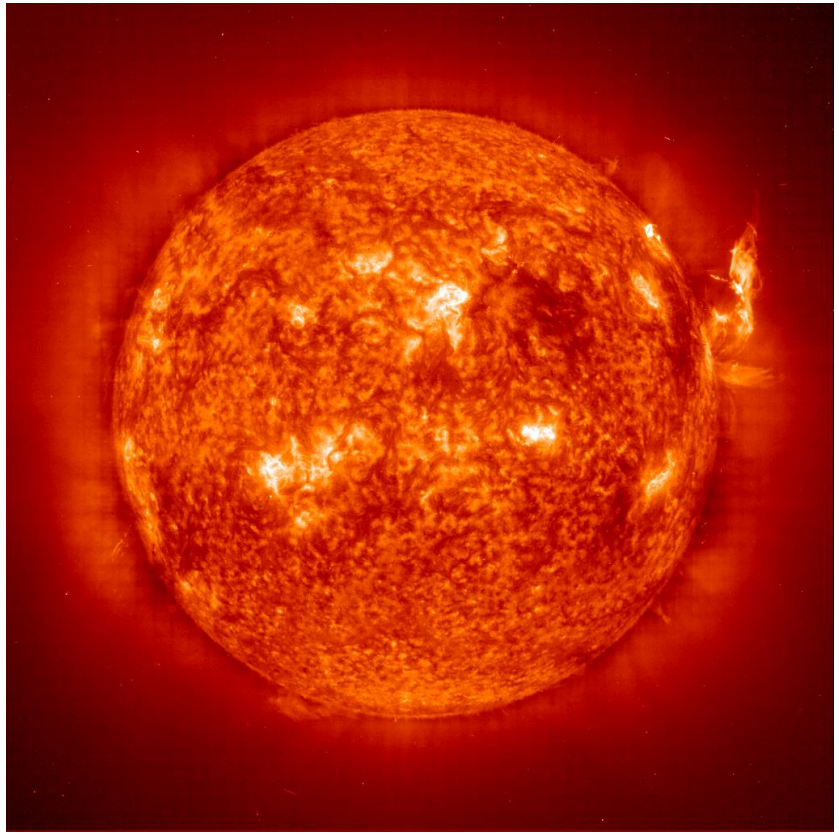
Present Status and Future Prospect of Nuclear Fusion

Prof. Dr. Yong-Su Na

What is nuclear fusion?

Origin of Star Energy

Le groupe d'étoiles des Pléiades (2002), Robert Gendler

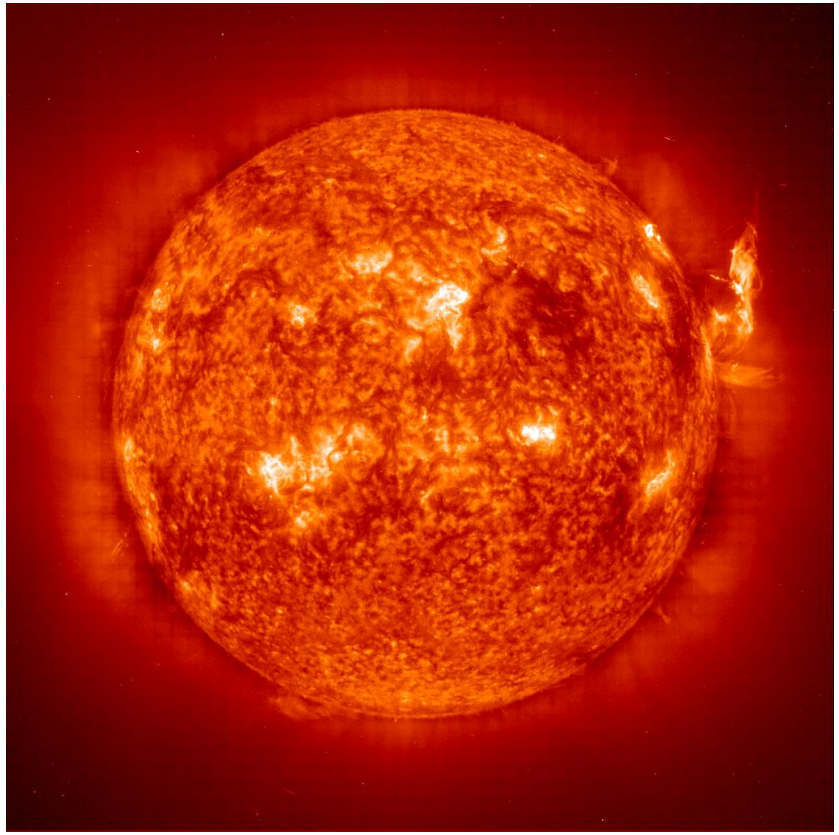


NASA/European Space Agency (1999)

Origin of Star Energy

Le groupe d'étoiles des Pléiades (2002), Robert Gendler

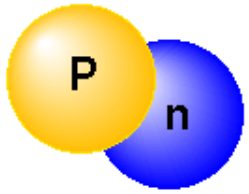
Thermonuclear fusion

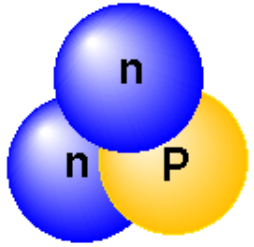


NASA/European Space Agency (1999)

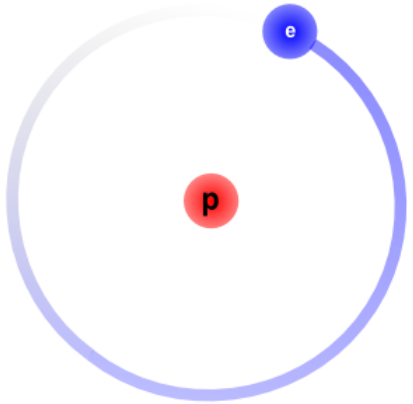
Nuclear Fusion Reaction

Deuterium (Deuteron)



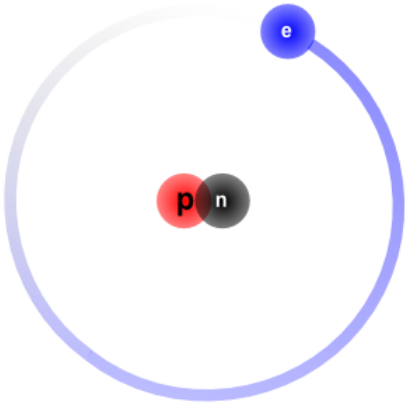


Tritium (Triton)



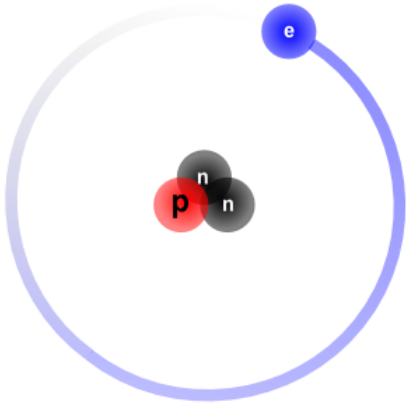
$^{1}_{1}H$

Hydrogen (H)



$^{2}_{1}H$

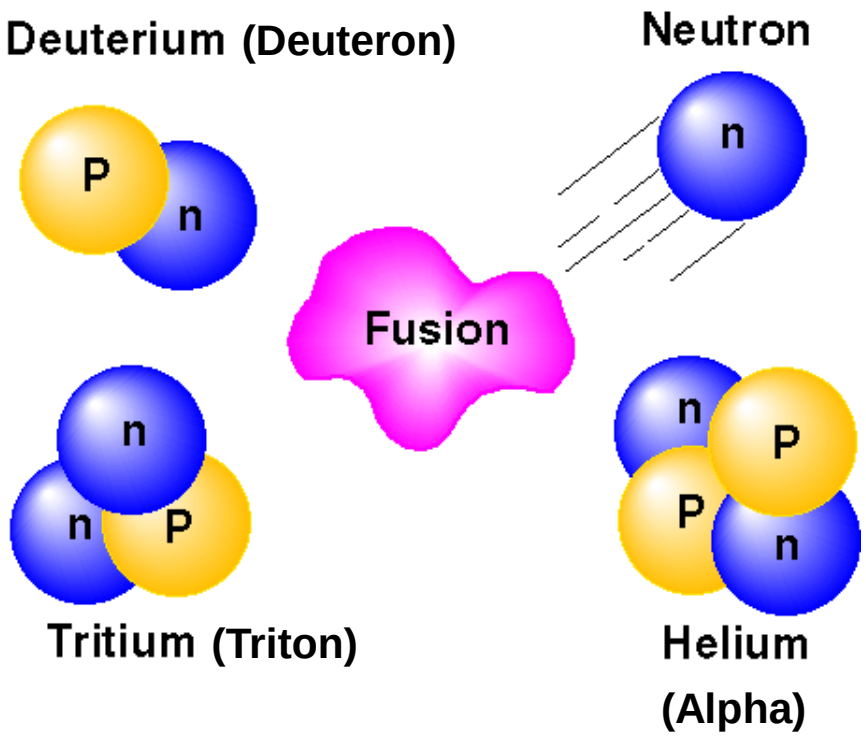
Deuterium (D)



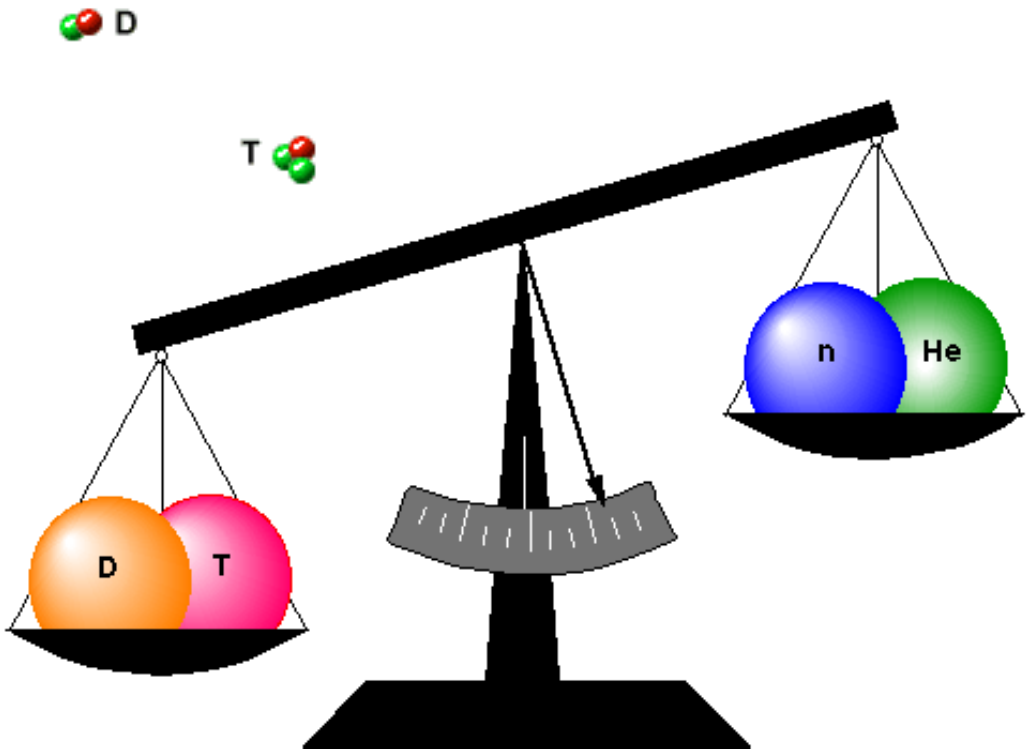
$^{3}_{1}H$

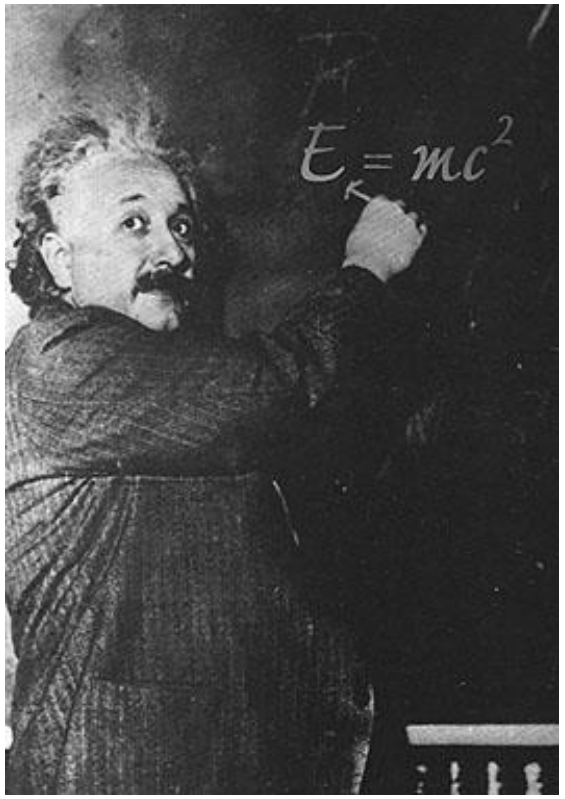
Tritium (T)

Nuclear Fusion Reaction



Nuclear Fusion Reaction

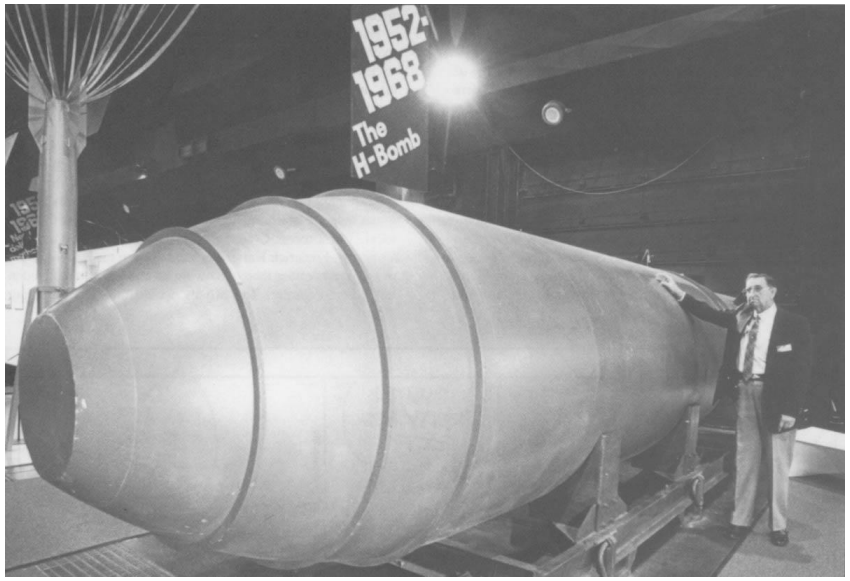




[출처]
http://www.meteoweb.eu/2011/09/e-possibile-superare-la-velocita-della-luce-teoria-della-relativita-a-rischio/88437/, Dec, 2014

Converting mass defect into energy → Fusion energy

Utilisation of Fusion Energy

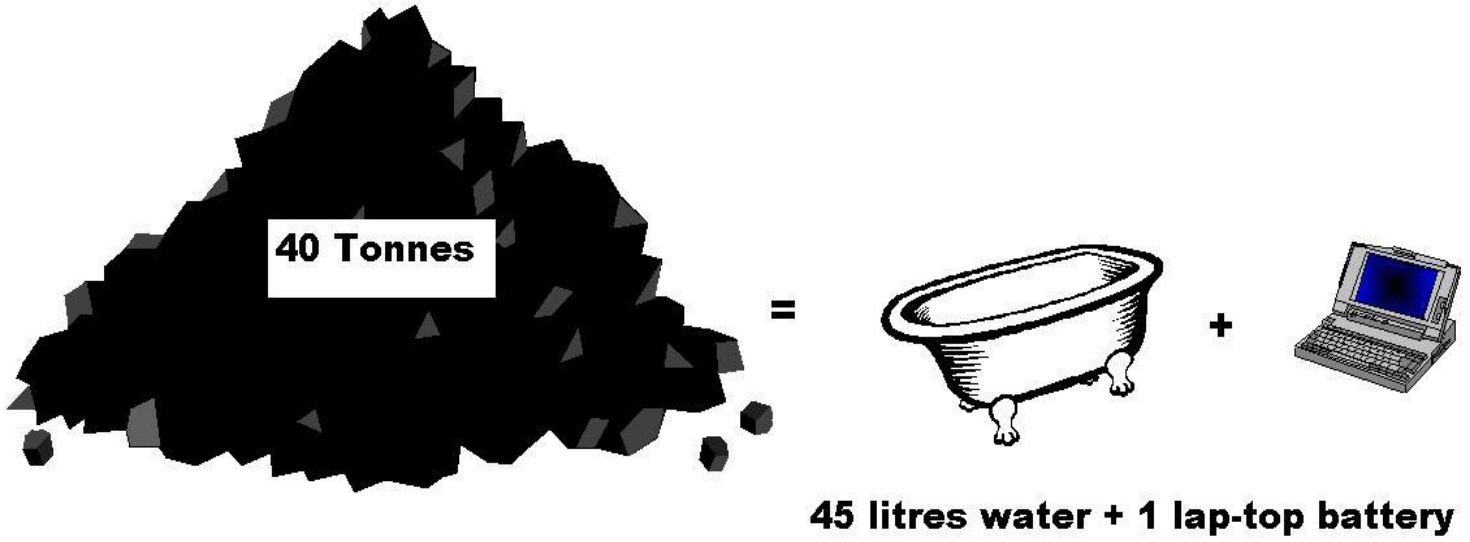


A Mark-17 Hydrogen bomb at the National Atomic Museum

Ivy Mike (1 November 1952)

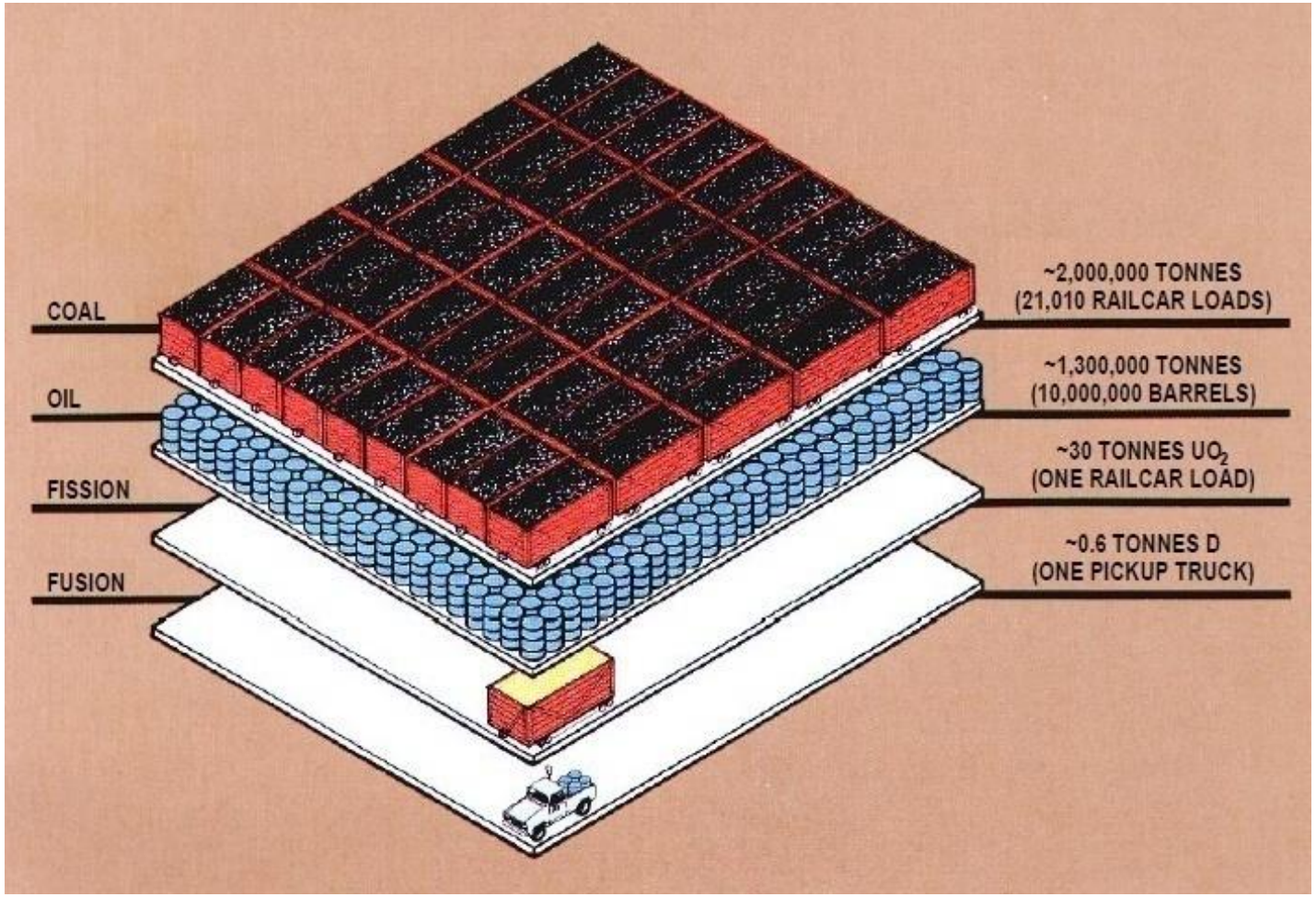
Peaceful use of the fusion energy?

Peaceful Use of the Fusion Energy



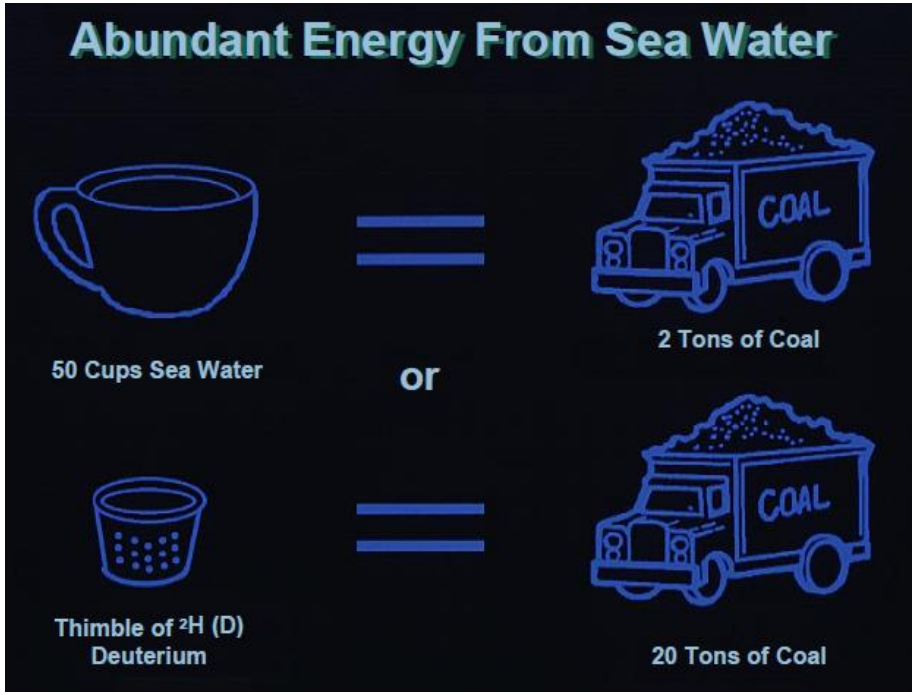
- Lithium in one laptop battery + half a bath-full of ordinary water (≥ one egg cup full of heavy water) = 200 MW

Peaceful Use of the Fusion Energy

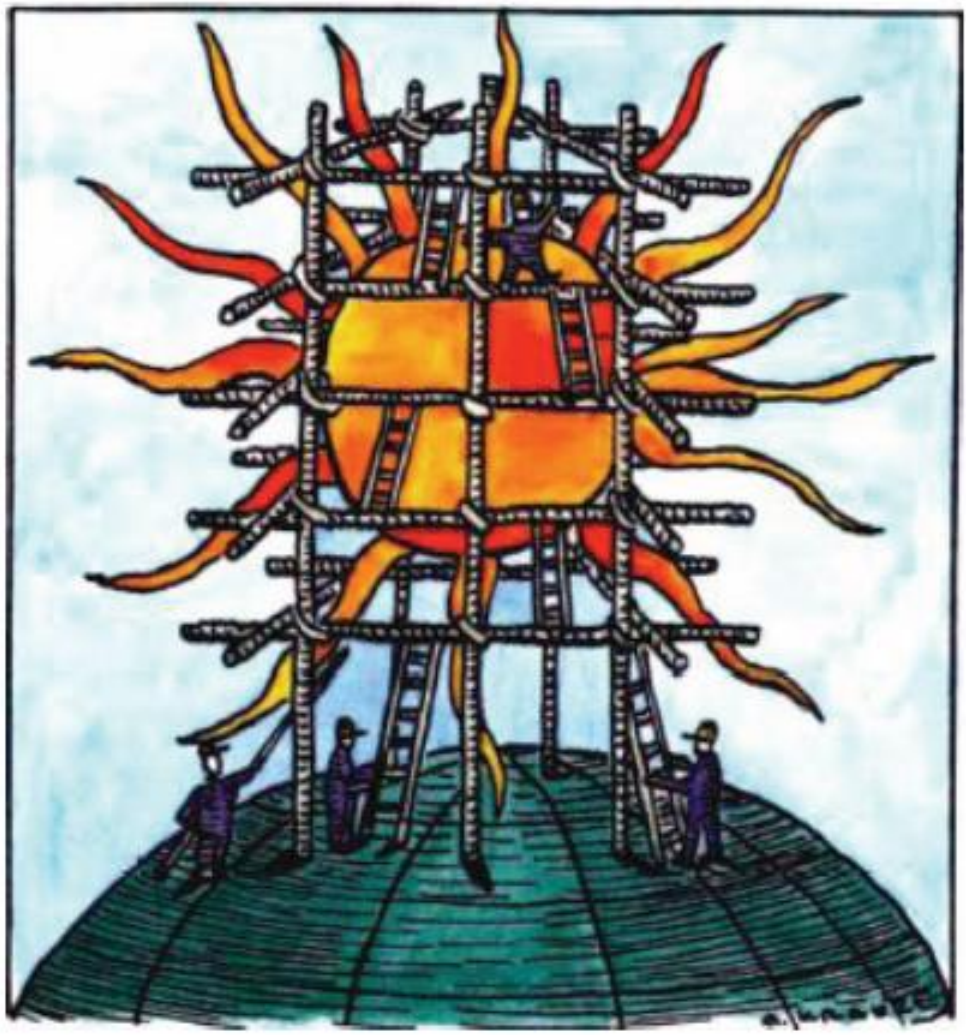


1,600,000 m^3

Peaceful Use of the Fusion Energy



Build a Sun on the Earth

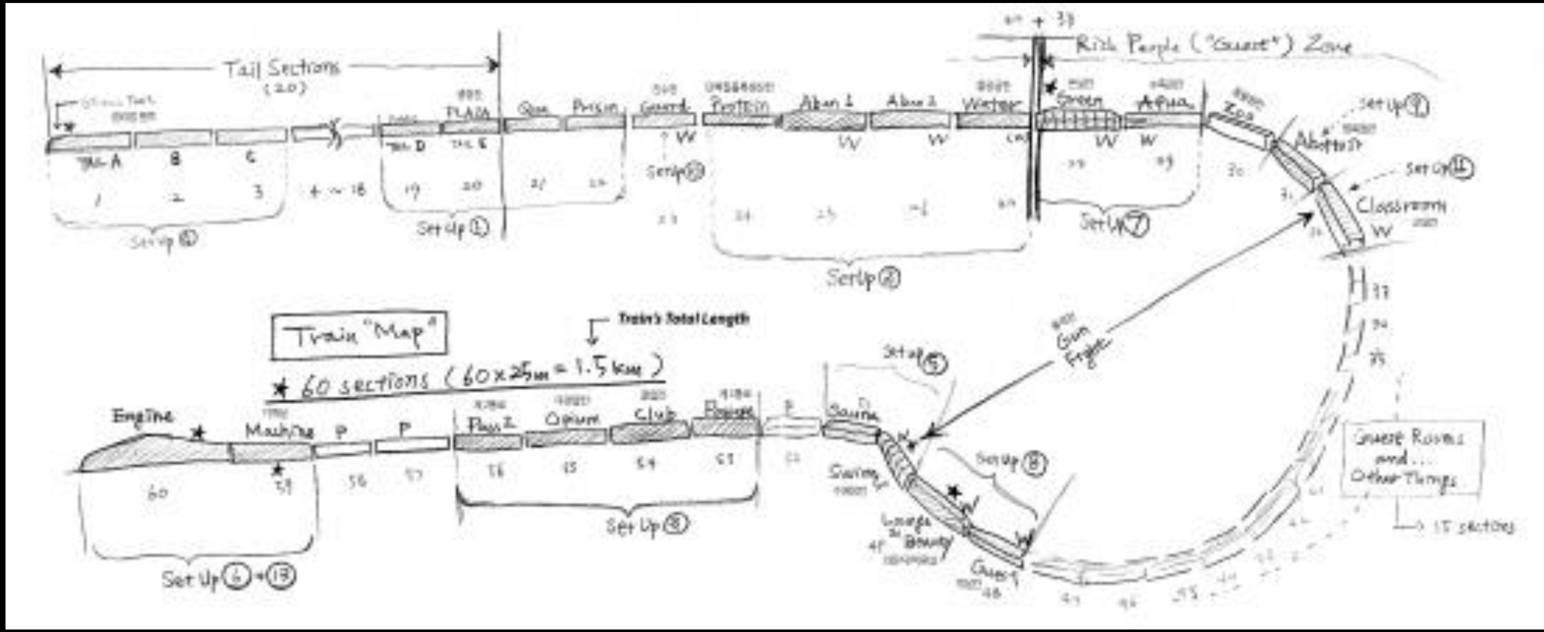


Iron man (2008), Disney

Iron Man

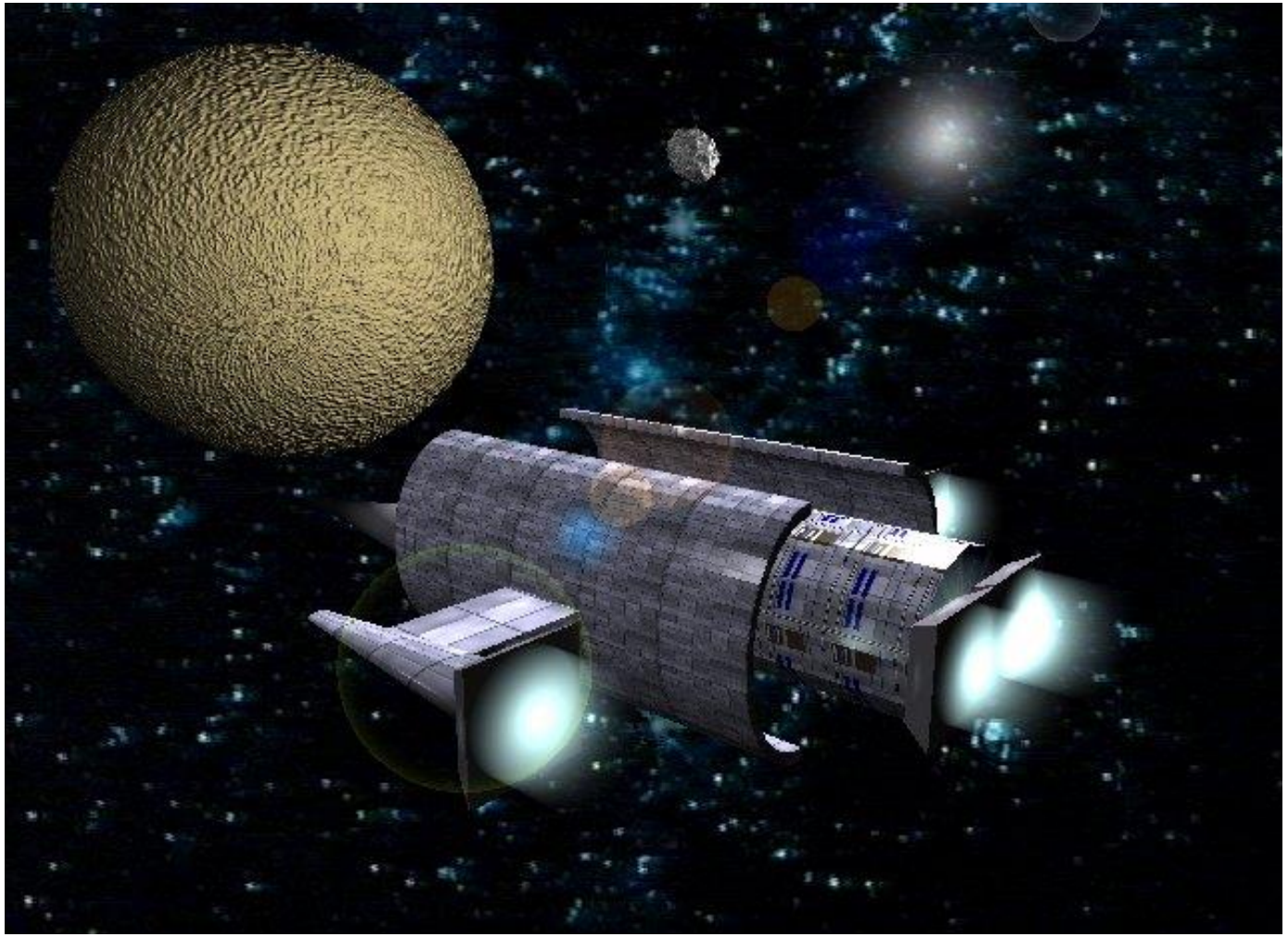

나는 닫힌 문을 열고 싶다
2013년 봉준호 감독의 새로운 세계
설국열차
SONG KANGHO
SNOWPIERCER 2013


제 작 모호필름 오퍼스픽처스
제공/배급 CJ엔터테인먼트

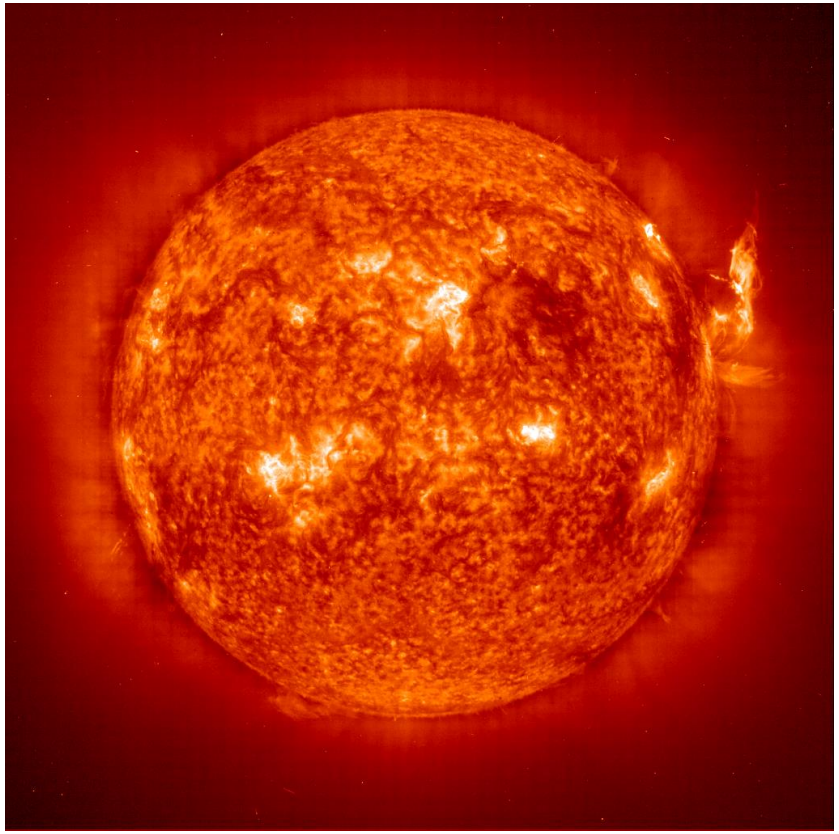

Tail Sections
(20)
Rich People ("Guest") Zone
Train "Map"
Train's Total Length
★ 60 sections (60×25m = 1.5km)
Engine
Machine
Opium
Club
Sauna
Zoo
Classroom
Gun Fight
Guest Rooms and... Other Things
15 sections

How to confine the hot sun?

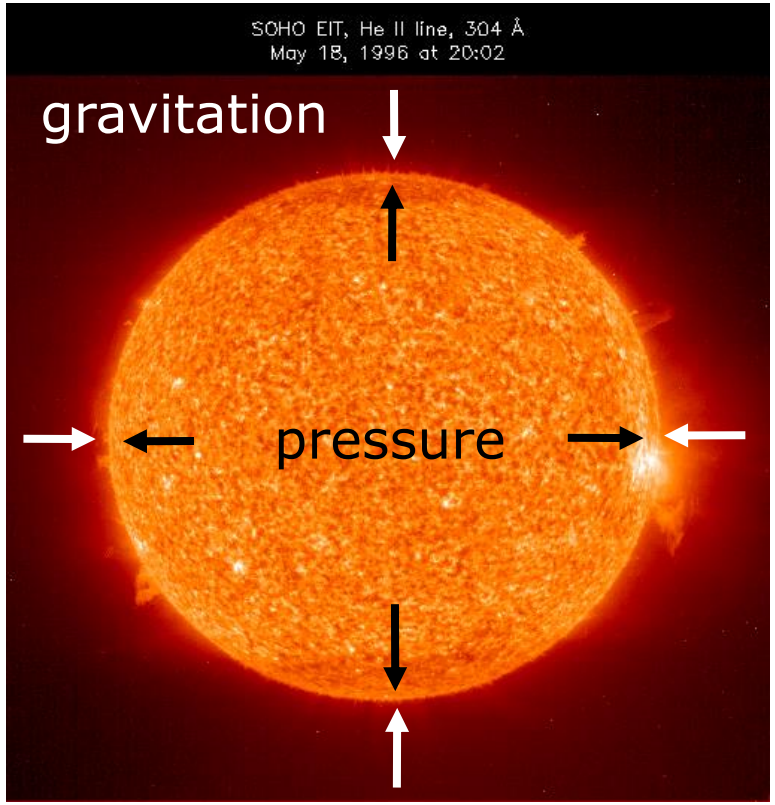
Confinement



Gravitational Confinement

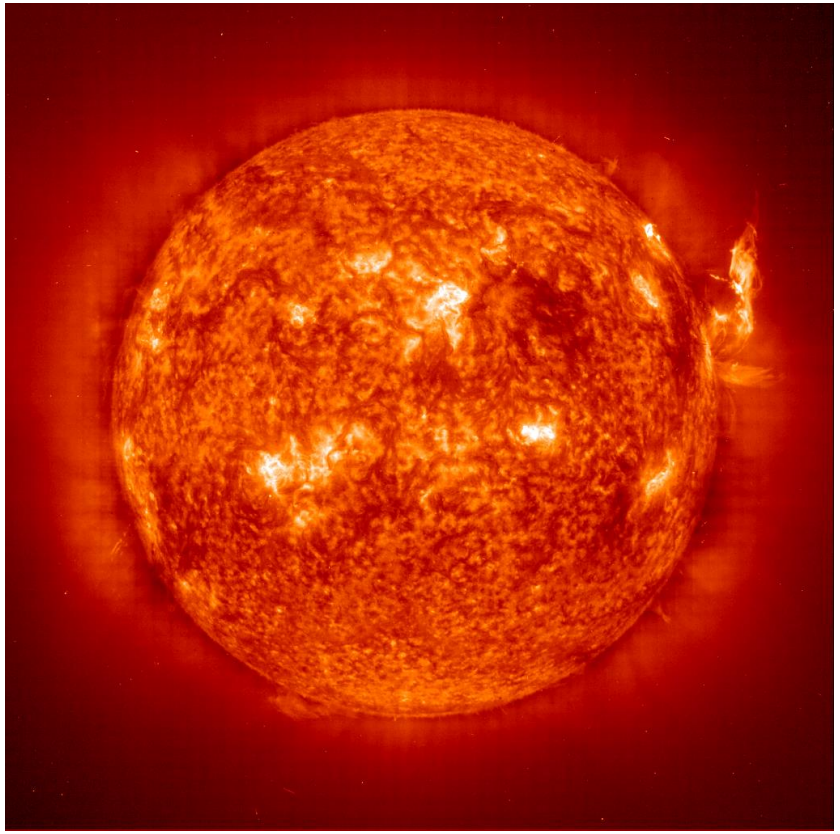


The sun

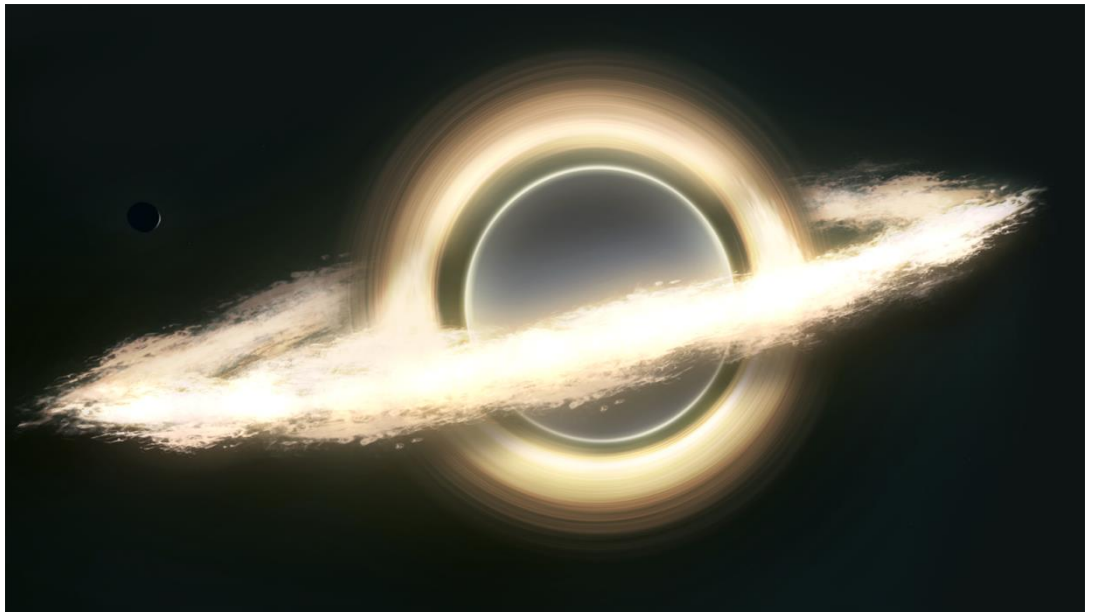


Equilibrium in the sun

Gravitational Confinement



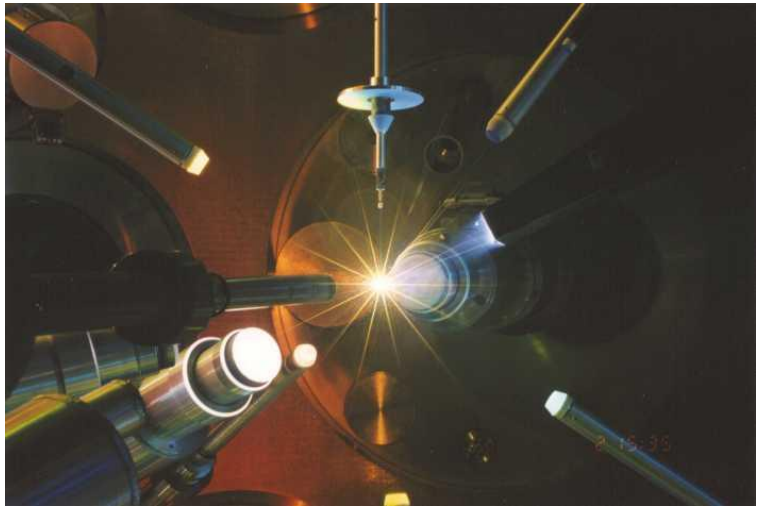
The sun



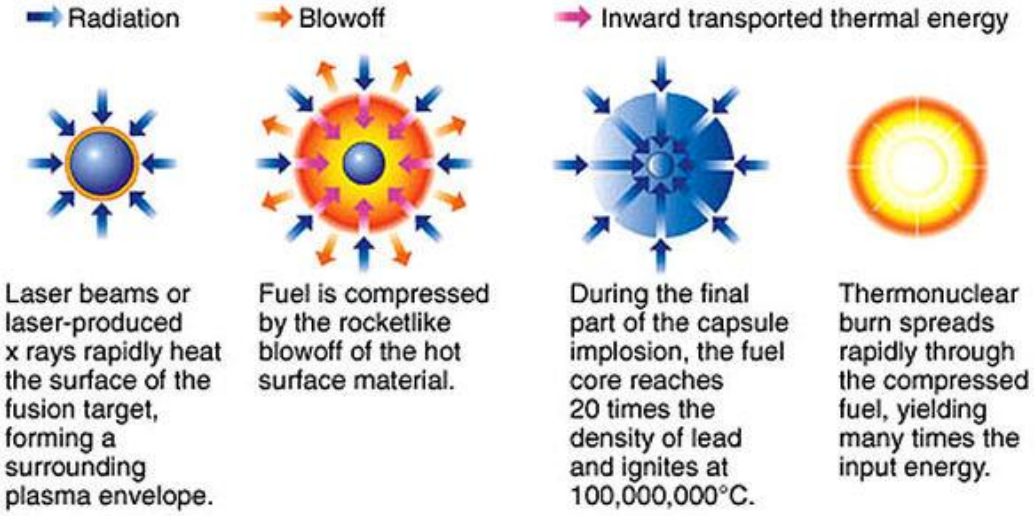
Black Hole

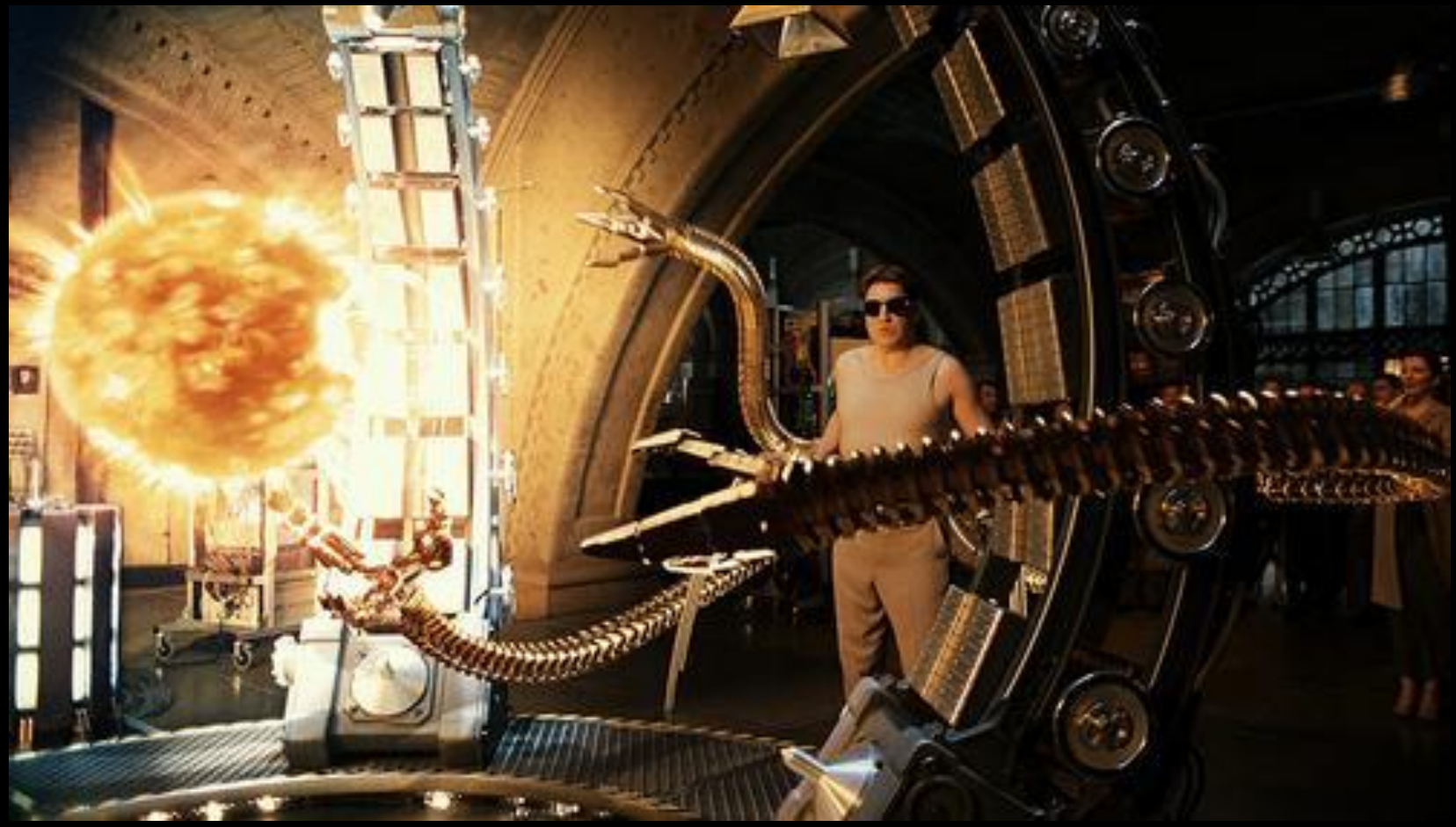
Interstellar (2014),
Warner Brothers/Paramount/Legendary

Inertial Confinement



Fusion fuel microcapsule (micro balloon)





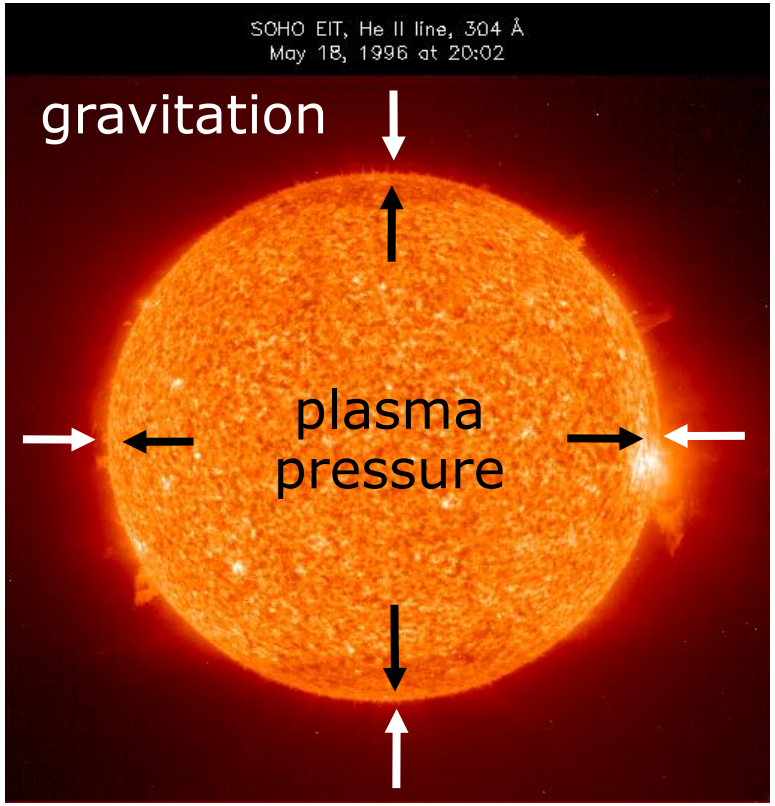
Spiderman 2 (2004), Columbia Pictures

Spiderman II

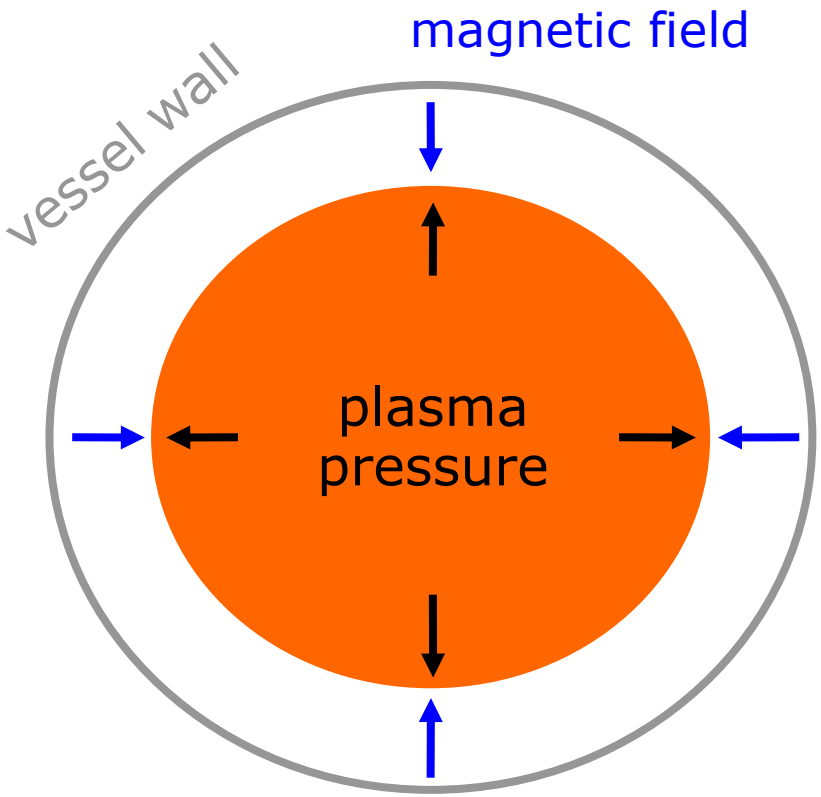
Spiderman 2 (2004), Columbia Pictures

Magnetic Confinement

- **Imitation of the Sun on Earth**

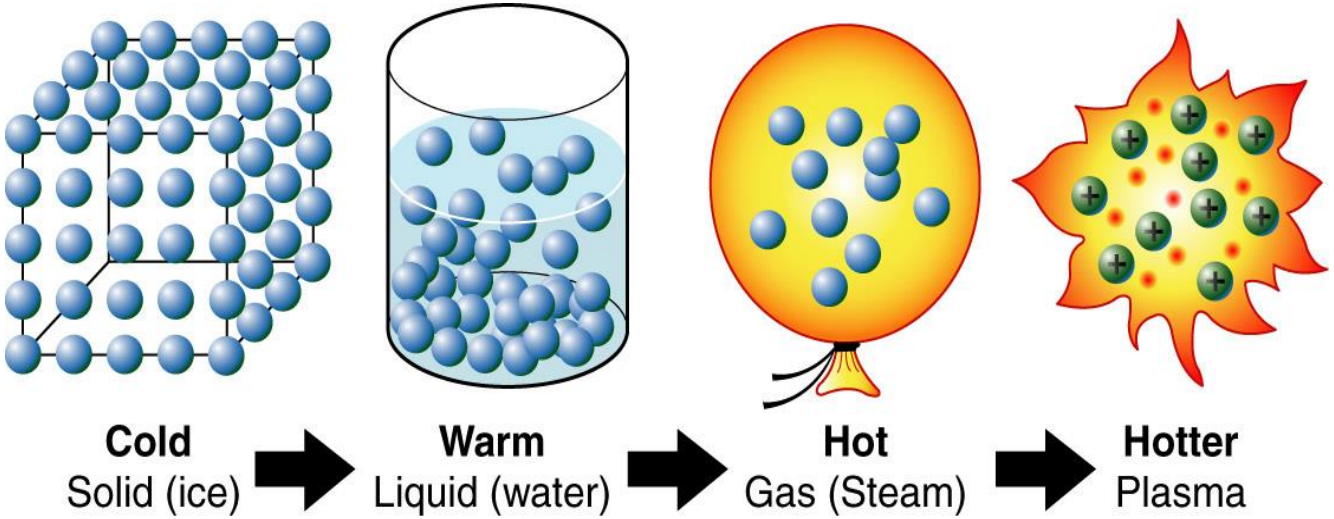


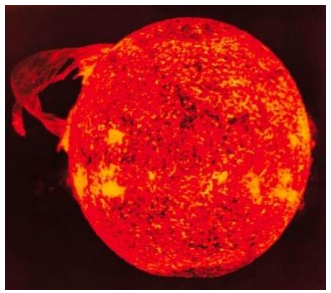
Equilibrium in the sun



Plasma on earth

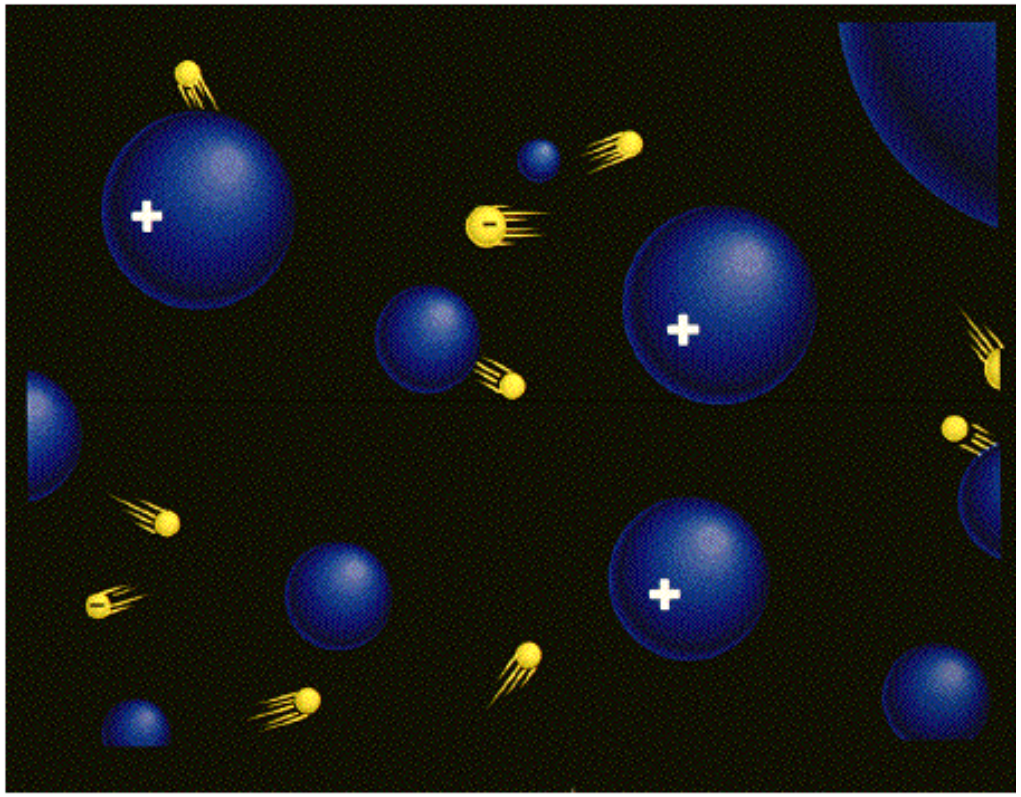
Plasma – The 4th State of Matter





The 4th state of matter

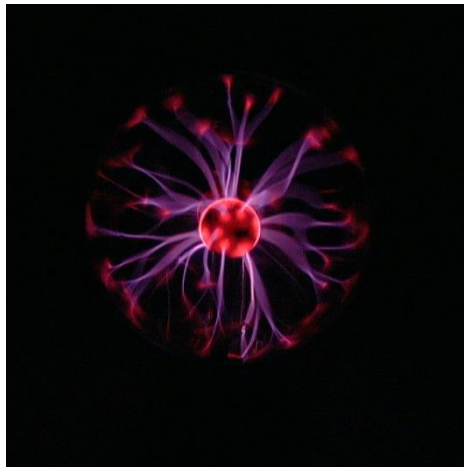
Plasma – The 4th State of Matter

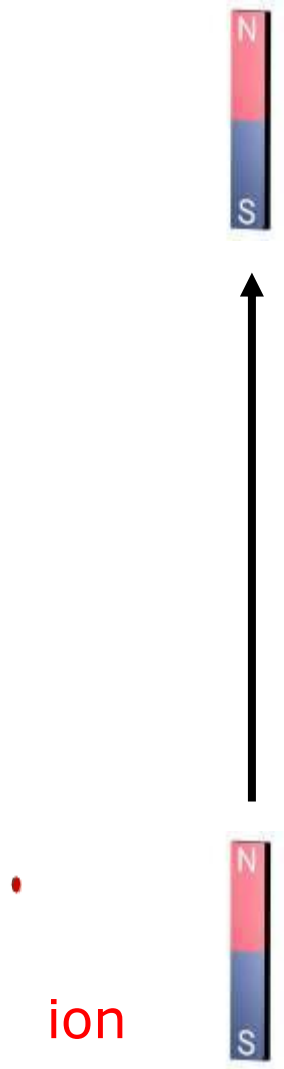


Ions and electrons are separated.

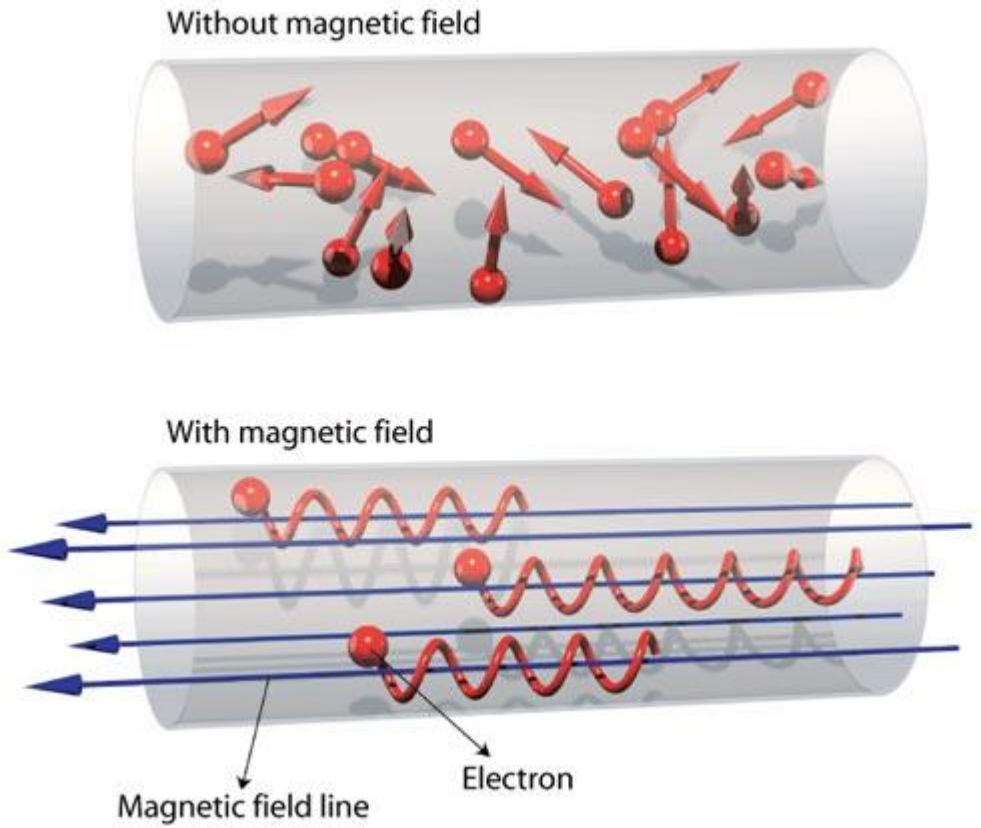
Plasma – The 4th State of Matter

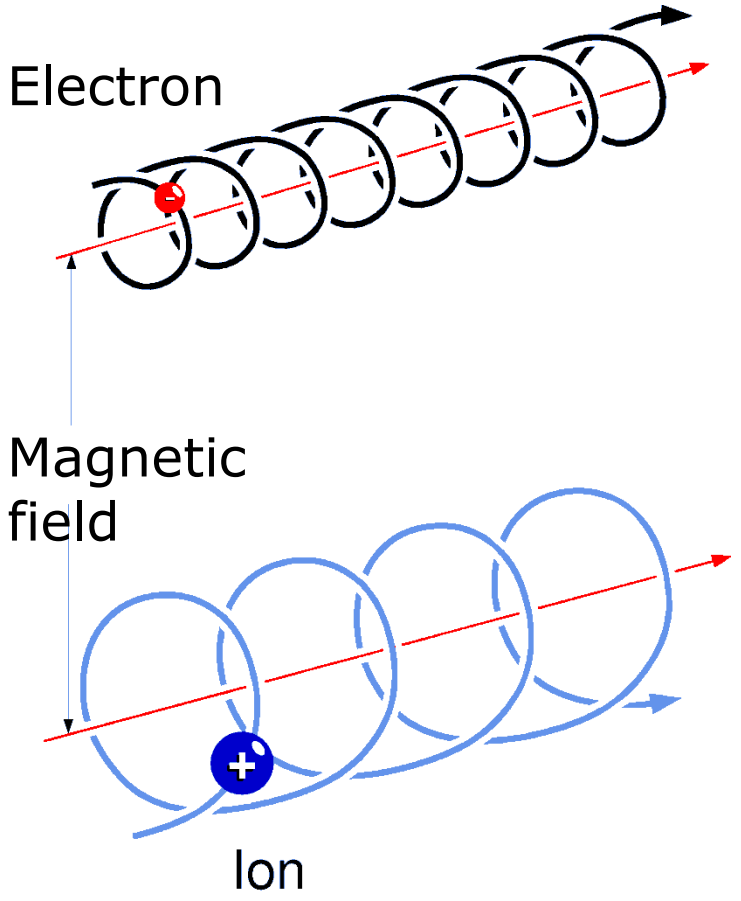
Magnetic Confinement



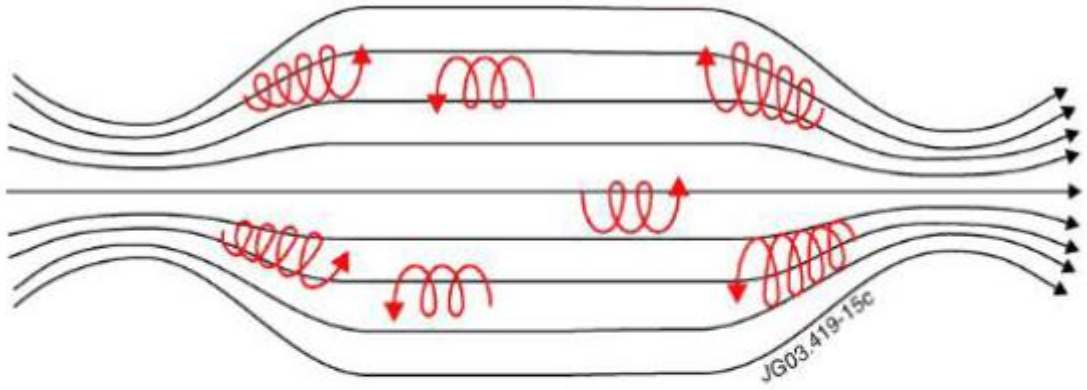


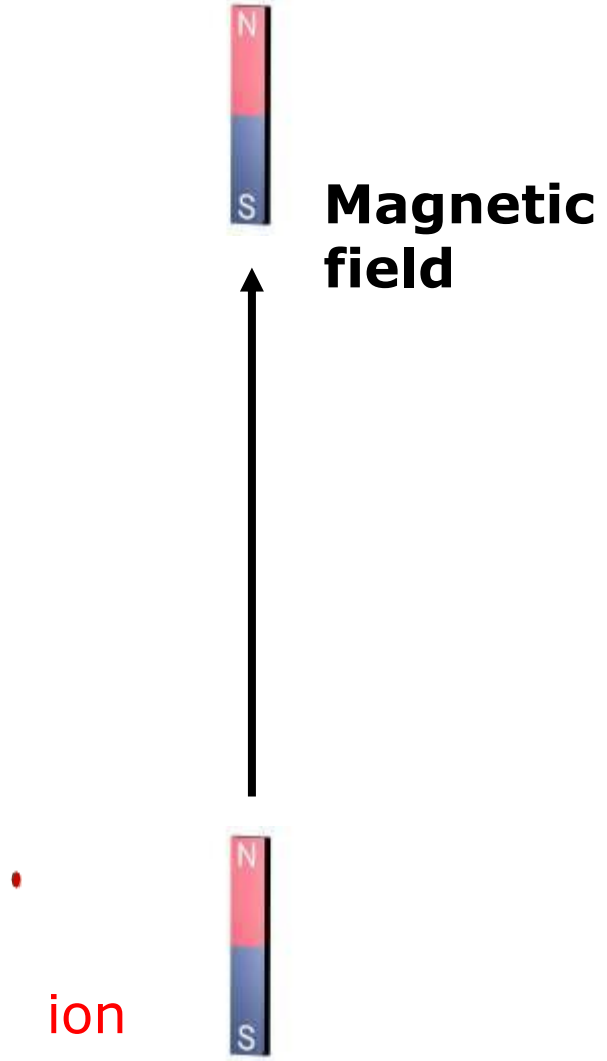
Magnetic Confinement



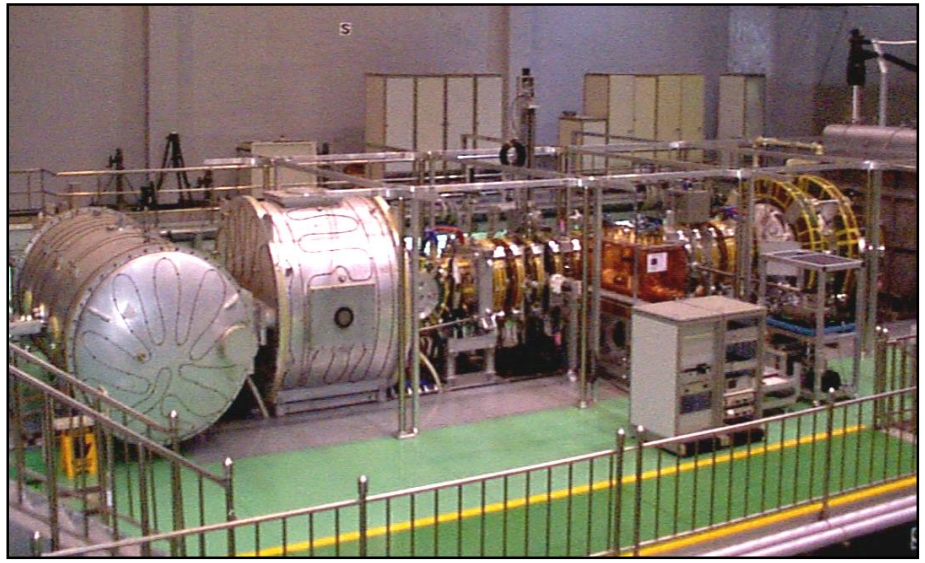


Magnetic Confinement



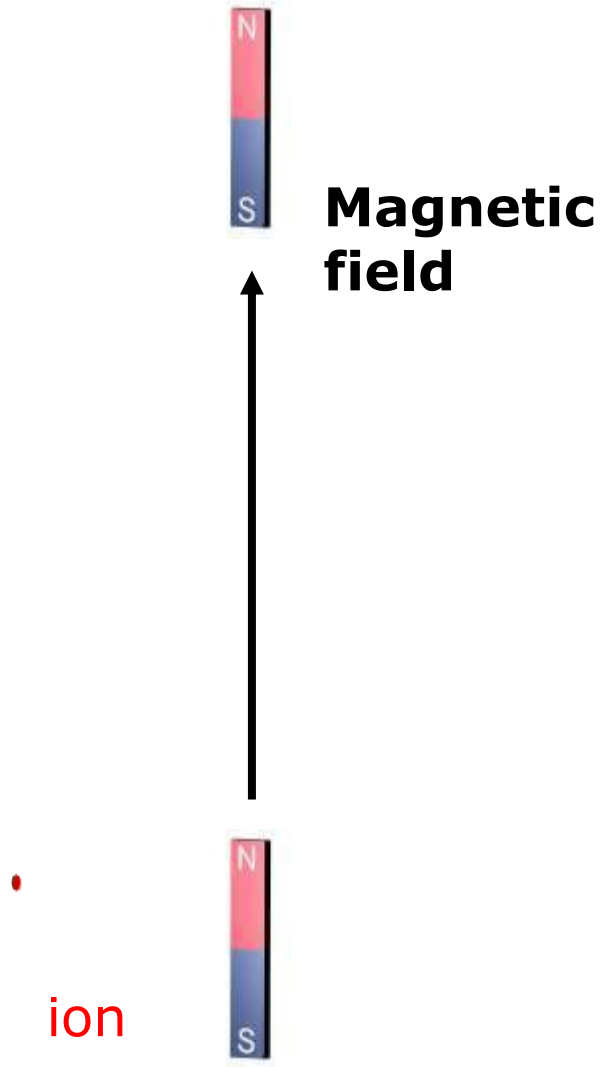


Magnetic Confinement

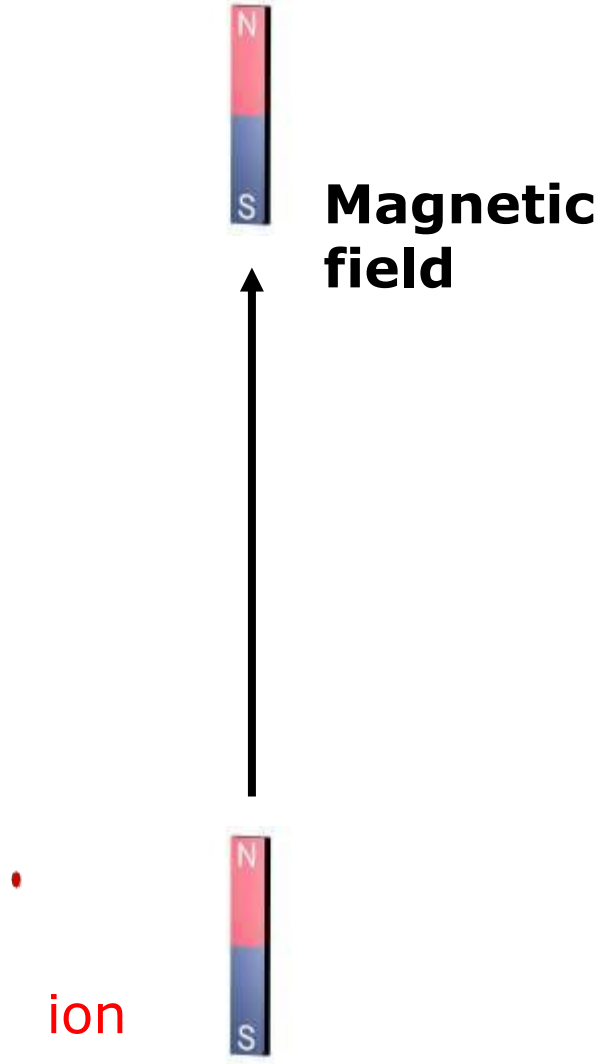


Mirror Machine

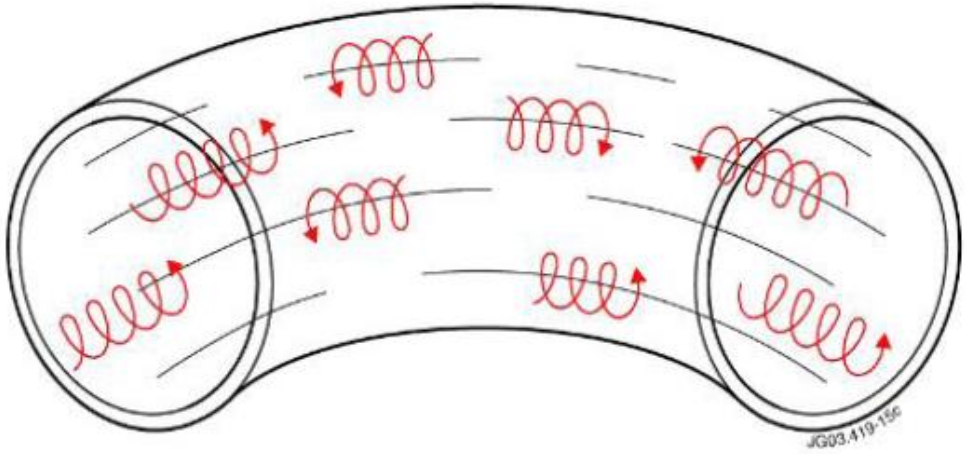
old Hanbit Device in NFRI

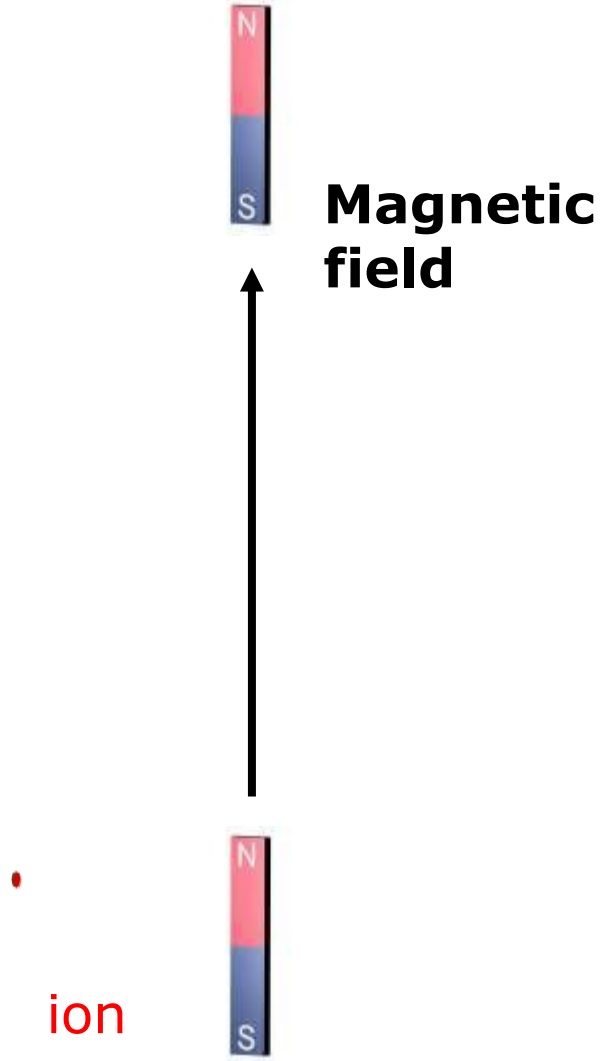


Magnetic Confinement



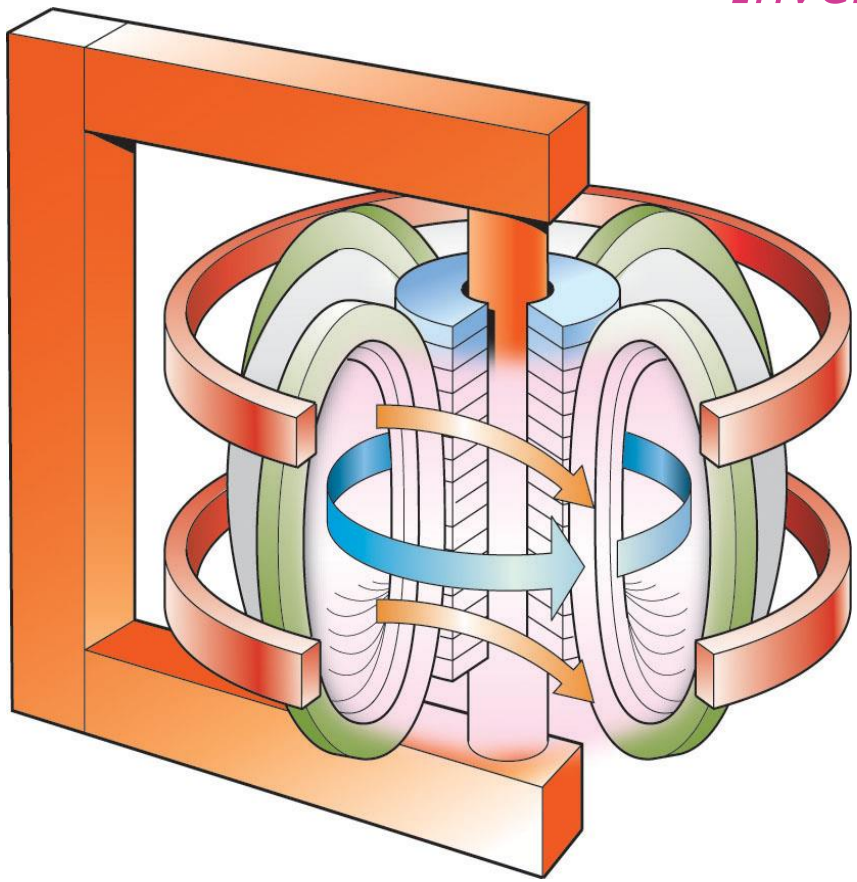
Magnetic Confinement

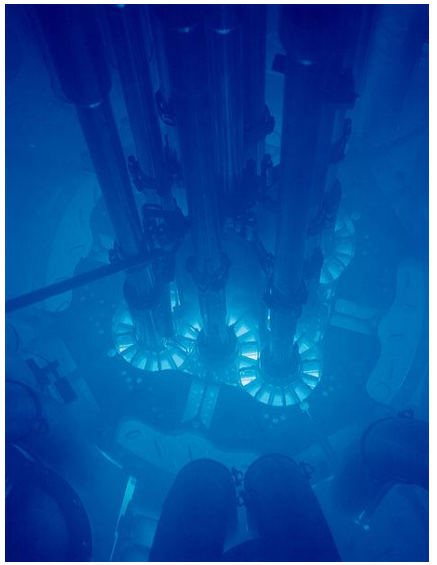




Tokamak

Invented by Tamm and Sakharov in 1952

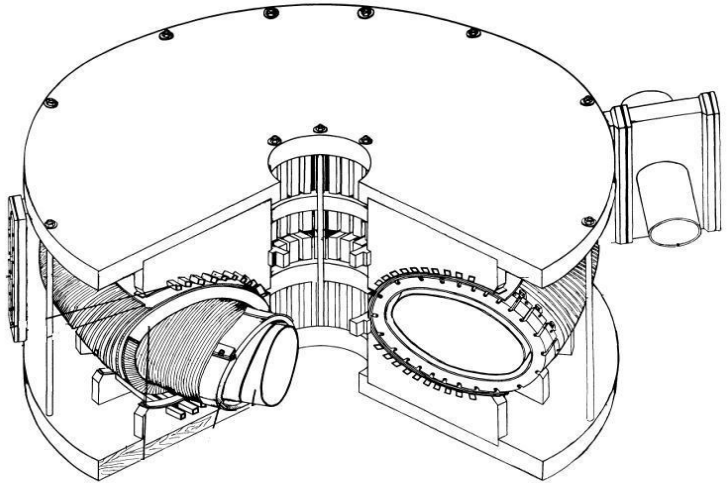




Toroidalnaja **ka**mera **ma**gnitnaja **k**atushka
(Toroidal chamber magnetic coil)

Tokamak

Invented by Tamm and Sakharov in 1952



Cutaway of the Toroidal Chamber in Artsimovitch's Paper *Research on Controlled Nuclear Fusion in the USSR*

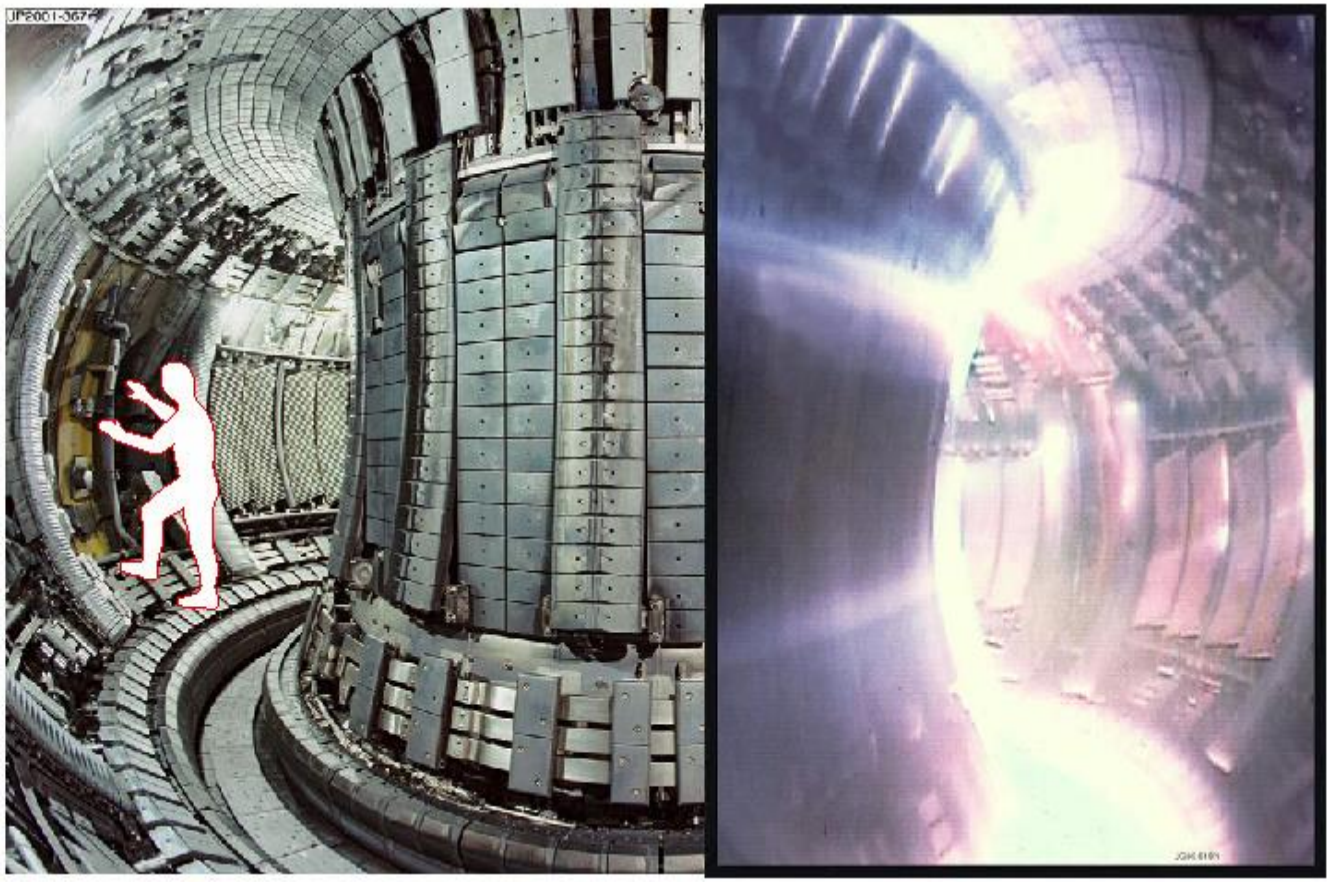
Toroidalnaja **ka**mera **ma**gnitnaja **k**atushka
(Toroidal chamber magnetic coil)

Iron Man

Iron man (2008), Disney

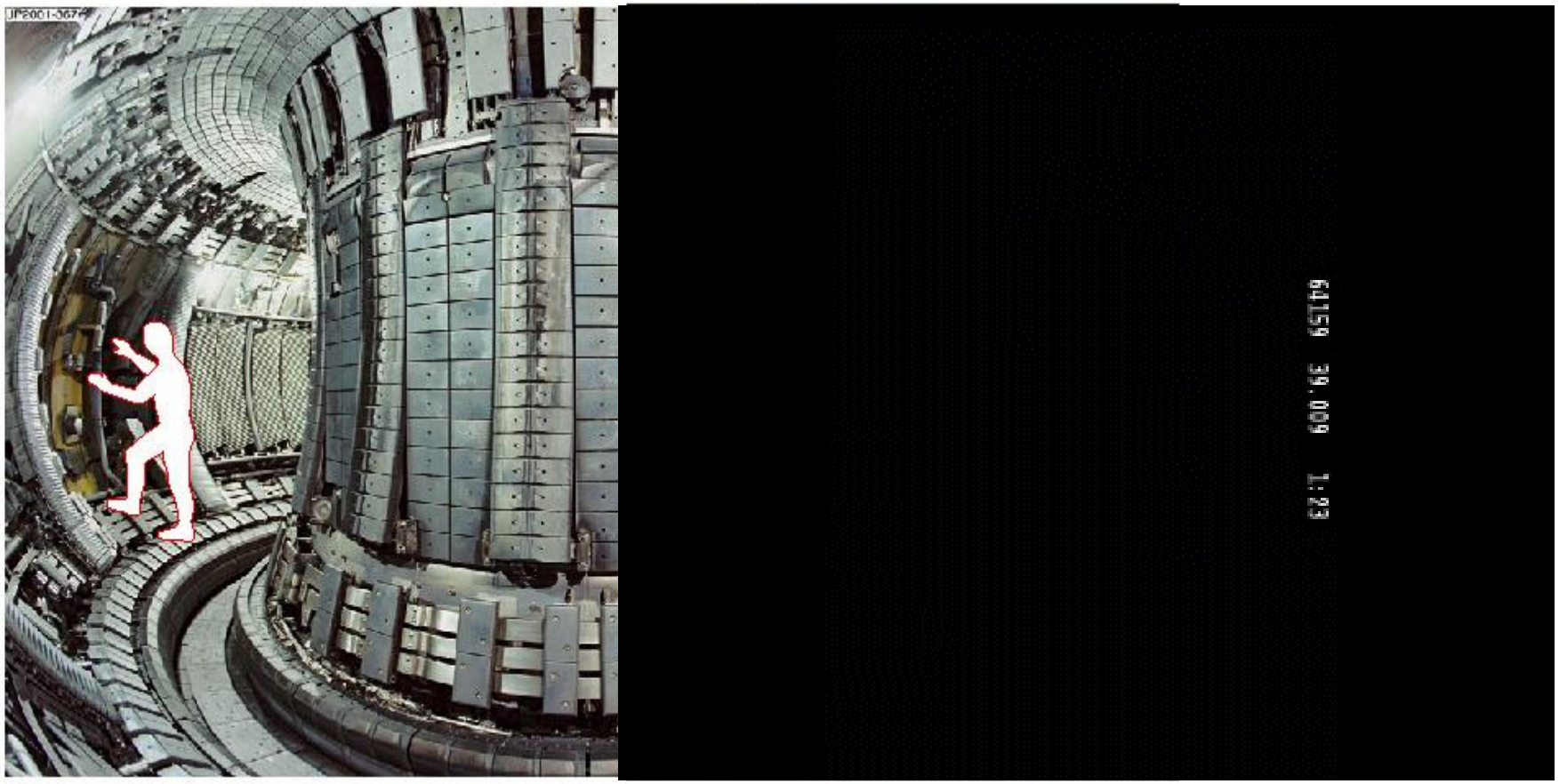
Tokamak

JET (Joint European Torus): R_0 = 3 m, a = 0.9 m, 1983-today



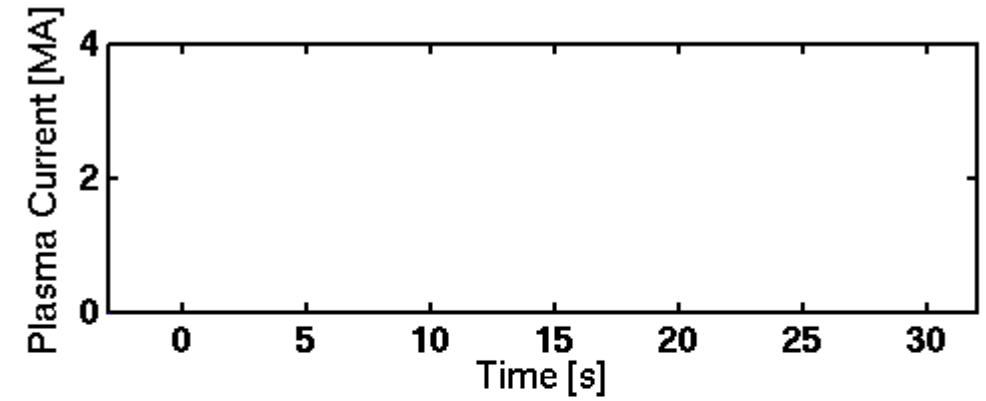
Tokamak

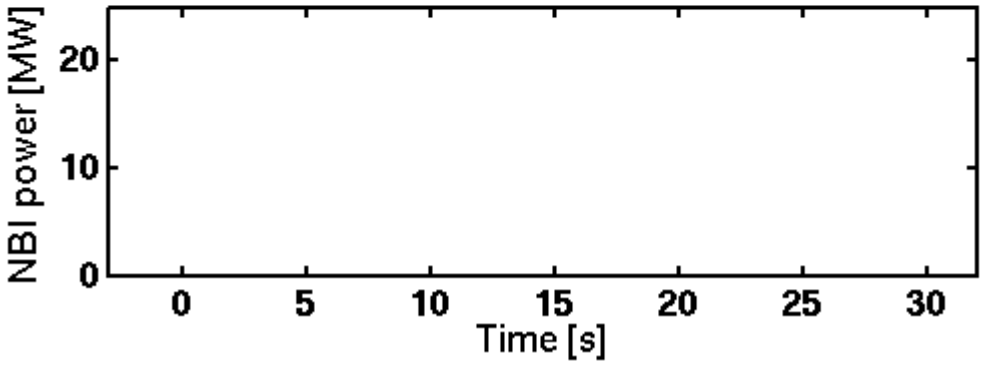
JET (Joint European Torus): R_0 = 3 m, a = 0.9 m, 1983-today



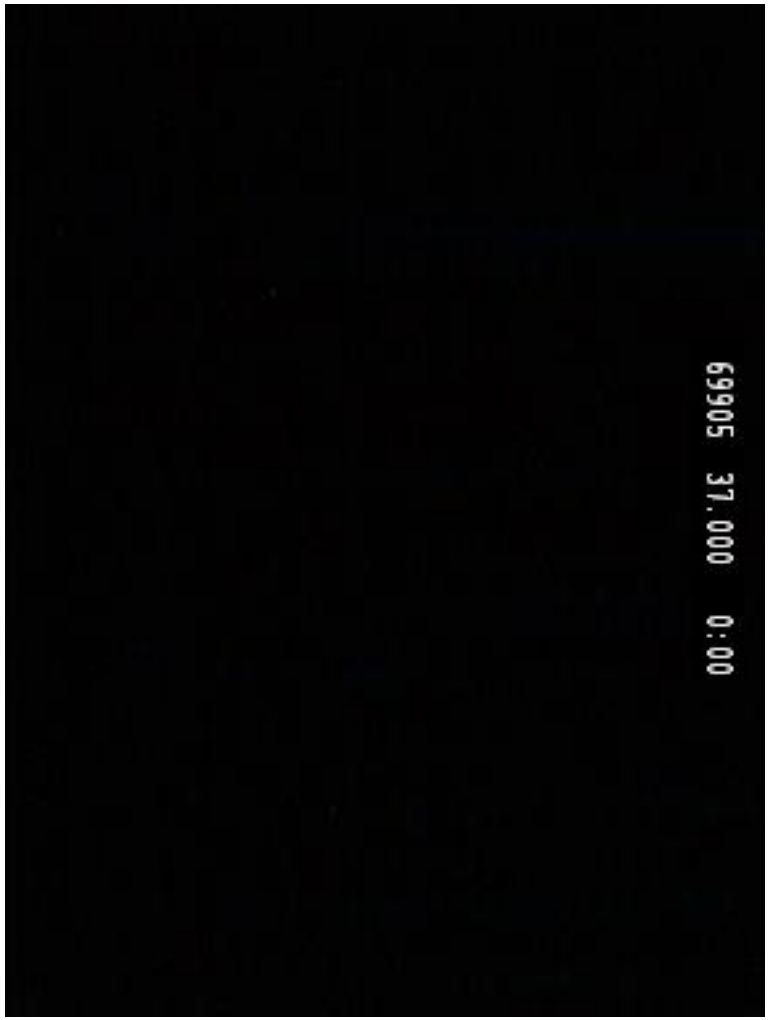
Tokamak

Plasma initiation	Current Ramp-up	High power phase	Plasma quench





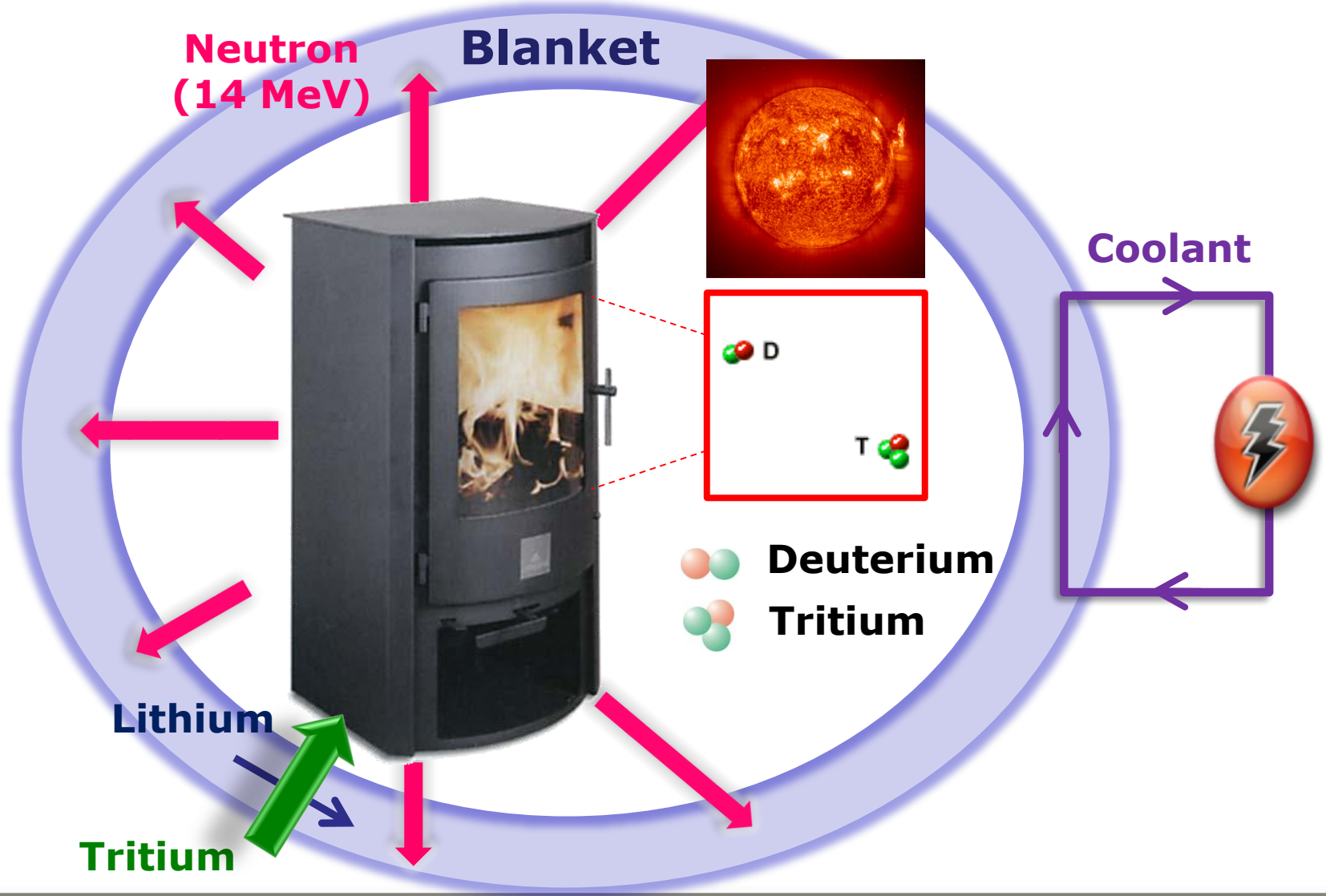
JET pulse 69905 (B_T=3.1T)



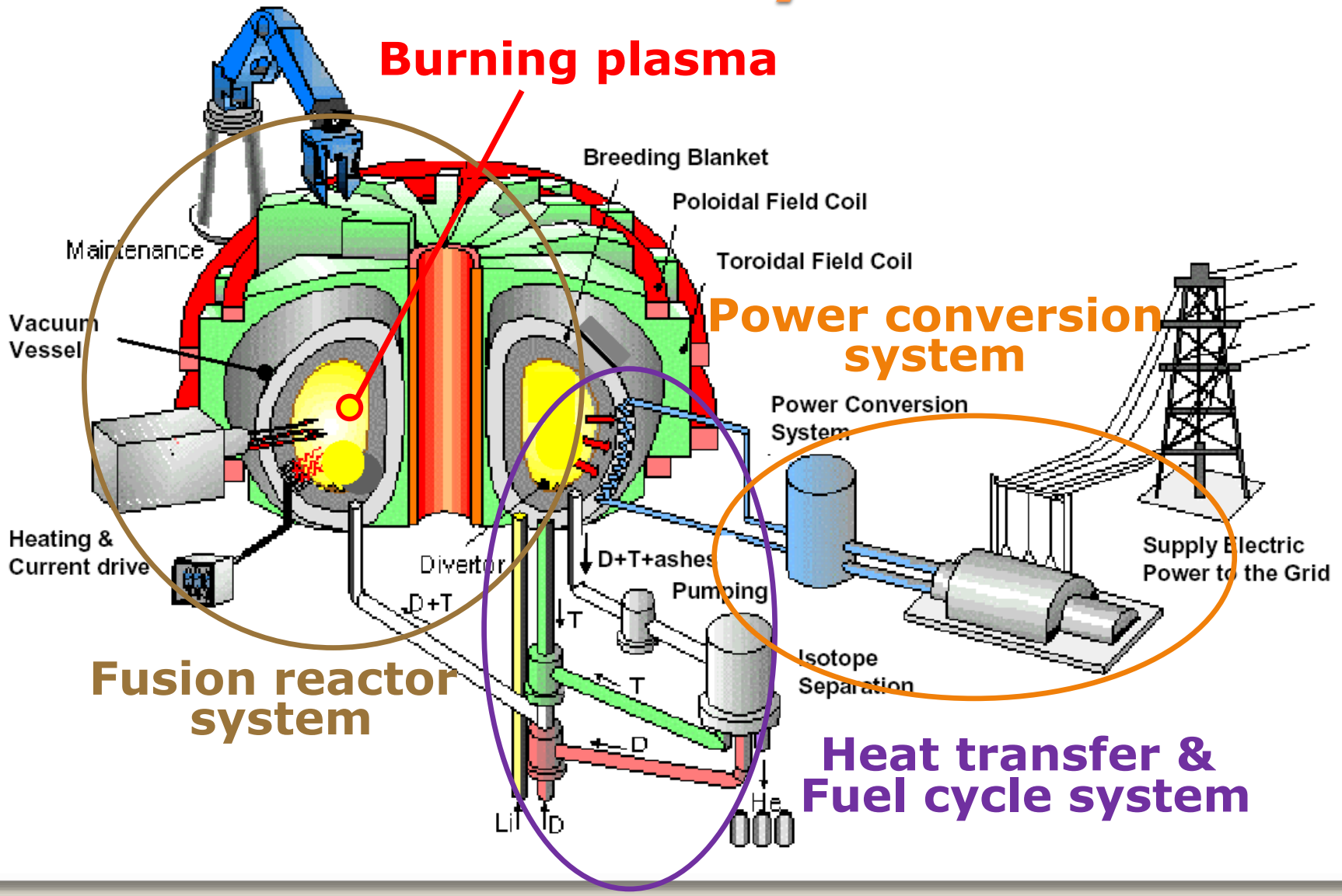
Tokamak

http://cafe.naver.com/gamebox26.cafe?iframe_url=/ArticleRead.nhn%3Farticleid=16140

Fusion Power Plant System

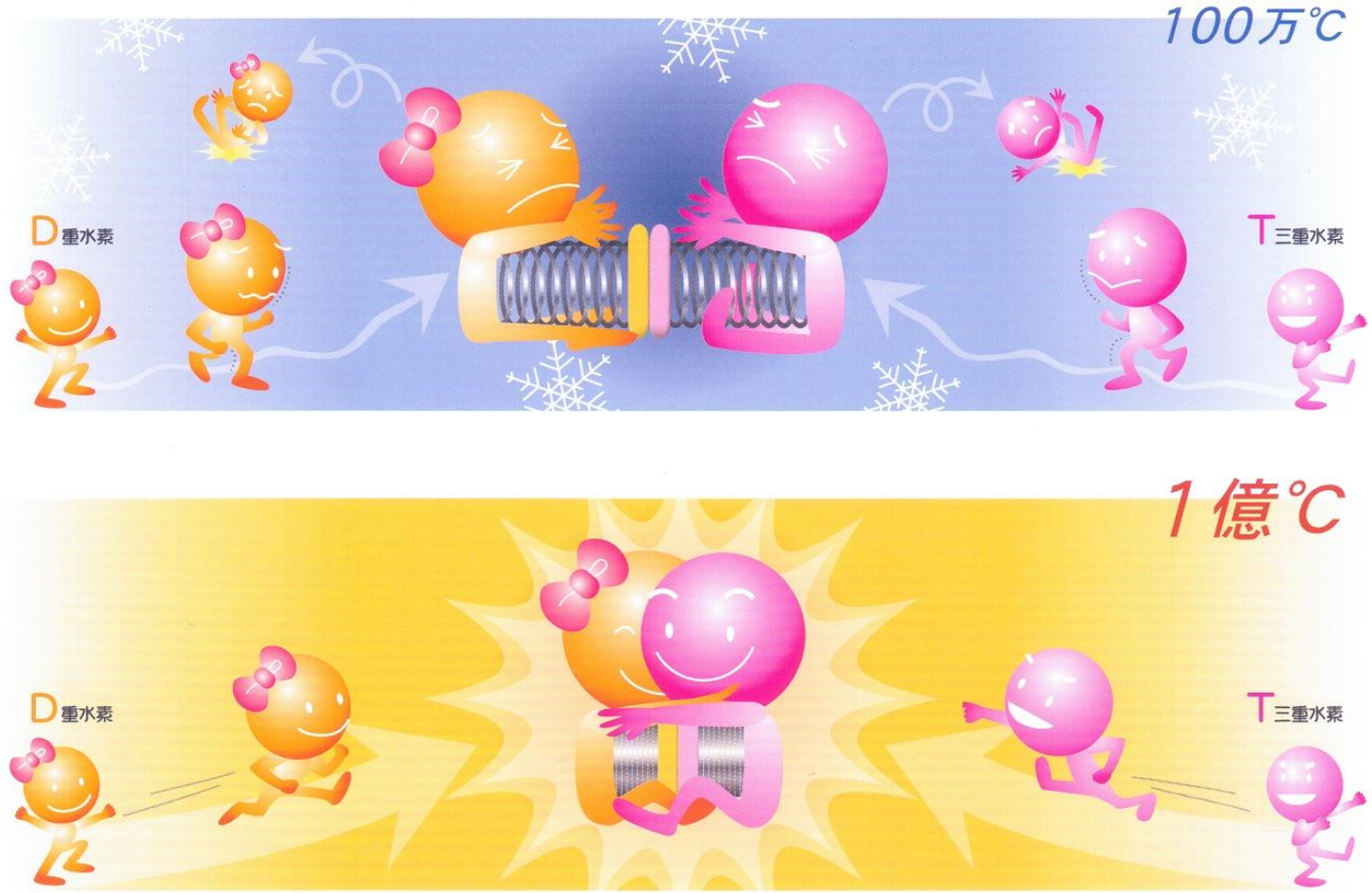


Fusion Power Plant System

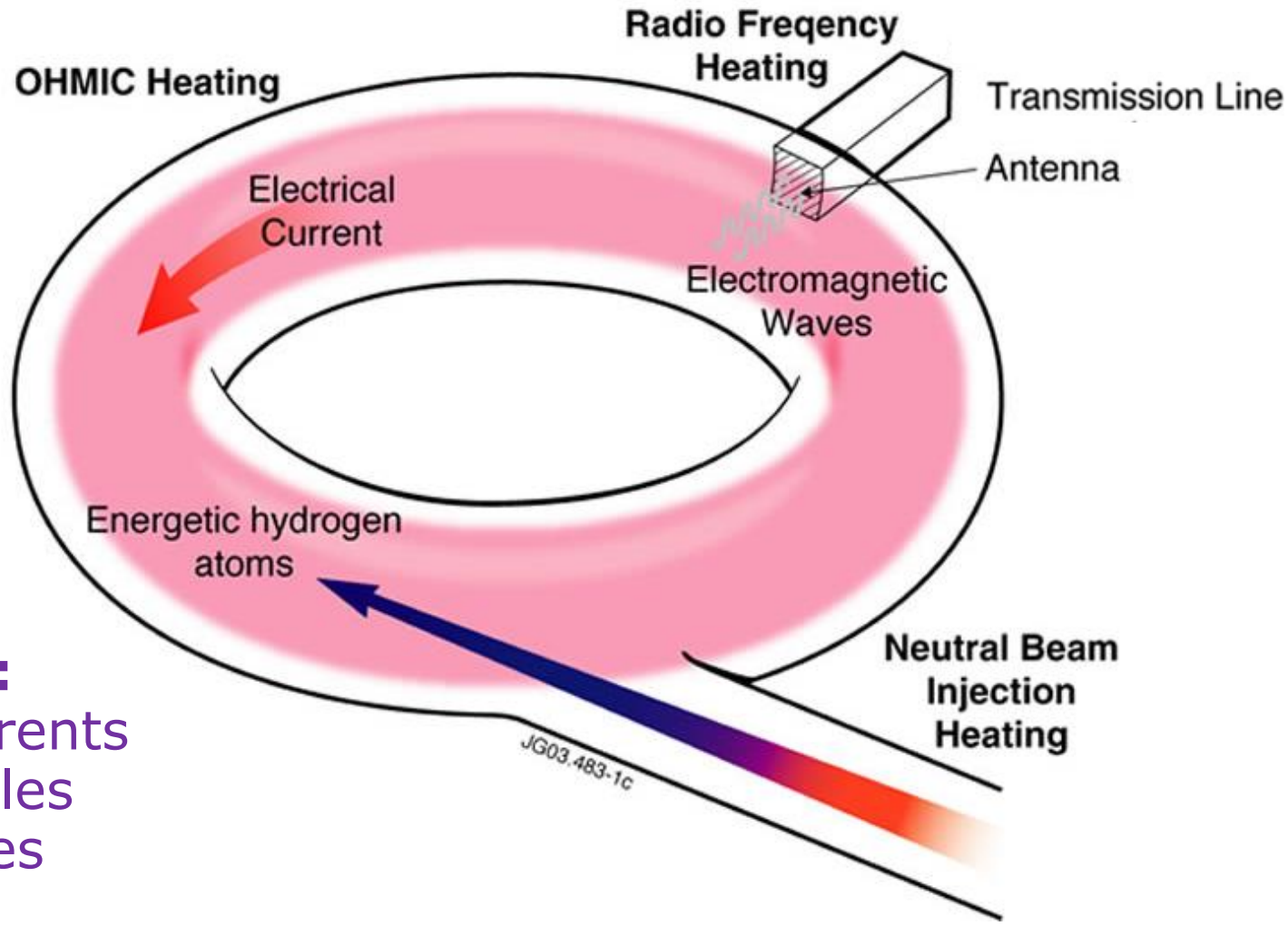


How to heat the plasma?

Why plasma heating?



Plasma Heating



Heating with:

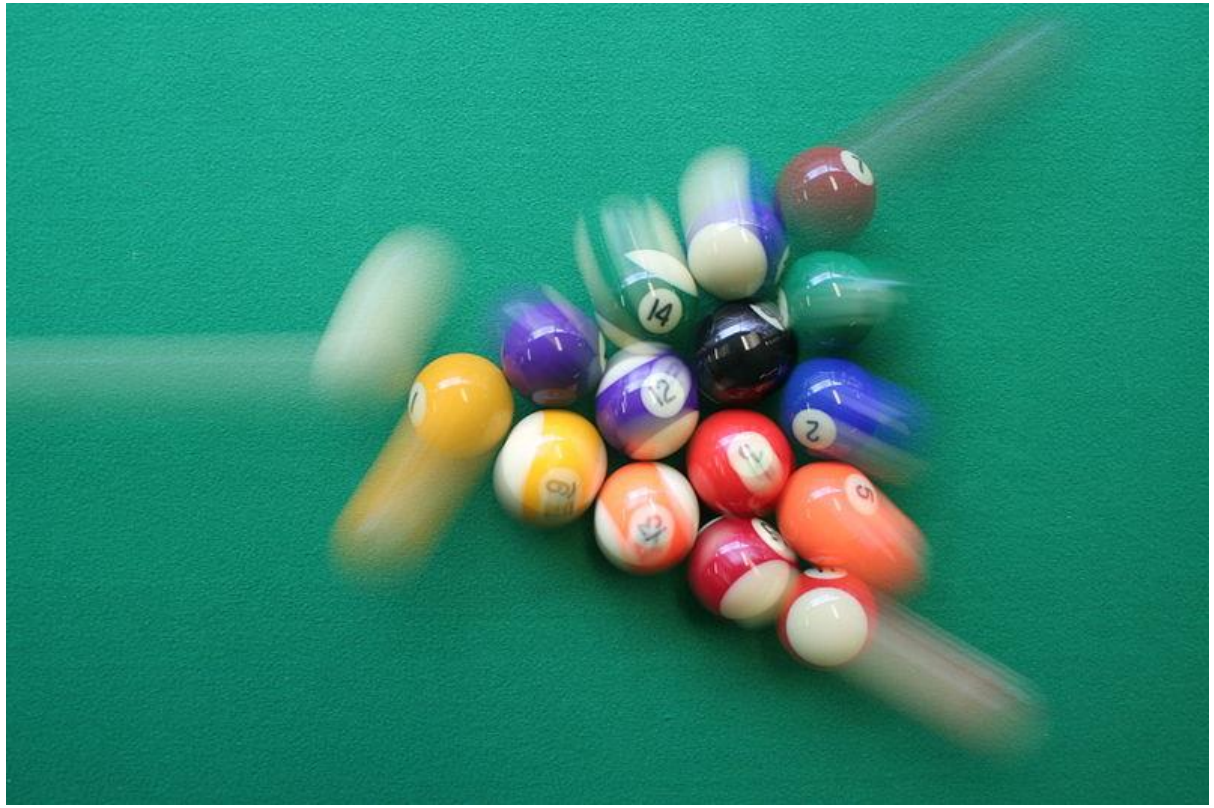
- ohmic currents
- fast particles
- microwaves

Plasma Heating– Ohmic Heating

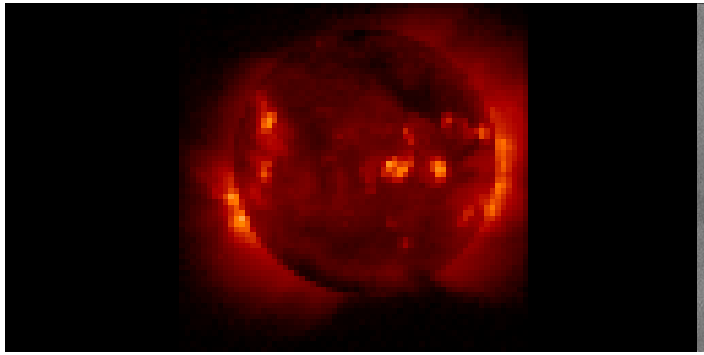
SAMIK Electric blanket

Auction, Korea (2014)

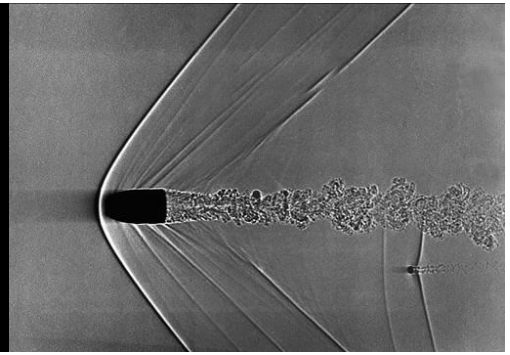
Plasma Heating– Neutral Beam Injection (NBI)



Plasma Heating– Neutral Beam Injection (NBI)



Plasma



Neutral beam

NBI

Andy Warhol

http://www.nasa.gov/mission_pages/galex/20070815/f.html

Plasma Heating– Neutral Beam Injection (NBI)

Injection of a beam of neutral fuel atoms (H, D, T) at high energies (E_b > 50 keV)

⇓

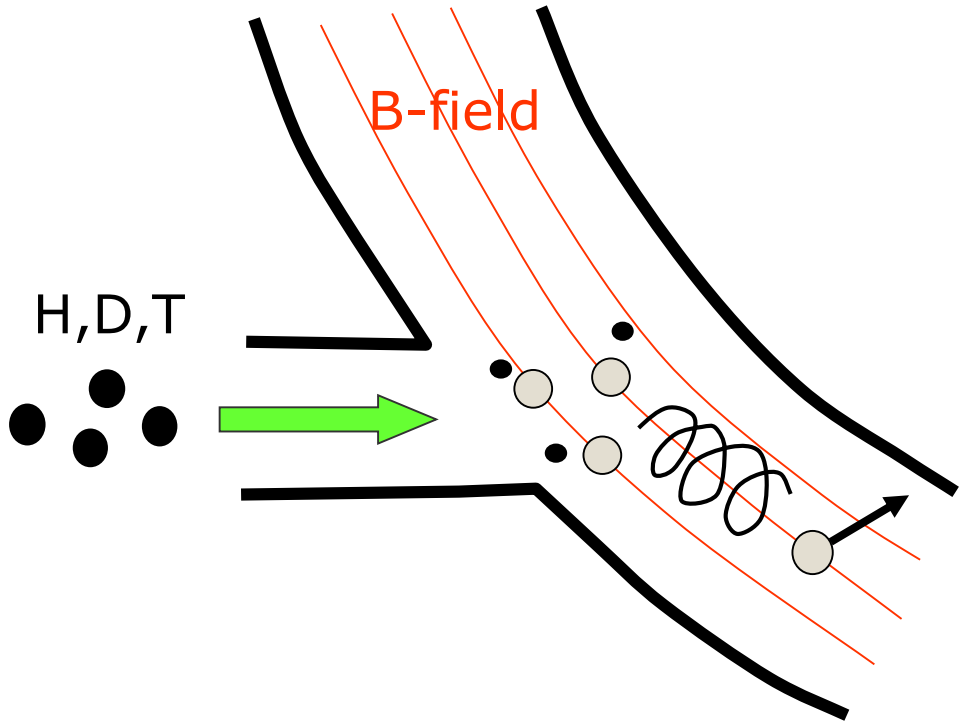
Ionisation in the plasma

⇓

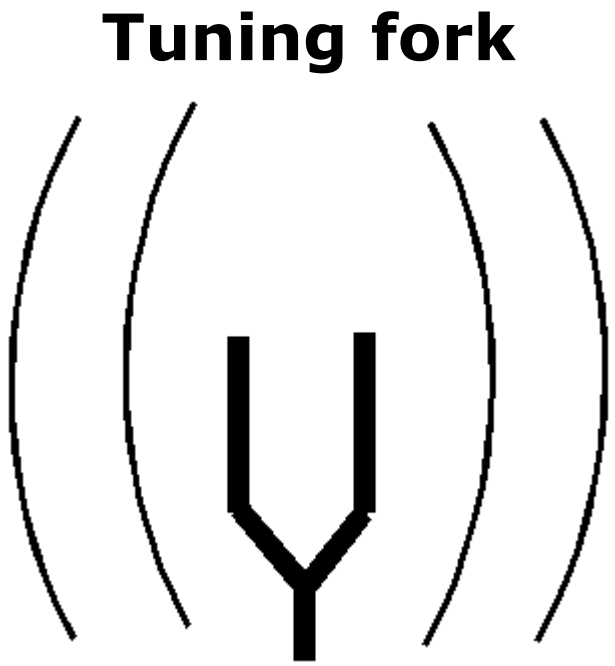
Beam particles confined

⇓

Collisional slowing down

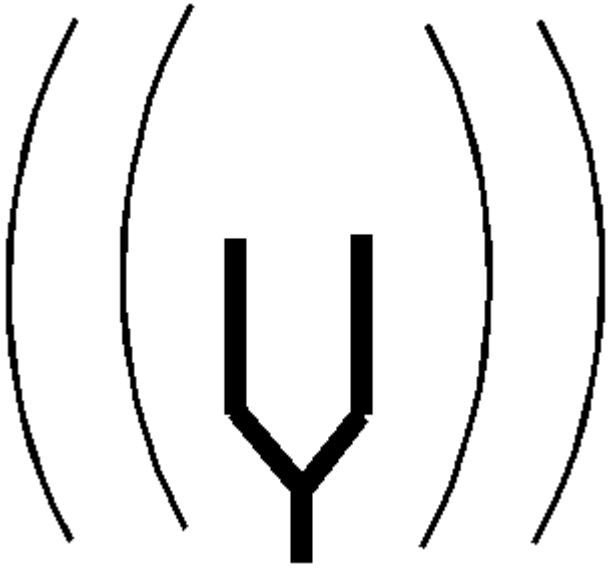


Plasma Heating– Wave (ICRH, ECRH, LHH)

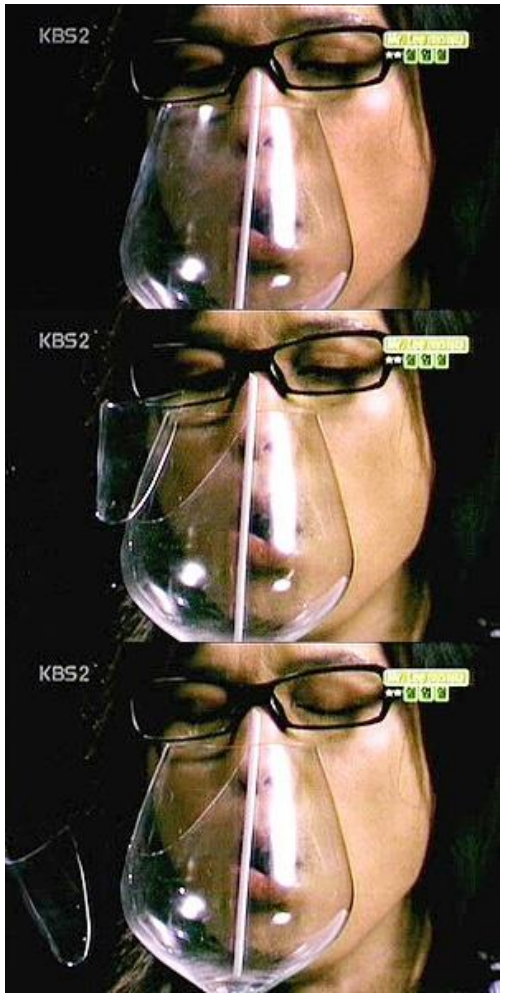


Plasma Heating– Wave (ICRH, ECRH, LHH)

Tuning fork

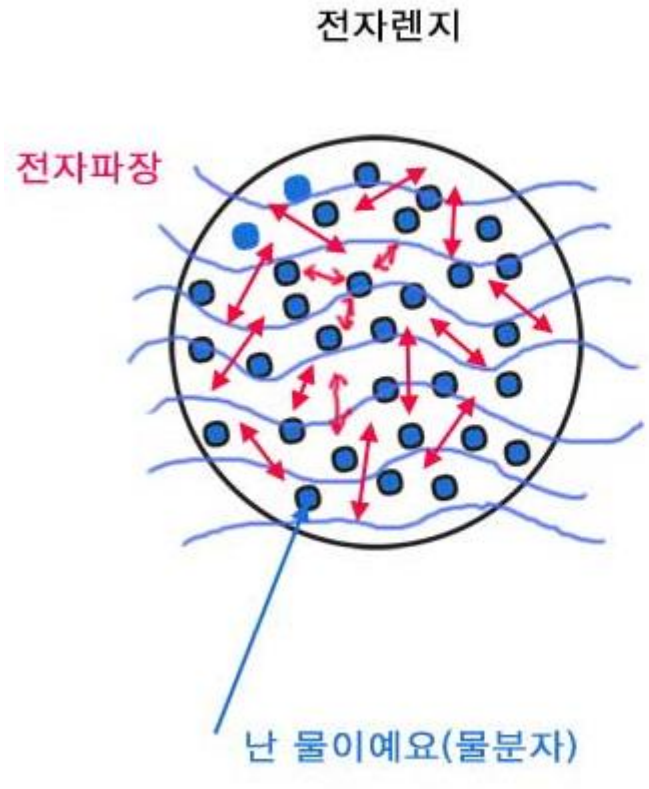


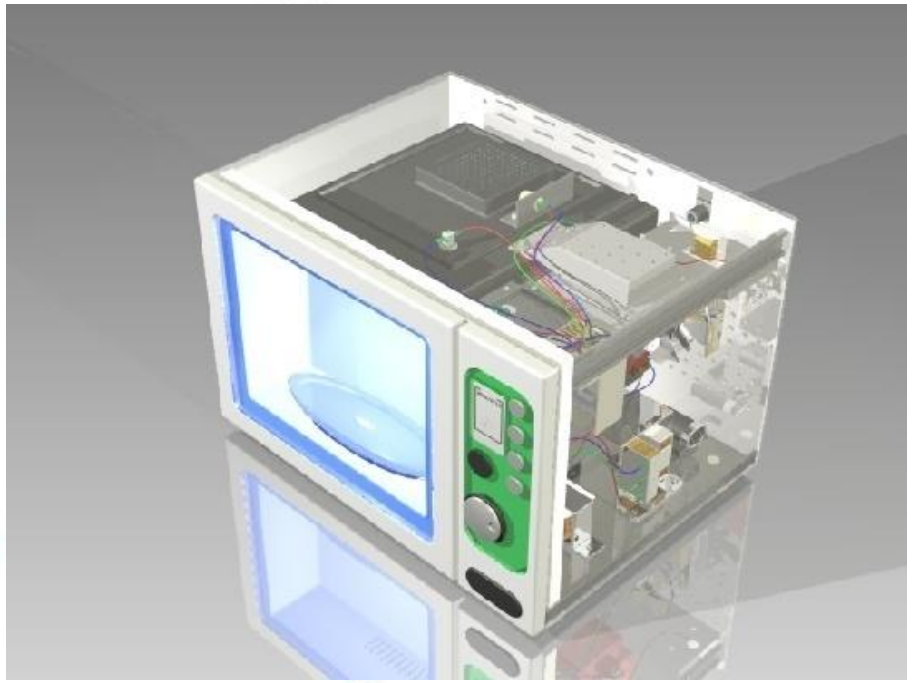
Resonance



KBS. 스펀지:목소리로 와인 잔 깨기. 2006.3.11
http://www.kbs.co.kr/end_program/2tv/enter/sponge/view/vod/1386311_1027.html

Plasma Heating– Wave (ICRH, ECRH, LHH)

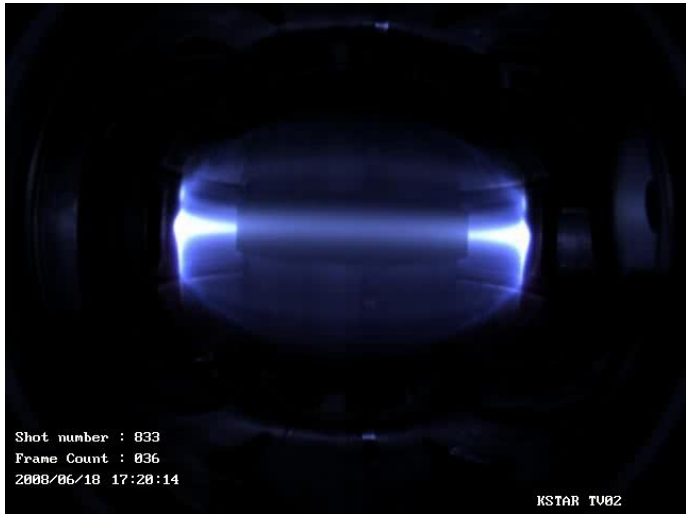




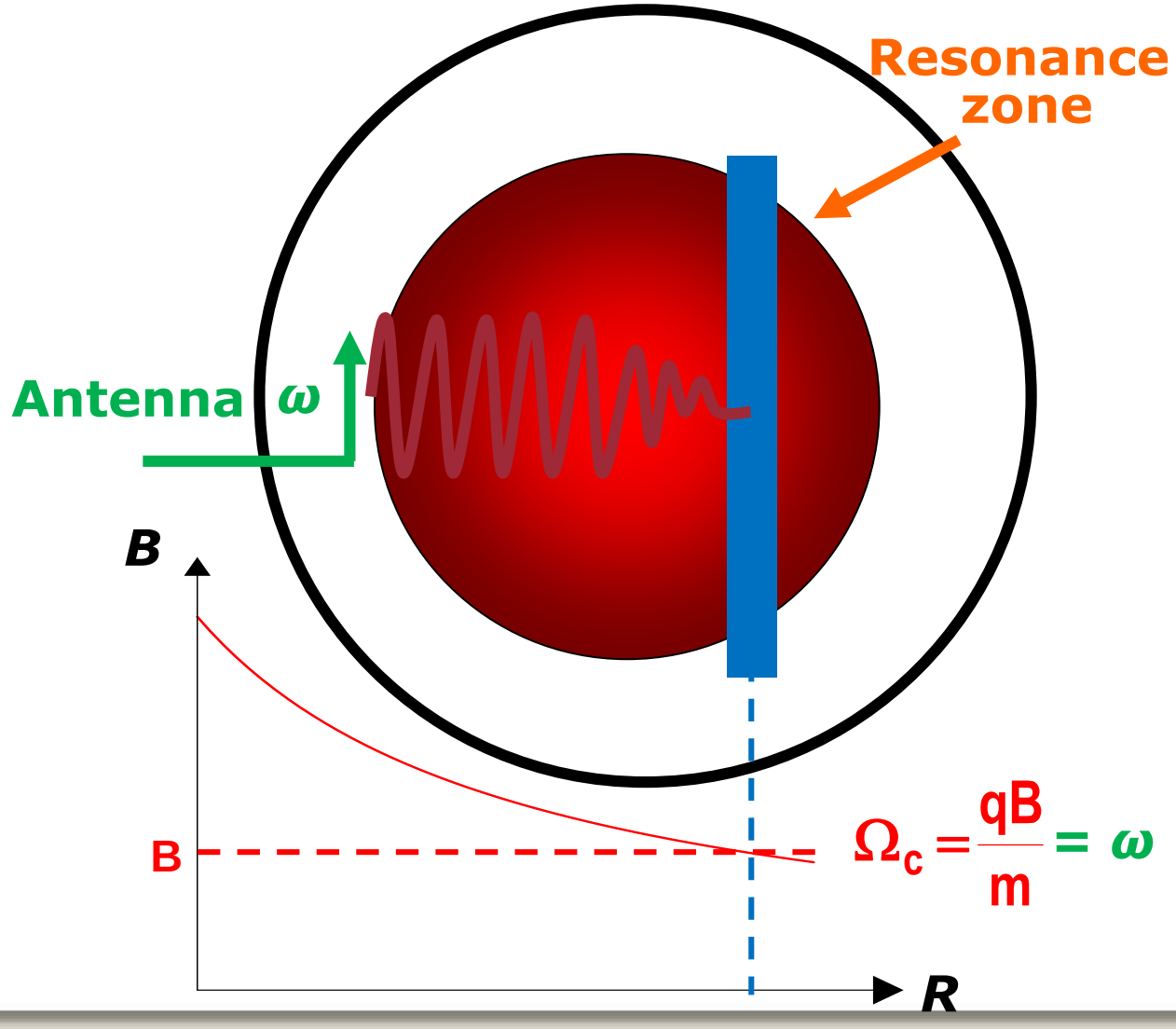
Microwave oven (2.45 GHz)

http://cafe.naver.com/nadobaker.cafe?iframe_url=/ArticleRead.nhn%3Farticleid=82
http://blog.naver.com/rlhyuny27?Redirect=Log&logNo=30029307561

Plasma Heating– Wave (ICRH, ECRH, LHH)



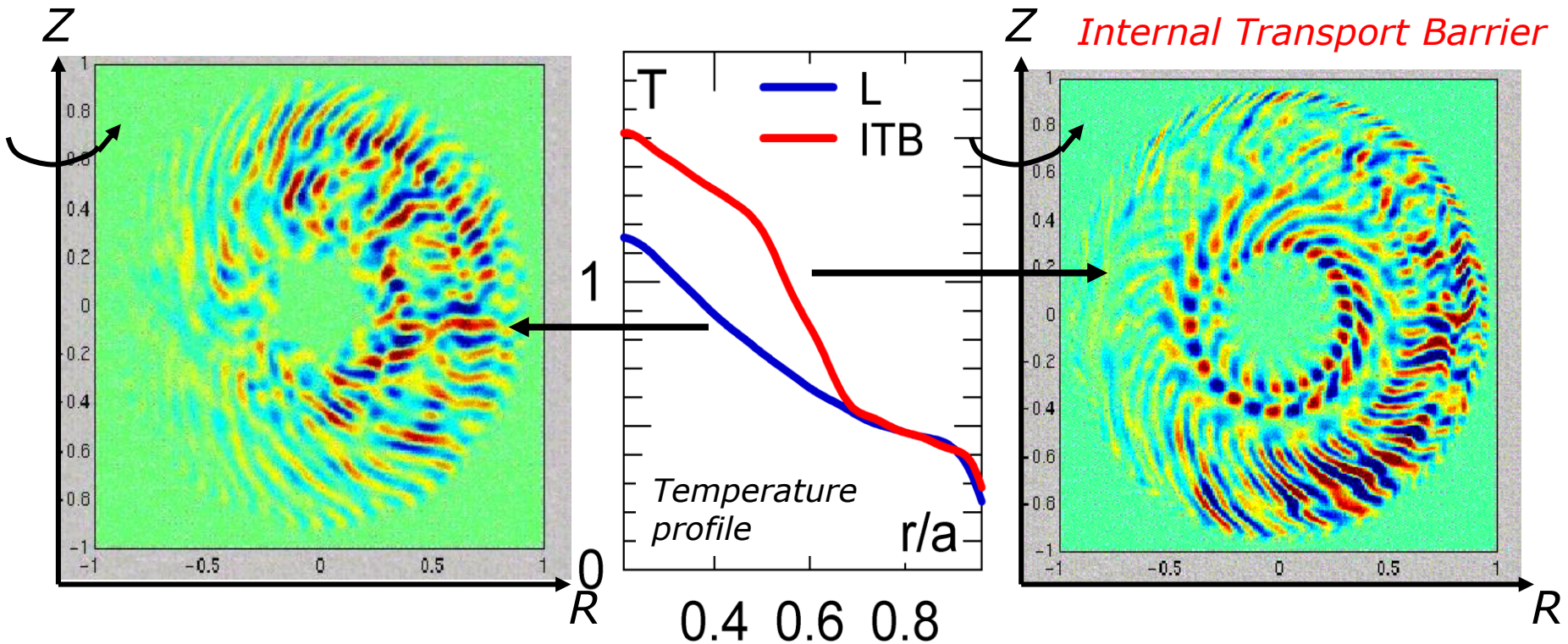
KSTAR first plasma



What are the critical issues?

Stabilisation of Plasma Turbulence

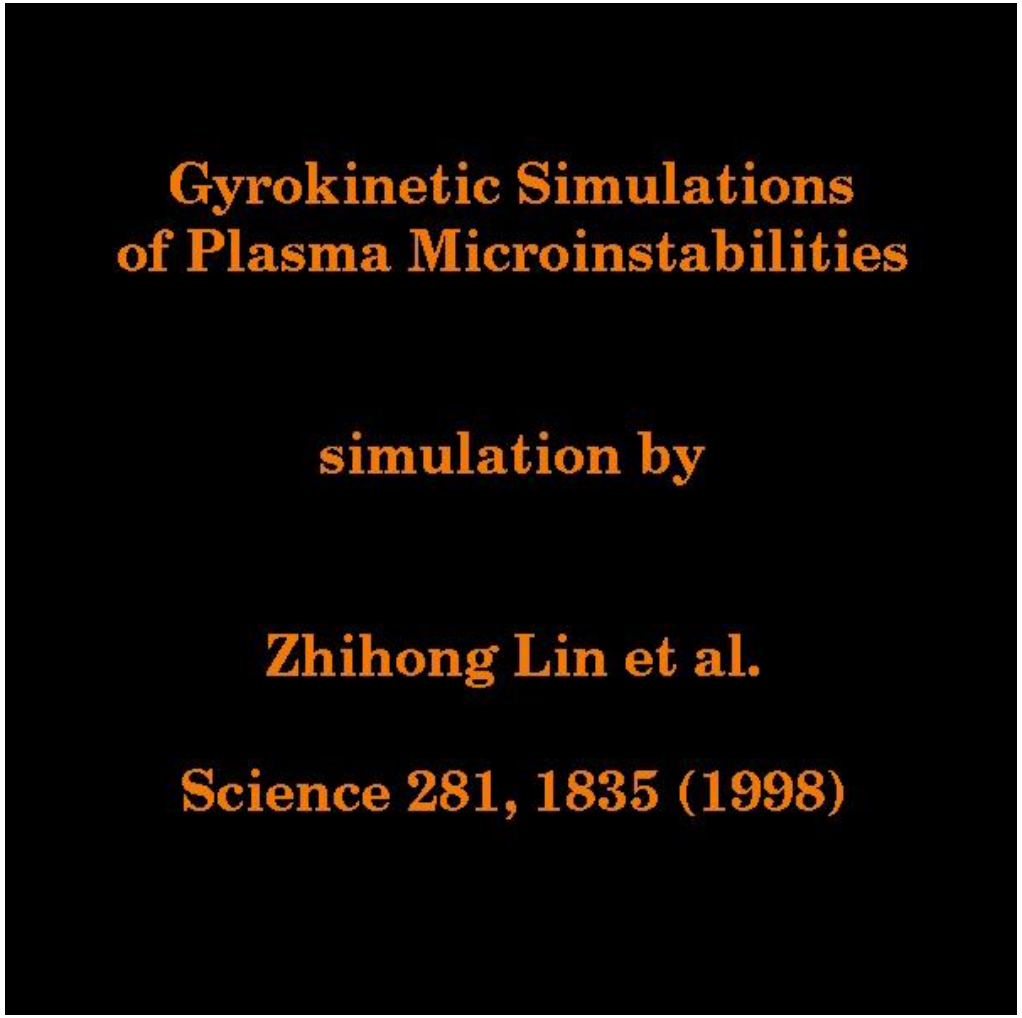
- **Turbulence stabilisation → Increase of plasma pressure**
  → High fusion power



Contour lines of electric potential

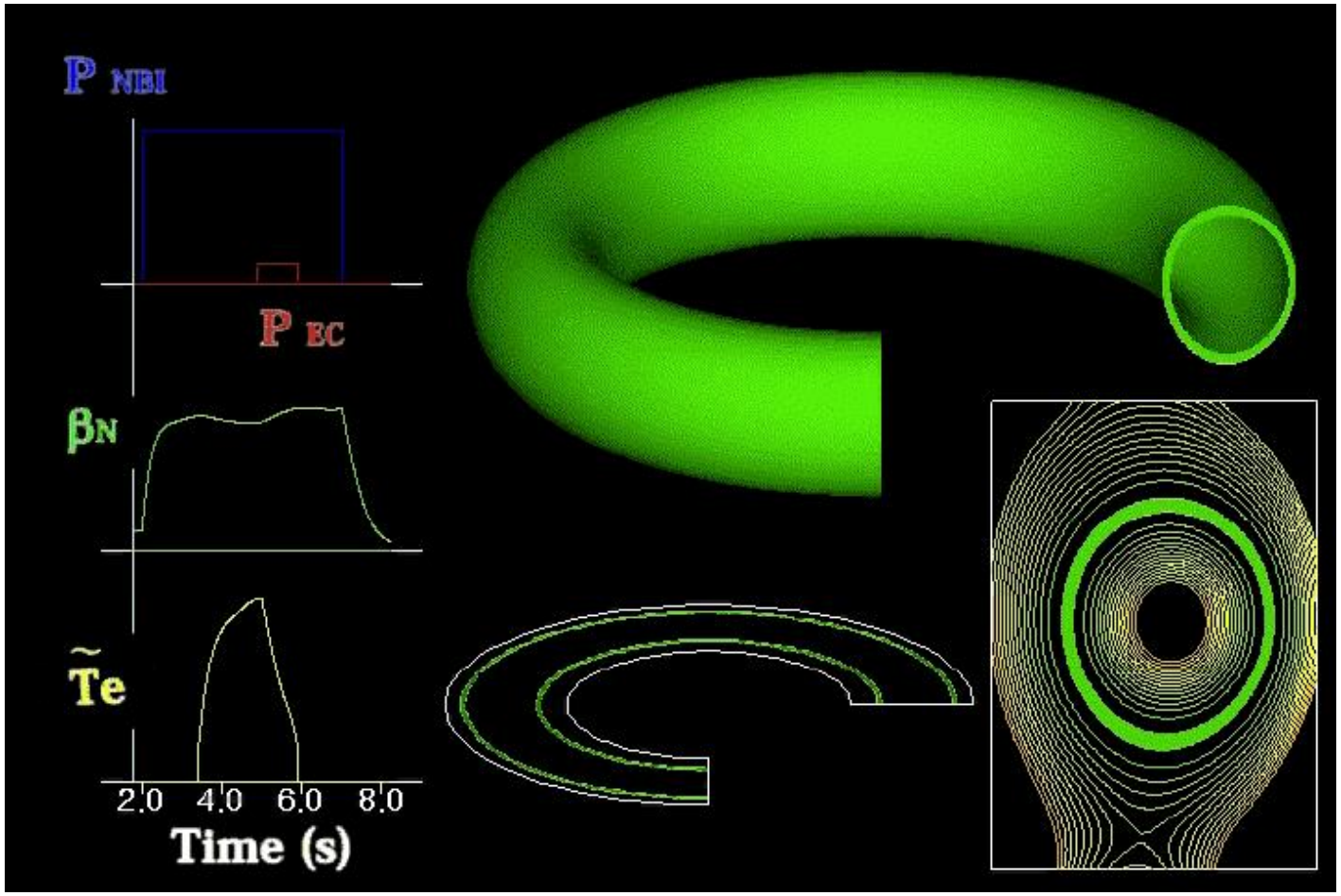
Contour lines of electric potential

Stabilisation of Plasma Turbulence

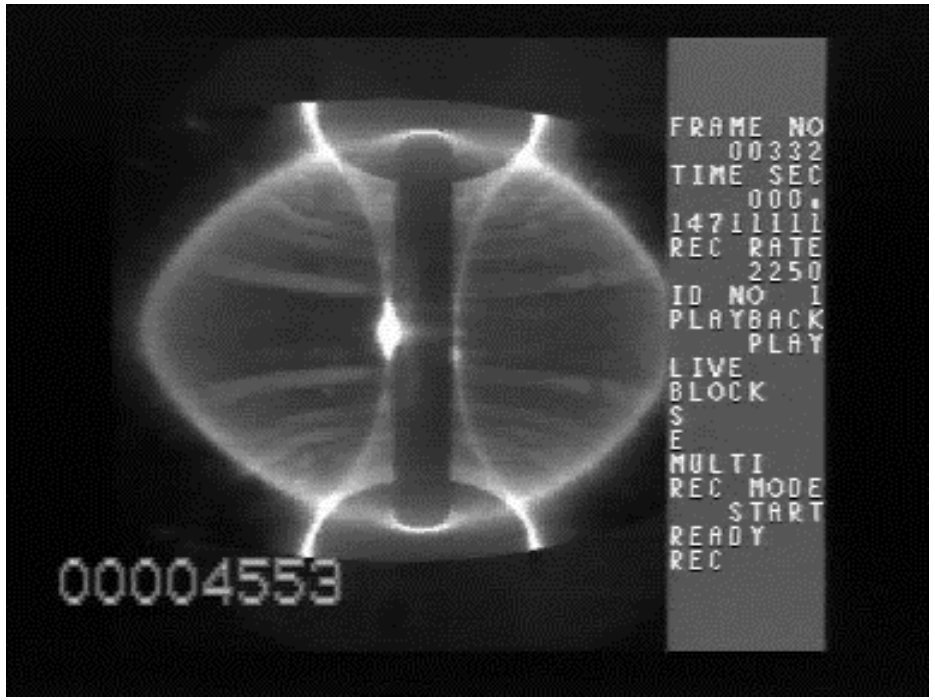


Suppression of Plasma Instabilities

- **Suppression of Neoclassical Tearing Mode by ECCD**

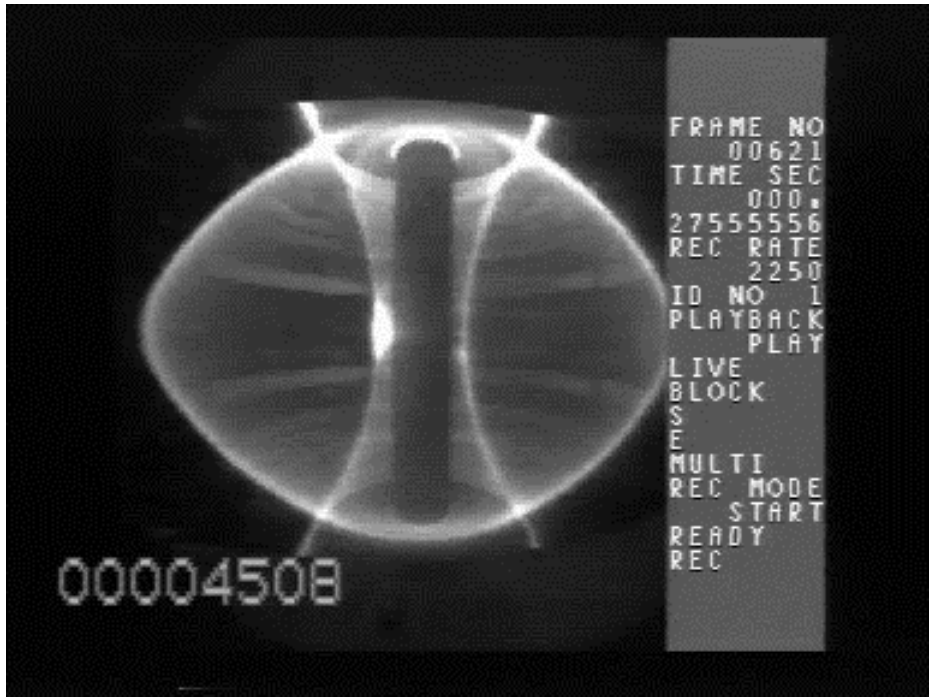


Edge Region Instability and Disruption



Edge Localised Mode

Vertical displacement event
→ Disruption

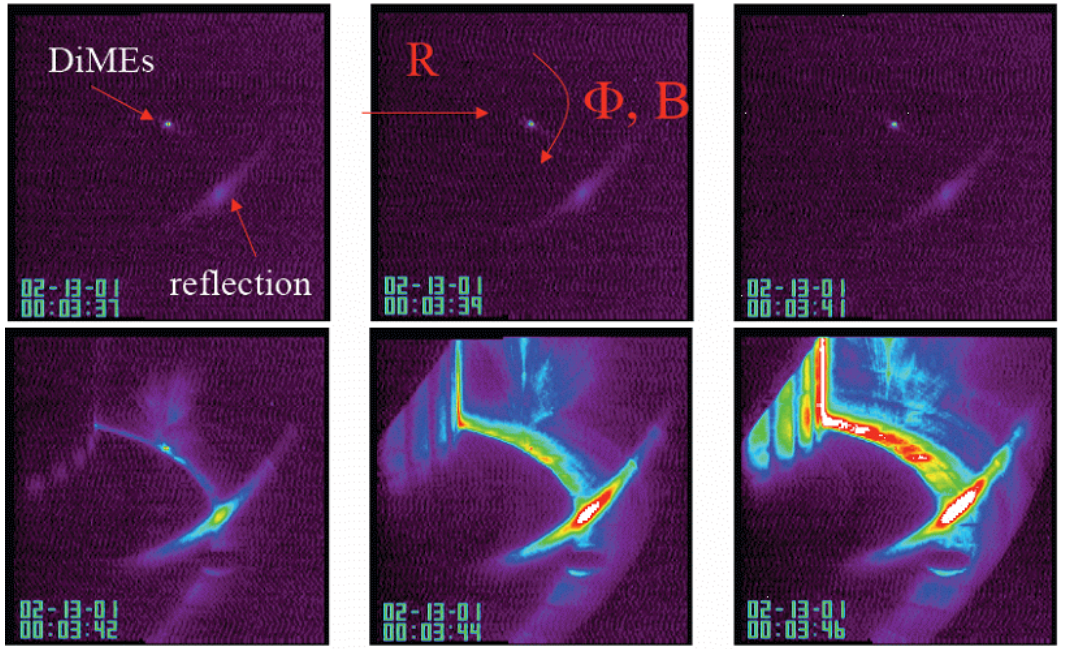


MAST
MEGA-AMPERE SPHERICAL TOKAMAK

The Sun Train

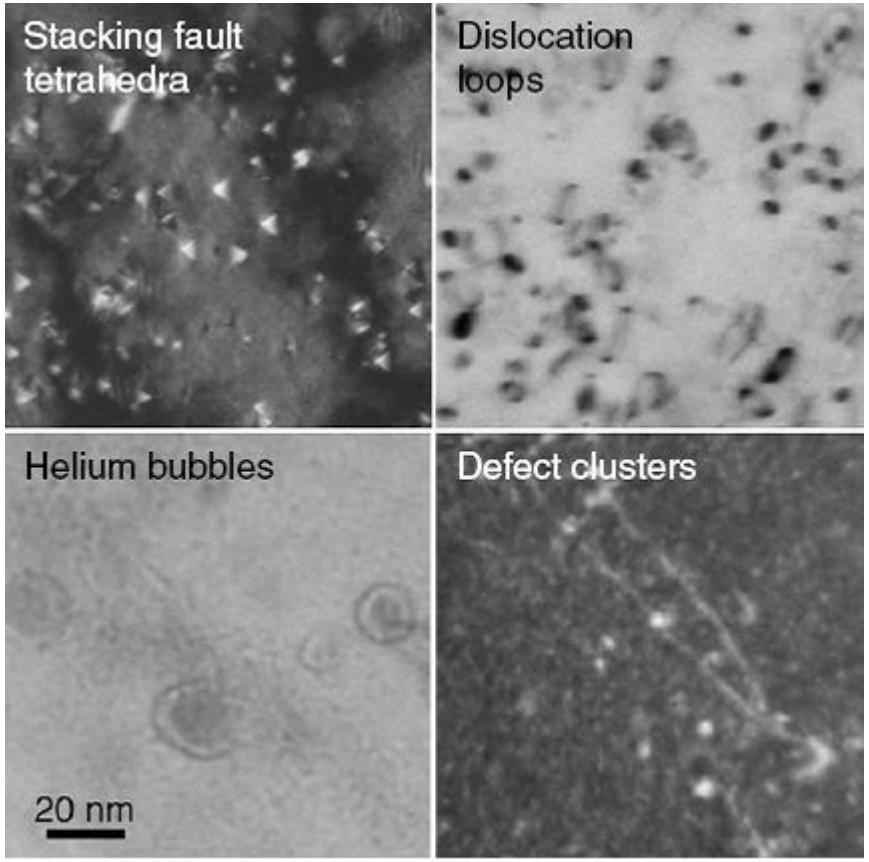
http://cafe.naver.com/gamebox26.cafe?iframe_url=/ArticleRead.nhn%3Farticleid=16140

Plasma– Wall interactions



- High heat flux to the surrounding materials

Radioactivation of Materials



- **Neutron impacts on materials**

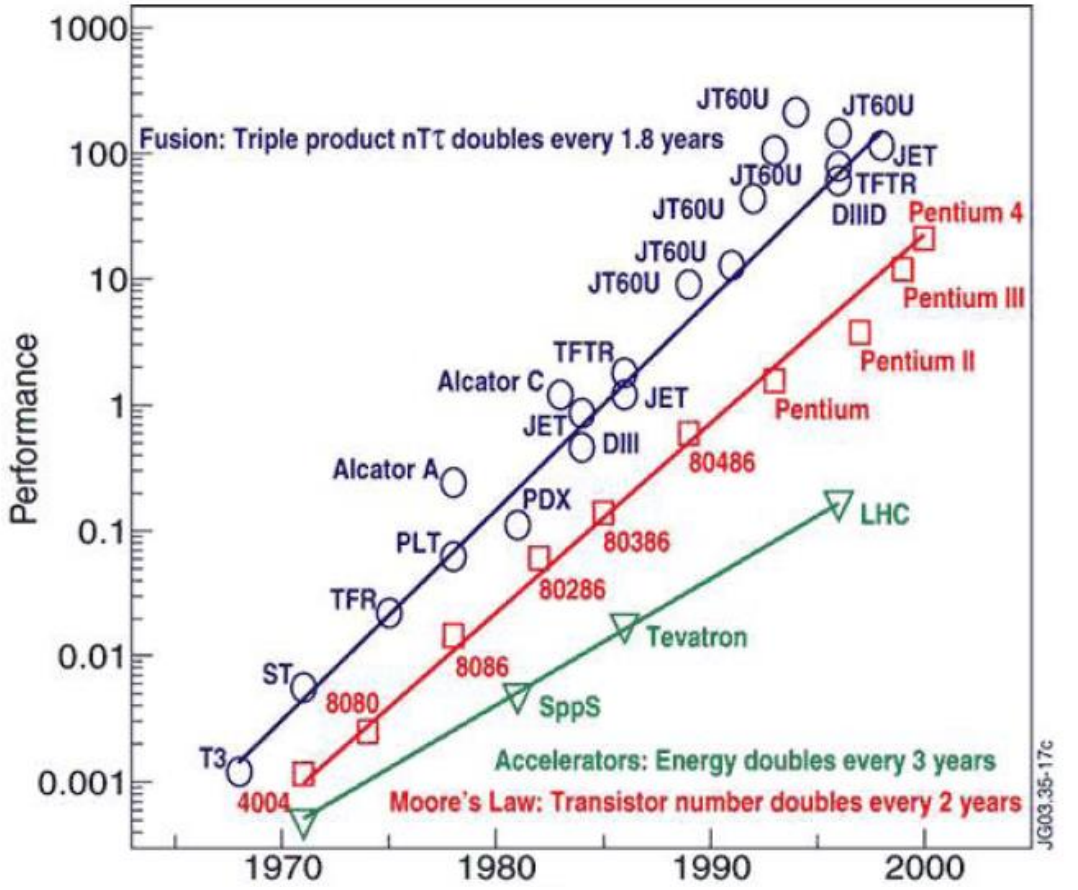
What are the current status and future prospect?

Status of the Tokamak Research

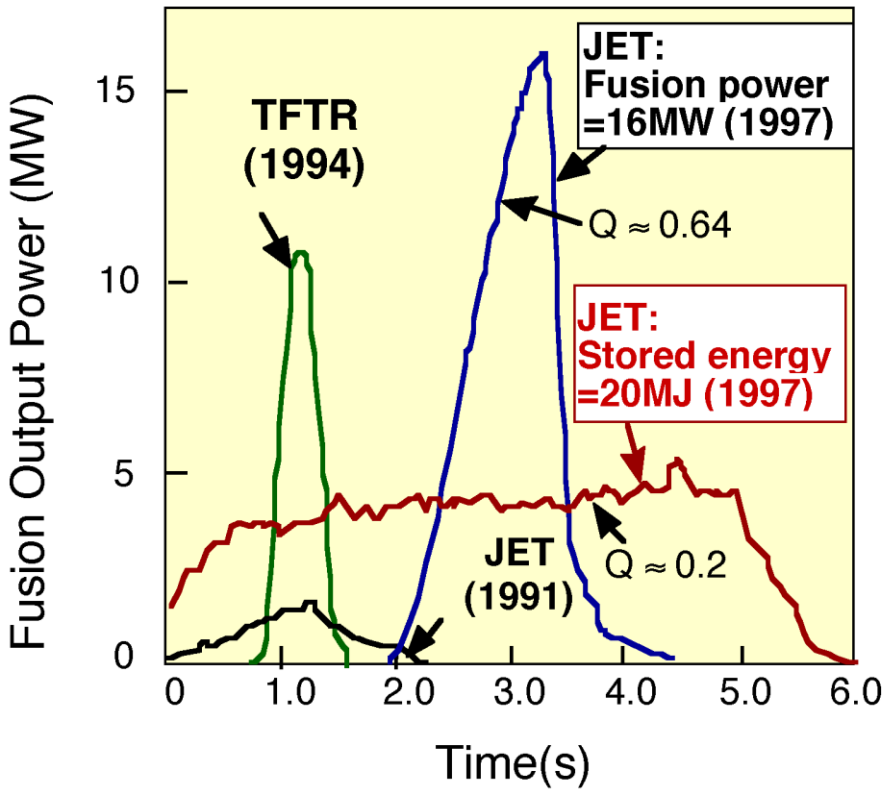
- Progress in fusion can be compared with the development of computer chips and particle physics accelerator energy.

- D-T Tokamaks produced significant fusion power:

  - TFTR (USA), JET (EU)



Status of the Tokamak Research

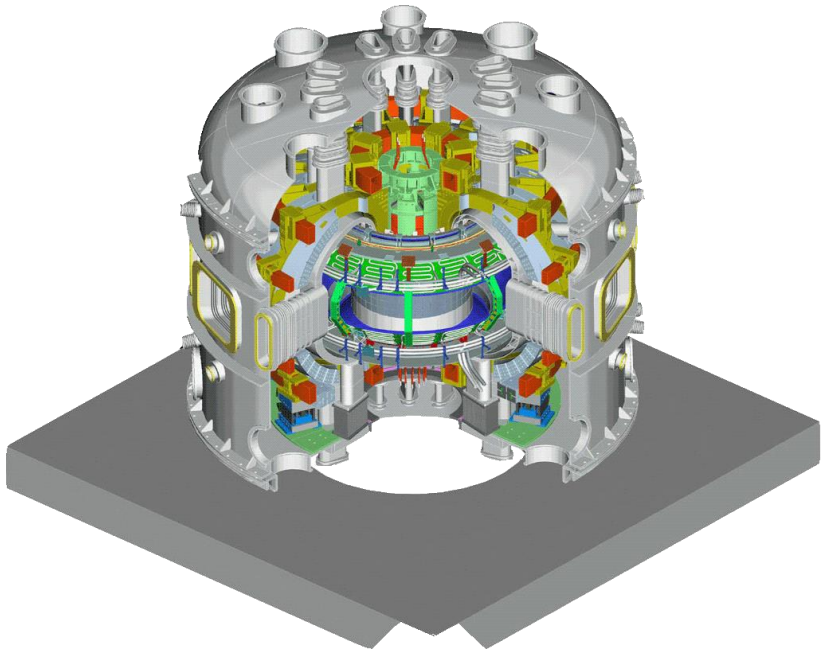


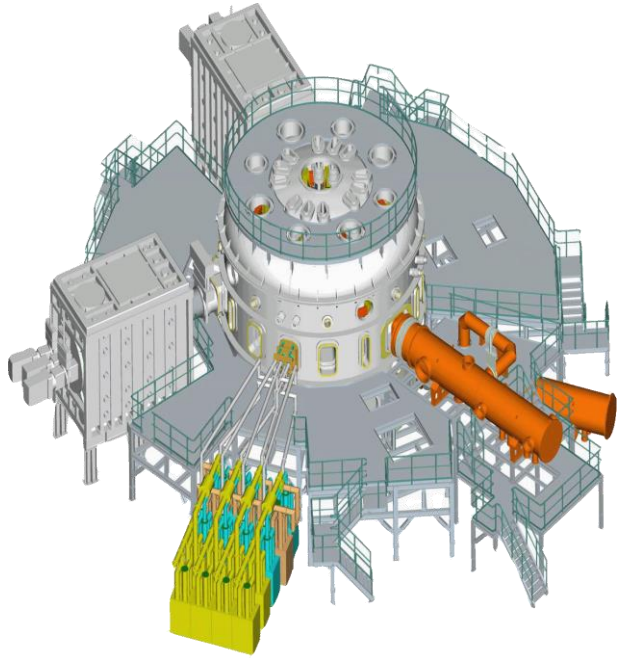
$$Q = \frac{\text{fusion output power}}{\text{input power}}$$

- **D-T tokamaks produced significant fusion power:**
  - TFTR (USA) ~10 MW in 1994
  - JET (EU) 16 MW (Q=0.64) in 1997

KSTAR Project

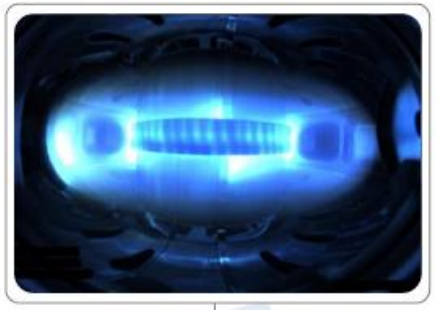
- **K**orea **S**uperconducting **T**okamak **A**dvanced **R**esearch
  - superconducting tokamak using ITER-relevant magnets
  - capability of reactor-relevant plasma performances





- Objective - To integrate optimized plasma performance and continuous operation as a step toward an attractive tokamak fusion reactor

KSTAR Project



1995
Launch of KSTAR Project

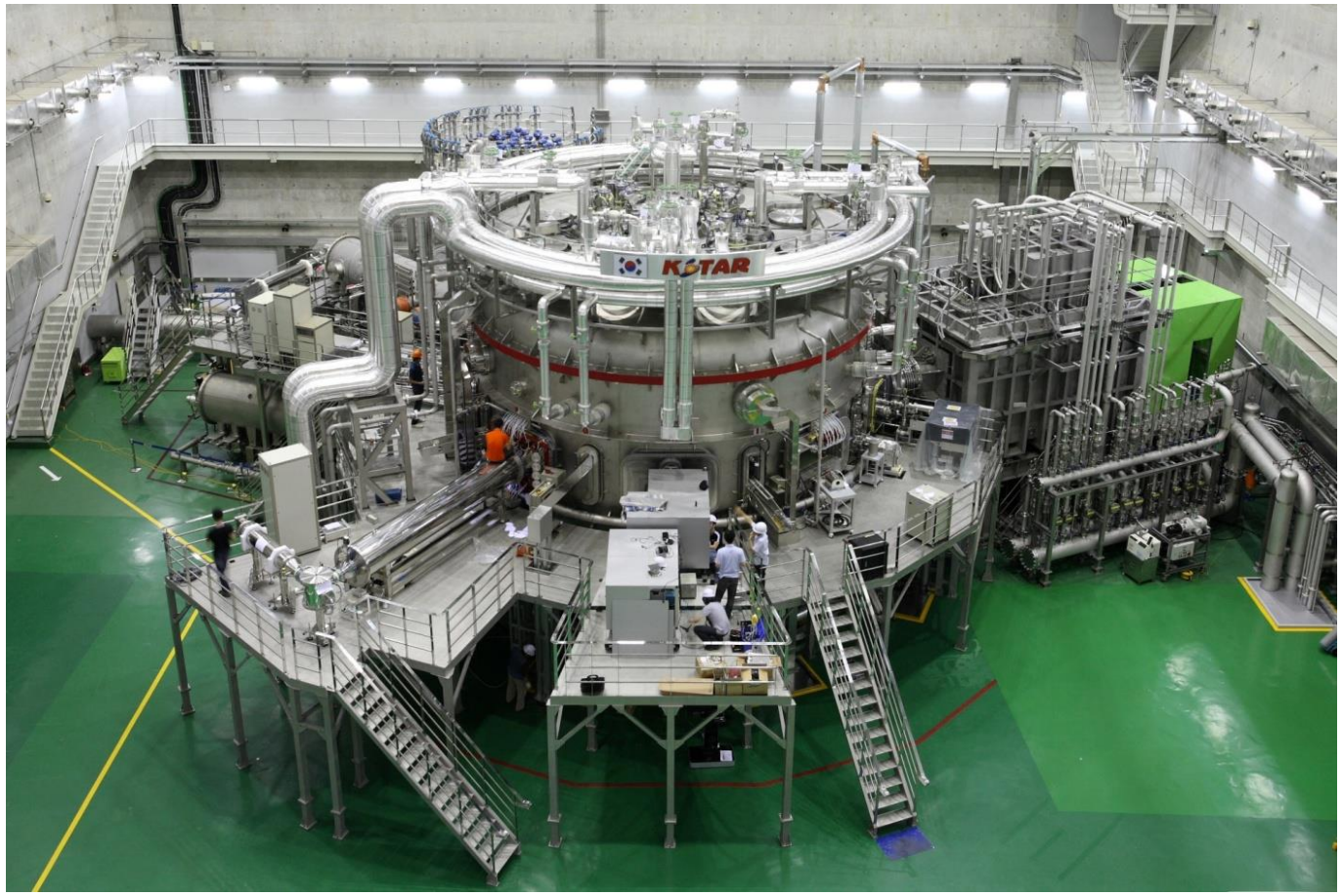
1995~1997
Basic Design and R&D

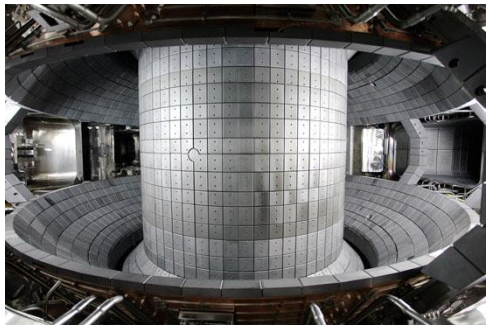
1998~2001
Engineering Design and Facility Construction

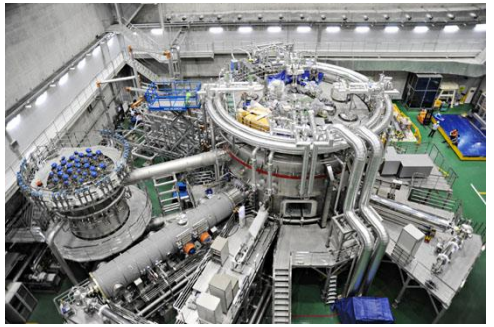
2002~2007
Construction of KSTAR

June 2008
First Plasma

KSTAR Project







"All the News That's Fit to Print"

The New York Times

Late Edition

Weather: Rain likely today, strong easterly winds; rain ending late tonight. Partly cloudy and warmer tomorrow. Temperatures: today 42-47, tonight 40-45; yesterday 38-62. Details, page C30.

VOL. CXXXV . . No. 46,601 NEW YORK, FRIDAY, NOVEMBER 22, 1985

80 cents beyond 75 miles from New York City, except on Long Island. 30 CENTS

Text of the Joint U.S.-Soviet Statement: 'Greater Understanding Achieved'

Special to The New York Times

GENEVA, Nov. 21 — Following is the text of the joint Soviet-American statement at the end of the summit meeting today, as made public by the White House:

By mutual agreement, the President of the United States, Ronald Reagan, and the General Secretary of the Central, Committee of the Communist Party of the Soviet Union, Mikhail S. Gorbachev, met in Geneva Nov. 19-21. Attending the meeting on the U.S. side were Secretary of State George P. Shultz; chief of staff, Donald T. Regan; Assistant to the President, Robert C. McFarlane; Ambassador to the U.S.S.R., Arthur A. Hartman; special adviser to the President and the Secretary of State for Arms Control, Paul H. Nitze; Assistant Secretary of State of European Affairs, Rozanne L. Ridgway; Special Assistant to the President for National Security Affairs, Jack F. Matlock.

Attending on the Soviet side were member of the Politburo of the Central Committee of the C.P.S.U., Minister of Foreign Affairs Eduard A. Shevardnadze; First Deputy Foreign Minister Georgi M. Korniyenko; Ambassador to the United States, Anatoly F. Dobrynin; head of the Department of Propaganda of the Central Committee of the C.P.S.U., Aleksandr N. Yakovlev; head of the Department of International Information of the Central Committee of the C.P.S.U., Leonid M. Zamyatin; assistant to the General Secretary of the Central Committee of the C.P.S.U., Andrei M. Aleksandrov.

These comprehensive discussions covered the basic questions of U.S.-Soviet relations and the current international situation. The meetings were frank and useful. Serious differences remain on a number of critical issues.

While acknowledging the differences in their systems and approaches to international issues, some greater understanding of each side's view was achieved by the two leaders. They agreed about the need to improve U.S.-Soviet relations and the international situation as a whole.

In this connection the two sides have confirmed the importance of an ongoing dialogue, reflecting their strong desire to seek common ground on existing problems.

They agreed to meet again in the nearest future. The General Secretary accepted an invitation by the President of the United States to visit the United States of America, and the President of the United States accepted an invitation by the General Secretary of the Central Committee of the C.P.S.U. to visit the Soviet Union. Arrangements for the timing of the visits will be agreed upon through diplomatic channels.

In their meetings, agreement was reached on a number of specific issues. Areas of agreement are registered on the following pages.

Security

The sides, having discussed key security issues, and conscious of the special responsibility of the USSR and the U.S. for maintaining peace, have agreed that a nuclear war cannot be won and must never be fought. Recognizing that any conflict between the U.S.S.R. and the U.S. could have catastrophic consequences, they emphasized the importance of preventing any war between them, whether nuclear or conventional. They will not seek to achieve military superiority.

Nuclear and Space Talks

The President and the General Secretary discussed the negotiations on nuclear and space arms.

They agreed to accelerate the work at these negotiations, with a view to accomplishing the tasks set down in the Joint U.S.-Soviet Agreement of Jan. 8, 1985, namely to prevent an arms race in space and to terminate it on earth, to limit and reduce nuclear arms and enhance strategic stability.

Noting the proposals recently tabled by the U.S. and the Soviet Union, they called for early progress, in particular in areas where there is common ground, including the principle of 50 percent reductions in the nuclear arms of the U.S. and the U.S.S.R. appropriately applied, we well as the idea of an interim I.N.F. agreement.

During the negotiation of these agreements, effective measures for verification of compliance with obligations assumed will be agreed upon.

Risk Reduction Centers

The sides agreed to study the question at the expert level of centers to reduce nuclear risk taking into account the issues and developments in the Geneva negotiations. They took satisfaction in such recent steps in this direction as the modernization of the Soviet-U.S. hot line.

Nuclear Nonproliferation

General Secretary Gorbachev and President Reagan reaffirmed the commitment of the U.S.S.R. and the U.S. to the Treaty on the Nonproliferation of Nuclear Weapons and their interest in strengthening together with other countries the nonproliferation regime, and in further enhancing the effectiveness of the treaty, inter alia by enlarging its membership.

The U.S.S.R. and the U.S. reaffirm their commitment, assumed by them under the Treaty on the Nonproliferation of Nuclear Weapons, to pursue negotiations in good faith on matters of nuclear arms limitation and disarmament in accordance with Article VI of the treaty.

The two sides plan to continue to promote the strengthening of the International Atomic Energy Agency and to support the activities of the agency in implementing safeguards as well as in promoting the peaceful uses of nuclear energy.

They view positively the practice of regular Soviet-U.S. consultations on nonproliferation of nuclear weapons, which have been businesslike and constructive, and express their intent to continue this practice in the future.

Chemical Weapons

In the context of discussing security problems, the two sides reaffirmed that they are in favor of a general and complete prohibition of chemical weapons and the destruction of existing stockpiles of such weapons. They agreed to accelerate efforts to conclude an effective and verifiable international convention on this matter.

The two sides agreed to intensify bilateral discussions on the level of experts on all aspects of such a chemical weapons ban, including the question of verification. They agreed to initiate a dialogue on preventing the proliferation of chemical weapons.

Mutual Regio

ministries and departments in such fields as agriculture, housing and protection of the environment have been useful.

Recognizing that exchanges of views on regional issues on the expert level have proven useful, they agreed to continue such exchanges on a regular basis.

The sides intend to expand the programs of bilateral cultural, educational and scientific-technical exchanges, and also to develop trade and economic ties. The President of the United States and the General Secretary of the Central Committee of the C.P.S.U. attended the signing

— a global task — through joint research and practical measures. In accordance with the existing U.S.-Soviet agreement in this area, consultations will be held next year in Moscow and Washington on specific programs of cooperation.

Exchange Initiatives

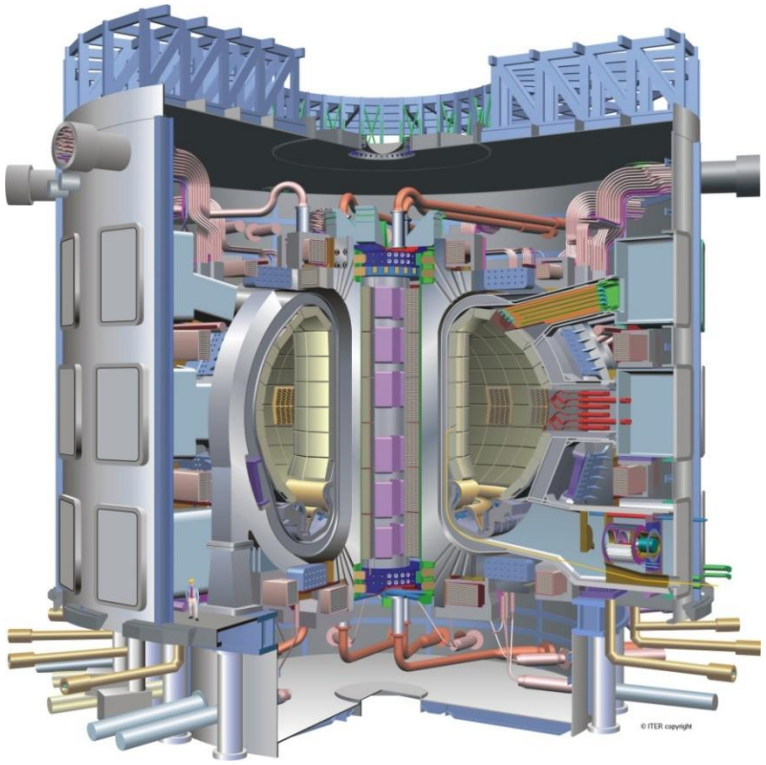
The two leaders agreed on the utility of broadening exchanges and contacts including some of their new forms in a number of scientific, educational, medical and sports

Fusion Research

The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentialy inexhaustible, for the benefit for all mankind.

ITER Project

- **I**nternational **T**hermonuclear **E**xperimental **R**eactor
  - "the way" in Latin
  - the essential next step in the development of fusion



- Objective - To demonstrate the scientific and technological feasibility of fusion power.
  - The world's biggest international research project

ITER Project

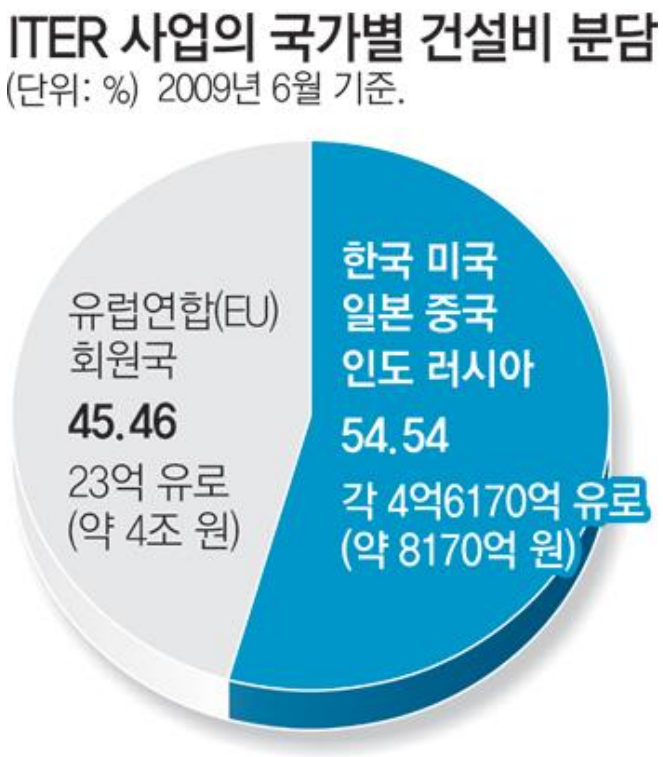
- **I**nternational **T**hermonuclear **E**xperimental **R**eactor
  - "the way" in Latin
  - the essential next step in the development of fusion

ITER 서명식, 2006.11.23, 과학기술부

ITER Project

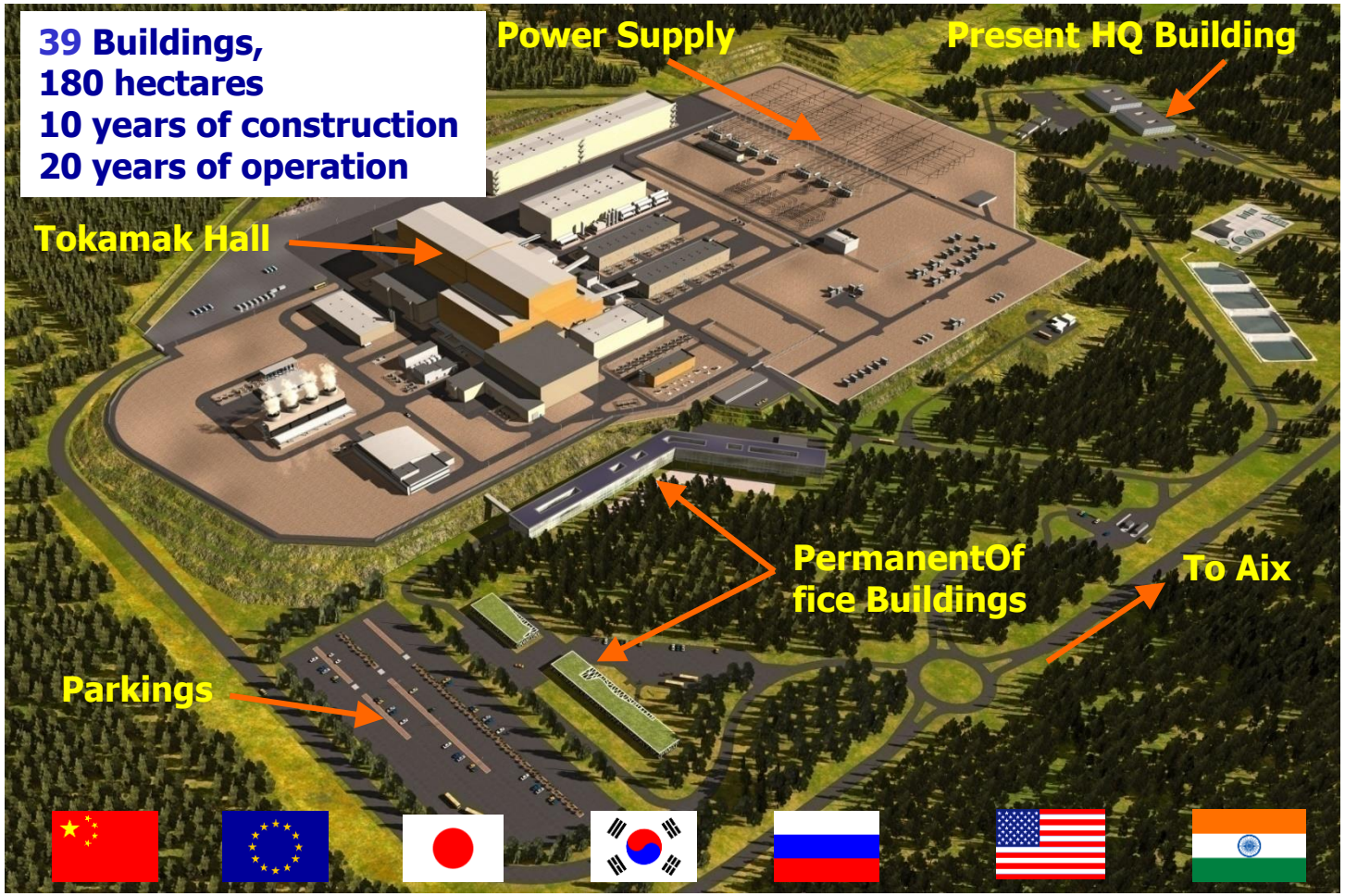
- **I**nternational **T**hermonuclear **E**xperimental **R**eactor
  - "the way" in Latin
  - the essential next step in the development of fusion

http://blog.naver.com/science_u



자료: 교육과학기술부

ITER Project



ITER Project

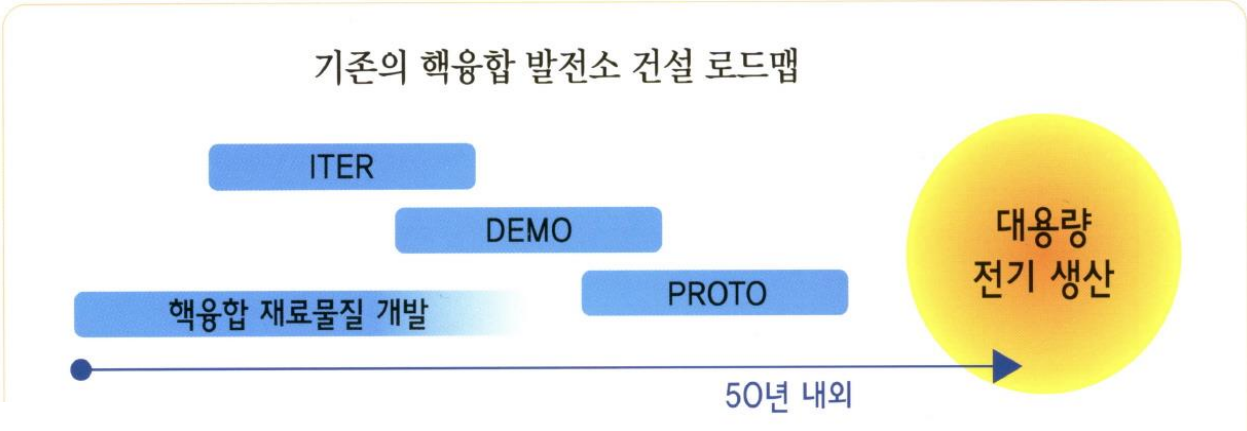
June 19, 2017

ITER Project

https://www.youtube.com/watch?v=uhwQlDxJuzQ

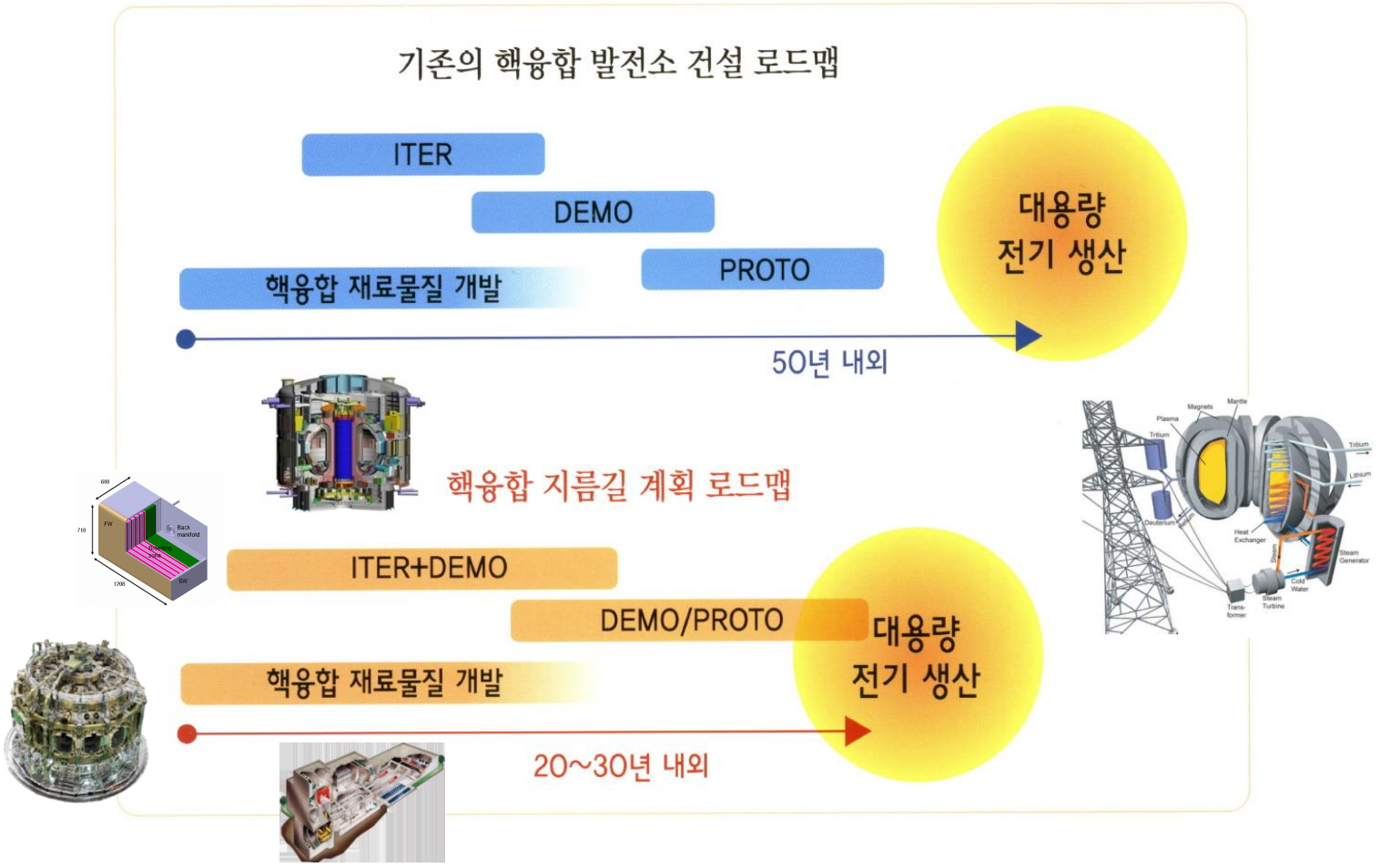
Fusion Energy Development

- **The Fast Track Approach**



Fusion Energy Development

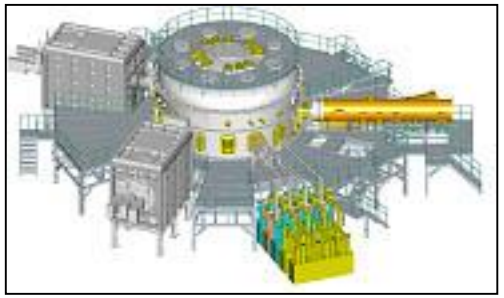
- **The Fast Track Approach**



Korean Plan for Fusion Energy Development

2007년 이후
KSTAR

- 고성능, 고효율 장시간 운전연구



~2025
ITER

- 연료 연구
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- 공학 연구

2040년대 중반
DEMO

- 실질적인 발전 실현
- 시스템 최적화
- 경제성 구현

2050년대
상용화

- 대용량 전기생산

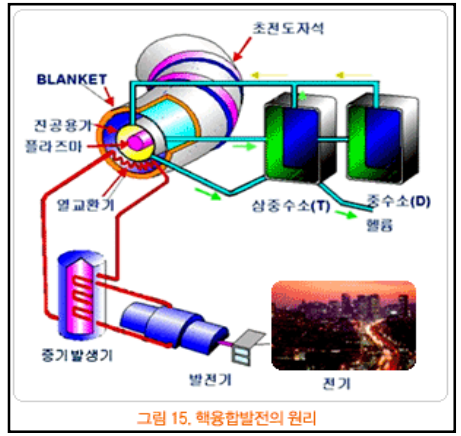


그림 15. 핵융합발전의 원리

Summary

I What is nuclear fusion?

II How to confine the hot sun?

III How to heat the plasma?

IV What are the critical issues?

V What are the current status and future prospect?

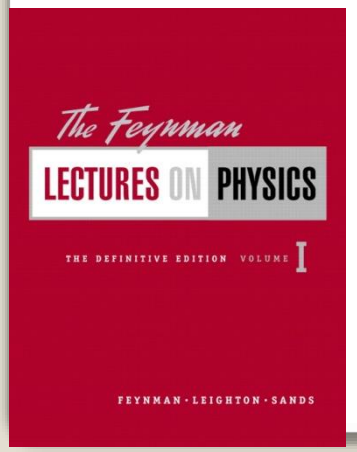
VI Closing remarks

"At the launch of Cambridge University's Big Data Institute, we recently asked the physicist Stephen Hawking to describe the one idea that would transform our society. He chose nuclear fusion – the process of releasing energy by transforming hydrogen atoms into helium,"

- November 18, 2016, BBC

"We have already obtained energy from uranium; we can also get energy from hydrogen, but at present only in an explosive and dangerous condition. If it can be controlled in thermonuclear reactions, it turns out that the energy that can be obtained from 10 quarts of water per second is equal to all of the electrical power generated in the Unites States. With 150 gallons of running water a minute, you have enough fuel to supply all the energy which is used in the United States today! Therefore it is up to the physicist to figure out how to liberate us from the need for having energy. ***It can be done****."*

Feynman Lectures on Physics I, p.4-8

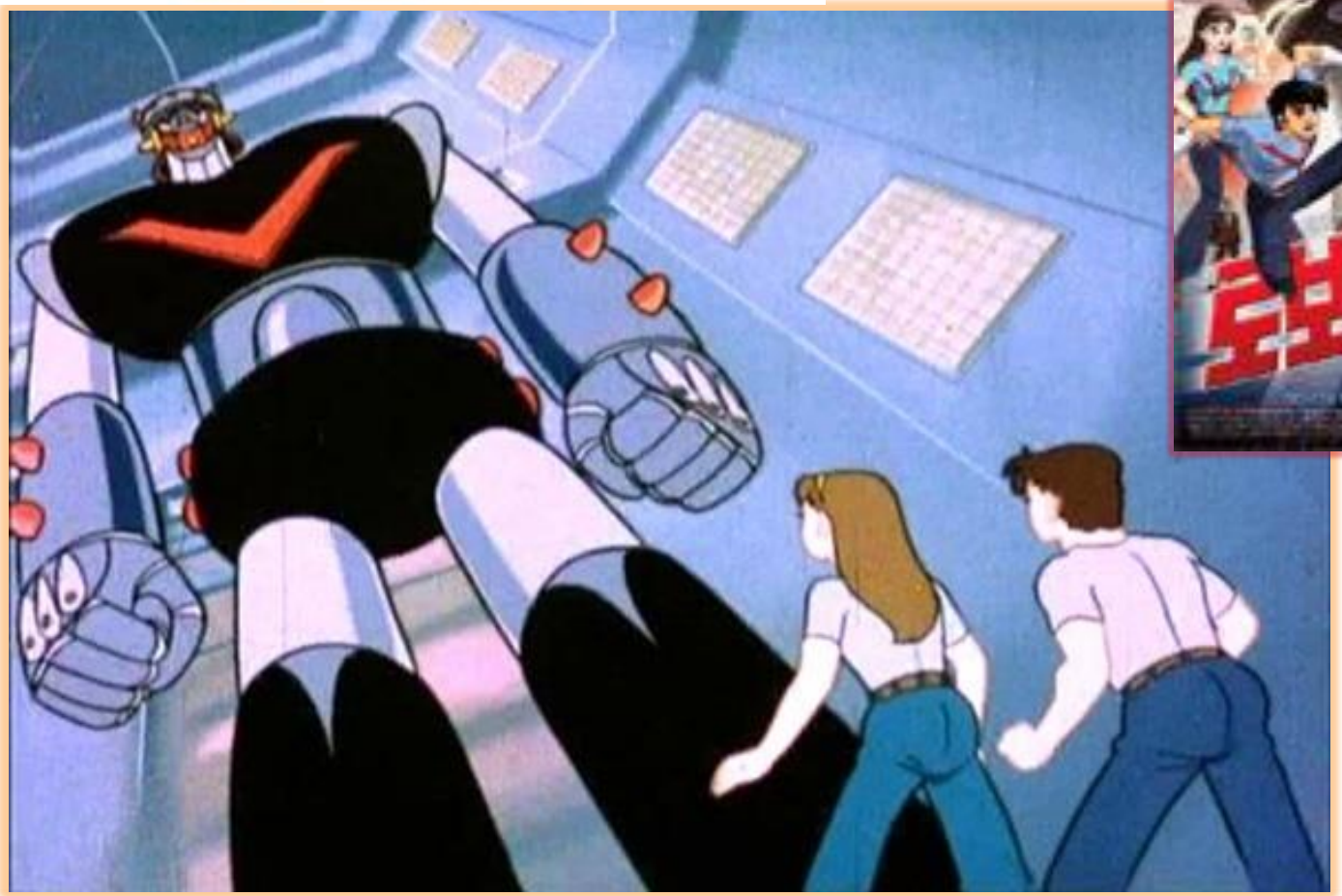


When he was asked how long it would take to build the first fusion power plant, the Soviet physicist Lev Artsimovich – one of the pioneers of tokamak research – replied that "fusion will be there when society needs it." That time is fast approaching, and with the construction of ITER finally about to start, efforts are now gearing up for the longer –term prospect of fusion energy.

- "Fusion: the way ahead, Physics World March 2006

"The entire cost of the fusion development programme is equal to only a week of spending in the international energy markets."

- I. Cook, IAEA 2005



로보트태권V (1976), 신씨네

"High temperature superconductivity will provide cheap power transmission and rapid transport, and nuclear fusion would give us an unlimited supply of clean energy,"

Stephen Hawking