50 Years of Fusion Research

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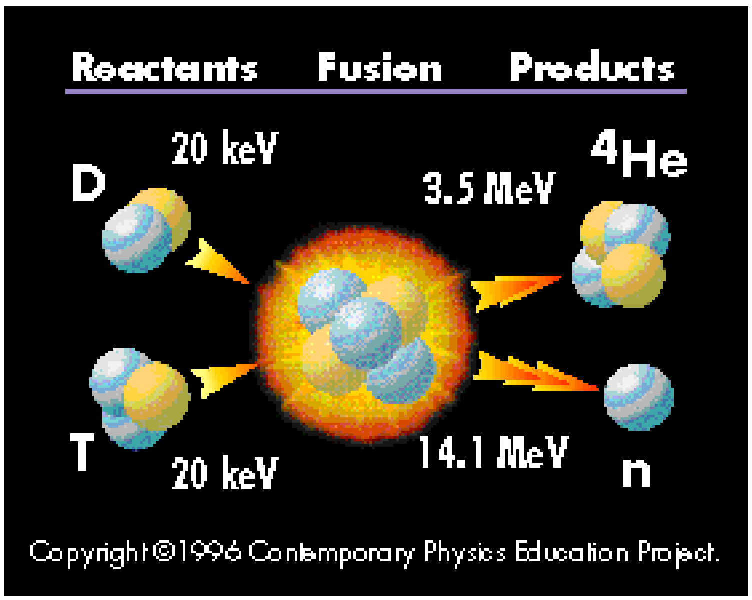
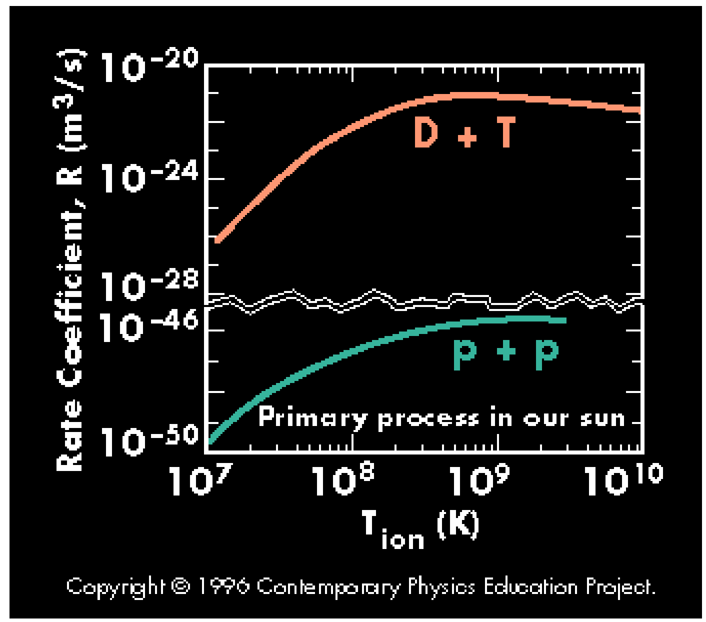
- How would a fusion reactor work ?
- What have we done in 50 years ?
- Where are we going with this ?

Nuclear Fusion is Simple

Fastest fusion reaction is: D + T => n (14 MeV) + α (3.5 MeV)



For first generation fusion reactors



Energy gain ≈ 450

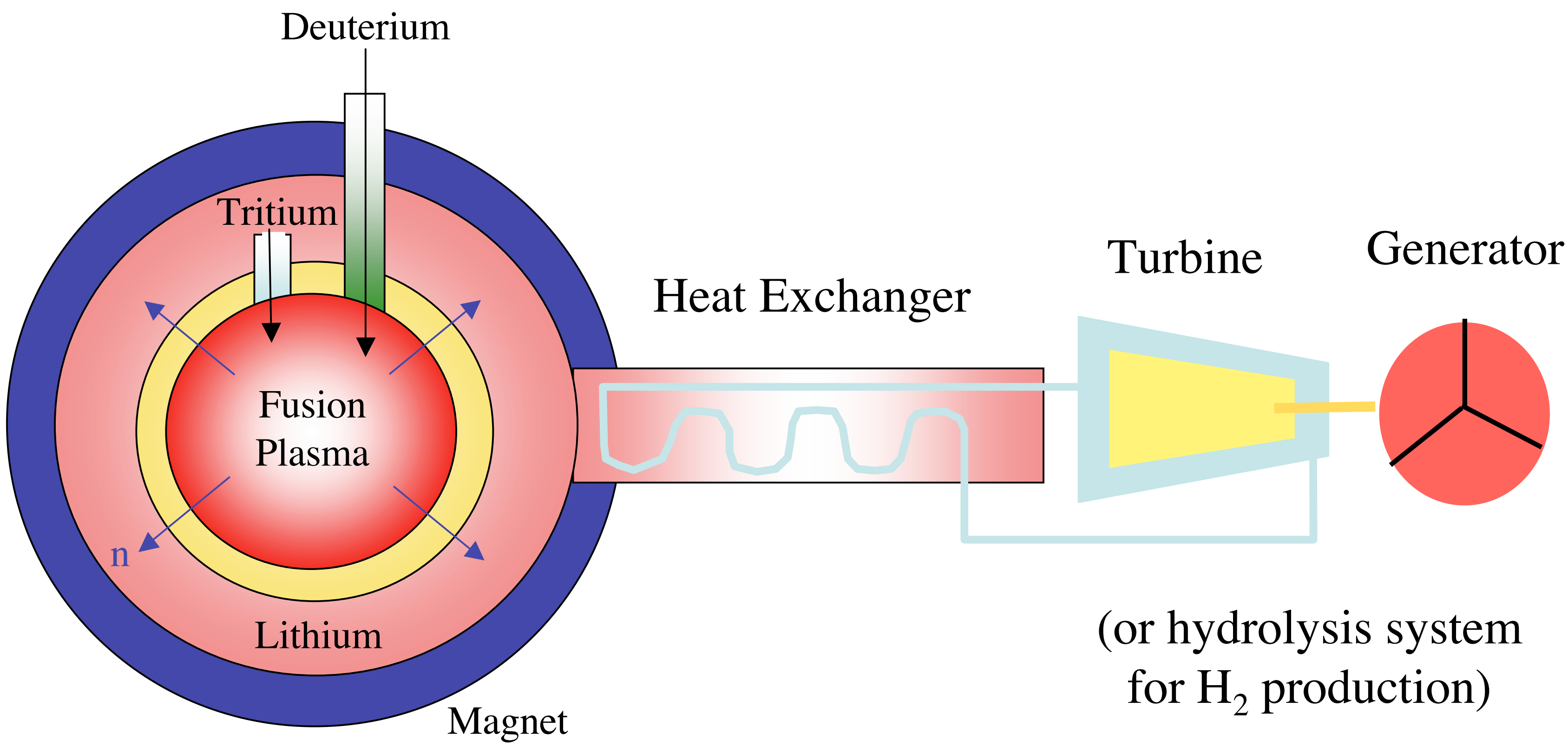
Needs a plasma at $T_{ion} \approx 10$ keV

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 is not present in Nature (13 year half-life), but slightly more than 1 tritium atom can be created for each D-T neutron in a lithium "breeding blanket"

  Li^6 + n -> T + He^4 + 4.8 MeV (7% natural Li)
  Li^7 + n -> T + He^4 + n - 2.5 MeV (93% natural Li)

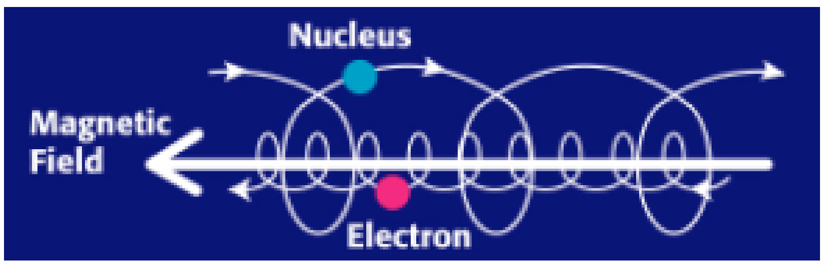
Design of a Fusion Reactor



Fusion neutrons supply heat
to generate electicity

Two Basic Approaches

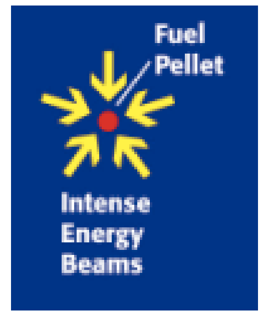
Magnetic fusion energy (MFE)



ion gyroradius ≈ 1 cm at
T_i = 20 keV and B = 20 kG

ion travels ≈ 10^3 km/sec
so is difficult to confine
in a laboratory plasma

Inertial fusion energy (IFE)



ion travels 0.1 cm/ns so
can be confined inertially

difficult to heat D-T fuel to
20 keV in a very small
space and short time

Requirements for Fusion Burning

"Burning" means self-heating by D-T alpha particles

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

Main Difficulties in Fusion Research

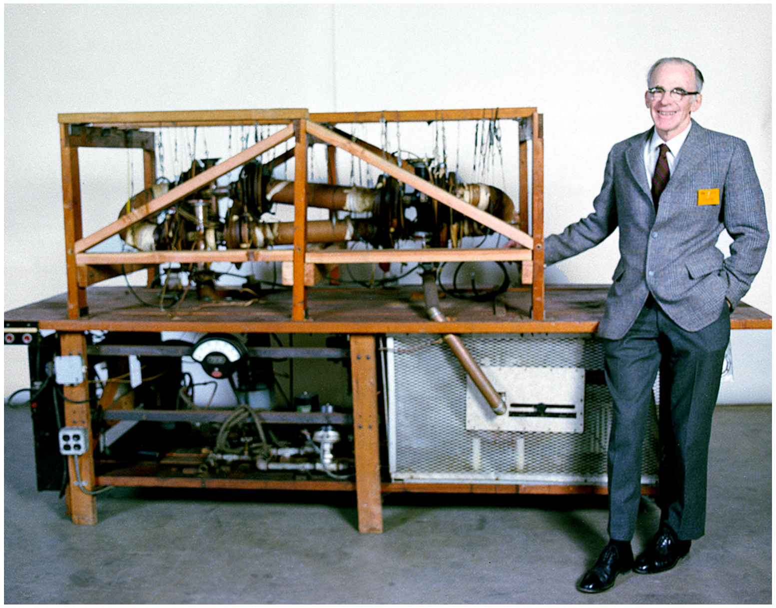
- The fusion power created must be larger than the power required to keep the D-T fuel at high temperature

  => near-term scientific goal of a “burning plasma”

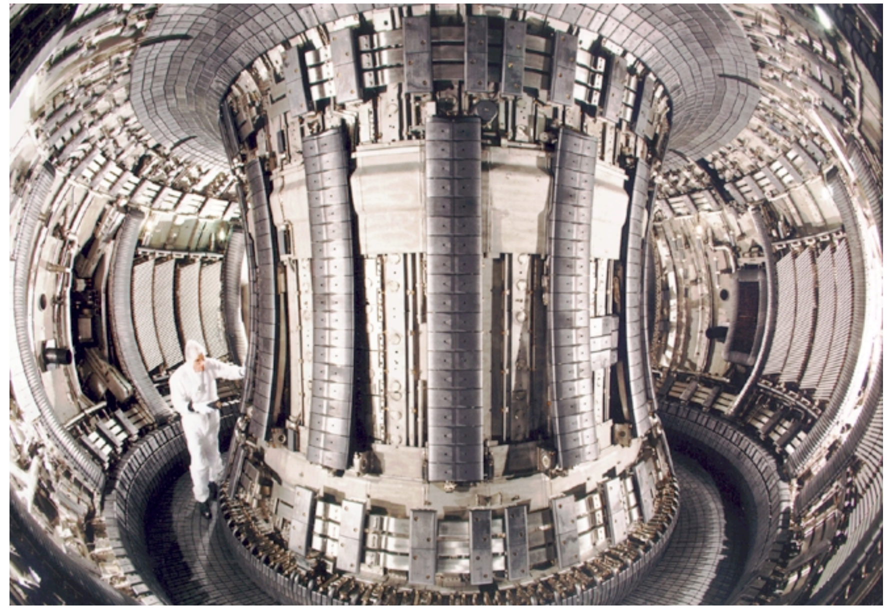
- The mechanical structure of the device must be capable of withstanding damage due to plasma bombardment and radiation damage due to 14 MeV neutrons

  => long-term engineering goal of improved materials

What Have We Done in 50 Years ?



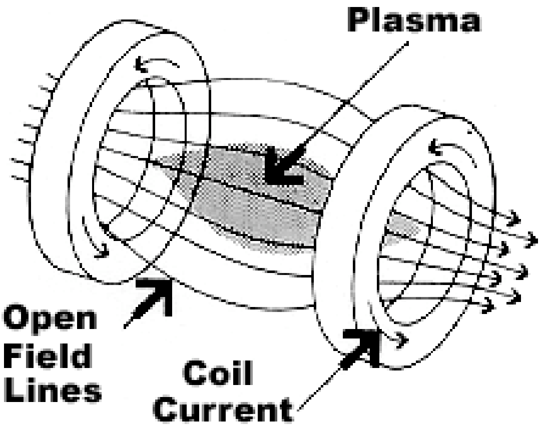
Model A Stellarator of 1953
(with Lyman Spitzer)
$n \approx 10^{13}$ cm^{-3} (?)
$T \approx 10$ eV (?)
$\tau_E \approx 10\ \mu$sec (?)



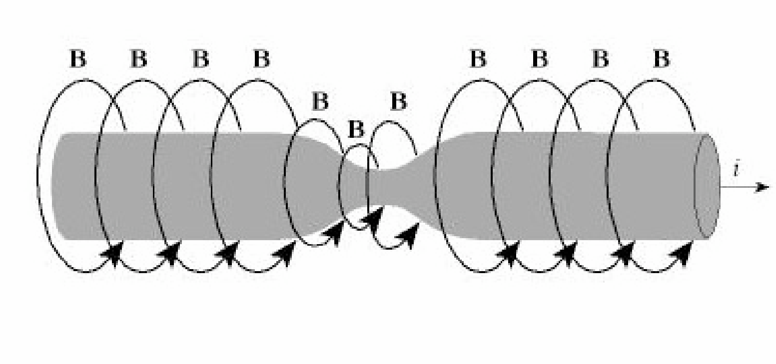
JET Tokamak in 2003:
$n \approx 10^{14}$ cm-3
$T \approx 20$ keV
$\tau_E \approx 1$ sec
$nT\tau_E \approx$ x5 from burning

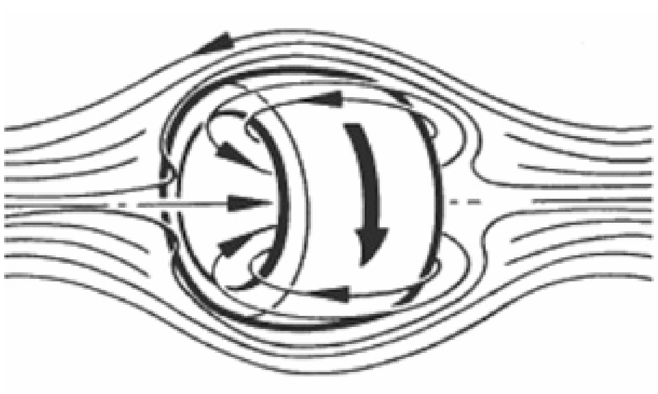
Early Ideas for Magnetic Confinement

magnetic mirror

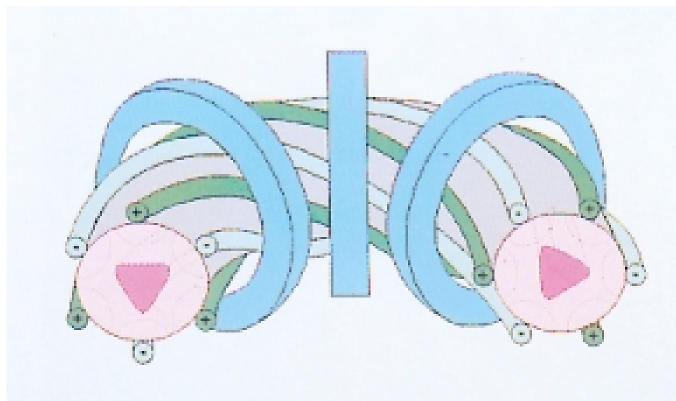


linear pinch





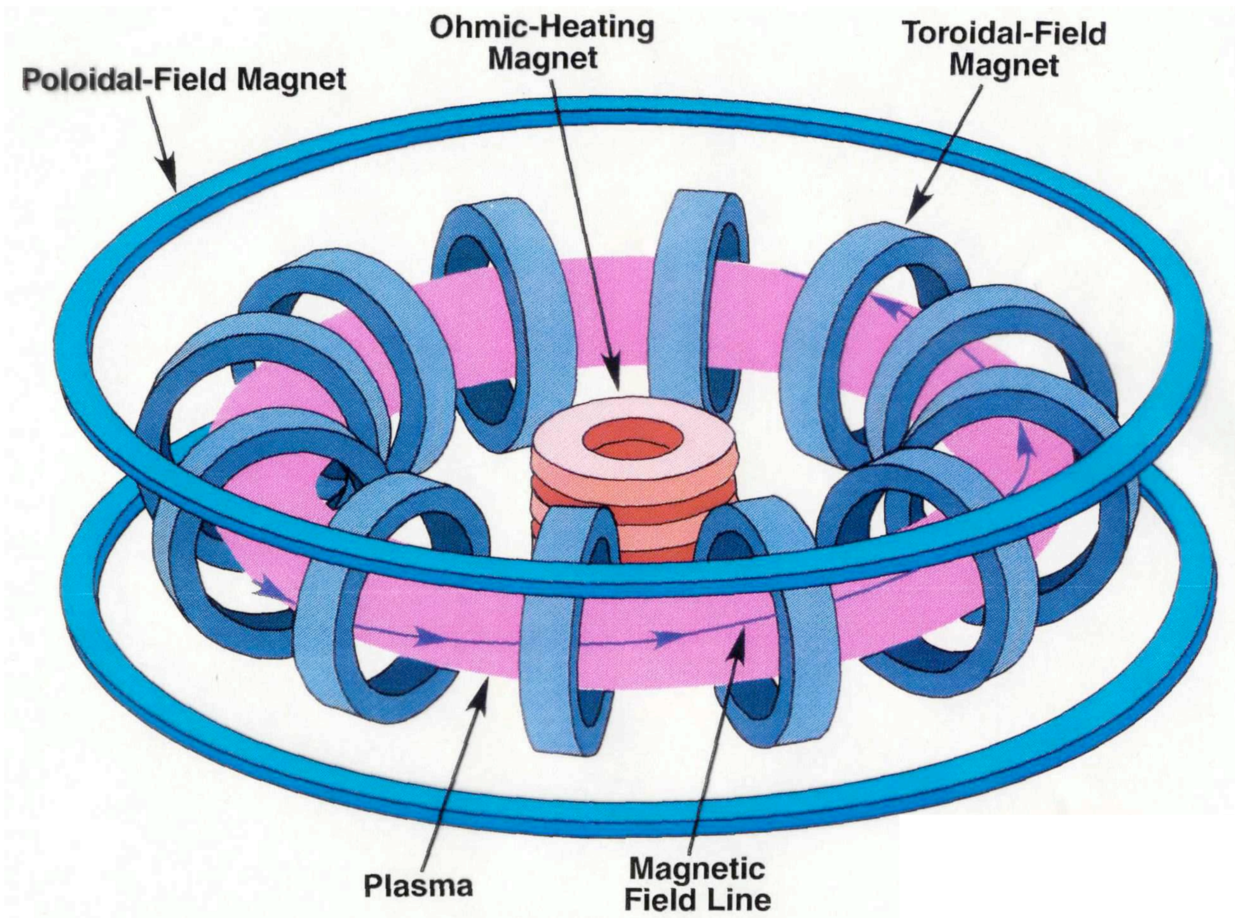
field reversed configuration



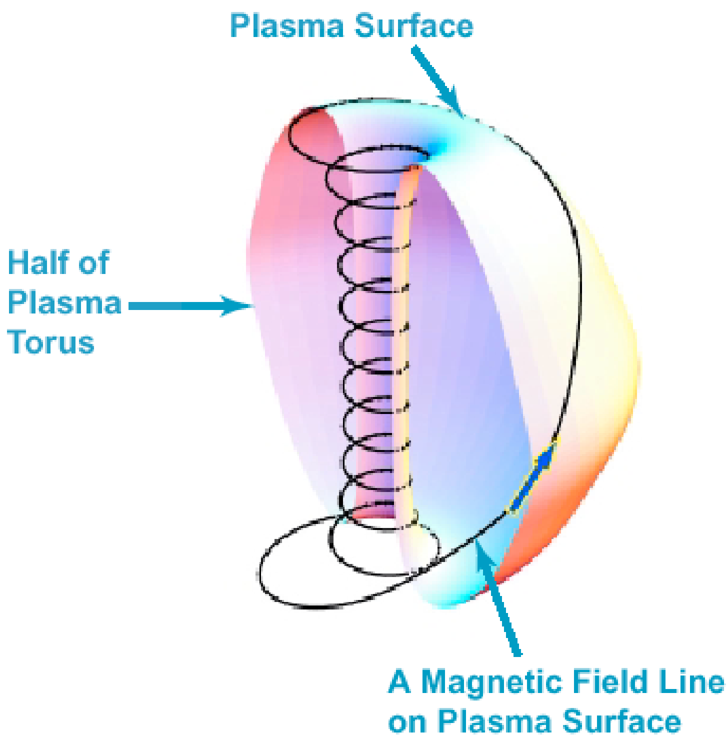
stellarator

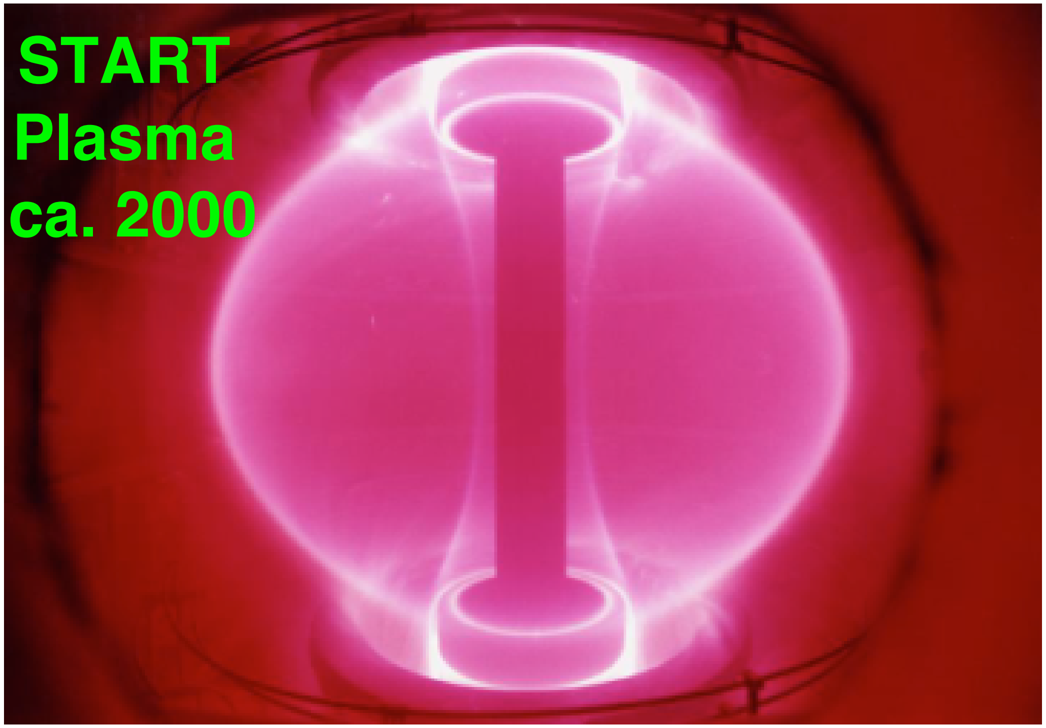
The Winner so Far: the Tokamak

Tokamak = toroidal magnetic chamber (Russian acronym)



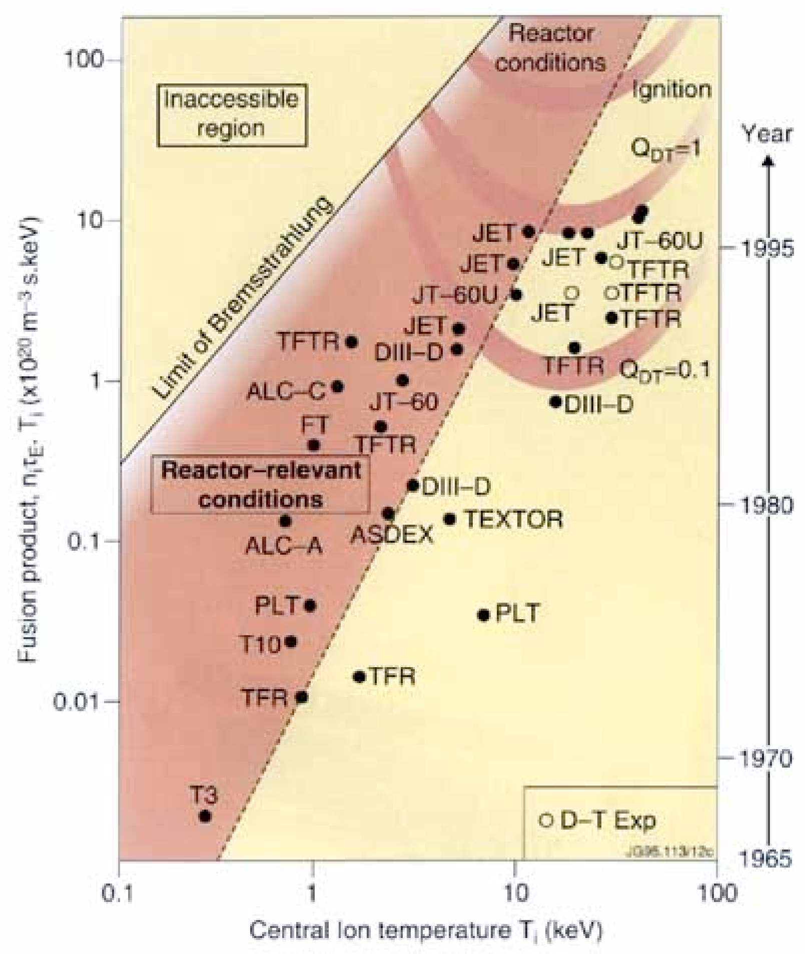
Example of Tokamak Confinement





Theoretically, confinement time due to classical collisional transport is easily long enough to make a reactor

History of $nT\tau_E$ in Tokamaks



$T \approx 20$ keV achieved

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

$\tau_E \approx 1$ sec achieved

(not quite simultaneously)

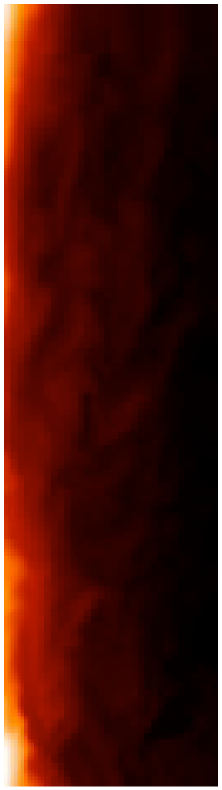
still need factor of ≈ 5
to create burning plasma

(improvements came mainly from increase in machine size)

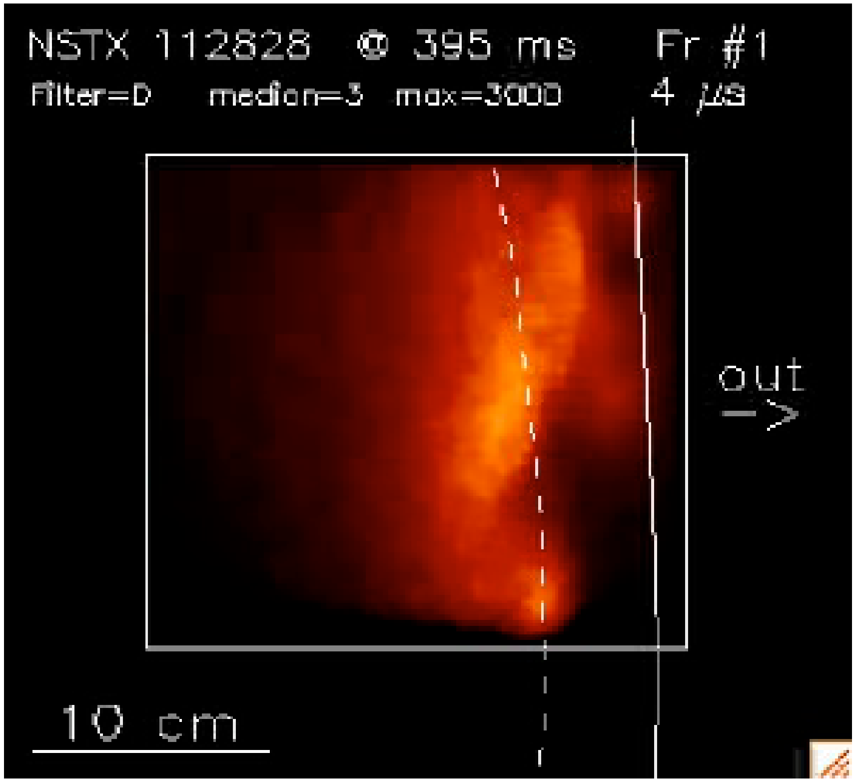
Current Research in Tokamaks

- Understanding confinement (microturbulence)
- Understanding pressure limits (MHD stability)
- Improving non-inductive current drive (with RF)
- Controlling plasma-wall interactions (impurities)
- Designing optimum burning plasma experiment

Understanding Plasma Turbulence

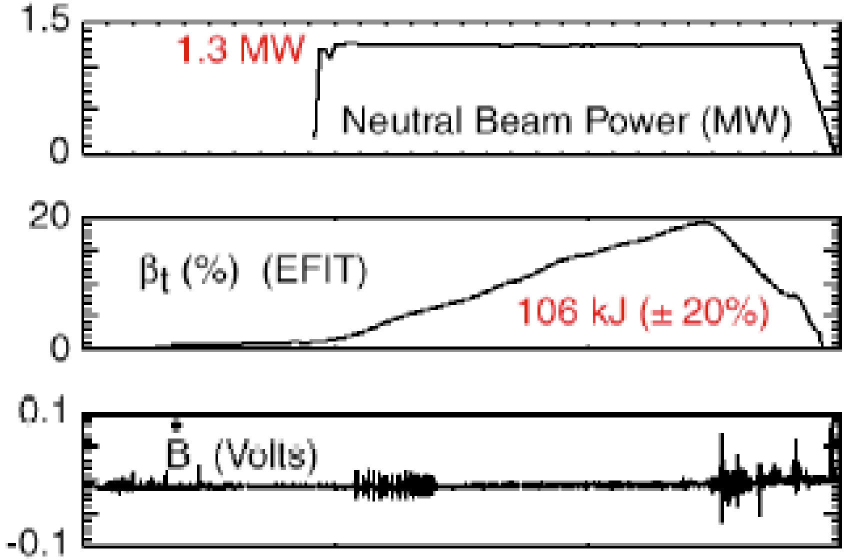


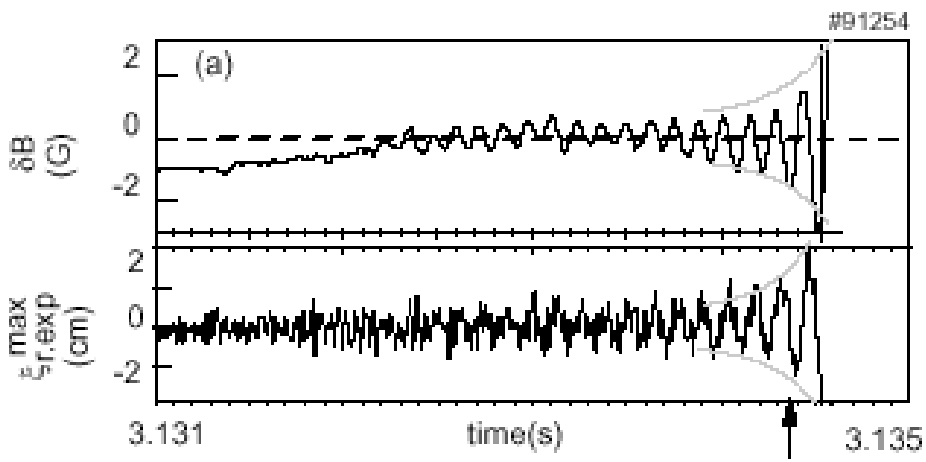
Edge turbulence simulation

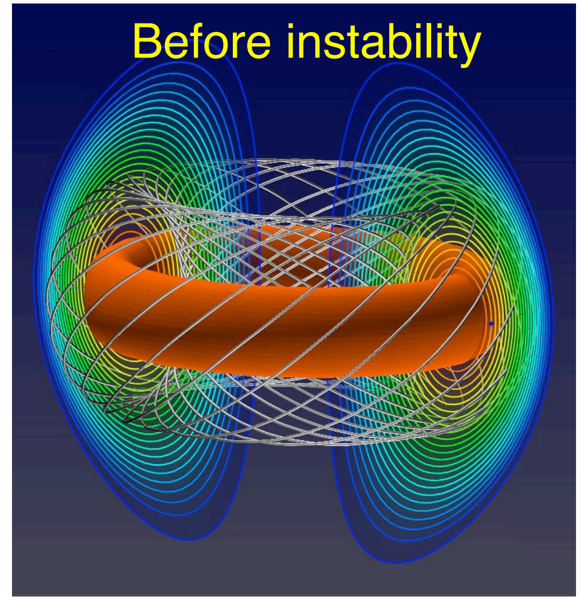


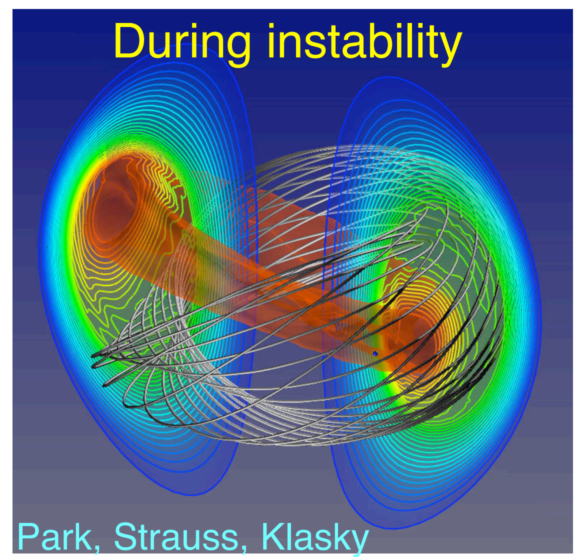
Edge turbulence measurement

Understanding Pressure Limits



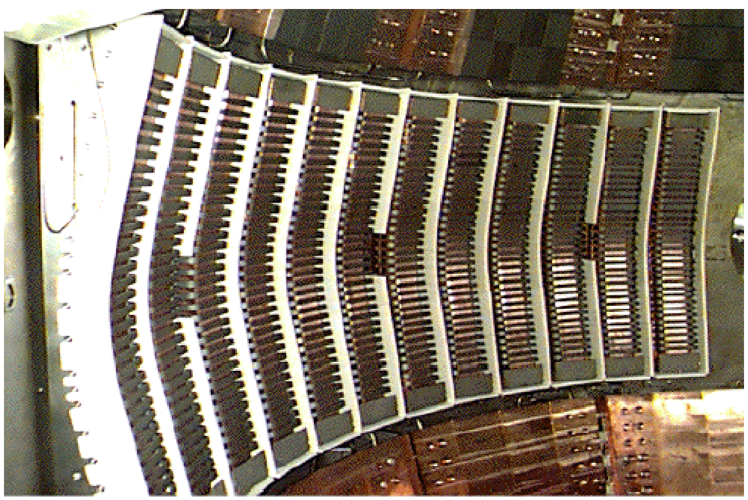




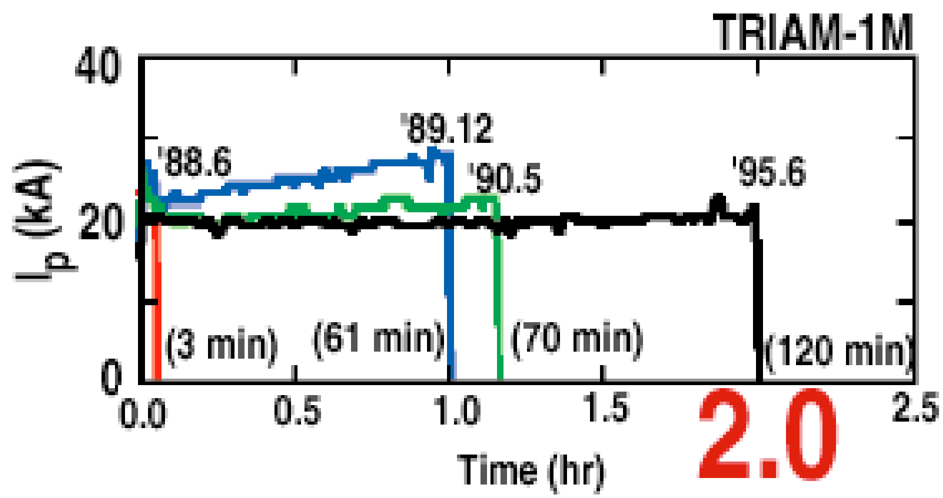


Improving Non-Inductive Current Drive

- 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

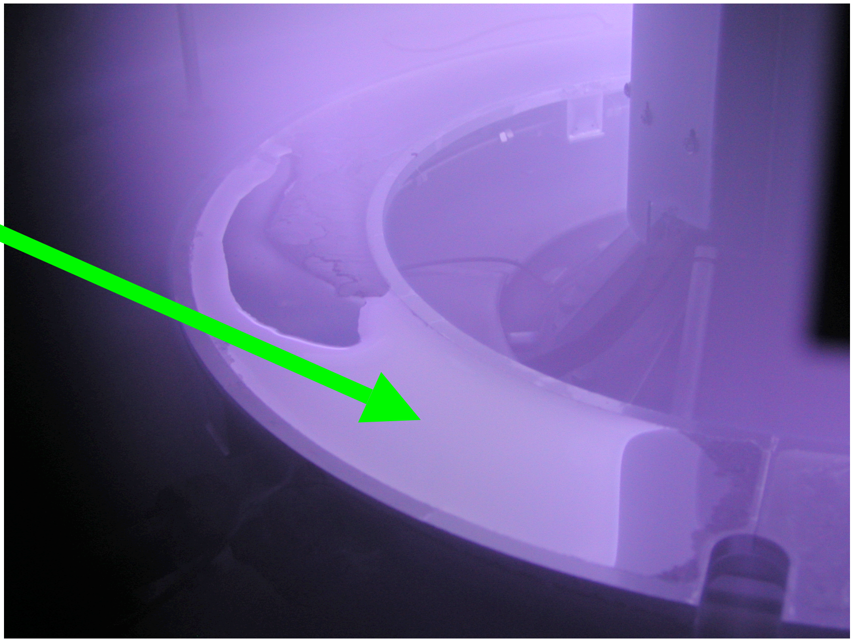


2.0 Hours!

Controlling Plasma-Wall Interactions

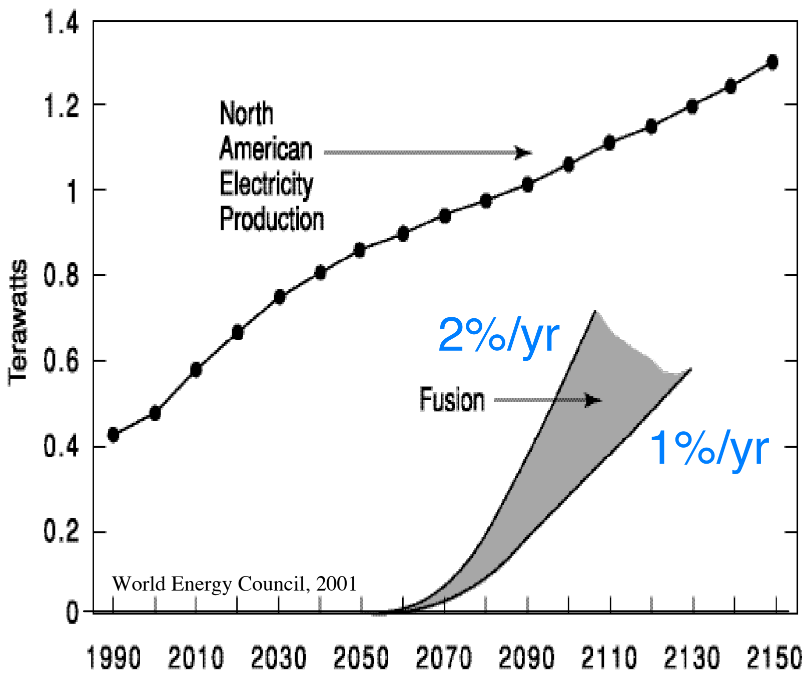
- Plasma flux to parts of first wall may be ≈ 1-10 MW/m^2
- Damaged first wall would be very hard to repair *in situ*

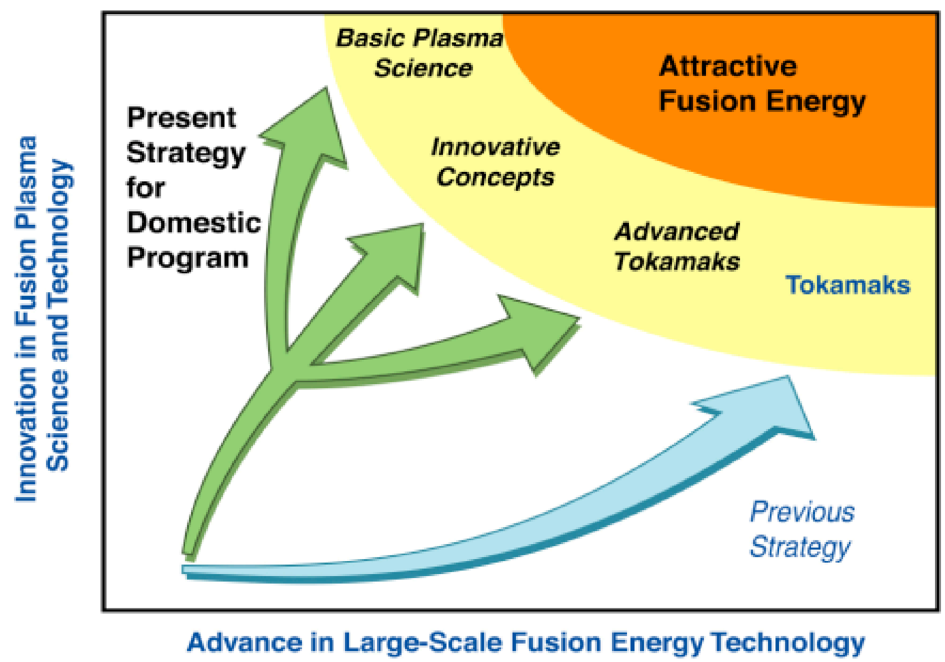
First test of liquid lithium wall in CDX-U



Possible flowing liquid lithium wall solution for tokamak reactor

Where are we Going with This ?

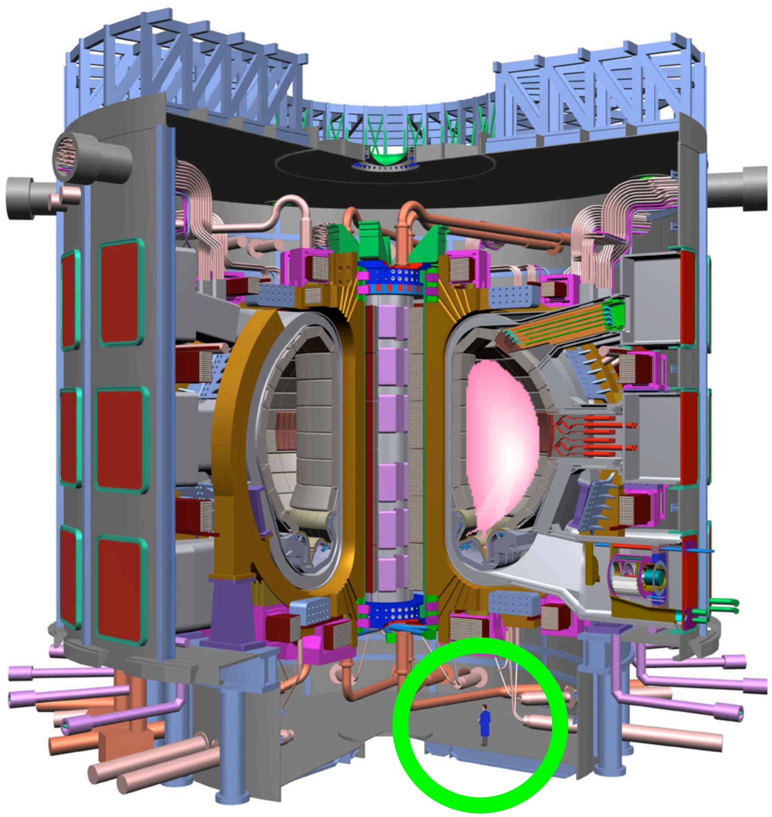




- Fusion energy might contribute significantly in ≈ 2050-2100

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

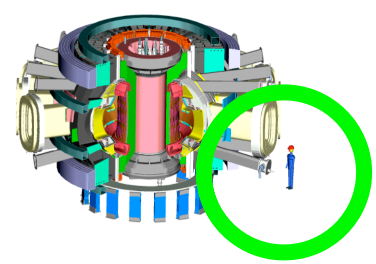
ITER and FIRE



ITER (superconducting)

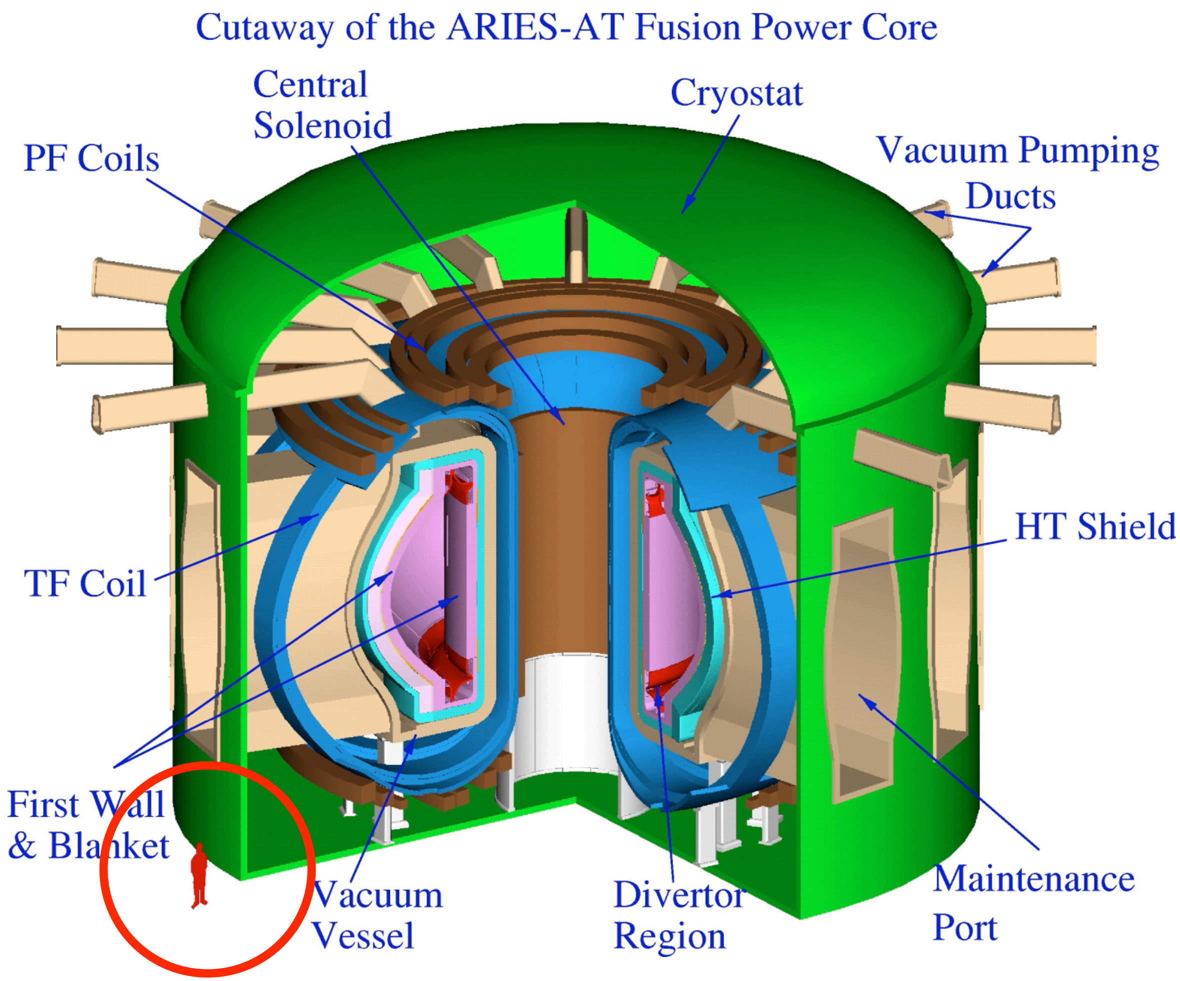
ITER Design Goals:

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



FIRE (copper)

Tokamak Reactor Design



Inertial Fusion Burning Plasma

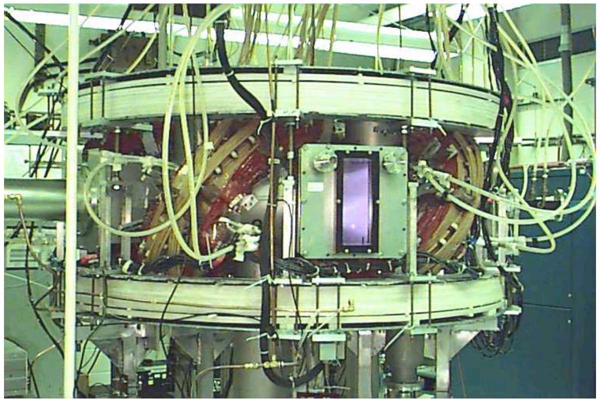
National Ignition Facility being built at LLNL


Laser Bay 2 beampath with support utilities installed.

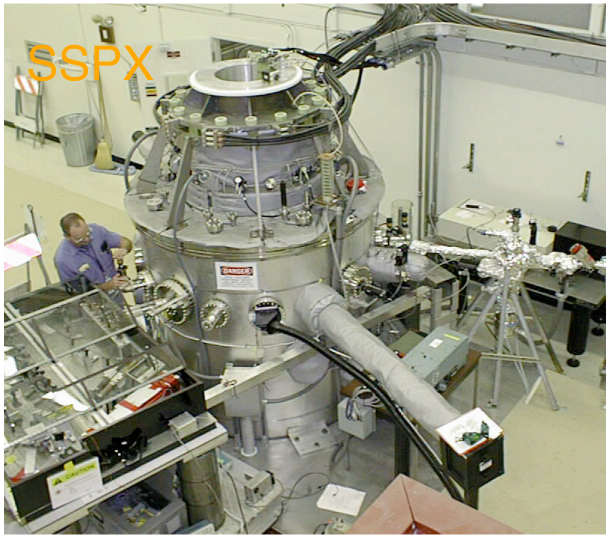
Designed for 1.8 MJ laser energy onto target capsule

Plan for ignition in 2007 (?)

Innovative MFE Experiments

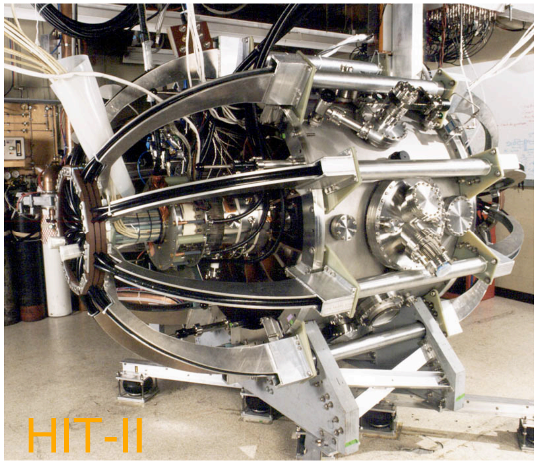


Compact Auburn Torsatron
Auburn University, Auburn Alabama

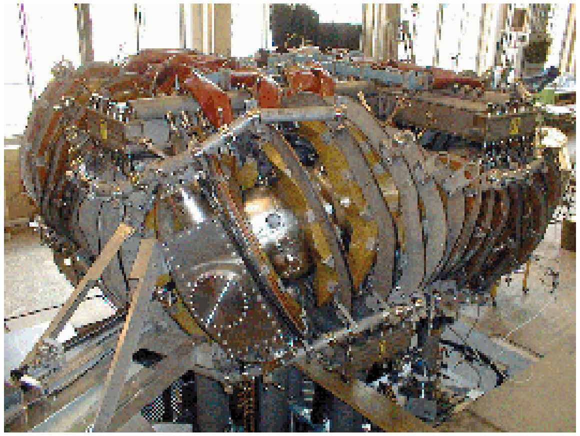


Sustained Spheromak Plasma Experiment
Lawrence Livermore National Laboratory

Levitated Dipole Experiment
Columbia University/Massachusetts Institute of Technology



Helicity Injected Torus-II Experiment
University of Washington, Seattle

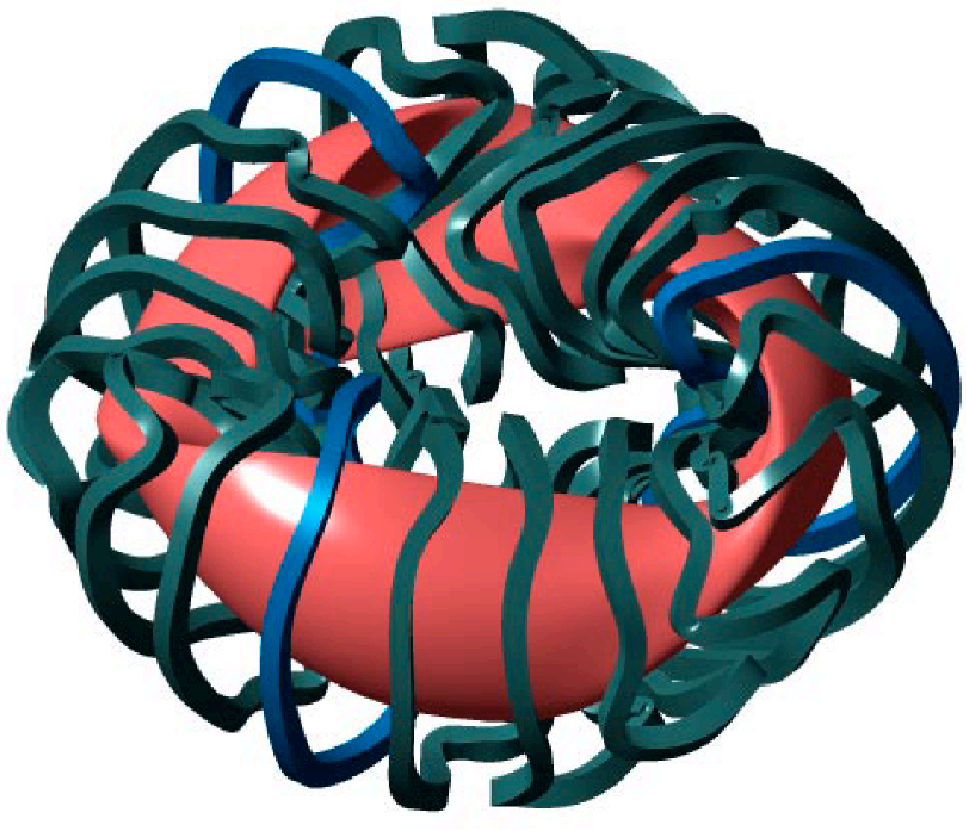


Helically Symmetric Experiment
University of Wisconsin, Madison

Compact Stellarator (NCSX)

Aims to combine best features of tokamak and stellarator

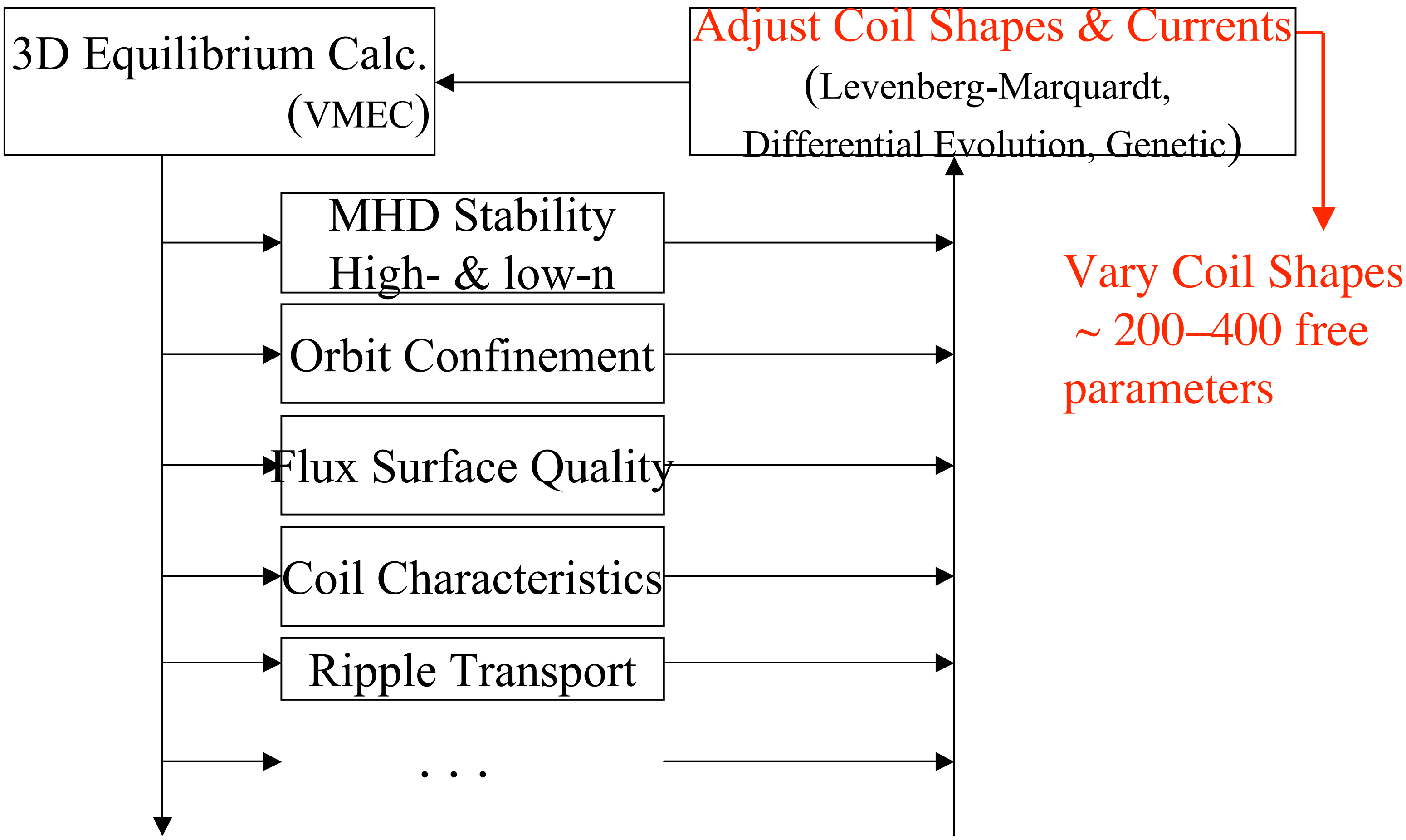
- needs no external current drive (like stellarator)
- large plasma for a given major radius (like tokamak)



R = 1.5 m
a = 0.5 m
B = 1.0 T
P = 6 MW
$\beta \approx 4\%$ (?)

NCSX : a Product of Parallel Computation

Direct optimization of coil shapes to achieve desired physics properties



Crucial for simultaneously achieving physics and engineering goals
Achieved using high-capacity advanced computing

Conclusions

- Making a fusion reactor will be very difficult
- Plasma physics problems are being solved
- Burning plasma seems to be the next step
- Fusion reactor possible by 2050 ?