Magnetic Fusion Energy Research

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Energy Research Workshop
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Fusion . . .

Fusion is the process by which the sun produces heat and sunlight, and if harnessed on earth, has the potential to provide a clean and unlimited source of energy.

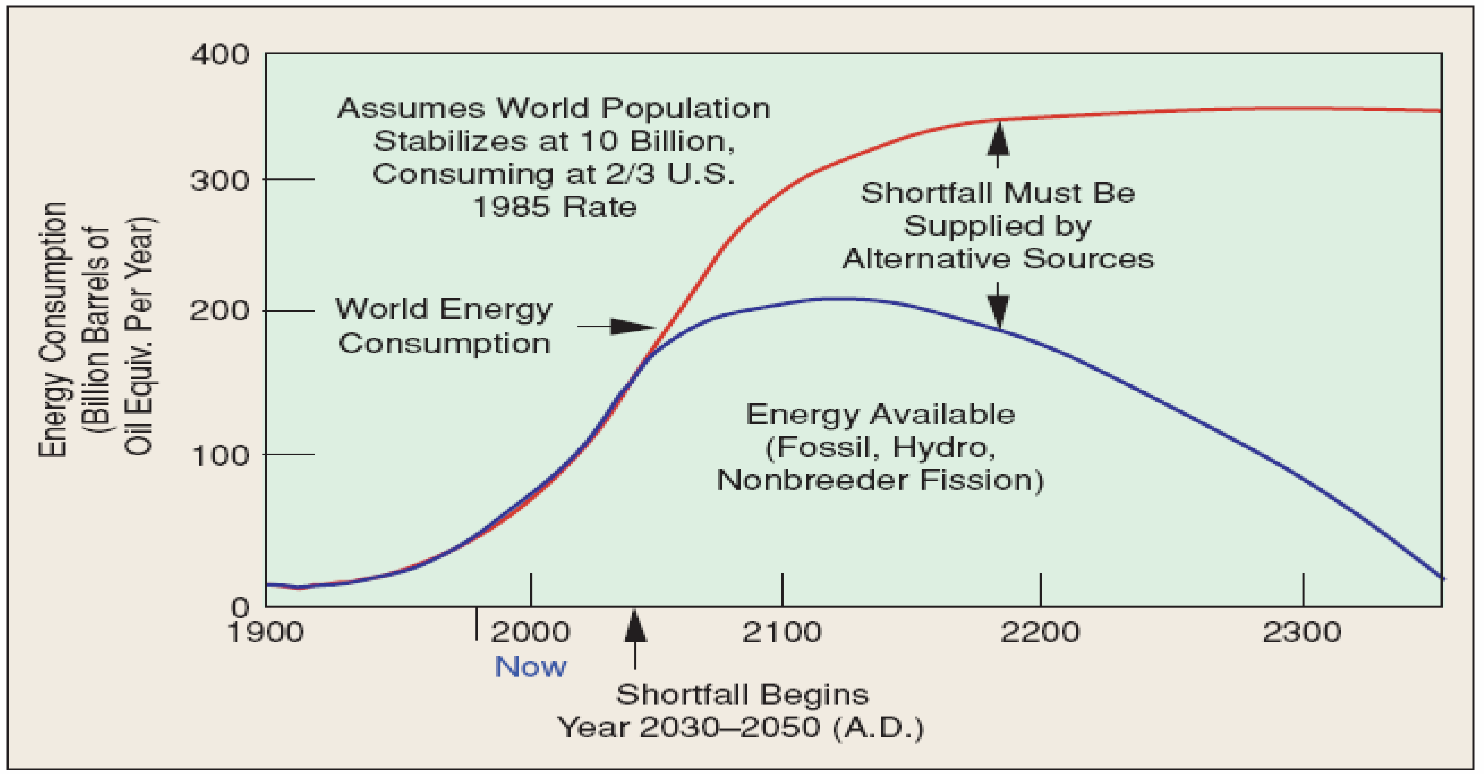
The sun and stars shine due to fusion, supporting all life on earth.
Fossil and nuclear fuels are stored fusion energy.

World Population and Energy Demand

- Over 21st century, world's population will increase from 6 billion to around 11 (8-14) billion people
  - – Increase in per capita energy use will be needed to raise standard of living in developing countries
- During the past two centuries:
  - – World population has increased by a factor of 6
  - – Life expectancy has increased by a factor of 2
  - – Energy use (mainly carbon based) has increased by a factor of 35
- New carbon free energy sources will be important
  - – A significant new carbon-free energy source is fusion energy
    - A practical energy source for future generations
  - – All energy sources will provide important contributions to the world's energy requirements

End of fossil fuel era

The fossil fuel era is almost over. If we continue to burn fossil fuels for energy, they will last only another few hundred years. At our present rate of use, experts predict a shortfall in less than fifty years.



A. Pironti and M. Walker, IEEE Control Systems **25**, 24 (2005)

Why Fusion Energy?

Advantages:

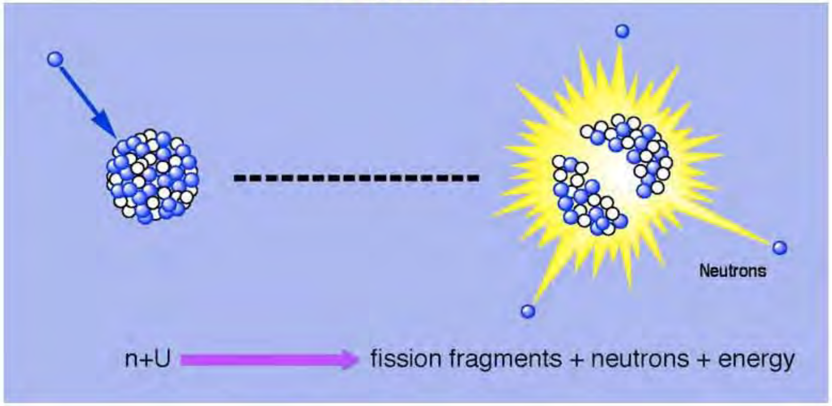
- Abundant, widely available, low cost fuel supply
  - Deuterium - inexhaustible supply from sea water
  - Tritium - Produced from Lithium, thousands of years supply
- No risk of Nuclear Accident
  - No meltdown possible
  - Large, uncontrollable release of energy impossible
- No air pollution or greenhouse gases
  - Reaction product is Helium
- Minimal or no high level nuclear waste
  - Careful material selection should minimize neutron activation
- No generation of weapon materials

Disadvantages:

- We do NOT know how to control it yet (very hard problem)
- Capital intensive

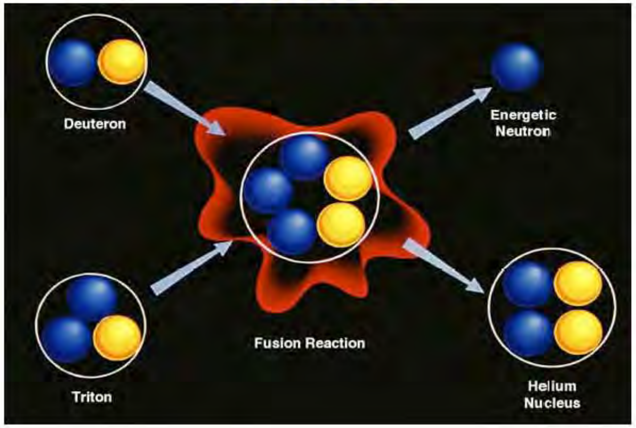
Fission is “EASY” and Fusion is “HARD”

FISSION



Fission initiated by electrically neutral particle [neutron] and can occur at room temperature in a solid: **“pile” the right stuff up and a chain reaction will occur!**

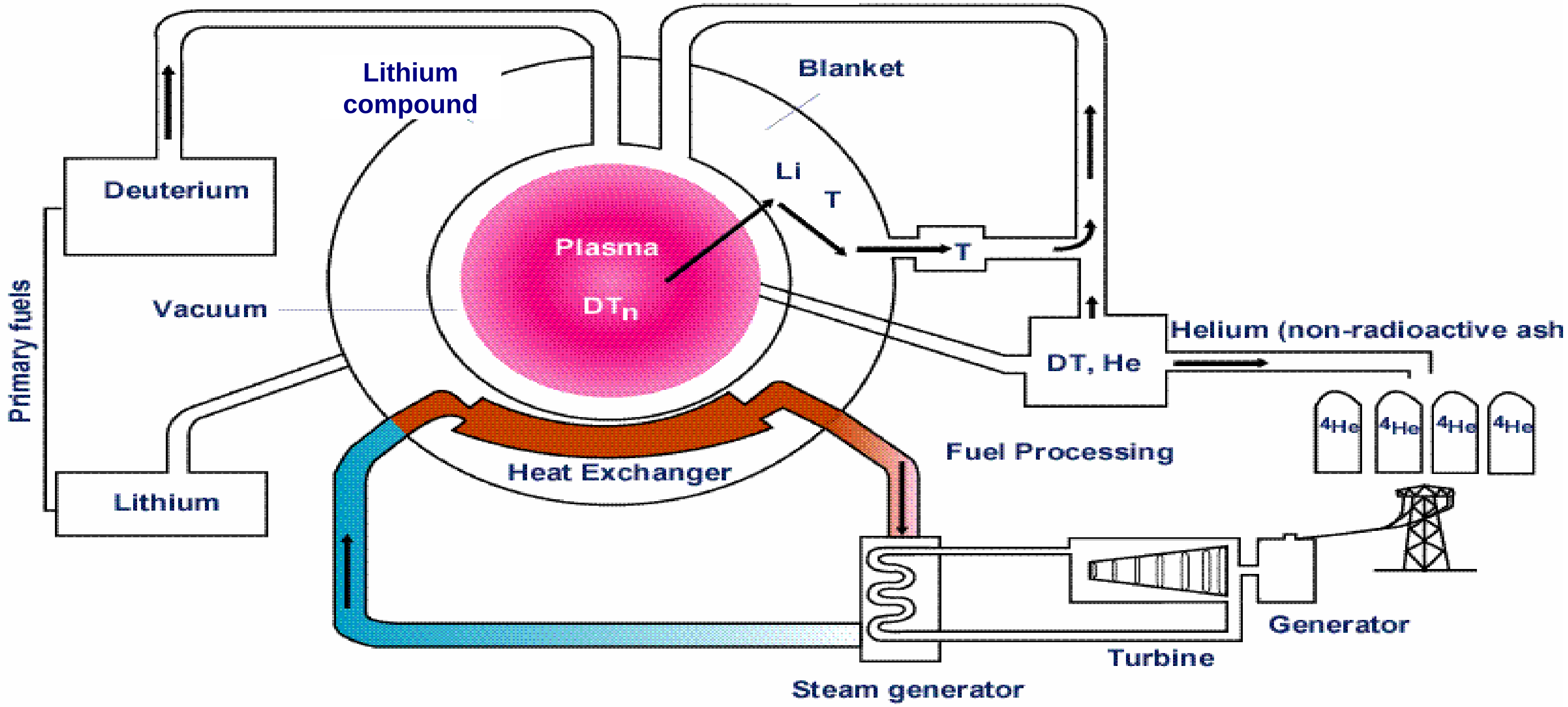
FUSION



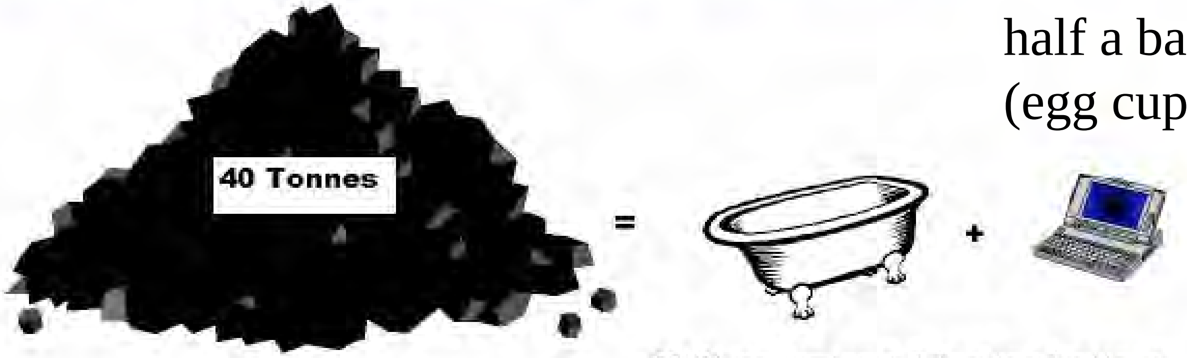
Fusion initiated by collision electrically charged particles at very high energy: **Threshold temperature for most reactive fusion reaction is about 200 million ˚F!**

1 gram of DT = 2,400 gallons of oil

Elements of a D-T Fusion Energy System



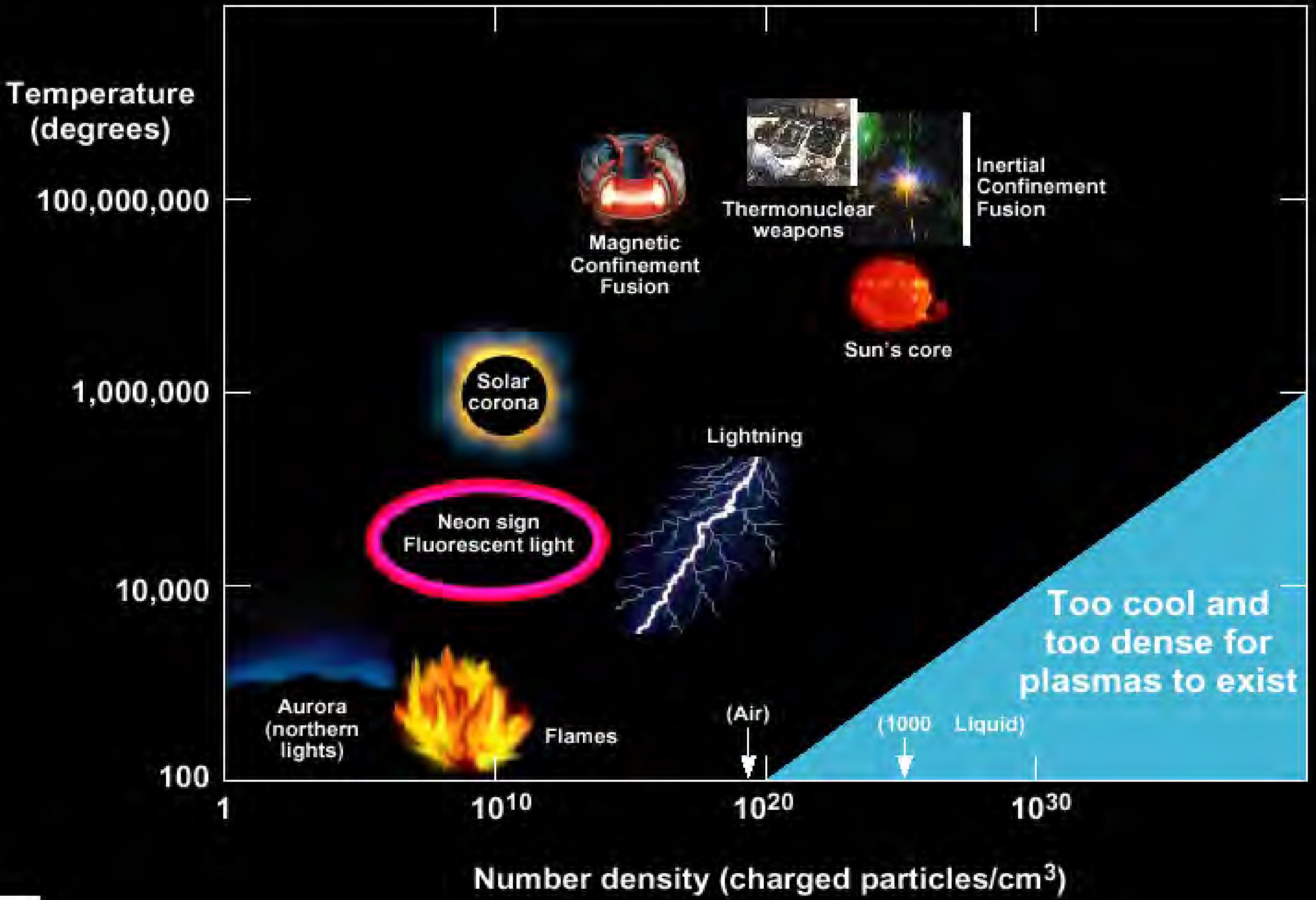
Raw fuel of a fusion reactor is water and lithium*



45 litres water + 1 lap-top battery

Lithium in one lap-top battery +
half a bath full of ordinary water
(egg cup full of heavy water)
⇒ **200,000 kW-hours**

Plasma—the 4th state of matter

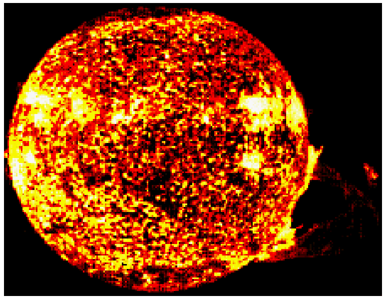


Confinement of Plasmas

Gravitational Confinement (300 W/m^3)

In a deep gravitational well, even fast particles are trapped.

This is the method used by the sun.

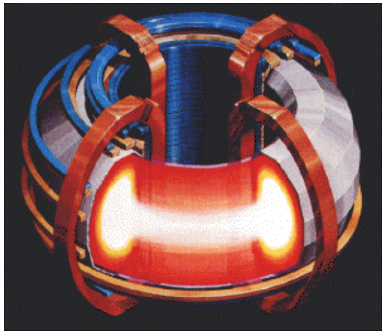


Inertial Confinement (10^{28} W/m^3)

Essentially imploding the hydrogen gases together with inertia, then holding them together long enough for fusion reactions to occur.

Magnetic Confinement (10^7 W/m^3)

Using the magnetic fields acting on hydrogen atoms which have been ionized.

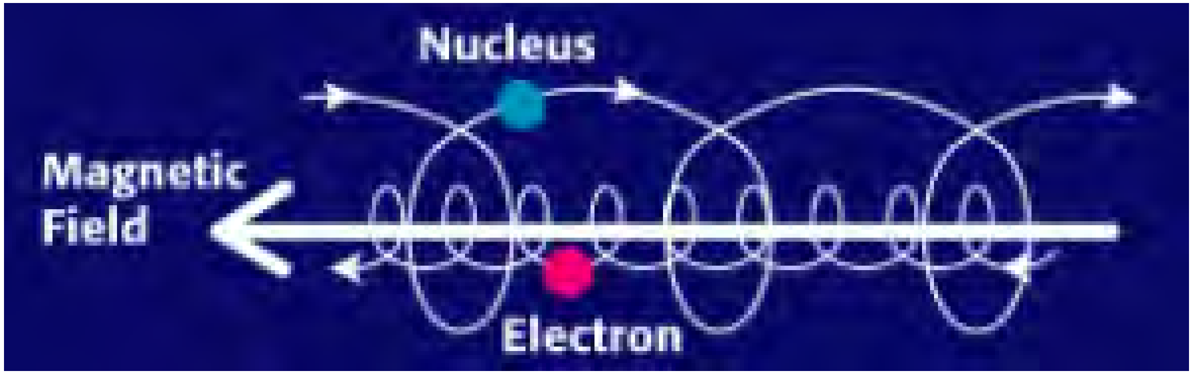


Magnetic Confinement of Plasma

Fast-moving electrically charged particles in a simple container would quickly strike the walls, giving up their energy before fusing

Magnetic fields exert forces that can inhibit and direct the motion of the particles

Ion gyroradius ≈ 1 cm at T_i = 20 keV
for typical magnetic field of B = 20 kG

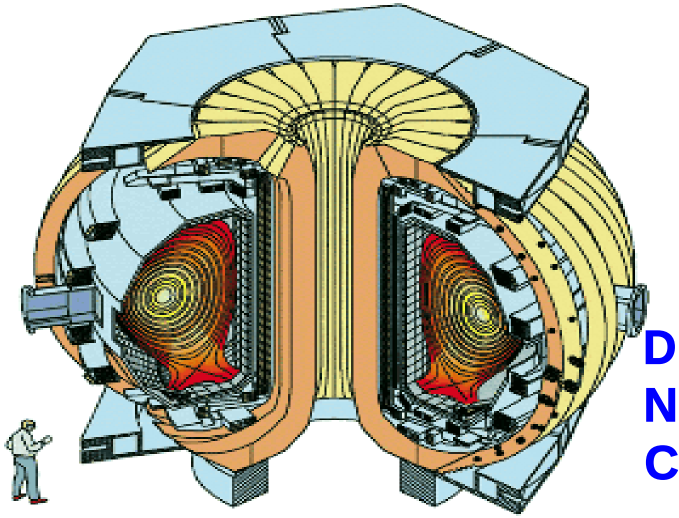


Fusion plasma ions move at ≈ 10^6 m/sec along the magnetic field lines so they need to be confined with end losses eliminated to sustain a fusion burn

Magnetic Confinement

Tokamak

TOroidalnaya **KA**mera ee **MA**gnitaya **K**atushka



DIII-D
NSTX
C-MOD

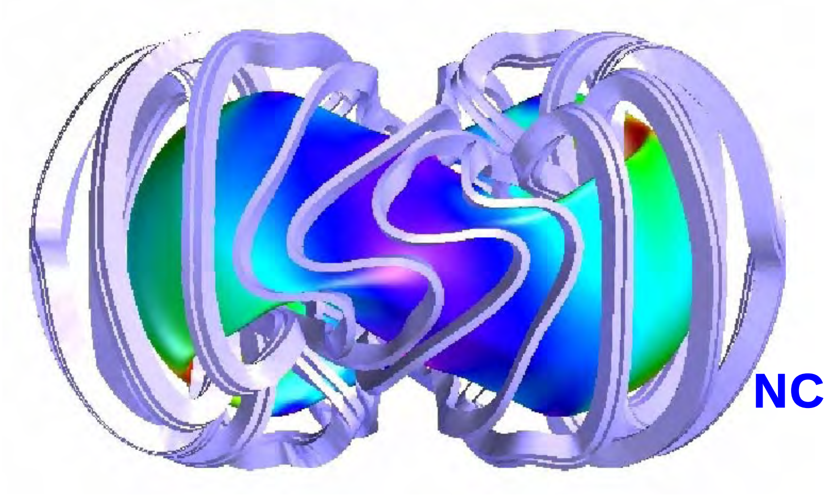
Poloidal field from plasma current

Pulsed (possible steady-state)

Axisymmetric – good confinement

Current is source of instability

Stellarator



NCSX

Poloidal field from external coils

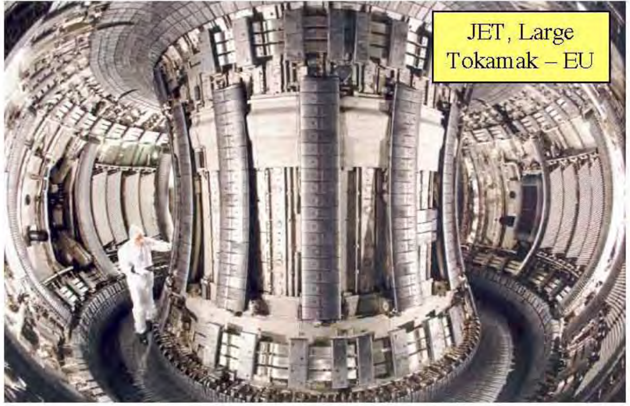
Intrinsically steady-state

Non-axisymmetric – good confinement hard to achieve

More difficult to build

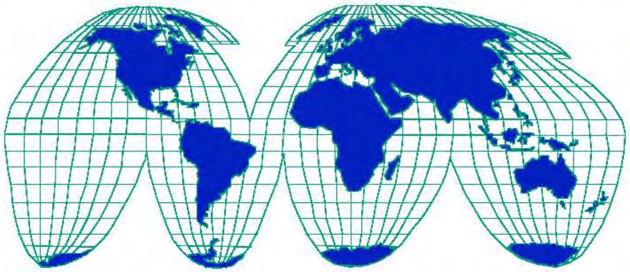
Magnetic Fusion Research is a Worldwide Activity: Optimizing the Configuration for Fusion


C-Mod, Tokamak MIT

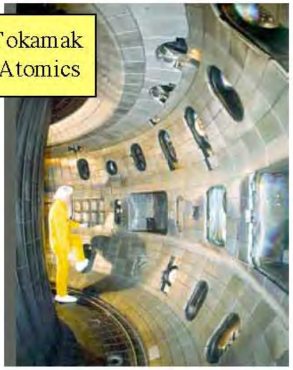

JET, Large Tokamak – EU

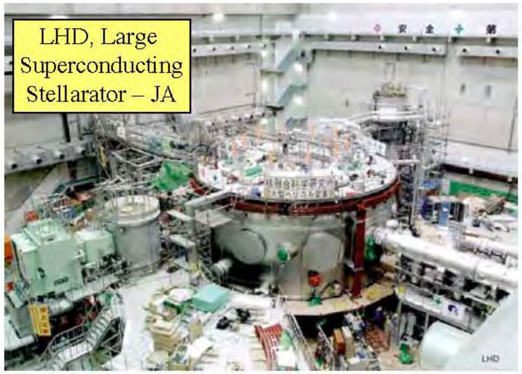

W7-X, Large Superconducting Stellarator – EU

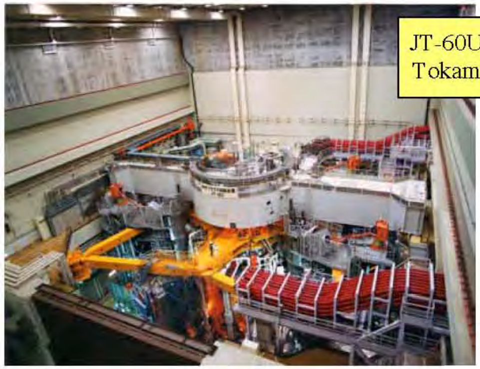

National Spherical Torus Experiment PPPL (also MAST – EU)




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


DIII-D, Tokamak General Atomics


LHD, Large Superconducting Stellarator – JA


JT-60U, Large Tokamak– JA

Power Balance

$$\tau_E = \frac{\text{Plasma Energy}}{\text{Power Loss (Heating Rate)}}$$

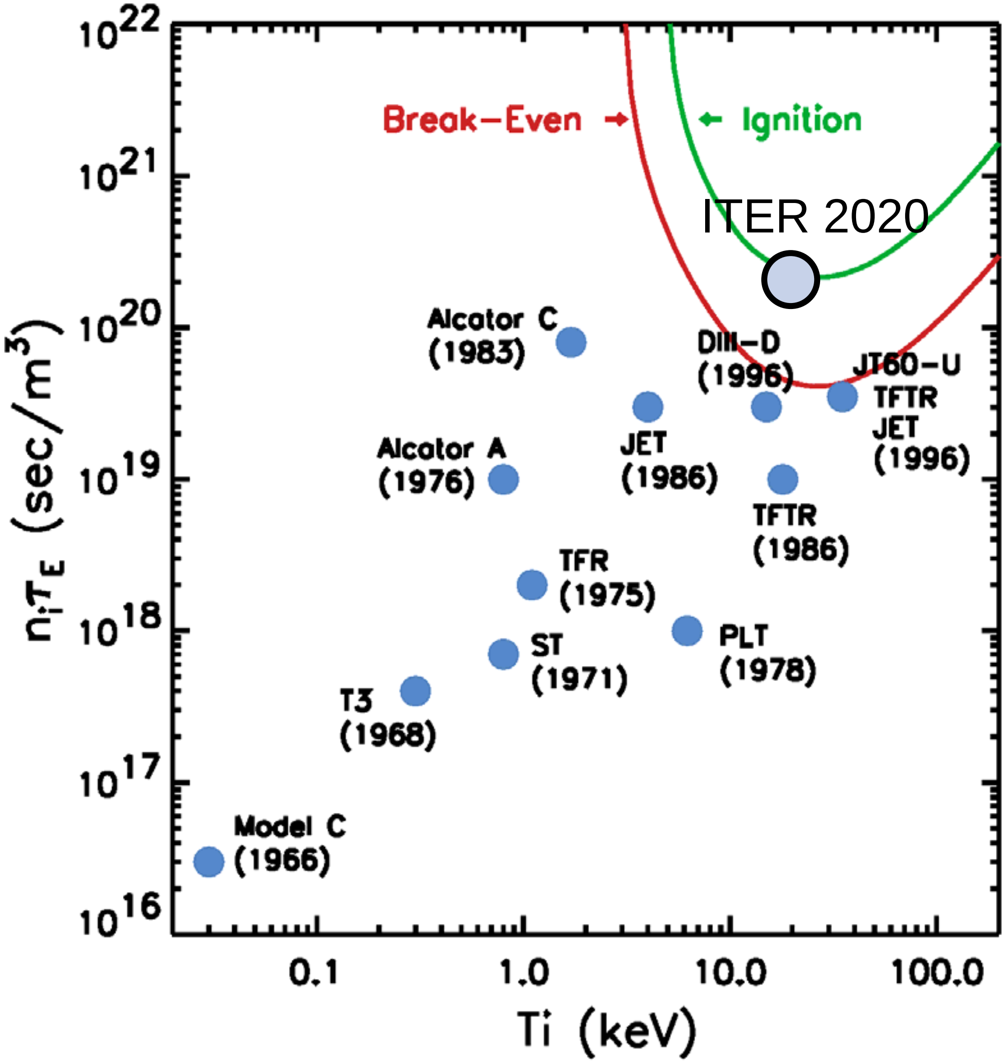
Break-Even:

$$P_f = P_{aux} = P_L - P_\alpha$$

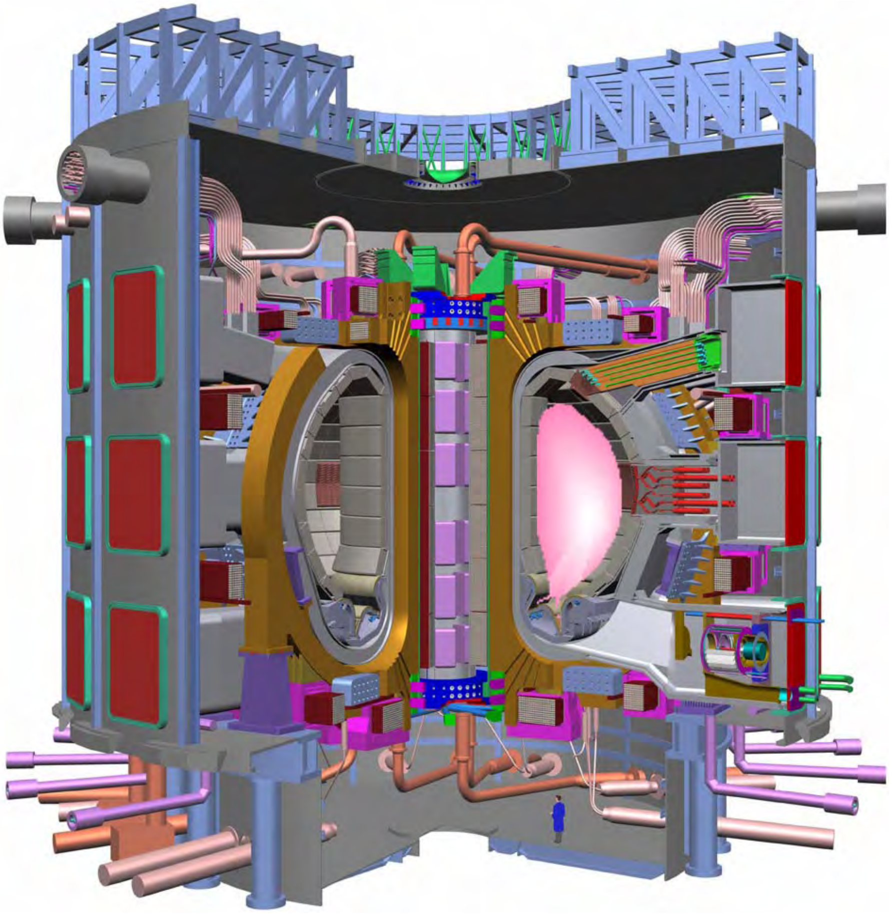
Ignition:

$$P_L = P_\alpha \quad (P_{aux} = 0)$$

Next step is ITER, a burning plasma experiment.



ITER Provides Cooperative Opportunity to Make a Sun on Earth



US has had major impact on ITER design

500 – 700 MW thermal fusion power

400sec – 1 hr pulse length

R=6.2m a=2m B=5.3T

Science Benefits:

Extends fusion science to larger size, burning (self-heated) plasmas.

Technology Benefits:

Fusion-relevant technologies.
High duty-factor operation.

Goal:

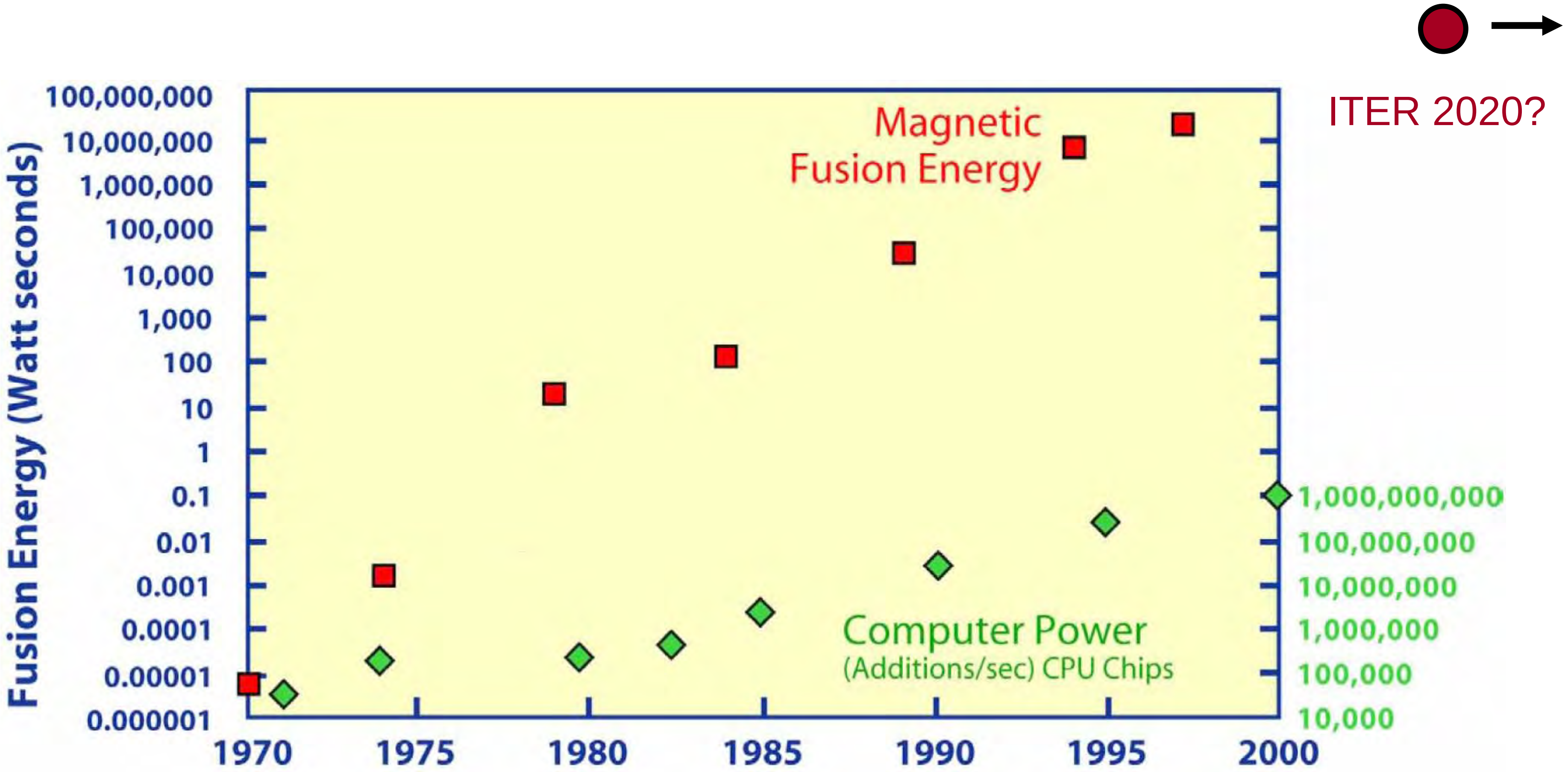
To demonstrate the scientific and technological feasibility of fusion energy.

ITER success would represent for fusion energy the same milestone as the first nuclear chain reaction by Fermi under the University of Chicago stadium in 1942 was for fission energy

Advanced computational modeling is essential for cost effective device design and for interpretation of experimental results

How Are We Doing?

By some measures we are outpacing the semiconductor industry



Fusion Research is Conducted Broadly Across the U.S.

ANL	Argonne National Laboratory
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PPPL	Princeton Plasma Physics Laboratory
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory

● NATIONAL LABORATORY ● UNIVERSITY ● INDUSTRY ● INTER-GOVT AGENCY

Fusion Research at Lehigh

Professor Arnold H. Kritz (Physics)

Dr. Glenn Bateman

Dr. Alexei Pankin

Dr. Tariq Rafiq

Frederico Halpern

Professor Eugenio Schuster (ME)

Jennifer Woodby, Majed Alsarheed, Yongsheng Ou,
Chao Xu, Lixiang Luo, Joseph Dalessio

Recent Physics Ph. D. degrees awarded

Thawatchai Onjun, Canh Nguyen

Lehigh Fusion Physics Group Research Grants

- **Fusion group base program on integrated modeling**
  - **New transport models to simulate advanced tokamak scenarios**
  - **Train graduate and undergraduate students**
- **PTRANSP**
  - **Full featured integrated modeling simulation code**
    - **Developed in collaboration with Princeton Plasma Physics Laboratory, Lawrence Livermore National Laboratory, and General Atomics**
- **Fusion Simulation Project**
  - **Large project to develop high-performance computer software for comprehensive predictive integrated modeling of magnetically confined burning plasmas**
- **Fund for the Improvement of Postsecondary Education**
  - **Lehigh is contributing to the development of a joint US-Russia educational program on advanced energy technologies**

Lehigh Fusion Physics Group Research Grants

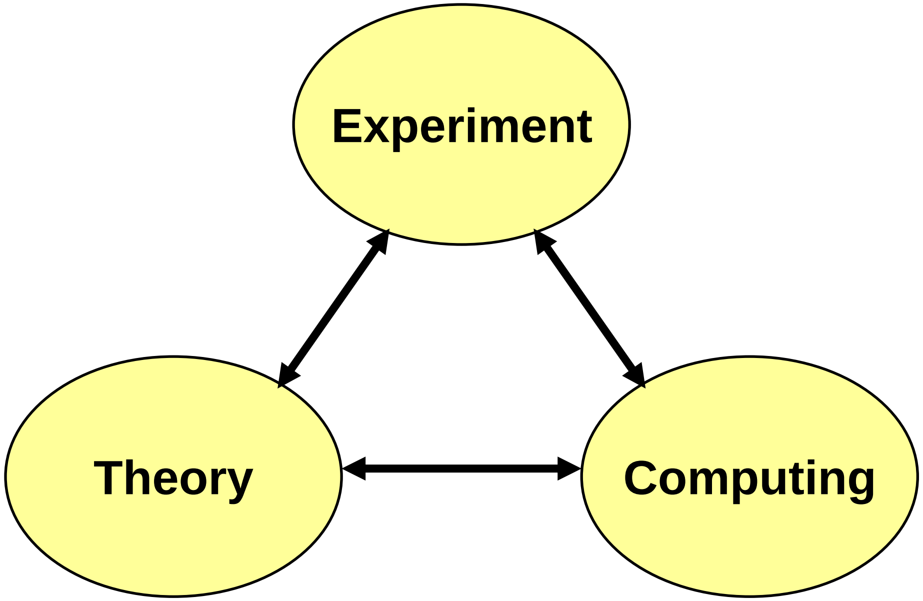
- Center for Plasma Edge Simulation (CPES)
  - Lehigh group is combining computer codes for first-principles simulations of plasma at edge of tokamaks
- Simulation of Waves Interacting with MHD (SWIM)
  - Lehigh group is implementing transport models and magnetic islands
- NIMROD code (with U. Wisconsin)
  - Extended magnetohydrodynamic (MHD) simulations of large-scale instabilities in tokamak plasmas
- Transport Common Interface Module
  - Subcontract with Tech-X Corporation in Boulder Colorado
    - As part of SBIR contract on “Framework for Modernization and Componentization of Fusion Modules”

Simulation Program

Within the past few years, advanced scientific computing has reached a point where it is on a par with laboratory experiment and mathematical theory as a major tool for scientific discovery.

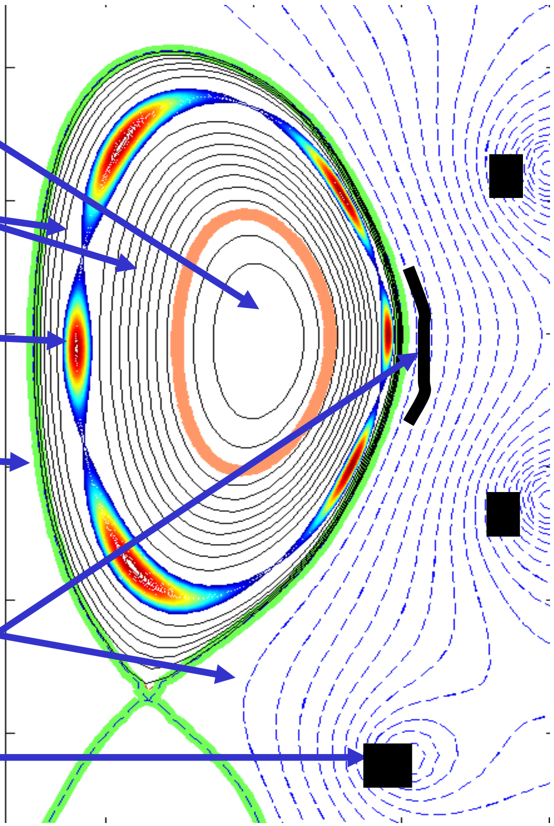
Major increases in computing power are enabling a new generation of simulation codes, based on reliable experimental and theoretical inputs, to lead the way to increased scientific understanding.

These in turn will lead to new theoretical and experimental discoveries.



Integrated Modeling of Tokamaks

- **Sawtooth Region (q < 1)**
- **Core Confinement Region**
- **Magnetic Islands**
- **Edge Pedestal Region**
- **Scrape-off Layer**
- **Vacuum/Wall/ Conductors/Antenna**



Core & Edge Transport

Plasma Turbulence

Large Scale Instabilities

MHD Equilibrium

Plasma-wall Interactions

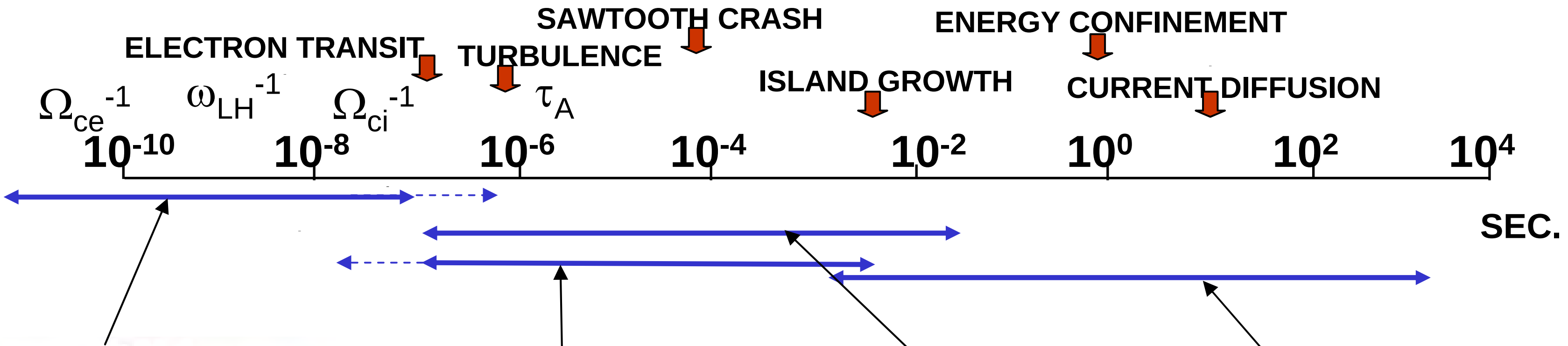
Atomic Physics

Radiation Transport

Energetic Particles

Heating & Current Drive

Challenge: Develop Practical Simulations to Link Across Huge Range of Timescales



ELECTRON TRANSIT

TURBULENCE

SAWTOOTH CRASH

ISLAND GROWTH

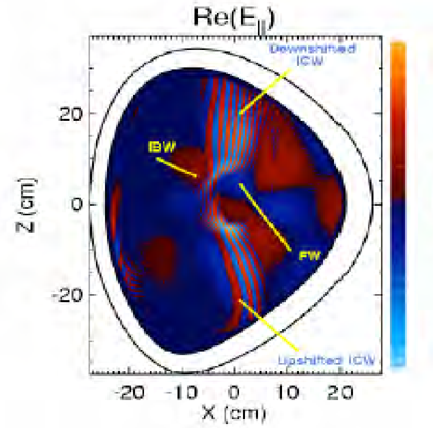
ENERGY CONFINEMENT

CURRENT DIFFUSION

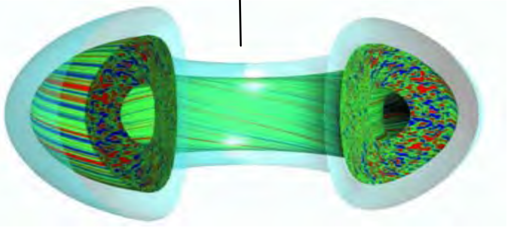
Ω_{ce}^{-1} ω_{LH}^{-1} Ω_{ci}^{-1} τ_A

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}

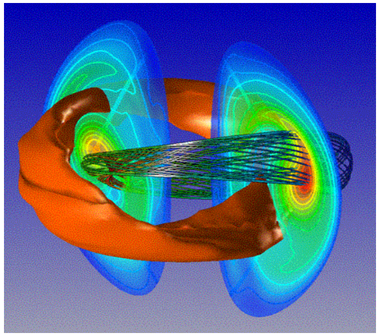
SEC.



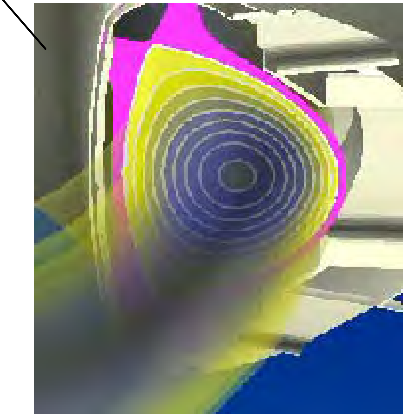
(a) RF codes



(b) Micro-turbulence codes



(c) Extended-MHD codes



(d) Integrated Plasma Simulations

Lehigh Fusion Control Group Grants

- **Control of Fusion Plasmas**
  - **Neoclassical tearing mode control**
  - **Resistive wall mode control**
  - **Current, kinetic and rotation profile control**
  - **Plasma shape and position control**
- **Sources of funding**
  - **National Science Foundation CAREER Award**
  - **Pennsylvania Infrastructure Technology Alliance (PITA)**
  - **General Atomics Subcontract (US Department of Energy)**

The Need for Control

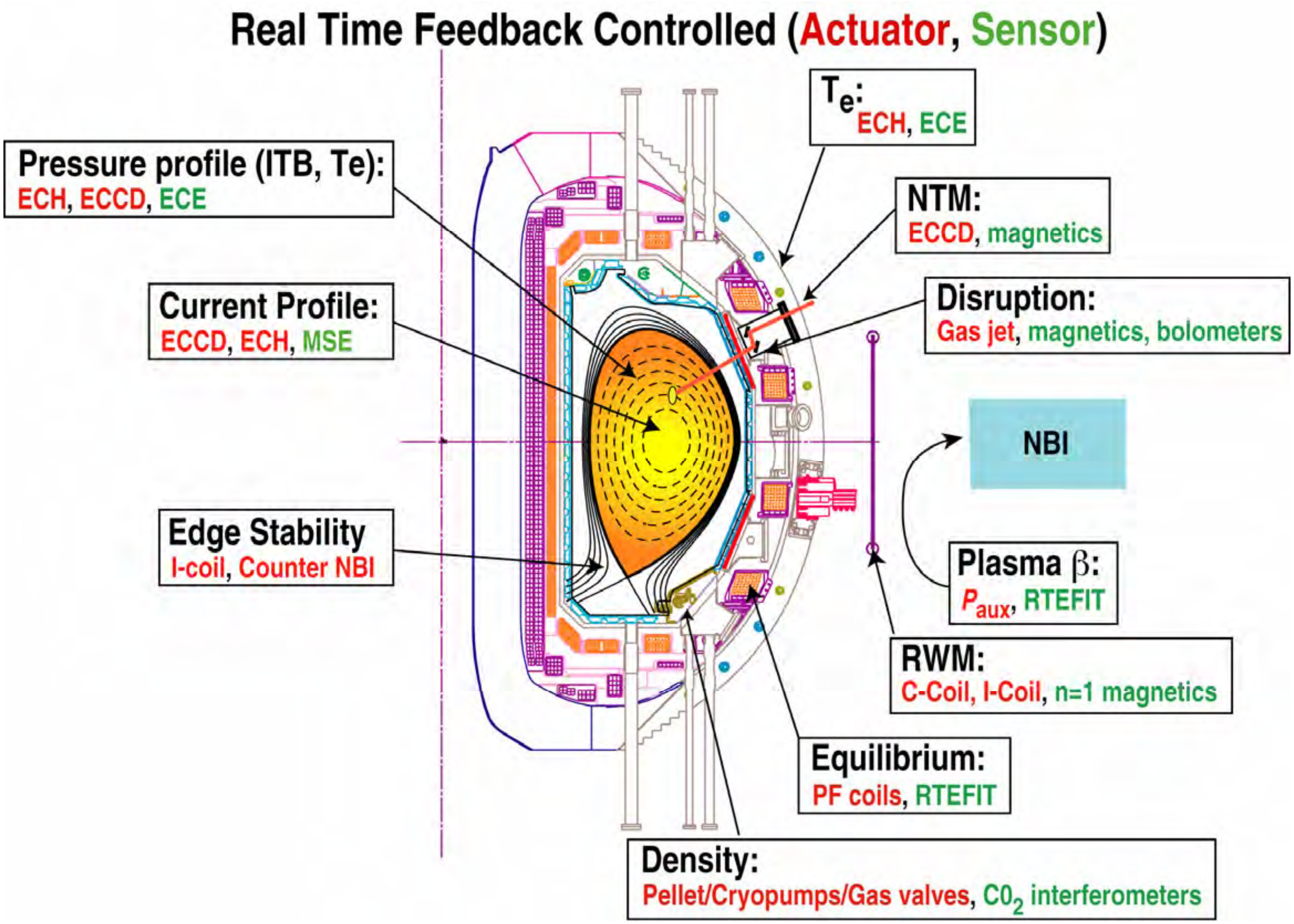
- **Increase fusion reactivity**
  - **Increased heat, pressure => increased fusion reactions**

- **Stabilize instabilities due to pushing performance limits**
  - **Increased heat, pressure => more unstable plasma**

- **Maintain desired plasma state**
  - **Distances/locations, density, confinement level, etc**

- **Mitigate consequences of events that cannot be controlled**
  - **Instabilities can lead to disruptions, which can**
    - **ablate wall materials,**
    - **damage structures from dissipation of magnetic and thermal energy**
  - **Loss of actuator can lead to loss of control**
  - **Loss of coolant can lead to device damage**

The Needs for Control



Real Time Feedback Controlled (Actuator, Sensor)

Pressure profile (ITB, Te):
ECH, ECCD, ECE

T$_e$:
ECH, ECE

NTM:
ECCD, magnetics

Disruption:
Gas jet, magnetics, bolometers

Current Profile:
ECCD, ECH, MSE

NBI

Edge Stability
I-coil, Counter NBI

Plasma β:
P_{aux}, RTEFIT

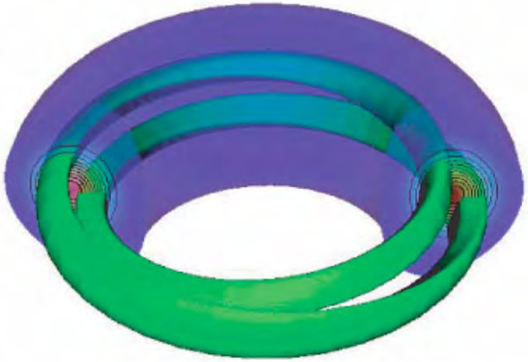
RWM:
C-Coil, I-Coil, n=1 magnetics

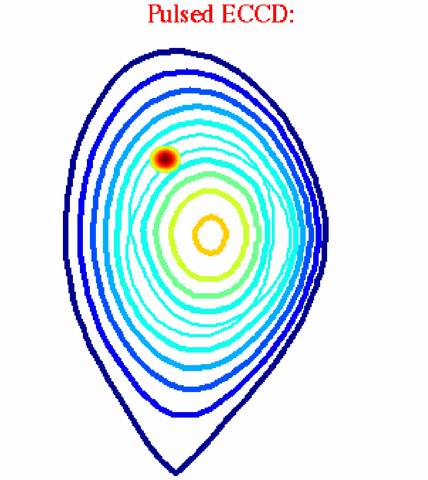
Equilibrium:
PF coils, RTEFIT

Density:
Pellet/Cryopumps/Gas valves, C0$_2$ interferometers

Magnetic Fusion Control

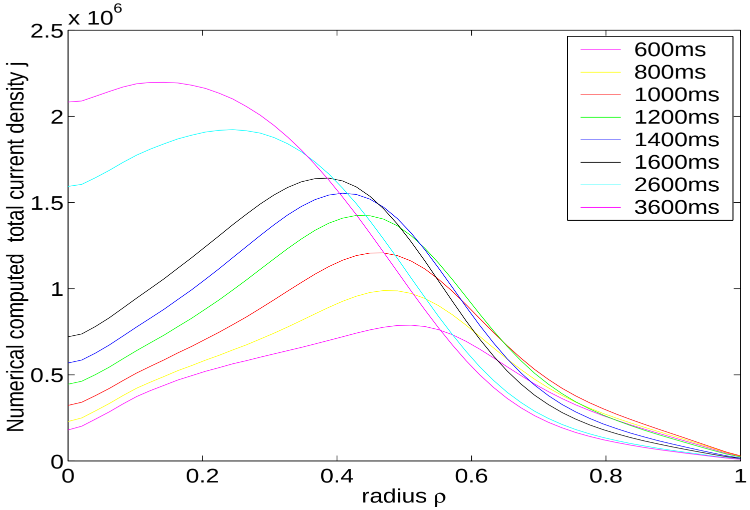
Neoclassical Tearing Modes (NTM) Stabilization





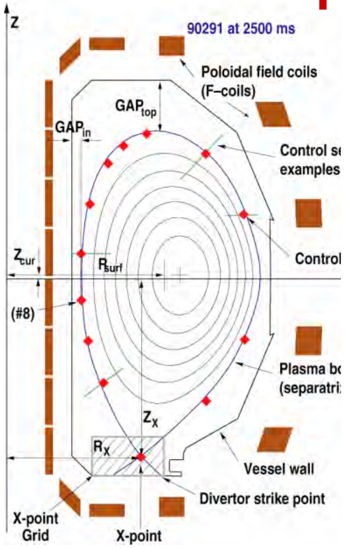
Jennifer Woodby

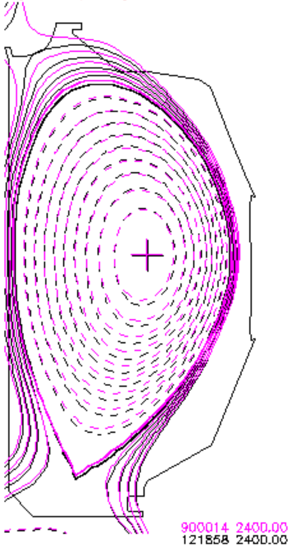
Plasma Current Profile Control



Yongsheng Ou, Chao Xu

Plasma Shape Control

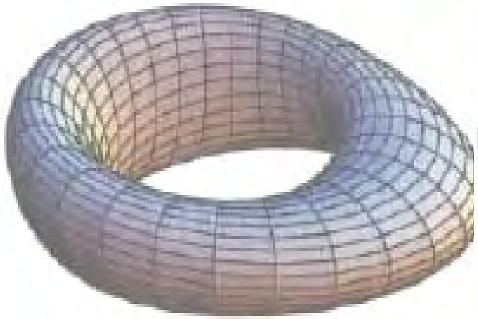


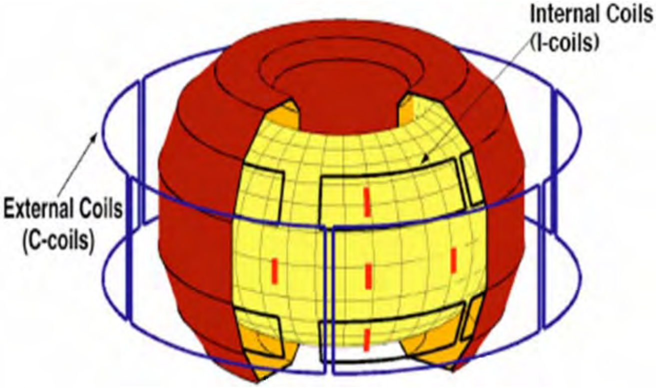


Majed Alsarheed

Resistive Wall Modes (RWM) Stabilization

Joseph Dalessio





Examples of Critical Issues for Fusion Devices

- Performance optimization and scenario modeling
  - Since each ITER discharge will cost about $1M, it is important to plan each discharge and to evaluate the results of each discharge carefully
  - Scenario modeling is needed to plan new experiments
- Plasma stability and feedback control
  - Real-time feedback control essential to avoid disruptions and to optimize the performance of burning plasma experiments
- Turbulence and confinement
  - Nonlinear computer simulation of turbulence is a grand challenge
- Material Issues
  - First Wall power handling, erosion issues and tritium retention
  - Blanket and neutron shielding
  - Structural components – low activation required
- Plasma RF heating techniques