The Physics and Simulation of Fusion Plasmas

Overview

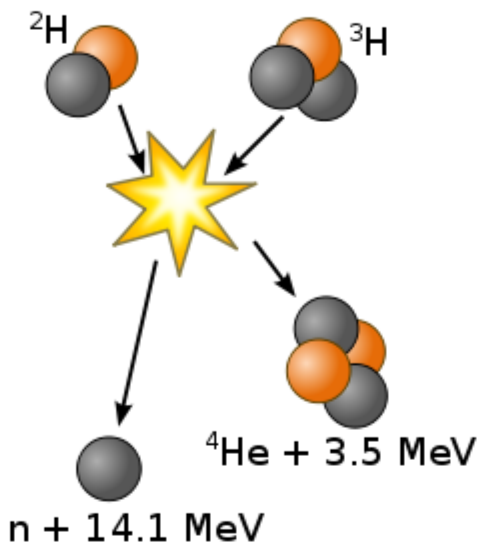
- It is now clear that a sustainable, globalized world economy requires development of CO_2-free sources of energy and electricity.
- Nuclear fusion has the potential to play a significant role as a part of the long-term solution to the challenge of global warming.
- To realize the promise of nuclear fusion, we need understand the nonlinear dynamics of plasmas on many different time and space scales, and to translate that physics understanding into accurate models which aid our understanding of current experiments, and help us design new ones.
- In this talk, I'll outline how we use our understanding of fundamental physical processes to model magnetically confined plasmas, and show how we are testing the predictions of those models against experiment on new and detailed levels.

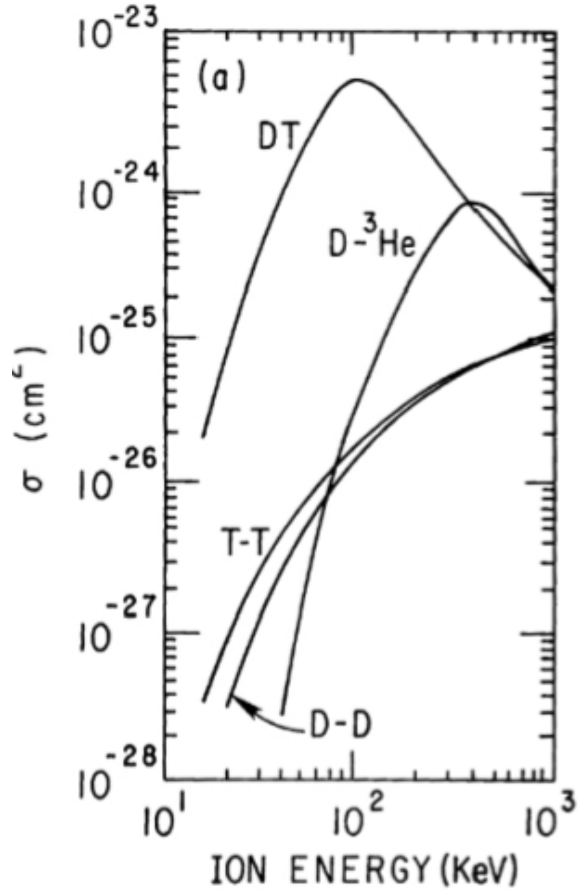
Using Plasmas for Fusion Energy

Using Nuclear Fusion as an Energy Source

- **What is fusion?** Process by which light nuclei combine to form a heavier nuclei, accompanied by a release of energy

- From an energy production standpoint, most promising are D-T fusion reactions because of large reaction cross-section





Nuclear cross sections

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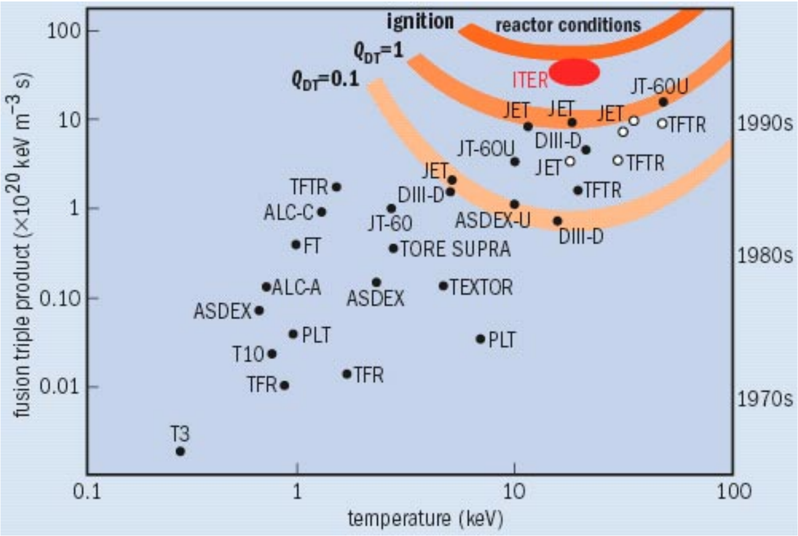
How Many Fusion Reactions Do We Need?

- **Lawson criterion:** require heating from fusion products to exceed system loss rate

$$n_D n_T \langle \sigma v \rangle E_{ch} \geq \frac{\text{system energy content } W}{\text{confinement time } \tau_e}$$

$$\rightarrow n\tau_e \geq \frac{12 k_b T}{E_{ch} \langle \sigma v \rangle}$$

  – For D-T, need $n\tau_e > 1.5 \times 10^{20}$ s / m^3 at minimum $k_b T = 25$ keV (= 290,000,000 °K)

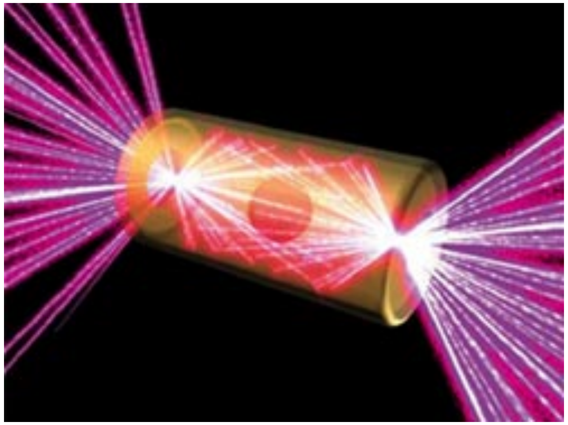


From R. Pitts, "Fusion: the way ahead" *Physics World*, March 2006

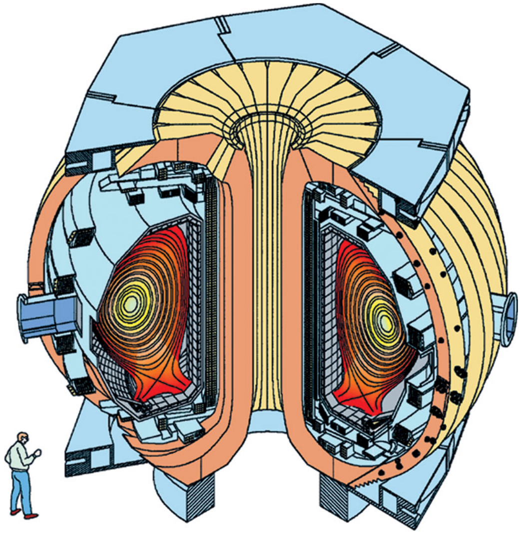
- **Fusion gain Q** = (fusion power generated)/(applied heating power)
  – Q = 1: breakeven, corresponds to fusion products producing 17% of total heating
  – Q = ∞: ignition, no external heating (Lawson criterion)
  – Typical fusion power plant envisioned to run at Q = 10 - 20

Two Approaches to High Q

- **Inertial confinement:** implode frozen D-T pellets
  - high n (10^{26} m^{-3}), small τ_e
  - Approach being taken at NIF facility
  - Inherently pulsed approached to energy generation

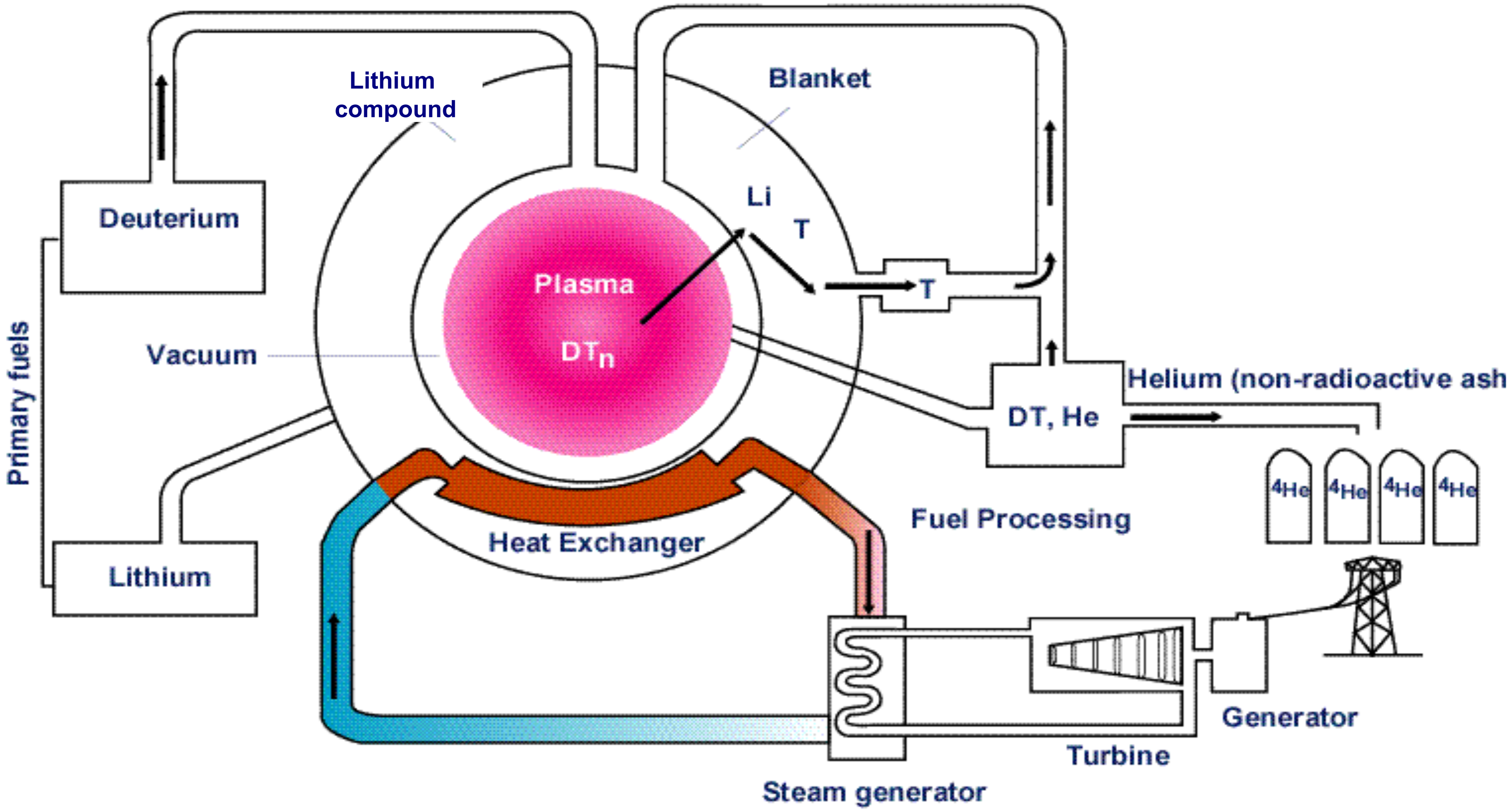


- **Magnetic confinement:** use strong magnetic fields to confine and insulate high temperature D-T plasma at lower density (10^{20} m^{-3}) for long time



- Either approach uses neutrons produced to breed T from Li in blanket modules outside vessel wall as well as boil water

Schematic of a Fusion Power Plant



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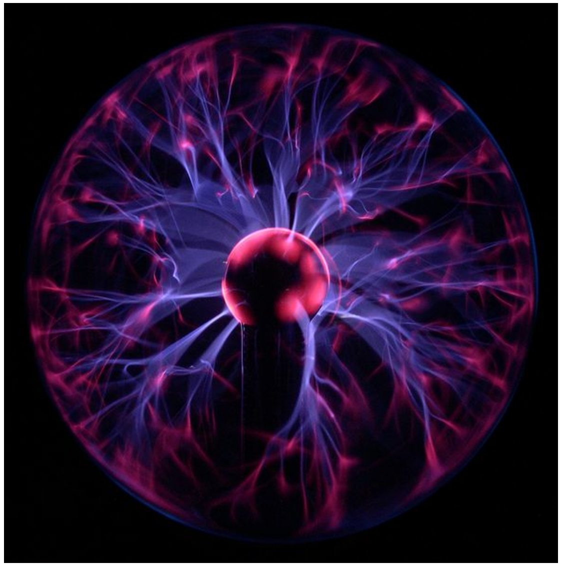
What is a plasma?



- Plasmas are sometimes referred to as "the fourth state of matter." At the most basic level, it consists of a electrically neutral collection of positively and negatively charged particles
  - In the context of fusion, it is material at that has been sufficiently heated to ionize

- The key defining feature of plasmas is the dominance of collective dynamics
  - In a neutral gas (the third state of matter), the dominant particle interactions are binary collisions
  - In a plasma, a wide variety of waves and instabilities can arise due to long-range interactions between particles via their electric and magnetic fields
  - As each charged particle in the plasma moves, other nearby particles adjust their positions and velocities (via the Coulomb force) to ensure the plasma remains electrically neutral on scales larger than the Debye length λ_D
  - In a MFE-relevant plasma, $\lambda_D < 10^{-5}$ m <<< system size

$$\lambda_D = \left(\frac{\varepsilon_0 k_b T}{q^2 n} \right)^{1/2}$$

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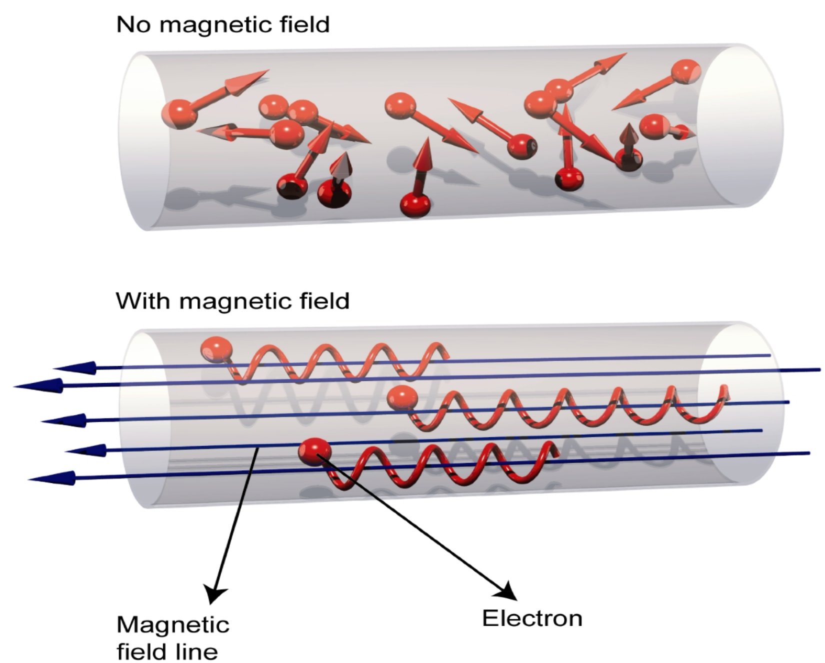
Review: Motion of a Charged Particle in a Magnetic Field

- In absence of magnetic field, particles bounce around randomly in container

- In magnetic field, motion governed by Lorenz force
$$m\frac{d\vec{V}}{dt} = q\vec{V} \times \vec{B}$$
  - Free streaming ‖ to B
$$m\frac{dV_{\parallel}}{dt} = 0 \rightarrow V_{\parallel} = const$$
  - Cyclotron motion to B
$$m\frac{d\vec{V}_{\perp}}{dt} = q\vec{V}_{\perp} \times B \rightarrow \vec{V}_{\perp} = V_{\perp}(0)\left\{\cos(\Omega t)\hat{x} - \sin(\Omega t)\hat{y}\right\},\ \Omega = qB/m$$



- Combination of ‖ free-streaming and cyclotron orbits leads to helical trajectories of individual particles

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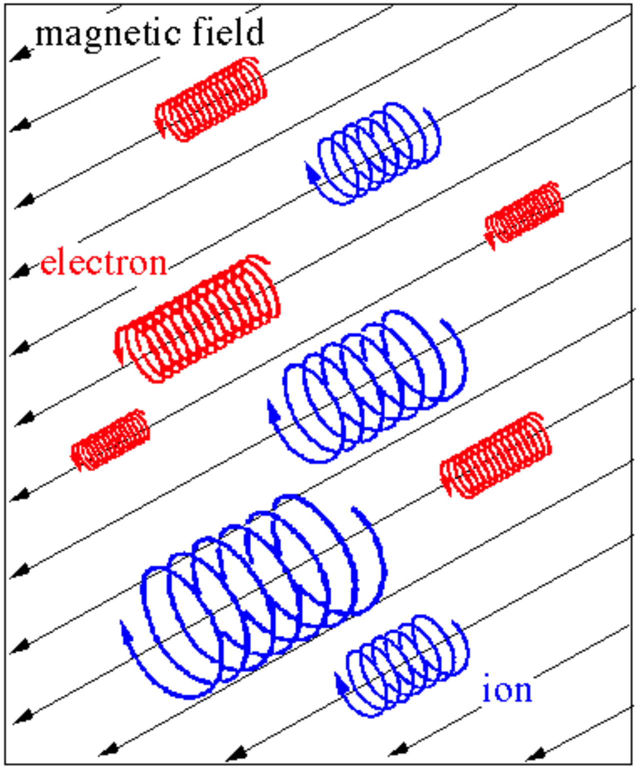
Magnetic Confinement Approach to Fusion

- Charged particles execute helical motion in presence of magnetic field
- Larmor radius of orbits $\rho = V_{th}/\Omega_c \propto 1/B$
  - can keep particles "tied" sufficiently close to a field line by increasing strength of magnetic field
  - For fusion-relevant temperatures and B = 1-10 T, find ion ρ = several mm, electron ρ is 60x smaller
- Create closed field lines by bending them into a torus
  - ideally ions (and electrons) never touch wall, and freely circulate until they collide and fuse
  - Slow diffusion across fields lines due to Coulomb scattering



- Bending field lines leads to drifts of particle guiding centers- can be solved by using helical field lines

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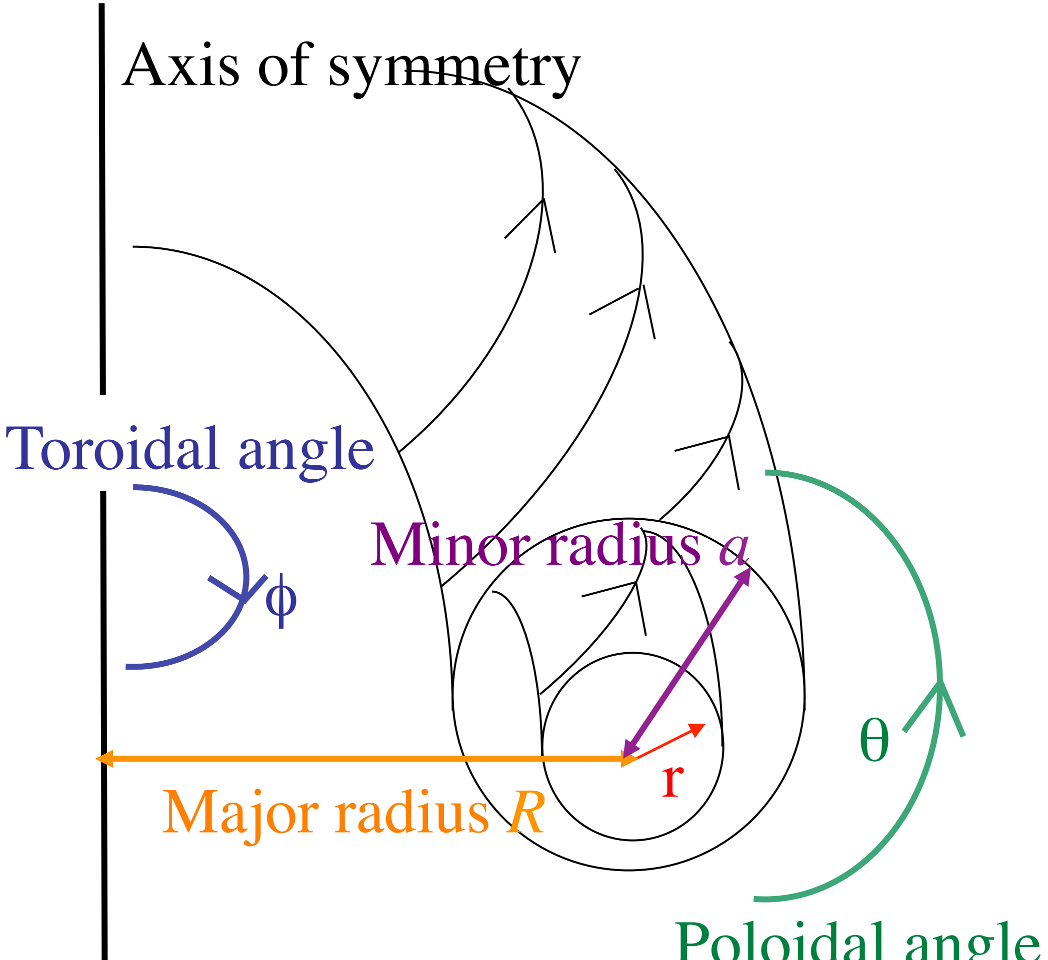
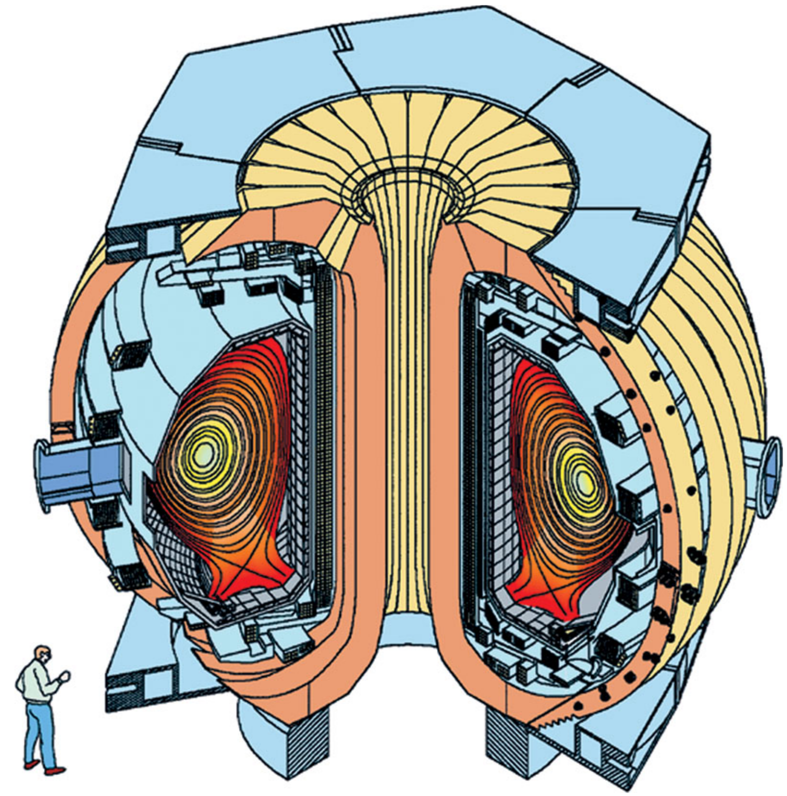
Overview of Tokamak Geometry





DIII-D tokamak

(at General Atomics in La Jolla)

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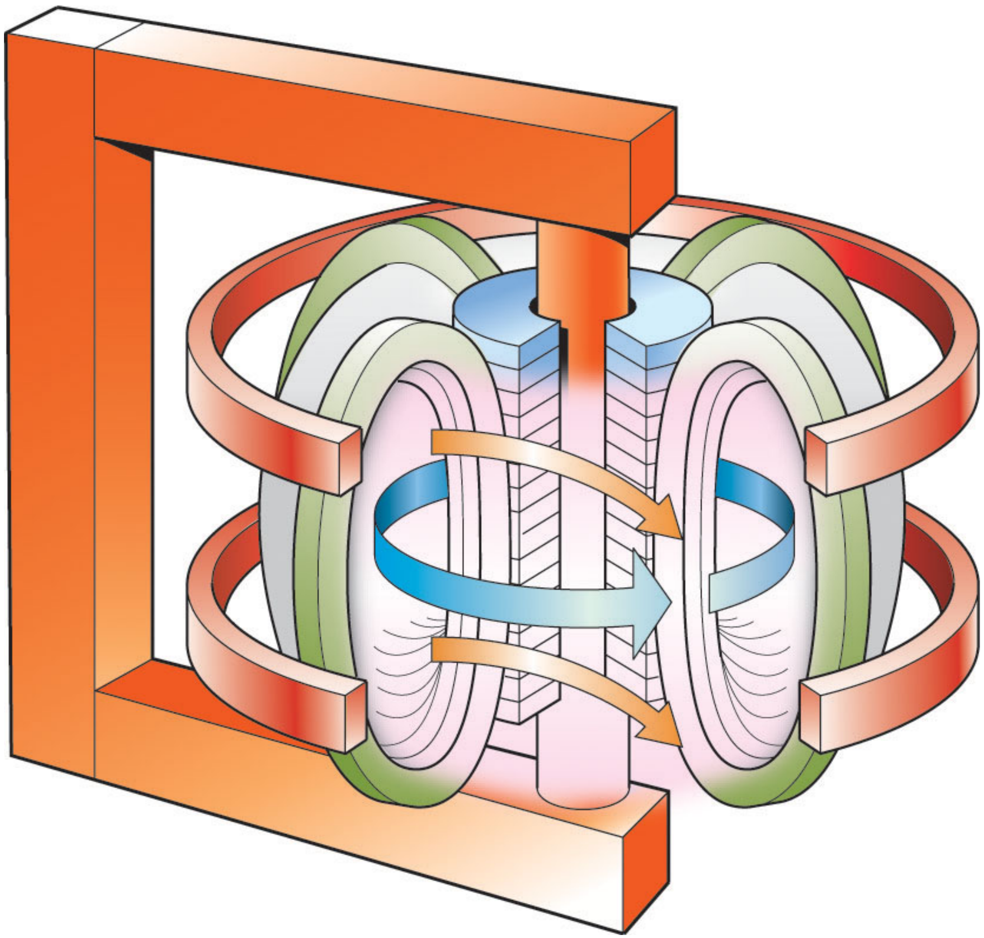
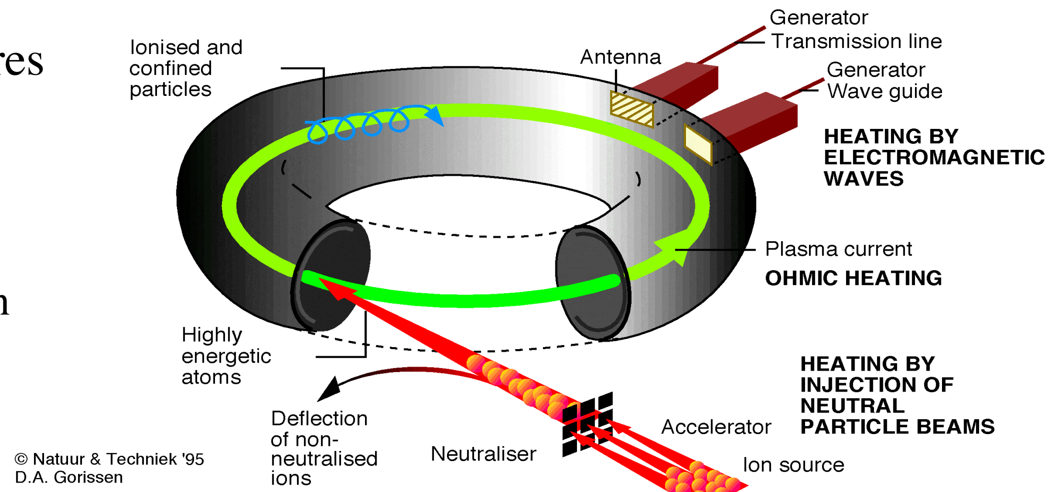
Use External Currents to Create Magnetic Field



- Run current through toroidal field coils to generate to generate toroidal field B_ϕ
  - $B_\phi \sim 1 - 2$ T in DIII-D
- Slowly ramp current through central solenoid to generate a toroidal current I_ϕ via transformer action
  - $I_\phi \sim 1 - 2$ MA in DIII-D
  - Generates poloidal magnetic field $B_\theta \sim 0.1\ B_\phi$
- Use poloidal field coils to provide additional control and stability

Limitations of Tokamaks



- Generating the poloidal field requires driving and maintaining a toroidal current in the plasma
  - Inductive drive is transient- not desirable for steady-state operation
  - Steady-state requires current drive via microwave heating or neutral beams
  - This plasma current can drive large scale instabilities which limit maximum attainable pressure and performance
- Transport across field lines is dominated by small-scale turbulence driven by the inherent pressure gradients
  - This transport is an order of magnitude or more greater than expected due to Coulomb scattering
  - Also limits the maximum attainable gradients- translates to a second limit on maximum achievable pressure and performance for a given machine, even if issue of large-scale stability is avoided

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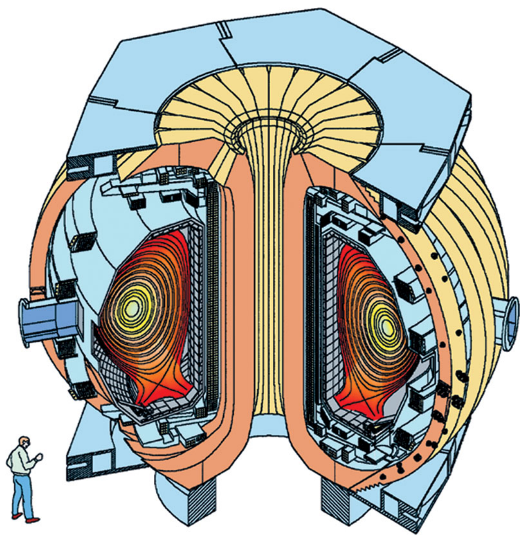
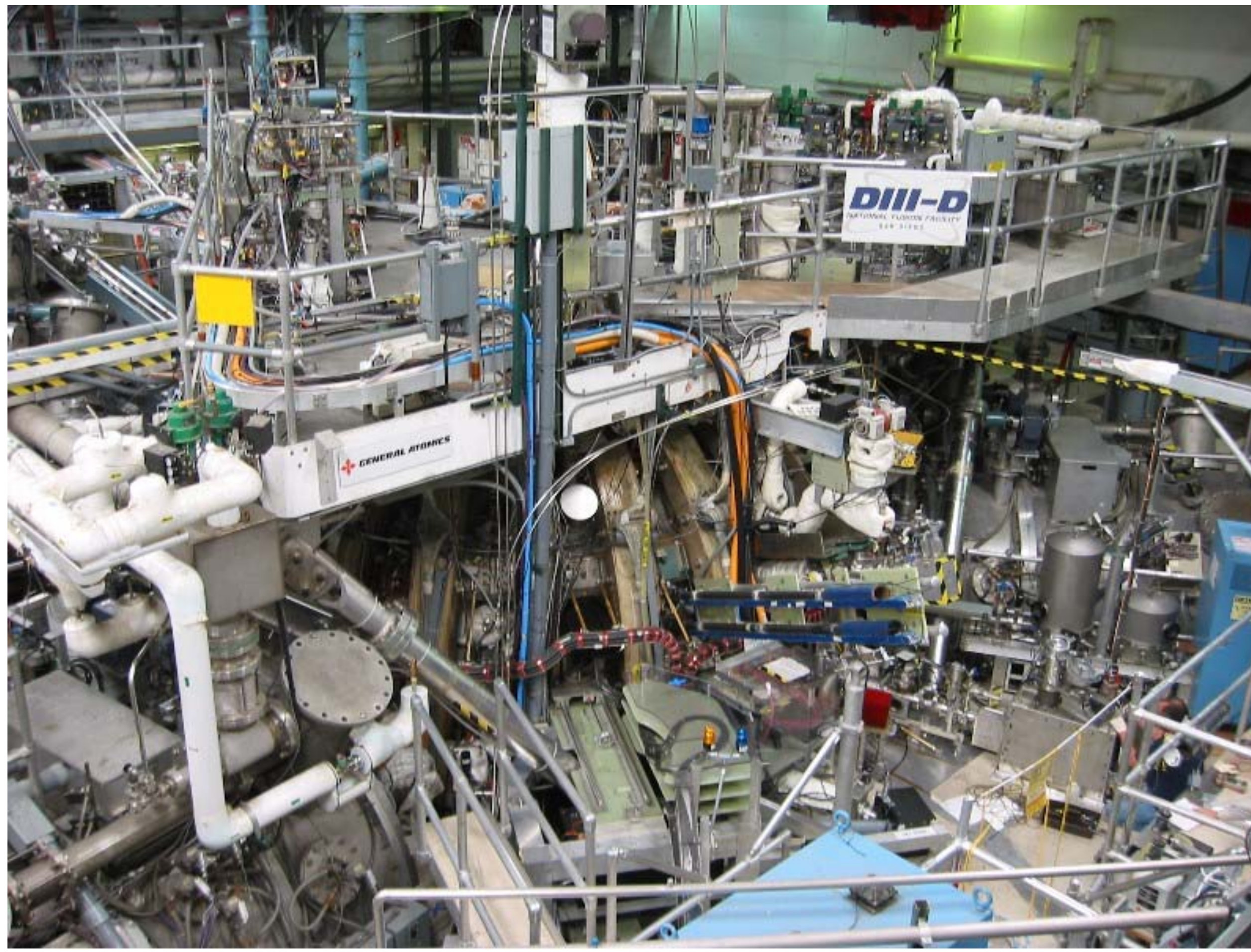
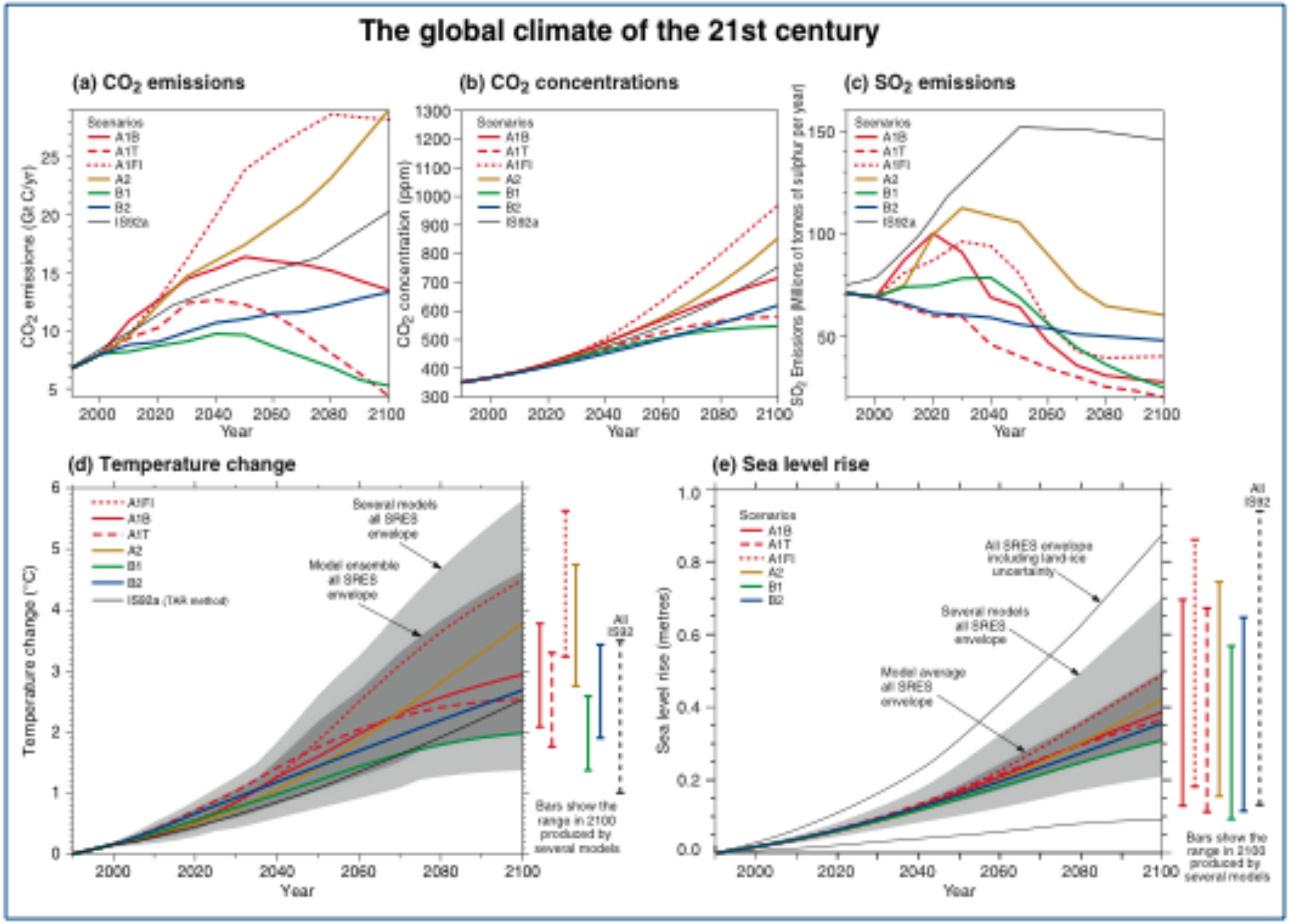
Concept vs. Reality





Why is Fusion (Which is at Least 30 Years Away) a Good Way of Addressing Climate Change?



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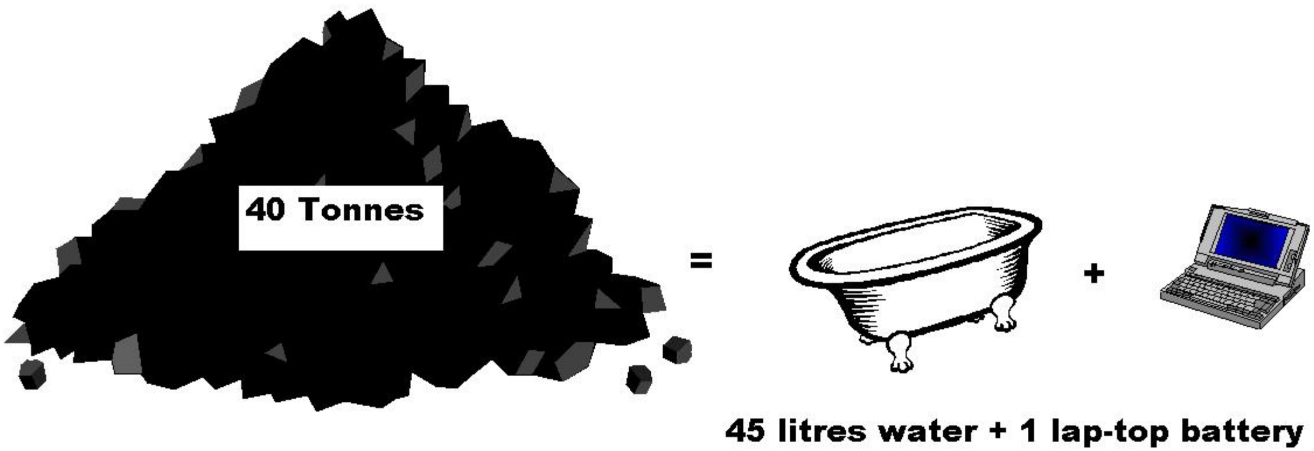
A: Long-Term Solution for Clean Energy

- 1 in 6000 H atoms is D- virtually unlimited supply
- Readily available Li to breed T
- Low activation levels, no possibility of runaway/meltdown
- Significantly reduced proliferation risk
- Compatible with existing electric grid
- Steady source for baseline demand- not weather dependant
- Ex: electricity supply for one family/year requires 0.08g D (= 4.3 kg water) and 0.02g Li
- Can power world for 1000's of years using known land-based Li sources, millions if take Li from sea

Fig. courtesy D. Bachelor

Economics and Energy Supply of Fusion

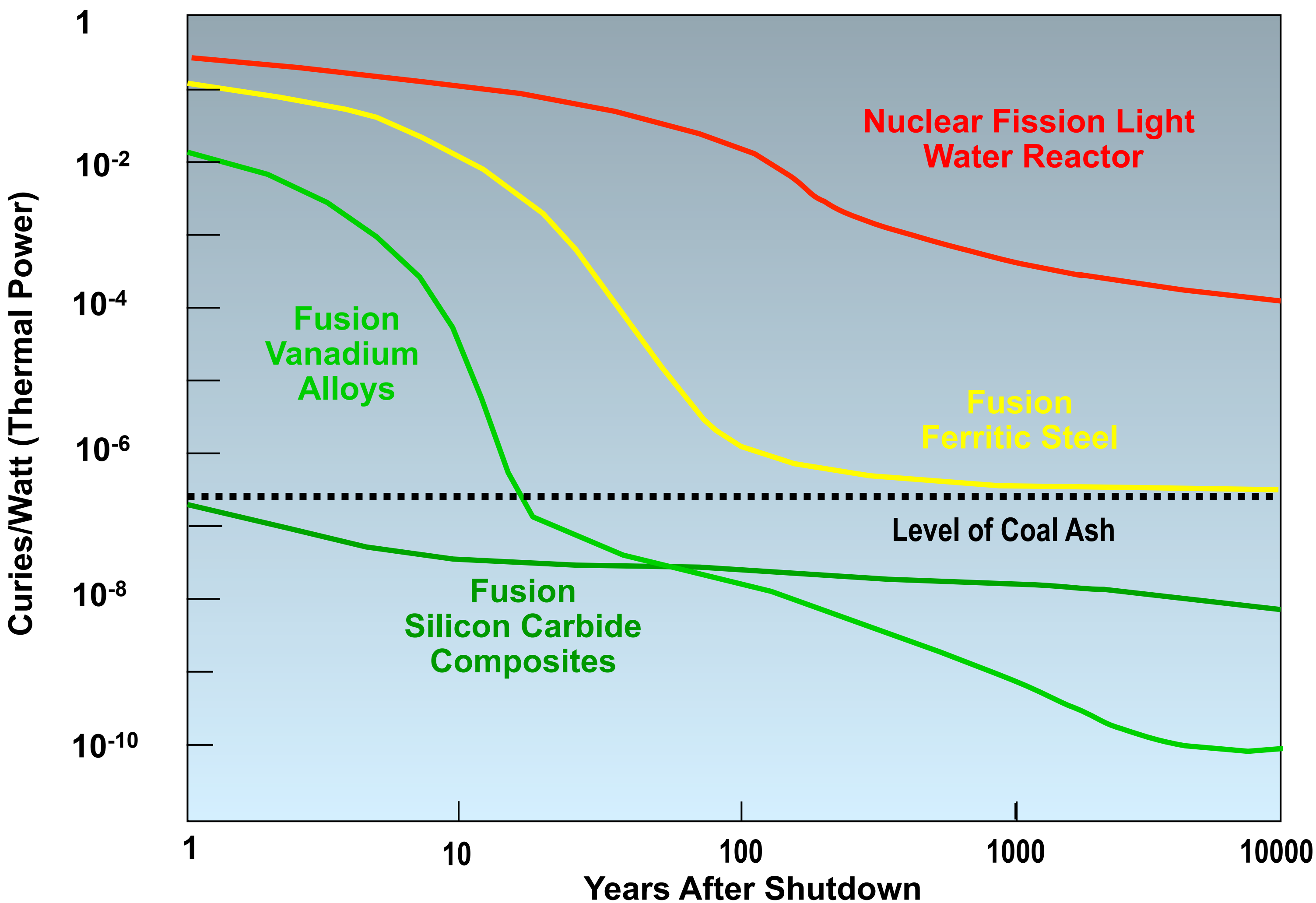
- A nice way of framing the issue by C. Llewellyn Smith



- Using the lithium in one laptop battery and deuterium from half a bathtub of water, we could generate 200,000 kW-hours of electricity, at costs competitive with current rates
- Enough to power average US household for **18** years at current usage rates

Fig. courtesy C. Llewllyn Smith

Fusion Waste: Much Better Than Fission



C. Holland/SDSU-CSRC/May11

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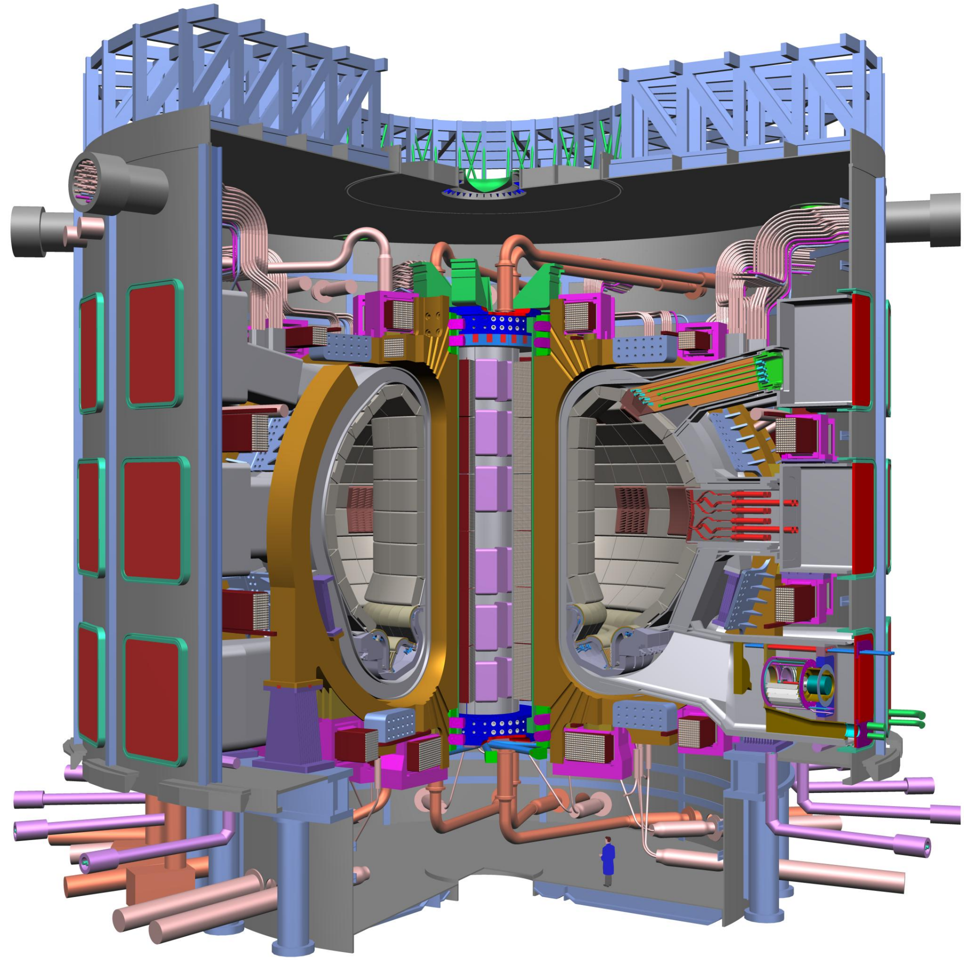
ITER is the Next Step in Realizing Magnetic Fusion as a Viable Energy Source for Society

- **Mission**: to demonstrate the scientific and technical feasibility of fusion power
- **Goal:** achieve 500 MW Fusion power for > 400 s with Q = 10
  – Current machines: 10 MW for 1 s with (effective) $Q \leq 1$
- **Key parameters:**
  – $R_{maj} = 6.2$ m
  – $I_{plasma} = 15$ MA
  – $B_0 = 5$ T
  – $T \geq 10$ keV
  – 73 MW external heating power
- Construction costs of > $10**b**



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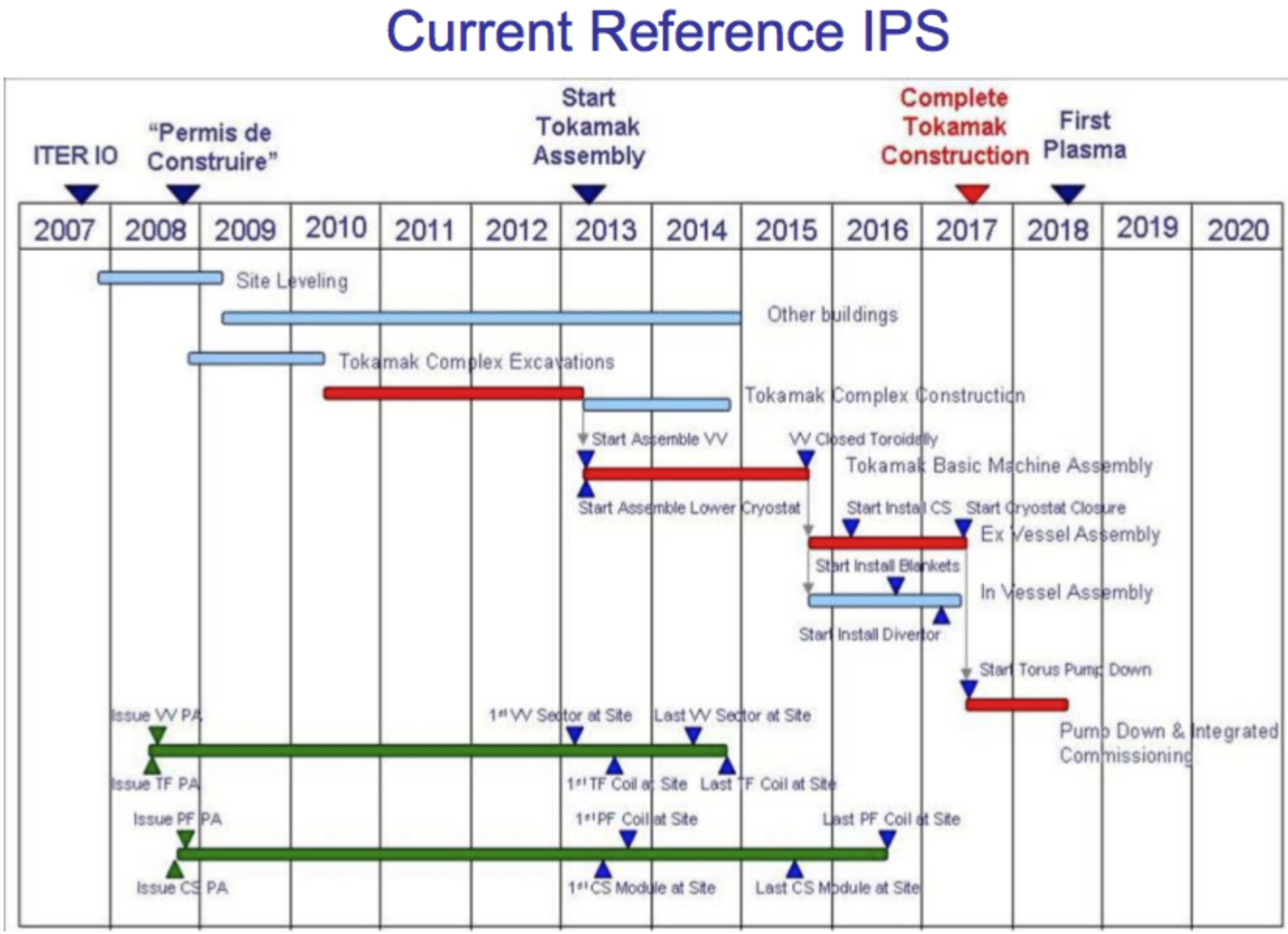
Construction at ITER Site in Cadarache Has Begun

Current Timeline Has First ITER Plasma in 2018



From Ikeda 2008 FPA talk

ITER Will be a Burning Plasma- a New Physics Regime

- In current day experiments, external heating and momentum sources generally dominate over internal ones, and discharge lengths are generally only several τ_e long, and less than the resistive diffusion timescale $\tau_r = a^2/\eta$
  - Allows us a fair amount of control over profile shapes

- In ITER, collisions between thermal and α-particles will be the dominant heating source, rotation speeds will be significantly reduced, and discharge lengths will be for many τ_e and τ_r

- Therefore, ITER will be a self-organizing system that "chooses" its own profiles (or at least has a much strong say than current day experiments)

An Example of Self-Organization in Current Experiments: the H-mode Regime

- Pre 1980- observed that τ_e ***decreased*** with increased heating power
  - The more energy you put in, the faster it left

- Landmark result first found at ASDEX experiment, subsequently confirmed on every other major machine-
  - at a critical level of injected power, plasma undergoes a sort of phase transition to a regime of significantly improved confinement- the "high confinement" (H-)mode
  - Refer to pre-transition plasma state as L-mode

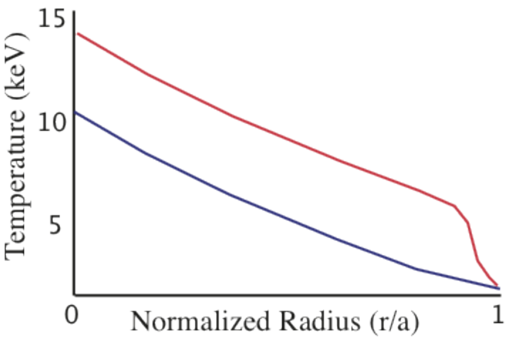


Fig. courtesy P.Snyder and K. Burrell

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- Dynamics now understood in terms of a boundary layer which forms with a significant level of equilibrium flow shear
  - The shear suppresses the small scale turbulence and the associated transport of particles and energy

- Now have a very large database of experimental results documenting the occurrence of when H-mode happens, **but no theory which can accurately predict when it happens**

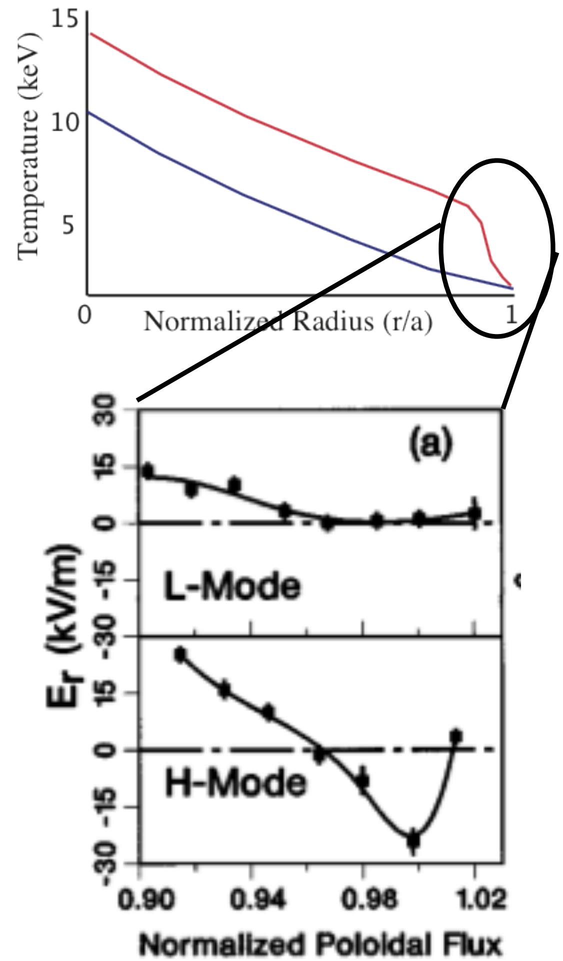

Fig. courtesy P.Snyder and K. Burrell

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The Need for Predictive Models

- Robust nonlinear phenomena and self-organization make direct extrapolation of current day experiments to future reactors difficult to do with significant confidence
  - Range of space and timescales relevant physics happens on is so large that there is no analog of the Navier-Stokes equations from which we can rigorously derive scalings laws for tokamak performance, or treat current-day experiments as “wind tunnels” for designing larger ones

- If we want to have greatest confidence in our designs for future experiments, we need to build predictive integrated models of plasma dynamics
  - Similar approaches being taken in combustion research and climate modeling

- Ideally these models need to be **first-principles based**- want to minimize or eliminate any free parameters in the models
  - If we have the essential physics right, should be able to explain today’s experiments and predict tomorrow's
  - As we test these models against experiment, **need to understand successes and failures in terms of physics, not parameterizations**

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Integrated Tokamak Models are Inherently Multiscale Descriptions of Plasma Dynamics

- Similar to a global climate model which couples “submodels” of the oceans, the atmosphere, land and biomass to predict the Earth’s response to natural and man-made forcings

- Tokamak integrated models different from GCMs in that all the different sub-components overlap in space- no separating boundaries

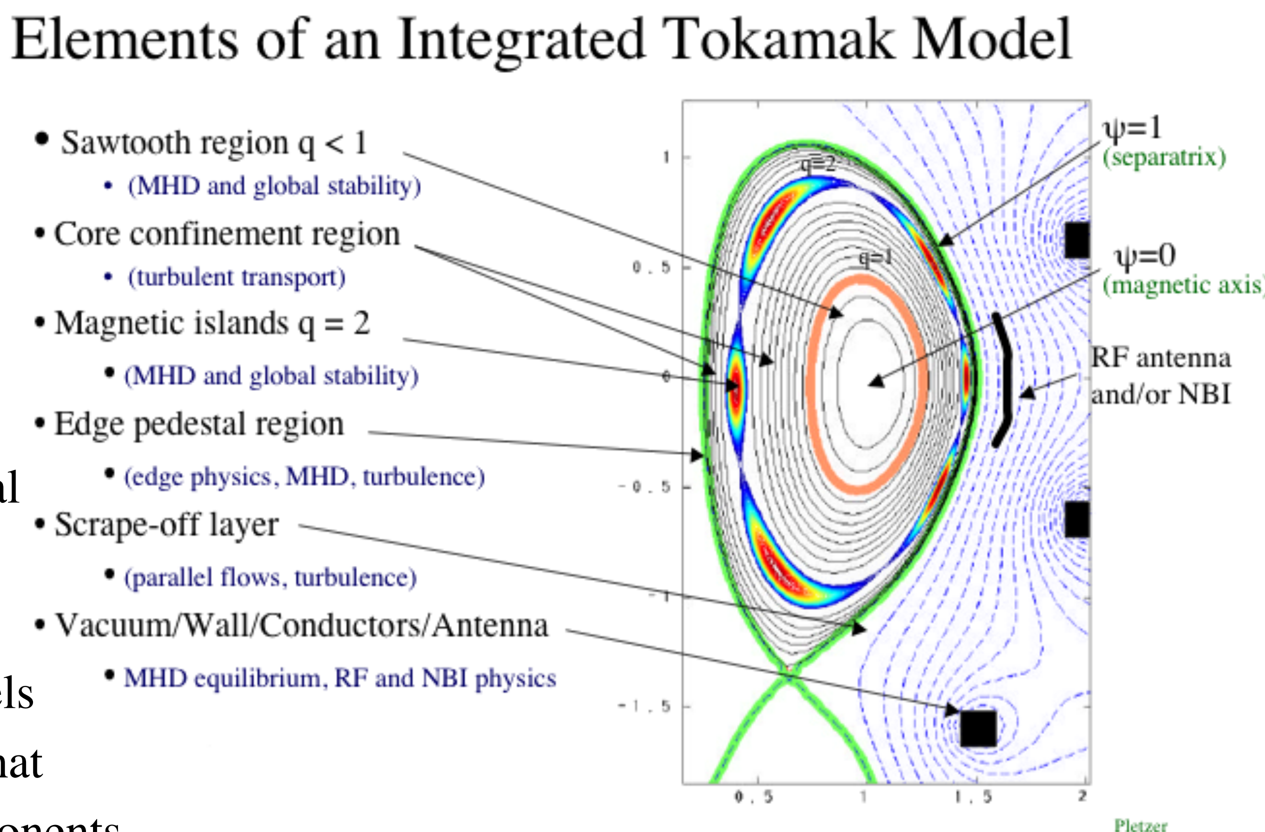

Fig. courtesy A. Pletzer

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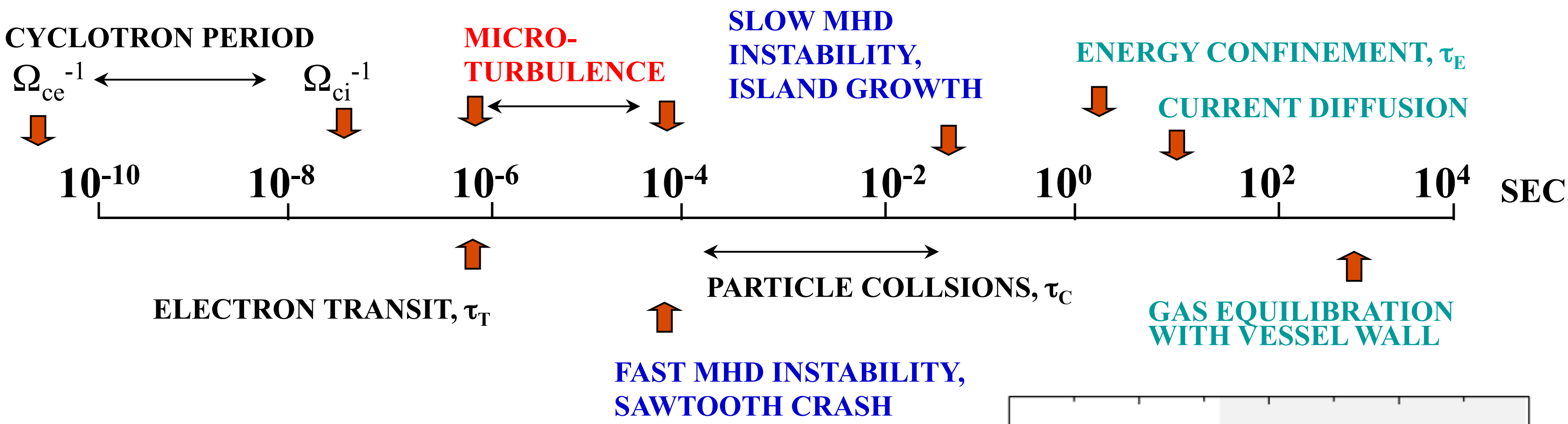
Wide Range of Relevant Scales in Tokamak Plasma Makes Life Interesting



10^{14} timescales and 10^{8} spatial scales make direct "whole tokamak" simulations impractical

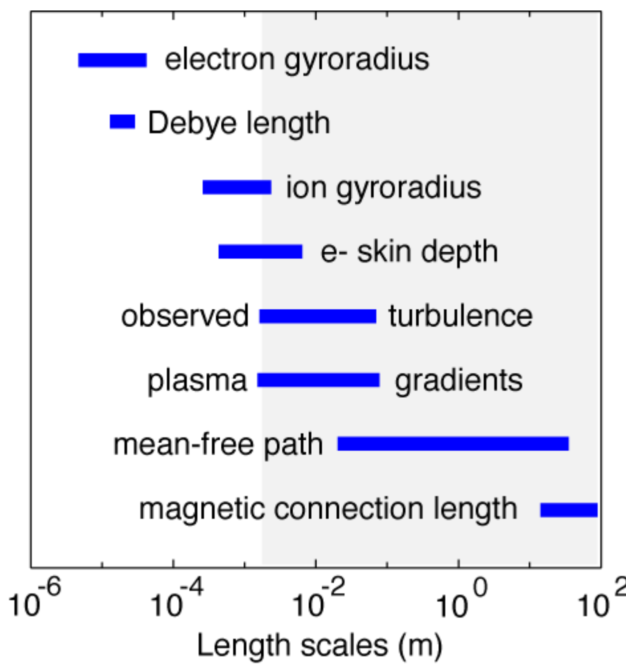
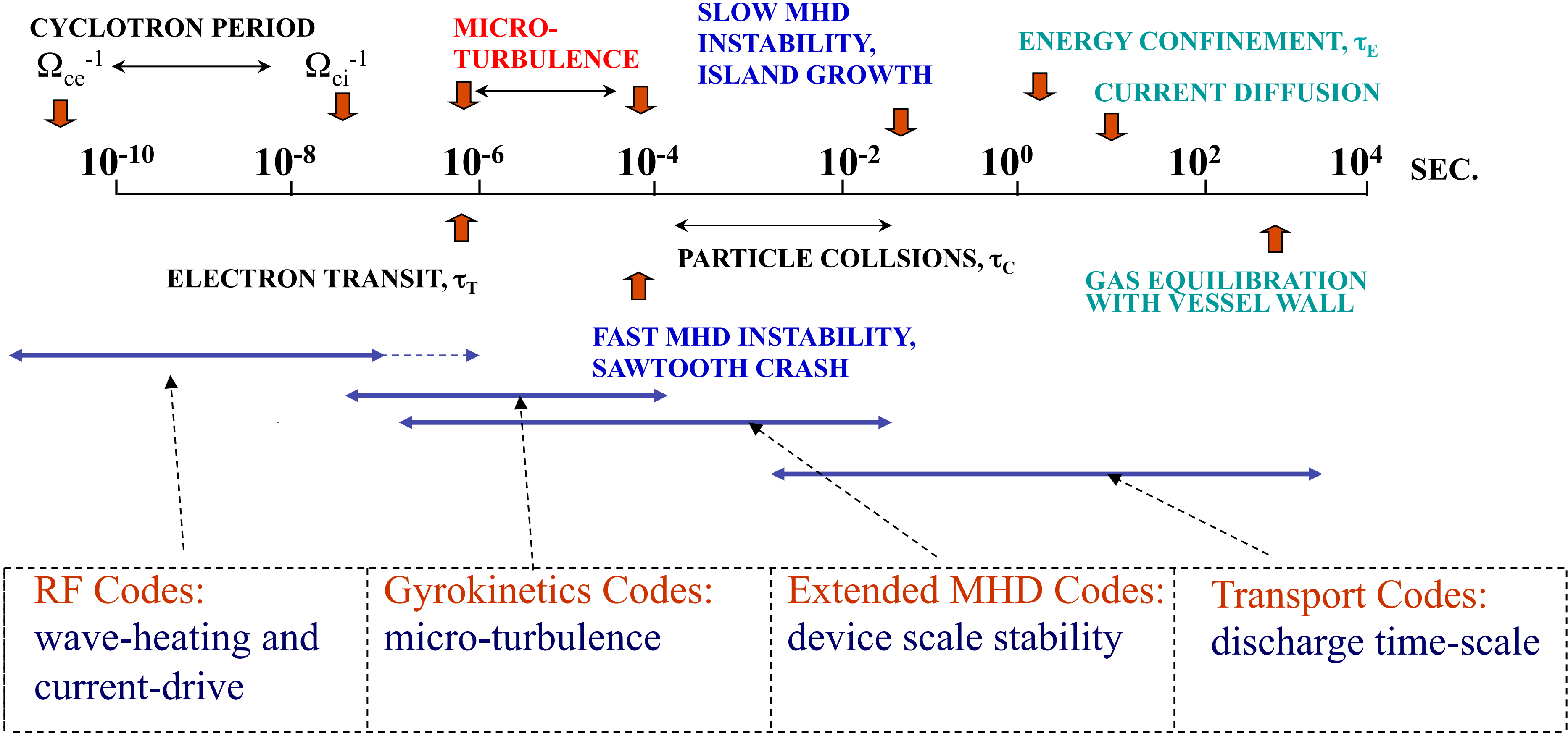


Fig. courtesy D. Bachelor

Wide Range of Relevant Scales in Tokamak Plasma Makes Life Interesting

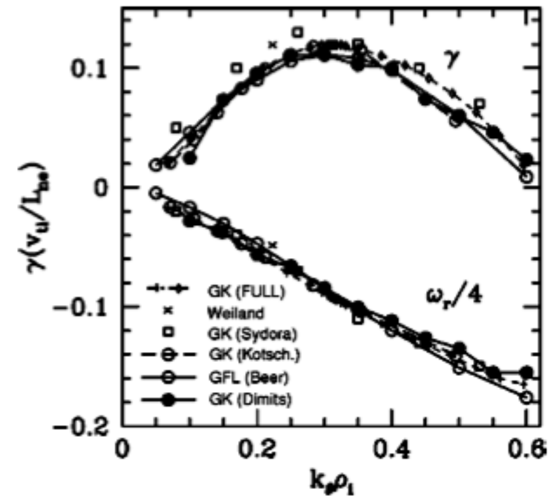


- Approach problem by developing models of various (overlapping) subranges of the plasma, and then intelligently and efficiently coupling the models together

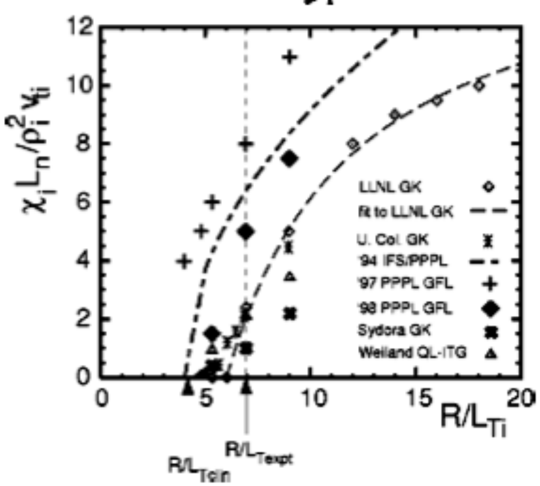
Fig. courtesy D. Bachelor

Use the Verification and Validation Process to Assess the Accuracy of Different Models and Codes

- **Verification:** The process of determining that the model implementation in a given code accurately represents the developer's conceptual description of the model and the solution to the model
  - This entails benchmarking against analytic solutions to the model and multi-code comparisons



- **Validation:** The process of determining the degree to which a model is an accurate representation of the real world, *from the perspective of the intended uses of the model* (emphasis added)
  - For our purposes, how well can the simulation reproduce experimental measurements, within experimental and computational uncertainties



Dimits et al, Phys. Plasmas 2000

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So Where Do We Stand?

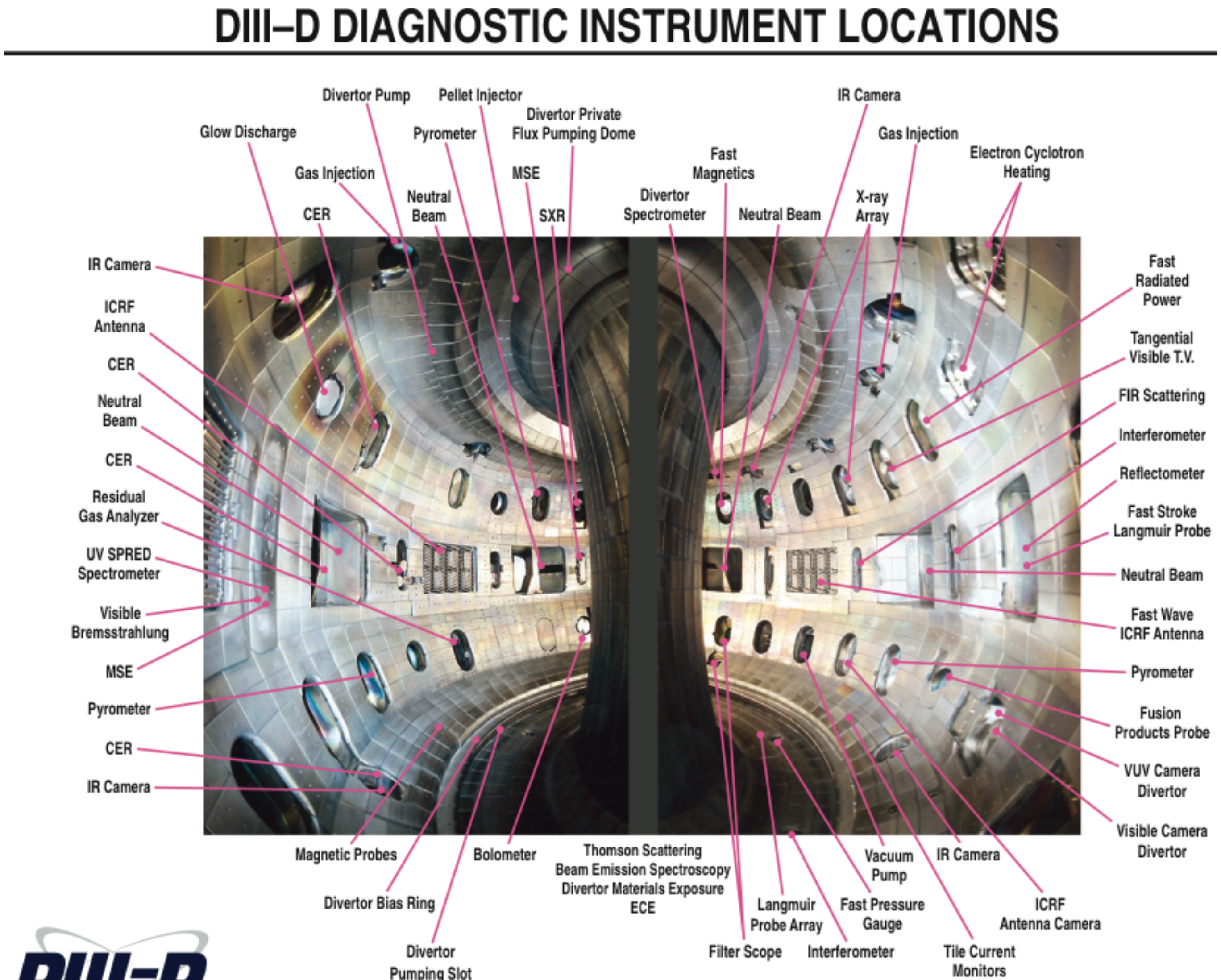
- Now have a set of theoretical models for describing different plasma scales:
  Maxwell-Boltzman -> gyrokinetics -> (extended) MHD -> transport equations
  - All are inherently ***nonlinear***

- Analytic theory provides the framework for how we understand the essential features and dynamics of each model, but often cannot give exact solutions or quantitative predictions for “real-world” conditions

- Numerical simulation and computing power have now evolved to the point that they can offer quantitative predictions in realistic conditions of individual phenomena, at the expense of significant complexity.
  - For each class of models, a range of verification tests have been done using checks against analytic theory and cross-code comparisons.

- **Next step**: validating the computational models and simulations
  1. Are the codes correctly predicting the experiments?
  2. If the they are (or aren’t), do we understand why, (or why not)?

Recent Improvements in Experimental Diagnostics Also Important Part of the Story



DIII–D NATIONAL FUSION FACILITY SAN DIEGO

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Example: High-Resolution Profile Measurements Now Possible by Sweeping Plasma Across Diagnostic View

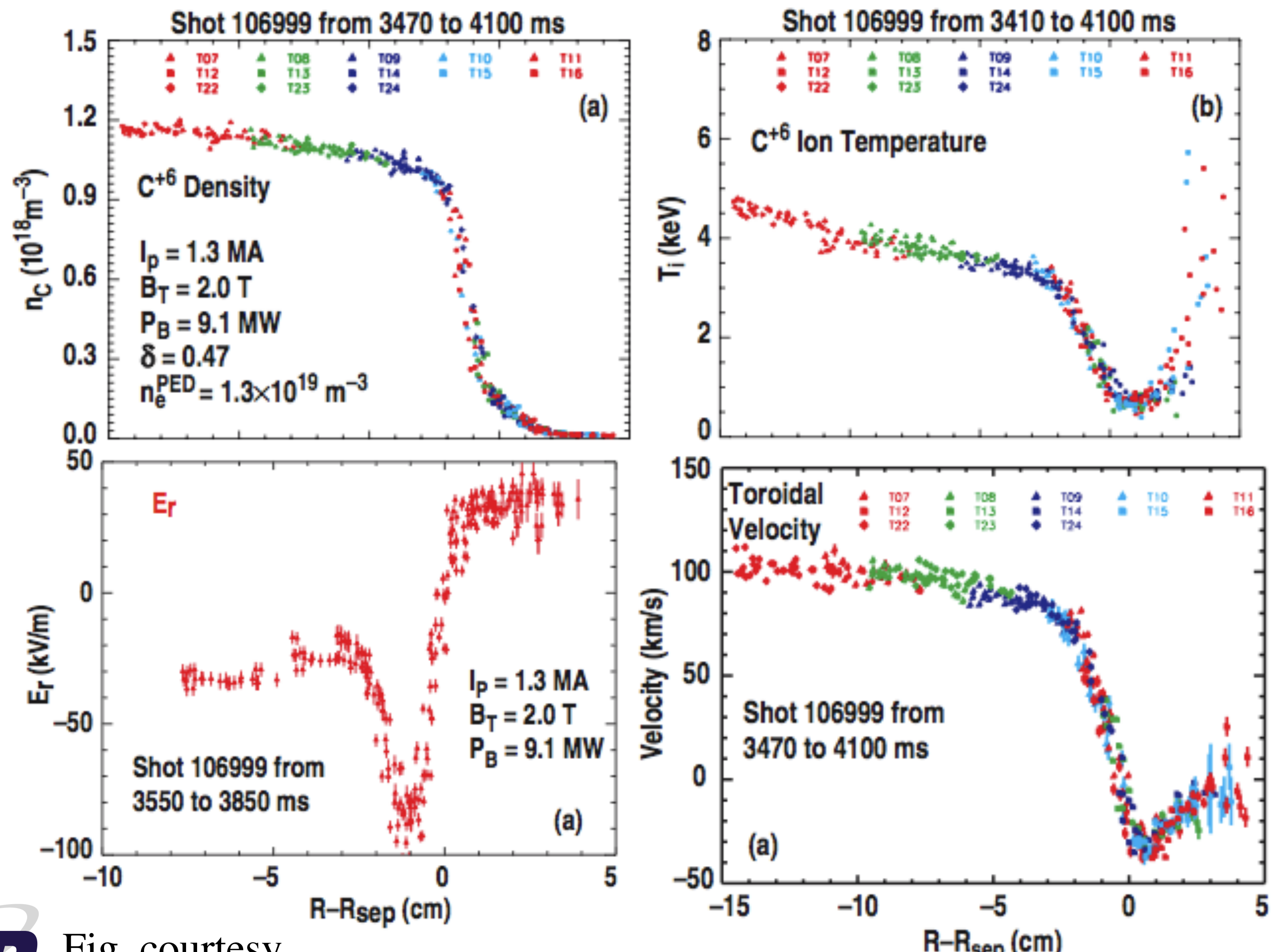


Fig. courtesy K. Burrell

Macroscopic Equilibrium and Stability

Plasma Equilibrium and Large-Scale Dynamics Governed by MHD Theory

- Magnetohydrodynamics (MHD) theory describes the motion of a current-carrying fluid (define $d/dt = \partial/\partial t + \vec{u}\cdot\vec{\nabla}$)

continuity

$$\frac{d\rho}{dt} + \vec{\nabla}\cdot\rho\vec{u} = 0$$

momentum

$$\rho\frac{d\vec{u}}{dt} = -\vec{\nabla}p + \vec{J}\times\vec{B}$$

energy

$$\frac{dp}{dt} + \gamma p\vec{\nabla}\cdot\vec{u} = 0$$

$$\frac{\partial\vec{B}}{\partial t} = -\vec{\nabla}\times\vec{E} \qquad \mu_0\vec{J} = \vec{\nabla}\times\vec{B}$$

Maxwell's equations

$$\vec{E} = \eta\vec{J} - \vec{u}\times\vec{B}$$

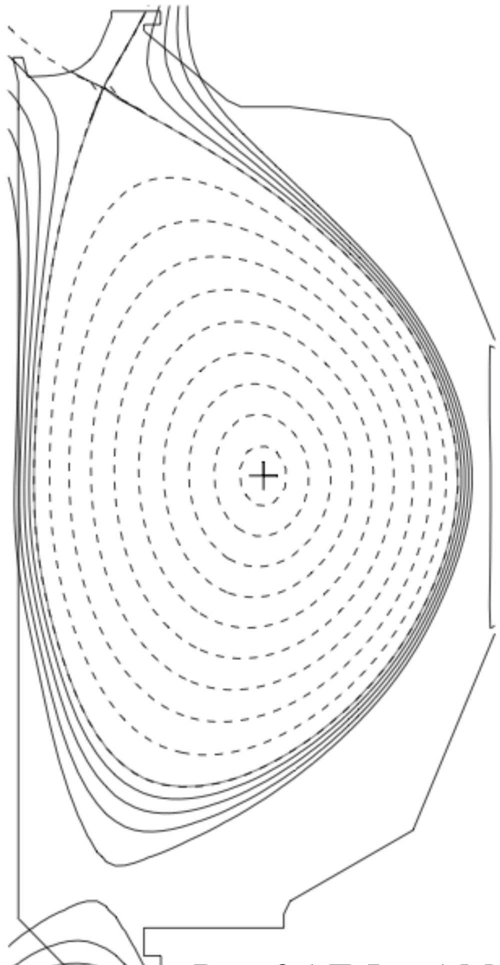
Ohm's law

- Key point is that steady-state force balance ($0 = -\vec{\nabla}p + \vec{J}\times\vec{B}$) implies pressure is constant along magnetic fields.

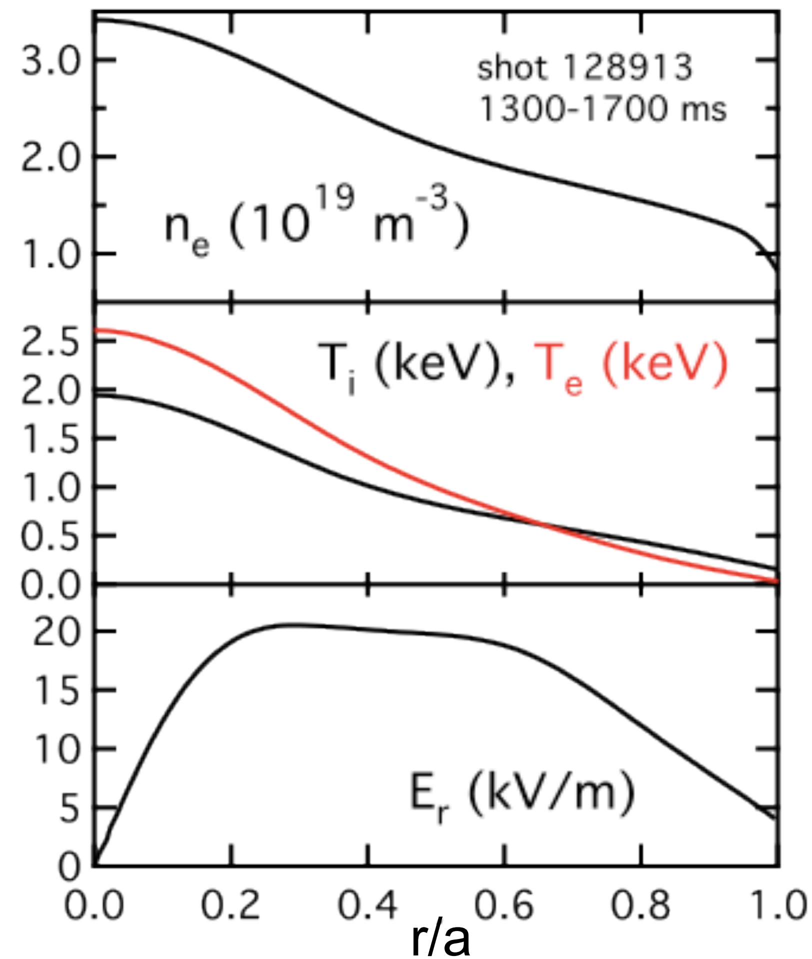
- Equilibrium consists of set of nested flux surfaces, with a constant pressure on each surface.

Typical Plasma Shape and Mean Profiles

128913
1500 ms



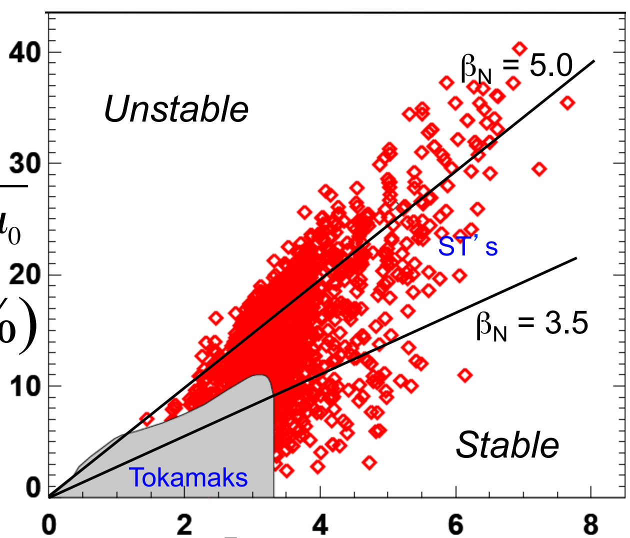
$B_T = 2.1$ T, $I_p = 1$ MA



Global High-Pressure Instabilities are Predictable and (generally) Avoidable

Experimental pressure limits are described by ballooning and kink instability theory:

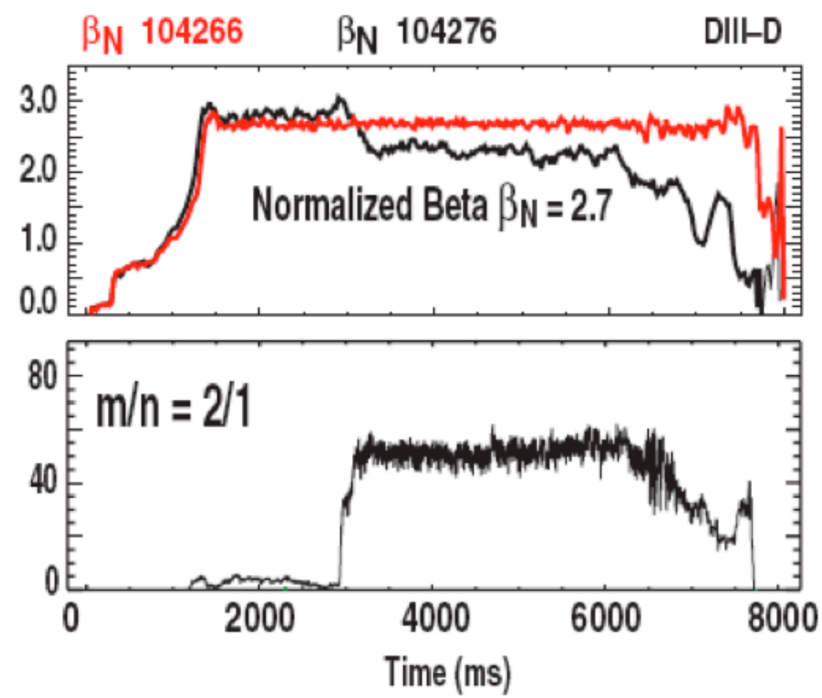
$$\frac{P}{B_T^2/2\mu_0} = \beta_T(\%)$$



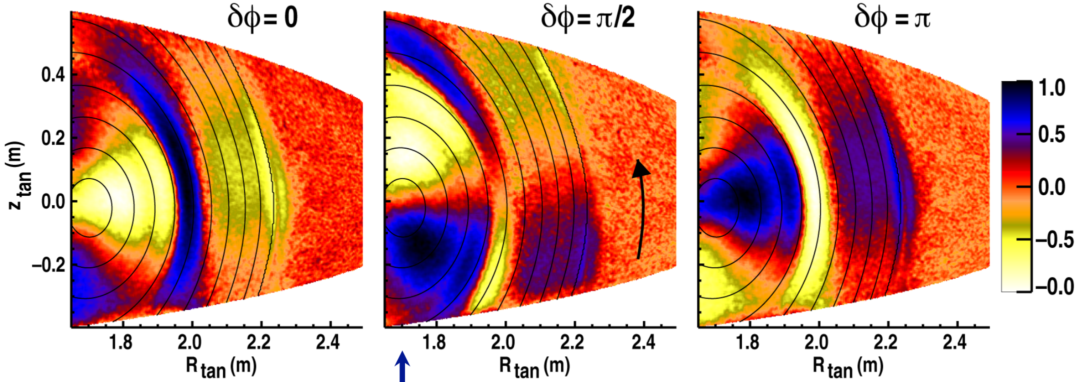
$$\frac{I}{aB_T} \quad \text{(MA/mT)}$$

$$\beta_N = \beta_T/(I/aB_T)$$

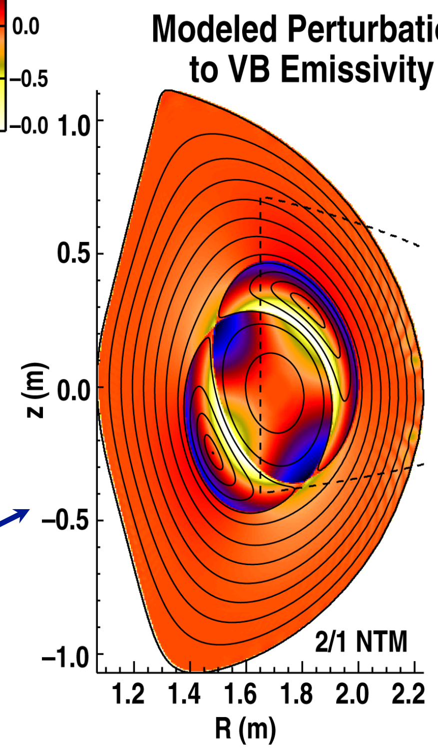
Precise control near β-limit is key to avoiding disruptions:

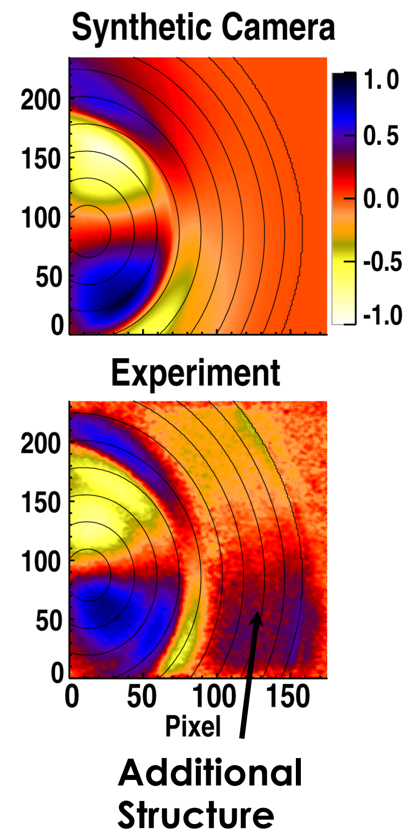


Can Now Directly Observe Core MHD Phenomena Using Fast-Framing Camera Diagnostic on DIII-D



- Fourier analyzed fast framing camera measurements of visible Bremsstrahlung clearly resolve NTMs in core of DIII-D plasmas
- Modeling reproduces many features but highlights the need for additional physics





M.A. Van Zeeland, J.H. Yu, M.S. Chu, et.al., *Nucl. Fusion*, **48** 092002 (2008)

Microturbulence and Transport

Turbulent Transport Modeling

- In the absence of MHD instabilities, the free streaming of ions and electrons along the magnetic field leads to slowly evolving pressure and rotation profiles which are approximately constant on each magnetic flux surface

$$\frac{3}{2}\frac{\partial(nT)}{\partial t} + \vec{\nabla}\cdot Q = S$$

- Both Coulomb collisions and small-scale turbulence drive radially outward fluxes of particles, momentum, and energy which determine level of confinement achieved in the confinement device
  - Believe we can do reasonable job on collisional fluxes using neoclassical transport theory
  - Challenge is to calculate sufficiently accurate turbulent fluxes, which are often 10-100x larger than collisional

$$Q = Q_{neo} + Q_{turb}$$

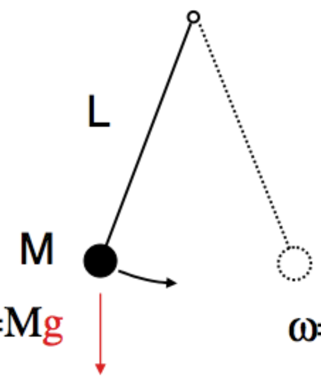
- Obtain the “experimental” values of theses fluxes by integrating over various (modeled) sources and sinks

$$Q(r) = \int_{V<V(r)} d^3x\, S(\vec{x})$$

- Goal of transport model is to predict these fluxes, for a given set of plasma parameters

A Simple Picture of Common Instability Drive

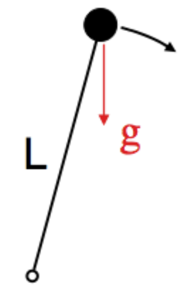
Stable Pendulum



F=Mg $\qquad \omega=(g/L)^{1/2}$

Unstable Inverted Pendulum

(rigid rod)



$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

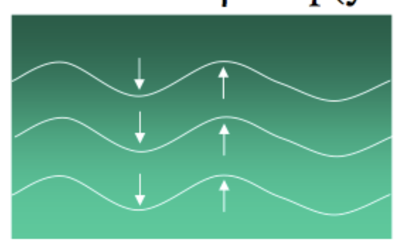
$\rho=\exp(-y/L)$

stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

$\rho=\exp(y/L)$



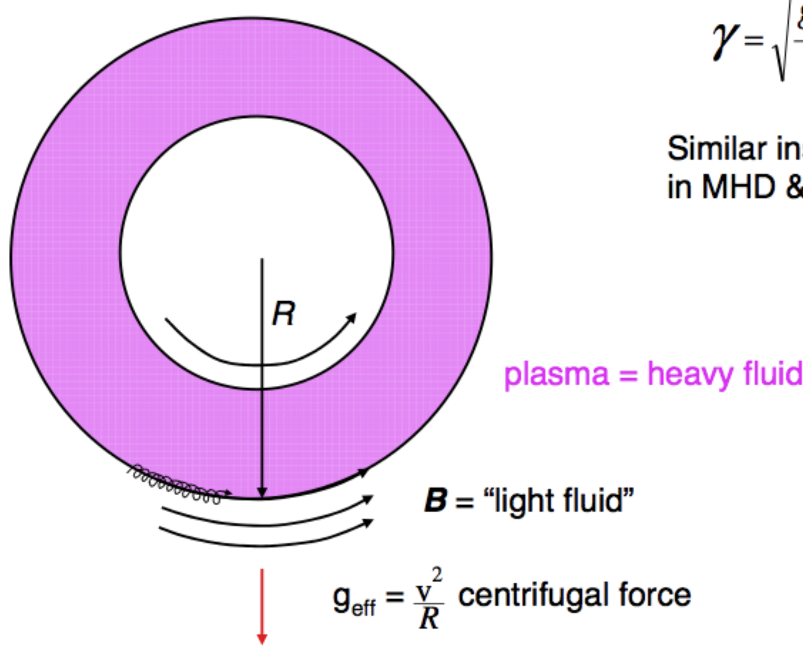
Max growth rate $\gamma=(g/L)^{1/2}$

Fig. courtesy G. Hammett

A Simple Picture of Common Instability Drive

"Bad Curvature" instability in plasmas
≈ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



Growth rate:

$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}} = \frac{v_t}{\sqrt{RL}}$$

Similar instability mechanism in MHD & drift/microinstabilities

$1/L = \nabla p/p$ in MHD,
$\propto$ combination of ∇n & ∇T in microinstabilities.

Fig. courtesy G. Hammett

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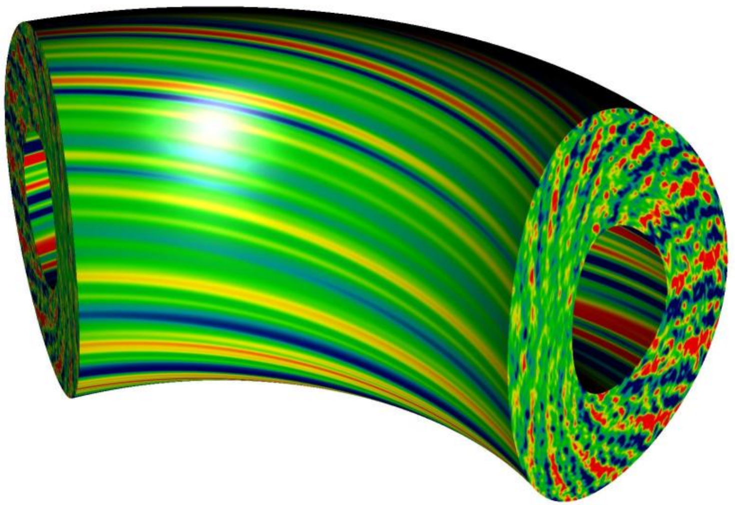
Large vs. Small-Scale Instability

- By using twisted field lines, bring plasma from "bad" to "good" curvature region
  - Leads to stabilization of instability on machine scale lengths



- Differences in dynamics of ions and electrons on ρ_i scales allows species to separate, creating finite charge density
  - Leads to mode structures which are highly elongated along field lines, but have short perpendicular scales

- Finite charge density creates electric fields which reinforce initial perturbation $\rightarrow$ **INSTABILITY!**

Quantitatively Accurate First-Principles Microturbulence Modeling Requires Massively Parallel Computing

- Accurate description requires solution of analytically intractable gyrokinetic equation

$$\frac{\partial h_a(\mathbf{R})}{\partial t} + \left(\mathbf{V}_0 + v'_{\|}\mathbf{b} + \mathbf{v}_{da} - \frac{c}{B}\nabla\hat{\Psi}_a \times \mathbf{b}\right)\cdot\nabla h_a(\mathbf{R}) - C_a^{GL}\left(\hat{f}_{a1}\right)$$
$$= f_{a0}\left[-\frac{\partial \ln(N_a T_a)}{\partial\psi}\hat{W}_{a1} - \frac{\partial \ln T_a}{\partial\psi}\hat{W}_{a2} + \frac{c}{T_a}\frac{\partial^2\Phi_0}{\partial\psi^2}\hat{W}_{aV} + \frac{1}{T_a}\hat{W}_{aT}\right]$$

$$\hat{W}_{a1}(\mathbf{R}) \doteq -\frac{c}{B}\nabla\hat{\Psi}_a \times \mathbf{b}\cdot\nabla\psi \ ,$$

$$\hat{W}_{a2}(\mathbf{R}) \doteq \hat{W}_{a1}\left(\frac{\varepsilon}{T_a} - \frac{5}{2}\right) \ ,$$

$$\hat{W}_{aV}(\mathbf{R}) \doteq -\frac{m_a R c}{B}\left\langle(\mathbf{V}_0 + \mathbf{v}')\cdot\mathbf{e}_\varphi\nabla\left(\hat{\phi} - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}\right)\times\mathbf{b}\cdot\nabla\psi\right\rangle_\xi \ ,$$

$$\hat{W}_{aT}(\mathbf{R}) \doteq e_a\left\langle\left(\frac{\partial}{\partial t} + \mathbf{V}_0\cdot\nabla\right)\left(\hat{\phi} - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}\right)\right\rangle_\xi \ .$$

$$\hat{\Psi}_a(\mathbf{R}) \doteq \left\langle\hat{\phi}(\mathbf{R}+\boldsymbol{\rho}) - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}')\cdot\hat{\mathbf{A}}(\mathbf{R}+\boldsymbol{\rho})\right\rangle_\xi$$

- Solve the equations via direct numerical simulation on large-scale clusters.
  - Typical simulations require several thousand processor-hours to obtain converged statistics.

NCCS Jaguar machine- world's 2nd fastest (as of Nov10) civilian computer: ~224,000 2.1 or 2.6 GHz cores
Image courtesy of the National Center for Computational Sciences, Oak Ridge National Laboratory

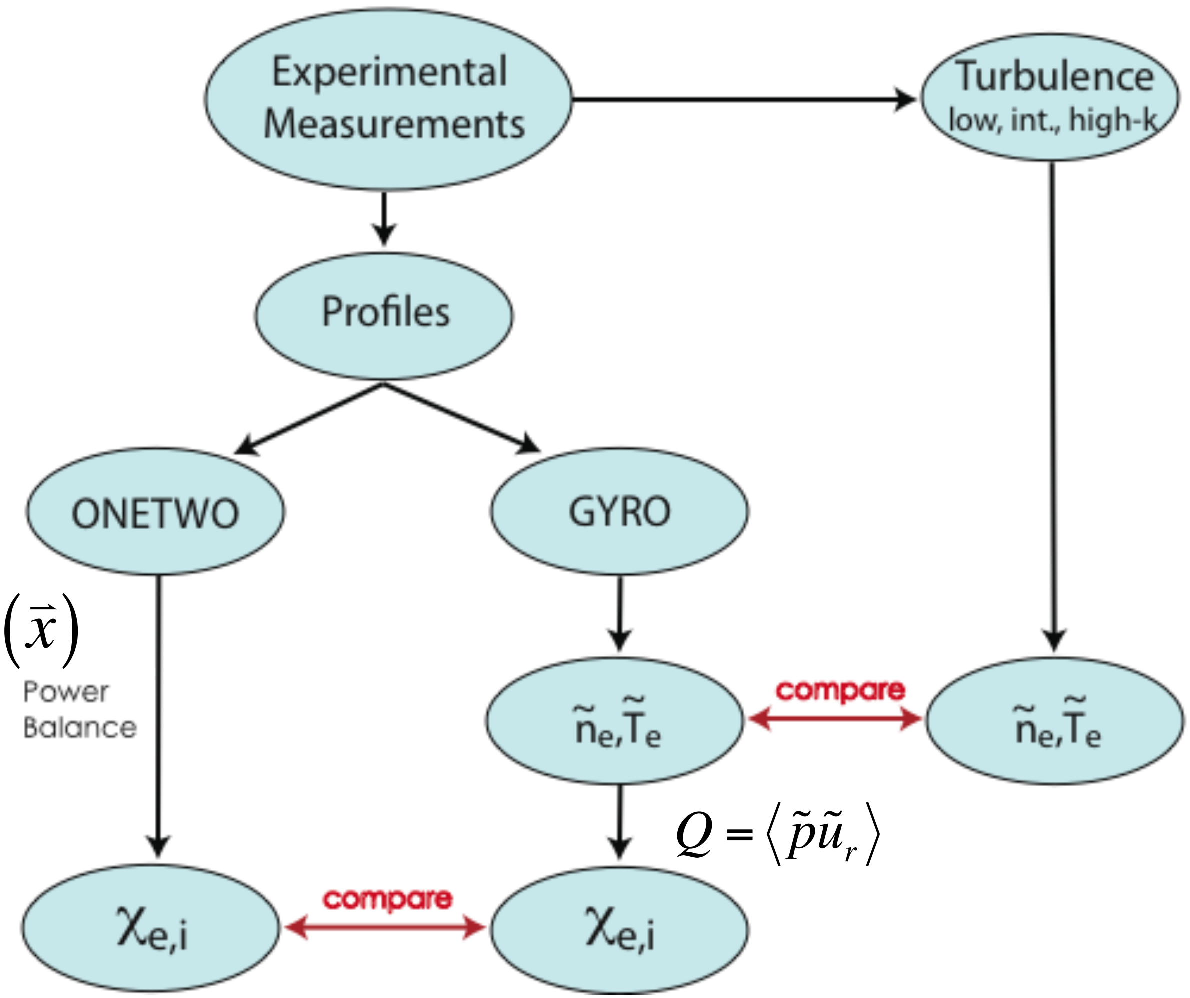
Visualizing the Microturbulence

DIII-D Shot 121717

GYRO Simulation

Cray X1E, 256 MSPs

Use Direct Measurements of Fluctuations Levels to Validate Essential Physics of Simulations



$$Q(r) = \int_{V<V(r)} d^3x\, S(\vec{x})$$

$$Q = \langle \tilde{p}\tilde{u}_r \rangle$$

$$Q = -n\chi \frac{dT}{dr}$$

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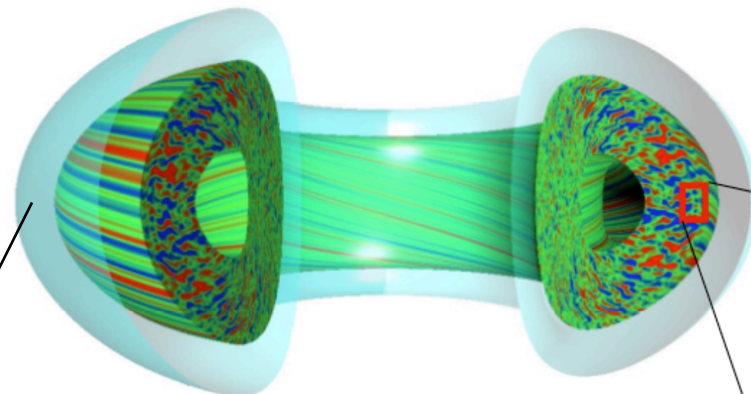
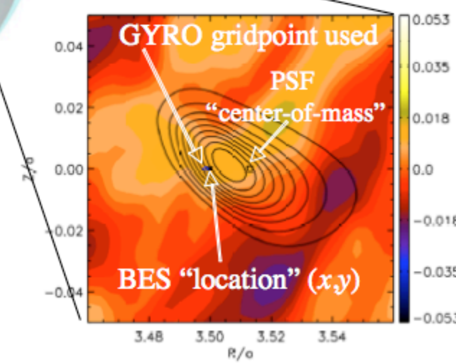
Predictions from computational models beginning to faithfully reproduce experimental observations

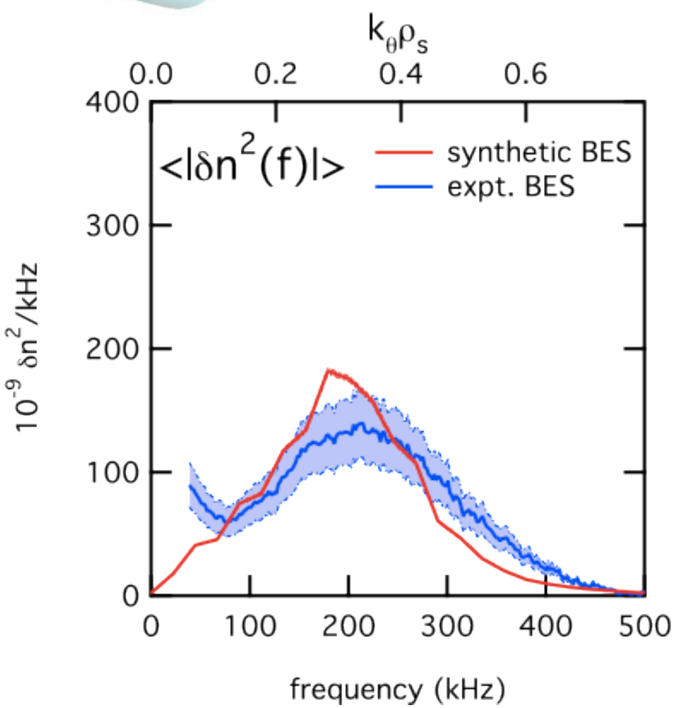
W/cm^2	Q_i	Q_e
Expt.	3.1	2.5
Model	3.8 ± 0.7	3.4 ± 0.3



GYRO is a Eularian continuum code that simulates plasma turbulence and transport with full physics and geometry, experimental profiles



- Emerging Standard Model for ion turbulence and associated transport
  - Reproduces net transport rates and fluctuation spectrum in core
  - But, radial variations, Te turbulence, and nonlinear details still need work…



C. Holland/SDSU-CSRC/May11

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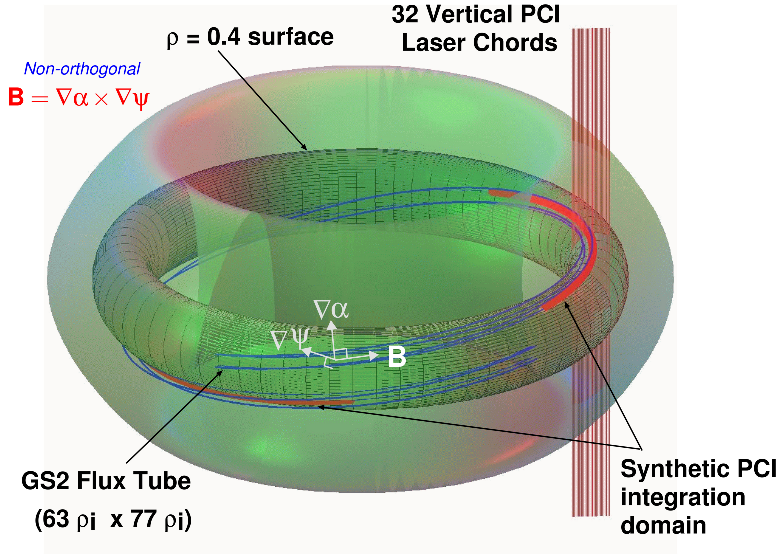
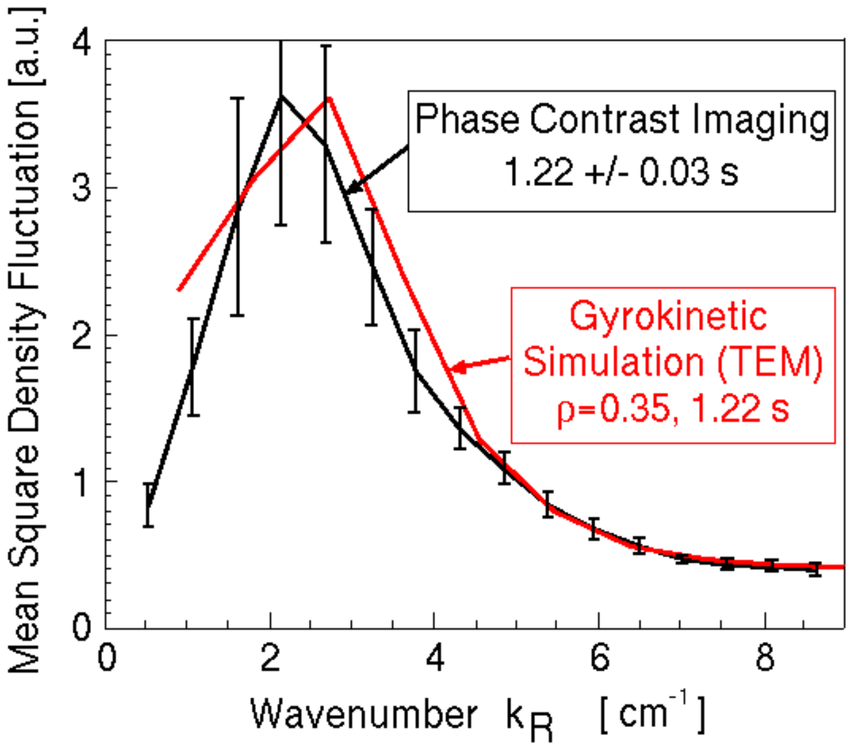
Synthetic PCI Diagnostic Enabled Direct Comparison of Nonlinear Gyrokinetic Simulations with Measured Alcator C-Mod Fluctuations

- First of kind comparison
- Measured wavelength spectrum closely reproduced by GS2
- Direct evidence of trapped electron modes in Alcator C-Mod ITB
- Complimentary synthetic PCI diagnostics for use with GYRO in development by L. Lin (MIT) and C. Rost (MIT)





D. R. Ernst et al., IAEA-CN-149/TH/1-3 (2006).

Energetic Particles

New Alpha Particle effects Expected in Burning Plasmas

- Fusion-produced alphas are super-Alfvenic
  - $V_\alpha >> v_{ion}$ ($T_{i,e} \sim$ 10-20 KeV)
- Hierarchy of alpha particle effects:
  - Confinement √
  - Slowing Down √
  - Heating √
  - Interaction with resonant unstable modes ?
    - *Few modes on present expts.*
    - *"Sea" of overlapping modes in BP*
    - *Can lead to redistribution and losses*

- **Alpha particles:**
  - High energy: $T_{\alpha,\mathrm{birth}}^{DT}$ = 3.5 MeV
  - Not "frozen" to B-field lines (require kinetic description)
  - Low density ($n_\alpha < n_{i,e}$), but comparable pressure ($p_\alpha \sim p_{i,e}$)
  - Non-Maxwellian "slowing down" distribution
  - Centrally peaked profile

$$\left|\nabla p_\alpha / p_\alpha\right|^{-1} \leq a/2$$

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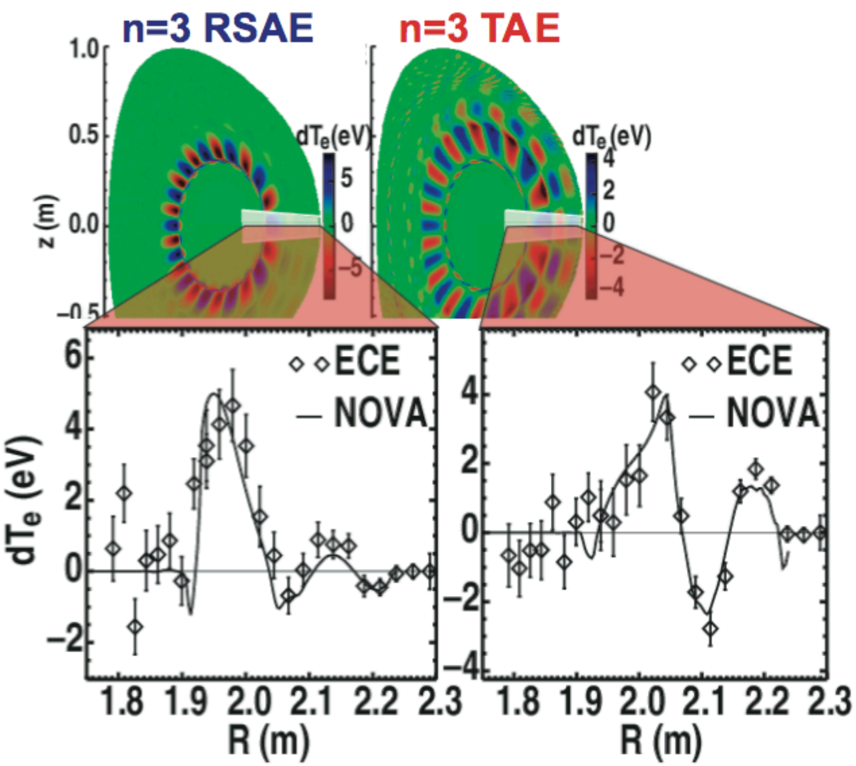
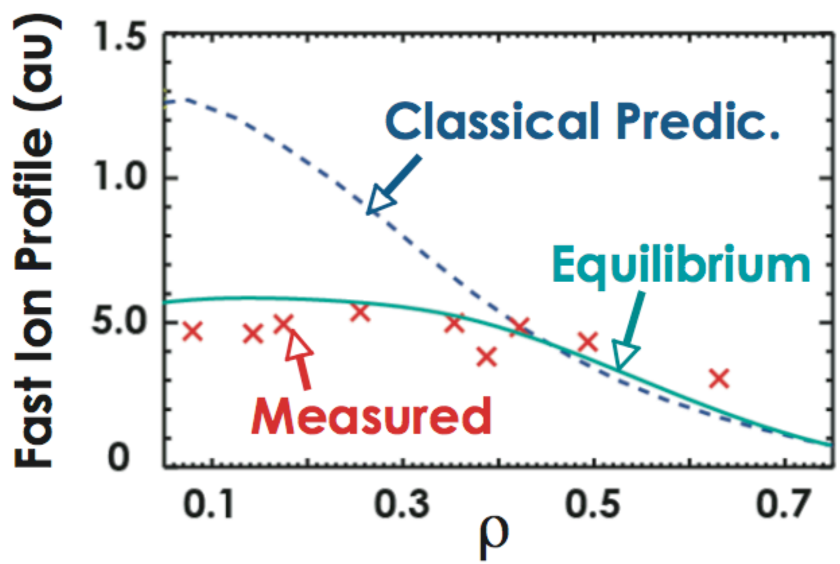
With Fast Ions, Experiments are Asssessing the Containment of Fusion α's

- **Fast-ions from high-energy beams serve as a proxy for fusion alphas in present experiments**
- **Under certain conditions, fast ions can cause "Alfven" modes which in turn can result in the loss of the fast ions**



Van Zeeland PRL 97, 135001 (2006)

The Fast Ion profile is flattened during periods of strong Alfvenic activity



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Future Directions

The Fusion Simulation Project

- Examples shown here illustrate the bottom-up approach of validating individual physics components

- Plasma/MFE community is now beginning to undertake the challenge of integrating these components together, with the goal of creating a validated, predictive model of an entire tokamak discharge

- **FSP mission:** "Produce a world-leading predictive simulation capability that will be of major benefit to the science and mission goals of the US Fusion Energy Science Program." (DOE Energy Undersecretary R. Orbach)

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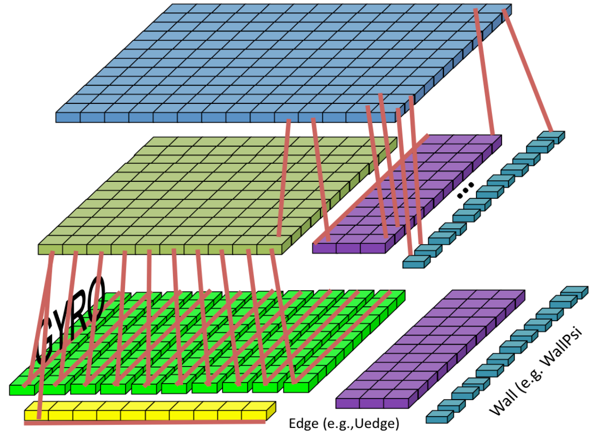
Three FSP Prototype Projects Underway Testing Integration of Different Subsets of Components

Partnership of OFES and OASCR under the aegis of SciDAC

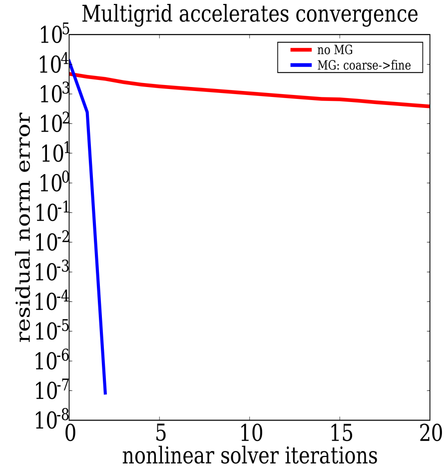
- **Center for Simulation of Wave Interactions with MHD (SWIM)**
  - Self-consistent modeling of how RF heating and current drive affects stability (both positively and negatively) of MHD instabilities
- **Center for Plasma Edge Simulation (CPES)**
  - Examining how microturbulence and MHD modes interact with each other and the vessel wall in plasma edge region
- **Fusion Application for Core-Edge Transport Simulation (FACETS)**
  - Developing efficient algorithms for coupling core and edge transport models for whole-device modeling
- **Each project envisioning production runs requiring 10^6 - 10^7 processor-hours**

Accomplishing FACETS goals has required extensive AM/CS/SE help

- Software engineering:
  - >1.5M lines of code under version control
  - >5M lines of code after code generation
  - Unlike TRANSP: Codes maintain separate repos
- Computer science: Performance analysis, processor layout, …
- Applied Math: Implicit solves, numerical analysis, …



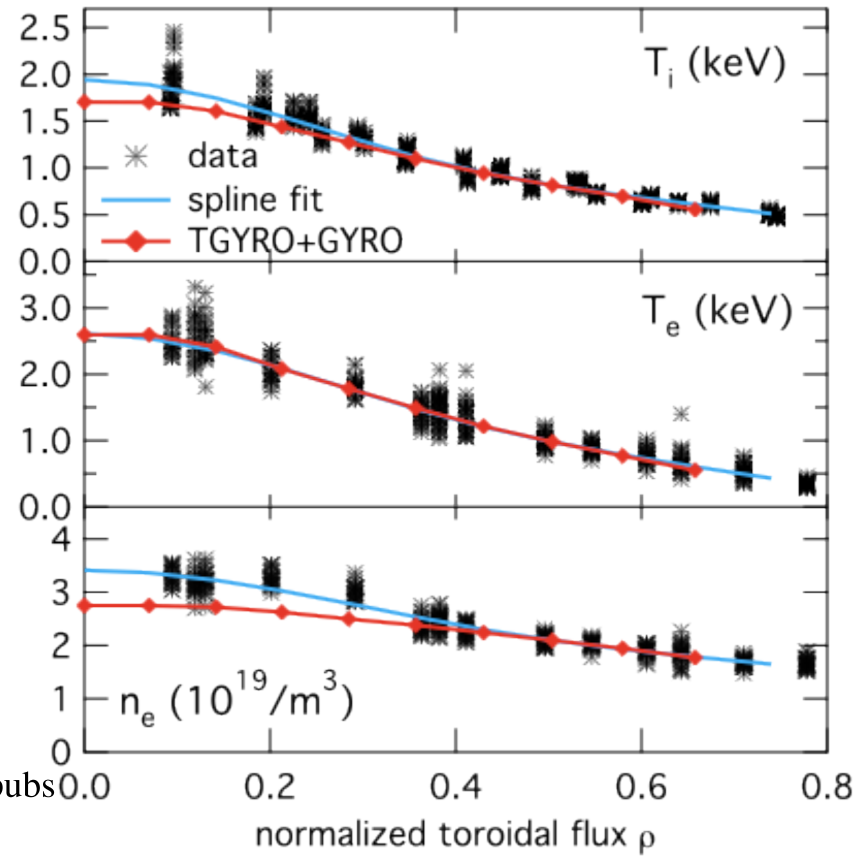
Processor decomposition in FACETS



TECH-X CORPORATION

Predictive Profile Modeling using Nonlinear Microturbulence Simulations

- First results from a new tool which uses nonlinear microturbulence code to predict density and temperature profiles arising from balance of turbulent transport and input heating
  - Requires many simulations- hundreds of thousands of processor-hours



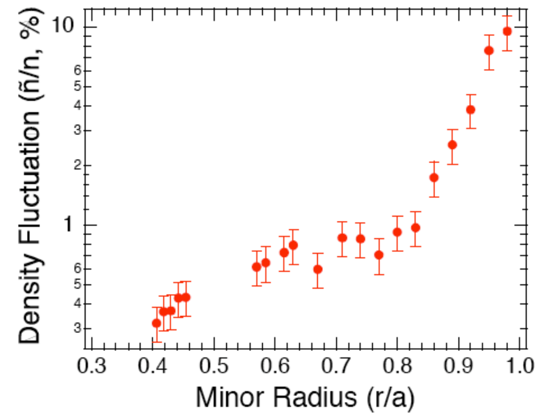
Ref: J. Candy, 2009 APS talk
http://fusion.gat.com/theory/Gyropubs

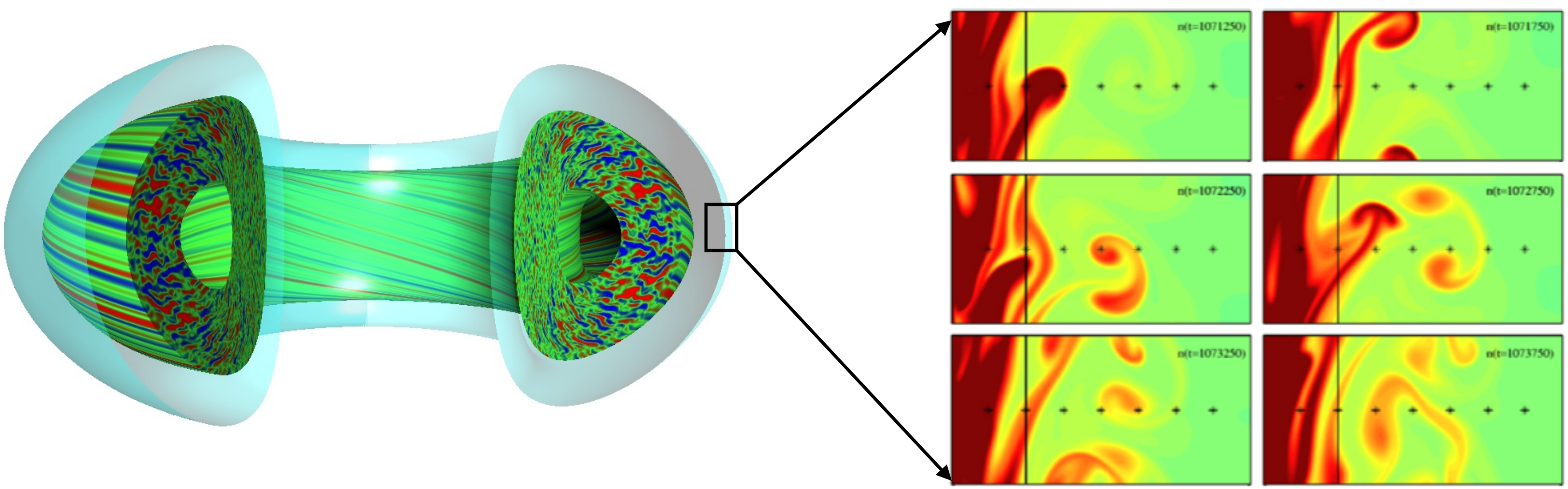
Edge Turbulence Qualitatively Different Than Core- Need New Models and Algorithms

- **Core turbulence**- small (~2-3% RMS level) fluctuations on top of a well-defined set of equilibrium profiles

- **Edge and Scrape-Off Layer**- large (10-100% RMS level) fluctuations, not always well-separated from equilibrium

- Edge turbulence is significantly more intermittent and “bursty” than core





O. E. Garcia *et al*, Phys. Plasmas **12** 062309 (2005)

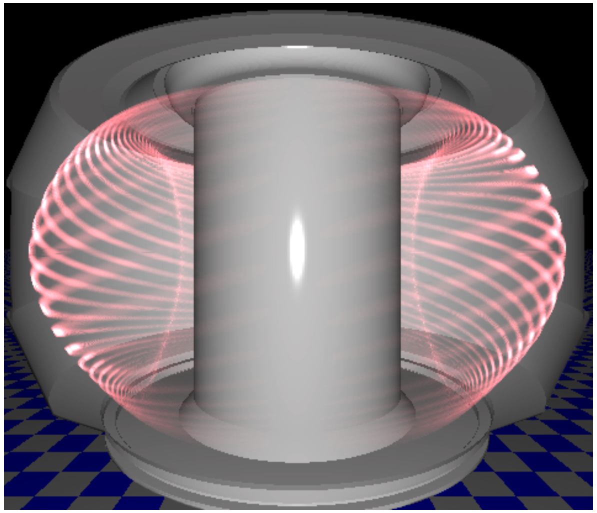
Bursty Edge Instabilities Present Challenge for ITER

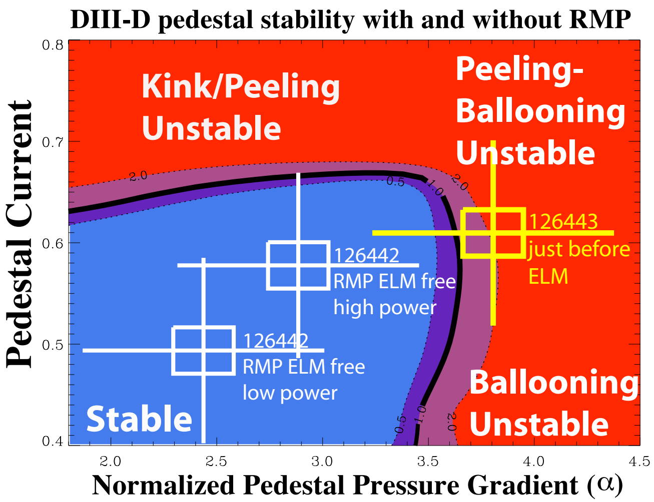
- Strong pressure gradients associated with H-mode edge can drive an instability which rapidly transfers 10-20% of total plasma energy to wall in < 1 ms
  - ITER design is such that it cannot tolerate a significant number of these edge localized modes (ELMS)

- Now have a validated model for predicting when ELMs will occur, based on MHD stability calculations

- ITER walls cannot tolerate many ELMs, but we still need to have a way of maintaining steep edge gradients to achieve target Q

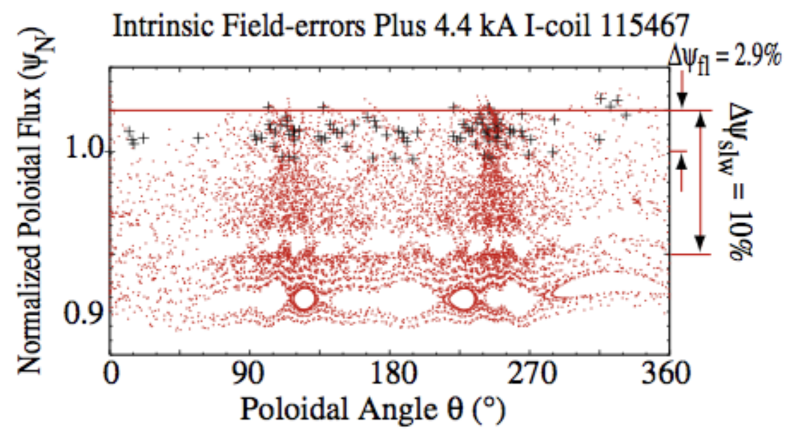
  → **need to suppress ELMs**

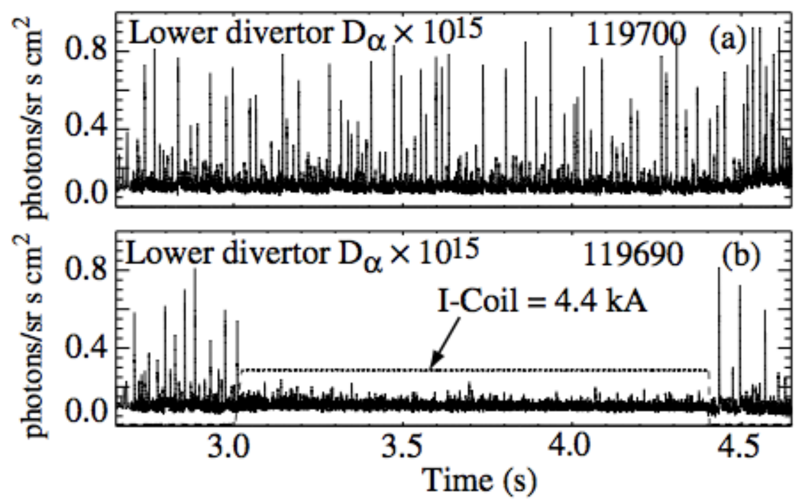




ELM Suppression by Field Ergodization

- Proposed solution- apply small perturbations to edge magnetic field which ergodize the field lines
- Observe that a such perturbations can lead to complete suppression of ELMs
- Currently an entirely empirical result- no current theory explains this observation
- A current issue of huge attention- understanding how the plasma responds to these perturbations
- Modeling will be key for understanding this crucial effect

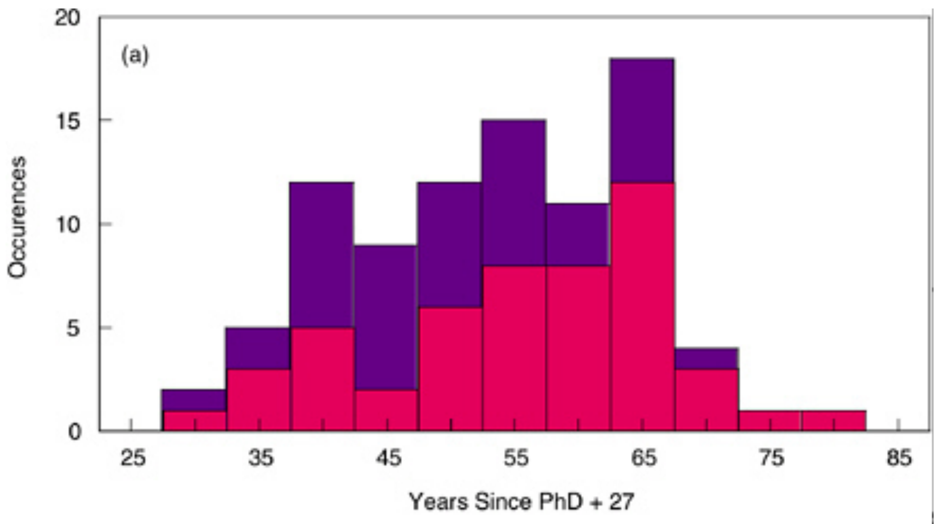




T. Evans *et al*., Nucl. Fusion **45** 595 (2005)

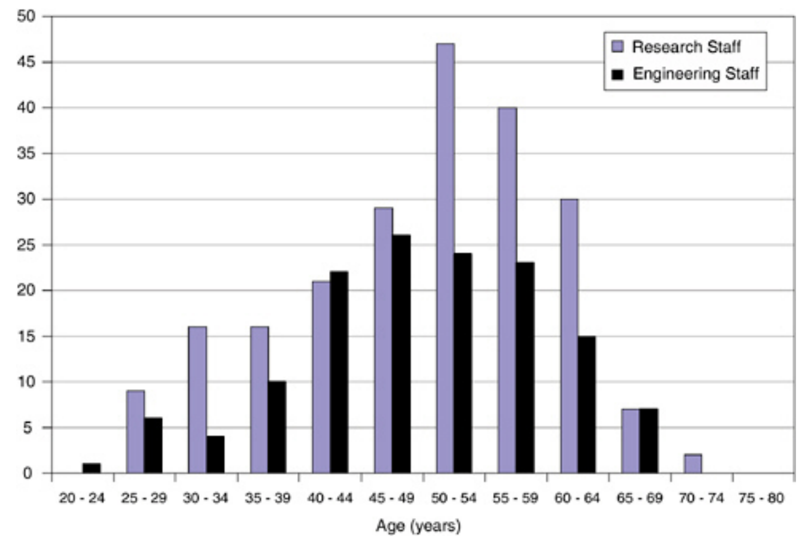
Fusion Demographics

- Significant skew in distribution, especially at PPPL, GA, and MIT (right)



University plasma faculty

Red is MIT, U. Maryland, UW-Madison, UT-Austin, UCSD, UCLA



PPPL, GA, and MIT staff

From NRC report “Burning Plasma: Bringing a Star to Earth” and UFA *Report on Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*

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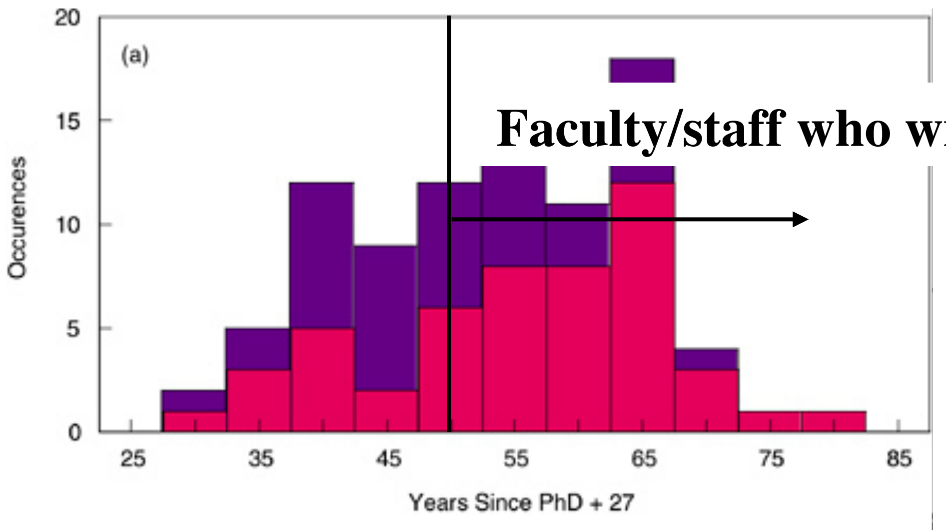
Fusion Demographics

- Significant skew in distribution, especially at PPPL, GA, and MIT (right)

Faculty/staff who will be 65 or older in 2017



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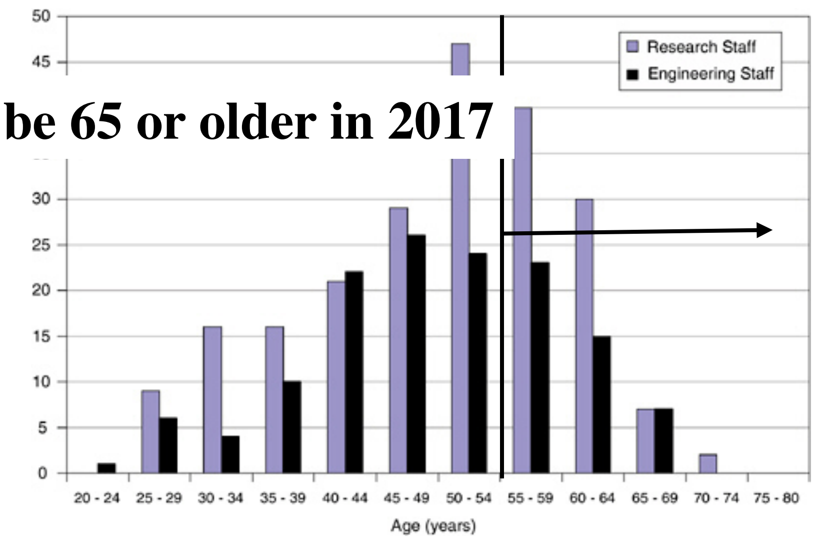


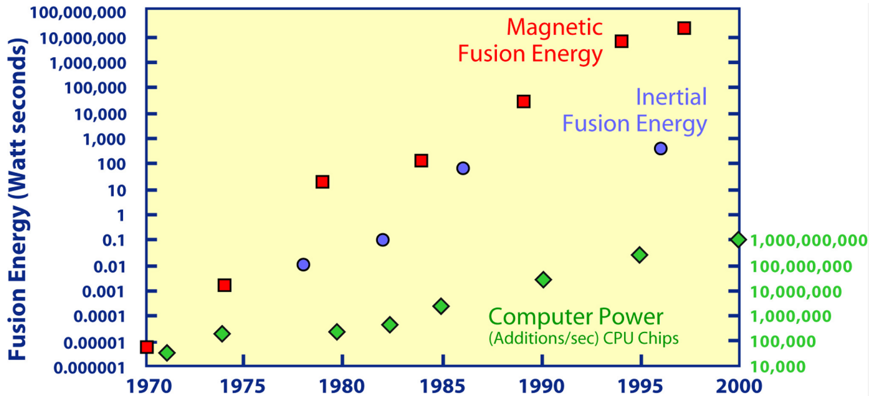
PPPL, GA, and MIT staff

- Need to begin **actively** recruiting new students and researchers to maximize the benefits of US participation in ITER

From NRC report “Burning Plasma: Bringing a Star to Earth” and UFA *Report on Age Distribution of Fusion Science Faculty and Fusion Science Ph.D. Production in the United States*

Summary and Outlook

- Fusion energy has the possibility of yielding a huge payoff in securing a green, long-term energy supply



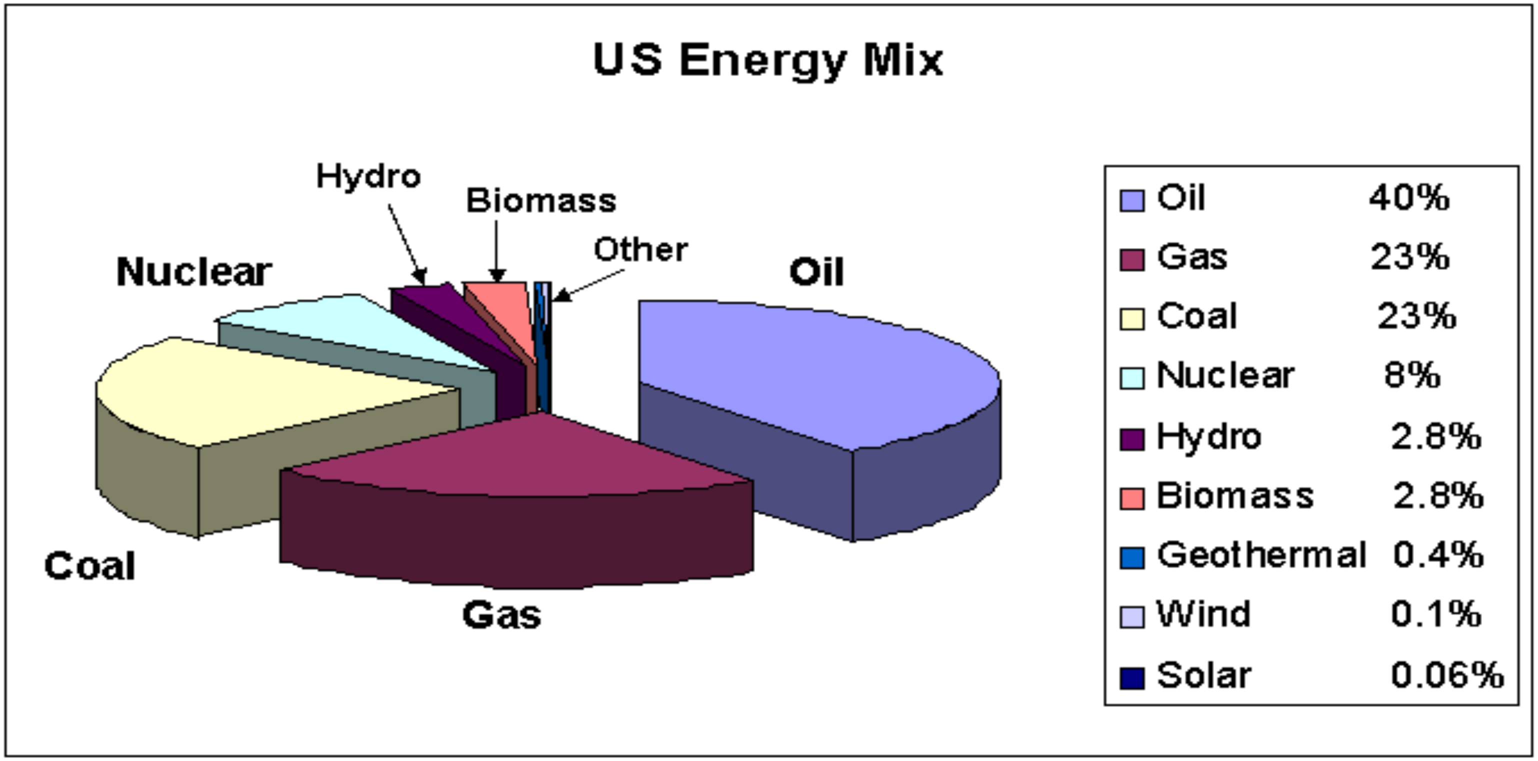
- The ITER experiment is moving forward, with the goal of demonstrating the scientific feasibility of the magnetic confinement approach to fusion

- In order to get the most science out of ITER, and optimize future reactors, we need validated, predictive integrated models of the plasma dynamics

- The combination of advances in computational models, high performance computing facilities, and diagnostic capabilities is allowing us to validate models of many different plasma phenomena

- We have begun the process of coupling models of physics on different scales, with the long-term goal of building a multi-scale predictive model of tokamak dynamics

Primary Energy Sources



**Thesis: It is Time to Move Beyond Fire…
Beyond Burning Things to Release Heat**

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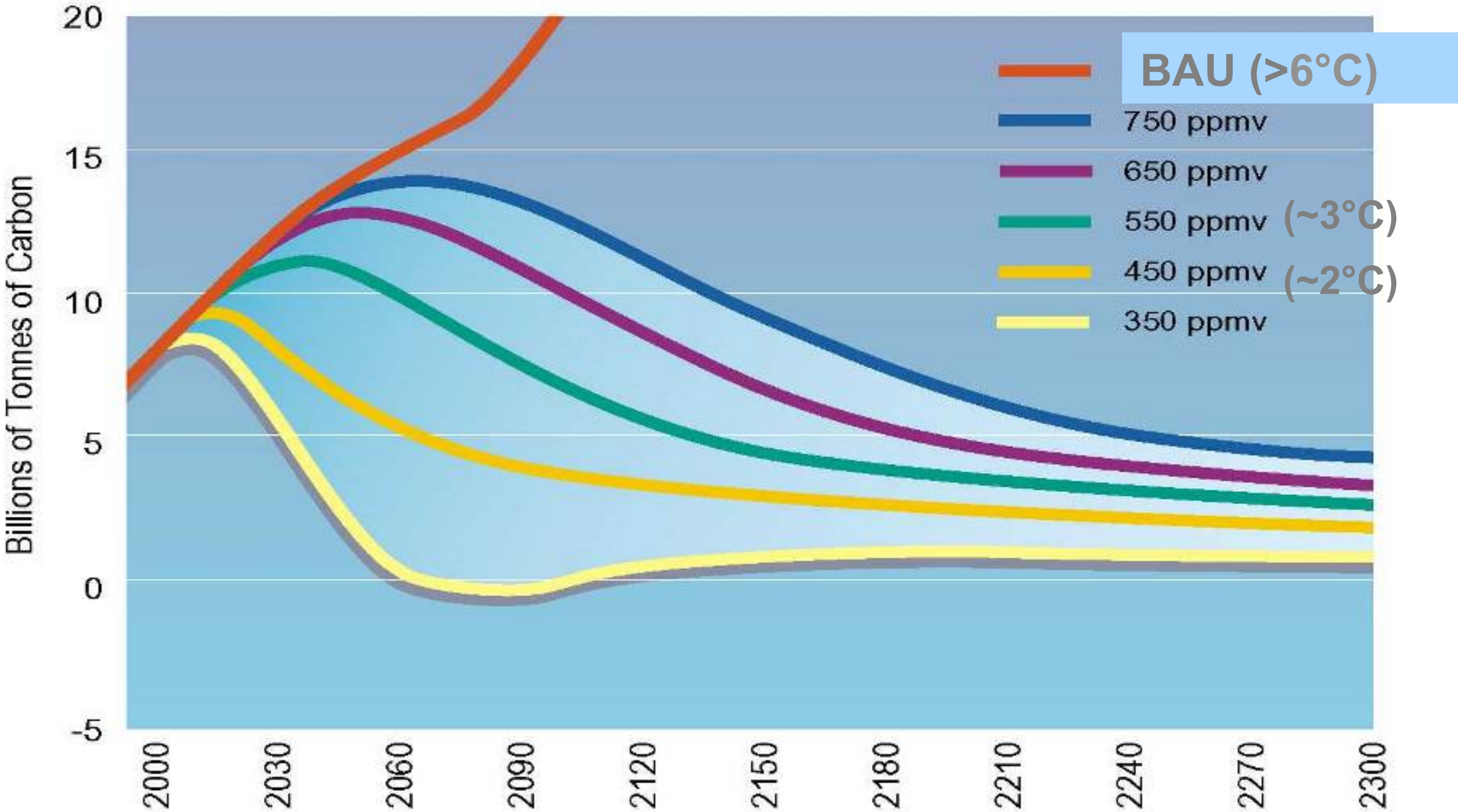
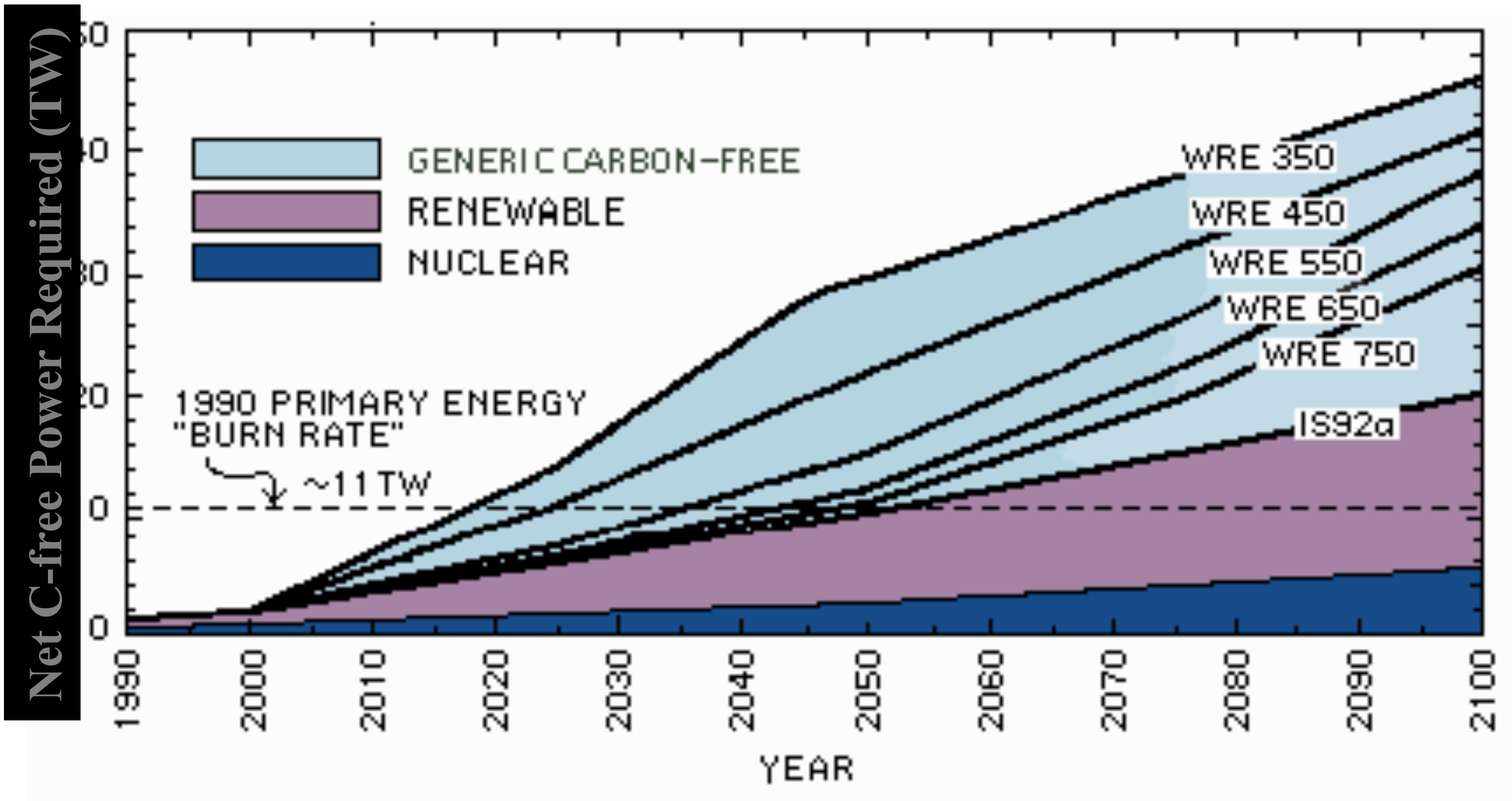
Emission paths for stabilizing CO_2 concentrations



The path to avoid ΔT_{avg} >2°C (gold) requires much earlier, more drastic action than path to avoid >3°C (green).

Source: IPCC, J. Holdren 2007 AAAS Plenary Lecture

Substantial Amounts of Carbon-free Power Required



Source: Hoffert et al, Nature 395, 881 (1999)

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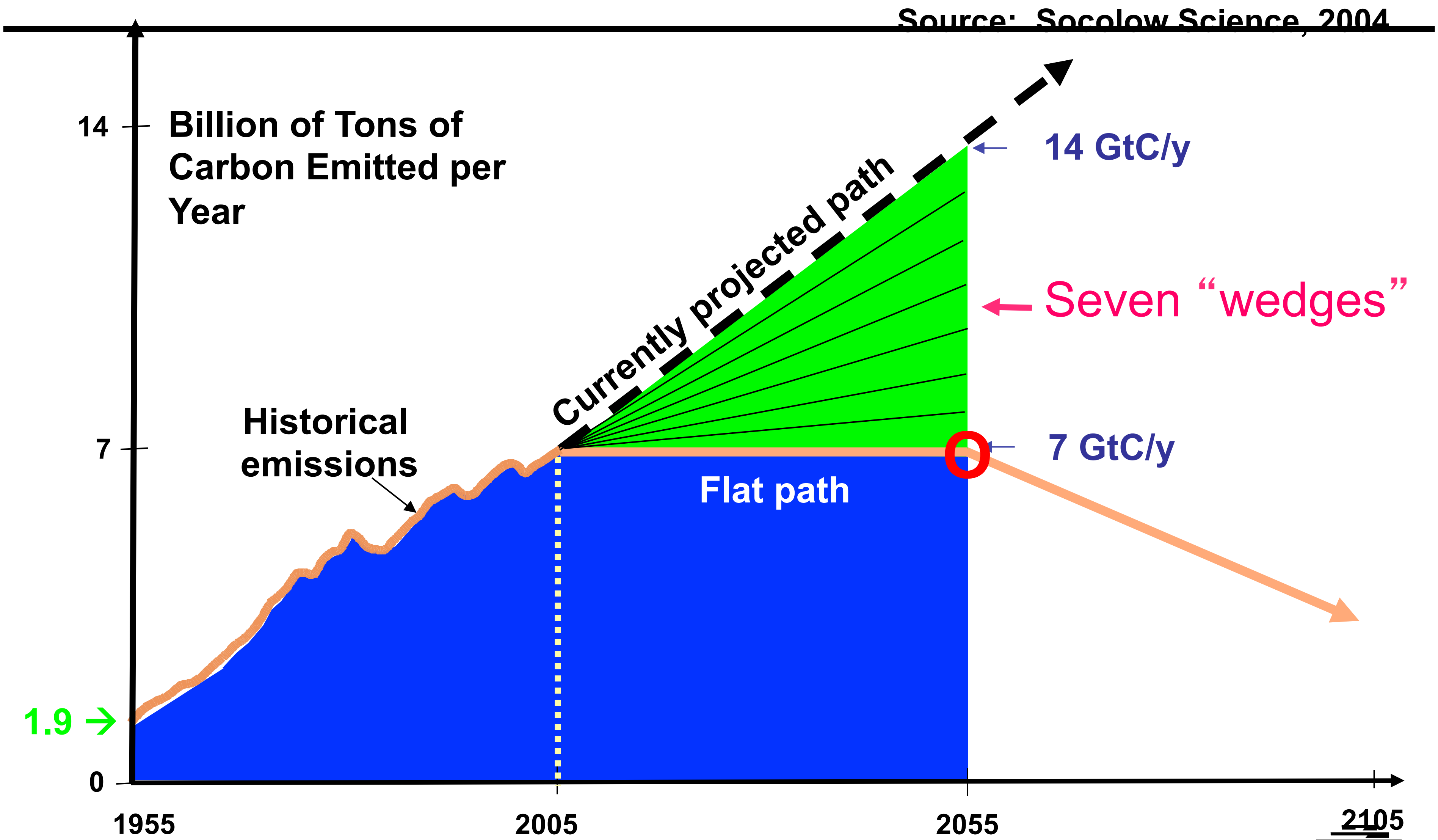
Existing Options

- Efficiency, Usage, & Carbon Intensity Improvements
  - Can Slow Rate of Increase But Not Reverse Trends
- Carbon Sequestration (G-tonnes/yr)
  - Large Potential … but Undemonstrated
- Solar & Wind
  - Requires Large Land Area (1000's km^2)
  - Energy Payback
  - Net Benefit?
- Bio-Fuels
  - Requires Large Land & Water Resources,
  - Net Climate Change Impact?
- Nuclear
  - Advanced Fission (but requires Pu Economy)
  - Fusion (Not Ready Until Mid-Century)

Solution Requires "Cocktail Approach"



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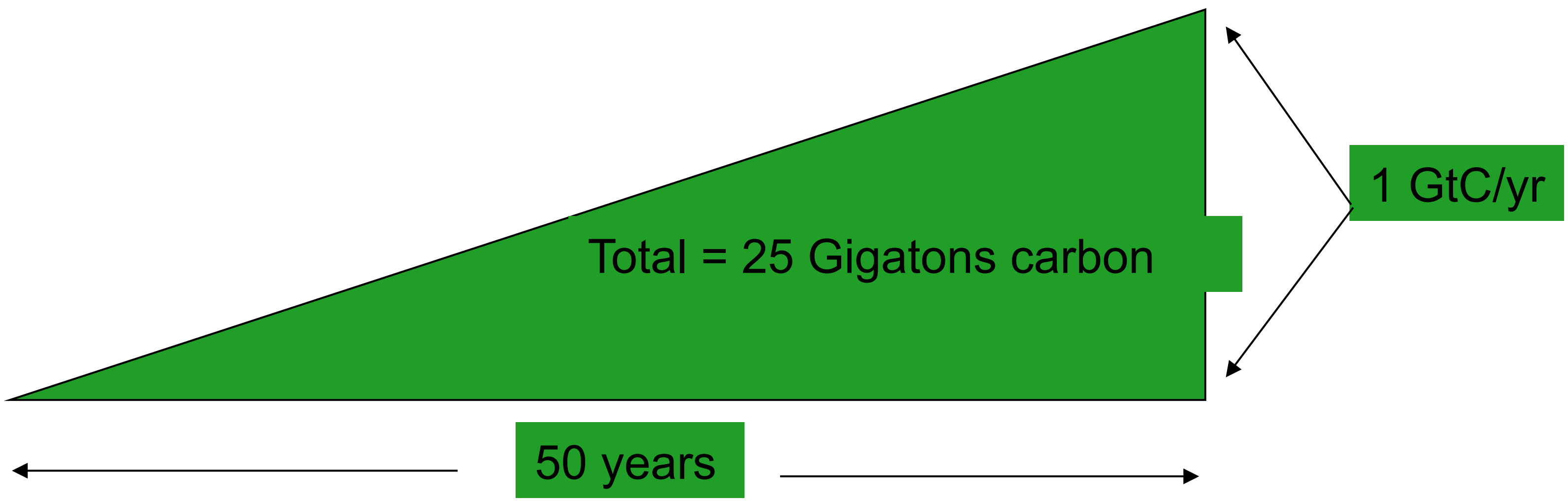
What is a “Wedge”?

Source: Socolow Science, 2004

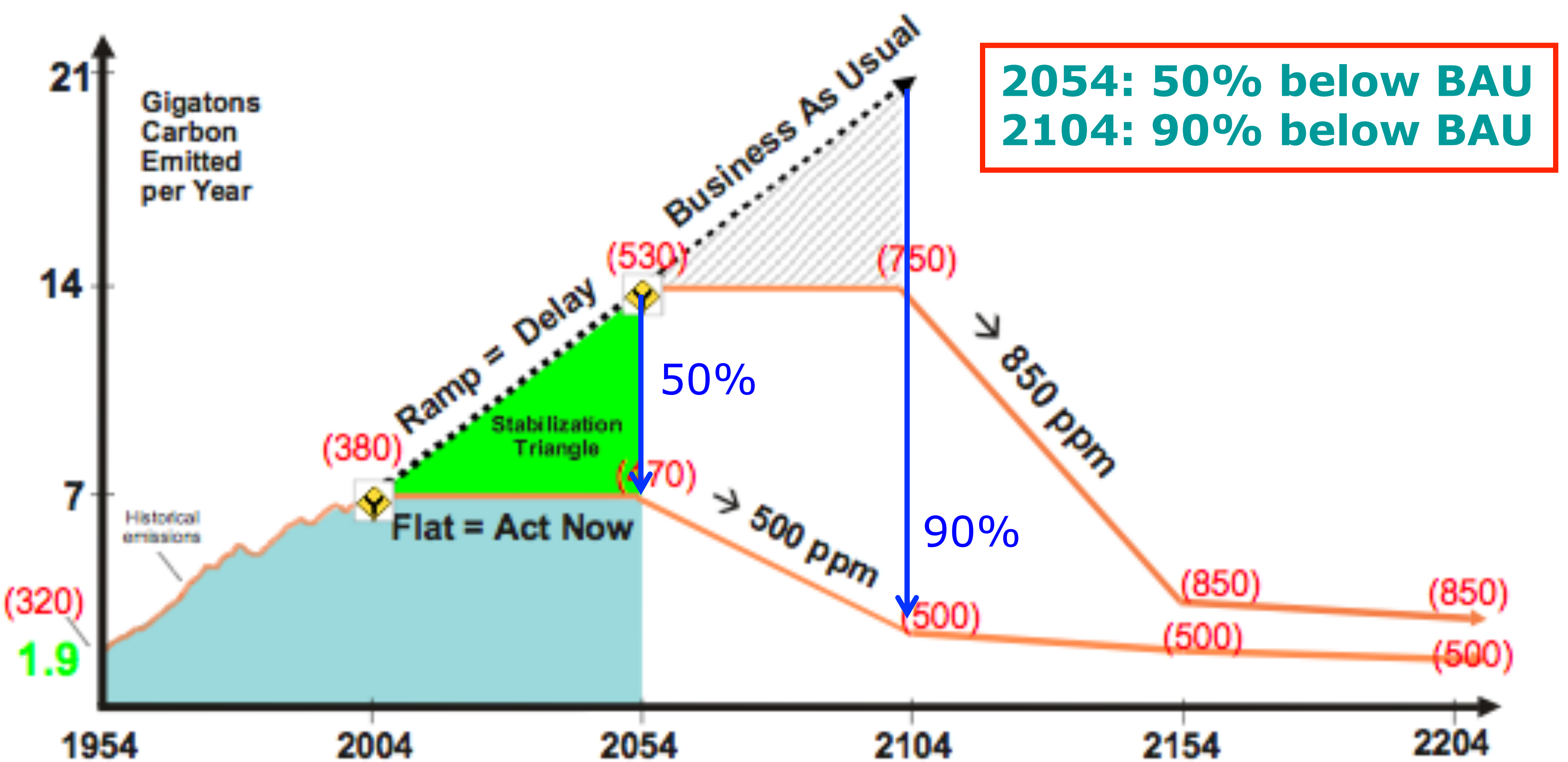
A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. A “solution” to the CO_2 problem should provide at least one wedge.

Require a **Long-Term** Revolution in Energy Technology

Source: Socolow, private communication



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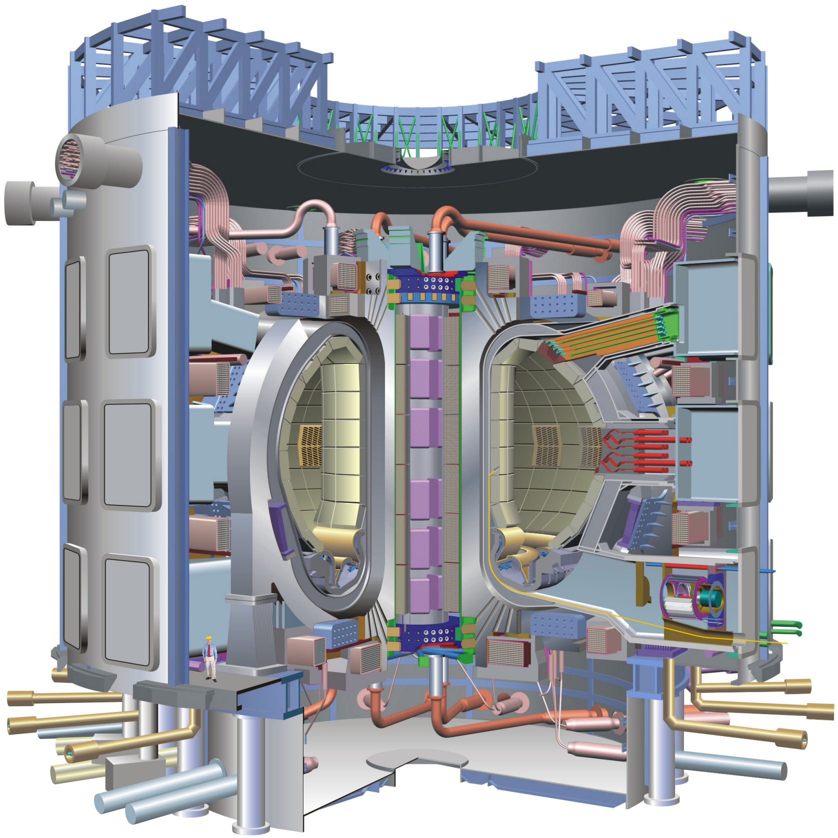
Possible Long-Term C-Neutral Primary Sources

Controlled Fusion



Graphic Courtesy of ITER

- Deep Rock Geothermal
- Large Scale Renewables w/ Long Distance Transmission or Energy Storage
- Advanced Fission
- Controlled Fusion

ALL THESE OPTIONS REQUIRE FURTHER RESEARCH & DEVELOPMENT

It Takes Time to Change Energy Infrastructure

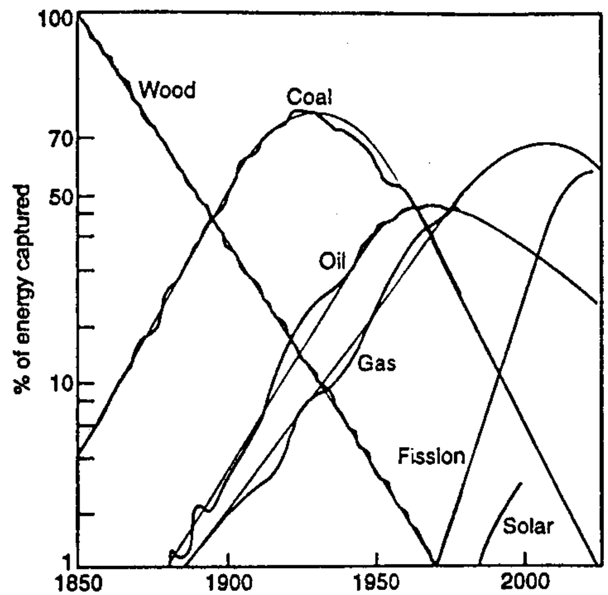


Fig. 3 Market penetration history and projection for the U.S. (Marchetti rule).

- Wood, Coal, Oil, Gas Based upon Historical Data
- See Gradual (~50 yr) Penetration & Decay Time-scale

Ref: Marchetti, C., Nakicenovic,N. Energy in a Finite World, Ballinger Pub. Cambridge, MA 1979 pp.253-279