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International Centre
for Theoretical Physics



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CIMPA/ICTP Geometric Structures and Theory of Control

1 - 12 October 2012

Overview of Nuclear Fusion via Magnetic confinement

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Joint-ICTP-IAEA College on Plasma Physics
International Center for Theoretical Physics, Trieste, Oct. 1, 2012

Overview of Nuclear Fusion via Magnetic confinement

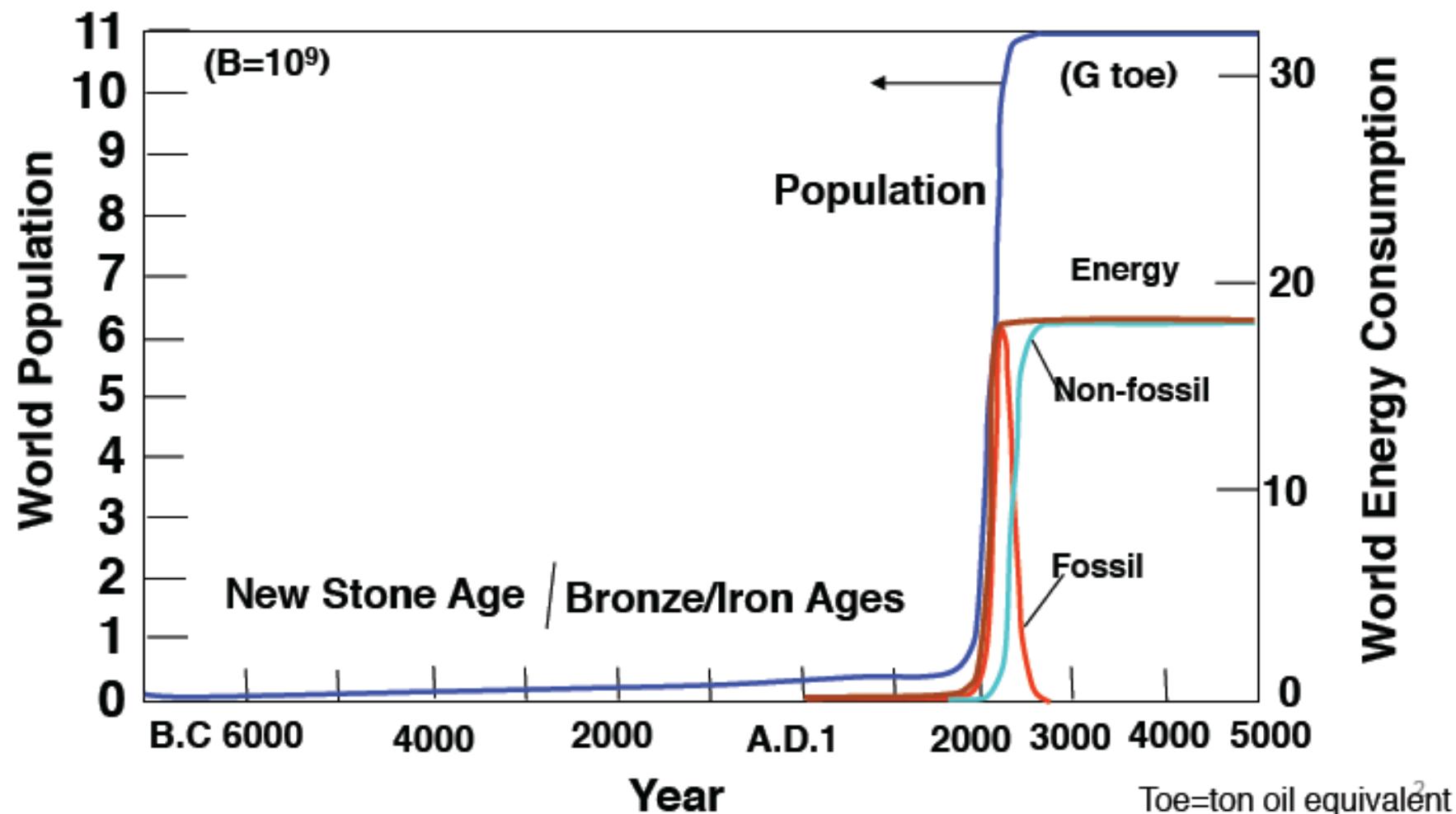
M. Kikuchi

Supreme researcher, JAEA, Japan
Chairman, Nuclear Fusion BoE, IAEA
Guest professor, Osaka University, Japan
Visiting Professor, Fudan University, China
Visiting Professor, SWIP, China

0. “ENERGY” is fundamental for human life for many millennium

BIG transition occurs in 20th century for both population and energy consumption.

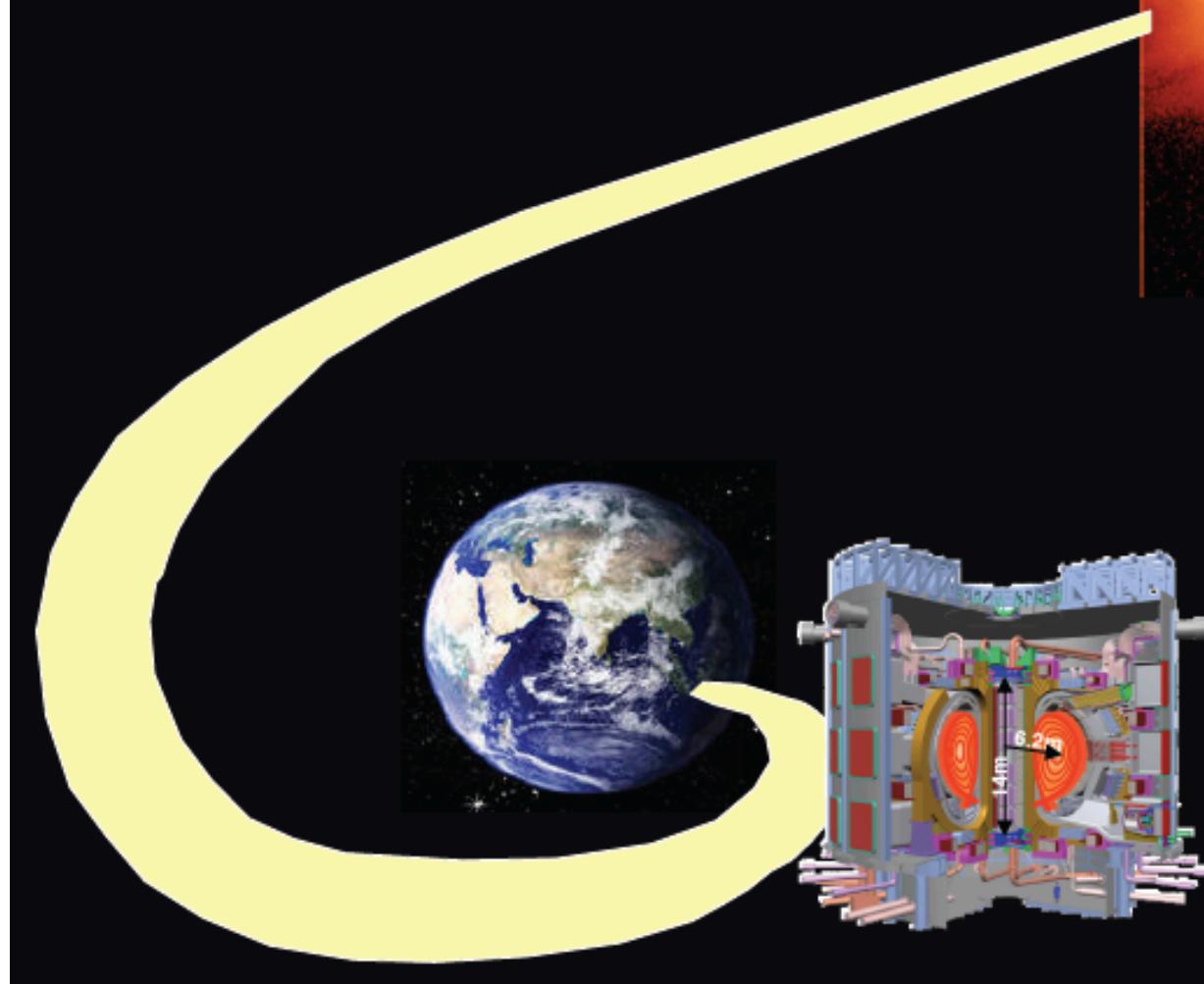
Question to 21st Century : Can we sustain large population & energy consumption .



Sun on the Earth

- Fusion Research -

1. Fusion research is to bring Sun on Earth



2. Start of Fusion Research and 50 years



1956 : 1st Geneva conference on peaceful use of atomic energy. 2nd from right is Prof. Homi Jehangir Bhabha, saying that way to be found to realize fusion in 20 years.

1958 : 2nd Geneva conference on peaceful use of atomic energy. Prof. Hideki Yukawa in center.



2008 : 22nd FEC in Geneva (50 year anniversary conference on Fusion Research)

3. IAEA conferences in 50 years

- 1958 : 2nd Geneva conference on peaceful use of atomic energy.
- 1961 : Saltzberg IAEA conference (Artsimovich, Rosenbluth,--)
- 1965 : Culham IAEA conference (Spitzer, Kadomtsev,--)
- 1968 : Novosibirsk IAEA conference (Artsimovich, --)
- 1971 : Madison IAEA conference (Octopole experiments)
- 1974 : Tokyo IAEA conference (JFT-2, T-6, ST, ATC, ORMAK, TFR,--)
- 1976 : Barcelona IAEA conference (T-10, PLT, ORMAK,--)
- 1978 : Innsbruck IAEA conference (PLT, T-10, DITE,--)
- 1980 : Brussels IAEA conference (PLT, T-10, Doublet-III,--)
- 1982 : Baltimore IAEA conference (PDX, Doublet-III, Asdex, ISX-B,--)
- 1984 : London IAEA conference (JET, TFTR, C-Mod, Doublet-III,--)
- 1986 : Kyoto IAEA conference (JT-60, JET, TFTR,--, DIII-D,--)
- 1988 : Nice IAEA conference (TS, TFTR, JET, JT-60,DIII-D,--)
- 1990 : Washington IAEA conference (TFTR, JET, JT-60,DIII-D,--)
- 1992 : Wurtzburg IAEA conference (JET, DIII-D, JT-60U, TS, JET/DT, TFTR,--)
- 1994 : Seville IAEA conference (TFTR, JT-60U, JET, DIII-D,--)
- 1996 : Montreal IAEA conference (ITER, TFTR, JT-60U, JET, AUG, DIII-D,Helical,--)
- 1998 : Yokohama IAEA conference (JT-60U, JET, LHD,ITER,DIII-D,--)
- 2000 : Sorrento IAEA conference (ITER, JT-60U, JET, DIII-D, LHD,--)
- 2002 : Lyon IAEA conference (JT-60U, JET, DIII-D, AUG, --)
- 2004 : Vilamoura IAEA conference (JT-60U, JET, DIII-D, LHD, AUG, NSTX, MAST,--)
- 2006 : Chengdu IAEA conference (DIII-D, JT-60U, LHD, theory,)
- 2008 : Geneva IAEA conference (JT-60U, DIII-D, EAST, LHD,NIF, --)
- 2010 : Daejeon IAEA conference (KSTAR, DIII-D, LHD, JET, JT-60U,--)

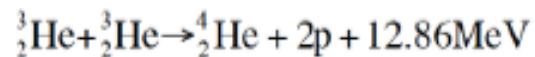
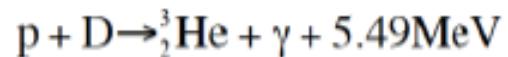
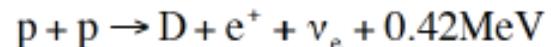
4. Sun and Earth

Gravitational Energy of Sun:

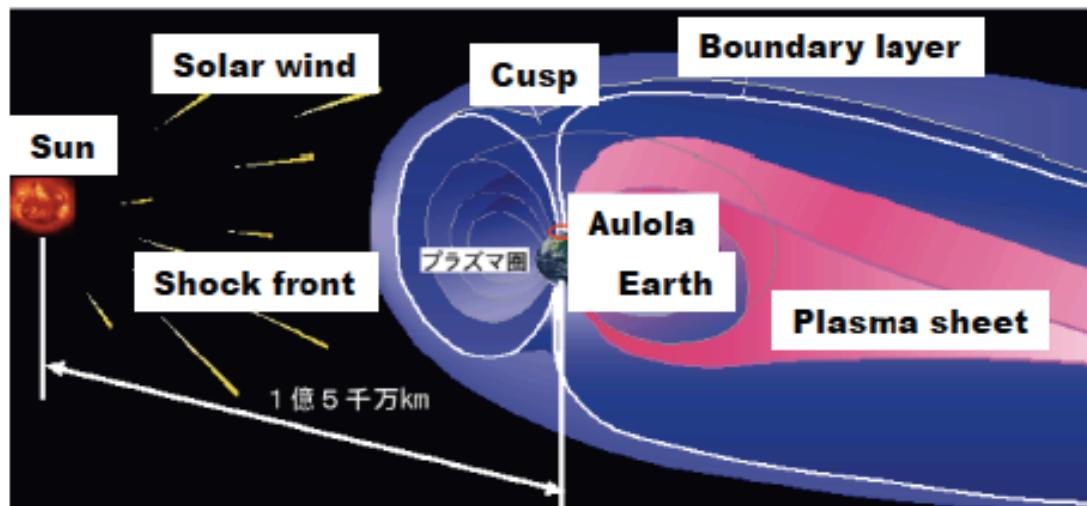
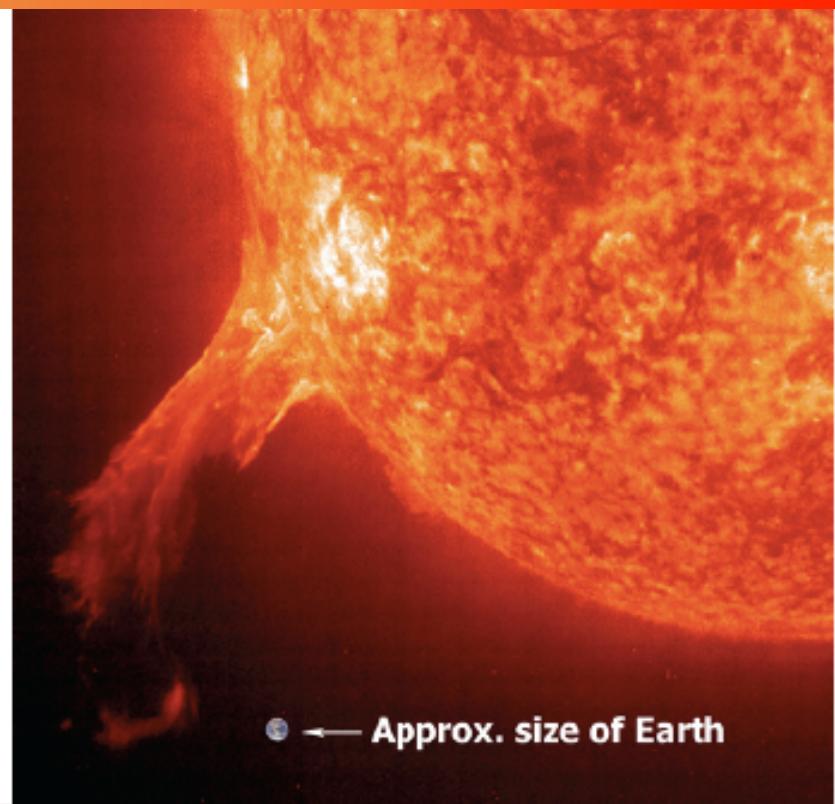
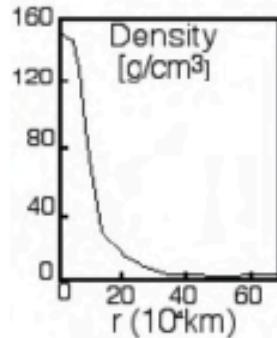
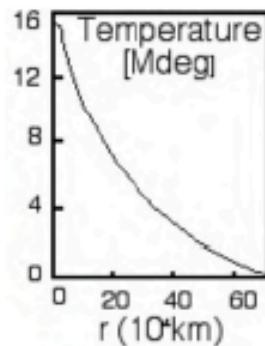
$$E_g = \frac{GM^2}{R_{\text{sun}}} = 3.8 \times 10^{41} \text{ Joule}$$

$$M_{\text{Sun}} = 2 \times 10^{30} \text{ kg}$$

T~keV



Star > Sun : CNO cycle (H. Bethe)

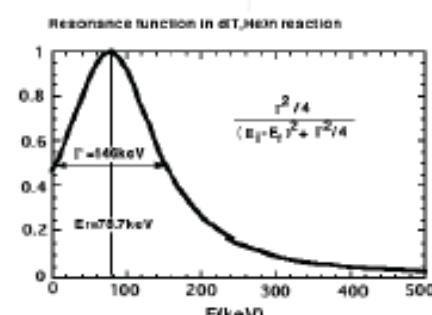
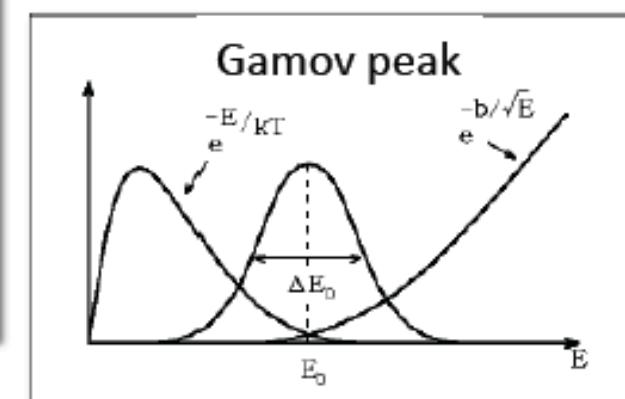
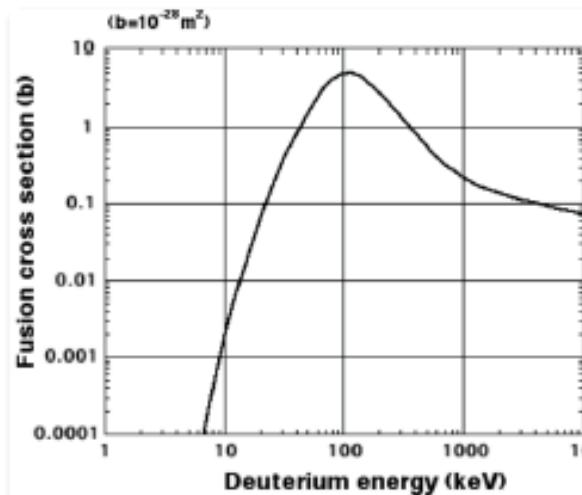
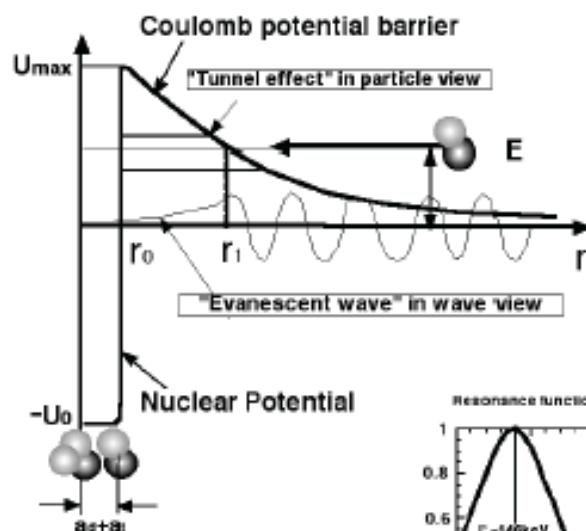


A. Eddington and H. Bethe

5. Bless by Nature

Nature gives a chance to realize fusion for human by 3 mechanisms

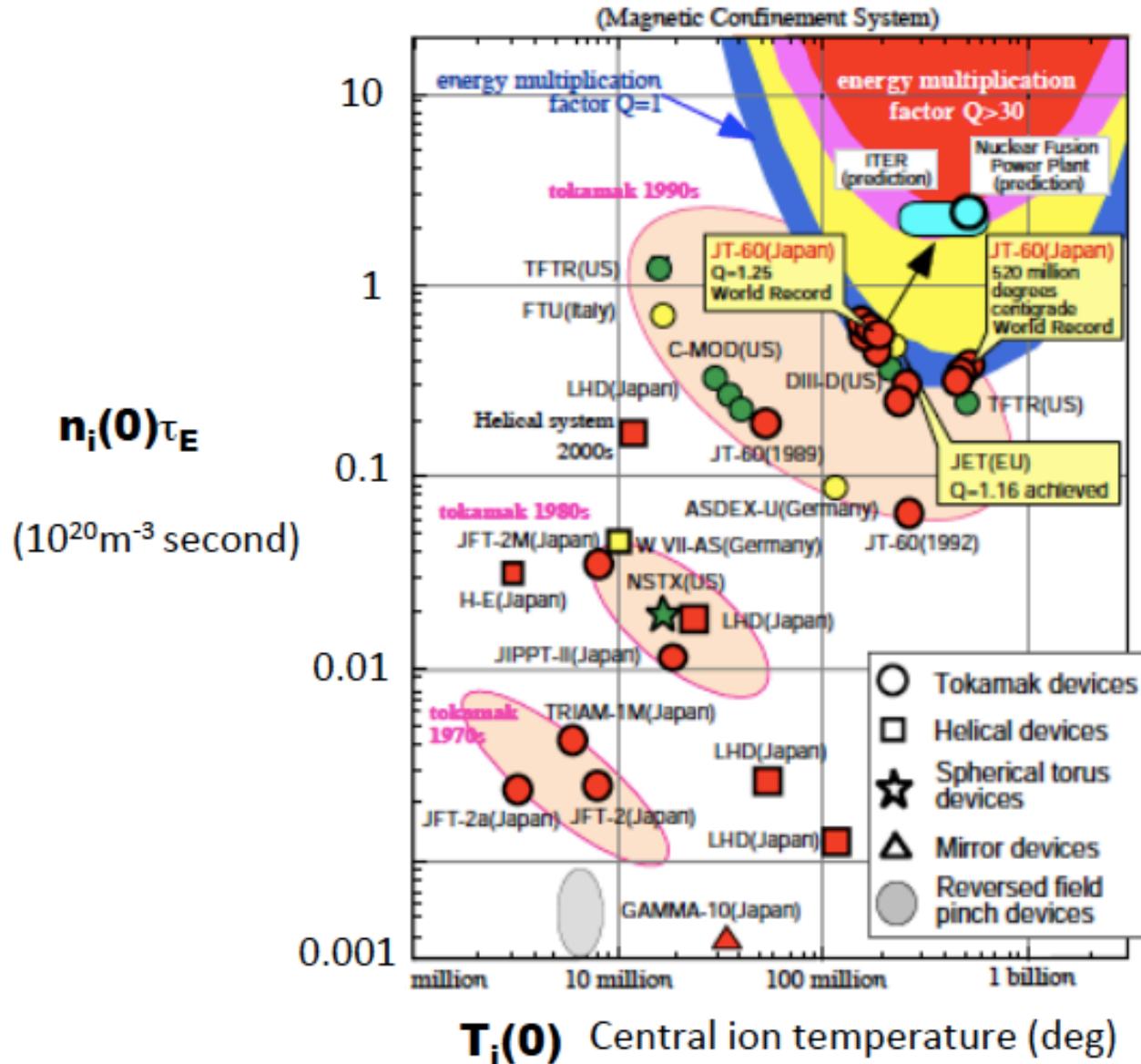
- [1] **Tunnel effect** to give fusion cross section at lower energy $< U_{\max}$ (480MeV)
- [2] **Nuclear resonance** to enhance cross section
- [3] **Gamov effect** to enhance fusion reaction rate



$$\sigma_r = \sigma_0 \frac{E_c}{E[\exp(\sqrt{E_c/E} - 1)]} \left[\frac{1}{1 + 4(E - E_r)^2 / \Gamma_i^2} + \alpha \right]$$

6. Fusion condition : Lawson Diagram

Plasma must meet certain conditions ($n_i(0)\tau_E$, $T_i(0)$) to deliver fusion power.



7. How we can introduce fusion power

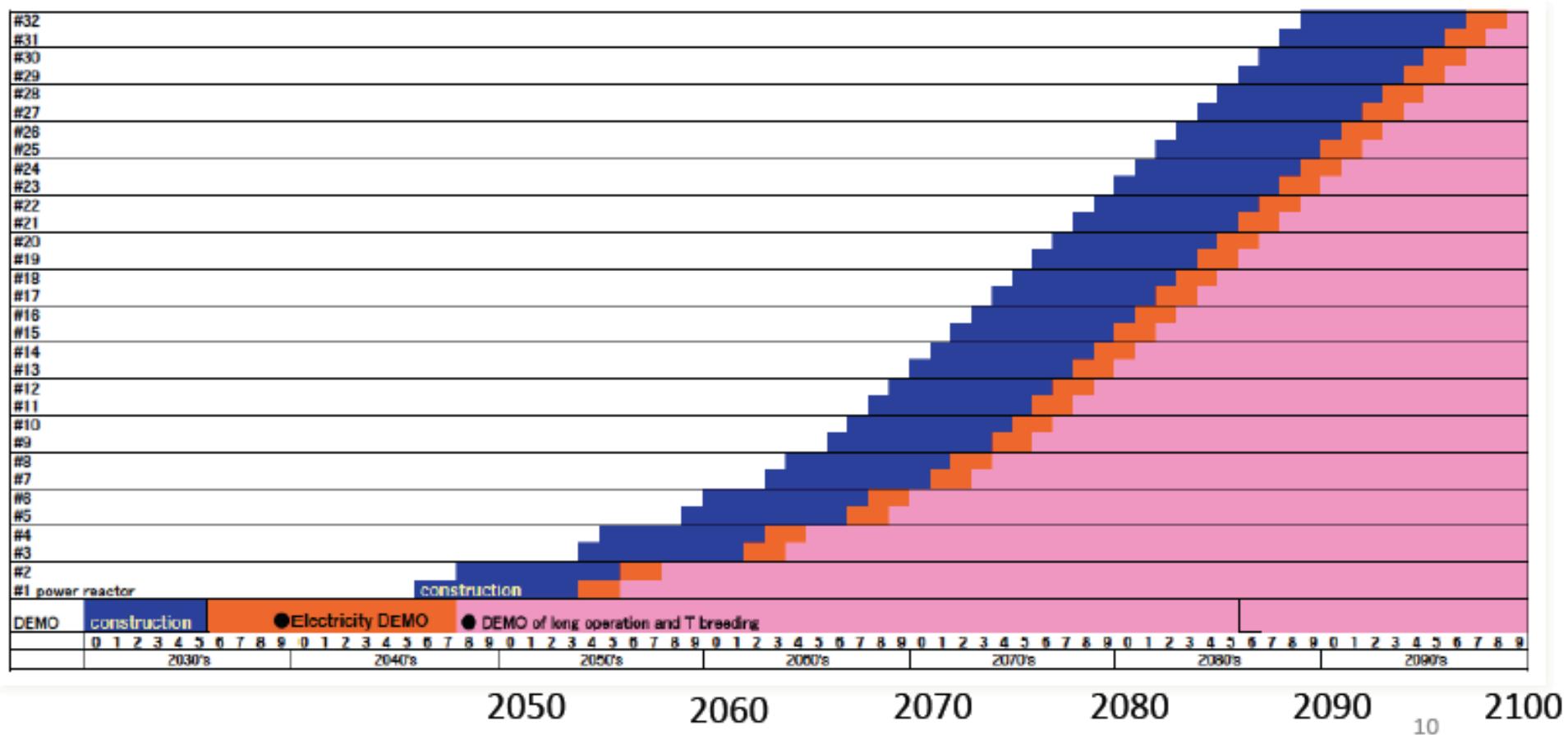
Fusion will not enter energy market in first half of this century

First quarter : ITER Era.

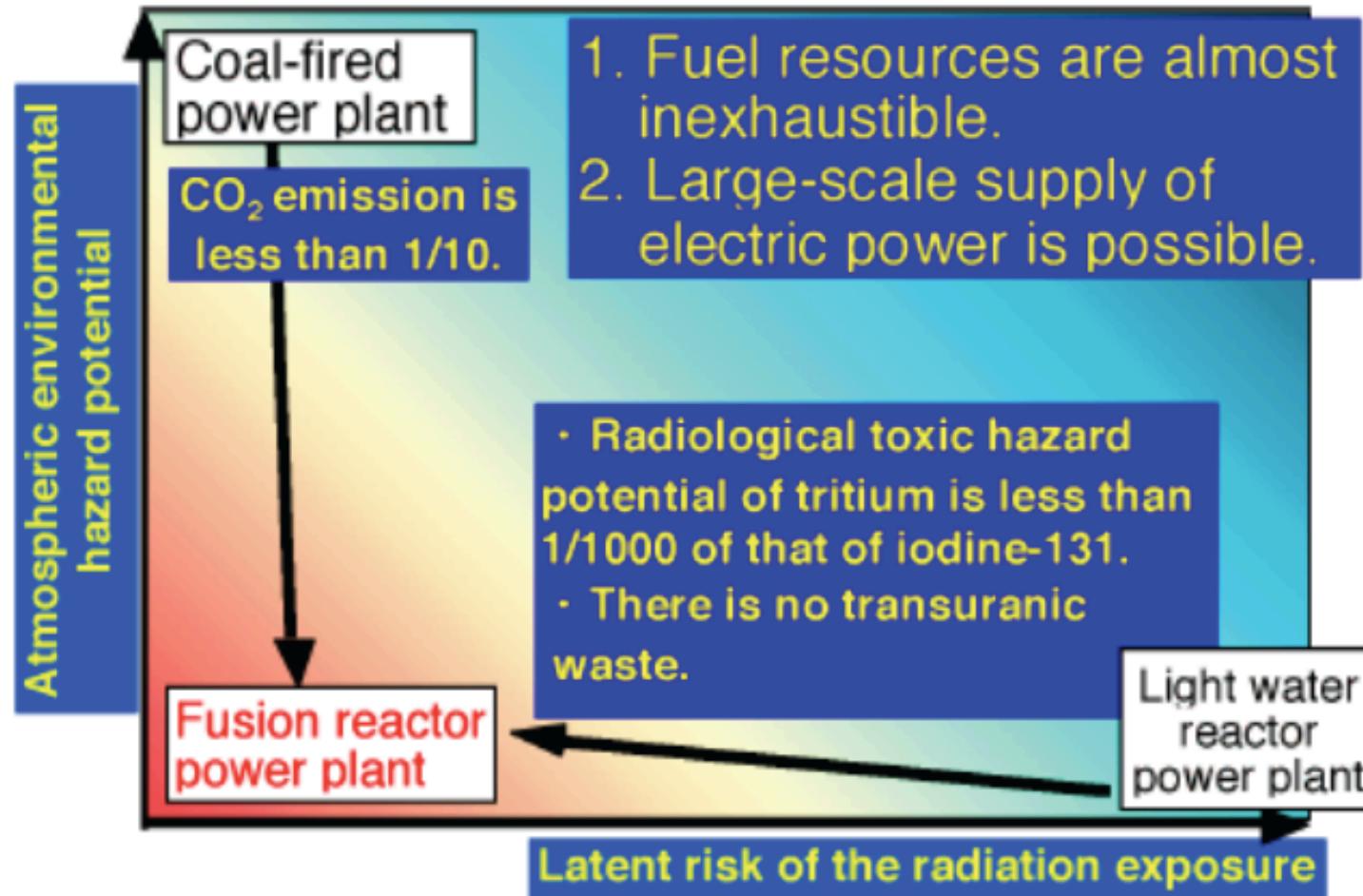
Second quarter : DEMO Era.

If ITER&DEMO are successful, we could move to commercialization in second half of this century.

It is important to make non-negligible contribution to energy.



8. Fusion has attractive features



1. Radiological hazard potential of T from operating Fusion is less than 1/1000 of that of ^{131}I from Fission.

16. Radiological Toxic Hazard Potentials of Fission and Fusion

Radiological toxic hazard potential or biological hazard potential (BHP) is a quantity to measure the influence of a radioactive nuclide that enters the human body.

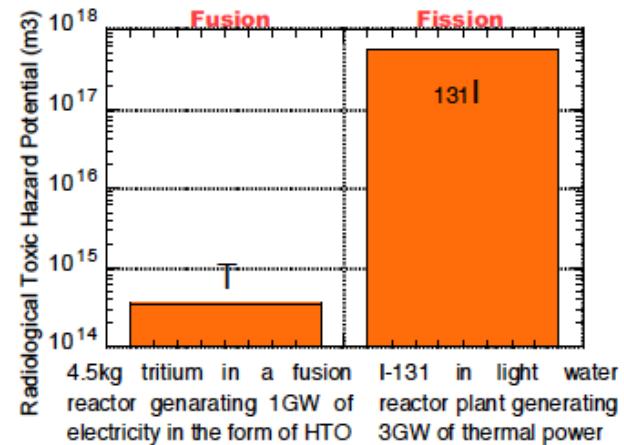
BHP = Radioactivity (Bq) / MPC (Maximum Permissible Concentration)
MPC =DAC (Derived Air Concentration)

MPC of ^{131}I : 10Bq/m^3 v.s. MPC of T : $5 \times 10^3\text{Bq/m}^3$

Selective concentration of I to specific organ of human body is a big issue.

**BHP of LWR is 1500 times that of Fusion
(at same power)**

	Tritium in a fusion reactor generating 1 GW of electricity (T: 4.5 kg, in the form of HTO)	Iodine-131 in a light-water reactor plant generating 3 GW of thermal output
Radioactivity (Bq)	1.7×10^{18}	5.4×10^{18}
Concentration limit in the air (Bq/m ³)	5×10^3	10
Radiological toxic hazard potential (m ³)	3.5×10^{14}	5.4×10^{17}
Relative ratio	1	1500



17. Long term Hazard Potential of Wastes (Fusion, Fission and Coal)

Materials will be radioactive in Fusion.

But, its hazard potential is relatively low.

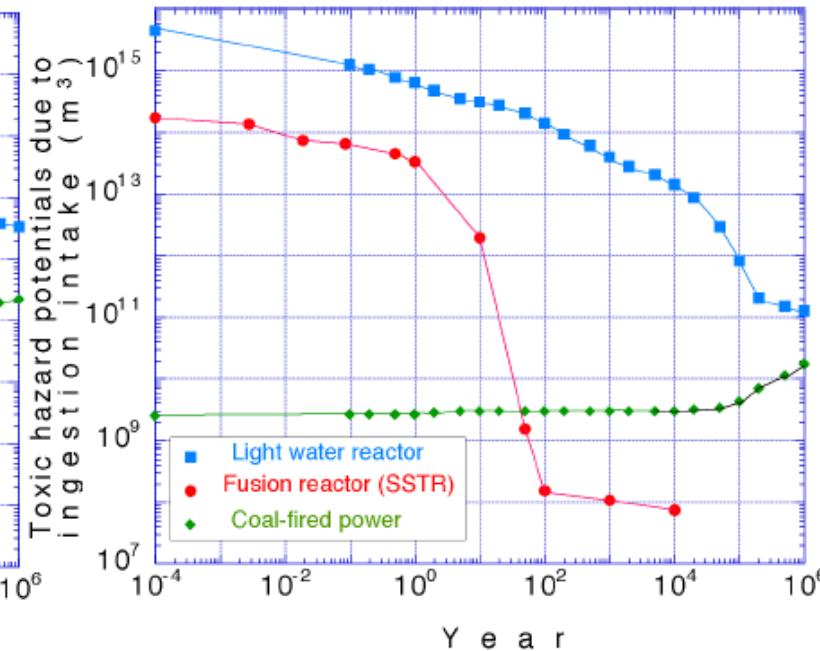
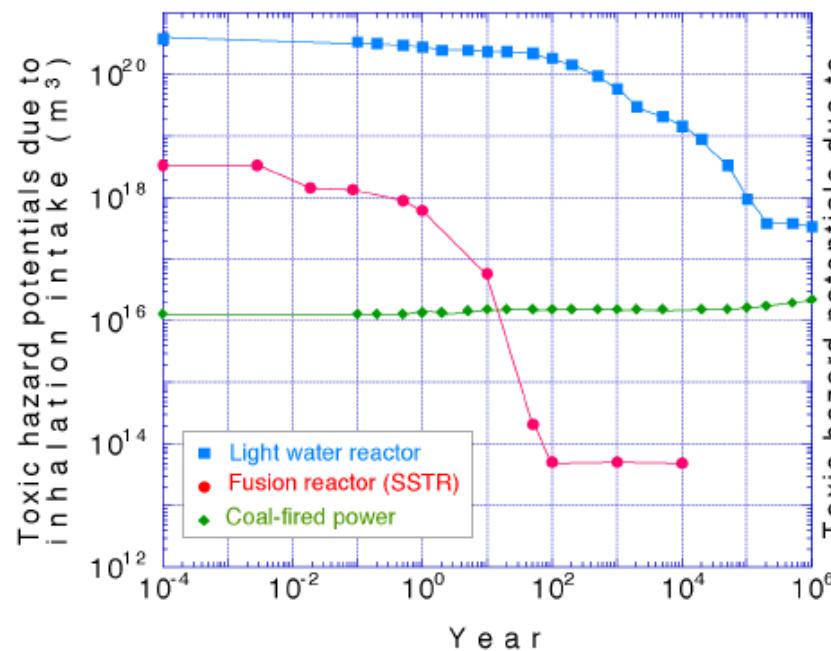
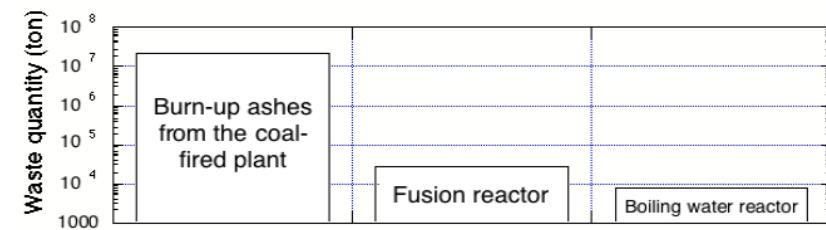
Inhalation intake : intake by breezing

Ingestion intake : intake as food

Fission waste has high risks lasting 100Millennium

Coal ash includes Th^{232} , U^{238} etc.

Hazard potential goes down in 100 years for Fusion.

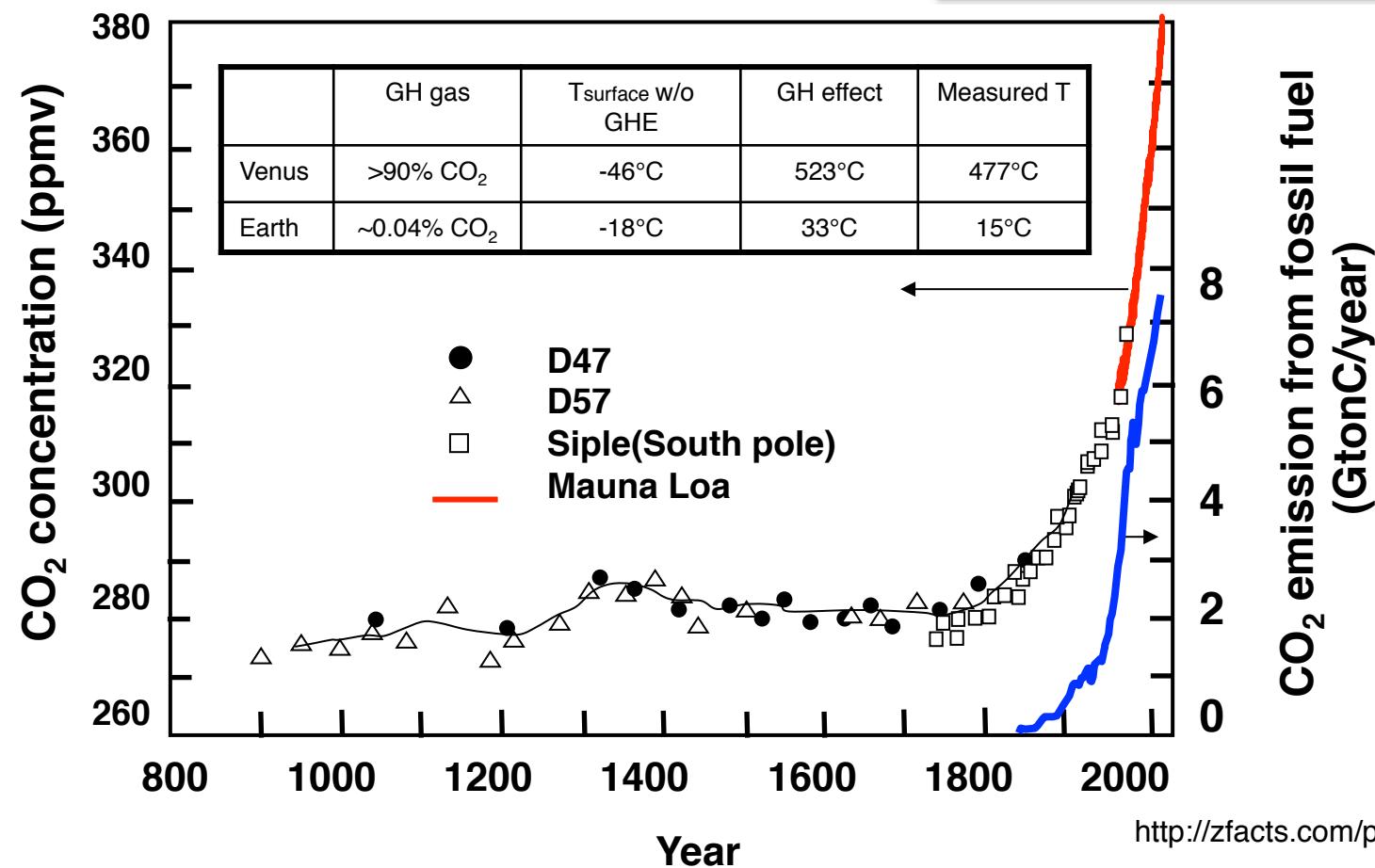
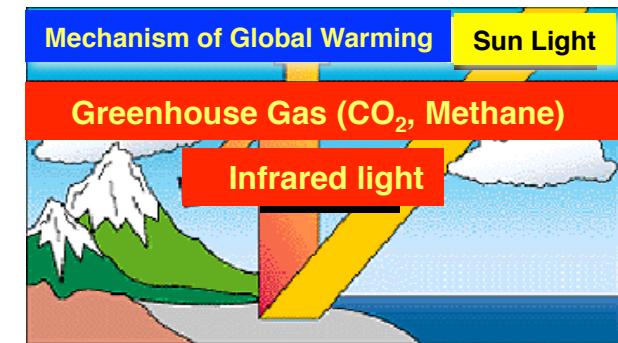


Environmental impact

- Fusion Research -

1. Increase of CO₂ concentration

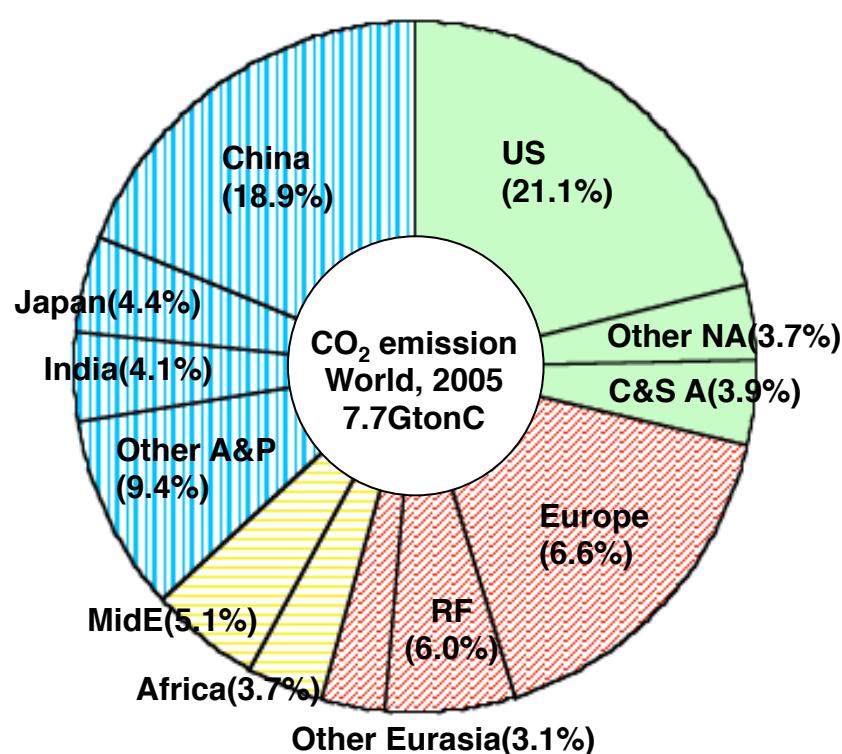
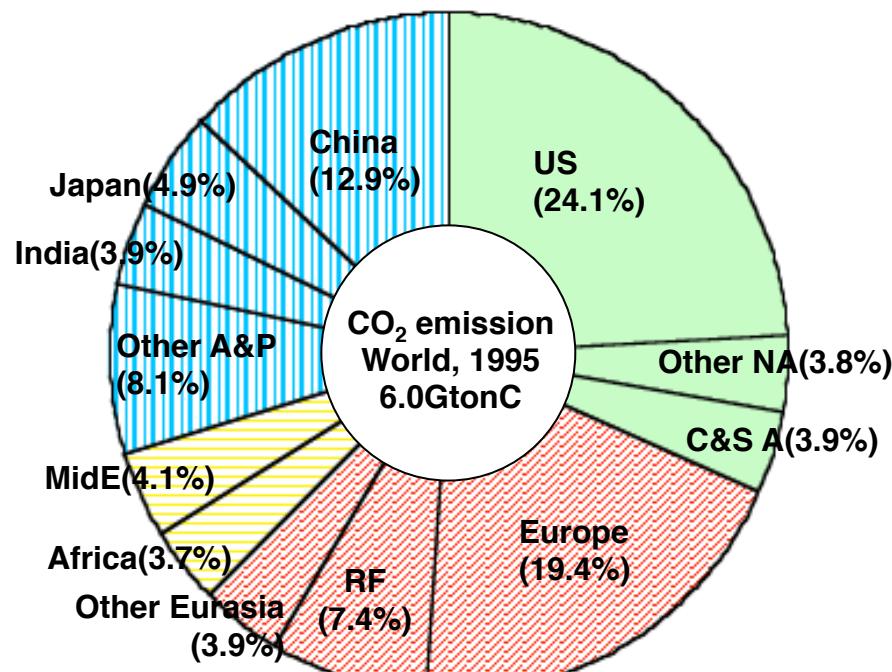
Increase of CO₂ concentration in the Air is ~100ppmv.
Significant greenhouse effect is expected if we do not stop.



2. World CO₂ emission is increasing rapidly

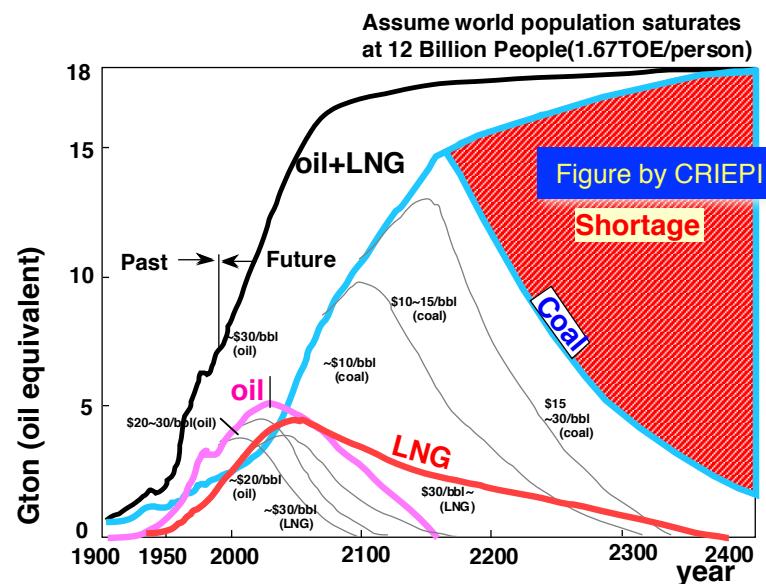
World CO₂ emission increases ~28%/10years between 1995 and 2005 while, it was agreed to reduce 5% from 1990 level in Kyoto Protocol (COP-3) in 2008-2012.

World effort is important to reduce CO₂ emission.



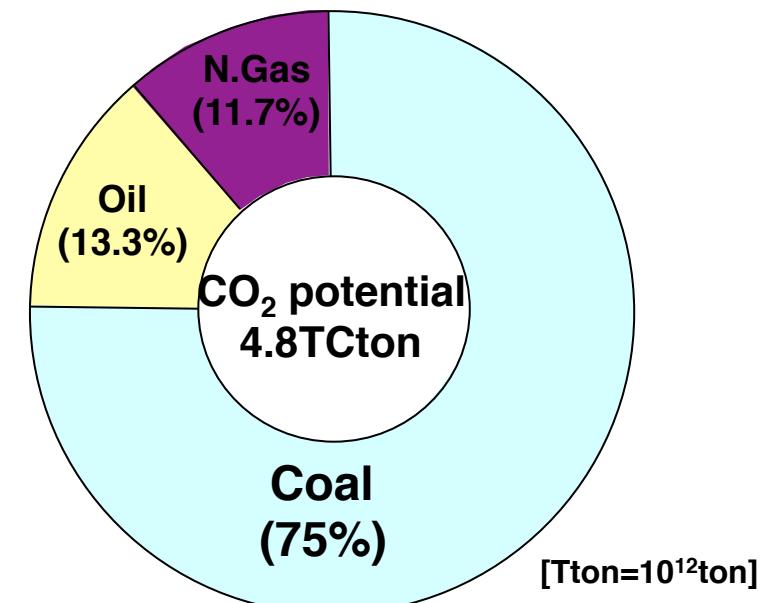
3. Expiration of fossil fuel leads to 4 times atmospheric CO₂

We have enough fossil fuels for century time scale



[Resource life] Coal : 231years, Nat. gas : 63years, Oil : 44 years

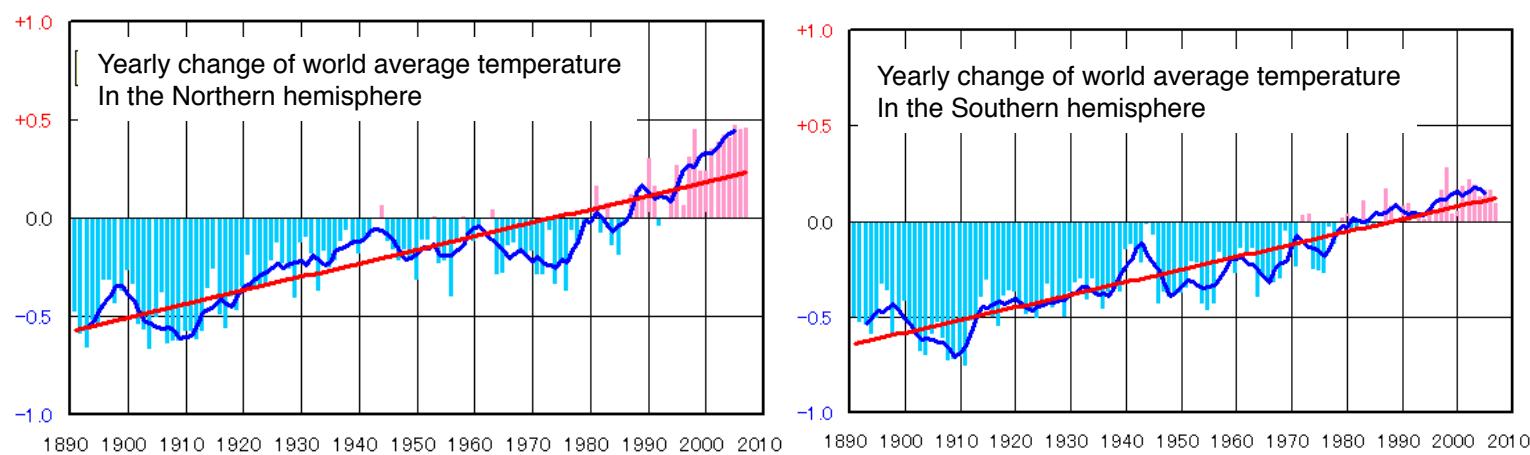
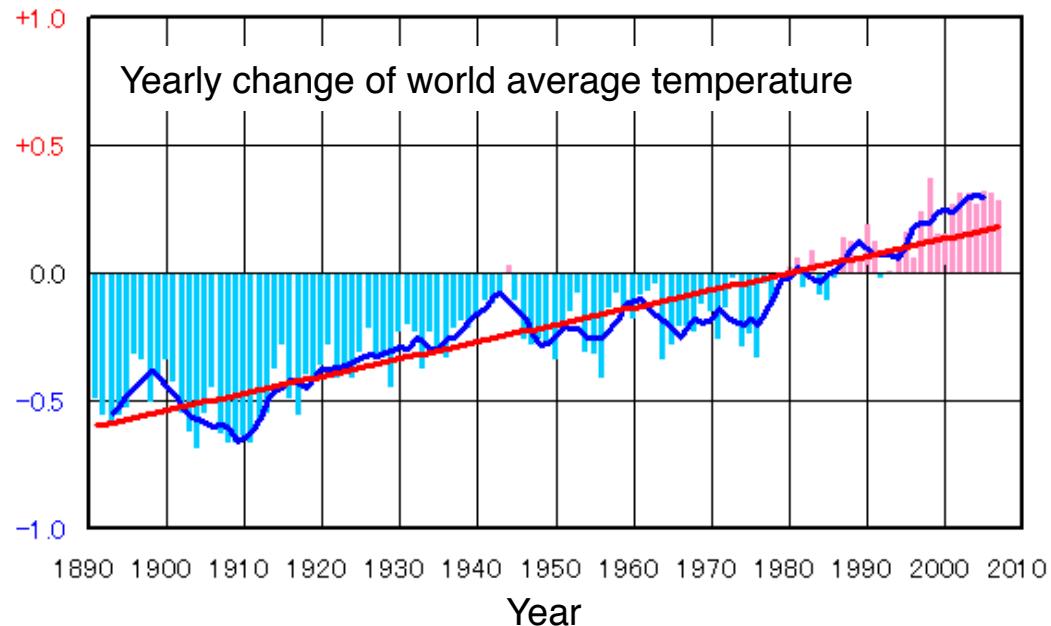
Problem is it emits 6.4 x CO₂ in Atmosphere



6.4/2=3.2 may be absorbed by sea/plants
After all, 1+3.2 =4.2 times CO₂

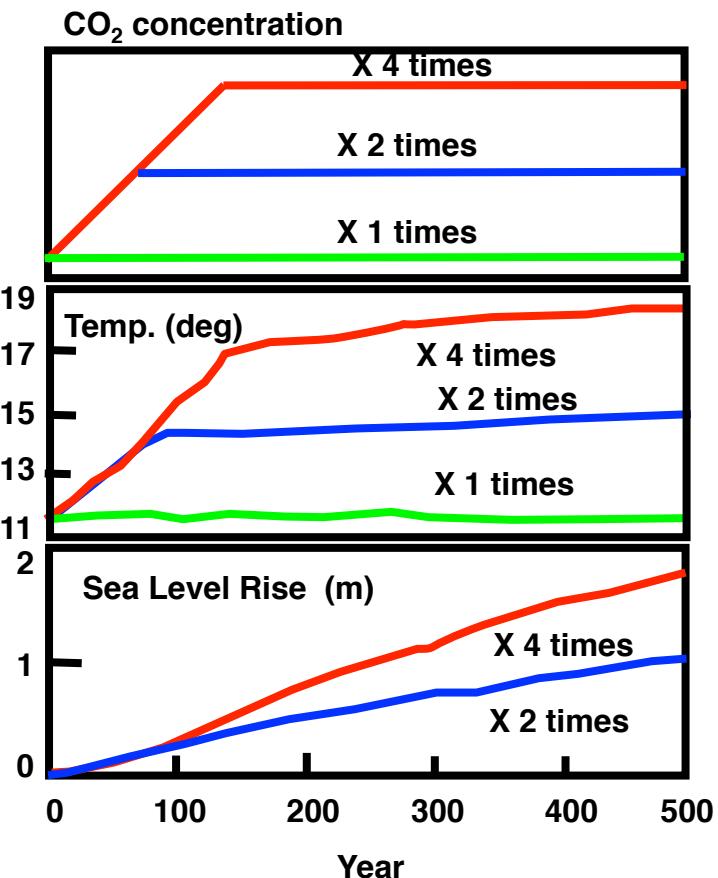
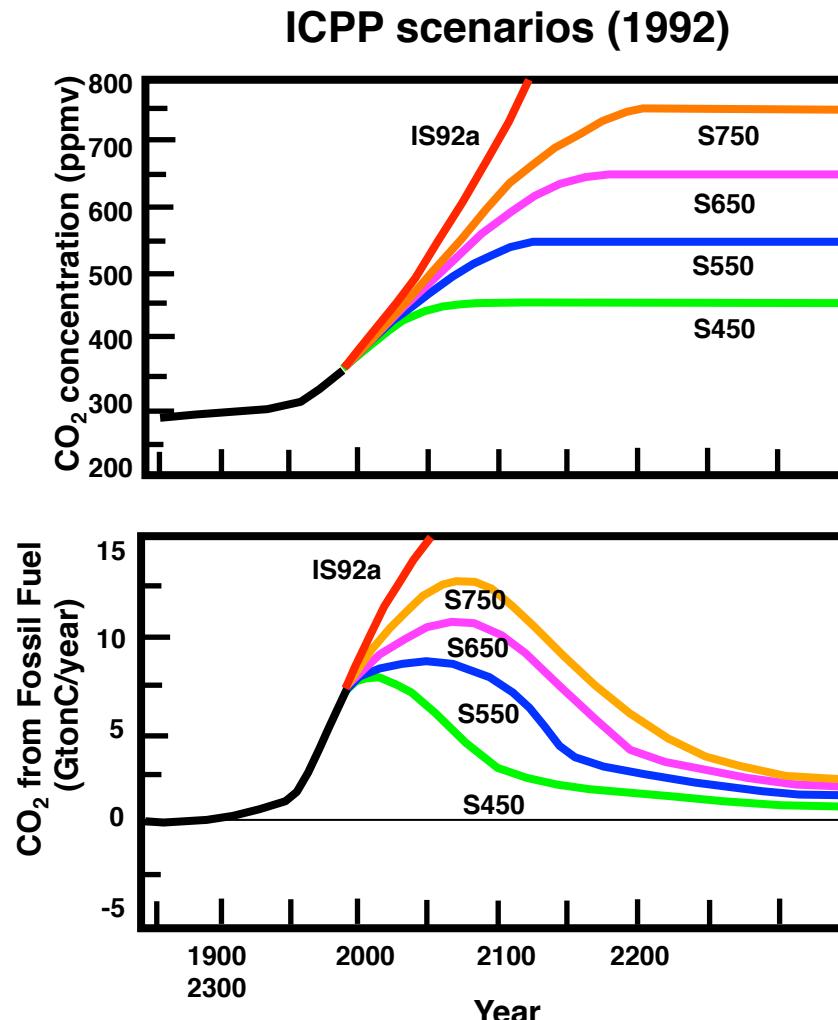
Environmentally unacceptable scenario!!

4. Increasing evidence of Global Warming



5. Climate change is irreversible process

Increase of CO₂ concentration in the Air is ~100ppmv.
Significant greenhouse effect is expected if we do not stop.

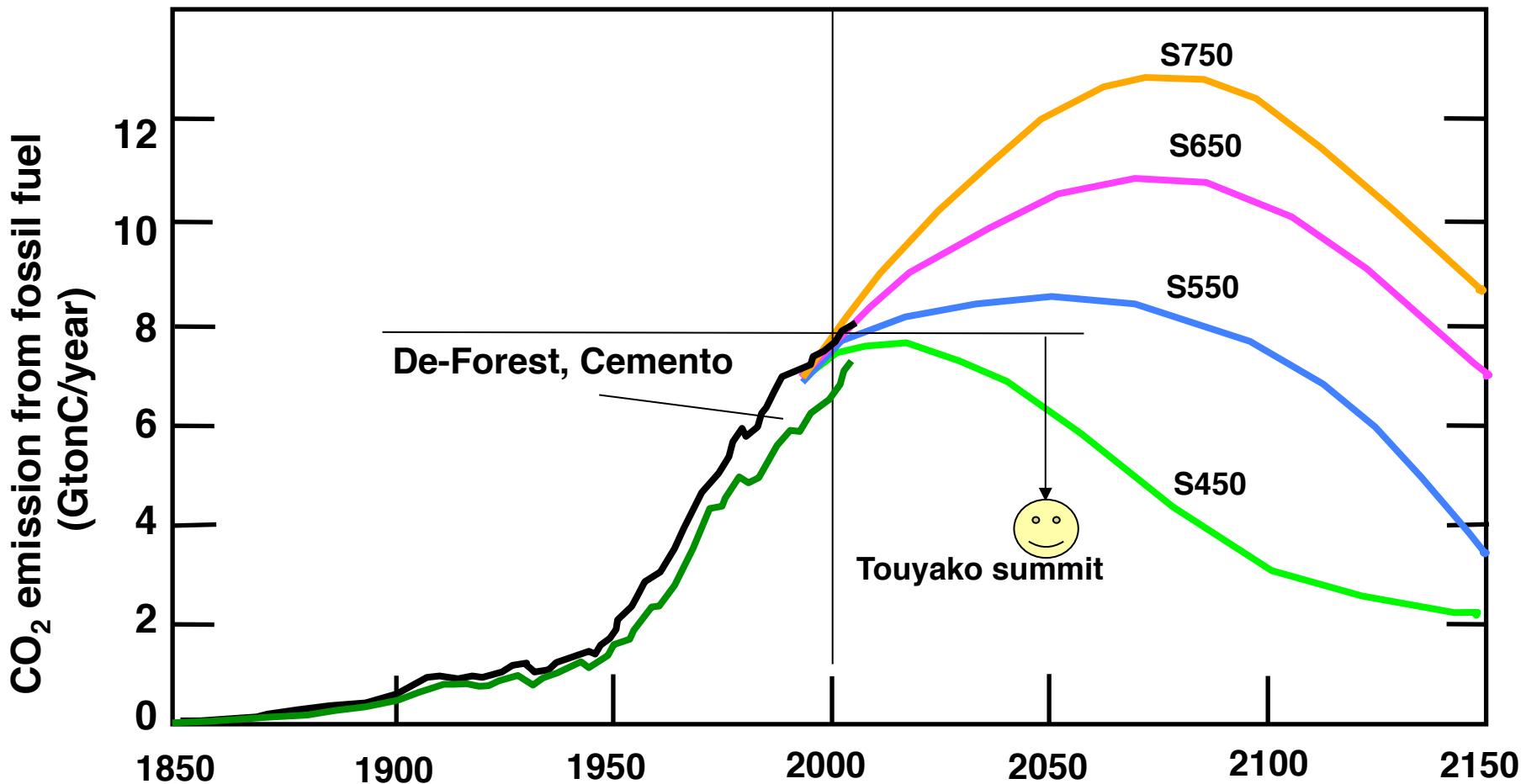


Y. Manabe, Symposium on Earth Frontier, 1997

6. Significant reduction of CO₂ emission required

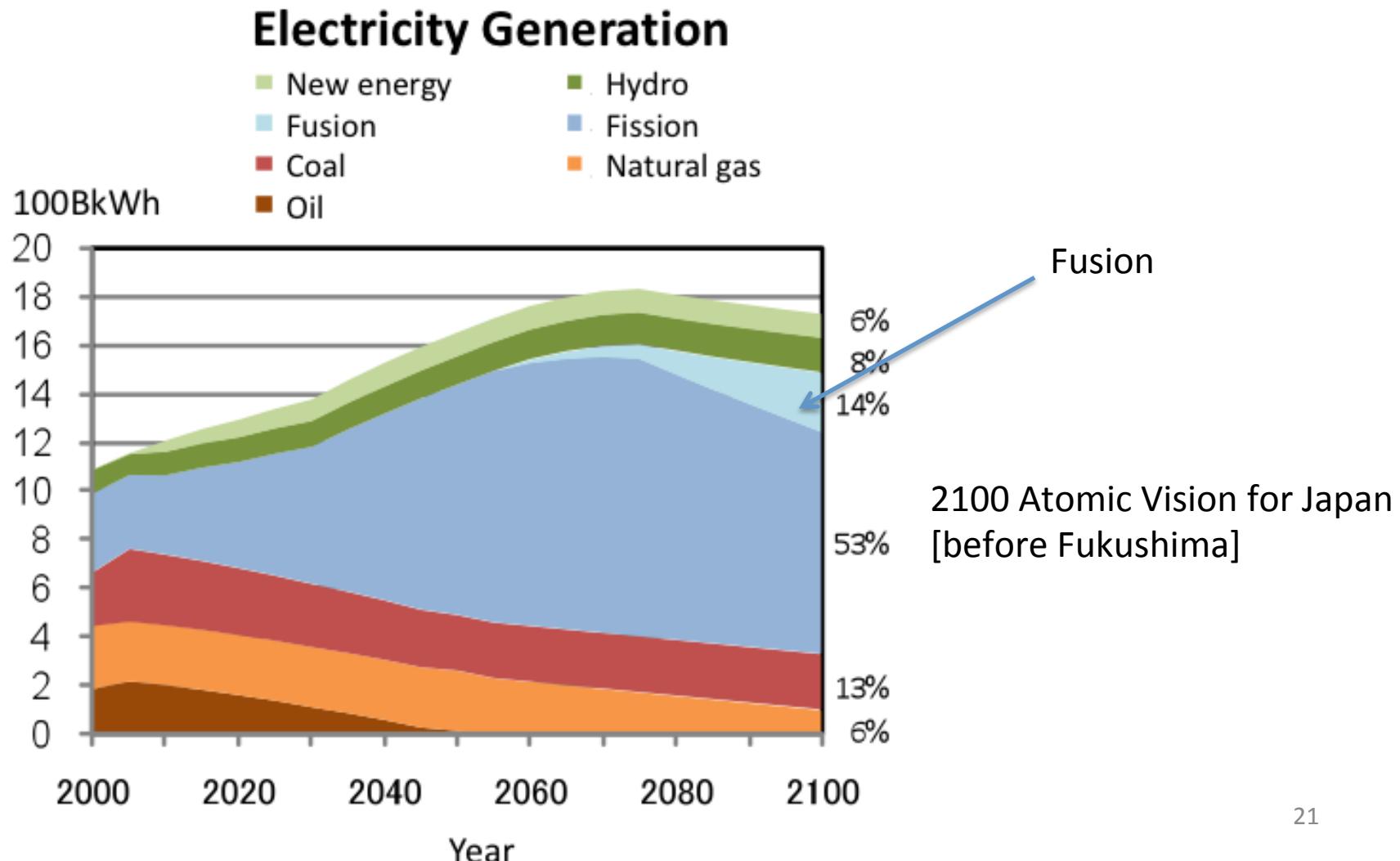
Revolution in energy sources (Fossil to Renewables & Nuclear)

Revolution in energy user sectors (Transportation(CAR), Industry(Steel), Living)



7. Carbon-free society should be realized in end of 21st century

Contribution to the CO₂ reduction in later half of this century by **fusion** have to be pursued by the international effort.

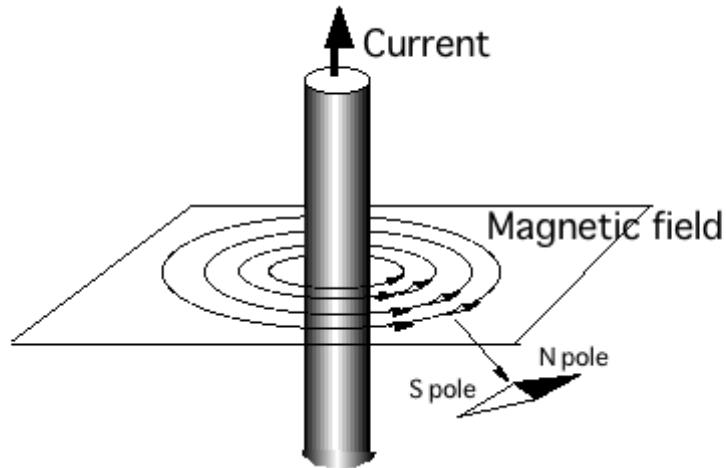


**Tokamak
and
the Steady State Tokamak
Reactor : SSTR**

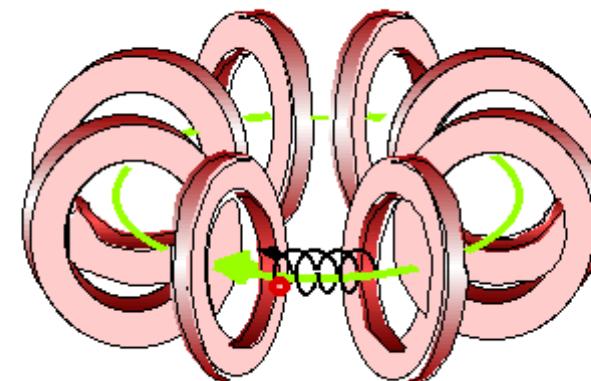
1. Tokamak Configuration

Tokamak-type magnetic configuration which is said to be closest to the fusion reactor, is shown in iv), superposition of ii) and iii) magnetic field lines.

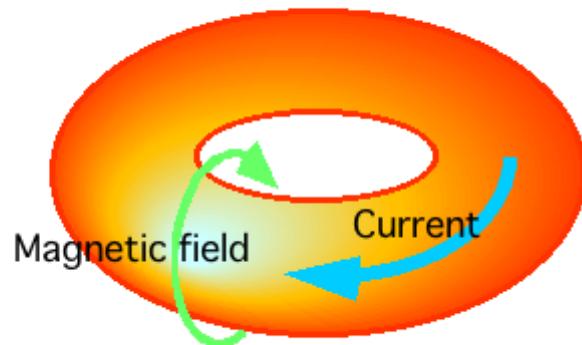
i) Magnetic field around the current



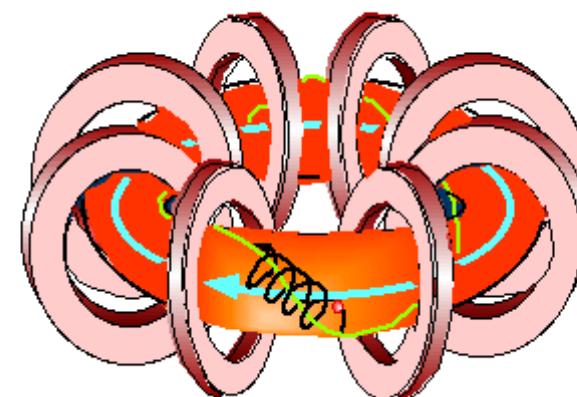
ii) Magnetic field by cylindrical circular coils



iii) Magnetic field by toroidal current



iv) Twisted field line by b)and c)

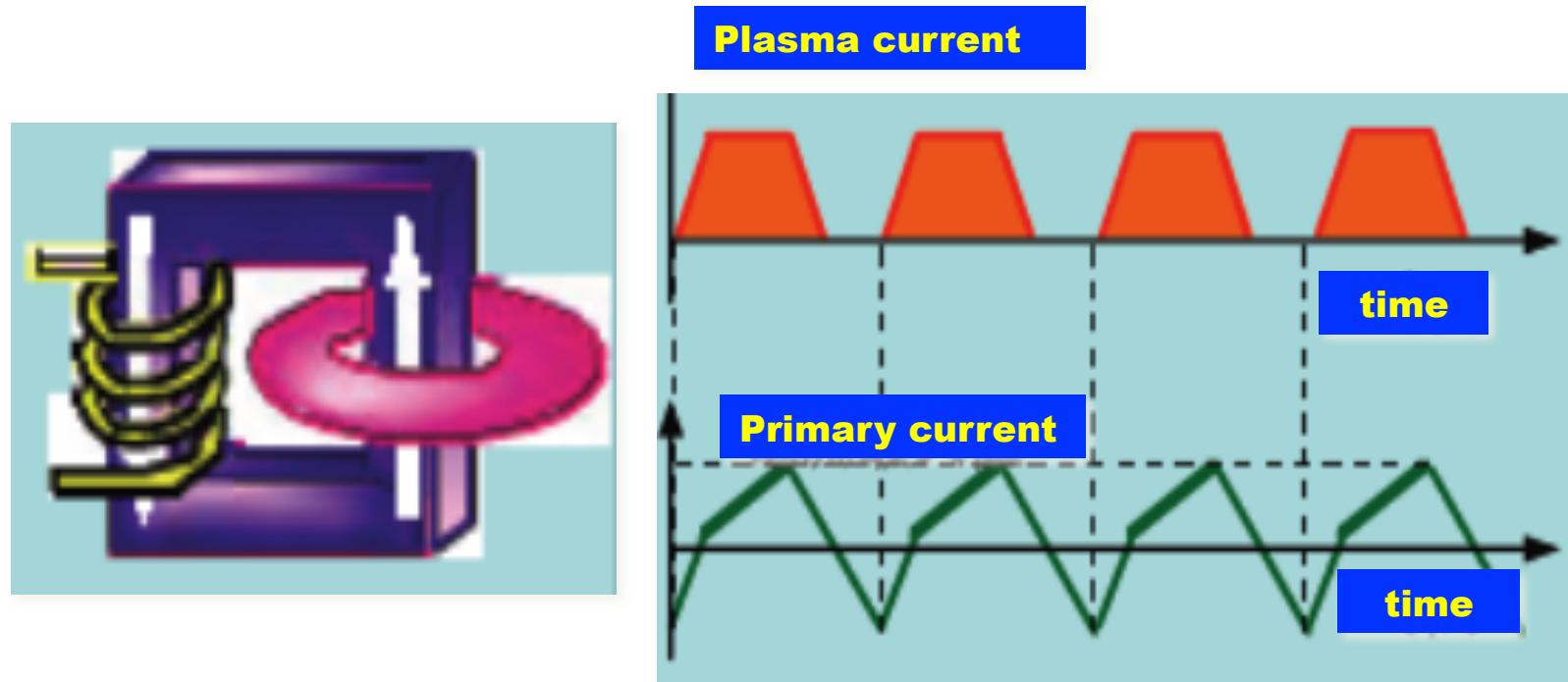


2. Tokamak is closest to fusion energy but is intrinsically pulsed.

“Plasma Current” is necessary for good confinement!!

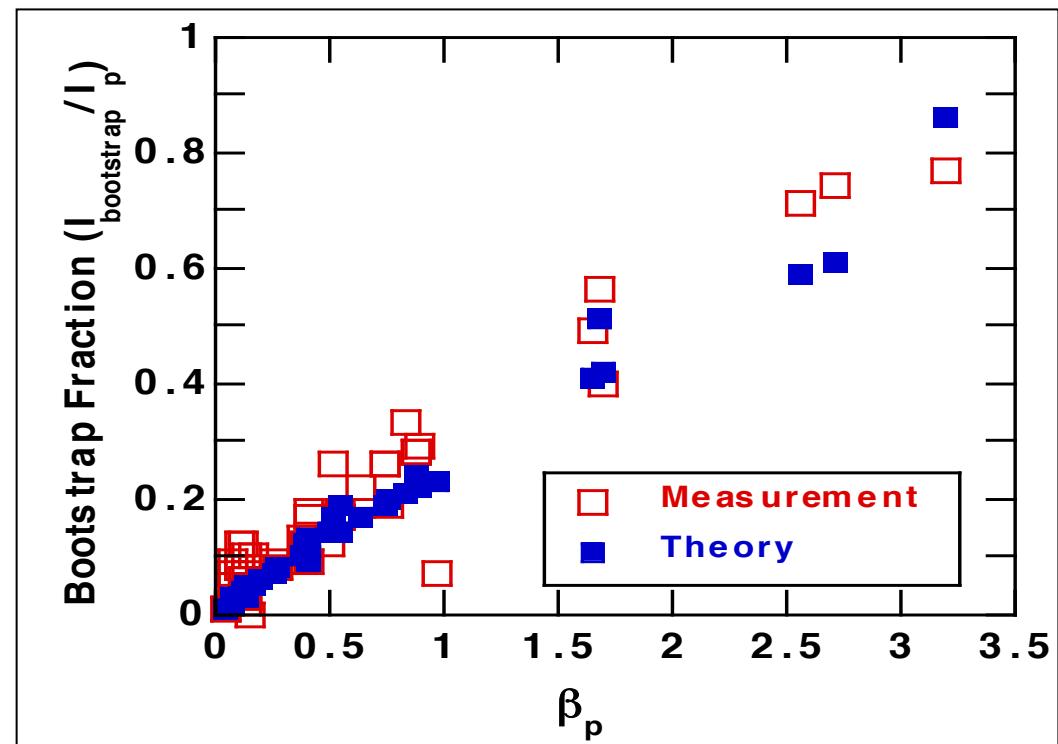
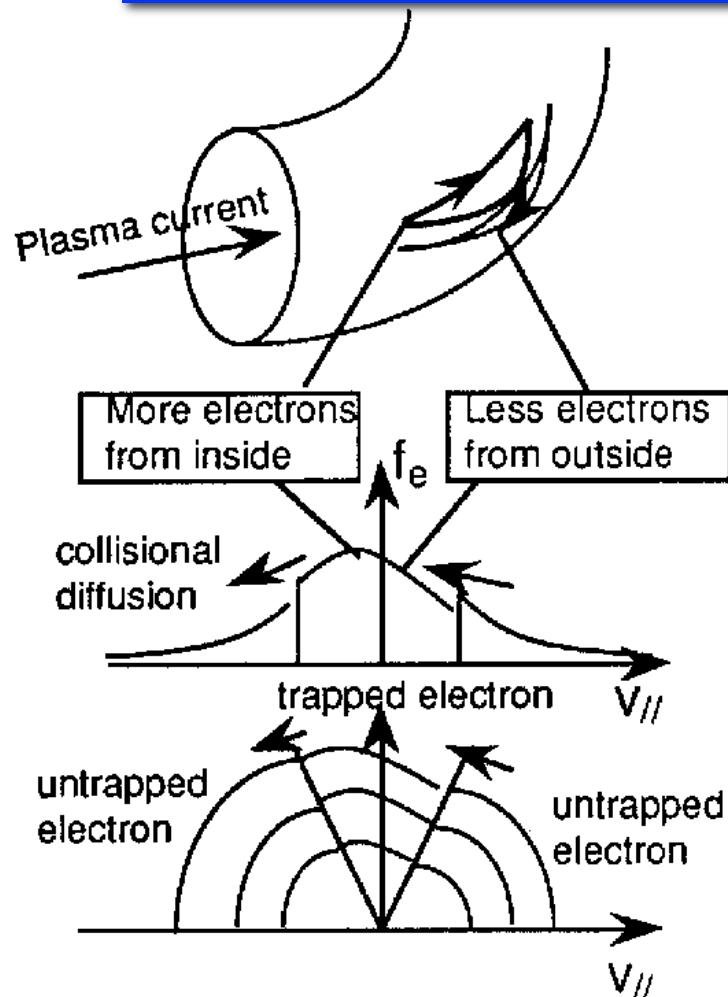
To sustain plasma current, **inductive loop voltage** is necessary.

-> Non inductive current sustainment is necessary.



3. Bootstrap current : driven by plasma pressure gradient

Observation of 80% bootstrap fraction in JT-60 is a significant turning point.

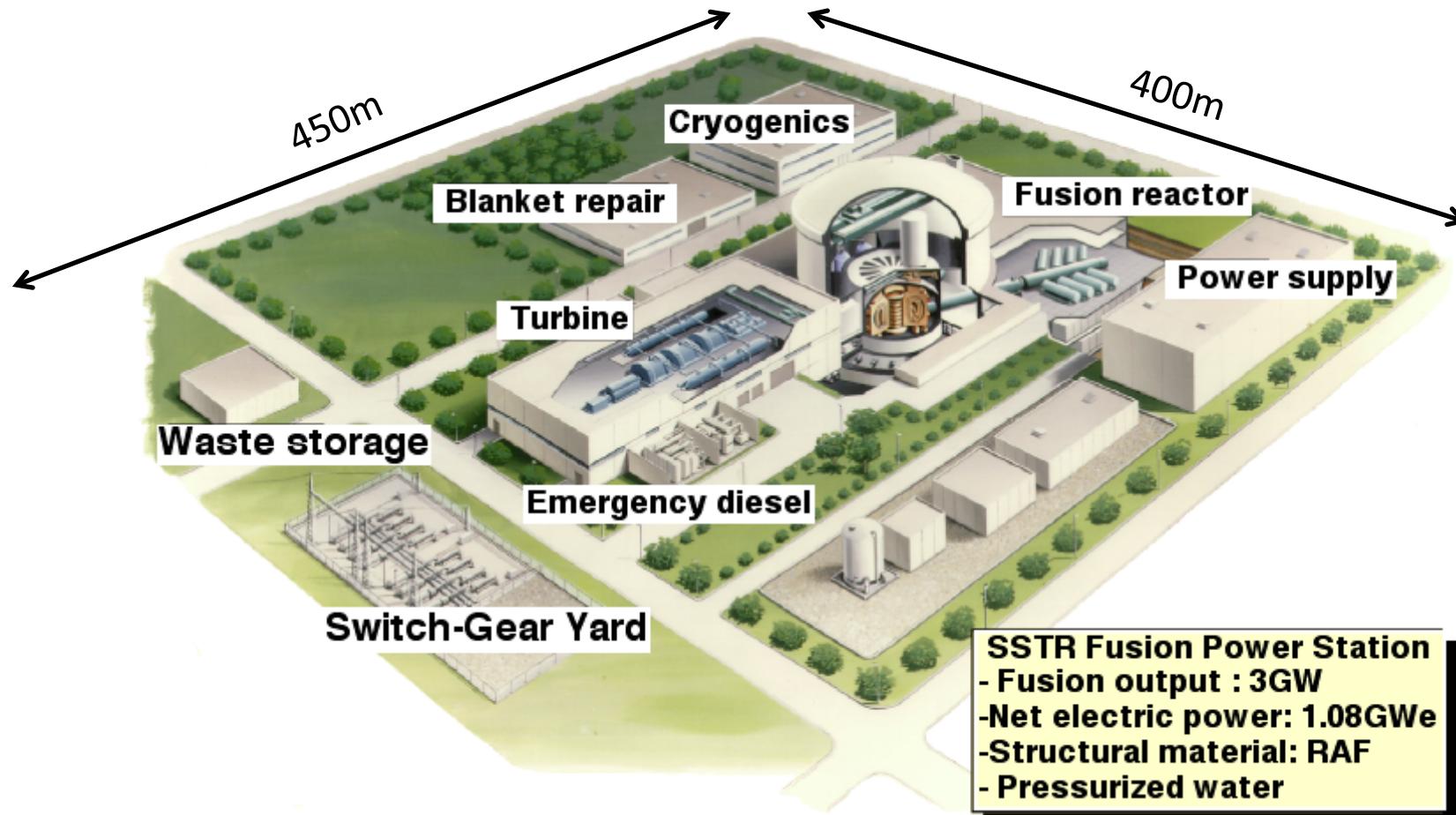


4. The Steady State Tokamak Reactor (SSTR): 1990

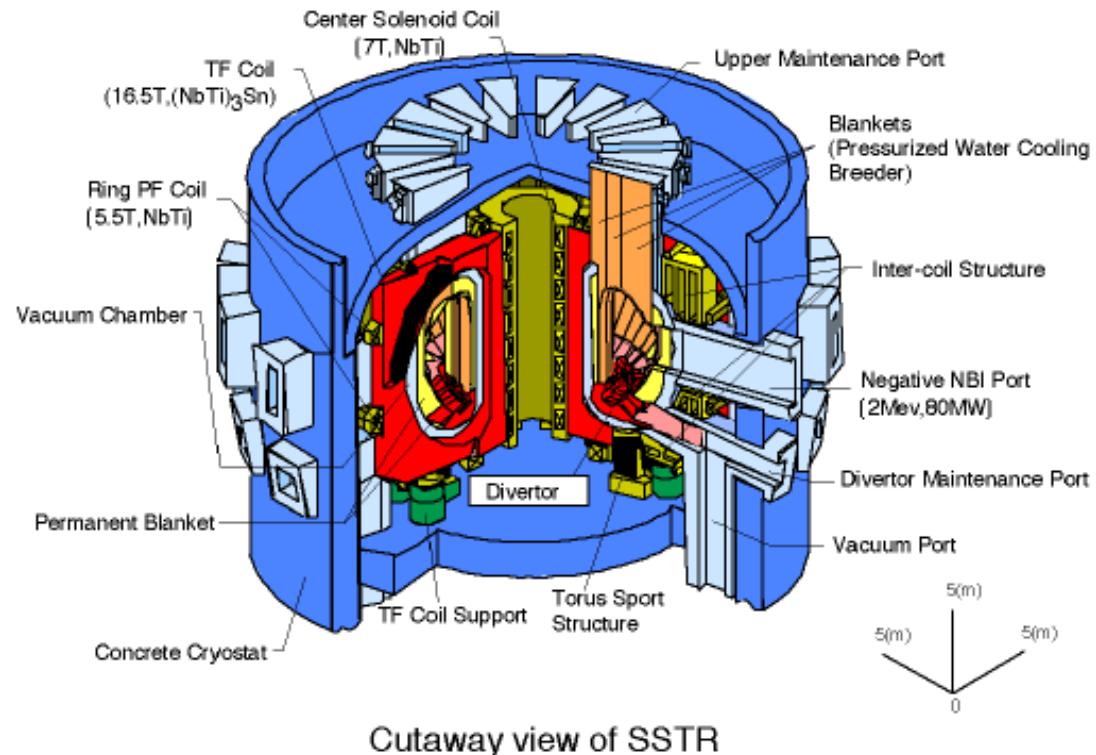
Tokamak Reactor Design based on use of bootstrap current for **continuous operation**.

[1] M. Kikuchi, Nuclear Fusion 30(1990)265. **(MK age : 36)**

[2] M. Kikuchi, et al., Fusion Engineering and Design 18(1991)195



5. Tokamak Reactor Parameters



		Design Value
Plasma Current	I_p	12MA
Toroidal Field Coil	B_t	9T
Major Radius	R	7m
Aspect Ratio	A	4.1
Elongation	κ_{95}	1.85
Normalized Beta	β_N	3.5
Fusion Output	P_F	3GW
Current Drive Power	P_{CD}	60MW
Net Electric Output Power	P_E	1.08GW
Fusion Gain	Q	50
Averaged Neutron Wall Load	$P_{neut.}$	3MW/m ²

How the fusion reactor looks like ?

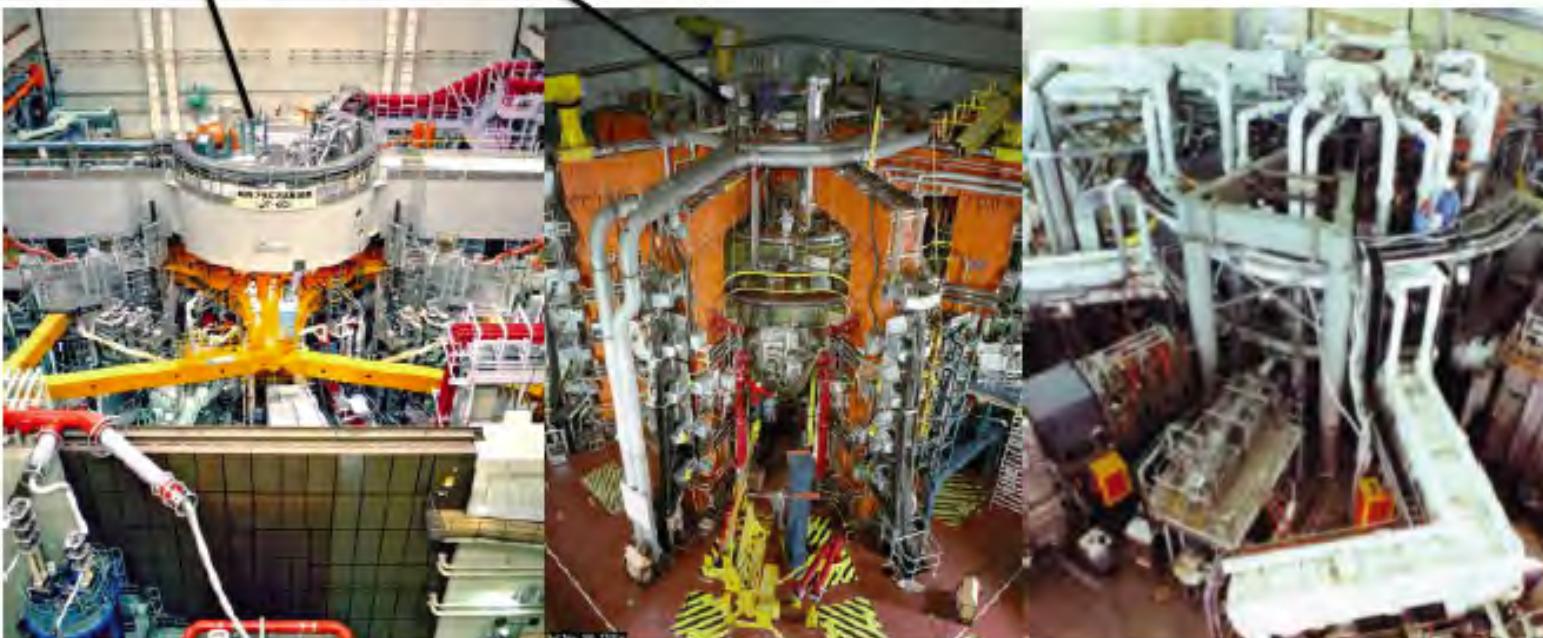
Magnetic Fusion Research and the ITER

1. International cooperation among Large Tokamaks



International cooperation played essential role in advancing fusion energy science.
Large tokamaks played essential role in moving to ITER.

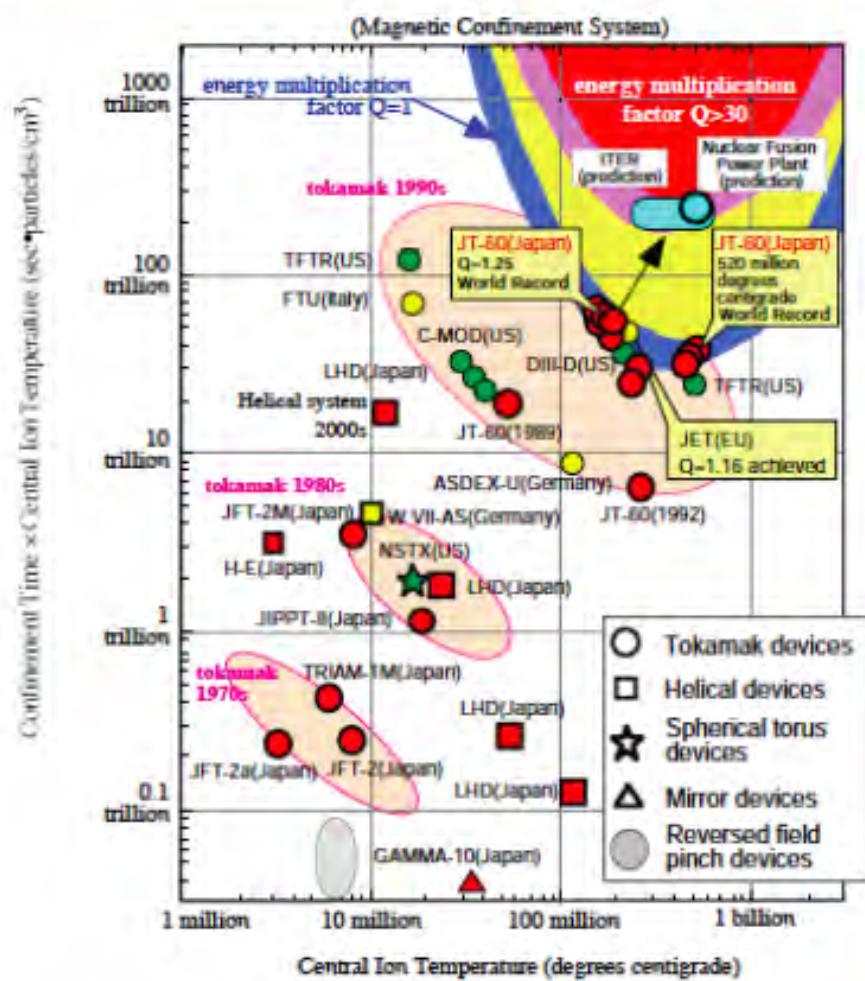
IEA/ITPA meeting in 2004 at Oxford



JT-60 (Japan, Naka) JET (EU, Oxford) TFTR (US, Princeton)²⁹

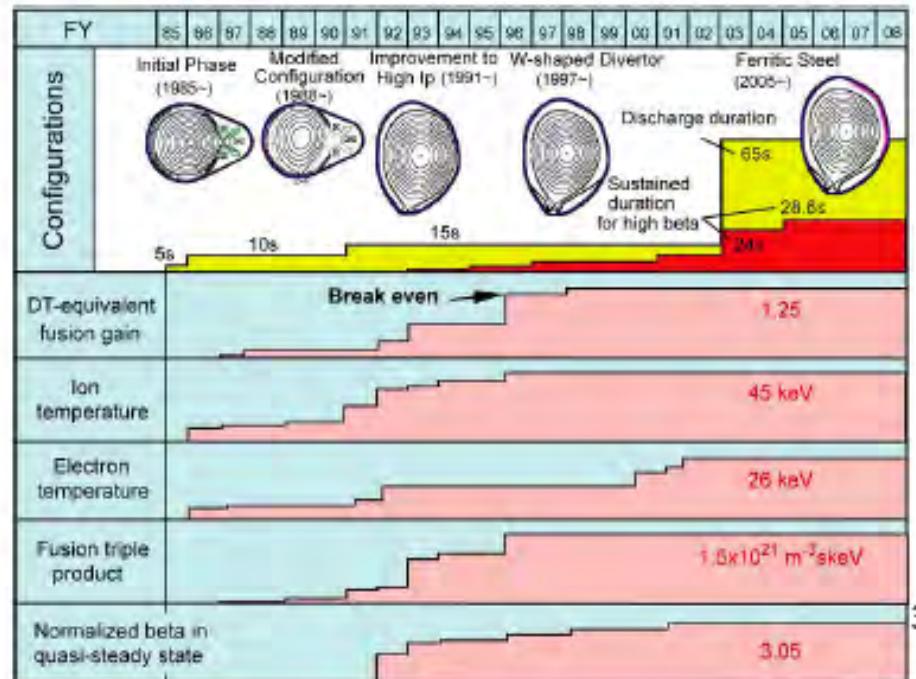
2. JT-60 Program is national project to achieve break-even ($Q^{eq}=1$)

- [1] JT-60 operated 1985-2008 for 23 years
- [2] Many world records in fusion performance including $Q^{eq}=1.25$ and $T_i(0)=45\text{keV}$.
- [3] Steady-state Tokamak Physics



PARAMETERS:

- $R_p = 3.3 \text{ m}$
- $V_{ol} \leq 100 \text{ m}^3$
- $I_p \leq 5.0 \text{ MA}$
- $B_t \leq 4.2 \text{ T}$
- $\Phi = 61 \text{ Vs}$
- $T_{dis} \leq 65 \text{ s}$
- $P_{PNB} \leq 40 \text{ MW}$
- $P_{NNB} \sim 5 \text{ MW}$
- $P_{IC} \leq 4 \text{ MW}$
- $P_{LH} \leq 7 \text{ MW}$
- $P_{EC} \leq 3 \text{ MW}$



4. Magnetic Fusion Research : Lack of long pulse demonstration

Tokamak

Short pulse (<30s) confinement is good
Research issue : Steady-state operation

Tokamak System



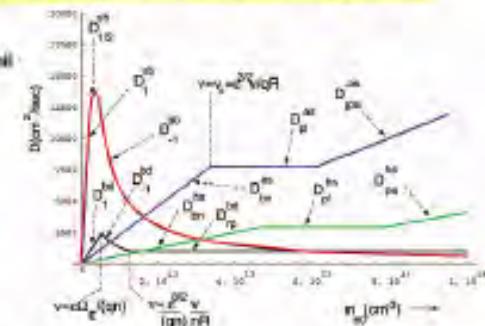
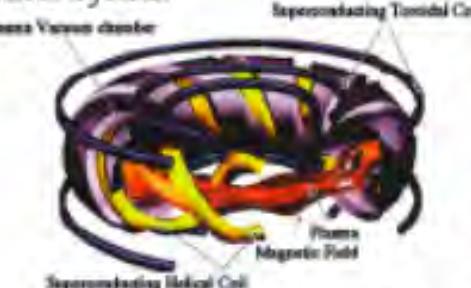
JT-60 Japan Atomic Energy Research Institute

Helical

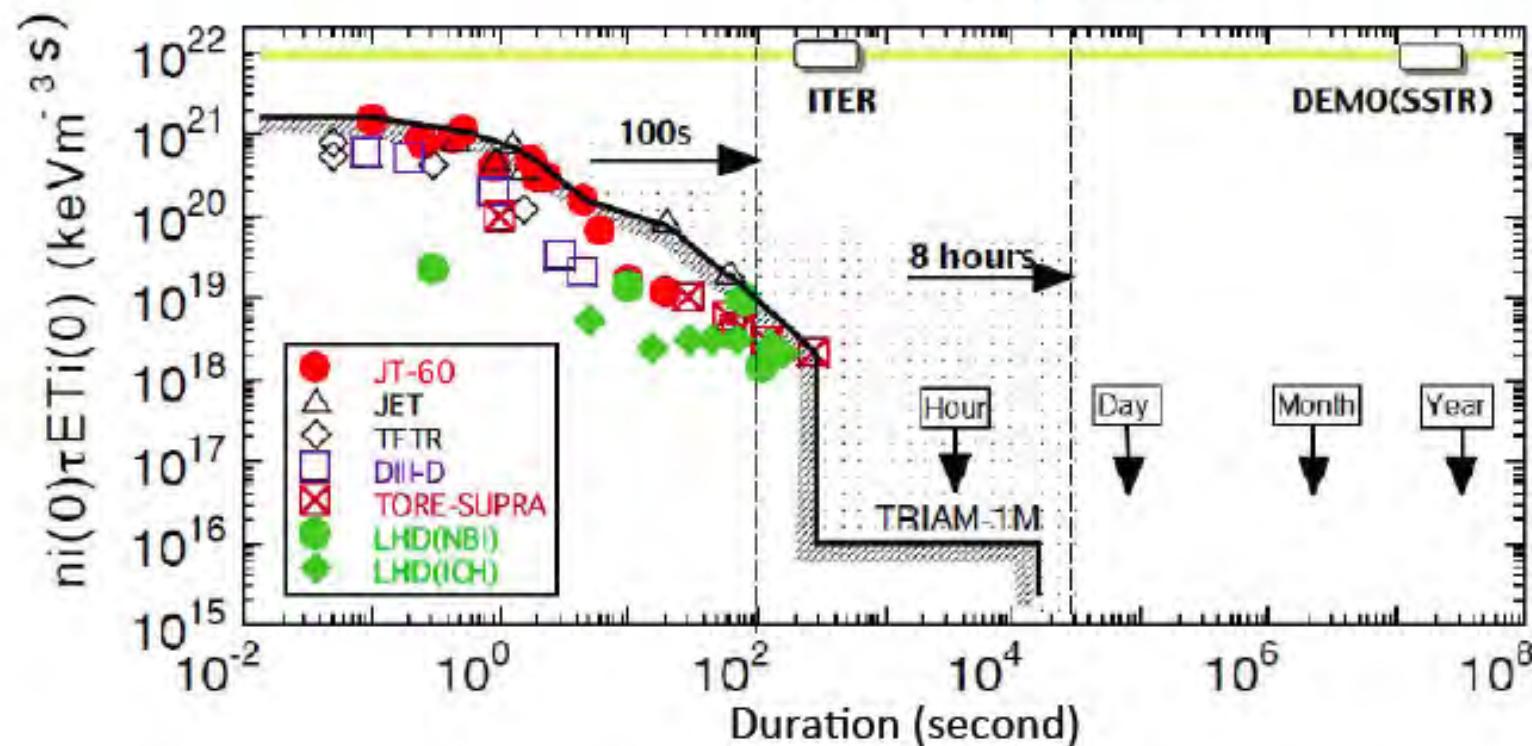
Intrinsically steady

Research issue: Confinement improvement at high T

Helical System



LHD National Institute of Fusion Science



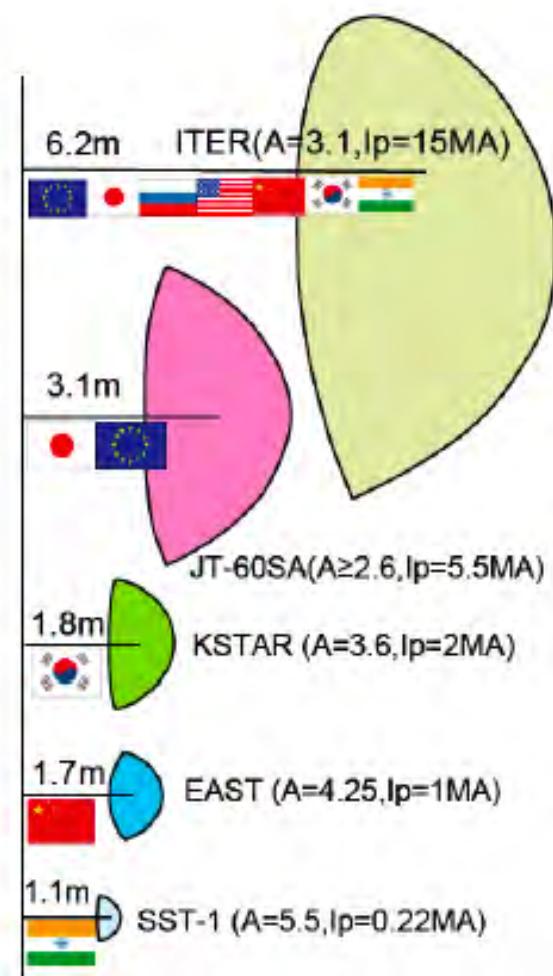
5. Next phase World Fusion Program

Strong new initiatives are in Asia such as China and Korea by building new superconducting tokamaks, named EAST and KSTAR in addition to normal conductor tokamak HL-2A.

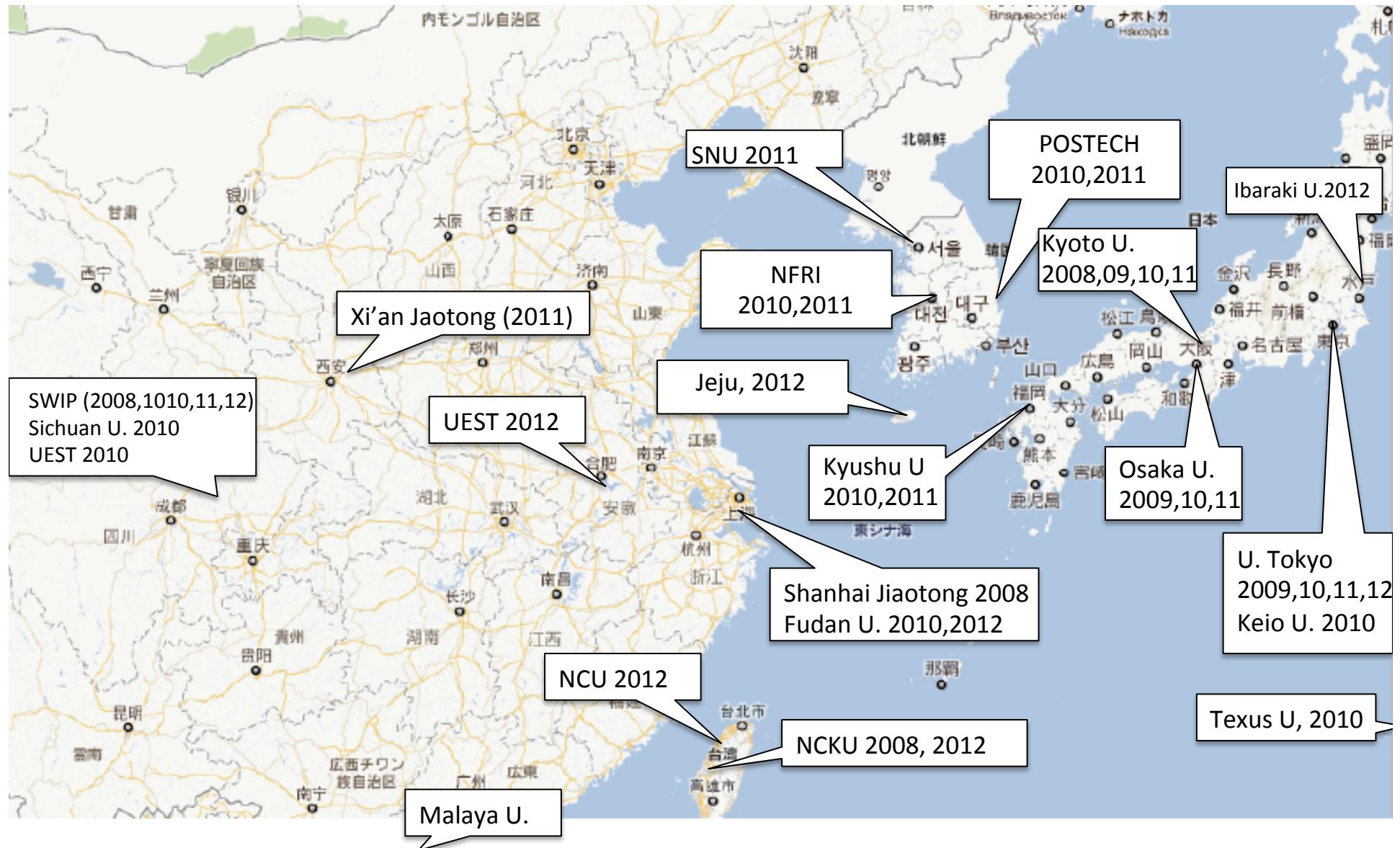


HL-2A in SWIP(Chengdu, China)
→ **HL-2M (3MA~DIII-D)**

EAST in IPP-CAS (Hefei, China)



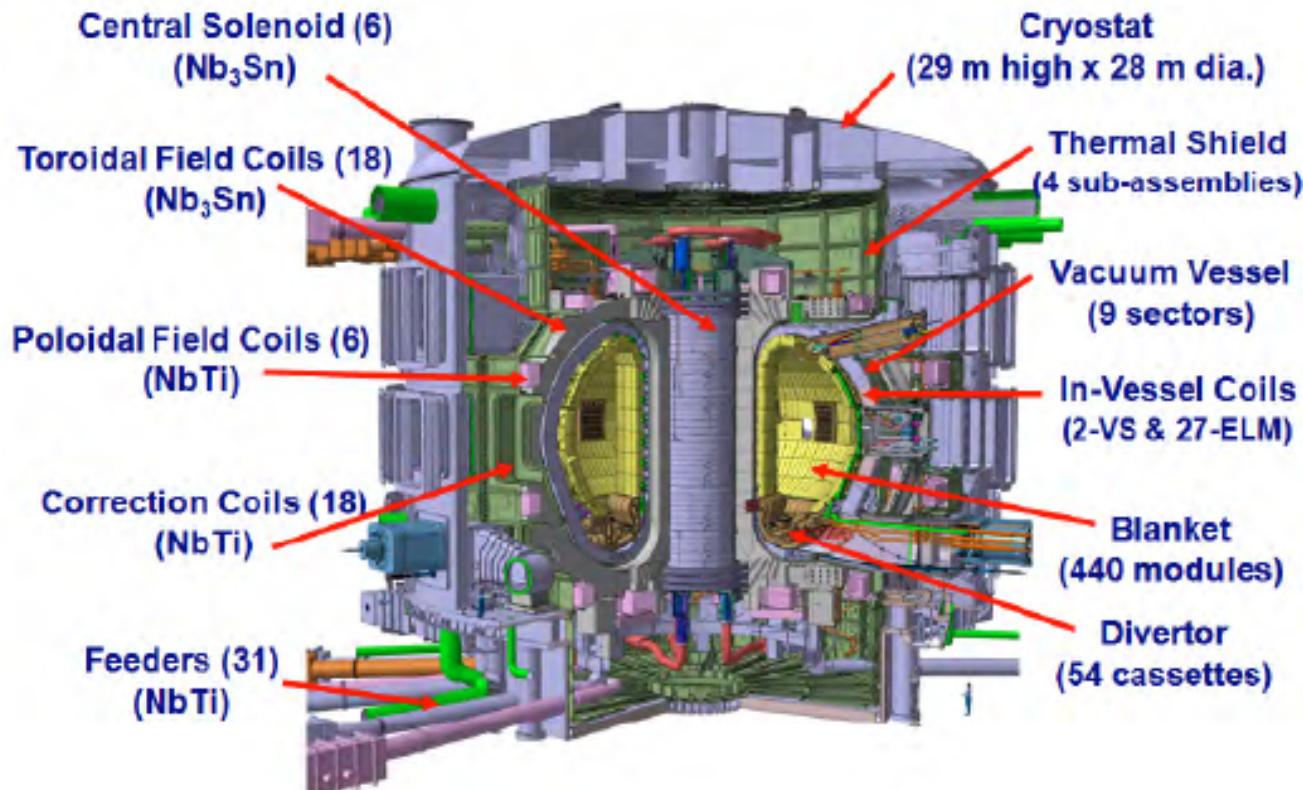
6. Asia is hot in fusion : Invited talks and Lectures in China/Korea/Japan



6. ITER

The principal physics goals of ITER

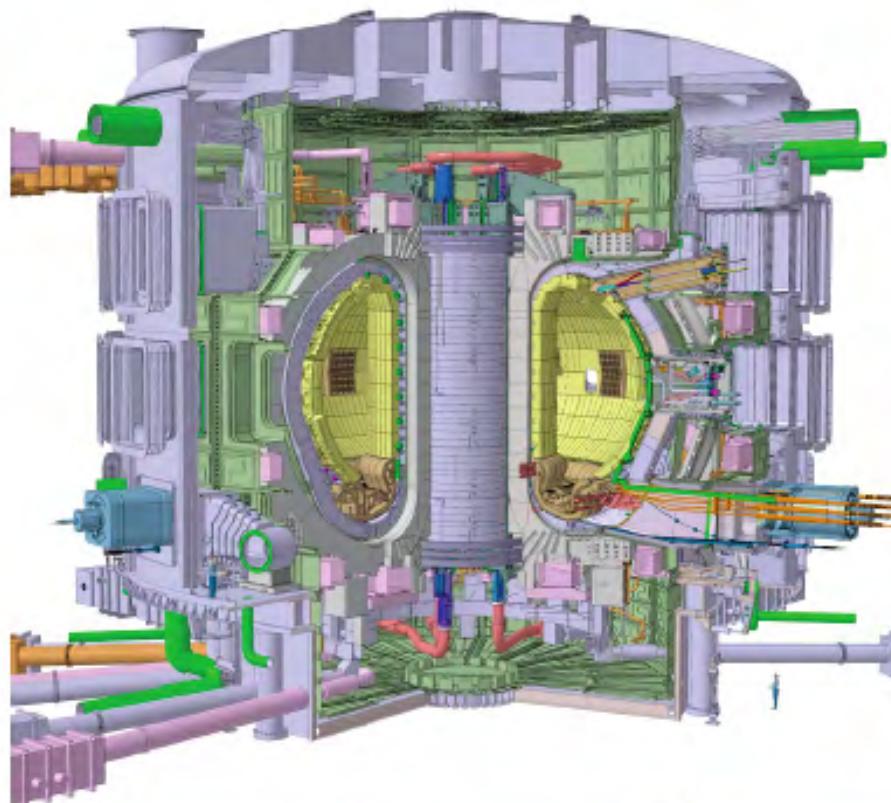
- 1) Achieve extended burn in inductively-driven plasmas with Q of at least 10 for a range of operating conditions, and of duration sufficient to achieve stationary conditions on the time scales characteristic of plasma processes.
- 2) Aim at demonstrating steady-state operation using non-inductive current drive with a ratio of fusion power to input power of at least 5.



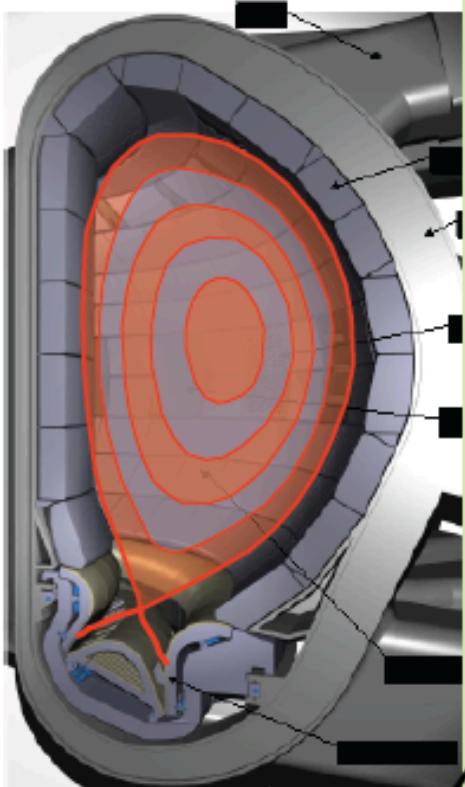
Plasma current	15MA
Toroidal field	5.3T
Major radius	6.2m
Minor radius	2.0m
Elongation κ_x/κ_{z0}	1.85/1.7
Triangularity δ_x/δ_{z0}	0.48/0.33
Fusion power	500MW
Q	10
Burn time	~400s

7. ITER construction started

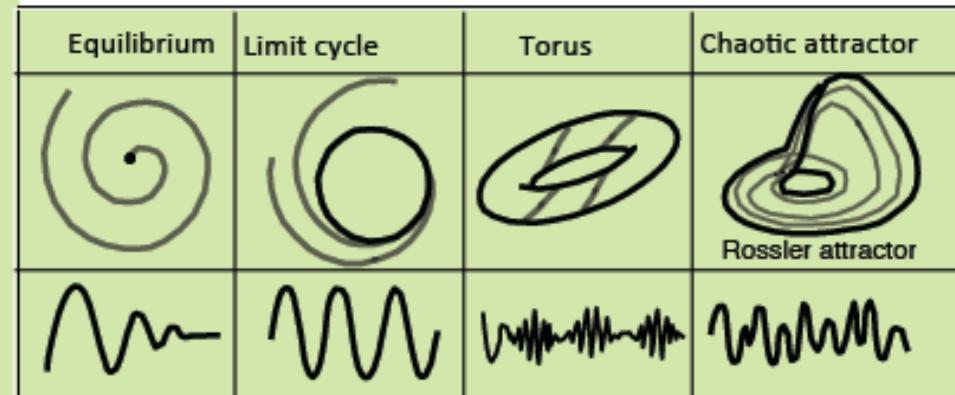
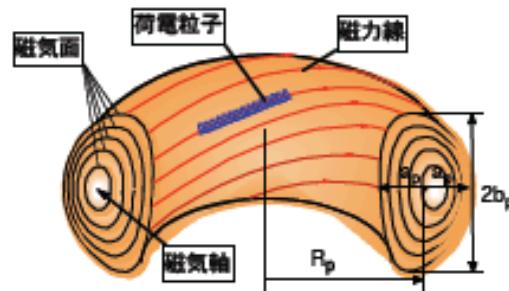
ITER DDG Prof. Motojima



7. ITER Burning Plasma is Complex System

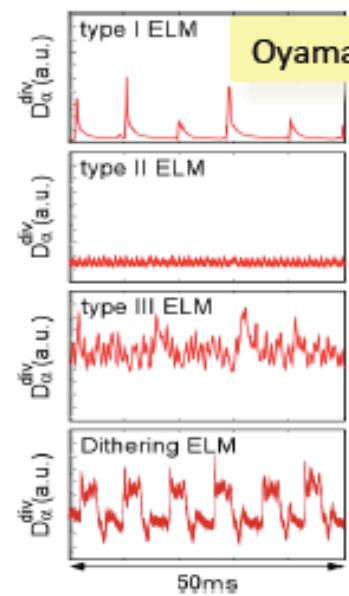


Equilibrium, transition

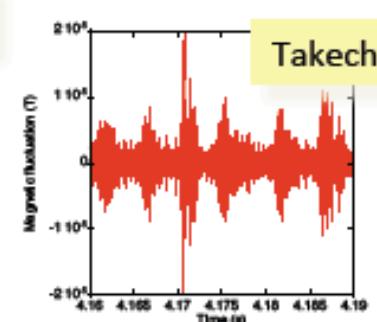


Phase space structure

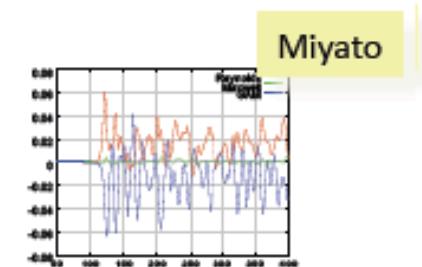
ELM?



TAE?

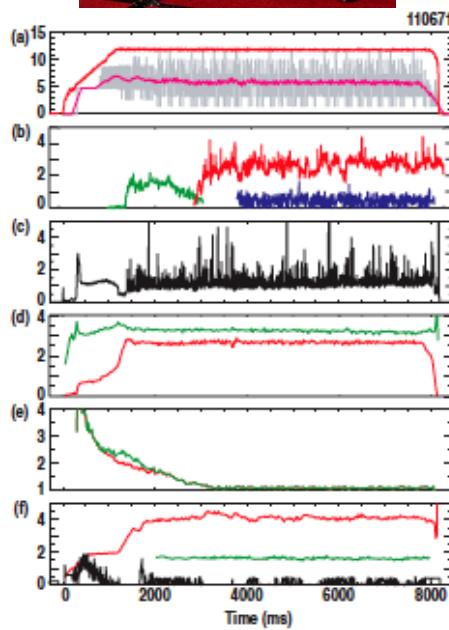


Turbulent transport ?



8. ITER Operation Scenarios validation is in progress

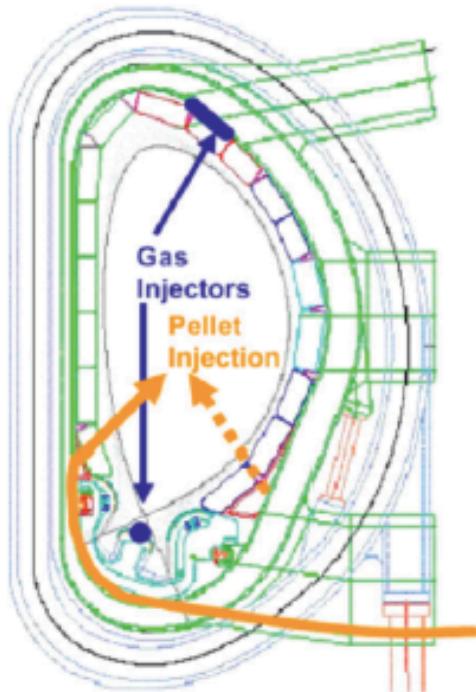
Nuclear Fusion Prize 2006
For Hybrid (T. Luce)



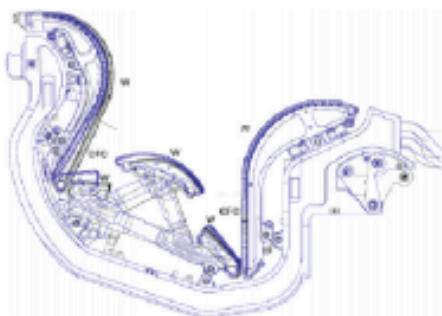
Parameter	Design Scenarios		
	Inductive	Hybrid	Steady-State
R/a [m/m]	6.2/2.0	6.2/2.0	6.35/1.85
Volume [m ³]	831	831	730
Surface [m ²]	683	683	650
B _T [T]	5.3	5.3	5.18
I _P [MA]	15.0	13.8	9.0
κ_x/κ_{95}	1.85/1.7	1.85/1.7	2.0/1.85
δ_x / δ_{95}	0.48/0.33	0.48/0.33	0.5/0.40
τ_E [s]	3.4	2.7	3.1
H ₉₈ (y,2)	1.0	1.0	1.57
β_N	2.0	1.9	3.0
$\langle n_e \rangle [10^{19} \text{ m}^{-3}]$	11.3	9.3	6.7
f _{He, axis} [%]	4.4	3.5	4.1
P _{FUS} [MW]	500	400	356
P _{ADD} [MW]	50	73	59
Q	10	5.4	6.0
Burn time [s]	500	1000	3000
Min rep time [s]	2000	4000	12000
P _{TOT} [MW]	151	154	130
P _{RAD} [MW]	61	55	38
P _{α} [MW]	100	80	71
P _{L-H} [MW]	76	66	48
W _{th} [MJ]	353	310	287

Not yet for
Steady-state

9. ITER Actuators (2) Density profile physics in progress.



Baylor : NF 2007



Kukushkin: NF2009

High field side Pellet Injector : Core fuelling
: Density peaking
Low field side Pellet Injector : ELM pacing

P T Lang et al: ELM pace making and mitigation by pellet injection in ASDEX Upgrade : one of 2007 NFP 10 nominees

Density peaking has strong influence on fusion performance. When ITG plays dominant role in transport, density will be peaked while it will flatten if TEM play major role as shown by Angioni NF2004.

2007 Nuclear Fusion Prize for physics of density peaking



C. Angioni

10. ITER Actuators : RMP is validated

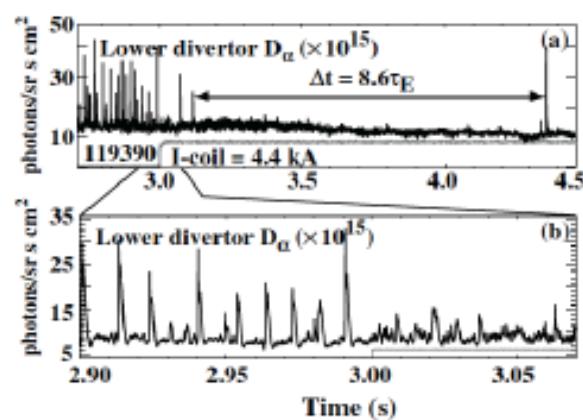
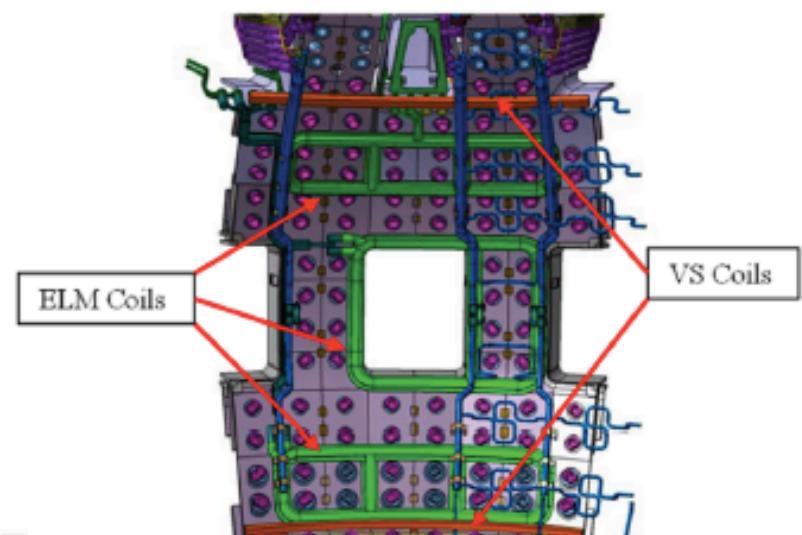
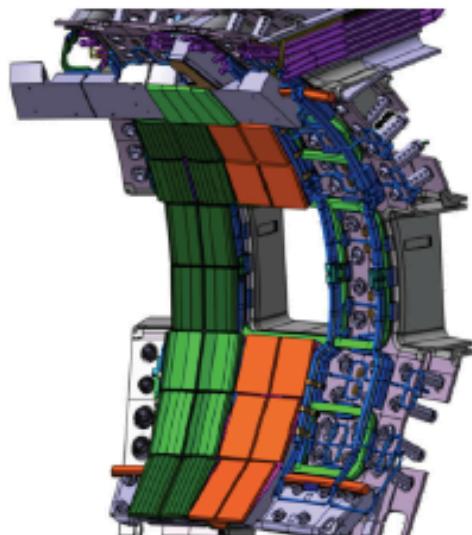
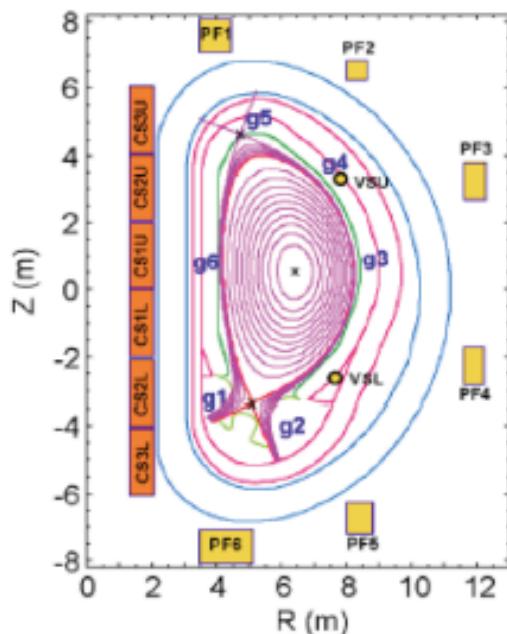
Shape, Position Control : PF1-PF6 (SC)

Fast vertical feedback control: VS coils (NC)

Plasma current control : CS1-CS6 (SC)

ELM control : ELM coils

RWM control : use ELM coils



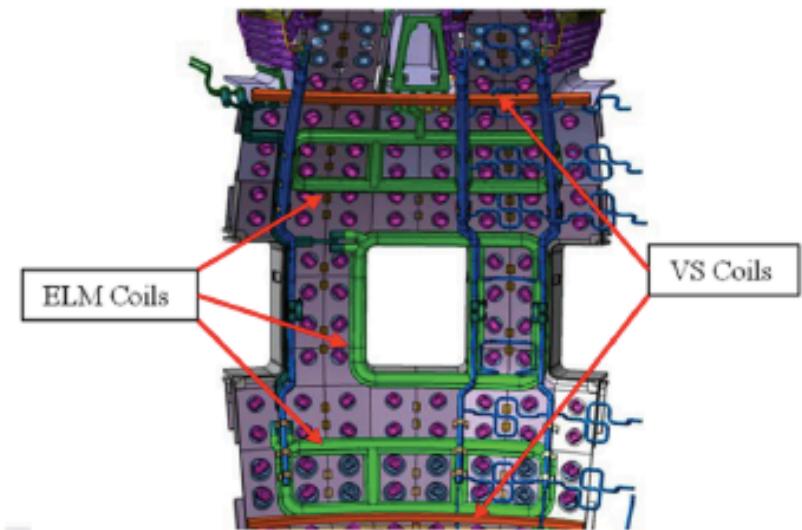
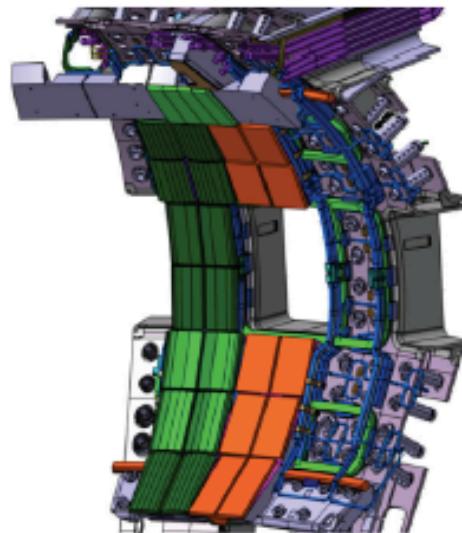
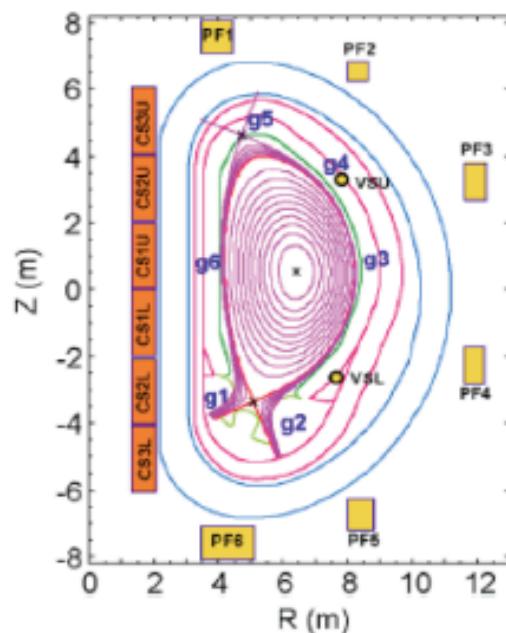
2008 Nuclear Fusion Prize for ELM suppression



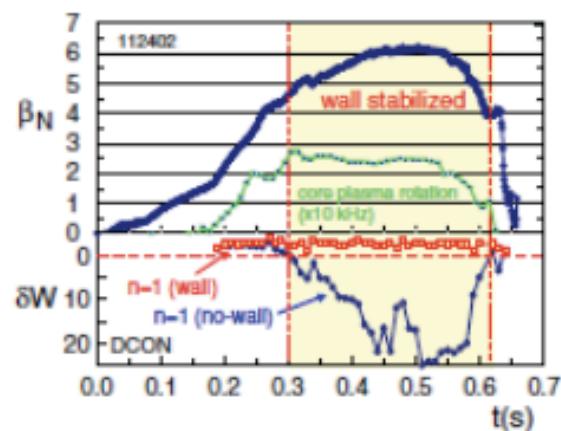
T. Evans

11. ITER Actuators : RWM mode control

RWM control : use ELM coils



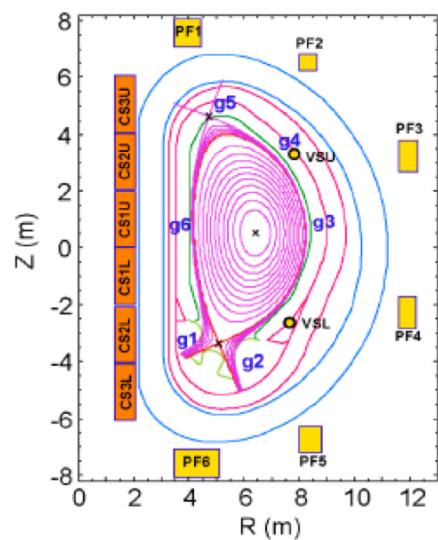
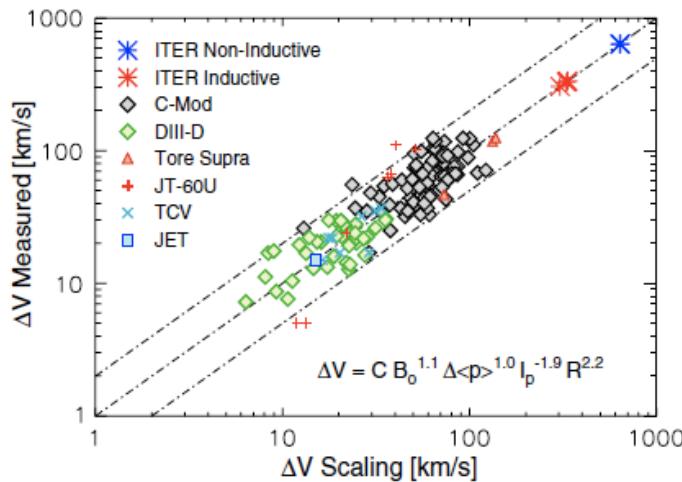
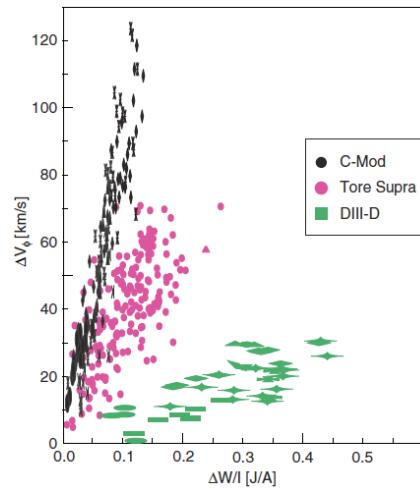
2009 Nuclear Fusion Prize for RWM suppression



S. Sabbagh

12. ITER Actuators : Intrinsic Rotation

RWM stability needs small toroidal rotation.
Intrinsic rotation may be sufficient.

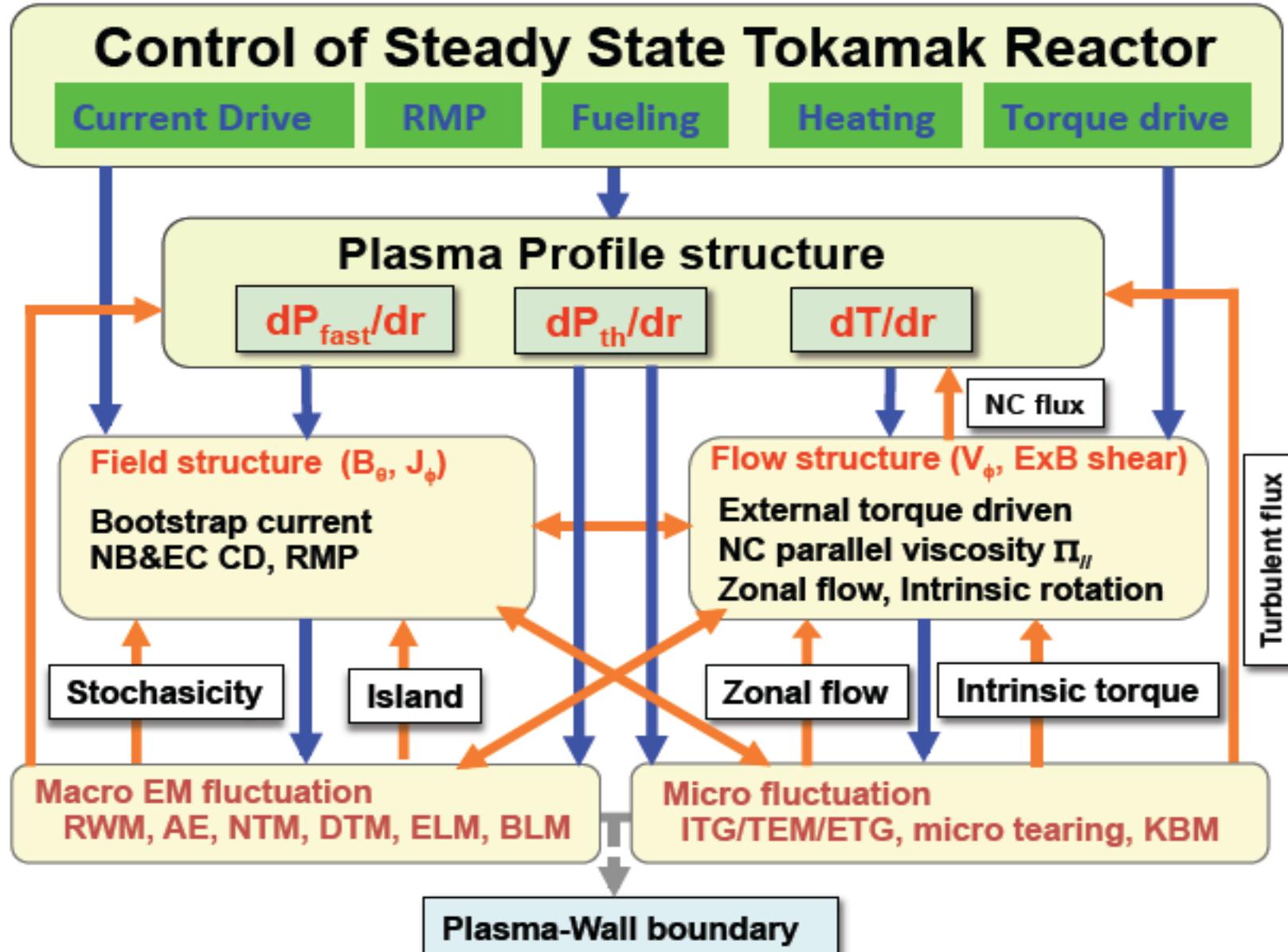


2010 Nuclear Fusion Prize for Intrinsic Rotation

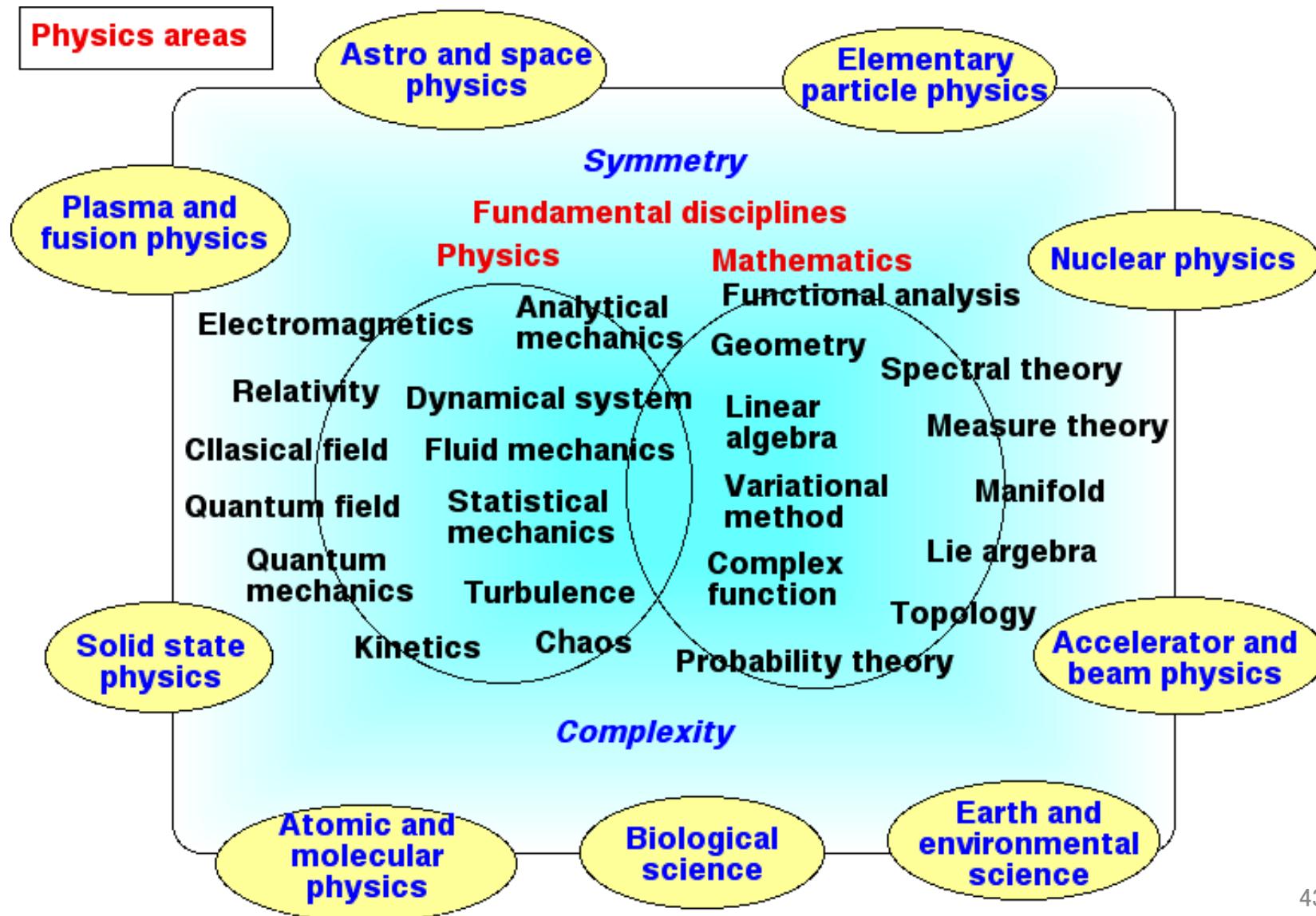


J. Rice

Physics in Steady State Tokamak Reactor



Fusion physics made significant progress benefited by fundamental disciplines



For your reference:

Mitsuru Kikuchi
Frontiers in Fusion Research
Physics and Fusion

Frontiers in Fusion Research provides a systematic overview of the latest physical principles of fusion and plasma confinement. It is primarily devoted to the principle of magnetic plasma confinement, that has been systematized through 50 years of fusion research.

Frontiers in Fusion Research begins with an introduction to the study of plasma, discussing the astronomical birth of hydrogen energy and the beginnings of human attempts to harness the Sun's energy for use on Earth. It moves on to chapters that cover a variety of topics such as:

- charged particle motion,
- plasma kinetic theory,
- wave dynamics,
- force equilibrium, and
- plasma turbulence.

The final part of the book describes the characteristics of fusion as a source of energy and examines the current status of this particular field of research.

Anyone with a grasp of basic quantum and analytical mechanics, especially physicists and researchers from a range of different backgrounds, may find *Frontiers in Fusion Research* an interesting and informative guide to the physics of magnetic confinement.

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Frontiers in Fusion Research

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Physics and Fusion

Springer

Concluding Remark

To realize Sun on the Earth is not an easy job.
But it is challenging and human being knows to
continue work for century as seen in construction
of Sagrada Familia church



Sagrada Familia 1882-future

