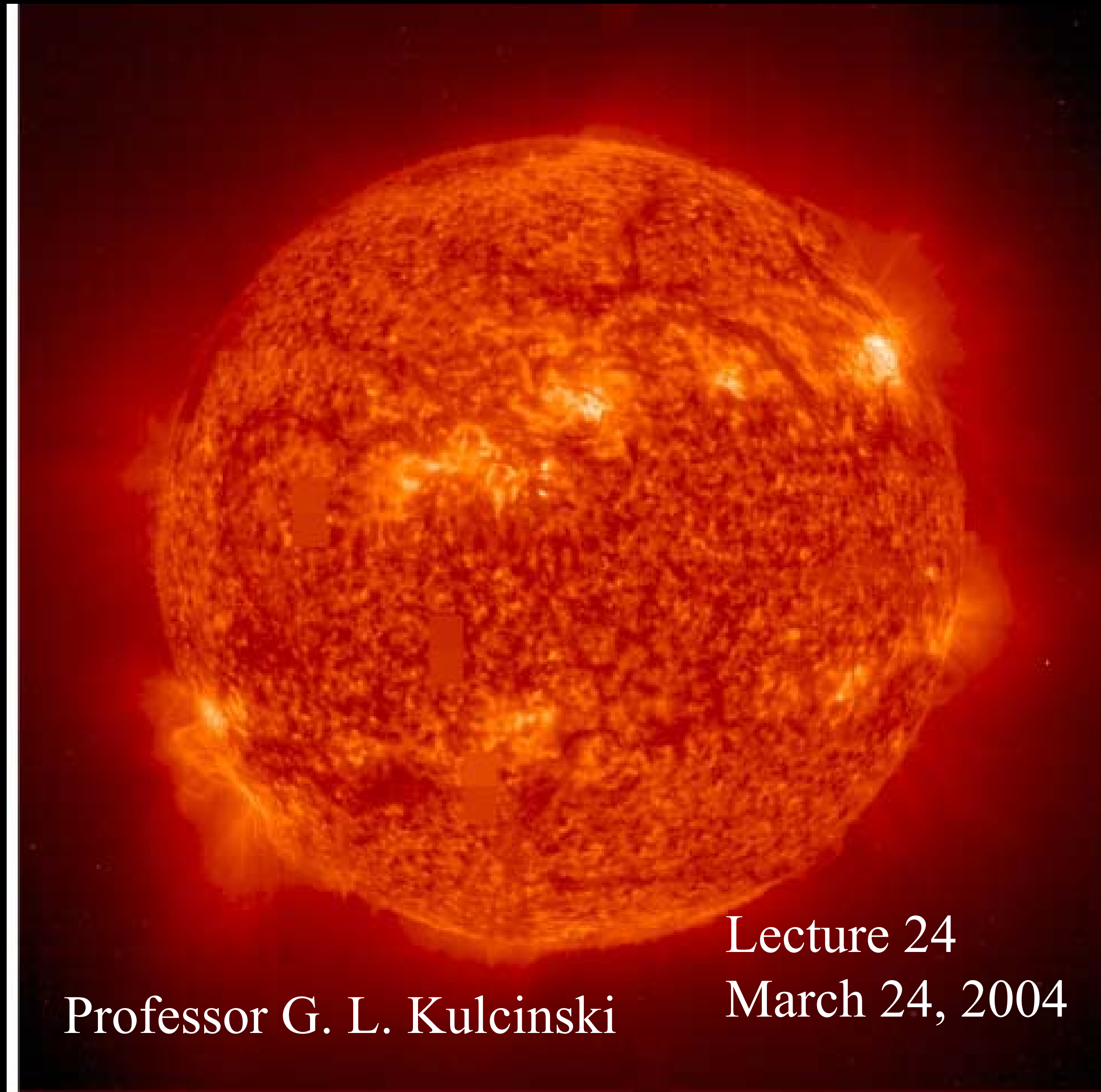
Principles of Fusion Energy



Professor G. L. Kulcinski

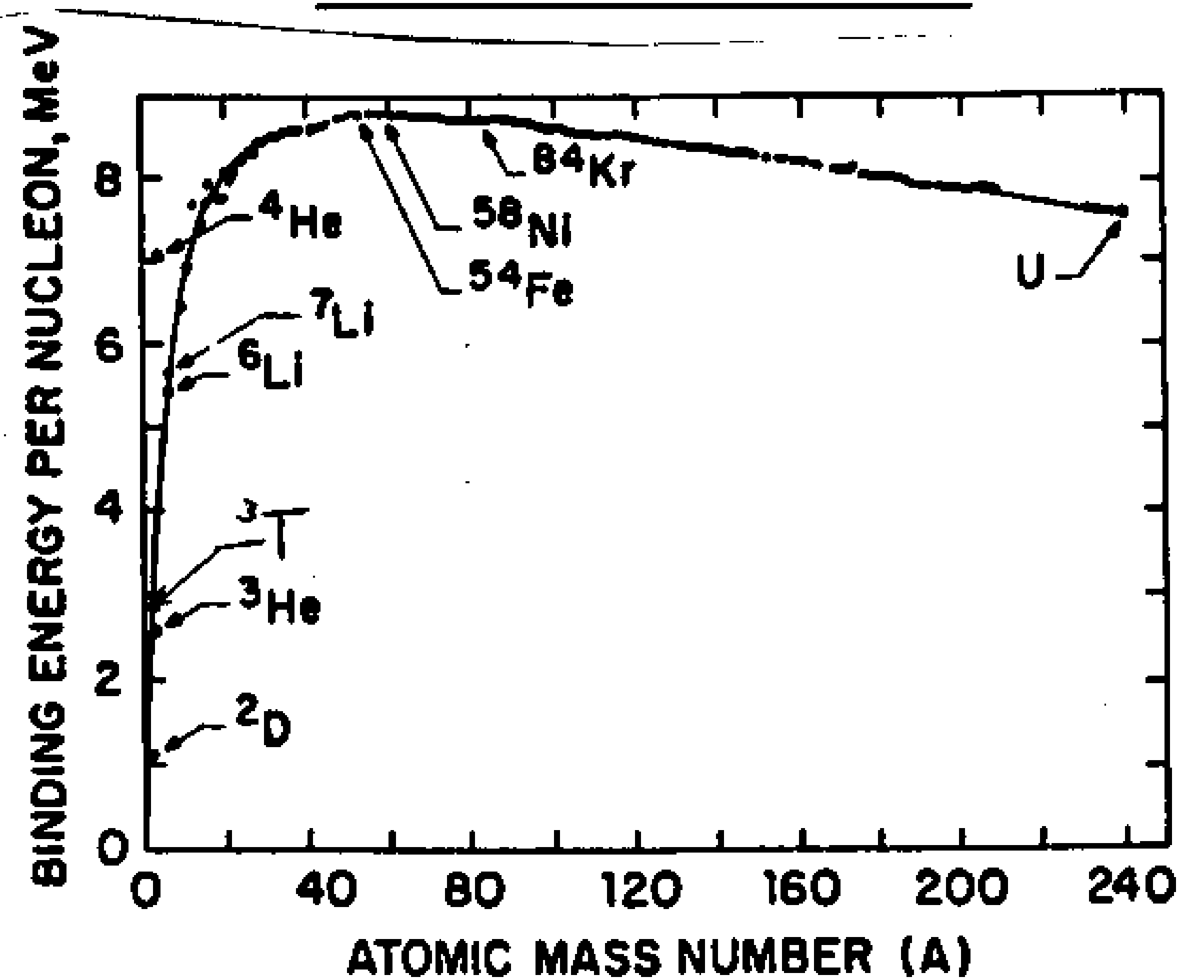
Lecture 24
March 24, 2004

Where Are We Now With Respect to Future Energy Supplies?

- Sometime in the mid-21st century the World will need a new source of safe, clean, and economical energy to replace fossil fuels

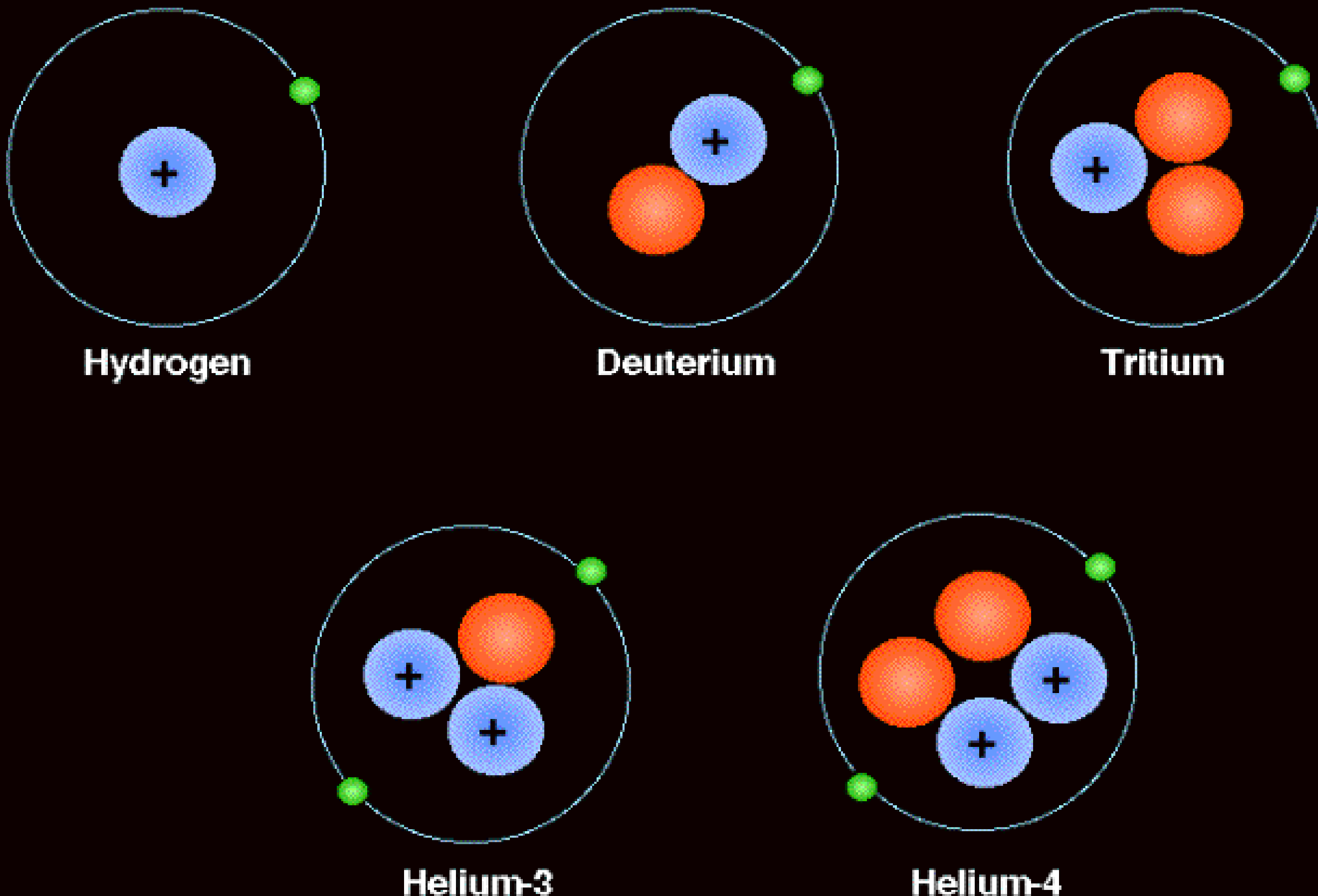
- The question now is will that energy be mainly fission or fusion?

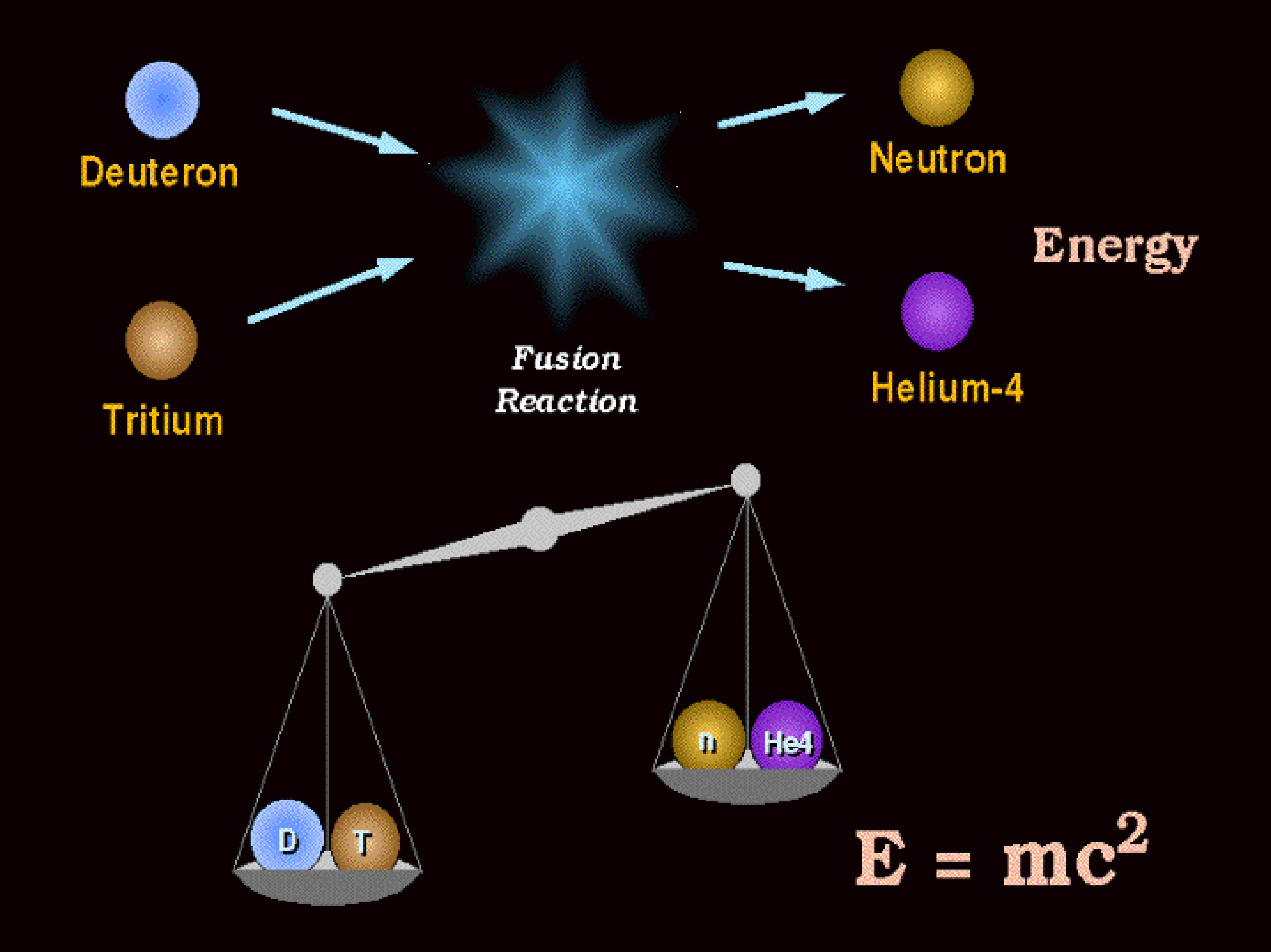
The Binding Energy Per Nucleon Increases When Heavy Elements are Fissioned and When Light Elements are Fused



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

Nuclear Structure of Important Light Isotopes




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

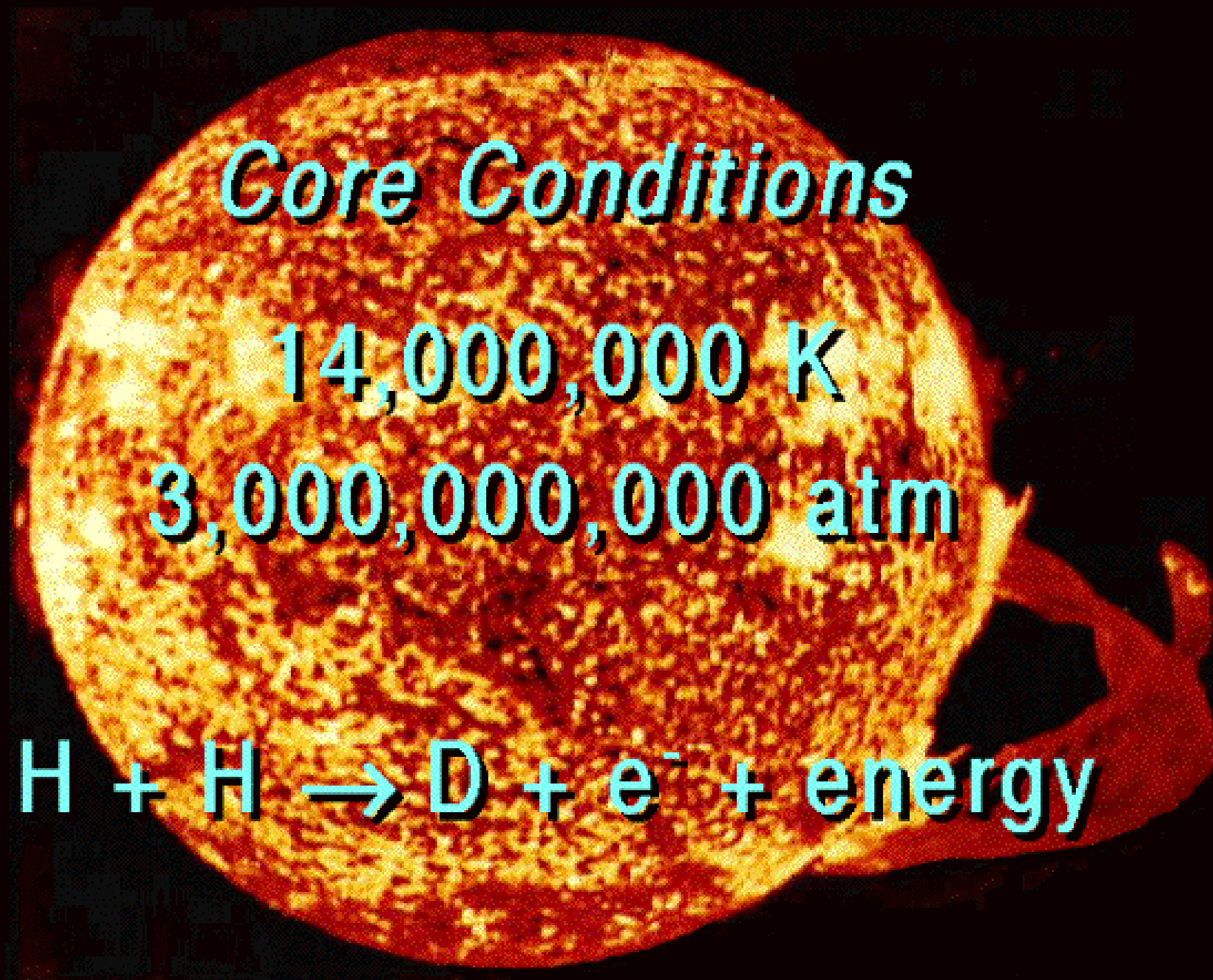
How do We Make Atoms Fuse?

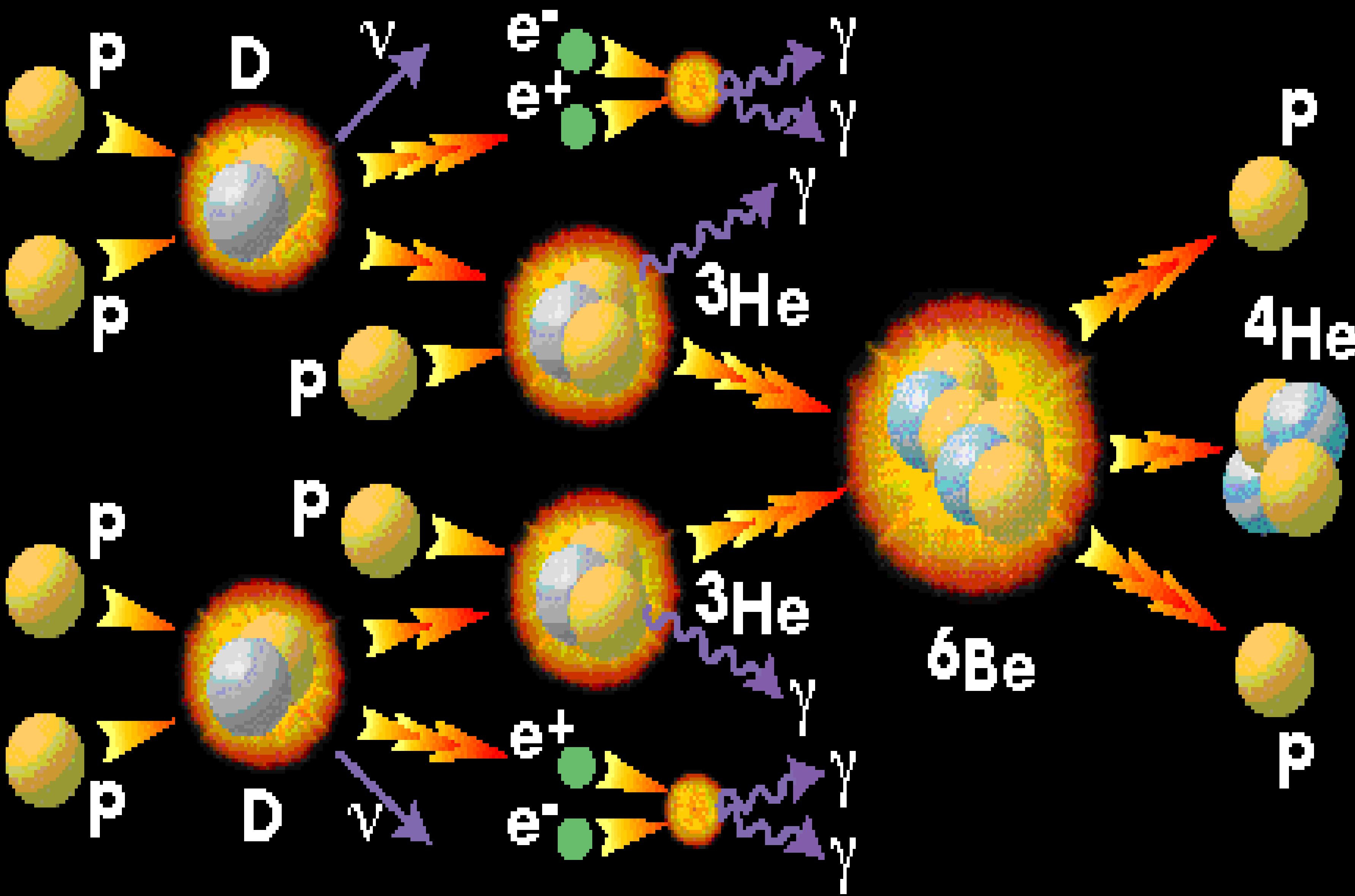
- Placing them under very high pressures at high temperature.
  - Gravity
  - Inertial confinement

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

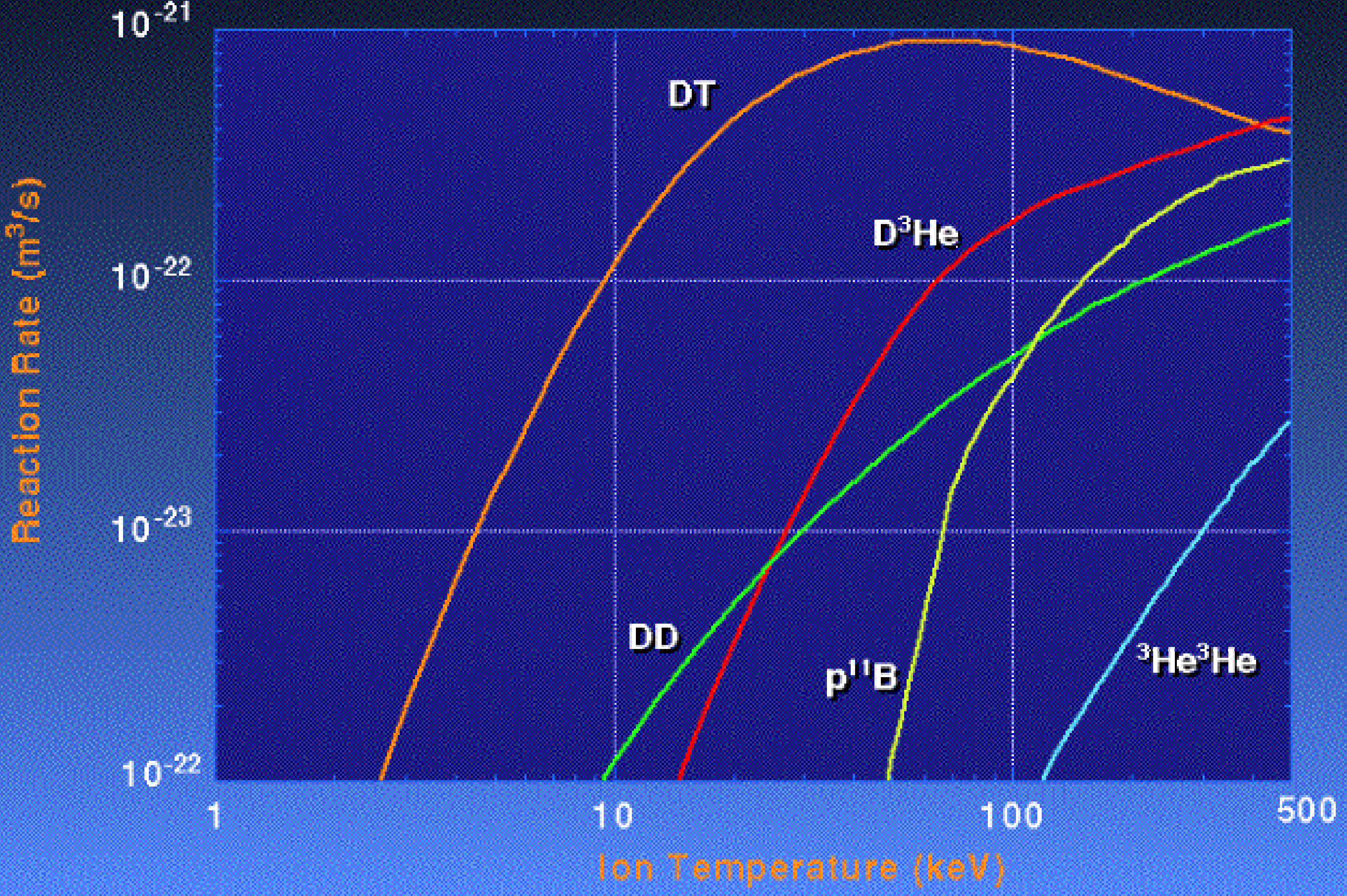
- Acceleration into each other at high velocities.
  - Electrostatic confinement

The Sun is a Very Efficient Fusion Reactor

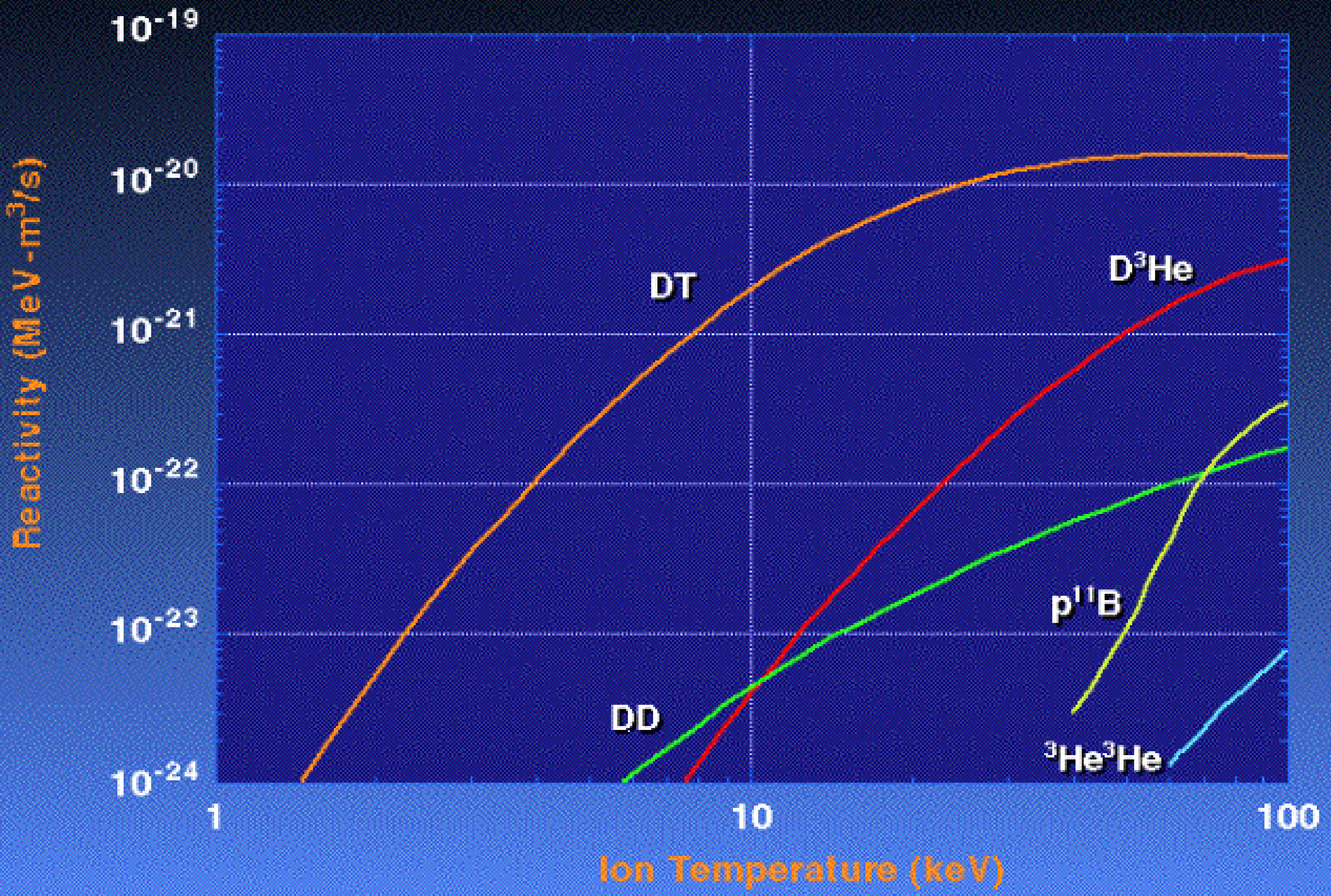


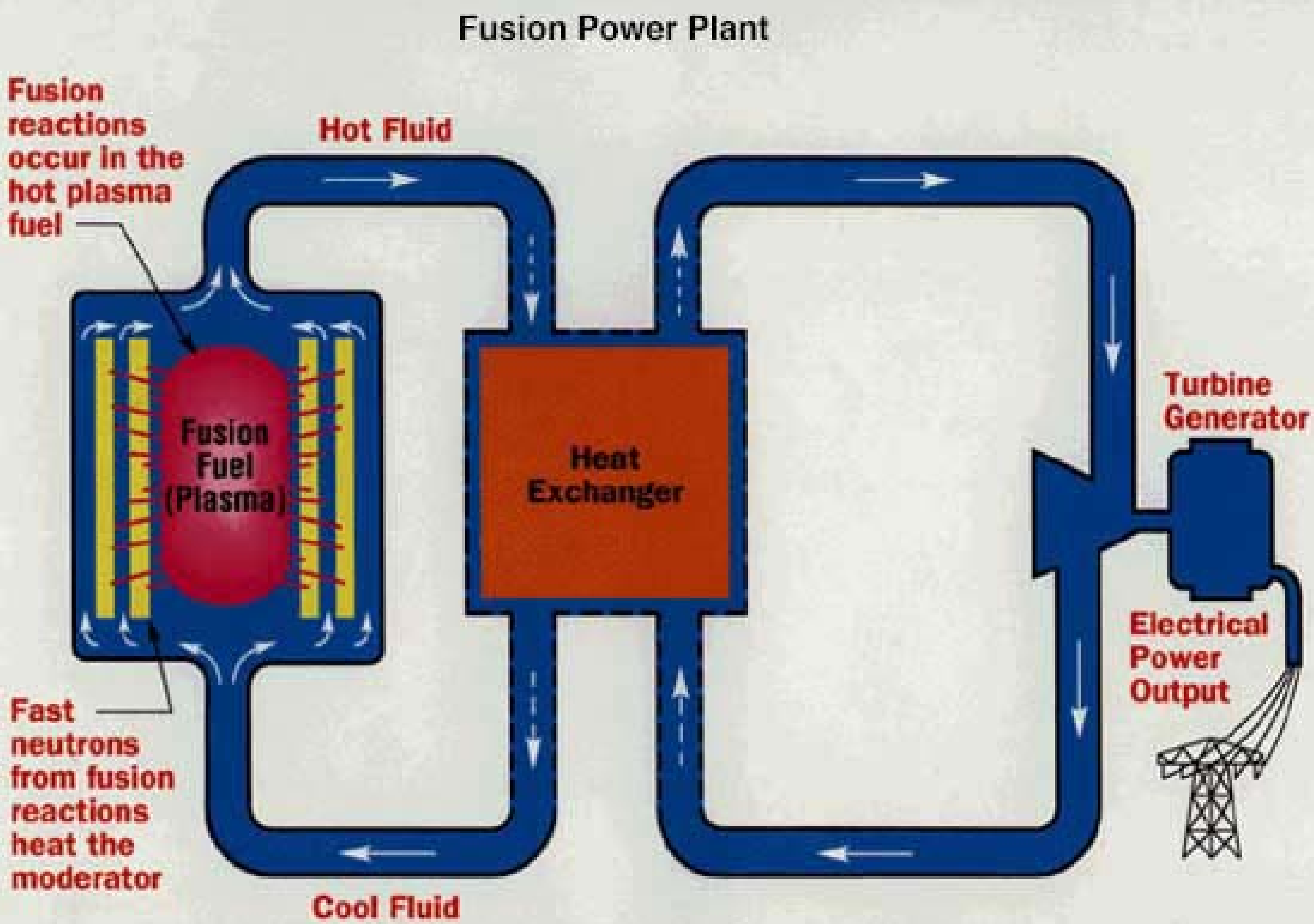

p
D
ν
e-
e+
γ
γ
p
γ
3He
p
4He
p
6Be
p
3He
γ
p
D
ν
e+
e-
γ
γ
p
p

Maxwellian Fusion Reaction Rates

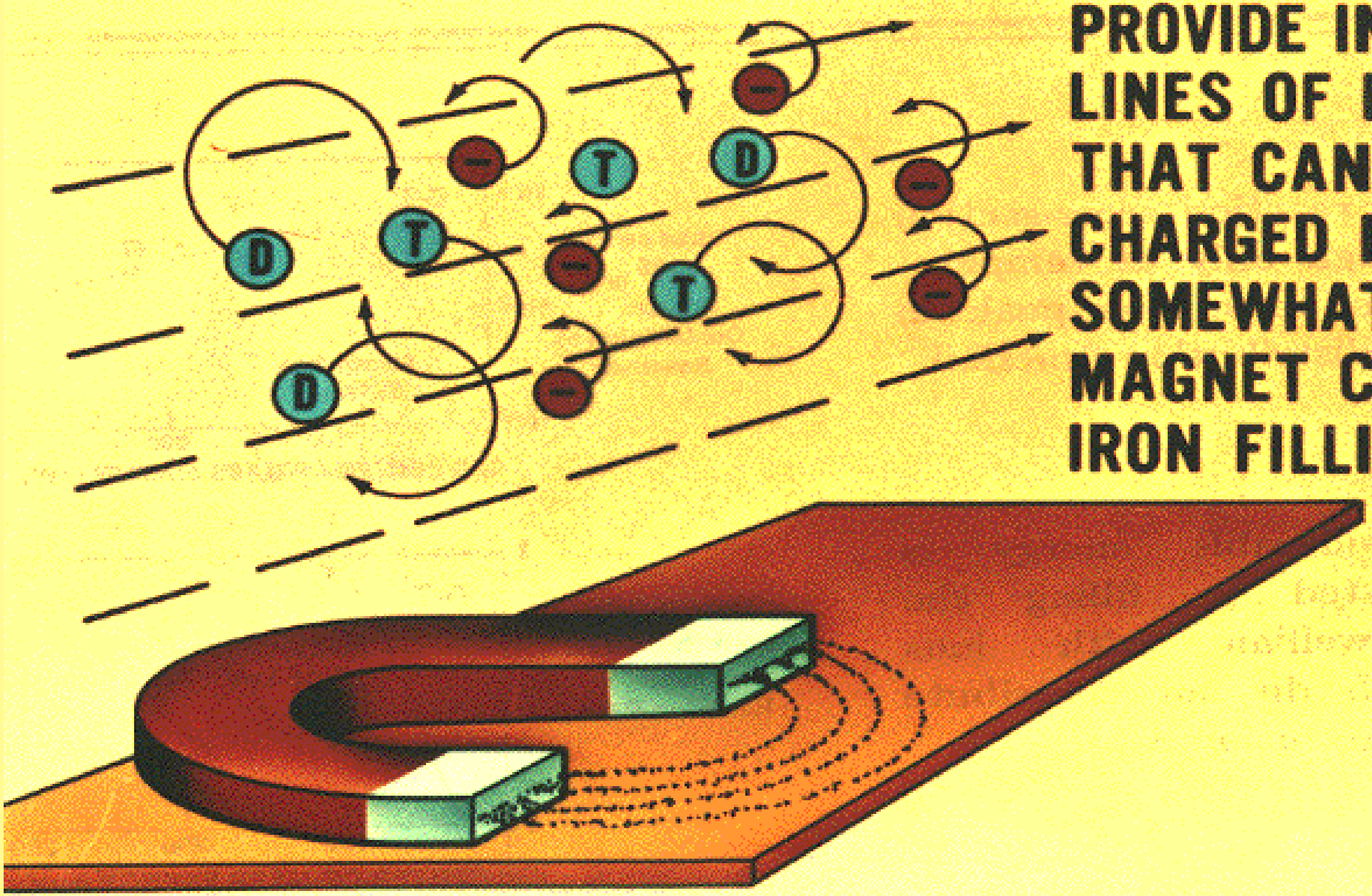


Maxwellian Fusion Reactivities ($\Sigma E_{fus}\sigma v$)




Fusion Power Plant
Fusion reactions occur in the hot plasma fuel
Hot Fluid
Fusion Fuel (Plasma)
Heat Exchanger
Turbine Generator
Electrical Power Output
Fast neutrons from fusion reactions heat the moderator
Cool Fluid

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



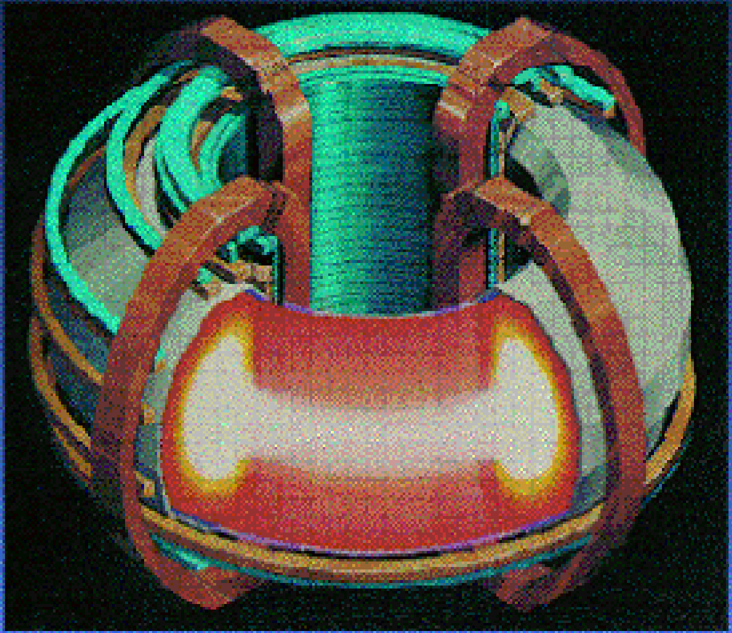
Where Do We Get Deuterium and Tritium From?

- 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

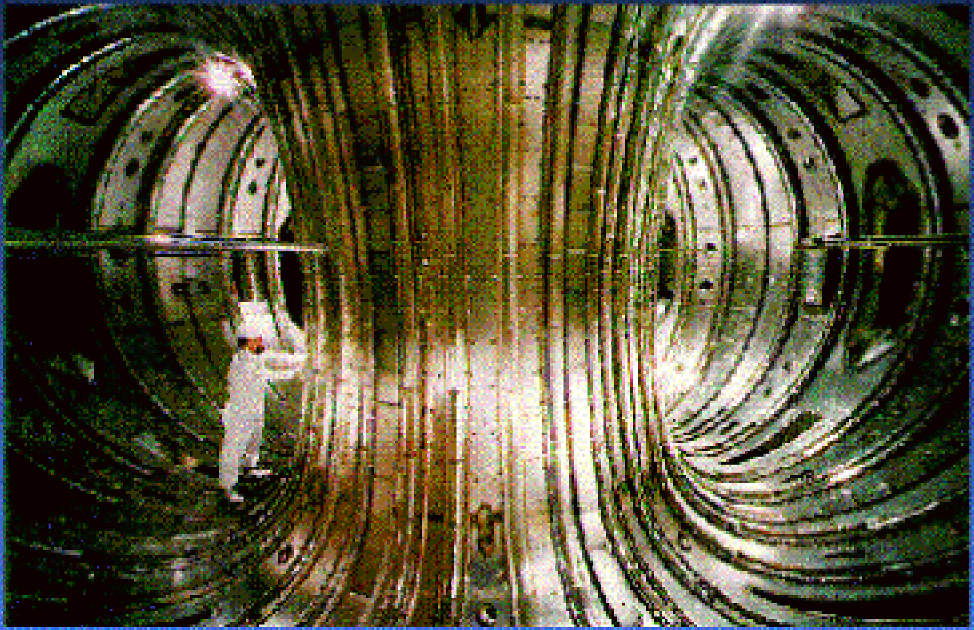
- Tritium:
  - Radioactive isotope-12.3 year half life
    - $^{3}H_{1} \text{---}> {}^{3}He_{2} + e^{-} + 28$ keV
  - Made from Li bombarded by neutrons
    - $^{1}n_{0} + {}^{6}Li_{3} \text{--}> {}^{4}He_{2} + {}^{3}H_{1} + 4.8$ MeV
    - $^{1}n_{0} + {}^{7}Li_{3} \text{--}> {}^{4}He_{2} + {}^{3}H_{1}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

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

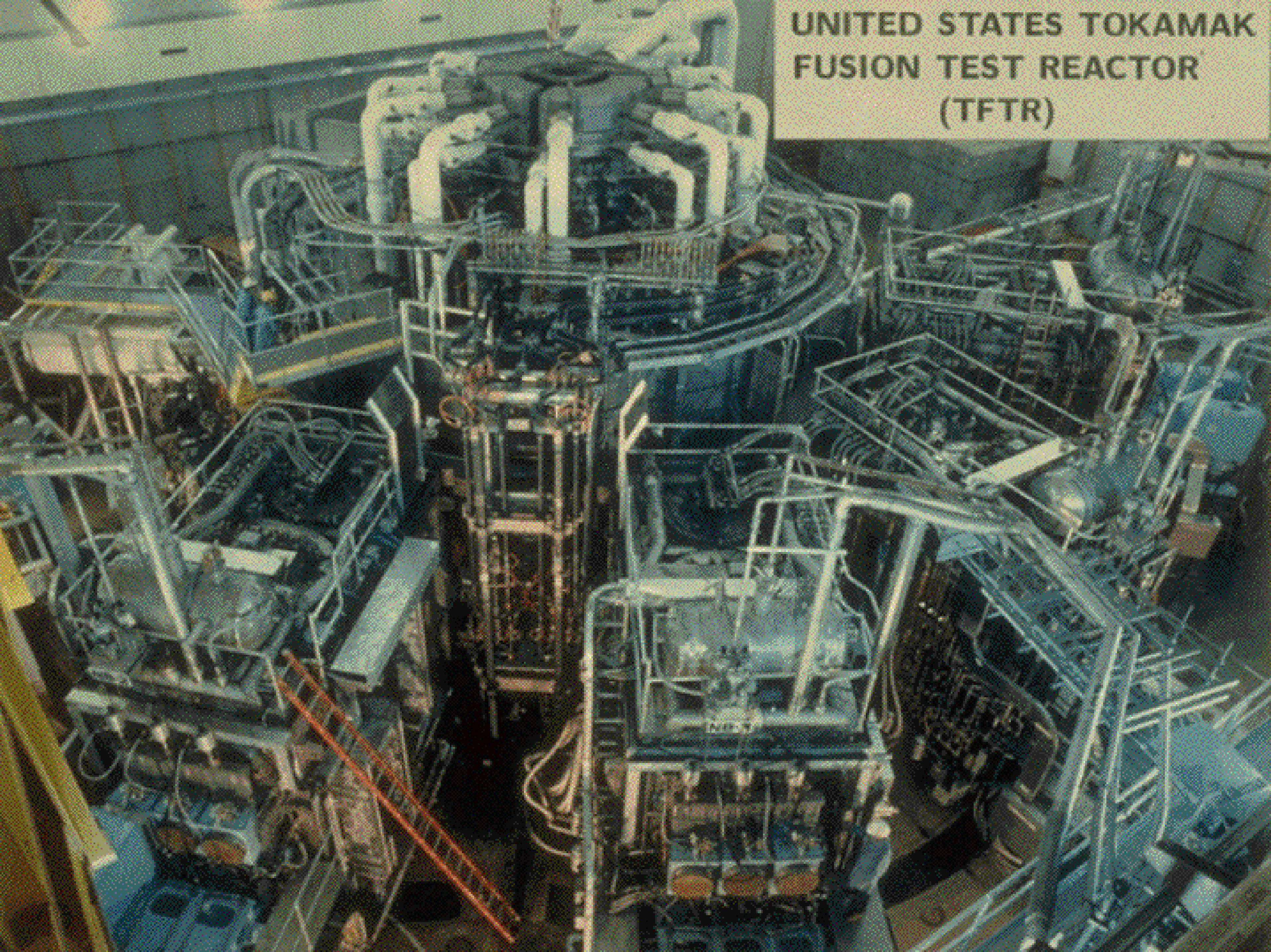
D + T –> n (14 MeV) + ^{4}He (3.5 MeV)

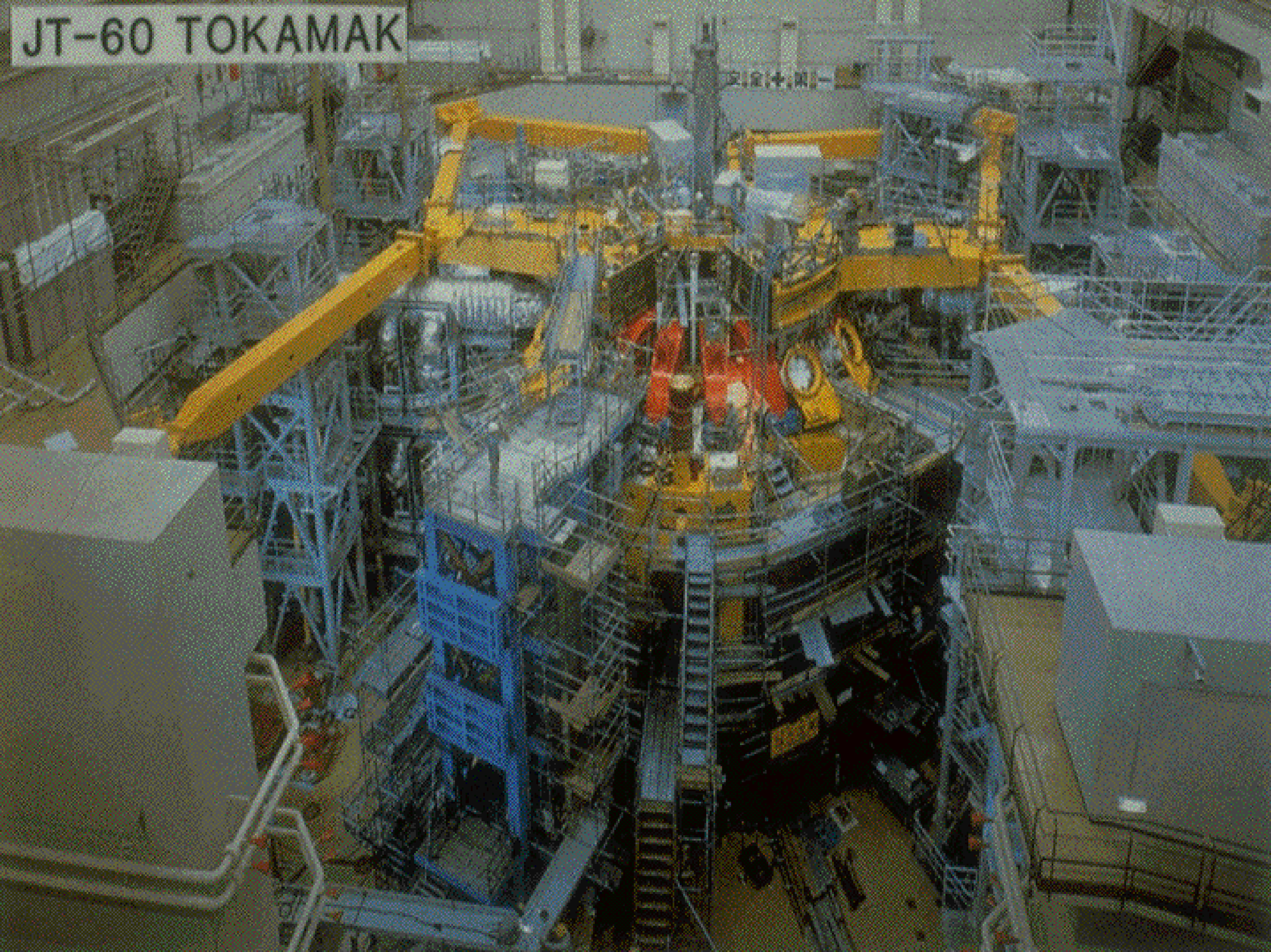


Schematic of a Tokamak

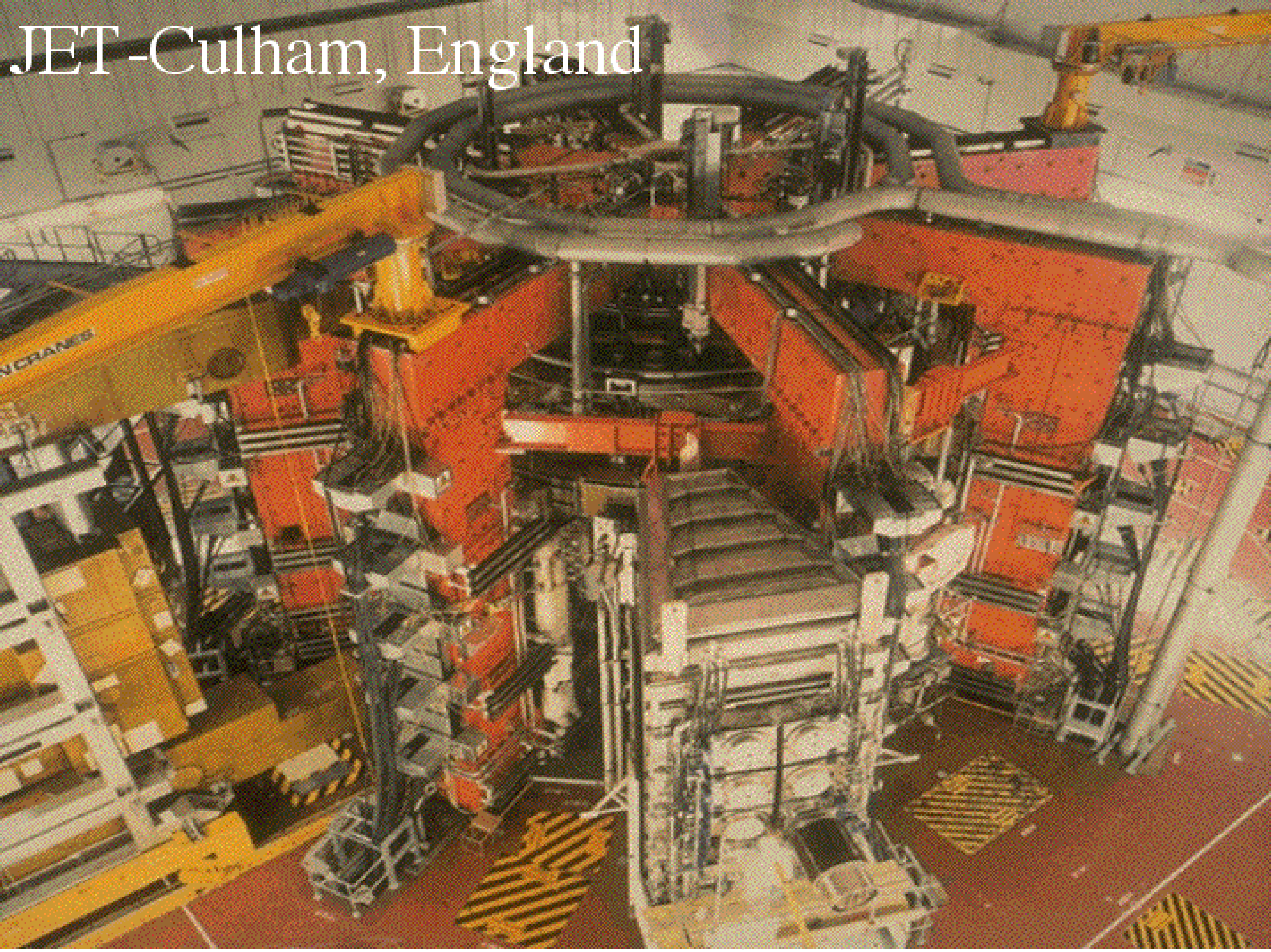


Joint European Torus – JET
~ 40 MW


UNITED STATES TOKAMAK
FUSION TEST REACTOR
(TFTR)


JT-60 TOKAMAK

JET-Culham, England



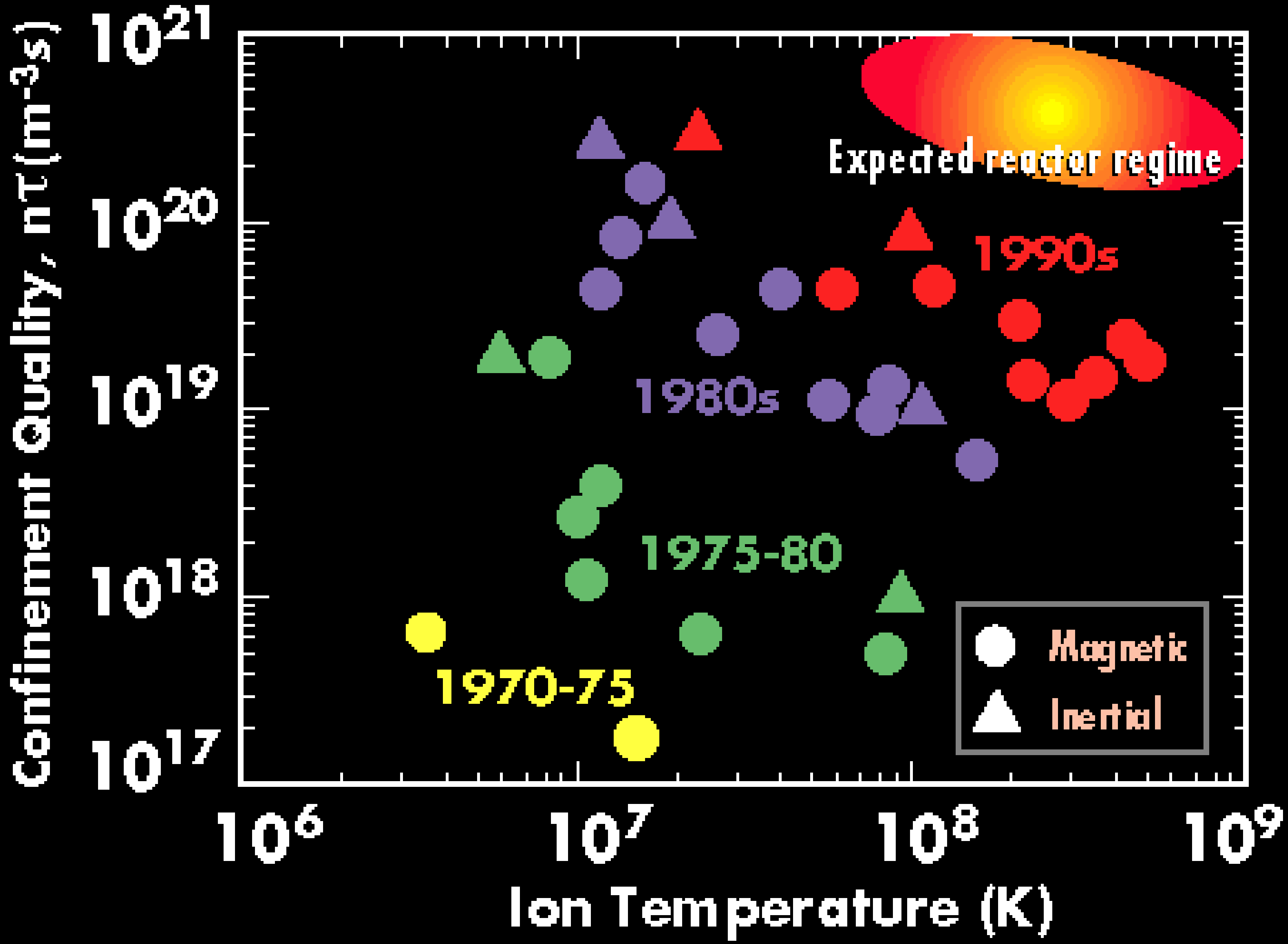
There Are Many Experimental Fusion Devices on the University of Wisconsin Campus

RFP – Physics

HSX - Electrical & Computer Engineering

Pegasus - Engineering Physics

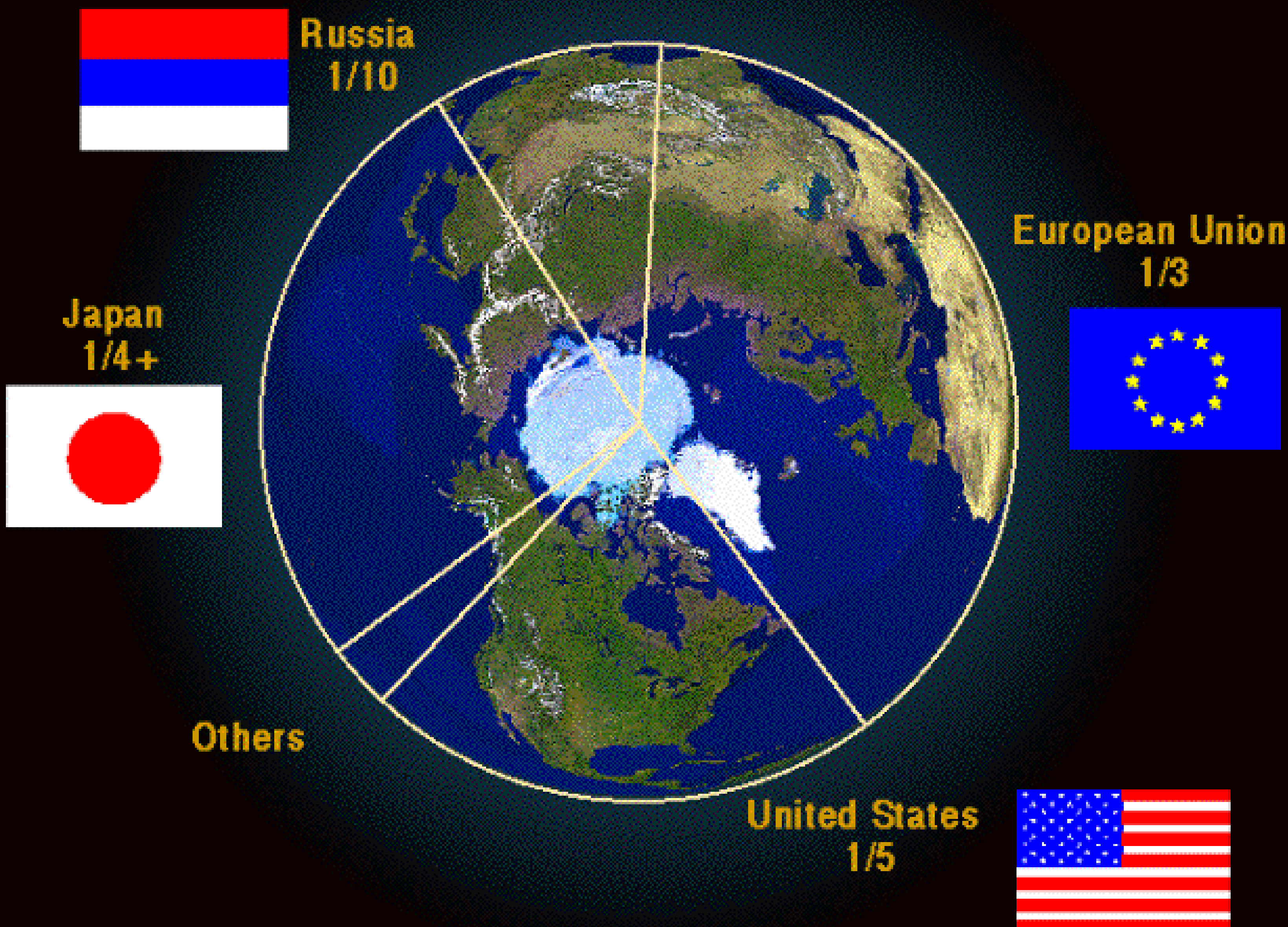
IEC - Engineering Physics



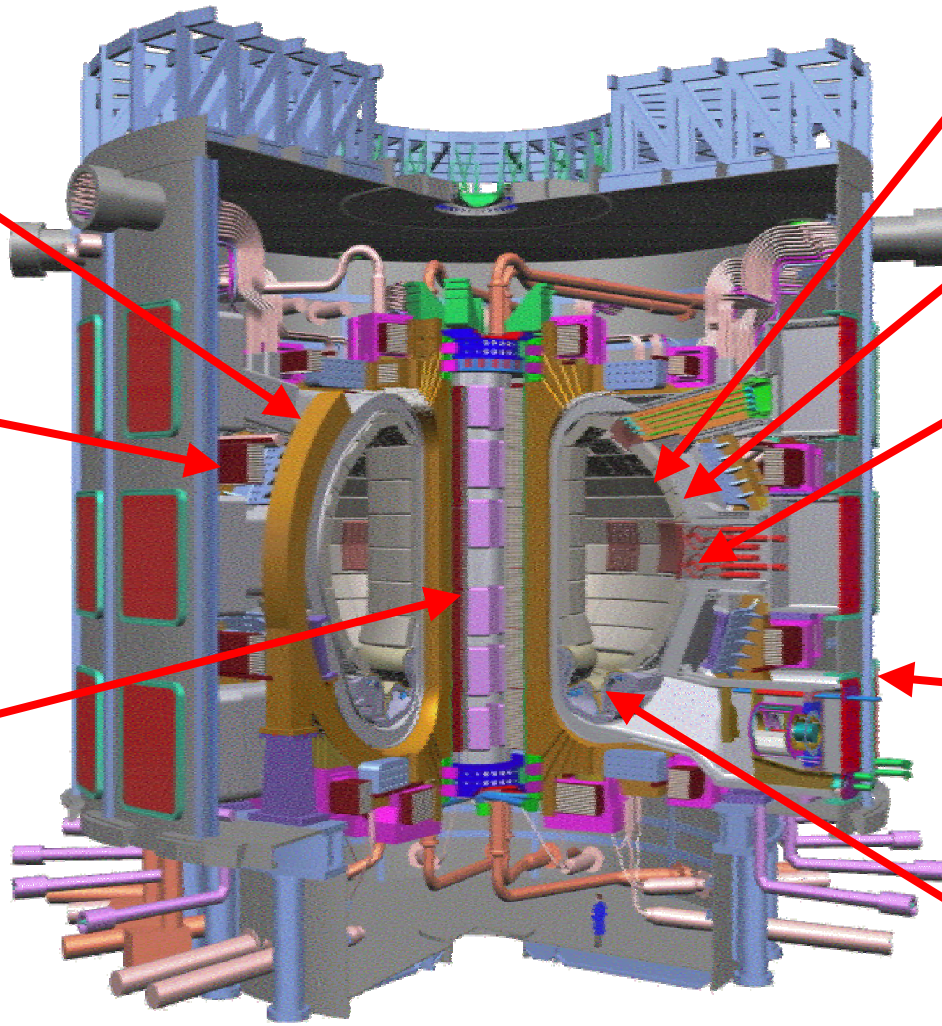
Confinement Quality, nτ(m-3s)
10²¹
10²⁰
10¹⁹
10¹⁸
10¹⁷
Expected reactor regime
1990s
1980s
1975-80
1970-75
Magnetic
Inertial
10⁶
10⁷
10⁸
10⁹
Ion Temperature (K)

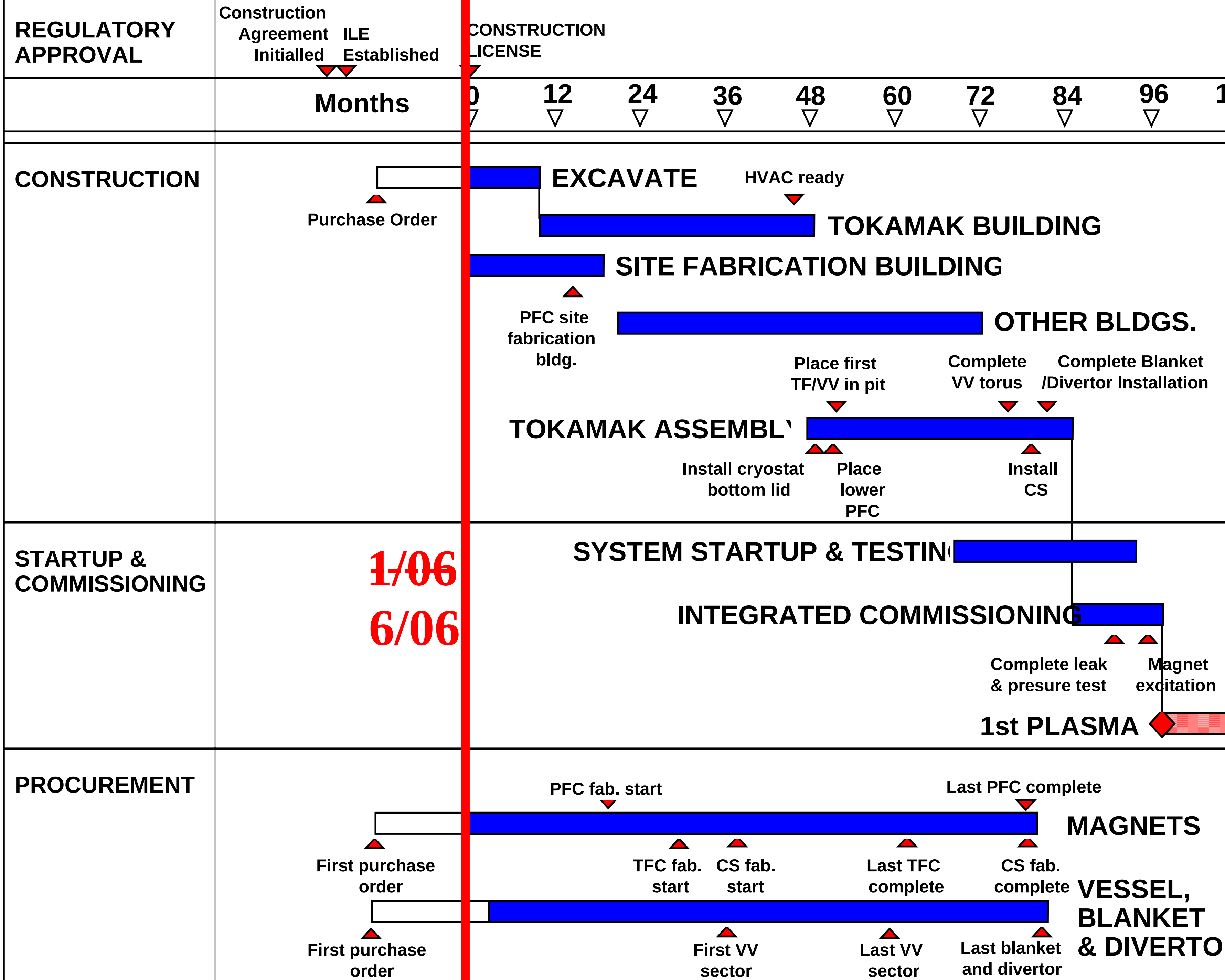
World Magnetic Fusion Effort

Major programs with fraction of total funding ($)



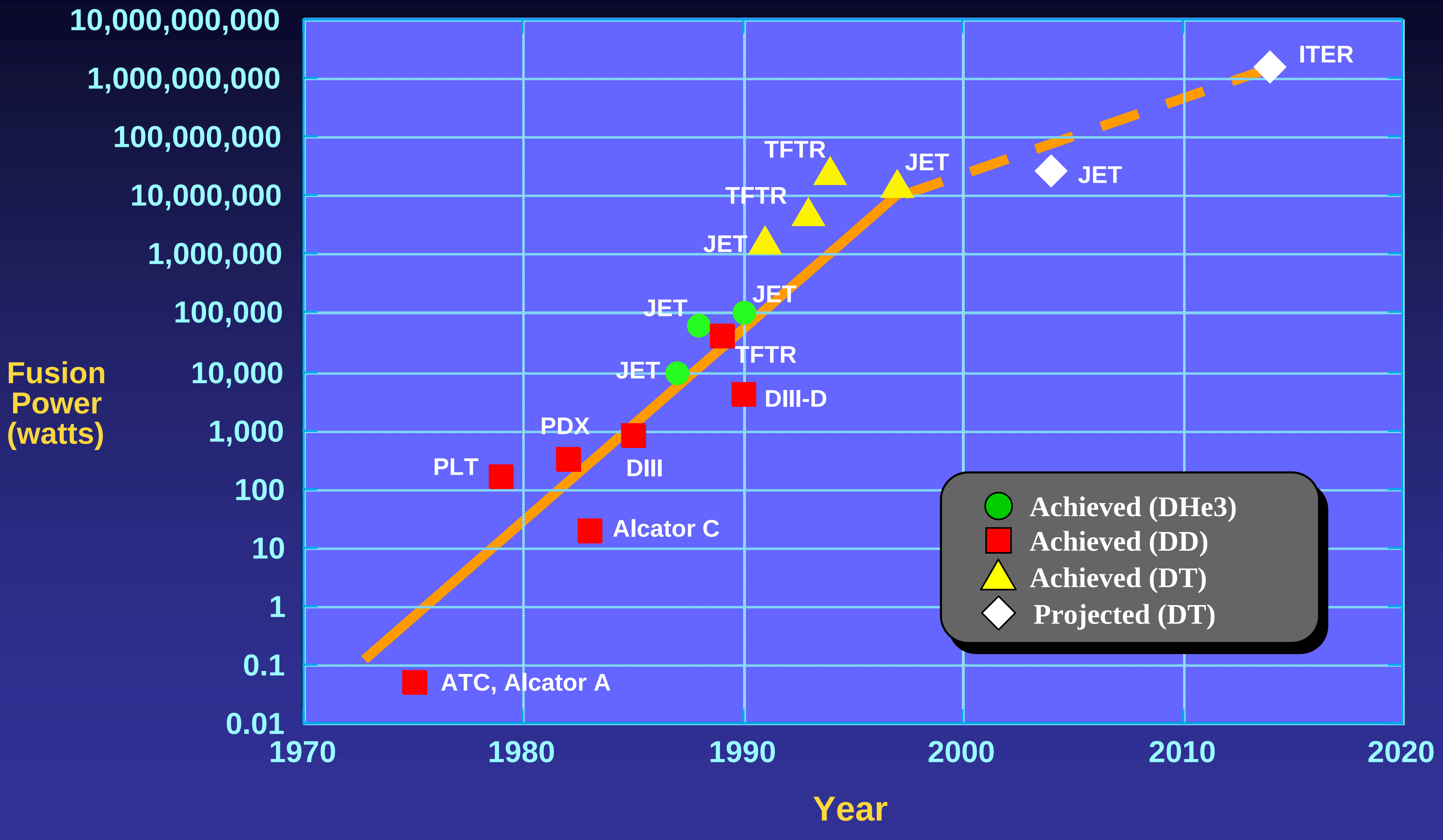
Major Components of ITER



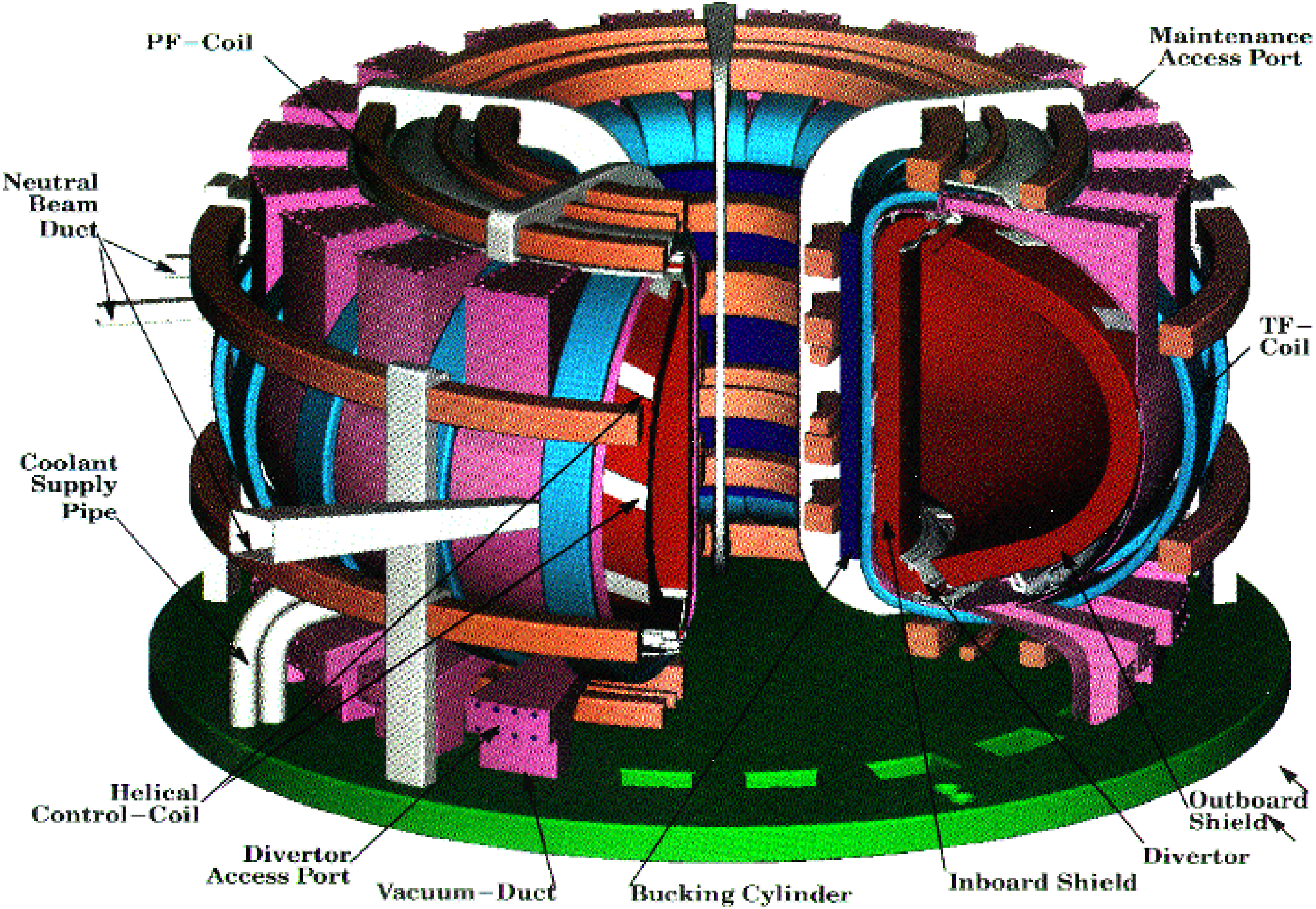


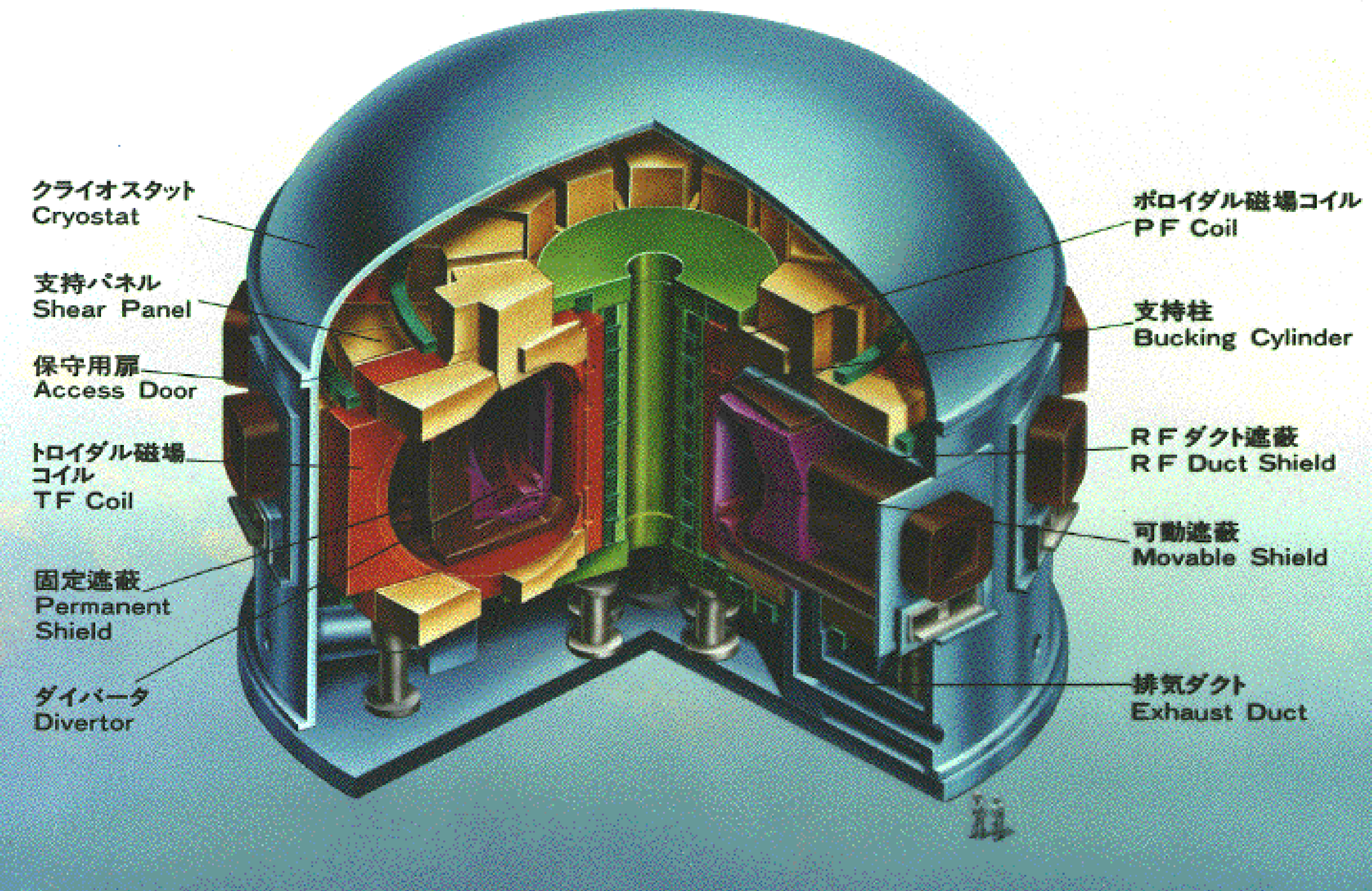
REGULATORY APPROVAL
Construction Agreement Initialled
ILE Established
CONSTRUCTION LICENSE
Months
0
12
24
36
48
60
72
84
96
CONSTRUCTION
EXCAVATE
HVAC ready
Purchase Order
TOKAMAK BUILDING
SITE FABRICATION BUILDING
PFC site fabrication bldg.
OTHER BLDGS.
Place first TF/VV in pit
Complete VV torus
Complete Blanket /Divertor Installation
TOKAMAK ASSEMBL
Install cryostat bottom lid
Place lower PFC
Install CS
STARTUP & COMMISSIONING
1/06
6/06
SYSTEM STARTUP & TESTIN
INTEGRATED COMMISSIONING
Complete leak & presure test
Magnet excitation
1st PLASMA
PROCUREMENT
PFC fab. start
Last PFC complete
MAGNETS
First purchase order
TFC fab. start
CS fab. start
Last TFC complete
CS fab. complete
VESSEL, BLANKET & DIVERTOR
First purchase order
First VV sector
Last VV sector
Last blanket and divertor

Progress in Magnetic Fusion Power



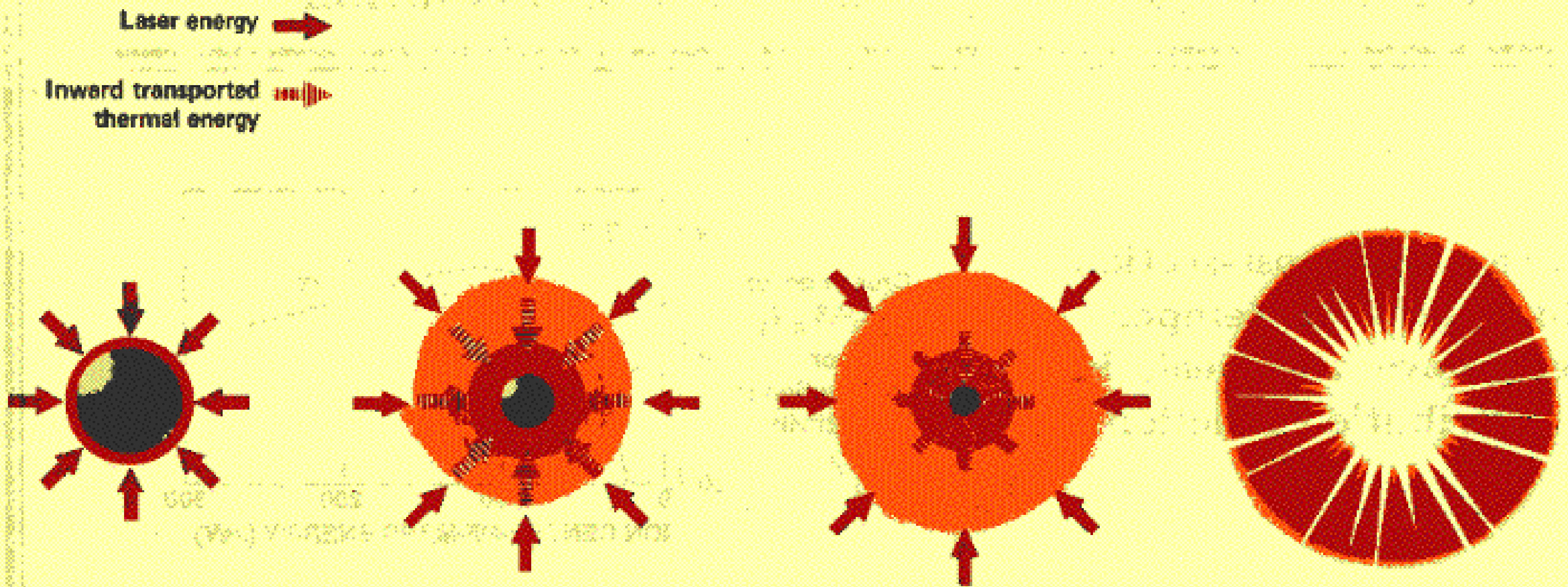
THE ARIES-III TOKAMAK FUSION REACTOR





核融合実験炉
Fusion Experimental Reactor (FER)

INERTIAL CONFINEMENT FUSION CONCEPT



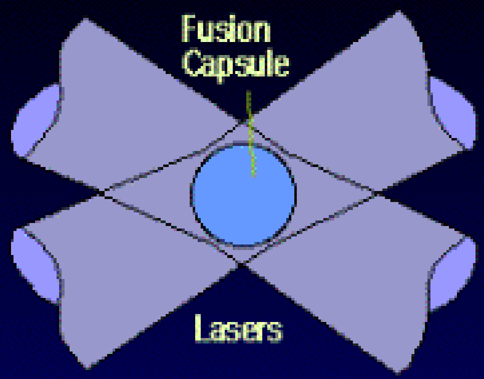
Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

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

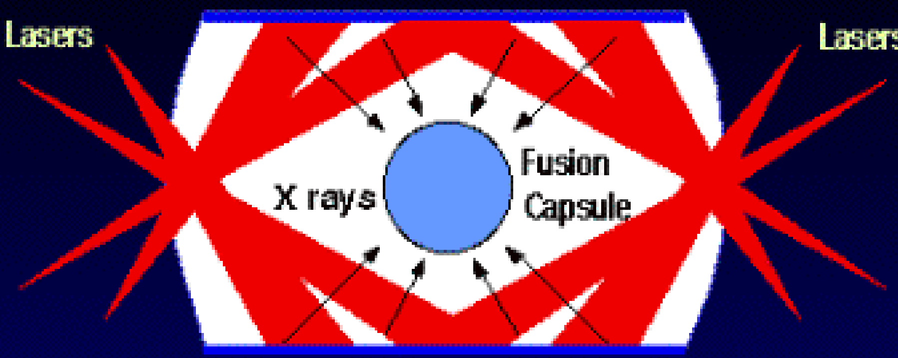
Ignition
With the final driver pulse, the fuel core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000°C.

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

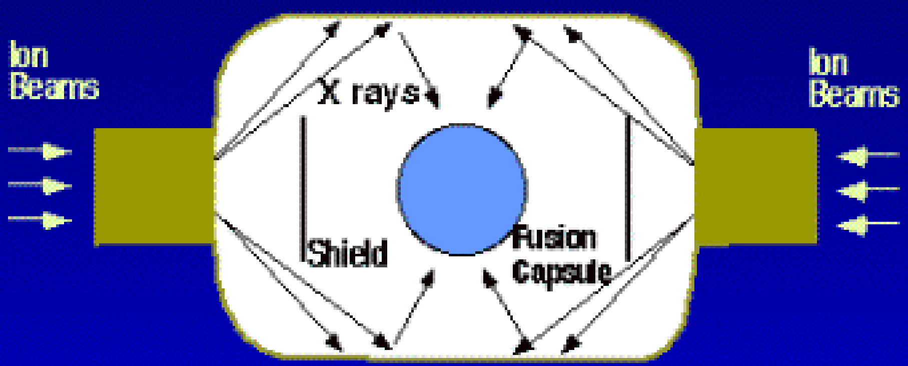
There Are Four Different ICF Target Designs



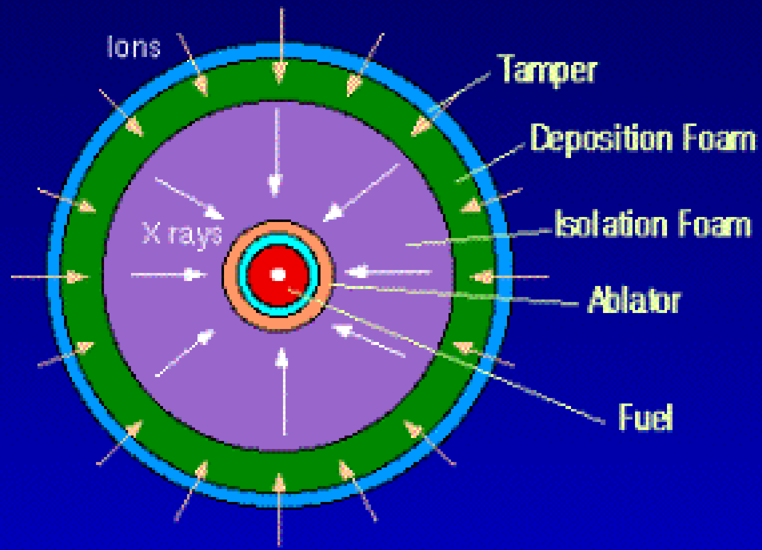
Direct Drive Lasers



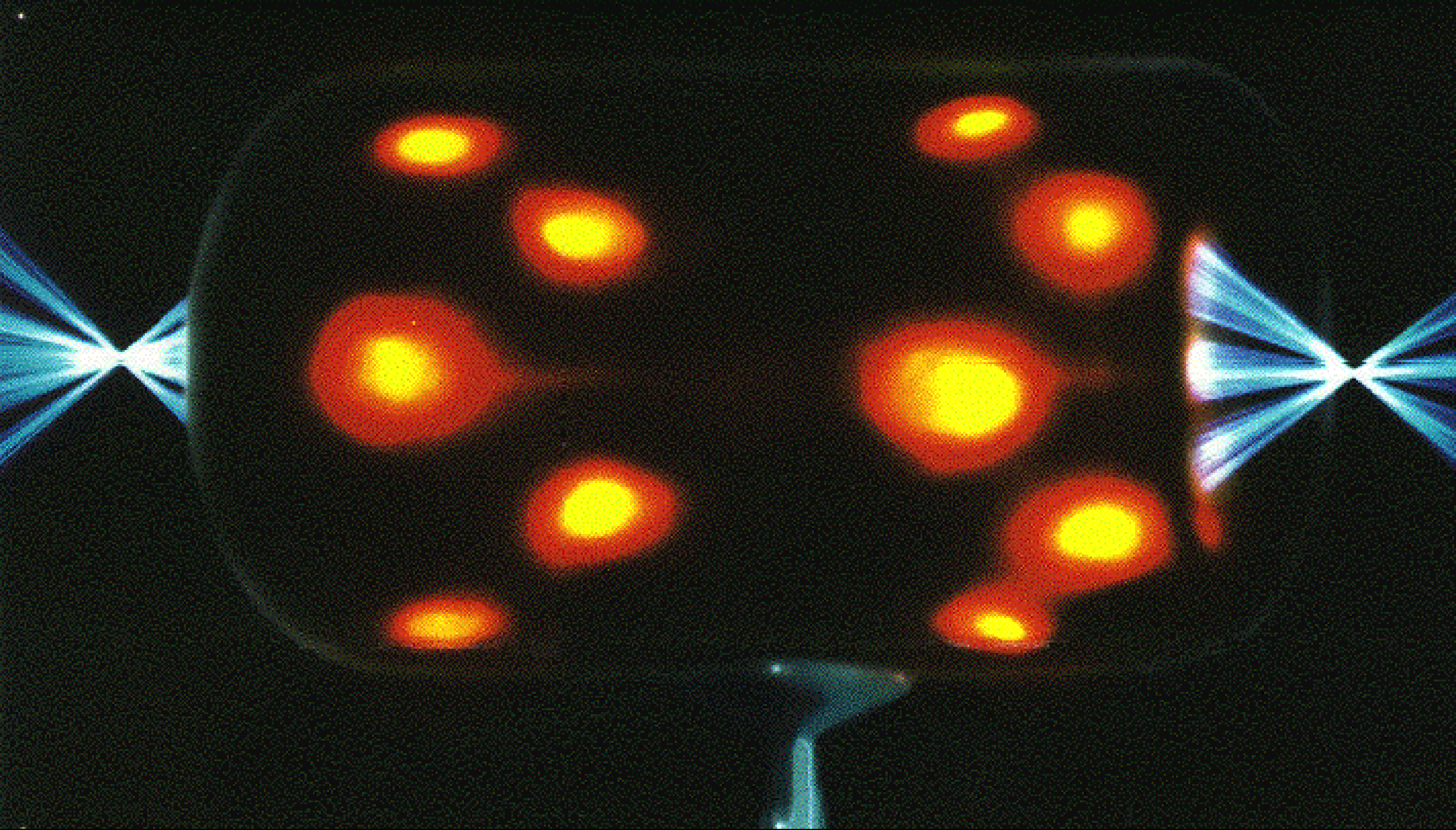
Indirect Drive Lasers

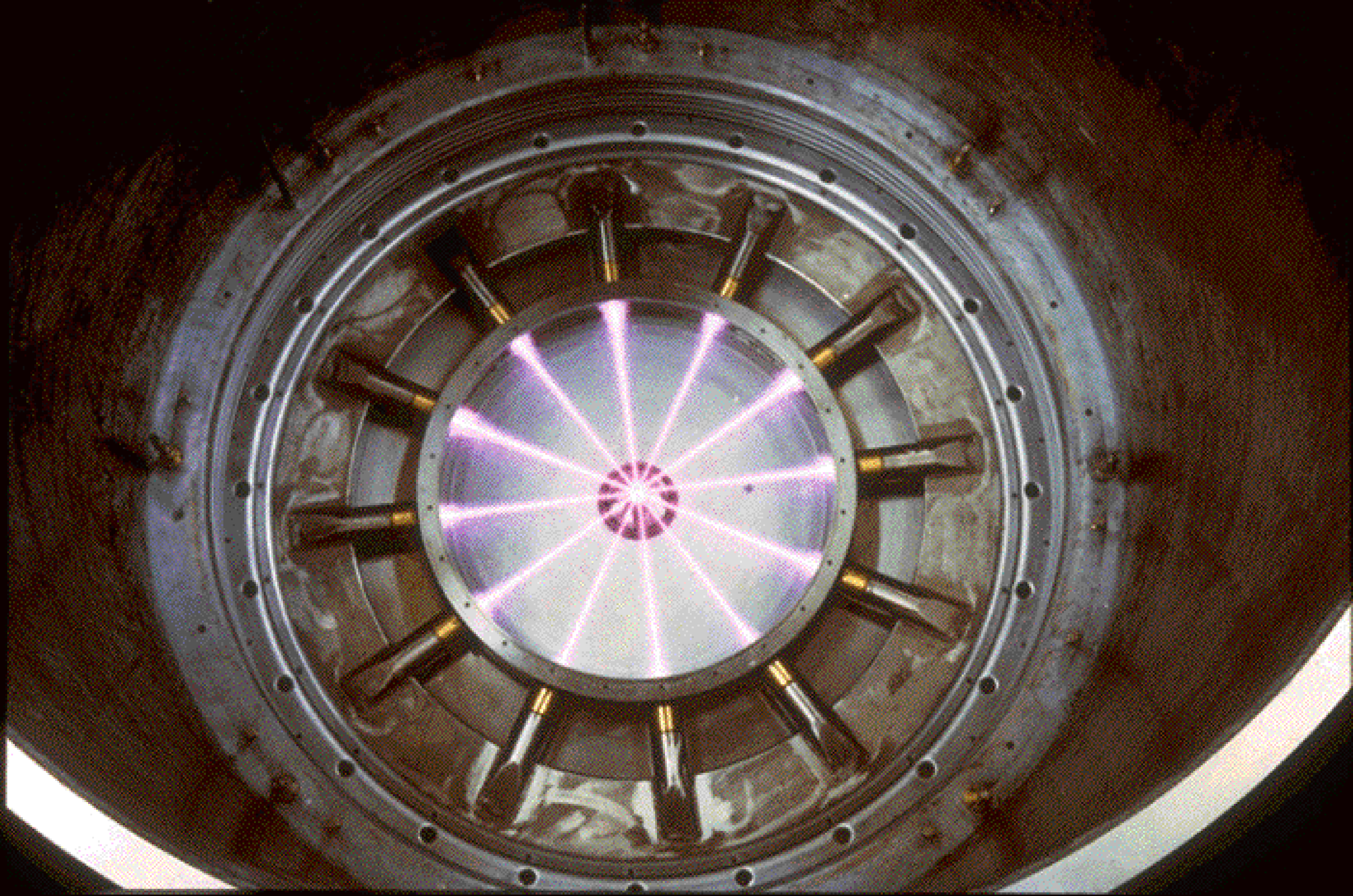


Indirect Drive Heavy Ions

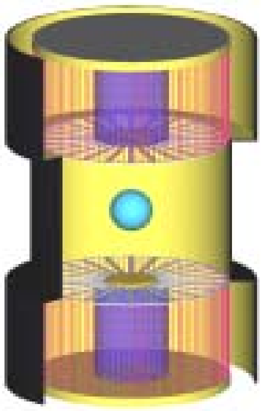
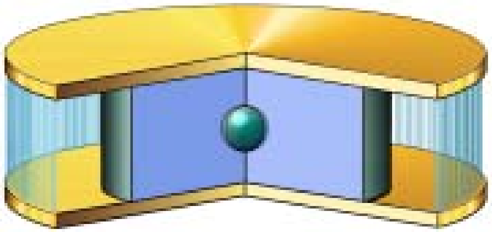


Indirect Drive Light Ions





Code calculations and analytic scaling predict z-pinch driver requirements for IFE DEMO

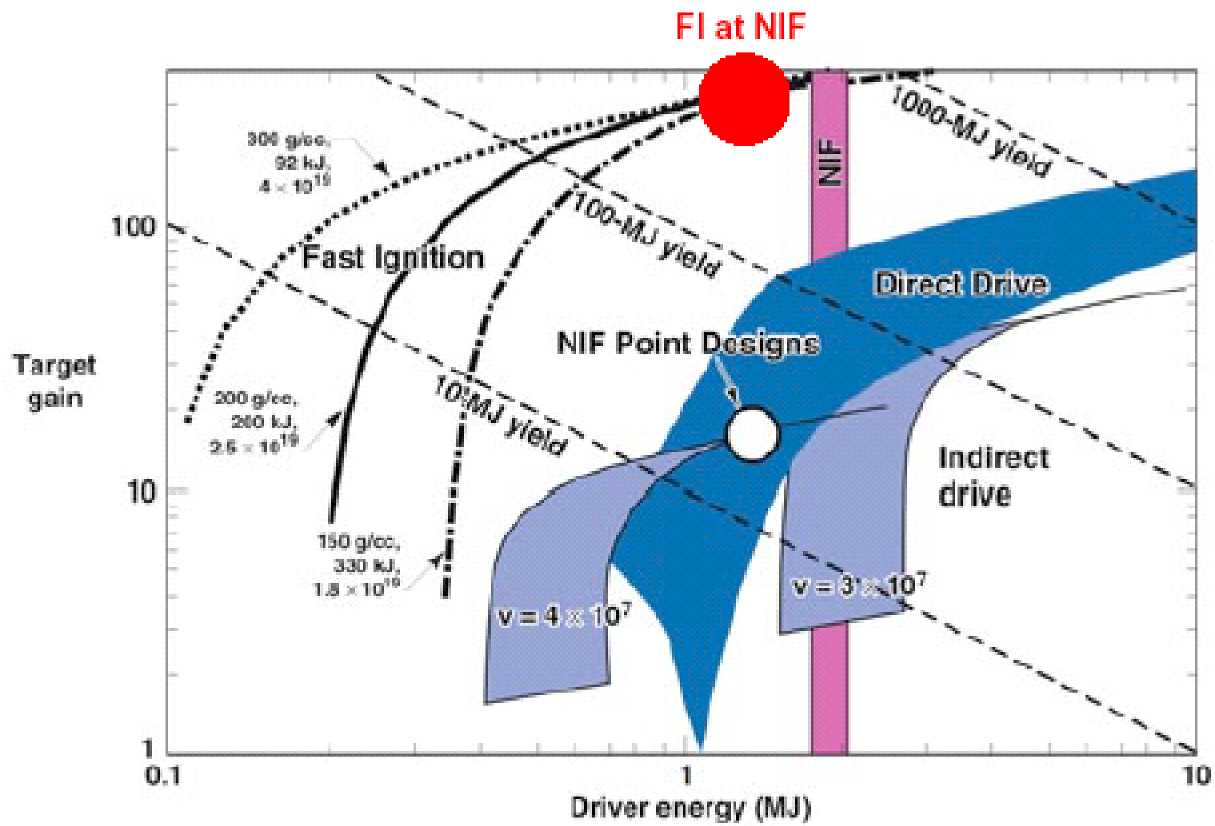
Double-Pinch Hohlraum	current /x-rays E_{abs} / yield	Dynamic Hohlraum	current /x-rays E_{abs} / yield
	2 x 62-68 MA 2 x (16-19) MJ 1.3 – 2.6 MJ 400 – 4000 MJ		54 – 95 MA 12-37 MJ 2.4 – 7.2 MJ 530 – 4400 MJ

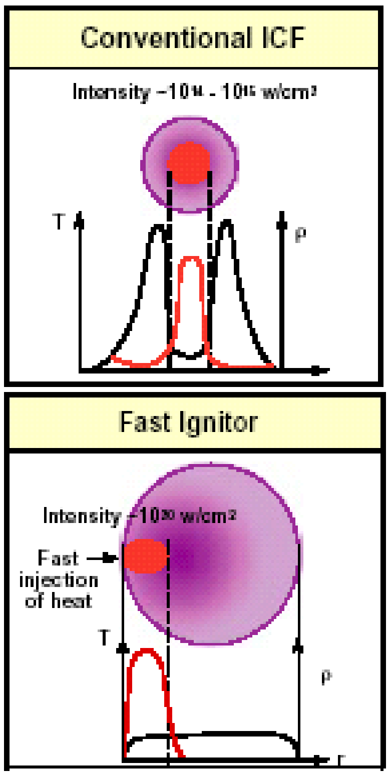
Based on these results, an IFE target for DEMO will require:

<u>double-pinch hohlraum</u>	<u>dynamic hohlraum</u>
36 MJ of x-rays (2x66MA)	30 MJ of x-rays (86 MA)
3000 MJ yield	3000 MJ yield
(G = 83)	(G = 100)

J. Hammer, M. Tabak, R. Vesey, S. Slutz, J. De Groot

There is worldwide interest in fast ignition which potentially gives more gain and lower threshold energy than indirect or direct drive

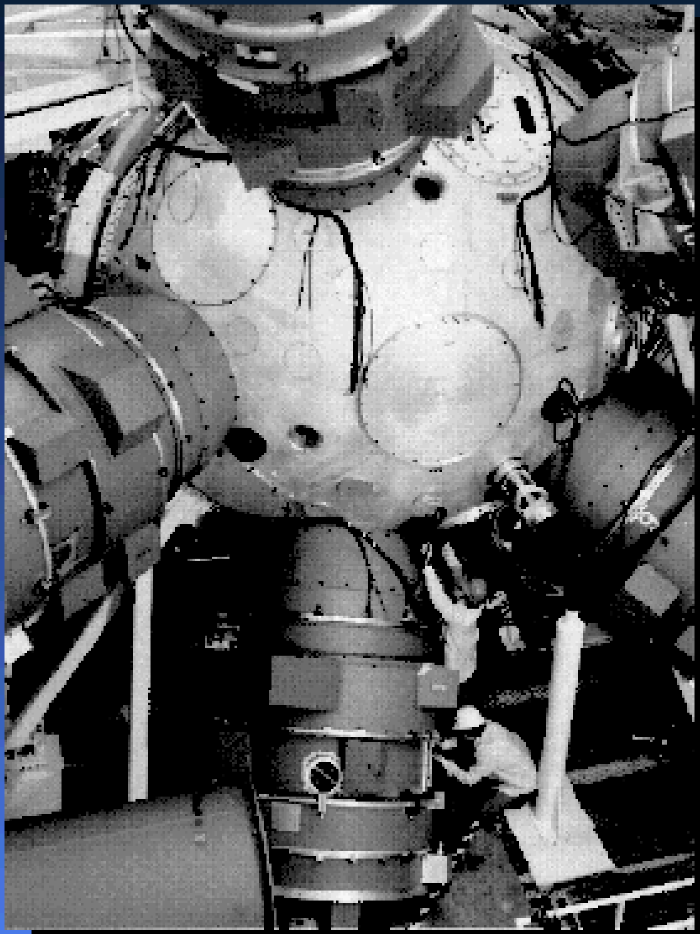




Higher gain is from reduced fuel density allowed by isochoric ignition

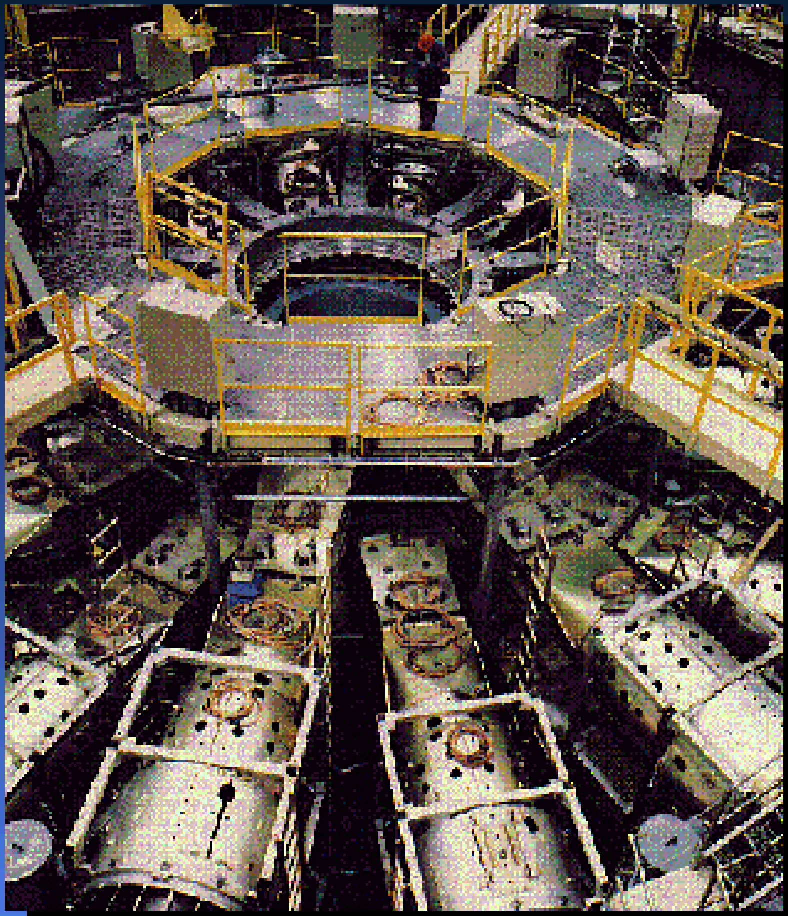
There Are Two Methods of Achieving Inertial Confinement Fusion

Lasers



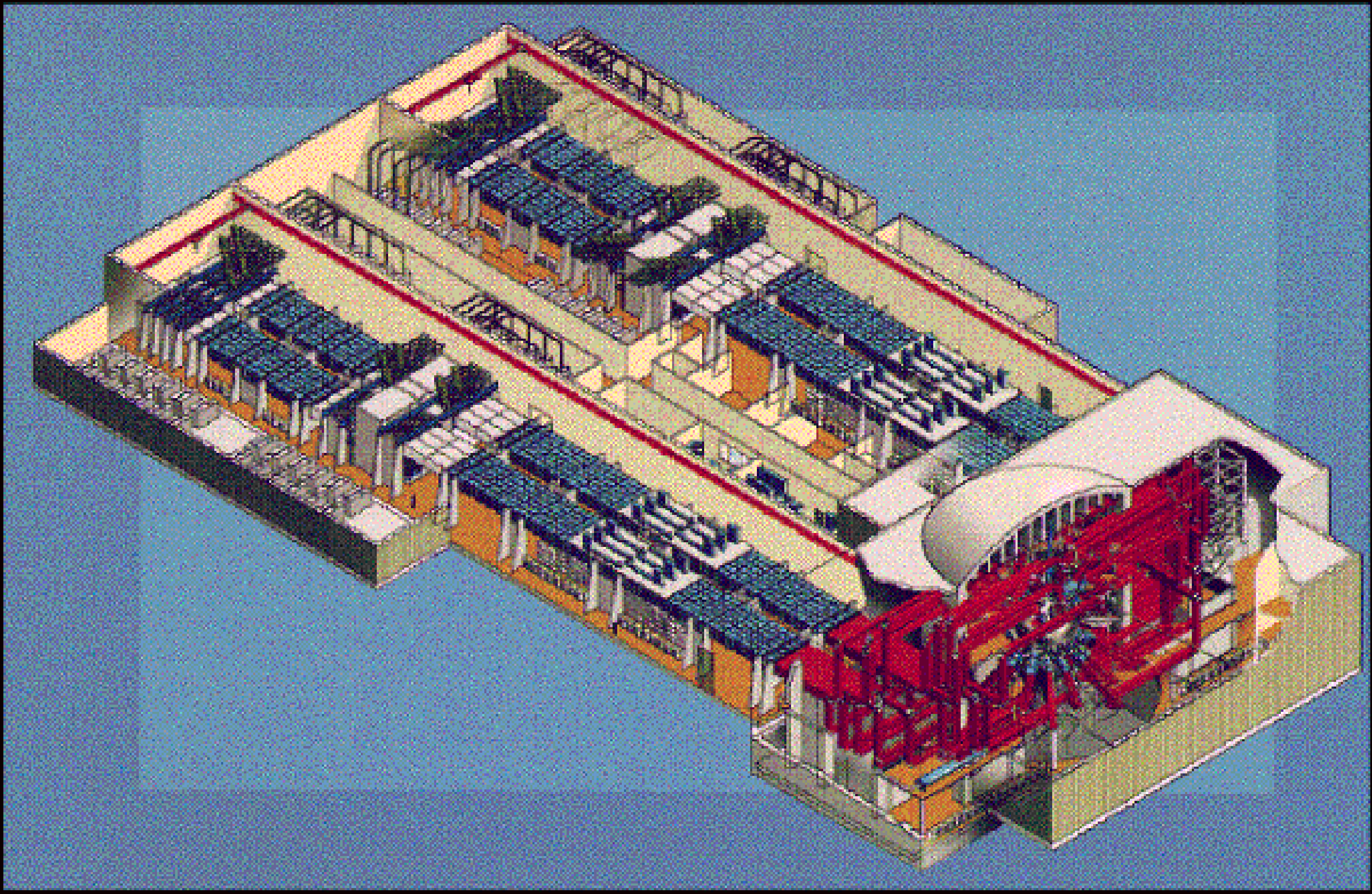
NOVA

Ions



PBFA-II

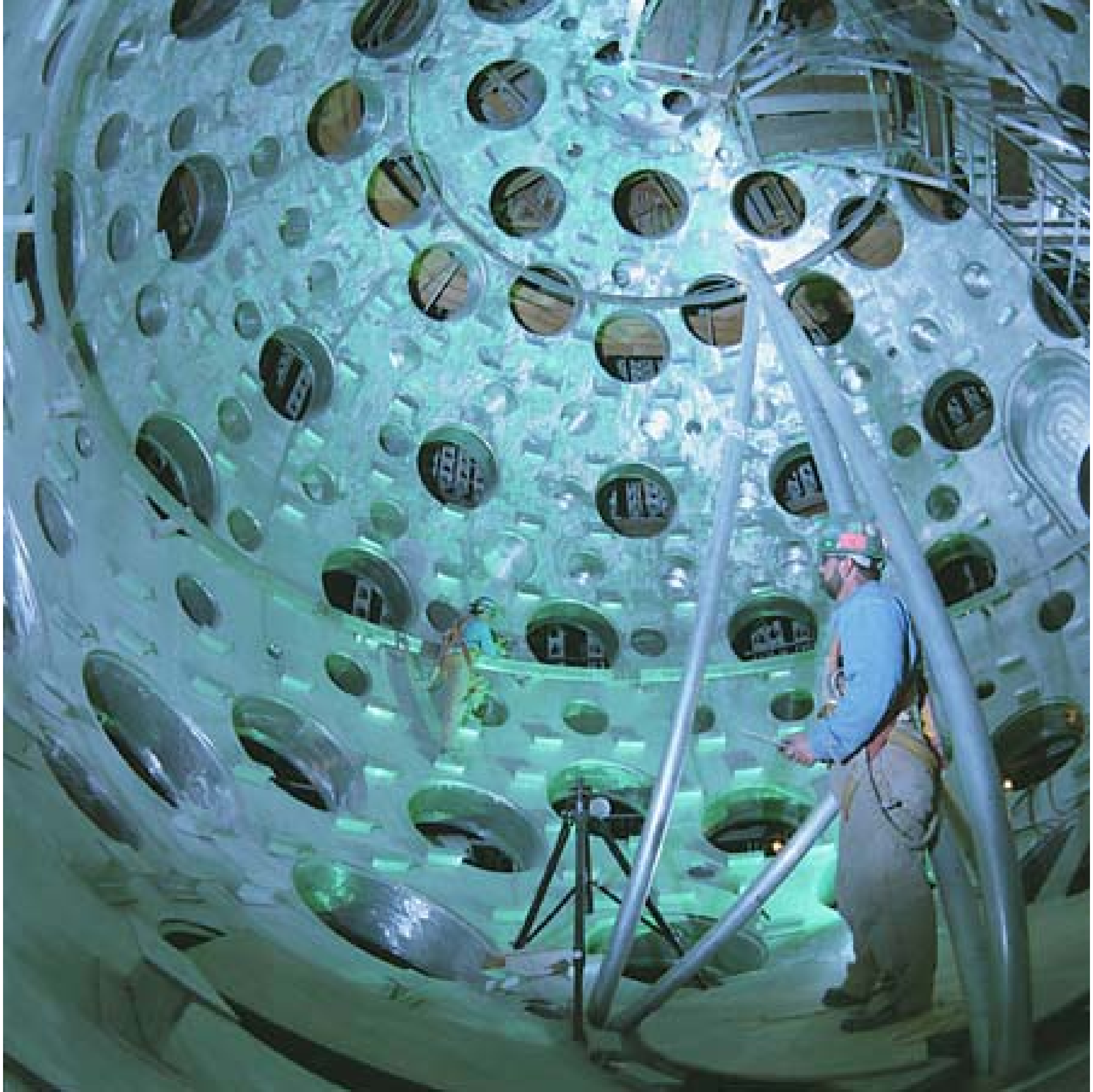
The National Ignition Facility Should Reach Breakeven Conditions in Inertial Confinement Fusion



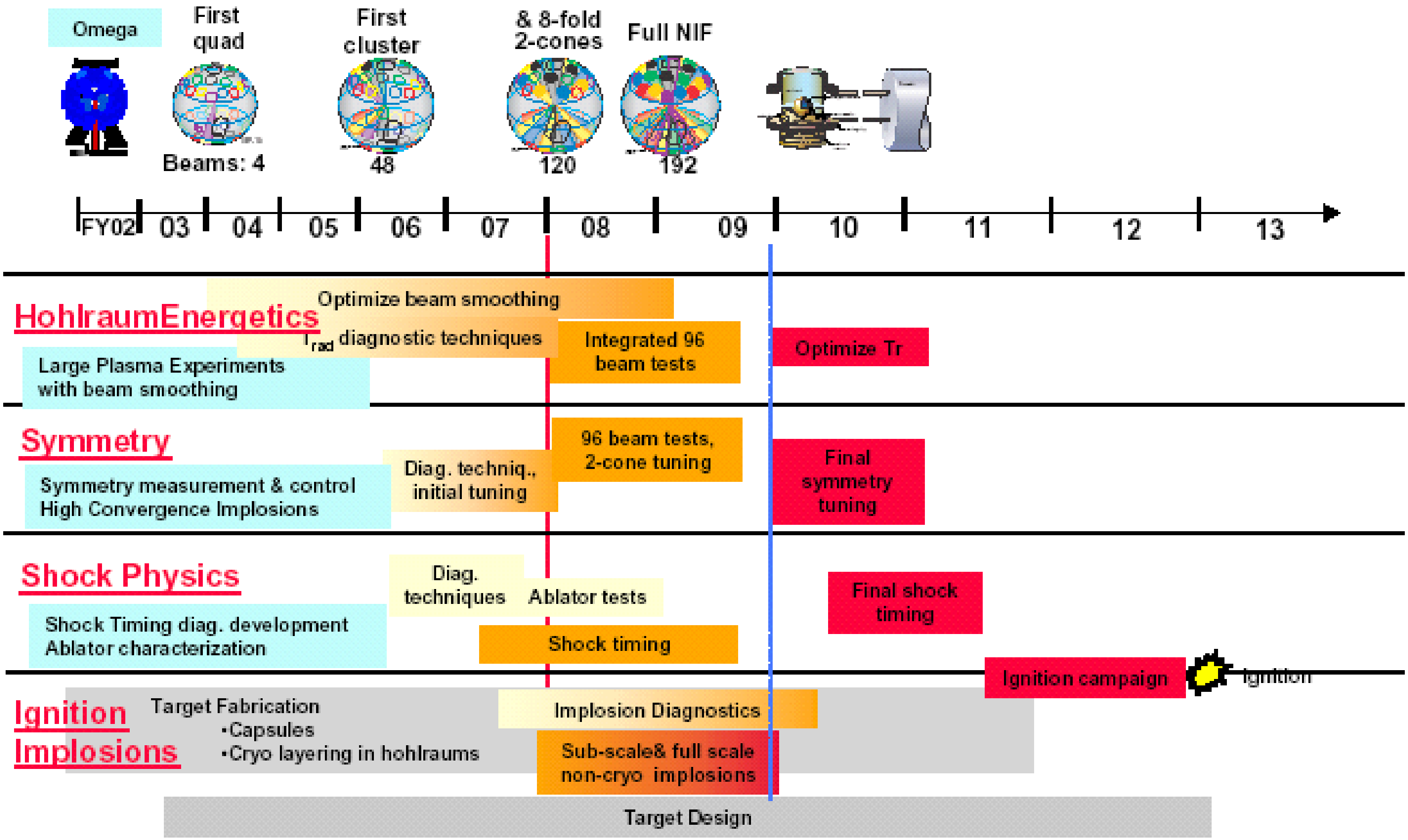
The National Ignition Facility

The Laser Bay is for NIF is Almost Complete

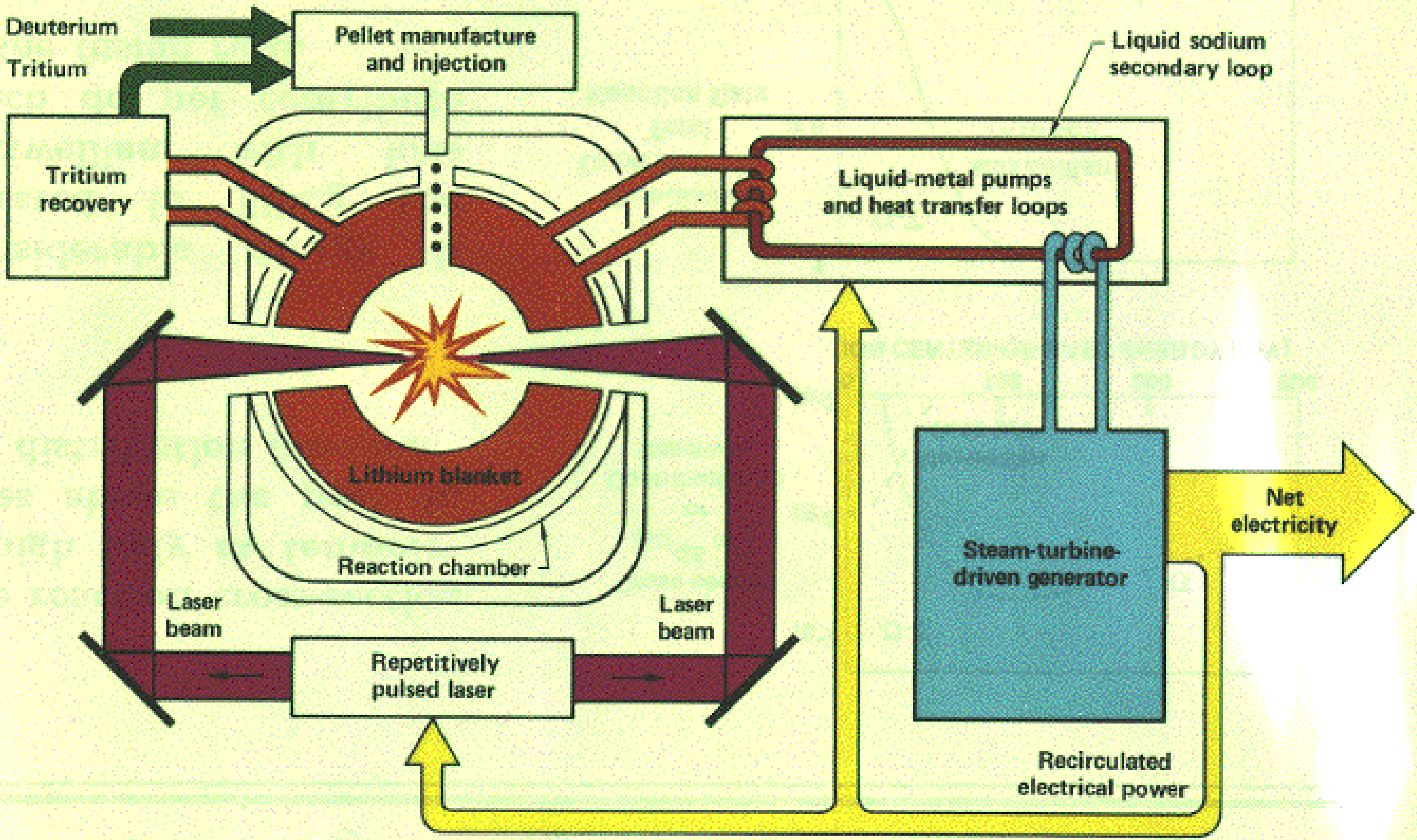
NIF Target Chamber upper hemisphere



The indirect drive Ignition Plan makes use of existing facilities, and early NIF, to optimize the final ignition design

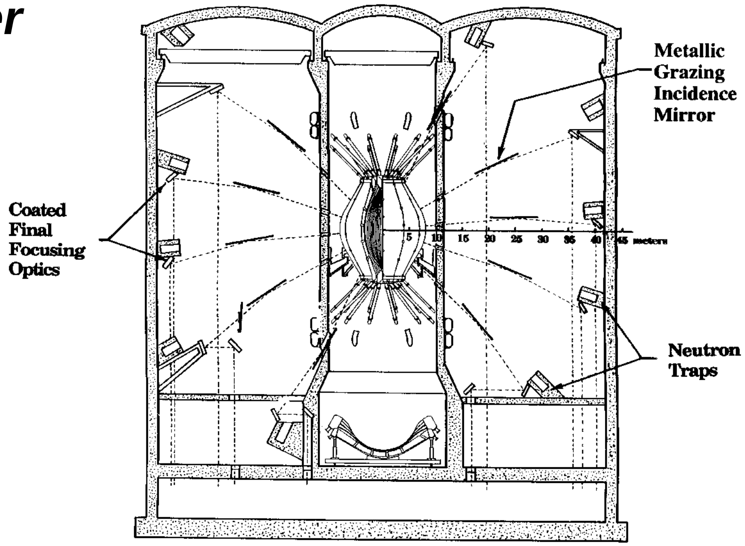


A FUNCTIONAL DIAGRAM OF A LASER FUSION POWER PLANT

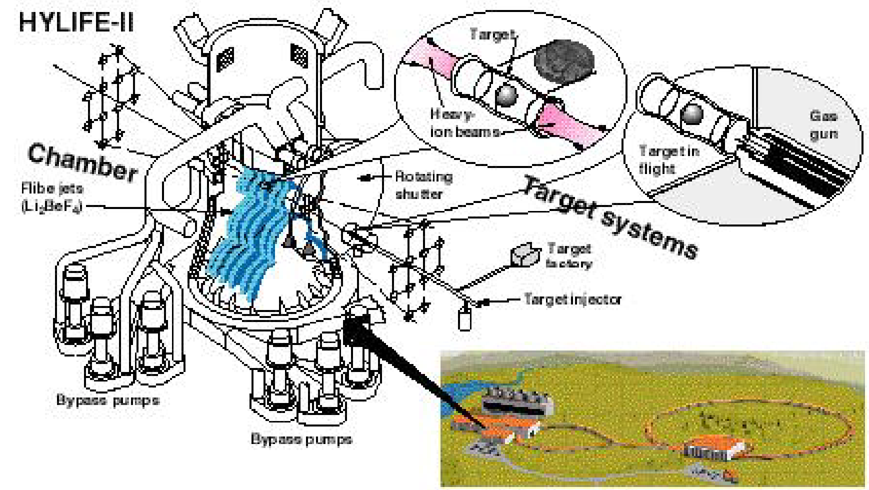


There are 4 Current ICF Drivers

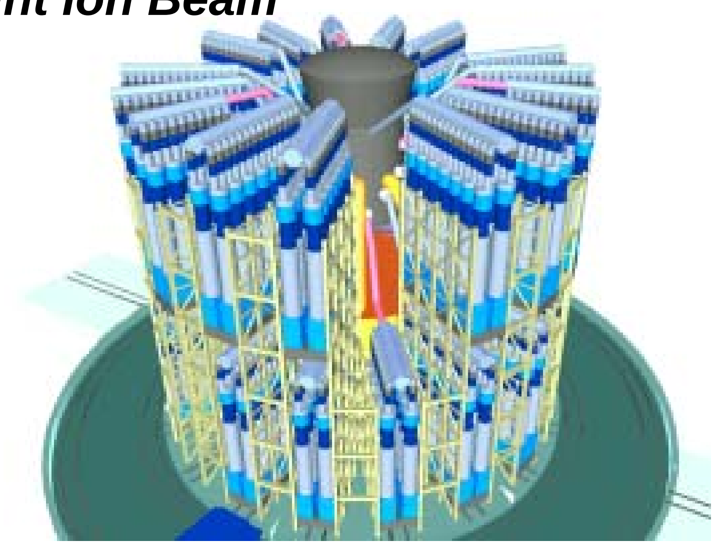
Laser



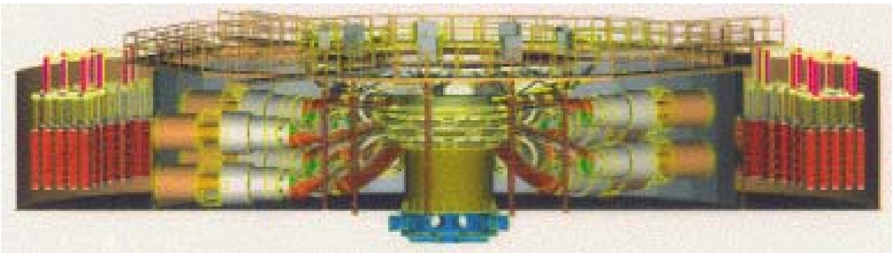
Heavy Ion Beam



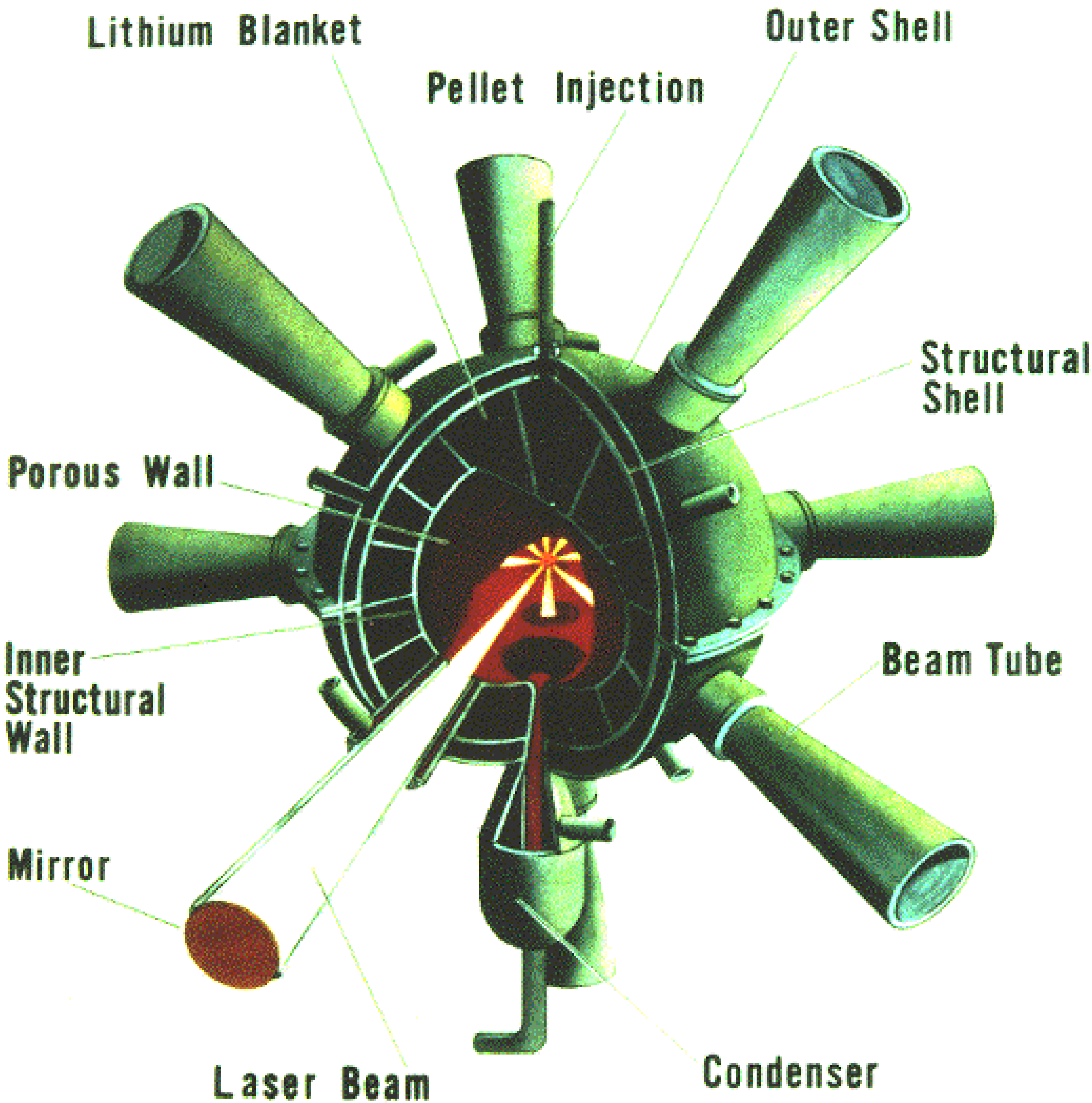
Light Ion Beam

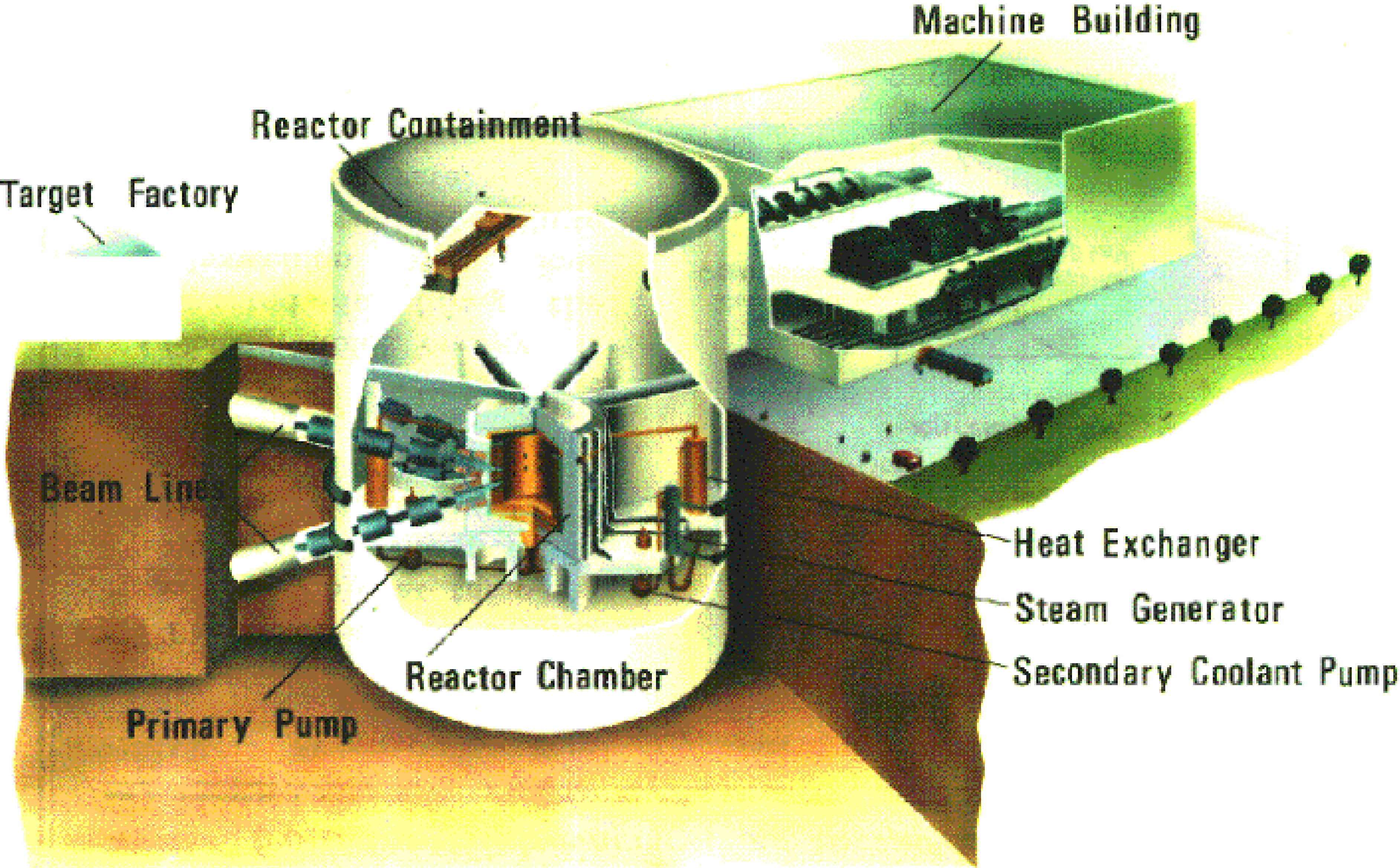


Z-Pinch – Energy application depends on finding a credible rep-rate concept

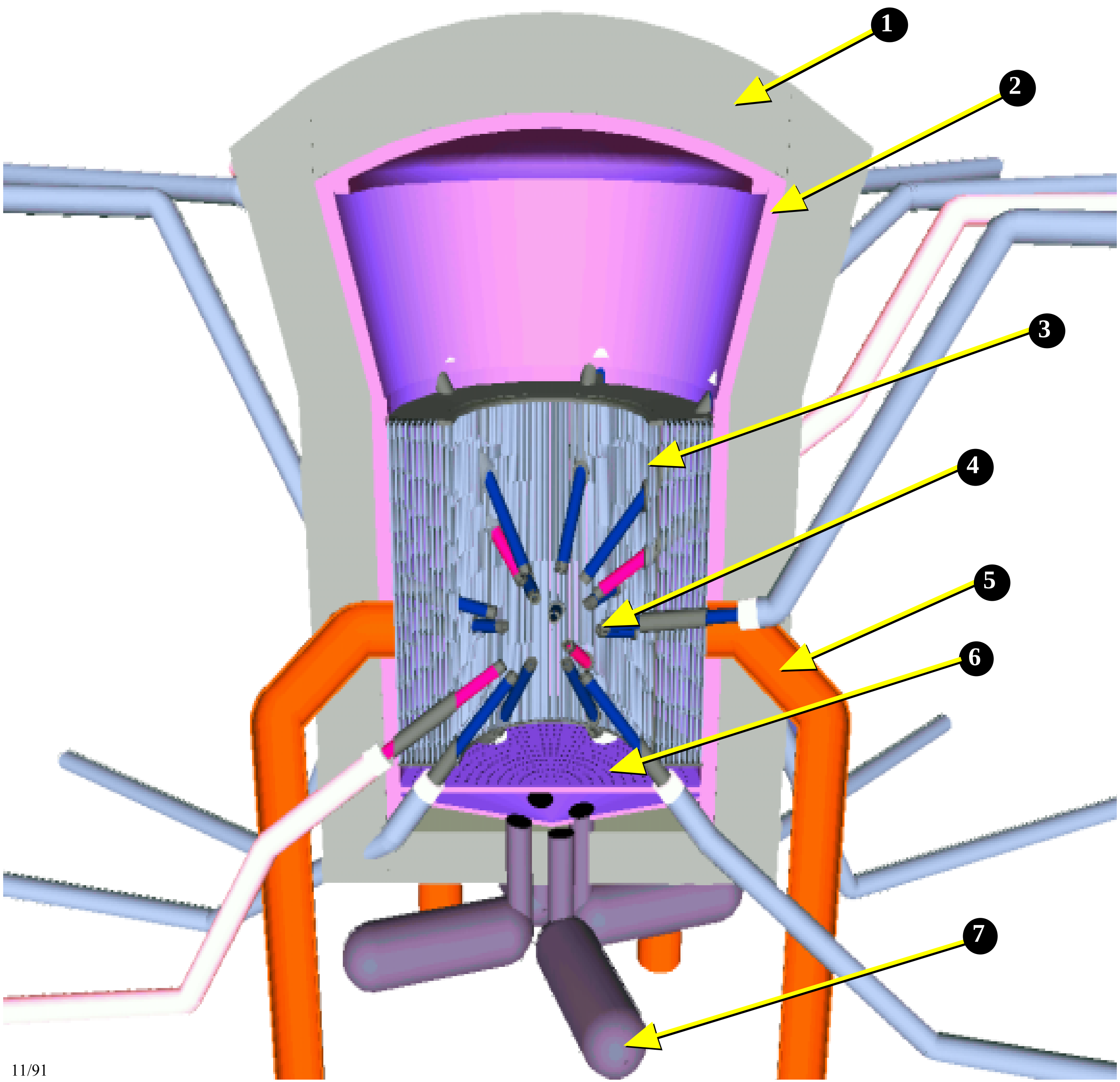


Light ion development currently on hold due to inability to focus adequately


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



HIBALL REACTOR BUILDING 940 MW_{el}



LIBRA-LiTE

Side View Reactor Chamber Cutaway

(1) Shield

(2) Reflector / vacuum chamber

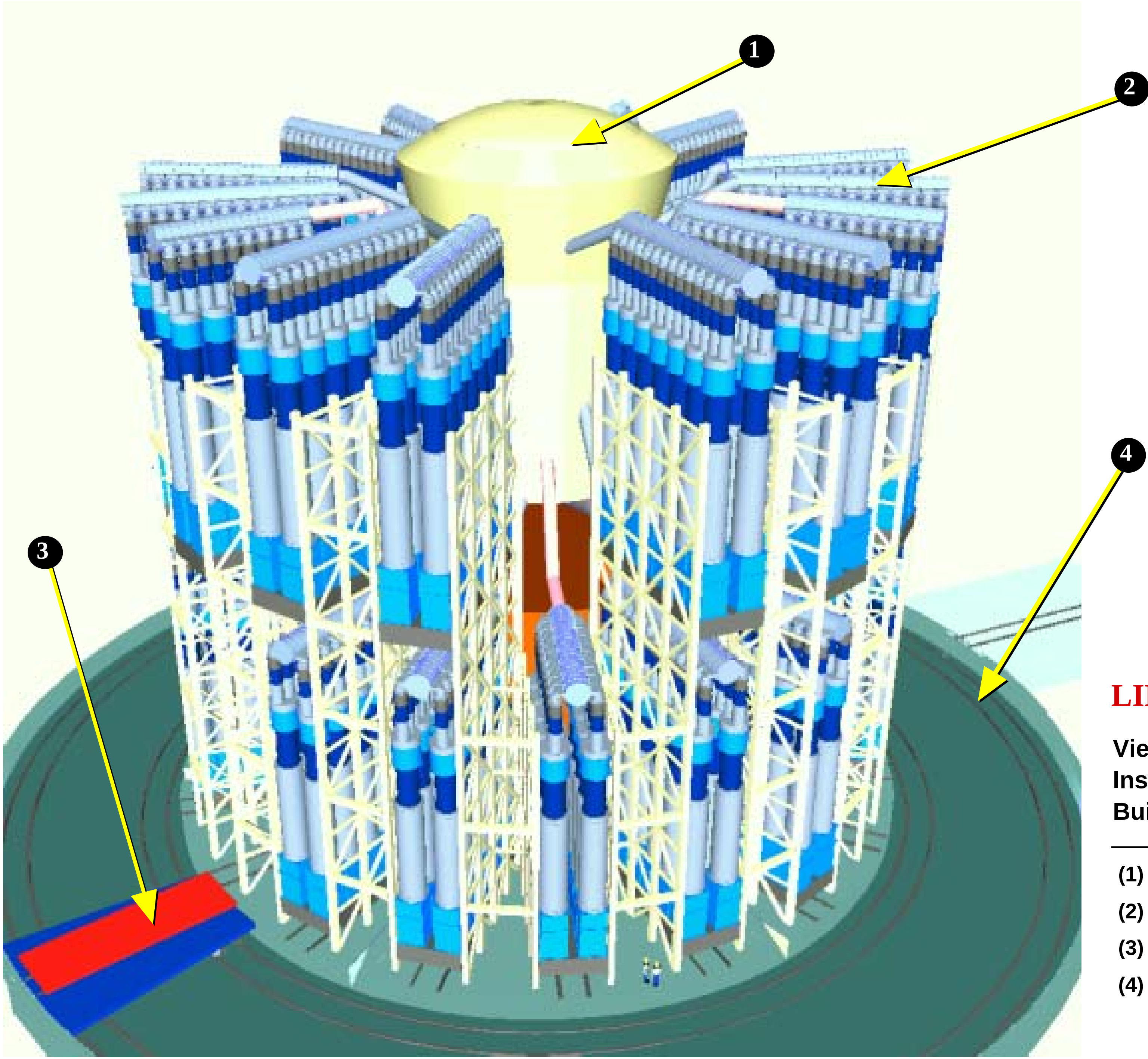
(3) INPORT units

(4) Final focus magnet

(5) Vacuum line

(6) Perforated plate

(7) IHX



LIBRA-LiTE

View of Reactor from Inside Containment Building

---

(1) Reactor chamber

(2) Driver

(3) Transport carriage

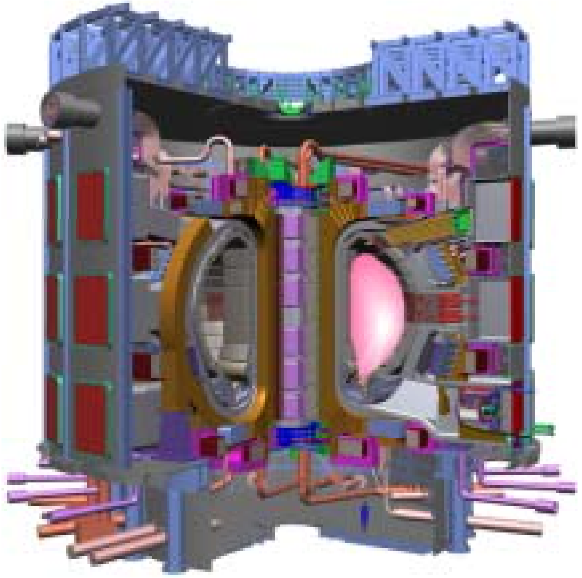
(4) Circumferential rails

The long-range goal of Z-Pinch IFE is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (~3 GJ) at low rep-rate (~0.1 Hz)

Z-Pinch IFE DEMO (ZP-3, the first study) used 12 chambers, each with 3 GJ at 0.1 Hz, to produce 1000 MWe

NIF and ITER Drive the Urgency of the Plan

NIF **ITER**



A strong parallel effort in the science and technology of fusion energy is required to guide research on these experimental facilities and to take advantage of their outcome.

Conclusions

- There is a substantial world research program (≈ 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