Towards Comprehensive Simulation of Fusion Plasmas

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Outline

- Fusion…the ultimate energy source
- Basics of Magnetic Fusion
- The Need for Computer Simulation
- Progress in Simulating Fusion Plasmas
- Projection to the Future
- Summary


Fusion Powers the Sun and Stars
Can we harness Fusion power on earth?

The Case for Fusion Energy

- Worldwide demand for energy continues to increase
  - Due to population increases and economic development
  - Most population growth and energy demand is in urban areas
    - Implies need for large, centralized power generation
- Worldwide oil and gas production is near or past peak
  - Need for alternative source: coal, fission, fusion
- Increasing evidence that release of greenhouse gases is causing global climate change
  - Historical data and 100+ year detailed climate projections
  - This makes nuclear (fission or fusion) preferable to fossil (coal)
- Fusion has some advantages over fission that could become critical:
  - Inherent safety (no China syndrome)
  - No weapons proliferation considerations (security)
  - Greatly reduced waste disposal problems (no Yucca Mt.)

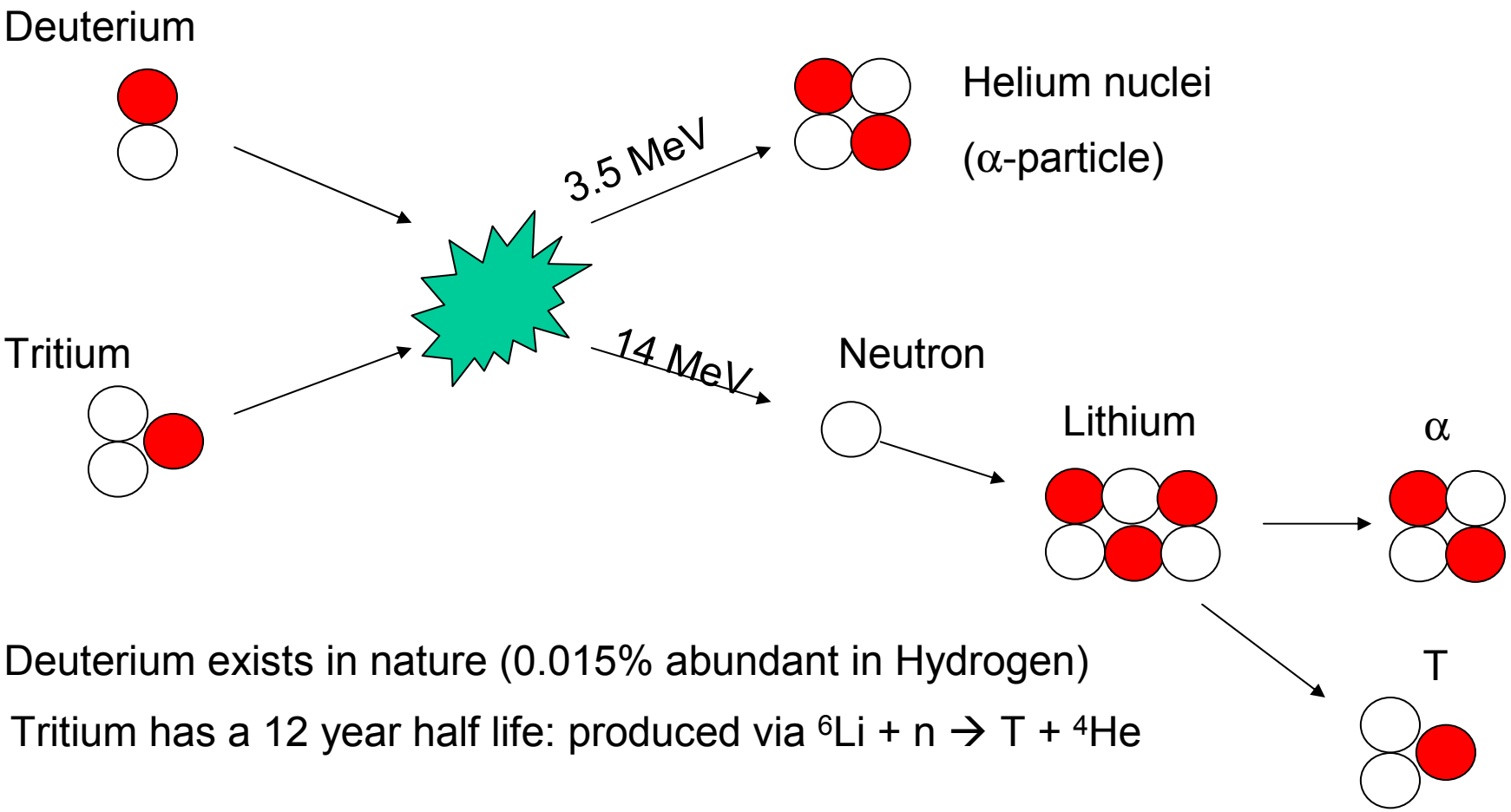
Presidential Leadership . . .

"I reaffirm America's commitment to the United Nations Framework Convention and its central goal, to stabilize atmospheric greenhouse gas concentrations at a level that will prevent dangerous human interference with the climate."

"(We will) set America on a path to slow the growth of our greenhouse gas emissions and, as science justifies, to stop and then reverse the growth of emissions."

- President George W. Bush
February 14, 2002

What is Fusion?
Controlled Fusion uses isotopes of Hydrogen



Deuterium exists in nature (0.015% abundant in Hydrogen)

Tritium has a 12 year half life: produced via $^{6}Li + n \rightarrow T + {}^{4}He$

Lithium is naturally abundant

Controlled Fusion Basics

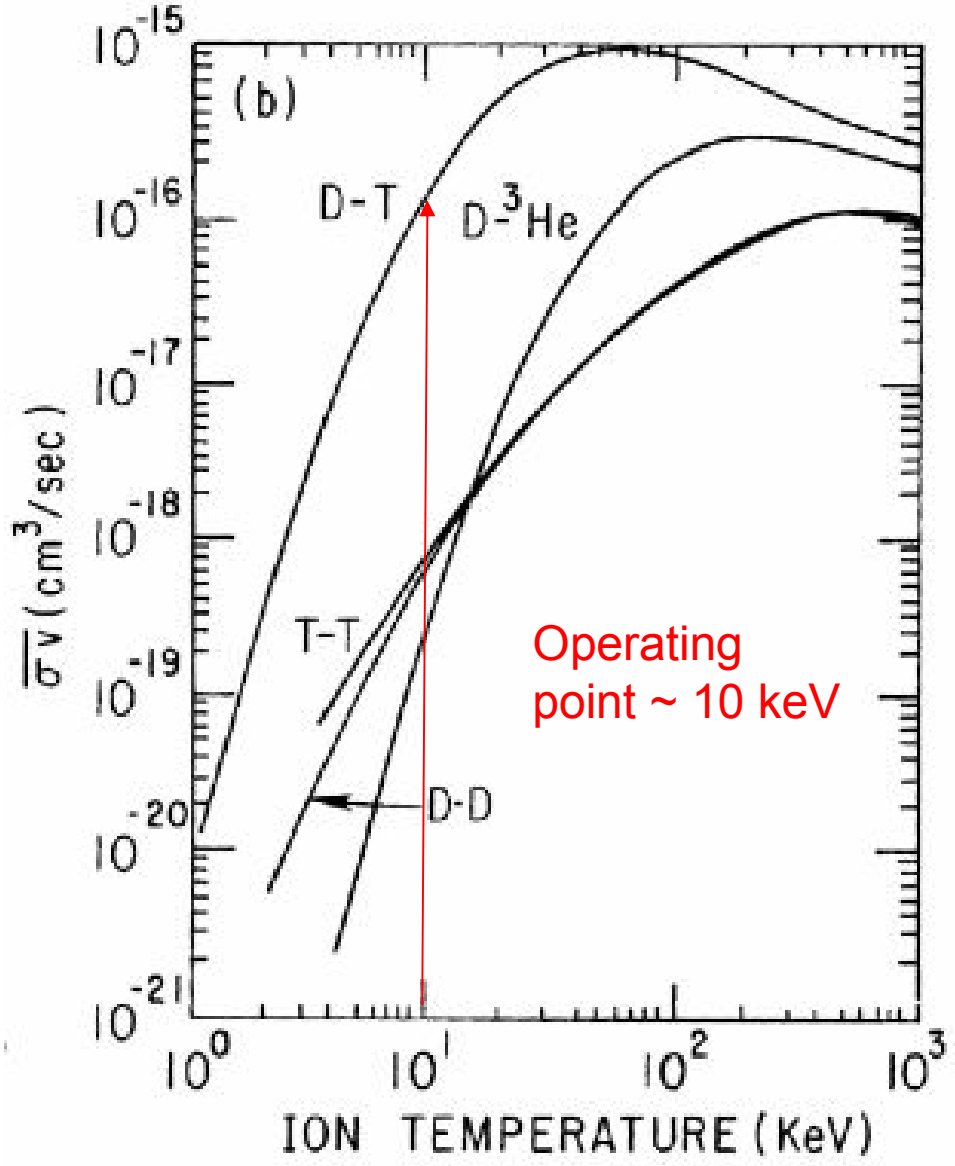
Create a mixture of D and T (plasma), heat it to high temperature, and the D and T will fuse to produce energy.

$P_{DT} = n_D n_T \langle\sigma v\rangle (U_\alpha + U_n)$

at 10 keV, $\langle\sigma v\rangle \sim T^2$

$P_{DT} \sim$ (plasma pressure)^2

Need ~ 5 atmosphere @ 10 keV



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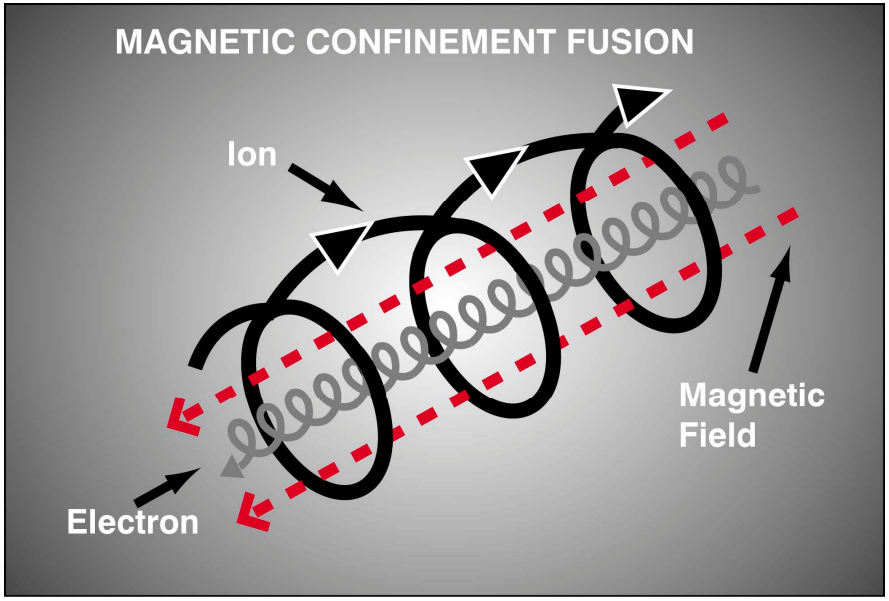
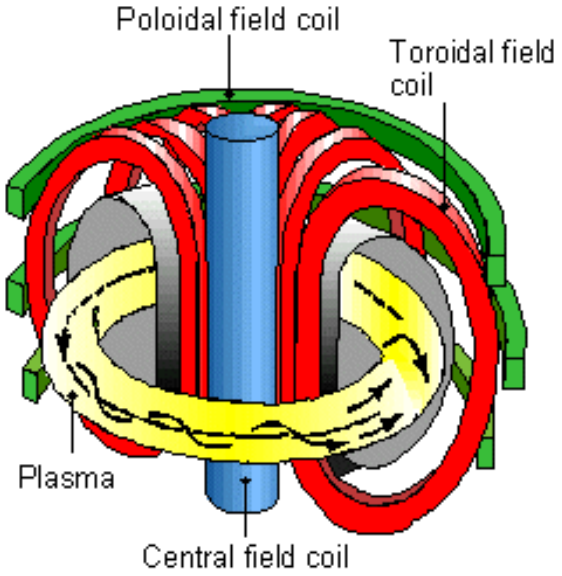
Toroidal Magnetic Confinement



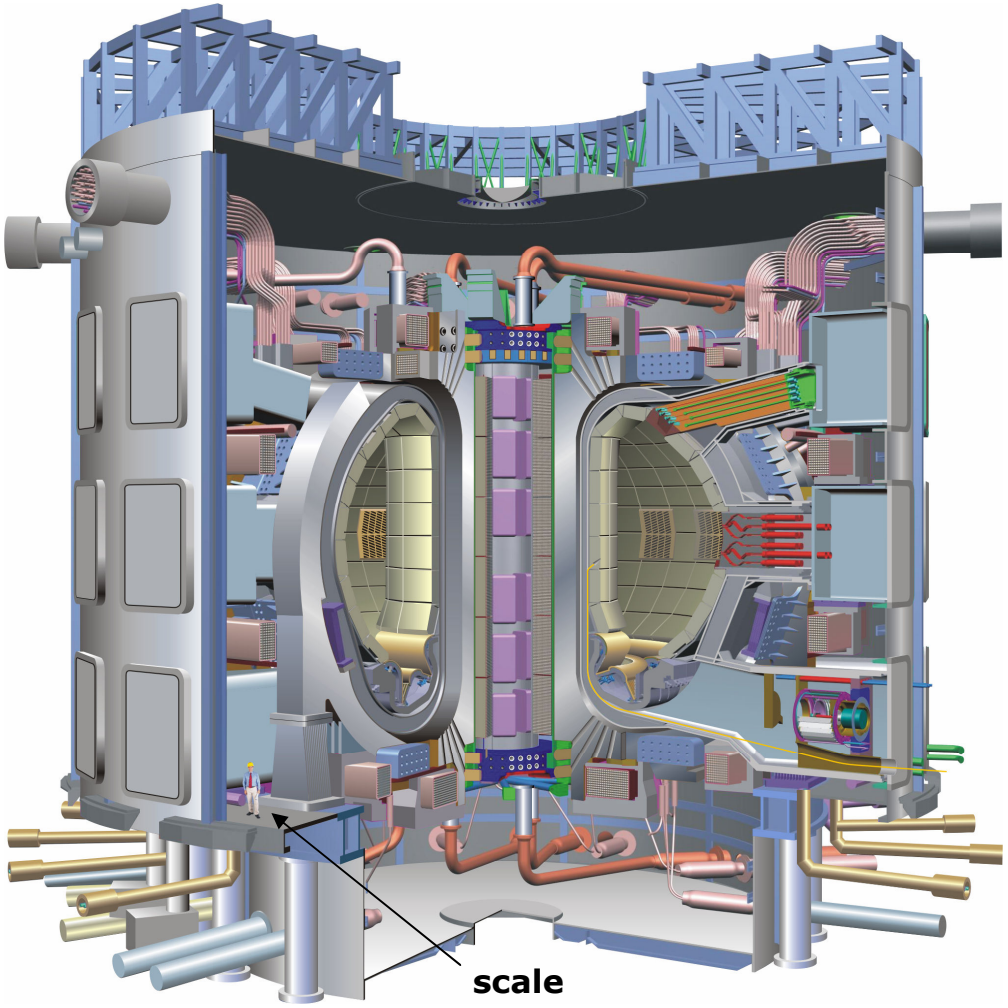


Charged particles have helical orbits in a magnetic field; they describe circular orbits perpendicular to the field and free-stream in the direction of the field.

TOKAMAK creates toroidal magnetic fields to confine particles in the 3rd dimension. Includes an induced toroidal plasma current to heat and confine the plasma

"TOKAMAK": (Russian abbreviation for "toroidal chamber"

The U.S. is an official partner in ITER



- 500 MW fusion output
- Cost: $ 5-10 B
- To begin operation in 2015

International
Thermonuclear
Experimental
Reactor:

- European Union
- Japan
- United States
- Russia
- Korea
- China

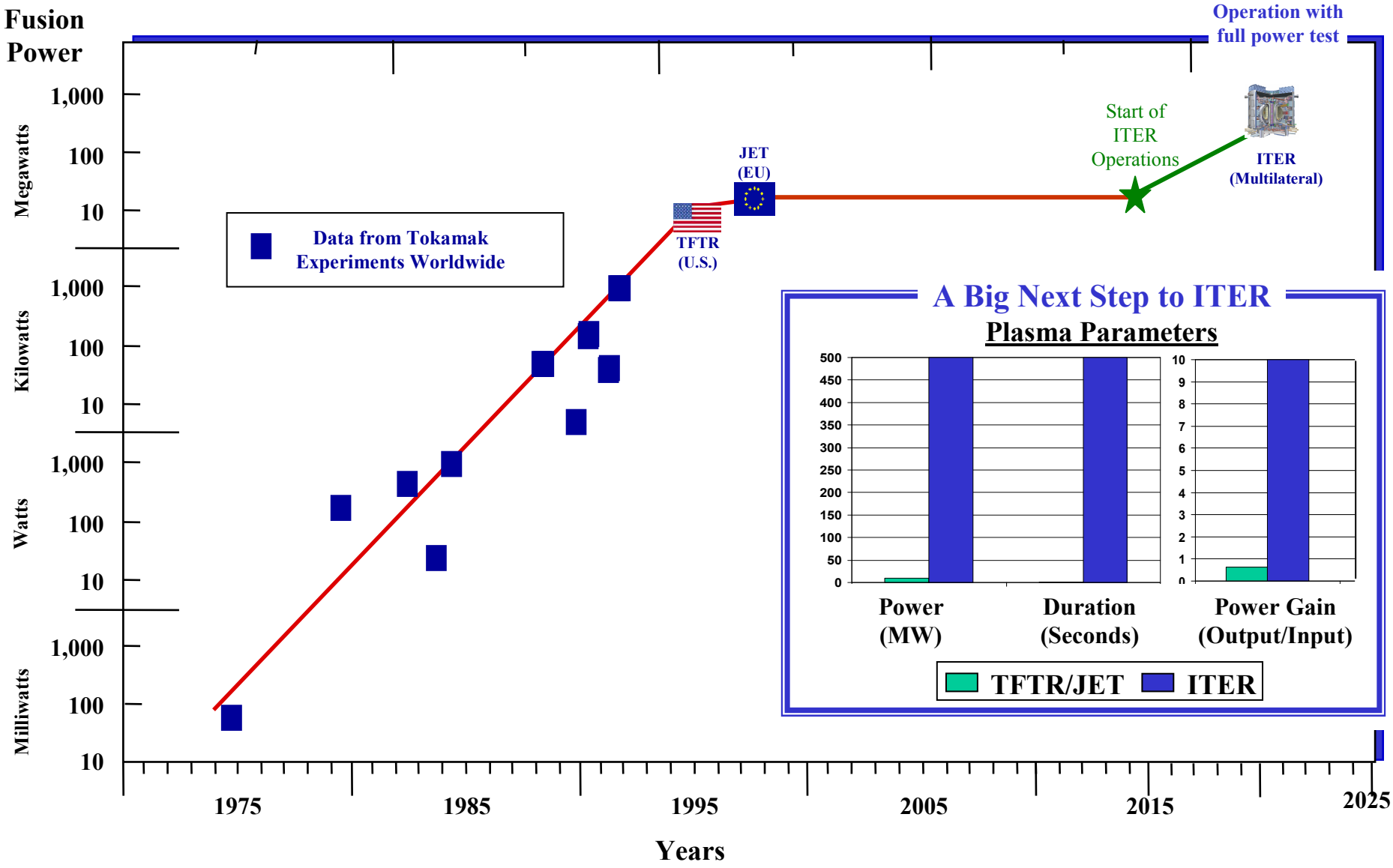
ITER has a site…
Cadarache, France

June 28, 2005
Ministerial Level Meeting
Moscow, Russia

ITER

Tore Supra

Progress in Magnetic Fusion Research and Next Step to ITER



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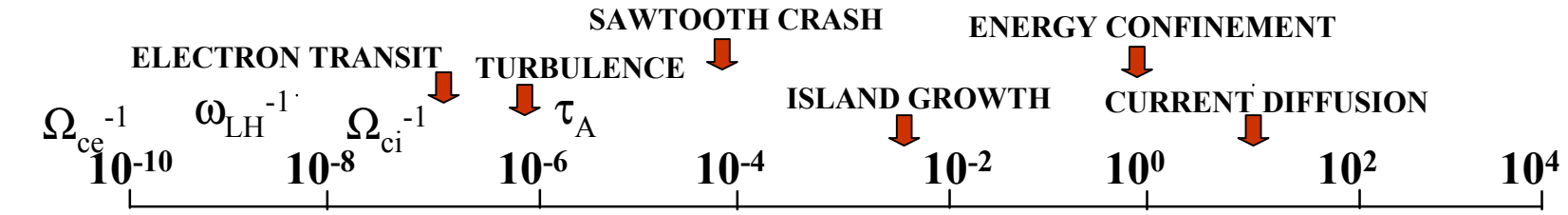
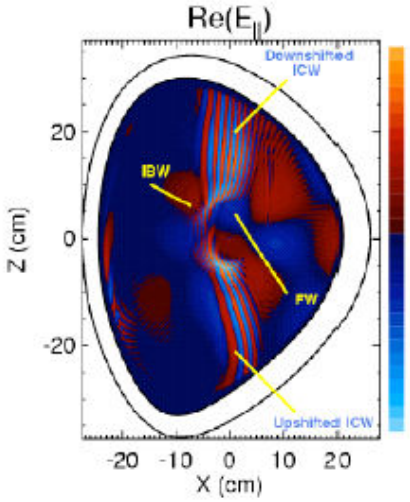
Simulations are needed in 4 areas

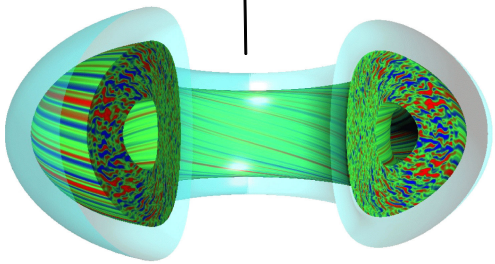
- How to heat the plasma to thermonuclear temperatures (~ 100,000,000^{o} C)
- How to reduce the background turbulence
- How to eliminate device-scale instabilities
- How to optimize the operation of the whole device

These 4 areas address different timescales and are normally studied using different codes

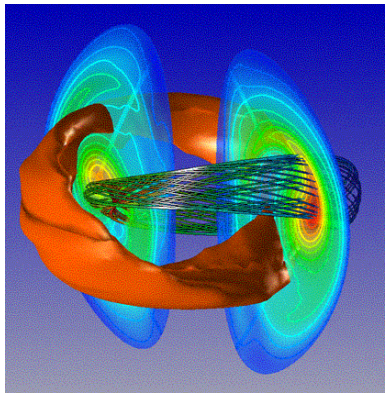




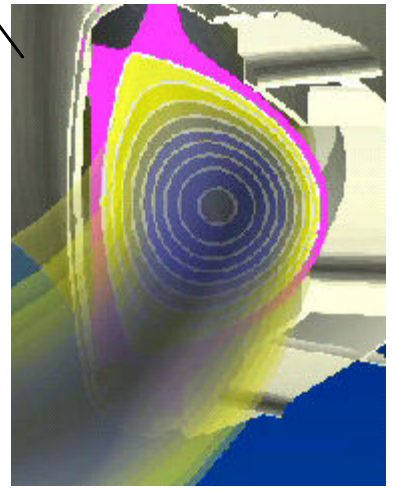
(a) RF codes



(b) Micro-turbulence codes



(c) Extended-MHD codes



(d) Transport Codes

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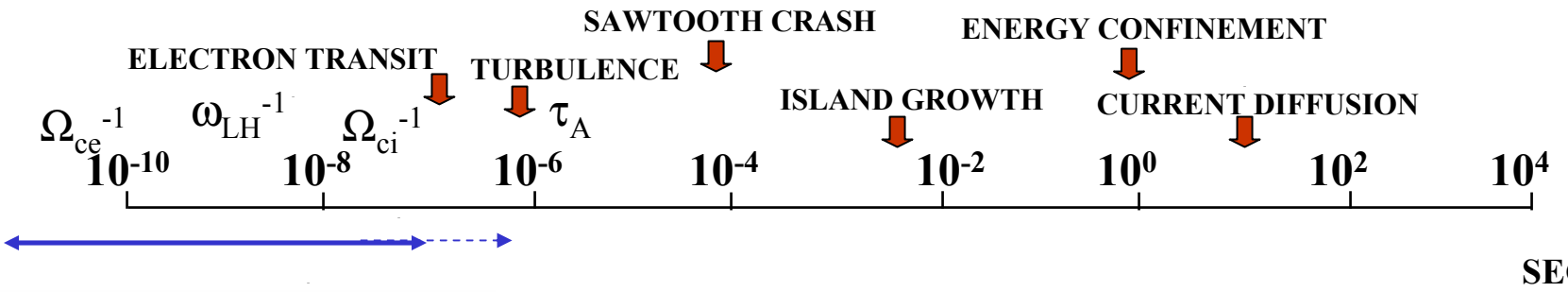
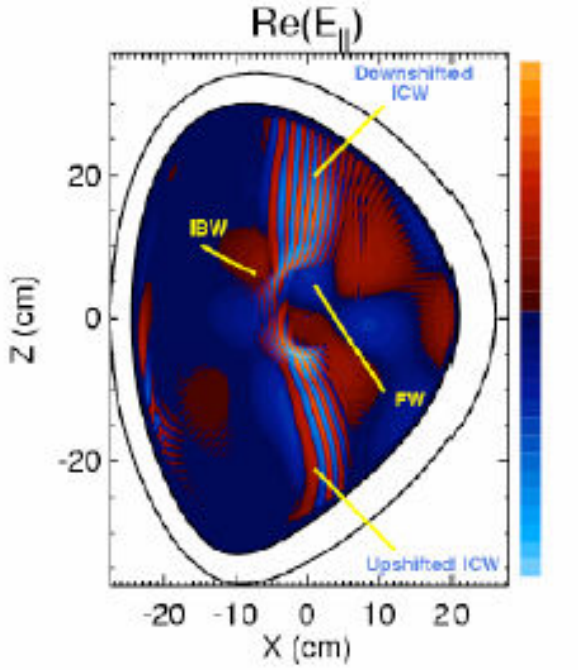
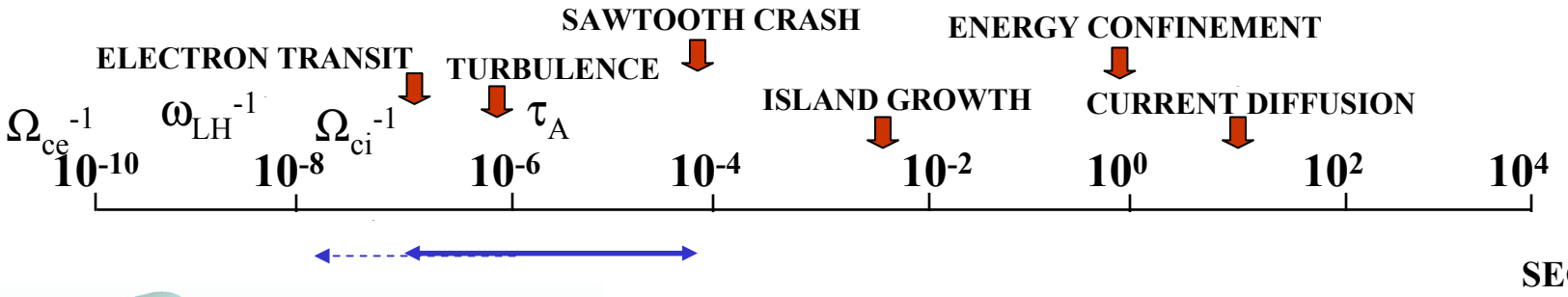
I. RF Codes predict heating and current drive from external antennas

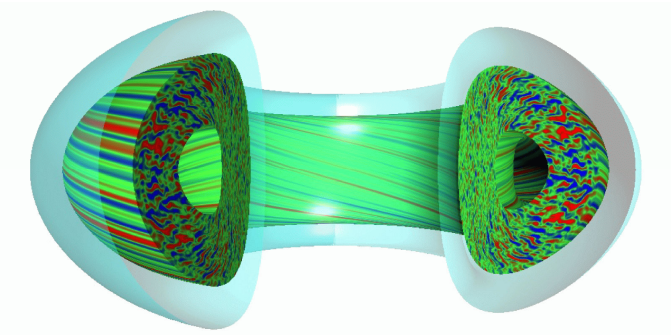


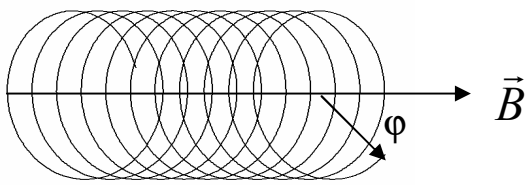


- "mode conversion" physics requires resolution of both small-scale and large-scale structures
- 220,000 coupled complex equations
- dense matrix operations
- 788 GB of Memory
- 358 minutes on 1936 processors at NERSC
- 1.9 teraflop/s (60% of peak performance)

II. Gyrokinetics codes solve for self-consistent transport in turbulent fields







Two major approaches to representing phase space:

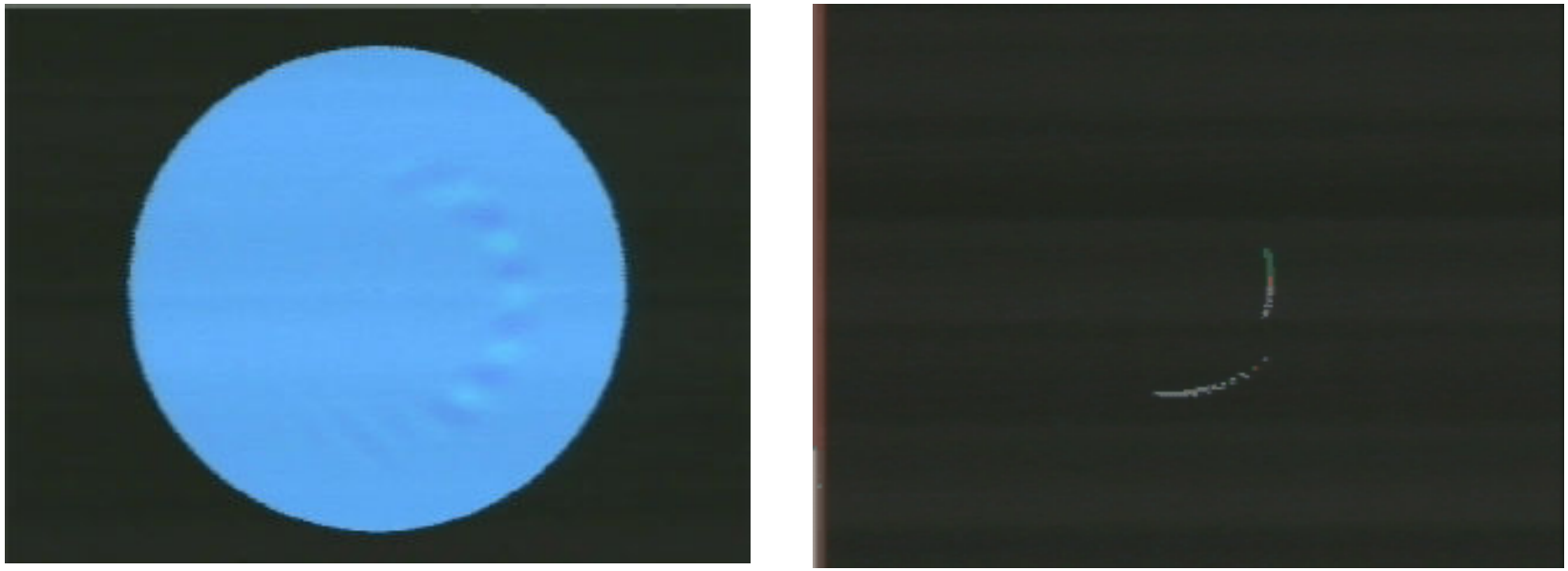
- 5D + time continuum code
- Collection of gyro-particles

• These codes parallelize and vectorize well

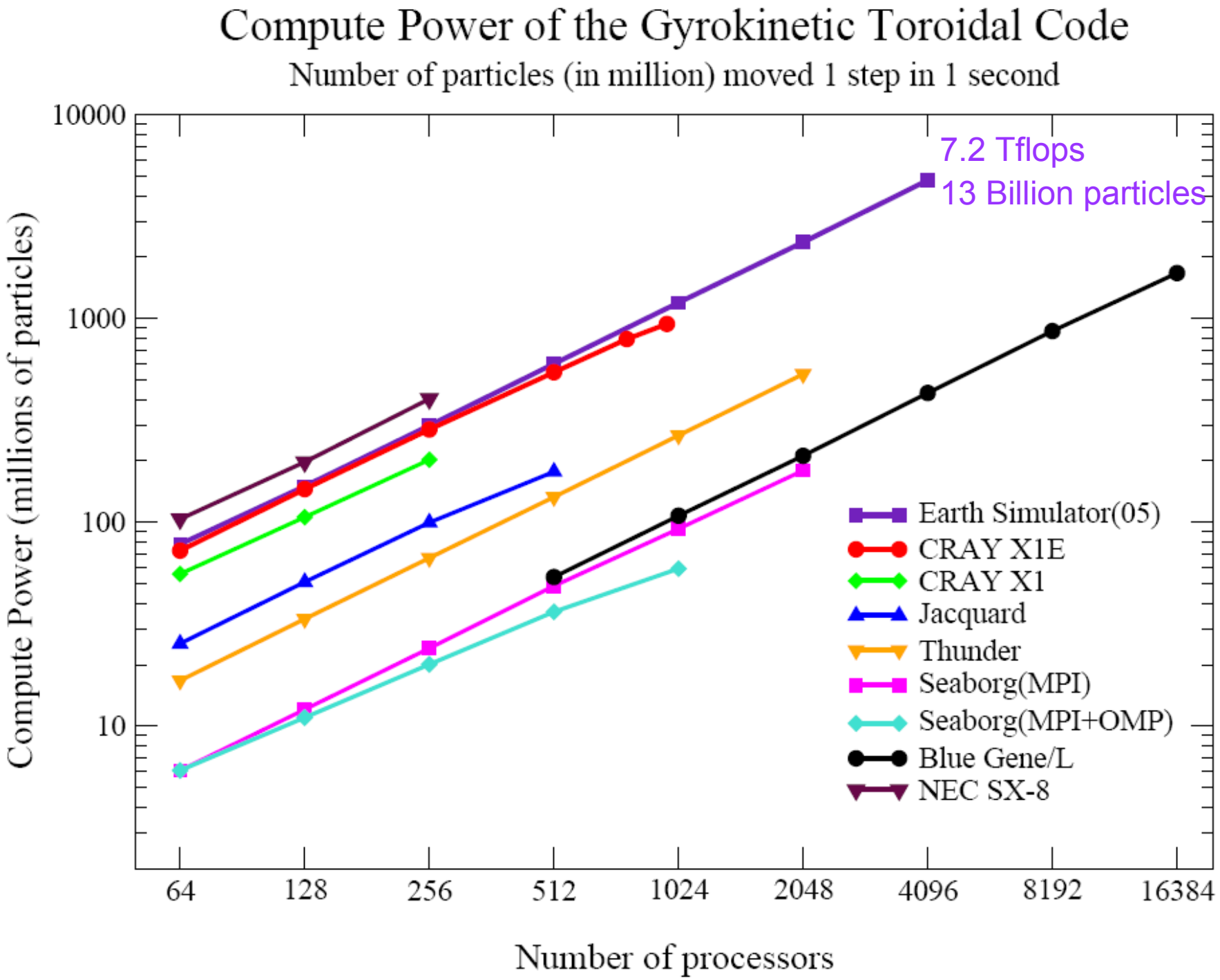
• 6 D phase space (3 ***R*** + 3 ***V***)

• Average over gyroangle to go from 6D to 5D

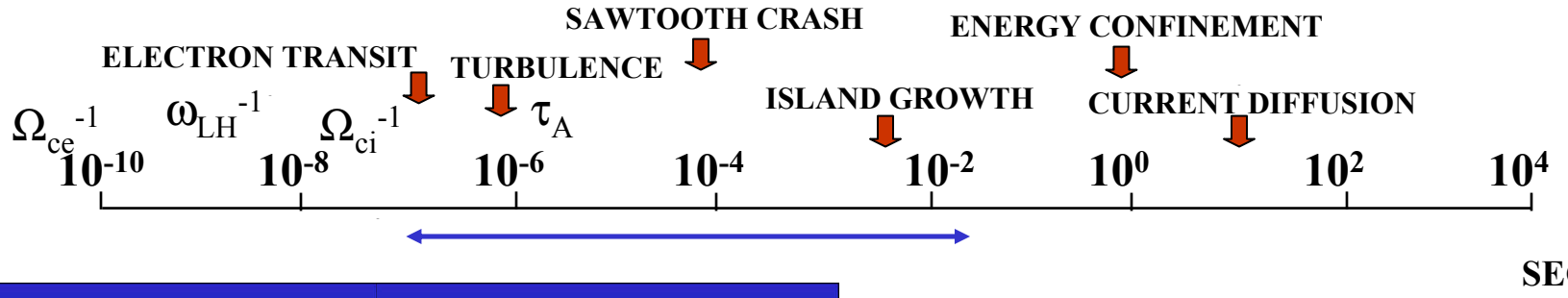
Gyrokinetics codes have provided new insight into turbulent transport processes

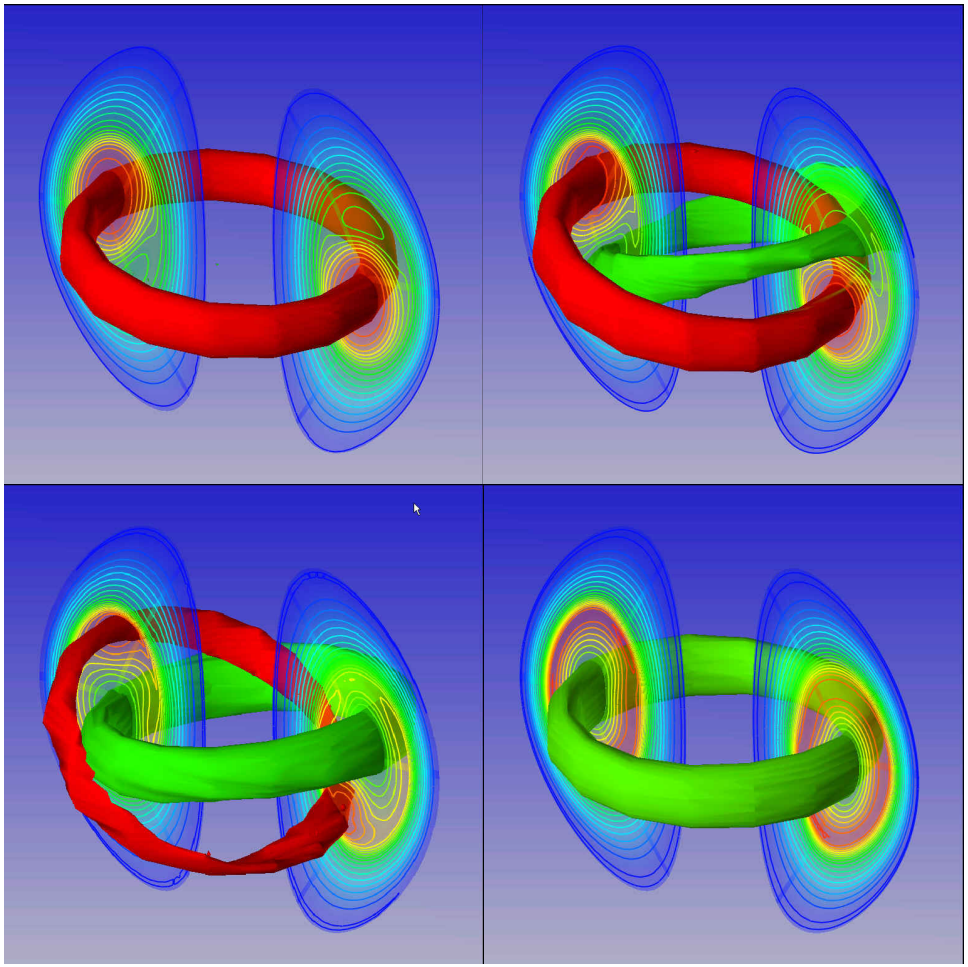


2D “slice” of 3D simulation shows potential (left) and particle motions (right). Turbulence produces global flows which break-up turbulent eddies.


Compute Power of the Gyrokinetic Toroidal Code
Number of particles (in million) moved 1 step in 1 second
Compute Power (millions of particles)
10000
1000
100
10
64
128
256
512
1024
2048
4096
8192
16384
Number of processors
7.2 Tflops
13 Billion particles
Earth Simulator(05)
CRAY X1E
CRAY X1
Jacquard
Thunder
Seaborg(MPI)
Seaborg(MPI+OMP)
Blue Gene/L
NEC SX-8

III. Extended MHD Codes solve 3D fluid equations for device-scale stability





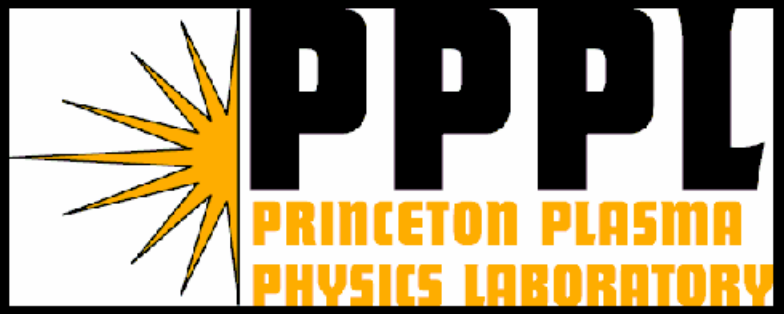
- Sawtooth cycle is one example of global phenomena that need to be understood
- Can cause degradation of confinement, or plasma termination
- These global codes typically exhibit good parallel scaling to 500-1000 processors
- Running time is dominated by elliptic solves
- Need to run for many time steps

M3D simulation of NSTX

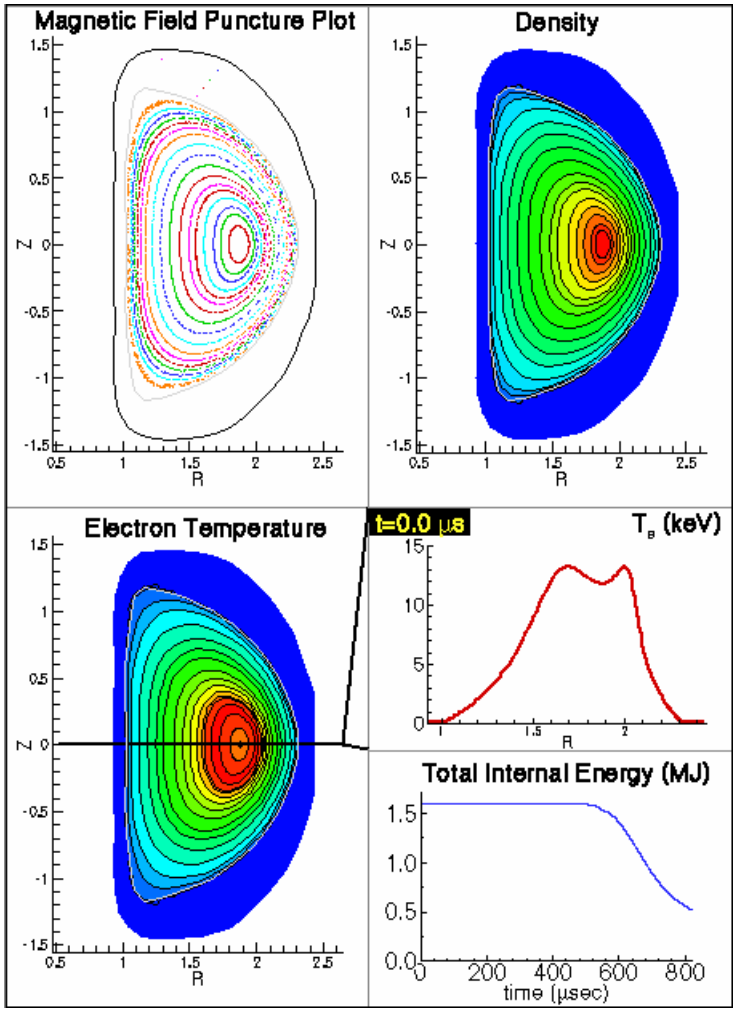
W. Park et al.

Visualization

S. Klasky et al.

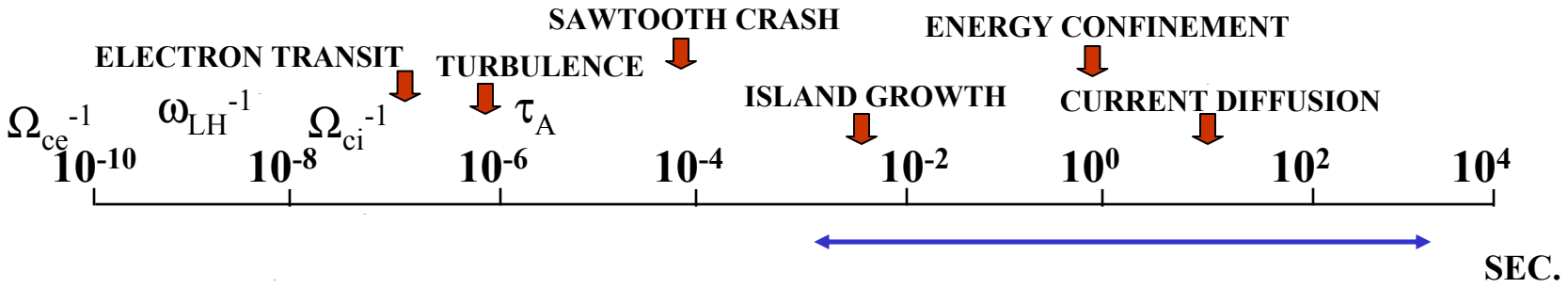


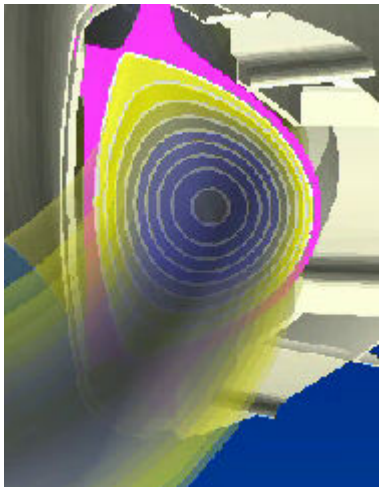
Simulation of a disrupting plasma



- 2D Cross section of 3D MHD simulation
- Plasma pressure was initialized at a value which exceeded the stability limit for this configuration
- Magnetic surfaces break up and magnetic field looses ability to confine plasma

IV. Transport Codes simulate the evolution of the whole discharge





- Transport codes or “integrated modeling codes” are including all physical effects relevant to describe a discharge

- Now using “reduced models” for some phenomena

- This is the present thrust of the program: Fusion Simulation Project

Example of Integrated Plasma Simulator: Present capability

simulation of an entire burning plasma tokamak discharge (FIRE)

Includes:

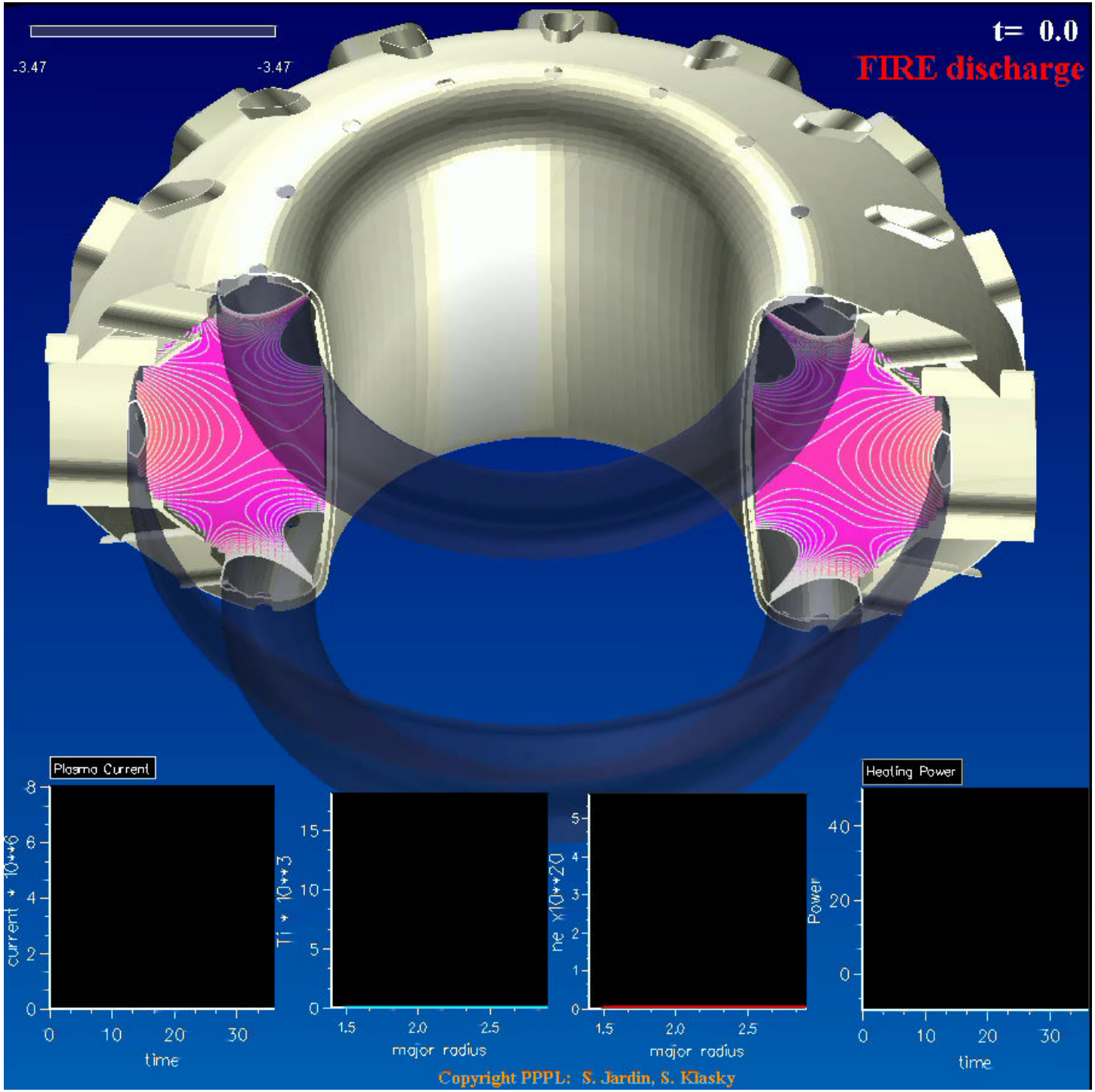
RF, ohmic, fusion product heating

Microstability-based transport model

L/H mode transition

Sawtooth Model

Evolving Equilibrium with actual coils



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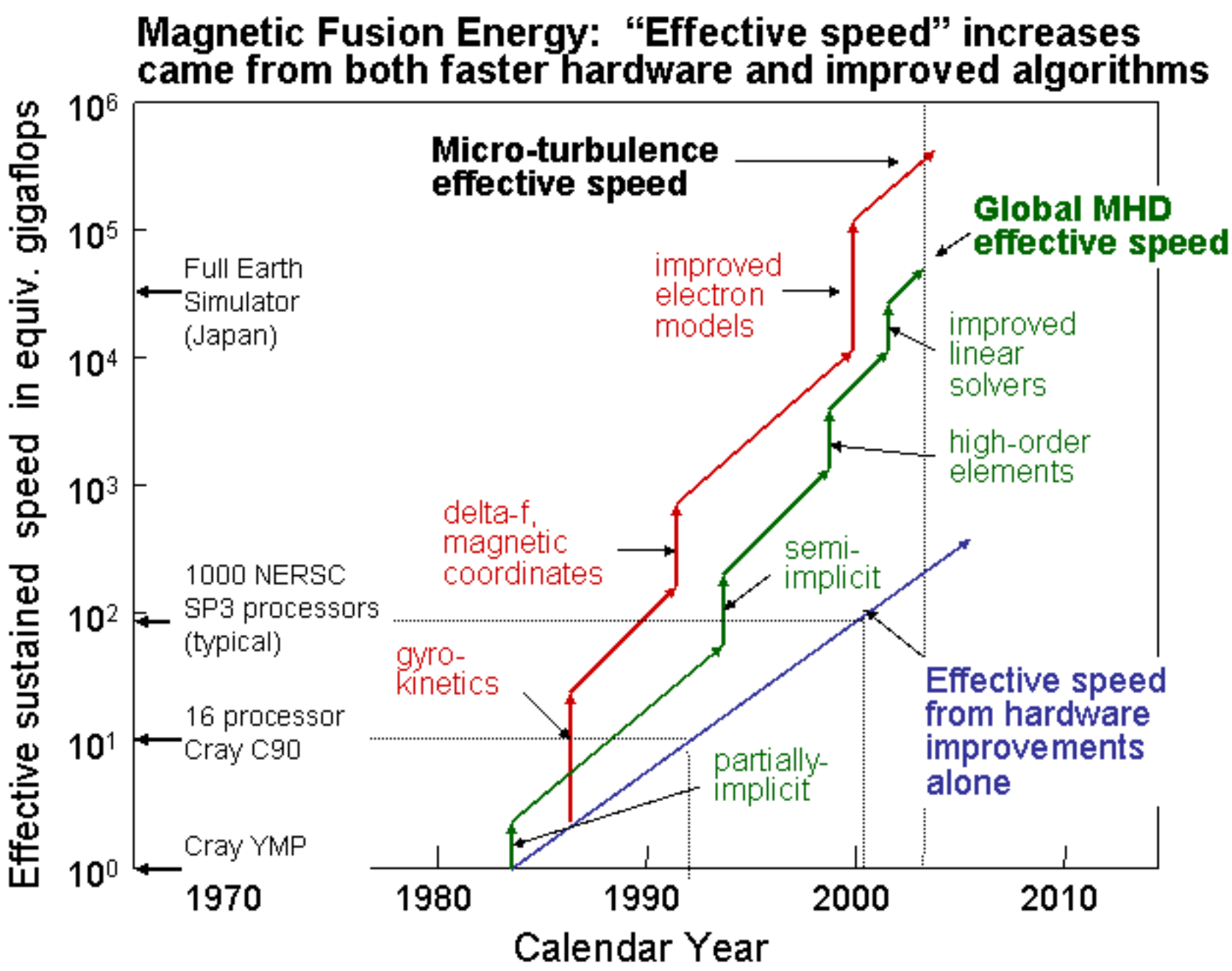
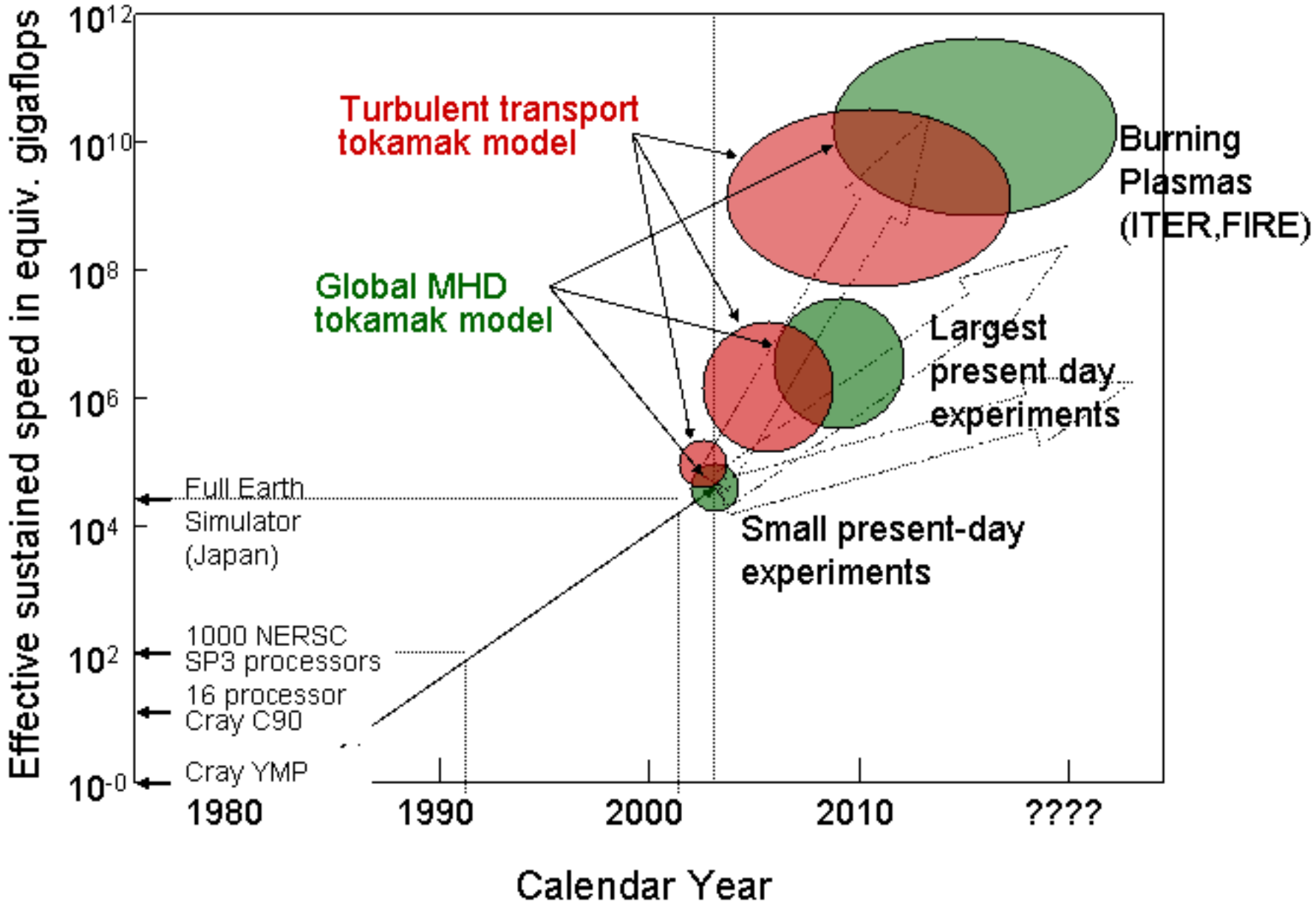

Magnetic Fusion Energy: "Effective speed" increases came from both faster hardware and improved algorithms
Effective sustained speed in equiv. gigaflops
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Full Earth Simulator (Japan)
1000 NERSC SP3 processors (typical)
16 processor Cray C90
Cray YMP
Micro-turbulence effective speed
Global MHD effective speed
improved electron models
improved linear solvers
high-order elements
delta-f, magnetic coordinates
semi-implicit
gyro-kinetics
partially-implicit
Effective speed from hardware improvements alone
1970
1980
1990
2000
2010
Calendar Year


Effective sustained speed in equiv. gigaflops
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{-0}
Turbulent transport tokamak model
Global MHD tokamak model
Burning Plasmas (ITER,FIRE)
Largest present day experiments
Small present-day experiments
Full Earth Simulator (Japan)
1000 NERSC SP3 processors
16 processor Cray C90
Cray YMP
1980
1990
2000
2010
????
Calendar Year

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Office of Management and Budget (OMB)
Long Term Measure for Fusion Energy Science:

- By 2015, demonstrate progress in developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects.

➢ I think we are on track to do this, but need to continue advances in computer hardware and algorithms