
BASIC PARAMETERS.
Plasma Major Radius 6.2m
Plasma Minor Radius 2.0m
Plasma Current 15.0MA
Toroidal Field on Axis 5.3T
Fusion Power 500MW
Burn Flat Top >400s
Power Amplification Q>10

Cost is > 8 Billion Euro.
Science and Engineering Challenges for Fusion: Large - Compact

Steve Cowley -- Culham, Imperial
Rob Akkers, Brian Lloyd, Colin Roach, Steve Lisgo and MAST team.
Arthur Stanley Eddington -- delivered the presidential address.

One of the many questions he addressed is:

Where does the energy radiated by the stars/sun come from?

F. W. Aston had measured the masses of elements and shown:

\[ M_{\text{hydrogen}} = 1.008 \text{ and } M_{\text{helium}} = 4.0 \]

“F. W. Aston's experiments seem to leave no room for doubt that all the elements (nuclei) are constituted out of hydrogen atoms bound together with negative electrons”.
Fusion and the Sun

Eddington assumed that the sun puts four hydrogens together to make helium:

\[ \text{H} + \text{H} + \text{H} + \text{H} \rightarrow \text{He} \]

Mass difference is energy by Einstein’s relation \( E = mc^2 \). Thus:

1.008 kilograms of hydrogen \( \rightarrow \) 1 kilogram of Helium + \( 7.5 \times 10^{14} \) J of Energy.

That will supply you with all your energy needs for about 10,000 years.

Eddington estimated the sun’s life expectancy to be 15 billion years from the mass and the radiated power -- quite close.
One possible solution for a long term energy supply is Fusion

“This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped”.
Arthur Stanley Eddington 1920.

I will try to explain the scientific challenge and why we are finally at the point of generating Fusion burning plasmas -- the gateway to energy production.
Which Fusion?

Tritium is bred from lithium using the neutron

\[
\text{Li}^6 + n \rightarrow \text{He}^4 + T
\]
This assumes no increase in OECD energy consumption (efficiency improvement balances growth)
Ultimate Fuel Resource for Different Energy Systems

Large resources in coal, fission breeder and fusion. Solar provides a large resource as well.

Source: WEC, BP, USGS, WNA
Is Fusion Possible?

For plasma at 10-20Kev temperatures (100-200MºC) D-T fusion power density is approximated by:

\[ P_{\text{Fusion}} = 0.08 P^2 \text{ (MW m}^{-3}\text{)} \]

We need >1MWm\(^{-3}\) for an economic system -- need a few Atmospheres of plasma pressure. Can we hold it with a magnetic field?

**Magnetic pressure** = \( P_{\text{Magnetic}} \sim 4 B^2 \) (atmospheres)

Figure of merit \( \beta = P/P_{\text{Magnetic}} \)
How do you hold something at 100 million degrees? The Magnetic Bottle.

At these temperatures gas $\rightarrow$ plasma, electrons and ions move independently.

Projeced particle orbits
Charged Particles stay inside plasma
Fusion Force Balance in ITER

\[ D + T \rightarrow He^4 + n \]

3.5MeV 14MeV

Superconducting Coils
central B field 5.2 Tesla
\( P_{\text{magnetic}} \sim 100 \) atmospheres

Central Temperature >20keV
\( P = \text{Plasma Pressure} \sim 7 \) atmospheres
Fusion Energy Balance in ITER

‘Baseline Performance’
Power in alphas captured by Plasma $P_\alpha \sim 100$MW.

Power in neutrons escaping Plasma $P_n \sim 400$MW.

$P_n + P_\alpha = P_{\text{Fusion}}$

$D + T \rightarrow \text{He}^4 + n$

3.5MeV  14MeV
Fusion Energy Balance in ITER

Turbulent Plasma Energy Loss

\[ P_{\text{loss}} = \frac{0.15P}{\tau_E} \text{ (MW m}^{-3}\text{)} \]

Confinement Time

External Plasma heating

\[ P_{\text{Heat}} \sim 50\text{MW} \]

Energy Balance

\[ \frac{P_{\text{Fusion}}}{5} + P_{\text{Heat}} = P_{\text{loss}} \sim 0.15 \frac{P}{\tau_E} \]

Energy Gain > 10
Why so Big?

.......... Turbulence

without turbulence machine size ~ 20- 50cm
Spitzer. 1951.

Random walk:
Step = \rho, \text{ larmor/cyclotron radius.}
Decorrelation rate = \nu = \text{collision rate}
Radius of plasma = a.

Collisions are rare and classical confinement can be very good.
Spitzer only needed $a = 20\text{cm}$, ($\tau_E > 4\text{s}$) for IGNITION.
Can’t be right. Observed transport is much larger.
Density fluctuations

DIII-D in San-Diego
Plasma is 1m across

Eddies are small compared to the device

Ray Fonck and George McKee
Gyro-kinetic simulation.

DIII-D Shot 121717

GYRO Simulation
Cray X1E, 256 MSPs

GYRO code simulations by Jeff Candy and Ron Waltz GA
Energy Confinement -- Random walk of heat/particles.

$L = \text{typical machine size}$

$\Delta = \text{radial eddy size } \propto \text{ion larmor Radius } \rho_i = \text{random step.}$

$N = \text{number of steps to random walk out of plasma}$

$\begin{align*}
L & \sim \sqrt{N} \rho_i \\
\rightarrow N & = \left( \frac{L}{\rho_i} \right)^2
\end{align*}$

For ITER $N \sim 10^6$. 
Energy Confinement -- Random walk of heat/particles.

Eddy turnover time =

\[ \tau_{eddy} = \left( \frac{L}{v_{thi}} \right) \]

\[ \tau_E \sim N \tau_{eddy} \sim \left( \frac{L^3}{\rho_i^2 v_{thi}} \right) \]

\[ \propto L^3 B^2 T^{-1} \]

Dramatic scaling with size!
Scaling approximately agrees with data BUT geometry dependant.
Why so Big? Physics and Cost of Electricity.

Almost no external heating: \( P_\alpha = \frac{P_{\text{Fusion}}}{5} \sim 0.01P^2 > P_{\text{loss}} \sim 0.18 \frac{P}{\tau_E} \)

\[ \rightarrow P\tau_E > 20 \]

Detailed design analysis shows plasma radius greater than \( \sim 2\text{m} \) (\( B \sim 5 \text{ tesla} \)) will ignite.

Capital Cost: \( \propto L^{2-3} \)  

Power Output: \( \propto P^2 L^3 \)

Detailed design analysis shows cost of electricity is reasonable (5-15 c/kWh) at GW level power station

Fusion Power is Possible.
EU Power Plant.

Blanket for tritium breeding and heat exchange. ~ 2MWm\(^{-2}\)

Neutron power crossing boundary

Superconducting magnets

2030...

Shielding

Plasma exhaust, power loading >10MWm\(^{-2}\)
MAST -- fusion performance in a compact device at modest cost. Why?

• Lower capital cost -- development easier.
• Higher efficiency -- larger $\beta = P/(4B^2)$.
• Rotationally enhanced confinement.
• Innovate improved REACTOR designs.
MAST - Compact Fusion
Stabilized when Stretching rate $\frac{dV}{dr} = \gamma_E >$ Eddy turnover rate ($\sim$ growth rate)
Some Moving Blobs of Tokamak Turbulence

Φ contours on outboard midplane: $\gamma_E = 0$ and $\gamma_E = 0.02 \sim 0.5 \gamma_{\text{max}}$
Heat Flux Flow: Shear “Suppression”

Roach et al. 2009

Optimum shearing rate Suppresses heat loss by factor >10


- no linear drive (~spherical, GS2)
- with linear drive (~spherical, GS2)
- with linear drive (~JET, GKW)
Rotationally Enhanced Confinement.
shape the energy of the future

interested in a phd in fusion research?
find out more at our open day at culham, oxfordshire, 25 november 2009

join us at the hottest place on earth to see how you can apply your knowledge to combat global warming. at ukaea culham, researchers run experiments at over 100 million degrees c to develop fusion, the ultimate clean energy source.

culham is the world's leading fusion laboratory with the european flagship machine jet and the uk research programme, centred on the maste experiment. much of our work is focused on international collaborations, including the large iterative tokamak project being built in france - the stepping stone to commercial fusion power.

we fund a range of phds each year in partnership with uk universities in:
• plasma physics - theory and experiments
• materials science
• engineering and technology.

the open day is being organised by ukaea culham and the fusion doctoral training network led by the university of york.

several leading universities will attend to describe phd opportunities in fusion and related research.

to register go to www.culhamphd.org.uk

register for our phd event on 25 november
www.culhamphd.org.uk/
Fusion Soon.

• Pretty certain we can now do fusion at large scale.

  We must get a fusion reactor online in the UK by 2040.

• It requires considerable investment -- political will is vital.

• Fusion at compact scale is more speculative -- but……