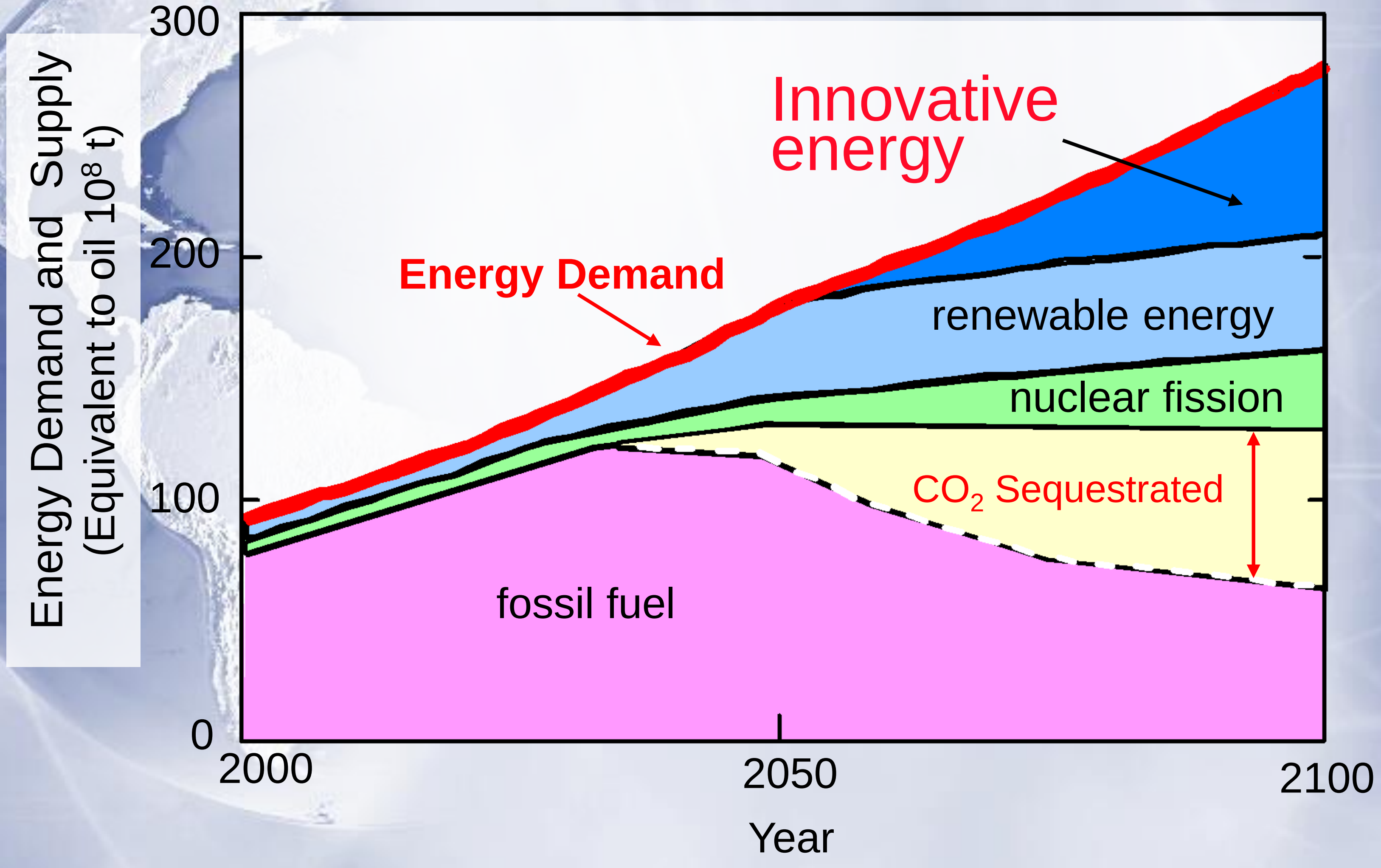
Design Studies and Plasma Confinement

T. Tsunematsu

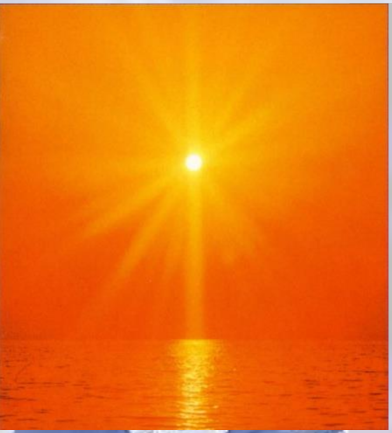
Japan Atomic Energy Agency

Why Fusion?

- Fusion as an Innovative Energy Candidate -



Why NOT Fusion !



High Energy Generation Rate

Fusion can generate energy equivalent to 8 tons of oil with 1g DT fuel

Fuel weight of 1 year in 1 GW Plant

Fusion：0.2 tons

Oil：1,400,000 tons

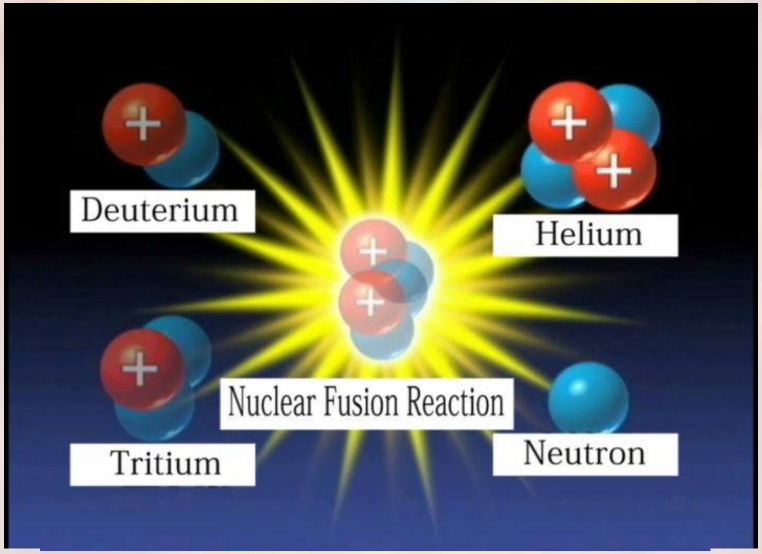
Plentiful Fuel Resource

Deuterium concentration in sea water:33g/m^3

Tritium can be produced by nuclear reaction with lithium in a fusion reactor.

Lithium concentration in sea water: 0.2g/m^3

Fusion: abundant and inexhaustible energy



Energy favorable for environment and safety

Ash is helium

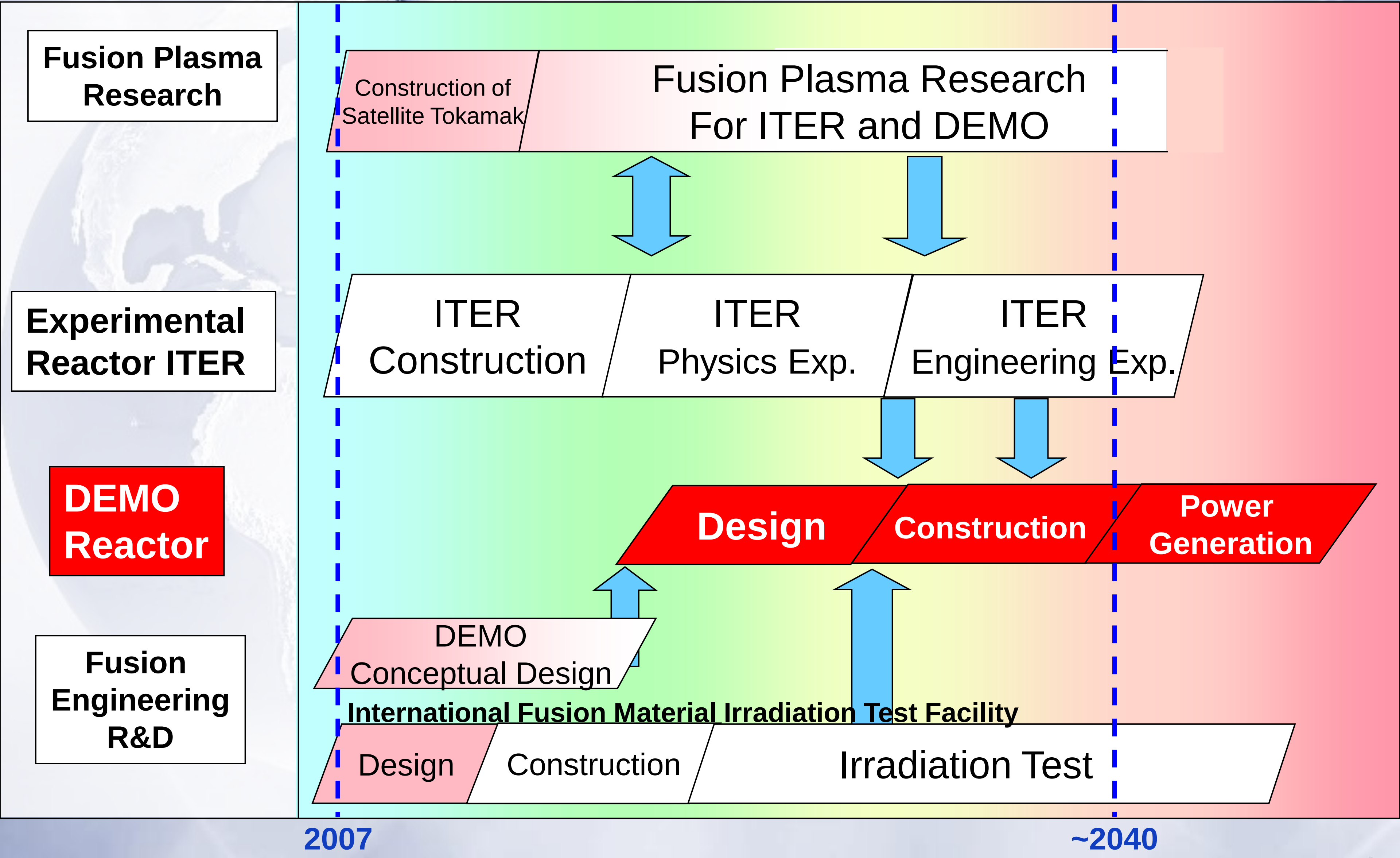
No carbon dioxide, nitric oxide

Reaction can be easily stopped by closing the fuel supply valve similar to a gas burner

Advanced Technologies

Fusion will promote advanced technologies such as superconducting magnet, robot, heat resistance materials, ion beam, microwaves etc..

Conceptual Step for Realization of Fusion Power



Fusion Plasma Research

Construction of Satellite Tokamak

Fusion Plasma Research For ITER and DEMO

Experimental Reactor ITER

ITER Construction

ITER Physics Exp.

ITER Engineering Exp.

DEMO Reactor

Design

Construction

Power Generation

Fusion Engineering R&D

DEMO Conceptual Design

International Fusion Material Irradiation Test Facility

Design

Construction

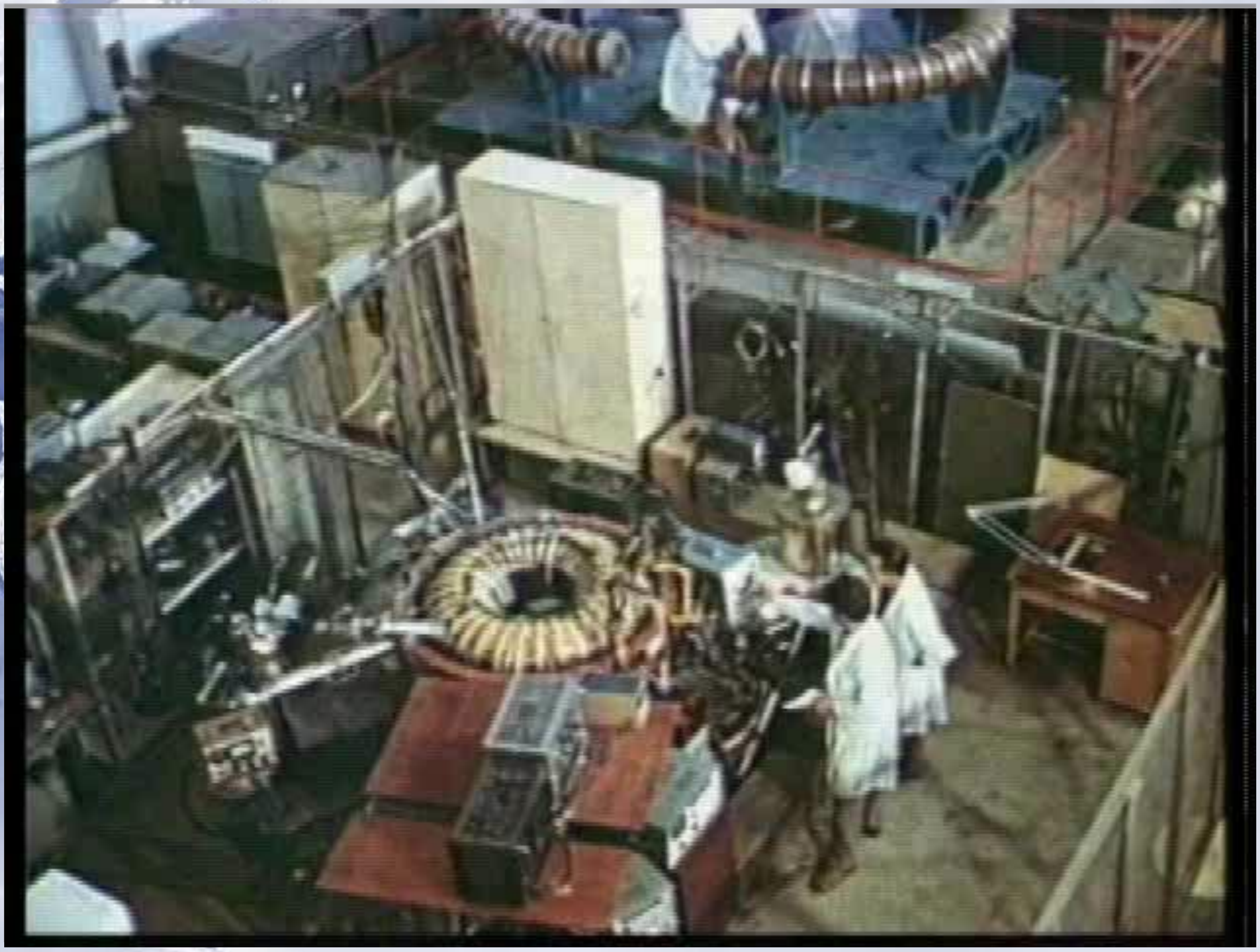
Irradiation Test

2007

~2040

T-3 Tokamak and L. A. ARTSIMOVICH

Novosibirsk, USSR(RF)



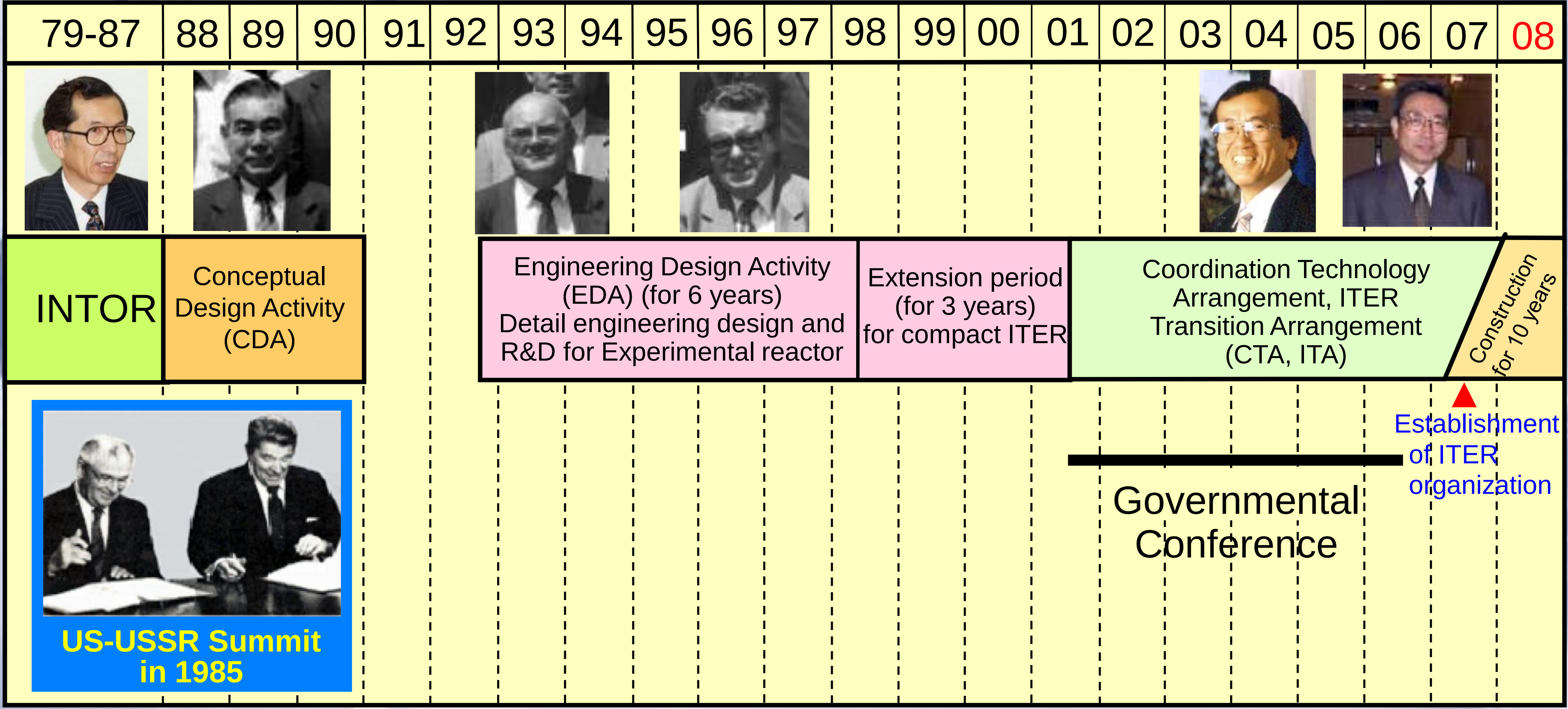
Historical Result ofT-3 Tokamak

T_e ~ 100-2000eV, T_i ~ 300 eV,
n_e ~ 10^{12}-$5x10^{13}$ cm^{-3}, τ_E ~ 10 ms.
From the presentation at the 3rd IAEA conference (1968, Novosibirsk)

This result was confirmed by the Thomson scattering measurement, which was performed by Culham group (1969).
Ref：M.J. Forrest, N.J. Peacock, D.C. Robinson, V.V. Sannikov, P.D. Wilcock;
“Mesurement of the Parameters in TOKAMAK T3-A by Thomson Scattering” CLM-R 107 (July, 1970)

Progress of International Project

year



79-87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08

INTOR

Conceptual Design Activity (CDA)

Engineering Design Activity (EDA) (for 6 years)
Detail engineering design and R&D for Experimental reactor

Extension period (for 3 years) for compact ITER

Coordination Technology Arrangement, ITER Transition Arrangement (CTA, ITA)

Construction for 10 years

Establishment of ITER organization

Governmental Conference

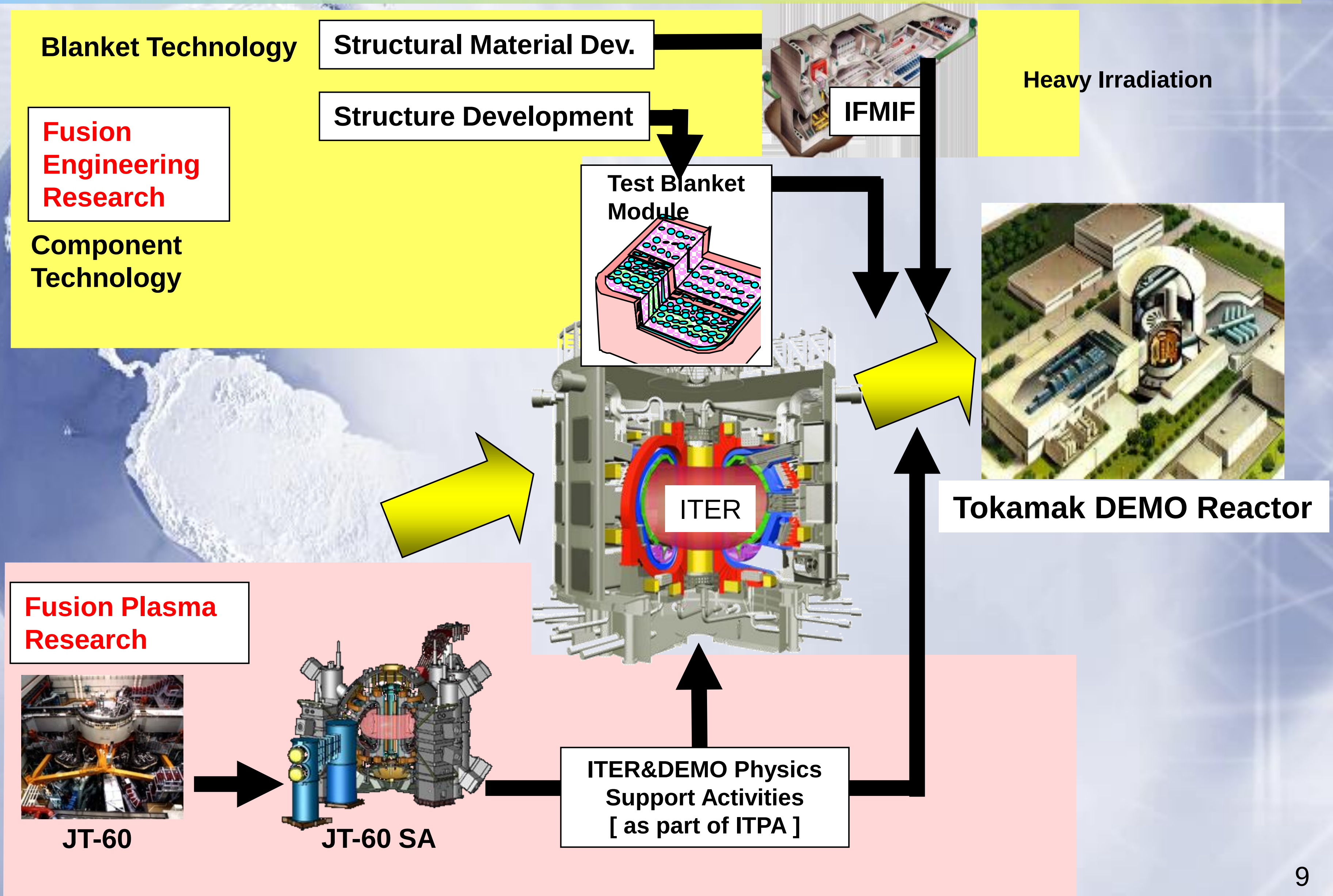
US-USSR Summit in 1985

INTOR: Review the possibility of construction for the next generation fusion machine under the international cooperation.
(Planned and managed by IAEA from 1979 to 1987)
Participants; Japan, US, EC, Soviet Union.
Chairman; Dr. S. Mori vice-president of JAERI

Major Results obtained through International Collaboration for Fusion Experimental Reactors

INTOR：	list up of key issues, Database (compilation of existing database in participating parties)
(1979~1987)	utilize data from medium or small size devices
ITER-CDA：	make an unified concept, determine a scenario for detailed design, expecting factor of 2 confinement improvement from L-mode,
(1988~1990)	(→ confinement improvement studies such as US TTF)
	kick-off for establishing an integrated database
ITER-EDA	：Detailed Design, R&D to obtain prospect for ITER construction
(1992~2001)	assuming H-mode confinement, intensive collection of disruption data, etc.
	establish a standard database (ITER Physics R&D, ITPA)
	set up of requirements to the ITER site and construction plan
ITER-CTA,ITA：	same as above
(2001~)	
From now：	ITER Construction, Operation, R&D, Decommissioning
(2008~)	

Road Map to Fusion DEMO Reactor -Example of Japan-



Blanket Technology

Structural Material Dev.

Structure Development

IFMIF

Heavy Irradiation

Fusion Engineering Research

Component Technology

Test Blanket Module

ITER

Tokamak DEMO Reactor

Fusion Plasma Research

JT-60

JT-60 SA

ITER&DEMO Physics Support Activities
[as part of ITPA]

ITER Project

Demonstration of high power amplification and extended burn of DT plasmas with steady-state as an ultimate goal

Demonstration of technologies essential to fusion power reactor

Integrated testing of the high-heat-flux and nuclear components required to utilize fusion energy for practical use

1988-1990: Conceptual Design Activities
1992-2001: Engineering Design Activities
2001-2002: Coordinated Technical Activities
2003-2006: ITER Transitional Arrangements
2005 June: Site Decision : Cadarache in France
2007- : ITER Construction

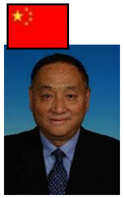
DG

Kaname Ikeda

DDG

Principal DDG

Safety/ Security



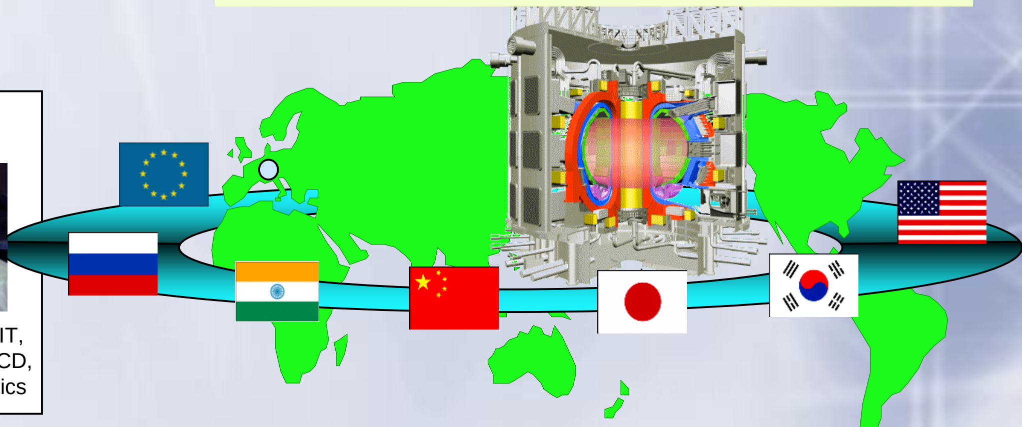
Adoministration

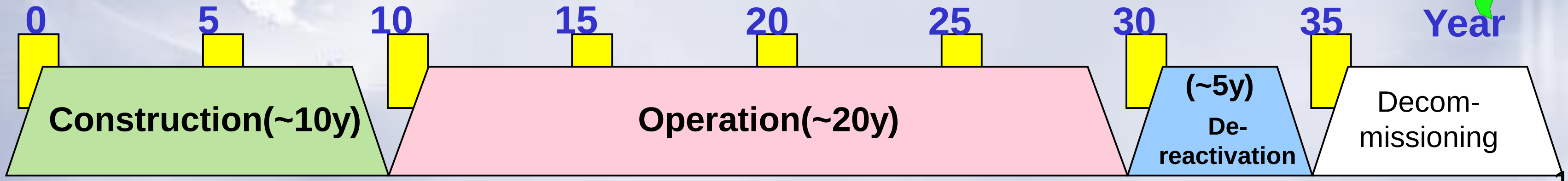
Fusion Science & Technology

Tokamak

Central Engineering & Plant Support

CODAC & IT, Heating & CD, & Diagnostics





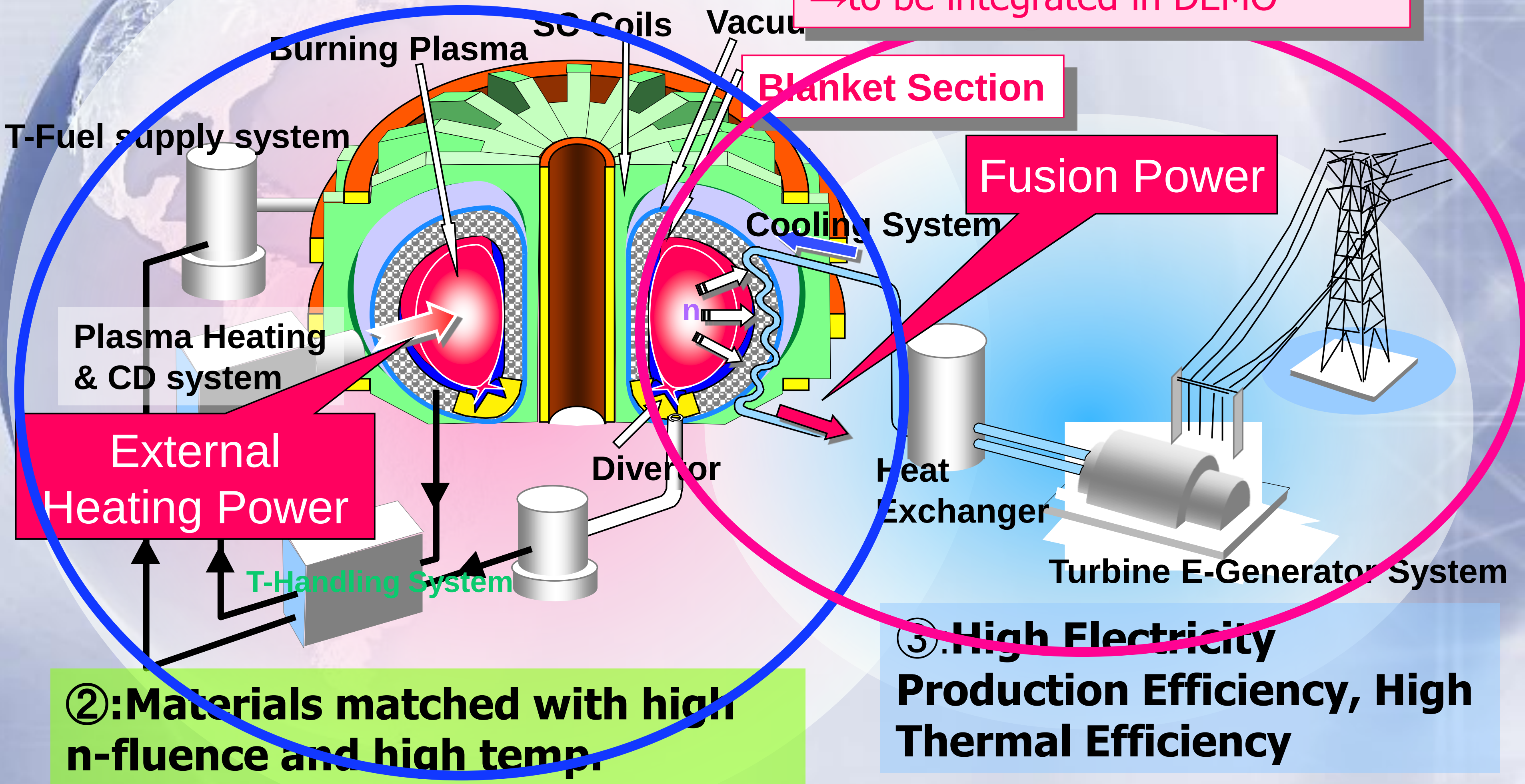
Concept for Fusion Power Plant

ITER：Demonstration of burning plasma

①: **High Q, High β**

- Tritium Breeding
- Power Generation

→to be integrated in DEMO



②:Materials matched with high n-fluence and high temp.

③:High Electricity Production Efficiency, High Thermal Efficiency

Technical Objectives of ITER (1)

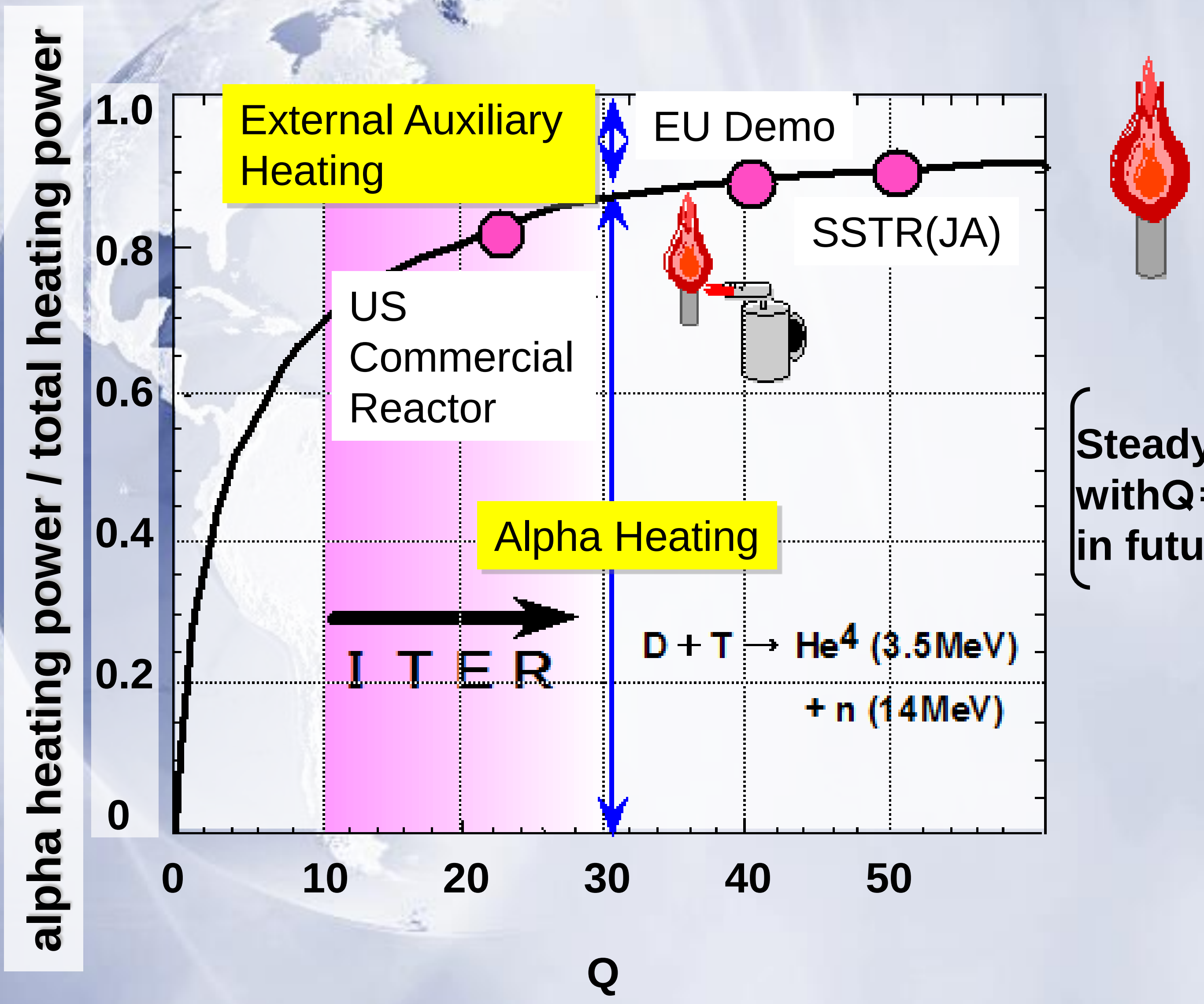
Plasma Performance:

- to achieve extended burn in inductively driven plasma with the ratio of fusion power to auxiliary heating power, Q, of at least 10 ($Q \geq 10$) with a burn duration between 300 and 500 s,

- to aim at demonstrating steady state operation using non-inductive current drive with $Q>5$,

- In addition, the possibility of controlled ignition should not be precluded.

Plasmas similar to power plant level will be achieved in the ITER



Steady-state operation withQ＝30~50 is needed in future power plants.

Technical Objectives of ITER (2)

Engineering Performance and Testing:

- demonstrate availability and integration of essential fusion technologies,
- test components for a future reactor,
- test tritium breeding module concepts; with a 14MeV neutron average power load on the first wall > 0.5 MW/m^2 and fluence 0.3 > MWa/m^2,
- the option for later installation of a tritium breeding blanket on the outboard of the device should not be precluded.

ITER Physics R&D

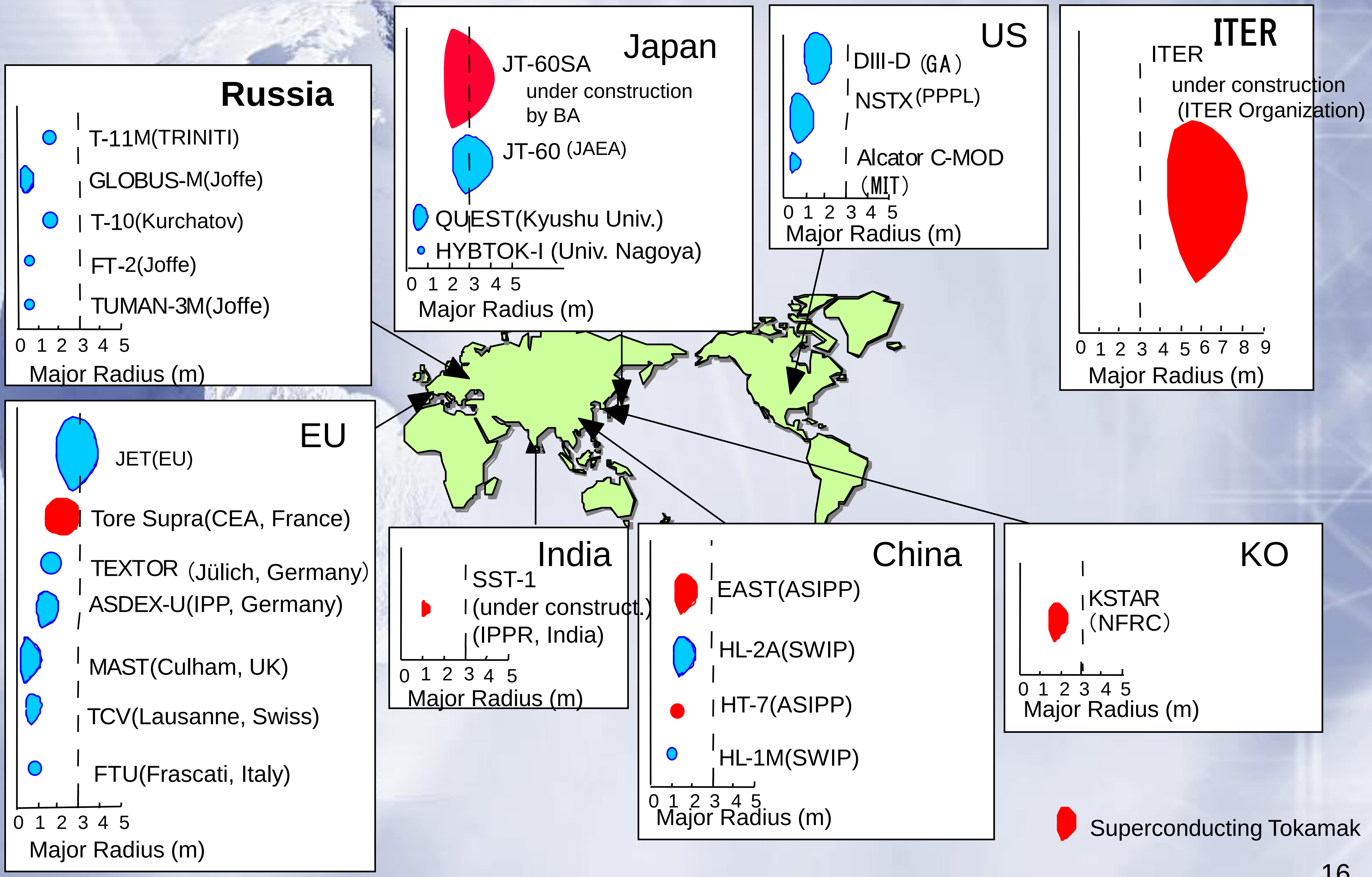
Expert Groups in EDA (1992 - 2001)

- Confinement & Transport
- Confinement Modeling and Database
- Disruption, Control, MHD
- Divertor
- Divertor Modeling and Database
- Diagnostics
- High Energy Particle Physics, Heating & Current Drive

Topical Physics Groups in ITPA (2001-)

- Transport Physics
- Confinement Database and Modelling
- Edge Pedestal Physics
- Scrape-off-layer and Divertor Physics
- MHD
- Steady State Operation
- Diagnostics

Tokamaks in the world



Russia

T-11M(TRINITI)

GLOBUS-M(Joffe)

T-10(Kurchatov)

FT-2(Joffe)

TUMAN-3M(Joffe)

Japan

JT-60SA under construction by BA

JT-60 (JAEA)

QUEST(Kyushu Univ.)

HYBTOK-I (Univ. Nagoya)

US

DIII-D (GA)

NSTX(PPPL)

Alcator C-MOD (MIT)

ITER

ITER under construction (ITER Organization)

EU

JET(EU)

Tore Supra(CEA, France)

TEXTOR (Jülich, Germany)

ASDEX-U(IPP, Germany)

MAST(Culham, UK)

TCV(Lausanne, Swiss)

FTU(Frascati, Italy)

India

SST-1 (under construct.) (IPPR, India)

China

EAST(ASIPP)

HL-2A(SWIP)

HT-7(ASIPP)

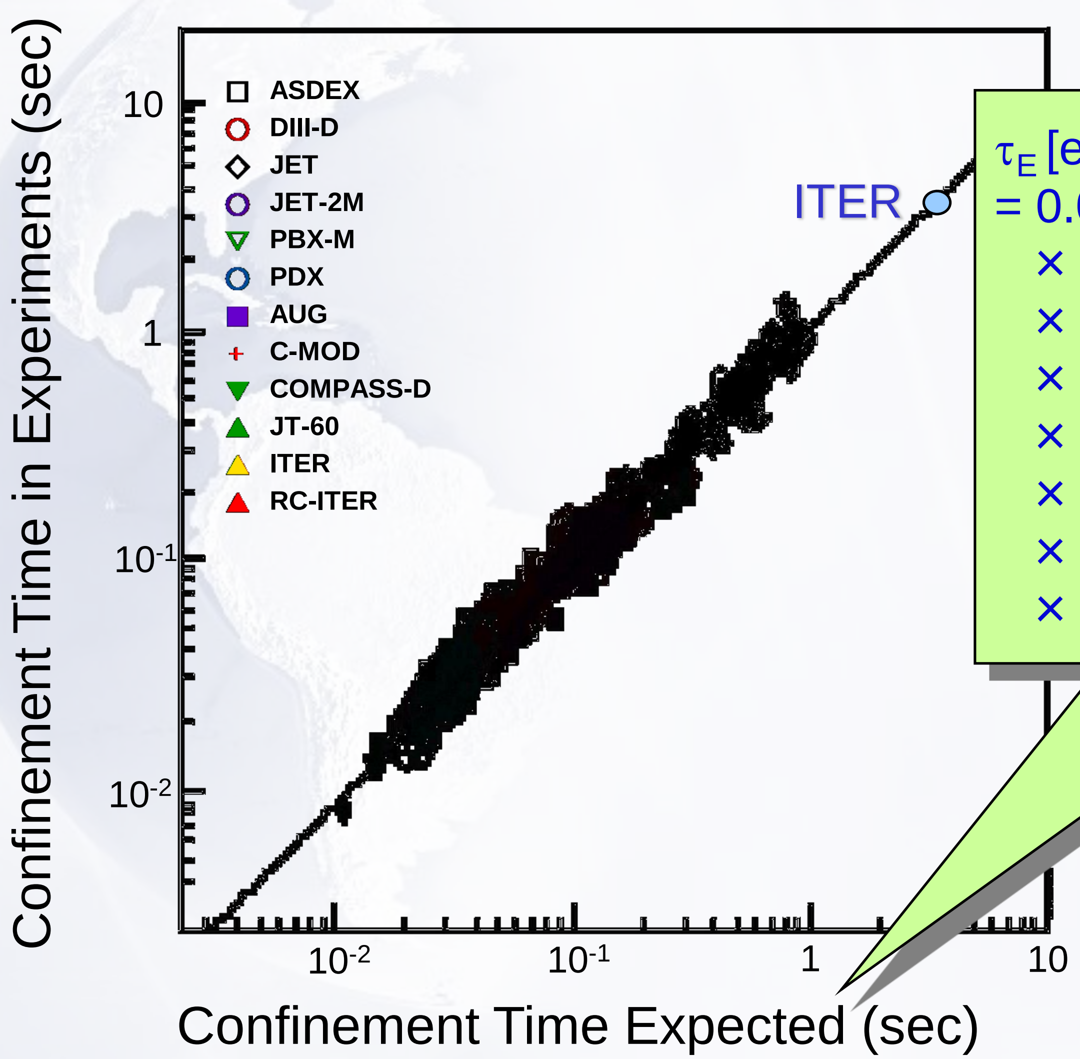
HL-1M(SWIP)

KO

KSTAR (NFRC)

Superconducting Tokamak

Energy Confinement in ELMy H-mode

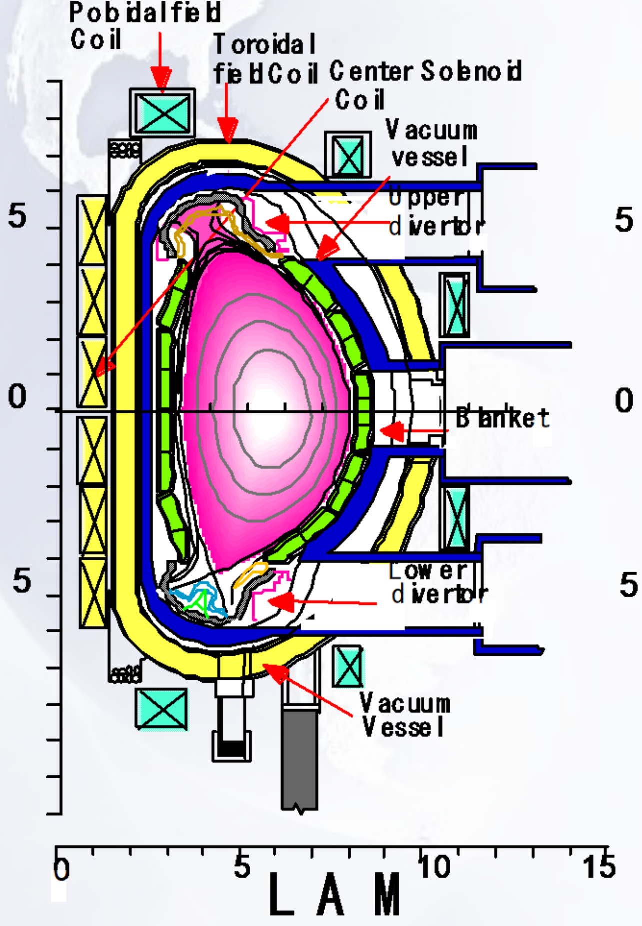


τ_E [expected](sec)
= 0.0562 · plasma current(MA)$^{0.93}$
× toroidal field(T)$^{0.15}$
× heating power(MW)$^{-0.69}$
× electron density(10^{19}m^{-3})$^{0.41}$
× ion mass number$^{0.19}$
× major radius(m)$^{1.97}$
× (minor radius/major radius)$^{0.58}$
× ellipticity$^{0.78}$

Selection of ITER Design

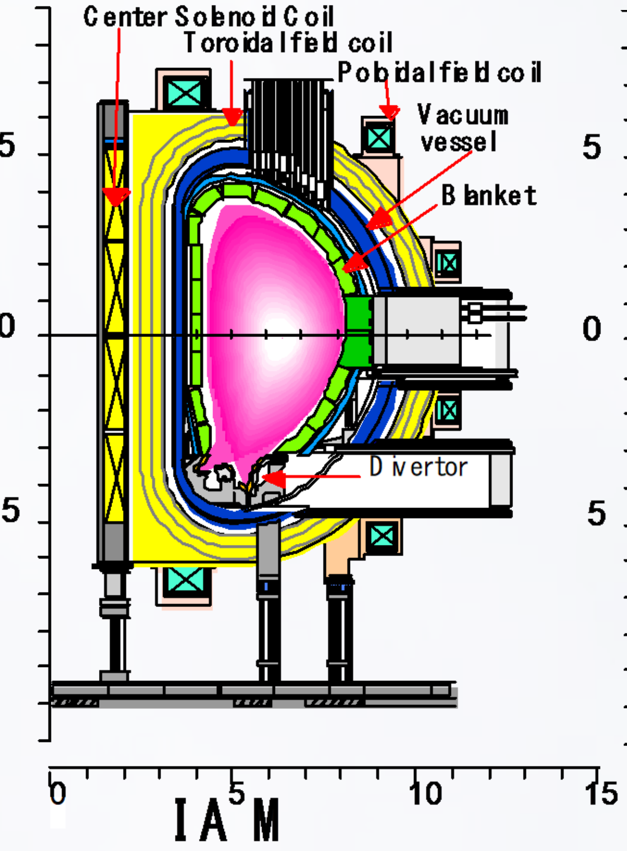
Major Radius : 6.45 m
Minor Radius : 2.33 m

B=4.25T



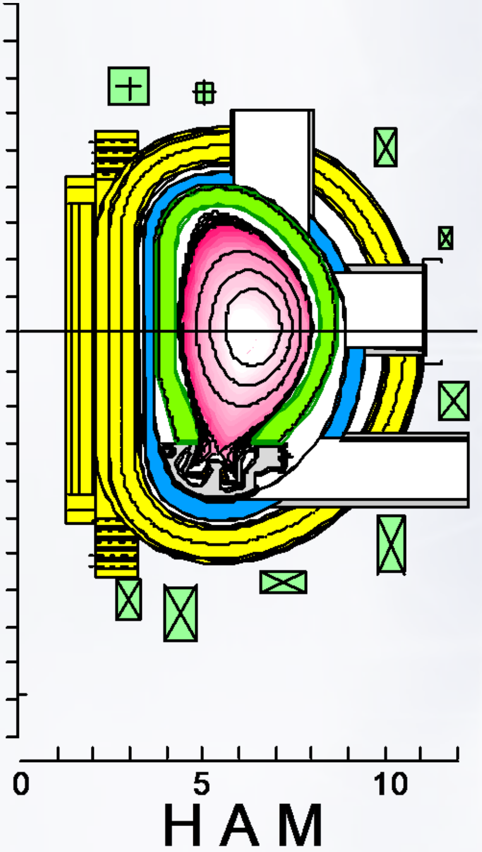
Major Radius : 6.2 m
Minor Radius : 1.9 m

B=5.4T



Major Radius : 6.3 m
Minor Radius : 1.8 m

B=6.58T



Main Parameters of ITER

Total fusion power	500 MW
Additional heating power	50 MW (75MW)
Q - fusion power/ additional heating power	≥ 10
Average 14MeV neutron wall loading	≥ 0.5 MW/m2
Plasma inductive burn time	300-500 s *
Plasma major radius (R)	6.2 m
Plasma minor radius (a)	2.0 m
Plasma current (Ip)	15 MA
Toroidal field at 6.2 m radius (BT)	5.3 T

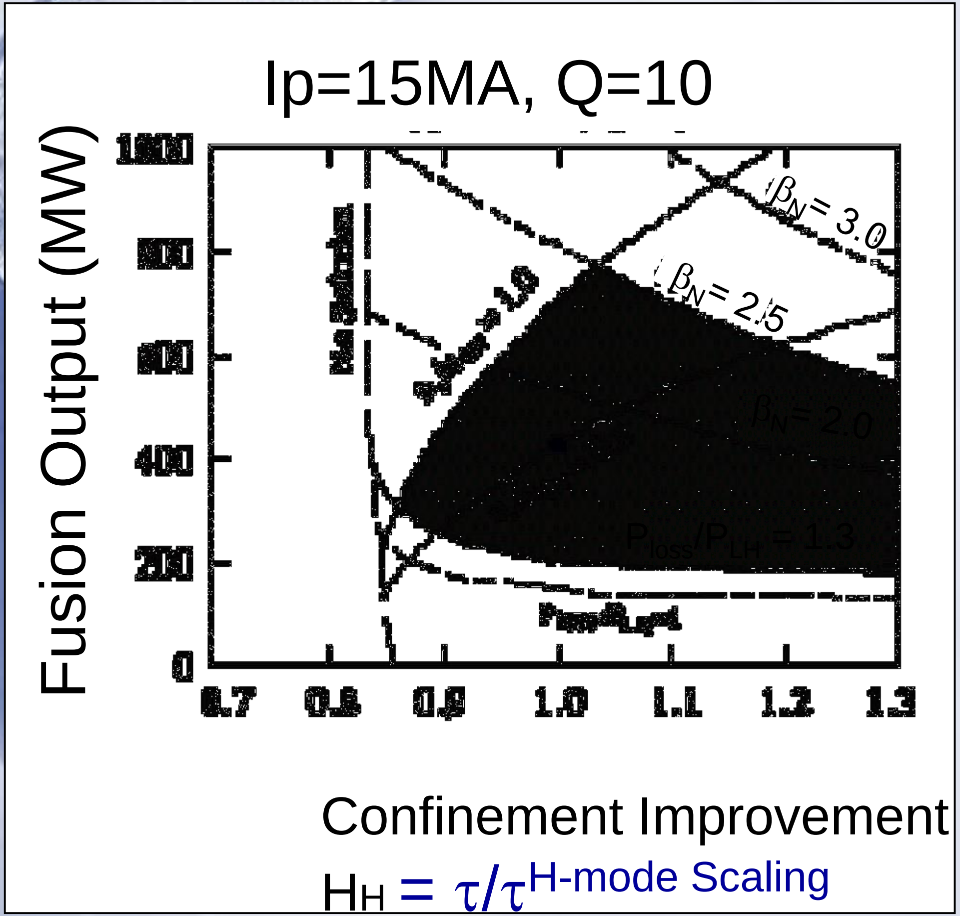
* under nominal operating conditions

Major Plasma Control Tools

- magnetic configuration
- heating & Current Drive
- fueling
- impurity injection
- particle exhaust
- First Wall (material, conditioning, etc.)

Heating & Current Drive System	Input Power (MW)		remarks
	The day one	Upgrade possibility	
NB(1MeV)	33	+ 17	
EC(170GHz)	20	+20	horizontal port and upper port
EC(～127GHz)	>2		plasma start-up
IC(～50MHz)	20	+20	
LH(5GHz)	-	+40	
Total	~75 MW	+ 37 MW	

Operation Space for Q=10



-density limit
<Greenwald density

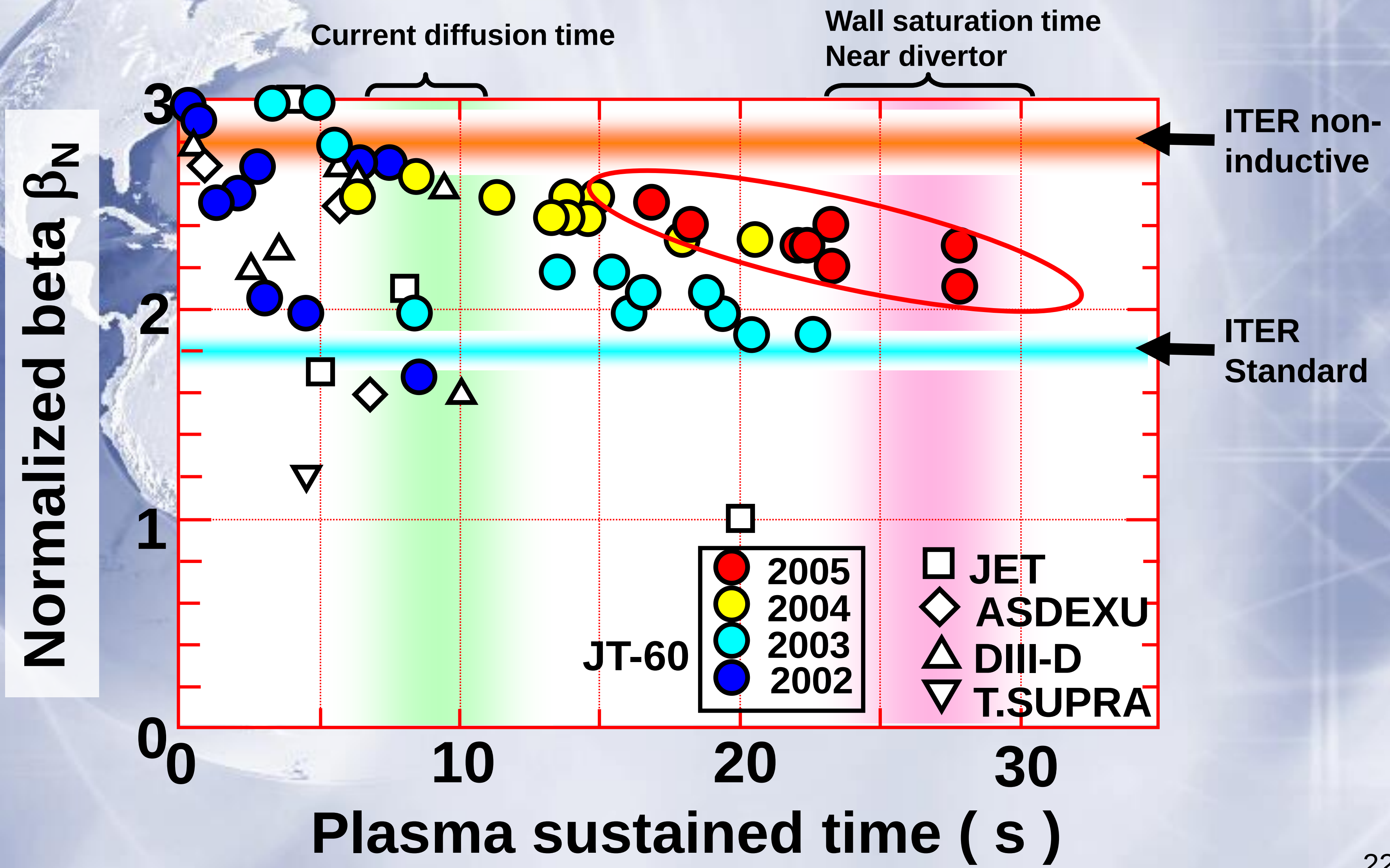
-normalized β
<2.5

-access to ELMy H-mode
P_{loss}>P_{LH} threshold power

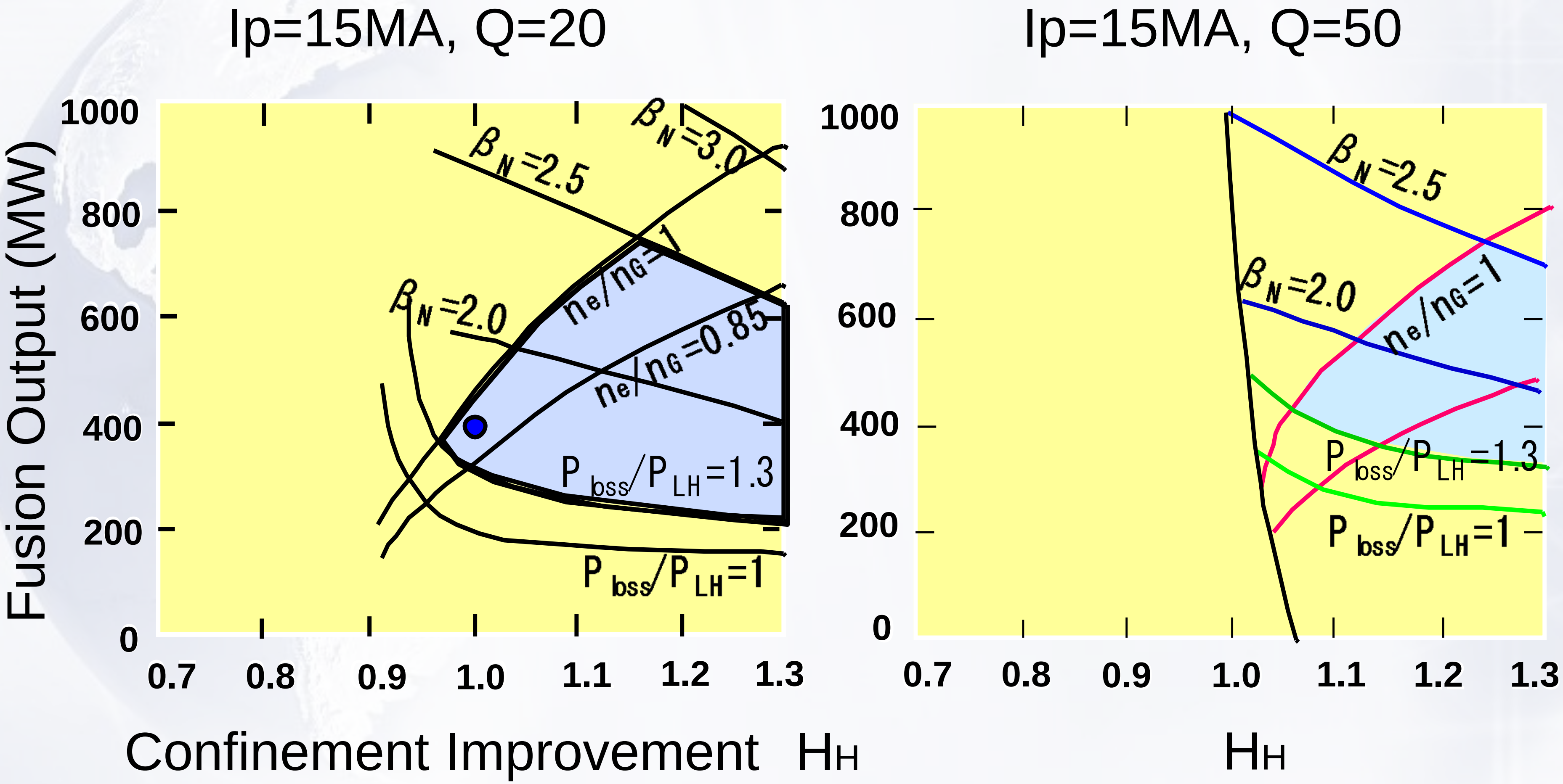
$$P_{LH} = 0.042 n_{20}^{0.73} B_t^{0.74} S^{0.98} \text{ (MW)}$$

~10% margin in confinement improvement

High normalized beta beyond the ITER standard operation has been sustained for about wall saturation time near the divertor



Operation Space for Q>10 (Inductive)

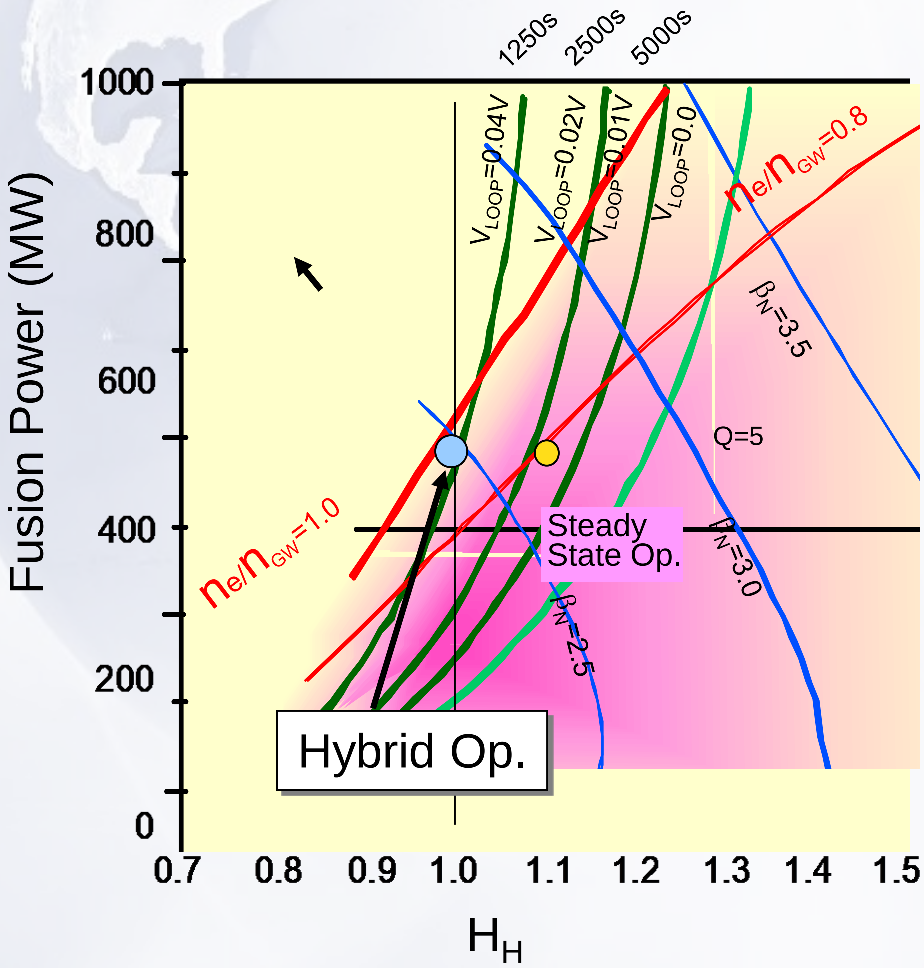


achievable with HH=1

achievable with HH~1.1

Long Burn with Inductive and Non-inductive Hybrid Operation

R/a=6.35/1.85m   Ip=12MA,
Weak Positive Magnetic Shear Mode, External Auxiliary Heating=100MW



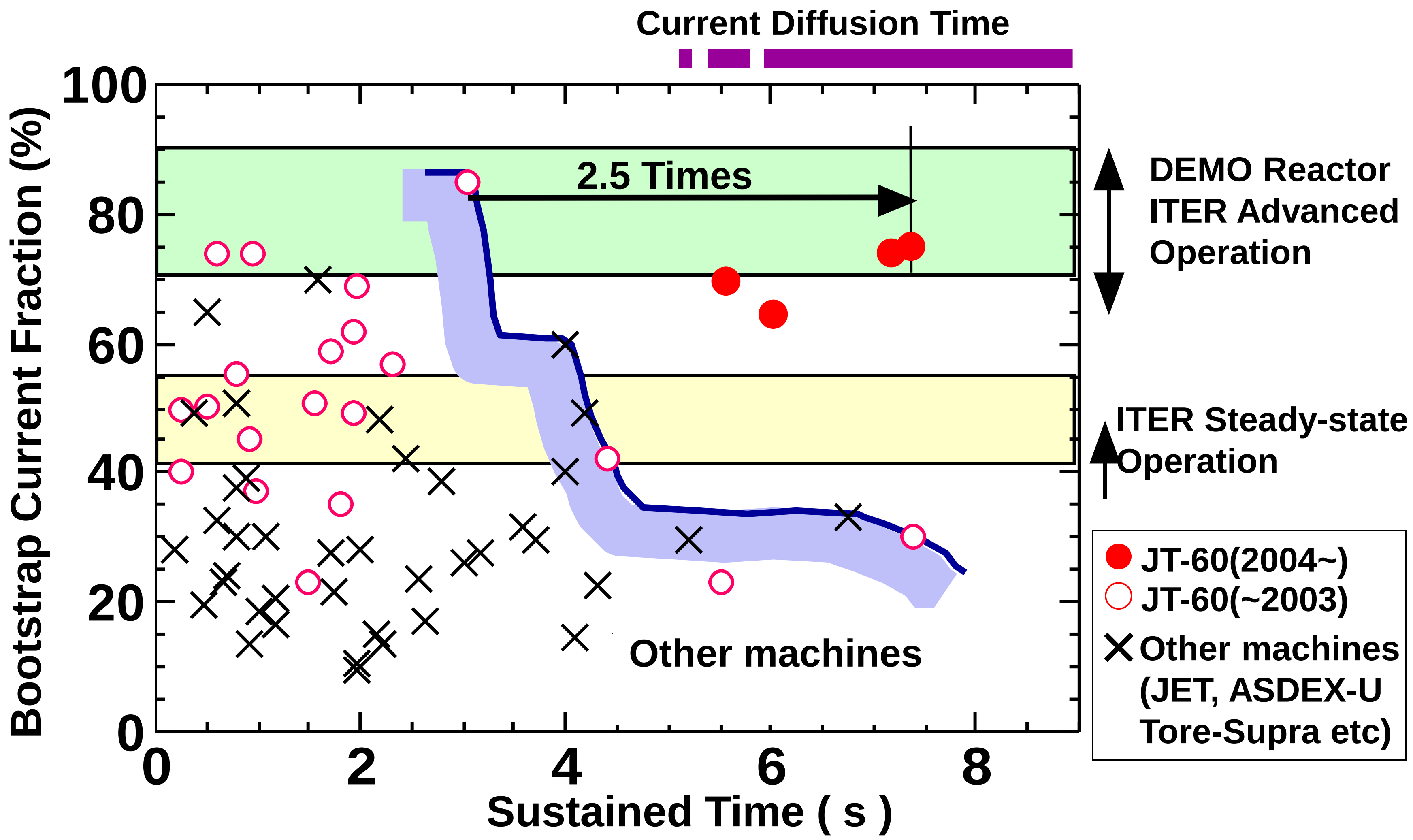
test breeding Blanket Modules [0.3 Mwa/m^2]

~5,000 Shots (~500MW,2500s Op.)

is achievable within fatigue life time.

Highly self-organized plasma was sustained

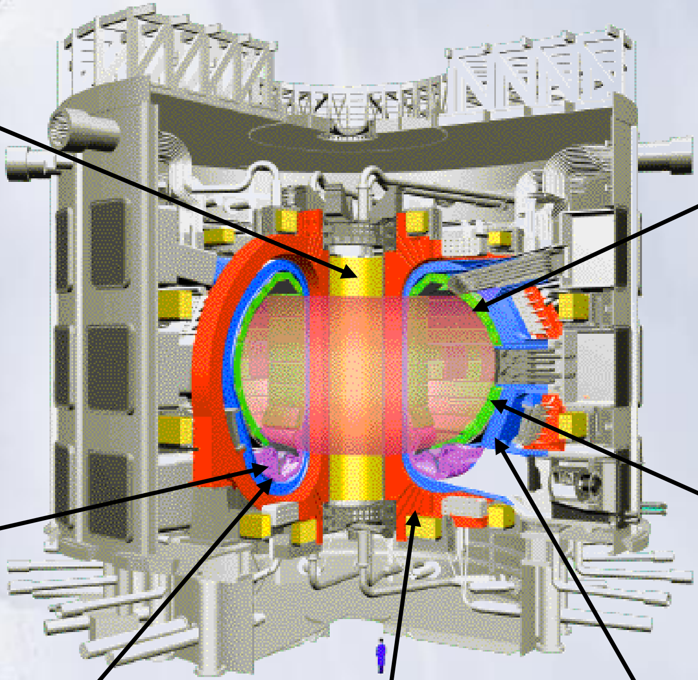
Key is pressure and current profile control near internal transoprt barrier with flexible beam heating/CD and fine diagnostics

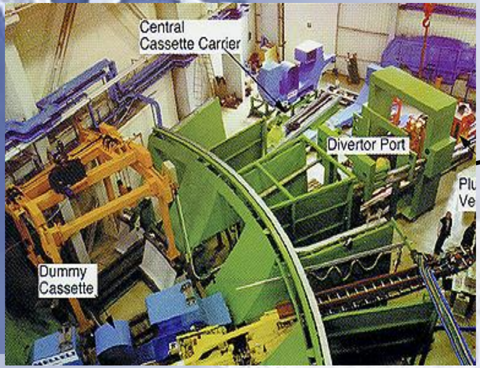


ITER 7 Major R&D in EDA

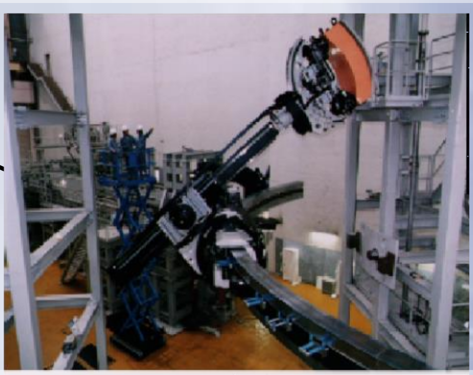
L1:Central Solenoid Model Coil

L4:Blanket Module





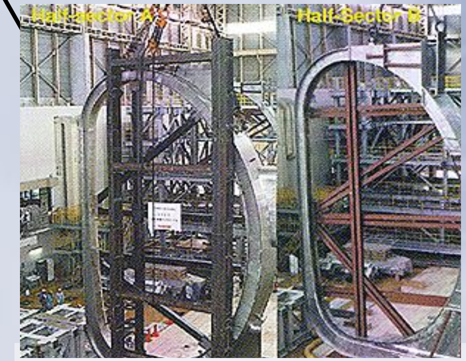
L7:Divertor Remote Handling



L6:Blanket Remote Handling

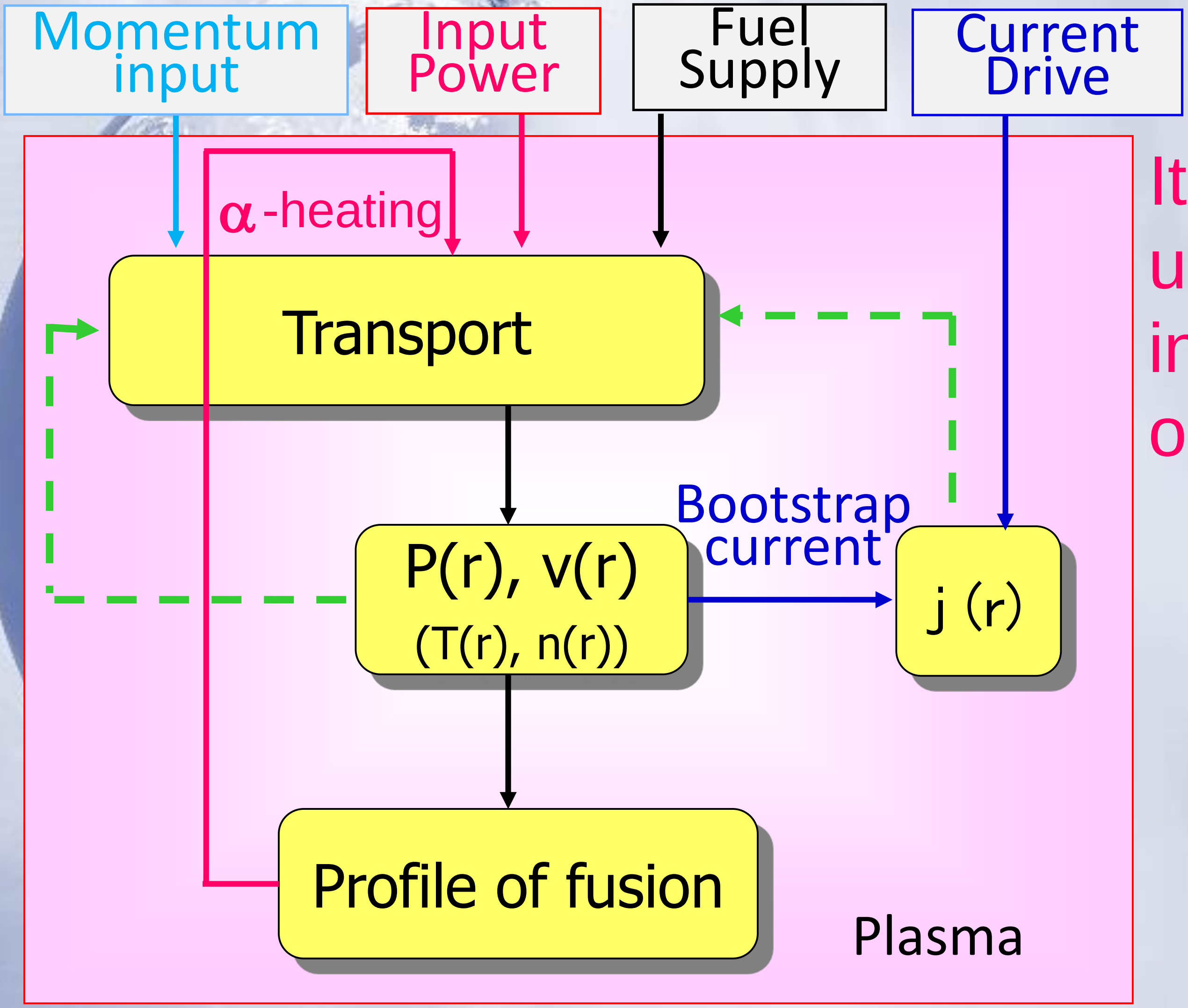
L5:Divertor Cassette

L2:TF Model Coil



L3:Vacuum Vessel Sector

Burning Plasma



Momentum input

Input Power

Fuel Supply

Current Drive

α-heating

Transport

P(r), v(r)
(T(r), n(r))

Bootstrap current

j (r)

Profile of fusion

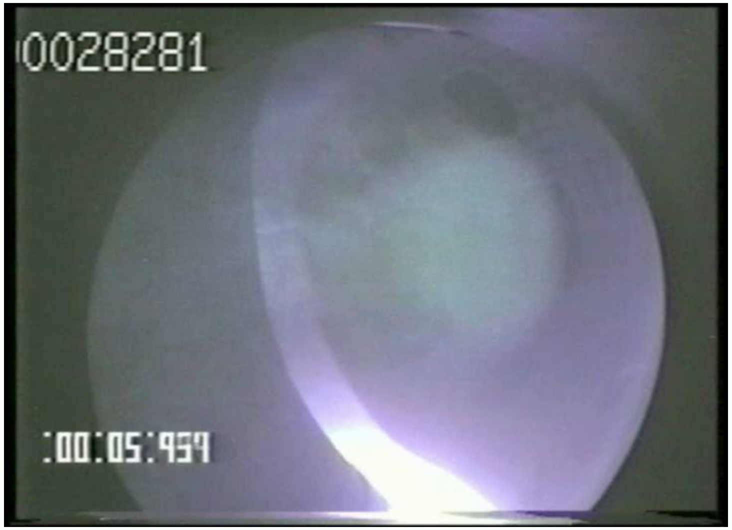
Plasma

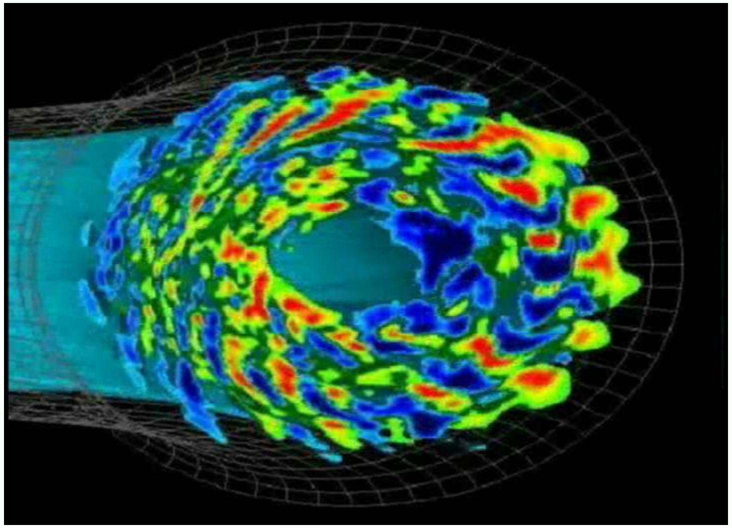
It is important to understand physics in highly self-organized plasma.

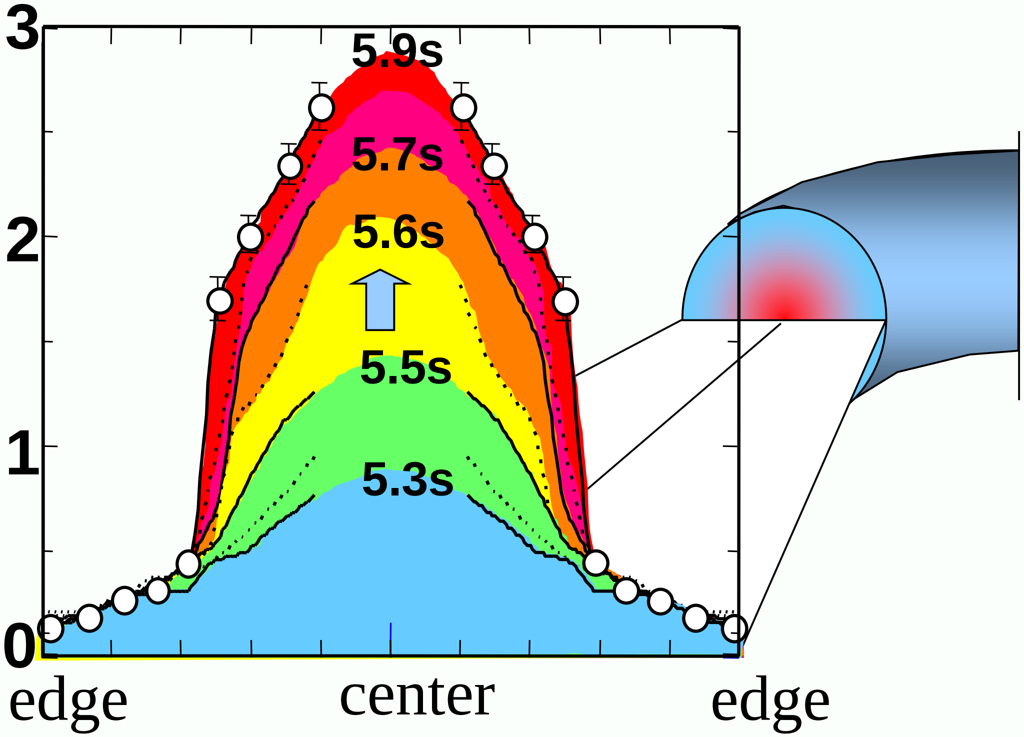
$$\frac{P_{alpha}}{P_{total}} \sim 1$$

$$\frac{I_{bootstrap}}{Ip} \sim 1$$

Discovery of Internal Transport barrier







Innovation of Thermal-Hydraulic Simulation

Remaining issues for the conventional thermal-hydraulic design method.

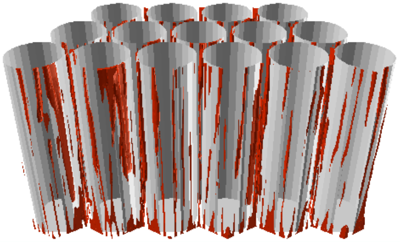
- Simple modeling of a complex thermal-hydraulic behavior in the blanket module based on the experimental correlations and numerical models.
- Data base of thermal-hydraulic properties in the blanket module.
- Large budget for preparation of the test facilities.

Upgrade
the Computer Performance

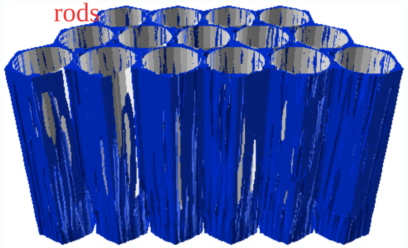
Application of the innovative thermal hydraulic Design Method.

- ●Development of simulation-oriented thermal-hydraulic design.
- ●Simulation of the complex thermal-hydraulic behaviors.
- ●Safety evaluation and optimization of the reactor. design only by computer simulation「Design by Analysis」.

An Example of two phase flow thermal-hyrdralic simulation for Fission reactor



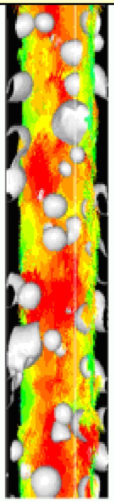
Mist Flow around the Fuel rods

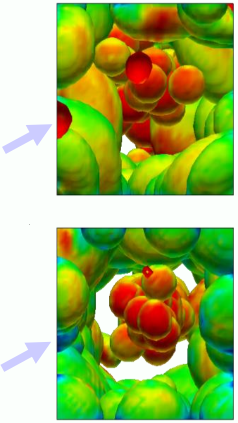


Liquid Flow around the Fuel rods

Macroscopic Analysis

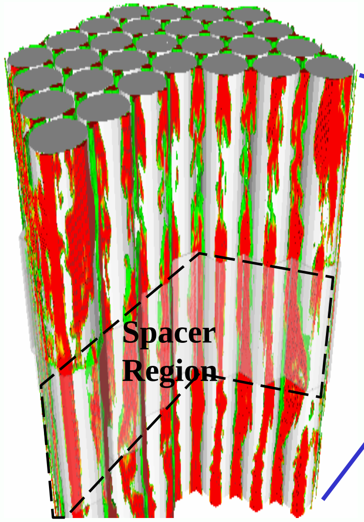
Past（VPP5000)





Holiz. closs-section

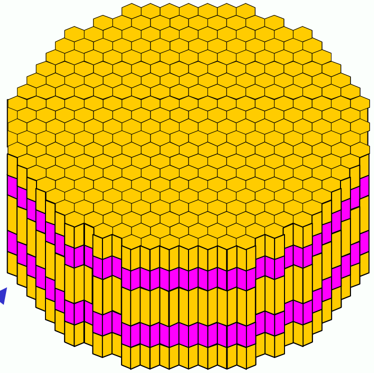
Behavior of Bubble formation around the fuel channel



Bubble behavior around the spacer

Microscopic Analysis

Current（Earth Simulator, JAEA Computer(Altix3900))



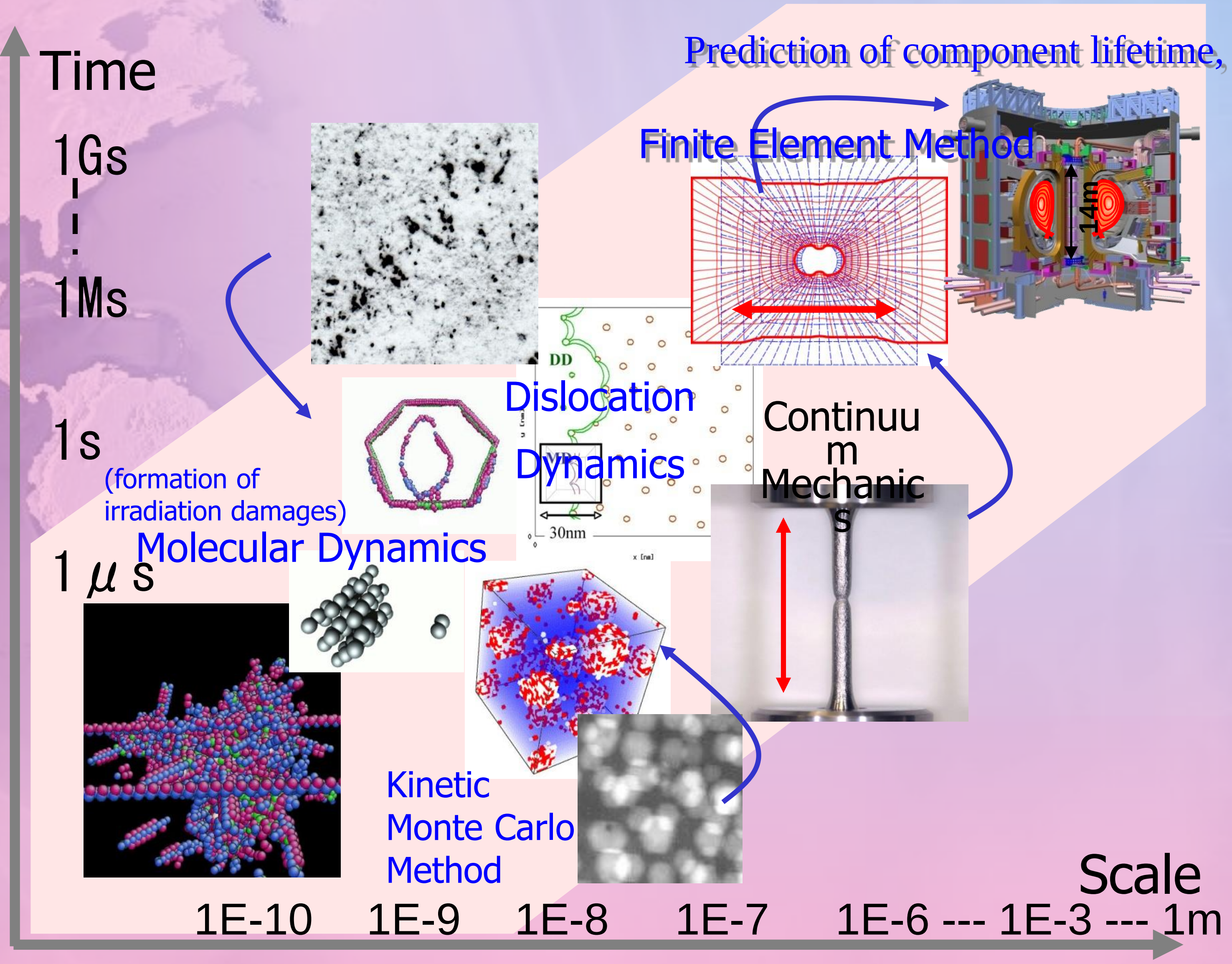
Thermal -hydraulic simulation of microscopic modeling

Prediction to the macroscopic and microscopic behaviors of the fluid.

Future（over 200TFlop/s)

Multi-Scale Simulation for Fusion Reactor Materials

Aim at establishing multi-scale modeling covered from the microscopic defect formation by the irradiation to the global mechanical properties.



Time

1Gs

1Ms

1s

1μs

(formation of irradiation damages)

Molecular Dynamics

Kinetic Monte Carlo Method

Dislocation Dynamics

Continuum Mechanics

Finite Element Method

Prediction of component lifetime, etc.

Scale

1E-10 1E-9 1E-8 1E-7 1E-6 --- 1E-3 --- 1m

Role of the Simulations

- Analysis of phenomena through modeling.
- Prediction of related phenomena.
- Comprehensive understanding to the background.
- Impact assessment of element research (to evaluate the “value” in the project).

Summary

ITER has been designed under international cooperation as a device based on knowledge and database obtained in present major tokamaks in the world, and also as a device that can be constructed by using proven technologies. This is a result of long-term international collaboration coordinated in a “proper” way.

For ITER and DEMO, a focused and wide research activities are required in more “proper way”. i.e. interactions among basic science and project. A “human-flow” among the research areas may be a useful and powerful way.