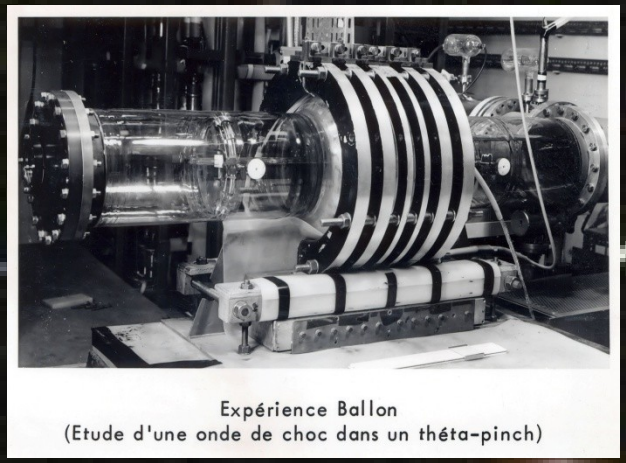
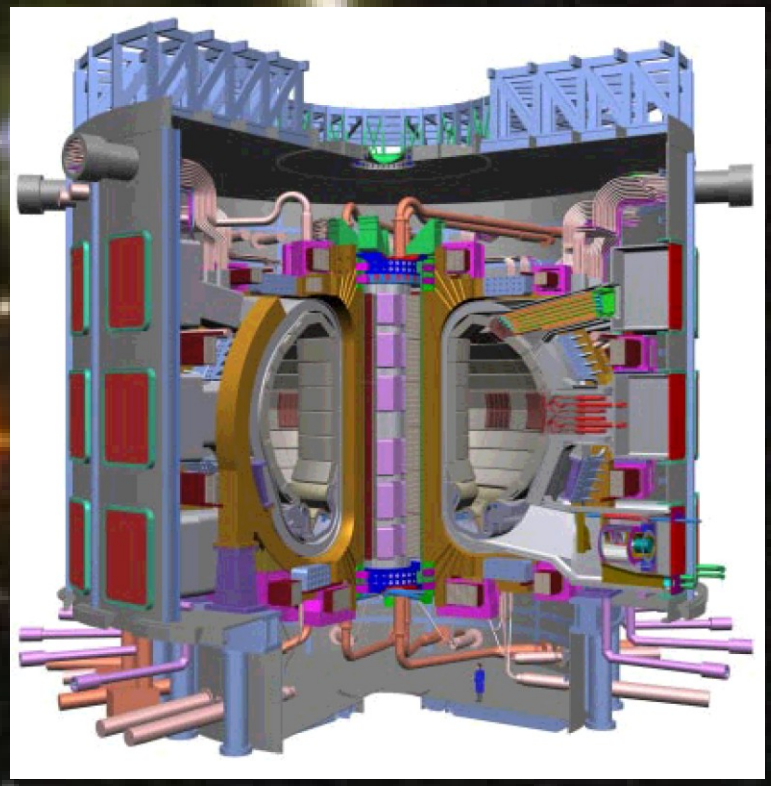


Robert and fusion science

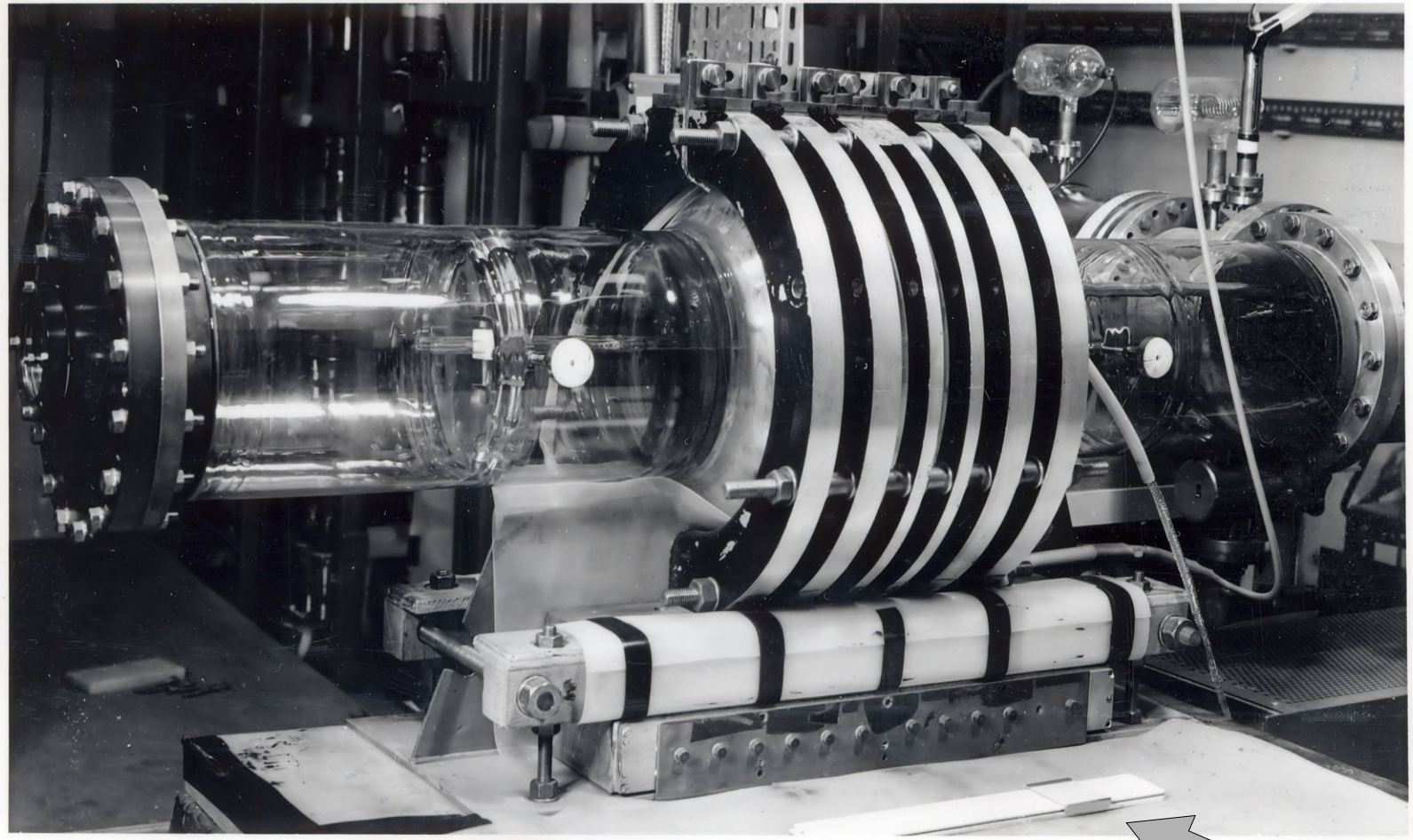
From infancy to ITER

Tore Supra



ITER

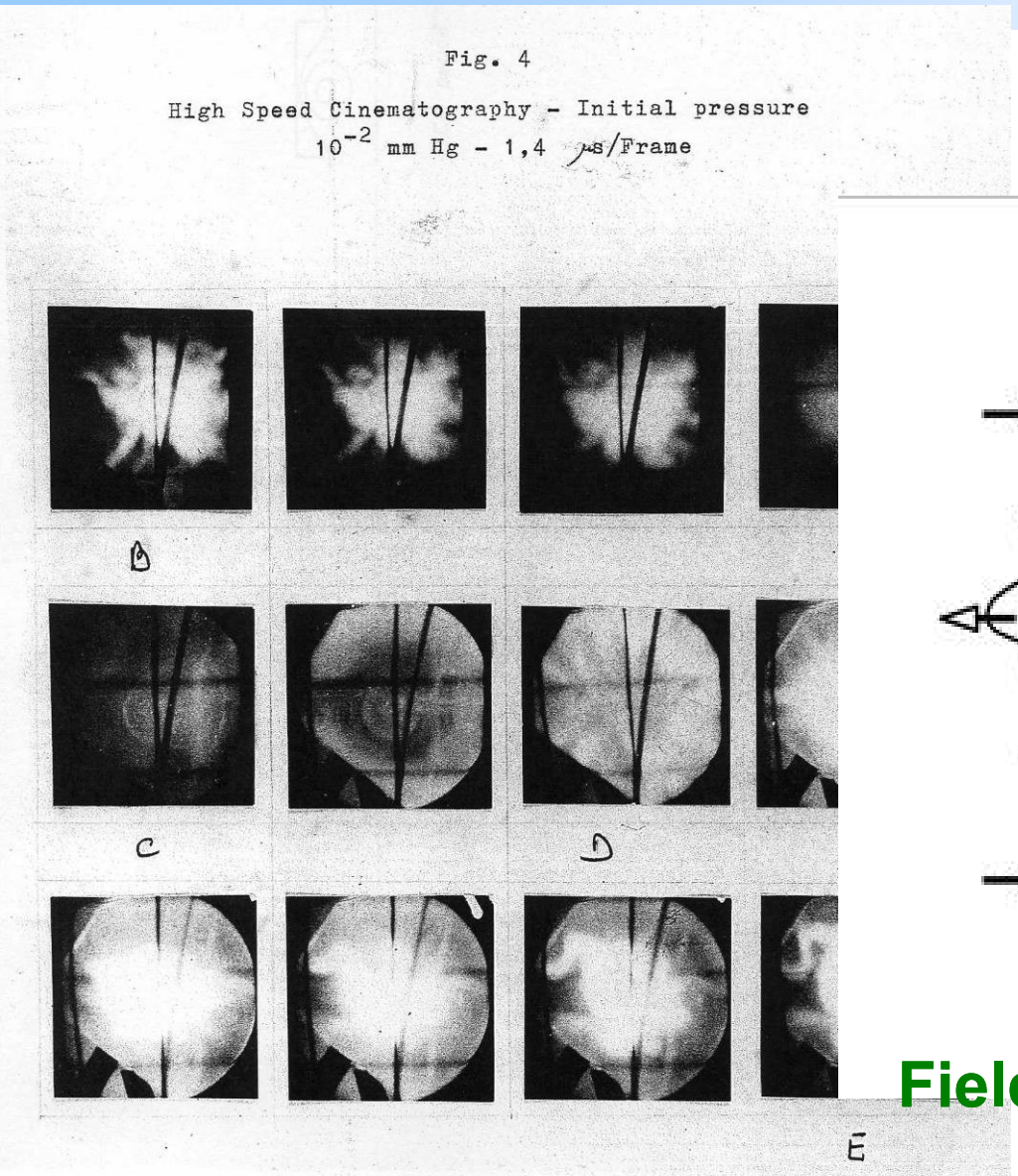
Early days 1958 - 1968:
No teachers but everything to learn

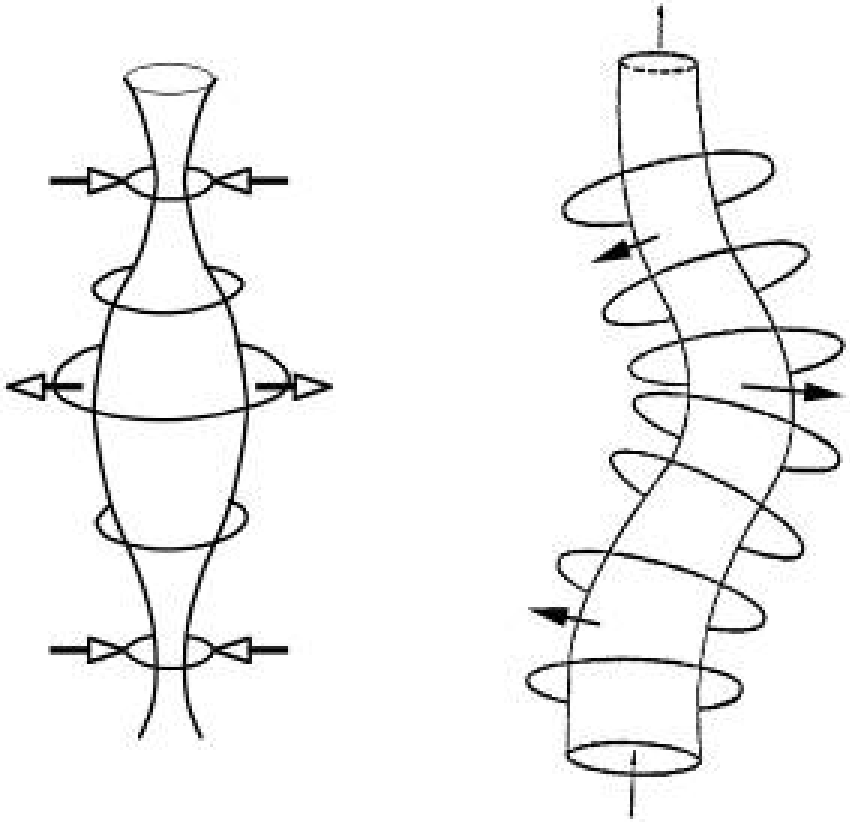


Slide rule

Expérience Ballon
(Etude d'une onde de choc dans un théta-pinch)

Instabilities





Field/plasma Interchange ➔ μs

1968:
2 revolutions reveal a revolutionist

1) Student revolution (May 68):

- A radical charismatic leader ➔ lab run for a month by general assemblies of the staff
  - **Staff representative for 2000 staff.**
- Advocates a democratic bottom-up approach of the programme **(to be mitigated later!!)**
  - **"Conseils d'unité" are created**

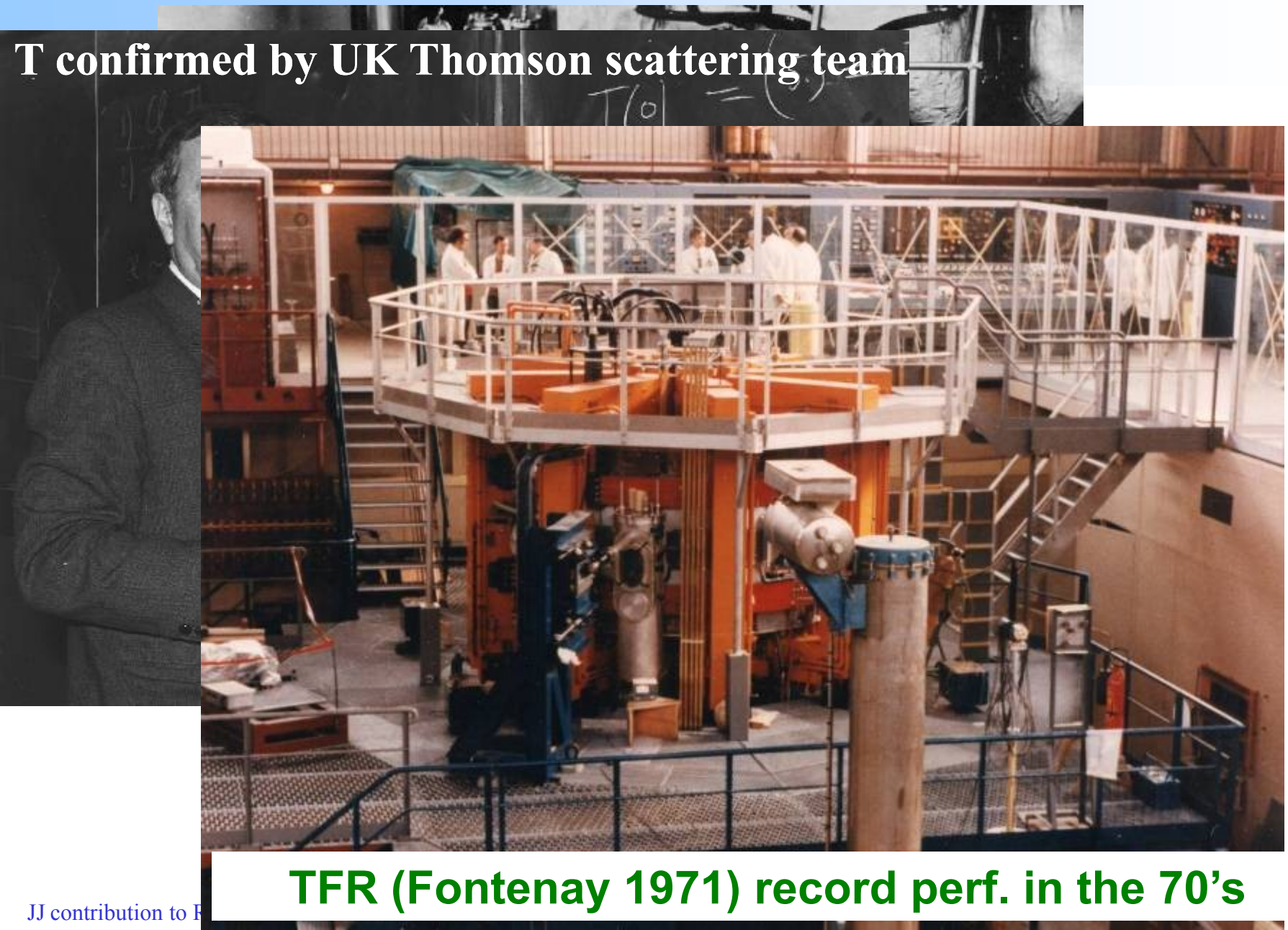
2) Tokamak revolution (Novosibirsk conf. Sept 68)

- Kurtchatov lab demonstrates plasmas with large-scale stability and good confinement (success of MHD)
- The French lab concentrates on Tokamaks

➔ **It builds the largest one, TFR**

➔ **Both the fusion lab and Robert change drastically**

Breakthrough in Kurtchatov (FEC 1968)



The eighties: scale-up and address small scale turbulence

TFR et al gave indications of scaling with size and field

- Small scale turbulence dominates, origin unclear
- How big should a fusion reactor be?
- Reach the thermonuclear conditions (additional heating)

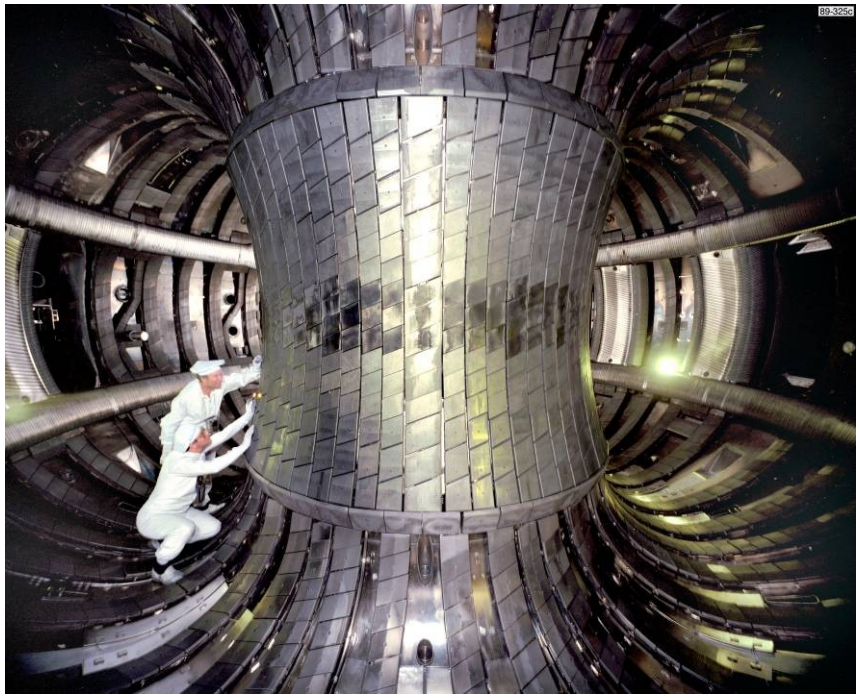
New larger devices are constructed:

- **European** ➔ **JET** a bold move on size and technology (Rebut) ➔ fusion power. Many contributions from CEA **(DSM then headed by Aymar)**
- **National** ➔ specific themes ➔ bold move of Aymar with **Tore Supra**, see A. Grosman

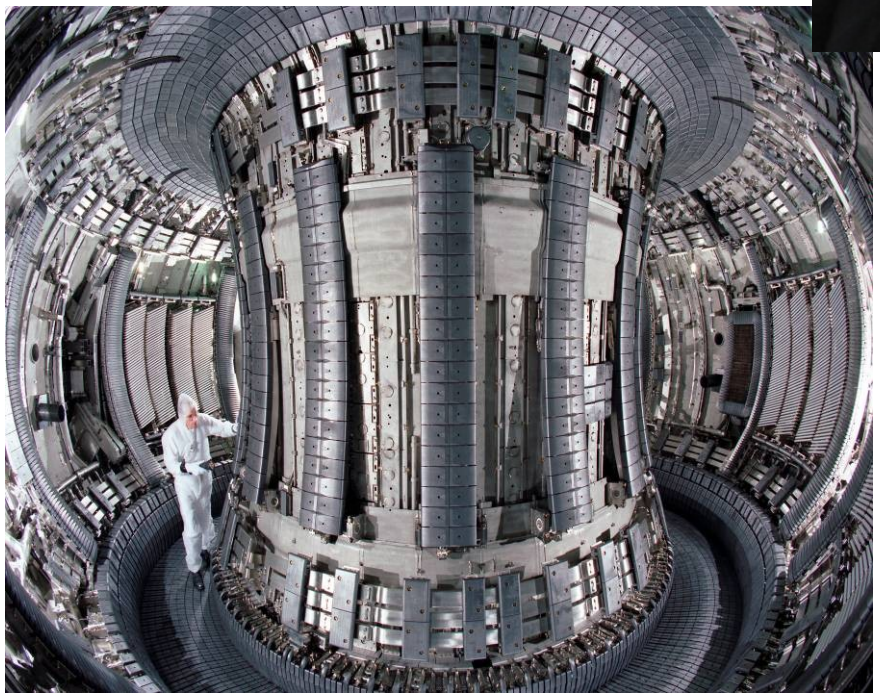
The gyro-Bohm character of turbulence is revealed ➔ possibility of a fusion reactor

Fusion for real in JET

1989



1994

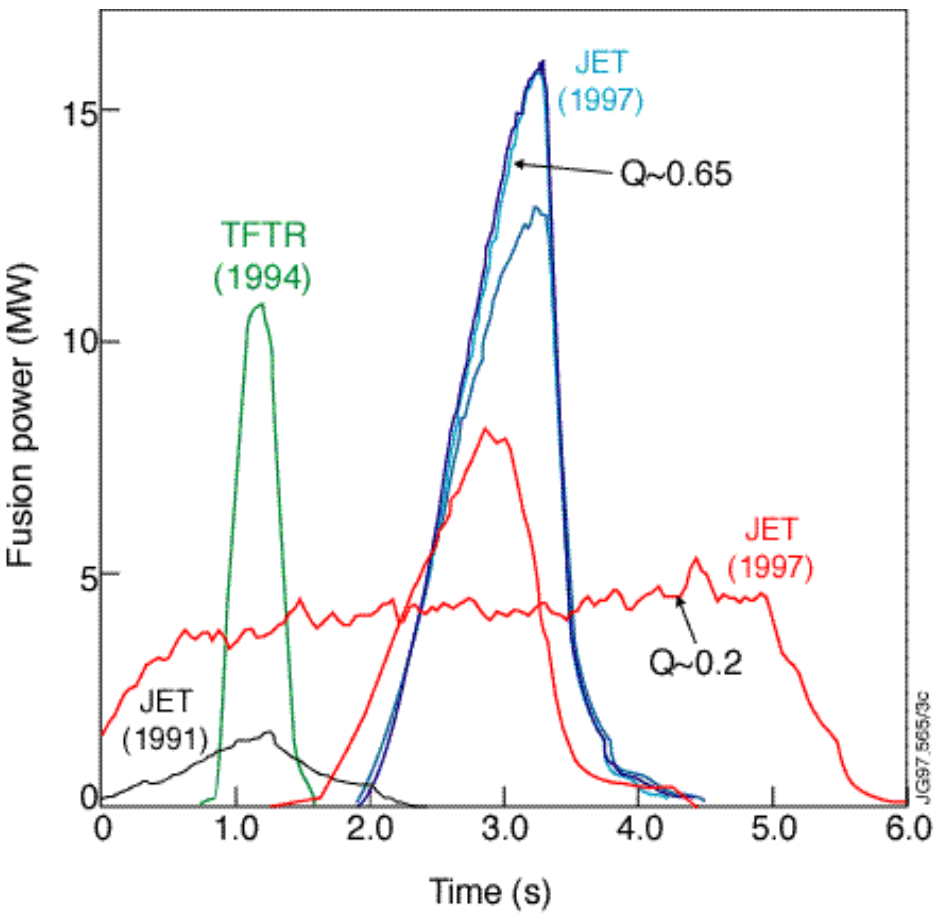


JET European facility predecessor of ITER

R. Aymar Member of the JET Council from 1988 – 1994
R. Aymar Member of the JET Scientific Council from 1988 – 1992

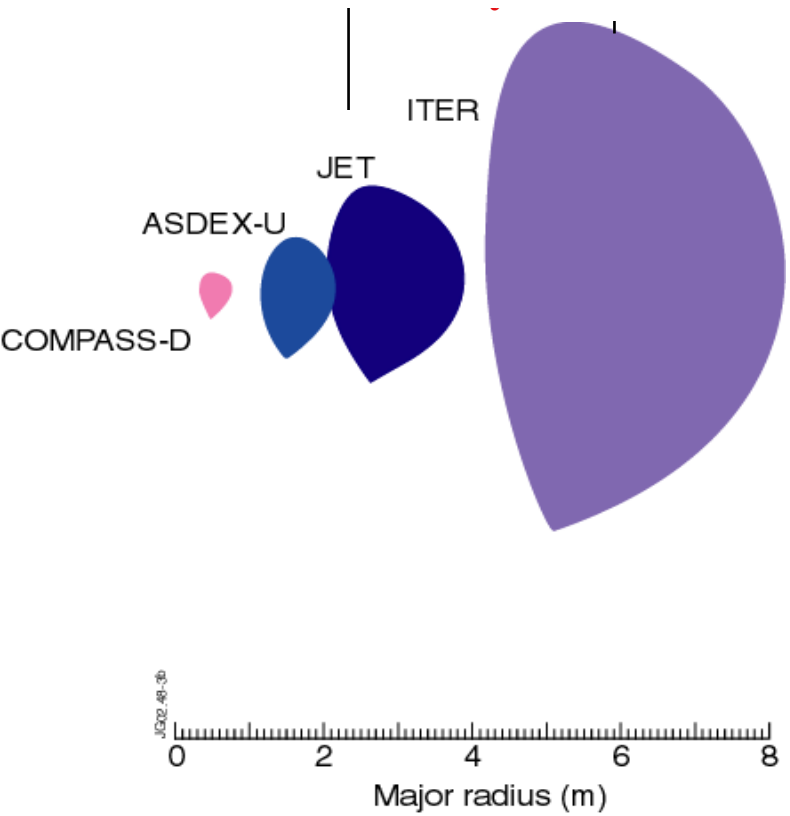
Period of intense activity: H-mode, 7MA, 1st tritium phase (2 MW)

DT fusion power

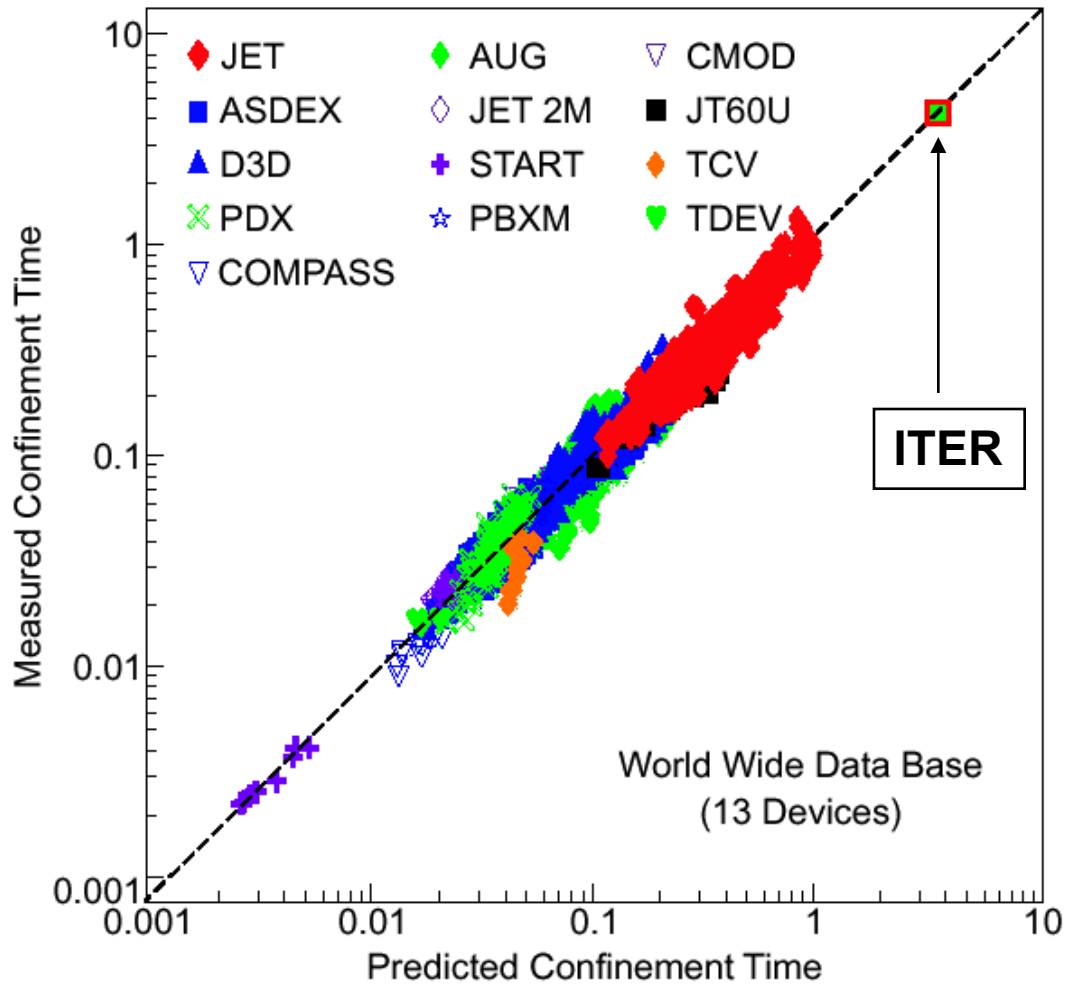


JET 1991 (EU):	1.7MW (90:10 D:T) First controlled DT fusion
TFTR 1994 (US):	11.5MW
JET 1997 (EU):	16.1MW, Q~0.6, transiently 4MW, Q~0.18, 22MJ, steady Alpha particle heating consistent with theory
JET 2003 (EU):	Trace tritium (93:7 D:T) for tritium transport, effect of MHD, neutron diagnostics
ITER 2019 --:	500-700MW, ultimately Q>10 (energy amplification)
Power plant:	1500-2000MW (thermal) Q~30-40

Similarity scaling experiments gives gyroBohm: $\omega_c \tau_E \equiv [\rho_*]^{-3}$

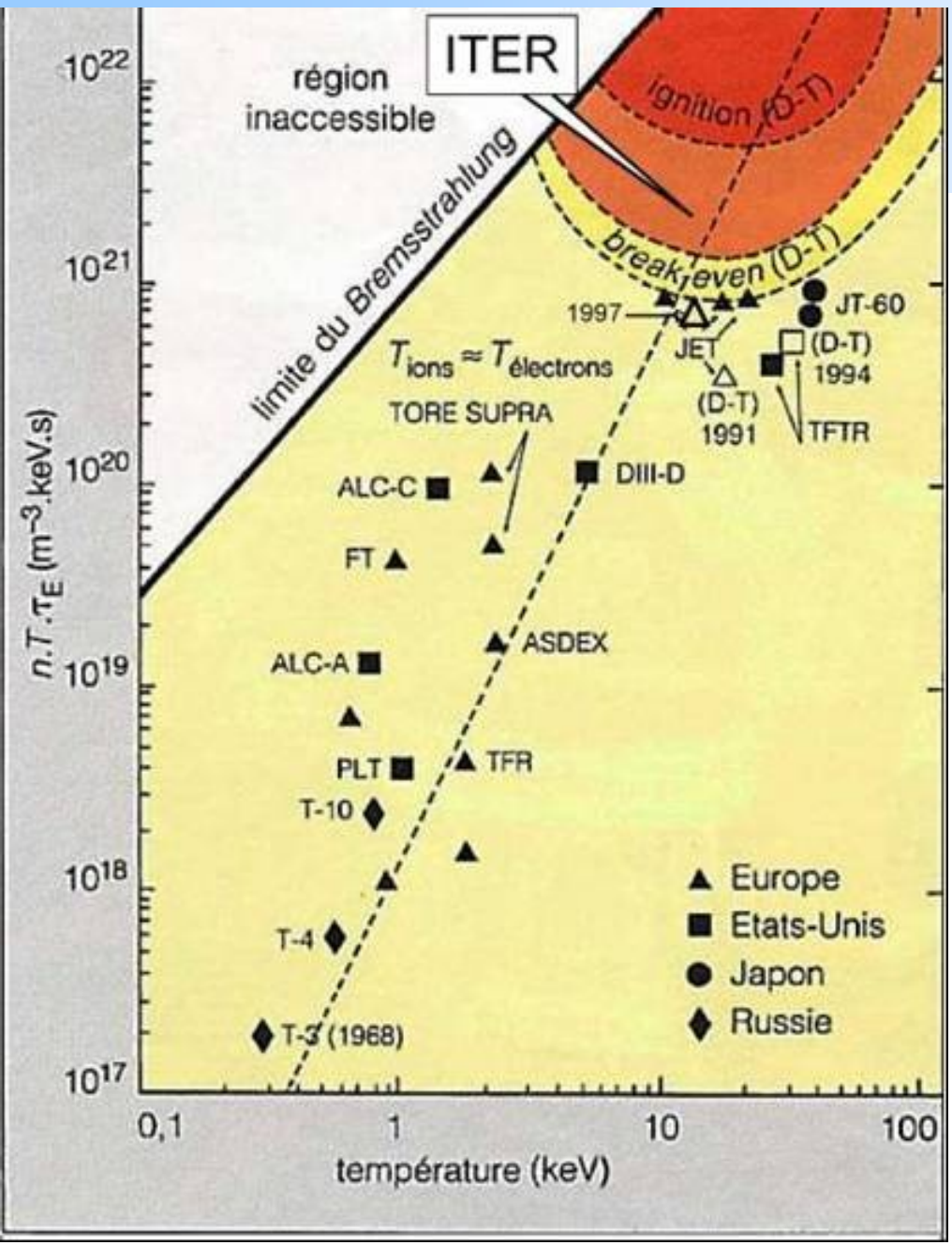


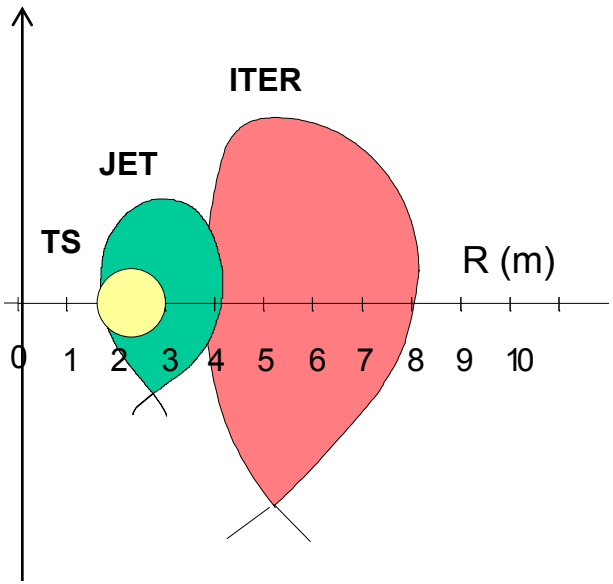
Cross section of EU D-shape Tokamaks compared to the ITER



Confinement law reduced to 3 dimensionless parameters: ρ^*, ν^*, β_N

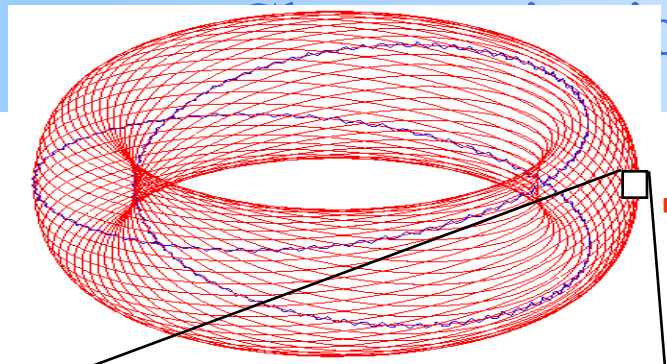
Progress


ITER
région inaccessible
limite du Bremsstrahlung
ignition (D-T)
break even (D-T)
$T_{ions} \approx T_{électrons}$
1997
JET
JT-60
(D-T)
1994
(D-T)
1991
TFTR
TORE SUPRA
DIII-D
ALC-C
FT
ASDEX
ALC-A
PLT
TFR
T-10
T-4
T-3 (1968)
Europe
Etats-Unis
Japon
Russie
$n.T.\tau_E$ (m^{-3}.keV.s)
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
0,1
1
10
100
température (keV)


ITER
JET
TS
R (m)
0
1
2
3
4
5
6
7
8
9
10

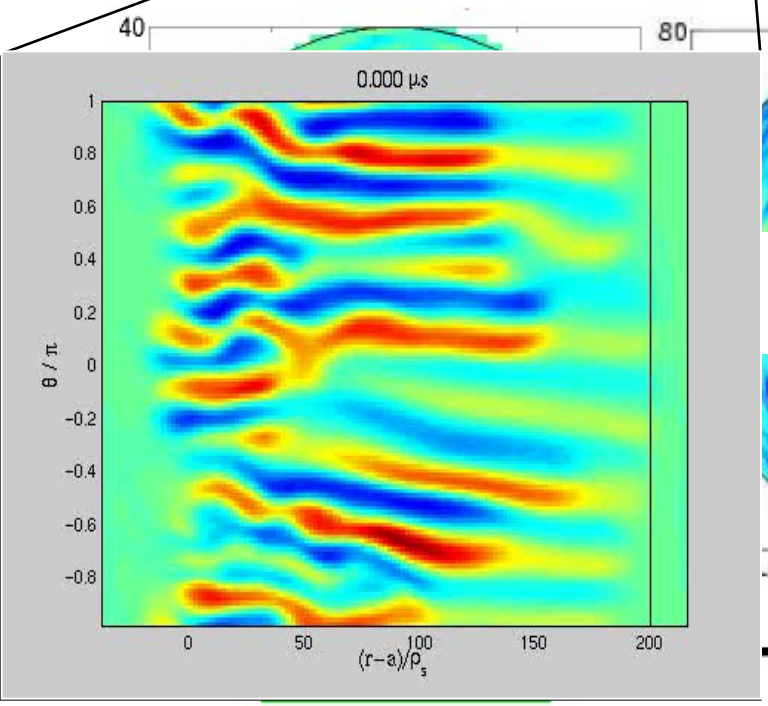
Understanding:

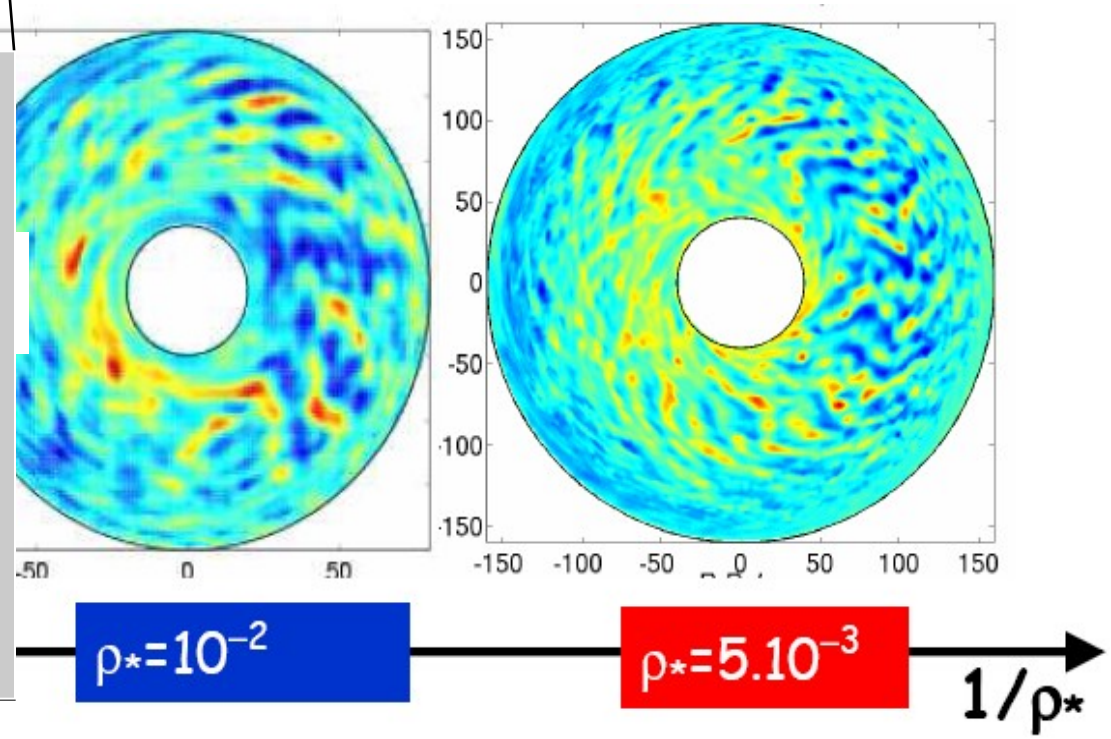
on of turbulent transport



Large convection cells, Streamers, Zonal flows

Sheared flows → Transport barriers





Intermittent edge transport

$$\omega_c \tau_E \equiv [\rho_*]^{-3}$$

Putting everything together:
ITER

- **Physics basis ➔ a power reactor can now be dimensioned**

  - International **ITER design team** started in ’92 under PH Rebut then R Aymar ’94 who holds firm the crisis of US withdrawal in ’97.

  ➔ ITER proposal endorsed by the partners in 2001

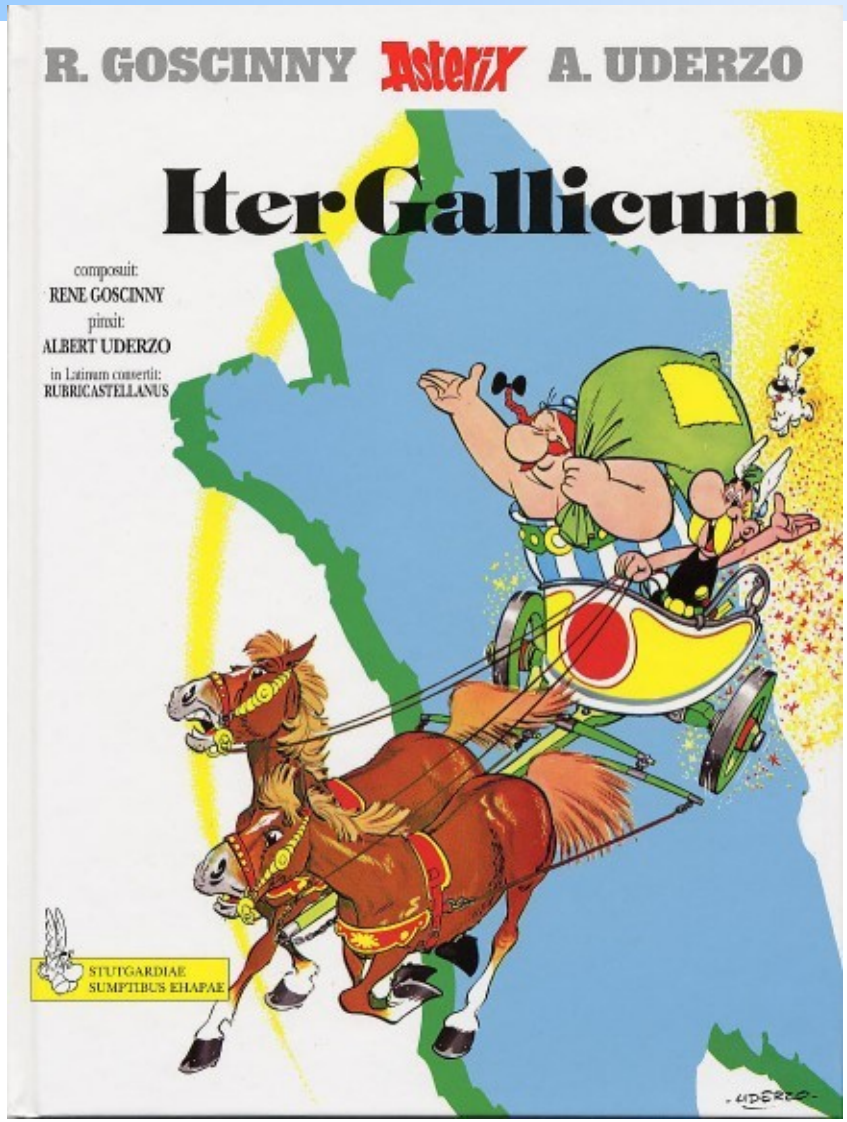
  - Publication of the monumental **“ITER physics basis”:** gives confidence to reach Q=10.

    . Fusion science now includes non linear MHD, small scale turbulence, self organisation with confinement barriers, accurate RF and particle heating schemes

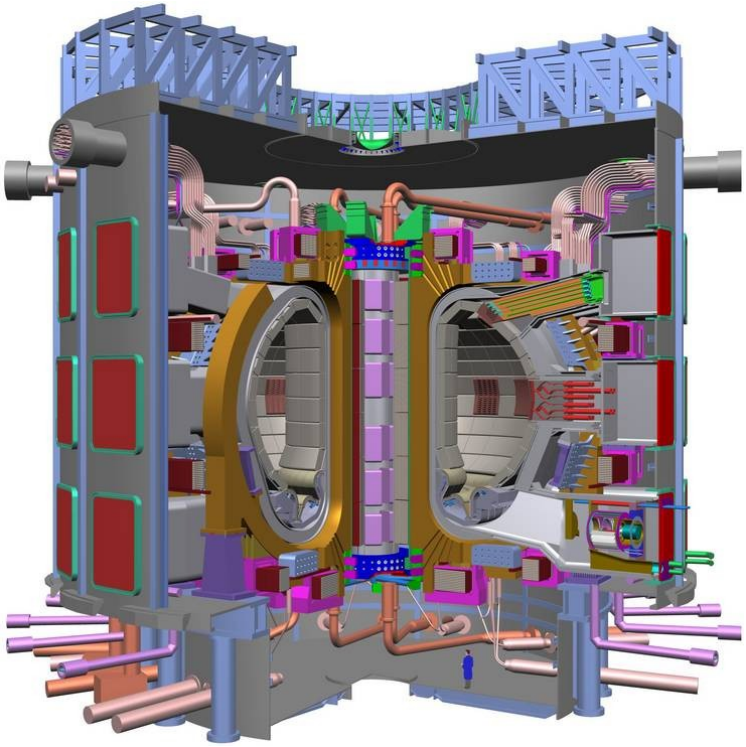
  - Relentless convincing power of RA to obtain ITER construction

    ➔ signature of the ITER agreement in 2006

ITER saga:
an artist view



Any resemblance ….
… would be fortuitous



Q > 10
Size ~ 2xJET

Presse conference

(dialogue réel !!)

Meetings, meetings …
Building a consensus, 7 partners, 34 countries…

In brief

Fusion scientists: owe a lot to R. Aymar

A charismatic leader, generosity in service

Acute sense of logical strategy, thriving in crisis

A heartfelt vote of thanks

from the entire fusion community