Engineering Issues in Fusion Reactor Design and Alternative Concepts

By
Hamid Shahani, PhD
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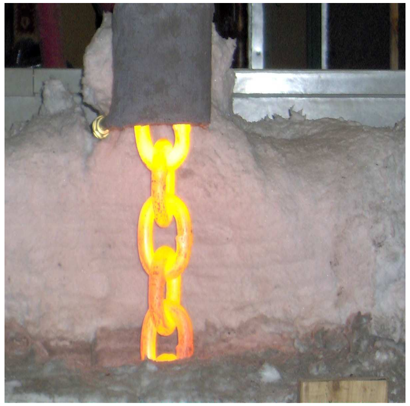

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Cryogenic Temperatures in Inertial Confinement

The target assembly for NIF's first integrated ignition experiment is mounted in the cryogenic target positioning system, or cryoTARPOS. The two triangle-shaped arms form a shroud around the cold target to protect it until they open five seconds before a shot.

500MW from half a gram of hydrogen: The hunt for fusion power heats up

By Sebastian Anthony on March 27, 2012 at 7:57 am | 44 Comments

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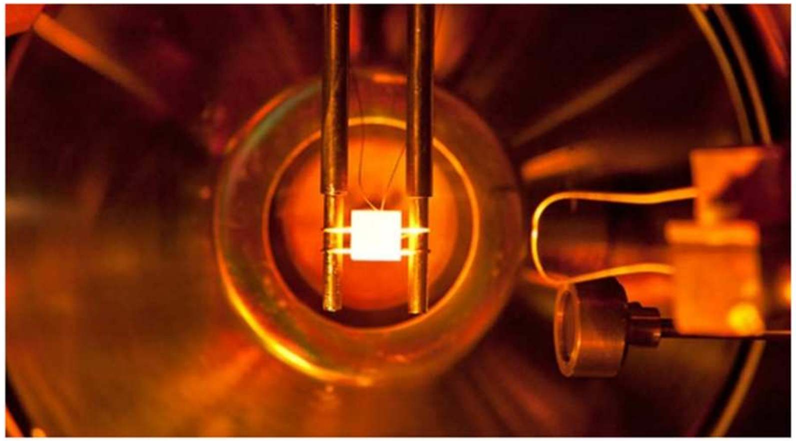

You've heard of the Manhattan Project — the Allied research and development program that resulted in two nuclear bombs being dropped on Japan and the end of World War II — and now it's time to learn about one of its successors, Project Matterhorn, a Cold War program to control and harness thermonuclear reactions to create *fusion power*.

Nuclear fusion occurs when two atoms fuse together (usually hydrogen) to form a heavier atom (helium), and releasing a vast amount of energy in the process. This process can only occur at incredibly high temperatures, such as the center of a star (such as our Sun). Every

Laser Arrays

The Nova laser, used for inertial confinement fusion experiments from 1984 until decommissioned in 1999.

Latest Update

So Far Unfruitful, Fusion Project Faces a Frugal Congress

National Ignition Facility

The giant laser at the Lawrence Livermore National Laboratory in California.

By WILLIAM J. BROAD
Published: September 29, 2012

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For more than 50 years, physicists have been eager to achieve controlled fusion, an elusive goal that could potentially offer a boundless and inexpensive source of energy.

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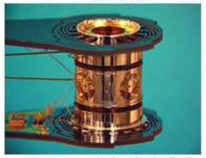


National Ignition Facility

The laser uses blasts of concentrated light to compress, heat and ignite tiny capsules of hydrogen fuel, above. The goal of the project is to one day achieve controlled fusion.

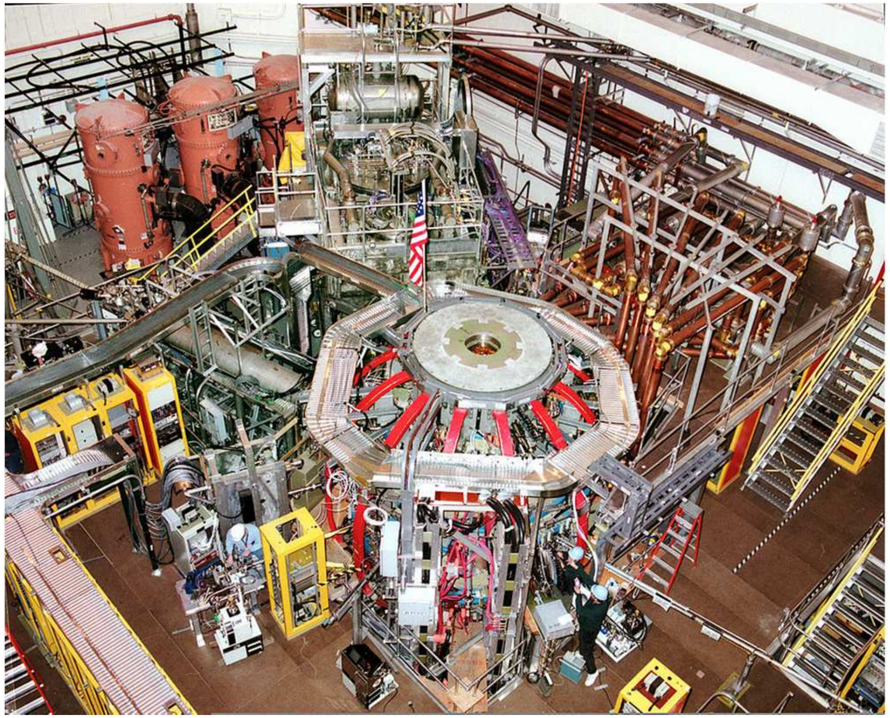
To do so, American scientists have built a giant laser, now the size of a football stadium, that takes target practice on specks of fuel smaller than peppercorns. The device, operating since 1993, has so far cost taxpayers more than $5 billion, making it one of the most expensive federally financed science projects ever. But so far, it has not worked.

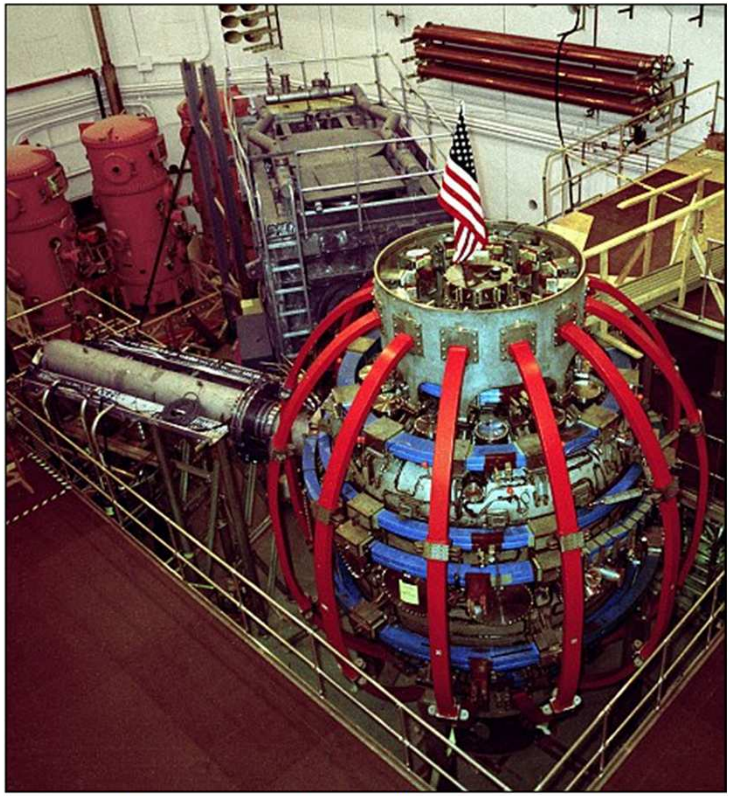
Unfortunately, the due date is Sunday, the last day of the fiscal year. And Congress, which would need to allocate more money to keep the project alive, is going to want some explanations.

- The New York Times

(Sunday September 30, 2012)

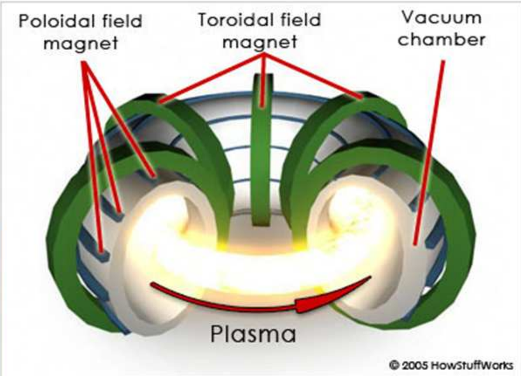
Tokama & Poloidal /Toroidal Magnets





Magnetic containment torus reactors use a different process to create fusion - but have proved to be expensive, and the goal of releasing more energy than is put in has remained elusive

Plasma Electric Current



Plasma toroid

Fusion Reactors: Magnetic Confinement

There are two ways to achieve the temperatures and pressures necessary for hydrogen fusion to take place:

- **Magnetic confinement** uses magnetic and electric fields to heat and squeeze the hydrogen plasma. The ITER project in France is using this method.
- **Inertial confinement** uses laser beams or ion beams to squeeze and heat the hydrogen plasma. Scientists are studying this experimental approach at the National Ignition Facility of Lawrence Livermore Laboratory in the United States.

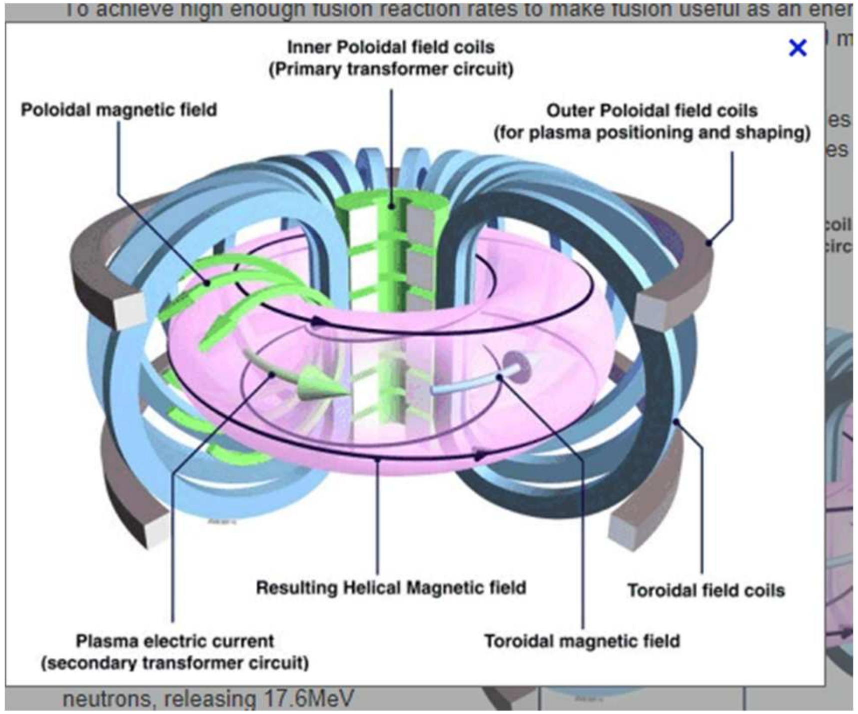
Let's look at magnetic confinement first. Here's how it would work:

Microwaves, electricity and neutral particle beams from accelerators heat a stream of hydrogen gas. This heating turns the gas into plasma. This plasma gets squeezed by super-conducting magnets, thereby allowing fusion to occur. The most efficient shape for the magnetically confined plasma is a donut shape (toroid).

A reactor of this shape is called a **tokamak**. The ITER tokamak will be a self-contained reactor whose parts are in various cassettes. These cassettes can be easily inserted and removed without having to tear down the entire reactor for maintenance. The tokamak will have a plasma toroid with a 2-meter inner radius and a 6.2-meter outer radius.

Let's take a closer look at the ITER fusion reactor to see how magnetic confinement works.

TOKAMAK
"Tokamak" is a Russian acronym for "toroidal chamber with axial magnetic field."



Principal Equation

IGNITION CONDITION: LAWSON BREAKEVEN CRITERION

Like a wood fire, fusion fire does not burn on its own. Fusion requires particular ignition conditions to be met. In an ignited plasma, a substantial number of particles must collide with one another with sufficient frequency and intensity. The magnetic field must thus confine a number of particles whose thermal energy must not be transferred too fast to the plasma container. This imposes requirements on the density, temperature, and thermal insulation of the plasma. These are:

1. An absolute plasma temperature of at least:

$$T = 273 + {}^{\circ}C = 100 \text{ x } 10^6 \, {}^{\circ}K.$$

2. An energy confinement time of:

$$\tau_e \geq 2 \text{ seconds.}$$

This measure for the thermal insulation gives the time that elapses till the thermal energy pumped into the plasma by heating equipment such as neutral beams, transformer action, or microwaves is again lost to the outside.

3. A plasma density of about

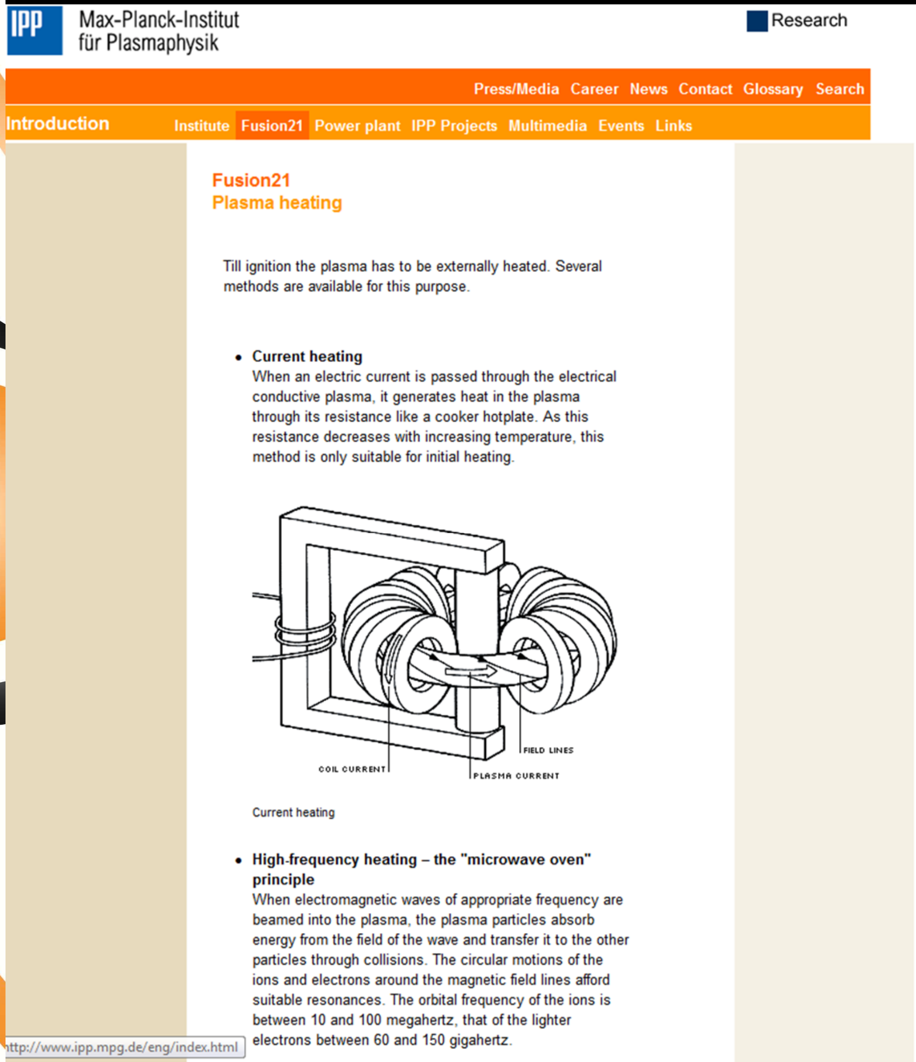
$$n = 10^{14} \text{ [particles/cm}^3\text{]}$$

This is 250,000 times less in density than the Earth's atmosphere. This extremely low density means that, despite its high temperature, a burning fusion plasma involves a power density scarcely larger than an ordinary light bulb.

4. Energy breakeven. The energy obtained from a plasma must exceed the energy input used to ignite it and the radiation losses from the plasma. This is expressed by the Lawson's breakeven criterion or the Lawson parameter as a product of the plasma density and energy confinement time:

$$n\tau_e \geq 2.0 \text{x} 10^{14} \left[\frac{\text{particles.sec}}{\text{cm}^3}\right] \qquad (2)$$

Confinement Time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Fusion21
Plasma heating

Till ignition the plasma has to be externally heated. Several methods are available for this purpose.

- **Current heating**
  When an electric current is passed through the electrical conductive plasma, it generates heat in the plasma through its resistance like a cooker hotplate. As this resistance decreases with increasing temperature, this method is only suitable for initial heating.

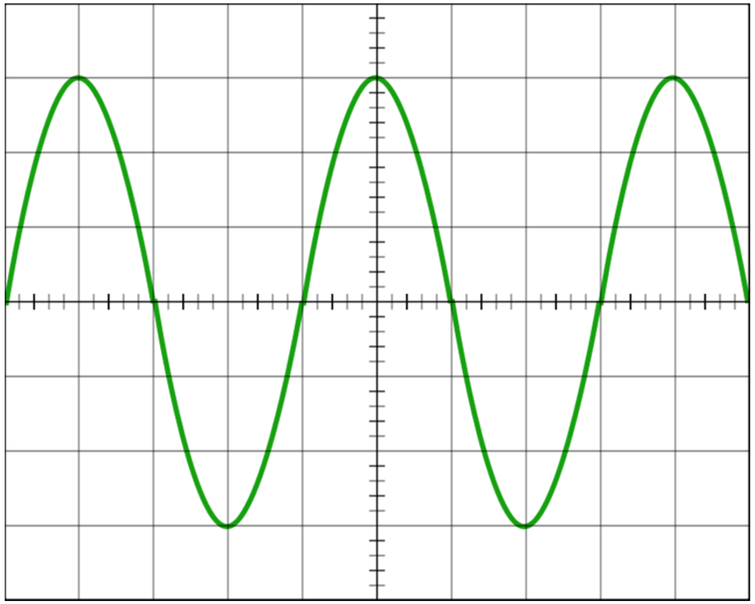
Current heating

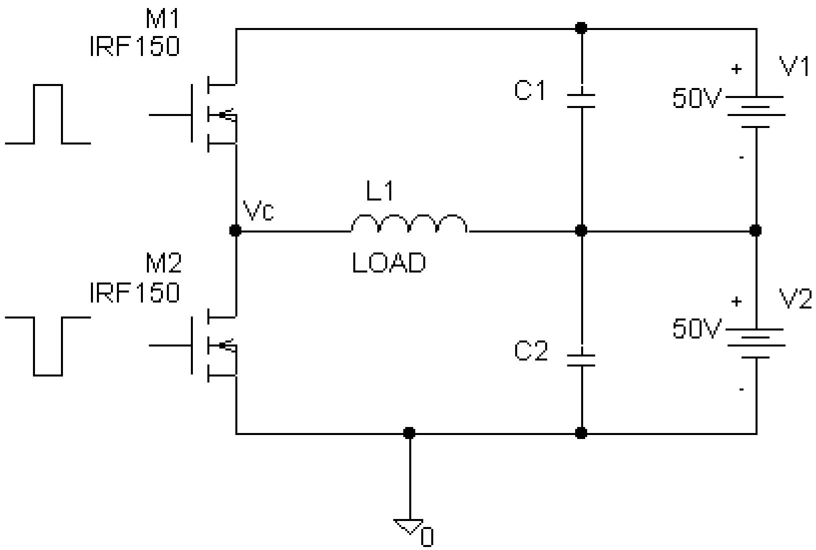
- **High-frequency heating – the "microwave oven" principle**
  When electromagnetic waves of appropriate frequency are beamed into the plasma, the plasma particles absorb energy from the field of the wave and transfer it to the other particles through collisions. The circular motions of the ions and electrons around the magnetic field lines afford suitable resonances. The orbital frequency of the ions is between 10 and 100 megahertz, that of the lighter electrons between 60 and 150 gigahertz.

ttp://www.ipp.mpg.de/eng/index.html

- Charged particles response to variation in electric/ magnetic field
- Confinement time is the time for transformer to reach maximum current at dI/dt=k, necessary to vary magnetic field to sustain circulation.

Current Source for Poloidal Magnet

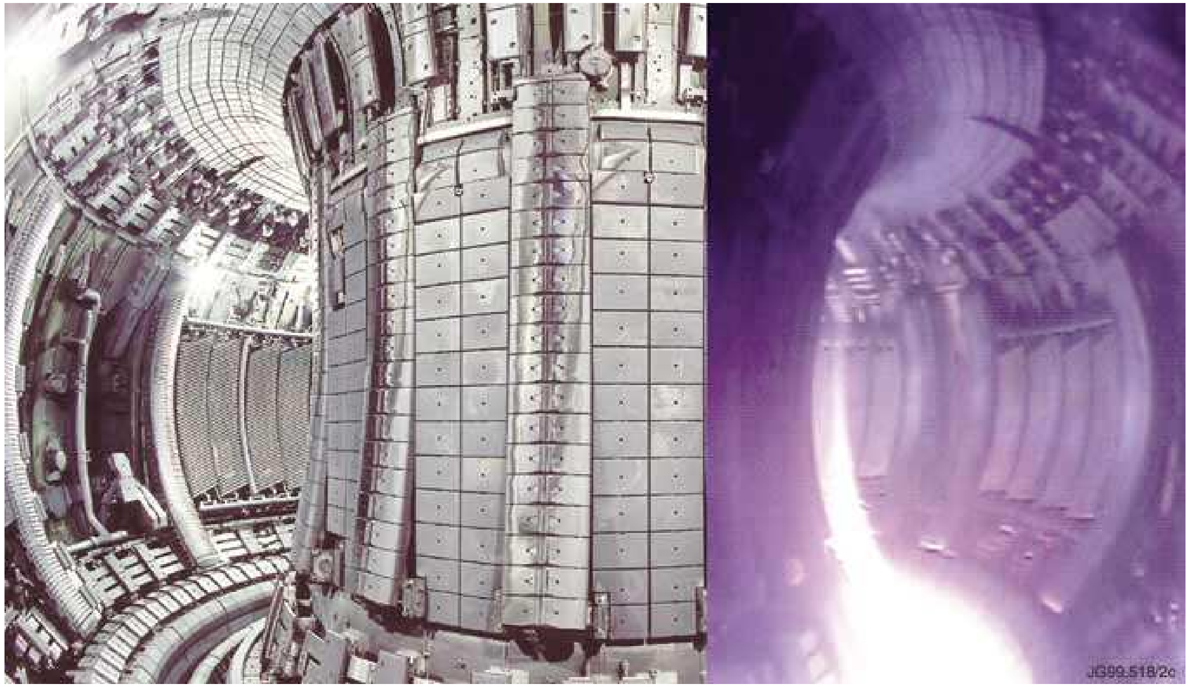




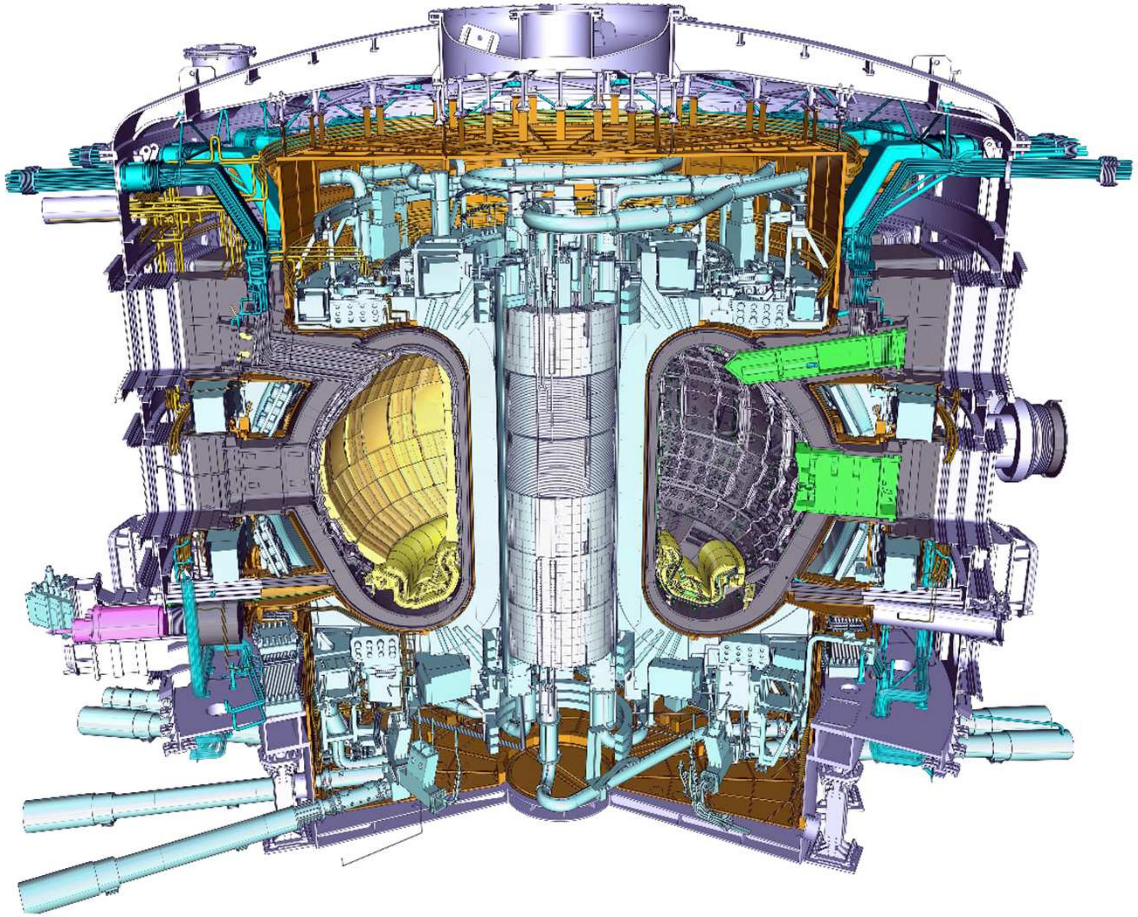
I = a.t + b

d Ø / dt α dI / dt

Effect of Poloidal & Toroidal Magnetic Forces on Plasma positioning



ITER Cross Section



Tokamak, Large or Small ?

- ITER, ID=2m, OD=6 m
  - Current: 1 MA, Confinement time 6 sec, = 160 A/mSec, Q=40!
- STOR-M, ID=0.125m,OD=0.46m
  - Current: 30 kA, Confinement time 5mSec, = 6000A/mSec, Q=385,000!

PPPL & Li Shield Solution

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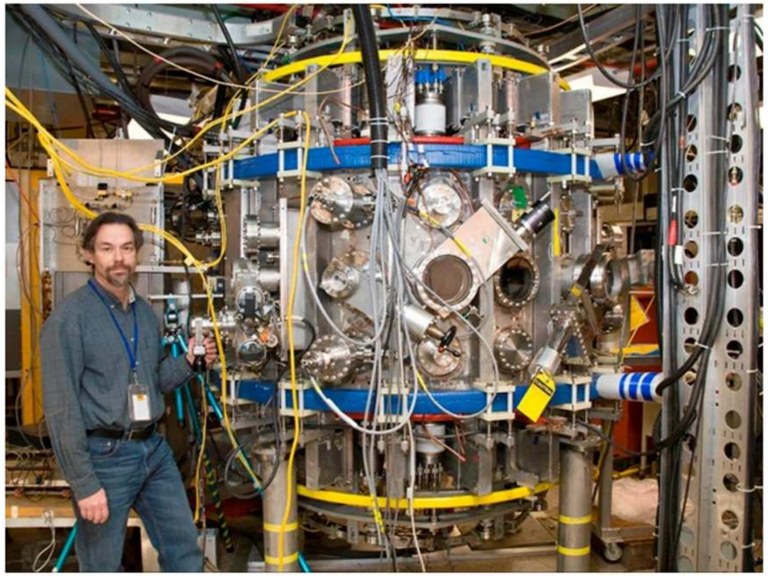

The Lithium Tokamak Experiment (LTX), where Bruce Koel and his coworkers are carrying out their lithium-related experiments.

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Photos: 1 2 3 4 5 6

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Another internal shot of the NSTX, with a human for scale.

Interior Shield with Mo Armor

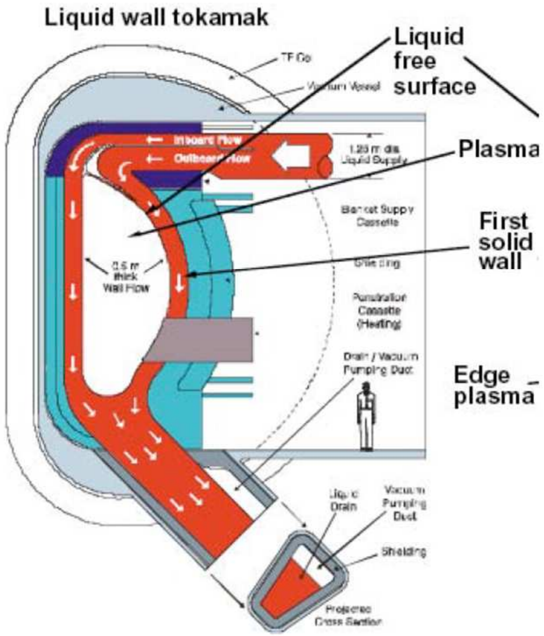
- ITER : 13 Billion dollars up to 2038
- Tc from 220 to 350 & 400M°C
- Cryogenic cooling of magnets below (-170°C)
- Li coating to absorb neutron and to produce T
- Lithium
  - melting point 180°C,
  - boiling point 1,342°C
  - extremely reactive
  - low viscosity!

Interior view of the tokamak showing the molybdenum armor tiles on the wall. Three Ion Cyclotron Range of Frequencies (ICRF) heating antennas are visible – two on the left with two copper straps each, and the four-strap "field-aligned" antenna (installed 2011) at right.

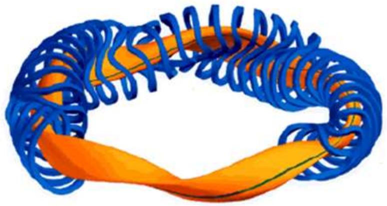
Effect of Wall Materials & Design on Magnetic Pattern/Plasma

- K(W)= 1.7, α = 0.7
- K(Mo)=1.4, α = 0.5
- K (Fe)= 0.75, α = 0.2
- K(Cu)= 4, α = 1.1
- K(Ag)= 4.2, α = 1.7

Structures developed to withstand a heat flux of 25 MW/m^2



The Idea Behind Stellarator



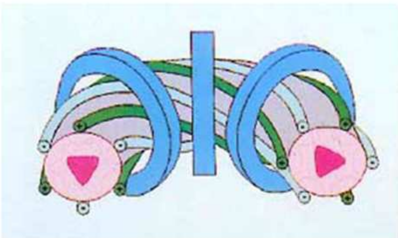


Figure 7. Two possible configurations for the Stellarator coils and magnetic field. In the lower configuration, toroidal coils and helical poloidal coils generate the resulting twisted toroidal magnetic field.

Figure 8: A stellarator configuration, showing the plasma and the magnetic coils

Figure 8. A single superconducting magnet coil for the 7-X Stellarator at Wendelstein, Germany.

General Fusion

Generator Design

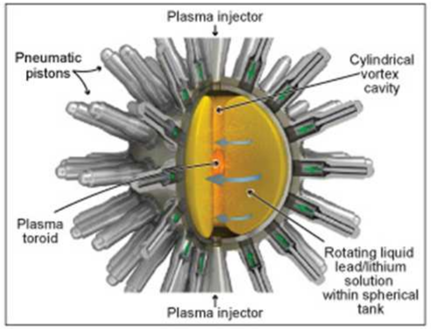
General Fusion is developing a full-scale fusion demonstrator to prove the viability of our approach. This builds upon our experimental work, which proved that magnetized plasmas can be compressed to thermonuclear conditions using acoustic means. Our approach has been further validated by a number of leading experts in the nuclear fusion scientific community, and through the due diligence of our private-sector and government investors.

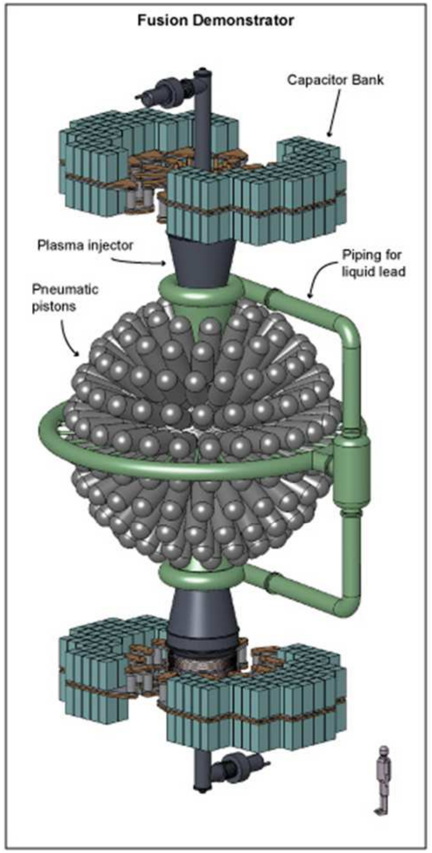
Our generator will operate in a repeating cycle, with each cycle culminating in a burst of fusion energy.

Each cycle will involve:

- creating plasma of deuterium and tritium,
- trapping the plasma within a magnetic field,
- compressing the magnetic field and the plasma within it to thermonuclear conditions, and
- capturing the heat that results from the fusion reaction and using it to generate electricity and power the next cycle.

Physically, our generator will consist of a spherical tank filled with a liquid mixture of lead and lithium. The liquid will be spun by tangential injection to create a vertical cylindrical vortex cavity in the centre of the sphere.



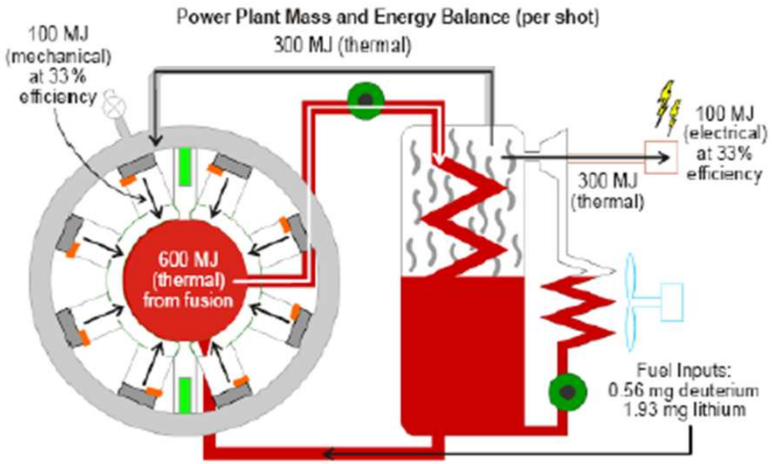


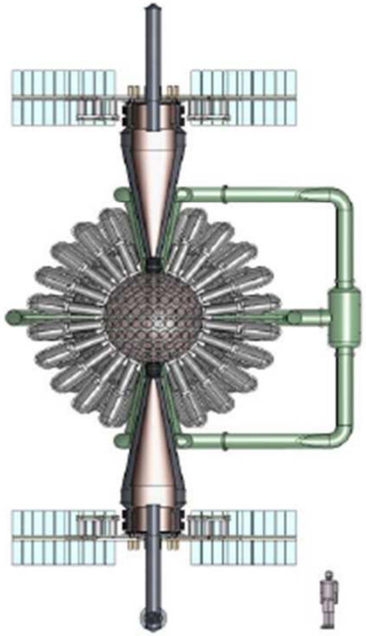
A plasma injector will be mounted on each end of the vortex cavity. Each plasma injector will heat a puff of deuterium-tritium gas to 1 million degrees using a high-voltage electrical discharge from a bank of capacitors. Each puff of gas will form in the midst of magnetic fields that will cause it to form a closed, toroidal (doughnut) shape and to peel off the end of the injector somewhat like a smoke ring.

General Fusion: Tc=1M°C?

Doug Richardson / General Fusion

- Acoustically-driven Magnetized Target Fusion concept.





General Fusion Patent Pending Concept

- To contain pneumatics etc., in liquid Pb & Li
- To discharge high power capacitors
  - Input energy, cycles and electrodes life time
- Acoustic generator and injection into reactor
- Maintenance of mechanical parts , MTBF and safety concerns

Norax Concept is Based On

- Its expertise in:
  - Induction heating
  - PACVD
  - DC magnetron
  - Microwave
  - PVD
  - Plasma Torch
  - Etc.,
- & know how:
  - To generate plasma
  - To manipulate and concentrate plasma
  - To transfer plasma at high speed

Norax's Concept

- Could possibly:
  - Generate plasma @ higher pressures (reducing Tc)
  - Transfer Plasma at theoretical speeds 1 to 50 km/sec
  - Raise the temperature as necessary, additive effect
  - Be in continuous process (not as pulsed)
  - Be applied as multiple jets to allow parallel operation for more power demand
  - Be integrated with present design of coal power plants

- Most of input energy used to generate plasma be recovered
- Have low maintenance cost as there is no moving parts