Industrial Production of Fusion Energy will be the Next Step

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- **ITER – the fastest way to burning plasma study**
- **ITER objectives**
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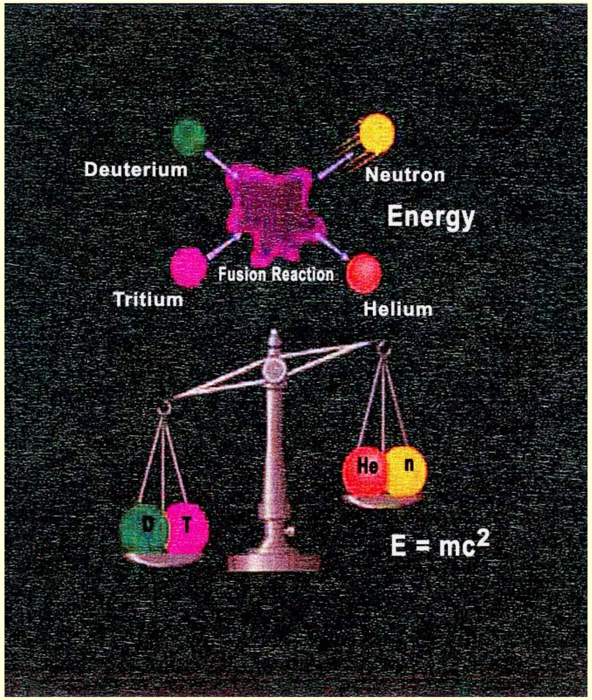
ITER – the fastest way to burning plasma study

Fusion Reaction

Deuterium and Tritium fuse at high energy (10 keV), producing Helium and an energetic (14 MeV) neutron

Mass is converted to energy according to Einstein's formula



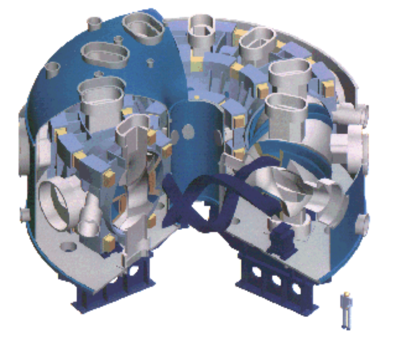
Construction in the Nearest Future of the First Experimental Thermonuclear Reactor will Give the Fusion a Vote of Confidence

- The future fusion energy can be based on different types of reactors with magnetic and inertial confinement
- Physical and experimental data base for tokamak and ITER design are sufficient for construction of the first experimental reactor
- The project is unique for its high probability of reaching the designed objectives
- The expected physical and engineering results are of high value for almost all candidate types of fusion reactors
- ITER is an illustration of advantages of international cooperation for resolving global issues

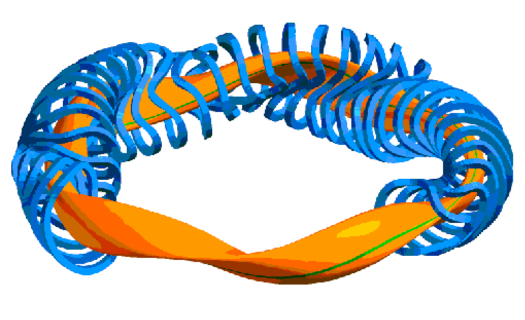
Controlled Fusion
is a Long-term, Inherently Safe, Ecologically Attractive Energy Source of the Future

- Practical abundance and general accessibility of fuel resources for fusion power
- Principal nuclear safety, assurance of no uncontrolled power excursion in fusion reactor and of its accidental destruction
- Relatively low content of radioactive materials in wastes and absence of long-lived components
- No large-scale mining and chemical poisoning of the environment

Stellarators



LHD (Japan) - the largest world currently operating torsatron (A = 6.5, R = 3.9 m, N = 10)



W7X (Germany) - advanced stellarator (under construction) (A = 10, R = 5.5 m, N = 5)

Last Exciting Results

In Theory:

Neoclassical transport can be strongly reduced (quasi - symmetry, quasi - isodynamicity and so on)
- in new advanced devices W7X (Germany), CHS - QA (Japan), NCSX, HSX, QPS (USA)

In Experiments:

Mercier β limit can be overcome (LHD, W7-AS)

Kurchatov Inst. (Russia) - IPP(Germany) - CRPP (Switzerland)

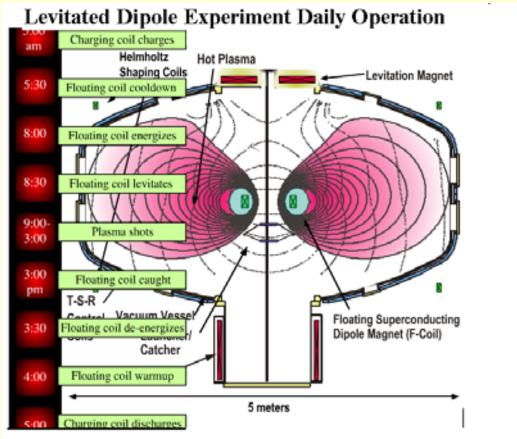
Configuration with poloidally closed contours of B. The contours of the second adiabatic invariant are closed inside the plasma column for all trapped particles. No losses of collisionless α - particles from the internal half of plasma column during considered time 10 seconds.

Stationary High-β Alternative Magnetic Fusion Trends

Reactor oriented trends:

1.Tandem Mirrors

GAMMA-10 experiment (Tsukuba, Japan).
Basic achievements: quasi-steady operation, MHD-stability, thermal barrier and potential barrier formation, suppression of loss-cone modes and improved longitudinal plasma confinement.



2. Levitated internal ring based toroidal systems

Theoretical study: physical concepts of LDX (MIT&Columbia Univ., USA) and MIRAGE (RRC KI, Russia) have been developed:

- β~1 FRC-like plasma equilibrium,
- stability in respect of global, interchange and ballooning modes,
- study of anomalous transport is in progress, recent results show an enhanced but acceptable transverse plasma losses.

Experimental study: LDX facility has started the operation in 2001.

Neutron source oriented trends:

1. Gas Dynamic Trap (GDT)

Physical concept of GDT-based highly intensive D-T neutron source (NPI, Novosibirsk, Russia):
total injection power – 60 MW, neutron flux – 2 MW, neutron exposed aria - ~0.5 m^2).
Experiments at GDT facility confirm the basic concept of the plasma confinement..

2. Linked Mirror Neutron Source (LMNS)

Physical concept of LMNS has been jointly proposed and developed in by IFS UT and RRC KI. The main advantage of LMNS is an improvement of the power efficiency up to 25-30% and extension of the neutron exposed area up to 2-3 m^2.

*Each of the above concept has its specific advantages,
but no one is so comprehensively developed as a tokamak is*

Inertial Confinement

- Inertial confinement is a promising approach to fusion but it needs long term development

- A principal feasibility of a micro explosion is unquestionable. The question of a minimal driver energy for pellets with Q>>1 is still open

- There is a solid but still not complete understanding of physics of energy fluxes interactions with pellets, of its implosion and burning. The experiments on the existing and developed facilities are required (lasers, Z-pinches, heavy ion beams)

- After demonstration of the pellet ignition with Q>>1, the main attention shall be given to the development of an acceptable for the power reactor highly efficient and reliable driver

- Inertial confinement is still an area where one could expect the appearance of new exotic ideas, such as for example fast ignition

ITER objectives

ITER Objectives

Programmatic

- Scientific and technological feasibility of fusion energy for peaceful purposes

Technical

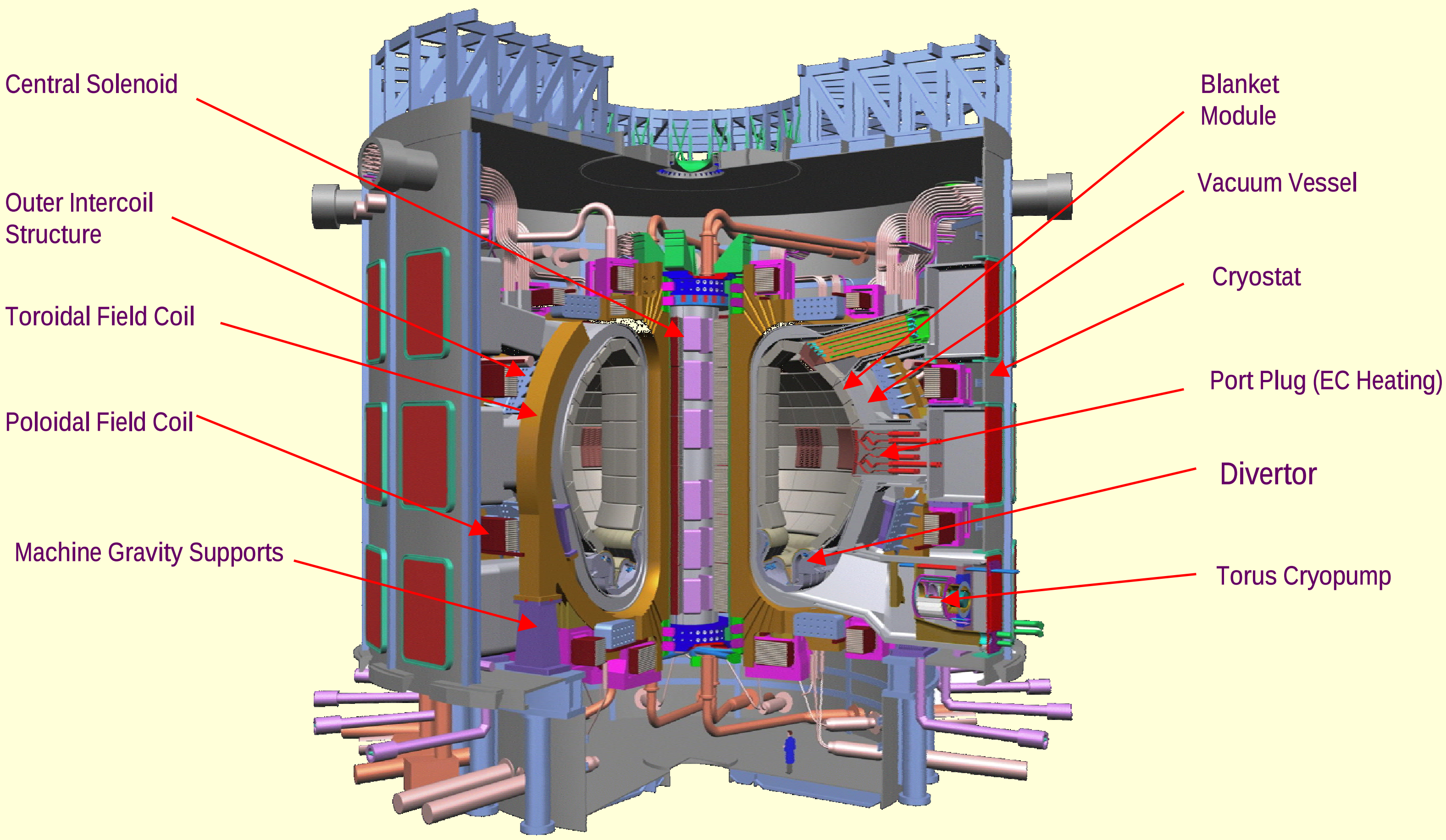
- Moderate Q, extended DT burning plasma, steady state ultimate goal
- Reactor-essential technologies in system integrating appropriate physics and technology
- Test high-heat-flux and nuclear components
- Demonstrate safety and environmental acceptability of fusion

Strategic

- Single device answering, in an integrated way, all feasibility issues needed to define a subsequent demonstration fusion power plant (DEMO) except for material developments to provide low activation and larger 14 MeV neutron resistance for in-vessel components

- **Device with $Q \geq 10$ and inductive burn of ≥ 300 s, aiming at steady state operation with $Q \geq 5$, with average neutron wall load ≥ 0.5 MW/m^2 and average lifetime fluence of ≥ 0.3 MWa/m^2**

ITER


Central Solenoid
Outer Intercoil Structure
Toroidal Field Coil
Poloidal Field Coil
Machine Gravity Supports
Blanket Module
Vacuum Vessel
Cryostat
Port Plug (EC Heating)
Divertor
Torus Cryopump

ITER Parameters

Total fusion power	500 MW (700 MW)*
Average 14 MeV neutron wall loading	0.57 MWm^{-2} (0.8 $MW\ m^{-2}$)
Plasma inductive burn time at 15 MA	> 400 s
Non-inductive burn time at 500 MW	3000 s
Plasma major radius (R) and minor radius (a)	6.2/2.0 m
Plasma current (I_p)	15 MA (17 MA)*
Vertical elongation at 95% flux surface/separatrix (κ_{95})	1.70/1.85 (1.85/2.0) **
Triangularity at 95% flux surface/separatrix (δ_{95})	0.33/0.48 (0.45/0.55) **
Toroidal field at 6.2 m radius (B_T)	5.3 T
Plasma volume	831 m^3

* The pulse length is limited to about 200 s

** The plasma shifted to the outboard and has minor radius of 1.85 m

ITER Engineering

Technology R&D

The overall philosophy for the ITER design has been to use established approaches through detailed analysis and to validate their application to ITER through technology R&D, including fabrication and testing of full scale or scalable models of key components.

Seven large projects were established to confirm the industrial fabrication processes and quality assurance for major key components of the basic machine and their maintenance scheme:

- central solenoid model coil (CS MC) and toroidal field model coil (TF MC) projects,
- vacuum vessel sector, blanket module, and divertor cassette projects,
- blanket and divertor remote handling projects.

Other R&D concerning safety related issues, auxiliary systems including heating and current drive systems, fuelling and pumping system, tritium process system, power supplies and diagnostics are also critical areas.

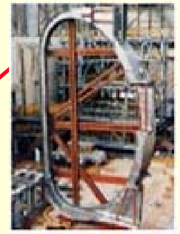
The technical output from the R&D confirms the manufacturing techniques and quality assurance incorporated in the ITER design, and supports the manufacturing cost estimates for important key cost drivers.

ITER Design and Technology

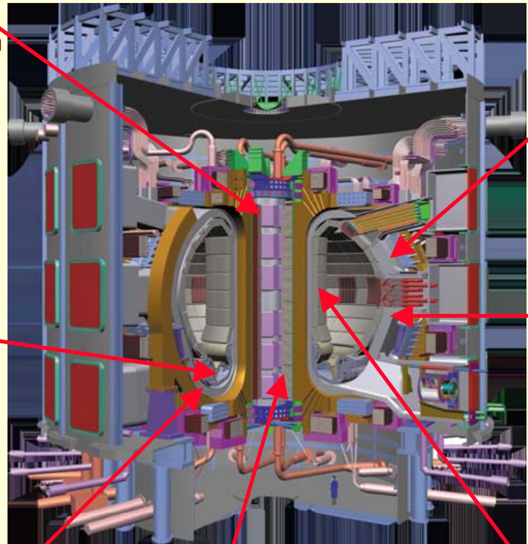
CENTRAL SOLENOID MODEL COIL

Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

VACUUM VESSEL SECTOR



Double-Wall, Tolerance ±5 mm



REMOTE MAINTENANCE OF DIVERTOR CASSETTE

Attachment Tolerance ± 2 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

DIVERTOR CASSETTE

Heat Flux >15 MW/m^2, CFC/W

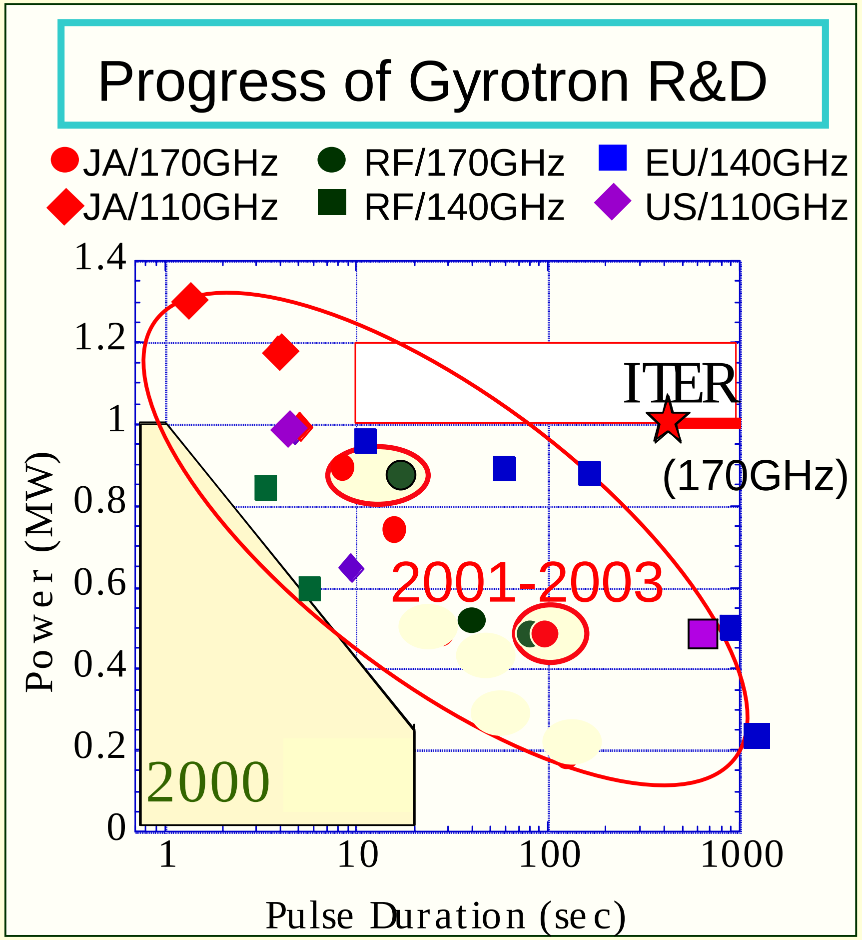
TOROIDAL FIELD MODEL COIL

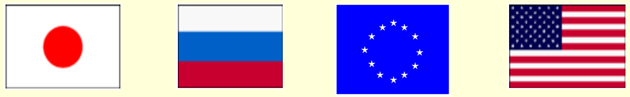
Height 4 m
Width 3 m
B_{max}=7.8 T
I_{max} = 80kA

REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

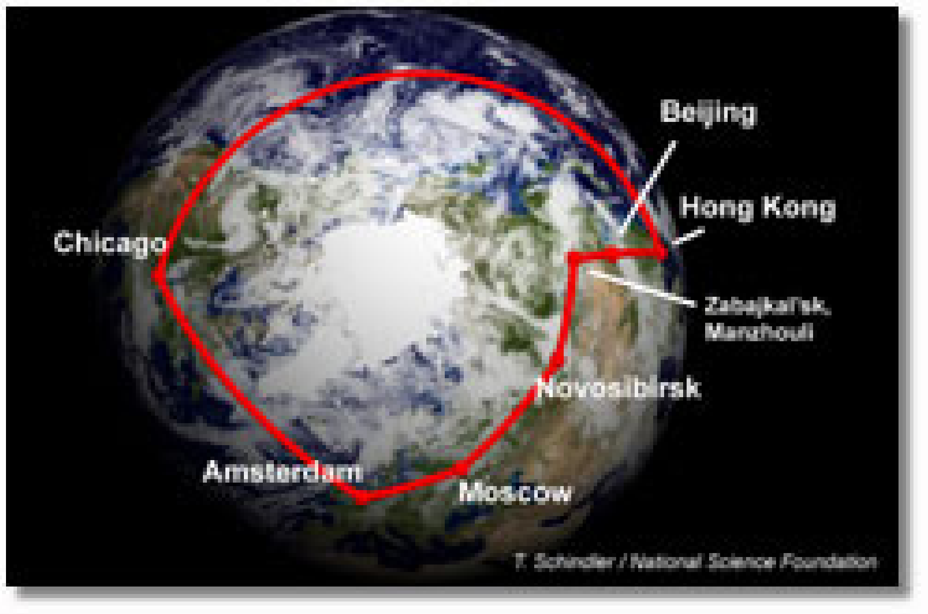
ECRF: Status of Gyrotron Development





Test of 170 GHz/1 MW in CW operation (> 400 sec) is in progress

Global Ring Network for Advanced Applications Development (GLORIAD)



- Network layer proposed as a 10 Gbps optical *ring* network linking Chicago - Amsterdam - Moscow - Novosibirsk - Khabarovsk - Beijing - Hong Kong - Chicago
- Network to provide a number of separately-managed circuits to *specific S&E communities* and provides additional bandwidth to *general S&E community*

Future of World Fusion Research and Power Development

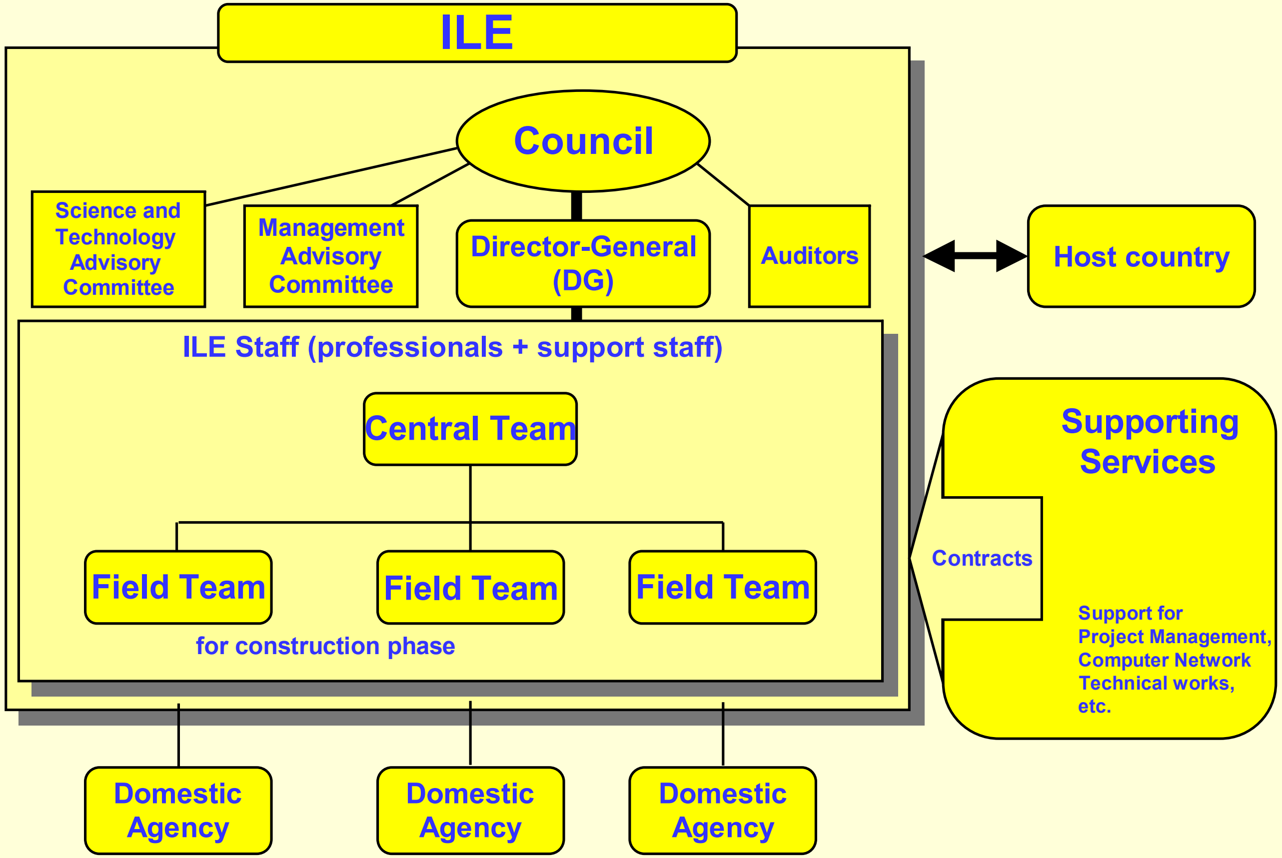
The Successful Implementation of ITER Project is a Historical Chance for Fusion Energy

- From the beginning the controlled fusion issue was considered as a global task of applied nature of creating a new energy source with inexhaustible fuel capacity
- The work was started at practically zero scientific foundation. To obtain sufficient basic knowledge in the field of hot plasma physics several decades were needed
- At present the available physical and engineering know-how allows to demonstrate both scientific and technical feasibility of a fusion reactor. This is one of the objectives of ITER
- The success of ITER will be a significant argument for the society and for the structures that determine financial trends in the developed countries in favour of fusion issue

Broadening the Scope of ITER

- Remote experimental control centre as focus for interaction with ITER
- Virtual plasma modelling laboratory, to bring together models for plasma behaviour on ITER and to make predictions, feeding back information subsequently from ITER operation
- "Satellite" tokamak providing support (and ability to rapidly evaluate new ideas) during ITER construction and operation
- DEMO design team
- DEMO materials test/qualification facility (IFMIF)

ITER Legal Entity



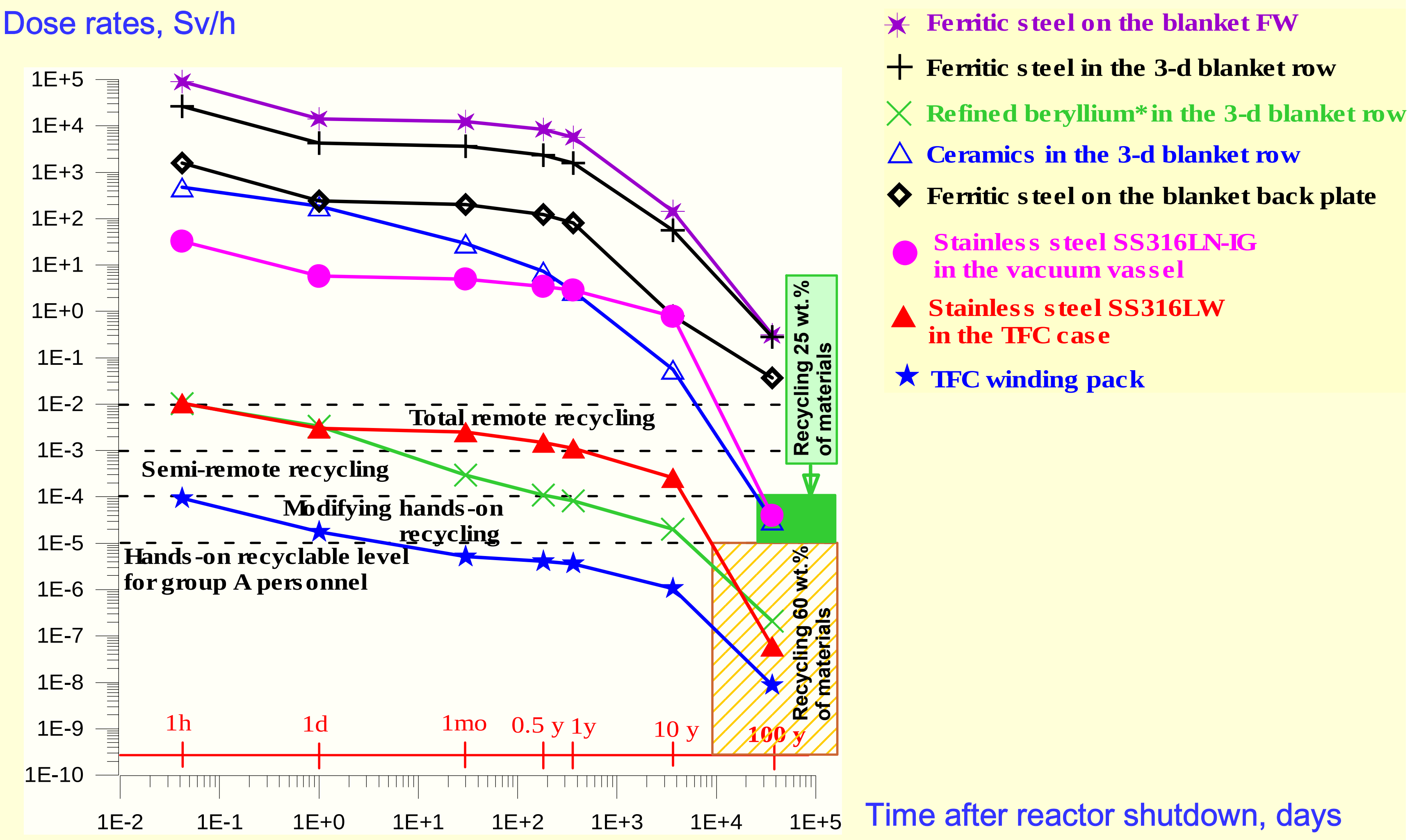
Fusion Offers a Safe, Long-term Energy Source with Abundant Resources and Essential Environmental Advantages

- Fusion power reactors exhibit passive safety – fusion reaction self termination
- Even the most unlikely accident would not require public evacuation. Nonattractive for terrorist attacks
- No fissile materials and actinides can be generated in fusion reactor
- Waste processing and refabrication are relatively simple.
- 30 years after shutdown 60 % of the reactor materials can be recycled, 40% can be placed in near-surface repositories
- Safety and environmental advantages of fusion reactors result in the decrease of energy production cost

Fusion Reactors Exhibit Passive Safety During Operation and in Case of Accident

- Immediate self-termination of the uncontrolled discharge scenario
- Afterheat in the reactor components is low after shutdown
- Design integrity remains in LOCA and LOFA events
- Radioactivity is concentrated in structural materials
- Possible release of radioactivity is limited to less than
  - ✓ 50g of tritium
  - ✓ 25g of corrosion products
  - ✓ 40-100g of spattering dust
- Radiation at the site boundary during the worst possible accident is 2-10 times lower than Permissible Dose for Population

Dose Rates
from Fusion Power Plant Reactor Materials



Essence of the Fast Track

First stage

ITER

IFMIF on the same time scale

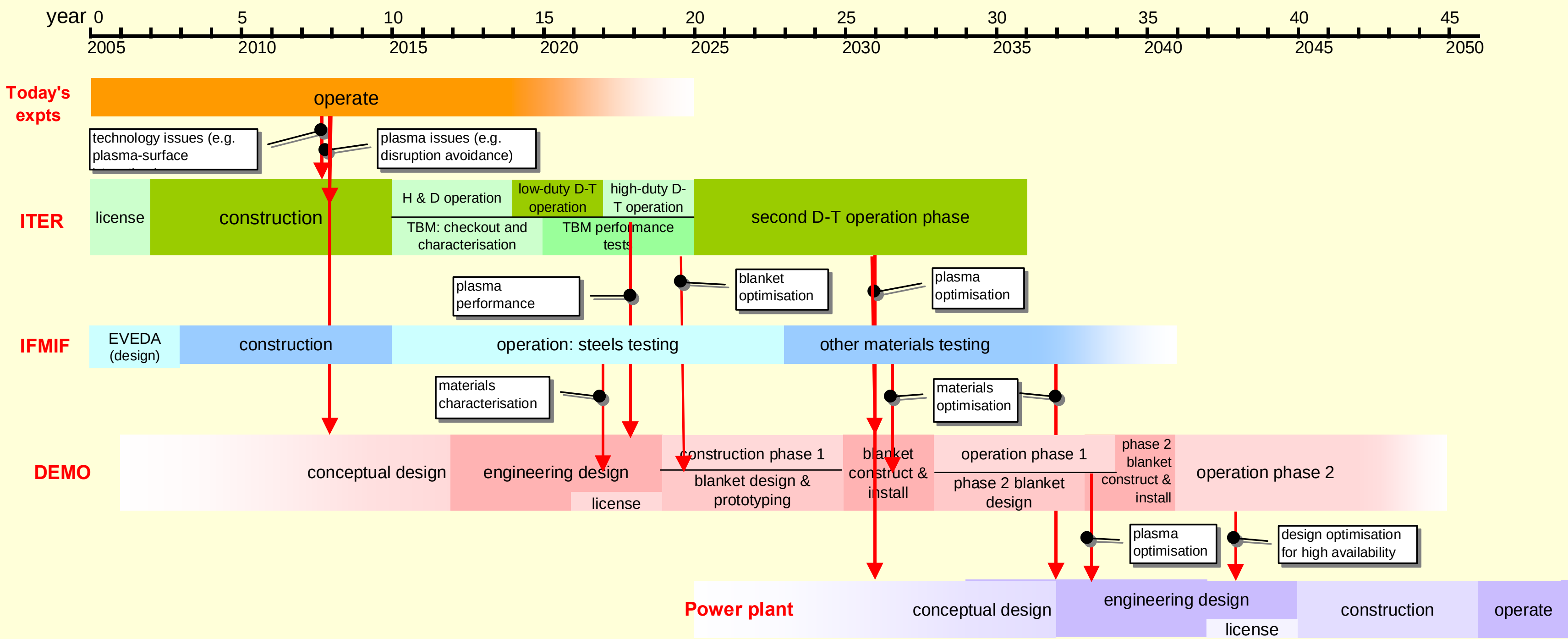
Second stage

DEMO - assumed ITER-like (final integration and reliability development). Realistically, there may be several DEMOs, roughly in parallel.

Third stage

Commercial power

PRELIMINARY

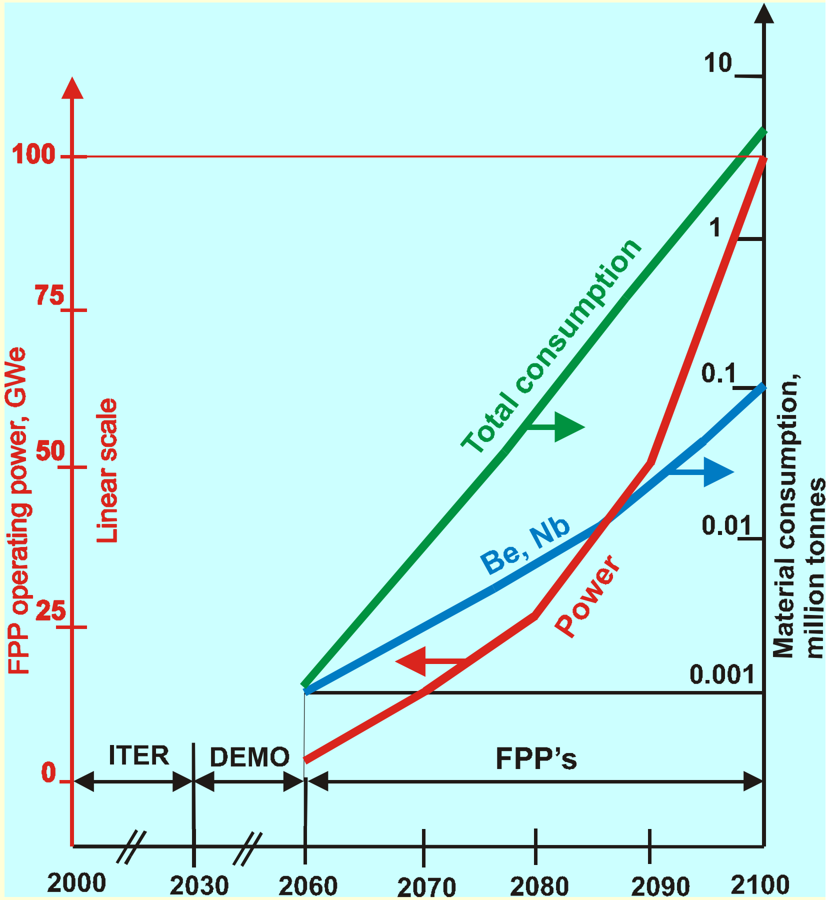


Fusion Power Reactor Application Areas

FPP - source of electricity production

Other possible usage:

- Hydrogen production
- Fusion power plant for water desalination
- Hybrid fusion reactors for nuclear fuel production
- Volumetric neutron sources with high neutron fluence for material irradiation
- Fusion power plant for technological heat generation or heat supply for population
- Transmutation of long lived elements of spent nuclear fuel



FPP utilization can begin in a middle of this century

Fusion Can Provide Hydrogen by Several Routes

- **Electric power generation → Electrolysis**
  - Proven technology
  - Overall efficiency ~24% (LWR), ~36% (Hi T Reactors)
    (efficiency of electric power generation x efficiency of electrolysis)
- **Electricity + Heat → High temperature electrolysis or Hybrid thermochemical cycles**
  - Need both electricity generation and high temperature process heat
  - Efficiencies up to ~ 50%
  - Developing technologies
- **High temperature heat → Thermochemical water-splitting**
  - A set of chemical reactions that use heat to decompose water
  - Net plant efficiencies of up to ~50%
  - Developing technology
- **Are there fusion-unique processes?**

Fusion Power Plant for Sea Water Desalination

Development of industry and agriculture demands a huge water consumption. Water supply problem is extremely essential in arid regions where fresh water resources are limited or virtually nonexisting. Request for additional water supply in the next 50 years will come also from industrial and agricultural sectors of many countries in the world.

The presently available river flow, km^3 /year	~6,300
Present global freshwater consumption km^3/year	~3,000
Present requirement in fresh water to satisfy human needs (according WHO estimation), km^3/yr	~6,000
Population growth in XXI century	2-2.5 times
Requirment in fresh water in XXI century to satisfy human needs, km3/yr	12,000 - 15,000

Major Parameters of Fusion Power Plant For Sea Water Desalination Based on RF DEMO Concept

Plant freshwater capacity, m^3/day	6,000,000
Plant lifetime, years	50
Total thermal power, MW(th)	~4,000
Plant capital cost, $M (1997)	8,000 - 12,000
Plant operating costs, $M/year	200 - 400
Estimated freshwater cost, $/ m^3	1-2

Fusion power plant can provide a region of some million population with water, heat and electricity

Disposal of Long-lived Elements of Spent Nuclear Fuel

Fusion power reactor can be used for transmutation of long-lived waste isotopes

It has neutron abundance for their burning

Three categories are considered:

- **minor actinides, in particular Np-237($t_{1/2}$= 2.1 10^6 years), Am-241 (432 years), Am-243 ($7{,}4 \cdot 10^3$ years), Cm-245 ($9{,}0 \cdot 10^3$ years) and some other**
- **some fission products in particular I-129 ($1{,}6 \cdot 10^7$ years), Tc-99 ($2{,}1 \cdot 10^5$ years)**
- **some isotopes existing in structural materials, for example, Mo-93 ($3{,}5 \cdot 10^3$ years) and others**

An average speed of burning can achieve 10% per FPY

Conclusions

- ITER Project is a unique example of international cooperation and not only in the framework of fusion issue

- A sufficient physical and engineering data base was established for the first experimental fusion reactor

- ITER is the single fast way to study burning plasma in the nearest future. Flexibility of ITER will allow exploration of large operation space of fusion power, beta, pulse length and Q values in various operation modes

- An active continuation of physical investigations, development of new diagnostics and materials is needed to prepare the next logical step – design of DEMO