Introduction to Magnetic Fusion

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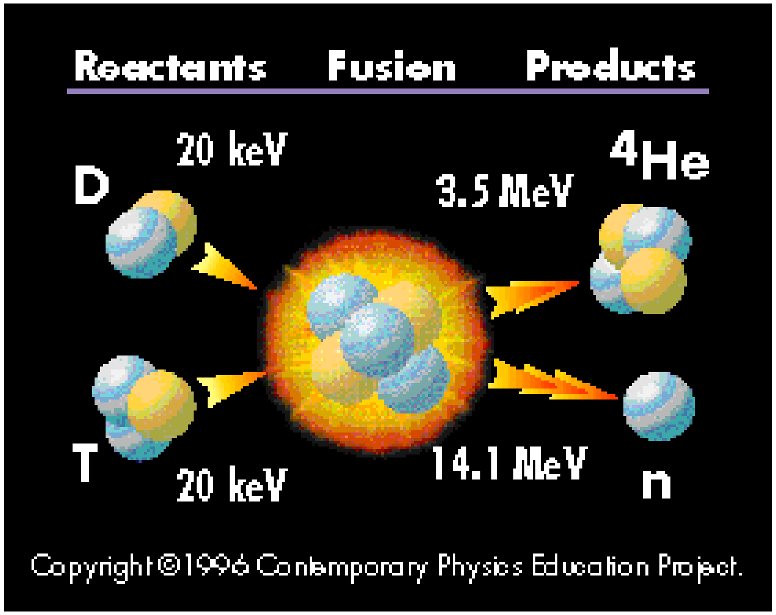
NUF June 9, 2008

- The Dream
- The Reality
- The Future

Unlimited Energy from Fusion



For first generation fusion reactors

Heat D+T to ~ 20 keV

Produces 17.6 MeV

Energy gain ~ 450

Deuterium in 1 gallon of water can produce the energy of 300 gallons of gasoline, if burned in a fusion D-T reactor

Tritium can be created from D-T neutrons in a Li "blanket"

Plasma

- Electrons start to break off atoms at ~ 1 eV (10,000 ºC)
- D,T atoms are fully ionized at T ~ 20 keV => *plasma*
- Energy tends to leave a plasma rapidly and cool it
    - radiation (visible @ 1 eV, x-rays @ 20 keV)
    - particle loss (ion speed ~ 1000 km/sec)

need to heat the plasma as fast as it cools at 20 keV

Fuel Can be Self-Heated by Alphas

Condition for self-sustaining D-T reaction ("ignition"):

alpha heating rate = plasma energy / energy loss time

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

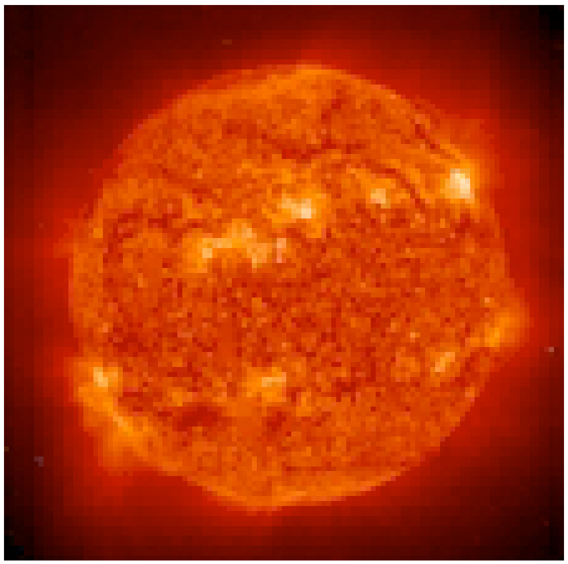
$$n \cdot T \cdot \tau_E \approx (10^{14}\ \text{cm}^{-3}) \cdot (20\ \text{keV}) \cdot (5\ \text{sec})$$

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

Energy for use comes out in the 14 MeV neutrons

Fusion Already Works

Sun

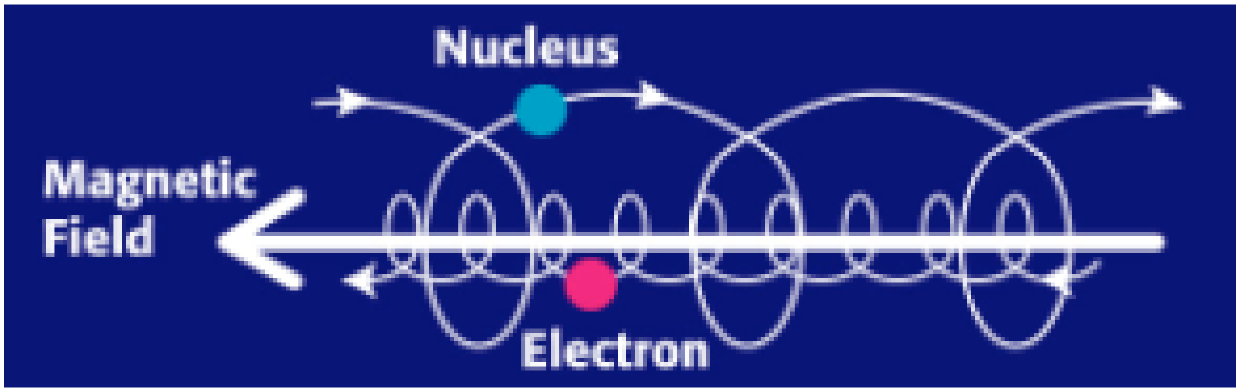


very long energy confinement due to gravity

H-Bomb

very short energy confinement due to inertia of fuel

Magnetic Confinement



- Both ions and electrons are free to move along B

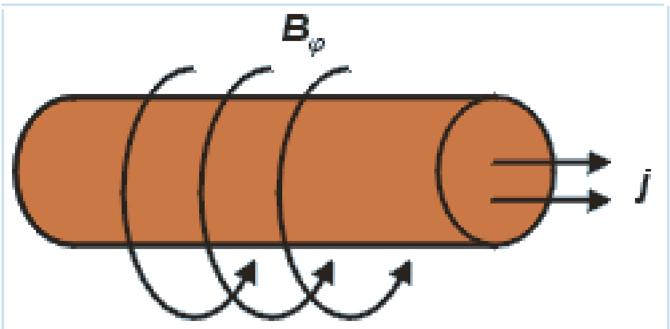
- Both ion and electrons are “confined” across B

$$m_i \, v_\perp^2 / r_{gyro} = e \, v_\perp \times B \Rightarrow r_{gyro} = m_i \, v_\perp / eB$$

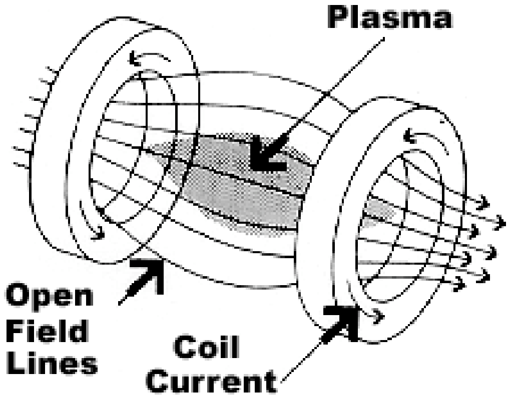
- For B= 10 kG at T_i = 20 keV, $r_{gyro} \sim 2$ cm (pretty good !))

Some Types of Magnetic Confinement

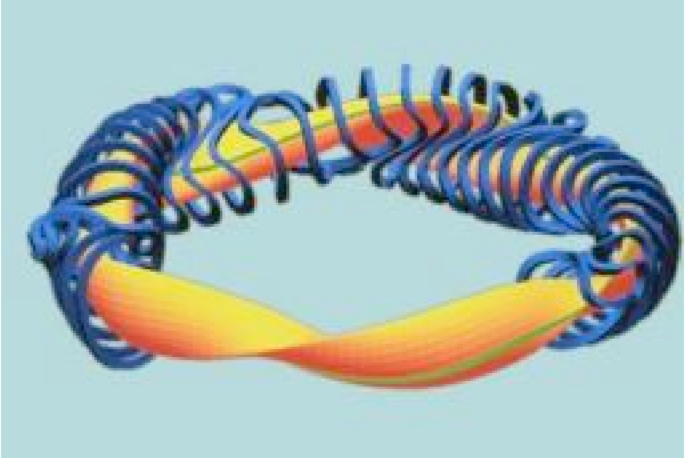
magnetic pinch



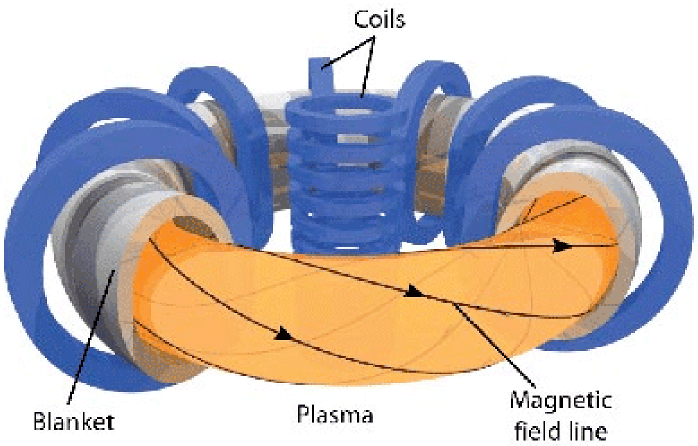
magnetic mirror



stellarator

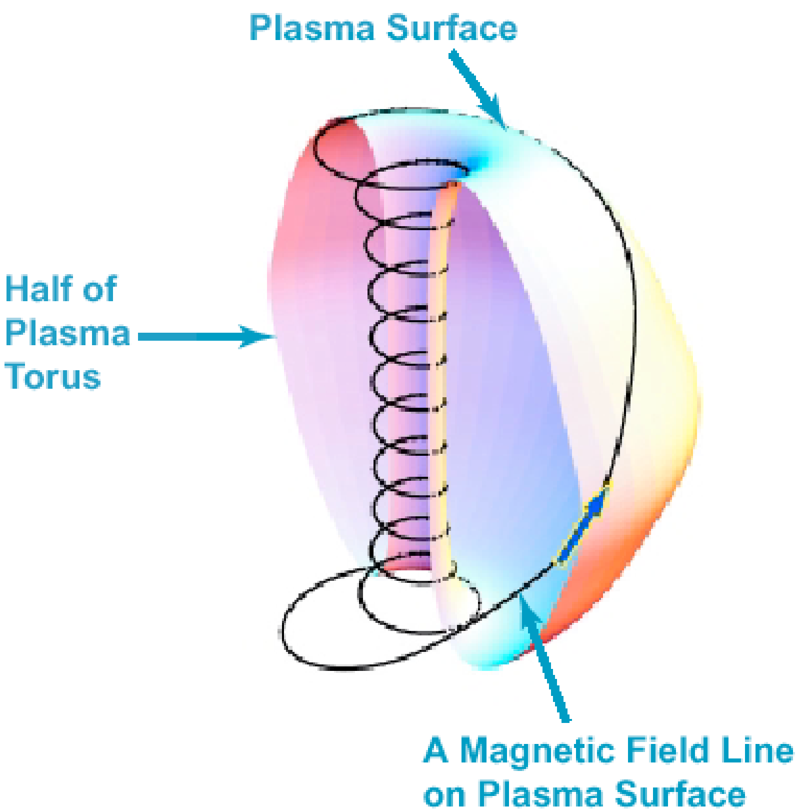


tokamak

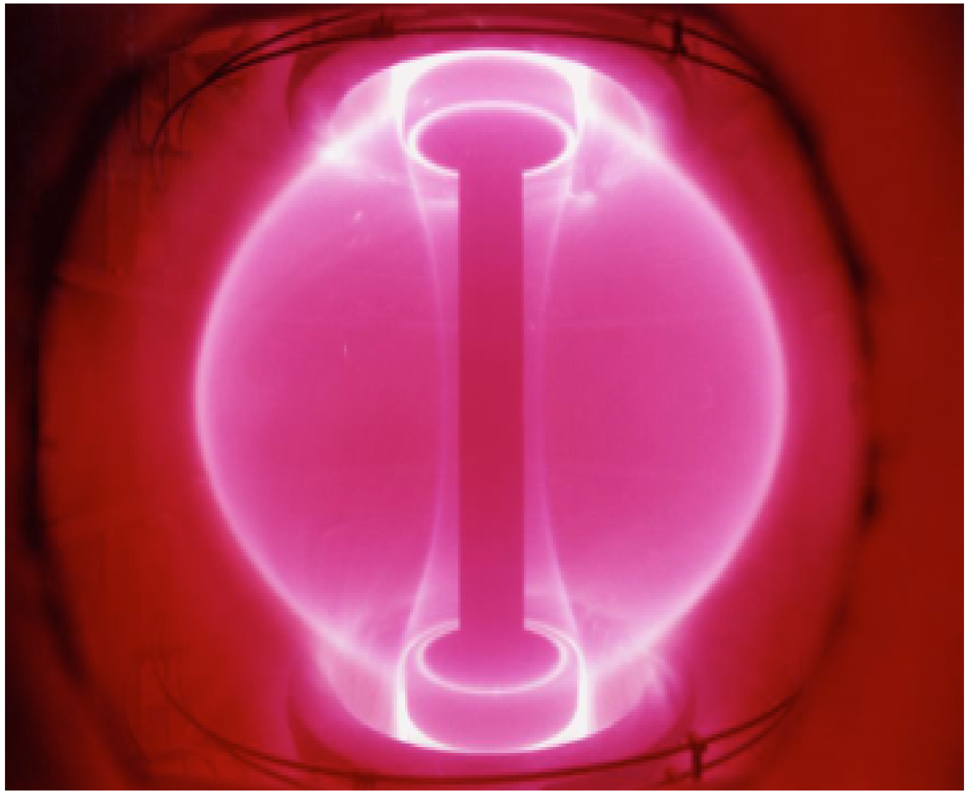


Example of Magnetic Confinement

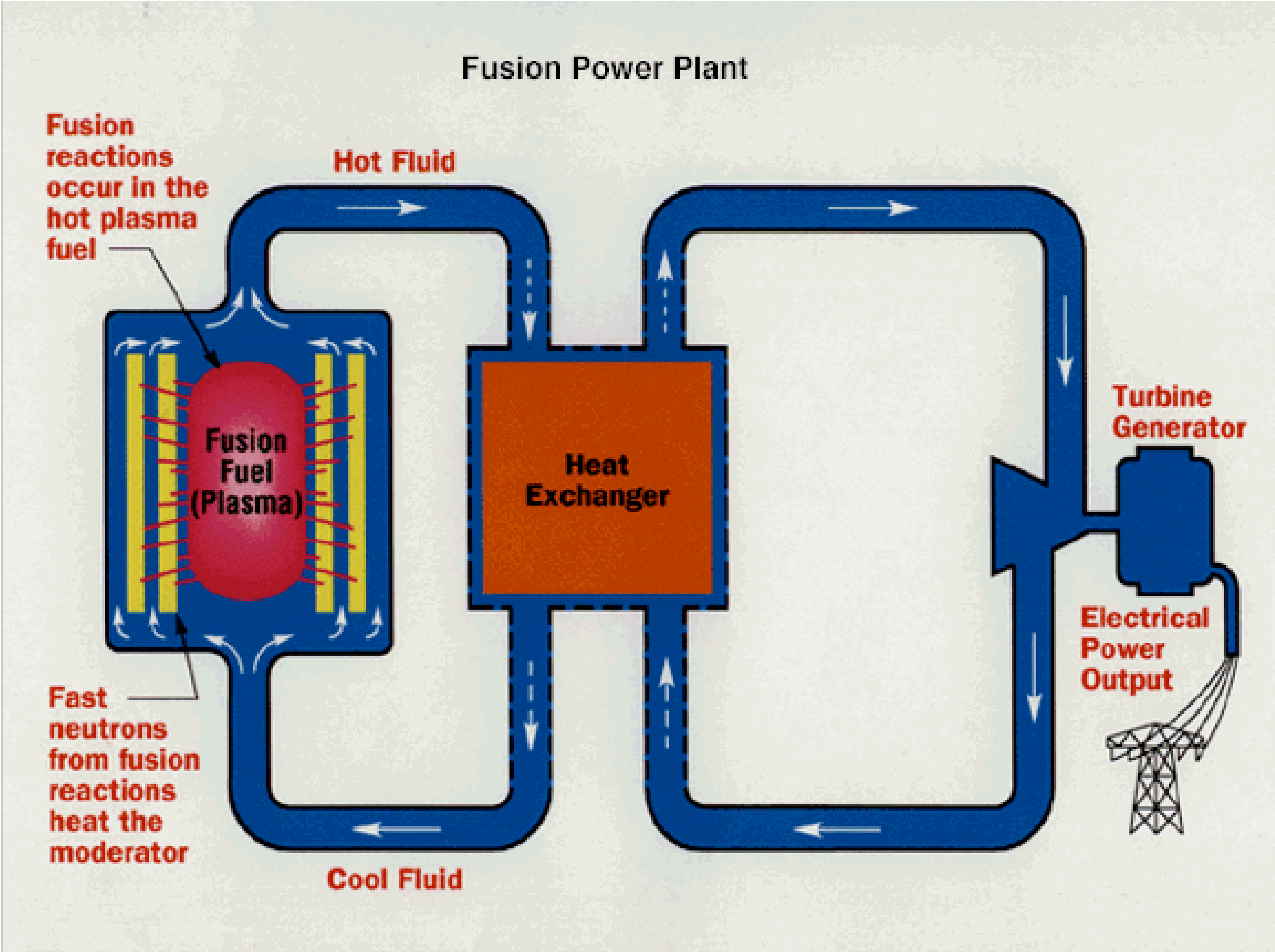
"magnetic surfaces"



START (Culham, ca. 2000)



Magnetic Fusion Power Plant

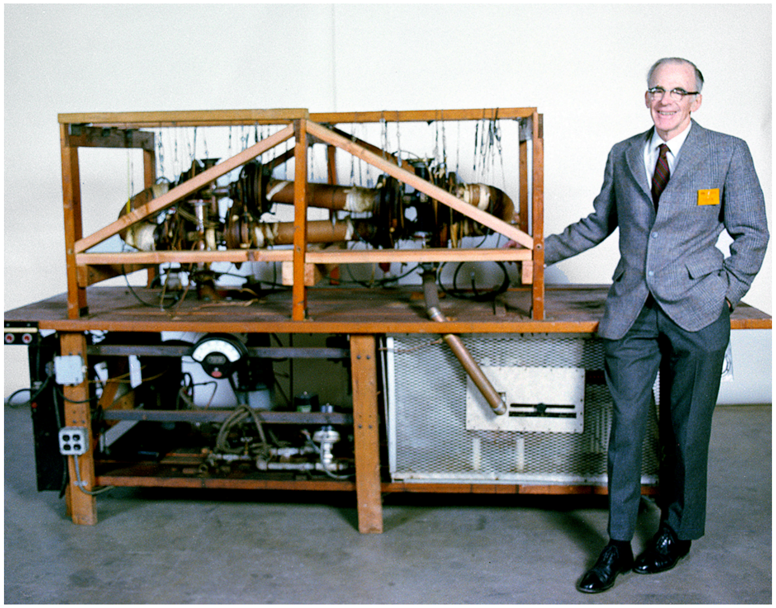


The Reality

- This dream was accepted internationally by 1958
- Many ideas were tried and a few have "survived"
- Best results so far are near D-T reactor conditions

The reality is that magnetic fusion is facing many serious scientific and engineering problems, and it is not yet clear that we can make a reactor

Progress in Magnetic Fusion



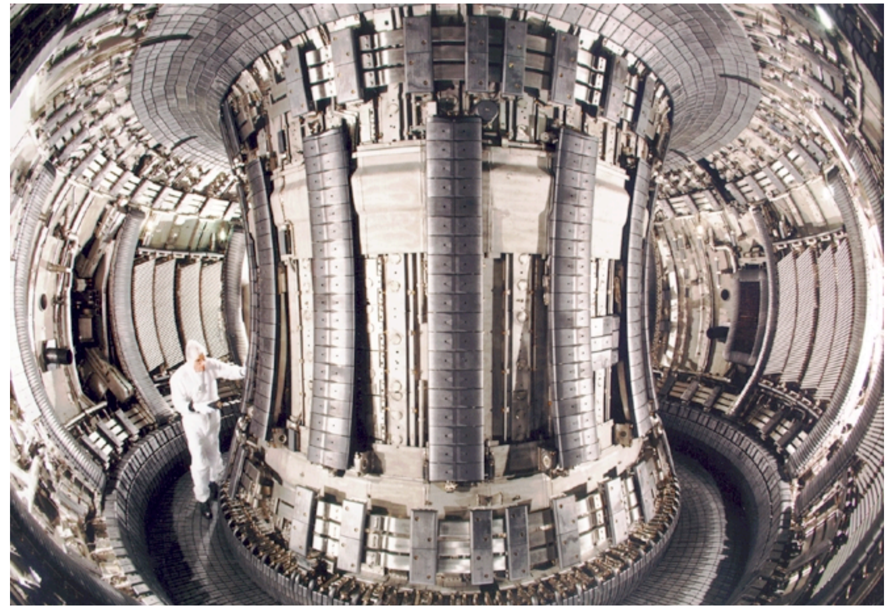
Model A Stellarator ca. 1953

$n \approx 10^{13}$ cm^{-3} (?)

$T \approx 10$ eV (?)

$\tau_E \approx 10$ μsec (?)

$nT\tau_E$ ~ 10^6 from ignition



JET Tokamak ca. 2003:

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

$T \approx 20$ keV

$\tau_E \approx 1$ sec

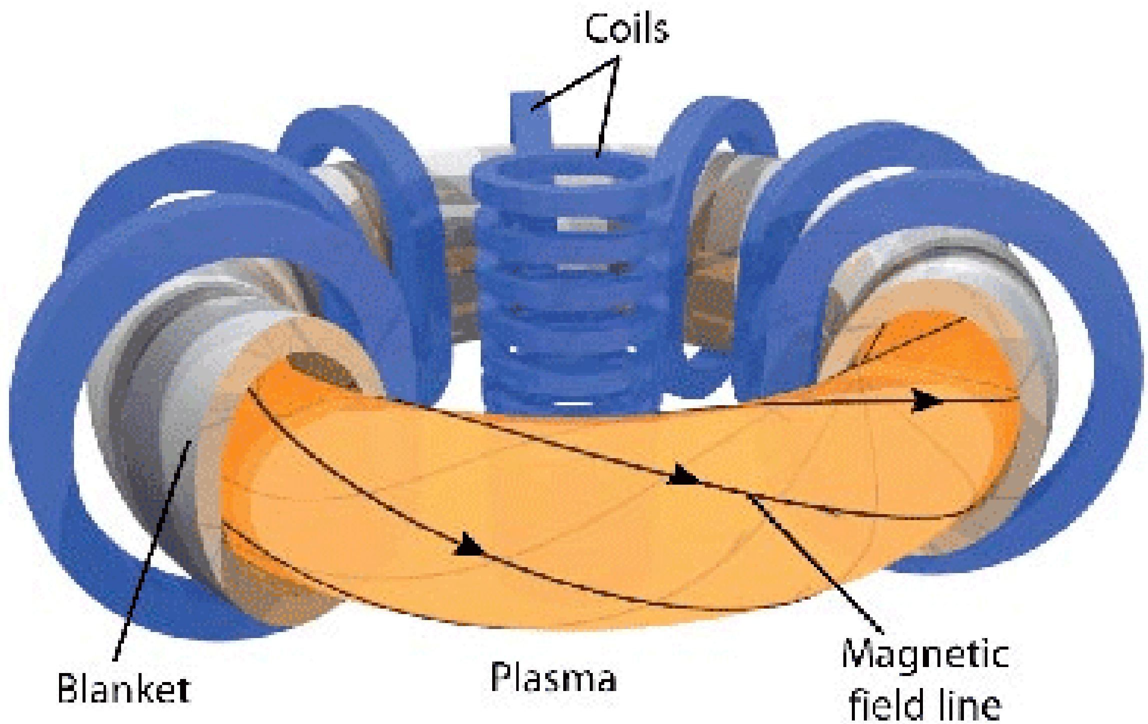
$nT\tau_E$ ~ 5 from ignition

What Happened to the Other Ideas ?

- Stellarators were largely abandoned in the 1960's due to poor confinement and stability (until the 2000's !?)
- Pinches were largely abandoned in the 1970's due to poor stability (needed ~ 80 m device for 'breakeven')
- Mirrors were abandoned in 1980's due to poor confinement (after 'breakeven' device was built and terminated)
- Tokamaks were invented in USSR in the 1960's and have dominated the world fusion program since the 1980's

The Tokamak

- Russian acronym for “toroidal magnetic chamber”
- Strong toroidal field plus large internal plasma current
- Relatively good stability, confinement, and simplicity



Some Problems with Tokamaks

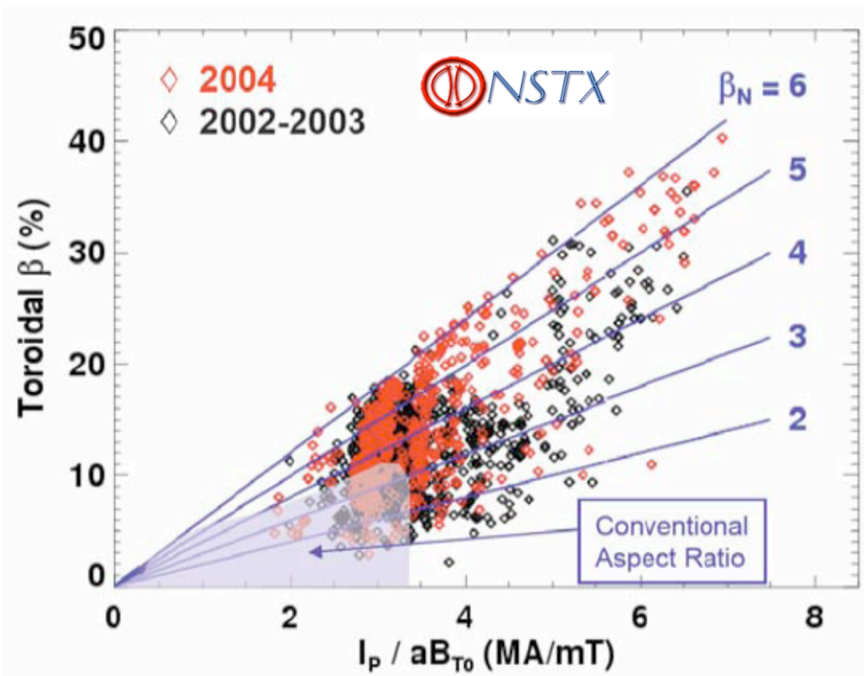
- Many problems remain to be solved before we can build a tokamak reactor

- Some of these problems are generic to all toroidal magnetic fusion devices:

  - pressure limits and macroscopic stability
  - confinement and “microscopic” stability
  - impurities and plasma-wall interaction
  - maintaining a steady-state plasma

Tokamak Pressure Limits

- Fusion plasma pressure is $P_{\perp}$=2nT ~ 6 atm [~ 6x10^5 Pa]
- Plasma pressure limit in B field is $\beta \equiv P_{\perp}/(B^2/2\mu_o) \sim 1$
- "MHD" instabilities can occur much lower, e.g. $\beta \leq 5\%$



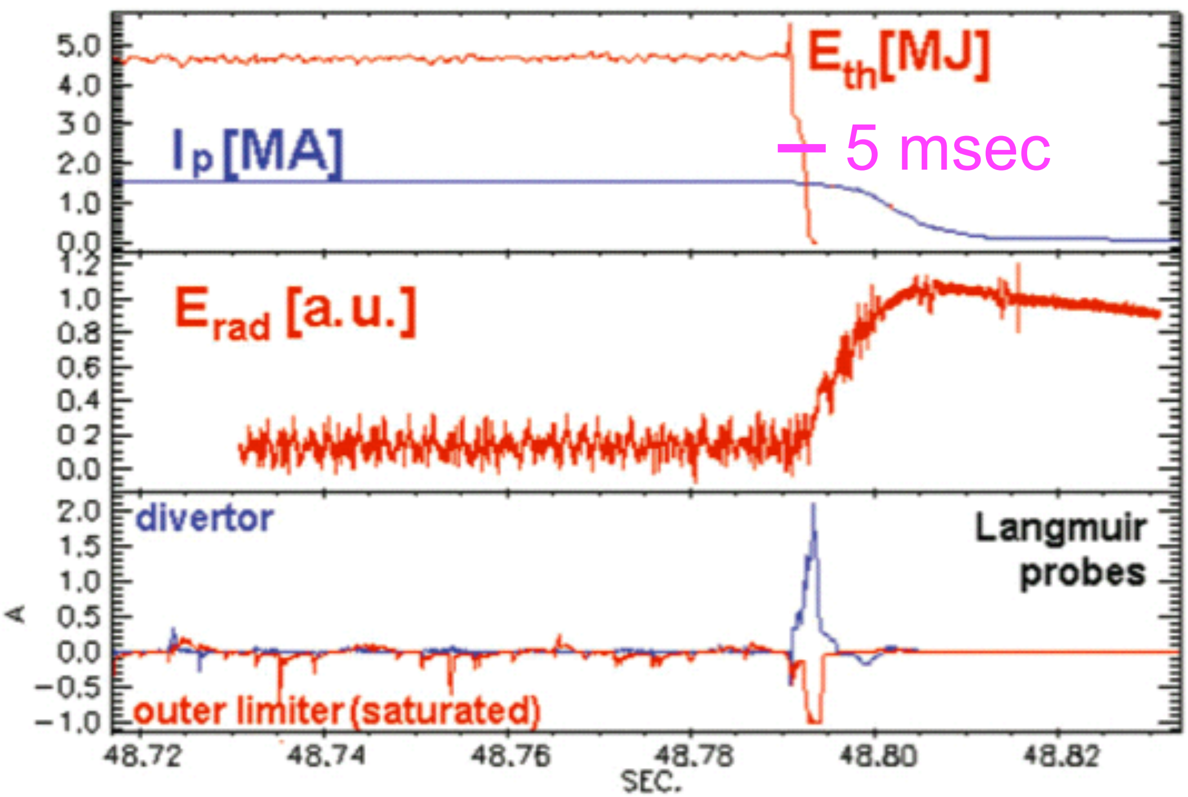
for conventional tokamaks

β ~ 5% => B ~ 5 Tesla

=> *needs superconducting magnets and massive support structures*

Effect of MHD Instability - Disruption

- Near beta limit, plasma can 'disrupt' in ~5 msec, leading to complete loss of plasma energy and plasma current



plasma energy
plasma current

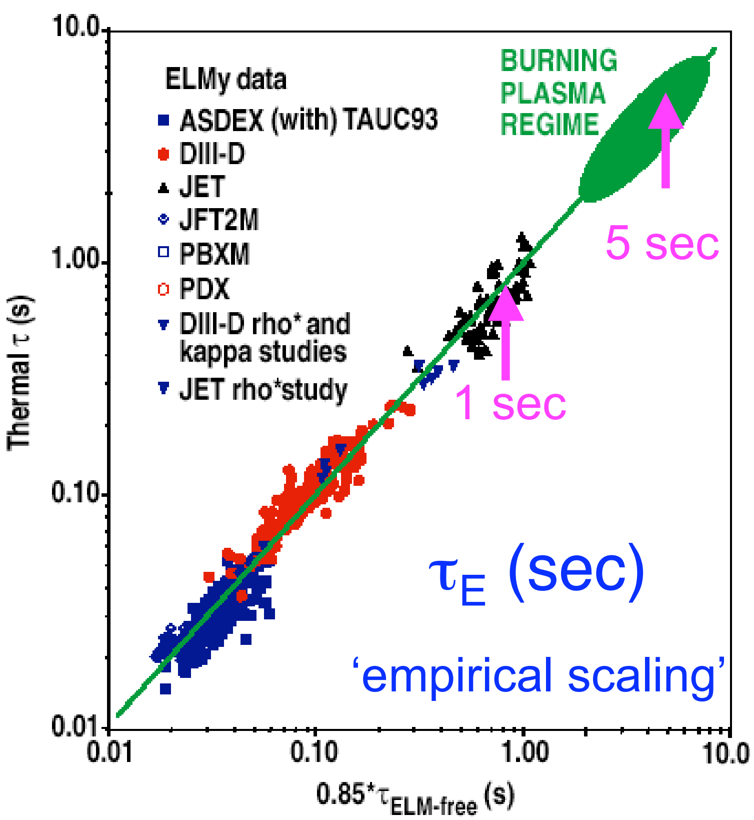
radiated power

wall particle and heat flux

JET, Riccardo, PPCF (2003)

Tokamak Plasma Confinement

- Confinement time τ_E is "anomalous" (≤ 100 x "classical")
- Empirical scalings used to extrapolate to reactor regime



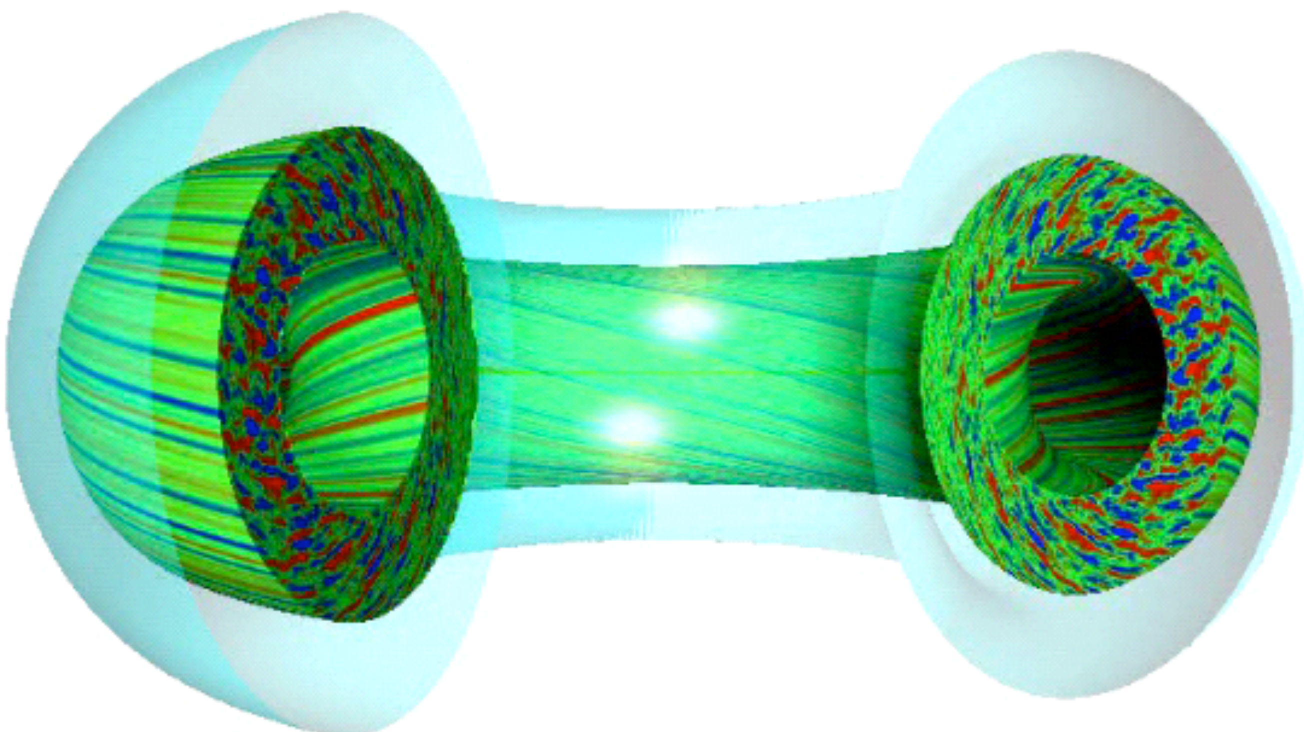
scaling in "engineering" variables

$$\tau_{\text{th},98y2} = 0.0562 I_p^{0.93} B_t^{0.15} n_{19}^{0.41} P_L^{-0.69} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} M^{0.19}$$

- main scalings: $\tau_E \propto I\, R^2 / P^{0.7}$
- no simple physical explanation for these global trends

Theory of "Anomalous" Transport

- Plasma transport is driven by small-scale turbulence
- Equations are complex but can be solved numerically
- Simulations can explain some transport to within ~ x2

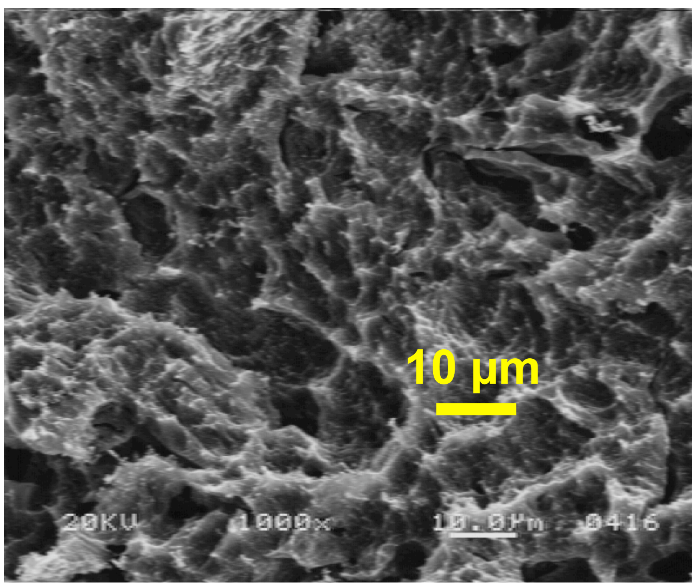


GYRO simulation of DIII-D tokamak (Candy)

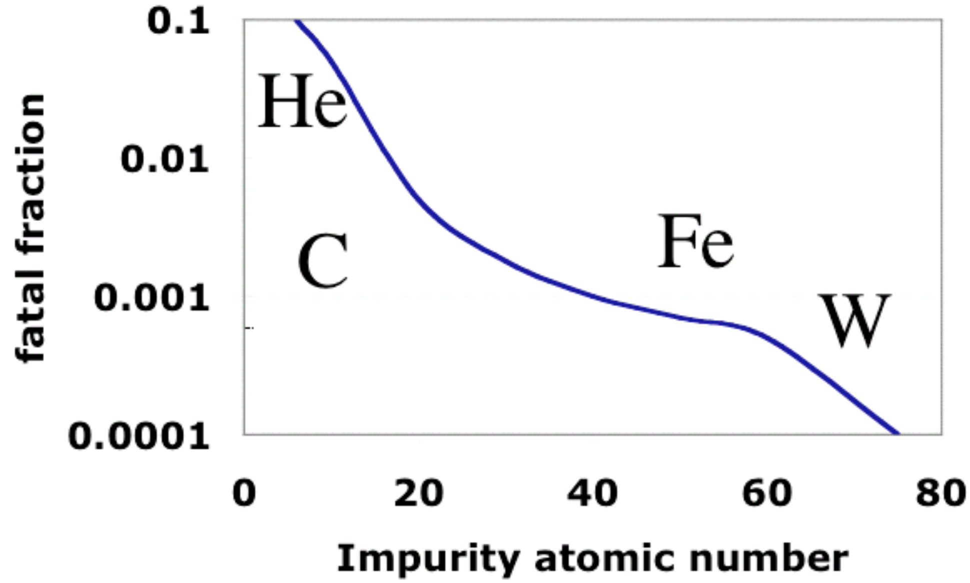
Impurities Can Destroy Plasma

- Low Z ions (helium 'ash', carbon) can dilute D-T fuel
- High Z ions (e.g. 10^{-4} g of W) can radiate away energy

plasma erosion of carbon



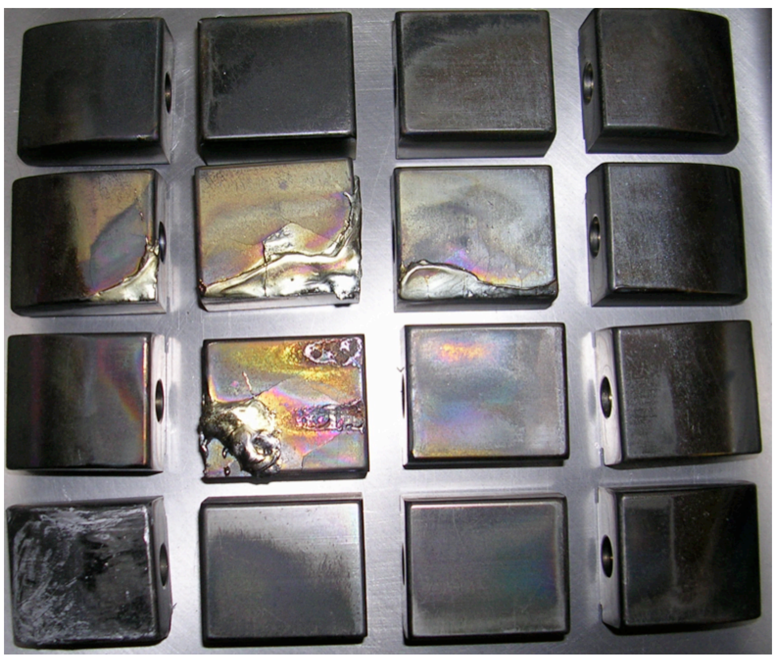
"fatal fraction"



Post PoP 1995

Plasma Can Destroy First Wall

- 20% of D-T fusion power goes to first wall (~ 1000 MW)
- First wall in a reactor may erode quickly (months ?)
- One disruption could open up a water cooling line



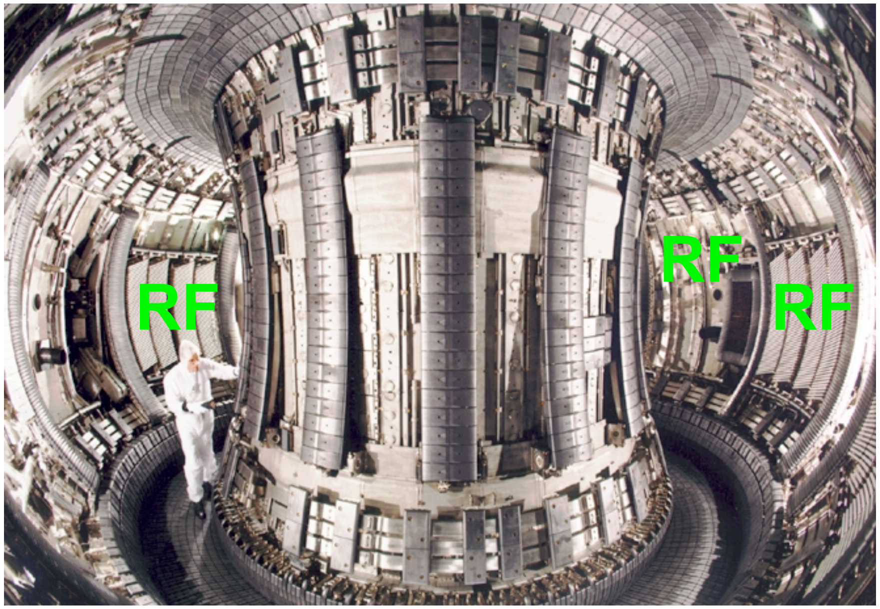
Moly tile surface in Alcator C-Mod tokamak

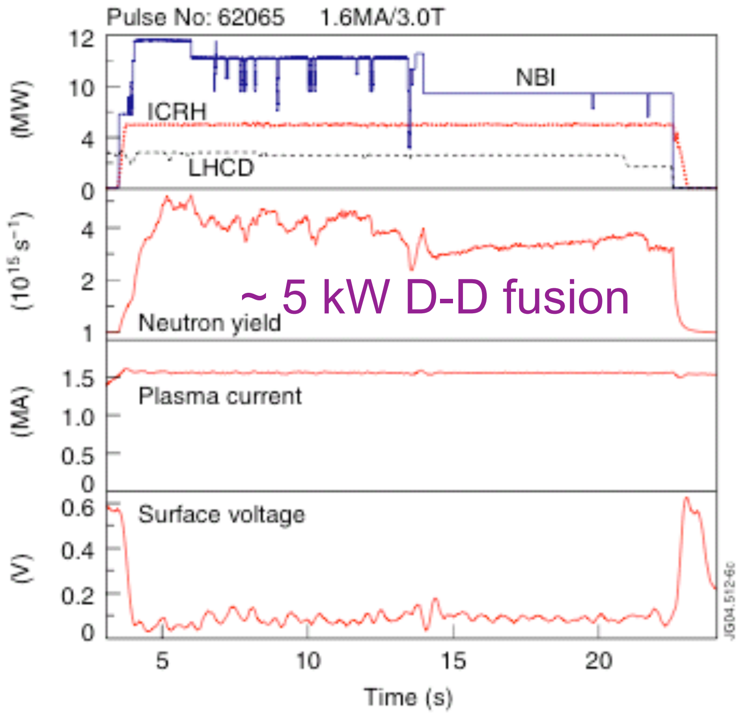
reached T_{melt} ~ 2900 K in < 2 seconds

Whyte, MIT

Steady-State Tokamak ?

- Ohmic heating and current drive last only a few seconds
- Longer plasmas can driven with RF and neutral beams
- So far high performance JET plasmas last ~ 20 sec





Summary of Magnetic Fusion Status

- Tokamaks are the most popular type of magnetic fusion
- Tokamaks have come close to D-T reactor conditions
- We have partial solutions to some reactor problems:
  - pressure limits and macroscopic stability
  - confinement and “microscopic” stability
  - impurities and plasma-wall interaction
  - maintaining a steady-state plasma

=> *motivates ambitious plans for the future*

The Future of Magnetic Fusion

- ITER and other tokamaks
- Revival of stellarators
- Innovative concepts

MFE Plans tend to be “Optimistic”

1977 plan - reactor in 1990

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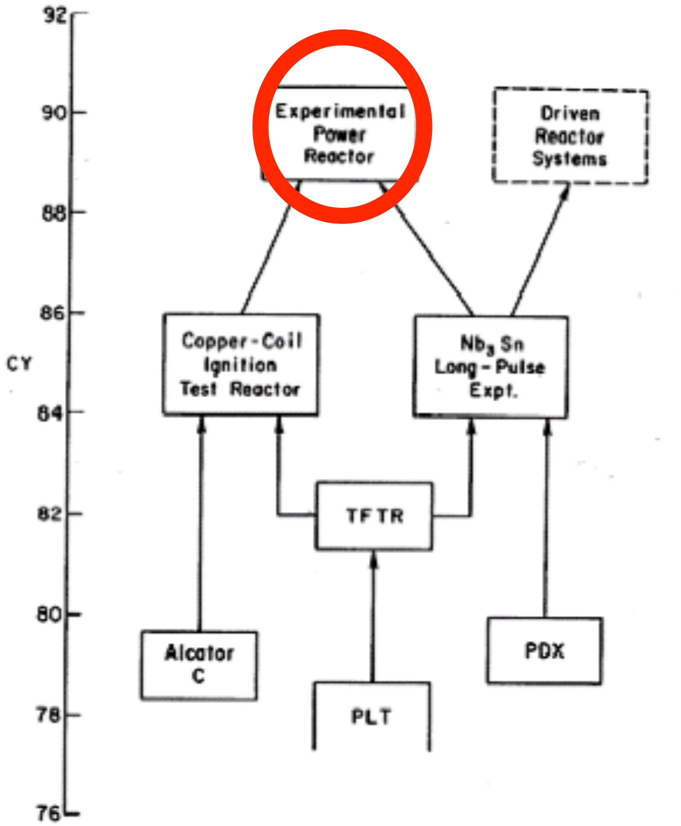
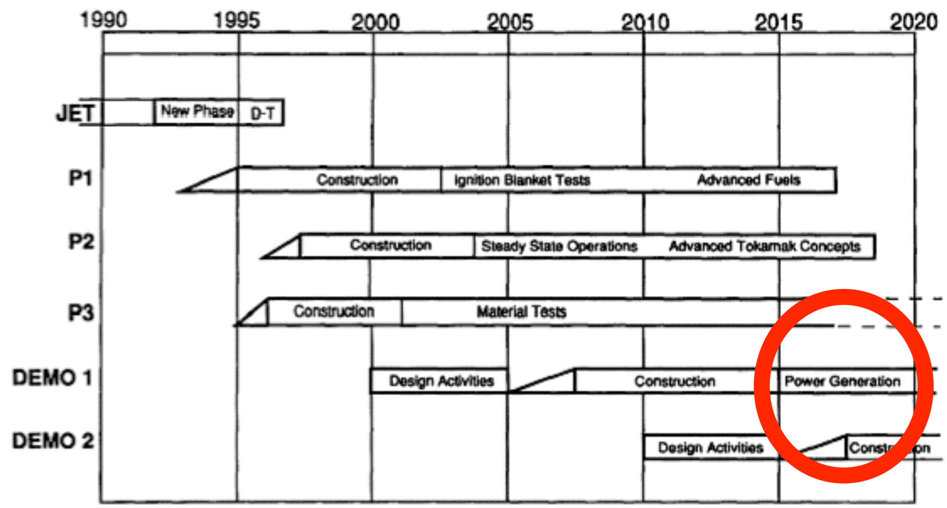


Figure 1. Outline of possible scenario for development of a tokamak Experimental Power Reactor.

Jassby, Furth, et al 1977

1991 plan - reactor in 2015

TABLE III. A time schedule for an ITER program.



Rebut et al, Phys. Plasmas 1991

see http://fire.pppl.gov/fusion_library.htm

ITER Tokamak

- Design started 1986, first plasma 2016 ("optimisticly")

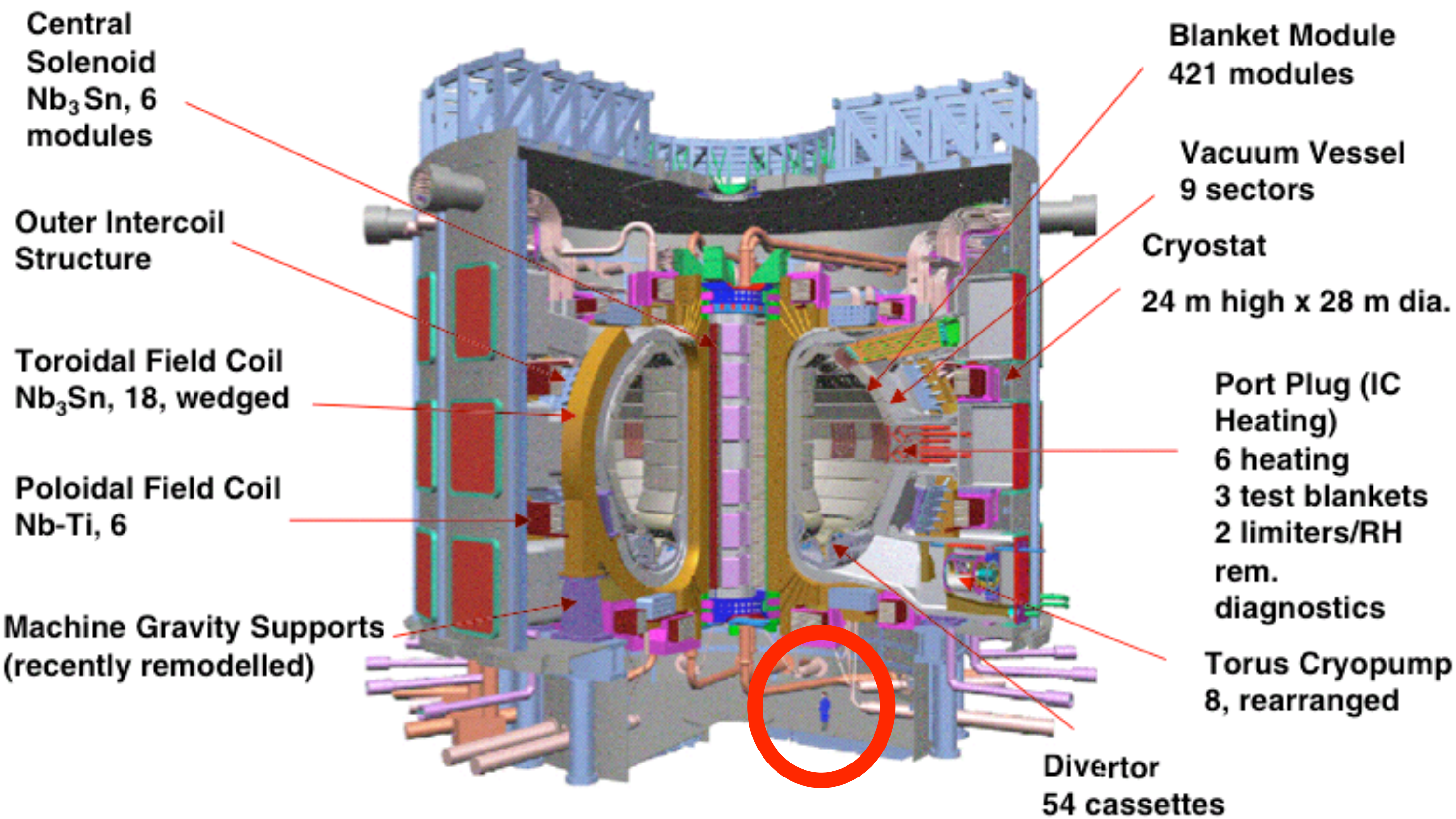


Figure 1. ITER tokamak and major components.

ITER Parameters and Capabilities

Table 2. ITER parameters and operational capabilities.

Parameter	Attributes
Fusion power	500 MW (700 MW)[a]
Fusion power gain (Q)	$\geqslant$10 (for 400 s inductively driven burn); $\geqslant$5 (steady-state objective)
Plasma major radius (R)	6.2 m
Plasma minor radius (a)	2.0 m
Plasma vertical elongation (95% flux surface/separatrix)	1.70/1.85
Plasma triangularity (95% flux surface/separatrix)	0.33/0.48
Plasma current (I_p)	15 MA (17 MA)[a]
Safety factor at 95% flux surface	3 (at I_p of 15 MA)
Toroidal field at 6.2 m radius	5.3 T
Installed auxiliary heating/ current-drive power	73 MW (110 MW)[b]
Plasma volume	830 m^3
Plasma surface area	680 m^2
Plasma cross section area	22 m^2

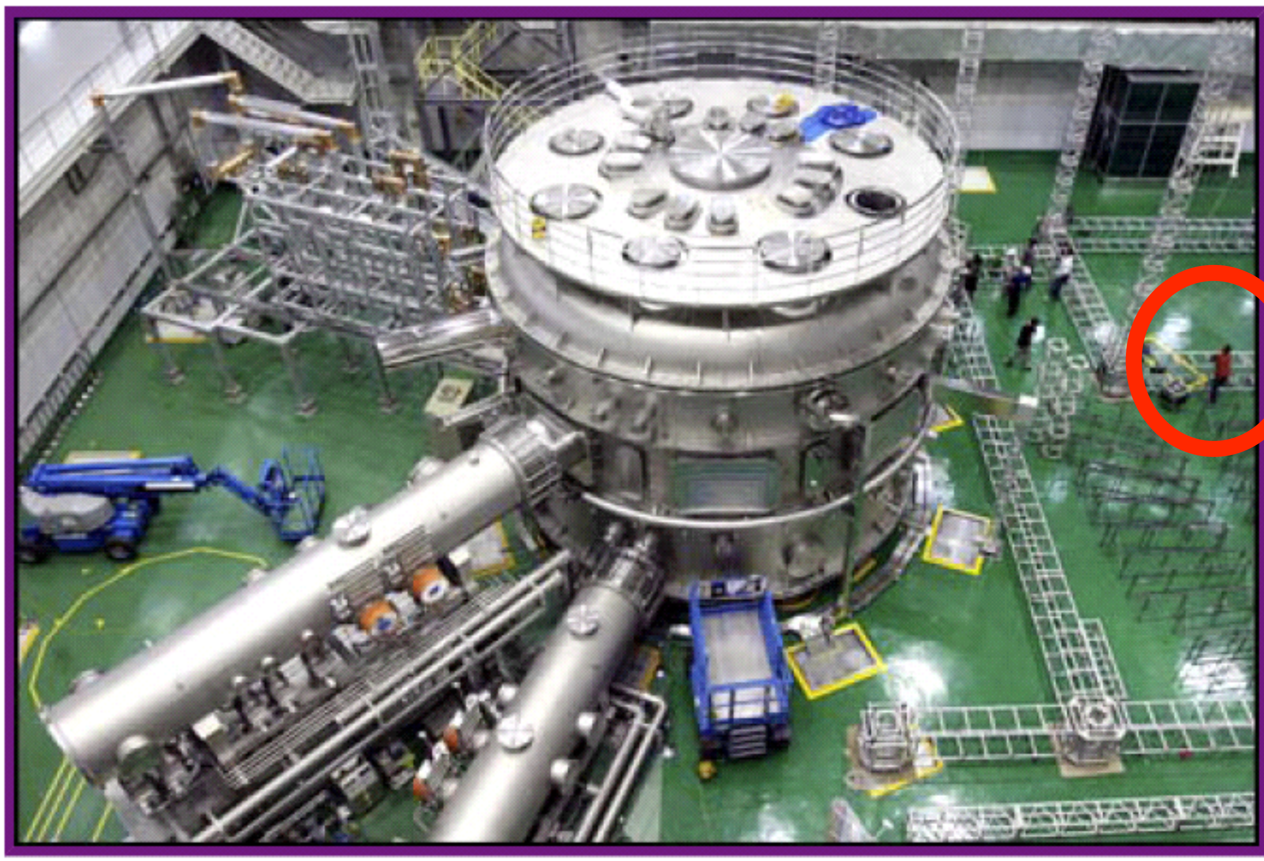
[a] Increase possible with limitation on burn duration.
[b] A total plasma heating power of 110 MW may be installed in subsequent operation phases.

Nucl. Fusion 47, S1 (2007)

- Design not yet finished
- Goal Q = 10 for 400 sec @ 500 MW D-T fusion power
- Will not and *could not* make net electrical power (Q_{Elect} ~ 1)

Korean Superconducting Tokamak

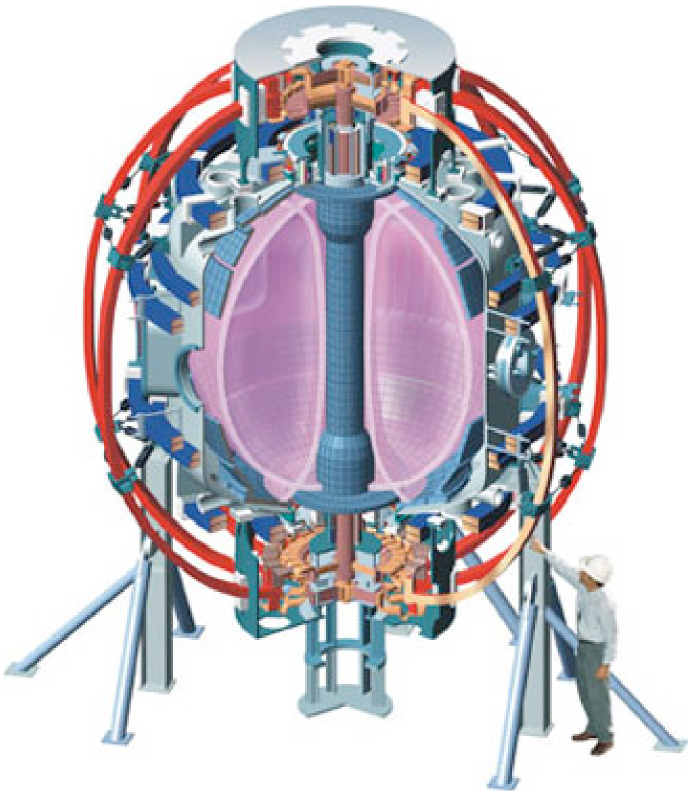
- Advanced tokamak designed for 300 sec pulses
- Similar devices being built in China and India



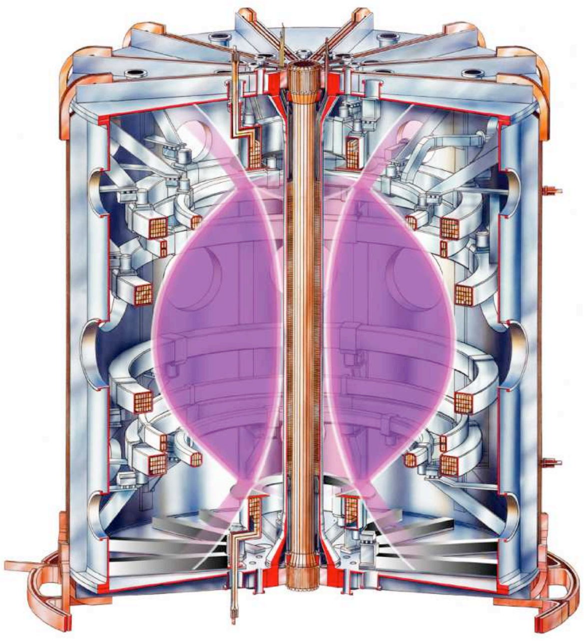
Spherical Tori (~ Tokamak)

- Higher β limits and more compact than normal tokamaks
- More difficult current drive and plasma-wall problems

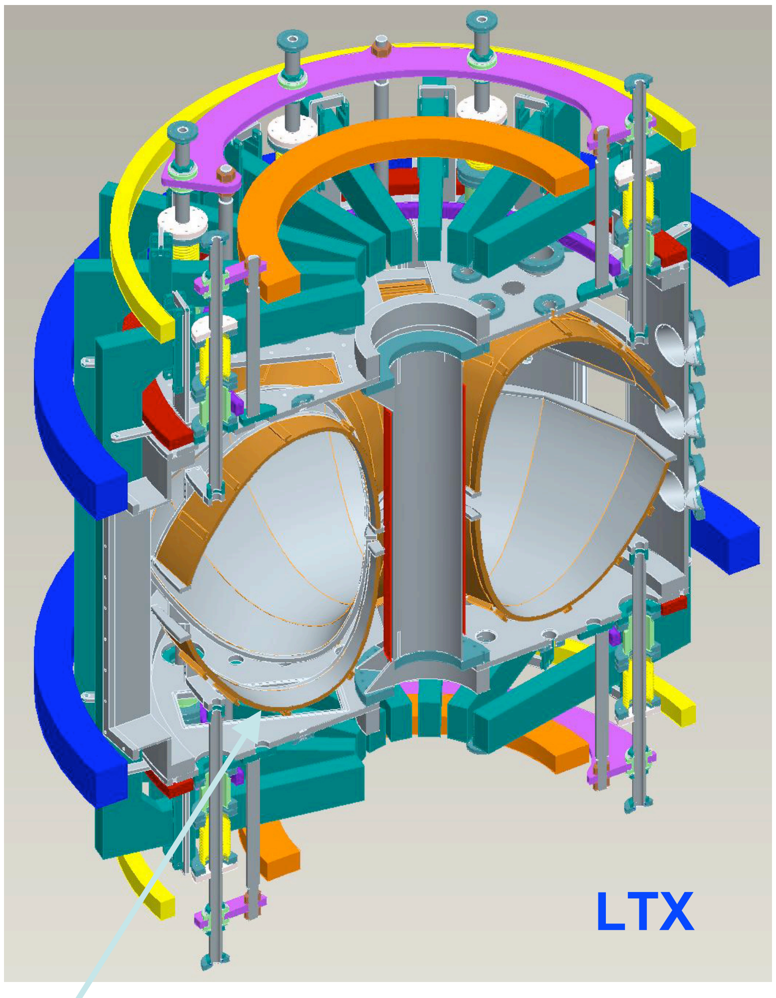
NSTX (USA)



MAST (UK)

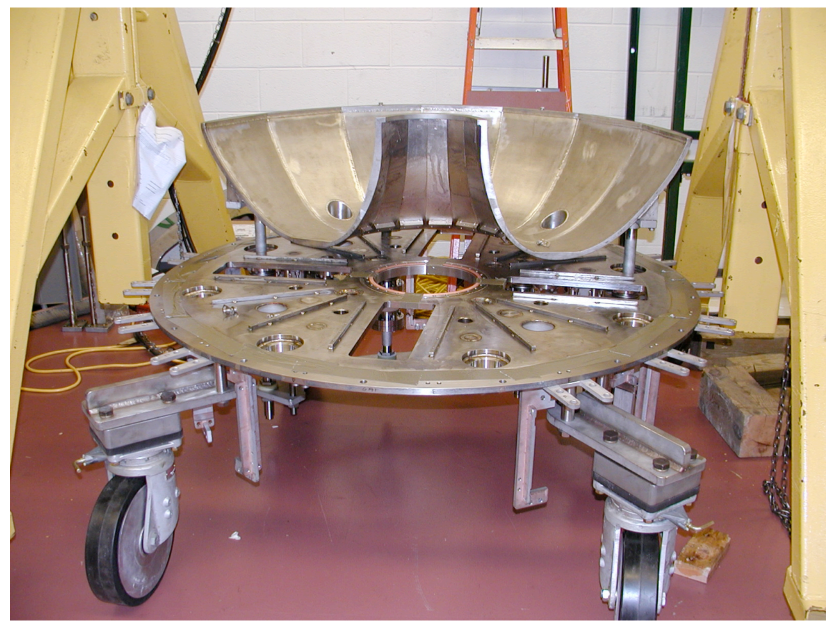


Lithium Tokamak eXperiment (LTX)



Liquid **lithium coated shell**

Each lower shell to be filled with ~100g of liquid lithium. Remainder of surface coated by evaporation.



D. Majeski

Why not Just Stay with Tokamaks ?

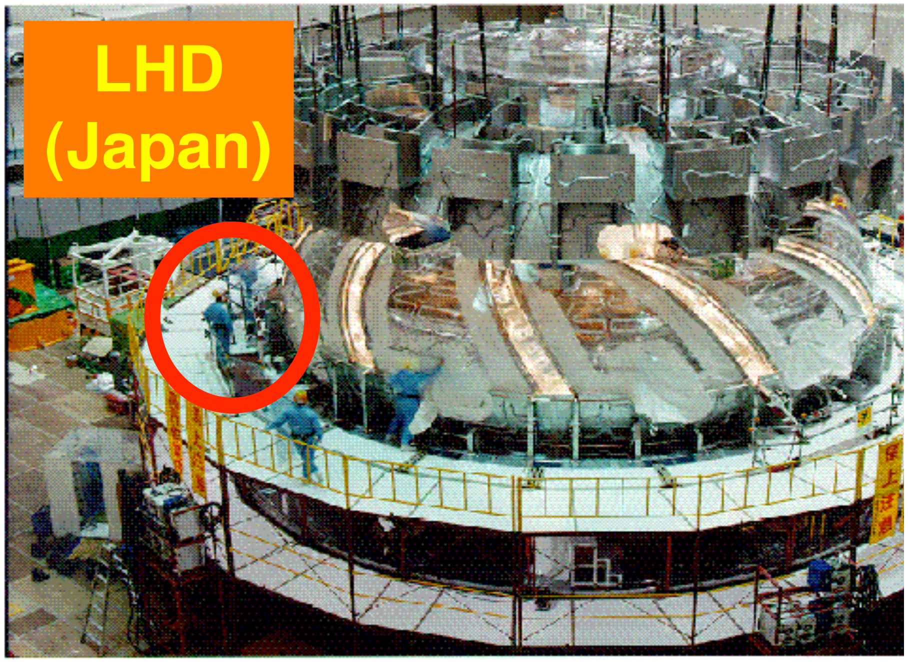
- Many difficult challenges in going from ITER to a DEMO:

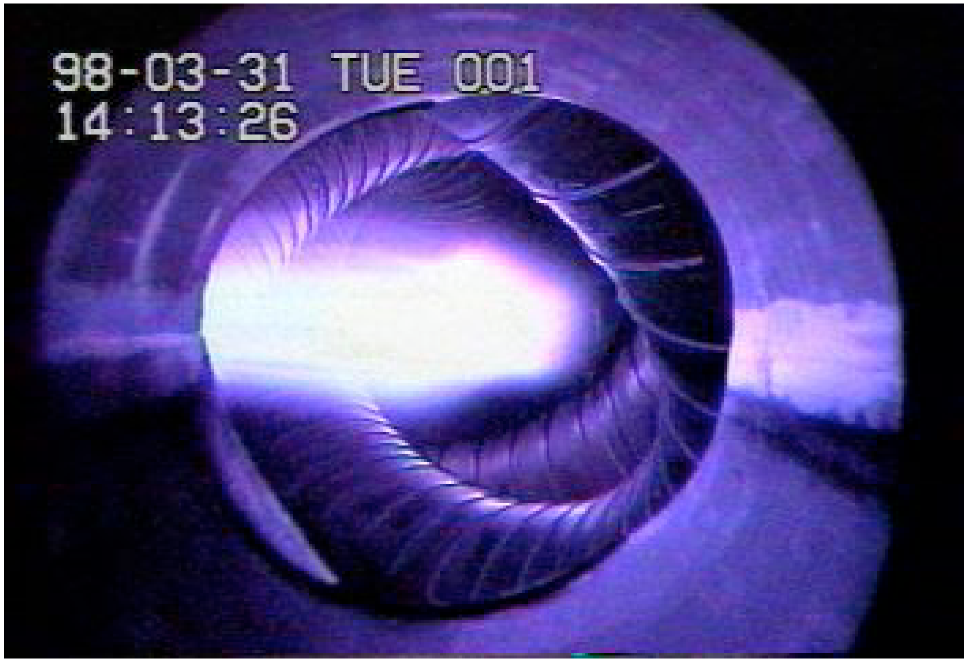
  - Q ~ 50 @ 4000 MW fusion power
  - month-long pulses w/burn control
  - tritium breeding and inventory
  - neutron damage to first wall
  - interior robotic maintenance
  - very high reliability (90%?)

- Even if a tokamak DEMO could be built, it would most likely be very complicated and very expensive

Stellarators are Being Revisited

- Large stellarators being built in Japan and Germany
- No need for external current drive, maybe no disruptions
- Confinement like tokamaks, but very complicated to build

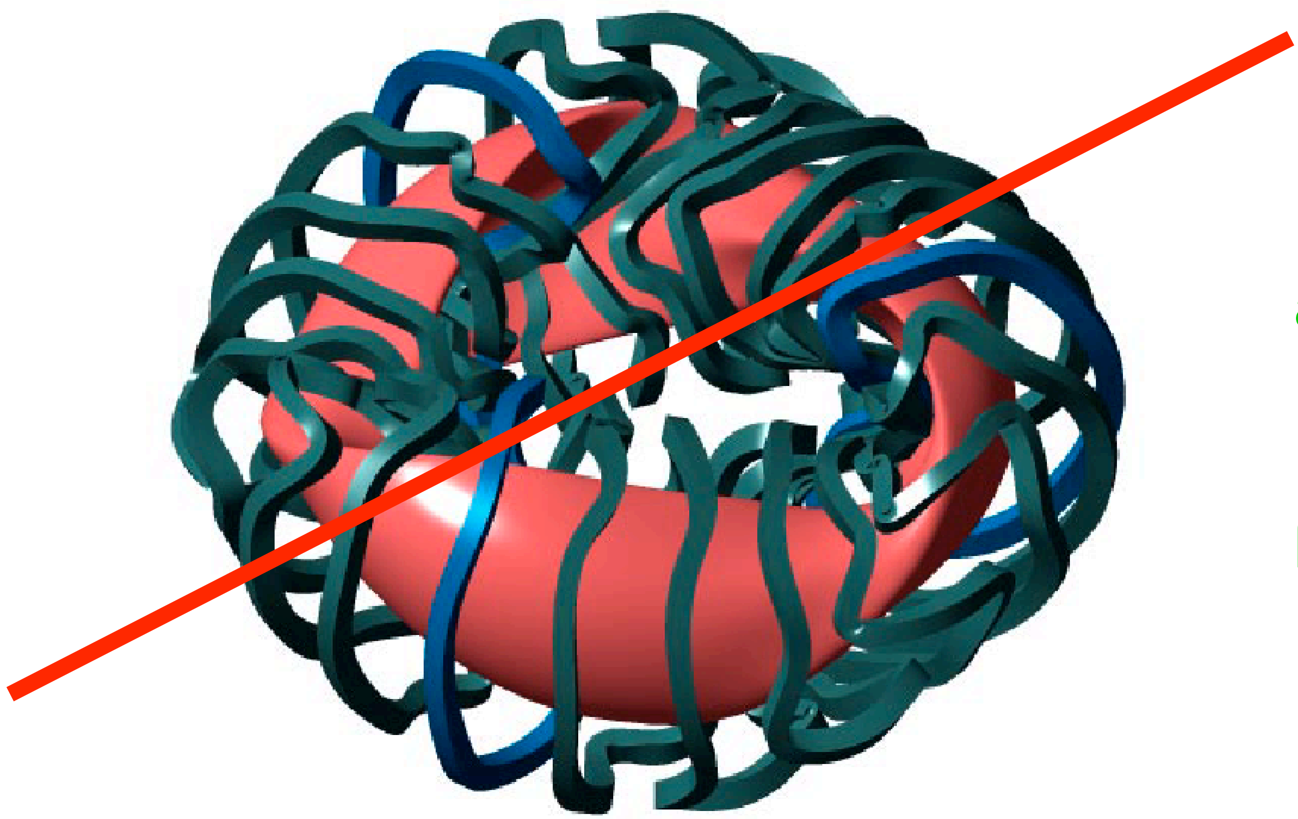




Photograph of the first plasma in the LHD.
A camera is aimed at the plasma through NBI (tangential) port.

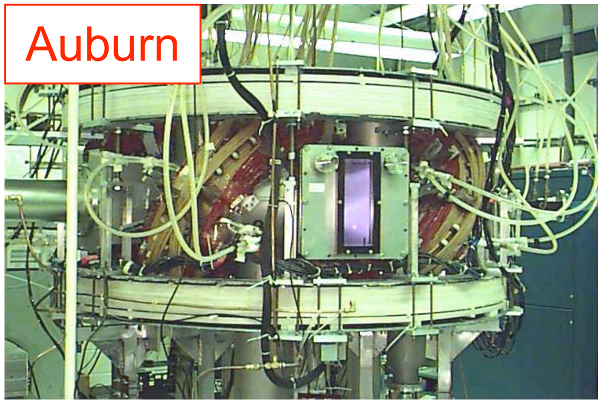
Compact Stellarator (NCSX)

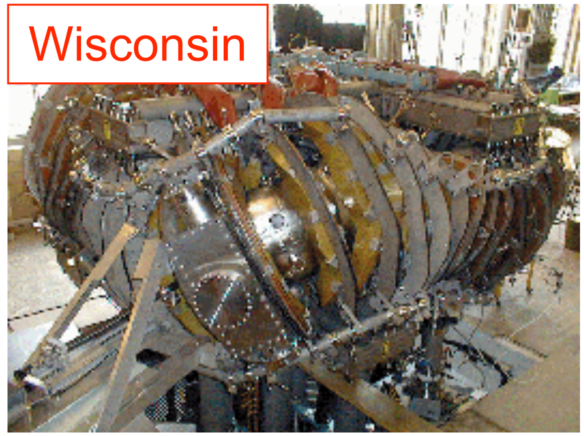
- Aims to combine best features of tokamak and stellarator
- Difficult to build but maybe more stable and steady-state

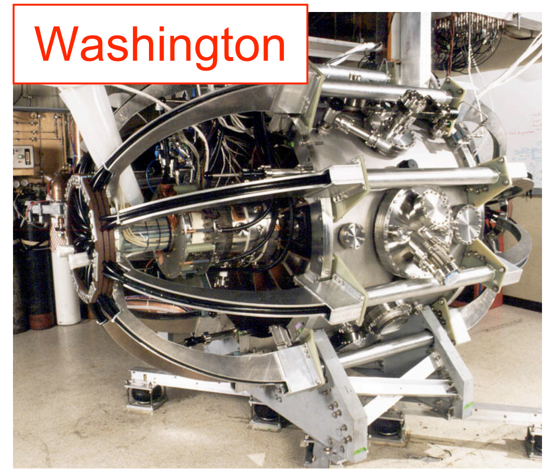


R = 1.5 m
a = 0.5 m
B = 1.0 T
P = 6 MW
$\beta \approx 4\%$

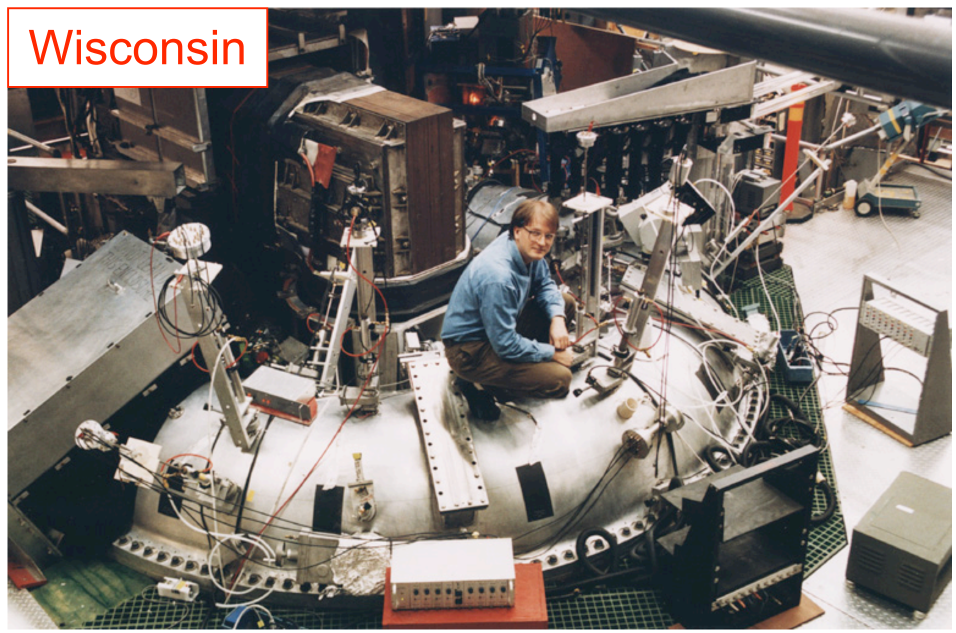
Some “Innovative Concepts”


Auburn


Wisconsin


Washington

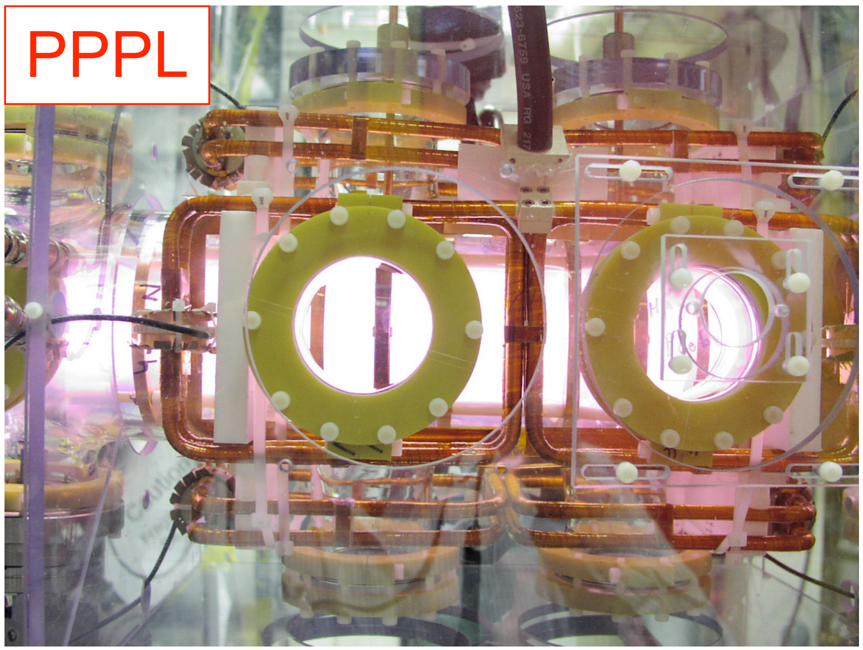

MIT/Columbia

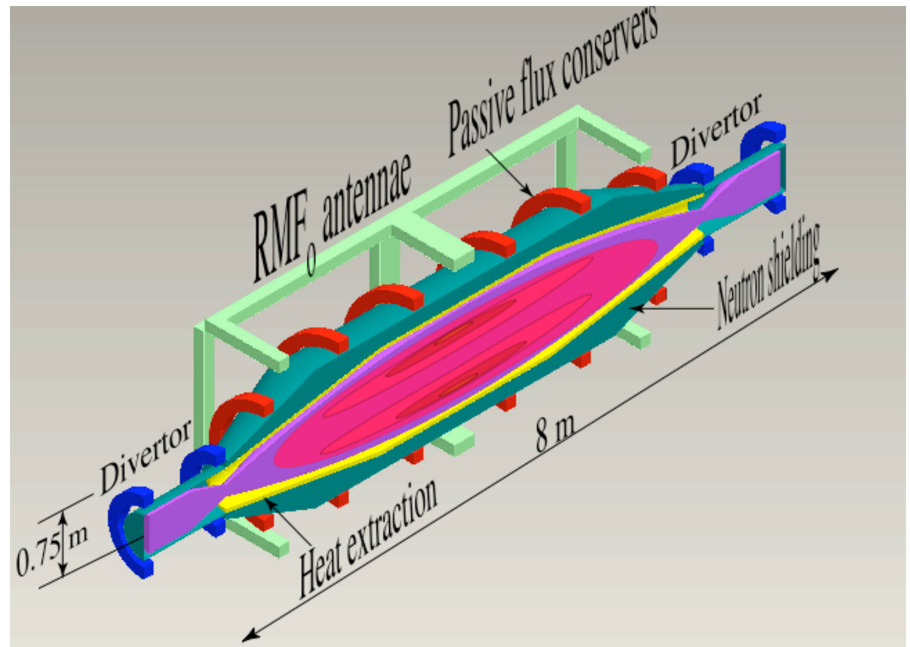

Wisconsin

The Dream Revisited

Conceptual design of a D-^{3}He fuelled RMF/FRC reactor

- a more rapid route to **practical** fusion power ?





S.A. Cohen

Potential Areas for "Breakthrough"

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

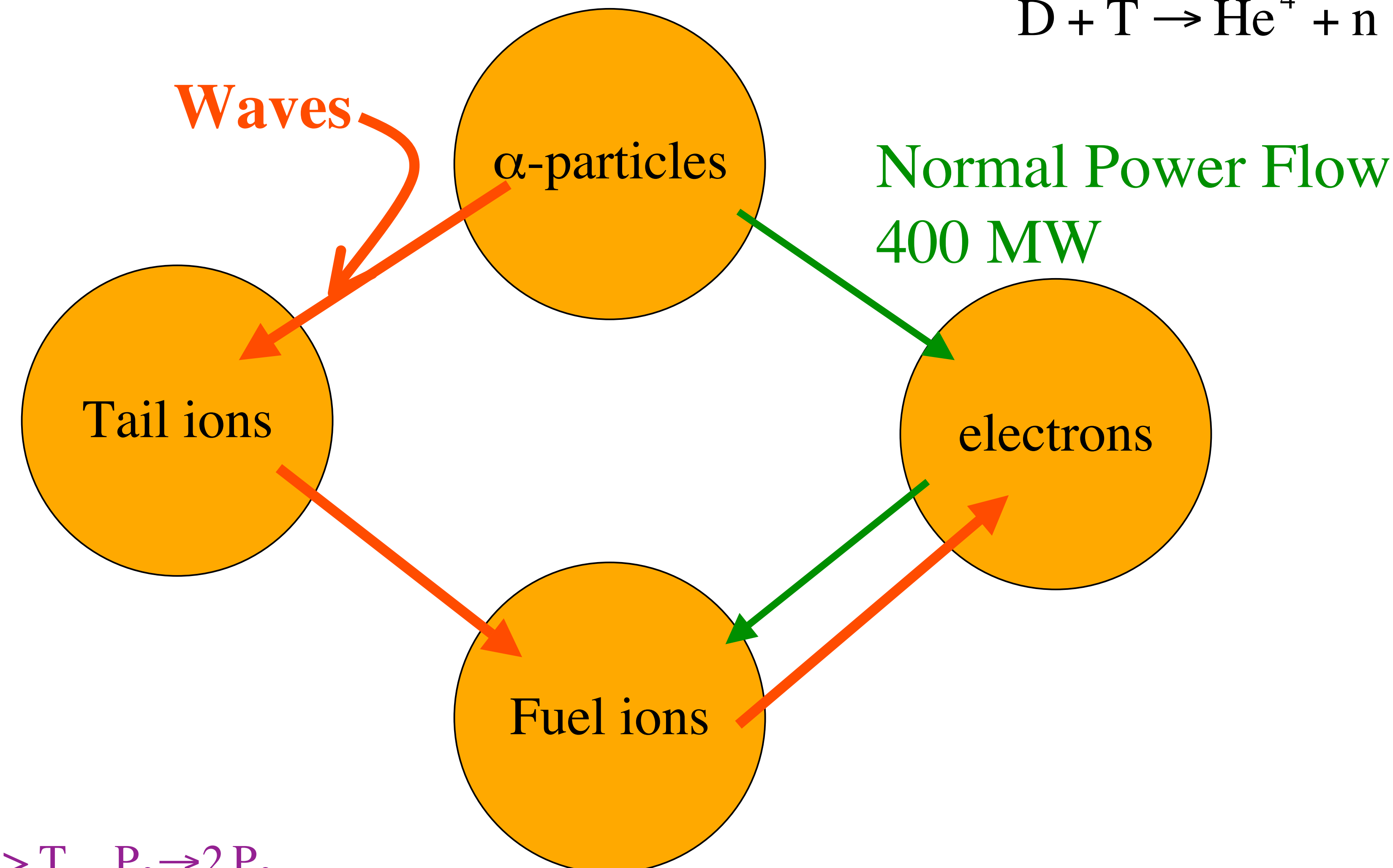
Technological innovations such as room temperature superconductors or radiation resistant materials

Physics surprises such as increased fusion cross section or a way to preferentially maintain hot ions

The Self Sustaining Fusion Reaction

Power Flow in a Fusion Reactor with "α-channeling"

$D + T \rightarrow He^4 + n$



Get $T_i > T_e$, $P_f \rightarrow 2\,P_f$

Fisch and Rax, 1992