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A brief history of controlled thermonuclear fusion

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A brief history of controlled thermonuclear fusion

Keynote speech

Joint ITER-IAEA-ICTP Advanced Workshop
on Fusion and Plasma Physics

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The past
A brief history of fusion research

Wendelstein Ia
Garching, 1960

A brief history of fusion research: pre-history

1905, Albert Einstein: $E = mc^2$

1919, Henry Norris Russell: concise summary of the astronomical hints on the nature of the stellar energy source: most important clue was the high temperature in the interior of stars.

1920, Francis W. Aston: precise measurements of atom masses: four hydrogen nuclei heavier than a helium nucleus.

1920, Arthur Eddington: interpreted Aston's measurement: sun could shine by converting hydrogen atoms into helium, releasing (according to $E=mc^2$) about 0.7% of the mass equivalent of the energy. In principle, this would allow the sun to shine for about 100 billion years.

1939, Hans Bethe: quantitative theory of fusion generation of energy in the sun and the stars (pp cycle).

A brief history of fusion research: birth

First fusion experiments: Cavendish laboratory in Cambridge 1930's.

Lord Rutherford, 1933: Realization that beam – target fusion is impossible:

„Anyone who looks for a source of power in the transformation of the atom is talking moonshine.“

After WW II and the Manhattan Project (nuclear fission bomb): increased interest in nuclear physics and fusion.

First man-made release of fusion energy: 1.11.1952 with H bomb.

Beginning world-wide serious interest in peaceful use of fusion physics.

A brief history of fusion research: first ideas

Magnetic confinement: Kantrowitz and Jacobs, 1938 (NACA, Langley)

„Kantrowitz and Jacobs got the notion that if a very hot plasma could be confined magnetically, a fusion reactor could be built. Jacobs, who had good rapport with NACA headquarters because of his promising work on laminar-flow airfoils, managed to get $5000 from George Lewis for construction of a big aluminum torus with a coiled magnetic device whose purpose would be, Jacobs said, to study the potential of atomic power for aircraft.

... Away went Jacobs and Kantrowitz, trying to excite the plasma to a high enough temperature to produce X-rays. But before they could achieve the necessary temperature, Lewis came by the laboratory one day and happened upon the fusion apparatus. Knowing that nonaeronautical experimental equipment of so radical and dangerous a nature was not appropriate for the NACA, Lewis canceled the project on the spot.

Jacobs and Kantrowitz both considered the cancellation a tragedy since experiments with the torus had led to several important discoveries.“

(source: NASA History Archive)

A brief history of fusion research: infancy

Several approaches in the early 1950's:

- Lyman Spitzer: started „Project Matterhorn“ at Princeton Plasma Physics Laboratory (PPPL) working on a „Figure-of-8“ stellarator.

- James Tuck, Los Alamos: magnetic pinch devices („Perhapstron“).

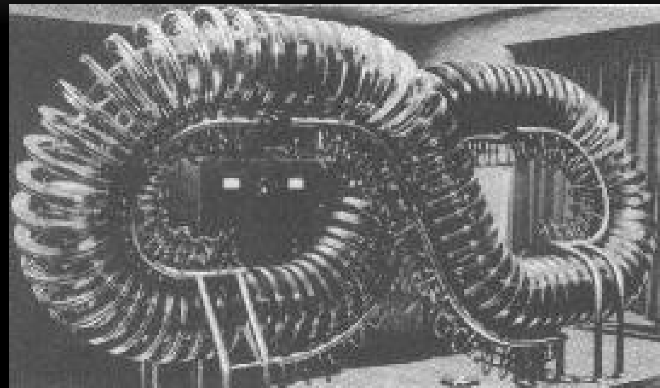
- Edward Teller: expanded work on the H-bomb at Lawrence Livermore Laboratory to include inertial confinement techniques.

- Cousins and Ware (UK) initally built small toroidal pinch; then large-scale experiment „Zero Energy Toroidal Assembly“ ZETA: stabilised toroidal pinch.

However, quite dissapointing results from all initial experiments:

- **instabilities limited confinement**
- **Bohm scaling found for all devices:** $\tau \sim B R^2 / T$

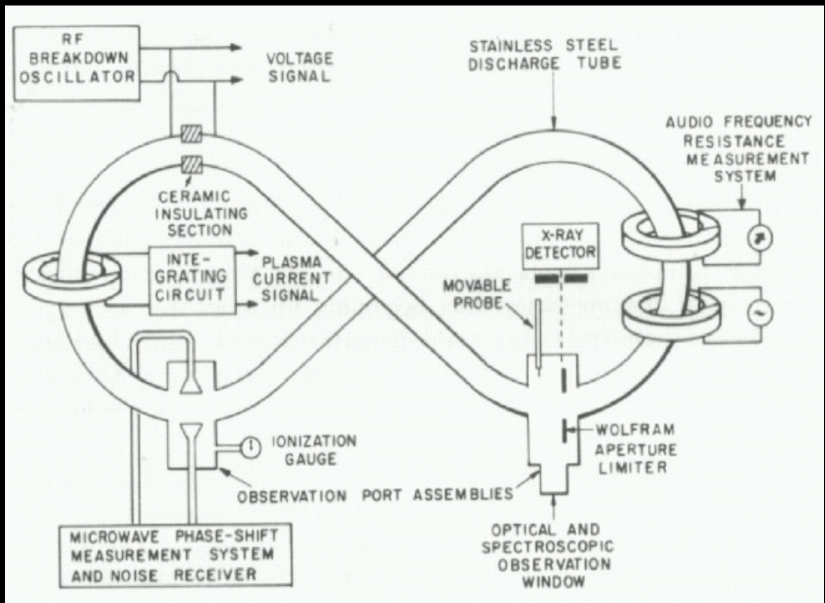
A brief history of fusion research: stellarators

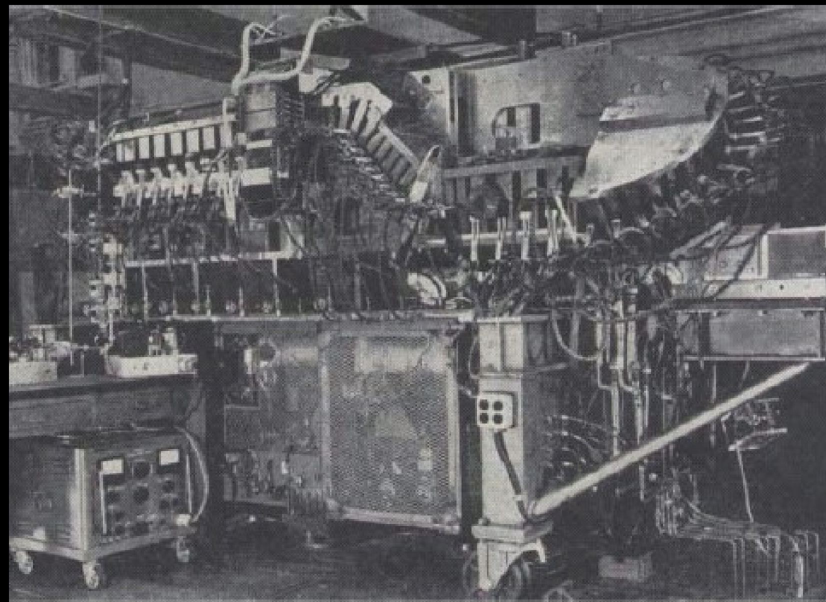


Early stellarators (1950-1965):

- PPPL B- and C- stellarator (US)
- Sirius (SU)
- Wendelstein I (IPP Garching)

Strong particle losses: field inhomogeneity



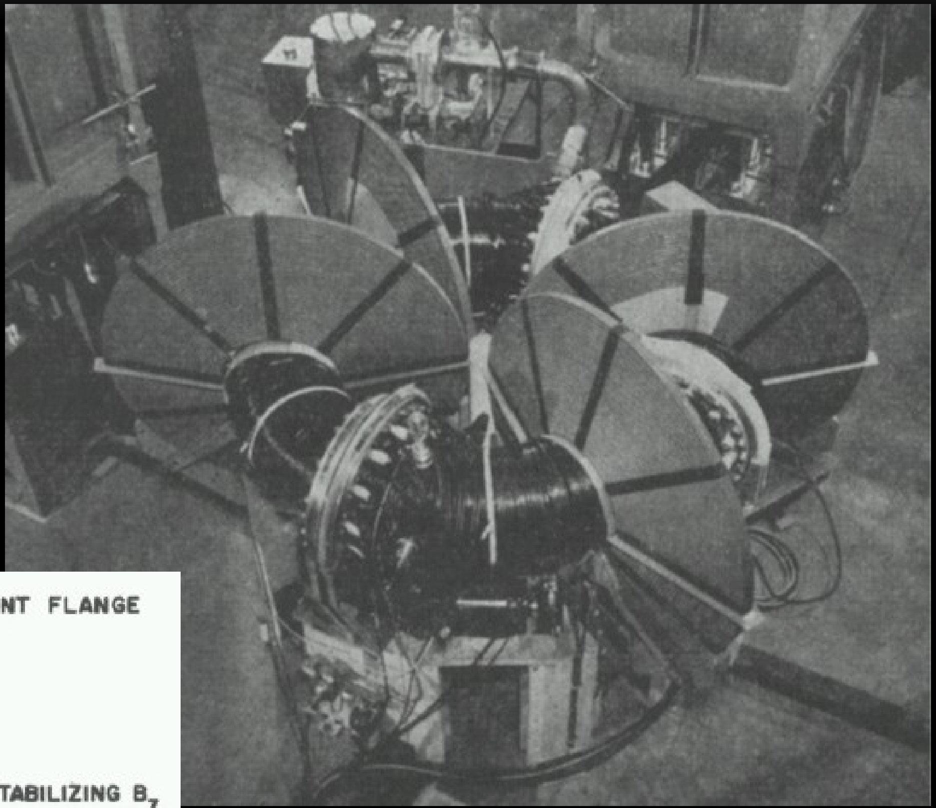


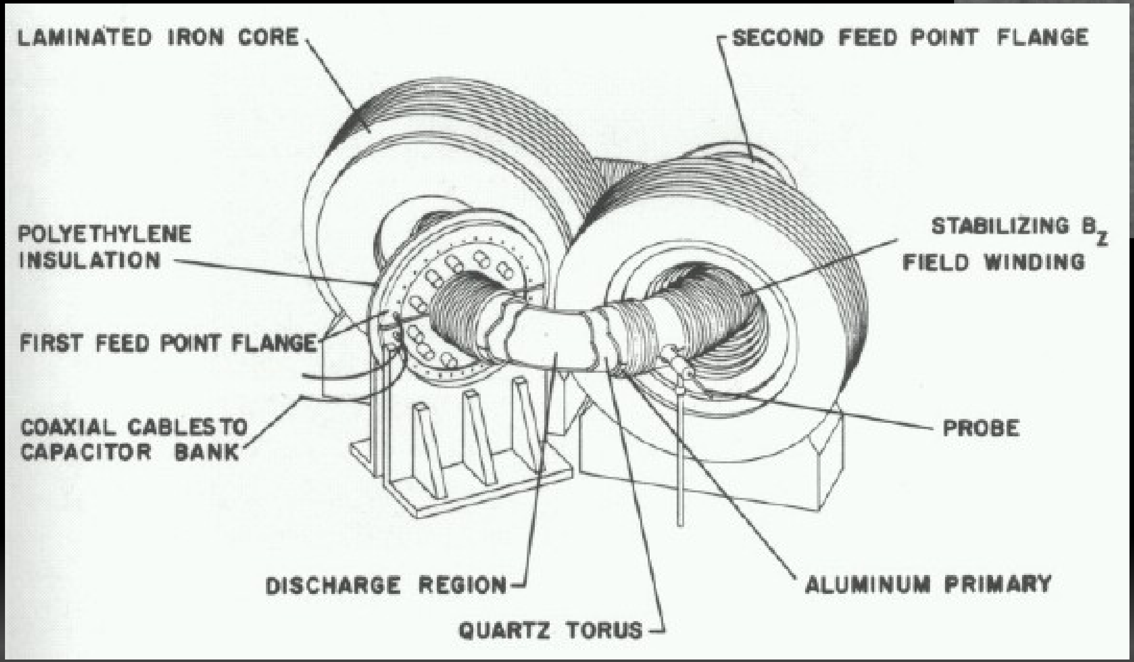
Model B-3 stellarator,
Princeton University

A brief history of fusion research: toroidal pinches

- ZETA (Culham)

- Perhapsatron (Los Alamos)





A brief history of fusion research: first tokamaks

Andrei Sakharov and Igor Tamm (1951):

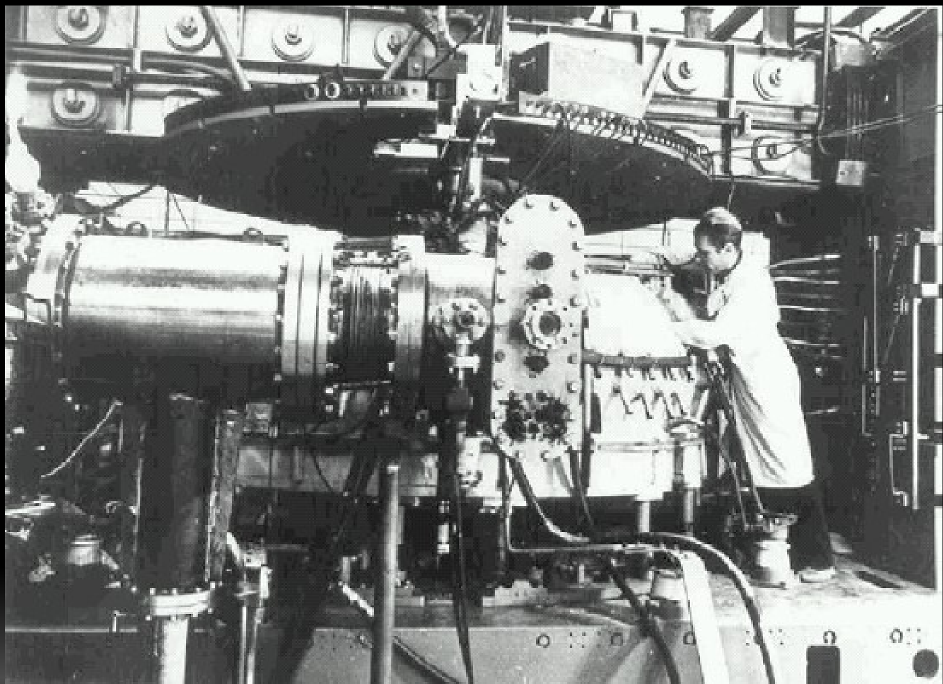
„A second method of antidrift stabilization, which is technically much more admissible and which it is therefore necessary to examine carefully, is the formation of an axial current directly in the plasma by the method of induction. It is not clear if, in using this method, the high temperature plasma is not destroyed at the moment when the induction current vanishes."

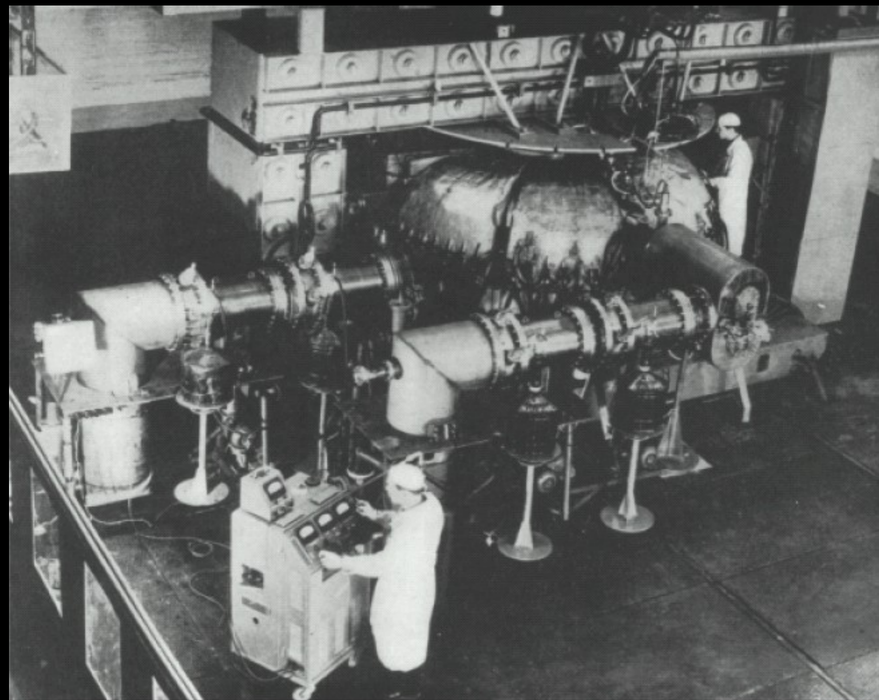
(First method proposed: levitated coil)

A brief history of fusion research: first tokamaks

T-3 Tokamak (Kurchatov, USSR):
<u>to</u>roidalnaya <u>ka</u>mera <u>ma</u>gnitnaya <u>k</u>atushka

- increased stability by larger B_{tor}
- temperatures in keV range
- $\tau > 30\ \tau_{Bohm}$





from 1969: general redirection of fusion research around the world to tokamak experiments

A brief history of fusion research: declassifed

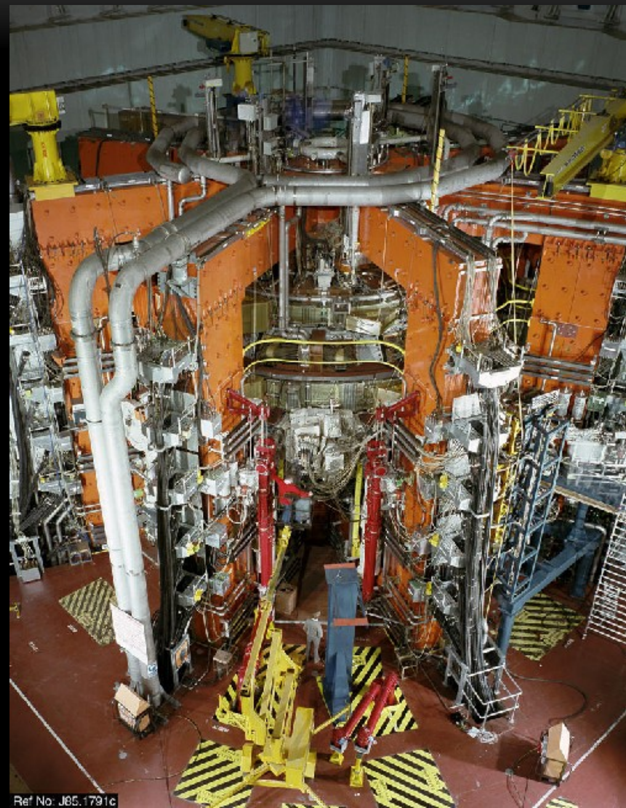
Geneva, 1958: 2nd Conference On Peaceful Uses Of Atomic Energy: US, SU and European states (UK) agree to declassify fusion research

Lev Artsimovich: "This problem [of fusion] seems to have been created especially for the purpose of developing close co-operation between scientists and engineers of various countries, working at this problem according to a common plan, and continuously exchanging the results of their calculations, experiments, and engineering developments."

- New experiments built in France, Germany, Japan etc in the early 1960's (ca 100 tokamaks built since then, but only a few stellarators)

- **IAEA** founded in 1958 with an objective to facilitate international cooperation for nuclear fusion R&D activities.

A brief history of fusion research:
the age of large tokamaks



After relatively better success of first tokamaks:
- development of many diagnostics
- decision to build very large machines:

  - TFTR (Princeton 1974): 1982
  - JET (Culham 1977): 1983
  - JT60 (Tokai 1977): 1985

Aim: approach $Q = P_{fusion} / P_{heating} = 1$ (breakeven)

For design adopted Alcator (or „INTOR“) scaling:

$\tau = 5x10^{-21}\ n\ a^2$ → JET mean minor radius: a = 1.5 m

1978 IAEA initiates reactor concept study: INTOR

A brief history of fusion research: INTOR study

1980 „International Tokamak Reactor“
INTOR concept study (based on Alcator scaling)

Suggested INTOR parameters (1980)		ITER-FDR (1998):	ITER- FEAT (2001):
Major radius, R_0	5.2 m	8.14 m	6.2 m
Minor radius, a	1.3 m	2.8 m	2.0 m
Elongation, $k = b/a$	1.6	1.6	1.70/1.85
Toroidal field at centre $B_t(0)$	5.5 T	5.68 T	5.3 T
Plasma current, I	6.4 MA	21 MA	15-17 MA
Average D–T density, n_i	$1.3–1.5 \times 10^{20}$ m^{-3}	0.98×10^{20} m^{-3}	1.1×10^{20} m^{-3}
Average ion temperature, T_i	10 keV	12.8 keV	8.9 keV
Average $\langle\beta\rangle$	5–6%	3 %	2.8 %
D–T thermal power, P_{th}	620–750 MW	1500 MW	500-700 MW
Burn time (s)	$\geqslant$100	> 1000	> 400

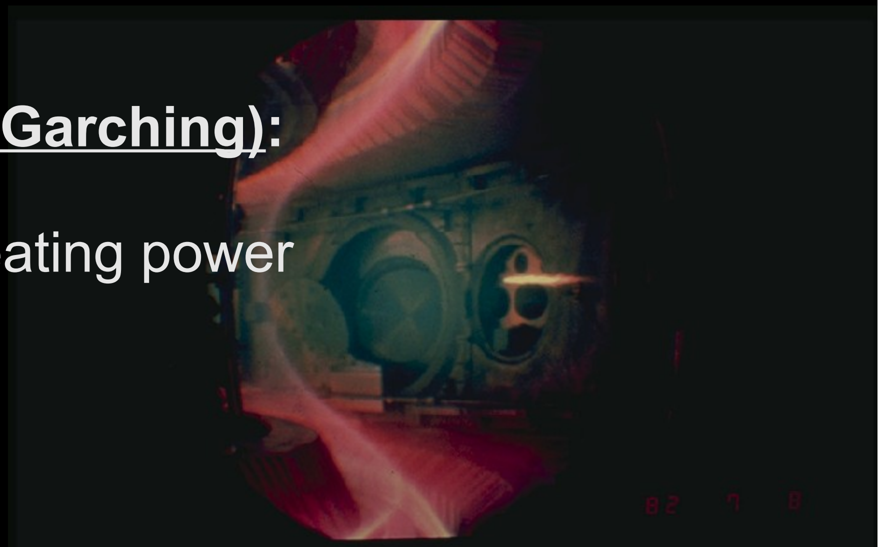
A brief history of fusion research: revolutions

Development of additional heating methods in the 1970's:
- hot particle (neutral beam) injection (NBI)
- radio frequency (RF) heating (at ion and electron cyclotron resonances)

→ Temperatures of several keV achieved in large devices in early 1980's

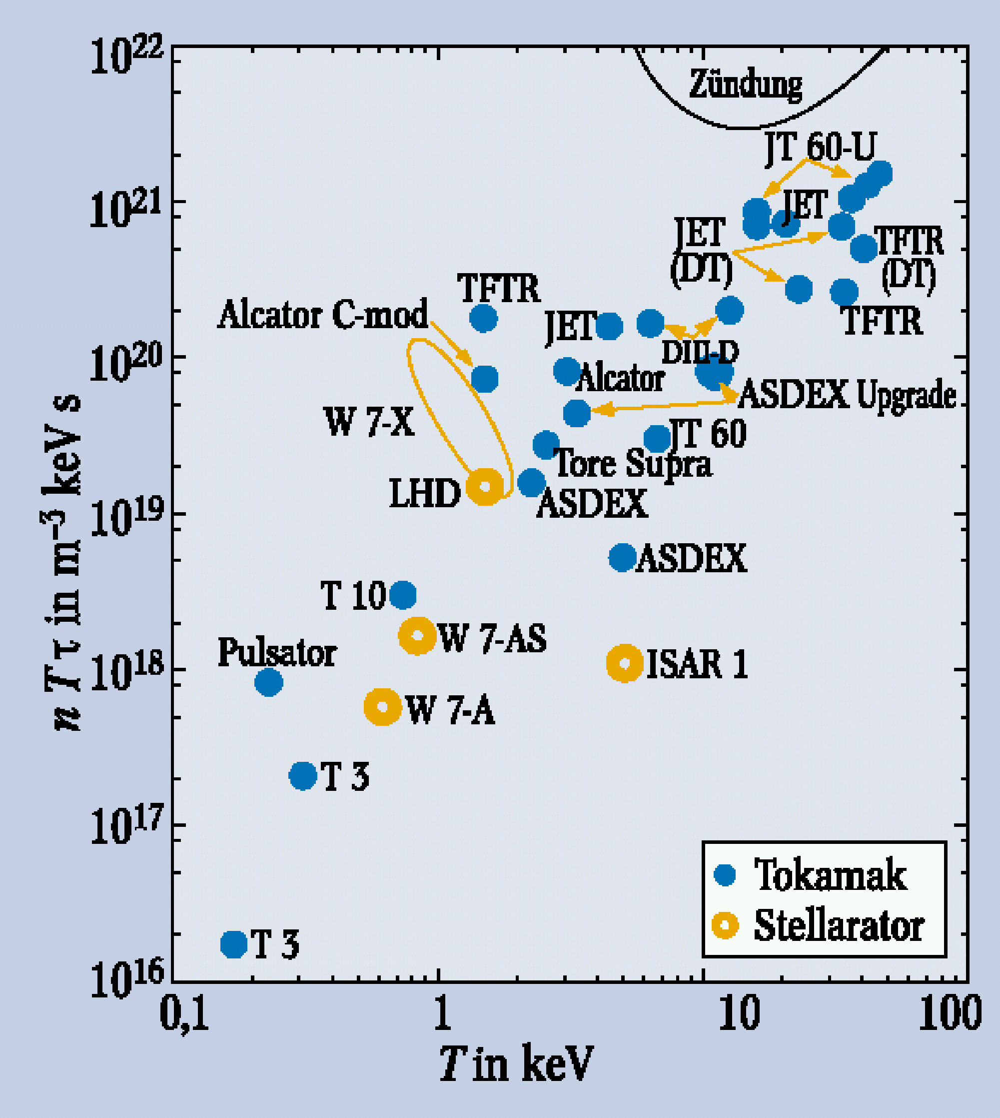
Thus: clarification on **confinement scalings** possible
→ τ deteriorates with increasing heating/temperature: INTOR scaling invalid !
→ „anomalous“ (turbulent) transport

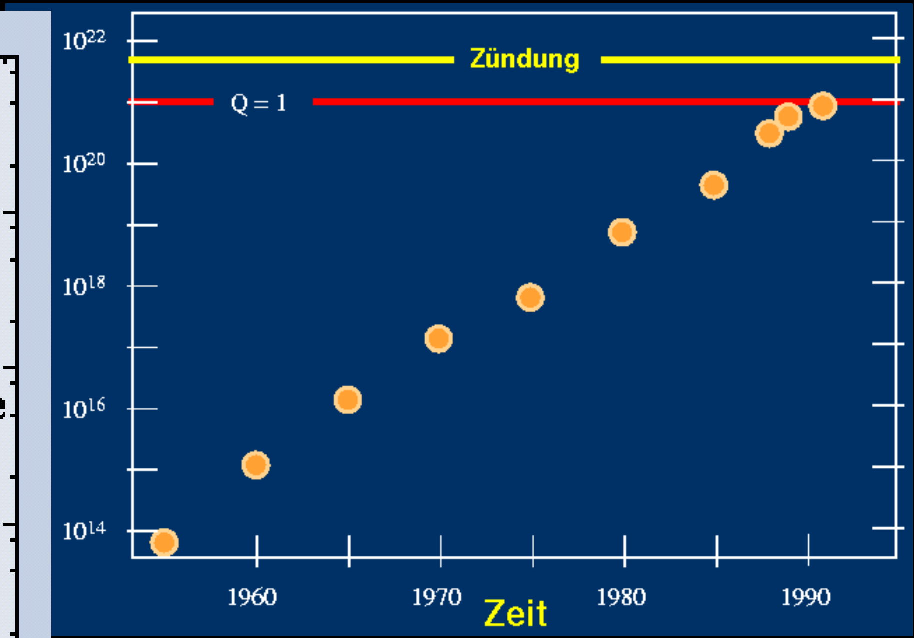
Discovery of the H-mode at ASDEX (IPP Garching):
→ abrupt transition to higher confinement
- at sufficiently high threshold level of heating power
- in a divertor tokamak



Improvements in plasma theory:
turbulence, tearing modes, MHD, ...

A brief history of fusion research: evolutions

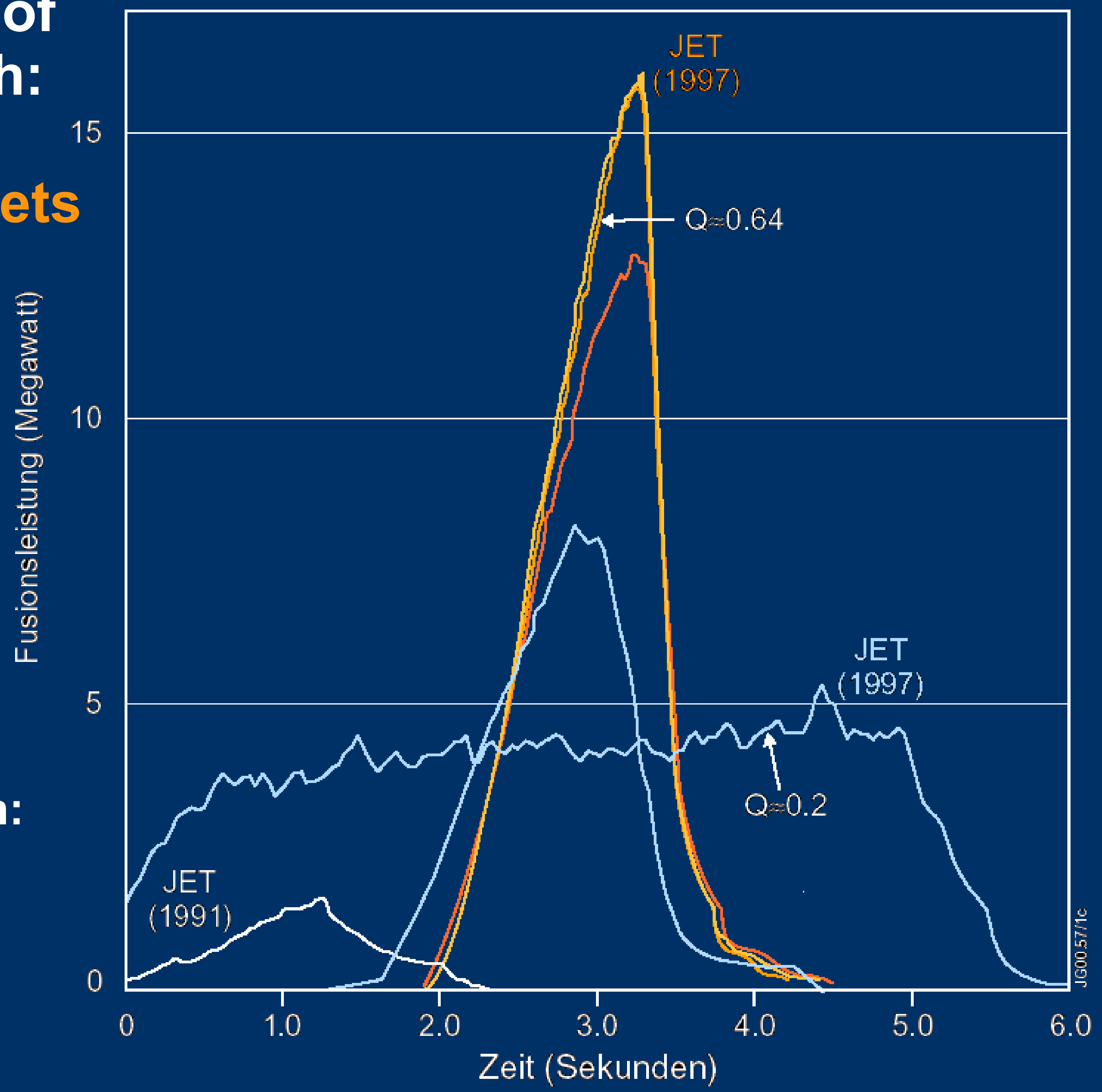




Development of the fusion product $n \cdot \tau \cdot T$ (m^3 s keV)

A brief history of fusion research:

as good as it gets



1997 D-T campaign:

Q = 0.64

P = 16 MW

A brief history of fusion research: ITER initiation

- 1985: Geneva Gorbachev-Reagan summit: fusion reactor initiative
- 1988-1990: ITER conceptual design activities by EU, US, USSR and Japan
- 1992: agreement on 6-year ITER design activities under auspices of IAEA
- 1998: ITER final design report, cost review and safety analysis (FDR)

However: parties did not appreciate the cost estimate of ca. 10^{10} $ ...

ITER Council: "*Continue efforts with high priority toward establishing option of minimum cost aimed at a target of approximately 50% of the direct capital cost of the present design with reduced detailed technical objectives, which would still satisfy the overall programmatic objective of ITER. The work should follow the adopted technical guidelines and make the most cost-effective use of existing design solutions and their associated R&D*."

→ EDA extended to July 2001 to cover this work
(in spite of US decision to leave project by end of 1999 fiscal year)

ITER - FDR 1998 specifications:
Plasma performance

The device should:

- achieve **extended burn in inductively driven plasmas** with the ratio of fusion power to auxiliary heating power of at least **$Q > 10$** for a range of operating scenarios and with a duration sufficient to achieve stationary conditions on the timescales characteristic of plasma processes.

- aim at **demonstrating steady-state operation** using non-inductive current drive with the ratio Q of fusion power to input power for current drive of at least **$Q > 5$**.

In addition, the possibility of controlled ignition should not be precluded.

ITER - FDR 1998 specifications:
Engineering performance and testing

The device should:

- demonstrate the availability and integration of technologies essential for a fusion reactor (such as superconducting magnets and remote maintenance);

- test components for a future reactor (such as systems to exhaust power and particles from the plasma);

- test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat, and electricity production.

ITER – FDR 1998 specifications:
Design requirements

- Engineering choices and design solutions should be adopted which implement the above performance requirements and make maximum appropriate use of existing R&D database (technology and physics) developed for ITER.

- The choice of machine parameters should be **consistent with margins that give confidence** in achieving the required plasma and engineering performance in accordance with physics design rules documented and agreed upon by the ITER Physics Expert Groups.

- The design should be **capable of supporting advanced modes** of plasma operation under investigation in existing experiments, and should **permit a wide operating parameter space** to allow for optimising plasma performance.

- The **option for later installation of a tritium breeding blanket** on the outboard of the device should not be precluded.

ITER - FDR 1998 specifications:
Design requirements

- In order to satisfy the above plasma performance requirements an **inductive flat top capability during burn of 300 to 500 s**, under nominal operating conditions, should be provided.

- In order to **limit the fatigue** of components, operation should be **limited to a few 10s of thousands of pulses**.

- In view of the goal of demonstrating steady-state operation using non-inductive current drive in reactor-relevant regimes, the machine design should be **able to support equilibria with high bootstrap current fraction** and **plasma heating dominated by alpha particles**.

- To carry out **nuclear and high heat flux component testing** relevant to a future fusion reactor, the engineering requirements are
    - Average neutron flux: 0.5 MW/m^2
    - Average fluence: 0.3 MWa/m^2

ITER - FDR 1998 specifications: Operation requirements

The operation should address the issues of burning plasma, steady state operation and improved modes of confinement, and testing of blanket modules.

- **Burning plasma experiments** will address confinement, stability, exhaust of helium ash, and impurity control in plasmas dominated by alpha particle heating.

- **Steady state experiments** will address issues of non-inductive current drive and other means for profile and burn control and for achieving improved modes of confinement and stability.

- Operating modes should be determined having sufficient reliability for nuclear testing. Provision should be made for low-fluence functional **tests of blanket modules** to be conducted early in the experimental programme. Higher fluence nuclear tests will be mainly dedicated to DEMO-relevant blanket modules in the above flux and fluence conditions.

In order to execute this program, the device is anticipated to **operate over an approximately 20 year period**.

ITER - FEAT 2001

July 21st, 2001:
ITER engineering design activities were successfully completed, and the final design report was made available to the ITER parties.

The design was underpinned by R & D work worth $650M, carried out by the ITER parties to establish the practical feasibility of the design.

The physics and technology experiments conducted in many fusion devices worldwide have provided a solid physics base for extrapolation to the ITER scale. A number of key high-technology components, such as superconducting coils, have been developed specifically and manufactured by industry and are ready for production.

ITER - partners

A number of changes occurred in the partners participating to the ITER project:

Following the collapse of the Sovjet Union, the Russian Federation took its place as ITER partner.

The USA temporarily opted out of the project in 1999, to return in 2003.

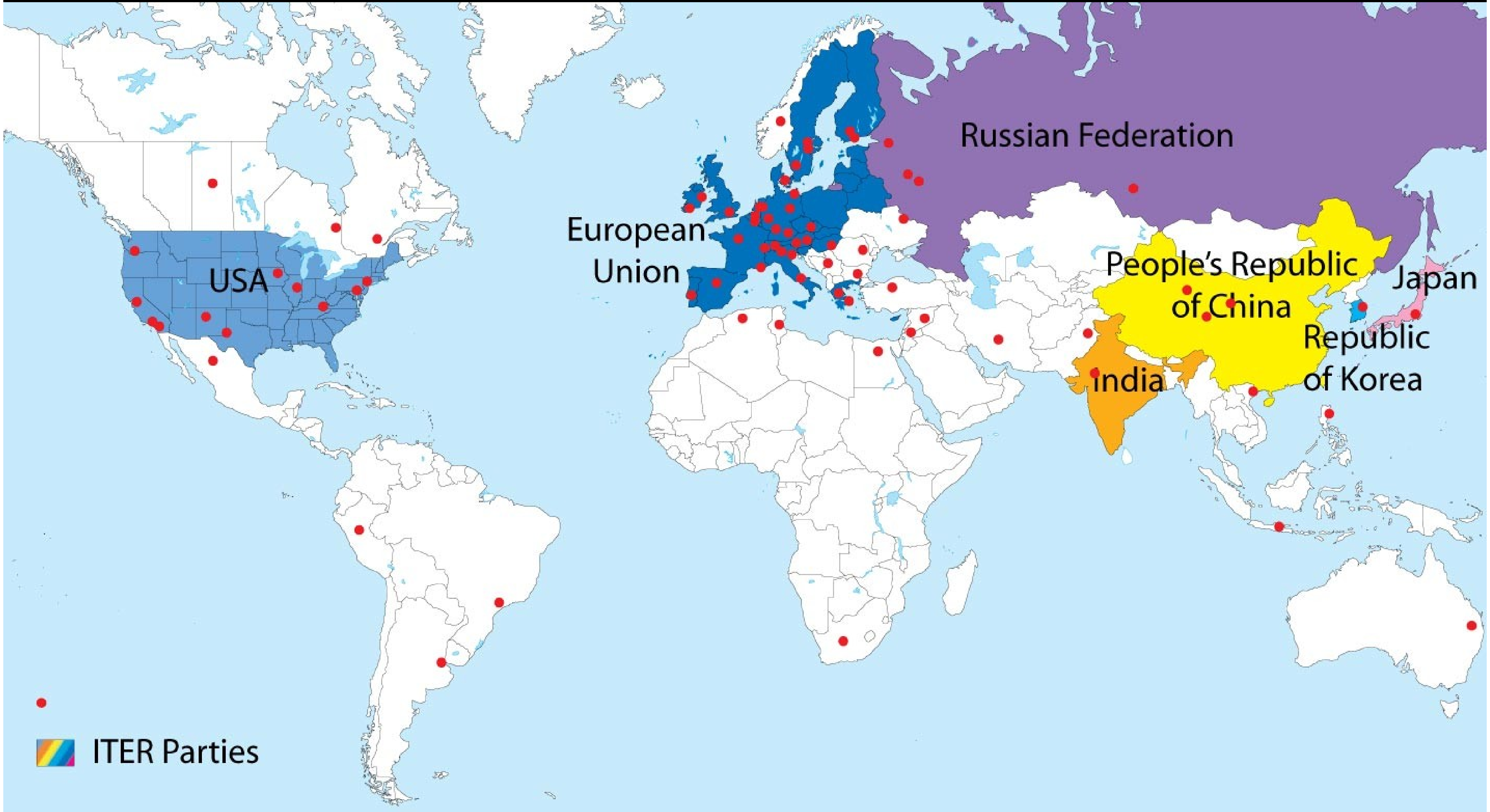
Canada become a partner in 2001, and left the project at the end of 2003.

The People´s Republic of China and the Republic of Korea both joined the project in 2003, and finally India joined in December 2005.

Presently, the partners are European Union, China, India, Japan, South Korea, the Russian Federation and the USA.

ITER - partners 2008

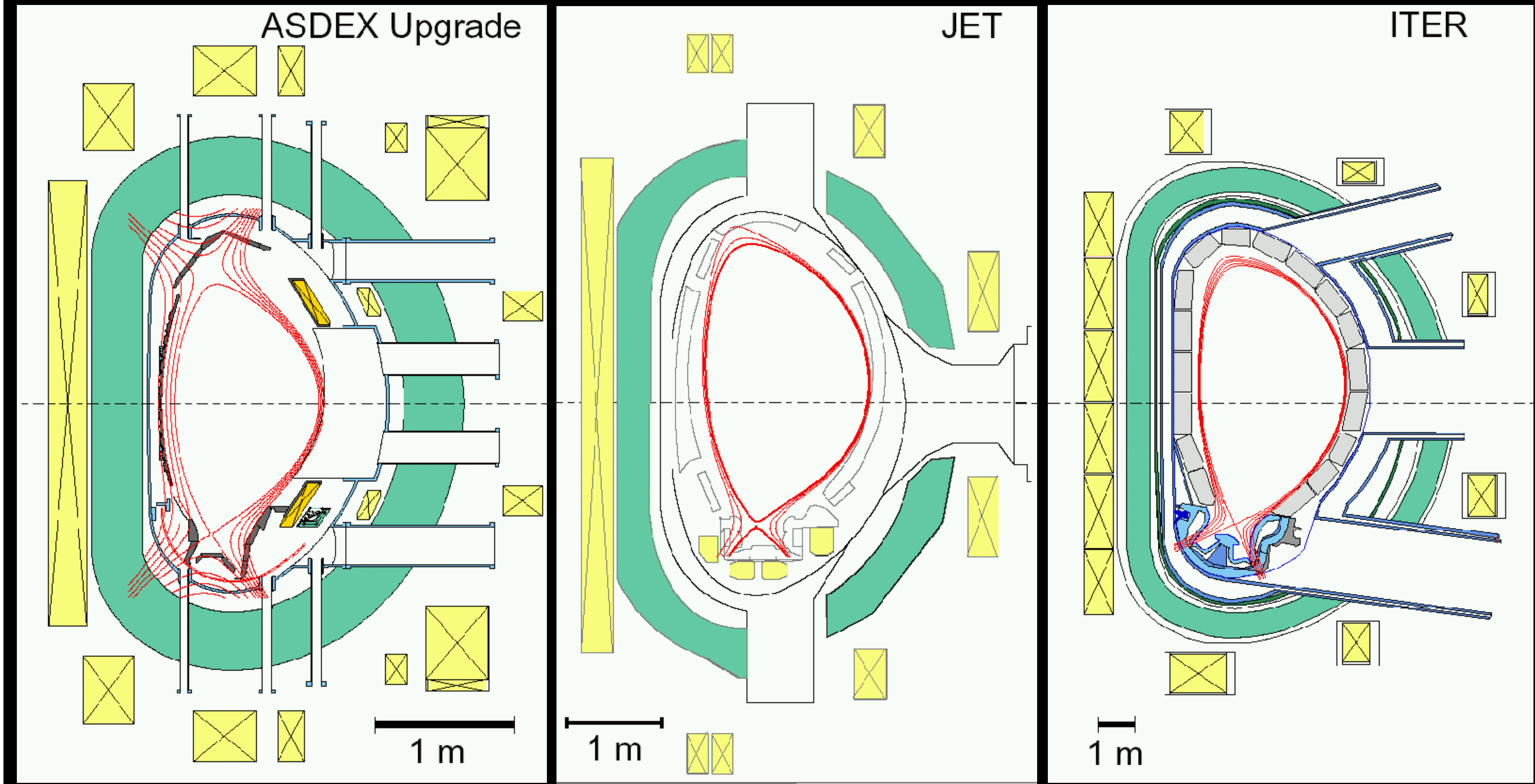
(figure: EFDA; red dots: fusion research laboratories)



ITER:
main plasma parameters and dimensions

Total Fusion Power	500 MW (700 MW)
Q - fusion power/additional heating power	> 10
Average 14MeV neutron wall loading	0.57 MW/m2 (0.8 MW/m^2)
Plasma inductive burn time	> 400 s
Plasma major radius (R)	6.2 m
Plasma minor radius (a)	2.0 m
Plasma current (Ip)	15 MA (17 MA)
Vertical elongation @ 95% flux surface/separatrix (k95)	1.70/1.85
Triangularity @ 95% flux surface/separatrix (d95)	0.33/0.49
Safety factor @ 95% flux surface (q95)	3.0
Toroidal field @ 6.2 m radius (BT)	5.3 T
Plasma volume	837 m^3
Plasma surface	678 m^2
Installed auxiliary heating/current drive power	73 MW

ITER: plasma cross section



(Figures have different scales!)

ITER - site selection

The process of selecting a location for ITER took a long time, and was finally successfully concluded in 2005.
Canada was first to offer a site in Clarington, in May 2001.
Soon after, Japan proposed the Rokkasho-Mura site,
Spain offered a site at Vandellòs near Barcelona,
and France proposed the Cadarache site in the south of France.

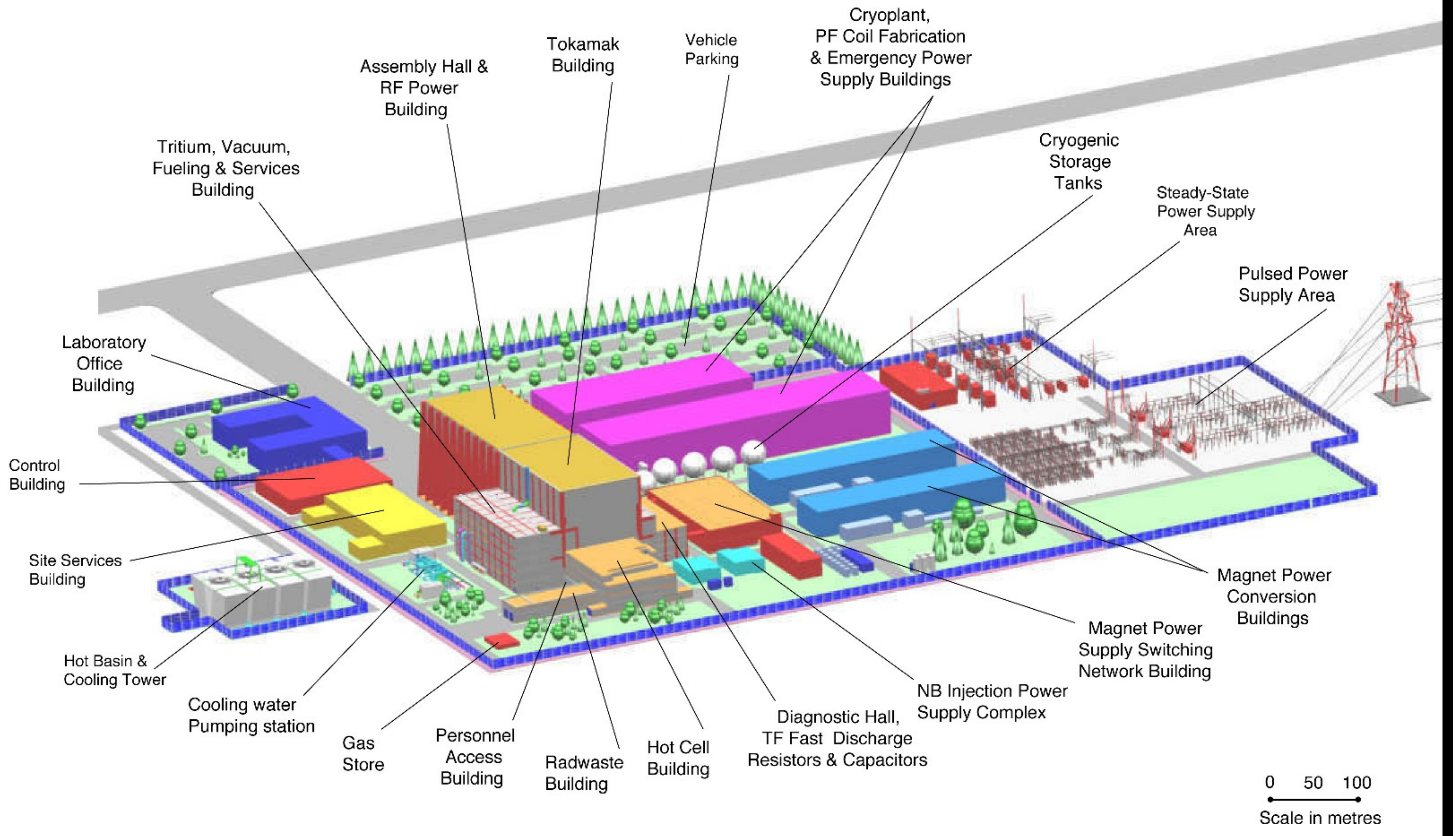
Canada withdrew from the race in 2003, and the EU decided in November 2003 to concentrate its support on a single European site, for which the French site Cadarache was chosen.
From that point onwards, the choice was between France and Japan.

On June 28, 2005 it was officially announced that ITER will be built in the EU at Cadarache. The negotiations that led to the decision ended in the EU and Japan having a "privileged partnership".

(Japan expected to fund 10%, was promised 20% of the research staff and the right to propose the Director General of ITER. In addition, a part of Europe´s contribution will be purchased in Japan. Another research facility for the ITER project will be built in Japan, for which the European Union has agreed to contribute about 50% of the costs.)

The Cadarache ITER site

The Cadarache ITER site



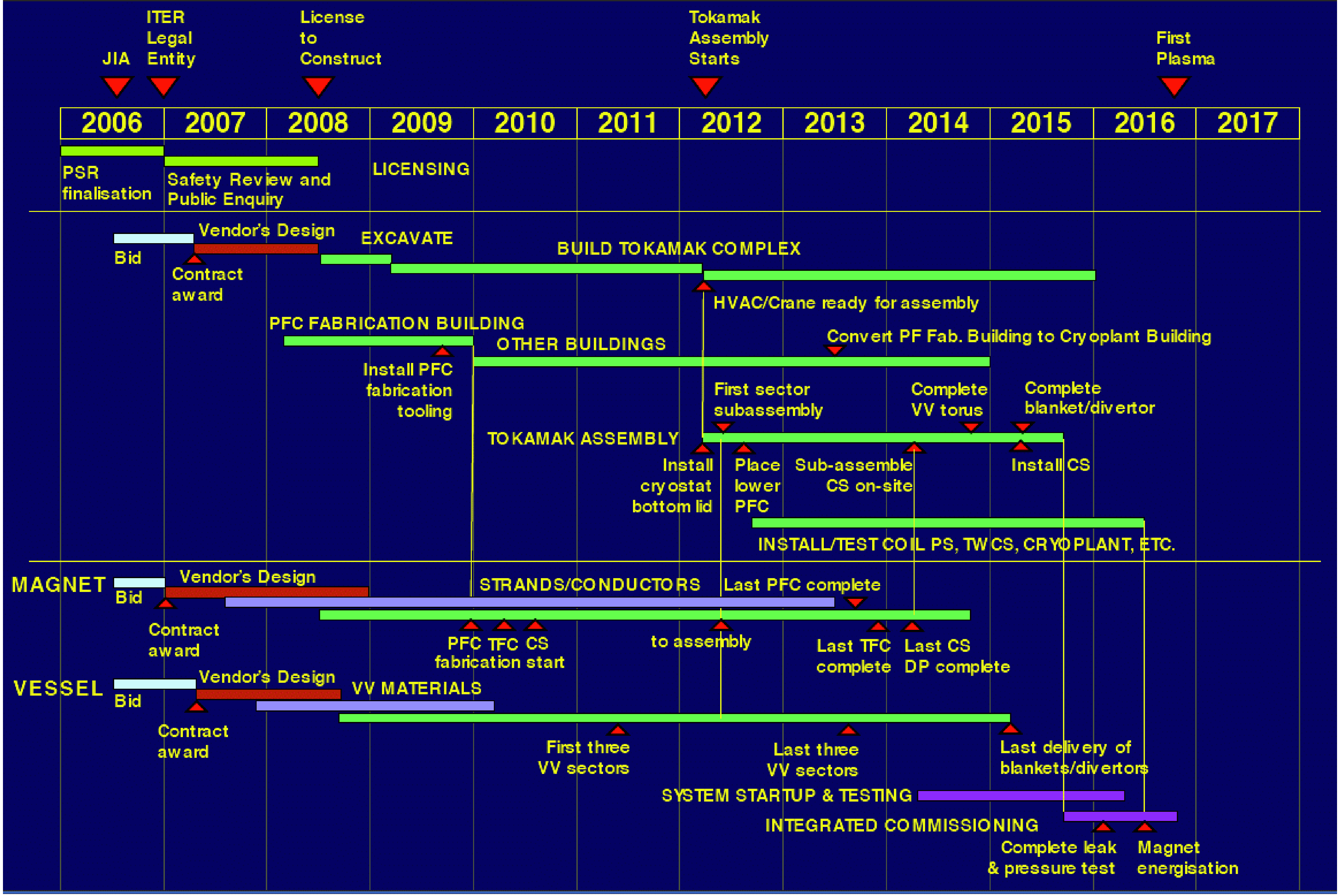
ITER Viewed From North East

ITER - official foundation in 2006

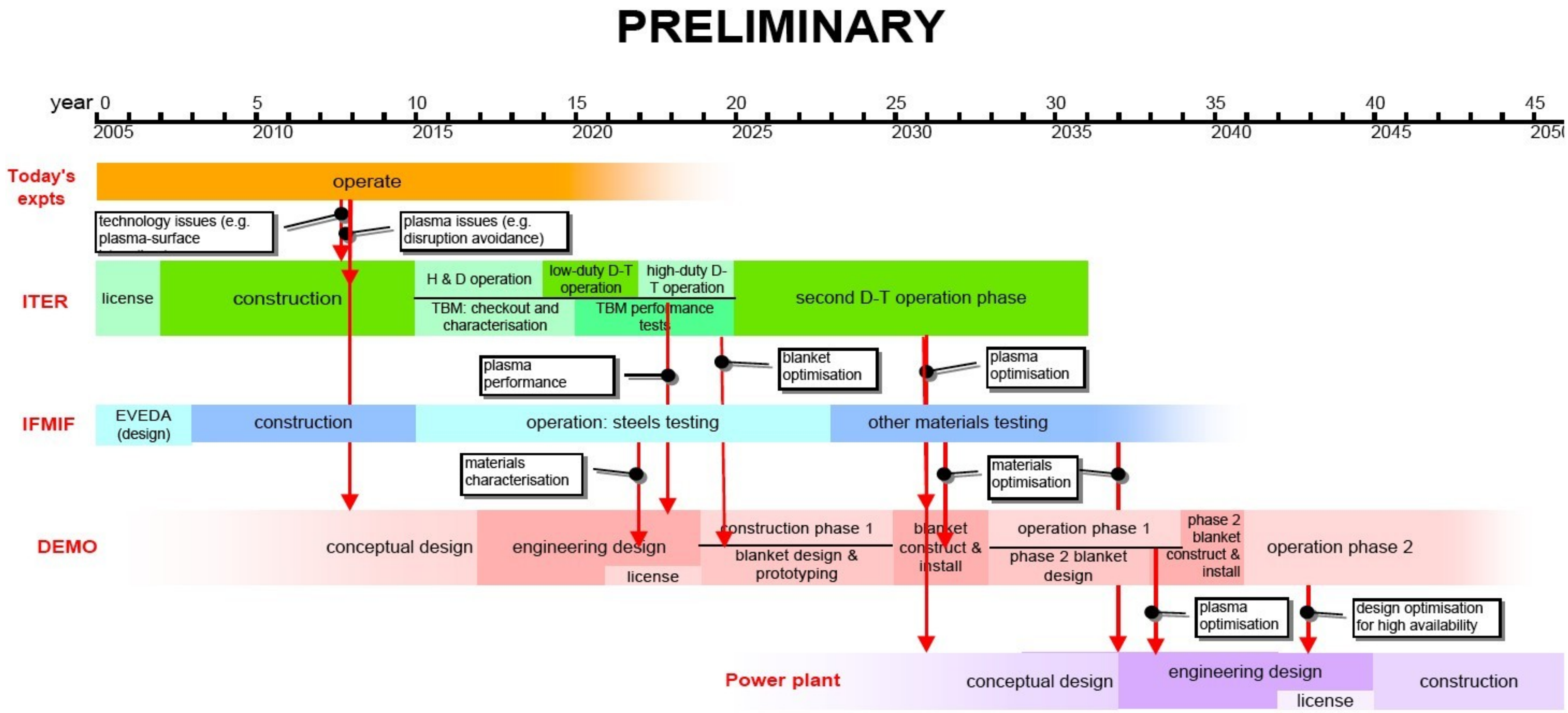
On 21.11.2006, Ministers from the seven Parties of the international nuclear fusion project ITER (China, European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States of America) came together to sign the agreement to establish the international Organization that will implement the ITER fusion energy project.

The signature took place at a ceremony at the Elysée Palace in Paris and was hosted by the President of the French Republic M. Jacques Chirac and by the President of the European Commission, M. José Manuel Durão Barroso.

ITER - (original) timeline



Beyond ITER



PRELIMINARY
year
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5
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15
20
25
30
35
40
45
2005
2010
2015
2020
2025
2030
2035
2040
2045
Today's expts
operate
technology issues (e.g. plasma-surface
plasma issues (e.g. disruption avoidance)
ITER
license
construction
H & D operation
low-duty D-T operation
high-duty D-T operation
TBM: checkout and characterisation
TBM performance tests
second D-T operation phase
plasma performance
blanket optimisation
plasma optimisation
IFMIF
EVEDA (design)
construction
operation: steels testing
other materials testing
materials characterisation
materials optimisation
DEMO
conceptual design
engineering design
license
construction phase 1
blanket design & prototyping
blanket construct & install
operation phase 1
phase 2 blanket design
phase 2 blanket construct & install
operation phase 2
plasma optimisation
design optimisation for high availability
Power plant
conceptual design
engineering design
license
construction