ASDEX Upgrade Letter

No. 5/October 2003

Foreword

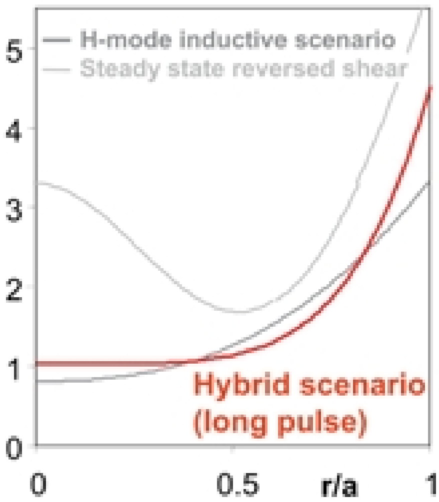
ASDEX Upgrade is currently in a shutdown phase to increase the tungsten coverage of the first wall surface to 75 per cent. The final aim of our tungsten programme is to demonstrate tokamak operation of a carbon free machine. The present installation of tungsten tiles in the upper divertor is an intermediate step on this route which will contribute to the ongoing decision process concerning the first wall material of ITER.

In parallel two steerable mirrors for an extended ECRH system are installed during this shutdown. With an ECRH power of up to 2 MW an improved and flexible tool for current profile control as well as for stabilisation of neo-classical tearing modes will be available in 2004.

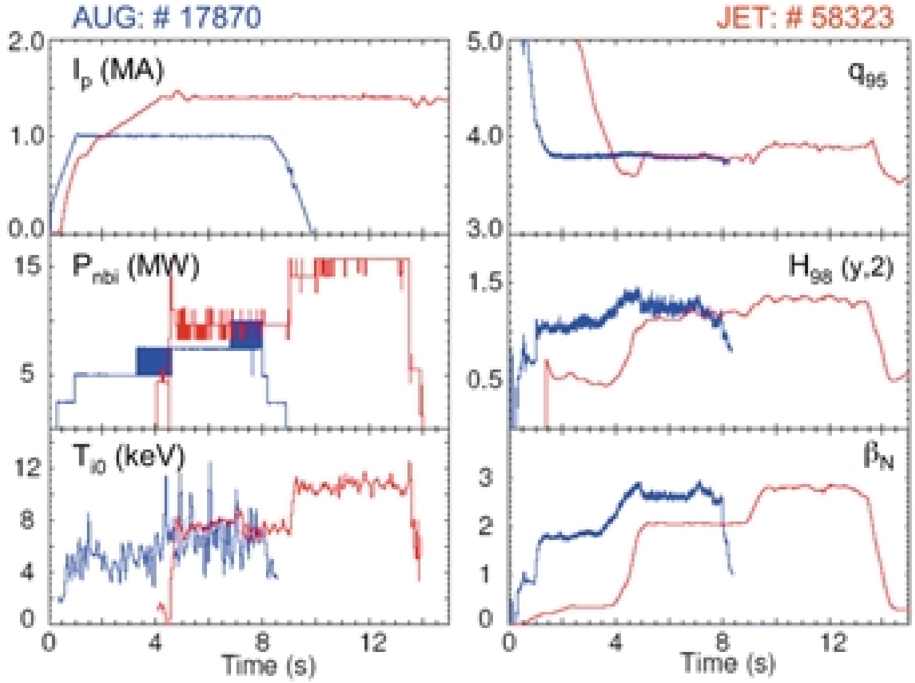
Preparation of the 2004 scientific Programme of ASDEX Upgrade is in the stage of collecting proposals. The 'Call for Participation' send to fusion labs worldwide lead to the submission of experimental proposals by scientists of 14 European Associations including IPP and the Close Support Unit Garching. In addition, joint experiments have been proposed in the frame of the ITPA with ALCATOR C-mod, DIII-D and JT-60U. A seminar at the end of October with all proponents of submitted proposals aims to establish a coherent programme for 2004.

The highlights of the last 6 months described in this letter regard one important contribution to ITER's portfolio of operating scenarios, a set of new diagnostic results that shed a quite distinctive light onto the nature of ELMs, and a technical development, which was driven by the operational necessities of ASDEX Upgrade, but has potential applications to large-scale electrical power generation – decades before the massive advent of fusion energy!

K. Lackner



▲ *Fig 1: Comparison of q-profiles for three scenarios.*



▶ *Fig 2: Improved H-Mode discharges at ASDEX Upgrade and JET.*

Confirmation of ASDEX Upgrade's 'Improved H-mode' Scenario by JET – Good news for ITER

In the year 1998 ASDEX Upgrade (AUG) obtained a new stationary regime of operation with improved core confinement for both electrons and ions in combination with an H-mode edge. The pressure increase in the core was at that time attributed to the formation of an internal transport barrier (ITB). However, quickly after this discovery, detailed transport analysis showed that in such a regime the temperature profiles remain in the so-called stiff regime. Its gradient does not exceed a critical gradient length set by the turbulence of the plasma and hence no ITB is produced. This new regime was called 'Improved H-Mode'. During recent years this regime has been further developed by AUG and DIII-D and is now known under the name 'ITER Hybrid Scenario'.

The key to reach the Hybrid regime is to obtain a different stationary profile of the safety factor (q-profile) with a central q value close to 1 and with very low magnetic shear - a hybrid of the reversed (used for the creation of ITBs) and the q-profile of standard H-modes (see fig. 1). This specific q-profile is obtained by heating during the current rise phase of the discharge, at moderate neutral beam power in order to avoid a reversed q-profile or the formation of an ITB. In the subsequent main heating phase the plasma pressure can be increased to $\beta_N \sim 3$. No strong neo-classical tearing modes (NTMs) occur due to the absence of sawteeth. Under these conditions non-inductive current fractions of typically ~50% in combination with benign MHD modes in the core (e.g. fishbones) maintain a inherently stationary q-profile on the current relaxation time scale (τ_R). Despite operating at higher edge q these discharges achieve values for (H_{89P} x β_N /q_{95}^2) ~ 0.40 providing a promising route to long pulse operation with Q=10 in ITER. AUG has demonstrated operation of this regime at 80% to 90% of the Greenwald density limit, in discharges with δ=0.43, with a confinement (H_{98}(y,2) = 1.1-1.2) while sustaining β_N = 3.5 (see AUG Letter No. 1 / March 2002).

Reactor and ITER relevance of a promising scenario is best proven by a successful demonstration on devices of different sizes. Therefore in the frame of the International Tokamak Physics Agreement (ITPA), IPP scientist conducted together with their colleagues from CEA, FOM and UKAEA experiments to establish this scenario on JET. The results of these experiments show that by matching the plasma shape, q-profile and ρ* of AUG, the Hybrid scenario can been obtained at 1.4MA/1.7T (see fig. 2). Stationary conditions are achieved with small NTM and fishbone activity in the core with similar β_N, H-factor, MHD and profiles as at AUG or DIII-D. The figure of merit for fusion gain, $H_{89}\beta_N/q_{95}^2$, reaches values up to 0.42 in JET at q_{95}=3.9.

Experiments up to 2.8MA/3.4T will follow to prove that the Hybrid scenario can be obtained at lower ρ* making use of the upgraded NBI heating system at JET. Recently, an intermediate step at 2.0MA/2.4T was already successful and demonstrates the potential of the Hybrid scenario to obtain improved confinement and stability over standard H-modes under stationary conditions.

Highlight

from a recent ASDEX Upgrade experiment

Type-I ELM target heat load structures

H-mode plasmas develop a pronounced edge transport barrier with rather steep edge gradients, which drive a variety of instabilities, especially quasi-periodic barrier relaxations, called Edge Localised Modes (ELMs). Good confinement is usually obtained in the type-I ELM regime with its sudden release of typically a few percent of the total stored energy on short time scales of about 0.1 ms-1 ms. The high resulting heat fluxes, however, may cause intolerable heat load particularly onto the divertor target plates in future experiments like ITER. Therefore, a detailed understanding of the energy deposition onto the target structures is of major interest.

Type-I ELMy H-Mode discharges in the upper single null configuration have been investigated with a new fast (~30μs) IR system. On the outer target plate about 3-5 narrow, non-axisymmetric and slightly inclined stripes are observed in radially outward positions in addition to the usual axisymmetric separatrix strike line (see fig. 3).

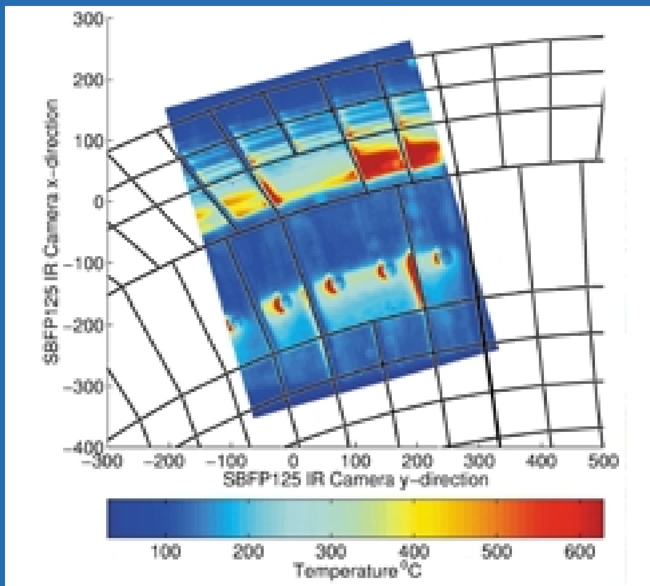


Fig. 3: Camera view of the target heat load pattern in the outer and inner upper divertor during a Type-I ELM.

This complex power load pattern can be qualitatively understood by considering the edge field line topology of poloidal divertor equilibria together with the assumption that energy transport to the divertor occurs essentially along field lines. When a narrow helical bundle of plasma loaded field lines starting at the main chamber low field side Scrape-Off-Layer (SOL) is followed up to the outer divertor target, its cross section is distorted by the strong upper X-point shear. At the target this results in a thin, toroidally elongated power deposition spiral asymptotically approaching the separatrix strike line. When several such helical SOL flares occur simultaneously during an ELM event at different toroidal locations, the corresponding spiral arms are superposed at the target plate and appear in a restricted observation area as a radial sequence of inclined stripes.

In order to verify this picture, the heating pattern during Type-I ELMs is mapped onto rectangular target coordinates and overlaid by the characteristic intersecting structure of field lines (see fig. 4), which are started at eight distinct toroidal positions $\Phi_{toroidal}$ in the outer midplane with an average distance of $\Delta\Phi_{toroidal} = 23°$. The increasing inclination of the single stripes when going radially outward is reproduced by the field line tracing model. Thus the target load pattern can be interpreted as the footprints of radial energy ejection from several toroidally displaced locations in the midplane and the related ELM mode structure in the main chamber can be characterized by an toroidal mode number. Statistical analysis of about 150 ELMs leads to an average toroidal mode number of around n≈14.

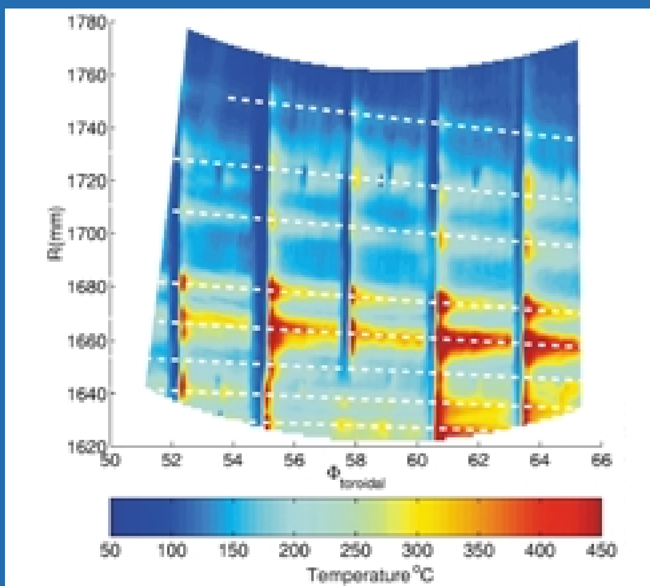


Fig. 4: Heat load pattern of the outer divertor target mapped onto target coordinates and overlaid with the intersection of 8 field lines starting at distinct toroidal positions in the outer midplane

Extended dynamic capabilities of power supplies

The electrical power and energy for AUG is provided by three separate networks based on flywheel generators EZ2, EZ3 and EZ4. Damage at couplings on the shafts of the synchronous generators EZ3 (144 MVA / 500 MWs) and EZ4 (220 MVA / 600 MWs) were discovered during a routine check. The damage can only be explained by subsynchronous resonances (SSR) which are excited by active power transients from the thyristor converter loads. The dynamic load curves of feedback controlled plasma discharges feature frequencies which can be equal to the natural frequency of the first torsional mode of a large generator shaft assembly. In order to protect the generators from SSR, torque sensors were installed near the coupling between the flywheel and the rotor (as indicated by an arrow in fig. 5).

They trigger a soft stop of tokamak operation if a predefined torque level is exceeded. Soft stops of this kind limited the operational window and the achievable plasma current flattop time of AUG significantly. Since the observed SSR phenomena is amplified by the low natural damping parameters of the generator shafts, novel feedback controlled DC circuits were developed which add torques to the rotor-shaft systems. They have the same effect as an increased level of damping. In each circuit the active power for damping the torsional resonance is provided by an inductor, acting as a buffer storage of magnetic energy (stored energy < 50 kJ). The current reference for the thyristor converter feeding this inductor is derived from torque sensor signals which enable to alternate the inductor current with the measured natural frequency of the shaft assembly. Thus, with proper phasing, torsional resonances in generator shaft systems weighing more than 100 tons can be damped with little additional power.

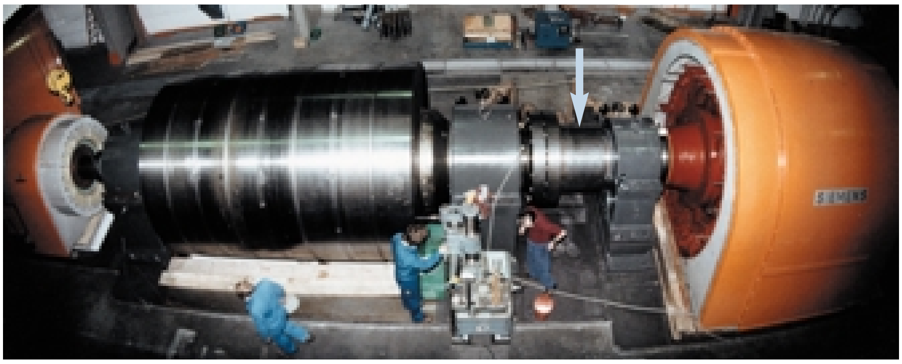


Fig. 5: Flywheel generator, position of torque sensors indicated by arrow.

Figures 6a,b show an example for the application of active damping on generator EZ3. Although the load curve in Fig. 6a shows no evident active power transients between t = 2 s and t = 6s, the curve contains a spectrum of frequencies in the range 20 – 30 Hz which is caused by feedback control of the plasma. Due to the low damping of the shaft, an active power oscillation with a frequency of 24 Hz and a power in the order of 1 MW can cause an increase of the torque amplitude up to a value of 1.11 MNm. This value corresponds to an active power of 175 MW at a generator speed of 1500 r.p.m and caused the EZ3 torque sensors to send a trip signal. Therefore the plasma discharge in fig. 6a was terminated due to SSR. Fig. 6b shows for a similar discharge the successful application of an active damping circuit. Despite the low damping power used (< 1 MW), torsional resonances can be reduced to tolerable values. In this case the duration of plasma operation was not limited by torsional resonances, although the time history of active power contains even more transients than in fig. 6a. Since April 2003, damping circuits have been routinely operated on both EZ3 and EZ4. They provide sufficient damping power to ensure that the execution of the experimental programme of AUG is not hampered by SSR phenomena anymore.

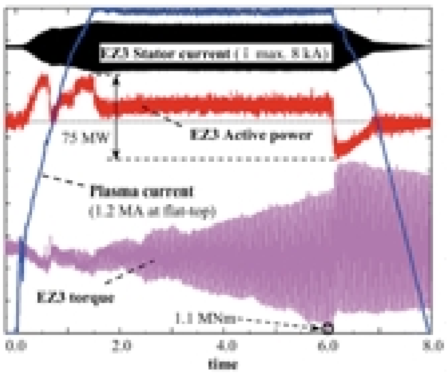


Fig. 6a: Measured generator current, active power and torque showing SSR on generatorEZ3.

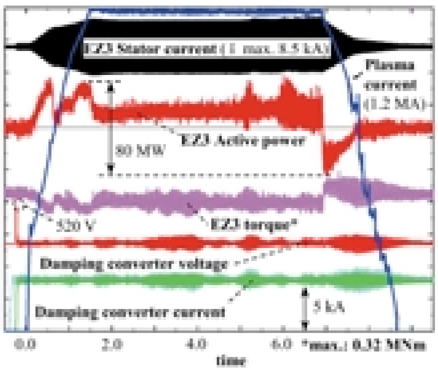


Fig. 6b: Active damping of SSR on generator EZ3 using a damping power of only 1 MW.

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