Michigan Memorial Phoenix Project Lecture
Department of Nuclear Engineering, University of Michigan
April 20, 2013

Worldwide Progress Toward Realizing Nuclear Fusion Energy

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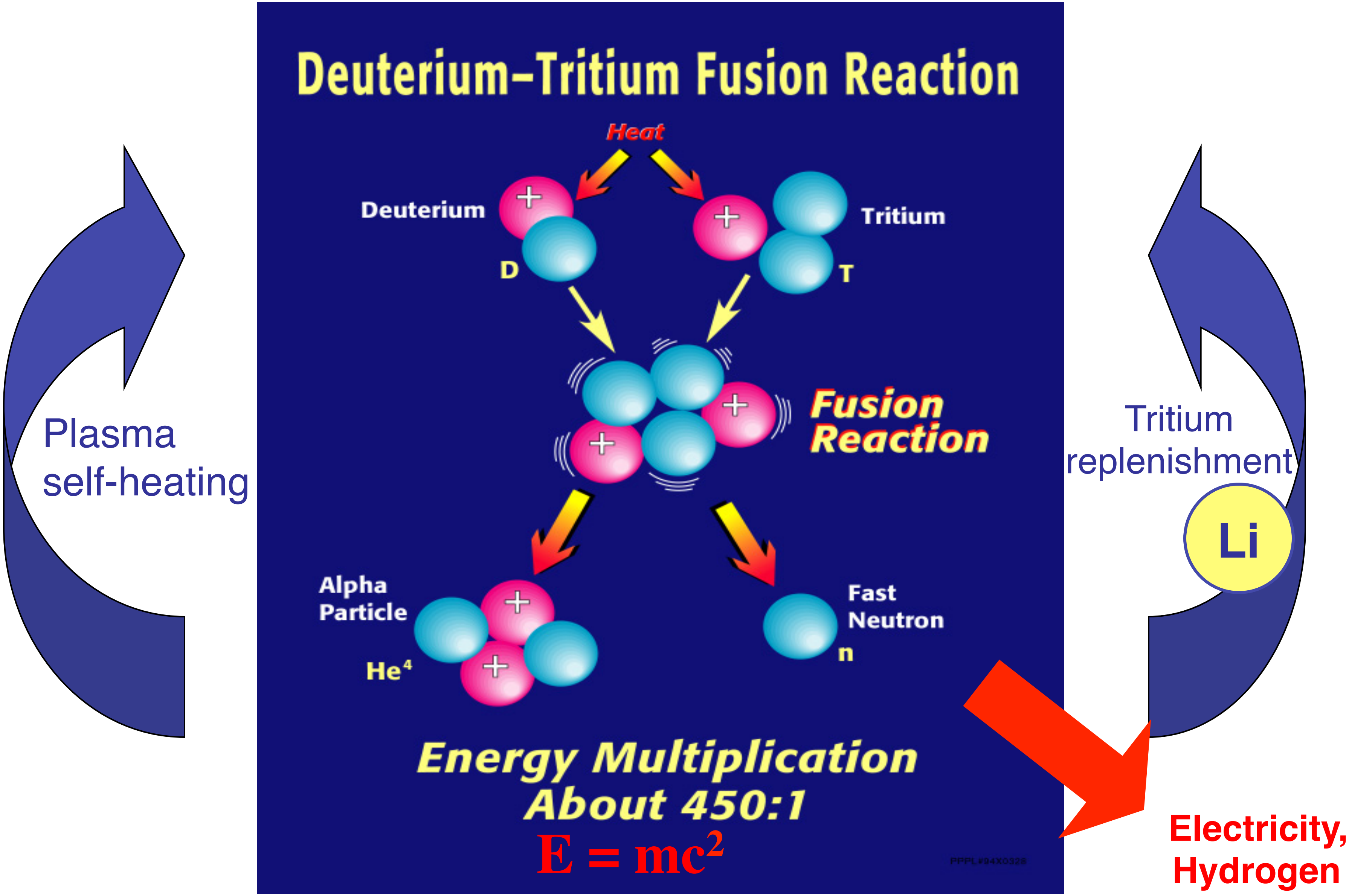
Acknowledge contributions from many scientists as indicated on individual slides to follow

Work supported by the US Department of Energy

OUTLINE

- Introduction to fusion reaction and plasmas
- Environmentally attractive features of fusion
- Magnetic confinement of hot plasma
- Scaling to the ignited plasma regime
- ITER particulars
- Supporting R&D for ITER
- Beyond ITER- plans toward the reactor
- Summary

Basic Fusion Reaction of Interest in the Laboratory



$E = mc^2$

Plasma self-heating

Tritium replenishment

Li

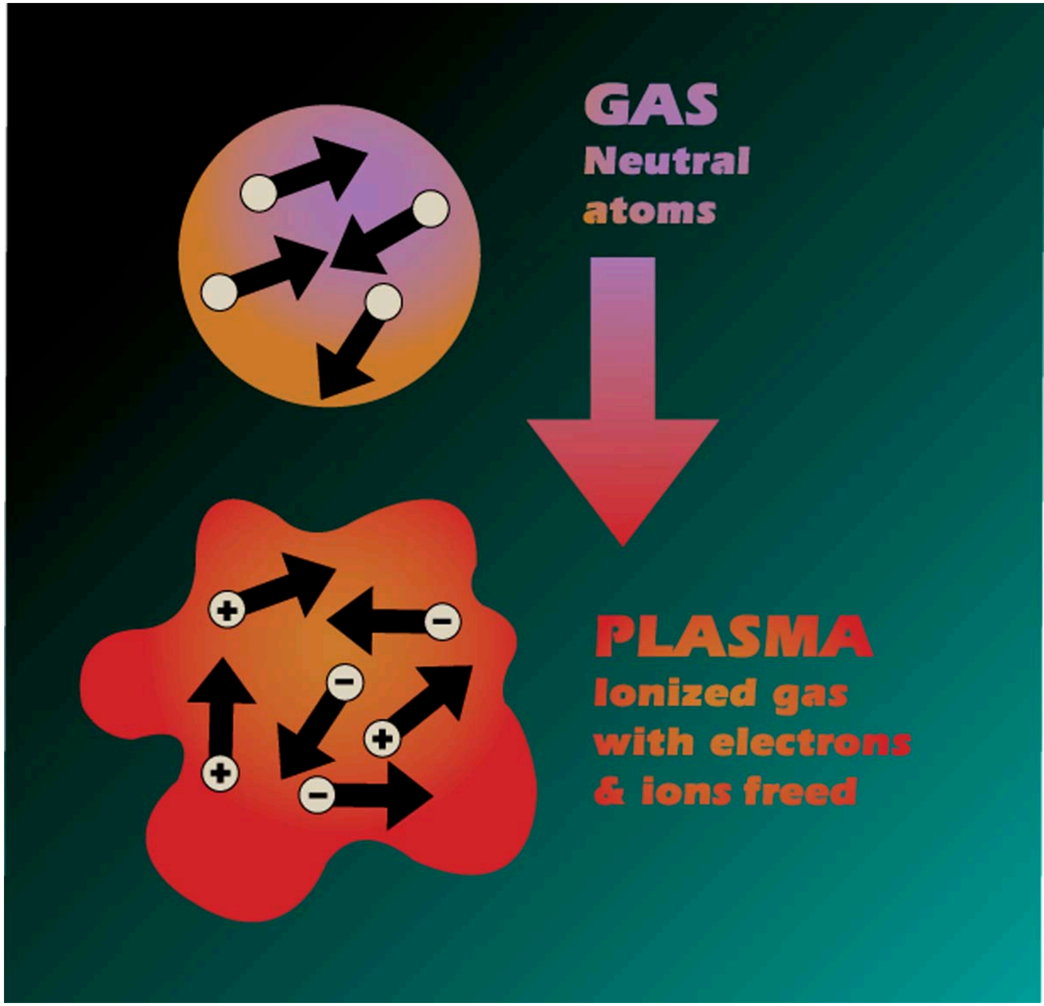
Electricity, Hydrogen

High Temperature Plasma, the "4th State of Matter" is Typically a Fully Ionized Gas

-High temperature plasma is the medium in which controlled fusion reactions can best be achieved

- Plasma responds to electric and magnetic fields, and is typically dominated by collective effects such as instabilities which saturate as turbulent fluctuations of density and EM fields

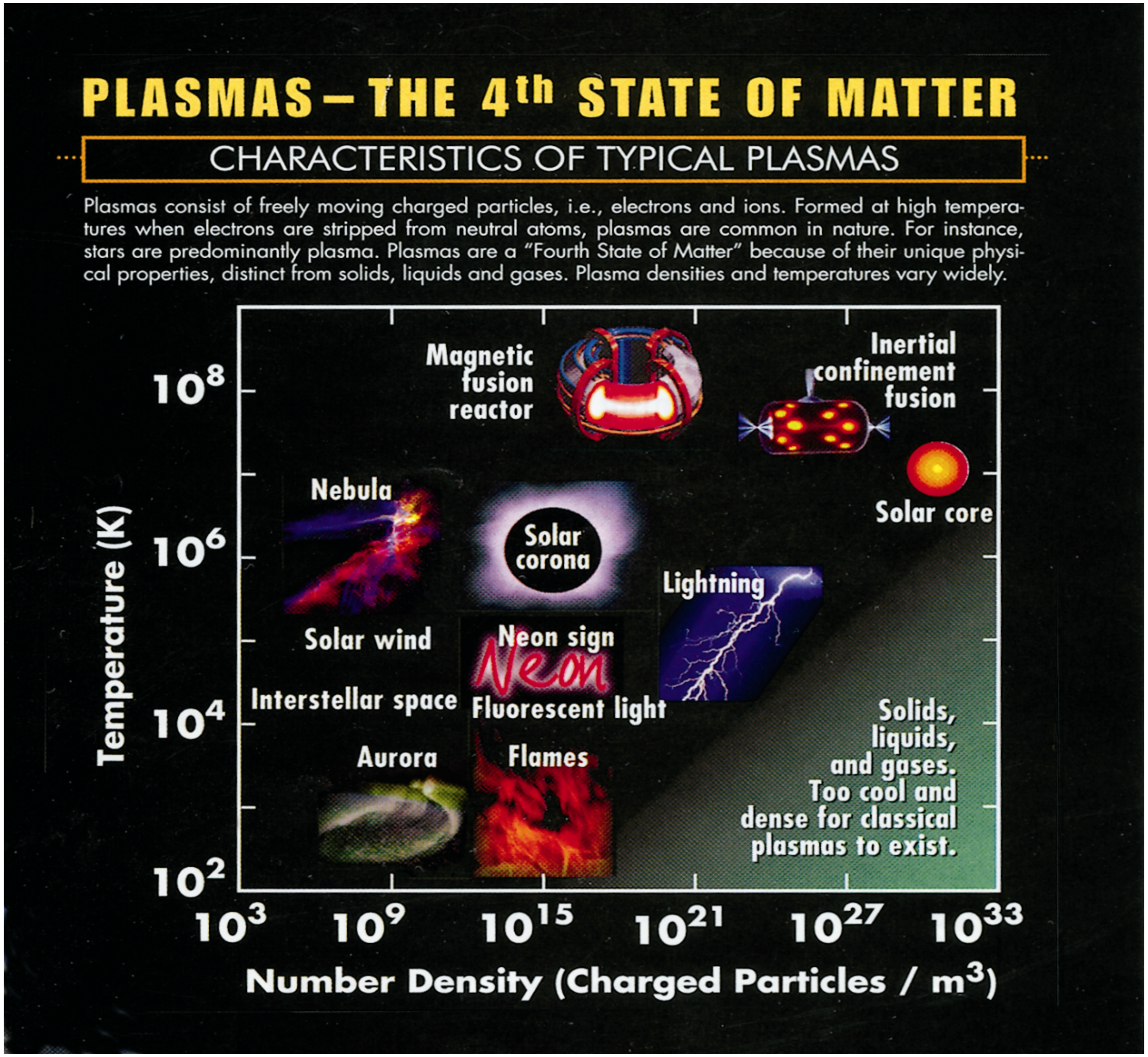
- The driving force underpinning instabilities is gradients in density and temperature as well energetic particles



99% of the Visible Matter in the Universe is in the Plasma State

Discharge tube temperatures:
$T_e = 1 \text{ eV} = 10{,}000 \text{ K}$

Fusion temperatures:
$10 \text{ keV} = 10{,}000 \text{ eV} = 10^8 \text{ K} = 100 \text{ million K}$

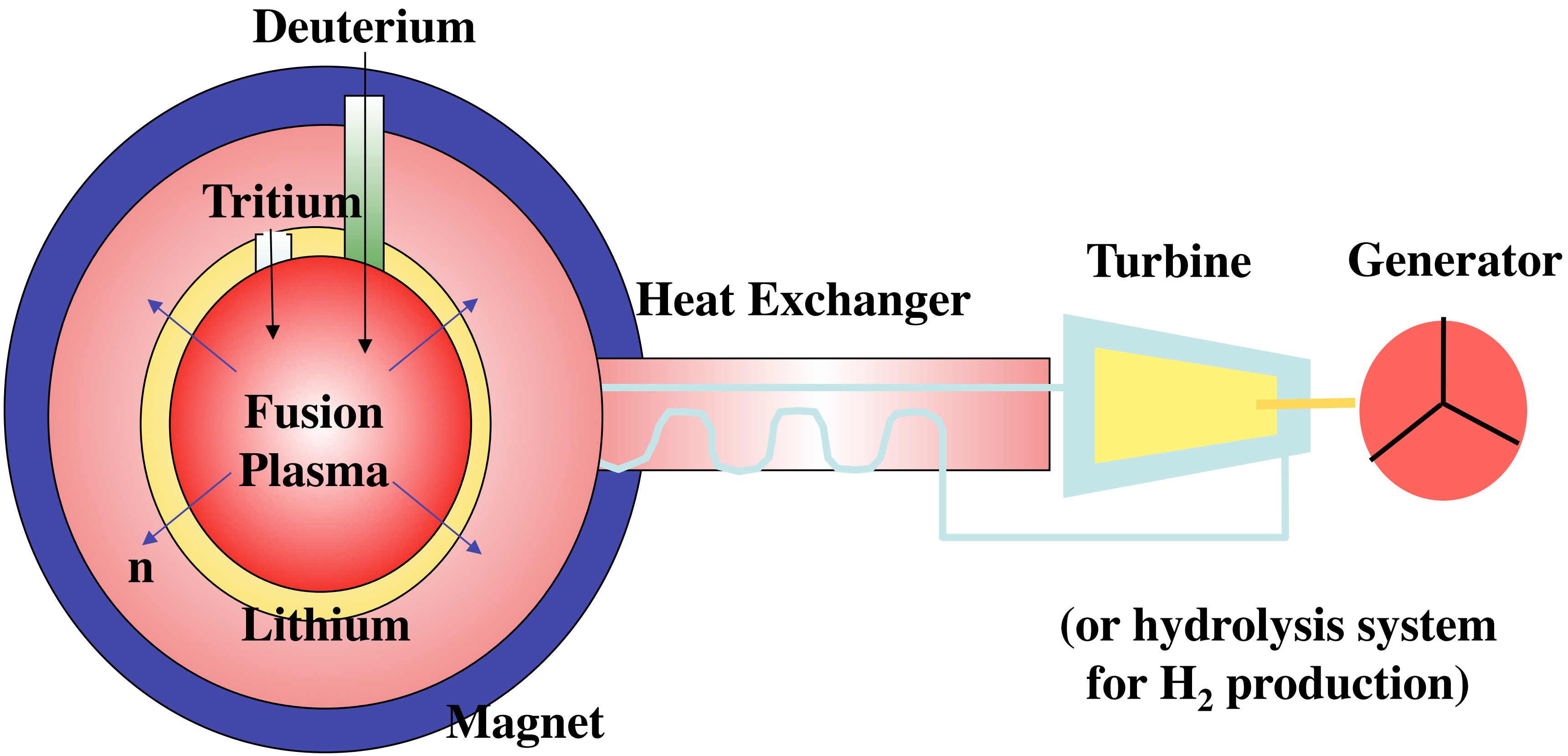


PLASMAS – THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.

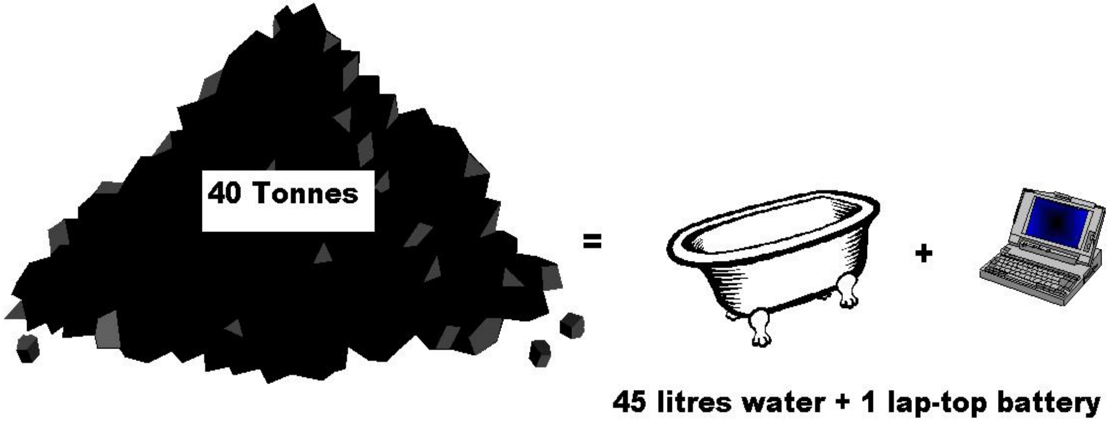
Fusion Power System Concept



(or hydrolysis system for H_2 production)

PSFC Fusion Fuel is Abundant in Nature

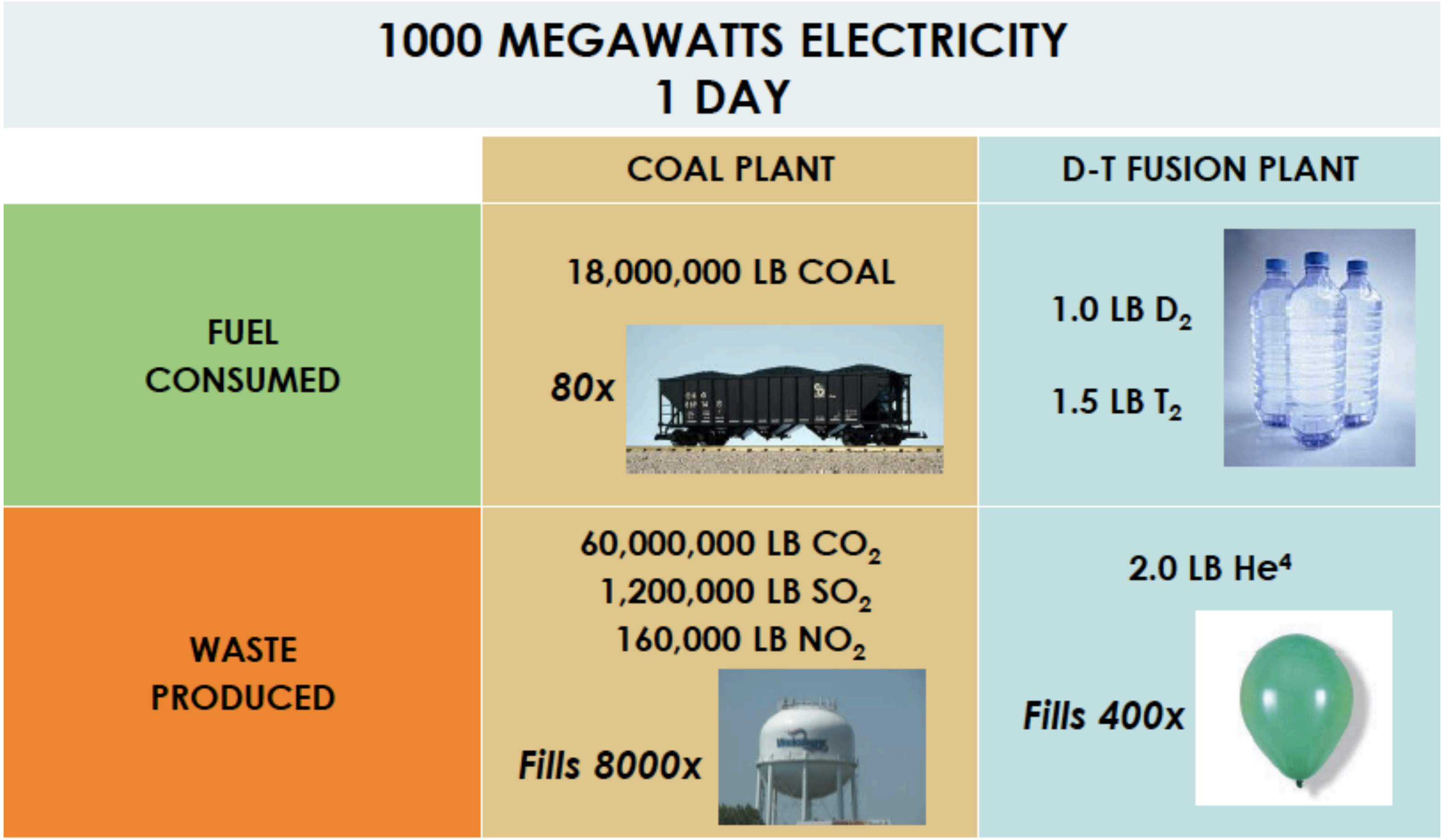
- Raw fuel of a fusion reactor is water and lithium*



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

- ⇨ deuterium/hydrogen = 1/6700
- ⇨ tritium from: neutron (from fusion) + lithium ⇒ tritium + helium

Enormous Amount of Energy from Fusion Fuel



1000 MEGAWATTS ELECTRICITY
1 DAY

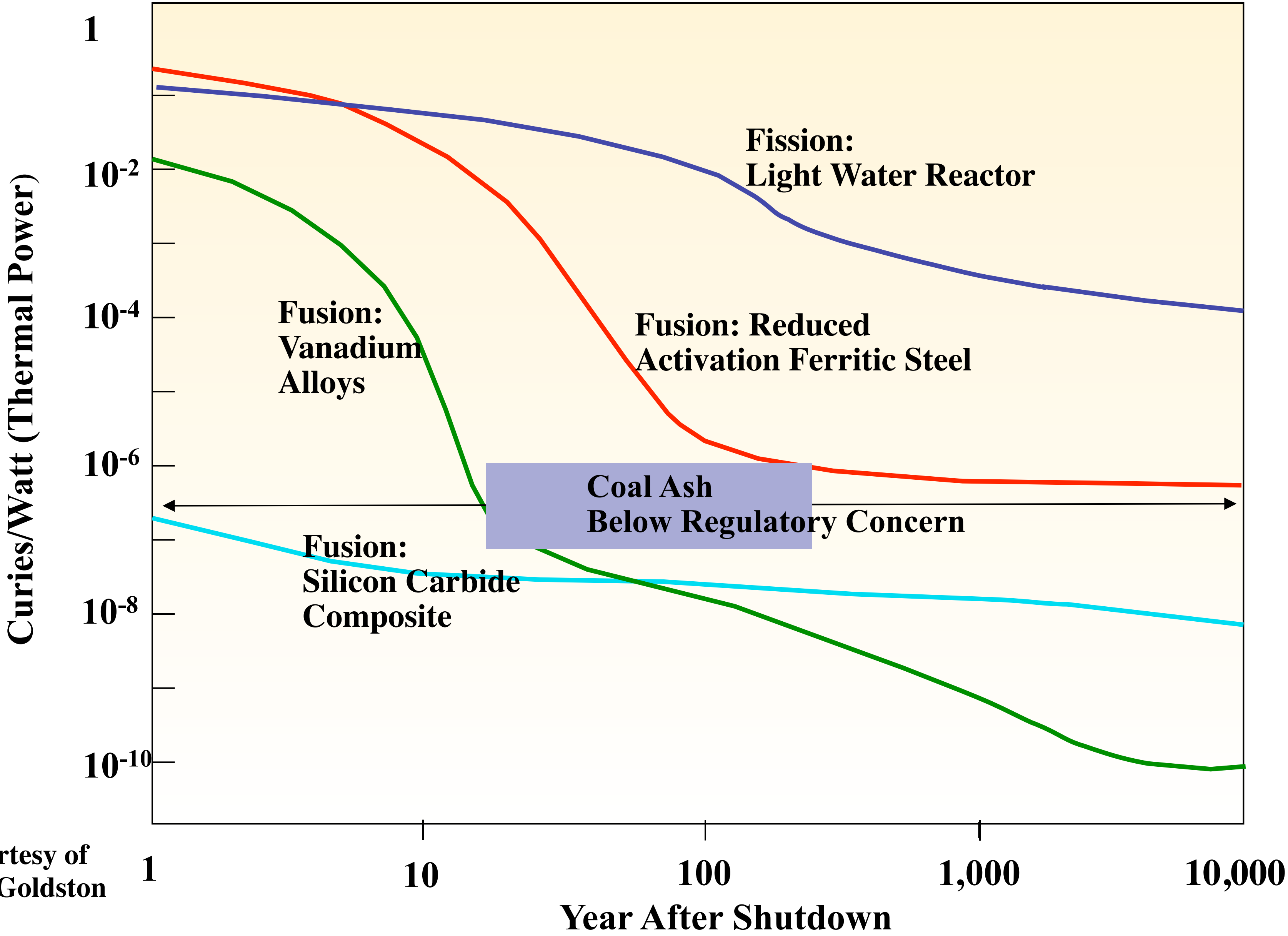
	COAL PLANT	D-T FUSION PLANT
FUEL CONSUMED	18,000,000 LB COAL 80x	1.0 LB D_2 1.5 LB T_2
WASTE PRODUCED	60,000,000 LB CO_2 1,200,000 LB SO_2 160,000 LB NO_2 *Fills 8000x*	2.0 LB He^4 *Fills 400x*

Courtesy of M. Wade, General Atomics

Fusion Is an Attractive Energy Source

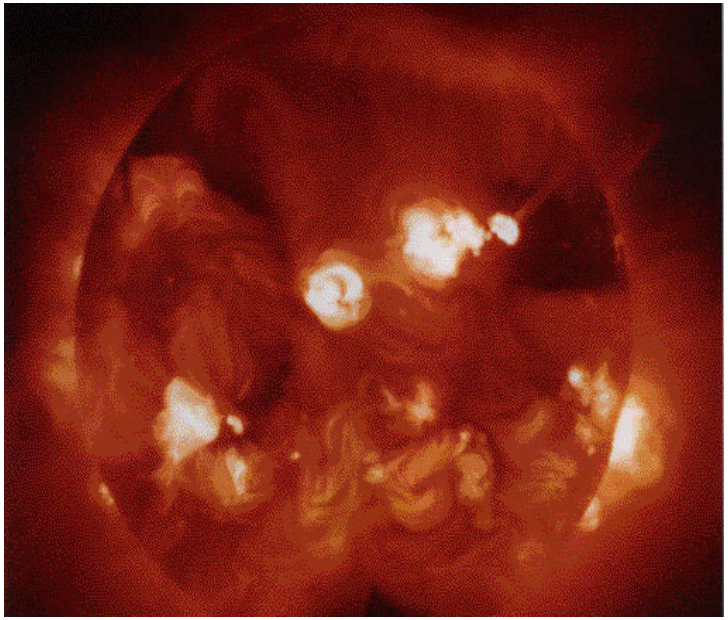
- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental advantages
  - No carbon emissions, short-lived radioactivity
- Can't blow up, resistant to terrorist attack
  - Less than 5 minutes of fuel in the chamber
- Low risk of nuclear materials proliferation
  - No fissile or fertile materials required
- Compact relative to solar, wind and biomass
  - Modest land usage
- Not subject to short term or regional weather variation
  - No large-scale energy storage nor long-distance transmission
- Cost of electric power estimated similar to fission

Comparison of Fission and Fusion Radioactivity After Shutdown

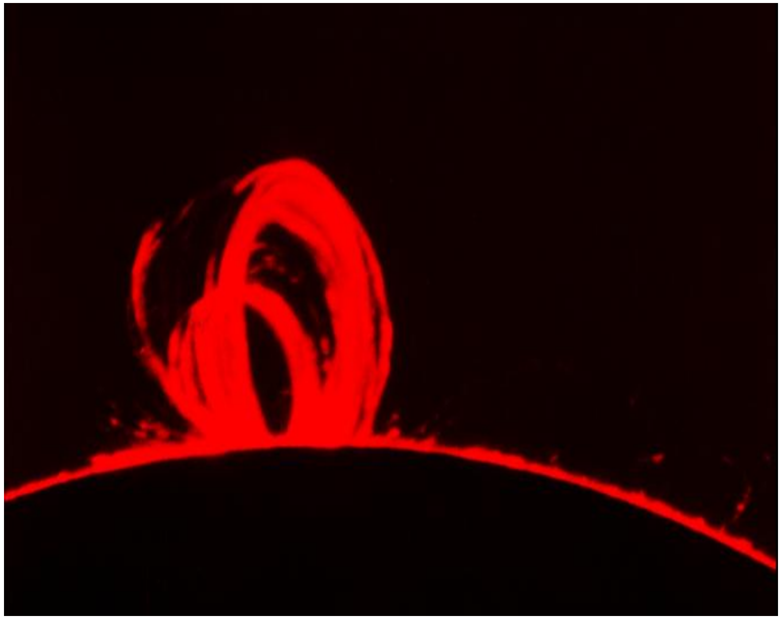


Courtesy of
R J Goldston

The Sun Confines Hot Plasma: Can We Do It in the Laboratory ?



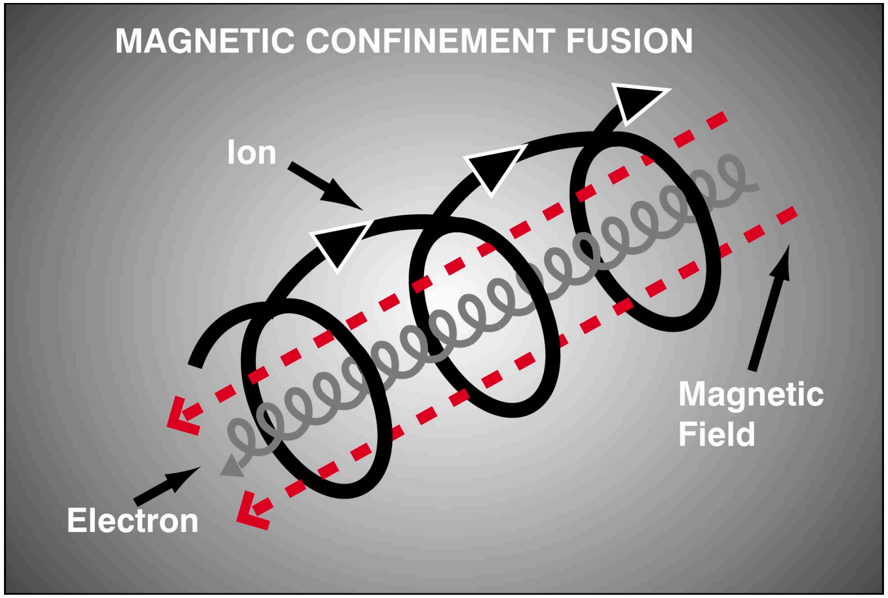
Gravitational Confinement



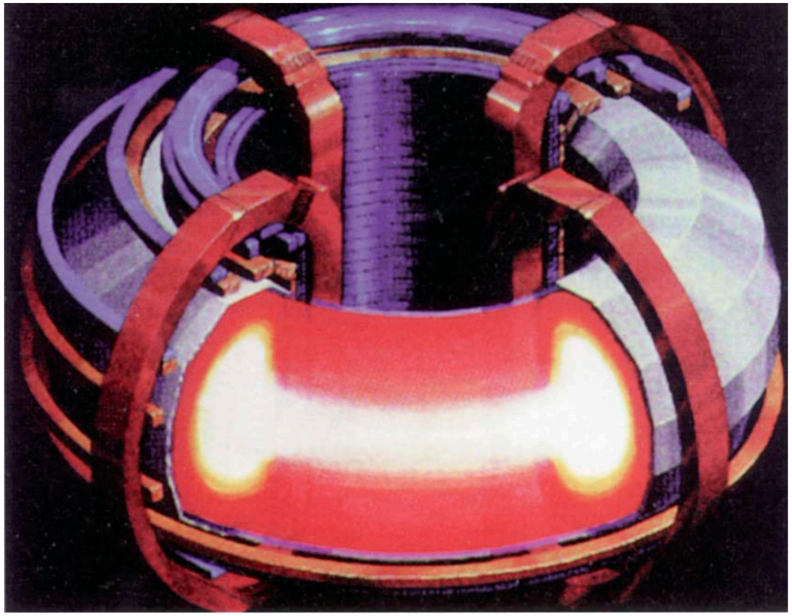
also Magnetic Confinement

- In Inertial Fusion Energy intense laser beams rapidly compress and heat fuel pellets which burn while their inertia holds them together (National Ignition Facility, LLNL)
- Toroidal magnetic traps in the laboratory can confine plasma which can then be heated with energetic ion beams or intense RF (microwave) power

Magnetic Confinement



Charged particles have helical orbits in a magnetic field; they describe circular orbits perpendicular to the field with gyro-radius $r_l = v_\perp/\Omega$, where $\Omega = qB/mc$

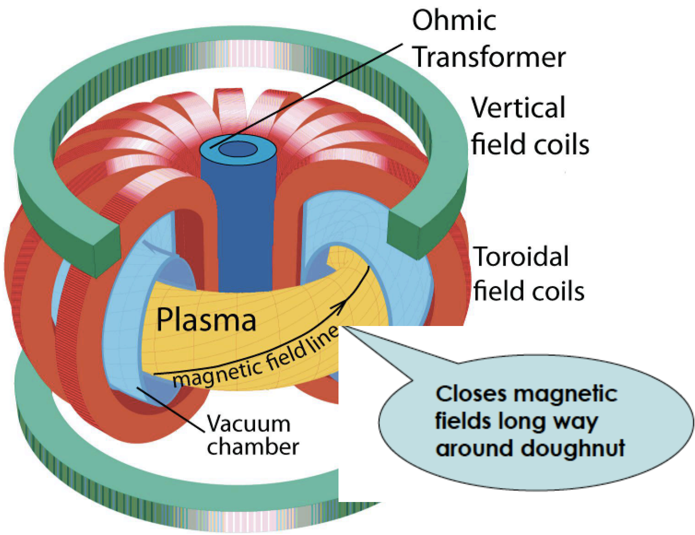


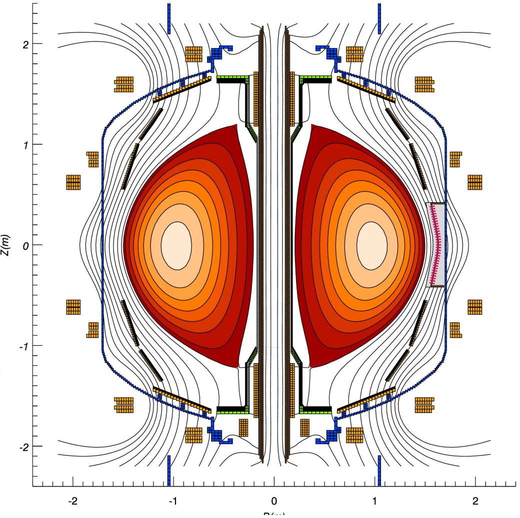
"TOKAMAK"

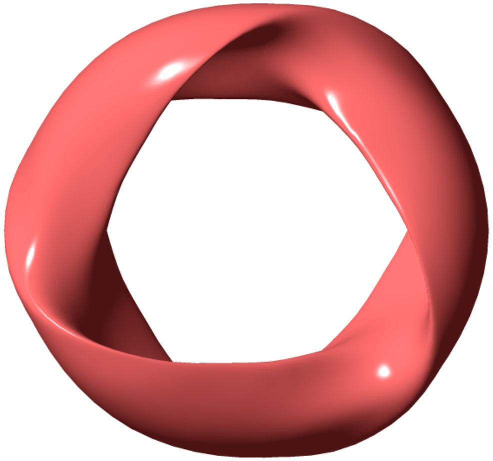
(Russian abbreviation for "toroidal chamber" with magnetic fields); includes an induced toroidal plasma current to form, heat and confine the plasma;

$B_T = 5$ T; $T = 10$ keV; $n = 10^{20}$ m^{-3};

Magnetic Plasma Confinement Concepts







Advanced Tokamak

Driven steady-state by ion beams, RF waves and pressure driven plasma currents; Requires superconducting magnets; Disruptions and MHD stability at the edge remain issues

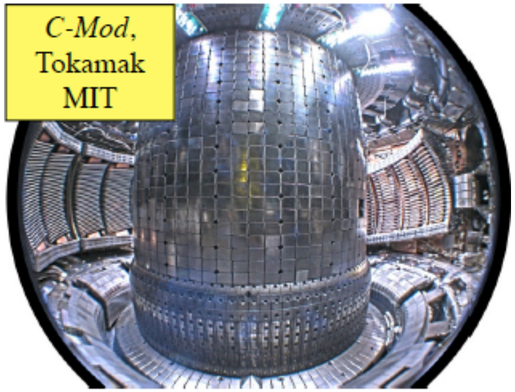
Spherical Torus

High fusion power density at low magnetic fields (copper magnets, high circulating power) ; extrapolation to reactor scale problematic; OK for component test facility

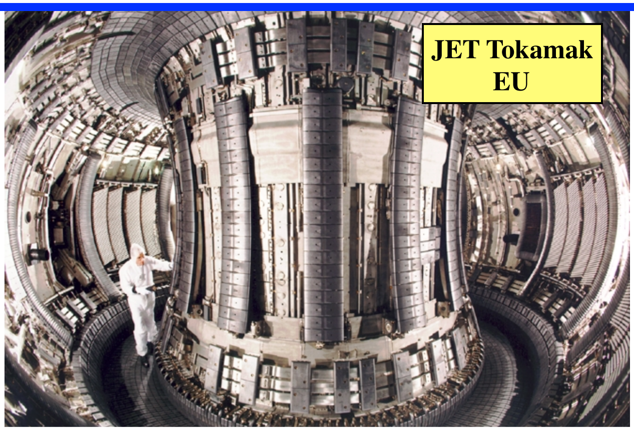
Compact Stellarator

Passive stability and steady-state operation; complexity of fabrication of superconducting magnets; Transport at reactor scale parameters remains an issue

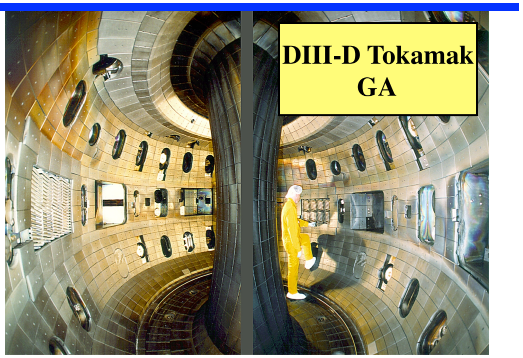
A Wide Range of Toroidal Magnetic Configurations is Being Studied Worldwide



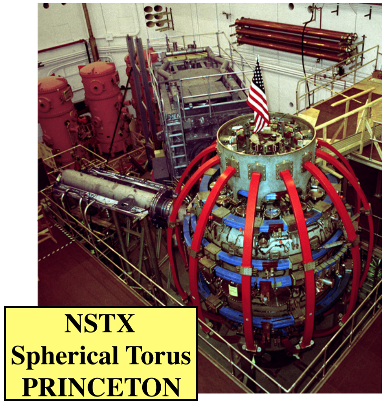
C-Mod,
Tokamak
MIT



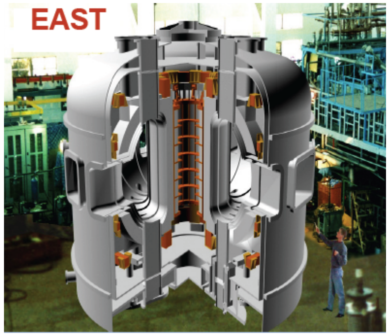
JET Tokamak
EU



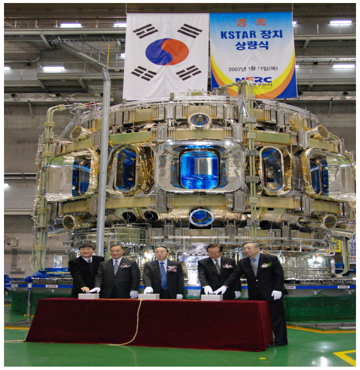
DIII-D Tokamak
GA



NSTX
Spherical Torus
PRINCETON

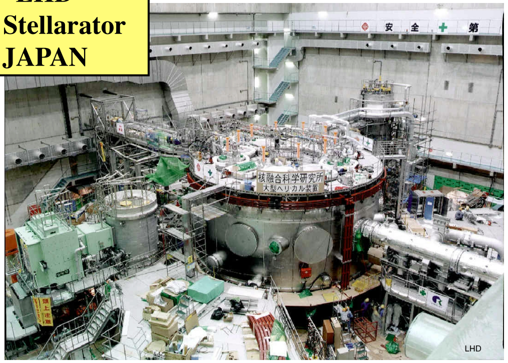


EAST
(SC Tokamak)
CHINA



KSTAR
SC Tokamak
KOREA

SC Tokamak
JAPAN



LHD
SC Stellarator
JAPAN

WENDELSTEIN
SC Stellarator –
EU

New Superconducting Tokamaks in Asia

EAST (China)

- R = 1.7m, a = 0.4m, Bt = 3.5T, Ip = 1MA.
- First plasma on September, 2006.
- First full superconducting tokamak.

SST-1 (India)

- R = 1.1m, a = 0.2m, Bt = 3.0T, Ip = 0.22MA.
- Fabrication and assembly completed.
- SC magnets cooled down for charging tests.

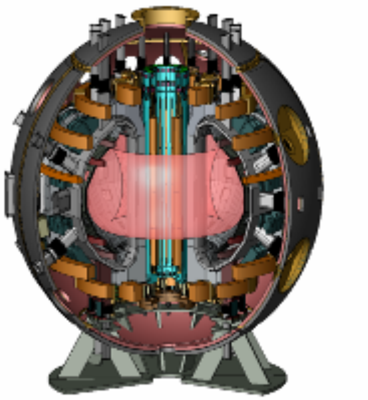
KSTAR (Korea)

- R = 1.8m, a = 0.5m, Bt = 3.5T, Ip = 2MA.
- Assembly will be finished and commissioning will be started in middle of 2007.

JT-60SA (Japan/EU)

- R = 3.06m, a = 1.15m, Bt = 2.7T, Ip = 5.5MA.
- Conceptual design is in progress. Fabrication to start in 2007.

KSTAR

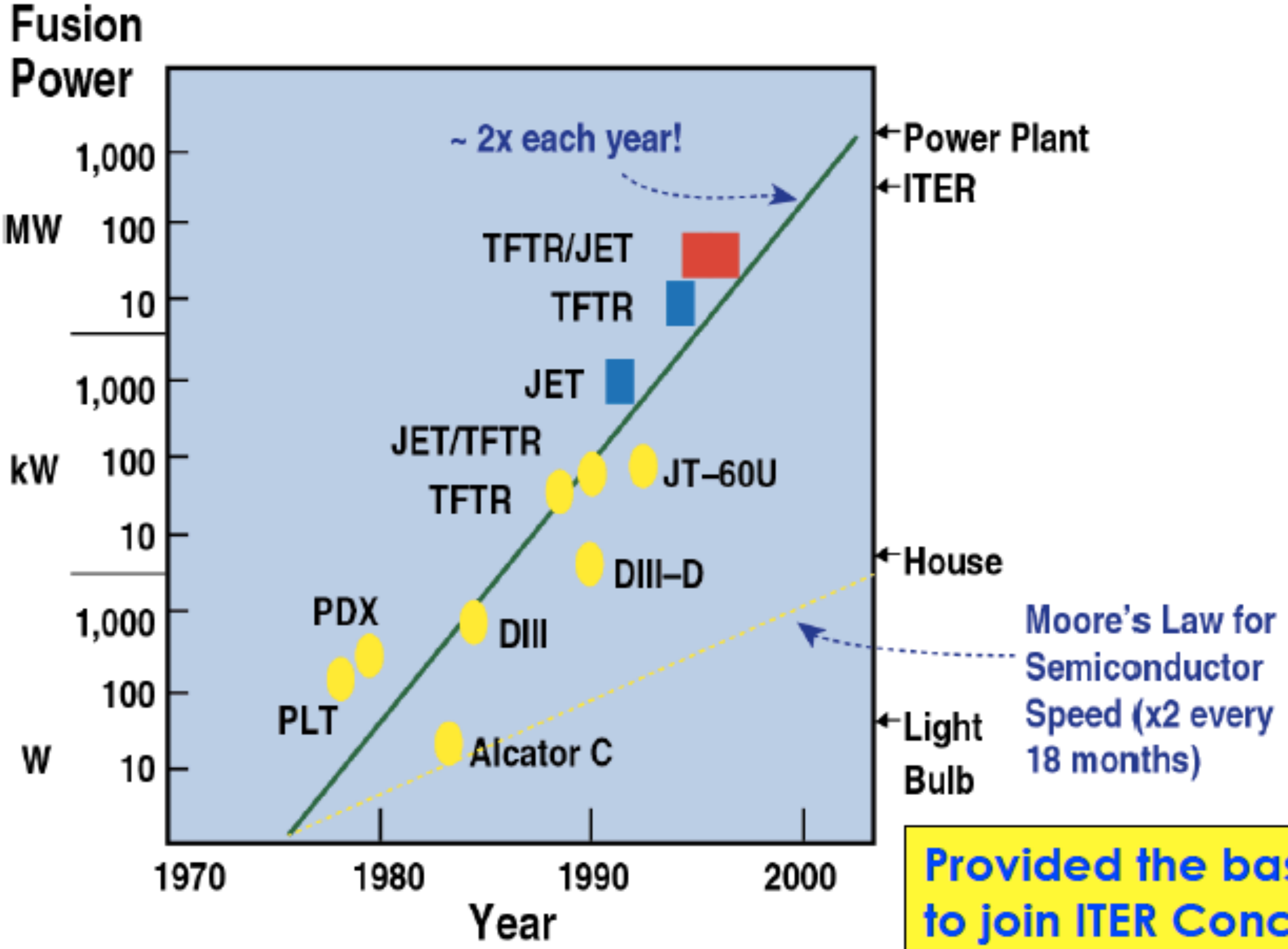


JT-60SA

Both DN and SN configurations are possible in all four tokamaks

Courtesy J. Jacquinot

Fusion Power Has Increased Rapidly as Increasingly Larger Machines Were Built



Moore's Law for Semiconductor Speed (x2 every 18 months)

Provided the basis for U.S. to join ITER Conceptual Design in 1988

The fraction of alpha particles in a fusing plasma is a measure of Fusion Energy Gain

$$D^2 + {}_1T^3 \rightarrow \underbrace{\underset{\underset{(3.5\ \text{MeV})}{\uparrow}}{{}_2He^4} + \underset{\underset{(14.1\ \text{MeV})}{\uparrow}}{{}_0n^1}}$$

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

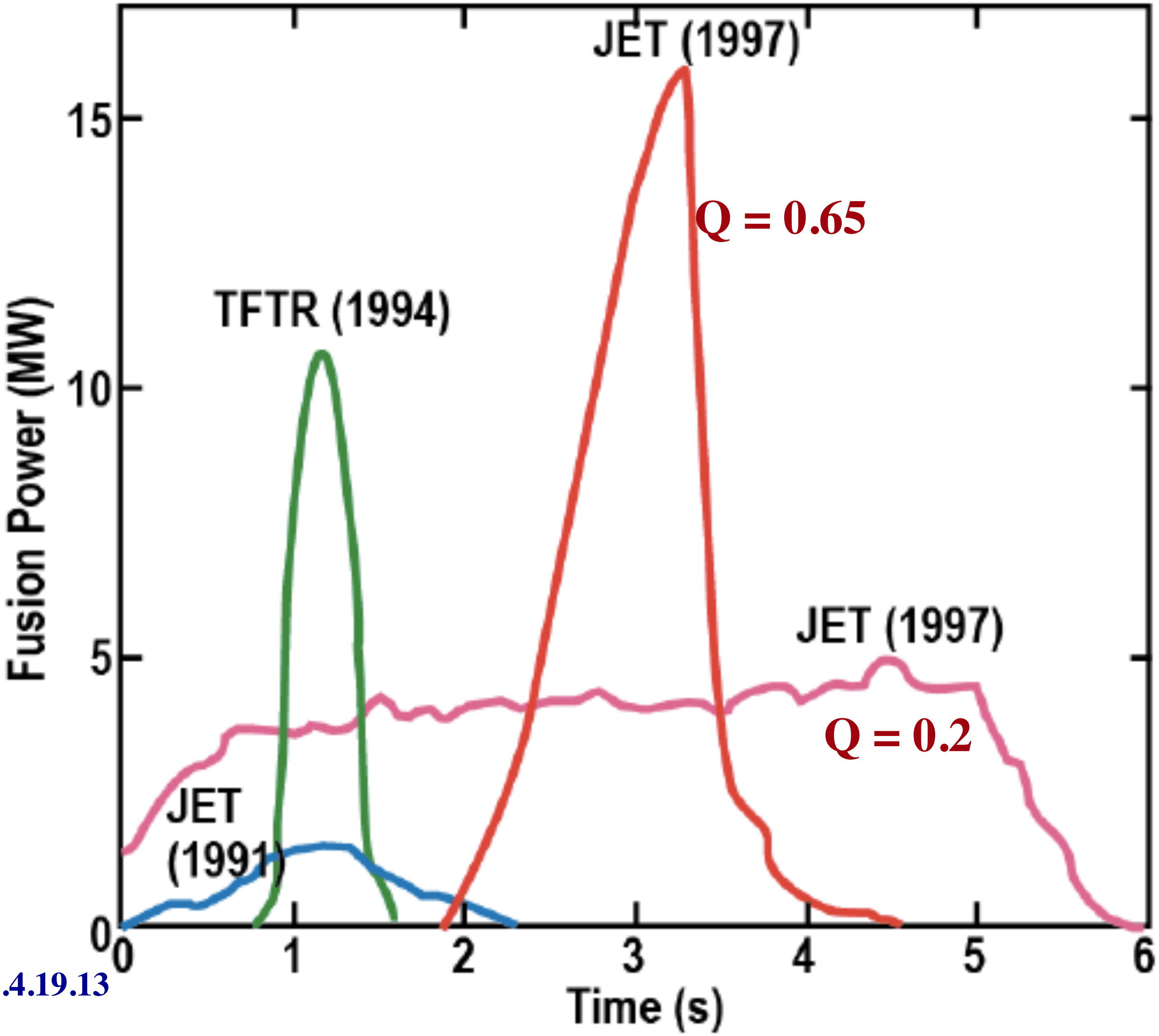
Fusion energy Gain: $Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5\,P_\alpha}{P_{heat}}$

Alpha heating fraction: $f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{heat}} = \frac{Q}{Q+5}$

Breakeven	Gain =1 (~now)	$f_\alpha = 17\%$
Burning	Gain=5	$f_\alpha = 50\%$
Plasma	Gain=10 (ITER)	$f_\alpha = 66\%$
Regime ↓	Gain=20(reactor)	$f_\alpha = 80\%$
	Gain=∞(ignition)	$f_\alpha = 100\%$

Courtesy of A. Hubbard

Significant Fusion Power Was Produced in D-T Plasmas in the 1990s



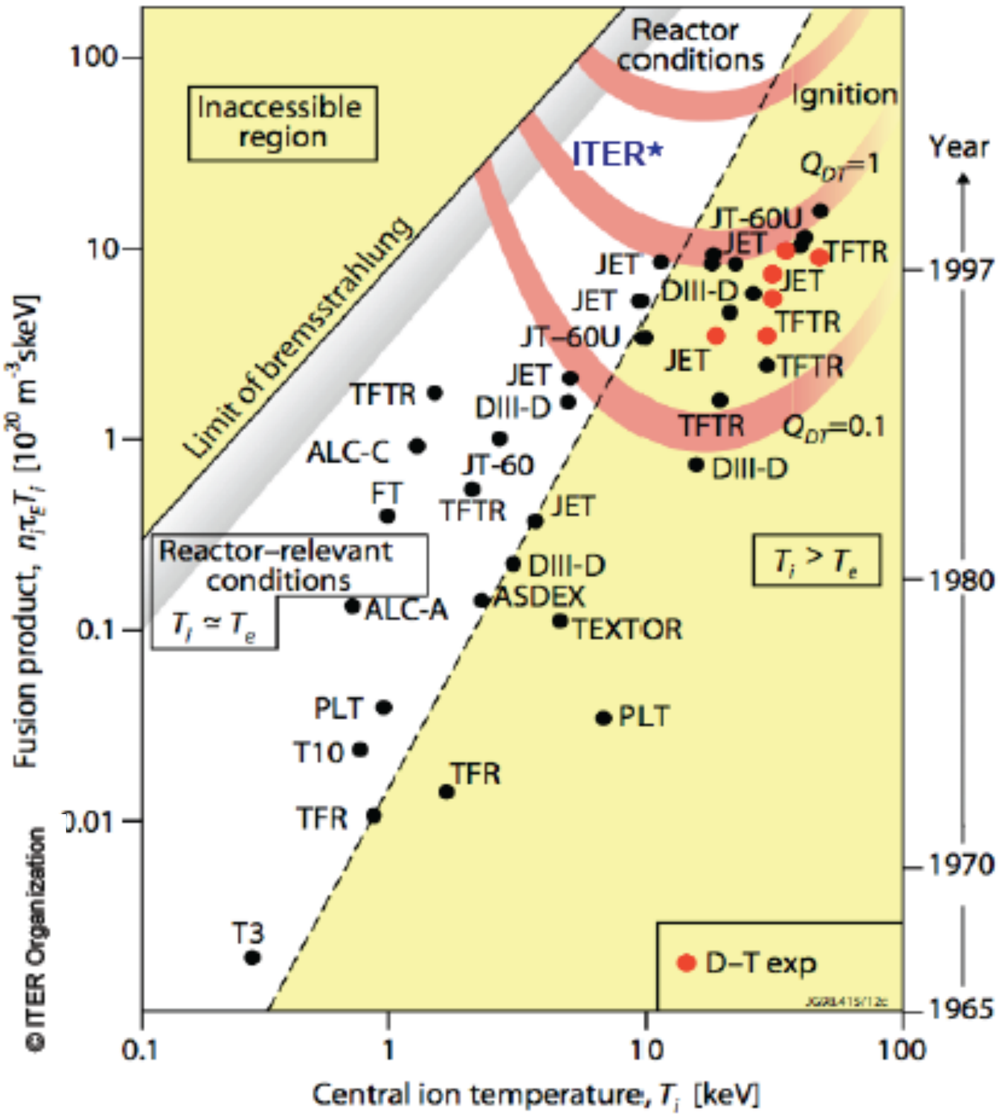
Fusion Performance Increased Rapidly with Machine Size and Heating Power

$$Gain = Q = \frac{Fusion\ Power}{Input\ Power} \sim n_i T_i \tau_E$$

Progress has been determined by scientific advances and larger, more powerful facilities

For D-T Ignition, require

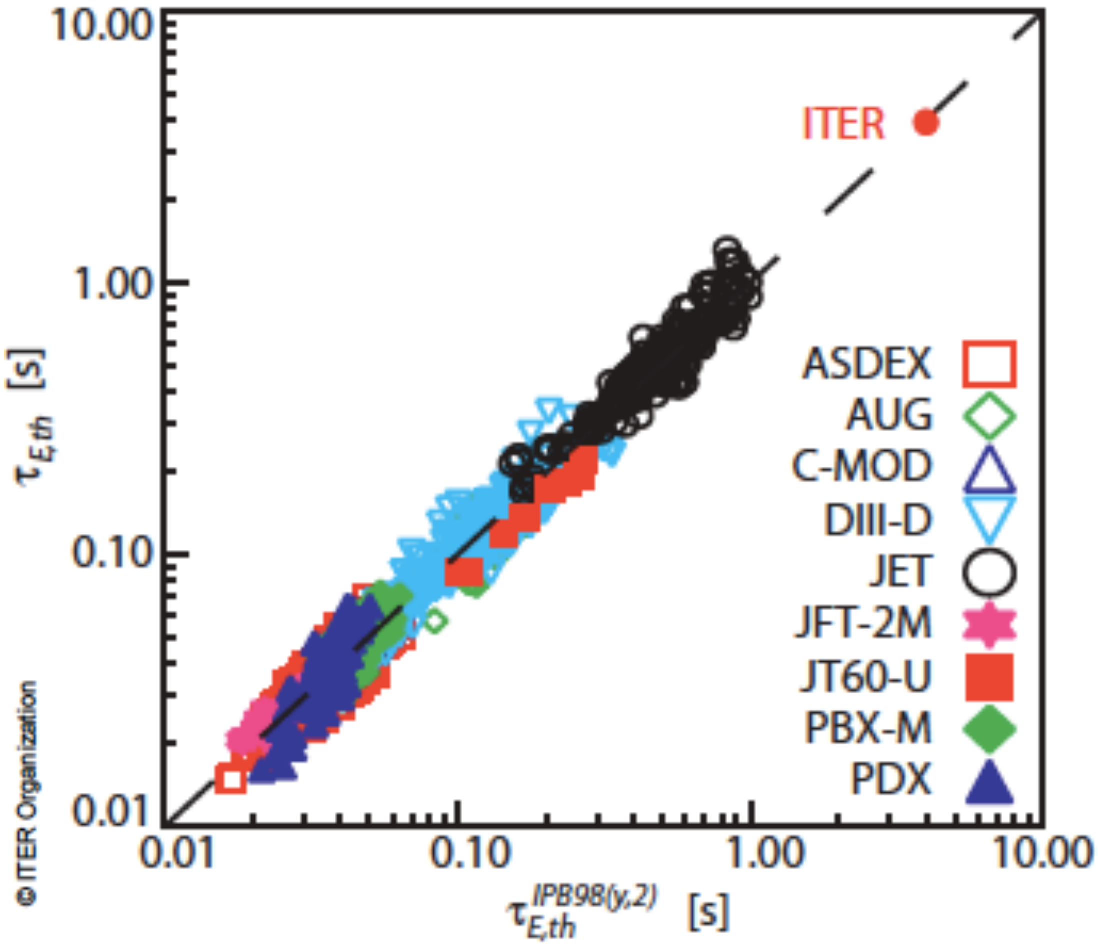
$N_i \tau_E T_i = 4 \times 10^{21} m^{-3}$ sec keV



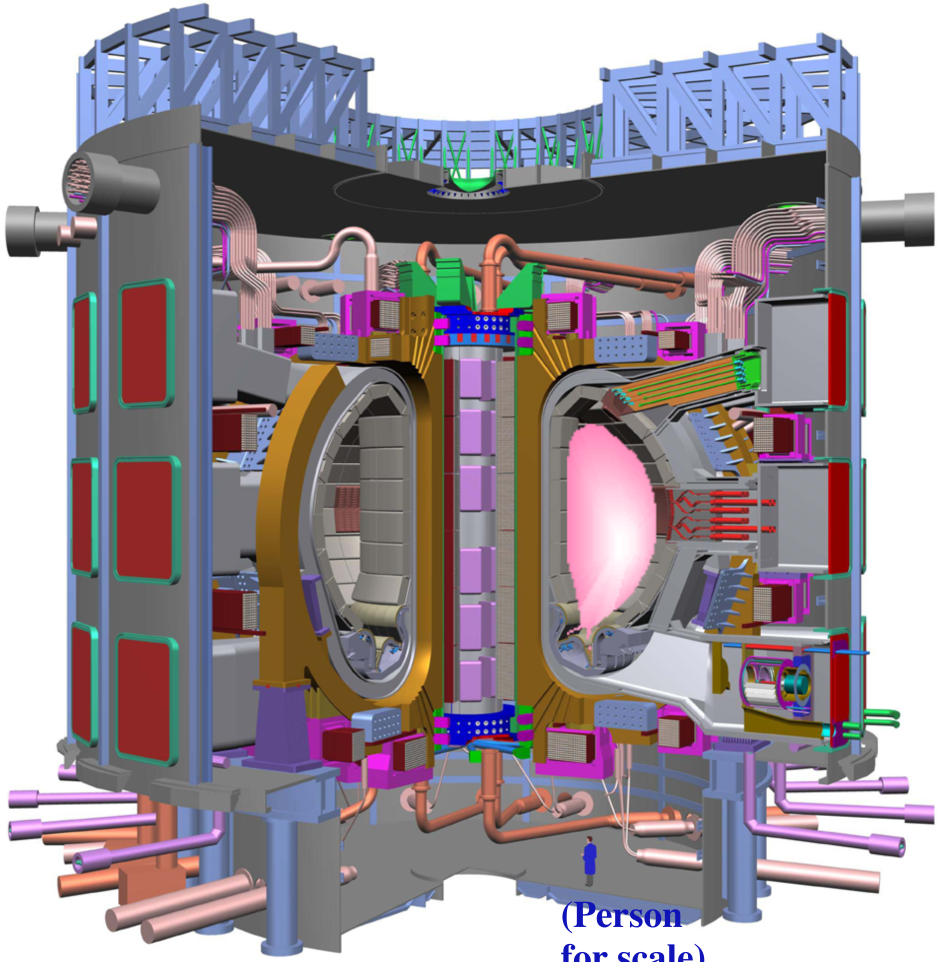
Large Database for Confinement Time Provides Optimism for ITER's Success

- **Nevertheless physics uncertainties remain: Much of the high performance data was obtained in beam heated plasmas where ion transport dominates**

- **In ITER (and Reactor) scale devices electrons and ions will be equilibrated and electron transport will dominate; its scaling is not as well understood as that of ions**



ITER’s Goal is to Demonstrate the Scientific Feasibility of High Gain (≥10) Fusion Burn



Science Benefits:

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

Technology Benefits:

Fusion-relevant technologies.

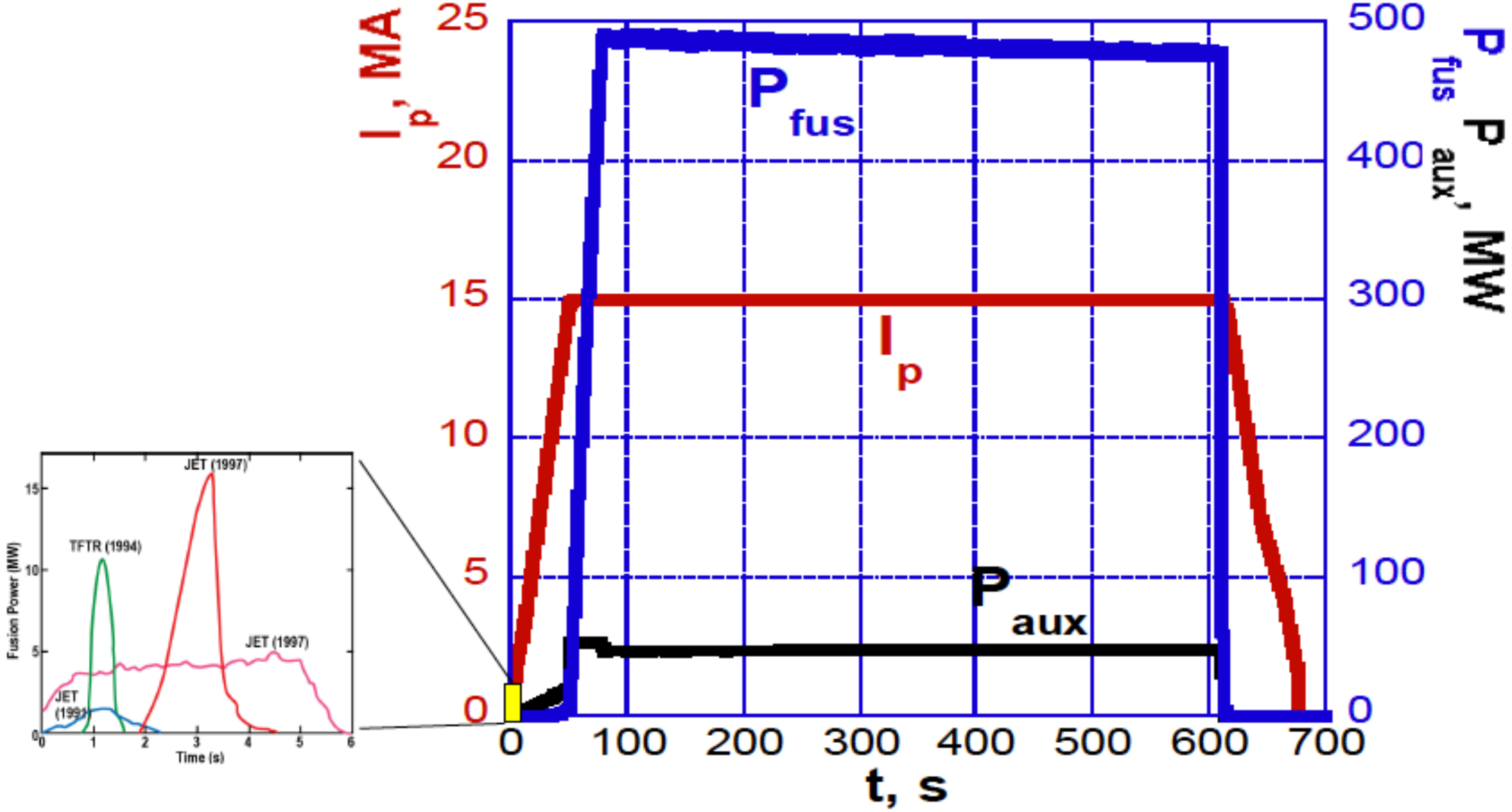
High duty-factor operation.

P_{fusion}	500 MW
P_{heat}	73 MW
Gain	Q ≥ 10
Pulse Length	300 - 3000s
Major Radius	6.2m
Minor Radius	2.0m
Plasma Current	15MA
Toroidal Field	5.3T
Heating/Current Drive Power	73MW
Cost ($2000)	$4.6B

US contribution: 1/9 of total cost; (EU: 45%)

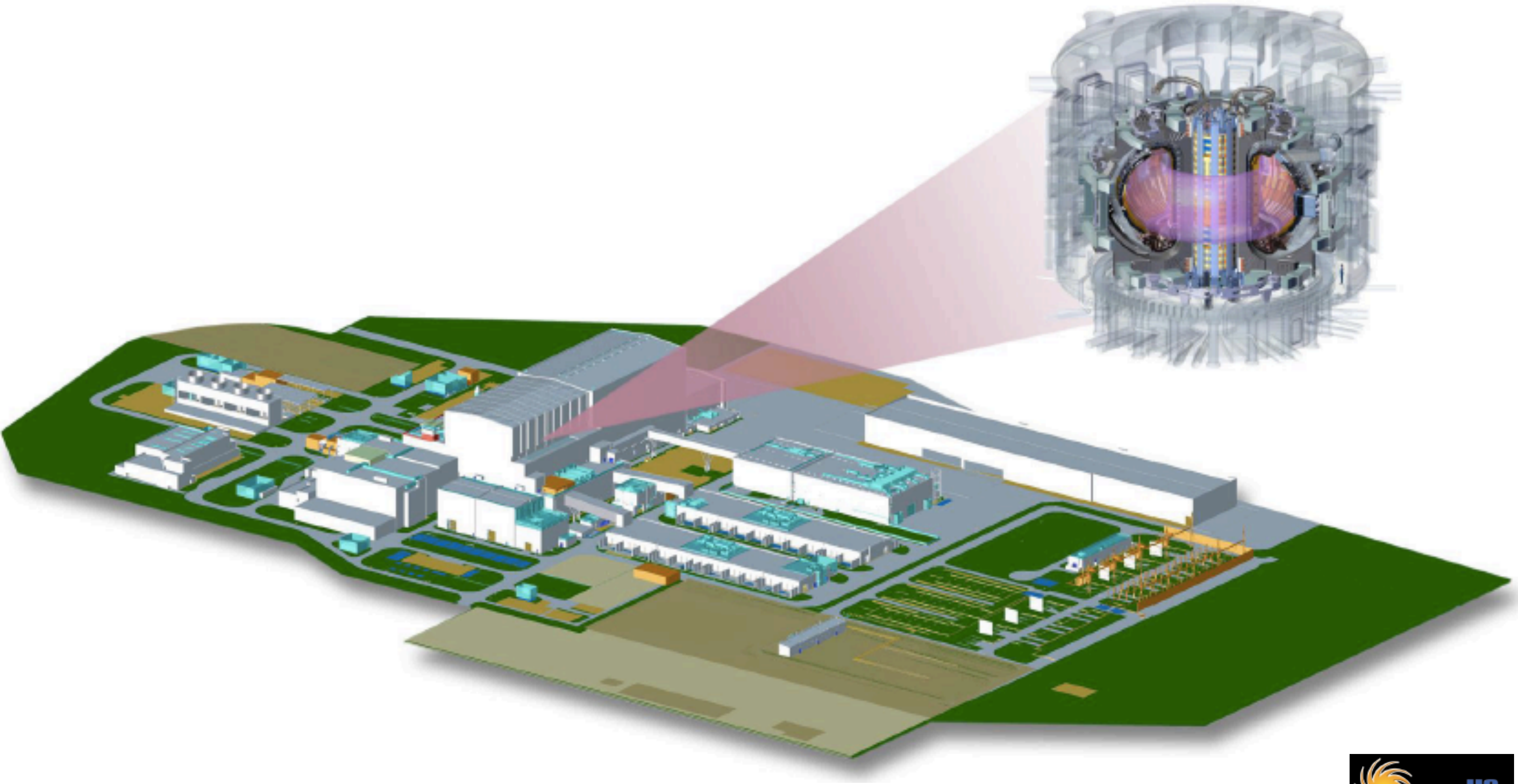
ITER will Demonstrate Long Pulse Burning Plasma Regimes and Dominant Alpha Particle Heating

ITER Simulation using models that accurately simulate today's devices

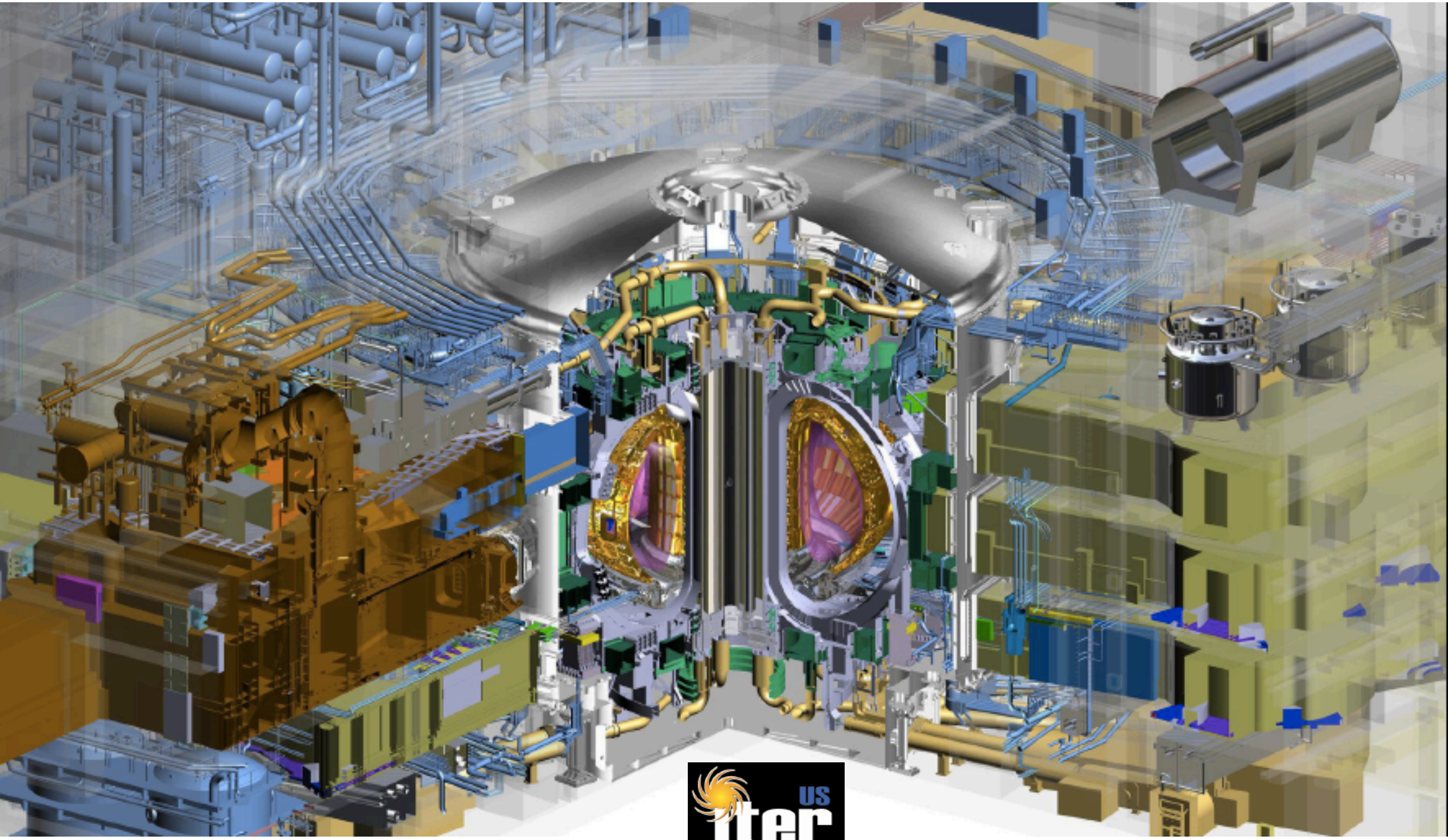


M. R. Wade, General Atomics, at GA Tech Fusion Symposium, Nov 2012

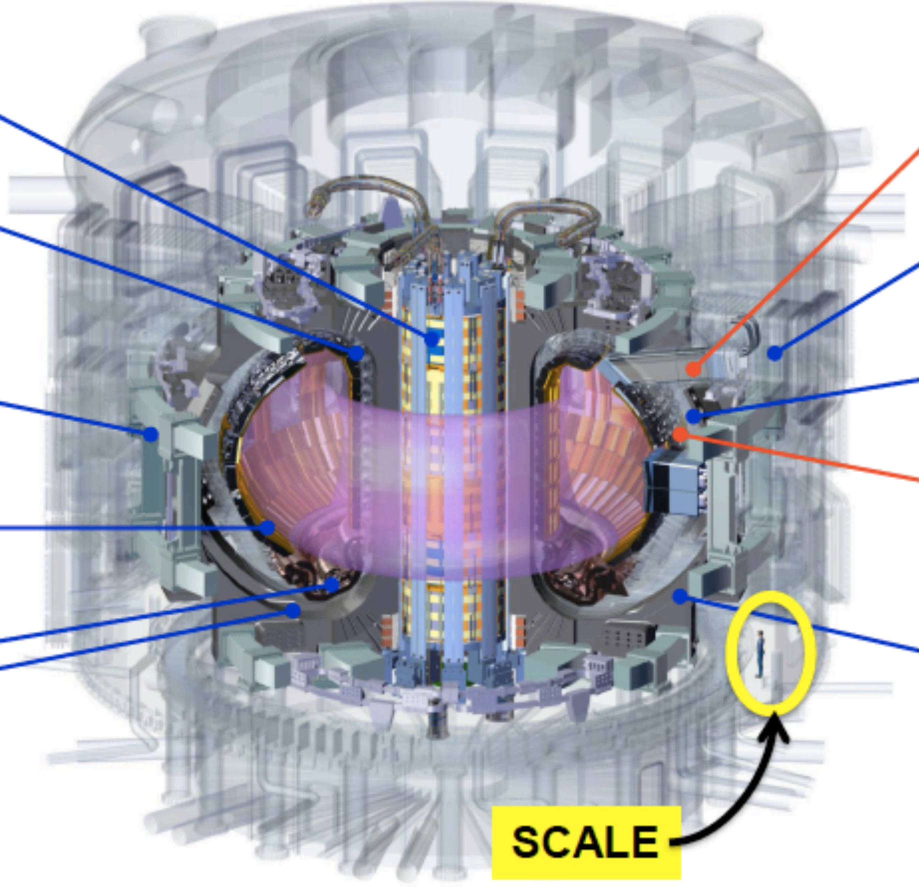
ITER is the Largest Scientific Enterprise Ever Undertaken



The Tokamak Core



US ITER Scope



ORNL
100% Central Solenoid Windings

ORNL
8% of Toroidal Field Conductor

ORNL
100% Pellet Injector
100% Disruption Mitigation

ORNL
Blanket/Shield
(design only)

ORNL
100% Tokamak Cooling Water System

PPPL
75% Steady State Electrical Network

PPPL
14% of Port-based Diagnostics

ORNL
88% Ion Cyclotron Transmission Lines

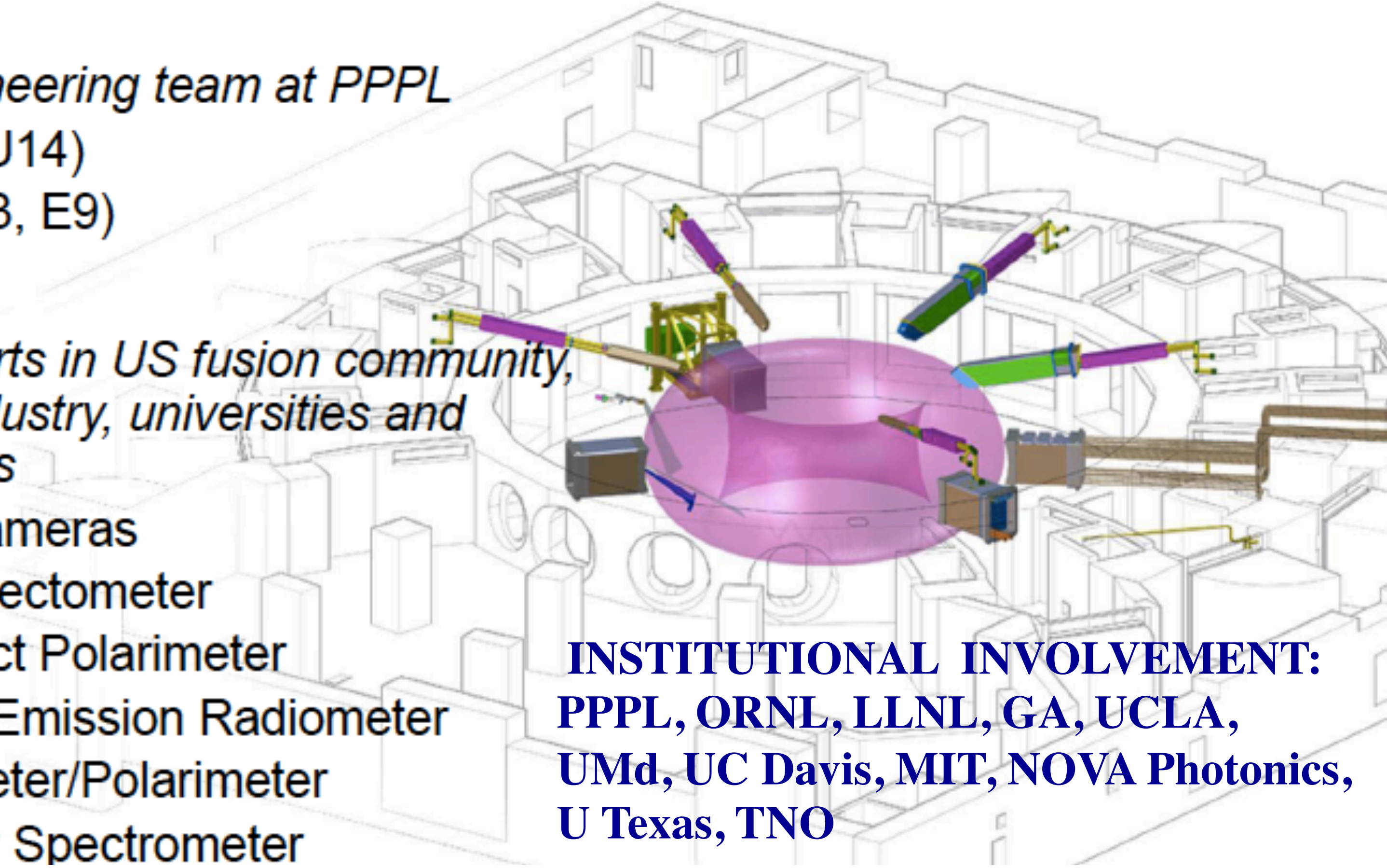
ORNL
88% Electron Cyclotron Transmission Lines

PPPL
In-Vessel Coils
(prelim. design only)

ORNL
100% Roughing Pumps, Vacuum Standard Components

SRNL
100% Tokamak Exhaust Processing System

US ITER Diagnostics Development



4 Port Plugs

Design led by engineering team at PPPL

Upper Ports (U11, U14)

Equatorial Ports (E3, E9)

7 Diagnostics

Design led by experts in US fusion community, with teams from industry, universities and national laboratories

Upper IR/Visible Cameras

Low Field Side Reflectometer

Motional Stark Effect Polarimeter

Electron Cyclotron Emission Radiometer

Toroidal Interferometer/Polarimeter

Core Imaging X-ray Spectrometer

INSTITUTIONAL INVOLVEMENT:
PPPL, ORNL, LLNL, GA, UCLA, UMd, UC Davis, MIT, NOVA Photonics, U Texas, TNO

ITER Construction by the EU is Well Underway

In late November 2012, the ITER Council met for the first time in the recently completed ITER Headquarters Building

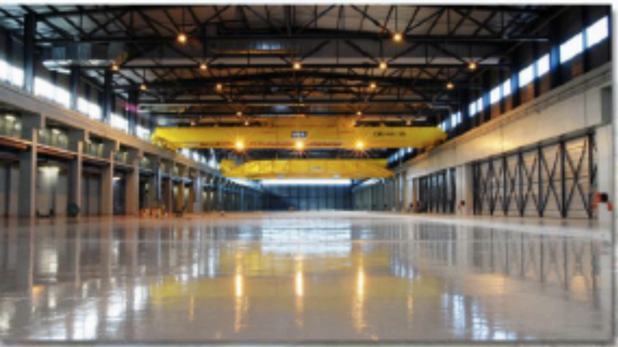
Photo: ITER Organization

In 2013, work will begin on the basement floor which will be supported on the columns and seismic bearings.

Photo: ITER Organization

The ITER switchyard substation was energized in June 2012.

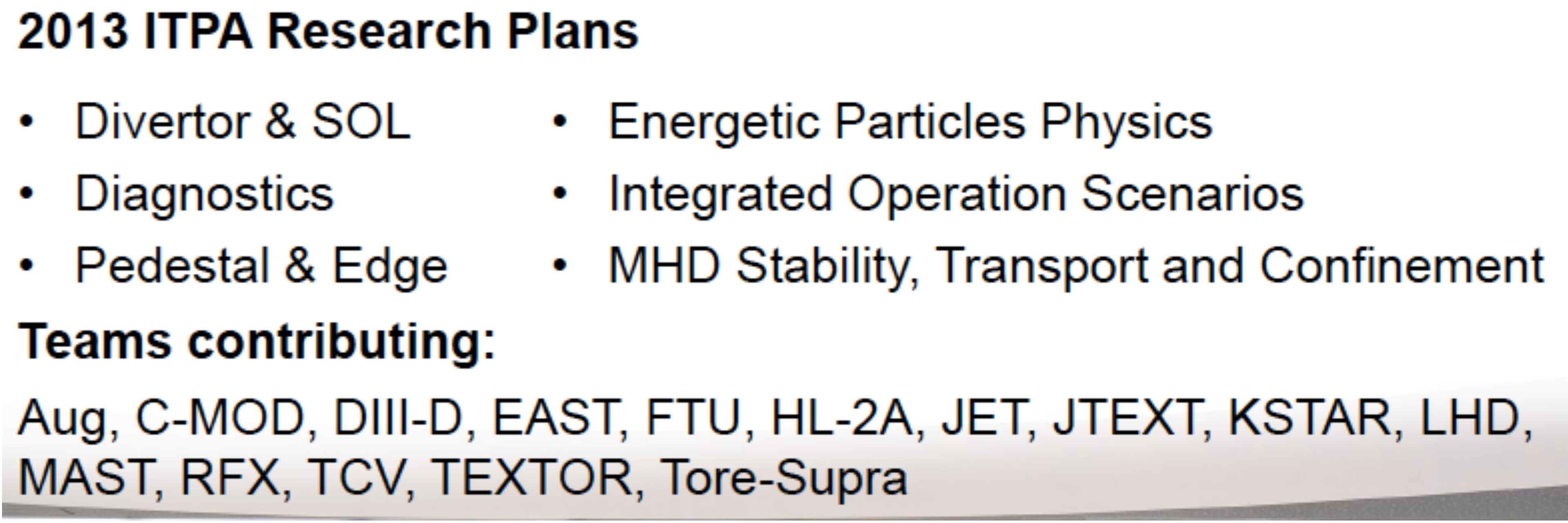
Photo: F4E



The interior of the Poloidal Field Coils Winding Facility shows the large yellow cranes which will be used in coil assembly.

Photo: ITER Organization

Ongoing Research Worldwide is Aimed at Optimizing ITER's Operation



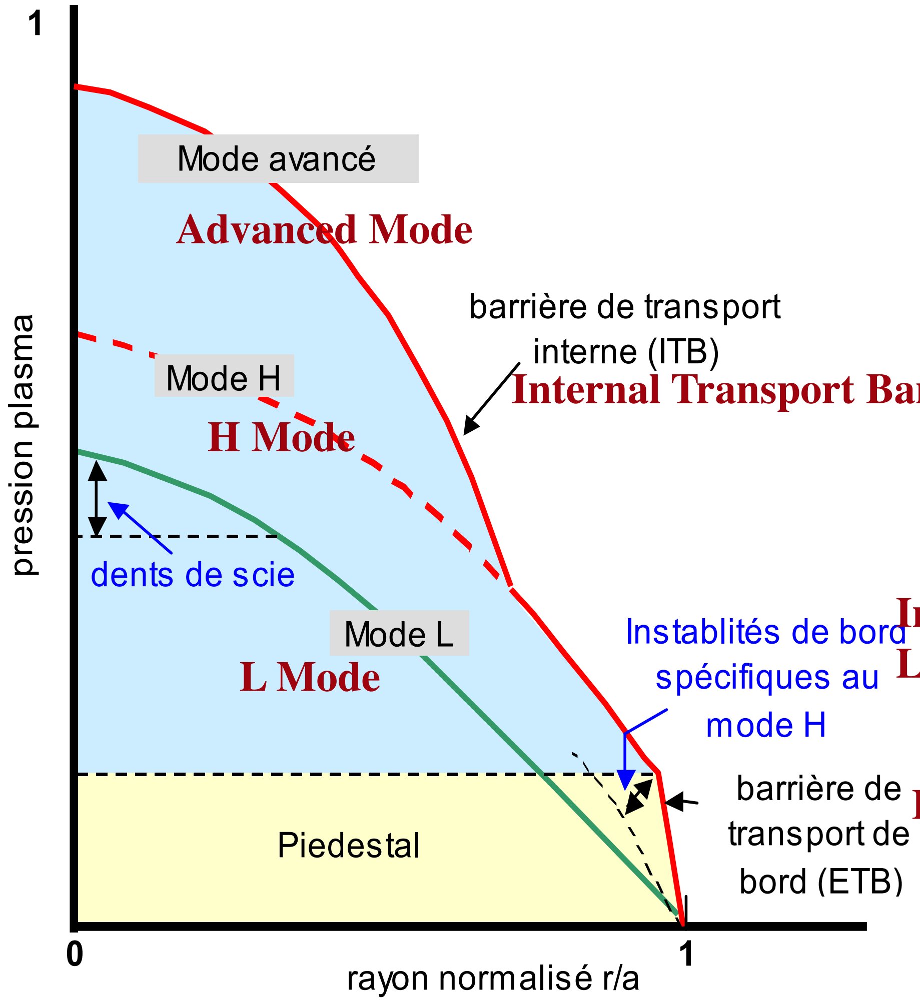
2013 ITPA Research Plans

- Divertor & SOL
- Diagnostics
- Pedestal & Edge
- Energetic Particles Physics
- Integrated Operation Scenarios
- MHD Stability, Transport and Confinement

Teams contributing:

Aug, C-MOD, DIII-D, EAST, FTU, HL-2A, JET, JTEXT, KSTAR, LHD, MAST, RFX, TCV, TEXTOR, Tore-Supra

Confinement Modes in Tokamak Depend on Complex “Self Organization”



Internal Transport Barrier

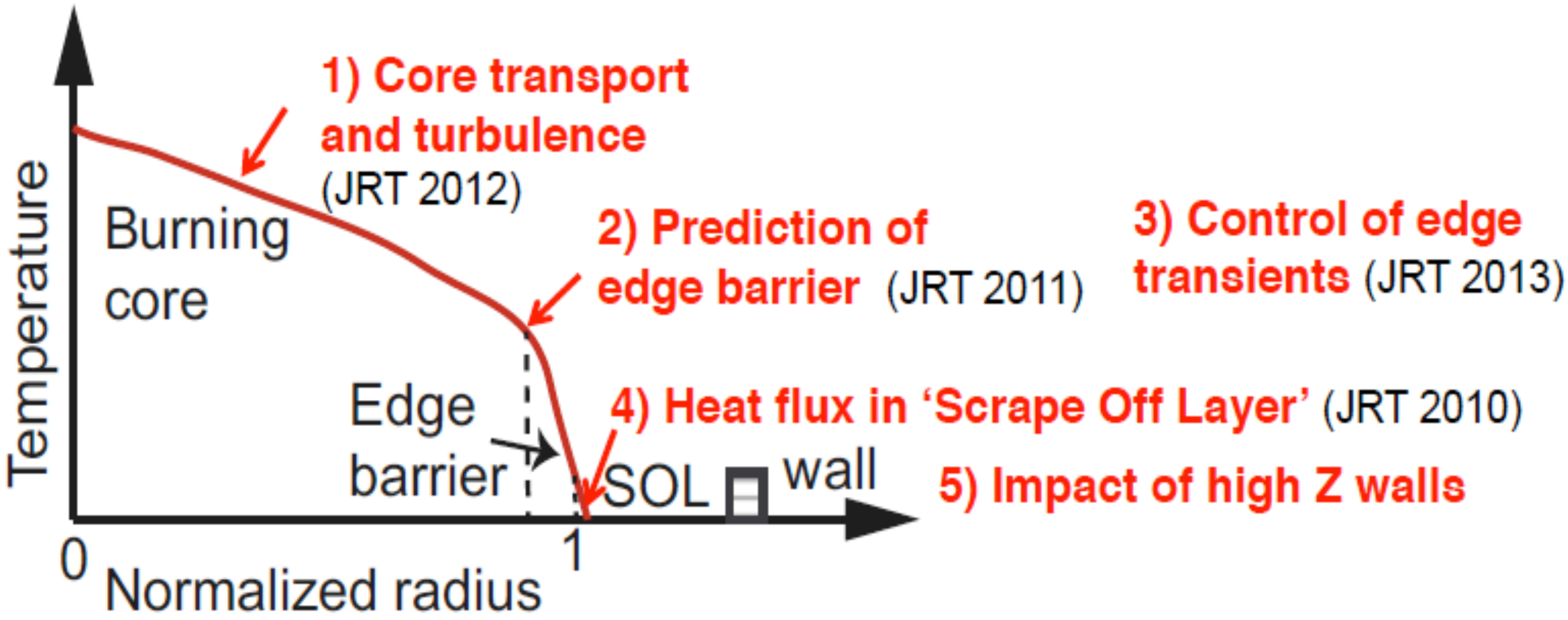
Instabilities specific to H mode (Edge Localized Modes, eg ELMS)

Edge transport Barrier

r/a (normalized minor radius)

Courtesy of Jean Jacquinot, Fr

Physics Issues for ITER being addressed by coordinated worldwide R&D program



1) Core transport and turbulence (JRT 2012)

2) Prediction of edge barrier (JRT 2011)

3) Control of edge transients (JRT 2013)

4) Heat flux in 'Scrape Off Layer' (JRT 2010)

5) Impact of high Z walls

Experiments :
➔ Core Transport is Turbulent

Heat flux equation:

$$\frac{3}{2} n\partial_t T + \nabla\cdot\phi_T = S$$

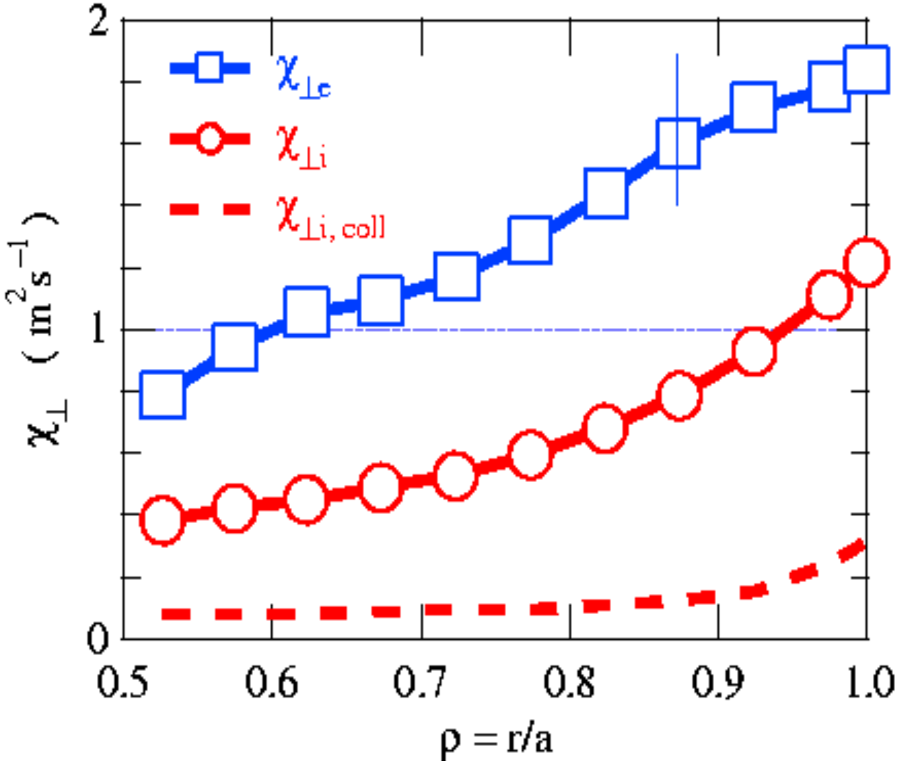
$$\phi_T = -n\chi_T\nabla T$$

$$\tau_E^{exp.} \sim \frac{a^2}{\chi_{turb.}}$$

$$\nu_{coll} \propto nT^{-3/2} \ll \omega_{turb}$$

~10^2-10^3 s^{-1}

~10^5 s^{-1}

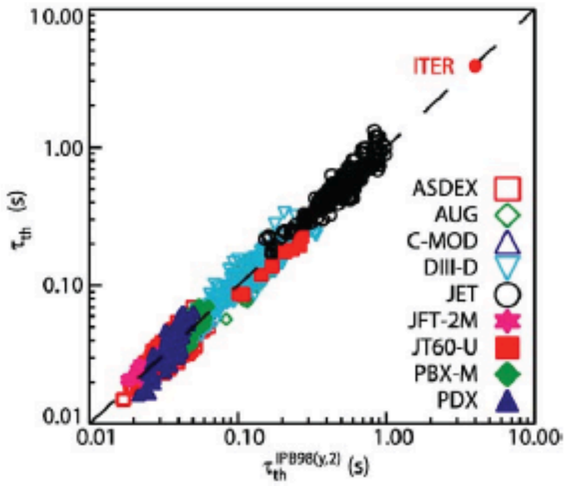


Tore Supra measurements typical

First-Principles Models of Core Transport are being Validated with Sophisticated Diagnostics

- In 1980-90's, fusion relied on empirical scaling of global τ_E.
- Did not reveal underlying physics, separate transport channels.

  Could regime change at large size? With electron vs ion heating?

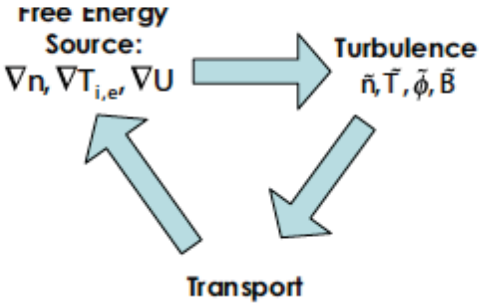


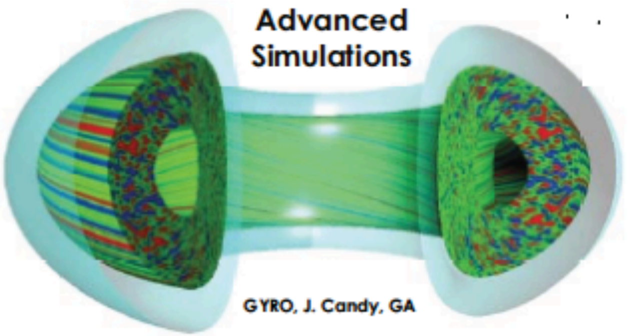
A. Hubbard, MIT, AAAS13 Fusion Symposium

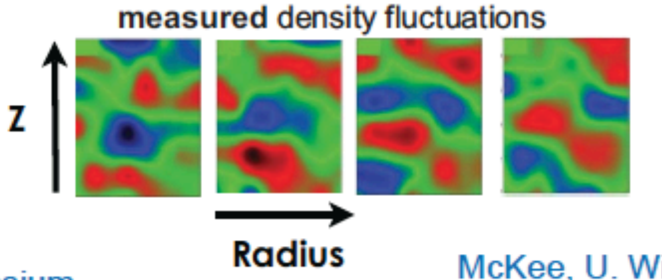
- **Plasma transport is mainly due to turbulence.**
- Low turbulence

  ⇨ Low transport

  ⇨ High confinement τ_E





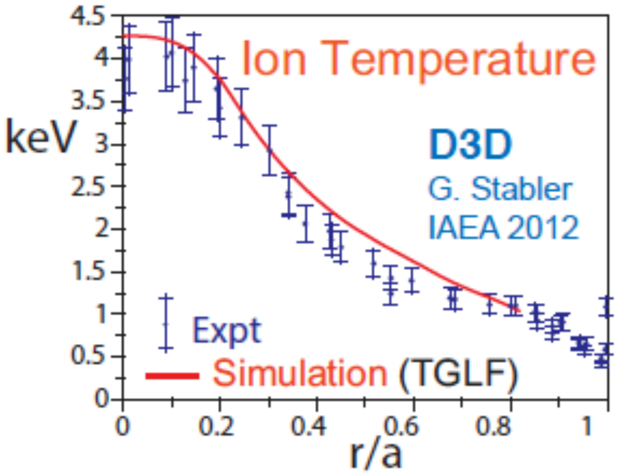


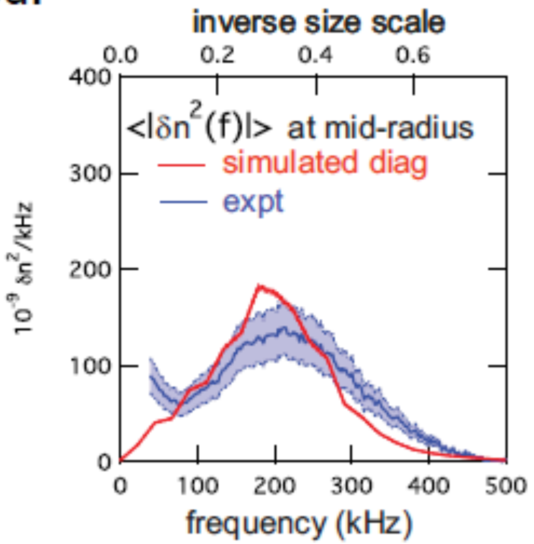
We now have **first-principles models**, and excellent **diagnostics** of turbulence of many parameters (n, T etc) and size scales (cm to sub-mm)

McKee, U. Wisc, APS review

Turbulent Core Transport Model Predictions for Ions Good, for Electrons not Always

- Predictions of **heat transport via ION channel** in the hot core and of larger scale turbulence are generally good.





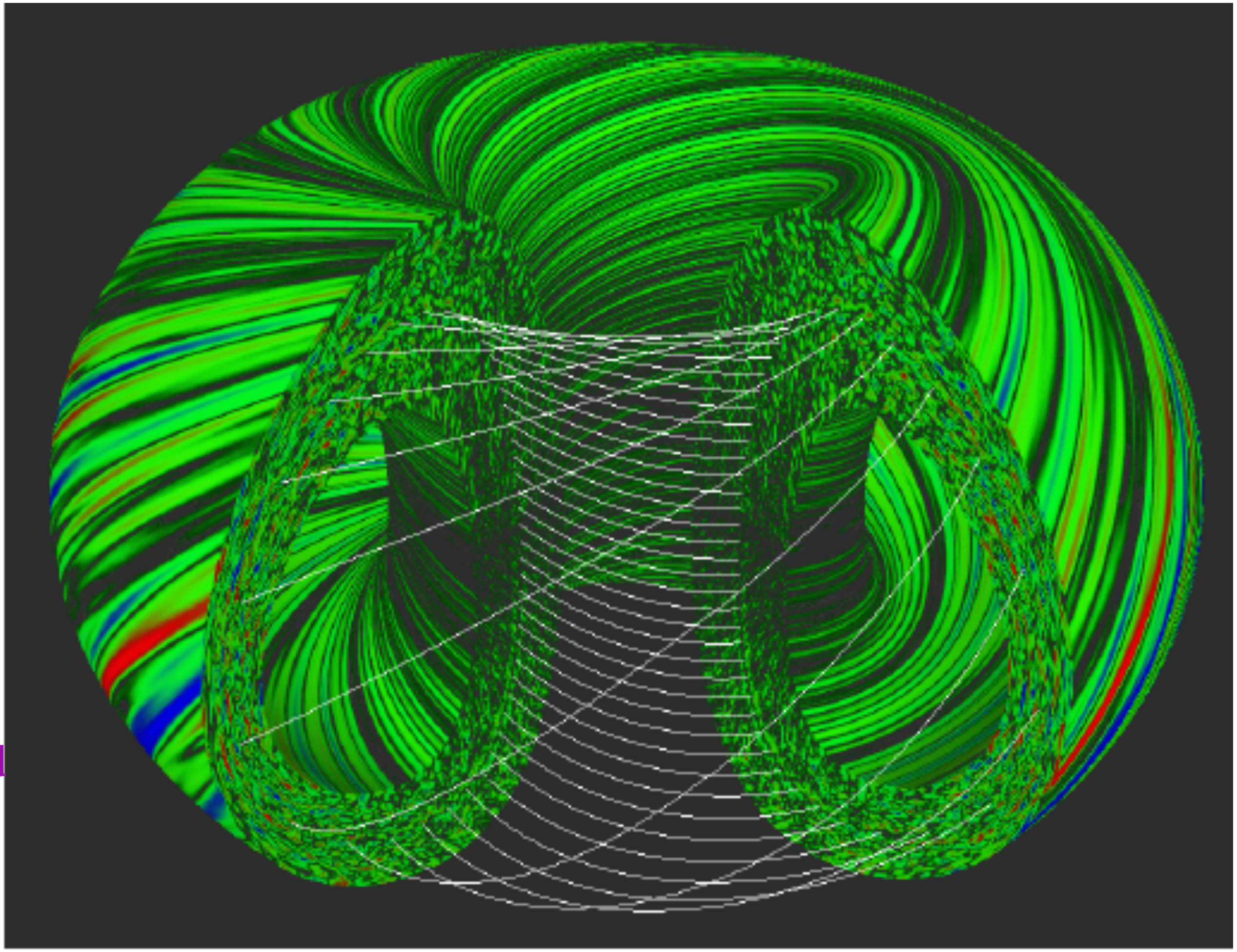
D3D
McKee

- **Heat transport via ELECTRON channel**, and due to smaller-scale turbulence, are often less accurately predicted.
- For the first time, can also predict and measure **particle transport** (diffusion and convection of main fuel ions and impurities). Good agreement so far.
- And, we are **learning to control, reduce transport.**

Our understanding of turbulent transport has been improving rapidly because of implementation of gyrokinetic theories on supercomputers

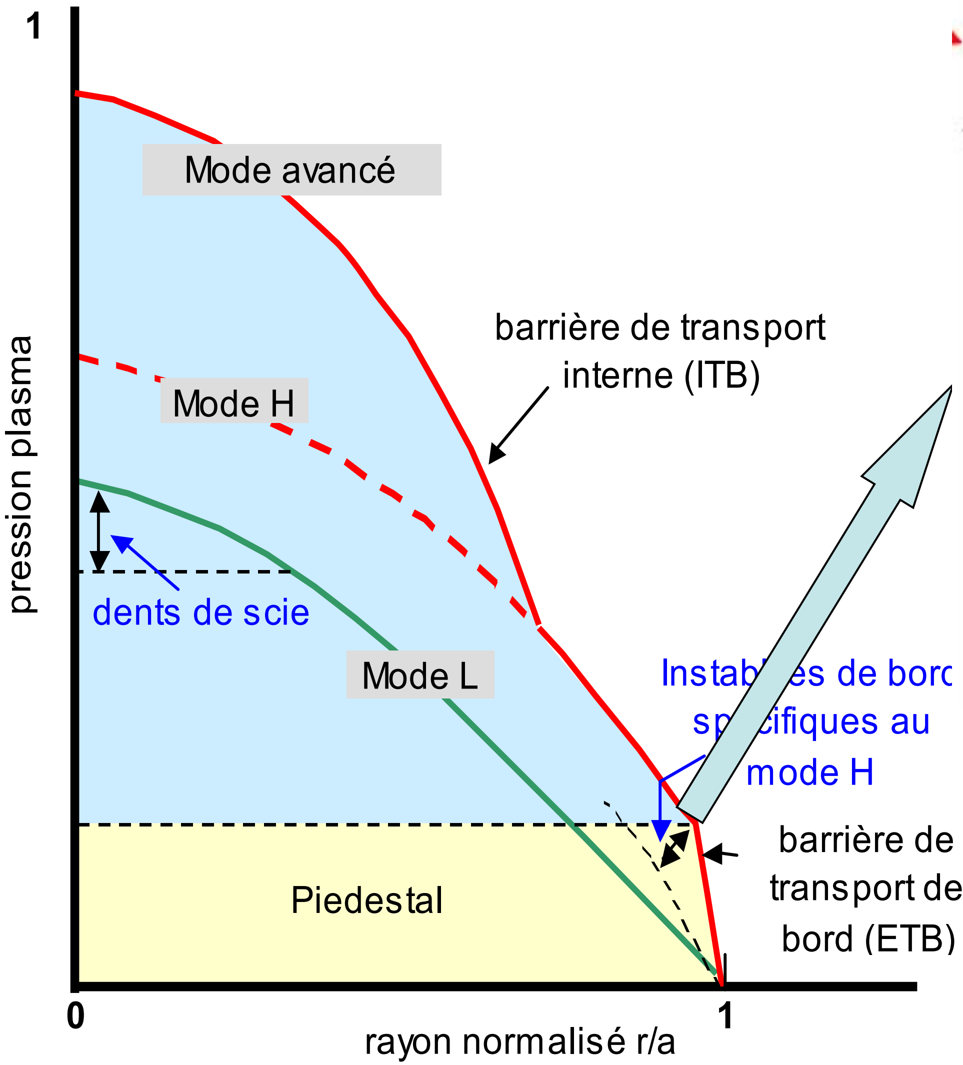
The radial correlation length of turbulent eddies is found to be broken up by strong ExB shear flow (self generated "zonal flows") which then reduces transport by factors of two or more (High confinement or H-mode; experimentally discovered more than a decade ago in Asdex);

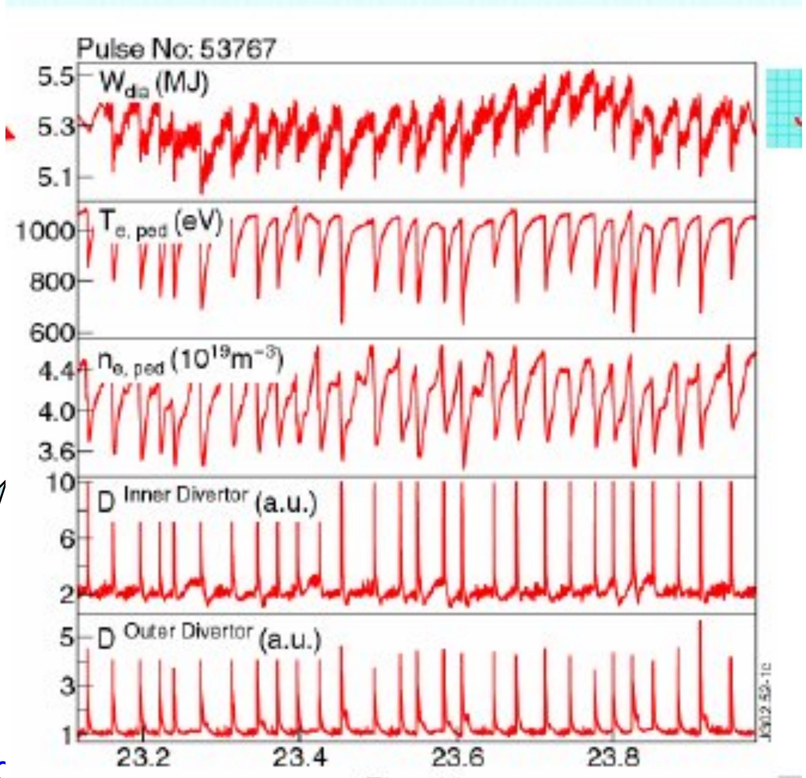
Similar to zonal flows in rotating fluids such as found on the surface of Jupiter;



Courtesy of J. Candy, GA

Edge Pedestal Height a Determining Factor in Central Temperatures but Susceptible to ELMS





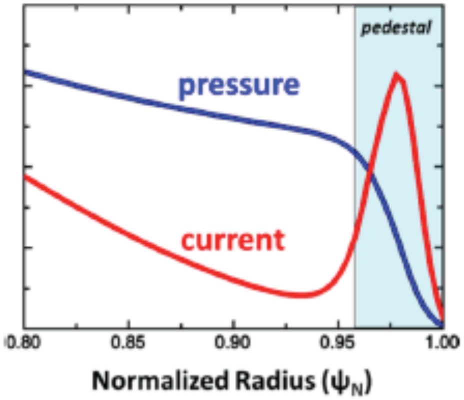
Mitigation:

- **Pellet pacing**
- **Ergodization of the surface**

J. Jacquinot, IAP, MIT

New Theoretical Model Predicts Barrier Pressure Limit via Stability Calculations

- In region of steep pressure and current gradients, profiles are limited by large-scale ‘Peeling-Ballooning modes’, and smaller scale ‘kinetic ballooning modes’.

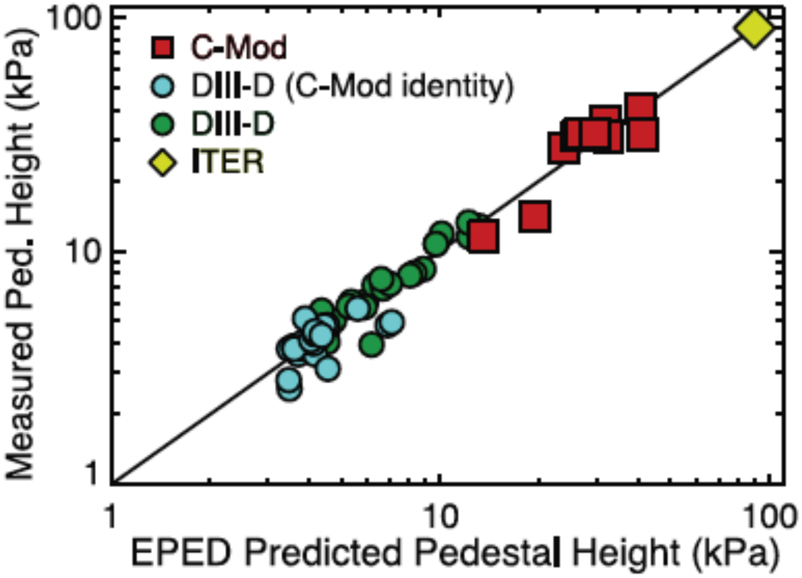


- Combining their thresholds gives a prediction for barrier width and pressure.
  P. Snyder, GA (EPED model)

- **Model agrees well with current experiments, allowing much more confident projection to ITER**

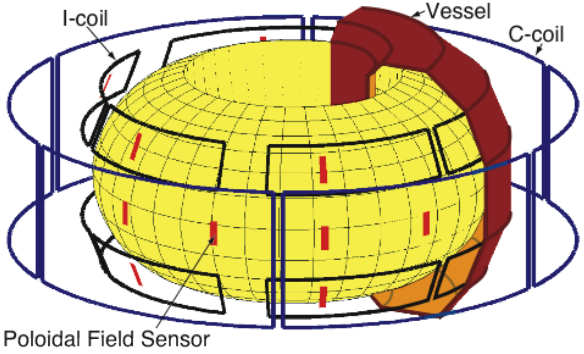
for n_{ped}~$7x10^{19}m^{-3}$

T_{ped} ~ 4.5 keV => Q ≥ 10

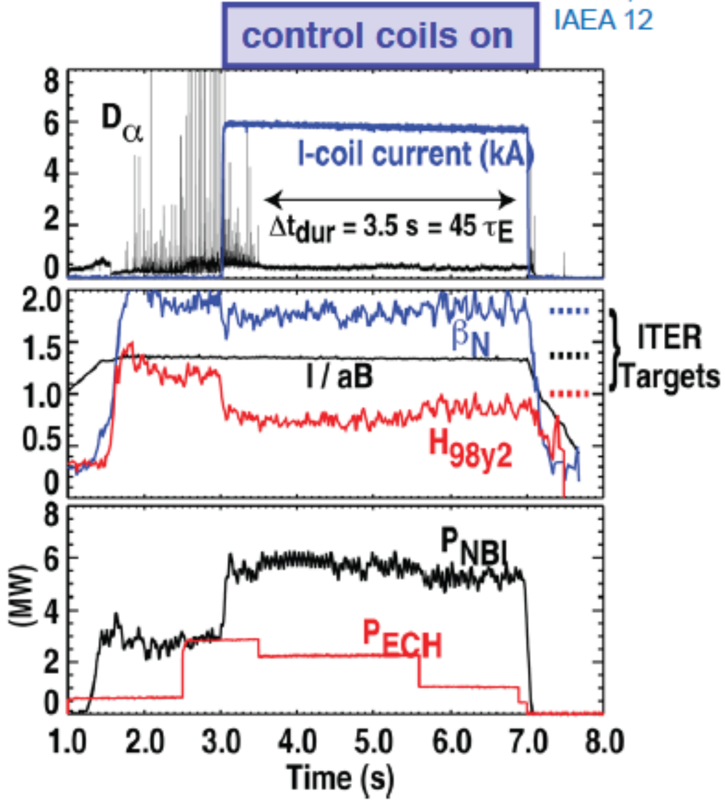


Methods Have Been Developed to Suppress or Mitigate ELMS

- Firing small **pellets** into the pedestal triggers more frequent (and smaller) ELMs.
- Adding **Magnetic Perturbations** via external coils modifies transport and profiles, suppressing ELMs in some conditions.
- Both techniques are recently developed on current experiments, and have led to plans for hardware additions on ITER.
  - A number of issues still remain, including prediction of pedestals and performance *without* large ELMs.



DIII-D, n=3 RMP
D. Hill, IAEA 12

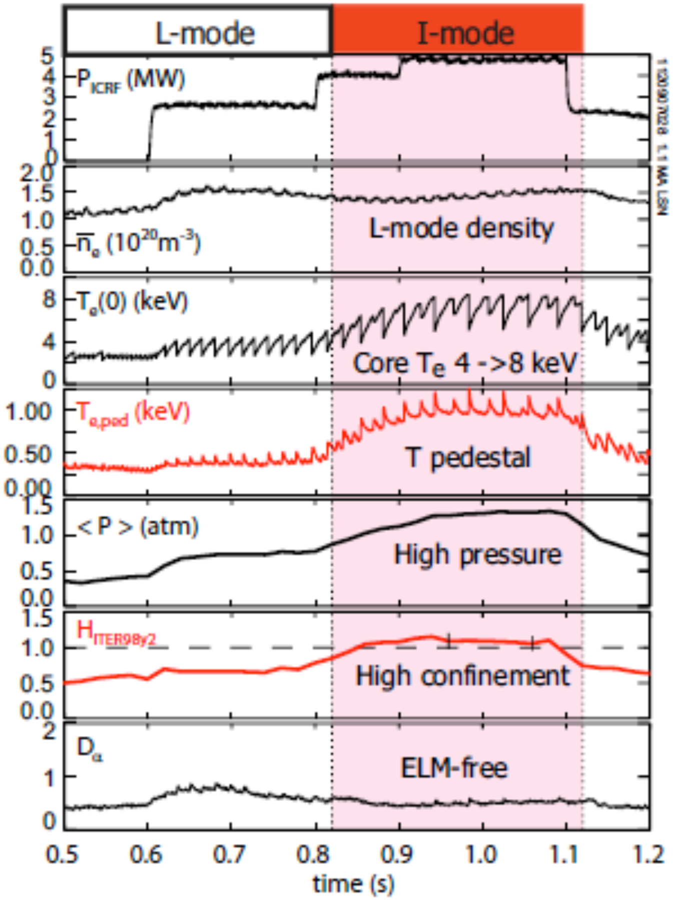


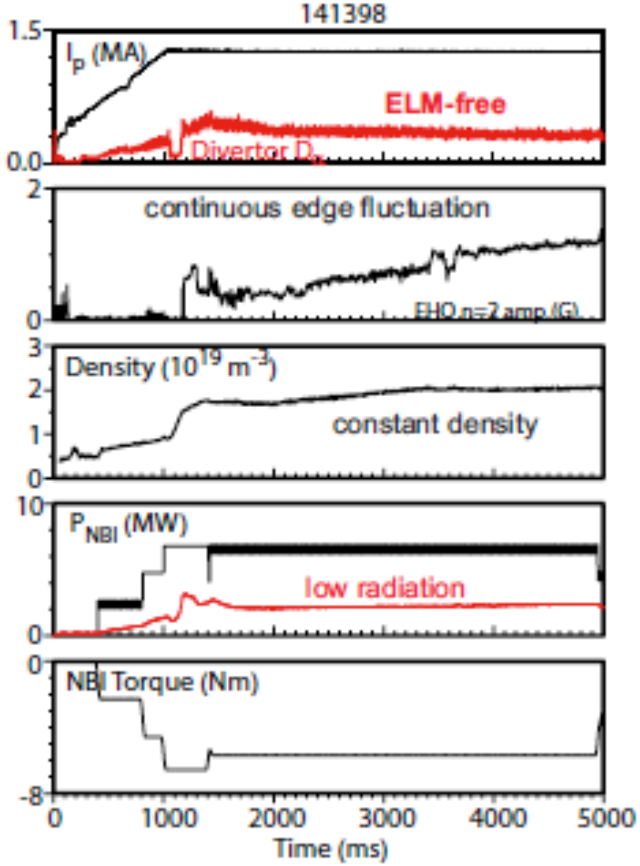
New High Confinement Regimes Naturally Free of Large Scale Instabilities Have Been Discovered

- **I-mode** features an energy barrier *without* a particle barrier, reducing impurities..

- **Quiescent H-mode** Strong edge rotational shear helps establish a stable barrier.

C-Mod
Hubbard
IAEA 2012

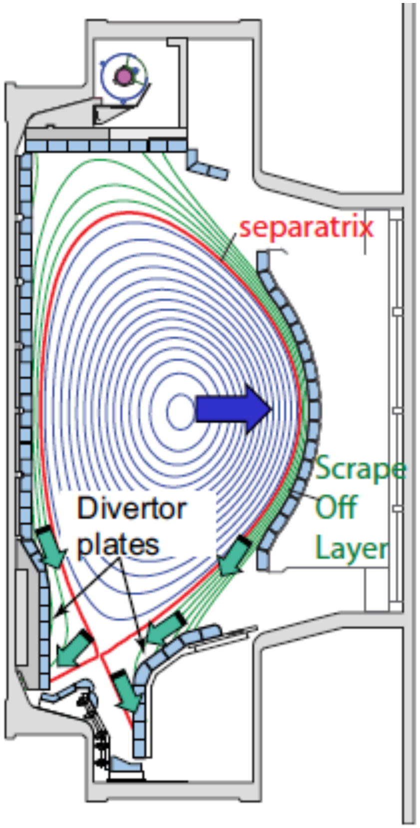


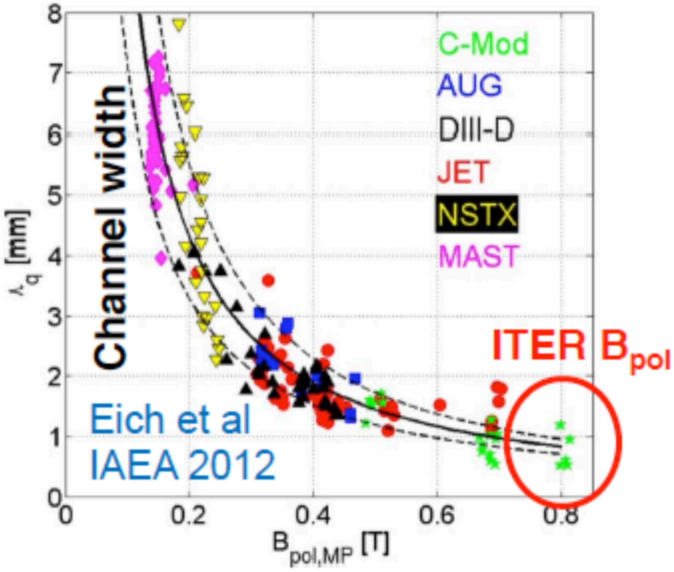


DIII-D
Burrell
APS 2011

Plasma Heat Flux to Material Surfaces will be a Challenge

- All the heat input to, or produced by, a burning plasma reaches the edge. Most then flows along field lines in the 'scrape off layer' to a robust 'divertor'.
  - The channel width λ_q determines the heat concentration.
- Surprising new result shows λ_q does not increase with machine size, varies with $B_{pol} \sim I_p$/size. Scaling implies only 1 mm on ITER – same as C-Mod!





- Other interpretations suggest λ_q is related to gradient in barrier, would be wider on ITER.
  - **Need improved physics basis!**

➔ ITER needs to radiate much of the heat in the divertor without contaminating the burning core plasma

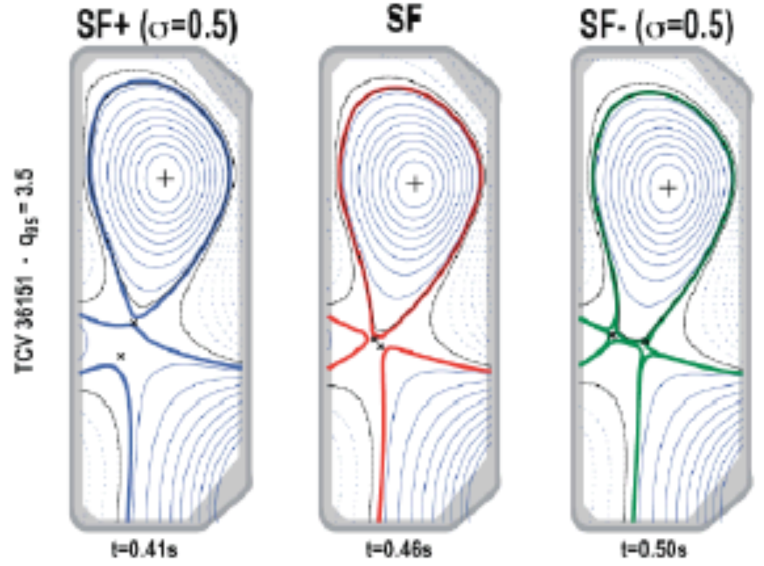
ITER will Provide a Power Plant Scale Test of the Extraction of Heat From an MFE Fusion Plasma

- **Long pulse, high heat flux operation can result in erosion or local damage.**
  - Nine years of JET operation has a comparable ion fluence to the divertor as~3 high power DT shots on ITER.
  - Where will the sputtered material migrate to?
  - Development of high recycling divertor, Edge Localized Modes and Disruption Mitigation are critical issues.
- **Dust has not been an issue in current experiments but there will be safety restrictions on ITER**
- **Tritium retention in graphite based on JET and TFTR experiments would be a serious concern.**
  - TFTR tiles 16% retention
  - JET 12% retention
- **Results from JET with tungsten divertor for reduced tritium retention are very encouraging.**

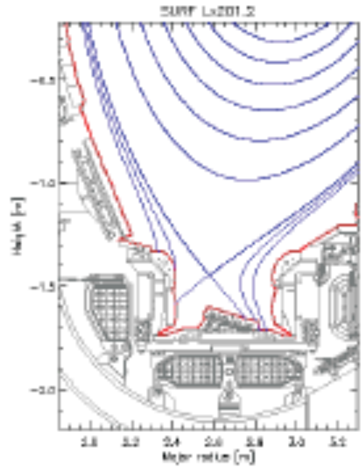
Plasma Exhaust: Configuration Solutions

Snowflake

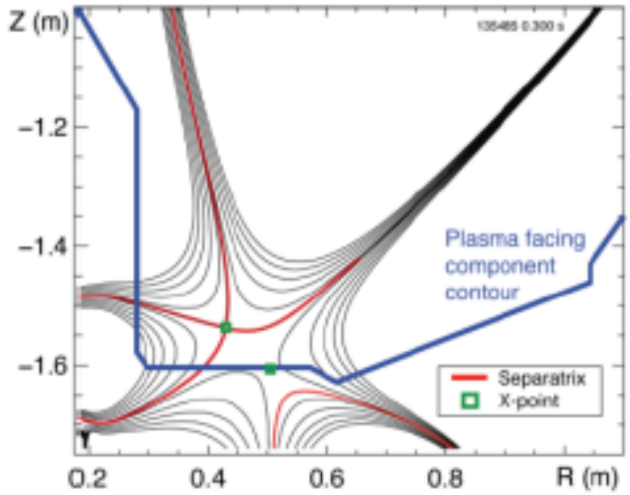
Use a high-order null (vs. **a simple X-point) to spread the divertor field lines over a wider surface area. Lower peak heat flux to target.**



Snowflake test in TCV (Switzerland)

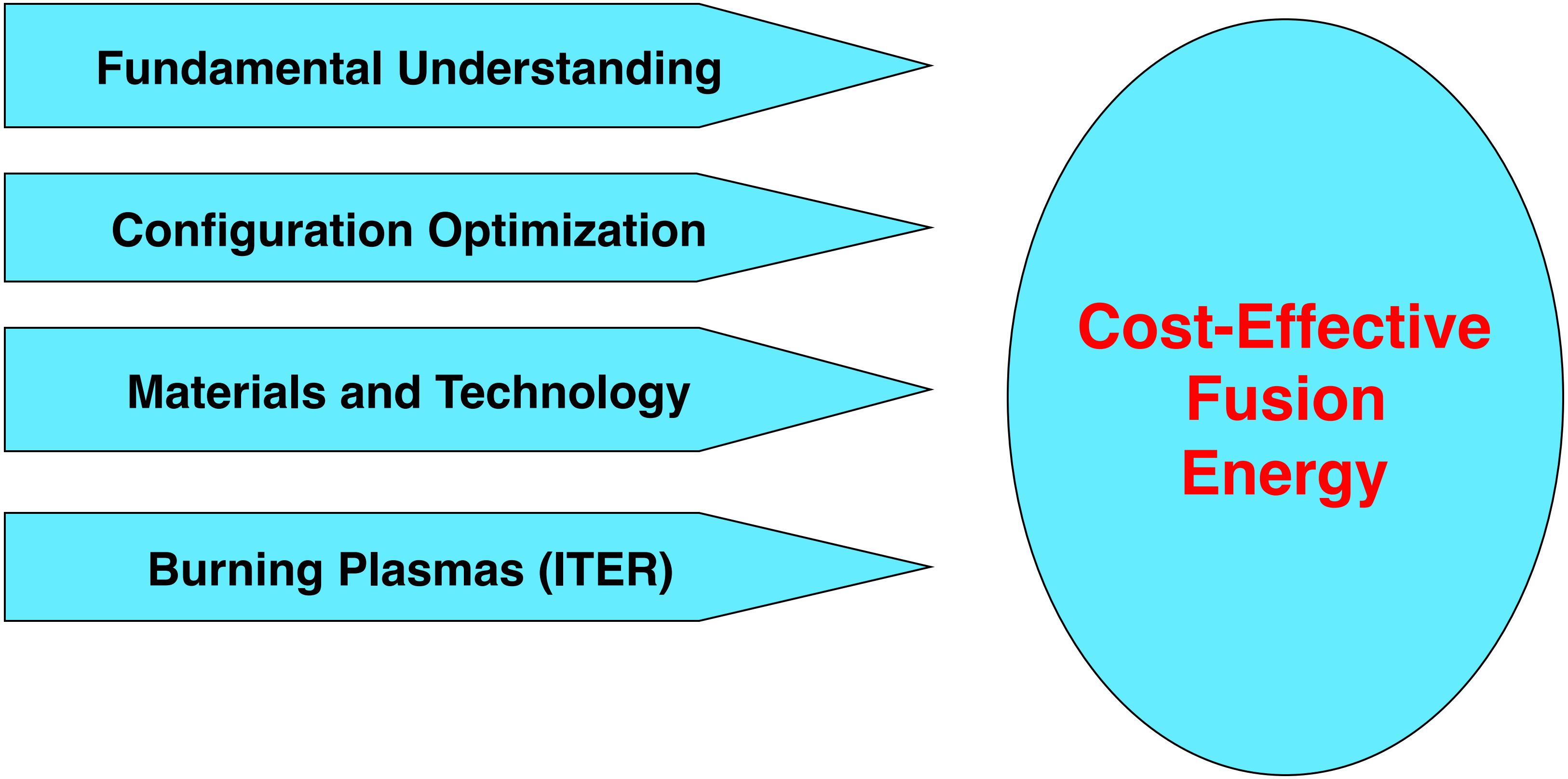


Standard X-point Divertor (JET)



Snowflake test in NSTX (U.S.)

Four Thrust Areas are Required for Practical Magnetic Fusion Energy



Fundamental Understanding

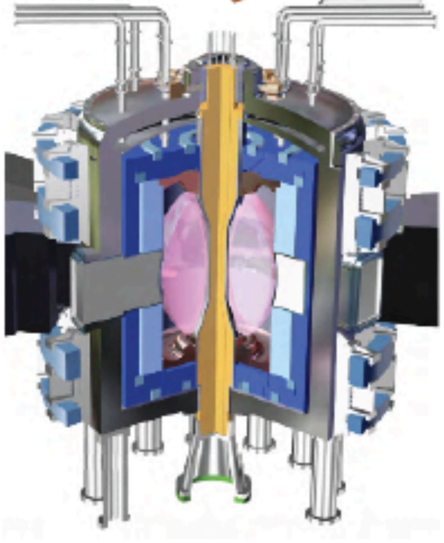
Configuration Optimization

Materials and Technology

Burning Plasmas (ITER)

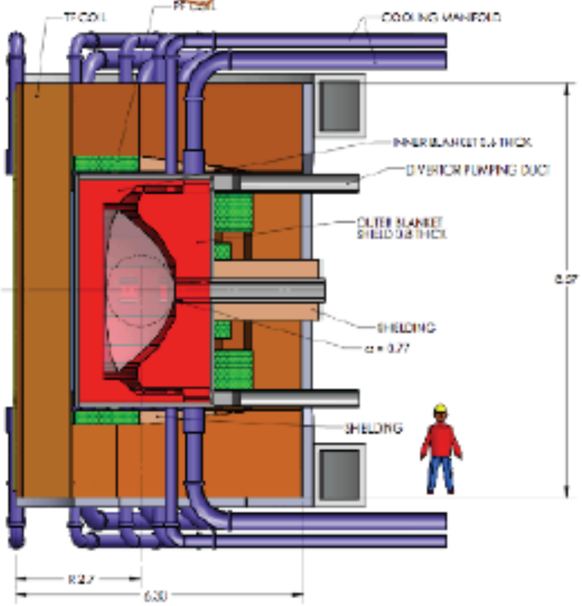
Cost-Effective Fusion Energy

Proposed Next Step in the US Fusion Program: FNSF
Fusion Nuclear Science Facility, a Low Gain, Long Pulse Burning Plasma Experiment for Materials Study



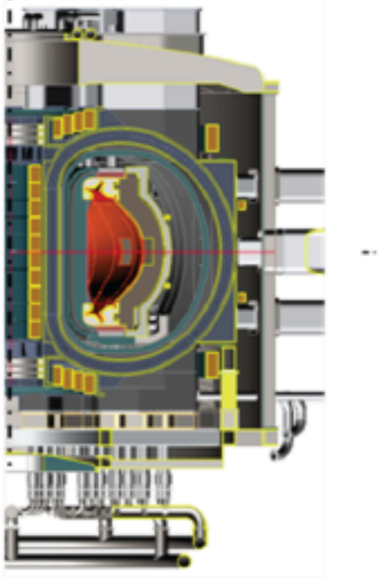
FNSF-ST– ORNL

Peng, *et al.*, F.S.&T. **60** (2011)



FNSF-AT – GA

Stambaugh, *et al.*, F.S.&T. **59** (2011)



Pilot Plant – PPPL

Menard, *et al.*, NF **51** (2011)

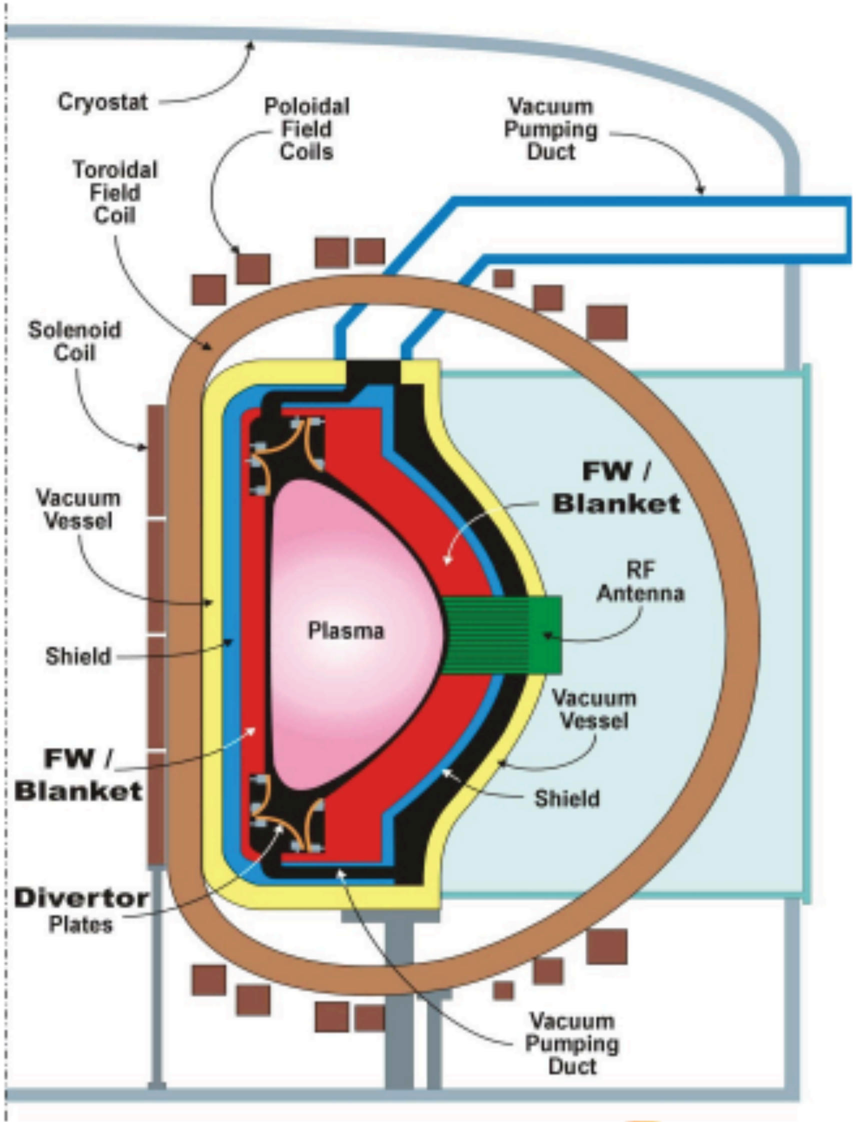
Fusion Power Extraction and Tritium Breeding

Functions of the Blanket–First Wall (FW) system

A. Nuclear and Plasma Power Absorption and Extraction

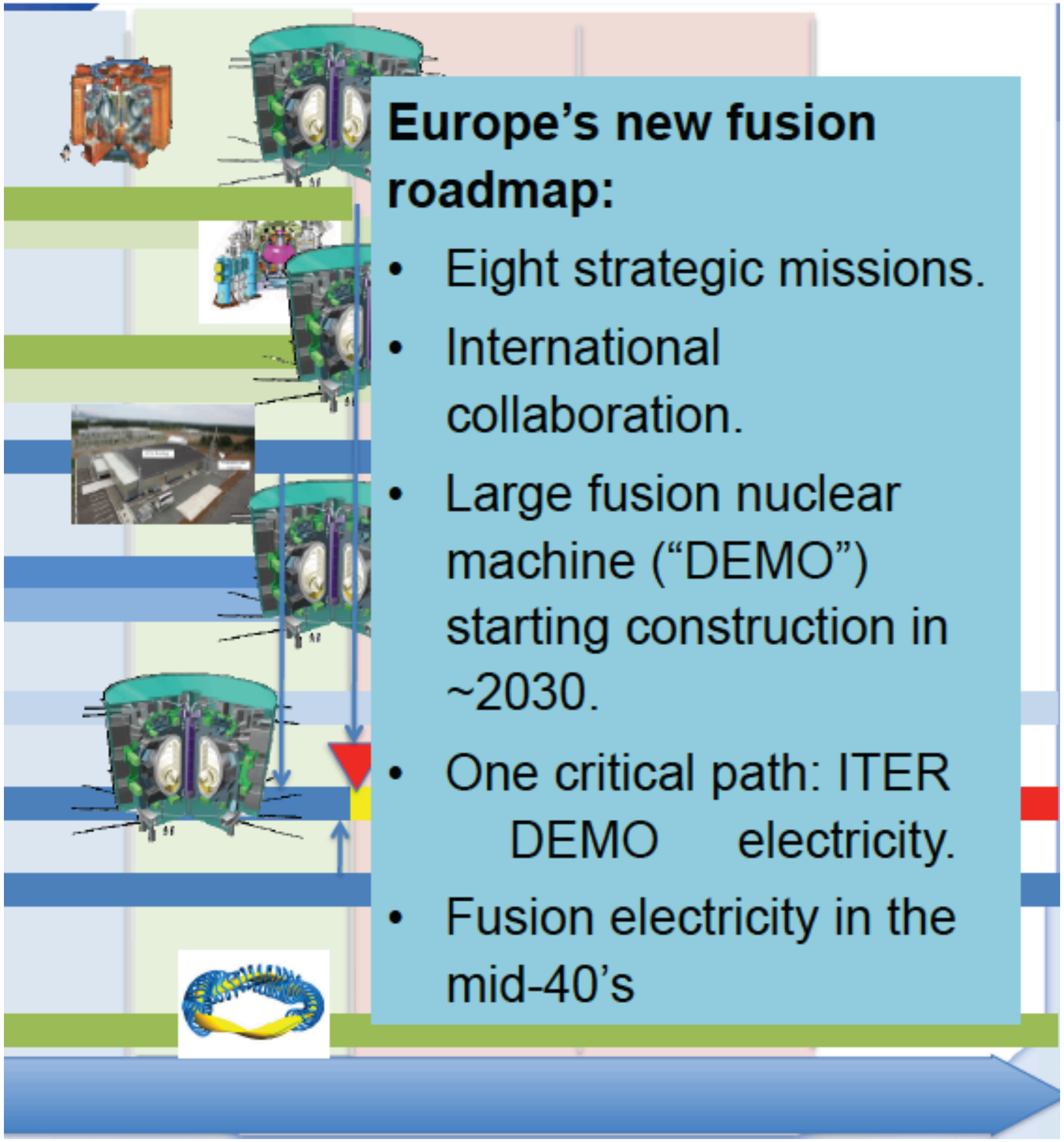
B. Tritium Breeding and Recovery

C. Radiation Shielding of the Vacuum Vessel and Magnets



EU Fusion Energy Development Path

EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

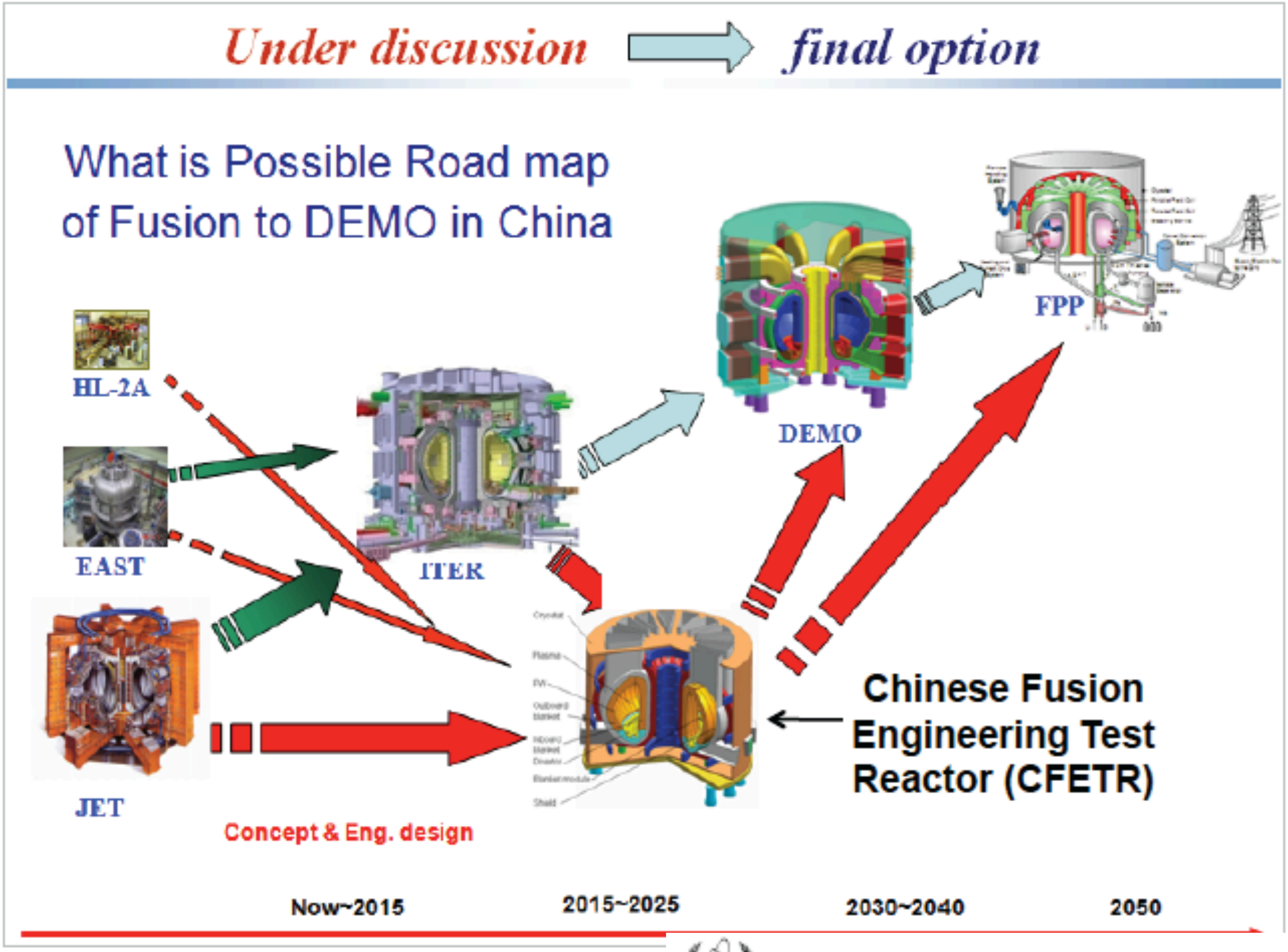


Europe's new fusion roadmap:

- Eight strategic missions.
- International collaboration.
- Large fusion nuclear machine ("DEMO") starting construction in ~2030.
- One critical path: ITER DEMO electricity.
- Fusion electricity in the mid-40's

H.G. Neilson, PPPL, AAAS 2013, Boston

Chinese Fusion Energy Development Path



Under discussion → *final option*

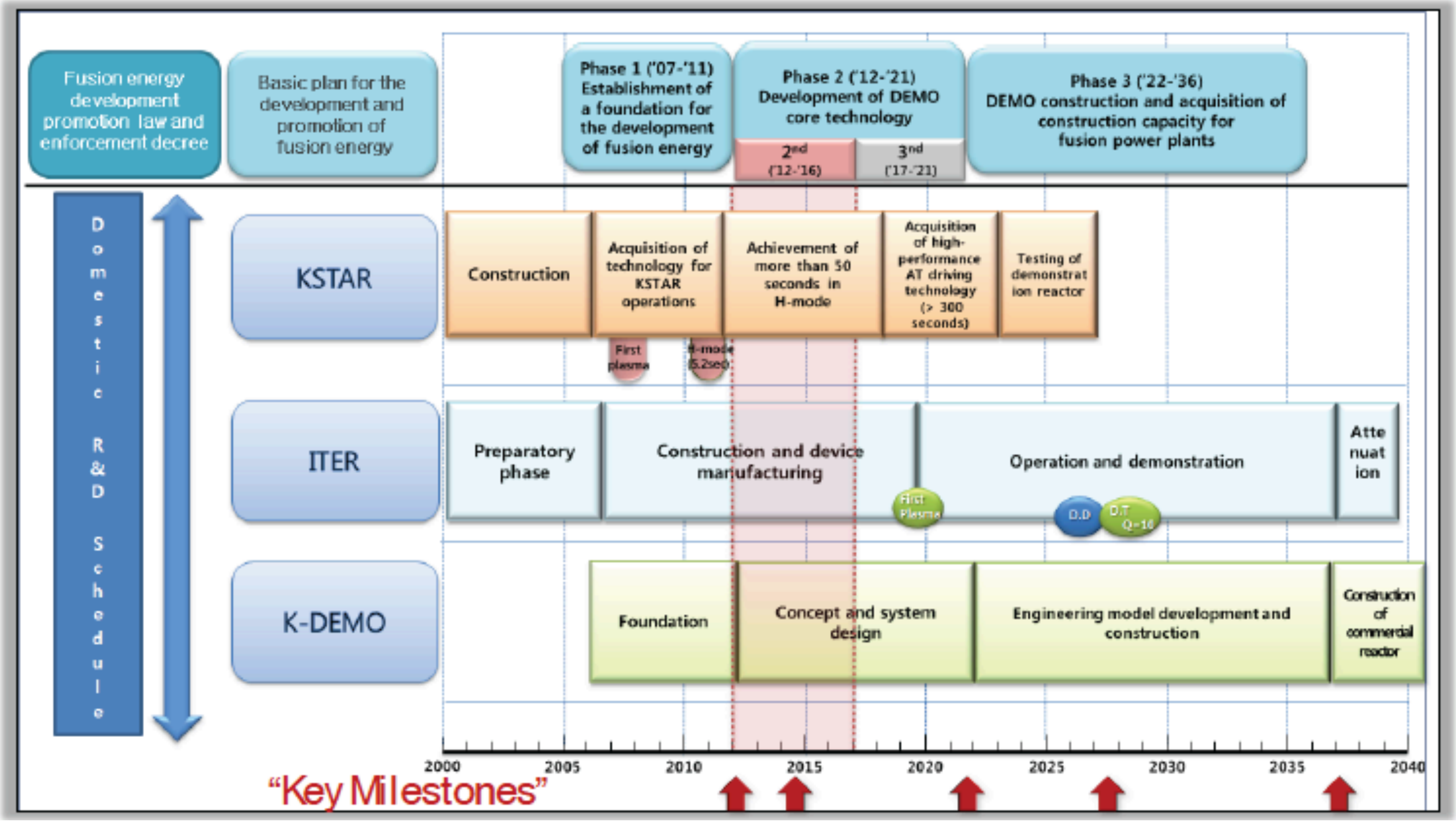
What is Possible Road map of Fusion to DEMO in China

Chinese Fusion Engineering Test Reactor (CFETR)

Concept & Eng. design

1th IAEA-DEMO Program workshop

Korean Fusion Energy Development Roadmap



Fusion energy development promotion law and enforcement decree

Basic plan for the development and promotion of fusion energy

Phase 1 ('07-'11) Establishment of a foundation for the development of fusion energy

Phase 2 ('12-'21) Development of DEMO core technology

2nd ('12-'16)

3rd ('17-'21)

Phase 3 ('22-'36) DEMO construction and acquisition of construction capacity for fusion power plants

Domestic R&D Schedule

KSTAR

- Construction
- Acquisition of technology for KSTAR operations
- Achievement of more than 50 seconds in H-mode
- Acquisition of high-performance AT driving technology (> 300 seconds)
- Testing of demonstration reactor

First plasma

H-mode (5.2sec)

ITER

- Preparatory phase
- Construction and device manufacturing
- Operation and demonstration
- Attenuation

First Plasma

D.D

D.T Q=10

K-DEMO

- Foundation
- Concept and system design
- Engineering model development and construction
- Construction of commercial reactor

"Key Milestones"

NFRI 국가핵융합연구소 National Fusion Research Institute

Advanced Project Division

Summary and Conclusions

- Fusion is an attractive energy source, available on a timescale to help address global climate change
- There is a timely opportunity for international collaboration (ITER) to advance fusion energy
- A strong domestic program in parallel with ITER is a must if fusion is to succeed - there are too many complex physics questions that remain to be answered
- Materials and advanced technology research will be comparably difficult and time consuming
- Fusion is a long range R&D program and education must be an essential element for its success