Nuclear Fusion (核融合)
as Clean Energy Source for Mankind

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政大「物理與生活」通識課程

Taiwan Energy Supply & Demand

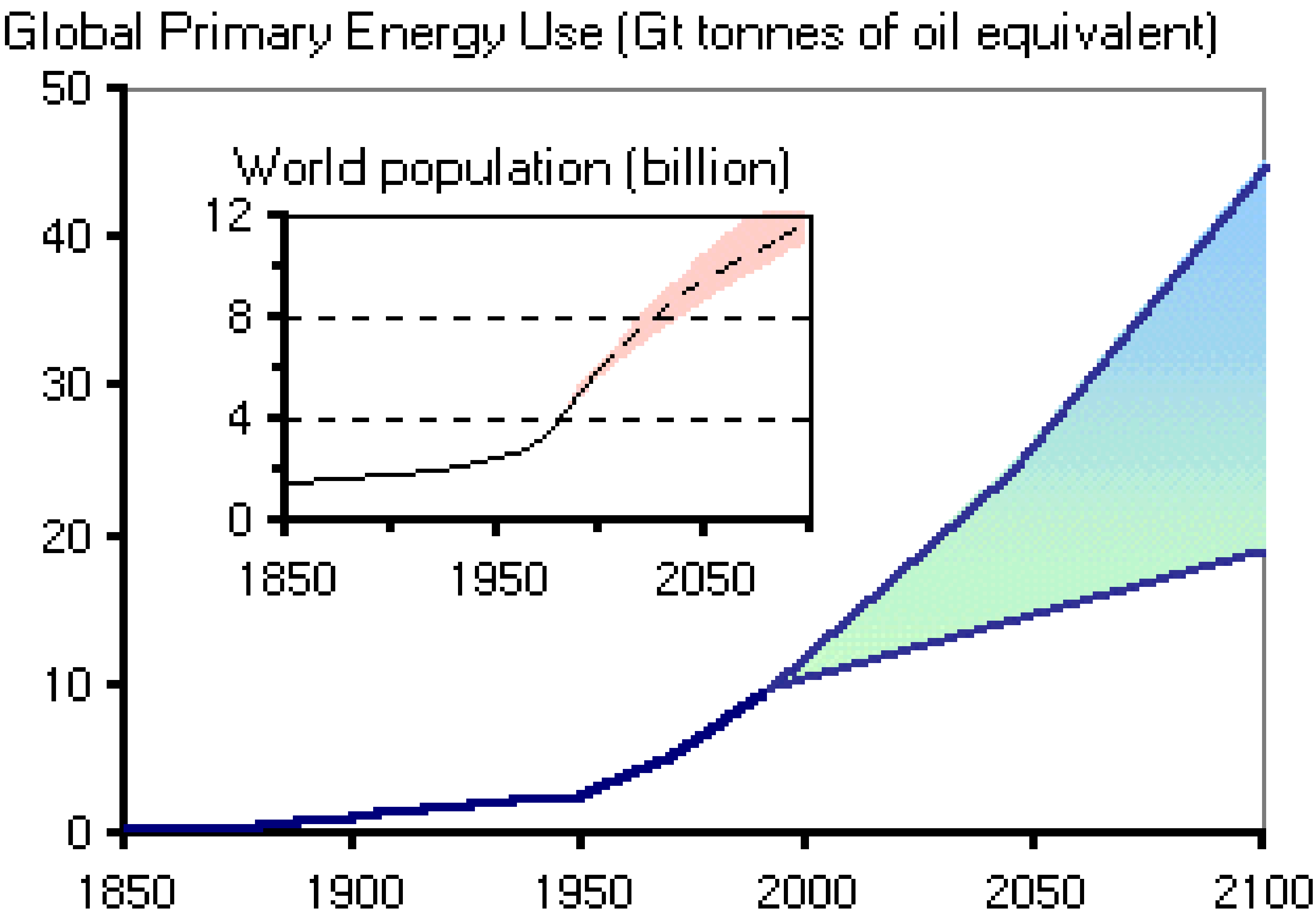
- **Taiwan total oil and natural gas reserve is estimated at ~500 million Barrels of Oil Equivalent (BOE)**

- **Taiwan consumes ~600 million BOE energy in 2000. 98% of Taiwan energy supply is imported – almost completely relying on world energy supply.**

- **Taiwan electricity supply: ~75% by fossil energy resources (coal 43%, natural gas 19%, oil 6%, cogeneration 7%); ~21% by nuclear fission power**

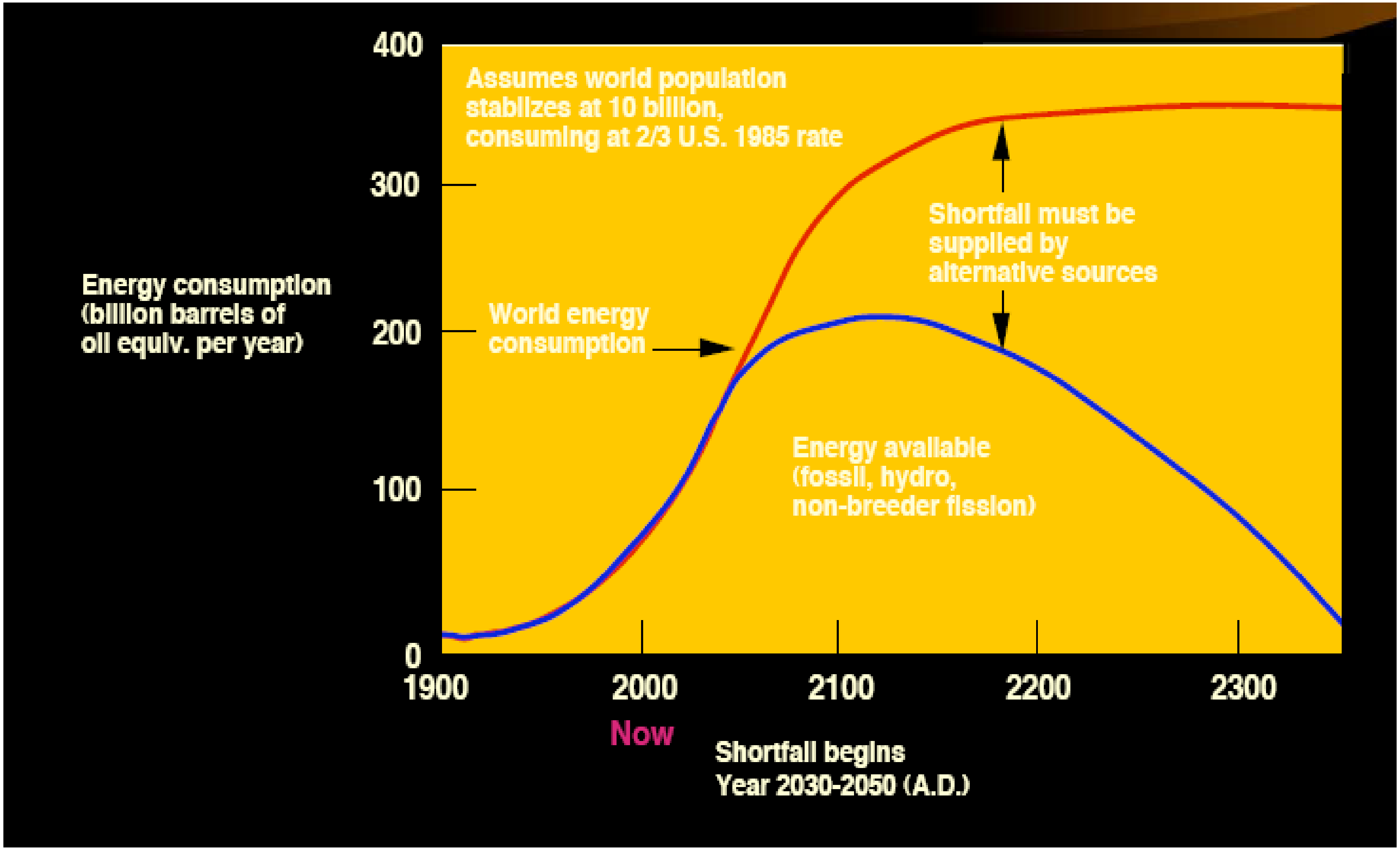
- **How will Taiwan get adequate energy supply?**
  - **Taiwan government aims to achieve ~30% energy supply from renewables (wind power, solar power, hydropower, geothermal, ocean wave & tidal power, biomass) by 2050**
  - **How about the other 70%?**

World Population & Energy Demand



1 ton of oil equiv. = 7.4 barrels of oil equiv.

World Energy Supply & Demand



At our rate of energy use, experts predict an energy shortage in about 30-40 years.

World Energy Supply & Demand

- World energy use is ~ $3T in 2004. **More than 90% of energy use is supplied by fossil energy resources (coal, oil, natural gas)**
- **Running out of fossil fuel (oil first)**
- **Fossil energy consumption has severe impact on climate and environment (CO_2, air polution, global warming)**
- **Energy & environment problems are worsened by growing world population; world energy need will double by 2050; CO_2 concentrations will double by 2100**
- **Nuclear fusion is a climate and environment friendly option for replacing fossil fuels!**

Fossil Fuel Energy Sources - Advantages and Disadvantages

	Advantages	Disadvantages
Coal (220 Years)	• Abundant	• Burns dirty • Causes acid rain, air pollution, CO_2
Oil (35 Years)	• Flexible fuel source with many derivatives • Transportable	• Finite supply • Causes air pollution •Produces CO_2
Natural Gas (60 Years)	• Burns cleanly • Transportable	• Finite supply • Produces CO_2

In US ~93% of coal is used for electricity generation; worldwide ~ 66% for electricity use (~75% by 2025) !

Coal Consumption (Billion Tons)

	2004	2025
N. America	1.1	1.6
Developing Asia	2.1	3.9
W. Europe	0.6	0.4
E. Europe	0.8	0.6
Total (world)	~ 5	~ 7

Rita Bajura, "A global perspective of coal and NG," Director,National Energy Technology Laboratory, Office of Fossil Energy, March 11, 2004. Web: Fire.pppl.gov

CO_2 Emission (Tons/MW)

Current Chinese plants	1.15
Current US plants	1.05
State of the art	0.8
US DOE 2020 goal	0.55 (~ same as gas turbine)

Present CO_2 levels higher than at any time during the past 420,000 years

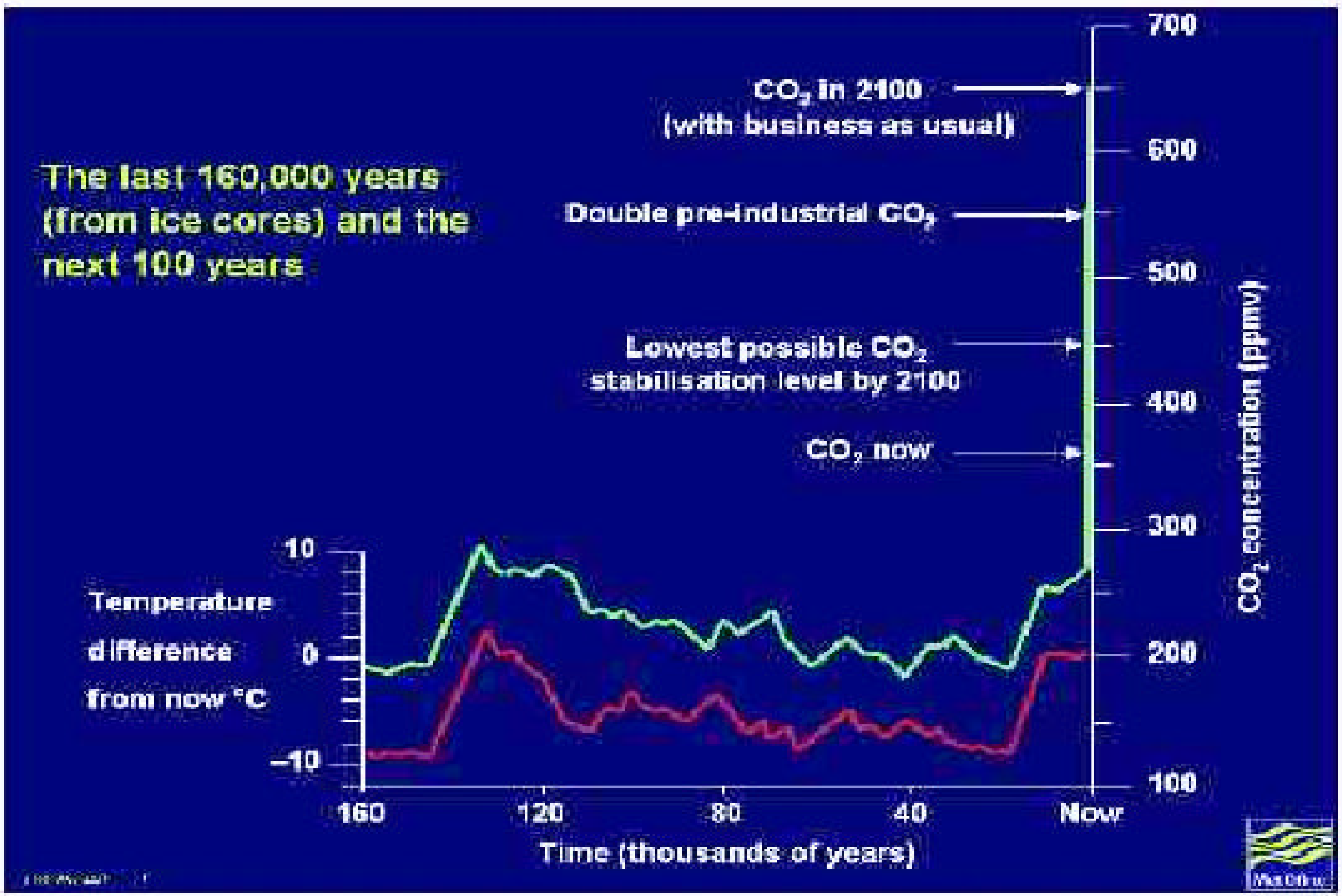


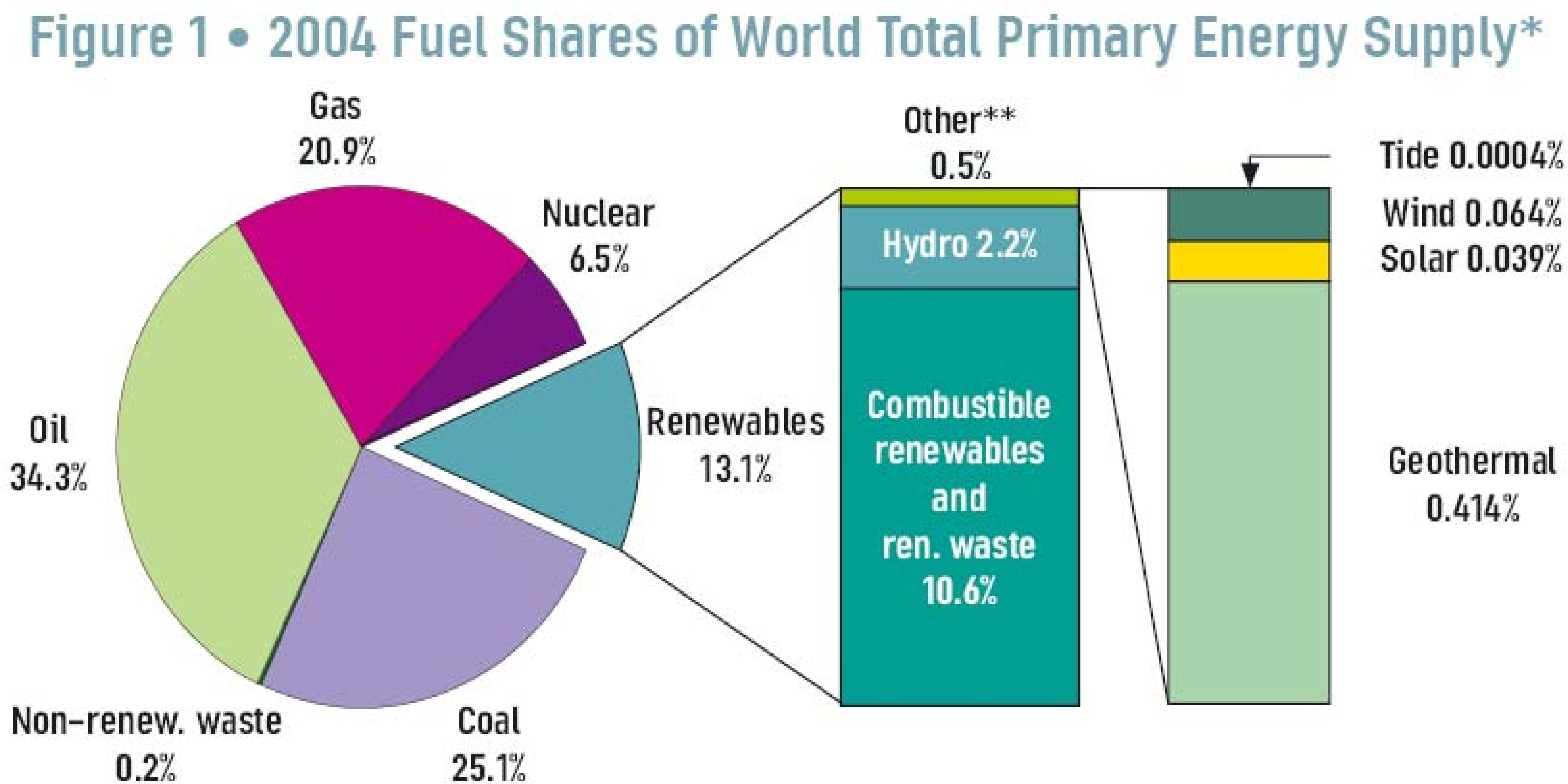
Figure from Sir David King, 31st EPS Presentation, “The challenge of climate change: Developing our low carbon energy”, 28, June 2004, London, UK

- Even with the adoption of all new technologies for fossil electical energy production, CO_2 concentrations will double by 2100
- CO_2 increases can be avoided only by non-fossil energy sources

Non-fossil Energy Source Advantages and Disadvantages

Energy Sources	Advantages	Disadvantages
Fission (Nuclear Power) (45 Years) (2700 Years-Breeder)	• Clean, no CO_2 • Does not produce immediate pollution	• Waste disposal is difficult • Safety concerns
Hydroelectric (mostly utilized)	• Clean, no CO_2	• Dam construction destroys habitats • Geographically limited
Wind (low utilization)	• Clean, no CO_2	• Huge numbers of windmills required for adequate power generation • Geographically limited
Geothermal (low utilization)	• Clean, no CO_2	• Geographically limited
Solar (under utilized)	• Clean, no CO_2	• Huge number of solar cells required for adequate power generation • Geographically limited

Sources: International Energy Agency Energy Statistics

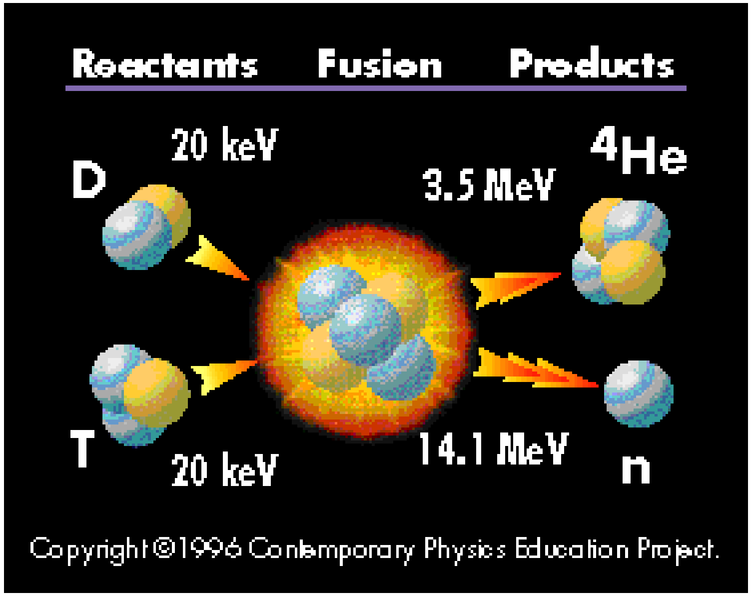


- **Taiwan government aims to achieve ~30% energy supply from renewables by 2050.**
- **> 70% energy must be supplied by fossil fuel and nuclear energy (fission & fusion). However, fossil fuel will run out first.**
- **Fusion is a viable clean energy source!**

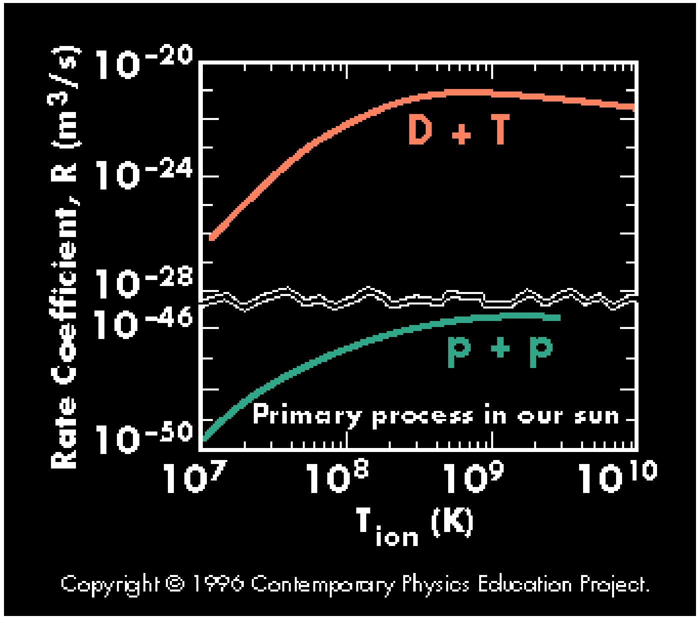
Nuclear Fusion

Fastest fusion reaction is:

D + T ➔ n (14 MeV) + ^{4}He (α-particle, 3.5 MeV)



For first generation fusion reactors



$E = mc^2$ (Mass lost fraction ≈ 0.38%)

Energy gain ≈ 450

20% goes to sustain fusion

80% goes to generate electricity

Needs a plasma at T_{ion} ≈ 10 keV (10^8 K)

Different Fusion Reactions

Reaction: Fuel	Reaction: Product	Ignition Temperature (millions of °C)	Ignition Temperature (keV)	Output Energy (keV)
D + T	^4He + n	220	20	17,600
D + ^3He	^4He + p	350	30	18,300
D + D	^3He + n	400	35	~4,000
	T + p	400	35	~4,000

^3He supply is very limited, but can be mined from the Moon.

ADVANTAGES OF FUSION

- **Abundant Supply of Fuel (deuterium and tritium)**
- **No Risk of Nuclear Accident**
  - **No reactor meltdown possible**
  - **Large uncontrolled release of energy impossible**
- **Minimal or No High Level Nuclear Waste**

  Careful material selection should minimize waste caused by neutron activation
- **No Air Pollution of Greenhouse Gases**

  Reaction product is Helium and neutron

Abudant Supply of Fusion Fuel

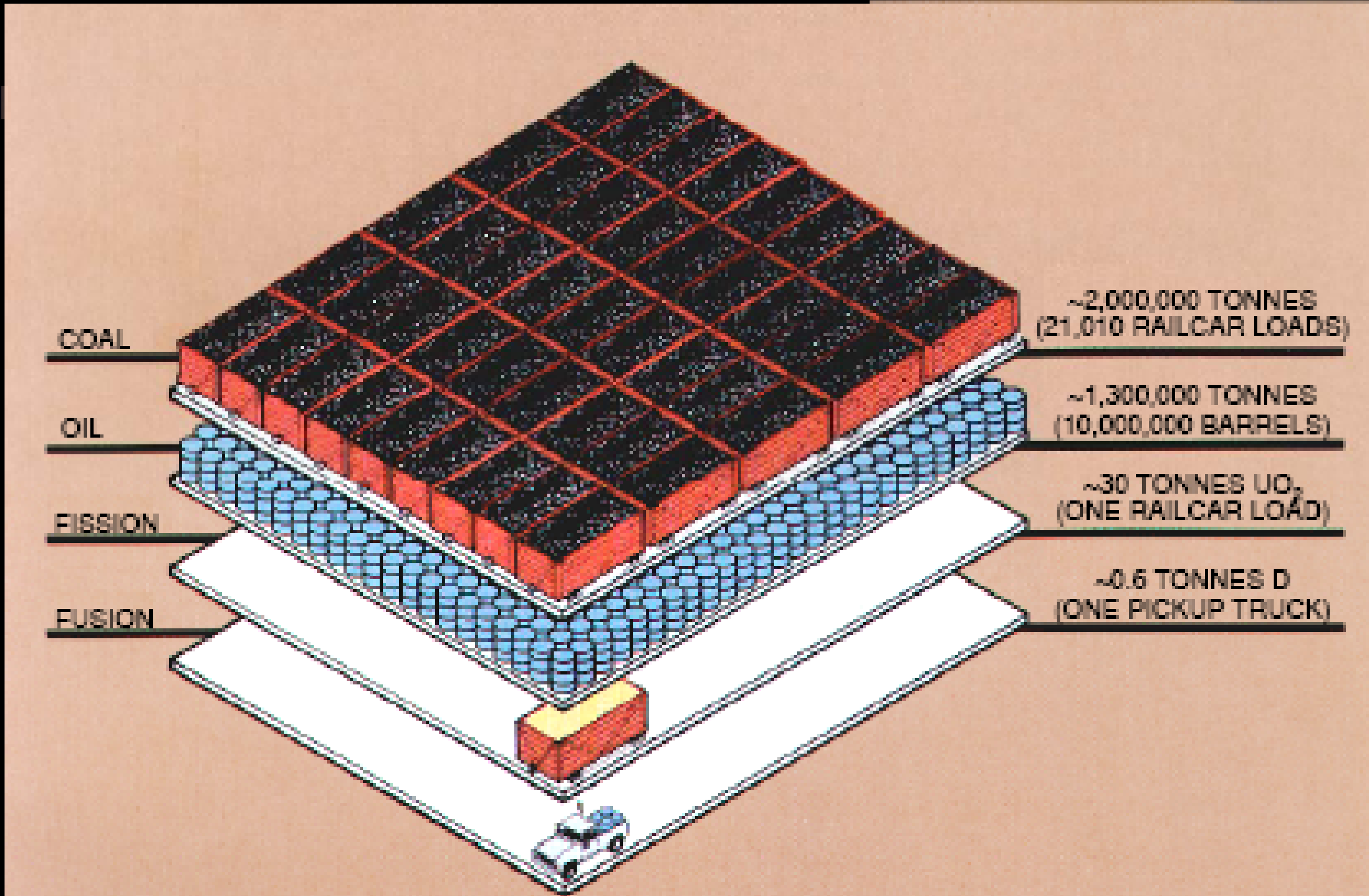
- Deuterium isotope ≈ 1/ 7000 of hydrogen atoms in water and can be extracted at a negligible cost (≈ $1/gr)
- Deuterium in 1 gallon of water has the same energy as 300 gallons of gasoline, if burned in a fusion D-T reactor
- Tritium is not present in Nature (13 year half-life), but slightly more than 1 tritium atom can be created for each DT neutron in a lithium "breeding blanket"

$Li^6 + n \rightarrow T + He^4$ (7% natural Li)
$Li^7 + n \rightarrow T + He^4 + n$ (93% natural Li)

DAILY FUEL CONSUMPTION
DAILY WASTE PRODUCTION
1,000 MEGAWATTS

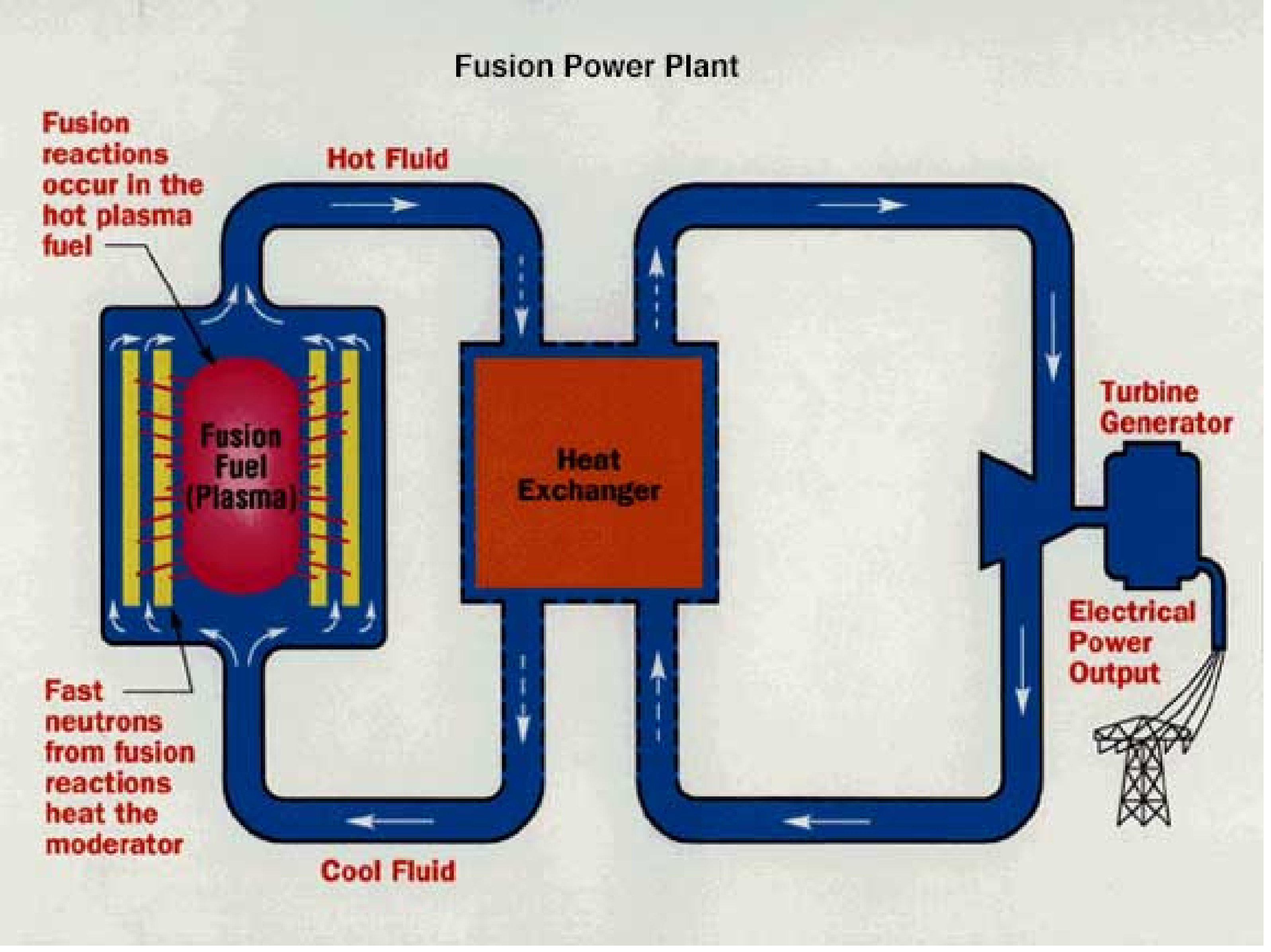
	COAL PLANT	D-T FUSION PLANT
FUEL	9,000 T. COAL	1.0 LB D_2 3.0 LB Li^6 (1.5 LB T_2)
WASTE	30,000 T. CO_2 600 T. SO_2 80 T. NO_2	4.0 LB He^4

FUEL NEEDED FOR ONE YEAR OF POWER PLANT OPERATIONS (1000 MWe)

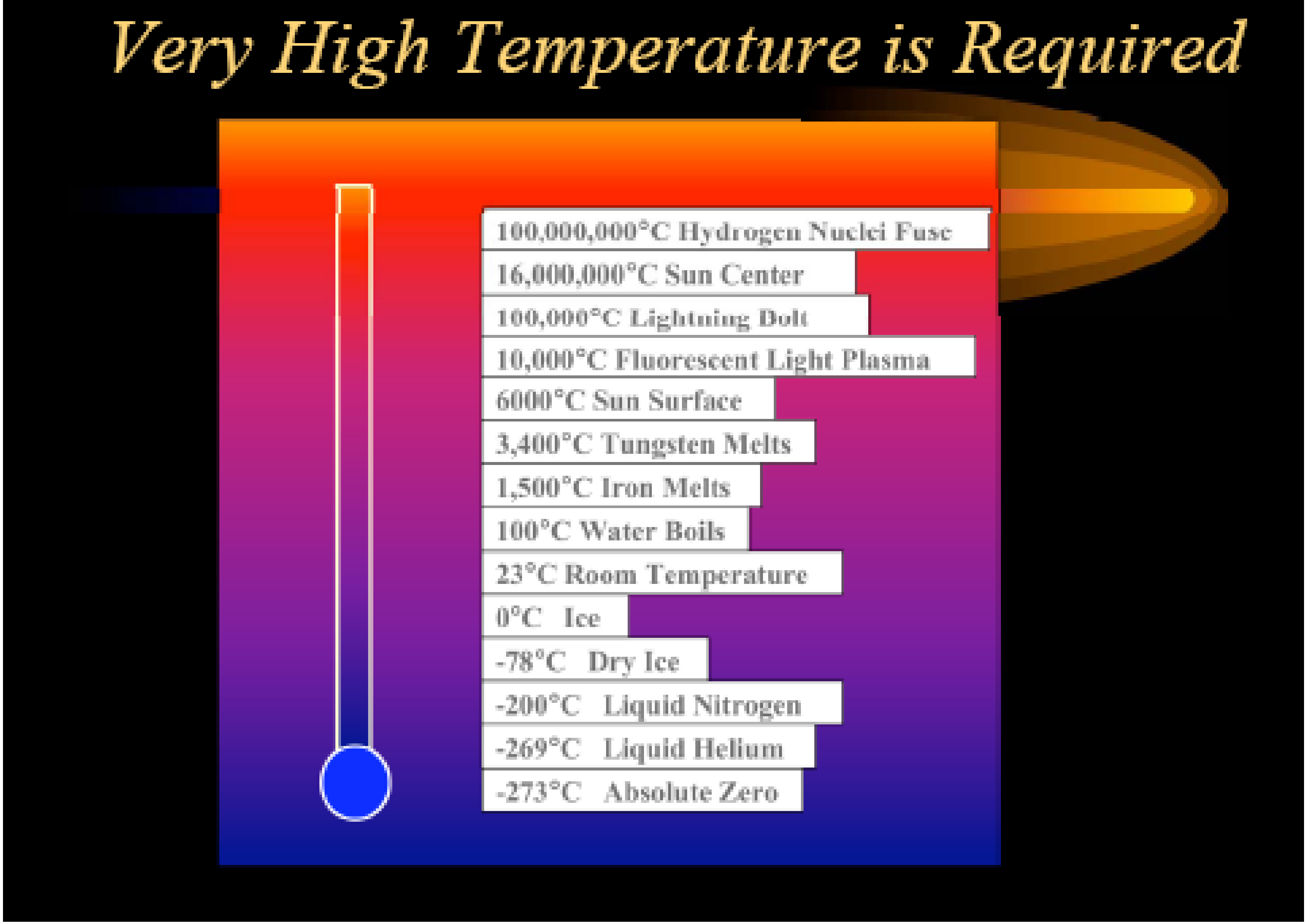


Fusion energy release from 1 gm of DT fuel equals the energy from 2400 gallons of oil

Fusion Power Plant

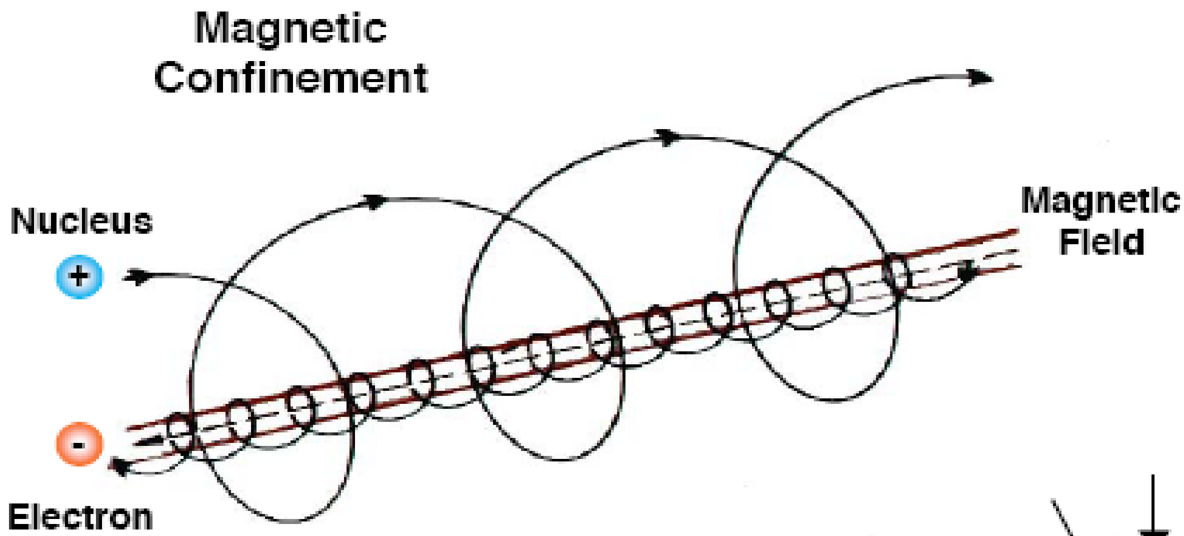


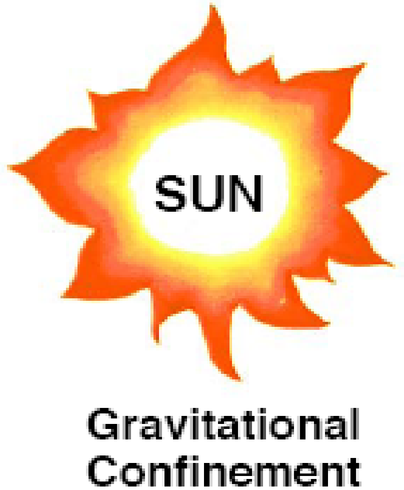
To overcome repulsive electrical force of like charged particles,

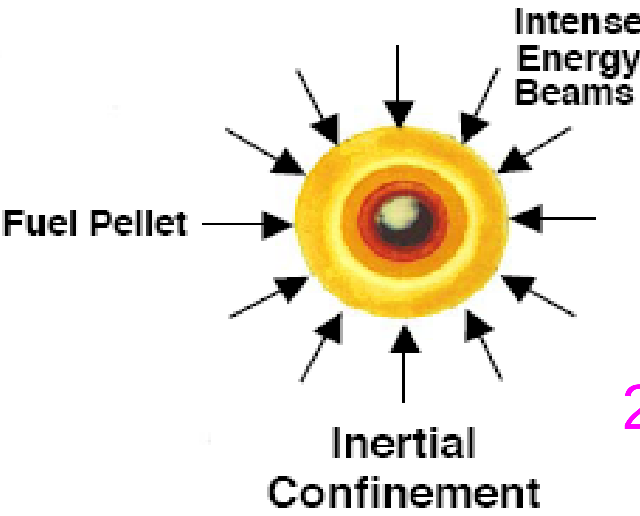


Three Basic Ways to Achieve Fusion

ion gyroradius ≈ 1 cm, T_i = 20 keV, B = 20 kG







difficult to heat D-T fuel to 20 keV in a very small space and short time

Main Criteria in Fusion Research

- The fusion power created must be larger than the power required to keep the D-T fuel at high temperature in sufficiently long time

  ➔ near-term scientific goal of a "burning plasma"

- The mechanical structure of the device must be capable of withstanding damage due to plasma bombardment and radiation damage due to 14 MeV neutrons

  ➔ long-term engineering goal of improved materials

Requirements for Fusion Burning

"Burning" means self-heating by alpha particles produced in DT reaction. To maintain self-sustained burning, it requires

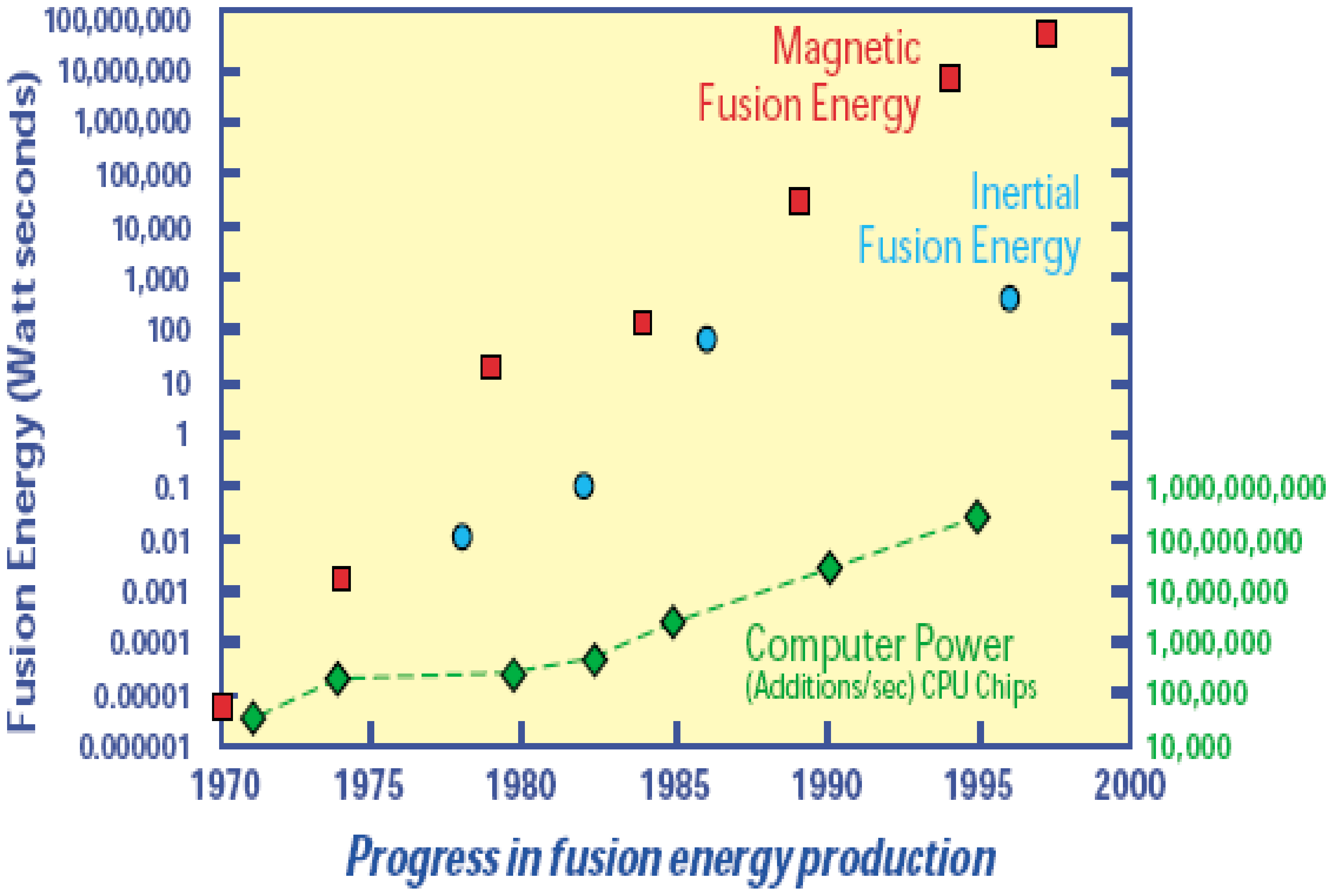
alpha heating rate > plasma energy loss rate

or, $\text{constant} \bullet n^2 T^2 > 3 n T / \tau_E$

[where τ_E is the plasma energy confinement time]

Thus, the condition to achieve self-sustained burning is

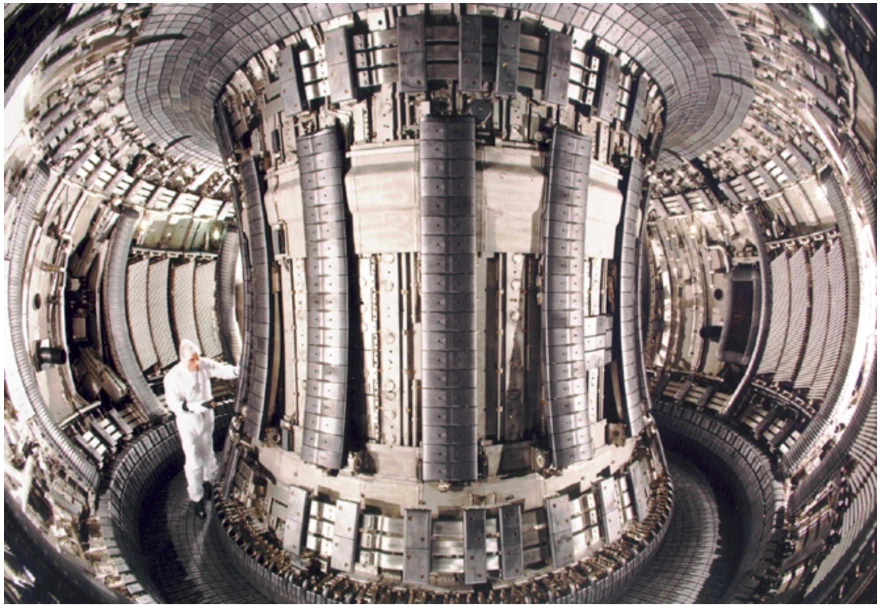
$n \bullet T \bullet \tau_E > (10^{14} \text{ cm}^{-3}) \bullet (20 \text{ keV}) \bullet (5 \text{ sec})$



Fusion Energy (Watt seconds)
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
Magnetic Fusion Energy
Inertial Fusion Energy
Computer Power
(Additions/sec) CPU Chips
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1970
1975
1980
1985
1990
1995
2000
Progress in fusion energy production

What Have We Done in Magnetic Confinement Research in Past 50 Years ?

Model A Stellarator of 1953
(with Lyman Spitzer)
$n \approx 10^{13}$ cm^{-3}
$T \approx 10$ eV
$\tau_E \approx 10\ \mu$sec

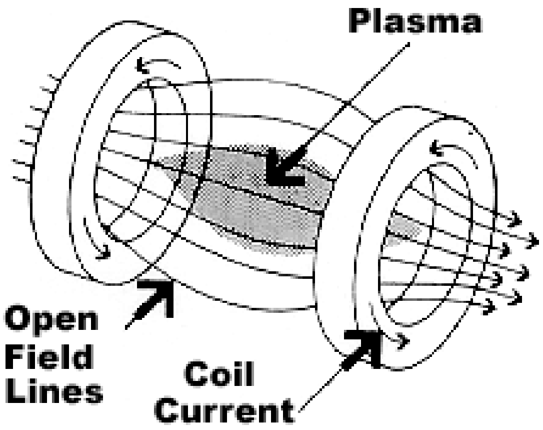


JET Tokamak in 2003:
$n \approx 10^{14}$ cm-3
$T \approx 20$ keV
$\tau_E \approx 1$ sec

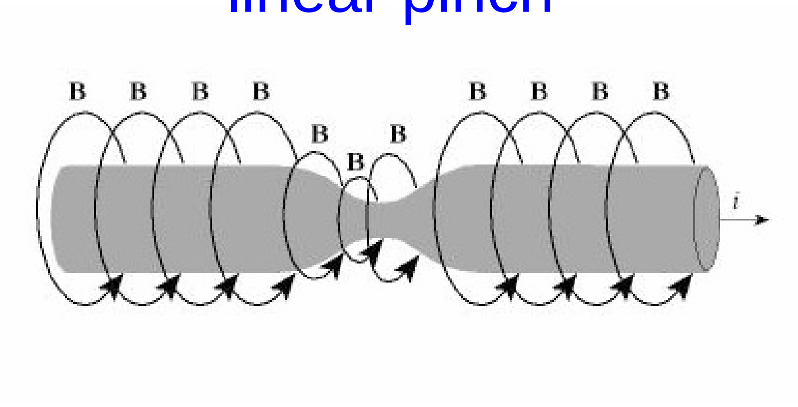
$nT\tau_E$ still needs a factor ≈ 5 from burning condition

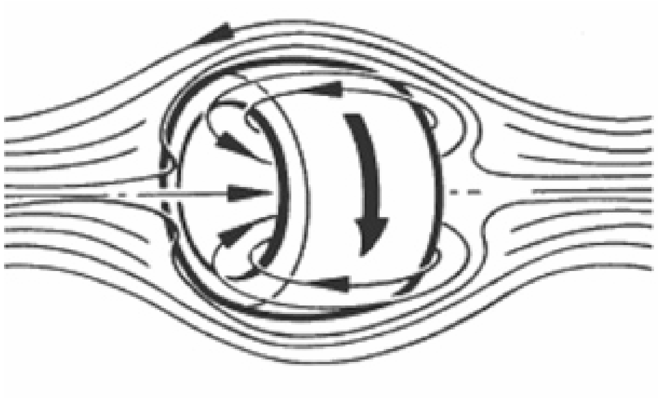
Early Ideas for Magnetic Fusion Research

magnetic mirror

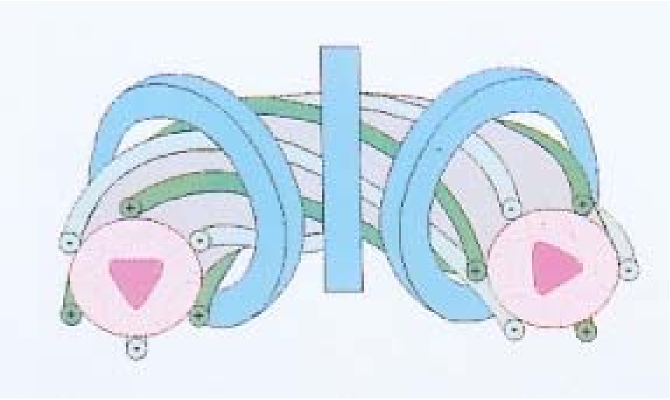


linear pinch





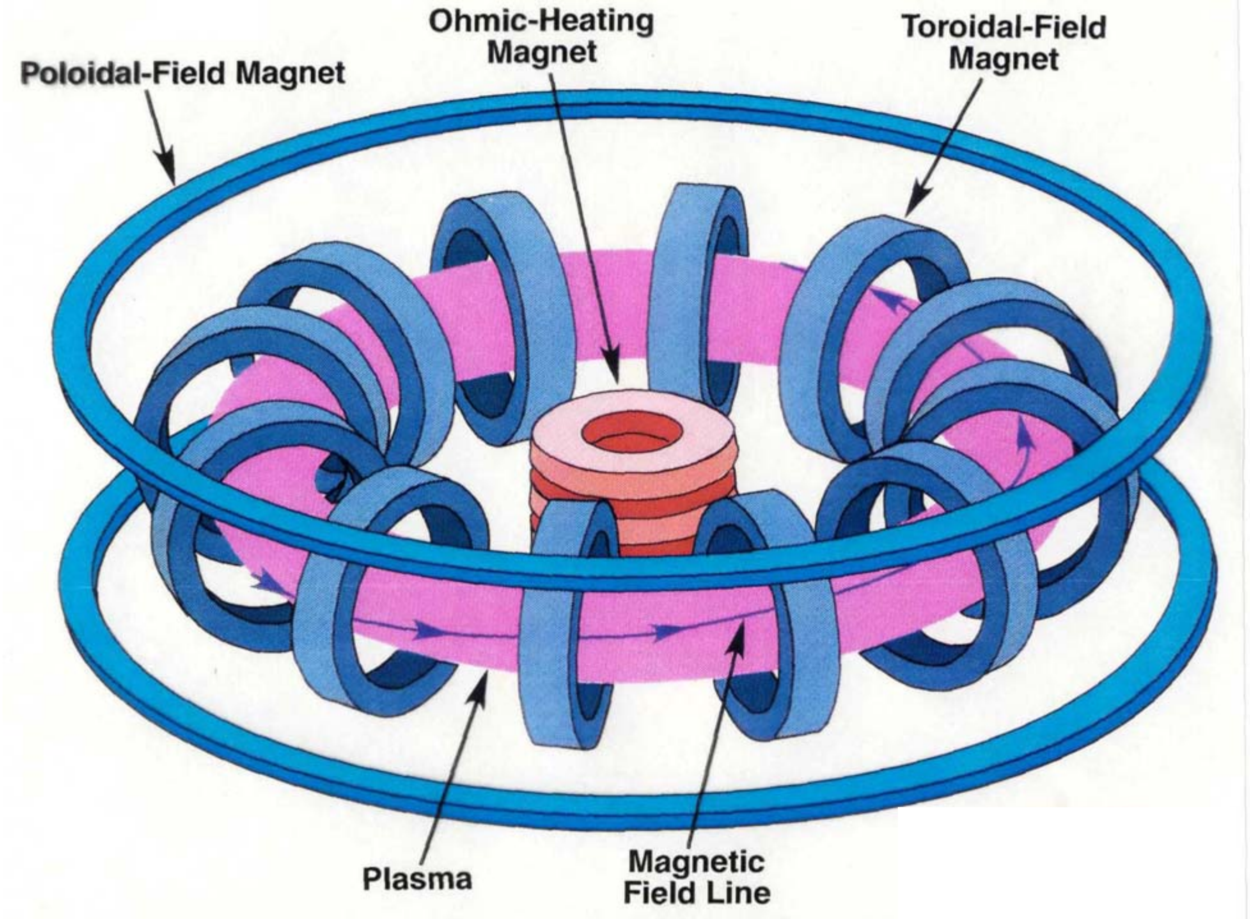
field reversed configuration



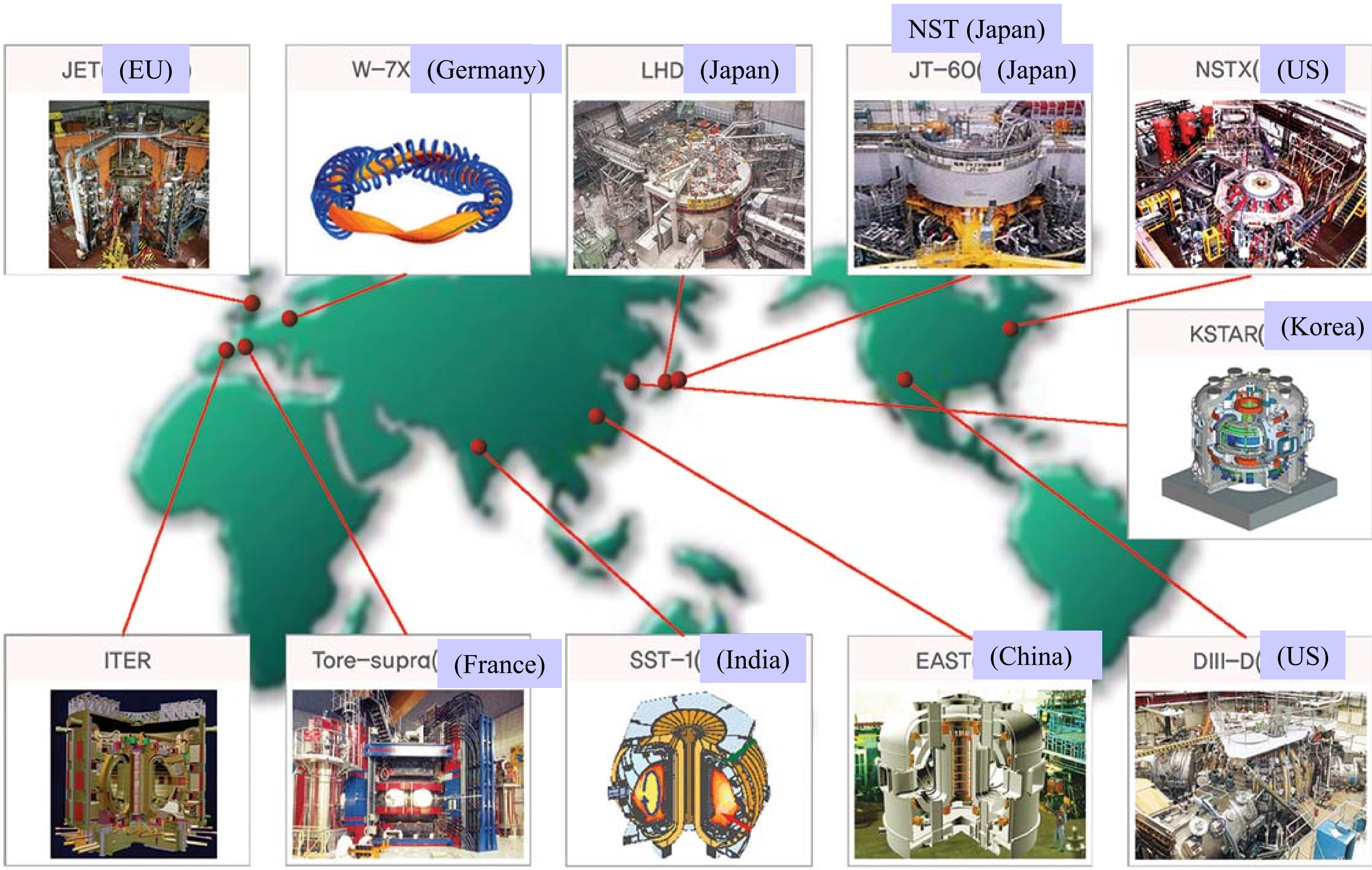
stellarator

The Winner so Far: the Tokamak

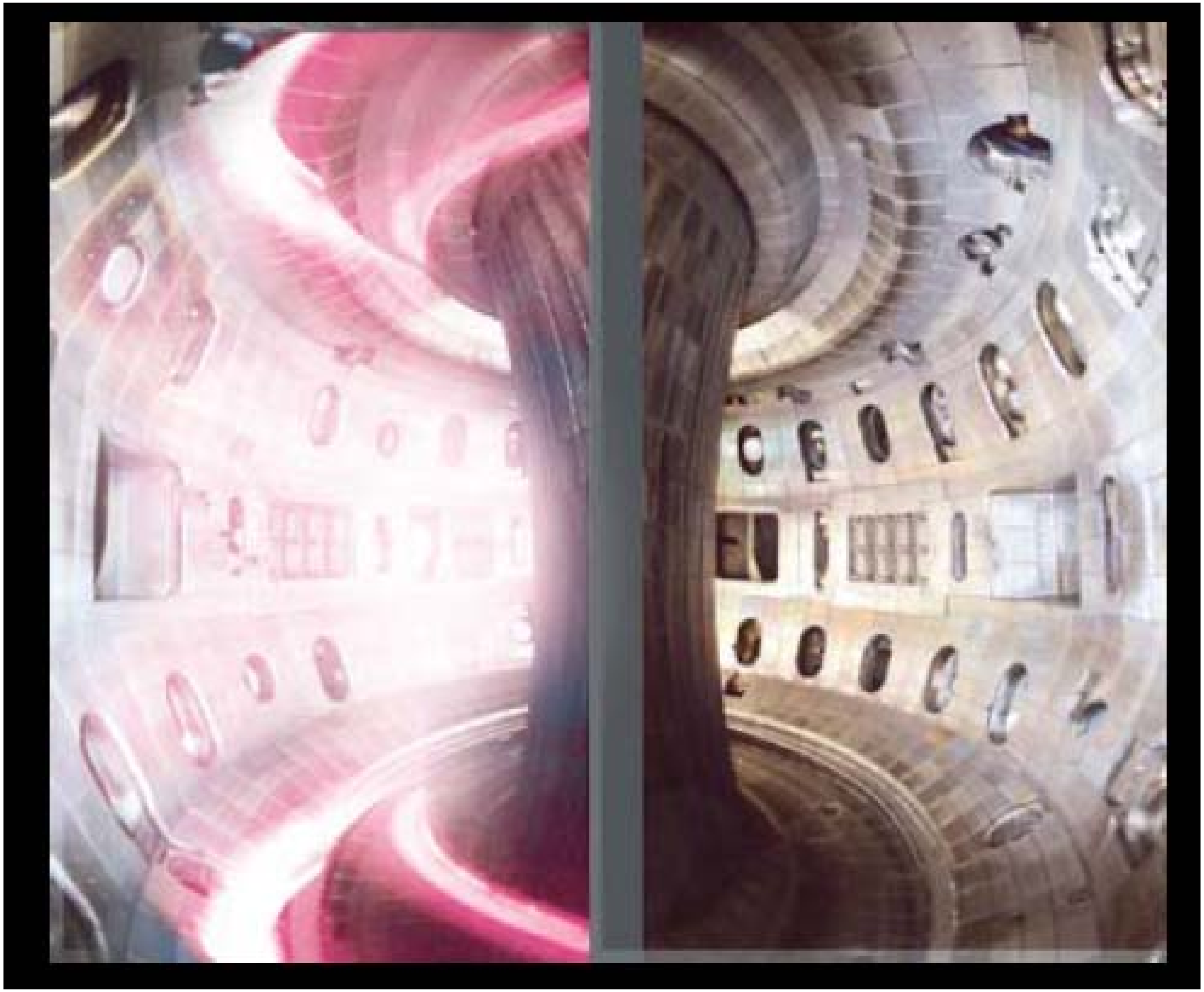
Tokamak = toroidal magnetic chamber (Russian acronym)



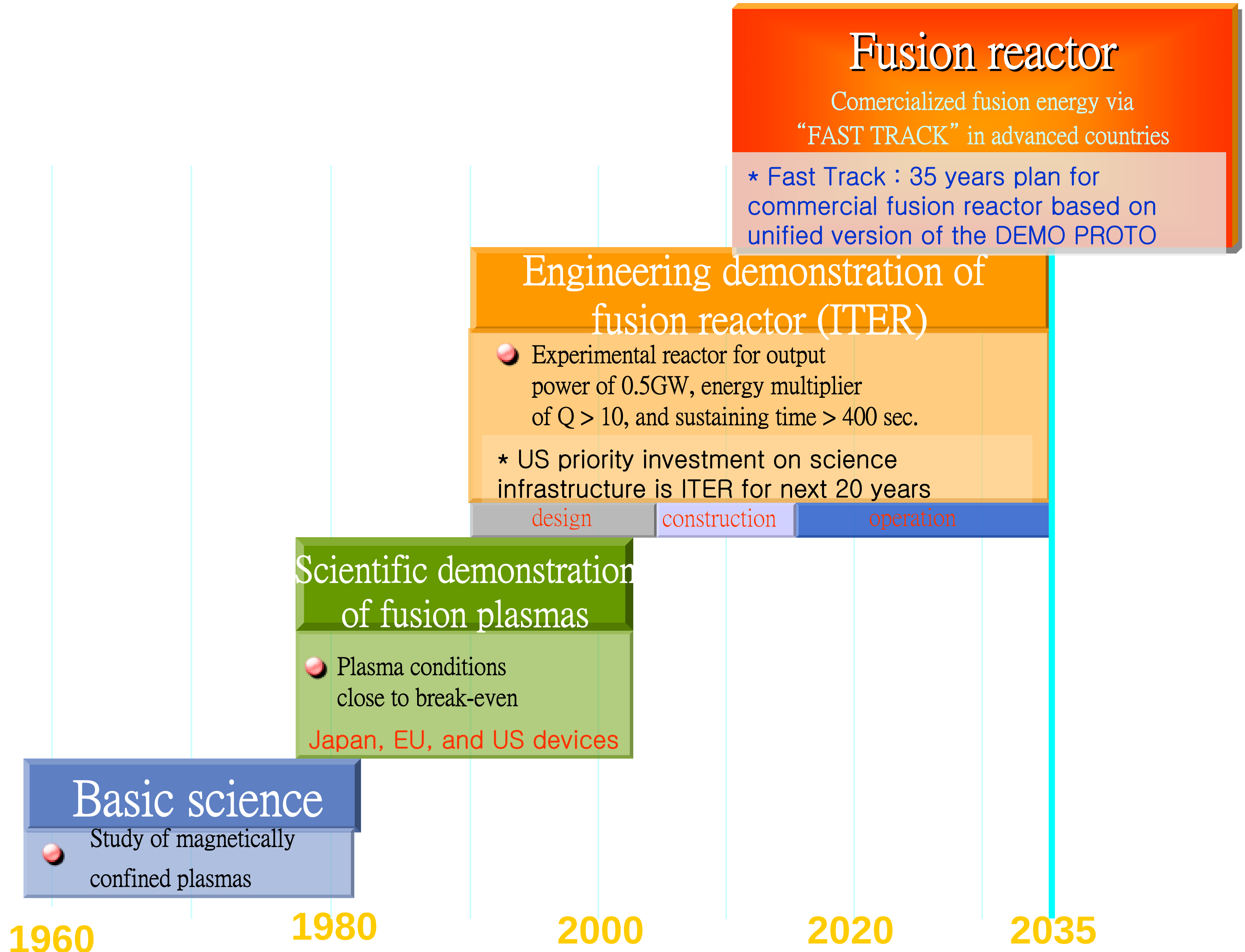
Present World Magnetic Fusion Devices



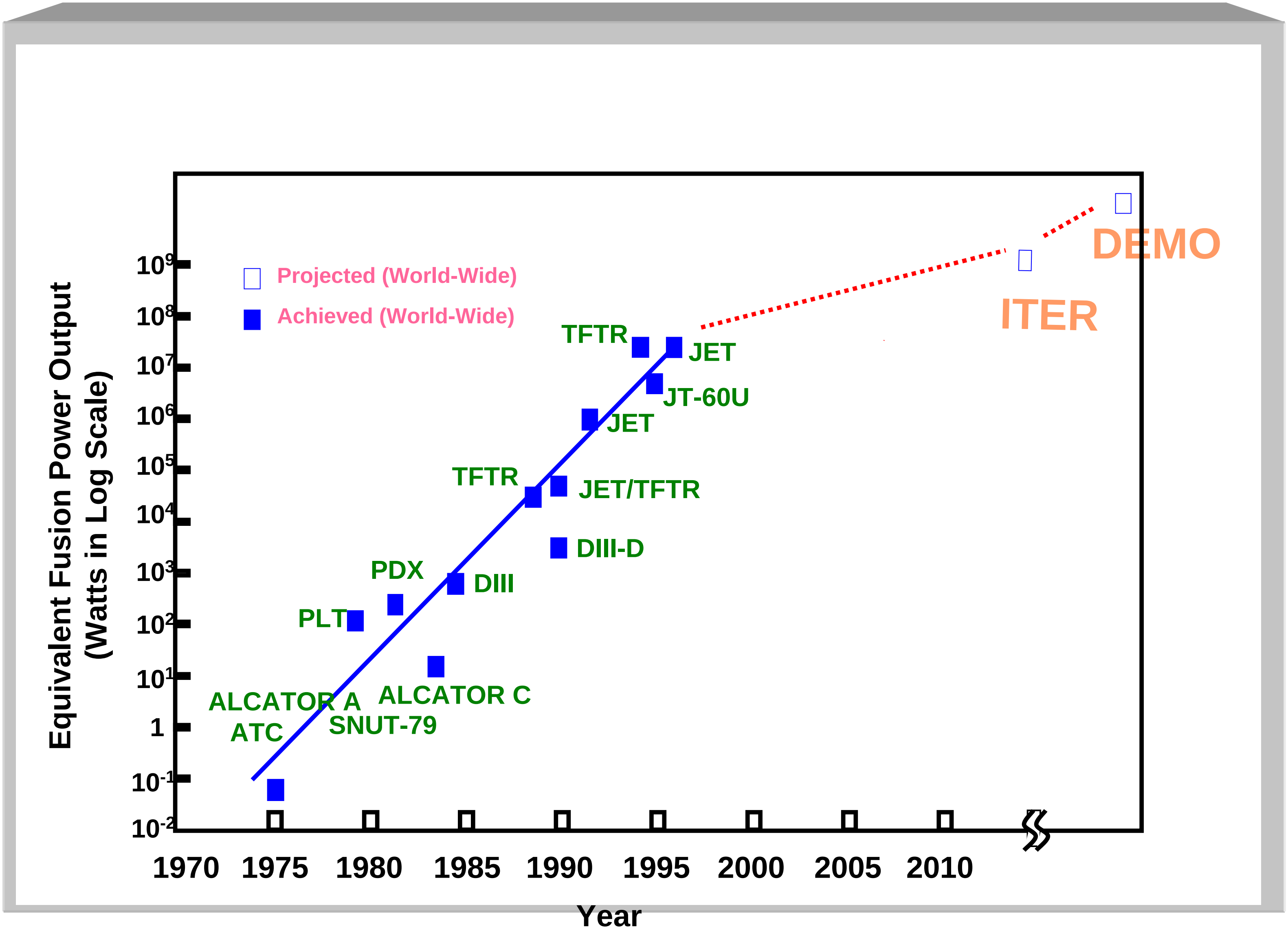
DIII-D with Plasma and No Plasma



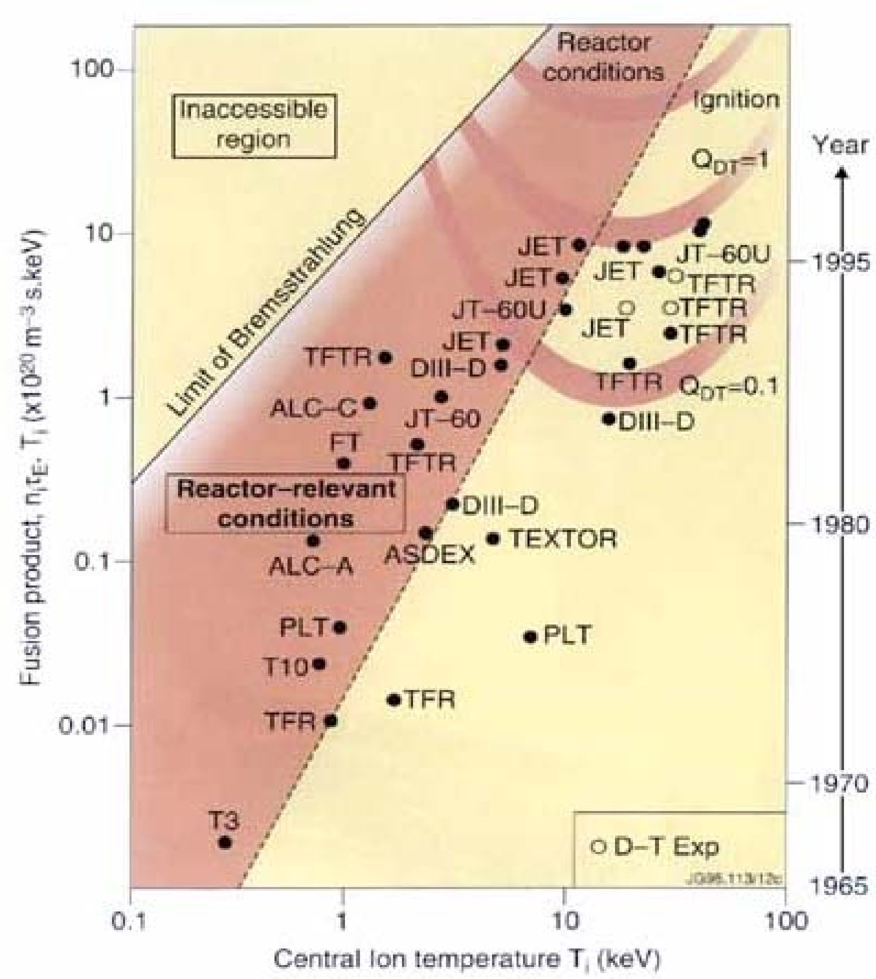
World Fusion Energy R&D History and Strategy



Progress of World Fusion Research



History of $nT\tau_E$ in Tokamaks



T ≈ 20 keV achieved

n ≈ 10^{14} cm^{-3} achieved

τ_E ≈ 1 sec achieved

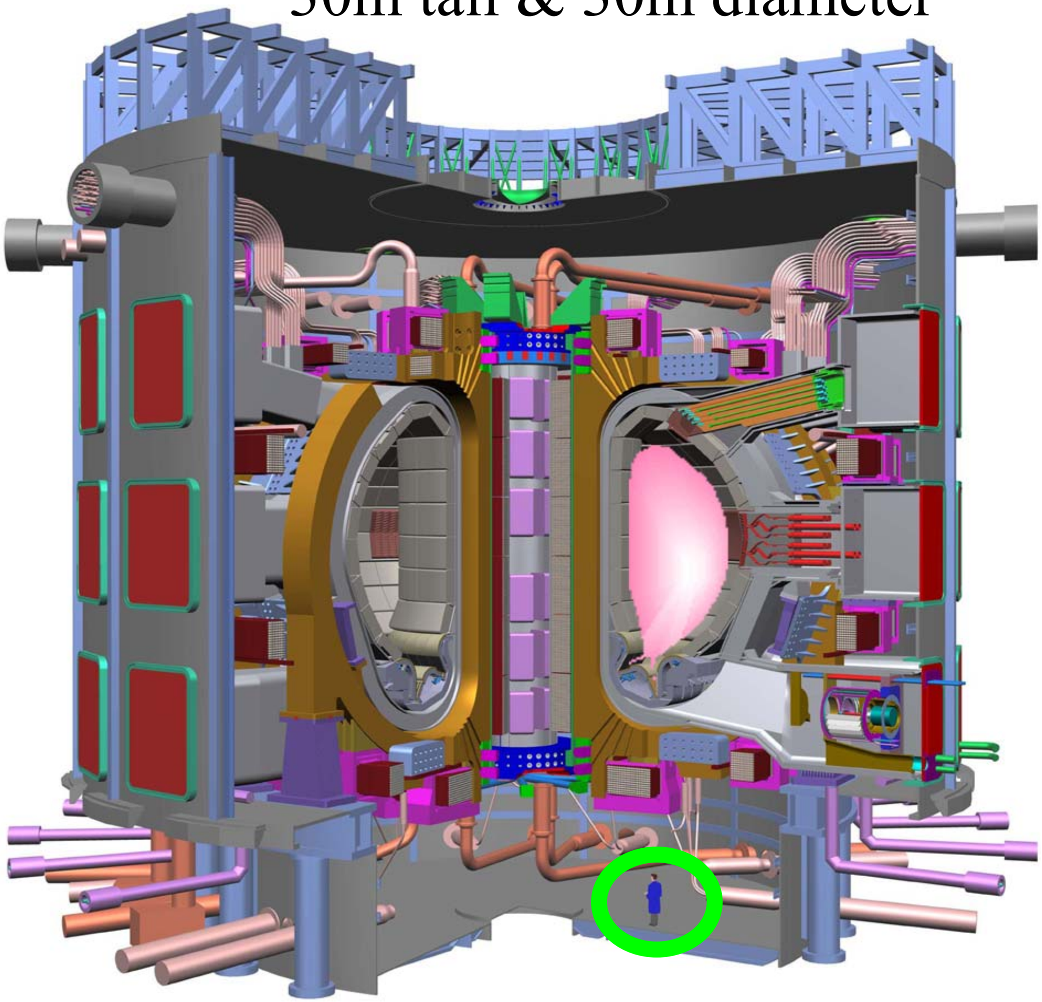
(but not quite simultaneously)

$nT\tau_E$ still needs a factor of ≈ 5 to create burning plasma

(improvements came mainly from increase in machine size)

ITER – A Burning Plasma Fusion Reactor

30m tall & 30m diameter



Site: France

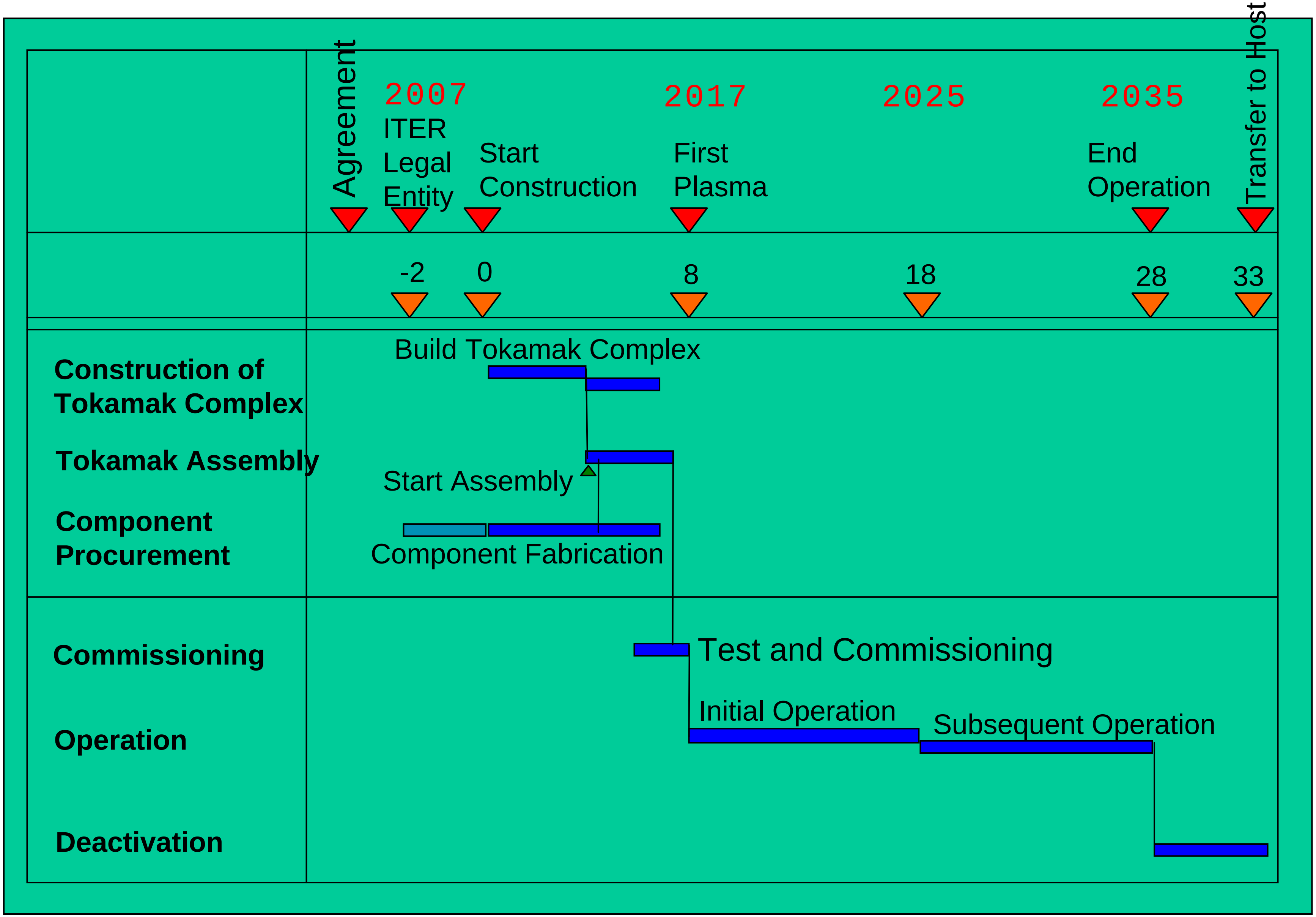
Construction:
2007-2017

Design Goals:

- Q $\approx$ 10 (burning plasma)
- 0.5 GW fusion power
- 500 sec long pulse

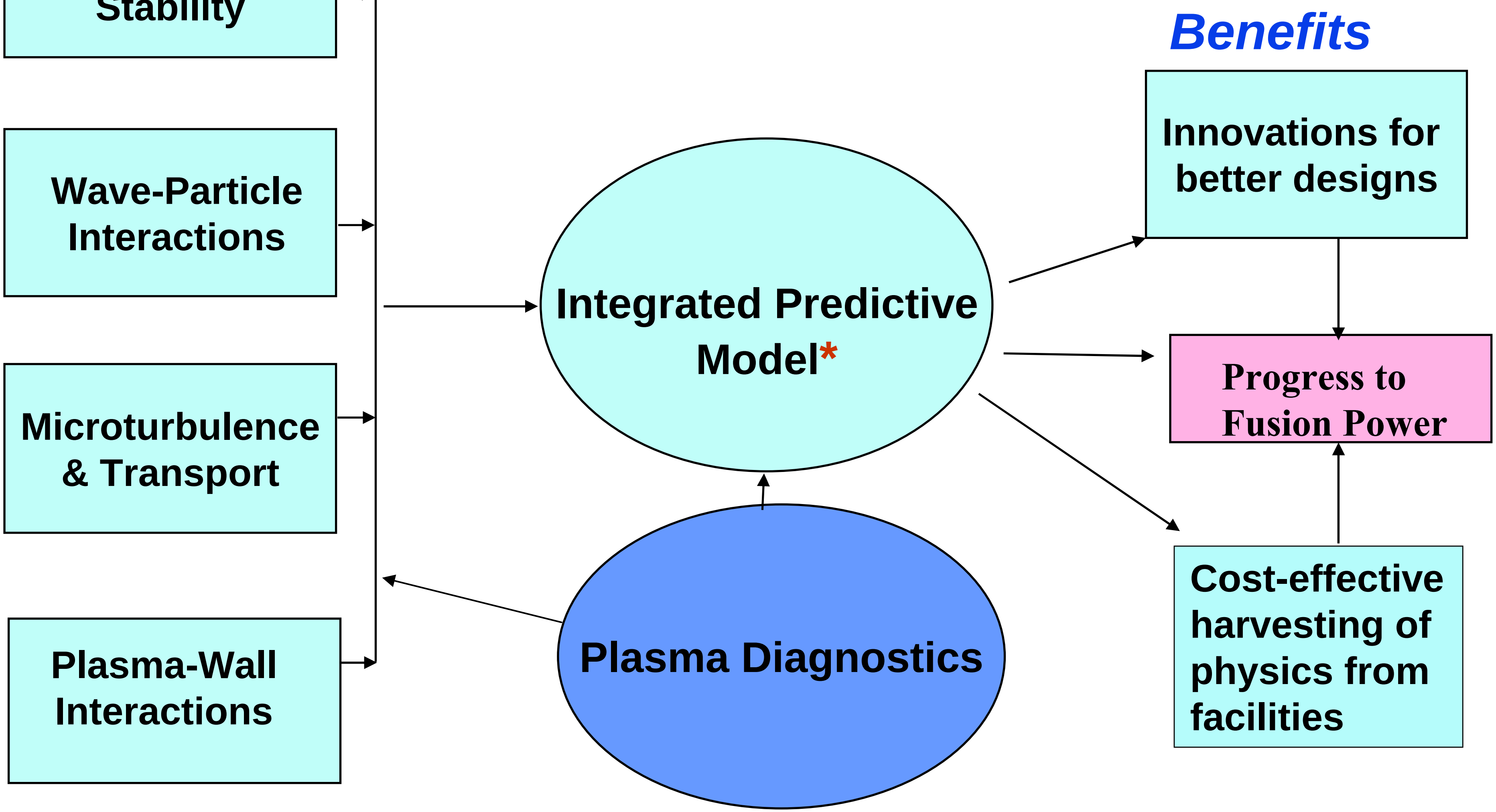
- 10B Euro ITER agreement was signed by 7 parties (EU, Japan, USA, Russia, China, Korea, India) in 2005.
- Taiwan 4th Nuclear Power Plant costs ~ $6B for 2.7 GW power

ITER Construction & Operation



*Major Fusion Science Areas**

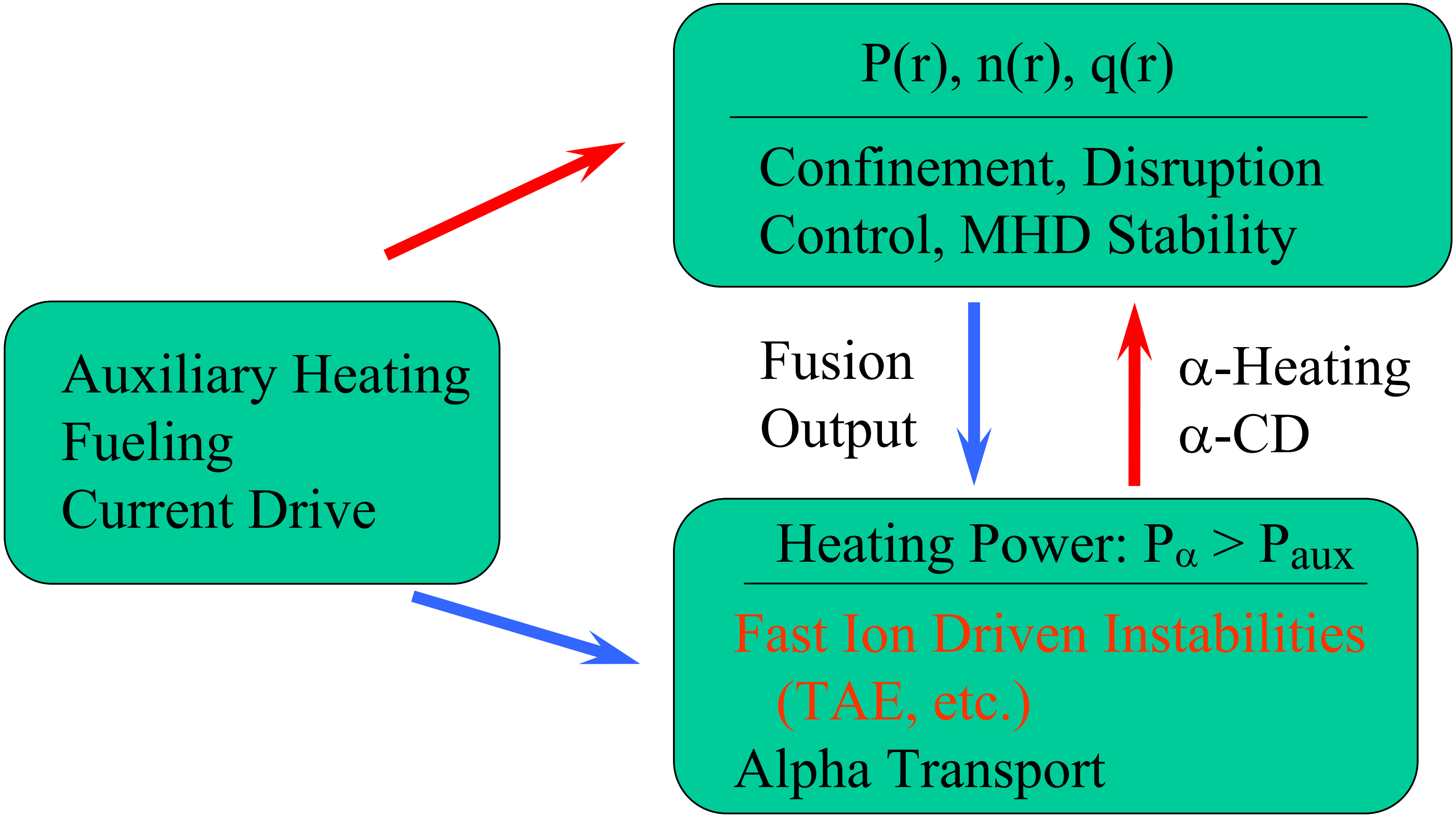
GOAL: Reliable predictions of complex properties of high temperature plasmas



***All with strong coupling to experiments**

Burning Plasmas Physics

α interaction with thermal plasmas is a strongly nonlinear process.

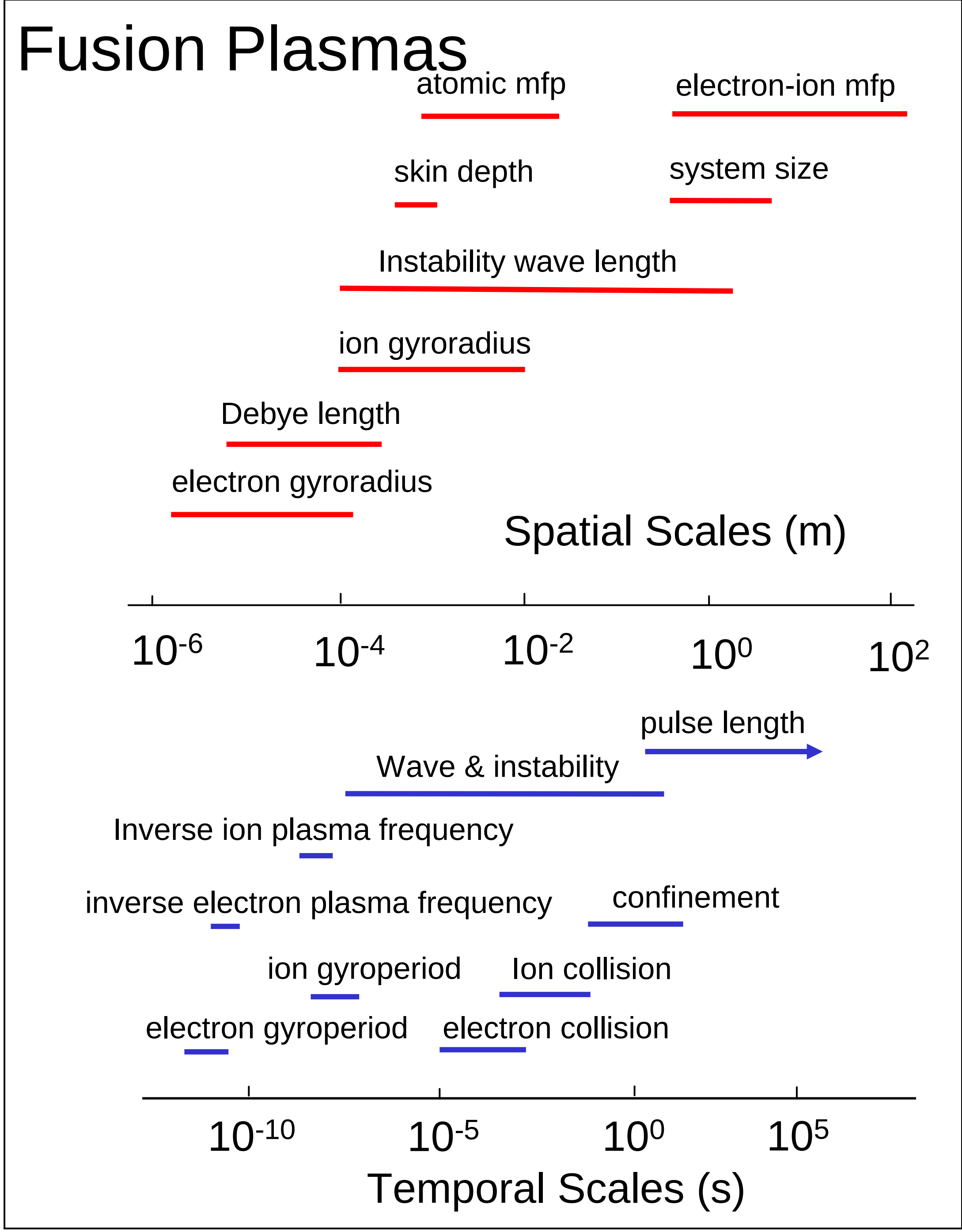


Must develop efficient methods to control profiles for burn control!

➔ Need nonlinear kinetic-fluid simulation codes!

Disparate Spatial & Temporal Scales in Fusion Plasmas Present Major Challenge to Theory & Simulations

- **Huge range of spatial and temporal scales**
- **Overlap in scales and nonlinearity often mean simplified ordering and theory not possible**



Major Fusion Technology Challenges

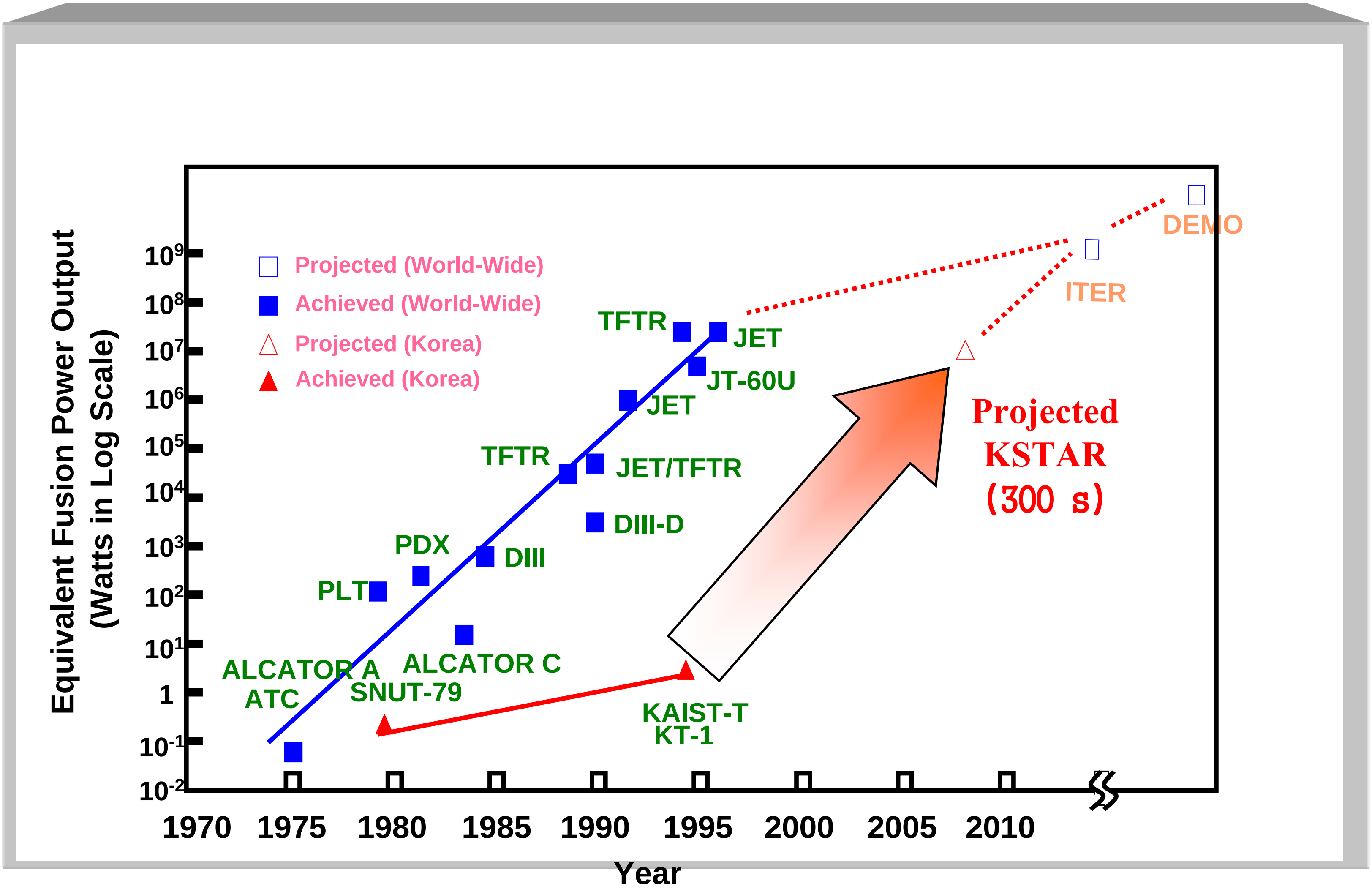
- **Materials development**
  - **Survive high heat flux (10 MW/m^2)**
  - **Retain strength despite neutron activation**
  - **Minimize production of activated wastes**
- **Develop safe and efficient Tritium handling techniques**
  - **Develop breeding technologies for Tritium from Lithium blankets**
  - **Minimize Tritium inventory for improved safety**
- **Reduce size, cost, and complexity to make competitive with other energy sources**

Fusion Research Spending

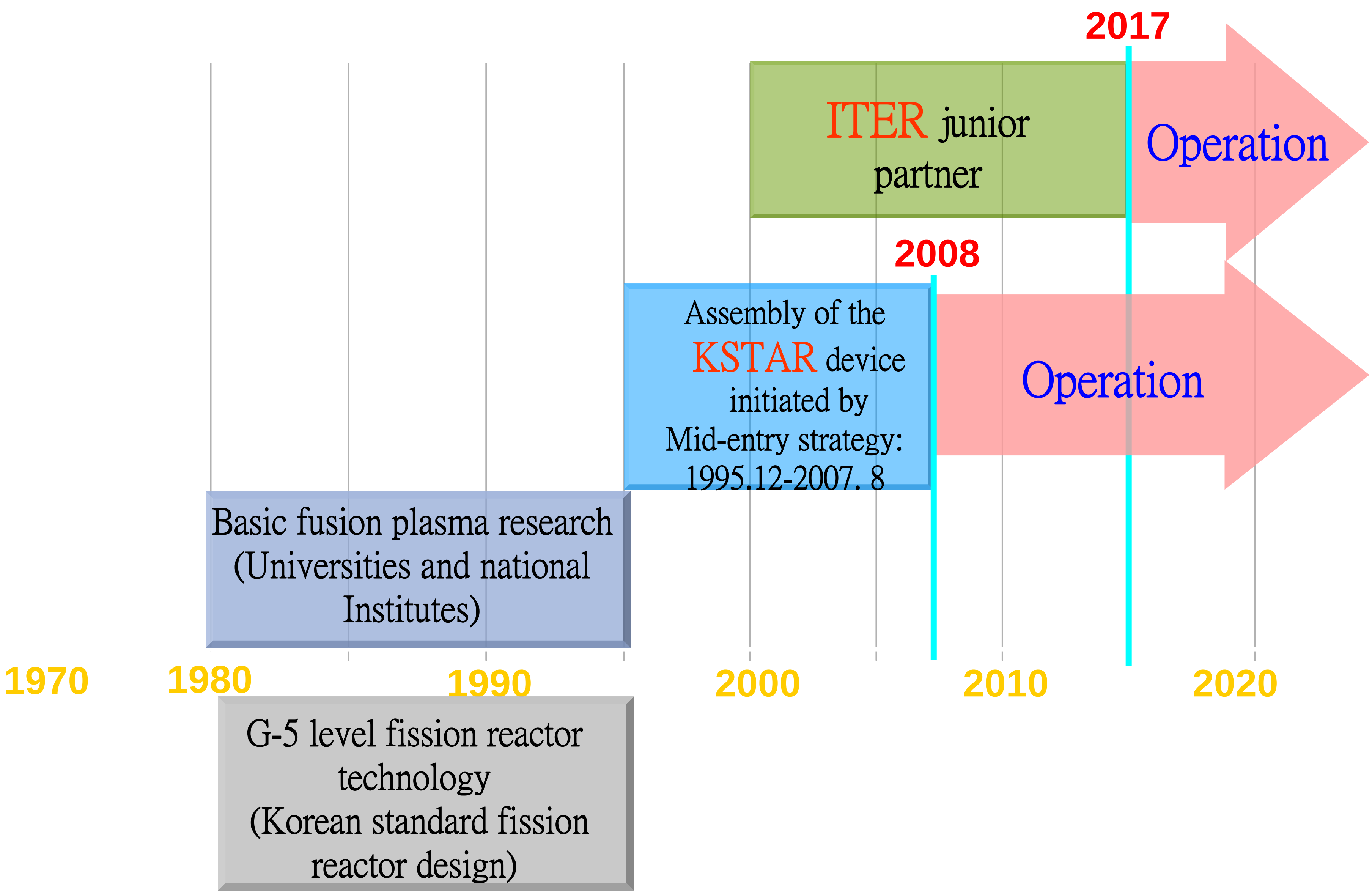
- ITER
  - **Agreement signed in June 2005 with construction cost ~$13B over 10 yrs, to be built in France**
  - **Participants: EU(40%) , Japan(10%), US(10%), Korea (10%), Russia(10%), China(10%), India(10%) representing > 1/2 of world population**
- 2006 US annual magnetic fusion budget ~ $300M
  - **One space shuttle launch costs ~$500M**
  - **Japan & EU each spends more than US**
  - **Developing nations increase fusion funding greatly since 2000**
- Korea's fusion investment
  - **K-STAR tokamak built mainly by Korean industries. Total investment ~ $ 1B during 1995-2005 including industry investment**
- **Taiwan's fusion & plasma science investment: none or negligible now! Now is the time for Taiwan to participate and grow!**

Korea Jump-Starts Fusion Program in 1995

- Approval of the KSTAR project in 1995
  - Mid-entry strategy

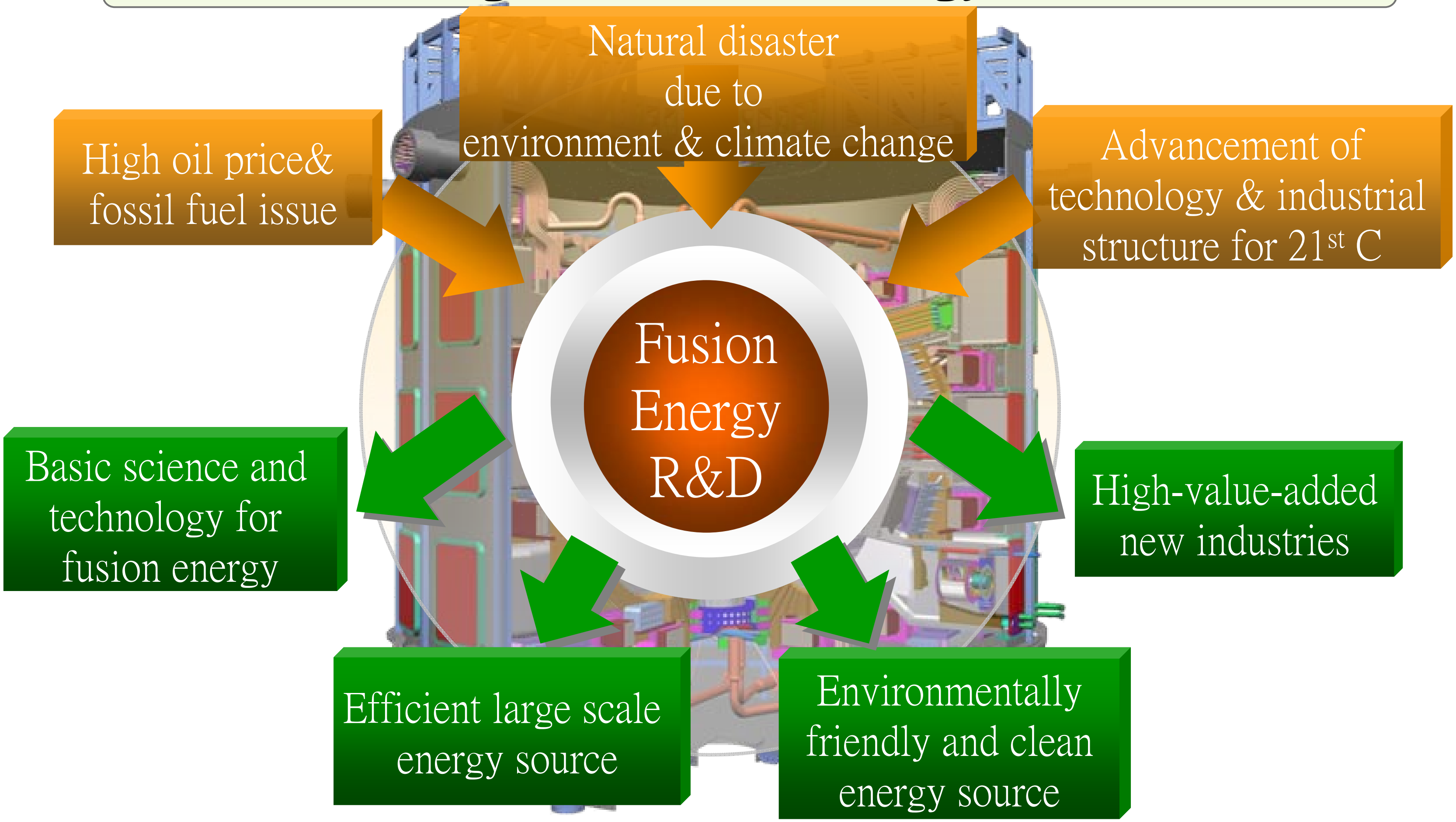


Korean fusion energy R&D history and strategy



Fusion Energy R&D

Fusion is large scale, high efficiency next generation clean energy source



Advanced science and state-of-the-art technology

Fusion Energy Research in Taiwan

- Present Taiwan's fusion & plasma science investment: none or negligible!
- Can Taiwan continue to ignore fusion research when nations representing more than 1/2 of world population are working on fusion energy research?
  - Assuming that ITER succeeds in producing output energy 5 -10 times of the input energy, it'd be too late for Taiwan to catch up in fusion technology if Taiwan does not have a fusion energy research program now.
- If Korea can afford to work on fusion energy research, why can't Taiwan?
  - YES! Taiwan can afford to initiate a moderate fusion energy research program.

Establish a Moderate Taiwan Fusion Energy R&D Program

- Initial Phase: Start a Taiwan Fusion Facility with fusion plasma science program:
  - develop expertise & manpower in fusion-related plasma theory and modeling, and small basic plasma experiments
  - establish international collaborations in tokamak fusion theory and experiments (e.g., with US, Japan, Korea)
  - participate in KSATR experiments (e.g., US contributes $4M and Japan contributes $6M to KSTAR in plasma diagnostics, particle heating source in exchange of participating in KSTAR experiments)

In conclusion,
it is very important to initiate a modest fusion energy research program in Taiwan!

For training scientific and engineering personnel in anticipation of success of ITER & future fusion devices

Thank you!