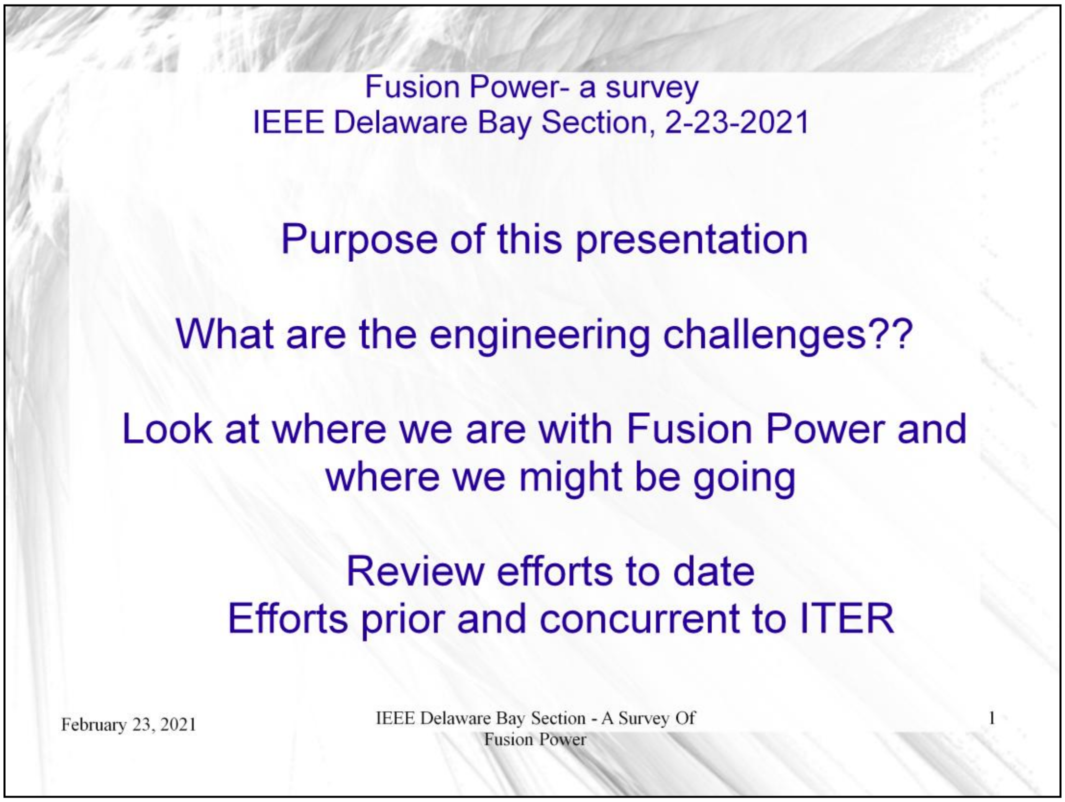


# Fusion Power- a survey
IEEE Delaware Bay Section, 2-23-2021

Purpose of this presentation

What are the engineering challenges??

Look at where we are with Fusion Power and where we might be going

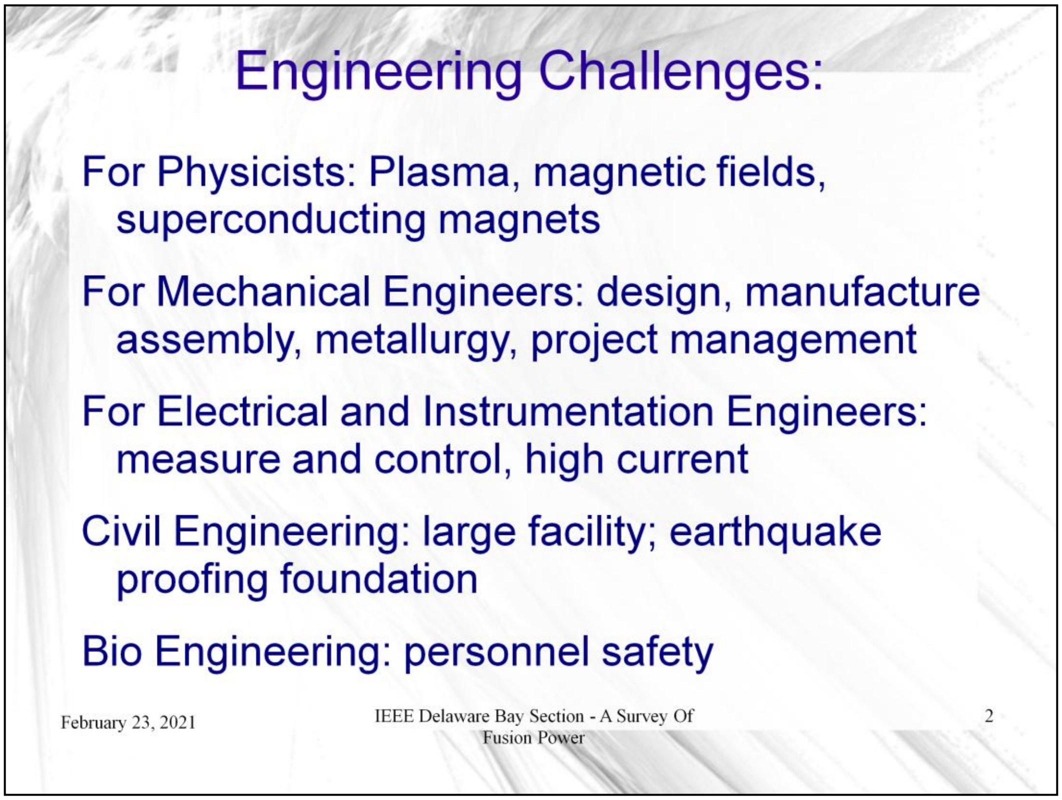
Review efforts to date
Efforts prior and concurrent to ITER

Progress since 1950: Ever larger research machines to reach increasing power outputs. Fusion takes more power than originally expected.

Tokamak type fusion machines have reached 70% break even power for a few seconds. Time limit due to magnetic instability and temperature shielding. Break even is defined as power output = energy input; supporting system power not included. Ultimate goal is continuous, self supported operation at the 100X level.

Inertial pulsed laser machines have reached near break even, but only for a few nanoseconds.  A final system would be pulsed operation.

Almost every major country has a Tokamak research facility.



## Engineering Challenges:

For Physicists: Plasma, magnetic fields, superconducting magnets

For Mechanical Engineers: design, manufacture assembly, metallurgy, project management

For Electrical and Instrumentation Engineers: measure and control, high current

Civil Engineering: large facility; earthquake proofing foundation

Bio Engineering: personnel safety

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Engineering Challenges, some examples:

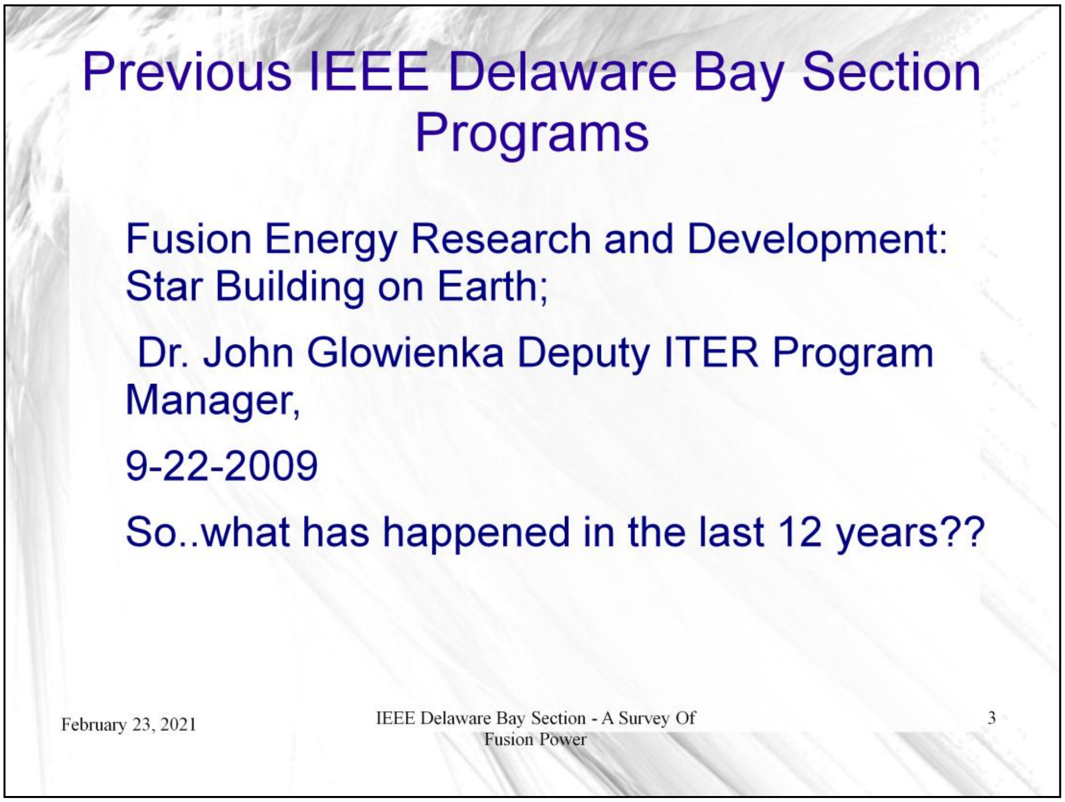
For Physicists: Plasma properties at 100,000,000 degC; magnetic fields, interaction with H ions, cyclotron heating of neutral particles,

For Mechanical Engineers: design of fusion source for a power plant; design, manufacture of very large machine parts built to tight tolerances, assembly of complex machines; Project management

For Electrical and Instrumentation Engineers: How to measure and control a hot plasma, metallurgy of magnets and vessel walls, design and construction of superconducting, liquid He support

Civil Engineering: Layout of a large facility; earthquake proofing foundation

Bio Engineering: protection of operating personnel from high energy particles



# Previous IEEE Delaware Bay Section Programs

Fusion Energy Research and Development: Star Building on Earth;

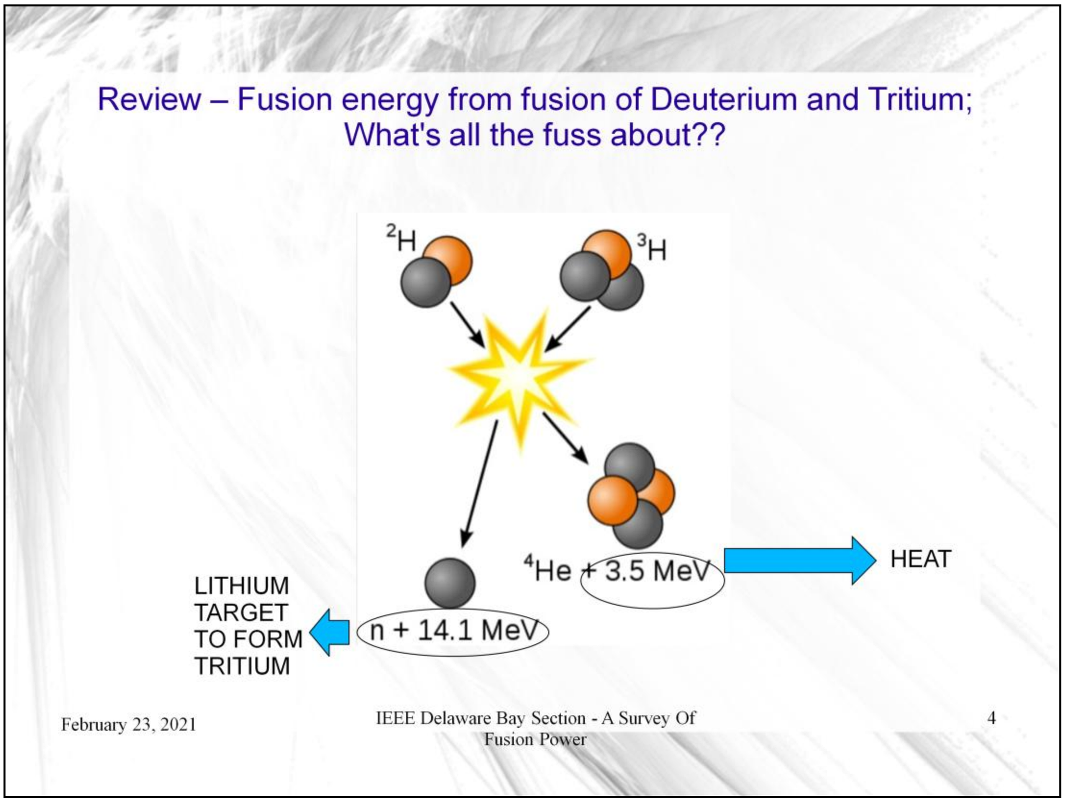
Dr. John Glowienka Deputy ITER Program Manager,

9-22-2009

So..what has happened in the last 12 years??

ITER project initiated in 2006, ground broken in 2010.

Major problems are (as usual) political, funding and design



## Review – Fusion energy from fusion of Deuterium and Tritium; What's all the fuss about??

$^{2}H$

$^{3}H$

$^{4}He + 3.5$ MeV

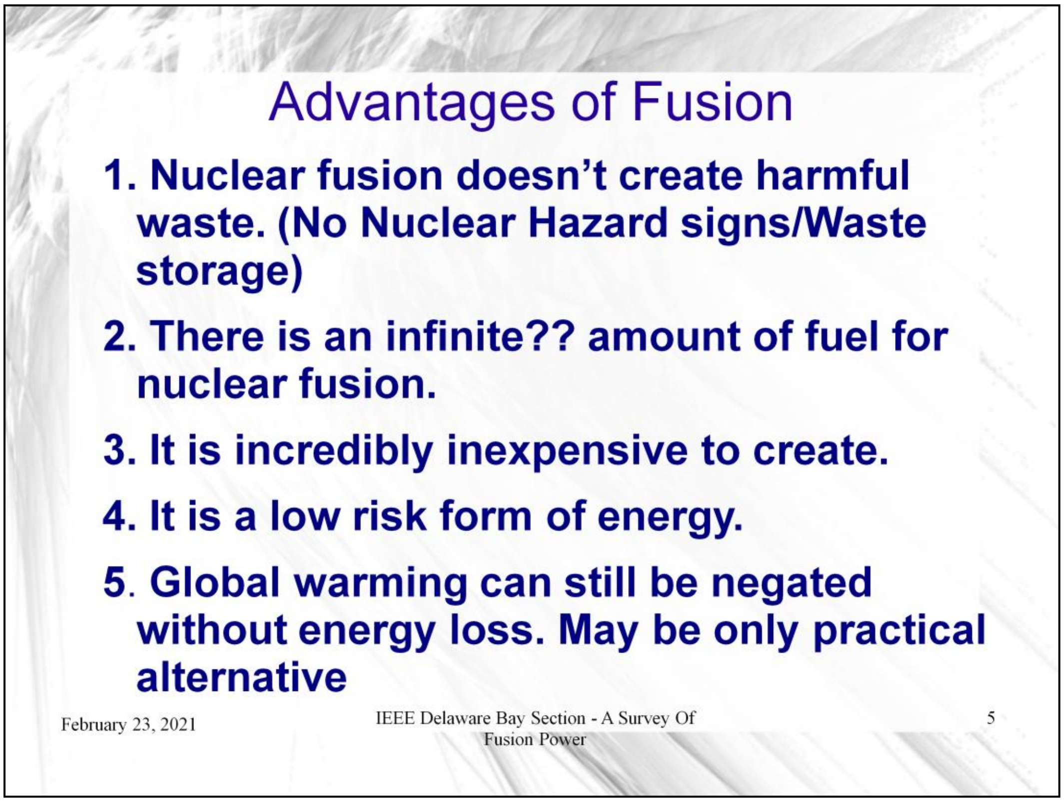
HEAT

LITHIUM TARGET TO FORM TRITIUM

n + 14.1 MeV

The 3.5 MeV is available for heat, which heats a liquid coolant. Also, some authors believe part of the 14.1 MeV is available due to interaction of neutrons on the vessel walls. From there on the process is similar to a steam or nuclear power source.Take the Hay Road plant, rip out the coal/gas fired part and replace with fusion part.

The H H fusion can also generate energy but is 1/40th of the DT-TR fusion



## Advantages of Fusion

1. **Nuclear fusion doesn’t create harmful waste. (No Nuclear Hazard signs/Waste storage)**
2. **There is an infinite?? amount of fuel for nuclear fusion.**
3. **It is incredibly inexpensive to create.**
4. **It is a low risk form of energy.**
5. **Global warming can still be negated without energy loss. May be only practical alternative**

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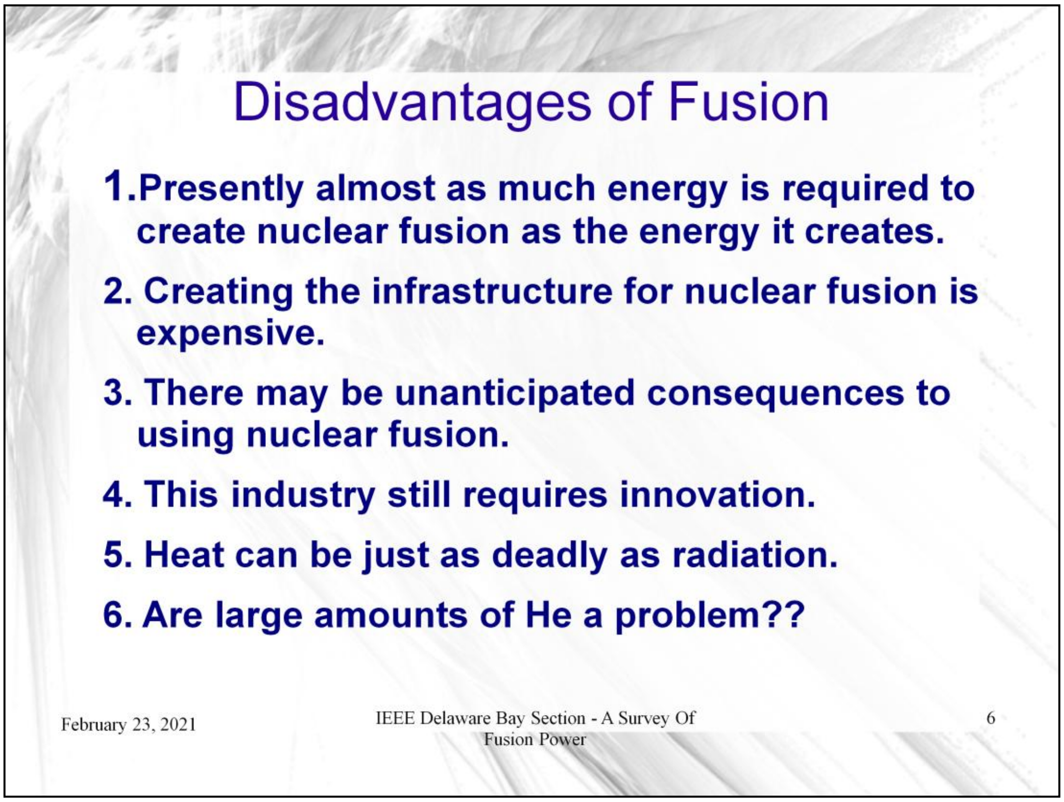
Don't have to use the word “nuclear”.

Tritium is radioactive with a lifetime of 10 years, but hopefully all the tritium will convert to He.

The cost of both the power plant and the fuel would be less than existing sources – according to prevailing theory.

The only “fuel” needed is sea water. to supply deuterium; tritium is generated from lithium. The tritium “breeder” idea is to be tested shortly using the JET Tokmak.



## Disadvantages of Fusion

1. Presently almost as much energy is required to create nuclear fusion as the energy it creates.
2. Creating the infrastructure for nuclear fusion is expensive.
3. There may be unanticipated consequences to using nuclear fusion.
4. This industry still requires innovation.
5. Heat can be just as deadly as radiation.
6. Are large amounts of He a problem??

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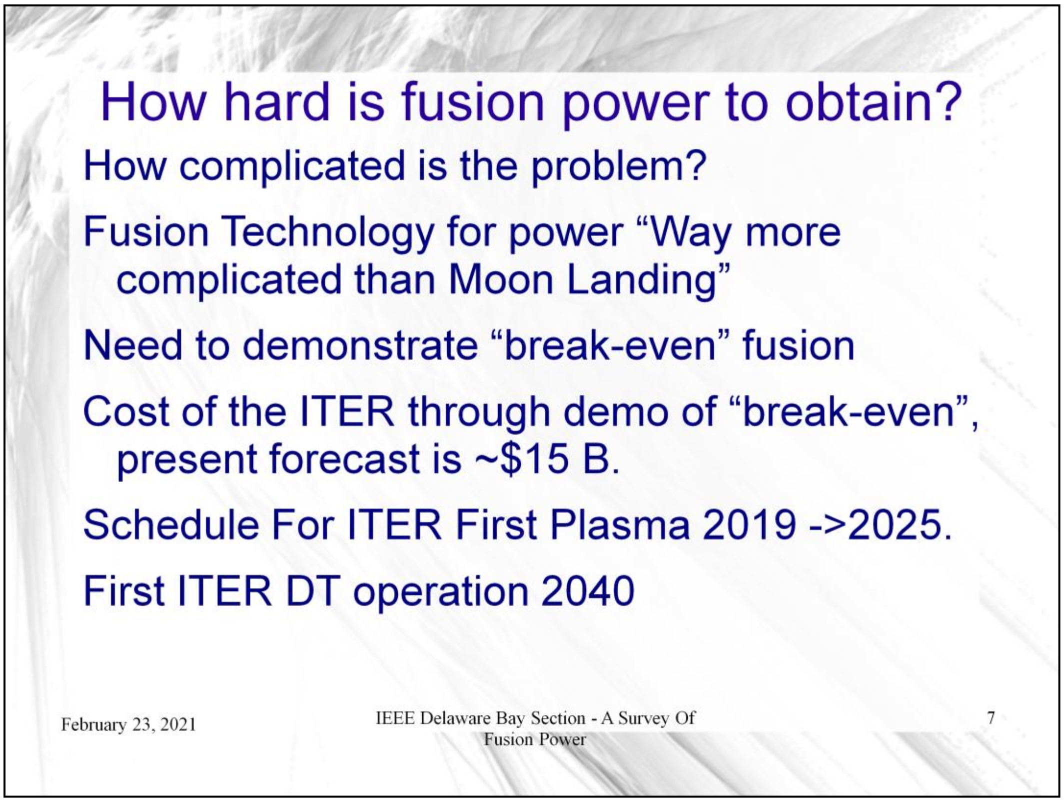
The present record for break-even is 0.7 in the JET for fraction of seconds

This does not include the support facilities, such as liquid He cooling plant, vacuum pumps, water pumps, etc

An example of consequences is fission, where the extent of waste disposal, pubic reaction and safety problems were not realized at the start

We don’t know if the tritium breeder idea will work. JET project is setting up a test.

The infrastructure for the ITER is expensive, but long range the fusion plant is expected to be much less expensive than conventional fuel plants.



## How hard is fusion power to obtain?

How complicated is the problem?

Fusion Technology for power “Way more complicated than Moon Landing”

Need to demonstrate “break-even” fusion

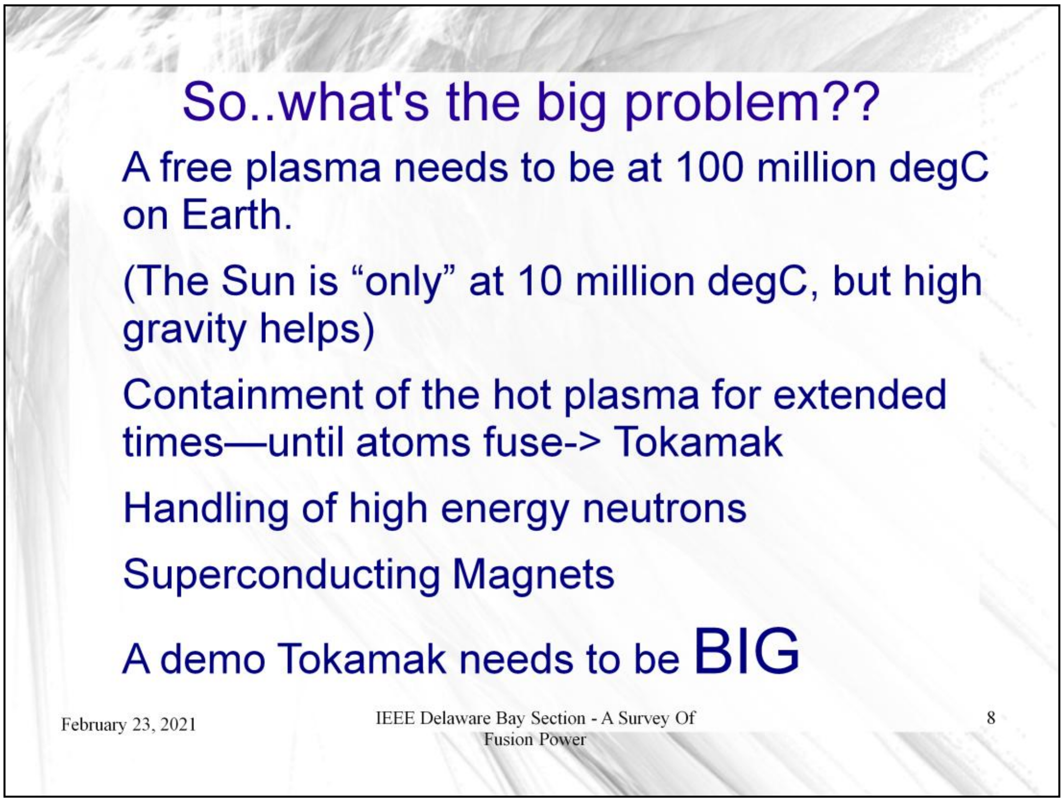
Cost of the ITER through demo of “break-even”, present forecast is ~$15 B.

Schedule For ITER First Plasma 2019 ->2025.

First ITER DT operation 2040

After ITER us next phase called DEMO, which is a power plant prototype. It will have less scientific instrumentation and be less costly?? Design of DEMO depends on findings from ITER

ITER was origninally International Thermonuclear Experimental Reactor. Now, somebody found that iter is Latin for “The Way”. Your choice.



## So..what's the big problem??

A free plasma needs to be at 100 million degC on Earth.

(The Sun is “only” at 10 million degC, but high gravity helps)

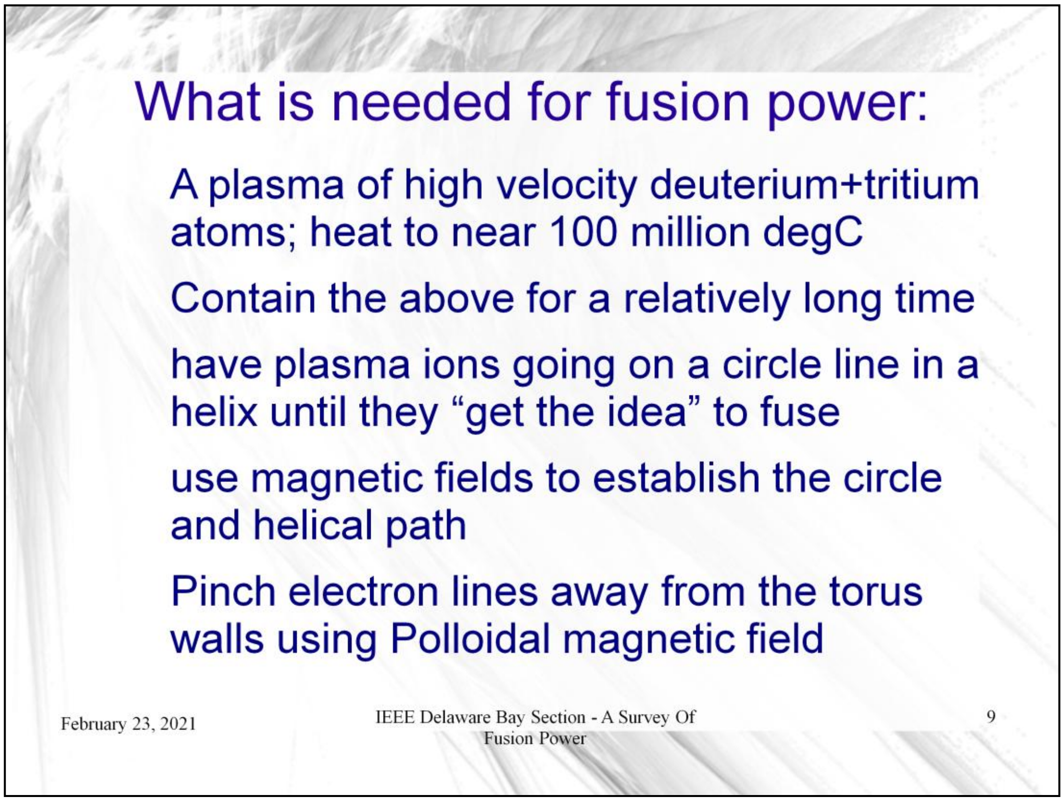
Containment of the hot plasma for extended times—until atoms fuse-> Tokamak

Handling of high energy neutrons

Superconducting Magnets

A demo Tokamak needs to be **BIG**

For heavier and more energy yielding element fusions, the temperature has to be much higher



## What is needed for fusion power:

A plasma of high velocity deuterium+tritium atoms; heat to near 100 million degC

Contain the above for a relatively long time

have plasma ions going on a circle line in a helix until they “get the idea” to fuse

use magnetic fields to establish the circle and helical path

Pinch electron lines away from the torus walls using Polloidal magnetic field

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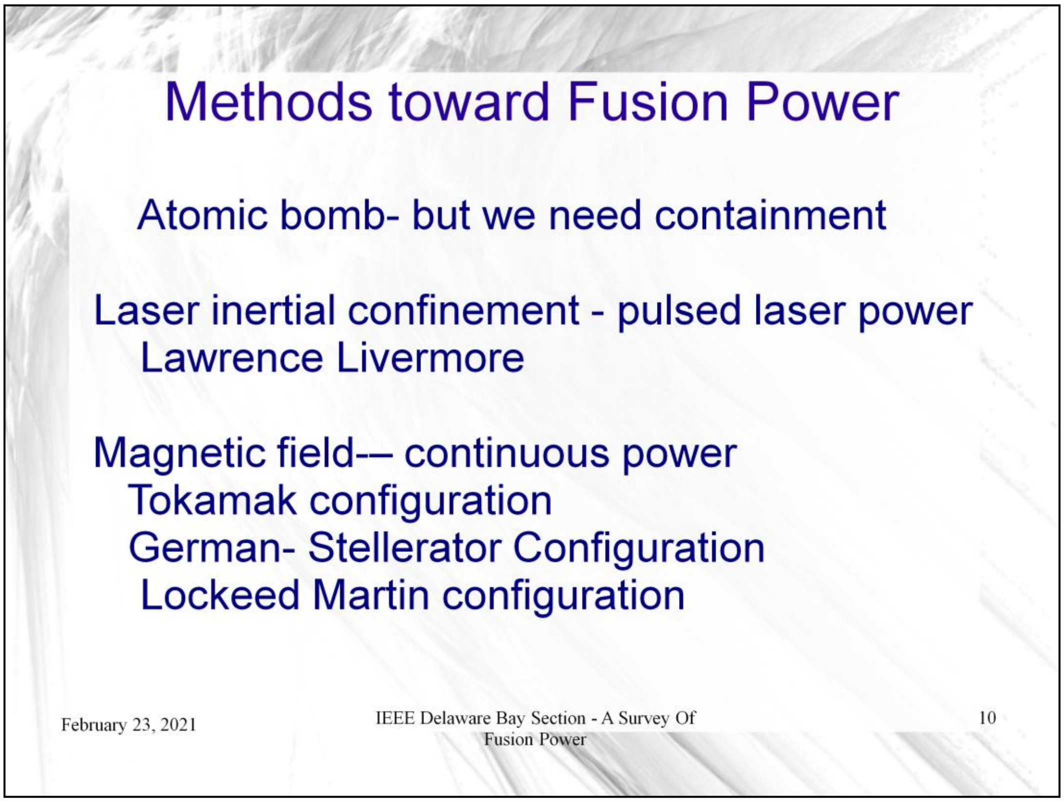
D/T reaction is “easiest” one that gives heat energy

Heavier nuclear reactions are possible but require more energy for fusion

The high temperature is needed to overcome the coulomb forces resisting fusion.

The theory is that particle velocity is equivalent to energy or heat.

The sun runs at 10 million degrees, but has much higher gravity than earth. Earth requires 100 million degrees. Until now, ions tend to become unstable in a relatively short time compared to what is needed for fusion to occur. A larger plasma volume is needed to allow us to control the ions better so they have more time to interact and “fuse”.



## Methods toward Fusion Power

Atomic bomb- but we need containment

Laser inertial confinement - pulsed laser power
Lawrence Livermore

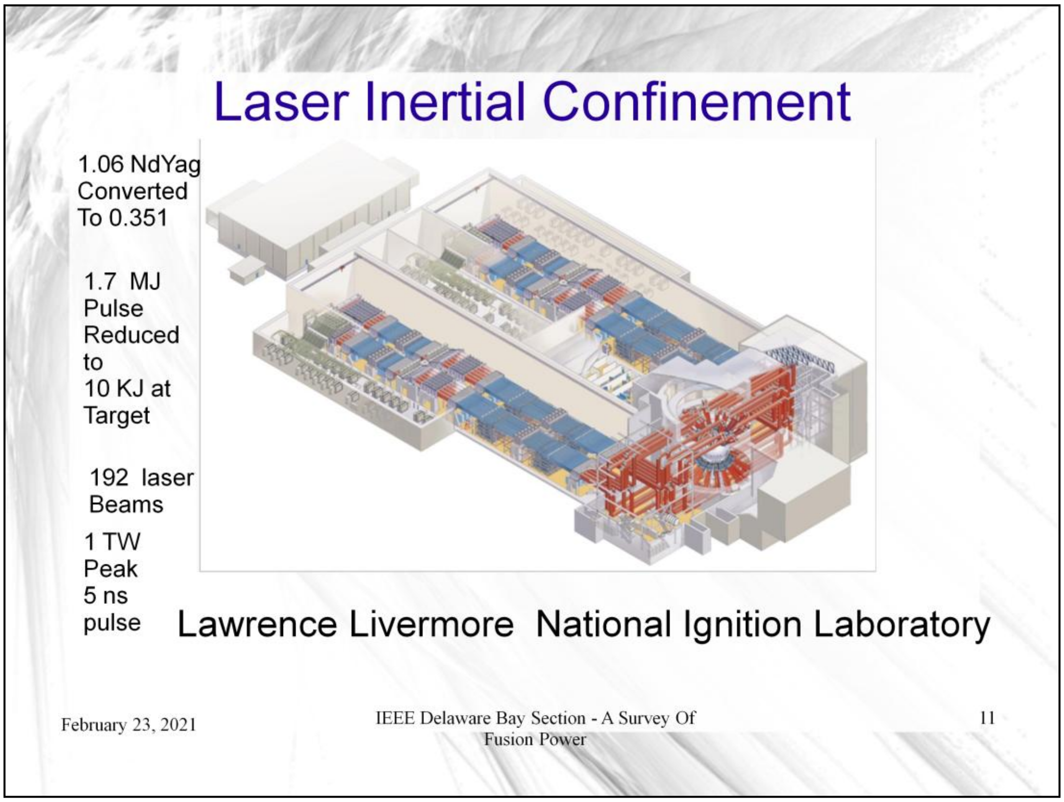
Magnetic field-– continuous power
Tokamak configuration
German- Stellerator Configuration
Lockeed Martin configuration

No one has even suggested using atomic energy as power source for a fusion power plant; what a relief!

Lawrence Livermore seems to have downgraded the importance of Fusion Power research, and turned to weapon research.

Tokamak was developed as a idea to contain ions in the 1950s.

Stellerator was developed in US, but dropped in favor of the Tokamak. Germany continues to pursue.



## Laser Inertial Confinement

1.06 NdYag
Converted
To 0.351

1.7 MJ
Pulse
Reduced
to
10 KJ at
Target

192 laser
Beams

1 TW
Peak
5 ns
pulse

Lawrence Livermore National Ignition Laboratory

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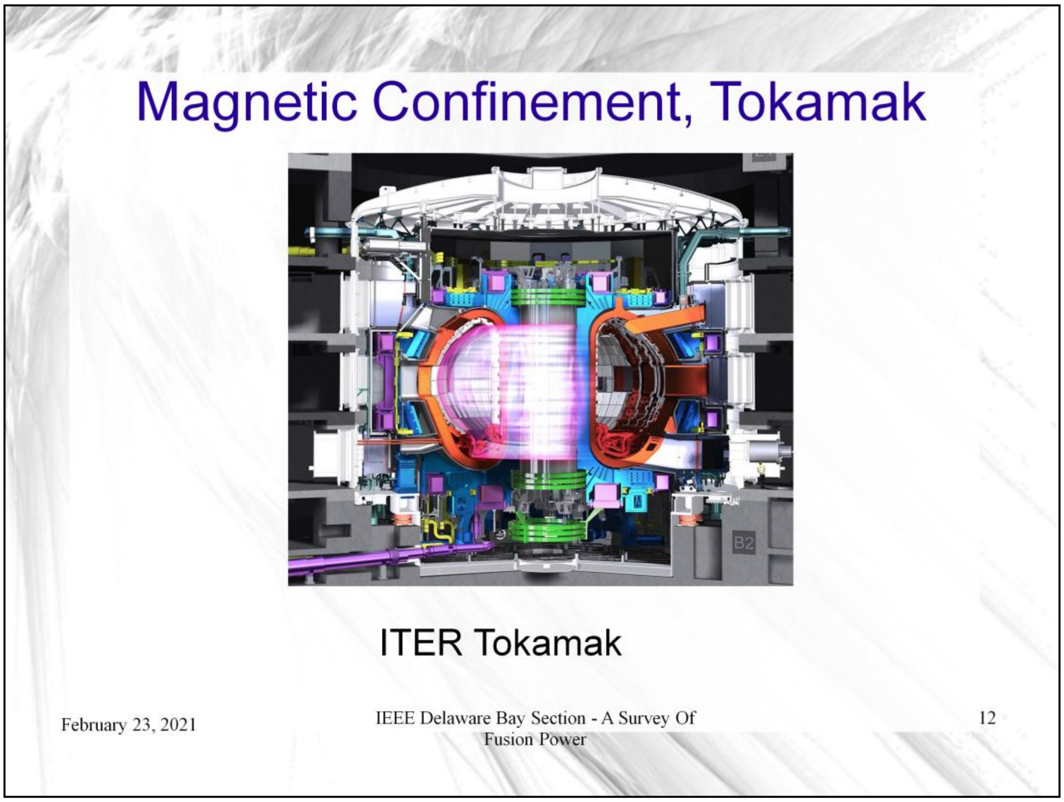
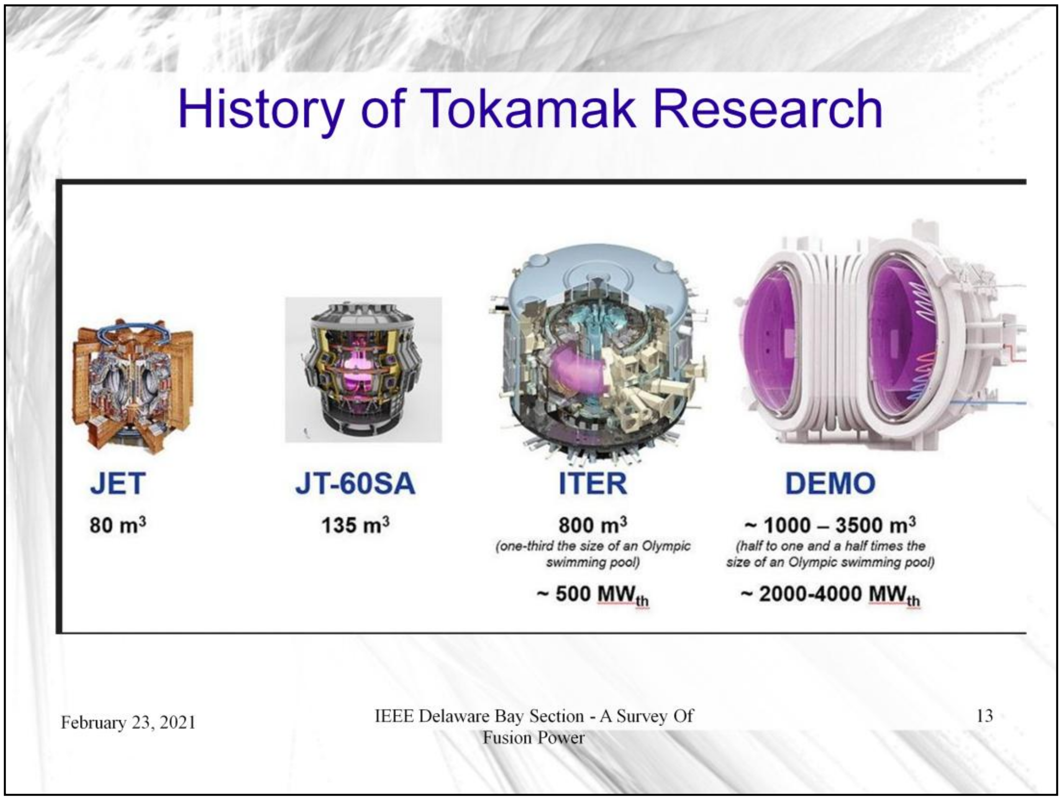
LL seems to have given up on break even for fusion; is becoming focused on military applications.



## Magnetic Confinement, Tokamak

ITER Tokamak

Original idea was to have a circular cross section “donut” shape. Later, a “spherical” approach was shown to have more capability, resulting in the “D” shaped cross section. This shape allows tighter magnetic coupling and a larger plasma volume.



# History of Tokamak Research

**JET**
80 m$^3$

**JT-60SA**
135 m$^3$

**ITER**
800 m$^3$
*(one-third the size of an Olympic swimming pool)*
~ 500 MW$_{th}$

**DEMO**
~ 1000 – 3500 m$^3$
*(half to one and a half times the size of an Olympic swimming pool)*
~ 2000-4000 MW$_{th}$

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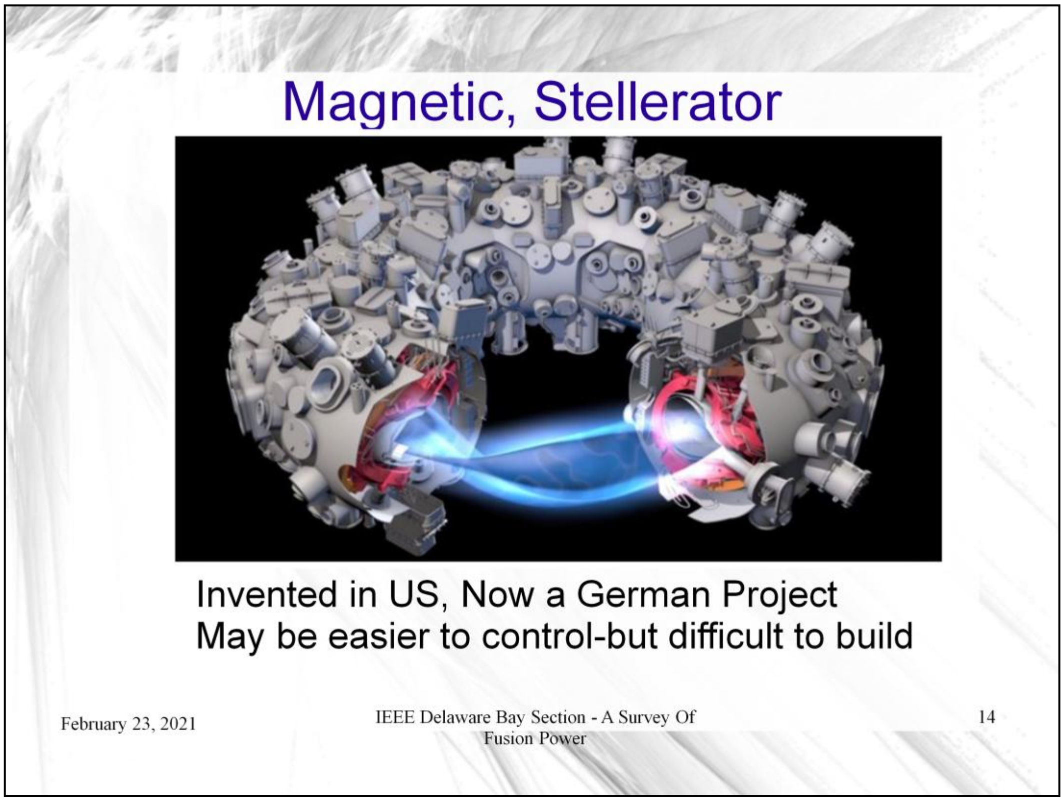
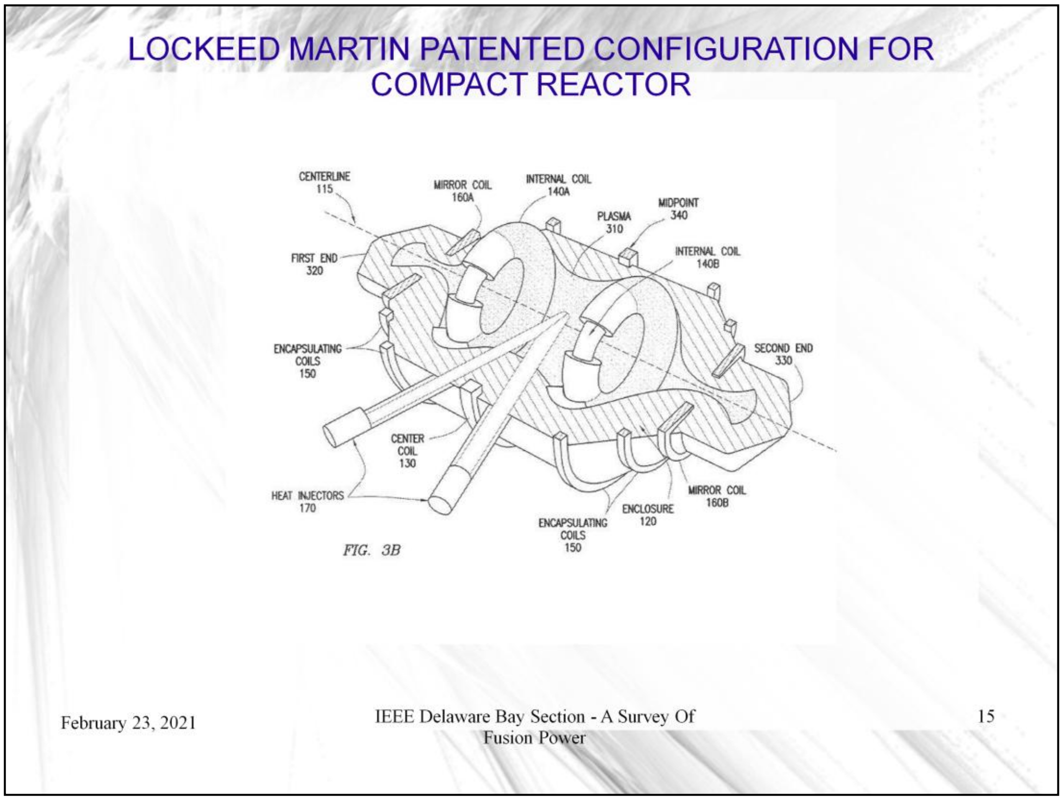
Tokamaks started “small”- the size of a single lab room. They have grown in size and power over the years.



## Magnetic, Stellerator

Invented in US, Now a German Project
May be easier to control-but difficult to build

The magnets produce a helix spiral on the entire plasma Originally, the engineering precision requirements to produce the plasma configuration were too high. As newer technology has solved some of these problems, hope has returned for this configuration.



## LOCKEED MARTIN PATENTED CONFIGURATION FOR COMPACT REACTOR

FIG. 3B

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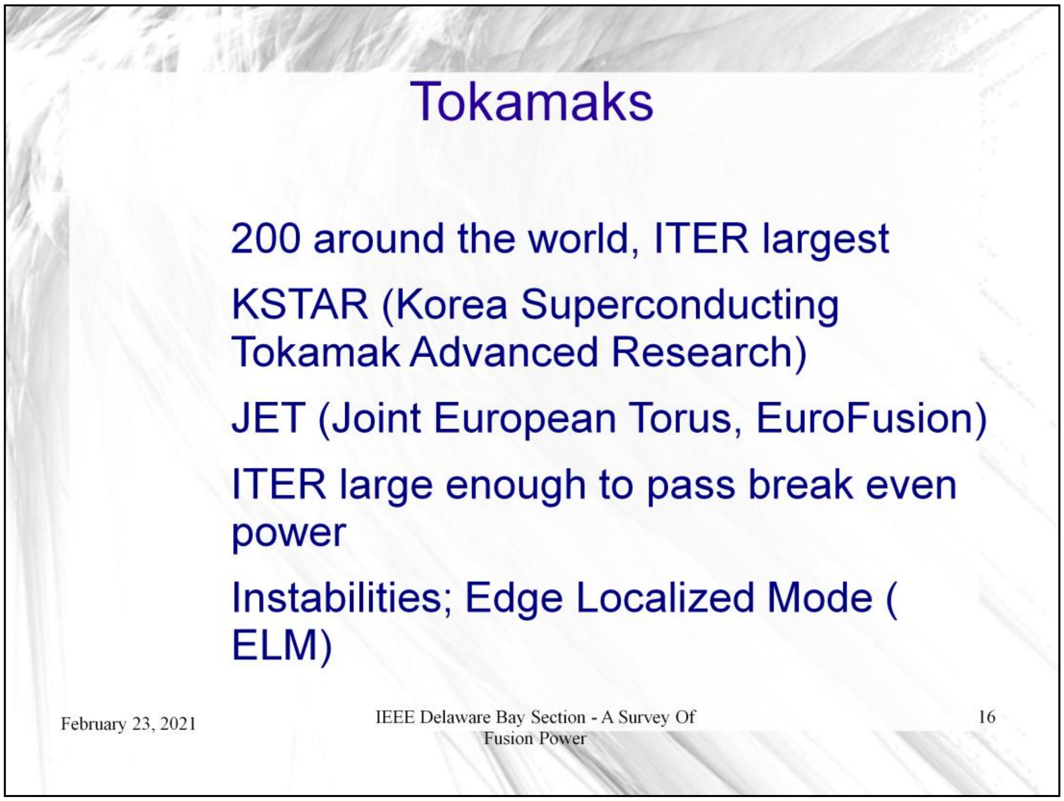
This is an attempt to reduce the size of a fusion reactor; applications to airplanes, small power plants are visualized. This project is reportedly supported in Lockeed's Skunk Works.

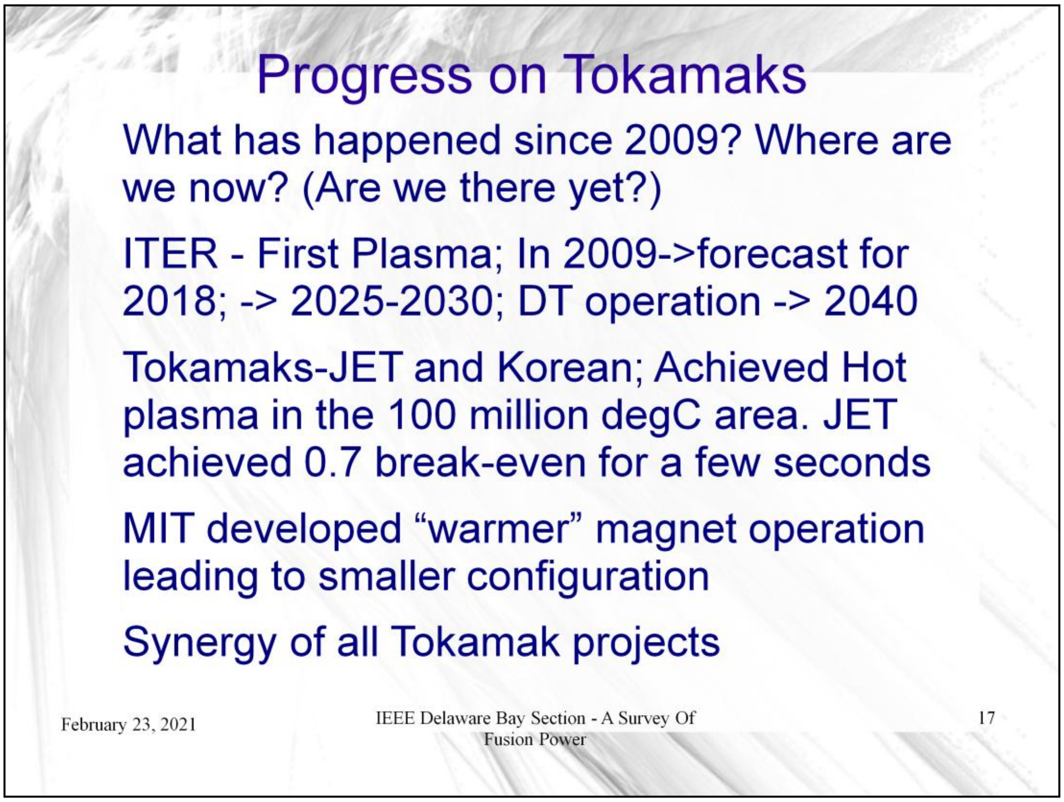


## Tokamaks

- 200 around the world, ITER largest
- KSTAR (Korea Superconducting Tokamak Advanced Research)
- JET (Joint European Torus, EuroFusion)
- ITER large enough to pass break even power
- Instabilities; Edge Localized Mode ( ELM)

The Japan Tokamak is slightly larger than JET, and is just now coming on line.

Both the Korean and JET have reported reaching plasma temperatures of 150 million degC (about 160 million degF)



## Progress on Tokamaks

What has happened since 2009? Where are we now? (Are we there yet?)

ITER - First Plasma; In 2009->forecast for 2018; -> 2025-2030; DT operation -> 2040

Tokamaks-JET and Korean; Achieved Hot plasma in the 100 million degC area. JET achieved 0.7 break-even for a few seconds

MIT developed “warmer” magnet operation leading to smaller configuration

Synergy of all Tokamak projects

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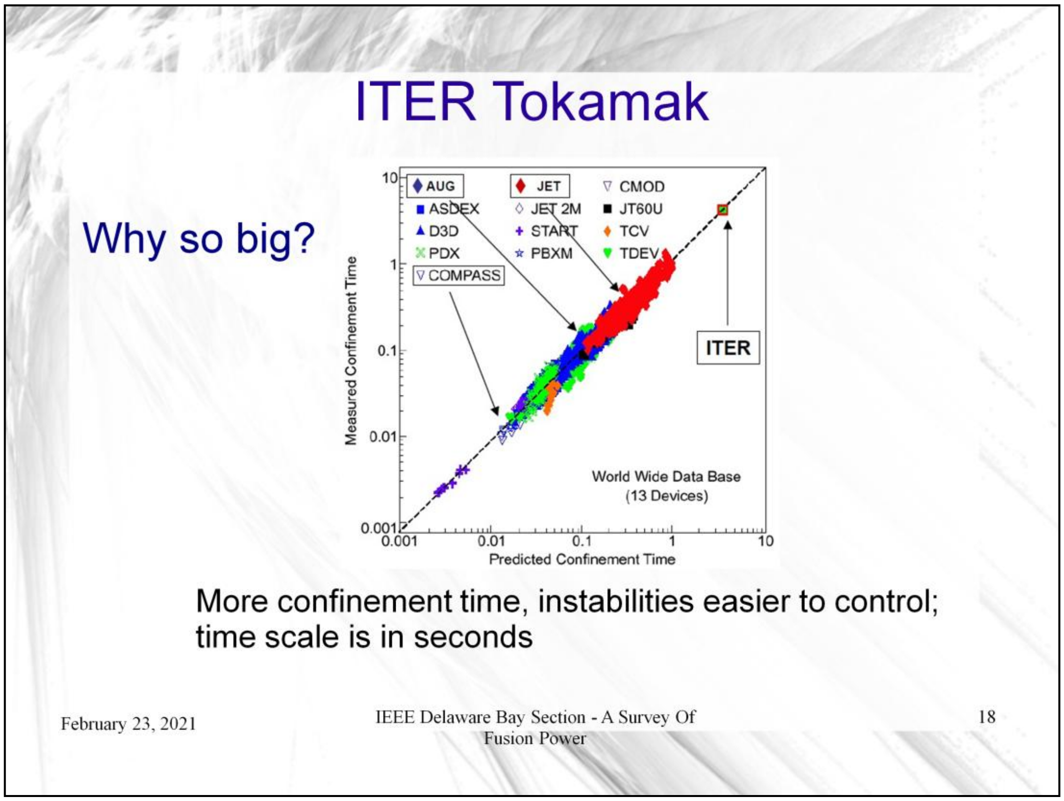
MIT work has split off to a commercial venture, Commonwealth Fusion Systems. It seems that the coronavirus has halted all essential work, as is the case with the ITER project.

As design issues arise with ITER, the total Tokamak community digs in to contribute. As design issues are solved, the results are usually incorporated in the smaller units.



## ITER Tokamak

Why so big?

More confinement time, instabilities easier to control; time scale is in seconds

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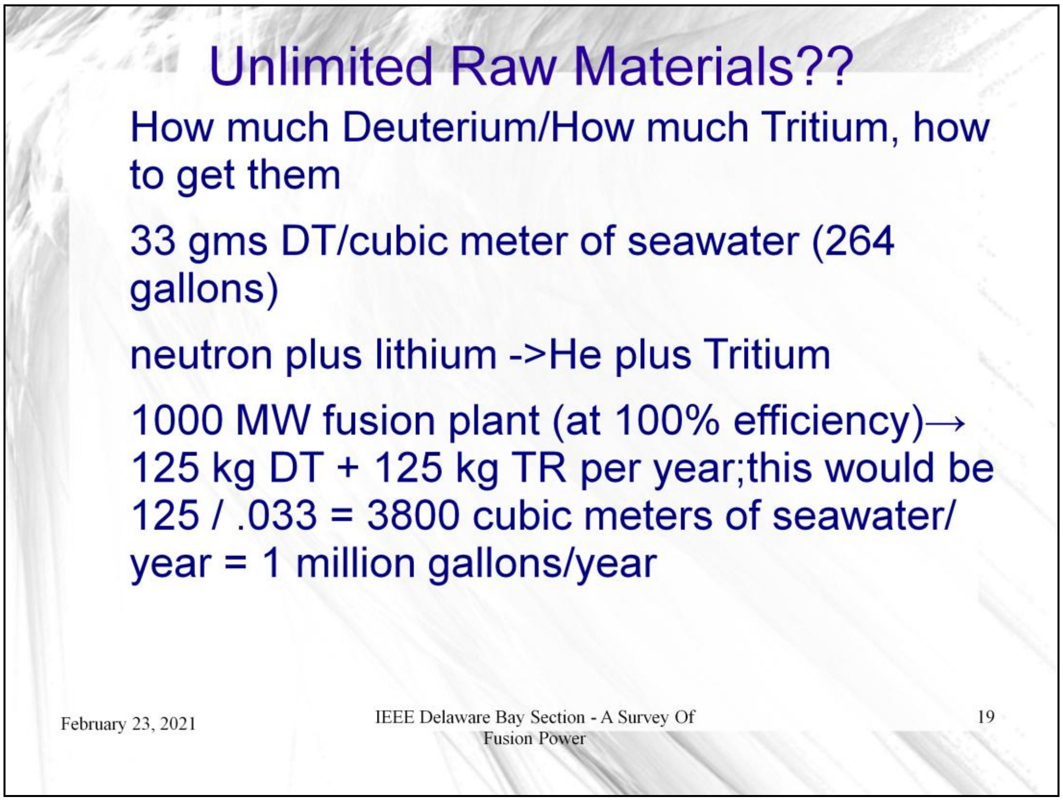
Scientists came to realize that a bigger plasma volume was needed for a Tokamak to reach a controlled and greater than break even operation. So far, break even has not been reached for even a few nanoseconds. Several theoretical studies show that the ITER volume is at the threshold of breakeven operation. Initially, ITER aims for 10X energy out/ energy required to heat the plasma; 50 MW in, 500 MW out.



## Unlimited Raw Materials??

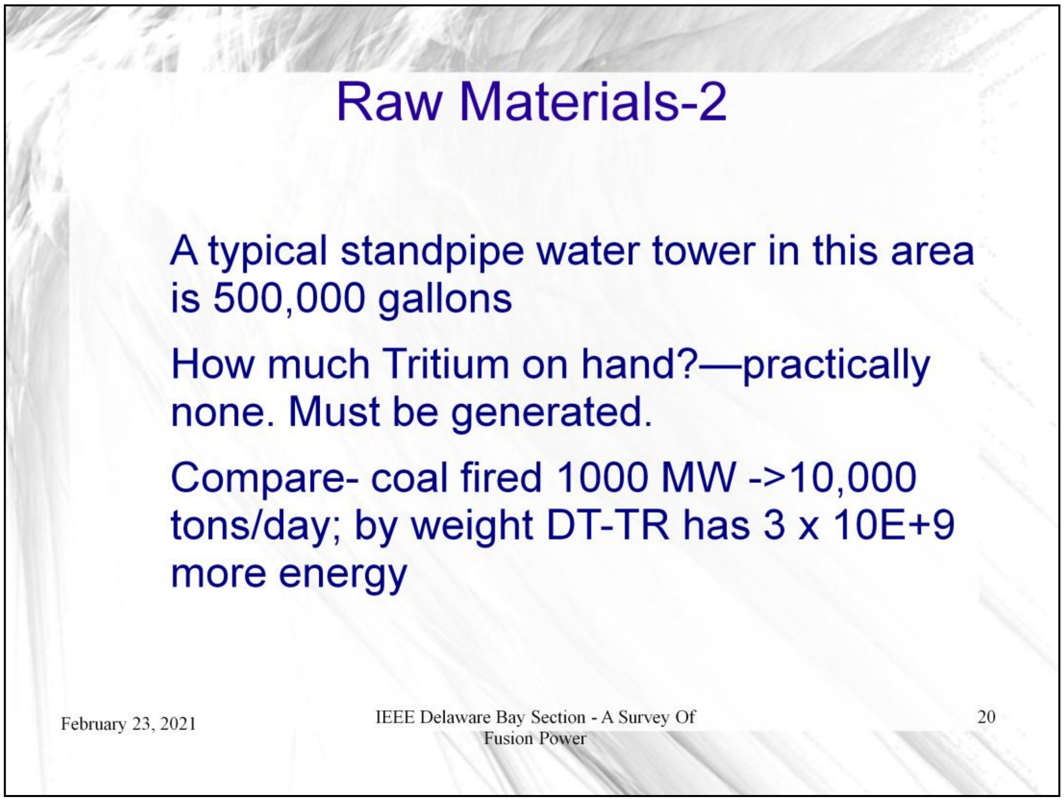
How much Deuterium/How much Tritium, how to get them

33 gms DT/cubic meter of seawater (264 gallons)

neutron plus lithium ->He plus Tritium

1000 MW fusion plant (at 100% efficiency)→ 125 kg DT + 125 kg TR per year;this would be 125 / .033 = 3800 cubic meters of seawater/ year = 1 million gallons/year

How to get Deuterium Hydrogen from water? From the web; First use a chemical process to separate H2O from D2O, them electrolysis to get D ions.



## Raw Materials-2

A typical standpipe water tower in this area is 500,000 gallons

How much Tritium on hand?—practically none. Must be generated.

Compare- coal fired 1000 MW ->10,000 tons/day; by weight DT-TR has 3 x 10E+9 more energy

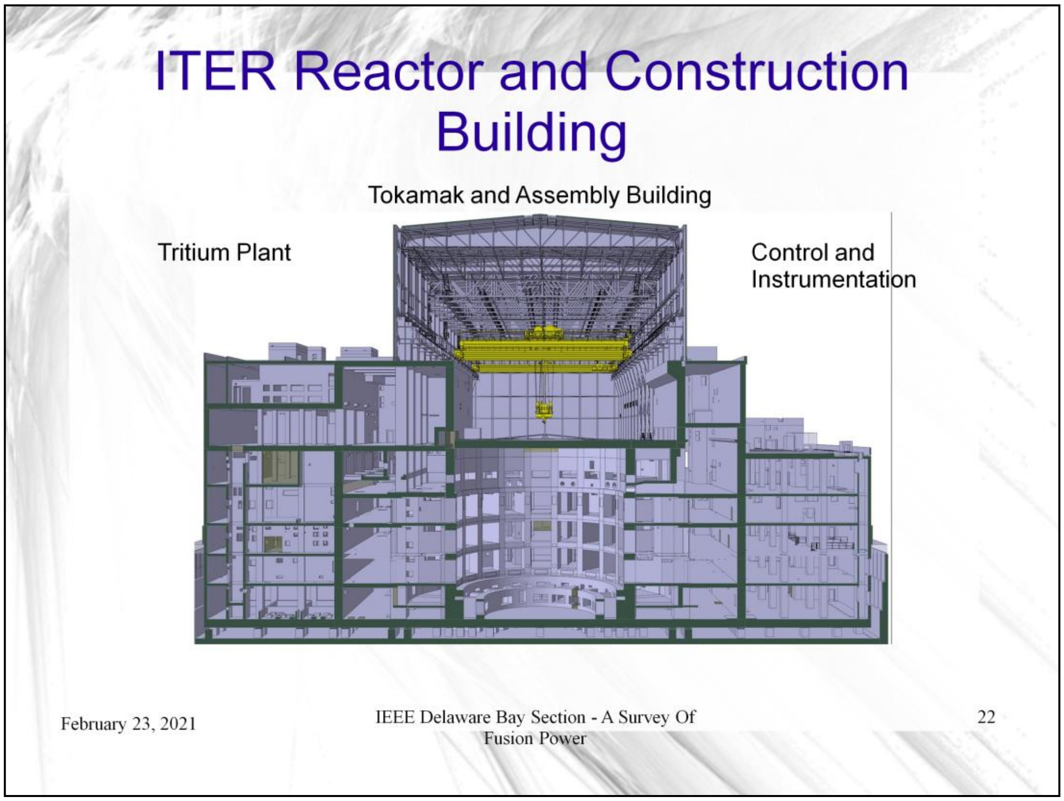
Out west there are 1.5 million gallon standpipe reservoirs

The standpipe reservoir in Brandywine Town Center is 500,000 gallons

# Plasma Measurements

100,000,000 degC temperatures. Theory is that T is atom velocity, so shoot laser beam and measure Doppler broadening of laser pulse.

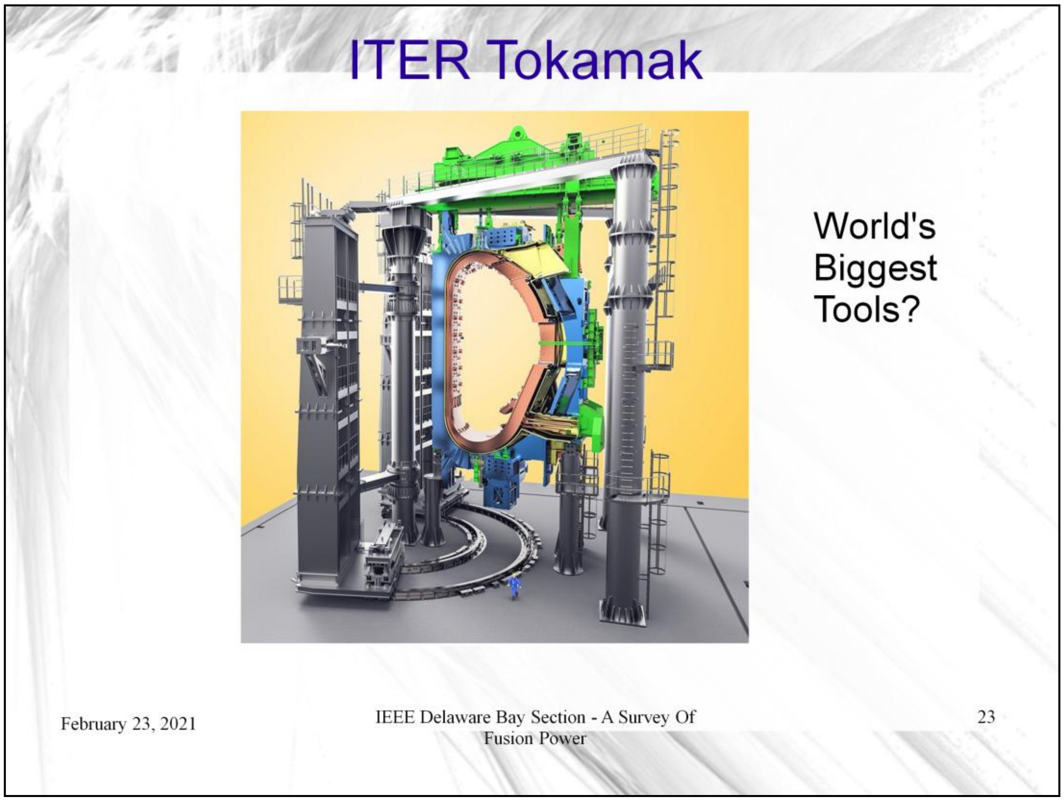
Particle Count. Use photon counters.



## ITER Reactor and Construction Building

### The seven-story Tokamak Complex

This detailed cutaway shows the buildings of the Tokamak Complex (Tritium, Tokamak and Diagnostics buildings, from left to right) and the seismic isolation system underneath the Complex. Once the Tokamak Building has been completed, and it matches the height of the Assembly Building, the temporary wall between them will come down and the rails for the heavy lift overhead cranes (in yellow) will be extended.



ITER Tokamak

World's
Biggest
Tools?

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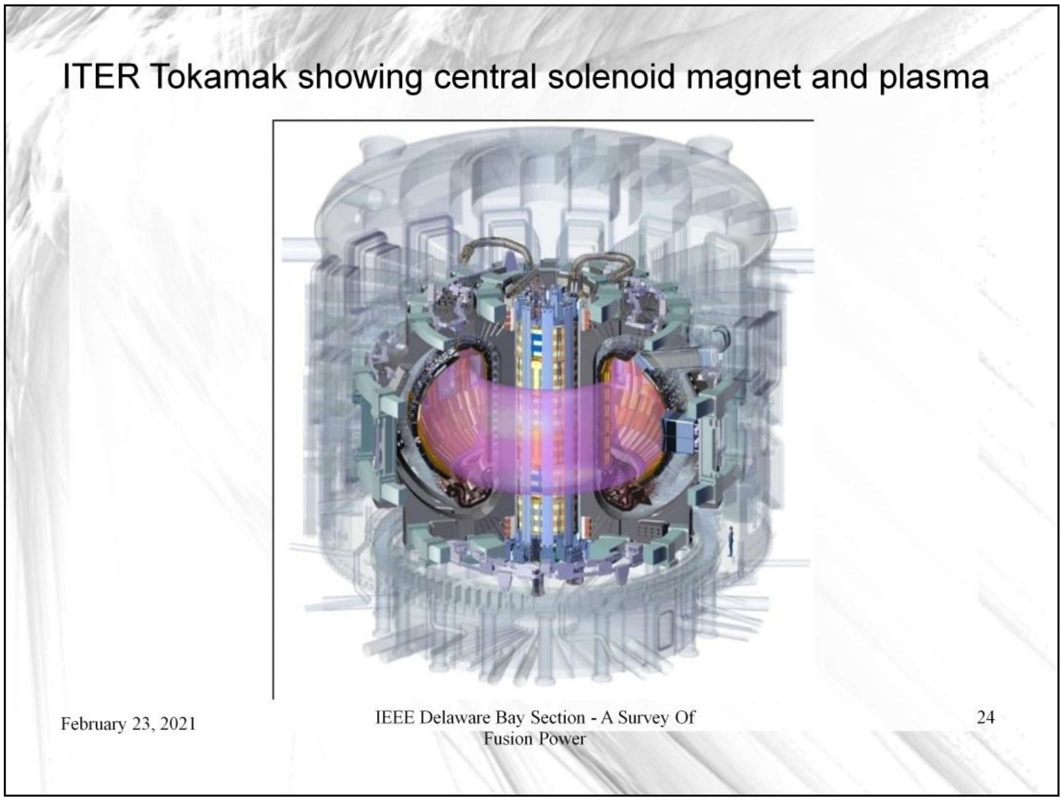
**Vacuum vessel sector sub-assembly tool**

Six stories high, made of 800 tonnes of steel, two Sector Sub-Assembly tools will work in concert to equip the nine sectors of the vacuum vessel before their transfer to the Tokamak Pit.



ITER Tokamak showing central solenoid magnet and plasma

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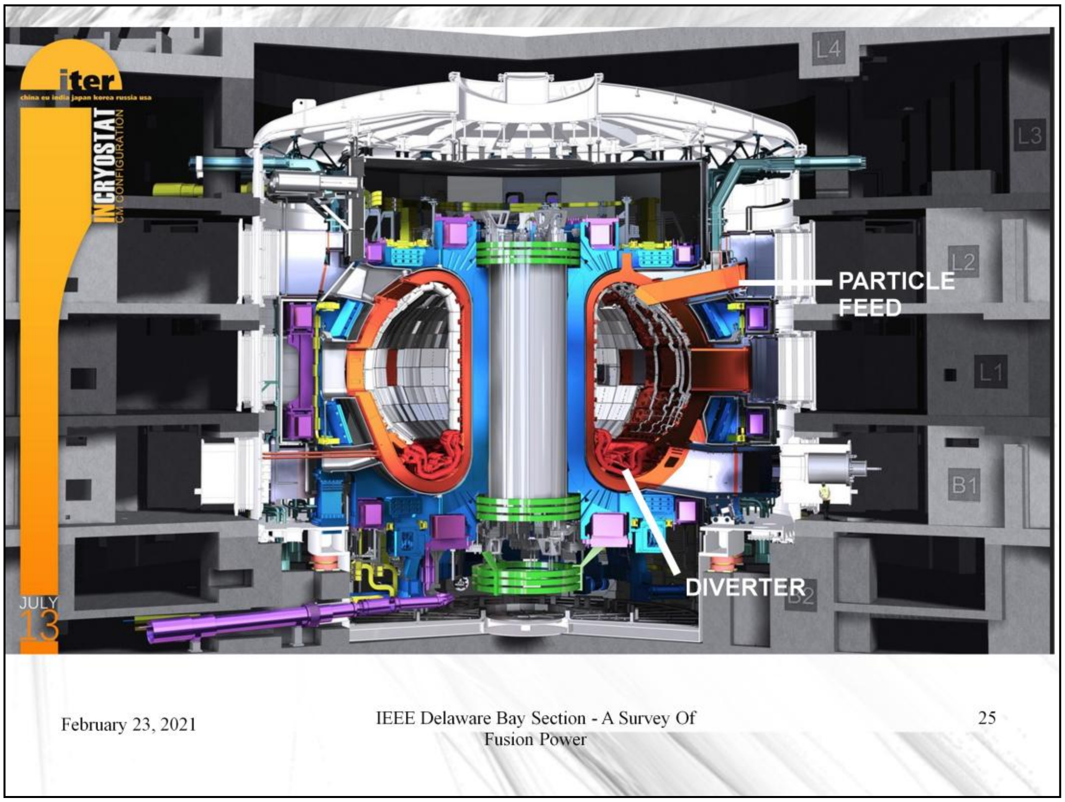
**Central solenoid**

A tall electromagnet--the central solenoid--is at the heart of the ITER Tokamak. It both initiates plasma current and drives and shapes the plasma during operation.



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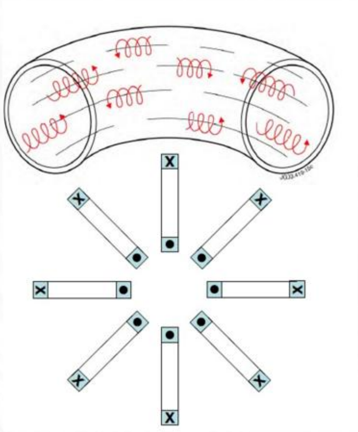
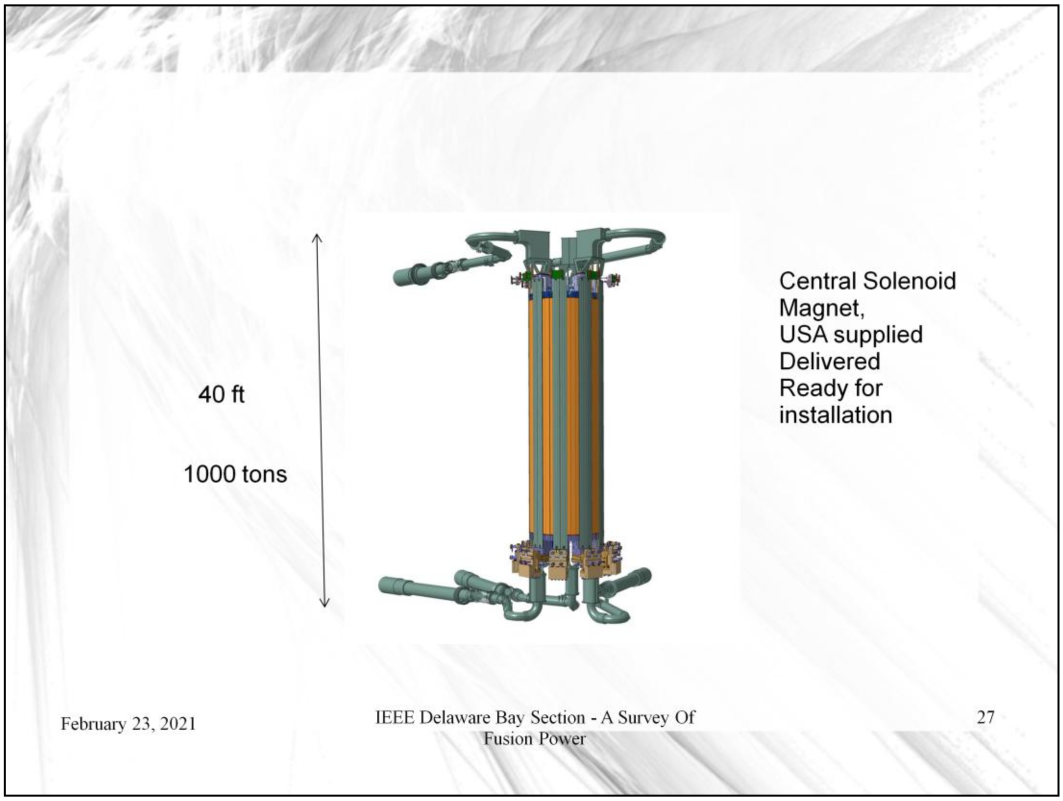
Note the Diverter and particle source feed sections

## Action of the Central Magnet and Toroid Magnet on the Plasma





40 ft

1000 tons

Central Solenoid
Magnet,
USA supplied
Delivered
Ready for
installation

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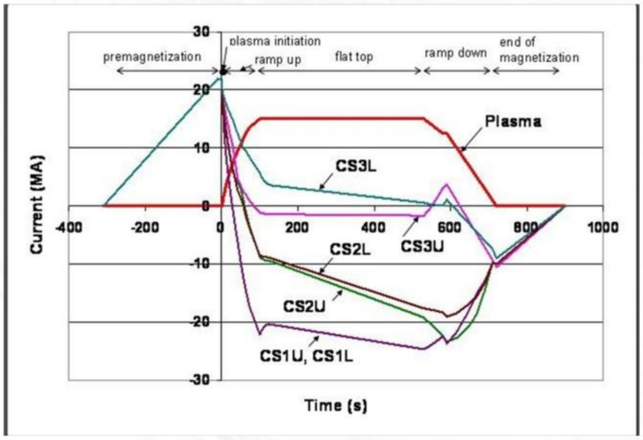
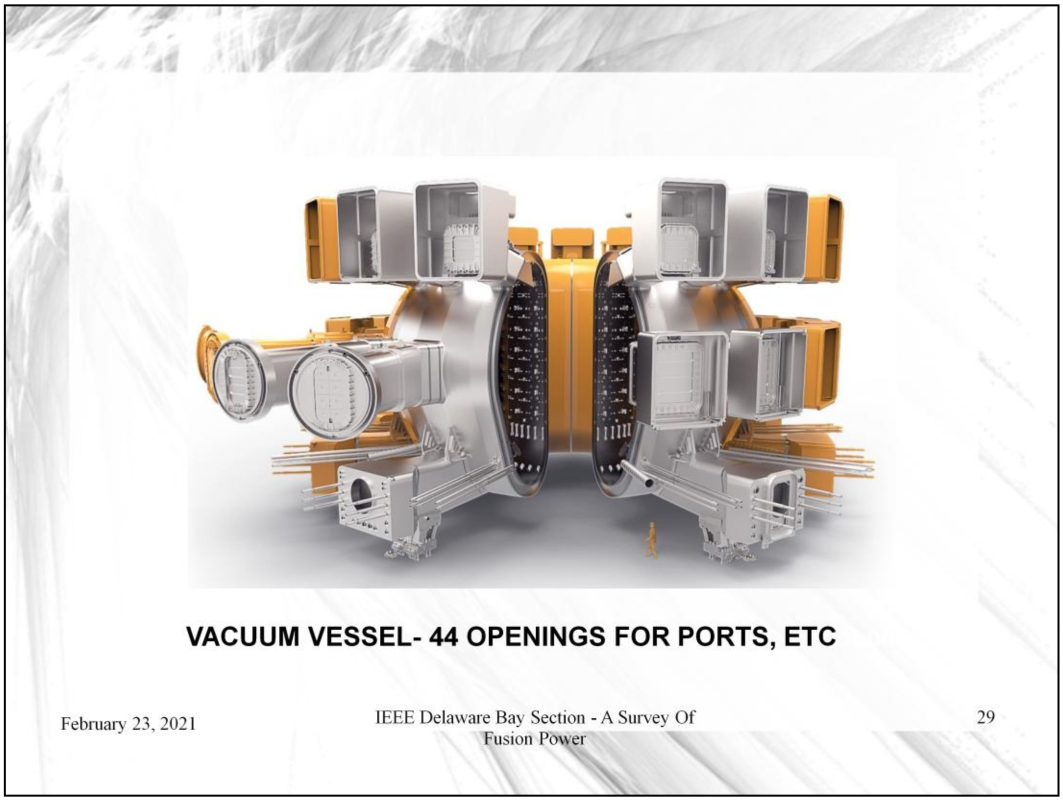
## Central solenoid

The central solenoid is the "backbone" of ITER's magnet system, allowing a powerful current to be induced in the ITER plasma and maintained during long plasma pulses. Thirteen metres tall, four metres wide and one thousand tonnes, it's also one of the largest components of the machine.



Central
Magnet
Control
Current



VACUUM VESSEL- 44 OPENINGS FOR PORTS, ETC

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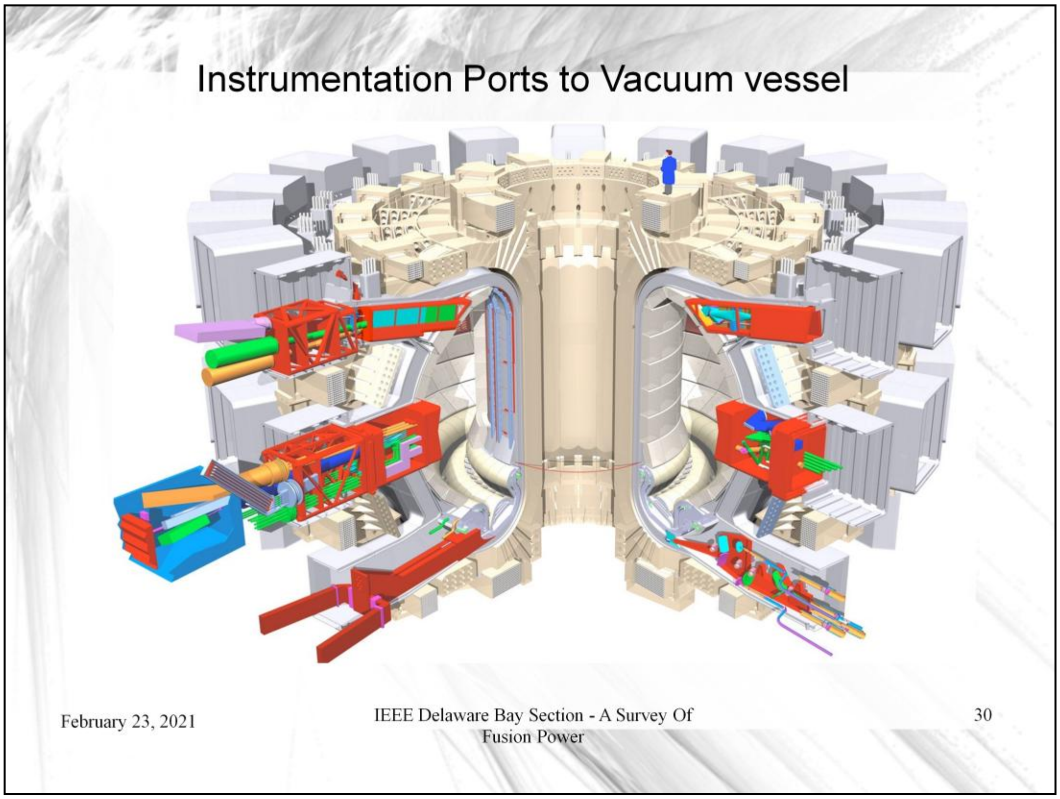
The stainless steel vacuum vessel houses the fusion reactions and acts as a first safety containment barrier. It is a double-walled, hermetically sealed steel container that is equipped with 44 openings, or ports, to allow access for remote handling operations, diagnostics, heating and vacuum systems.



## Instrumentation Ports to Vacuum vessel

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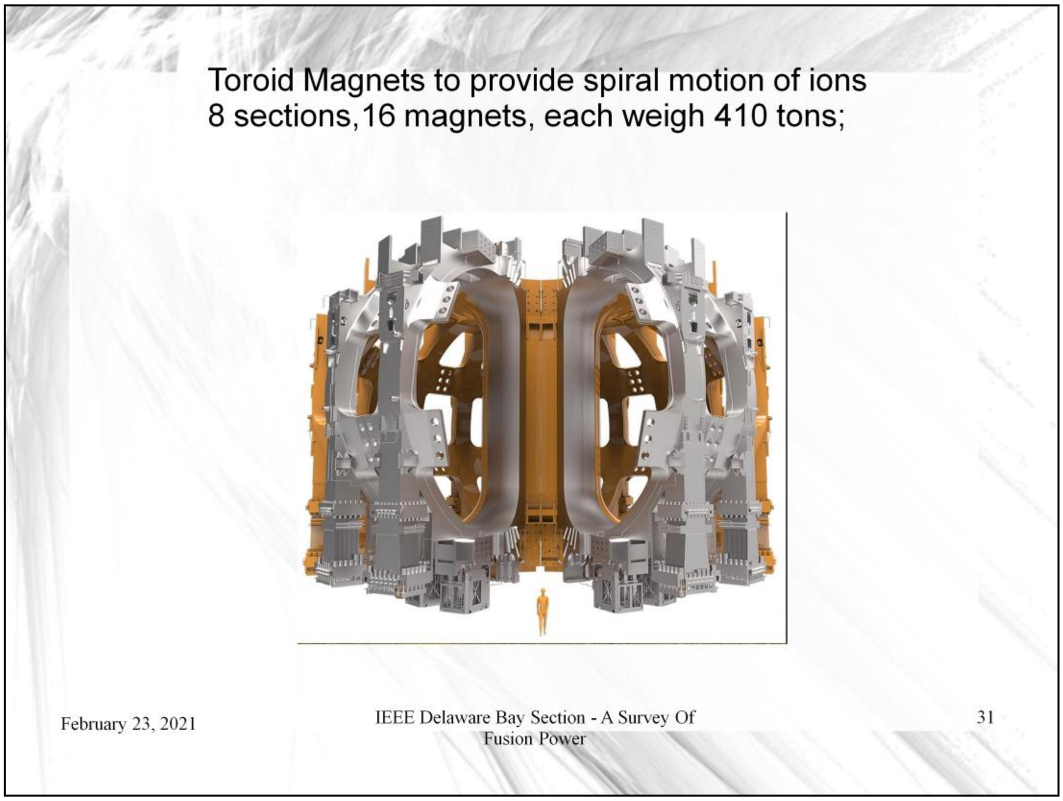
The instrumentation and control bays as they enter into the toroidal vacuum vessel.

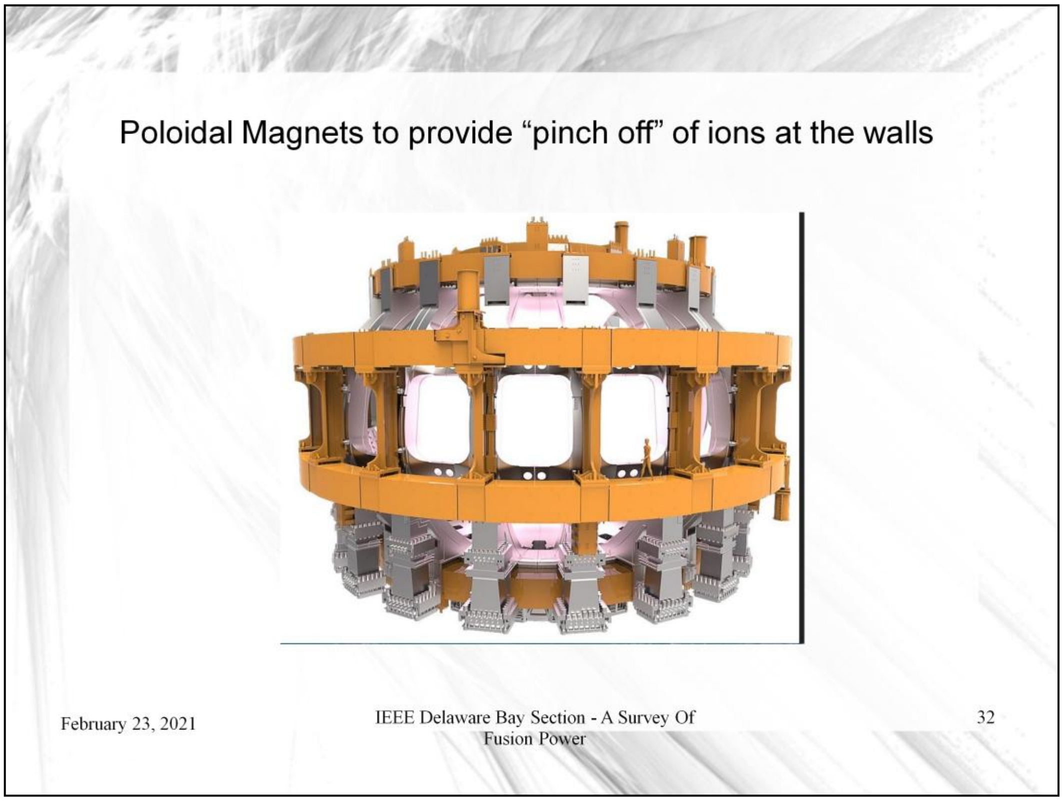


Toroid Magnets to provide spiral motion of ions
8 sections,16 magnets, each weigh 410 tons;

**Toroidal field coils**

Eighteen "D"-shaped toroidal field magnets will surround the torus-shaped vacuum vessel to confine the plasma particles. Measuring 17 metres in height, 9 metres in width, and weighing in at 310 tonnes each, these coils rank among the largest components of the ITER machine.

The coils are arranged in 9 sections and assembled using the tool shown earlier.



Poloidal Magnets to provide “pinch off” of ions at the walls

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**Poloidal field coils**

Six ring-shaped poloidal field magnets will surround the toroidal field magnet system to shape the plasma and contribute to its stability by "pinching" it away from the walls. The largest coil has a diameter of 24 metres; the heaviest is 400 metric tons.

Vacuum Cryostat containing the Tokamak

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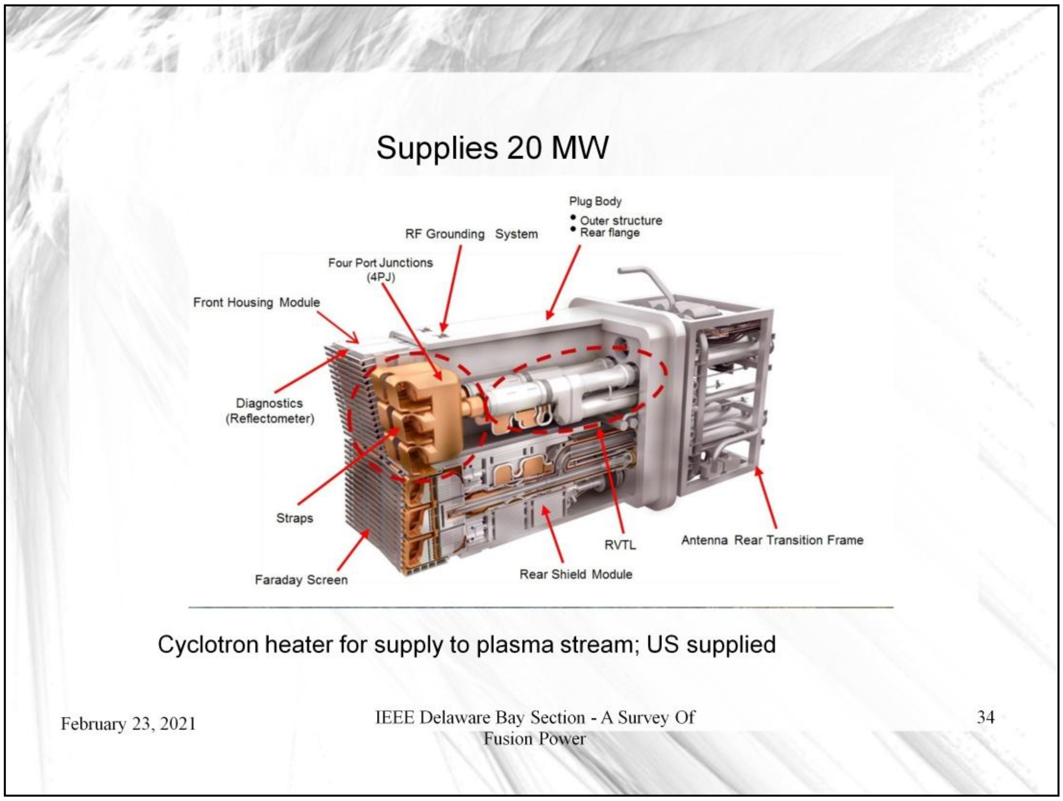
**The ITER cryostat**

16,000 $m^3$ in volume, 30 metres in height and as many in width—the ITER cryostat is not only one of the world's largest vacuum chambers, it's also by far the most complex.



Supplies 20 MW

Cyclotron heater for supply to plasma stream; US supplied

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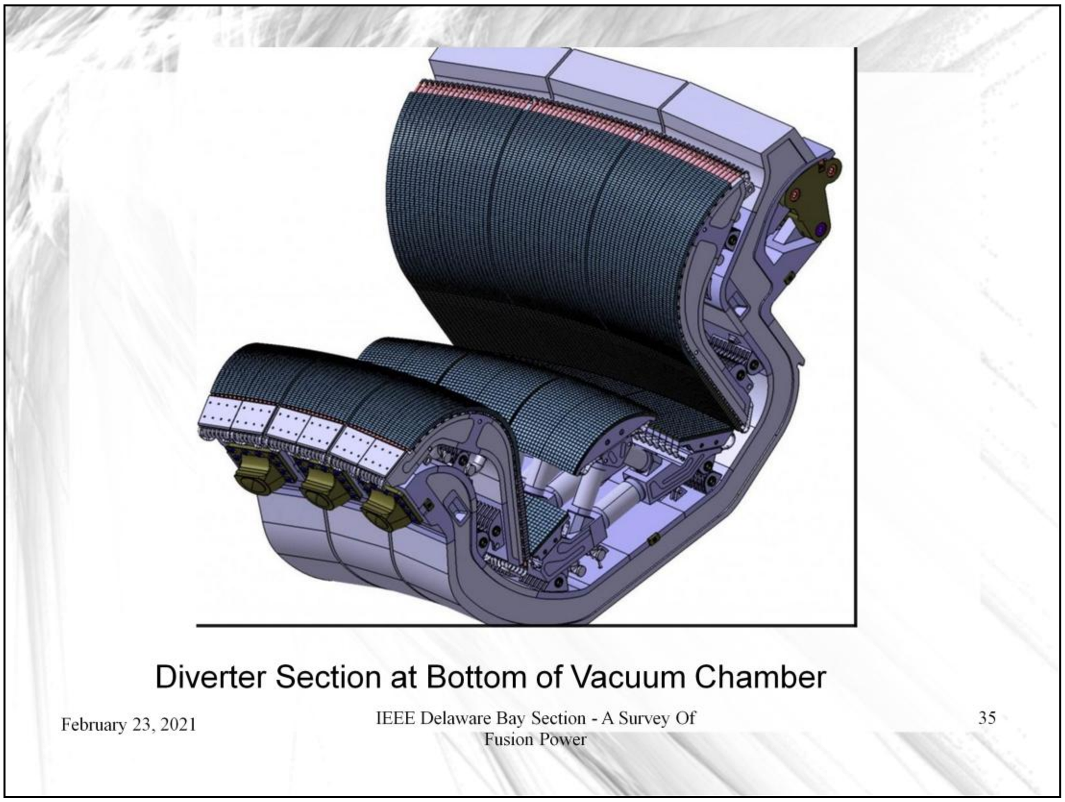
**ITER's ion cyclotron antenna**

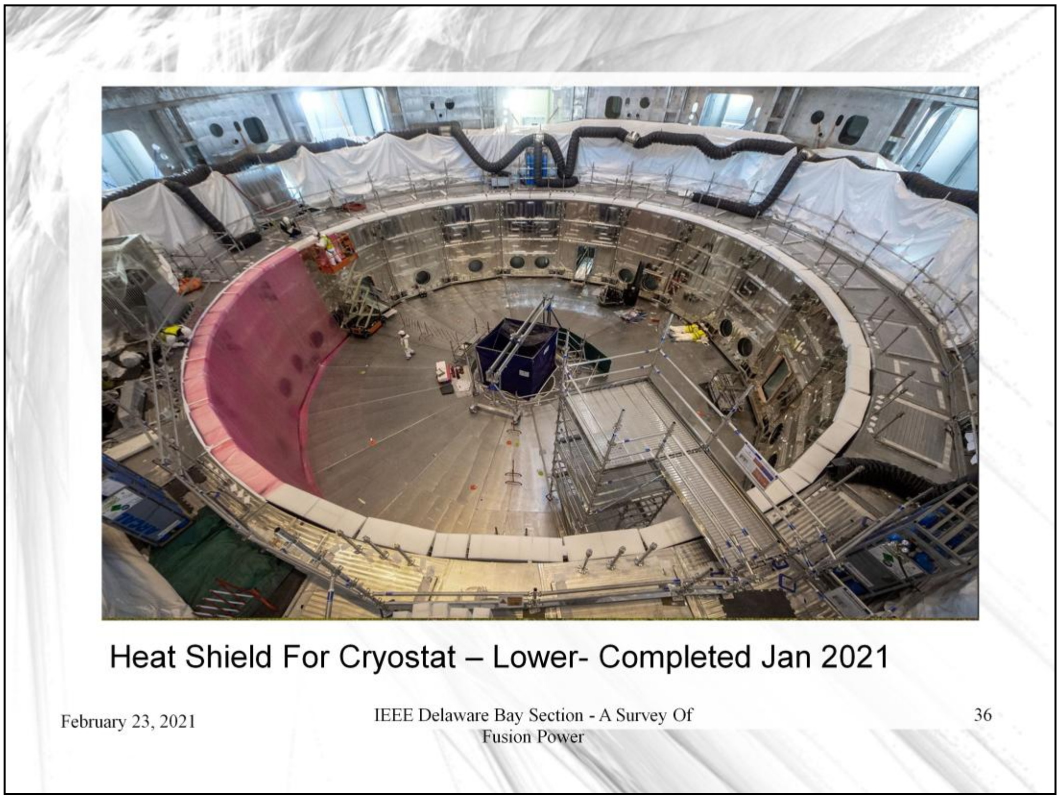
One of the two 45-ton ion cyclotron accelerator and resonant particle heating antenna systems that will deliver 10 MW of heating power each into the ITER machine. Heating frequency is in the 75 to 350 GHZ range.

Individual tubes about 50 mm diameter heat and accelerate neutral particles that hit the plasma ions to impart energy**.**



Diverter Section at Bottom of Vacuum Chamber

The diverter section is located at the bottom of the toroid, and carries away waste gases and heat. This is in the most intense magnetic field section, and also the hottest part overall. Materials technology has only recently provided materials of steel and ceramic alloy which can survive.



Heat Shield For Cryostat – Lower- Completed Jan 2021

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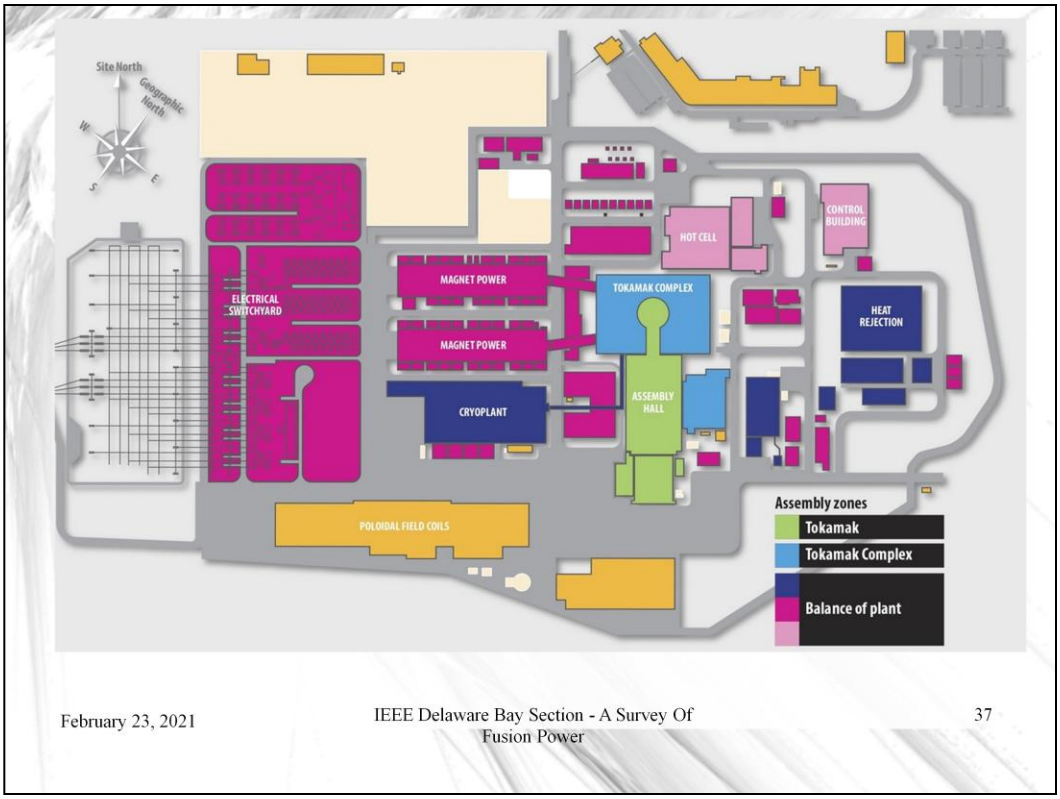
The cyostat heat shield is the first element to be inserted into the ITER Tokamak. The building environmental shield surrounding is in place, and is several feet of concrete. Elements to be placed in the Tokamak in the near future are being assembled in the part of the building behind the Tokamak area, and will use heavy lifting cranes to move and place them.

The concrete containment walls are seen in the background. Personnel will operate behind these walls. No personnel can be inside the containment walls due to high energy neutron flux.



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Most of the building structure is completed. This was funded and supplied by the EU.  Note the green area, where the parts from a number of nations arrive and are assembled into final parts, tested and then craned into the spherical Tokamak area.

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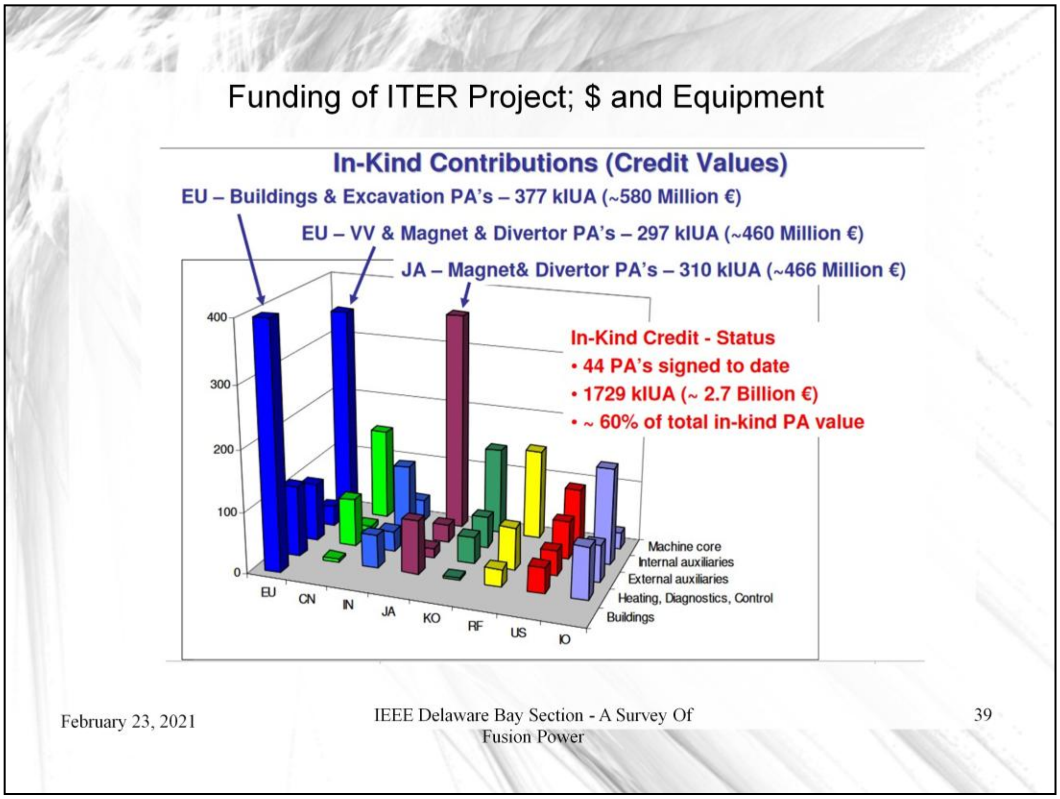
Layout of  plant. The site is about 500 acres. Located in southern France. It will reqire abut 600 MW when the Tokamak is being fired up, and about 100 MW at other times.



## Funding of ITER Project; $ and Equipment

**In-Kind Contributions (Credit Values)**

EU – Buildings & Excavation PA's – 377 kIUA (~580 Million €)

EU – VV & Magnet & Divertor PA's – 297 kIUA (~460 Million €)

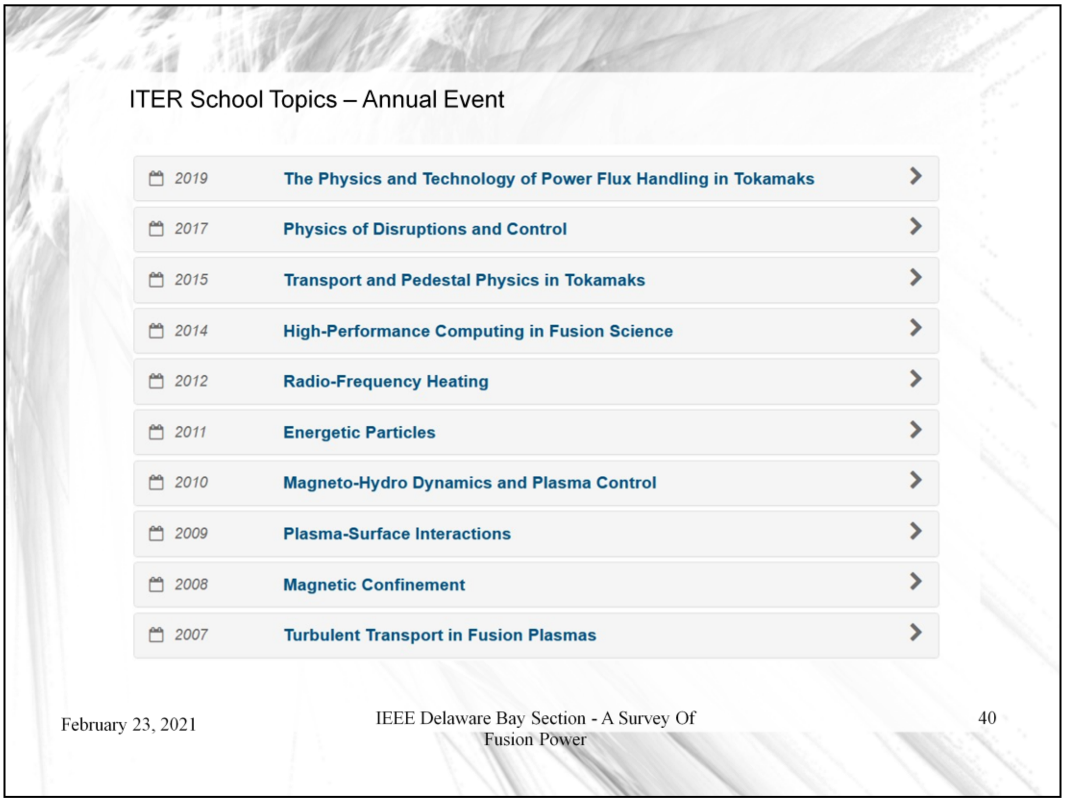
JA – Magnet& Divertor PA's – 310 kIUA (~466 Million €)

**In-Kind Credit - Status**

- 44 PA's signed to date
- 1729 kIUA (~ 2.7 Billion €)
- ~ 60% of total in-kind PA value

EU supplies 45% of the funding. The rest of the nations, 9% each. The funding is either money or parts.

China, the European Union (yes, including England), India, Japan, Korea, Russia and the United States.



## ITER School Topics – Annual Event

| | |
|---|---|
| 2019 | **The Physics and Technology of Power Flux Handling in Tokamaks** |
| 2017 | **Physics of Disruptions and Control** |
| 2015 | **Transport and Pedestal Physics in Tokamaks** |
| 2014 | **High-Performance Computing in Fusion Science** |
| 2012 | **Radio-Frequency Heating** |
| 2011 | **Energetic Particles** |
| 2010 | **Magneto-Hydro Dynamics and Plasma Control** |
| 2009 | **Plasma-Surface Interactions** |
| 2008 | **Magnetic Confinement** |
| 2007 | **Turbulent Transport in Fusion Plasmas** |

ITER International School. Note the heavy concentration on Plasma Physics and control of plasma.