FUSION ENERGY: CONCEPTS, PROGRESS AND PROSPECTS

Stephen O. Dean, President
Fusion Power Associates

Presented to
Mid Atlantic Senior Physicists Group
November 16, 2016

FPA PURPOSE AND GOALS

The purpose of Fusion Power Associates is to ensure the timely development and acceptance of fusion as a socially, environmentally and economically attractive source of energy.

To fulfill this purpose, we have adopted four primary goals:

To bring about a smooth, timely transition from research on fusion science and technology to engineering development and practical applications.

To foster cooperation among all public and private organizations, including government, universities, national laboratories and industry.

To establish increased public awareness and understanding of the potential applications of fusion science and technology.

To foster the use of fusion science and technology in both commercial and government applications, including such areas as energy, space and national security.

Member Institutions

Columbia University, Dept. of Applied Physics

Chinese Academy of Sciences, Inst. of Nuclear Energy Safety Technology

General Atomics

Lawrence Berkeley National Laboratory, Heavy Ion Fusion

Lawrence Livermore National Laboratory, Laser S&T Program

Lawrence Livermore National Laboratory, Fusion Energy Program

Los Alamos National Laboratory, Fusion Energy Program

MIT Plasma Science and Fusion Center

National Instruments, Inc.

Oak Ridge National Laboratory, Fusion Energy Division

Osaka University, Institute of Laser Engineering

Princeton Plasma Physics Laboratory

Sandia National Laboratories, Pulsed Sciences Program

Savannah River National Laboratory

Schafer Corporation

SLAC National Accelerator

Tri Alpha Energy, Inc.

University of California, Lab Management Office

University of California at Los Angeles

University of California at San Diego

University of Rochester, Lab for Laser Energetics

University of Texas, Fusion Research Institute

WEB SITE
http://fusionpower.org

- Fusion Power Associates web site has links to useful information, such as:
- Presentations on all aspects of fusion from our annual meetings.
- Links to fusion web sites around the world.
- Fusion Program Notes on current events

TOPICS

- What is Fusion?
- Why Fusion?
- Concepts
- Progress and Prospects
- Issues

What is Fusion?

Fusion is the process that generates light and heat in the Sun and other stars

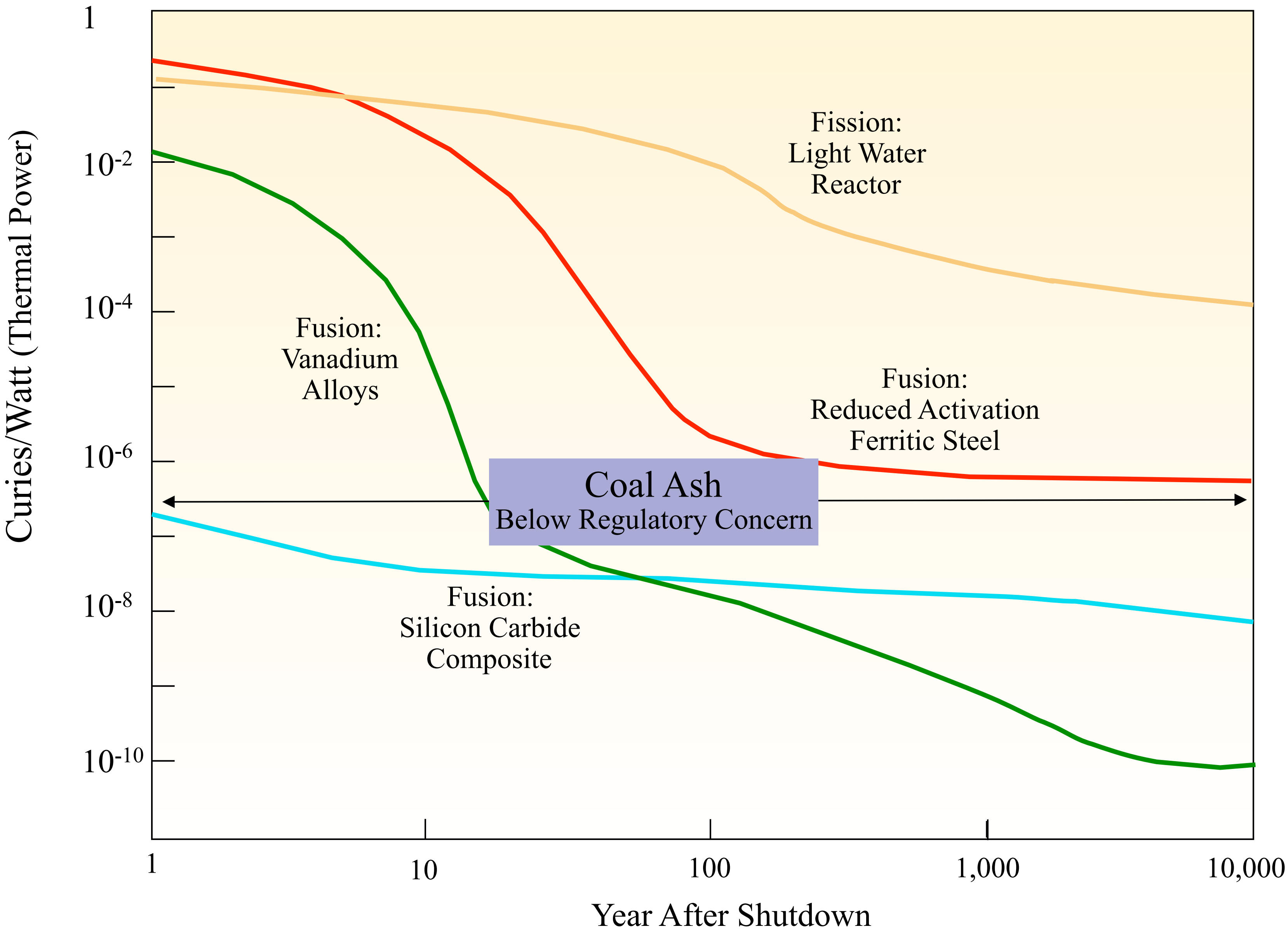
It is most easily achieved on earth by combining the heavy isotopes of hydrogen (deuterium and tritium) to form isotopes of helium

WHY FUSION

Fusion fuel (deuterium and lithium) is abundant, widely available and low cost

The fusion reaction itself produces no radioactive waste; activated structure has relatively low hazard potential and relatively short half-life

Fusion will not Require Geological Storage



WHY FUSION

While the primary goal of fusion development is central station electric power plants, fusion plants may also be useful for

Hydrogen production

Desalination of water

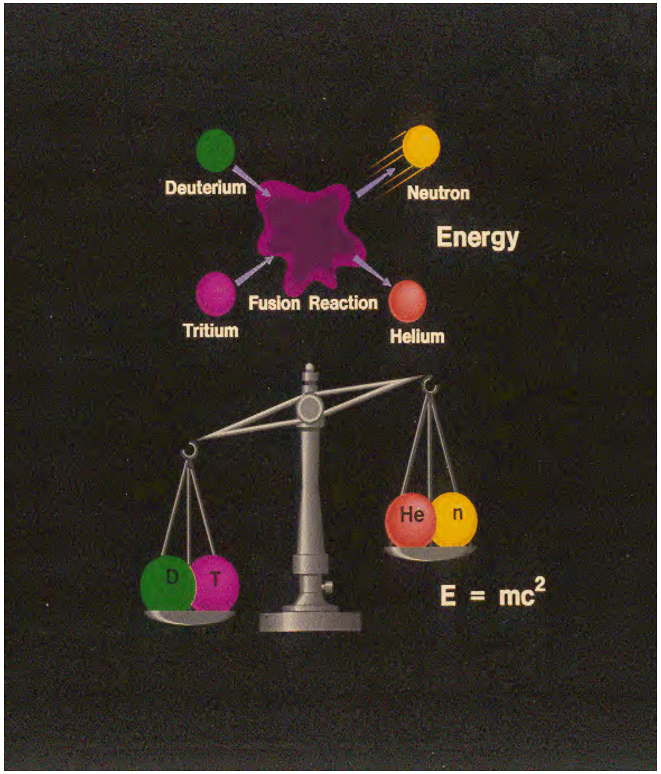
Production of fuel for fission reactors

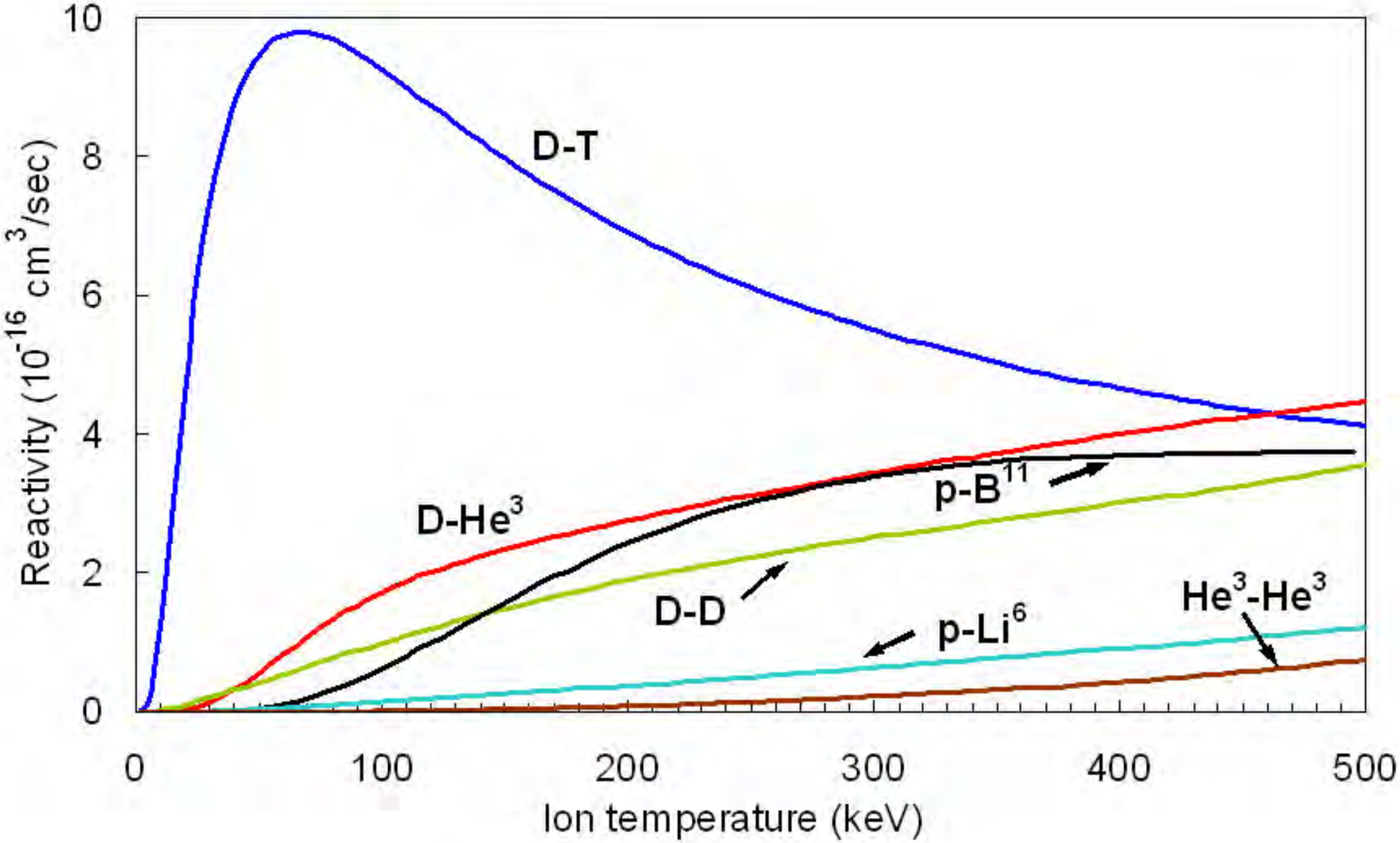
Deactivation of fission reactor waste

PRIMARY FUSION REACTION

Deuterium and Tritium fuse at high energy (10 KeV), producing helium and an energetic (14 MeV) neutron

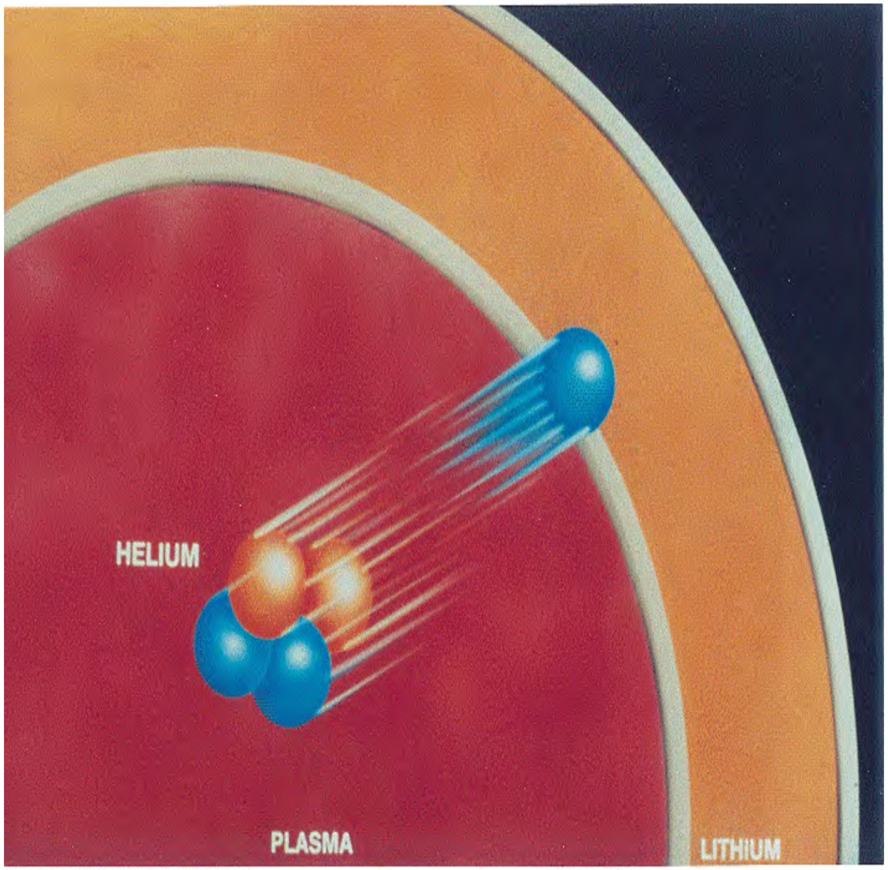
Mass is converted to energy according to Einstein's formula





10
8
6
4
2
0
Reactivity (10-16 cm3/sec)
D-T
D-He3
p-B11
D-D
p-Li6
He3-He3
0
100
200
300
400
500
Ion temperature (keV)

FUSION POWER PLANT



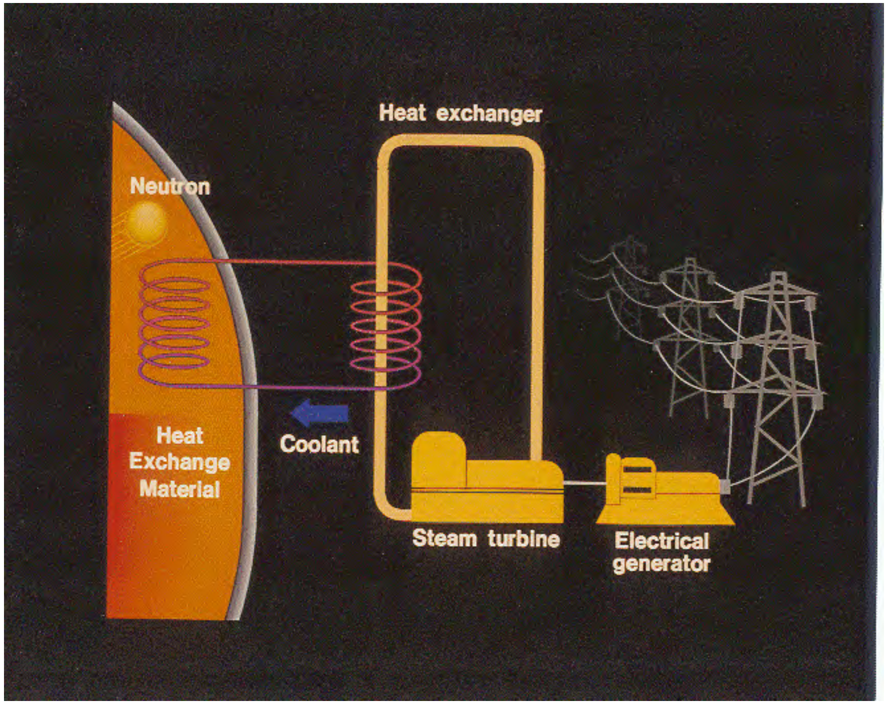
The helium nucleus gives up its energy to the plasma, thus sustaining its temperature

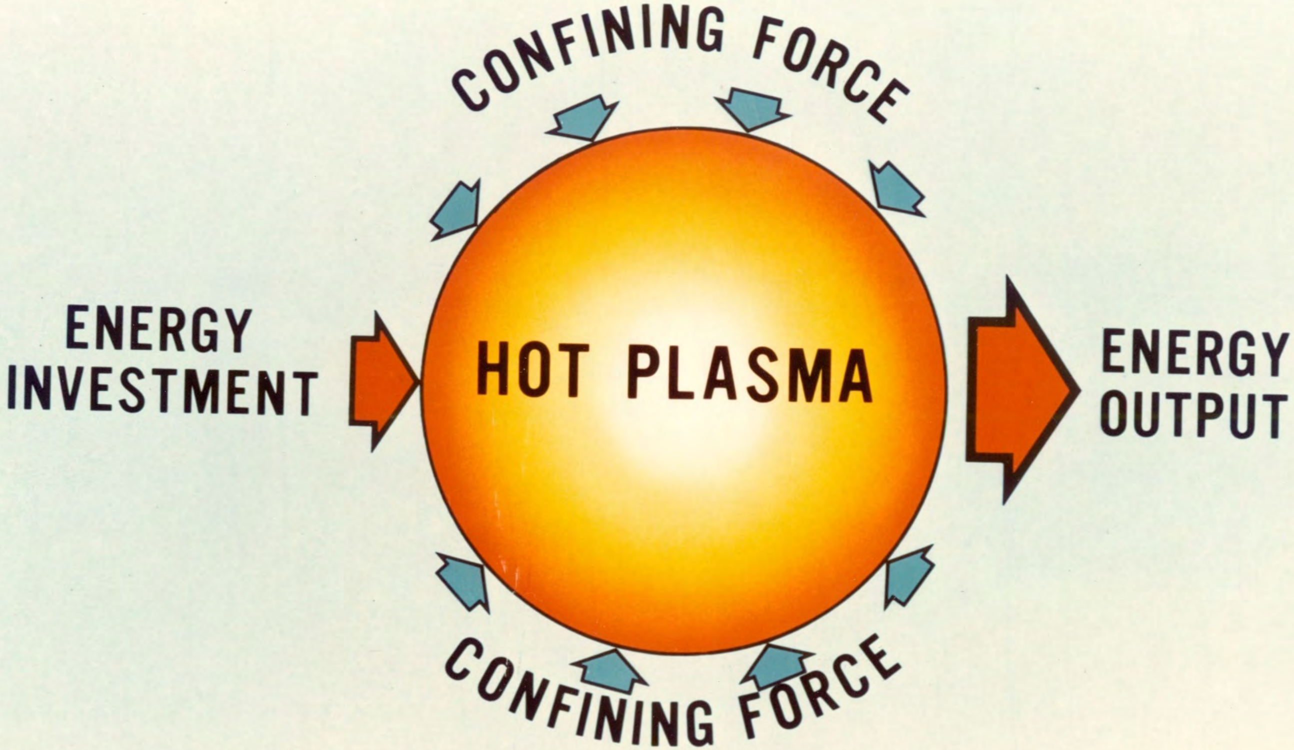
The energetic neutron is captured in a moderator blanket, heating it and reacting with lithium to produce tritium fuel

FUSION POWER PLANT

A conventional heat exchange system removes heat from the moderator blanket

Heat is converted to electricity by a conventional power conversion system





SPECIFICALLY,

$T_{ION} > 5KEV\ (50,000,000°)$

$n\tau > 5\times10^{13}\ cm^{-3}$ -SECONDS

TECHNICAL APPROACHES

Fusion fuel is heated, creating hot "plasma."

It must then be confined long enough to release net energy.

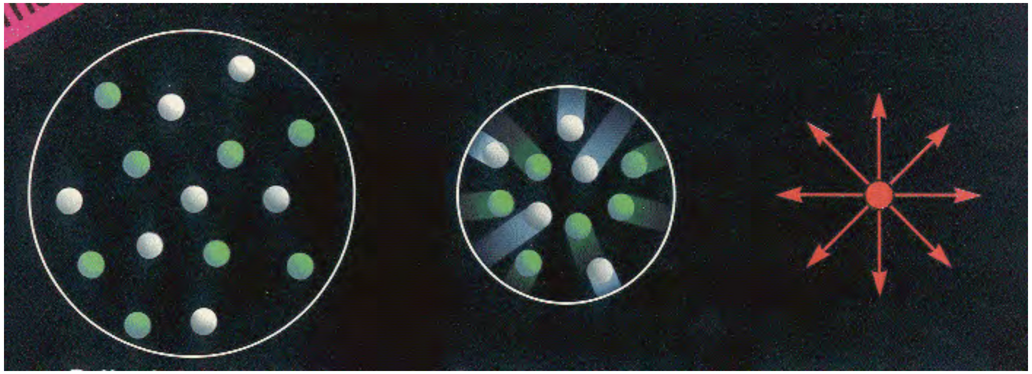
There are three main technical approach categories:

Magnetic Confinement: At low, sub-atmospheric density, the fuel must be confined for many seconds.

Inertial Confinement: At high, greater than solid density, the fuel must be confined for small fractions of a second.

Magneto-Inertial Confinement: At intermediate density the fuel must be confined for a relatively large fraction of a second.

INERTIAL CONFINEMENT



A capsule containing deuterium and tritium is irradiated by x-ray, laser or particle beams,

compressing and heating the fuel to ignition

INERTIAL FUSION "DRIVERS"

Capsules containing fusion fuel may be "driven" by various energy sources

Four drivers are currently under development for energy applications:

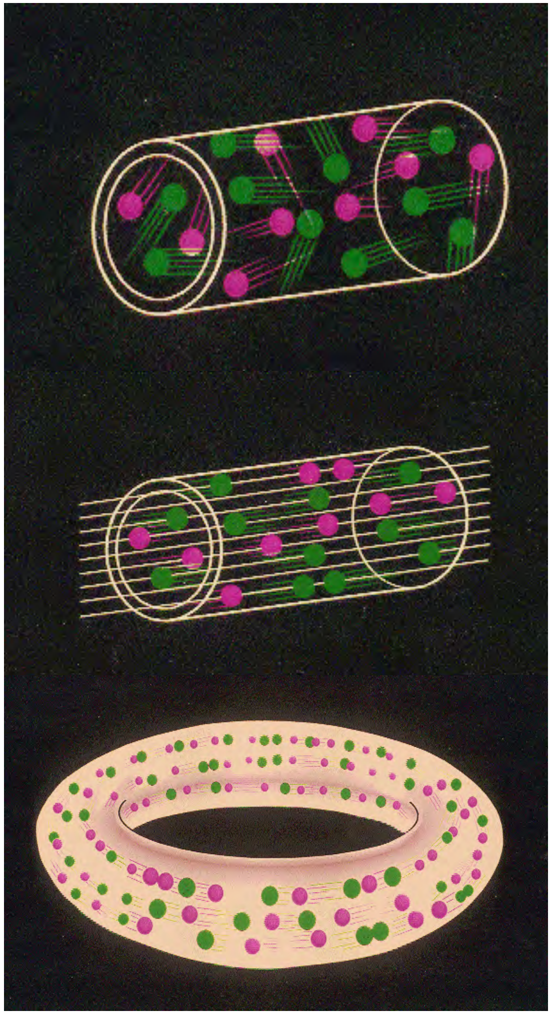
- Krypton Fluoride Lasers
- Diode-pumped solid state lasers
- Heavy-ion accelerators
- Z-pinch X-rays

NATIONAL IGNITION FACILITY
NIF

Laser-based National Ignition Facility (NIF), under construction and in partial operation at LLNL, is aimed at achieving ignition beginning in 2010.


NIF-0506-11956

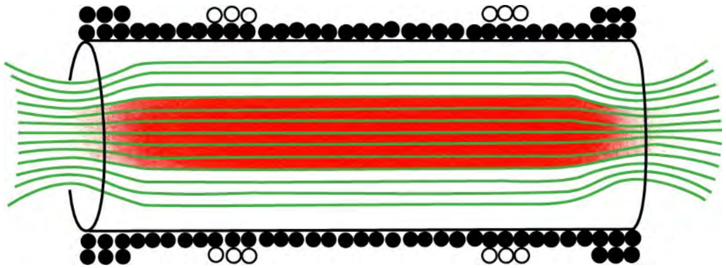
MAGNETIC CONFINEMENT

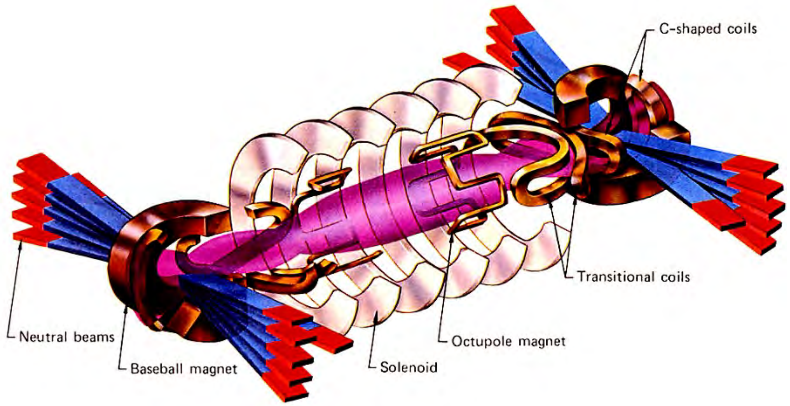


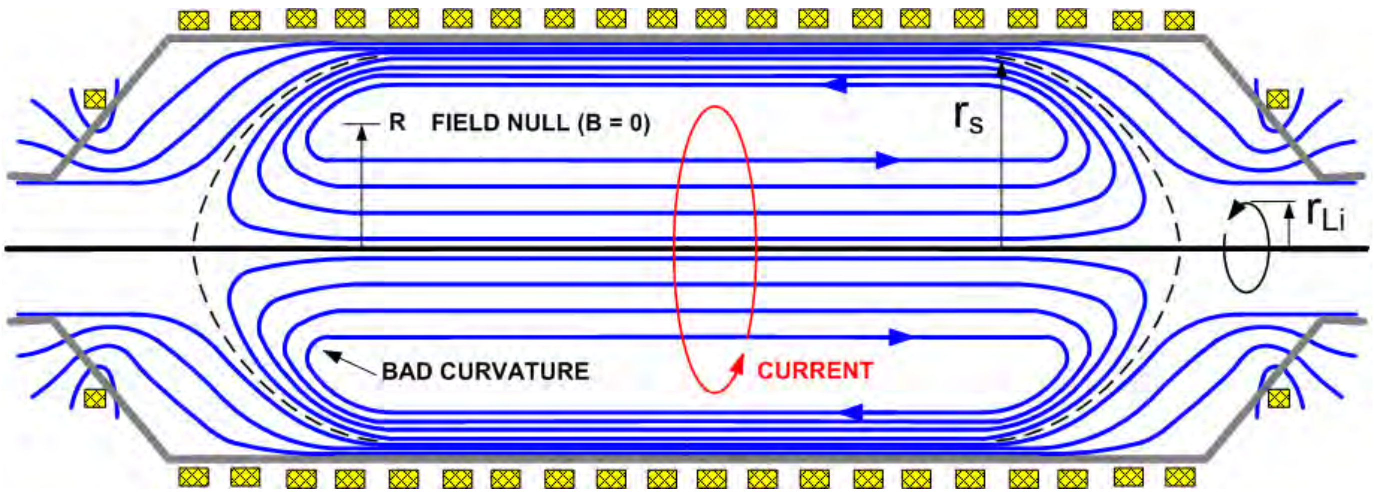
Fast-moving particles in a simple container would quickly strike the walls, giving up their energy before fusing

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

Magnetic fields can be fashioned into complex configurations sometimes called magnetic bottles




C-shaped coils
Transitional coils
Neutral beams
Baseball magnet
Solenoid
Octupole magnet


R
FIELD NULL (B = 0)
r_s
r_{Li}
BAD CURVATURE
CURRENT

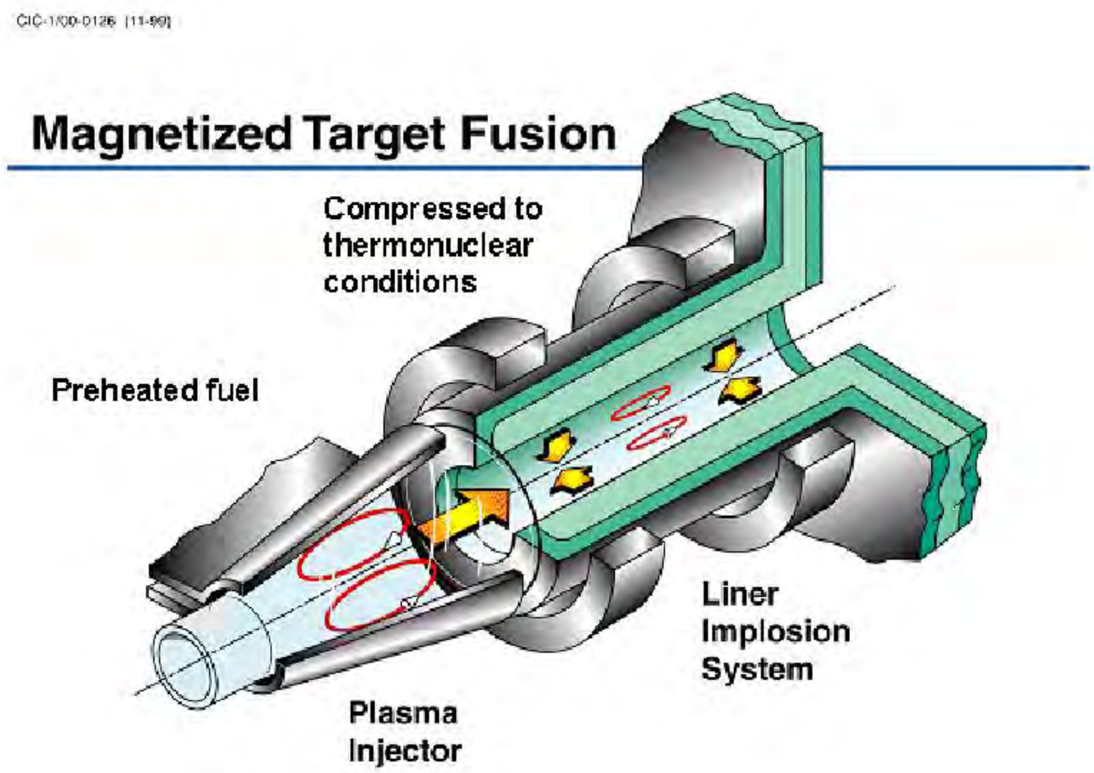
The fundamental parameter space of controlled thermonuclear fusion

Irvin R. Lindemuth and Richard E. Siemon
Department of Physics, University of Nevada, Reno NV 89557

We apply a few simple first-principles equations to identify the parameter space in which controlled fusion might be possible. Fundamental physical parameters such as minimum size, energy, and power as well as cost are estimated. We explain why the fusion fuel density in inertial confinement fusion is more than 1011 times larger than the fuel density in magnetic confinement fusion. We introduce magnetized target fusion as one possible way of accessing a density regime that is intermediate between the two extremes of inertial confinement fusion and magnetic confinement fusion and that is potentially lower cost than either of these two.

See talk at Fusion Power Associates 2010 annual meeting at http://fire.pppl.gov/fpa10_Fusion_principles_Lindemuth.pdf

MAGNETO-INERTIAL FUSION



Building the ALPHA ARPA-E community:
A portfolio of intermediate density approaches

Plasma liner implosion by merging supersonic plasma jets

Staged magnetic compression of field-reversed configuration plasmas.

Shear-flow stabilized Z-pinch pushed to higher density and fusion conditions

Scalable ion beam driver based on microelectromechanical systems (MEMS) technology

Piston-driven implosion of rotating liquid metal liner as fusion driver

"Plasma rope" plumes as a potential magneto-inertial fusion target.

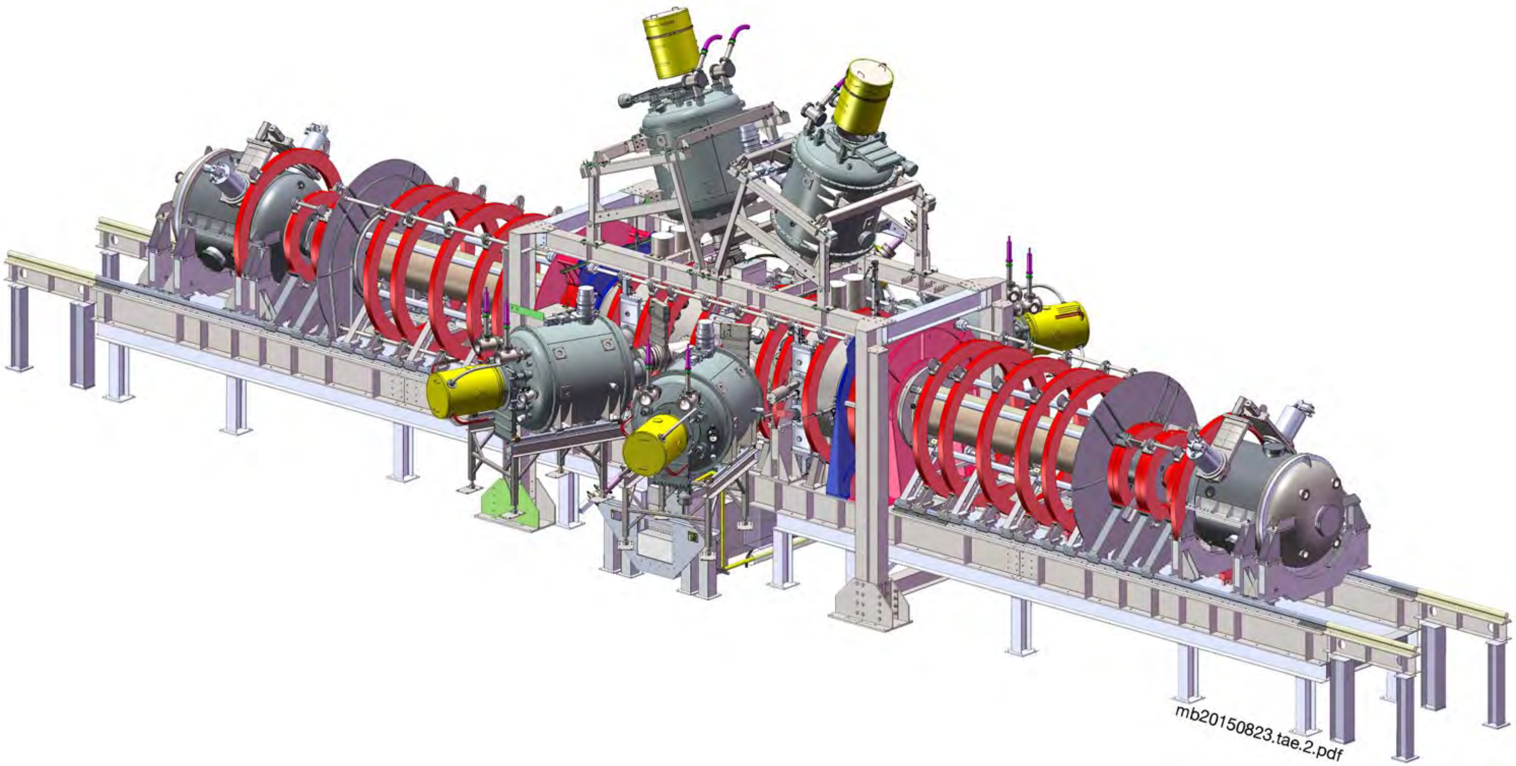
Compression and heating of high energy density, magnetized plasmas at fusion relevant conditions

Staged Z-pinch – a radially-imploding liner on a target plasma

Investigate collisions of plasma jets and targets to characterize fusion scaling laws

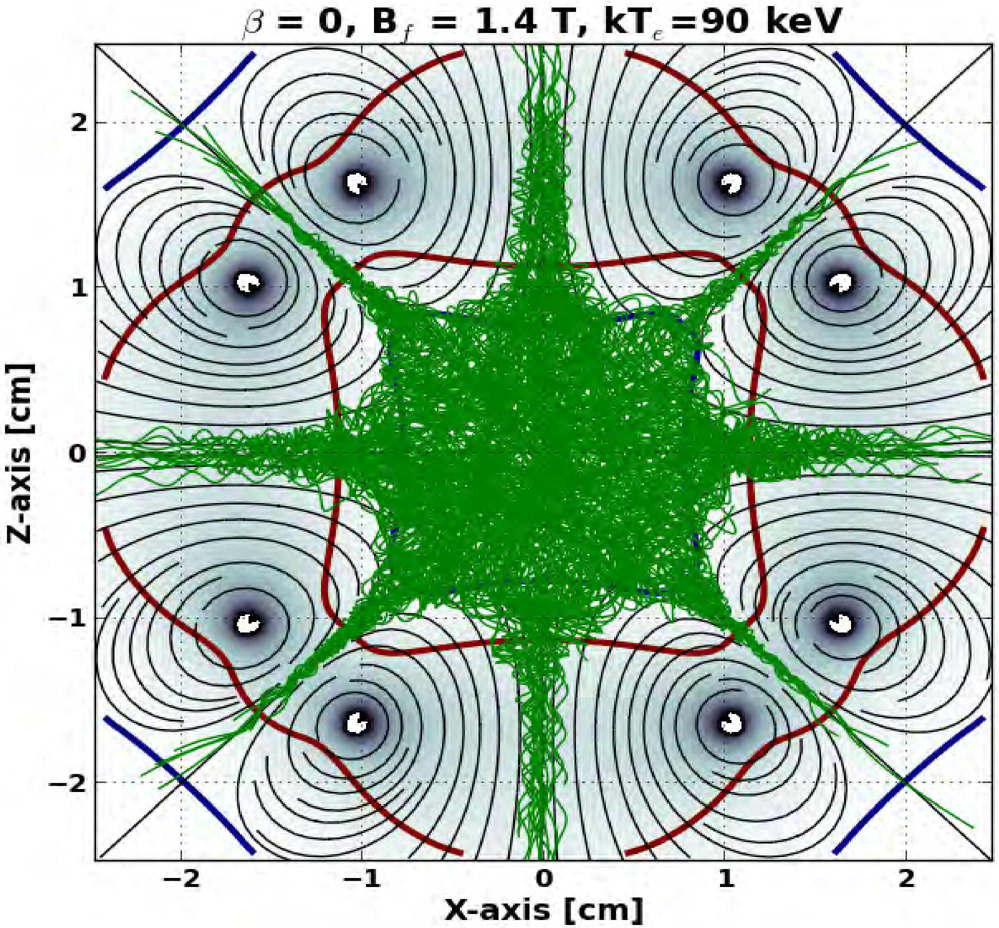
Tri Alpha Energy, Inc

See talk at Fusion Power Associates 2015 annual meeting at
http://fire.pppl.gov/fpa15_TAE-Progress_Binderbauer.pdf

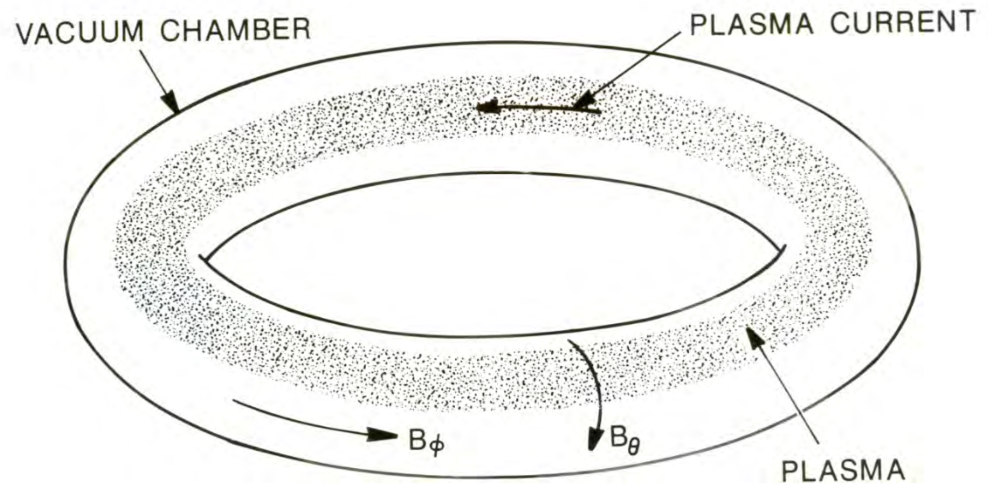


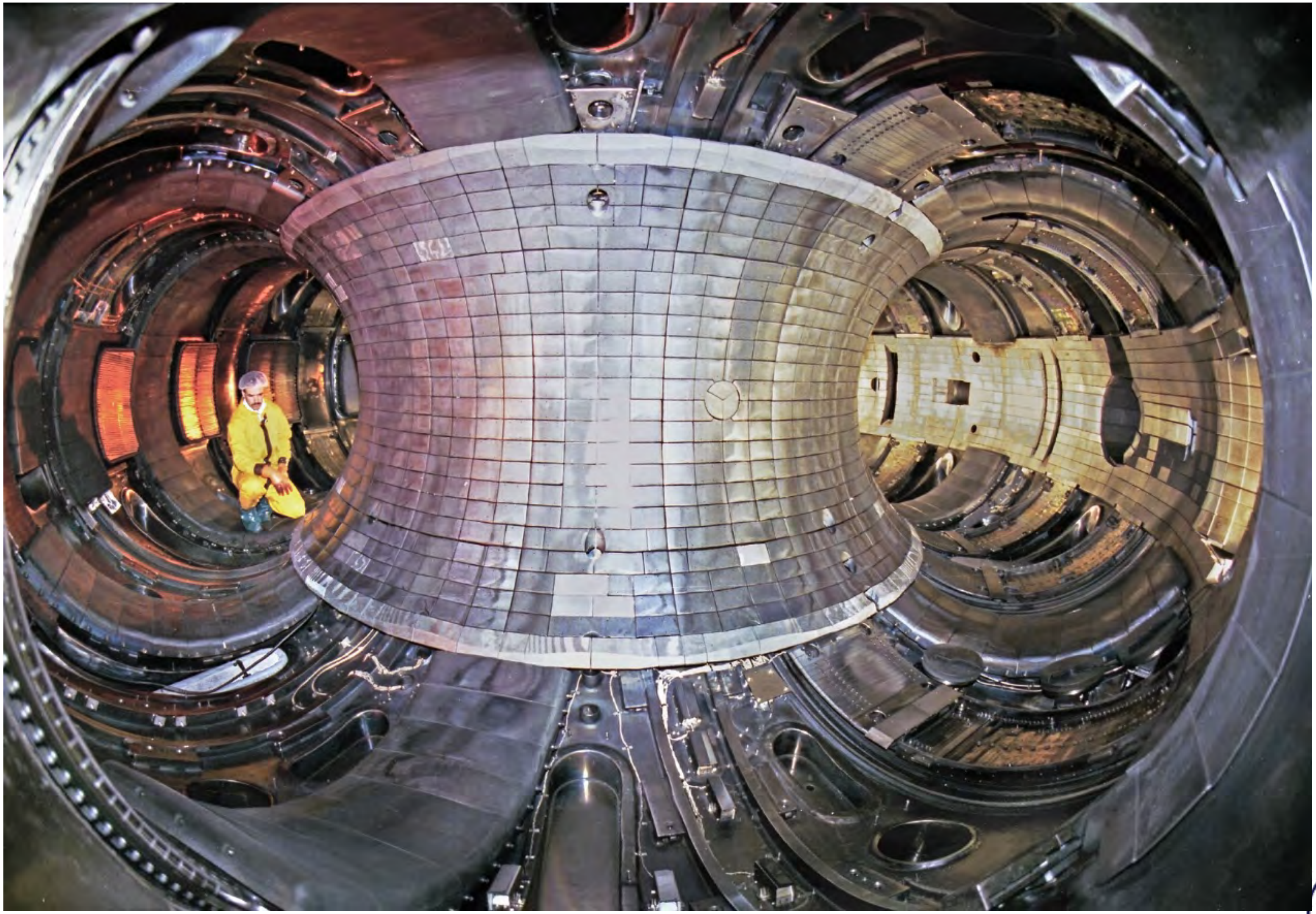
Inertial Electrostatic Confinement (Polywell)

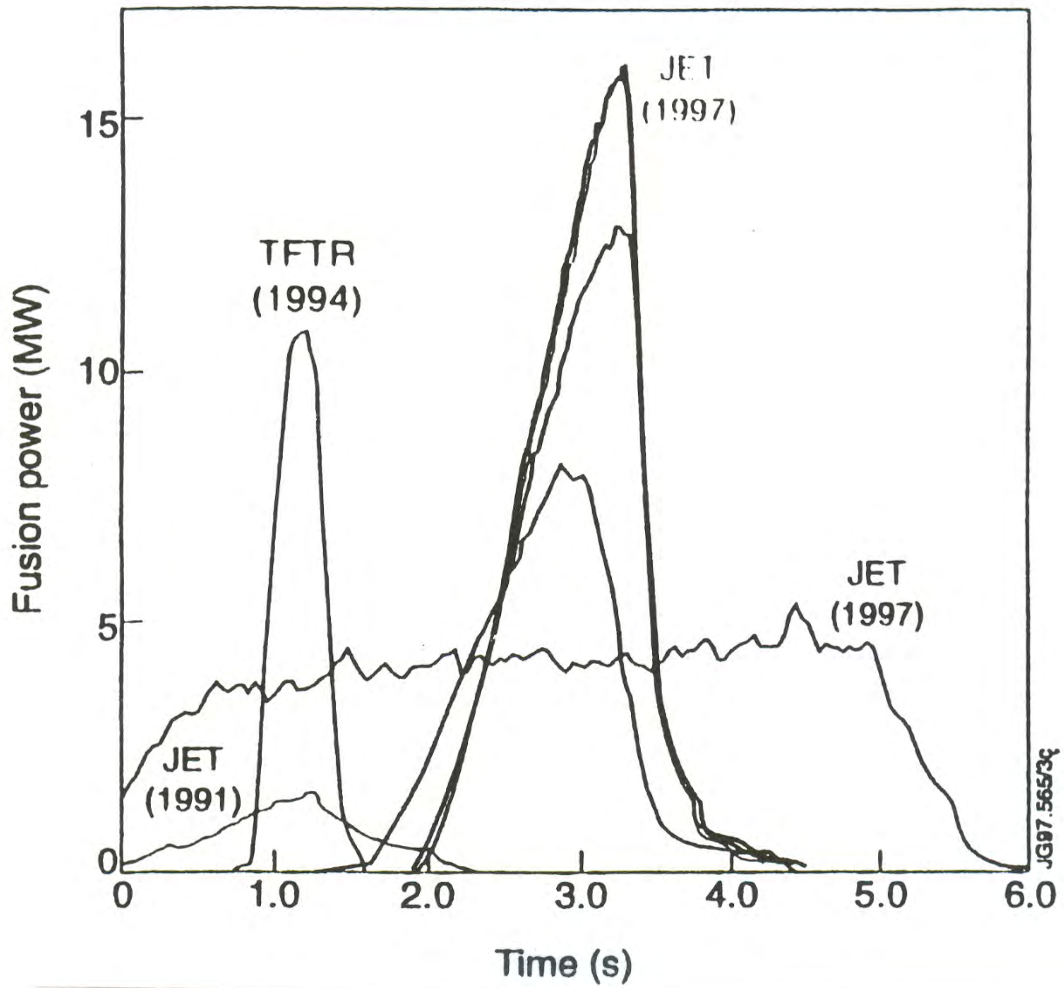
See talk at Fusion Power Associates 2014 annual meeting at
http://fire.pppl.gov/FPA14_IECM_EMC2_Park.pdf



TOKAMAK

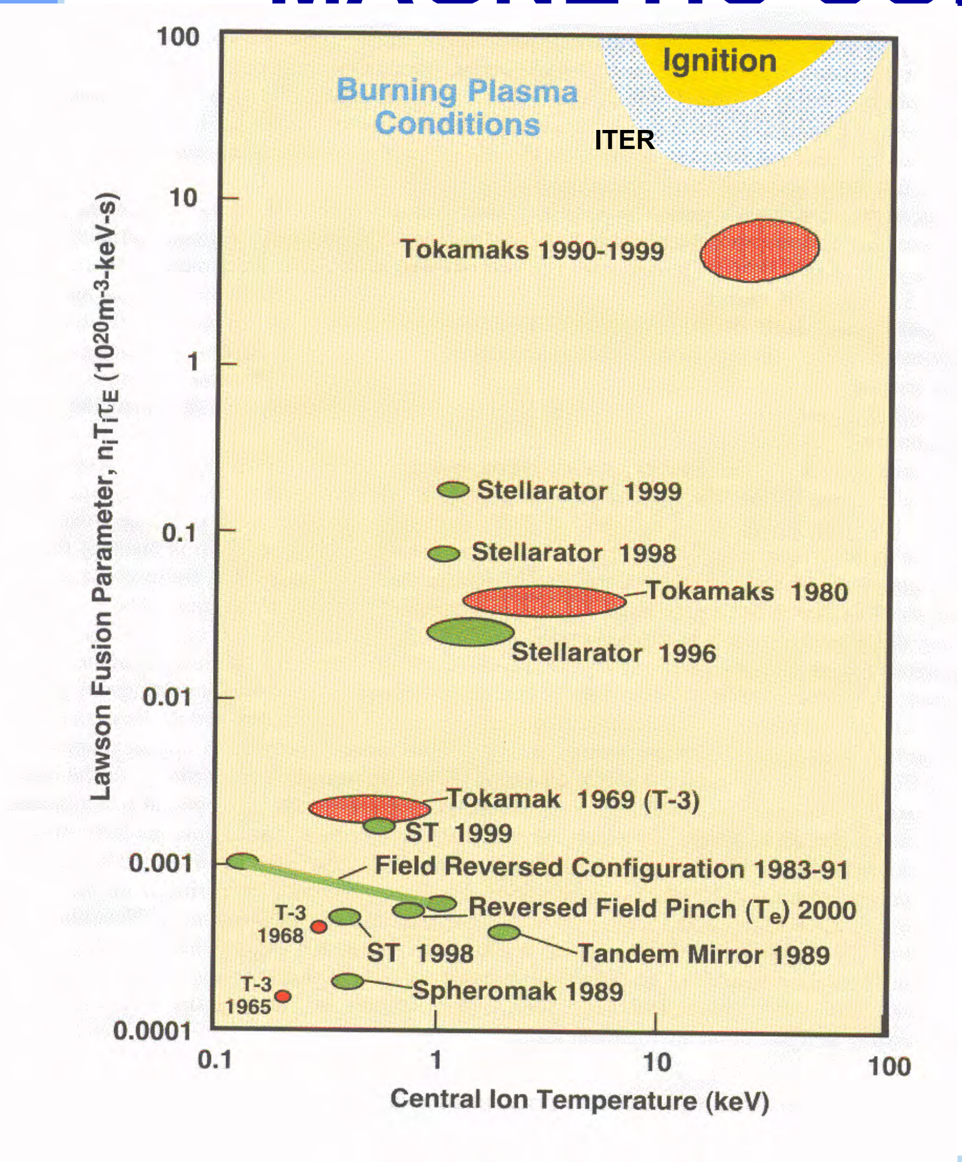






JET
(1997)
TFTR
(1994)
JET
(1997)
JET
(1991)
Fusion power (MW)
0
5
10
15
0
1.0
2.0
3.0
4.0
5.0
6.0
Time (s)

MAGNETIC CONFIGURATIONS



There are many configurations, but the most successful to date has been the tokamak

ITER, a tokamak engineering test reactor, is aimed at achieving fusion conditions around 2025.

Determining τ_E

The empirical fit for τ_E is determined by first collecting a large number of data sets of the type just described from different discharges on the same device. Second, the complete data set from a given device is then combined with similar data sets from many other devices forming the overall database. These overall data are used to determine the empirical fit to τ_E.

The pioneering work in this area was carried out by Goldston. He postulated that the overall data could be modeled by an empirical fit to τ_E of the form

$$\tau_E = C\, B_0^{\alpha_1}\, I^{\alpha_2}\, \overline{n}^{\alpha_3}\, a^{\alpha_4}\, R_0^{\alpha_5}\, \kappa^{\alpha_6}\, A^{\alpha_7}\, P^{\alpha_8}. \tag{14.154}$$

By means of a numerical regression analysis Goldston was able to determine values for the constant C and the exponents α_j. Since his original work the database has increased substantially. In fact, there is now a rather large database, containing thousands of data sets, for both L mode and H mode discharges. The unknown parameters are slowly but constantly improving in time as more data are included in the analysis.

$$\tau_E = C\, B_0^{\alpha_1}\, I^{\alpha_2}\, \bar{n}^{\alpha_3}\, a^{\alpha_4}\, R_0^{\alpha_5}\, \kappa^{\alpha_6}\, A^{\alpha_7}\, P^{\alpha_8}.$$

C = Empirically-derived constant

B = Magnetic field strength

I = Plasma current

n = plasma electron density

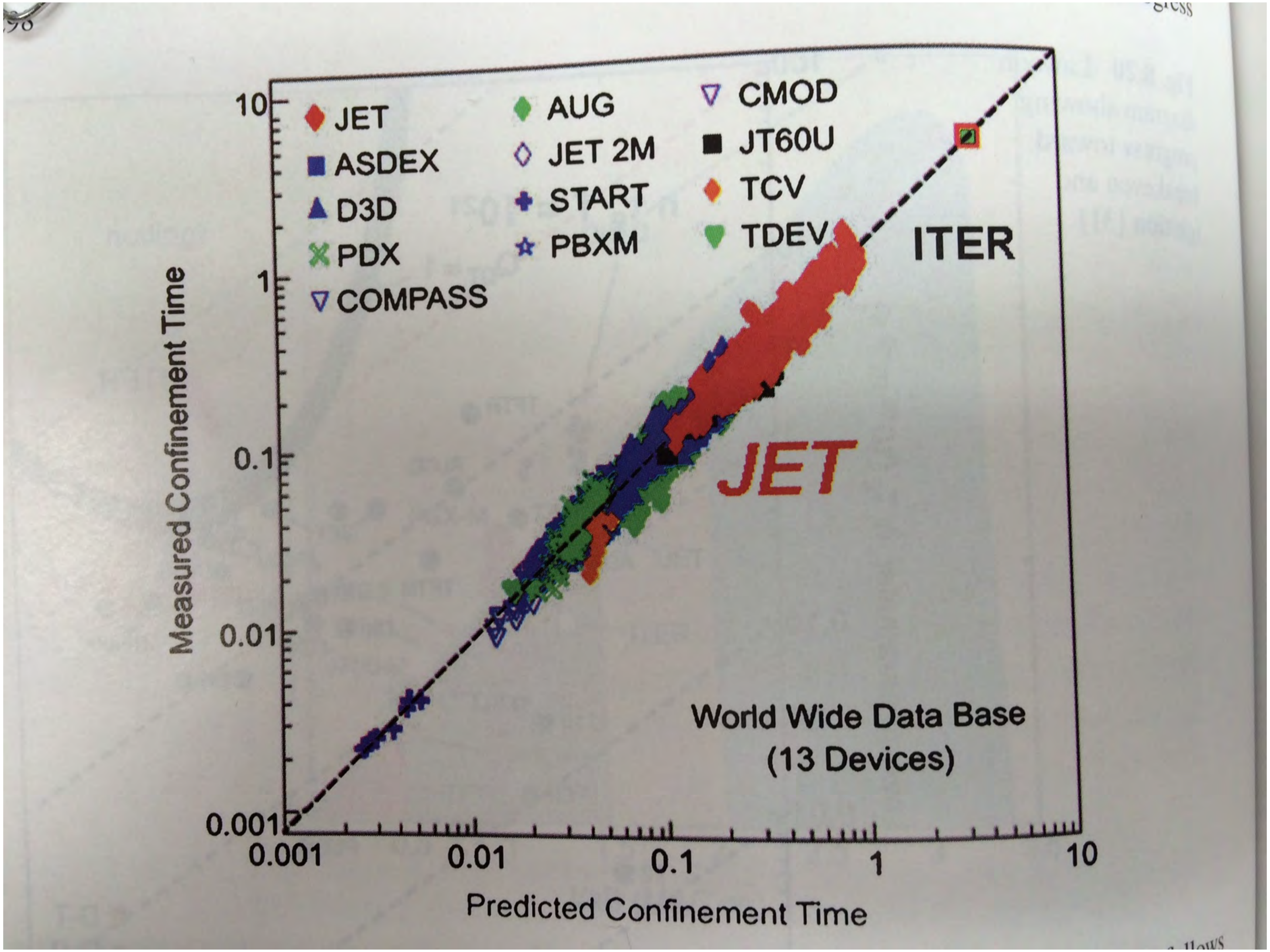
a = plasma minor radius

R = plasma major radius

k = plasma elongation

A = average atomic mass of plasma ions.

P = power input to plasma



JET
ASDEX
D3D
PDX
COMPASS
AUG
JET 2M
START
PBXM
CMOD
JT60U
TCV
TDEV
ITER
JET
World Wide Data Base
(13 Devices)
Measured Confinement Time
Predicted Confinement Time
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10

ITER ENGINEERING TEST REACTOR

A joint venture of the European Union, Japan, Russia, United States, China, India and Korea, sited in France

Construction initiated in 2007

Begin operation in 2016 (original target)

Begin operation in 2025 (current target)

Operation with fusion fuel in 2032

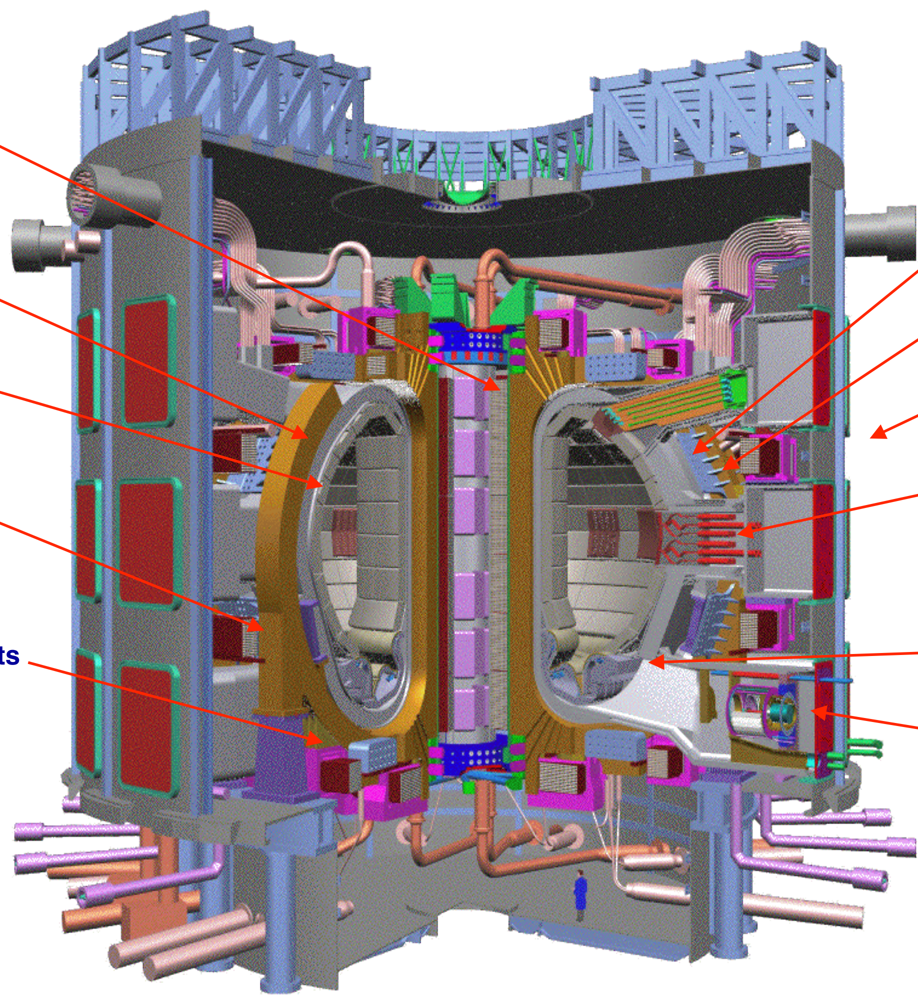
Design Specifications:

Fusion Power: 500-700 Mw (thermal)

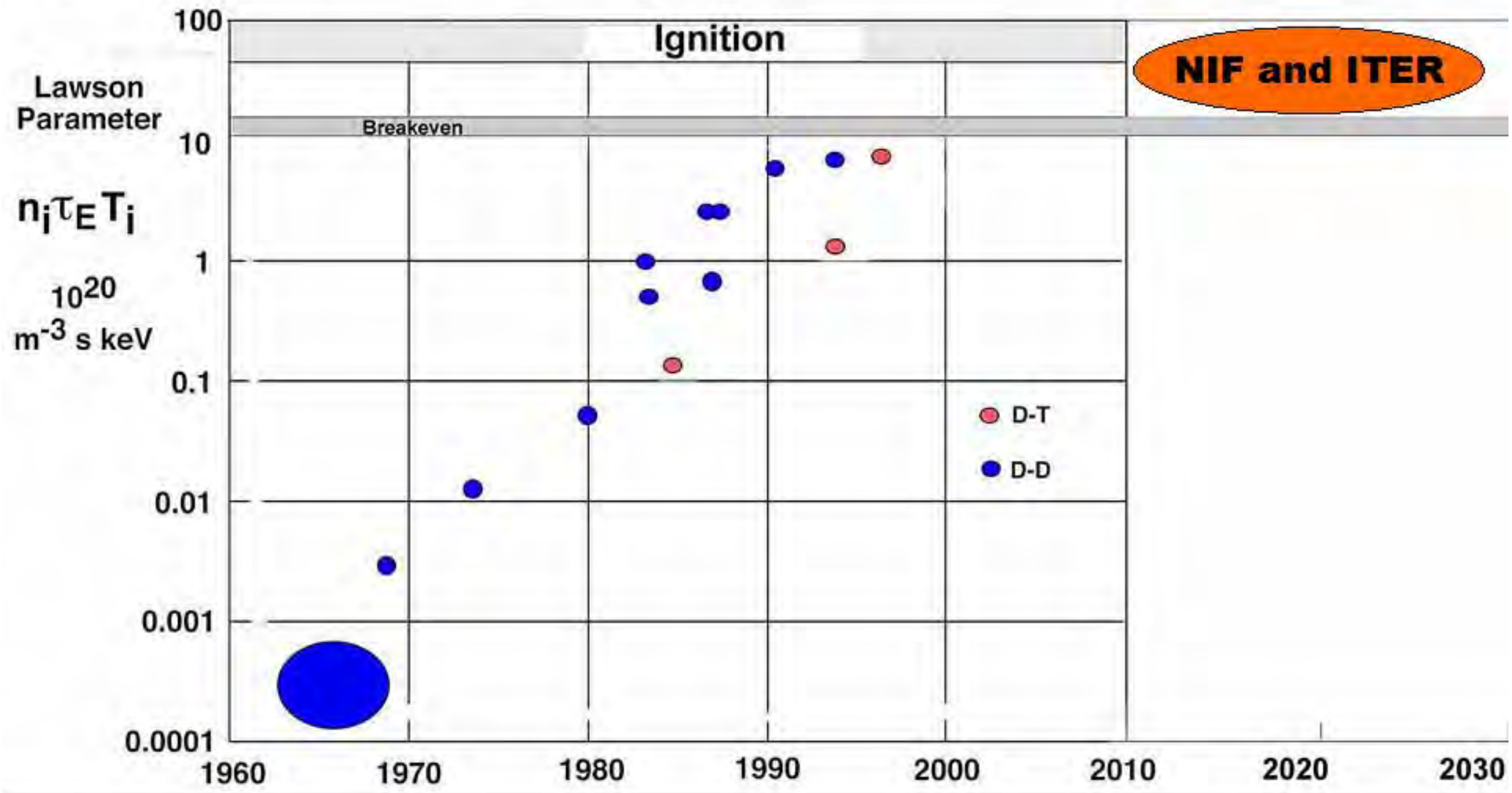
Burn time: 300 s (upgradable to steady state)

ITER

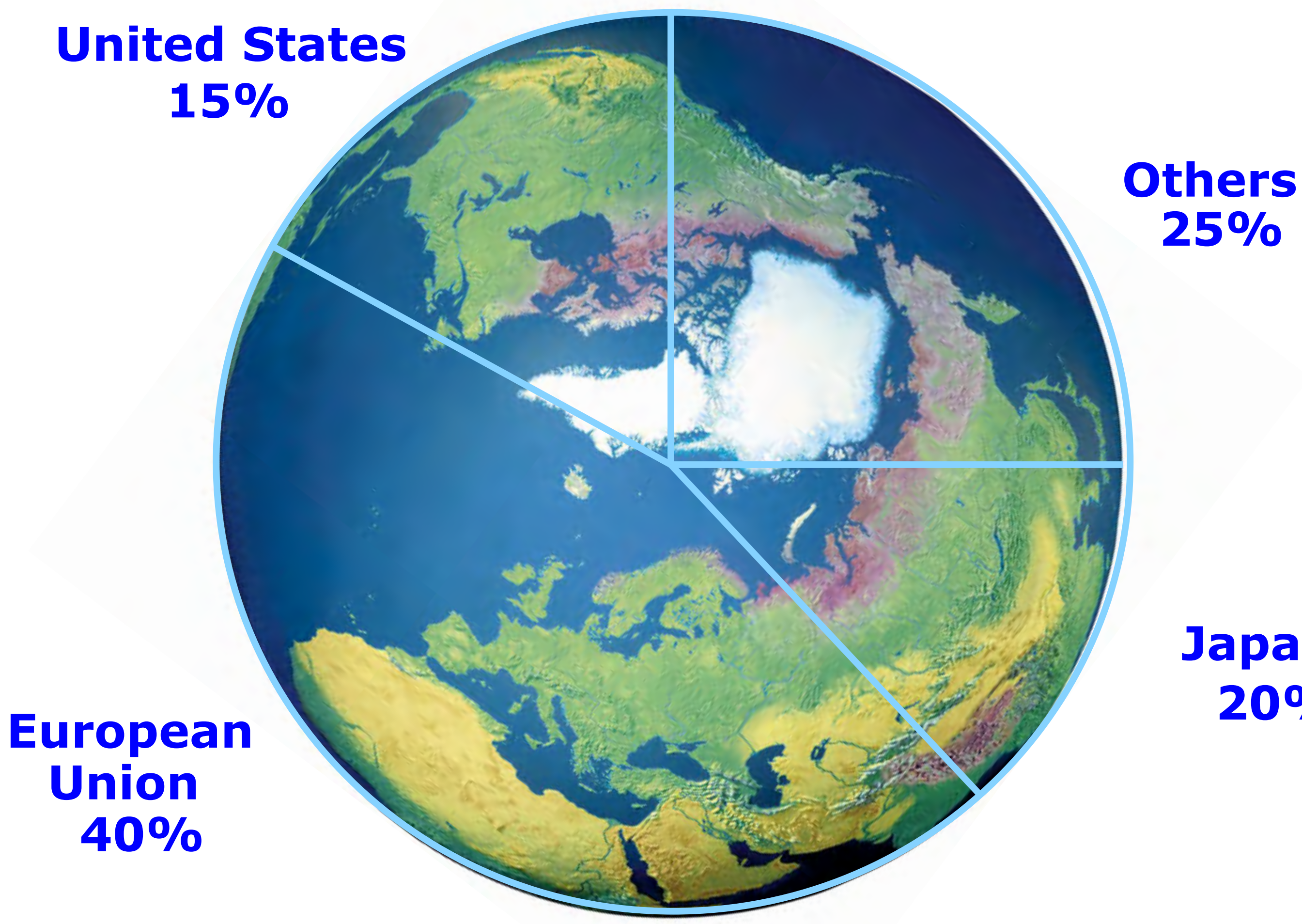
INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR



Fusion Progress and Projections



The U.S. is about 1/6 of the World Magnetic Fusion Effort



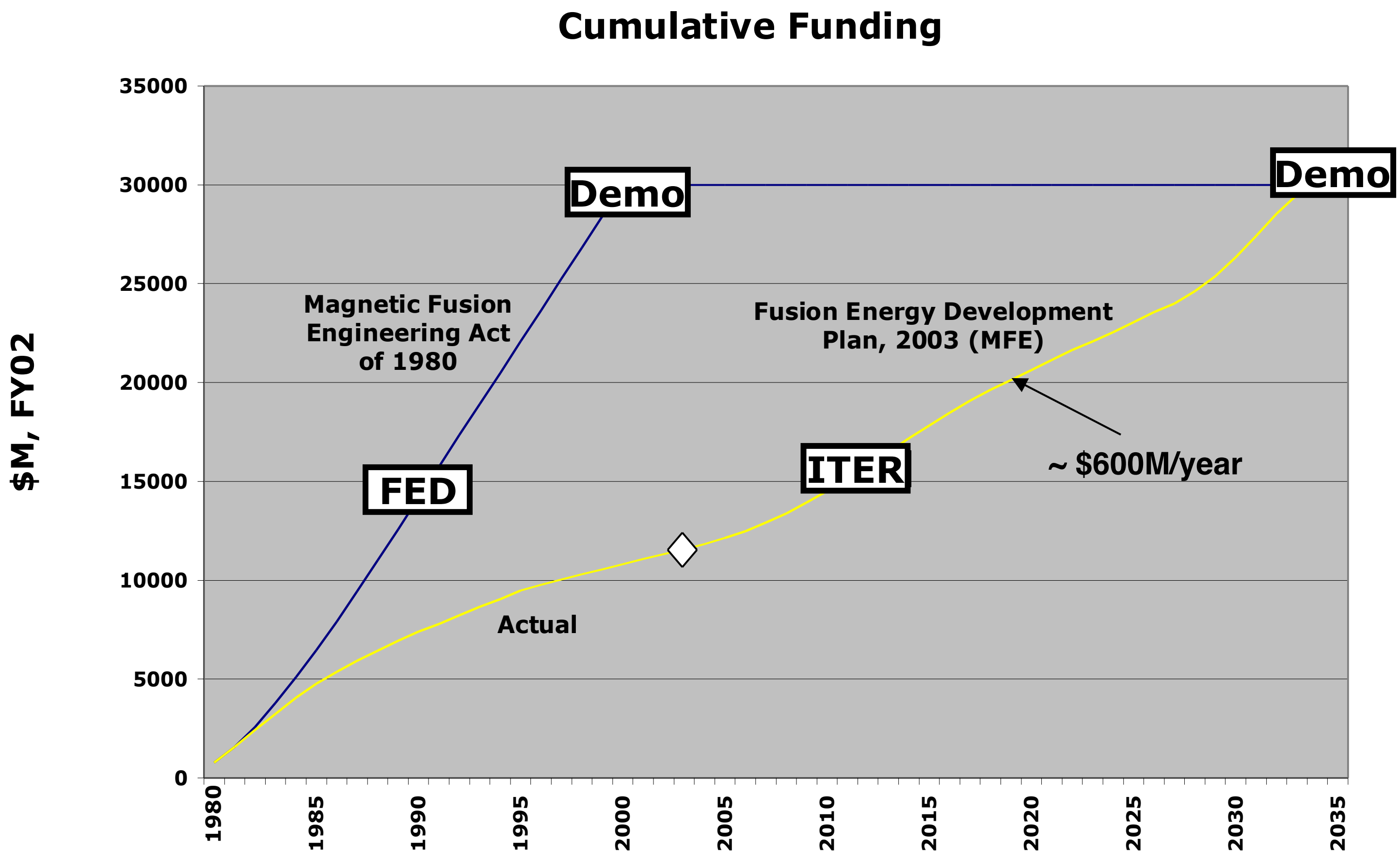
US: $438M/yr
World: ~$3B/yr
(FY 2016)

The U.S. must leverage investment in ITER.

Beyond NIF and ITER

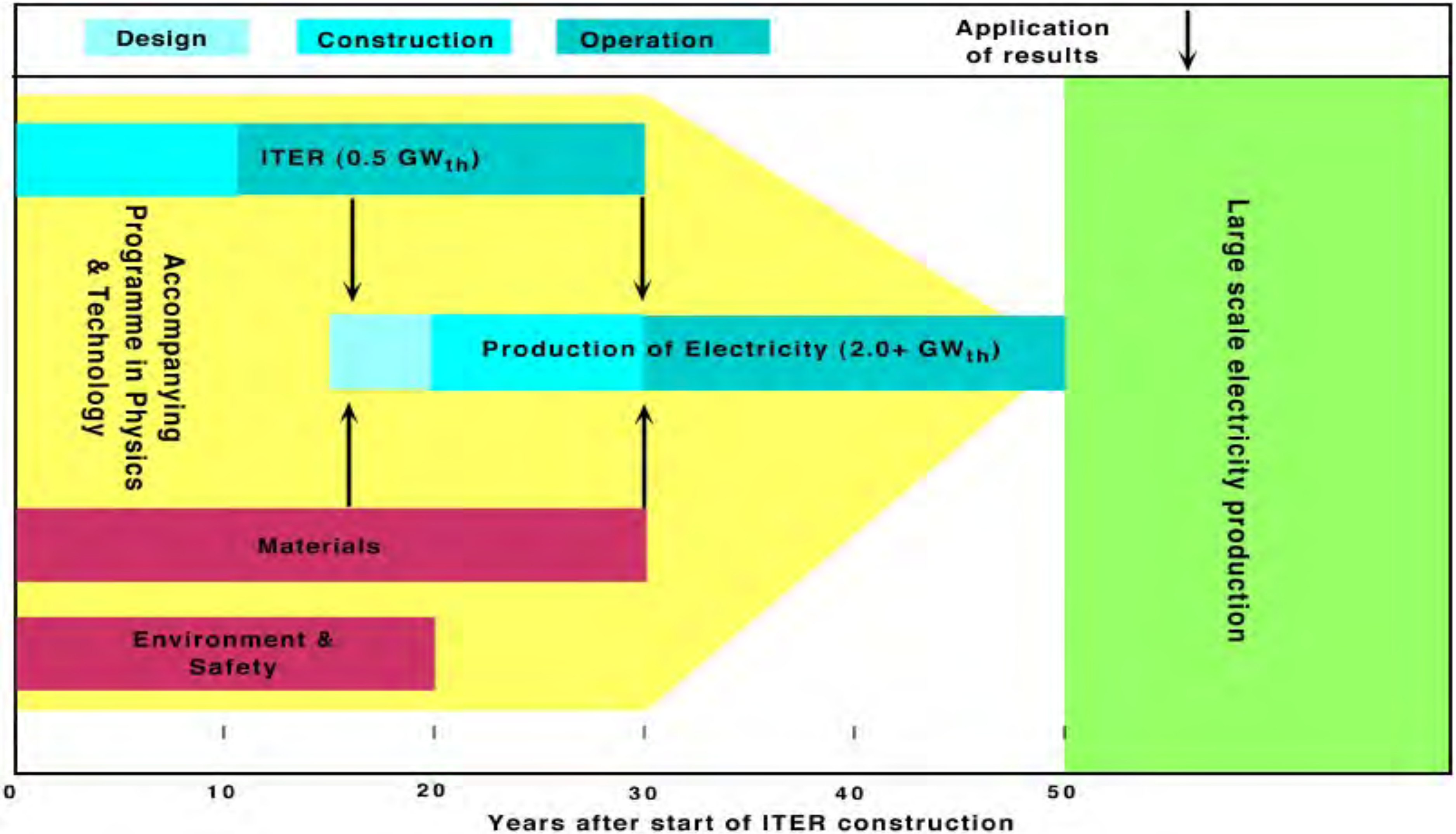
- A number of projections to power plant operation have been made, though there is no official government timetable for fusion
- There are large uncertainties in these projections due to technical unknowns and to lack of firm funding commitments
- The projections range from 15 to 50 years, with a mean around 30-35 years

Fusion can be Brought on Line at the Cost Projected in 1980, on a Timescale to Help Address the Long-term Issue of Climate Change

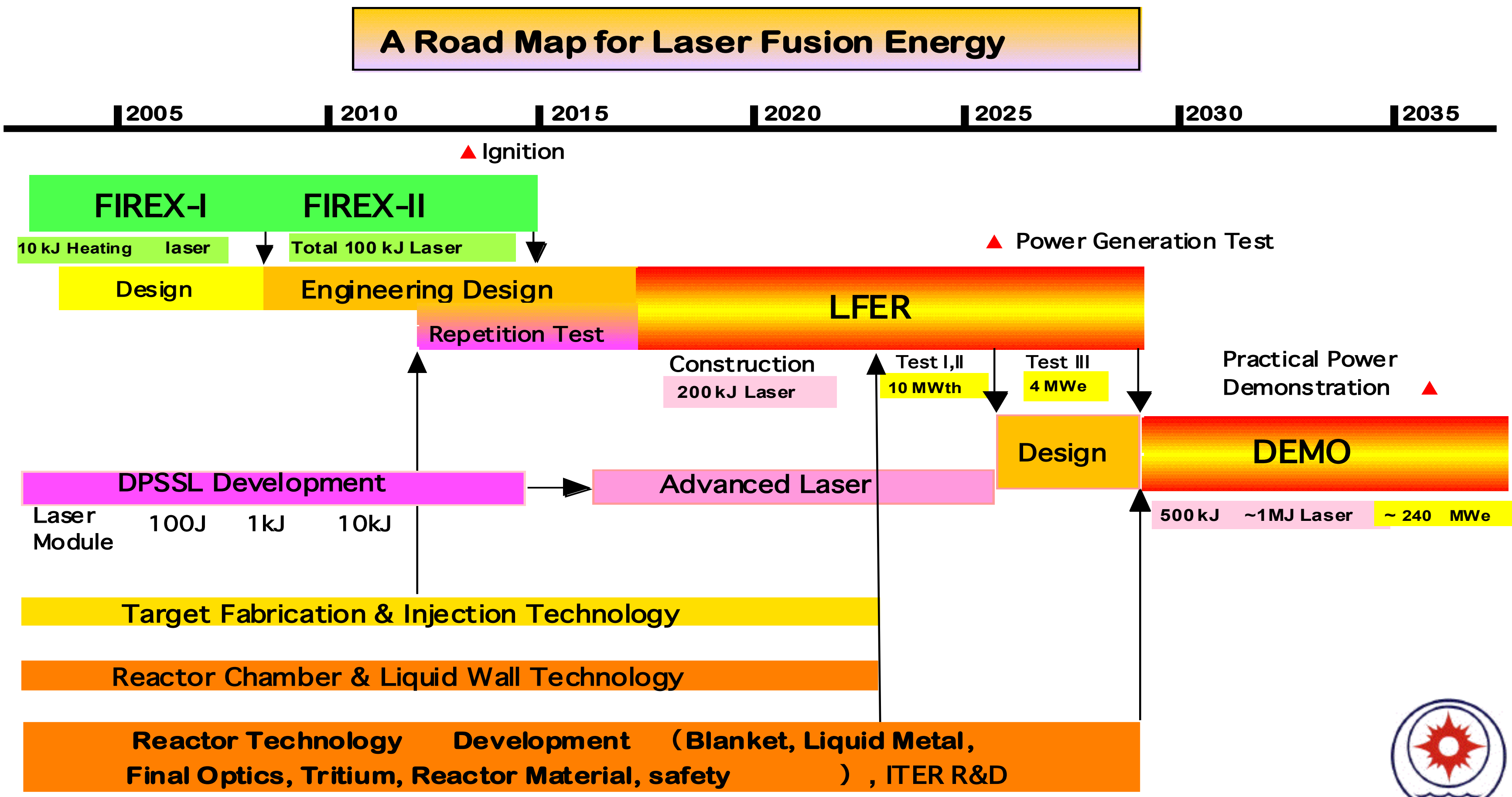


Because of the large size of the energy market, fusion R&D is a good investment for the world.

European Magnetic Fusion Roadmap



JAPAN INERTIAL FUSION ROADMAP



ISSUES

For Magnetic Fusion, the primary issues are optimizing the configuration for effective confinement of the fuel and extending from pulsed to steady-state operation.

For Inertial Fusion, the primary issues are optimizing the techniques for compressing the fuel in a stable manner and extending from single pulse to repetitive pulse operation.

For both, identifying materials that provide long life and low induced radioactivity in a harsh, neutron-rich environment.

For both, optimizing the total system to reduce projected development and capital cost and demonstrating methods for ensuring reliability and cost-effective maintenance.

Fusion Funding

- FY 2016 Appropriations
  - Magnetic: $438 M
  - Inertial: $511 M
-

For detail on progress on a variety of fusion concepts, see talks at Fusion Power Associates annual meetings, posted at http://fusionpower.org/AnnualMeetings.html

2016 meeting will be on December 13-14 at Hyatt Regency Capitol Hill Hotel in DC
For agenda and registration information: http://fusionpower.org/RegistrationForm.html