THE PROMISE OF FUSION ENERGY

General Atomics

The following slide show is a compilation of slides from many previous similar slide shows that have been produced by different members of the fusion and plasma physics education community. We realize that some of the information contained herein must be updated. Please send comments, complaints, and suggestions to: rick.lee@gat.com. This slide show is intended to be used by students and teachers; downloading this file for educational purposes is highly encouraged.

OVERVIEW

- History of (magnetic) fusion research
- Fusion compared with other energy sources
- Physics and process of fusion energy production
- Methods of fusion plasma confinement
- Tokamaks: General Atomics DIII-D
- US and international fusion efforts
- The future and promise of fusion

EARLY HISTORY OF FUSION RESEARCH

- 1951: Argentina's dictator Juan Peron funds fusion research on remote island, soon announces complete success! (Never heard from again…)
  - Resulting news stories galvanize US establishment of fusion energy research

- 1953: Project Sherwood established (classified fusion energy research)

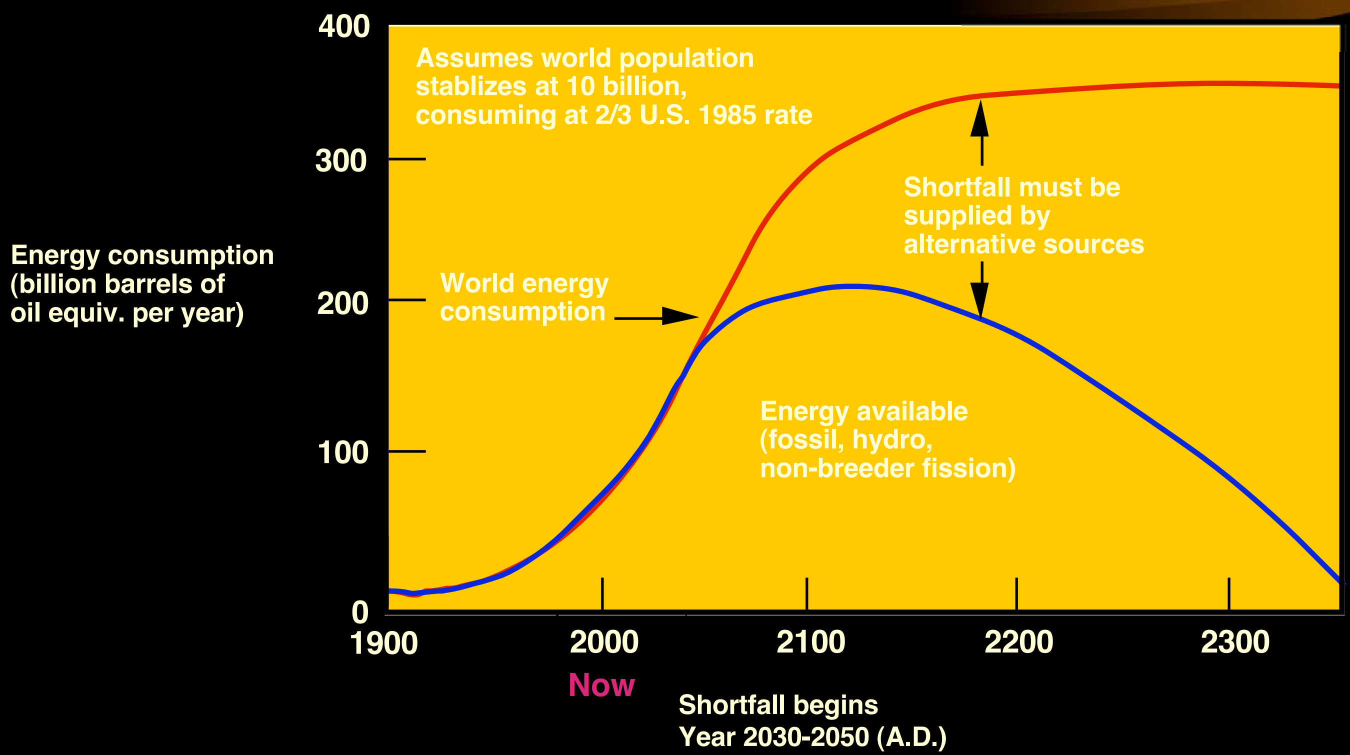
- September 1958: Project Sherwood declassified (2nd Atoms for Peace Conf., Geneva), fusion research becomes open worldwide

- Late 1960's: Russian announcement of 200eV electron temperature in tokamak (2 million degrees K)
  - Artsimovich tours US and convinces many; Princeton bets it's wrong!
  - US delegation visits Moscow, measures high temperatures…
  - Princeton loses the bet...

- Early 70's: tokamaks at every major lab In the US (and worldwide)!

The Coming Era of Fusion Energy

The fossil fuel era is almost over. If we continue to burn fossil fuels for energy, they will last only another few hundred years. At our present rate of use, experts predict a shortfall in less than fifty years.



Fossil Fuel Energy Sources - Advantages and Disadvantages

	Advantages	Disadvantages
Coal (220 Years)	• Abundant	• Burns dirty • Causes acid rain, air pollution, CO_2
Oil (35 Years)	• Flexible fuel source with many derivatives • Transportable	• Finite supply • Causes air pollution • Produces CO_2
Natural Gas (60 Years)	• Burns cleanly • Transportable	• Finite supply • Produces CO_2

Non-fossil Energy Source Advantages and Disadvantages

Energy Sources	Advantages	Disadvantages
Fission (Nuclear Power) (45 Years) (2700 Years-Breeder)	• Clean, no CO_2 • Does not produce immediate pollution	• Waste disposal is difficult • Safety concerns
Hydroelectric (mostly utilized)	• Clean, no CO_2	• Dam construction destroys habitats • Geographically limited
Wind (low utilization)	• Clean, no CO_2	• Huge numbers of windmills required for adequate power generation • Geographically limited
Geothermal (low utilization)	• Clean, no CO_2	• Geographically limited
Solar (under utilized)	• Clean, no CO_2	• Huge number of solar cells required for adequate power generation • Geographically limited

ADVANTAGES OF FUSION

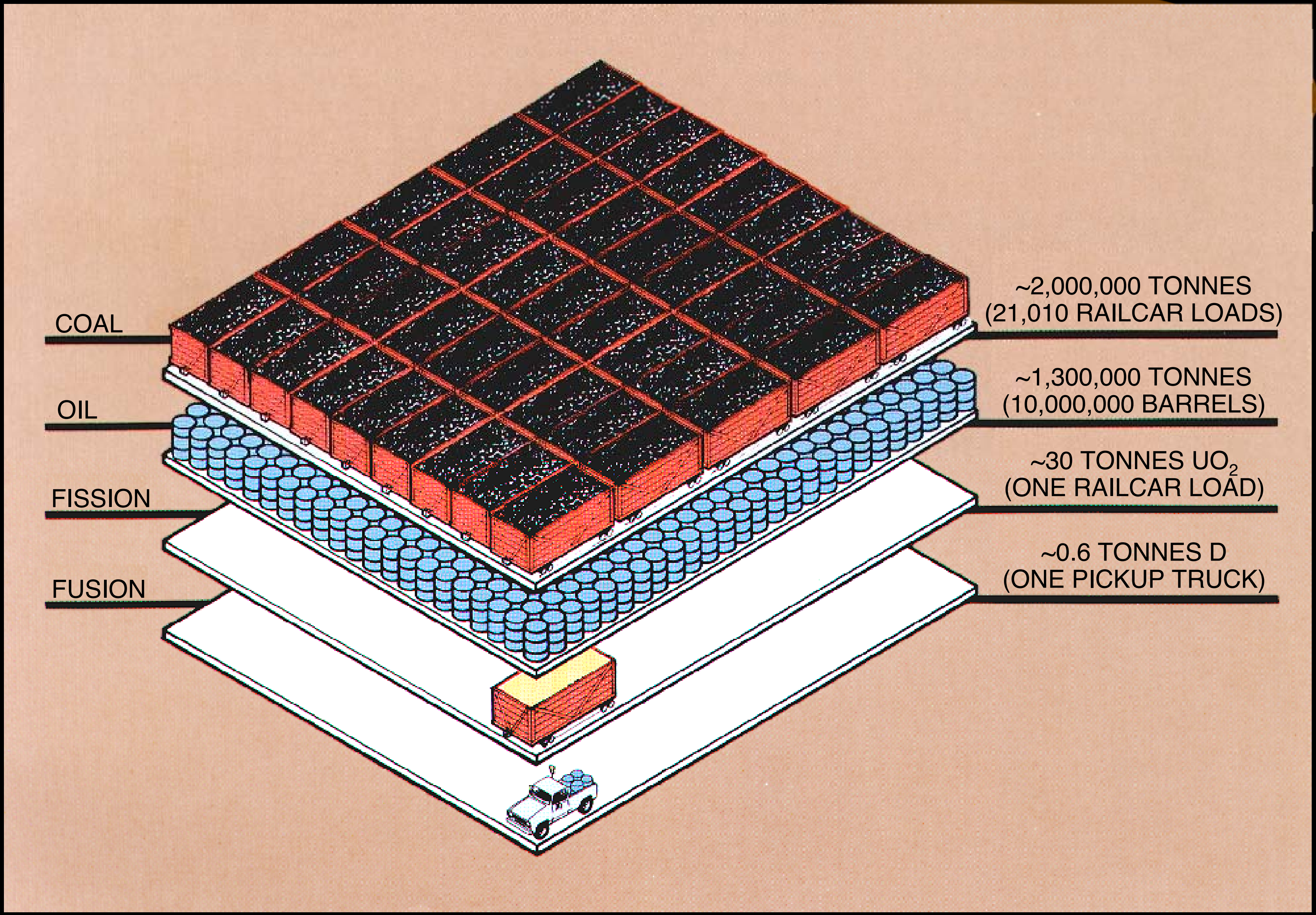
- **Abundant Fuel Supply**
  - **Deuterium - inexhaustible supply from sea water (1 part/ 6,500 H_20)**
  - **Tritium - produced from Lithium, thousands of years supply**

- **No Risk of Nuclear Accident**
  - **No meltdown possible**
  - **Large uncontrolled release of energy impossible**

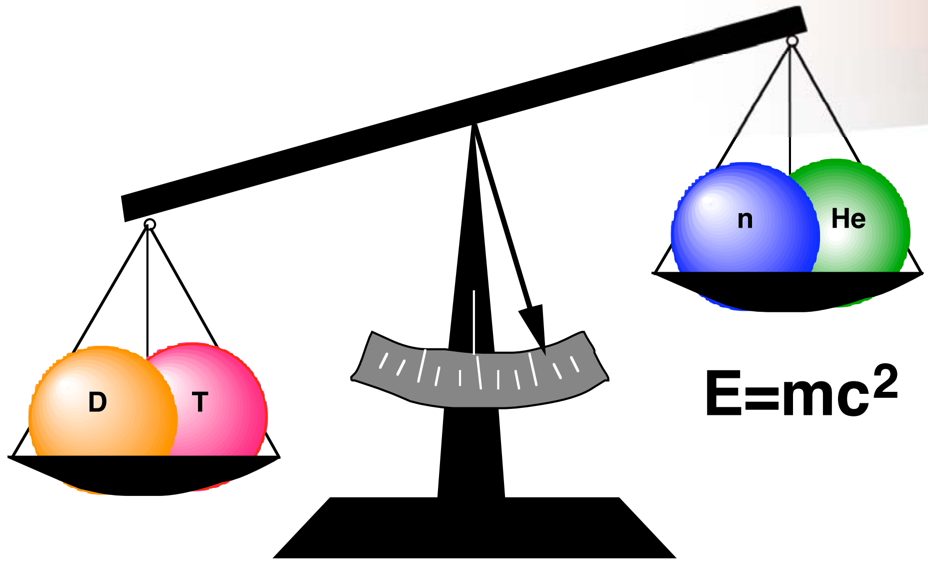
- **No Air Pollution of Greenhouse Gases**
  - **Reaction product is Helium**

- **Minimal or No High Level Nuclear Waste**
  - **Careful material selection should minimize waste caused by neutron activation**

FUEL NEEDED FOR ONE YEAR OF POWER PLANT OPERATIONS (1000 MWe)



Mass Converted to Energy in Fusion is 450 Times the Energy Input

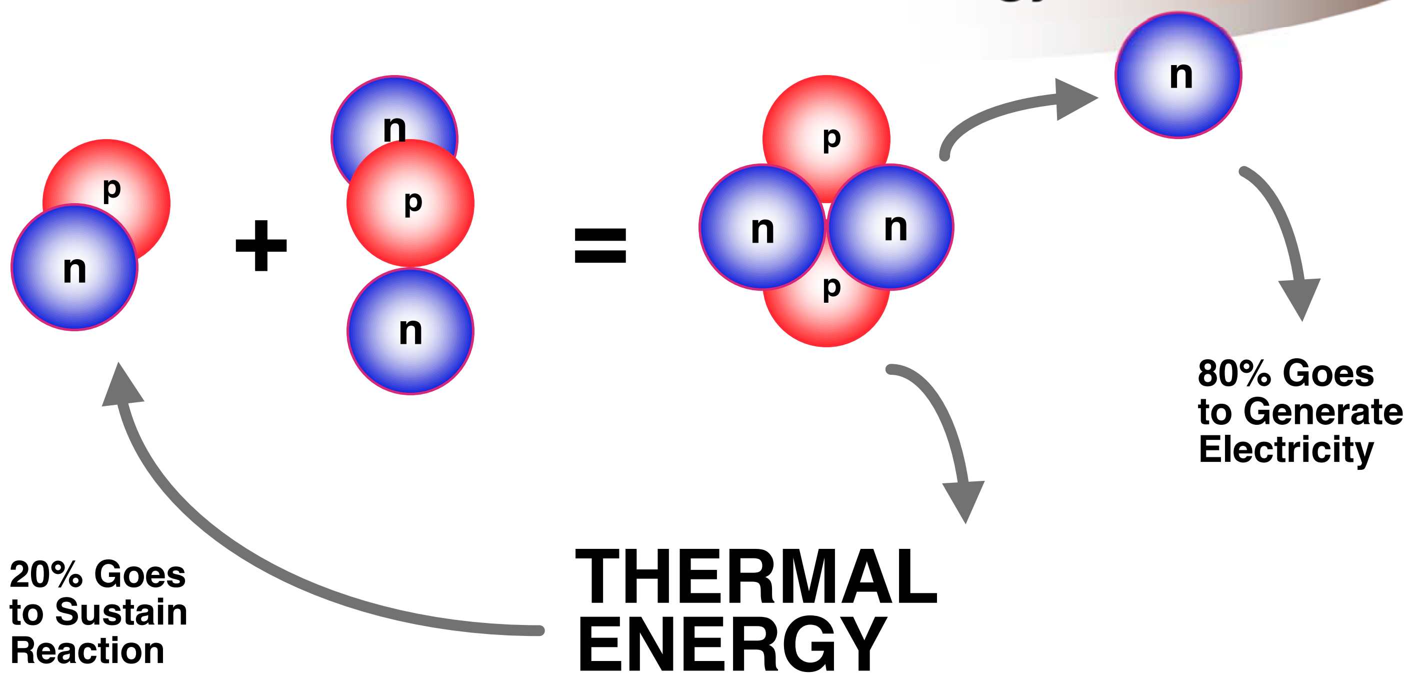


$E=mc^2$

- The fraction of mass "lost" is just 38 parts out of 10,000
- Nevertheless, the fusion energy released from just 1 gram of DT equals the energy from about 2400 gallons of oil

Fusion Process

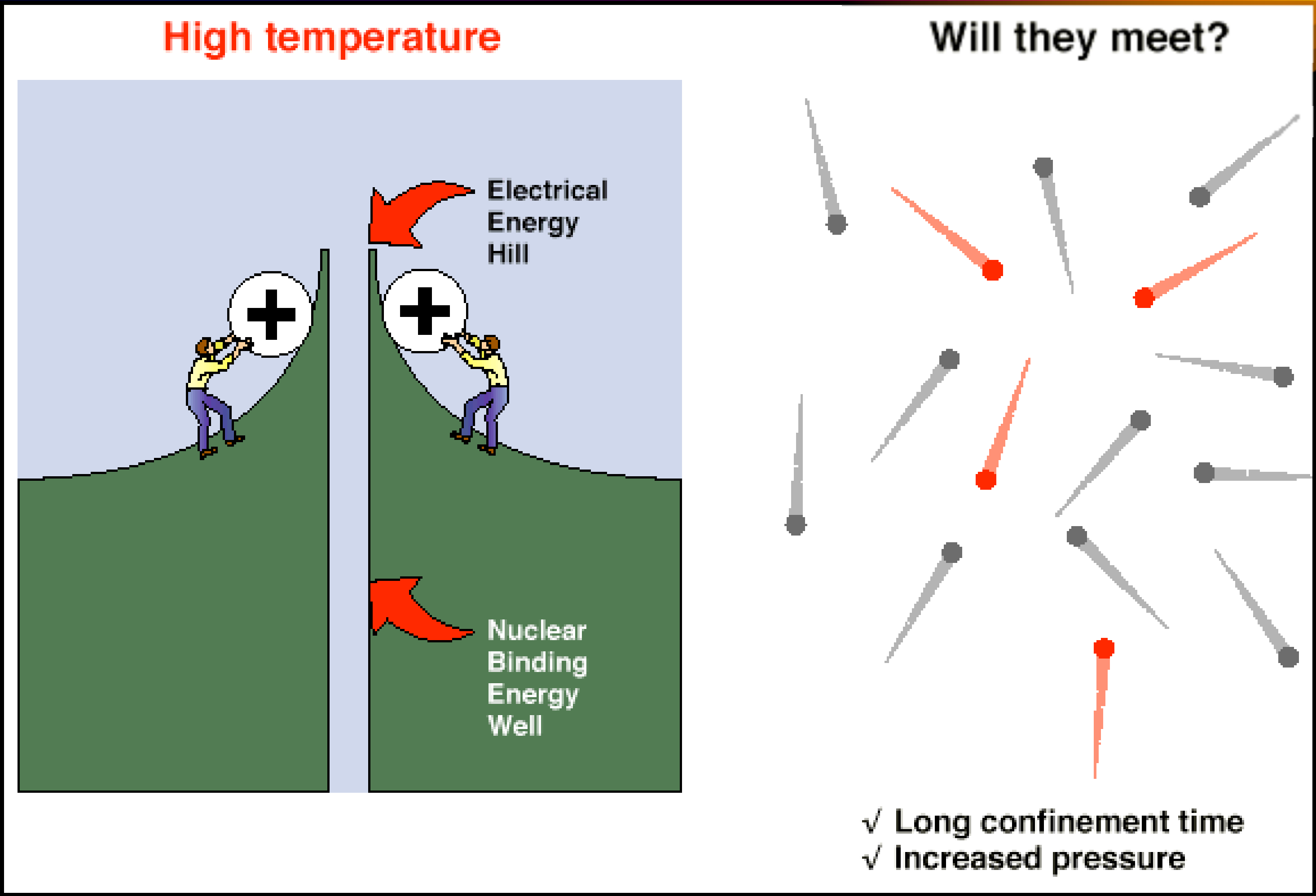
Deuterium + Tritium = Helium + n + Energy



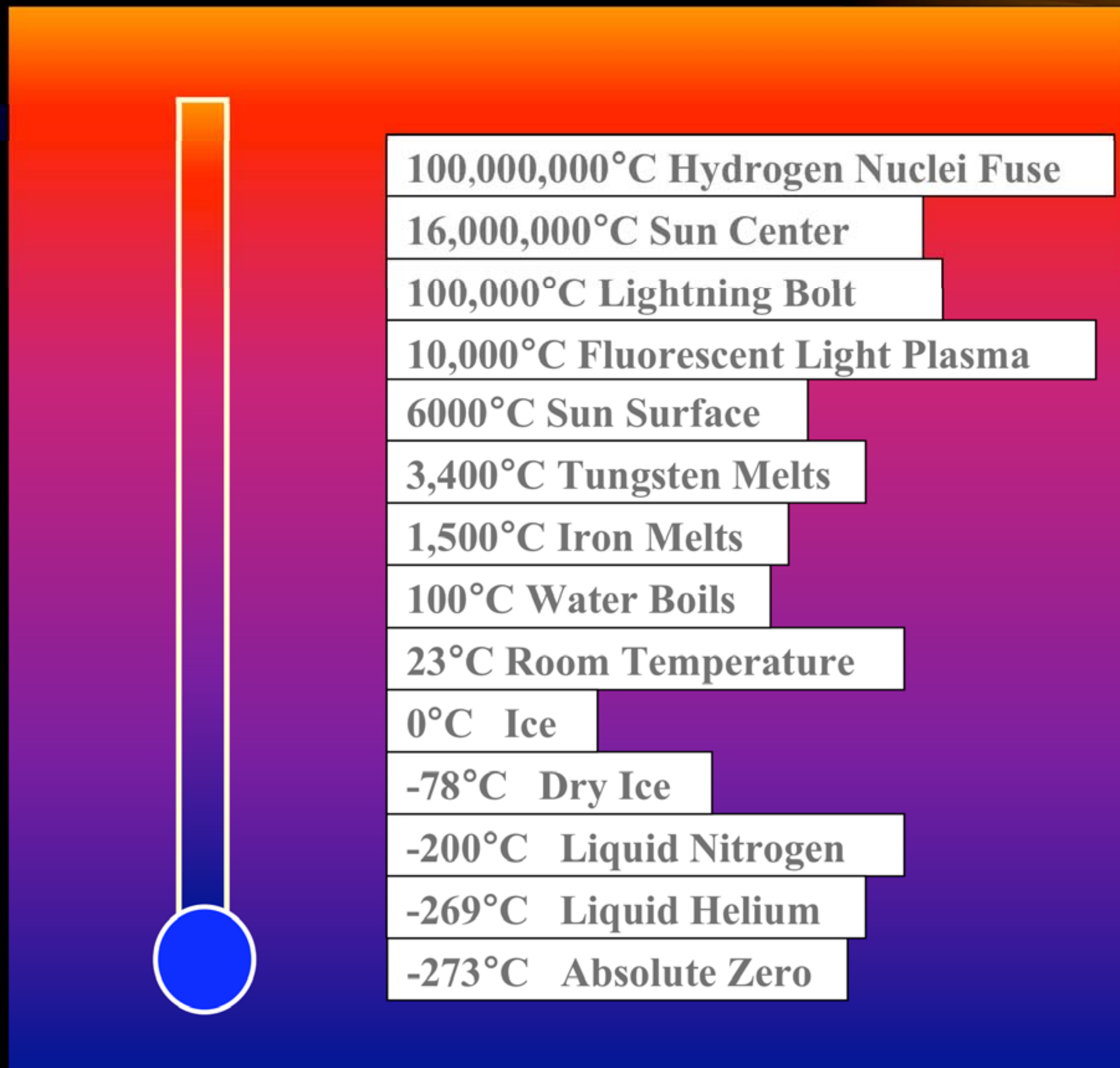
Different Fusion Reactions Require Different Temperatures and Have Different Energy Yields

Reaction: Fuel	Reaction: Product	Ignition Temperature (millions of °C)	Ignition Temperature (keV)	Output Energy (keV)
D + T	^{4}He + n	220	20	17,600
D + ^{3}He	^{4}He + p	350	30	18,300
D + D	^{3}He + n	400	35	~4,000
	T + p	400	35	~4,000

Like Charged Particles Repel Each Other



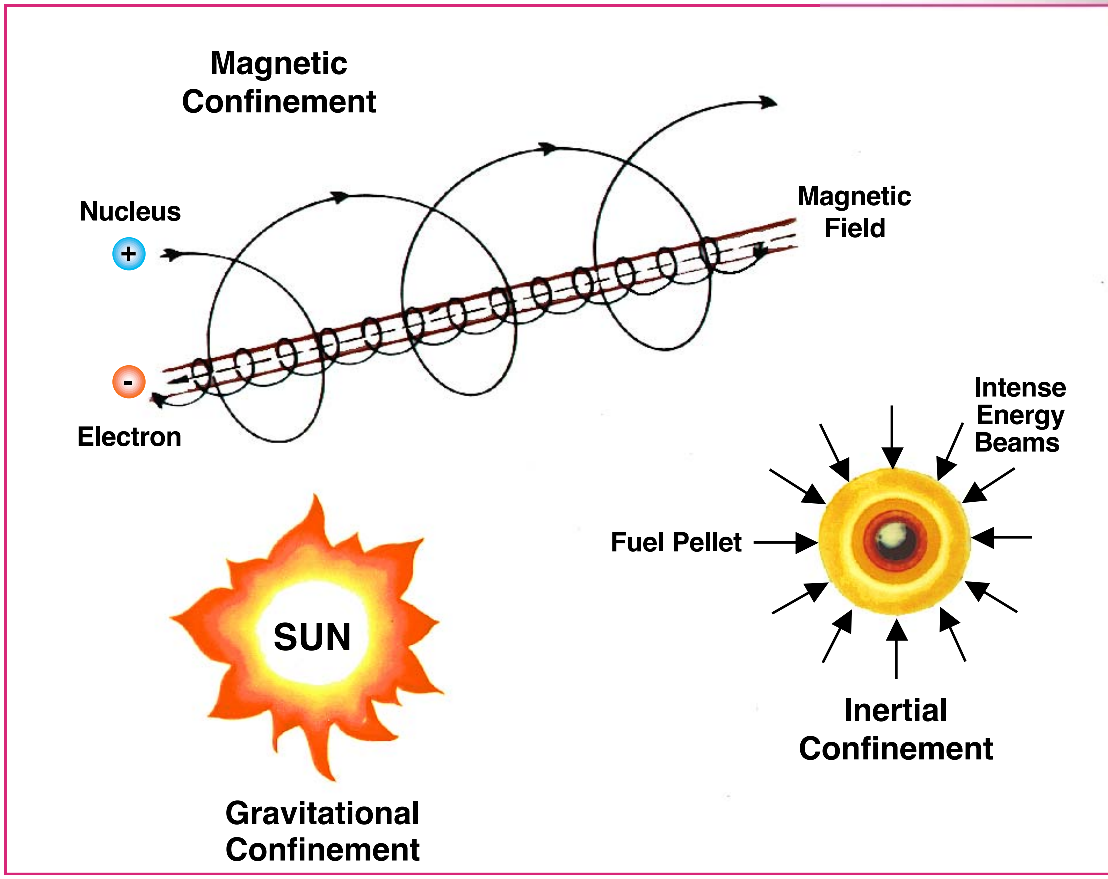
Very High Temperature is Required



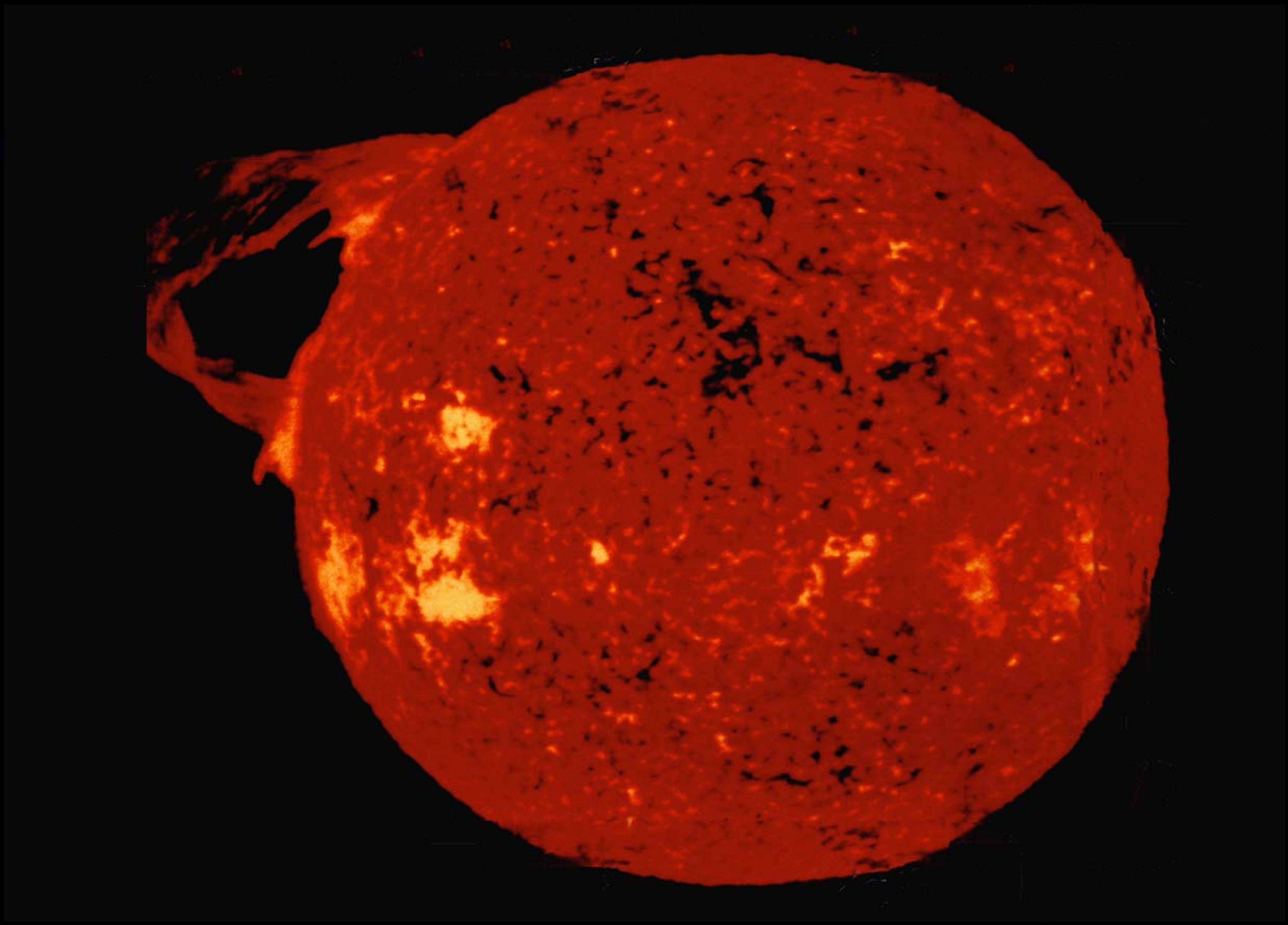
Methods to Heat Deuterium-Tritium Fuel

- Compressing the fuel
- Internal Electric Current
- Neutral Particles
- Microwaves
- Lasers

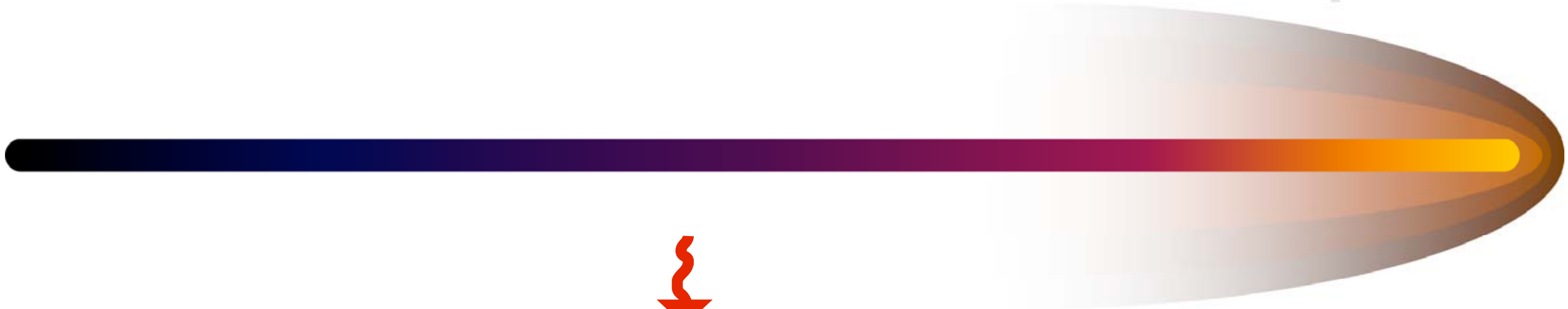
Fusion Confinement Can be Accomplished in Three Different Ways



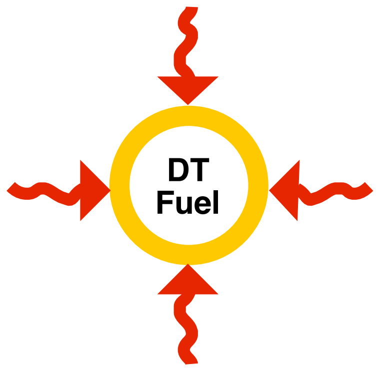
GRAVITATIONAL CONFINEMENT WORKS



Inertial Confinement Fusion Concept

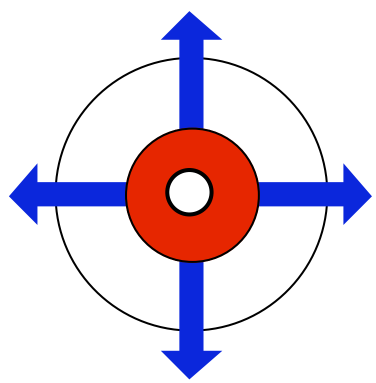


Heating
of
ablator



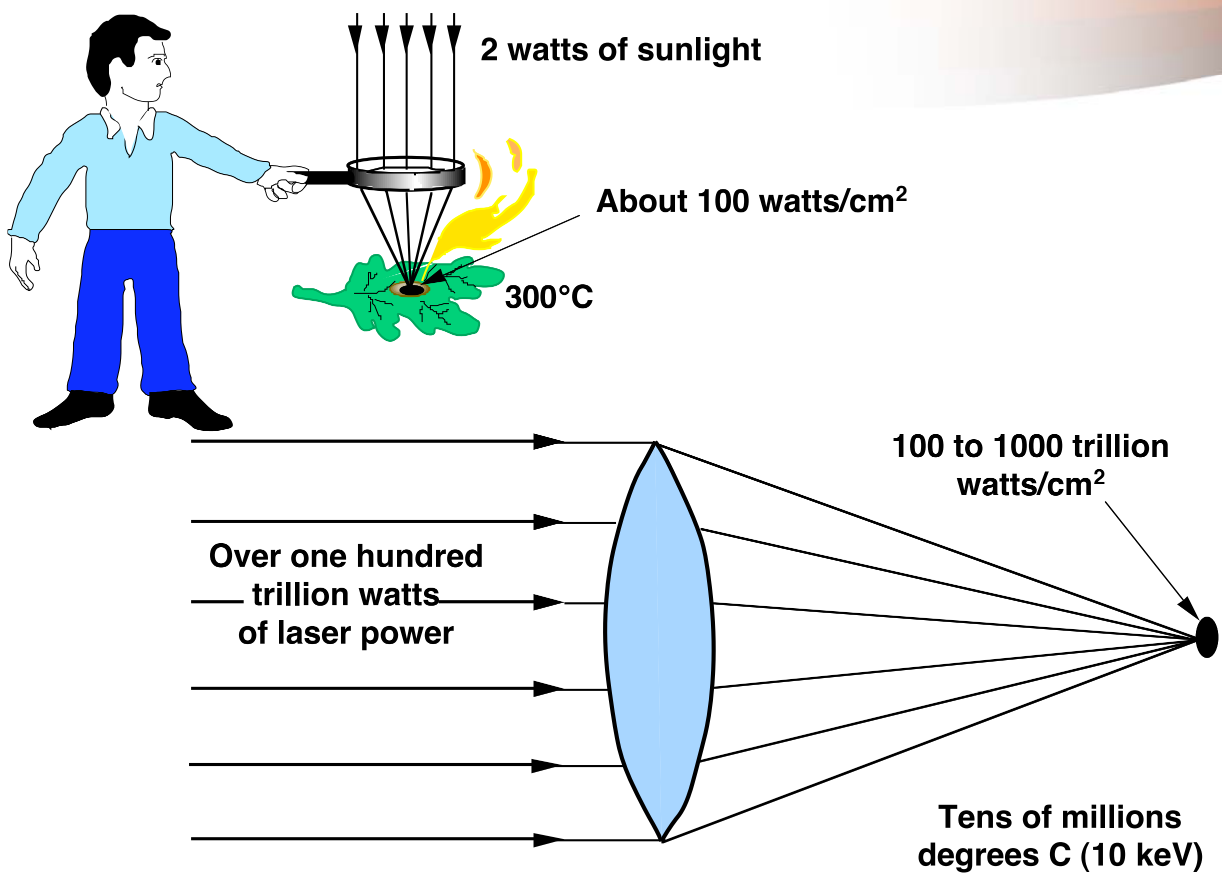
Use high power
laser to heat
outer surface of pellet

Ablation
and
compression

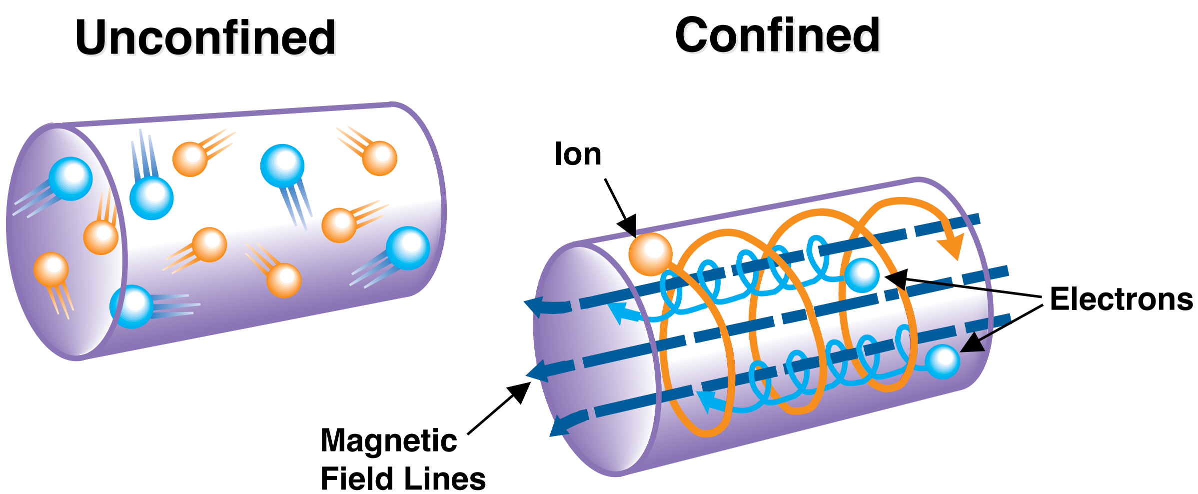


Outward streaming ablator
material produces an inward
directed, rocket-like
force that compresses
the DT fuel

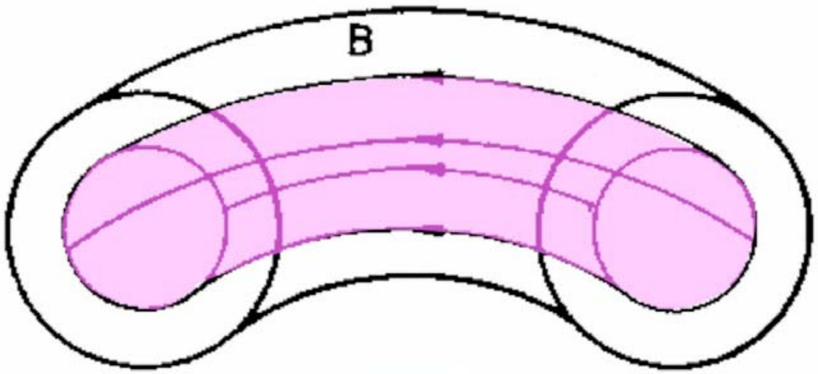
High Power Lasers can Deliver the Intensity Required for Fusion Ignition



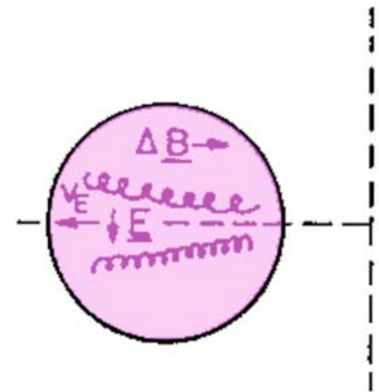
Magnetic Fields Can Hold Plasmas Away from a Vessel Wall

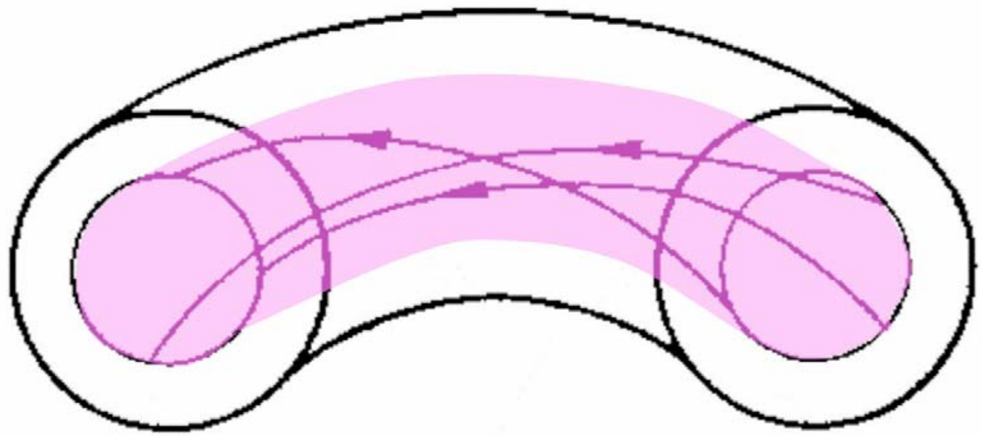


Toroidal System Bends the Magnetic Field Into a Closed "Doughnut"



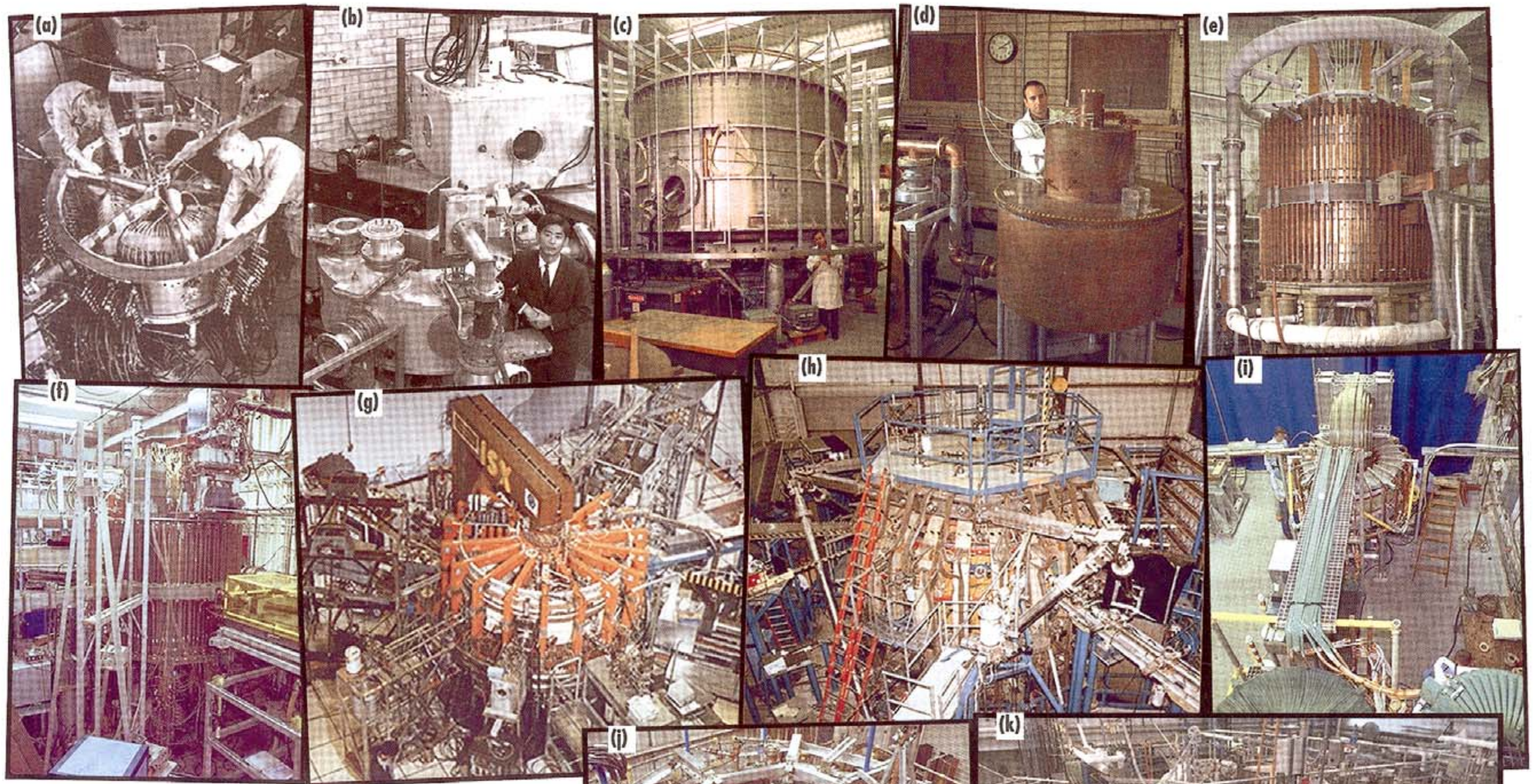
Pure toroidal field

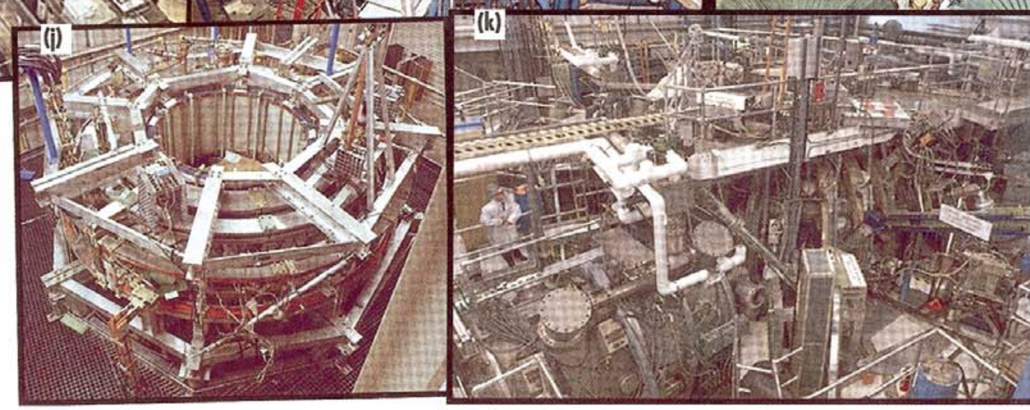




Toroidal plus poloidal field

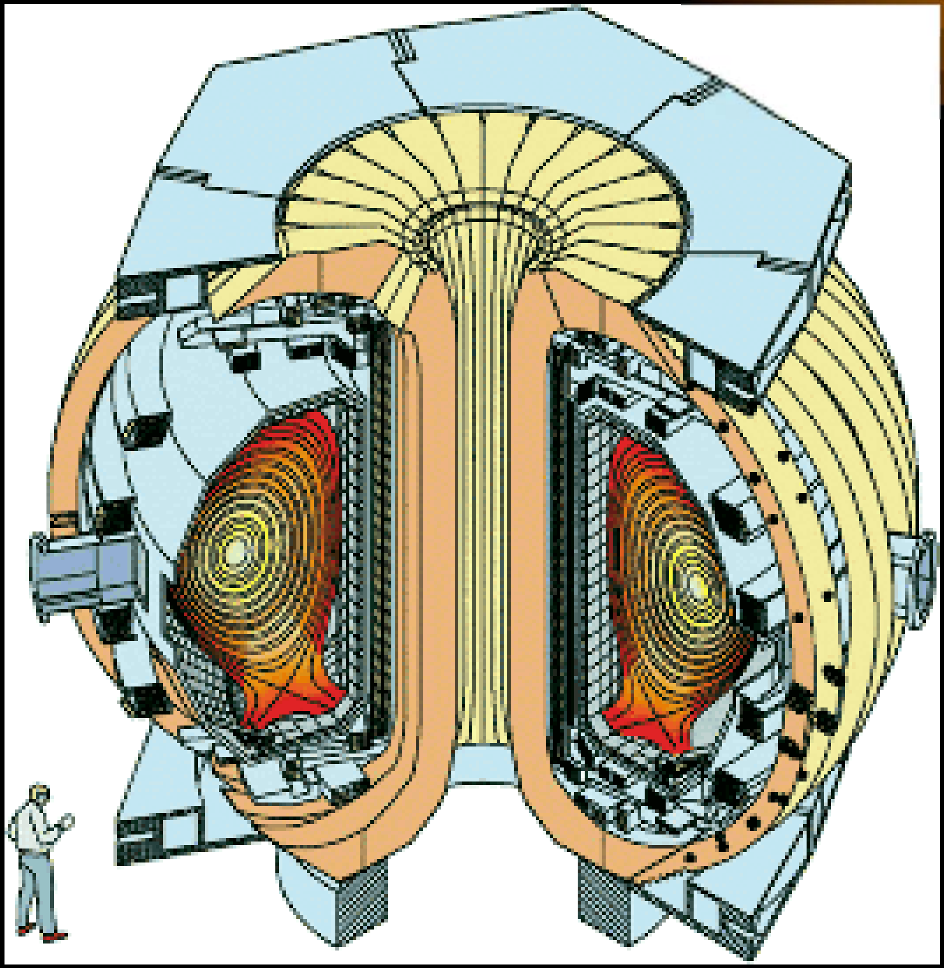
FUSION RESEARCH AT GENERAL ATOMICS 1960-PRESENT

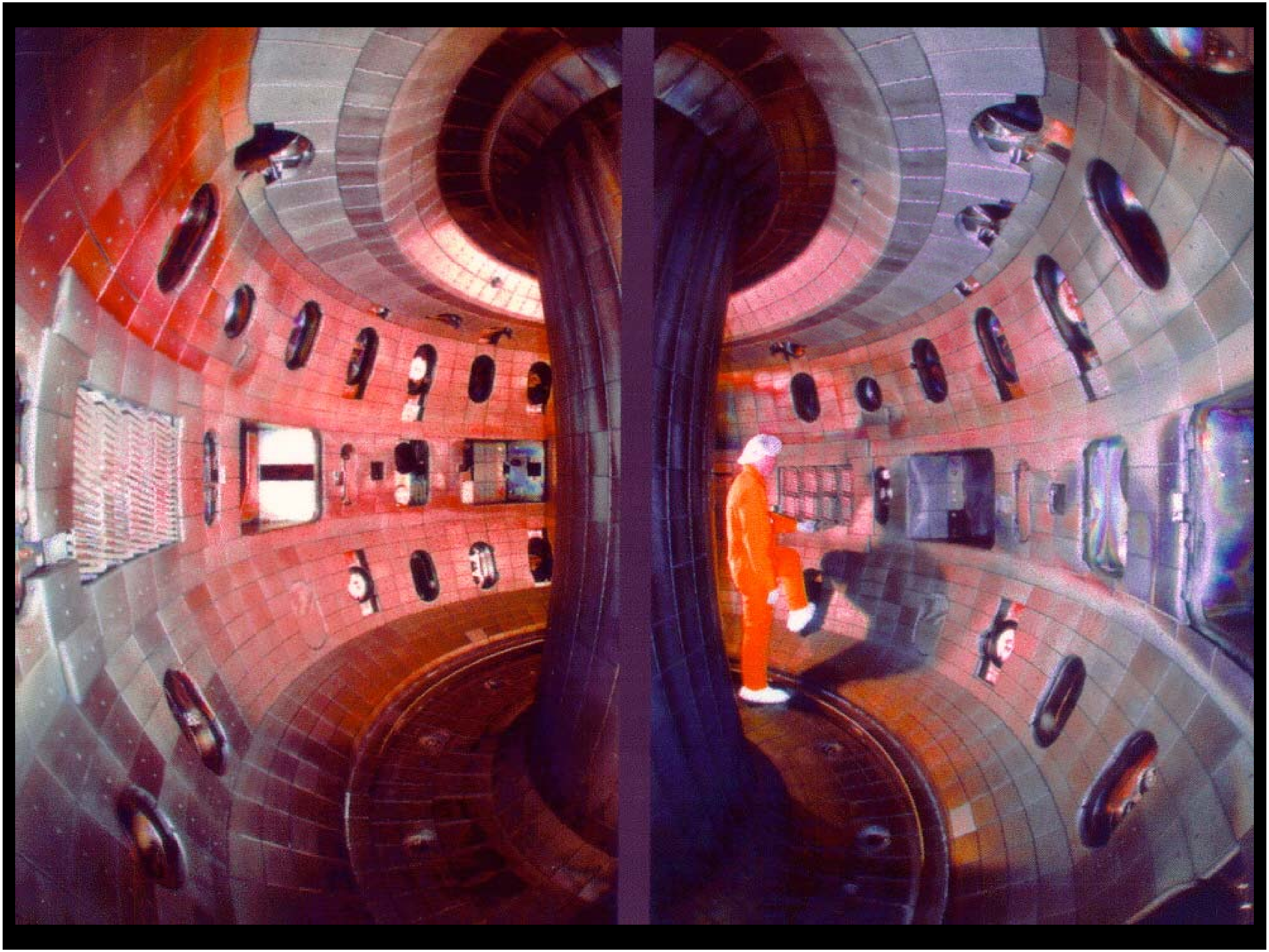




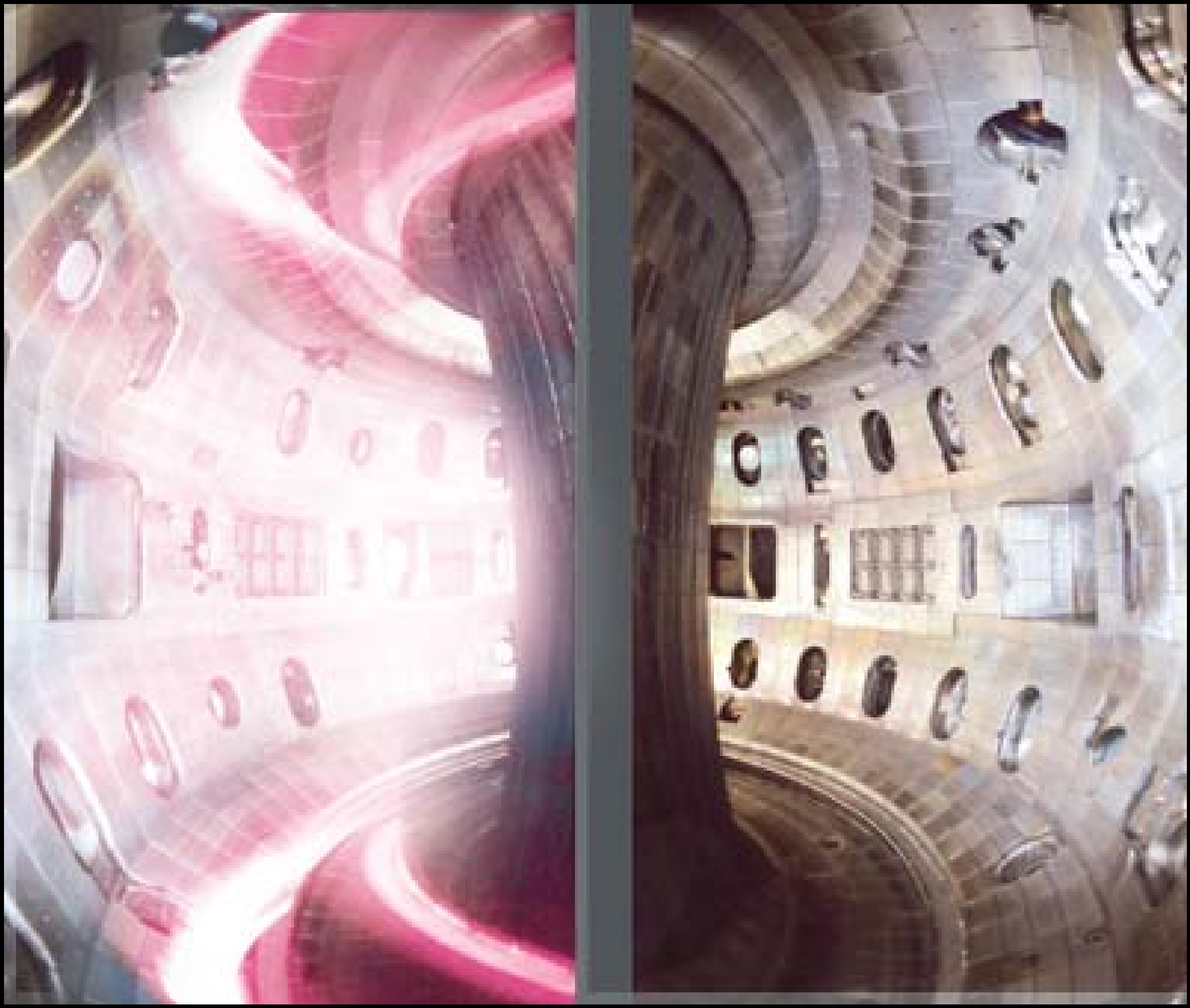
(a) **Toroidal Pinch** (1960)
(b) **Toroidal Multipole** (1966-1967)
(c) **DC Octopole** (1969-1977)
(d) **Doublet I** (1968-1969)
(e) **Doublet II** (1971-1974)
(f) **Doublet IIA** (1974-1978)
(g) **ISX-A, ORNL** (1977-1978)
(h) **Doublet III** (1978-1984)
(i) **Multipinch** (1984-1985)
(j) **OHTE** (1981-1988)
(k) **DIII–D** (1986-Present)

DIII-D Tokamak Operated by General Atomics, San Diego

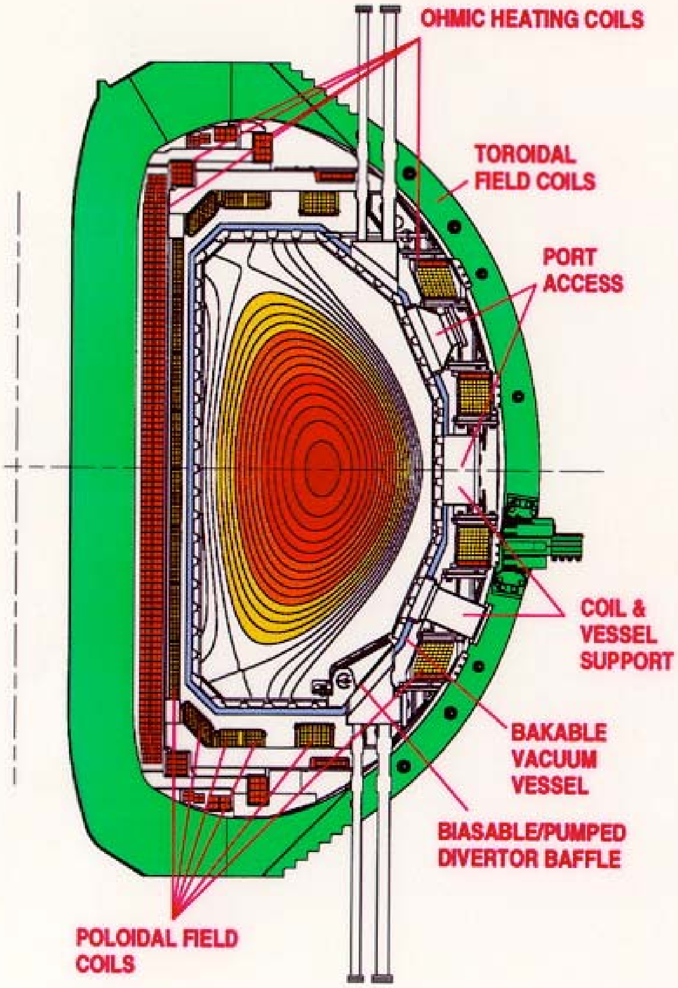




DIII-D with Plasma and No Plasma



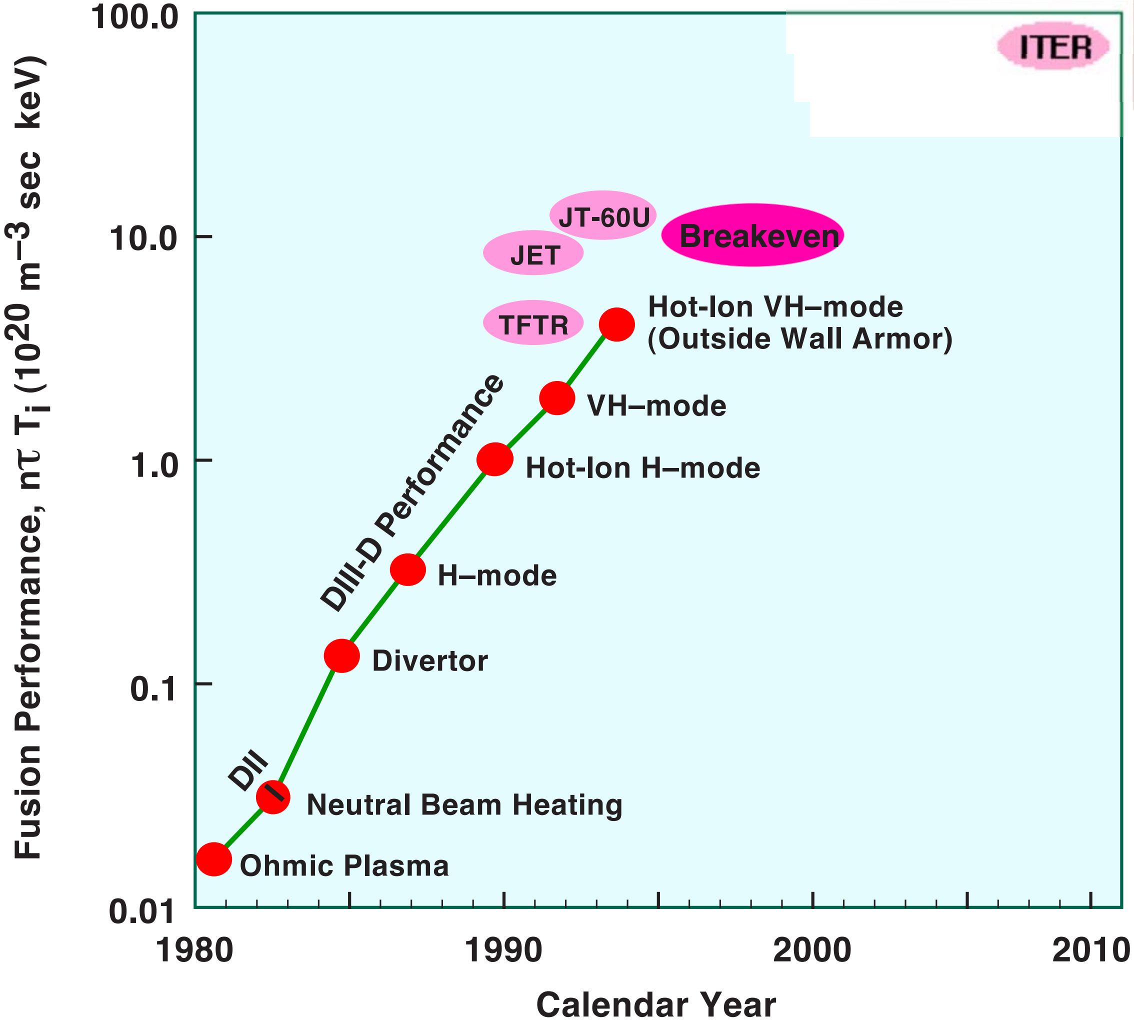
DIII–D TOKAMAK CAPABILITIES



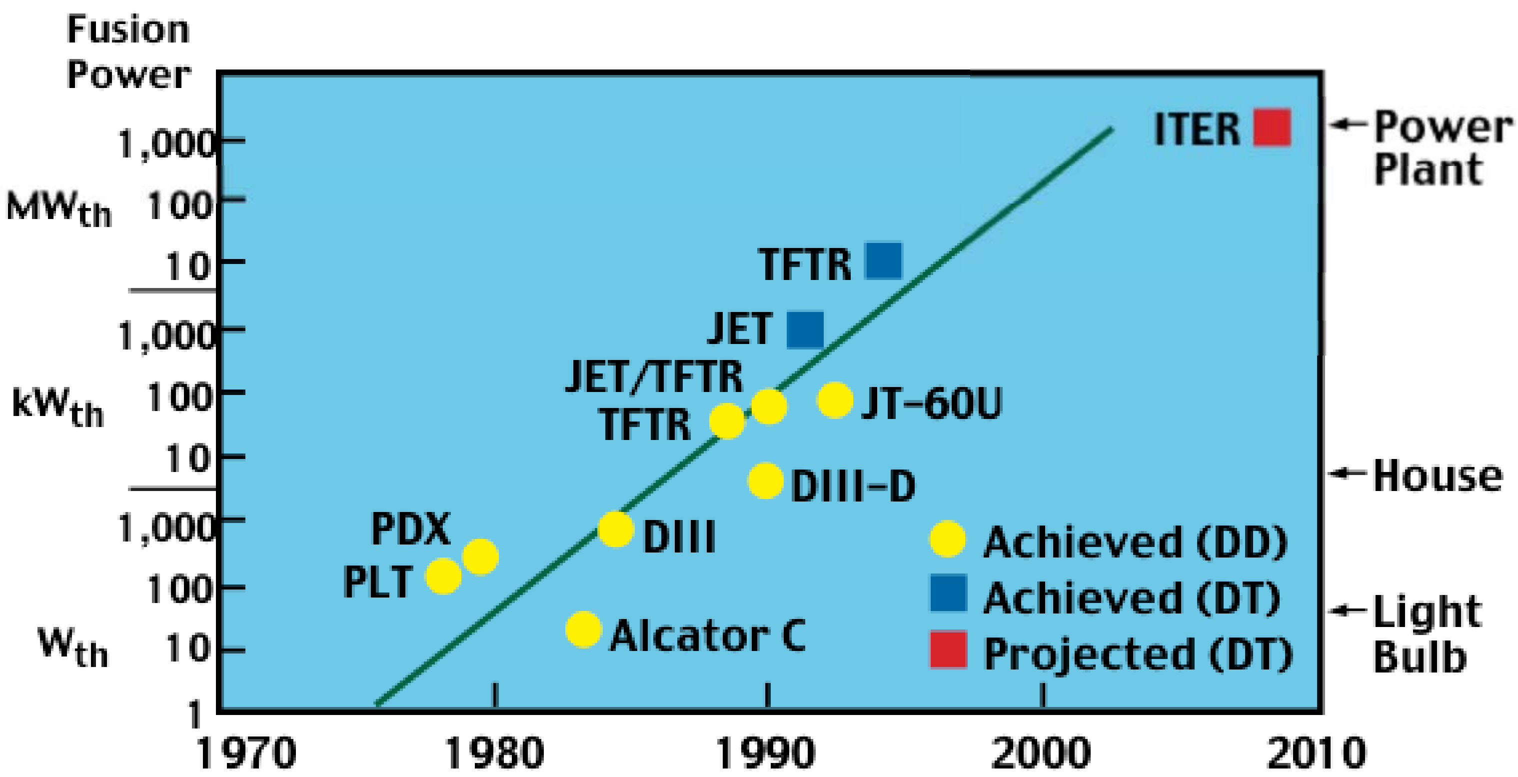
	PRESENT	PROPOSED
Major radius	1.67 m	
Minor radius	0.67 m	
Maximum toroidal field	2.2 T	
Available OH flux	5.0 V–s	7.5 V–s
Maximum plasma current	3.0 MA	3.5 MA
Neutral beam power (80 keV)	20 MW	
ECH power (110 GHz)	2 MW	10 MW
ICH power (30–120 MHz)	6 MW	
Current flattop (divertor at 2 MA)	5 s	10 s

GENERAL ATOMICS

Huge Progress Has Been Made Toward the Goal of Fusion Energy Production



PROGRESS IN MAGNETIC FUSION POWER



Alcator C: Massachusetts Institute of Technology

DIII & DIII-D: General Atomics Tokamak Experiment

ITER: International Thermonuclear Experiment Reactor

JET: Joint European Torus

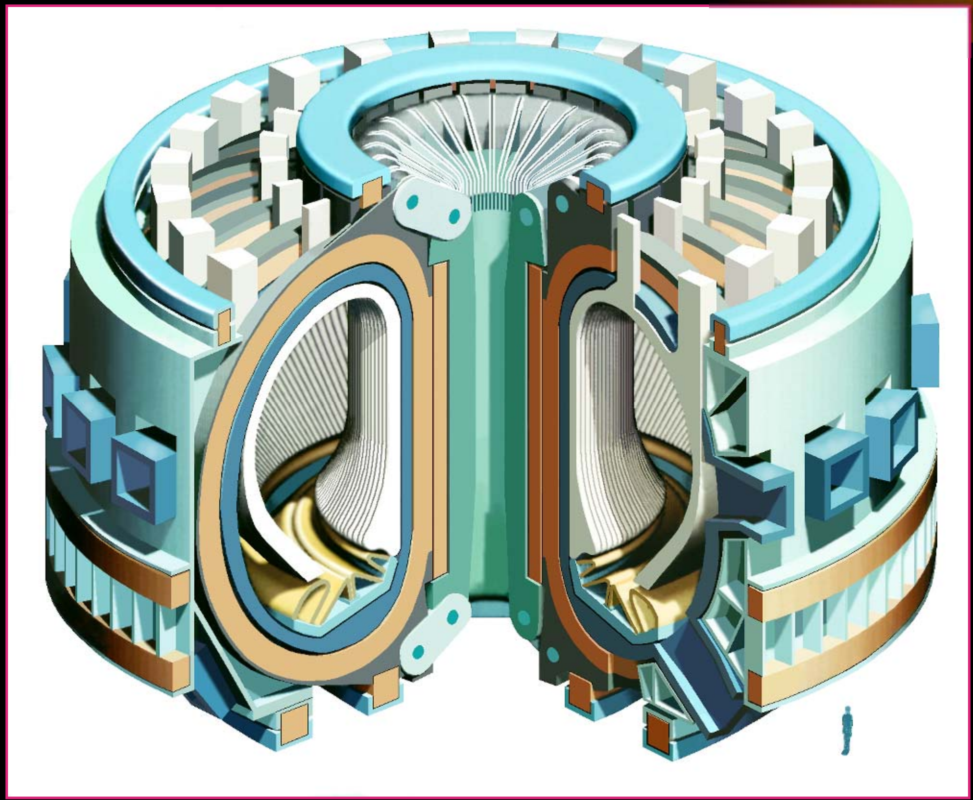
JT-60U: Japanese Tokamak Experiment

TFTR: Princeton Plasma Physics Laboratory

PDX: Princeton Divertor Project

PLT: Princeton Large Tokamak

ITER
(International Thermonuclear Experimental Reactor)



30 meters diameter
30 meters tall

Technical Challenges for Fusion Development

- Materials development
  - Survive high heat flux (10 MW/m^2)
  - Retain strength despite neutron activation
  - Minimize production of activated wastes

- Develop safe and efficient Tritium handling techniques
  - Develop breeding technologies for Tritium from Lithium blankets
  - Minimize Tritium inventory for improved safety

- Reduce size, cost, and complexity to make competitive with other energy sources

Prospect for Fusion Energy

- Most of the key problems have been solved! Now the goal is to make a fusion reactor *competitive*...
- Major international experimental reactor expected to be built ~2010 (ITER).
- Demonstration reactor could be built ~2030 - 2040.
- With sufficient funding, Fusion could be a major energy source at the end of this century.