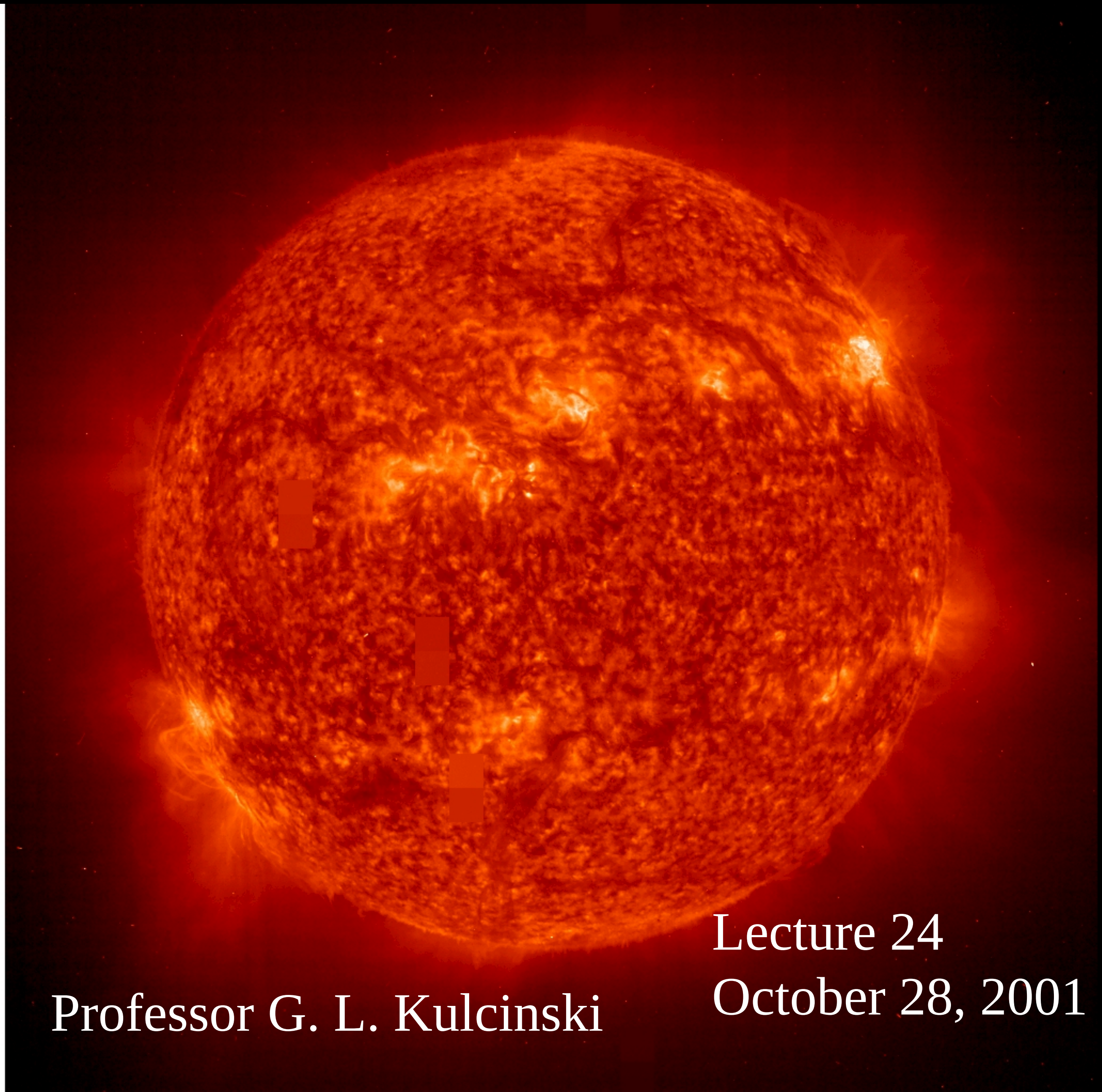
Principles of Fusion Energy



Where Are We Now With Respect to Future Energy Sources?

Some time in the mid-21st century, the world will need a new safe, clean, and economical source of energy to satisfy the needs of both developing and developed nations.

The question is now how much energy is needed, when, and where will it come from?

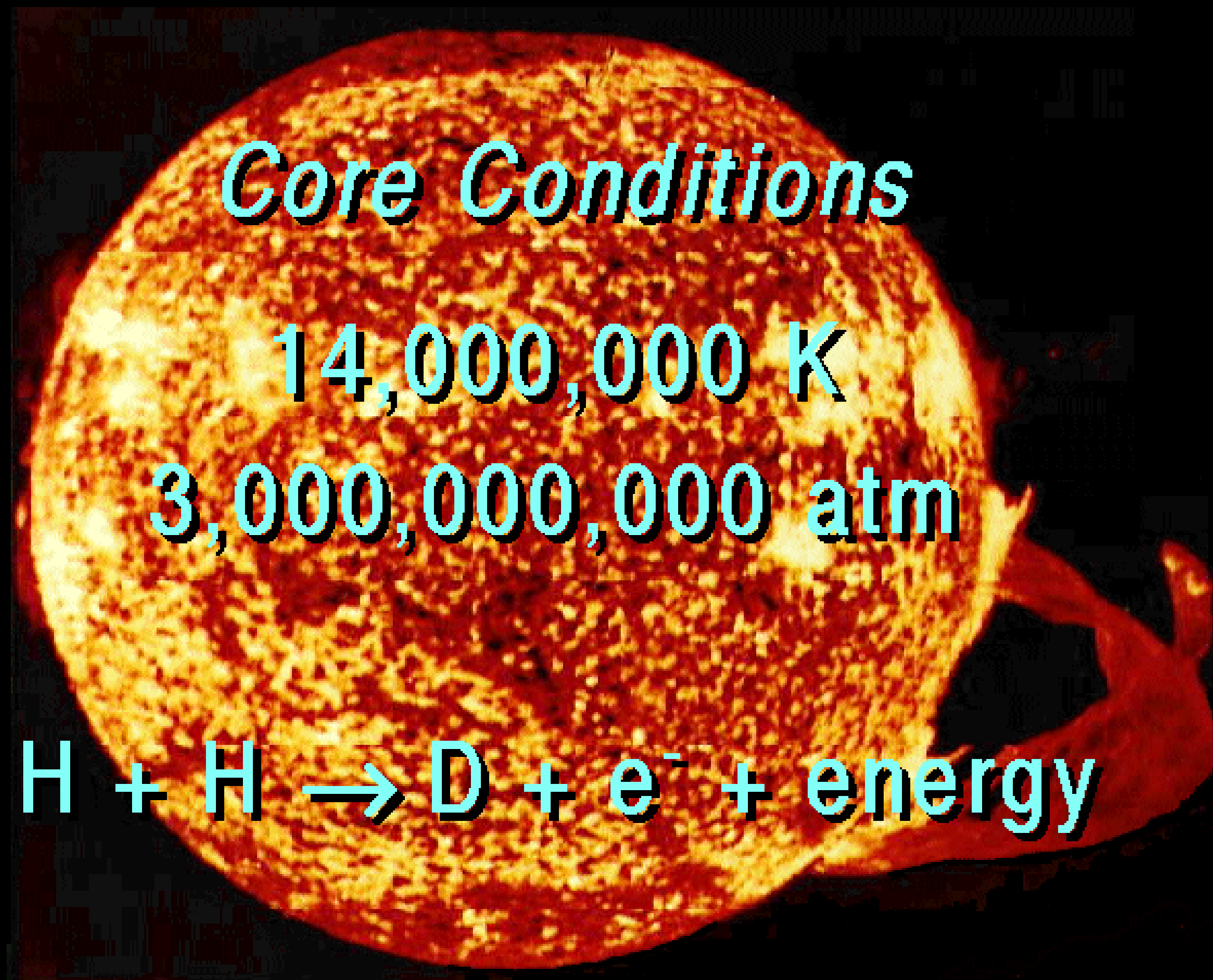
How do We Make Atoms Fuse?

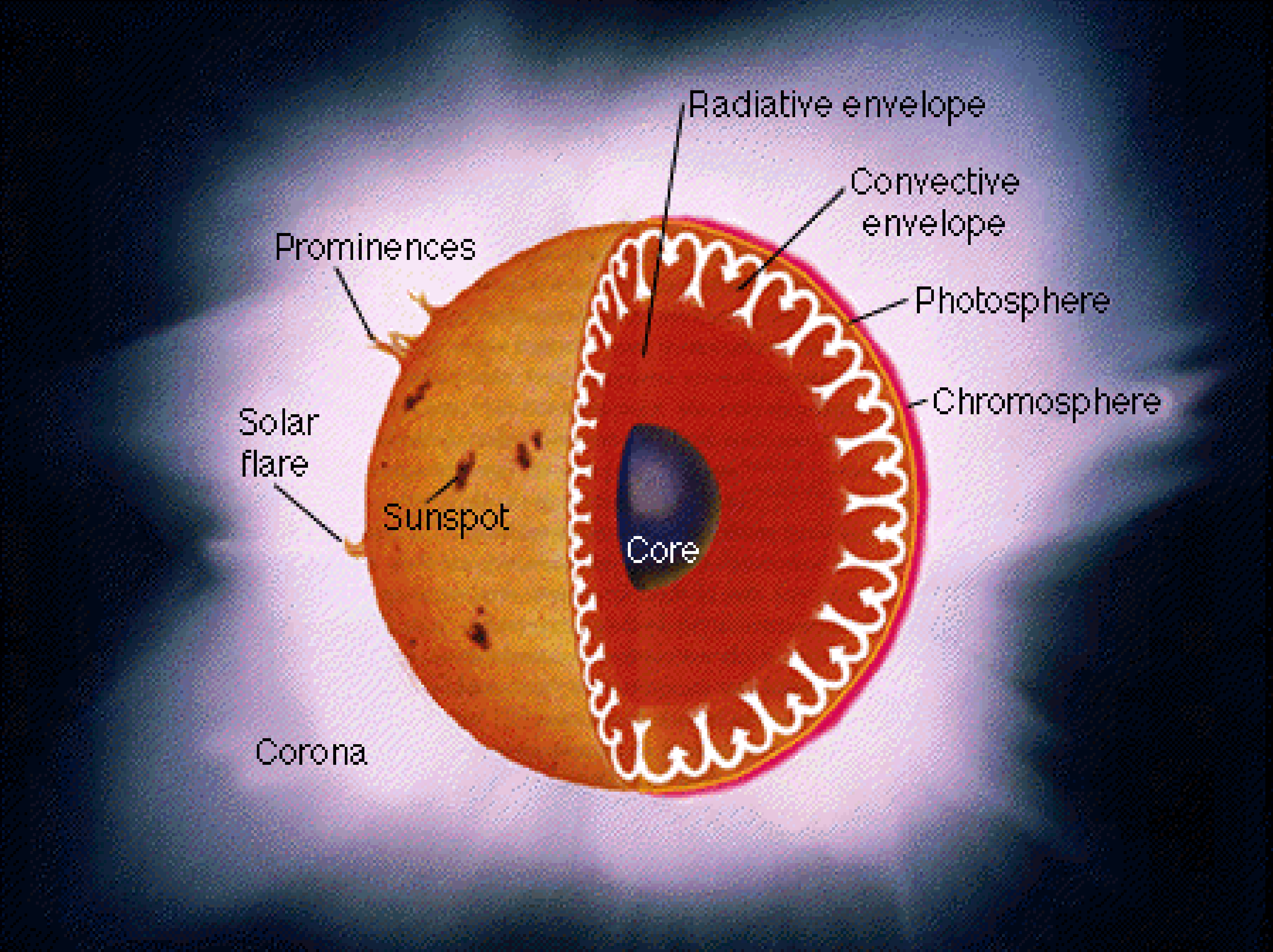
- Placing them under very high pressures at high temperature.
  - Gravity
  - Inertial confinement

- Heating them to very high temperatures (i. e., high velocities) and running them into each other.
  - Containment with high magnetic fields

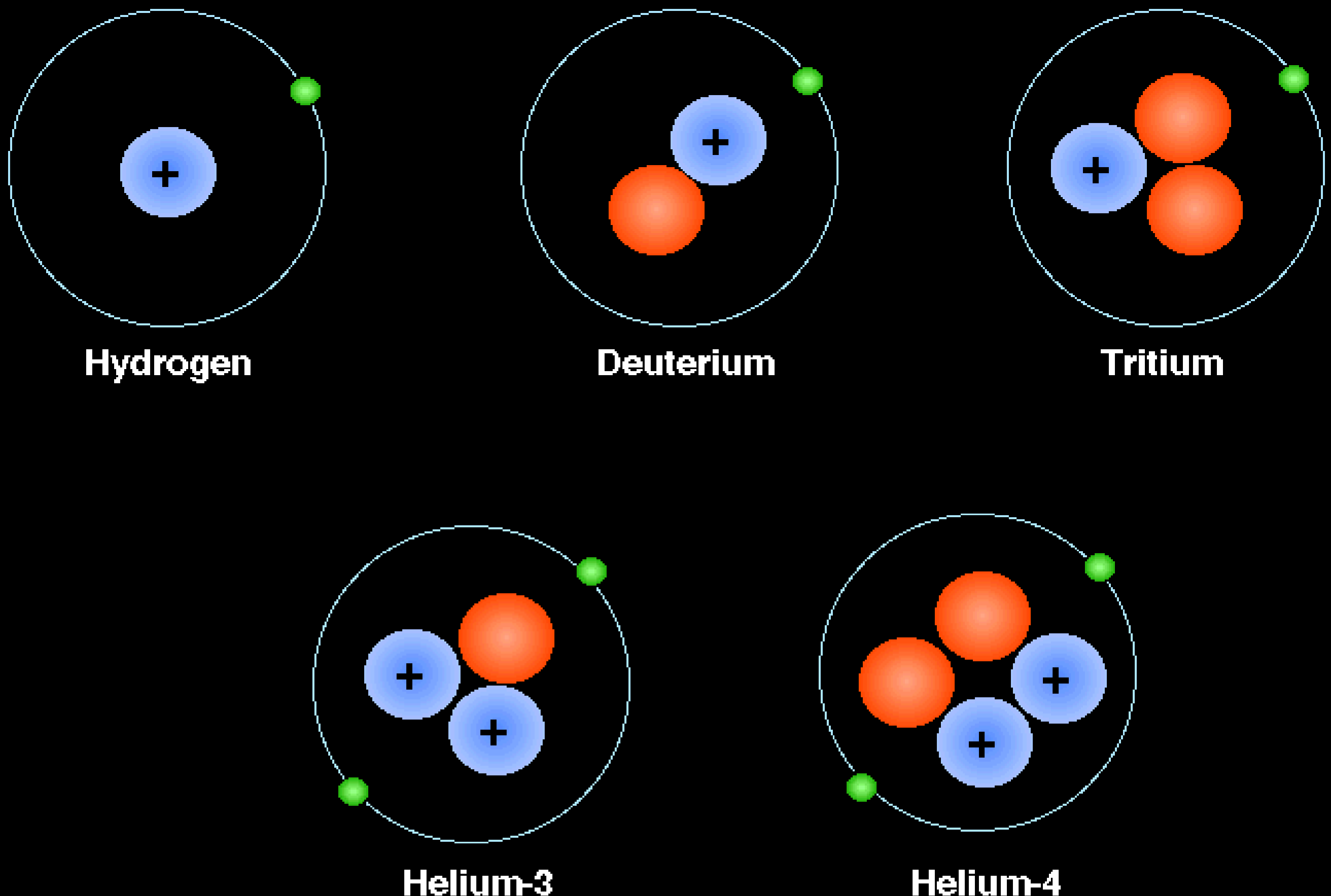
- Acceleration into each other at high velocities.
  - Electrostatic confinement

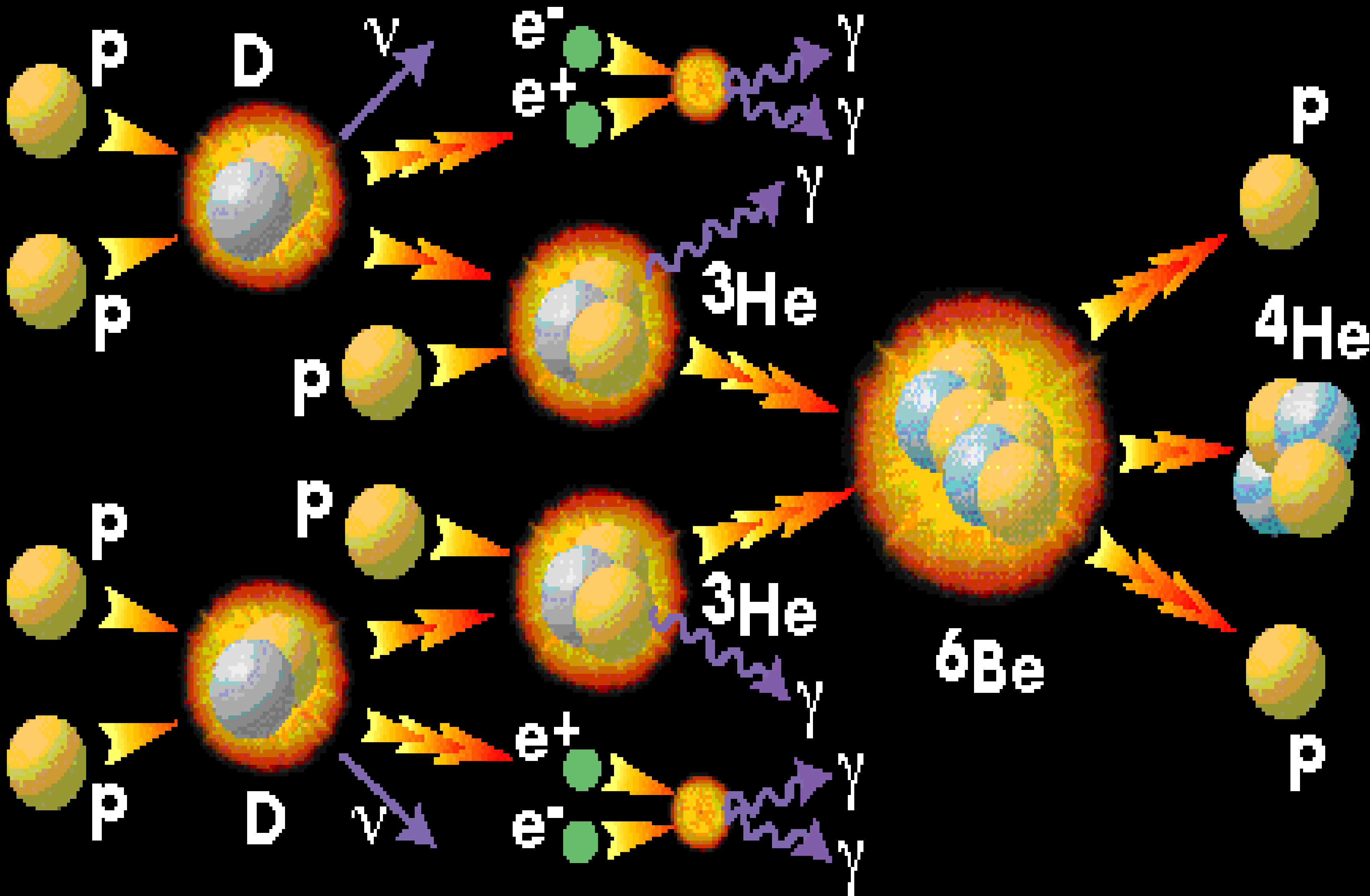
The Sun is a Very Efficient Fusion Reactor



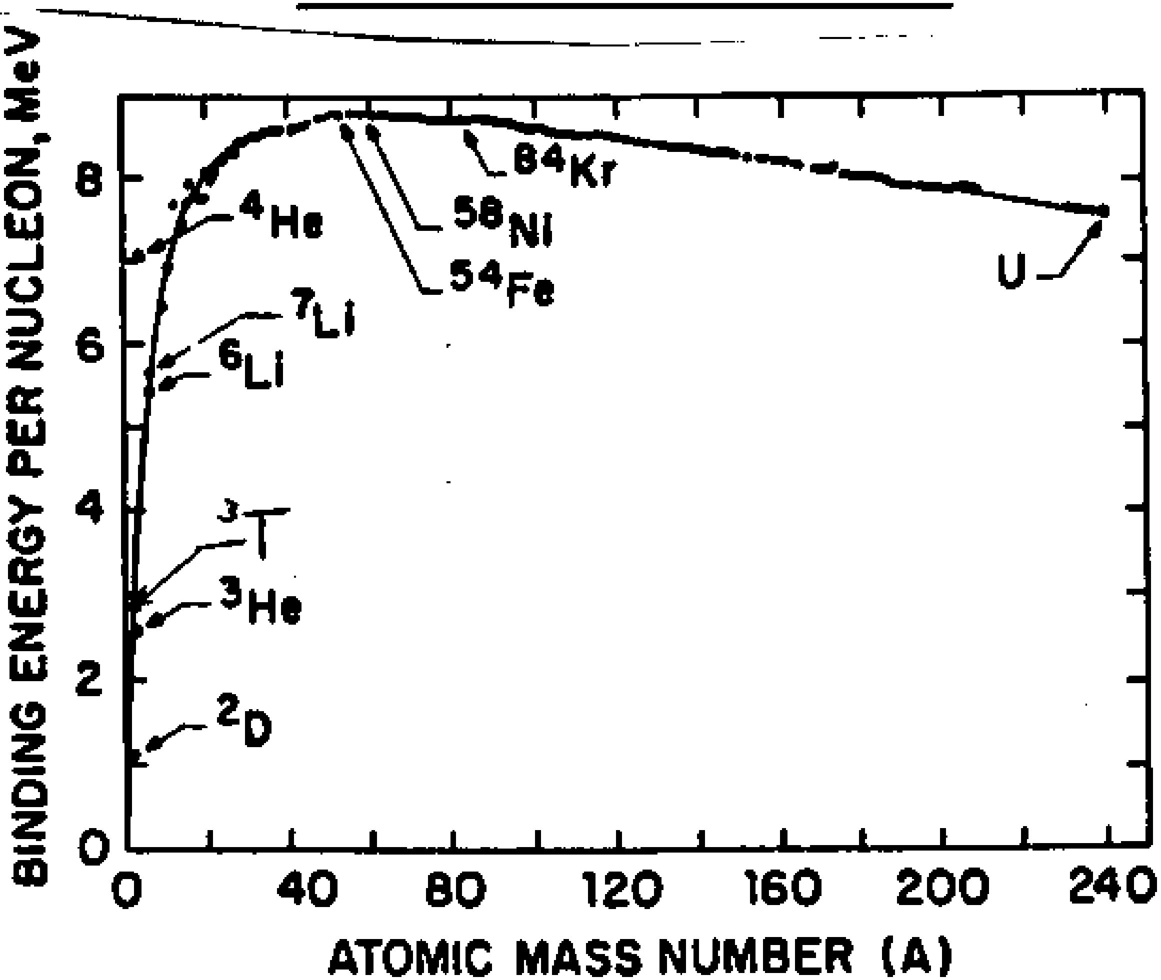

Radiative envelope
Convective envelope
Prominences
Photosphere
Chromosphere
Solar flare
Sunspot
Core
Corona

Nuclear Structure of Important Light Isotopes

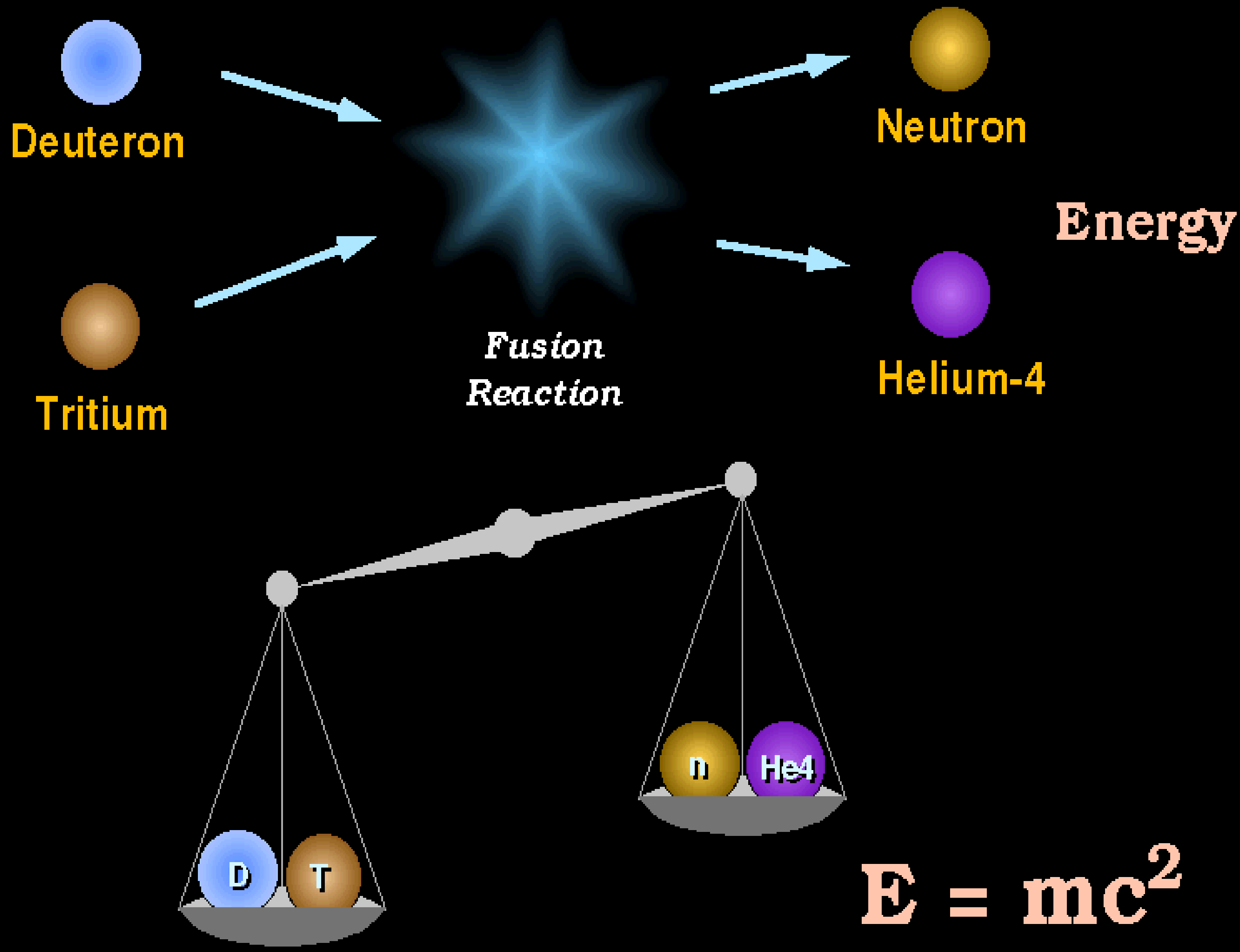



p
D
ν
e-
e+
γ
γ
p
p
3He
γ
p
4He
6Be
p
3He
p
p
γ
e+
γ
p
D
ν
e-
γ
p

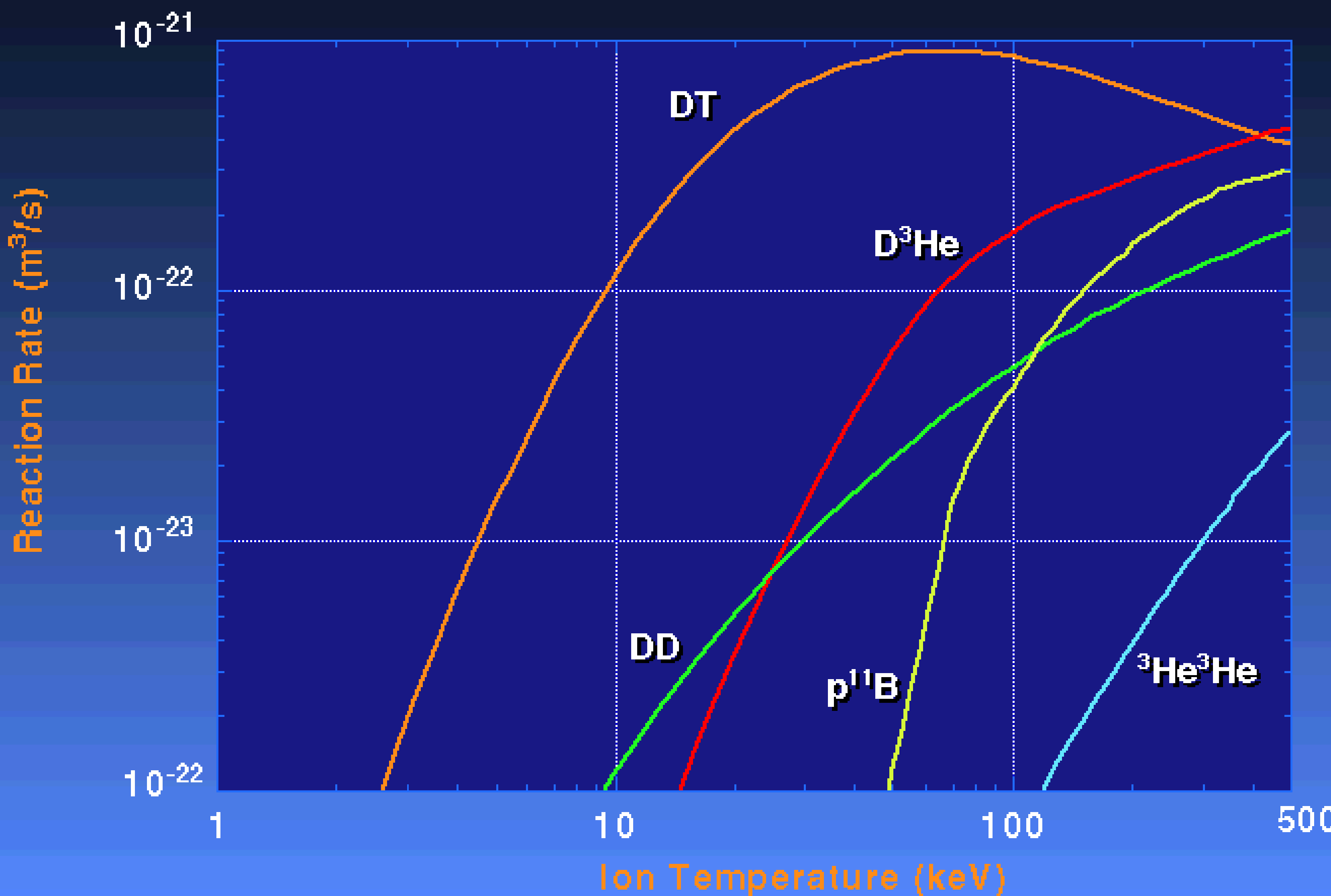
The Binding Energy Per Nucleon Increases When Heavy Elements are Fissioned and When Light Elements are Fused



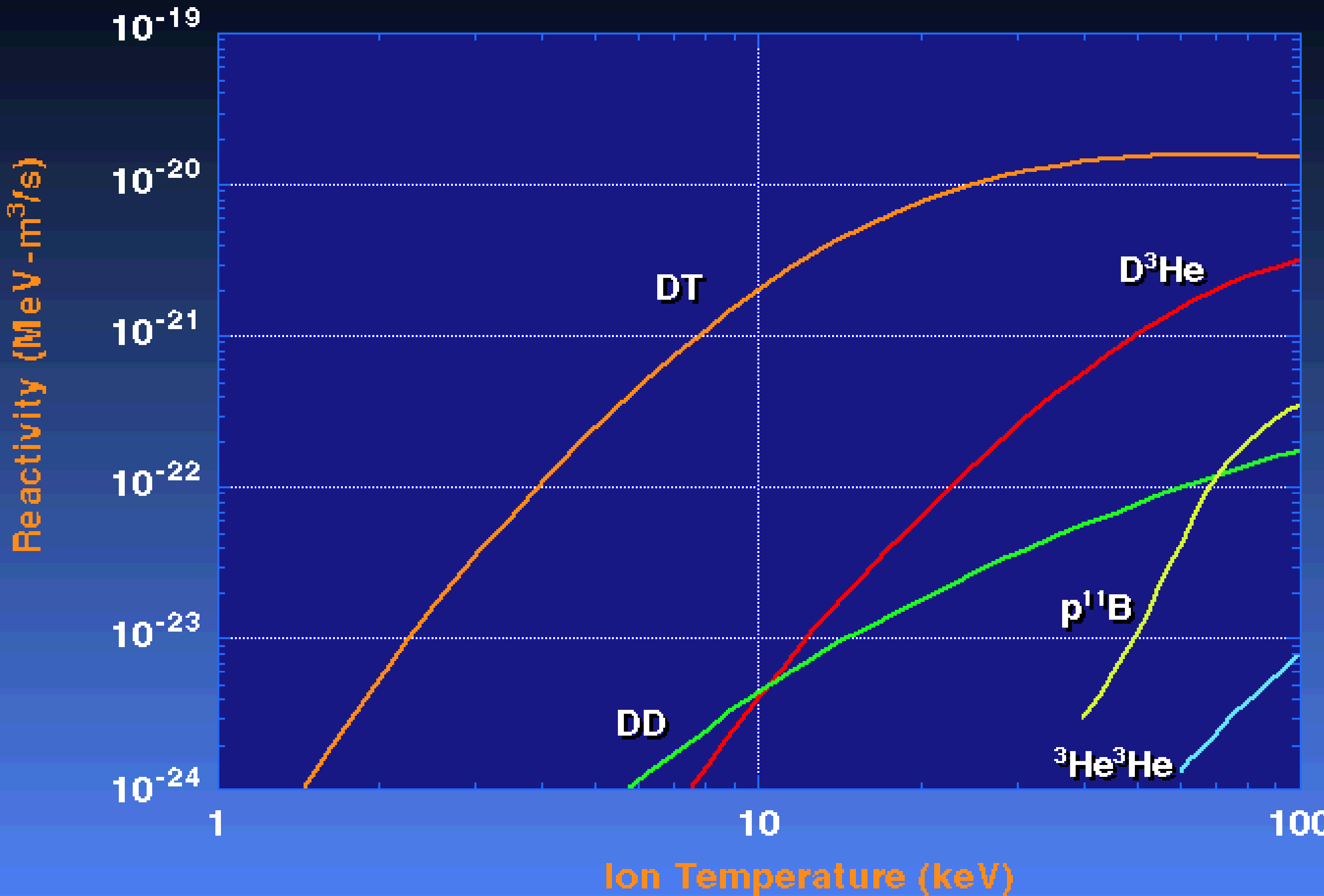
After R. A. Gross, 1984, Fusion Energy, J. Wiley & Sons


Deuteron
Tritium
Fusion
Reaction
Neutron
Helium-4
Energy
D
T
n
He4
E = mc2

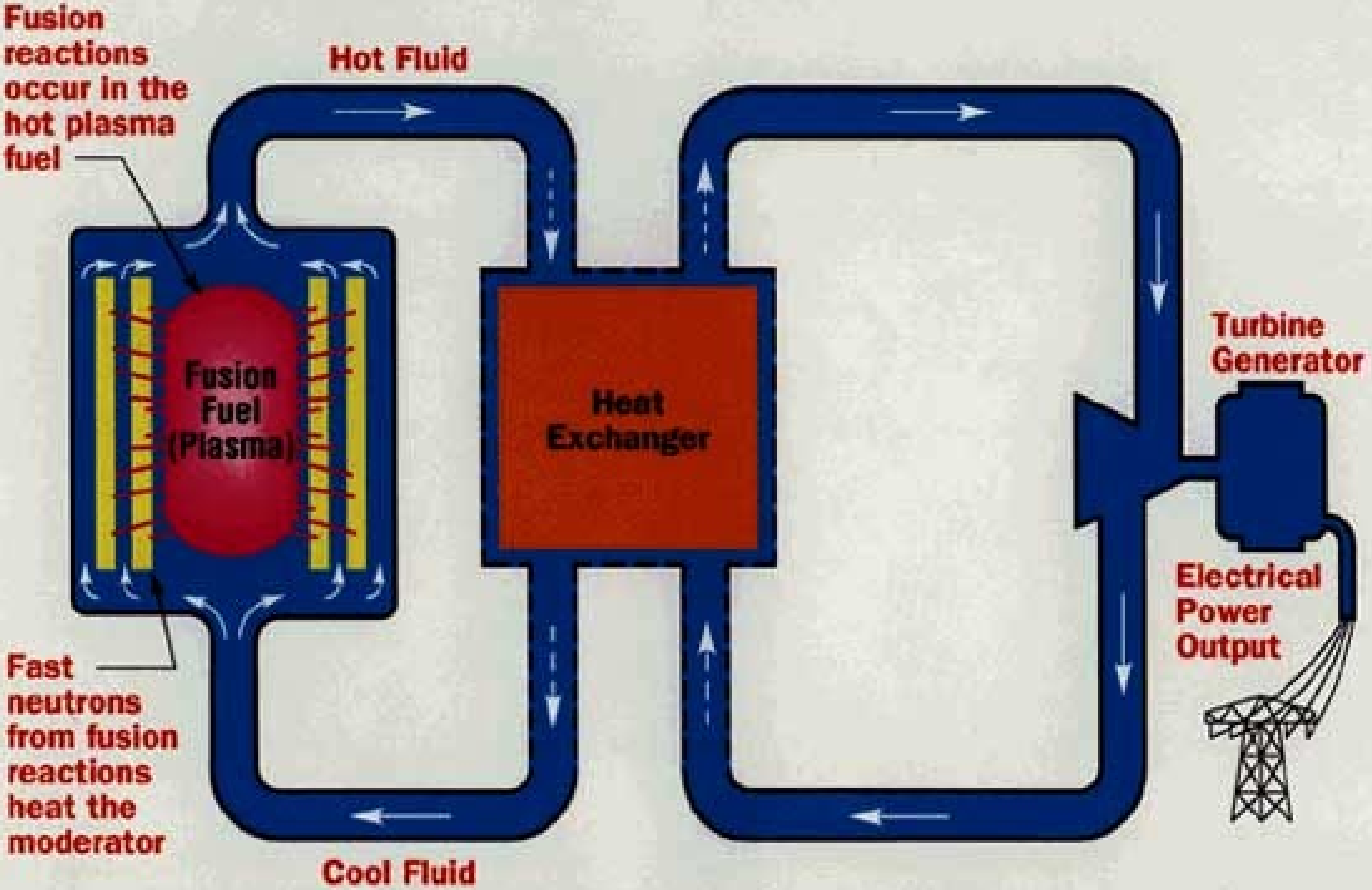
Maxwellian Fusion Reaction Rates



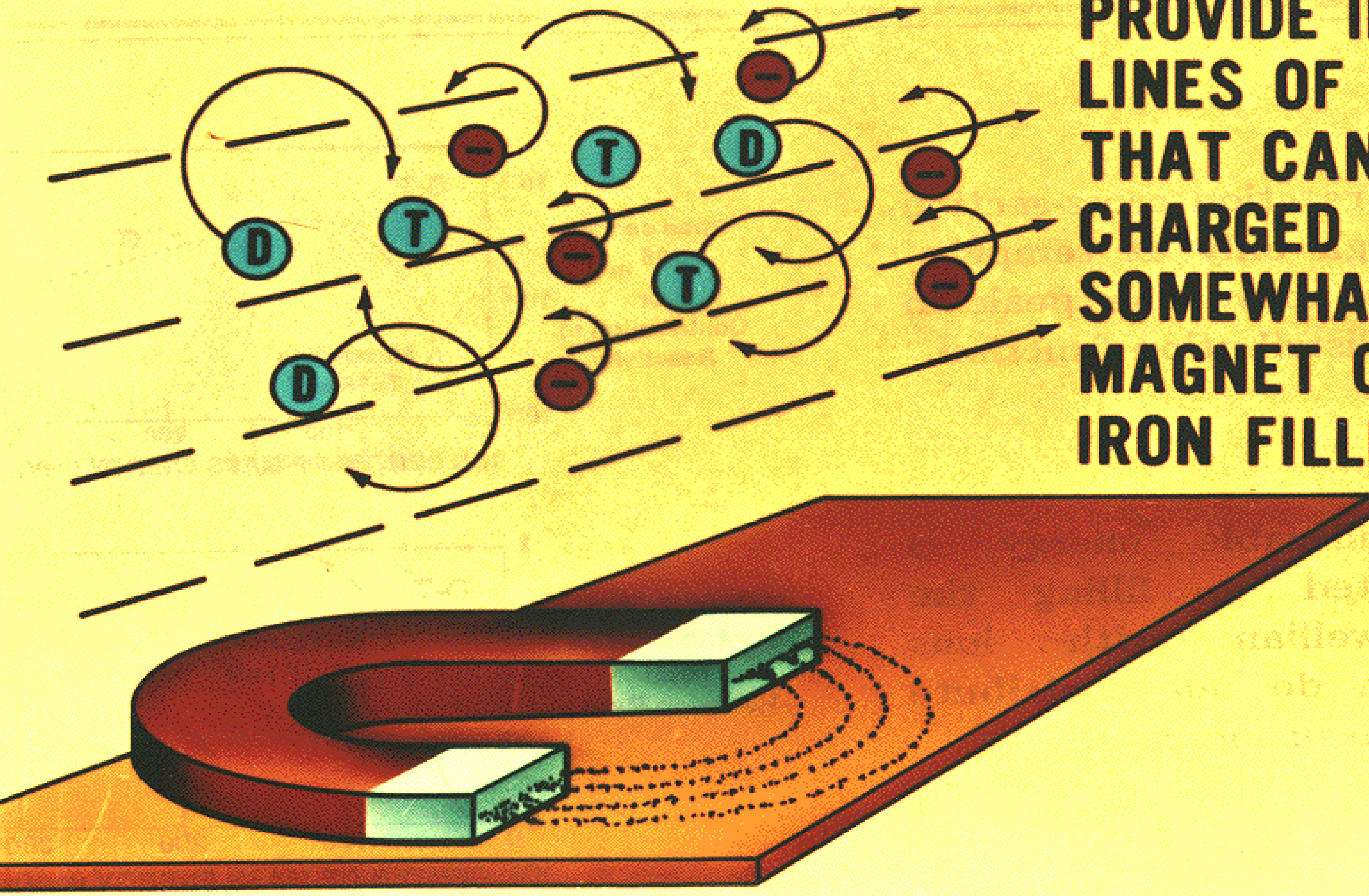
Maxwellian Fusion Reactivities ($\Sigma E_{fus}\sigma v$)



Fusion Power Plant



MAGNETIC FIELDS PROVIDE INVISIBLE LINES OF FORCE THAT CAN HOLD CHARGED PARTICLES SOMEWHAT LIKE A MAGNET CAN HOLD IRON FILLINGS



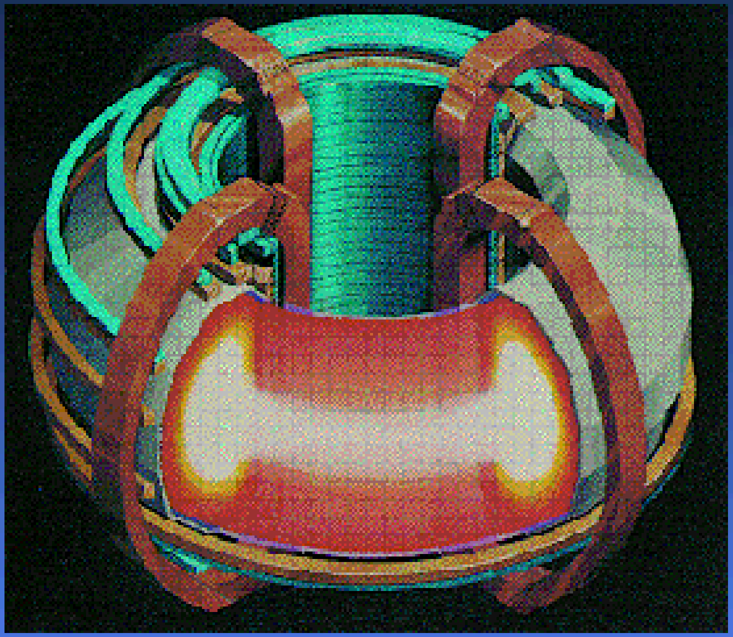
Where Do We Get Deuterium and Tritium From?

- Deuterium:
  - Stable isotope
  - 0.015 mole % in hydrogen bearing compounds
    (1 atom in every 6670 hydrogen atoms)
  - Estimated inventory on Earth-5,000 billion tonnes

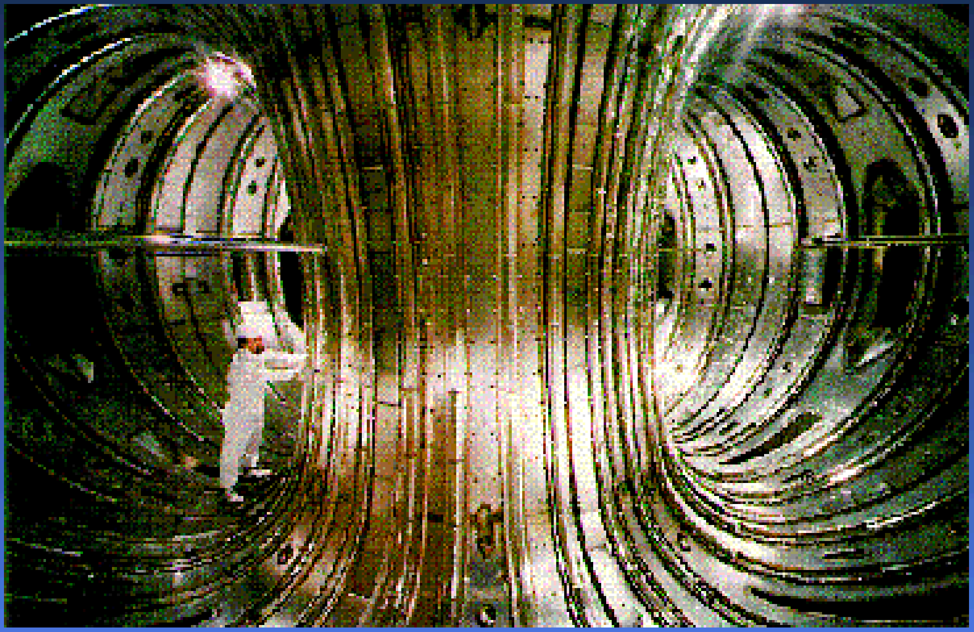
- Tritium:
  - Radioactive isotope-12.3 year half life
    - $^{3}H_{1}$---> $^{3}He_{2}$ + e^{-} + 28 keV
  - Made from Li bombarded by neutrons
    - $^{1}n_{0}$ +$^{6}Li_{3}$ --> $^{4}He_{2}$ + $^{3}H_{1}$ + 4.8 MeV
    - $^{1}n_{0}$ +$^{7}Li_{3}$ --> $^{4}He_{2}$ + $^{3}H_{1}$ + $^{1}n'_{0}$ - 2.5 MeV

The Tokamak is the Leading Magnetic Fusion Concept for the DT Fuel Cycle

D + T -> n (14 MeV) + ^{4}He (3.5 MeV)

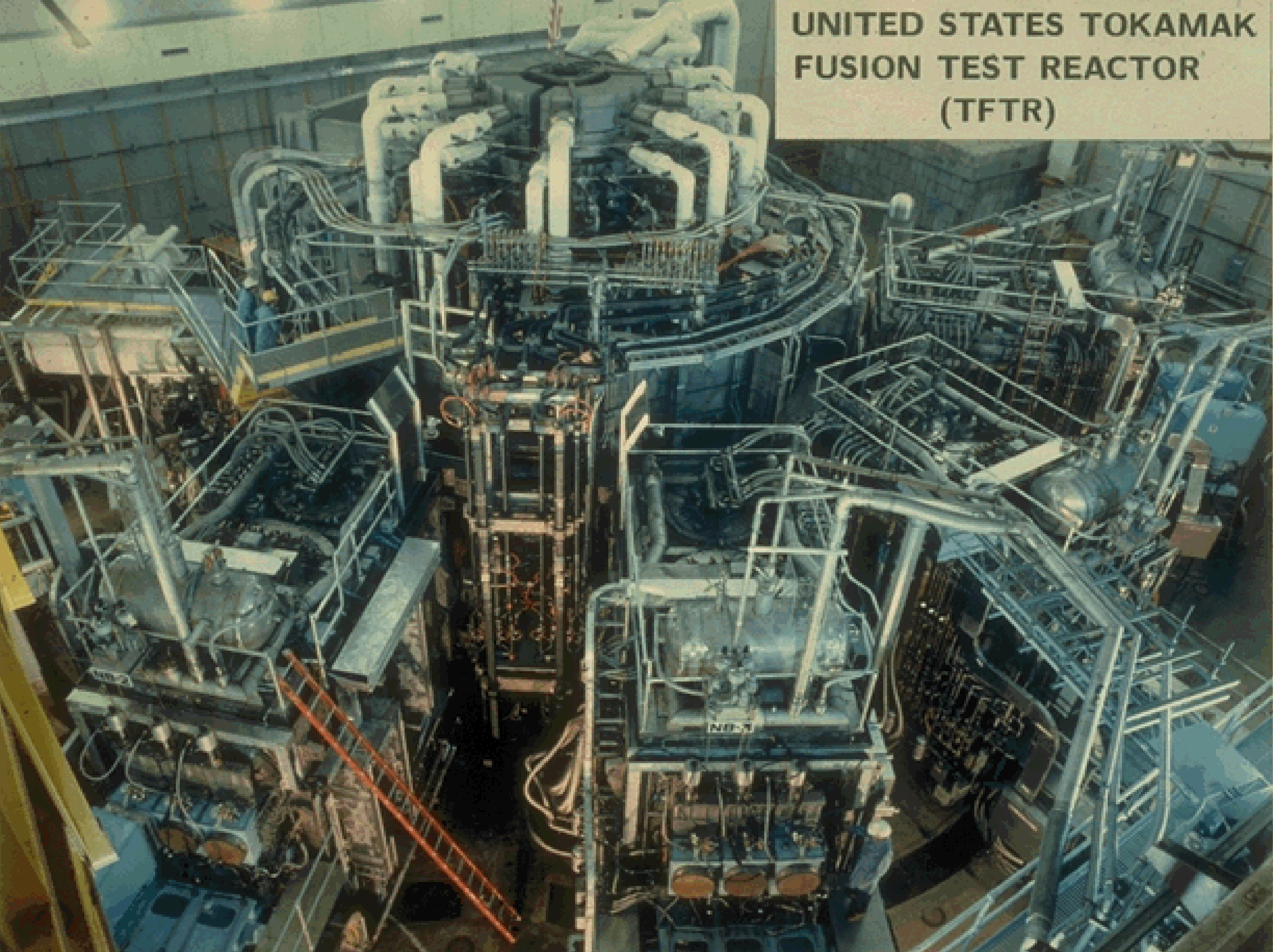


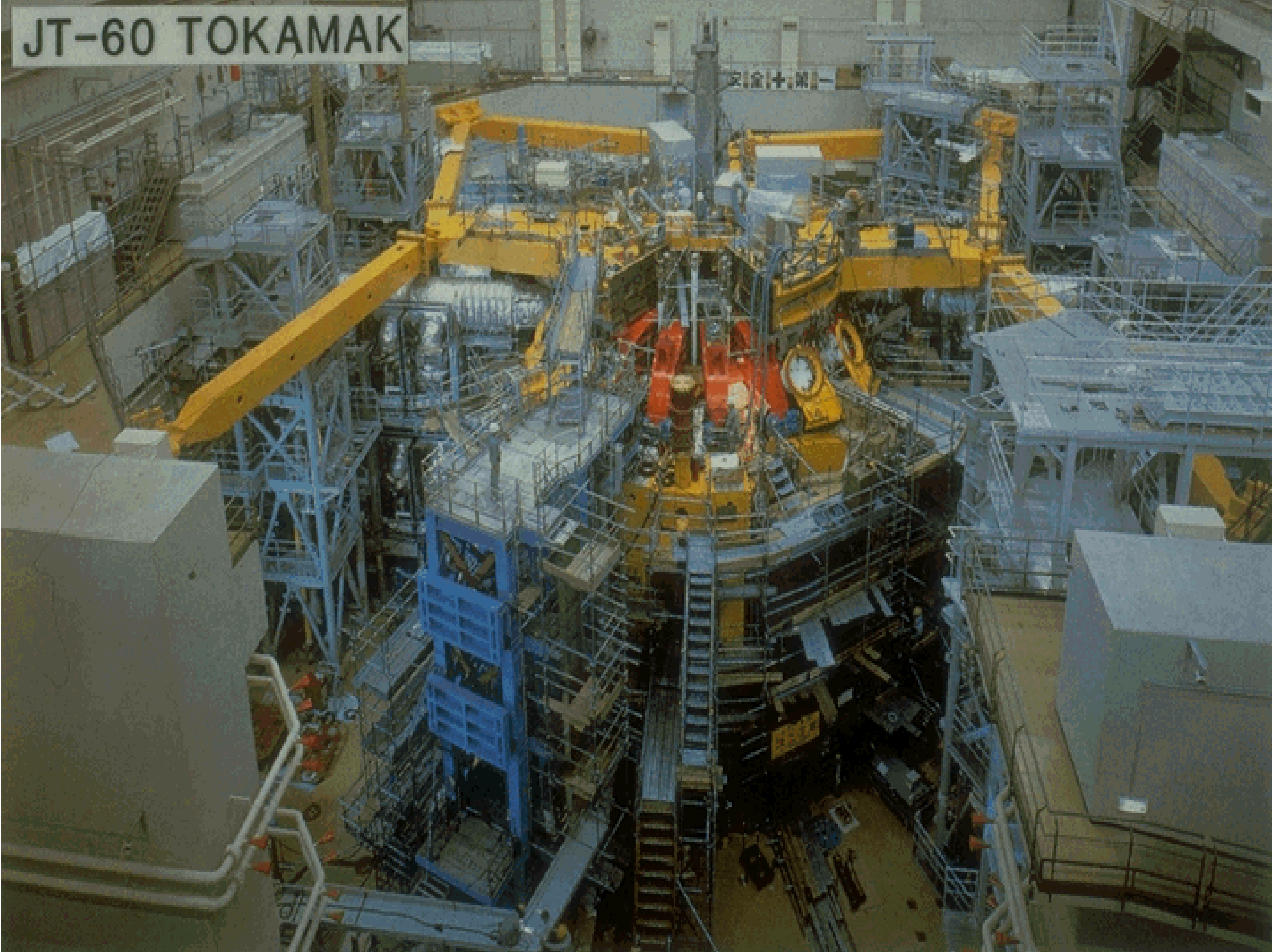
Schematic of a Tokamak



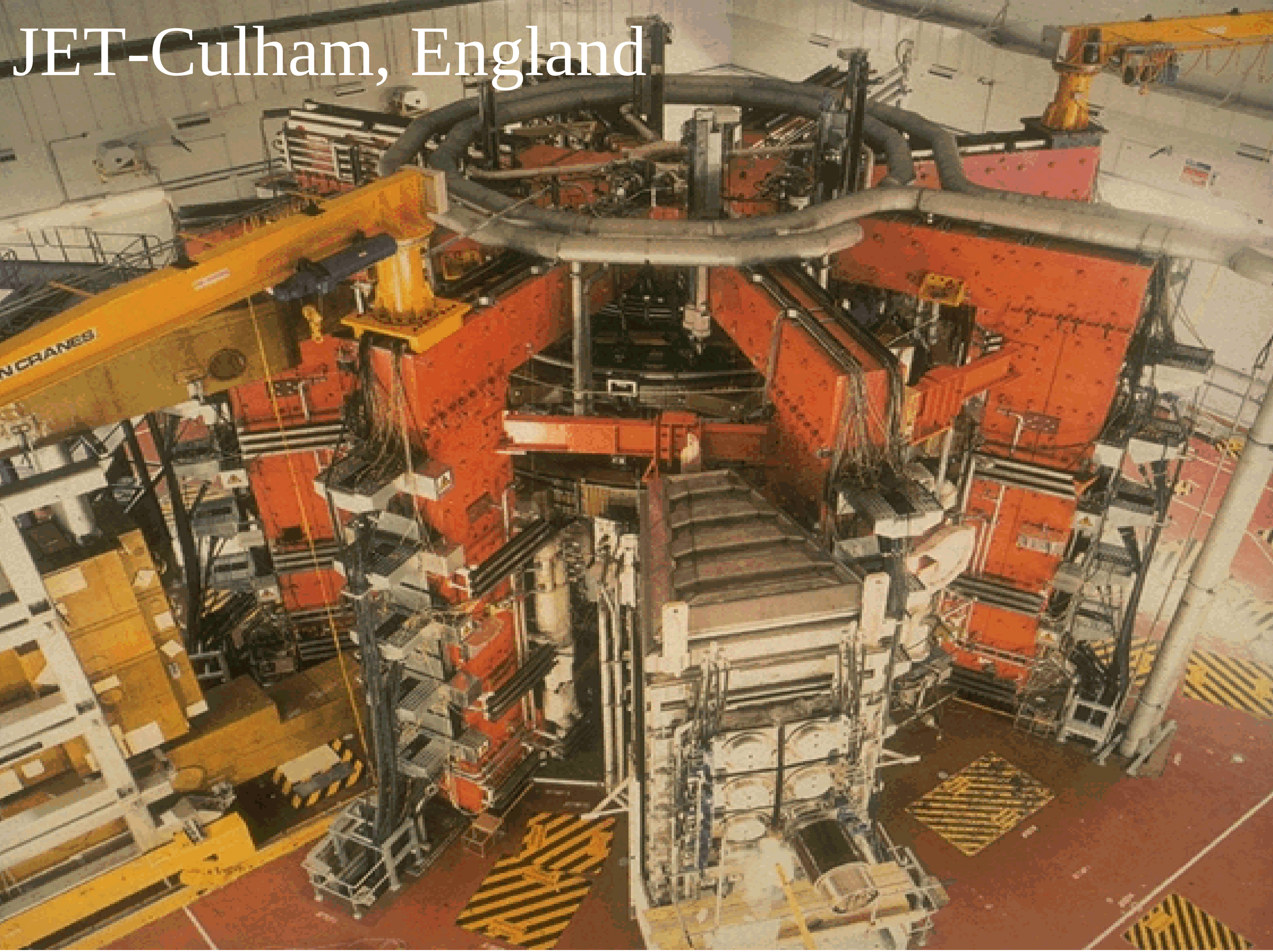
Joint European Torus – JET

~ 40 MW


UNITED STATES TOKAMAK
FUSION TEST REACTOR
(TFTR)

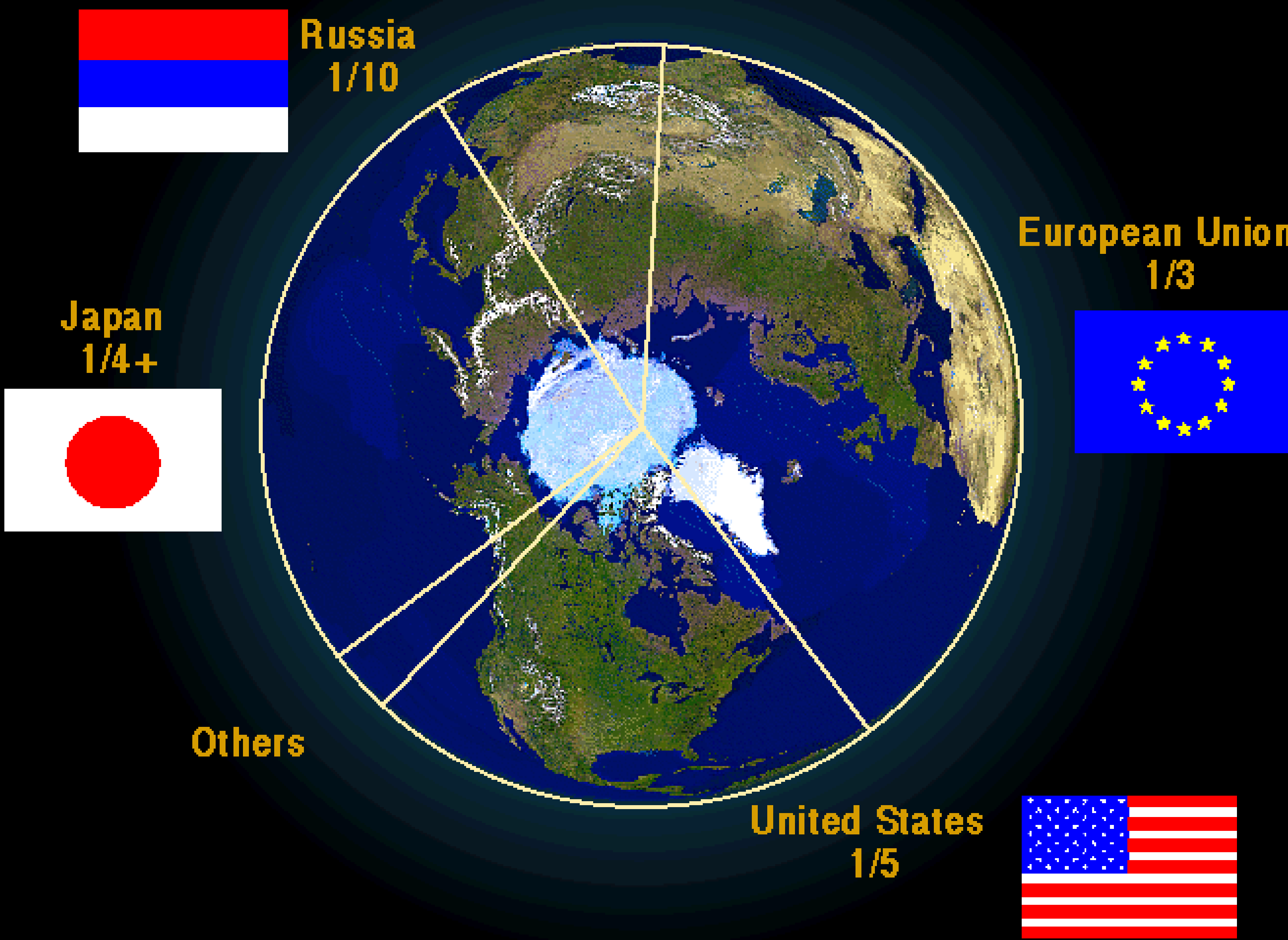

JT-60 TOKAMAK
安全第一

JET-Culham, England

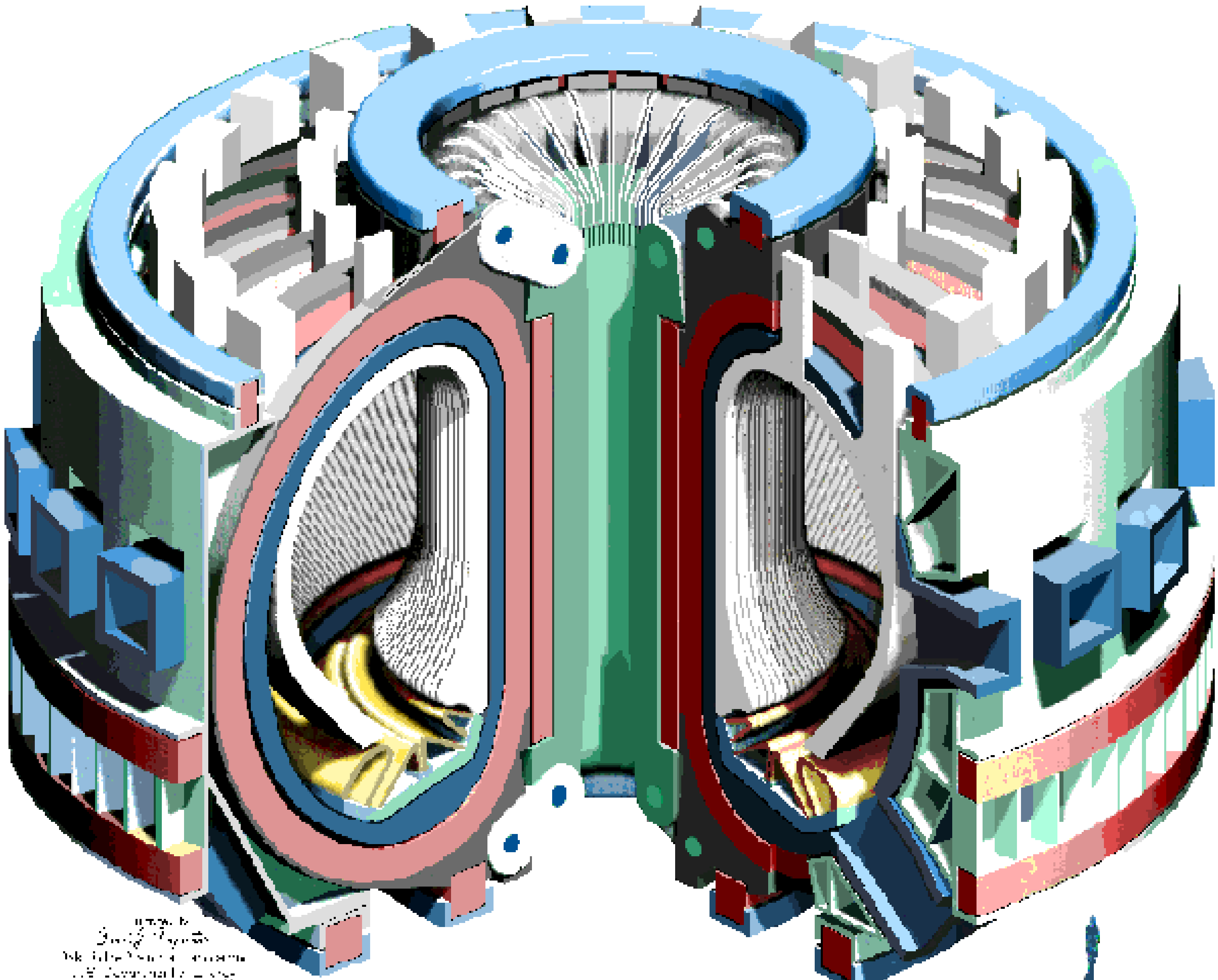


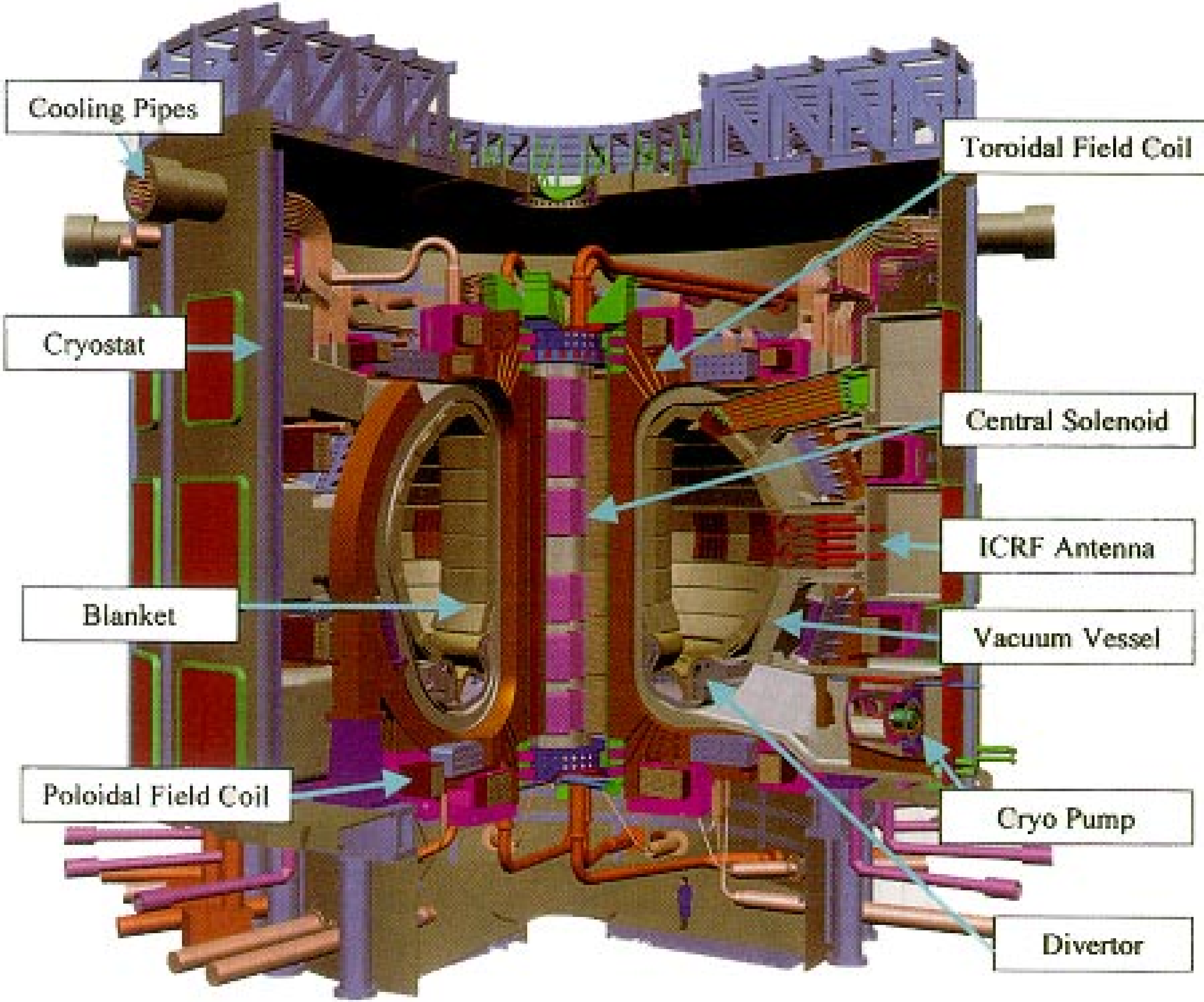
World Magnetic Fusion Effort

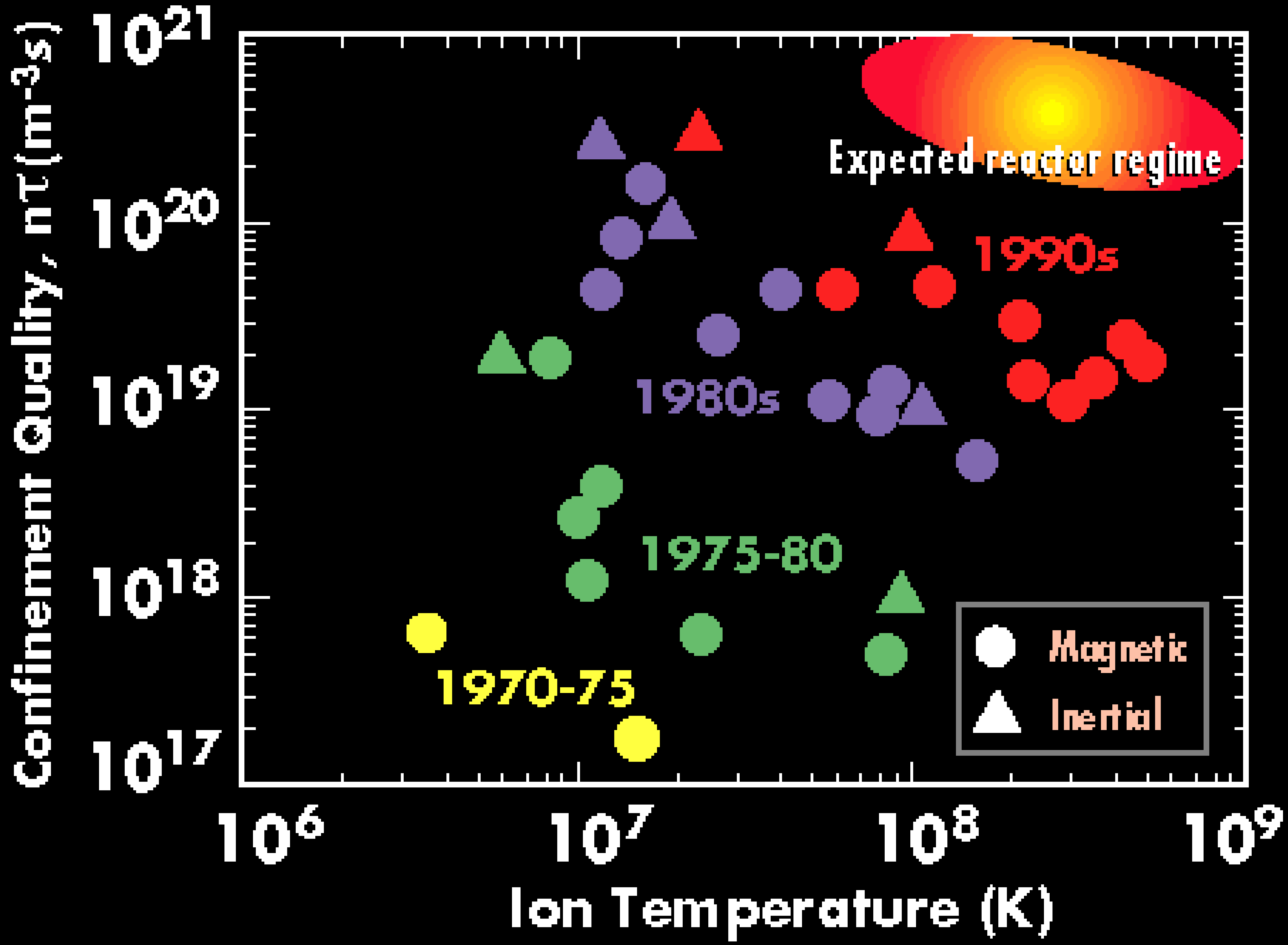
Major programs with fraction of total funding ($)



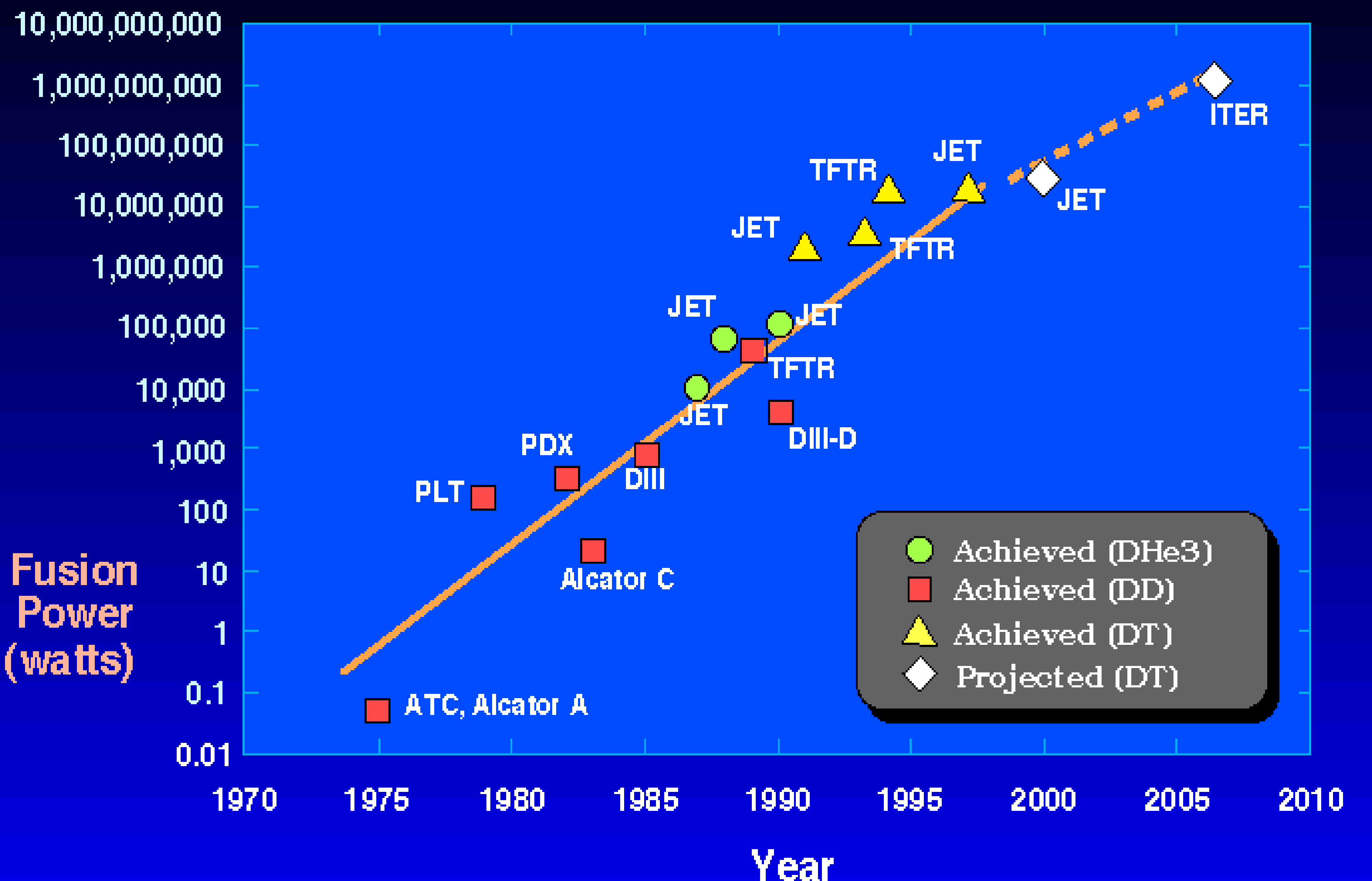
The Current ITER is Designed to Produce Between 1000–3000 MWt



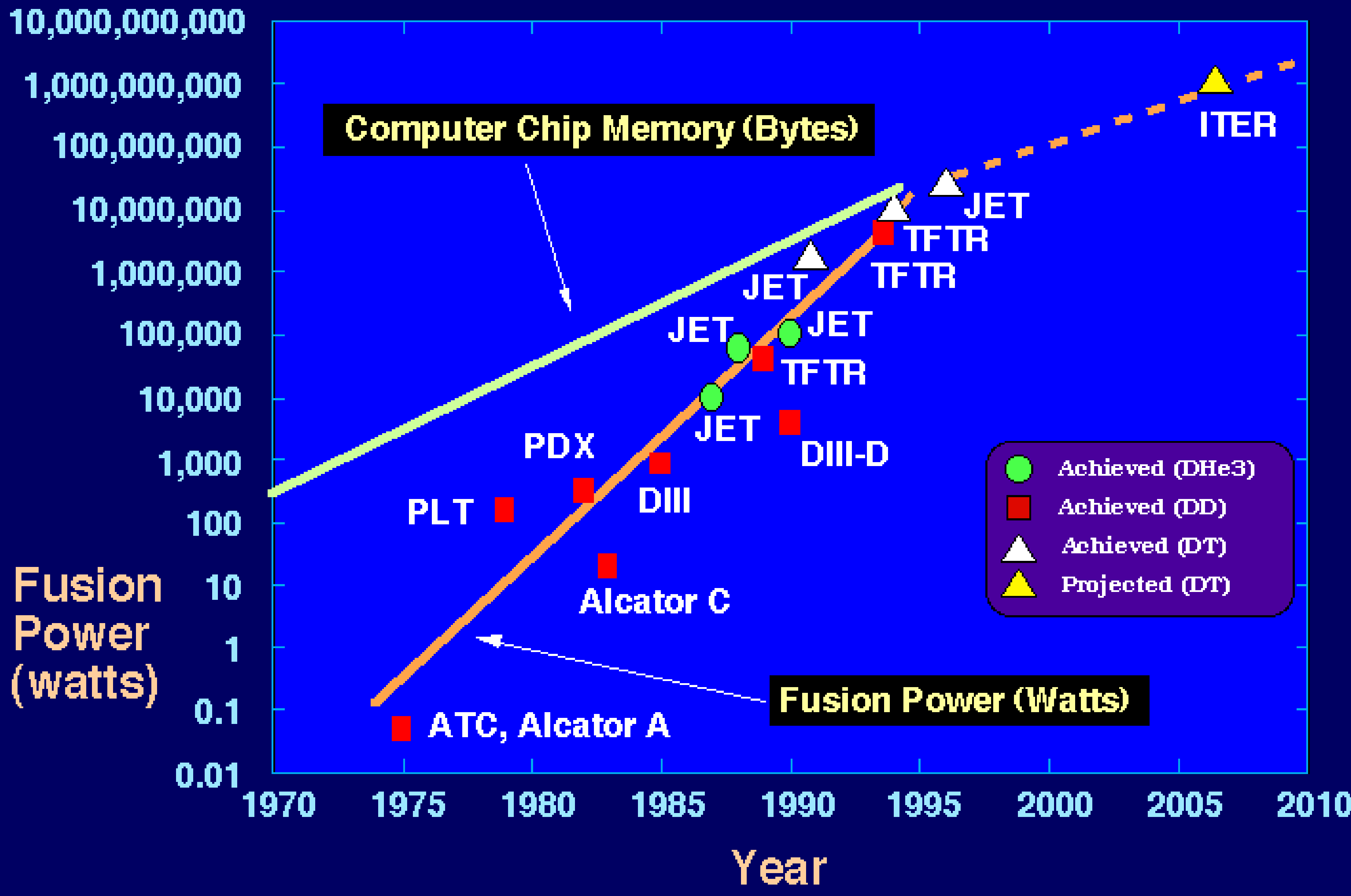

Cooling Pipes
Toroidal Field Coil
Cryostat
Central Solenoid
ICRF Antenna
Blanket
Vacuum Vessel
Poloidal Field Coil
Cryo Pump
Divertor


Confinement Quality, nτ(m^-3s)
10^21
10^20
10^19
10^18
10^17
Expected reactor regime
1990s
1980s
1975-80
1970-75
Magnetic
Inertial
10^6
10^7
10^8
10^9
Ion Temperature (K)

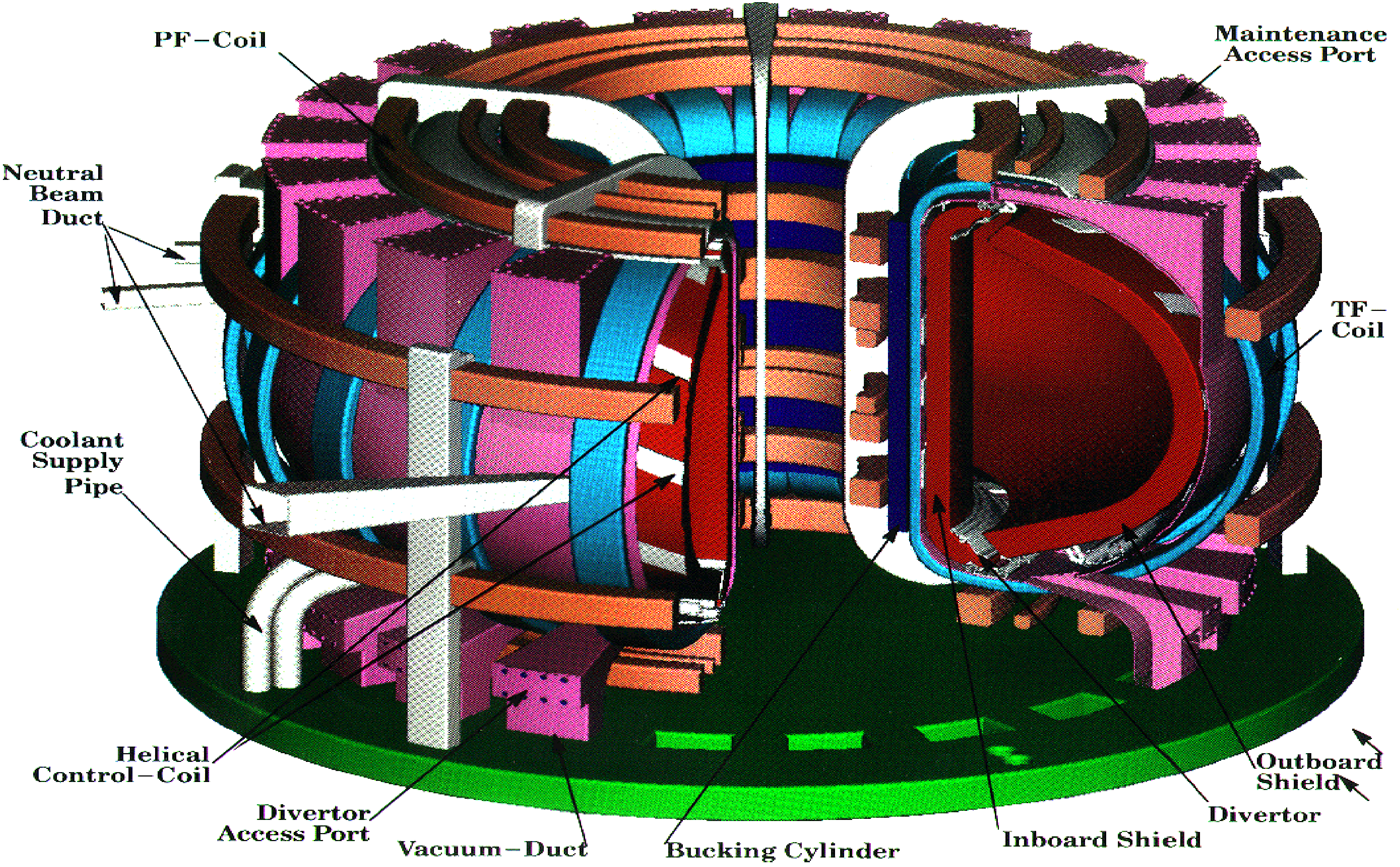
Progress in Magnetic Fusion Power

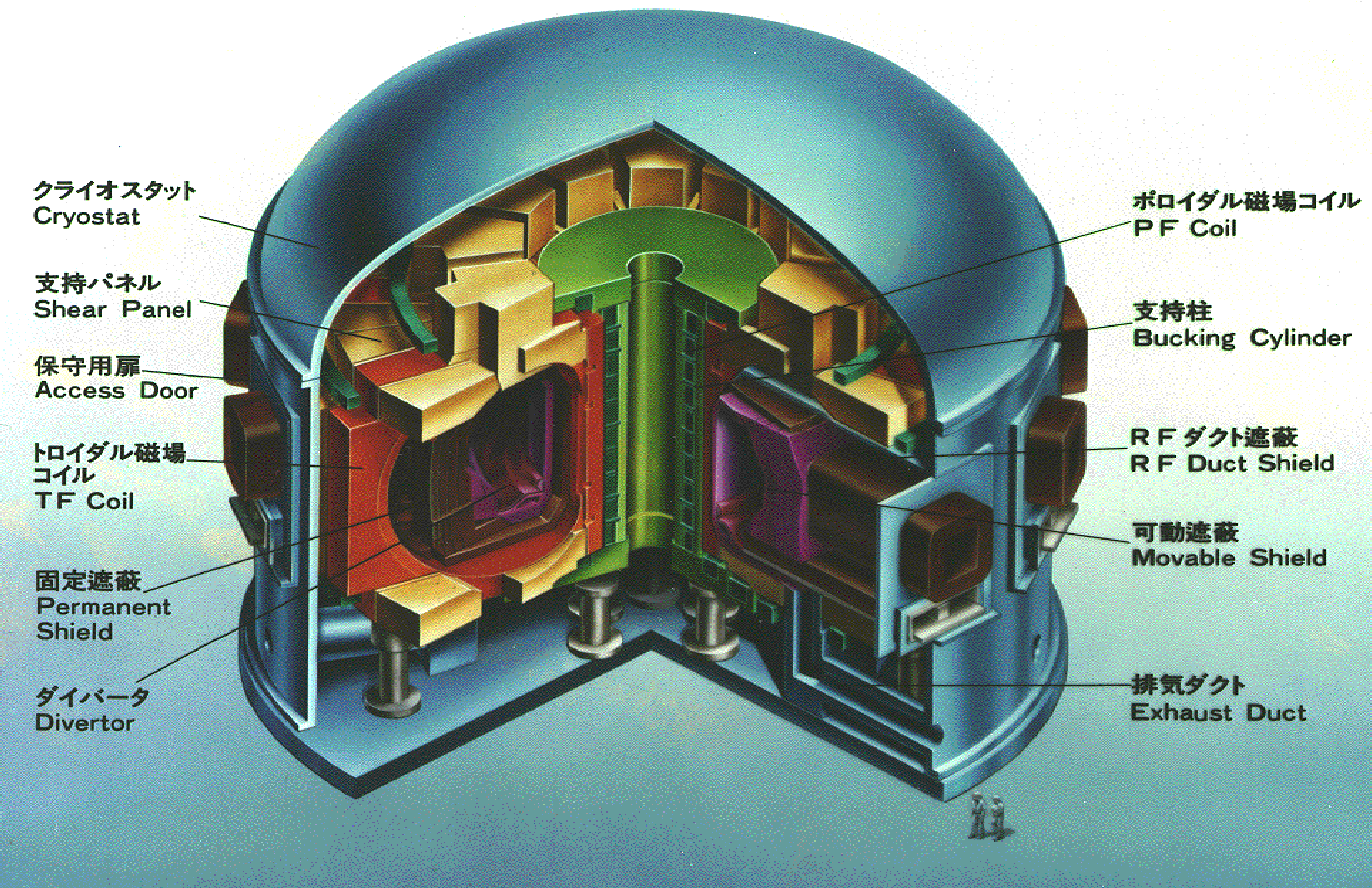


Magnetic Fusion Has Made Outstanding Progress During the Past 15 Years



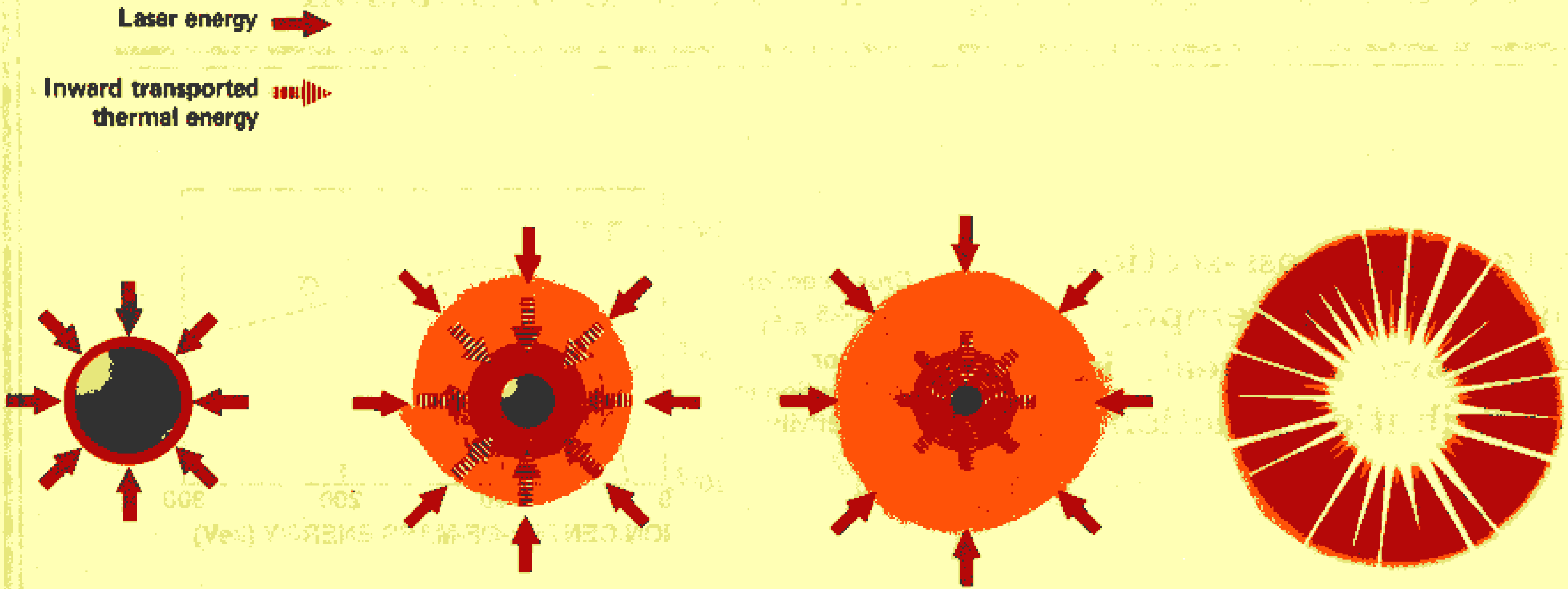
THE ARIES-III TOKAMAK FUSION REACTOR





核融合実験炉
Fusion Experimental Reactor (FER)

INERTIAL CONFINEMENT FUSION CONCEPT



Atmosphere Formation

Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression

Fuel is compressed by rocket-like blowoff of the surface material.

Ignition

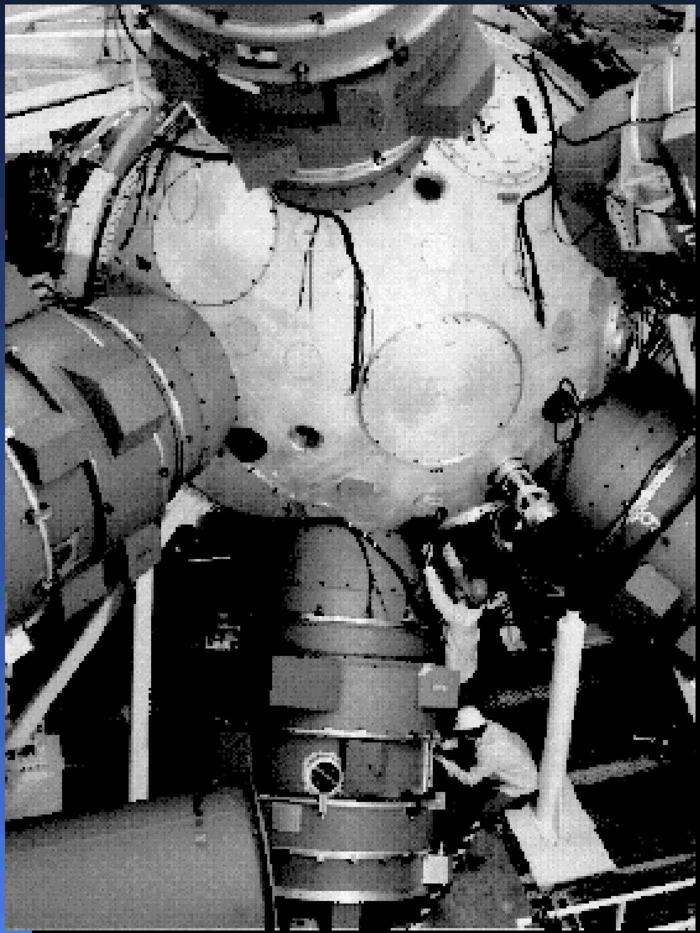
With the final driver pulse, the fuel core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000°C.

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

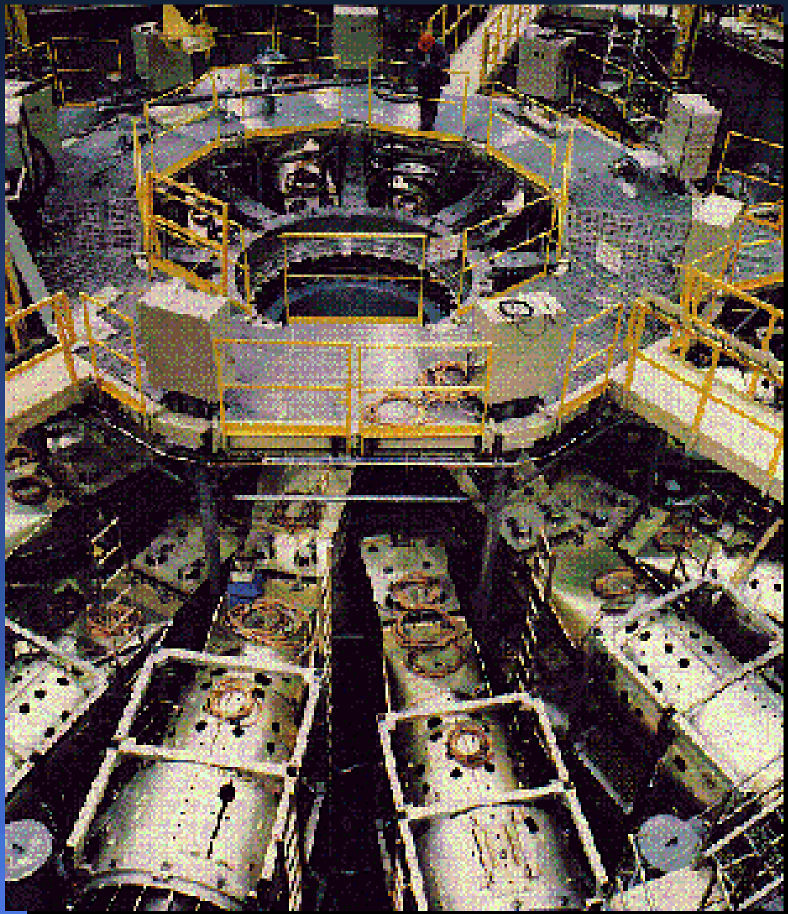
There Are Two Methods of Achieving Inertial Confinement Fusion

Lasers



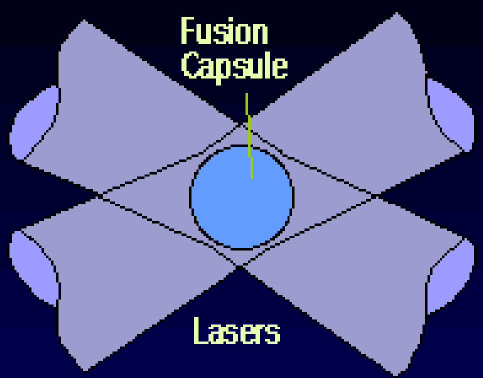
NOVA

Ions

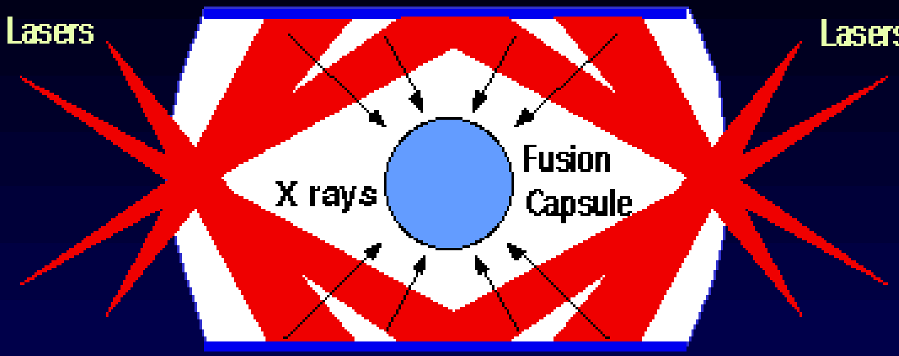


PBFA-II

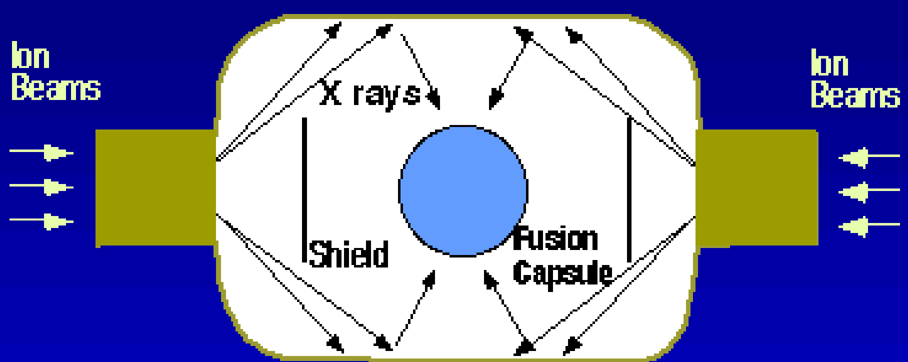
There Are Four Different ICF Target Designs



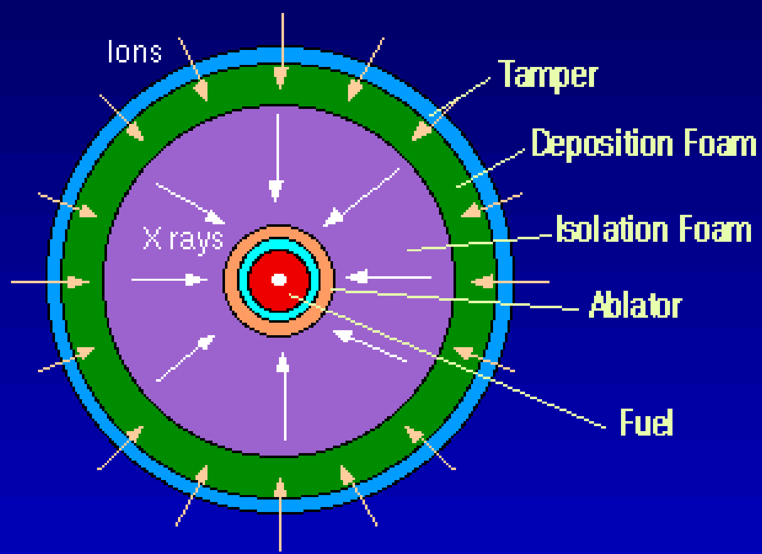
Direct Drive Lasers



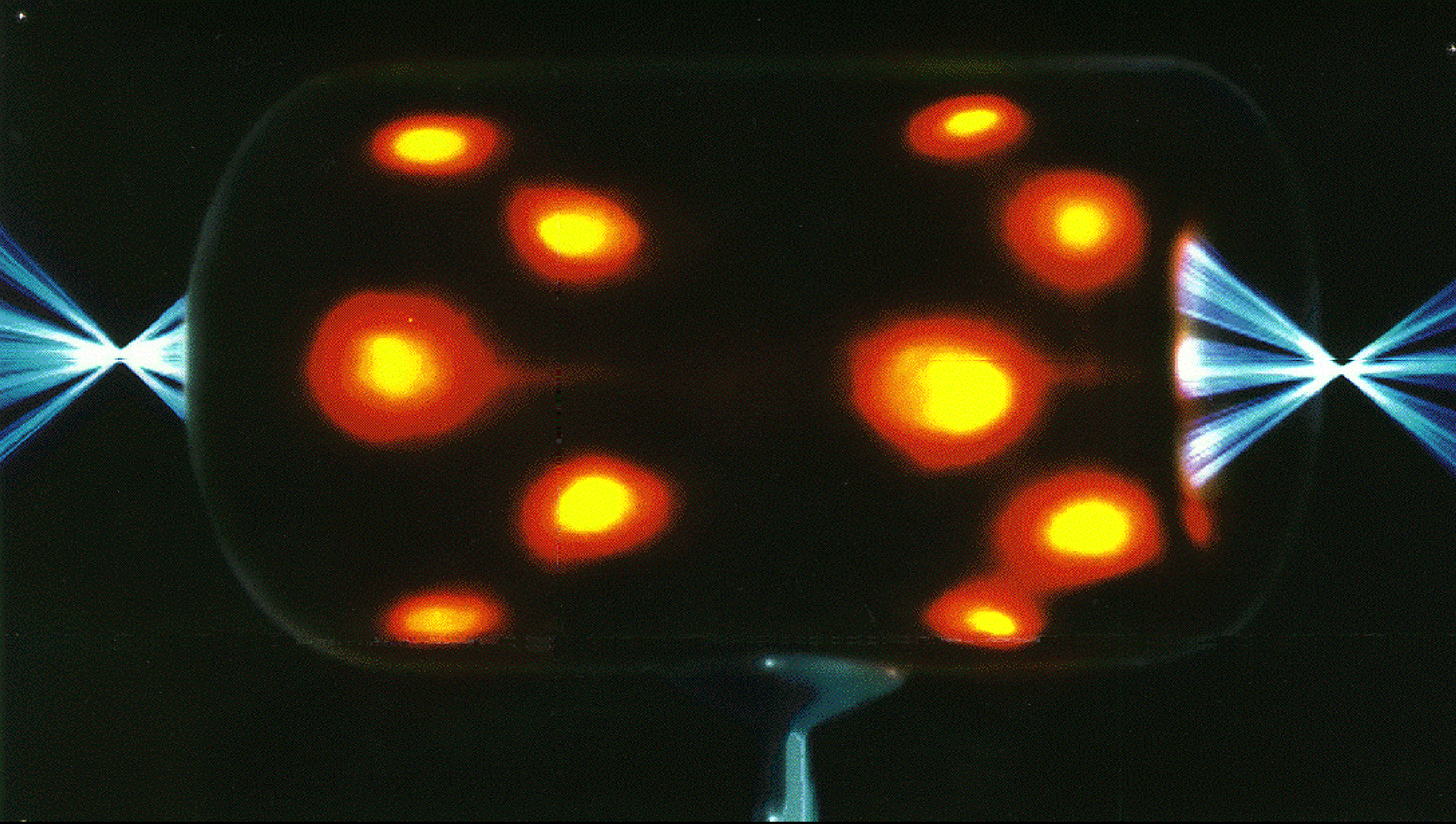
Indirect Drive Lasers



Indirect Drive Heavy Ions

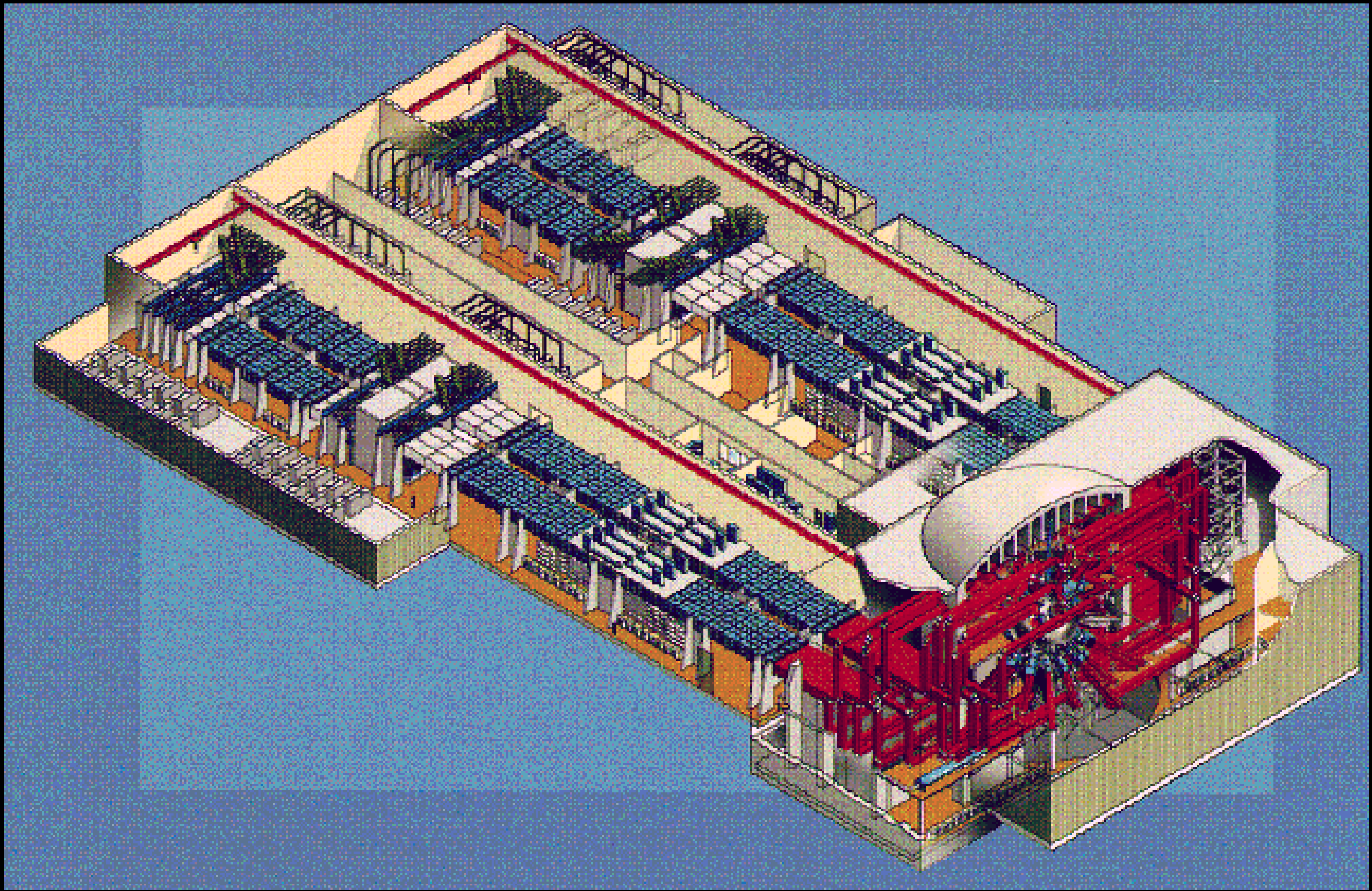


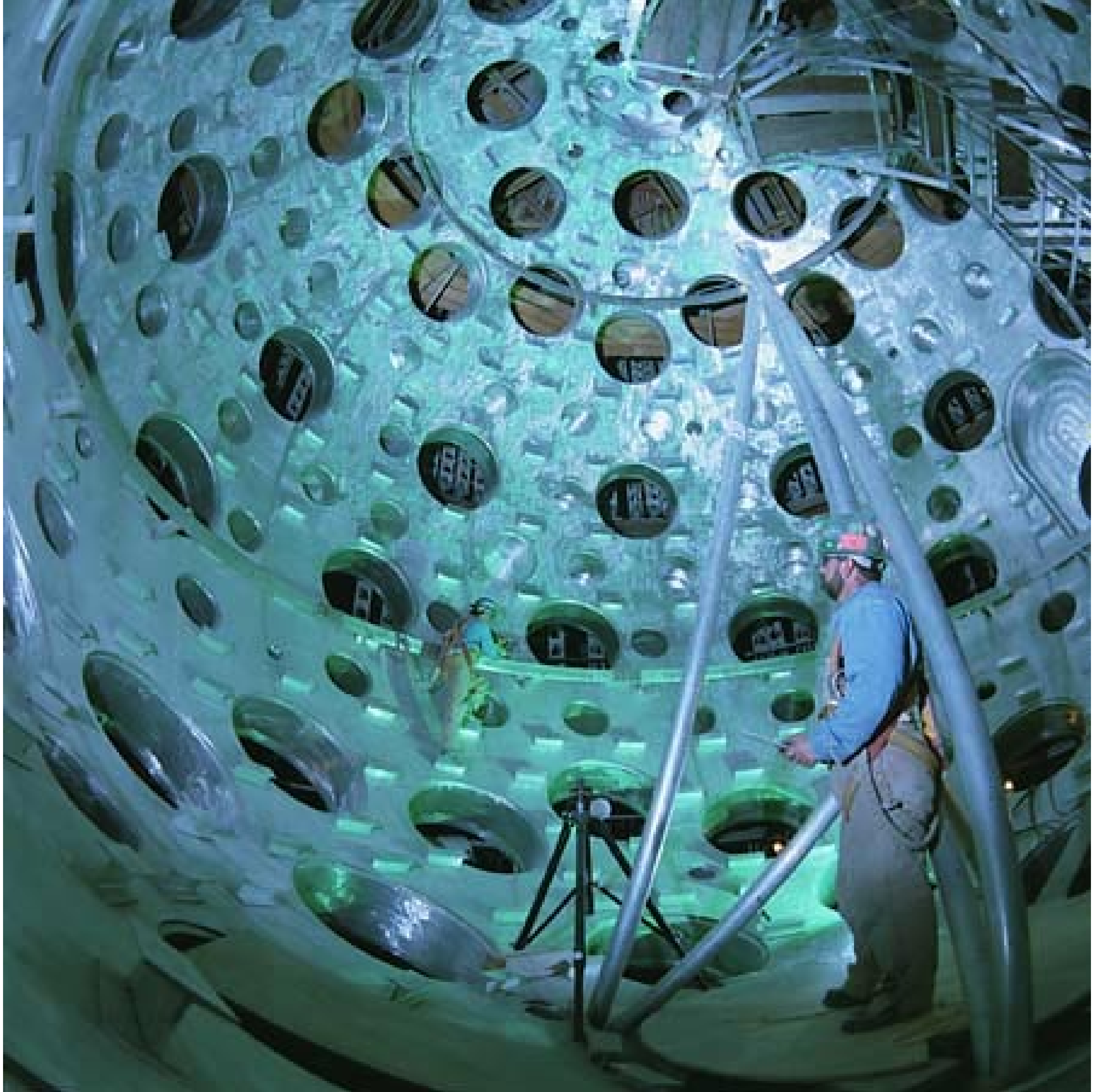
Indirect Drive Light Ions

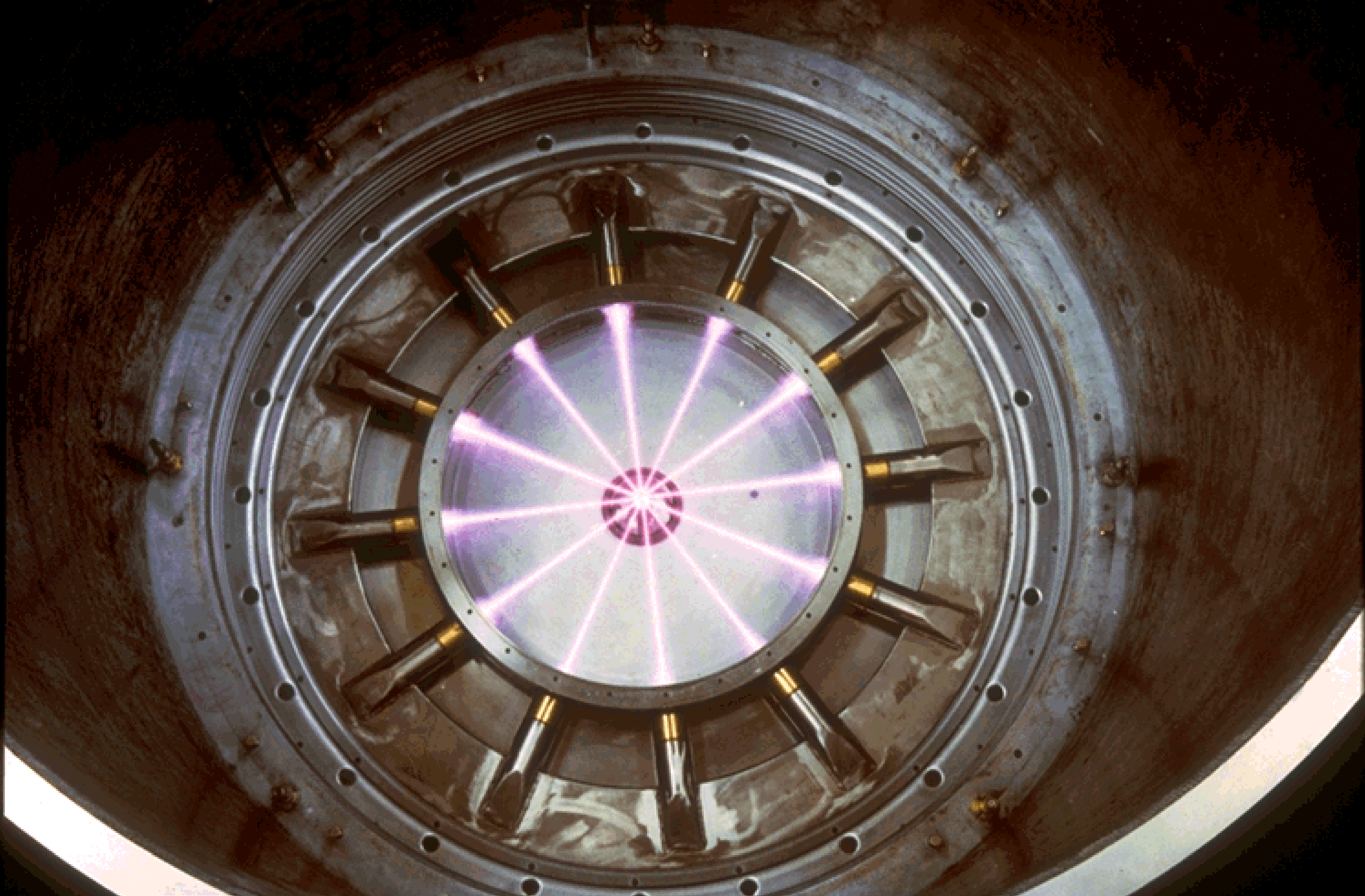


Nova Laser Bay

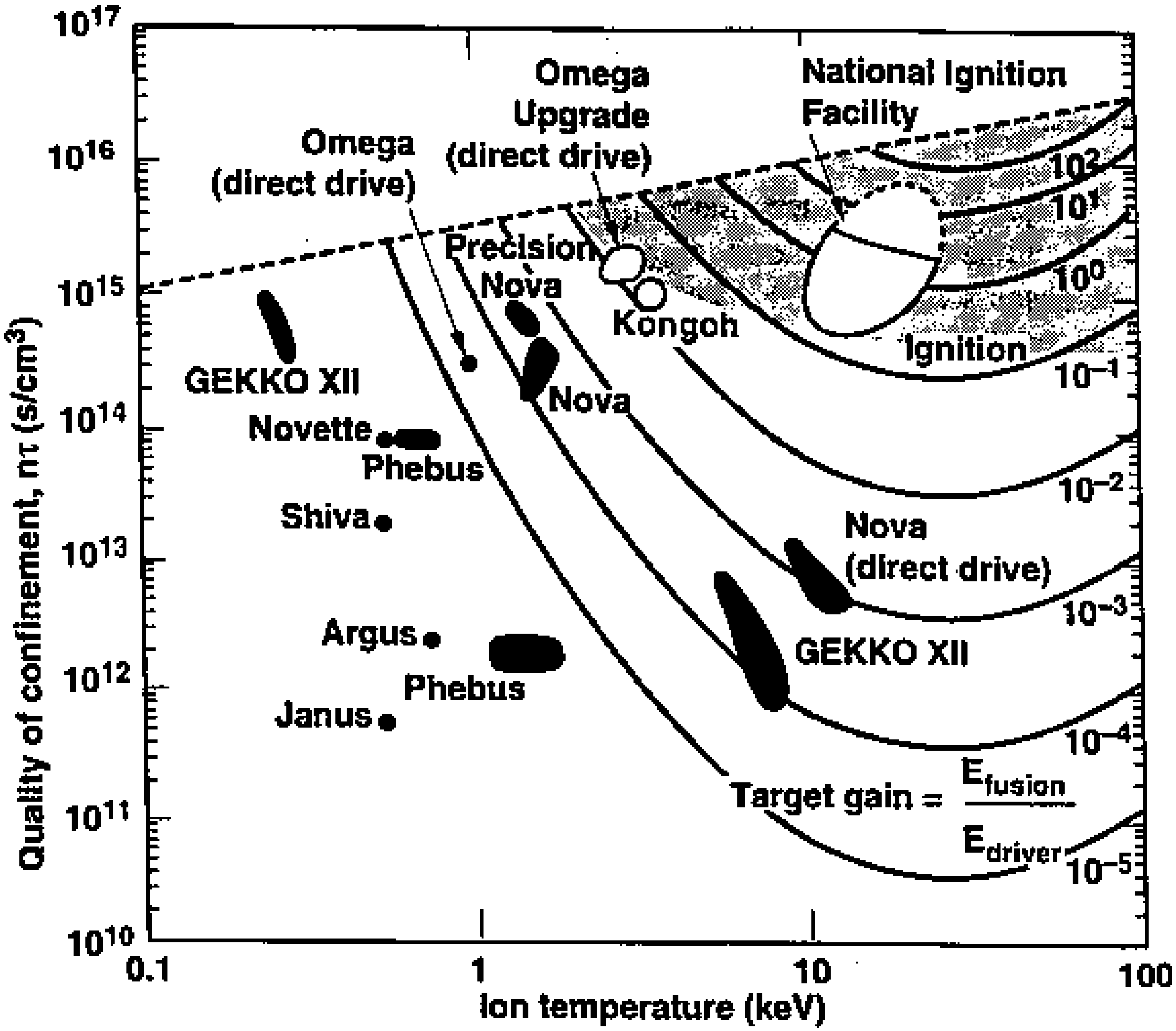
The National Ignition Facility Should Reach Breakeven Conditions in Inertial Confinement Fusion





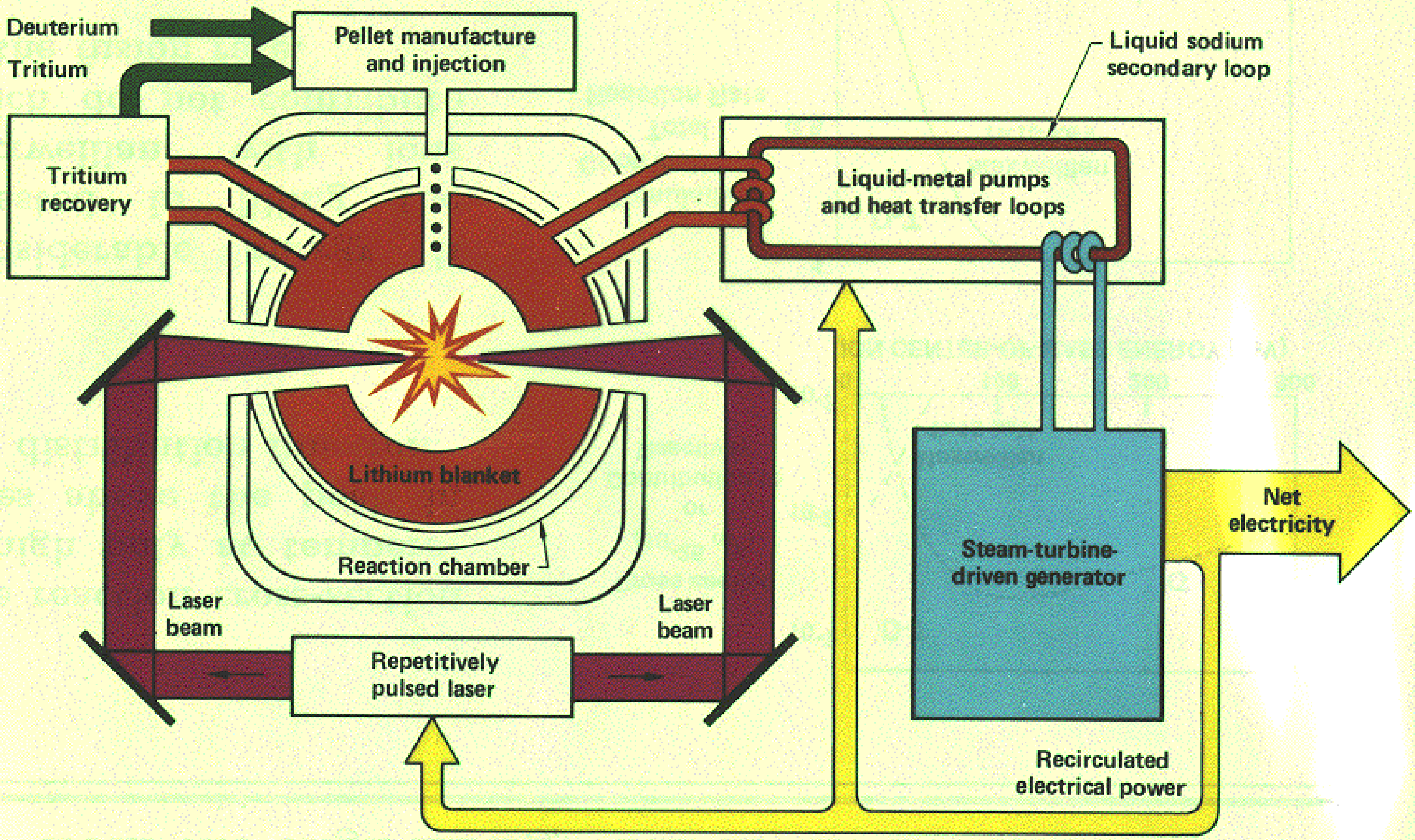


Inertial Confinement Fusion is on the Verge of Ignition and Breakeven

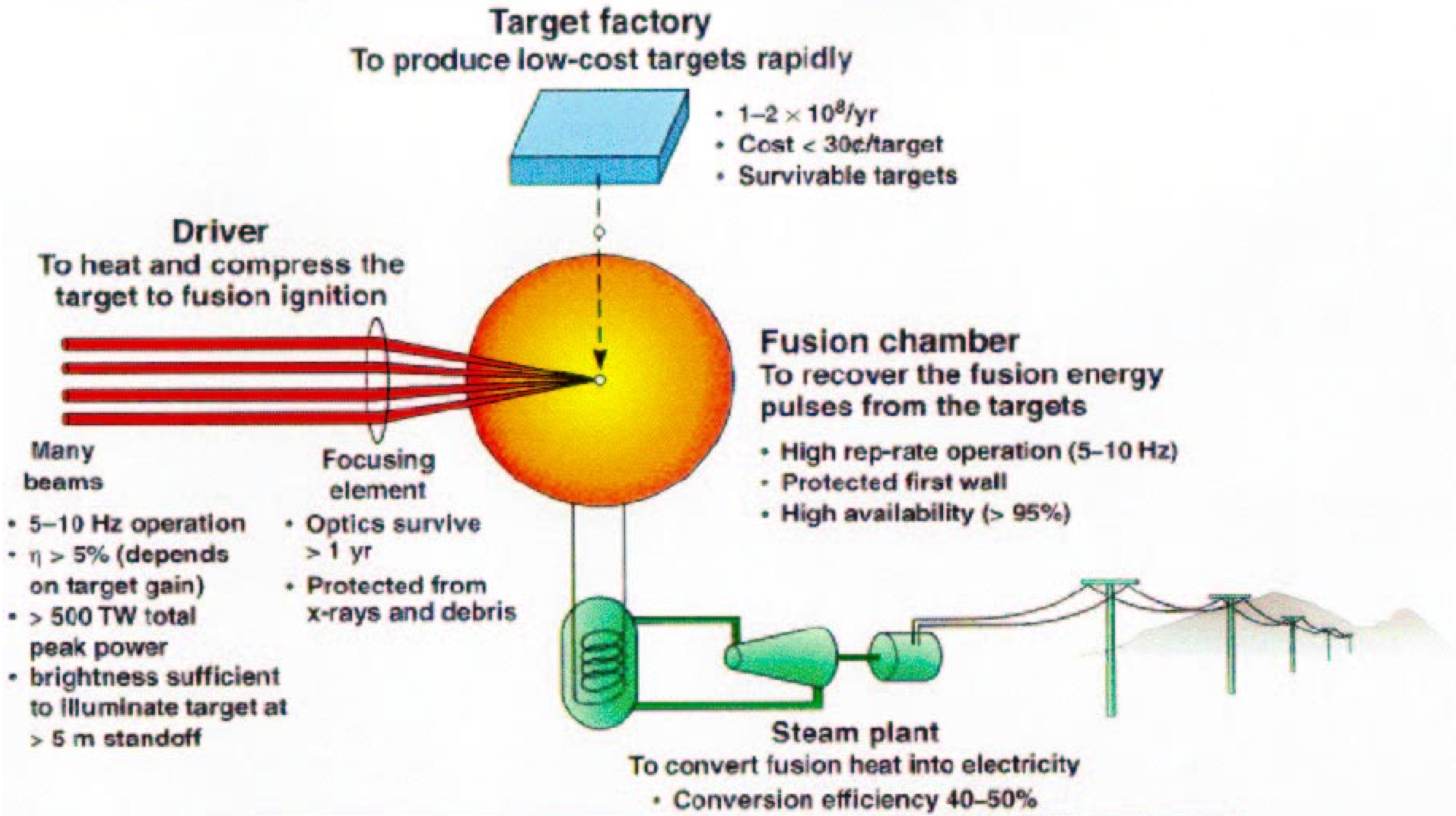


After J. Lindl et. al., 1995, Physics of Plasmas, Vol. 2, No. 11, p. 3933

A FUNCTIONAL DIAGRAM OF A LASER FUSION POWER PLANT



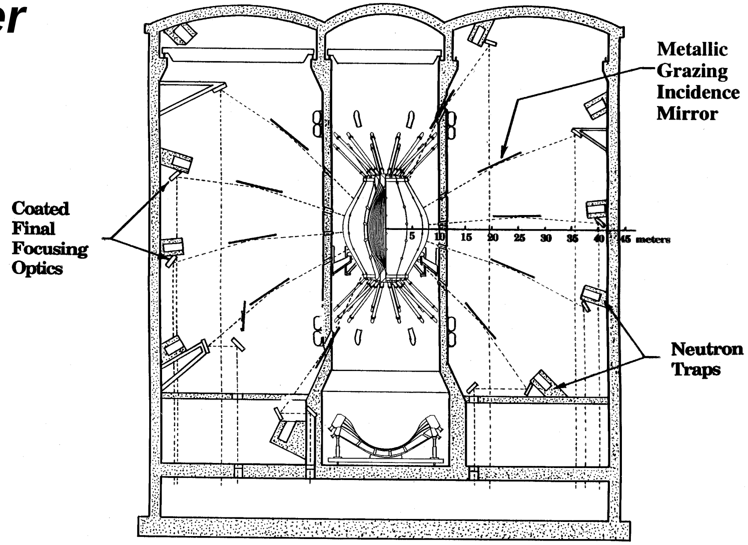
Inertial fusion energy (IFE) power plants of the future will consist of four parts



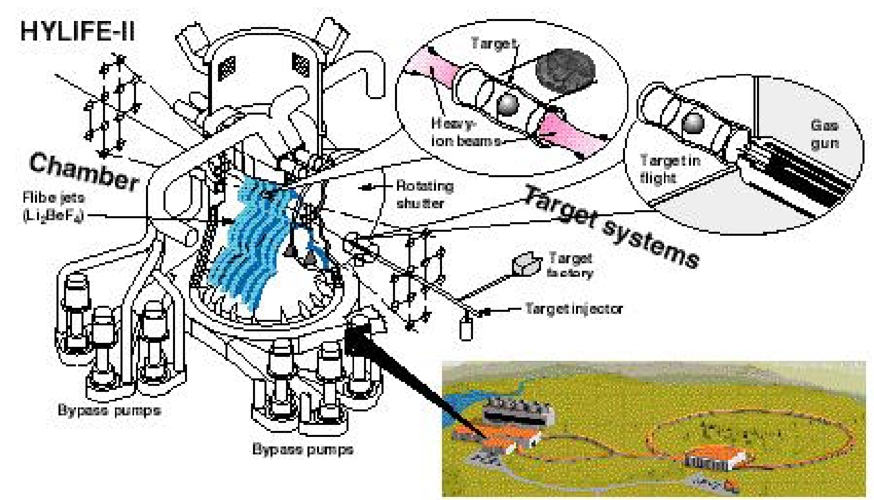
An IFE power-plant would ignite five to ten targets per second to produce as much electricity as today's one gigawatt power plant

There are 4 Current ICF Drivers

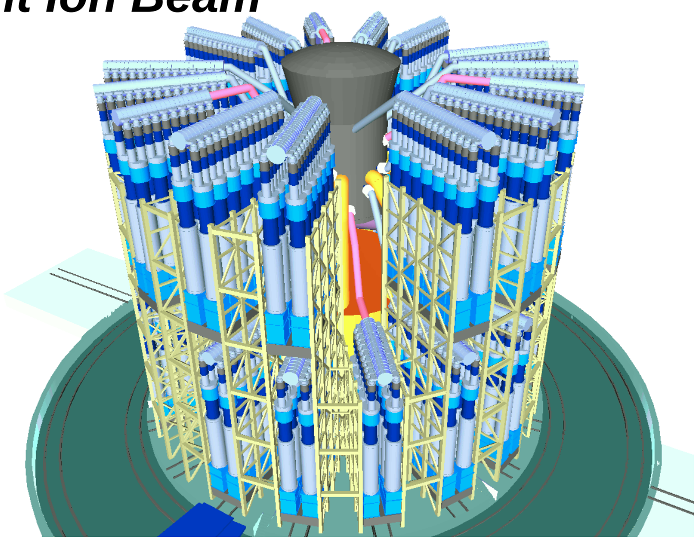
Laser



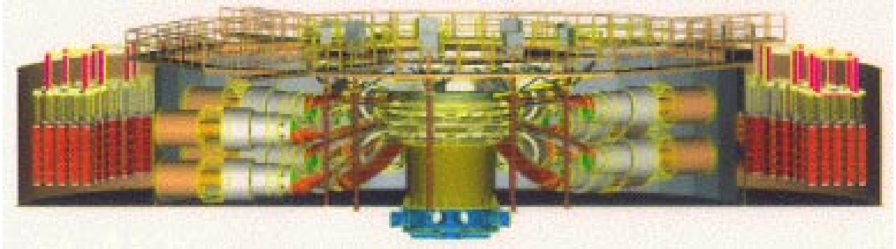
Heavy Ion Beam



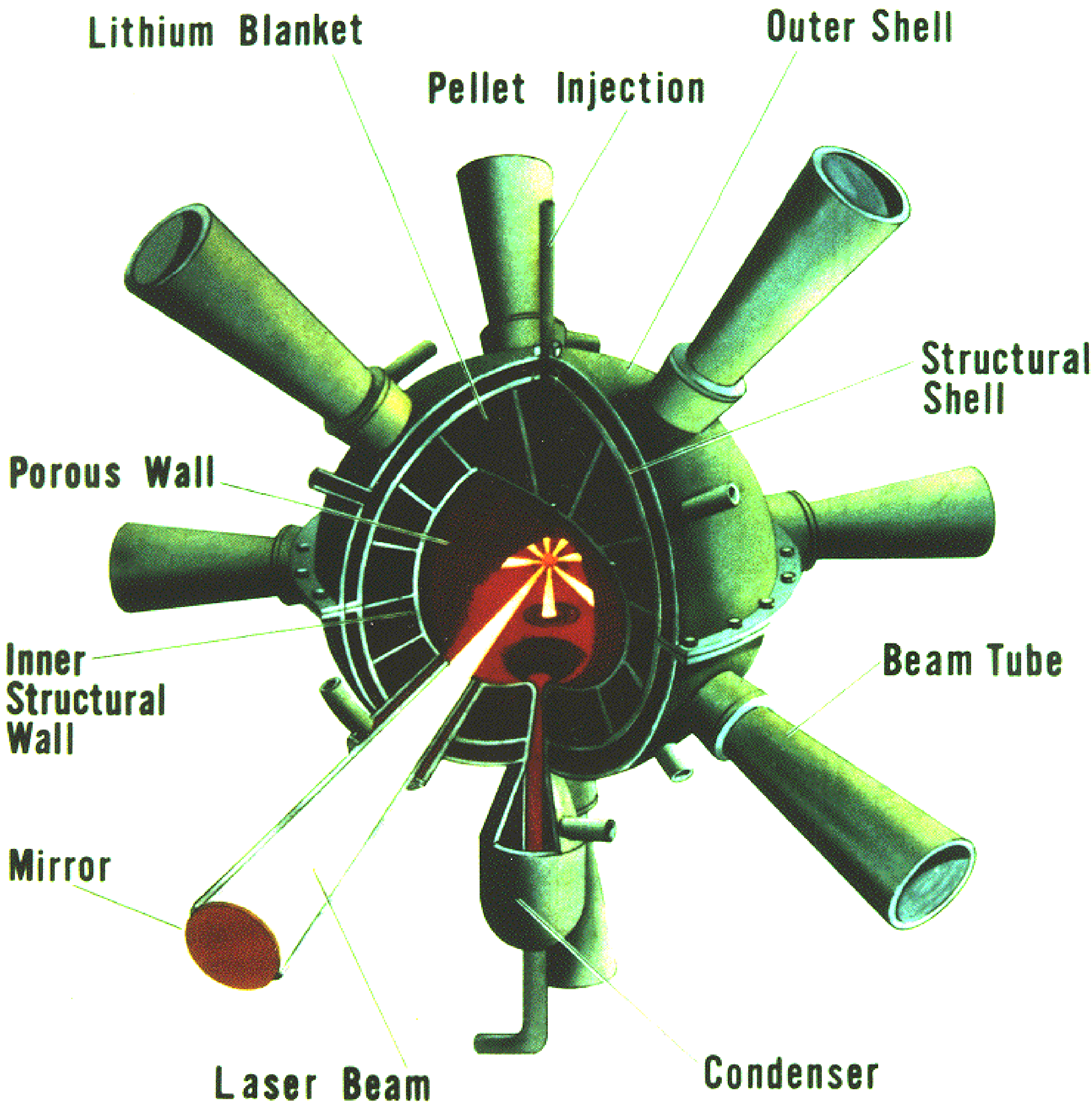
Light Ion Beam

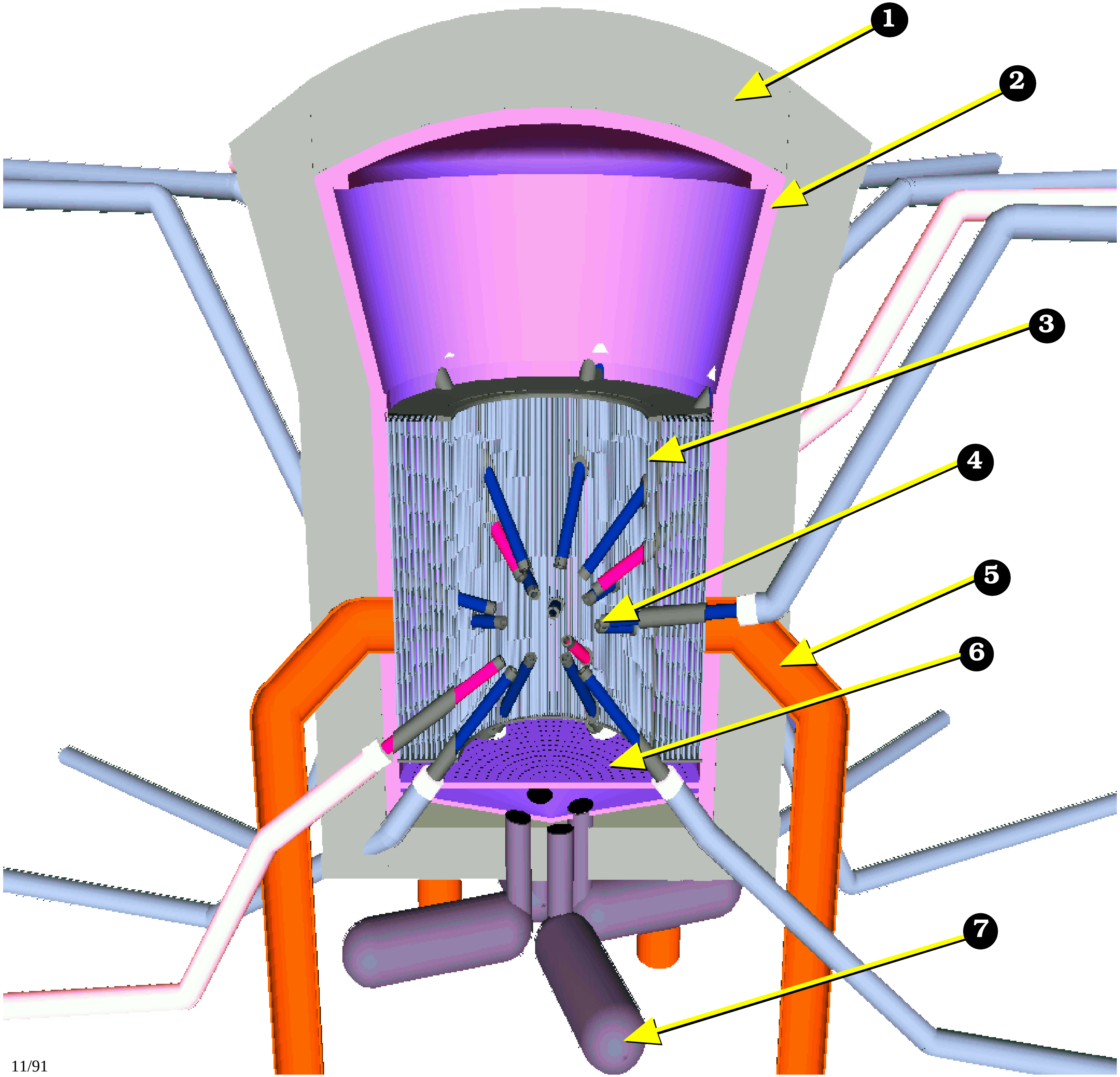


Z-Pinch – Energy application depends on finding a credible rep-rate concept



Light ion development currently on hold due to inability to focus adequately


Lithium Blanket
Outer Shell
Pellet Injection
Structural Shell
Porous Wall
Inner Structural Wall
Beam Tube
Mirror
Laser Beam
Condenser



LIBRA-LiTE

Side View Reactor Chamber Cutaway

(1) Shield

(2) Reflector / vacuum chamber

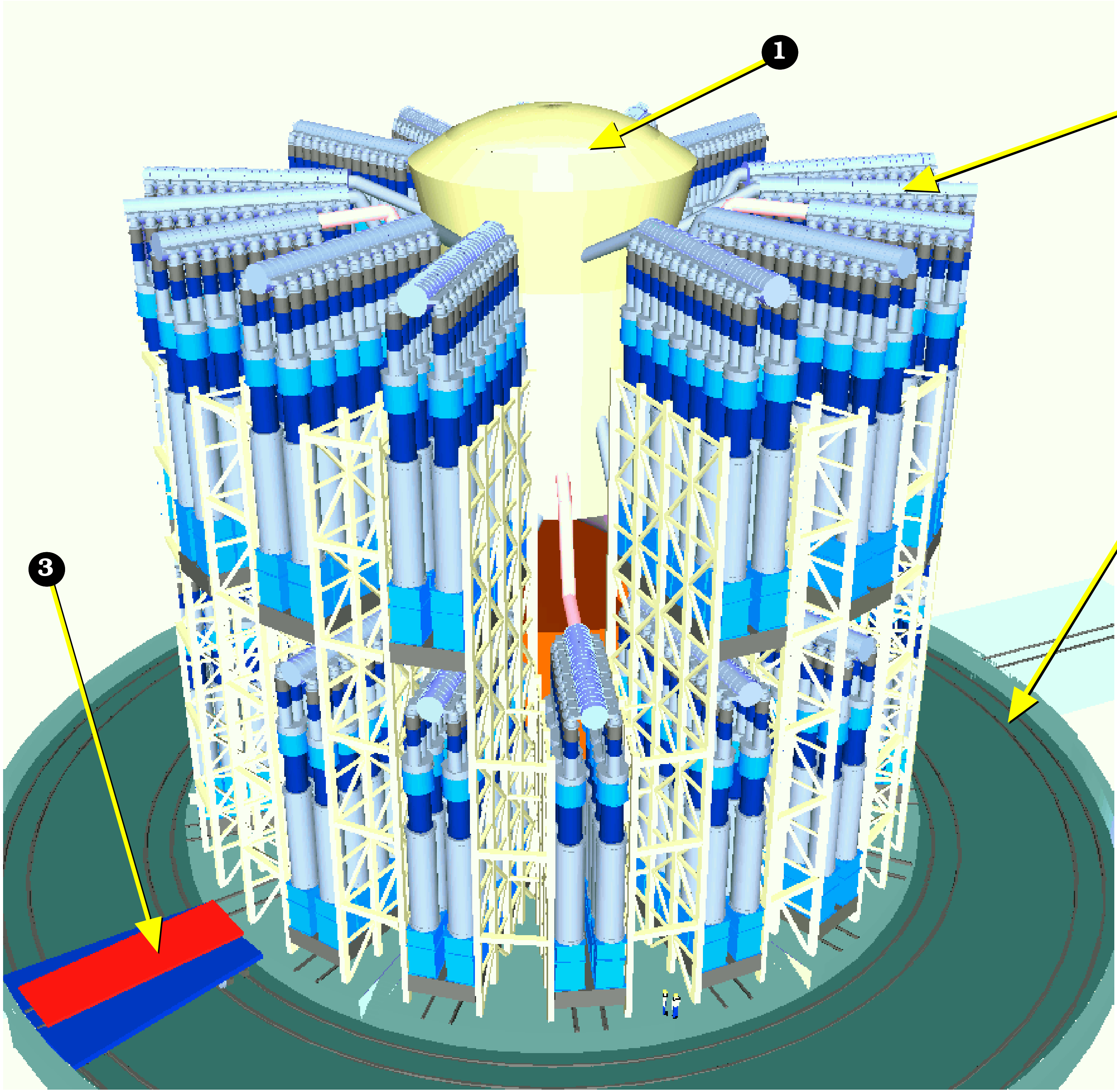
(3) INPORT units

(4) Final focus magnet

(5) Vacuum line

(6) Perforated plate

(7) IHX



LIBRA-LiTE

View of Reactor from Inside Containment Building

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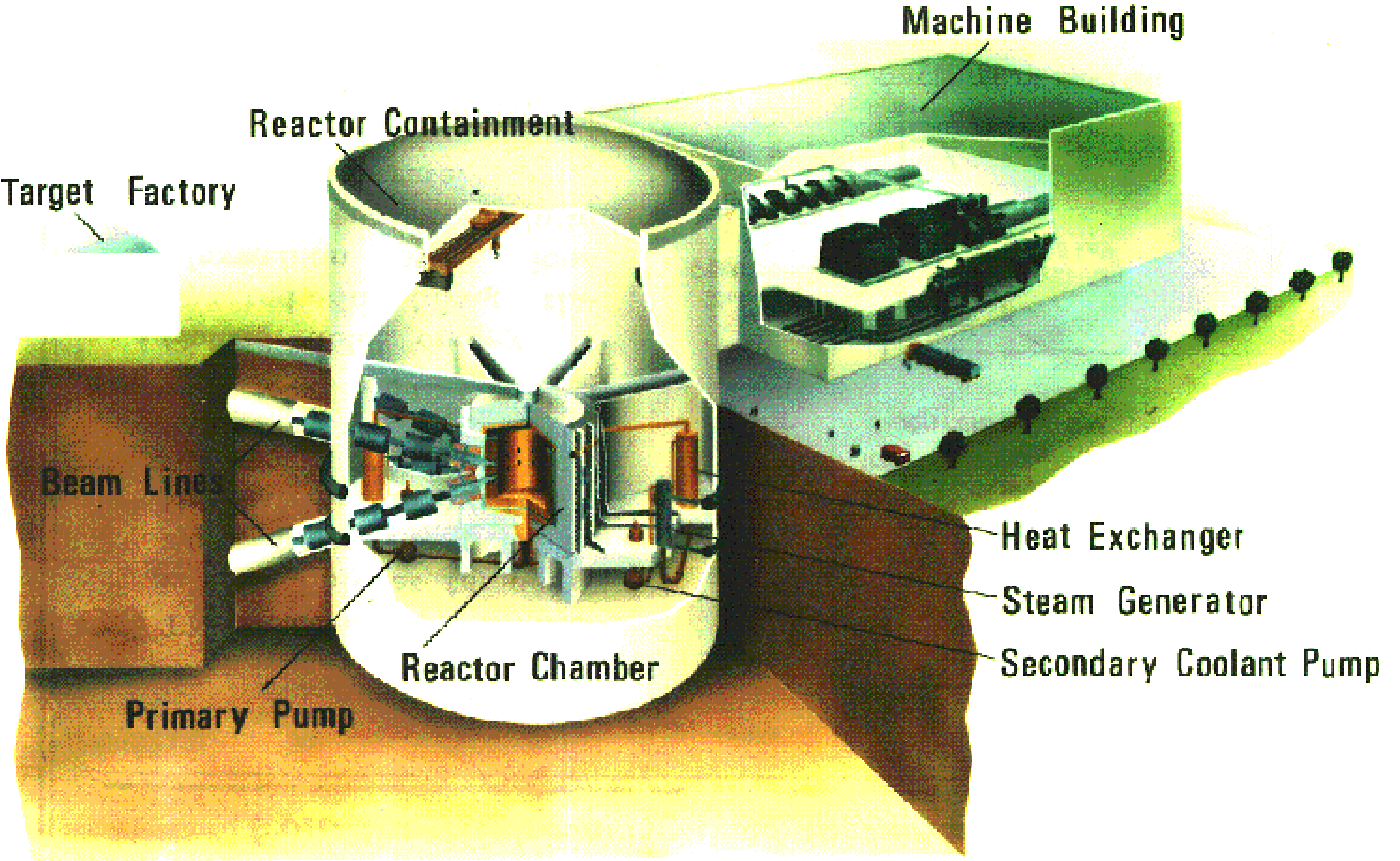
(1) Reactor chamber

(2) Driver

(3) Transport carriage

(4) Circumferential rails



HIBALL REACTOR BUILDING 940 MW_{el}

Conclusions

- There is a substantial world research program ($\approx$ 2 \$B/y) to harness Fusion as a major energy source in the 21st Century
- While most of the world program is concentrated on magnetically confined plasmas, the inertial fusion program will probably reach ignition and breakeven first.
- Both inertial and magnetic confinement approaches are concentrating on the DT fuel cycle
- Advanced fusion fuel cycles will require a different approach