Magnetic Confinement Fusion Research: History and Fundamentals

Michael Bell

former Head of NSTX Experimental Research Operations

Princeton Plasma Physics Laboratory

Princeton University

presented to the

Joint ICTP-IAEA College on Plasma Physics

International Center for Theoretical Physics, Trieste

October 2012

Topics

- Nuclear fusion as a fundamental source of energy
- Fusion reactions for energy production
- Conditions for fusion and the Lawson criterion
- Inertial and magnetic confinement approaches
- Magnetic confinement systems
- Emergence of the tokamak
- Plasma heating
- The large tokamaks and the start of ITER
- Current research directions

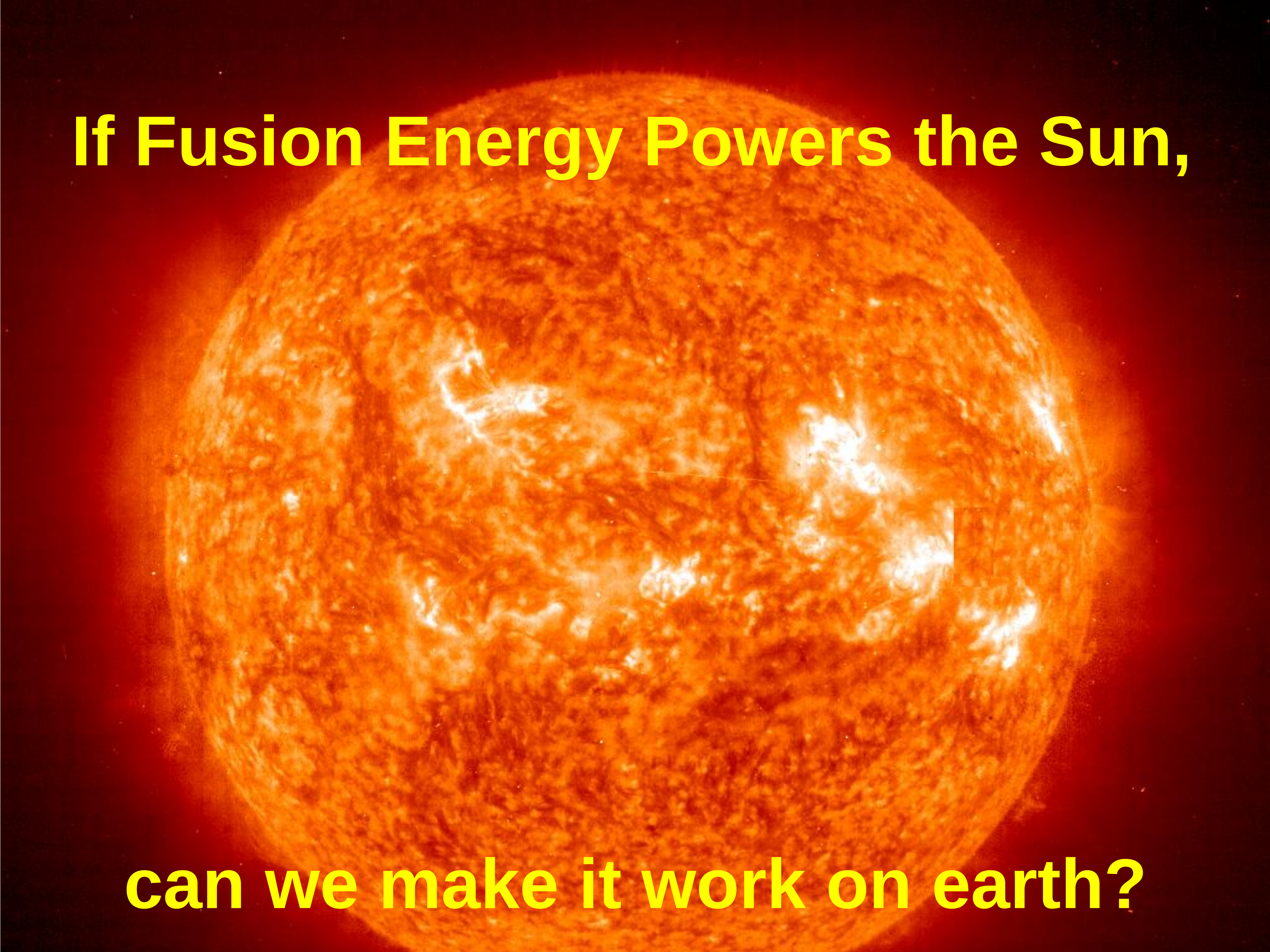
Fusion Energy Has Powered Our Planet and Economy *and Continues to Do So*

- Since the formation of the solar system, the sun has showered us with energy from fusion reactions in its core
  - Energy comes predominantly from proton-proton fusion occurring in the hot (~15 million K), dense (~150 g.cm^{-3}) core (<1/4 solar radius)
  - Energy slowly (~10^{7} years) radiates, diffuses and convects to the solar surface where it radiates into space approximating a “black body at ~6000K
- Photosynthesis produces biofuels (wood, peat) and laid down the deposits of carbon-based fossil fuels (coal, oil, gas)
- Solar energy drives the wind and waterfalls which historically provided mechanical power
- Developments in solar photovoltaic cells (and other technologies) are beginning to provide a significant source of electricity, *but*
  - Energy storage and transmission are needed for solar electricity to work

About 70 Years Ago, the Possibility of Tapping Nuclear Energy on Earth Was Discovered

- By a combination of *good luck and great skill* an entirely new source of energy, fission of heavy nuclei, was developed
- Fission uses the “fossil fuel” of rare unstable (radioactive) nuclei
  - Created by different fusion processes under extreme conditions in prehistoric supernovae as stars depleted their proton fuel
- Fission power plants now provide a significant fraction of the electrical power in many countries
  - 70% in France
  - Reliable “base-load” power without green-house gas emissions
- However, nuclear fission energy does have problems
  - Long-lived, biologically hazardous radioactive waste
  - Creates possibilities for nuclear weapons proliferation
  - After-heat from decay of unstable fission products
  - Engineering management: Three-Mile Island, Chernobyl, Fukushima

  $\Rightarrow$ Public mistrust


If Fusion Energy Powers the Sun,
can we make it work on earth?

The Beginnings of Fusion Energy Research

1928 Concept of fusion reactions providing energy radiated by stars proposed [R. Atkinson & F.G. Houtermans, Physik, **54** (1929)]

- Physicist James Jeans is skeptical that fusion can occur in stars; Arthur Eddington retorts: *“I suggest he find a hotter place”*

1932 Fusion reactions discovered in laboratory by Mark Oliphant

- Using deuteron beam from an electrostatic accelerator

1935 Basic understanding of fusion reactions - tunneling through Coulomb barrier (electrostatic repulsion) - G. Gamov *et al.*

- Nuclei must collide with kinetic energy 10 – 100 keV

1939 H. Bethe develops fusion power cycle for the stars

- Nobel prize 1967 "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

Ernest Rutherford Demonstrates Fusion in a Public Lecture in 1934

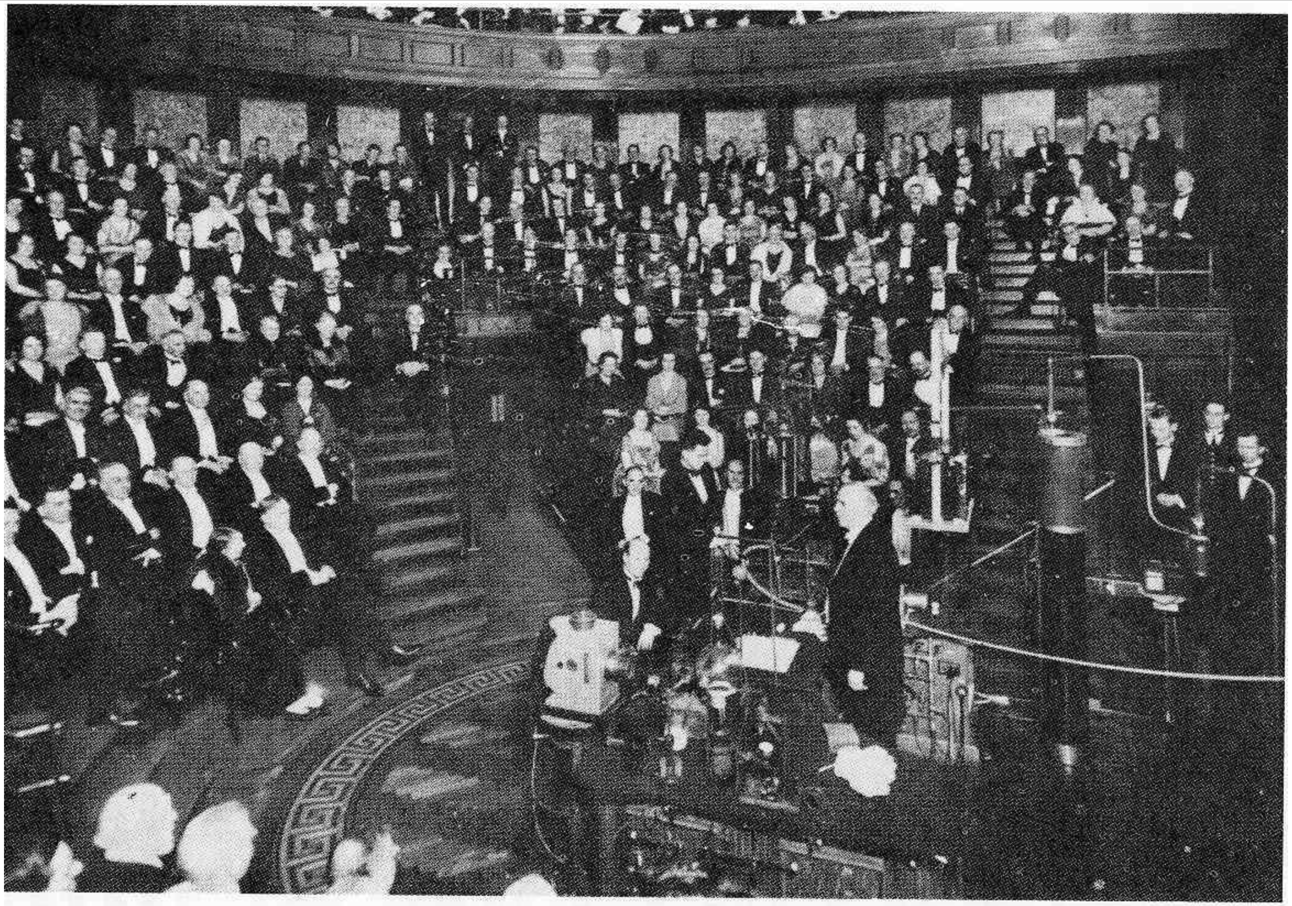


Figure 3.6.3 Rutherford demonstrating deuterium fusion at the Royal Institution, 1934. The Metropolitan-Vickers transformer is to the extreme right of the apparatus. Reproduced by kind permission of Sir Mark Oliphant from his book *Rutherford: Recollections of the Cambridge Days* (Amsterdam: Elsevier, 1972)

- Rutherford felt possibility of generating power using beam - solid target fusion was *"moonshine."*

Fusion Reactions of Interest for Terrestrial Fusion Power

- Proton-proton fusion is much too improbable for energy production
- Use reactions involving the strong nuclear force

$$^{2}D^{+} + {}^{2}D^{+} \xrightarrow{50\%} T^{+}\ (1\text{MeV}) + p^{+}\ (3\text{MeV})$$

$$^{2}D^{+} + {}^{2}D^{+} \xrightarrow{50\%} {}^{3}He^{++}\ (0.8\text{MeV}) + n^{0}\ (2.5\text{MeV})$$

$$^{2}D^{+} + {}^{3}T^{+} \longrightarrow {}^{4}He^{++}\ (3.5\text{MeV}) + n^{0}\ (14\text{MeV})$$

$$^{2}D^{+} + {}^{3}He^{++} \longrightarrow {}^{4}He^{++}\ (3.6\text{MeV}) + p^{+}\ (15\text{MeV})$$

- “Fuel” nuclei ($^{2}D^{+}$, $^{3}T^{+}$, $^{3}He^{++}$) must collide with energy >10keV

Fusion Reactions of Interest for Terrestrial Fusion Power

- Proton-proton fusion is much too improbable for energy production
- Use reactions involving the strong nuclear force

$^{2}D^{+} + {}^{2}D^{+}$ → (50%) T^{+} (1MeV) + p^{+} (3MeV)

$^{2}D^{+} + {}^{2}D^{+}$ → (50%) $^{3}He^{++}$ (0.8MeV) + n^{0} (2.5MeV)

$$^{2}D^{+} + {}^{3}T^{+} \longrightarrow {}^{4}He^{++}\ (3.5\text{MeV}) + n^{0}\ (14\text{MeV})$$

$$^{2}D^{+} + {}^{3}He^{++} \longrightarrow {}^{4}He^{++}\ (3.6\text{MeV}) + p^{+}\ (15\text{MeV})$$

- “Fuel” nuclei ($^{2}D^{+}$, $^{3}T^{+}$, $^{3}He^{++}$) must collide with energy >10keV
- D-T reaction has the highest cross-section
- “Fusion products” (He, n) are very energetic
  - Energy “payoff” is large

Need to Obtain Fusion Fuels not Naturally Occurring on Earth

- Deuterium occurs naturally and can be extracted from water
- Tritium is unstable (radioactive half-life 12.7yr) - no natural source
  - Obtained from n+D reactions in heavy-water fission reactors
- ^{3}He is produced by radioactive (β) decay of tritium
  - It has also been suggested that it could be mined from lunar rocks
- For DT fusion reactors, need to "breed" tritium by another fusion reaction

$$\mathbf{n^{0} + {}^{6}Li^{3+} \longrightarrow {}^{4}He^{++}}\ (2.1\text{MeV}) + \mathbf{{}^{3}T^{+}}\ (2.7\text{MeV})$$

- This uses the energetic neutron from DT fusion to recreate the T consumed
- $^{6}Li^{3+}$ occurs as 6% of natural lithium which is fairly abundant
- The overall fusion reaction cycle is therefore

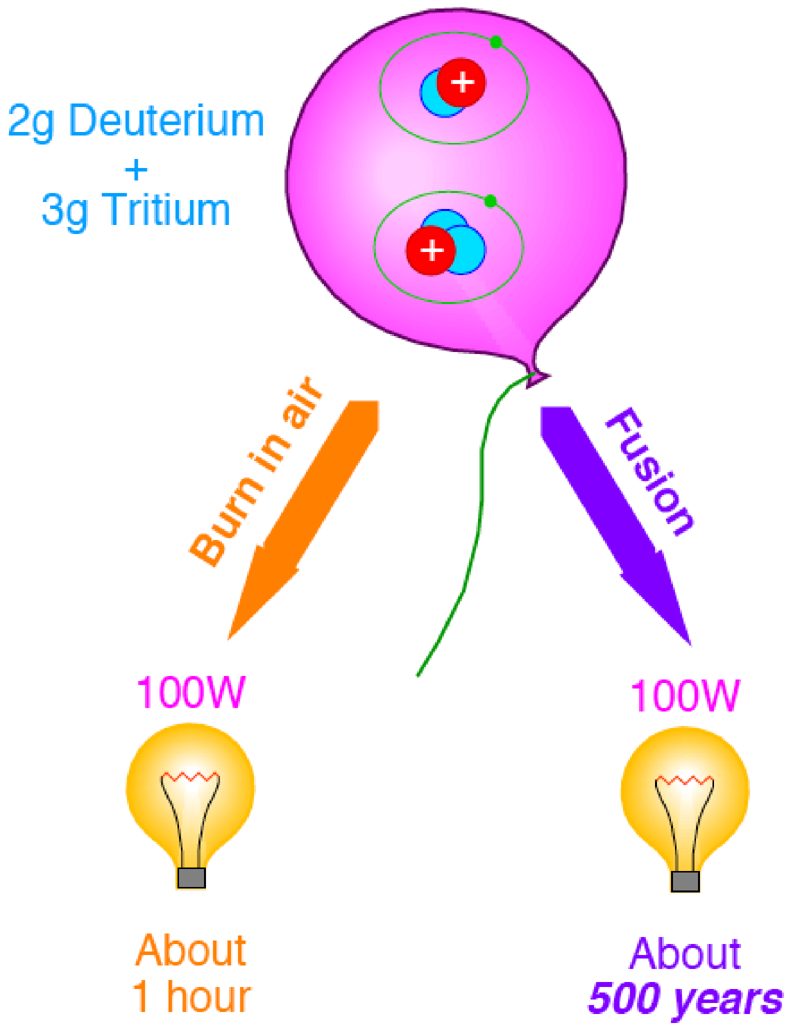
$$\mathbf{{}^{2}D^{+} + {}^{6}Li^{3+} \longrightarrow 2\ {}^{4}He^{++} + 22.4\text{MeV}}$$

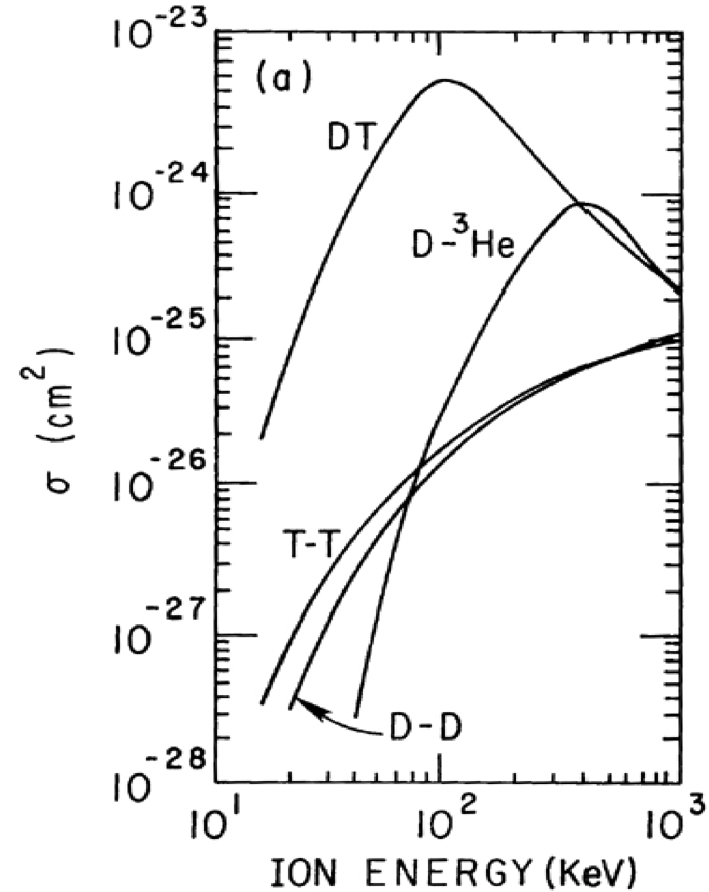
- The n^{0}+^{6}Li reaction would occur in a solid or liquid "blanket" containing lithium surrounding the hot DT fusion reaction region
- Most of the energy from DT fusion will be captured as **heat** in the blanket

DT Fusion Could Be An Abundant, Safe and Reliable Energy Source

- Worldwide, long term availability of low cost fuel (D, Li)
  - Reduces geopolitical instability due to competition for energy resources
- No CO_2 production
  - Reduced pollution and global climate change
- No possibility of runaway reaction or meltdown
  - No after-heat from fission product decay
- Relatively short-lived radioactive waste
  - Reduced need for long-term storage but tritium management an issue
- Lower risk of nuclear proliferation
  - All nations can have the full fusion fuel cycle with minimal oversight
- Steady power source that can be located near markets
  - No need for energy storage or large land use
- *Can we make it cost-competitive with future coal, fission?*

DT Fusion is Energy Intensive *but* Fusion Reaction Cross-Sections are Small





- Coulomb (electrostatic elastic) collisions between nuclei are much more probable than fusion

Energy Production by DT Fusion

- Although fusion reactions can be produced by accelerating D or T ions into a solid target, it is not possible to achieve energy gain this way
  - Coulomb collisions slow most of the ions before they can fuse with a nucleus
- At energies required for DT fusion (>10keV), collisions strip nuclei of bound electrons and they become ions: fuel becomes a ***plasma***
  - Electrons must remain for charge neutrality but play no role in fusion reactions
  - The light electrons (m_e:m_p = 1:1836) profoundly affect plasma properties
- Consider a thermalized plasma with local D, T particle densities n_D, n_T. The fusion power production from a volume V is

$$P_{DT} = E_{DT} \int n_D \, n_T \, \overline{\sigma_{DT} v} \, dV$$

where E_{DT} = 17.6MeV = 2.8×10^{-12}J and $\overline{\sigma_{DT} v}$ is the reaction *rate coefficient* calculated by integrating the fusion cross-section over the Maxwellian distribution of particle velocities $f_M(v)$

$$\overline{\sigma_{DT} v} = \int \sigma_{DT}(E) \, v \, f_M(v) \, dv$$

- For T_{DT} = 10keV ≈ 10^8K, $n_D = n_T = 5 \times 10^{19} m^{-3}$, P/V ≈ $0.8 MWm^{-3}$

Lawson Criterion* for DT Fusion Energy Gain

- A hot plasma needs energy input to balance losses by radiation, thermal diffusion
- We define an **energy confinement time τ_E** as the plasma thermal energy divided by its rate of heat loss, so for a volume V of locally equilibrated ($T_e = T_i$) plasma

$$P_{loss} \propto \int_V nTdV / \tau_E$$

- For plasma around the optimum DT fusion temperature (~15keV) with $n_D = n_T$

$$\overline{\sigma_{DT}v} \sim T^2 \quad \Rightarrow \quad P_{DT} \propto \int n^2T^2dV$$

- Ratio of fusion power to heating power to maintain steady state ($P_{heat} = P_{loss}$)

$$Q \equiv P_{DT}/P_{heat} \propto (\int_V n^2T^2dV/V) / [(\int_V nTdV/V) / \tau_E] = (\langle n^2T^2\rangle/\langle nT\rangle)\tau_E$$

- In terms of measurable quantities and for $P_{DT} << P_{loss}$, this is often approximated as

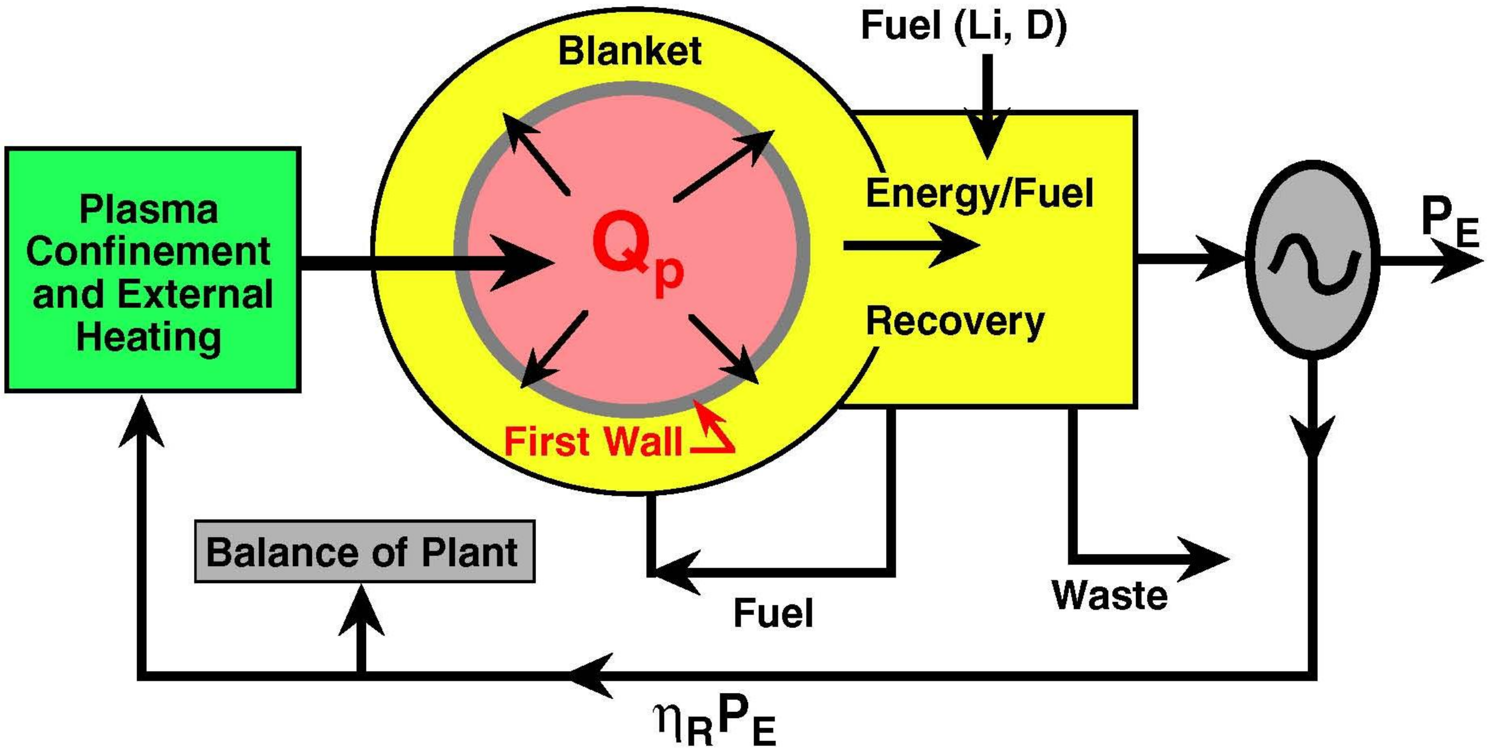
$$Q \propto n_{e,max} \cdot T_{i,max} \cdot \tau_E$$

- Energetic (14.1MeV) neutron from DT fusion escapes from plasma but charged 3.5MeV alpha particle can be trapped and heat plasma by Coulomb collisions
- Fusion **ignition** occurs when alpha heating balances plasma losses. This requires

$$\mathbf{n_e \cdot T_i \cdot \tau_E = 6 \times 10^{21}\ m^{-3} \cdot keV \cdot s}$$ *(with the same approximation)*

* J.D. Lawson, Proc. Phys. Soc. B, **70** (1957) 6

Elements of a Fusion Power Plant



Key Plasma Performance Metrics

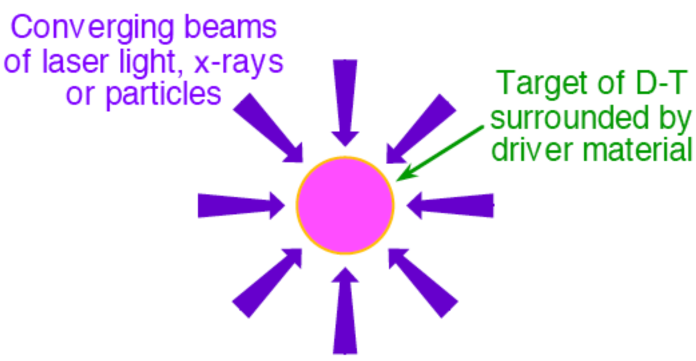
- Fusion Gain (Q_p)
- Fusion Energy Density
- Duty Cycle/Repetition Rate

Key Engineering Metrics

- First Wall Lifetime
- Availability/Reliability
- Environment and Safety
- System Costs

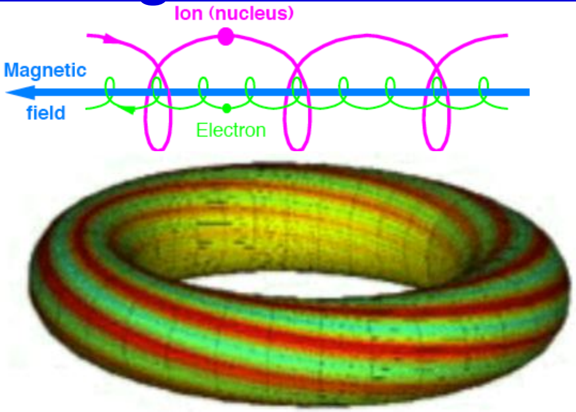
Many Fusion Concepts Have Been Tried, *but* Essentially Only Two Now Remain

Spherical Implosion



- Drive transient implosion of tiny fuel pellet (<mm) with
  - Lasers
  - Particle beams
  - Collapsing bubbles?
- Very high density: 100 x solid
- "Inertial" confinement: **"τ_E" < 1ns**
- Stability of implosion critical

Toroidal Magnetic Confinement



- Charged particles spiral around magnetic field (**F** = *q***v** × **B**)
- Make field lines close on themselves to eliminate end losses
  - Ions travel many km before undergoing a fusion reaction
- Low density: 10^{-9} x solid
- Good confinement: **τ_E > 1s**

- Also hybrid approach: **magnetically insulated implosion**

Inertial Confinement Fusion (1940s-early 50s)

1940s First ideas on using fusion reactions to boost fission bombs

1950 Edward Teller given approval to develop fusion bomb "Super"

- Two stage concept (Ulam-Teller), second driven by radiation

A Soviet Army sergeant Oleg Lavrentiev (d. Feb 2011), proposed fusion-bomb concept to Beria (Deputy Premier), and gridded electrostatic confinement for fusion energy production

- Idea sent to Andrei Sakharov and Igor Tamm, who conceive **tokamak** concept for purely magnetic confinement

1951 Greenhouse-Cylinder - radiation compression of 1cm D-T pellet

1952 First US H-bomb, Ivy-Mike (liquid D_2), exploded

1954 Castle-Bravo (solid-LiD) exploded at Bikini Atoll: **15MT yield**

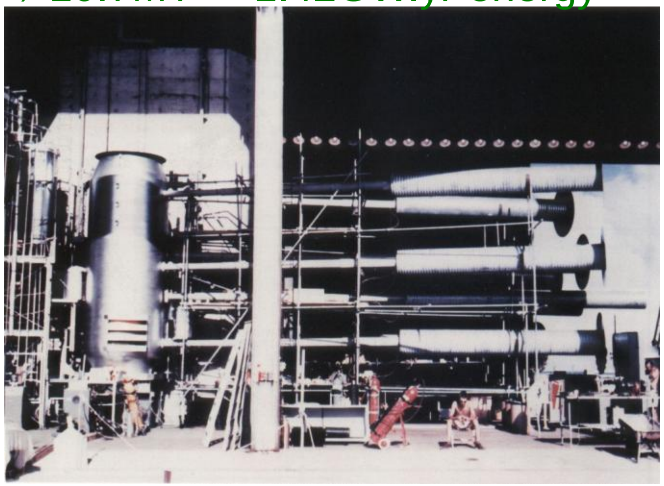
References -

"Dark Sun" by Richard Rhodes, 1995

"History of Soviet Fusion", V.D. Shafranov, Physics-Uspekhi **44**(8) 835-865 (2001)

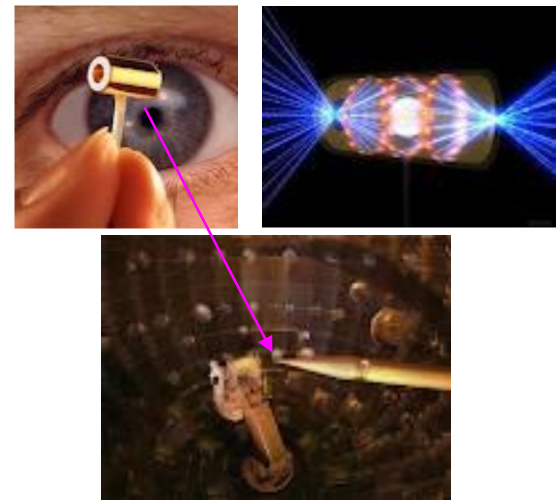
Inertial Confinement Works but Has Not Yet Been Achieved on a Manageable Scale for a Power Source

1952 Ivy-Mike "sausage" (~80 tons)
$\Rightarrow$ 10.7MT = 1.42GW.yr energy



W-80 nuclear warhead

NIF "hohlraum" capsule



- Compression of small D-T pellets to fusion ignition now being studied at the National Ignition Facility (Lawrence Livermore Natl. Lab.)
  – Using "indirect drive" by x-rays generated in a tiny (mm) cavity by intense frequency-tripled Nd-glass laser radiation (192 beams)
  – Laser inefficiency makes it difficult to achieve Q = 1 by this route
- "Direct drive" implosions also being investigated using lasers, particle beams or x-rays produced by exploding wires

Early Years of Magnetic Confinement Fusion Research

1940s Concept of using a magnetic field to confine a hot plasma for fusion

1947 G.P. Thomson and P.C. Thonemann began classified investigations of toroidal "pinch" RF discharge, eventually leading to ZETA, a large pinch at UKAEA Harwell, England in 1956

1949 R. Richter in Argentina, backed by President Peron, claimed to have achieved controlled fusion

– turned out to be bogus, but news piques interest of astrophysics professor Lyman Spitzer at Princeton

1950 Spitzer conceived "stellarator" (while on a ski lift) and proposes experiments to US Atomic Energy Commission ($50K!)

– "Project Matterhorn" initiated at Princeton

1950s Classified US Project Sherwood on controlled thermonuclear fusion

1958 Magnetic fusion research declassified. US and others unveil results at 2nd UN Atoms for Peace Conference in Geneva

Requirements for Magnetic Confinement DT Fusion Energy Development Were Understood Very Early

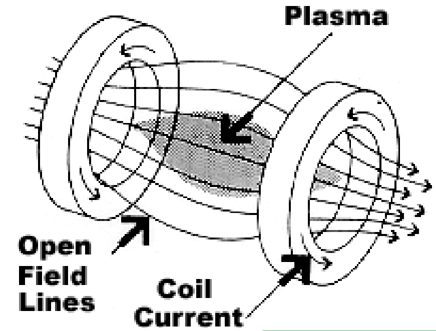
- Plasma conditions for self-sustaining fusion defined by Lawson criterion

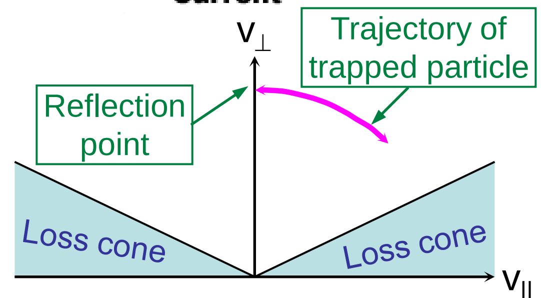
  T_i ~ 10 – 20 keV, $n\tau_E \approx (6 - 3) \times 10^{20} m^{-3} \cdot s$

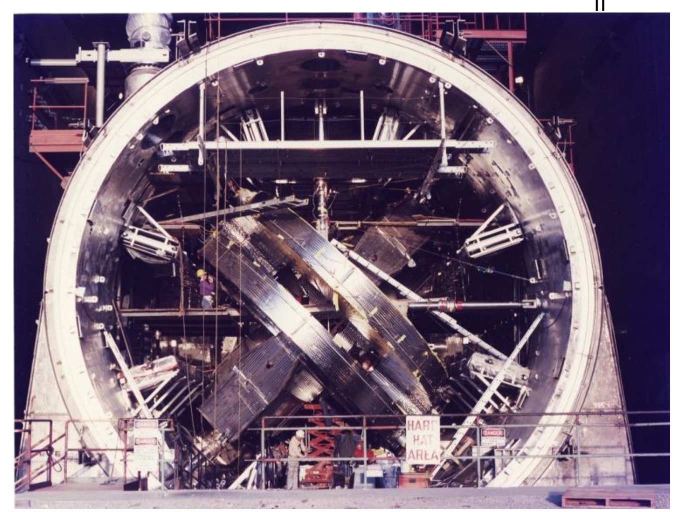
- Fusion power density ~ 5 MWm^{-3} ⇒ plasma pressure ~ 10 atm
  - Need to maximize **$\beta = 2\mu_0 \langle p \rangle / B_{max}^2$**
- Control interaction of plasma with surrounding material wall
  - ~ 2 MWm^{-2} thermal load on wall
  - Prevent impurities from diluting fuel and radiating energy
- Neutron wall loading ~ 4 MWm^{-2} for economic feasibility
- Self-sufficient tritium breeding to complete the fuel cycle
- High-duty cycle, essentially steady-state

Digression: Magnetic Mirror Confinement

- Create regions of higher magnetic field surrounding a central region with lower field
- Conservation of magnetic moment $\mu = mv_{\perp}^2/2B$ of gyrating charged particles causes them to be reflected from higher field “mirrors” at ends
- However, there is a region in the distribution function of particles, the “loss cone”, that can escape through the mirrors and be lost
  - Many schemes to minimize these losses were devised and tried *but*
  - Plasma instabilities tend to scatter particles into the “loss cone”
- Mirror confinement fusion reached its zenith in 1986 with construction of MFTF-B at Lawrence Livermore National Laboratory
  - Device was mothballed after completion



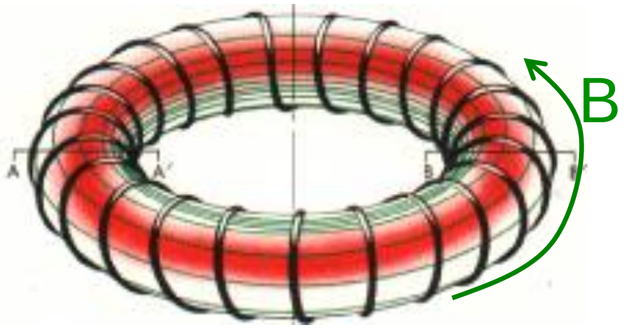


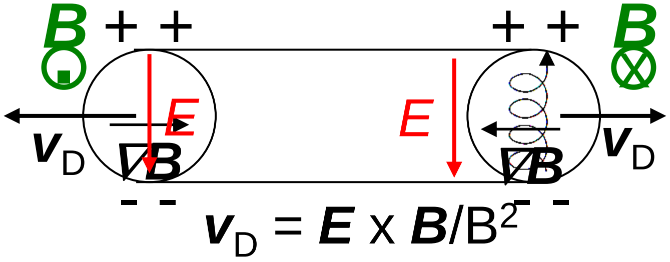


http://www.flickr.com/photos/llnl/5794563833/sizes/l/in/set-72157626754270259/

Toroidal Magnetic Confinement Schemes - "Closed" Traps

- Particles spiral around straight field lines *but in a torus*
  - Curvature and gradient in **B** cause single particles to drift vertically
  - Charge separation at the edges produces a downward **E** field that drives outward drift of plasma





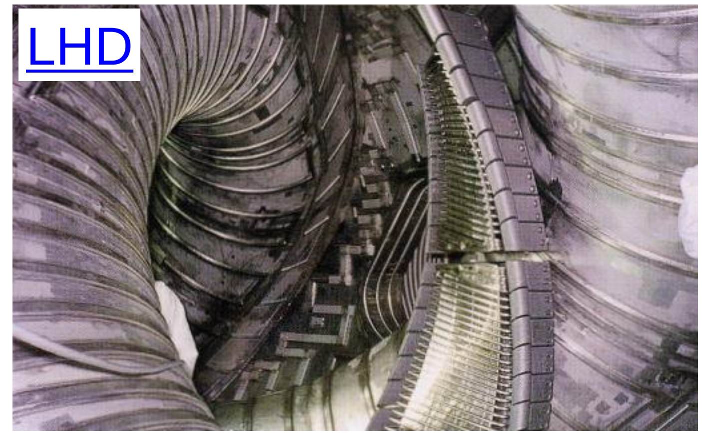
- Introduce *rotational transform* (helical twist) to field lines so drifts are compensated over several transits
  - external windings, geometrical modification ⇒ ***stellarators***
  - toroidal current in the plasma itself ⇒ ***tokamaks***
- Toroidal symmetry improves particle orbits

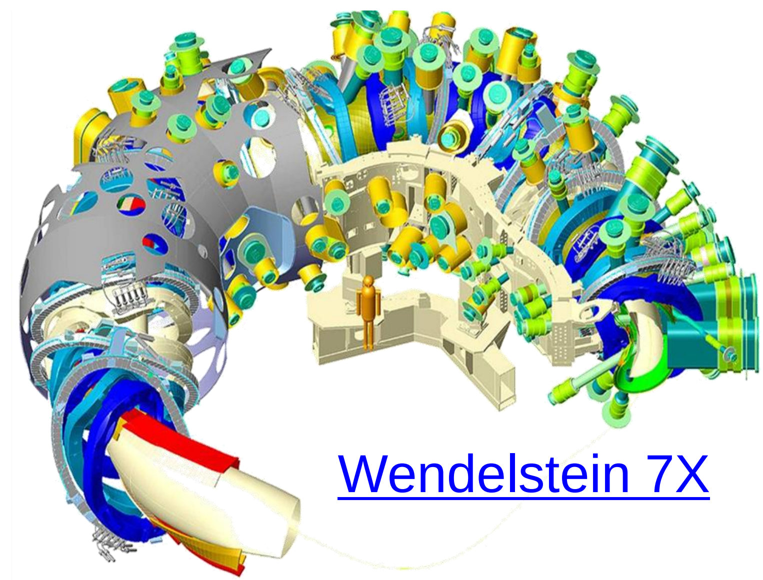
In *Stellarators* Rotational Transform Is Created by Twisting the Axis or External Coils (or Both)

Twisted axis stellarator

- Early stellarators had small plasma relative to magnetic field volume
- Modern designs avoid this through extensive numerical modelling and optimization of coil configuration
  - Large **superconducting** stellarators in Japan (LHD - operating) and Germany (W-7X - under construction)

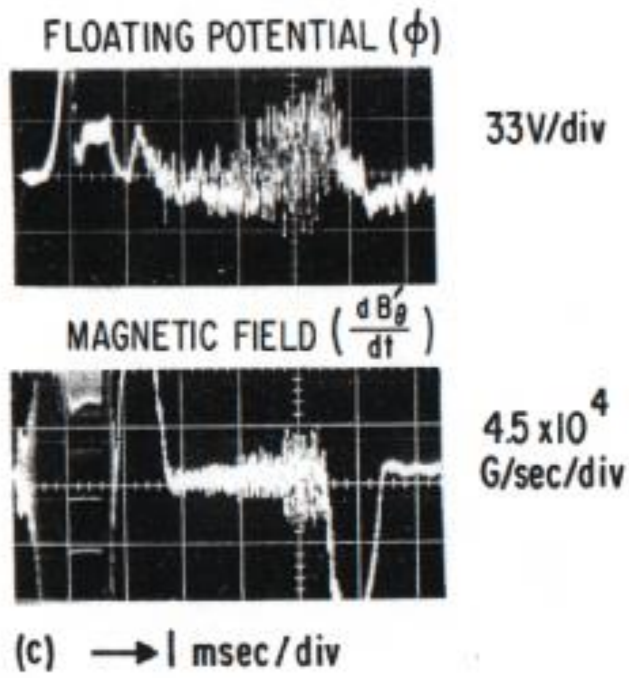
Twisted coil stellarators

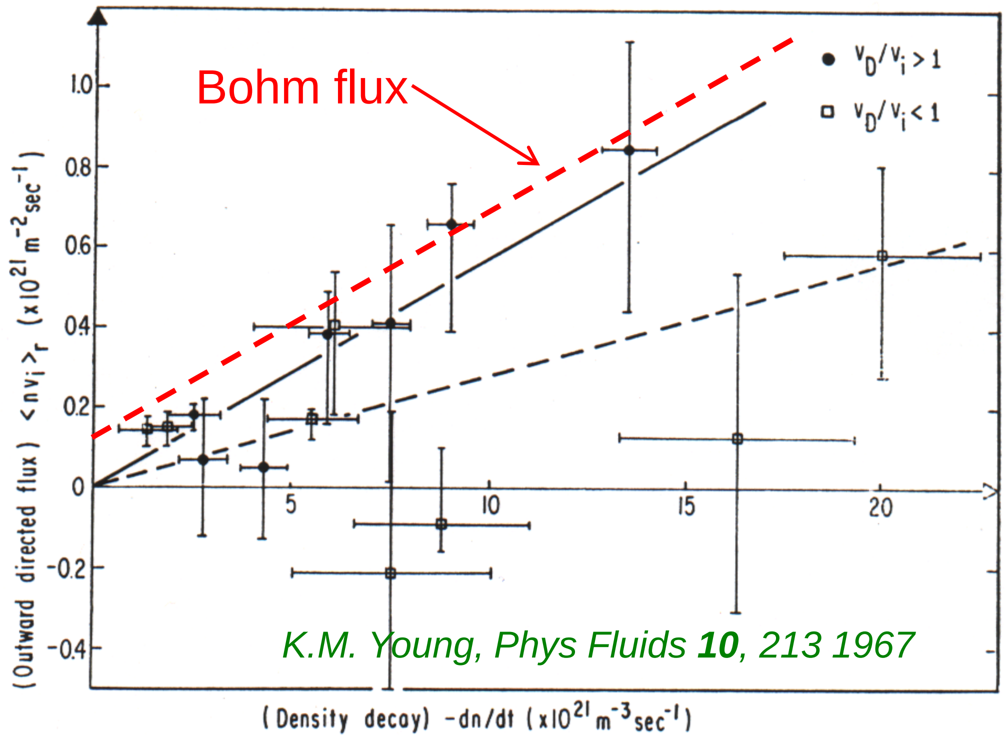




Stellarators in Early 1960s - The Depths of Despair

- Stellarator experiments in the late ’50s were plagued with instabilities
  - Confinement limited by fluctuations leading to “Bohm diffusion”
- **Model C Stellarator** at Princeton was large to reduce deleterious effects of impurities and wall neutrals, *but*
  - Results 1961-66 again showed Bohm diffusion ⇒ poor confinement

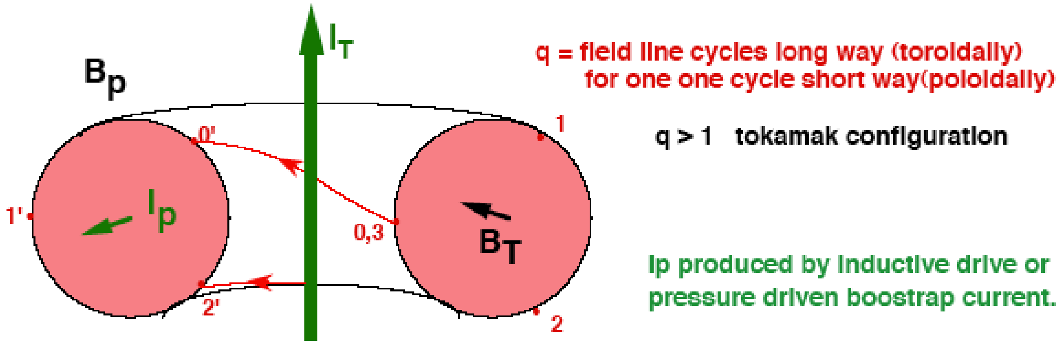


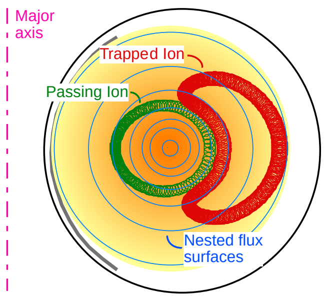


*K.M. Young, Phys Fluids **10**, 213 1967*

Toroidal Confinement - The Tokamak Approach

- Toroidal plasma current adds a *poloidal* magnetic field to the externally applied toroidal field causing field lines to spiral

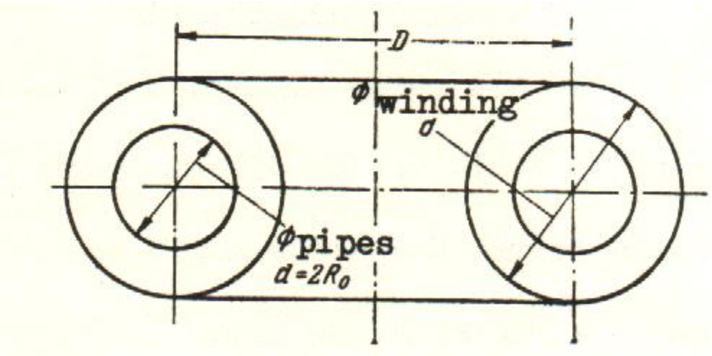




- Field lines form nested ***flux surfaces*** surrounding a ***magnetic axis***
- Collisions cause plasma to ***diffuse*** outward from one surface to the next
- Variation of the toroidal field from outside to inside ($B_T \propto 1/R$) ***traps*** some particles in local magnetic mirrors
  - ***Trapped particles*** have larger orbit excursions, adding to diffusion
- A challenge is to drive toroidal plasma current continuously and efficiently
  - Trapped particles plus a *pressure gradient* drive ***"bootstrap"*** current

The First Tokamak Reactor Design ~ 1955

- I. Tamm (1951) and A. Sakharov (1952)
  - Objective: D-D reactor producing T or ^{233}U for weapons
  - R_0 = 12m, a_p = 2 m
  - water-cooled copper coils B = 5 T
  - P_{fusion} = 880 MW (assuming "classical" heat losses)



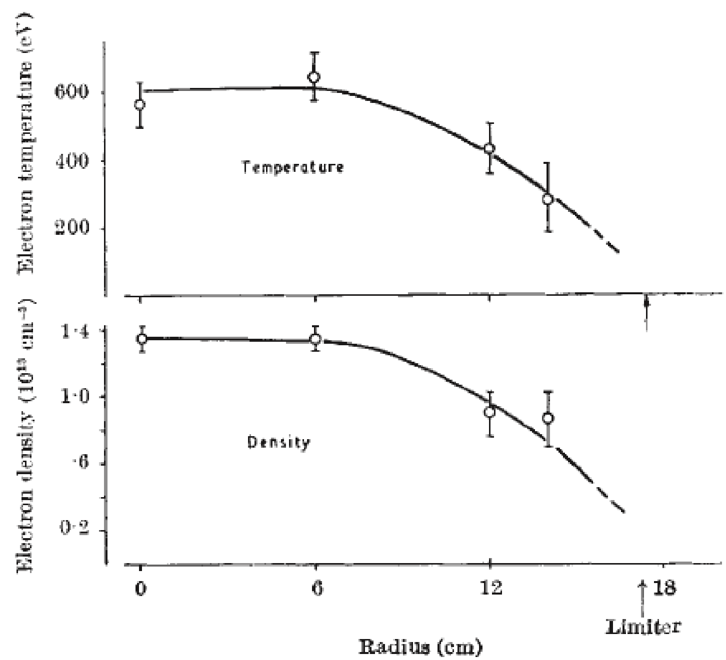
- First openly discussed at Geneva 1958 after declassification
- There was skepticism and resistance in the west
  - Concern that the plasma current was a source of instability
  - Maintaining the toroidal current - stellarators were steady-state
- Group at Australian National University investigated a tokamak-like device - "slow toroidal θ-Z pinch" or "Liley torus" in the mid-late 60s

Ref: V.D. Shafranov, "History of Soviet Fusion" Physics-Uspekhi **4** 835-865 (2001)

The Late 1960s - The Tokamak Emerges

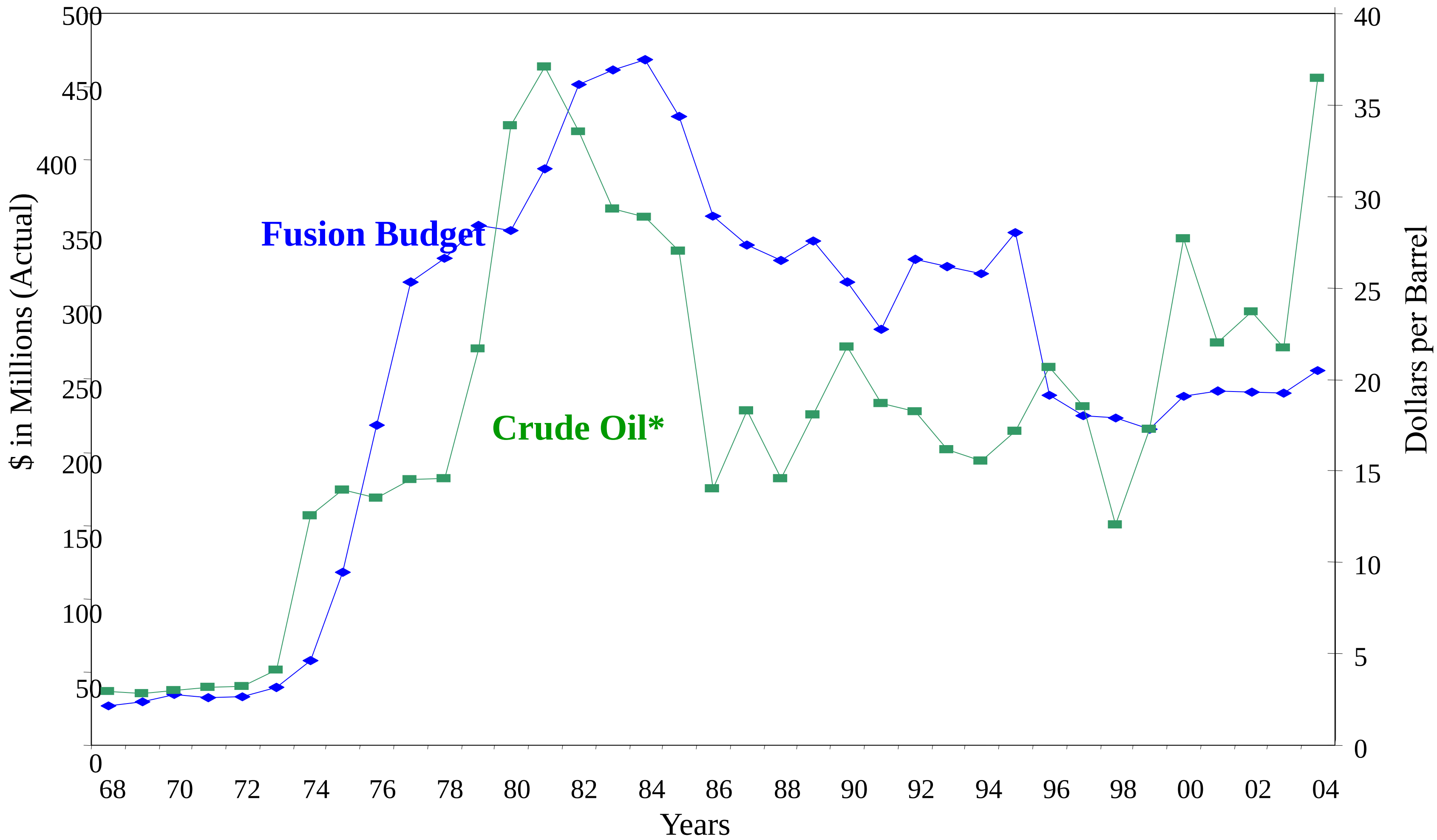
- Led by L.A. Artsimovich, tokamaks at Kurchatov Institute, Moscow, progressed through a sequence to **T-3**
  - R = 1.0 m, a = 0.20m, B = 4T, I_p < 200 kA
- Results at 1968 IAEA Conference in Novosibirsk: **$T_e \approx$ 1 keV** and **$\tau_E/\tau_{Bohm} \approx$ 50** – met with skepticism

- Team from UK (D. Robinson, N. Peacock) took a Thomson Scattering system to T-3
- Confirmatory results were obtained and presented at Dubna meeting in 1969
- Within 6 months, Model C stellarator at PPPL was converted to the **Symmetric Tokamak (ST)**
- Led to an explosion in tokamak research worldwide, culminating in **TFTR** (US), **JET** (EU), **JT-60** (Japan), now **ITER** (international)



N.J. Peacock, D.C. Robinson et al. *Nature* ***224*** *(1969) 488*

1973 Oil Embargo - Energy R&D Explodes in US



*In Actual $'s from Energy Information Administration/Annual Energy Review 2004 Table 9.1, Crude Oil Price Summary, Refiners Acquisition Costs, Imported, Nominal. Web Site: eia.doe.gov. Year 2004 is estimated based on 9 months record.

In 1970s, a Succession of Tokamaks Investigated Plasma Heating Schemes

- First tokamaks were “Ohmically” heated by toroidal current induced in plasma to produce confinement: local heating ηJ^2
- Plasma resistivity $\eta \propto T_e^{-3/2}$ decreases with electron temperature
  - Maximum T_e ~ few keV and T_i < 1keV since ions heated by electrons
- New methods of “auxiliary heating” to supplement Ohmic heating were needed to produce fusion temperatures
  - Compressional heating by varying B: *successful but transient*
  - Increasing plasma resistivity by exciting plasma turbulence
  - Injecting **beams of energetic neutral atoms (NBI)** which ionize, become trapped and transfer their energy to the plasma
  - Injecting powerful **RF electromagnetic waves** to excite plasma waves which can deposit their energy in electrons or ions
    - Ion cyclotron resonance (**ICRH**): 10 – 100 MHz
    - Electron cyclotron resonance (**ECRH**): 20 – 150 GHz
    - Lower hybrid resonance (**LHH**): 2 – 5 GHz

The Success of Neutral Beam Injection (NBI) Heating Led to the TFTR Era at PPPL

July 1973 US DOE proposes a superconducting D-T ignition device
– Not yet well defined but it would have represented a huge step

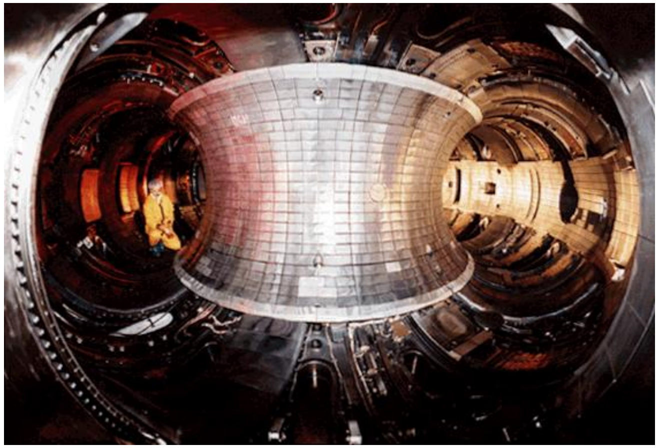
Dec 1973 PPPL suggests smaller "Two-Component Torus" with intense NBI then being developed for the Princeton Large Torus (PLT)

– Harold Furth: *"If what you want is fusion neutrons ..."*

July 1974 DOE selects PPPL approach – goal: significant D-T fusion power

Dec 1975 **PLT** starts operation – similar design with NBI, but smaller

Mar 1976 **TFTR** construction starts



Aug 1978 PLT T_i = 5.5 keV

– Success of NBI heating

– Allays fears of instabilities at high T_i

Dec 1982 **First TFTR plasma – ~50 kA**

ASDEX-U (Germany) discovers **H-mode** in NBI-heated tokamak with a magnetic divertor

Competition Between TFTR, JET (EU) & JT-60U (Japan), Propelled Fusion Research Forward for Over a Decade

1986 TFTR "Supershots" – Confinement × 2–3, record T_i, P_{DD}

1988 TFTR confirms the "bootstrap" current in supershots

1990 TFTR evidence that Ion Temperature Gradient (ITG) modes determine transport: $T_i(0) \propto T_i(a)$ – marginal stability

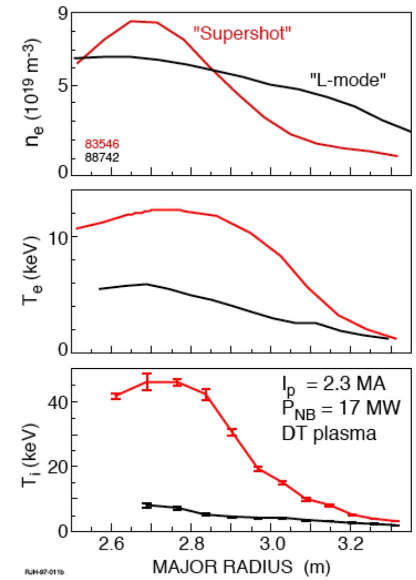
1995 TFTR & DIII-D discover benefits of negative magnetic shear → internal transport barriers; role of sheared plasma flow in suppressing ITG mode

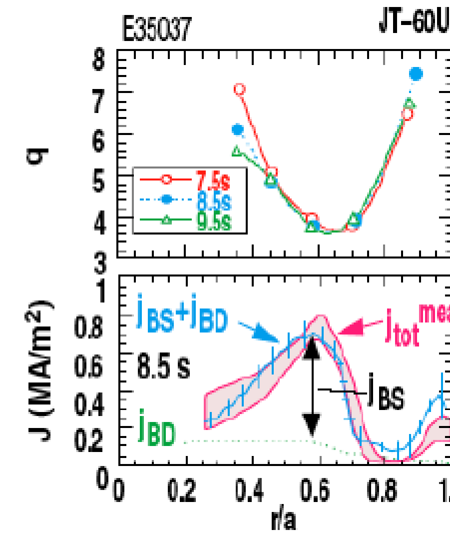
1988 JET achieves high fusion performance hot-ion H-mode in shaped divertor plasmas

1990s JET utilizes beryllium plasma facing components, investigates several divertor configurations and RF heating

1996 JT-60U installs high-energy (0.4MeV) negative-ion neutral beam system

1999 JT-60U sustains negative shear for 2.6 s in a quasi-steady state by fully non-inductive current drive (bootstrap current ~75% plus NINBI-CD)





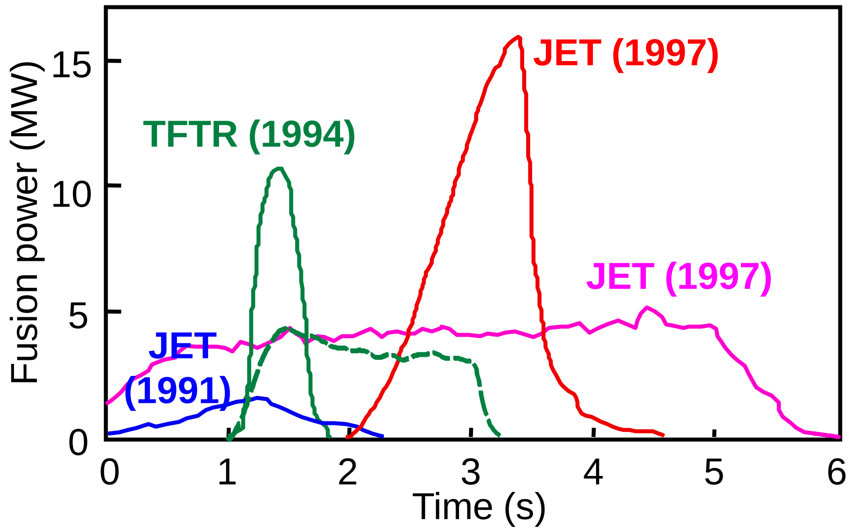
First DT Experiments in JET and TFTR Yielded a Wealth of Physics

1991 JET "Preliminary Tritium Experiment" producing P_{DT} > 1MW

1993 TFTR D-T experiments begin – leading to P_{DT} = 10.7MW, favorable isotope scaling, alpha-particle heating, alpha-driven instabilities, RF heating; tritium and helium "ash" transport, tritium retention in walls

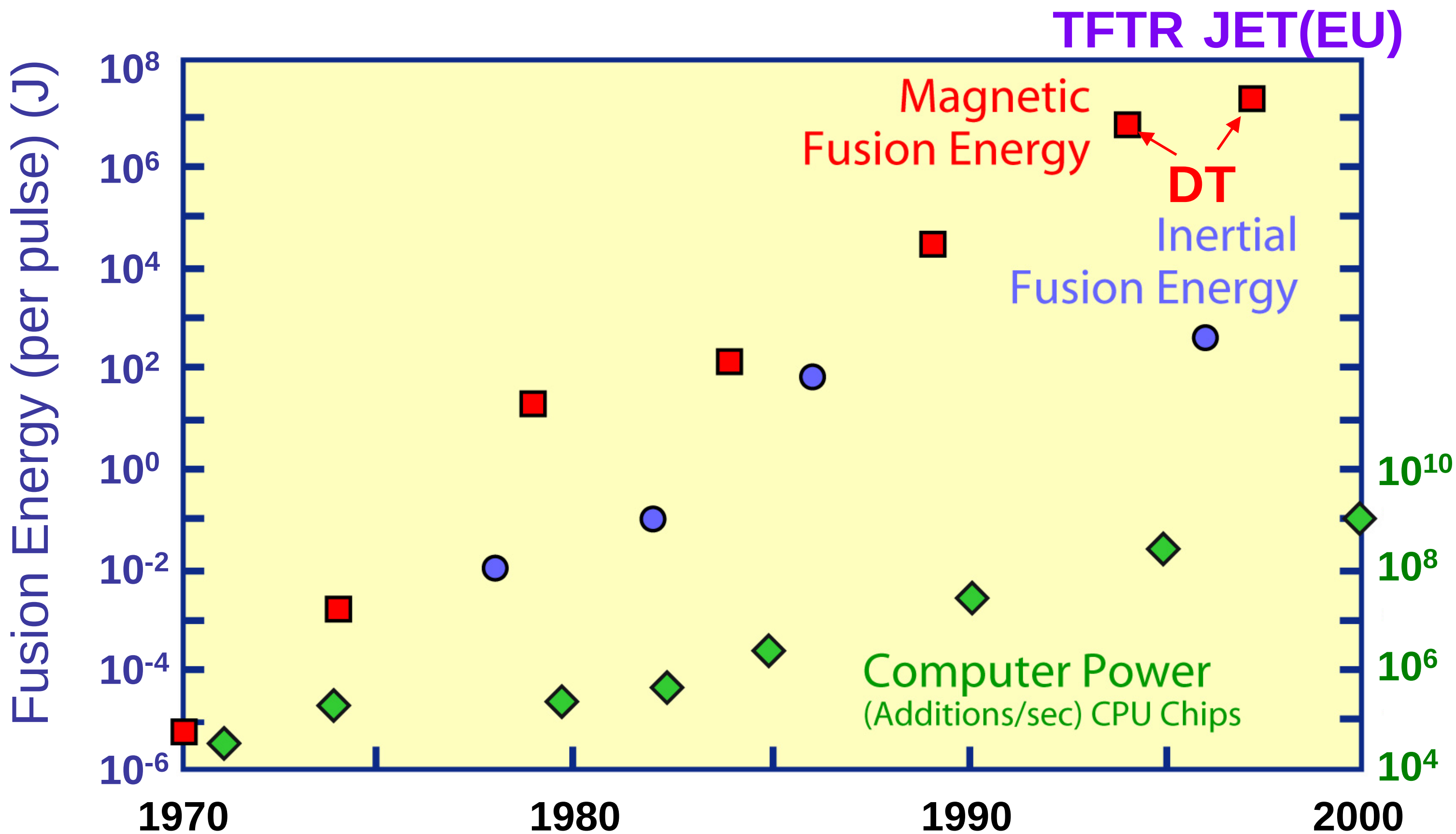
1997 TFTR shut down after >60000 plasma shots, >1000 with D-T fuel

1998 JET resumes DT experiments – leading to P_{DT} = 16MW, alpha-particle heating; H-mode and "hybrid" mode in DT; different isotope scaling



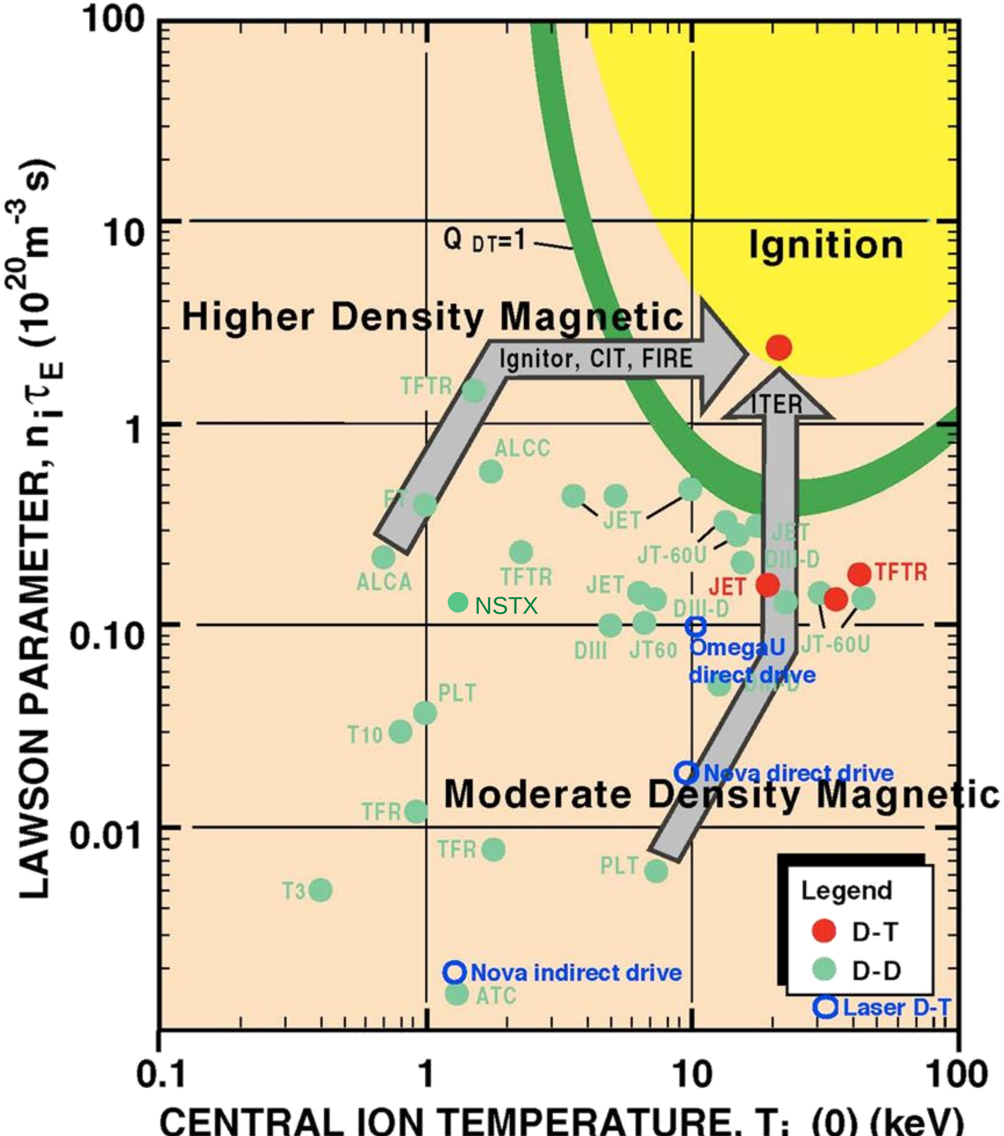
2015 JET plans to resume DT operation with its "ITER-like Wall"

From 1970 through 1997, Progress in Fusion Energy Output Even Outpaced Computer Speed



- Progress in performance followed major investments in 1980s
- In mid-90s, budgets for fusion research decreased and have remained almost static so progress has slowed

After ~60 years, MFE Has Progressed ~10% of Way to DT Fusion Ignition



- "Lawson diagram" shows steady progress in tokamaks on two "fronts"
  - Achieved T_i required, but need 10 × $n\tau_E$
  - Achieved $n\tau_E$ ≈ 1/2 required, but need 10 × T_i
- Requirements depend on plasma profiles, impurities, synchrotron radiation, *etc.*
- Curves similar for ICF but modified by bremsstrahlung absorption

Data compiled by D. Meade

Since 2000, Magnetic Confinement Research Has Pursued Two Tracks

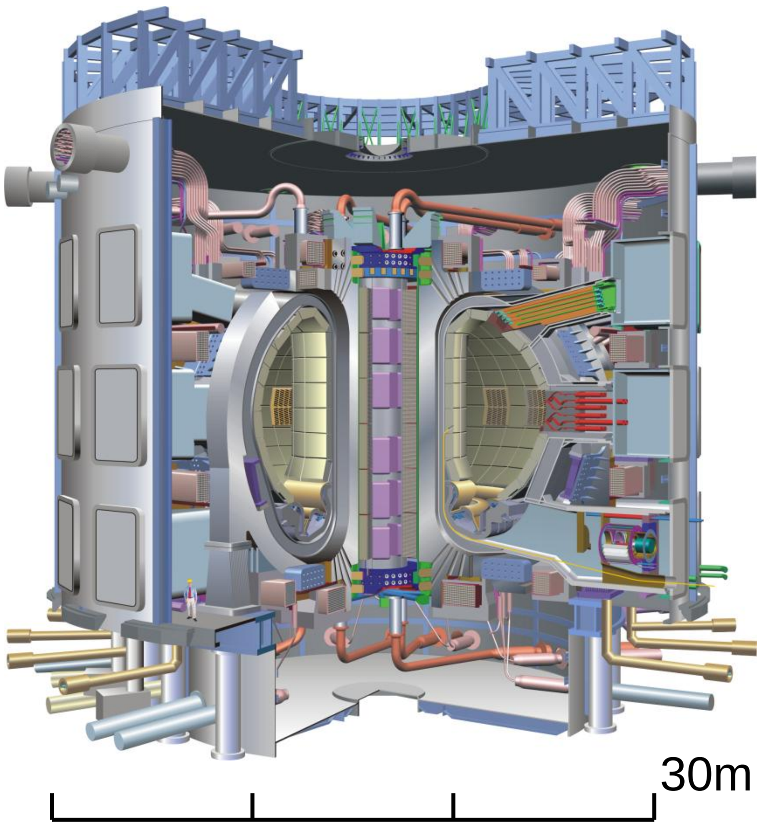
- **ITER:** tokamak to produce and study ignited (Q ≥ 10) DT plasmas
  - – Originated in 1985 (Gorbachev-Reagan summit)
  - – Large superconducting tokamak: R = 6.2m, I_p = 15MA
  - – Implementing agreement signed November 2006 between **EU, Japan, Russia, USA, Korea, China, India**
    - US had pulled out in 1999 but rejoined in 2003
    - Ageement delayed by competition between EU and Japan for host site
  - – Being built in Cadarache, France: cost estimated at ~20B Euro
  - – **First plasma operation in 2020, D-T operation in 2027**
- **Innovation:** use existing devices or new confinement concepts to improve the prospects for magnetic fusion
  - – New devices include advanced stellarator at IPP Greifswald, Germany
  - – Research may also benefit ITER by improving its design margins, relaxing its requirements and broadening its operating regime

ITER will Demonstrate the Scientific and Technological Feasibility of Fusion Power

- ITER is a dramatic step towards self-sustained fusion reactions
  - **500 MW(th) for >400 s with gain Q >10**

but ...

- ITER is not a self-sufficient power-producing plant
- New science and technology are needed for a demonstration power plant
  - 2500 MW(th) with gain >25, in a device with similar size and field
  - Higher power density
  - Efficient continuous operation
  - Tritium self-sufficiency



- Extensive research programs will be needed to address these issues

TFTR, JET and JT-60U Achieved Many of the Plasma Parameters Expected to be Produced in ITER

	TFTR	ITER
Central pressure $\beta(0)$ %	6	6
Collision frequency ν_e^* (10^{-2})	1	0.8
Electron density (10^{20} m^{-3})	1.0	1.1
T_i (keV)/T_e (keV)	36/13	18/20
Fuel mixture D/T	1	1
Toroidal field B_T (T)	5.6	5.3
Fusion Power Density (MWm^{-3})	2.8	1

- **Confinement was the outstanding issue *and remains so***

	TFTR	ITER
Confinement time (s)	0.2	2.5

- **Most reliable solution: *bigger device with higher current***

	TFTR	ITER
Normalized gyro-radius ρ_i/a (10^{-3})	6.5	2

Ref: http://www.iter.org/a/index_use_5.htm

ITER is a Huge Construction Project Involving Many Technical and Management Challenges

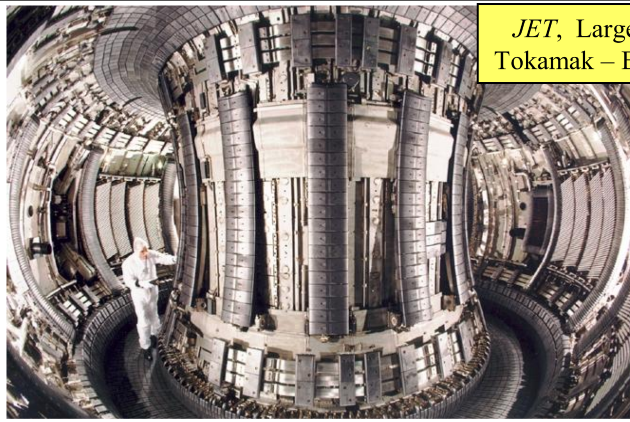
- The ITER parties contribute specified equipment and systems which must fit and function together
- Most visible progress is at the ITER site but many construction tasks are now underway

Tokamak seismic pit and foundation

Poloidal field coil winding building

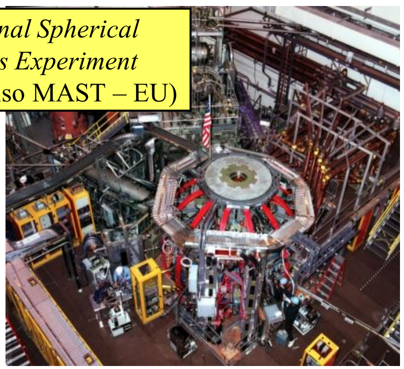
Experiments Around the World Are Investigating and Attempting to Optimize the Magnetic Configuration

C-Mod, Tokamak MIT

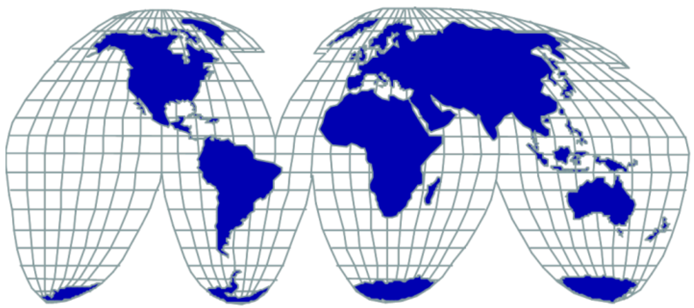


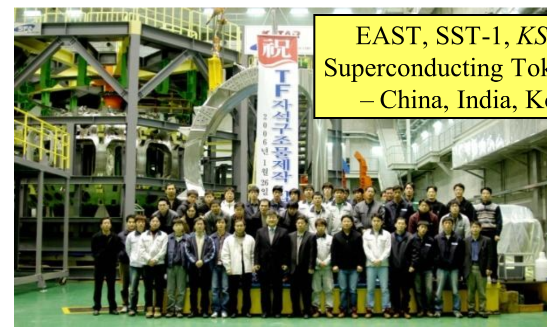
JET, Large Tokamak – EU

W7-X, Large Superconducting Stellarator – EU

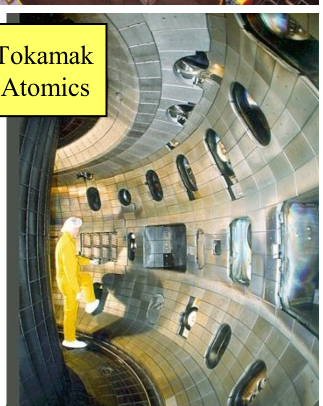


National Spherical Torus Experiment PPPL (also MAST – EU)



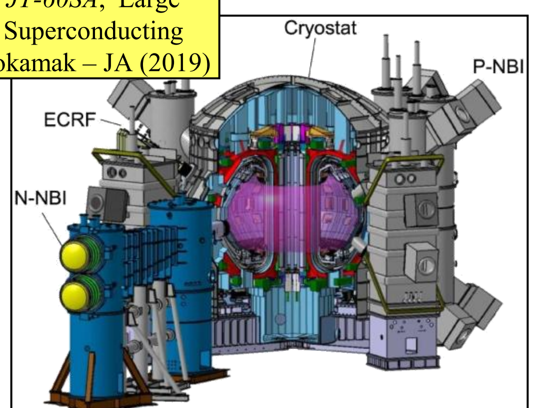


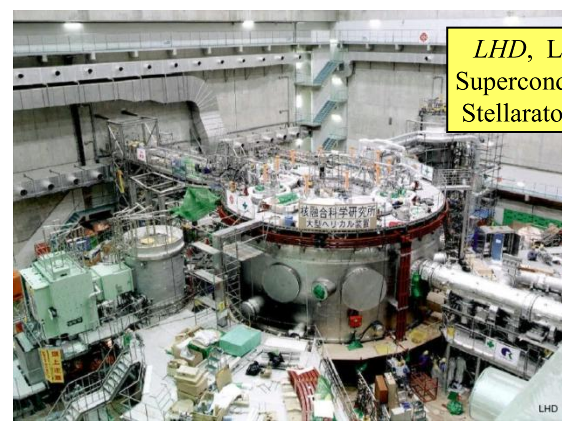
EAST, SST-1, *KSTAR* Superconducting Tokamaks, – China, India, Korea



DIII-D, Tokamak General Atomics

JT-60SA, Large Superconducting Tokamak – JA (2019)





LHD, Large Superconducting Stellarator – JA

Magnetic Confinement Fusion Research is Now at a Crossroads

- **We must demonstrate that ignited DT plasmas can be produced and controlled in ITER**
  - After 60 years of research, this is the crucial step
  - ITER requires an unprecedented level international cooperation
  - Information from the existing tokamak program is needed to make critical choices remaining on aspects of its design and operation
- **At the same time, we should look beyond ITER to a fusion power plant**
  - Electricity from a tokamak based on the ITER design would not currently be competitive with other sources
  - Are there configurations that can achieve the needed confinement in steady-state?
  - Smaller unit size is a great advantage for introducing new technology
- ***Finding the optimum balance between these efforts will determine whether magnetic fusion energy can succeed in meeting its potential***