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SEVENTH MEETING OF THE ITER PHYSICS EXPERT GROUP ON ENERGETIC PARTICLES, HEATING AND STEADY STATE OPERATIONS

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The seventh meeting of the ITER Physics Group on Energetic Particles, Heating and Steady State Operation was held at CEN/Cadarache from 14 to 18 September 1999. It was the first one following the redefinition of the Expert Group structure at the ITER Physics Committee in October 1998. It was also the first one without participation of US physicists. The meeting was well attended, with a large participation from all the ITER EDA Parties. The success of the meeting was due to the strong involvement of the Co-Chair, Professor Miyamoto, to the help of the Central Team and of Dr Rimini (JET) as well as of Dr Nguyen (CEN/Cadarache) regarding the local organization. The objectives of the Meeting were:

1. Review and implications for ITER of the results achieved since last meeting, including APS, EPS conferences on: fast particles confinement and fast particles excited modes; heating and current drive system (NBI, ICRH, LHCD, ECRH); and steady state aspects.

2. Re-evaluation of the physics of energetic particles, heating and steady state operation in RTO/RC ITER such as central current drive scenarios, heating and current drive efficiency of high energy negative NBI, MHD effects of energetic particles in reversed shear configuration, RF stabilization of the neoclassical tearing mode (NTM), toroidal and poloidal rotation induced by ICRH.

3. Consequences of new objectives/design of RTO/RC ITER including high Q operation, steady state and fast particle behaviour on proposed heating systems.

The Meeting started with a review by the Chairman of the Changes to the Expert Group and of the Urgent Physics Research Areas as defined by the ITER Physics Committee. Then the new design and physics issues of Reduced Technical Objectives/Reduced Cost (RTO/RC) ITER were reviewed. For the most part of the first two days of the Meeting, a series of presentations were made. Subsequently, the participants split into smaller groups aiming at summarizing the discussions and identifying priority actions. The topics of these groups were: Energetic Particles, Ion Cyclotron Resonance Heating (ICRH), Lower Hybrid Current Drive (LHCD) including stabilization of neoclassical tearing modes, Electron Cyclotron Resonance Heating and Current Drive, Neutral Beam Injection (NBI) and Steady State Aspects. The findings of these groups, briefly summarized below, were presented to all participants on the third and final day of the Meeting, with a broad consensus on the priority actions.

Energetic Particles

The conclusions from modelling studies of Alfvén eigenmodes were sometimes somewhat contradictory. A high $q_0 = 4.5$ reversed shear configuration is strongly unstable to low frequency drift KAE, suggesting that operation at q_0 closer to $q = 2$ will be safer. It was also found that when q_{min} is slightly below an integral, for instance $2.5 < q_{min} < 3$, a slight change of q_{min} causes a considerable change of AE frequency and stability. Negative shear configurations are not necessarily more stable than positive shear. Other analysis indicates that high n TAE modes are less dangerous in reversed shear than in monotonic shear. For monotonic shear,

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it has been found that TAEs are more stable in the LAM proposal than in the IAM proposal for a given Q, but at Q = 10 destabilizing effects are still not very important.

New results on TAEs modes driven by the Negative Ion Beam system on JT-60U (360keV, 4MW) were presented with various b_{fast} (0.1 to 0.6%), various velocities (v_b/v_a = 0.4–0.9), various current profiles, including reversed shear configurations. The results agree qualitatively very well with the results of the Nova-K code. Comparison between the Penn code and JET experiments indicates the stabilizing effects of high edge magnetic shear and of a weak central shear.

Calculations have indicated that alpha ripple losses of RTO/RC ITER are of the same level as in FDR-ITER. In particular, up to 10% of alpha power can be lost in IAM for a reversed shear configuration. They are reduced to less than 1% if the ripple amplitude can be reduced by <1.5. It is to be noted that NBI ripple losses are small both for DT and for non-active operation.

Experimental data from JFT2-M have shown that TF ripple can be reduced from 2.2% to 1.1% by Ferritic Steel insertion. The corresponding surface ripple losses of NBI are reduced from 10% to 5%. These encouraging results indicate that ripple losses will be acceptably low in a 13MA positive shear pulse operation. A ferritic steel insert could significantly reduce the 16% losses predicted for a 9MA steady state RS configuration.

Ion Cyclotron Resonance Heating

The design of the antenna has been re-assessed, leading to higher voltage handling capability (42kV for 20MW coupled power). Variations of the Resonant Double Loop antenna are being investigated. The benefit of a better coupling is compensated by the more stringent technical requirements.

A comparison of ELMs between NBI and ICRH (JET) has indicated that for an identical gas flow and with a power well above the L to H power threshold, type I ELMs were obtained with a similar pedestal height. This is in agreement with Asdex results although sawteeth activity is very different for the two heating methods. Mode conversion H-^{3}He and minority ^{3}He, scenarios relevant for the non-active phase of ITER, have been successfully tested on Asdex. Alfvénic activity driven by ICRH has been stabilised by 300keV NBI on JT-60U. Internal Transport Barriers with similar ICRH and NBI heating have been obtained in JET (similar electron and ion temperatures).

Bulk ion heating scenarios are available at $2f_{cr}$, especially with the addition of ^{3}He minority. An efficient current drive efficiency is obtained at higher frequency (60MHz). Off-axis mode conversion current drive might be sufficient for neo-classical tearing mode stabilization. "Heavy minority" heating scenarios are also available for the non-active ITER phase.

Lower Hybrid Current Drive

The main design concepts produced for ITER EDA can be kept for RTO/RC ITER, with the advantage that coupling and thermal load of the LHCD launcher will be improved.

Stabilization and control of NTM with LHCD have been demonstrated on Compass-D, leading to operation at high beta values.

Advanced scenario discharges with ITBs with full current drive were produced in JT-60U with LHCD, and steady discharges with b_N in the range 1.5–1.7 have been achieved.

Electron Cyclotron Resonance Heating and Current Drive

110GHz gyrotron (1MW/2s, 0.3MW/5s) with diamond window (steady-state temperature reached) and depressed collector has been operated in JT60-U. Commissioning of a 118GHz gyrotron (~ 0.4MW/~ 16s) with a record energy of 6.2MJ has just been done at CEN/Cadarache.

The latest generation of experiments with poloidal steering and control of deposition/CD profiles has started. First results of off-axis CD efficiency (TCV, DIII-D) have been reported, which somewhat exceeds predictions of existing codes. Full current drive has been achieved on TCV for 1.9s (1.5MW/125kA) at $1 \times 10^{19} m^{-3}$. Promising NTM stabilization experiments in ASDEX-U (d.c. scheme) have been reported. Very notably, transport barriers with $T_e > T_i$ using counter-ECCD have been observed in Asdex U.

Extensive calculations confirm performance in RTO/RC ITER comparable to that achievable in ITER-FDR. Initial calculations for the non-active phase have been carried out. The potential performance in this case may be limited by $3w_e$ damping. The performance with poloidal steering is investigated. It is important to incorporate real launcher geometry.

Detailed calculations required for NTM stabilisation in ITER have been carried out. Results suggest that a power lower than 30MW is sufficient but there are still some uncertainty in the exact requirements.

Experiment and theory suggest that d.c. schemes are sufficient but an accurate control of the location is required. NTM avoidance by profile control (ECRH) is also demonstrated (COMPASS-D, TCV). 'Top' launch in ITER offers certain advantages for NTM stabilisation schemes, eg. flux expansion, deposition localisation, reduced sensitivity to launch angles etc.

Neutral Beam Injection

The NBI energy of 1MeV is considered to be a good optimum for RTO/RC ITER and gives good beam penetration and current drive efficiency without excessive shinethrough at lower densities. A large beam tangency radius is desirable for high current drive efficiency. In practice this is limited by engineering constraints and this is considered satisfactory in present IAM design. The vertical beam power footprint, both the power profile and the vertical displacement from the plasma magnetic axis, has a strong influence on the heating and current drive in the plasma core. The optimization of this profile is highly sensitive to plasma transport and MHD assumptions and further simulation work is required in this area. The choice of vertical beam power footprint influences the requirements for port access. It may, however, be difficult to rigidly define the optimum vertical power profile for all modes of operation and some capability to vary the shape of the power footprint could be incorporated in the design.

Steady-State Aspects

High Performance plasmas with Internal Transport Barriers (ITBs) were sustained in Optimized Shear scenarios for as long as the additional heating power can be applied (JET). The key technique was to utilize Argon puff to modify edge current to optimize plasma current profile against pressure profile: $b_N = 2.5$ together with $H_{89} = 3$ were maintained for 4 s. This supports JT-60U results. High performance ELMy plasmas with $H_{89x}b_N = 9$ were maintained for the maximum duration time of the NBI: $16t_E$ (2s) (DIII-D). Probably ITBs were formed. ECCD can drive all the plasma current, and even more in quasi steady-state conditions (TCV). Efficiencies are consistent with predictions. Counter-ECCD has prevented central q to fall below q = 2 (ASDEX-U). As a result, good core confinement was maintained with $T_e > T_i$. It was shown that the b limit can be increased by increasing triangularity. High performance ELMy Reversed Shear plasmas were maintained in full current drive conditions: $f_{BS} = 75\%$ and $f_{NBCD} = 25\%$ (tentative evaluation), $I_p = 0.8$MA, $B_t = 3.4$T, $b_N = 2$, H = 3.6, $P_{NB} \sim 5$MW (JT-60U). It has also been attempted to raise sustainable b_N in LHCD reversed shear discharges. So far, b_N values in the range of $b_N = 1.5$–1.7 with have been achieved.

After a wide discussion on the findings of the groups, a broad consensus was reached on the following research priorities:

- Results of ferromagnetic insertion in JFT-2M experiments should be examined in more detail. Realistic ferromagnetic insertion (allowing port existence) should be studied.
- Extend understanding of AE damping and drive by comparisons of fluid and gyrokinetic models with experiments. Improvement of predictive capability of theory is needed, such as the drift kinetic Alfvén eigenmode. Transport of energetic particles related to AE shall be studied.

- More comparisons between ICRF and NBI in ELMy H-modes shall be made (compare edge pedestal core confinement). Modelling and experimental simulation of ICRH scenarios for the non-active phase, in particular at reduced B_T, shall be studied.

- Experiments and modelling for stabilization of NTM's using Mode Conversion CD. Destabilization of sawteeth in discharges with high fast-particle content and NTM stabilisation with minority ICRH CD.

- More assessment of ICRH toroidal rotation is needed. Extrapolation of present heating results mainly rests on positive NBI database with high ratio of i/e heating, significant fuelling and rotation drive. More data with ICRH and ECRH should be included in the database.

- Study tools to improve the coupling capability of LHCD in relevant scenarios: gas feed, edge ionization, gap control. Active control should be a goal. The LHCD antenna design has to be completed in order to take into account the port constraints in RTO/RC ITER and the present Passive-Active Multijunction concept has to be validated on present tokamaks.

- The effect of ion versus electron heating in ITB formation shall be studied. Investigations of edge conditions in advanced scenarios with ITBs in order to assess LHCD and ICRH coupling properties of such plasma.

- Investigate NTM stabilization with LHCD on present tokamaks with ITER relevant plasma scenarios. Compare ECCD and LHCD NTM stabilization. Further evaluation of requirements for NTM stabilization current drive efficiency at rational surfaces JCD(r) required for stabilization, supported by experimental data where possible and further analysis of stabilization terms. 'Robust' schemes are required.

- Further evaluation of poloidal vs. toroidal steering (2D steering very difficult) for both outside and top ECRH launch taking into account engineering constraints and operating flexibility is urgently required. Bearing in mind the strong desire to utilize a single frequency for all applications, an urgent assessment of the optimum frequency is required.

- Current Profile Control issues include: b limit, alignment of j_{driven} (p) with jb_N(p) with fb_N > 50% in steady-state, control of ITB controllable with j(p) and demonstration with real time control of the influence of current profile on confinement.

- Integration of issues in a consistent steady state scenario (Integrated Scenario), including: the consistency of the CD/Heating systems from the ITB formation phase to the steady-state phase, the importance of rotation control and the amount of spare power needed to suppress MHD modes. The robustness of ITB in conditions of low fuelling, smaller torque input and dominant electron heating is another issue. The relationship between wide ITBs, ELM penetration and the control of edge pressure/current is also very important to establish.

- Study steady-state scenarios without ITBs.

LIST OF PARTICIPANTS

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