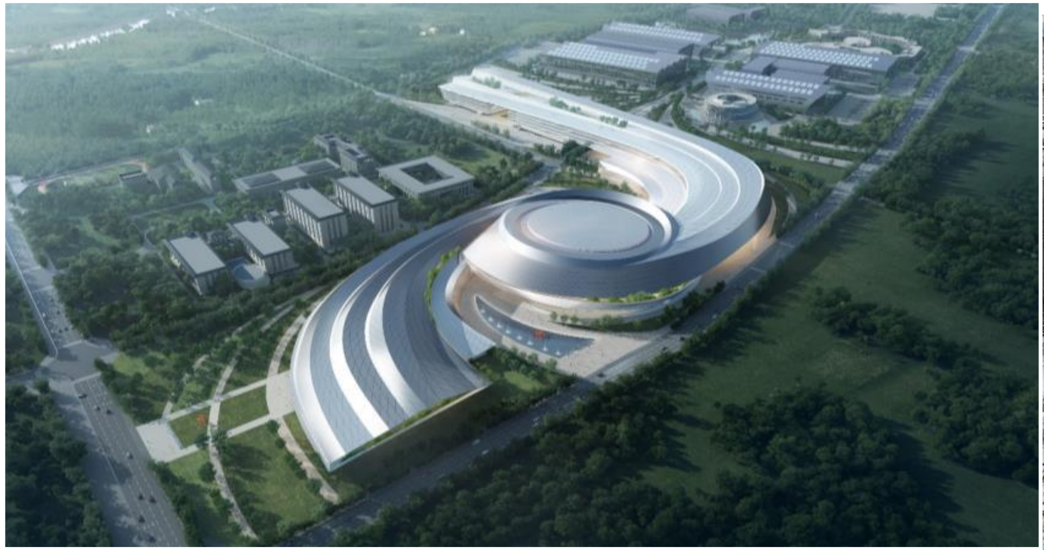
China

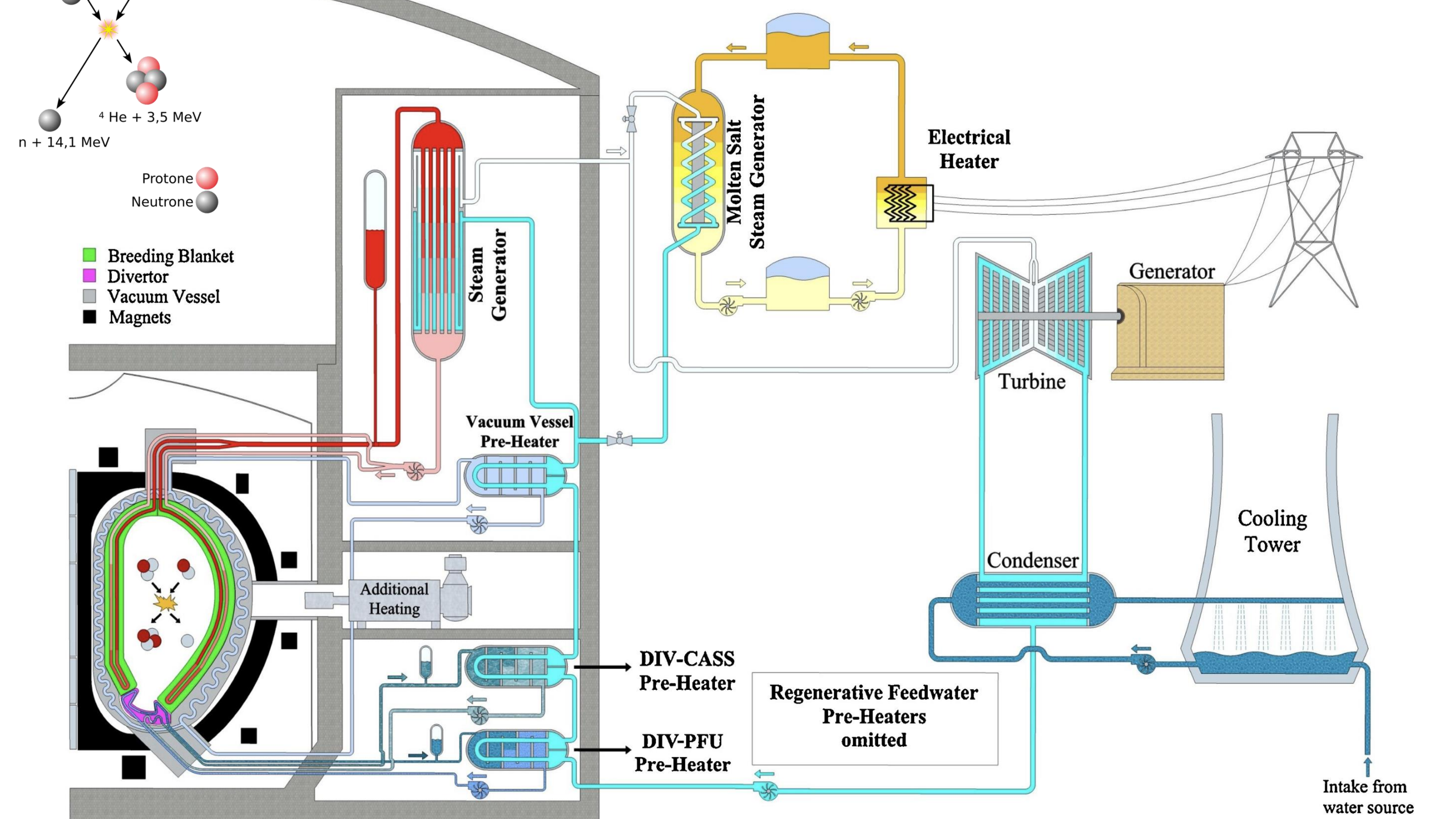
BEST (Burning experiment superconducting Tokamak)

- Site selectd in March 2019
- Construction started in January 2023
- First plasma in 2027
- Burning plasma with Q<5 (10MW for 100s, 150MW for 10s)
- Steady-state with Q>1 (20MW for hrs, 40MW for 1.000 s)
- R = 3.6 m
- a = 1.1 m

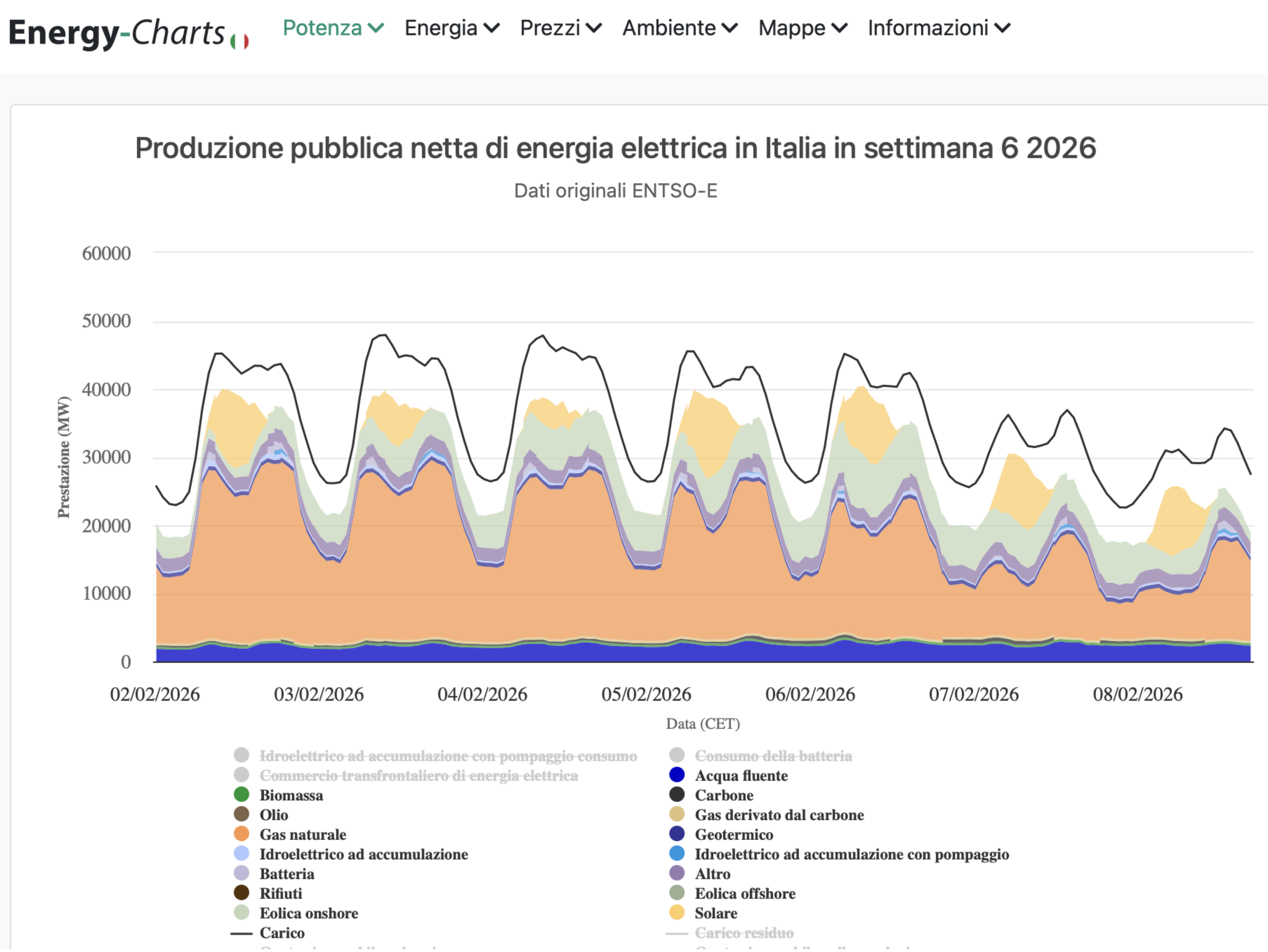








^{4} He + 3,5 MeV
n + 14,1 MeV
Protone
Neutrone
Breeding Blanket
Divertor
Vacuum Vessel
Magnets
Steam Generator
Molten Salt Steam Generator
Electrical Heater
Generator
Turbine
Vacuum Vessel Pre-Heater
Additional Heating
Cooling Tower
Condenser
DIV-CASS Pre-Heater
DIV-PFU Pre-Heater
Regenerative Feedwater Pre-Heaters omitted
Intake from water source



Carico di rete Nazionale compreso fra 50 e 25 GW

Roadmap Eurofusion 2012

Preface

A long-term perspective on fusion is mandatory since Europe has a leading position in this field and major expectations have grown in other ITER parties on fusion as a sustainable and secure energy source. China, for example, is launching an aggressive programme aimed at fusion electricity production well before 2050. Europe can keep the pace only if it focuses its effort and pursues a pragmatic approach to fusion energy. With this objective EFDA has elaborated the present roadmap.

ITER is the key facility in the roadmap: ITER construction is fostering industrial innovation on a number of enabling technologies. Its licensing, completion of construction and successful operation will be fundamental milestones towards the fusion power plant. Thus ITER success is the most important overarching objective of the programme.

Still, the realisation of fusion energy has to face a number of technical challenges. For all of them candidate solutions have been developed and the goal of the programme is now to demonstrate that they will also work at the scale of a reactor. Eight different roadmap missions have been defined and assessed. They will be addressed by universities, research laboratories and industries through a goal-oriented programme detailed here for the Horizon 2020 period. This effort cannot be pursued only at European level – all the opportunities from international collaborations need to be exploited.

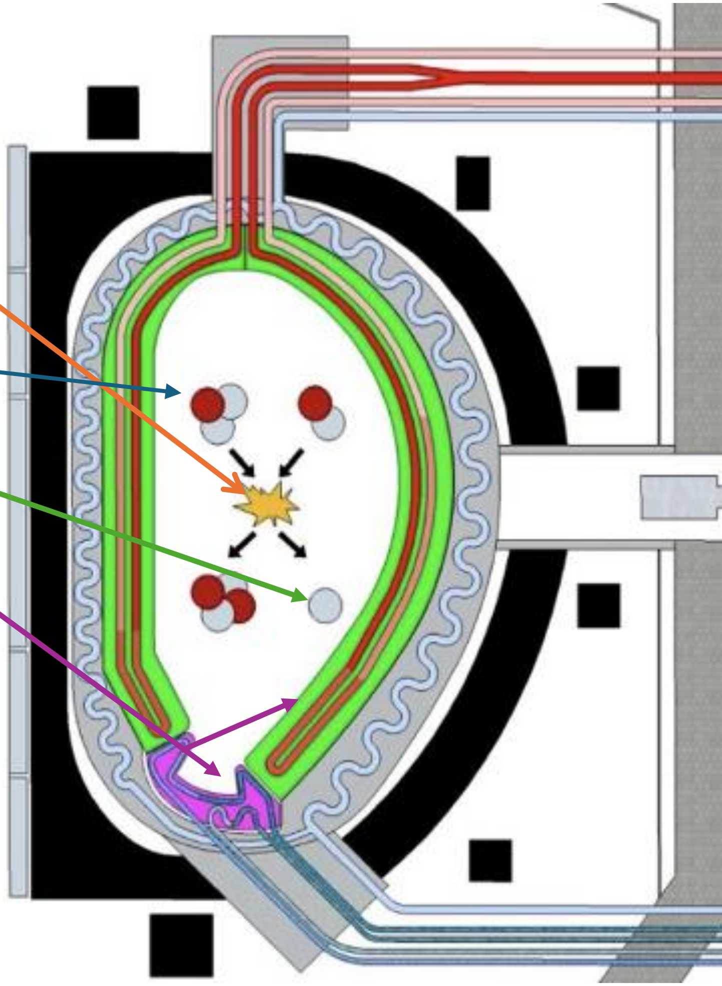
According to the present roadmap, a demonstration fusion power plant (DEMO), producing net electricity for the grid at the level of a few hundred Megawatts is foreseen to start operation in the early 2040s. Following ITER, it will be the single step to a commercial fusion power plant.

Defining, designing, building and operating DEMO requires the direct involvement of industry in the fusion programme that in the coming decades will move from being science-driven, laboratory-based towards an industry-driven and technology-driven venture. This transition requires strengthening the available engineering resources, and has to be facilitated already during Horizon 2020 by specific measures in support of training and education.

The success of the roadmap relies on the assumption that adequate resources will be made available by the European Commission and the EURATOM Member States. Coherently with the pragmatic approach advocated here, resources will be focussed on few well-defined objectives. As a consequence, the amount of resources for the roadmap will not exceed the amount originally recommended by the Council for FP7 outside the ITER construction, with the vast majority of resources being devoted to the ITER preparation. This will ensure that Europe will fully benefit from the large investment in the ITER construction.

Roadmap «Missions»

Table of content



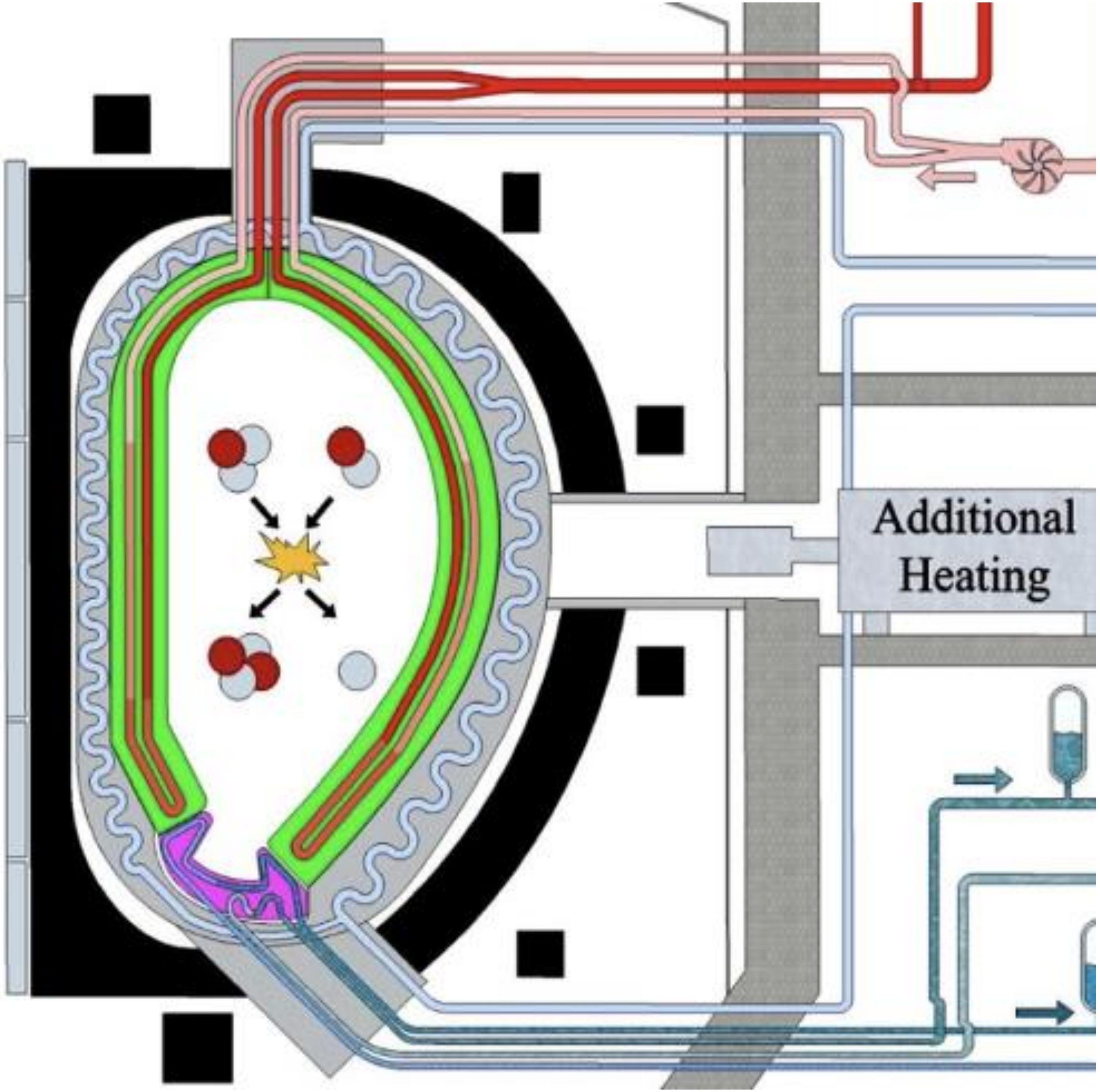
Plasma regime

Specifically, plasma regimes of operation in a fusion reactor need to integrate:

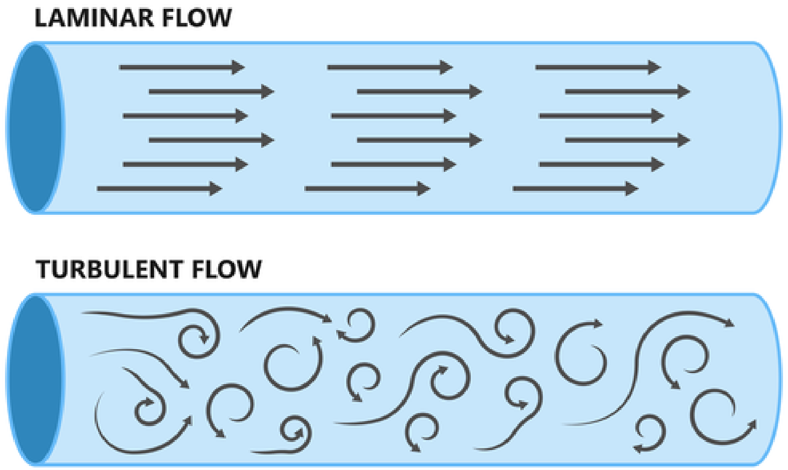
1. **Burning-plasma conditions** in which fusion generated alpha particles are the **dominant** heating mechanism;
2. High density for achieving high fusion power and reactor-relevant values of the neutron wall load (~1-2MW/m2);
3. Large radiated power from a mantle surrounding the hot plasma core (to reduce the power conducted to the divertor and achieve acceptable divertor heat load);
4. Avoidance/mitigation of off-normal events (ELM, disruptions);
5. Diagnostics and actuators compatible with the reactor environment.

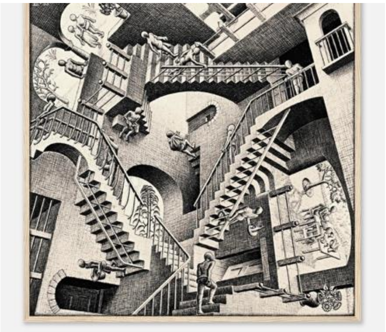
Requirements 1-5 are common to all magnetic fusion concepts. Plasma regimes that can achieve these conditions for long pulses (~8h in a Fusion Power Plant (FPP), relying in part on plasma current driven inductively by the tokamak's central solenoid) have been already demonstrated in tokamaks and could be the basis for a conservative DEMO reactor.

……….



- Plasma turbolento ed instabile
- Si sporca a causa della interazione con le pareti
- Il divertore screma lo strato più esterno nel tentativo di espellere i prodotti di fusione (He) e le impurezze, ma portando via una quantità rilevante di energia





Mission 2: heat and particle exhaust

The main challenge for the realization of a fusion power plant is the heat exhaust problem. The power that crosses the magnetic separatrix is diverted along the magnetic field line to a remote region (the divertor) where it is exhausted on actively cooled divertor targets.

Iter ipotizzando 500 MWt di potenza di plasma con 50 MW di riscaldamento addizionale

400MW trasportati dai neutroni e 150 MW di potenza trasportata dalle particelle, supponendo che di questa il 40% sia irradiato dal plasma di bulk, rimangono 90 MW da smaltire, se anche solo 60 arrivano (33% irradiato) alle piastre del divertore di ITER (massimo 2 m^2) significa 30 MW/m^2, al di sopra dei limiti della tecnologia attuale.

Bisogna ulteriormente aumentare la potenza irradiata…..

Senza dimenticare che il divertore serve:

ad estrarre l'elio e le impurezze non il calore, che invece dovrebbe essere utilizzato per produrre energia

Se l'elio e le impurezze non si estraggono efficacemente il reattore NON funziona

Se si estrae troppo trizio si complica tutto

Se si estrae il gas che dà luogo al detacment si rompe tutto

Mission 3: Material Damage in a Fusion Reactor

The internal components of a Fusion Reactor will be subjected to an intense bombardment of high energy neutrons (up to loadings of $2MWm^2$) from the plasma deuterium-tritium (D-T) fusion reaction. The neutron spectrum has a peak at the energy released in the D-T reaction (14.1 MeV):

2D + 3T 4He (3.5MeV) + n (14.1MeV)

Several critical phenomena are known to occur when neutrons are incident on material surfaces.

radiation "hardening", radiation embrittlement , radiation swelling and radiation-induced thermal creep……

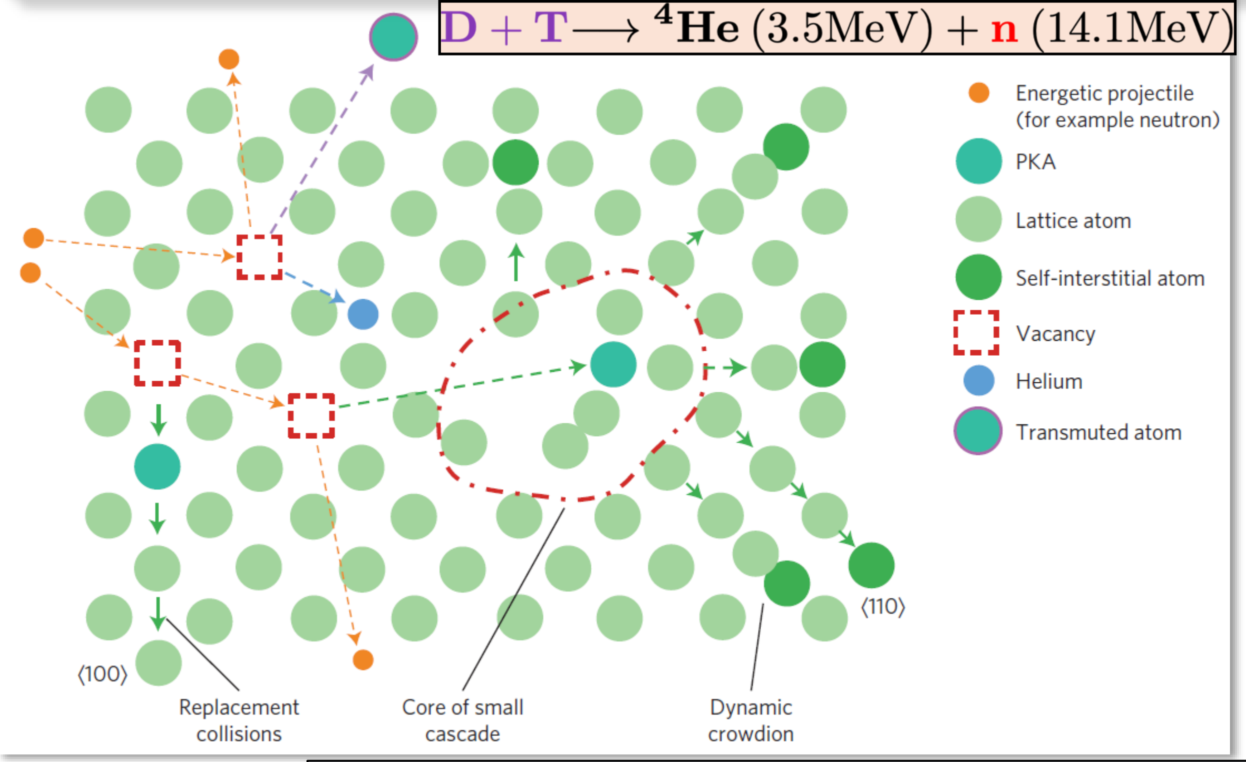
These are primarily the result of displacements of atoms within the lattice following inelastic neutron-atom collisions, with the resultant formation of self-interstitial atoms and vacancies in the lattice that diffuse and aggregate to create a variety of extended defect complexes.

Metals and alloys with a 'body-centred-cubic (bcc)' crystal lattice structure, including iron and ferritic steels, and tungsten, show better resistance to prolonged irradiation, in terms of much lower swelling and lower embrittlement, than metals with face-centred-cubic (fcc) lattices. For example, the only class of steels that shows low swelling in the high-dose ~ 200 dpa limit, at temperatures close to 420°C, are ferritic (bcc) steels [3.2].

The effect of neutron collisional lattice damage is measured in'*displacements per atom (dpa)*' and

Mission 3: Material Damage in a Fusion Reactor

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



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

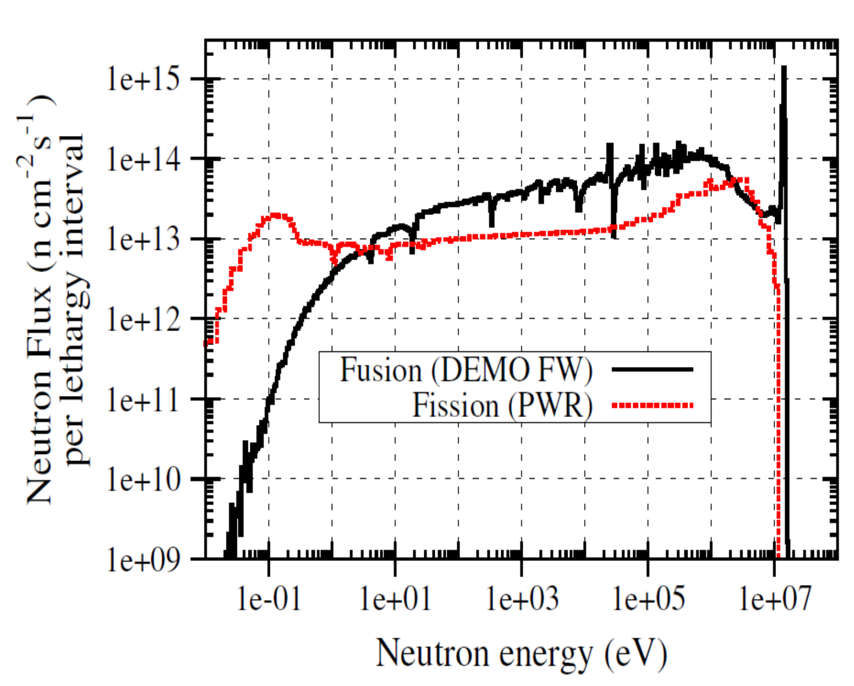
Neutrons reactions with materials:

- **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.

Fusion neutrons **energy spectrum** is different (higher energy) than in fission reactors: **peak at 14 MeV** not present in fission.

The experience on neutron damage in **fission reactors not** directy **applicable** to fusion reactors. Much **higher gas production** in fusion structural materials.



Mission 3, materials

To develop full scientific and engineering characterisation, and **theoretical understanding** of:

- **Neutron resistant structural materials** able to withstand high levels of 14MeV neutron flux and maintain their structural and thermo-mechanical properties, including in a welded condition, in a sufficiently wide window of operation and for a sufficiently long lifetime exposure (fluence) for DEMO reactor and Fusion Power Plant;
- **High heat flux and Plasma Facing Materials** able to withstand the combined effects of 14 MeV neutron flux and high intensity plasma ion/neutral bombardment and maintain their mechanical and thermo-mechanical properties and erosion resistance in a sufficiently wide window of operation and for a sufficiently high combined fluence for DEMO reactor and Fusion Power Plants;

Mission 4: tritium self sufficiency and fuel cycle

The main functions of the blanket/fuel cycle system can be summarised as follows:

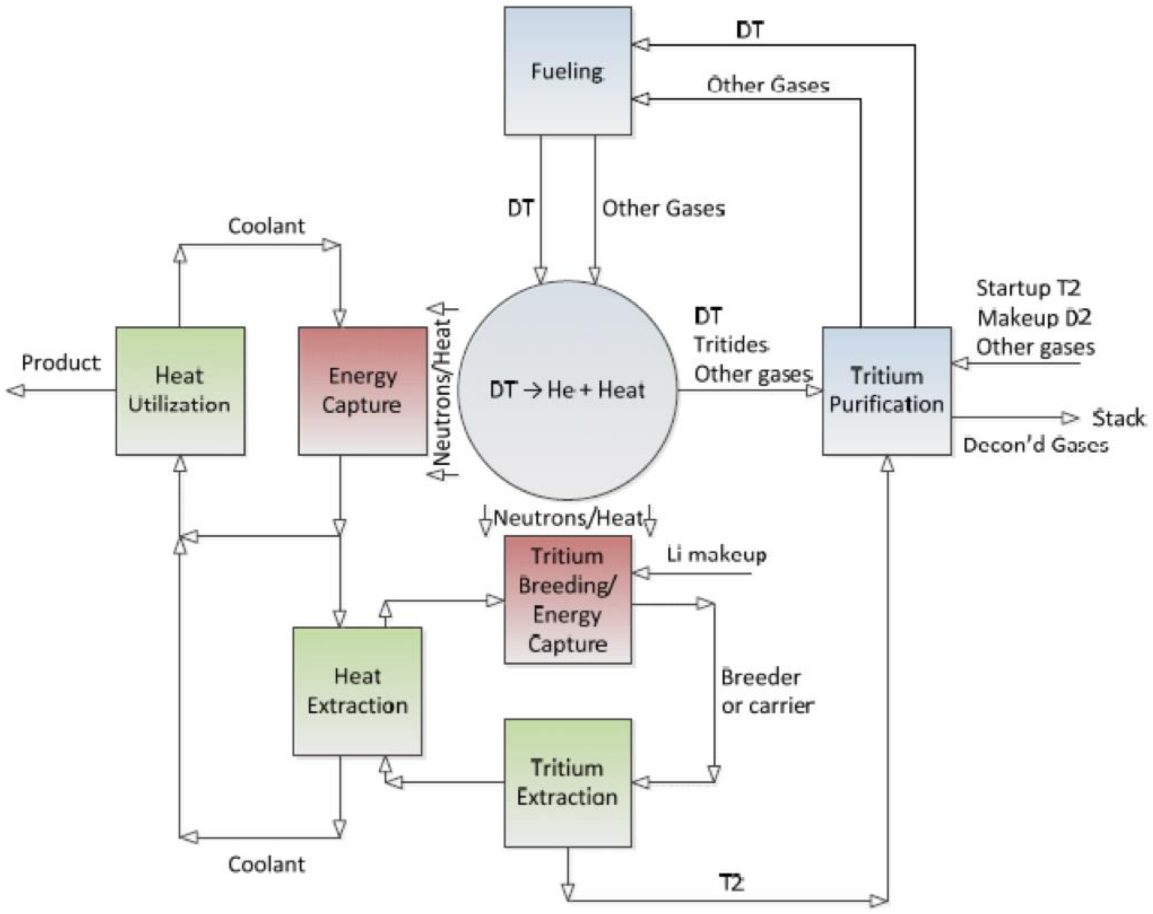
- **Blanket tritium breeding and heat production**: utilize and manage fusion neutrons by breeding tritium, converting neutron energy to heat. This region is exposed to high neutron fluence, especially in the first ~20 cm closest to the plasma.•

Blanket tritium and heat extraction: generate high-grade heat suitable for conversion to electricity through a heat exchanger and turbine cycle (see Mission 6 BoP). Extract tritium from the breeding blanket and send it to the purification and recycle loop.

- **Tritium recovery and recycle**: recover unburned tritium from the reactor exhaust and tritium extracted from the breeding blanket. This region must handle large tritium nventories and must prevent tritium release to the environment.

Accountancy of tritium in the fuel cycle for both safety and proliferation, given that kilogram quantities of tritium are circulating daily through the system, is another aspect of this challenge.

At the moment **civilian tritium mostly comes from CANDU fission reactors.**



Produzione all'interno del reattore

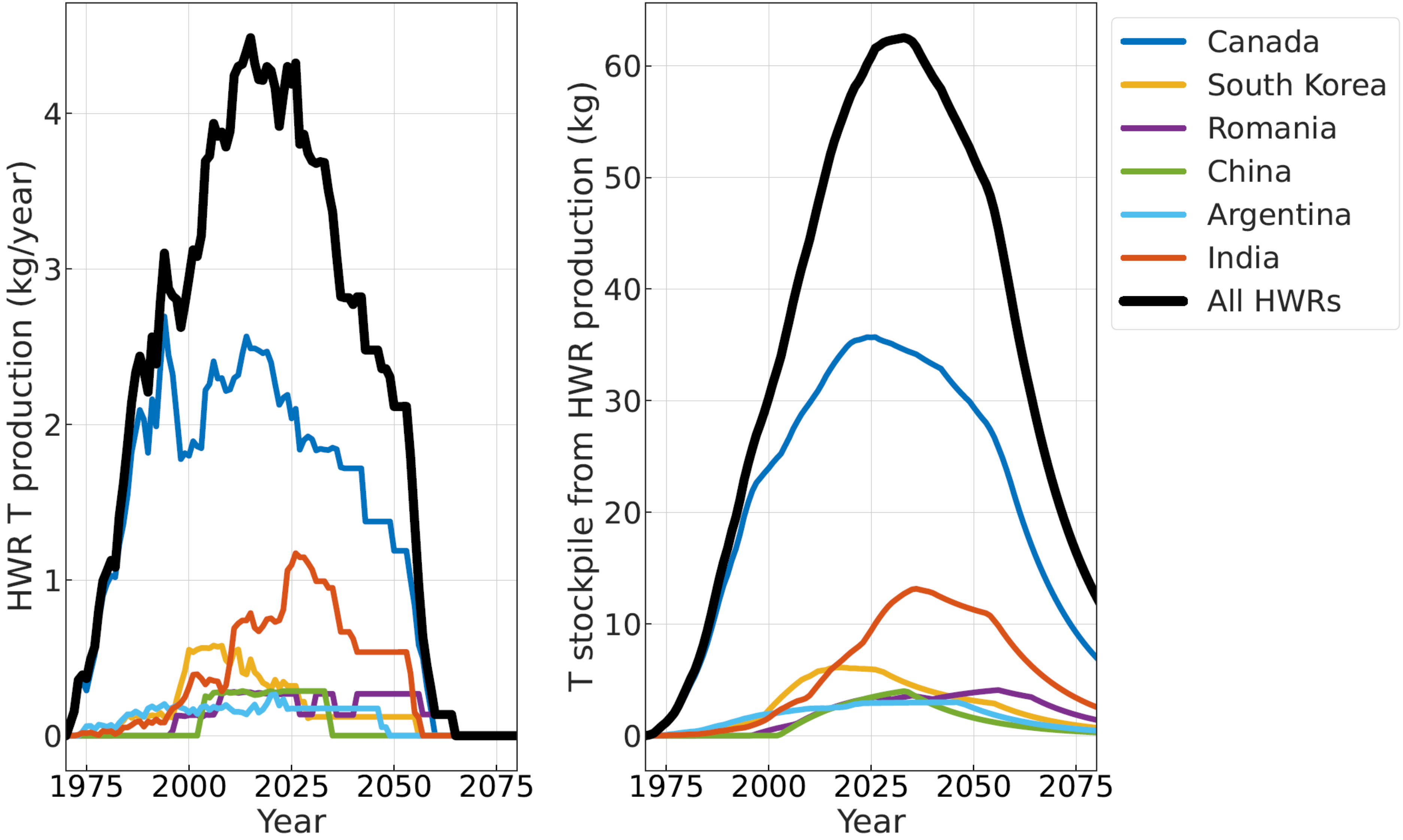
Il trizio non esiste in natura al contrario dell'uranio (il cui prodotto di decadimento è il radon...)
Anche se autoprodotto dal reattore (da verificare) per le fasi sperimentali e di accensione di un eventuale reattore servono rilevanti quantità di trizio

- **Lithium-6 Reaction:** 6Li+n→4He(2.05MeV)+T(2.73MeV)
- **Lithium-7 Reaction:** **7Li+n→4He+T+n′−2.47MeV** bassa probabilità

Duplicazione neutronica, **Reazione (n,2n):**

- ^{9}Be+n→2(^{4}He)+2n
- ^{208}Pb+n→^{207}Pb+2n

Global T production and stockpiles



Global tritium demand

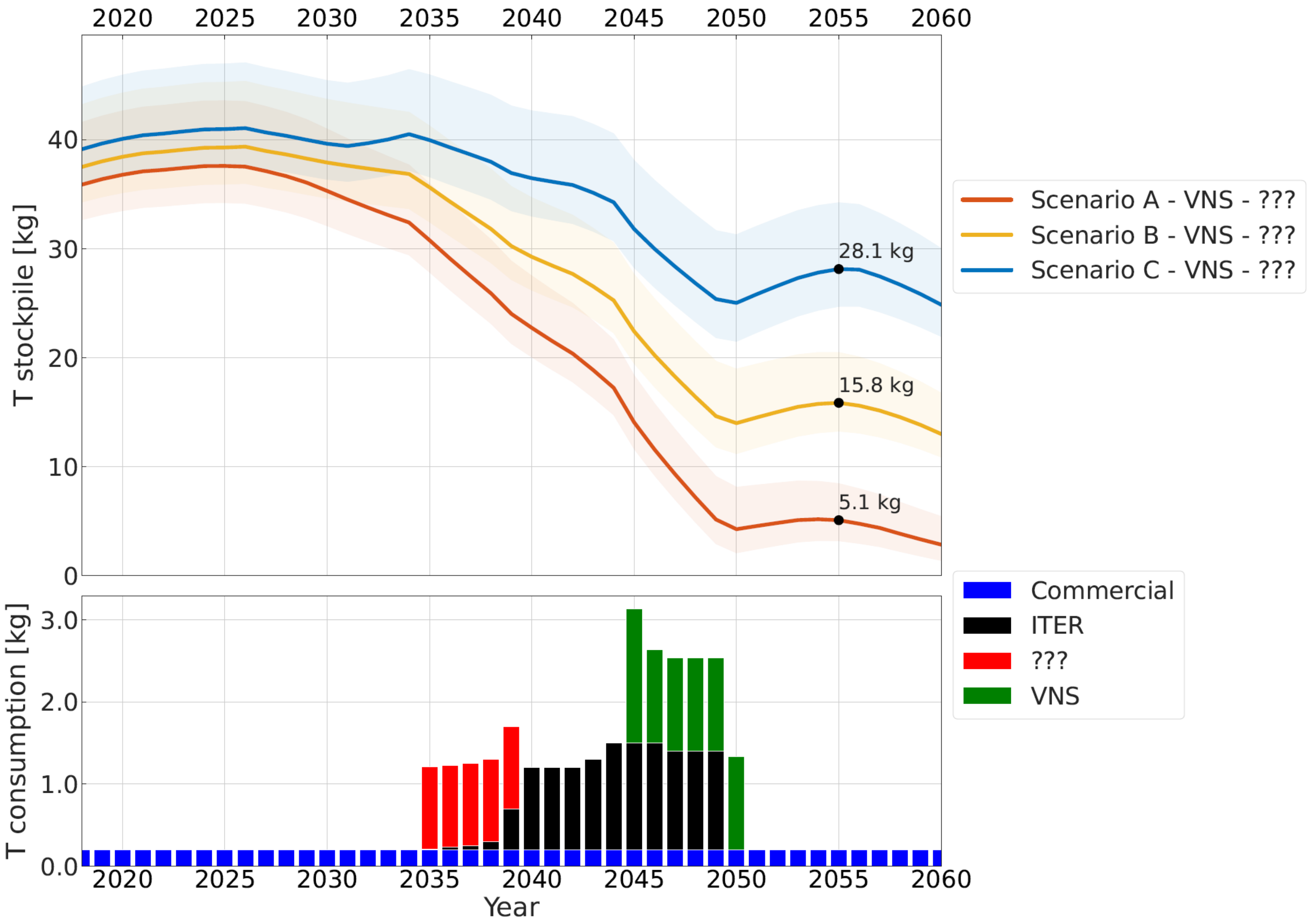
- **Commercial demand:**
- Ontario Power Generation group in Canada sells T at approximately 25-30 M$/kg [1]
- Commercial sales between 0.1-0.3 kg per year (since ~1980)
- As far as I am aware, at present this is the only pathway to large-scale purchases of tritium

- **Fusion demand:**
- ITER demand totals 12.3 kg for the full D-T campaign over 15 years
- ITER is obviously delayed… here I assume ITER D-T takes place in 2040, and that the full campaign takes places
- VNS, if takes place as planned, would consume 6.8 kg of T over 7 years [9]. No date set, but I assume 2045 here
- There are many fusion businesses that would also happily purchase tritium in the years to come:
  - CFS -> SPARC
  - UKIFS -> STEP
  - Tokamak Energy -> ???
  - Proxima -> ???
  - Gauss -> ???
  - …aggiungo io BEST????
- The exact quantities and dates are not clear, here I have modelled this as 5 kg over 2035-2040

It’s tough to make predictions, especially about the future.

Niels Bohr

Supply and demand scenario: ITER – VNS – ???



Supply and demand - discussion

- Of course, if multiple private fusion enterprises are successful, the demand for tritium will increase.
- Under normal circumstances, an increase in demand for a rare commodity would lead to increased supply and price balancing. However:
  - Drivers for detritiation are not linked to tritium sales… drivers are regulatory, safety case, and environmental risk and worker dose rate reduction
  - **Supply unlikely to increase with demand**…
  - Ontario Power Generation group sells tritium at zero production cost! [10] at 25-30 M€ / kg
  - Cernavoda detritiation cost estimated at 275 M€/unit (excl. capital cost) [11] i.e. ~158 M€ / kg
  - Cost unlikely to decrease with demand… detritiation is expensive
- Further limitations to supply:
  - Supply rate limited by detritiation facility capacity: cannot arbitrarily increase to cope with demand
  - Supply coincides with planned or opportunistic HWR maintenance / refurbishment
  - **“Stockpiles” likely not fully recoverable**

Tritium supply: conclusions and outlook

- Clearly, if private fusion demand is high, it is possible that an EU-DEMO device cannot purchase sufficient tritium commercially.
- The only side of the equation the fusion community can act upon is the demand, e.g.:
  - Limit machines with TBR < 1
  - ITER not running its full D-T campaign…
  - Engage with private fusion enterprises to avoid a tritium rush
  - Improve fuel cycle to reduce start-up inventories for reactors
- **Recommendation: EUROfusion should consider engaging with OPG to purchase tritium options, and/or with private fusion enterprises.**

- NOTE: D-D start-up theoretically possible, but complicated for the fuel cycle, and is slow and expensive.

Mission 5: Implementation of fusion safety

5.4 Main risks and risk mitigation strategies.
(see Annex 14 for more details).

Risks	**Risk Mitigation**
DEMO design that does not sufficiently make use of fusion specific safety features.	Start activity by definition of Safety Design Requirements for DEMO Define the safety approach and criteria.
Limits on tritium releases in gaseous and liquid effluents difficult to meet	Development and demonstration of large-scale high-reliability and high-efficiency detritiation technologies (both water detritiation and air detritiation)
Large quantities of tritiated waste and of radioactive waste requiring geological disposal.	Develop recycling options. Develop and demonstrate large-scale, efficient detritiation systems from solid waste, identify isotope concentration levels acceptable in materials to avoid/minimise radioactive wastes requiring geological disposal.

The vacuum vessel can meet the low failure rate criteria with robust construction and double walls that confined tritium, neutron activated materials, and chemically toxic materials. Unfortunately, there are very many vacuum vessel penetrations that are necessary to operate the tokamak. The integration challenge was determining the boundary perimeter for these penetrations. The designers required many **vacuum vessel interfaces to the vacuum pumping system, the radiofrequency plasma heating systems, the fuelling system, the diagnostics and their ports, penetrations for cooling system piping, and the maintenance access ports with port plugs**. All of these systems extended the vacuum vessel strong barrier boundary and are part of the first confinement barrier, so their robustness has to be demonstrated as part of the licensing process.

Mission 6: Demo design

Definition of an EU-DEMO design point robust to epistemic plasma physics uncertainties

M. Coleman1,2,∗, H. Zohm1,3, C. Bourdelle F. Maviglia1,5, A.J. Pearce2, M. Siccinio, A. Spagnuolo1,6 and S. Wiesen1,7

Nucl. Fusion 65 (2025) 036039

«DEMO is in a pre-conceptual phase, mainly waiting for ITER results, or any result able to validate the calculation codes in close reactor conditions»

DEMO AIMS:

- (i) Demonstrate tritium self-sufficiency
- (ii) Produce net electricity
- (iii) Operate safely and reliably over a reasonable time-span
- (iv) Act as a component test facility, in particular for breeding blankets

• Mission 6: Demo design Demo in fase pre-concettuale

For instance, let us say we have a reactor for which we have the low and high estimates of fusion power from table 1 (Pfus = 1.6–3.0 GW). From previous EU-DEMO studies (e.g. [3]) we have Pel,net/Pfus ≈ 0.25, which we can use as a crude metric to estimate the net electric output for a given fusion power
.
Assuming that the reactor could otherwise handle this range of fusion power, and using the aforementioned metric to propagate the uncertainty on Pfus, such a reactor could in theory produce Pel,net ≈ 400–750 MWe.

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Definition of an EU-DEMO design point robust to epistemic plasma physics uncertainties

M. Coleman[1,2,*], H. Zohm[1,3], C. Bourdelle[1,4], F. Maviglia[1,5], A.J. Pearce[2], M. Siccinio[1,3], A. Spagnuolo[1,6] and S. Wiesen[1,7]

[1] EUROfusion, Boltzmannstr. 2, Garching 85748, Bavaria, Germany

Table 1. P_{fus} as calculated by different transport models for a representative EU-DEMO design point. Small variations in H can lead to large variations in P_{fus}. Data from [26].

	P_{fus} (GW)	W_{th} (GJ)	$H_{98(y,2)}$
QuaLiKiz [21, 22]	3.0	1.45	1.00
TGLF-SAT0 [27]	2.4	1.3	0.99
TGLF-SAT1 [28]	2.0	1.2	0.98
TGLF-SAT1geo [29]	1.7	1.1	0.94
TGLF-SAT2 [30]	1.6	1.05	0.89

Nel dubbio usano il codice di sistema PROCESS

P_{fus} 1652MWt. P_{el}=350+/-50 MWe netti

Mission 7: competitive cost of electricity.

Secondo la road-map del DOE un Tokamak sarà difficilmente conveniente per la produzione di elettricità

DEMO:Circa 1400 m^2
Iter 800m^2

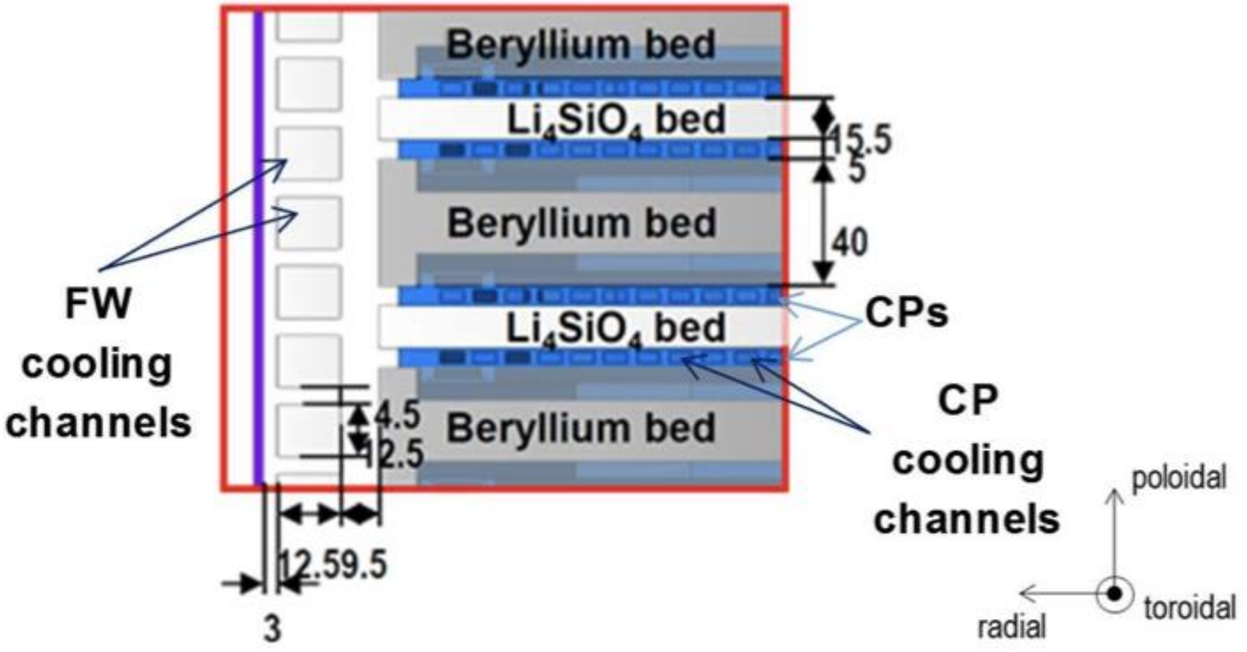


Fig. 3. Radial-poloidal cross section of a HCPB BM, showing the alternate structure of breeder, neutron multiplier and cooling plates (adapted from [2]).

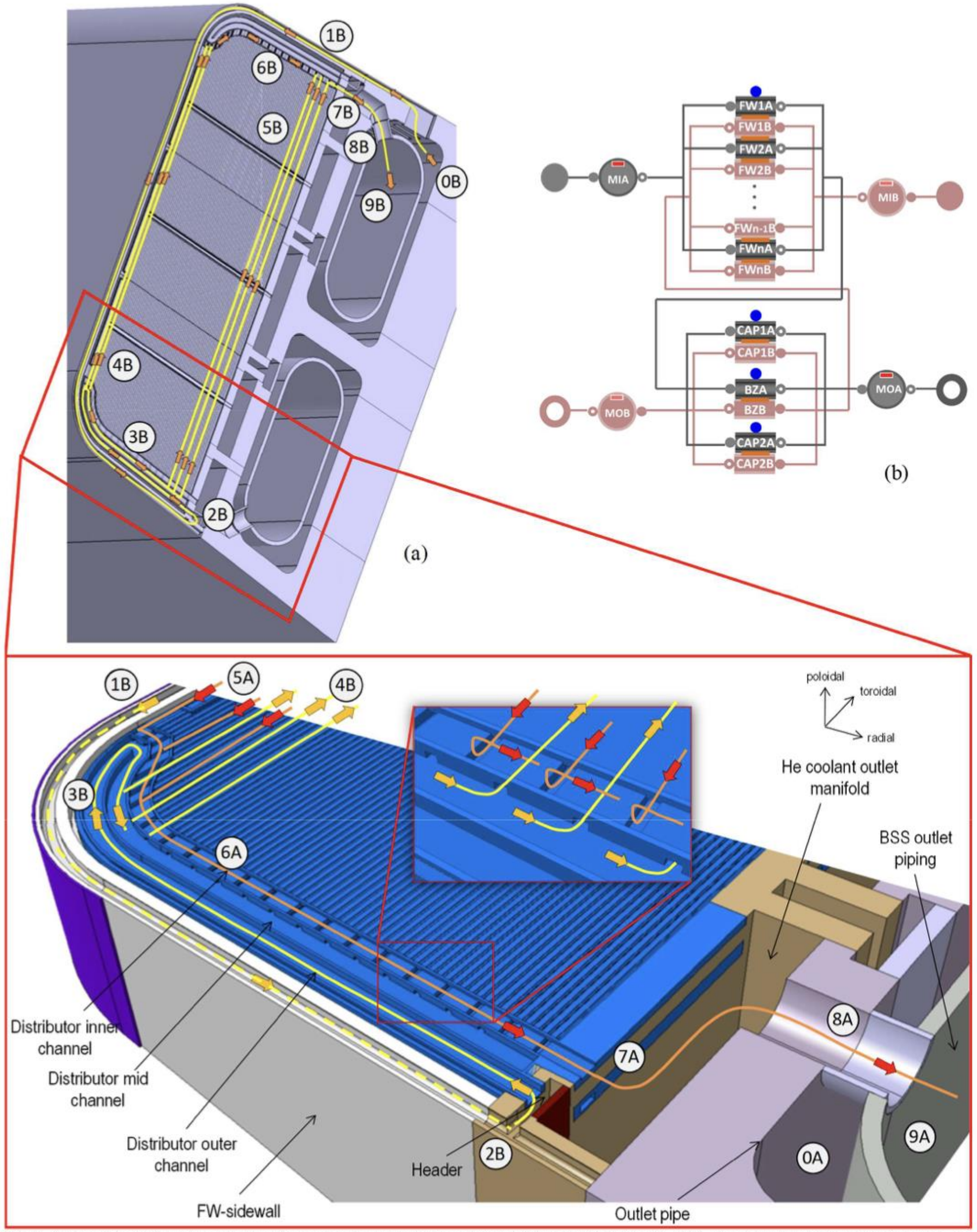
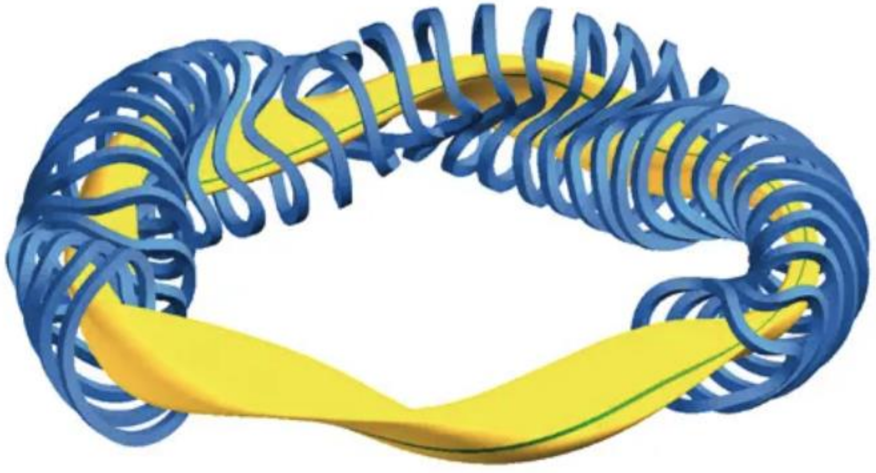
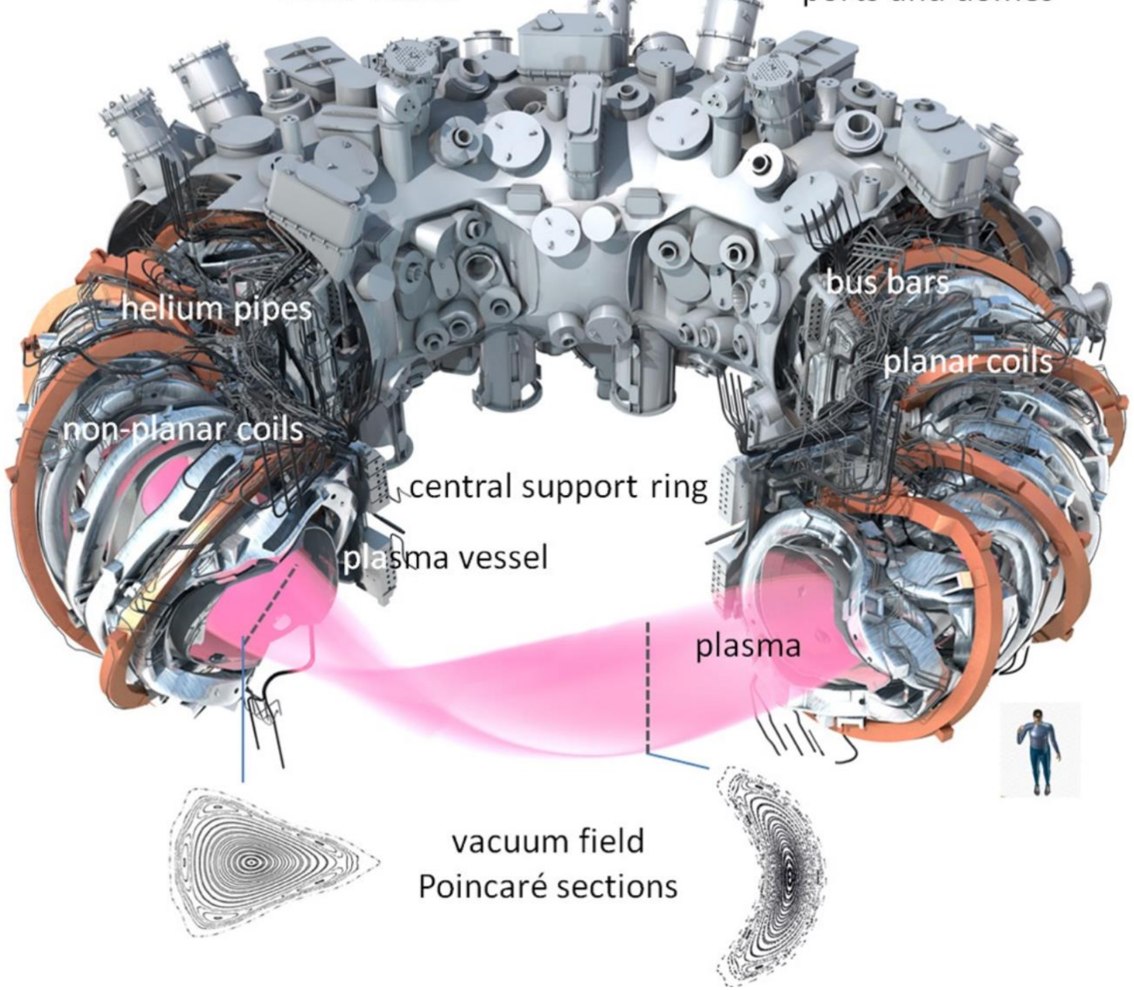


Fig. 4. Scheme (a) and block diagram (b) of the coolant flow path inside a HCPB BM (adapted from [2], [4], [13]). The coolant is distributed initially from the manifold in the BSS (bullet 0) to the FW square cooling channels (bullet 1), and it is successively collected and redistributed (bullets 2 and 3, respectively) to the CP rectangular cooling channels (bullets 4 and 5) by a rather complex system of internal manifolds, before being collected again in a manifold inside the CP at first (bullet 6) and in a BM-wide manifold (bullet 7), which finally delivers the hot coolant to the outlet manifold inside the BSS (bullets 8 and 9).

Mission 8: Stellarator development

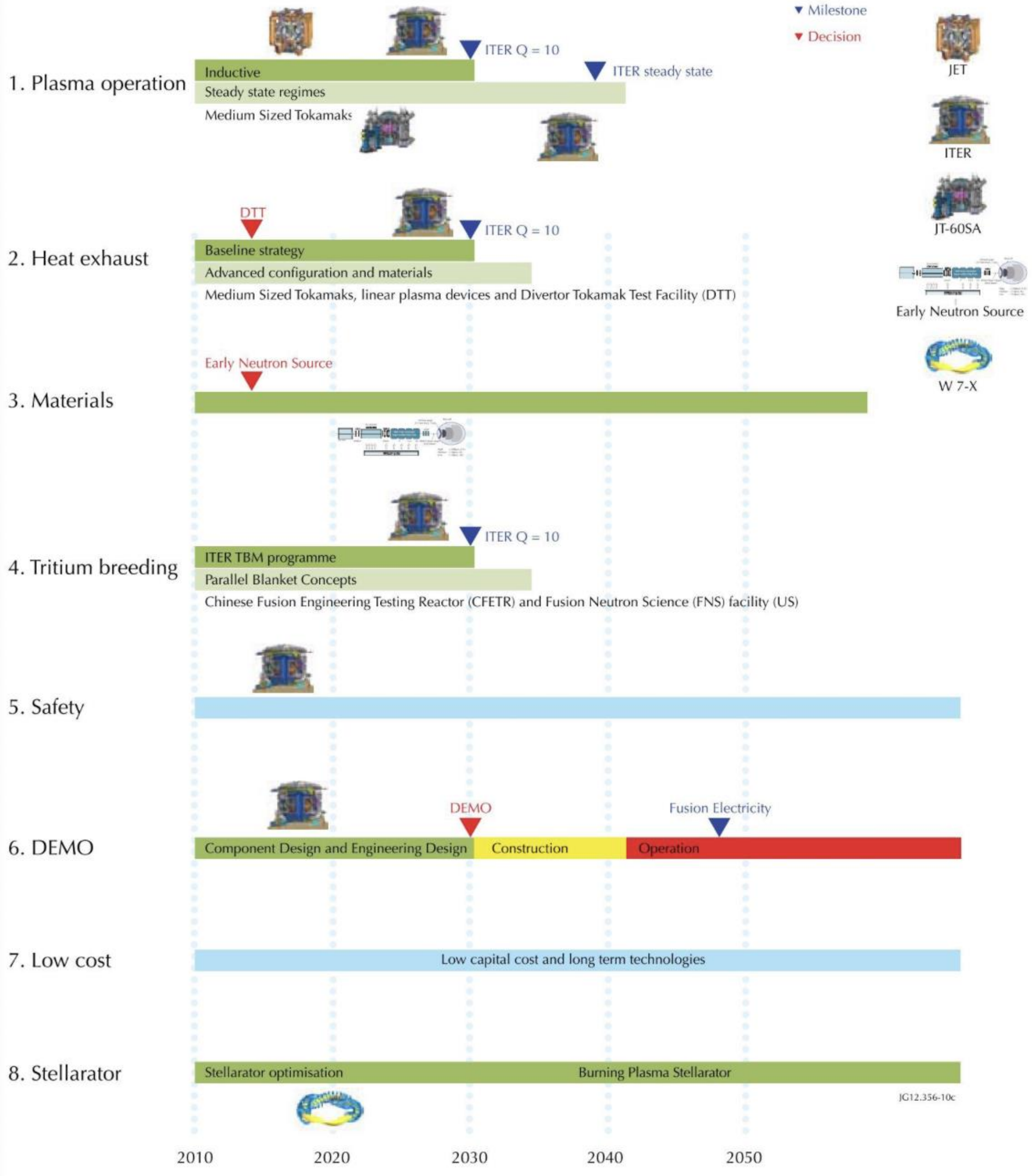


The first contracts to industry for experiment components were placed in 1996. After the main installation was completed in 2014, the commissioning started. The first plasma was produced end of 2015. Since then, experimental phases have alternated with upgrading phases, which served to make the device fit for operation under reactor-relevant conditions.



Wendelstein 7-X

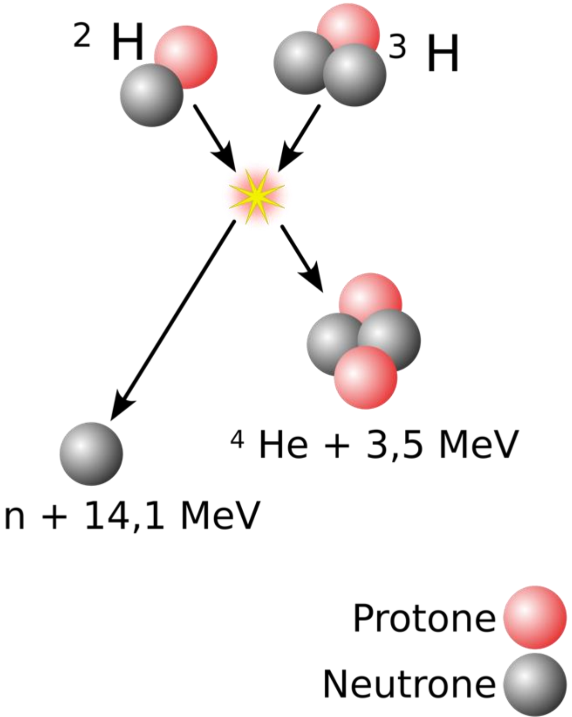
Progettazione iniziata anni ’90;Terminato nel 2014 ha subito molte modifiche
Ultimamente ha effettuato una campagna sperimentale
Macchina in continua, non impulsata
Dimensioni enormi, magneti di grandi dimensioni R_0=5.5 m diametro del criostato 16 m, complessa e costosa da realizzare, blanket molto difficile da costruire, limiti per aspect ratio
Ha mantenuto il plasma in condizioni di elevate prestazioni per 43 s



The missions to the realisation of fusion electricity

I valori dichiarati sono i target di progetto, sino ad oggi **sempre rimandati**
La scienza avanza formulando ipotesi e poi provando a dimostrarle
La mancata dimostrazione di un obiettivo in seguito ad un esperimento è un successo
La mancanza dell'esperimento un insuccesso
gli enunciati di per sé, non hanno alcun fondamento scientifico

Purtroppo a volte si applica un metodo che nulla ha a che vedere con il metodo scientifico, il metodo induttivo
Karl Popper critica radicalmente il metodo induttivo nella scienza, definendolo un "mito" incapace di giustificare le teorie universali a partire da osservazioni particolari. Sostiene che l'induzione non garantisce la verità, poiché un numero finito di casi non può confermare una legge generale



Questo non significa che se prendo 100 miliardi di miliardi di nuclei di deuterio e trizio, li metto nel contenitore che dico io, li scaldo e provo a tenerli vicini, che questi continueranno cheti cheti a scaldarsi fra di loro e a produrre energia: **deve essere dimostrato sperimentalmente**

Le previsioni su quando, su come e su se ciò avverrà, non hanno base scientifica

Roadmap Eurofusion 2018

European Research Roadmap
LONG VERSION to the Realisation of Fusion Energy

The success of the fusion endeavour in Europe will depend on two further elements: (1) funding from the European Union and from participating countries, and (2) attracting and developing outstanding and innovative scientists and engineers for the community and industry.

This research roadmap describes the steps to realise the ambitious goal of developing future fusion power plants for wide deployment.

September 2018

Tony Donné
[EUROfusion Programme Manager]

Roadmap 2018 (vs 2012)

4. How to face the challenges – the missions for the realisation of fusion

Mission 1 – Plasma regimes of operation

Mission 2 – Heat-exhaust systems

Mission 3 – Neutron tolerant materials

Mission 4 – Tritium self-sufficiency

Mission 5 – Implementation of the intrinsic safety features of fusion

Mission 6 – Integrated DEMO design and system development

Mission 7 – Competitive cost of electricity

Mission 8 – Stellarator

Table of content

Roadmap stages

5.1 First period (up to 2030):

Build ITER and Broader Approach projects;

Secure ITER success;

Lay the foundation of DEMO

5.2 Second period (2031-2040):

Exploit ITER up to its maximum performance and prepare DEMO construction

5.3 Third period (beyond 2040):

Complete the ITER exploitation; IFMIF upgrade;

Construct and operate DEMO;

Lay the foundation for fusion power plants

11. Progress along the Fusion Roadmap since 2012

Mission 1

1) The EU programme has addressed operational issues of tokamaks with metallic wall for an efficient preparation of ITER, DEMO and the **commercial** fusion power plant.
2) Some of the changes in behaviour between carbon and metallic walls appears to be due to detailed changes in the edge pedestal observed on ASDEX Upgrade and JET linked to the gas fuelling used. First models have been developed
3) Encouraging discoveries have been made on the role of fast ions to reduce core transport…These findings, recently simulated in sophisticated integrated modelling coupled with first principles codes, underline the need for improved understanding, and expand beyond empirical scaling.
4) The European Transport Simulator used for integrated plasma modelling has undergone major development
5) ITER and DEMO need effective disruption mitigation tools, which depend on the dynamics of disruption and runaway electron beam formation
6) ITER (and DEMO) need edge pedestals (H-mode) if the fusion power is to be high enough.
7) ITER will have a preparatory non-active phase in hydrogen and helium
8) ITER will have ICRH heating which needs to be made as efficient as possible.
9) The lifetime of ITER divertor components is shortened by ELMs, and it is important to know how well ELMs need to be mitigated to allow sufficient lifetime.
10) ITER needs precise calibration of the neutron detectors

11. Progress along the Fusion Roadmap since 2012

Mission 2

Deuterium retention studies (post-mortem analysis of retrieved PFCs and gas balance studies) in metallic wall tokamaks have demonstrated a significant reduction (by factor of 10-15) of the deuterium fuel retention with metallic first walls as compared to the previously used carbon-based first walls. The dust levels have been reduced by two orders of magnitude compared with the carbon wall.

ITER needs to be able to operate even when the metal wall components have some melted areas.

The ITER first wall components need to survive erosion for long periods before they are replaced,

For the preparation of ITER non-active operation in helium, the feasibility of using Ion Cyclotron Wall Conditioning in He plasmas was demonstrated

To protect the plasma facing components in ITER and DEMO, the divertor has to operate in partial or full detachment, and on DEMO the radiative losses from seed impurities in the main plasma need to be high. Radiative scenarios with detached plasmas have been demonstrated on different tokamaks and the effect of extrinsic impurity seeding in the core plasma explored with W divertors in different scenarios and machine sizes.

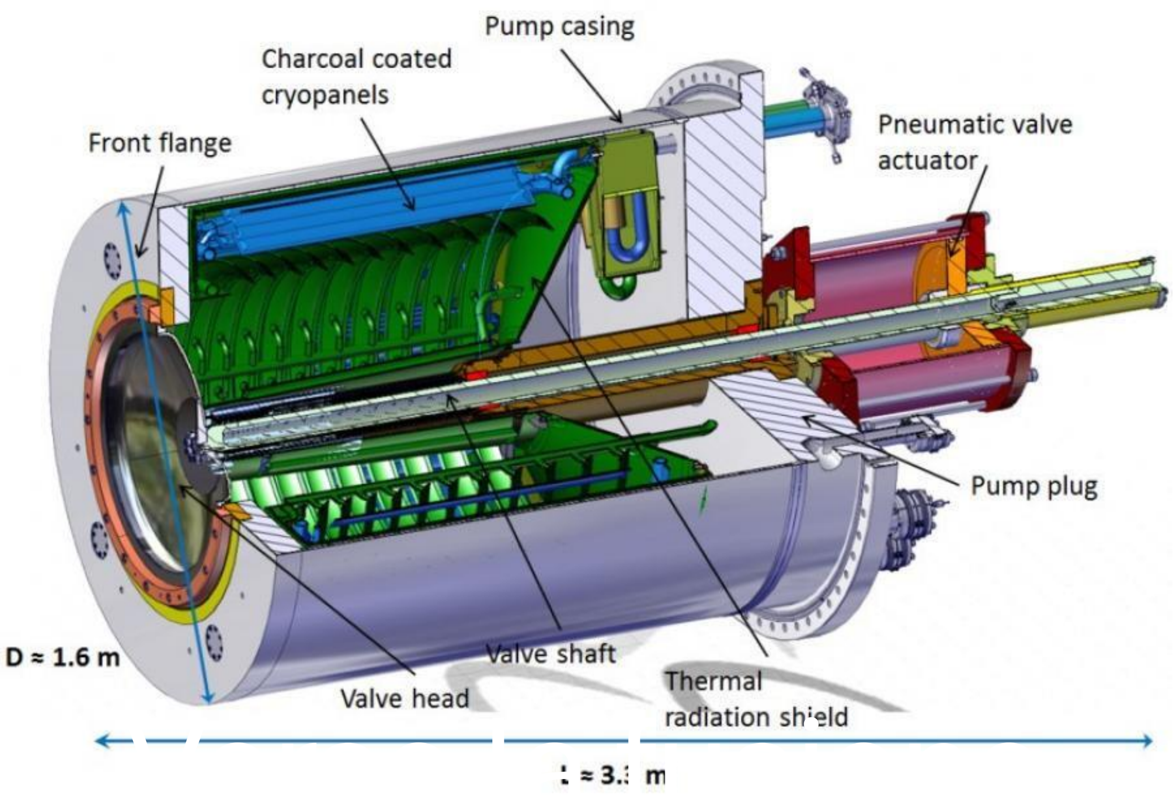
Major progress was also made in understanding filamentary transport across the Scrape-Off-Layer (SOL) in view of determining the power loads to the divertor and first wall of the machine

A credible exhaust solution for DEMO requires new experimental data and models. Following an extensive gap analysis in the field of plasma exhaust physics and technology, a number of upgrades of existing devices to study alternative power exhaust solutions (both alternative divertor geometries and materials) were initiated.

Vacuum Pumping System for ITER's Deuterium Tritium Operational Campaign

Pumping of plasma exhaust gases through vacuum pumping system for non-inductive plasma pulse maintaining safe tritium inventory limit

Matthias Dremel, Indranil Banerjee, Hughes Shaun, Robert Pearce



Progettate per 50.000 cicli
1 ciclo circa 10 minuti. → 500.000 minuti 83000 ore, circa 9 anni
Valvole per 30000 cicli, 5 anni
Costo 3 M€ l'una, 8 pompe
Dispendio energetico rilevante, cicli per desorbimento acqua a 450K
DEMO avrà il triplo del volume. Il reattore?

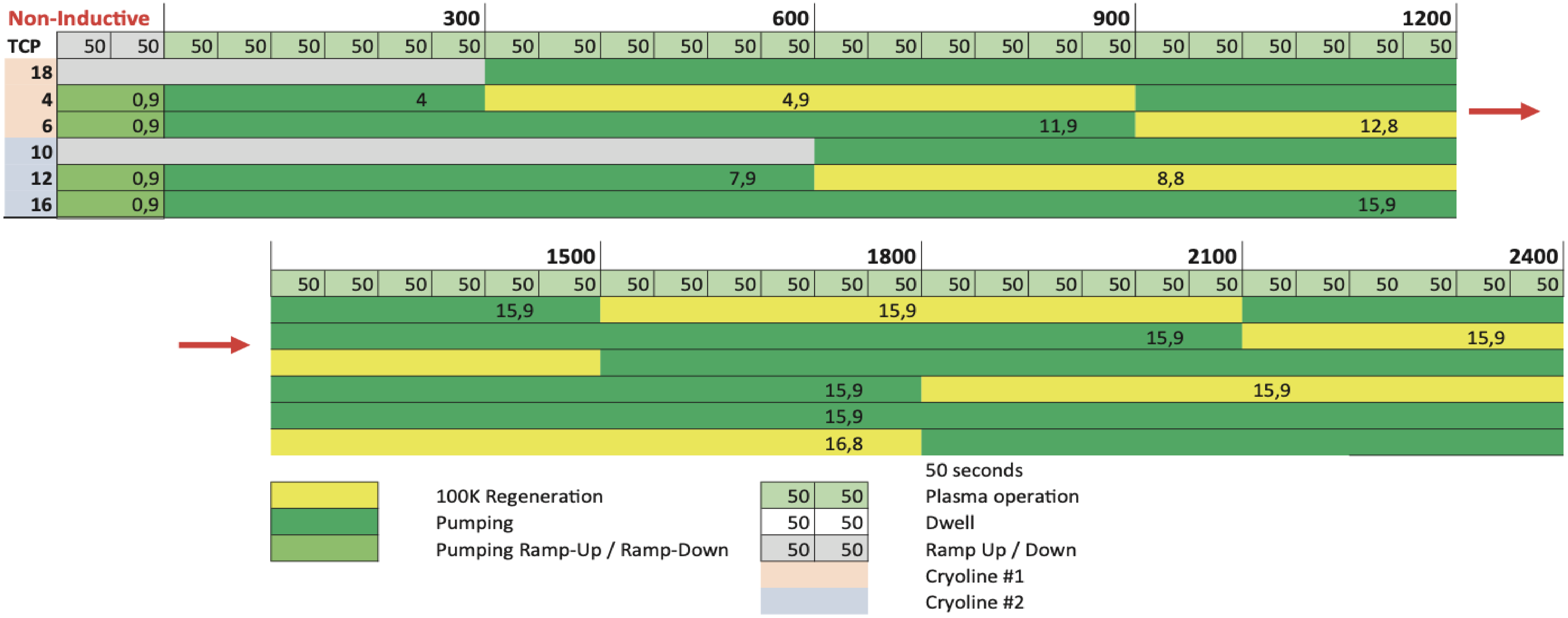


FIGURE 3: Operational pattern of six TCPs for 3000-second long plasma pulse indicating molar DT inventory in the box. Four TCPs pumping with two TCPs in regeneration mode in any instant.

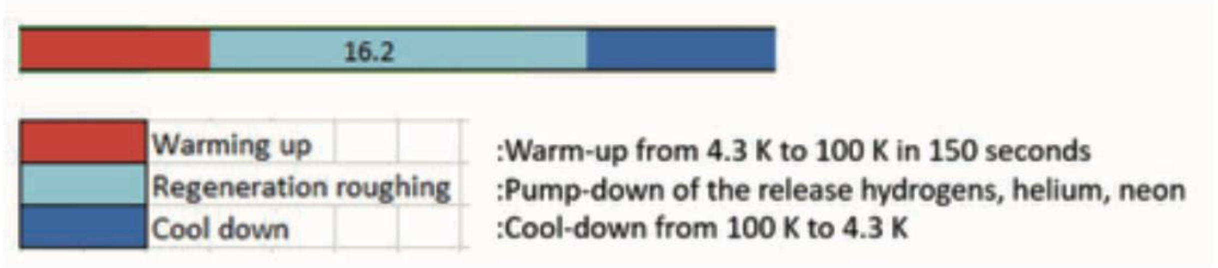


FIGURE 4: Schematic of 100 K regeneration cycle as used during plasma pulse

Vacuum Pumping System for ITER's Deuterium Tritium Operational Campaign

Pumping of plasma exhaust gases through vacuum pumping system for non-inductive plasma pulse maintaining safe tritium inventory limit

Matthias Dremel, Indranil Banerjee, Hughes Shaun, Robert Pearce

Mission 3: neutron tolerant materials

DEMO requires the development, qualification and validation of (blanket) structural materials that are neutron tolerant and that can withstand 20 – 50 dpa with acceptable loss of performance.

Irradiation campaigns are underway for the baseline materials EUROFER97, tungsten and copper alloy

High Heat Flux Materials: Significant progress was made in both the maturity of newly developed fabrication technologies as well as in a growing database

Design and construction rules for mechanical components of nuclear installations:

detailed mechanical, thermo-physical and high heat flux characterization, including: plasma facing materials: particle and fibre reinforced

W materials fabricated by technologies without the final deformation step; heat sink materials: particle and fibre reinforced Cu-based materials;

W-laminates which are options for both plasma facing as well as heat sink materials;

joining technologies (W/Cu or W/CuCrZr, W/steel) and interfaces for alternative concepts (W/Cu function-ally graded materials, thermal barriers).

Functional Materials addressing insulators and optical reference materials:

Radiation stability of metallic mirrors was tested at higher doses in ion irradiation including He effects for down-selection of materials and fabrication options;

Surface dielectric properties of commercial diamond windows were characterised using different surfacetreatments, resulting in down-selection to three remain-ing options;

Irradiation modelling: Predictive capabilities wereachieved in certain areas of fusion materials modelling,

ion penetration depth profiles, and sputtering by energetic ions in the physical sputtering regime. These were done in preparation to approach the key issue of providing a set of multiscale predictive models for simulating changes of physical and mechanical properties due to exposure to neutrons under fusion power plant relevant conditions.

Early Neutron Source: The IFMIF-DONES PreliminaryEngineering Design Report was released, demonstrating that the facility is ready from the technical point of view for a site decision.

11. Progress along the Fusion Roadmap since 2012

Missions 4,5,6,7

For Mission 4 (Tritium Self-Sufficiency) the most attractive design options for the DEMO breeding blanket have been identified and four concepts were investigated until the endof 2017.

For Mission 5 (Safety and Environment) initial safety analyses are in progress ......

For Mission 6: (DEMO design) molte chiacchiere

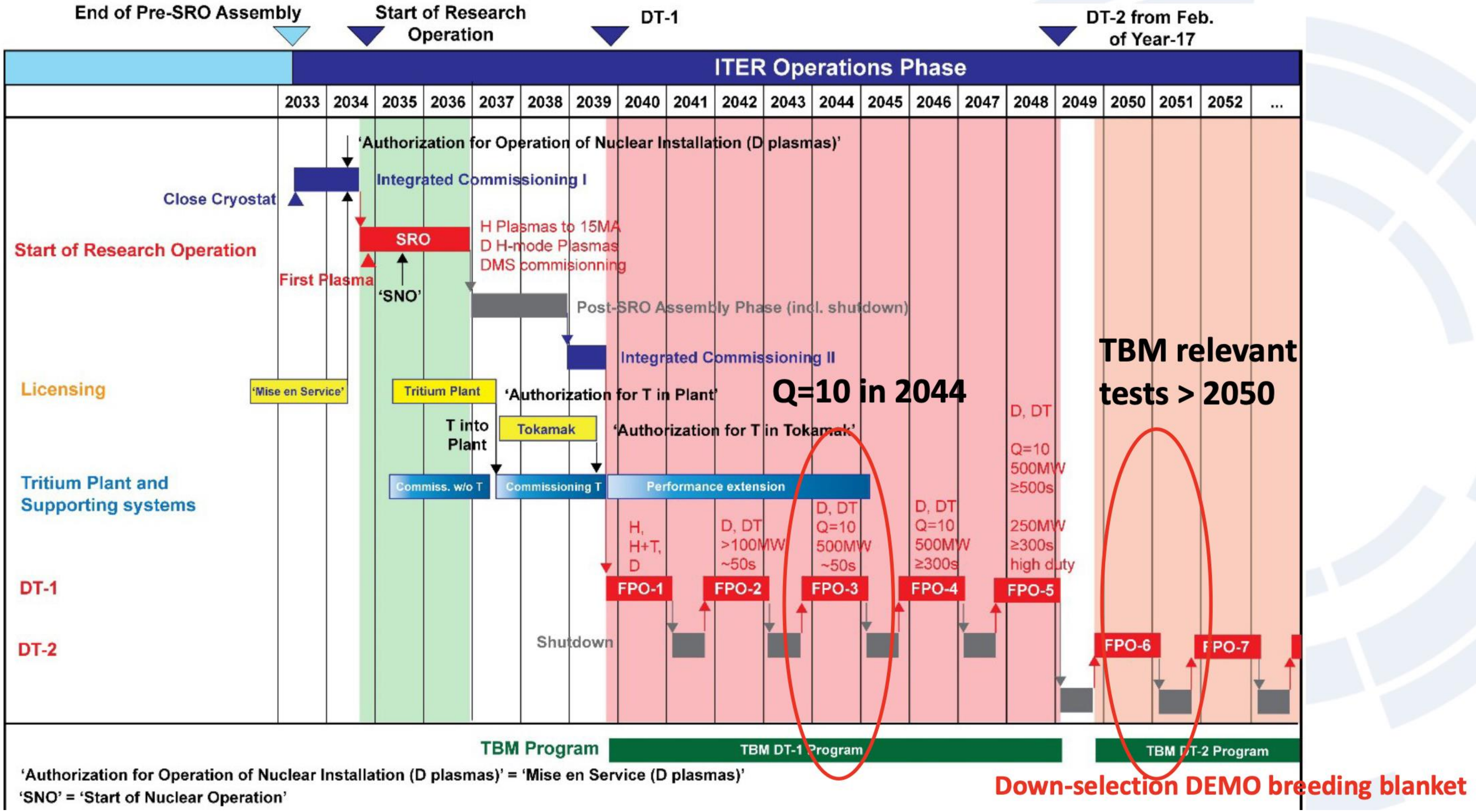
The high-level DEMO requirements have been defined

Sensitivity studies have been performed to determine the impact of uncertainties

A close contact has been established with Gen IV fission and ITER to learn from their project execution experience.

Competitive costs of electricity **(Mission 7)** has focused on reliability and availability (major overall factors in the costs of electricity), notably effective remote maintenance strategies, and early work on reducing costs of components by suitable design (e.g., the magnets). A wider scope is planned for the coming years as described above.

1. New Context: **Timeline for the new baseline 2024 IRP**



Ultima roadmap DOE 10/25

The Roadmap Strategy: Build-Innovate-Grow

Scopo del DOE: Deliver Fusion Science& Technology (FS&T) Infrastructure

- In the long-term 5-10 years, DOE will deliver a platform of small-to-midscale tritium fuel cycle and blanket system test stands and capabilities to address key science and technology gaps
- Magnetic Fusion Energy (MFE): Bridging the scientific gap between current confinement physics knowledge and a robust understanding of sustained burning plasma dynamics, which is crucial for high-confidence extrapolation to FPPs and beyond, will necessitate a combination of existing and future infrastructure investments.

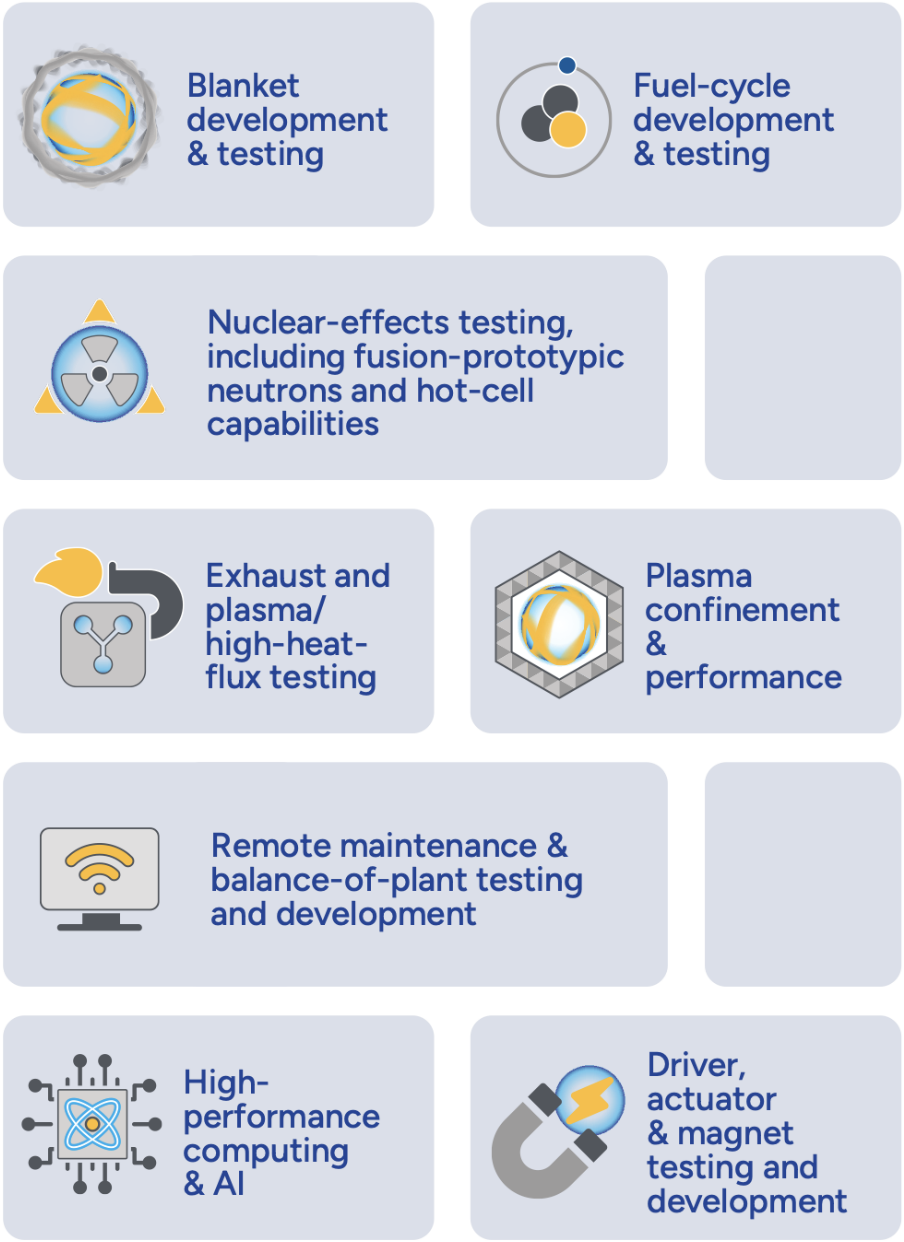


Figure 4. *Eight distinct infrastructure streams critical for progress towards the development of fusion power plants have been identified.*

Core Challenge Areas

Structural Materials Science & Technology	The design, development and qualification of materials, structures and systems that can withstand the high neutron flux, thermal loads and environmental stresses of a fusion power plant. It includes research on physical and mechanical properties, manufacturing and qualification of materials that form the core vessel, support structures and in-vessel components.
Plasma-Facing Components and Plasma-Materials Interactions	The design and testing of materials, structures and systems that can withstand the high neutron flux, thermal loads and environmental stresses of a fusion power plant. It includes research on physical and mechanical properties, manufacturing and qualification of materials that directly interact with the plasma. It includes solid and liquid metal walls, advanced composites, chamber and divertor design and technology along with the understanding of plasma-material interactions needed to manage challenges such as erosion, fuel retention and dust.
Advancing Confinement Approaches	The physics and engineering of creating, sustaining and controlling high-performance burning plasmas. It includes turbulence and transport, stability, coupling, core-edge integration and disruption avoidance, with the goal of achieving fusion-relevant confinement regimes and sustained energy output.
Fuel Cycle and Tritium Processing	The technologies and processes needed to produce, handle and recycle fusion fuels in a closed loop. It includes exhaust and separation systems, storage and inventory control, accountancy and development of supporting technologies like permeation barriers and detritiation systems.
Blanket Science & Technology	The development of blanket concepts (e.g., solid, liquid, molten salt), materials compatibility studies, thermal hydraulics, tritium transport modeling and integrated testing to validate performance and maintainability.
Fusion Plant Engineering & System Integration	The design and integration of the entire plant system, beyond the fusion engine. It includes balance-of-plant technologies such as power conversion and plant-wide control systems, as well as remote maintenance and robotics. It also includes the codes, models, tools and platforms for fully integrated power plant modelling.

Figure 6. *The core Challenge Areas*

Table of content

Liquid-Metal PFCs

The use of liquid walls with a fusion engine could become a game-changing technology to address the significant heat exhaust challenges in commercial fusion power plants. The unmitigated parallel heat flux anticipated in a compact, high-field tokamak or spherical tokamak based fusion power plant is estimated to be greater than 10 GW m-2 in the divertor, which is significantly more than the MW m-2 heat fluxes generated by a propane torch

Cost

For reasons related to confinement physics and engineering, the lowest-cost fusion power plant may not be a tokamak.
Roadmap to deliver a low-cost fusion power plant include advancing the understanding of the following: energetic particle and burning plasma physics relevant to a high-fusion-gain fusion power plant; plasma-material interactions and material choices for exhaust solutions; transport and stability physics for sustaining disruption-free, high-average po

IFE-DOE

Inertial Fusion Energy (IFE): IFE has entered a groundbreaking era, marked by significant achievements at the National Ignition Facility (NIF). In 2022, NIF successfully achieved a burning plasma, a pivotal step towards harnessing fusion energy. Since this initial success, NIF has repeatedly demonstrated burning plasma conditions, with eight successful ignition experiments to date. The most recent of these experiments set a new energy yield record that delivered an impressive 8.6 MJ, more than four times the 2.08 MJ of energy input to the target

Chinese roadmap Jangang Li 2019

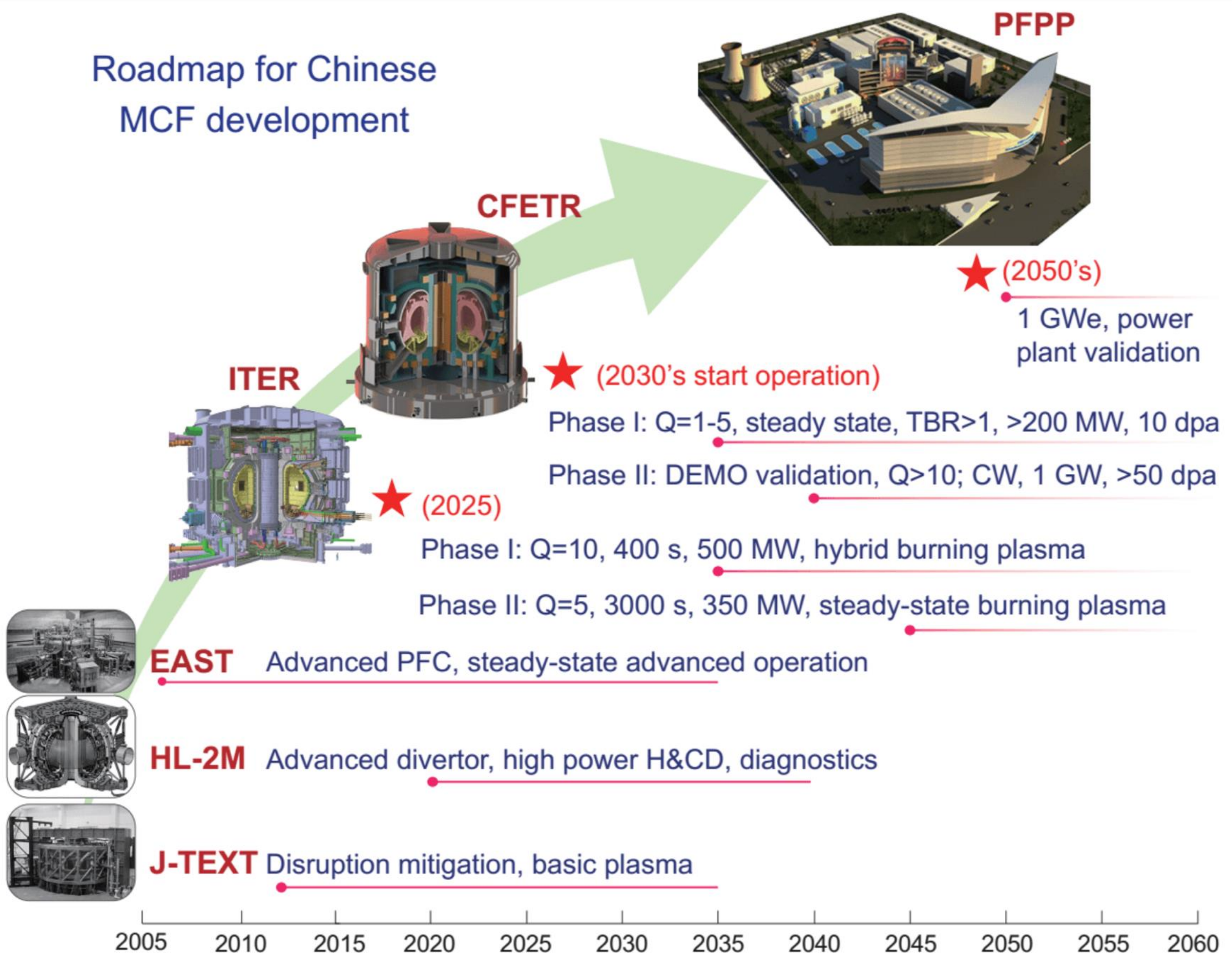


Fig. 1 Roadmap per lo sviluppo dell'energia da fusione a confinamento magnetico in Cina


同心聚变 全球共燃
合肥聚变宣言
HEFEI FUSION DECLARATION
Hefei Fusion Declaration
子体国际科学计划项目启动暨BEST
TERNATIONAL SCIENCE PROGRAM ON FUSION BURNING PLASMA & RELEASE

Costruzione iniziata nel 2023

- **Key Schedule and Goals for BEST (Hefei):**
- **Construction Completion:** The facility is scheduled to finish construction by the **end of 2027**.
- **First Plasma:** Initial plasma experiments are anticipated in late 2027, with the project entering a new stage of burning plasma research.
- **Performance Goals:**
  - **Fusion Power:** Generate 20 to 200 megawatts of fusion power.
  - **Energy Gain:** Achieve a fusion gain factor of $1<Q<5$ (producing more energy than consumed).
  - **Operational Goal:** Achieve net energy gain and demonstrate electricity generation by around 2030.

/ Hefei | chinadaily.com.cn | Updated: 2025-11-24 23:41

…ing Plasma Experimental Superconducting Tokamak, or BEST, facility, which … periment device, is under construction in Hefei, Anhui province, on Saturday … "artificial sun", it is scheduled for completion by the end of 2027. ZHAO MI…

R=3.6m. a=1.1m (Compact design for high-field performance).

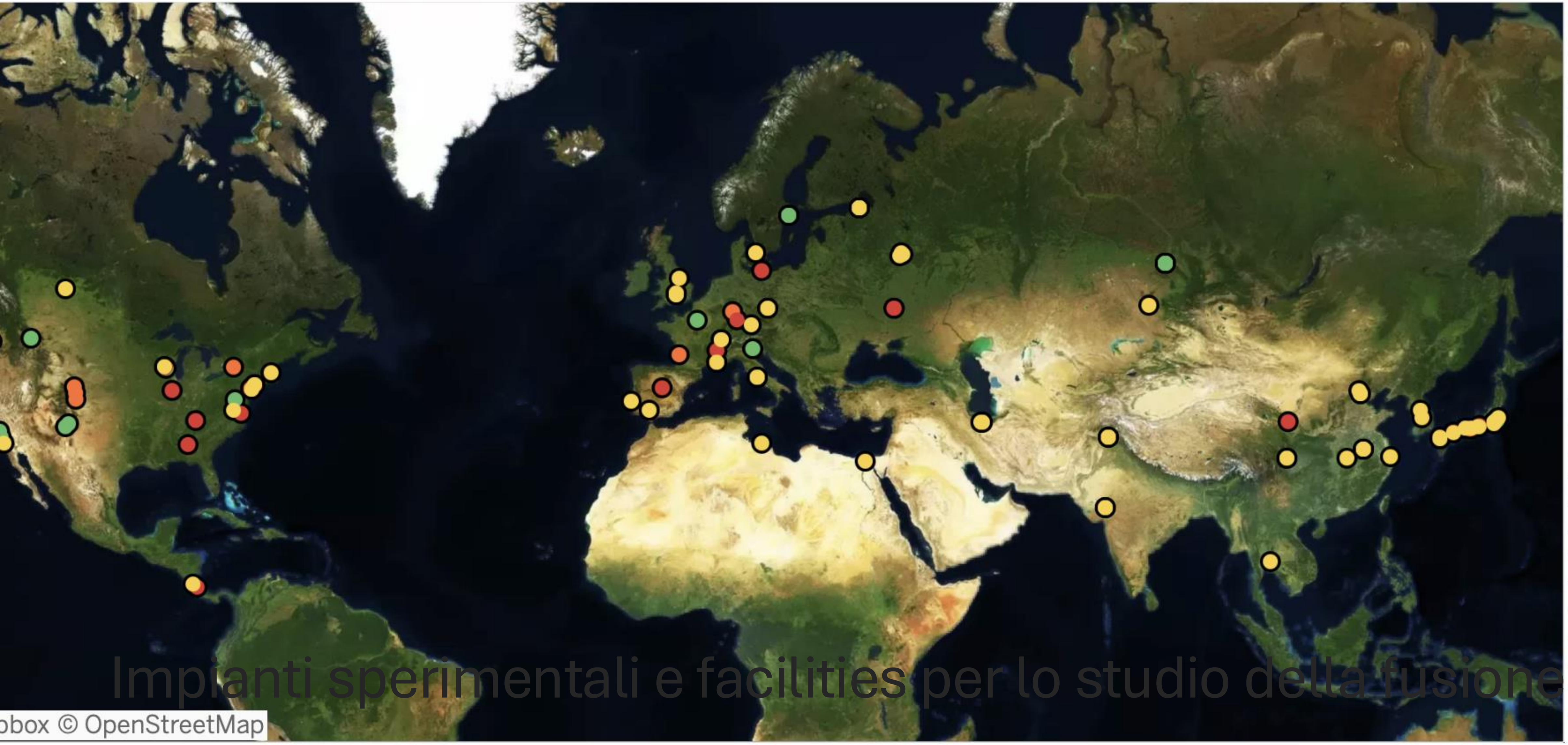
- **Magnetic Field (Bt):** 6.15 T, utilizing superconducting technology to confine plasma at over 100 million degrees Celsius
- **Plasma Current (Ip):** 4–7 MA.
- **Goal:** To test advanced steady-state D-T operation, tritium breeding/cycling, and high-heat-flux materials (divertor).

Sviluppo degli impianti per lo studio della fusione nel mondo

Tokamaks	Stellarators/Heliotro..	Laser/Inertial	Altern. Concepts
82	31	18	51

Exp	Plant
154	28

Toka
Stella
Lase
Alter

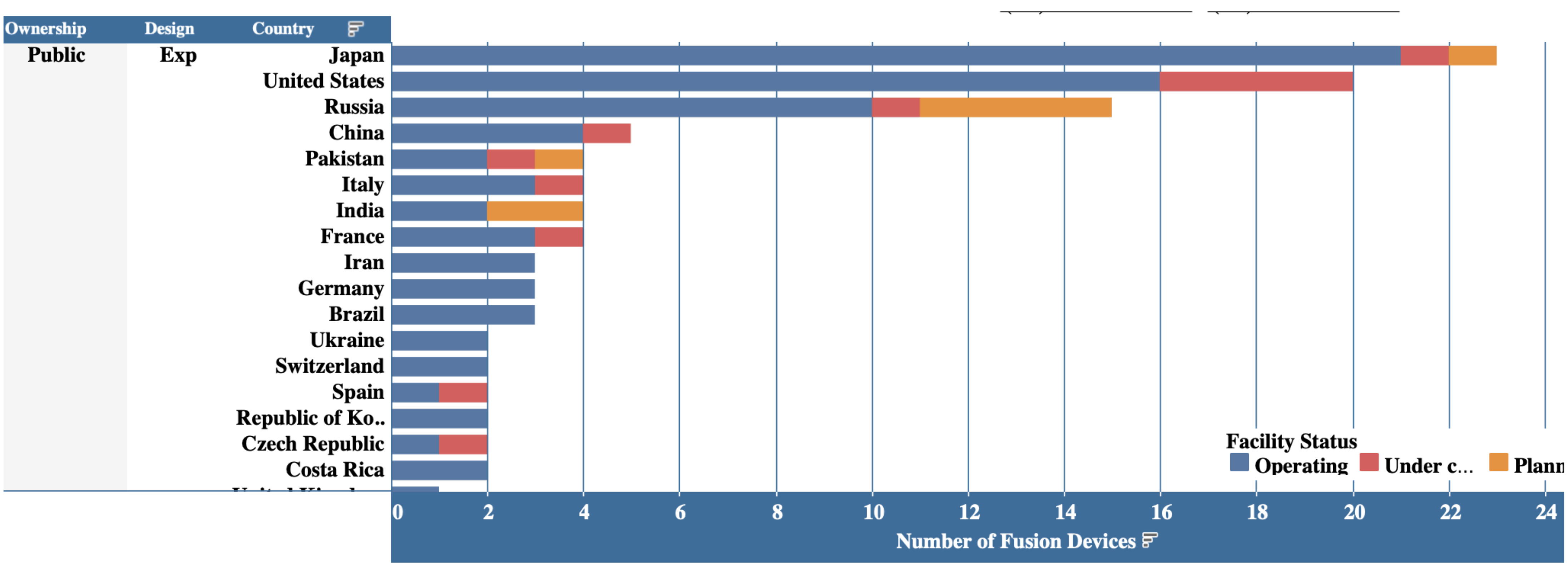


Country
United
Japan
Russia
China
United
Germa
France
India
Italy
Pakista
Sweden
Brazil
Canada
Iran
Republ
Costa F
Czech I
Europe
Spain
Switzer
Ukrain
Austral
Denma
Egypt
Israel
Kazakh
Libya
New Ze
Portug
Thailar

erating	Under construction	Planned
03	19	60

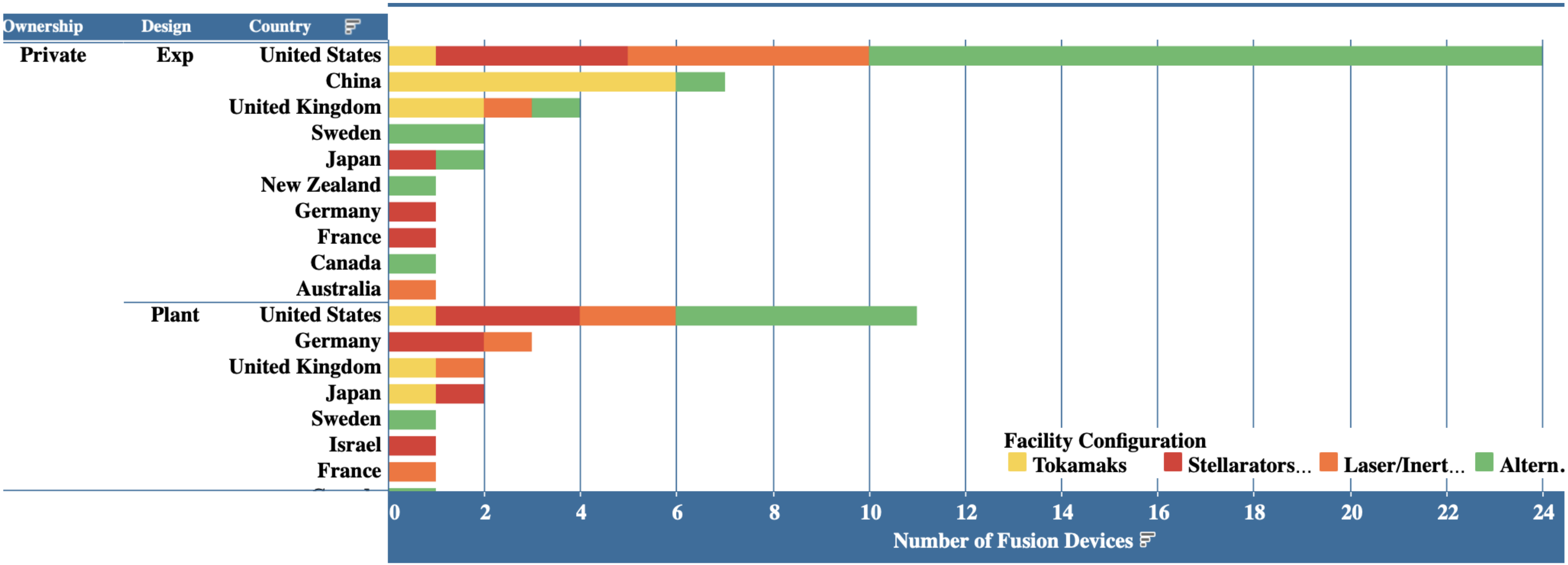
Public	Private
116	66

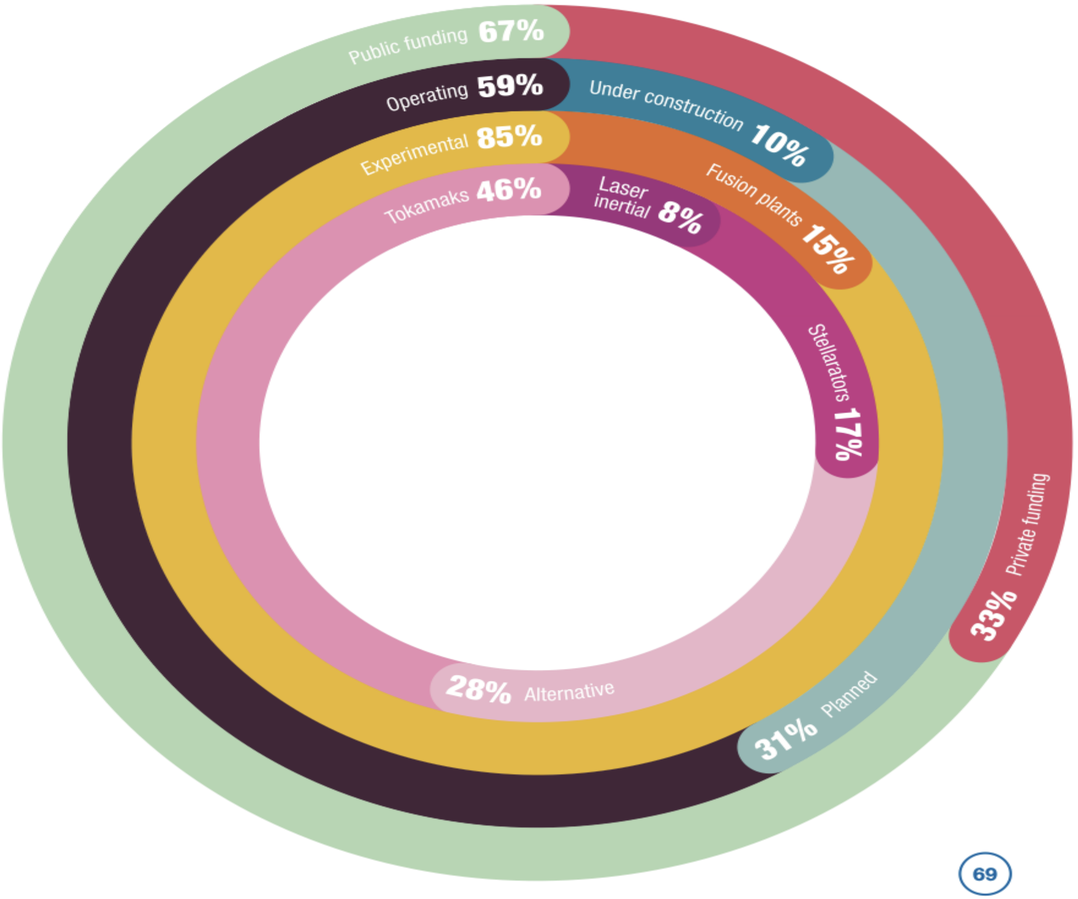
Impianti sperimentali pubblici per lo studio della fusione



Fonte IAEA fusion portal
https://nucleus.iaea.org/sites/fusion-portal/SitePages/FFDB.aspx?web=1

Impianti sperimentali privati per lo studio della fusione





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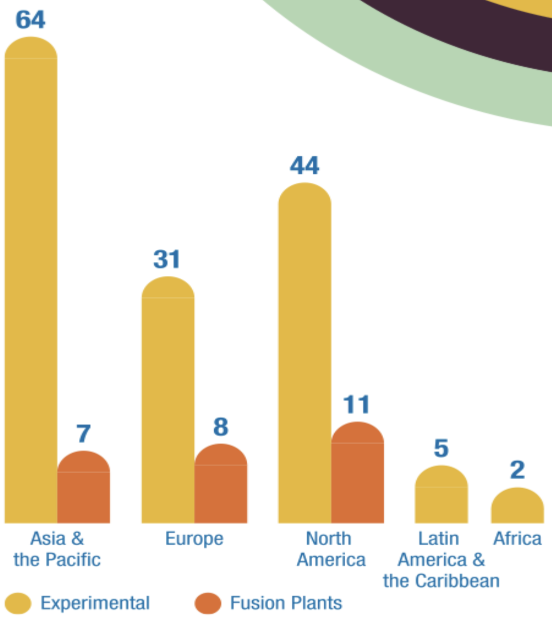


70

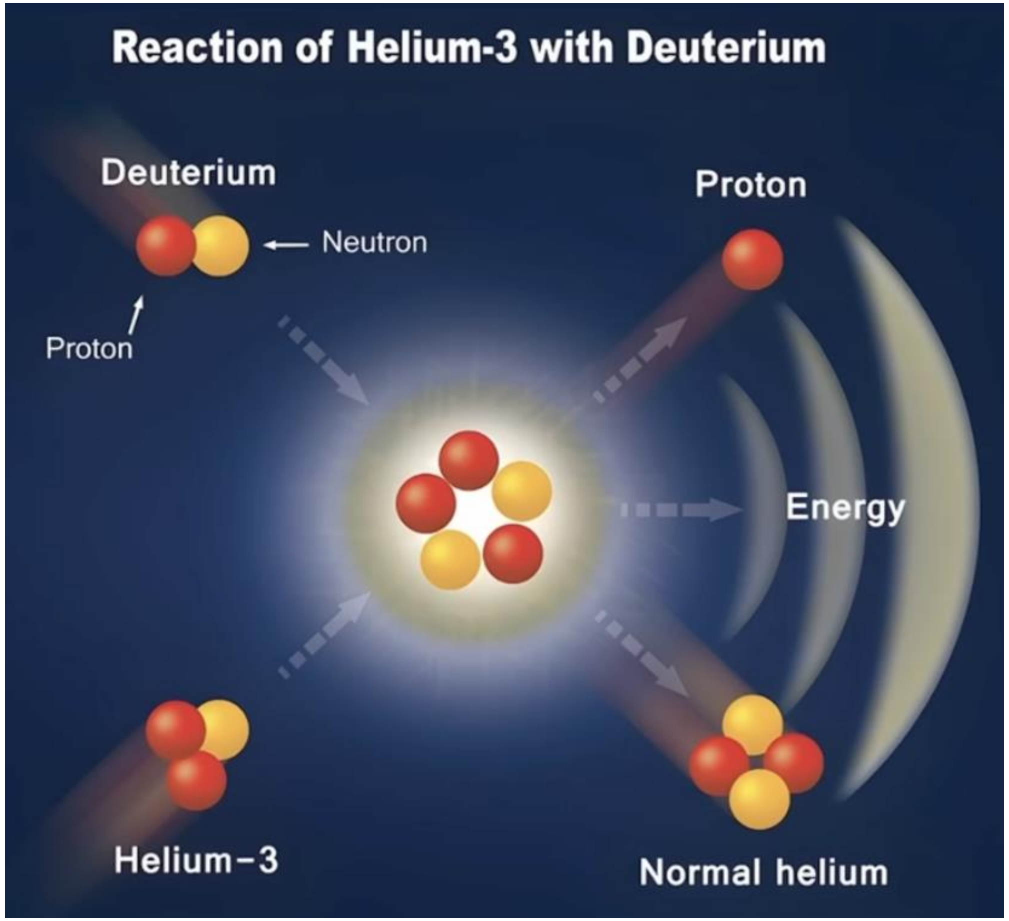
69 The range of fusion devices, their operating status and ownership (public vs private funding) in 2025 [67].

70 The number of fusion devices operating, under construction or being planned per region in 2025 [67].

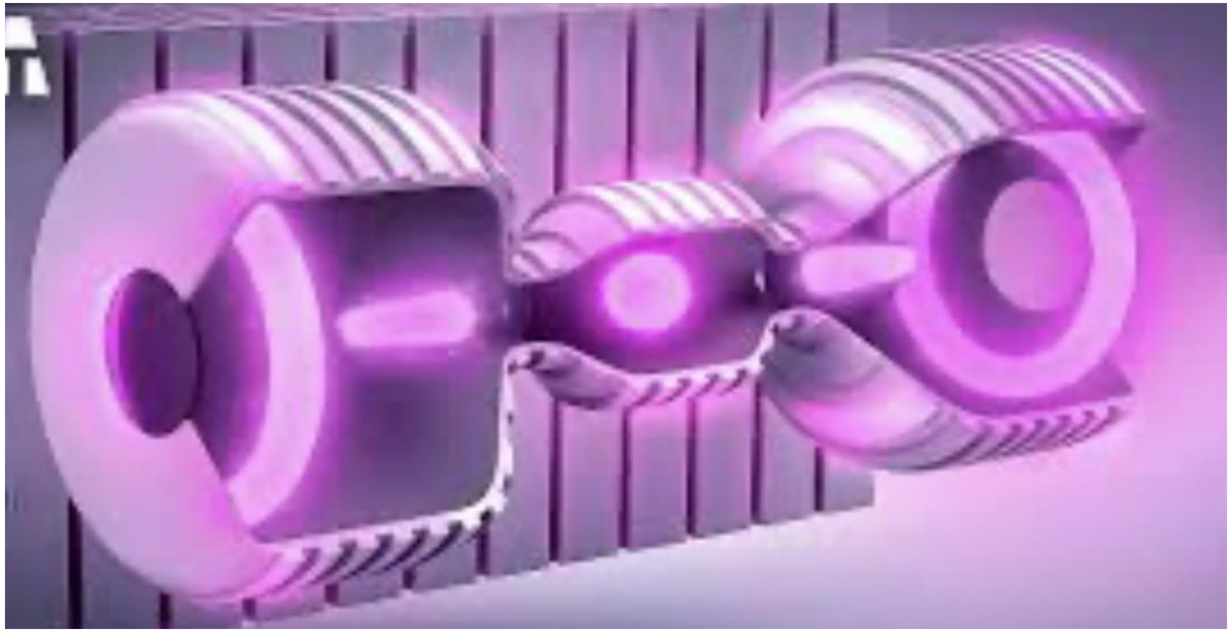
The IAEA Fusion Device Information System (FusDIS) web site [67]

Helion venderà energia elettrica a Microsoft PPA a partire dal 2028 utilizzando il suo reattore da 50MWe a conversione diretta che diventeranno 500 MWe a partire dal 2030; nel 2014 era il 2020, nel 2020 il 2024, nel 2024 il 2028……..

$$^2_1H +^3_2 He \rightarrow^4_2 He\ (3.6\ \text{MeV}) + p\ (14.7\ \text{MeV}).$$



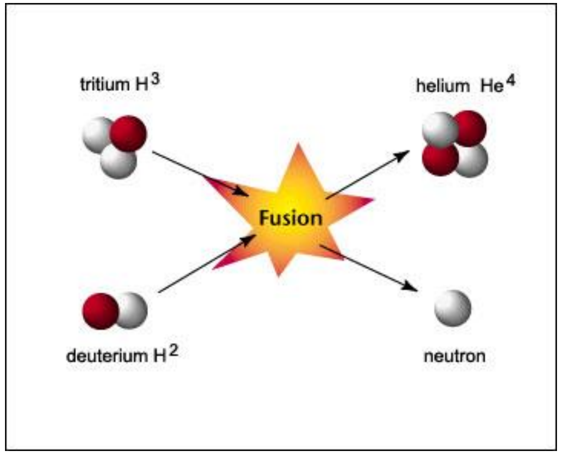
Ha raccolto oltre 1 B$



CFS ha stipulato PPA da 1B$ per la vendita di energia elettrica dal suo impianto ARC da 400MW a partire dal 2035

A che punto siamo

Fattore di guadagno Q



- $Q_{scientifico} = P_{in}/P_{fus}$ Pareggio Q=1
- $Q_{ingegneristico}\ (P_{in}/0.3) = P_{fus} * 0.8 * 0.8 * 0.35$
- $P_{in} = 20$ MW → $60MW_e$ alla spina pareggio con Q=15 ovvero

  $P_{fus} = 300MW_{th} * 0.2 = 60\ MW_e$

- Con bilancio completo (criogenia, sistema da vuoto, pompe idrauliche, diagnostiche, analisi e immagazzinamento dati, ecc........,

  In realtà la potenza immessa in rete inquadrata in modo olistico

Stato della fusione

Macchine con supporto europeo

- Il Jet è stato il faro della ricerca europea
- ITER nel 2006 annunciato primo plasma nel 2016 https://news.newenergytimes.net/2021/10/26/iter-timeline-delayed-again-first-experiments-most-likely-in-2031/, in ritardo di 20 anni previsione 2035, DT speriamo 2042-2044
- DTT , nel 2020 annunciato primo plasma 2025, in ritardo di 7 anni, 2032. Full power anni '40, no DT, indispensabile NBI, indispensabili 45 MW
- JT60-SA in ritardo di circa 10 anni, scarica politica 2023, ancora in fase di sistemazione, annunciata prima campagna sperimentale per fine 2026, no DT. Riparazioni con probabilità di successo non totale
- RFX in ritardo indefinito, ferma da molti anni
- L'Europa manifesta la sua crisi culturale anche nella fusione

Cina e USA entrano in competizione diretta anche su questo campo

USA

- SPARC (Smallest Possible ARC, where ARC for Affordable, Robust, Compact) rapida costruzione (4 anni), annunciato ritardo di 1, probabilmente 2 anni, DT previsto ma ancora non programmato, probabile inizio anni '30, $Q>1$, teoricamente fino a 11.

CINA

- BEST (Burning Experiment Superconducting Tokamak) in rapidissima costruzione previsto entrata in funzione novembre 2027, DT early '30, $Q=5$
- **La corsa fra Cina e USA vede in forte ritardo l'Europa**

Per l'inerziale USA molto avanti, almeno noi abbiamo il vecchio ABC

La macchina europea JET

- Ha consentito all'Europa di mantenere la leadership sulla fusione per 40 anni, persa poi a causa dei ritardi di ITER

- Costruita in tempi accettabili

- Funzionato per 40 anni

- Accolto scienziati da tutti i team, la divisione PLAS ha sempre incoraggiato la partecipazione alle attività della macchina;

- Contributo Enea sia con partecipazione e coordinamento campagne sperimentali, diagnostiche, che con ricercatori in in distacco

- team sperimentale di alto livello

- Prodotto ottimi risultati, molto utili

- Gli esperimenti sono un successo se producono risultati, sia che questi siano in accordo con le aspettative

che in contrasto, ma anche in chiave opaca, producendo ulteriori interrogativi; **questo è il percorso della Conoscenza**;
sono un fallimento se non producono risultati.
Se i risultati si distorcono secondo il piacere delle lobby del momento diventano una sconfitta per la comunità scientifica

Accendere un piccolo sole è difficile, molto difficile, ma può essere di grande sollievo per l'umanità: se mai l'energia dovesse scarseggiare un giorno gli uomini si distruggeranno per averne il controllo.

Cerchiamo di prevenire questo momento.

Le campagne sperimentali con trizio

Due macchine a fusione hanno ad oggi immesso trizio all'interno del Tokamak,

TFTR (USA) e JET (UK) entrambe con l'obiettivo di raggiungere Q=1.

La prima ha effettuato una campagna di misure nel 1994, ha prodotto 10.7 MW di fusione a fronte di un input di 39.5 MW, con $Q_{sci}=0.27$

https://minds.wisconsin.edu/bitstream/handle/1793/10484/file_1.pdf?sequence=1&isAllowed=y

Il **Jet** ha effettuato tre campagne: **DTE1** nel 1997, **DTE2** nel 2021 entrambe indirizzate anche alla ricerca delle massime performances, e **DTE3** nel 2023 indirizzata principalmente su studi specifici quali materiali, confinamento, ma che ha anche ottenuto la migliore prestazione in termini di energia prodotta.

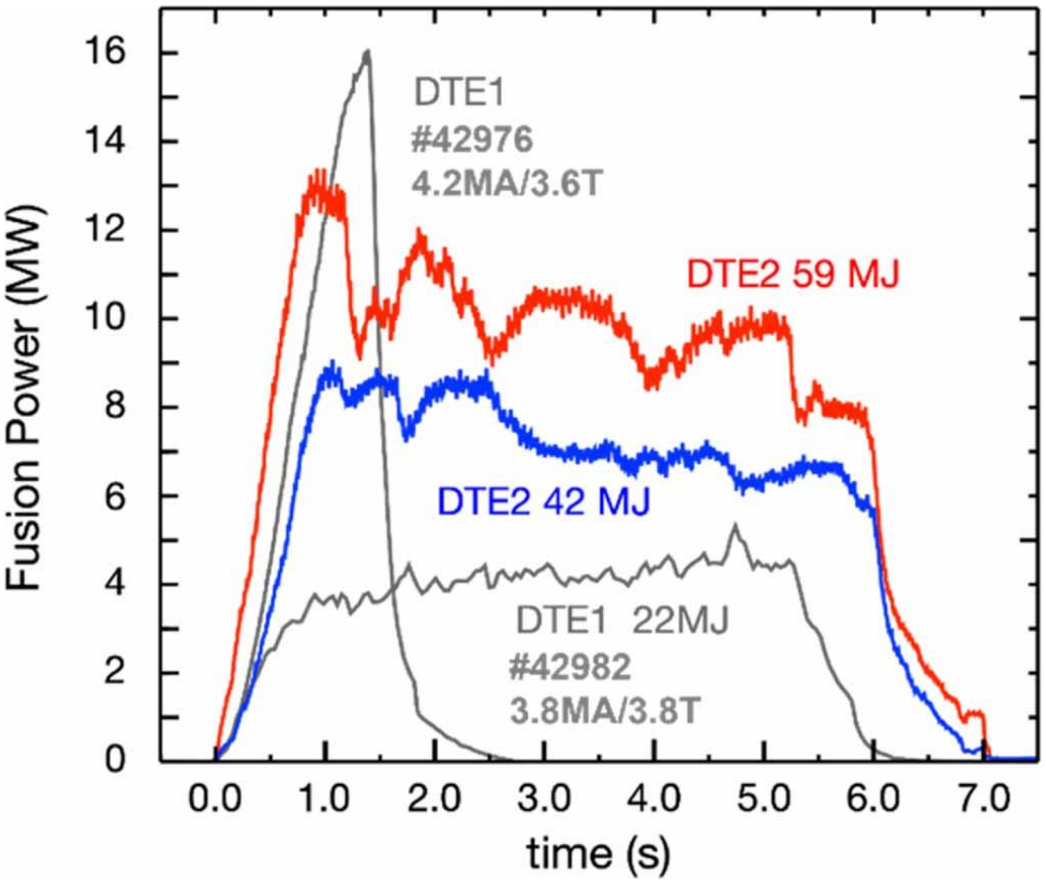
- Per il Jet è interessante il confronto fra i risultati ottenuti nelle campagne DTE1 e DTE2 del 1997 e del 2021, per spari che avevano fra gli obiettivi anche quello di ottenere dalla macchina le massime performance possibili.

The **Tokamak Fusion Test Reactor** (**TFTR**) was an experimental tokamak built at Princeton Plasma Physics Laboratory (PPPL) circa 1980 and entering service in 1982. Shut down in 1997

JET (Joint Europena Torus) progettato negli anni '70 e realizzato a Culham (UK) ha iniziato a funzionare nel 1983. Da allora ha avuto diversi corposi aggiornamenti. Ha terminato la sua attività nel 2023

Campagna DTE1, 1997

Di seguito è mostrata la figura 1 riportata sull'articolo scientifico https://iopscience.iop.org/article/10.1088/1741-4326/ad3e16, primo autore Costanza Maggi**, la voce ufficiale del team sperimentale del JET.** Tutte le successive informazioni sono tratte dal suddetto articolo.



Le migliori scariche ottenute in DTE1:

Il primo picco traccia grigia con 16 MW di potenza di fusione (campagna 1997) si ottiene in un regime privo di interesse reattoristico (hot Ion mode) con gli ioni più caldi degli elettroni; ma siccome in un reattore sono gli elettroni che riscaldano gli ioni questo regime non è di interesse, perdipiù in un regime fortemente transitorio (circa 100 ms). Corrisponde al Q più alto mai ottenuto su un Tokamak Q=0.68. Evidentemente è un **breve transiente**

Il secondo risultato **traccia** grigia ottenuto in DTE1 (1997) corrisponde ad un regime definito stazionario **(ELMy H-Mode),** in realtà la scarica viene terminata volontariamente a causa del manifestarsi dell'inizio della formazione di un GiantELM (Edge Localized Mode), una piccola disruzione. Pertanto, non è definibile come stazionario, ma un regime nel quale si sviluppano fenomeni potenzialmente dannosi incompatibili con le modalità di funzionamento di un reattore, o anche di ITER.

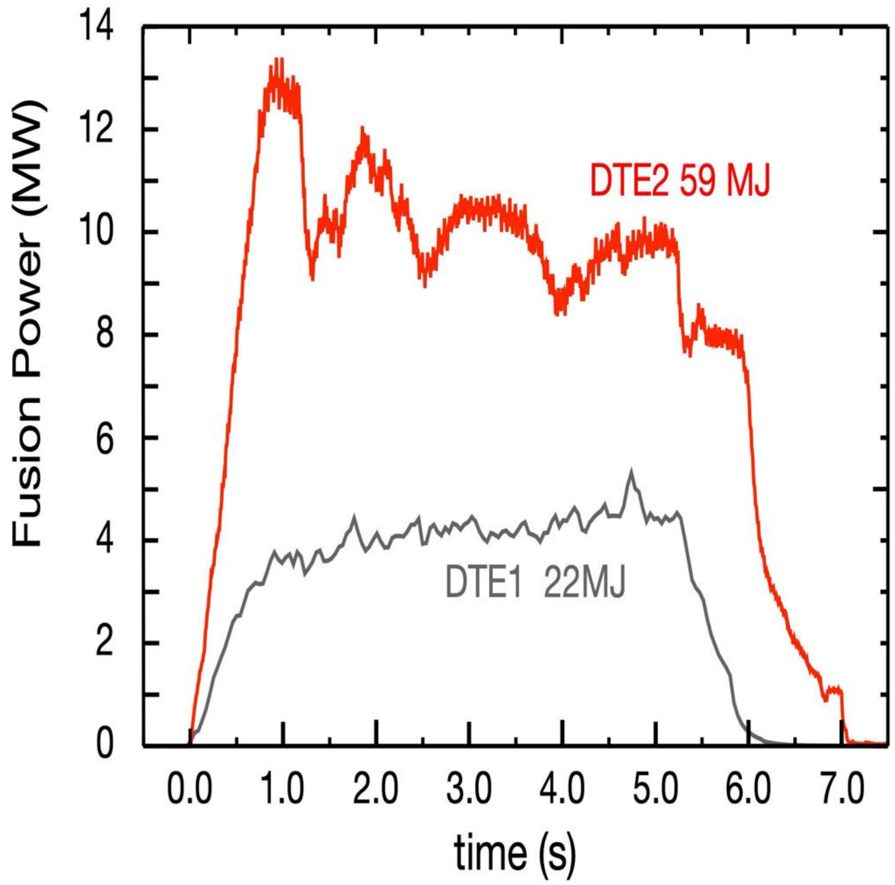
In queste condizioni si ottiene un Q=0.25, praticamente lo stesso valore del TFTR.

Campagna DTE2, 2021

Nella nuova campagna, effettuata a 24 anni di distanza, dopo profende modifiche tecnologiche,

- nuovo divertore
- Nuovo materiale di prima parete (ITER relevant, da carbonio a tungsteno berillio)
- Potenziamento dei sistemi di riscaldamento addizionale passati da 25 a 40 MW.
- Estensivamente remotizzato (remote handling system)
- Continui aggiornamenti (€1.6 billion for the period 2014-2018)

Confronto campagne



Questo è il grafico riportato sul sito di ITER (https://www.iter.org/node/20687/jet-makes-history-again), la didascalia è:

The results confirm that sustained high-fusion energy production is achievable using the D-T fuel mix planned on ITER and future devices. They also show that the fusion community has the capability to model what will happen in a fusion reactor. (UKAEA)

il grafico riporta il confronto tra energia prodotta nella migliore scarica del 1997 DTE1 e la migliore del 2021, DTE2: 22 e 59 MJ, rispettivamente in 6 e 7 s.
E' evidente che la curva relativa alla campagna recente, quella rossa, **mostra esattamente il contrario di quanto riportato nella didascalia,** la potenza di fusione **decresce durante la scarica ovvero il plasma non tende ad accendersi, ma più energia si mette dentro più diminuisce la potenza da fusione**

Base line scenario è quello che se applicato su ITER si pensa di avrà in DT un Q=10, le massime prestazioni.

Purtroppo, **non si riesce al JET ad ottenere un regime stazionario**, come si vede dalla traccia della potenza di fusione (DT fusion power), che raggiunge il valore massimo di potenza da fusione dopo circa due secondi, per poi iniziare a calare.

Il picco di potenza è di 8.3MW, a fronte di 34 MW in ingresso, ovvero **ancora Q=0.25**, ma perdipiù in condizioni palesemente non stazionarie, e con un plasma che pur in presenza di un input di potenza costante diminuisce nel tempo la potenza di fusione prodotta.

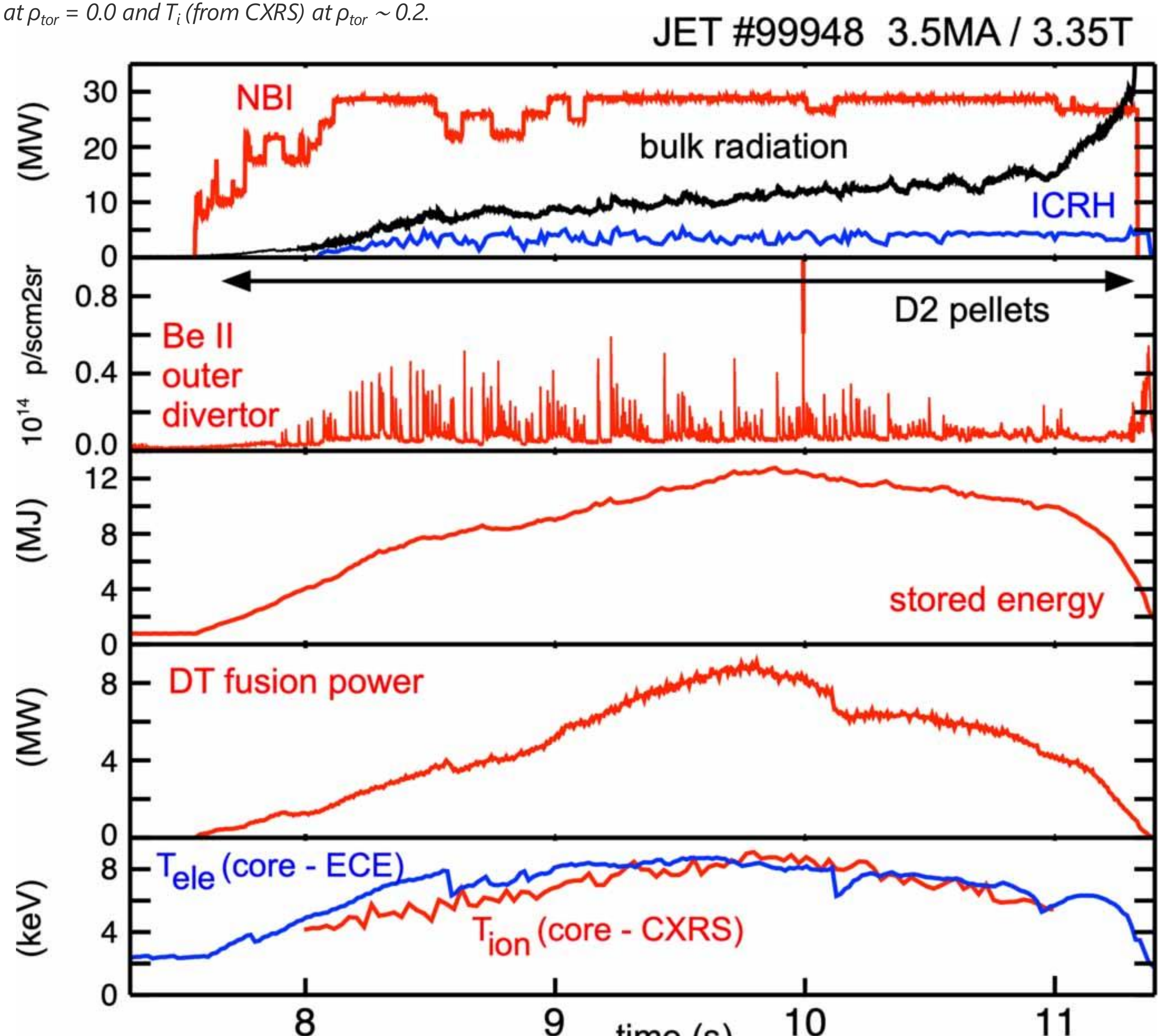
Questo è dovuto al ristagno di impurezze ad alto Z, tungsteno, all'intero del plasma che fanno aumentare notevolmente la "bulk radiation" (curva nera).

E' evidente che qualora si aumentasse di più la potenza in input il plasma collasserebbe immediatamente, anche con rischi di danneggiamento della macchina.

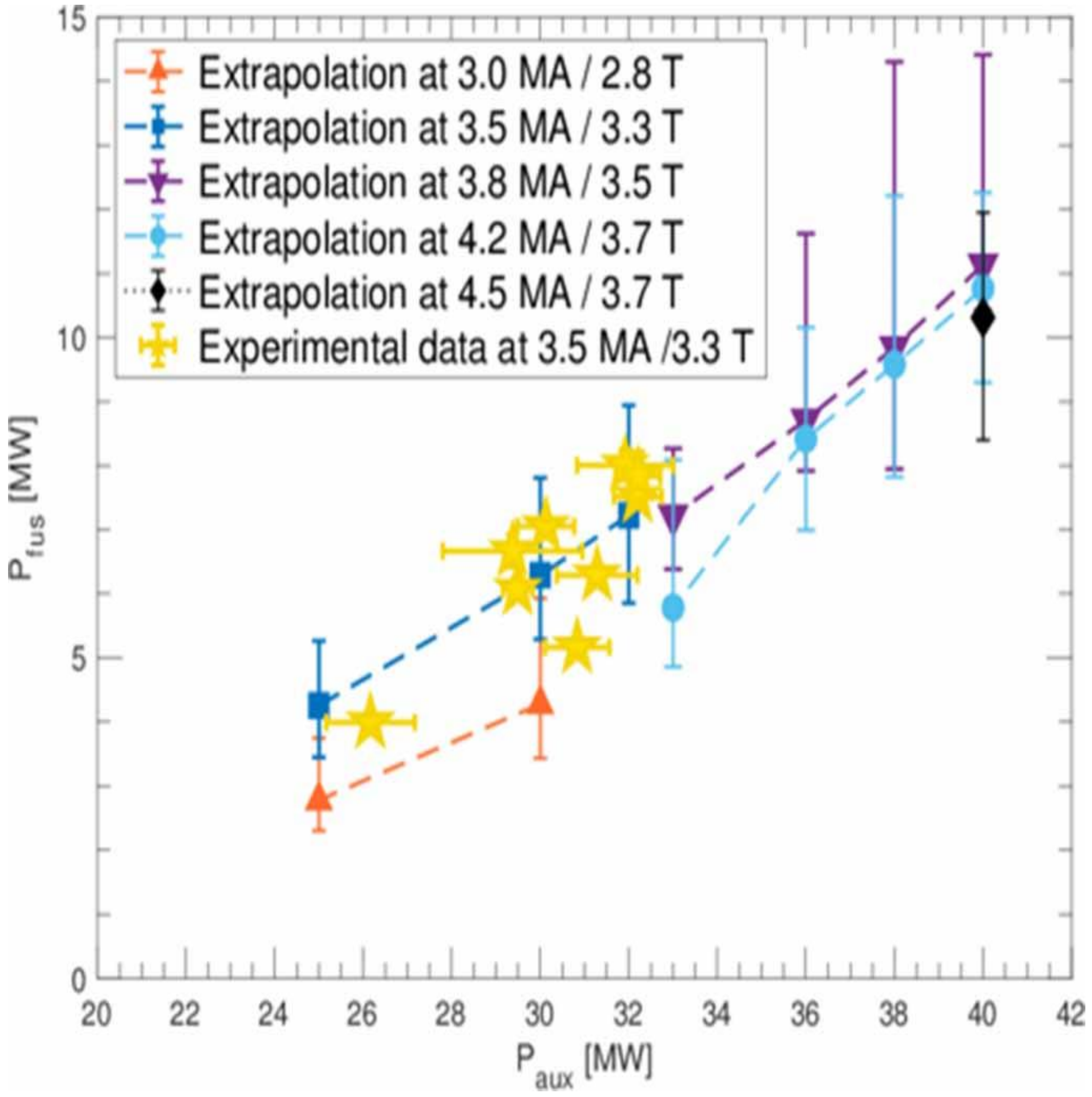
Pertanto, questa che è riportata come la migliore scarica ottenuta dal JET nel regime più "reactor relevant" possibile, è poco confortante.

Lo stesso Q di 24 anni prima, scarica contaminata da impurezze, potenza di fusione decrescente così come le temperature elettronica e ionica.

Figure 2. *Best performing 50–50 D–T JET baseline scenario pulse in DTE2 (#99948, 3.5 MA/3.35 T, 30 MW NBI, 4 MW ICRH, D-pellet pacing). From top to bottom panel: (1) NBI power, bulk plasma radiation and ICRH power; (2) outer divertor Be II line intensity used as ELM marker; (3) plasma stored energy; (4) D–T fusion power; (5) core* T_e *(from ECE) at* $\rho_{tor} = 0.0$ *and* T_i *(from CXRS) at* $\rho_{tor} \sim 0.2$.



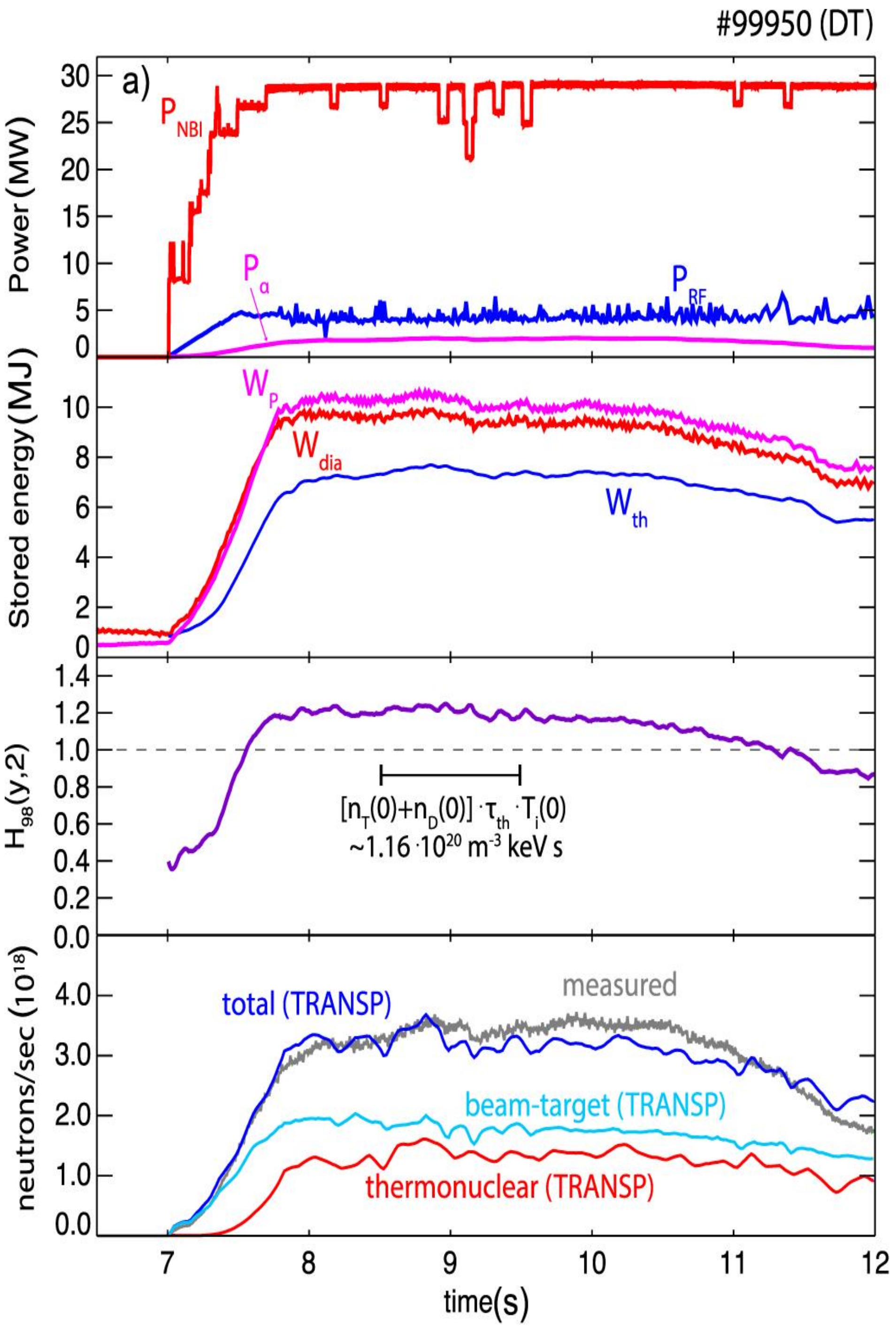
Simulazioni a piena potenza



Non potendo immettere più potenza il team del Jet ha provato a vedere mediante simulazioni cosa sarebbe potuto succedere estrapolando alle condizioni estreme raggiungibili nel JET (40MW di potenza addizionale), ovviamente **trascurando la l'aumento** della radiazione che fa collassare il plasma, insomma in condizioni ipoteticamente ottimali. I risultati sono ancora più scoraggianti, il Q non cresce (vedi figura) **arriva al massimo a 11 MW di fusione a fronte di 40 MW in input**, la massima potenza disponibile al JET. E questo in condizioni ideali molto migliorative rispetto a quelle reali.

Rimane $Q=0.27 \pm 0.07$

Figura 3 *Estrapolazione ottenuta dai codici alle condizioni di massima potenza disponibile al Jet. Le stelle gialle sono i punti sperimentali ottenuti, gli altri punti estrapolazioni di diversi parametri.*



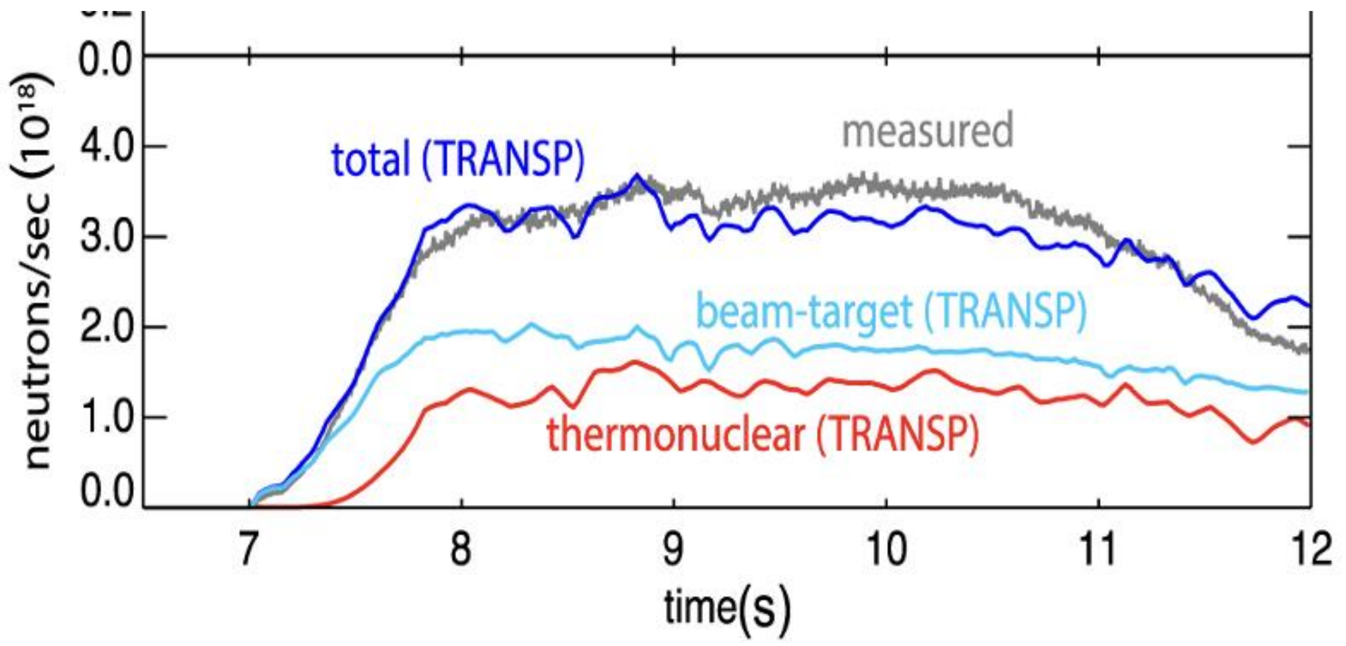
Hybrid scenario

Le stesse misure sono state ripetute con uno scenario di plasma diverso (Hybrid scenario) potenzialmente ritenute per alcuni aspetti più reactor relevant in quanto lo scenario candidato alle operazioni di ITER con impulsi lunghi (>1000s); in tali condizioni il Q previsto è di 5.

Andando a scegliere la parte della scarica a Pfus massimo, si ottiene **Q=0.32 se mediato su un secondo**, mentre **mediando su 5 secondi si ottiene Q=0.25**. Questo con 34MW di potenza addizionale. Nella campagna DTE1, in condizioni di potenza da fusione crescente con il tempo, si era ottenuto su 5 secondi Q=0.18, ma in tal caso la Pin era 23.8 MW. Estrapolando per Q=5 servirebbero 660 MW

Figura 4 Time traces of main parameters of the JET DTE2 hybrid H-mode pulse #99950 (2.3 MA/3.45 T, 50–50 D–T), which set a new record fusion energy of 45.8 MJ in a 50–50 D–T mixture. Reproduced from [51]. © EURATOM 2023. CC BY 4.0.

Beam target



In figura 4 è inoltre riportato il risultato della simulazione ottenuta mediante il codice **TRANSP** (https://www.sciencedirect.com/science/article/pii/S0010465525001134) ; **Scopo del calcolo è separare il contributo alle reazioni di fusione ottenuto da interazione diretta target (vedi traccia azzurra), da quelle che invece avvengono all'interno del plasma.** E' infatti evidente che le prime nulla hanno a che fare con il funzionamento di un reattore, ma sono l'effetto di interazione fra il beam ed il plasma utilizzato come un bersaglio, sostanzialmente gli esperimenti condotti dagli acceleratoristi per gli studi di fisica pura, a ben altre energie. Il codice stima una percentuale del 60% da beam target ed il restante 40% realmente termonucleari, all'interno del plasma.

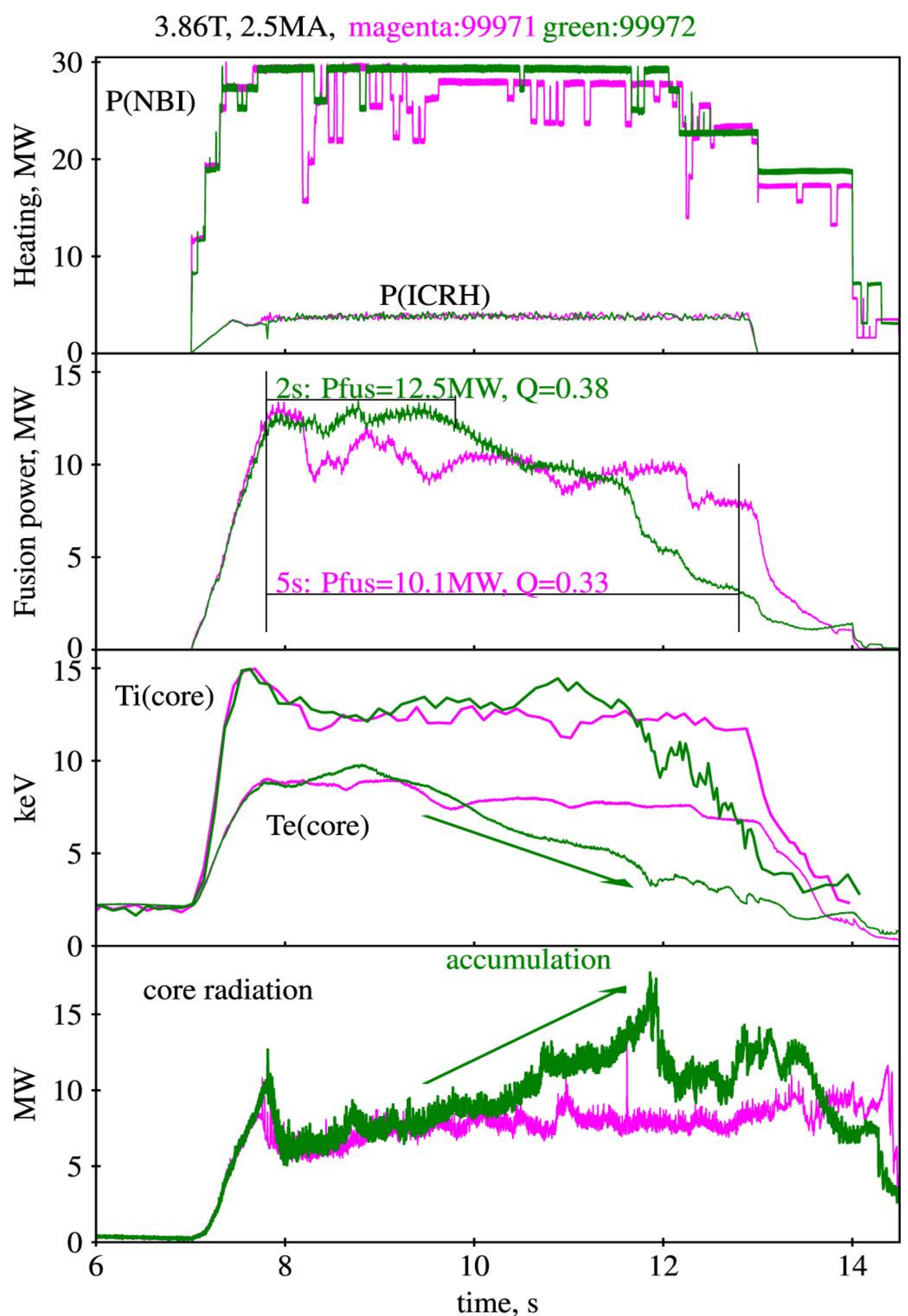
Ma non è viene riportato l'errore da attribuire al risultato, né come il codice sia stato validato, visto che misure relative alle due frazioni non ce ne sono.

Nel recente articolo che descrive il codice (https://www.sciencedirect.com/science/article/pii/S0010465525001134) **è riportato**:

"While interpretive analysis can be challenging due to the difficulty in isolating separate aspects of the problem, it provides a comprehensive understanding of the complex interactions within the tokamak plasma, which is crucial for optimizing its performance. "

Si tratta di un codice che acquisisce gli input da altri codici che evidentemente è utilizzato più per provare a comprendere che per fornire risultati numerici; evidentemente una stima dell'errore del risultato è fuori dalla portata di questo strumento.

Ammesso che risultati di un codice senza valutazione dell'errore e senza riferimenti alla sua validazione, agli input utilizzati e come desunti, possano avere un qualche interesse, si evince che non solo il Q è estremamente modesto, **ma in gran parte ottenuto con reazioni beam target**, che nulla hanno a che fare con il plasma reattoristico. Essendo la potenza di beam aumentata nell'ultima campagna è evidente che si ottiene più energia da fusione, ma non è dato saper se ce ne sia la benché minima percentuale da fusione termonucleare, e non da interazione diretta beam taget.



Scarica record

Nel tentativo, o nella necessità, di ottenere risultati migliori, si è cercato di spostare i parametri del **plasma completamente al di fuori** del possibile interesse reattoristico, realizzando un plasma di solo trizio sul quale vengono sparati, mediante la NBI, atomi di deuterio ad elevata energia, circa 120kEv.

In questo modo l'esperimento è evidentemente il più possibile beam driven, ovvero è un esperimento relativo ad un fascio di particelle (D) che urtano su un target (il plasma di T)

Questo non ha nulla a che vedere con la fusione magnetica, i Tokamak, i reattori e gli scenari di plasma ad essi estrapolabili, dove necessariamente il plasma deve essere 50%D e 50% T.

In tal caso si è riuscito ad ottenere il record di produzione di energia di 59 MJ, sempre con un Q bassino, fra 0.33 per 5 s e 0.38 per 2 s, comunque in condizioni non stazionarie, ma con potenza di fusione calante, ovvero un plasma che più lo si scalda più si raffredda.

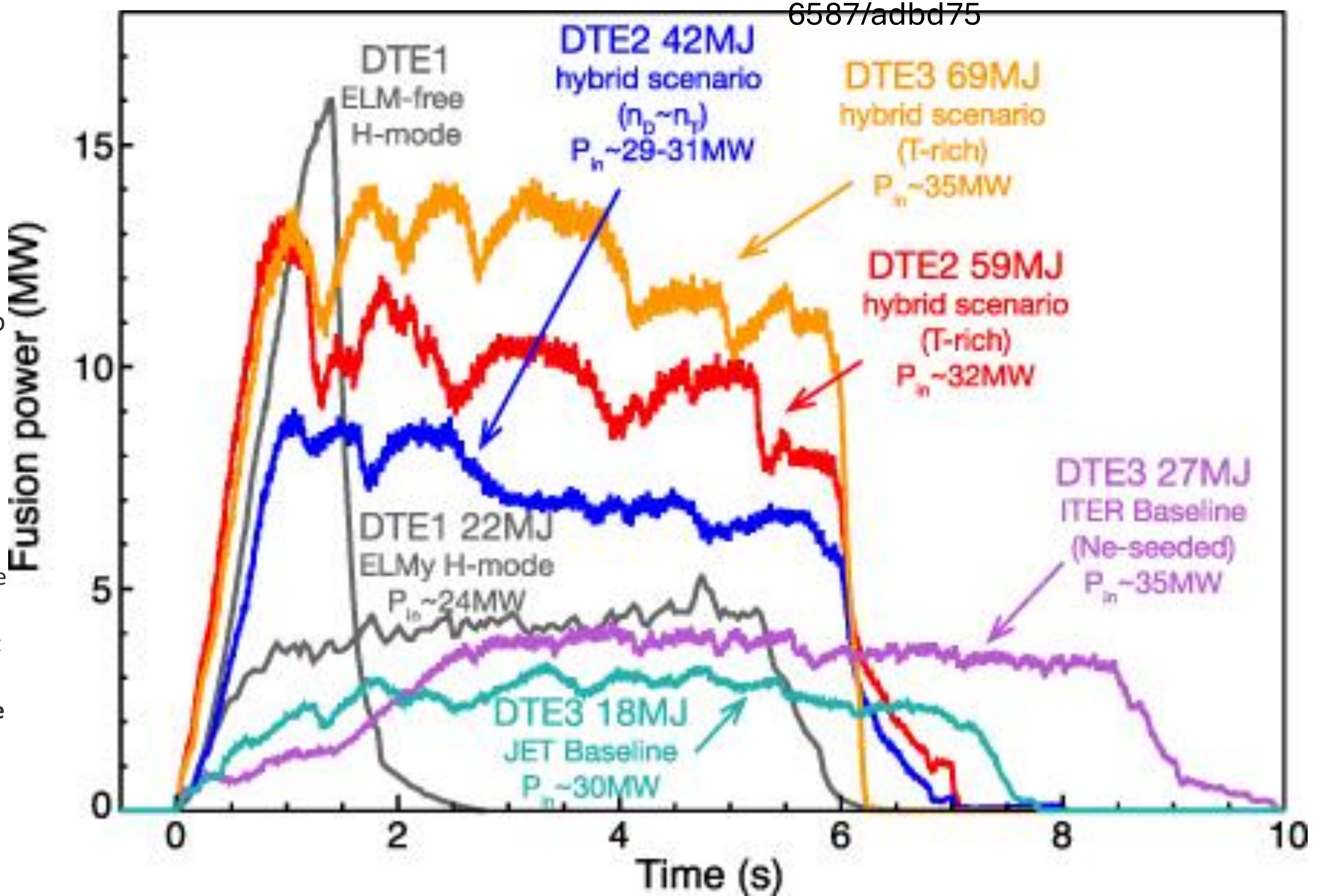
Risultato completamente inutile e quantitativamente deludente.

Comparison of the two best performing T-rich hybrid pulses at similar input engineering parameters: #99971 ***(magenta), with sustained high fusion power = 10.1 MW for 5 s*** *and #99972 (green) with higher P_{fus} = 12.5 MW for 2 s, but degrading later in the discharge due to core impurity accumulation. Reproduced from [38].*

Overall DT campaigns

https://iopscience.iop.org/article/10.1088/1361-6587/adbd75

Fusion power produced in JET in DTE1 (ELM-free H-mode #42976 and ELMy H-mode #42982, in grey), DTE2 (hybrid scenario with #99869 in blue, T-rich hybrid scenario #99971 in red) and DTE3 campaigns (T-rich hybrid scenario #104522 in orange, Ne-seeded ITER baseline scenario #104600 in purple, JET baseline scenario #104663 in teal).



The tritium stored in different regions of the vessel should be limited to comply with safety regulations. During operations, excessive tritium retention would mean that operations cannot continue until the tritium inventory is reduced below the safety limits. **In addition, high tritium retention limits the amount of tritium that can be used to fuel the plasma, placing additional demands on the tritium breeding ratio in fusion power plants.** Therefore, the quantification of the fuel retention and the characterisation of the tritium cycle is crucial information for ITER and any future fusion device.

Tutto da rifare?

A key message from these results is that, in the absence of performance degrading MHD or impurity effects, **a higher heating power would be expected to lead to a further increase in the fusion powe**r. If this could be maintained at a constant level, a higher 5 s averaged fusion power would result. **The experimental fusion power obtained is a non-linear function of input power, best fitted with a quadratic (or higher order) function, as illustrated in figure 23**. In this figure **only data during the power ramp-up and in the heating flattop is included**. It should be noted that the low input power points are generated **mostly in the power ramp-up phase**, which means that the fusion powers determined for these points include the transient phase at the H-mode entry. This means that the trend in figure 23 may be slightly different to that of an input power scan in otherwise similar conditions. This trend is similar to observations in Deuterium only.

Bisogna modellizzare e validare, teoria ed esperimenti

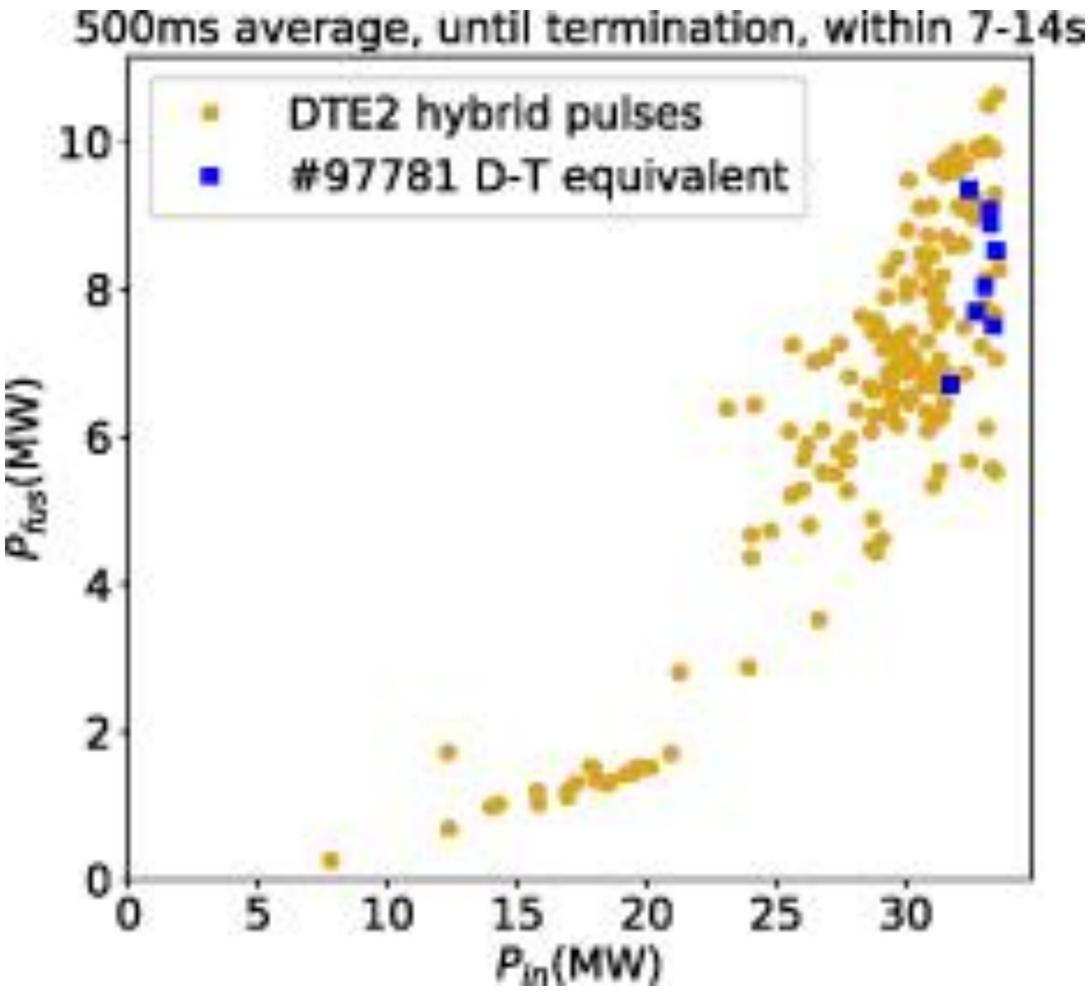


Figure 23. Obtained fusion power compared to D-T equivalent fusion power from pre-D-T reference as function of input power (ITB phase removed).

Nuclear Fusion, Volume 63, Number 11, J. Hobirk *et al*

Conclusioni JET

- I risultati forniscono una enorme quantità di informazioni, indispensabili per procedere

- I risultati ottenuti in termini di Q_{sci} sono sostanzialmente gli stessi di 24 anni prima (se non inferiori) e gli stessi di TFTR (27 anni prima)
- Le condizioni ottenute sono molto distanti da quelle pensabili in un futuro reattore (percentuale di particelle alfa trascurabile), e ottenute in condizioni o palesemente non stazionarie o marginalmente tali, spesso in scenari privi di significatività scientifica, bisogna fare di più
- L'aumento della potenza in ingresso da 25 a 34 MW sembra peggiorare le cose. Ciò significa che siamo ancora lontani dal riuscire ad ottenere condizioni prossime alle reazioni a catena necessarie all'autoriscaldamento del plasma, quelle condizioni alle quali la fusione inerziale sembra si stia affacciando.
- In molti casi più si scalda il plasma più questo si raffredda, cosa che fa dubitare che ulteriore potenza addizionale avrebbe potuto migliorare i risultati, come anche mostrano le simulazioni effettuate in condizioni ideali.
- La evoluzione tecnologica della macchina si è rivelata parzialmente efficace, visto che non si riescono a controllare le impurezze ad alto Z che entrano nel core del plasma, aumentandone la radiazione, ma la ritenzione del trizio è migliorata

Conclusioni 2

- Rimane ancora molta incertezza su quali potrebbero essere gli scenari di plasma futuri, in realtà ancora non si è trovato uno scenario soddisfacente, ITER avrebbe dovuto fornire questa informazione, speriamo arrivi quanto prima e che sia positiva
- **è necessario intensificare gli sforzi per approfondire la comprensione dei fenomeni di base, tanta teoria e tante simulazioni, tanti esperimenti ma in condizioni rappresentative.**
- E' necessario comprendere meglio i meccanismi che regolano la diffusione delle impurezze e cercarla di ostacolarle (barriere di trasporto), o riuscire ad estrarle prima che inizino ad entrare nel core del plasma. In DTE3 dei passi in avanti sono stati fatti
- Si evidenzia un importate effetto isotopico che porta ad una maggiore produzione di impurezze a causa della presenza del trizio, con massa maggiore rispetto al deuterio . E' pertanto evidente che gli esperimenti necessari ad un ulteriore progresso non **possono che essere con macchine in DT**, pena la non rappresentatività delle misure per un futuro reattore.
- **E' oltremodo chiaro che in queste condizioni, il contributo di ditte esterne o di accordi pubblico privato sono di marginale utilità; i fisici del plasma sono i soli in grado di comprendere cosa succede e provare ad immaginare una soluzione. Queste persone lavorano in ENEA o in luoghi simili, non di certo nelle industrie,** che hanno il compito primario di far tornare i conti economici

Bilancio energetico di un ipotetico reattore

Demo electricity consumption

Table 2. EU-DEMO Project Plant Breakdown Structure (PBS) with expected powers and connection to the distribution grid.

PBS	PBS Description	Power		Distribution
		Active (MW)	Reactive (MVAR)	
11	Magnet System	0	0	Passive
12	Vacuum Vessel (VV)	0	0	Passive
13	Divertor System	0	0	Passive
14	Blanket (HCPB) [1]	0	0	Passive
16	Blanket (WCLL) [1]	0	0	Passive
18	Limiter	0	0	Passive
20	Cryostat	0	0	Passive
21	Thermal Shields	0	0	Passive
22	Tritium, Fueling, Vacuum	12.2	7.7	SSEN
25	Tritium Extraction and Removal (HCPB) [1]	3.0	1.9	SSEN
27	Tritium Extraction and Removal (WCLL) [1]	3.0	1.9	SSEN
30	ECRH System (main power) [2,3]	125.0	60.5	PPEN
30	ECRH System (auxiliary power) [2]	6.0	2.9	SSEN
31	NBI System (main power) [2,3]	125.0	60.5	PPEN
31	NBI System (auxiliary power) [2]	6.0	2.9	SSEN
32	ICRH System (main power) [2,3]	125.0	60.5	PPEN
32	ICRH System (auxiliary power) [2]	6.0	2.9	SSEN
40	Plasma Diagnostic & Control System	6.1	3.0	SSEN
49	VV PHTS	9.7	4.7	SSEN
50	Breeding Blanket PHTS (HCPB) [1,3]	165.6	54.4	SSEN
52	Breeding Blanket PHTS (WCLL) [1]	59.4	19.5	SSEN
54	VV Pressure Suppression System (HCPB) [1]	2.3	0.0	SSEN
56	VV Pressure Suppression System (WCLL) [1]	4.6	2.9	SSEN
58	Divertor & Limiter PHTS (HCPB) [1]	19.5	12.1	SSEN
59	Divertor & Limiter PHTS (WCLL) [1]	10.0	6.2	SSEN
60	Remote Maintenance (RM) System [4]	5.0	3.1	SSEN
61	Assembly	4.6	2.2	SSEN
63	Radwaste Treatment and Storage	3.0	1.5	SSEN
70	Balance of Plant (HCPB) [1]	12.0	5.8	SSEN
72	Balance of Plant (WCLL) [1]	12.0	5.8	SSEN
80	Site Utilities	3.1	1.9	SSEN
81	Cryoplant & Cryodistribution	101.8	63.1	SSEN
82	Electrical Power Supply (main power) [3]	300.0	300.0	PPEN
82	Electrical Power Supply (auxiliary power)	21.0	10.2	SSEN
83	Buildings	54.8	26.6	SSEN
85	Plant Control System	3.6	1.7	SSEN
87	Auxiliaries	90.9	56.4	SSEN

[1] The PBSs referred to the HCPB and WCLL options are alternative: once the final configuration will be selected, only one of the two reported powers will be requested in DEMO. [2] The powers reported for the H&CD systems (PBSs 30, 31 and 32) were estimated for the reference solution with related efficiencies (see Section 5.3). [3] Since the powers absorbed by these PBSs are not constant, their peak powers are reported. While the PPEN loads (PBSs 30, 31, 32 and 82) may be very variable, the load of PBS 50 is reduced to 20% in some phases as described in Section 5.5. [4] Even if RM System is connected to the SSEN, it mainly operates during specific maintenance phases and not during plasma phases in Table 1.

HCPB version > 500MWe

Energies **2020**, *13*(9), 2269; https://doi.org/10.3390/en13092269

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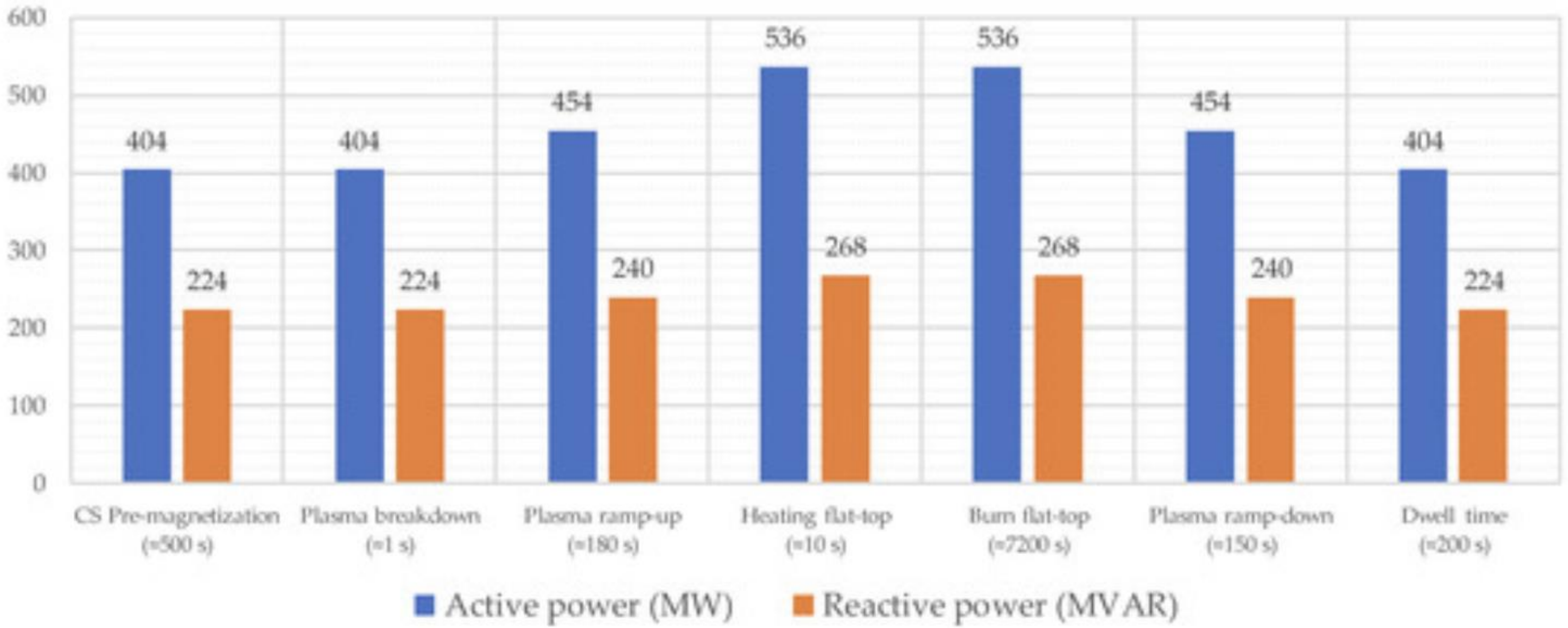
13	Divertor System	0	0	Passive
14	Blanket (HCPB) [1]	0	0	Passive
16	Blanket (WCLL) [1]	0	0	Passive
18	Limiter	0	0	Passive
20	Cryostat	0	0	Passive
21	Thermal Shields	0	0	Passive
22	Tritium, Fueling, Vacuum	12.2	7.7	SSEN
25	Tritium Extraction and Removal (HCPB) [1]	3.0	1.9	SSEN
27	Tritium Extraction and Removal (WCLL) [1]	3.0	1.9	SSEN
30	ECRH System (main power) [2,3]	125.0	60.5	PPEN
30	ECRH System (auxiliary power) [2]	6.0	2.9	SSEN
31	NBI System (main power) [2,3]	125.0	60.5	PPEN
31	NBI System (auxiliary power) [2]	6.0	2.9	SSEN
32	ICRH System (main power) [2,3]	125.0	60.5	PPEN
32	ICRH System (auxiliary power) [2]	6.0	2.9	SSEN
40	Plasma Diagnostic & Control System	6.1	3.0	SSEN
49	VV PHTS	9.7	4.7	SSEN
50	Breeding Blanket PHTS (HCPB) [1,3]	165.6	54.4	SSEN
52	Breeding Blanket PHTS (WCLL) [1]	59.4	19.5	SSEN
54	VV Pressure Suppression System (HCPB) [1]	2.3	0.0	SSEN
56	VV Pressure Suppression System (WCLL) [1]	4.6	2.9	SSEN
58	Divertor & Limiter PHTS (HCPB) [1]	19.5	12.1	SSEN
59	Divertor & Limiter PHTS (WCLL) [1]	10.0	6.2	SSEN
60	Remote Maintenance (RM) System [4]	5.0	3.1	SSEN
61	Assembly	4.6	2.2	SSEN
63	Radwaste Treatment and Storage	3.0	1.5	SSEN
70	Balance of Plant (HCPB) [1]	12.0	5.8	SSEN
72	Balance of Plant (WCLL) [1]	12.0	5.8	SSEN
80	Site Utilities	3.1	1.9	SSEN
81	Cryoplant & Cryodistribution	101.8	63.1	SSEN
82	Electrical Power Supply (main power) [3]	300.0	300.0	PPEN
82	Electrical Power Supply (auxiliary power)	21.0	10.2	SSEN
83	Buildings	54.8	26.6	SSEN
85	Plant Control System	3.6	1.7	SSEN
87	Auxiliaries	90.9	56.4	SSEN

[1] The PBSs referred to the HCPB and WCLL options are alternative: once the final configuration will be selected, only one of the two reported powers will be requested in DEMO. [2] The powers reported for the H&CD systems (PBSs 30, 31 and 32) were estimated for the reference solution with related efficiencies (see Section 5.3). [3] Since the powers absorbed by these PBSs are not constant, their peak powers are reported. While the PPEN loads (PBSs 30, 31, 32 and 82) may be very variable, the load of PBS 50 is reduced to 20% in some phases as described in Section 5.5. [4] Even if RM System is connected to the SSEN, it mainly operates during specific maintenance phases and not during plasma phases in Table 1.

Overall plant energy consumption



Nominal SSEN active and reactive powers in each plasma phase, option HCPB

Demo ultima versione dichiara 1652 MWth e 350 MWe netti in rete, ovvero 536+350=886 prodotti, rendimento del 54%, impossibile. Considerando 33% si hanno 545 MWe

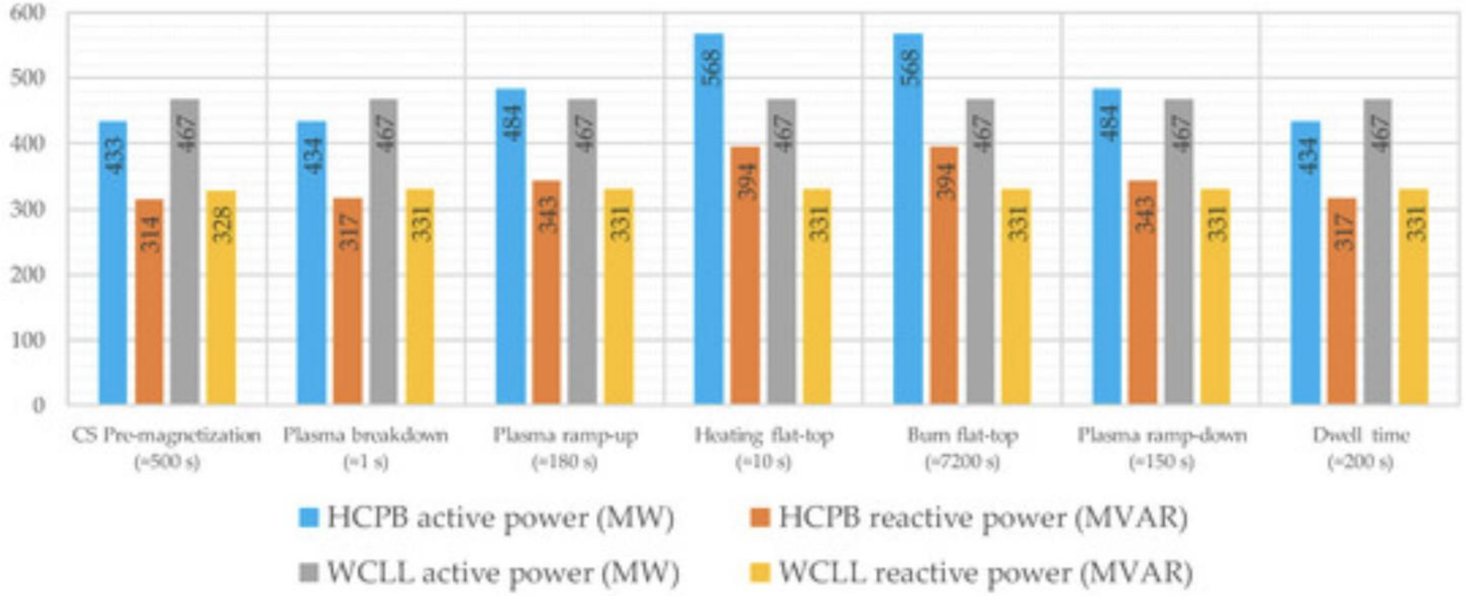


Figure 9. Total steady state electrical powers requested from the grid at the DEMO HV connection point in the two PHTS-PCS cases (HCPB and WCLL).

Produrrà mai energia?

- Un EPR ha il 36/37% di efficienza, misurata.
- Se DEMO avesse la stessa efficienza 1652X0.37 =611MWe, confrontabili ai consumi durante la scarica: Il DEMO team si limita a dire che assume una efficienza overall del 20% già epurata dei consumi della macchina, con un valore di MWe netti in rete di 350+/-50.Dalle referenze non si traggono informazioni utili
- Quindi, considerando i 536 MWe di autoconsumo, produrrebbe 886MWe....54% di rendimento 🤭
- La complessità delle geometrie di un reattore a fusione rendono difficile credere ad una sua maggiore efficienza rispetto ad uno a fissione, un pentolone con a bagno gli elementi di combustibile che scambiano direttamente con il refrigerante senza perdere un W
- Demo assume che il liquido di raffreddamento del divertore possa essere mandato in turbina malgrado la permeazione da trizio
- Con un conto realistico *0.8 neutron energy*0.8 geometric factor=0.64*1.2 exothermal reaction=0.77*0.33=0.25 , quindi con 1652 MWth= 413 MWe da cui detrarre gli oltre 500MWe dei consumi elettrici...quando in funzione

Per il reattore finale avesse la stessa potenza termica di un EPR 4.6 GWt*0.33= 1530 MWe.......consumi >>>>9x536????MWe......dwell time-20%??.......load factor-30%....

Il blanket sembra vada rimpiazzato ogni 5 anni, se si trovano materiali idonei, il divertore almeno sostituite le tegole, tutto in remote handling, tempi e costi proibitivi

Un EPR ha 4.6 GWt, produzione lorda 1.77 GWe, netta 1.65 GWe load factor 85-95% (misurato)

Prestazioni di un futuro reattore

- *NWL = 80 %* P_{fus} / A_{Wall}, with A_{wall} being the surface area of the plasma-facing wall. Too low values of the *NWL* correspond to an unattractively large device with respect to the produced fusion power. We consider a *NWL* target of ∼1 MW/m^2 as reasonable, which lays in between the ITER target of 0.57 MW/m^2 [26] and ∼2 MW/m^2 as considered for fusion power plants in the PPCS [36].
- 1.0 MW/m3

- The target for the **net electric output** of the DEMO plant is defined in [1] as "*hundreds of MW of electricity*". With common assumptions regarding the heat conversion efficiency and recirculating power for various DEMO systems, this translates into a requirement for the fusion power of P_{fus} = *∼2000* MW, which corresponds to a net electricity output of 400–500 MW, Fusion Engineering and Design,Volume 204, July 2024, 114518
- Rendimento 20-25%

Ma la fusione è prestazionale?

- Formula1 1050 CV, cica 750kW, volume 1.6l, circa 500kW/l
- Panda 45 kW, volume 1l, 45 kW/l, autotreno 13l 450kW, 35kW/l

- Reattore fusione 1 MW/m^3 (ipotetici) progettazione 2025, limitato dal neutron load factor, 1 MW/m^2
- Reattore fissione 89,3 MW/m^3 (misurati), progettazione 2000 Nuclear Engineering and Design, Volume 187, Issue 1, January 1999, Pages 79-119

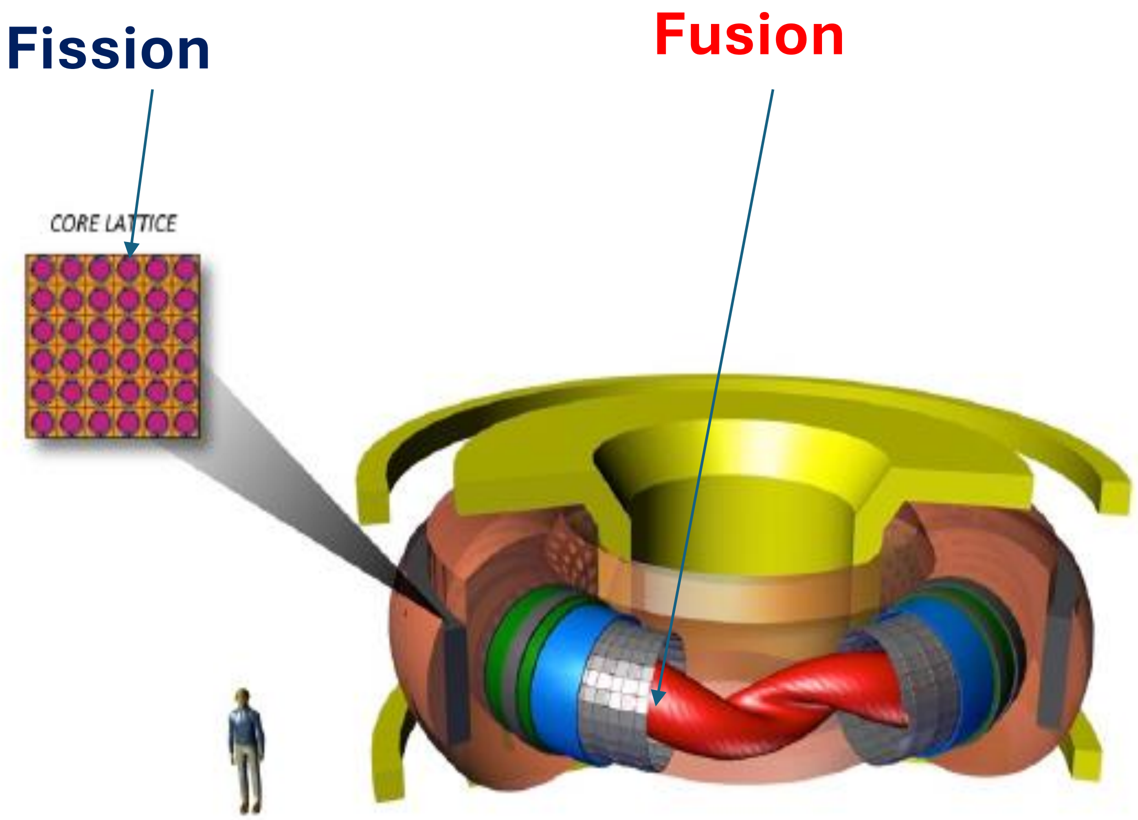
Fusion-fission hybrid systems

In a hybrid reactor, the neutron flux emerging from **nuclear fusion reactor** is used to induce fissions (or transmutations) in a **fission blanket** in subcritical mode (k<1).

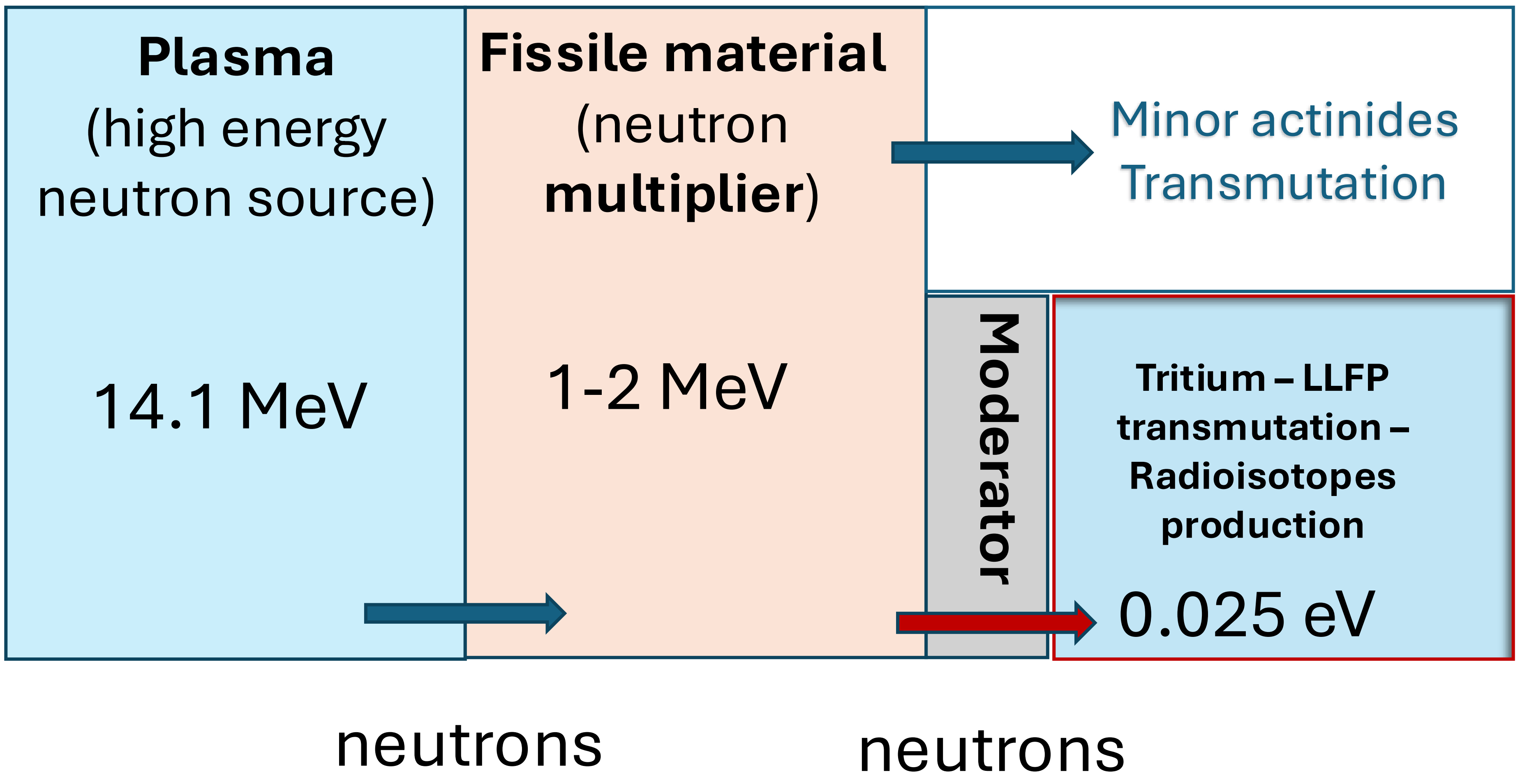
FFHS can contain a blanket for:

- Energy generation
- Radioactive waste transmutation
- Nuclear fuel production (fertilization)
- **Tritium breeding (currently produced by CANDU reactors)**

These systems could represent an intermedia step towards the industrialization of nuclear fusion



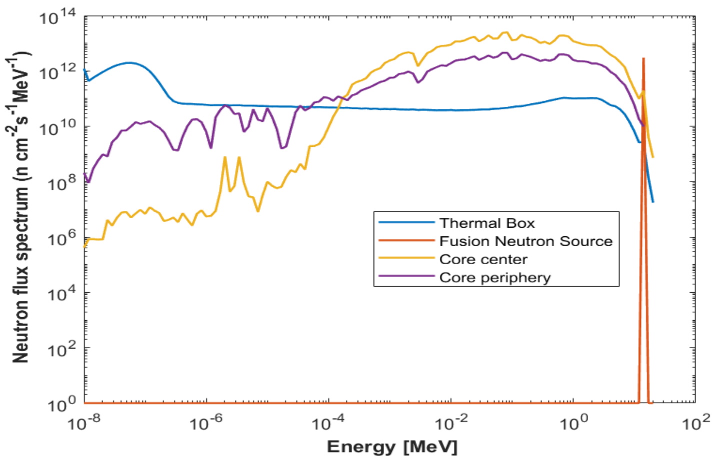
Fission blanket design

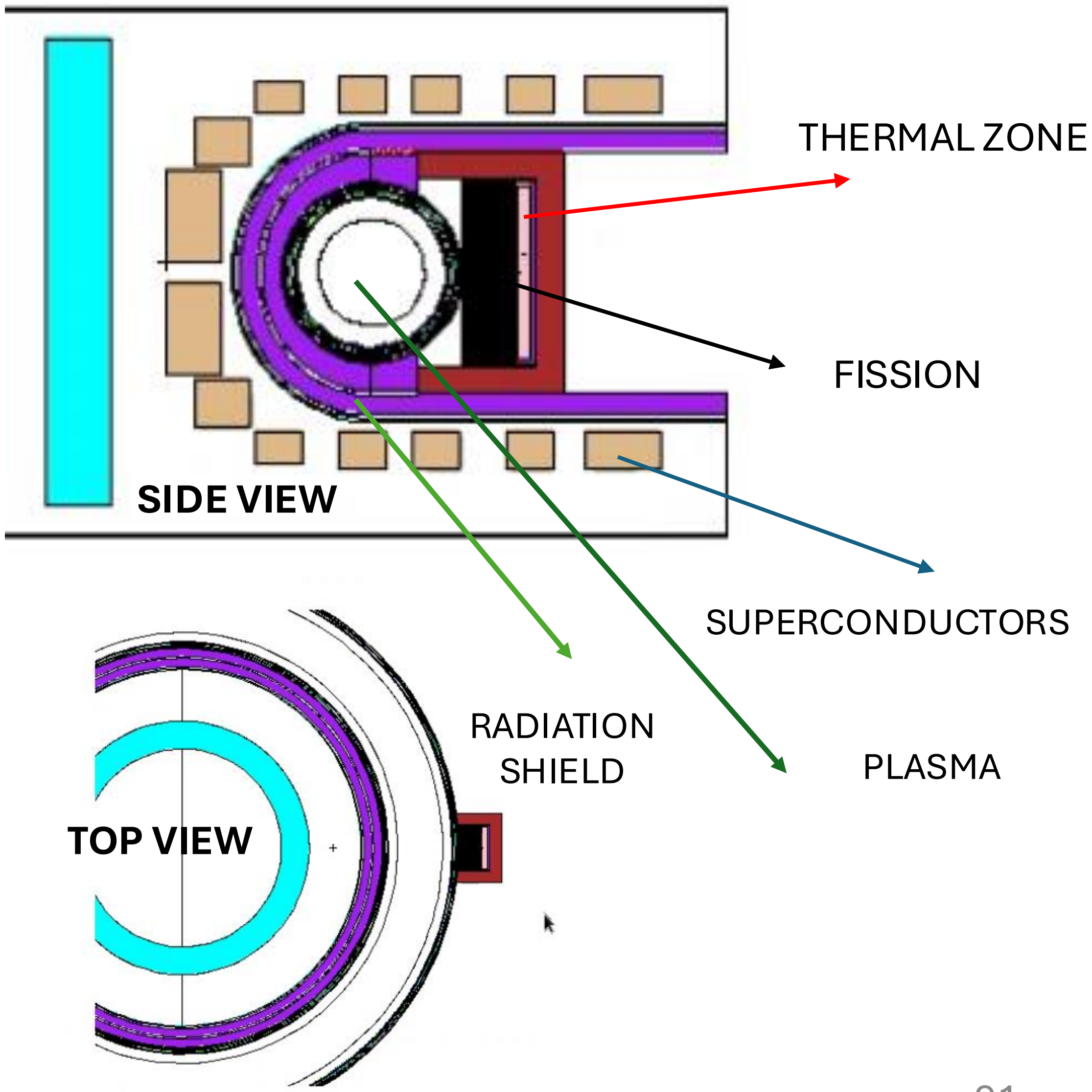


Blanket design

An RFP-based hybrid system concept has been studied (R=6 m, a=0.8 m).
The fission blanket proposed is characterized by a multi-zone design:

- A **fast core** (fuel MOX- cooling fluid Molten salt)
- A **thermal neutron spectrum zone** for **tritium breeding** (FLiBe)





La Cina si allontana

World's first fusion-fission plant aims to generate 100MW nuclear power by 2030

The Xinghuo reactor, a joint venture between China Nuclear Industry 23 Construction Corporation and Lianovation Superconductor, aims for a Q value exceeding 30.

Finanziamento 2.76 Miliardi di $

Ma quale dovrebbe essere il Q sufficiente?

- Un reattore a fusione ha consumo un ordine di grandezza maggiore di uno a fissione
- Fissione 5-7% della produzione di energia elettrica, principalmente pompe per raffreddamento
- Per un reattore a fusione ci sono molti elementi in più
  - Criogenia, 15%, 110 MW
  - Sistemi da vuoto, 2-3% 20MW
  - Riscaldamento ausiliario 15%, 130MW
  - Impianto detriziazione 2% , 15 MW
  - Blanket 15-30% 100-200MW
  - Power supplies, 20 MW
  - Neutroni persi dove depositano loro energia, impianto di condizionamento.....

I consumi allo stato stazionario, quando il plasma è acceso sono dell'ordine di circa 500 MW

Inoltre:

- alla accensione può servire il doppio
- Alternanza fasi acceso fasi spento, 20% del tempo?
- Manutenzione e incidenti, load factor 50%?

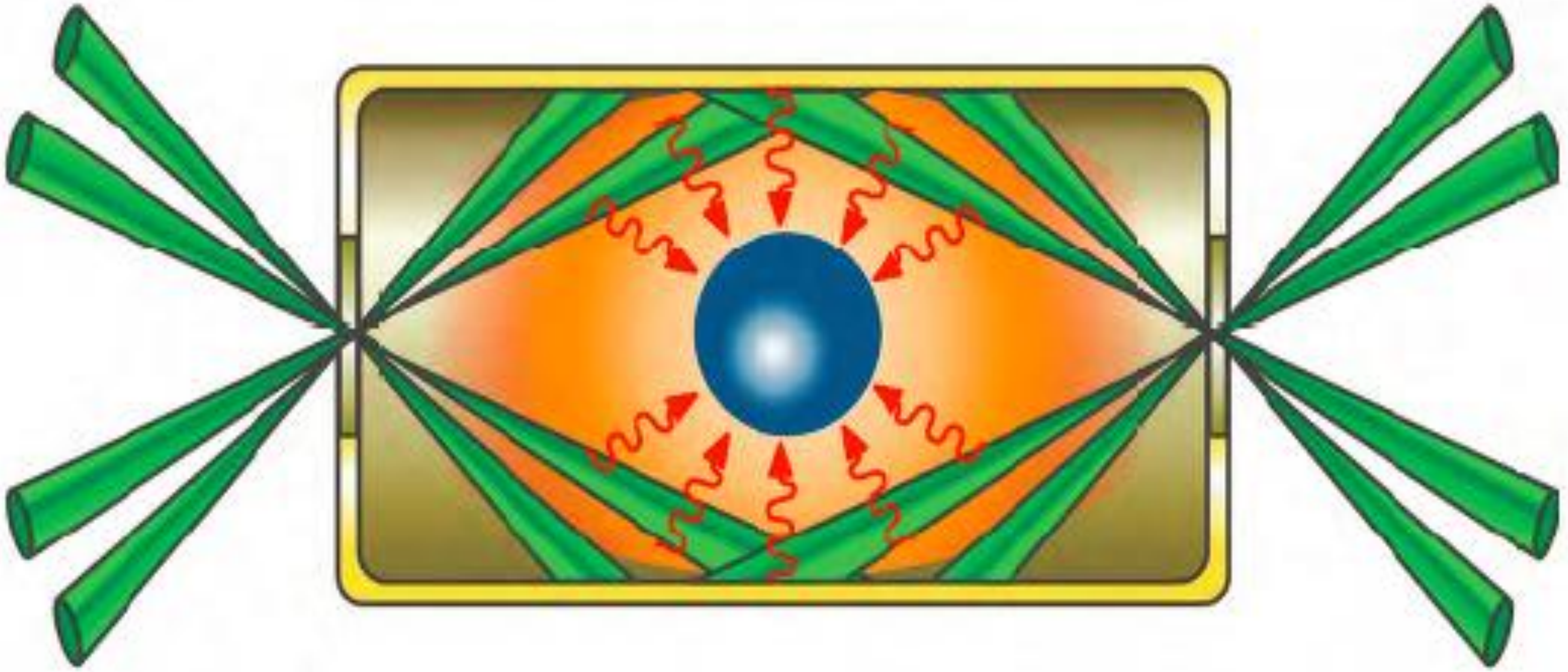
Per mettere in rete 400 MWe ne deve produrre 900MWe. Per 900MWe ne servono almeno 4 GWt, ma i consumi aumentano all'aumentare della potenza termica......

In realtà l'immissione in rete dell'energia andrebbe decurtata del ciclo completo in senso olistico

- ✓ Energia per la costruzione
- ✓ Energia per estrazione e lavorazione dei materiali
- ✓ Energia per il decommissioning
- ✓ Energia per la manutenzione
- ✓ Petrolio consumato nella realizzazione dei lavori (autocarri e ruspe.......)
- ✓ ....

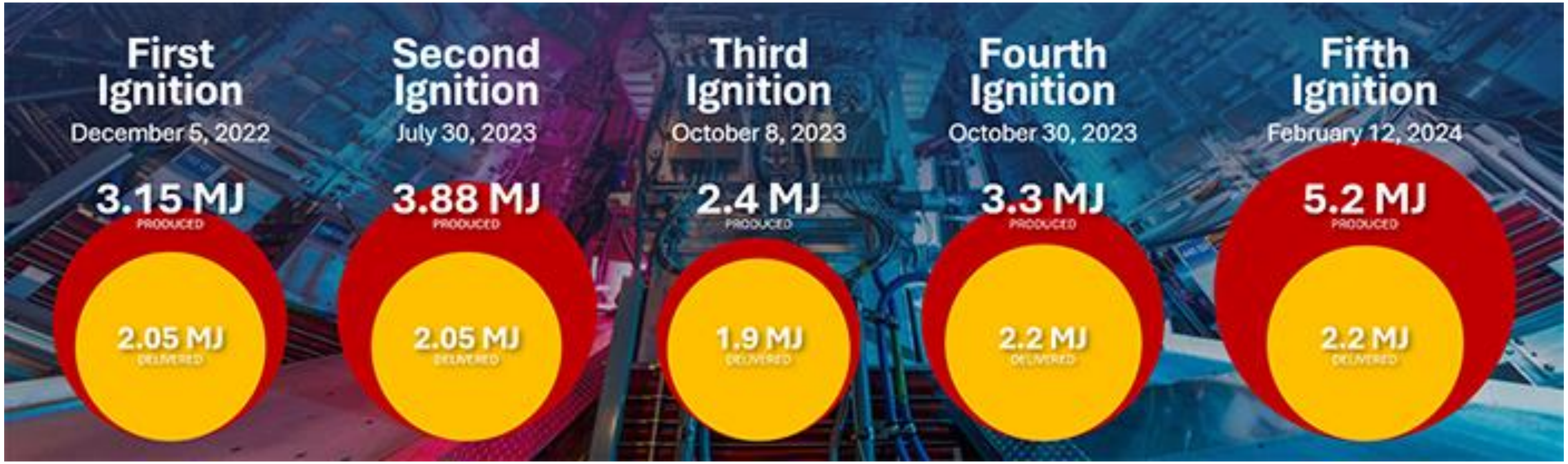
inerziale

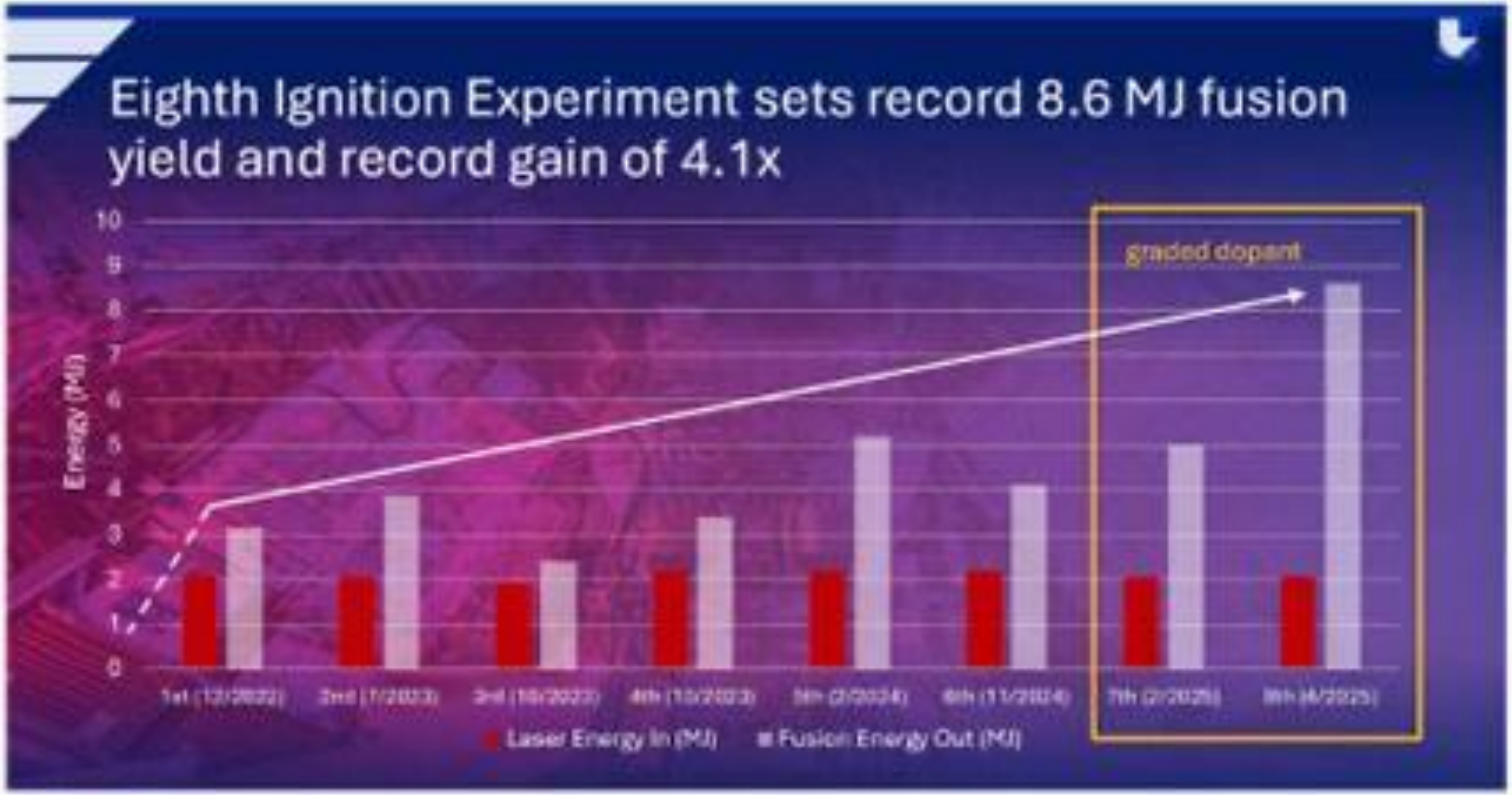
Inerziale: indirect drive



A new starting point: the NIF success from December 2022 up to February 2024

- On December 2022 at the National Ignition Facility (NIF) (Lawrence Livermoore National Laboratories) èan historical result has been obtained; the first time in the world a energy production by nuclear fusion reaction larger than the input energy
- Ignition was experimentally demonstrated; a milestone in the human knowledge
- a gain of 153% was otained
- The result was repeated with increasing values: an increase of 7% in the input energy lead to a 70 % increase of the produced energy, **as forecasted by theoretical model**





A fronte di un incremento dell'1.5% dell'energia in ingresso hanno ottenuto un incremento del 110% (Q=4.1) di energia prodotta. Risultato che conferma ancora di più quanto già visto in precedenza , si sta entrando in un regime di parametri in cui si iniziano ad innescare reazioni a catena.

Si conferma quanto previsto dalla teoria.

Previsto incremento energia dei laser fino a 2.7MJ (+20%) e successivamente 3.0MJ

Materiali microstrutturati (FOAM)
e irraggiamento diretto: miglioramento dell’efficienza

Irraggiamento diretto studi del laser ABC dal lontano 1991:

aumento di un fattore 6 dell’efficienza di trasferimento

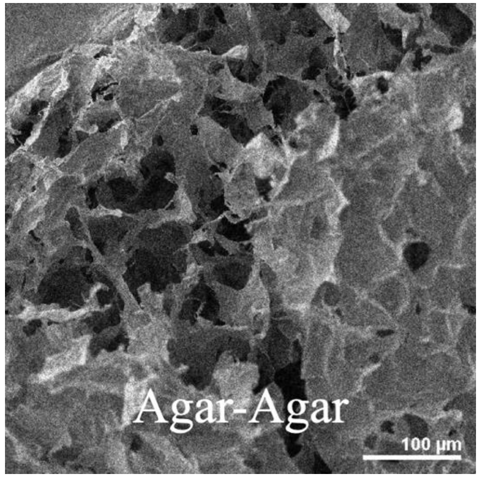
Leadership internazionale

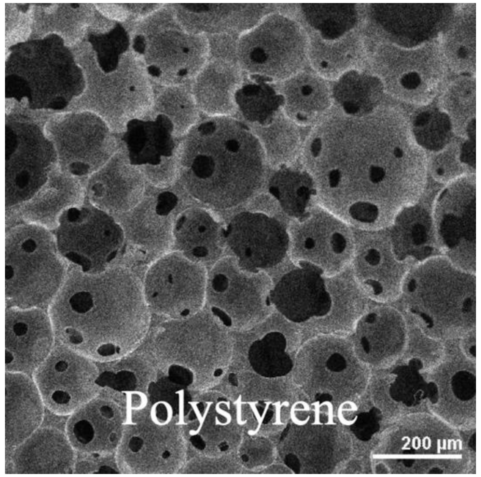
Conduzione dei gruppi europei micro e nano structured materials e progetto Hiper+ (road map europea)

Il tal caso si contorna il bersaglio con una schiuma che uniforma la radiazione con maggiore efficienza di trasferimento energetico.

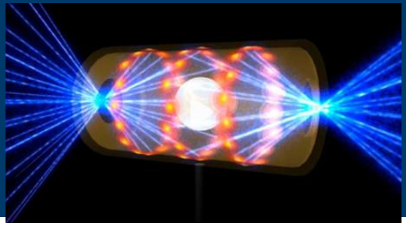
Su ABC, **grazie a raffinato sistema di diagnostiche di elevata accuratezza e numerosità,** si caratterizza il funzionamento di varie schiume;

Produzione mediante stampante 3D





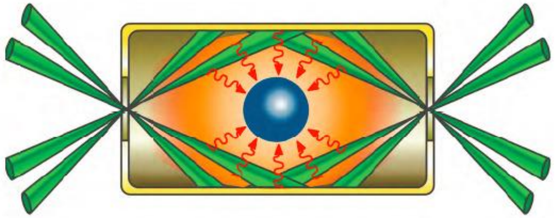
Overall efficiency low



The overall efficiency was quite low of the order of 1% but the facility was designed to obtain ignition (Q=1) not for maximize efficiency and the concept is 30 years old

In order to increase efficiency two roads have to be covered

1. Laser efficiency: in 1982 blue diode realization by Nakamura (nobel prize) shocked the illumination concept; this innovation is transforming laser efficiency of more than one order of magnitude. From 1% to 20-50%
2. Indirect drive (15% efficiency) has to be replaced by direct drive (90% efficiency): study are performed also on the ABC laser
3. Efficienza dell'ordine del 20% è teoricamente raggiungibile, ma già ricomprende le alimentazioni elettriche, non c'è la criogenia, possible funzionamento in continua (10Hz)
4. Le reazioni ottenute sono rappresentative della dinamica reale



Inertial advantages/disadvantages

- No criogenics hundred's MW
- No superconducting magnets
- Un limited space for neutron dumping
- Simpler geometry and machine accessibility
- No dwell time (????)
- Some results, not only forecast
- Higher predictibility
- Increasing interest

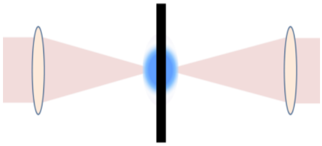
- only indirect drive test
- No developed reactor plan (road map)
- High repetition rate and high power 10 Hz still not technologically achieved
- Exact target positioning critical
- Target manufacturing critical
- Vacuum chamber cleaning extremely critical
- No forecast possible

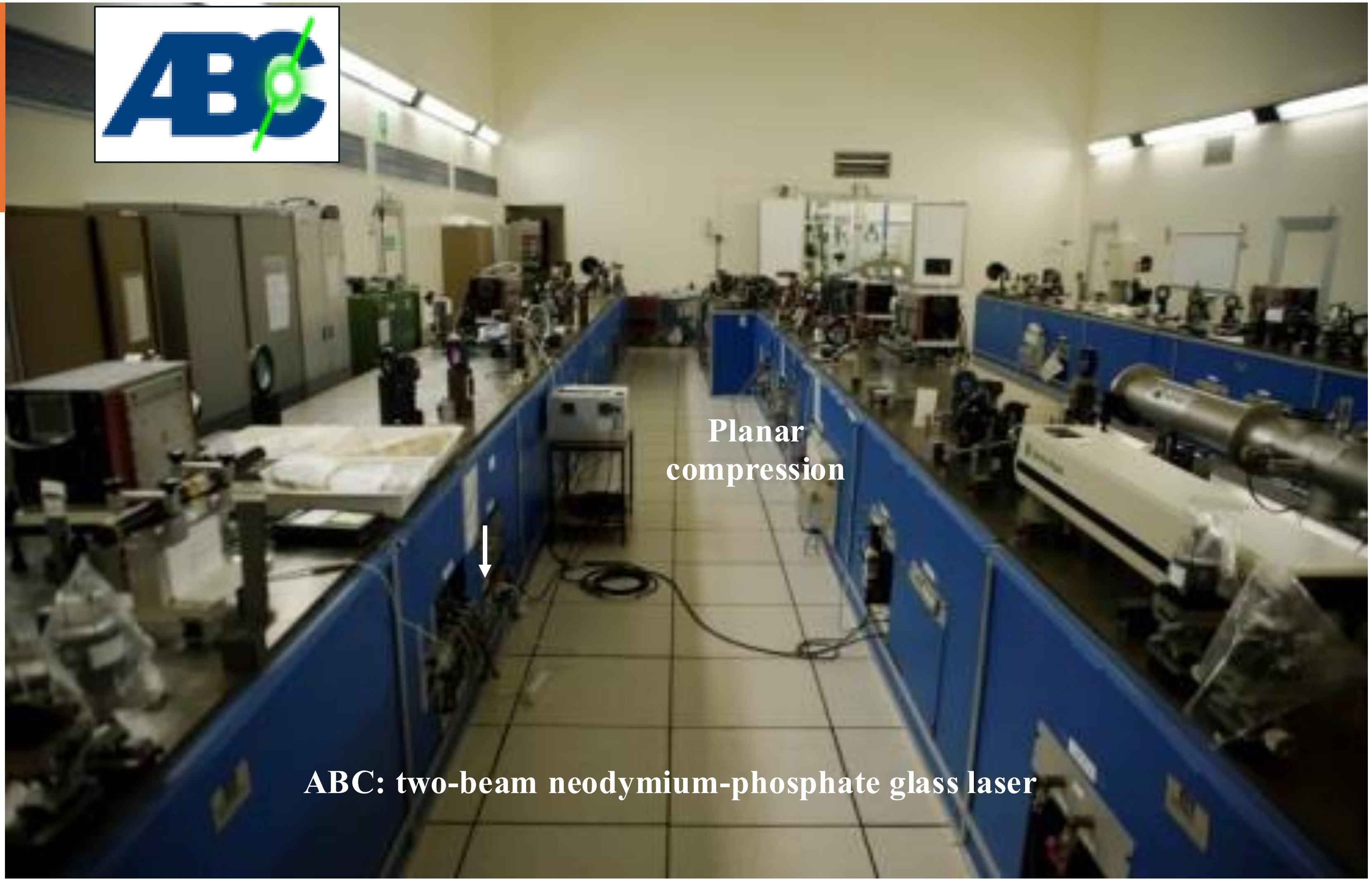
Chi sa fa,
chi sa poco scrive,
chi sa nulla parla.....

Laser ABC dell'ENEA

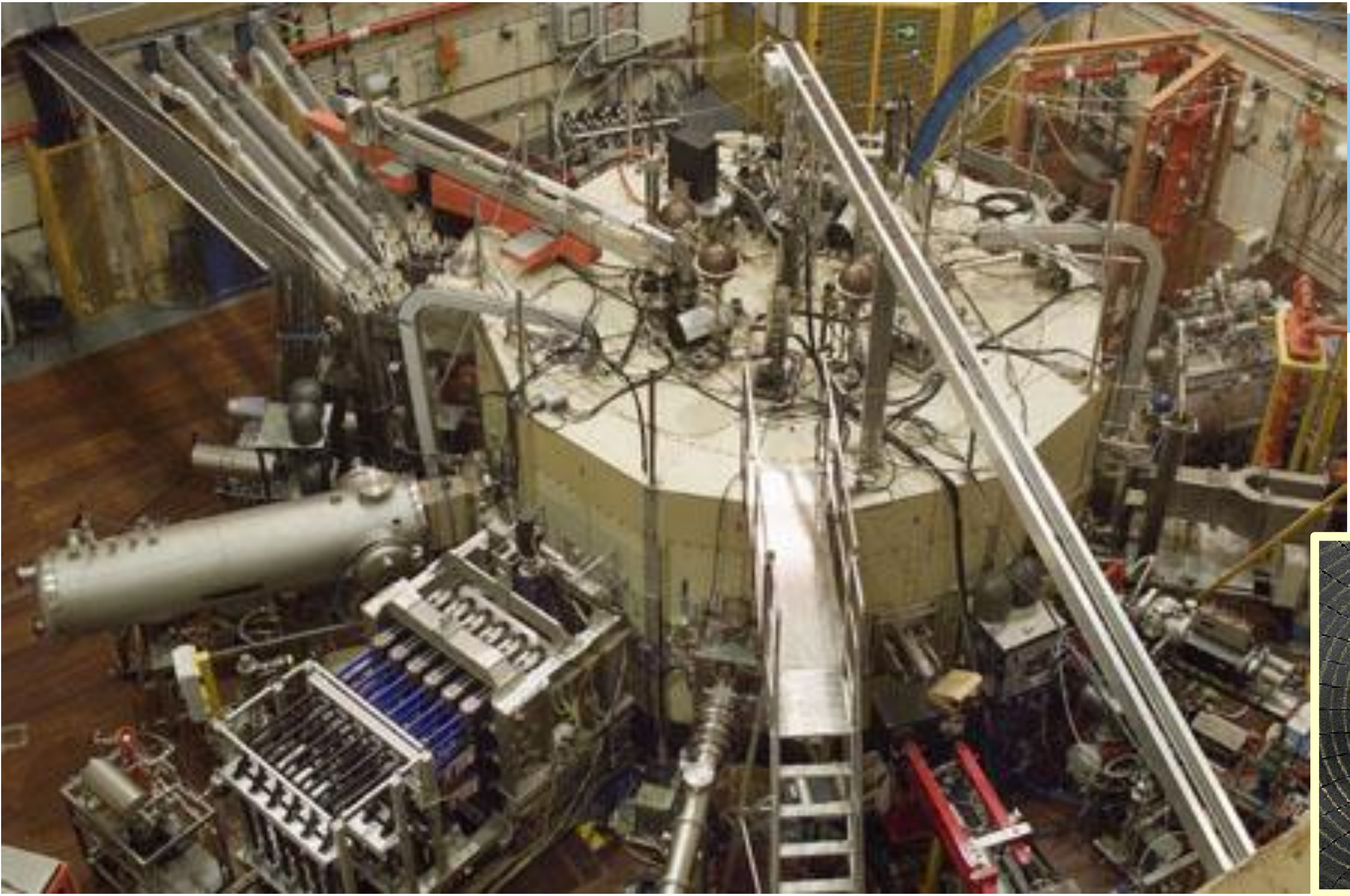
Unico esperimento di fusione nucleare funzionante in Italia

- Laser con la maggiore energia-per-impulso in Italia: 100 J x 2 fasci
- Neodimio vetro fosfato:
  - lunghezza d'onda 1054/527 nm
  - durata 3 ns
  - potenza 30 GW
  - Intensità $2x10^{15}$ Wcm^{-2}
- Notevole numero di **diagnostiche operative**
- Studi di fisica di base in compressione planare, direct drive

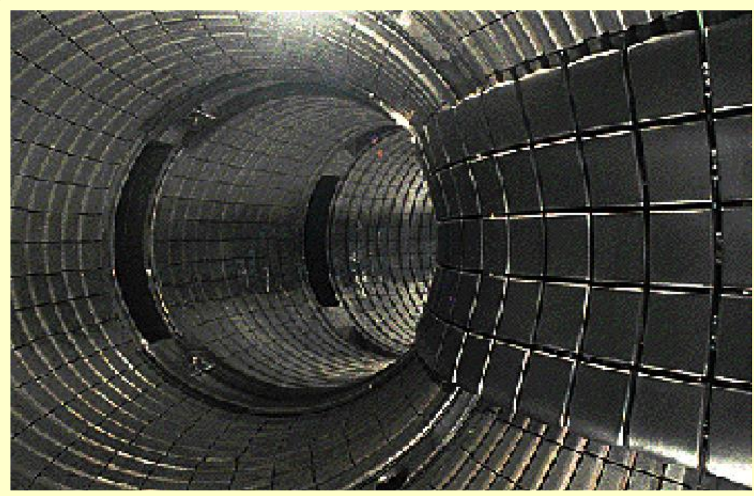




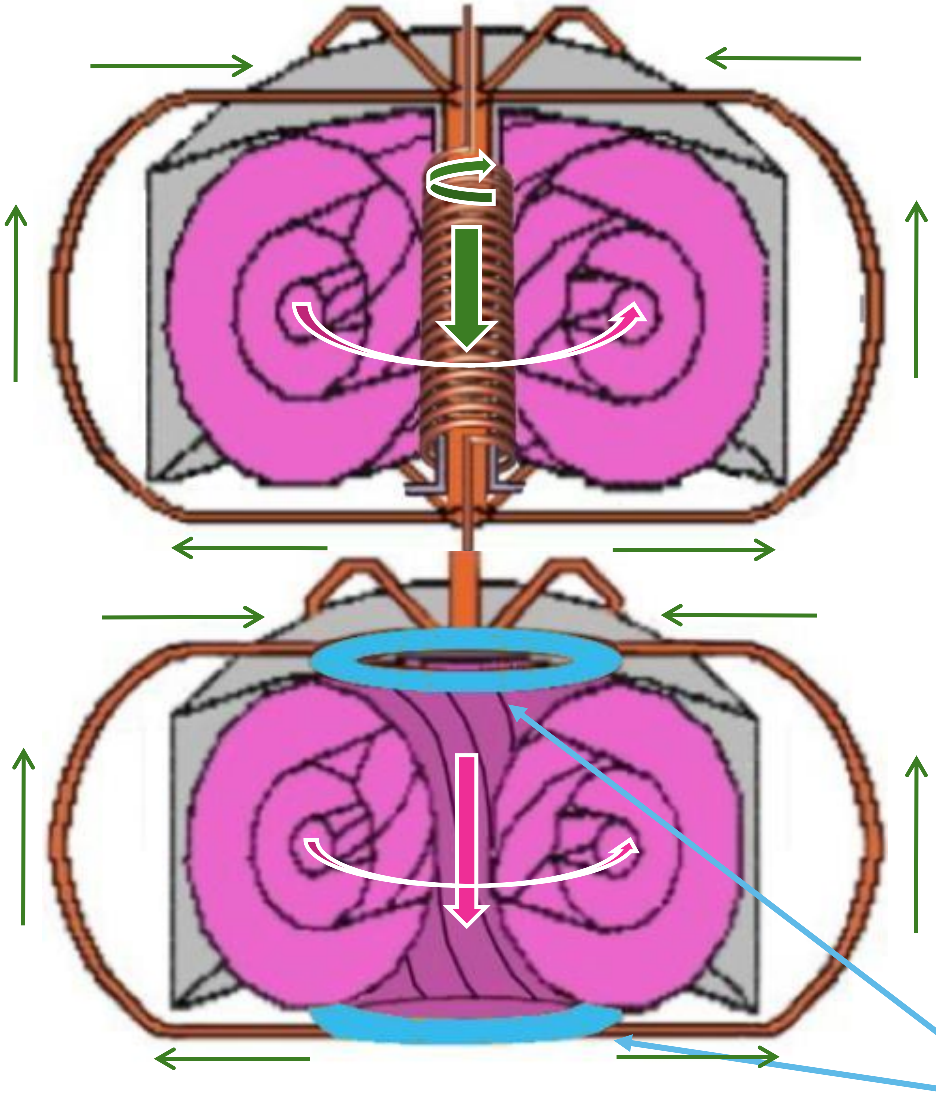
Frascati Tokamak Upgrade (FTU) 1988-2019



- Major radius 0.93 m
- Minor radius 0.3 m
- Magnetic field 2 - 8 T
- Full metal first wall
- TZM toroidal limiter
- Density 6.0 10^{20} m^{-3}



PROTO-SPHERA e il TOKAMAK



Tokamak convenzionale:

superfici magnetiche del plasma toroidale

circondano un "palo centrale metallico"

...geometria toroidale della camera da vuoto

- **PROTO-SPHERA:**

superfici magnetiche del plasma toroidale

circondano un "palo centrale di plasma"

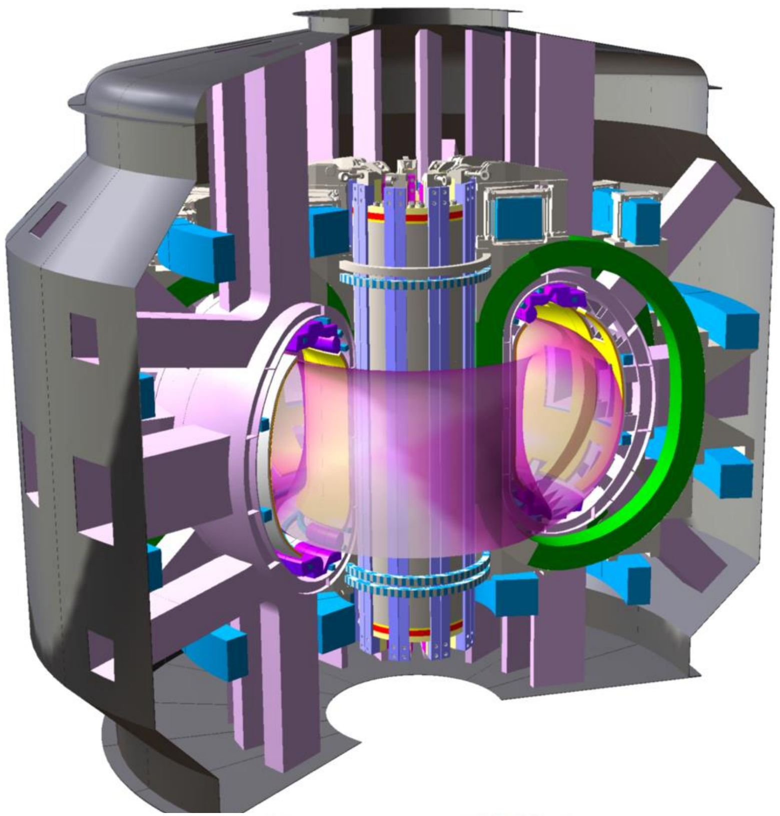
sottili gambe di ritorno chiudono la

corrente elettrica all'esterno (senza magneti toroidali)

...geometria cilindrica della camera da vuoto

...elettrodi necessari entro la camera da vuoto

The DTT proposal



First plasma expected 2032

Superconducting tokamak
Under construction at ENEA Labs, in Frascati

Member of EUROfusion

Conclusioni generali

- Che Madre Natura abbia scritto le proprie regole prevedendo la possibilità per l'umanità di avere produzione industriale di energia da fusione nucleare sulla terra, ad oggi, non è dato sapere
- Se poi ciò possa avvenire in ciambelle cave mediante confinamento magnetico o in pasticche compresse da radiazione, non è noto
- **Bisogna dimostrare che è possibile accendere un plasma e mantenerlo acceso per periodi molto lunghi;** Servono esperimenti per provare a riuscire a capire quali possano essere i parametri di un plasma potenzialmente idoneo a produrre energia in grandi quantità, in modo stabile sicuro ed efficiente
- **Il trizio non esiste, il suo reperimento è particolarmente difficoltoso, è radiottivo e difficilmente maneggiabile**
- **Il blanket è un componente complesso , costoso poco durevole, intrinsecamente poco efficiente e il cui funzionamento è da dimostrare**
- **Che il divertore sia idoneo ad espellere le ceneri della reazione, ovvero l'elio in modo compatibile con il mantenimento del cuscino di gas necessario ad evitare il contatto diretto del plasma con il divertore (detachment) , con l'asportazione delle impurezze, con il bilancio del deuterio e del trizio, non stato verificato**
- **I carichi termici sul divertore non sono sostenibili**
- **Seri problemi di sicurezza e licensing si affronteranno con il crescere della potenza delle macchine**
- **La complicazione è tale da far dubitare su una accettabile grado di affidabilità**

Conclusioni generali 2

- I materiali ad oggi non sono stati provati alle fluenze di neutroni previste, che ne esistano di idonei non è dato sapere
- Il costo di un tokamak ad oggi è concettualmente neanche confrontabile con la produzione di energia elettrica da fissione
- L'efficienza globale dell'impianto deve essere notevolmente aumentata, ad oggi sembrerebbe in forse la produzione netta di energia in quantità accettabili con l'investimento necessario, questo sembra contrastare con l'uso della criogenia
- Qualunque previsione sui tempi si è rivelata sempre sbagliata
- Una eccessiva esaltazione di risultati modesti e banalizzazione di una sfida enormemente complessa non giova alla credibilità della comunità scientifica: gli scienziati si devono distinguere per una informazione corretta e realistica
- Il grande flusso di soldi in arrivo è benvenuto e può, nell'immediato portare a dei benefici, ma potrebbe essere nel medio termine un boomerang
- **La corsa verso la fusione è una maratona, che va corsa a passo di marcia, tenendo sempre un piede per terra**

Commenti benvenuti

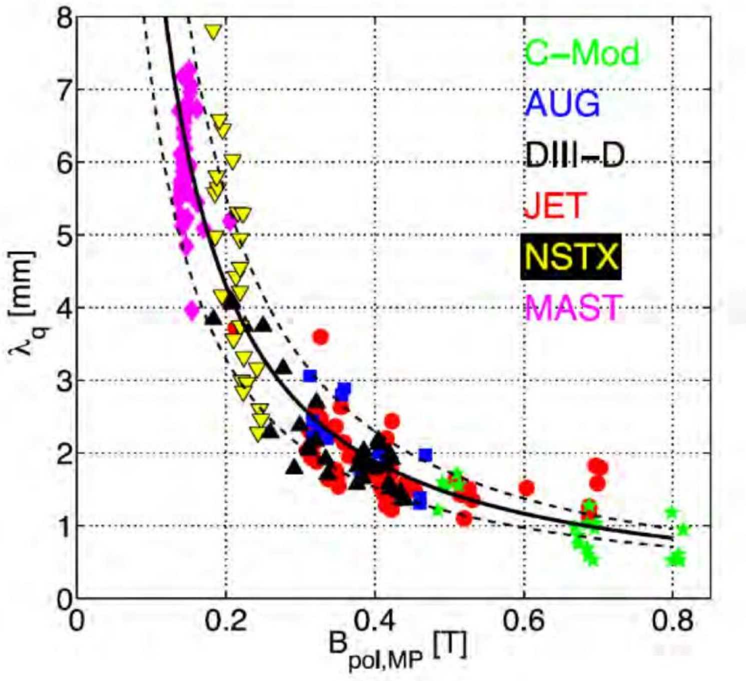
Grazie

Fusion Roadmap: SOL (Scrape-Off Layer)

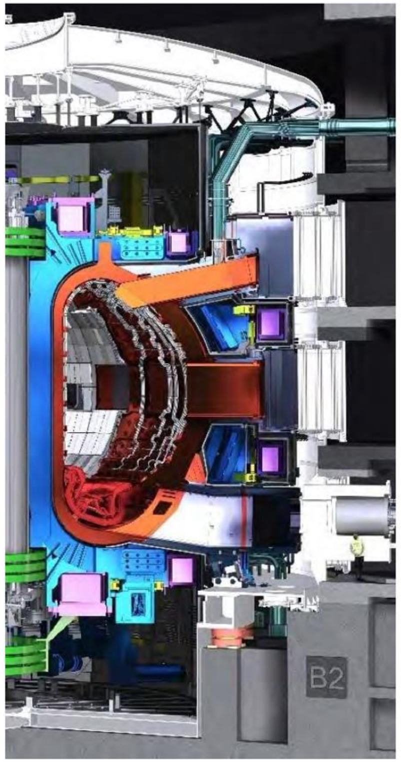
From a multimachine scaling of the upstream heat flux width the SOL power flow decay length scales as: $\lambda_q \propto B_{pol}^{-1}$ and does not depend on R

Power flux $q_\vartheta = {}^{P}/_{2\pi R \lambda_q} \propto \frac{P}{R}$

for ITER and DEMO:
$\lambda_q \approx 1\ mm$, P/R ≈ 15 MW/m



T.Eich. et al. NF 53 (2013) 093031



Effective surface 1-2 m^2

Power flux: tens of MW/ m^2

Q vero

- Il Q scientifico perde senso
- Il Q ingegneristico deve essere olistico

	P_{SOL} (MW)	λ_q (mm)	R (m)	$q_{//}$ (GW/m^2)	q_{pol} (GW/m^2)
JET	~30	~3.5	~3	~0.7	~0.2
ITER	~90	~2	~6	~1.8	~0.6
DEMO*	~150	~1	~9	~5	~2

Figure 3. Divertor heat exhaust challenge in a tokamak: P_{SOL} is the total power flowing in the SOL channel, λ_q is the decay length of the heat flow at the outboard midplane, R is the major radius, $q_{//}$ is the heat flow parallel to the magnetic field, q_{pol} is the poloidal component of the heath flow.

TABLE 2-I
DEVICE AND PLASMA PARAMETERS FOR DEMO, ITER, DTT AND THE MAIN EXISTING EUROPEAN TOKAMAKS [2.44],[2.44].
ASSUMPTION: ¶P_{SEP}=0.8*P_{EFF}

		DEMO	ITER	DTT	JET	AUGD	MAST-U	TCV	WEST
Major radius	R (m)	8.77	6.20	2.15	2.98	1.65	0.8	0.88	2.50
Minor radius	a (m)	2.83	2.00	0.70	0.95	0.50	0.60	0.24	0.5
Toroidal field	B_t (T)	5.80	5.30	6.0	3.20	2.40	0.84	1.45	3.7
Plasma current	I_P (MA)	20.3	15.0	6.0	3.50	1.50	2.00	0.45	1
Elongation	k	~1,6	~1.8	~1.8	1.7	1.6	<2.5	<2.2	1.4
Aspect ratio	$A = \varepsilon^{-1}$	3.1	3.1	3.1	3.1	3.3	1.3	3.7	5
Average atomic mass	$\bar{A}$	2.5	2.5	2	2	2	2	2	2
Heating power	P_{heat} (MW)	450	120	45	35	27	7.5	2.5	16
Effective heating power	P_{eff} (MW)	300	100	45	35	27	7.5	2.5	16
Power across LCFS	P_{sep} (MW)	150÷200	87	36¶	28¶	21.6¶	6.0¶	2.0¶	12.8
	P_{sep}/R (MW/m)	17.1÷23	14	16.7	9.4	13.1	7.5	2.3	5
Average temperature	$\langle T \rangle$ (keV)	12.5	8.5	6.2	3.4	2.5	3	0.9	2
Average electron density	$\langle n_e \rangle$ (10^{20}m^{-3})	0.9	1.0	1.7	0.9	0.9	1.0	0.8	0.8
Normalised ion gyroradius	ρ_* (10^{-3})	1.6	2.0	3.8	4.0	8.5	22	17	5.0

Table 1. P_{fus} as calculated by different transport models for a representative EU-DEMO design point. Small variations in H can lead to large variations in P_{fus}. Data from [26].

	P_{fus} (GW)	W_{th} (GJ)	$H_{98(y,2)}$
QuaLiKiz [21, 22]	3.0	1.45	1.00
TGLF-SAT0 [27]	2.4	1.3	0.99
TGLF-SAT1 [28]	2.0	1.2	0.98
TGLF-SAT1geo [29]	1.7	1.1	0.94
TGLF-SAT2 [30]	1.6	1.05	0.89

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Quanti neutroni

- 1MeV= 1.6 10^{-13} Joule, 15 MeV =2.5 10^{-12}
- 1GW*1 s =1GJoule
- 10 ^{21} reazioni/s = 2.5 10^{9} W

- =10 ^{21} neutroni