Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

"Produrre l'Energia del Futuro"

Le ricerche sulla fusione nucleare: ITER, DTT

*Roma SAN **PIETRO IN VINCOLI, aula del Chiostro 12/04/2019***

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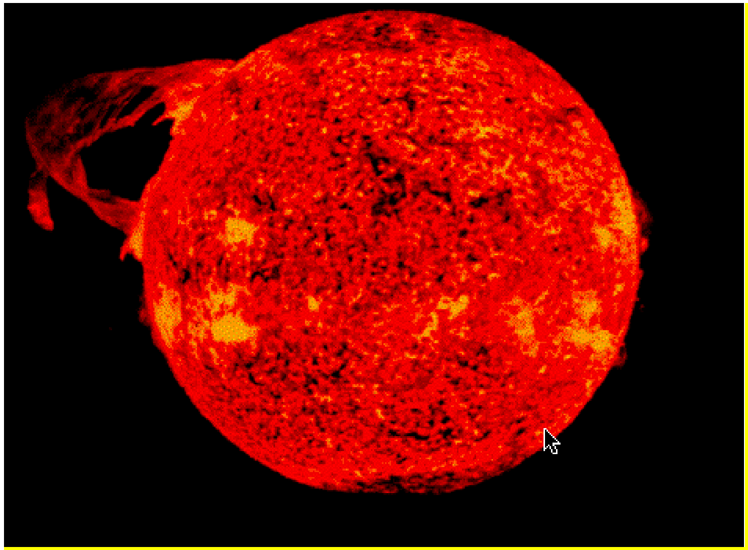
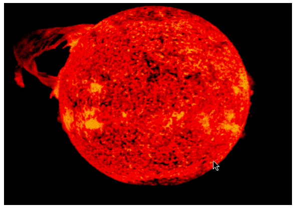
LA RICERCA E L'INDUSTRIA PER LA NUCLEAR YOUNG GENERATION


Portare l’energia delle stelle
sulla terra
Perché ?



Perché la fonte di energia del **sole** e delle altre stelle sono le **reazioni nucleari di fusione**

Ogni secondo nel sole circa 700 t di H si trasformano in He. Queste reazioni producono 4×10^{26} watt (!) di cui meno di un miliardesimo cade sulla terra.

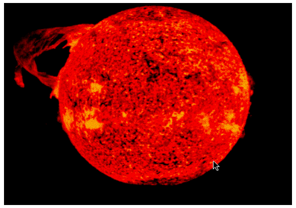


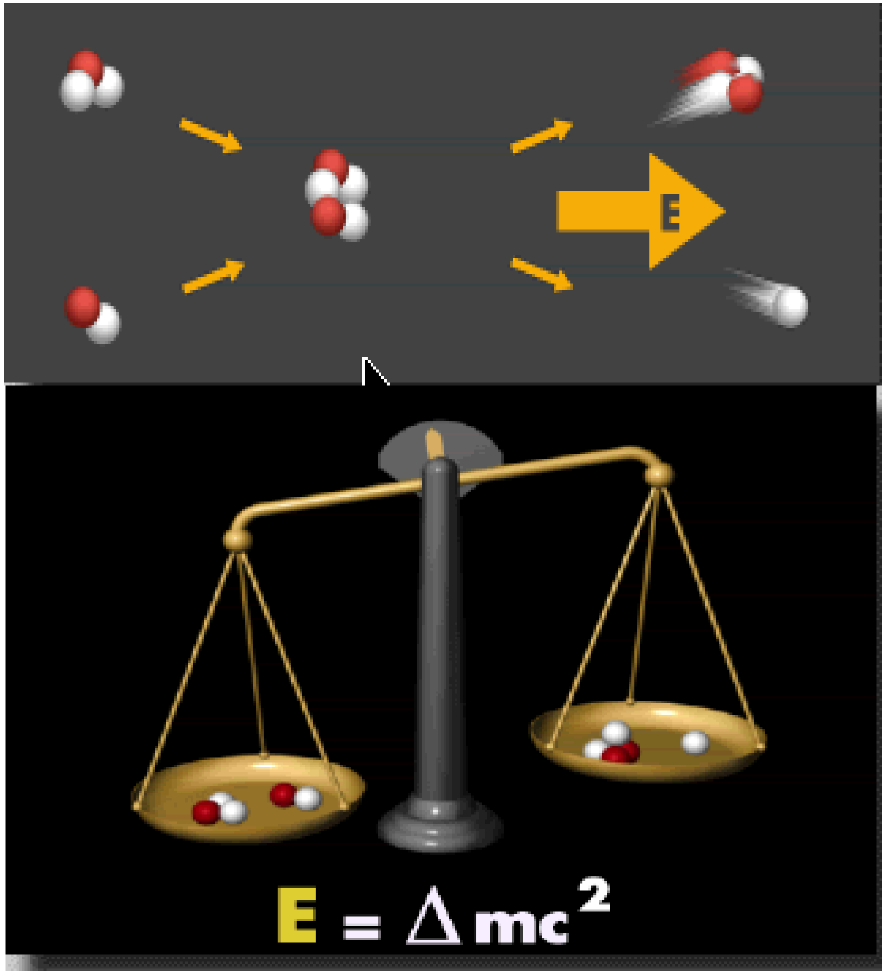
Fonti Energetiche :

- Solare
- Idroelettrica (evaporazione)
- Eolica (riscaldamento atmosfera)
- Combustibili fossili, biomasse (fotosintesi)

hanno origine dalle

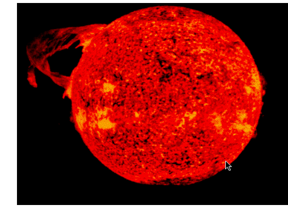
Reazioni di Fusione





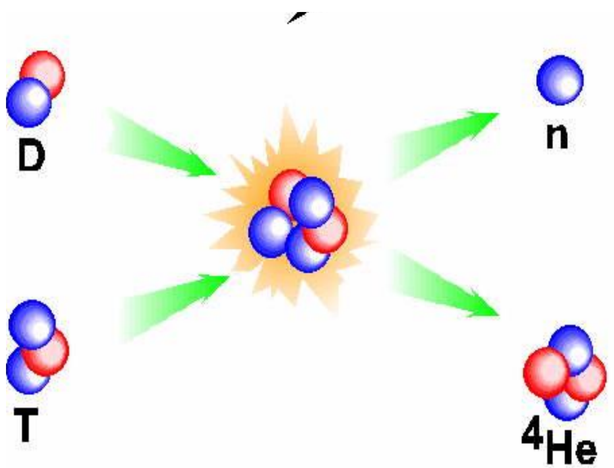
La reazione di Fusione

La **fusione nucleare** é il processo nel quale nuclei di elementi leggeri si fondono insieme per formare nuclei più pesanti con un difetto di massa che viene trasformata in energia secondo la legge di Einstein **$E=mc^2$**



La reazione di fusione su cui sono attualmente concentrati gli studi è:

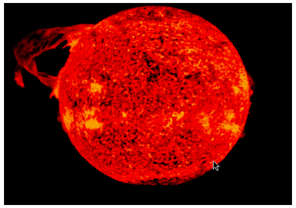
D + T -----> ^{4}He(3.5 MeV) + n (14.1 MeV)



Il Deuterio è contenuto nell'acqua
Il Trizio si produce dal Litio con la Reazione

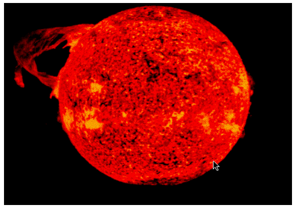
^{6}Li + **n** --> ^{4}He + **T**

^{7}Li + **n** --> ^{4}He + **T** + n



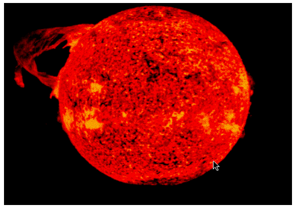
I Vantaggi della fusione

- E’ una fonte di energia che utilizza combustibili che sono abbondanti ed ampiamente disponibili in tutto il mondo.
- Il Deuterio contenuto nell’acqua di mare é sufficiente per trecentomilamilioni di anni
- Il litio, abbondante sulla terra e negli oceani, é sufficiente per circa 2000 anni



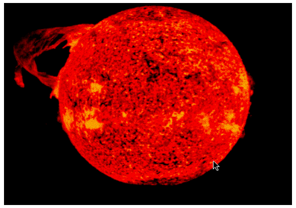
I Vantaggi della fusione (continua)

- La fusione non produce gas responsabili dell'effetto serra (CO_2) o le piogge acide (SO_2, NO_2)
- I reattori a fusione sono intrinsecamente sicuri: eventi tipo Cernobyl o Fukushima non sono fisicamente possibili e anche nel caso di maggior incidente non sono necessarie misure di evacuazione per la popolazione



I Vantaggi della fusione (continua)

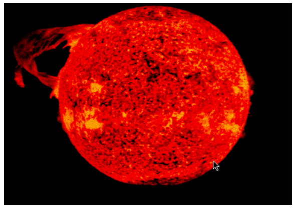
- I combustibili non sono interessati da problemi di proliferazione nucleare
- Le reazioni di fusione non producono scorie radioattive però...

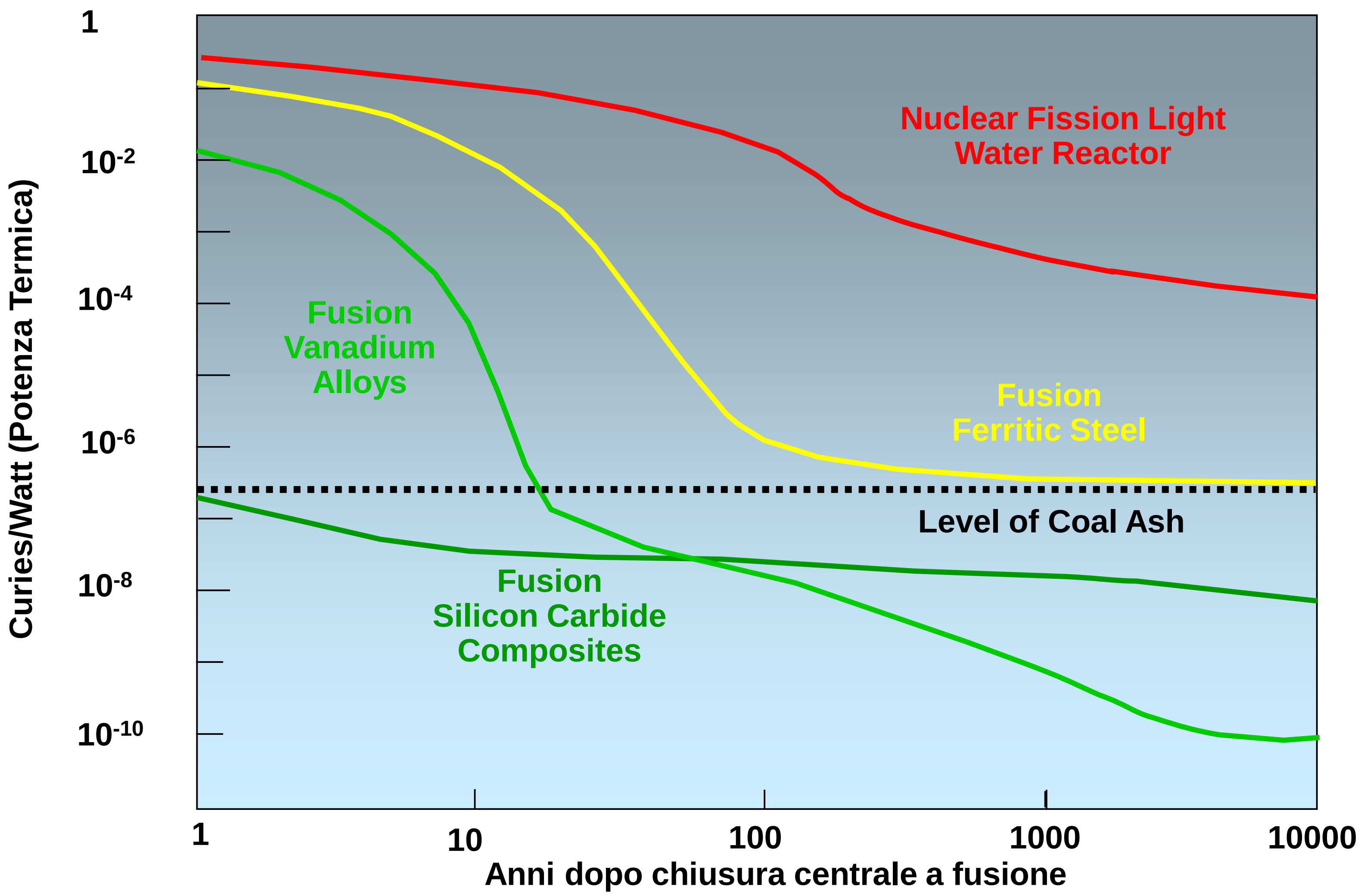


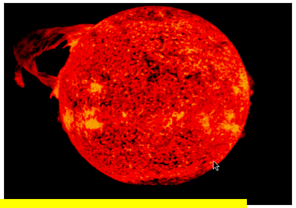
I Vantaggi della fusione (continua)

… la struttura della macchina a causa dei neutroni prodotti diventerà radioattiva. Questo effetto può essere minimizzato con una accurata scelta di materiali a bassa attivazione che, dopo un tempo inferiore a cento anni, non costituiranno più un pericolo. In questo modo le future generazioni non erediteranno scorie che devono essere depositate in luoghi sicuri per secoli.

Basso Impatto sull'ambiente

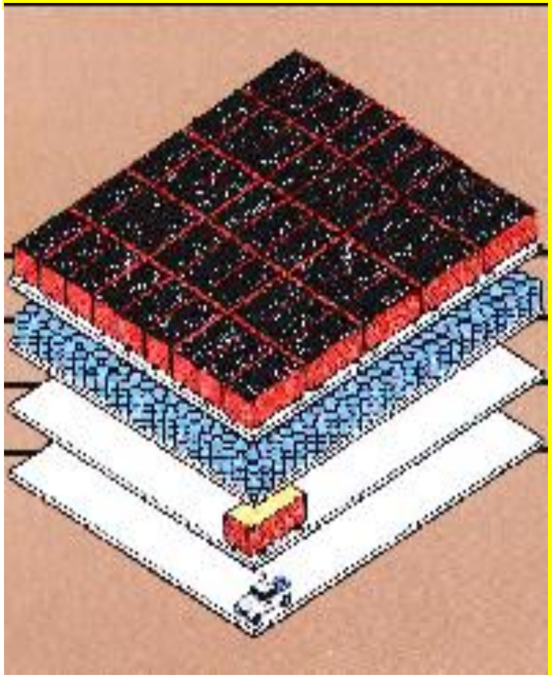






I Vantaggi della fusione (continua)

Le reazioni di fusione liberano una quantità enorme di energia

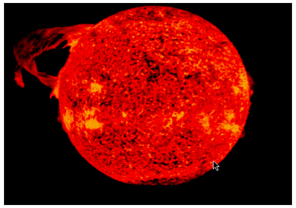


Carbone 2.000.0000 Tonnellate

Petrolio 1.300.000 Tonnellate

Ossido di Uranio 30 Tonnellate

Deuterio 0.25 Tonnellate



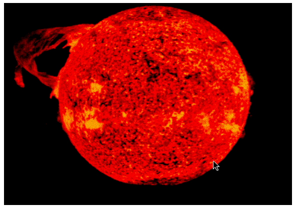
I Vantaggi della fusione (continua)

10g D da 500 l di acqua + 15g di T

Forniscono ad un cittadino europeo l'elettricità di cui ha bisogno durante **tutta** la sua vita

e

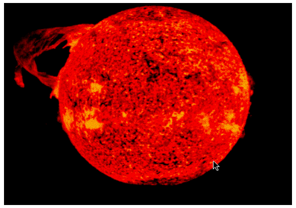
può ancora bere 500 litri di acqua!!!

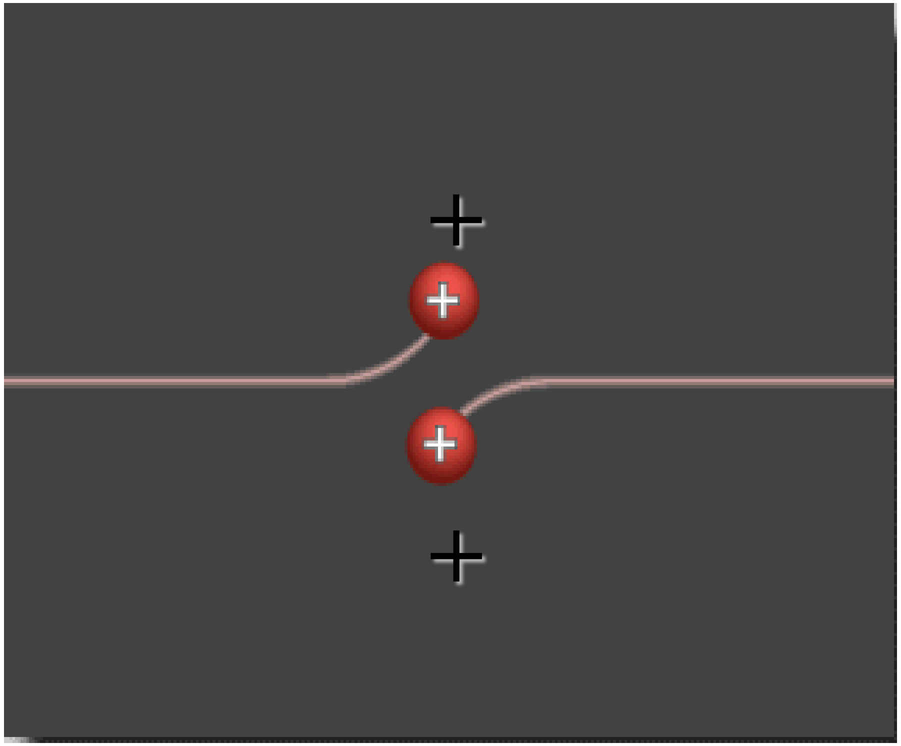


Gli **Svantaggi** della fusione

- I reattori a fusione sono tecnicamente complessi e richiedono un alto investimento di capitali

- I progressi scientifici sono stati molto rapidi ma per un reattore commerciale é richiesto ancora molto tempo (almeno 30 anni)

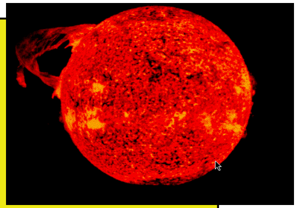


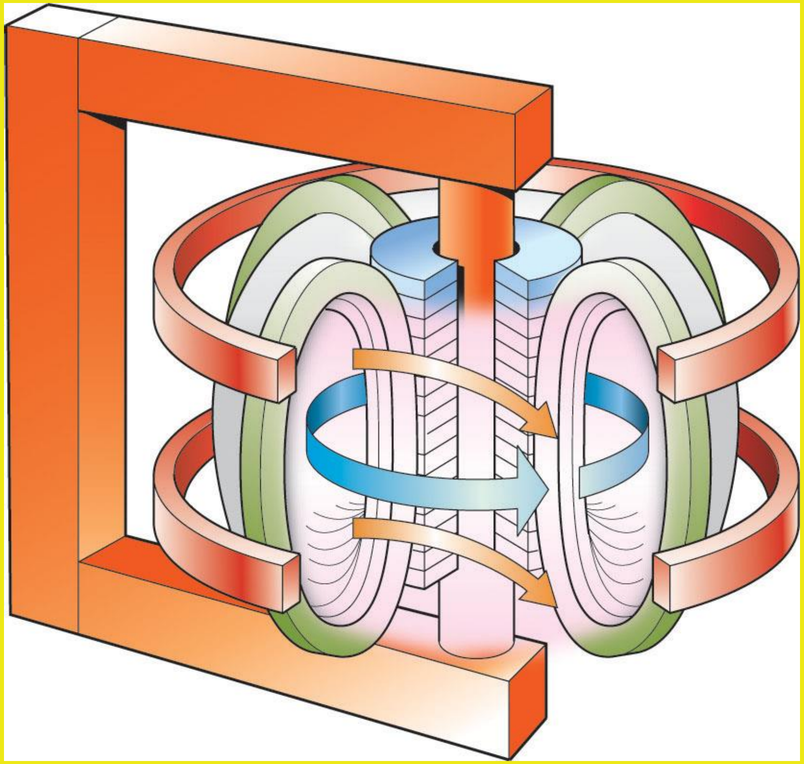


I Principi fisici

Per portare a contatto di fusione i nuclei del D e del T - **ambedue carichi elettricamente** - bisogna superare la repulsione elettrostatica

IL Tokamak

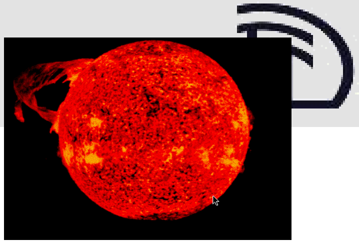


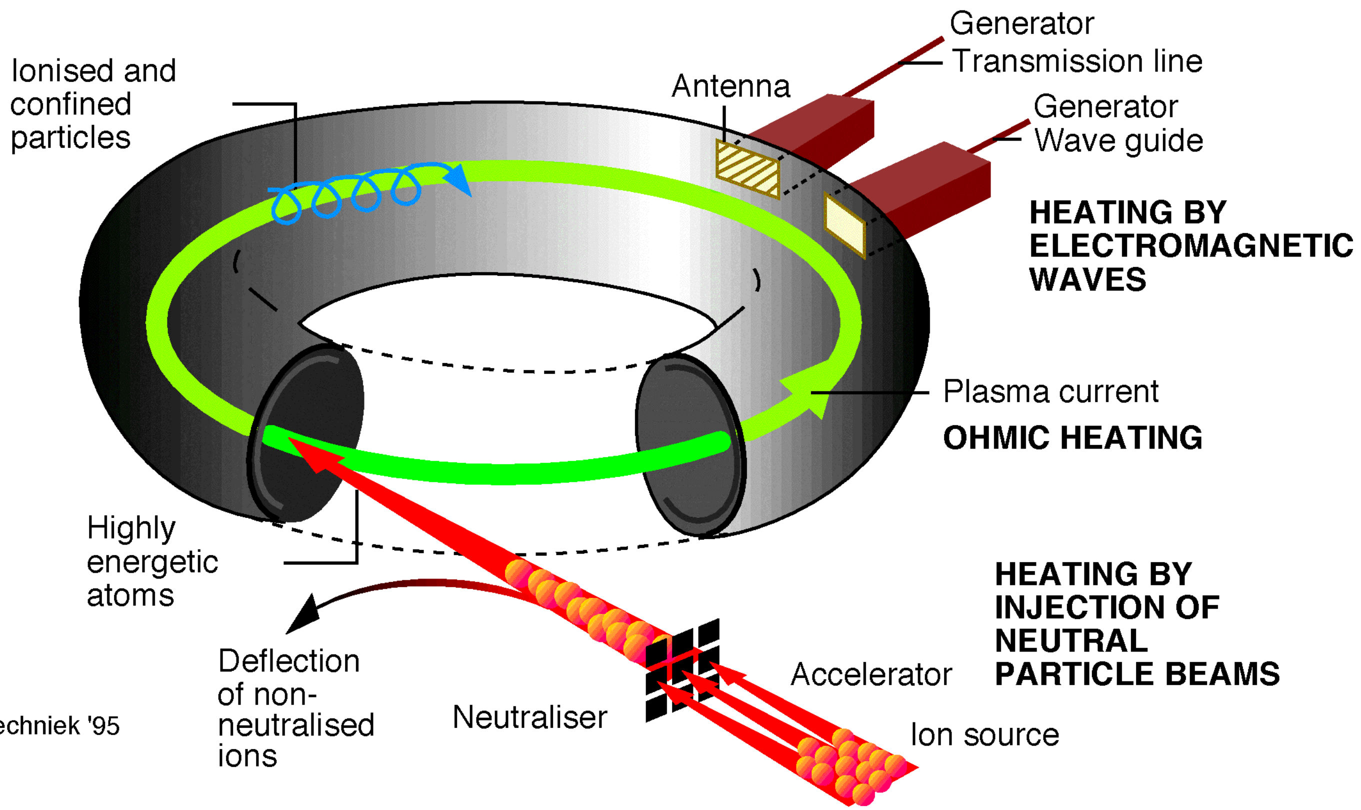


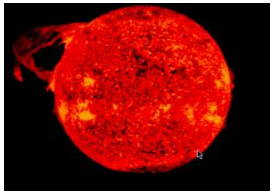
Russo: Toroydal'naya Kamera i Magnitnaya Katushka

Camera toroidale con bobine magnetiche

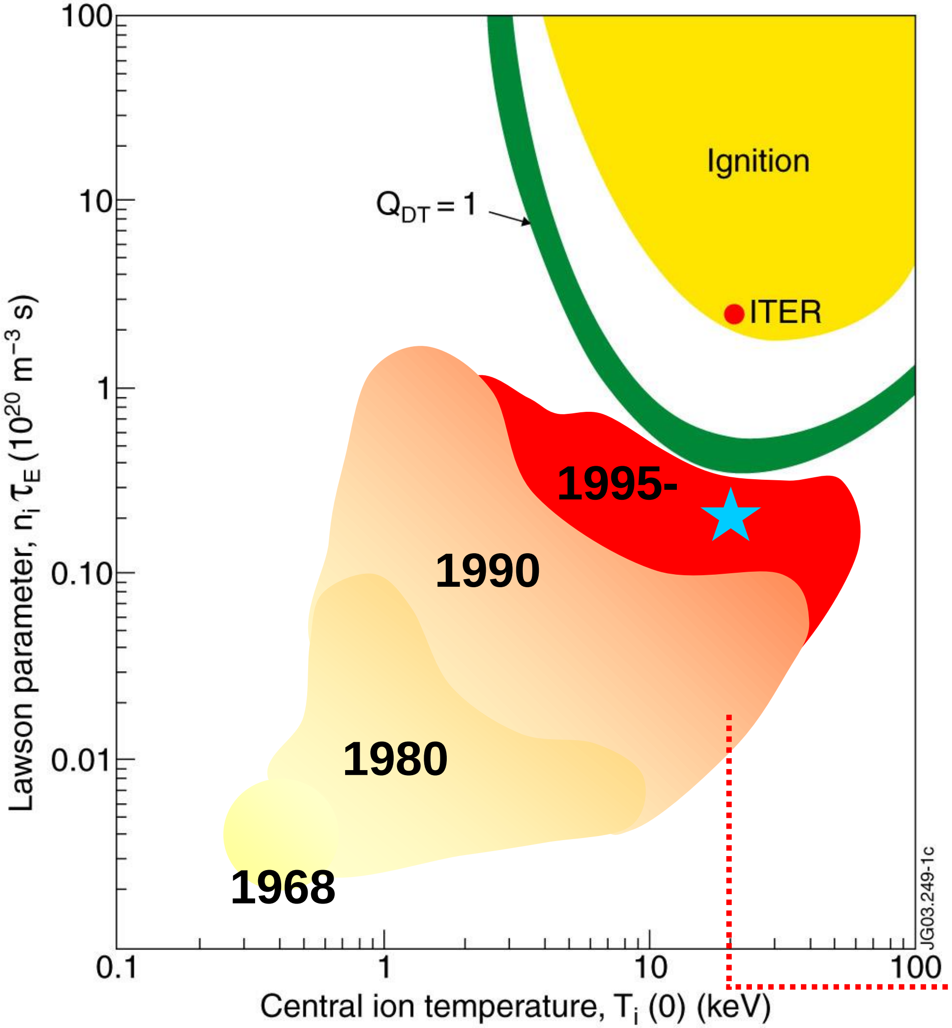
Riscaldamento del plasma







Progressi nelle Ricerche sulla Fusione



$$n \times \tau_E \times T > 10 \text{ bar s}$$

$Q = P_{fusion} / P_{input}$

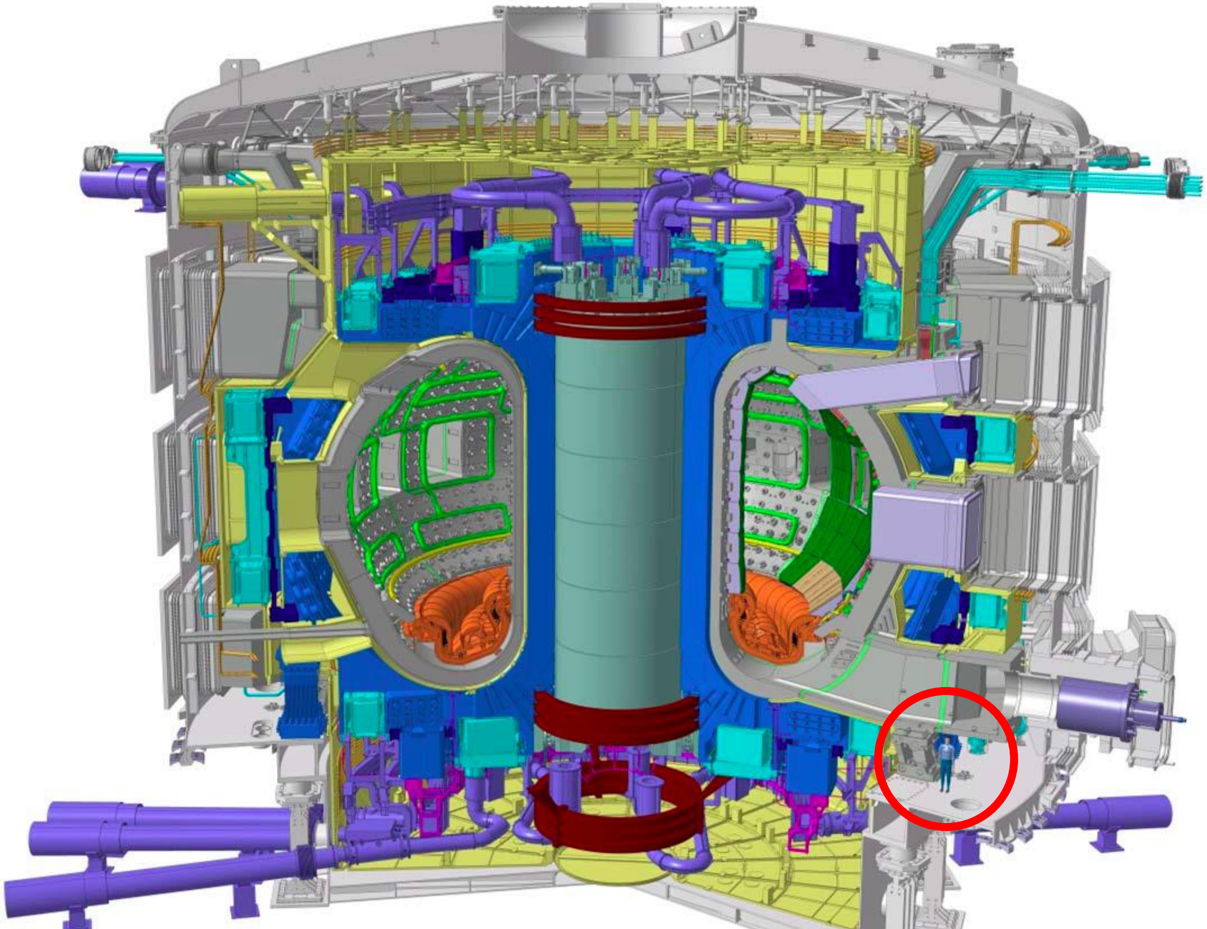
Ignition → $Q = \infty$

Breakeven → $Q = 1$

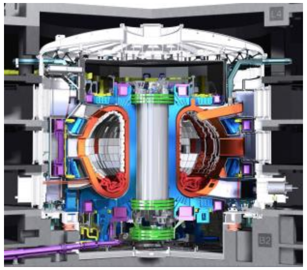
JET (1997) → $Q = 0.65$

T ~ 200 million degrees

ITER



ITER



ITER è una collaborazione internazionale per costruire il primo esperimento scientifico capace di produrre un plasma che si auto-sostiene e di produrre energia dalle reazioni di fusione. **P≥500 MW, Q≥10**

La missione di **ITER** è dimostrare la fattibilità tecnico-scientifica della fusione nucleare per la produzione di energia

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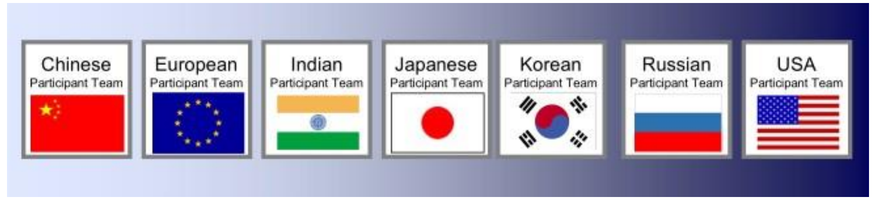
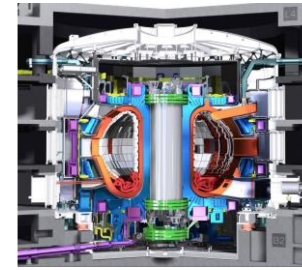
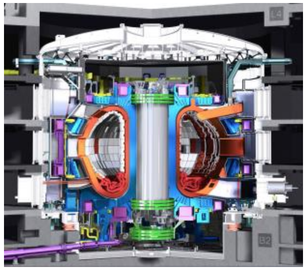
I Partners di ITER







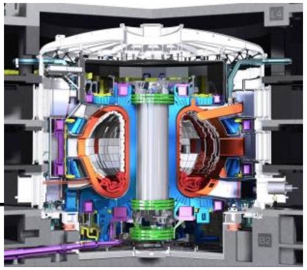
ITER

ITER sarà un macchina nucleare: 1.5 X 10^{20} neutrons/s

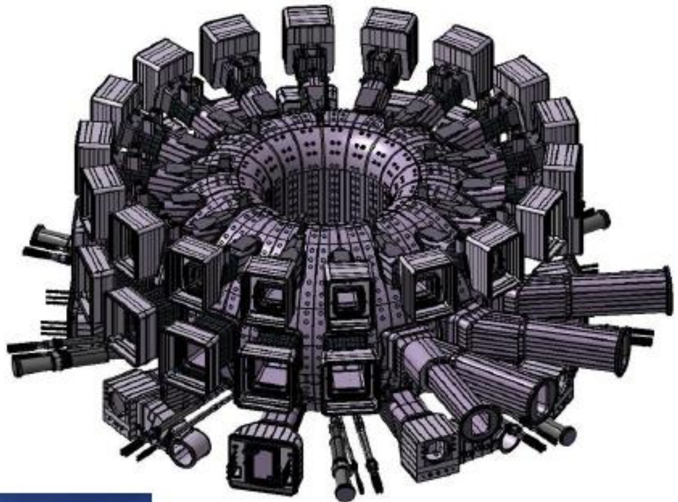
Tokamak	B(T)	Ip (MA)	Vol (m^3)	R(m)
FTU	8	1.6	1.5	0.935
JET	3.5	5	100	3.1
ITER	5.3	15	840	6.2
DTT	6	5.5	33	2.11

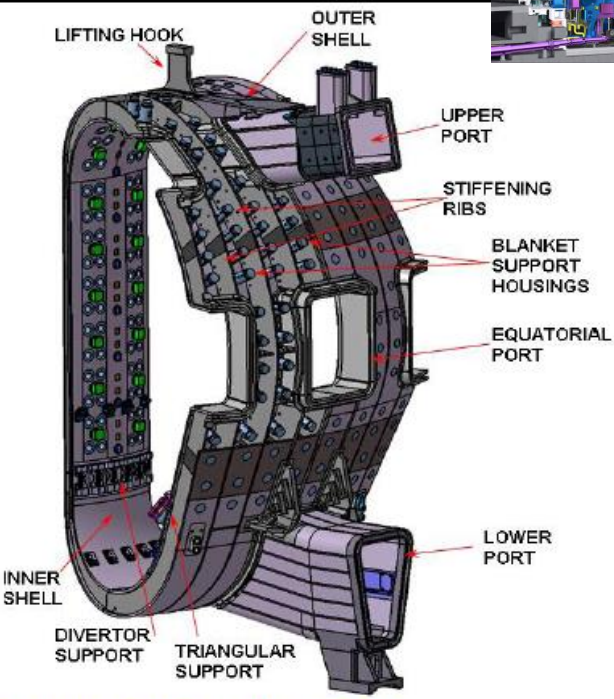
Veduta aerea del sito di ITER (Sett.2015)

Veduta aerea del sito di ITER (Marzo 2019)



Vacuum Vessel



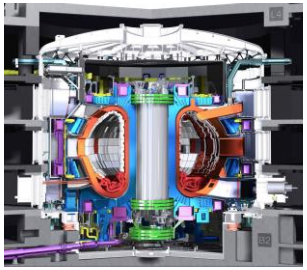


VV & In-vessel components
mass: ~8000 t
19.4 m diameter
11.3 m tall

Eiffel Tower
mass: ~7300 t
324 m tall

9 X 40° sector (~600 t each)
Double-wall structure
Shielding and cooling water between shells (304 SS + 1 - 2 % boron, SS 430 ferromagnetic)
40° sector fabrication at factory (~600 t)
34 Port (upper equatorial and divertor)

ITER- Milestones



In November 2017, the ITER Project passed the 50 percent milestone of work scope completed to First Plasma.

Main construction milestones:

2006	Signature of the ITER Agreement
2007-2009	Land clearing and levelling
2010-2014	Ground support structure and seismic foundations for the Tokamak
2014-2021	Construction of the Tokamak Building (access for first assembly activities in 2018)
2010-2021	Construction of the ITER plant and auxiliary buildings for First Plasma
2018-2025	Assembly phase 1
Dec 2025	First Plasma

Dal sito web : **www.iter.org**

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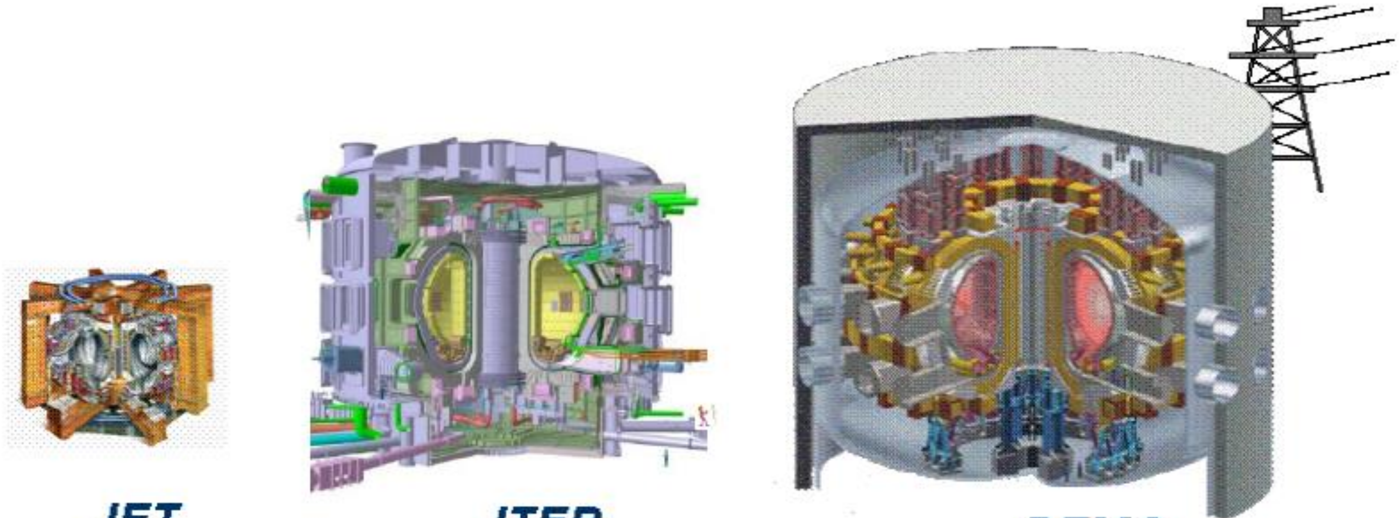
ITER is the next significant step Toward a Power Producing Fusion Reactor demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

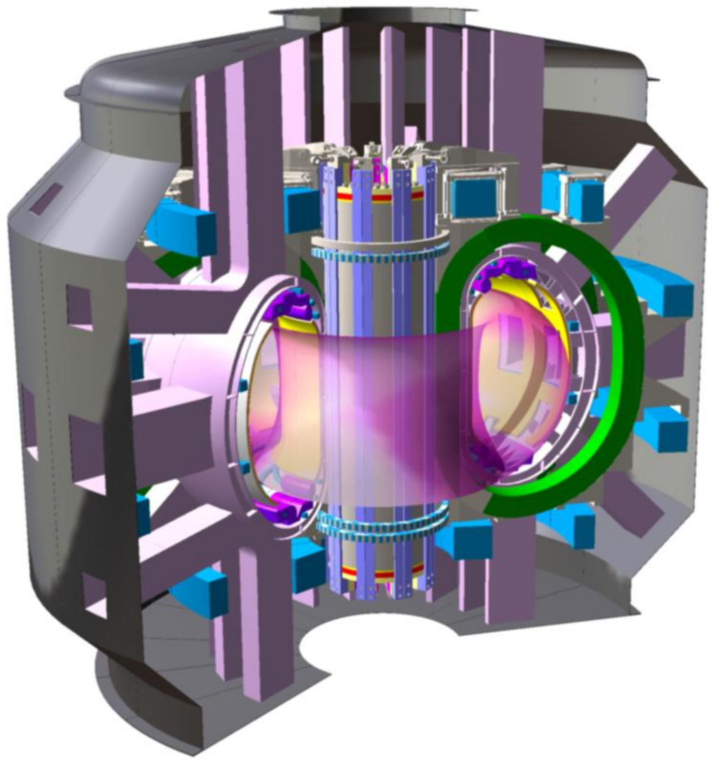


JET	ITER	DEMO
$80\ m^3$	$800\ m^3$	$\sim 1000 - 3500\ m^3$
$\sim 16\ MW_{th}$	$\sim 500\ MW_{th}$	$\sim 2000 - 4000\ MW_{th}$

- Dominant self heating ---------------->

iter china eu india japan korea russia usa

The DTT proposal



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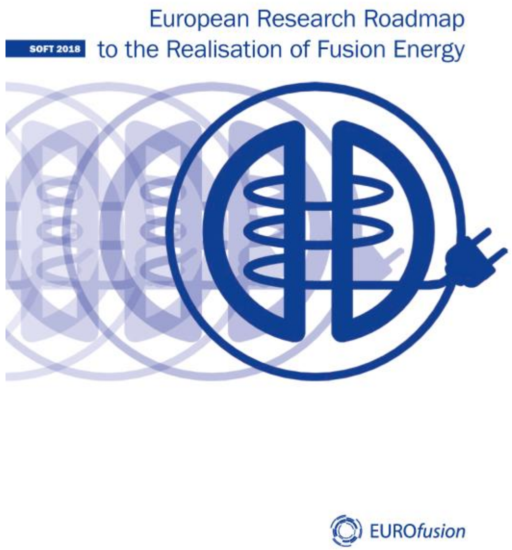
Università degli Studi della Campania Luigi Vanvitelli

European Strategy towards the realization of fusion energy



Eight missions on the path towards fusion electricity:

1) Plasma regime of operation
2) **Heat-exhaust system**
3) Neutron resistant materials
4) Tritium self-sufficiency
5) Implementation of intrinsic safety features of fusion
6) Integrated DEMO design and system development
7) Competitive cost of electricity
8) Stellarator

"If alternate exhaust strategies were to be only explored in the event of ITER showing that the baseline exhaust strategy cannot be extrapolated to DEMO, the realisation of fusion would be delayed by at least 10 years…. "

Tony Donné, William Morris, et al.

"European Research Roadmap to the Realisation of Fusion Energy A road map to the realisation of fusion energy" www.euro-fusion.org/fileadmin/user_upload/EUROfusion/Documents/2018_TopLevel_Roadmap.pdf

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Heat exhaust challenge

To mitigate the risk that “the conventional approach” (ITER solution) discovers showstoppers, it is important to develop alternative solutions.

In the recent years two possible alternatives have been proposed:

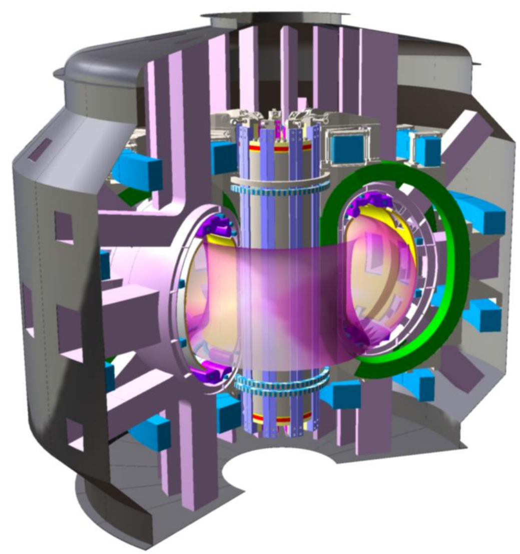
- Modification of the magnetic topology in the divertor region (snowflakes, X-divertor, Super-X divertor, Double null) to decrease the divertor plates power flux
- Liquid metal as PFC

But for a full development, these alternatives (one or both) need a dedicated facility allowing for a direct extrapolation to DEMO

DTT design boundary conditions

Physics parameters relevant for ITER/DEMO and core – edge integration

Budget

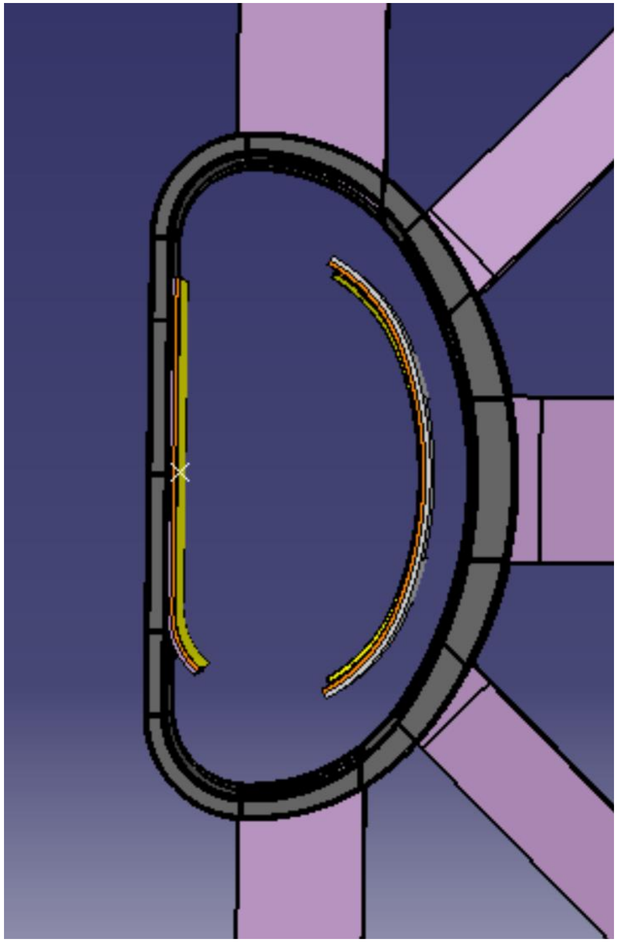


No tritium handling

Technology choices relevant for DEMO

DTT: today at the start of Realization Design

	present proposal
R (m)	2.11
a (m)	0.64
A	3.29
Vol (m^3)	29
q_{95}	3
I_p (MA)	5.5
B_T (T)	6
H_{98}	1

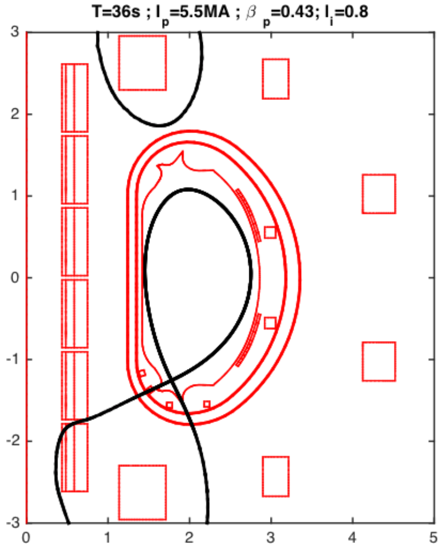


DTT with R_0 = 2.11 m (2,0% less than the original proposal !!)

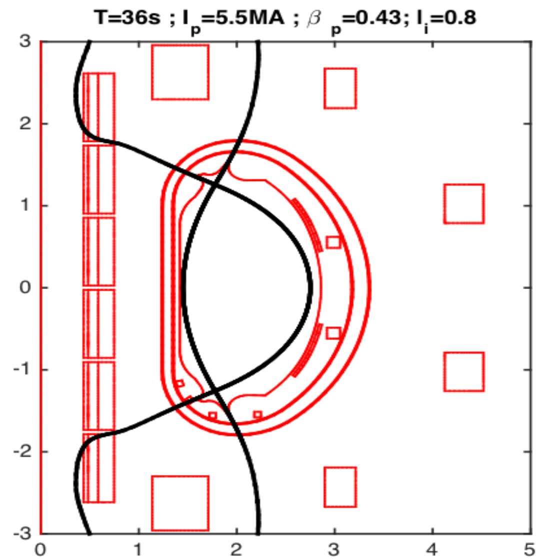
Same performance but increased flexibility at fixed budget

DTT: Present magnetic flexibility

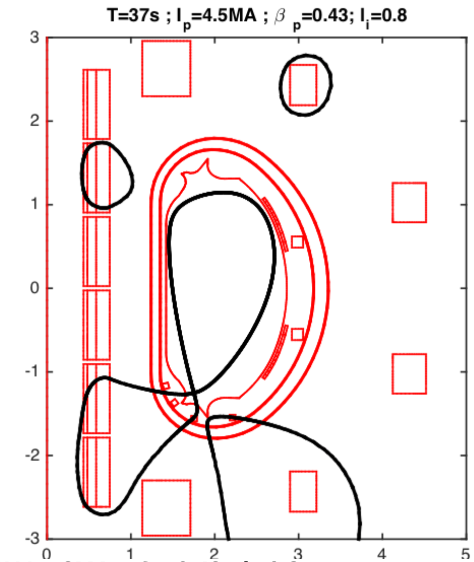
Single Null
5.5MA

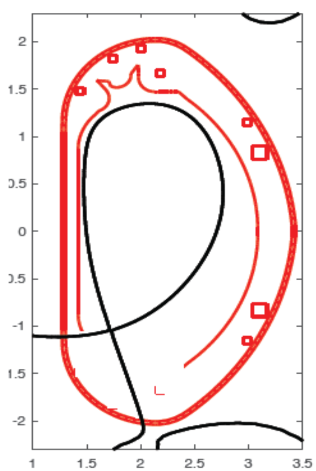


Double Null
5.5MA

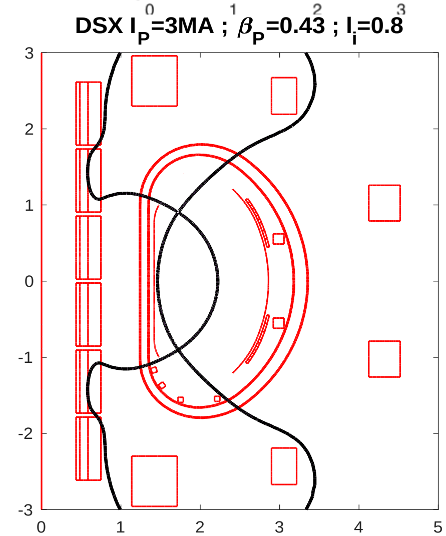


Snowflake
4.5MA





X-Divertor
5MA

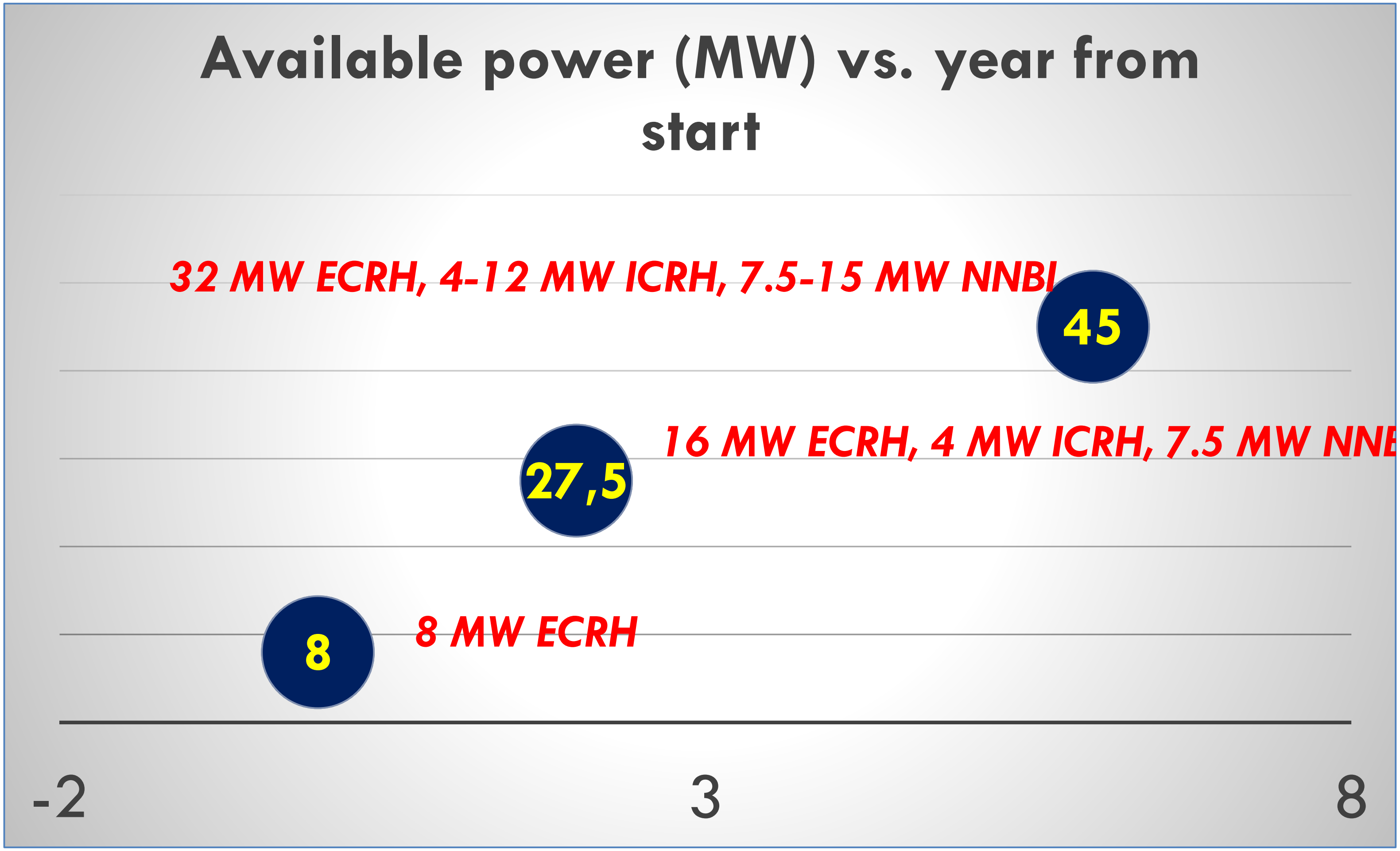


Super-X
3MA

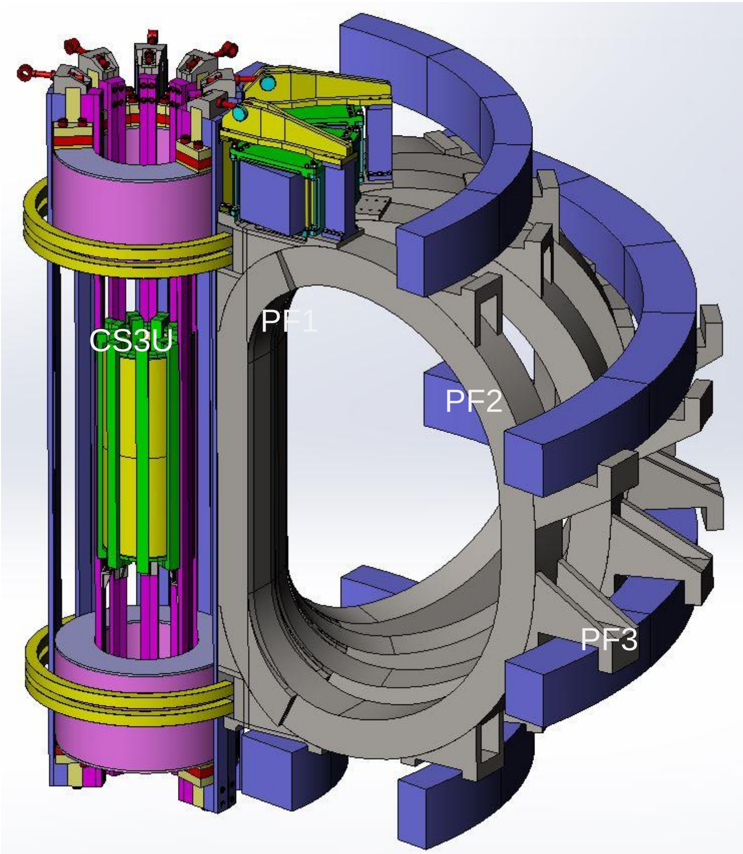
Additional heating mix

Heating 45 MW

$P_{sep}/R \sim 15$ (ITER=14 DEMO=17)



Magnet System - overview



18 TF coils:
Nb_3Sn Cable-In-Conduit Conductors
6 *Double-Pancakes* (4 regular + 2 side)
B_{max} = 11.7 T; I_{op} = 26.9 kA
ΔT_{margin} = 1.6 K

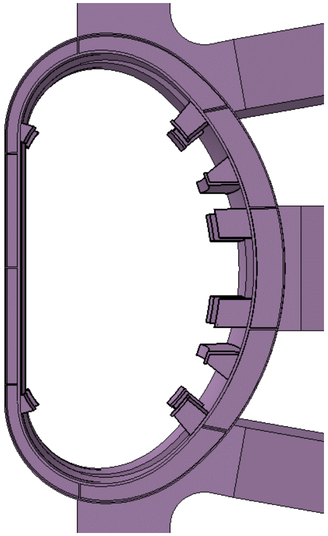
6 CS module coils
Nb_3Sn Cable-In-Conduit Conductors
graded *Layer Wound*
B_{max} = 14 T, 12 T, 8.5 T; I_{op} = 28 kA
ΔT_{margin} = 1.3 K

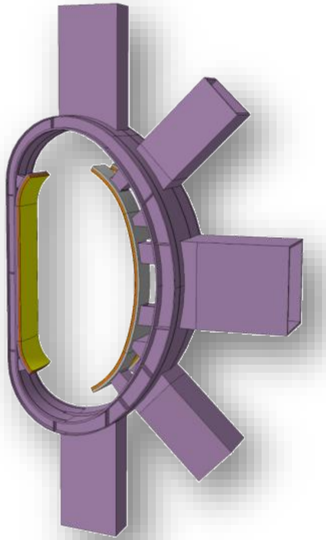
6 PF coils
NbTi Cable-In-Conduit Conductors
Double-Pancakes winding
B_{max} = 2.5 – 5.5 T; $I_{op\text{-}max}$ = 10 – 30 kA
ΔT_{margin} = 1.5 K – 2.0 K

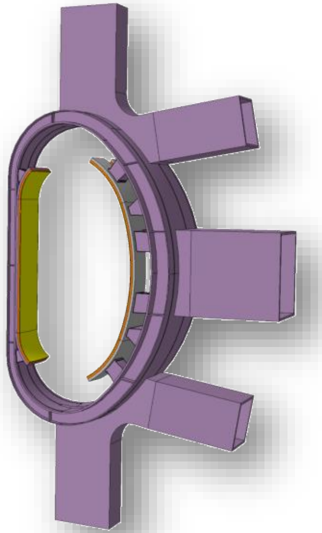
On-going design of an innovative additional HIGH TEMPERATURE SUPERCONDUCTOR (HTS) coil to be inserted into the Central Solenoid to obtain a 10% flux increase and to use DTT also as a test bed for the development of the next generation magnets

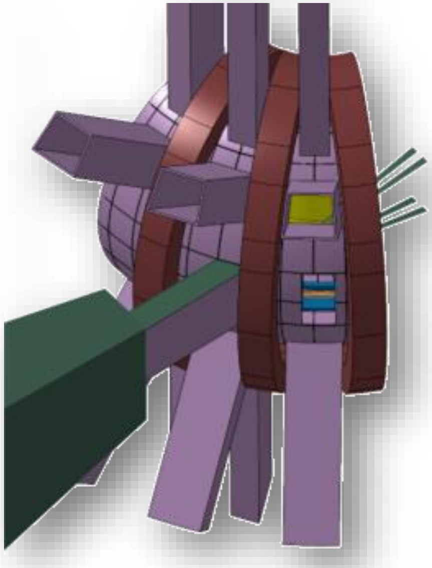
Vacuum vessel

- Double wall structure.
  - inner shell 15 mm thick
  - outer shell 15 mm thick
- SS AISI 316 L(N)
- Between the shells borated water at 50-80 °C



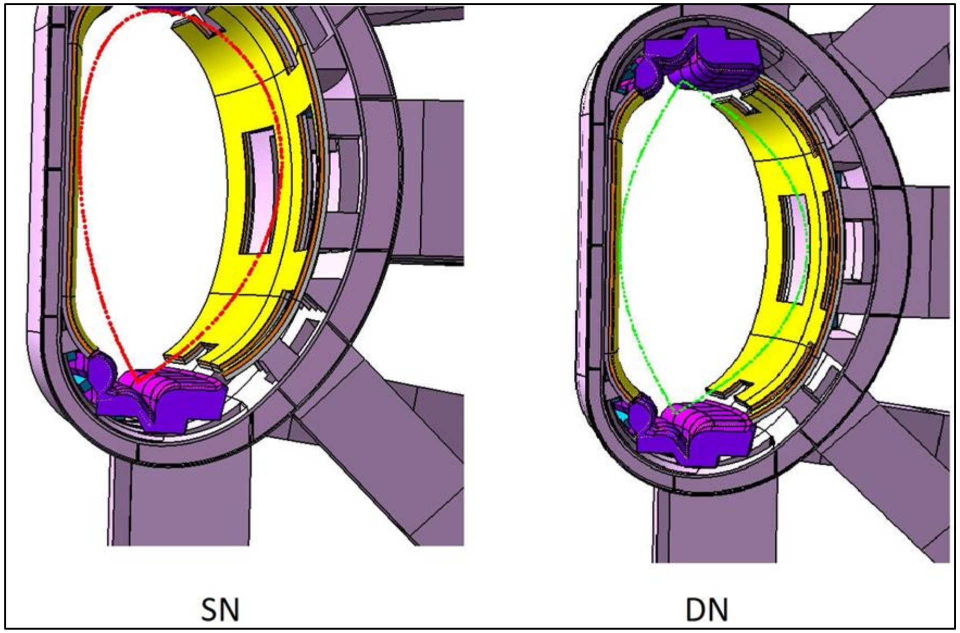


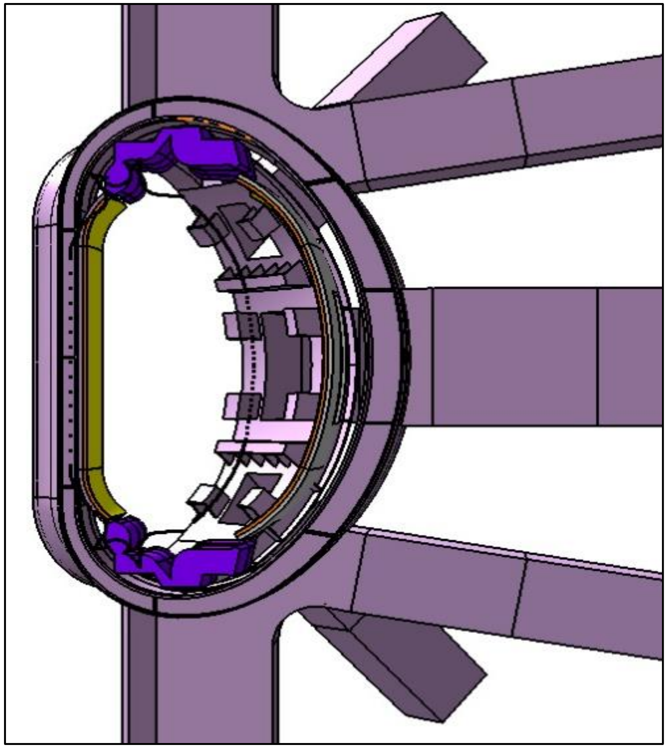




Divertor

DTT divertor is segmented in 54 toroidal sectors or cassettes (symmetric wrt the equatorial plane in the upper part for the DN configuration).
Each divertor cassette comprises a cassette body, which supports the plasma facing components (PFCs), an inner (IVT) and outer vertical target (OVT) and a dome.

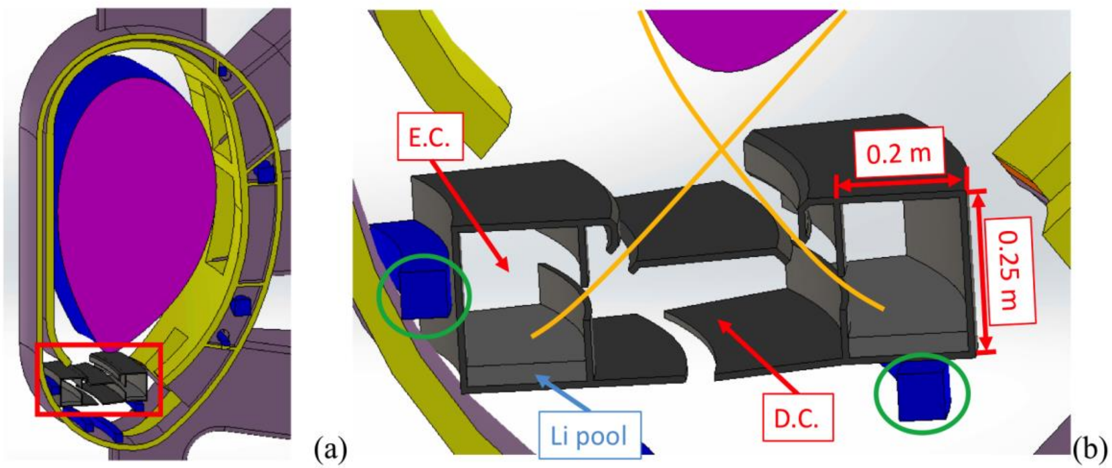


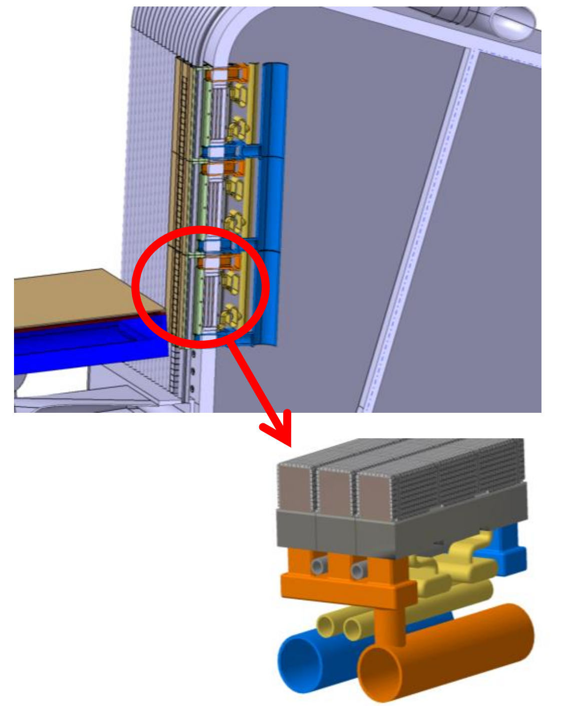


The divertor configuration identified from outcome of the PEX studies (around 2022-23)

Flexible liquid divertor geometry

As regarding liquid metals divertor, we are in the framework of EUROfusion workpackage on liquid metal we are involved in the capillary porous system conceptual design of a divertor for DEMO and DTT but We are even thinking a quite different solutions like the possibilities to have “boxes/pools” of liquid metal specially for Li for which evaporation is very important.
(Zanino[1], Goldston[2])



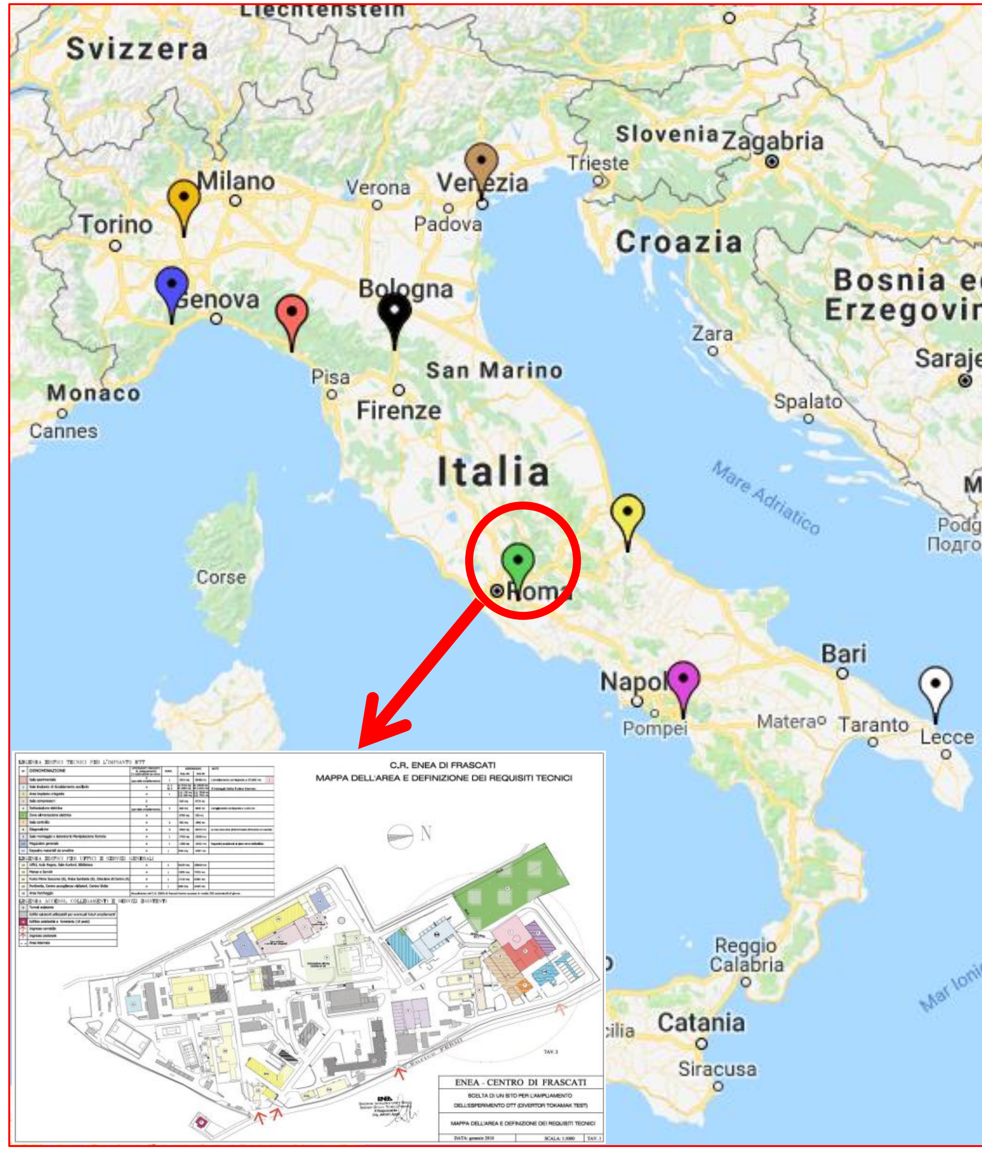


1) R. Zanino IAEA (2016) Kyoto
2) R. Goldston , IAEA P.E. WS-Wien 2015

Italian DTT Site

9 sites were proposed from all over Italy

- "Casale Monferrato" (TO)
- "Ferrania" (SV)
- "La Spezia" (SP)
- "Porto Marghera" (VE)
- "CR ENEA Brasimone" (BO)
- "Cittadella Della Ricerca" (BR)
- **"CR ENEA Frascati" (RM)**
- "Capitolo San Matteo" (SA)
- "Manoppello" (PE)

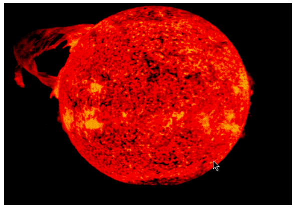


ENEA

Milestones and hold points

Apr 2018	Frascati selected as DTT site
July 2018	Design Review of major components
End 2018	Launch of procedure for the calls for tenders (SC strands)
Spring 2019	DTT Interim Design Report
Mid 2019	Establishment DTT Consortium
Mid 2019	Loan activated by EIB
2022-2023	Decision on divertor configuration (outcome PEX)
2022-2025	Assembly and commissioning

Conclusioni

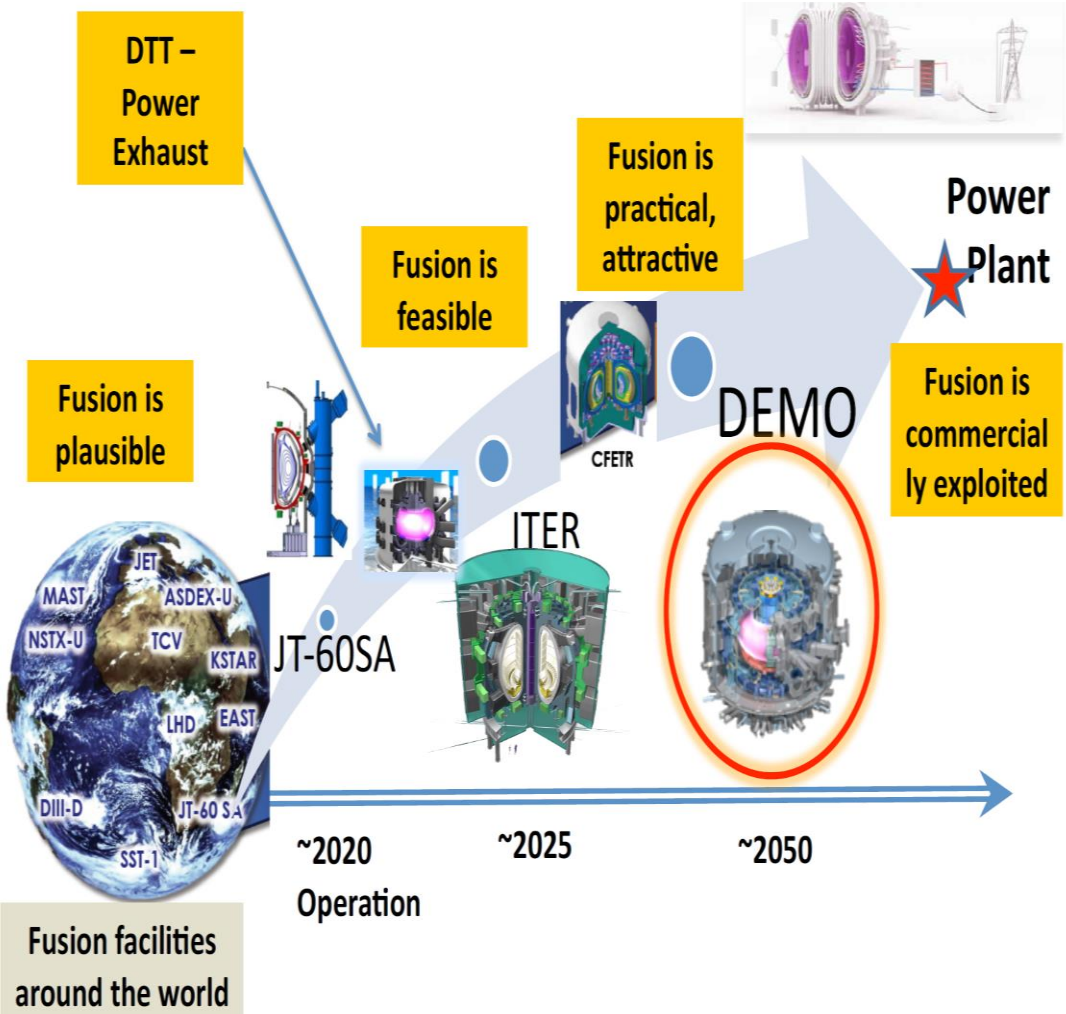


- "Imbrigliare l'energia delle stelle " è un passo fondamentale verso la soluzione del problema della generazione di elettricità che sia compatibile con l'ambiente, sicura e disponibile a tutti
- La realizzazione di una centrale elettrica a fusione è una affascinante grande sfida tecnologica e scientifica


Grazie per l'attenzione

Backup slides

Foreword



JET (Since 1983): to study plasma behaviour in conditions and dimensions close to a fusion reactor Including DT Ops

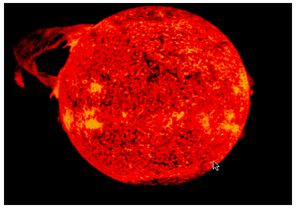
JT-60SA : addressing key physics issues for ITER and DEMO non-inductive steady-state operations at high β_N (with $Q_{DT} \approx 1$)

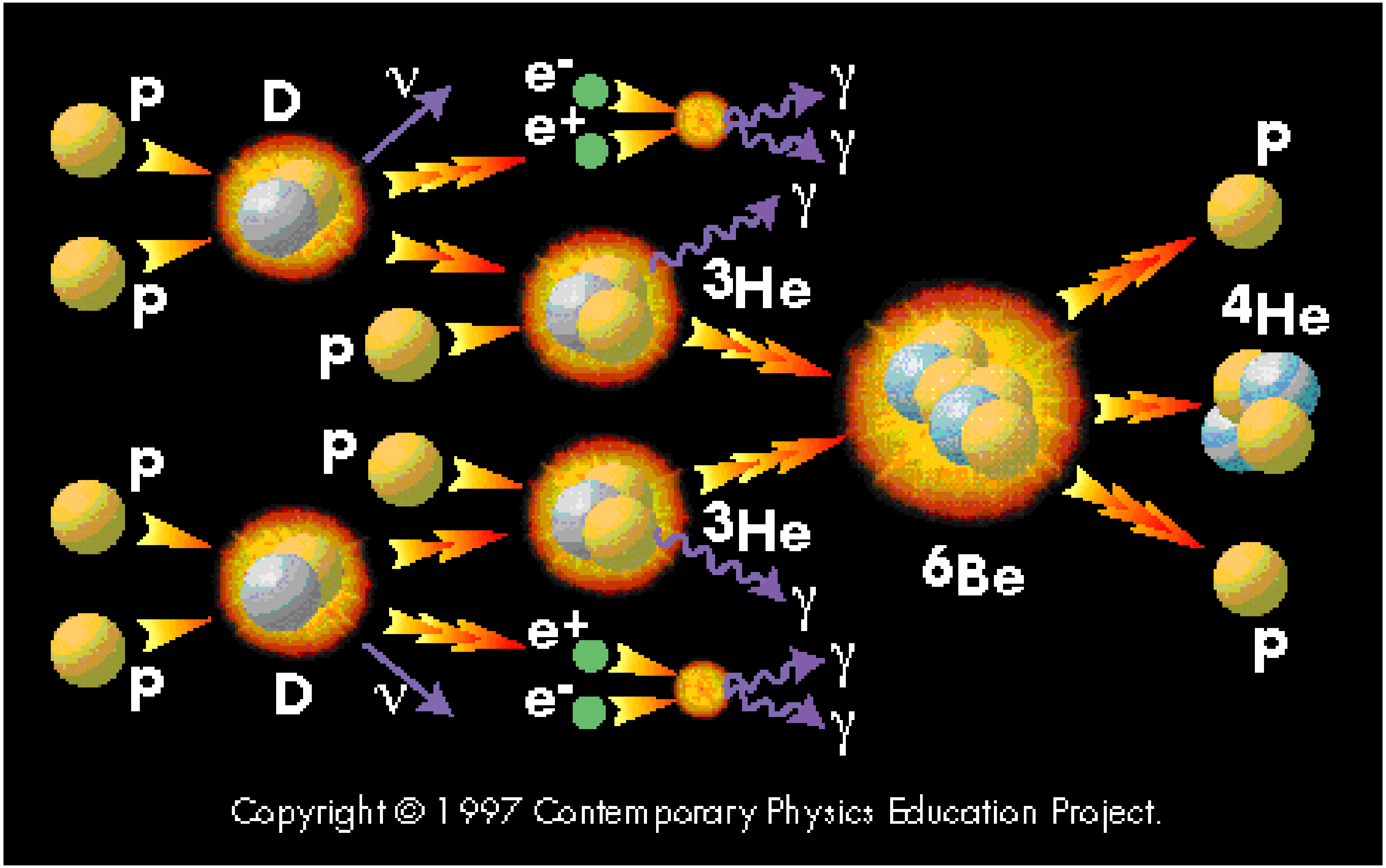
ITER : reactors-scale international experiment designed to study burning plasmas with $Q \approx 10$

DTT : a facility to develop and test *integrated*, controllable power *exhaust solutions* for DEMO including plasma, PFCs, control diagnostics/actuators

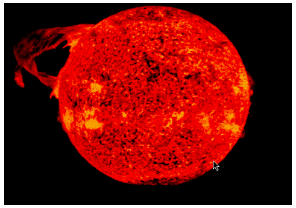
DEMO : expected to be the first fusion plant to provide electricity to the grid

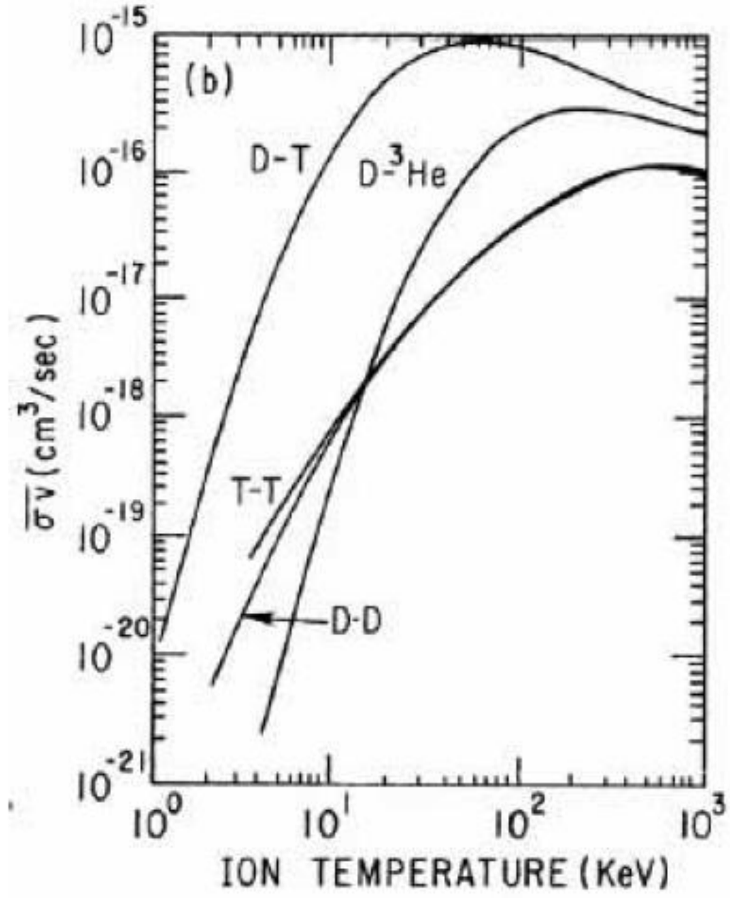
Star Nuclear Reactions





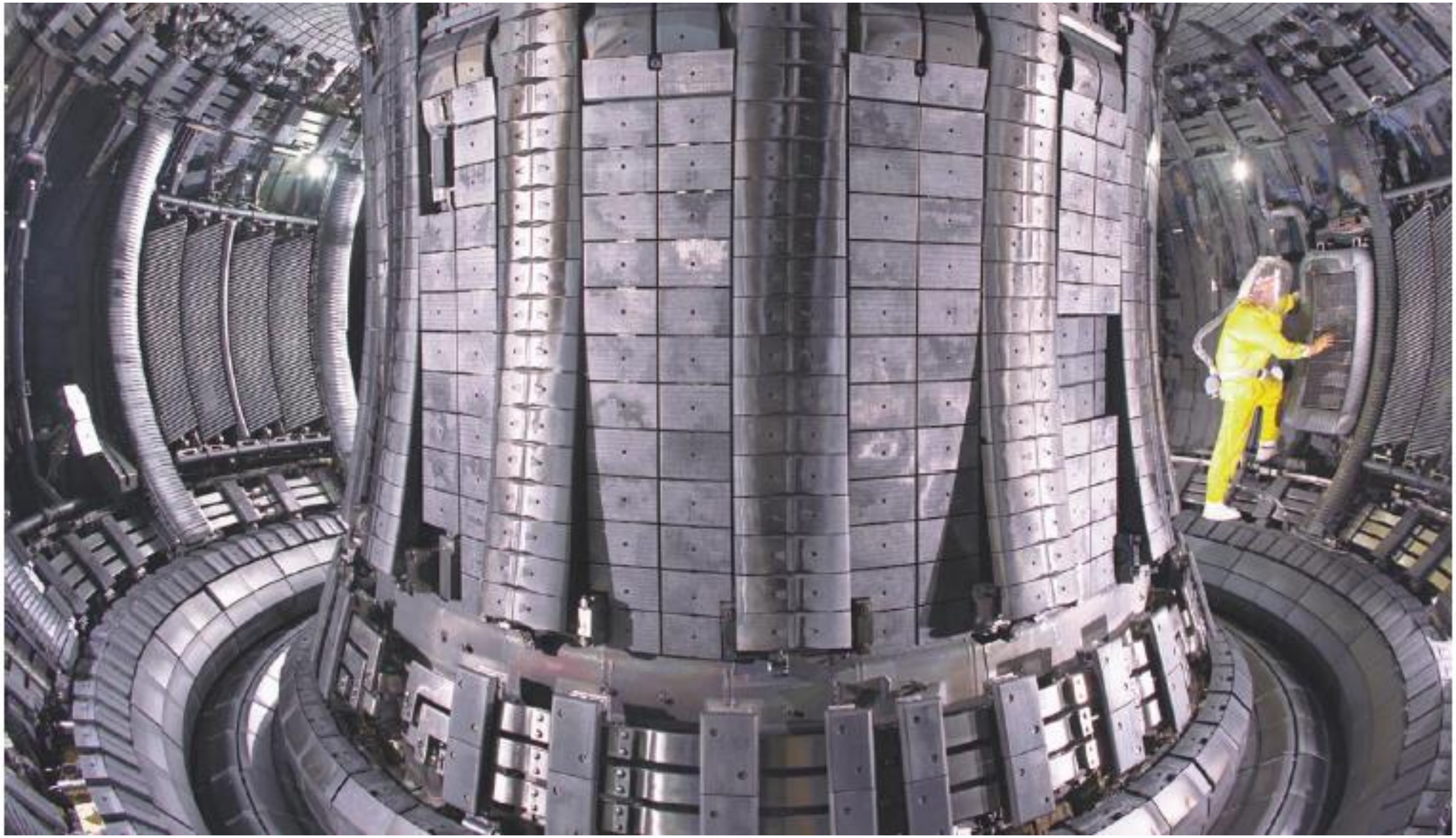
Relevant Fusion Reactions





JET

<u>J</u>oint <u>E</u>uropean <u>T</u>orus



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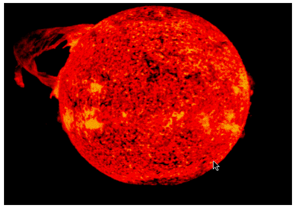
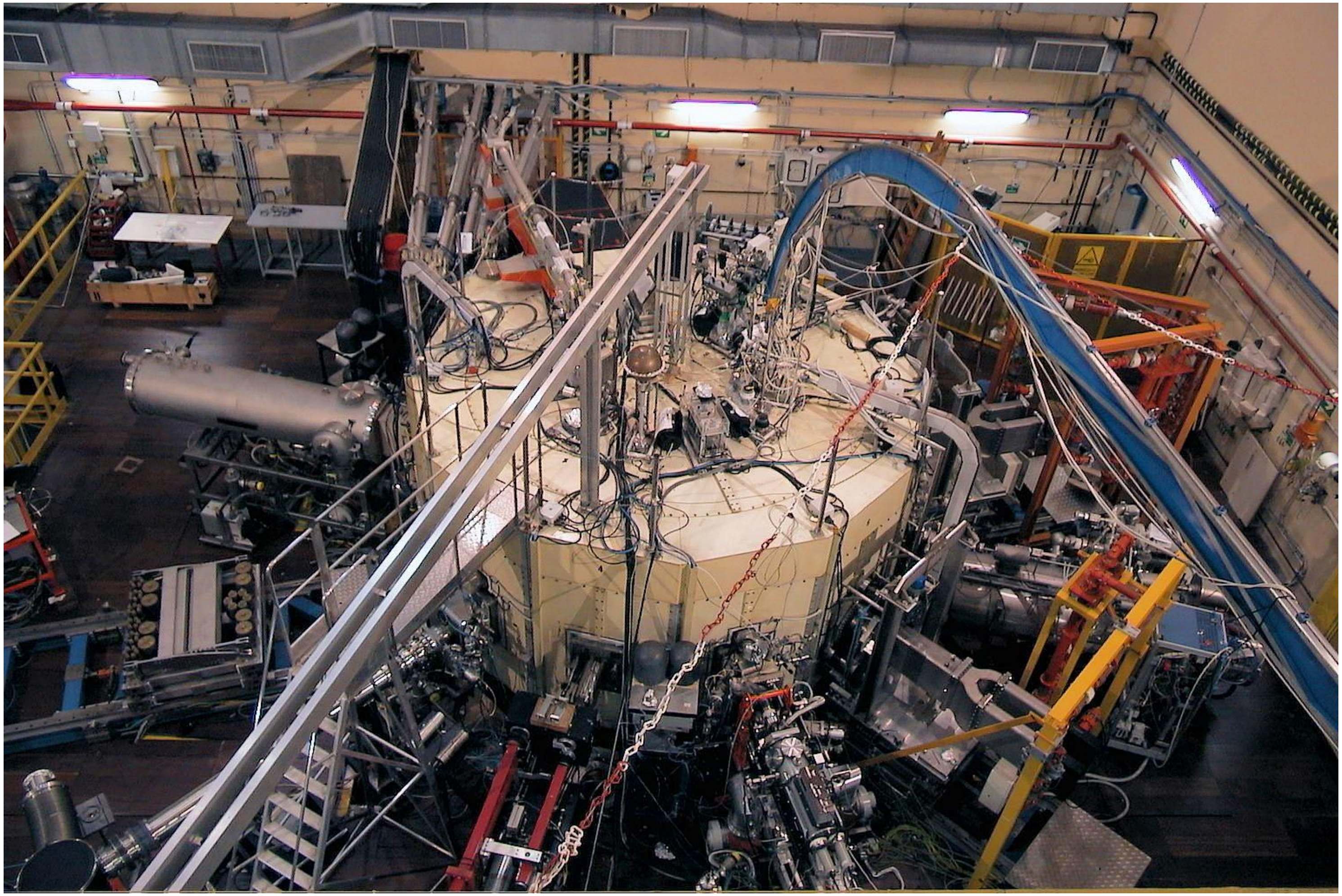
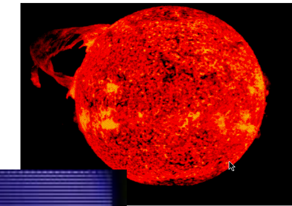
Frascati Tokamak Upgrade
FTU

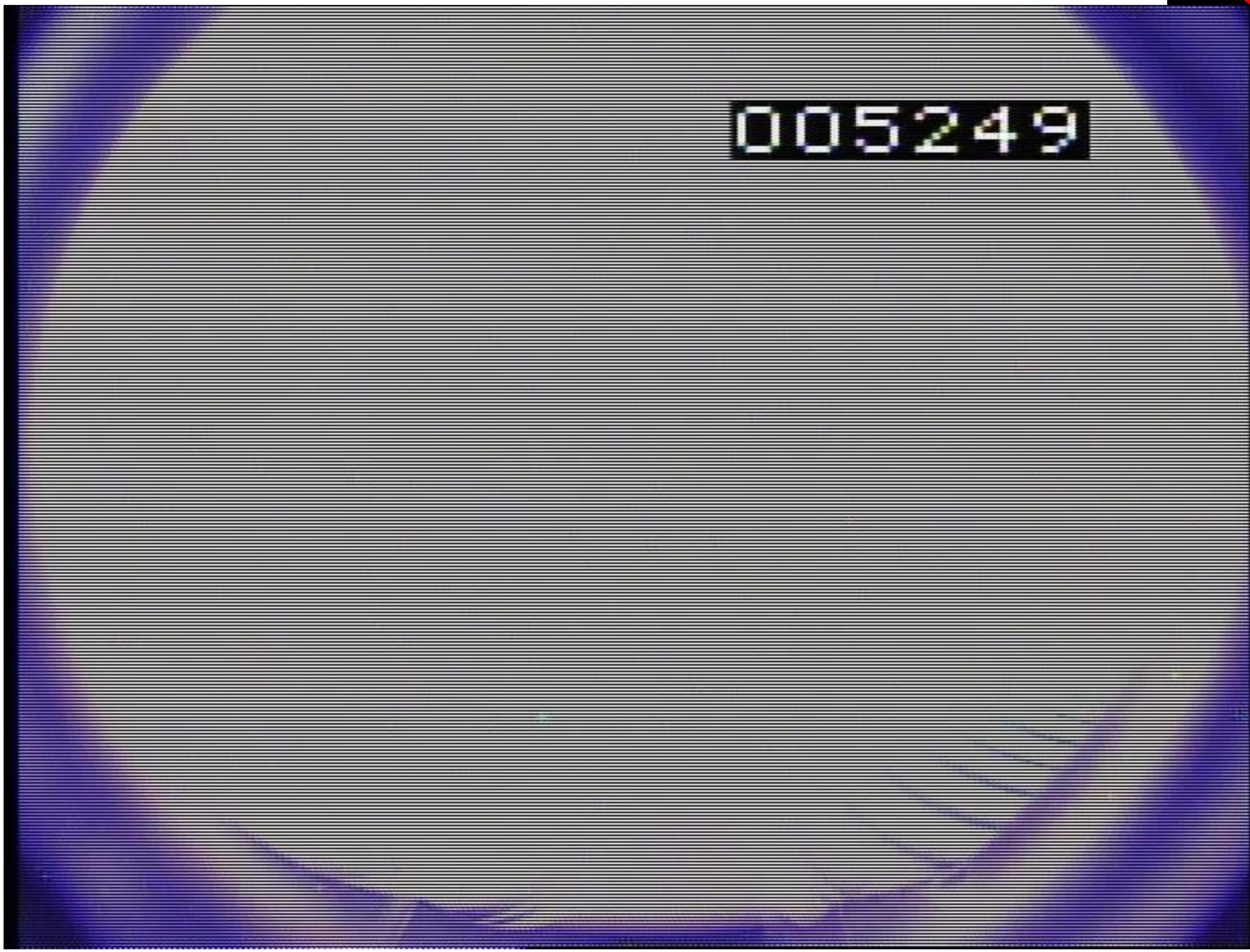




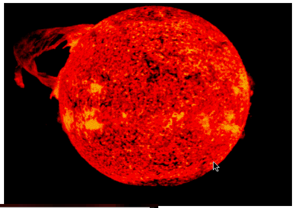
Convegno AIN 12/04/2019

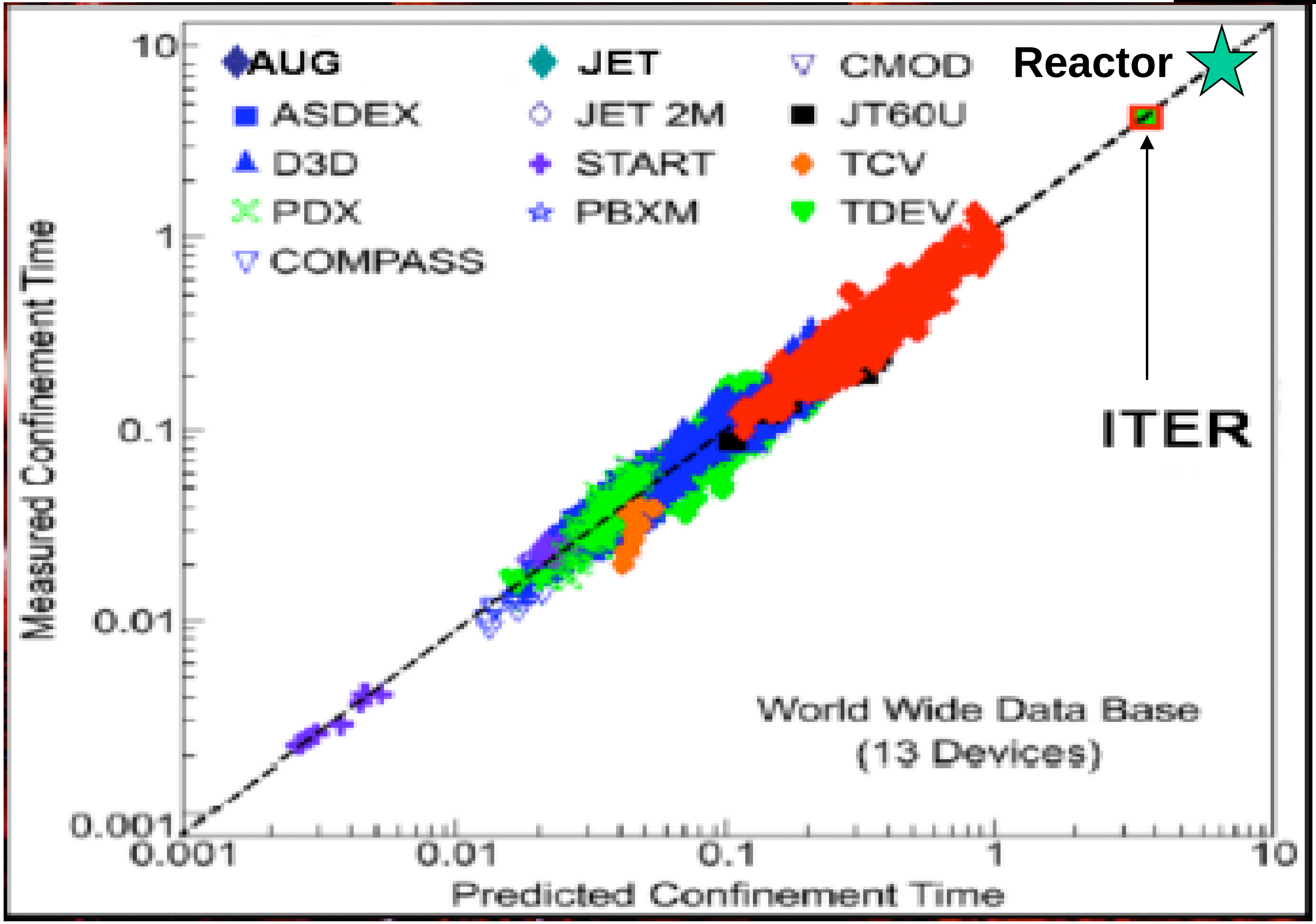
Un esperimento su FTU

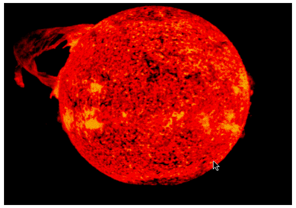




Progressi nelle Ricerche sulla Fusione







Verso il reattore a fusione

In un reattore ovviamente si deve produrre più potenza di quella necessaria a mantenere il reattore in operazione.

Il guadagno Q è definito come il rapporto tra la potenza di fusione e la potenza esterna entrante nel plasma.

Risorse Finanziarie DTT

Il finanziamento alla realizzazione di DTT è cosi suddiviso:

	MEURO
BEI	250
Partener Internazionali (Cina in kind)	30
EUROFUSIO	60
Regione Lazio	25
MIUR	40
MISE	40
Fondi Strutturali Europei	24
Totale	**499**

Italian DTT Site

At the end of November 2017, ENEA launched a public announcement for the selection of the DTT site. The Candidatures could be only proposed by the Italian Regions.

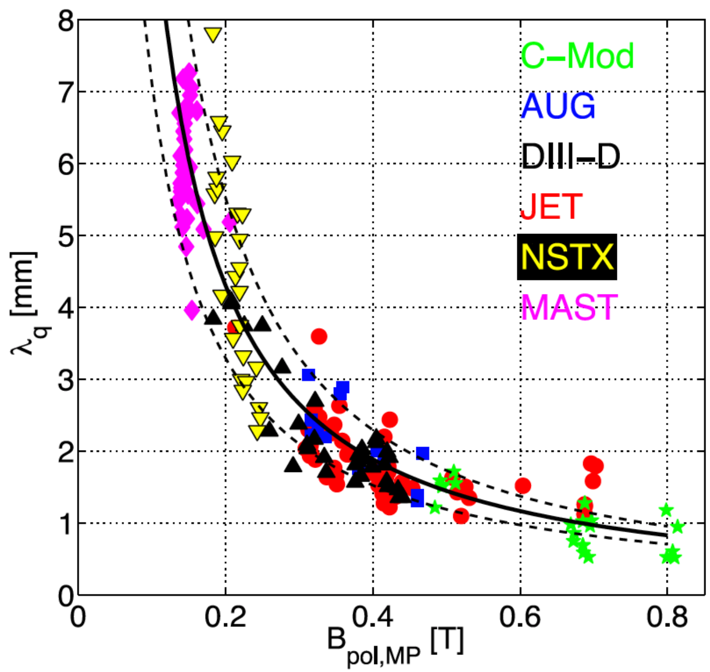
The challenge

- High field
- High power
- Compact
- ITER/Demo relevant divertor/edge physics
- …and not only a power dump !
  - Flexible scenarios – core/edge integrated
  - Control tools (coils, etc..)
  - High performance tokamak

Heat exhaust challenge

From a multimachine scaling of the upstream heat flux width the SOL power flow decay length scales as:

$$\lambda_q(mm) = 1{,}35 P_{SOL}^{-0.02} R^{0.04} B_p^{-0{,}94} \varepsilon^{0.42} \qquad \varepsilon = a / R_0$$



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

→ λ_q doesn't depend on R

To define the challenge of heat exhaust it has been pointed out:

$$\frac{P}{R}(MW/m) \quad or \quad \frac{PB}{R}(MWT/m)$$

as relevant metric

For ITER and DEMO $\lambda_q \approx 1mm$

DTT flexibility

Requests from Eurofusion Frascati 2017 Workshop

1. DTT flexible to accommodate the best candidate divertor concept decided by Eurofusion by 2022/2023
   - *conventional, snowflake, super-X, double null, liquid limiter..*
2. up-down symmetry (double null configurations)
3. additional power coupled to the plasma must guarantee significant results in view of DEMO
4. additional power mix reliable and suitable for various operating conditions

DTT parameters

	DTT	ITER	DEMO
R (m)	2.11	6.2	9.1
a (m)	0.64	2	2.93
n/n_G	0.45	0.85	1.2
I_p (MA)	5.5	15	19.6
B (T)	6	5.3	5.7
P_{tot} (MW)	45	120	460
P_{sep} (MW)	32	87	150
P_{sep}/R	15	14	17
<T> (keV)	6.1	8.5	13.1
<n> ($10^{20}m^{-3}$)	1.72	1	0.9
β_N	1.5	1.6	2.25
ν^*	2.5	2.3	1.4
ρ^*	2.8	2.0	1.5

Combination of high density and low collisionality is unprecedented