Title	Comparing diamagnetic flux measurements and modelling on ASDEX Upgrade
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Publication date	2017-11-30
Original Citation	Giannone, L., Fischer, R., Geiger, B., Rittich, D., Bock, A., Fuchs, J. C.; Gude, A., Maraschek, M., McCarthy, P. J., Suttrop, W., Schuhbeck, K. H. and the ASDEX Upgrade and MST12 Teams (2017) 'Comparing diamagnetic flux measurements and modelling on ASDEX Upgrade', 44th European Physical Society Conference on Plasma Physics, Belfast, Northern Ireland, 26 - 30 June, P5.133 (4pp). Available at: http://ocs.ciemat.es/EPS2017PAP/pdf/P5.133.pdf (Accessed: 25 August 2021)
Type of publication	Conference item
Rights	© 2017, the Authors. Published by the European Physical Society
Download date	2024-04-25 05:31:19
Item downloaded from	https://hdl.handle.net/10468/11785

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Comparing diamagnetic flux measurements and modelling on ASDEX Upgrade

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Abstract

The diamagnetic flux is the small difference in toroidal flux with plasma and without plasma. This measurement contains valuable information about the fast-ion confinement since energetic particles can significantly contribute to the plasma pressure and modify the diamagnetic flux. The diamagnetic flux diagnostic at ASDEX Upgrade [1] can therefore be used to investigate fast-ion transport in advanced scenario and resonant magnetic perturbation (RMPs) discharges.

Introduction

A detailed understanding of fast ion transport is needed to guarantee the performance and safety of a future fusion reactor as the generated fast helium ions are responsible for plasma heating and can damage the first wall. In addition, the positive current carried by fast ions from neutral beam injection (NBI) can be used in future tokamak reactors to ensure steady-state operation. A clear modification of the fast ion radial profiles was observed when switching from on-axis to off-axis sources in neutral beam current drive experiments on ASDEX Upgrade [2]. When operating RMP coils on MAST, an increase in fast ion losses was inferred from the sharp drop in neutron rates and fast ion D_α (FIDA) light emission [3].

The demonstration of steady-state advanced scenario plasmas, where the plasma current will be sustained by electron cyclotron and neutral beam current drive, is the goal of a number of supporting experiments on ASDEX Upgrade for ITER [4]. These discharges feature a variety of MHD modes that could degrade plasma confinement by the redistribution of fast ions.

The measured and predicted diamagnetic flux will be compared in discharges with on-axis and off-axis neutral beam heating with an applied n=2 perturbation generated by the RMP coils and in advanced scenario discharges on ASDEX Upgrade. The transport code, TRANSP [5], and equilibrium reconstruction code, IDE [6], are used to calculate an expected value of the diamagnetic flux using measured plasma pressure profiles and simulations of fast ion population contributions without constraints on the measured diamagnetic flux.

Fast ion redistribution discharges

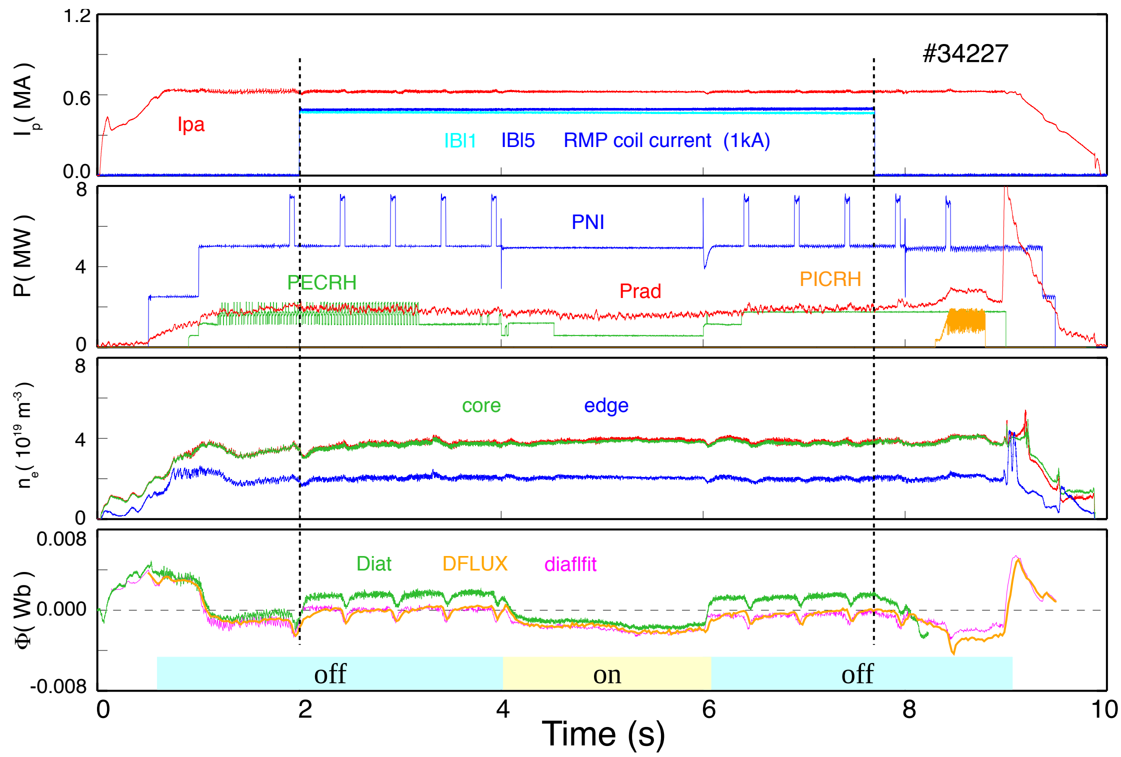

Figure 1: *Comparison of measured and modelled diamagnetic flux in a discharge where off-axis neutral beam heating is replaced by on-axis heating between 4 s and 6 s. The measured diamagnetic flux, Diat (green) and the predicted values from TRANSP (orange) and IDE (magenta) are shown. In the phase without RMP's up to 2 s, a small difference in the measured and predicted value of diamagnetic flux is observed. This difference is significantly enhanced during the off-axis NBI phase in the time interval from 2 s to 4 s when RMP coil currents are applied.*

In Fig. 1, the measured diamagnetic flux and the predictions by TRANSP and IDE are plotted for a discharge where the off-axis NBI is replaced by on-axis NBI between 4 s and 6 s. In the phase of off-axis NBI heating without RMP's up to 2 s, there is only a small difference between the measured and predicted values of diamagnetic flux. However, with the application of RMPs after 2 s, this difference is significantly enhanced to a value of 1.5 mWb. This suggests that the radial fast-ion density profile is flattened by RMP induced fast-ion losses and the reduction in plasma pressure leads to an increase in the diamagnetic flux.

The observed difference between measured and predicted flux is smaller in the on-axis NBI heating phase. This is expected since the more core-localised on-axis fast-ion populations are less prone to radial transport by the edge-localised error fields from the RMPs. This small difference is not present in a similar discharge without RMP coil current and therefore is thought to be a perturbation due to the RMP coils.

The direct impact of RMPs on the diamagnetic loop measurement has been addressed in vacuum discharges with RMP coil excitation in an n=1 and n=2 configuration. The maximum impact on the diamagnetic flux measurement is only 0.3 mWb. This perturbation is generated by the toroidal component of the magnetic field produced by the poloidal sections of the RMP coil windings. However, 0.3 mWb cannot explain the observed difference between the measurement and simulations in the presented experiment with off-axis NBI.

Advanced scenario

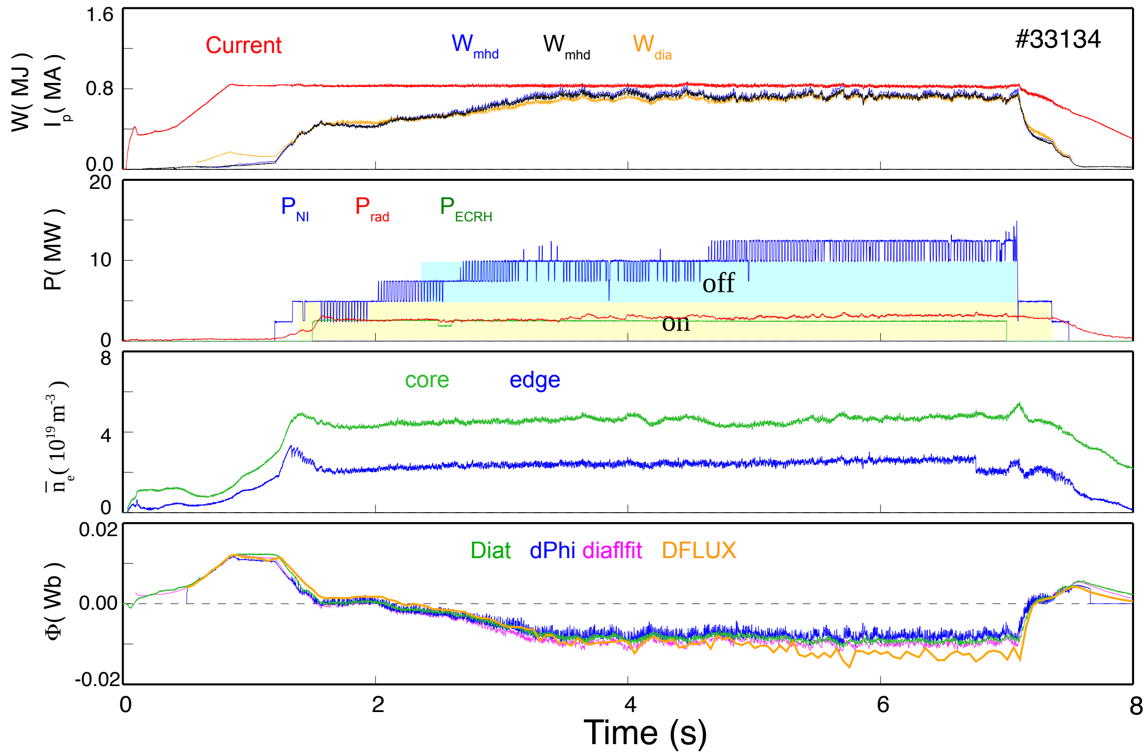

Figure 2: *Comparison of measured and modelled diamagnetic flux in an advanced scenario discharge. The time dependence of applied on-axis and off-axis NBI heating is shown. The measured diamagnetic flux, Diat (green) and predicted values from values calculated from the real-time, dPhi (blue) and IDE (magenta) magnetic equilibrium codes are in good agreement. The diamagnetic flux predicted by TRANSP (orange) differs from the measured value from 4.6 s to 7 s with the addition of a further on-axis beam. The plasma energy calculated from the diamagnetic flux (orange), W_{dia}, is in good agreement with the values, W_{mhd}, calculated from the real time (blue) and offline (black) equilibrium code.*

In Fig. 2, the measured diamagnetic flux is compared to that predicted by the TRANSP simulation for an advanced scenario discharge. Also plotted are the calculated values of diamagnetic flux by IDE and the real-time equilibrium code, JANET. The steady state phase of this discharge has an estimated value of 1.5 for the central safety factor produced by 2 MW electron cyclotron current drive. The measured and predicted values of diamagnetic flux are in good agreement until 4.6 s. The first two NBI sources used have on-axis deposition and the final two sources have off-axis deposition, while the final NBI source switched on at 4.6 s has on-axis deposition. The FIDA measurements show a definite redistribution of fast ions in this final phase of the discharge. Additionally, the IDE equilibrium reconstruction recognises that the plasma pressure contribution by fast ions needs to be reduced. Relaxing the pressure profile fitting constraints leads to a better fit of magnetic probe measurements. The predicted diamagnetic flux by IDE and measured diamagnetic flux lie closer together than the diamagnetic flux predicted by TRANSP.

Conclusion

The measured diamagnetic flux and the predicted values by TRANSP and IDE were found to be in good agreement for the on-axis NBI heating phase of a discharge with an n=2 perturbation generated by RMP coils. Radial transport by the edge-localised error fields from the RMPs have a reduced impact on the core localised fast-ion populations. Total plasma energy reduction due to fast ion pressure profile modification is suggested as a possible cause of the discrepancy of 1.5 mWb between the measured and predicted values of diamagnetic flux when applying the RMP coil perturbations to the off-axis NBI heating phase. In advanced scenario discharges, the measured and IDE modelled diamagnetic flux were found to be in good agreement. The FIDA measurements suggest that the discrepancy of measured diamagnetic flux and TRANSP simulations in some advanced scenario experiments can possibly be explained in terms of a fast ion profile redistribution.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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