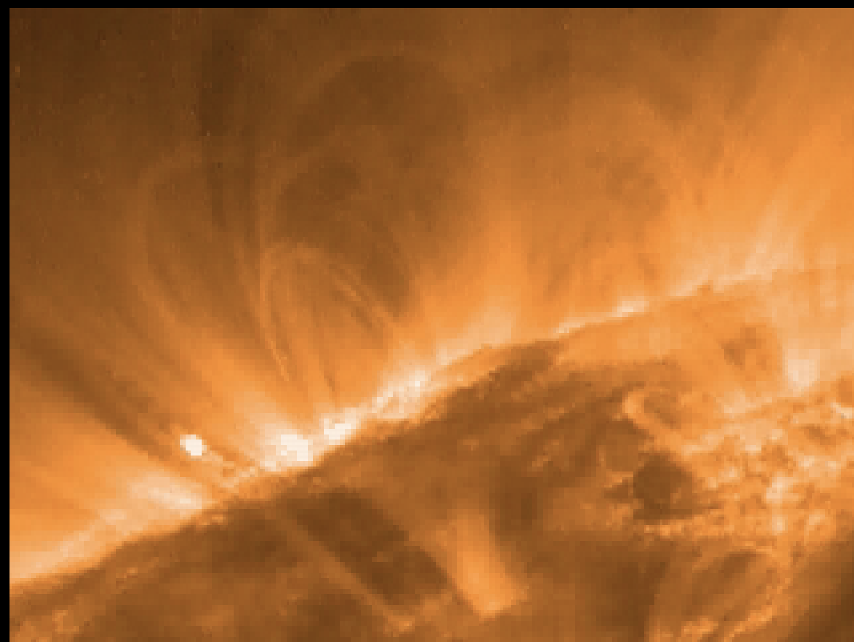
Fusion Energy: Creating a Star on Earth

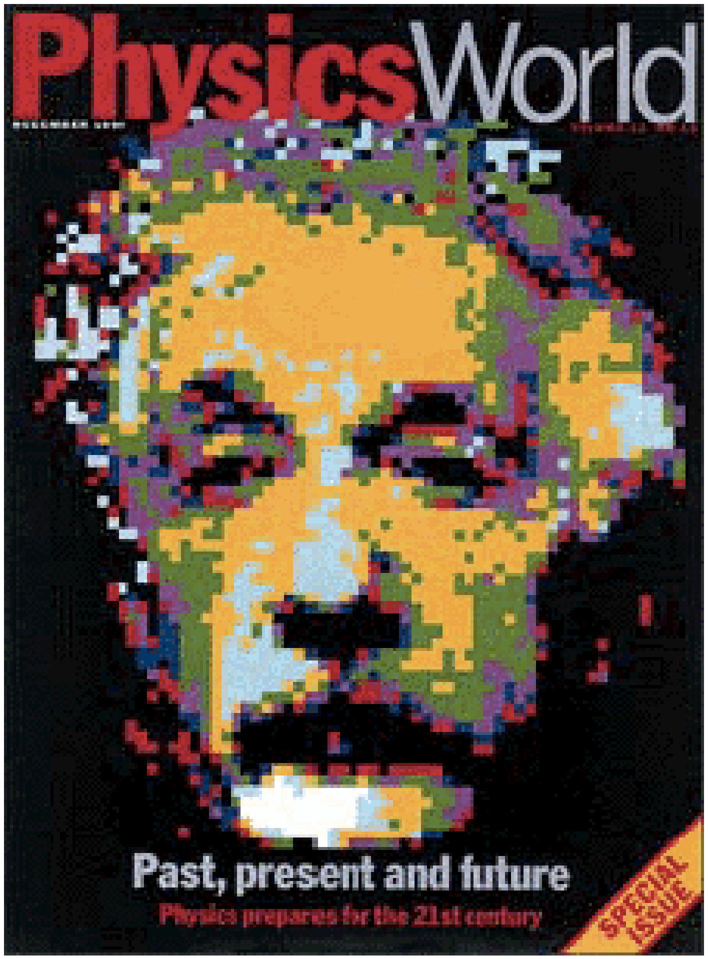


Andrew Post-Zwicker
Princeton University
Plasma Physics Laboratory

A Campus Nestled in the Woods of New Jersey

Fusion is an Outstanding Physics Challenge and is Connected to other Outstanding Challenges

December 1999



<u>Ten Outstanding Physics Challenges</u>

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-T_c superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view

Fusion

- ***The Energy Source of the Future***
- ***Always has been…***
- ***Always will be!***

Plasmas are very common!

- **Natural Plasmas**

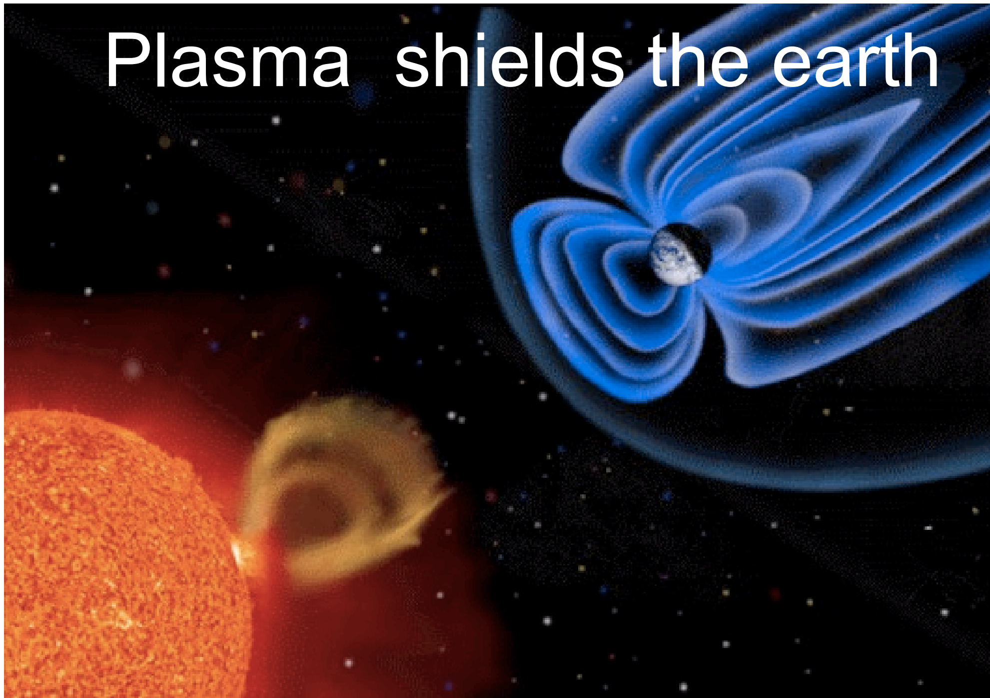
  Flames
  Lightning
  Aurora, ionosphere
  Stars

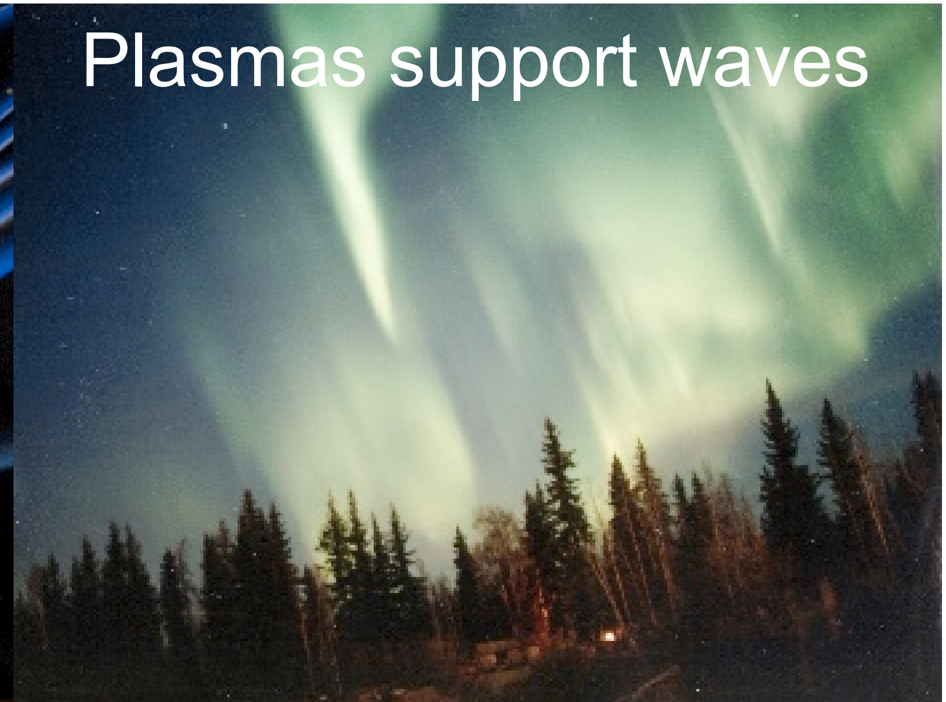
- **Created Plasmas**

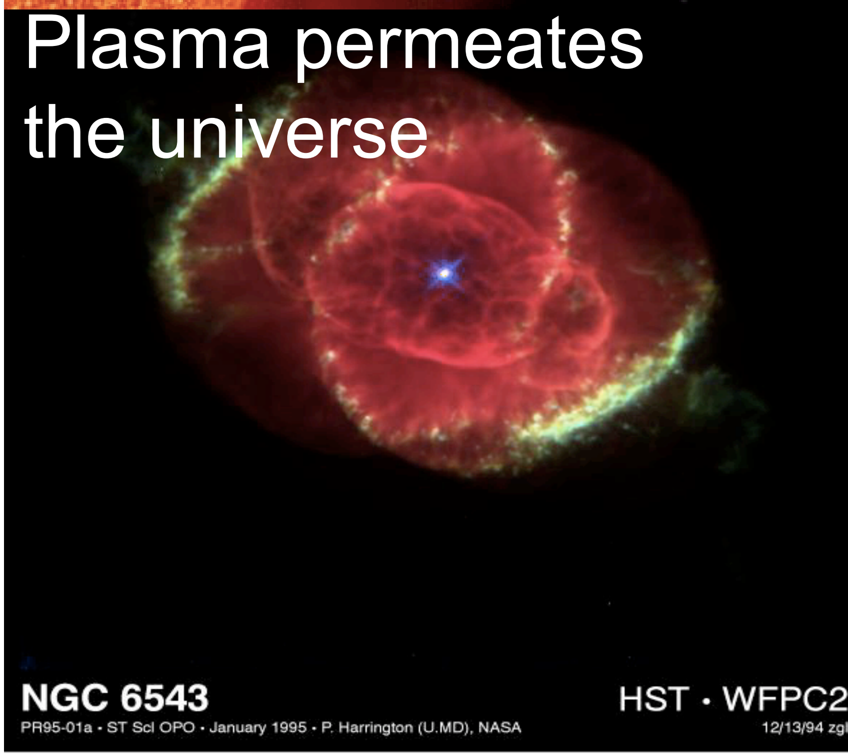
  Fluorescent lights, neon signs
  Arc welding, arc furnaces
  Power switches
  Semiconductor chip manufacture

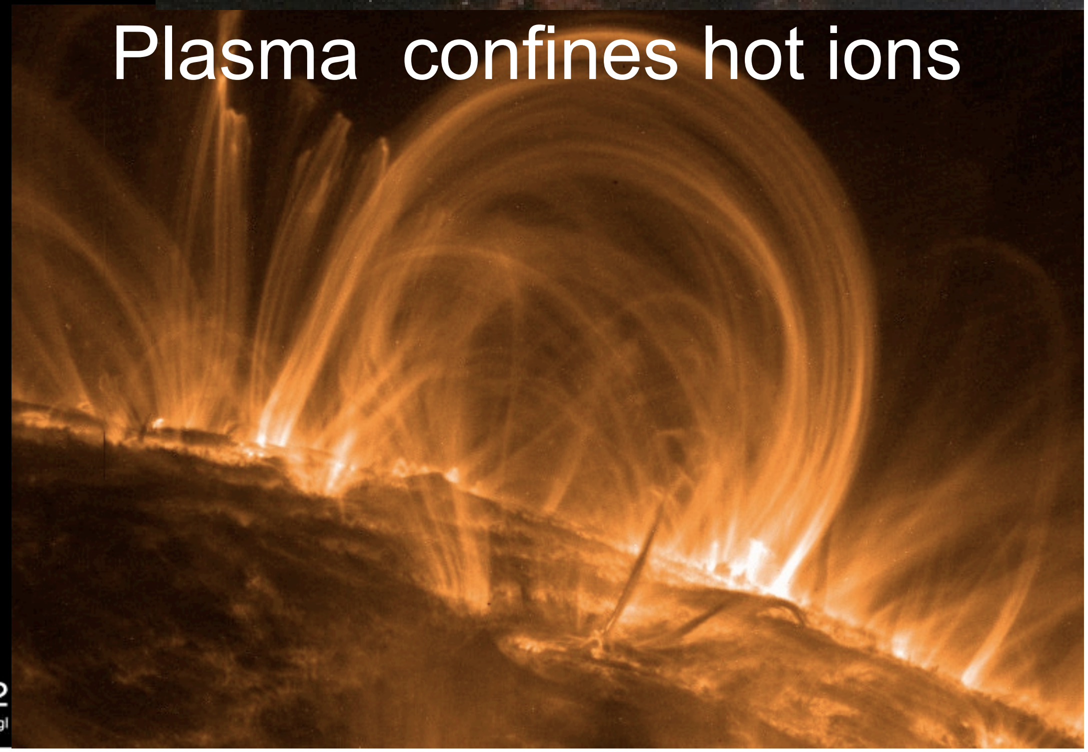
Why are we interested in plasmas?

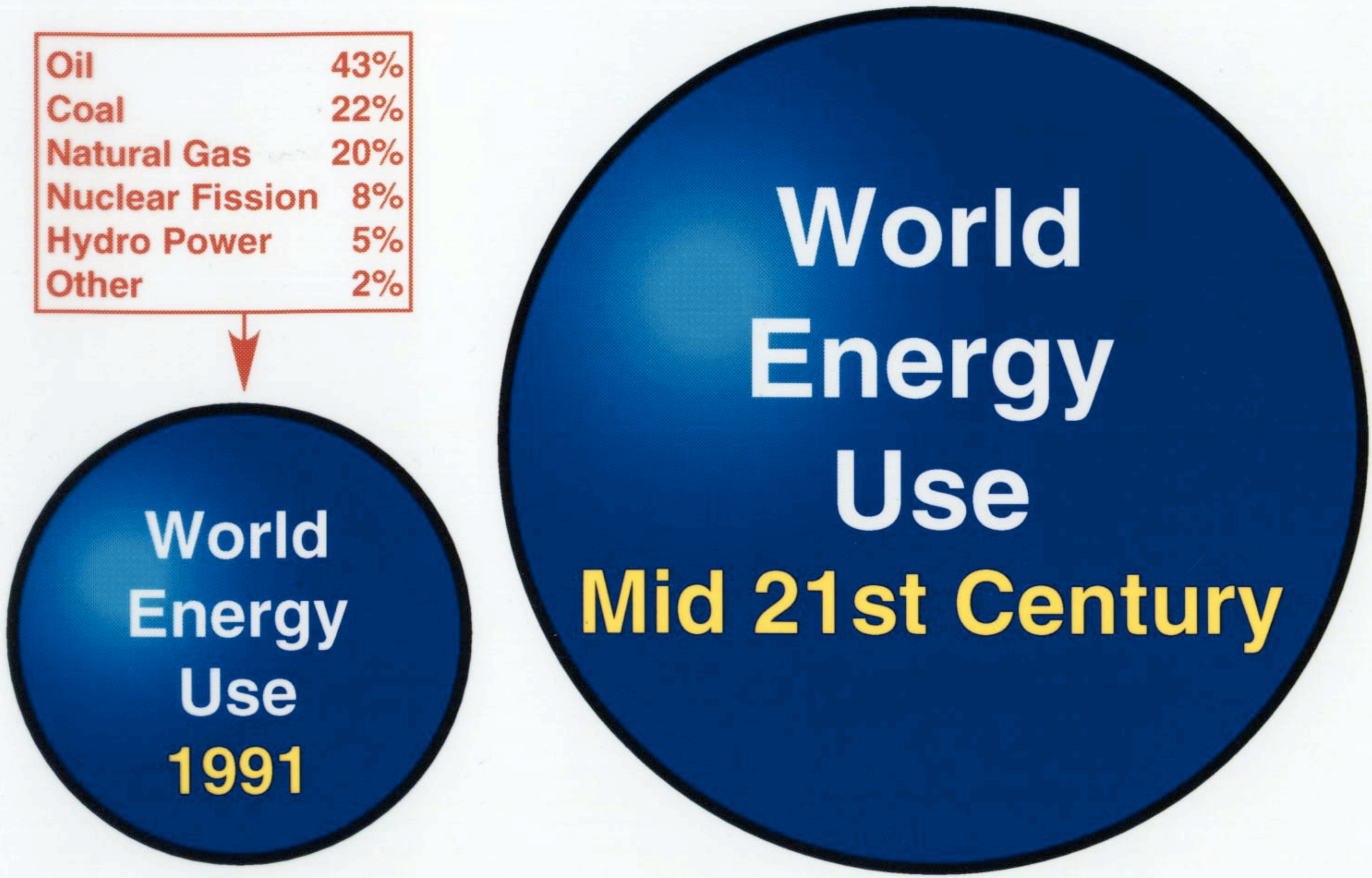
- Fusion Energy
  - Potential source of safe, abundant energy.
- Astrophysics
  - Understanding plasmas helps us understand stars and stellar evolution.
- Upper atmospheric dynamics
  - The upper atmosphere is a plasma.
- Plasma Applications
  - Plasmas can be used to build computer chips and to clean up toxic waste.


Plasma shields the earth


Plasmas support waves


Plasma permeates
the universe
NGC 6543
HST • WFPC2
PR95-01a • ST ScI OPO • January 1995 • P. Harrington (U.MD), NASA
12/13/94 zgl


Plasma confines hot ions



PPPL#91X0528

How Would it Work ?

- Nuclear fusion of deuterium-tritium
- Requirements for ignition of DT fuel
- Methods for hot plasma confinement
- Conceptual design of a fusion reactor

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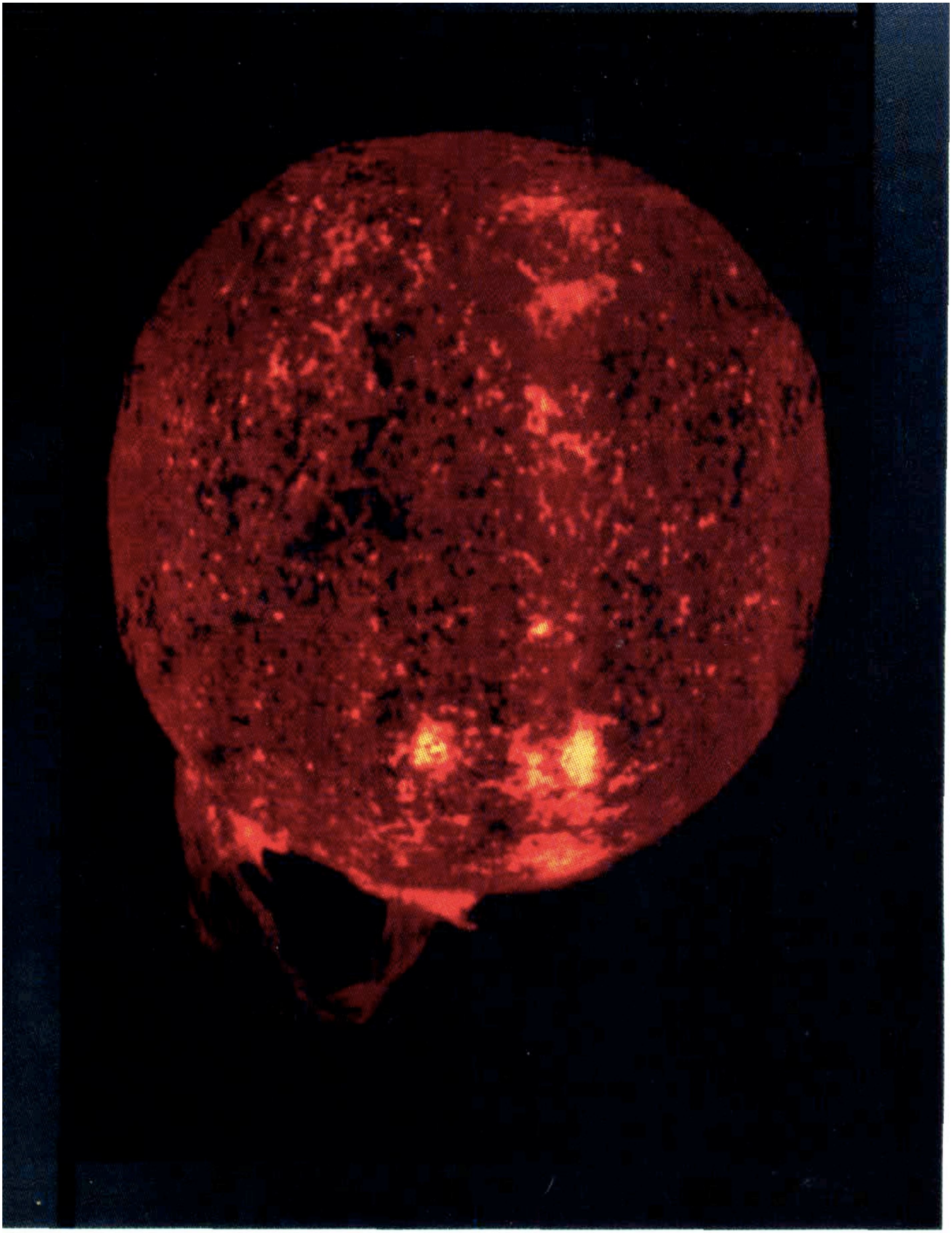

Fusion Fuel is Readily Available

- Deuterium isotope ≈ 1/ 7000 of hydrogen atoms in all water and can be extracted at a negligible cost (≈ $1/gr)
- Deuterium in 1 gallon of water has the same energy as 300 gallons of gasoline, if burned in a fusion D-T reactor
- Tritium can be created from D-T neutrons in a Li "blanket"

  $Li^6 + n \rightarrow T + He^4 + 4.8$ MeV (7% natural Li)

  $Li^7 + n \rightarrow T + He^4 + n - 2.5$ MeV (93% natural Li)

- For a 1000 MW Fusion Reactor buring D-T fuel for 1 year:

  Input: 400 lbs Deuterium + 600 lbs Tritium (1300 lbs. Li)

  Output: 900 lbs of helium + activated structure

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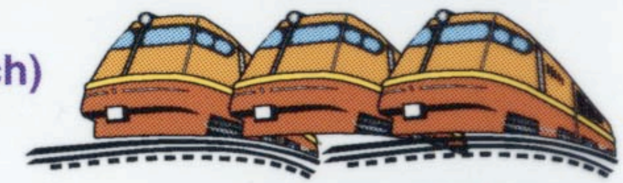
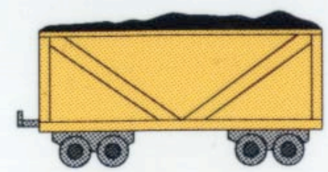
Annual Fuel Requirements for a 1000 MW_e Power Plant

Coal	2,500,000 ton	250 trains (100 cars each) (160 lbs/sec)	
Oil	11,000,000 barrels	11 super tankers (15 gallons/sec)	
Fission	28 tons UO_2	1.5 rail car load (150 lbs/day)	
Fusion	400 lbs. D 600 lbs T (from 1300 lbs. of lithium-6)	pickup truck	

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What Conditions are Needed for D-T Fusion?

- **Two important properties of a fusion-grade plasma**
  - **density (n)**
    - **the number of plasma particles in a specific volume**
  - **confinement time (□)**
    - **how long the plasma can contain its heat**
- **To achieve fusion energy gain, the product**
  - **(n x □) must exceed a threshold**

•“Ignition” means plasma self-heating by D-T alpha particles

•alpha heating rate = plasma energy loss rate

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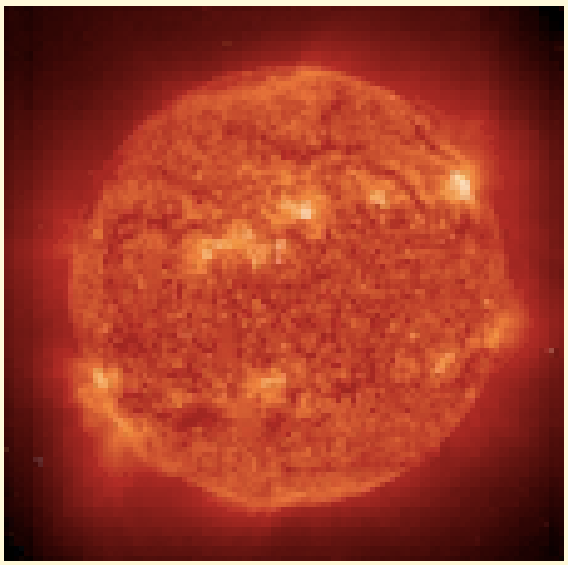
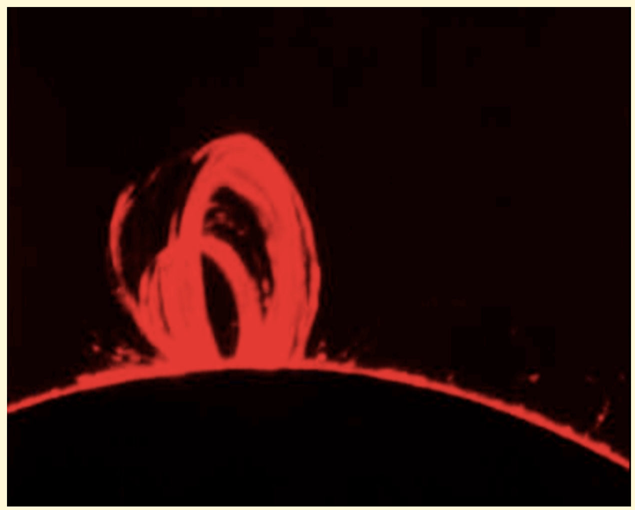
When Burned in a Fusion Reactor, the Fusion Fuel from the Top Two Inches of Lake Erie Equals <u>1.6 TIMES THE KNOWN WORLD OIL RESERVES.</u>

Methods of Hot Plasma Confinement

Fusion plasma ions move at $\approx 10^6$ m/sec so need to be confined to sustain a fusion burn



Gravitational Confinement

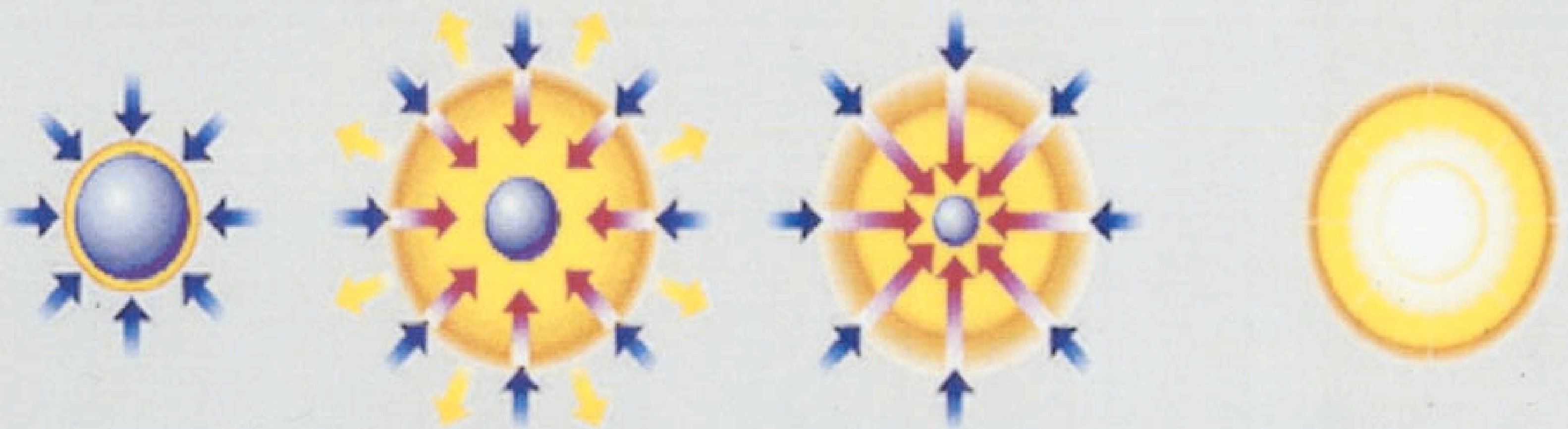


Magnetic Confinement

Inertial Confinement

The Inertial Confinement Fusion Concept

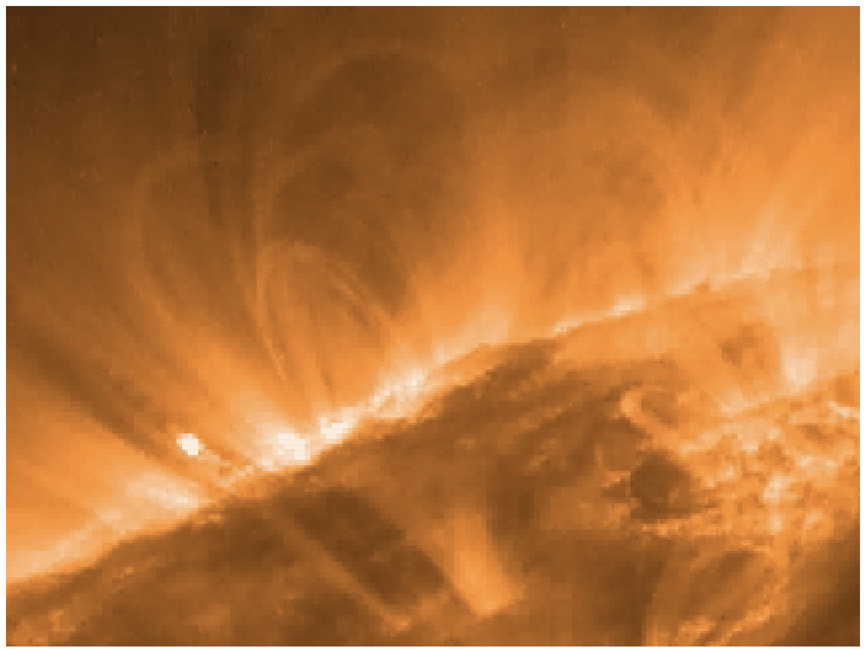
- Laser energy
- Blowoff
- Inward transported thermal energy



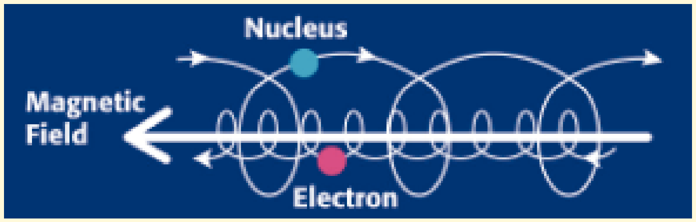
Atmosphere formation	Compression	Ignition	Burn
Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.	Fuel is compressed by the rocket-like blowoff of the hot surface material.	During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.	Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Magnetic Trapping of Solar Plasma

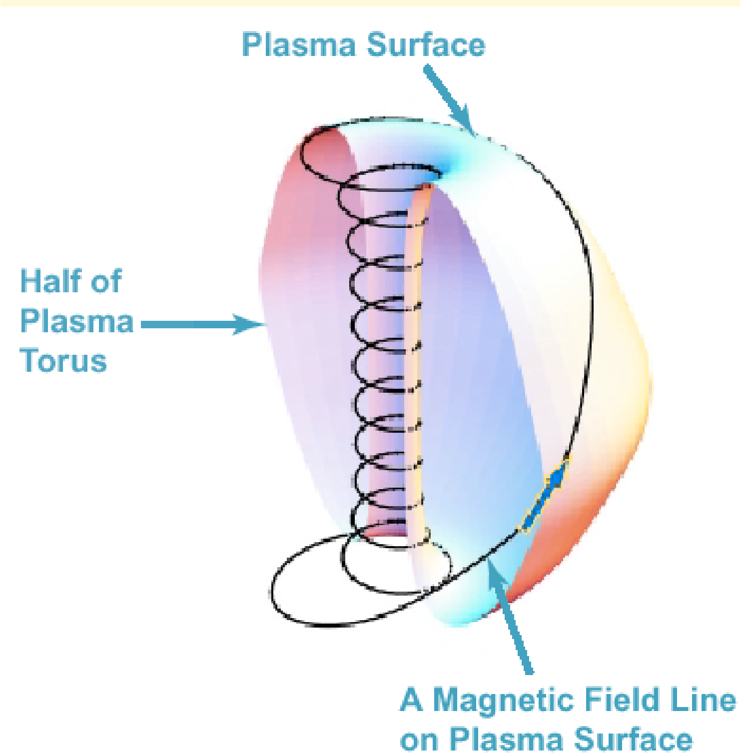
TRACE Solar Imager satellite

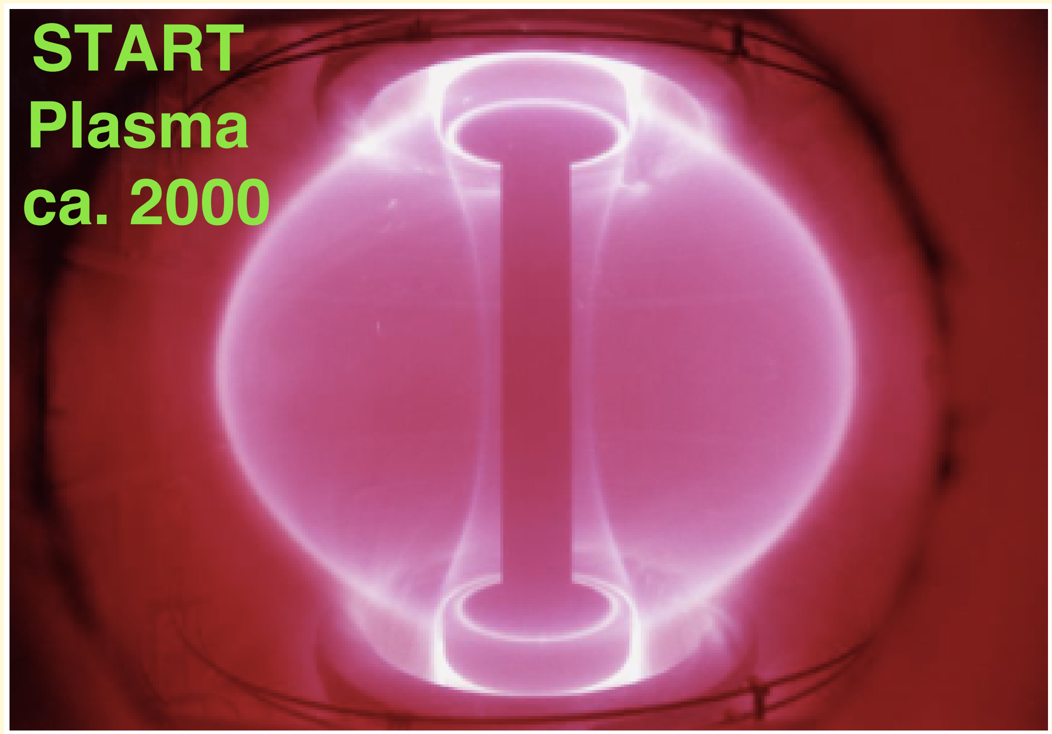


Magnetic Confinement of Plasma



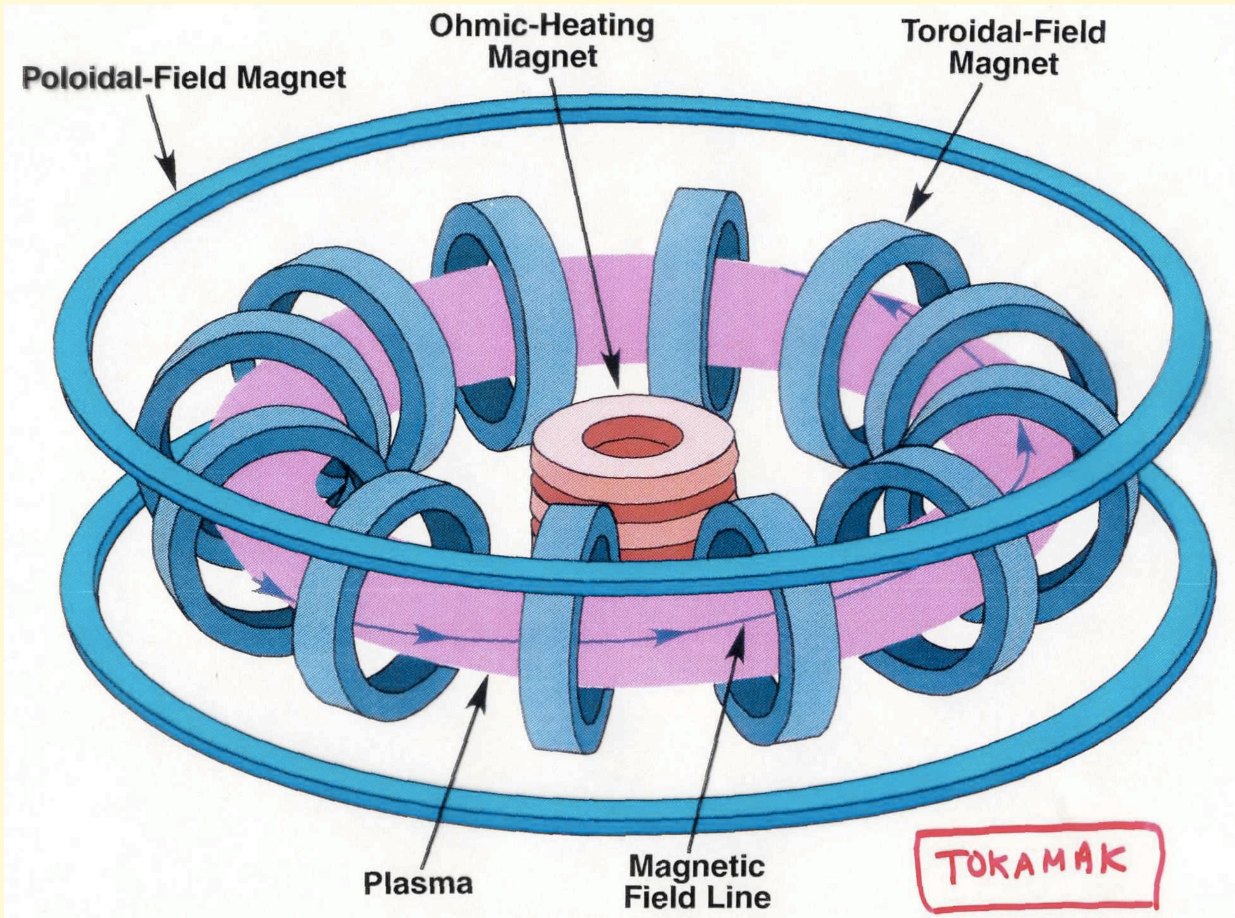
Ion gyroradius $\approx$1 cm at $T_i = 20$ keV for typical magnetic field of $B = 20$ kG





The Tokamak

Tokamak = toroidal magnetic chamber (Russian acronym)



How can we heat plasmas to fusion temperatures?

- **Electrical Resistance Heating**
  - like a toaster oven
  - As the plasma heats up, it becomes a better conductor (resistance decreases)
- **Neutral Injection Heating**
  - Energetic neutral atoms can cross the magnetic field and enter the plasma
  - In the plasma, the neutrals transfer their energy via collisions
  - Use particle accelerators to produce energetic atoms
- **Radio Wave Heating**
  - Inject waves which can be absorbed by the plasma (analogous to microwave cooking)

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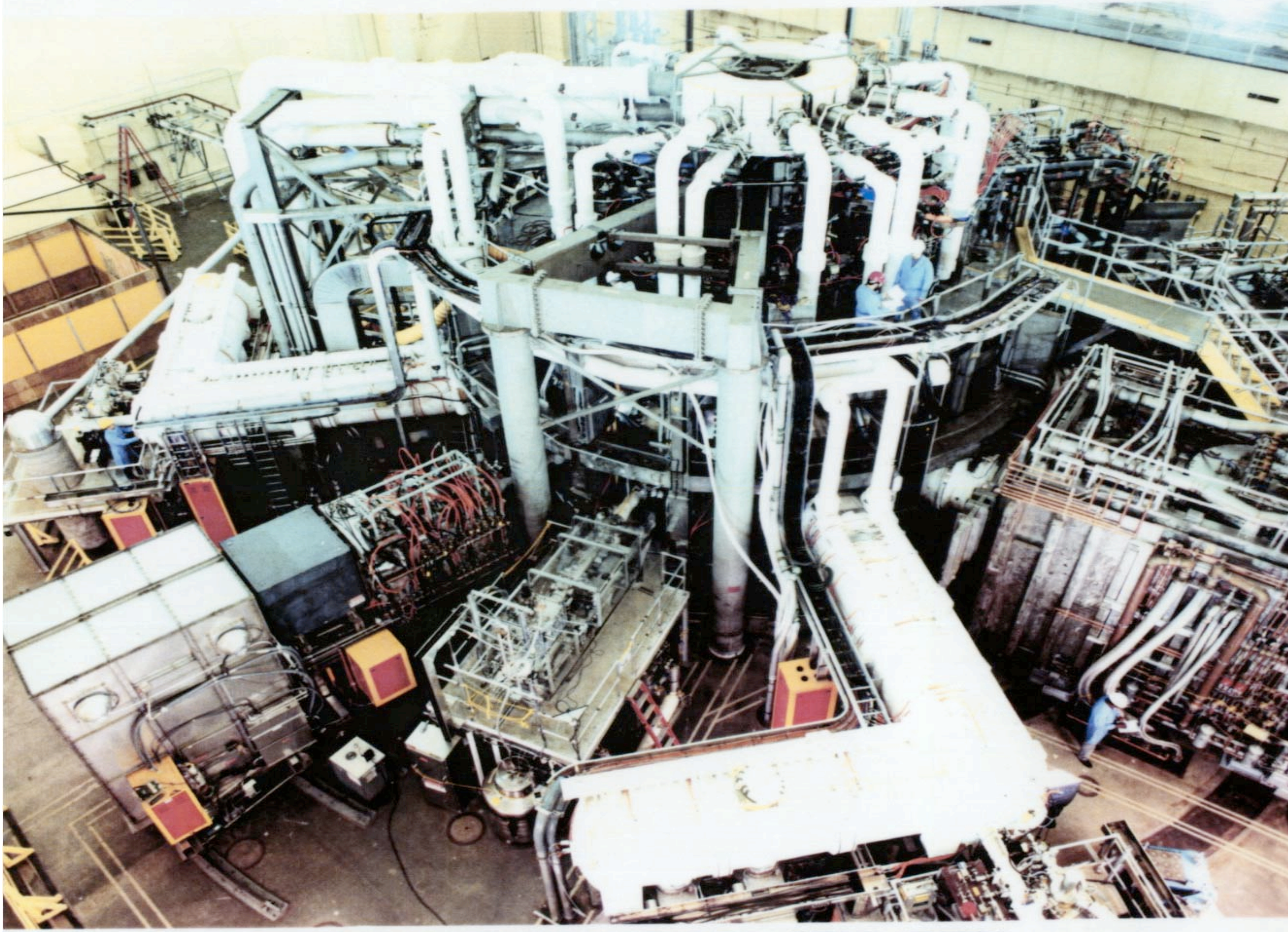
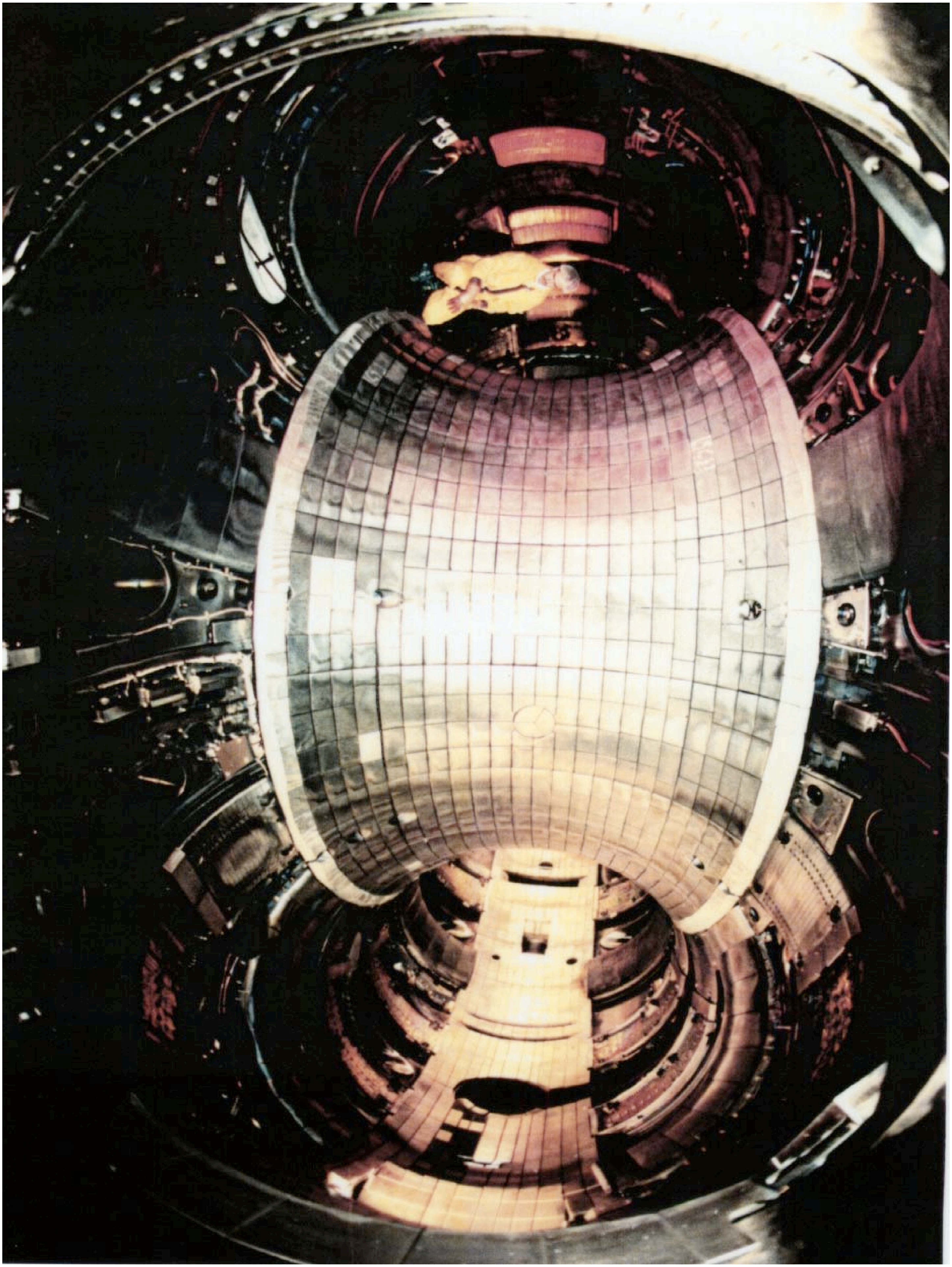
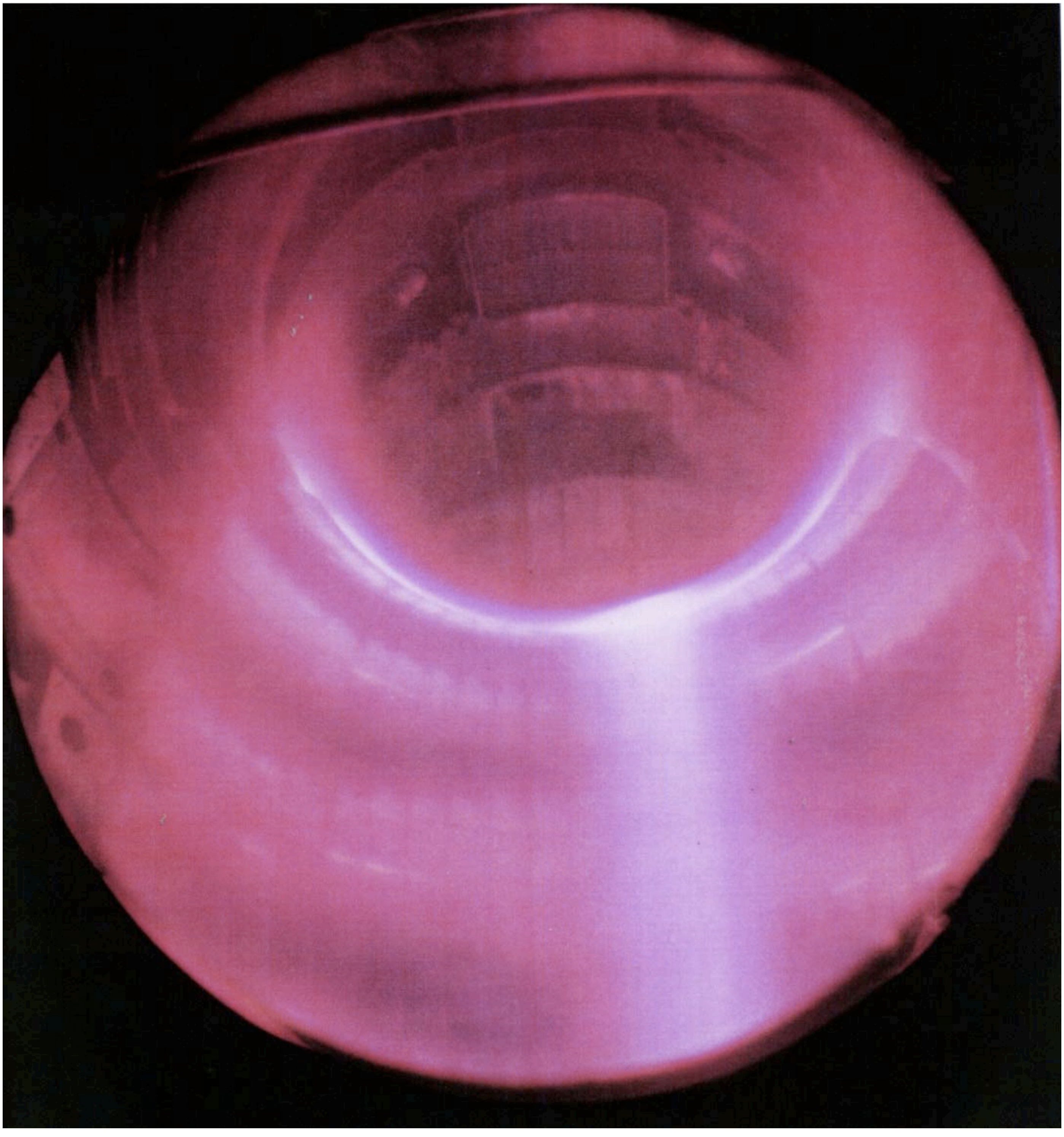


TOKAMAK FUSION TEST REACTOR (TFTR)

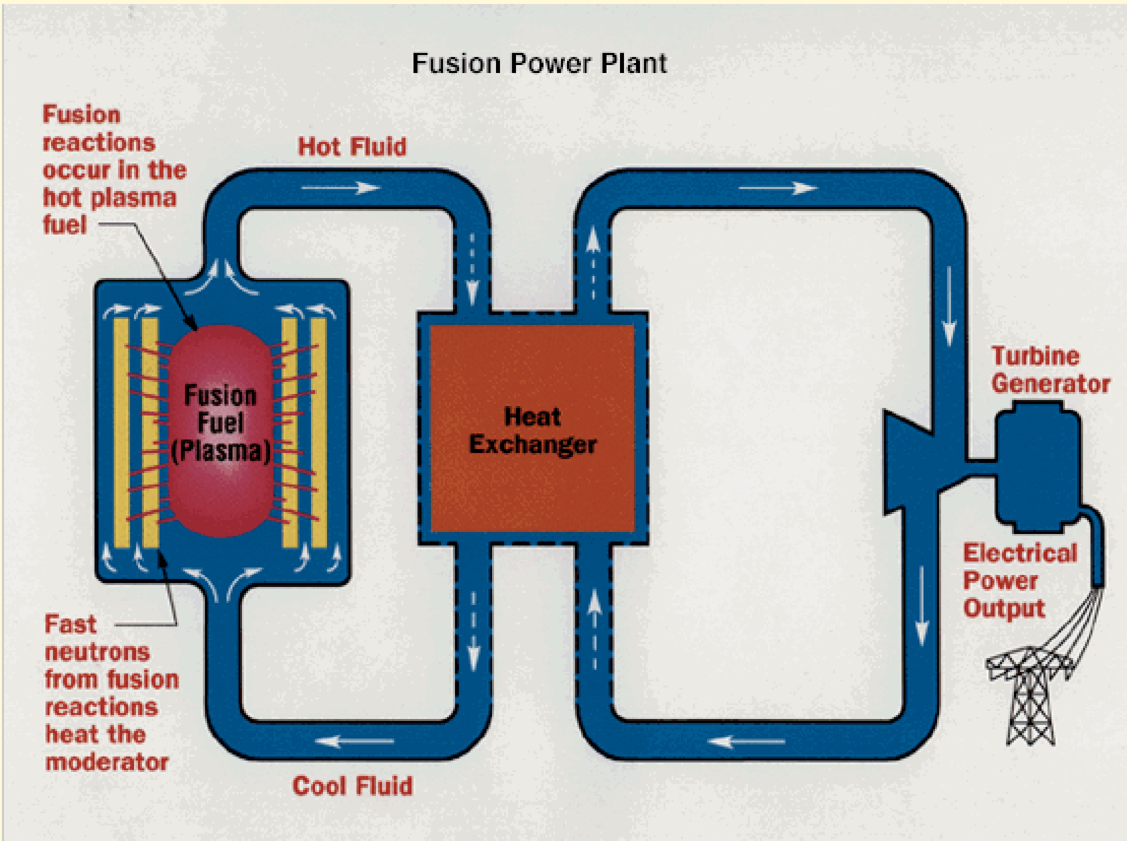




How can we measure what is happening in the plasma?

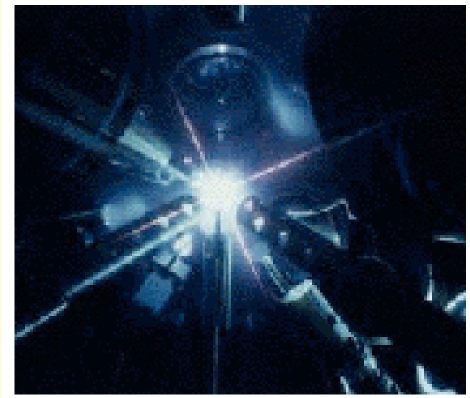
- **Magnetic Field Structure**
  - use coils outside the plasma
- **Escaping Radiation and Particles**
  - Identify impurities and radiated power losses
  - Measure temperatures of ions and electrons
  - Measure fusion reactions from neutrons
- **Probe Beams of Electromagnetic Waves**
  - measure density and temperature
  - measure fluctuations and turbulence which spoil confinement

Conceptual Design of a Fusion Reactor

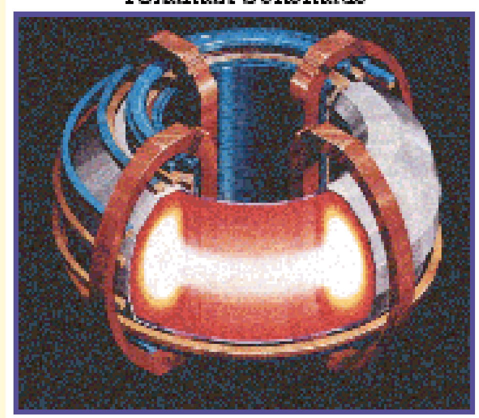


Fusion neutrons supply heat to generate electricity

Laser-beam-driven Fusion



Tokamak Schematic



Possible Fusion Reactor “Cores”

What Have We Done ?

- Overview - 50 years of fusion research
- Recent results in magnetic fusion in:
  - plasma confinement
  - plasma pressure limits
  - steady state plasmas
  - plasma-wall interaction

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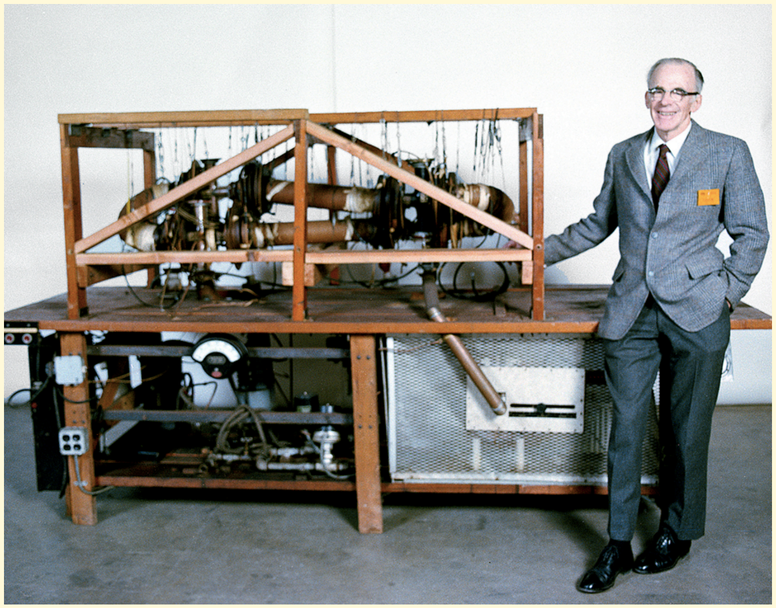
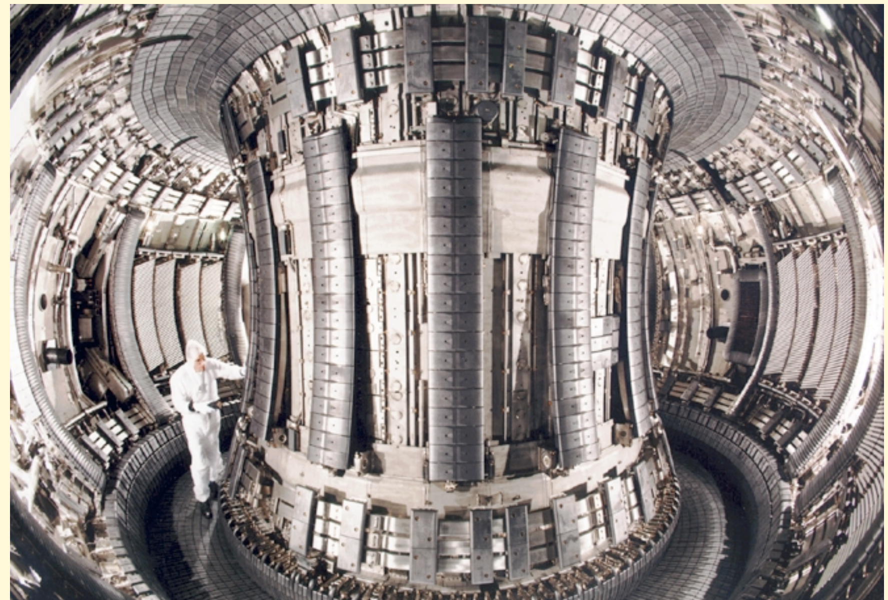
Fifty Years of Fusion Research

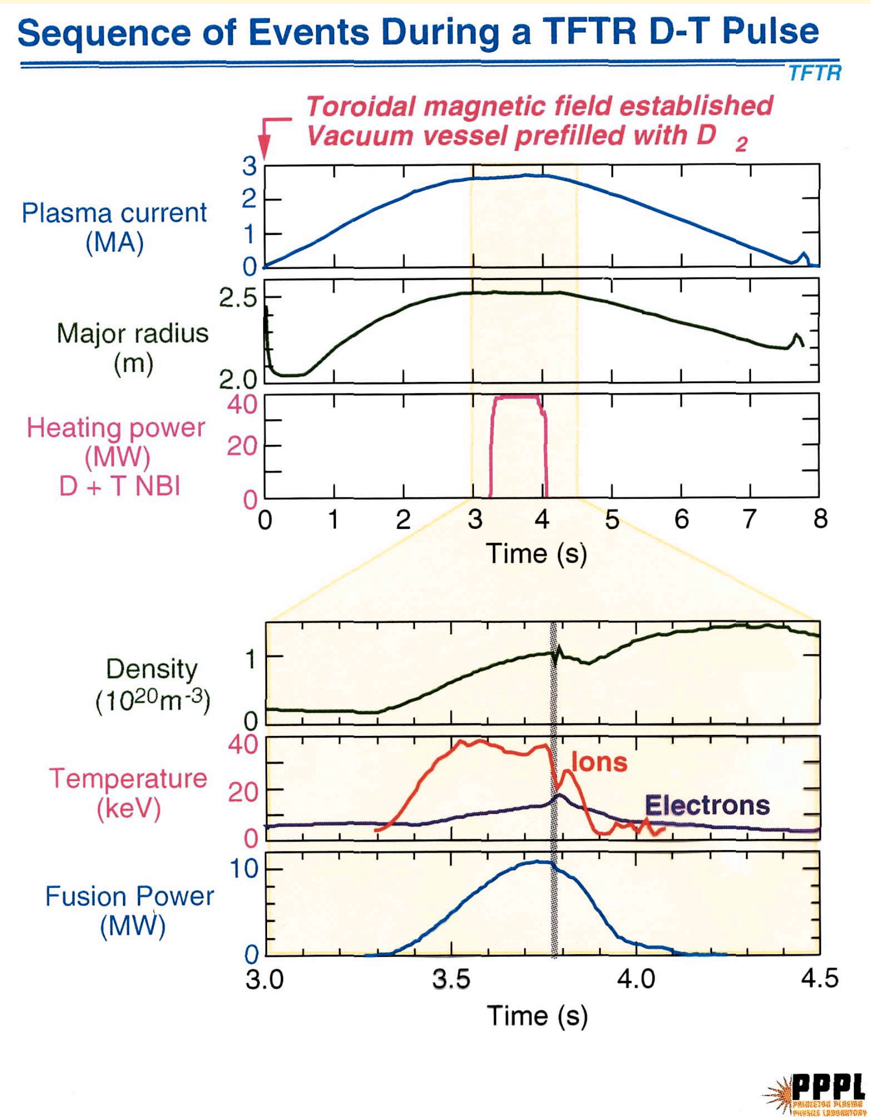


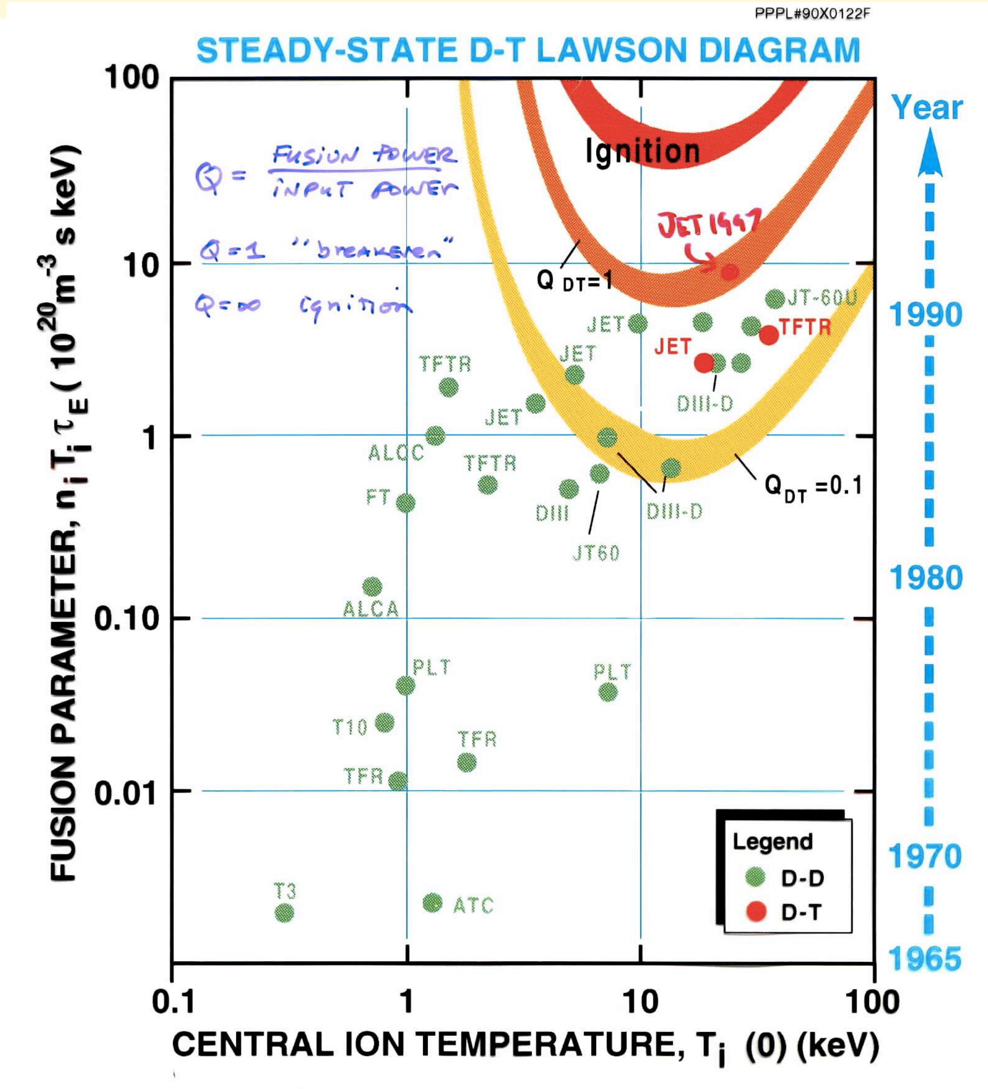
Model A Stellarator ca. 1953
(with Lyman Spitzer)
$n \approx 10^{13}$ cm^{-3} (?)
$T \approx 10$ eV (?)
$\tau_E \approx 10$ μsec (?)



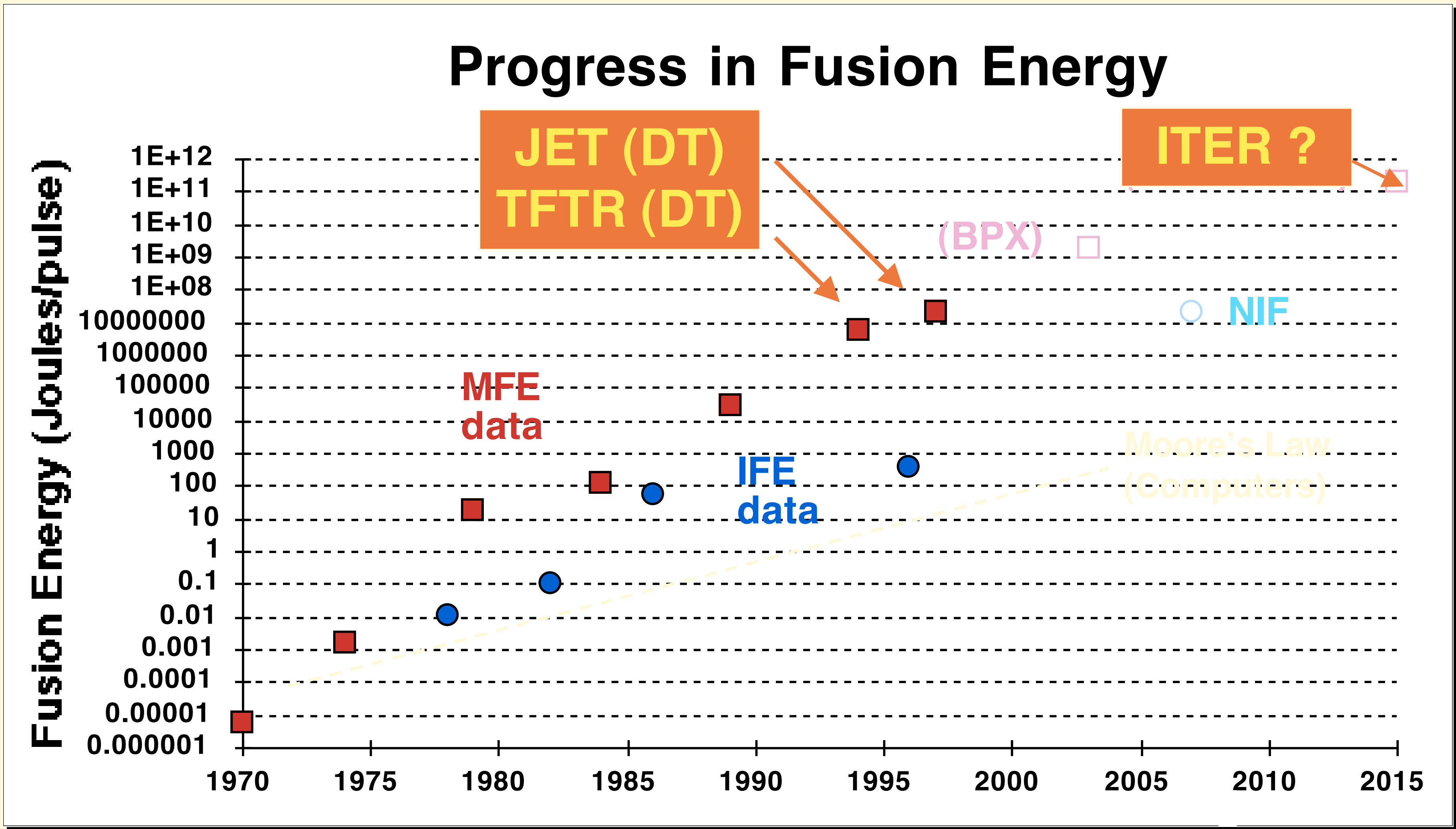
JET Tokamak ca. 2000:
$n \approx 10^{14}$ cm-3
$T \approx 20$ keV
$\tau_E \approx 1$ sec
$nT\tau_E$ ≈ x 5 from ignition

Measurements of nTτ_E in Tokamaks

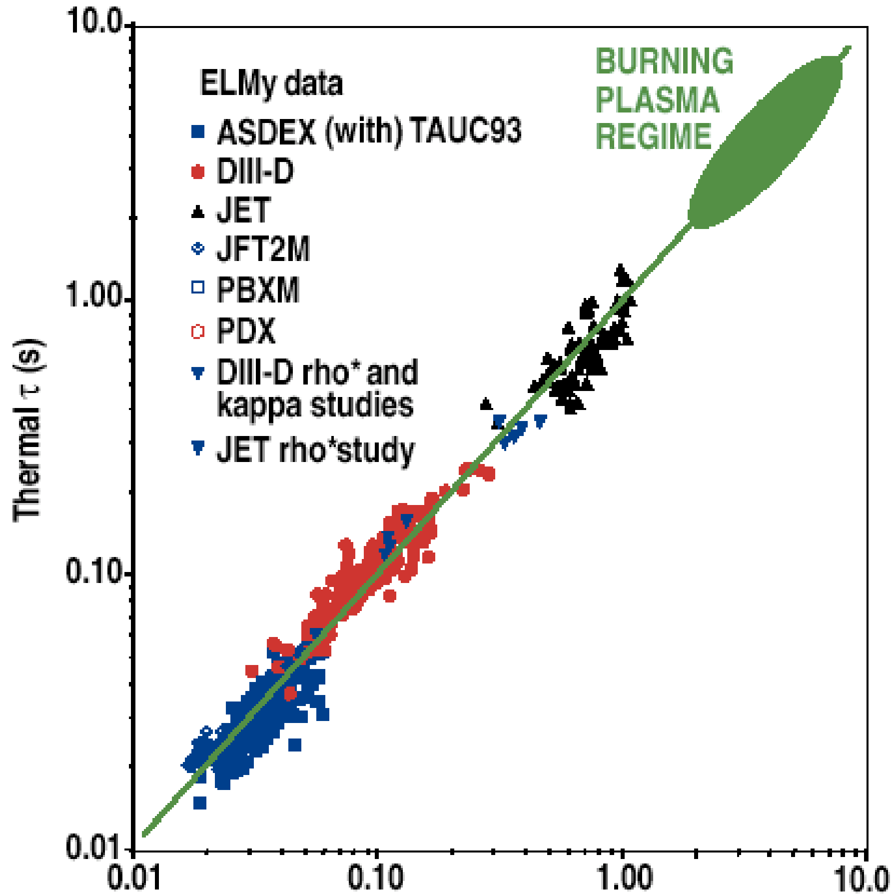




Fusion Energy Made per Pulse



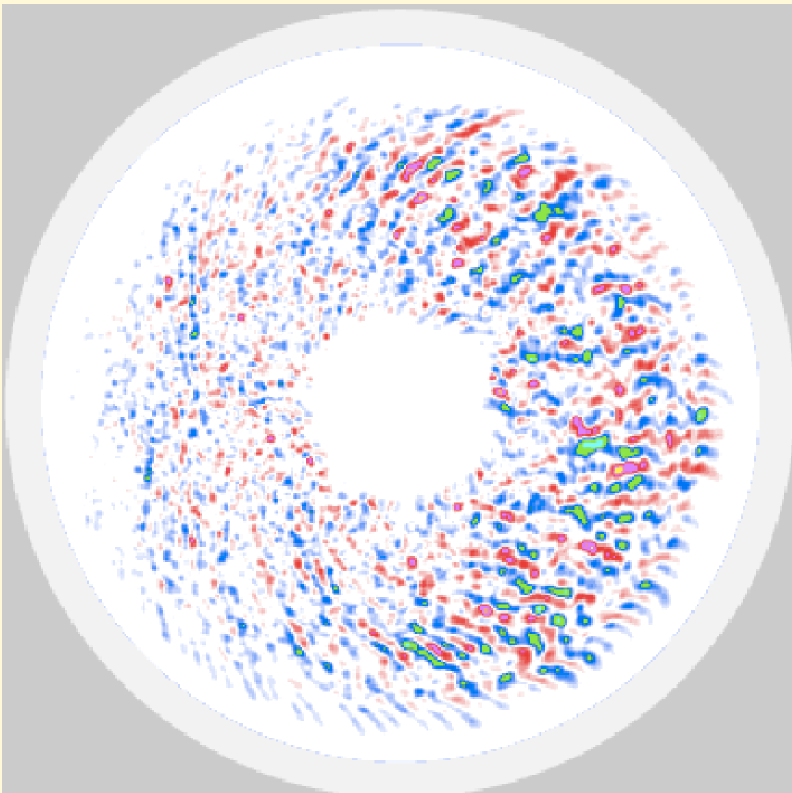
Plasma Confinement Scaling is Known



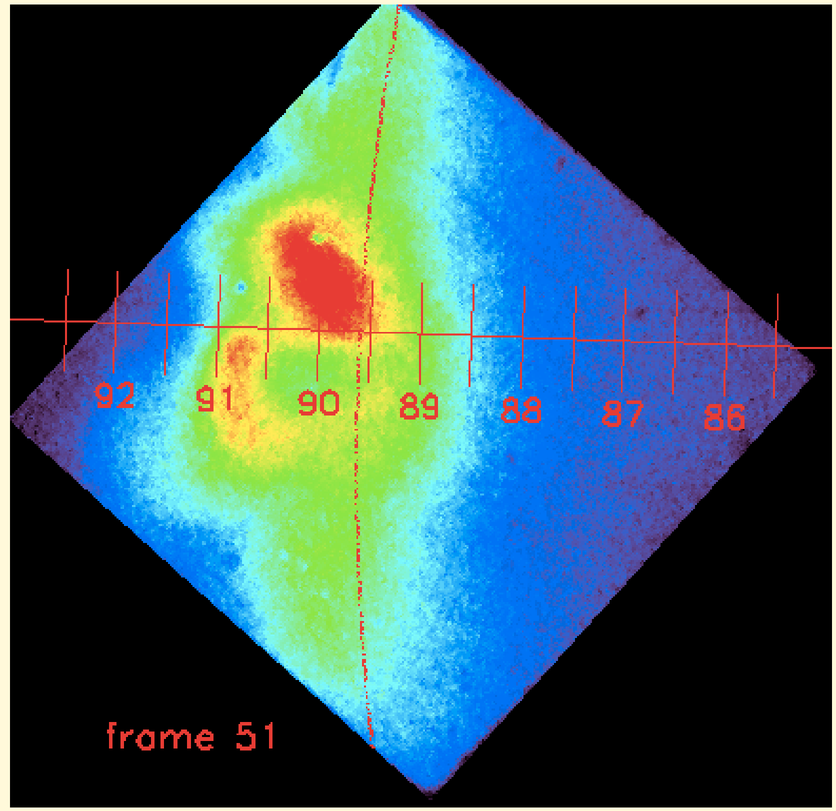
$$\tau_E = 0.031\, I_p^{1.06}\, B^{0.32}\, P^{-0.67}\, M^{0.41}\, R^{1.79}\, n_e^{0.17}\, \varepsilon^{-0.11}\, \kappa^{-0.6}$$

Empirical τ_E scaling

Confinement and Plasma Turbulence



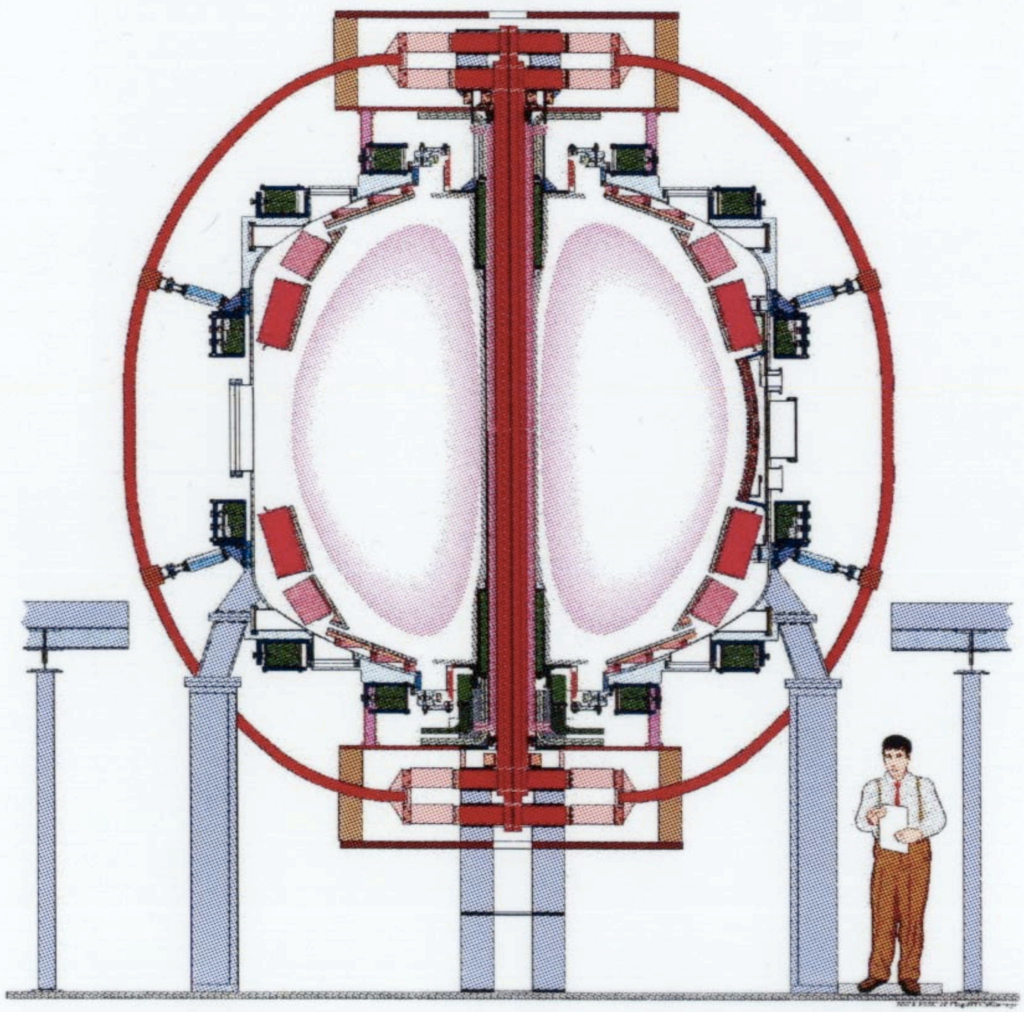
Turbulence Simulation
of ITG mode in Core



Turbulence measurement
(not necessarily ITG mode)

NATIONAL SPHERICAL TORUS EXPERIMENT
U.S.A.

NSTX



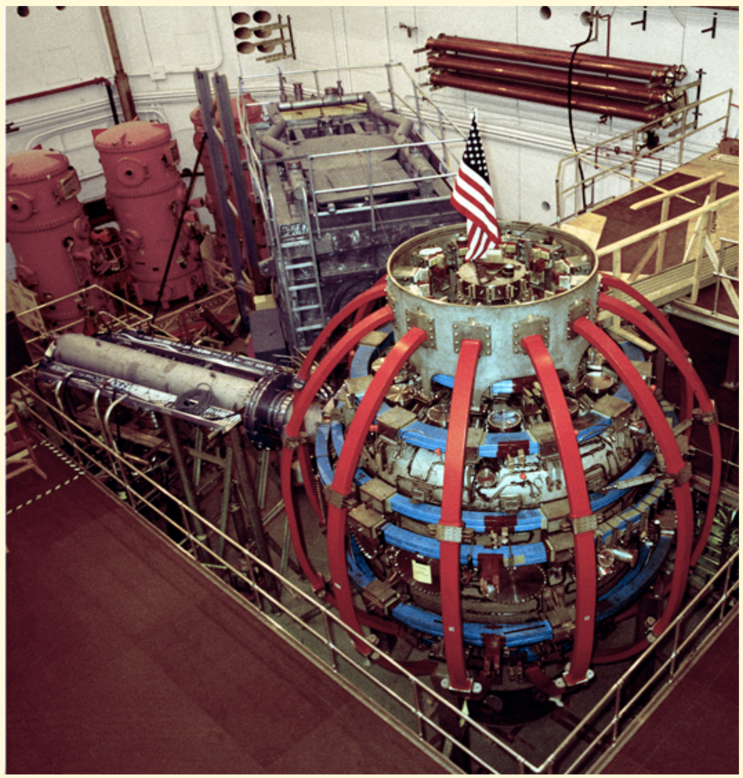
Baseline Parameters

- Major radius
  ≤ 85 cm
- Minor radius
  ≤ 68 cm
- Plasma current
  1 MA
- Toroidal field
  0.3–0.6 T
- Heating and current drive
  6–11 MW
- Flat-top time
  5–1.6 s

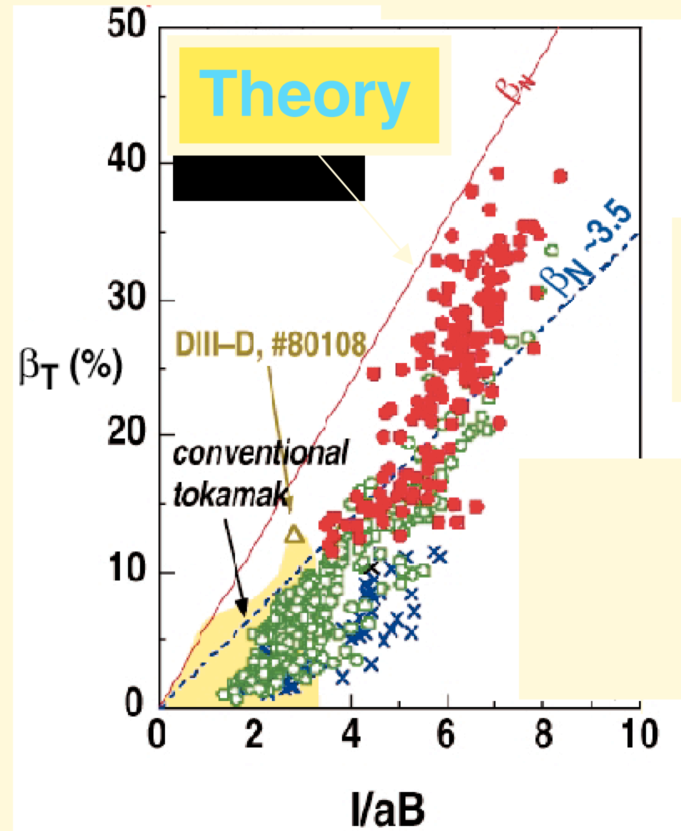
Joint Project of: Columbia University, ornl, PPPL, UW

Plasma Pressure Limited by B Field

$\beta \equiv 2nT/B^2$ measures efficiency of magnetic confinement

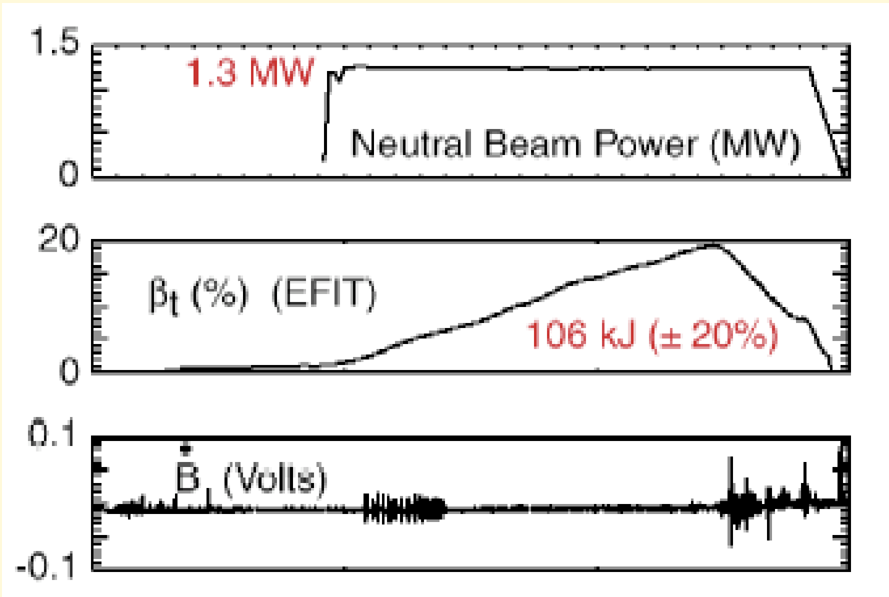


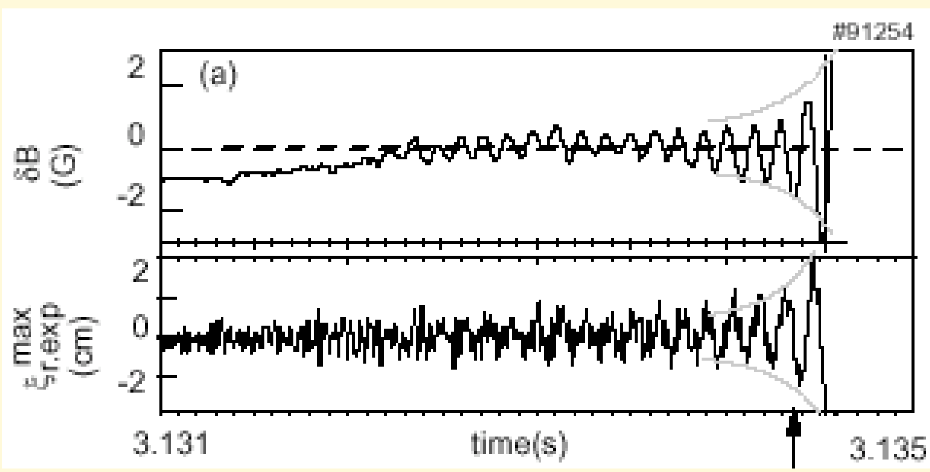
NSTX has reached β_T=20%

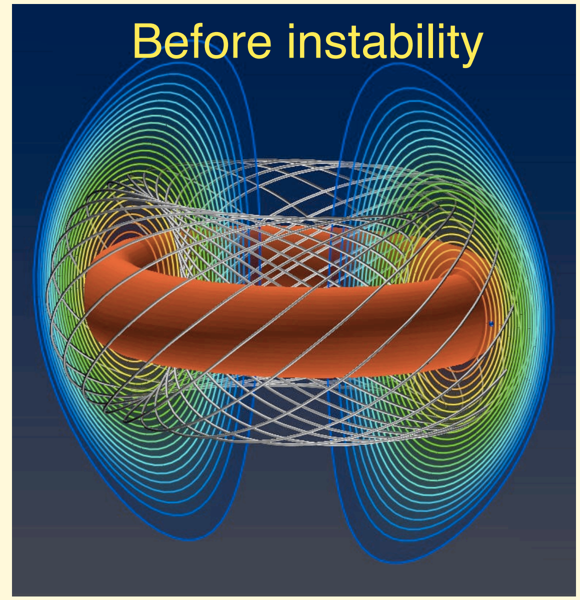


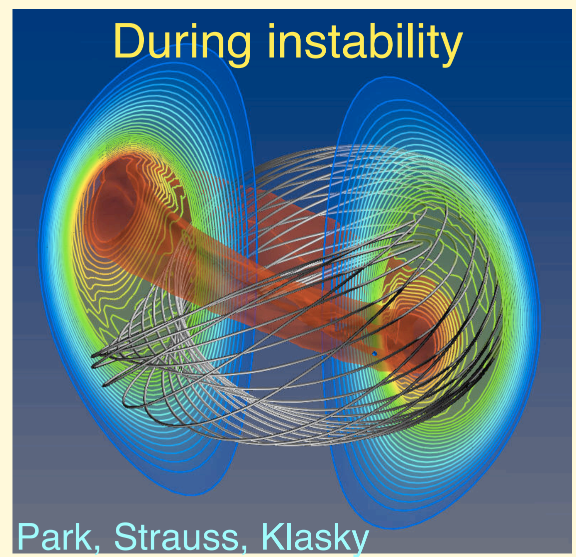
β limits ≈ agree with theory

Magnetic Instabilities at Pressure Limit



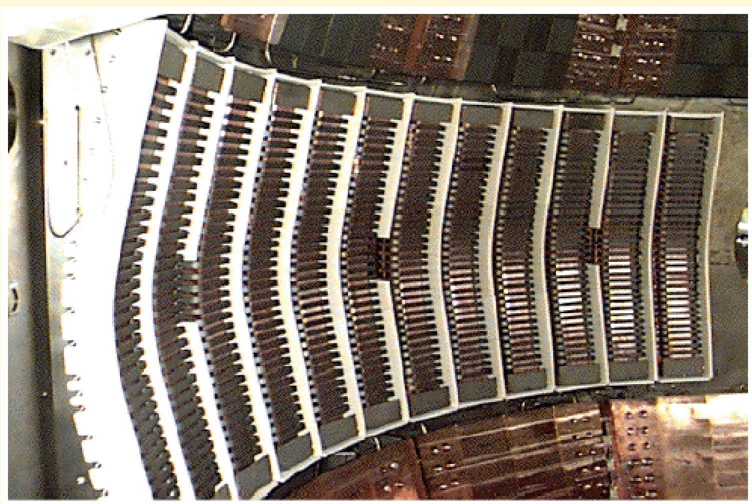




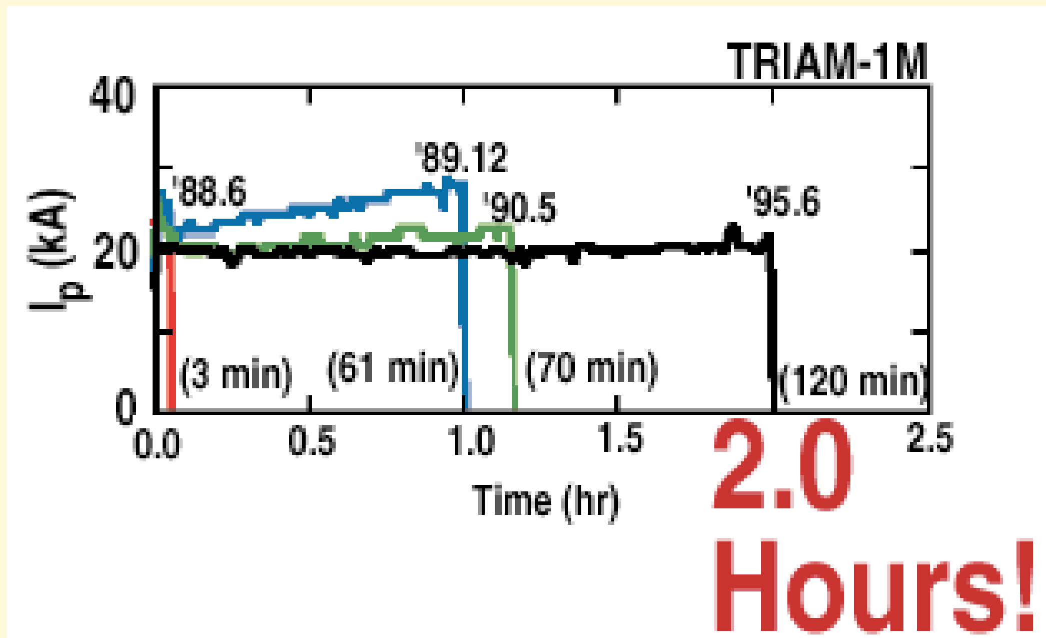


Tokamaks Need a Current Drive

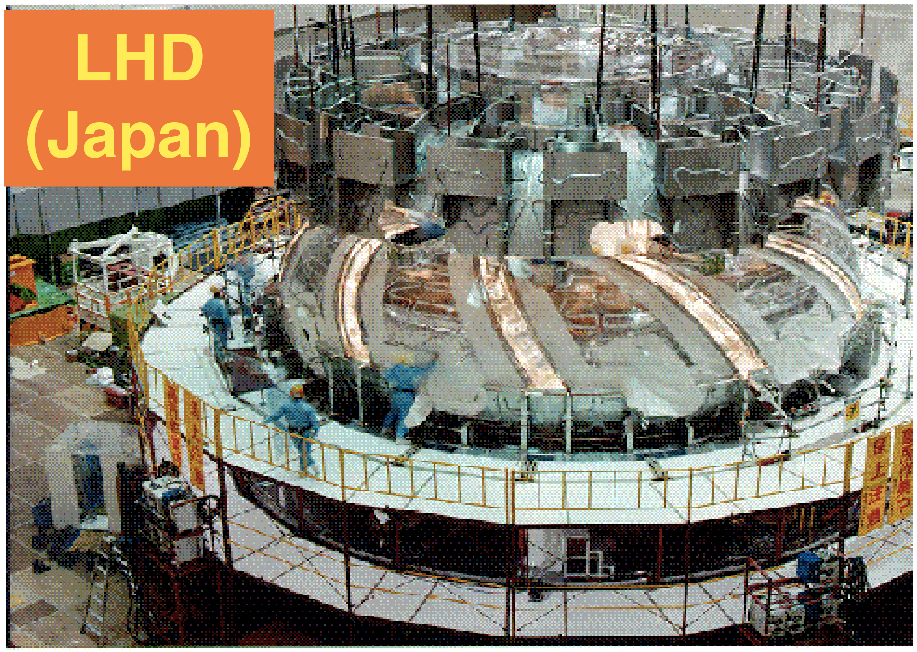
- Toroidal current up to 3 MA has been driven by:
  - damping of EM waves (MW-level RF / microwaves)
  - momentum of injected particle beams (≤ 0.5 MeV)
  - density gradient driven "bootstrap" current effect

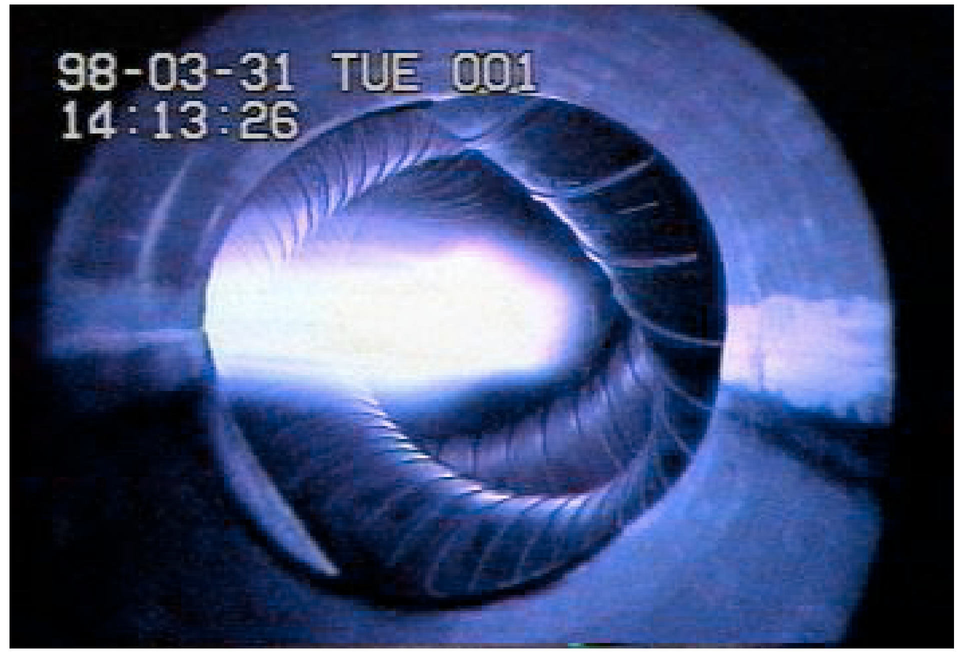


RF Antenna in NSTX



Stellarators Don't Need Current Drive





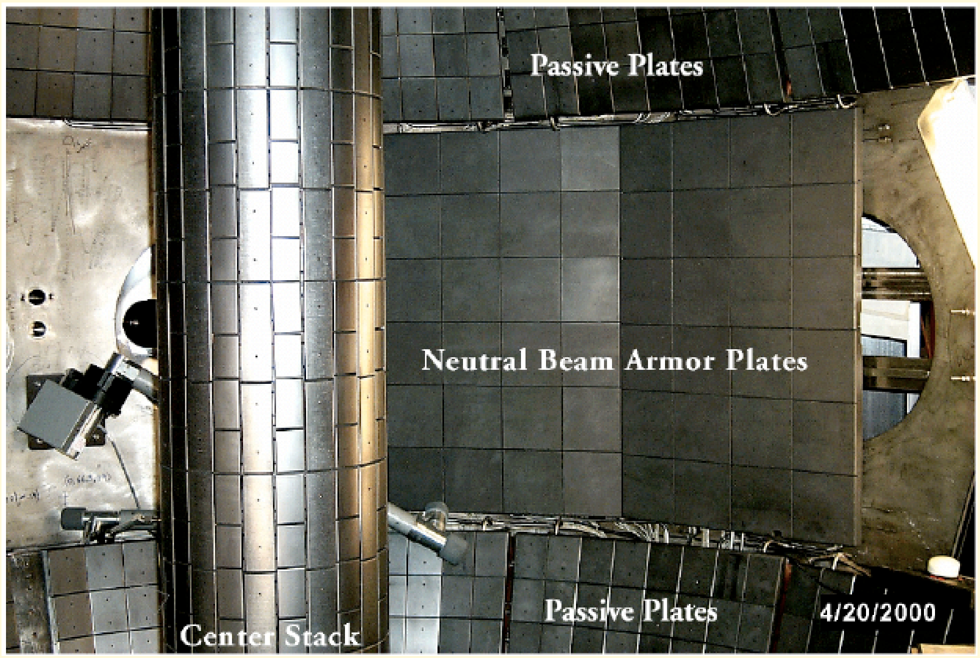
Photograph of the first plasma in the LHD.
A camera is aimed at the plasma through NBI (tangential) port.

Superconducting helical coils can create "steady-state" magnetic confinement without toroidal current

Plasma Loss can Vaporize the Wall

Reactor plasma loss rate ≈ 600 MW, but the plasma itself can only tolerate ≈ .01 gr of wall material

Inside NSTX



Carbon composite wall

Where are we Going ?

- Fusion Energy Goal and Strategy
- ITER and the Tokamak Fusion Reactor
- NIF and the Inertial Fusion Reactor
- Potential Improvements

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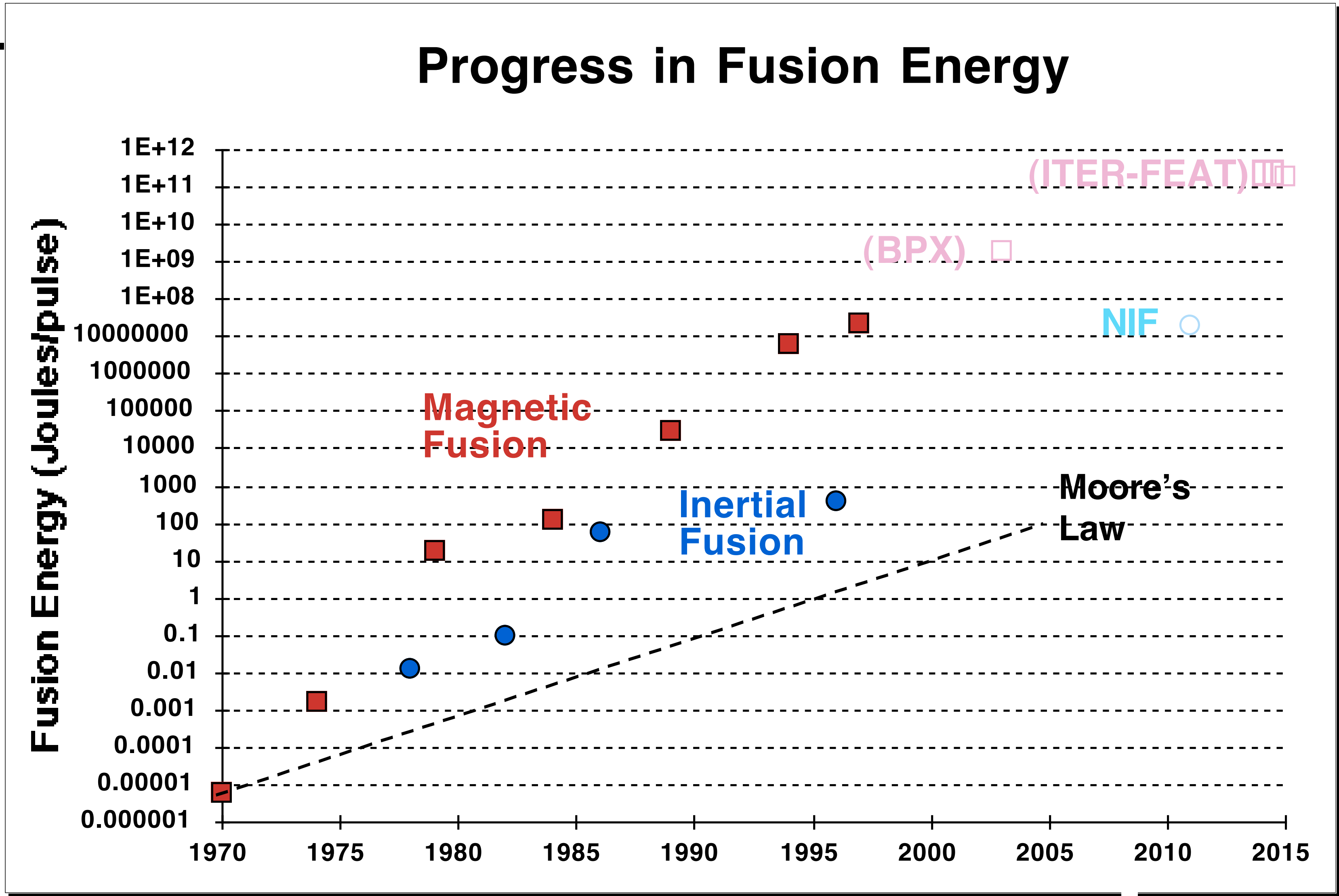
Reality: Fusion Energy has Outpaced Computers!
The challenge is to make it practical



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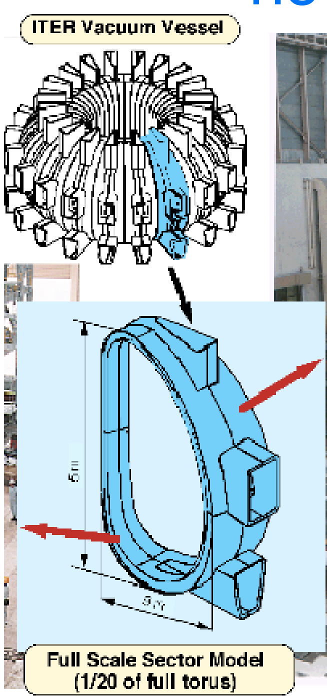
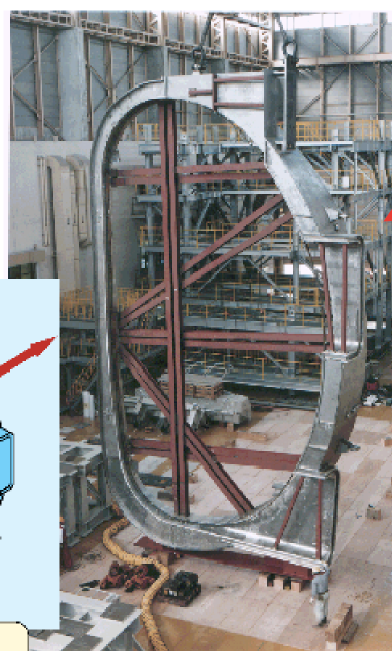
International Tokamak Experimental Reactor (ITER)

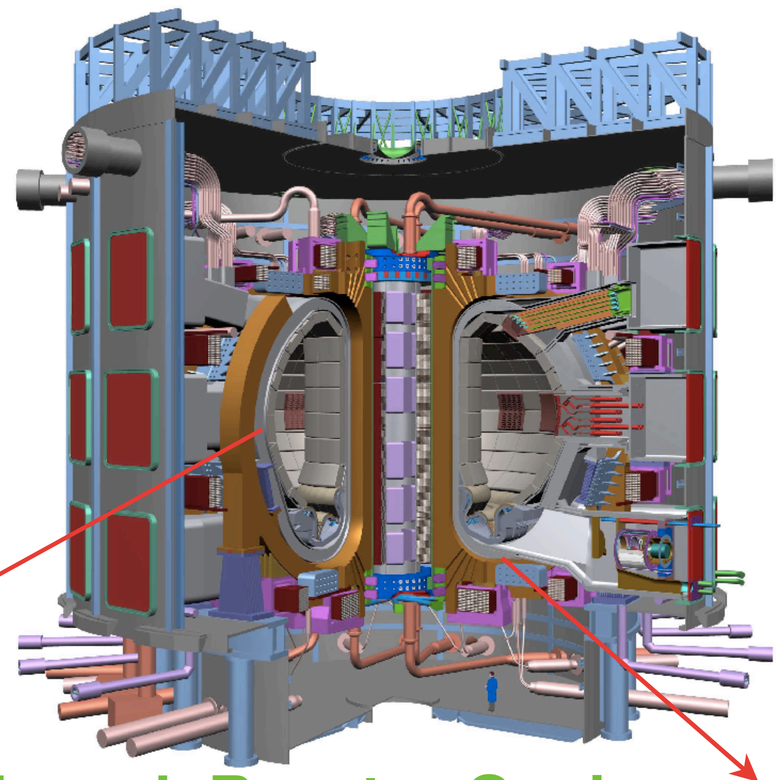
Design Goals:

- $Q \approx 10$ (--> ignition)
- 0.5 GW fusion power
- 500 sec long pulse
- no electricity output



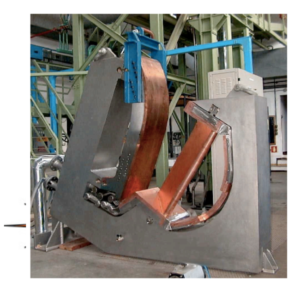


Sector-A (1/2 Sector)

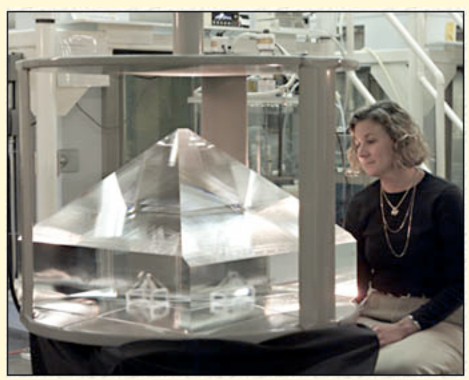


Tokamak Reactor Goals:

- $Q \geq 20$
- ≥ 3 GW fusion power
- steady-state pulse
- 5¢ / kW-hr electricity



NIF and Inertial Fusion Energy



NIF Design Goals:

- $Q \geq 1$ using laser
- ≥ 2 MJ fusion / pulse
- ≈ 1 nsec pulse length
- "stockpile stewardship"

IFE Reactor Goals:

- $Q \approx 100$ using GeV ions
- ≈ 600 MJ fusion / pulse
- ≈ 5 pulses / sec
- 5¢ / kW-hr electricity

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Fusion Reactor Engineering

- May need to replace first wall modules periodically
  - plasma erosion + neutron damage ($\leq$ 30 dpa/yr)
- Need to breed and recycle tritium fuel on-site
  - need $\geq$ 1 T / neutron and recycle $\approx$ 1 kG tritium
- Reactor must be reliable, maintainable, and available
  - and safely handle off-normal events and disposal

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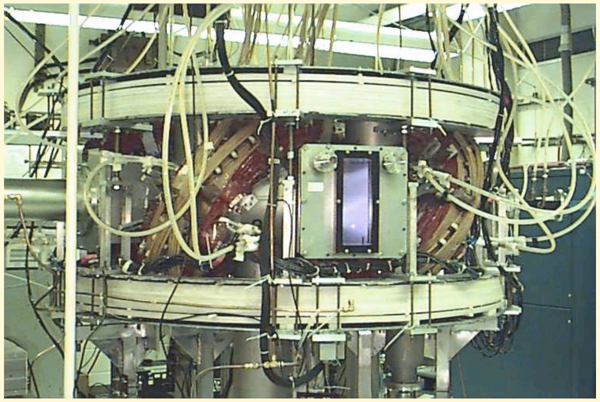
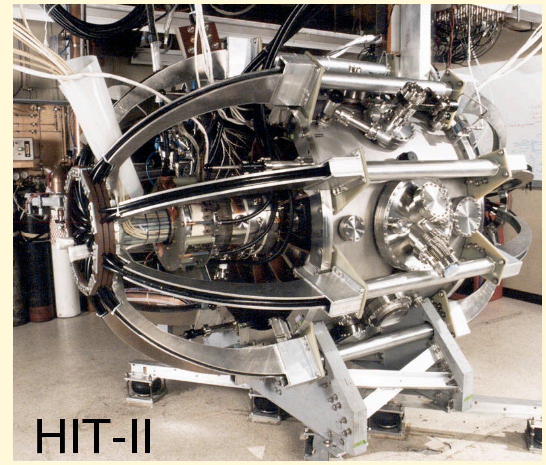
Innovative Confinement Concepts



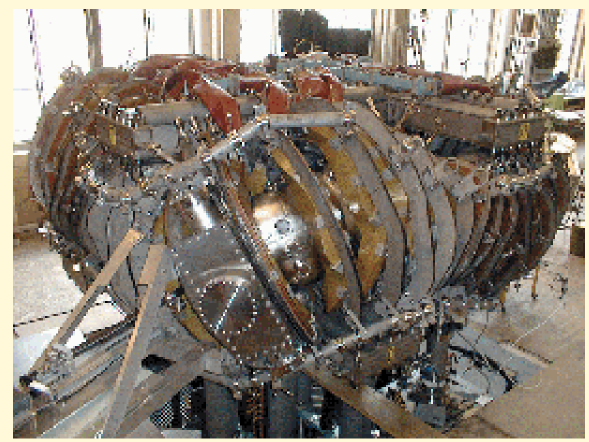
Compact Auburn Torsatron
Auburn University, Auburn Alabama

Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory

Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology



Helicity Injected Torus-II Experiment
University of Washington, Seattle

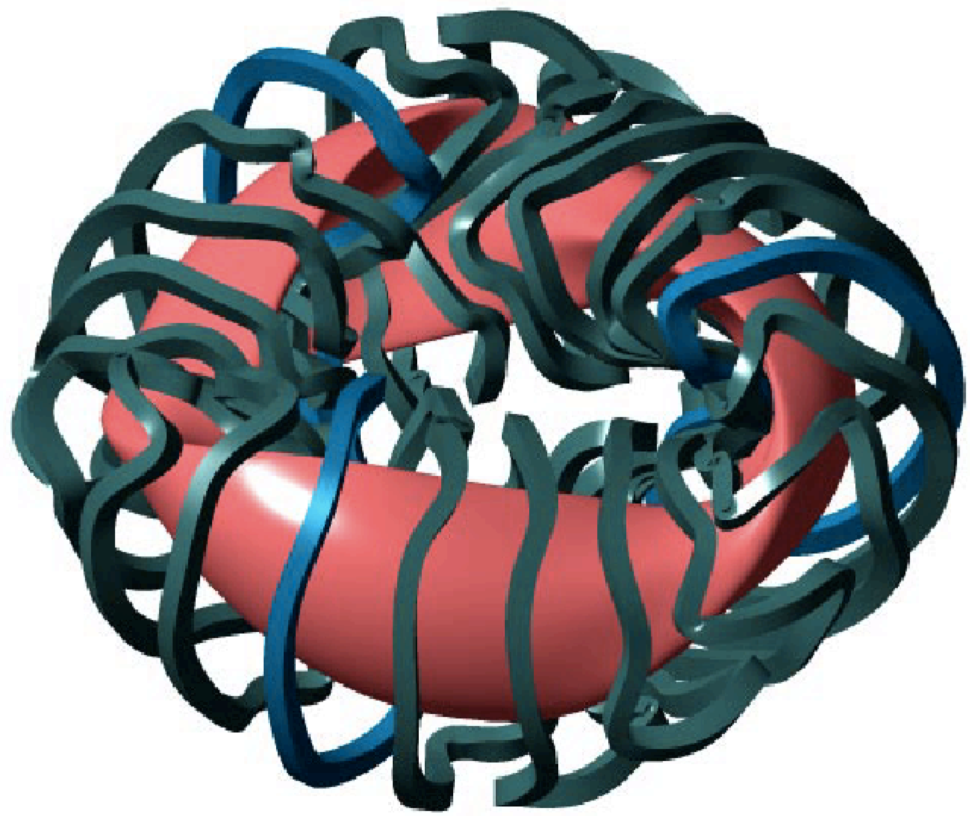


Helically Symmetric Experiment
University of Wisconsin, Madison

Compact Stellarator Design (NCSX)

Aims to combine best features of tokamak and stellarator

- needs no external current drive (like stellarator)
- large plasma for a given major radius (like tokamak)



R = 1.5 m
a = 0.5 m
B = 1.0 T
P = 6 MW
□ ≈ 4% (?)

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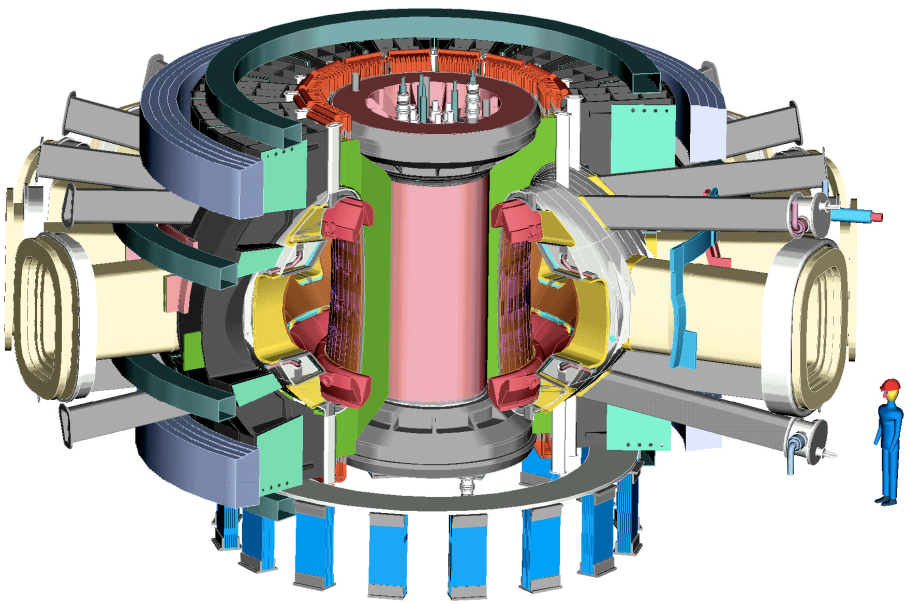
Fusion Ignition Research Experiment (FIRE) designed to explore dominant fusion alpha heating regime



FIRE 2000

Design Goals

- $R = 2.0$ m, $a = 0.525$ m
- 10 T for ≈ 20s burn time
- Ip = 6.5 MA
- $\tau_E \sim 0.55$s
- $P_{alpha} \sim 40$ MW > $P_{aux} \sim 20$ MW (RF)
- $P_{fusion} \sim 200$ MW
- Preliminary cost estimate
  - Tokamak = $323 M
  - Aux, PS, Bldg = $870 M

Attain, explore, understand and optimize alpha-dominated plasma to provide scientific basis for design of attractive MFE systems

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Potential Areas for "Breakthrough"

Computational capability to find an optimized configuration for plasma confinement without costly experiments

Technological innovations such as room temperature superconductors or radiation resistant materials

Physics surprises such as increased fusion cross section or a way to convert neutrons directly to electricity

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Conclusions

- Plasma science is making good progress

  main difficulty is the physics of plasma instabilities
  which limit plasma confinement and pressure

- We have initial fusion reactor designs

  based on MFE and IFE, but they so far seem to
  be too expensive and complicated to be practical

- But future energy options are limited

  important to determine whether fusion reactors
  can be made into an attractive energy source

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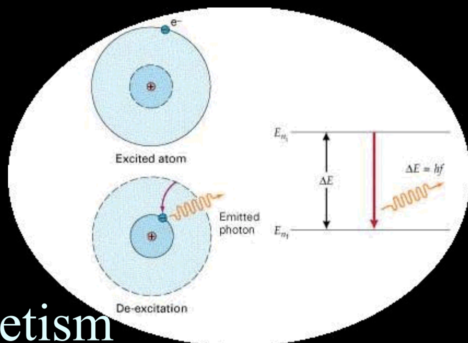
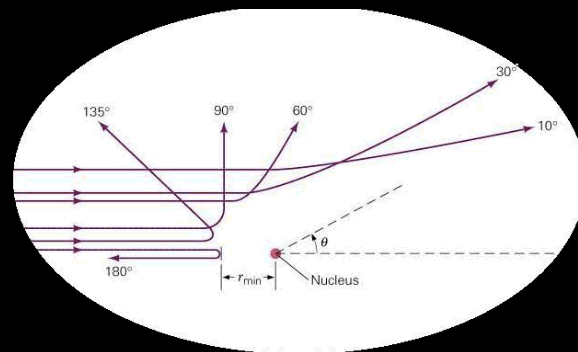
Using Plasma to Teach Physics: An Integrated Approach

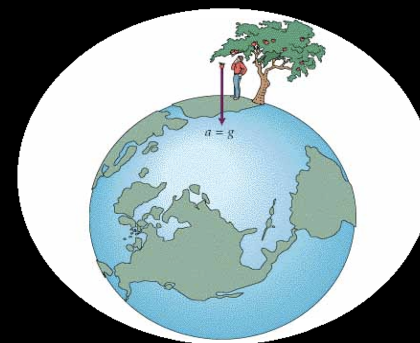
•Atomic and Quantum Physics



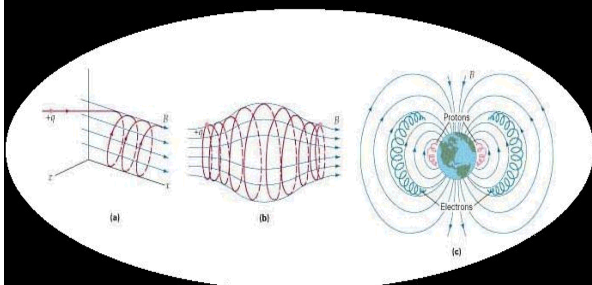
•Conservation of



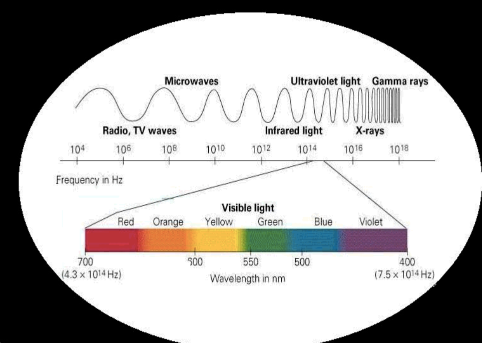
•Dynamics



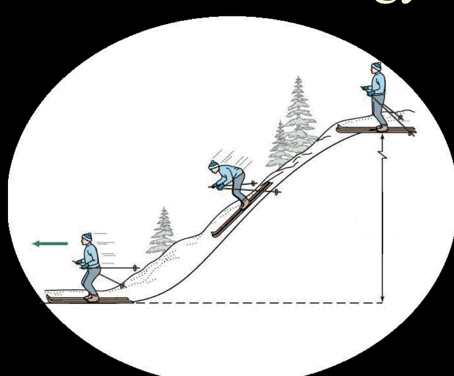
•Electromagnetism



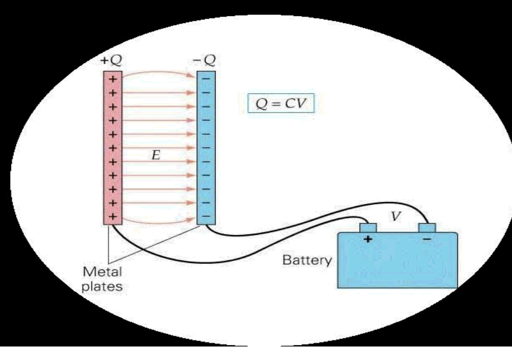
•Electromagnetic waves



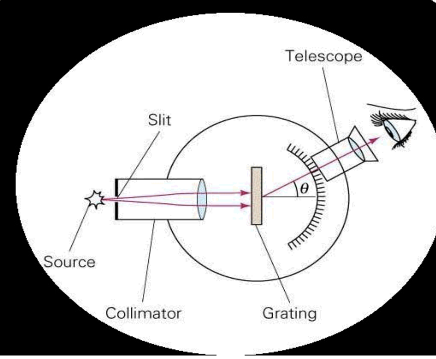
•Conservation of Energy



•Electrical Circuits



•Optics



Illustrations from Wilson, Buffa, College Physics, Prentice Hall science-education.pppl.gov

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