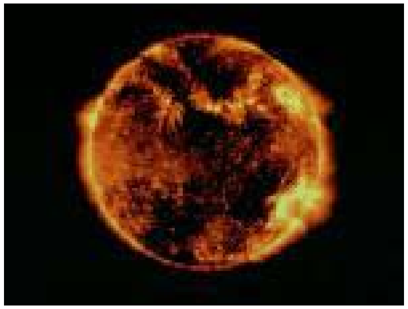
Lecture 20: Fusion as a Future Energy Source?



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28 Oct 2010

Thanks to many people for contributions and graphics!

Outline

- ❑Introduction
- ❑Fusion and Plasma Physics
- ❑Magnetic Confinement
- ❑Science and Technology Issues
- ❑History
- ❑Next Steps
- ❑Prospects: Fusion As An Energy Source

Overview

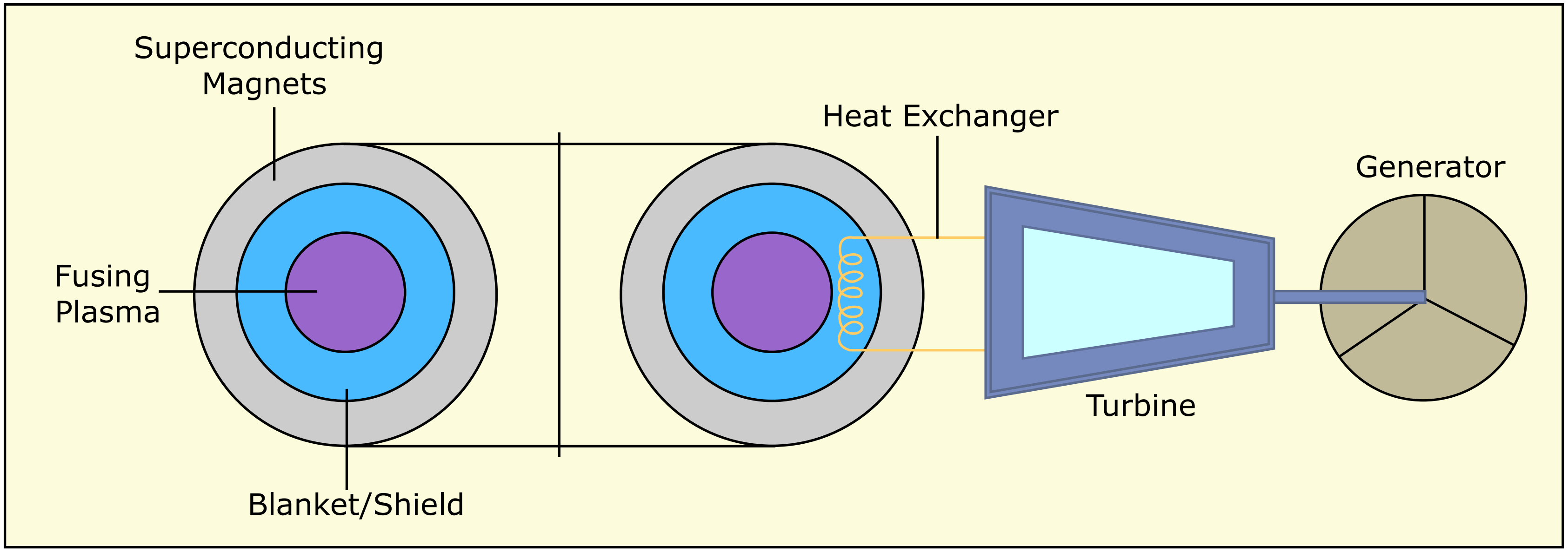
Fusion 101

- Fusion is a form of nuclear energy
- Combines light elements (in our case, hydrogen isotopes) to form heavier elements (He)
- Releases huge amount of energy (multiple MeV/nucleon)
- The reaction powers the stars and produces the elements of the periodic table
- For 50 years, scientists and engineers have been working to exploit the fusion reaction as a practical energy source.

Long Term Goals

- Produce baseload electricity in large power plants – 1 GWe/unit

How Would We Get Useful Power From Fusion?



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- ❑ At its simplest, a fusion reactor would be a "firebox" for conventional electricity generation. (Heat could be used in "off-peak" hours to make hydrogen for transportation.)

Pros and Cons of Fusion

Pros

- Abundant, high energy density fuel (D + Li)
- No greenhouse gases (nor NO_X, SO_X, particulate emission)
- Safe – no chain reaction, ~1 sec worth of fuel in device at any one time
- Minimal "afterheat", no nuclear meltdown possible
- Residual radioactivity small; products immobile and short-lived
- Minimal proliferation risks
- Minimal land and water use
- No seasonal, diurnal or regional variation – no energy storage issue

Cons

- We don't know how to do it yet (turns out to be a really hard problem)
- Capital costs will be high, unit size large (but with low operating costs)

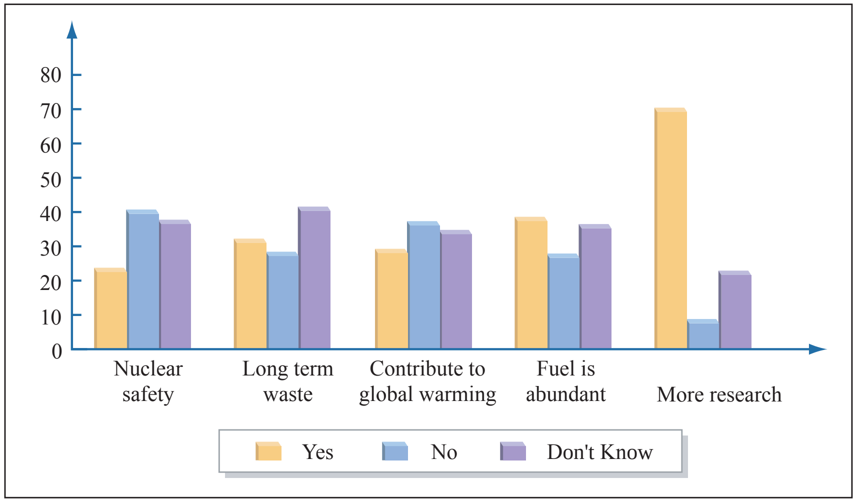
Challenges For Practical Fusion

- ☐ Plasma physics
  - Create, confine and sustain hot plasmas that produce net energy
- ☐ Taming the plasma material interface
  - Minimize heat and particle loads (consistent with 1)
  - Develop materials and strategies to handle what remains
- ☐ Harnessing fusion energy
  - Fuel cycle – tritium breeding, inventory control
  - Structural materials – maintaining structural, thermal and electrical properties under intense neutron bombardment
  - Reliability, Availability, Maintainability, Inspectability

Public concerns and perceptions

Socio-Economic study group (Netherlands by Beurskens)

- Doesn’t produce CO_2 ?
- Is safe against major nuclear accidents?
- Don't Know
- Fuel is abundant?



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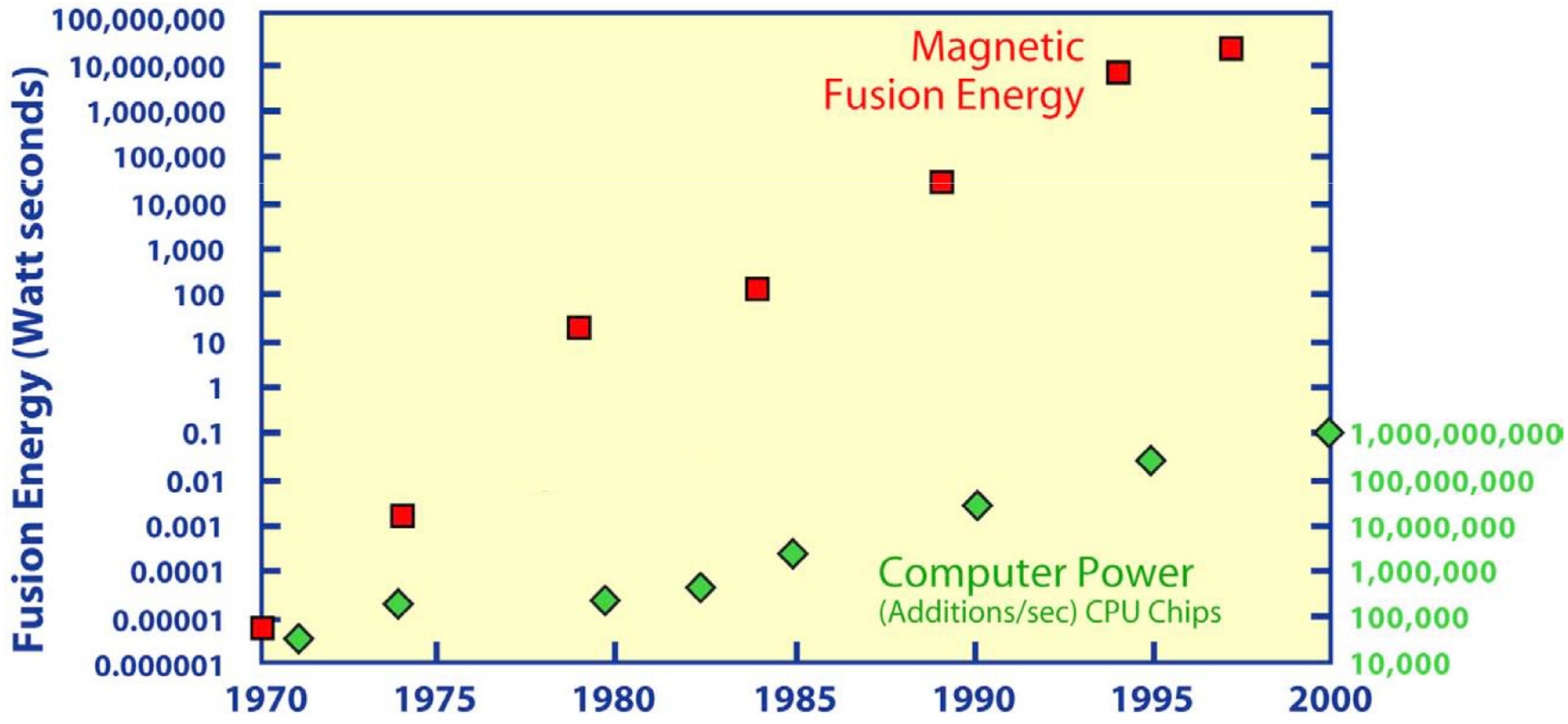
Opponents

- Don’t like nuclear or large scale.
- Too much spending on fusion, could be better spent on other options.
- Fusion doesn’t work and is always “50 years away”.

How Are We Doing? – By Some Measures We Are Outpacing The Semiconductor Industry

Each step gets more difficult and more expensive

ITER 2020?



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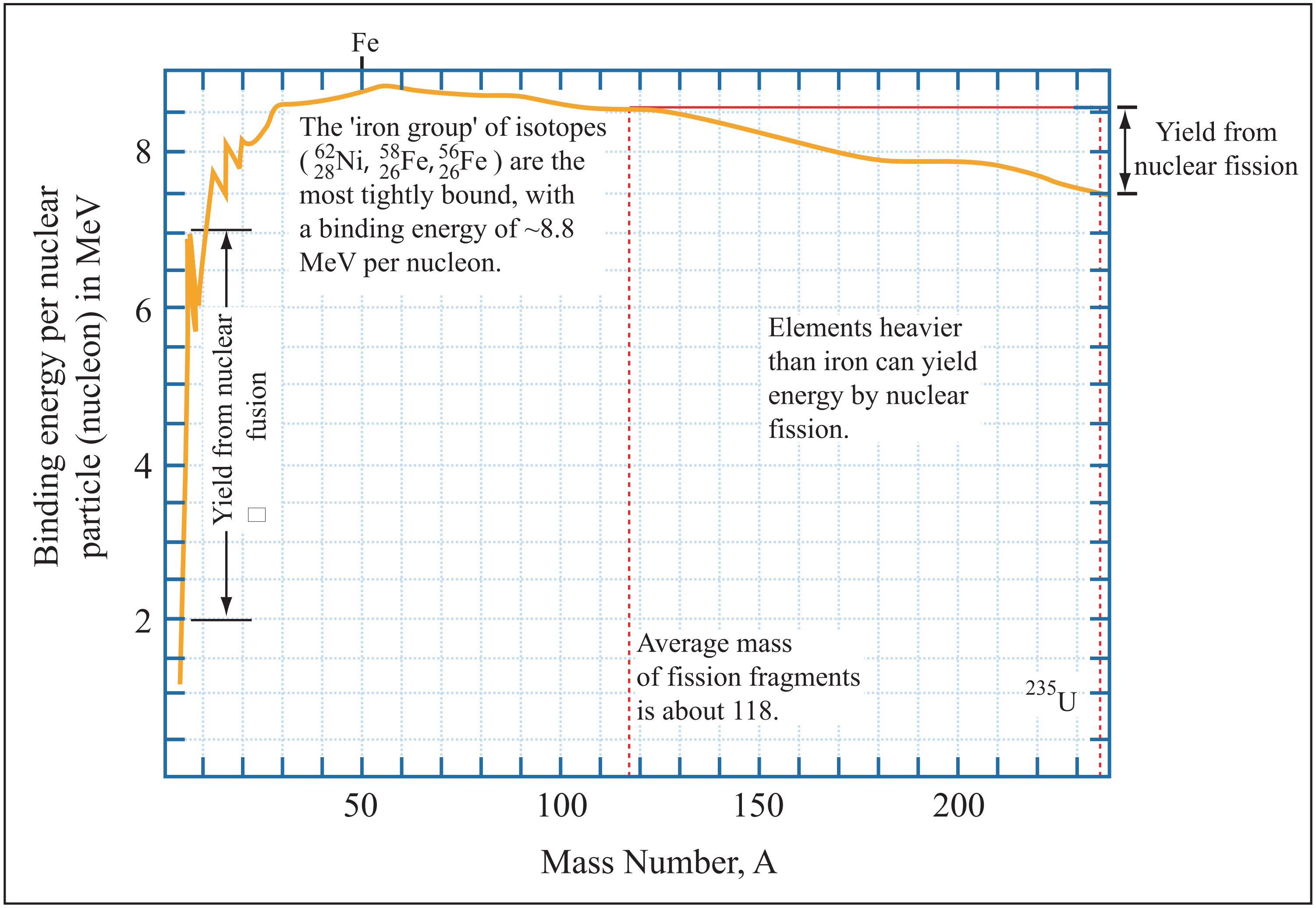
Fusion and Fission work at opposite ends

The binding energy curve shows the *nuclear* energy available from fusion



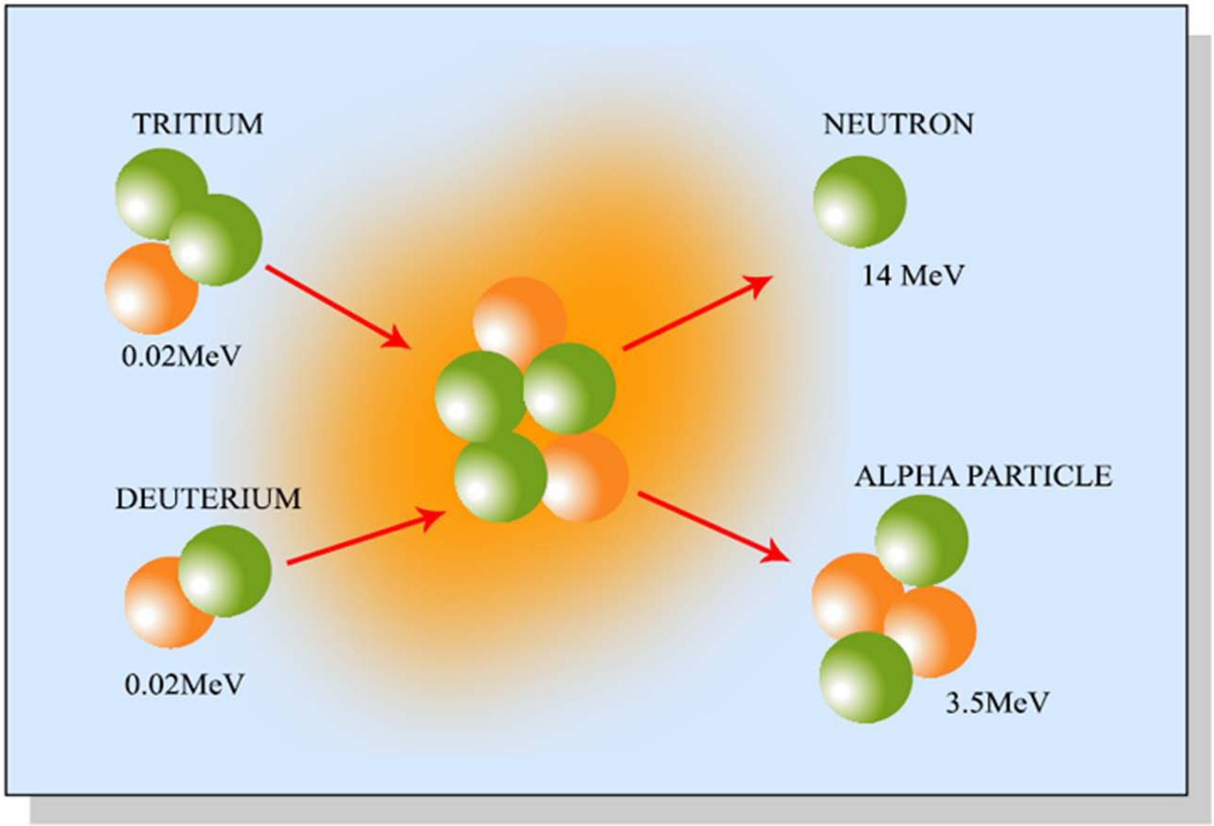
The 'iron group' of isotopes ($^{62}_{28}$Ni, $^{58}_{26}$Fe, $^{56}_{26}$Fe) are the most tightly bound, with a binding energy of ~8.8 MeV per nucleon.

Elements heavier than iron can yield energy by nuclear fission.

Average mass of fission fragments is about 118.

Image by MIT OpenCourseWare.

DT Reaction Is Most Accessible Energetically



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- Alpha particle : $_2He^4$

  20 % of reaction energy

  ==> Confined

  ==> Plasma Self Heating

- Neutron : $_0n^1$

  80 % of reaction energy

  ==> Not Confined

  ==> Energy output and Tritium production

Tritium breeding

$_0n^1 + {_3}Li^6 = {_1}T^3 + {_2}He^4$

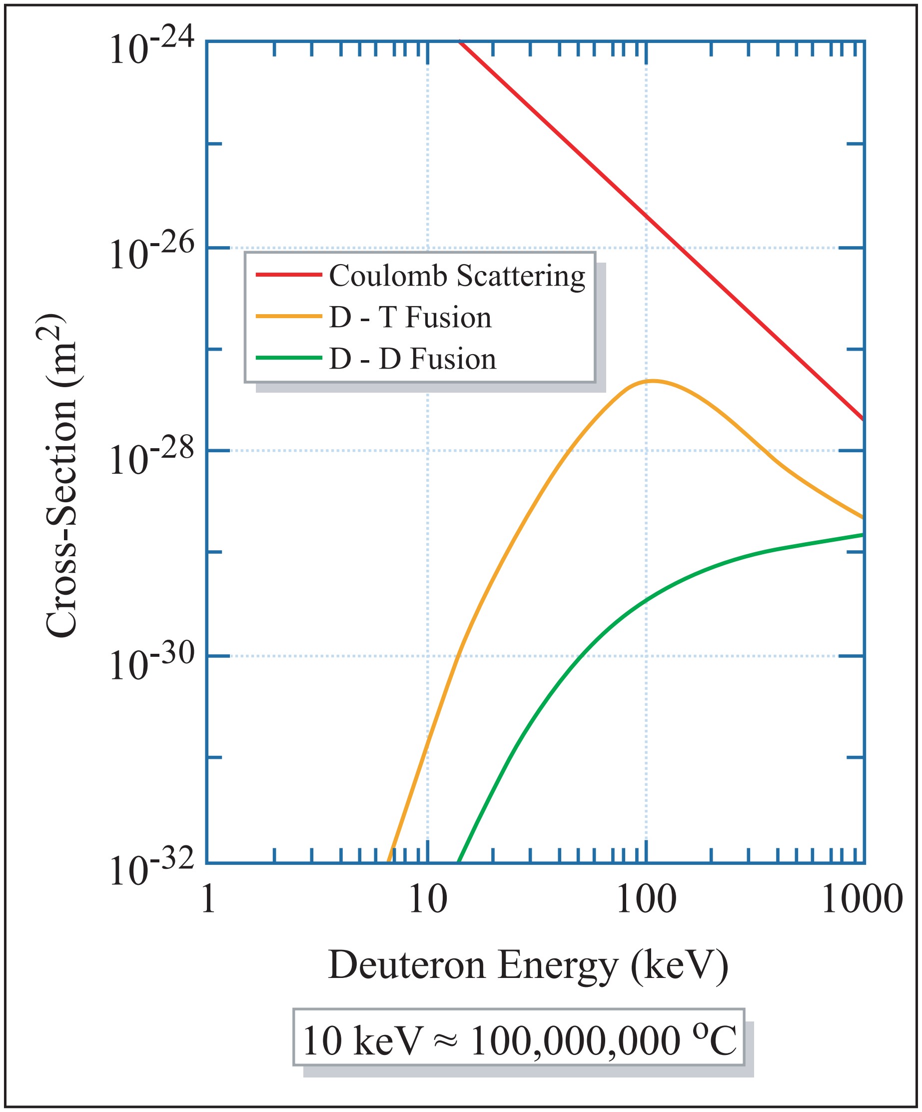
(Net Reaction is $_1D^2 + {_3}Li^6 = 2\ {_2}He^4$)

Tritium Breeding Would Be Required

- Deuterium is plentiful ~ 0.015% of hydrogen
  - Take 1 gallon water, extract D, fuse ⇒ energy equivalent to 300 gallons gasoline
  - Tritium decays rapidly, must be "manufactured"
- Breeding reaction: ${}_0n^1 + {}_3Li^6 = {}_1T^3 + {}_2He^4$ (+ Energy)
  - Overall, tritium is a catalyst for: ${}_1D^2 + {}_3Li^6 = {}_2He^4 + {}_2He^4$ (+ Energy)
  - Li is plentiful in the earth's crust
- Tritium breeding ratio (TBR=tritons/neutron) must be bigger than 1 to make up for geometrical limitations and natural decay
  - There are endothermic reactions, for example ${}_0n^1 + {}_3Li^7$, which produce multiple neutrons.
  - TBR ~ 1.05-1.1 is believed achievable.

The Probability Of D-T Fusion Is The Greatest When The Nuclei Have About 100 Kev Of Kinetic Energy

- Even at the optimum energy, the nuclei are much more likely to scatter elastically than to fuse!
- Multiple scatterings thermalize the constituent particles.
- At the energies involved, matter becomes fully ionized ® plasma.



10 keV ≈ 100,000,000 °C

Image by MIT OpenCourseWare.

The Physics Of The Fusion Reaction And Elastic Scattering Leads Us Directly To The Need For Confined Plasmas

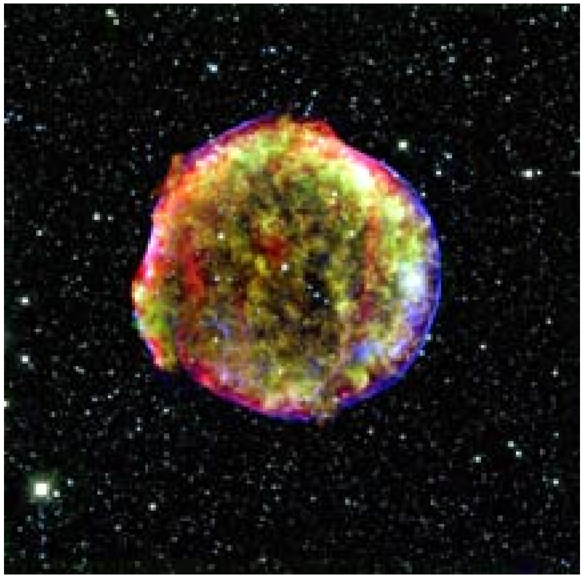
- ☐ Because scattering is much more likely, nuclei must be confined for many interaction times.
- ☐ These multiple scatterings thermalize the constituent particles.
- ☐ At the energies involved, matter becomes fully ionized ⇒ **plasma.**
- ☐ In all senses, we can think of plasmas as a 4th state of matter

In plasma physics, we measure temperature in eV

1 eV = 11,600 °K **10 keV ≈ 100 million degrees**

(Typical fusion plasma temperature)

Plasmas Are Ubiquitous In Nature



- Most of the **visible** universe is composed of plasma

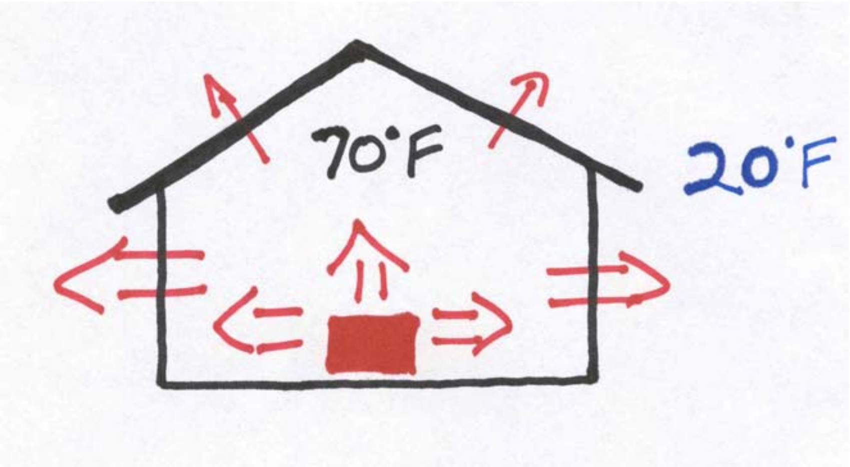
Photos from NASA/MPIA, Mircea Madau on Wikimedia Commons, Javier Giménez and Paul Jonusaitis on Flickr.

Essential Properties Of Plasmas

- Very hot (minimum 5 eV; 60,000°K)
  - Electrons stripped from atomic nuclei
  - Excellent electrical conductivity
  - Significant interaction with electromagnetic fields and radiation
- Quasi-neutral
  - But small deviations lead to strong plasma-generated electric and magnetic fields
- The quest for controlled fusion energy lead to the rapid development of the science of plasma physics
  - Important for understanding of astrophysics, space sciences, etc.

Confinement: A Simple Analogy

- ❑ Our goal: get the required temperature with the least amount of heating power
- ❑ Energy confinement time is the ratio of stored energy to heating rate.
- ❑ In a fusion reactor that heat would come from the fast α particles (charged, so they are confined by the magnetic field)



$$\tau_E(\text{sec}) \equiv \frac{Total\ stored\ energy\ (Joules)}{Heating\ rate\ (Watts)}$$

Confinement Requirements For Fusion: The Lawson Criterion

$$Fusion\ Power = n_D\, n_T \cdot Rate\ per\ ion \cdot Energy\ per\ reaction$$

$$Fusion\ Power \propto n^2 F(T)$$

$$Loss\ Power = Confinement\ Loss + Radiation\ Loss$$

$$Loss\ Power = \frac{3nT}{\tau_E} + n^2 R(T)$$

For steady state, Fusion Power = Loss Power

$$n^2 F(T) = \frac{3nT}{\tau_E} + n^2 R(T)$$

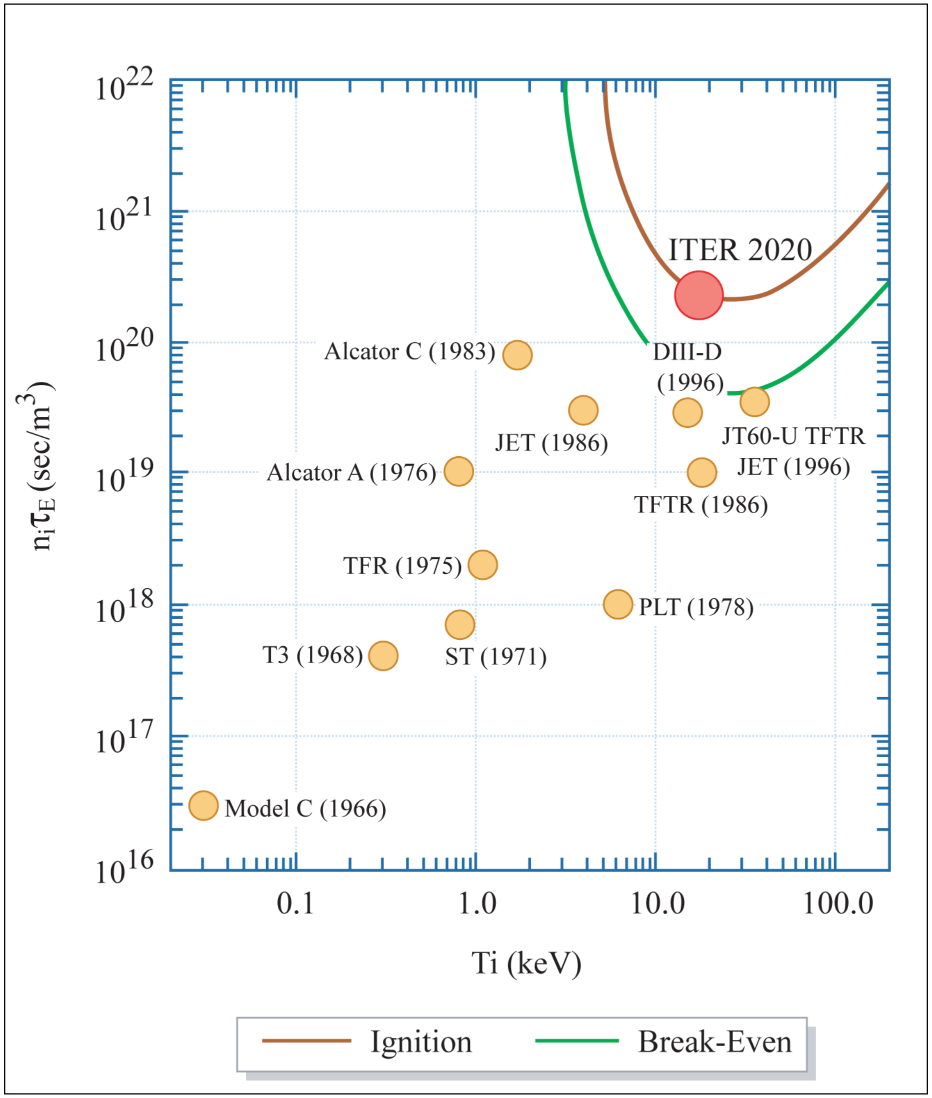
$$n\tau_E F(T) = 3T + n\tau_E R(T)$$

$$n\tau_E = \frac{3T}{F(T) - R(T)} = G(T)$$

- ❑ A quantitative statement of the requirements for good confinement **and** high temperature

Break-Even And Ignition Curves In “Lawson” Space

- ❑ The ignition curve is defined in an analogous manner – but just use charged-particle energy
- ❑ Engineering considerations suggest practical device has $n_e \sim 10^{20}/m^3$ with $\tau_E \sim$ 5-10 sec
- ❑ Next step is ITER, a burning plasma experiment.



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Approaches To Fusion Energy

- ☐ **Gravitational Confinement** (300 W/m^3)
  - In a deep gravitational well, even fast particles are trapped.
  - Very slow: $\tau_E \sim 10^6$ years, burn-up time = 10^{10} years

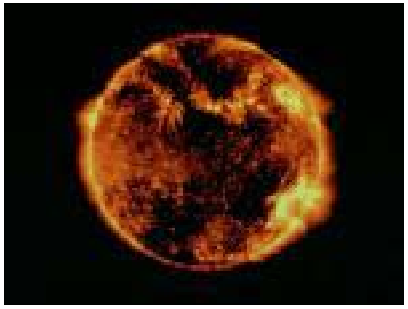


Photo by NASA Visible Earth, Goddard Space Flight Center Scientific Visualization Studio.

- ☐ **Inertial Confinement** (10^{28} W/m^3)
  - Heat and compress plasma to ignite plasma before constituents fly apart.
  - Works for the H-bomb
  - Unlikely (IMHO) this will lead to practical energy source.

Courtesy of Lawrence Livermore National Laboratory. Used with permission.

- ☐ **Magnetic Confinement** (10^7 W/m^3)
  - Uses the unique properties of ionized particles in a magnetic field

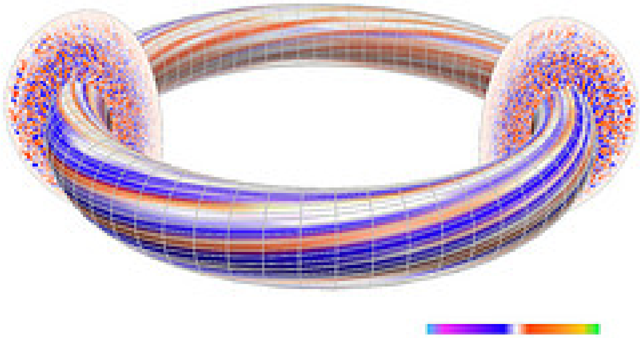


Image by Argonne National Laboratory on Flickr.

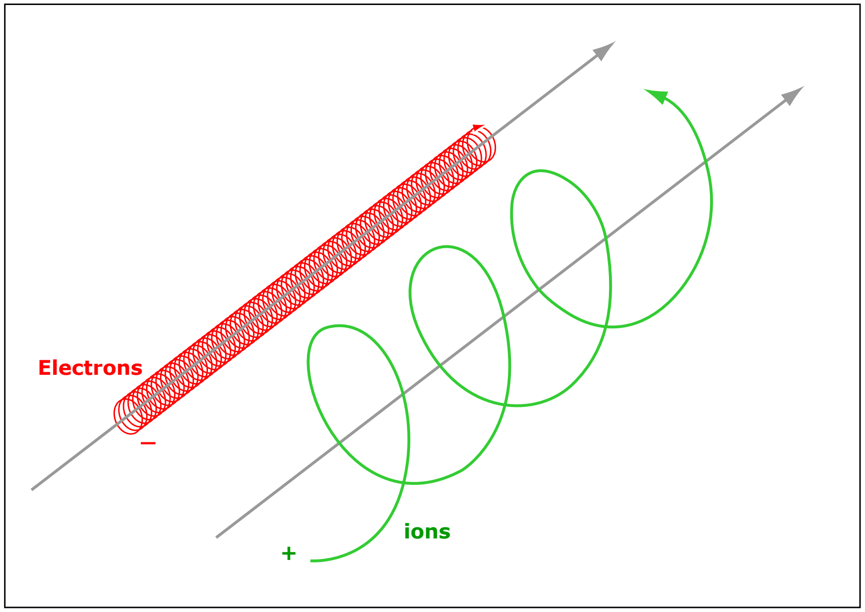
Gyro-motion Of Charged Particles Enables Magnetic Confinement

Gyro-radius $\rho = \frac{mV_\perp c}{qB} \propto \frac{\sqrt{mT}}{B}$

Gyro-frequency $\omega_c = \frac{eB}{mc}$

At B = 5T, T = 10keV

- ☐ ρ_e = 0.067 mm
- ☐ ρ_i = 2.9 mm
- ☐ R/ ρ_i > 1,000
- ☐ ω_e = 8.8 x 10^{11} rad/sec (µwaves)
- ☐ ω_i = 4.8 x 10^8 rad/sec (FM radio)



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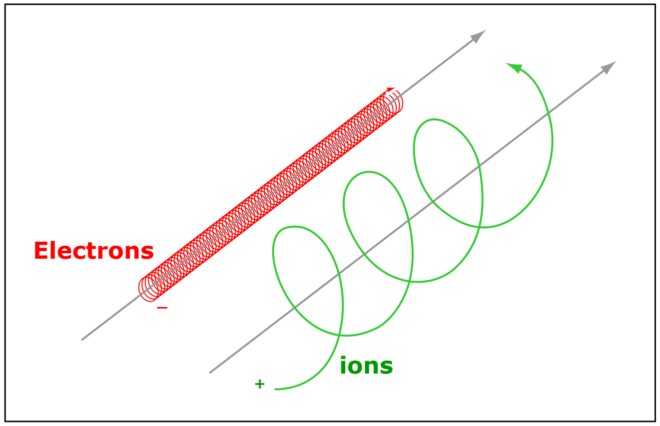
Ionized particles are deflected by the Lorentz force and bent into circular orbits.

In The Simple Example Shown, There Is No Confinement At All Parallel To The Magnetic Field



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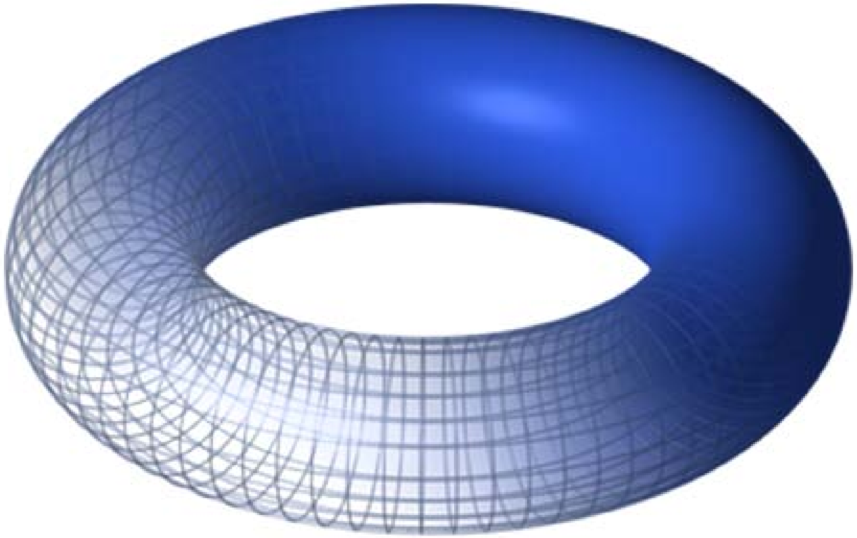


Image by Kieff on Wikimedia Commons.

- ☐ At the temperatures involved, ions are moving at over 1,000 km/s
- ☐ For a practical device, the end losses must be eliminated

Voila! Eliminate the ends.

A torus is a unique topologically. It is the only 3D shape where a non-singular vector field can be tangent to the surface everywhere.

Why Is The Scientific Problem So Difficult?

Many body problem – need statistical treatment

Basic description of plasma is 7D → *f*(x, v, t), evolution determined by non-linear Boltzman equation + Maxwell's equations

Particle sources

$$\frac{\partial f}{\partial t} + \mathrm{v}\cdot\nabla f + \frac{q}{m}\left[E + \mathrm{v}\times B\right]\cdot\nabla_{\mathrm{v}} f = C(f) + S(f)$$

convection in space

convection in velocity space

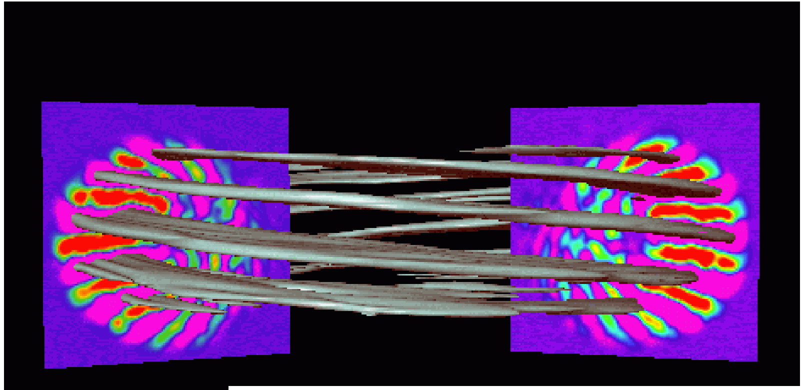
Collisional relaxation toward Maxwellian in velocity space

- Intrinsic nonlinearity (plasma distributions can easily generate E and B fields)
- High dimensionality
- Extreme range of time scales – wall equilibration/electron cyclotron O(10^{14})
- Extreme range of spatial scales – machine radius/electron gyroradius O(10^{4})
- Extreme anisotropy – mean free path in magnetic field parallel/perp O(10^{8})
- Sensitivity to geometric details

With Closed-form Solution Impossible: Computer Simulation Has Been A Key Element Of The MFE Program

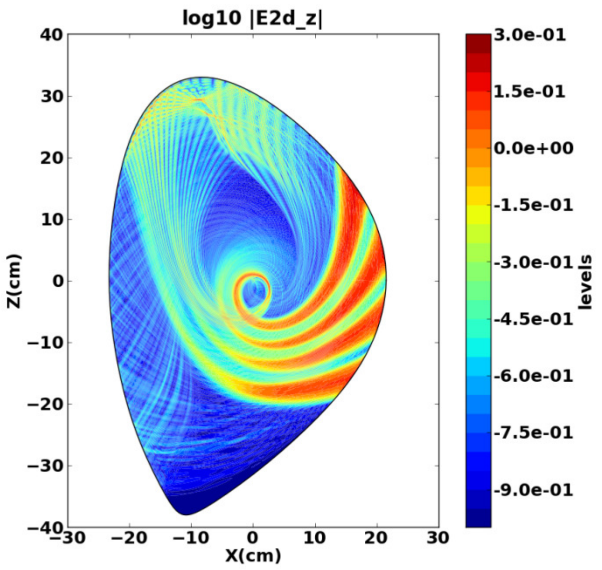
Image removed due to copyright restrictions. Please see Fig. 12 in Lynch, V. E., et al. "Numerical Tokamak Turbulence Calculations on the CRAY T3E." *Proceedings of the 1997 ACM/IEEE Conference on Supercomputing*. ACM, 1997. ISBN: 9780897919852.

<- Microturbulence modeling
Fluid macro stability ->



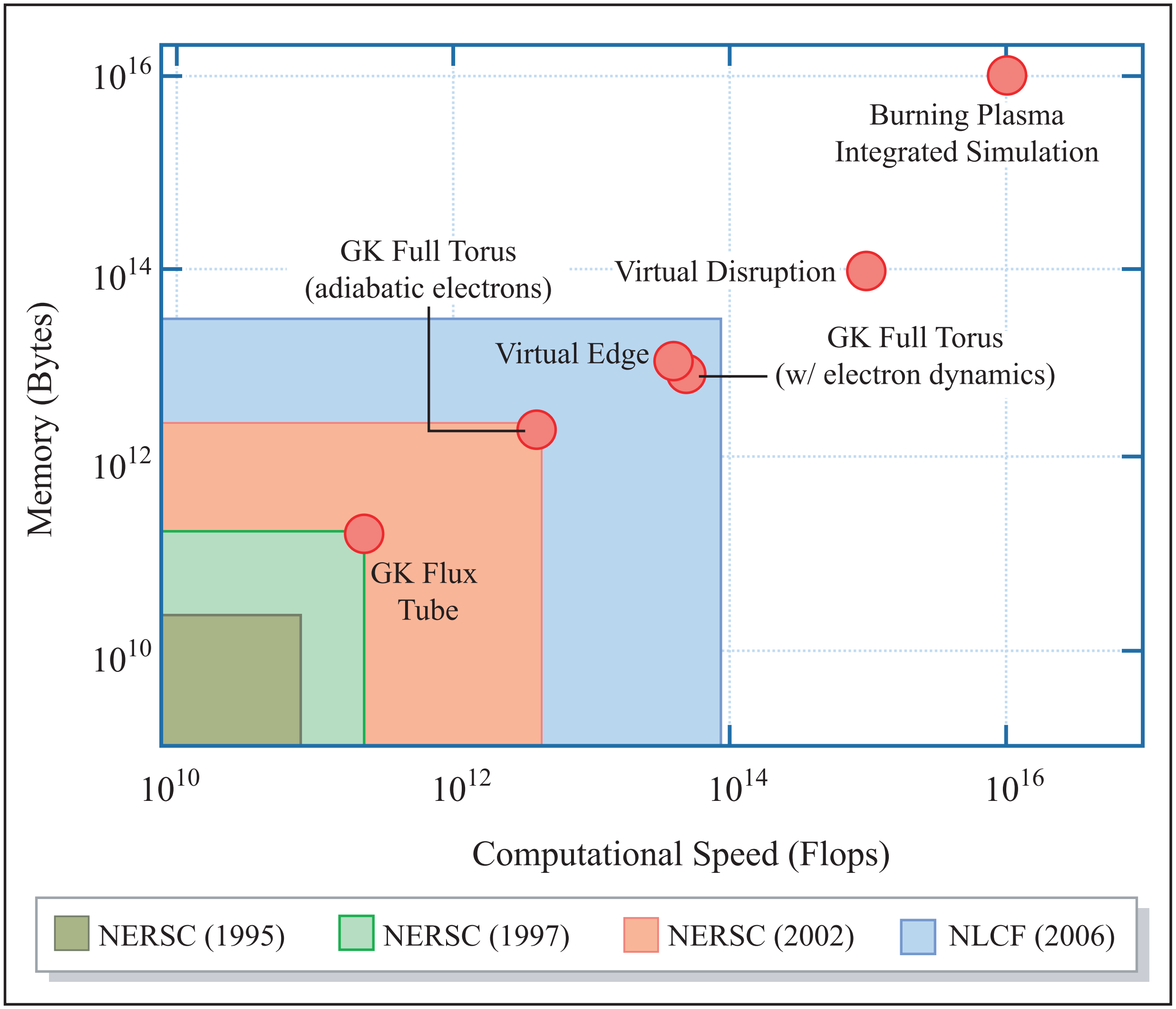
Curtesy of Scott Parker. Used with permission.

- Simulations require many grid points ($\rho/R<<1$) and good time resolution (τ_A/τ_E, $\tau_C/\tau_E << 1$)
- Plasma physics was perhaps the earliest (unclassified) science program to make use of supercomputing and data networks
- MFECC founded at LLNL1974, MFEnet 1975 ⇒ NERSC (LBNL), NLCF (ORNL)
- Good success in creating parallel algorithms
- Strong interactions with experiments are required to validate physical models



Current Drive modeling with 4.6 GHz lower-hybrid waves

Progress Is Paced By Hardware And Algorithm Development



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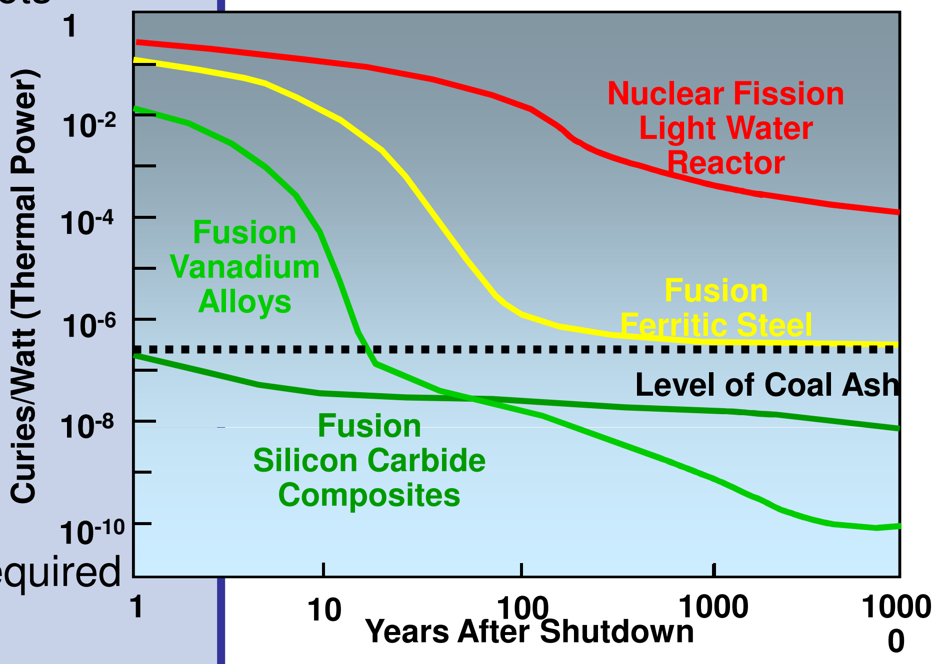
Diagnostics - Measurement And Control

- An amazing range of sophisticated technologies are employed for diagnostics – progress has been phenomenal
- All main parameters in space & time:
  - T_e, T_i, n_e, magnetic field, current profile, plasma position, shape
- All energy and particle inputs
  - external heating systems (RF waves, beams)
  - fusion heating processes (alphas - e.g. fast ions)
  - gas, beam and pellet fuelling
- Causes of energy, particle loss/performance limits
  - impurities, neutrals, turbulence, instabilities
- All energy and particle loss paths:
  - photons and particles direct from core, and neutrons
  - power and particles reaching plasma facing components (divertor)

Some Of The Engineering Challenges

- Very large, high-field, superconducting magnets
  - Mechanical and thermal stresses
  - Proximity to high neutron flux
- Material Issues
  - First Wall
    - Power handling
    - Erosion – high energy and particle fluxes
    - No tritium retention
  - Structural components – low activation required
- Blanket/Shield
  - Protect coils from neutron flux
  - Need tritium breeding ratio above 1
- Heating and current drive sources
- Steady state – high availability required



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Historical Interlude

- <1950: Program grew out of Manhattan project (+UK+USSR)
  - Magnetic confinement concept developed
- 1950: Tokamak invented (Sakharov & Tamm)
- 1951: Stellarator invented (Spitzer)
- 1957: Declassification
  - Problem turned out to be harder and of less military value than anticipated
- 1958: Geneva conference – 1st World's Fair of fusion research
- 1958-1968 V. Slow progress

Please see Lawson, J. D. "Some Criteria for a Useful Thermonuclear Reactor." U.K. Atomic Energy Research Establishment, December 1955, GP/R 1807.

Historical Interlude (2)

- 1965: USSR claims for T3 tokamak – 1000 eV
- 1969: Confirmed by Peacock, Robinson et al.
- 1970s: The tokamak age (dozens built worldwide)
- 1978: PLT achieves 6 keV with Neutral Beam Heating
- 1982-1983: Enhanced confinement regimes discovered
- 1983: Alcator-C reaches Lawson number for confinement

Image remove due to copyright restrictions. Please see Fig. 4 in Greenwald, M., et al. "Energy Confinement of High-Density Pellet-Fueled Reactors in the Alcator C Tokamak." *Physical Review Letters* 53 (July 1984): 352-355.

Historical Interlude (3)

☐ >1990:
  - First DT experiments in JET (EU) and TFTR (US)
  - Advanced diagnostic systems deployed, providing unprecedented measurements
  - Simulations advance and provide accurate predictions of some nonlinear phenomena
  - The return of the Stellarator

Photos of the Large Helical Device, National Institute for Fusion Science, Japan removed due to copyright restrictions.

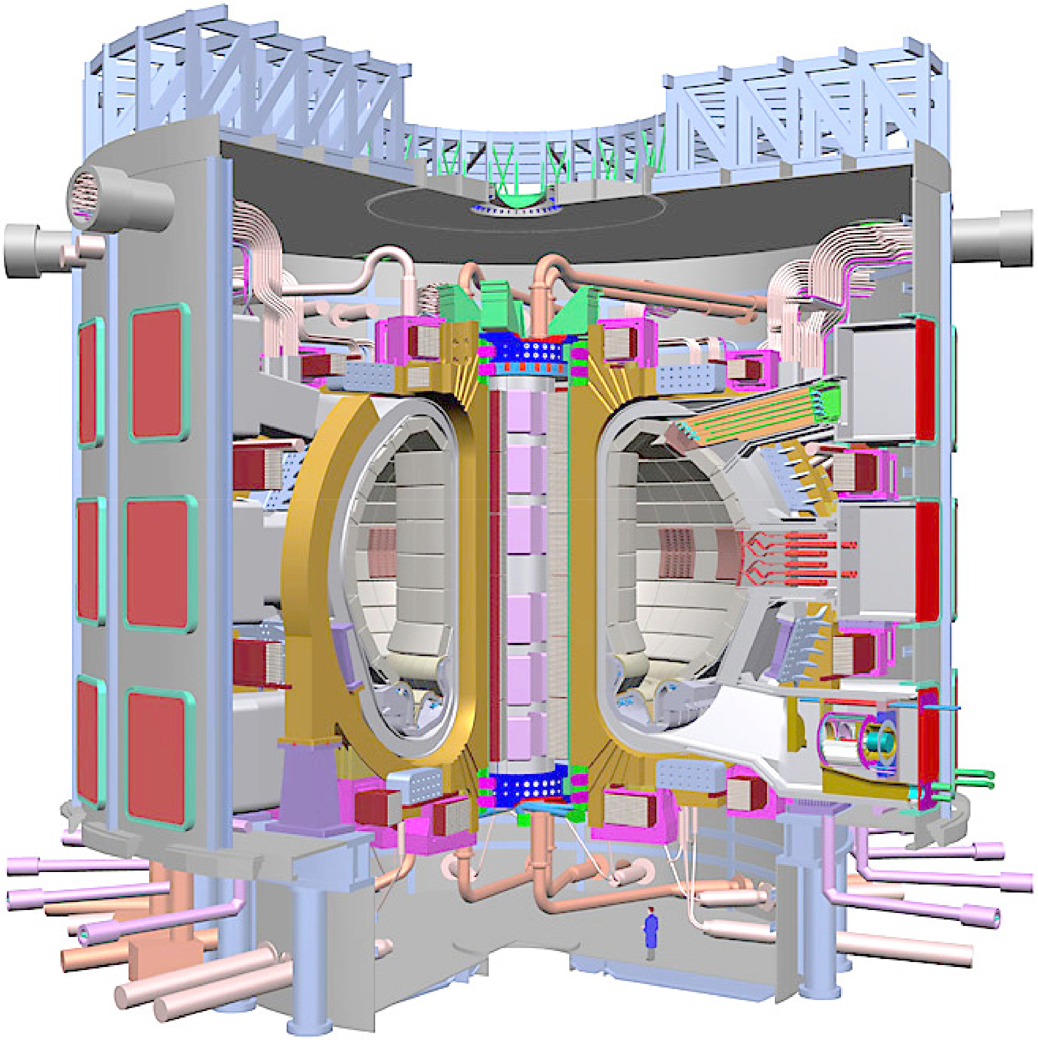
A Range of Toroidal Magnetic Configurations is Being Studied Worldwide

Photos removed due to copyright restrictions.

Please see (clockwise from top left): Alcator C-Mod, MIT Plasma Science and Fusion Center, USA; Joint European Torus, EFDA; Wendelstein 7-X, Max Planck Institut für Plasmaphysik, Germany; Korea Superconducting Tokamak Advanced Research (KSTAR), National Fusion Research Institute, Korea; JT-60, Naka Fusion Institute, Japan; Large Helical Device, National Institute for Fusion Science, Japan; DIII-D, General Atomics, USA; National Spherical Torus Experiment, Princeton Plasma Physics Laboratory, USA.

The Next Step: ITER

- ITER (International Thermonuclear Experimental Reactor)
- Mission: Demonstrate the scientific and technological feasibility of fusion energy
- China, EU, India, Japan, Korea, Russia, US
- Site: Cadarache, France
- Construction ~2007-2015
- Construction cost ~ $10B
- Political origin: 1985 Geneva summit



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ITER Site: Adjacent To Existing Lab

P_{fusion}	500MW
Q	> 10
Pulse	500 - 2500s
Major Radius	6.2m
Minor Radius	2.0m
Plasma Current	15MA
Toroidal Field	5.3T
Heating/Current Drive Power	73MW

ITER Represents A Substantial Scale-Up

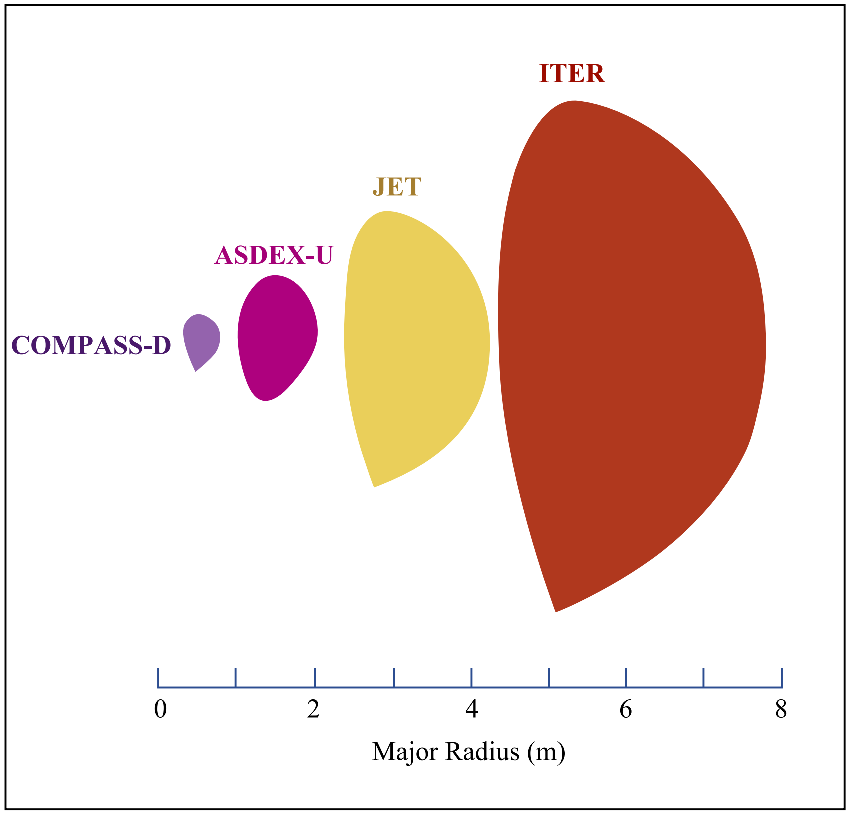


Image by MIT OpenCourseWare.

Graph comparing normalized confinement of multiple fusion reactors has been removed due to copyright restrictions.

Major Scientific And Technological Issues For ITER

- Scaling of edge pedestal and plasma transport with normalized size
  - An ITER scale experiment can operate with $\rho_i/R < 10^{-3}$
- Confinement and thermalization of fusion alpha particles
  - Fast particles can drive instabilities
- Performance limiting macroscopic instabilities
  - Includes operating limits and control strategies
- Disruption avoidance and mitigation
  - Current driven instabilities – possible Achilles heel
- Power and exhaust
  - Wall interactions and tritium retention
- Neutron effects and tritium breeding

On Beyond ITER

- (Ambitious) plans are in place to have a demonstration power reactor on line by 2035
  - US 35 year plan (2003)
  - EU “fast track” plan (2004)

In parallel with ITER

- IFMIF: International Fusion Materials Irradiation Facility
  - Would use beam-generated neutrons to qualify small samples of materials
- CTF: Component Test Facility
  - Small size, low fusion power, driven DT plasma-based device
  - For testing “components” like blankets or divertor modules
- DEMO ~2035-2040
  - Prototype commercial reactor(s) (Probably several)
  - Higher power density and much higher duty factor than ITER
- Commercial Reactor ~2050

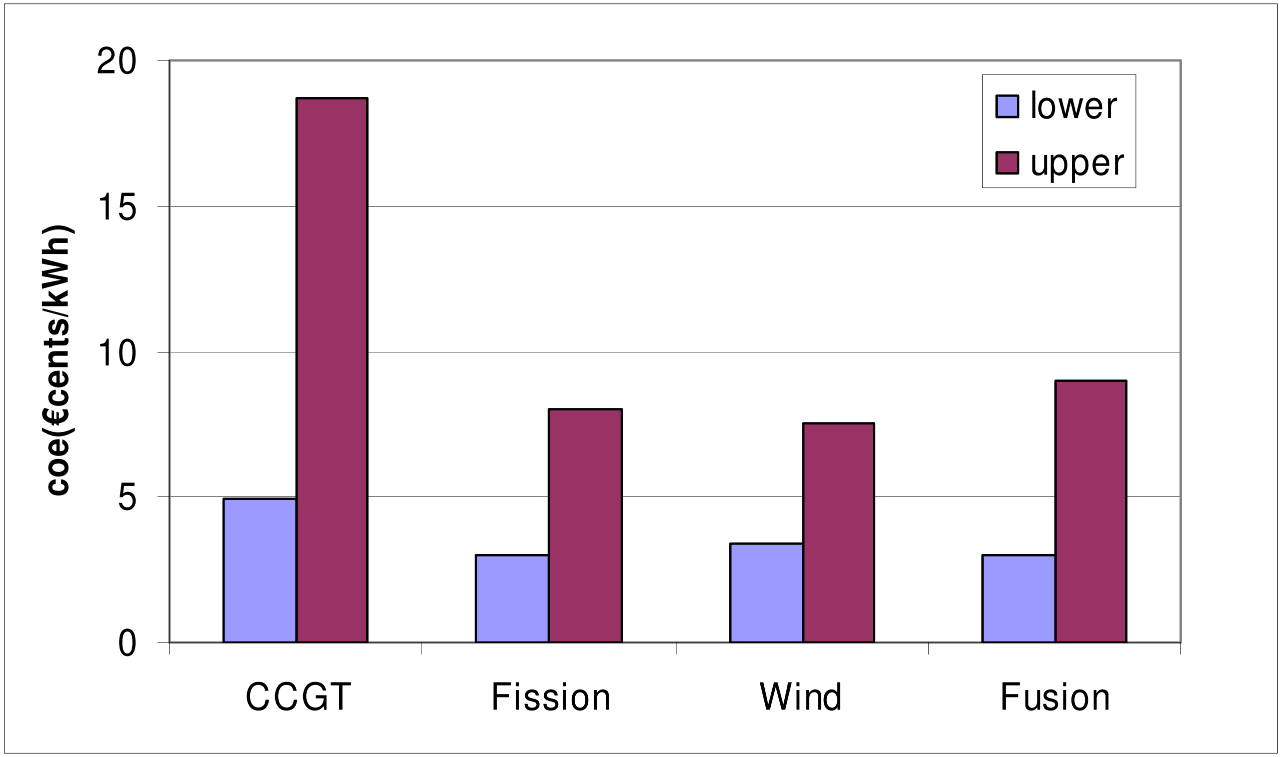
Magnetic Fusion Energy Can Be Developed At The Cost, But Not The Schedule, Anticipated In 1980.

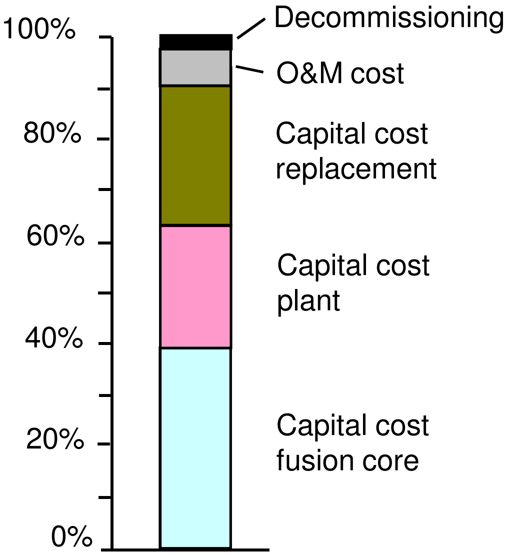
Graph showing U.S. funding for magnetic fusion research over time removed due to copyright restrictions. Please see slide 5 in Goldston, Rob. "The Development Path for Magnetic Fusion Energy." Princeton Plasma Physics Laboratory, 2006.

How Would Fusion Fit Into The World Energy Picture?

Graph illustrating various scenarios for world energy consumption removed due to copyright restrictions. Please see Fig. 1 in Schmidt, J. A. "Socio-Economic Aspects of Fusion." PPPL-4010, October 2004.

Some Cost Comparisons For Energy Sources





Combined Cycle Gas Turbine estimate Includes projected fuel price increases but no carbon tax.

Wind is near term technology but with no standby or storage costs.

Based on data from “Projected Costs of Generating Electricity” IEA, 1998 Update.

Summary

- Fusion holds out the possibility of a safe, environmentally benign power source
- Fusion has cost ~$30B worldwide and may cost another $30B to prove. Too few inexhaustible options not to try - need more funding for all possible sources.
- The science and technology are extremely challenging
- But… steady progress has been made
- We're poised to take a major step, an experiment to demonstrate the scientific and technological feasibility of fusion energy

References

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- ITER, http://www.iter.org
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The End

What Are The World's Energy Options

Nothing obviously easy

- ☐ **Burning fossil fuels (currently 80%)** → climate change + pollution: must see if large-scale CO_2 capture and storage is possible, and can be made safe and cheap
- ☐ **Nuclear fission** – safety, proliferation concerns (but cannot avoid if we are serious about reducing fossil fuel burning; at least until fusion available)
- ☐ **Biofuels** – can this be made carbon neutral? Land and water use issues
- ☐ **Solar** - need breakthroughs in production and storage
- ☐ **Wind, Tidal** – storage and land use issues, but could fill niche
- ☐ **Fusion** – environmentally benign, but success is not 100% certain
- ☐ With so few good options, we should aggressively pursue all alternatives

Note: World's energy costs approaching $10 Trillion/year

Why Are Cost Estimates Similar? (Except for Fuel)

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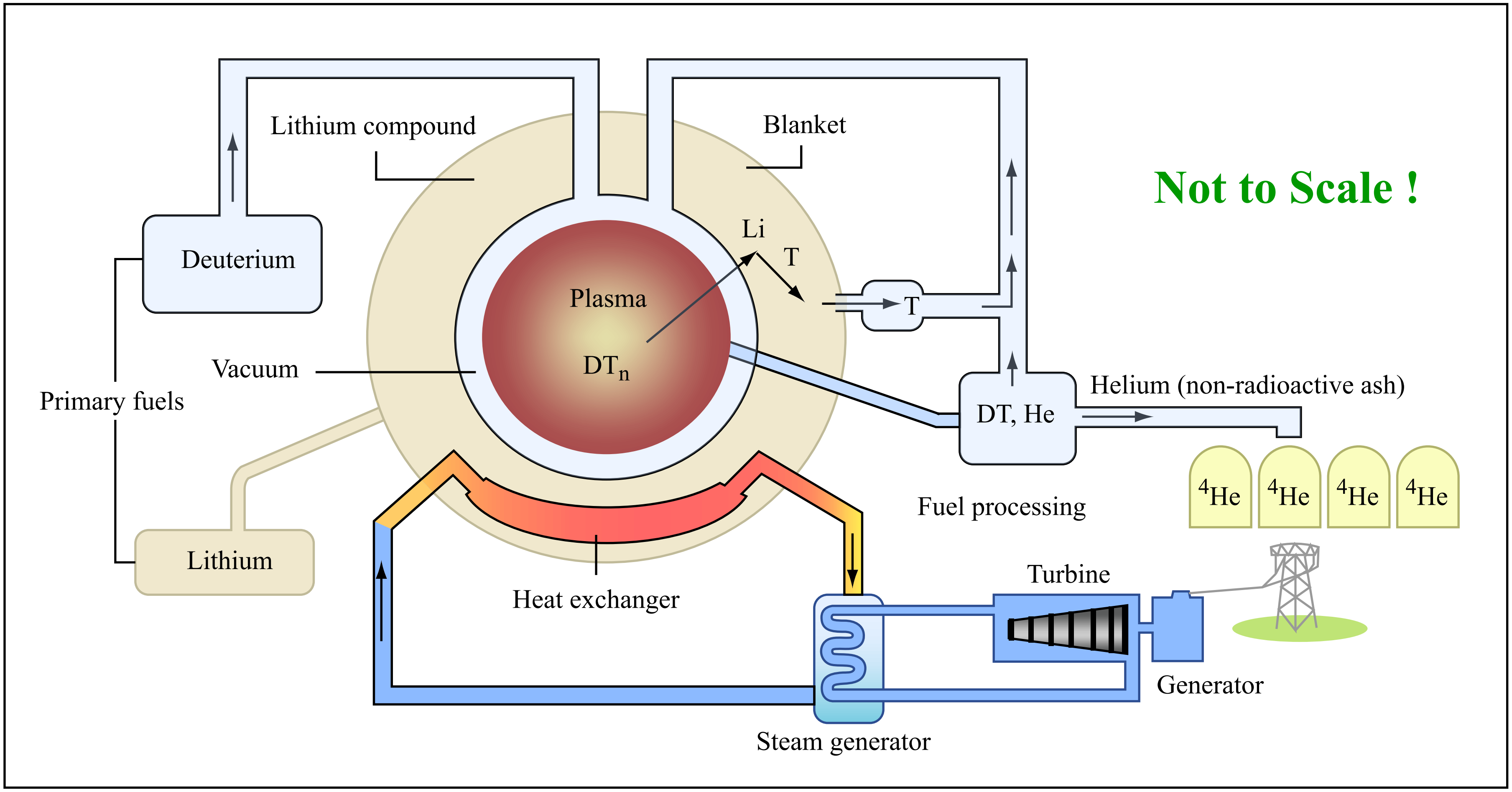
Please see Fig. 4 in Maisonnier, D., et al. "Annexe 6: Plant Model C." *A Conceptual Study of Commercial Fusion Power Plants*. Final Report of the European Fusion PPCS, April 13, 2005, EFDA-RP-RE-5.0.



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Please see Fig. 7 in Cook, I., et al. Safety and Environmental Impact of Fusion. April 2001, EFDA-S-RE-1.

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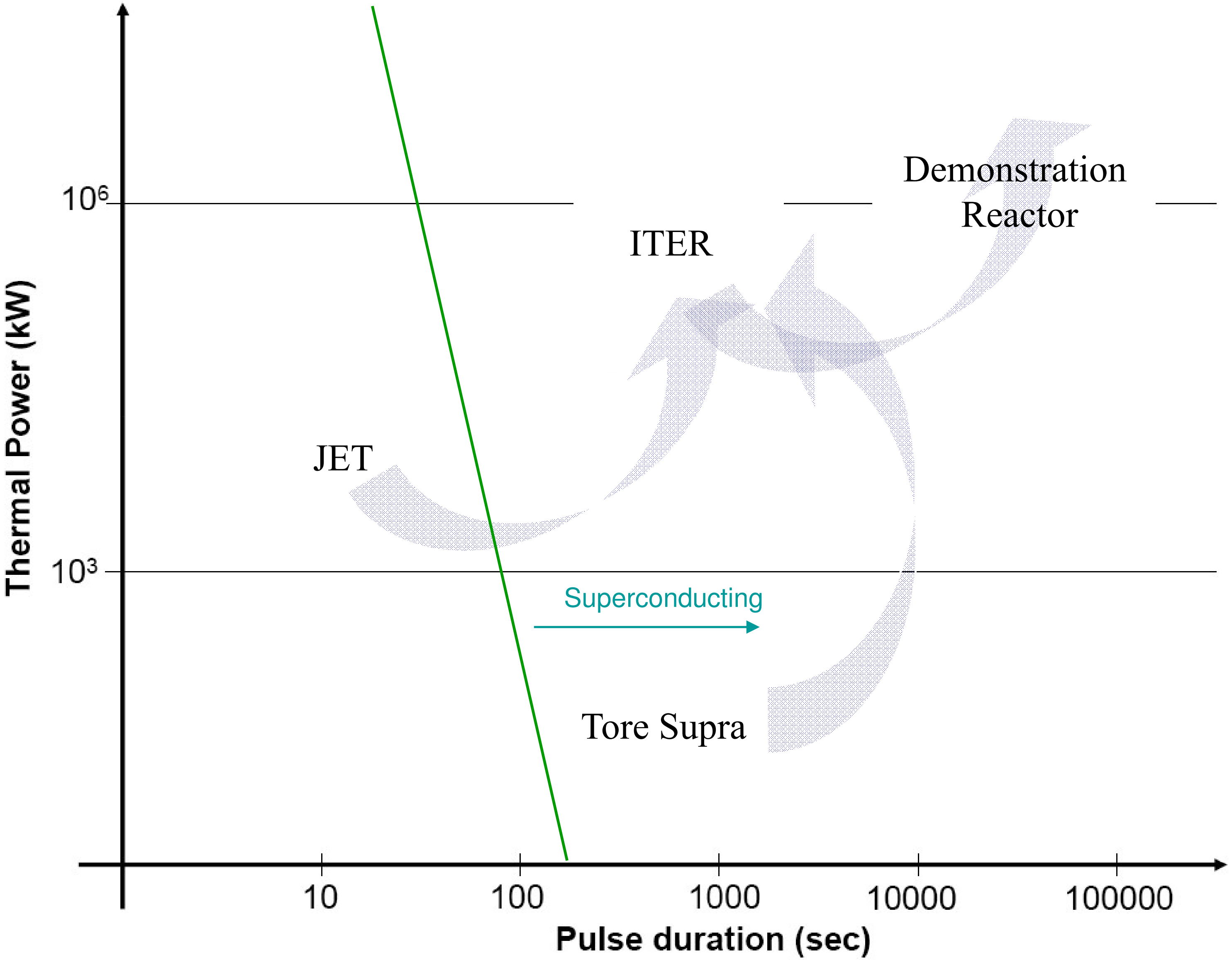
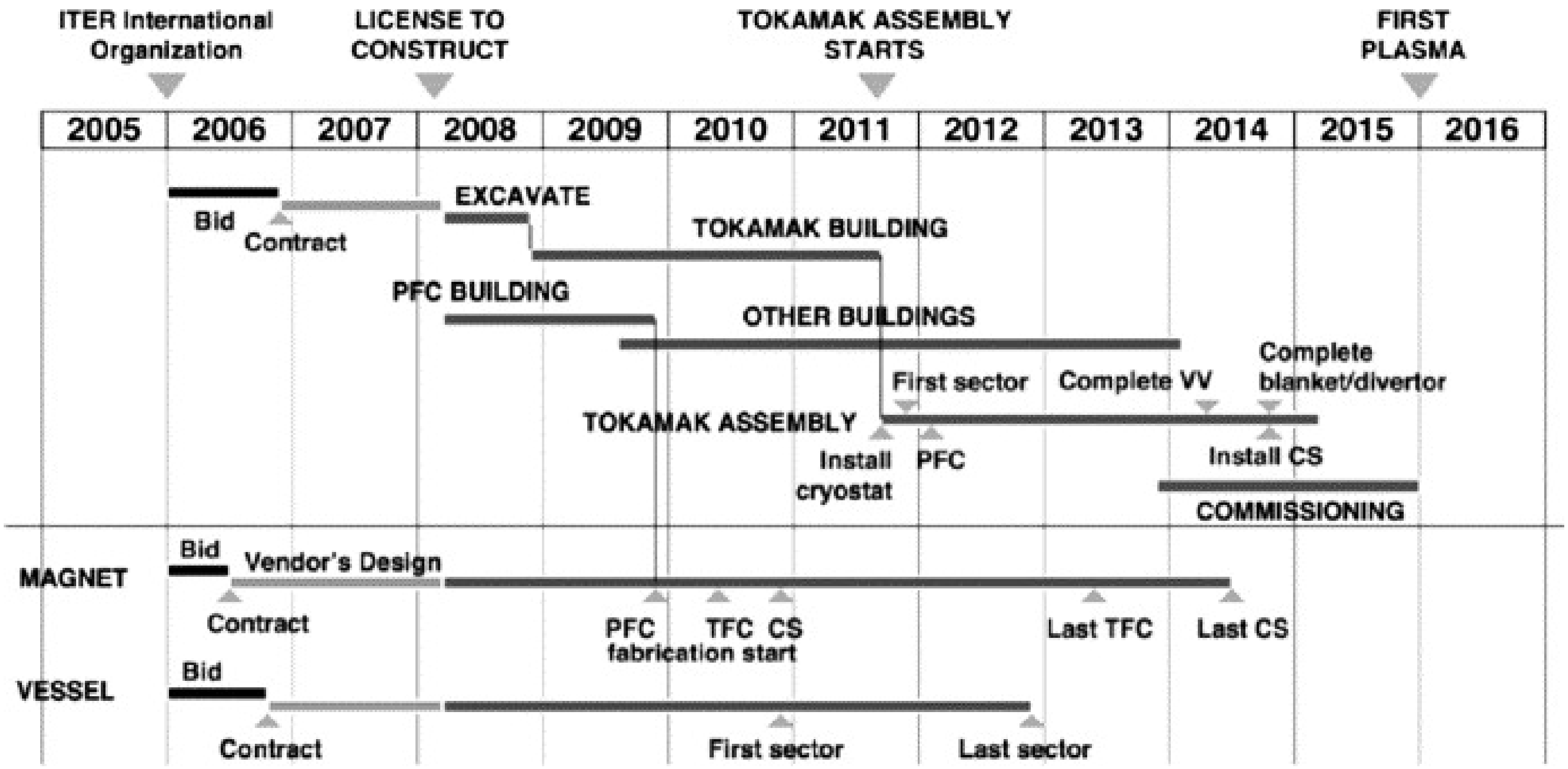
Please see Fig. 12 in Maisonnier, D., et al. *A Conceptual Study of Commercial Fusion Power Plants*. Final Report of the European Fusion PPCS, April 13, 2005, EFDA-RP-RE-5.0.

Need To Increase Power And Pulse Length



ITER Construction Schedule



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Magnetic Confinement In Toroidal Devices

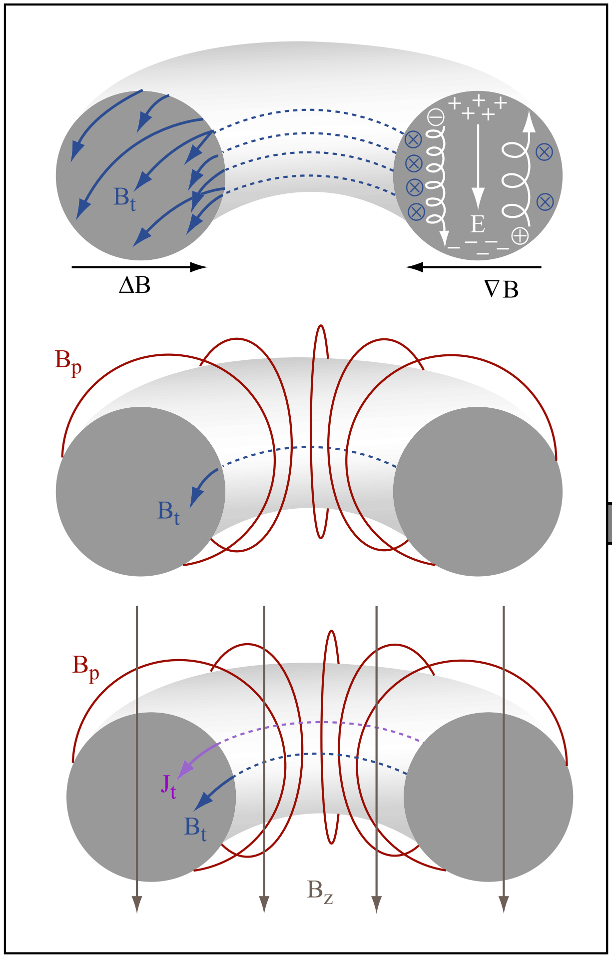


Image by MIT OpenCourseWare.

E×B drift

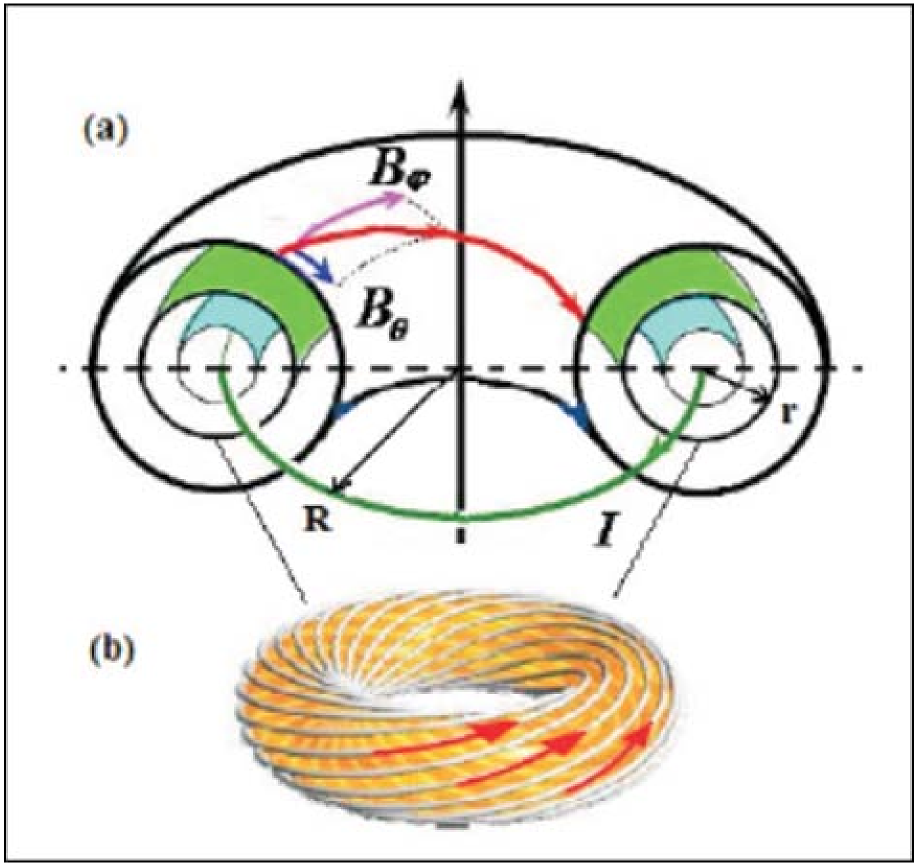
Hoop Stress

- ❑ Solution 1: Torus solves the end-loss problem
- ❑ Problem 2: In a simple toroidal field, particle drifts lead to charge separation

- ❑ Solution 2: Add poloidal field, particles sample regions of inward and outward drift.
- ❑ Problem 3: Hoop stress from unequal magnetic and kinetic pressures.

- ❑ Solution 3: Add vertical field, to counteract hoop stress.
- ❑ Magnetic confinement experiments are variations on this theme.

Plasma Is Confined On Closed Nested Flux Surfaces

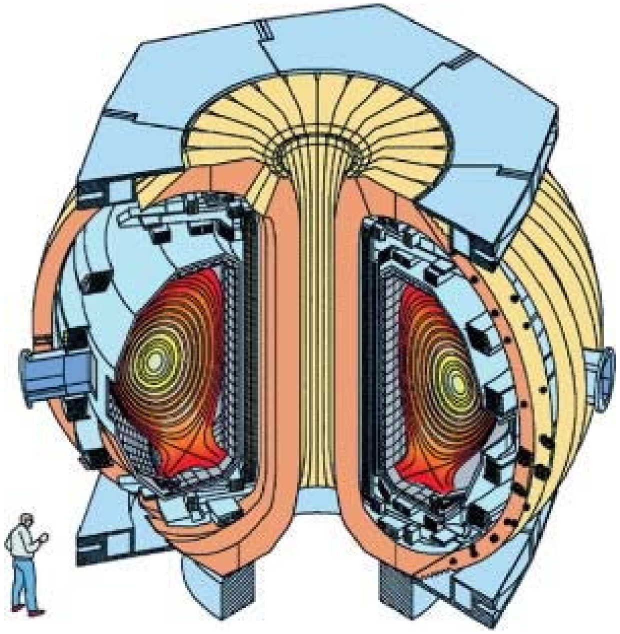


Tan, B.-L., and G.-L. Huang. "Neoclassical Bootstrap Current in Solar Plasma Loops." *Astronomy & Astrophysics* 453 (2006): 321-327. Reproduced with permission (c) ESO. http://dx.doi.org/10.1051/0004-6361:20054055

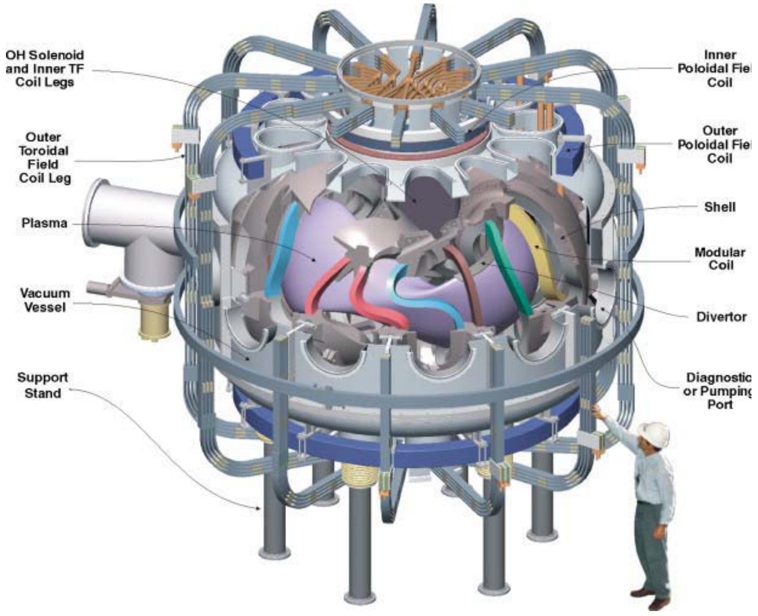
- ❑ Magnetic field lines are helical and lie on closed, nested surfaces – flux surfaces, Ψ = const.
- ❑ Vertical ∇B drift averages to zero as particle follows helical field
- ❑ To lowest order, particles are “stuck” on flux surfaces

Two Strategies To Create This Configuration

Tokamak



Stellarator



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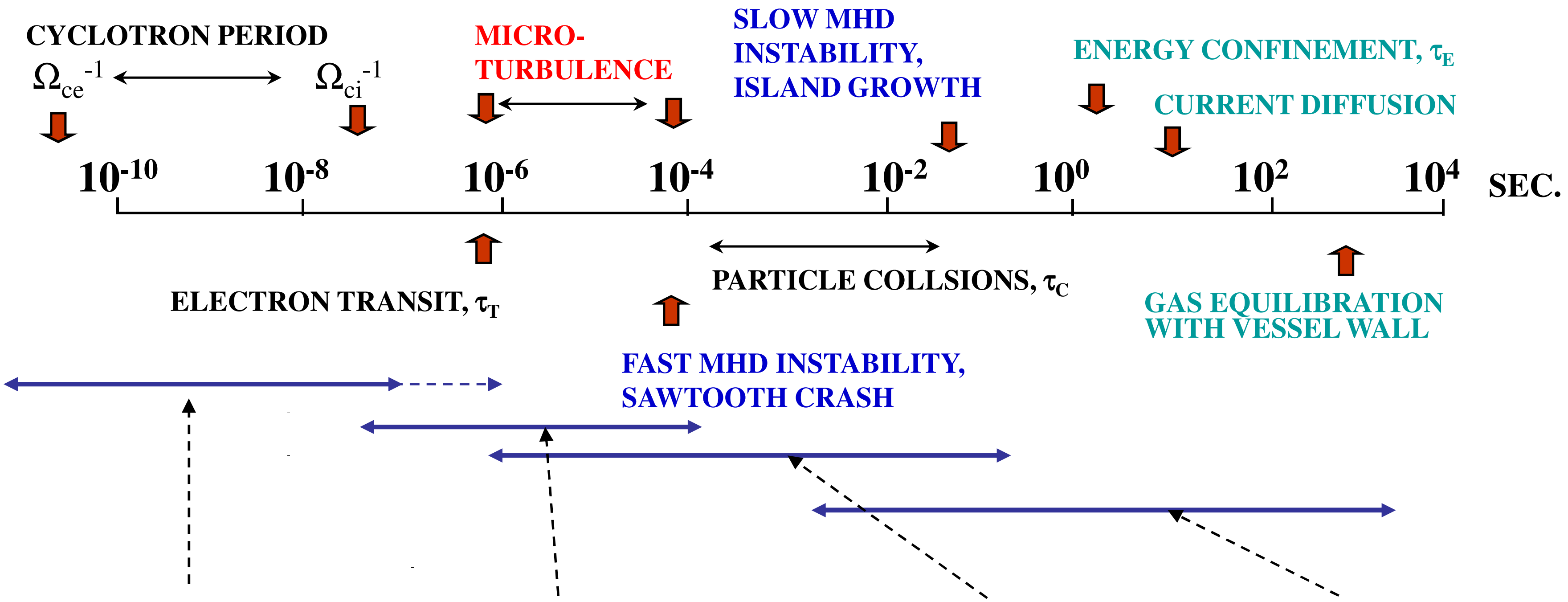
- Poloidal field from current in the plasma itself.
- Axisymmetric – good confinement
- Current is source of instability

- Poloidal field from external coils
- Intrinsically steady-state
- Non-axisymmetric – good confinement hard to achieve
- More difficult to build

Progress Has Been Made By Dividing Up The Problem Principally By Time Scale



CYCLOTRON PERIOD

Ω_{ce}^{-1} ↔ Ω_{ci}^{-1}

MICRO-TURBULENCE

SLOW MHD INSTABILITY, ISLAND GROWTH

ENERGY CONFINEMENT, τ_E

CURRENT DIFFUSION

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

ELECTRON TRANSIT, τ_T

PARTICLE COLLSIONS, τ_C

GAS EQUILIBRATION WITH VESSEL WALL

FAST MHD INSTABILITY, SAWTOOTH CRASH

RF:
wave-heating and current-drive

Gyrokinetics:
micro-turbulence

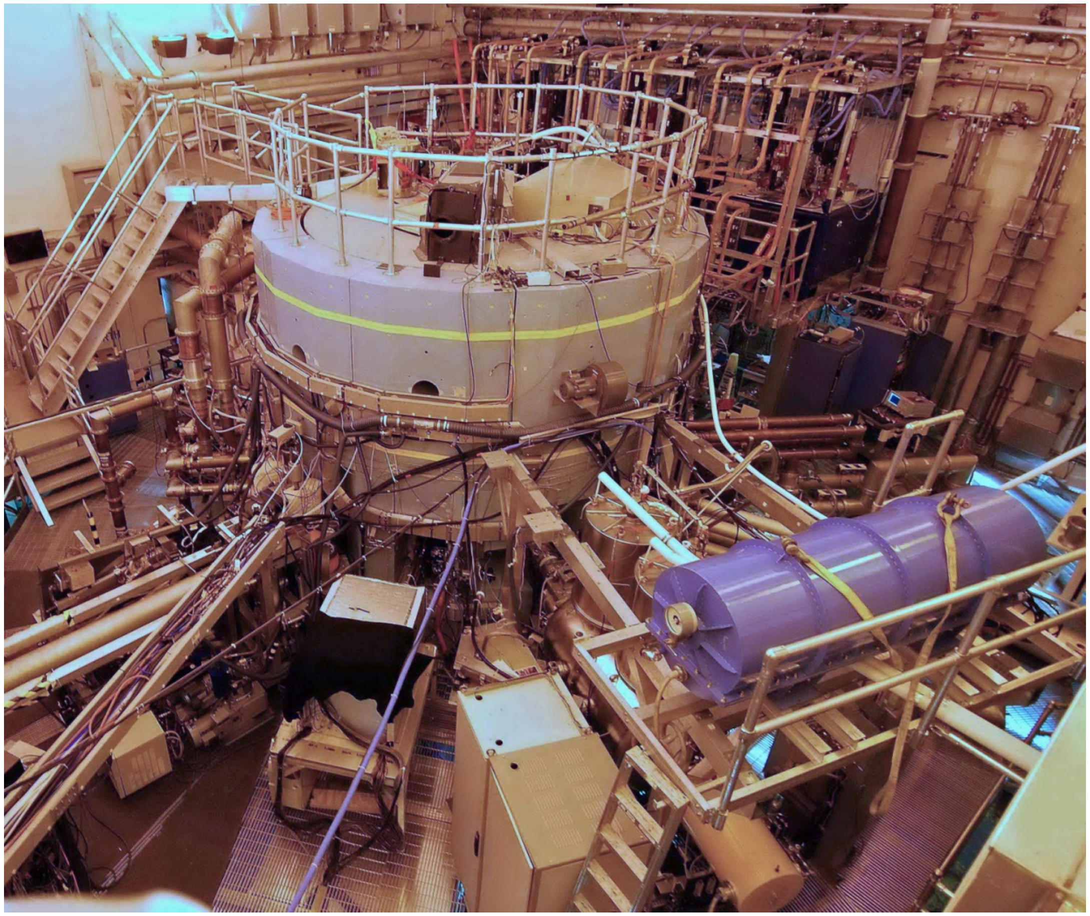
Extended MHD:
device scale stability

Transport Codes:
discharge time-scale

Topical Science Areas

- ☐ MHD Magneto-hydrodynamics (Mostly fluid description)
  - Basic plasma equilibrium is well understand
  - Macroscopic stability, operating limits, performance limits
- ☐ Transport and confinement (primarily kinetic description)
  - Collisional transport understood (and small)
  - Transport dominated by turbulence
- ☐ Wave-particle interactions
  - Heating, current drive, fusion alpha confinement
- ☐ Boundary physics
  - Edge turbulence and transport (collisional plasma)
  - Plasma-wall interactions

Alcator C-Mod Tokamak Experiment at MIT



Research sponsored by U.S. Department of Energy

One of three major fusion facilities in the U.S. MFE program

Total staff ~ 100 including ~ 30+ graduate students – training the next generation of scientists and engineers

We collaborate with more than 40 other universities and labs: domestic and international

Plasma Physics: Prediction Via Advanced Simulations

Plasma physics is a many body problem – requires statistical treatment

Basic description of plasma is the Boltzmann equation

The equation of motion in a 6 Dimensional phase space   f(x, v, t)

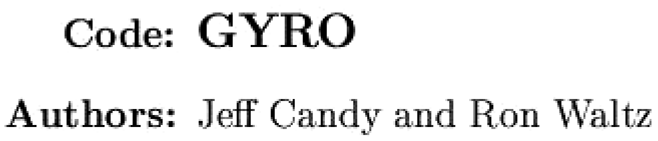
- Intrinsic nonlinearity
- Extreme range of time scales O(10^{14}) and spatial scales O(10^{4})

With closed-form solution impossible, computer simulation has been a key element of the MFE program

- Plasma physics was perhaps the earliest (unclassified) science program to make use of supercomputing and data networks
- MFECC, MFEnet founded at LLNL 1974 □ NERSC, ESnet (LBNL), NLCF (ORNL)

Strong interactions with experiments are required to validate physical models

Plasma Turbulence Simulation

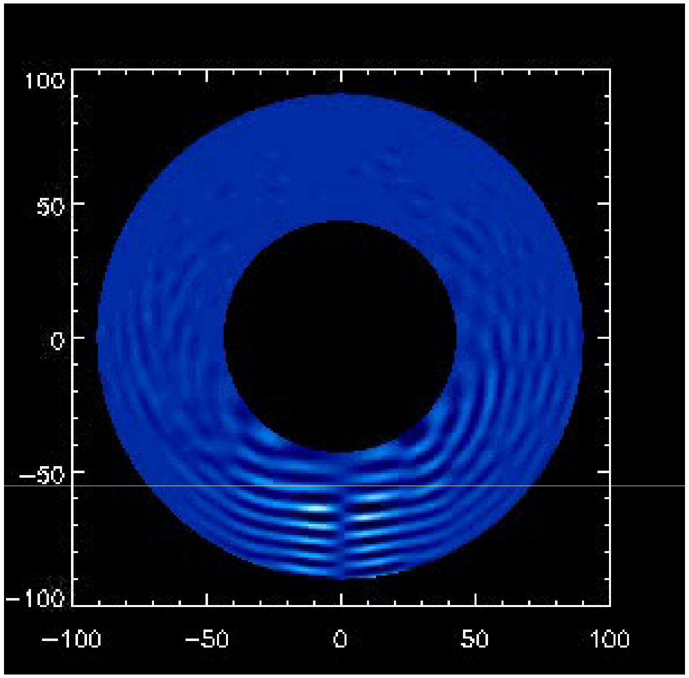


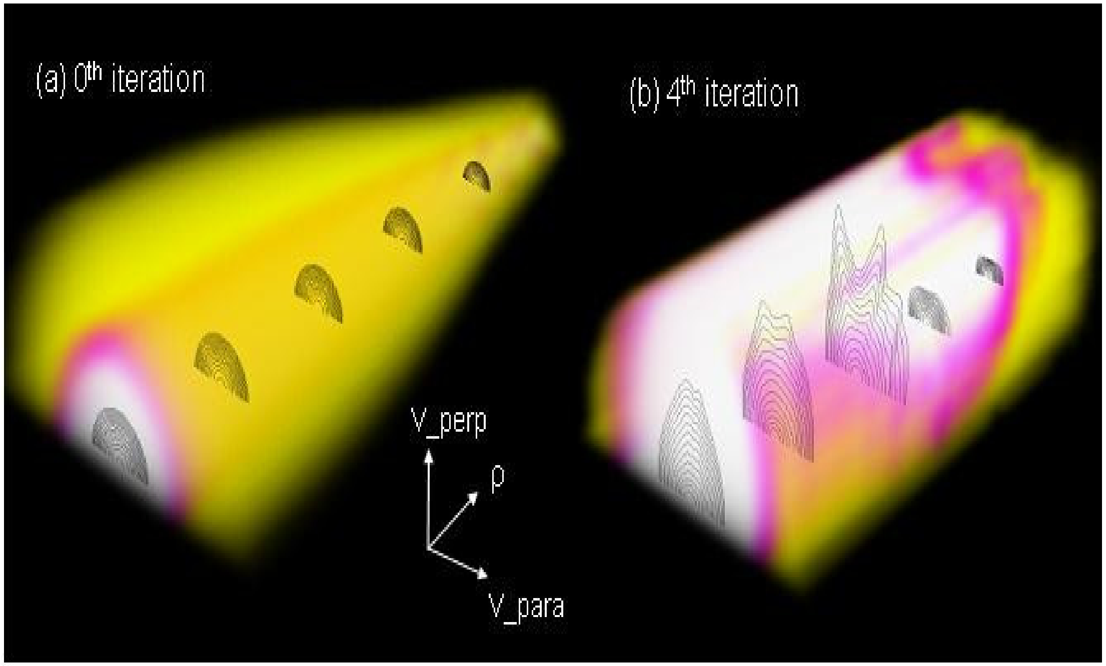
Code: **GYRO**

Authors: Jeff Candy and Ron Waltz

- Ion gyro-scale turbulence
- Note period of linear growth
- Saturation via self-generated “zonal flows”

Wave Particle Physics





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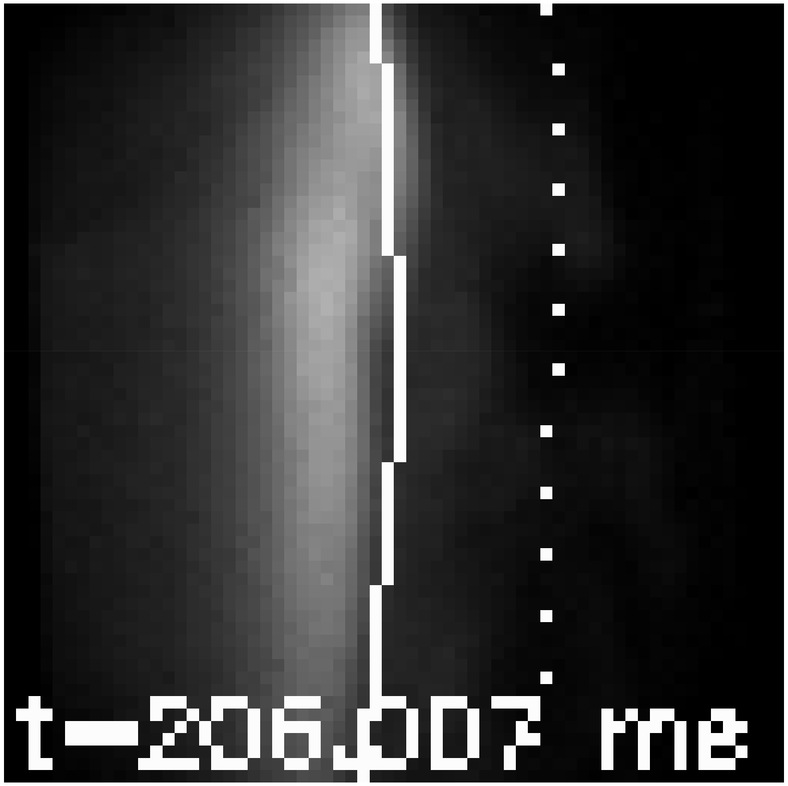
- ❑ Problem: Solve wave equation in presence of plasma dielectric
- ❑ Weakly nonlinear problem
- ❑ Challenge is to calculate plasma response
- ❑ Plasma response is non-local (requires solution of integral equation)

Boundary Physics

- Problem: The interaction of the very hot boundary plasma (only 50,000K) with material objects
- While plasma is much cooler at edge, heat fluxes can easily damage wall
- Involves turbulent transport + atomic physics + properties of materials



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