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

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Taiwan Energy Supply & Demand

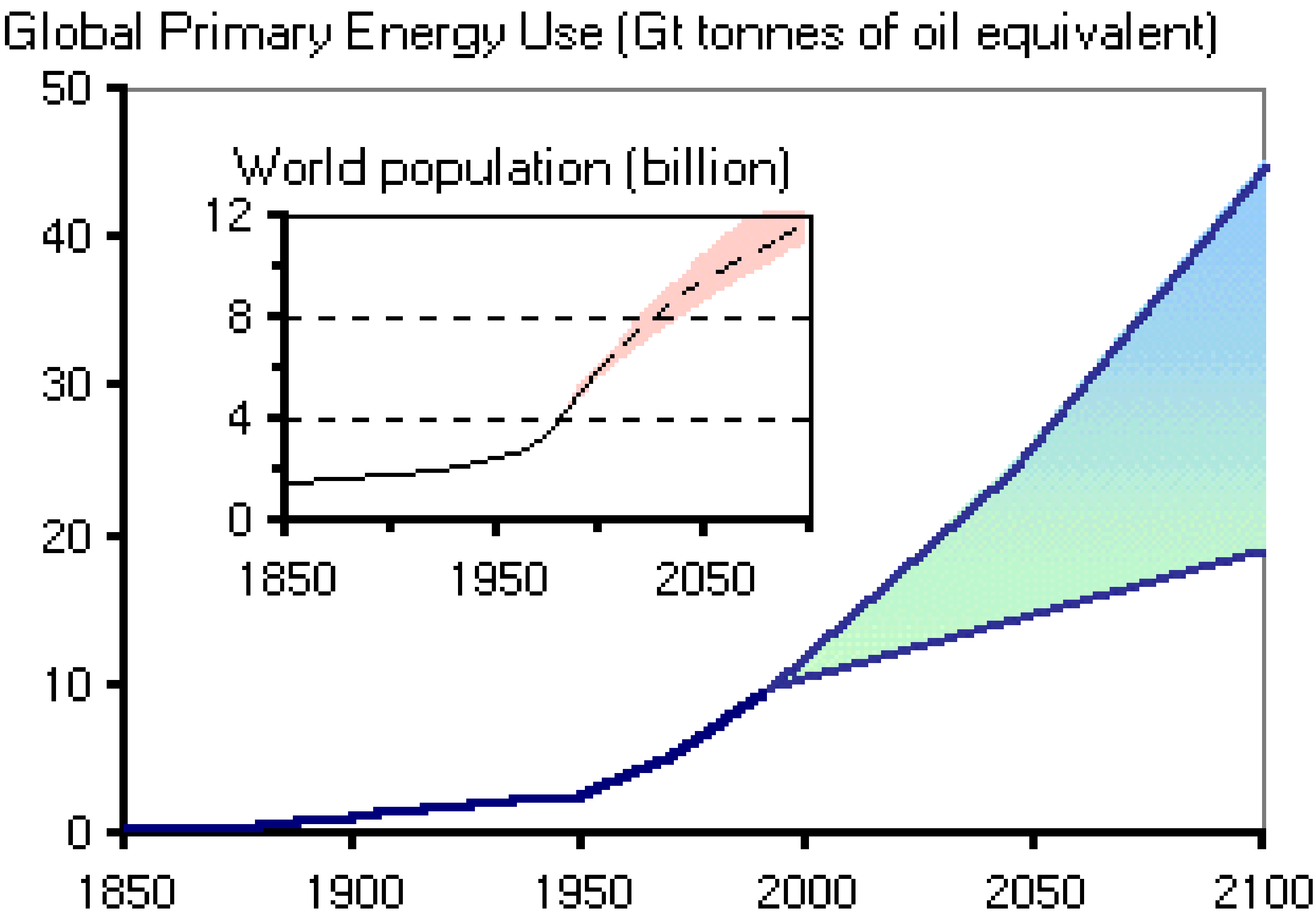
- **Taiwan total oil and natural gas reserve is estimated at ~500 million Barrels of Oil Equivalent (BOE)**

- **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**

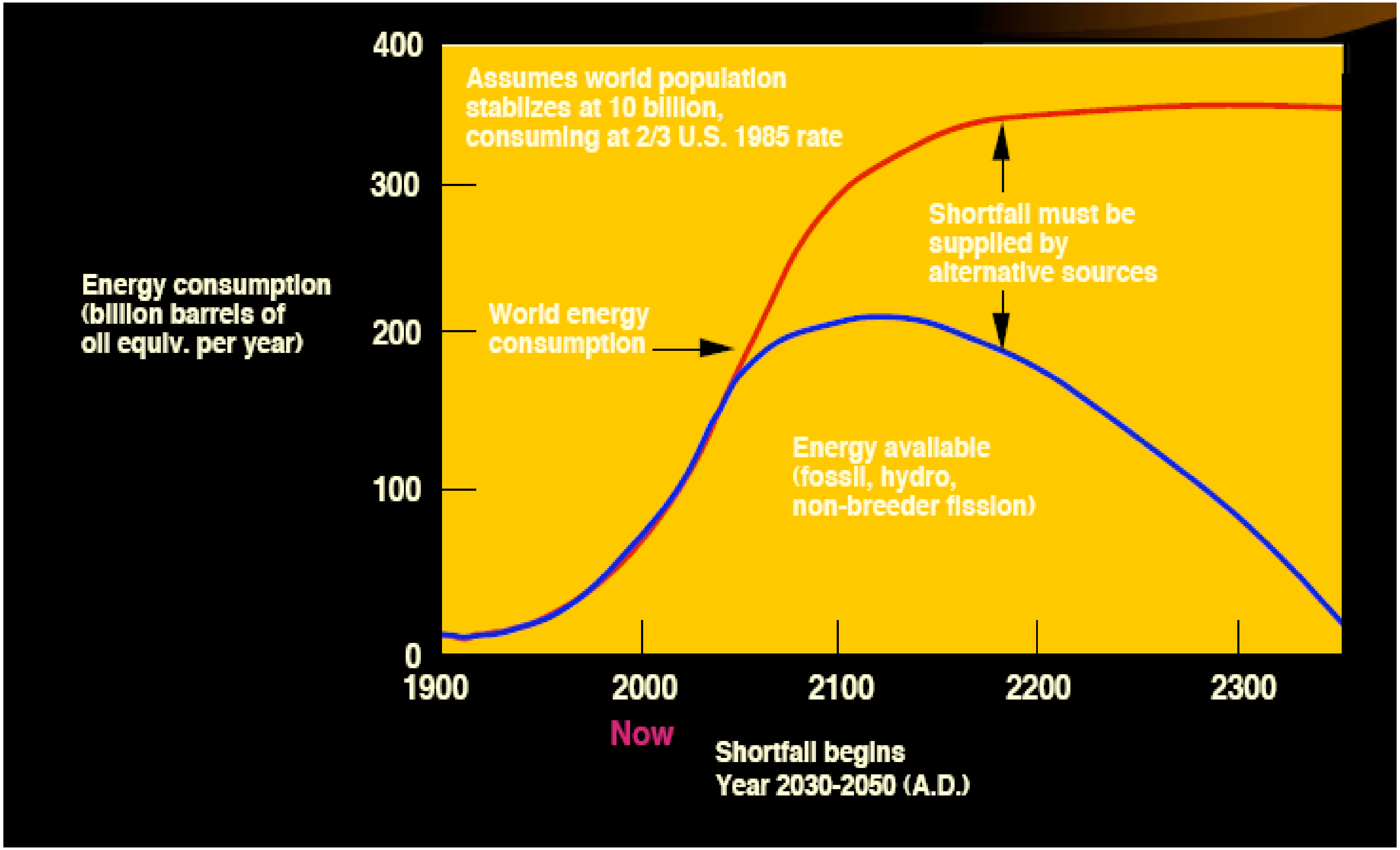
- **How will Taiwan get adequate energy supply?**
  - Taiwan aims to achieve ~30% energy supply from renewables (wind power, solar power, hydropower, geothermal, ocean wave & tidal power, biomass) by 2050
  - How about the other 70%?

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 20-40 years.

World Energy Supply & Demand

- World energy use is ~ US$ 3T in 2004 (~US$ 10T in 2007). **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, green house effect, 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!**

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

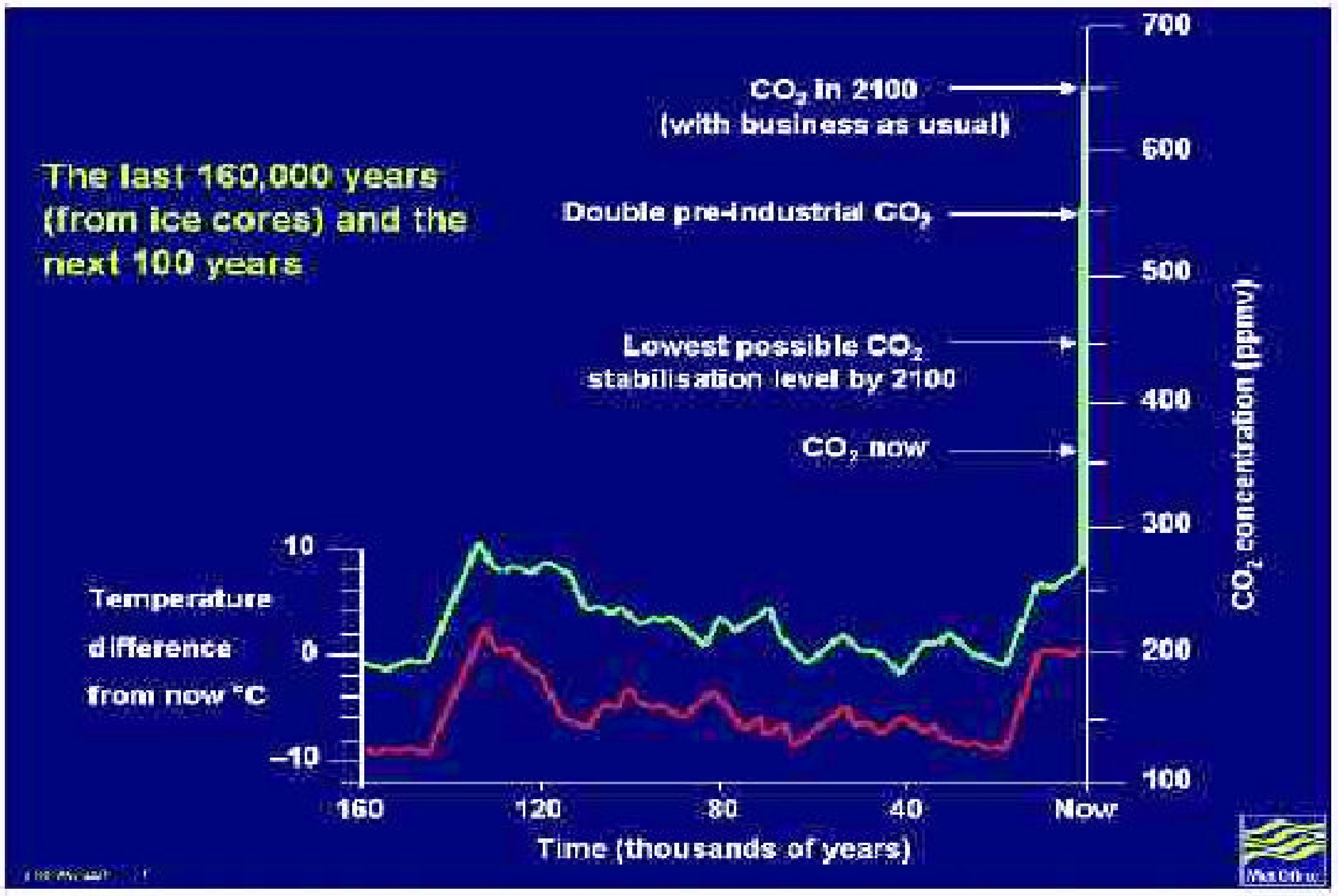


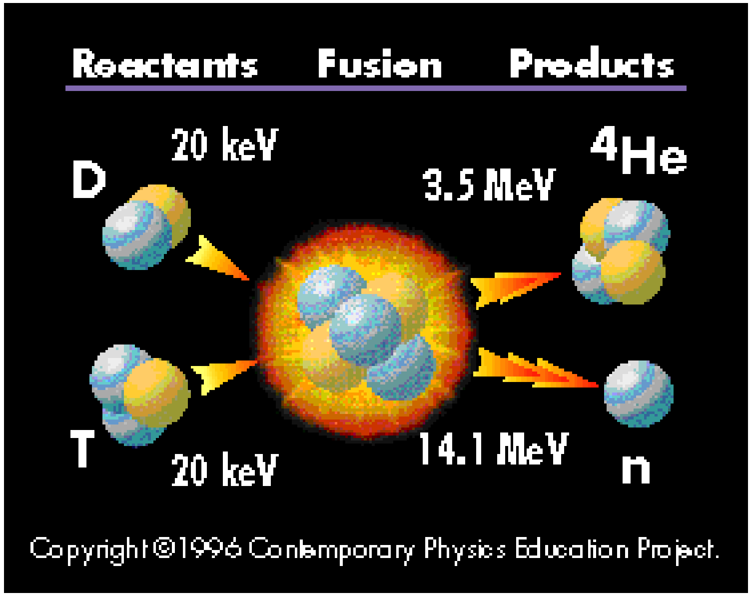
Figure from Sir David King, 31st EPS Presentation, "The challenge of climate change: Developing our low carbon energy", 28, June 2004, London, UK

- 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

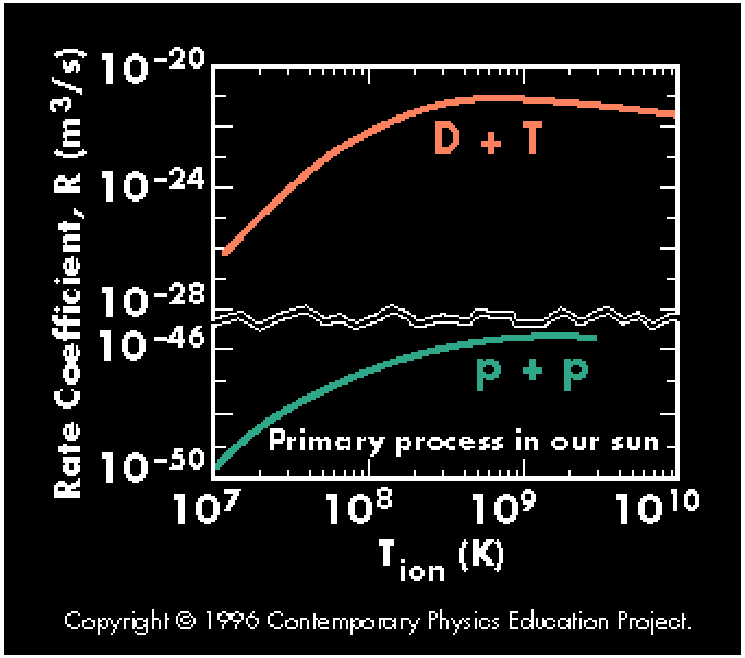
Nuclear Fusion

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 $\approx$ 0.38%)

Energy gain $\approx$ 450

20% goes to sustain fusion

80% goes to generate electricity

Needs a plasma at

$T_{ion} \approx$ 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	^{4}He + n	220	20	17,600
D + ^{3}He	^{4}He + p	350	30	18,300
D + D	^{3}He + n	400	35	~4,000
	T + p	400	35	~4,000

^{3}He 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

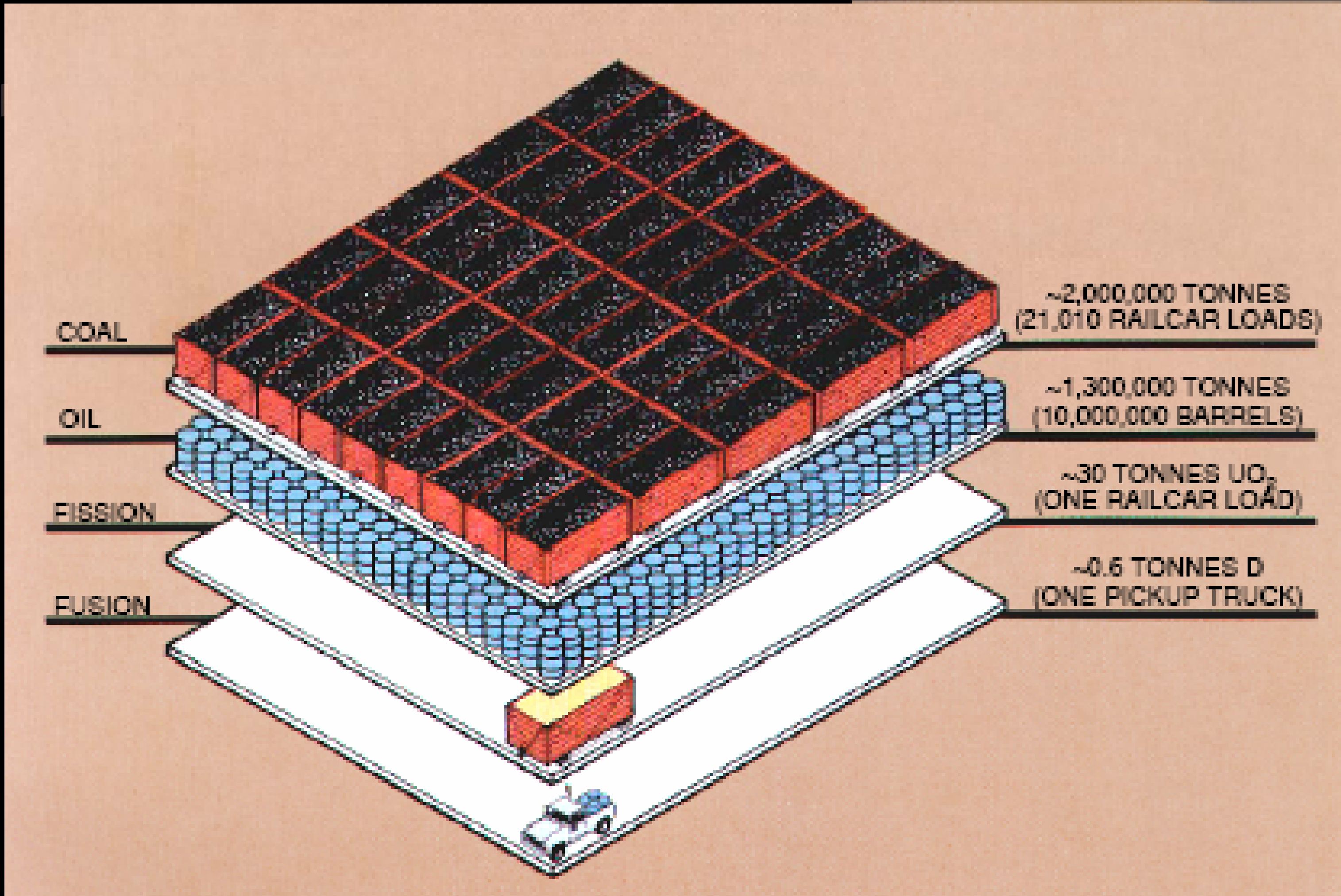
Abudant Supply of Fusion Fuel

- 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)

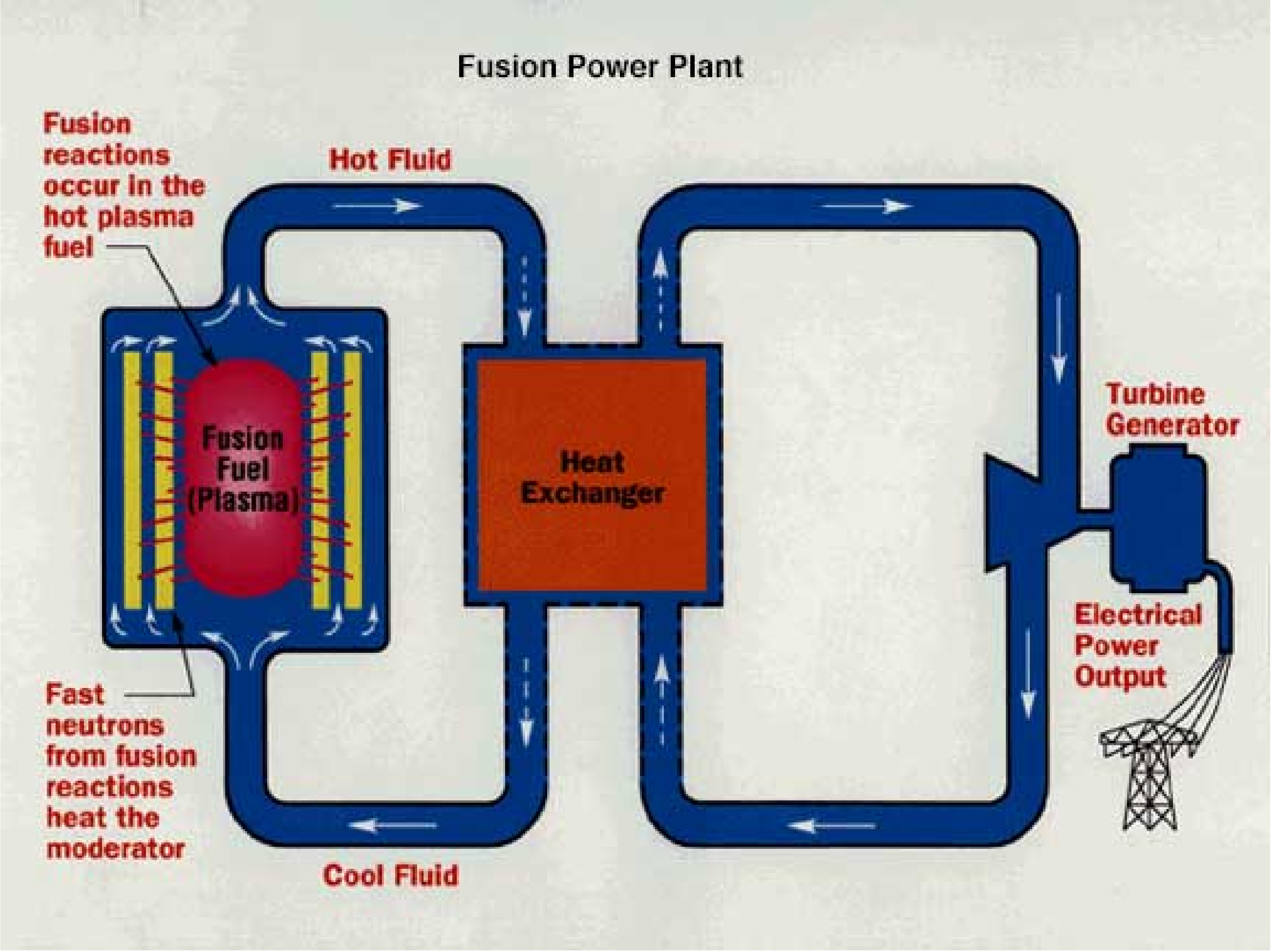
$Li^7 + n \rightarrow T + He^4 + n$ (93% natural Li)

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



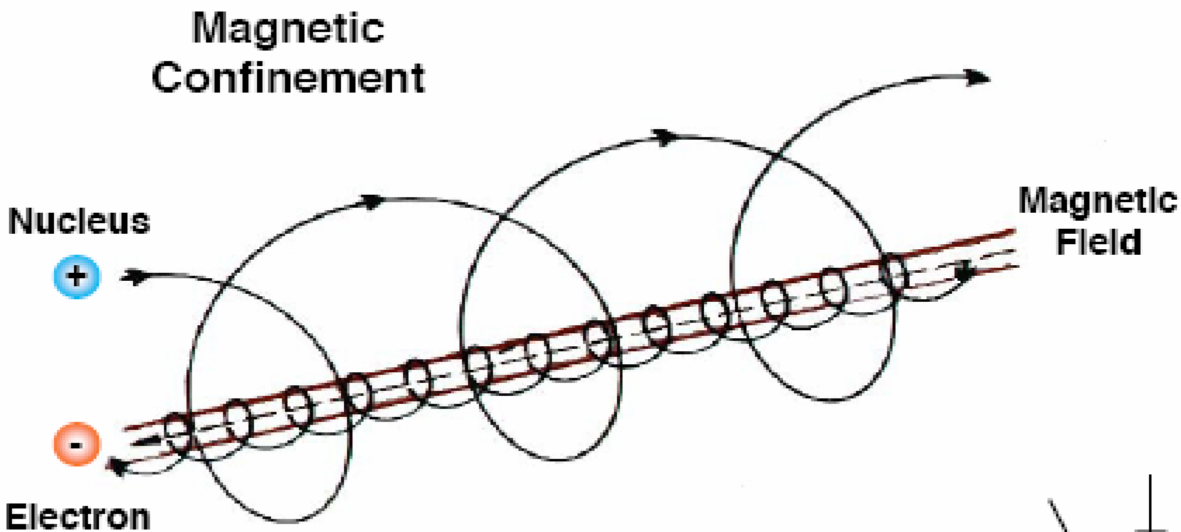
Fusion energy release from 1 gm of DT fuel equals the energy from 2400 gallons of oil

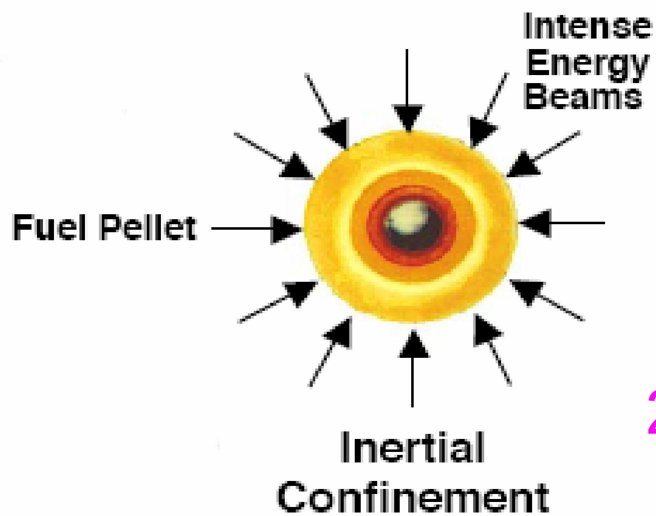
Fusion Power Plant



Three Basic Ways to Achieve Fusion

ion gyroradius $\approx$ 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 Difficulties in Fusion Research

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

→ 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 D-T alpha particles

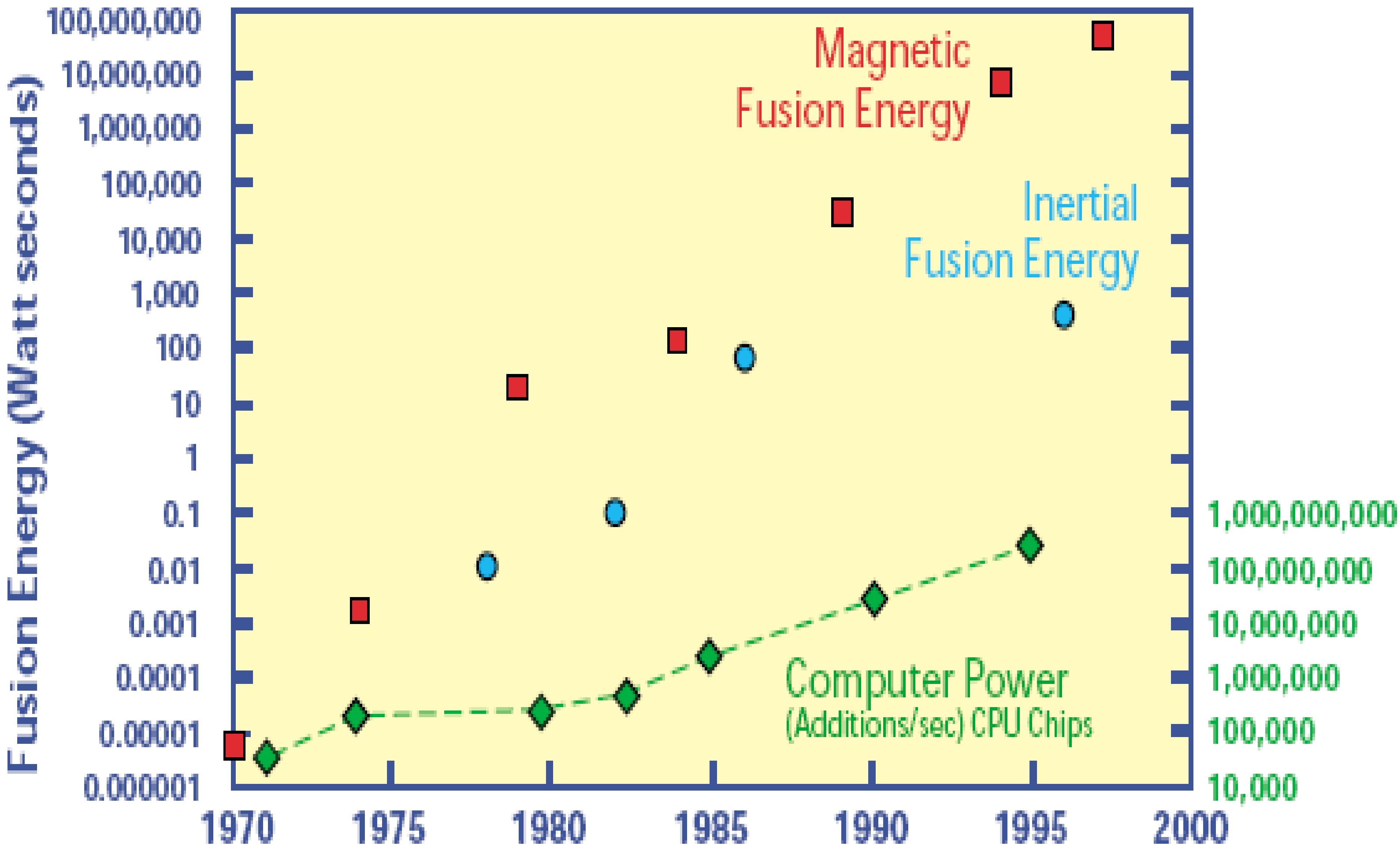
alpha heating rate = plasma energy loss rate

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

[where τ_E is the plasma energy confinement time]

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

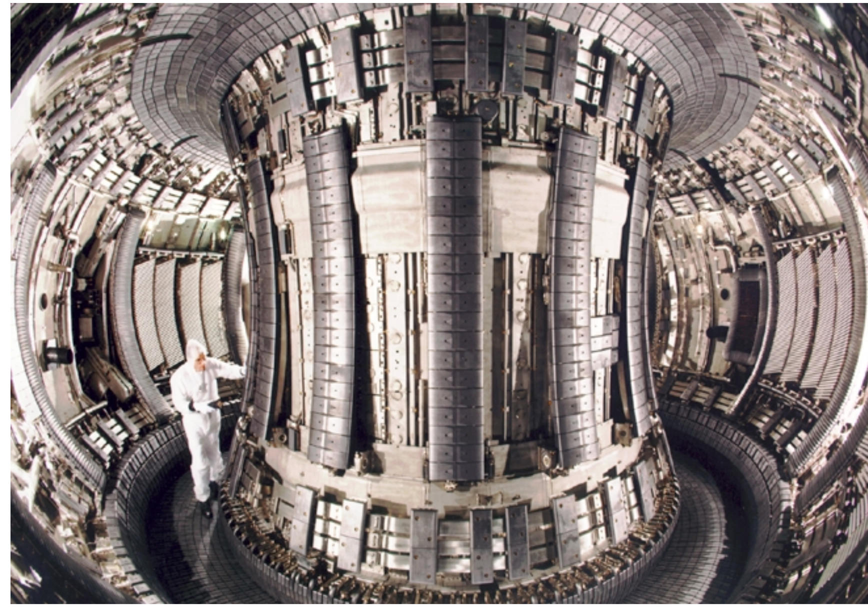
or $n \bullet T \bullet \tau_E \approx (10^{24}\ \text{cm}^{-3}) \bullet (20\ \text{keV}) \bullet (0.5\ \text{nsec})$ -- IFE



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
$\tau_E \approx 10$ μsec

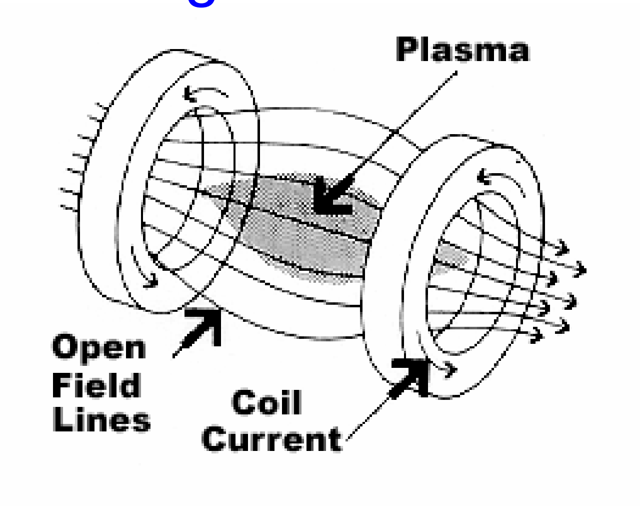


JET Tokamak in 2003:
$n \approx 10^{14}$ cm-3
$T \approx 20$ keV
$\tau_E \approx 1$ sec

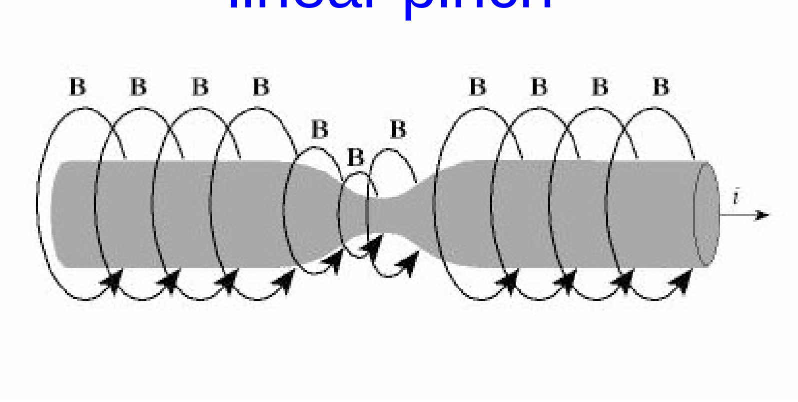
$nT\tau_E$ still needs a factor ≈ 5 from burning condition

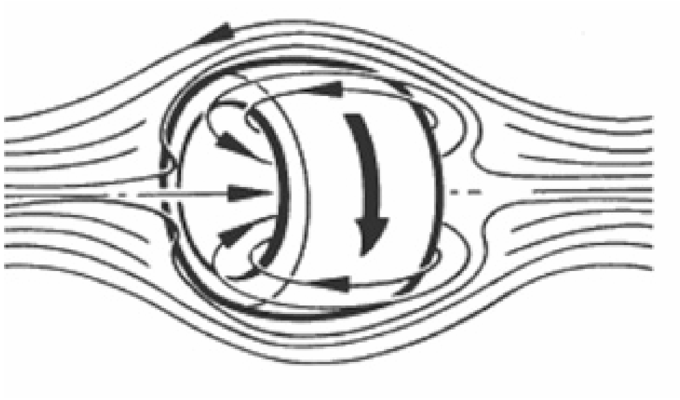
Early Ideas for Magnetic Fusion Research

magnetic mirror

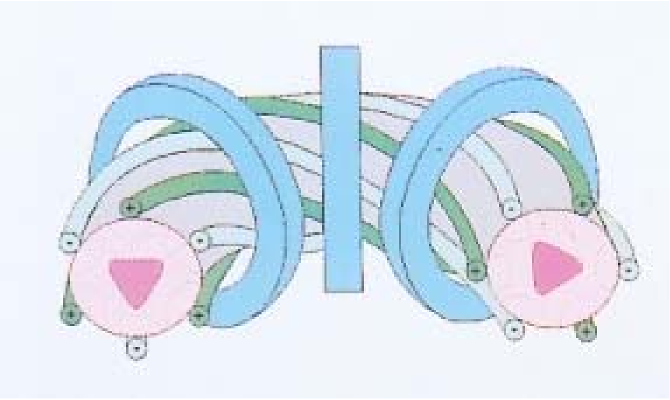


linear pinch





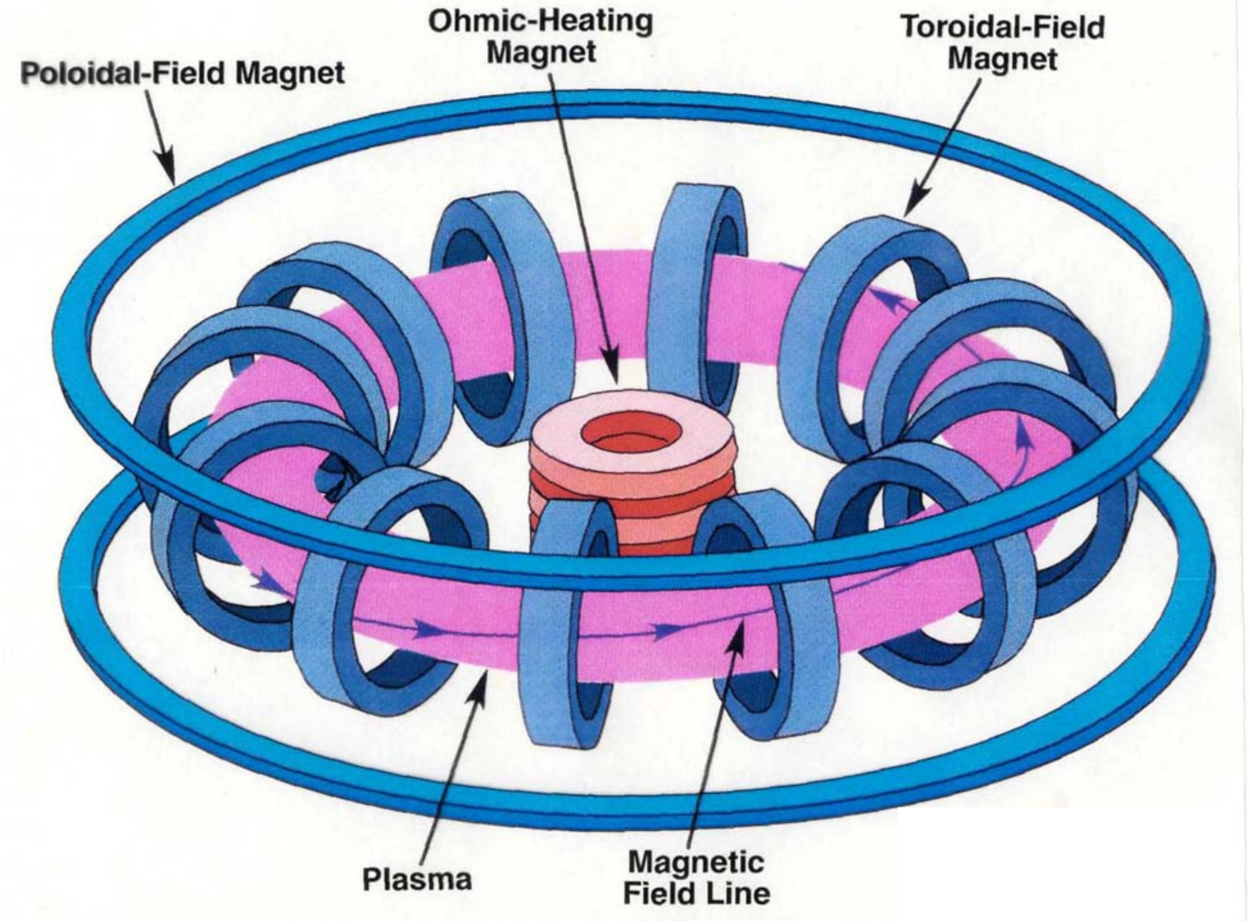
field reversed configuration



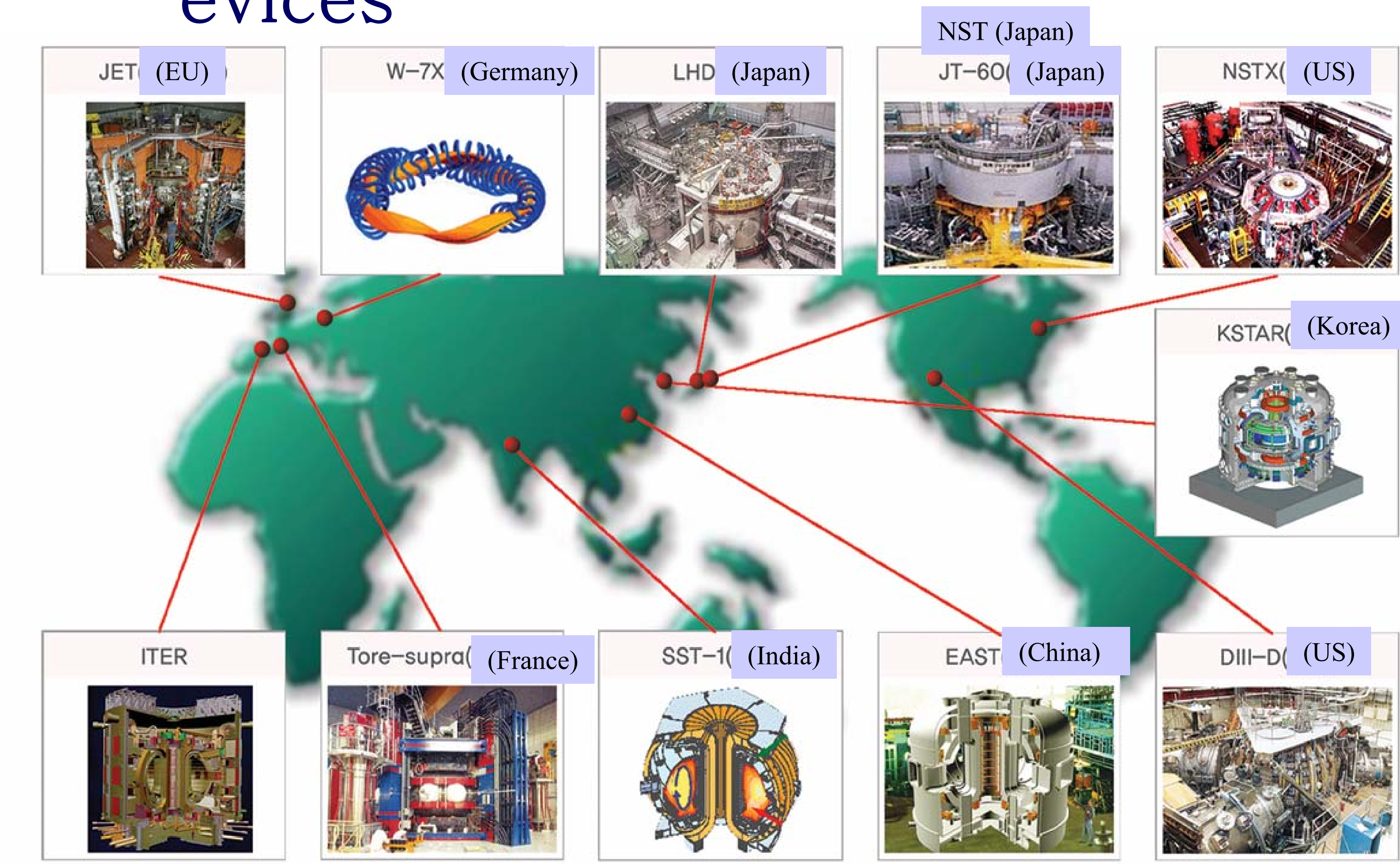
stellarator

The Winner so Far: the Tokamak

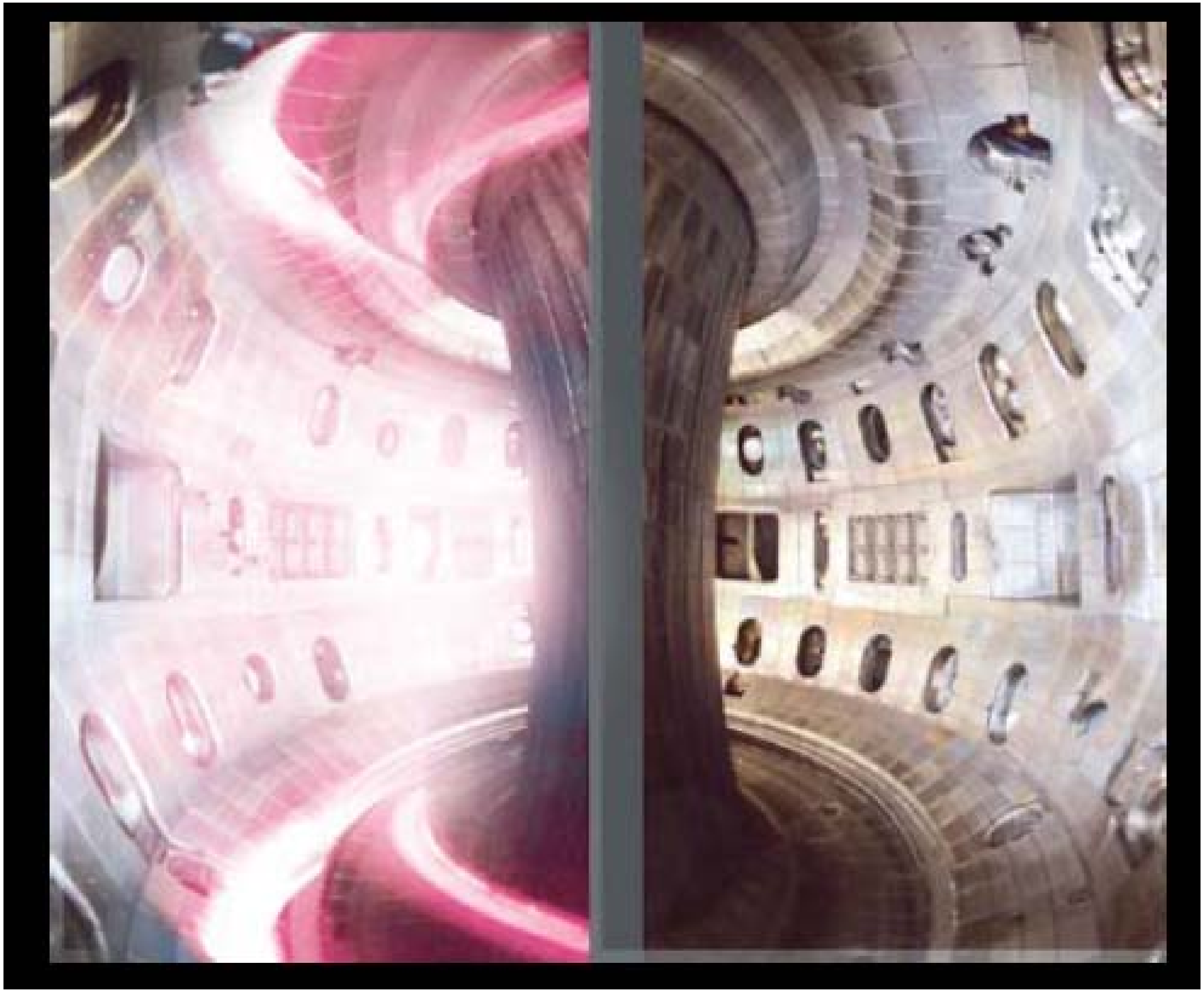
Tokamak = toroidal magnetic chamber (Russian acronym)



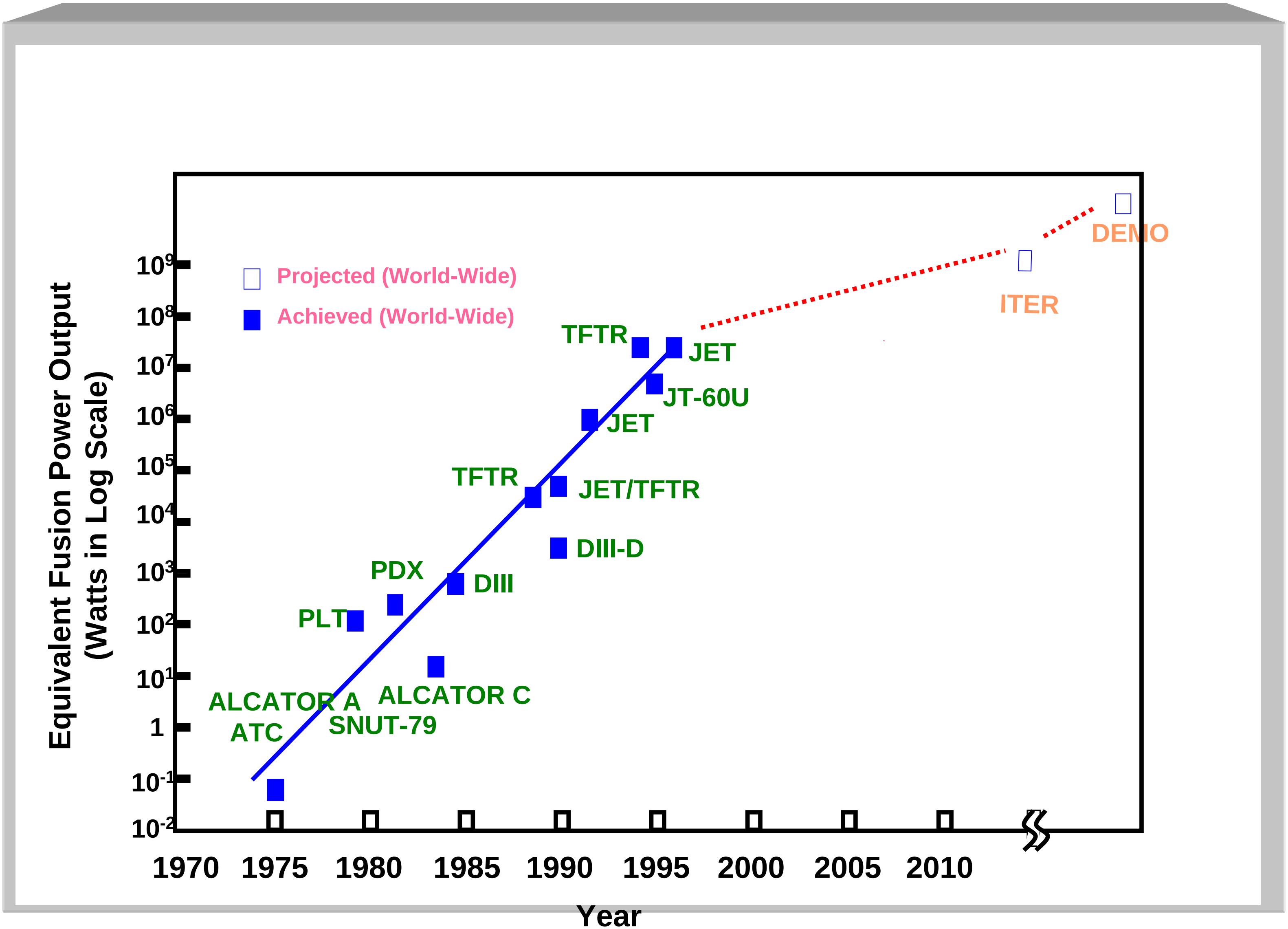
Present World Magnetic Fusion Devices



DIII-D with Plasma and No Plasma

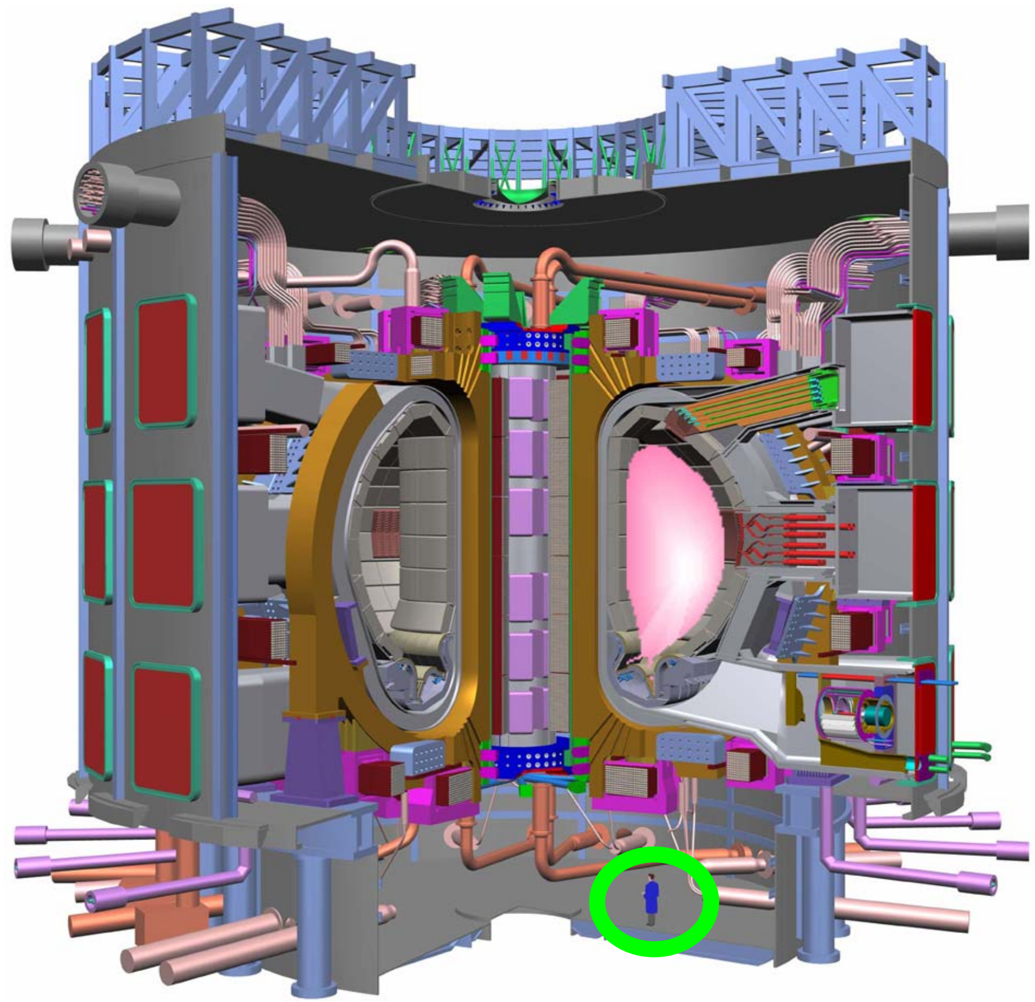


World Fusion Program Progress



ITER – A Burning Plasma Fusion Reactor (~2015)

30m tall & 30m diameter



Design Goals:

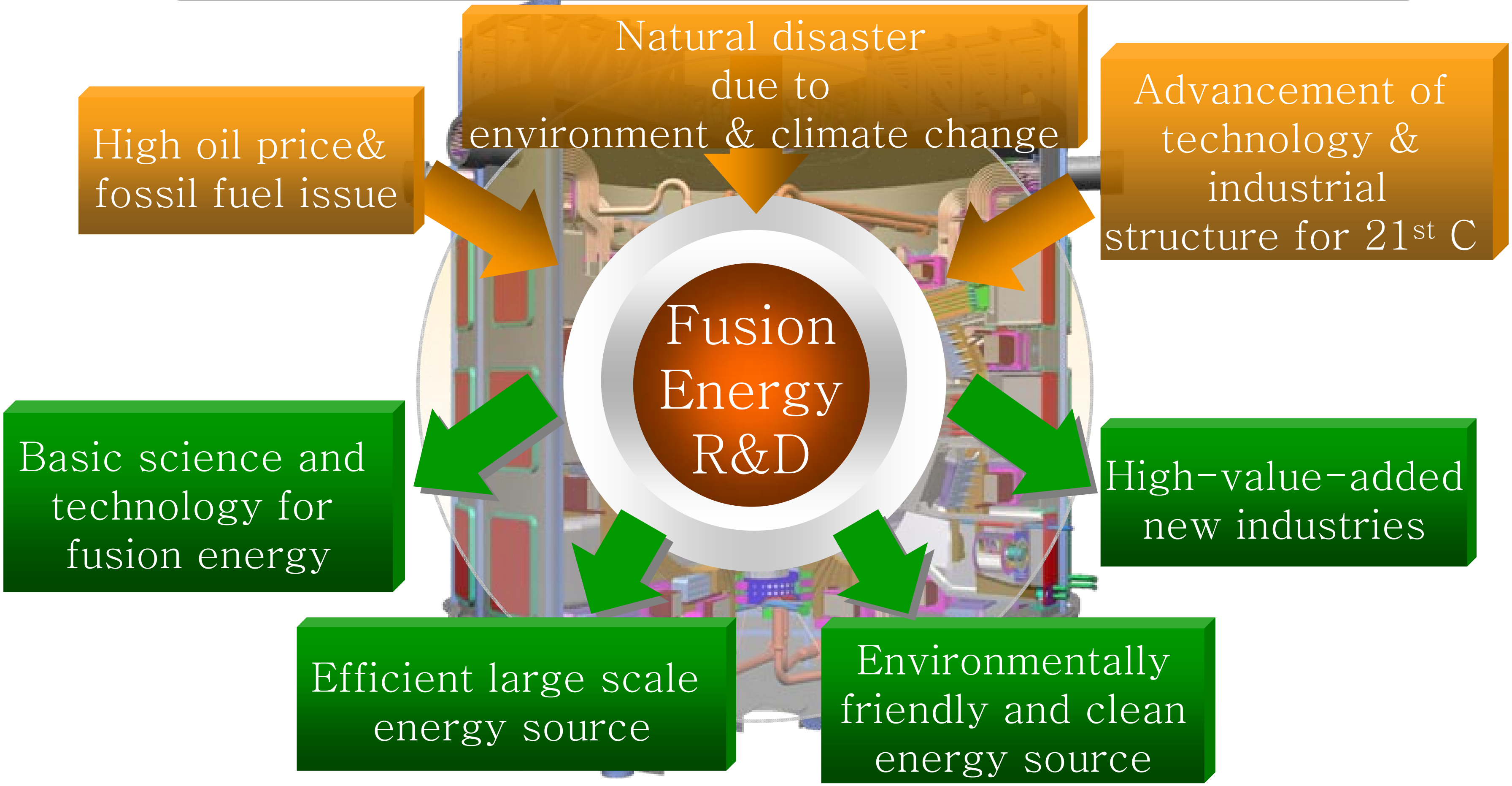
- Q $\approx$ 10 (burning plasma)
- 0.5 GW fusion power
- 500 sec long pulse
- no electricity output

Formal ITER construction agreement (cost 5B Euro) was signed by 7 parties in 2006 (total cost over 30 yrs is estimated at 10B Euro).

Taiwan 4th Nuclear Power Plant construction costs ~ \$6B for 1.375 GW power

Fusion Energy R&D

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



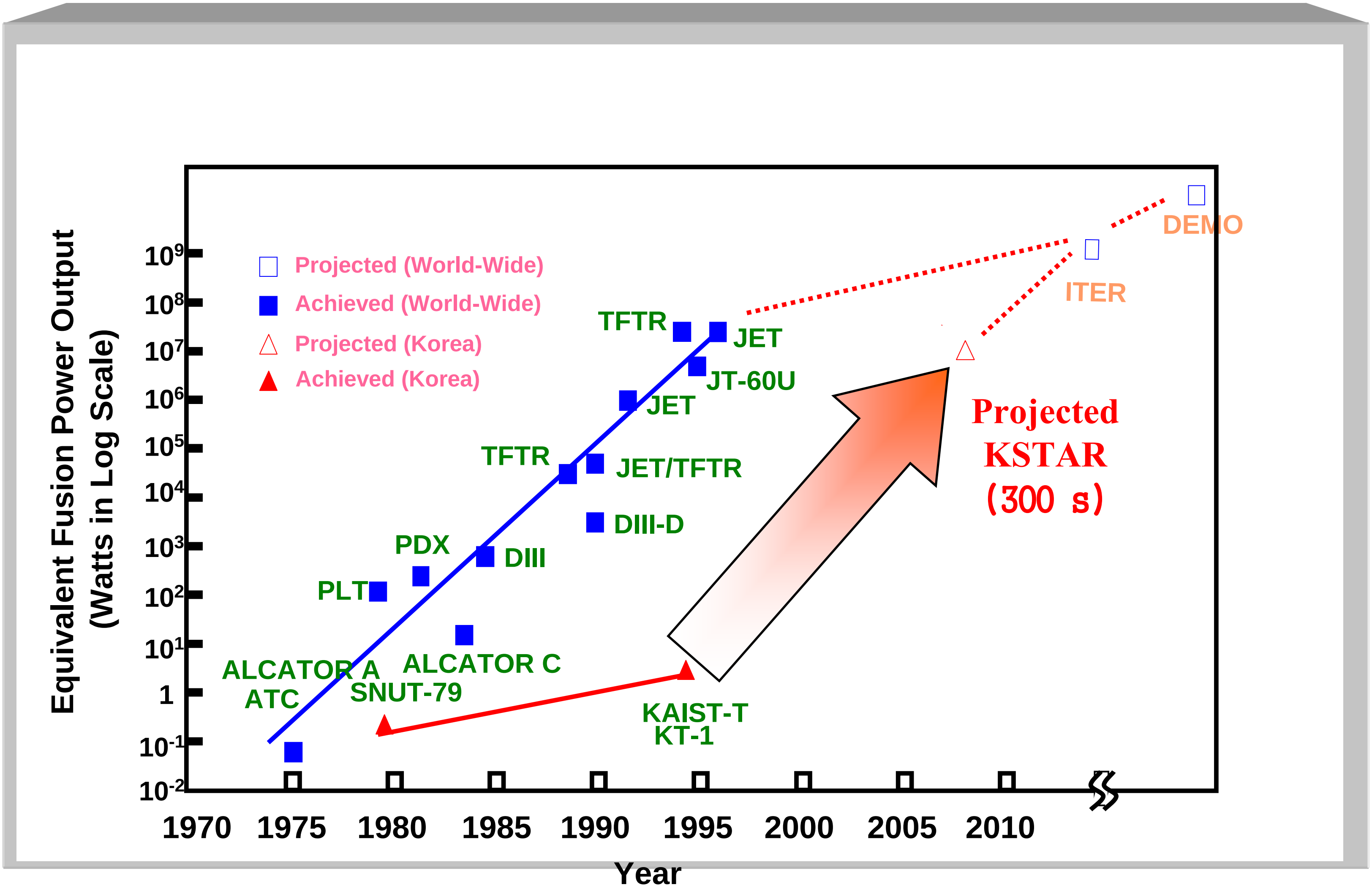
Advanced science and state-of-the-art technology

Fusion Research Spending

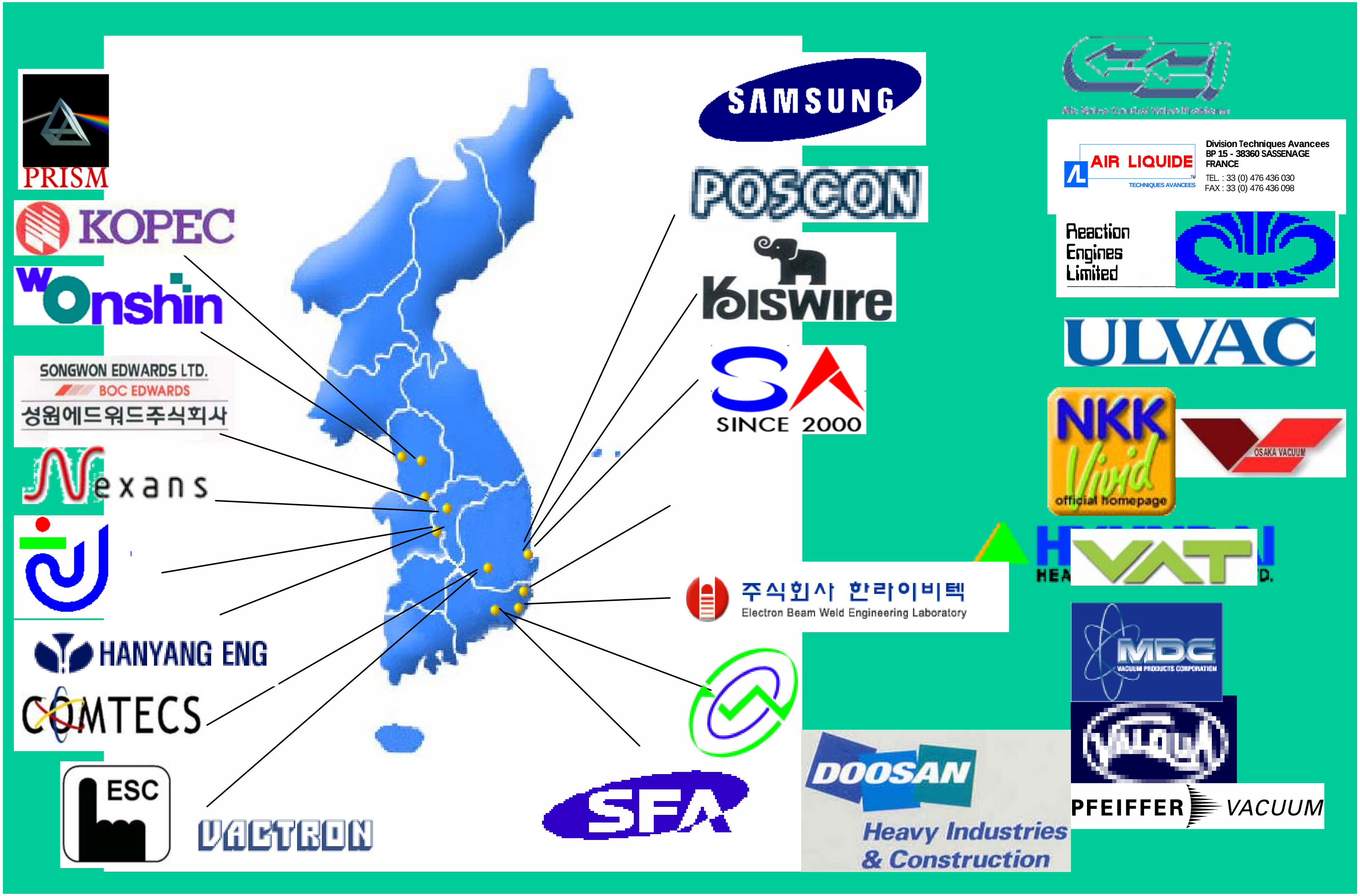
- ITER
  - **Agreement signed in June 2005 with total cost ~$13B over 10 yrs, to be built in France**
  - **Participants: EU(40%) , Japan(10%), US(10%), Korea (10%), Russia(10%), China(10%), India(10%) representing ~ ¾ of world population**
- 2006 US annual magnetic fusion budget ~ $300M
  - **One space 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 industries in KSTAR



Fusion Energy Research in Taiwan

- **Present Taiwan's fusion & plasma science investment: none or negligible!**
- **Should Taiwan continue to ignore fusion research when nations representing more than ¾ 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

Thank you!

國立功成大學「電漿與太空科學中心」成立目標

本中心於2006年8月1日成立，主要希望成立全國第一個磁化電漿科學研究中心，同時也要成為台灣衛星科學酬載研製的重鎮，進而培養本國的電漿與太空科學研究人才及衛星科學酬載自製能力。

國立功成大學「電漿與太空科學中心」研究重點

- **電漿科學**：發展磁化電漿理論與和電漿量測，參與核融合反應系統裝置的控制研究，成立核融合電漿科學團隊來負責托克馬克核融合反應爐物理的理論及實驗研究。

- **太空科學**：太空物理與太空衛星的科學儀器發展，目前中心已經建構太空儀器實驗室，主要的目標為參與國際合作太空科學衛星科技研究計畫，並為台灣衛星建製科學儀器。

NCKU Plasma and Space Science Center
國立功成大學「電漿與太空科學中心」

- **Established in August, 2006**
- **Expertise and capability in:**
  - **Theory, simulation & modeling:**
    plasma theories for space and astrophysical plasmas, magnetic fusion, and laboratory plasma devices
  - **Laboratory plasma experiment:**
    devices for basic plasma sciences, plasma diagnostics and experiments, tokamak fusion experiments
  - **Space science**
    satellite in-situ and remote sensing instruments for observing space plasmas, etc.
  - **astrophysics:**
    solar and astrophysical plasmas, ground-based telescopes, etc.

Plasma Science Division

- Initial experimental efforts:
  - Build up plasma diagnostics capability & expertise
  - Participate in diagnostics development for tokamak experiments in collaboration with collaborators
- Cooperation agreement with international collaborators
  - Personnel exchange: students, staff
  - Recruit visiting professors in teaching & research
- Plasma teaching lab
  - Duplicate a teaching plasma lab at PPPL
- Magnetic mirror plasma device
  - Build magnetized plasma devices for studying basic plasma physics relevant to fusion research
- Experimental personnel
  - Hire experimental plasma physicists, lab engineers, and
  - Enroll graduate and undergraduate students

Space Science Division

- Initial experimental efforts:
  - Develop instrument building capability & expertise
  - Provide scientific instruments for NSPO needs
- International cooperation
  - Partners: Japan, Canada, USA
  - Personnel exchange: students, staff
  - Recruit visiting professors in teaching & research
- Instrument lab
  - Clean room
  - Plasma chamber
  - Test equipments, etc.
- Experimental personnel
  - Hire lab staff and enroll students
  - Hire space physicists in data analysis, instrument, satellite mission

Finally, a graduate Institute of Space, Astronomy and Plasma Sciences (ISAPS) (太空天文與電漿科學研究所) will begin student enrollment in Sept., 2008.

Thank you!