Can We Make a Fusion Reactor ?

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National Undergraduate Fellowship Program
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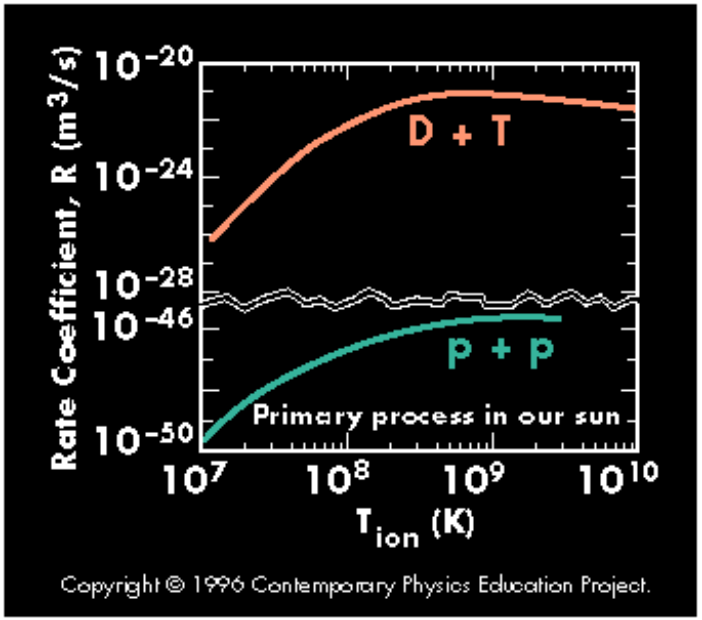
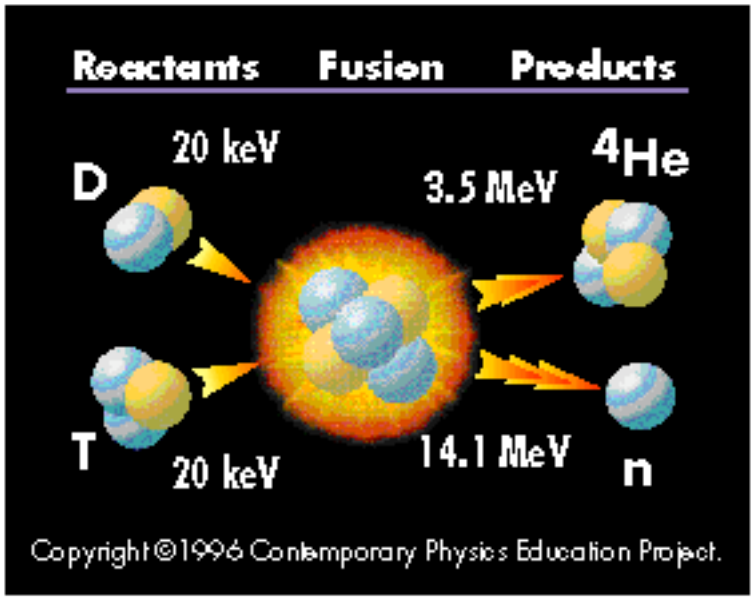
- How would it work ?
- What have we done ?
- Where are we going ?

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

Nuclear Fusion of D-T is Easy





For first generation fusion reactors

Best at $T_{ion} \geq 10$ keV

Energy gain ≤ 450

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

Requirements for Ignition of D-T Fuel

"Ignition" means plasma self-heating by D-T alpha particles

D-T Fusion Ignition condition:

alpha heating rate = plasma energy loss rate

$$\text{constant} \cdot n^2 T^2 \approx 3\, n\, T / \tau_E$$

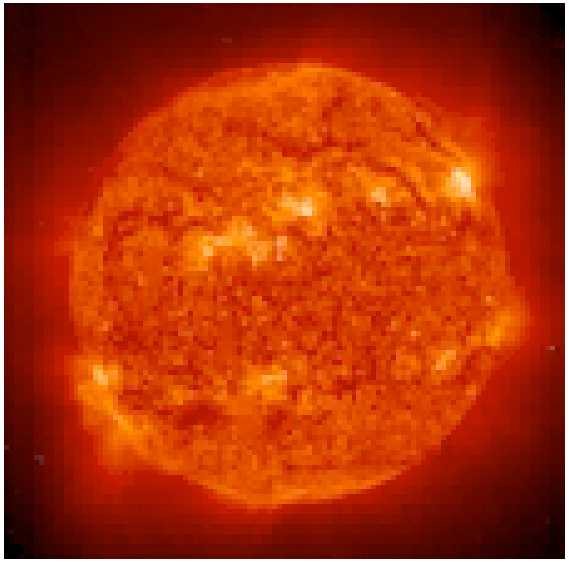
[where τ_E is the plasma energy confinement time]

=> $n \cdot T \cdot \tau_E \approx (10^{14}\ \text{cm}^{-3}) \cdot (20\ \text{keV}) \cdot (5\ \text{sec})$ -- MFE

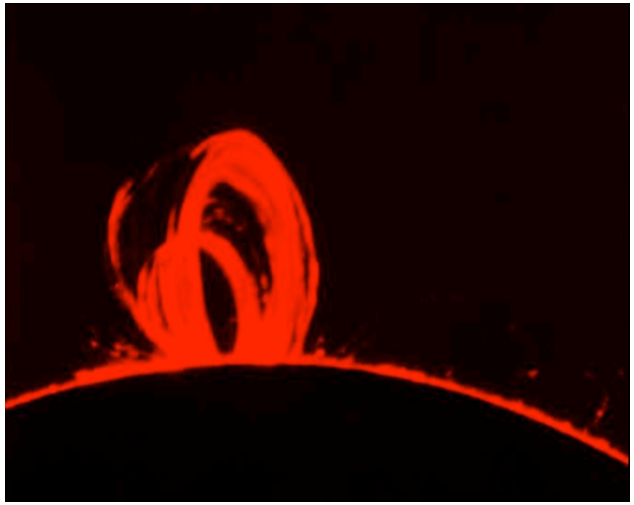
or $n \cdot T \cdot \tau_E \approx (10^{24}\ \text{cm}^{-3}) \cdot (20\ \text{keV}) \cdot (0.5\ \text{nsec})$ -- IFE

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



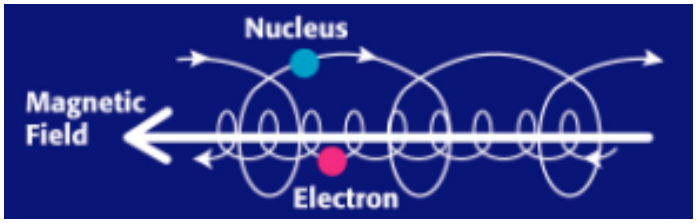
Gravitational Confinement



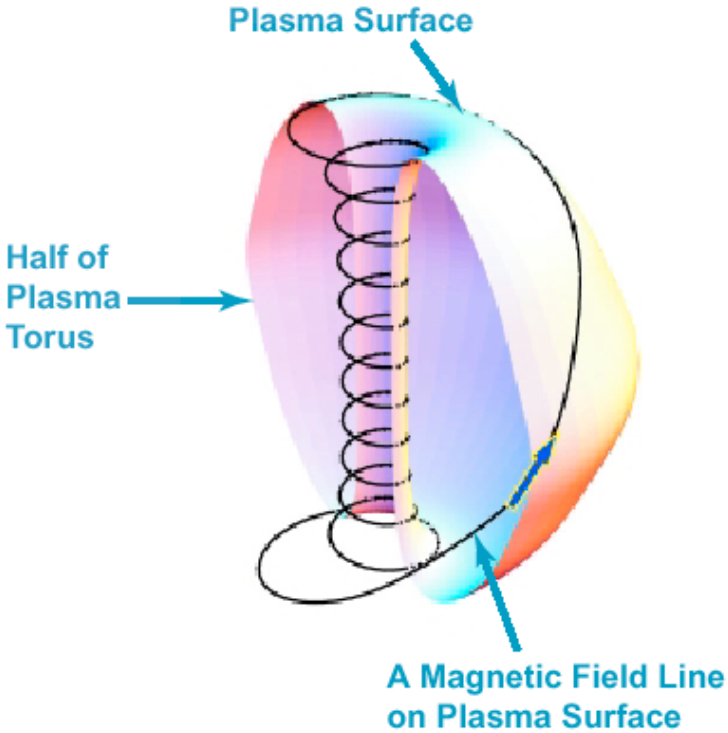
Magnetic Confinement

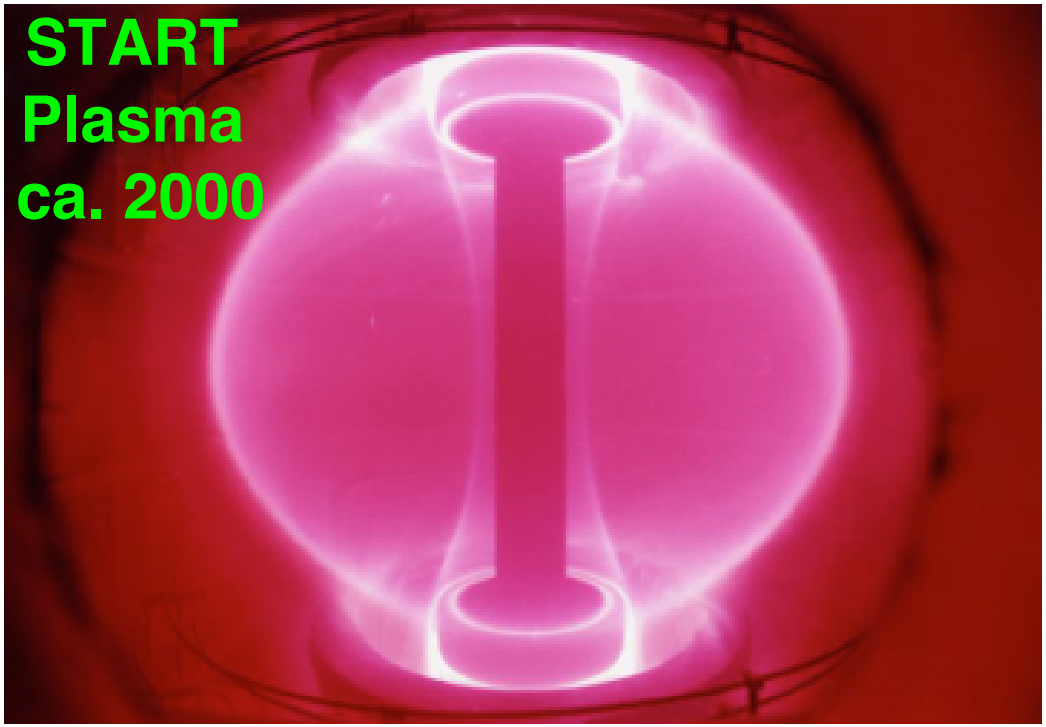
Inertial Confinement

Magnetic Confinement of Plasma



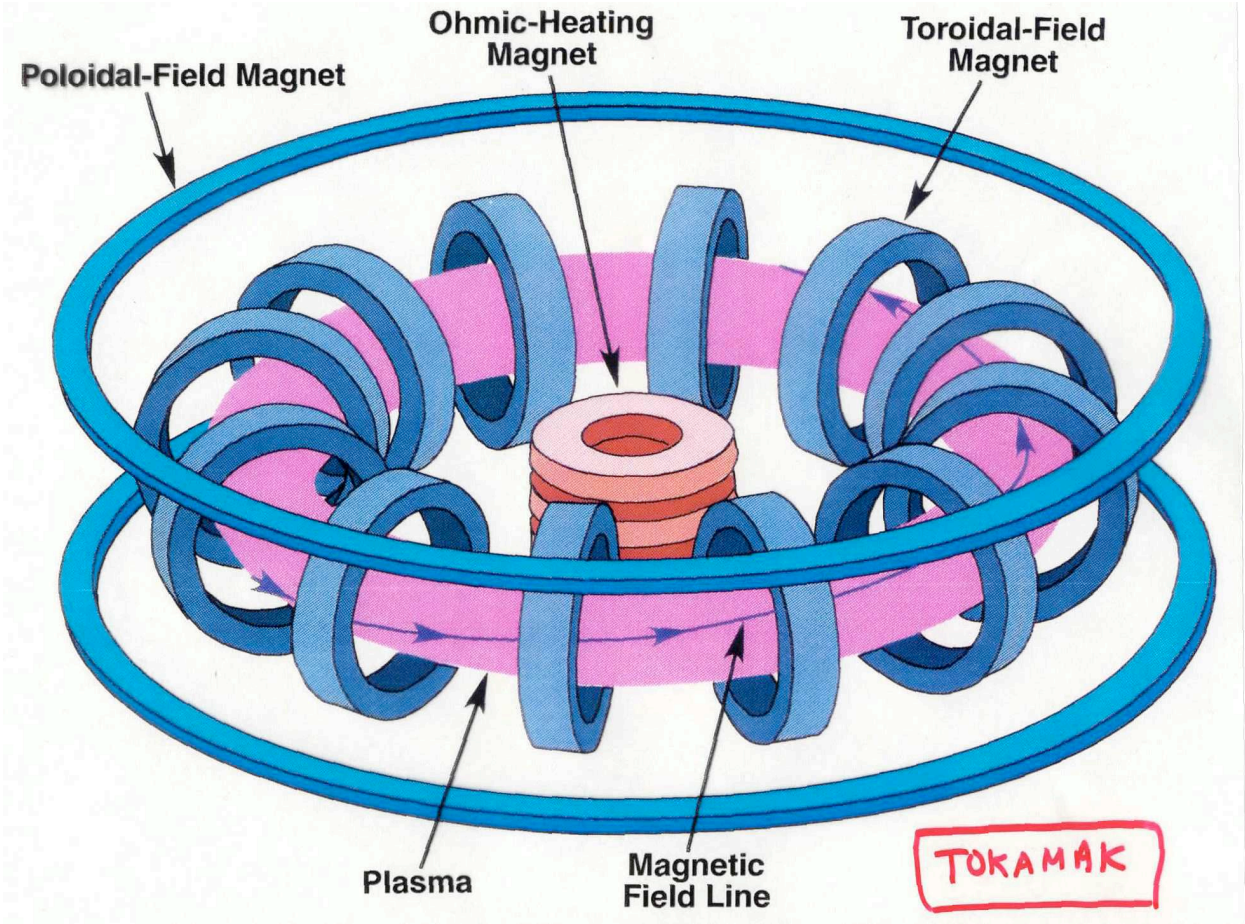
Ion gyroradius ≈1 cm at T_i = 20 keV
for typical magnetic field of B = 20 kG



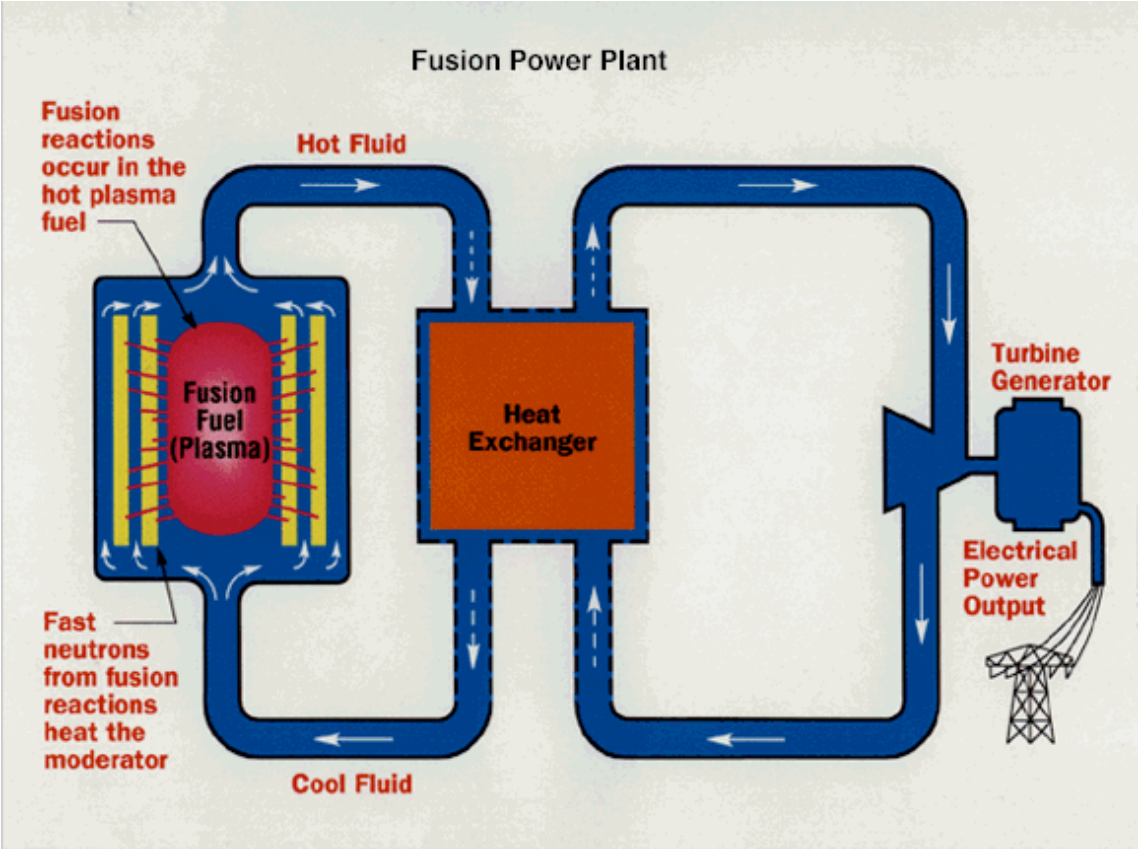


The Tokamak

Tokamak = toroidal magnetic chamber (Russian acronym)

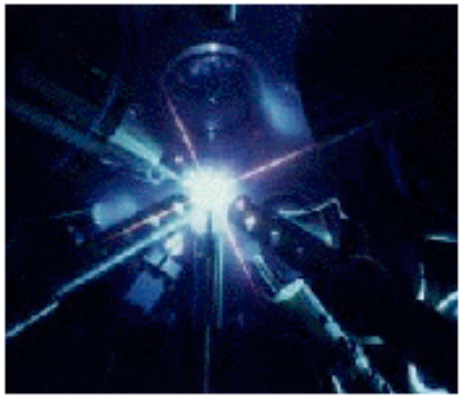


Conceptual Design of a Fusion Reactor

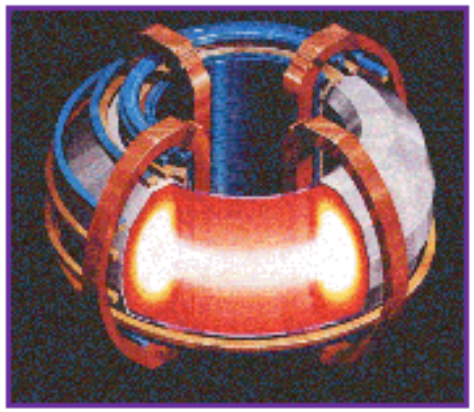


Fusion neutrons supply heat to generate electicity

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

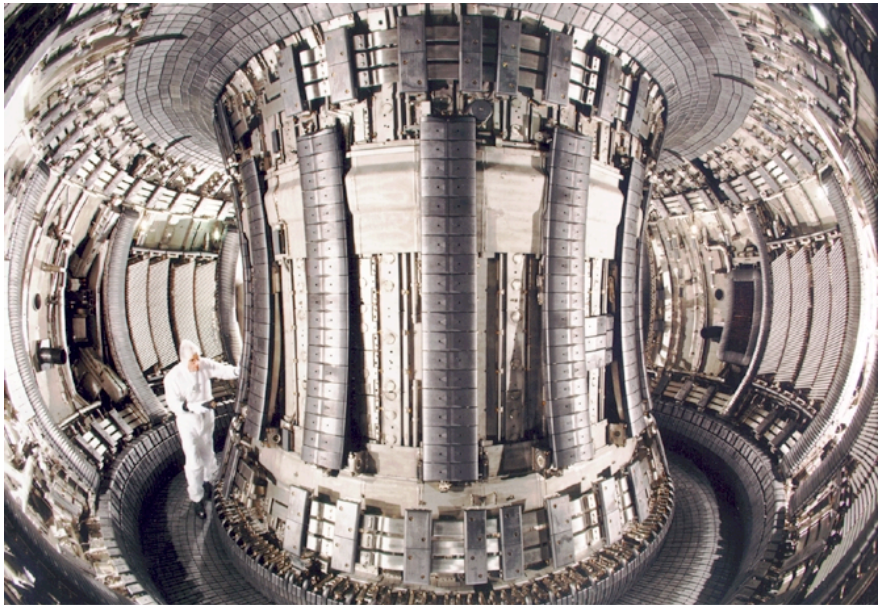
Fifty Years of Fusion Research

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:

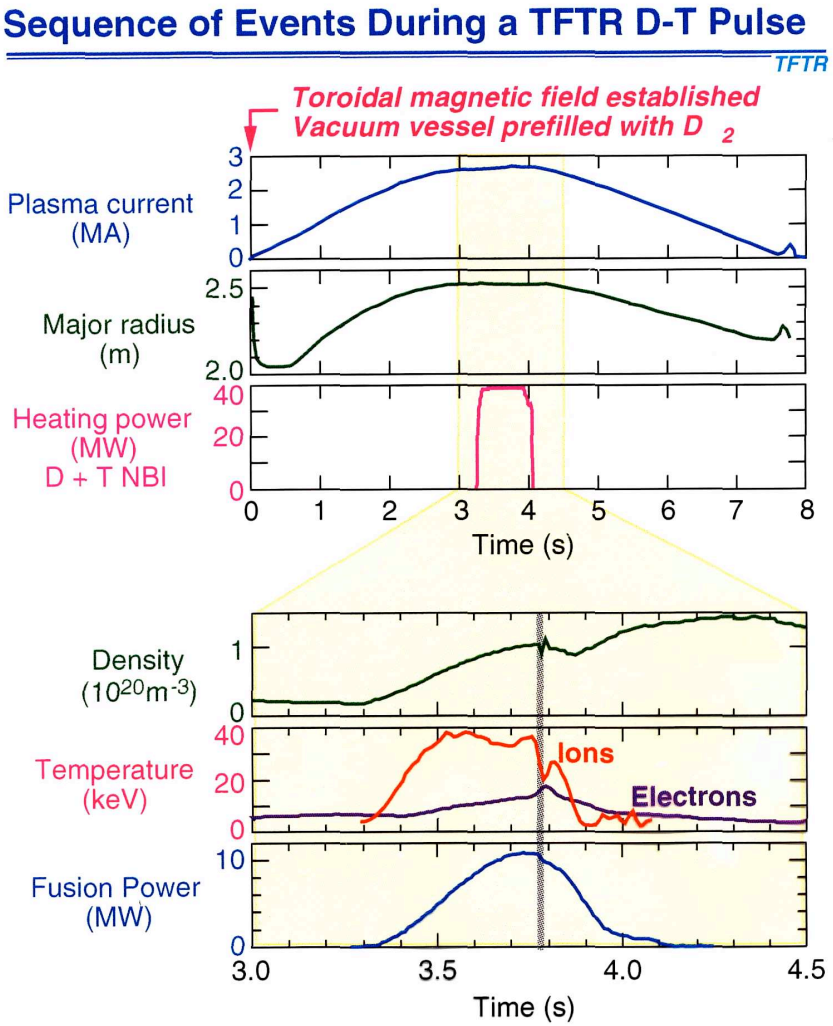
$n \approx 10^{14}$ cm-3

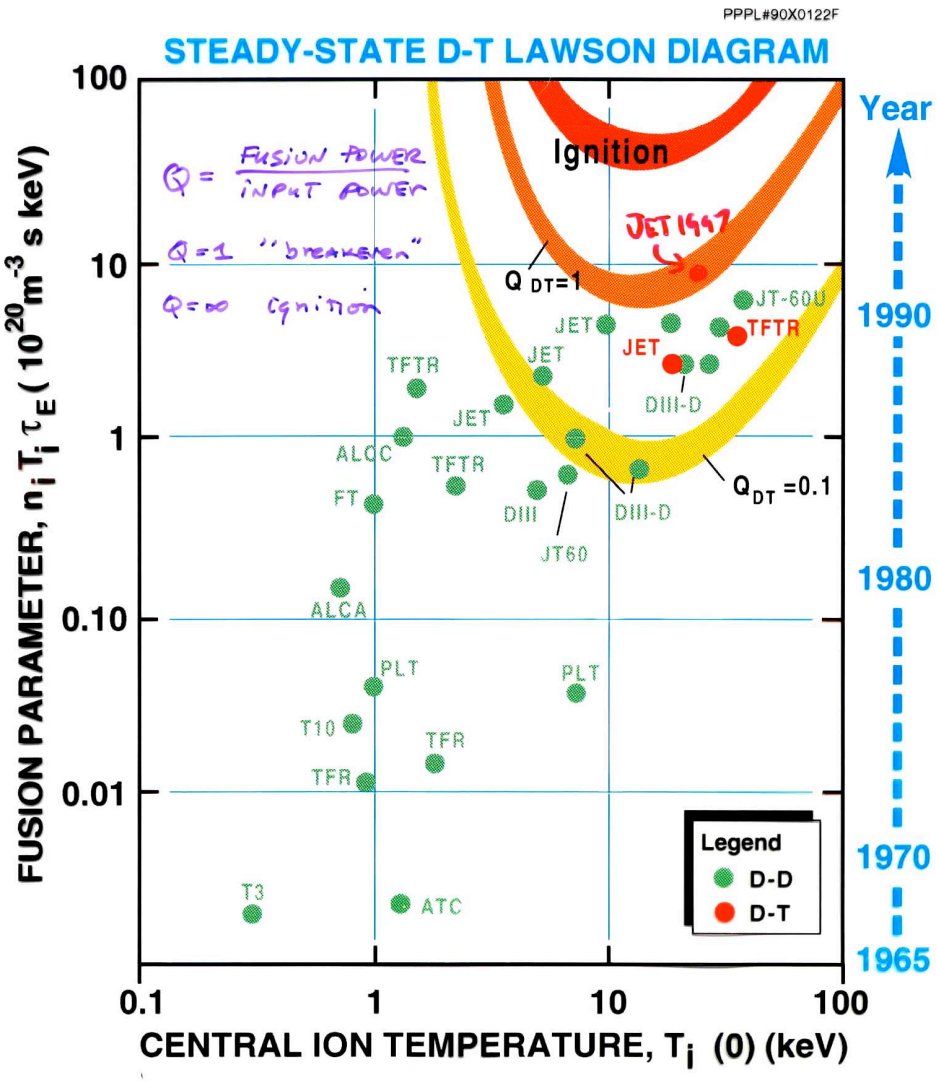
$T \approx 20$ keV

$\tau_E \approx 1$ sec

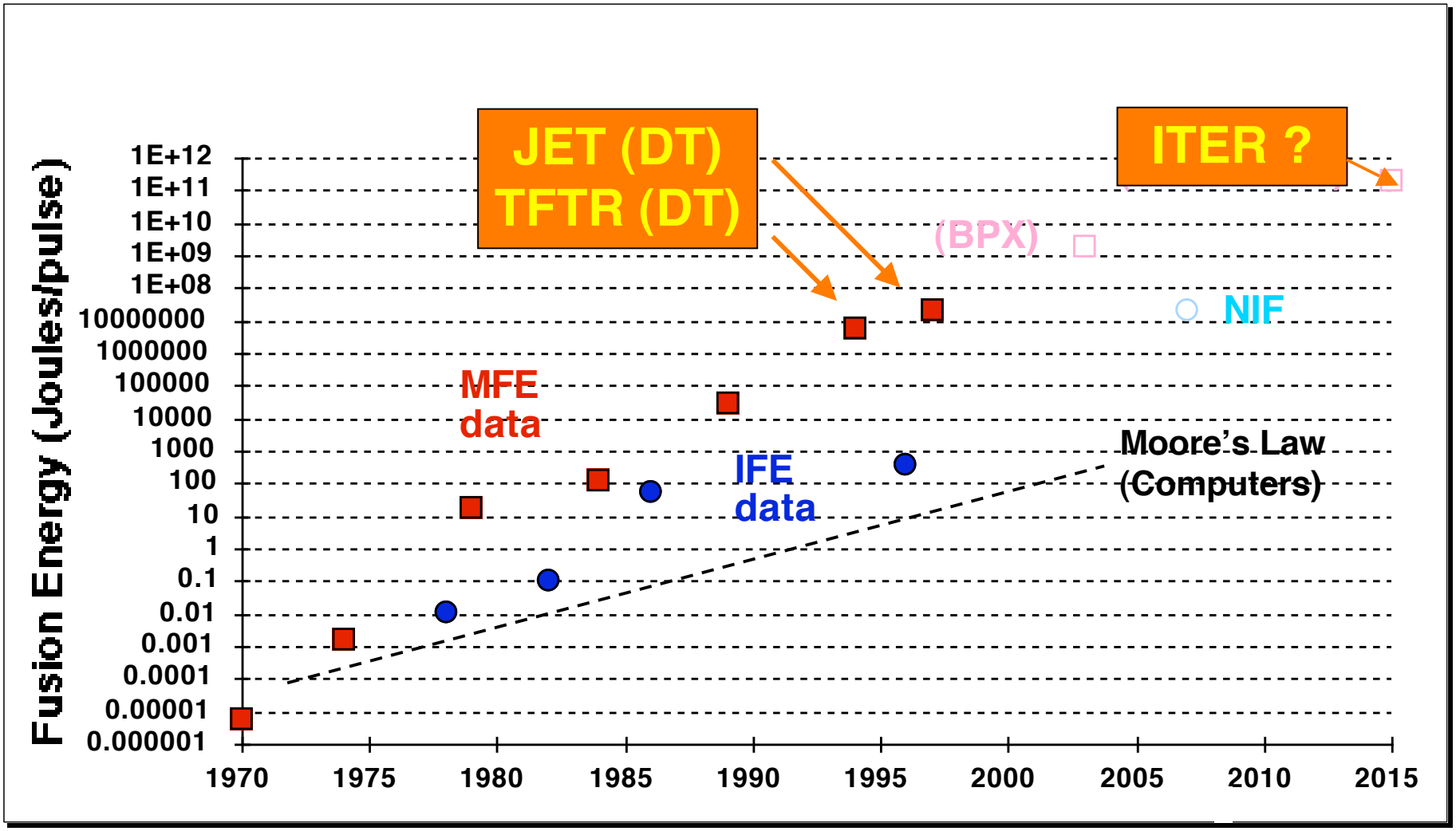
$nT\tau_E \approx$ x 5 from ignition

Measurements of $nT\tau_E$ in Tokamaks

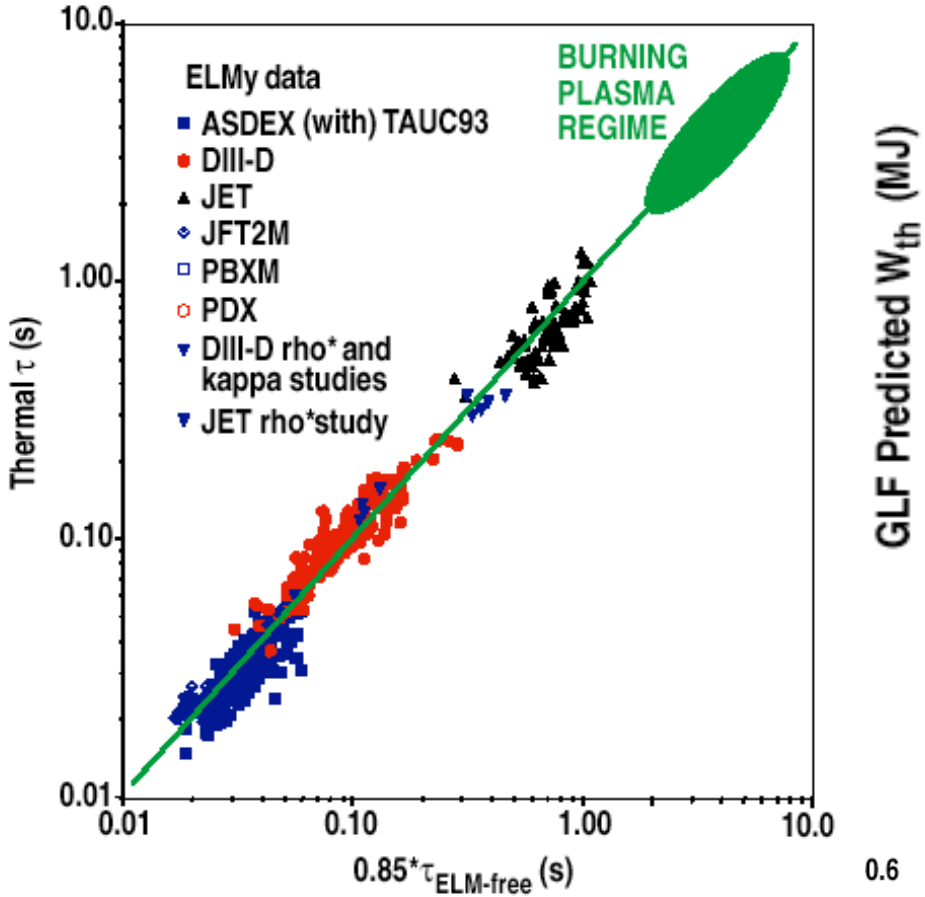


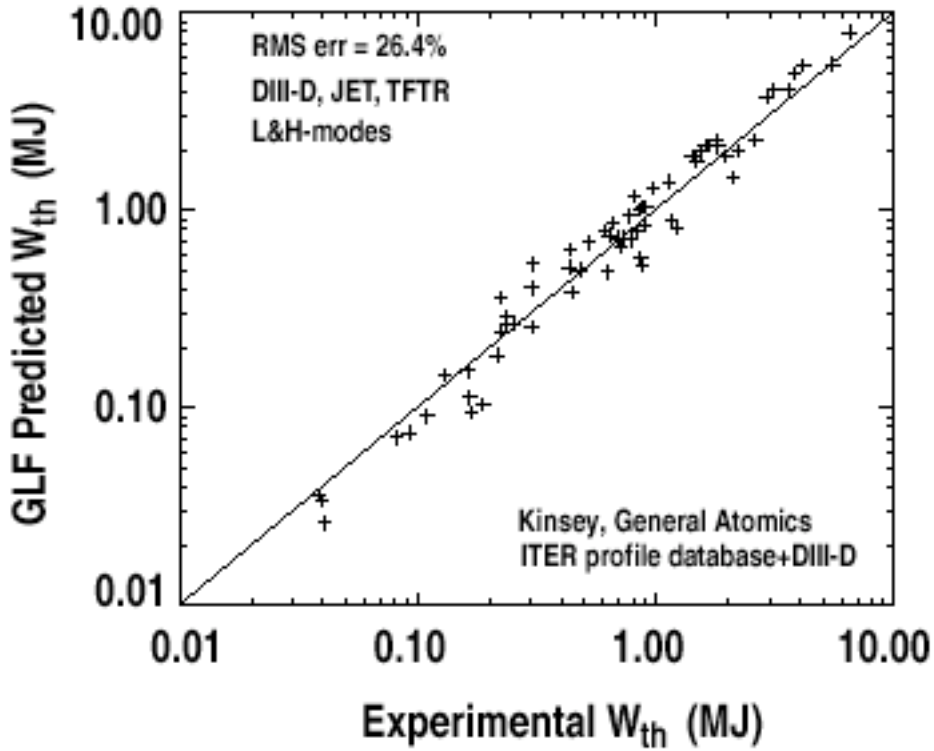


Fusion Energy Made per Pulse



Plasma Confinement Scaling ≈ Known





0.6

Empirical τ_E scaling

Theoretical turbulence model vs. experiment

Confinement and Plasma Turbulence

Code: GYRO

Authors: Jeff Candy and Ron Waltz

High Speed Imaging of Edge Turbulence in NSTX

with Princeton Scientific Instruments PSI-4 camera

viewing HeI(587.6 nm) light at 100,000 frames/sec

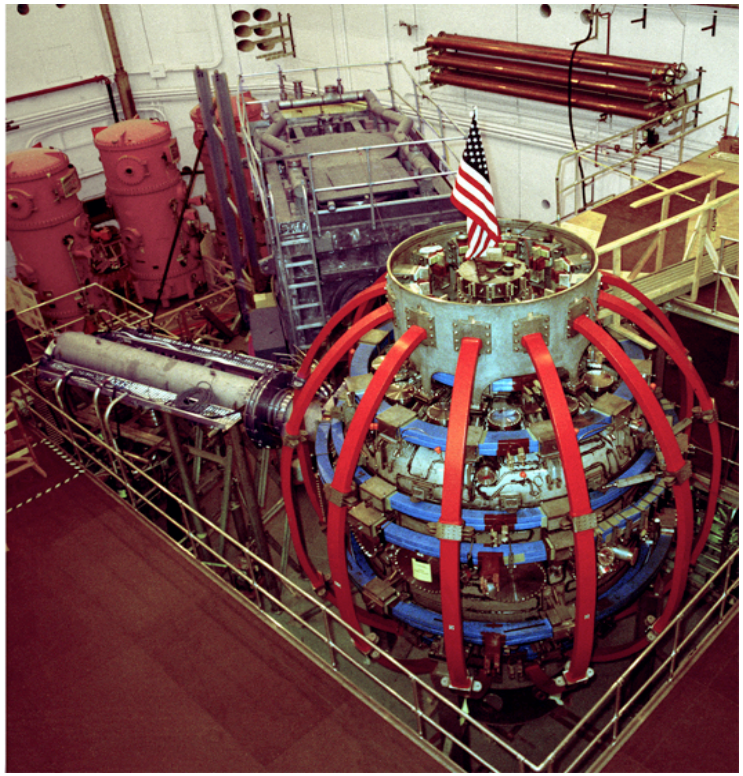
2002

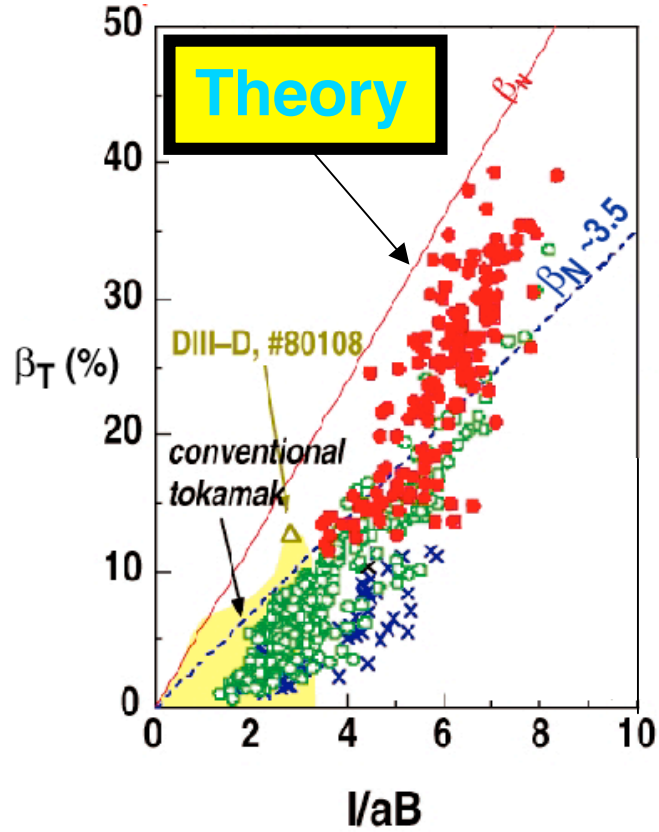
Turbulence simulation of tokamak core

Edge turbulence measurement (He light emission)

Plasma Pressure Limited by B Field

$\beta \equiv 2nT/B^2$ measures effficiency of magnetic confinememt

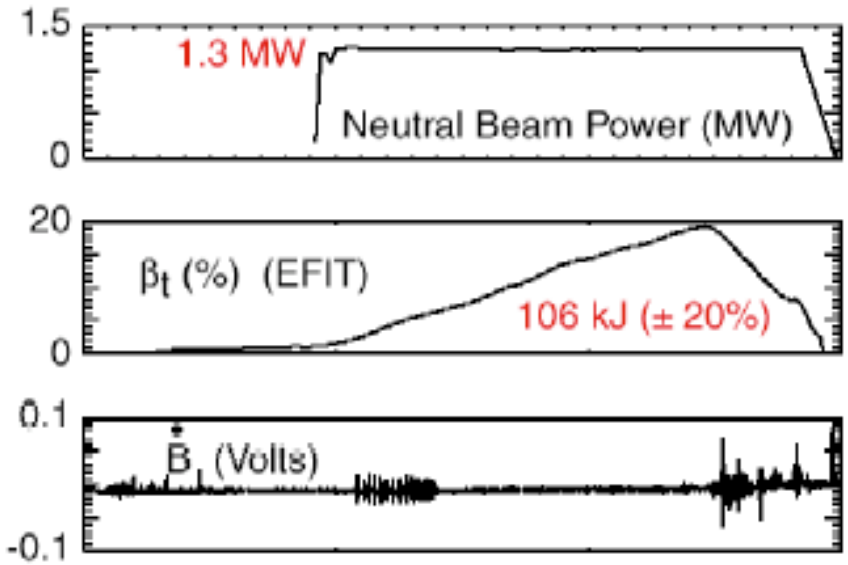


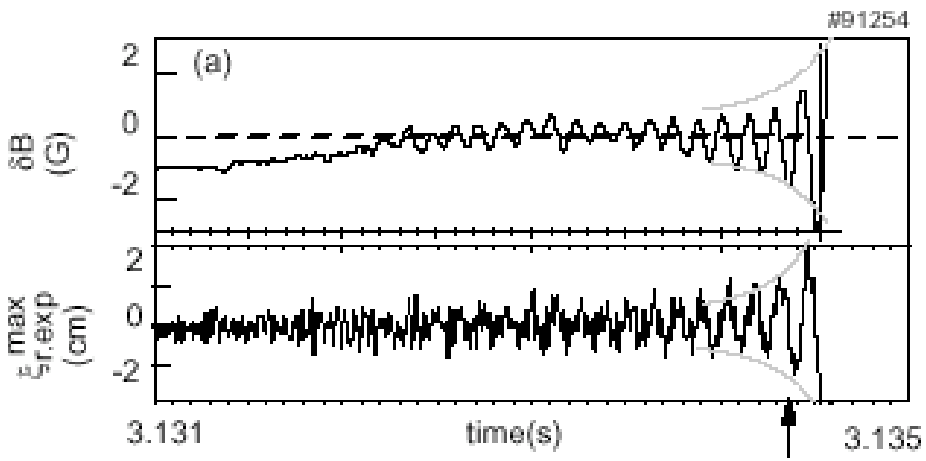


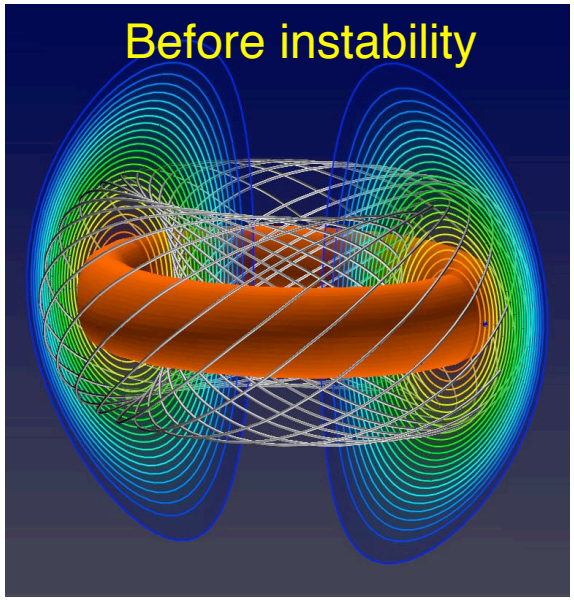
NSTX has reached β_T=20%

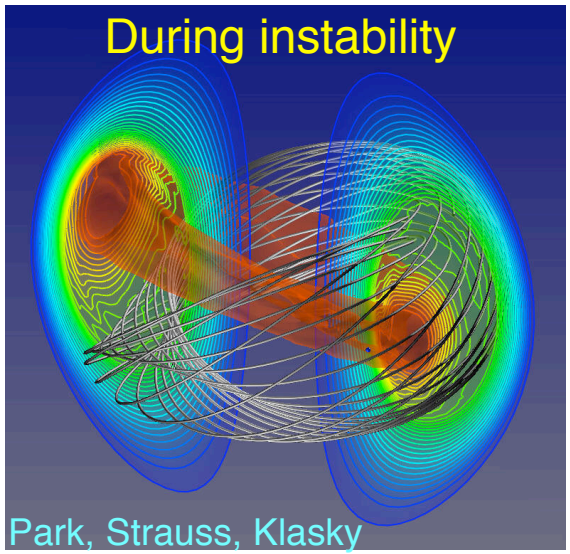
β limits ≈ agree with theory

Magnetic Instabilities at Pressure Limit



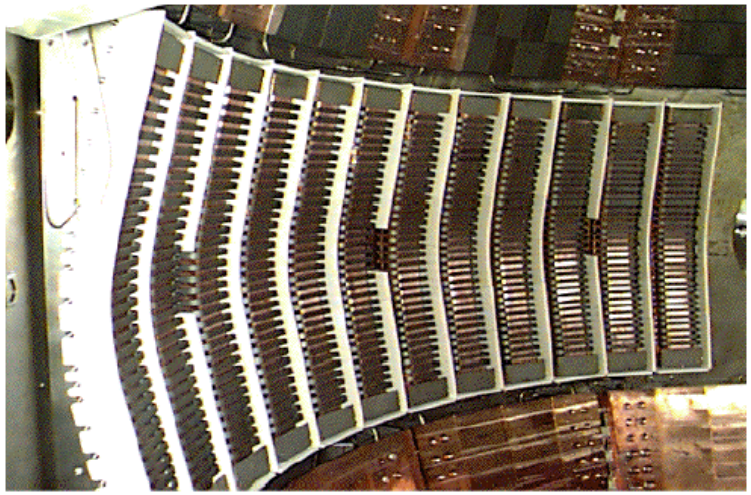




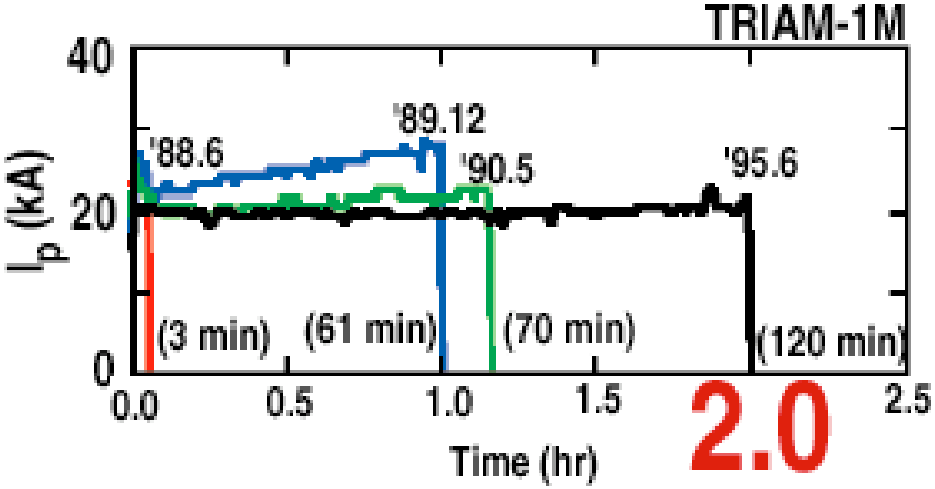


Tokamaks Need a Current Drive

- 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

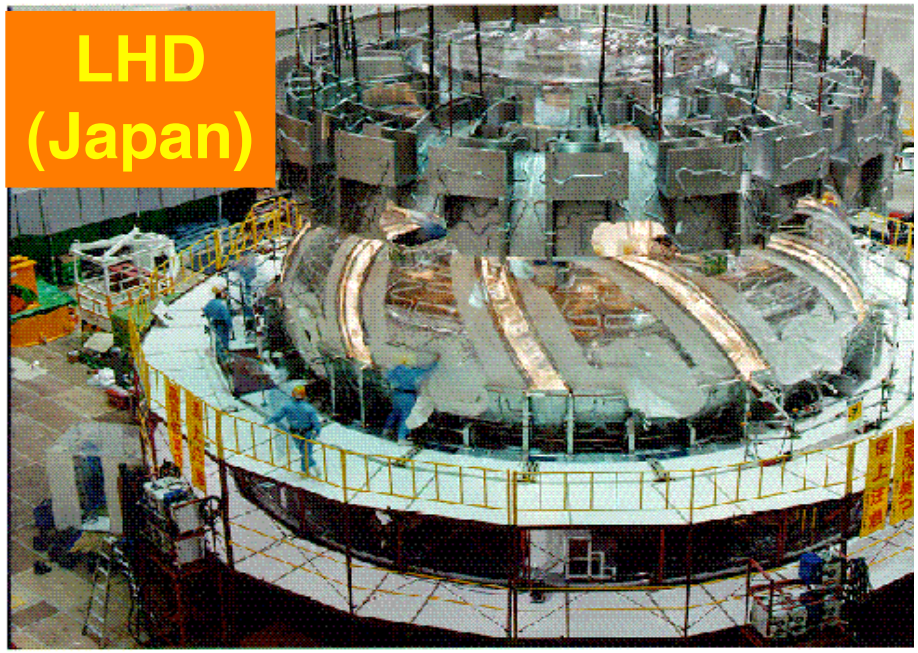


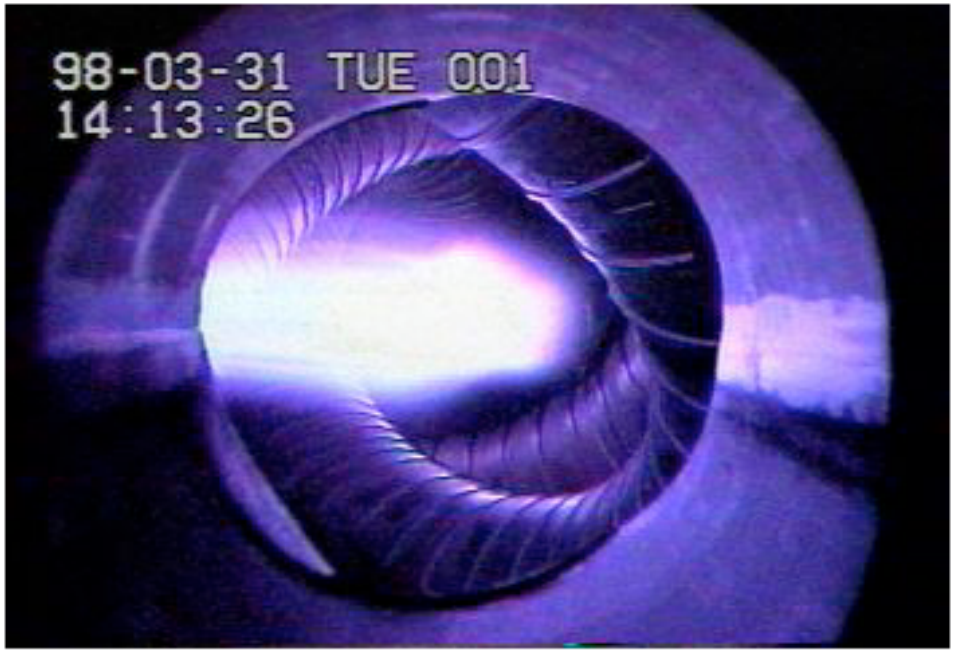
RF Antenna in NSTX



2.0 Hours!

Stellarator Don't Need Current Drive



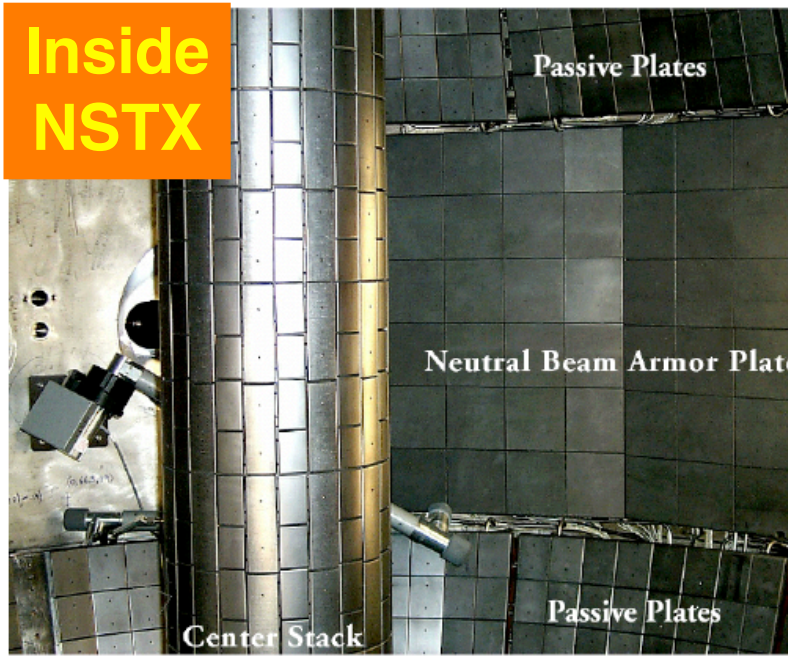


Photograph of the first plasma in the LHD.
A camera is aimed at the plasma through NBI (tangential) port.

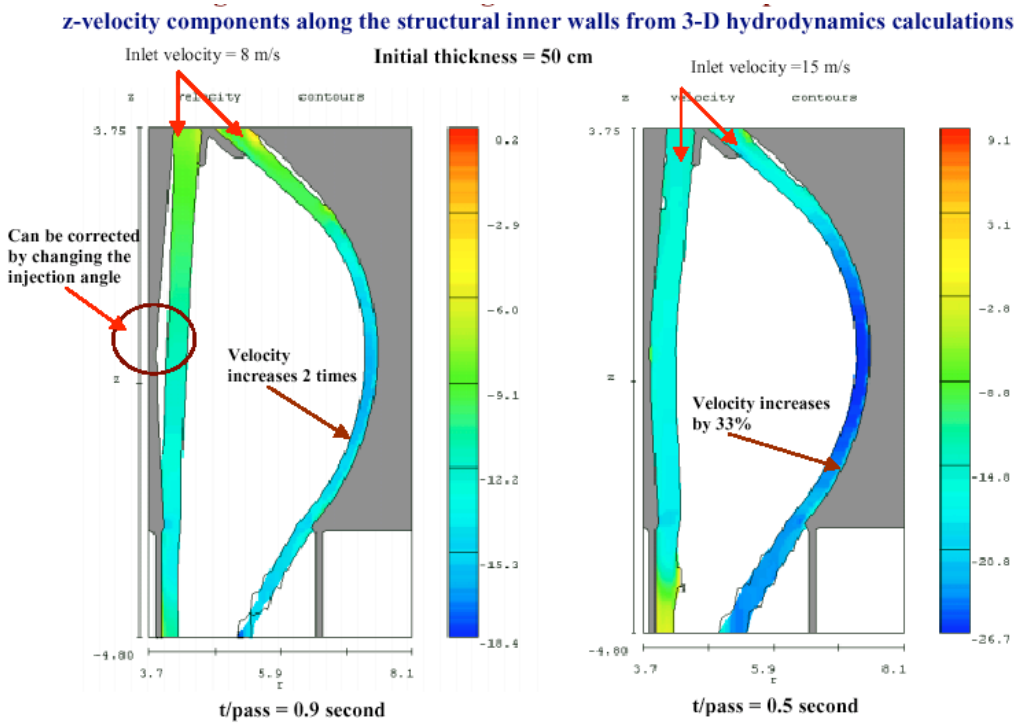
Superconducting helical coils can create "steady-state" magnetic confinement without toroidal current

Plasma Loss can Vaporize the Wall

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



Carbon composite wall

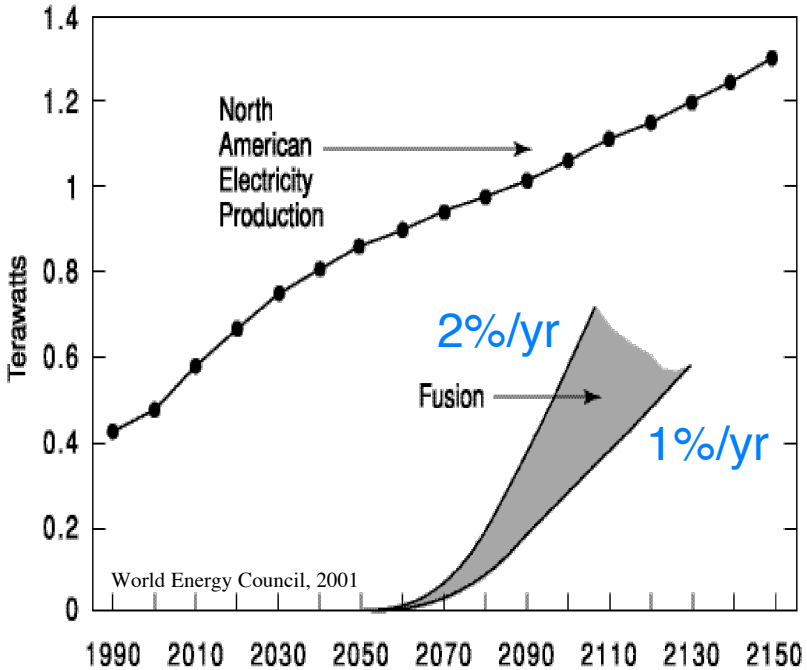


Flowing liquid wall CFD (Abdou et al)

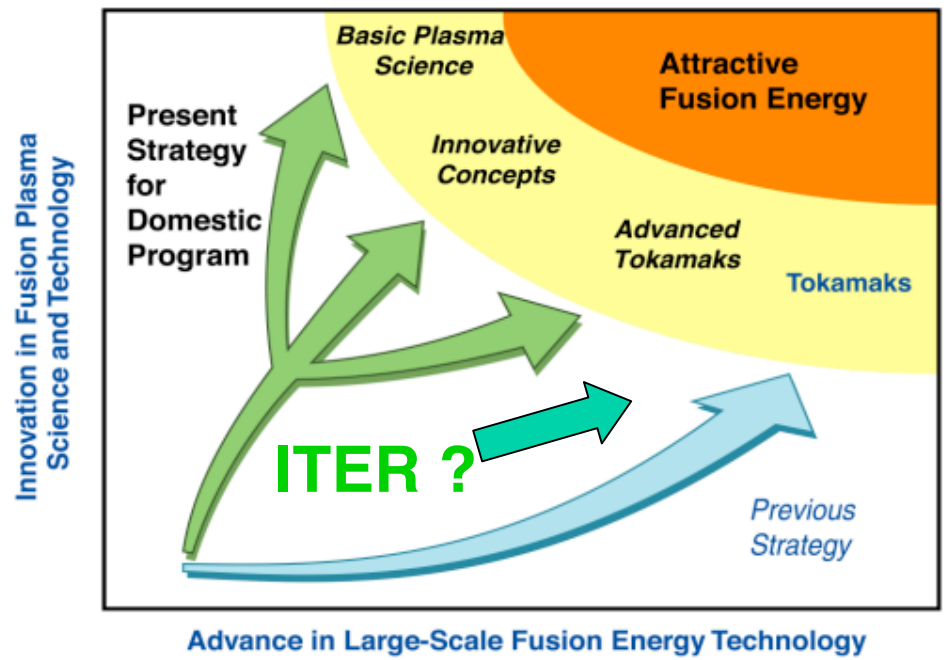
Where are we Going ?

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

Fusion Energy Goal and Strategy

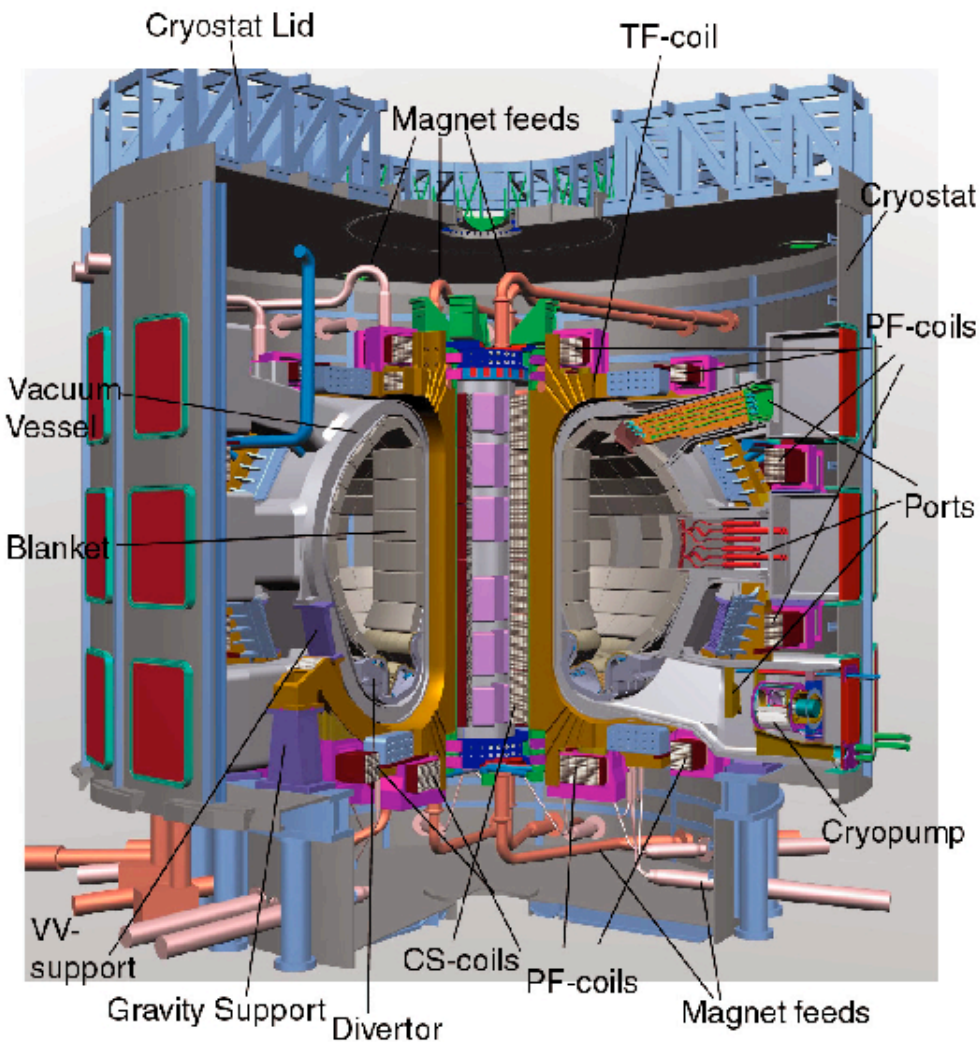


- Fusion energy might contribute significantly in ≈ 2050-2100



- Portfolio of innovative concepts, including inertial fusion energy
- Broader scientific areas of inquiry

ITER and the Tokamak Fusion Reactor



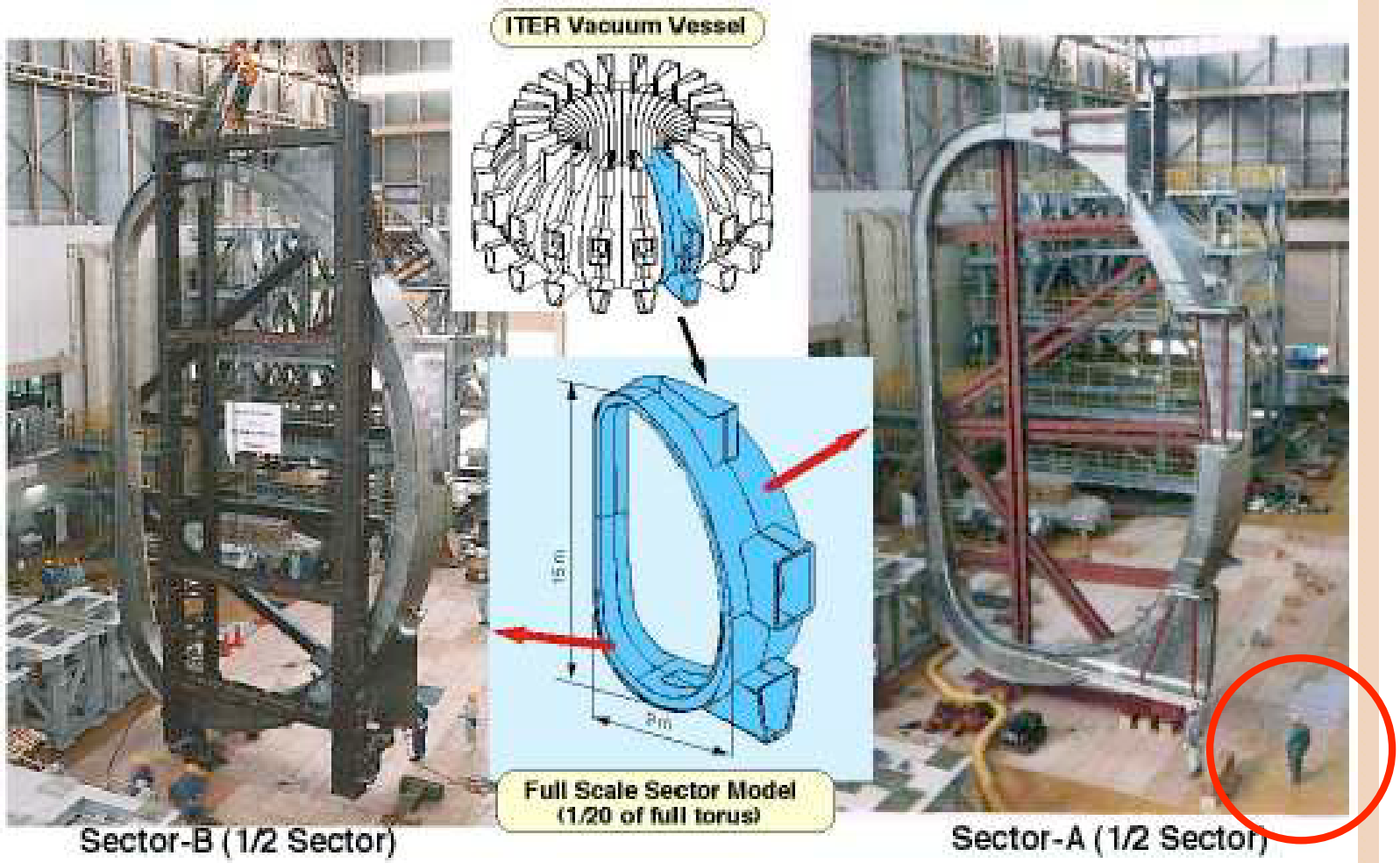
ITER Design Goals:

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

Tokamak Reactor Goals:

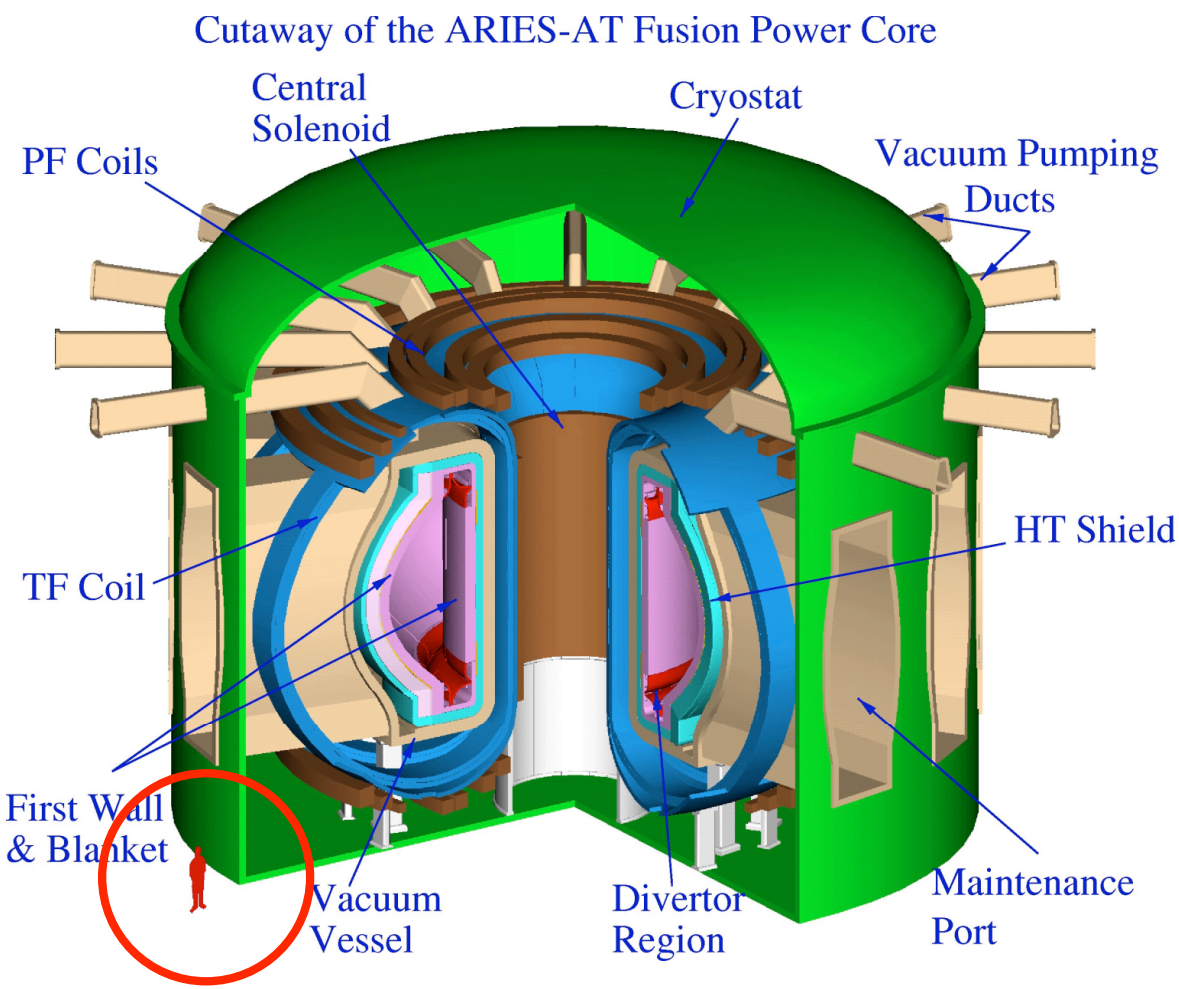
- Q ≥ 20
- ≥ 3 GW fusion power
- steady-state pulse
- 5¢ / kW-hr electricity

ITER Can Be Built by ≈ 2015 for ≈ $ 5B



View of full-scale sector model of ITER vacuum vessel completed in September 1997 with dimensional accuracy of ± 3 mm

Tokamak Reactor Design



Estimated Cost of Electricity

1 GWe 4.75¢ / kW-hr

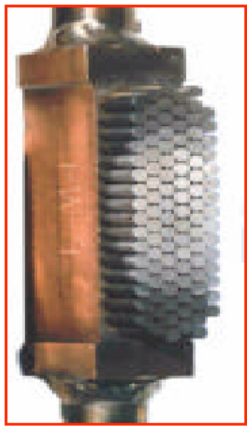
4 GWe 3.4¢ / kW-hr

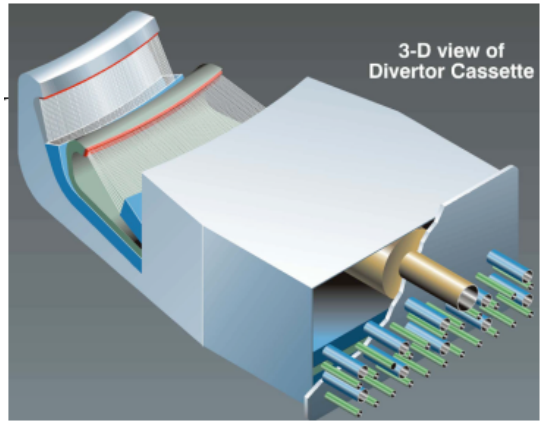
(for H_2 production)

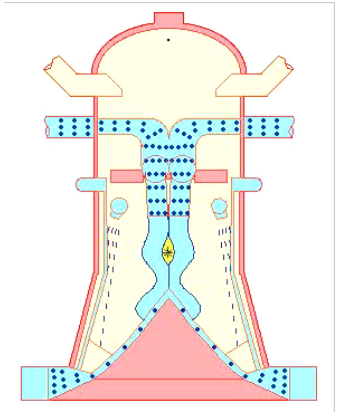
R&D is needed to confirm the science and technology.

Fusion Reactor Engineering

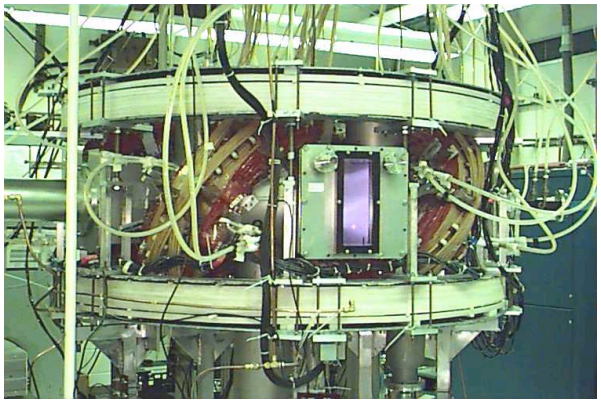
- May need to replace first wall modules periodically
  - plasma erosion + neutron damage (≤ 30 dpa/yr)
- Need to breed and recycle tritium fuel on-site
  - need ≥ 1 T / neutron and recycle ≈ 1 kG tritium
- Reactor must be reliable, maintainable, and available
  - and safely handle off-normal events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





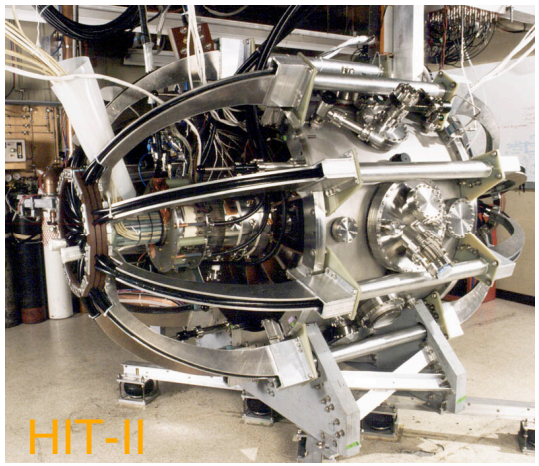


Innovative Confinement Concepts



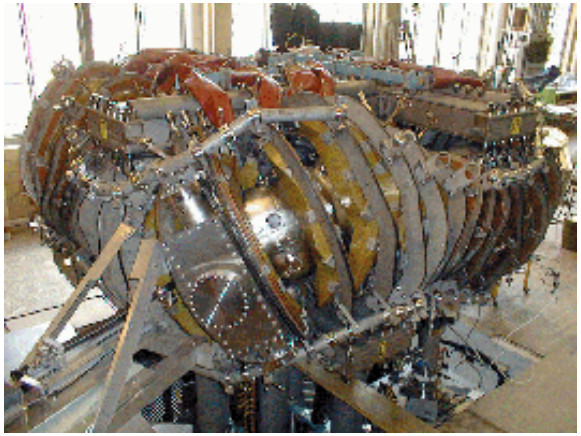
Compact Auburn Torsatron
Auburn University, Auburn Alabama

Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology



Helicity Injected Torus-II Experiment
University of Washington, Seattle

Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory

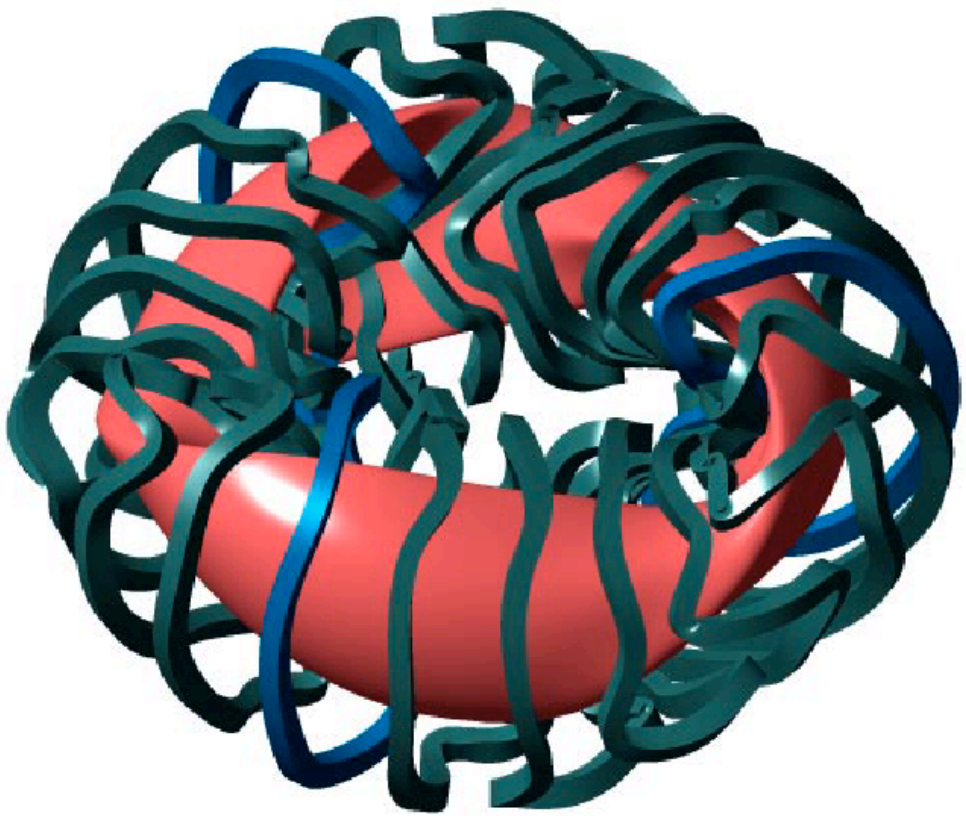


Helically Symmetric Experiment
University of Wisconsin, Madison

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
$\beta \approx 4\%$ (?)

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

Conclusions

- Plasma science is making progress

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

- Energy from magnetic fusion is possible

  plasma conditions for ignition are almost obtained, and could be created in the next-step tokamak

- Conceptual fusion reactor designs exist

  but tokamak approach may be too expensive, and alternate concepts are still very far from ignition