

Current Status of Discussion on Roadmap of Fusion Energy Research and Development in Japan

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Acknowledgement

A.Komori (NIFS) Y.Kamada (JAEA), K.Itoh (NIFS),
M.Enoeda(JAEA), S.Konishi (Kyoto Univ.),

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MFE Roadmapping in the ITER Era
Princeton, 7-10 Sep., 2011

Three major critical issues

1. Society's observation of fusion has dramatically changed since the accident of the Fukushima Dai-ichi nuclear power station
2. Current Japanese policy requires a *certain* economical feasibility in DEMO
3. Definition of DEMO is critical for decision
 - ← What is the role of the first DEMO in Japan ?

Structure of decision making and execution

Cabinet Office

Council for Science Technology Policy (CSTP)

Science and Technology Basic Plan (every 5 year)

Japan Atomic Energy Commission (JAEC)

Promotion plan of fusion R&D issued in 2005

Ministry of Education, Culture, Sports, Science and Technology (MEXT)

Council for Science and Technology

- Working Group for Fusion Research

Japan Atomic
Energy Agency
(JAEA)

National Institute
for Fusion Science
(NIFS)

Universities

programmatic approach
under governmental decision

academic approach
integration of bottom-up commitment
from universities

4th Science and Technology Basic Plan 2011-2015 by CSTP

✓ Original document before the Fukushima Dai-ichi accident

Exploration of ocean, telecommunication, space transportation and satellite, new energy, ~~atomic energy of fast breeder reactor and fusion~~, high-performance computing, global positioning system, information security should be promoted from the aspect of national security and fundamental national technology

✓ Revised document after the Fukushima Dai-ichi accident

R&D for safety, prevention of disaster, proliferation and nuclear security of atomic energy should be greatly reinforced.

R&D of technology for atomic energy such as a fast breeder reactor should be conducted in line with the energy policy and the atomic energy policy.

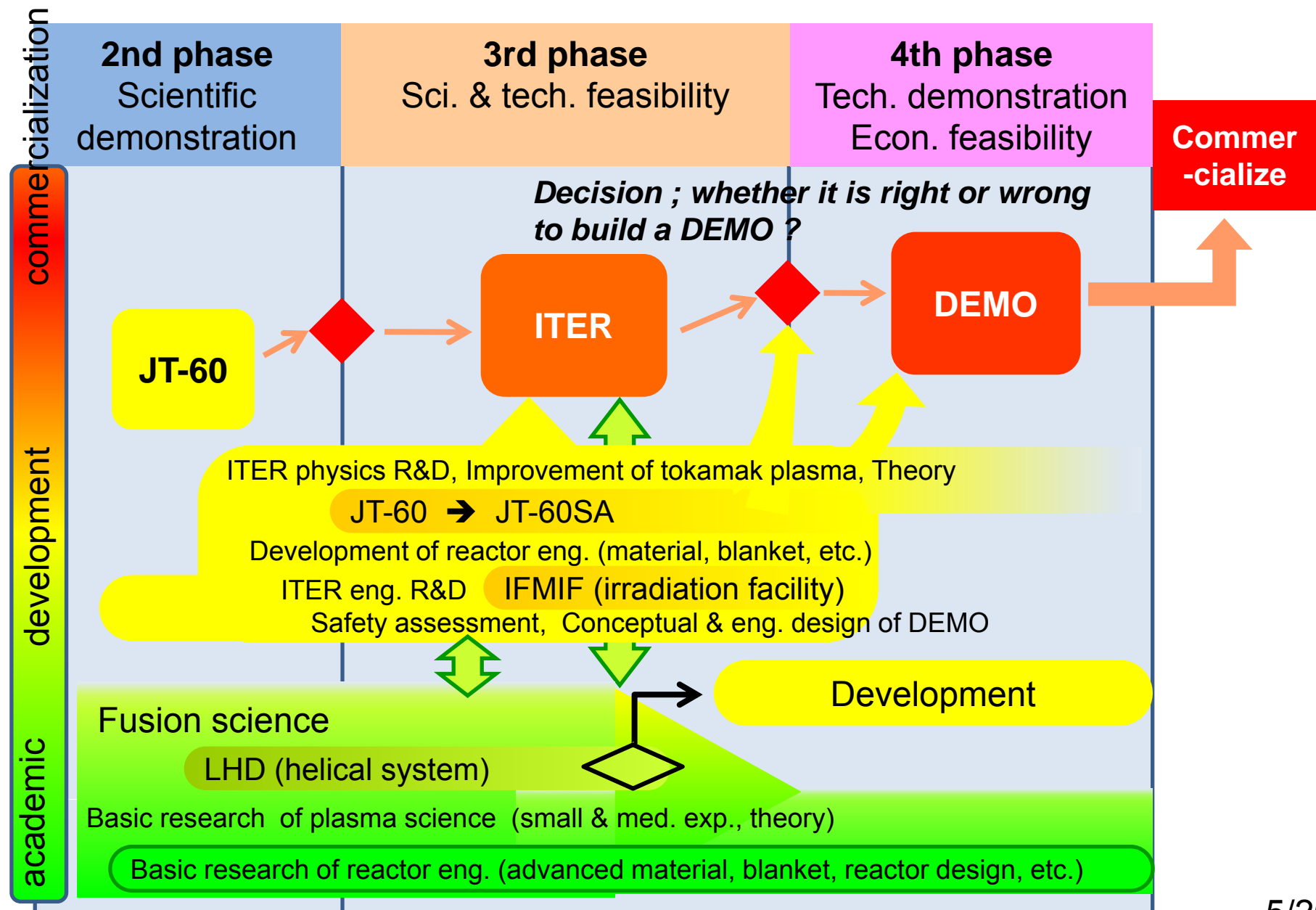
R&D of fusion should be promoted with attention to consistency with the energy policy and the atomic energy policy, at the same time, its characteristics and the status of R&D.

“Safety” becomes a much more important key-word than before

Discussion on “Assessment of fusion energy” has been just launched in the Japan Society of Plasma and Fusion Research

Roadmap of Fusion Development

in Promotion Plan of Fusion R&D by JAEC issued in 2005



Requirements for DEMO, whatever form is chosen

in Promotion Plan of Fusion R&D by JAEC issued in 2005

1. Demonstrate power generation by technology which can be used in practical implementation
2. Incorporate the projection of a *certain* economical feasibility for practical implementation

Points in Check & Review in Fusion R&D 1.

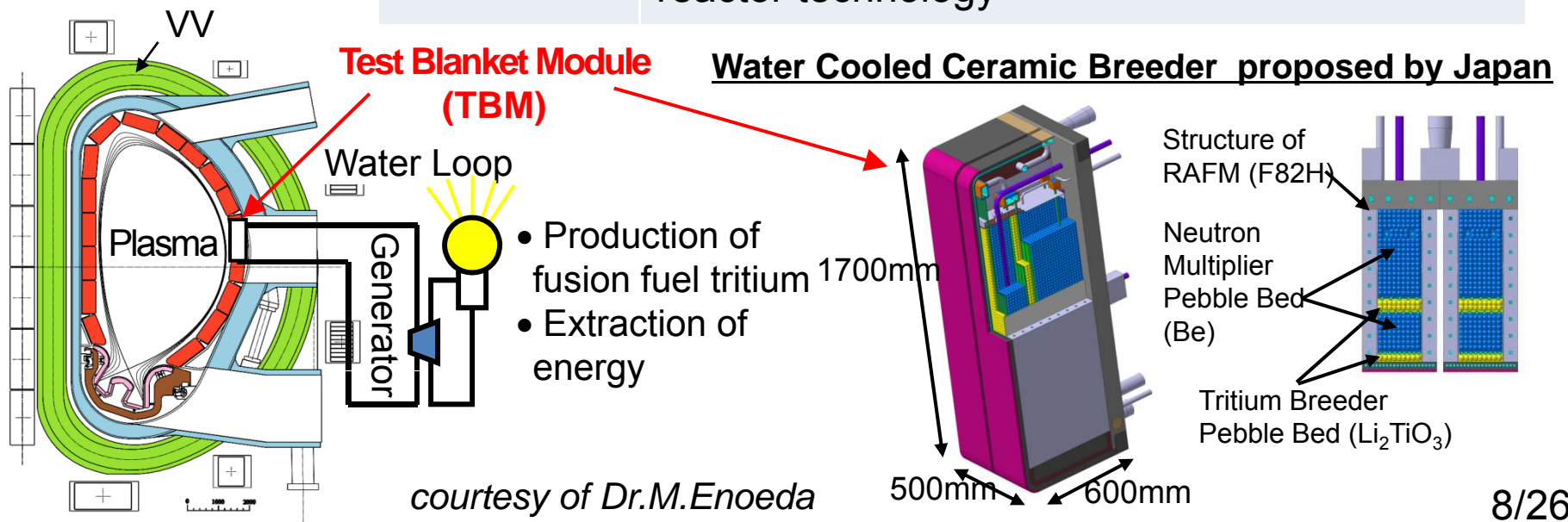
in Promotion Plan of Fusion R&D by JAEC issued in 2005

Issues	Criterion in decision to the 4th phase
1. Demonstration of burning control under the self-heating	<ul style="list-style-type: none">• Demonstration of $Q \geq 20$ for several 100 seconds and burning control in ITER
2. Demonstration of non-inductive steady state operation with $Q \geq 5$	<ul style="list-style-type: none">• Demonstration of non-inductive current-driven plasma with $Q \geq 5$ for $\geq 1,000$ seconds in ITER
3. Establishment of integrated technology	<ul style="list-style-type: none">• Establishment of integrated technology through operation and maintenance of ITER, and confirmation of safety technology
4. Establishment of high-beta steady-state operation to make a projection of economical feasibility	<ul style="list-style-type: none">• Achievement of steady-state operation with high-beta collisionless plasma ($\beta_n = 3.5-5.5$) in JT-60 SA and so on.

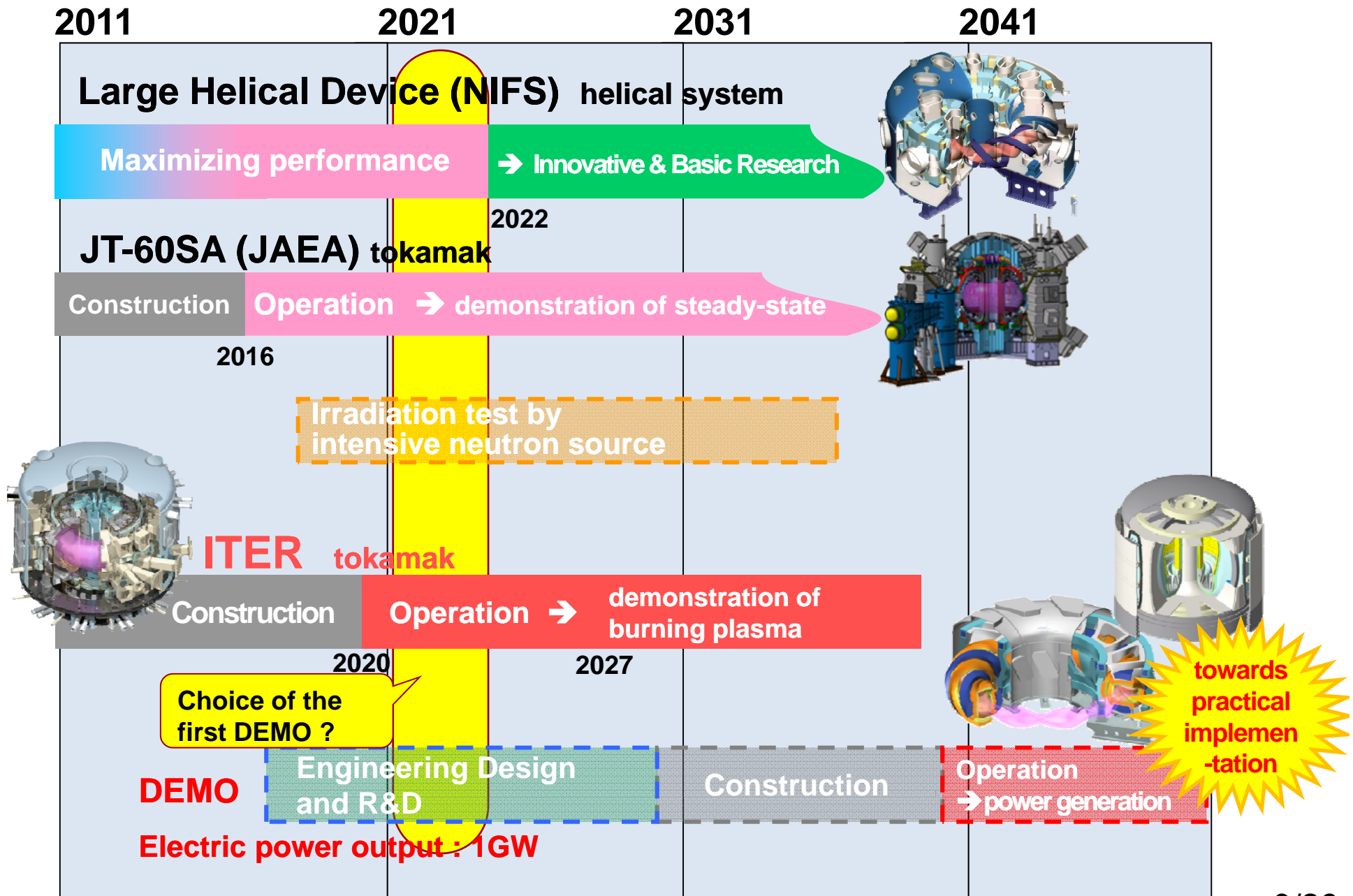
Points in Check & Review in Fusion R&D 2.

in Promotion Plan of Fusion R&D by JAEC issued in 2005

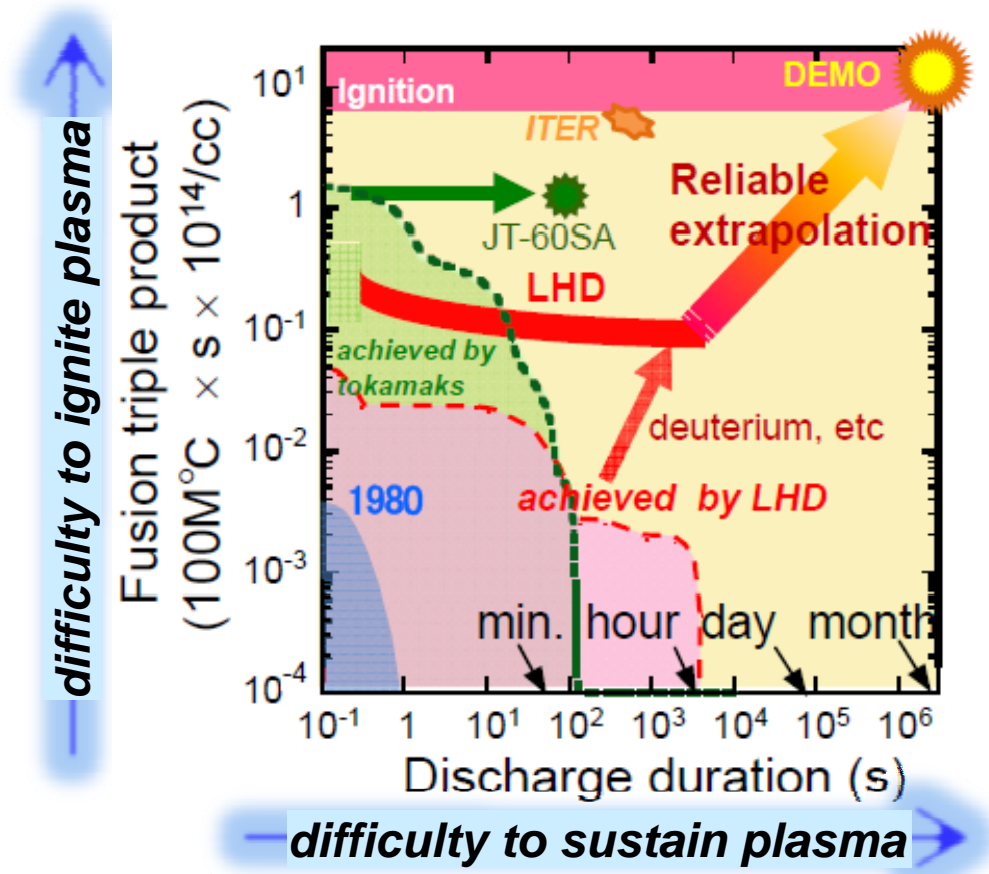
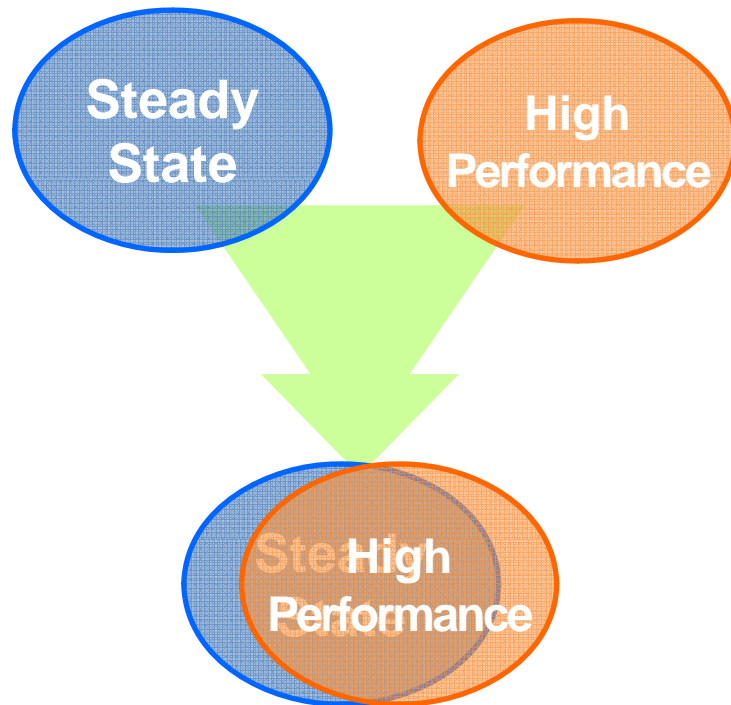
Issues	Criterion in decision to the 4th phase
5. R&D of material and reactor technology for DEMO	<ul style="list-style-type: none"> • Demonstration of breeding and retrieval of tritium, heat removal, power generation of blanket in DT experiment in ITER • Completion of validation of irradiation data for low-activation ferritic steel up to 80 dpa
6. Conceptual design of DEMO	<ul style="list-style-type: none"> • Completion of conceptual design of DEMO consistent with developed fusion plasma and reactor technology



Towards Realization of Fusion Energy by Magnetic Confinement



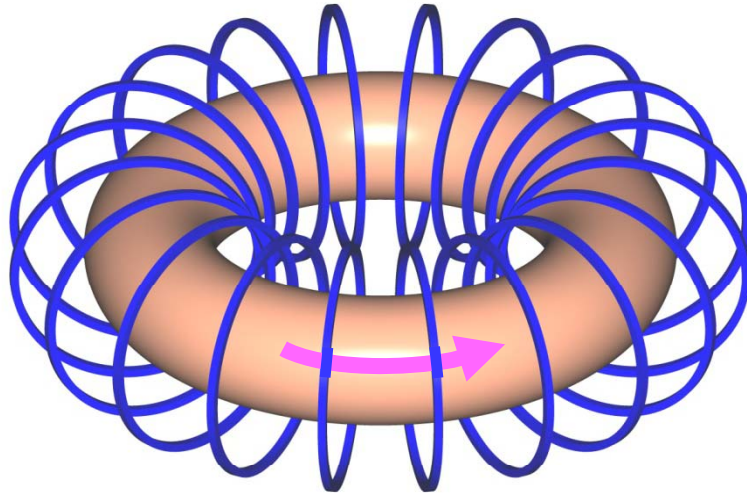
Strategic Convergence and Development of Fusion Experiments



- Keys for early realization of DEMO**
- (1) Demonstration and control of burning plasma → **ITER**
 - (2) Steady state operation
 - **JT-60SA** : non-inductive current drive at high β with minimizing circulation power
 - **LHD** : high performance plasma to convince us of burning

Magnetic Confinement Fusion

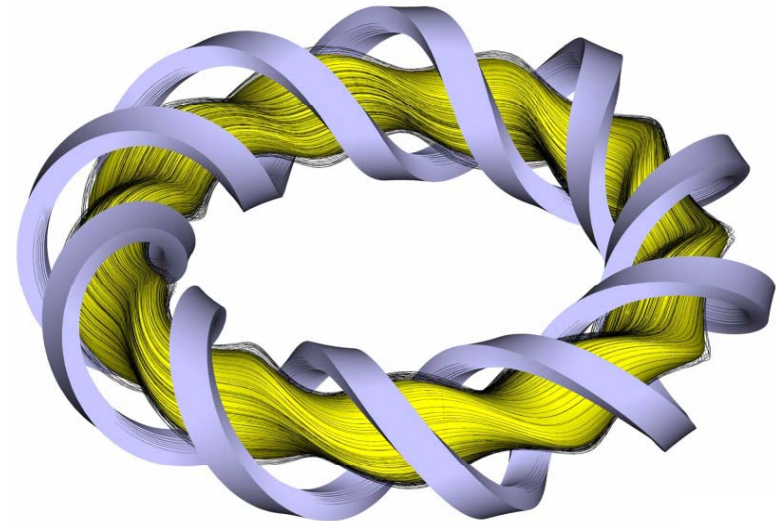
Tokamak



Plasma current > 10 million amperes

Approximately 2-D, Transient
Devices: ITER, JT-60SA, etc..

Helical system



Plasma current = 0

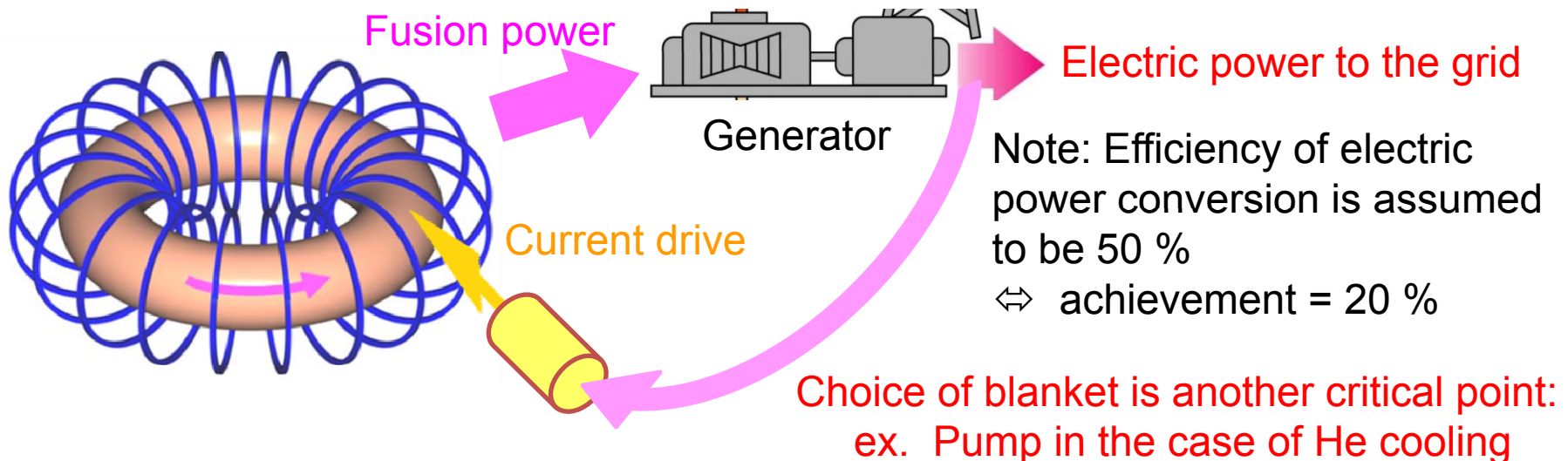
Intrinsically 3-D, Steady-state
Devices: LHD, W7-X(Germany) , NCSX

Share large commonality as well as contrast

- ➔ accelerate establishment of scientific basement for rational decision of DEMO in slightly over a decade

Reduction of circulating power is critical

	Japan	EU	
Reactor design	Slim-CS <i>(innovative)</i>	PPCS-A <i>(conventional)</i>	PPCS-D <i>(innovative)</i>
Plasma current	17 MA	31 MA	14 MA
Fraction of self-generated current	75 %	45 %	76 %
Generated electric power	1.2 GW	2.1 GW	1.1 GW
Electric power required for current drive	0.14 GW	0.93 GW	0.15 GW
Circulating power	tolerable	large	tolerable

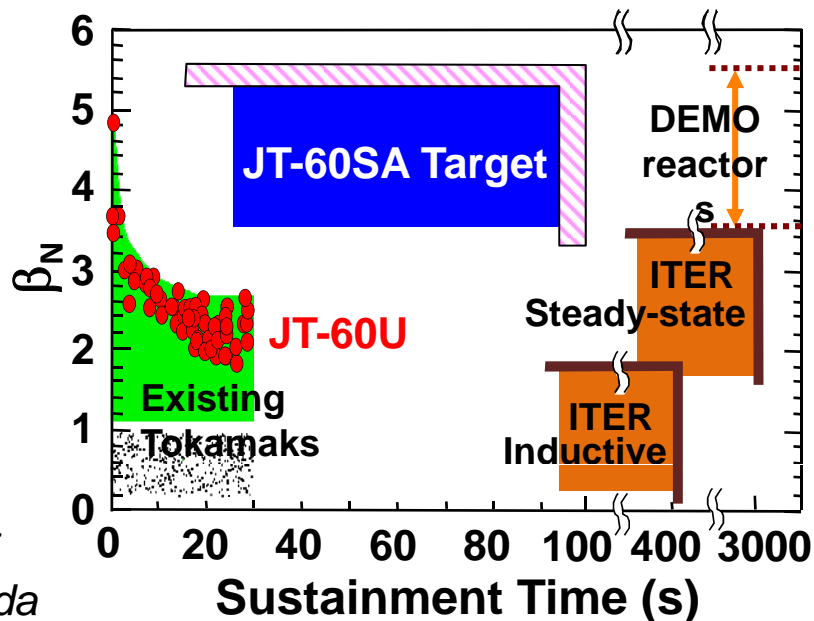


JT-60SA Project

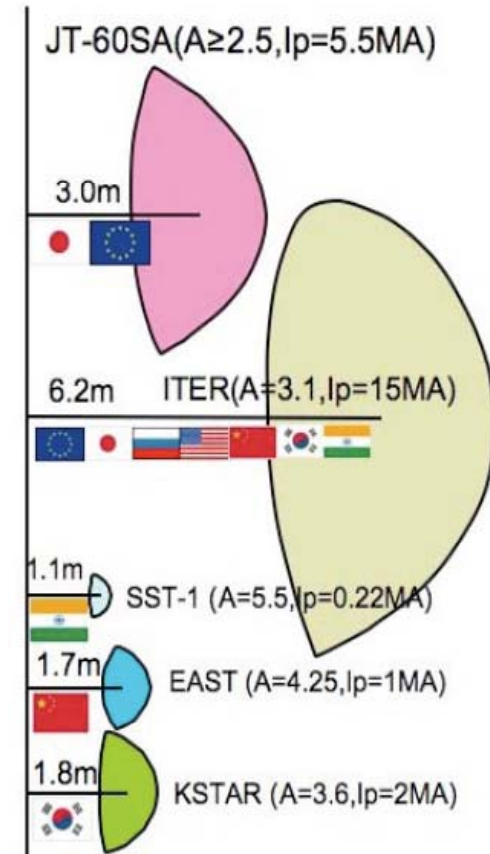


- ✓ Conducted under the BA Satellite Tokamak Programme by EU and Japan, and the Japanese National Programme.
- ✓ Project missions
 - Support exploitation of ITER
 - Complement ITER with resolving key physics and engineering issues for DEMO reactors.

A fully superconducting, highly shaped tokamak capable of confining break-even equivalent class deuterium plasmas lasting for a duration (typically 100s) longer than the timescales characterizing the key plasma processes with high heating power 41MW.



courtesy of
Dr.Y.Kamada



JT-60SA should pursue full non-inductive steady-state operations with high β_N ($>$ no-wall ideal MHD stability limits).

JT-60SA device has been designed in order to satisfy the central research needs for ITER and DEMO

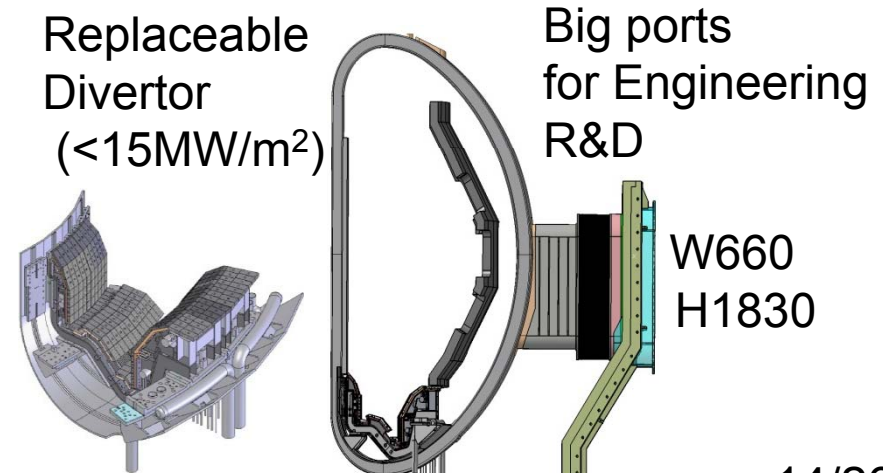
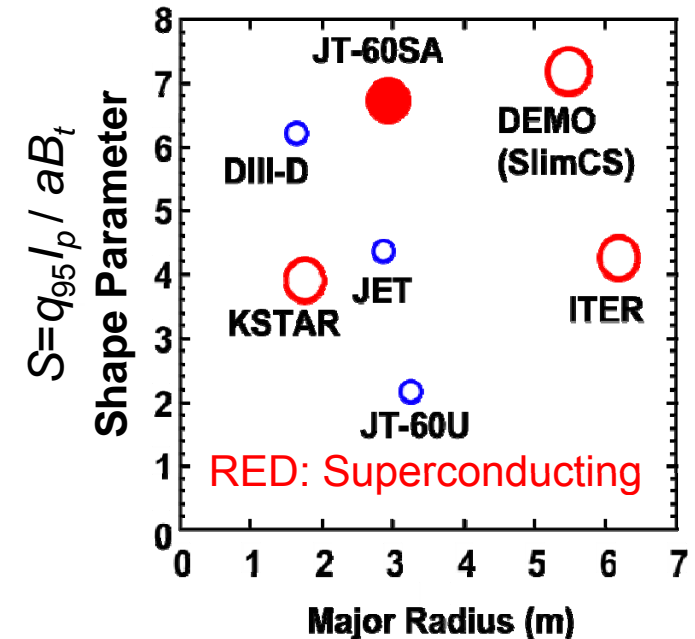


for ITER

- H-mode / Pedestal / ELM (incl. RMP, pellet, ...)
- Local Ripple & TBM Test
- Wall Heat Load
- Disruption & mitigation etc.
 - (database, control tech. : Intensive Gas puff)
- Integrated control
 - (operation scenarios, plasma actuators, diagnostics ...)

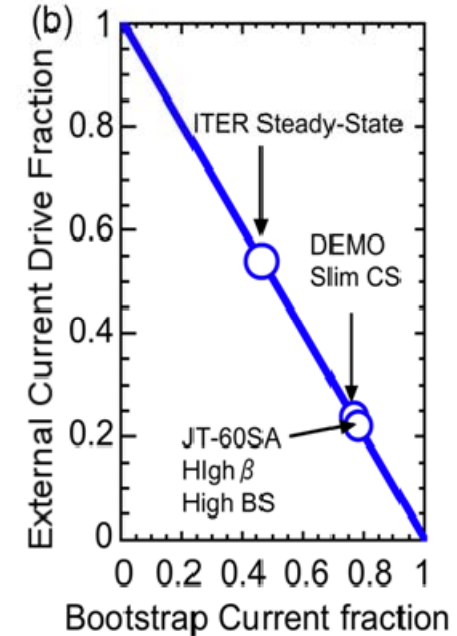
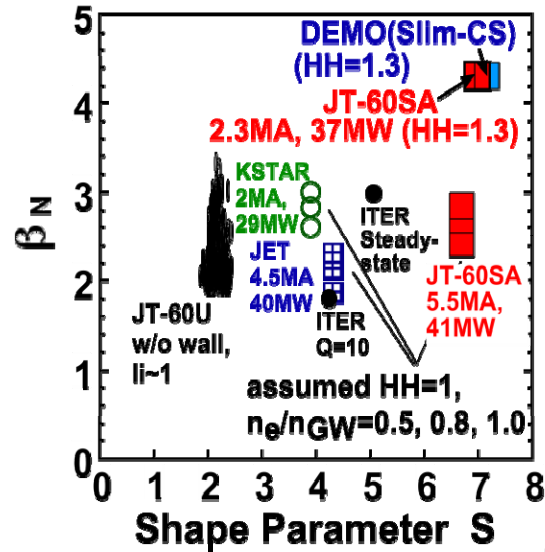
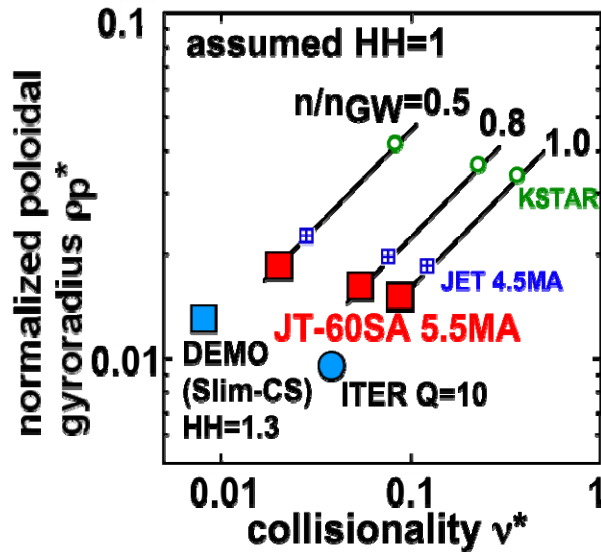
for DEMO

- High beta high bootstrap steady-state
- Requirements for CS
- Heat & particle controllability in steady-state
- Control of Highly self-regulating plasmas
- Needs for DEMO commissioning
- Divertor concept tests
- Blanket, first wall material tests
- etc.



JT-60SA Plasma Regimes for ITER & DEMO

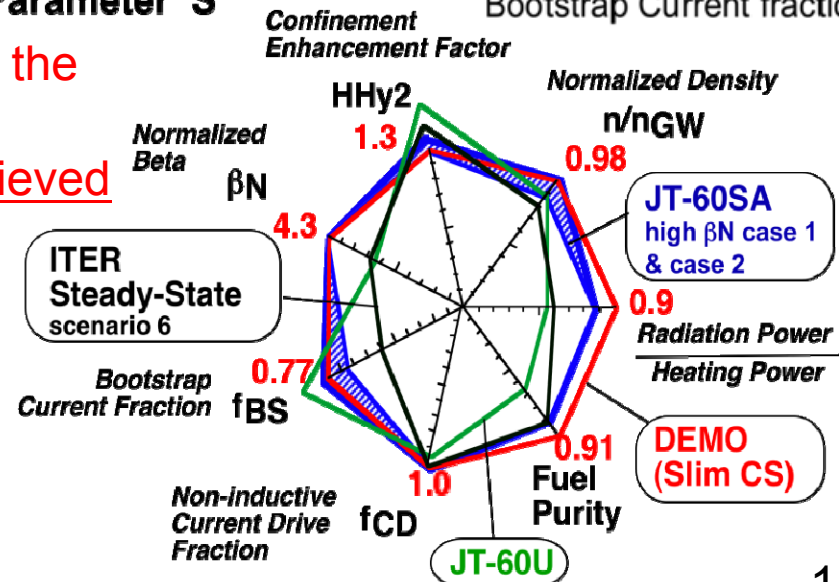
ITER & DEMO-relevant Regimes :
Non-dimensional Parameters & Integrated Performance



'Simultaneous & steady-state sustainment of the key performances required for DEMO' (= highly self regulating) has never been achieved → the goal of JT-60SA.

Decide the practically acceptable DEMO parameters (phys. & engineering).
Develop & demonstrate a practical set of DEMO plasma controls.

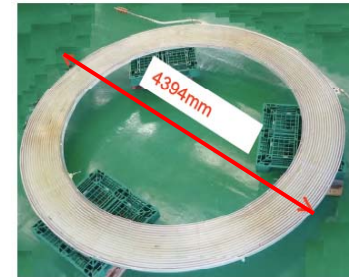
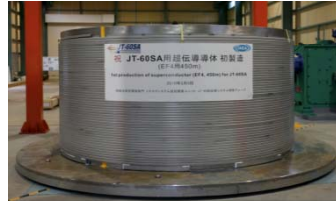
courtesy of Dr. Y. Kamada



JT-60SA: Status of Procurements



By 2011 July, 15 Procurement Arrangements (PAs) have been concluded (JA: 8PAs, EU: 7PAs) = 70% of the total cost of BA Satellite Tokamak Program.



PF Coil Manufacture Building & PF Conductor Manufacture Building

SC Conductor with length of 500 m for EF Coil

Superconductor double pancakes for EF

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Construction											
Operation		Preparation	Disassembly	Assembly						Experiment	



Material for V.V.



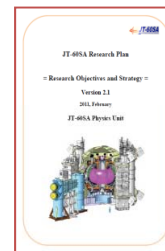
Prototype of VV and welding test



Trial production of VV outboard 20 deg



Building for Vacuum vessel sector assembly



JT-60SA Research Plan V2.1



The first VV 40 degree sector

Commissioning

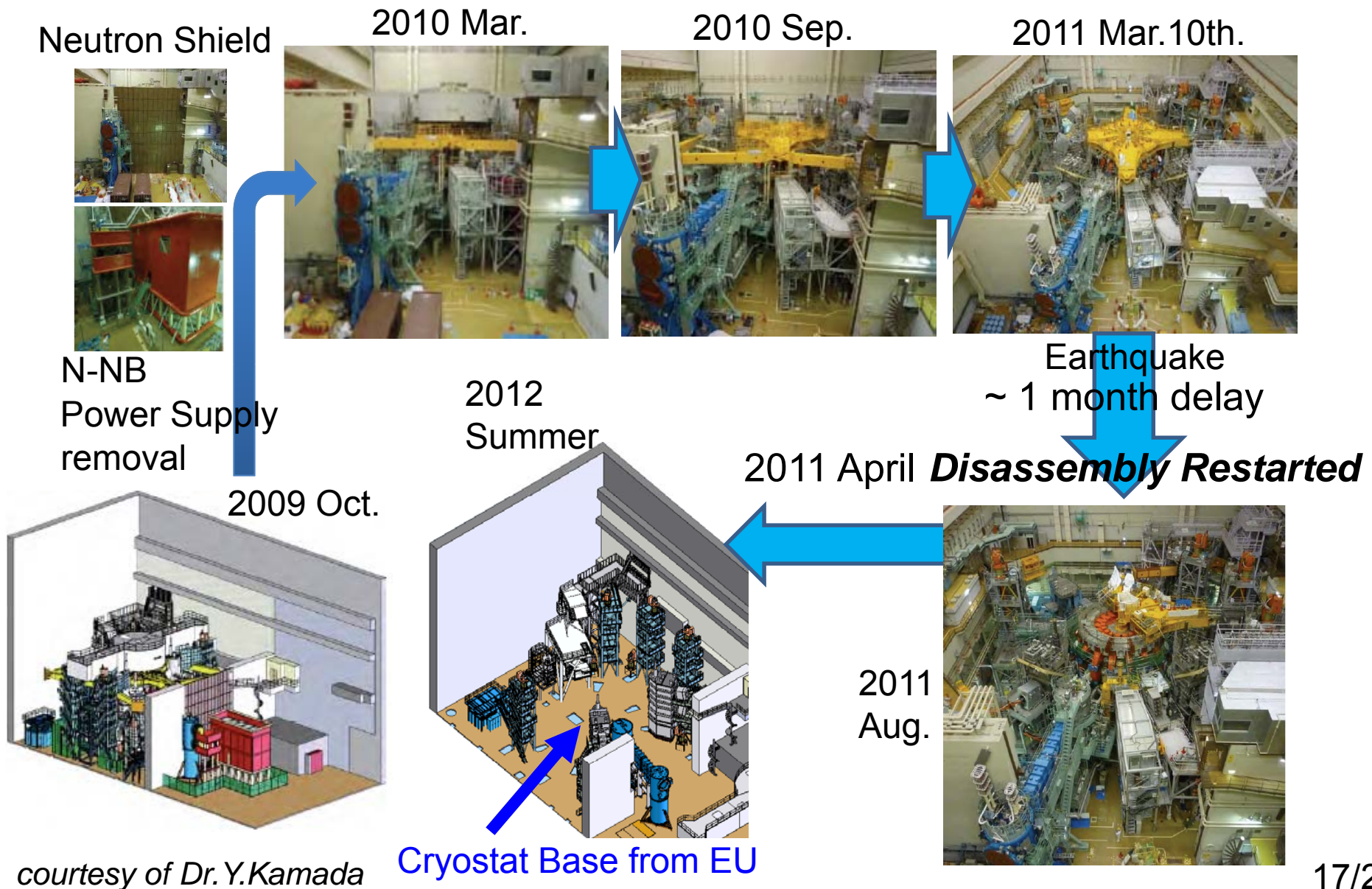
Integrated Test

courtesy of Dr. Y.Kamada

JT-60 Torus Disassembly

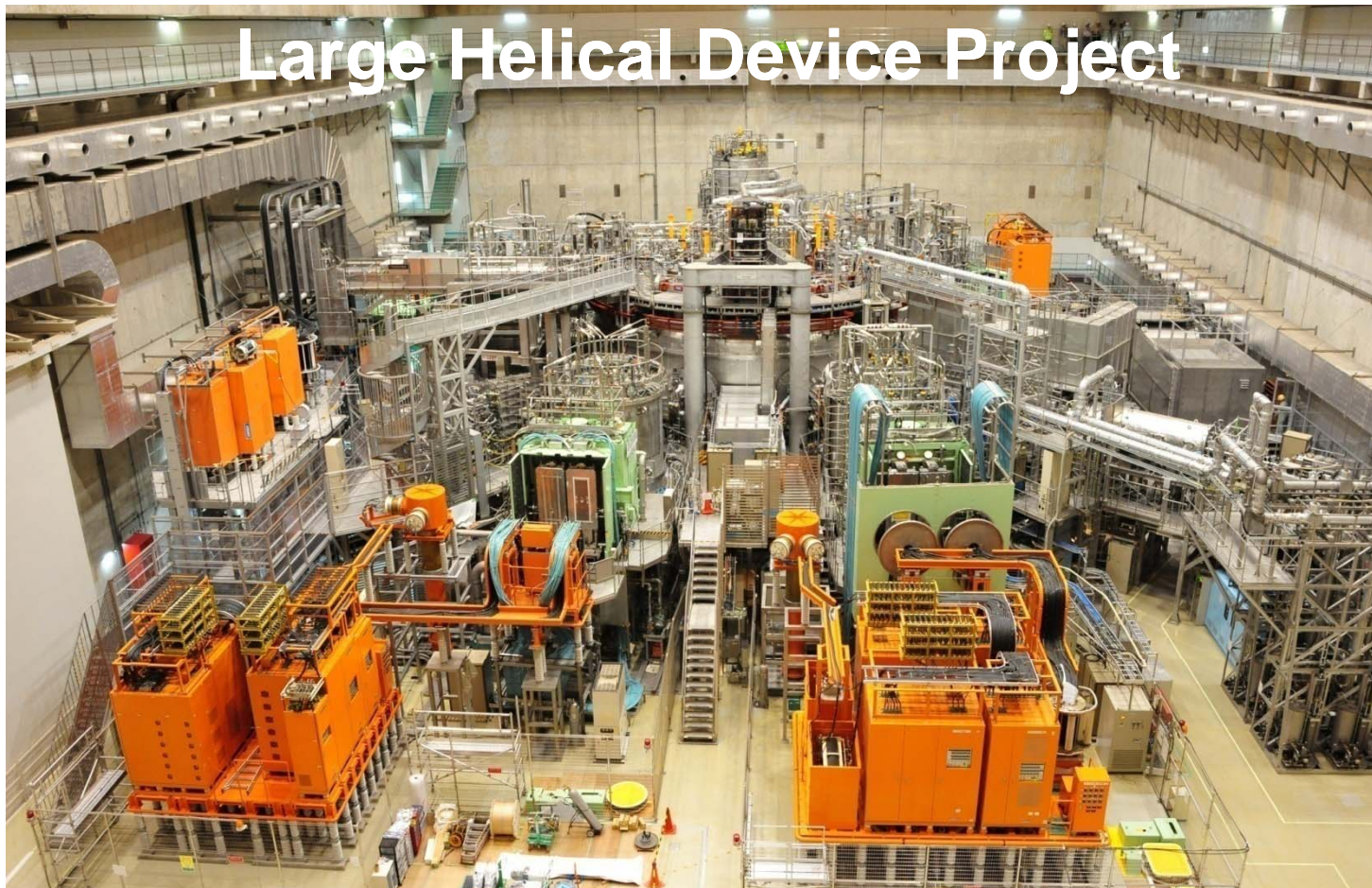


The first experience of disassembly of radio-activated large fusion device in Japan



courtesy of Dr. Y. Kamada

Cryostat Base from EU



Large Helical Device Project

- The world largest helical system
- Intrinsic advantage and engineering capability of steady-state operation
- Complementary/alternative role to tokamak approach

The goal of the LHD project

- ✓ Establish scientific basement for a helical DEMO reactor
- ✓ Comprehend physics of toroidal plasmas



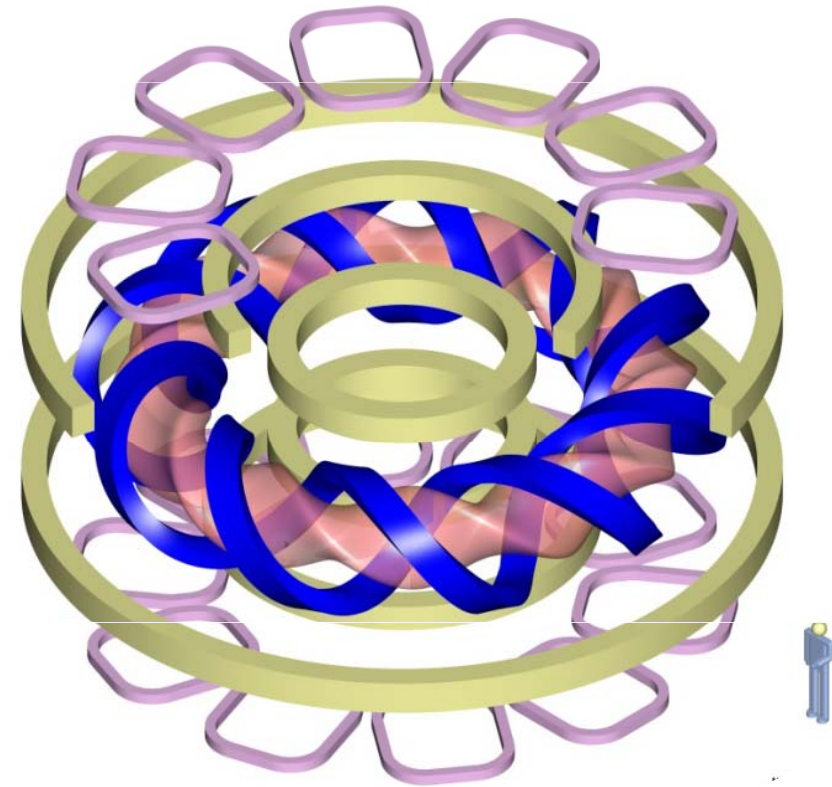
LHD has worked very well for 13 years

✓ **Operation for 13 years**

→ engineering base of a large-scale superconducting and cryogenic system for fusion reactor development

Heating capability		
NBI	29	MW
ECH	3.5	MW
ICH	2	MW

< LHD basic dimension >	
• Outer diameter	13.5 m
• Cold mass	820 ton
• Total weight	1500 ton
• Magnetic field	3 T
• Magnetic energy	0.77 GJ
Several-month-long operation, 14 times since 1998	
• Operational time of He compressor	: 65,000 hours
	→ Duty = 99.1 %
• Coil excitation number	: 1,400 times
• Plasma discharges	: 107,000 shots



A large number of opportunities for diversified collaboration on physics



Progress of plasma parameters is very encouraging

Long pulse : >1keV plasma for 1 hour

High beta : $\beta = \frac{\text{plasma kinetic pressure}}{\text{pressure of magnetic field}}$

$\langle\beta\rangle = 5.1\%$ at $B = 0.425\text{ T}$
 $\langle\beta\rangle \approx 5\%$ is maintained
for > 100 energy confinement time τ_E

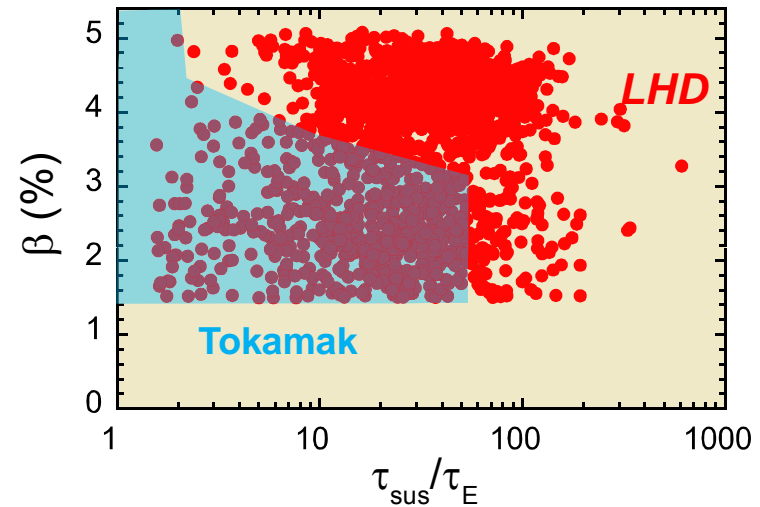
High density

$n_e(0) = 1.2 \times 10^{21} \text{ m}^{-3}$
1.5 atmospheric pressure at $B = 2.5\text{ T}$
→ an innovative concept of
ignition at $T(0) = 6\text{-}7\text{ keV}$

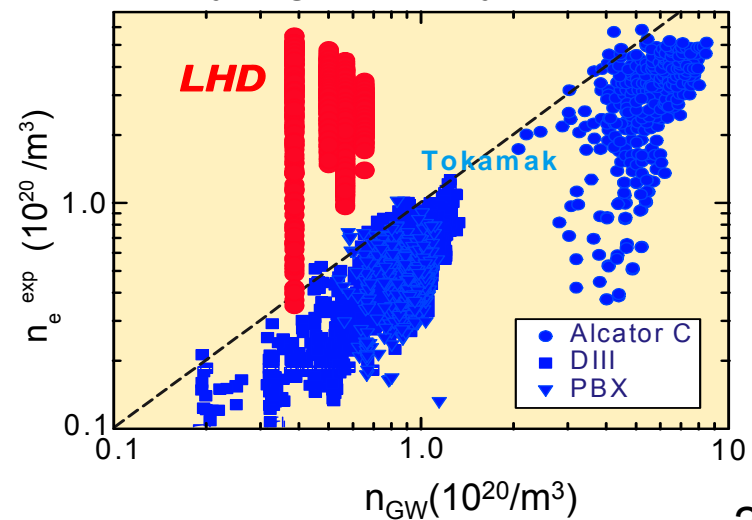
High ion temperature

$T_i = 6.4\text{ keV}$ at $n_e = 1.6 \times 10^{19} \text{ m}^{-3}$
accompanied phenomena to expel
impurities

Quasi-steady state high beta



Very high density operation





Machine capability is planned to be maximized in a coming few years

1. Upgrade of heating power
2. Closed helical divertor
3. Deuterium experiment

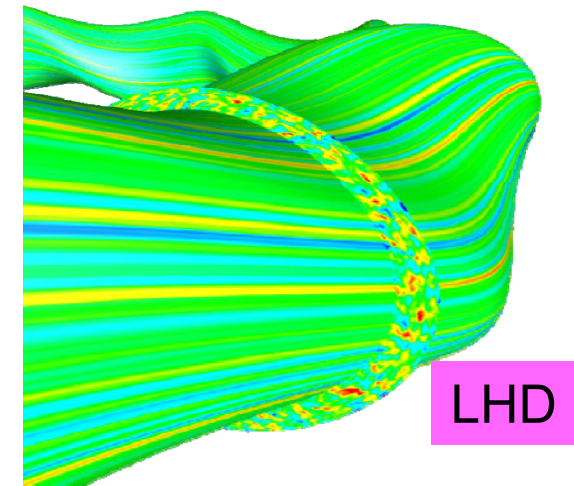
CY		2011	2012	2013	2014
JFY		2011	2012	2013	2014
Exp. Camp.		15th	16th	17th	18th
NBI	Tangential	16 MW	←		
	Perpendicular	13 MW	←	→18 MW	
ECH	Max	3.5MW	4.5MW	6 MW	
	CW	0.5MW	0.8MW	1 MW	
ICH	Max	2 MW	3 MW	6 MW	
	CW	1 MW	1.5 MW	3 MW	
Divertor	Baffle & Dome	2/10	8/10	→10/10	
	Cryo-pump	0/10	6/10	→10/10	

How can we approach comprehensive understanding ?

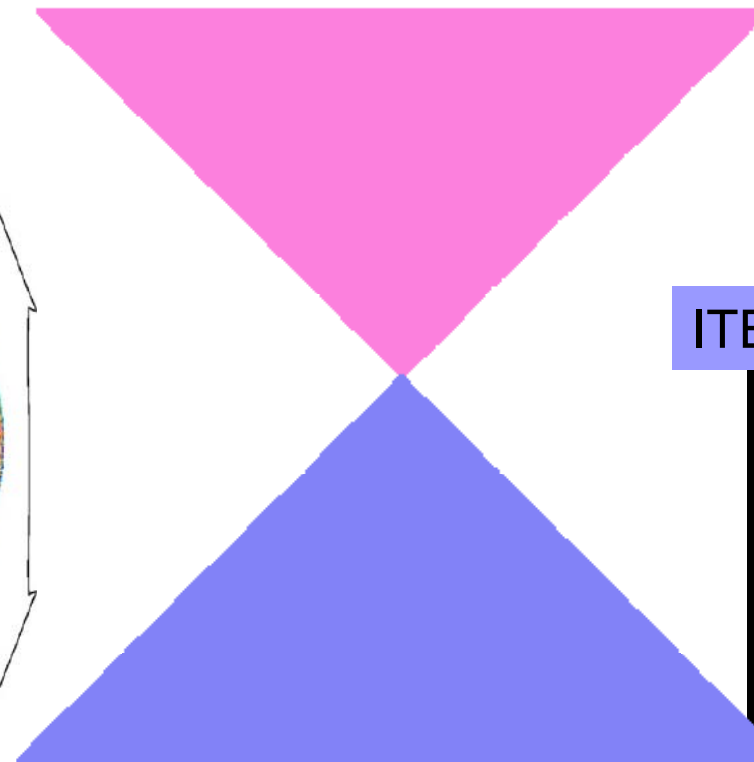
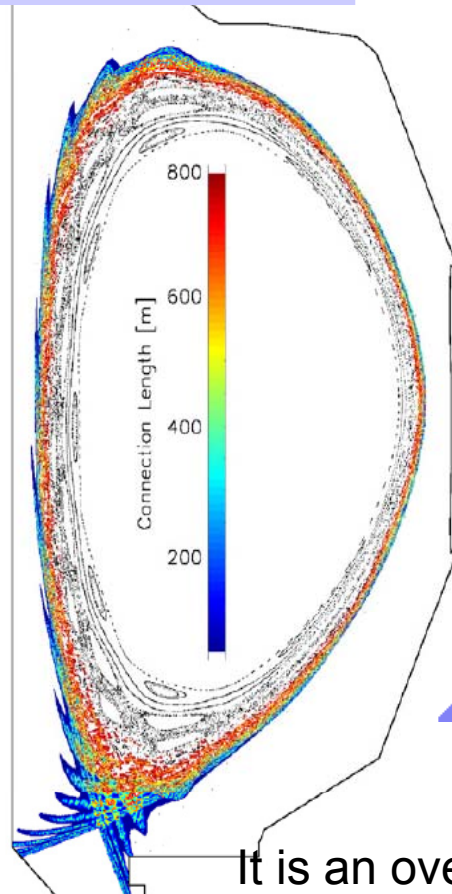
2-D and 3-D are not in a binary opposition !

3-D effect, which dissolves in 2-D, appears as the outcome when the constraints due to 2-D degeneracy are lifted.

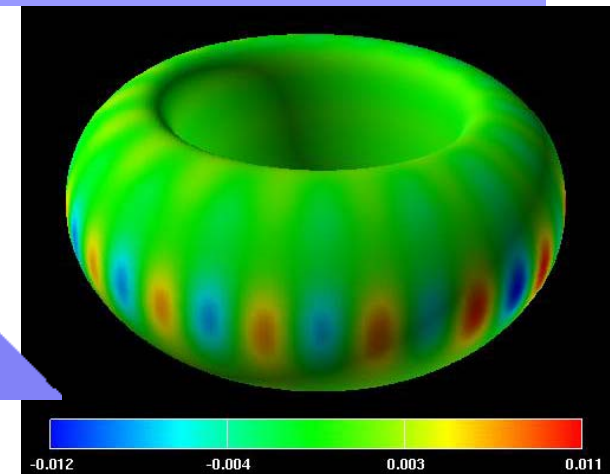
3-D physics



DIII-D with RMP



ITER with TF and TBM

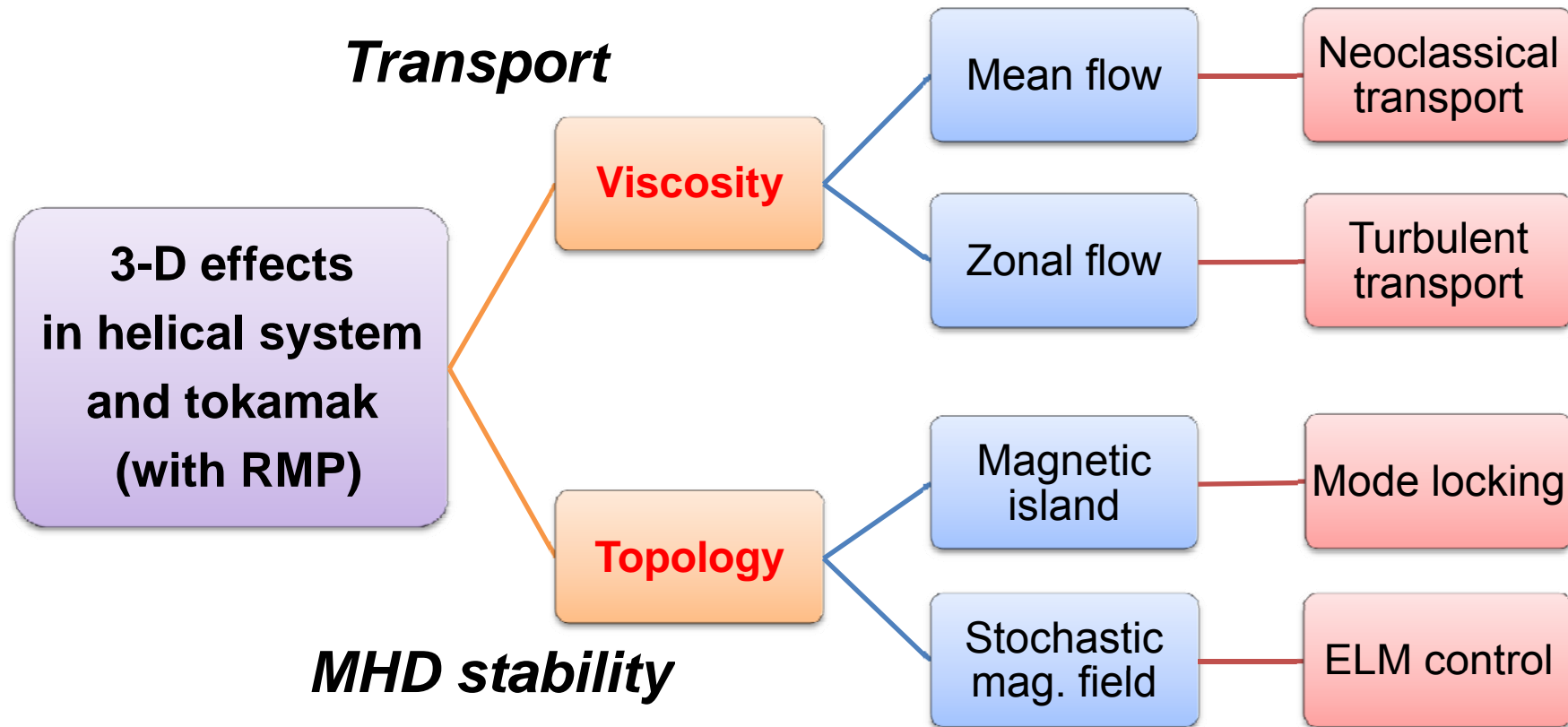


2-D physics

It is an over simplified approach to assume that 3-D effects are complexity specific to 3-D machines and 3-D magnetic fields.



3-D Effects in Toroidal Plasma



3-D equilibrium and transport are determined self-consistently



Fusion Eng. Research Project has started towards steady-state helical DEMO reactor

2011

2016

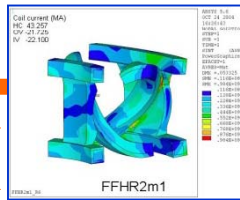
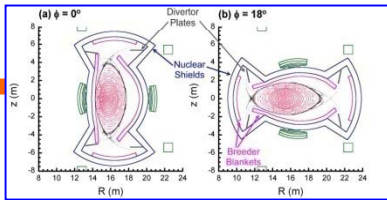
2022

2027

2036FY

Step by step advancement of reactor design

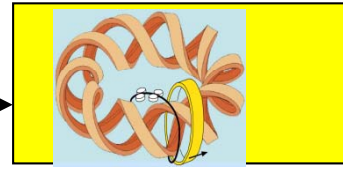
Conceptual design → Basic design → Improved basic design



Establishment of engineering base

Full-scale, full-condition testing

Large-scale high-field superconducting magnet



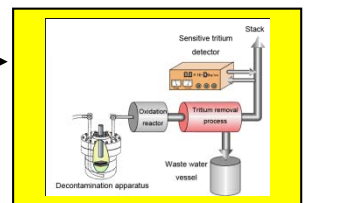
Long-life liquid blanket



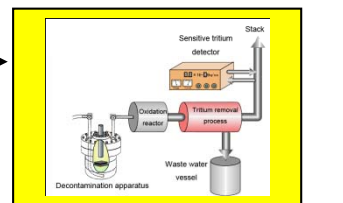
Low activation structural materials



High heat flux plasma facing wall



Tritium control



Engineering design

Construction
Licensing

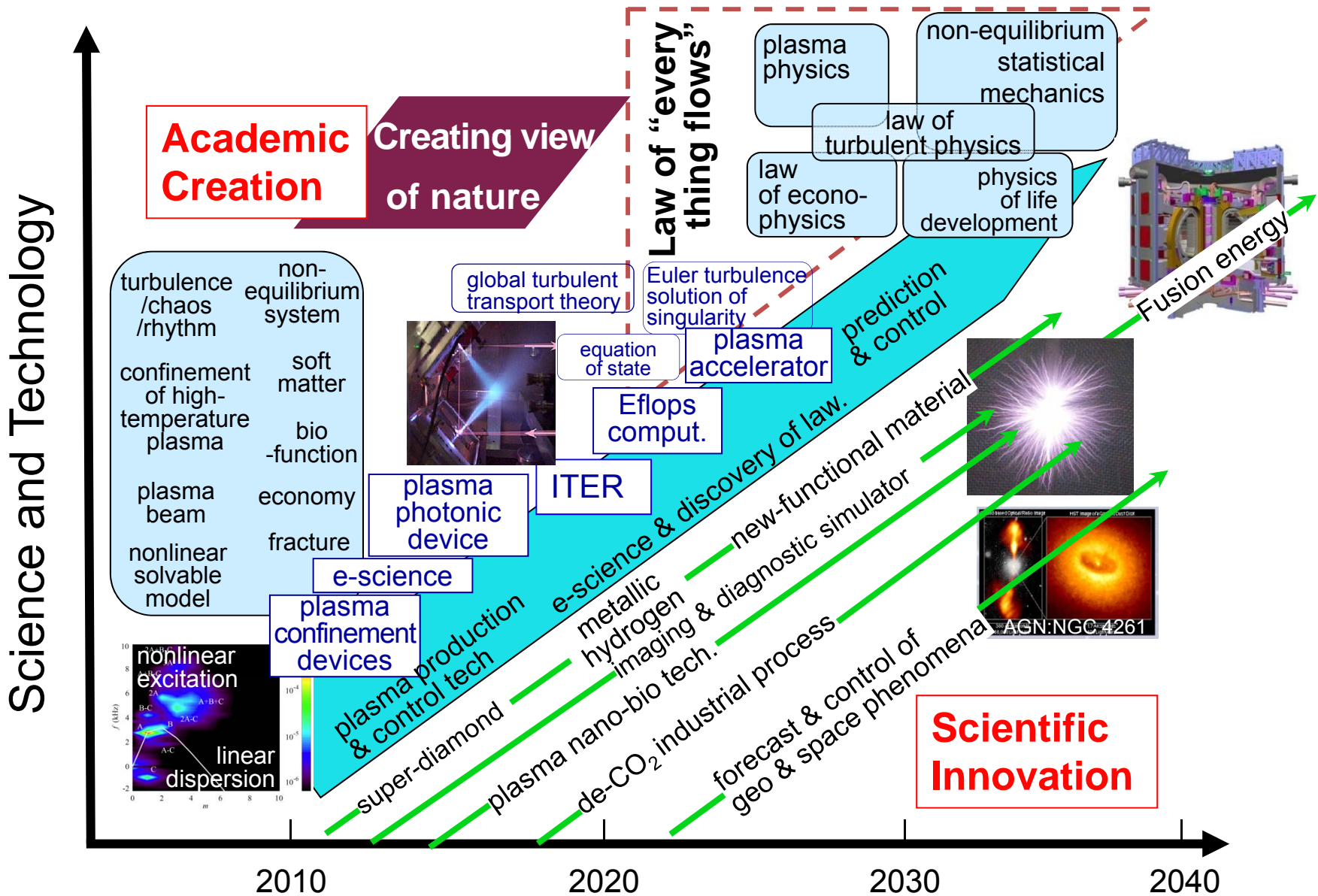
Operation

With universities

Based on "Scientific Road Map" (by Section III, Science Council of Japan)

Physics of plasmas/non-equilibrium system

Ta Panta rhei (everything flows): Thorough investigation of dynamism and turbulence



courtesy of Prof. S.-I.Itoh, and Prof. K.Itoh

Approaches to resolve major critical issues

- 1. Society's observation of fusion has dramatically changed since the Fukushima Dai-ichi accident*
→ Assessment of **safety**, efforts to get **support from society** and **self-definition** should be emphasized and accelerated much more than before.
- 2. Current Japanese policy requires a certain economical feasibility in DEMO*
→ Demonstration of steady-state high-performance plasma relevant to DEMO by LHD and JT-60SA
- 3. Definition of DEMO is critical for decision*
← What is the role of DEMO ?
ITER, ..., DEMO -2, DEMO -1, DEMO ±0, DEMO + 1, ...
→ Stimulate intensive discussions on multiple levels with outcome of this WS