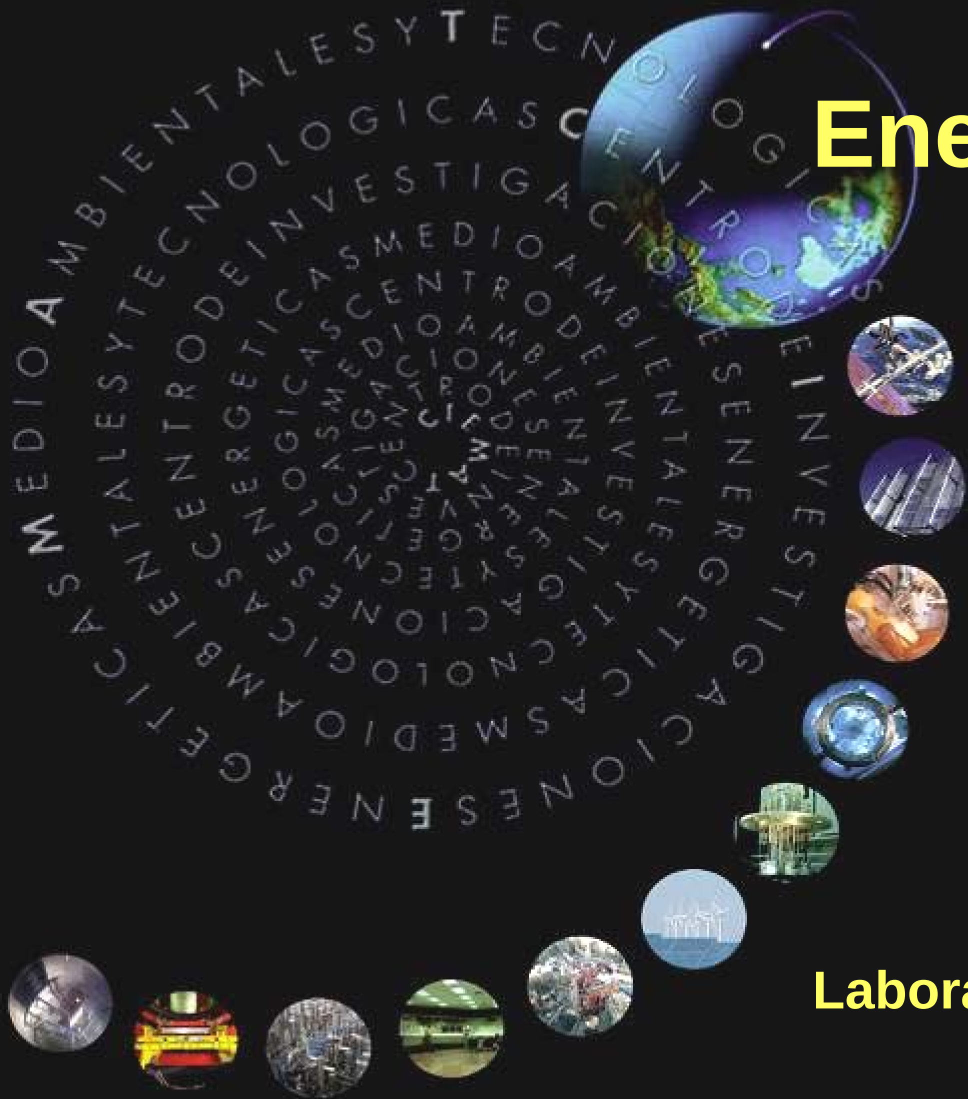
ENERGÍA DE FUSIÓN NUCLEAR

Joaquín Sánchez
Laboratorio Nacional de Fusión
CIEMAT

Energía de Fusión Nuclear



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MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Energía

La población mundial consume 12.000 GW (2.300 w/persona)

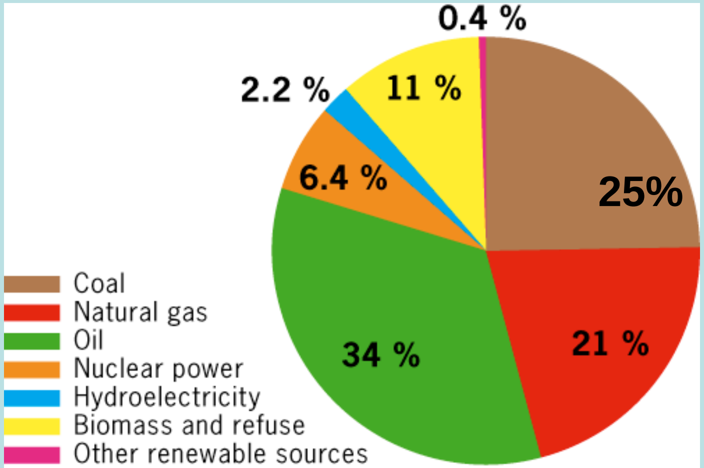
Consumo desigual:

OCDE 6000 W/persona (1100 M)
Resto 1500 W/persona (5000 M)

Se espera un crecimiento de al menos 50% para 2030

80% de la energía: combustibles fósiles

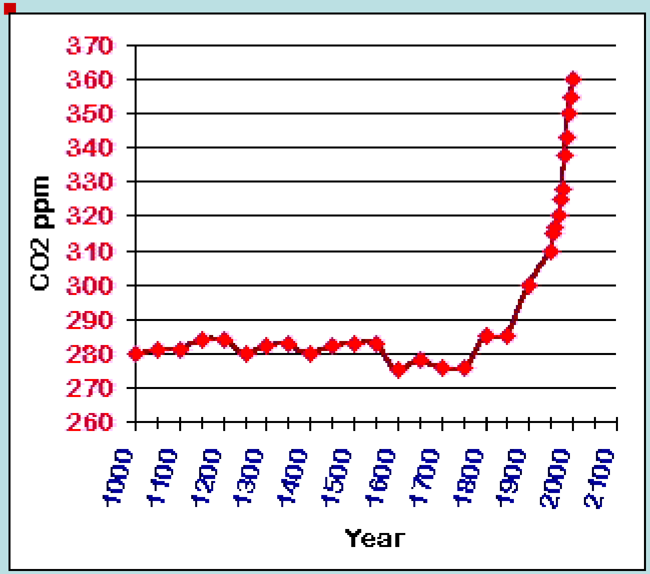
80% energía : combustibles fósiles



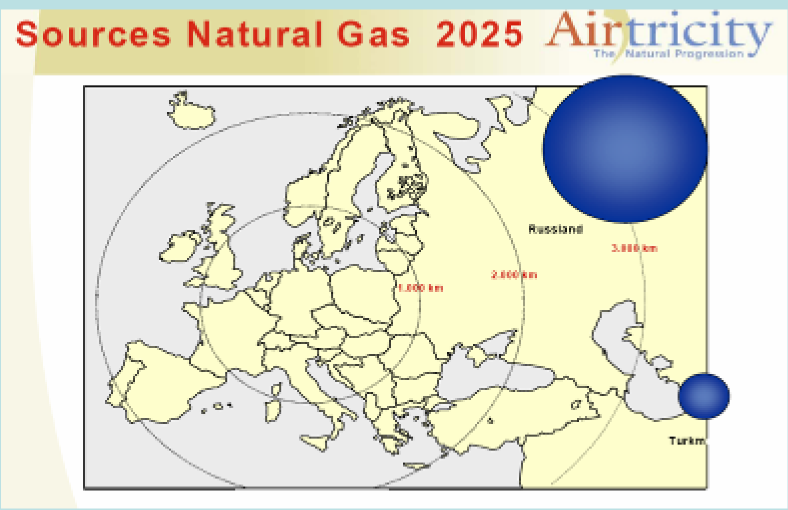
(IEA World Energy Outlook 2006)

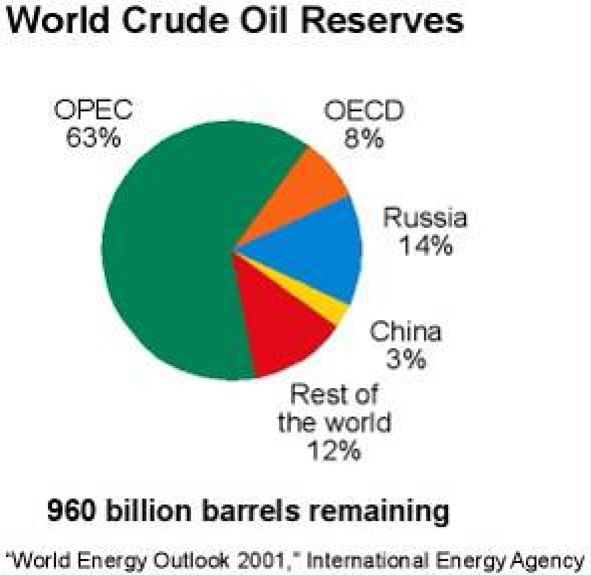
Problemas:

- Contaminación
- Emisión de CO2



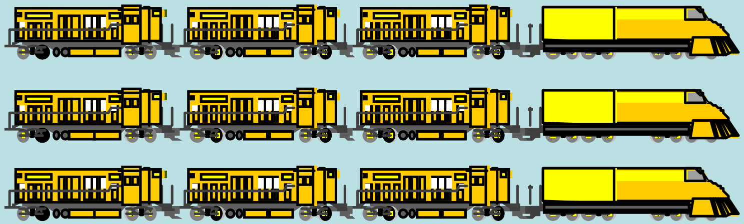
- Garantía de suministro, precio



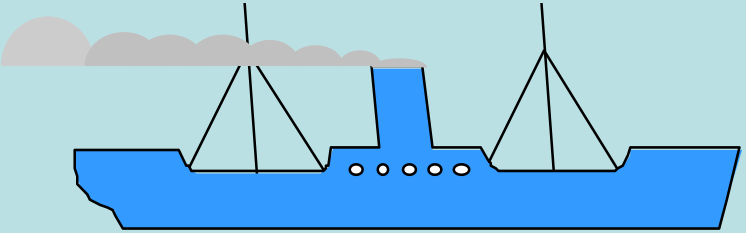


Central Eléctrica 1000 MWe

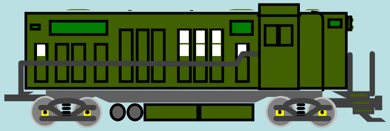
Carbón
- 250 trenes
  100 vagones cada uno
- 2.500.000 Toneladas



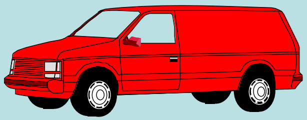
Petróleo
- 10 superpetroleros
- 11.000.000 Barriles



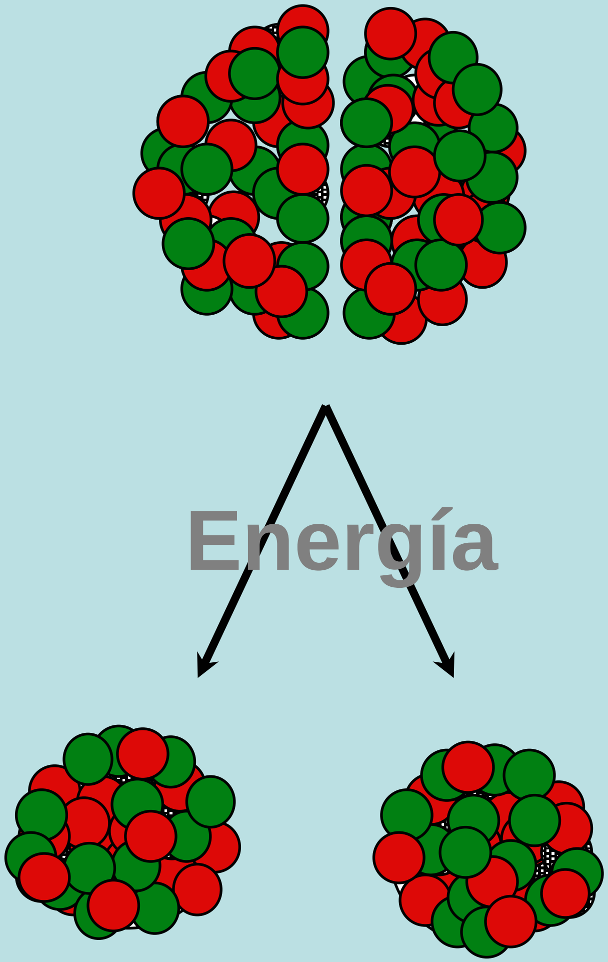
Fisión
- Un vagón
- 28 toneladas



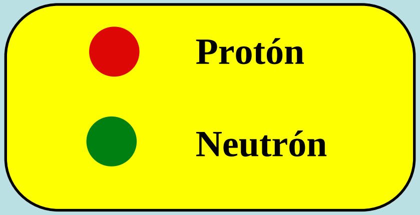
Fusión
- Furgoneta
- 1000 Kgs.

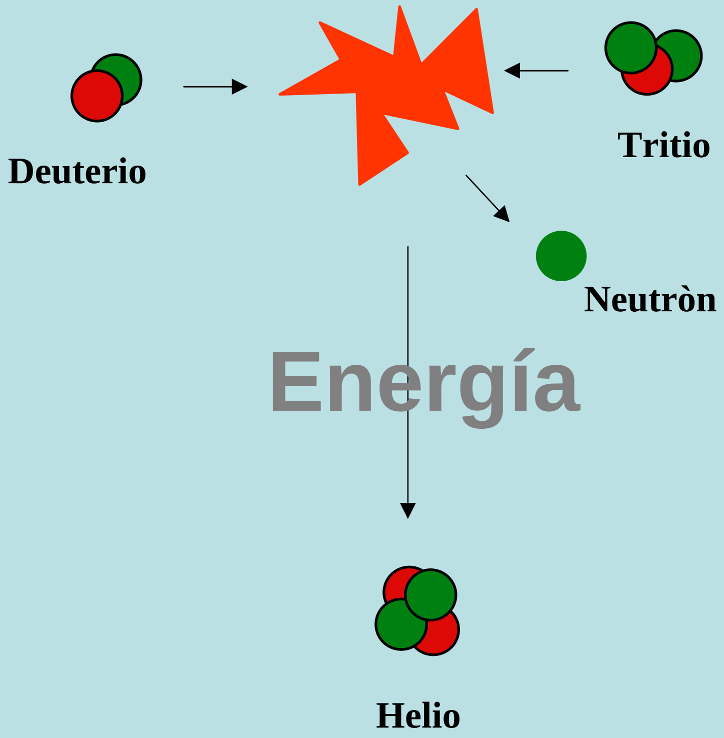


Fisión-Fusión



Fisión





Fusión

Reacciones posibles

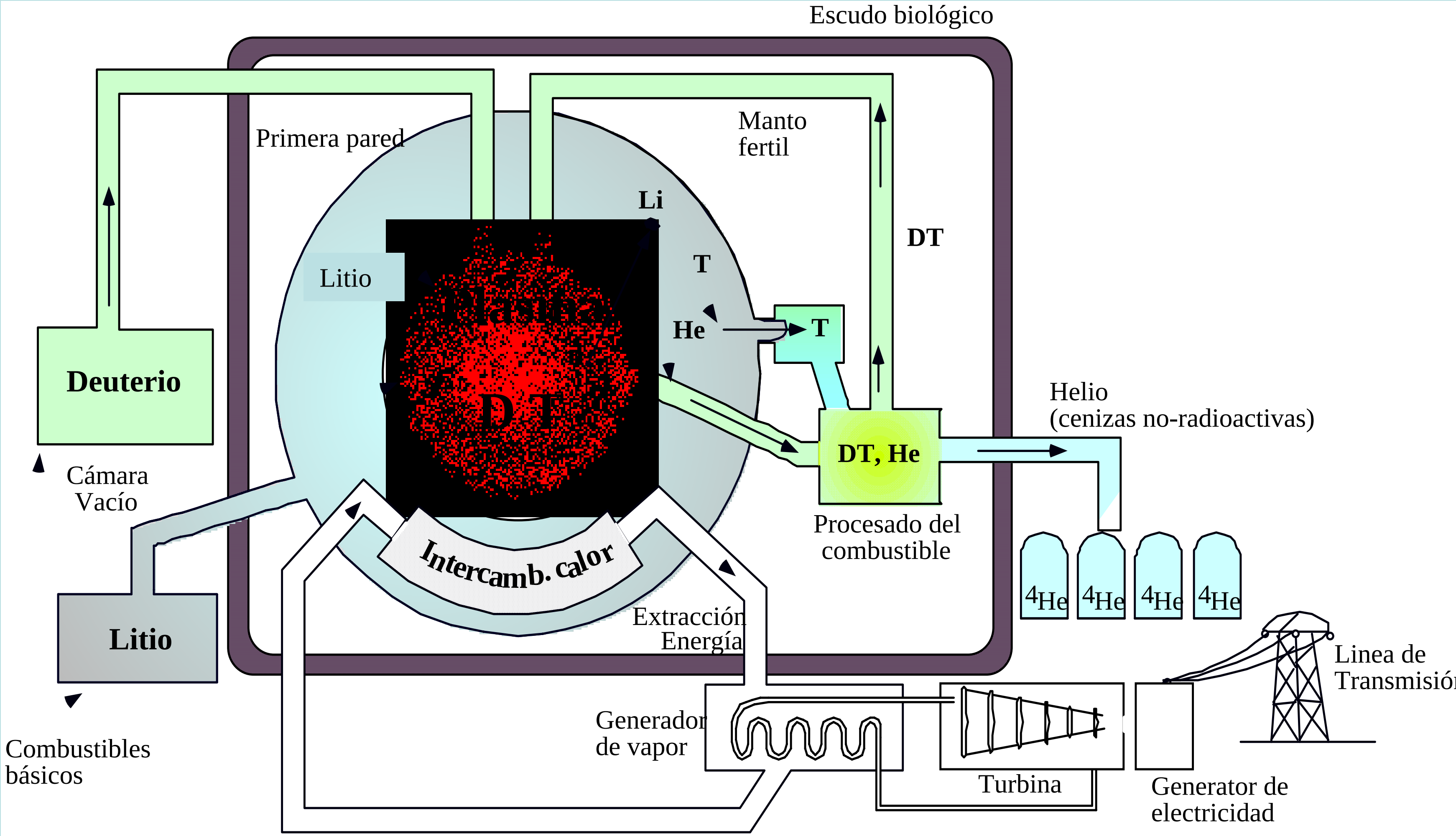
$${}_1D^2 + {}_1D^2 \rightarrow {}_1T^3 + {}_1H^1 + 4.03\ \mathrm{MeV}$$

$${}_1D^2 + {}_1D^2 \rightarrow {}_2He^3 + {}_0n^1 + 3.27\ \mathrm{MeV}$$

➢➢➢➢➢➢ $${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1 + 17.6\ \mathrm{MeV}$$

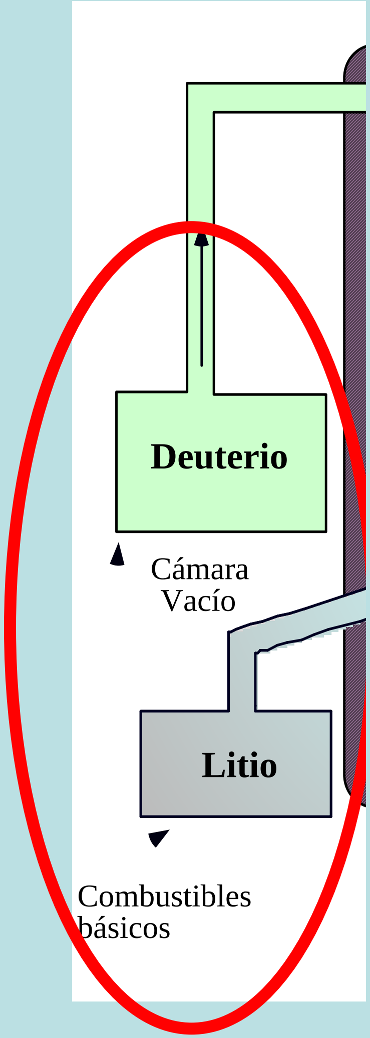
$${}_1D^2 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + 18.3\ \mathrm{MeV}$$

Planta de Fusión



$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 \text{ (3.6 MeV)} + {}_0n^1 \text{ (14 MeV)}$$

Planta de Fusión



El "combustible":

- **Deuterio** del agua del mar: 0.33 mg/litro

(Tritio) : se obtiene in-situ a partir del Litio mediante la reacción:

$$\mathbf{Li_6 + n \rightarrow He_4 + T_3\ (+4.8\ MeV)}$$

- **Litio**: de sales marinas o minas de sal

Abundante y distribuido por todo el planeta

- El litio de la batería de un portátil: energía que consume un europeo durante 20-30 años

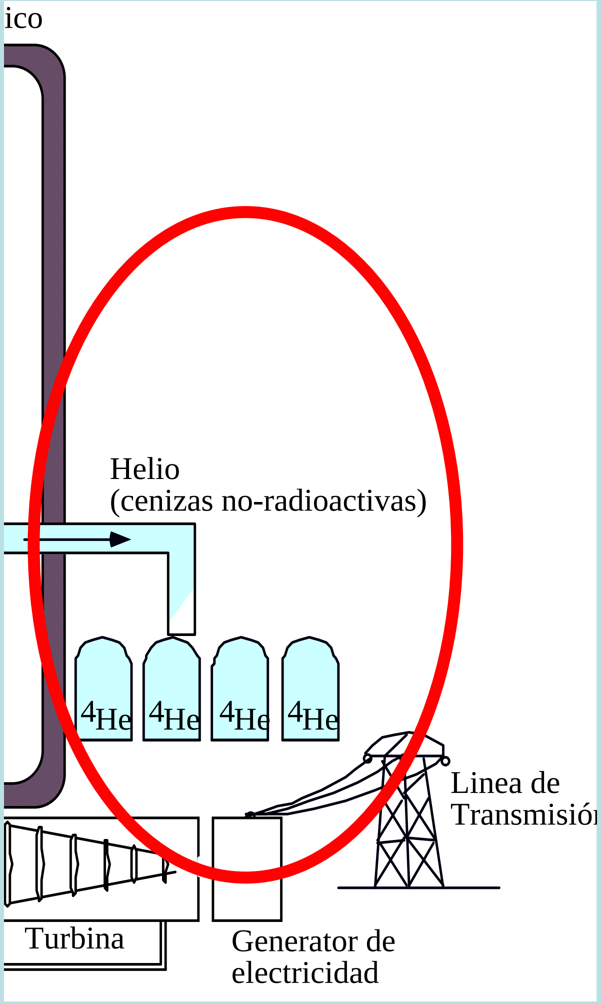
- Reservas estimadas para >10.000.000 años a 15000 GW

Planta de Fusión

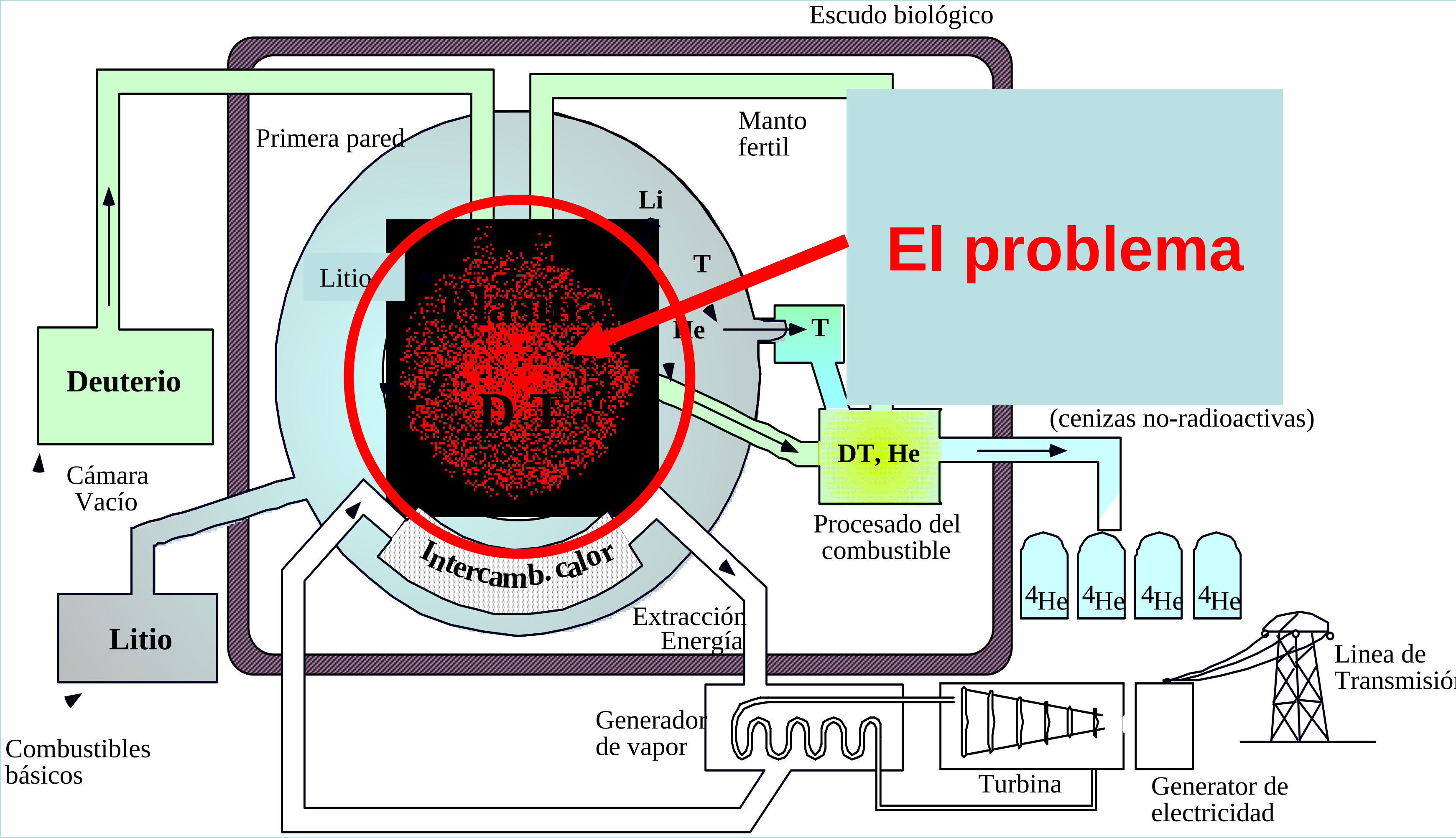
las “emisiones”

Helio: Inocuo para las personas y el medio ambiente.

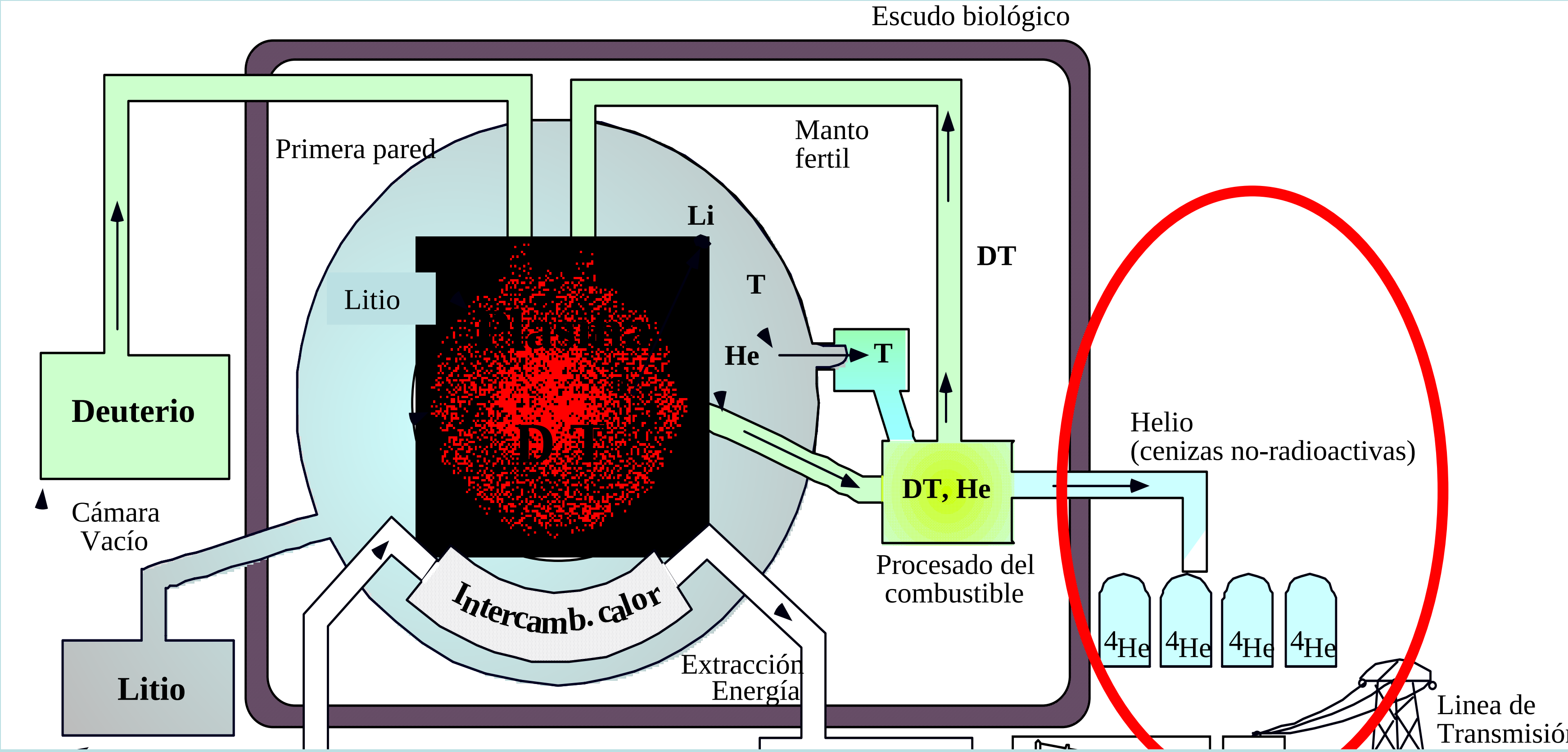
- **Cantidades mínimas** (6000 T/año para 15 TW vs / 10^{10}T CO_2)
- **No se acumula**
- **Valioso para la industria**



Planta de Fusión



Planta de Fusión

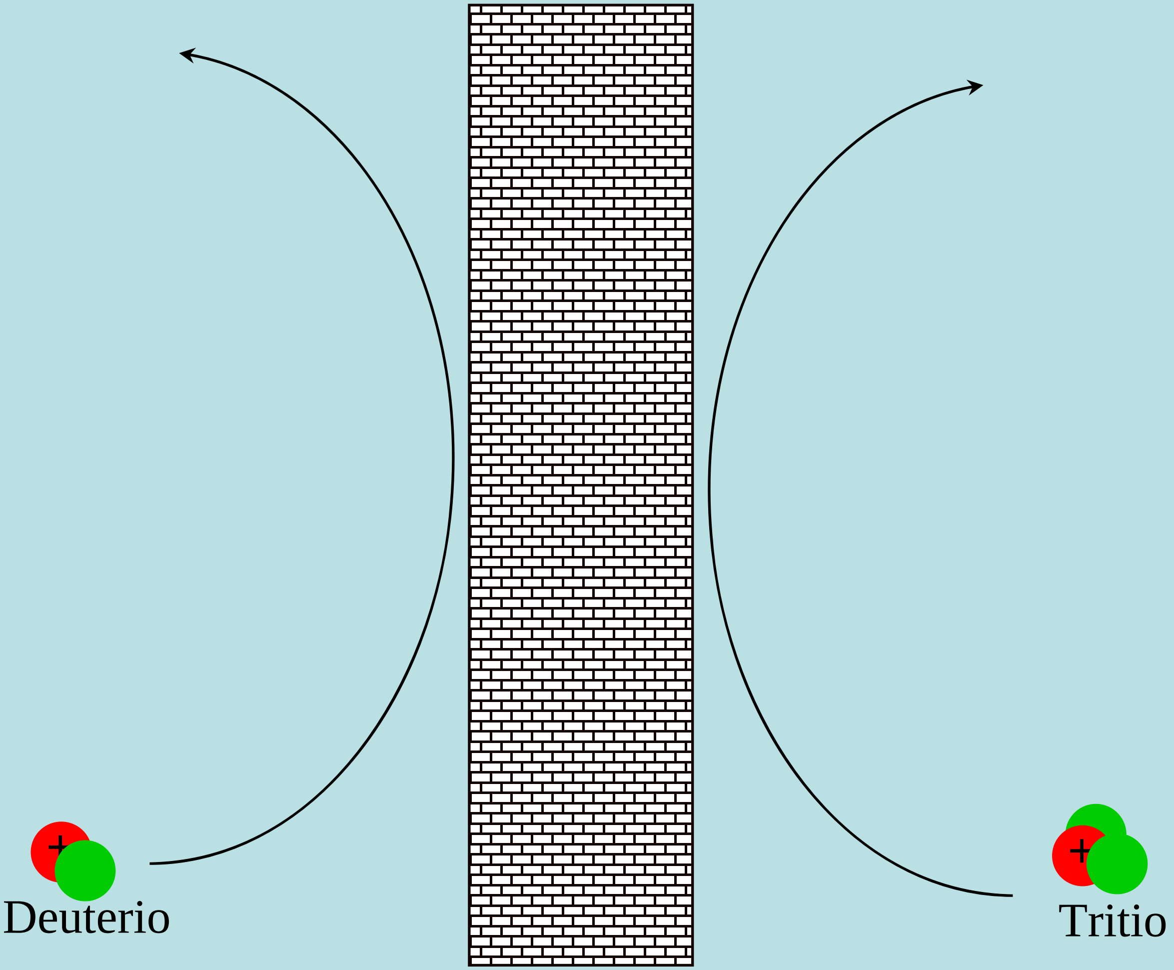


Seguridad intrínseca

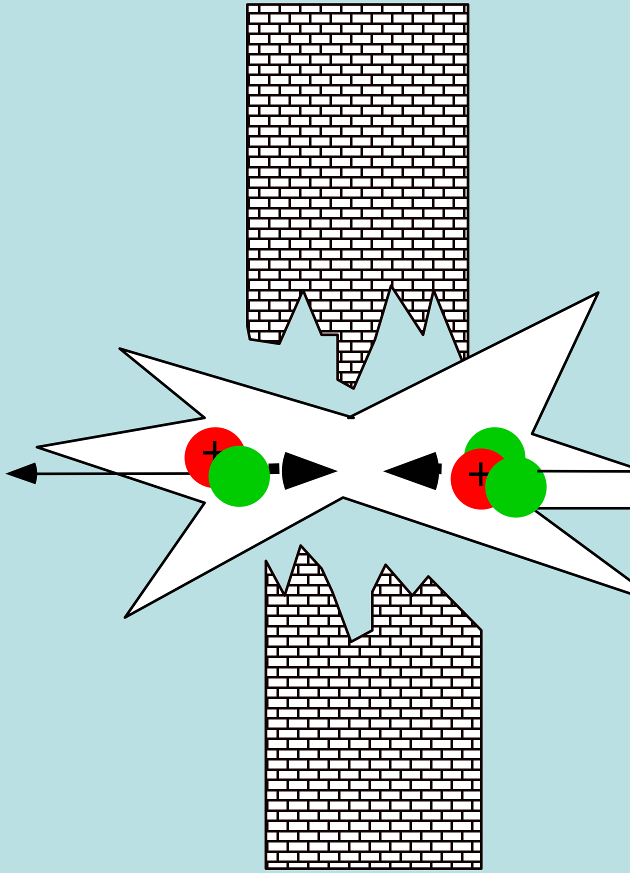
- La reacción se extingue tan pronto como el sistema se sale del “punto óptimo”
- No hay almacenamiento de Tritio

Barrera Culombiana

Fuerzas Repulsivas Eléctricas de Largo Alcance



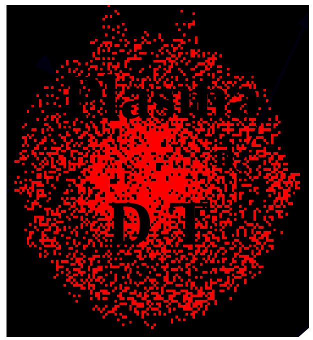
Fuerzas Nucleares de Corto Alcance



Plasma de Fusión

Nucleos D – T han de colisionar a alta velocidad

E =15-20keV



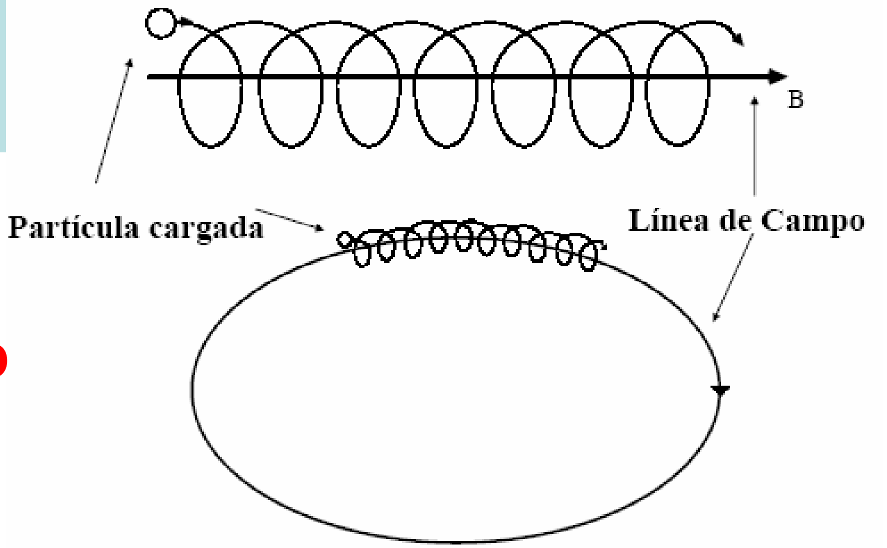
Accesible mediante aceleradores, pero no rentable.

Solución:
Plasma con partículas a 15 keV:

Temperatura del plasma:
170.000.000 ºC

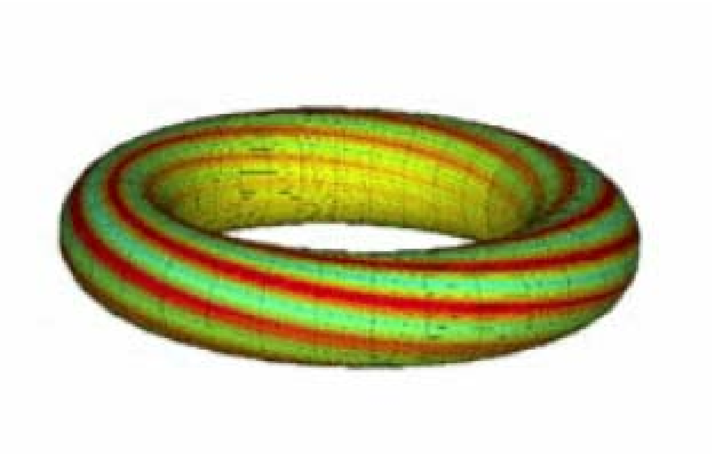
Plasma de Fusión

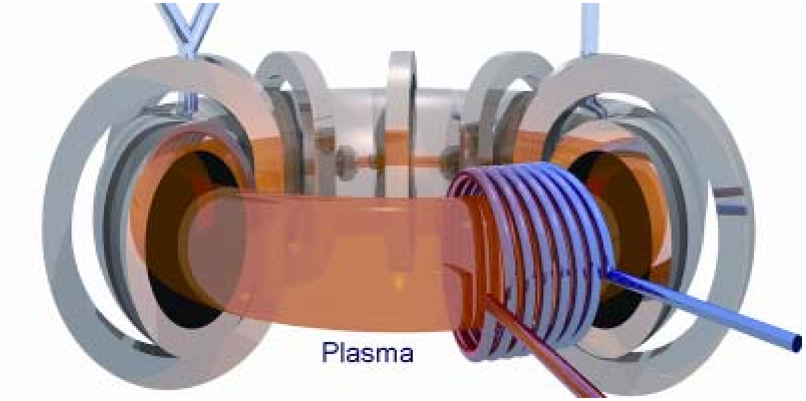
Temperatura del plasma:
170.000.000 ºC



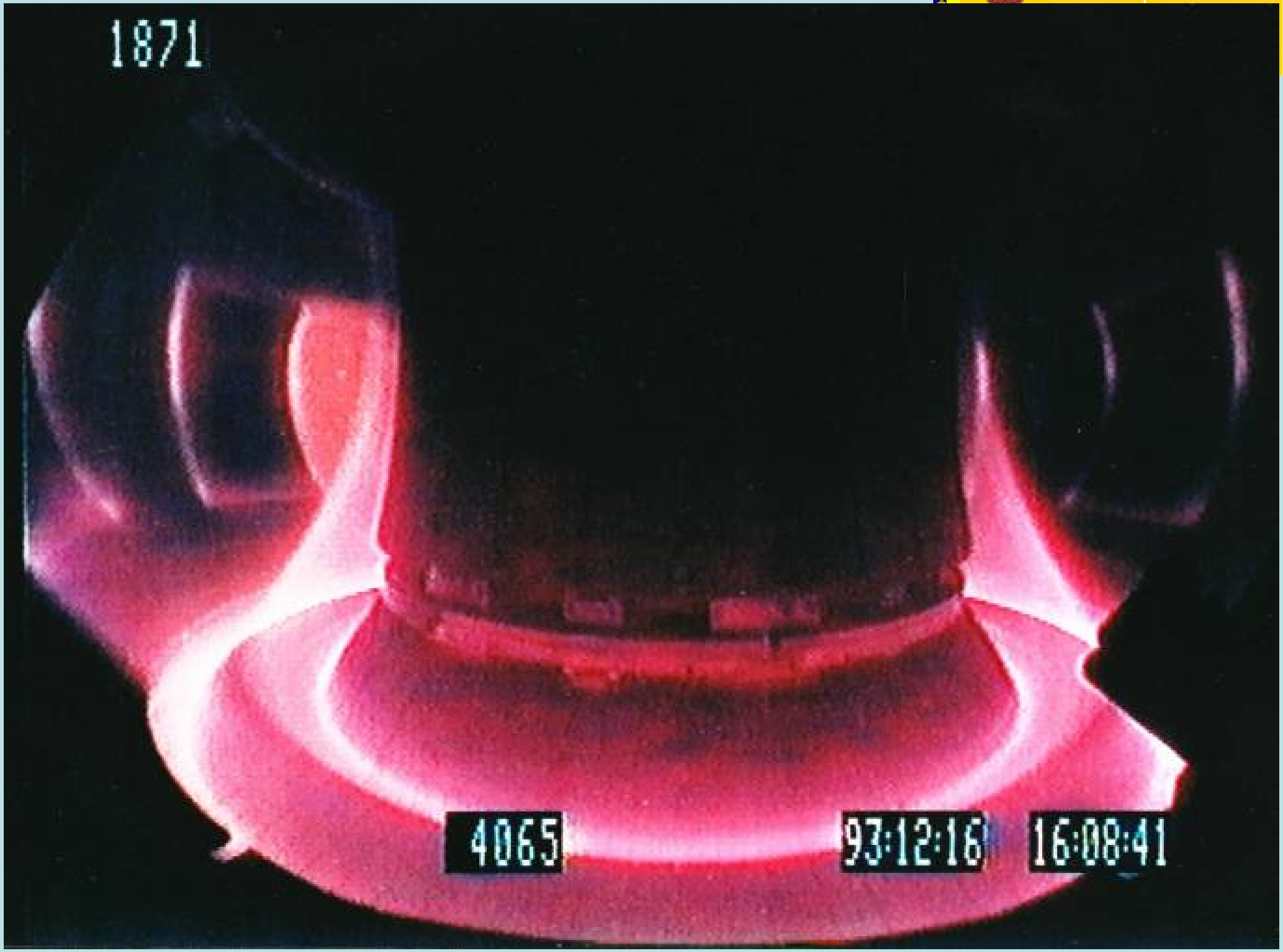
“Recipiente inmaterial”

Confinamiento magnético





Tokamak



ASDEX upgrade Tokamak Plasma
Max-Planck Institute für Plasmaphysik
IPP-Euratom Association, Garching, Germany

Historia de la Fusion

Hans Bethe
30's

Proyecto Manhattan
1942

Explosiones termonucleares
1952-53
A. Sakharov-E. Teller

Confinamiento Magnético

Concepto Tokamak
A. Sakharov- L. A. Artsimovich
1950-65

JET
1983-

ITER
2018

Concepto Stellarator
L. Spitzer
1951

LHD (Japon)
WVII-X (Alemania)
TJ-II (España)
1998

Confinamiento Inercial

Invención Laser
1960

Nature
Nuckolls
1972

LMJ (Francia)
NIF (USA)
2010

¿Cuarenta años para la Fusión?

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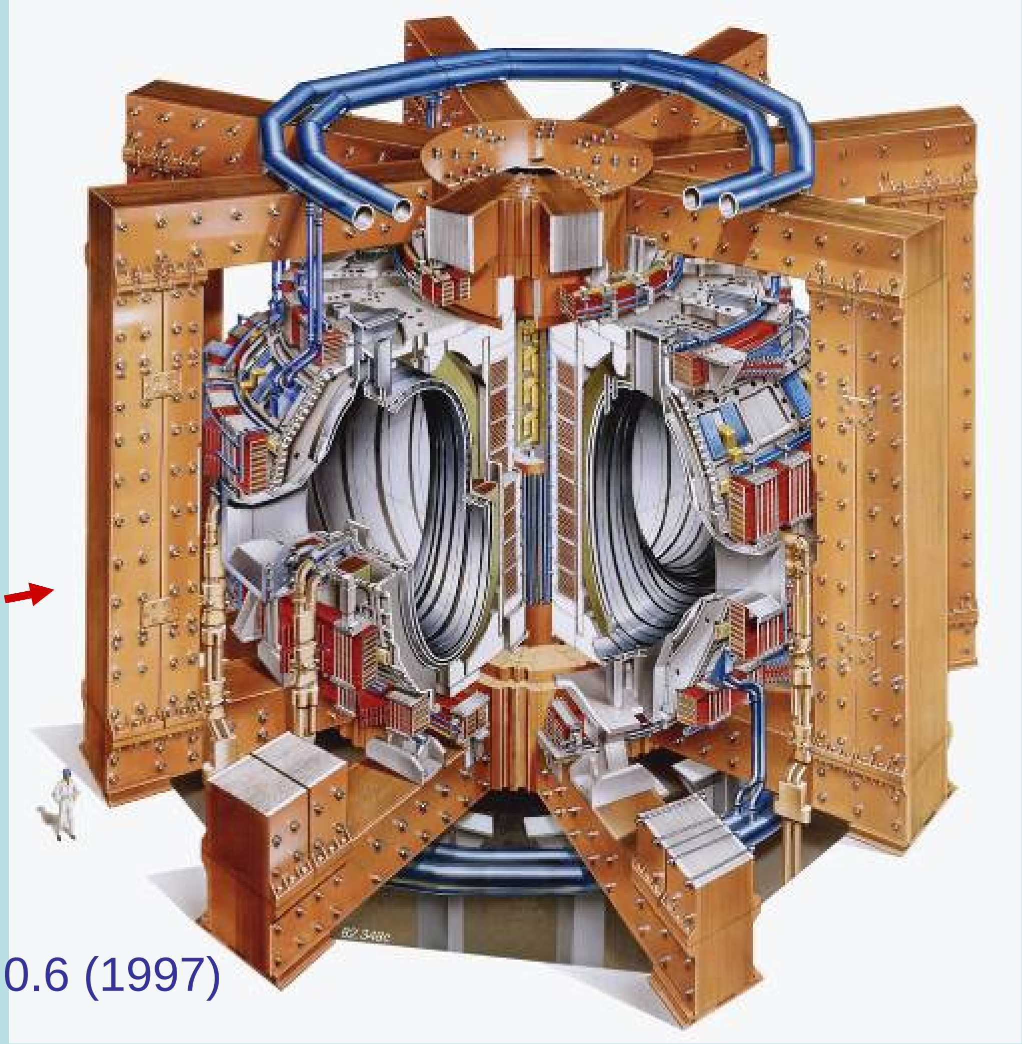
Para confinar un gas a 300 MºC se necesita:

- **Campo magnético (<10T)**
- **Tamaño (1000 m³ para alcanzar ignición)**

T3: ~1 m³, ~ 3 M ºC
Primer "tokamak" (1969)



JET: ~100 m³, ~ 300 M ºC
16 MW de fusión, ganancia 0.6 (1997)

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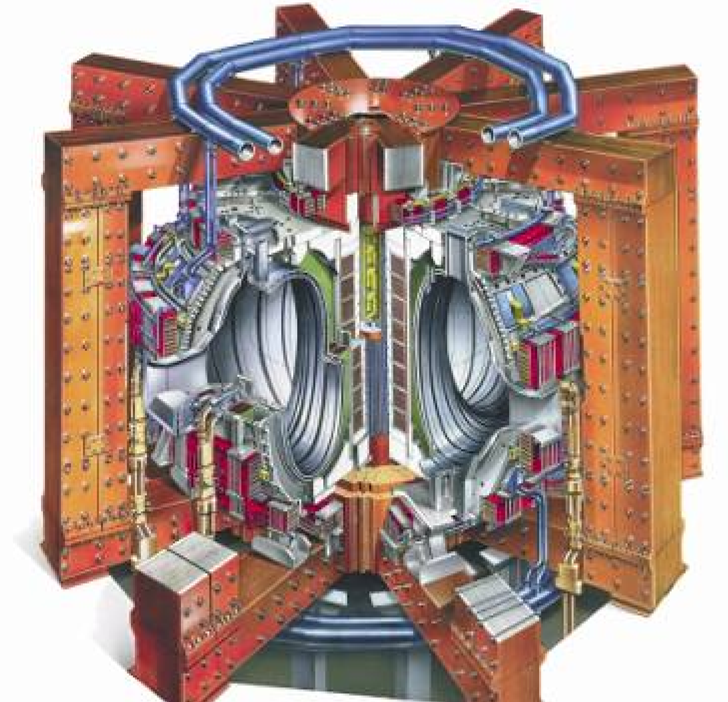
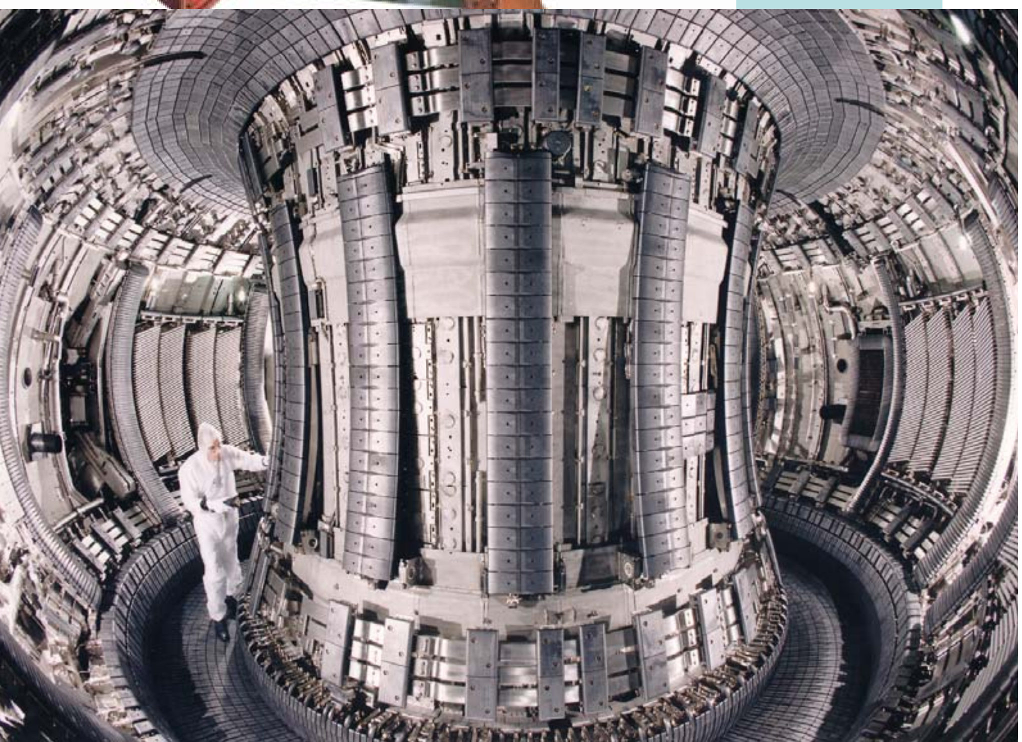
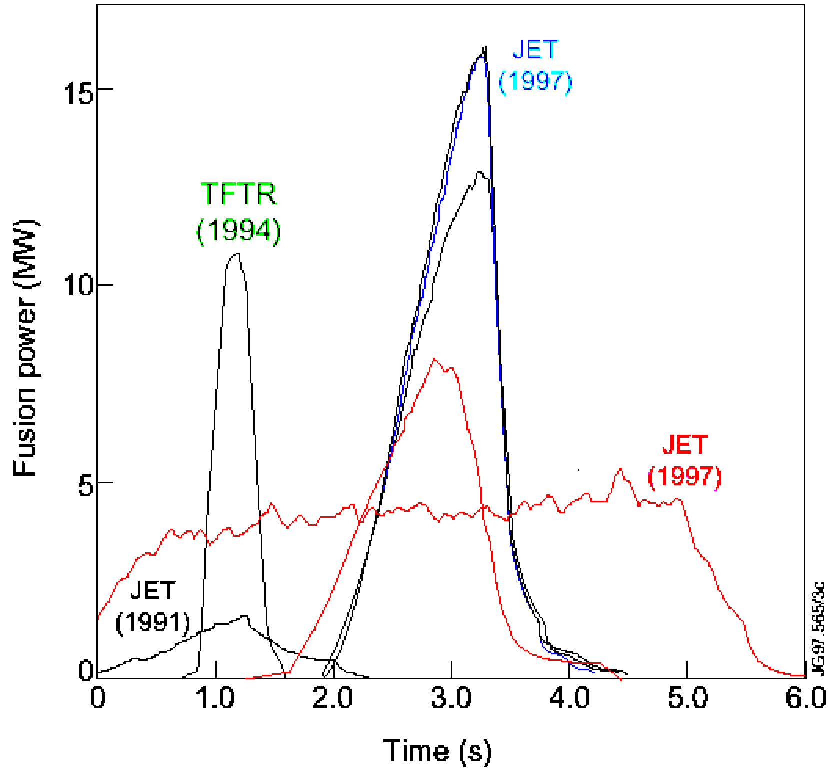
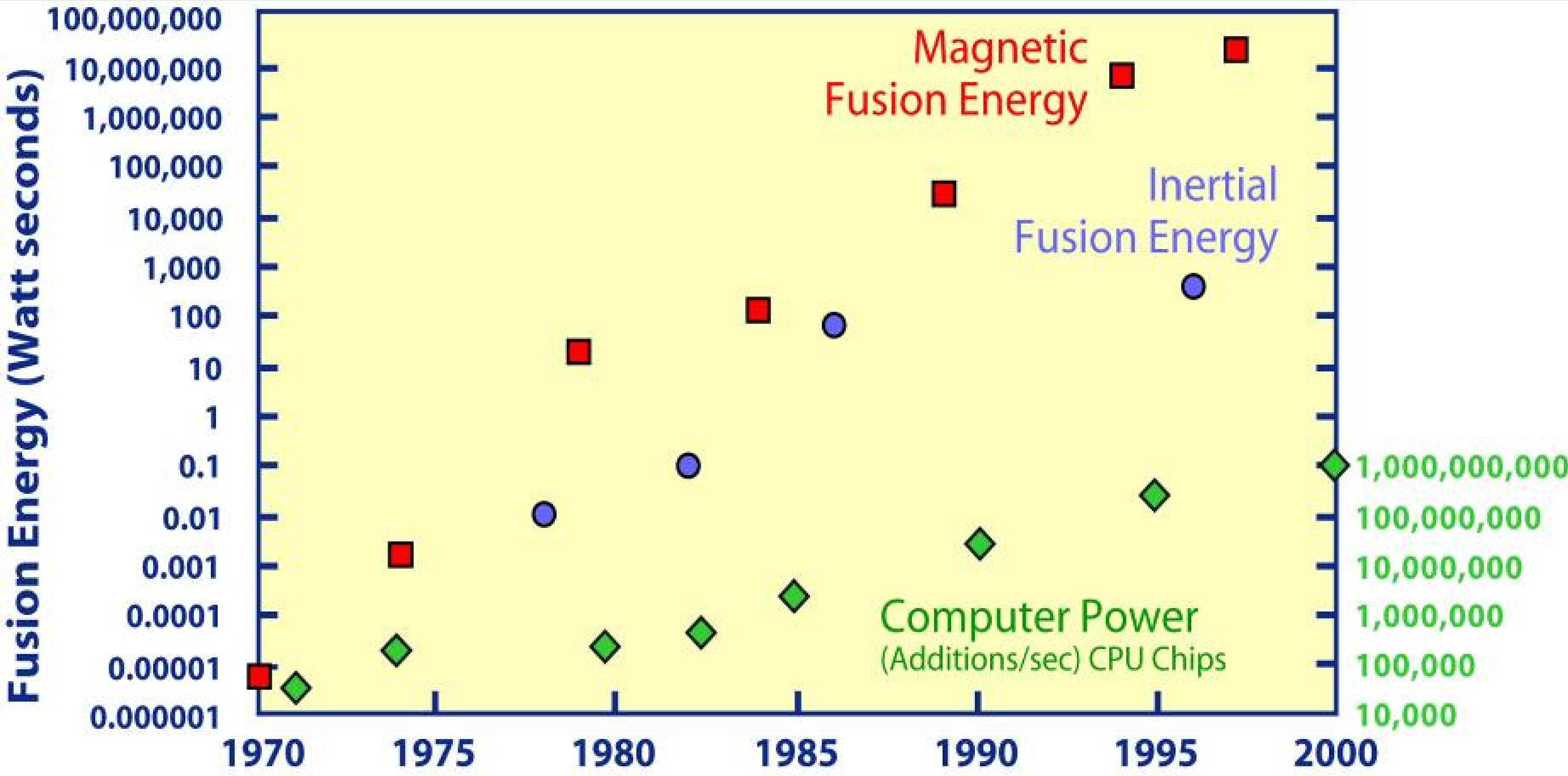
Tokamak JET (U.E.)







Progreso



Fusion Energy (Watt seconds)
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
1970
1975
1980
1985
1990
1995
2000
Magnetic
Fusion Energy
Inertial
Fusion Energy
Computer Power
(Additions/sec) CPU Chips
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000

ITER: el próximo paso

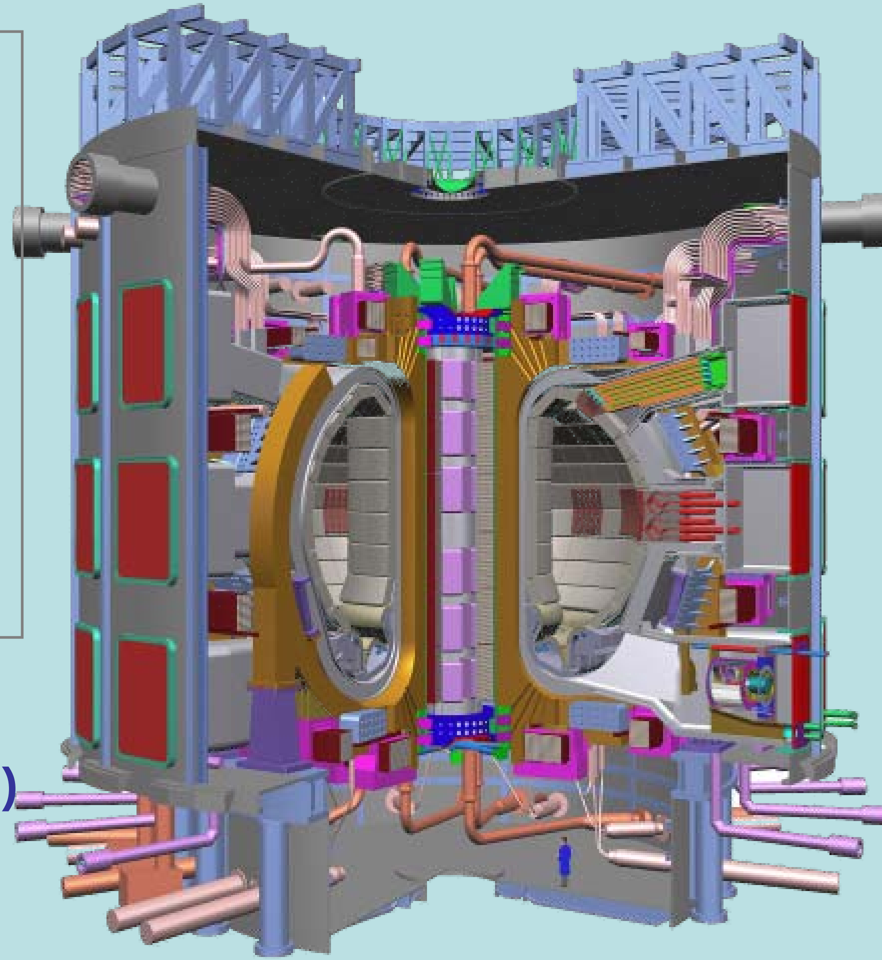
Objetivos:

Demostrar la viabilidad científica de la fusión

Ganancia energética Q
Q>10 durante 500 s

Q> 5 durante 1500 s

Tests tecnológicos (materiales, módulo generador de tritio...)

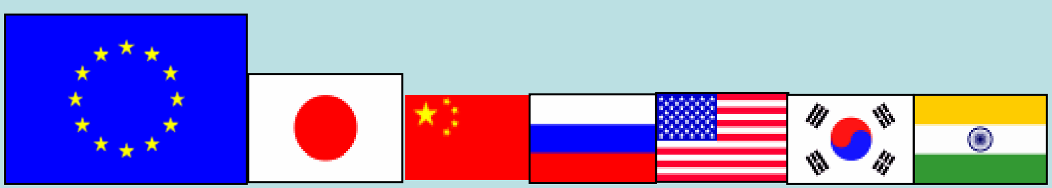


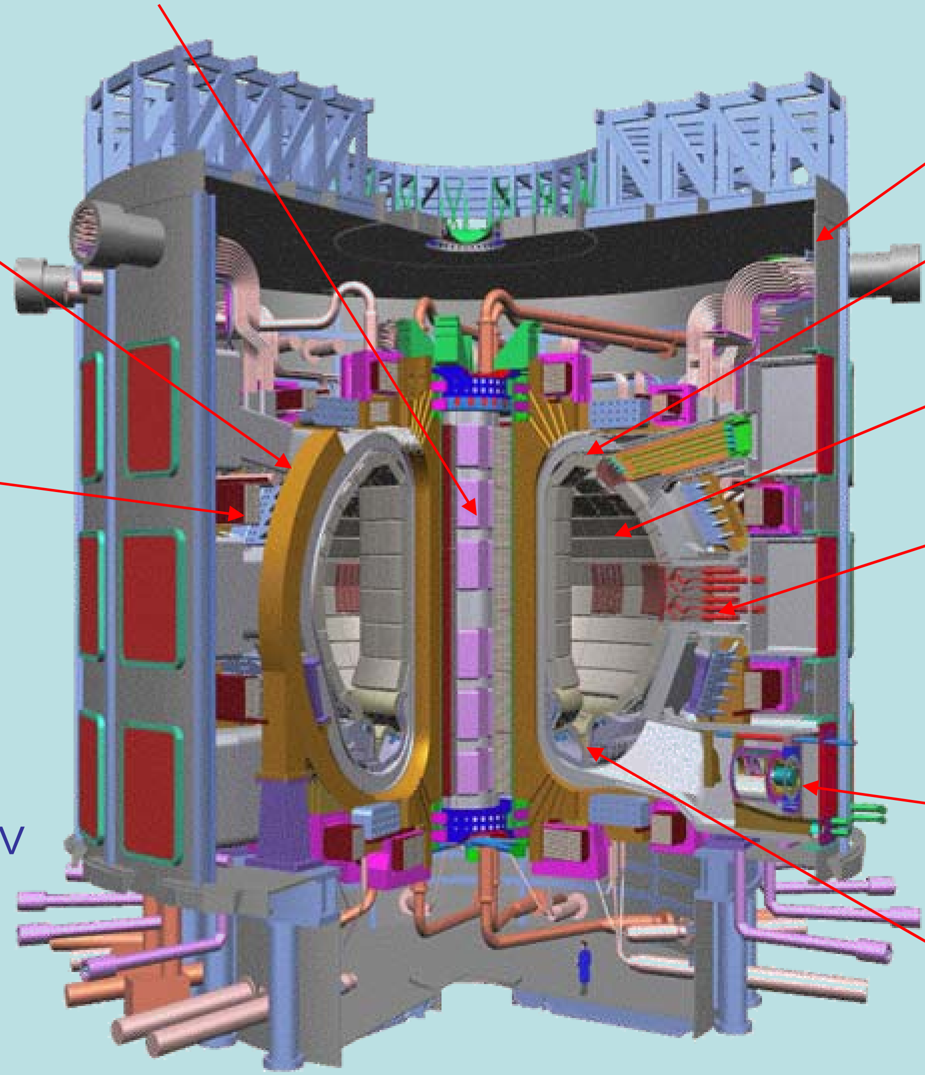
Socios:

Europa
Japón
China
Rusia
EEUU
Corea S
India

Coste: 5000 M€ (del año 2000)

Construcción: 2007-16





Major plasma radius 6.2 m

Plasma Volume: 840 m^3

Typical Temperature: 20 keV

Fusion Power: 500 MW

Machine mass: 23350 t (cryostat + VV + magnets)

- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

I+D previa: 2001

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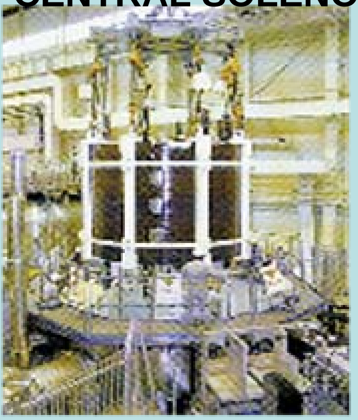
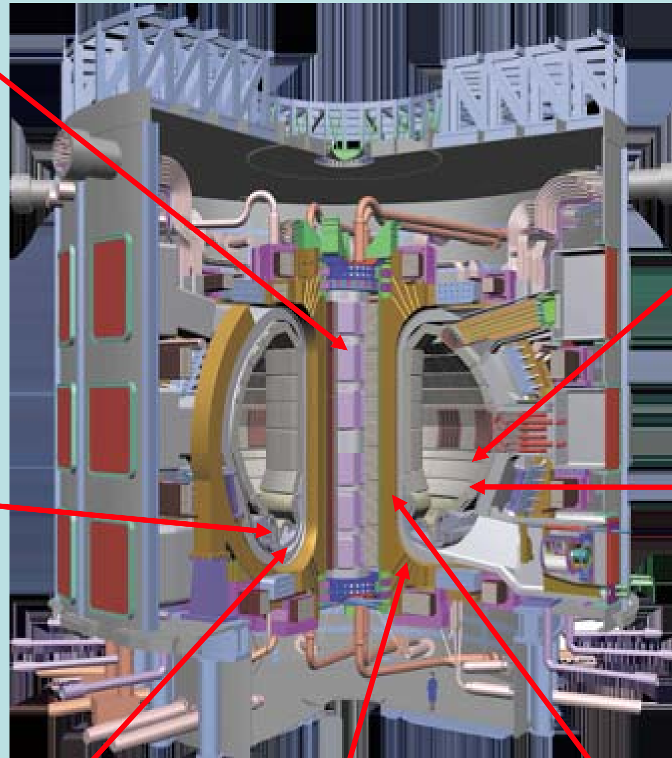
CENTRAL SOLENOID MODEL COIL



Radius 3.5 m
Height 2.8m
B_{max}=13 T
0.6 T/sec



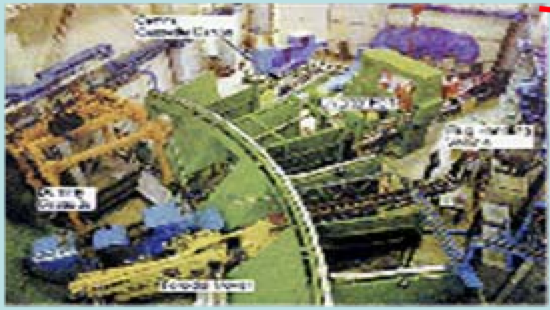
VACUUM VESSEL SECTOR

Double-Wall, Tolerance ± 5 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

REMOTE MAINTENANCE OF DIVERTOR CASSETTE



DIVERTOR CASSETTE

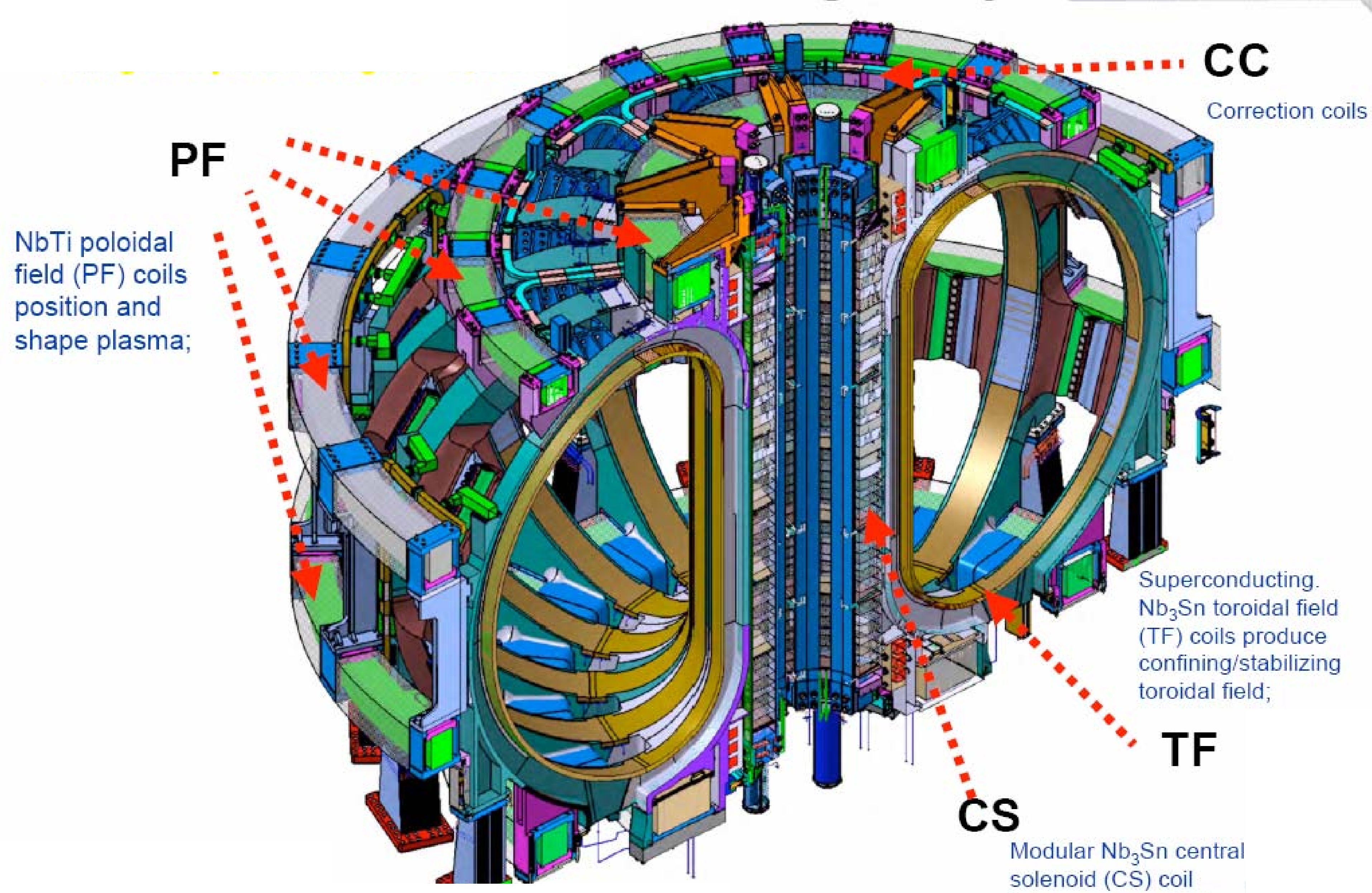
Heat Flux 20 MW/m^2
Attachment Tolerance ± 2 mm

TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
B_{max}=7.8 T

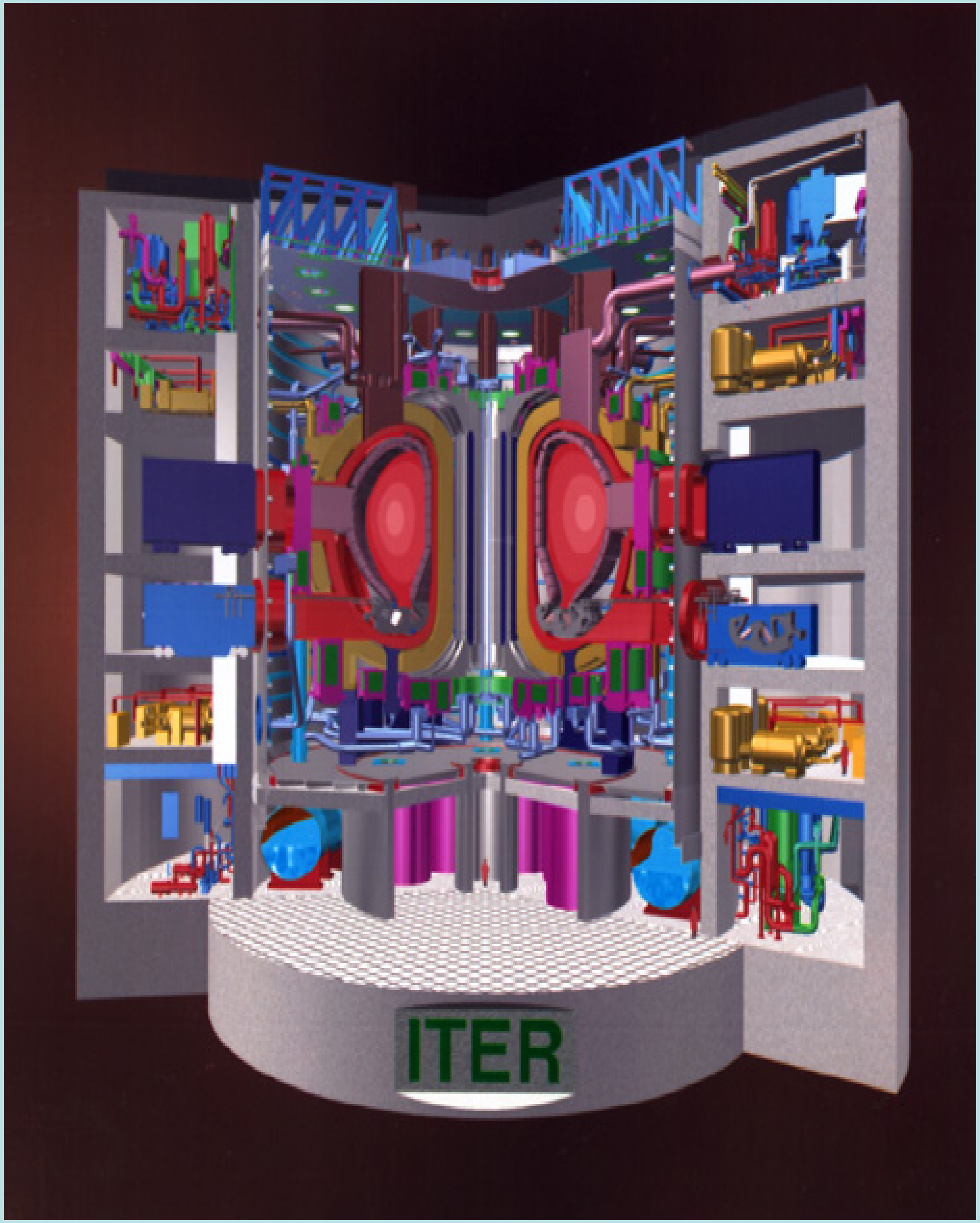
REMOTE MAINTENANCE OF BLANKET

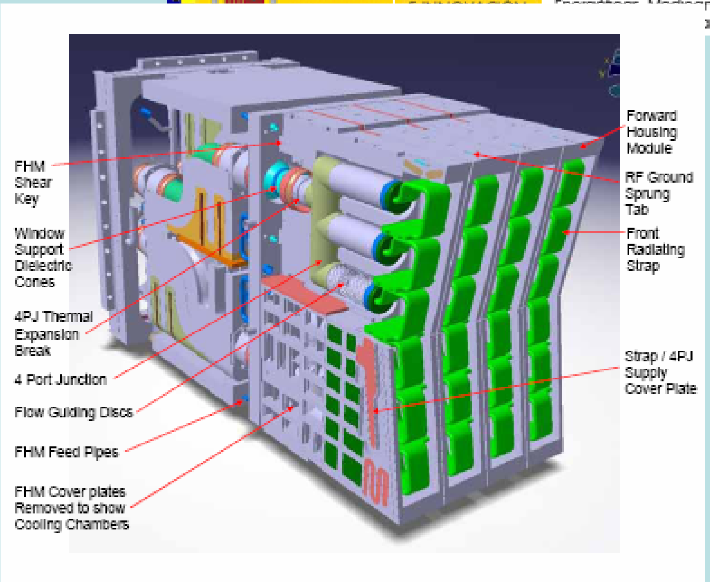
4 t Blanket Sector
Attachment Tolerance ±0.25 mm

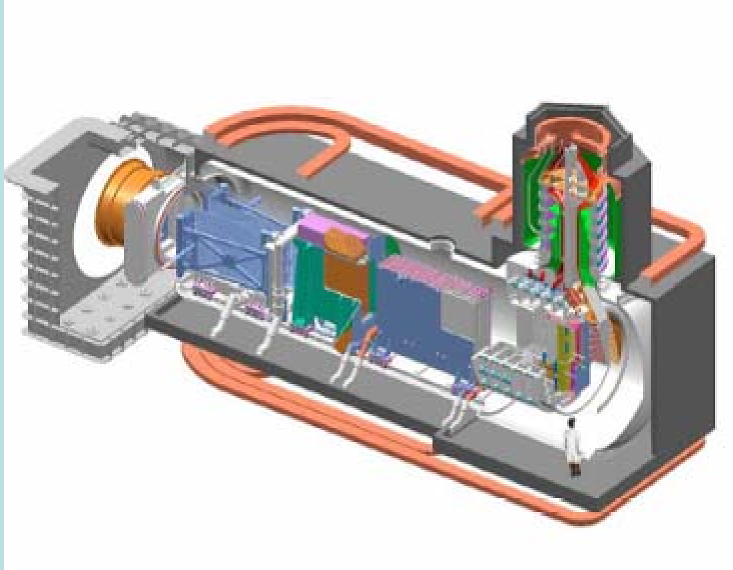


Airbus 380: 10^6 componentes CATIA

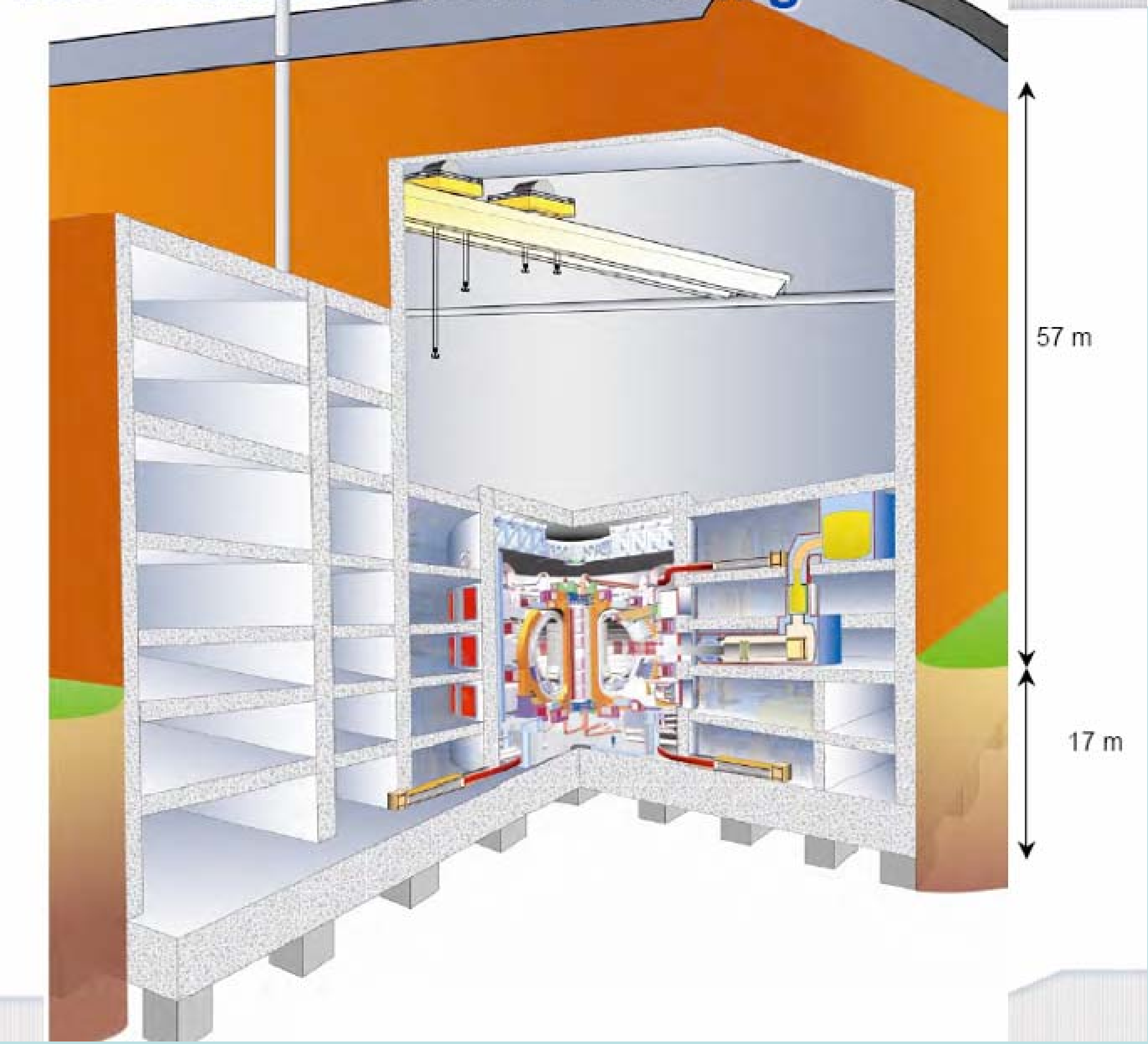
ITER: 10^7 componentes


ITER


FHM Shear Key
Window Support Dielectric Cones
4PJ Thermal Expansion Break
4 Port Junction
Flow Guiding Discs
FHM Feed Pipes
FHM Cover plates Removed to show Cooling Chambers
Forward Housing Module
RF Ground Sprung Tab
Front Radiating Strap
Strap / 4PJ Supply Cover Plate



The tokamak in the Building



Obra civil cerca del 15% del coste del proyecto

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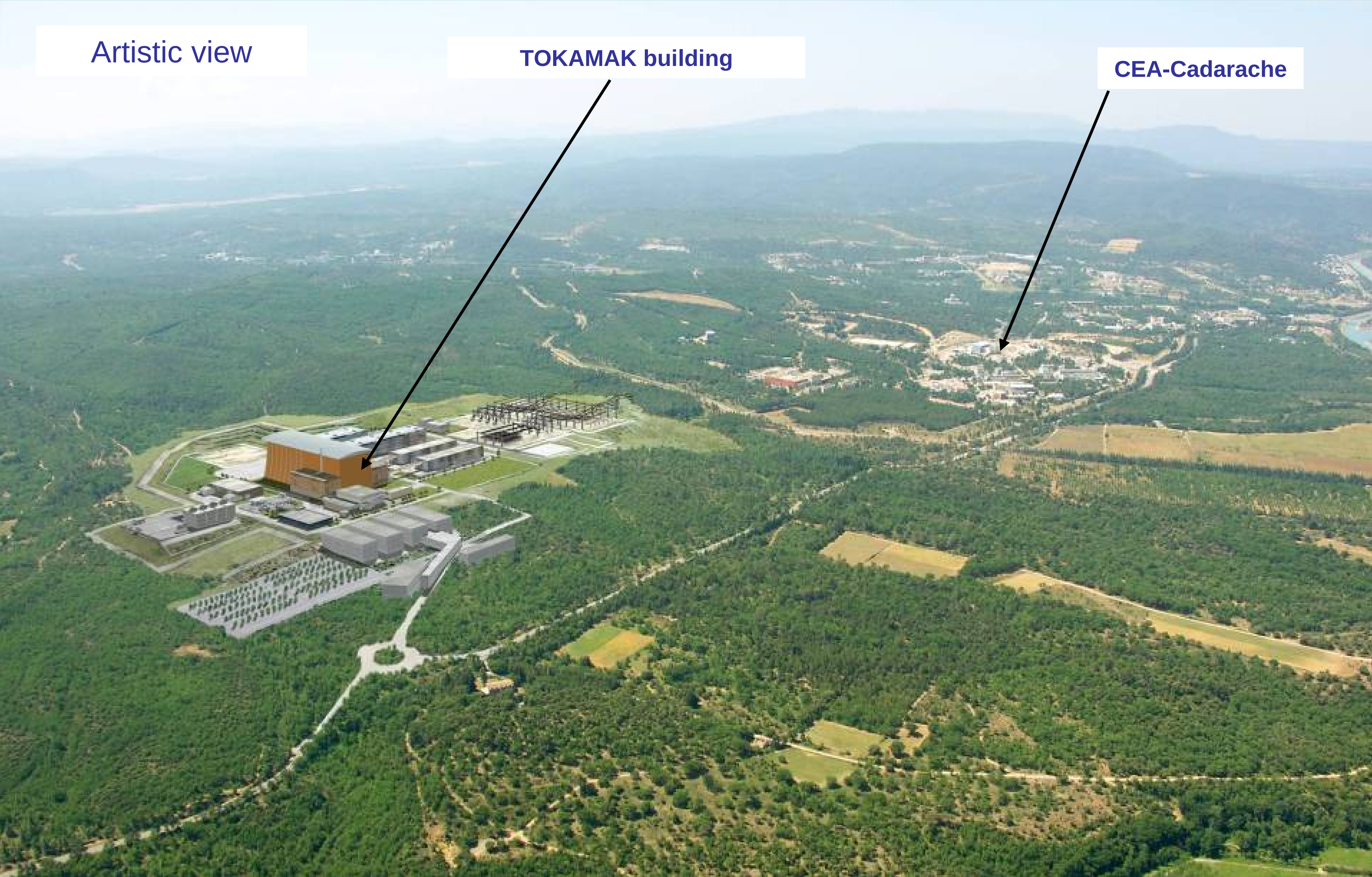
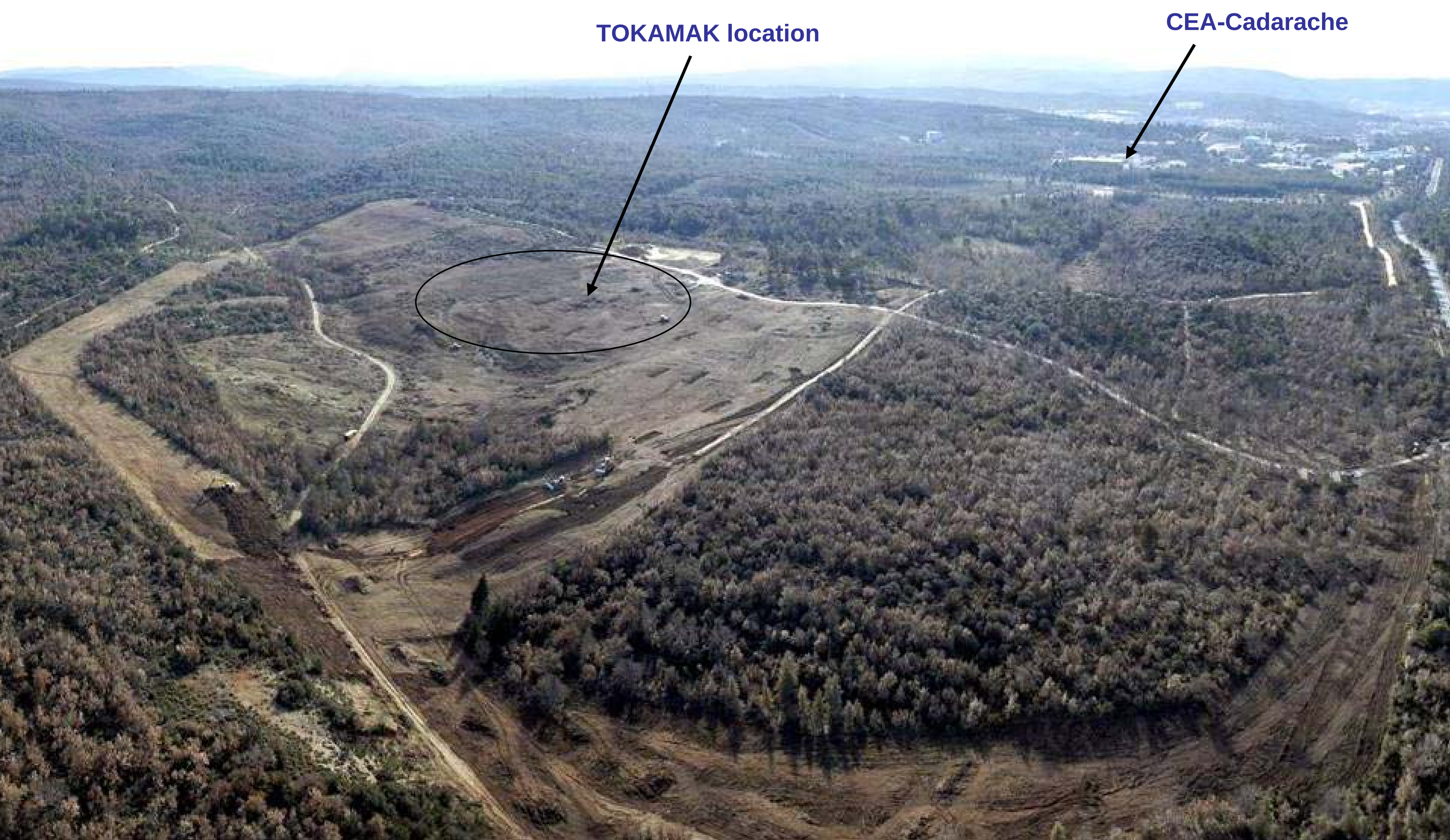
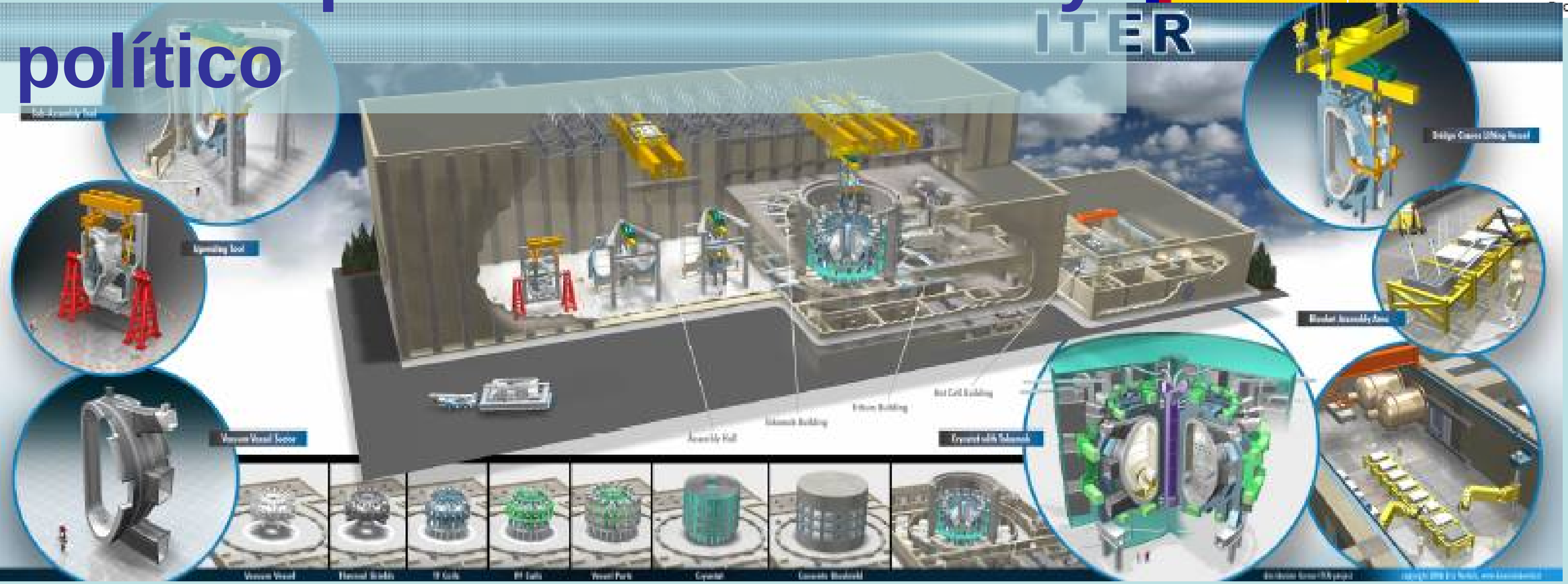


Aerial view



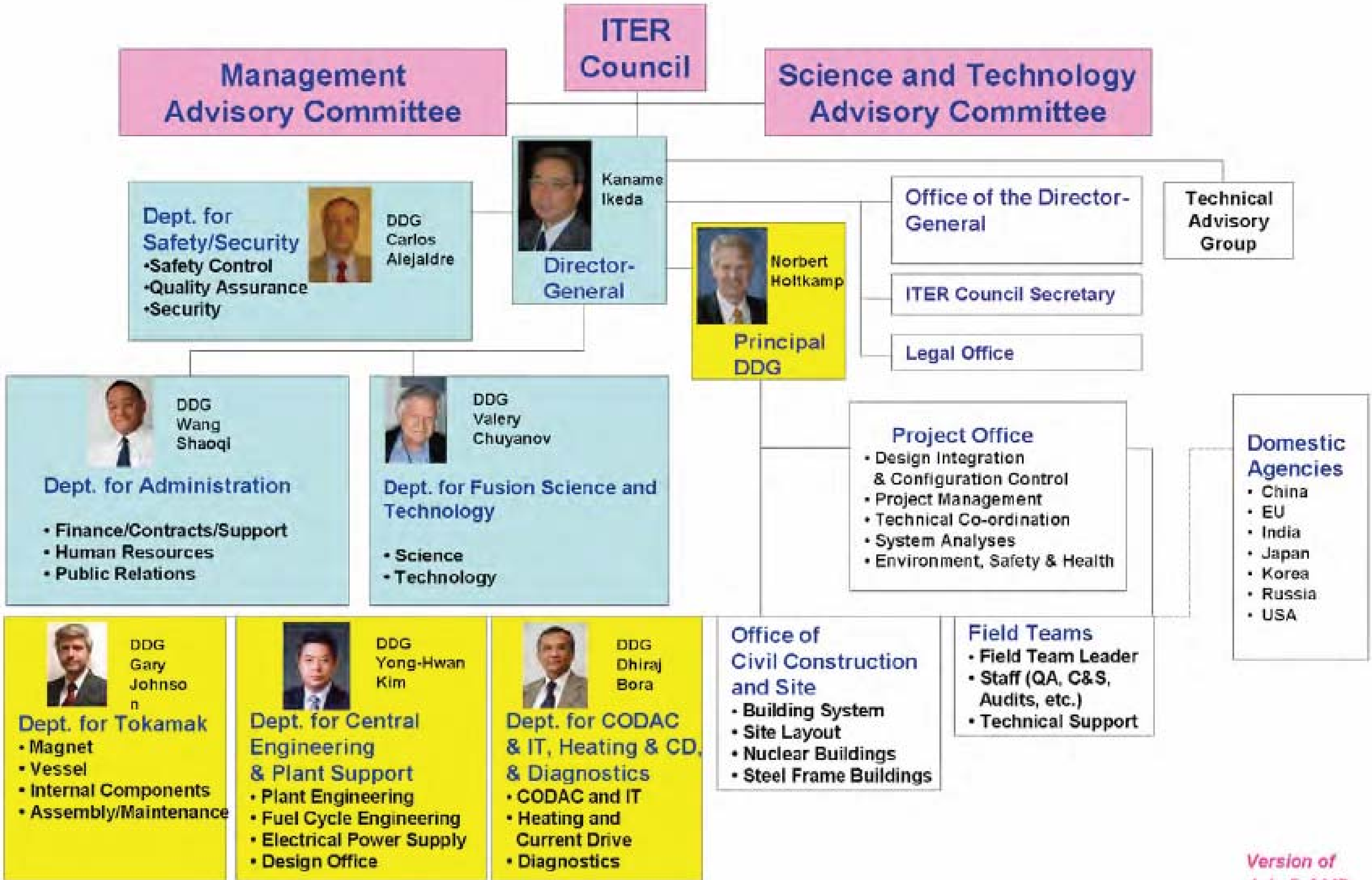
ITER: experimento científico y político



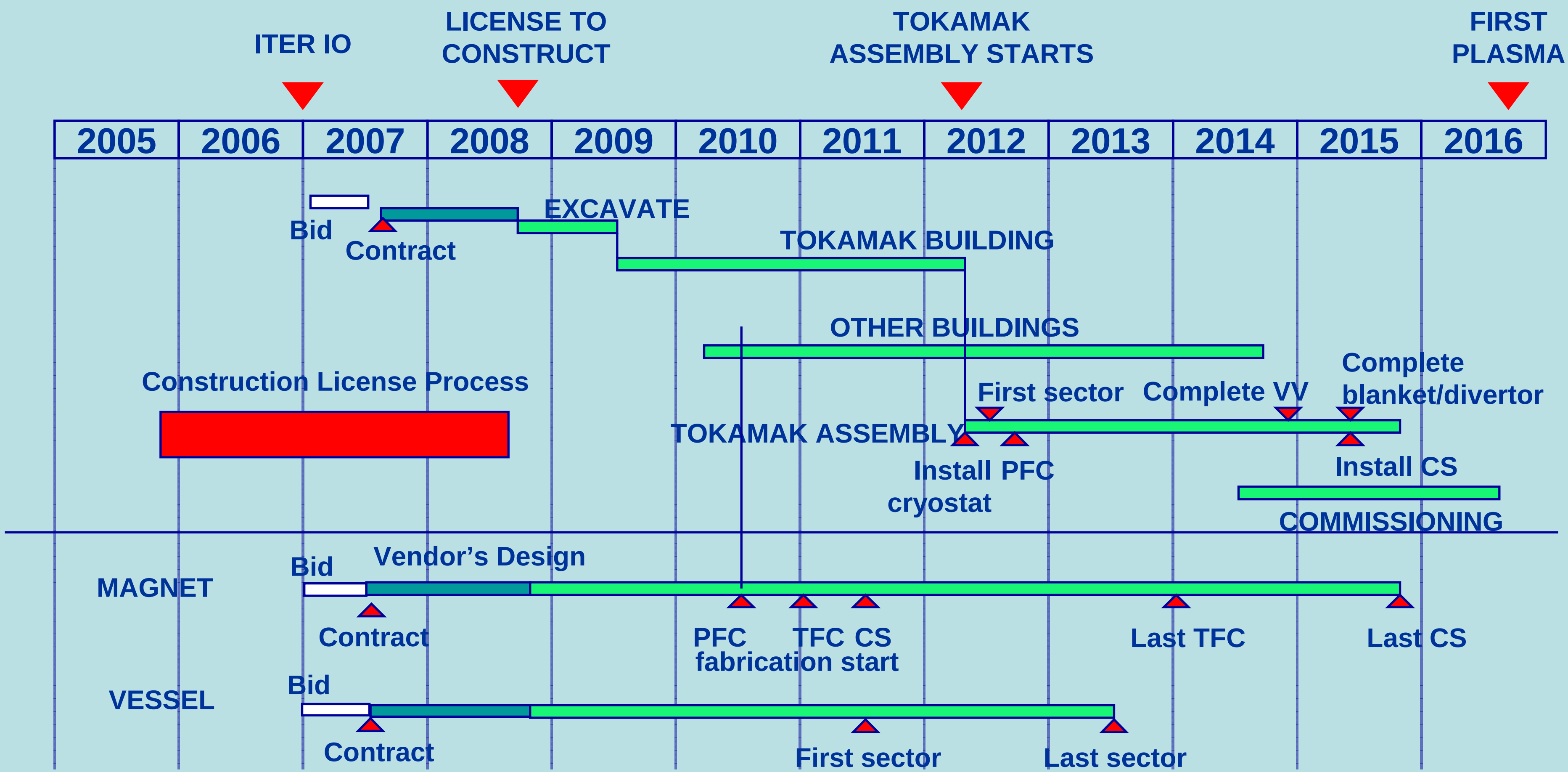
Solo 10% gestionado por el DG de ITER

90% son aportaciones de los socios en especie

Management Structure of ITER Organization



Version of July 5, 2007

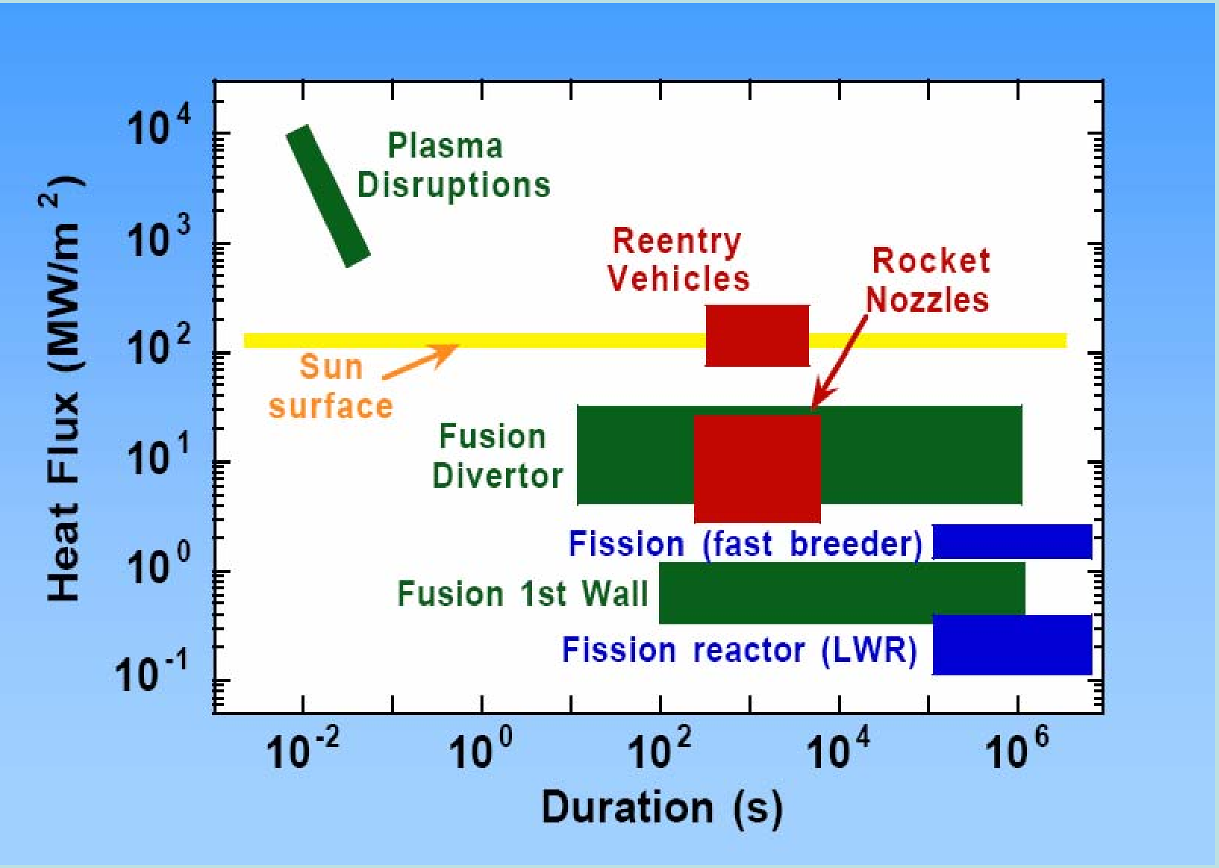

ITER IO
LICENSE TO CONSTRUCT
TOKAMAK ASSEMBLY STARTS
FIRST PLASMA
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Bid
Contract
EXCAVATE
TOKAMAK BUILDING
OTHER BUILDINGS
Construction License Process
First sector
Complete VV
Complete blanket/divertor
TOKAMAK ASSEMBLY
Install PFC
cryostat
Install CS
COMMISSIONING
MAGNET
Bid
Vendor's Design
Contract
PFC
TFC
CS
fabrication start
Last TFC
Last CS
VESSEL
Bid
Contract
First sector
Last sector

ITER demostrará la viabilidad de la Fusión pero aún faltará:

-**Física:** estado estacionario
optimización del campo B (coste)
reactores 2ª generación: “stellarators”

-**Tecnología** Materiales
Autosuficiencia en Tritio
Disponibilidad (24x7)
Mantenibilidad

Tecnología (I) Materiales: Carga térmica



Alternativas:

CFCs, Tungsteno, “mechas” de Litio líquido

Materiales: Daño por irradiación

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Irradiation parameter		ITER*	DEMO*
Total neutron flux	[n/(s cm^2)]	4 x 10^{14}	7.1 x 10^{14}
Hydrogen production	[appm/FPY]	445	780
Helium production	[appm/FPY]	114	198
Damage production	[dpa/FPY]	10	19
H/dpa ratio	[appm/dpa]	44.5	41
He/dpa ratio	[appm/dpa]	11.4	10.4
Nuclear heating	[W/cm^3]	10	22
Wall load	[MW/m^2]	1.0	2.2

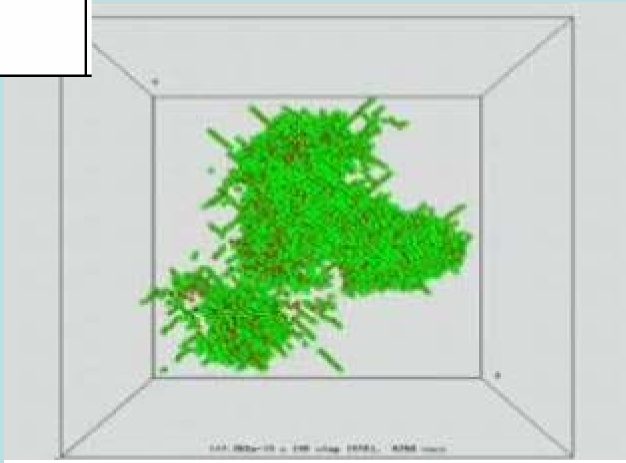
Activación

Daño estructural (dpa´s)

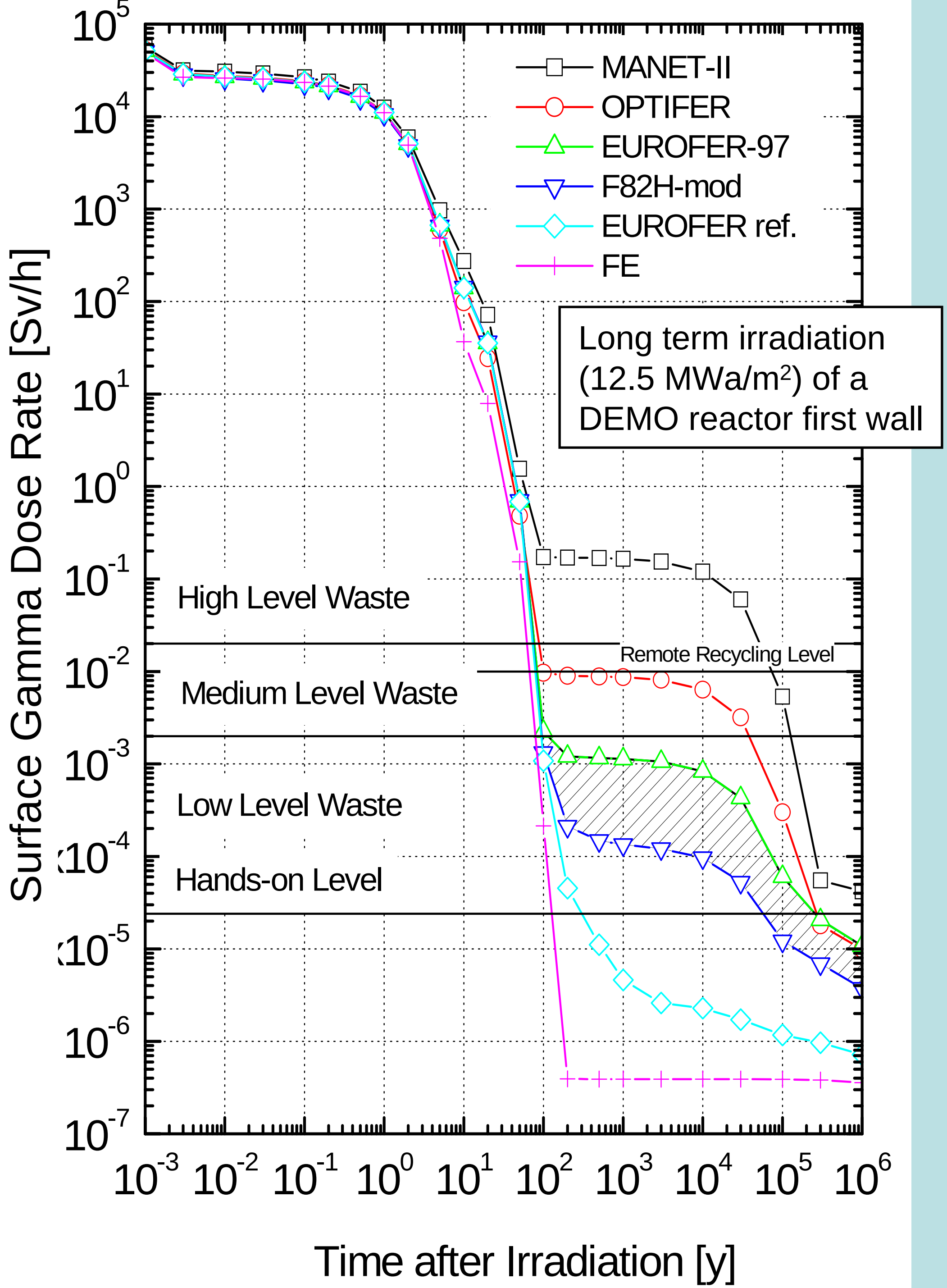
Burbujas de He /H

Candidatos (material estructural):

- **Aceros martensiticos "EUROFER"**
- **Vanadio**
- **SiC/SiC**



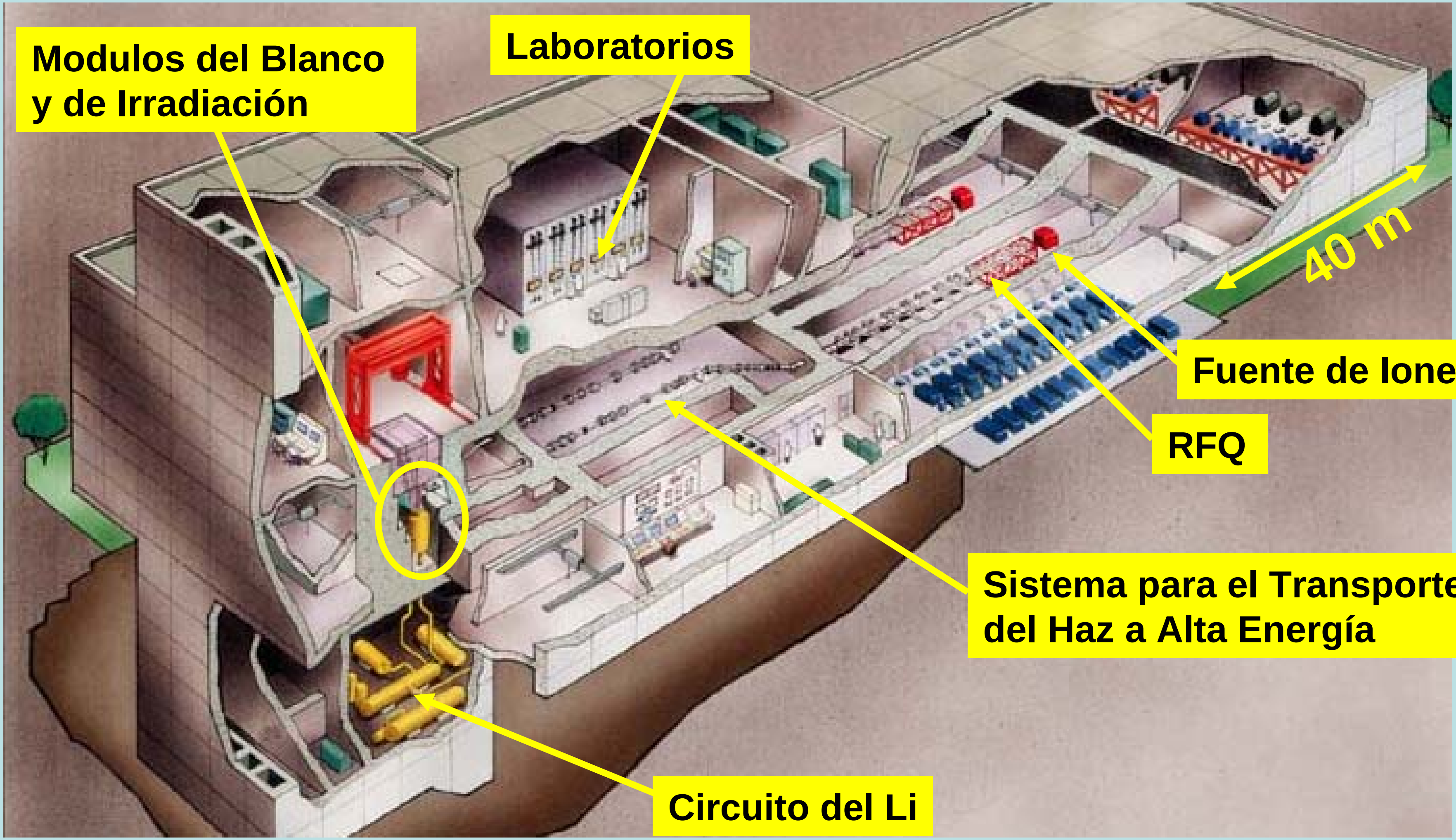
Molecular dynamics calculation of displacement damage due to neutron impact.



Objetivo:
baja activación

Materiales reciclables después de <100 años

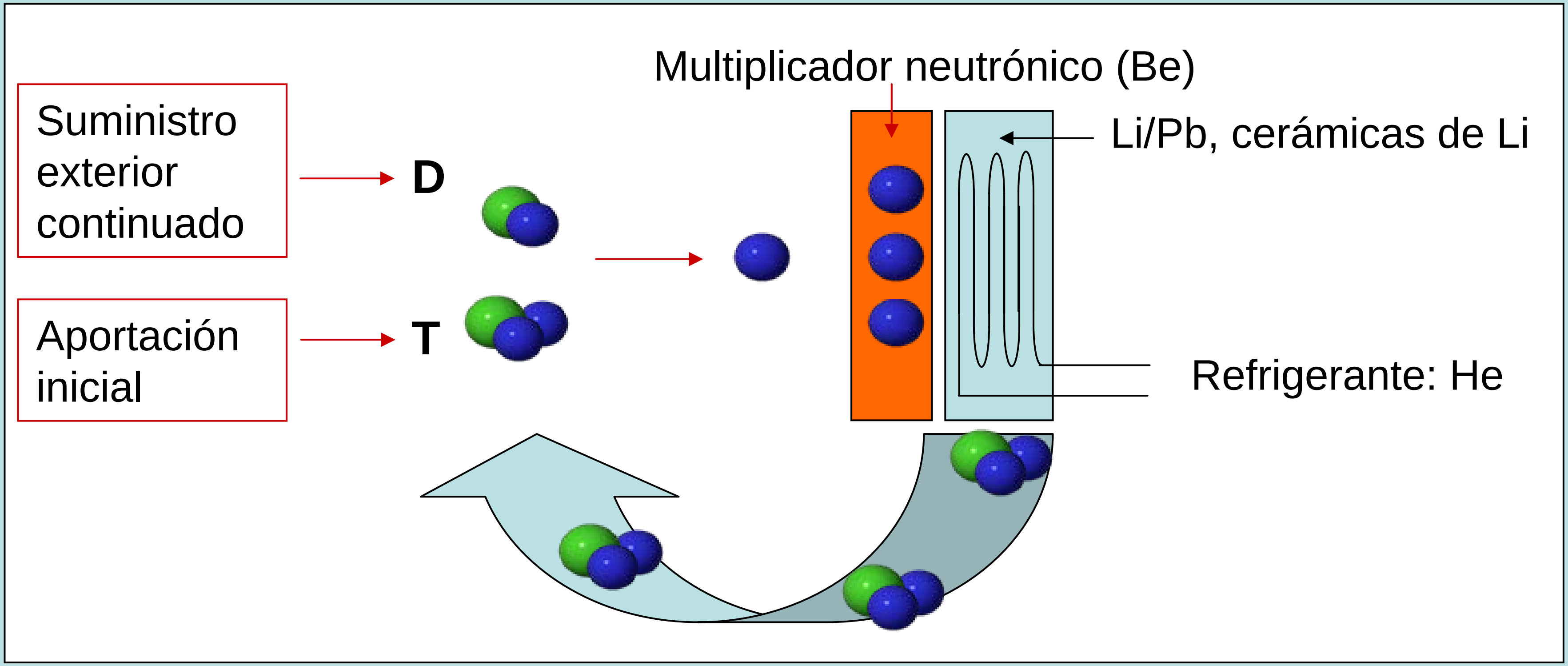
La fuente de neutrones de 14 MeV: IFMIF



Previsto 2015, presupuesto 1000 M€ (pendiente acuerdo internacional)

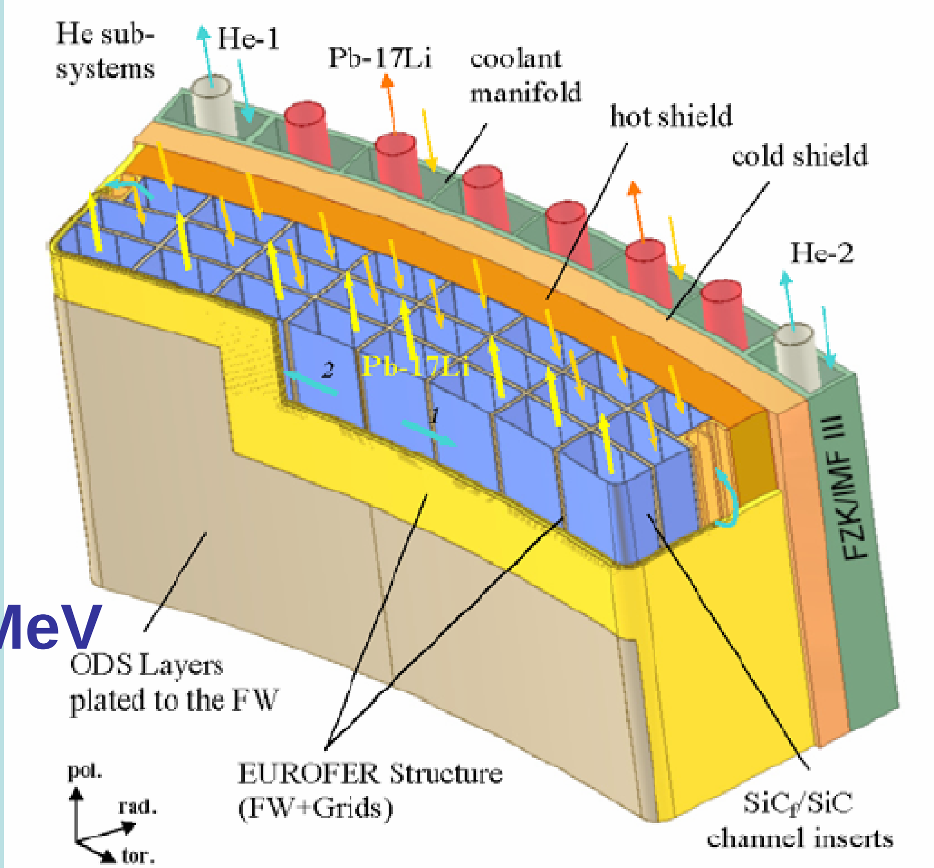
Tecnología (II)

Manto reproductor de Tritio (“breeding blanket”)



Es necesario cerrar el ciclo: ganancia ~ 1.2

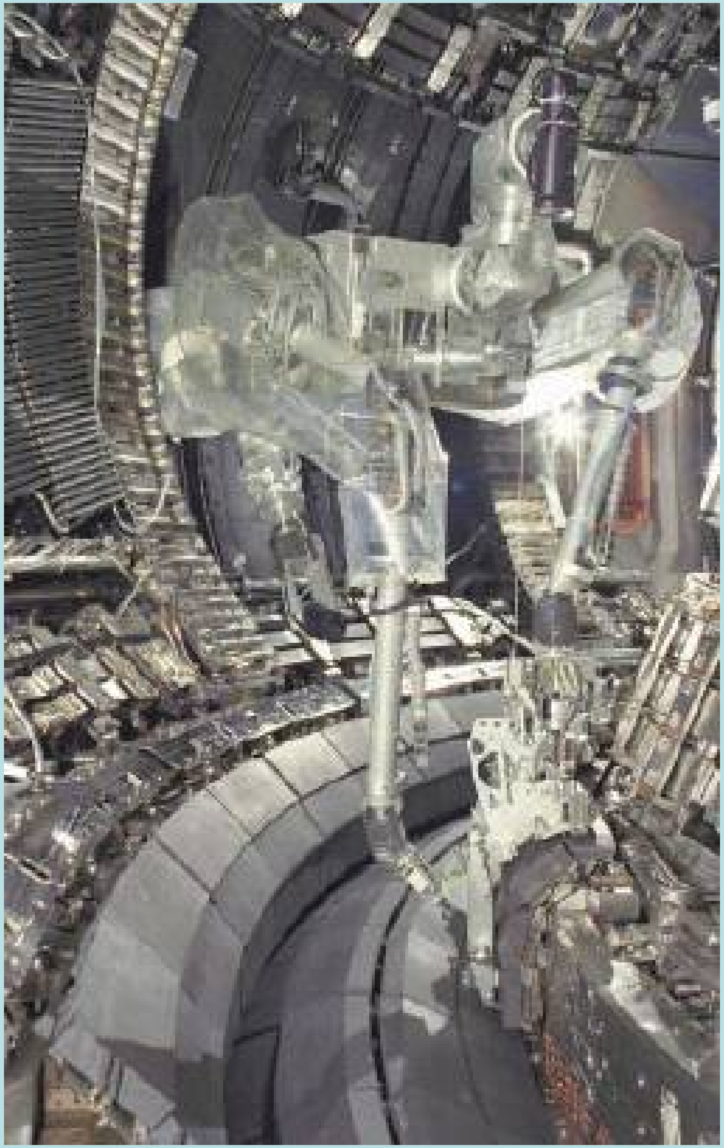
Tareas del “Blanket”



- **Reproducir Tritio**
- **frenar los neutrones de14 MeV**
- **Extraer energía (5 MW/m^2)**
- **Evitar permeación de T**

Tecnología (III)

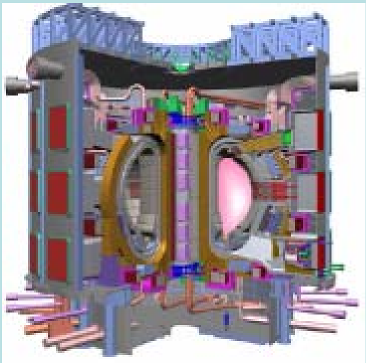
- RAM
  - Mantenimiento remoto
  - Fiabilidad de un sistema muy complejo
- Tecnologías “convencionales”
  - Intercambiadores He/agua
  - Conservación del He
- Superconductores de alta temp.
- Optimización del precio kW.h



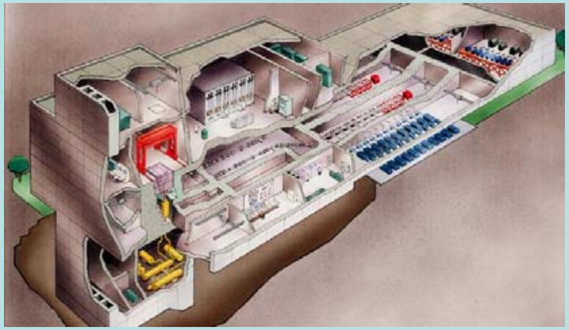
La hoja de ruta hacia el reactor comercial

	2005	2015	2025	2035
ITER	construct	operate	operate	
IFMIF	design / construct	operate	operate	
DEMO	explore concept / R&D	design	construct	power production

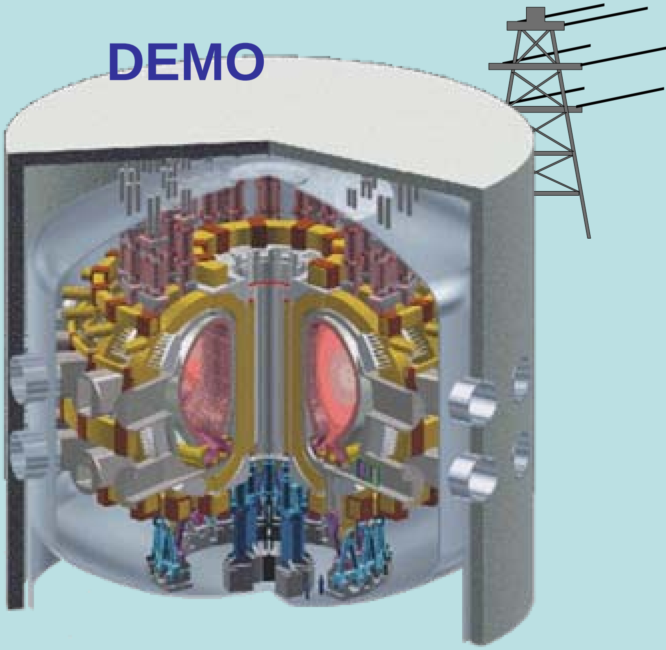
ITER



IFMIF



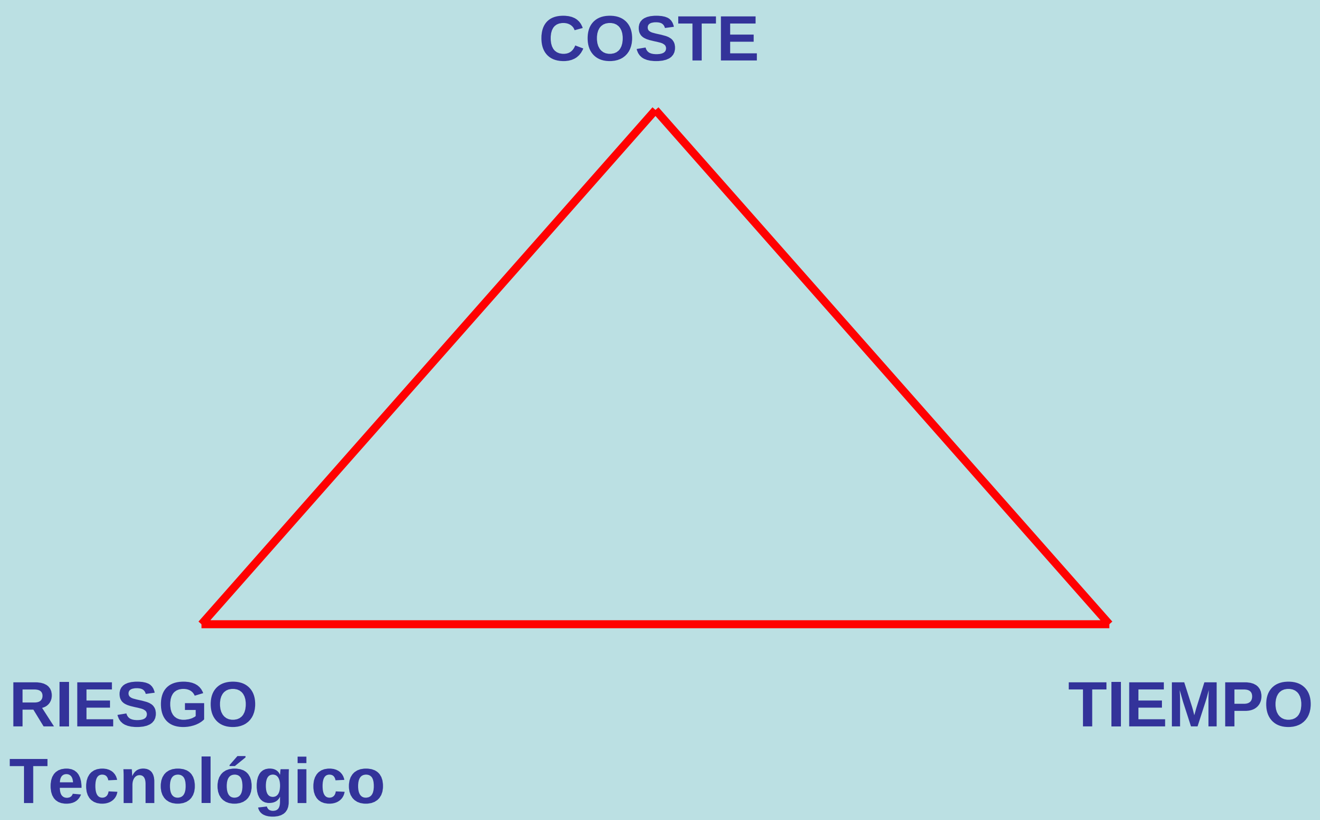
DEMO



¿ se puede acelerar ?

Aunque las inversiones en Fusión son modestas en términos del gasto mundial en energía son muy elevadas para los presupuestos públicos de investigación.

La investigación progresa reduciendo al máximo la posibilidad de fracasos en cada paso.



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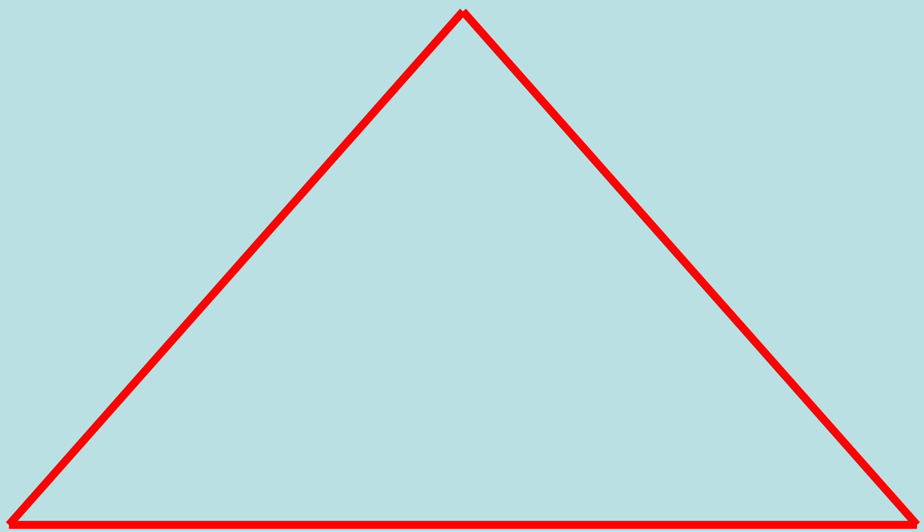
COSTE (ITER ~ consumo mundial de energía de un día)



RIESGO Tecnológico

TIEMPO

"All the News That's Fit to Print"

The New York Times

Late Edition

Weather: Rain likely today, strong easterly winds; rain ending late tonight. Partly cloudy and warmer tomorrow. Temperatures: today 43-47, tonight 40-45; yesterday 38-62. Details, page C30.

VOL.CXXXV.. No. 46,601 NEW YORK, FRIDAY, NOVEMBER 22, 1985 — 50 cents beyond 75 miles from New York City, except on Long Island. 30 CENTS

ext of the Joint U.S.-Soviet Statement: 'Greater Understanding Achieved'

pecial to The New York Times

EVA, Nov. 21 — Following is of the joint Soviet-American nt at the end of the summit today, as made public by the louse:

utual agreement, the Presi- the United States, Ronald and the General Secretary of tral, Committee of the Com- Party of the Soviet Union, Mi- Gorbachev, met in Geneva 21. Attending the meeting on side were Secretary of State P. Shultz; chief of staff, Don- egan; Assistant to the Presi- bert C. McFarlane; Ambas- the U.S.S.R., Arthur A. Hart- ecial adviser to the President Secretary of State for Arms Paul H. Nitze; Assistant Sec- f State of European Affairs, L. Ridgway; Special Assist- e President for National Se- ffairs, Jack F. Matlock. ling on the Soviet side were of the Politburo of the Cen- mmittee of the C.P.S.U., of Foreign Affairs Eduard rdnadze; First Deputy For- ister Georgi M. Korniyenko; dor to the United States, F. Dobrynin; head of the De- t of Propaganda of the Cen- mittee of the C.P.S.U., Alek- Yakovlev; head of the De- t of International Informa- e Central Committee of the Leonid M. Zamyatin; to the General Secretary of tral Committee of the , Andrei M. Aleksandrov.

comprehensive discussions the basic questions of U.S.- lations and the current inter- situation. The meetings were d useful. Serious differences n a number of critical issues. acknowledging the differ- their systems and ap- to international issues, eater understanding of each ew was achieved by the two They agreed about the need ve U.S.-Soviet relations and ational situation as a whole.

In this connection the two sides have confirmed the importance of an ongoing dialogue, reflecting their strong desire to seek common ground on existing problems.

They agreed to meet again in the nearest future. The General Secretary accepted an invitation by the President of the United States to visit the United States of America, and the President of the United States accepted an invitation by the General Secretary of the Central Committee of the C.P.S.U. to visit the Soviet Union. Arrangements for the timing of the visits will be agreed upon through diplomatic channels.

In their meetings, agreement was reached on a number of specific issues. Areas of agreement are registered on the following pages.

Security

The sides, having discussed key security issues, and conscious of the special responsibility of the USSR and the U.S. for maintaining peace, have agreed that a nuclear war cannot be won and must never be fought. Recognizing that any conflict between the U.S.S.R. and the U.S. could have catastrophic consequences, they emphasized the importance of preventing any war between them, whether nuclear or conventional. They will not seek to achieve military superiority.

Nuclear and Space Talks

The President and the General Secretary discussed the negotiations on nuclear and space arms.

They agreed to accelerate the work at these negotiations, with a view to accomplishing the tasks set down in the Joint U.S.-Soviet Agreement of Jan. 8, 1985, namely to prevent an arms race in space and to terminate it on earth, to limit and reduce nuclear arms and enhance strategic stability.

Noting the proposals recently tabled by the U.S. and the Soviet Union, they called for early progress, in particular in areas where there is common ground, including the principle of 50 percent reductions in the nuclear arms of the U.S. and the U.S.S.R. appropriately applied, we well as the idea of an interim I.N.F. agreement.

During the negotiation of these agreements, effective measures for verification of compliance with obligations assumed will be agreed upon.

Risk Reduction Cente

The sides agreed to study th tion at the expert level of cer reduce nuclear risk taking i count the issues and developm the Geneva negotiations. The satisfaction in such recent s this direction as the moderniz the Soviet-U.S. hot line.

Nuclear Nonprolifera

General Secretary Gorbach President Reagan reaffirme commitment of the U.S.S.R. a U.S. to the Treaty on the Nonp ation of Nuclear Weapons an interest in strengthening to with other countries the nonpr tion regime, and in further enh the effectiveness of the treaty alia by enlarging its members

The U.S.S.R. and the U.S. re their commitment, assumed by under the Treaty on the Nonpro tion of Nuclear Weapons, to p negotiations in good faith on m of nuclear arms limitation and mament in accordance with A VI of the treaty.

The two sides plan to conti promote the strengthening of t ternational Atomic Energy A and to support the activities agency in implementing safeg as well as in promoting the pe uses of nuclear energy.

They view positively the pract regular Soviet-U.S. consultatio nonproliferation of nuclear wea which have been businesslik constructive, and express their to continue this practice in the fu

Chemical Weapons

In the context of discussin curity problems, the two sides firmed that they are in favor of a general and complete prohibition of chemical weapons and the destruction of existing stockpiles of such weapons. They agreed to accelerate efforts to conclude an effective and verifiable international convention on this matter.

The two sides agreed to intensify bilateral discussions on the level of

ministries and departments in such fields as agriculture, housing and protection of the environment have been useful.

Recognizing that exchanges of views on regional issues on the expert level have proven useful, they agreed to continue such exchanges on a regular basis.

The sides intend to expand the pro-

— a global task — through joint research and practical measures. In accordance with the existing U.S.-Soviet agreement in this area, consultations will be held next year in Moscow and Washington on specific programs of cooperation.

Fusion Research

The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermo-nuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentialy inexhaustible, for the benefit for all mankind.

Fusión en España: CIEMAT

Se forma un grupo de investigación en 1975

El **tokamak TJ-I** comienza operación en 1983

El Torsatron **TJ-IU** fue construido en CIEMAT y posteriormente cedido a la Universidad de Kiel en 1999 **(ahora TJK)**

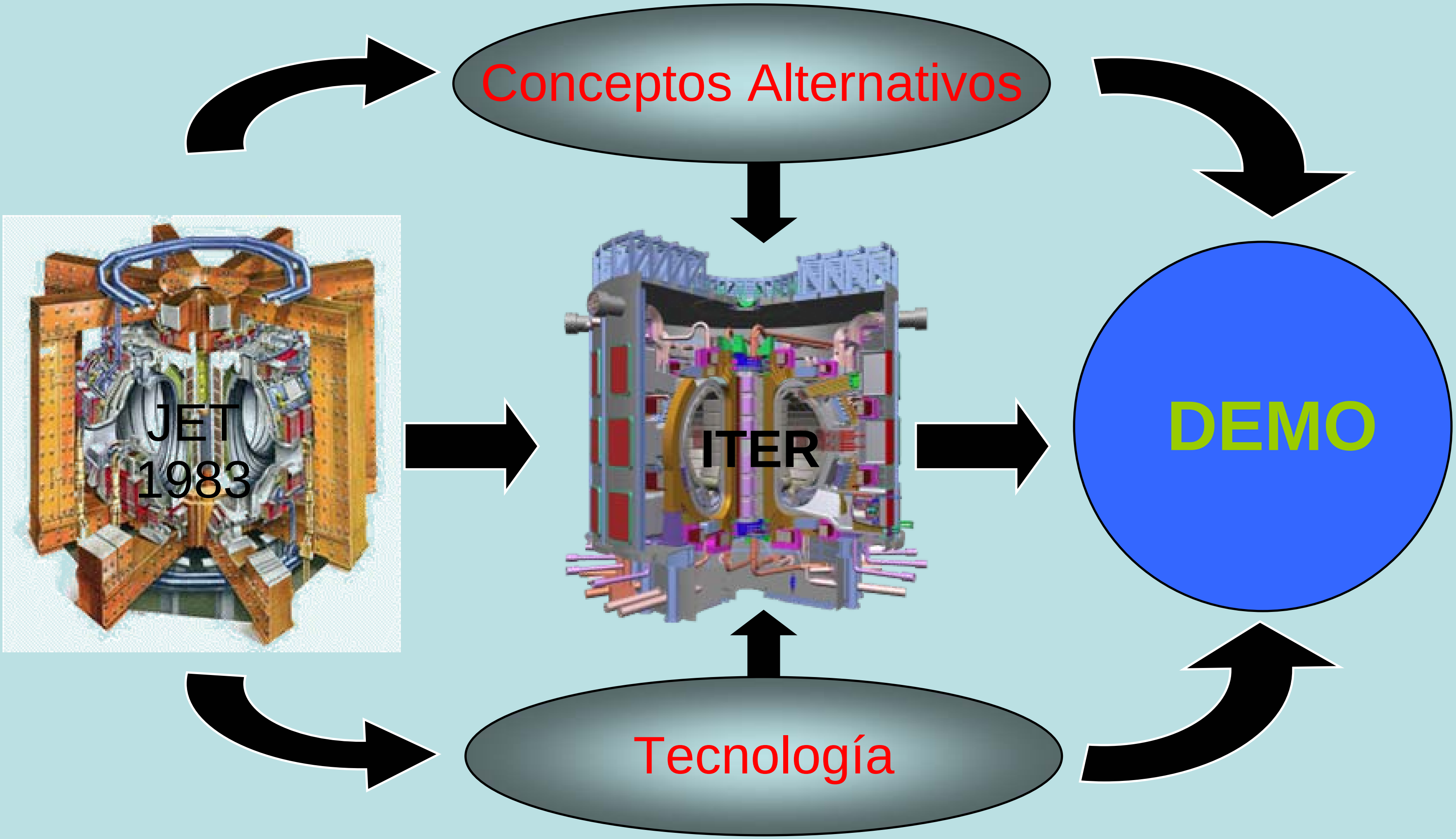
Teure Leihgabe aus Madrid

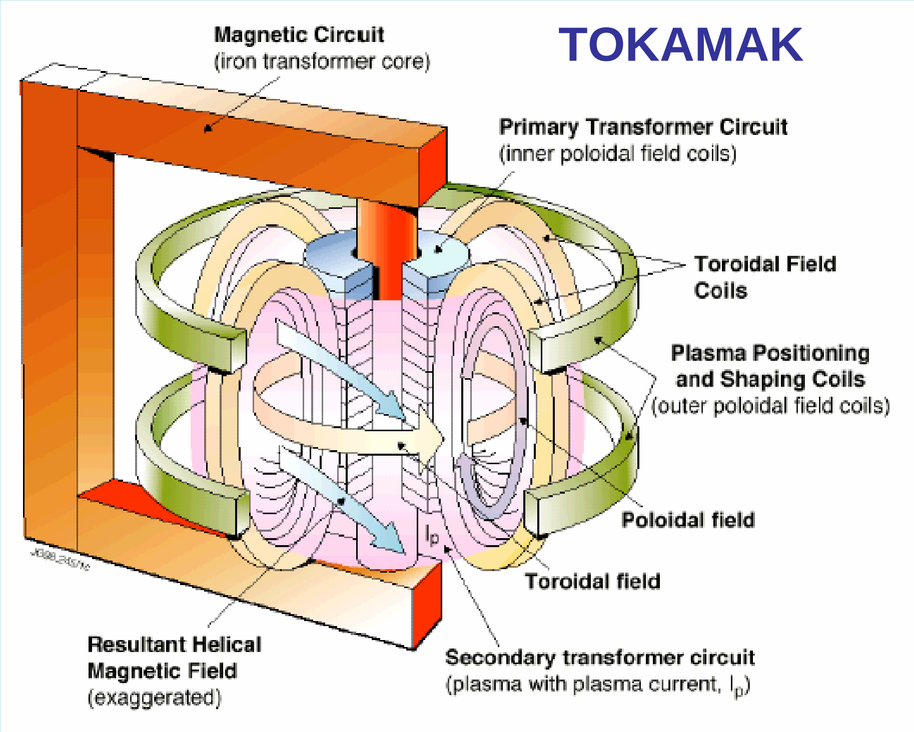
TJ-II (1998)

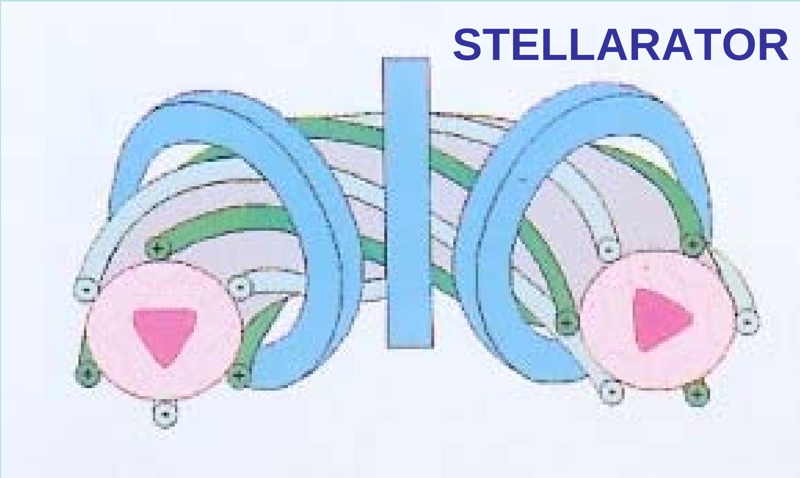
El Stellarator **TJ-II** comienza operación en 1998 (Grupo de 120 personas)

Laboratorio de **materiales** CIEMAT: referencia europea en materiales aislantes

Estrategia española







Campo poloidal es producido por la corriente inducida en el Plasma

- Ingeniería más sencilla
- Mejor transporte de energía y partículas
- Mayores tamaños
- Mas cerca de alcanzar “ignición”
- ITER es un Tokamak

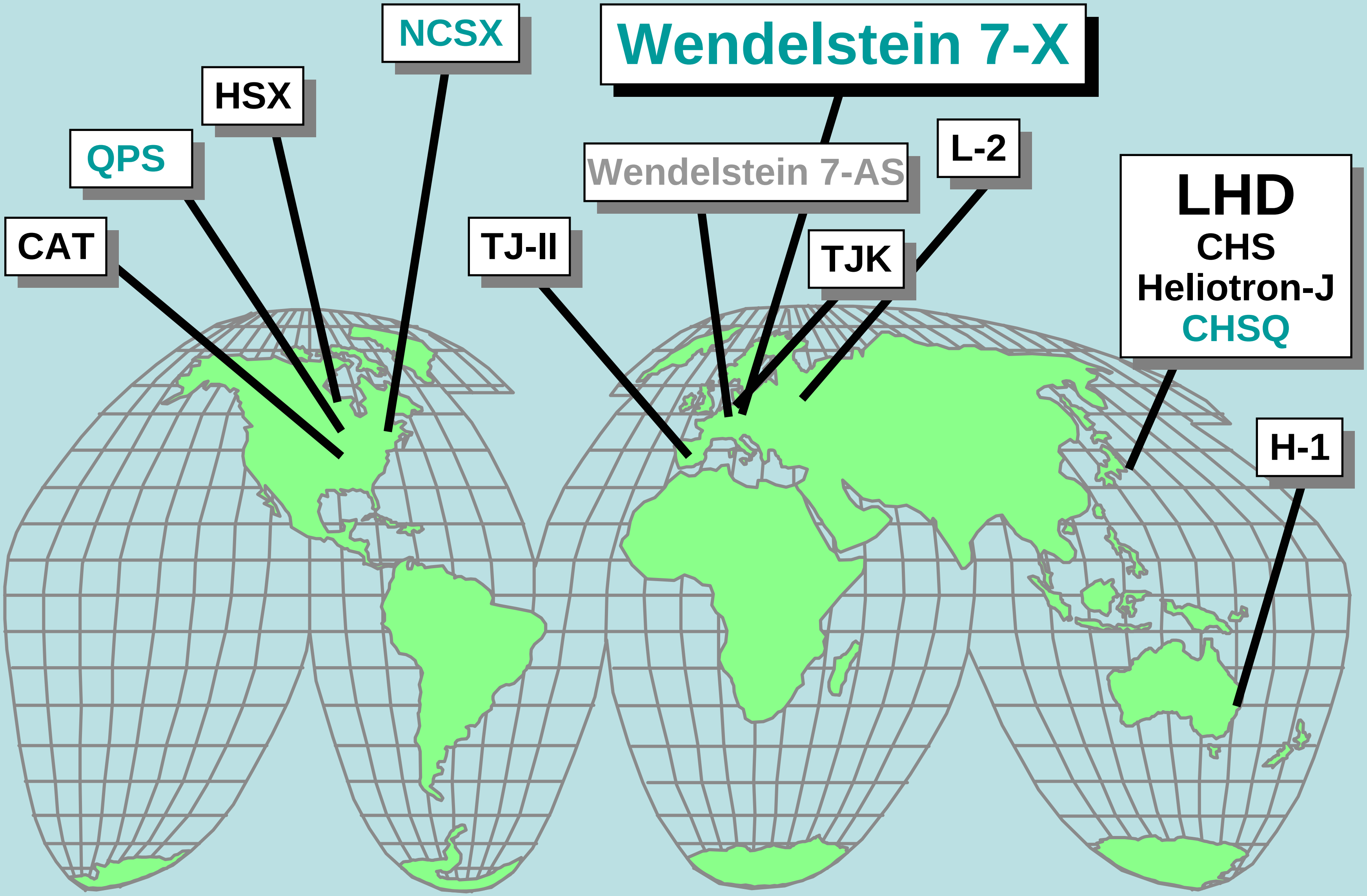
Pero: operación pulsada, disrupciones

Campo poloidal es producido por corrientes externas al Plasma

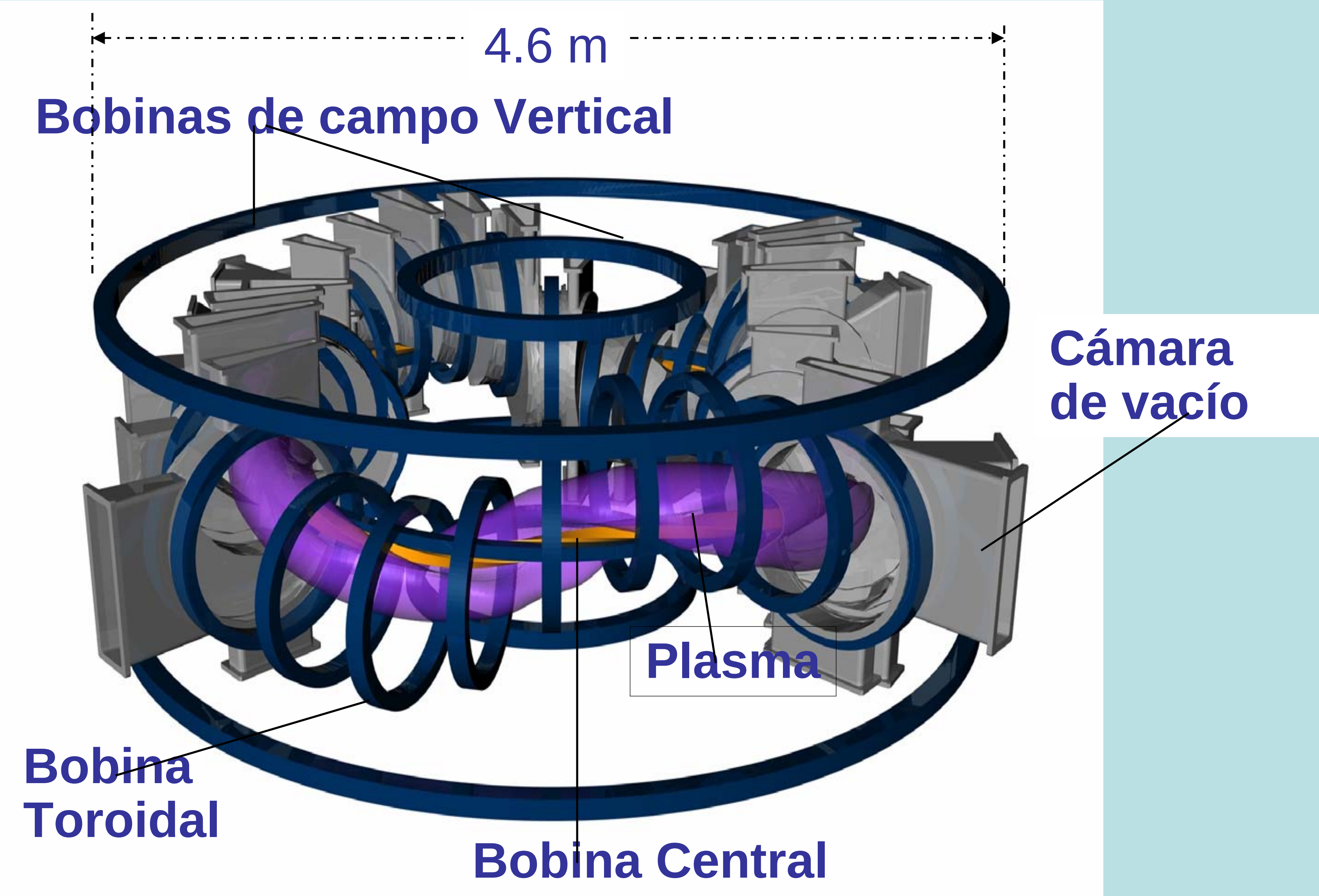
Ingeniería mas compleja
- Transporte mayor (?)
- Tamaños menores
- Factor 30 detrás de los tokamaks

Ventajas: operación estacionaria, no disrupciones
Candidato óptimo para el reactor comercial

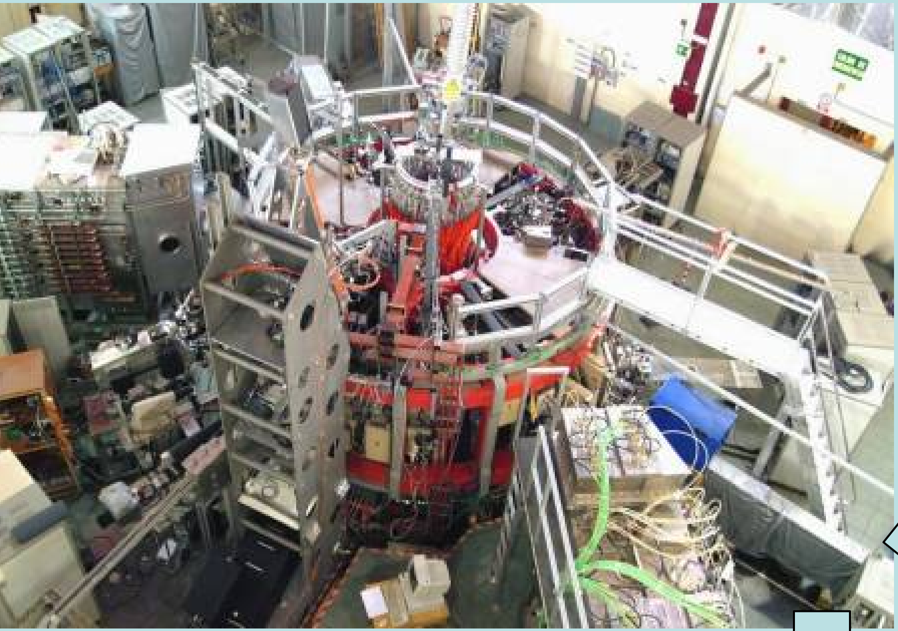
Stellarators en el mundo:



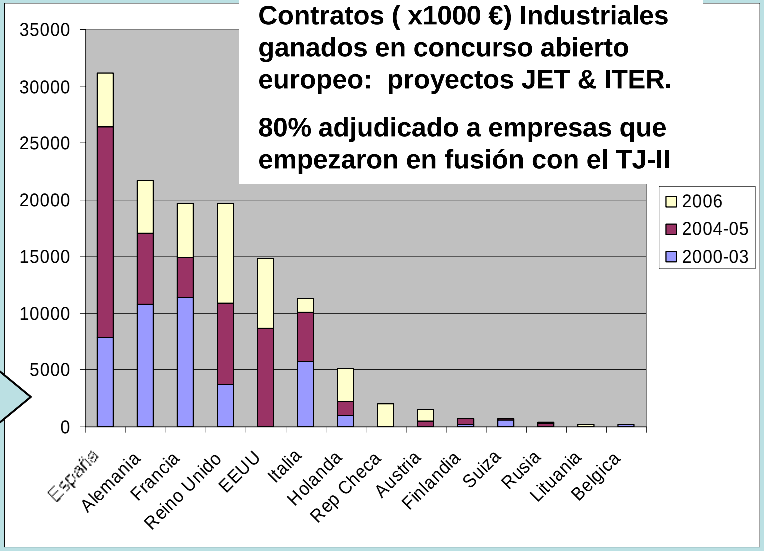
TJ-II


4.6 m
Bobinas de campo Vertical
Cámara
de vacío
Plasma
Bobina
Toroidal
Bobina Central

INSTALACION SINGULAR TJ-II

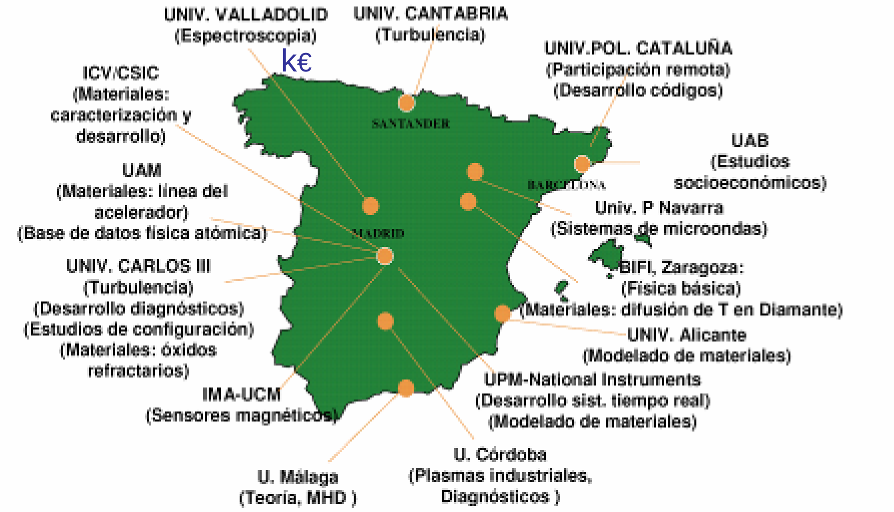


Implicar a la Industria



Implicar al sistema nacional de I+D

•DOCTORADO PLASMAS & FUSION, MENCION DE CALIDAD (2005-
•EUROPEAN MASTER FUSION PHYS. & ENGINEERING, ERASMUS MUNDUS (2006-

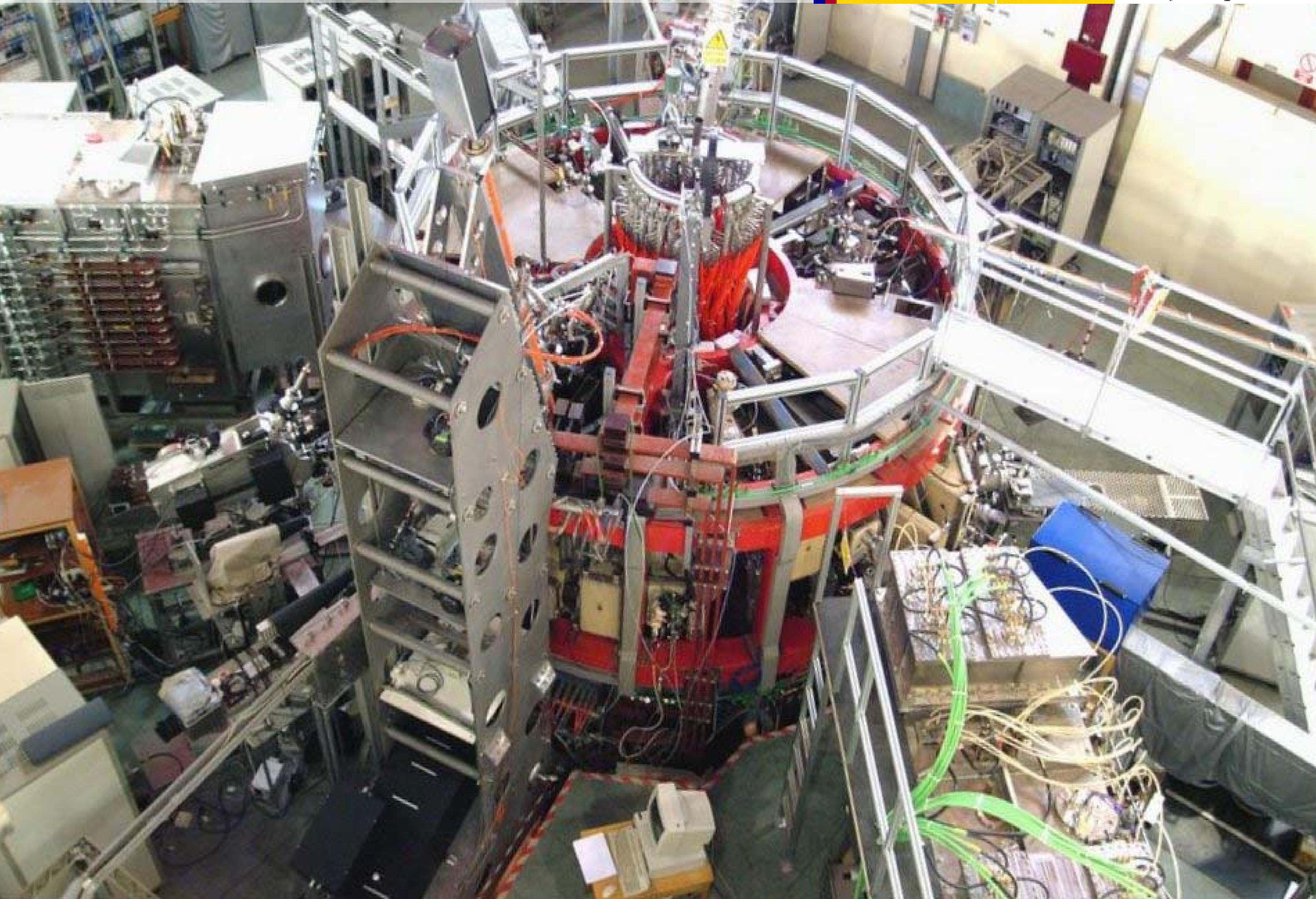


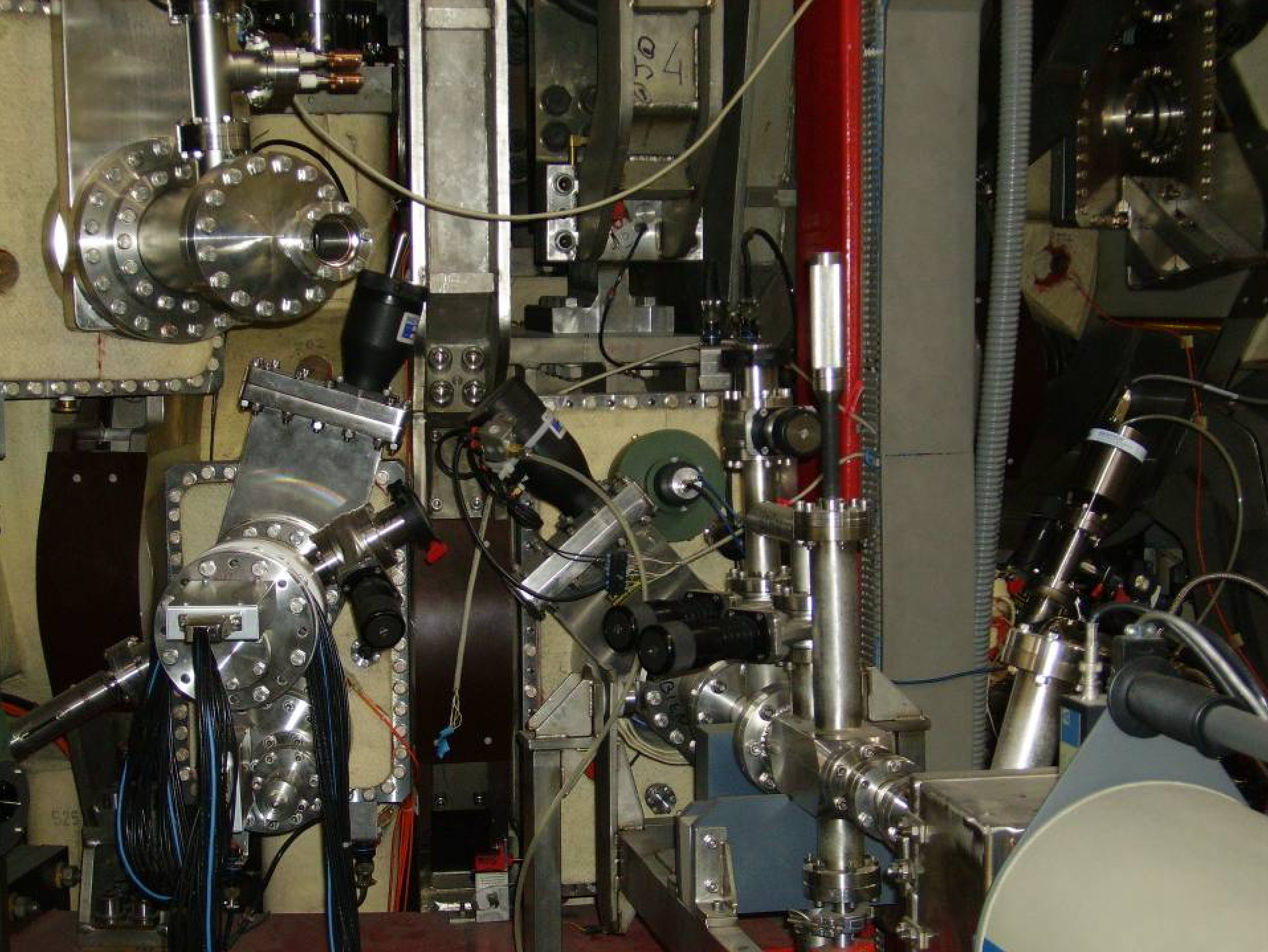
LABORATORIO DE MATERIALES

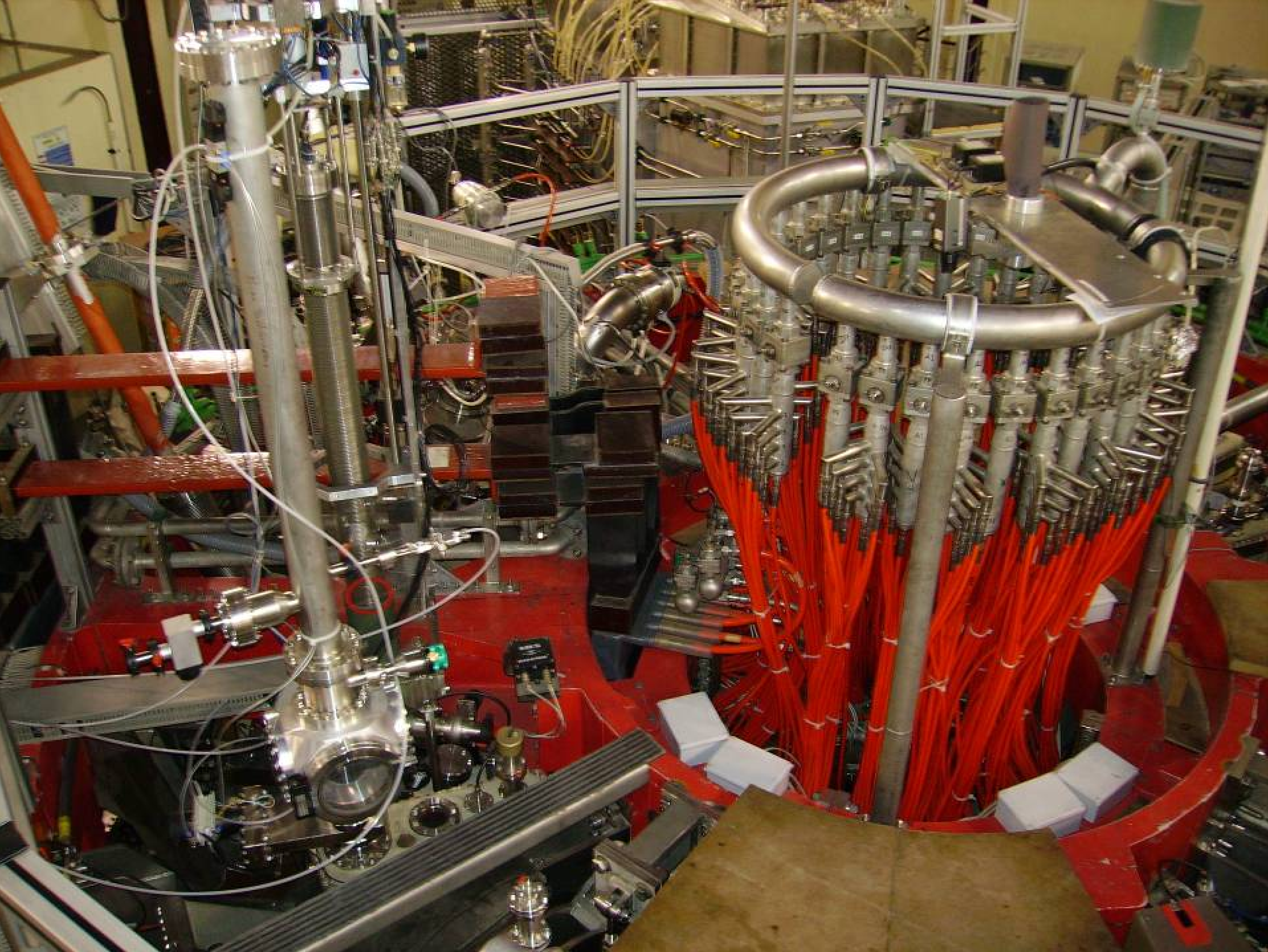
Instalación singular TJ-II

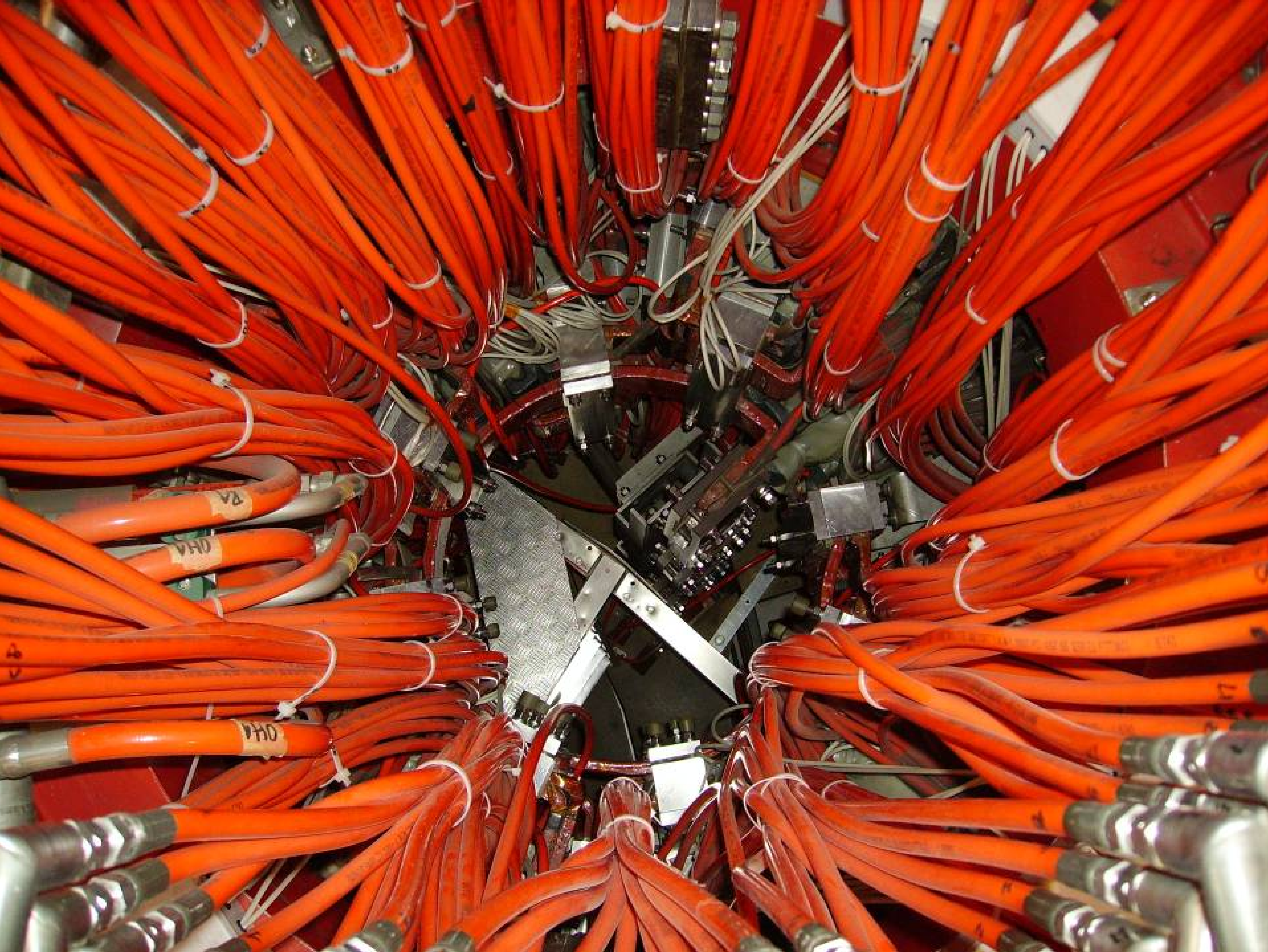
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

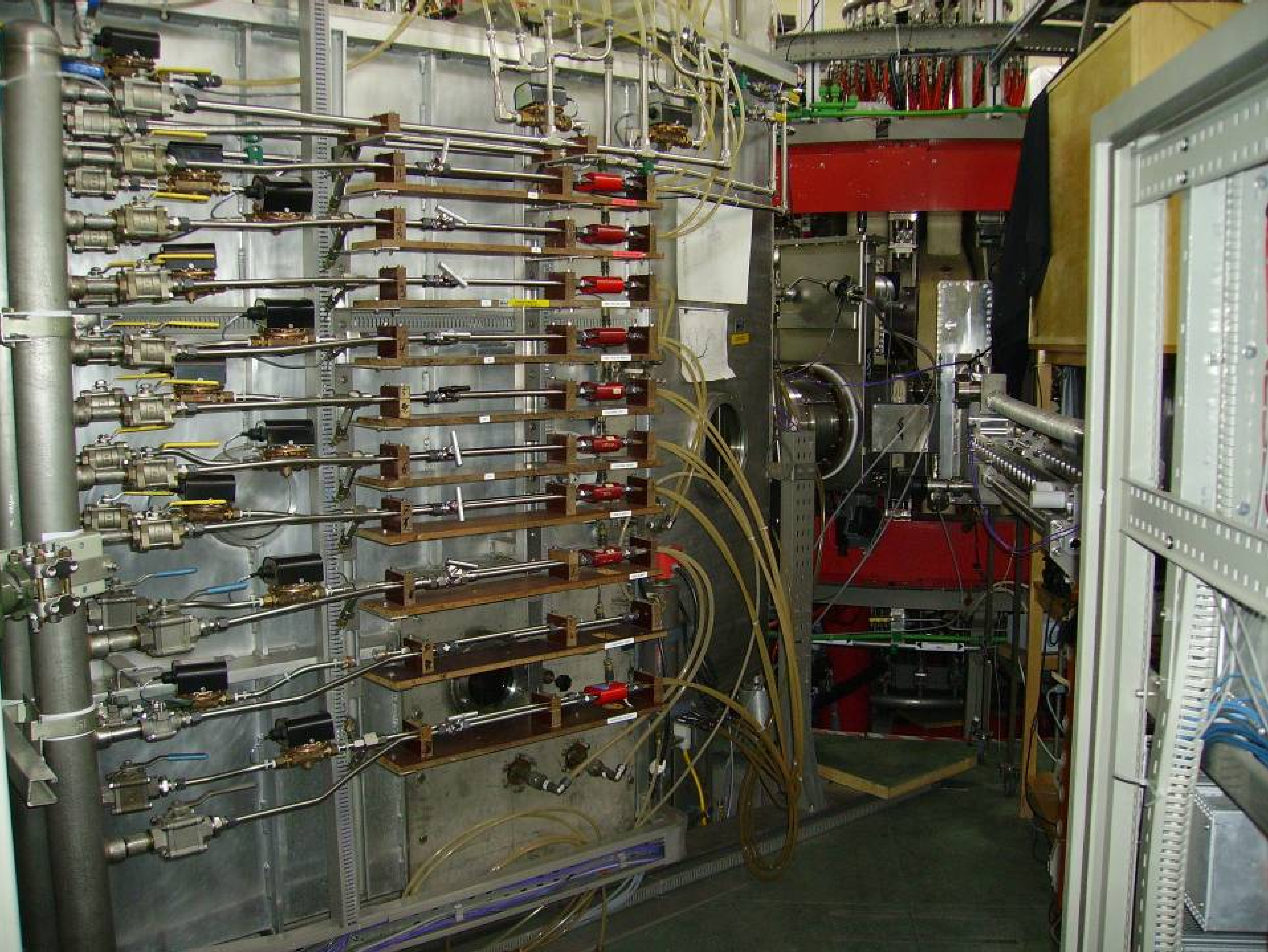
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

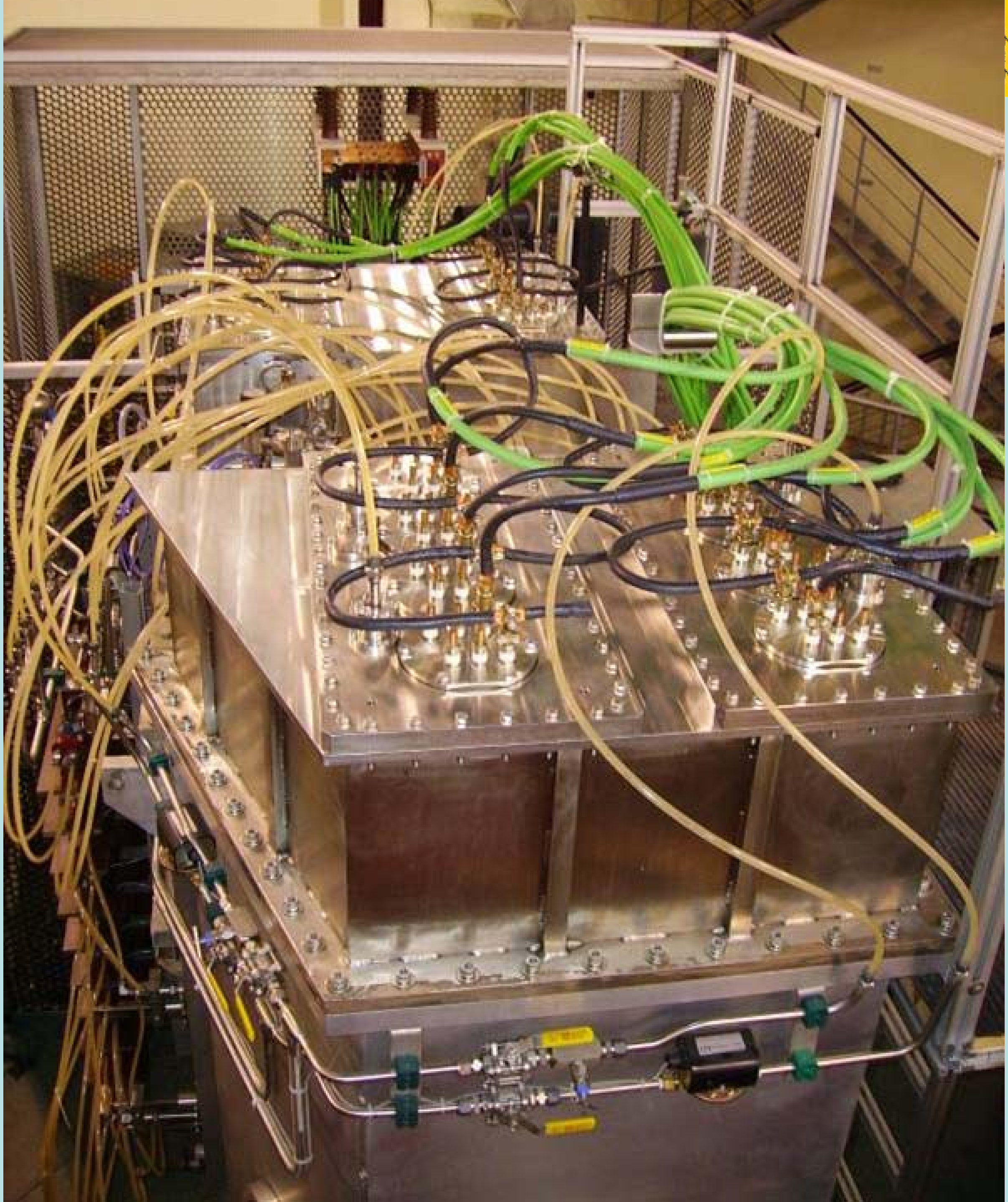


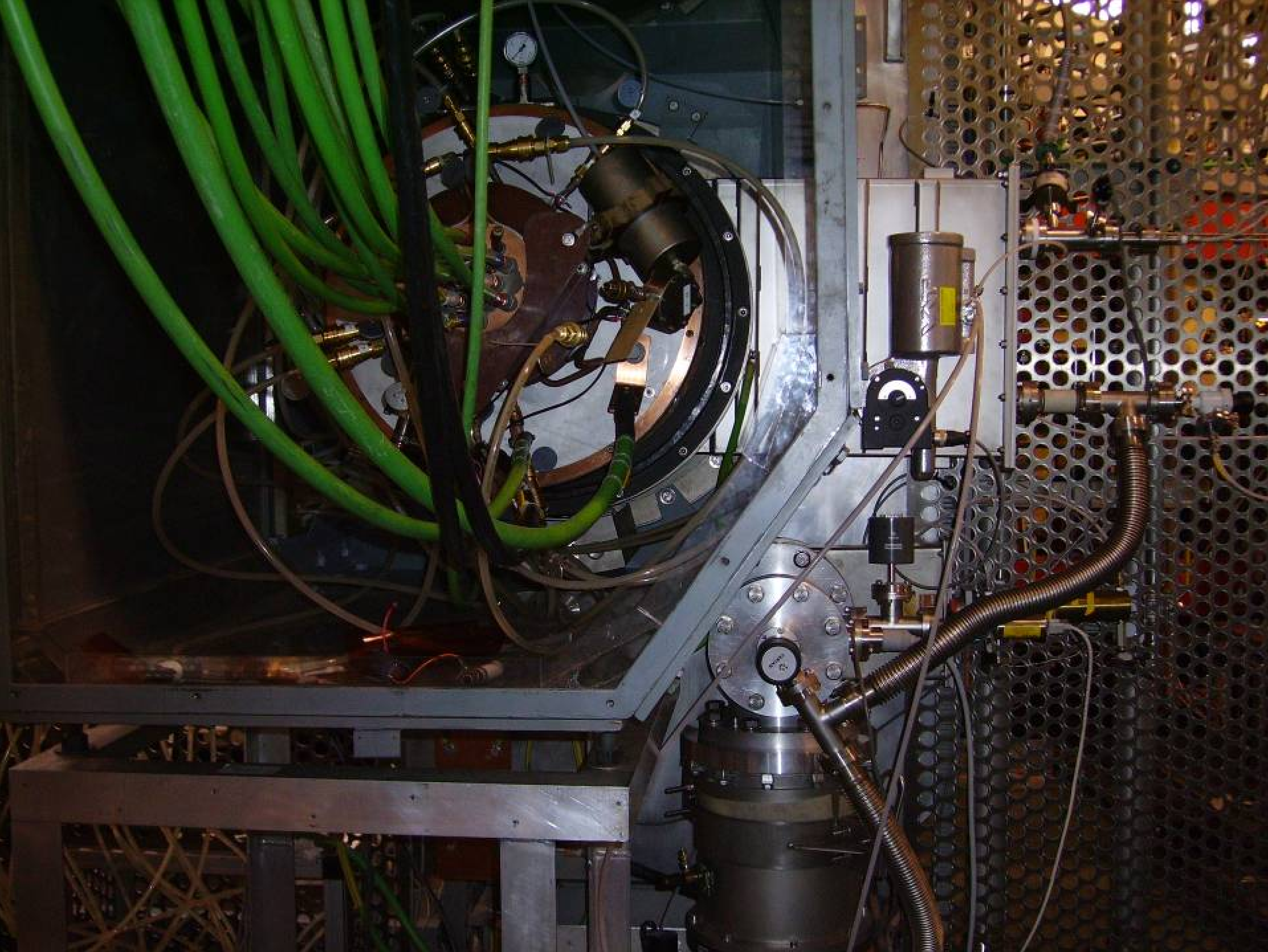


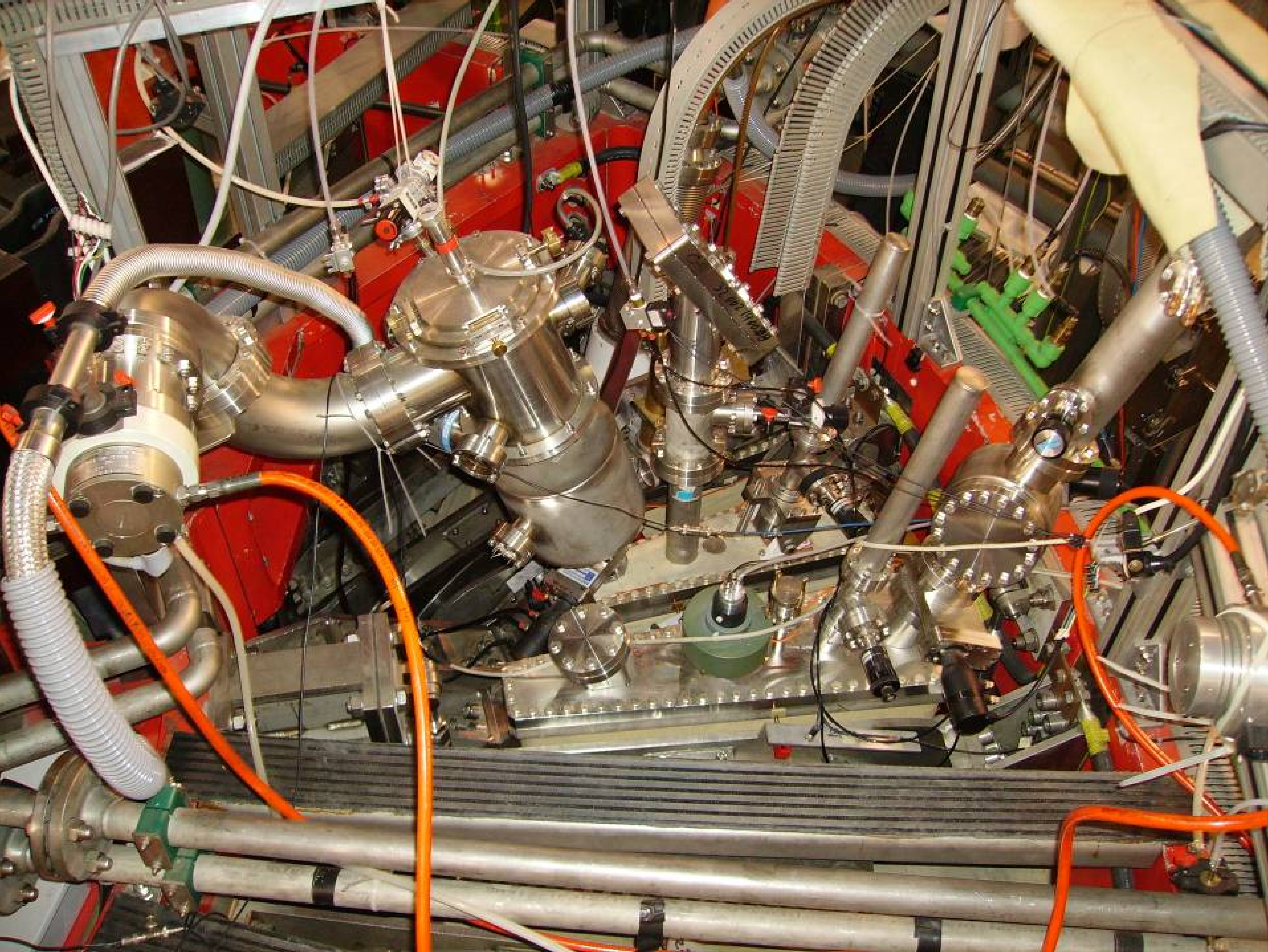


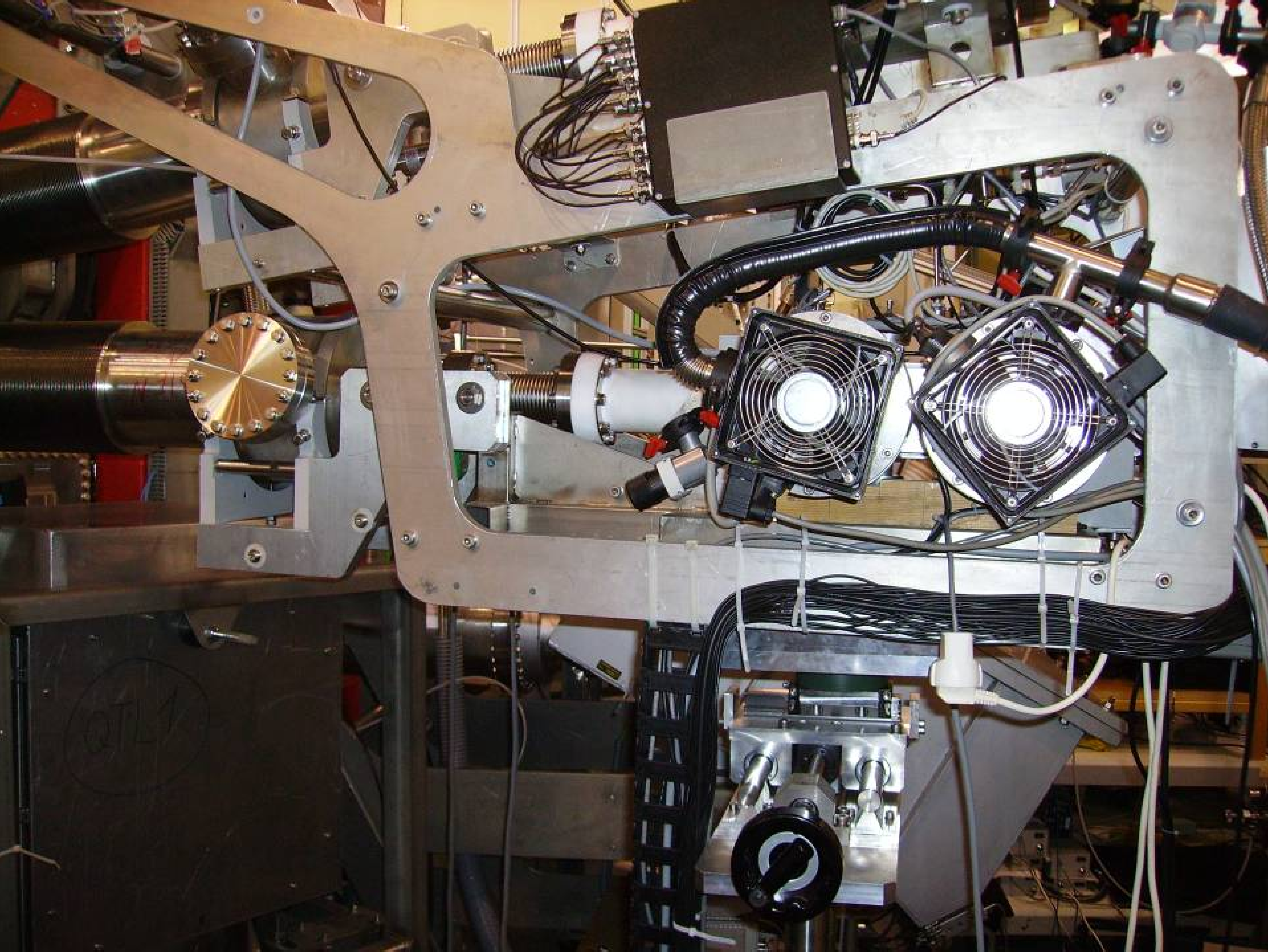


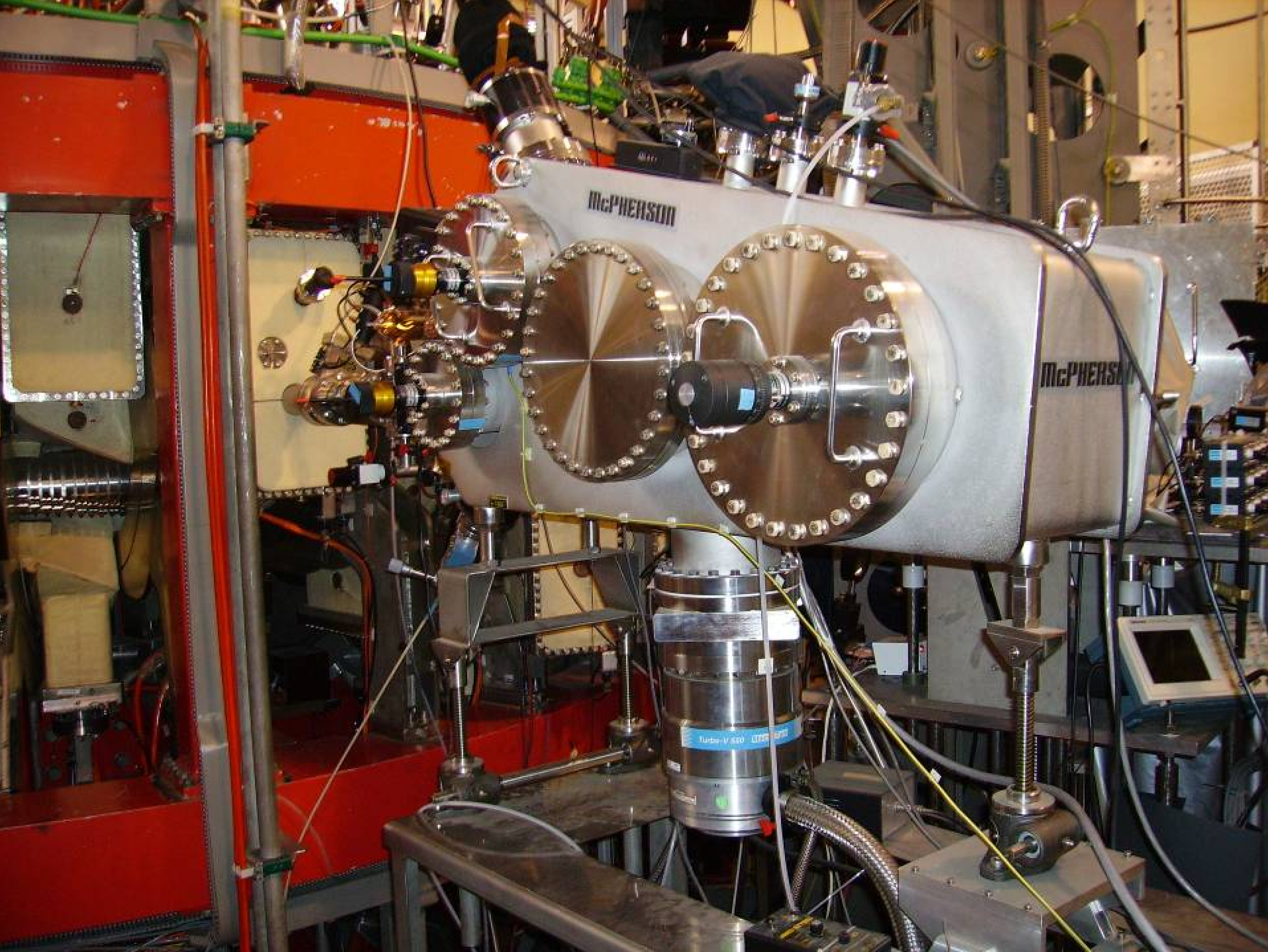








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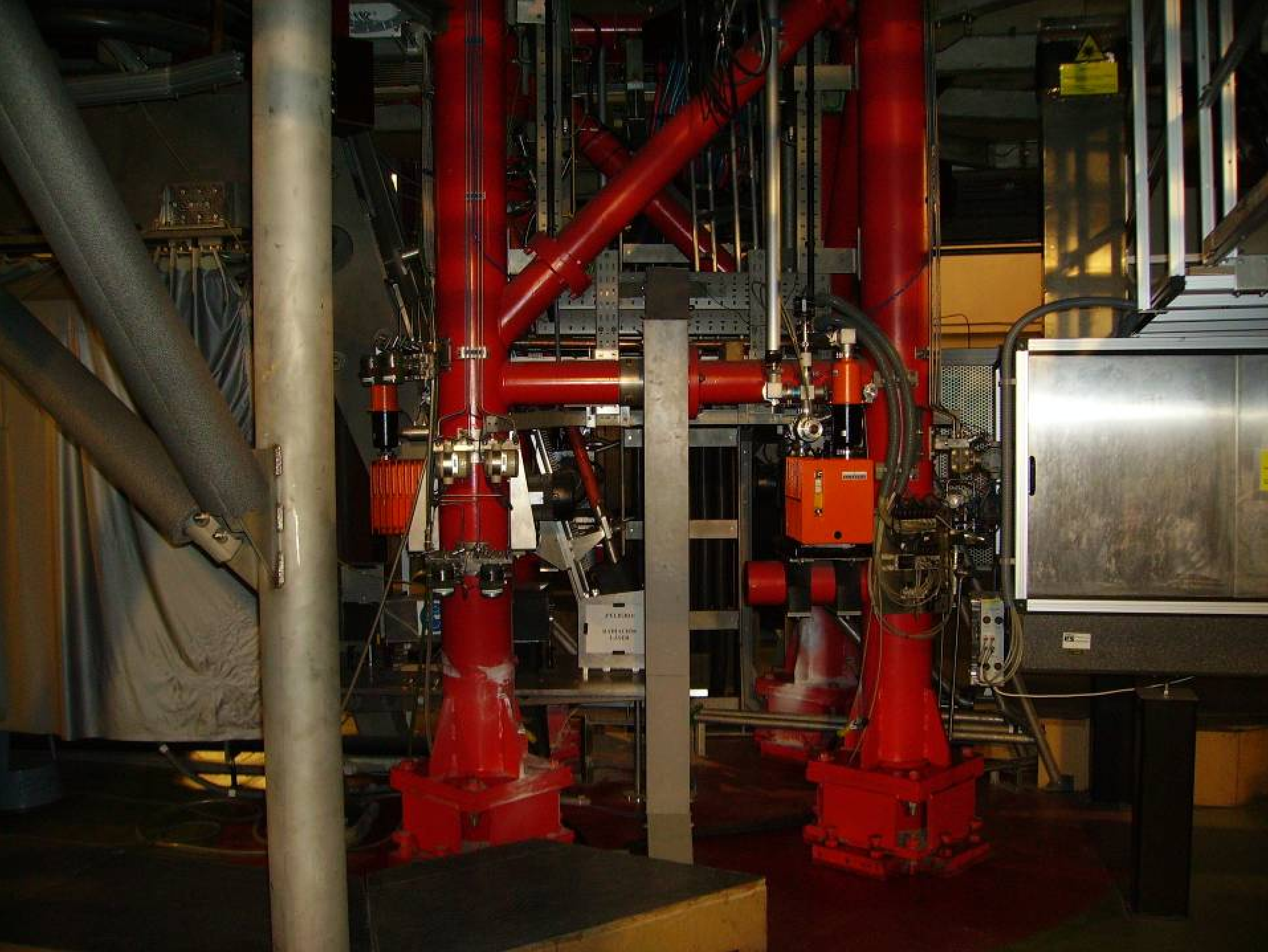

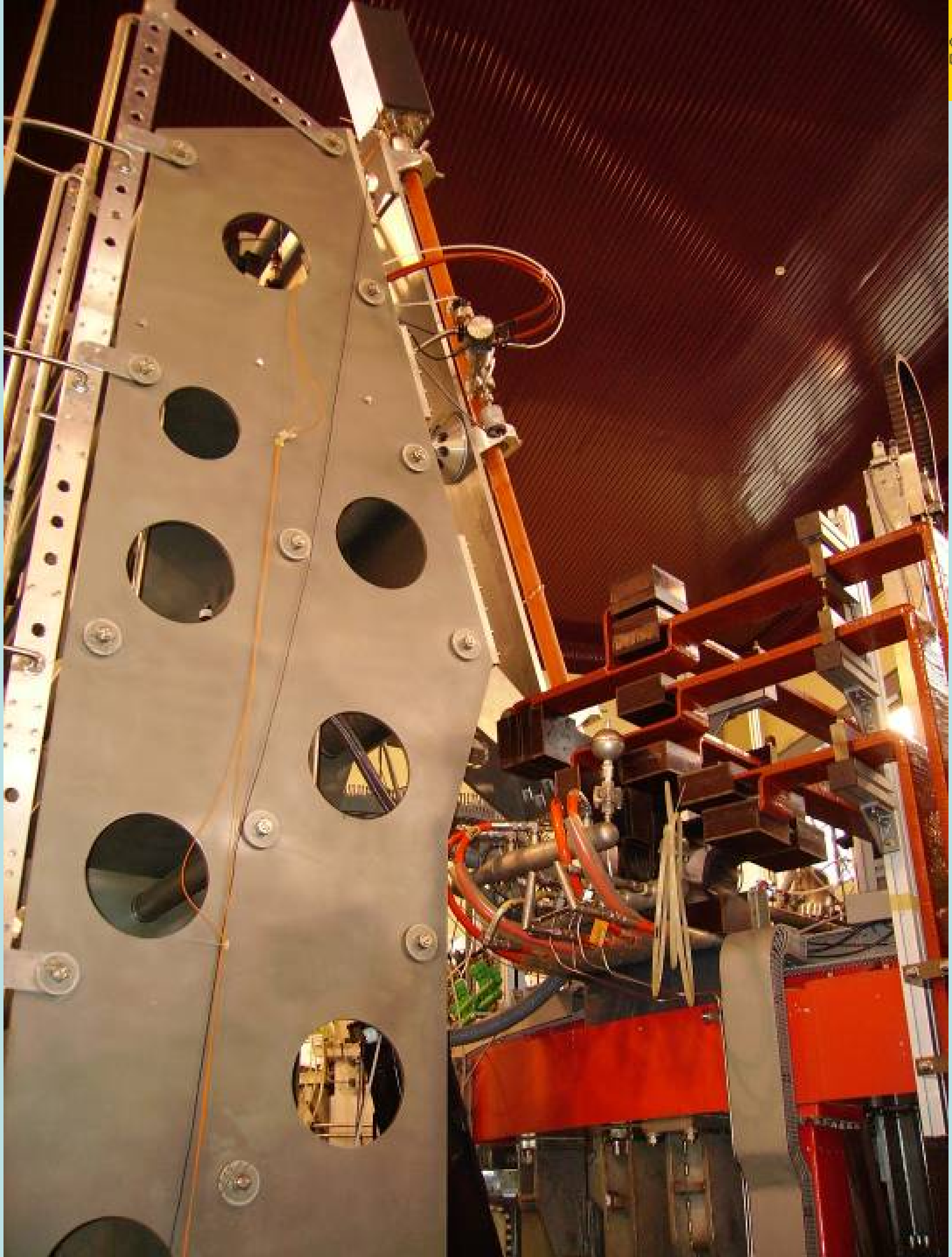

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