Magnetic Confinement Fusion at the Crossroads

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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)]

- J. Jeans is skeptical; A. Eddington retorts: *"I suggest he find a hotter place"*

1932 Fusion reactions discovered in laboratory by M. Oliphant

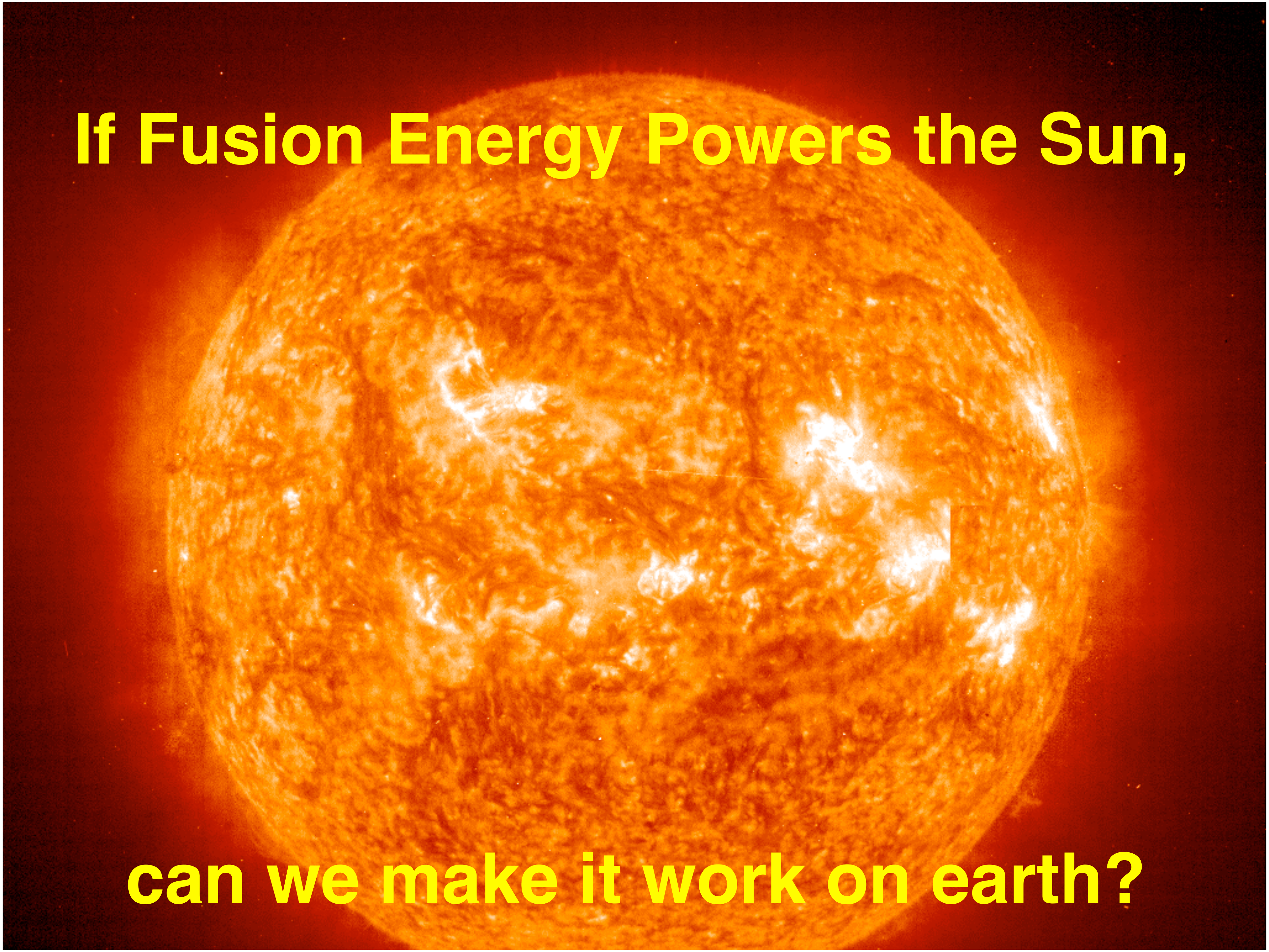
- Lord Rutherford felt possibility of fusion power using beam - solid target approach was *"moonshine."*

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

- **fusion requires high temperatures**

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"


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

Fusion Reactions of Interest for Terrestrial Fusion Power

$$D^{+} + D^{+} \longrightarrow {}^{3}He^{++}\ (0.82\ \text{Mev}) + n^{0}\ (2.5\ \text{MeV})$$

$$\longrightarrow T^{+}\ (1\ \text{MeV}) + p^{+}\ (3\ \text{MeV})$$

$$D^{+} + {}^{3}He^{++} \longrightarrow {}^{4}He^{++}\ (3.6\ \text{MeV}) + p^{+}\ (14.7\ \text{MeV})$$

Plasma

$$D^{+} + T^{+} \longrightarrow {}^{4}He^{++}\ (3.5\ \text{MeV}) + n^{0}\ (14.1\ \text{MeV})$$

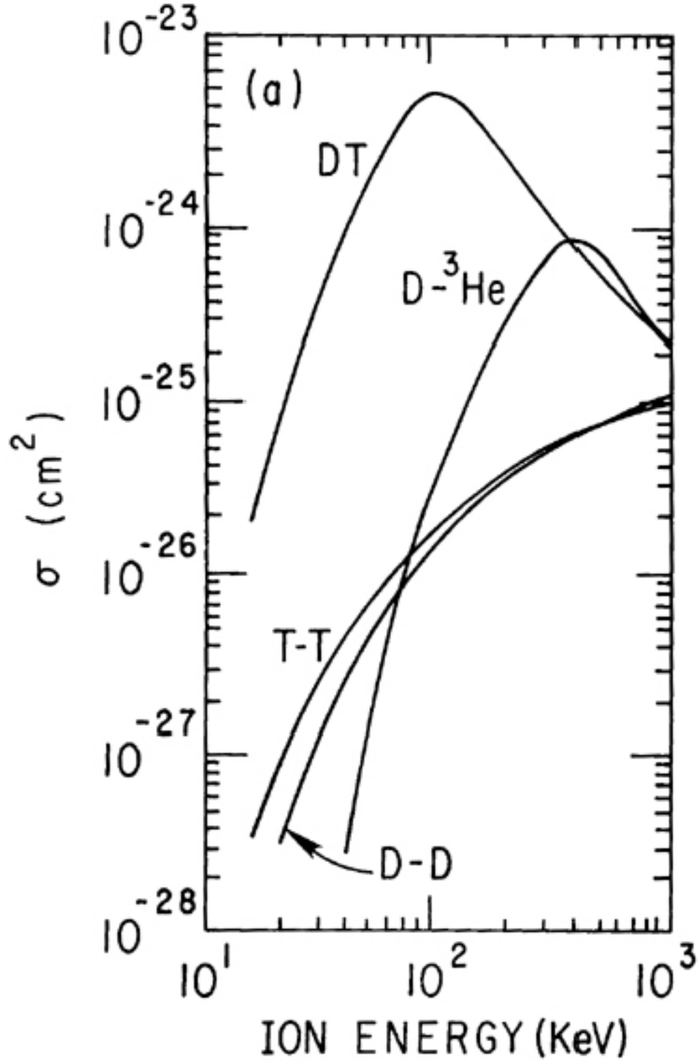
Solid

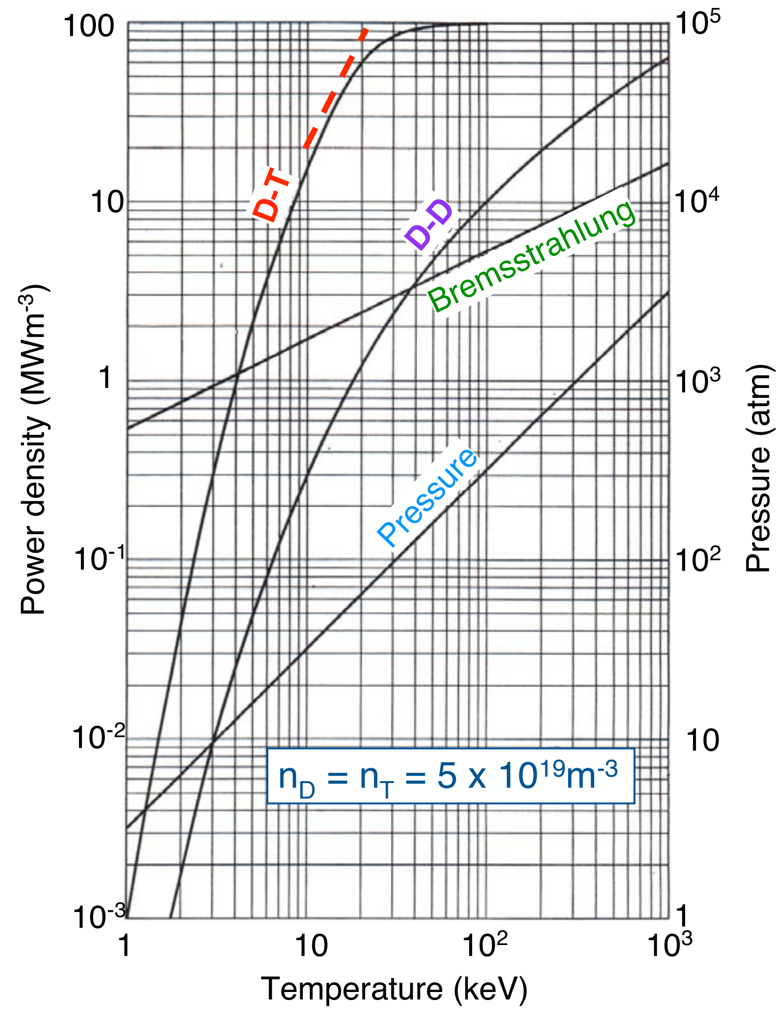
$$Li^{6} + n \longrightarrow {}^{4}He\ (2.1\ \text{MeV}) + T\ (2.7\ \text{Mev})$$

Overall fuel cycle

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

D-T Fusion Cross Sections and Reaction Rates

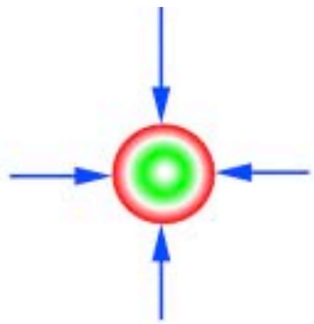


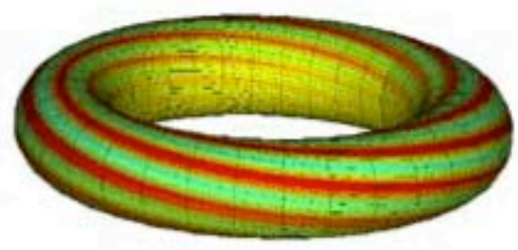


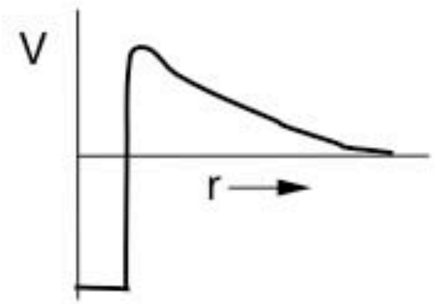
For T = 10 – 20 keV, $<\sigma v> \sim T^2$

$P_{DT}/Vol \sim n_D n_T <\sigma v> \sim n^2 T^2 \sim$ pressure^2

Three Fusion Concepts Now Remain







Spherical Inertial

gravitational - not on earth

transient compression

drive (laser-D/I, beam)

radial profile

time profile

electrostatic ?

"bubble" implosion?

Toroidal Magnetic

surface of helical B lines

twist of helix

twist profile

plasma profile

toroidal symmetry

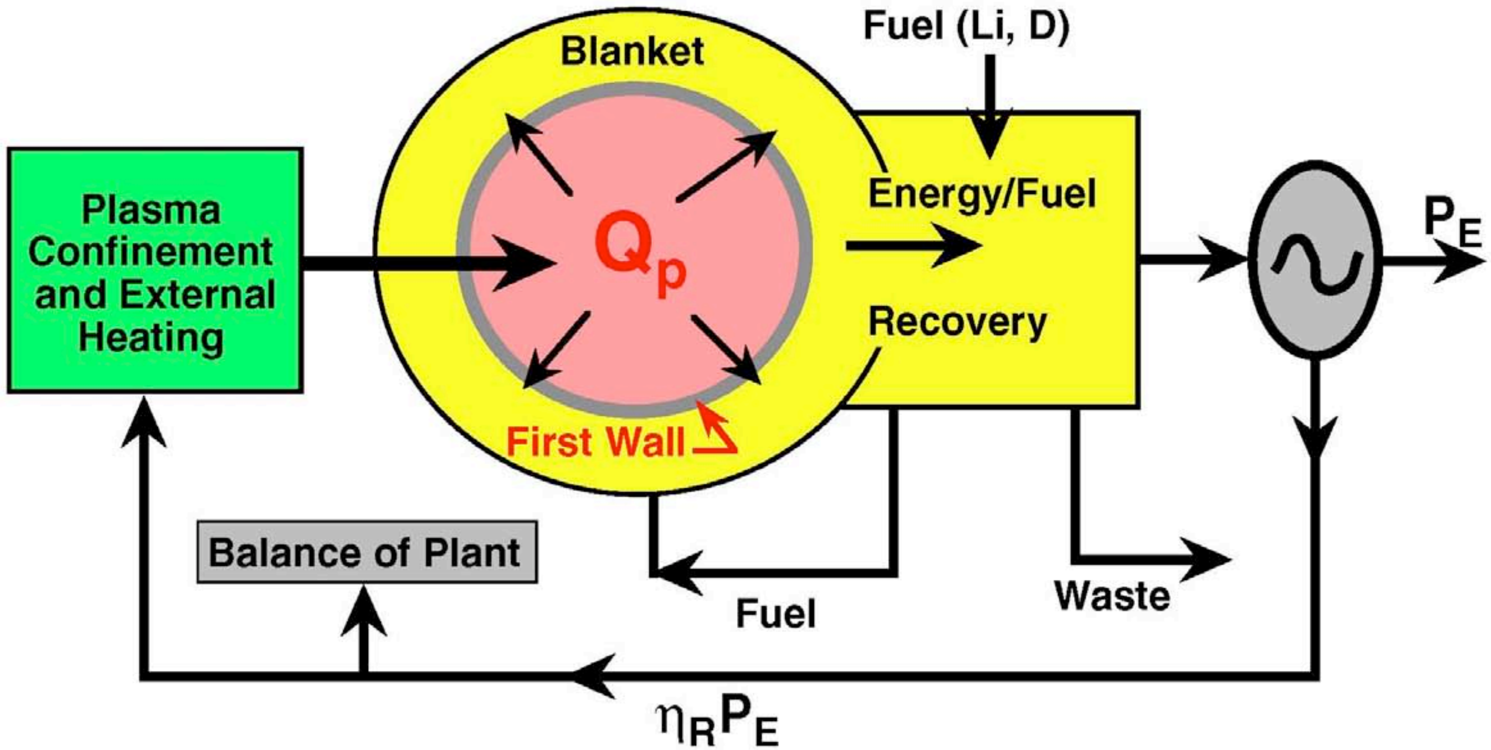
Reactivity Enhancement

muon catalysis

polarized nuclei

others?

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

Inertial Confinement Fusion (1940s-early 50s)

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

1950 E. Teller given approval to develop fusion bomb “Super”

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

O. Lavrentiev, Soviet Army sergeant, proposed fusion-bomb concept to Beria, and gridded electrostatic confinement for fusion energy

– Sent to Sakharov and Tamm, who conceive **tokamak**

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**

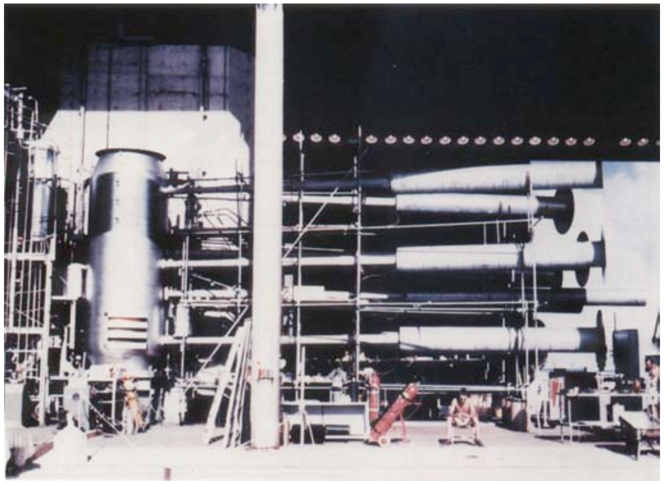
References -

“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 Been Achieved on a Manageable Scale for a Power Source

Ivy-Mike "sausage" (~80 tons)



Ivy-Mike test (1952, 10.7MT)

W-80 warhead

- Compression of small D-T pellets to ignition planned for the National Ignition Facility (Lawrence Livermore Lab.) in 2010
  - Using "indirect drive" by x-rays generated in a 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 claimed to have achieved controlled fusion

– turns out to be bogus, but news piques interest of Lyman Spitzer at Princeton

1950 Spitzer conceived “stellarator” (while on a ski lift) and makes proposal to AEC ($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 D-T Fusion Energy Development Were Understood Very Early

PPPL PRINCETON PLASMA PHYSICS LABORATORY

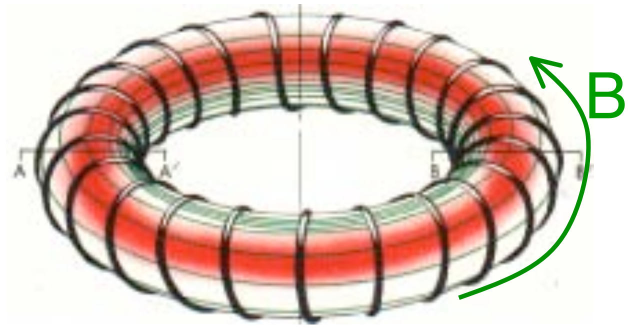
- Plasma conditions: ***Lawson Criterion*** *(isothermal, isobaric plasma)*

  $Q \equiv P_{out}/P_{in} > 10$ requires $T_i \sim 10 - 20$ keV, $n\tau_E \approx (6 - 3) \times 10^{20} m^{-3} \cdot s$
  - plasma heating, fueling, confinement, radiation losses
- Fusion power density ~ 5 $MWm^{-3} \Rightarrow p \sim 10$ atm
  - Need to maximize $\boldsymbol{\beta = \langle p \rangle / B_{max}^2}$
  - MHD stability and coil engineering
- Control interaction of plasma with surrounding material wall
  - ~ 2 MWm^{-2} thermal load on wall
  - low impurity levels, low tritium retention
- Neutron wall loading ~ 4 MWm^{-2} (needed for economic feasibility)
  - material damage ~ 40 dpa/yr with low radioactive waste
  - self-sufficient tritium breeding to complete the fuel cycle
- High-duty cycle, essentially steady-state

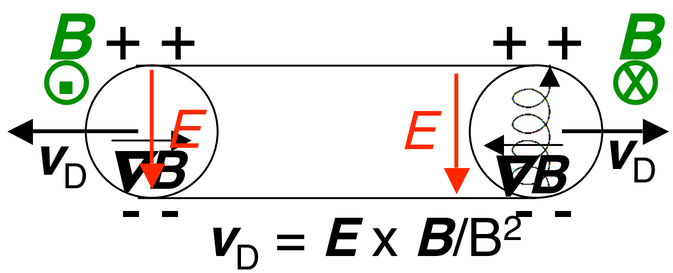
J.D. Lawson, Proc. Phys. Soc. B, **70** (1957) 6

Toroidal Magnetic Confinement Schemes - "Closed" Traps

- Plasma in a simple torus doesn't have an equilibrium



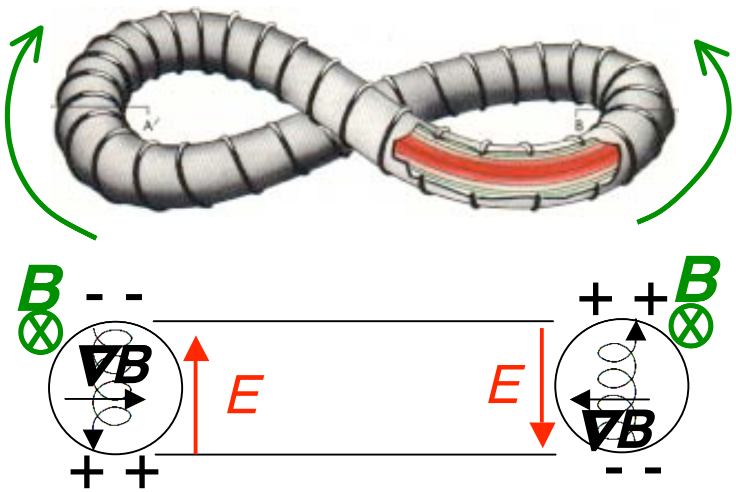
  - Curvature and gradient in B cause single particles to drift vertically
  - Charge separation at the edges produces a downward E field that drives outward drift of plasma



- Introduce *rotational transform* (helical twist) to field lines so drifts are compensated over several transits
  - external windings, geometrical modification
  - toroidal current in the plasma itself

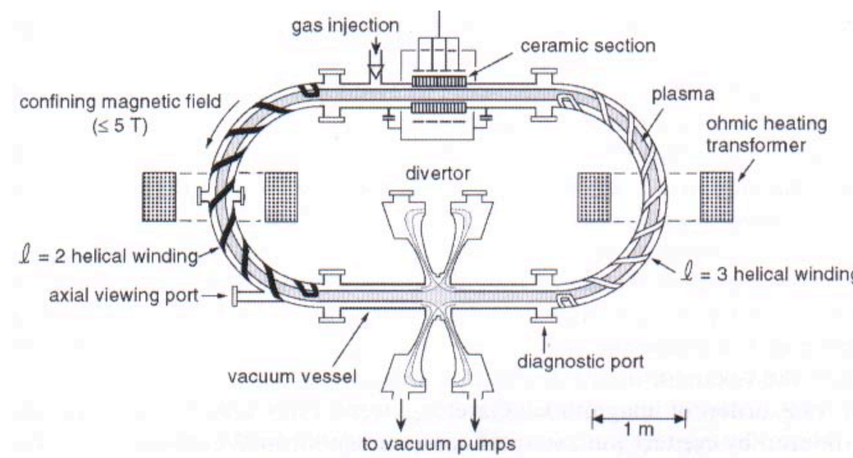
In *Stellarators* Rotational Transform Is Created by Twisting the Axis or External Coils (or Both)

Figure 8 stellarator



- Used in first stellarator experiments and stellarator power plant studies
- Original Figure-8 designs had very small plasma volume relative to magnetic field volume

Helical coil stellarator

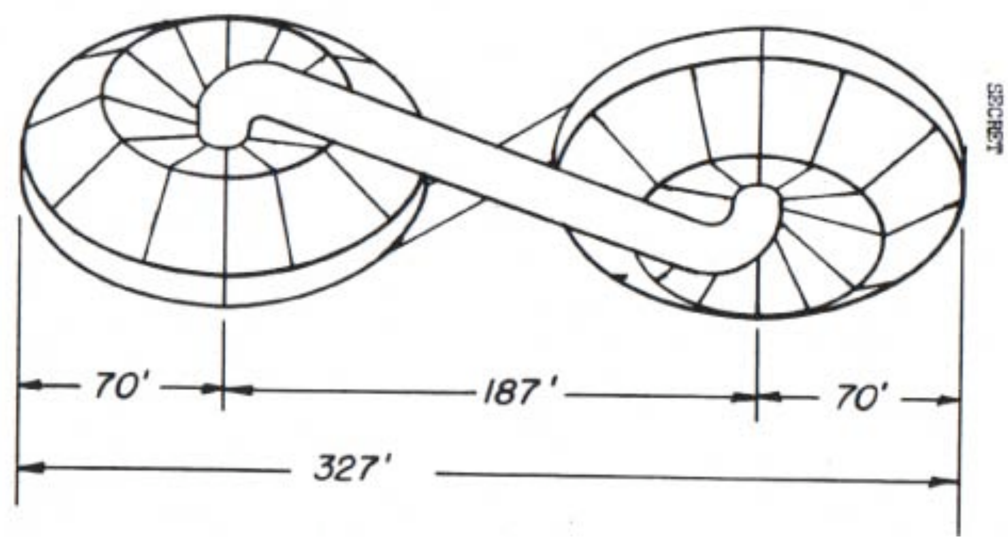


- Model C "race track" stellarator
  - ℓ = 3 winding (trefoil) on one U bend
  - ℓ =2 winding (ellipse) on other
- Transitions from U-bends generated large *magnetic islands*

- *Modern stellarators attempt to avoid these pitfalls through extensive numerical modelling and optimization of coil design*

The First Stellarator Reactor Design ~ 1955

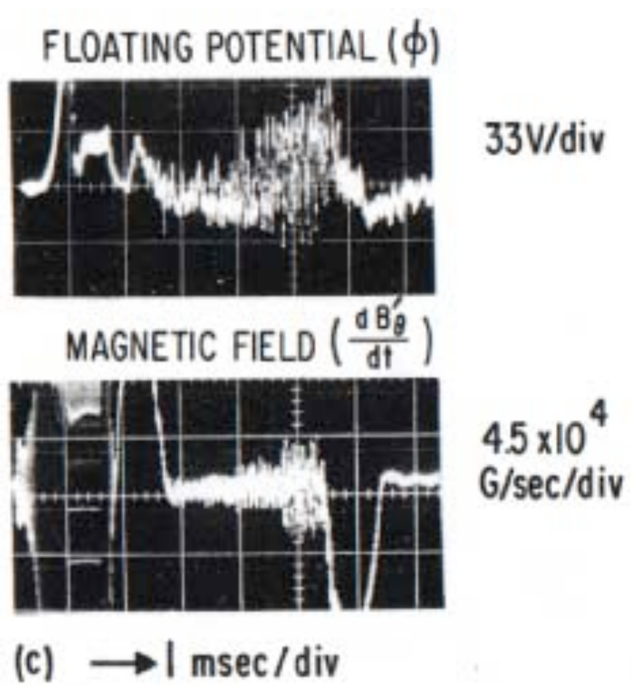
- In 1954, Spitzer commissioned a study of a stellarator reactor - **Model D**
- Figure 8 device with water-cooled copper coils and a divertor chamber in each U-bend

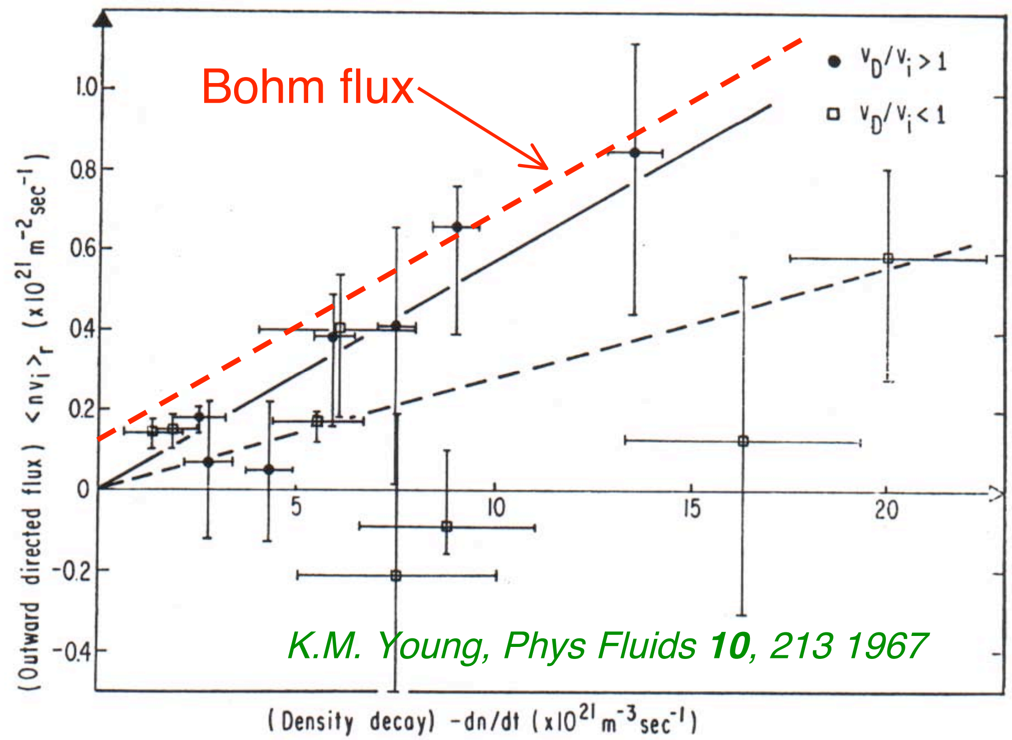


- Parameters of **Model D** D-T reactor:
  - confinement assumed to be classical
  - T~10 keV, n ≈ 10^{21} m^{-3},
  - β = 0.24, B = 7.5 T, a_p = 0.45 m, R_0 = 24m
  - P_{fusion} = 17 GW (90 MWm^{-3}), P_n = 6 MWm^{-2}, P_{elec} = 4.7 GW

The Early 1960s - The Depths of Despair

- Stellarator experiments in the late ’50s were plagued with instabilities
  - Confinement limited by fluctuations causing “pump out”, “Bohm diffusion” or “anomalous diffusion”
- Model C was large to reduce complications of impurities (divertor) and wall neutrals (a = 5 cm), *but*
  - Experiments 1961-66 confirmed Bohm diffusion

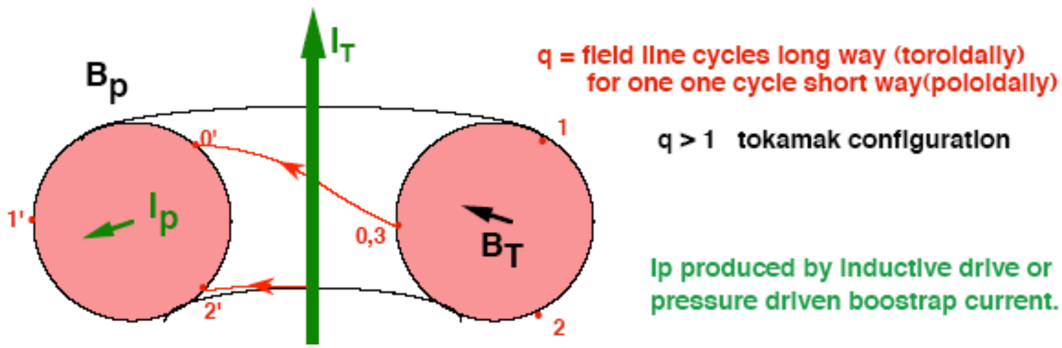


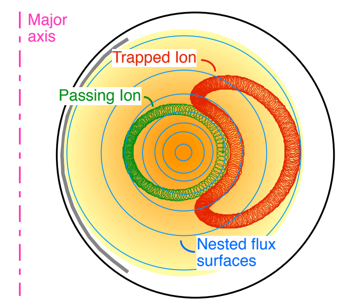


K.M. Young, Phys Fluids **10**, 213 1967

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 drift outward from one surface to the next
  - This *neoclassical* (Pfirsch-Schlüter) diffusion adds to classical diffusion
- Variation of the toroidal field from outside to inside *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

- Tamm (1951) and Sakharov (1952)
  - Objective: producing nuclear material for weapons
- Parameters of a D-D reactor producing T or ^{233}U
  - collisional (classical) heat loss only
  - $T = 100$ keV, $n = 10^{20} m^{-3}$
  - $Ba = 10$ Tm, water-cooled copper coils
  - $\beta = 1$, $B = 5$ T, $a_p = 2$ m, $R_0 = 12$m
  - $P_{fusion} = 880$ MW

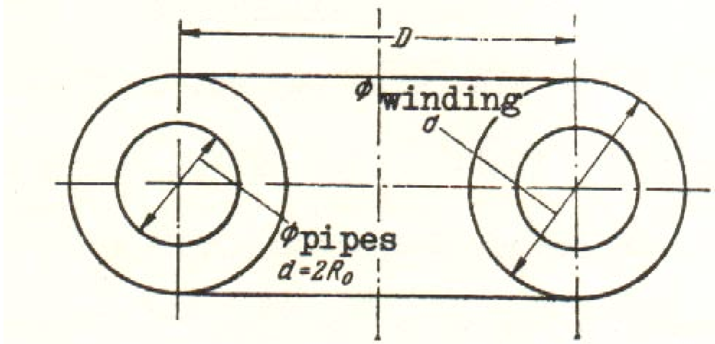


Fig. 2.

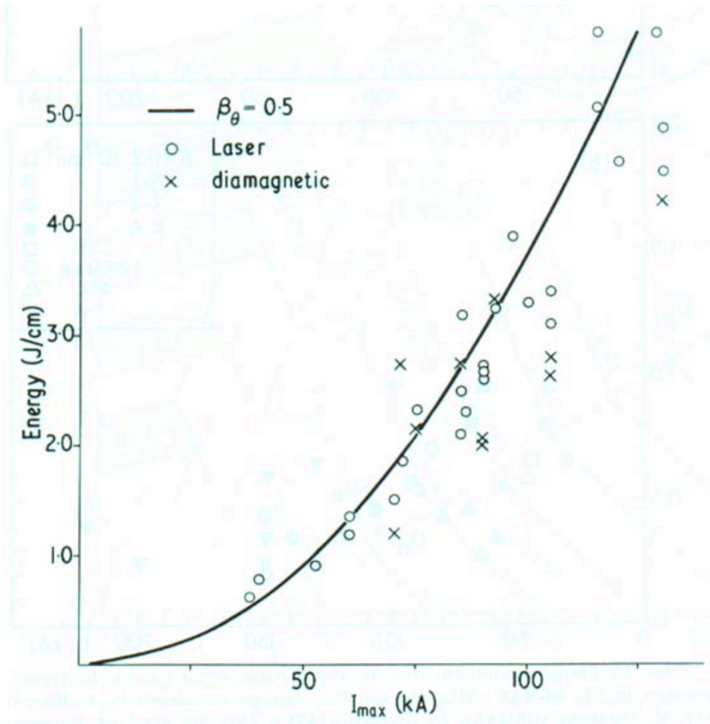
- Concept first discussed with the west at Geneva 1958 after declassification
- There was skepticism and resistance in the west
  - Concern that the plasma current was a source of instability
  - Maintaining the toroidal current - stellarators were steady-state
- A group at Australian National University 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)*

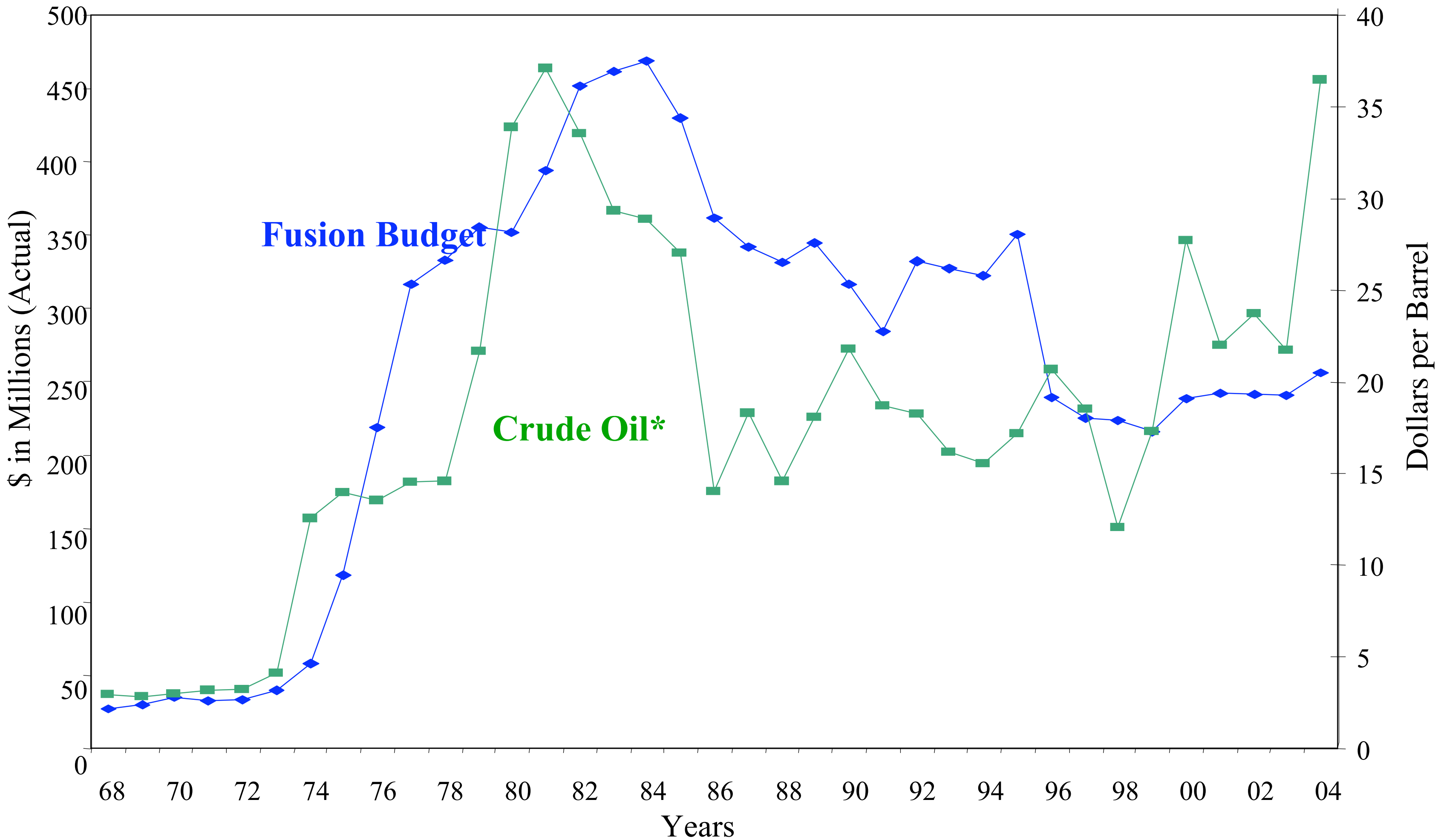
The Late 1960s - The Tokamak Emerges

- At Kurchatov Institute under L. Artsimovich, tokamaks progressed through a sequence to T-3
  - B = 4T, a = 0.20m, R = 1.0 m, I_p < 200 kA, Ohmically heated
- Measurements in T-3 presented at the 1968 IAEA Conference in Novosibirsk indicated $T_e \approx 1$ keV and $\tau_E/\tau_{Bohm} \approx 50$

- A team from UKAEA Culham (D. Robinson and N. Peacock) took a Thomson Scattering system to T-3
- Confirmatory results were obtained and presented at Dubna 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)



1973 Oil Embargo - Energy R&D Explodes



*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.

The Beginning of the TFTR Era at PPPL

July 1973 DOE proposes superconducting D-T ignition device at ORNL: FIBX
– Parameters were not yet well defined

Dec 1973 PPPL counter proposal for Two-Component Torus (H. Furth)
"If all you want is neutrons" – intense neutral beam heating, simple

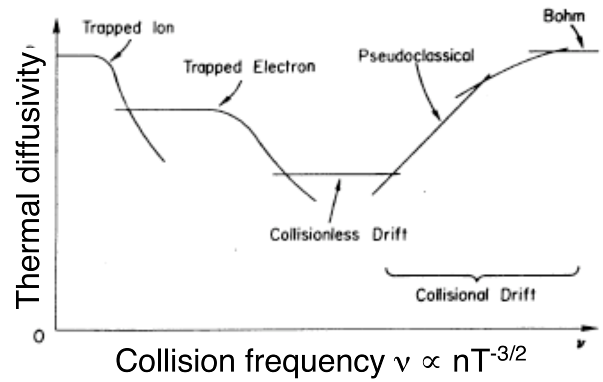
July 1974 DOE selects PPPL design – goal: significant D-T fusion power

Dec 1975 PLT starts operation – similar design with NB heating, but smaller

Mar 1976 TFTR construction starts

Aug 1978 PLT T_i = 5.5 keV
– Trapped Ion Mode vanquished!

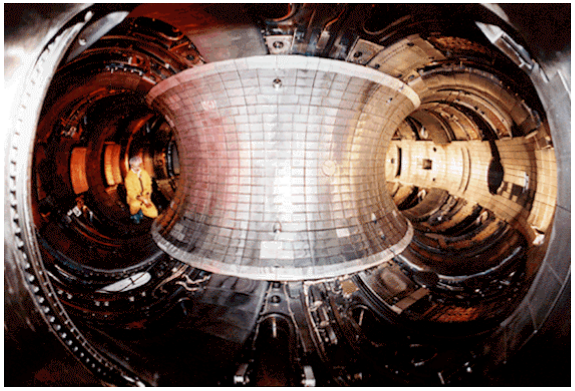
Dec 1982 First TFTR plasma – ~50 kA



Status of Tokamak Physics at the Start of TFTR

- Reliable operation at current <1MA with pulse lengths up to 1s
- Neutral beam injection (NBI) heating up to ~8MW;
  RF heating up to ~5MW (ion cyclotron, electron cyclotron, lower hybrid);
  Compressional heating (transient)
- High ion temperatures, ~ 7keV, with NBI in PLT
- Global scalings for energy confinement:
  - "Alcator" scaling for ohmic heating ($\propto$ density): τ_E up to 50ms
  - "L-mode" scaling for NB heating (**$\tau_E \propto I_p P_h^{-1/2}$**): τ_E ~ 20ms

  $\Rightarrow$ poor predictions for DT performance of TFTR
- H-mode just discovered (ASDEX, Germany) in NB-heated divertor plasmas with improved confinement times (~2 × L-mode)
  - TFTR did not have a divertor but its competitors the Joint European Torus and JT-60 (Japan) did



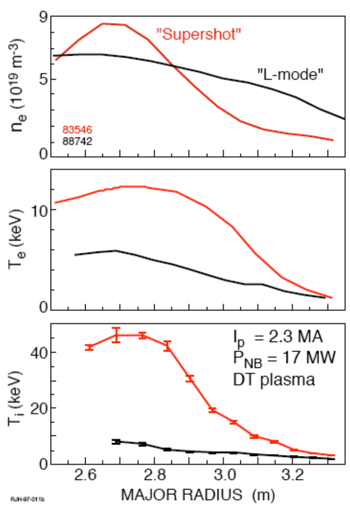
TFTR, in Competition with JET, JT-60U, Propelled Fusion Research Forward for Over a Decade

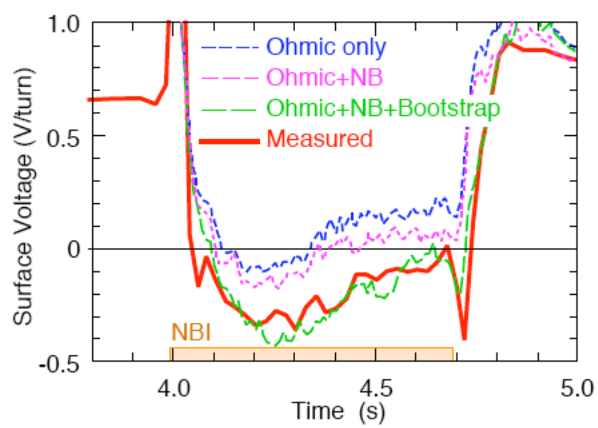
Feb 1986 Record $n\tau$ using pellet injection – still stands

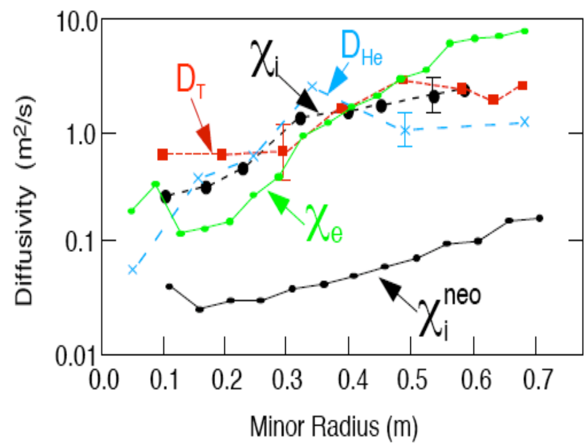
June 1986 "Super shots" emerge with NBI – record T_i (eventually to 40keV), P_{DD}
- Confinement 2 – 3 x L-mode prediction, little power degradation
- Control of plasma interaction with surrounding wall was key

~1988 Confirmation of the neoclassical "bootstrap" current in supershots
- important for possibility of a steady-state tokamak

~1990 Evidence that Ion Temperature Gradient (ITG) modes determine transport
$k_r\rho_i \ll 1$, $\delta T_i/T_i \approx 3\text{-}4\ \delta n/n$, $T_i(0) \propto T_i(a)$ – marginal stability



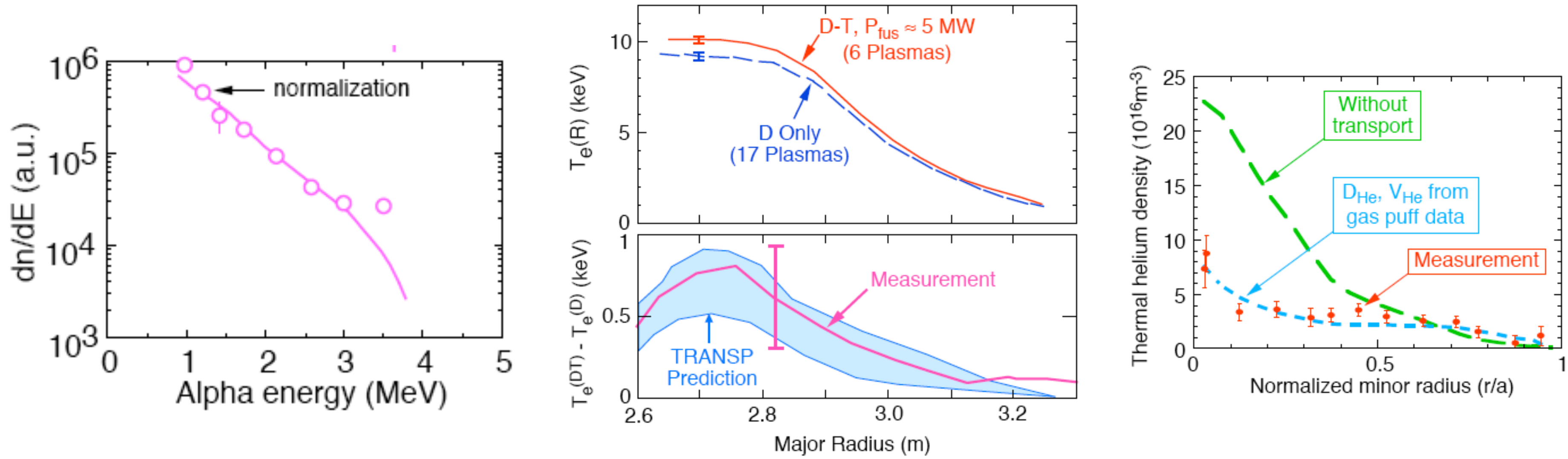




First D-T Experiments Yielded a Wealth of Physics

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

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



1995 Discovery (simultaneous with DIII-D) of benefits of reversed magnetic shear – Basis for "advanced tokamak" designs: better confinement

1996 Confirmation of role of sheared plasma flow in suppressing ITG turbulence

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

Since TFTR, Magnetic Confinement Research Has Pursued Two Tracks

- **ITER:** build a device to produce and study ignited ($Q \geq 10$) DT plasmas
  - Originally International Thermonuclear Experimental Reactor, now **"The Way"**
    - 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
    - Delayed by competition between EU and Japan for host site
  - To be built in Cadarache, France: cost estimated at 10B Euro
  - First plasma operation in 2016, D-T operation in 2021
- **Innovation:** use existing devices or new confinement concepts to improve the prospects for magnetic fusion
  - New devices include advanced stellarators at PPPL and IPP Greifswald, DE
    - Benefit from advances in computation and simulation
  - Research may also benefit ITER by improving its design margins, relaxing its requirements and broadening its operating regime

TFTR Achieved Many of the 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*

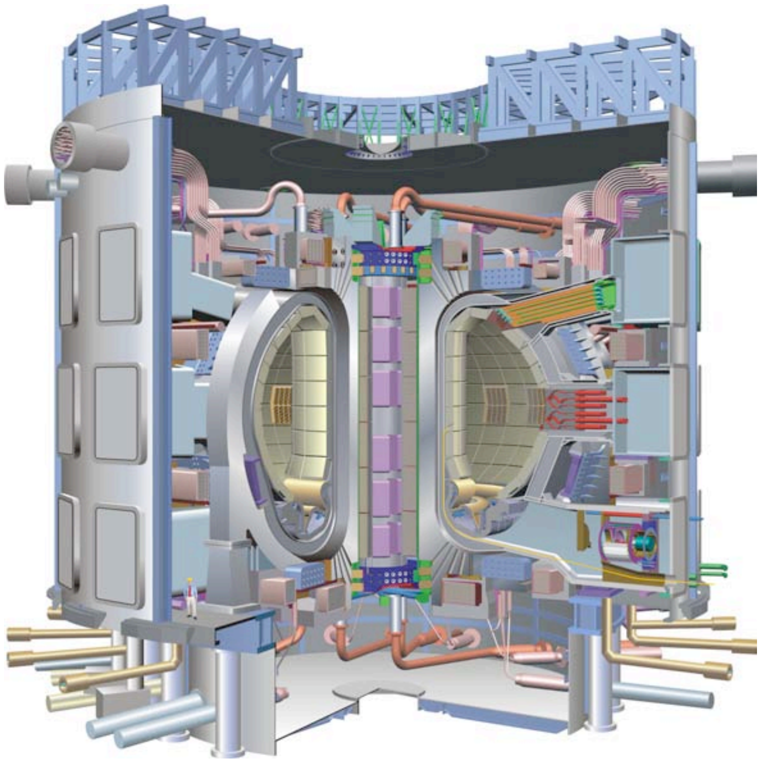
	TFTR	ITER
Normalized gyro-radius ρ_i/a (10^{-3})	6.5	2

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

ITER 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 >10**

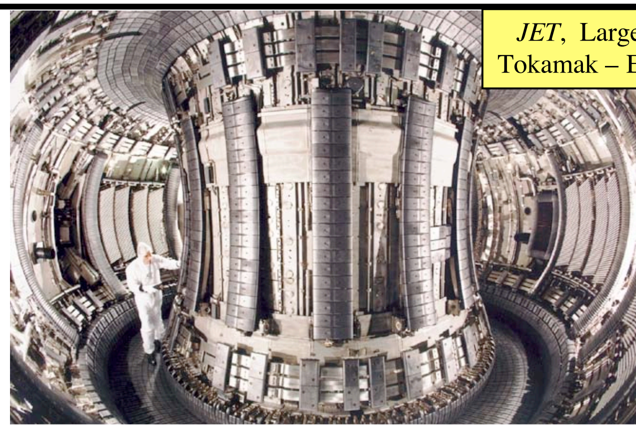
  but ...
- ITER is not a self-sufficient power-producing plant
- New science and technology are needed for a demonstration power plant
  - 2500 MW(th) with gain >25, in a device with similar size and field
  - Higher power density
  - Efficient continuous operation
  - Tritium self-sufficiency
- Research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



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

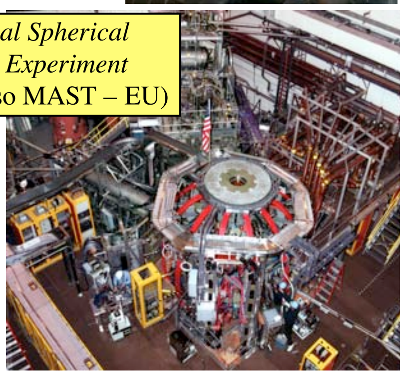
C-Mod, Tokamak MIT

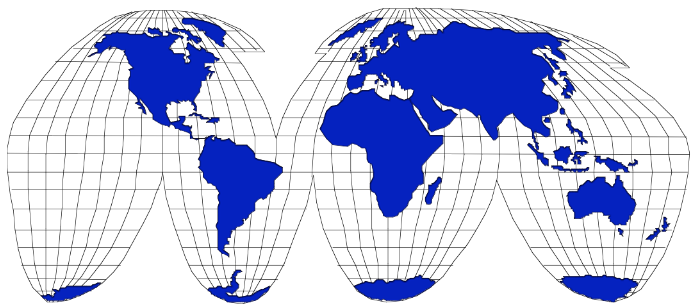
JET, Large Tokamak – EU



W7-X, Large Superconducting Stellarator – EU

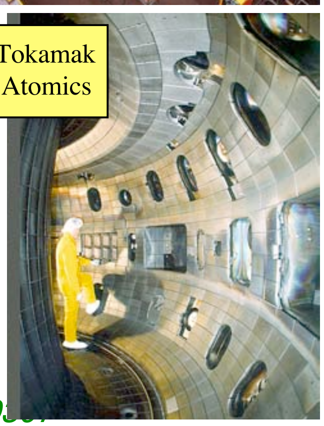
National Spherical Torus Experiment PPPL (also MAST – EU)





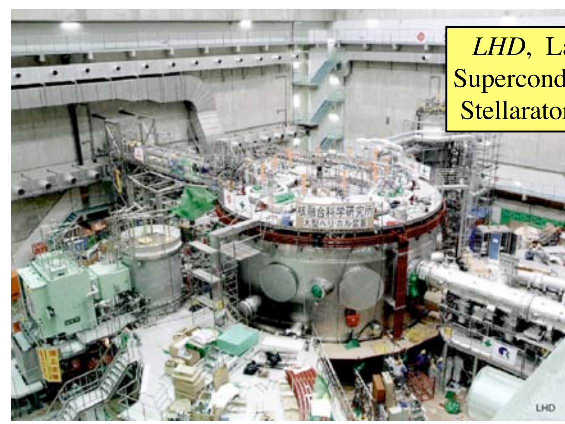
EAST, SST-1, *KSTAR* Superconducting Tokamaks, – China, India, Korea

DIII-D, Tokamak General Atomics



JT-60U, Large Tokamak– JA

LHD, Large Superconducting Stellarator – JA



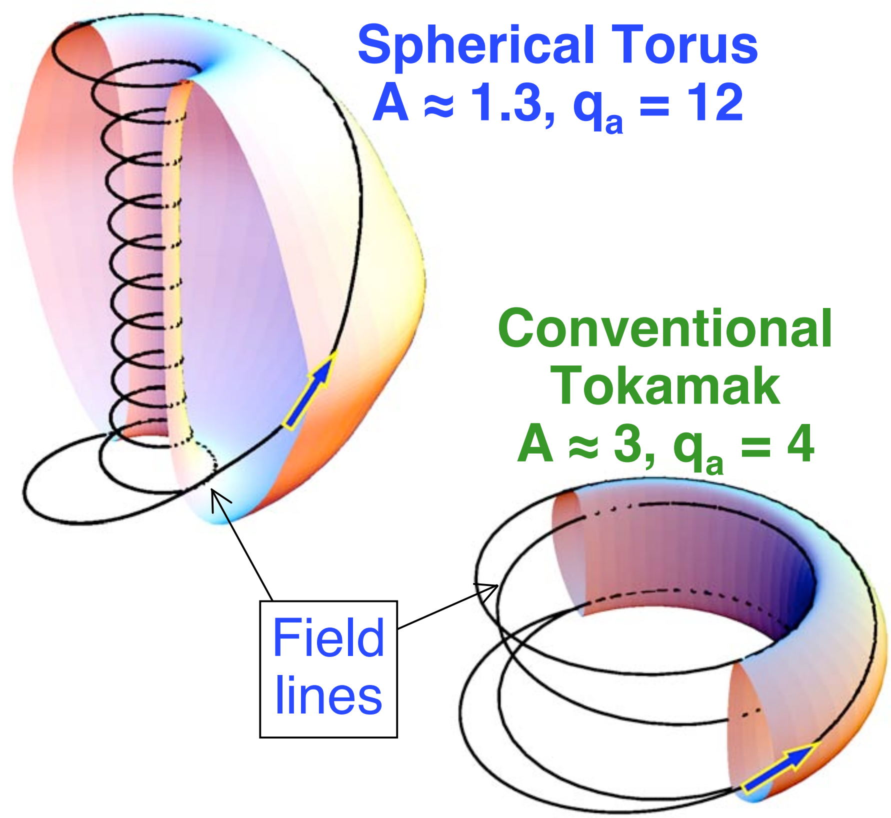
"Spherical Torus" Extends Tokamak to Extreme Toroidicity

- Motivated by potential for increased β *[Peng & Strickler, 1980s]*

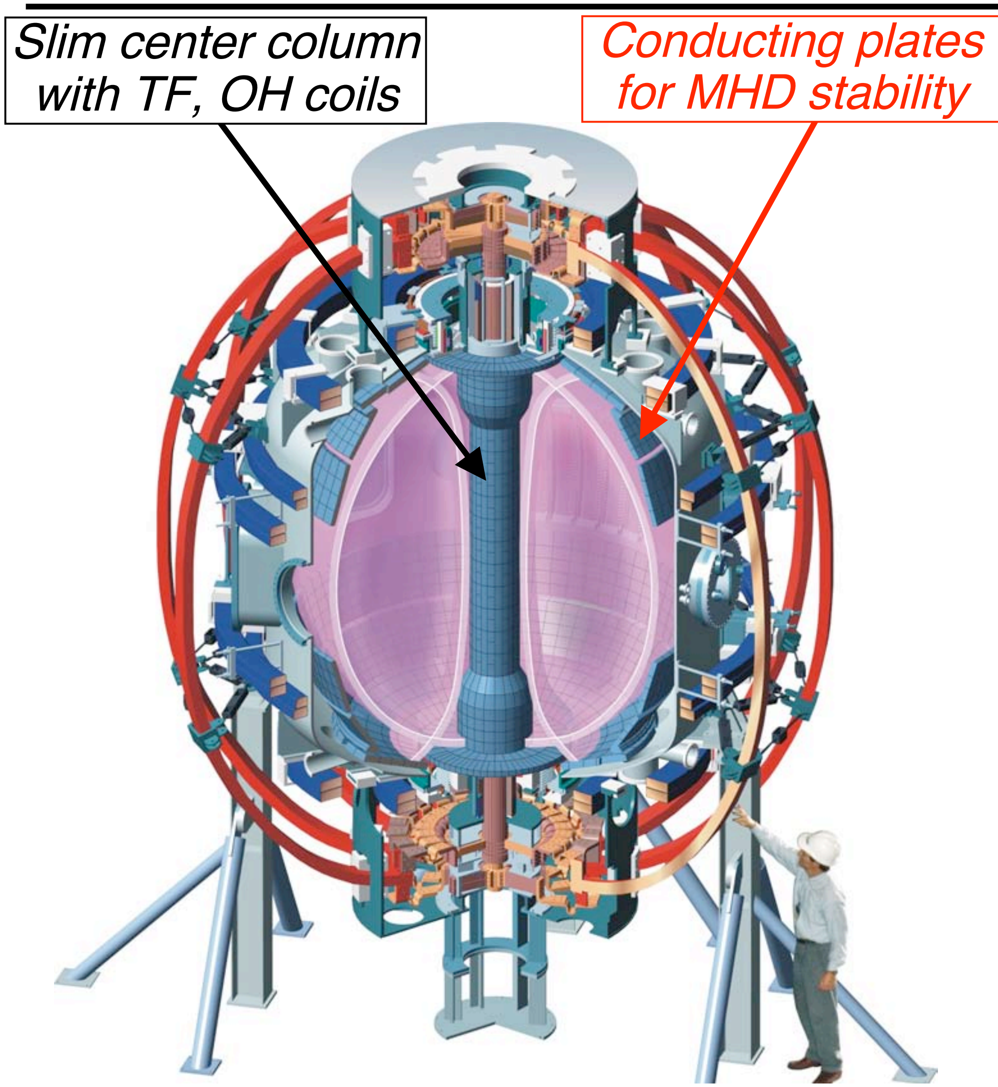
$$\beta_{max}\ (= 2\mu_0\langle p\rangle/B_T^2)\ =\ C\cdot I_p/aB_T\ \propto\ C\cdot\kappa/\mathbf{A}q$$

B_T: toroidal magnetic field on axis;
$\langle p\rangle$: average plasma pressure;
I_p: plasma current;
a: minor radius;
κ: elongation of cross-section;
A: aspect ratio (= R/a);
q: MHD "safety factor" (> 2)
C: Constant ~3%·m·T/MA
[Troyon, Sykes - early 1980s]

- Confirmed by experiments
  - **β_{max} ≈ 40%**
    [START (UK) 1990s]

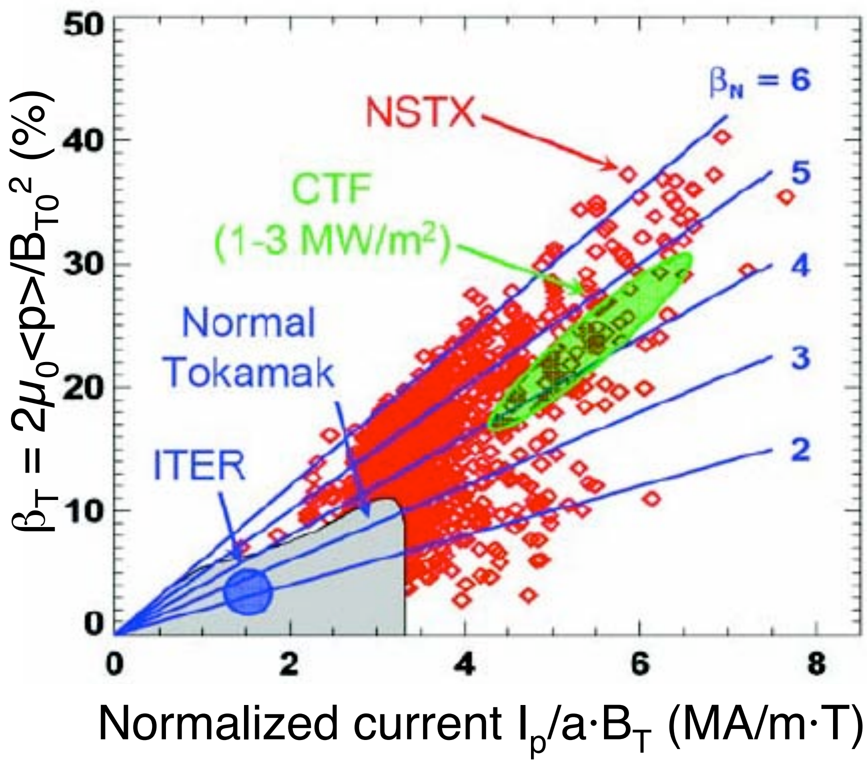


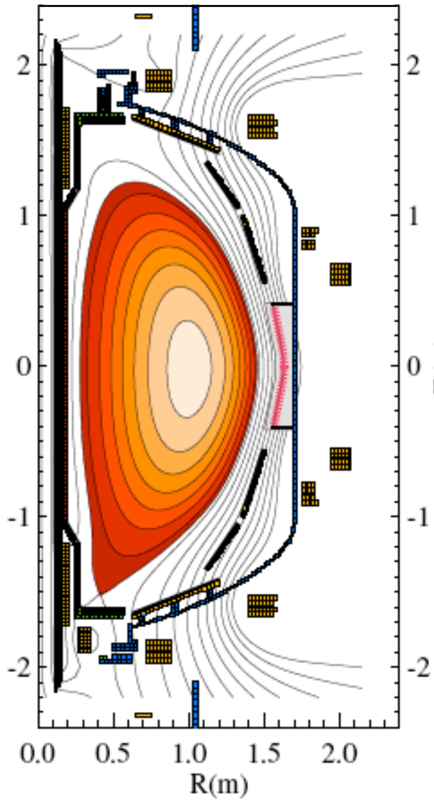
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



Aspect ratio A	1.27
Elongation κ	2.5 (3.0)
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6 (0.55) T
Pulse Length	1.5s
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 3 keV

NSTX Extends the Stability Database Significantly





- $A = 1.5$
- $\kappa = 2.3$
- $\delta_{av} = 0.6$
- $q_{95} = 4.0$
- $l_i = 0.6$
- $\beta_N = 5.9\%\cdot$m·T/MA
- $\beta_T =$ 40% (EFIT)
  34% (TRANSP)

- Seeing benefits of
  - Low aspect ratio
  - Cross-section shaping
  - Stabilization of external modes by conducting plates

NSTX Approaches Normalized Performance Needed for a Spherical Torus - Component Test Facility (ST-CTF)

Design optimization for a moderate Q driven ST-CTF:

- Minimize B_T required for desired wall loading ⇒ Maximize $\langle p \rangle / B_T^2 = \beta_T$
- Minimize inductive current ⇒ Maximize $f_{bs} \propto \varepsilon^{0.5}\beta_P$
- Do this simultaneously ⇒ Maximize $f_{bs}\beta_T \propto \varepsilon^{0.5}\beta_P\beta_T$

Goal of a driven ST-CTF:

DT neutron flux = 1 – 4 MW/m²

Achievable with:

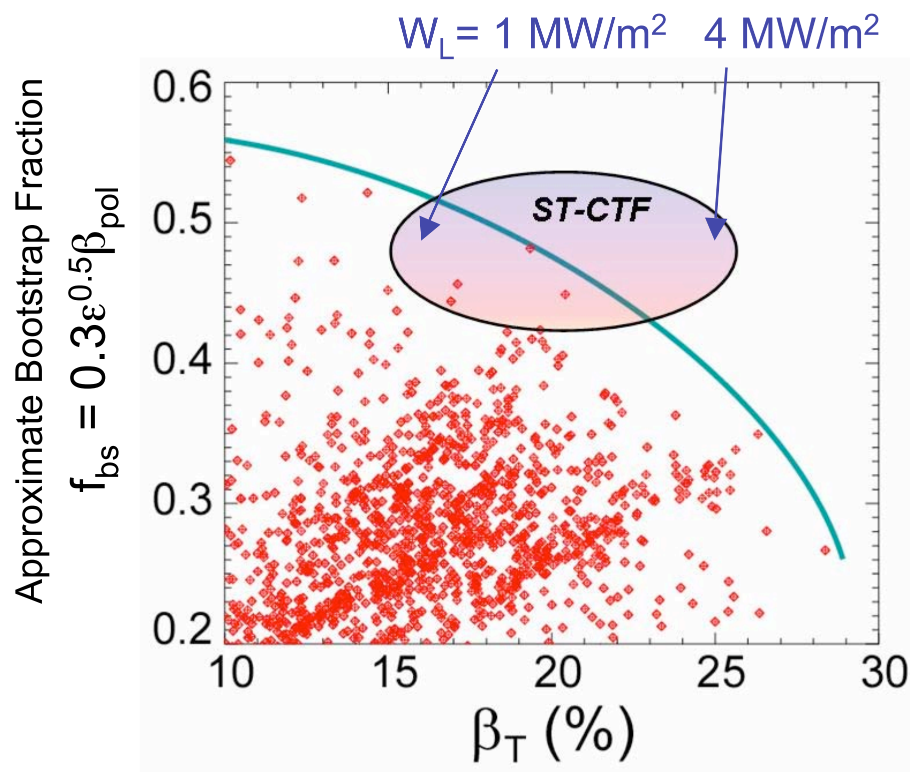
$A = 1.5$, $\kappa = 3$,

$R_0 = 1.2$m, $I_P = 8 – 12$MA

$\beta_N \sim 5$ %.m.T/MA, $H_{98y,2} = 1.3$

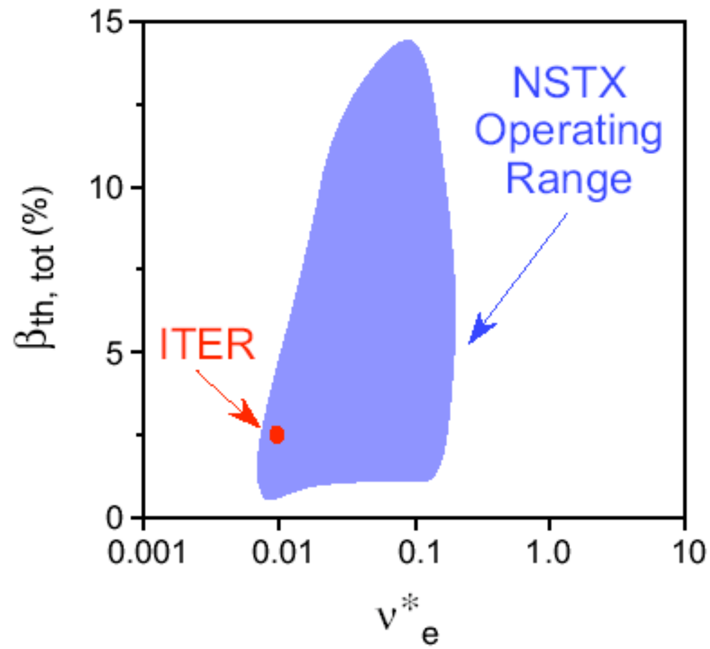
$\beta_T = 15 – 25\%$

$f_{BS} = 45 – 50\%$



NSTX Provides a Novel Vantage Point from which to View Plasma Transport and Turbulence

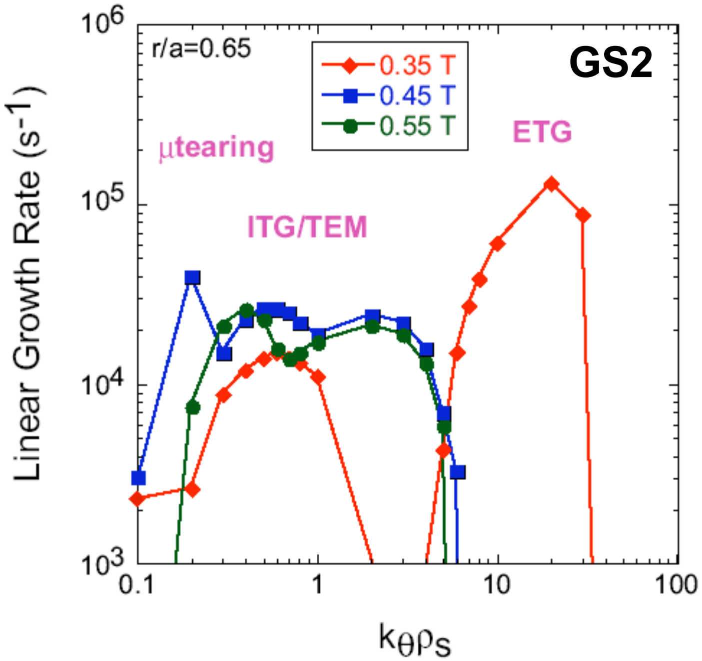
- Operates in a unique region of dimensionless parameter space: R/a, β_T, (ρ^*, ν^*)
  - Large range of β_T spanning electrostatic to electromagnetic turbulence regimes
- Routine operation in "H-mode" confinement regime
- Dominant electron heating with NBI
  - Relevant to α-heating in ITER
- Strong rotational shear driven by NBI affects transport
  - Ion transport approaches neoclassical
  - Electron transport anomalous
- Localized electron-scale turbulence measurable (ρ_e ~ 0.1 mm)



Calculations Suggest Electron Temperature Gradient Mode Dominates Electron Transport at Low B_T

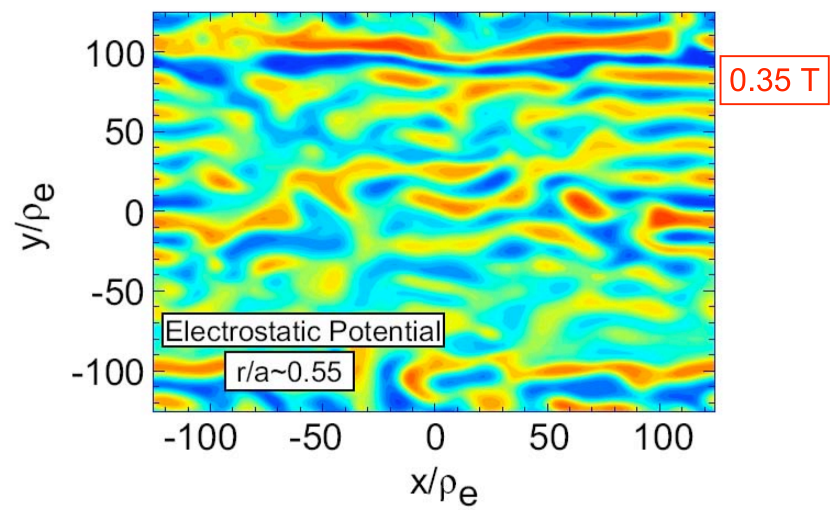
GS2 calculations show ETG linearly unstable at lowest B_T

- 0.35T: R/L_{Te} 20% *above* $\nabla T_{e,crit}$
- ≥0.45T: R/L_{Te} 20-30% *below* $\nabla T_{e,crit}$



Non-linear simulations (up to 250ρ_e) show formation of radial streamers

- FLR-modified fluid code [W. Horton *et al.*, PoP **11** (2004)]

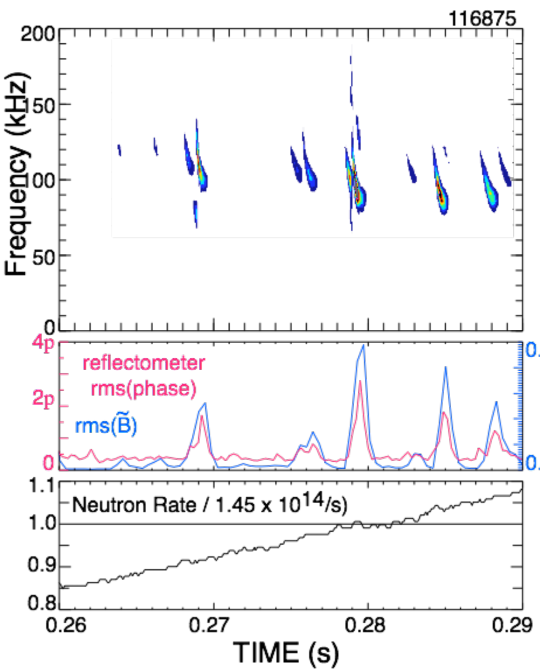


- Good agreement between experimental and theoretical saturated transport level at low magnetic field in NSTX

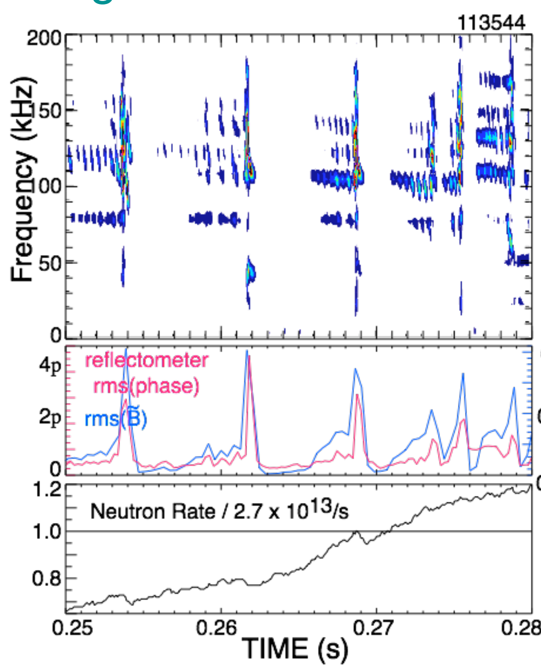
NSTX Accesses Fast-Ion Phase-Space Regime Overlapping With and Extending Beyond ITER

- **ITER** will operate in new regime for fast ion transport
  - Fast ion transport expected from **interaction of many modes**
  - NSTX can access multi-mode regime via high $\beta_{fast} / \beta_{total}$ and v_{fast} / v_{Alfven}

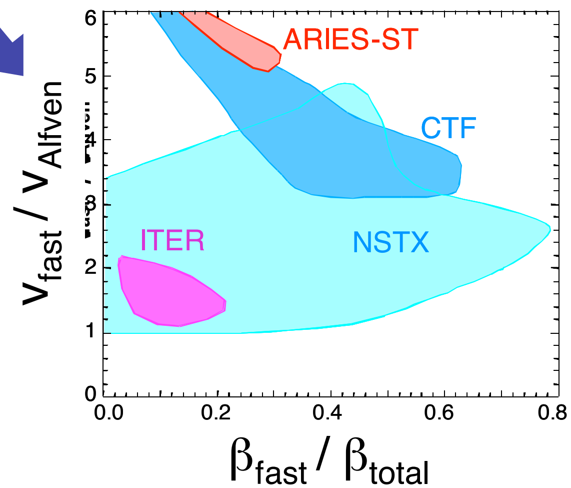
Multi-mode TAE bursts in NSTX induce larger fast-ion losses than single-mode bursts

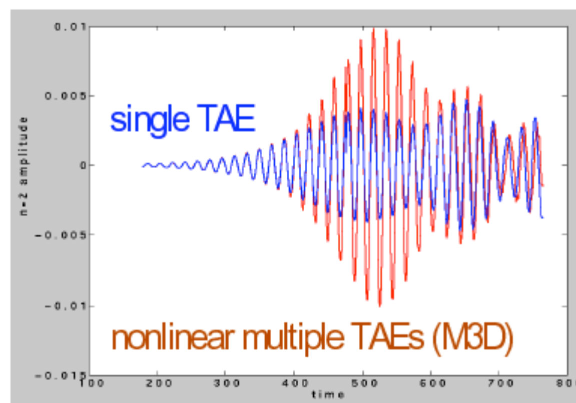


1% neutron rate decrease



5% neutron rate decrease





E. Fredrickson, Phys. Plasmas **13**, 056109 (2006)

NSTX Is Making Good Progress Toward the ST-CTF While Contributing to the Physics Basis of ITER

- Ability of the ST to achieve high β now well established
- Advanced mode stabilization methods and diagnostics are being applied to improve performance
  - Dynamic Error Field Correction and RWM feedback suppression
- Unique tools available to study transport and turbulence
  - Excellent laboratory in which to study core electron transport
- Investigating fast-ion instabilities
  - Capability to mimic ITER situation
- Developing non-inductive startup and sustainment schemes
  - CHI, also current drive by RF plasma waves
- Developing methods for heat flux and particle control
  - Lithium coating of plasma-facing components, radiative divertors

Magnetic Confinement Fusion Research is Indeed at a Crossroads

- We must demonstrate that ignited DT plasmas can be produced and controlled in ITER
  - After almost 60 years, 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 some aspects of its design
- At the same time, we must look beyond ITER to a fusion power plant
  - Electricity from a tokamak based on the ITER design would be not 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 research efforts will determine whether fusion energy can succeed in meeting its potential*