The Development of Commercial Fusion Energy in the EU
“ITER”, “Fast Track”, “Ultra Fast Track”

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ITER Design Review Coordinator
Research Centre Karlsruhe – KIT Campus North

KIT has ~ 8000 employees – half in Campus North

KIT = Karlsruhe Institute of Technology
Program Topic "Energy"

Programs in KIT-CN ~ 200 to 400 employees

Fusion Program has 230 employees and ~ 31 M€ budget per year
Outline

- What are the problems concerning the worldwide energy production and use
  - Climate change, finite Oil and Natural Gas resources

- Possible solutions for these problems and their potential
  - Renewals, Nuclear Fission, Fusion, Transport – electric (battery, fuel cells)

- Fusion as mid- to long-term solution for part of the problem
  - ITER and its mission
  - The Fast Track to Fusion Energy (DEMO)
  - The Ultra Fast Track

- Summary and Conclusions
The Climate Change Problem

Die Langfristperspektive

Nordhemisphäre-Temperatur (IPCC)
Jahresanomalien 1000 - 1998

Paläoklimatolog. Rekonstruktion und direkte Messungen

Mann et al., 1999; IPCC, 2001
The Problem of limited Oil Resources
- Total World Potential and available Reserves

**Ressources**: Part of the total resources which has been either discovered but is not yet economically accessible, or geologically indicated, estimated in situ amount or for other reasons not part of the oil reserves.

**Reserves**: This is the part of the total resources which has been accurately measured and which can be utilised within today’s technical and economical boundary conditions.

Quelle: BGR
A selection of different prognosis for conventional and non-conventional oil production

- US-DOE 1999
- Odell 1998, conv. + non-conv., EUR > 800 Mrd. t
- Odell 1998, only conv., EUR ca. 540 Mrd. t
- Campbell 1997, only conv., EUR ca. 250 Mrd. t
- Edwards 1997, conv. + non-conv., EUR > 500 Mrd. t

- Edwards 1997, only. Without NGL, EUR 385 Mrd. t
- WEC 1999, conv. + non-conv.
- Shell 1995, conv. + non-conv., EUR ca. 600 Mrd. t
- Hiller 1999, only conv., EUR ca. 350 Mrd. t
- Hiller 1999, conv. + non-conv., EUR ca. 580 Mrd. t

EUR estimated ultimate recovery
The Problem of limited Gas Resources
- Total World Potential and available Reserves

![Graph showing gas resources and production]

- **Ressourcen**: 222 Bill. m³
- **Reserven**: 153 Bill. m³
- **Gefördert**: 65 Bill. m³

Production until 2025
Considering a growth of

Quelle: BGR
Installation of modern coal power stations in the EU, JA and China

Accumulated Power [MW]

- EU: European Technology (without Japan)
- JP: Japan
- CL: China local

Quelle: Dr. Gasteiger; Alstom VGB-Kongress Okt. 2004
The Coal option

Distribution of coal

Lasts ~ 200 years depending on possible increase of use

Quelle: BGR
The Nuclear Option
Distribution of Uranium Resources

Lasts ~ 80 years depending on increase of use (without breeding)
The Renewable Option

Global energy use
indicating primary energy sources with the focus

Source: BP (until 2003), World Energy Council
Electric power production from Renewables in Germany

% der Gesamtstromerzeugung in Deutschland

Regenerative Stromerzeugung [TWh/a]

- Wasser
- Wind Land
- Wind Offshore
- Europ. Verbund
- Biomasse, biog. Abfälle
- Fotovoltaik
- Geothermie


- AUSBAU (Bandbreite)
- REF nach Energierapport IV (2005)

Electric power production from Renewables in Germany

0 %

11,1 %

19,6 %

28,2 %

151
Energy usage in Germany
indicating the primary energy sources

Struktur des Primärenergieverbrauchs
in Deutschland 2006
Gesamt 14.464 PJ

- Braunkohle: 10,9%
- Steinkohle: 13,0%
- Kernenergie: 12,6%
- Erdgas: 22,8%
- Mineralöle: 35,7%
- Sonstige u. Stromsaldo: -0,3%
- Erneuerbare Energien: 5,3%

Quellen: Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), nach Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Arbeitsgemeinschaft Energiebilanzen; nach Wirkungsgradmethode; vorläufige Angaben, Stand Februar 2007
What are possible solutions to the above problems?

- If renewables alone can’t solve the problem then there are just three more options with different time scales:
  - Coal – lasts in the order of 200 hundred years – climate change impact!
  - Nuclear fission – lasts not much longer than oil and gas without breeding
    - new generation of fission power plants required – research need!
  - Nuclear Fusion – lasts millions of years – needs development – time!!

- In order to tackle our climate change and energy problem mankind will have to develop all options in parallel and utilise the different possible timescales
  - Most important is to develop energy sources which can be deployed in China and India as well – their economic growth is accelerating the problems

- Will fusion energy come in time to help solving the above problems?

- The development scenarios for fusion (ITER, Fast Track, Ultra Fast Track)
Schematic View of a future Fusion Power Reactor
200 million degrees required for maximum cross section
Needed resources for a D-T-Fusion Power Plant, ~1000 MW electrical:

Deuterium D₂: ~ 100 kg/a → in 5 \times 10^{16} kg Oceans

Sufficient for 30 billion years !!

Tritium T₃: ~ 150 kg/a

breeding with Lithium reaction →

Only 300 kg Li₆ needed per year

\[ ^6\text{Li} + n \rightarrow ^3\text{T} + ^4\text{He} + 4.8 \text{ MeV} \]

About 10^{11} kg Lithium in landmass
Sufficient for 30’000 years

About 10^{14} kg Lithium in oceans
Sufficient for 30 million years !!

Considering all energy is produced by fusion
The Fusion Performance is measured by the Triple Product

Triple Product = the product of density \([10^{20} \text{m}^{-3}]\), Temperature [KeV] and Energy Confinement Time [s] = \(6 \times 10^{21} \rightarrow \text{ignition}\)
The ITER Machine

Doughnut-Shaped Plasma

- V: 840 m$^3$
- R/a: 6.2 m / 2 m

Vertical elongation: 1.85
Triangularity: 0.45

- Density: $10^{20}$ m$^{-3}$
- Peak Temperature: 17 keV

- Fusion Power: 500 MW
- Plasma Current: 15 MA
- Toroidal field: 5.4 T
Energy and Particle Confinement is Turbulence driven

Turbulent energy transport sets in at a critical temperature gradient which depends on the local temperature.

Radial size of turbulent structures can be reduced by ExB shear and by magnetic shear.
We can explain the blue profile types by physic models!!

q profiles for standard and advanced scenarios

Pressure profiles for standard and advanced scenarios

Standard H-mode

~zero shear

Reversed shear

Strong

Weak

~zero shear

Standard H-mode
A Pedestal Model which is able to reproduce experiments (by G. Janeschitz)

$ExB$ velocity shear $\Rightarrow$ pedestal in MMM model (appreciably lower than experiment)

- additional magnetic shear stabilization is therefore postulated.

MMM transport gives good profile shape $\Rightarrow$ threshold for additional shear stabilization.

$$
\chi = \chi_{MMM} / \left\{ \left[ 1 + \left( \frac{\omega_{EB}}{G \gamma_0} \right)^2 \right] \cdot \max \left( 1, (s - t)^2 \right) \right\}
$$

$$
\omega_{EB} = \frac{RB_\theta}{B} \frac{\partial}{\partial r} \left( \frac{E}{RB_\theta} \right) \text{ where } E = \nabla p_i / (n_i e)
$$

second factor in denominator - additional shear stabilization

$t \downarrow \Rightarrow$ stabilization $\uparrow$, radial extent $\uparrow$

first factor in denominator - $E \times B$ velocity stabilization.

$G$ is adjustment factor in the $E \times B$ velocity stabilization

stabilization for $\omega_{EB} \sim G \gamma_{ITG}$

$0.5 < G < 2$ (K.H. Burrell, Phys. Plasmas 4 (1997) 1499)

$G \downarrow \Rightarrow$ stabilization $\uparrow$

adjust $t$ & $G$ to fit JET discharge ($t=0.5$, $G=0.5$)
Modeling starts to be able to describe transport

=> predictive capability

with ETG transport added to electrons and corrected fuelling
One-dimensional modelling of the plasma core:

The core model used is the MMM model together with the above pedestal model and a parameterisation table of 2D SOL modelling results.

It predicts that ITER will have a wide range of $Q > 10$ operation (up to 1 GW of fusion power).

It also shows how the different physics limit border the operation space.

Operational and objective limits: Power, $Q=5$, LH transition, low temperature limit on alpha power, auxiliary power, edge density limit.
Direct Construction Cost
~ 5 billion €

Licensing/Construction
9 years

Operation
20 years
~ 250 million Euro/year

International Organization
600 staff
Visiting researchers

Staffing Cost ~ 1 billion € for first 10 years

ITER Site
Cadarache France

Temporary ITER Offices
The ITER Design and Technology has been underpinned by R&D

**CENTRAL SOLENOID MODEL COIL**
- Radius 3.5 m
- Height 2.8 m
- $B_{\text{max}}=13$ T
- $W = 640$ MJ
- $0.6$ T/sec

**REMOTE MAINTENANCE OF DIVERTOR CASSETTE**
- Attachment Tolerance $\pm 2$ mm

**DIVERTOR CASSETTE**
- Heat Flux $>15$ MW/m$^2$, CFC/W

**VACUUM VESSEL SECTOR**
- Double-Wall, Tolerance $\pm 5$ mm

**REMOTE MAINTENANCE OF BLANKET**
- 4 t Blanket Sector
- Attachment Tolerance $\pm 0.25$ mm

**TOROIDAL FIELD MODEL COIL**
- Height 4 m
- Width 3 m
- $B_{\text{max}}=7.8$ T
- $I_{\text{max}} = 80$ kA

**BLANKET MODULE**
- HIP Joining Tech
- Size: 1.6 m x 0.93 m x 0.35 m

The ITER Design Review

A Design review took place during 2007 coordinated by G. Janeschitz where 150 leading scientists from all over the world participated.

~ 80 design changes were proposed and will be implemented in order to include new physics results and to solve some design problems which were known but could not be acted on due to lack of manpower.

A firm technical basis to start the construction of ITER exists now and the procurement of the long lead items has started with sending the Procurement Arrangement for the TF coils superconducting cables to the DAs of the parties.

13 issues pointed out by STAC remain to be tackled until May again in a world wide effort coordinated by G. Janeschitz.
### The Work on the 13 ITER STAC Issues

**Coordinated by G. Janeschitz**

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<th>Topic Title</th>
<th>Support Contact Person</th>
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<td>01.b</td>
<td>Shape Control / Poloidal Field Coils</td>
<td></td>
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<td>01.c</td>
<td>Flux Swing in Ohmic Operation and CS</td>
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<td>P. Thomas</td>
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Vertical Stability

High elongation ~ 1.85 (1.7 in “Big ITER”)

Thick *double-walled* vacuum vessel

Saturation of P2 and P5 in certain conditions

- The range of $li(3)$ between 0.7 and 1.0 has been specified for the design of the ITER PF system.

- There is a problem with vertical stability in most discharge phases but they are gravest in Ip ramp-up and ramp-down (high $I_i$)
Connection of toroidal rings of blanket modules provides improved passive stability characteristics:

<table>
<thead>
<tr>
<th></th>
<th>Stability margin (CREATE)</th>
<th>Stability margin (EFDA)</th>
<th>Growth rate (ms)</th>
<th>$M_\phi$</th>
<th>BAP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No blanket rings</td>
<td>0.27</td>
<td>0.37</td>
<td>68</td>
<td>3°</td>
<td>20.8</td>
</tr>
<tr>
<td>Blanket rings 1 &amp; 5</td>
<td>0.31</td>
<td>0.43</td>
<td>94</td>
<td>9°</td>
<td>31.1</td>
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<tr>
<td>Blanket rings 2 &amp; 4</td>
<td>0.33</td>
<td>0.44</td>
<td>98</td>
<td>11°</td>
<td>33.0</td>
</tr>
<tr>
<td>Blanket rings 7 &amp; 11</td>
<td>0.28</td>
<td>0.38</td>
<td>75</td>
<td>7°</td>
<td>25.2</td>
</tr>
<tr>
<td>Blanket rings 8 &amp; 10</td>
<td>0.29</td>
<td>0.39</td>
<td>79</td>
<td>9°</td>
<td>26.9</td>
</tr>
<tr>
<td>All blanket rings</td>
<td>0.39</td>
<td>0.52</td>
<td>150</td>
<td>22°</td>
<td>52.5</td>
</tr>
</tbody>
</table>

Solution: Improve Passive Stabilization

Analysis of disruption forces
Analysis of equilibrium/ control implications

Option of increasing voltage in PF coils from 6 to 9kV rejected by IO

A Portone et al, September 2007
ELM suppression by ergodization

Ergodization works for D3D (and JET).
WG-1 has proposed to use a set of 36 Resonant Magnetic Perturbation coils similar to DIII-D.
The Work on Elm Control Coil Integration

Integration of ELM control coils ~ 120 kAturns between the VV shells
Summary Working Schedule – bottom-up accel.

- **ITER IO**
  - Established

- **LICENSE TO CONSTRUCT**
  - Contract

- **START TOKAMAK ASSEMBLY**
  - EARTHWORKS
  - Other Buildings
  - Tokamak Building
  - Machine Assembly (51 months)

- **COMMISSIONING**

- **FIRST PLASMA**

- **2006** - Procurement & Fabrication
- **2007** - 1st sector
- **2008** - 1st sector
- **2009** - 1st sector
- **2010** - 1st sector
- **2011** - 1st sector
- **2012** - 1st sector
- **2013** - 1st sector
- **2014** - 1st sector
- **2015** - 1st sector
- **2016** - 1st sector
- **2017** - 1st sector
- **2018** - 1st sector
- **2019** - 1st sector
- **2020** - 1st sector
Road Map to the Fusion Reactor (Fast Track)

- **JET**: Plasmaphysics – Tokamak, Stellarator
- **ITER**: DEMO
- **14-MeV-Neutronsourc IFMIF**: Fusion Technology
- **Electrical Power Production**: Comercial Fusion Power

Timeline:
- 2005
- 2010
- 2015
- 2020
- 2025
- 2030
- 2035
- 2040
- 2045
- 2050
Broader Approach i.e. a World Fusion Programme, i.e. FAST TRACK
Main Technology Developments needed for DEMO; FZK contributes

- High Temperature Super Conducting Coils (40 to 77 K)
- He cooled Breeding Blanket and T-extraction
- Low Activation Structural Material for the “In Vessel” Components which can withstand the large neutron fluence (150 dpa end of life)
Biggest Problem: How to achieve good ac-loss properties?

Twisting concepts are difficult to implement with YBCO coated conductors but new concept of a Roebel type conductor has been tested by FZK:

Planned: Development of ac-loss optimized concepts
Demonstration of a RACC Cable ($\approx$ 1m) in the kA class

Target: To construct an HTS Fusion Demo-Solenoid $\approx$ 2013!
DEMO Fusion Core (FZK)

**Blanket**
- Transient thermal + electromagnetic loads
- Remote replacement 3 - 5 years (80...150 dpa)

**Divertor**
- Transient thermal + electromagnetic loads + large surface heat flux
- Remote replacement 1.5 - 2.5 years

- Pebble Bed Blanket 400-550°C
- Vertical Manifold ~320°C
- Strong Ring Shield ~320°C
- Vacuum Vessel ~100°C
FZK Solid breeder concept

- L>>p

- Helium Coolant

- Cooling/stiffening plate

- Beryllium

- Purge Gas

- Ceramic Breeder

- Lithium-Ceramics

- Cooling plate

- Cooling plates

- FIRST WALL

- PLASMA

- Neutron Energy (eV)

- Cross-Section (barns)

Li-6(n,α) and Li-7(n,n,α) Cross-Section

- 6Li (n,α) threshold 2.8 MeV

- 7Li (n,n,α) 2.8 MeV

- 9Be (n,2n) threshold 2.5 MeV
Development of the HCPB TBM for ITER

HELUM at 8 MPa

Temperature: 300 to 500 °C
HCPB integration

“hot ring shield concept”

“maintenance by using a limited number of ports”

elements of attachment concept
TBM System Development
a large prototypical He loop is built in FZK (HELOKA)
** Heater: Allows heating up to 330°C
Additional internal and surface heaters in test section
Hot loop side can be operated up to 550°C

HELOKA-HP/TBM
- Qualification for ITER
- Development of Helium Loop Technologies
- 80 bars, (max 100 bars)
- 500°C**
- 1.4 kg/s
- pulsed load operation
*ITER scenarios
- long term operation
- Graphite radiation surface heaters
Multiple Jet Cooled Divertor: Modular Concept

Armor (W)
Cap (W Alloy)
Cooling finger
He 600°C
He 700°C
Cartridge (Steel)

9-finger-module

13 MWm^{-2} have been achieved in HHF Tests
Successful HHF tests of improved mockups showing excellent results

2. series: #17 (FZK, thermomechanically optimised)

Test conditions:
• 10 MW/m²
• 30s / 30s sharp power ramp
• $T_{He,in}$ 550°C, 10 MPa, mfr 7 g/s

✓ Withstood 89 temperature cycles, w/o significant damage
(exp. terminated after slight temperature rise on tile top surface)
✓ He Loop and thimble still intact.

3. series: #22 (Efremov, EDM manufactured)

←before tests
after 100 cycles →

✓ Excellent performance.
✓ No any damages.
✓ No leaks.
✓ Stable surface temperature from cycle to cycle.
Structural Materials development for DEMO (FZK – World Leader)

EUROFER – Steel for the blanket and divertor
W- alloys for the divertor

EUROFER-ODS

ITER
30 dpa/year
High neutron energy not available in fission reactors

DEMO
3 dpa/lifetime

Materials

FZK develops and qualifies European reference materials
Fusions-Material-Laboratory

Materialprüfzelle

Metallographiezelle
Activation of the material by neutrons

Transmutation in radioactive isotopes by neutron capture (all neutron energies – higher neutron energies responsible for gas production)

Time dependence of the $\gamma$ dose rate after irradiation with fusion neutrons of up to 12.5 MWa/m$^2$
Strategy for recovery of irradiation embrittlement:
Annealing for example at 550 °C/2h

- How often can this recovery be repeated?
- What happens if larger concentrations of He are present?
- In a Fusion Reactor the He production is 100 times larger per dpa
Irradiation of DEMO-relevant structural materials by 14 MeV neutrons – neutron flux twice of DEMO
Road Map to the Fusion Reactor (can we accelerate this?)

My personal opinion

Ultra Fast Track

ITER
Plasmaphysics – Tokamak, Stellarator

14-MeV-Neutrons source IFMIF

Electrical Power Production

Comercial Fusion Power

Fusion Technology

Ultra Fast Track – Start of DEMO / PROTO Construction

Ultra Fast Track

Commercial power delivery starts Transition from demostration to commercial power

JET
Can we accelerate fusion development further?

- The answer is yes by approximately 20 years => “Ultra Fast Track”

- if the construction of a combined DEMO – PROTO starts in 2015 and the built-up of a team, the design and the R&D in 2010!!
  - Development and construction cost ~ 15 billion € spread over 15 years
  - A moderate increased economical risk (availability, cost of electricity) versus the Fast Track has to be accepted

- Even in this “Ultra Fast Track” scenario ITER and the Broader Approach are essential elements which also would have to be accelerated
  - Increase of ITER costs ~ 20%, i.e. ~ 1 billion € spread over 10 years
  - IFMIF needs to be constructed earlier (start 2011), cost ~ 1 billion €
How would an Ultra Fast Track reactor look like?

- The starting point would be the design of the large ITER machine from the 90th
  - It will be modified to allow stronger plasma shaping and to incorporate a He cooled solid breeder blanket (R ~ 8.5 m) and a He cooled divertor => (~ 1.5 GW electric net output)

- The “in vessel” components and their material (EUROFER) would be the only new development beyond the existing ITER technology !!

- What is the contribution of ITER, IFMIF and JT60SA?
  - ITER and JT60SA need to develop the operation scenario for PROTO
  - IFMIF needs to qualify the structural material (EUROFER) for the “in vessel” components – staged operation license may be also required
  - All of the above can be performed in parallel to the construction of PROTO
During this Talk

- 16 500 000 000 kWh primary energy was used worldwide
- 4 950 000 t CO$_2$ was released into the atmosphere
- more than 10 500 new cars and trucks were produced
- The world population increased by 18 000

- It is time to act and develop new CO$_2$ free energy sources
Investitionen in Neuanlagen zur Nutzung erneuerbarer Energien in Deutschland 2006
rd. 11,3 Mrd. €

- Biomasse Strom; 1.350 Mio. €; 12%
- Biomasse Wärme; 1.520 Mio. €; 13%
- Wasserkraft; 70 Mio. €; 1%
- Windenergie; 2.900 Mio. €; 26%
- Solarthermie; 900 Mio. €; 8%
- Photovoltaik; 3.990 Mio. €; 35%
- Geothermie; 580 Mio. €; 5%

Quelle: Zentrum für Sonnenenergie-und Wasserstoff-Forschung Baden-Württemberg (ZSW), 2007, vorläufige Angaben
Struktur der Stromerzeugung aus erneuerbaren Energien in Deutschland 2006

Gesamt: 72,7 TWh

Windenergie 42,0%

Wasserkraft 29,7%

Geothermie < 0,01%

Deponiegas 1,4%

Klärgas 1,2%

Biogas 7,4%

Fotovoltaik 2,8%

biogene Festbrennstoffe 9,1%

biogener Anteil des Abfalls 5,0%

biogene flüssige Brennstoffe 1,4%

gesamte Biomasse: rd. 23 %
(ohne Deponie- und Klärgas)

Quelle: BMU nach Arbeitsgruppe Erneuerbare Energien - Statistik (AGEE-Stat), vorläufige Angaben, Stand Februar 2007
Solarthermisches Kraftwerk in Almeria, Spanien

Zwei Solarkraftwerke mit jeweils 0,5 MW elektrischer Leistung

Quelle: DLR
Syngas aus Biomasse

Biomasse: Holz, Stroh, Heu ...

1. Schnelle Pyrolyse
   - ~ 500°C
   - τ < 10 s

2. Bahntransport
   - Energiedichte mit Faktor 10

3. Flugstromvergasung

4. Gasreinigung mit Wärmerückgewinnung
   - ~ 500°C
   - τ < 10 s
   - ~ 60 bar

5. Synthesegas
   - ~ 1200°C
   - ≥ 60 bar
   - τ 2-3 s

6. Kraftstoffsynthese
   - ~ 60 bar
   - Synfuel
   - H₂
   - Chemikalien

7. Stromerzeugung
   - GuD
   - Strom + Nutzwärme

CO₂

bioliq®
Biomass to Liquid Karlsruhe
Thermal Shield

- Cryostat thermal shield close to the magnet structures and supported in the central region by the TF coils

- Most labyrinths eliminated

- Reduced thermal radiation to 4K structures

- Separation of cold volume from the part crossed by water pipes

- Reduced total surface (and cost) of the TS.
ITER Toroidal Field Magnets

- Cable (38 mm): 3x3x4x5x6 = 1080
- Initial Triplex
- Central Tube
- Nb$_3$Sn Strand
- Sub-Cable Lapping
- Jacket (Incoloy 908)
- Insulation Tape
ITER-FEAT coil assembly
ITER Model Coil, High Temperatur SC Current Leads

Toska Facility

ITER Model Coil

HTS Current Lead

10 cm
Structure of the CS Model Coil

CS Insert Coil (JA)

Inner Module (US)

Outer Module (JA)

Winding Structure

Conductor Structure

2m

Cable (38 mmφ)
3x3x4x5x6 = 1080

Central Tube

Insulation Tape

Jacket (Incoloy 908)

Cable Lapping

Sub-Cable Lapping

Initial Triplex

Nb3Sn Strand
CS Model Coil R&D

Max. field 13.5T, max. current 46kA, stored energy 640MJ (max. in Nb$_3$Sn)
Ramp-up 1.2T/s (goal 0.4) and rampdown rates of -1.5T/s (goal -1.2) in insert coils, and 10,000 cycle test.
CS Model Coil R&D

Closing of the Test Cryostat (JA)
Dimensional accuracy after welding sector halves \( \pm 3 \) mm
Detailed shaping of the First Wall to shadow all exposed edges

Inner Wall

- Bi-directional design
- X-point can move

Near 2nd X-point

36 of 440 modules

Toroidal direction

- Inner Strike
- Outer Strike

1.7m – 2m

- Flat surfaces may suffice

In situ separable FW

On Outer Wall

260 of 440

~1.4m
Electrical Straps implementation

CAD view of 3 adjacent strapped shield modules
Blanket Module R&D

Drilling of forged steel block (Shield block cooling channels)

Bending of ice-plugged steel block (10,000 ton press machine)

Steel block after solution heat treatment (1010-1054 °C)

Assembly of steel tubes and DS Cu plates

Final assembly of FW and shield block

Canning for HIPing
Divertor Prototypical Vertical Target and cassette Mock-ups

Under high heat flux testing in the Le Creusot e-beam facility, it sustained:

- 1000 cycles at 18 MW.m\(^{-2}\) on the W macro-brush armour
- 2000 cycles at 20 MW.m\(^{-2}\) on the CfC armour.

Finally, the CfC armour was shown to survive > 30 MW.m\(^{-2}\) in a CHF test.
ITER Components - FZK Contributions

Central Solenoid
\( \text{Nb}_3\text{Sn} \)

Outer Intercoil Support Structure

Toroidal Field Coils
\( \text{Nb}_3\text{Sn}, 18 \text{ Coils} \)

Poloidal Field Coils
\( \text{Nb-Ti} \)

QA and Testing Current Leads

Machine Support Structure

Materials Qualification

Vacuum Vessel

Cryostat

Upper Port Plugs

ECRH

Equatorial Port Plugs:
- Test Blanket Modules
- Diagnostics
- Torus Cryopumps
- Tritium-Plant

Divertor Test module
ECRH: 170 GHz 2 MW Gyrotron Development

Gyrotron with superconducting magnet
Development of a 2MW Coaxial Gyrotron for ITER

- **1st gyrotron prototype:**
  - SC magnet delivered finally by manufacturer
  - To CRPP (Nov 07)
  - prototype tube installed in the SC magnet, conditioning starting now
  - beginning of gyrotron tests: Dec 2007

- **experimental pre-prototype tube:**
  - testing of a RF output system with a new launcher done. A new code for an improved system is under development
  - operation of the pre-prototype tube
    - with a modified coaxial insert to reduce parasitic low frequency oscillations worked
  - operation with a broad band RF output window (Brewster window)
Development of the ITER ECRH Top Port Plugs (I)

- Structural integration of the mm-wave system of the front steering launcher into the ECH upper port structure

A detailed design was developed composed of detachable blanket shield module (BSM) of the main structure setting the frame.

The main frame was modified to a slim wall concept with single and double wall sections. This provides access the central section of the internal shields and the mitre bends.

Modelling of baking temperatures

- 8 Circular waveguides
- Bottom hatch (bolted cover plate removed)
- Steering mirrors
- Internal shield (mirror section)
- Internal shield (beam section)
- Focusing mirror
- Valves and windows

Development of the ITER ECRH Top Port Plugs (I)
Development of the ITER ECRH Top Port Plugs (I)

- Structural integration of the mm-wave system of the front steering launcher into the ECH upper port structure

A detailed design was developed composed of detachable blanket shield module (BSM) of the main structure setting the frame.

The main frame was modified to a slim wall concept with single and double wall sections. This provides access the central section of the internal shields and the mitre bends.
Development of the ITER ECRH Top Port Plugs (II)

- Development of the torus window of the front steering launcher for common use at the equatorial and upper port

- Installation of the test platform for the launcher handling test facility and initialising tests on the thermo-hydraulic performance

A torus window design for the front steering launcher was fixed on the basis of the indirect cooling design with cooling separated from the CVD diamond disks.

A prototype torus window was manufactured and is being prepared for joint high power experiments with the equatorial launcher design group.

The water loop allowing thermohydraulic tests of the structural system under ITER conditions was installed and put into experimental operation. Alternative manufacturing routes for double wall structure have been studied with promising outcome and first prototypes for thermohydraulic testing are to be received from industrial manufacturing still this year.
FZK proposes to design and procure the inner Fuel Cycle for ITER
(with exception of the fuelling system)
ITER Torus Cryopumps

80 K Shield  4.5 K Panels

Valve
ITER Torus Cryopump Prototype tested in FZK
Vacuum Pumping

- Design activities: cryopumps for the Neutral Beam Test Facility (re-design after change from circular to rectangular beam line vessel) and the ITER cryostat
- Contract supervision of the manufacturing of the ITER prototype torus cryopump
- R&D activities: post mortem evaluation of the model pump, modelling and validation of ITER vacuum flows by ITERVAC code development and validation experiments in the TRANSFLOW facility; preparation of the TIMO-2 facility for testing the prototype ITER torus cryopump.

Model cryopump dismantled
Tritium Technology

- New license to operate TLK was assigned by the Local Government. 5 g tritium was bought from Canada and shipped to TLK
- The modelling of the entire fuel cycle was continued. Studies on tritium accountancy and tracking were conducted to develop a strategy for minimizing the uncertainties in tritium accountancy
- Detailed analyses of the ITER ISS-WDS process design reviewed with the possibility of processing highly tritiated water in WDS
- The TRENTA facility which consists of a water detritiation system in combination with a cryogenic distillation system now in operation

cryogenic distillation column with 2.7 m active length and 55 mm diameter.
ITER Safety: Effective Burning Rates of Graphite Dust – H – Air Mixtures

Measurement using small and medium sized open-end combustion tubes

Tested mixtures: 4-micron graphite dust/
hydrogen/air

Concentrations: \([\text{H}_2] = 9 \div 17\) vol. %;
\(C_{\text{dust}} = 100 \div 600\) g/m³

Geometry: Open-end combustion tube
15 cm inner diameter, 3 m length
(PROFLAM I facility)

Results:

- Addition of graphite dust generally lowers the efficient flame velocity in \(\text{H}_2/\text{air}\) mixtures.
- However, for each hydrogen concentration there is a dust concentration at which the flame velocity is higher than that in the pure \(\text{H}_2/\text{air}\) mixture.
- The obtained data will be used to validate 3D CFD code modeling explosion scenarios of severe accidents in ITER.
Example:

"Backward" arc in VACARC:
A ring of the quite robust glass-epoxy insulation acts like a nozzle that shapes the arc column into a rocket-like jet. This effect enhances the arc length, the arc power and its propagation velocity.

This finding must be further investigated and included in the model. The analyses in ITER DDD’s usually base on short arc lengths.

Documentation of MAGS with regard to ITER licensing procedure:

• Discussion with EFDA on QA requirements in progress.
• Documentation for INTRA code made available by EFDA as guideline or template.
Development of an Integrated Plasma Model

- One-dimensional modelling of the plasma core:

- further validation activities postponed

- initial neon scaling implemented

- Major ongoing activity: Development of ITER operating window
  - accomplished: influence of B and k
  - ongoing: influence of peak power at divertor plate, reduced transport, seeded impurities, helium scaling, and pumping speed

Operational and objective limits: Power, Q=5, LH transition, low temperature limit on alpha power, auxiliary power, edge density limit
Organisation Chart of the TBM Consortium

Governing Board

Project Leader
- Deputy PL 1
  - TBM HCPB Design & Specifications Division (FZK)
    - Design and specification
    - Materials; manufacturing
    - DEMO predictive tools
    - PbLi loop engineering
  - TBM HCLL Design & Specifications Division (CEA)
    - Design and specification
    - Materials; manufacturing
    - DEMO predictive tools
- Deputy PL 2
  - He Loops and Testing Division (ENEA)
    - HCS engineering
    - Helium purification
    - Qualification and testing
- Deputy PL 3
- Deputy PL 4
  - System Installation & Diagnostics Division (HAS)
    - Diagnostics (CIEMAT)
    - Installation in ITER (CEA)

Project Leadership

Management Support & Design Integration Team

Support & Design Division

Integration Team
Demo Blanket Test Modules in ITER

- Vakuumbehälter
- Abschirmplatten
- Zwischenstück
- Port Plug
- Flansch
- Übergangsstück
- Kryostat
- Abschirmblanket
- Port (leer)
- Test Blanket Modul
- leere Position für weiteres Test Blanket Modul
- Befestigung des Test Blanket Moduls
EU HCPB-TBM integration in ITER

- Detailed design of TBM HCS in TCWS-vault of ITER
- Development of maintenance strategies
- Update of space requirements for integration in ITER
TBM system integrated inside port cell 16 of ITER
(systems for both TBMs are shown)
Remote Maintenance of the Divertor - cassette toroidal and radial mover
Divertor Remote Handling Test Platform

Central Cassette Carrier

Divertor Port

Plug Handling Vehicle

Dummy Cassette

Toroidal Mover
In Vessel Transporter for Blanket Maintenance

DIMENSIONS RELATE TO ROOM TEMPERATURE (293K)

In-Vessel Transporter (IVT)
(Rail Mounted Vehicle System)

Swing Arm
Diverter Port
Upper Port
IVT Rail
In-Vessel Transporter
Blanket Receiver
Vacuum Vessel
Rail Support System
EQUATORIAL PORT
RH Transfer Cask

G. Janeschitz – talk at UCLA January 2008
KIT - Die Kooperation von Forschungszentrum Karlsruhe GmbH und Universität Karlsruhe (TH)
Vehicle Manipulator System for Blanket Maintenance
Payload~4 ton, Arm length~6m

Positioning 0.5 mm and 0.1°, rail deployed 90° around torus in ~ 30 min.