Fusion Power, Who Needs it - An Updated Assessment !!

P. K. Kaw

Institute for Plasma Research
Bhat, Gandhinagar 382 428
Gujarat, INDIA

Fusion Power, Who Needs it ?

At the IAEA Fusion Energy Conference at Wurzburg , in 1992, I gave a talk with the above title and made the following points :

- The global fusion energy program is proceeding at a pace that is less than ambitious and has not been able to access budgets consistent with its technical accomplishments.

This happened to be so, because

- Nations which had the technological and financial resources to launch an aggressive fusion R & D program were energy comfortable and felt that there is no urgency to do so .

- Nations which had tremendous energy needs and discomfort because of developing nature of their economies and the poor quality of life of their citizens did not possess the technological and financial resources to drive an aggressive fusion R & D program.

- It was finally recommended that an ambitious and accelerated global fusion R & D program needs to be launched with a partnership between the mature programs of the developed countries and the young programs of the developing countries.

- . Today, I wish to take a fresh look at this question and discuss the current situation with you, since it has changed and may have lessons which have wider implications for international collaboration in science and technology.

OUTLINE

❖First we shall take a look at the global energy problem

Consumption Patterns

Constraints to Growth

Alternatives

Role of Modern Technologies like Fusion

❖**Next we shall look at fusion as a long term candidate requiring R & D**

Fusion energy

Present status

International collaboration

❖Conclusions

Global Energy Perspectives

It is recognized now more than ever that there is a wide disparity in the per capita energy consumption of nations with developed and developing economies.

As the latter economies become stronger, they need more energy for GDP growth and for improving the quality of life of their citizens.

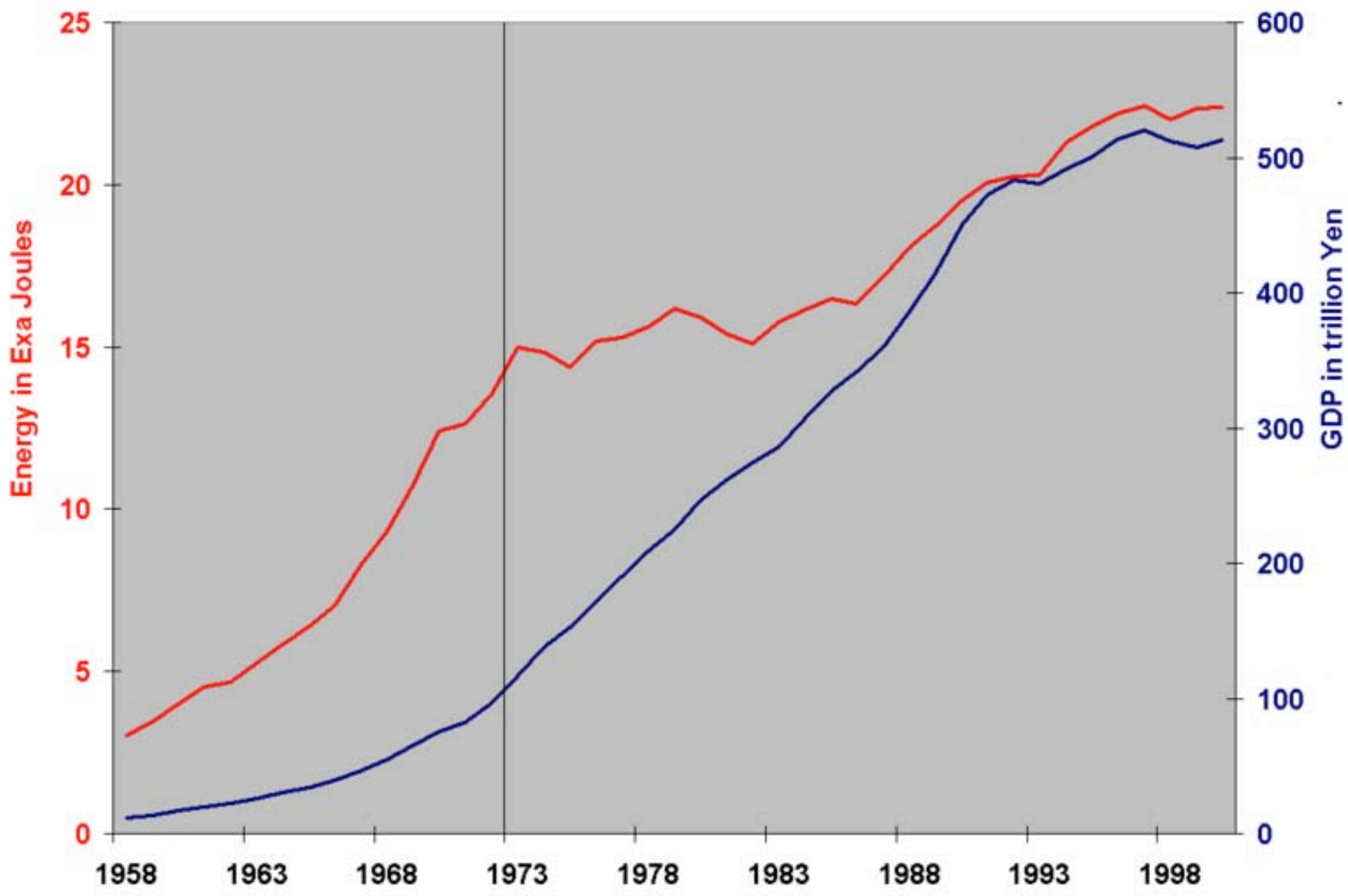
Per Capita Consumption of Electricity in Different Countries (1990 and 2003)

1 Unit ≅ 1 KWH

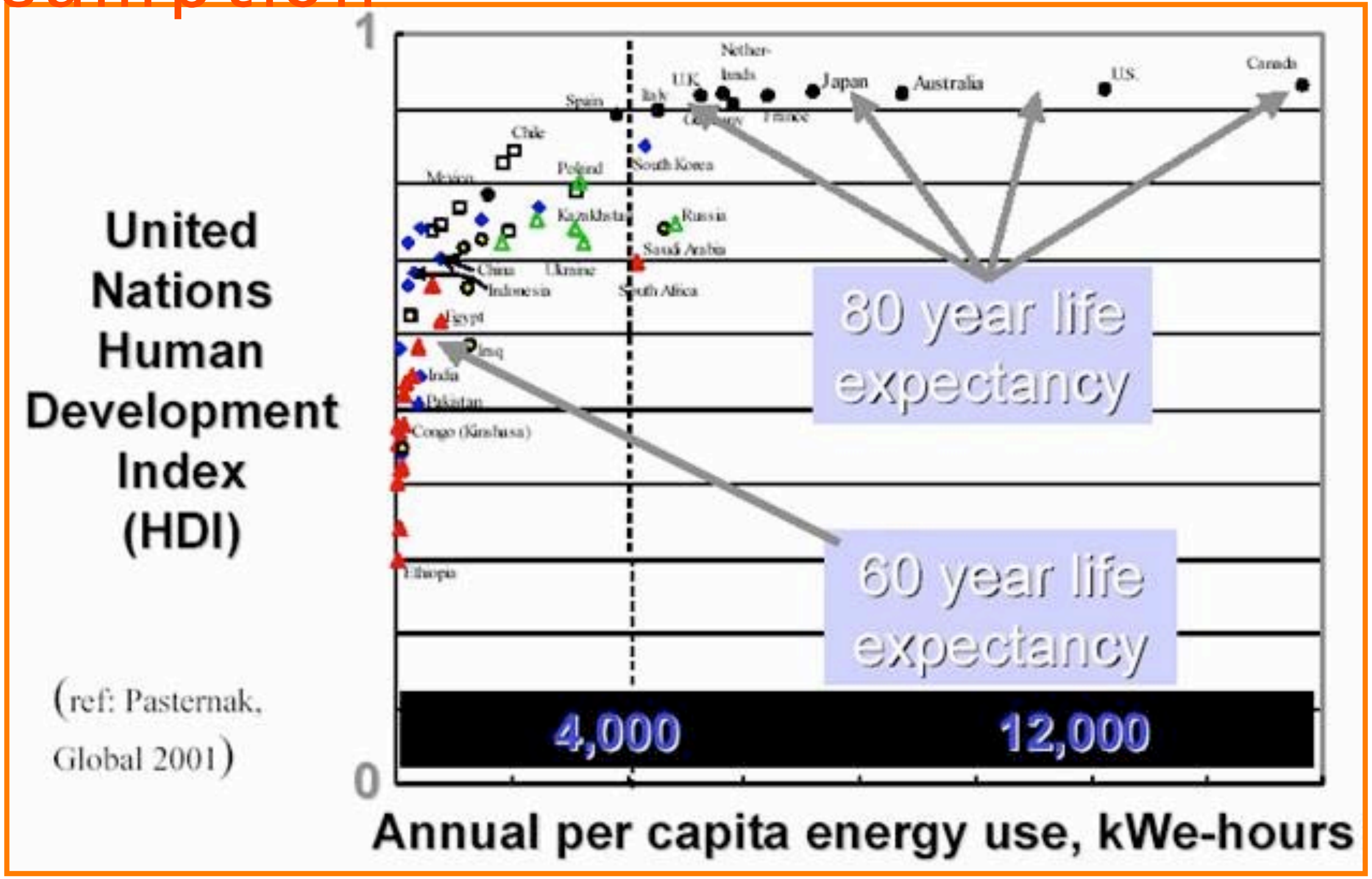
	1990	2003
Canada	16160	17210
USA	11690	13240
UK	5360	6200
Japan	6510	7810
Brazil	1460	1880
China	511	1380
India	280	440

≅~ 1/6 of World Average

GDP vs Energy Consumption in Japan



Quality of Life & Electricity Consumption



- In past 50 years a number of nations have become independent. Today 80% of the world's population (~ 5.3 billion) is clawing it's way up the development curve.

- This translates into massive energy hunger for the globe as a whole.

Year	Population (Billions)	X	Kilowatts Per Person	=	Total Energy (Terrawatts)
1990	1.2		7.5		9.0
	4.1		1.1		4.5
					13.5
2025	1.4		7.5		10.5
	6.8		2.2		15.0
					25.5

$\boxed{\text{Doubling}}$ of world requirements in $\boxed{35}$ years.

Enhancement in needs of Developing Economies far exceeds that of Developed world.

CONSTRAINTS TO GROWTH

- How is this additional power likely to be generated?

- Massive increase in use of fossil fuels because it is priced low by externalizing a lot of real costs

- Has resulted in serious degradation of ***local*** and ***regional*** environment.

- Beyond 2020, the impact on **global** environment is likely to be staggering! Clear evidence from IPCC 2007 report. Greenhouse gas emissions will dramatically increase. Temperature rise of 4-6^{0}C possible by 2100. Severe changes in mean sea level, precipitation, climate patterns, soil productivity etc. likely.

- Unbridled growth in world **fossil** consumption not tenable! Hence if we have to depend on fossil fuels, global economic growth might have to be constrained !!

Distribution of Generation Methods
China and India

Supply Option	China 1990 (GW)	China 2020 (GW)	China Revised 2020 (GW)	India 1990 (GW)	India 2020 (GW)
Thermal (Coal, Oil, Gas)	115	400	(770)	54.5	340
Hydro	5	55	(150)	19	40
Renewables	--		(60) --	10	20
Nuclear	--	45	(20)	1.5	20
Total	120	500	(1000)	65	420

Alternatives

Given a constrained growth scenario, what are the choices world is confronted with?

A Voluntary reduction of per capita energy consumption in industrialized nations.

B **Stagnation** of per capita energy consumption (hence of economic growth) in developing world

C Impact of modern energy technologies on
-- increased use of non-fossil energy sources
-- conservation & efficiency improvement
-- environmental remedies etc.

A Only possible in an ideal world

Unless C is made available, B most likely choice because of inertia!

But choice B for any length of time would be disastrous for global prosperity because the world markets are now part of an intricately interconnected economic web and stagnation of one part of the global economy influences the growth of the other.

Choice C is the most sensible choice.

How Can Modern Energy Technologies Help?

- Conservation and efficiency improvement technologies which extract a high standard of living from low per capita energy consumption.

- Fossil fuel movement
  - → Natural Gas
  - → Clean Technologies (Mandatory use of precipitators clean-coal, flue gas clean up)
  - → Reduced Use by increased cost. Internalize all costs (environment clean-up, security of oil-rich regions, irreplaceable)
  - → Accept targets per capita for greenhouse gas emissions

✓ Economic investment in new energy technologies (Returns from selling technologies worldwide!

R & D in Energy Technologies

- All nations must invest in energy R&D.
  - -- conservation
  - -- Non-fossil energy sources
  - -- New energy technologies – e.g Fusion Energy

- Investment on R & D in new energy technologies should be viewed as long term insurance (Holdren 1990, Yoshikawa 1998) and international collaboration between developing countries and developed countries needs to be promoted.

- So , answer to the question “Fusion Power, Who Needs it?” in the current day context is

WE ALL NEED IT URGENTLY (within 30-40 years) FOR SUSTAINABLE DEVELOPMENT AND PROSPERITY OF THE GLOBE AS A WHOLE .

Fusion-The quest for STARFIRE

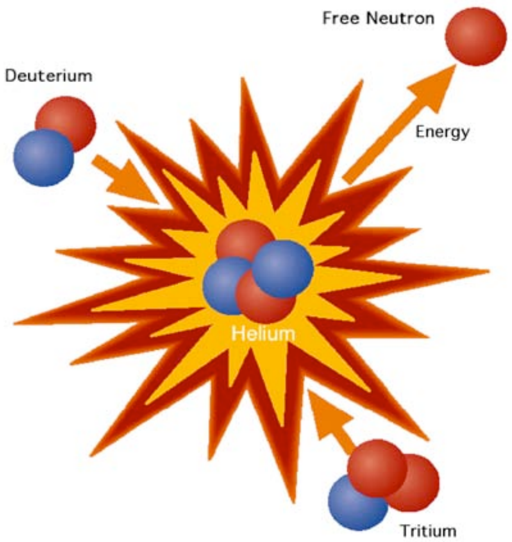
- Sun and the stars have been burning brilliantly for billions of years using nuclear fusion

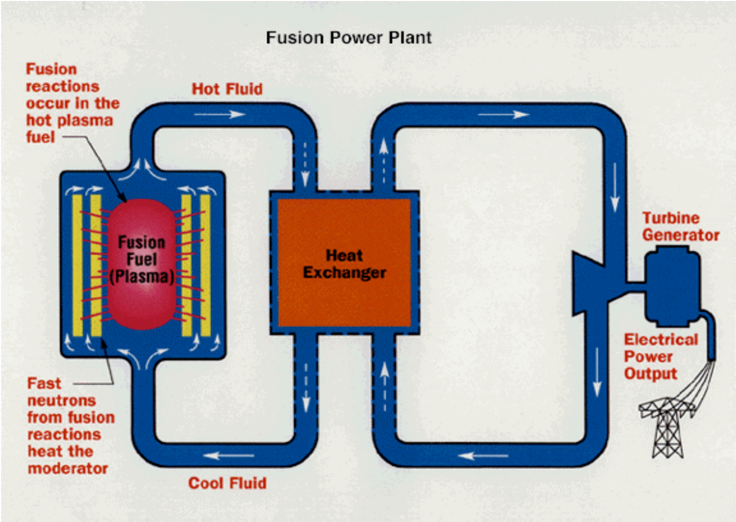
- It is a nuclear process :

  D + T = He + n + energy

- Energy from neutrons converted into electrical power

- Fusion requires matter at millions of degrees in the plasma state





How to achieve Fusion?

D + T ⟶ He +n +17.6MeV

- Heat the fuel mixture to 100 million degrees and get conditions such that

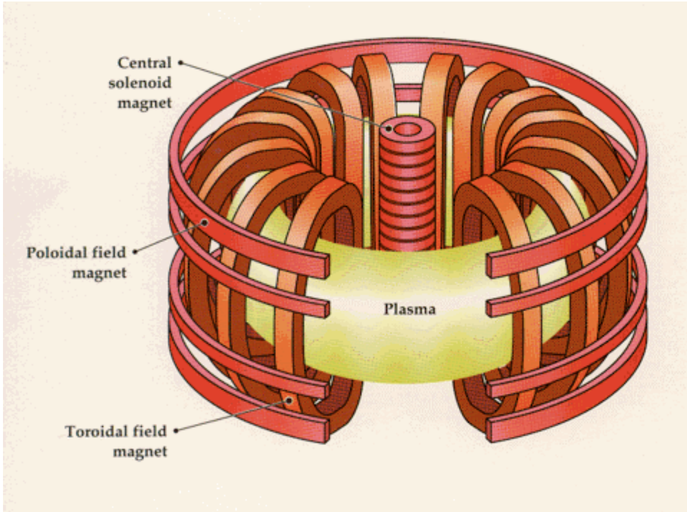
Density x **Temp** x **confinement time > $5.10^{21} m^{-3}$ keV secs.**

- Ignition of thermonuclear Fire !
- He nuclei keep the fuel hot. Neutrons take energy out, trapped in blanket like fission reactor.
- Mixture at sub-atmospheric densities ($\sim 10^{20}$ m^{-3}) to be held and thermally isolated for seconds.

Fuel is in a Plasma State

Magnetic Confinement Fusion

- In the Sun and the stars : Gravitation confines the plasma
- In labs magnetic field confines it away from material walls
- The most efficient magnetic confinement devices are Tokamaks (*first developed in Russia*)



Here the plasma is confined in magnetic cages created by a combination of plasma currents and external coils. Plasma is heated to 10^8 degrees by the currents and injected neutral beams and microwaves.

International Cooperation

Magnetic fusion has long history of International Cooperation :

- It started in 1956 with the Soviets declassifying their efforts on Controlled Thermonuclear Reaction expts, which led to the Geneva Conference of 1958 where the results from the West and the Soviets were freely exchanged.
- Thereafter, a free exchange of information on magnetic fusion experiments has been going on at the IAEA Fusion Energy Conferences which are held every two years. These Conference proceedings have become a veritable repository of information and history of magnetic fusion.

- In the 70’s and 80’s, the magnetic bottle invented by Russians Sakharov and Tamm, the tokamak, was extensively researched upon by teams in US, Europe and Japan. Very impressive experimental results were obtained on large tokamaks like TFTR, JET and JT-60 showing the potential of these devices as the core of future fusion reactors.

Science of FUSION

- Fusion involves the confinement of a hot 10^8 ^0K D-T plasma away from material walls. This is achieved by the use of a magnetic bottle created by external coils and plasma currents (TOKAMAK).

- Fundamentally a tokamak is a driven, dissipative, far from thermodynamic equilibrium system in which pressure gradients are maintained by external sources and the confinement times are determined by non-linear self-consistently driven super thermal fluctuations of electromagnetic fields.

- The last decade has unravelled a complex of bifurcation phenomena through which the plasma can be goaded into states of considerably improved confinement and reduced turbulence levels!

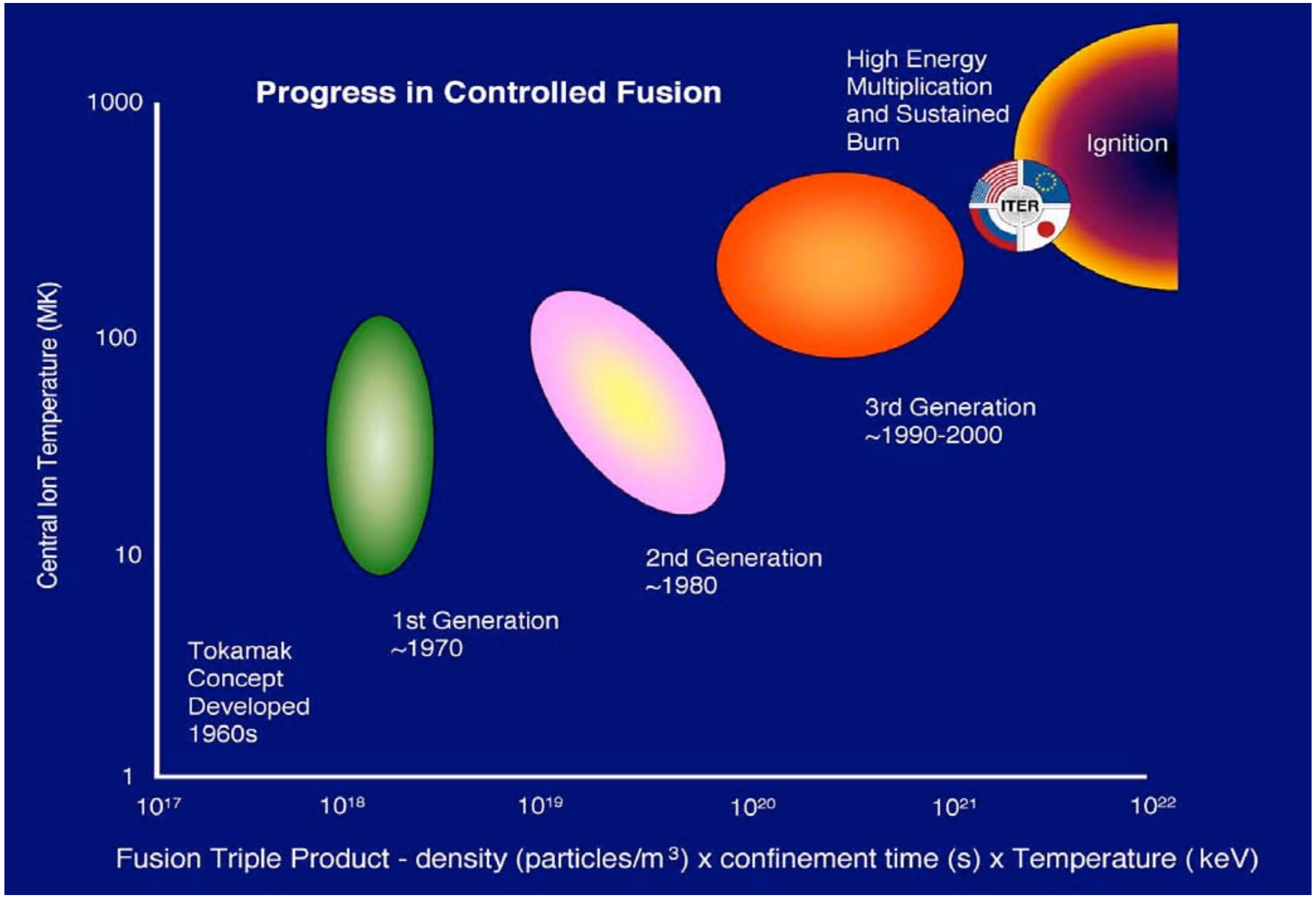
- The fundamental physics of such far from equilibrium systems is beautiful, deep and sublime. The basic principles, when understood, will throw new light over large areas of physics – including perhaps the physics of living matter!

- What plasma physicists are doing right now is to develop intuition based on experiments and computer simulations- to enable one to design and operate a fusion reactor. This search is pragmatic and similar to the one adopted by designers of large aircrafts in which the lift is determined by the turbulence around the wings.

- Empirical scaling laws and phenomenological modeling have been developed to predict performance. First principles simulation codes are being attempted but are still in their infancy.

Phenomenal progress in past decade

- Temperatures upto 400 million degrees obtained by injecting tens of Mwatts of microwave and neutral beam power.
- $nT\tau$ within striking distance of ignition.
- Fusion power output ~ 16 Mwatts sustained for seconds.
- Reactor Size plasmas (millions of Amps of current and several cubic meters in volume) manipulated



Progress in the critical parameters for fusion reactor experiments

Next Step Experiments

- Steady State device physics
- Study of Burning plasmas
- Study of Fusion materials.

Steady State Devices-New Asian Programs

In last decade or so China, India and South Korea have taken up the challenge of Steady State Devices in their domestic programs. Only experiments of their kind in the world. Experiments are still small but in an interesting parameter space where they will cover physics problems due to long pulses for the first time.

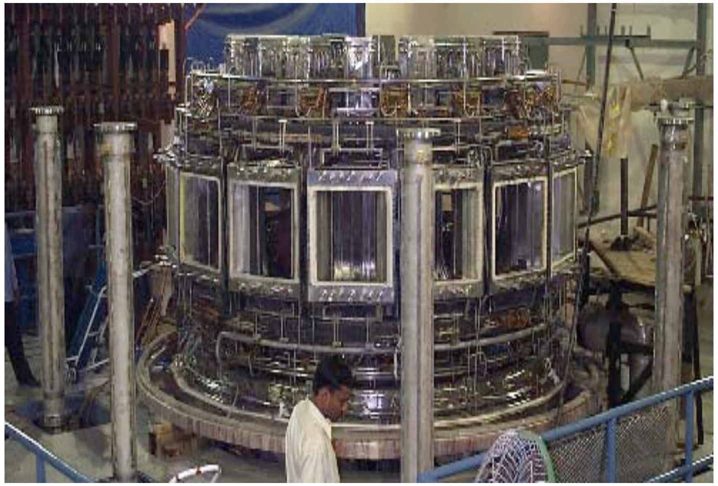
China : Sixties start , momentum in 80's and 90's
Two Instts., Several tokamaks HL-2 series at SWIP
Superconducting devices HT-7, EAST at Hefei

India: Eighties, ADITYA
Superconducting SST 1 at Gandhinagar

Korea: Nineties
Superconducting KSTAR

Investment ~ ½ Billion USD.
Major activity first time taken up by countries which feel the urgent need!

EAST TOKAMAK

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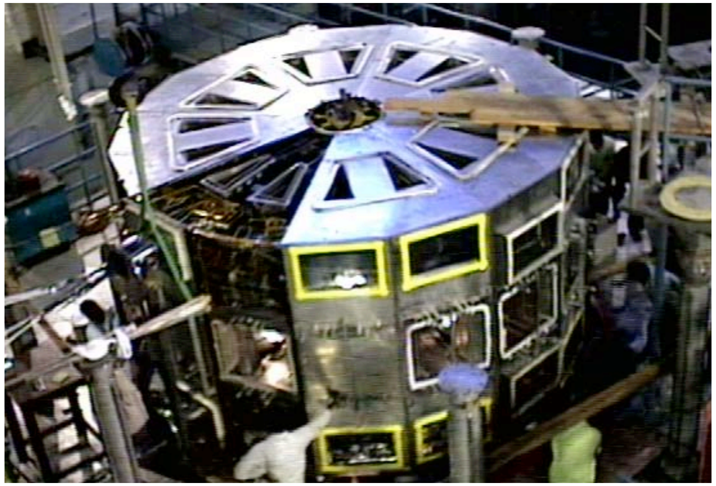


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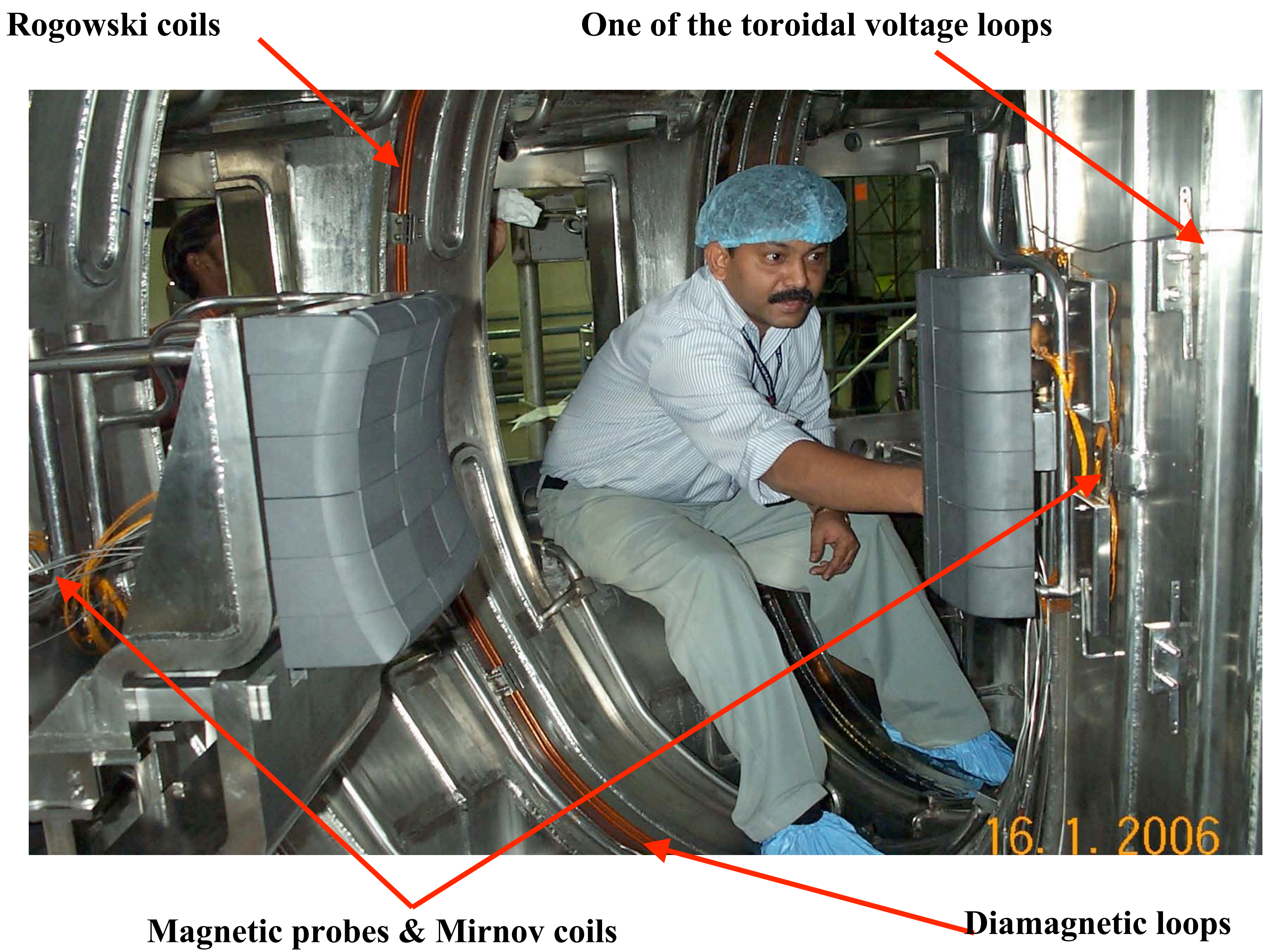
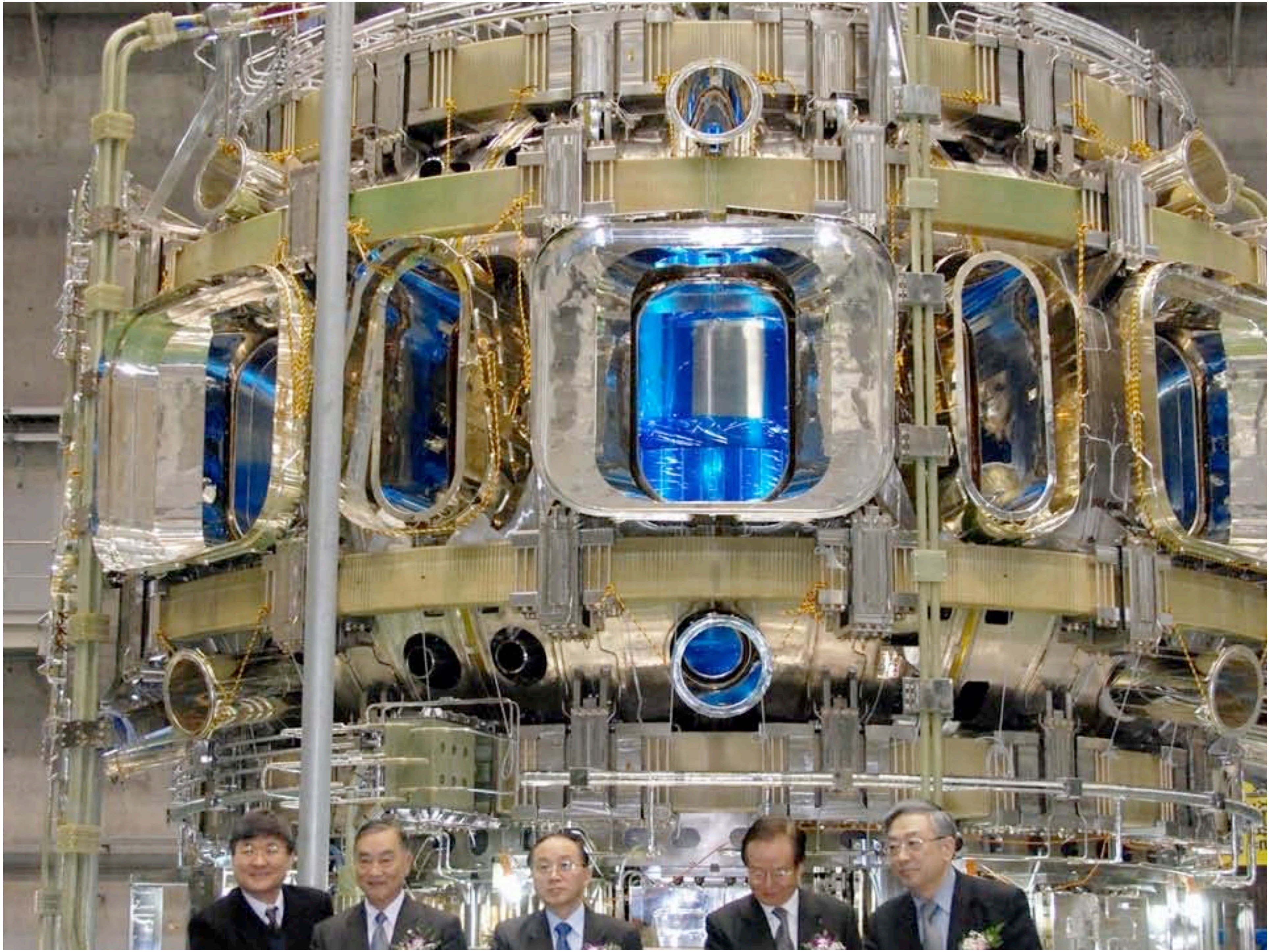

Rogowski coils
One of the toroidal voltage loops
16. 1. 2006
Magnetic probes & Mirnov coils
Diamagnetic loops



Next Step Experiments

- Steady State device physics
- Study of Burning plasmas
- Study of Fusion materials.

•Burning plasma physics and some material studies can best be carried out in a large reactor plasma size experiment. ITER is such an experiment. It is however, conservatively designed and expensive and is to be built by several countries working together.

•From the mid 1980's IAEA has been fostering the design and construction of an International Tokamak Experiment following a US-Soviet initiative. This eventually metamorphosised in the 90's into the ITER experiment with US, Russia, Japan and Europe as partners.

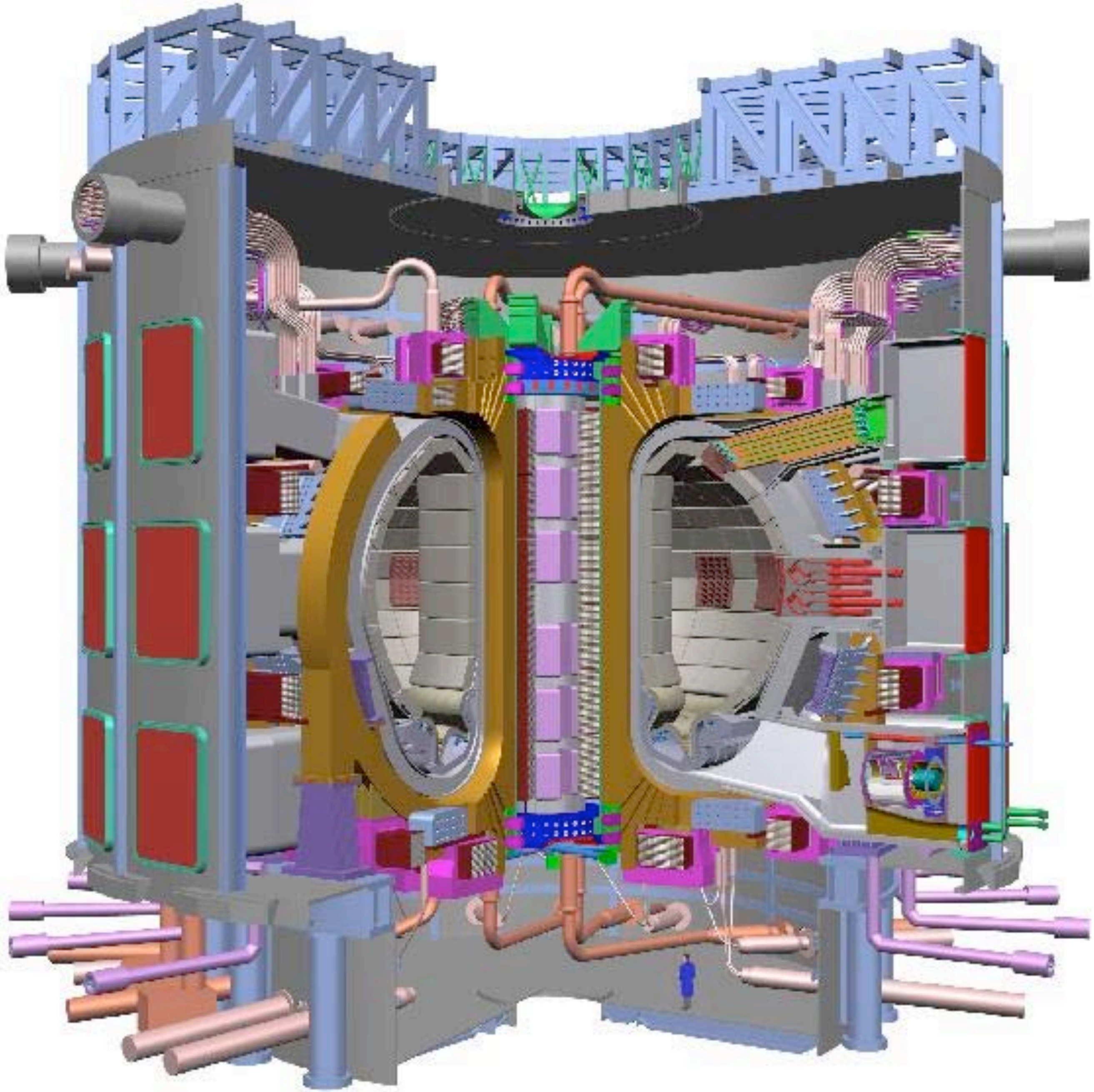
• The partners took some time to arrive at a consensus on details of the design, agreement, construction site, etc. Finally, early in this decade they were ready to sign an agreement when China, Korea and India also expressed an interest to join the partnership. They were accepted because of the increased maturity of their programs and in 2006, the seven party ITER agreement was signed.

ITER: International Thermonuclear Experimental Reactor

- Is the flagship experiment being built at a cost of ~ 5 billion euros
- Original parties: US, Russia, Europe, Japan.
- Recent Additions: China, Korea, India.
- Each partner contributing equipment worth 1/11 of total cost; host Europe contributing about 5/11 of cost
- Experiment ready by 2016-18. Will pave the way for DEMO reactor demonstrating electricity production by ~ 2035.
- First commercial reactors available in 2045-2050.

ITER Parameters

Plasma Major/Minor radius	6.2m/2.0m
Vertical Elongation	1.7
Plasma Current	15 Mamps
Toroidal Field	5.3 T
Pulse duration	> 300 secs
Fusion Power	500 Mwatt
Plasma Volume	837 m^3



ITER

- The ITER partnership is unique in many ways:

It involves nations representing more then half of the world’s population.

It is attacking a major scientific challenge on a problem facing the whole globe with everybody working together.

Nations like China, India and Korea with younger fusion programs are working shoulder to shoulder with nations with more mature programs, contributing in equal measure (a total of ~ 27 %) , sophisticated hardware and financial and human resources .

The agreement addresses difficult issues like sharing of intellectual property rights.

This collaboration is likely to work because :

- All parties are convinced that making fusion technologies work will genuinely ease the long term global energy problem with beneficial effects for everybody.

- Developing countries like China, India etc are gaining economic strength and see merit in spending on R&D on topics which can directly impact their growth.

- The fusion programs of countries like China, India and Korea have acquired a certain degree of maturity.

- Organizations like IAEA have done a fantastic job of fostering free exchange of scientific and technological information in fusion through biennial conferences, publications, nuclear fusion journal and technical committee meetings.

The ITER Collaboration has beneficial consequences for the world fusion programs :

• Upscaling of the skill sets of the design and fabrication engineers of younger programs by vigorous direct interaction with senior engineers having experience.

• Improved confidence and ambition of the long term domestic fusion programs (e.g. in India we have chalked out and finalized a multi-decade fusion program with TBM's, prototype development work, SST 2 and DEMO studies, fusion materials development studies etc.)

• Increased probability that many partners will participate in and contribute to other international activities of interest to fusion such as IFMIF, CTF, BA, IEA implementing agreements, DEMO etc.

Conclusions

- The globe is seen more and more as an intricately interconnected web environmentally and economically, where the prosperity of one part is determined by the economic growth of another.

- Since the economic growth of developing countries is crucial to global prosperity and since it is intimately tied to per capita energy consumption, it makes sense to cooperate in methods of clean non-fossil methods of energy production.

♦Technologically, the nascent fusion programs of developing nations have now come of age and matured and they can significantly contribute to the hardware, manpower etc.

♦Financially, many developing nations are acquiring significantly growing economies and they can spare funds for scientific and technological enterprises which directly promise to contribute to their growth.

♦Organizations like IAEA which play a crucial role in the dissemination of scientific information worldwide do play a critical role in the incubation of international cooperation programs.

External conditions have sufficiently changed so that the call for global collaboration, which was only a cry in the wilderness at the Artsimovitch lecture in 1992 , is becoming a reality today. Thus :

- Urgent Need for new energy technologies like fusion is felt by every one
- Everyone feels that they have something to give and take from collaboration
- IAEA has done its homework and kept parties talking
- There is enough goodwill from all sides to solve difficult political issues

- The question “ Fusion Power, Who Needs It” has the new answer:

WE ALL DO AND URGENTLY TOO !! And we shall strive to achieve it by working together.

- If ITER collaboration proves successful and paves the way for DEMO and commercial fusion reactors, more than half of humanity can look back with pride and say “ We did not shove the problem facing us under the rug but looked it in the eye and solved it by working together.”

- Other global problems waiting for S & T solutions such as environment clean up, climate change mitigation, potable water and food for everyone, population control, eradication of infectious diseases etc may be interested in learning from the fusion experience.