INTRODUCTION TO MAGNETIC NUCLEAR FUSION

S.E. Sharapov

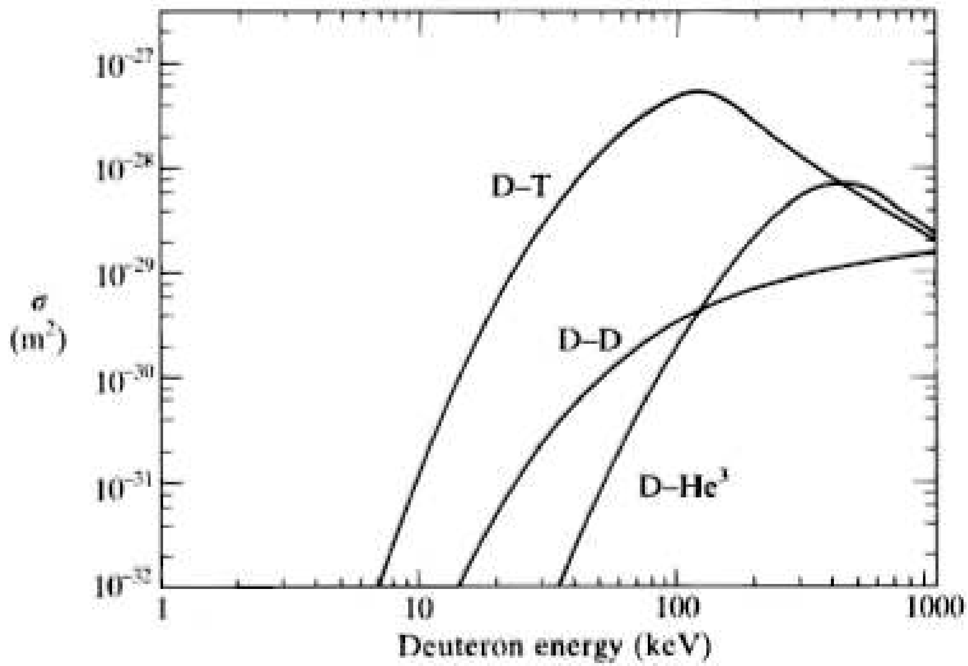
Euratom/CCFE Fusion Association,
Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

With acknowledgments to
B.Alper for use of his transparencies

OUTLINE OF LECTURE 1

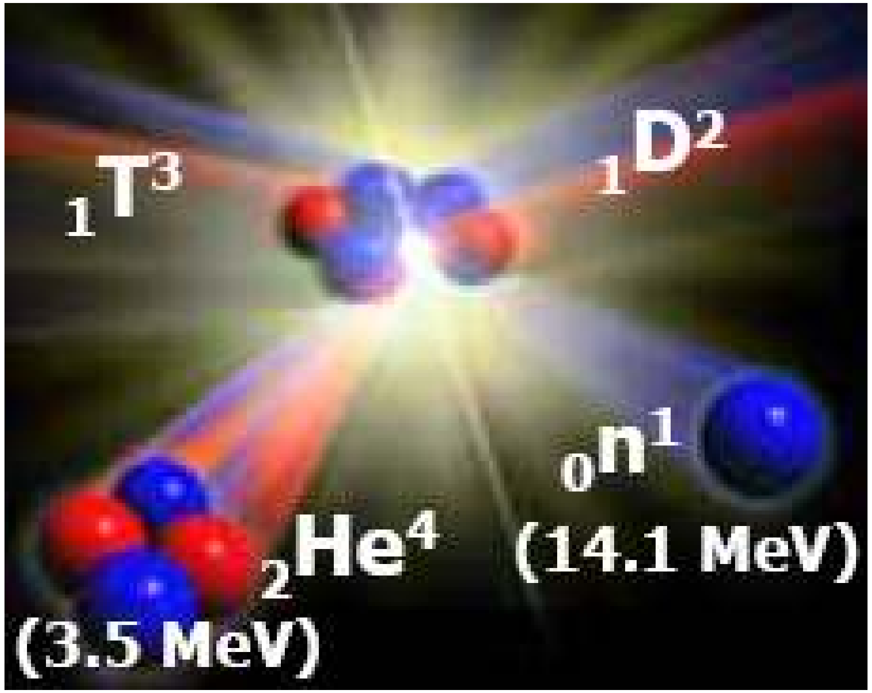
- **Nuclear fusion**
- **Magnetic confinement of plasma**
- **Tokamaks**
- **Three main avenues of achieving burning/ignited plasmas in magnetic fusion**
- **Stellarators**
- **Summary**

NUCLEAR FUSION



- Nuclear Fusion powering the stars and the Sun is (surprisingly!) possible on Earth
- This is thanks to large cross-section (a measure of the ability to fuse) of D-T reaction
- The aim of the fusion research is to use the fusion for power generation on Earth

NUCLEAR FUSION OF HYDROGEN ISOTOPES D&T



- **Nuclear fusion reaction D+T = He + n +17.6 MeV of hydrogen isotopes deuterium (D) and tritium (T) is the "easiest" to access.**

ENVIRONMENTAL ADVANTAGES OF D-T FUSION

- Deuterium is naturally abundant (0.015% of all water), Tritium must be obtained from lithium, $^{6}Li + n = T + {}^{4}He$. Raw materials are water & lithium.

- To generate 1GW for 1 year (equivalent to a large industrial city):

  COAL: 2.5 Mtonnes – produces 6 Mtonnes CO_2;
  FISSION: 150 tonnes U – produces several tonnes of fission waste;
  FUSION: 1 tonne Li + 5 Mlitres water.

- Fusion gives no “greenhouse” gasses.

- Fusion reactor structure will become activated but will decay to a safe level in < 100 years. Tritium is radioactive: half life is 13 years.

- No plutonium or long-lived (thousands of years) active waste from fuel cycle.

PLASMA

- How to make the nuclear forces work? Nuclei of D and T must approach each other to a "nuclear" distance ~10^{-12} cm, but they need to overcome the Coulomb electrostatic force between two positive nuclei!

- The solution: provide the colliding nuclei with kinetic energy larger than the Coulomb potential energy, i.e. the fuel must be hot enough. Optimum fusion rate for D-T achieved at $T_D \approx T_T \approx 20$ keV (200 Mdeg)

- At that temperature, the hot DT fuel is a plasma – a mixture of positively charged nuclei ("ions") and negatively charged electrons

PLASMA IS THE FOURTH STATE OF MATTER

— *Increasing Temperature* ⟶

Solid	⟶	Liquid	⟶	Gas	⟶	Plasma
	Melts		*Vaporises*		*Ionises*	

- **As temperature increases, the confinement problem becomes more and more difficult**
- **Plasmas conduct electricity and can be controlled by magnetic fields**

THERE ARE THREE CONDITIONS FOR NUCLEAR FUSION

- Fuel must be hot enough, $T_i \approx 20$ keV (200 Mdeg), to overcome Coulomb force between D and T;

- Hot plasma must be insulated from walls
  Energy confinement time τ_E = Plasma energy/ Heat loss is high enough

  Plasma with energy $W = n\,T\,V$ (V is the volume of plasma) cools down as

$$dW/dt = - W/\tau_E$$

in the absence of any heating sources

- Fuel density n_D and n_T must be high enough that fusion reactions occur at a suitable rate. Maximum density is limited by impurities and instabilities

SELF-SUSTAINING FUSION REACTION

- Fusion alpha-particles (20% of fusion energy, $P_\alpha = 0.2\, P_{FUSION}$) heat the plasma and balance heat loss, i.e. the energy balance for steady-state is

$$dW/dt = - W/\tau_E + P_\alpha = 0$$

- Neutrons (80% of energy) breed new tritium and generate steam.

- The “ignition” condition for self-sustaining fusion reaction

$$n\, T\, \tau_E > 5 \times 10^{21}\ m^{-3}\ keV\ s\ (\approx 10\ atm\ s)$$

The primary aim of nuclear fusion research is to maximise the fusion triple product

POSSIBLE METHODS OF FUSION PLASMA CONFINEMENT

Gravity (Sun and stars) – works well but dimensions are too large;

Inertial (Hydrogen bomb, lasers or beams) – works well, needs pressure 10^{12} atm for very short times 10^{-11} s.

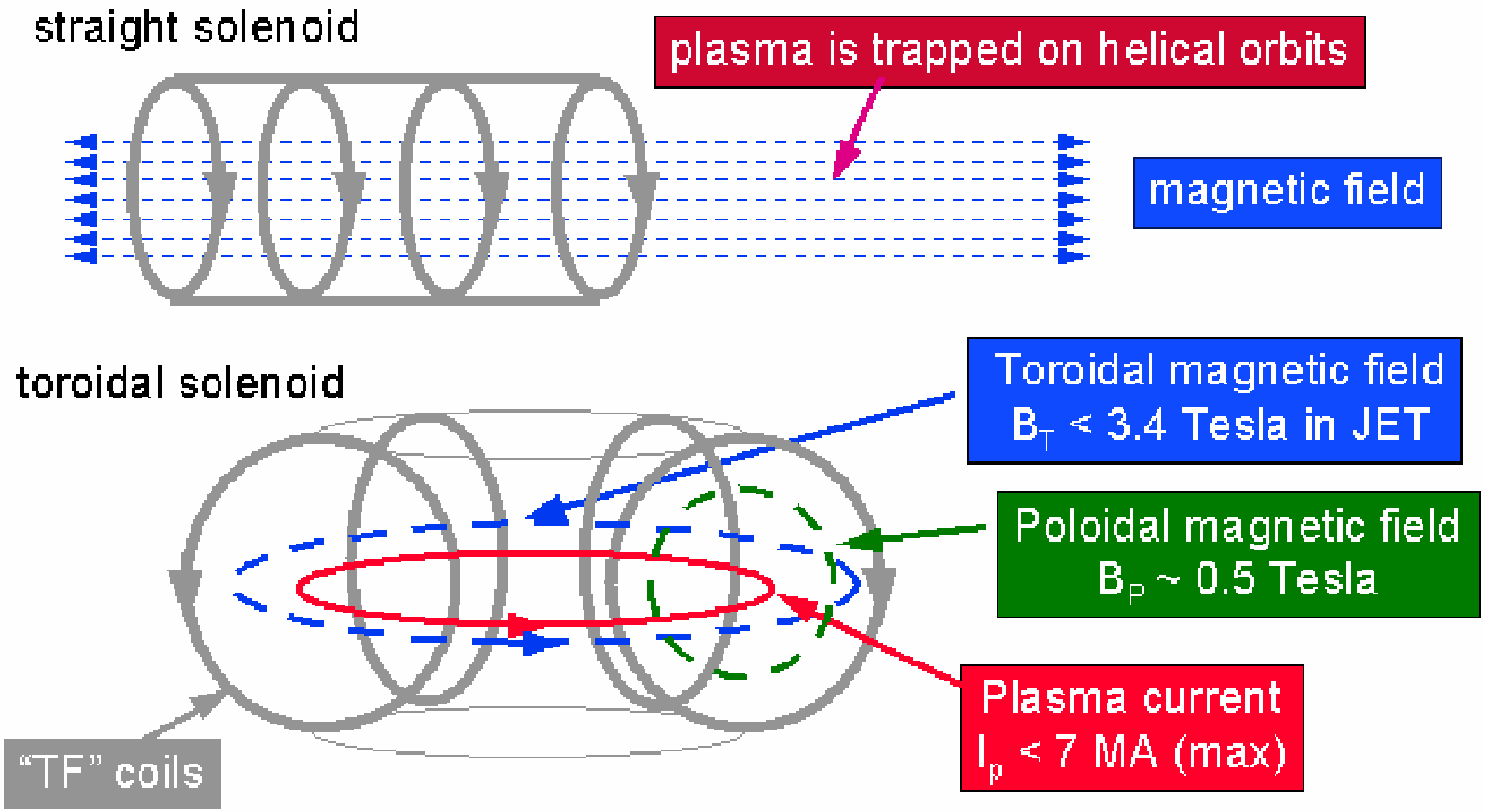
Largest H-bomb tested was 10 x [all explosive used in 2nd World War]
http://www.youtube.com/watch?v=NiyUSv2Z07A

Magnetic – few atms x few seconds, plasma is confined by magnetic field B.

THE IDEA OF MAGNETIC CONFINEMENT:

In the presence of strong magnetic field, charged particles of plasma are trapped on helical orbits attached to magnetic field lines

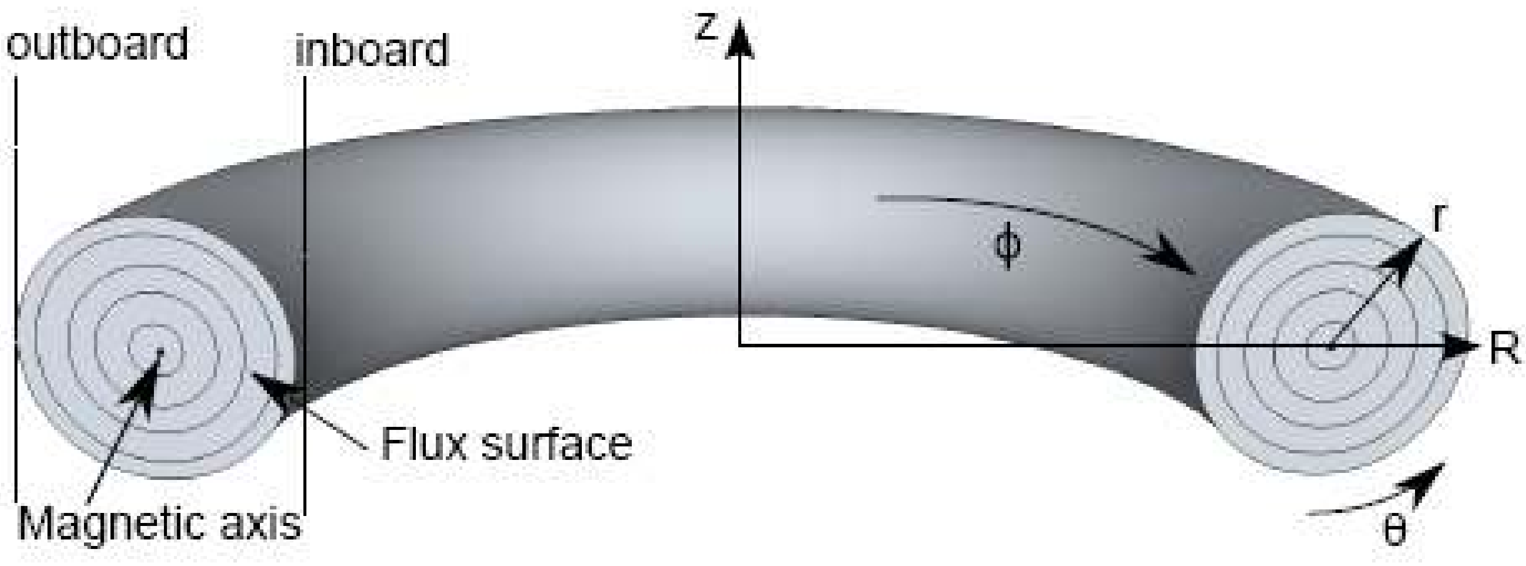
MAGNETIC CONFINEMENT OF PLASMA



TWO MAIN TOROIDAL PLASMA CONCEPTS

- **Tokamaks**
- **Stellarators**

TOKAMAKS: THE TERMINOLOGY



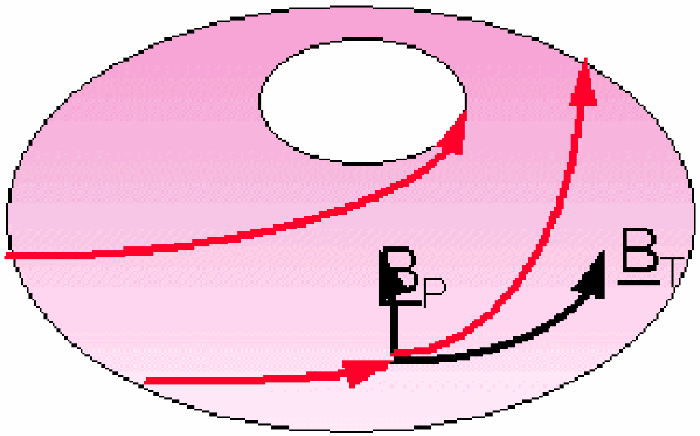
Schematic of the geometry of a tokamak.

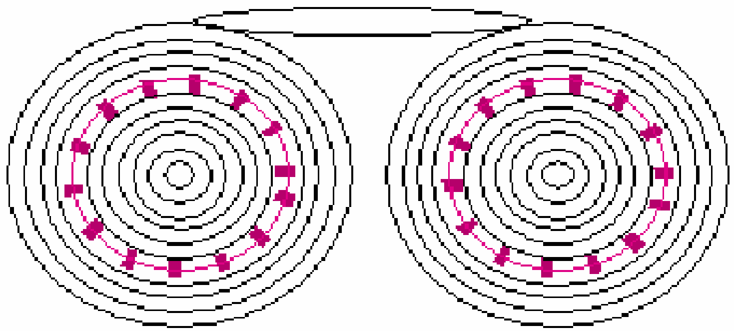
ϕ is the toroidal direction, ϑ is the poloidal direction

MAGNETIC SURFACES IN TOKAMAKS

The magnetic field line wraps helically around the Torus and maps out a magnetic surface.

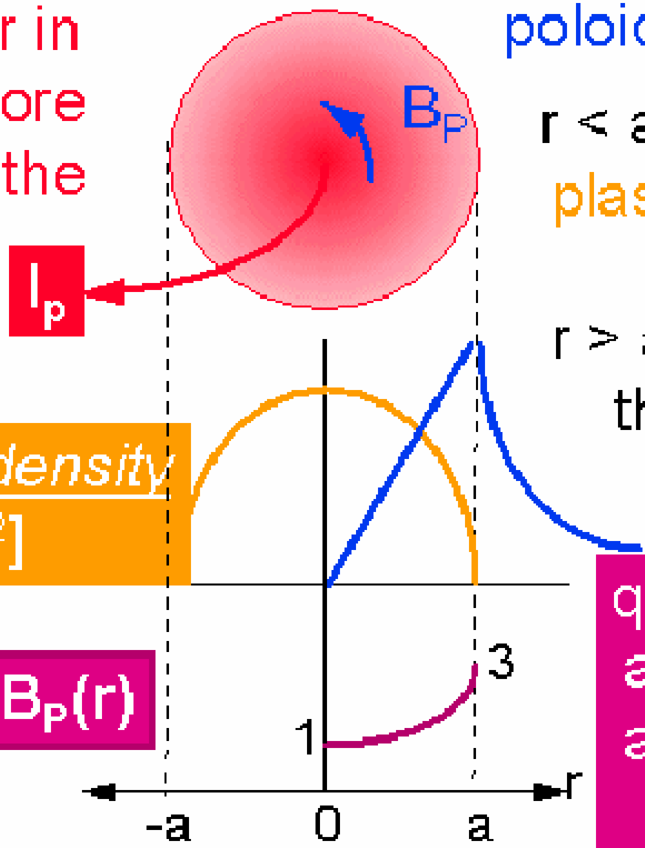
Field lines at different radii lie on different magnetic surfaces which are nested inside each other.





PLASMA CURRENT AND SAFETY FACTOR $q(r)=rB_T/R_0B_P(r)$

Plasma is hotter in the centre so more current flows in the centre than at the edge



poloidal field

$r < a$: $B_P(r)$ depends on plasma current <u>density</u>

$r > a$: $B_P(r)$ depends on the plasma current

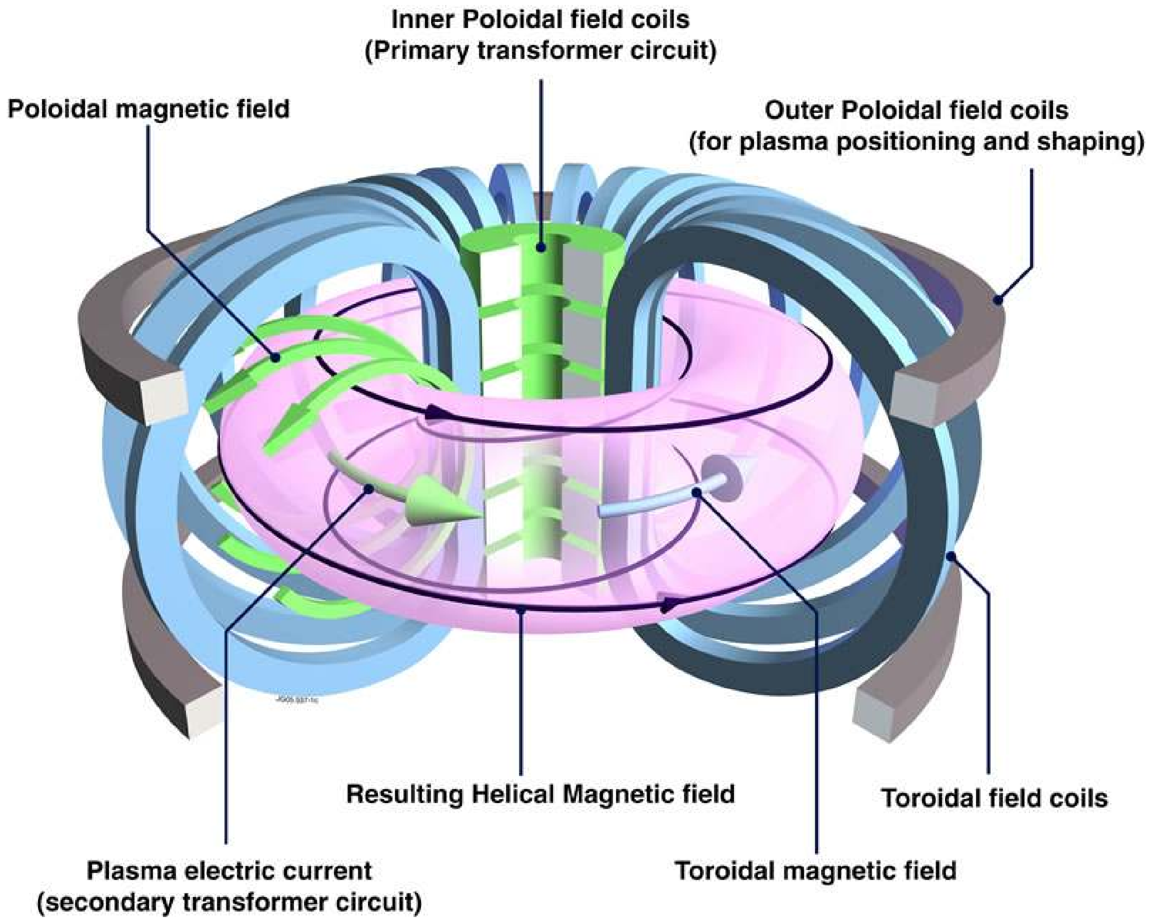
$B_P(r) \sim I_P/r$

plasma current *density*
$J_P(r)$ [A m^{-2}]

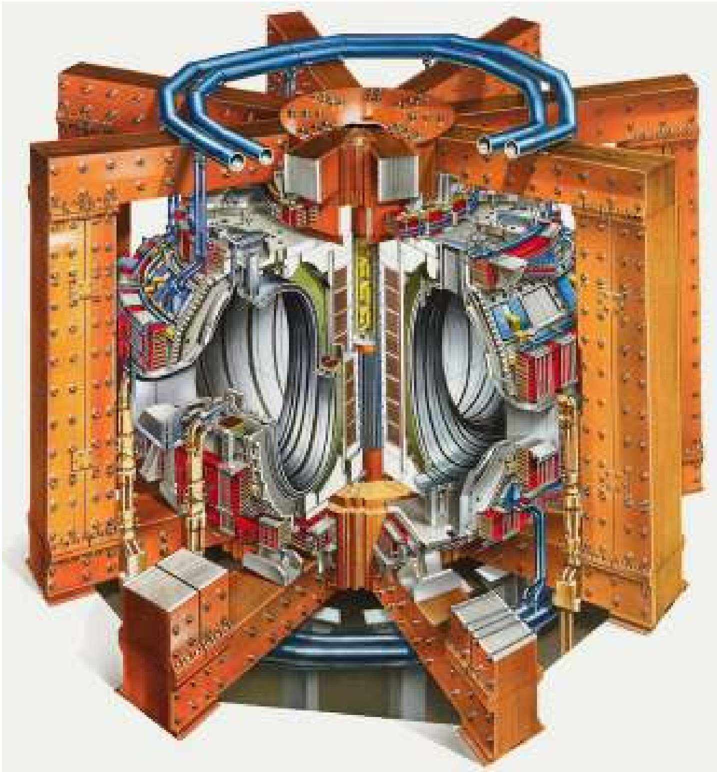
$$q(r) = r^2B_T / R_0 B_P(r)$$

q is usually close to 1 at the plasma centre and typically about 3 at the edge

THE COILS

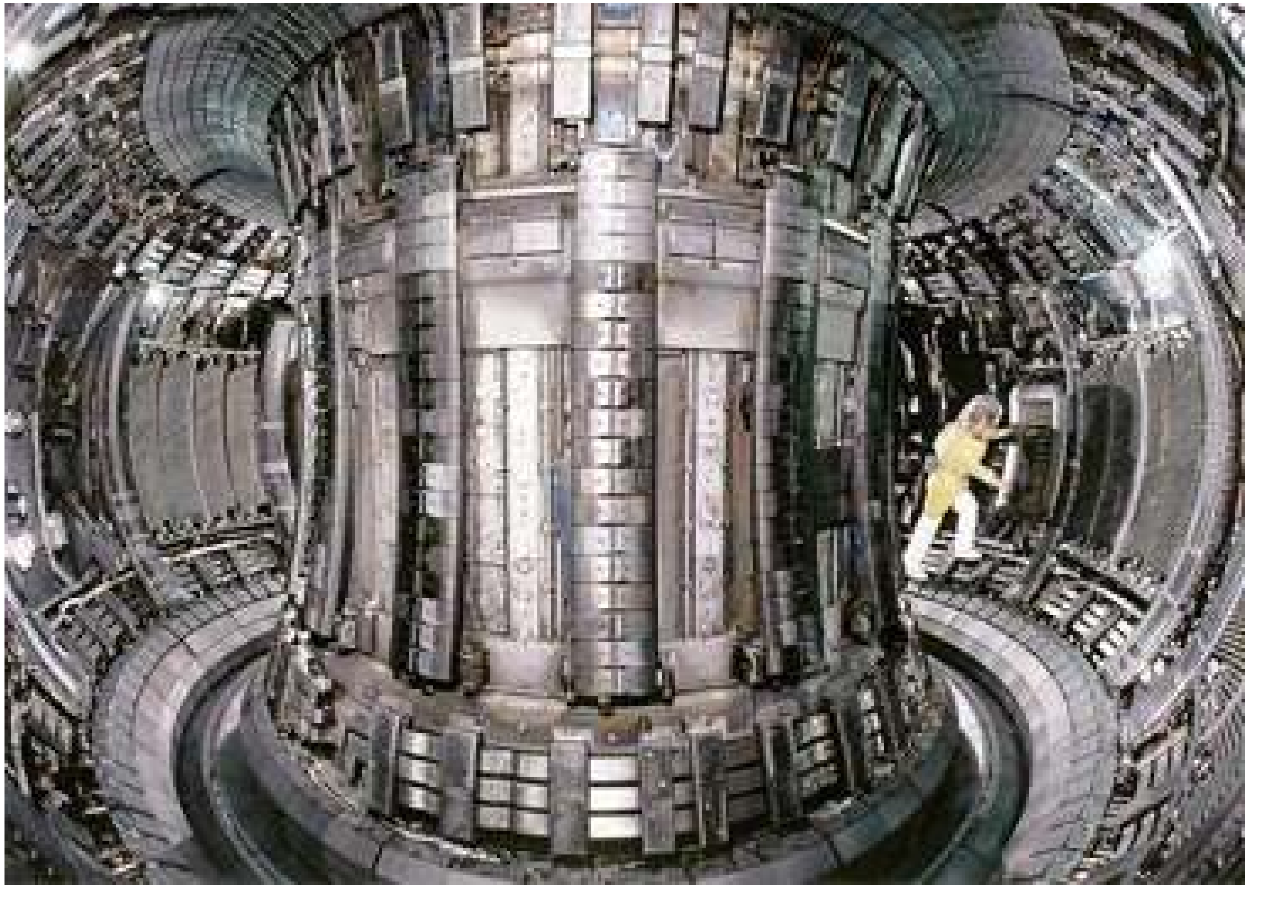

Inner Poloidal field coils
(Primary transformer circuit)
Poloidal magnetic field
Outer Poloidal field coils
(for plasma positioning and shaping)
Resulting Helical Magnetic field
Toroidal field coils
Plasma electric current
(secondary transformer circuit)
Toroidal magnetic field

TOKAMAK JET (JOINT EUROPEAN TORUS)



Volume = 100 m^3; B$_{max}$ = 4 T; I$_{max}$ = 7 MA; P$_{FUS}$ = 16 MW

TOKAMAK JET (JOINT EUROPEAN TORUS)



TOKAMAK JET (JOINT EUROPEAN TORUS)

Quantity:	$\mathcal{R}_{n,out}$ $(10^{18}\mathrm{s}^{-1})$	I_φ (MA)	B_φ (T)	P_{out} (MW)	T_e (keV)	T_i (keV)	n_e $(10^{19}\mathrm{m}^{-3})$	n_i $(10^{19}\mathrm{m}^{-3})$
Typical:	1-4	1-3	1-4	5-10	5-15	25-40	2-6	1-5
Record (D-T):	5.7	4.0	3.6	16.1	14	27	4.5	3.5
Record (D-D):	0.056	3.2	3.5	0.04	11	37	5.9	5.9

- **Table showing typical DT, record DT (JET pulse # 42976), and record DD (JET pulse # 40554) neutron rates $R_{n,\ out}$, together with the corresponding machine and plasma parameters**

SUMMARY OF PROGRESS ON TOKAMAKS

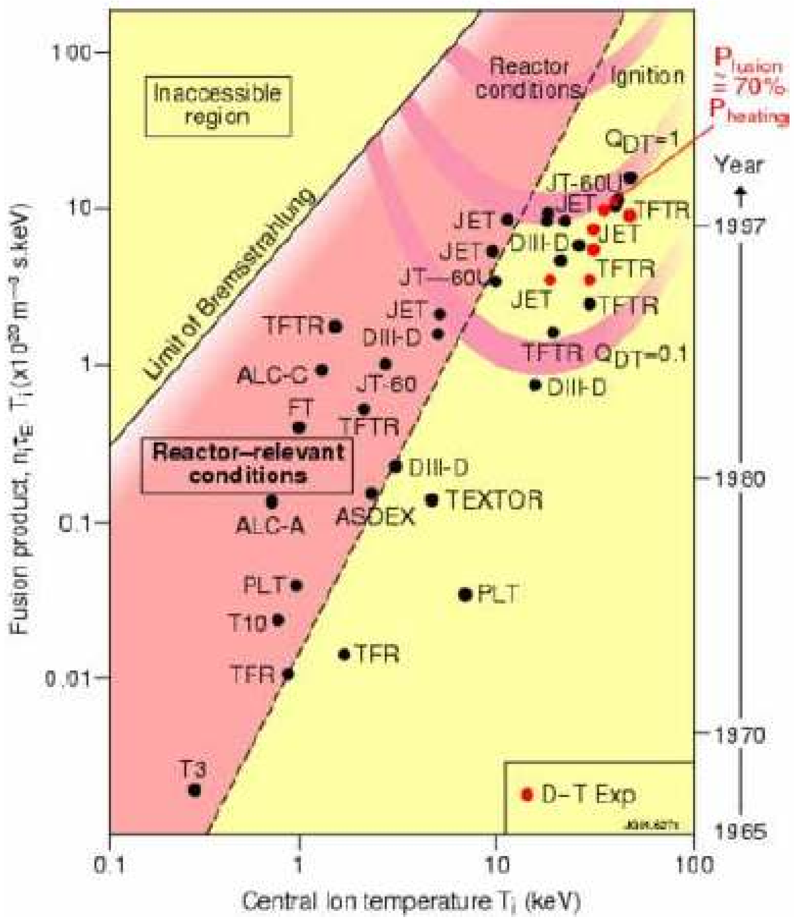
n T τ_E (in D-D plasma)

- **1970 – 25,000 times too small for ignition**
- **1983 – 100 times too small**
- **1995 – only 5 times too small**

Fusion power (in D-T plasma)

- **1991 – JET – 1.7 MW (10% T; 10 MW heating)**
- **1995 – TFTR – 10 MW (50% T; 40 MW heating)**
- **1997 – JET – 16 MW (50% T; 22 MW heating)**

FUSION TRIPLE PRODUCT APPROACHING BREAK-EVEN



THE NEXT STEP ON TOKAMAKS: BURNING PLASMA

- New element in burning plasmas: plasma is self-heated by fusion alphas → plasma is exothermic and highly nonlinear medium

- The leading-order effects may be identified in accordance with $Q=P_{FUS}/P_{IN}$,

Q ≈ 1 – at the threshold
Q ≈ 5 – alpha-effects on heating profile and Alfvén instabilities
Q ≈ 10 – nonlinear coupling between alphas, MHD stability, bootstrap current, turbulent transport, interaction plasma-boundary
Q ≥ 20 – burn control and transient ignition phenomena

- Reliable modelling is hardly possible for each of these regimes, we really need experimental data

WAYS OF ACHIEVING IGNITION IN MAGNETIC FUSION

- **The "ignition" condition for self-sustaining fusion reaction**

$$n\,T\,\tau_E > 5 \times 10^{21}\ \text{m}^{-3}\ \text{keV s}\ (\approx 10\ \text{atm s})$$

- **The ignition criterion for magnetic fusion can be better expressed via B and** $\beta = P_{plasma}/P_{magnetic} = 4\mu_0(nT)/B^2$ **as**

$$\beta\,\tau_E\,B^2 > 4\ \text{T}^2\ \text{s}$$

Three main avenues exist for magnetic fusion:

1) **Increasing energy confinement time** τ_E

2) **Increasing magnetic field B**

3) **Increasing** β

INCREASING ENERGY CONFINEMENT TIME

- Increasing τ_E: larger size fusion reactors since energy balance for steady-state is determined by $P_\alpha = 0.2\, P_{FUSION}$:

$$\frac{dW}{dt} = -\frac{W}{\tau_E} + P_\alpha = 0$$

$$\downarrow$$

$$P_\alpha = \frac{W}{\tau_E} = nT\frac{V}{\tau_E}$$

- For a desired power P_{FUSION}, achieving ignition via the increase of τ_E means a larger size machine. For 1 GW power the volume must be ≈ 1000 m^3
- Next step international project ITER ≈ 1000 m^3 will approach ignition
- Note: Largest volume present day machine is JET ≈ 100 m^3. This means that so far tokamak experiments were all performed at sub-critical volumes

INCREASING MAGNETIC FIELD

- Increasing B: technologically challenging to obtain B > 5 T !!!

  Present-day Alcator C-MOD (US),

  Next step: IGNITOR (Italy) requires B=13 T

THE IGNITOR POJECT

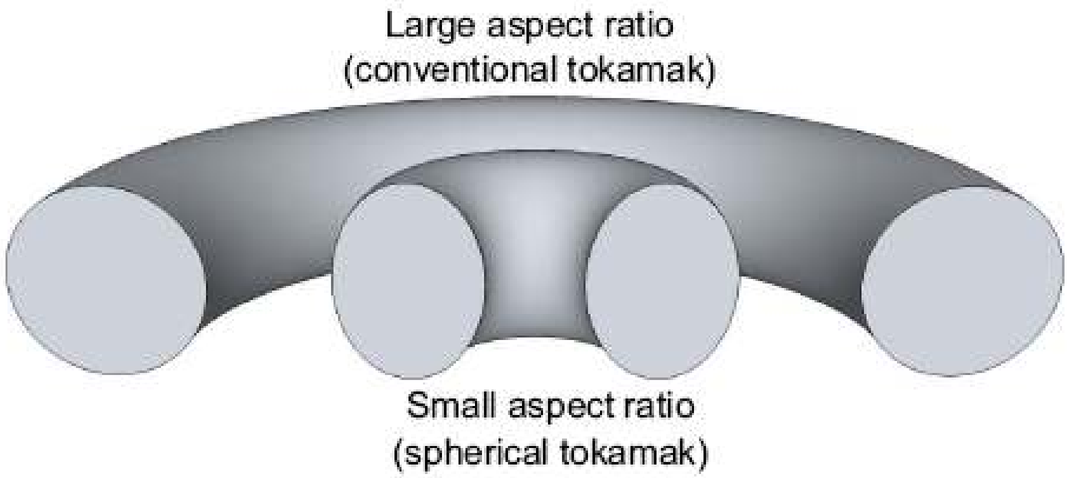
Parameters	Symbol	Value	Unit
Major Radius	R_0	1.32	m
Minor radius	a,b	0.47, 0.86	m
Aspect ratio	A	2.8	
Elongation	κ	1.83	
Triangularity	δ	0.4	
Toroidal magnetic field	B_T	$\lesssim 13$	T
Toroidal current	I_p	11	MA
Maximum poloidal field	$B_{p,max}$	$\lesssim 6.5$	T
Mean poloidal field	$\overline{\overline{B}}_p \equiv I_p/\sqrt{ab}$	$\lesssim 3.44$	T
Poloidal current	I_θ	$\lesssim 9$	MA
Edge safety factor (@11MA)	q_ψ	3.6	
Confinement strenght	$S_c \equiv I_p \overline{\overline{B}}_p$	38	MA T
Plasma Surface	S_0	$\lesssim 34$	m^2
Plasma Volume	V_0	$\lesssim 10$	m^3
ICRF heating (140 MHZ)	P_{RF}	6 (*)	MW

(*) The maximum ICRF power compatible with IGNITOR design parameters is 24 MW

INCREASING BETA

- Beta is limited by MHD instabilities at a level of few %. In contrast to technological difficulties in first two ways of achieving ignition, this is controlled by law of nature.

- Spherical tokamaks with a/R ≈ 1 achieve volume averaged $<\beta> \approx 40\%$ Present day MAST (UK), NSTX (US), next step project, e.g. STPP (UK)



THE SPHERICAL TOKAMAK POWER PLANT (PROJECT)

Parameter	Value
Major radius/minor radius (m)	3.42/2.44
Elongation	3.2
Triangularity	0.55
Plasma current (MA)	31
Centre rod current (MA)	30.2
Safety factor on axis, at edge	3, 15
Line-avge, central density ($\times 10^{19}m^{-3}$)	10.8, 12.6
Greenwald density ($\times 10^{19}m^{-3}$)	16.6
Average temperature (keV)	22
β(%), β_N	59, 8.2
Internal inductance, $l_i(2)$	0.21
Z_{eff}	1.6
Fusion power (GW)	3.1
CD power (MW)	50
Auxiliary CD (MA)	2.3
Pressure driven current (MA)	28.7
Confinement $H_{IPB98(y,1)}$, $H_{IPB98(y,2)}$	1.4, 1.6
τ_{He}^*	4
Avge neutron wall loading (MWm^{-2})	3.5
Peak neutron wall loading (MWm^{-2})	4.6

Table 1: Base-line parameters for the STPP.

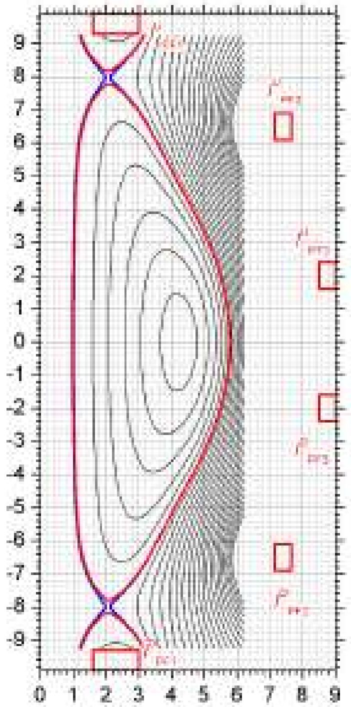


Figure 2: Poloidal cross-section of the free boundary equilibrium reconstruction showing the positions of the PF coils.

H.R.Wilson et al., 19th IAEA Conf., Lyon, 2002, IAEA-CN-94/FT/1-5

STELLARATORS

MAIN PROPERTIES OF STELLARATORS

• The stellarator is currently the principal rival to the tokamak as a fusion device using magnetically confined plasmas

• In a stellarator the helical fields required for confinement and stability are provided by currents in the external conductors only.

• This avoids the need for a transformer to generate a loop voltage to drive a plasma current.

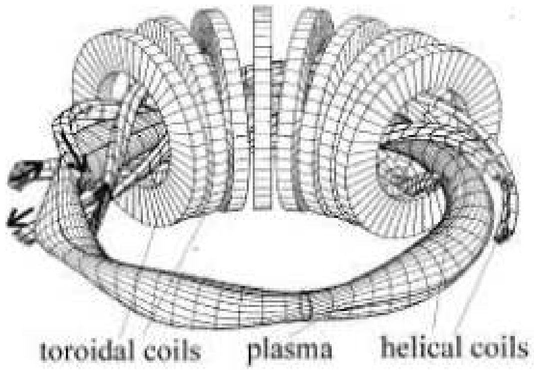
• Thus, steady-state operation is possible in such a device.

• There is greater flexibility in the magnetic geometry but this can lead to complex coil designs.

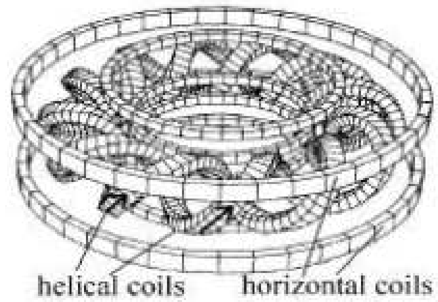
• The *rotational transform, iota, (~1/q)* is more generally used than q in a stellarator. Also, parameters (l,m) are used to define machine geometry. For example, a machine with 2 helical coils which spiral 4 times round the vessel has a (2,4) geometry.

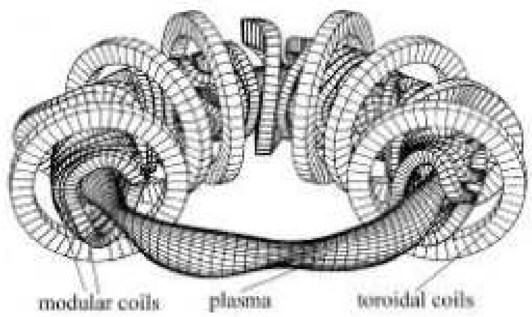
STELLARATOR TYPES

Classical - Wendelstein 7-A

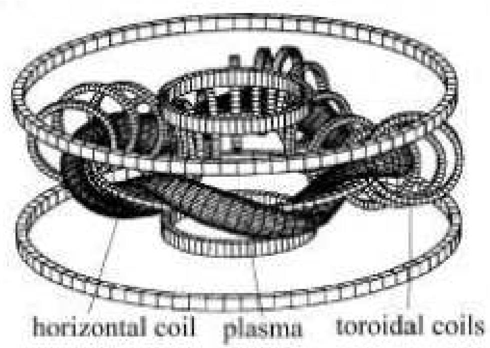


Torsatron (ATF)





Modular - Wendelstein 7-AS



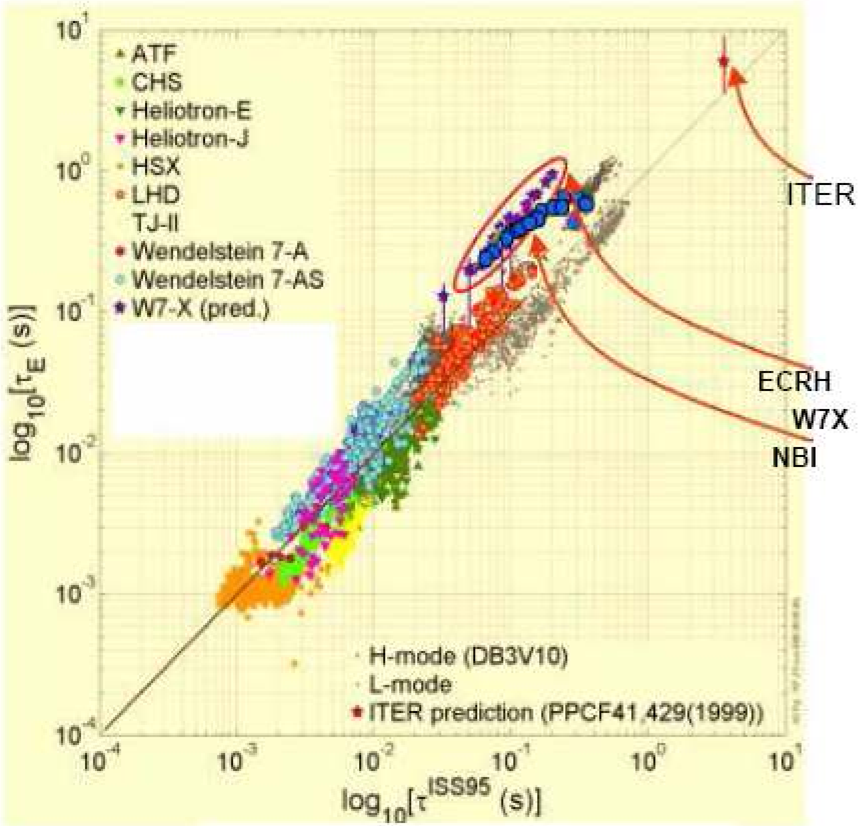
Heliac - TJ-II

PERFORMANCE OF STELLARATORS

- Compared to tokamaks of similar size and power, the performance of stellarators is favourable.

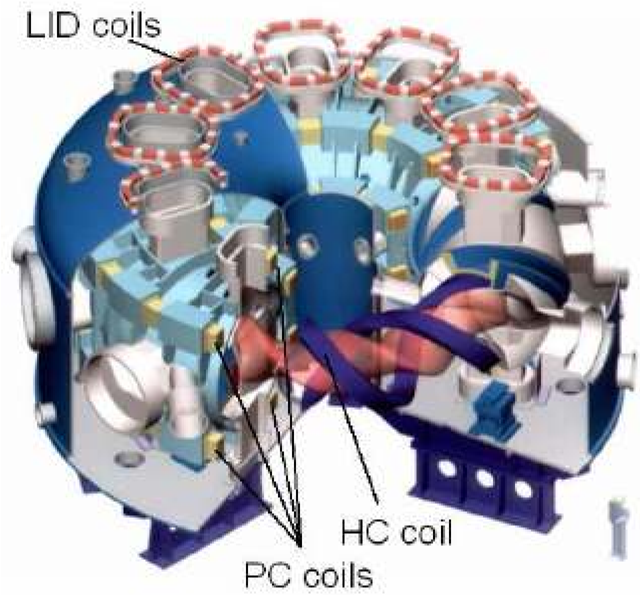
- Most smaller machines have now ceased operation (including W7-AS) with **TJ-II** in Madrid the only modern European machine in operation.

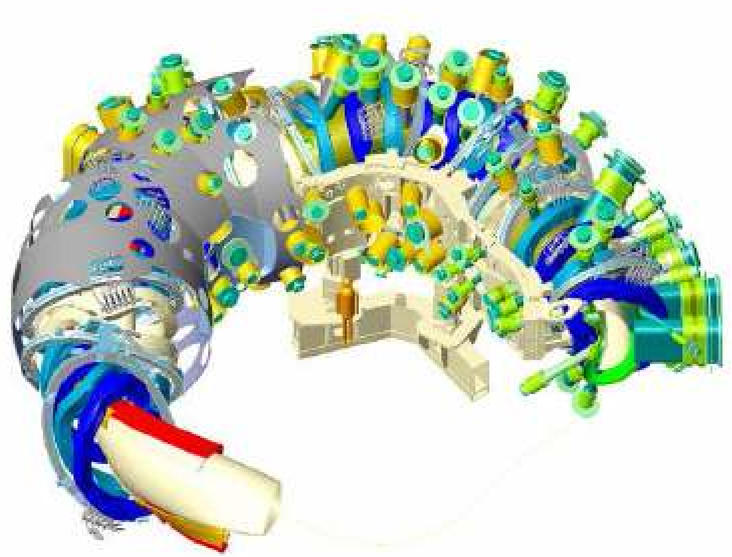
- The world programme is now centred on 2 new large machines: **LHD** in Japan and in future **W7-X** in Germany.



$$\tau^{ISS95} = 0.256 a^{2.21} R^{0.65} P^{-0.59} n_{20}^{0.51} B^{0.83} \iota_{2/3}^{0.4}$$

TWO LARGEST STELLARATORS





LHD

R_{ax} = 3.4 – 4.1 m, a =0.65 m
V_{pl} = 30m^3
B =2.9 T, $\iota(0)$ = 0.35, $\iota(a)$ = 1.5
high shear, 10 field periods, l = 2

W7-X

R_{ax} = 5.5 m, a =0.53 m
V_{pl} = 30m^3
B = 3.0 T, $\iota(0)$ = 0.88, $\iota(a)$ = 0.97
low shear, 5 field periods

LARGE HELICAL DEVICE

Torsatron - (2,4)

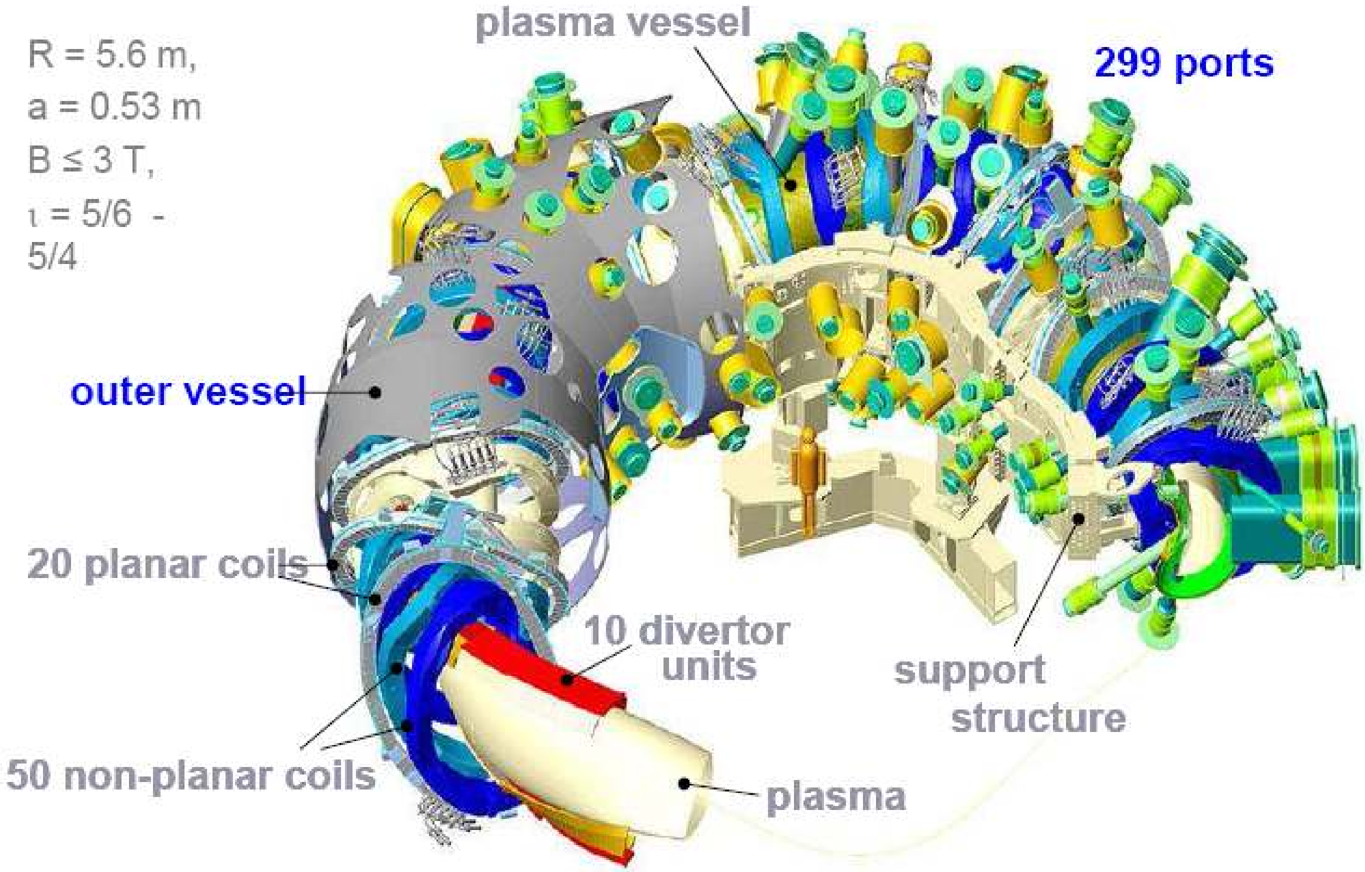
Operational for a several years (Japan)

Table 1. LHD plasma parameters

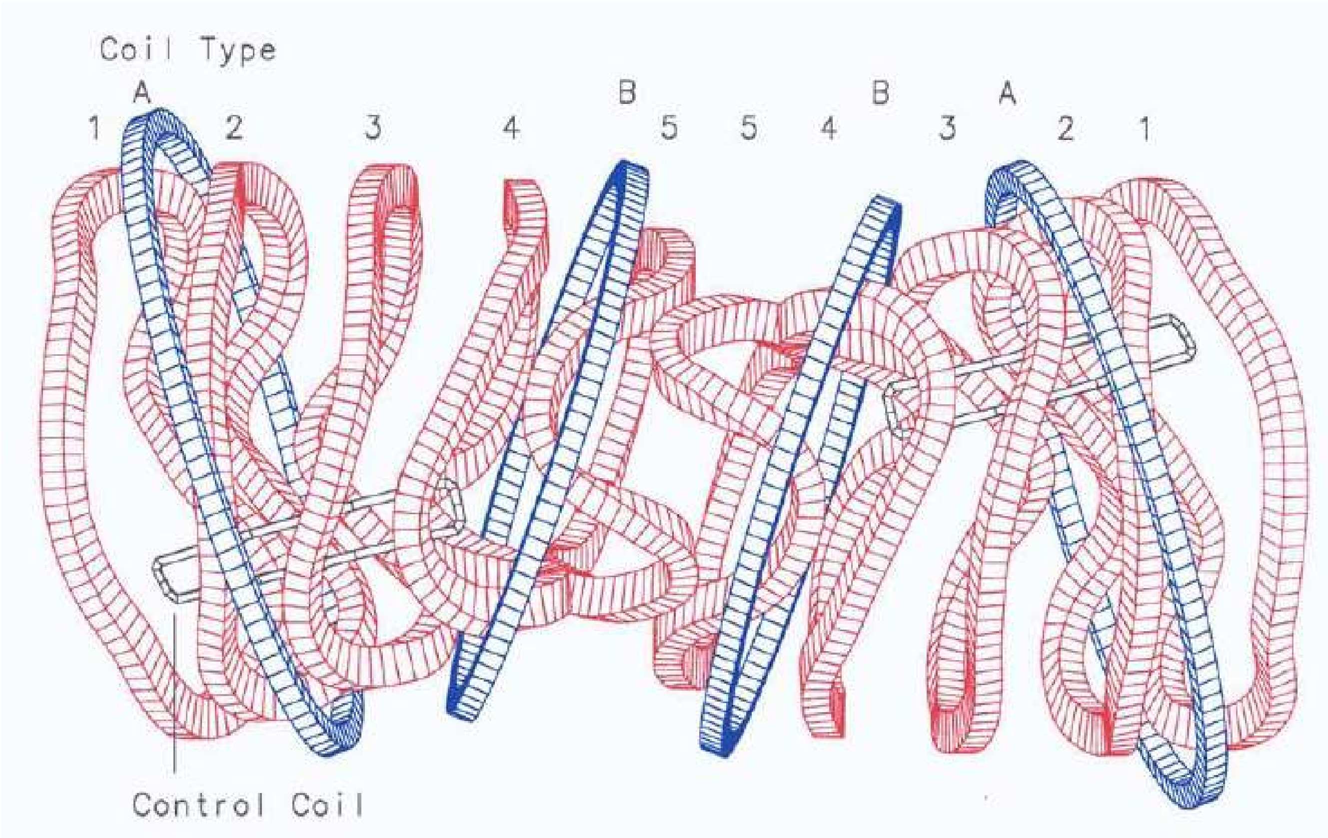
	T	n_e
High Electron Temperature	10 keV	6.0×10^{18} m^{-3}
High Ion Temperature	5 keV	$1.2\ 10^{19}$ m^{-3}
High Confinement	1.1 keV	6.5×10^{19} m^{-3}
$\tau_E = 0.3$ s, $nT\tau_e = 2.1 \times 10^{19}$ keV m^{-3}, $P_{abs} = 2$ MW,		
Maximum Stored Energy	$W_p = 1.16$ MJ	
Highest Beta	$\langle\beta\rangle \sim 3.2\%$ at $B = 0.5$ T	
Maximum Density	1.5×10^{20} m^{-3}	

W 7 – X COMPONENT ASSEMBLY

R = 5.6 m,
a = 0.53 m
$B \leq 3$ T,
ι = 5/6 - 5/4



W 7 – X COILS



STELLARATORS VERSUS TOKAMAKS

The main advantages claimed for the stellarator are:

- Steady-state operation - very small plasma current; no transients in superconducting field coils
- Disruption Free
- Field defined equilibrium
- Suppression of Neoclassical Tearing Modes
- Can operate at higher densities - radiation not β limited

But

- Complicated coil system - complex forces on coils
- Large surface area to volume - confinement/wall interactions
- Complex divertor - tight design tolerances
- Smaller ports - diagnostics/heating
- Bootstrap currents may be undesirable
- Impurity accumulation

SUMMARY

- D-T fusion is the most attractive avenue: for generating 1 GW power for 1 year one needs 1 tonne Li + 5 Mlitres water
- To overcome the Coulomb electrostatic force between two positive nuclei D and T, high kinetic energy is needed corresponding to 20 keV → plasma
- Plasma can be confined by magnetic field in, e.g. toroidal solenoid
- The triple-product ignition criterion $n\,T\,\tau_E > 5 \times 10^{21}\ m^{-3}$ keV s for magnetic fusion yields $\beta\,B^2\,\tau_E > 4\ T^2$ sec
- Three main avenues are being developed for approaching ignited plasmas: high- τ_E (large volume), high-B, and high- β (spherical tokamaks) machines
- Today's research aims on tokamaks are focussed on preparing for burning ITER plasmas
- Stellarators allowing steady-state operation are the principal alternative to tokamaks