International Tokamak Physics Activity (ITPA)

A paradigm for international collaboration in science

by
R.D. Stambaugh
Chair, ITPA Coordinating Committee

American Association for the Advancement of Science
Annual Meeting

Boston, MA

February 16, 2008
International Tokamak Physics Activity (ITPA)

Origin

• ITPA was formed by four parties (EU, Japan, Russia, US)
  – Tokamak physics toward burning plasmas
  – Broader tokamak participation
  – Connection to stellarator community
• Formed with the endorsement of the IFRC and the FPCC
• Now Includes all 7 ITER members (EU, Japan, Russia, US, Korea, China, India)
Agreed principles for conducting the International Tokamak Physics Activity (ITPA)
September 3, 2001 Coordinating Committee

The International Tokamak Physics Activity (ITPA) aims at cooperation in development of the physics basis for burning tokamak plasmas. .......achievement of a broad physics basis useful for all fusion programs, for the ITER design, and for general tokamak research worldwide.

The ITPA shall consist in providing:

- Validated experimental data according to an agreed format;
- Analyzed results of experiments to advance understanding of fusion plasma physics;
- The organization, management, and updating of qualified databases;
- Theoretical models and simulation results to explain and reproduce experimental results;
- Studies of fusion plasma performance in burning plasma tokamak devices, such as ITER; and
- Identification and resolution of key diagnostics issues which might arise both in plasma control and in analysis of a burning plasma experiment, such as ITER.
The ITPA organization includes a Coordinating Committee and seven Topical Physics Groups. While the membership of these international Topical Groups is limited to 5 from each party in order to maintain a continuity and coherence, the meetings are open to other scientists also.

Management support is provided by the ITER International Team.
<table>
<thead>
<tr>
<th>EU</th>
<th>JA</th>
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* Chair; ** Co-Chair; *Chairing Committee Contact Person; "Stellarator (15 March 2007); M. Shimada; michiya.shimada@iter.org"
Meetings and Workshops

- The Topical Groups hold about two meetings annually to review the worldwide progress in their topical area, to discuss open scientific issues, and to recommend research topics that should be carried out and their priorities. One of these meetings is usually around a major international conference to minimize travel.

- The Coordinating Committee meets about once a year to review the work of Topical Physics Groups, to consolidate their recommendations, and to develop an annual list of ITPA research tasks for the world tokamak community to work on.
## ITPA Meetings Completed and Planned in 2007

<table>
<thead>
<tr>
<th>Topical Group</th>
<th>Location</th>
<th>Date</th>
<th>Comment</th>
</tr>
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<tbody>
<tr>
<td>Diagnostics</td>
<td>Princeton, USA</td>
<td>26-30 Mar.</td>
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<tr>
<td>Transport Physics</td>
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<tr>
<td>Confinement DB &amp; Modelling</td>
<td>Lausanne, Switzerland</td>
<td>7-10 May</td>
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<tr>
<td>Pedestal and Edge</td>
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<tr>
<td>Sol and Divertor Physics</td>
<td>Garching, Germany</td>
<td>7-10 May</td>
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<tr>
<td>Steady State Operation</td>
<td>NFRC, Daejeon, Korea</td>
<td>9-11 May</td>
<td>Before the IAEA-TM on Steady State Operation</td>
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<tr>
<td>MHD</td>
<td>General Atomics</td>
<td>21-24 May</td>
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<td>Coordinating Committee</td>
<td>Cadarache</td>
<td>18-20 noon June</td>
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<tr>
<td>Transport Physics</td>
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<tr>
<td>Confinement DB &amp; Modelling</td>
<td>Naka</td>
<td>1-3 Oct.</td>
<td>After H-mode WS(26-28 Sept., Tsukuba)</td>
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<tr>
<td>Pedestal and Edge</td>
<td>IPP-Garching</td>
<td>11-12 Oct.</td>
<td>After IAEA TM on Energetic Particles(8-10 Oct.)</td>
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<tr>
<td>MHD</td>
<td>IPP-Garching</td>
<td>October 2007</td>
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<tr>
<td>SSO</td>
<td>Chengdu, China</td>
<td>29 Oct. – 2 Nov.</td>
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<td>SOLDIV</td>
<td>Toledo, Spain</td>
<td>January 7-10, 2008</td>
<td>In conjunction with PSI paper selection meeting</td>
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<tr>
<td>IEA/ITPA Joint X Planning</td>
<td>JET-UK</td>
<td>November 29-30, 2007</td>
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</table>
Definition of High Priority Research Tasks: a small number of R&D tasks which provide a focus for the Topical Group's activities in a timeframe of 1-2 years and which should be determined on the basis of their likely importance, both in increasing understanding of fusion plasmas and in providing increased confidence in achieving significant fusion gain in proposed long-pulse burning plasma facilities, as well as on the probability of achieving significant progress within this timeframe.
## ITPA High Priority Research Tasks 2006–2007

| Diagnostics | Development of methods of measuring the energy and density distribution of confined and escaping α’s.
|            | Review of the outstanding radiation effects work for ITER.
|            | Determination of life-time of plasma facing mirrors used in optical systems.
|            | Development of measurement requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion.
|            | Continue development of the new disruption DB including conventional and advanced scenarios to initially study fast Ip quenches and halo currents.
|            | Develop disruption mitigation techniques particularly at high performance and by noble gas injection and understand influence of MHD on impurity penetration. Validate 2 and 3-D codes, in particular MHD and radiation models, on gas injection. Develop reliable disruption prediction methods.
|            | For NTMs complete 2/1 ρ* scaling studies, validate ECCD control models against data (including modulation), develop sawtooth seed island control to high beta and high fast particle regimes, initiate development of a 3D MHD model (including seeding) and specify diagnostics for NTM detection.
|            | For RWMs understand mode damping through cross-machine experiments. Study n≠1 RWMs. Continue benchmark tests of theory models for RWM feedback and experimentally study feedback control at low rotation. Study coil systems for RWM control in ITER and specify diagnostics.
|            | Understand intermediate-n AEs; redistribution of fast particles from AEs; and perform theory-data comparisons on damping and stability.
|            | Specify for ITER the low frequency noise in the diagnostic signals used in feedback loops (for both RWM and vertical control).
# ITPA High Priority Research Tasks 2006–2007

<table>
<thead>
<tr>
<th>Pedestal and Edge</th>
<th>Divertor and SOL</th>
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</table>
| • Improve Predictive Capability of Pedestal Structure through Profile Modeling and Experimental Studies  
  - Dimensionless cross machine comparisons to isolate physical processes; assess dependence on roh* , ripple, rotation, and shape.  
  - Measurement and modeling of inter-ELM transport  
  - Establish profile database for modeling joint experiments including effects of neutrals  
  - Physics based empirical scaling  
  - Collaboration with CDBM to improve scalar database characteristics and utilization.  
  • Improve Predictive Capability of ELM characteristics through experimental studies and theory / modeling analysis, and develop small ELM and quiescent H-mode regimes and ELM control techniques  
  - Define physics requirements for pellet injection as ELM control schemes in ITER  
  - Define physics requirements for ergodic field application as ELM control schemes in ITER  
  - Integrate observations of ELM crash dynamics and initiate comparisons with developing models  
  • Categorize small ELM regimes based on cross machine comparisons  | • Understanding of Tritium retention, and development of efficient T removal methods.  
  - Compare tile-side D retention level (difficult to remove) across tokamaks  
  - Characterize macroscopic (overall) D-retention in tokamaks and laboratory experiments  
  - Compare ionization of various D/T removal techniques for carbon PFC tokamaks  
  • Understand the effect of ELMs/disruptions on divertor and first wall structures  
  - Update specification of power levels and areas of deposition during ELMs and disruptions  
  - Development of more precise 2-3D measurements of where power goes in disruptions/ELMs  
  • Improve measurements & understanding of plasma transport to targets and walls, for better predict heat load, and effects on the core plasma  
  - Exploring the role of non-diffusive radial transport (i.e. blob/turbulence) on wall heat/particle loadings, macroscopic transport($\chi$ and D), and driving SOL flows (parallel transport).  
  - Neutral density benchmarking of physic models in current experiments and ITER.  
  - Code-code comparisons with no drifts(at this stage), and drift  
  • Understand how conditioning and operational techniques can be scaled to reactor devices  
  - Implications of a metal wall for startup, fuel retention, density control and core impurity levels  
  • Compare startup/ramp-down experiences, and evaluate influence of limiter configuration on SOL |
## ITPA High Priority Research Tasks 2006–2007

<table>
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<th>Task Area</th>
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| **Steady State Operation**      | • Continue the focussed modelling activity on ITER Hybrid and Steady state scenarios, using standard (and common) sets of input data.  
• Assess requirements for real-time control in ITER and increase collaboration in joint experiments on real time control.  
• Pedestal studies: Experiments to document pedestal in advanced scenarios, modelling of pedestal, pedestal conditions in ITER (maximum T\text{\_ped}).  
• Code benchmarking of LHCD and NBCD and implications for ITER.  
• The current rise of advanced scenarios, in particular requirements for the ITER start up phase. This subject should be studied in collaboration with the DSOL TG; the scenario for start up and use of outboard limiters should be optimised together. |
| **Transport Physics**            | • Utilize upgraded machine capabilities to obtain and test understanding of improved core transport regimes with reactor relevant conditions, specifically electron heating, Te\text{\_e}~Ti and low momentum input, and provide extrapolation methodology  
• Develop and demonstrate turbulence stabilization mechanisms compatible with reactor conditions, e.g. s-c\text{\_st}-stabilization, shear flow generation, q-profile. Compare these mechanisms to theory  
• Study and characterize rotation sources, transport mechanisms and effects on confinement and barrier formation  
• Quantitative tests of fundamental features of turbulent transport theory via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings |
| **Confinement Database and Modelling** | • Resolve the differences in β scaling in H-mode confinement  
• Develop a reference set of ITER scenarios for standard Hmode, steady-state, and hybrid operation and submit cases from various transport code simulations to the Profile DB  
• Resolve which is the most significant confinement parameter, ν* or n/n\text{\_G}  
• Understand the aspect ratio dependence of the L-H power threshold  
• Understand the collisionality dependence of density peaking  
• Develop common technologies for integrated modeling, e.g. frameworks, code interfaces, data structures |
## ITPA Manages the Planning and Execution of Joint Experiments Among the ITPA Parties’ Tokamak Programs

### Joint Experiments 2006-07

<table>
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<th>Category</th>
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<tr>
<td>Dropped</td>
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<tr>
<td>Deferred to 2007</td>
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<tr>
<td>Prepare for 2007</td>
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<tr>
<td>New Results Obtained</td>
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<tr>
<td>New Proposals</td>
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<td><strong>Total</strong></td>
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<td><strong>Total Active</strong></td>
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### Topical Group - Proposal Title - Keypersons - Devices - Ctg - Comments/Recommendations/Results

<table>
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<tr>
<th>Topical Group</th>
<th>Proposal Title</th>
<th>Keypersons</th>
<th>Devices</th>
<th>Ctg</th>
<th>Comments/Recommendations/Results</th>
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<tbody>
<tr>
<td>MHD, Disruptions &amp; Control</td>
<td>Comparison of sawtooth control methods for neoclassical tearing mode suppression</td>
<td>O. Sauter, R Pinsker, R La Haye (DIII-D), H. Zohm (AUG), S. Coda (JET), R Buttery (JET), J Menard (NSTX), T Goodman (TCV), Yi Liu (HL2A), S</td>
<td>AUG, DIII-D, JET, NSTX, TCV, HL2A, Cmod, FTU, JT-60U</td>
<td>E</td>
<td>Report, new results</td>
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<tr>
<td>MHD, Disruptions &amp; Control</td>
<td>Low beta error field experiments</td>
<td>S Wolfe, I Hutchinson (C-Mod), T Hender (JET), M. Schaffer (DIII-D), T. Scoville (DIII-D), R Koslowski (TEXTOR), D Howell (MAST), Menard (NSTX)</td>
<td>C-mod, TEXTOR, MAST, DIII-D, NSTX, JET (done)</td>
<td>E</td>
<td>Report; closed 2006, work finished</td>
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ITPA-IEA_JointX_Master_List_07_v5.xls  
Spokesperson in **Green**  
For machines, **red** = committed, **green** = considering, **blue** = not participating, **black** = already finished
Modelling cross-benchmarking effort very effective

- Effort underway to compare the various edge modelling codes
  - Initially just EDGED2D (JET) and SOLPS
  - UEDGE (LLNL) and SOLDOR (JAEA) now added

- Very simple case still leads to significant differences across models
ECRH:
Remarkable effort on code benchmarking: Now ready for publication. → use in assessing NTM stabilisation using ECCD, gives confidence for “standard” off-axis current drive for steady state scenarios, and provides a sound modelling basis for the choice of the ITER launcher systems.

ECCD, off axis
Comparisons of ICRH Codes

ICRH code comparisons: ITER SCENARIO 2

• Power balance - TORIC
  P(2ΩT) ~ 50 %
  P(ELD) ~ 35%
  P(D) ~ 1.8%
  P(alpha) ~ 14 %
  Numerical profiles from spreadsheet, Bi-maxwellian distribution for alphas

• Power balance – AORSA2D
  P(2ΩT) ~ 45 %
  P(ELD) ~ 38%
  P(D) ~ -0.5%
  P(alpha) ~ 17 %
  Approximate analytic profiles, slowing down distribution for alphas.

• PSTELION (full wave 3D,N=27)
  P(2ΩT) ~ 58 %
  P(ELD) ~ 41%
  P(D) ~ 1%
  P(alpha) ~ 0.2 %
  Bi-maxwellian distribution for alphas

Showing good progress but physics is much more complex (compared to ECRH/ECCD).
### ITPA Maintains the Tokamak Databases of the ITPA Parties

<table>
<thead>
<tr>
<th>Database</th>
<th>Responsible ITPA Topical Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Diagnostic DB</td>
<td>Diagnostics</td>
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<tr>
<td>Radiation Effects Database</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>Disruption DB</td>
<td>MHD</td>
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<tr>
<td>DB on Steady State scenarios</td>
<td>SSO</td>
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<tr>
<td>ITB DB</td>
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<tr>
<td>Transition DB</td>
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<tr>
<td>Energy Confinement time DB</td>
<td>CDB&amp;M</td>
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<tr>
<td>Profile DB</td>
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<tr>
<td>Pedestal Scalar DB</td>
<td>Edge Pedestal</td>
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<tr>
<td>Pedestal DB</td>
<td>Edge Pedestal</td>
</tr>
<tr>
<td>ELM DB</td>
<td>SOL&amp;Divertor</td>
</tr>
</tbody>
</table>

**Graph 1:**
- **Regression fit** against $\rho_{i\theta}^*$ alone:
  - $\beta_{pe} = 5.5 \rho_{i\theta}^{1.08}$
- **Points:**
  - JET
  - DIII-D
  - ASDEX U
  - ITER

**Graph 2:**
- **Type I ELMs**
  - $v^*_{ITER}$
  - Maximum tolerable ELM size
  - RMP ELM suppression
  - QH-mode
Multi-machine global confinement database and multiple theoretical models used to project confinement in ITER

- **Empirical Confinement Scaling**
  \[ \tau_{E, \text{th}} \text{, ELMy} = 0.85 \tau_{E, \text{th}} \text{, ELM-free} \]
  \[ = 0.031 I_p^{1.06} B^{0.32} \]
  \[ P^{-0.67} M^{0.41} R^{1.79} n_e^{-0.17} \epsilon^{-0.11} \kappa^{-0.6} \]

- **Dimensionless Wind Tunnel Scaling** provides a more fundamental basis.

- **Theory Models** also used to project confinement.
Pedestal Physics and Turbulence Codes Project ITER Performance

BASIC PEDESTAL PHYSICS + GLF23 TRANSPORT CODE (CALIBRATED TO GYRO CODE) = PERFORMANCE PROJECTIONS FOR ITER
International Database Shows ELMS Will Be too Large in ITER at the ITER Collisionality
Edge Localized Resonant Magnetic Perturbations Eliminate ELMs at ITER’s Pedestal Collisionality

- Flexible control of poloidal (m) spectrum with n=3, even and odd parity, toroidal phasing
- Pumping used to reduce $\nu^*_e$ initially in weakly shaped (low $\delta$) plasmas and recently in high $\delta$ ITER similar shapes
Various locations investigated
(Cryostat, VV coolant passage, Port plugs, vacuum)
Focus here on the previous in-vacuum options
ELM VV02 Configuration

- (3) coils per sector (27 total)
- Approximate cross section 120mm x 120mm
- Coils contained in an actively cooled shell, bolted onto VV welded rail
MHD High Priority areas - RWMs

- Moving to multi-machine studies in this area
- Several machines have non-axisymmetric coils for RWM MHD spectroscopy
MHD High Priority areas - RWMs

- DIII-D/JET similarity expt
- Plasma equilibrium, profiles well matched
- RFA agrees when geometry effects accounted for
- Further more accurate VALEN correction in progress
MHD High Priority areas - RWMs

- Critical rotation for RWM scales as $1/q^2$
MHD High Priority areas - RWMs

- Way forward is to use data to benchmark theory models $\rightarrow$ ITER predictions

Hender and Liu IAEA 2004

- Semi-kinetic model $\sim$ benchmarked on DIII-D and JET data $\Rightarrow$ for ITER intrinsic rotation very marginal for RWM stability
Inter-machine scaling of spontaneous plasma rotation

- On ITER, spontaneous (intrinsic) rotation may be comparable to NBI induced rotation rates. First international, multi-machine database for intrinsic rotation (J. Rice 2006 IAEA). Rotation scaling in terms of Mach number \( M_A \) developed from the international database.
**TEARING MODES**

**Classical**
- Finite resistivity
- Current can diffuse and form clumps — magnetic islands — on rational q flux surfaces
- Driven by $\nabla J$
- Growth time 10s of milliseconds

**Neoclassical**
- $\nabla P=0$ in island removes equilibrium bootstrap current
- Helical current perturbation amplifies seed island
- Providing auxiliary current drive predicted to stabilize NTM

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![Graph showing βp vs Width with markers indicating unstable and saturated states with $I_{rf}/I_p$ values.](PEST-III)

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$MFE—Tokamak$
MHD High Priority areas - NTMs physics

Onset $\beta$

- Understanding that seeding plays a key role in NTM triggering
- Extensive cross machine studies (MDC-3) show $\beta_{\text{crit}} \sim \rho_i$

Critical $\beta$

Regression fit against $\rho_{i\theta}^*$ alone:

$\beta_{pe} = 5.5 \rho_{i\theta}^{*1.08}$
MHD High Priority areas - NTMs ECCD Feedback

- Extensive benchmarking in progress to validate ECCD NTM stabilisation requirements for ITER

\[
\frac{\tau_R}{r_s} \frac{dW}{dt} = r_s \Delta' + a_2 \frac{j_{bs}}{j_{||}} \frac{L_q}{W} \left[ 1 - \frac{W_{marg}^2}{3W^2} - K_1 \frac{j_{ec}}{j_{bs}} \right]
\]

\begin{align*}
&\text{JT-60U No ECCD} \\
&\text{JT-60U ECCD (} \Delta R = 0.5 \text{ cm)} \\
&\text{DIII-D No ECCD} \\
&\text{DIII-D ECCD (} \Delta R = 1 \text{ cm)} \\
&\text{AUG ECCD (} \Delta R = 0.5 \text{ cm)} \\
\end{align*}

\text{Saturated island}

\text{AUG No ECCD}

\text{JT-60U No ECCD}

\text{DIII-D No ECCD}

\text{DIII-D ECCD (} \Delta R = 1 \text{ cm)}

\text{AUG ECCD (} \Delta R = 0.5 \text{ cm)}

\text{JT-60U ECCD (} \Delta R = 1 \text{ cm)}

R La Haye, R Buttery, H Zohm, N Hayashi et al IAEA TCM Como 2005
• Proposed 20 MW, 170 GHz, “high launch” ITER system adequate to mitigate either or both the 3/2 and 2/1 NTMs
  – good alignment and modulation should keep both islands small
• Removing the metastable condition with unmodulated ECCD is problematic
Multiple Machine Results Point the Way To Very Long Pulse or Steady-State Operating Modes in ITER

Presented at the IAEA 2004
Volume 47, Number 6, June 2007

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PROGRESS IN THE ITER PHYSICS BASIS

PREFACE

Progress in the ITER Physics Basis
K. Ikeda
Full text: Acrobat PDF (68.4 KB)

Chapter 1: Overview and summary
Abstract References Full text: Acrobat PDF (1.96 MB)
ITPA Has Participated in the ITER Design Review

- ITPA participation invited by PDDG Norbert Holtkamp in October, 2006
- Working Group was formed to prepare a strawman set of issue cards
- Strawman set of issue cards went to the Topical Groups
- Topical Groups considered them in their fall 2006 meetings.
  - Altered the strawman set
  - Recommended deletions, consolidations, and additions
  - Issue Card set sent to ITPA CC in special meeting after IAEA 2006
  - ITPA CC made alterations, deletions, and sent that list to ITER-IT
- Many ITPA members are participated in the Design Review
- Topical Group meetings in the spring of 2007 used to discuss design review issues as framed by the ITER Design Review Working Groups
- Joint Experiment work acquired an immediate design review focus.
Welcome to the ITPA WWW site

The International Tokamak Physics Activity (ITPA) aims at cooperation in development of the physics basis for burning tokamak plasmas. The ITPA continues the tokamak physics R&D activities that have been conducted on an international level for many years resulting in achievement of a broad physics basis useful for all fusion programs, for the ITER design, and for general tokamak research worldwide.