Overview of the History of Magnetic Fusion

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Los Alamos National Laboratory

Plasma Summer Series
Lecture
July 27, 2005

Why Fusion Research?

- Controlling fusion on earth is a Grand Challenge.
- Our long term research goal is Energy. Our short term goal is Science.
- Excellent recruiting tool: Still easily attracts high caliber students and staff. (Idealism)
- Requires and utilizes wide variety of skill sets of interest to the lab.
- Contains both science, energy and defense components within fusion R&D issues.

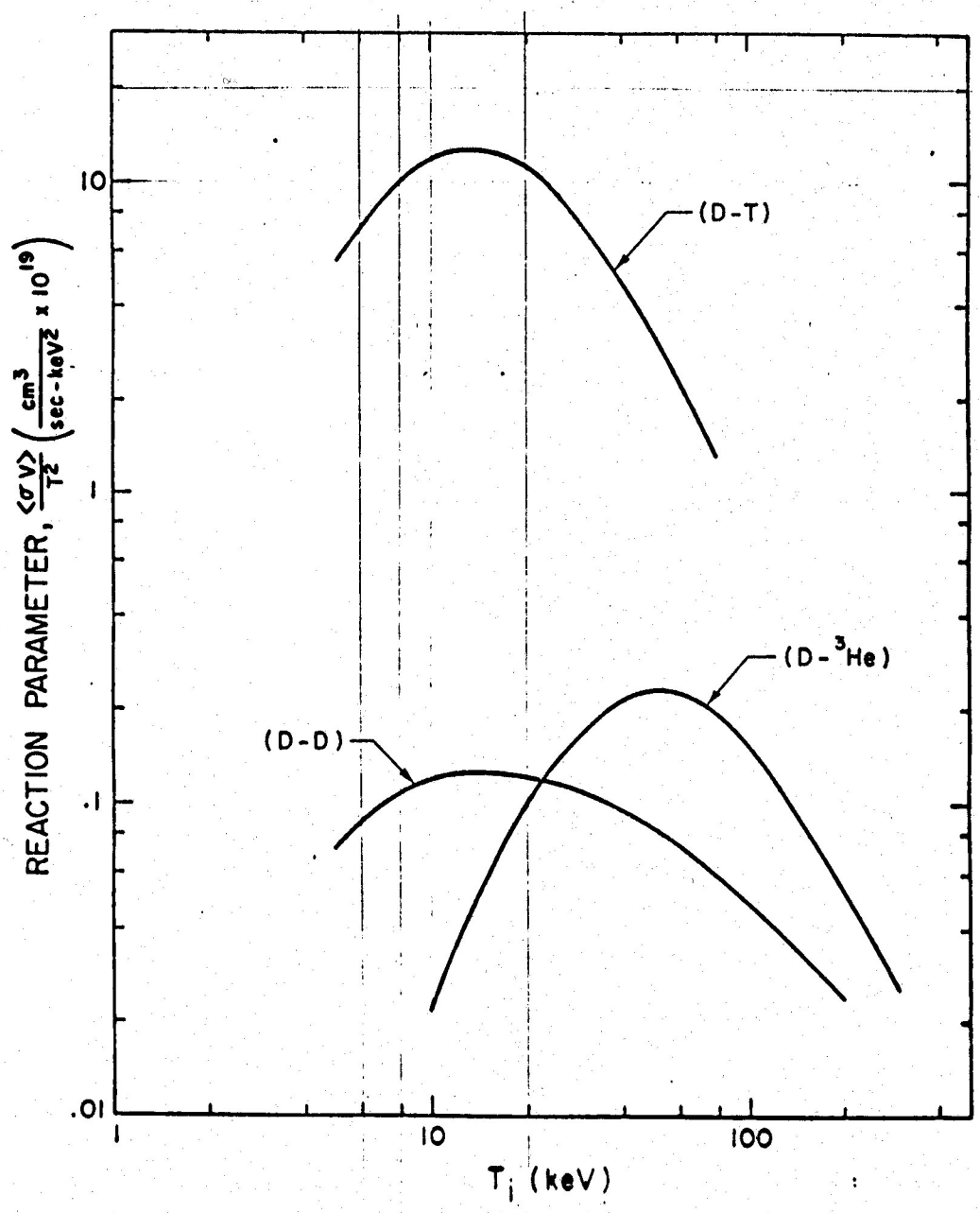


Figure 3.5 The Maxwellian averaged fusion rate parameter, $\langle\sigma v\rangle/T^2$, as a function of ion temperature for three fusion fuel cycles (Ref. 3).

The power of 14.2-MeV neutrons emitted per m^3 is

$$p_n = (14.2/3.5)P_\alpha. \tag{3.4}$$

Figures 3.4 and 3.5 show $\langle\sigma v\rangle$ and $\langle\sigma v\rangle/T^2$ versus T for various possible fusion reactions. Note that $\langle\sigma v\rangle/T^2$ shows a broad maximum in each case.

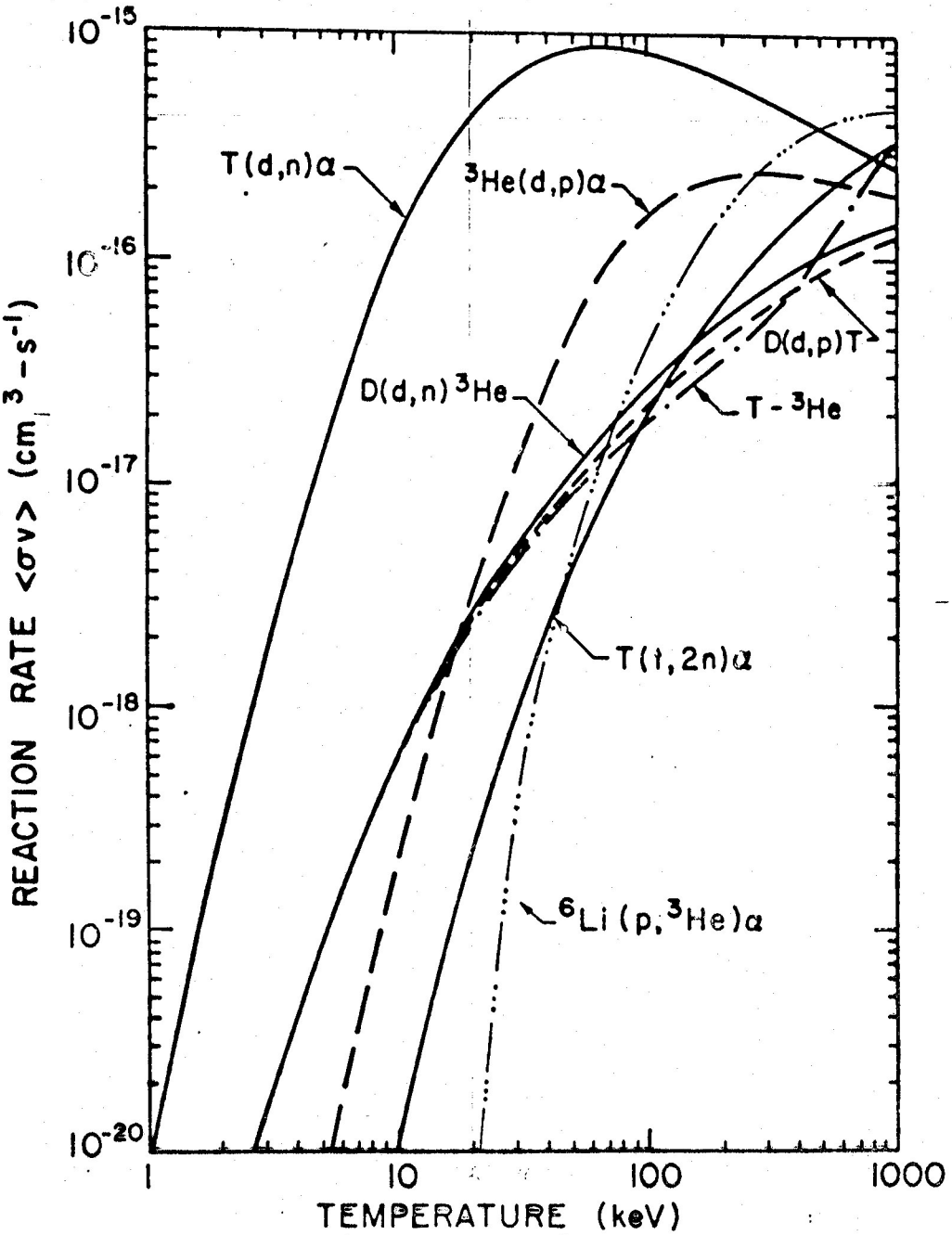


Figure 3.4 The maxwellian averaged fusion reaction rate, $\langle\sigma v\rangle$, as a function of ion temperature for the main fusion reaction cycles (Ref. 2).

IGNITION AND LAWSON CONDITIONS FOR DEUTERIUM-TRITIUM FUEL

IGNITION CONDITION

$$\frac{3nT}{\tau_E} + b\,n^2 T^{1/2} = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha$$

(Plasma power loss) (Fusion-alpha power)

$$n\tau_E = \frac{3T}{\frac{1}{4}\langle \sigma v \rangle E_\alpha - b\,T^{1/2}}$$

LAWSON CONDITION

fusion α's

$$\frac{3nT}{\tau_E} + b\,n^2 T^{1/2} = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha$$

Losses – conduction + transport Bremsstrahlung neutrons

$$+ \eta_t \left(\frac{3nT}{\tau_E} + b\,n^2 T^{1/2} + \frac{1}{4} n^2 \langle \sigma v \rangle E_n \right)$$

(Electrical conversion of plasma power loss plus fusion-neutron power)

$$n\tau_E = \frac{3T(1-\eta_t)}{\frac{1}{4}\langle \sigma v \rangle (E_\alpha + \eta_t E_n) - (1-\eta_t)\,b\,T^{1/2}}$$

$n = n_e = 2n_D = 2n_T$

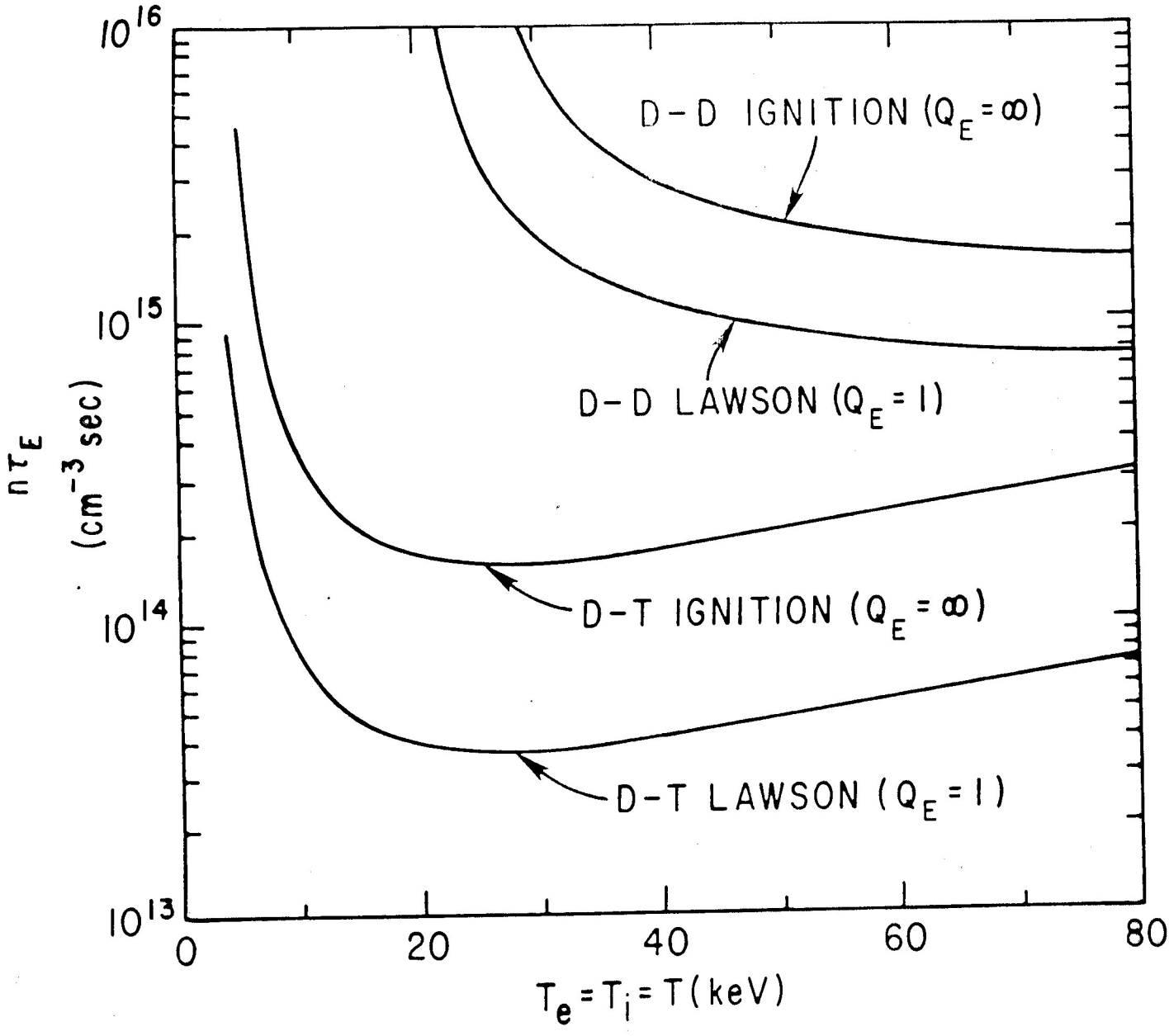
$E_\alpha = 3.5$ MeV

$b = 3.65 \times 10^{-15}$ with T in keV

$\eta_t = 0.33$

$T = T_e = T_i$

$E_n = 14.1$ MeV + 4.8 MeV
neutron blanket



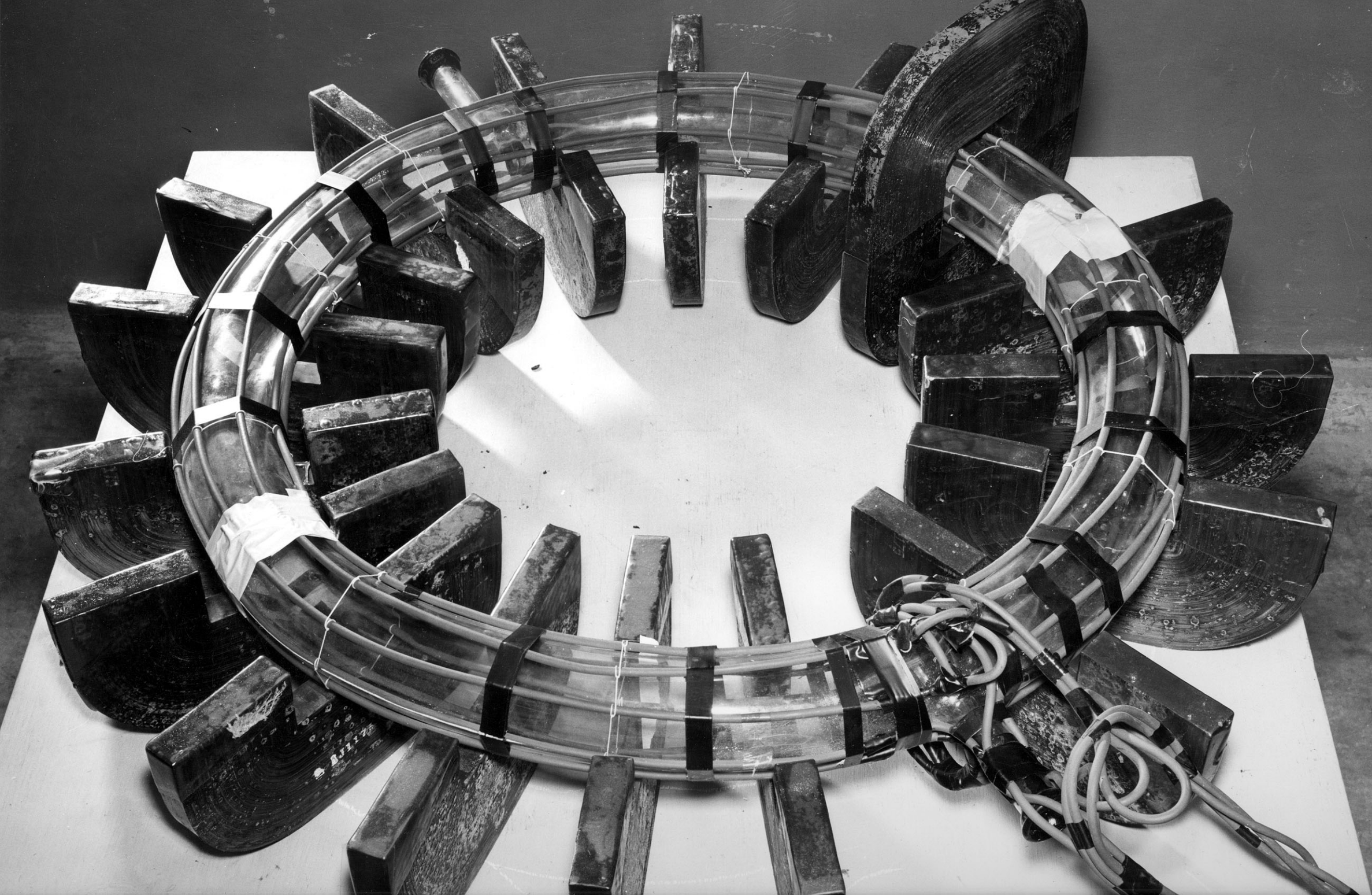
$$Q_E = \frac{\text{Electrical Power Output}}{\text{Input Power to Plasma}}$$

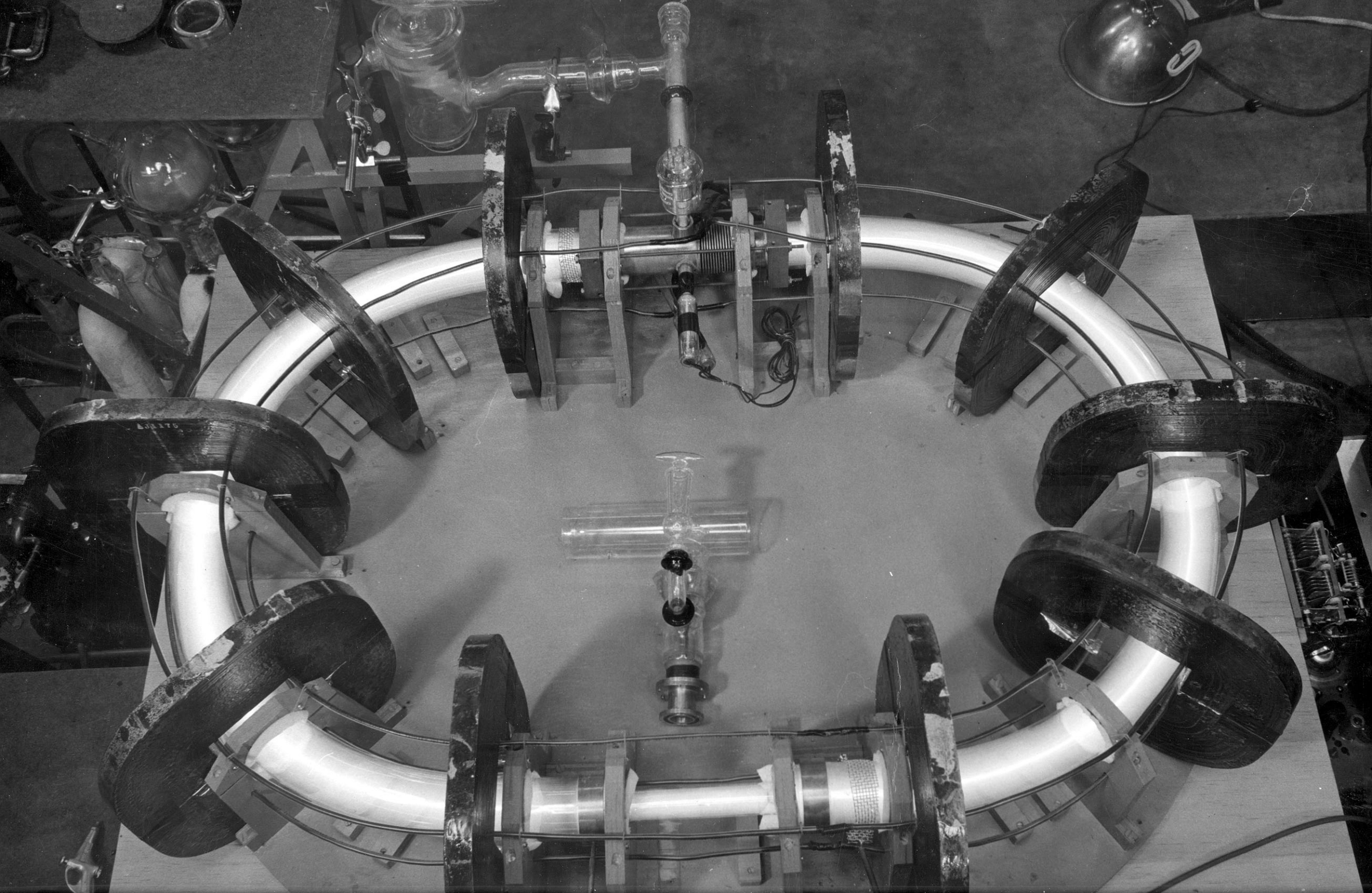
<u>IGNITION</u>. Input power = 0.

$Q_E = \infty$

<u>LAWSON</u>. Input power = Electrical power output

$Q_E = 1$





San Francisco Chronicle Jan-3, 1958

N.Y. Times May 7, 1958

SIR DAVID ECCLES
"You look for the chap with the fattest wallet"

Trade Chief's Report

British H-Power Near, Official Says

By Arthur Hoppe

Great Britain is on the threshold of attaining unlimited peacetime power through taming the hydrogen bomb, a top British official said here yesterday.

"We are very nearly there," Sir David Eccles, president of Britain's Board of Trade, told a press conference.

Asked if this meant the production of electric power through thermonuclear energy within "the next several years," he replied: "We hope so."

There have been hints, reports and rumors in the press that the British scientists have

S. P. to Drop Two Commuter Train Trips

Southern Pacific announce plans yesterday to discontinue two "after-peak hour

BRITAIN INDICATES REACTOR ADVANCE

Plans Hydrogen Fusion Unit to Yield More Heat Than Is Needed to Run It

By KENNETT LOVE
Special to The New York Times.

LONDON, May 6—Britain hopes to begin construction this summer of a hydrogen fusion reactor theoretically capable of producing more energy than will be used to run it.

Informed sources disclosed today that designs were nearing completion at the Atomic Energy Research Establishment at Harwell for a thermonuclear reactor twenty times more powerful than the Zeta apparatus. Zeta is believed here to have achieved the world's first true thermonuclear reactions in experiments that began last August at temperatures ranging from two to 5,000,000 degrees centigrade.

According to its designers, the new reactor should be able to heat heavy hydrogen (deuterium) gas to 100,000,000 degrees centigrade. At this temperature, which is hotter than the core of the sun, hydrogen fusion reactions are theoretically capable of producing a net surplus of energy. The reaction thus would be capable of sustaining itself.

This would be a major breakthrough in the race to tame the hydrogen bomb for the peaceful production of energy.

The estimated cost of the projected reactor is £5,000,000 ($14,000,000), or nearly seventeen times the cost of Zeta.

Significance of Title

Unofficially designated Zeta II, the new device will be built generally on the same principle as Zeta I, according to authoritative informants.

Zeta I is shaped like a doughnut ten feet in diameter. The bore of the ring-shaped tube, called a torus, is slightly more than three feet. The gas, or plasma, of the deuterium nuclei inside the torus is heated by pulsed electrical discharges of 200,000 amperes.

Zeta I is now undergoing modifications to increase its heating capacity to 25,000,000 degrees. Additional condensers are being installed to raise amperage. Additional coils to strengthen the magnetic inner tube are being wound onto

ty that the report would not contain absolute confirmation that Zeta had achieved true thermonuclear reactions.

The neutrons emitted by gas inside Zeta during the electrical pulses could be produced by collisions between accelerated neutrons and relatively cold and stationary neutrons. Isolated fusion reactions from this type of nuclear collision cannot sustain the process.

Thermonuclear fusion results from collisions of uniformly agitated nuclei in random motion, which either fuse on impact or bounce with undiminished momentum to try again in subsequent collisions.

The number of neutrons released by Zeta thus far has not been sufficient to enable scientists to determine beyond doubt what type of fusion produced them. However, Britain's top nuclear physicists have declared they were 90 per cent certain that the fusions were thermonuclear in that they accorded with theoretical predictions. The neutrons emitted are particles left over after two nuclei fuse to become a single nucleus of a heavier element.

The design of the new apparatus shows that Britain's Atomic Energy Authority is content to concentrate on an approach like that for Zeta to the goal of producing industrially useful thermonuclear power.

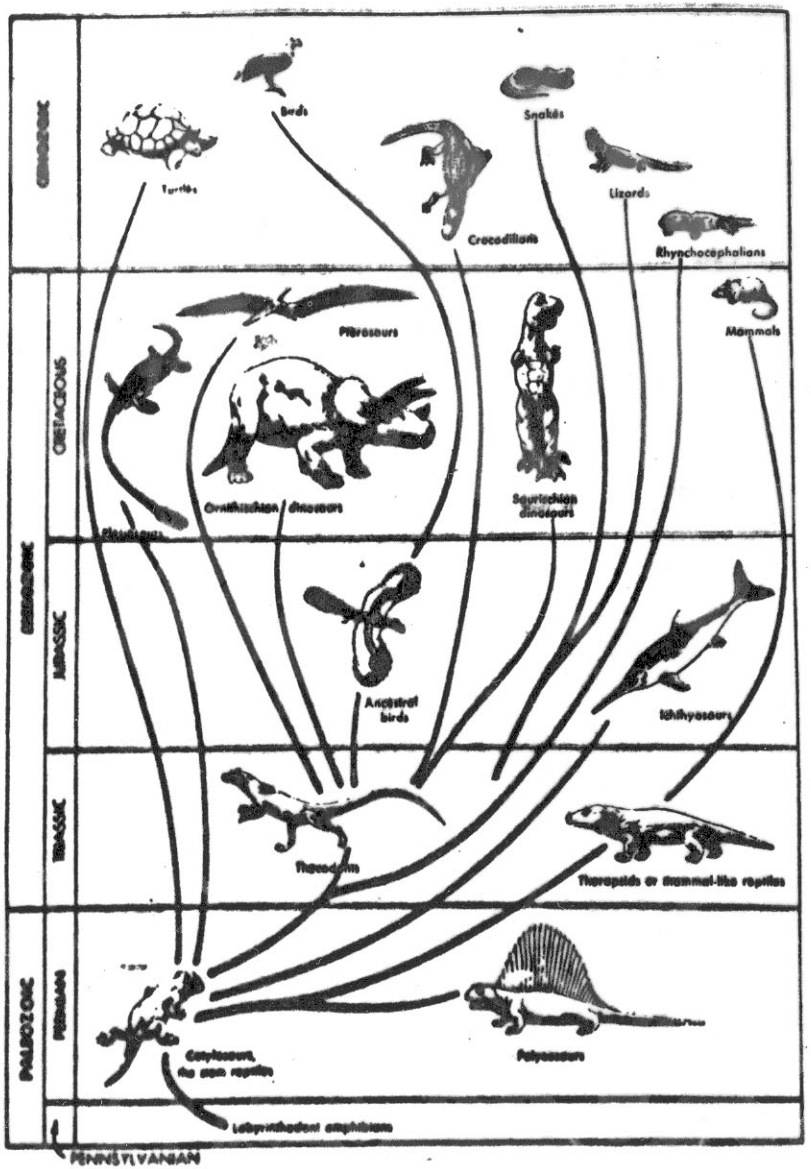
Sugar Workers Reject Rise

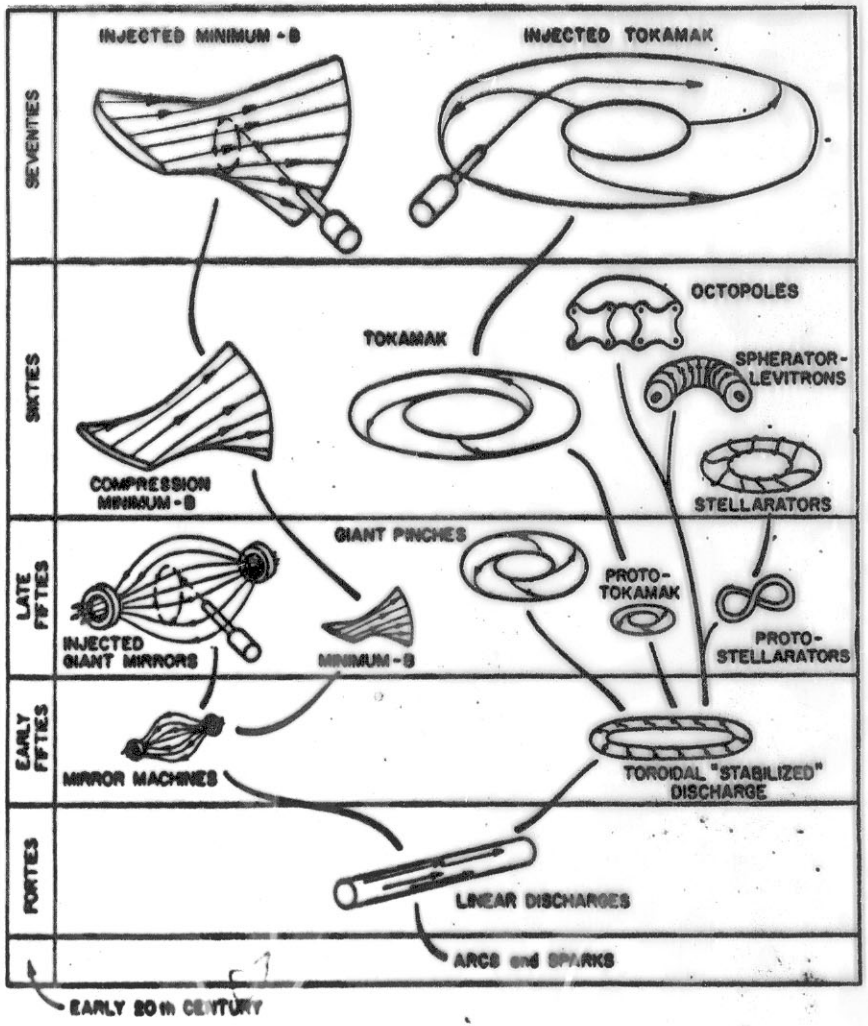
HONOLULU, May 6 (AP)—Hawaiian sugar workers re-

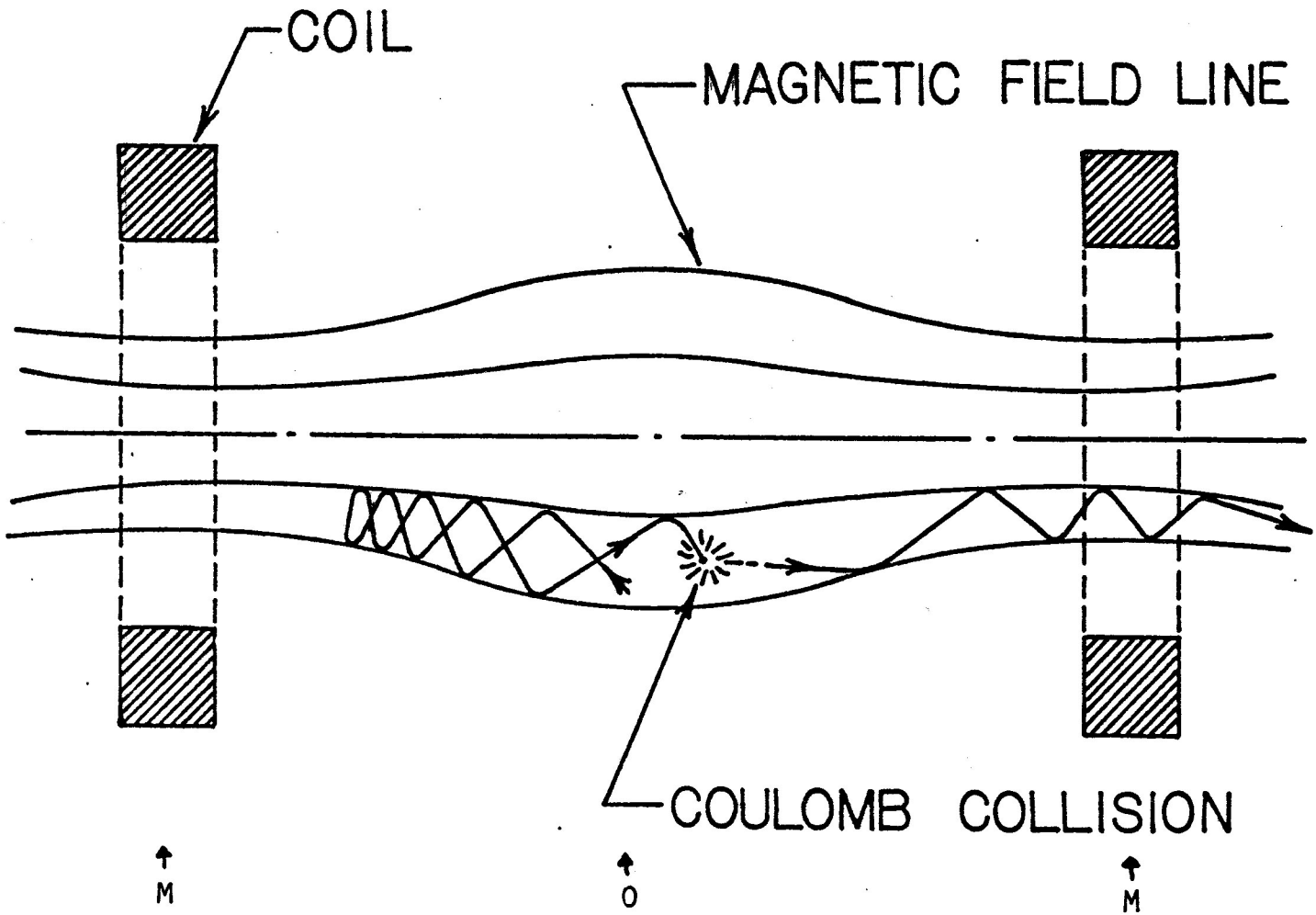
20th Anniversary

"The experiences of the past have amply demonstrated the futility of the policy, 'Every man for himself, the devil take the hindmost.' We are beginning to realize that no man can live unto himself alone. Selfish individualism has gotten us nowhere. Altruistic cooperation points the way out."—John D. Rockefeller Jr. in a talk at the Center Theatre in March, 1938, inaugurating the Greater New York Fund.

Your generous response with your fellow employes at your place of business will help support the altruistic cooperation exemplified in the Greater New York Fund for twenty years. More than 425 services benefit from the current campaign.


CENOZOIC
MESOZOIC
PALEOZOIC
CRETACEOUS
JURASSIC
TRIASSIC
PENNSYLVANIAN
Turtles
Birds
Snakes
Crocodilians
Lizards
Rhynchocephalians
Mammals
Pterosaurs
Ornithischian dinosaurs
Saurischian dinosaurs
Plesiosaurs
Ancestral birds
Ichthyosaurs
Thecodonts
Therapsids or mammal-like reptiles
Pelycosaurs
Labyrinthodont amphibians


SEVENTIES
SIXTIES
LATE FIFTIES
EARLY FIFTIES
FORTIES
INJECTED MINIMUM-B
INJECTED TOKAMAK
OCTOPOLES
TOKAMAK
SPHERATOR-LEVITRONS
COMPRESSION MINIMUM-B
STELLARATORS
GIANT PINCHES
PROTO-TOKAMAK
INJECTED GIANT MIRRORS
MINIMUM-B
PROTO-STELLARATORS
MIRROR MACHINES
TOROIDAL "STABILIZED" DISCHARGE
LINEAR DISCHARGES
ARCS and SPARKS
EARLY 20th CENTURY



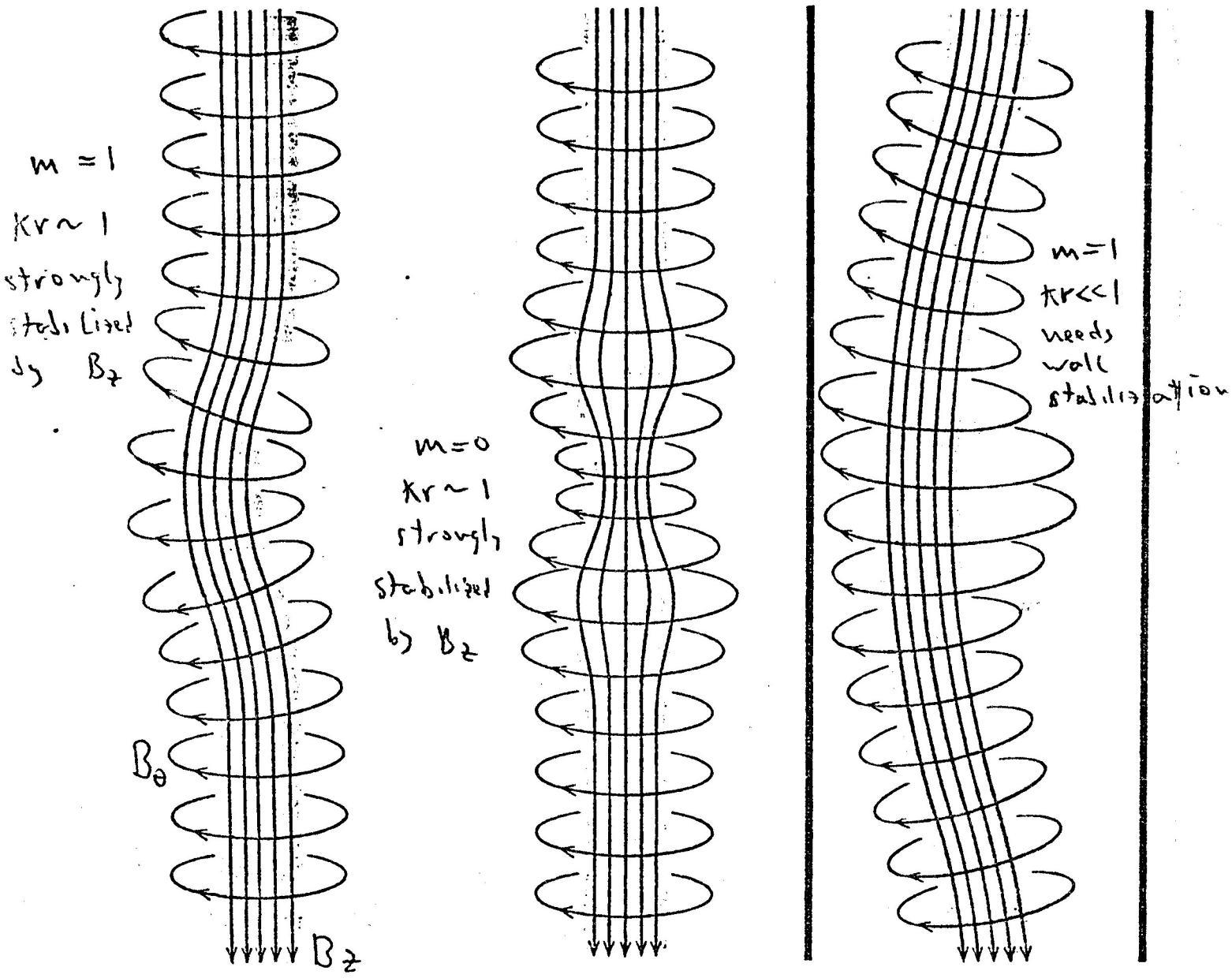
CLASSICAL LOSS PROCESS OF OPEN SYSTEM

CONSERVATION OF $\mu = W_\perp/B$ IMPLIES CONFINEMENT FOR

$$(W_\perp/W)_O > B_O/B_M = 1/R_M$$

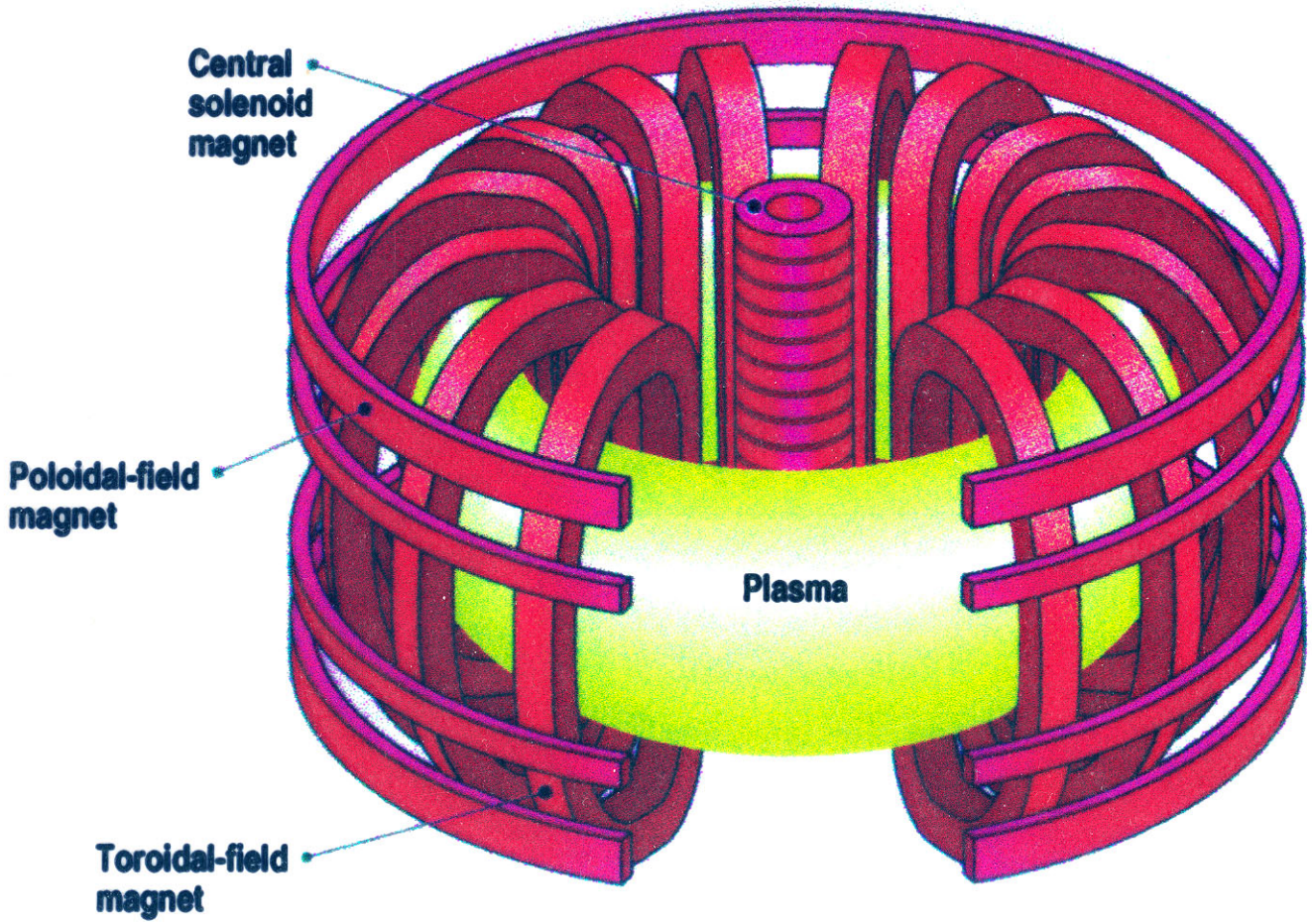
WHERE "O" REFERS TO THE MIDPLANE AND "M" TO THE MIRROR. (PPL 713737)

MHD Instabilities of "Stabilized" Pinch



STABILIZED PINCH might be achieved by putting a magnetic field (*long arrows*) through a plasma. Tension would straighten kinks (*left*) and mutual repulsion would resist constrictions (*center*). Circular lines hold plasma away from conducting wall (*right*).

TOKAMAKS USE MAGNETIC FIELDS TO CONTAIN A PLASMA OF HOT GASES



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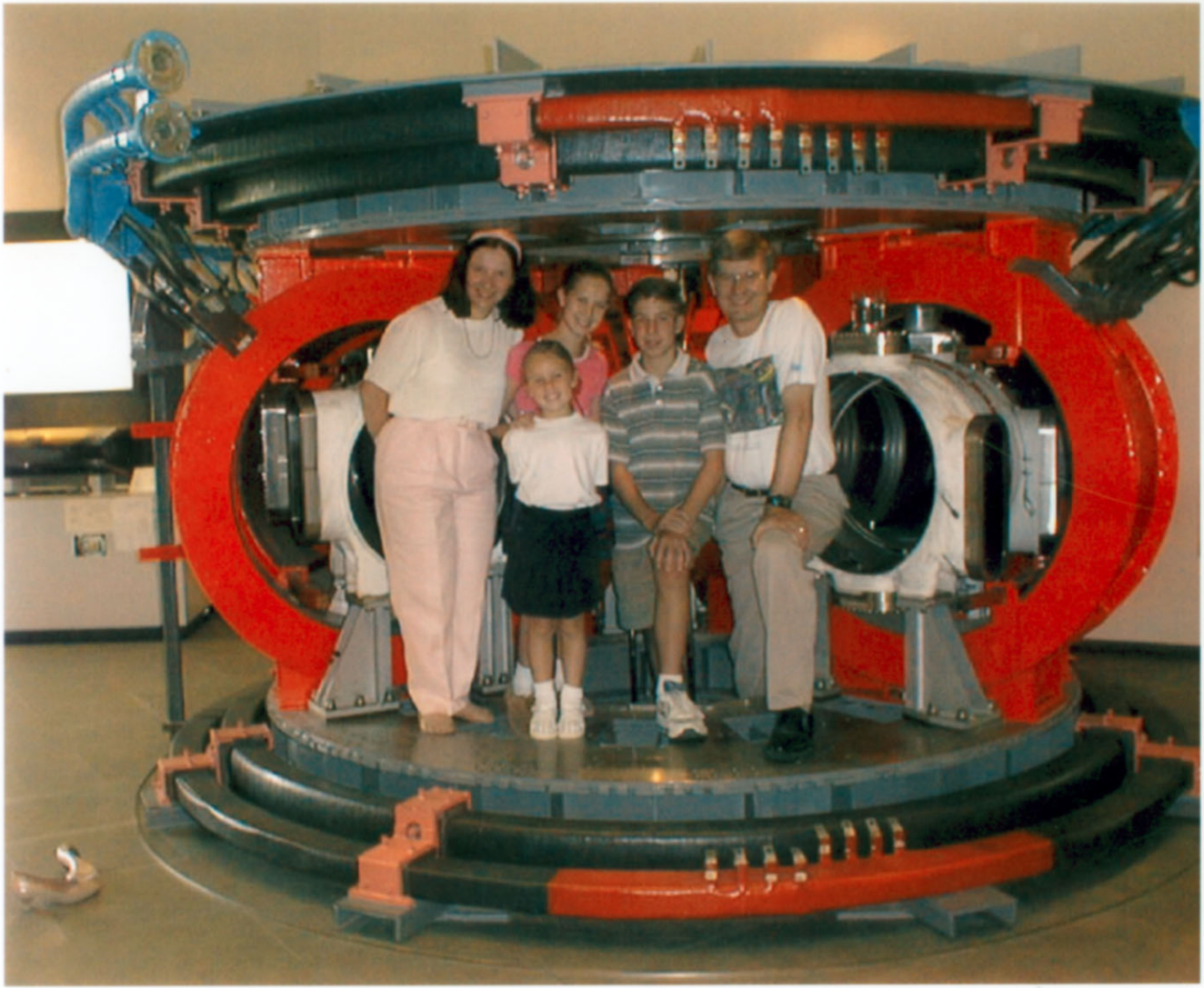
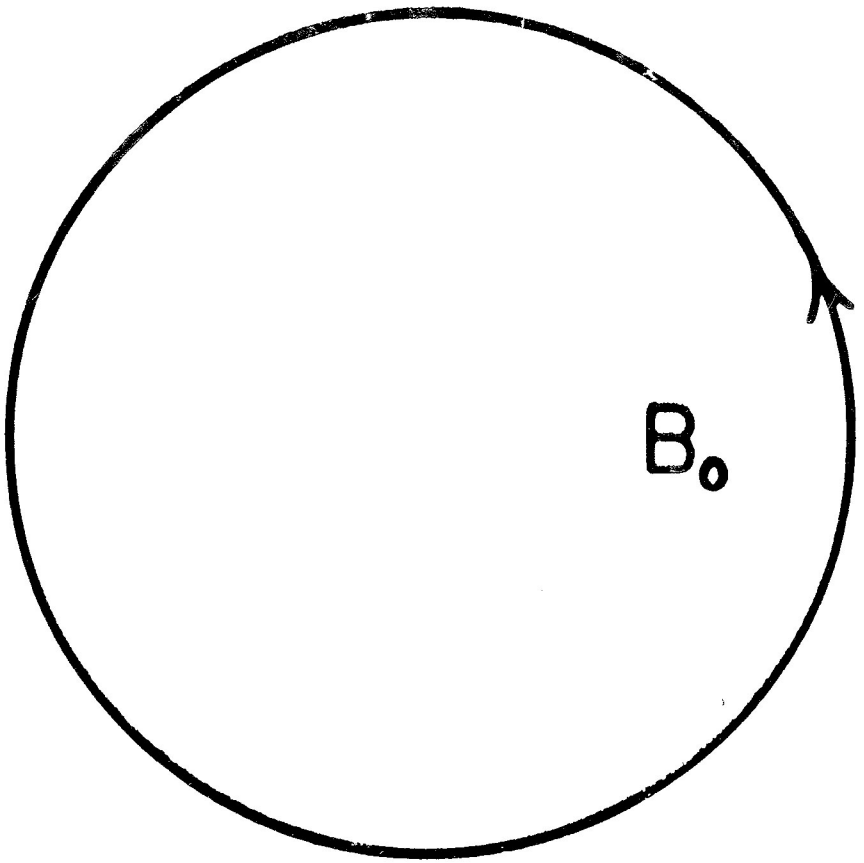
GENERAL ATOMICS

Glen and Family Inside JFT2





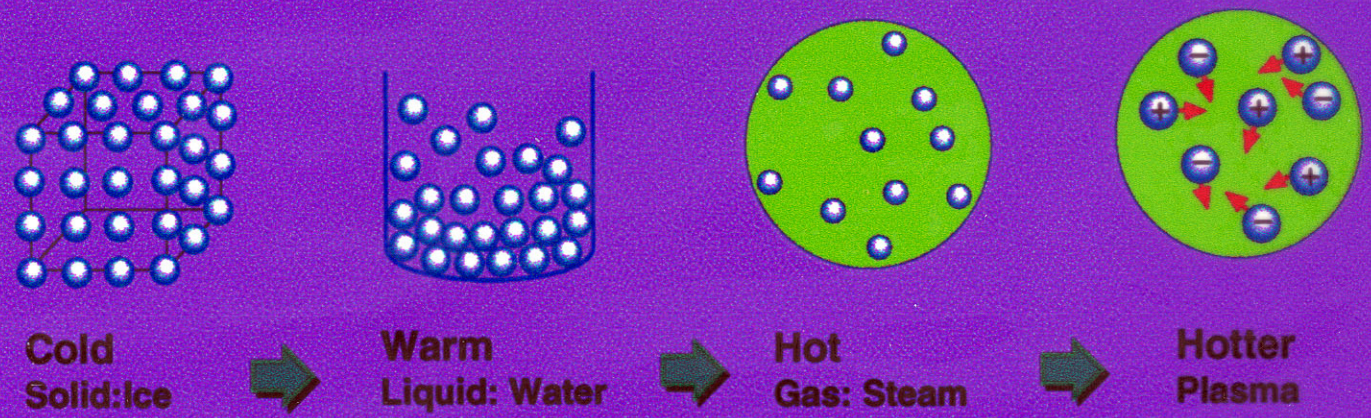
ZT–H 4MA Reversed Field Pinch

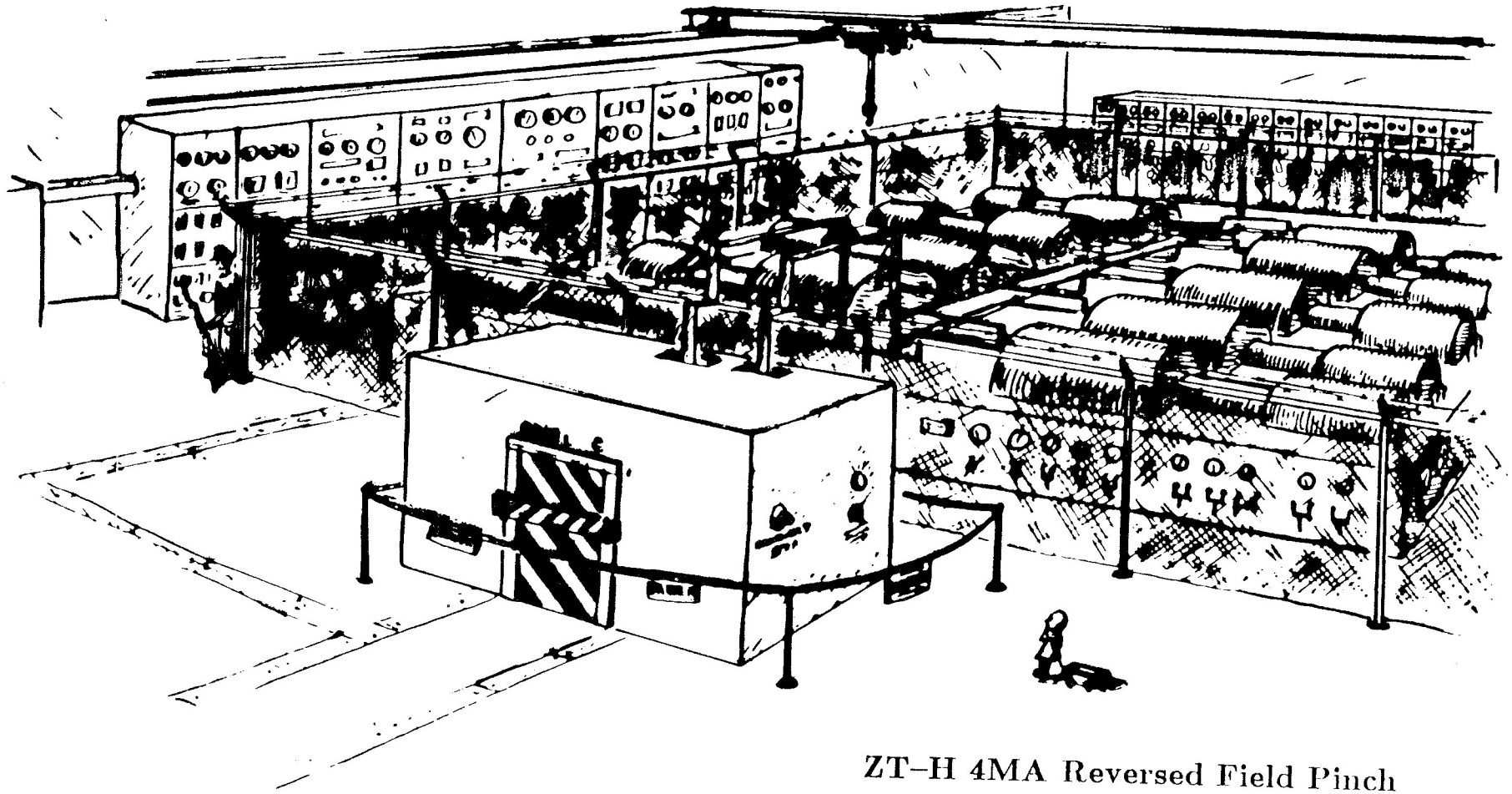
THEORICAL PHYSICSTS' DESIGN

(Lowest Order Only)

Fusion Energy

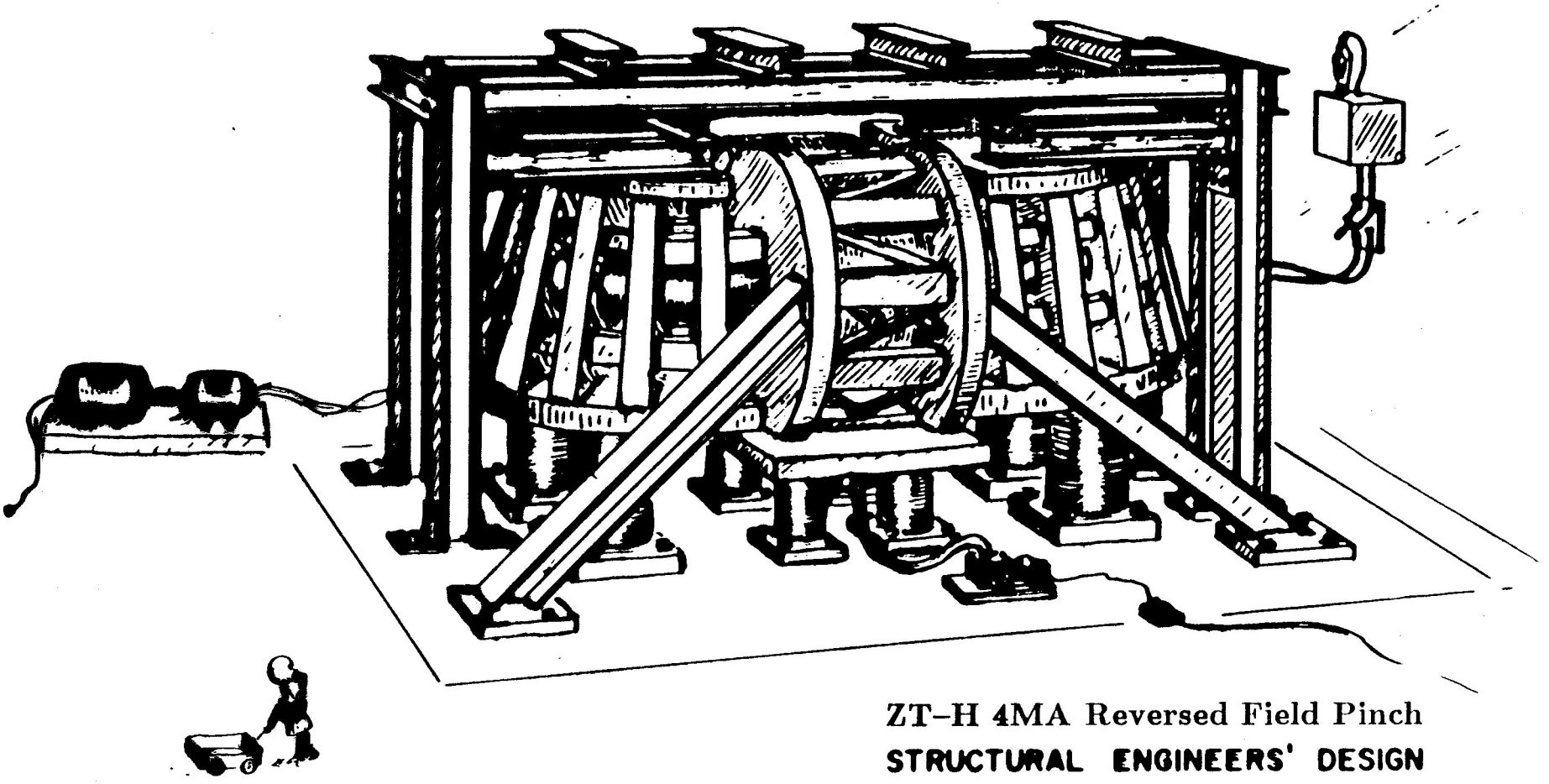
Plasma is sometimes referred to as the fourth state of matter





ZT–H 4MA Reversed Field Pinch

POWER ENGINEERS' DESIGN

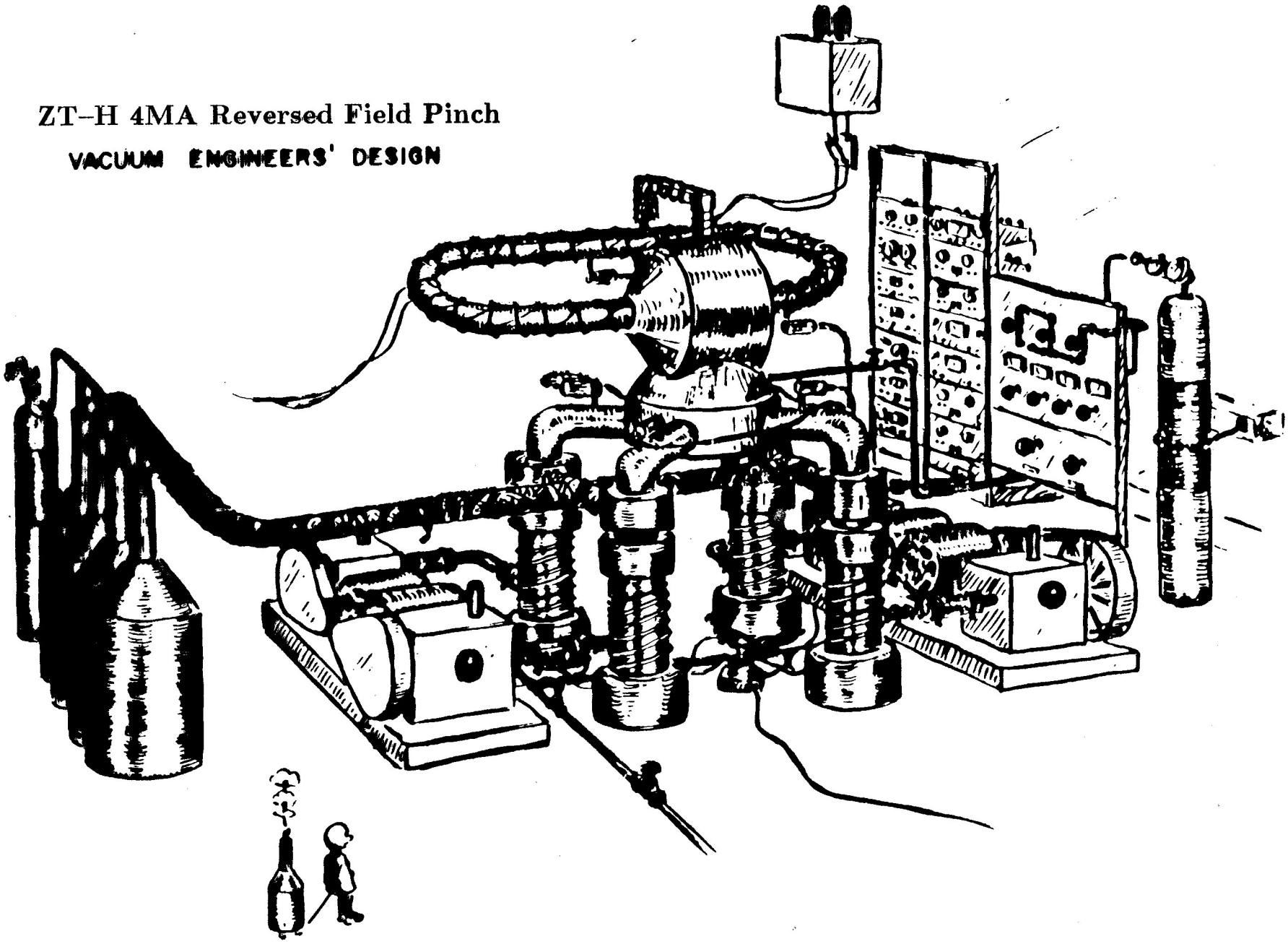


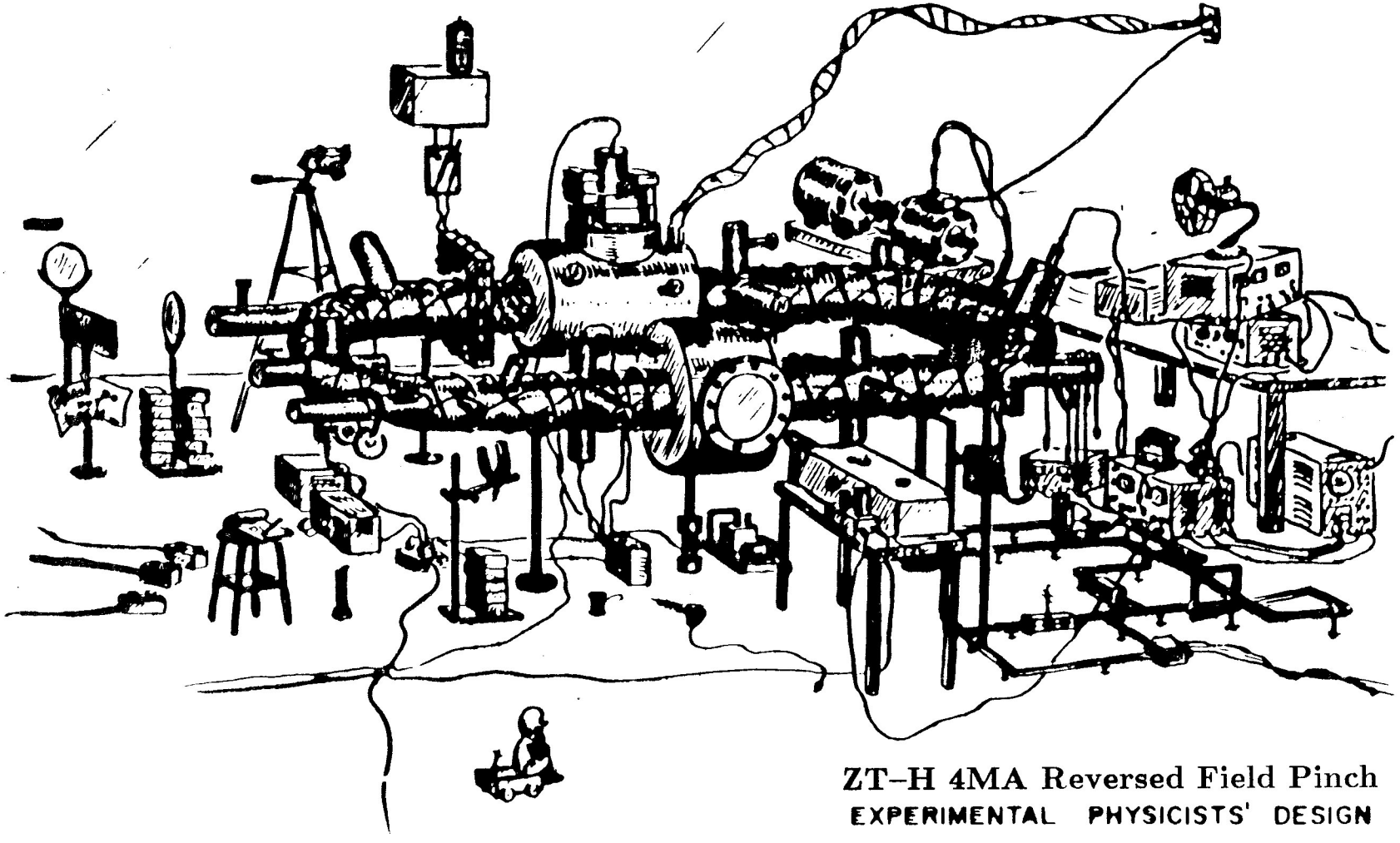
ZT–H 4MA Reversed Field Pinch

STRUCTURAL ENGINEERS' DESIGN

ZT–H 4MA Reversed Field Pinch

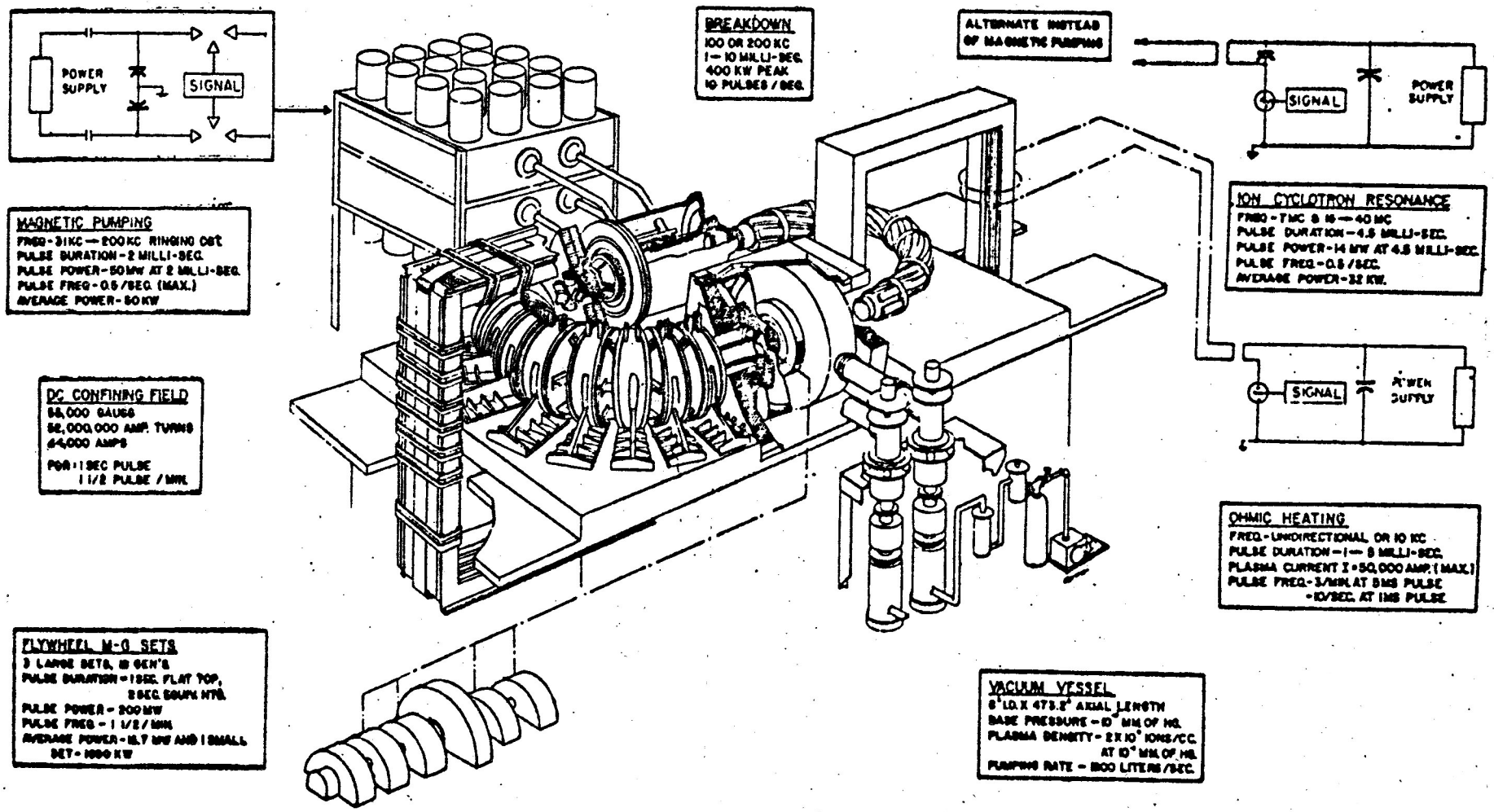
VACUUM ENGINEERS' DESIGN

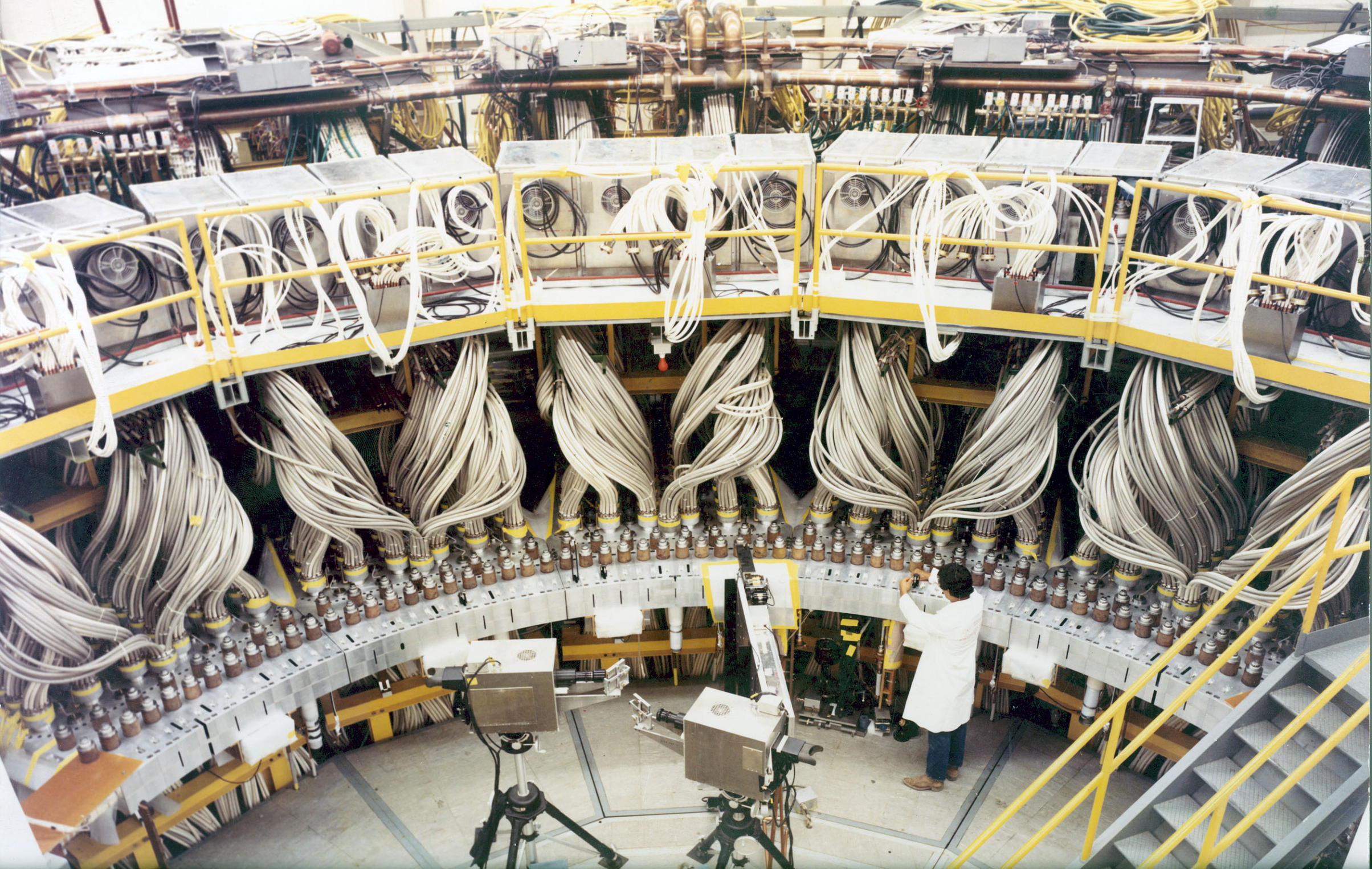




ZT–H 4MA Reversed Field Pinch
EXPERIMENTAL PHYSICISTS' DESIGN

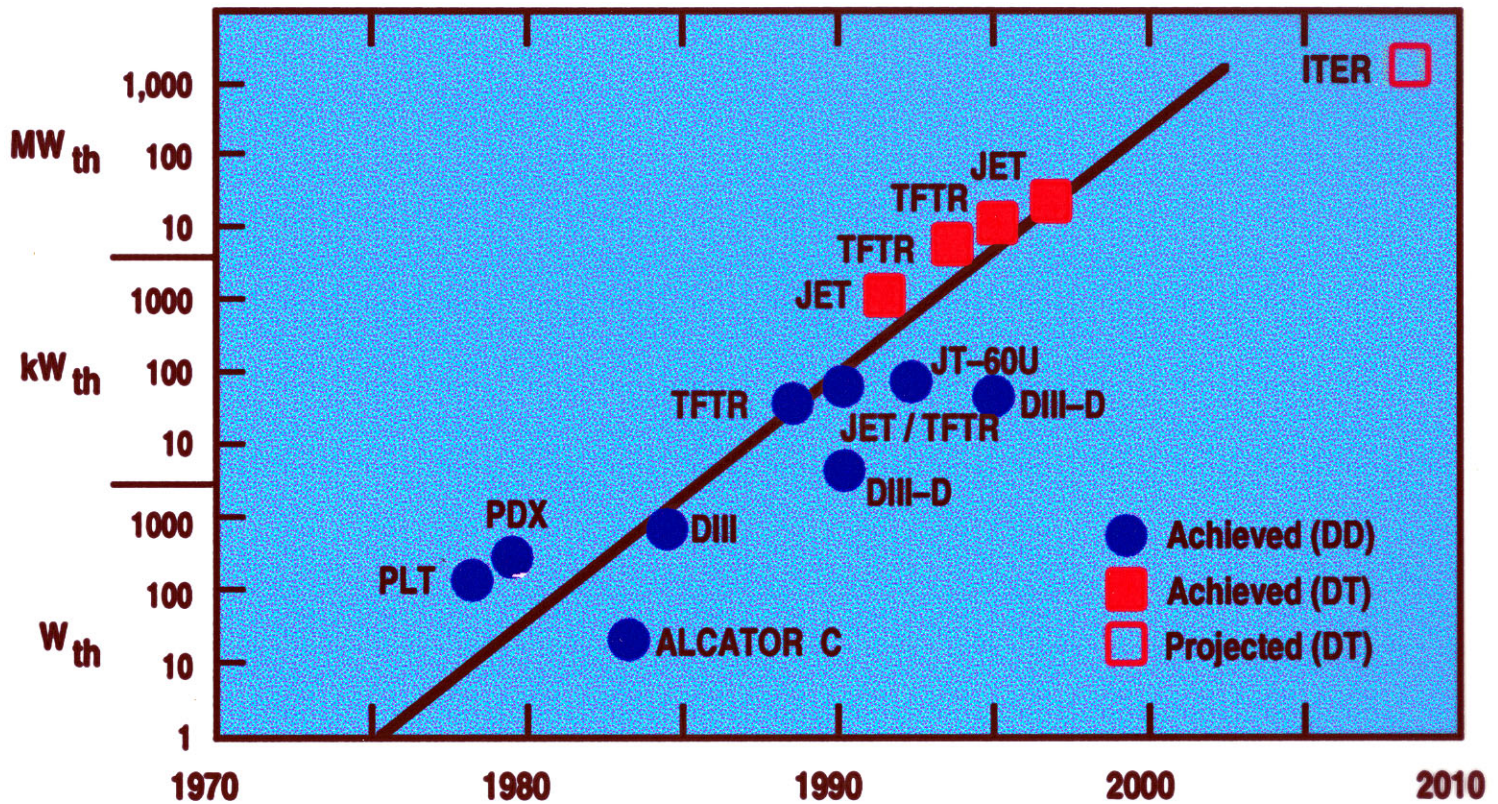
MODEL 'C' STELLARATOR





PROGRESS IN MAGNETIC FUSION

FUSION POWER



PLT	Princeton Large Tokamak
PDX	Princeton Divertor Experiment
JET	Joint European Torus
DIII & DIII-D	General Atomics Tokamak Experiments
TFTR	Princeton Plasma Physics Laboratory
ALCATOR C	Massachusetts Institute of Technology
ITER	International Thermonuclear Experimental Reactor
JT-60U	Japanese Tokamak Experiment

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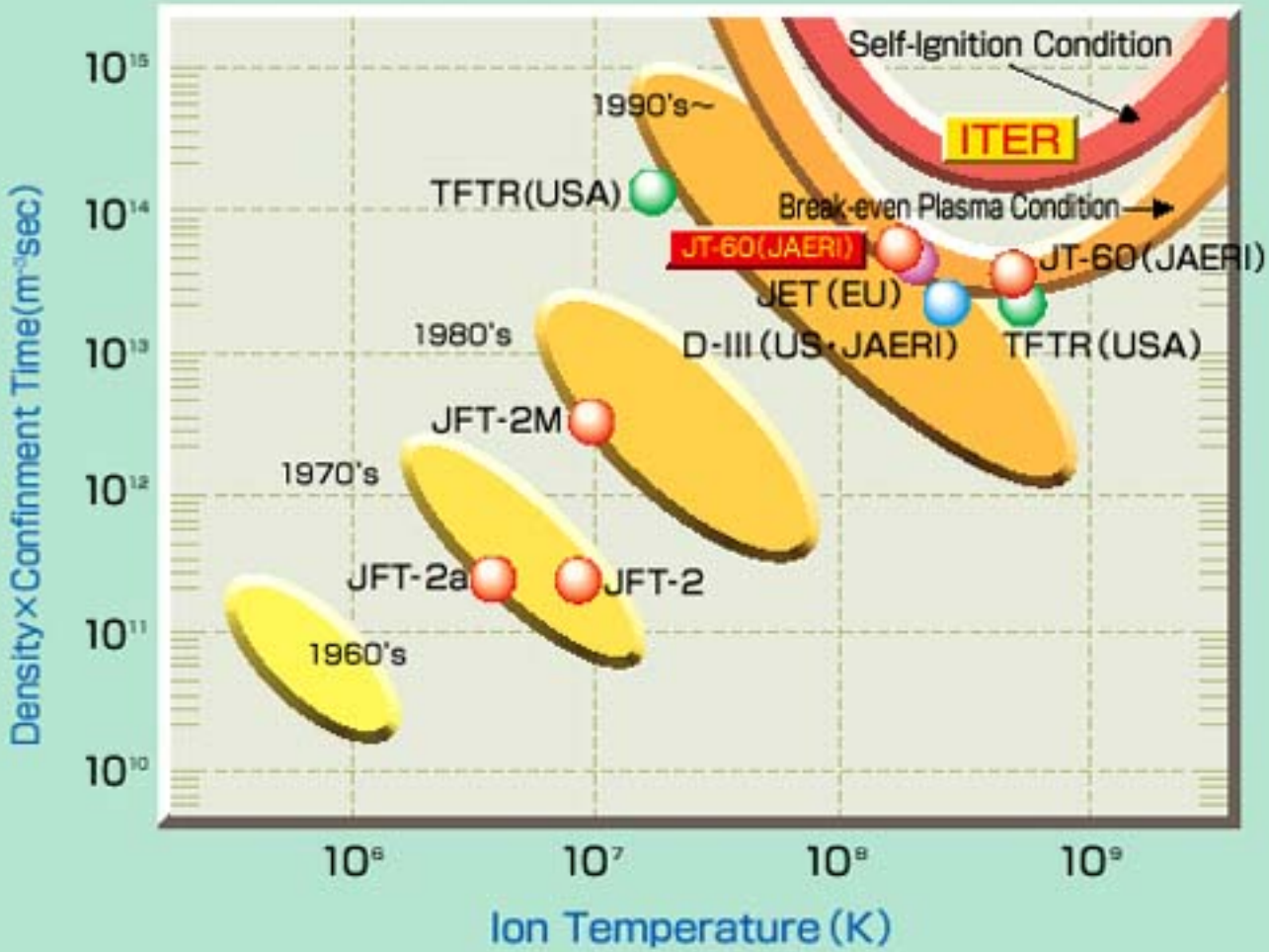
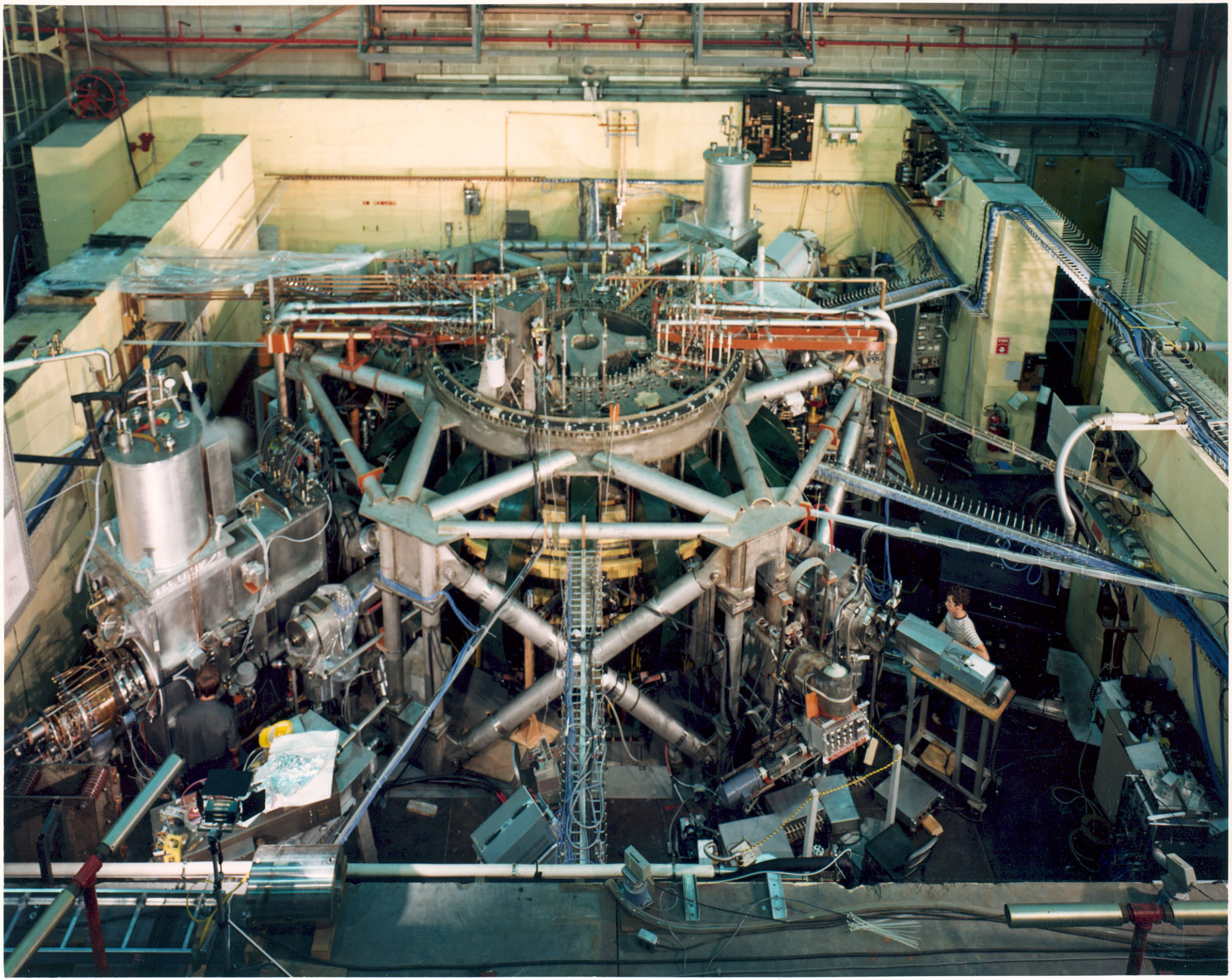
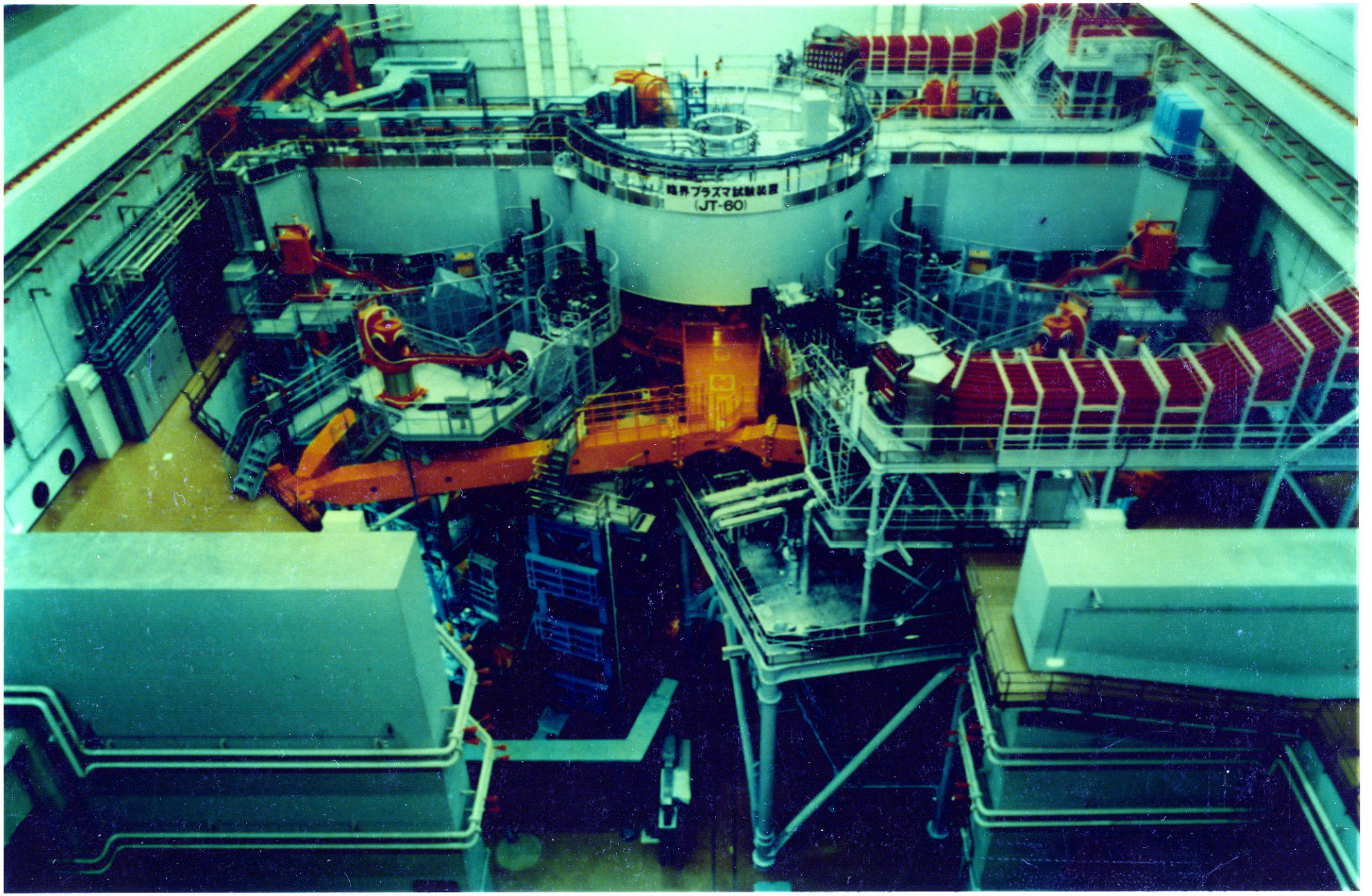
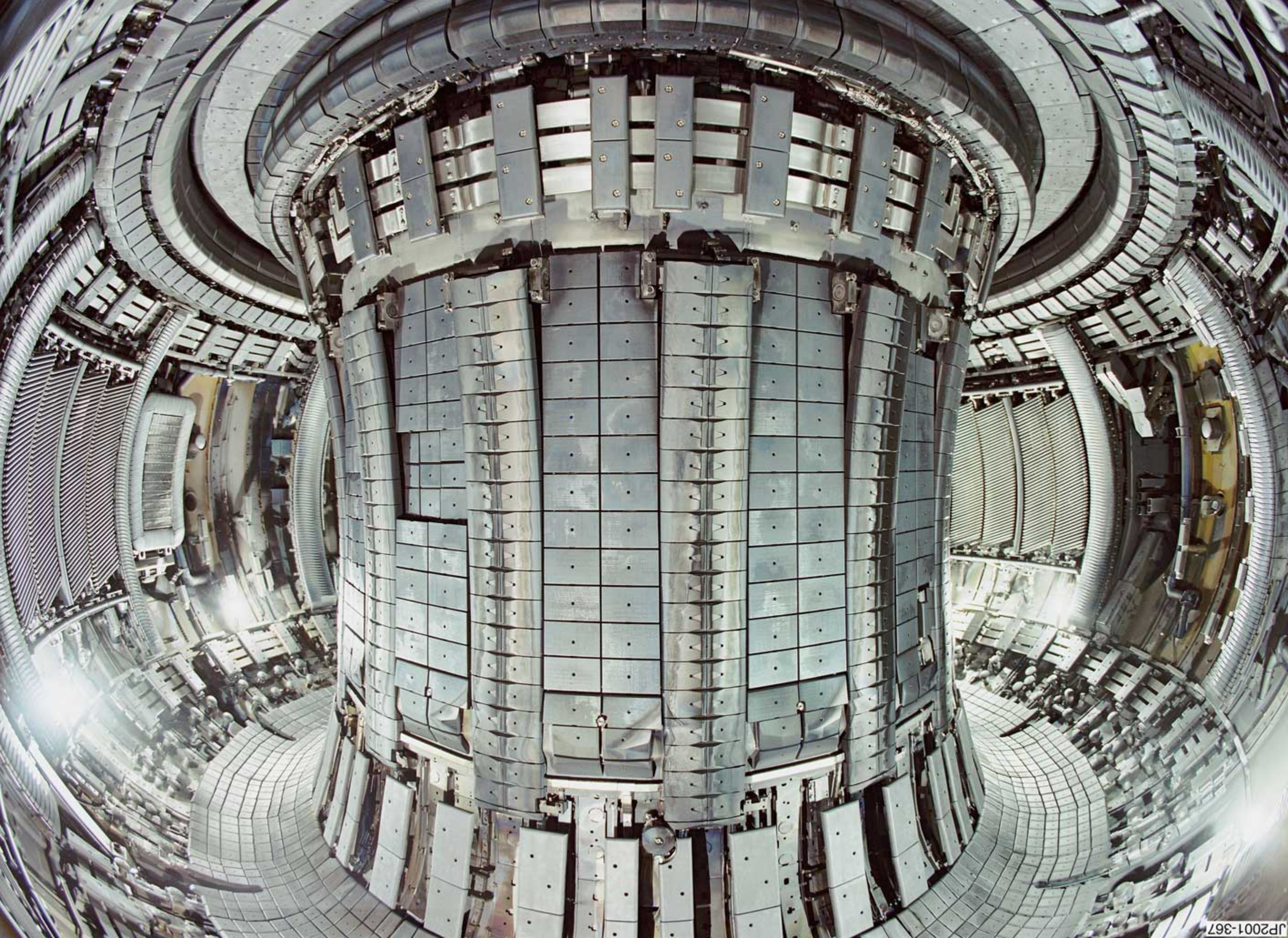
GENERAL ATOMICS

World Progress of Tokamak Plasmas






臨界プラズマ試験装置
(JT-60)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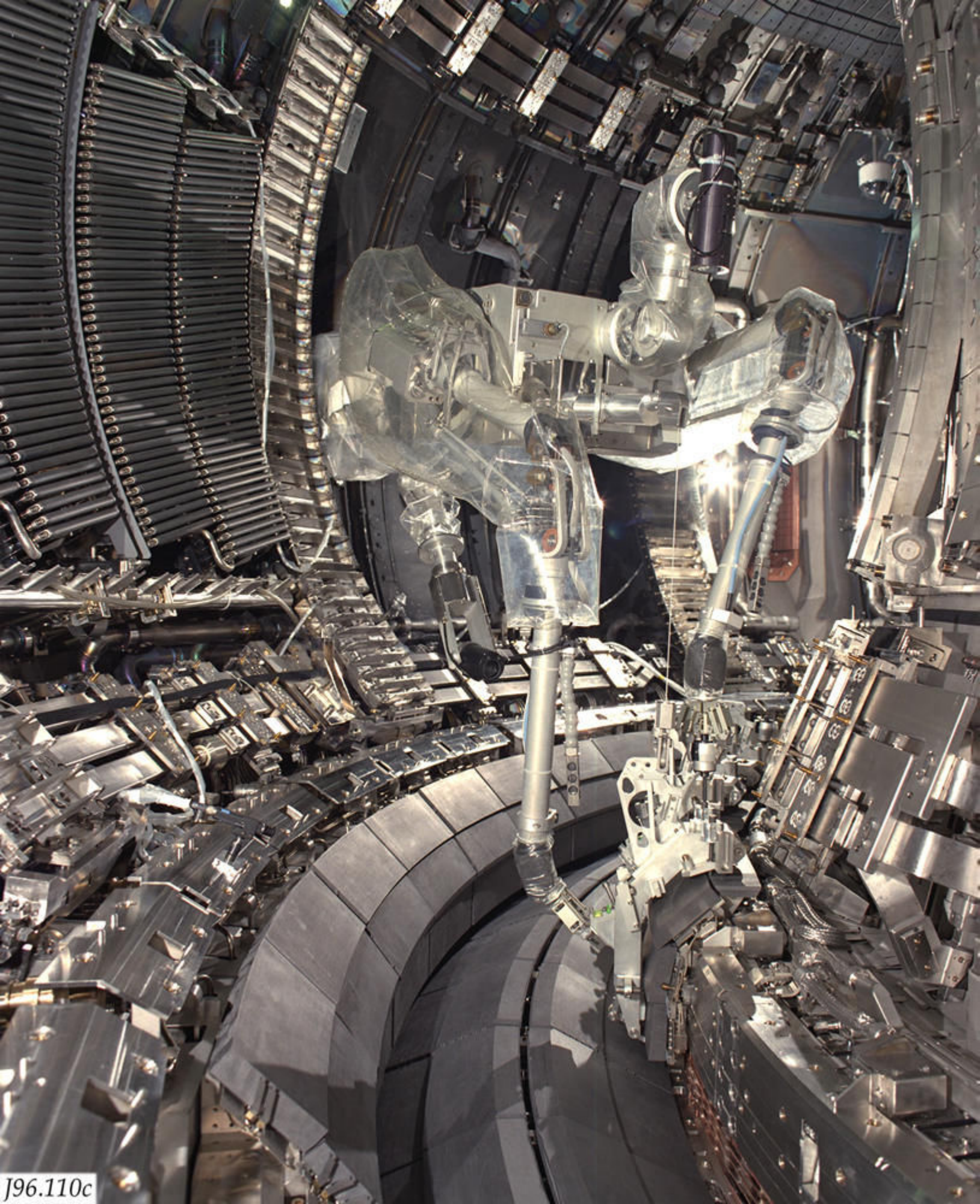
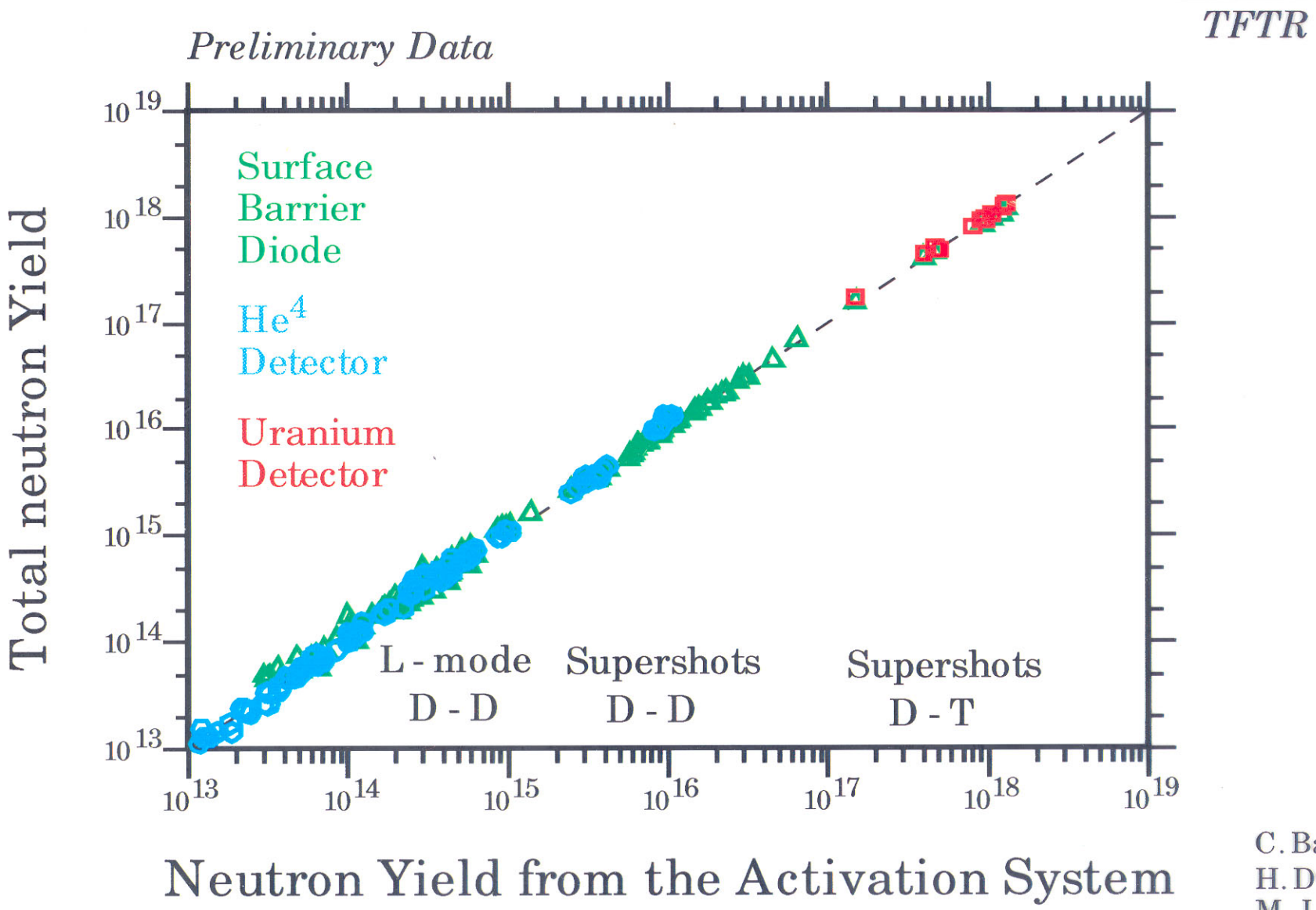
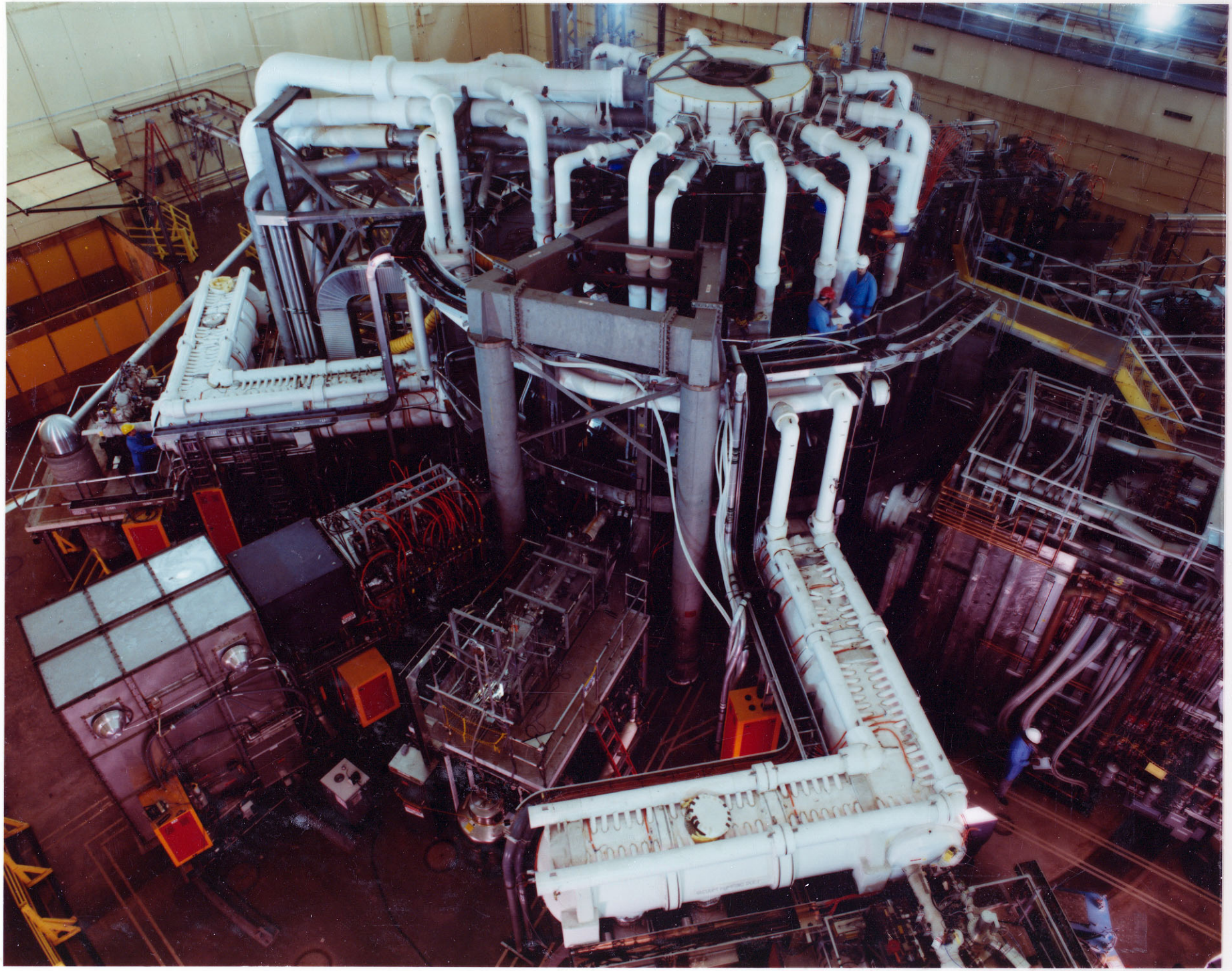


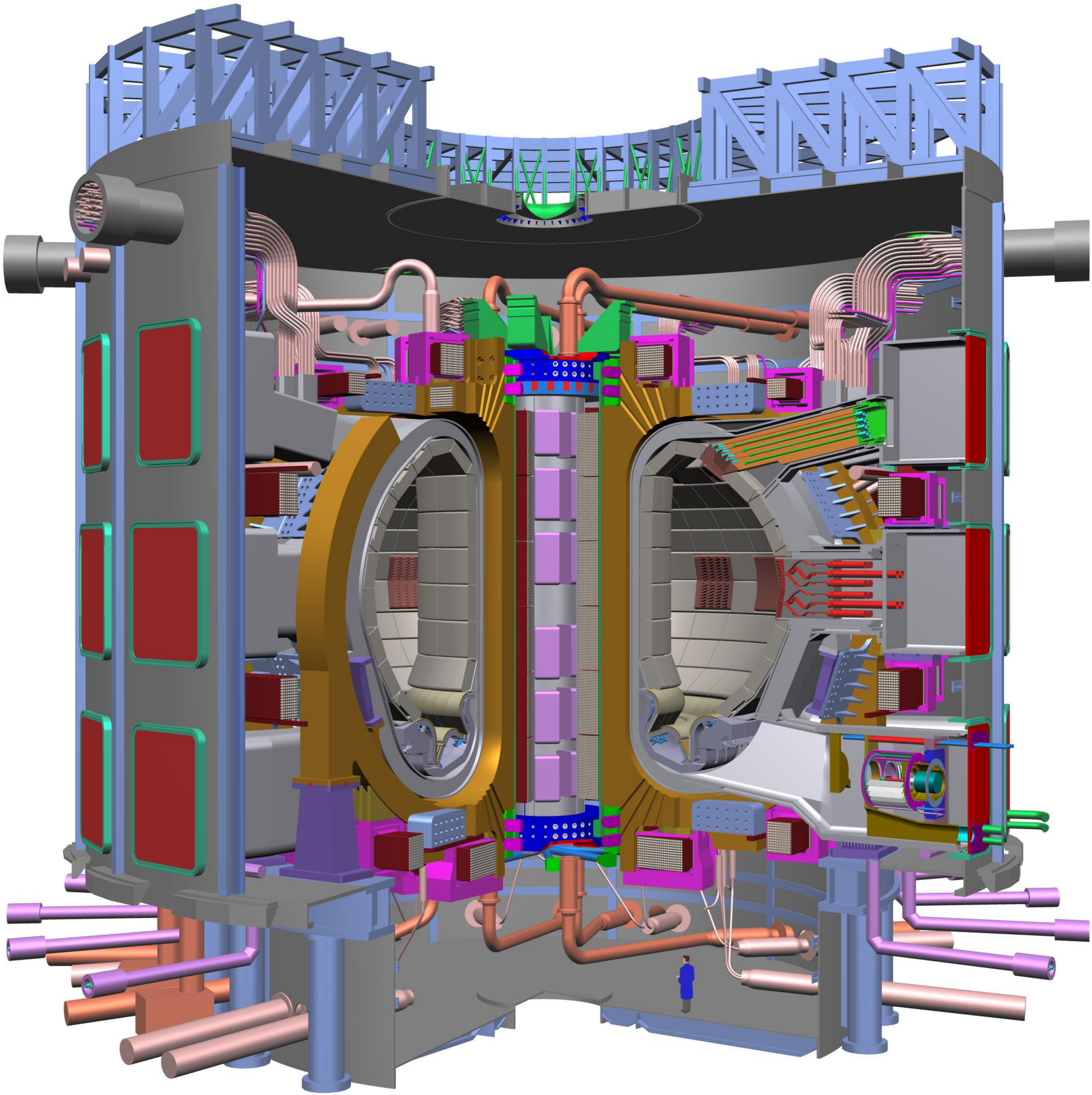
J96.110c

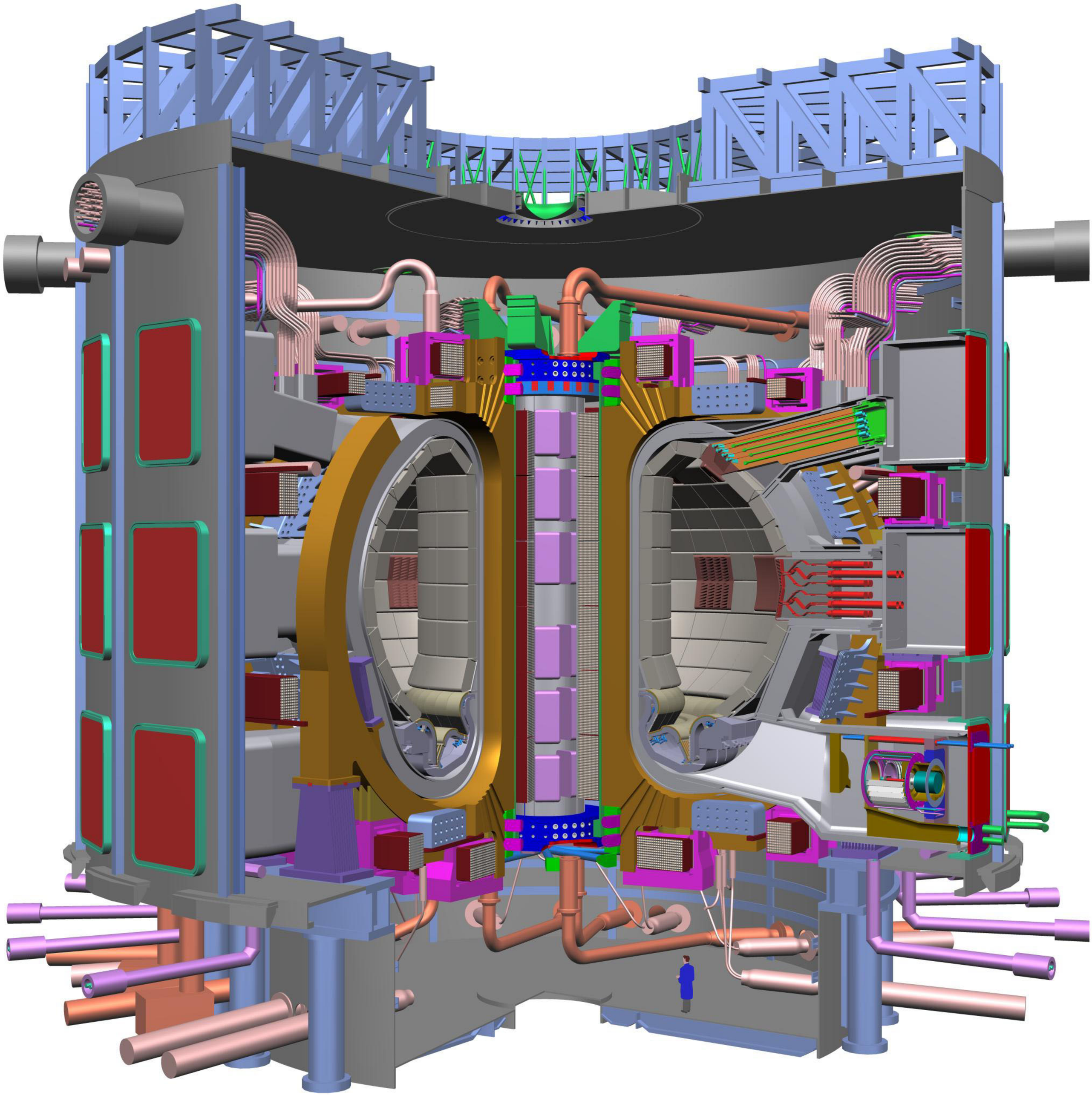
Neutron measurements span a factor of one million



C. Barnes. LANL
H. Duong. GA
M. Loughlin. JET
D. Jassby
L. Johnson
J. Strachan

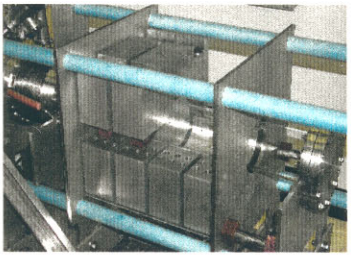




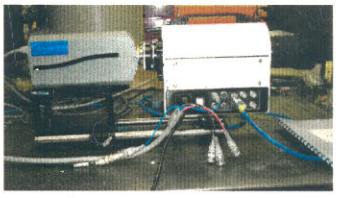


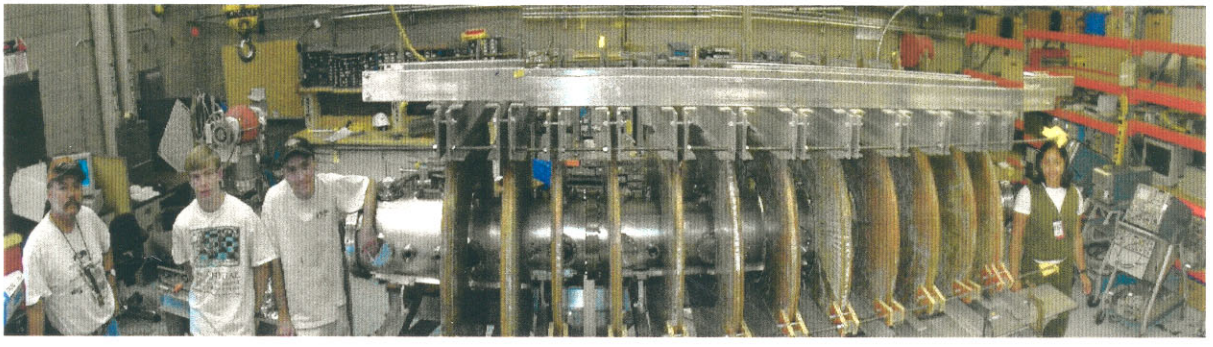
MFE Team Projects

MTF
Magnetized
Target Fusion



NSTX
National Spherical Torus Experiment

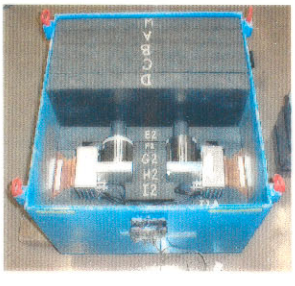


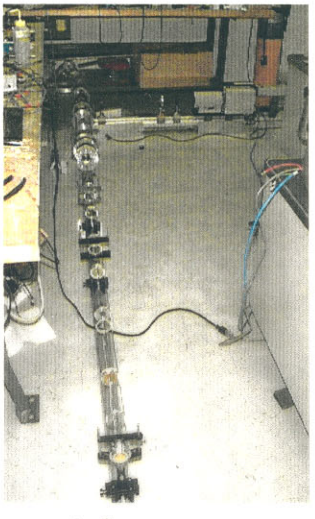


RSX
Reconnection Scaling Experiment

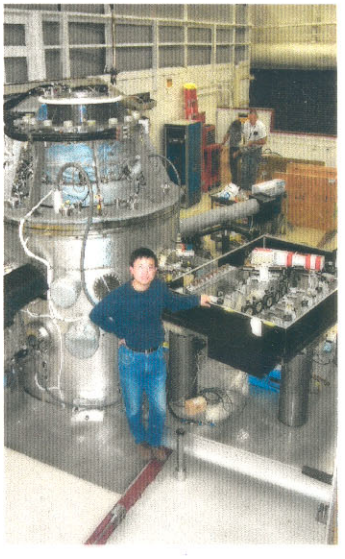
RMF
Rotating Magnetic Field

US/Japan
Adv. Diagnostics





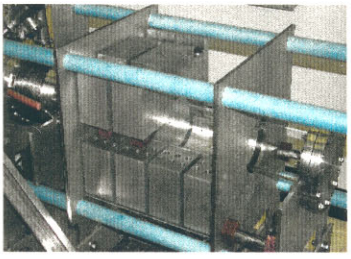
Alcator
IR Imaging



SSPX
Sustained Spheromak
Physics Experiment

MFE Team Projects

MTF
Magnetized
Target Fusion



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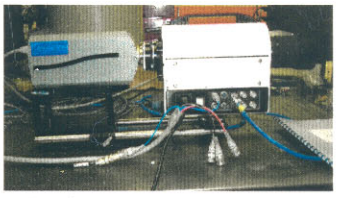

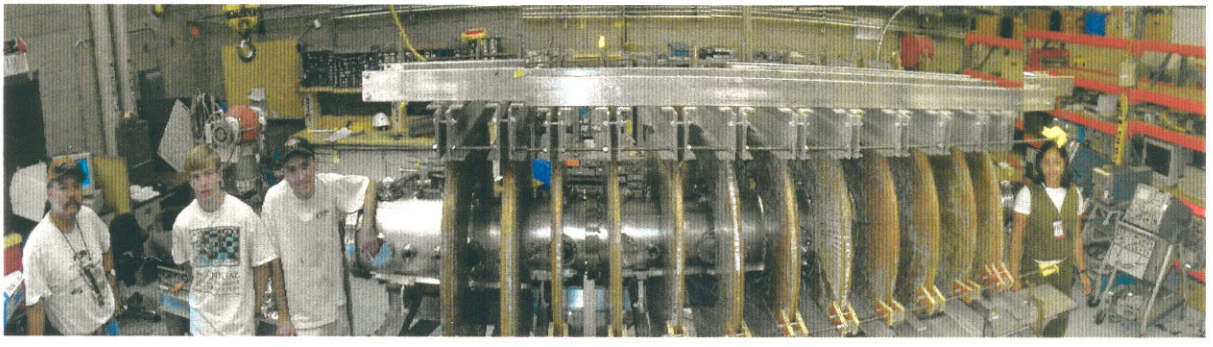

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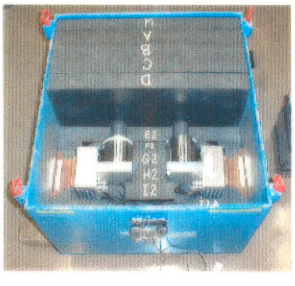
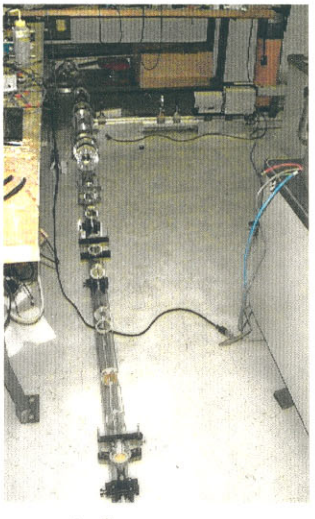
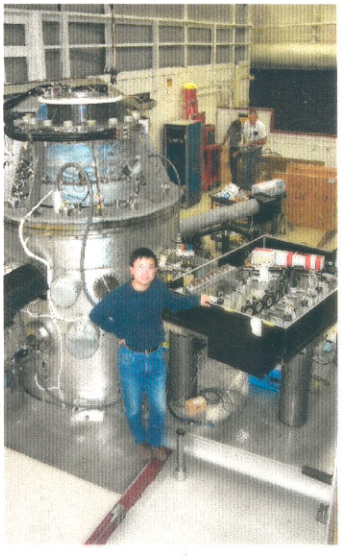
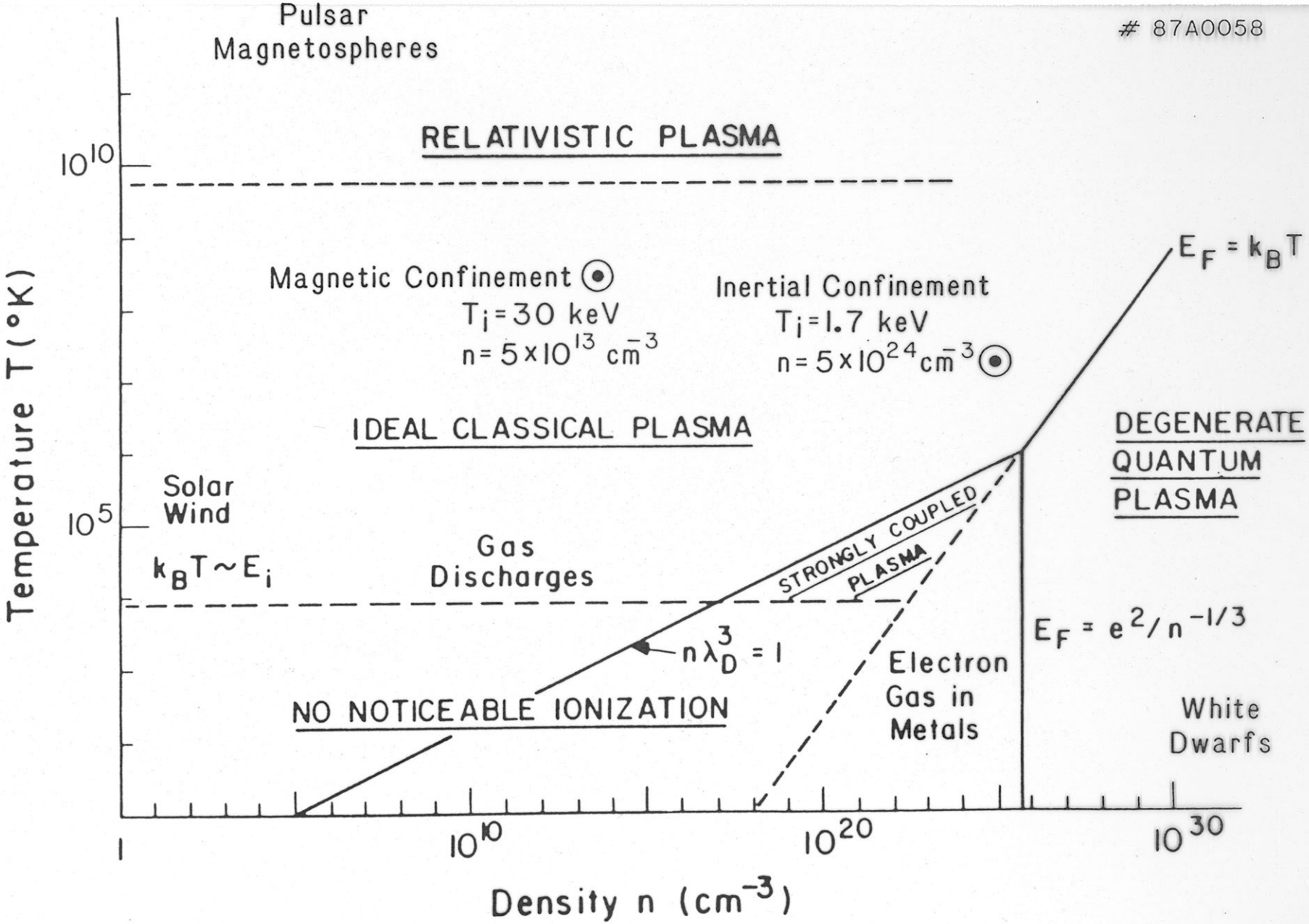




Alcator
IR Imaging



SSPX
Sustained Spheromak
Physics Experiment


87A0058
Pulsar Magnetospheres
RELATIVISTIC PLASMA
10^{10}
Magnetic Confinement
$T_i = 30$ keV
$n = 5 \times 10^{13}$ cm^{-3}
Inertial Confinement
$T_i = 1.7$ keV
$n = 5 \times 10^{24}$ cm^{-3}
$E_F = k_B T$
IDEAL CLASSICAL PLASMA
DEGENERATE QUANTUM PLASMA
Solar Wind
$k_B T \sim E_i$
10^5
Gas Discharges
STRONGLY COUPLED PLASMA
$n\lambda_D^3 = 1$
$E_F = e^2/n^{-1/3}$
Electron Gas in Metals
NO NOTICEABLE IONIZATION
White Dwarfs
Temperature T (°K)
1
10^{10}
10^{20}
10^{30}
Density n (cm^{-3})

Field Reversed Configuration (FRC)

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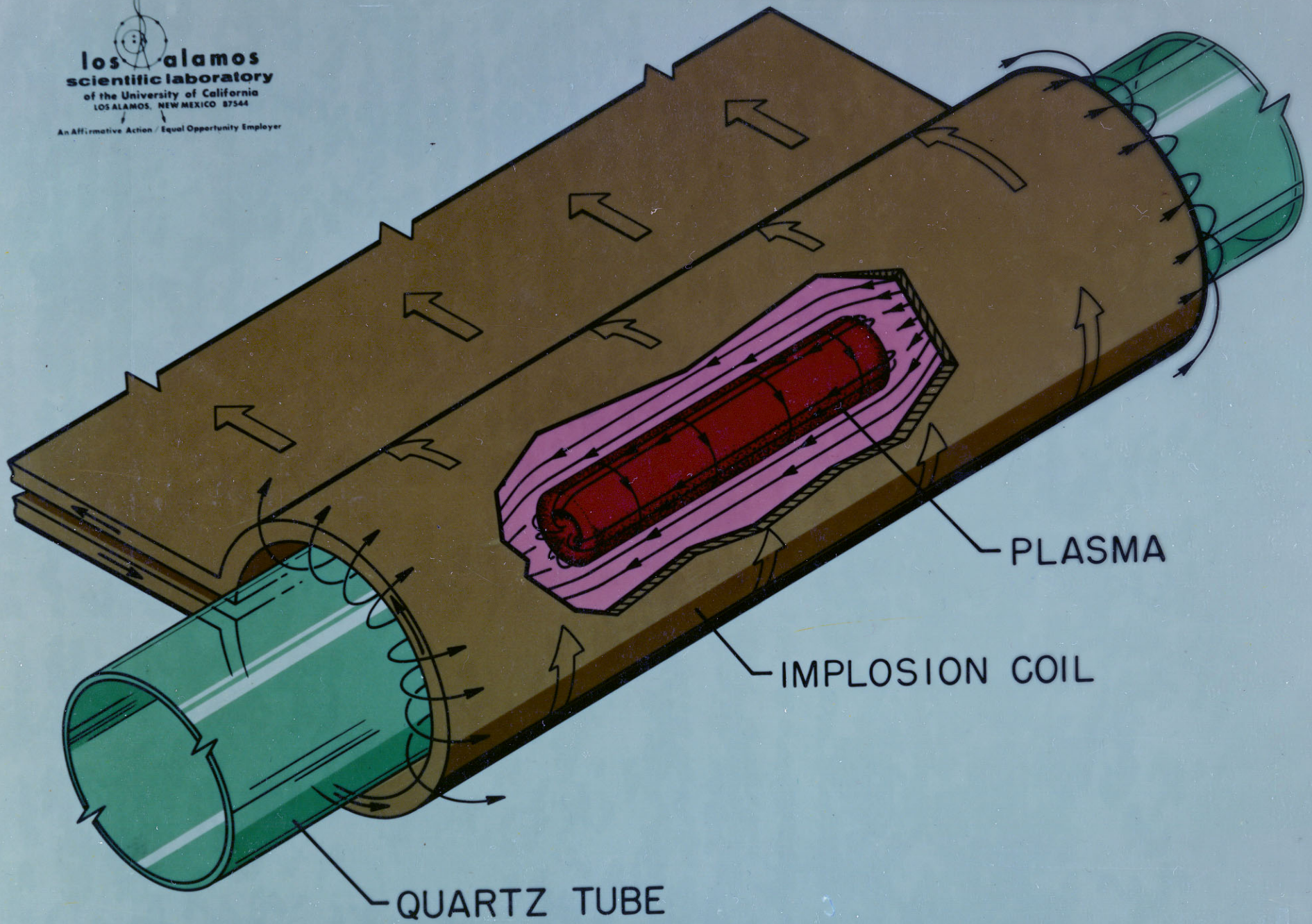

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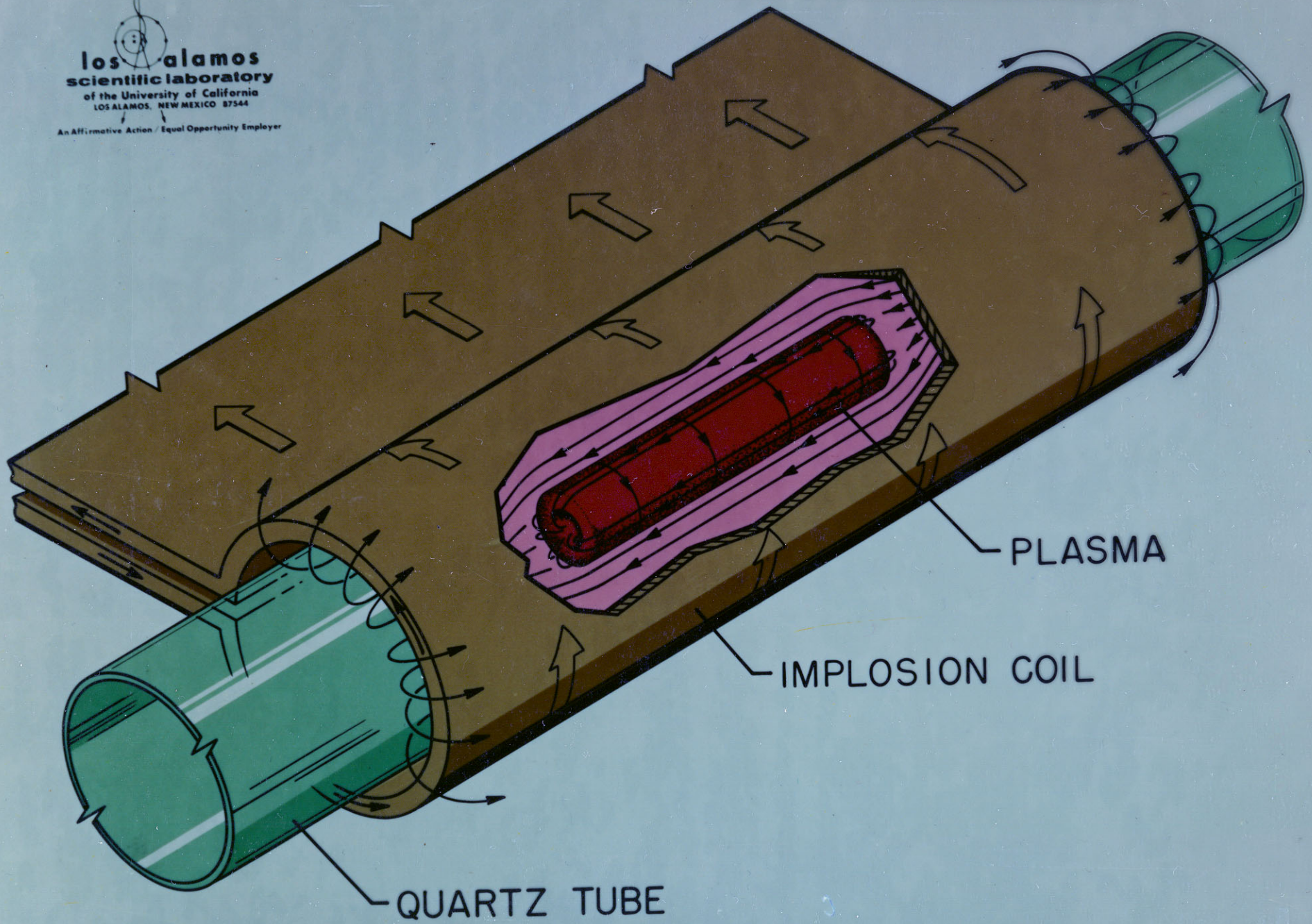

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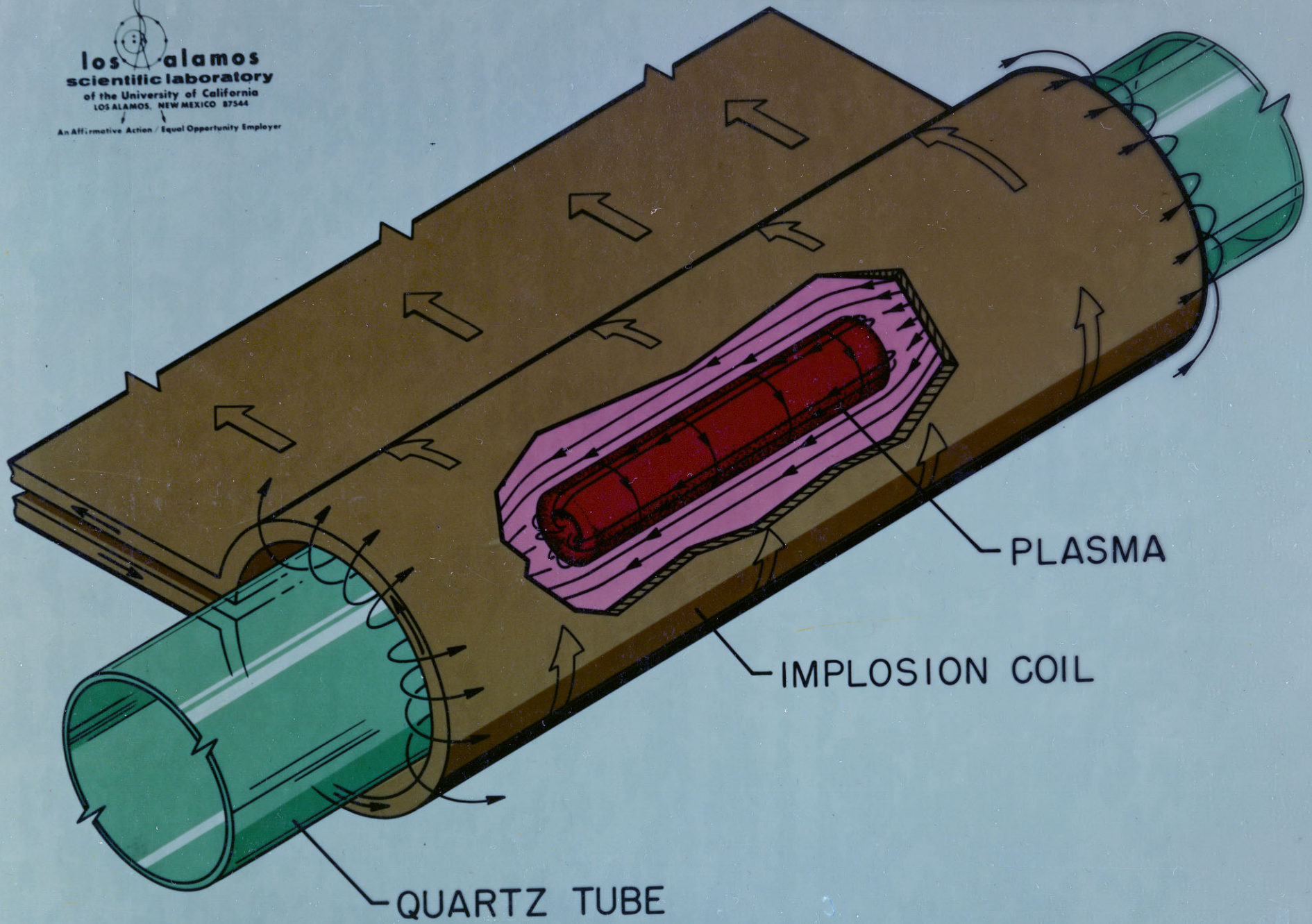
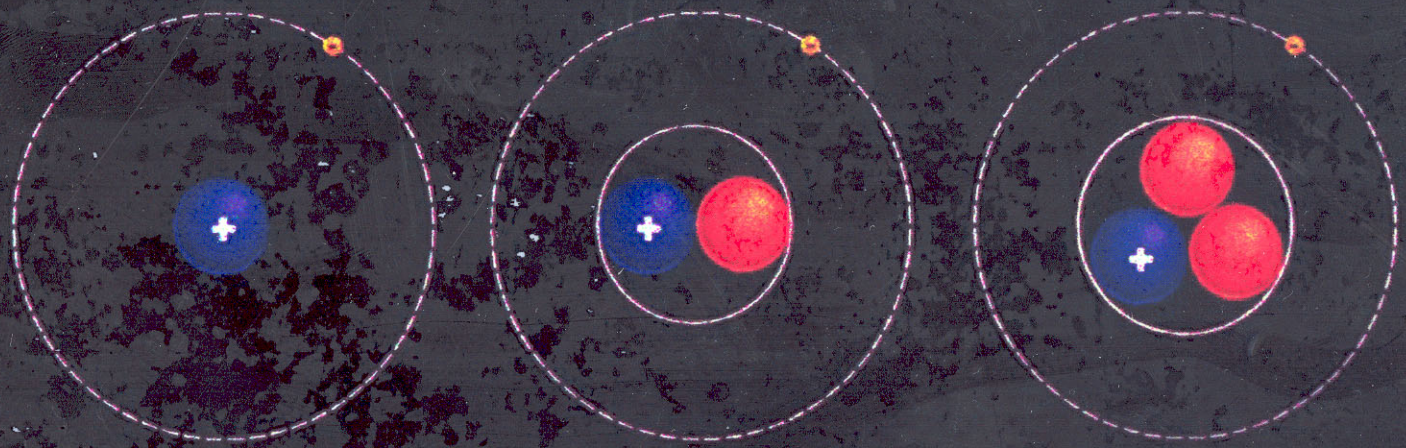


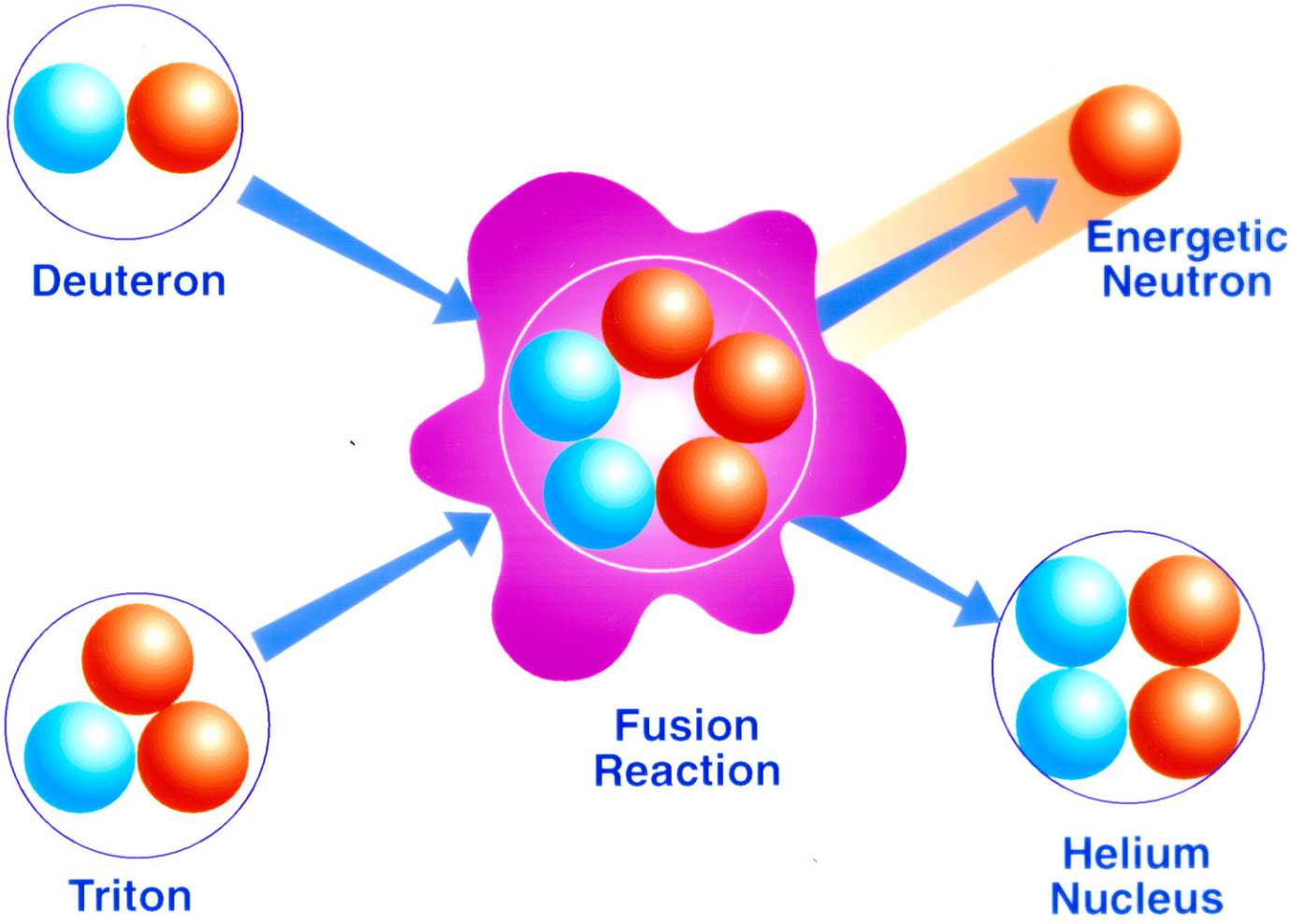


Hydrogen = $_1H^1$ Deuterium = $_1H^2$ Tritium = $_1H^3$

$_1H^1$ $_1H^2$ $_1H^3$

CIC-1/99-0440 1/99

Deuterium-Tritium Fusion



$$1 \begin{cases} D + D \longrightarrow He^{3} + n + 3.25 \text{ Mev} \\ D + D \longrightarrow T + p + 4 \text{ Mev} \end{cases}$$

$$2 \quad D + T \longrightarrow He^{4} + n + 17.6 \text{ Mev}$$

TABLE 1 FUSION REACTIONS

1. <u>D-T</u> $D + T \longrightarrow n(14.1) + {}^{4}He(3.5)$

2. <u>Catalyzed D-D</u>

$$D + D \longrightarrow n(2.45) + {}^{3}He(0.82)$$
$$D + D \longrightarrow p(3.0) + T\ (1.0)$$
$${}^{3}He + D \longrightarrow p(14.7) + {}^{4}He(3.6)$$
$$T + D \longrightarrow n(14.1) + {}^{4}He(3.5)$$

(The T and ${}^{3}He$ products are burned up at the same rate as produced. At least 80% of the tritium but only 20% of the ${}^{3}He$ is burned up before diffusion out of the discharge; the rest must be injected back.)

3. <u>D - ${}^{3}He$</u> $D + {}^{3}He \longrightarrow p(14.7) + {}^{4}He(3.6)$

(Some D-D reactions also occur. The tritium product is burned)

4. <u>Catalyzed p - ${}^{6}Li$</u>

$$p + {}^{6}Li \longrightarrow {}^{3}He + {}^{4}He + 4.0\ MeV$$
$${}^{3}He + {}^{6}Li \longrightarrow p + 2\,{}^{4}He + 16.8\ MeV$$

(The ${}^{3}He$ is fed back to be burned up at the same rate as produced. In addition, there are 12 ${}^{6}Li$ - ${}^{6}Li$ reactions, some of which give low-energy neutrons.)

5. <u>p - ${}^{11}B$</u> $p + {}^{11}B \longrightarrow 3\,{}^{4}He\ (8.7\ MeV)$

(${}^{4}He$ - ${}^{11}B$ reactions during ${}^{4}He$ deceleration produce a very small neutron flux.)

D.L. Jassby

July 1977

NOMENCLATURE

① $T(d,n)^4He$

② $^3He(d,p)^4He$

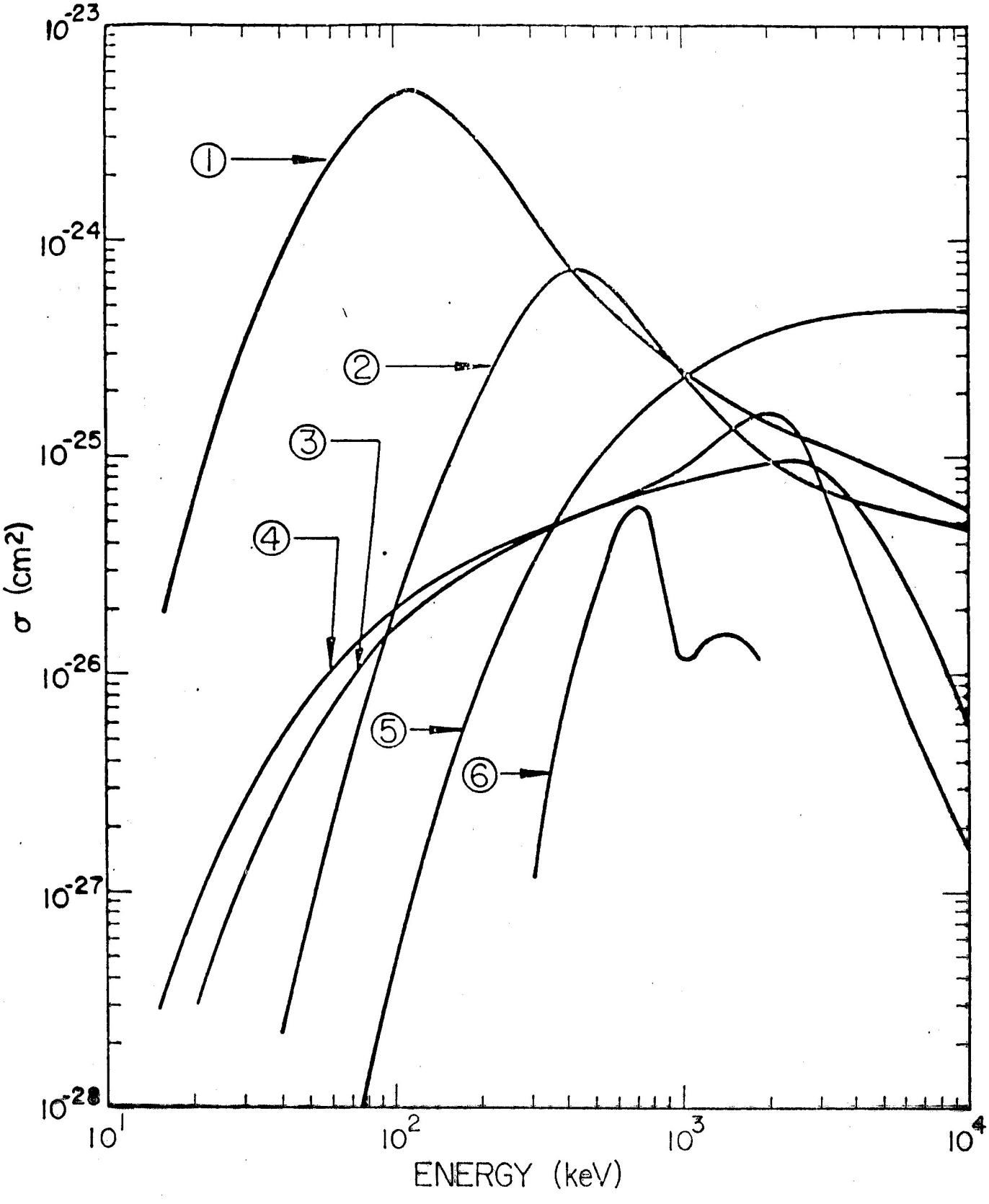
③ $D(d,p)T$

④ $T(t,2n)^4He$

⑤ $T(^3He,X)Y$

⑥ $^{11}B(p,2\,^4He)^4He$

G. H. Miley, et. al., U. of Illinois
COO-2218-17 (1974)



Cross sections for several prominent fusion reactions.

(Nomenclature found on p. 8.1)