Capacity Building in Nuclear Fusion: Role of Small Tokamaks

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Plan of the Talk

What is fusion and why do we need it ?

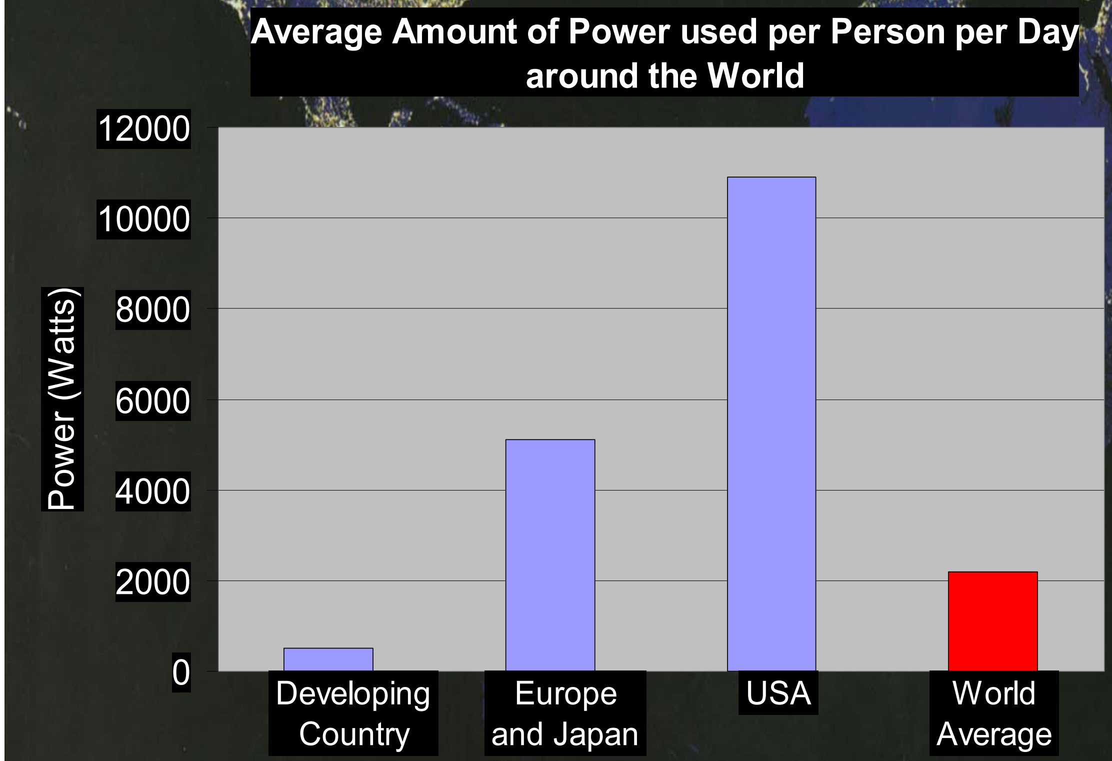
World Fusion research

Role of Small Tokamaks in Fusion Research

Spherical Tokamak concept and ST route to fusion

Global Energy Demand

Typical energy usage in the developed world is enormous.



World population is almost 6 billion people

Total world power consumption = 11 million million Watts !!!

In 50 years, the population will have doubled

Energy usage may have increased by a factor of 2-3

Saudi saying "My father rode a camel. I drive a car. My son flies a plane. His son will ride a camel".

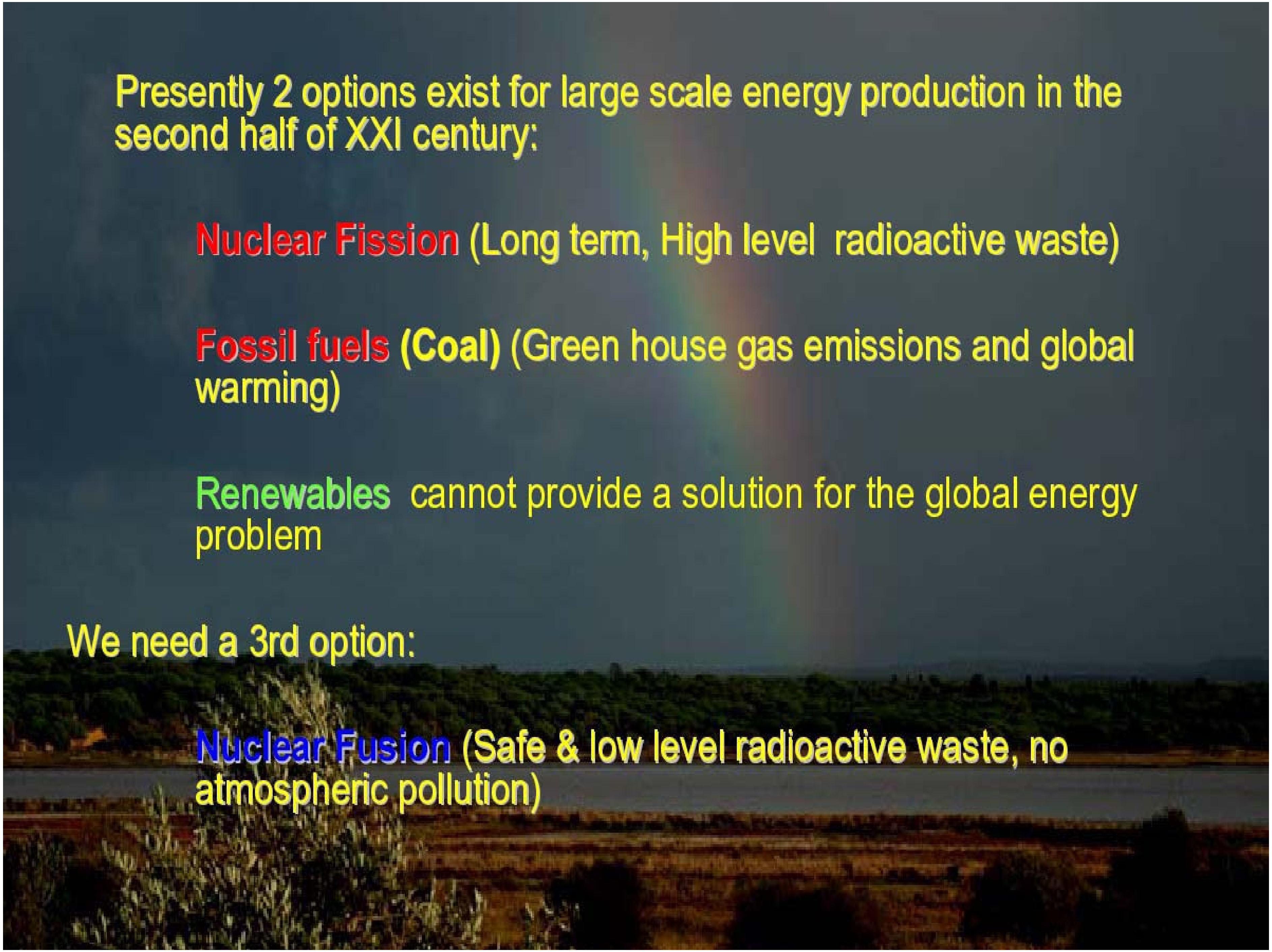
Is this true?

We hope, no!

FOCUS FOR RESEARCH

Must explore all avenues (solution = cocktail). Note - highly interdisciplinary: socio-economic, biological and physical sciences

- **Energy efficiency - yes** (will ameliorate but not solve problem)
- **CO_2 capture and sequestration - yes** (but big challenges, risks, and will add costs)
- **Renewables - yes** (but, apart from solar, do not have potential to meet large fraction of global demand). **Solar - yes** (enough in principle, but currently very expensive and mostly not where needed)
- **Energy storage - yes** (essential for large scale use of intermittent sources)
- **Nuclear fission - yes** (at least until fusion available)



Presently 2 options exist for large scale energy production in the second half of XXI century:

- Nuclear Fission (Long term, High level radioactive waste)
- Fossil fuels **(Coal)** (Green house gas emissions and global warming)
- Renewables cannot provide a solution for the global energy problem

We need a 3rd option:

- Nuclear Fusion (Safe & low level radioactive waste, no atmospheric pollution)

A 21st Century Solution - FUSION

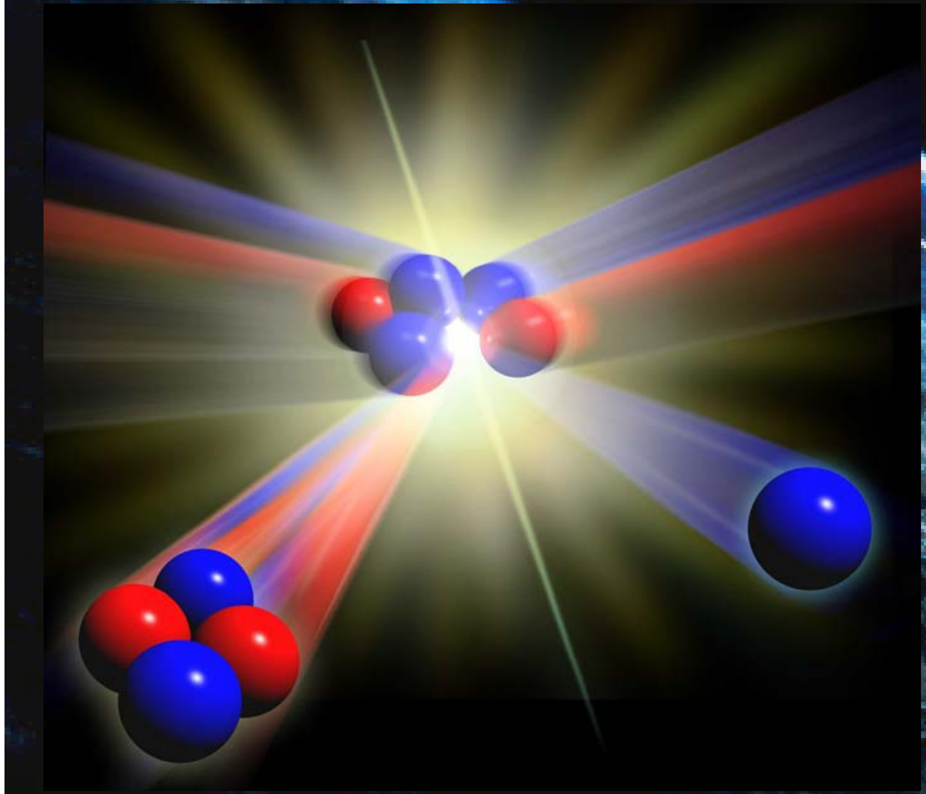
So what is Fusion?

UKAEA

Fusion
Working
with Europe

FUSION ...

...occurs when two light nuclei are forced together, producing a larger nucleus



The combined mass of the two small nuclei is greater than the mass of the nucleus they produce

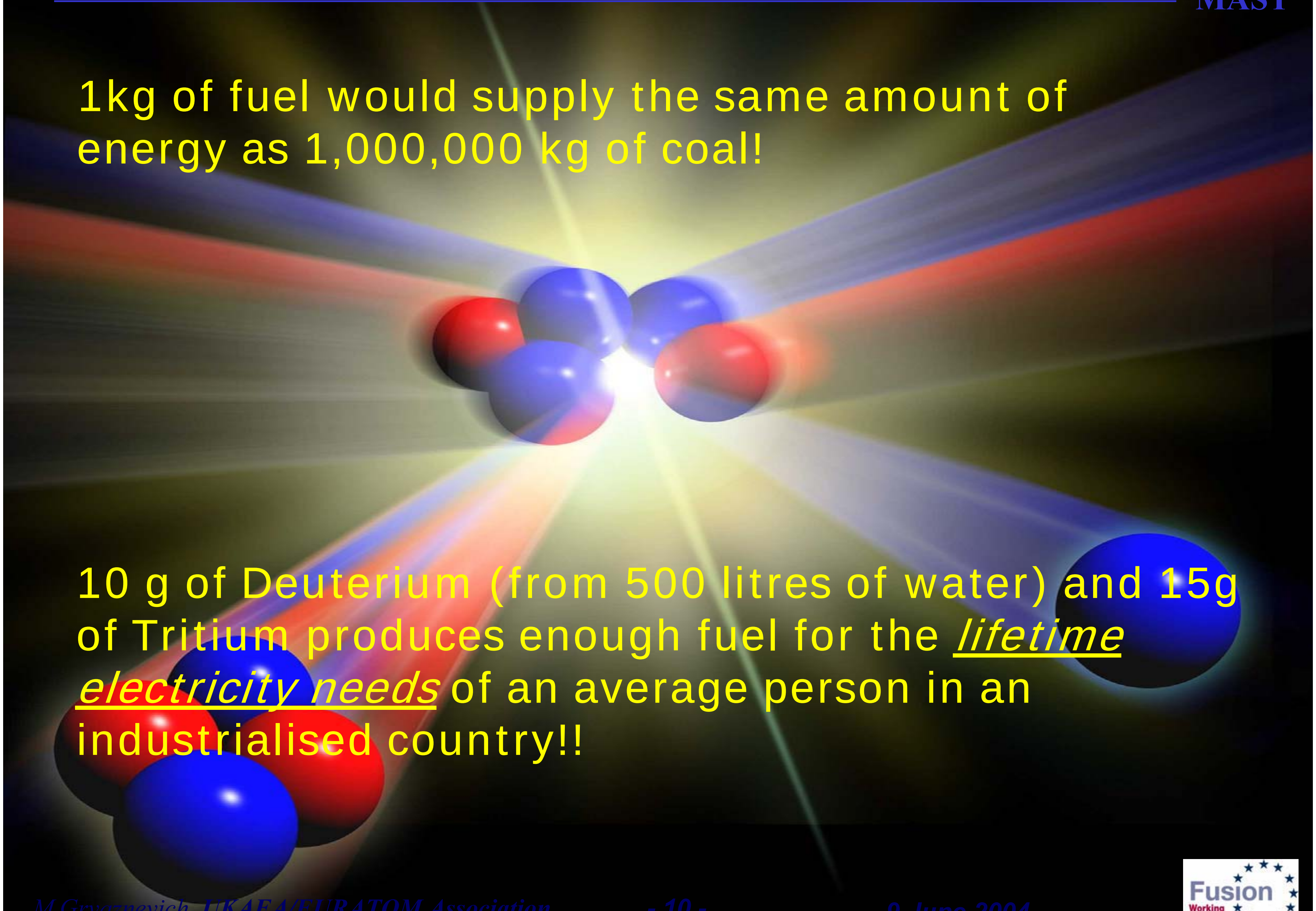
The extra mass is changed into energy

We can calculate the energy released using Einstein's famous equation:

$$E = mc^2$$

UKAEA

Fusion
Working
with Europe



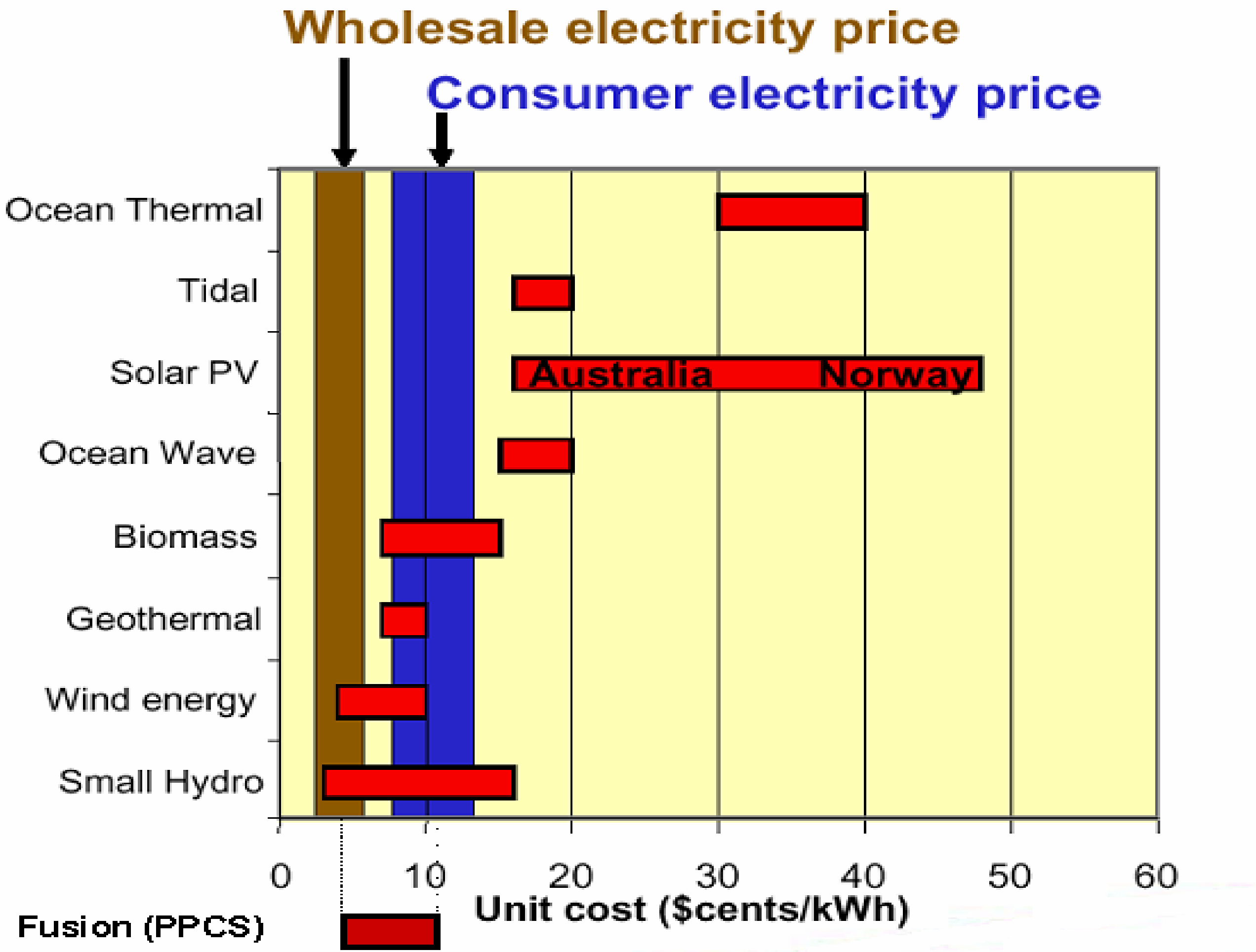
1kg of fuel would supply the same amount of energy as 1,000,000 kg of coal!

10 g of Deuterium (from 500 litres of water) and 15g of Tritium produces enough fuel for the *lifetime electricity needs* of an average person in an industrialised country!!

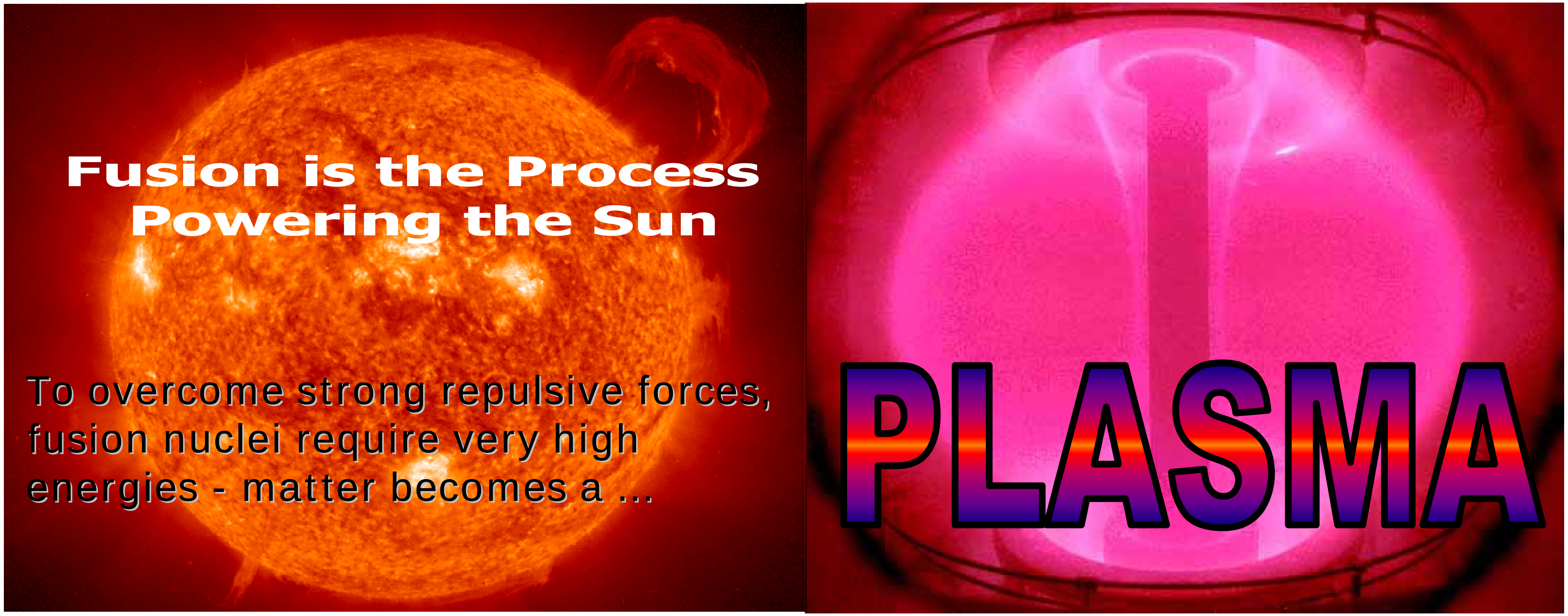
How much will it cost?

Cost comparisons

Results from Shell Renewables + Fusion Power Plant Conceptual Studies



Great Balls of Fire!
Fusion in the 21st Century

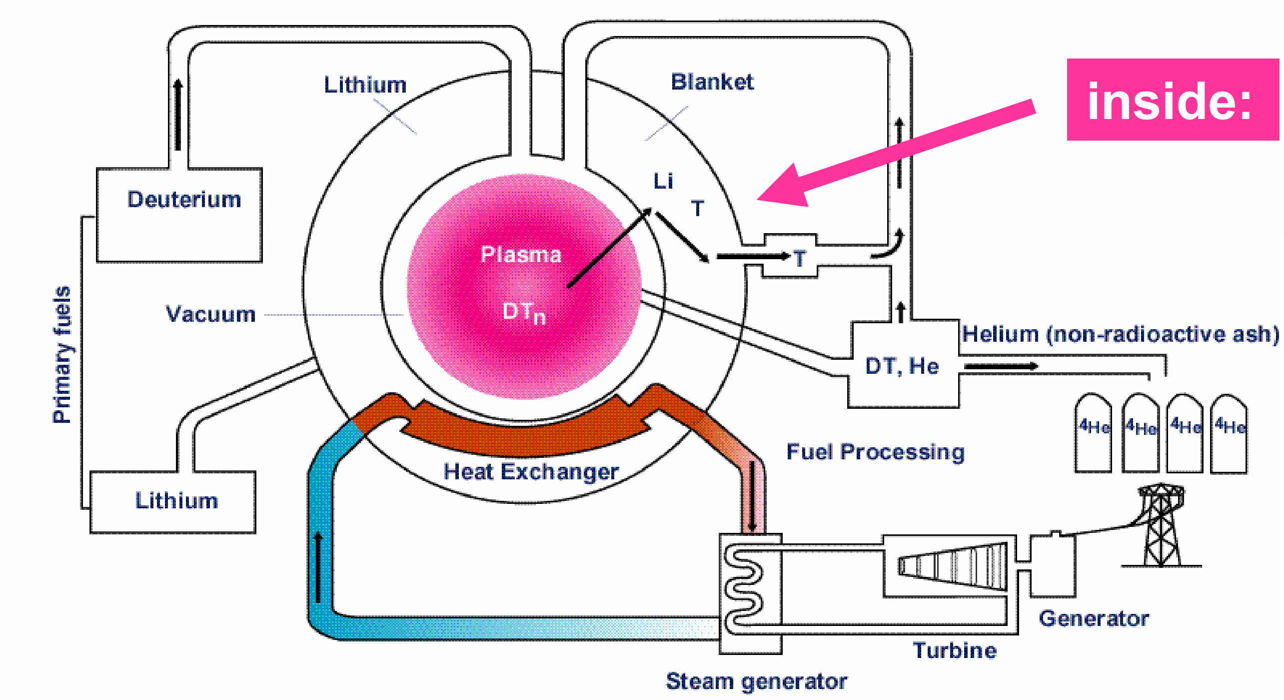


Fusion is the Process
Powering the Sun

To overcome strong repulsive forces, fusion nuclei require very high energies - matter becomes a …

What is Fusion Power Plant ?

> "…Our vision is of a power station, sited perhaps on the coast, with a pipe bringing water from the sea, helium leaving by the chimney and electrical power flowing into the grid. We do not know what to put inside the power station (*laughter*)…" **- Bass Pease, 1956**



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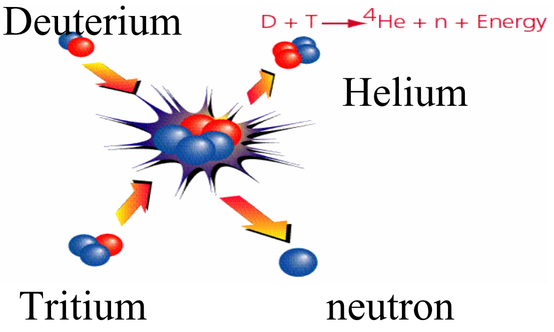
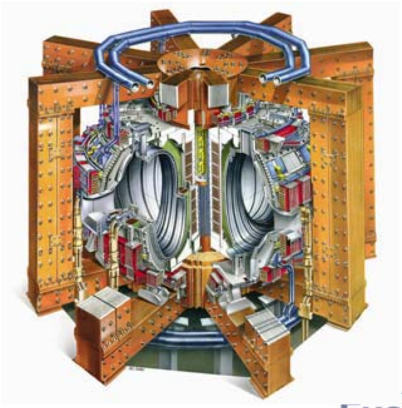


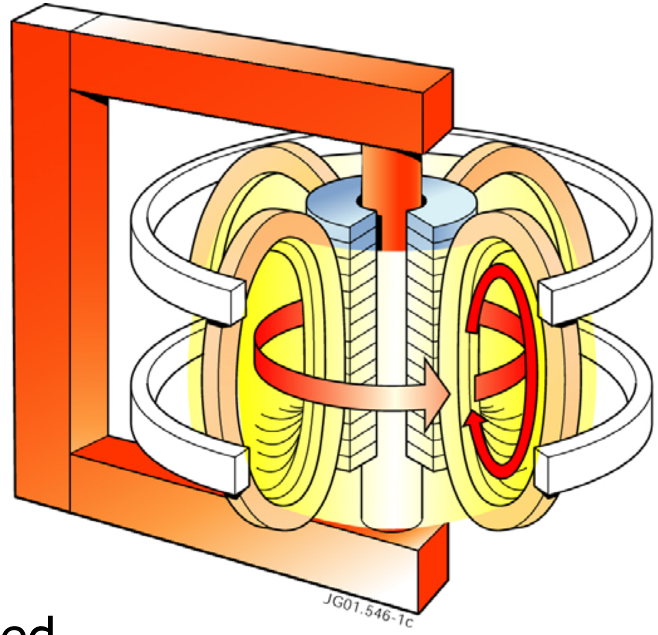


What is the TOKAMAK ?

- **Tokamak**, from the Russian words:
  to*roidalnaya* ***ka****mera and* ***ma****gnitnaya* ***k****atushka*
  meaning "**toroidal chamber**" and "**magnetic coil**"

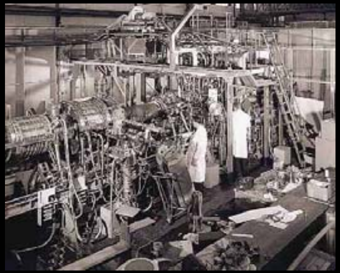
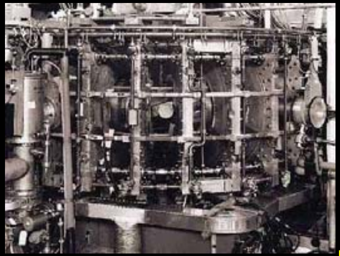
A **tokamak** is a toroidal plasma confinement device with:

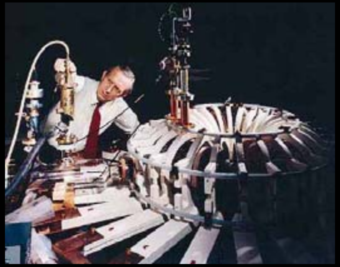
- Toroidal Field coils to provide a toroidal magnetic field
- Transformer with a primary winding to produce a toroidal current in the plasma



- The current generates a poloidal magnetic field and therefore twisted field lines which creates a perfect "trap"
- Other coils shape the plasma

Magnetic fusion experiments around the world


Experiments all over the world progress the understanding of plasma physics and improve plasma performance and confinement.

World Fusion Activities

- International magnetic fusion research budget is 1-2 BEuro/year

Main Tokamaks around the world

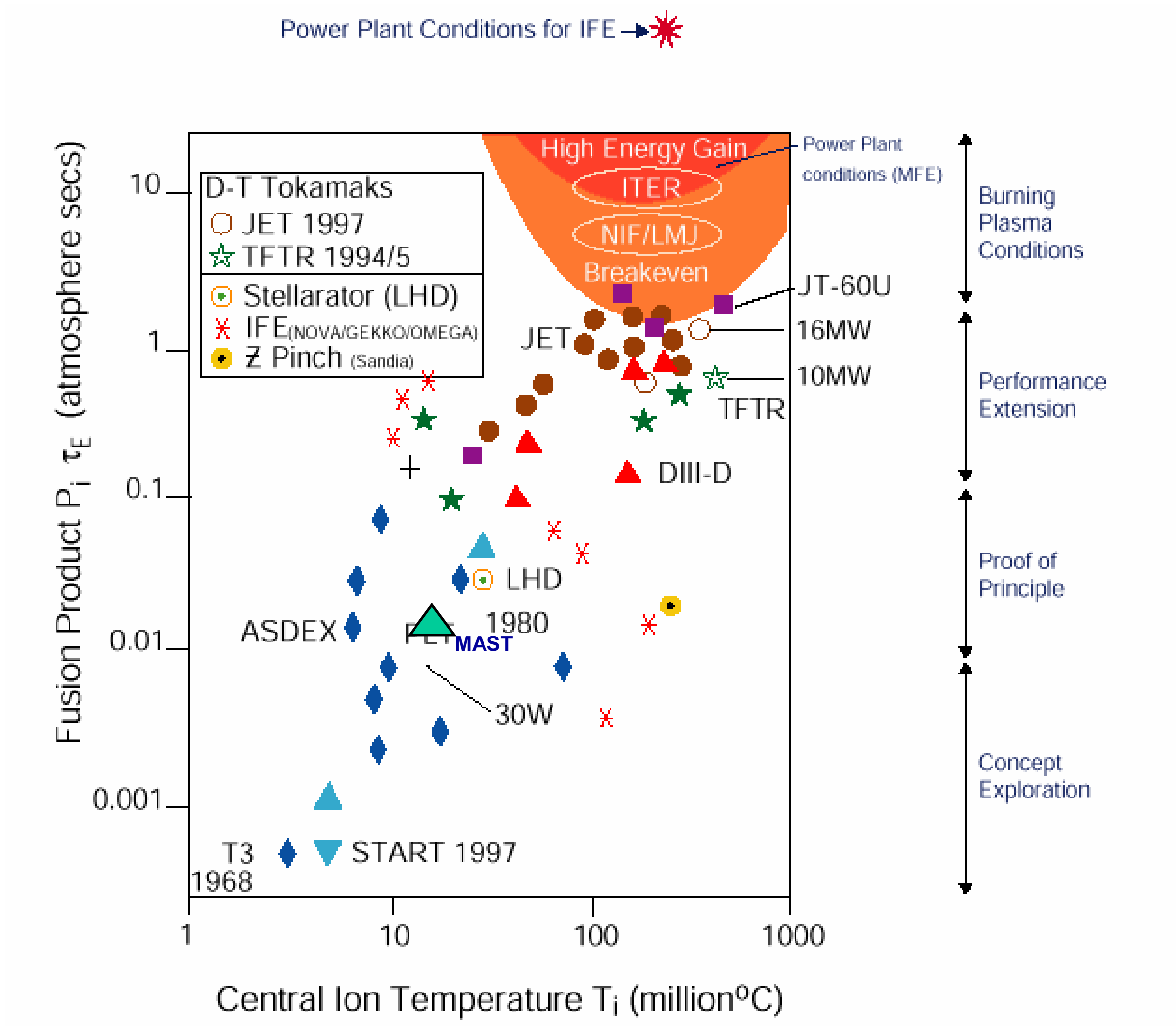
Present status:

- 53 tokamaks are operational *(plus stellarators, pinches, spheromaks)*

Asia: ***24*** (12 in Japan, 5 in China)
Europe: ***15*** (6 in Russia, 2 in UK, 2 in Germany)
America: ***12*** (7 in USA, 3 in Brazil)
Africa: ***2***

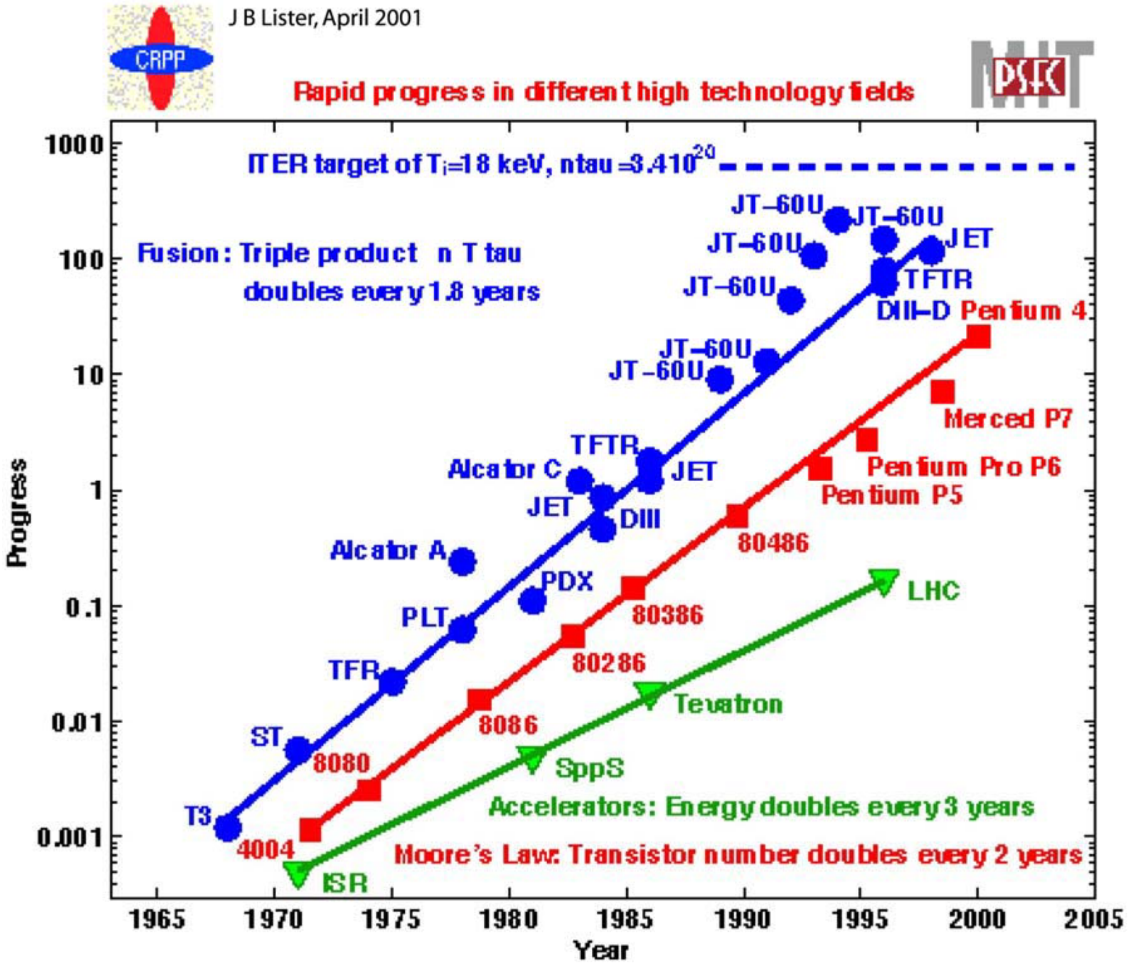
Tokamak	Tore Supra (France)	Asdex-U (Germany)	Textor (Germany)	JET (European Union in the UK)	TFTR (USA) (machine closed)	DIIID (USA)	JT-60U (Japan)
Plasma Configuration	Limiter	Divertor	Limiter	Divertor	Limiter	Divertor	Divertor
Specificity	**Long Pulse**	**Tungsten Wall**	**Plasma Surface Interactions**	**Tritium Remote Handling**	**Tritium**	**Active MHD Stabilisation**	**Negative Neutral Beams**
Major radius	2.36 m	1.65 m	1.75 m	**2.96 m**	2.48 m	1.67 m	3.45 m
Toroidal field	4.5 T	4 T	2 T	3.45 T	**5.2 T**	2.2 T	4.4 T
Plasma current	1.7 MA	1.6 MA	0.65 MA	**7 MA**	2.5 MA	3.5 MA	5 MA

Major Progress Towards Fusion Power

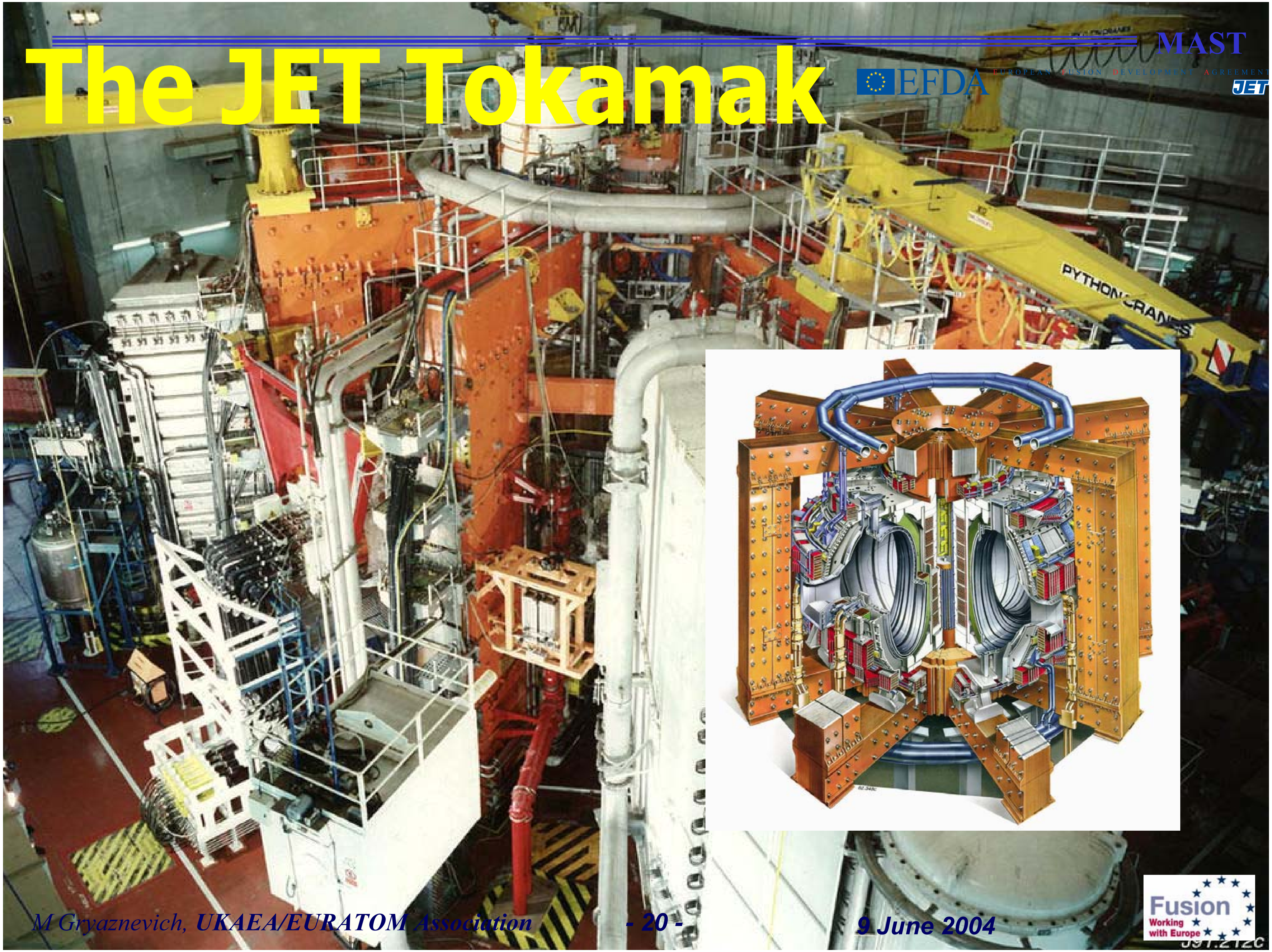


Major Progress Towards Fusion Power

- Progress in fusion rivals/betters other fields
- Note the progress within a single device (e.g. JET, JT-60U)
- Physics, engineering, technology have made huge strides

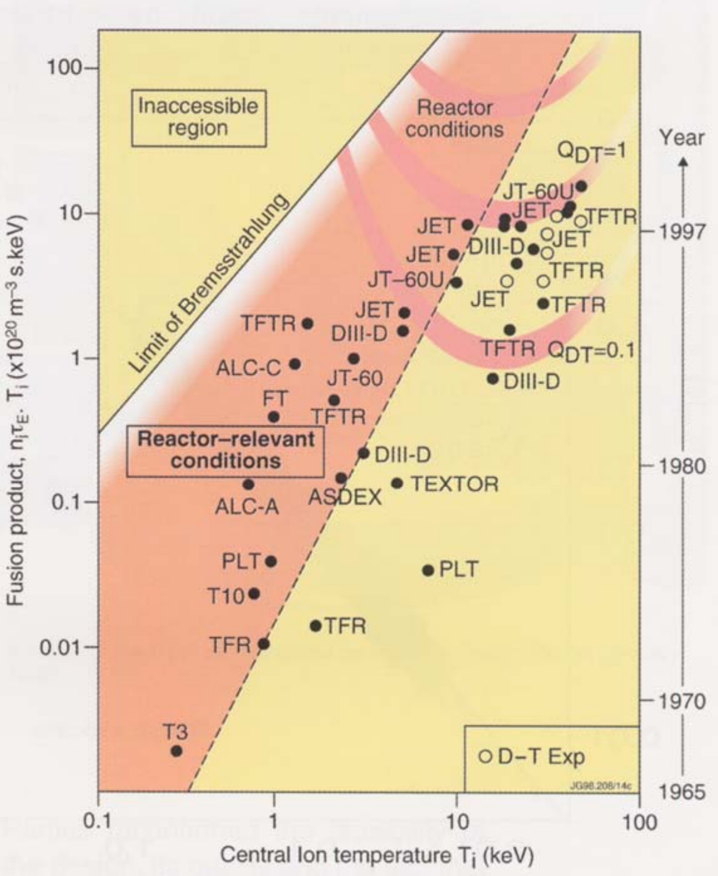


The JET Tokamak

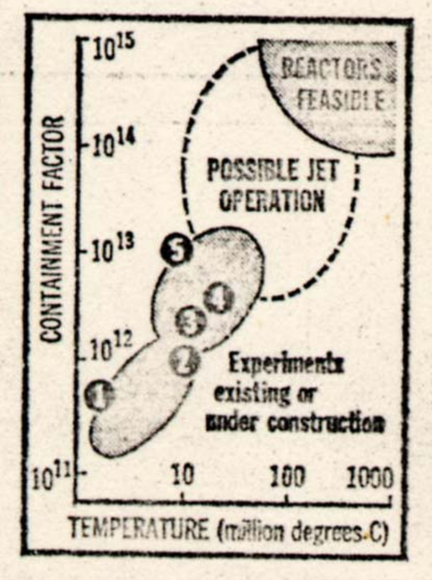


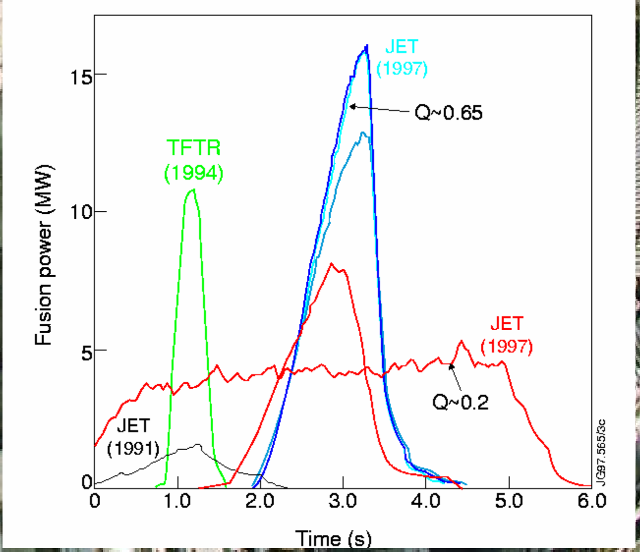
Progress on JET:

J94.43c



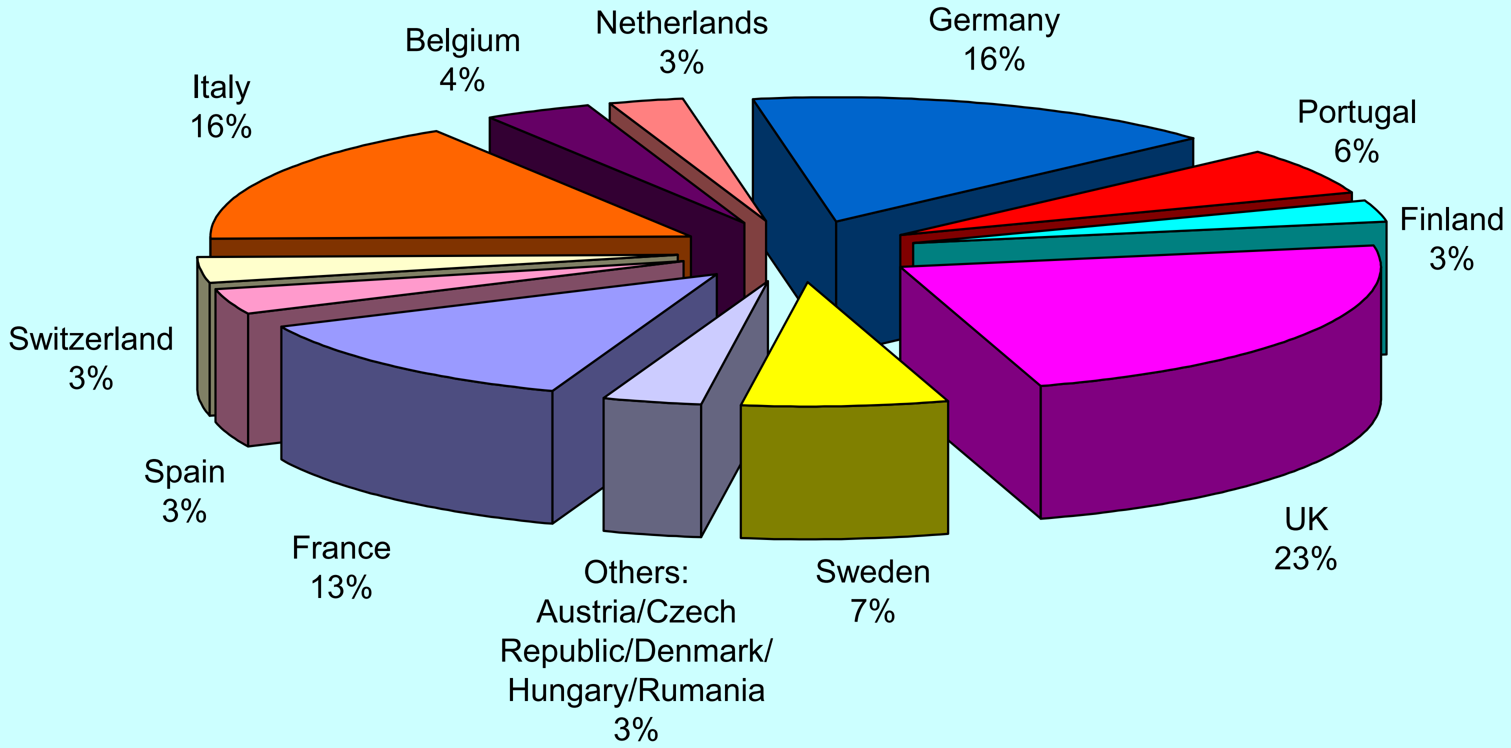
This plot shows how, over several decades of research, the key performance parameters of fusion devices (the plasma ion temperature and the fusion triple product) have moved towards the conditions required for a reactor.





UKAEA Operates JET on Behalf of Scientists in Euratom Member States

Participation by European Countries on JET Campaigns C1-C14



JET’s achievements

JET is the largest tokamak in the world.

It is the only existing device to use T (as well as D) and observe fusion neutrons.

Robotic technology has proved that remote maintenance of tokamak is possible.

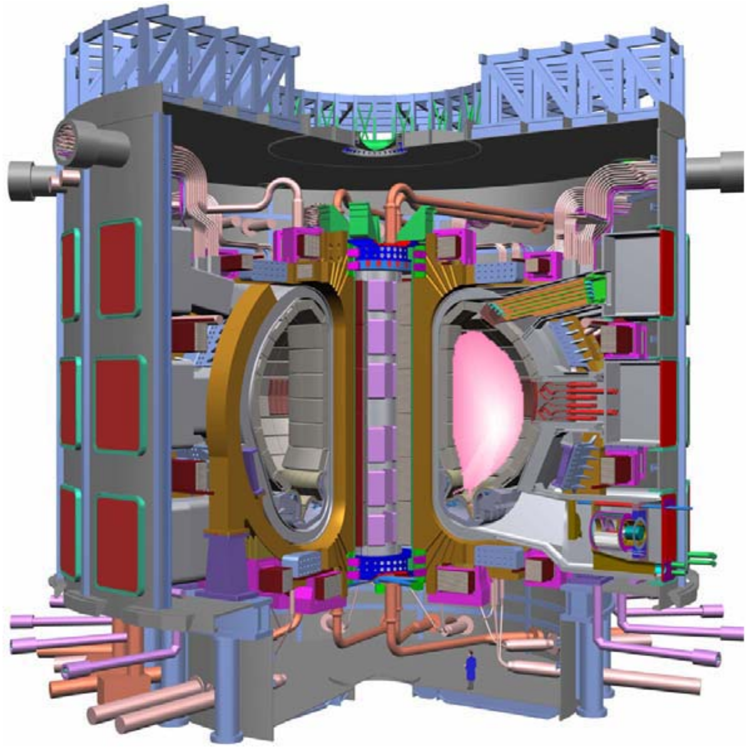
The Future for Fusion Power

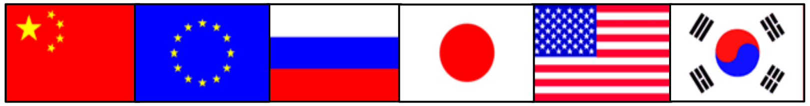
	When?	Fusion Power	Pulse duration	Q
 JET	1997	16MW	~1 second	<1
 ITER	2015-2020	500-700MW	<30 minutes	>10
 Power Plant	~2050 (?)	~1500-2000MW	~1 day	~50

The Nearest Future - ITER

“International Thermonuclear Experimental Reactor”

- To demonstrate integrated physics and engineering at ~GW level
- Superconducting coils, power-plant-level heat fluxes, “nuclear” safety
- Reliability and availability a key aspect
- Its design is realistic, detailed and reviewed like no other fusion device





Negotiations

- Began in July 2001 with the following aims
  - draft Joint Implementation Agreement
  - agree how the procurement and costs will be shared
  - define how the project will be managed
  - select ITER construction site
  - identify the Director General and senior staff.
- Deadlocked over choice of construction site.

← Cadarache or Rokkasho →

Large scale prototypes have been made already

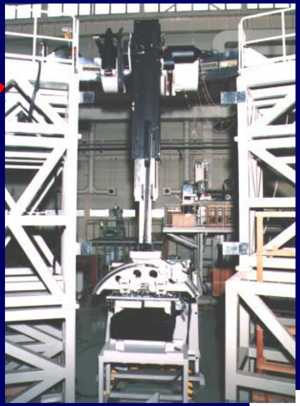
ITER
7 Large
Technology
R&D's

Central Solenoid Model Coil
JA-US-EU-RF

TF Model Coil
EU-RF

VV Sector
JA-US-EU-RF

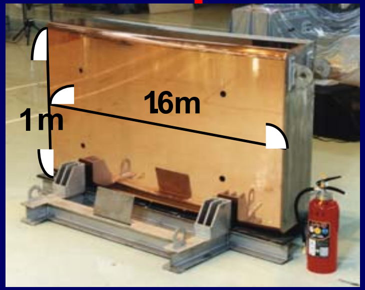
Divertor Cassette Remote Handling
US-JA-EU



Blanket module Remote Handling
EU-JA-US

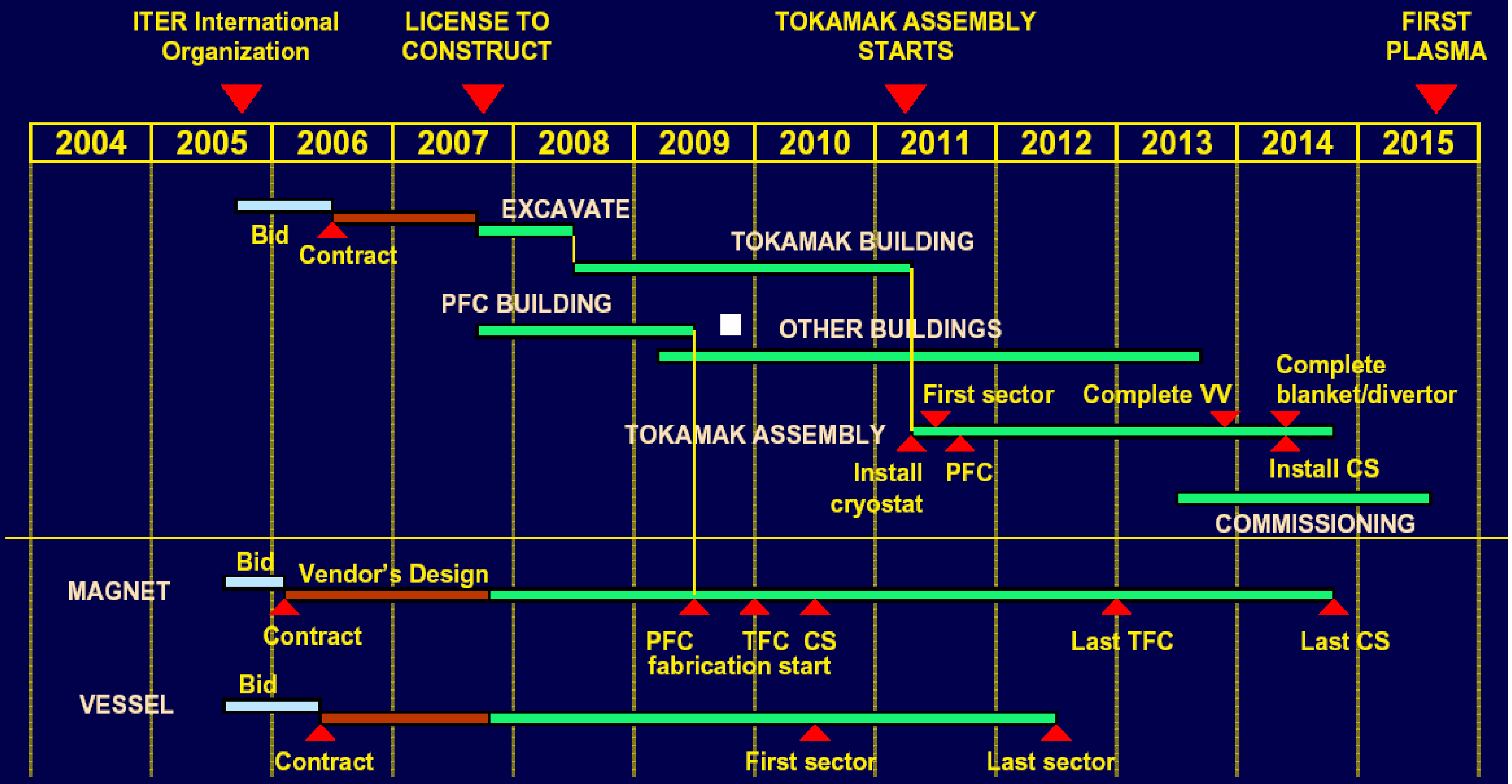
Divertor Cassette

US-JA-EU-RF



Blanket Module
EU-JA-US-RF

Construction Schedule



ITER International Organization

LICENSE TO CONSTRUCT

TOKAMAK ASSEMBLY STARTS

FIRST PLASMA

2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Bid

Contract

EXCAVATE

TOKAMAK BUILDING

PFC BUILDING

OTHER BUILDINGS

TOKAMAK ASSEMBLY

First sector

Complete VV

Complete blanket/divertor

Install cryostat

PFC

Install CS

COMMISSIONING

MAGNET

Bid

Vendor's Design

Contract

PFC

TFC

CS

fabrication start

Last TFC

Last CS

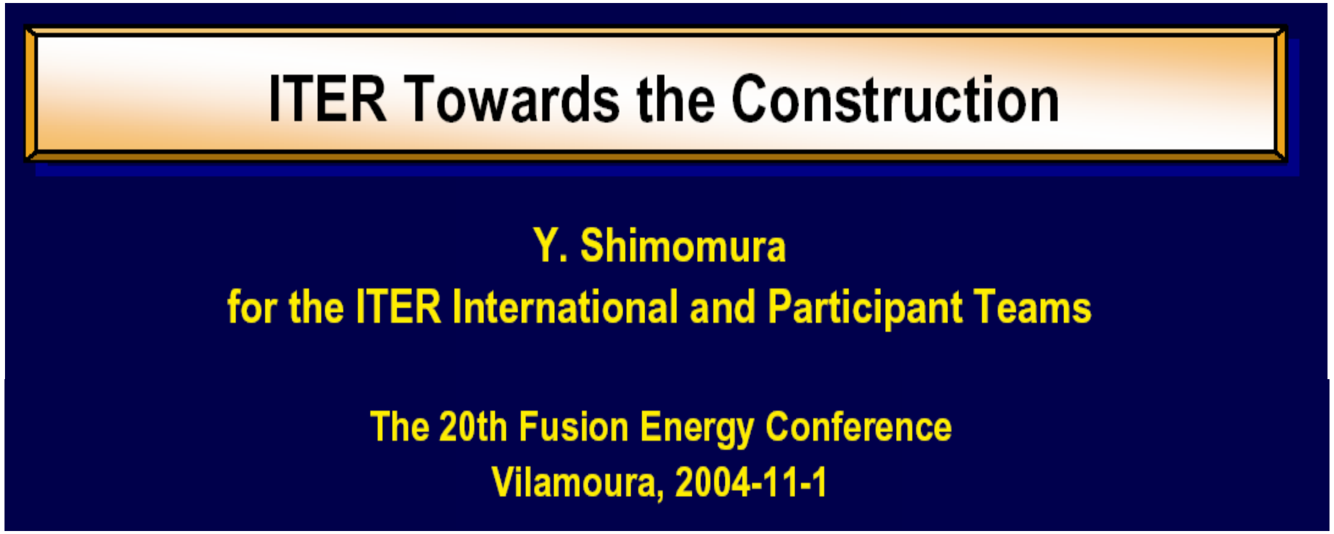
VESSEL

Bid

Contract

First sector

Last sector

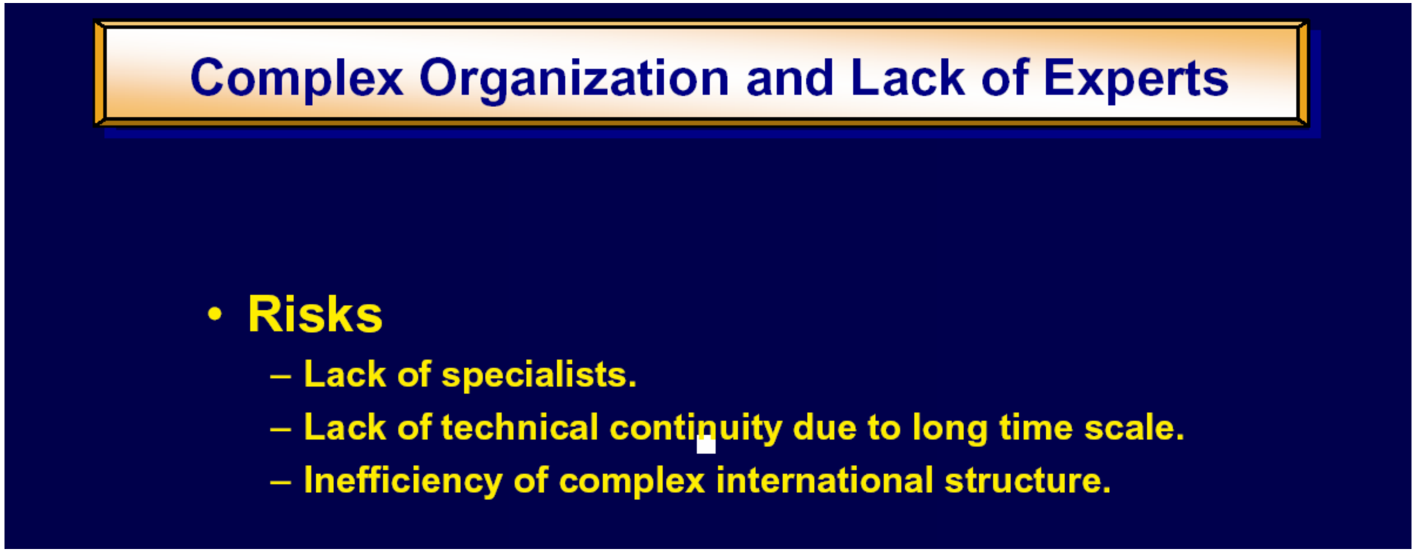


ITER Towards the Construction

Y. Shimomura
for the ITER International and Participant Teams

The 20th Fusion Energy Conference
Vilamoura, 2004-11-1

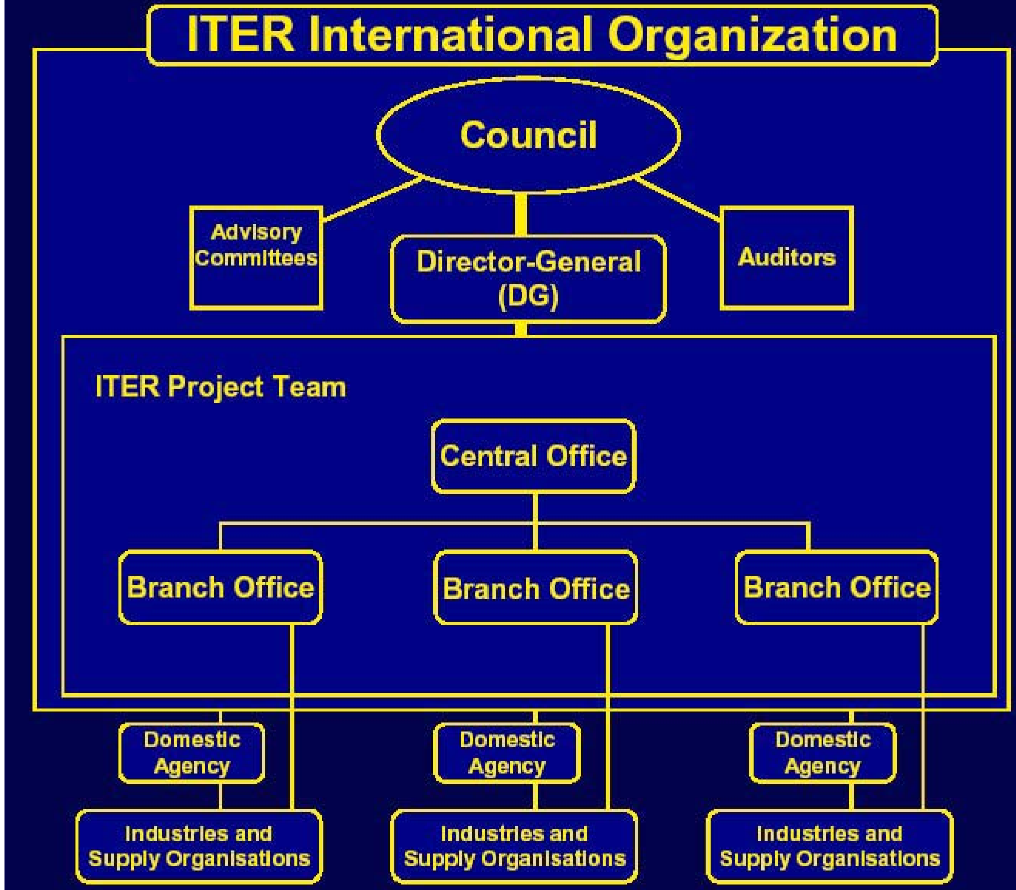
… among other problems:



Complex Organization and Lack of Experts

- **Risks**
  - Lack of specialists.
  - Lack of technical continuity due to long time scale.
  - Inefficiency of complex international structure.

ITER Organisation (during construction)



- Staff regulations, DG power in choosing and rewarding staff, and Parties ability to provide good staff, are vital to project success:

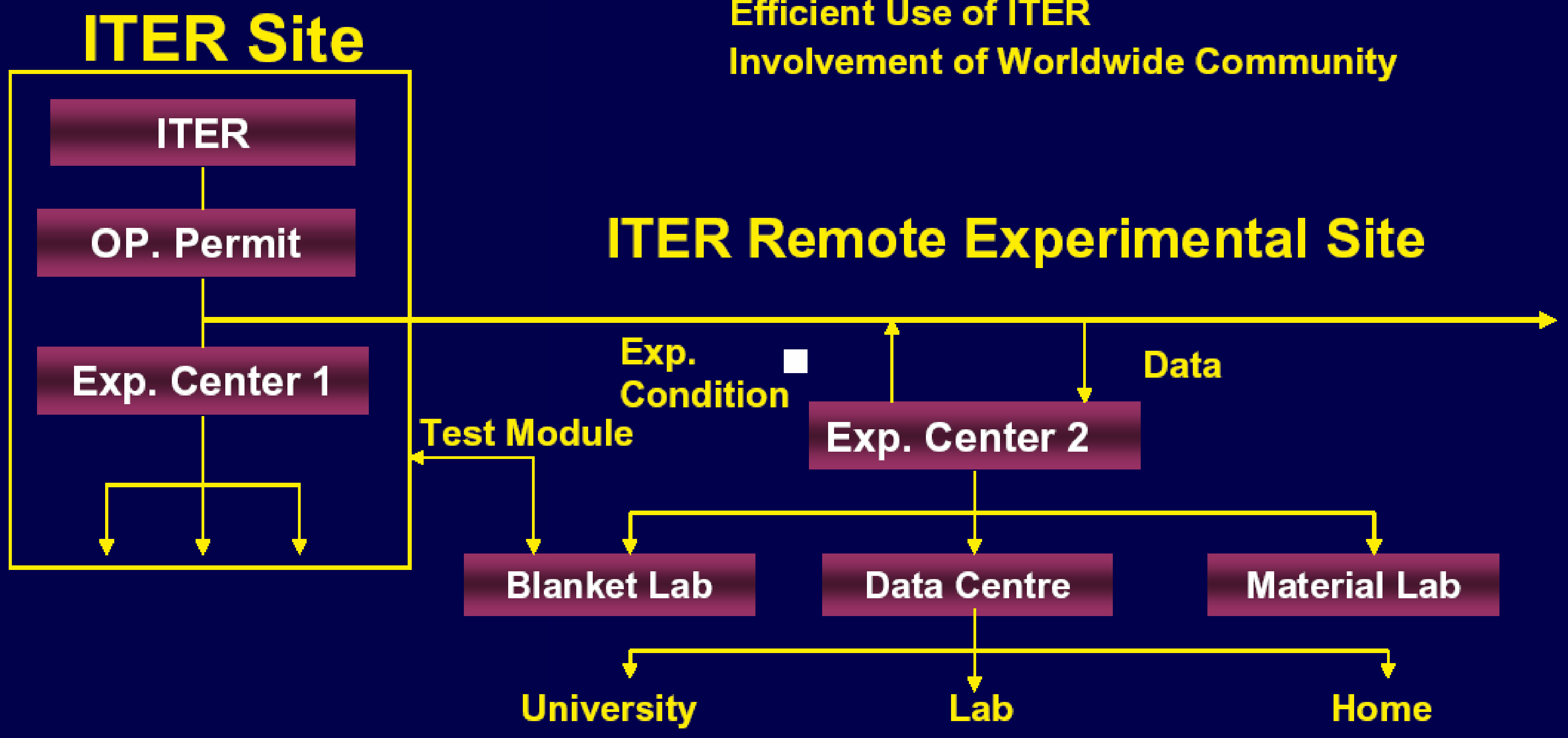
  - to attract the right staff at the right time.

  - to keep them as long as they are needed by the project.

- Minimize inefficiencies and duplication of roles among ITER International Organization, Domestic Agencies and Suppliers.

Worldwide Experimentation on ITER

Efficient Use of ITER
Involvement of Worldwide Community



ITER Site

ITER

OP. Permit

Exp. Center 1

Test Module

ITER Remote Experimental Site

Exp. Condition ■

Data

Exp. Center 2

Blanket Lab

Data Centre

Material Lab

University

Lab

Home

Example: 3 shift/day on site (night shift for monitoring and support of remote experiment)
1 or 2 shift(s)/day on remote experimental sites

Several issues on the way to Power Plant can not be addressed to ITER

- Large scale material studies
- Plasma-facing surface, divertor and blanket lifetime
- Tritium self-sufficiency
- Electricity generation at high aviability

And several ITER problems should be resolved by complementary activities, for example:

- remote participation and world-wide communication
- training and education of staff

Fusion activities complementary to ITER

- **4 medium size tokamaks under construction:**

  KSTAR (Korea), HT-7U (China), SST-1 (India), KTM (Kazakhstan). Note: all in Asia!
- **a big stellarator under construction (W7-X, Germany)**
- **IFMIF - material test facility, design**
- **CTF (component test facility), preliminary studies**
- **NIF - US inertial fusion project, under construction**
- **3 large fusion devices operational (JET, JT-60U, LHD)**
- **11 medium size tokamaks are operational**
- **… plus ~ 70 small size devices**

Role of Small Tokamaks in Fusion Research

Present status:

- 42 small tokamaks are operational

Asia: ***22*** (10 in Japan, 5 in China)
America: ***10*** (5 in USA, 3 in Brazil)
Europe: ***8*** (6 in Russia)
Africa: ***2***

Small tokamaks have an important role in fusion research:

- Research on small tokamaks has created a scientific basis for the scaling-up to larger tokamaks
- Well-known scientific and engineering schools have been established through research on small tokamaks
- Because of compactness, flexibility, low operation costs and high skill of their personnel, small tokamaks continue to contribute to many areas of Fusion research, well recognised by big tokamaks and ITER

Role of Small Tokamaks in Fusion Research

Physics:

- Direct contribution to mainstream fusion research

Technology:

- A test-bed of new tools, materials and technologies for large machines
- Improvement and development of diagnostics

Training and education:

- Expertise development and capacity building of students, post graduate students and training of personnel, in particular in developing countries

Role of Small Tokamaks in Fusion Research

Contribution to mainstream fusion research:

- *Plasma confinement and energy transport*
- *Plasma stability in different magnetic configurations*
- *Plasma turbulence and its impact on local and global plasma parameters*
- *Processes at the plasma edge and plasma-wall interaction*
- *Scenarios of additional heating and non-inductive current drive*
- *Plasma breakdown and start-up*
- *New methods of plasma profile and parameter control*
- *Development of novel plasma diagnostics*
- *Benchmarking of new numerical codes, and so on*

Role of Small Tokamaks in Fusion Research

Other important contributions of small tokamaks:

Remote participation and world-wide communication:

- Small tokamaks are suitable and important for broad international cooperation, providing the necessary environment and manpower to conduct dedicated joint research programmes and develop communication tools

Training and education:

- Experimental work on small tokamaks is very appropriate for the education of students, scientific activities of post-graduate students and for the training of personnel for large tokamaks
- These may be achieved through promotion of mobility, exchange of equipment, joint experiments, training courses, schools etc

Present status of research on small tokamaks:

- On small tokamaks, research is carried out mostly on the basis of *domestic programmes* and only in a few cases also in the frame of an international co-operation
- Assessment of the output from the small tokamak research programmes has shown the ***need for stronger links*** between the small and large tokamaks and ***better co-ordination of the collaboration*** between small tokamak research projects

New opportunities for small tokamaks:

- Combined efforts within a network of small and medium size tokamaks will further enhance the contribution of small tokamaks
- **A new concept** of interactive co-ordinated joint research using small tokamaks in the scope of the **IAEA Co-ordinated Research Project (CRP),** which has started in 2004, should be a **new step** in better co-ordination of this collaboration and in improvements of links between the small and large tokamaks

Joint Research Using Small Tokamaks:

IAEA Co-ordinated Research Project (CRP) “Joint Research Using Small Tokamaks” has started in 2004, 9 tokamaks are already participating in the project.

T-10	Russian Research Centre "Kurchatov Institute", Moscow, Russia
GUTTA	St. Petersburg State University, Zubov Institute of Computational Mathematics and Control Processes, St. Petersburg, Russia
SUNIST	SUNIST United Laboratory, Department of Engineering Physics, Tsinghua University, Beijing P.R.China
EGYPTOR	Plasma Physics Department, NRC, Atomic Energy Authority, Enshass, Egypt
ETE	Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil
TCABR	Universidade de São Paulo, São Paulo, Brazil
ISTTOK	Associação Euratom/IST, Centro de Fusão Nuclear, Instituto Superior Técnico, Centro de Fusão Nuclear, Lisbon, Portugal
CASTOR	Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
STOR-M	PPL, University of Saskatchewan, Canada

Joint Research Using Small Tokamaks:

Objectives of this approach are:

- to achieve a **network of fusion research** using the innovative possibilities of small tokamaks

- to insure deeper **integration** of small tokamaks in national, regional, and international fusion activities

- to increase the number of the **collaborative experiments**

- to promote fusion research in **developing countries** and open wider possibilities for **young scientists**

- Work packages for the different research activities can be carried out under the supervision of the members of the CRP thus providing a clear future perspective for small tokamaks in a co-ordinated approach
- This will help to improve the quality of the scientific output from the small tokamak research activities

Joint Research Using Small Tokamaks:

- **This interactive joint research project will provide co-ordination and guidance for integration of small tokamak projects. The output will consist of:**

  - an established informational network of small tokamak projects resulting in improvements in communication among small tokamak groups working worldwide

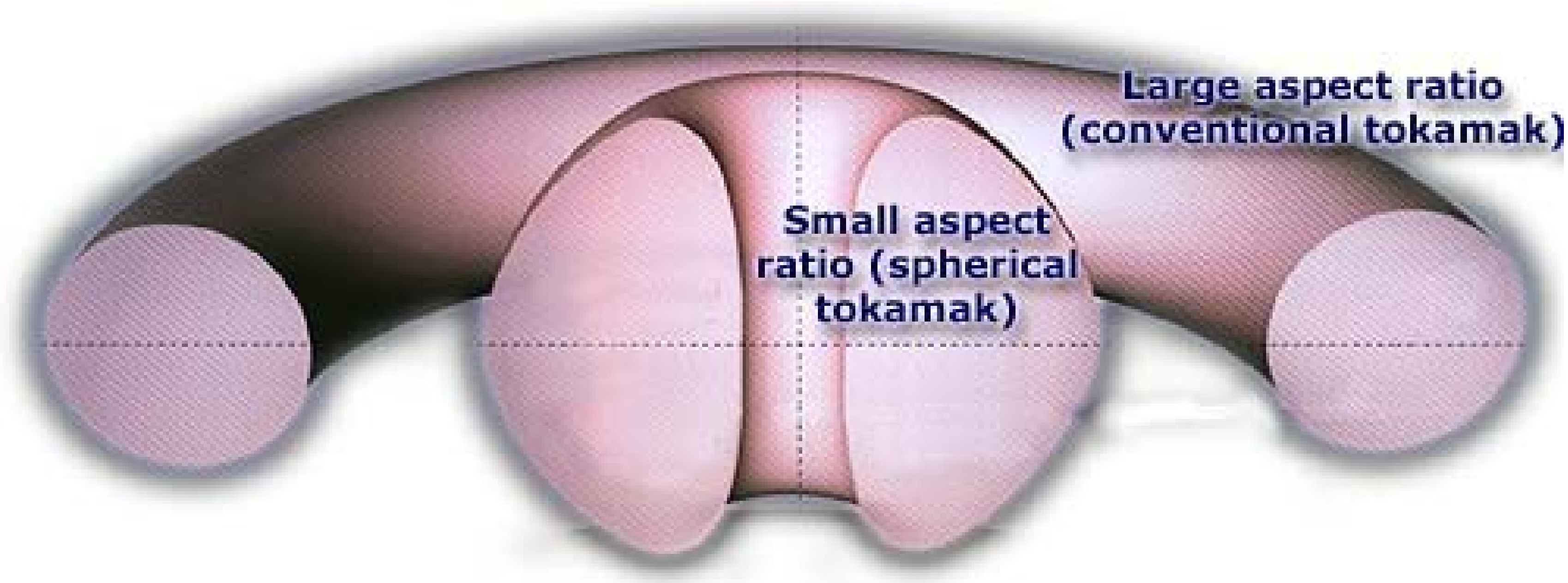
  - practical advice and assistance via IAEA on further integration with the national programmes of large tokamaks, ITER and other international projects as well as contribution to mainstream nuclear fusion R&D

  - co-ordinated plan of collaboration between small tokamak projects to support and promote a free exchange of scientific and technical personnel, equipment and diagnostics

  - joint presentations of the scientific results achieved on small tokamaks under international collaboration

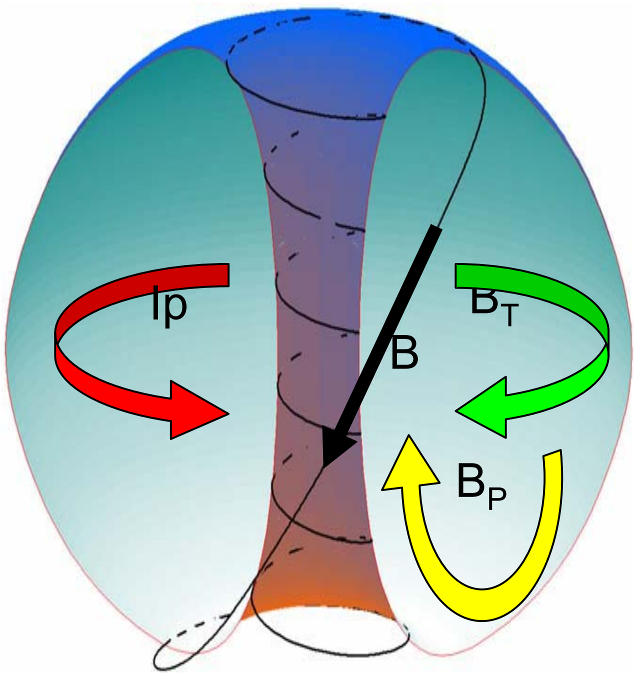
History and the Present Status of Spherical Tokamak Research

Can we improve the tokamak?



What is "Spherical Tokamak"?

Spherical tokamak (A=R/a<2) is obtained from a conventual one by decrease of major radius to technology limit

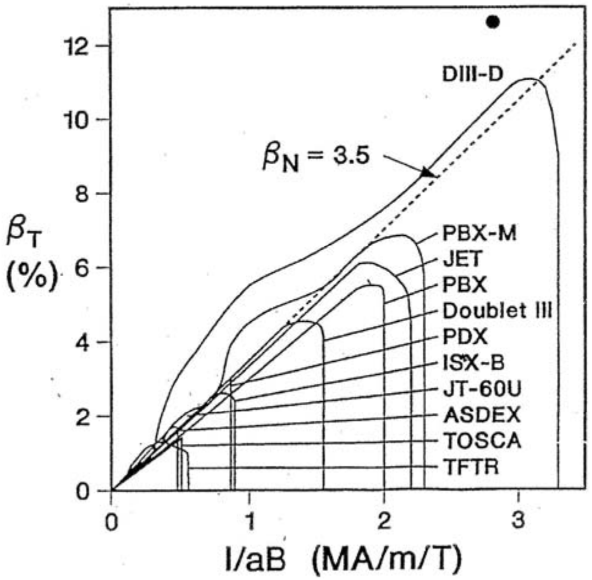


- Strong toroidicity increases field line length in high field, favorable curvature region and stabilize interchange modes (less turbulence)
- MHD modes kink safety factor increases in ST geometry $q_{edge} \propto (1+\kappa^2)aB_T/I_PA$ and provides high current in low magnetic field
- High natural elongation provides better vertical stability (high elongation)
- Strong edge magnetic shear stabilize ballooning modes allowing higher plasma pressure (high-β)
- Smaller volume requires less auxiliary heating

- The main advantage of an ST is possibility of high plasma pressure achievement, which was predicted theoretically and confirmed experimentally on START, MAST and NSTX

Theory: the Troyon limit $\beta_T = \beta_N I / aB$ can be written as $\beta_T = 5\beta_N \kappa / Aq_j$ and low A, high k are features of the ST

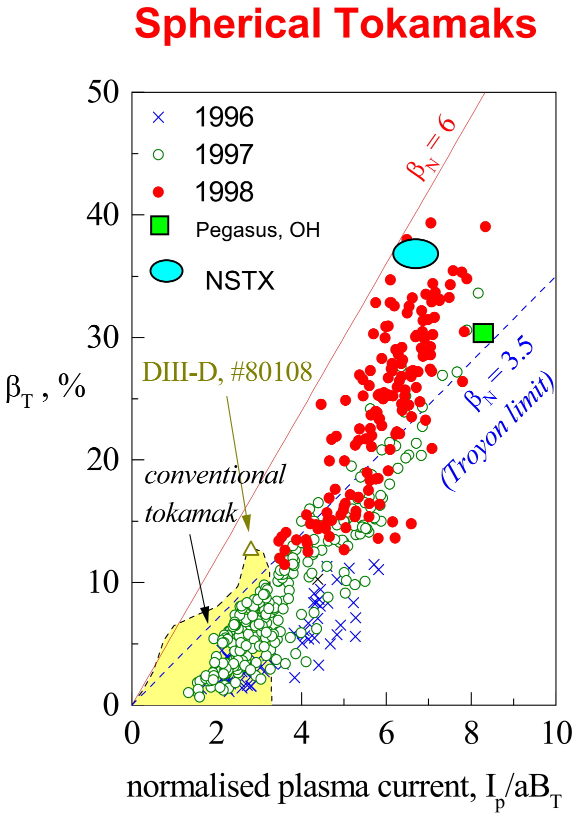
Experiment:



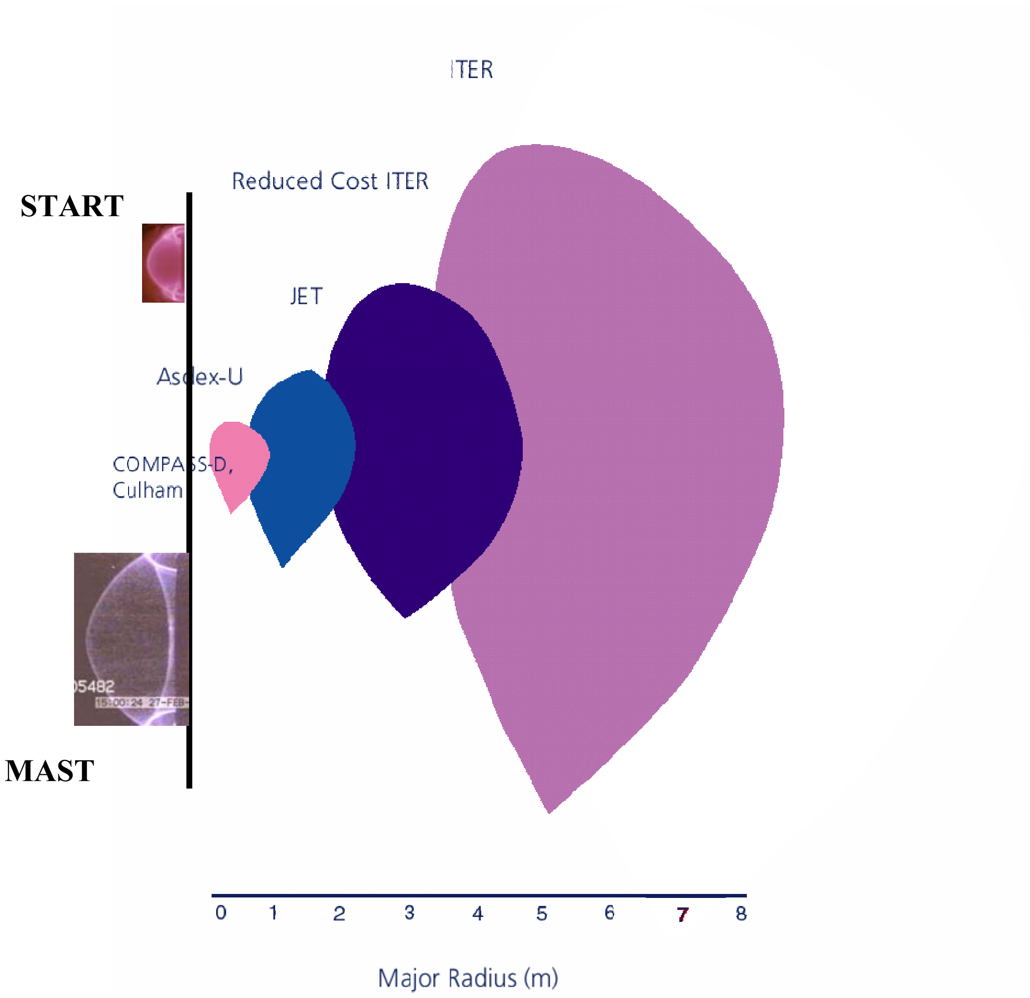
For each tokamak, the right-hand limit to operation is the onset of the low-q limit at $q_a \sim 2$

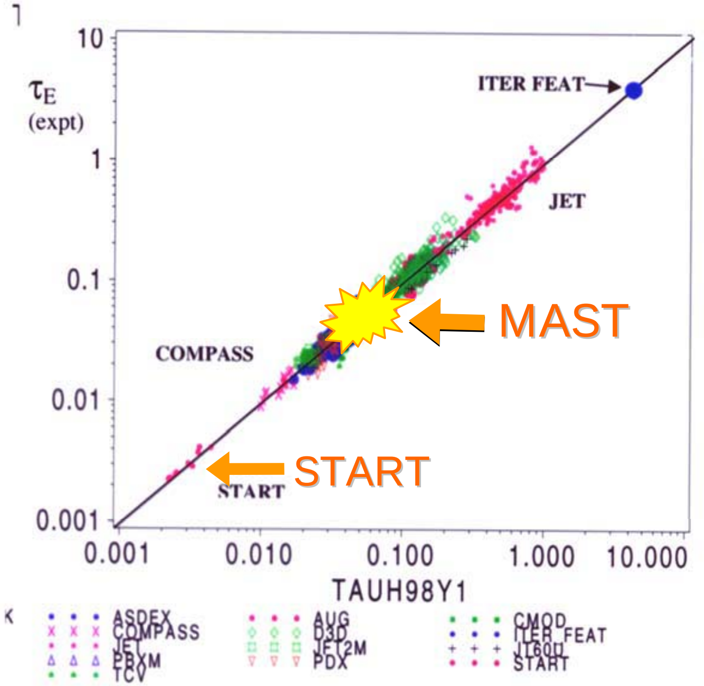
Large A, circular section machines (eg TFTR) meet this limit at low I/aB and so have low β

Strait, APS 1993



STs have at least as good confinement as conventional aspect ratio tokamaks:





Results from devices around the world, START and MAST data are in good agreement with ITER scaling

Role of Spherical Tokamaks in Fusion Research

Present status:

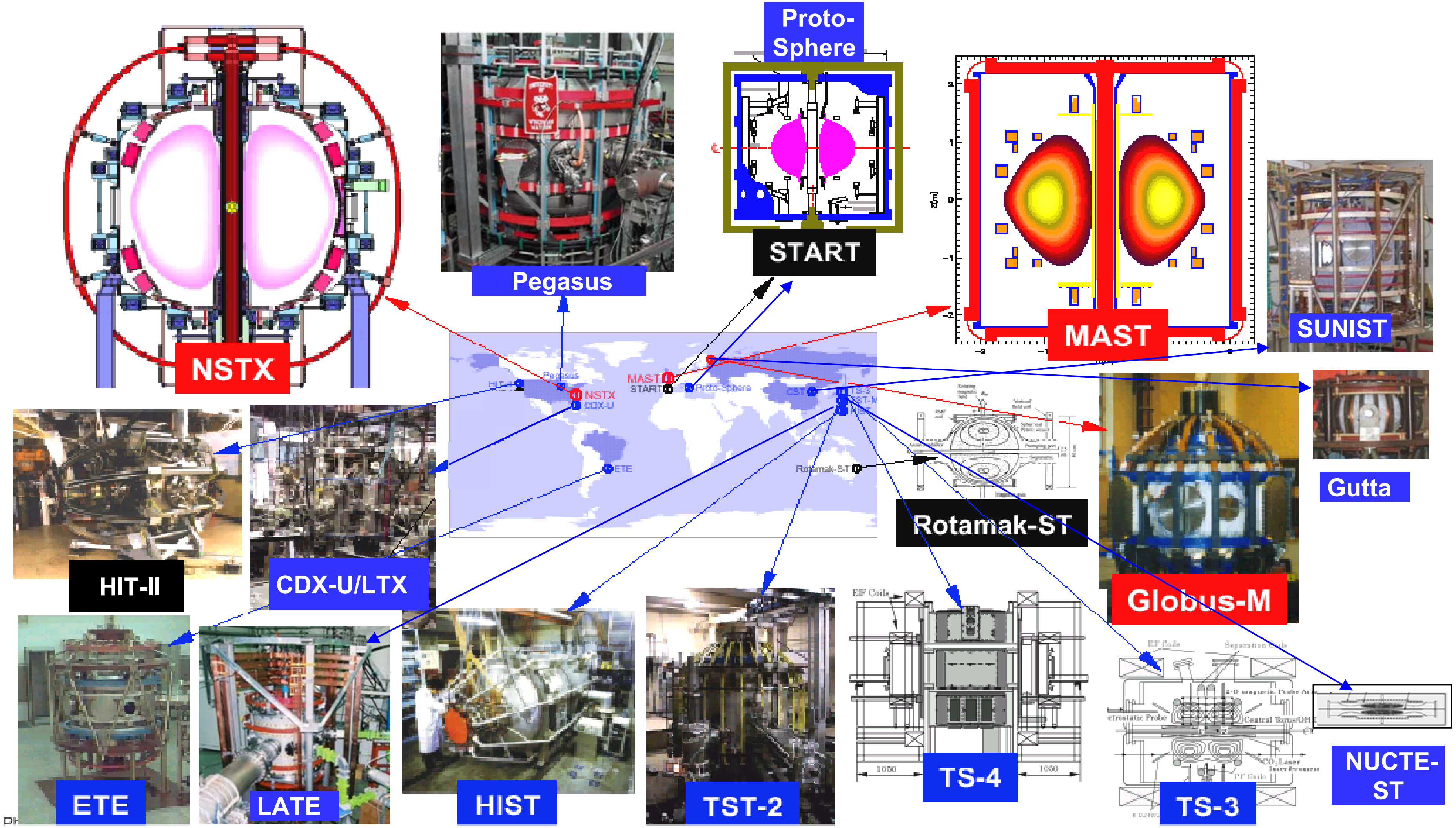
- 15 spherical tokamaks are operational

Asia: ***8*** (6 in Japan, 1 in China, 1 in Turkey)
America: ***4*** (3 in USA, 1 in Brazil)
Europe: ***3*** (2 in Russia, 1 in UK)

STs have an important role in fusion research:

- Very low construction and operation costs - sutable for universities and developing countries
- 13 new STs have been built during last decade, only one conventional tokamak
- Due to good plasma stability at low aspect ratio, spherical tokamaks are very reliable and easy to operate
- At the same time STs show very good performance: the highest plasma pressures in tokamak have been achieved in STs (START, NSTX)

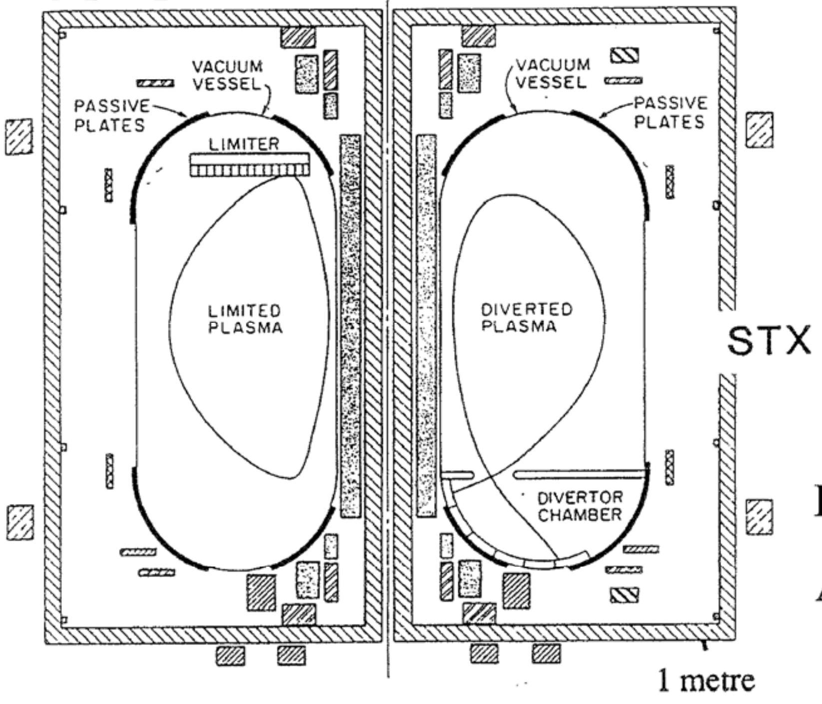
A sphere full of Spherical Tokamaks



Some History...

1985 - 7:

- Peng & Strickler [1] published a summary of the physics of low A
- Robinson [2] advocated low A as a means of obtaining RFP efficiency with tokamak stability
- Peng proposed building STX at ORNL



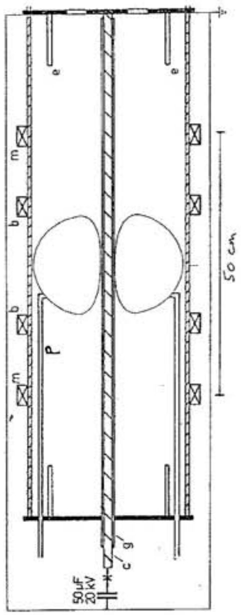
Estimated cost $6M

Aspect ratio A ~ 1.67

[1] Y-K M Peng & D Strickler, NF 26 769 (1986)]

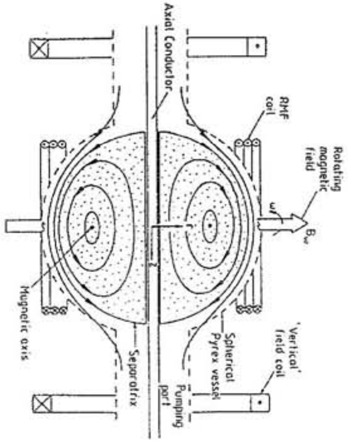
[2] D C Robinson, in Fusion Energy & Plasma Physics, World Scientific Press p601 (1987)

Some early Spherical Tokamaks (to scale)



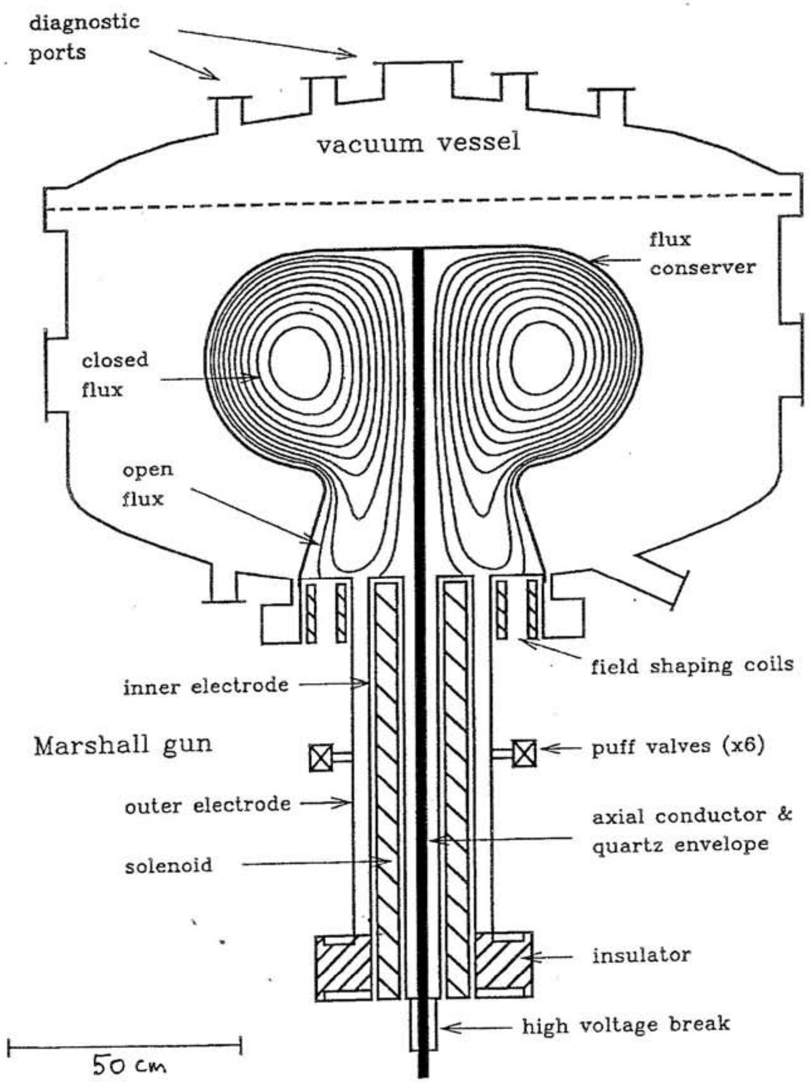
Heidelberg Spheromak + TF rod

Bruhns et al, NF **27** 2178 (1987)



Lucas Hts Rotamak + TF rod

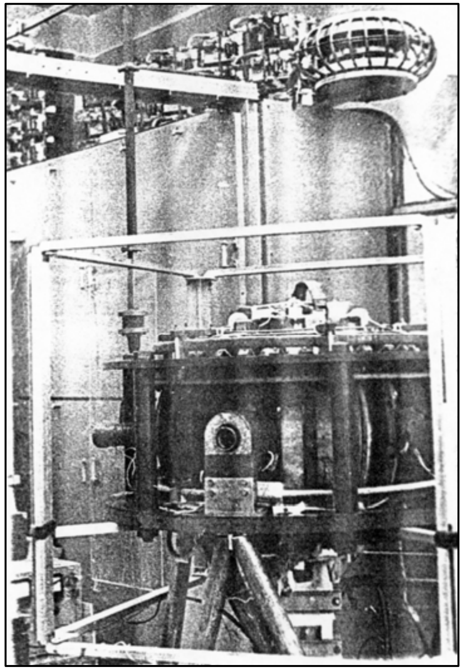
G A Collins et al, NF **28** 255 (1988)



SPHEX + TF rod, UMIST

P K Browning et al, PRL **68** 1722 (1992)

GUTTA, IOFFE, USSR (1980-1985)



GUTTA, Ioffe Institute, 1983

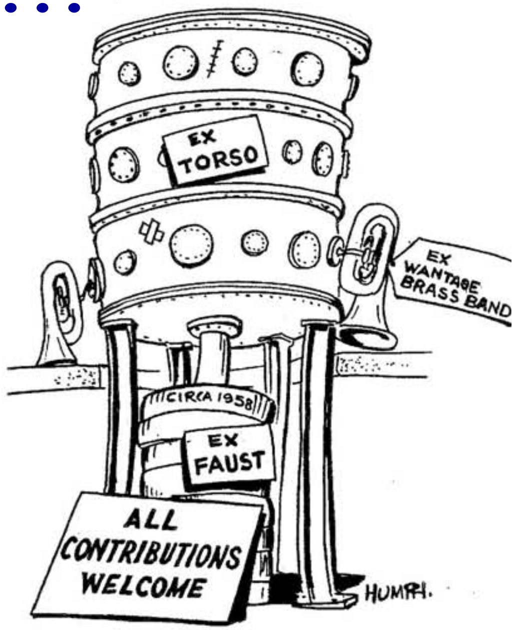
- GUTTA was the first attempt to built a spherical tokamak
  G.M. Vorobyev, Ioffe Institute, 1980-86

Main parameters:
major radius – R = 16 cm
minor radius – a = 8 cm
aspect ratio – A ~ 2
vessel elongation – k = 2
plasma current < 150kA
toroidal field - 1.5 T

GUTTA is now operational at St. Petersburg State University, Russia

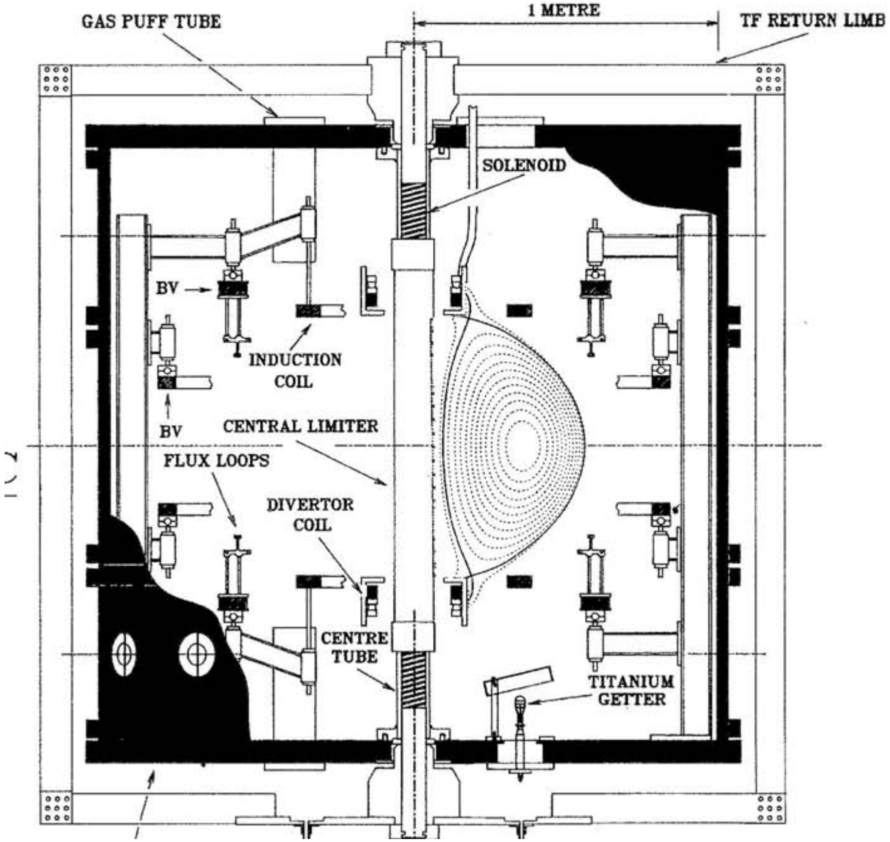
Plasma is seen through a port in GUTTA - 2004

Some Recent History...



1988 - 91

- STX abandoned
- Robinson & Todd design low-budget START experiment at Culham

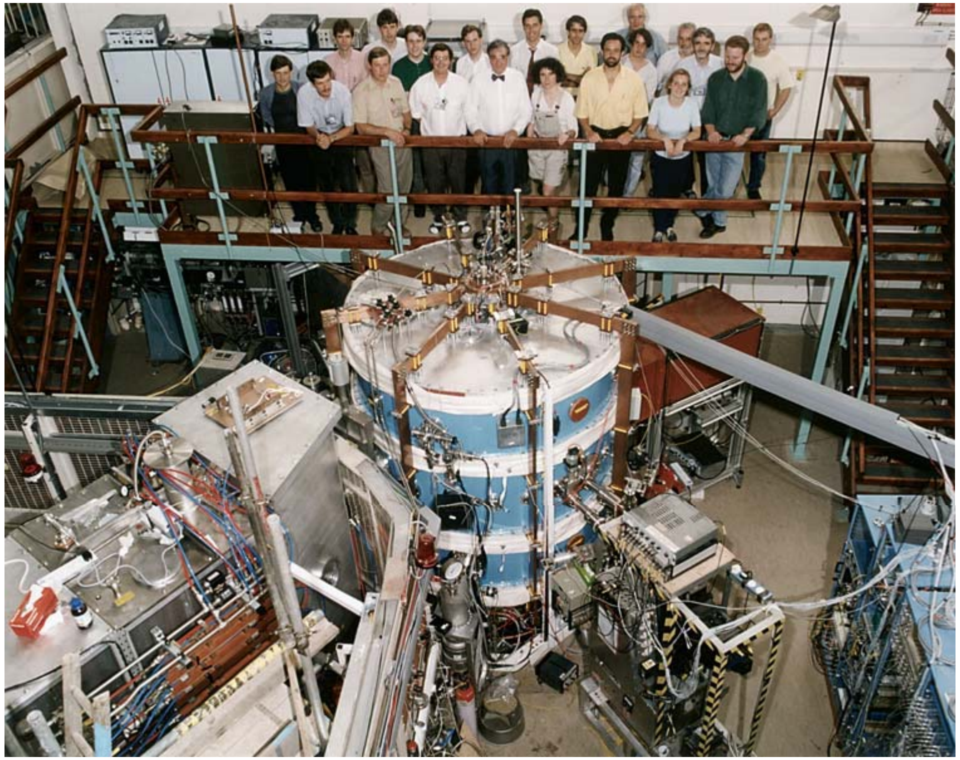


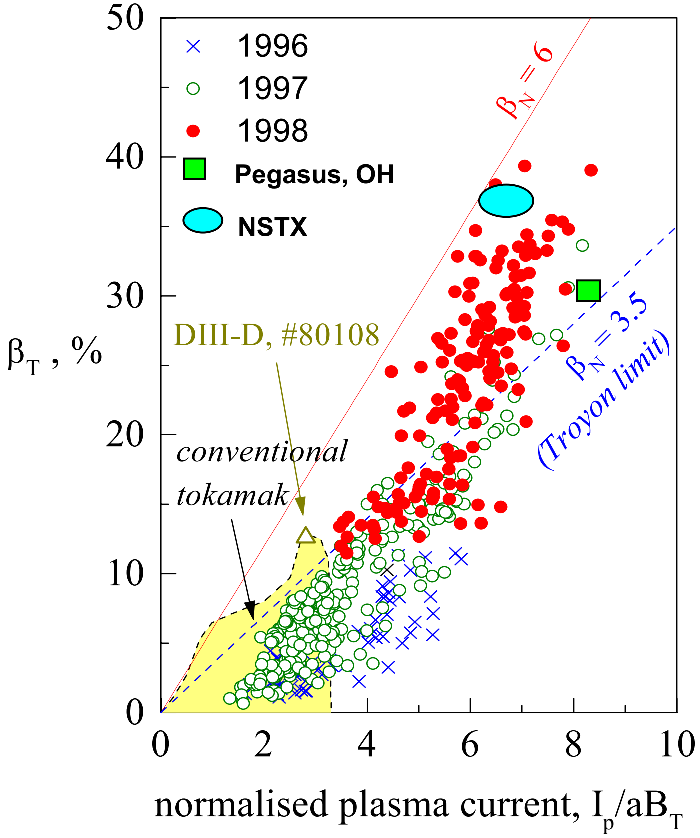
First plasma in START, Jan 1991

Initial build cost ~ £0.1M;

Aspect ratio A ~ 1.25

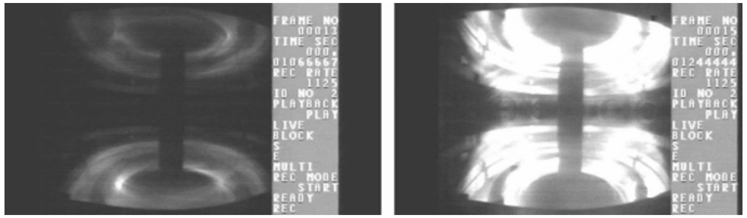
START, UKAEA (1990-1998)





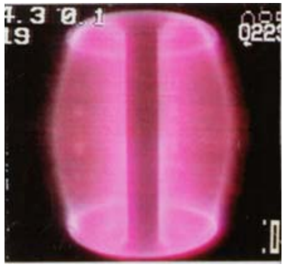
START attained world record tokamak beta values by a combination of high shape factor (~ I/aB) and high β_N.

Main Results from START:

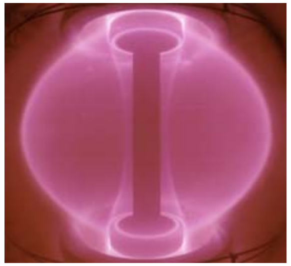


merging-compression

high elongation

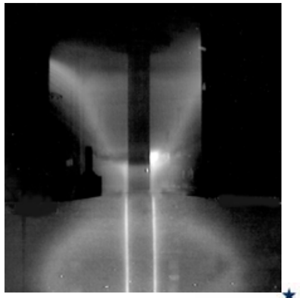


- New method of plasma formation without use of solenoid flux (merging-compression)
- Good global stability: no disruptions in first 34000 shots
- L and H-mode confinement is at least as good in other tokamaks
- Neutral beam heating is as efficient as in other tokamaks
- Exhaust power load has favourable outboard asymmetry
- Record β = 40% in tokamaks has been achieved

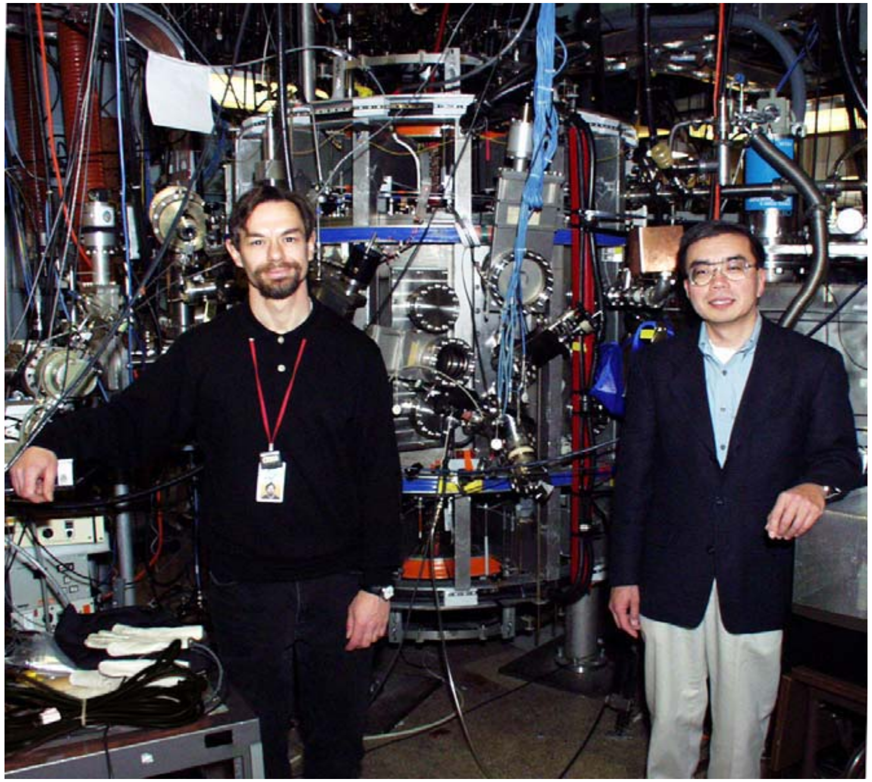


H-mode

natural exhaust



CDX-U, PPPL

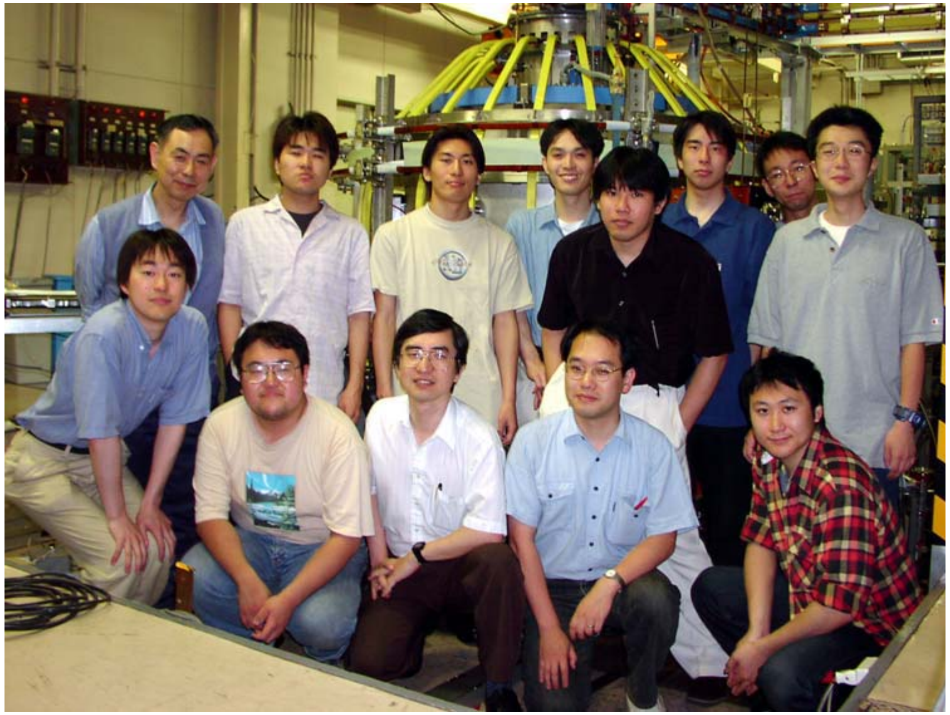


First plasma: Oct 1993

	achieved
Major radius R (m)	0.34
Minor radius a (m)	0.22
Elongation	< 1.6
Aspect ratio (R/a)	>1.5
Plasma current (MA)	0.1
TF rod current (MA)	0.4
Toroidal field at R (T)	0.2
RF Aux. heating (MW)	0.2
Pulse length (s)	0.025
Plasma volume (m^3)	0.5

CDX-U is dedicated to a multi-institutional effort to study liquid lithium effects in spherical torus plasmas

TST-2, Tokyo



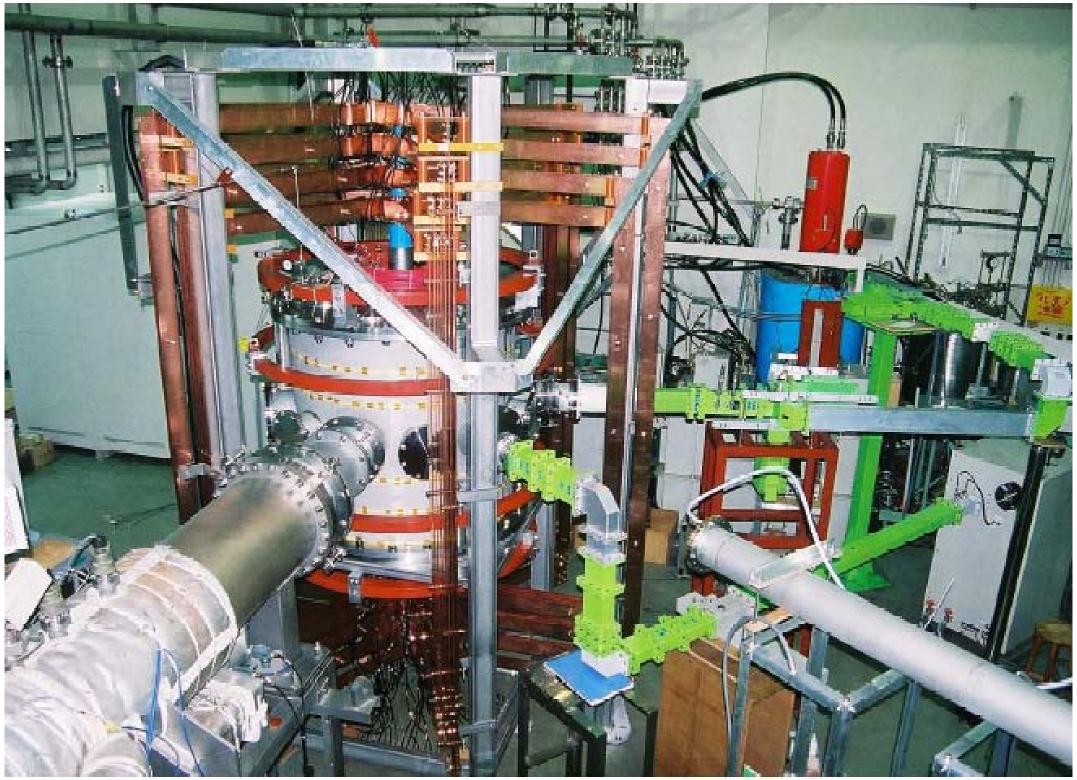
First plasma: Sept 1999

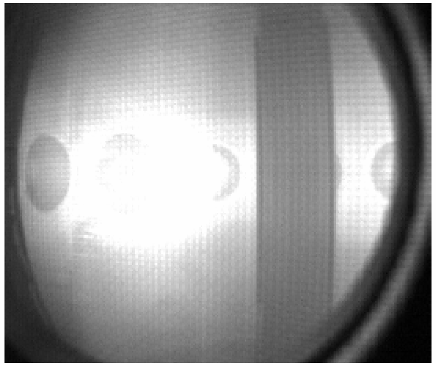
TST-2	design	(achieved)
Major radius R (m)	0.36	(0.36)
Minor radius a (m)	0.23	(0.23)
Elongation	< 1.8	(1.8)
Aspect ratio (R/a)	1.6	(1.6)
Plasma current (MA)	0.2	(0.11)
TF rod current (MA)	0.72	(0.38)
Toroidal field at R (T)	0.4	(0.21)
Aux. heating HHFW (MW)	0.5	(0.001)
Pulse length (s)	0.05	(0.1)
Plasma volume (m^3)	0.5	(0.5)

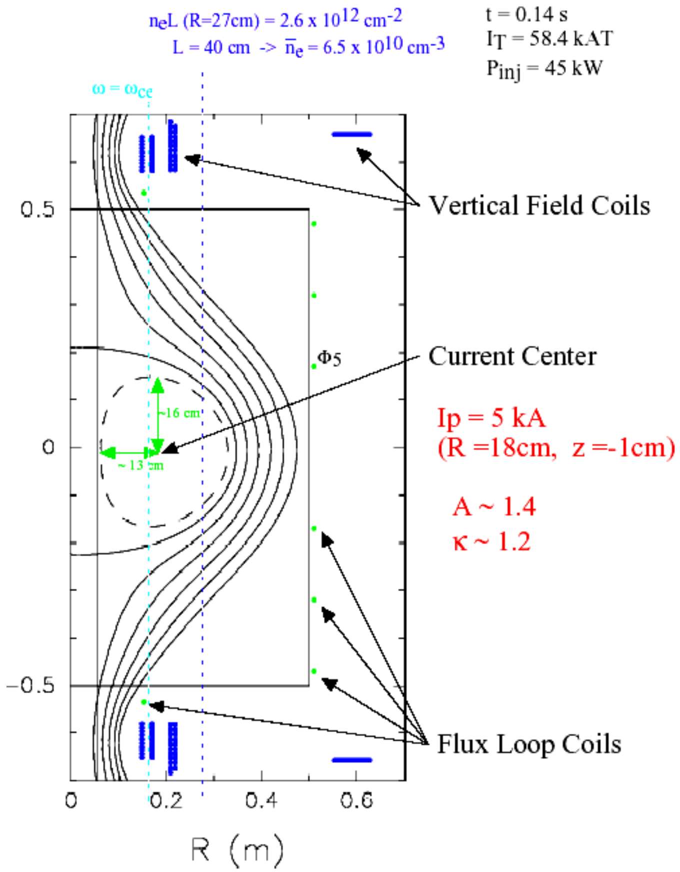
Key research thrusts:

- university research
- RF physics: formation, EBW
- fluctuations and transport

LATE, Kyoto Univ.





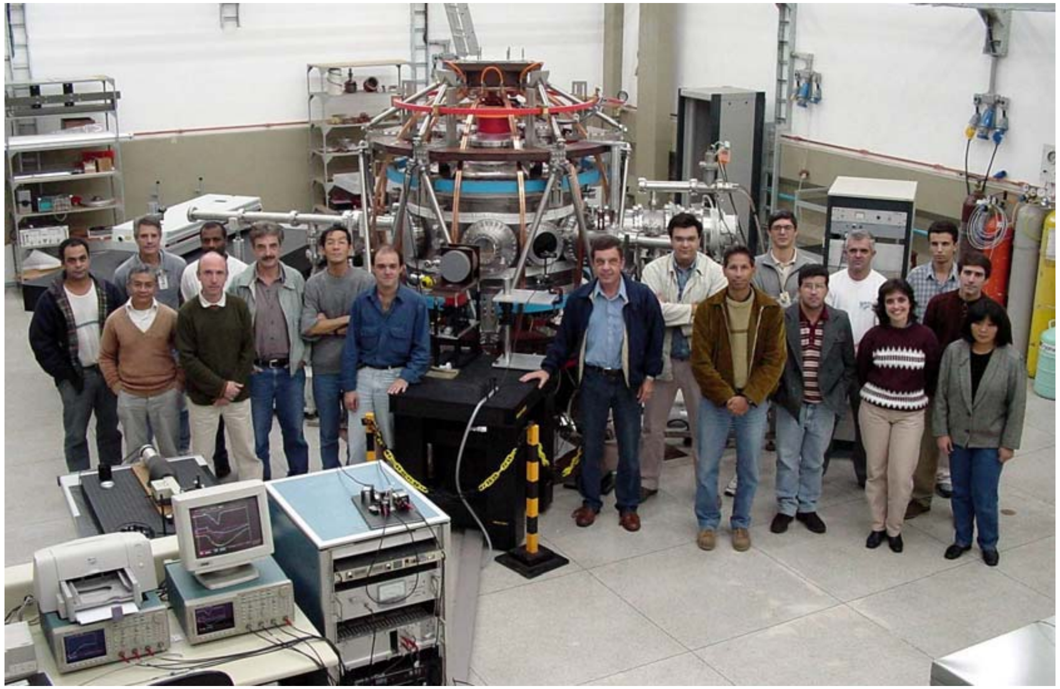


Key research objectives:

non-solenoid start-up and sustainment - 5sec pulse duration

EBW heating and current drive

ETE, at INPE, Brazil



First plasma: November 2000.

	design	(achieved)
Major radius R (m)	0.3	(0.3)
Minor radius a (m)	0.2	(0.2)
Elongation	< 2	(?)
Aspect ratio (R/a)	1.5	(?)
Plasma current (MA)	0.4	(0.03)
TF rod current (MA)	0.9	(0.1)
Toroidal field at R (T)	0.6	(0.067)
Aux. heating	-	
Pulse length (s)	0.1	(0.005)
Plasma volume (m^3)	0.35	(?)

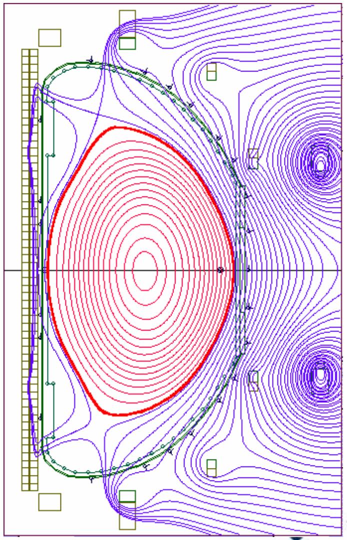
Key research objectives:
- **Investigation of parameter space in ohmic regime**
- **Study of plasma edge physics**

GLOBUS-M, St Petersburg

First plasma: November 2000.

	design	(achieved)
Major radius R (m)	0.36	(0.37
Minor radius a (m)	0.24	(0.24)
Elongation	2.2	(1.8)
Aspect ratio (R/a)	1.5	(1.5
Plasma current (MA)	0.5	(0.35)
Toroidal field at R (T)	0.6	(0.35)
Aux. Heating, MW	-	(0.3)
Pulse length (s)	0.3	(0.3)

Key research objectives:
- **Confinement studies**
- **NBH, ICRH, EBW, LH studies**
- **Diagnostics development**



Pegasus, Univ. Wisconsin

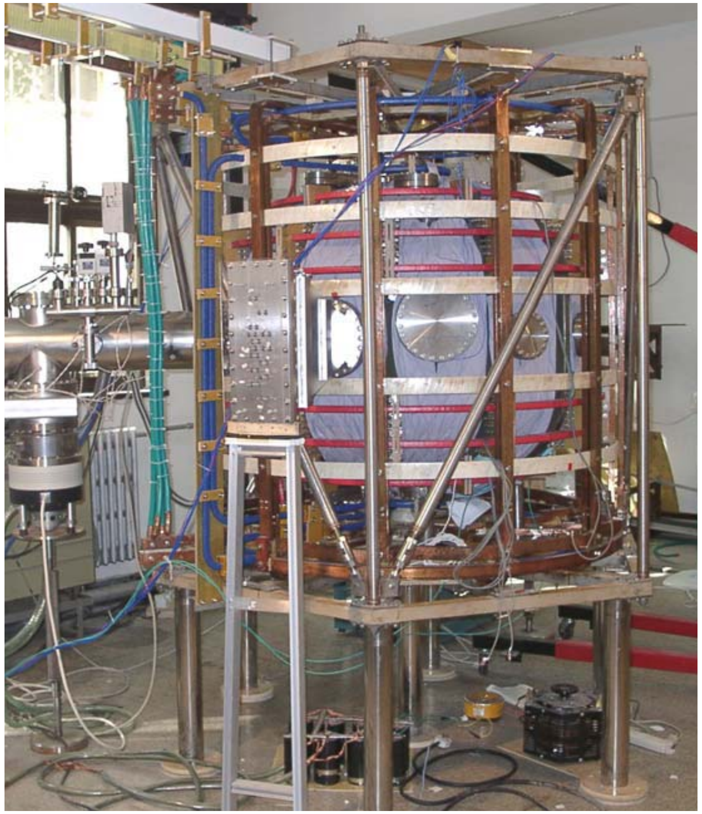
First plasma: June 1999

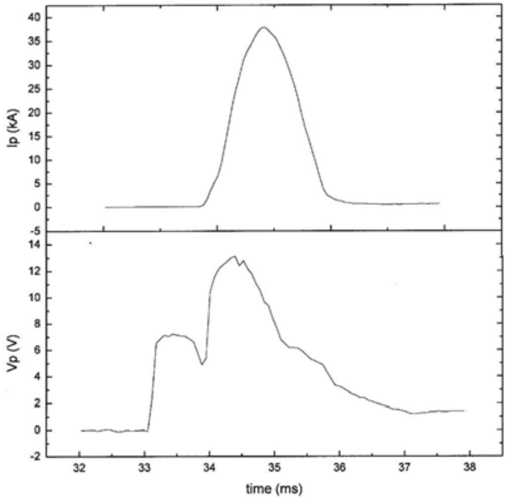
	design	(achieved)
Major radius R (m)	0.4	(0.45)
Elongation	< 3	(3.7)
Aspect ratio (R/a)	1.1	(1.1)
Plasma current (MA)	0.14	(0.3)
TF rod current (MA)	0.2	(0.225)
Toroidal field at R (T)	0.1	(0.15)
Aux. heating (HHFW, EBW)	-	(?)
Pulse length (s)	0.25	(0.06)

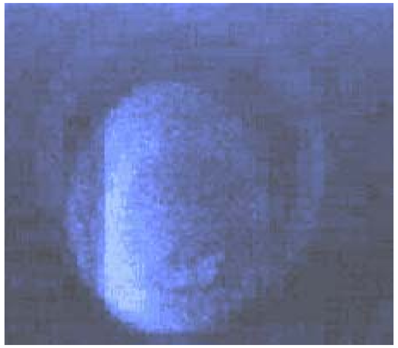
Exploration of A ⇒ 1 regime

SUNIST

Institute of Physics, Chinese Academy of Science
Department of Engineering Physic, Tsinghua University
Southwestern Institute of Physics
Institute of Plasma Physics, Chinese Academy of Science







the first SUNIST plasma on Nov. 4, 2002

Key research objectives:

- **Investigation non-inductive current ramp, CHI**
- **EBW**
- **core and edge fluctuations study**

ST proof-of-principle research - present status

MAST(UK), NSTX, Pegasus, CDX-U, HIT-II (US), Globus-M (RF), ETE(Brazil), TST-2 (Japan) and other STs are providing physics basis for Next Step ST devices and also contribute to ITER

	START	**MAST**	**NSTX**
R,m	0.35	0.85	0.85
a,m	0.27	0.65	0.68
k	1.5 - 3	2.4 (3)	2.5
I_p,MA	0.31	1.2 (2)	1.5 (1.0)
B_t,T	0.3 - 0.6	0.5	0.45
P_{aux}, MW	1 NBI +0.2 EC	3 NBI (5) + 1 EC (1.5)	5 NBI (5)+ 4 FW(6)
τ_{pulse}, s	< 0.06	0.65 (5)	0.55 (5)

Red – design values

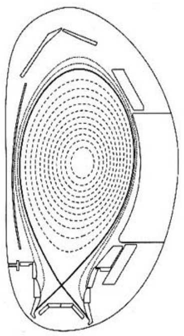
Recent results:

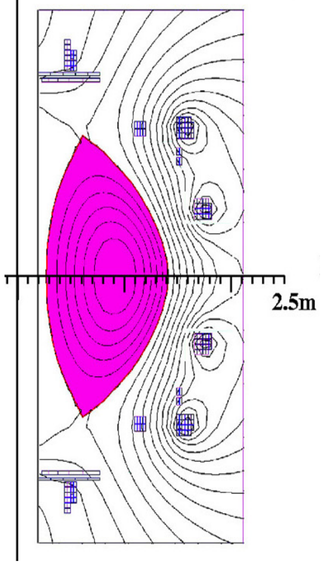
NSTX:

β_t~40%; β_N **~ 7** >$\beta_N^{(no-wall)}$; β_{pol}~ 2, H_{pby2}~1.8, T_e~ 3.5keV;

MAST:

β_N **~ 6** >$\beta_N^{(no-wall)}$; β_{pol}~ 2, H_{pby2}~ 2; T_i, T_e~ 3keV; G > 2

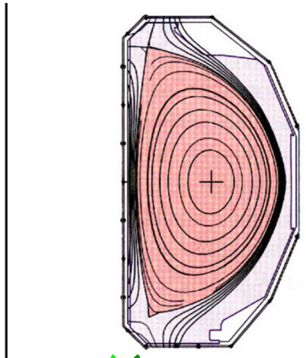


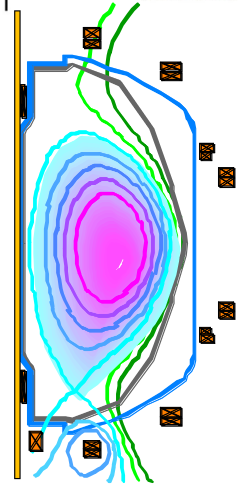


MAST and ASDEX-Upgrade in Europe ⇐

Large STs have similar cross-section and main plasma parameters with conventional aspect ratio tokamaks of similar size

⇒ **NSTX and DIII-D in USA**





NSTX, Princeton

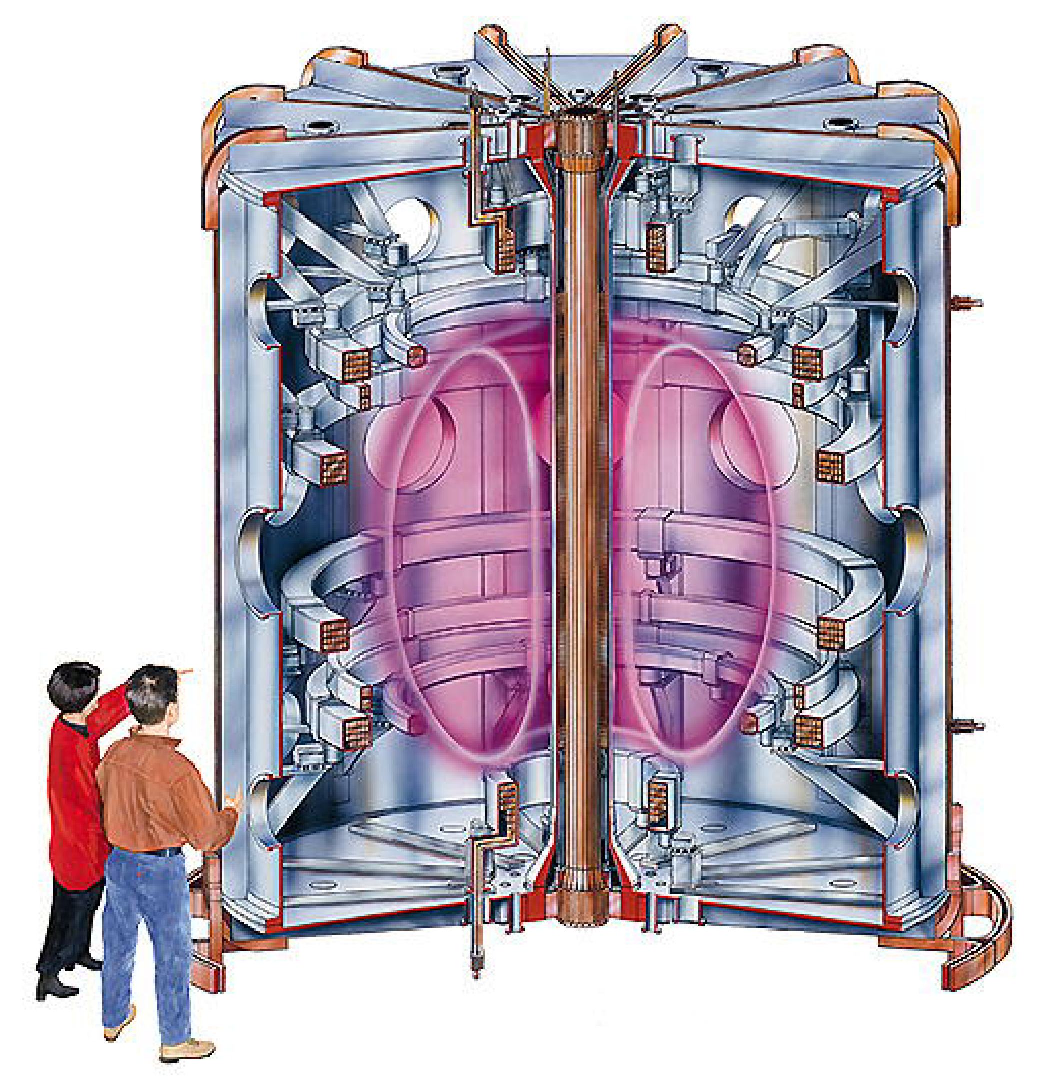
NSTX team, June 2001

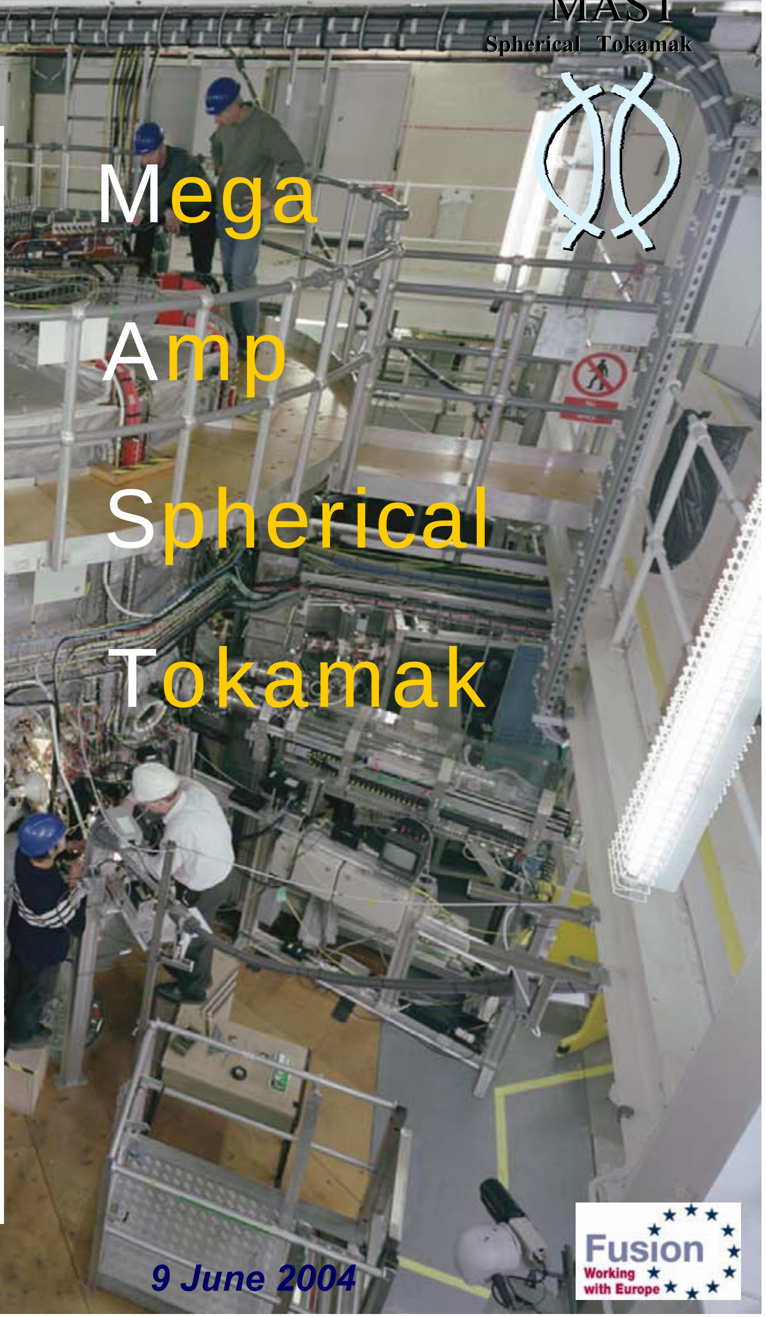
CP2002-35

MAST

MAST
Spherical Tokamak

MAST





Mega

Amp

Spherical

Tokamak

MAST, UKAEA

MAST team:

J.Ahn, R.Akers, L.C.Appel, E.R.Arends, K.Axon, C.A.Bunting, R.J.Buttery, C.Byrom, P.G.Carolan, D.Ciric, N.J.Conway, G.F.Counsell, M Cox, G.Cunningham, A C Darke, J.Dowling, M.R.Dunstan, A.R.Field, S J Fielding, S.J.Gee, R.S.Gorman, M.P.Gryaznevich, R J Hayward, P.Helander, M.Hole, M B Hood, P.Jones, A.Kirk, I.P.Lehane, B.Lloyd, G.P.Maddison, S.Manhood, R.Martin, G.J.McArdle, H.Meyer, K.McClements, M.A.McGrath, A.W.Morris, S.K.Nielsen, M P S Nigtingale, A.Patel, T.M.Pinfold, M.Price, J.Qin, C.Ribeiro, D C Robinson, V.Shevchenkov, S.Shibaev, K Stammers, A.Sykes, A.E.E.Tabasso, D.M.A.Taylor, D.Terranova, N.P.J.Thomas-Davies, M.R.Tournianski, A.Thyagaraja, M.Valovič, M.J.Walsh,S E V Warder, J.Waterhouse, H.Wilson, Y.Yang, S.You, and the ECRH and NBI teams

and to our collaborating Universities and Laboratories:

Imperial College
OF SCIENCE, TECHNOLOGY AND MEDICINE

Queen's University
Belfast

THE UNIVERSITY OF STRATHCLYDE
IN GLASGOW

WSL
The way to success

UNIVERSITY COLLEGE, CORK
Coláiste na hOllscoile Corcaigh

AARHUS UNIVERSITET

University College Dublin
An Coláiste Ollscoile, Baile Átha Cliath

Inside MAST

2001:

M Gryaznevich

A Sykes

D C Robinson

Inside the MAST vessel

MAST started operating in 2000

MAST Goals:

- to advance key tokamak physics issues for optimal exploitation of ITER

- to explore the long-term potential of the spherical tokamak (ST).

Success of the first four years of physics operations on MAST was based on:

- **Comprehensive diagnostics**
- **Flexibility of Magnetic Configuration**
- **Reliable operations in H-mode (OH or NBH) and easy H-mode access**
- **Low MHD and good confinement at high beta**

MAST has made considerable progress in addressing key issues for ITER and the ST concept:

Detailed transport analysis using high quality diagnostics and codes

- ELMy H-mode $\tau_E \sim \tau_E^{IPB98(y,2)}$ at low f_{ELM}, χ_i ,$\chi_e \rightarrow \chi_i^{neo}$
- ITBs with $\chi_i \rightarrow \chi_i^{neo}$ (co-NBI) and $\chi_e \rightarrow \chi_i^{neo}$ (cntr-NBI)

Extension of ITPA databases, removal of degeneracies & improvement of scaling laws, e.g. H-mode threshold, pedestal energy

Increased understanding of H-mode access

Preliminary indications of NBCD in agreement with predictions

Favourable divertor target power distribution

New insight into ELM structure and impact on plasma facing components

First demonstration of effective toroidally asymmetric divertor biasing

β_N values ($\beta_N > 5, > 5l_i$) approaching the ideal no-wall limit.

Tests of NTM physics - strong stabilising role of field curvature effects

Investigation of impact of energetic particle driven modes

Main Question still remains:

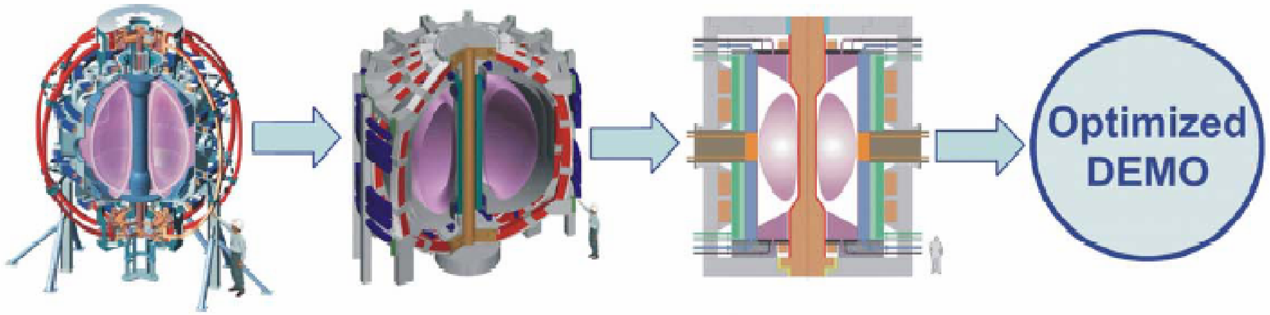
Is the ST a viable route to fusion?

Main SS issues:
formation
sustainment
exhaust

- Basics of Operational Power Reactor Regime

The Benefits of Projected ST Properties Include Potential Cost-Effective PE and CTF Devices

NSTX



Device	NSTX	NSST	CTF	DEMO
Mission	Proof of Principle	Performance Extension	Energy Development, Component Test	Economy of Fusion Electricity
R (m)	0.85	1.5	1.2	~2.5
a (m)	0.65	0.9	0.8	~1.8
κ, δ	2, 0.8	2.7, 0.6	3, 0.4	~3.4, 0.5
I_p (MA)	1.5	5 – 10	12	~20
B_T (T)	0.3 – 0.6	1.1 – 2.6	2.4	~2
P_{fusion} (MW)	–	10 – 50	≥ 70	~2000
t-pulse (s)	1 – 5	50 – 5	Steady state	Steady state
TF coil	Multi-turn	Multi-turn, LN_2	Single-turn	Single-turn

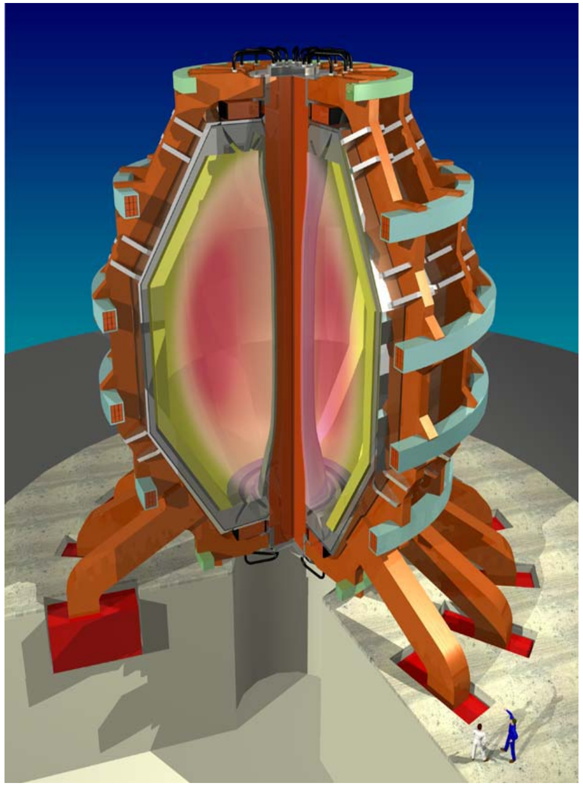
Progress towards Energy

Current Trends, DC 3/24-28/0

ST Power Plant and Material Test Facility Designs

- Several designs of Next Step STs, Volume Neutron Sources and Power Plants based on the ST concept have been proposed during the last ten years:

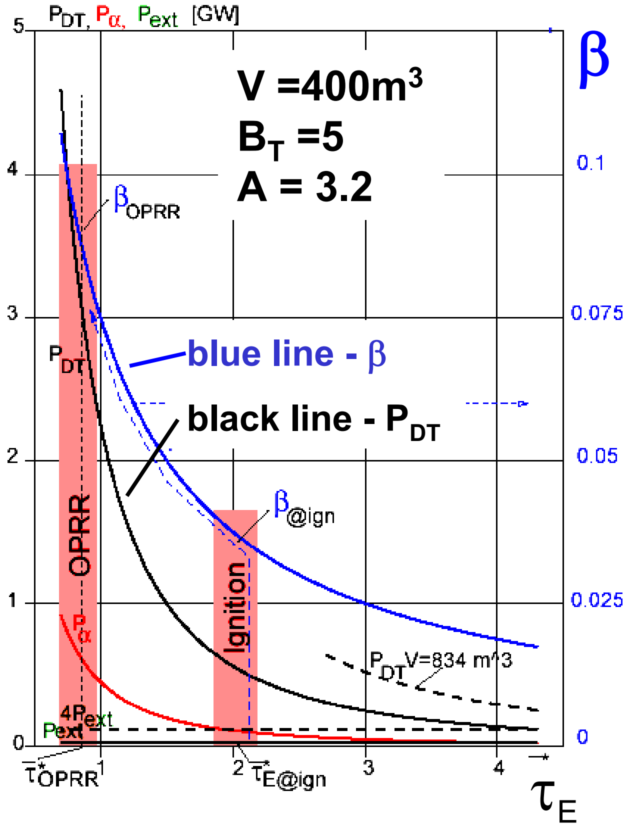
	Pilot Plant	FDF	FED VNS	VNS	VECTOR -SC	ARIES-ST	ST PP
	GA	GA	PPPL	UKAEA	JAERI	ARIES	UKAEA
Q	1.8	5.5	3	~ 1		~40	~50
R, m	1.05	1.12	1.3	0.57	2.8	3.2	3.4
a, m	0.75	0.7	0.93	0.36	1.4	2	2.4
R/a	1.4	1.6	1.4	1.6	2	1.6	1.4
k	2.5	3	3	2.3		3.4	3.2
δ	0.8	0.8	0.6	0.4		0.64	0.55
I_p, MA	15	10.2	10	6.8	19.4	30.8	31
B_t, T	2.8	3.62	2	2.5	5	2.14	1.8
P_{aux},MW	44	42	45.5	25		70	70
β_N	8.5	4.15	4.65	4.4	6.5	7.5	8.2
β_t %	62	18	25	34	18	54	59
Wall load	8		2	1.5	9.7	4.1	3.5
$f_{non-ind}$	0.9	0.9	0.5	0.33	0.9	0.99	0.95

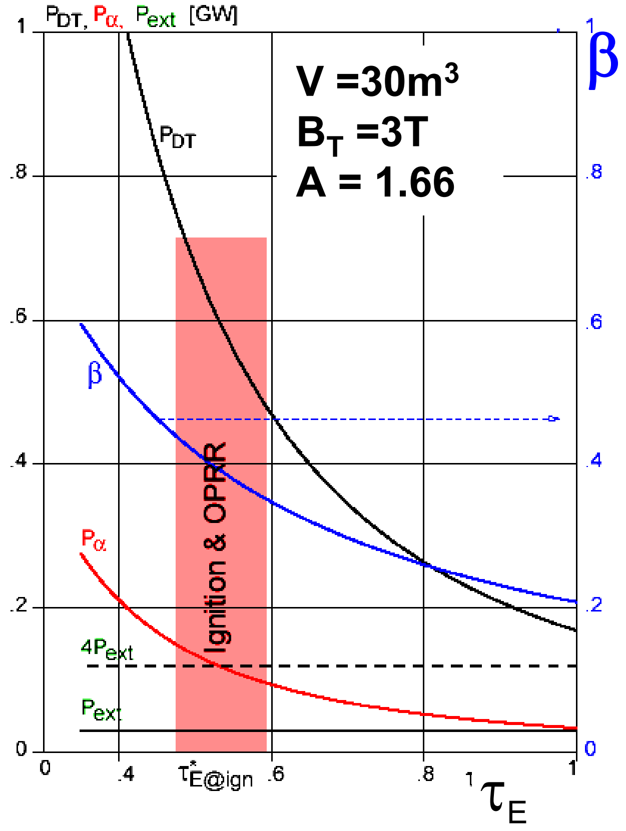


- **How these projects are supported by research results from STs?**

Operational Power Reactor Regime in STPP and conventional aspect ratio reactor

- In a conventional aspect ratio reactor OPRR and Ignition Regime have different requirements: ignition requires high τ_E, commercial operation requires high β :





Three rules:

Ignition condition should be fulfilled during both ignition and OPRR:

$nT\tau_E$~1.6 or $B^2\beta\tau_E$~ 4

at ignition: P_{ext}~$0.25P_\alpha$

At optimum temperature fusion power is:

$$P_{DT} = 5\int P_\alpha dV \sim 2V/\tau_E^2$$

In a Spherical Tokamak Reactor ignition and operations regimes may overlap!

Is the ST a viable route to fusion?

The ST has a number of promising features, eg

simpler construction than conventional tokamaks
good confinement,
low halo currents,
high density operation,
good stability (particularly at high elongation).

But questions remain to be addressed by experiments and theory:

How does confinement scale?
Are there options for handling the exhaust?
What is the pressure limit (β_N~ 6 already achieved)?
Can we demonstrate non-inductive current drive (and start-up)?
Fundamental plasma physics at high β~1

We are entering an exciting era

The role that the ST has to play in the development of fusion should become clear **in the next few years**