Self consistency of magnetic probe and flux loop response to poloidal field currents on ASDEX Upgrade

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Introduction

The reconstruction of magnetic equilibria in ASDEX Upgrade relies on an accurate test of the parameters assumed for the position and orientation of the magnetic probes and flux loops and their calibration factors [1]. The simplest test, carried out in the first shot of the day, is to ensure that the integrators are delivering the expected response within an allowed error range to the flow of currents in individual poloidal field coils. The magnetic probe and flux response to the individual currents in the poloidal field coils can be written as :

$$\underline{\underline{M}}\underline{I} = \underline{b} \tag{1}$$

where the terms of the matrix equation are the mutual inductance, M_{ij}, of the magnetic probe or flux loop with index i for the poloidal field current of index j, I_j, and the response of the magnetic probe or flux loop, b_i. The coefficient M_{ij} can be derived from the known position of the magnetic probe or flux loop and the coordinates of the poloidal field coil using the Green's function for the magnetic field generated by a current hoop [2]. The poloidal field coils and passive stabilizing loop, PSL, are simulated as a finite number of filaments, with each filament carrying an applicable number of turns.

Real time Grad Shafranov solver

Magnetic probe and flux loop difference responses to the vacuum field produced by individual currents in the poloidal field coils are also calculated with a real time Grad Shafranov solver. The algorithm for the solution of Poisson's equation in cylindrical coordinates using discrete sine transforms, DST, along the Z axis and a tridiagonal solver [3, 4] has been adapted for solving the Grad-Shafranov equation for the poloidal flux, ψ. This algorithm is an alternative to the commonly used cyclic reduction algorithm [1, 5, 6]. A magnetic equilibrium for discharges with plasma current can be reconstructed in 3.0 ms per iteration on a 33 x 65 grid using 40 magnetic probe and 18 flux loop difference signals. The calculation of six coefficients describing the current profile that is the best weighted least squares fit to the measurements closely follows the documented procedure [1, 6]. Without plasma current, the value of ψ on the spatial grid resulting from the currents in the poloidal field coils is calculated. The magnetic probe and flux loop difference signals are then calculated using interpolation on the spatial grid.

An alternative algorithm for solving the Grad-Shafranov equation has been developed [7]. The magnetic probe and flux loop difference response are calculated from the Green's functions of the current loops on the grid. The sparseness of the current sources on the grid reduces the size of the matrix-vector multiplication and a single BLAS subroutine call can perform the calculation. The final calculation of the Grad-Shafranov equation reduces the operation count by treating the second solver step in a novel way. By setting the current source to zero in the second solver step, the DST can be significantly simplified and accelerated. These improvements reduce the cycle time for magnetic equilibrium reconstruction to 0.7 ms per iteration.

Measurements and simulations with poloidal field coil currents

The currents flowing in the poloidal field coils, each with a flat top of 4 s, are shown in Figure 1. The response of magnetic probes to these current pulses is shown in Figure 2. The 80 channels of data are acquired at 5 kHz with a dual quad core Xeon 5365 PCIe system connected to a PXI chassis [8]. Up until 12 s, the currents in the poloidal field coils are less than 10 A. This period is used to calculate the time dependent drift correction to the signals. The calculated magnetic field probe and flux loop differences are shown in Figure 3. A systematic correction factor of 1.01 has been applied to the magnitude of the poloidal field current pulse. This is necessary to force the mean difference of the measured signals to zero. Calibration shots with a current source with an accuracy of 0.1% are planned to improve the calibration procedure. A review of the gain factors of the integrators and the positions of the probes and flux loops seeking to identify the remaining differences between measured and simulated signals can then be carried out. During the current ramp in the poloidal field coil, there is up to 40 kA of current flowing in the PSL. It is seen in Figure 3, that the measurements and simulations are in better agreement in the phase of the current ramp when the absolute value of current in the PSL is decreasing compared to the phase when the absolute value of current in the PSL is increasing. This can be understood as being the result of a change in in the current distribution in the PSL, with surface currents flowing in the poloidal current pulse rise or fall and volume currents flowing in the poloidal current flat top. The simulations are to be extended by finite element modeling of the time dependent behavior of the current distribution in the PSL.

The magnetic probe measurements prior to a plasma discharge are shown in Figure 4. The ramp up of toroidal magnetic field starts at -6.5 s. Prior to -4 s, there are no other currents

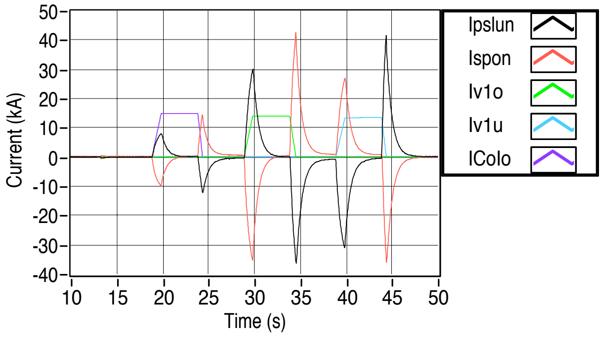

Figure 1: *Currents in the poloidal field coils and the passive stabilization loop (Ipslon, Ipslun).*

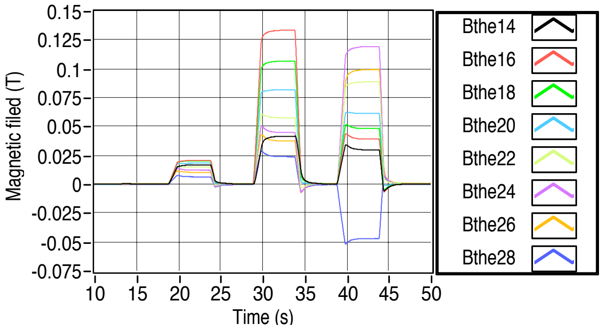

Figure 2: *Magnetic probe response for current pulses in the poloidal field coils.*

flowing in the poloidal field coils and the signals are due to misalignment of the magnetic probes with respect to the toroidal magnetic field. This signal is compensated by subtracting a term proportional to the value of magnetic field. From -4 s to 0 s the currents in the poloidal field coils in preparation for a tokamak discharge are ramped up. The difference between the measured and interpolated response from the real time Grad-Shafranov solver is shown in Figure 5. A calculated and measured magnetic probe signal difference of less than 2 mT in either Figure 3 or Figure 5 cannot be achieved even when the simulations in the vacuum field response are improved by carrying out a 3 point calculation along the 30 cm length of the magnetic probe.

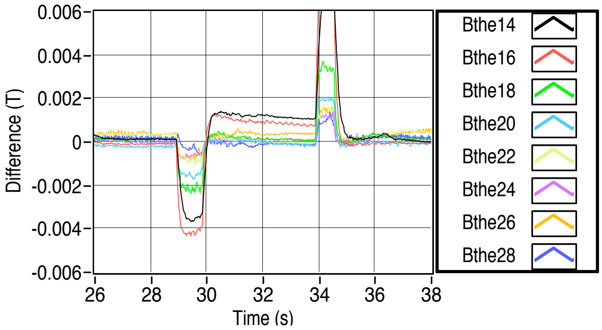

Figure 3: *Measured and calculated probe response difference for a current pulse.*

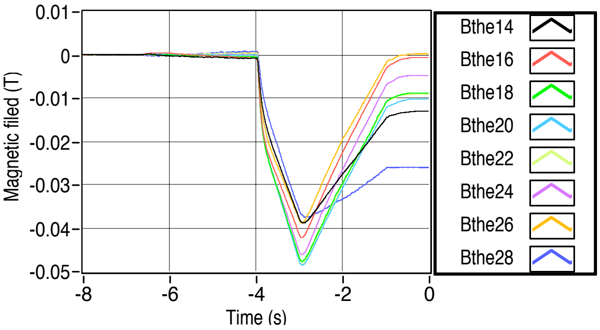

Figure 4: *Magnetic probe response for poloidal field currents prior to discharge.*

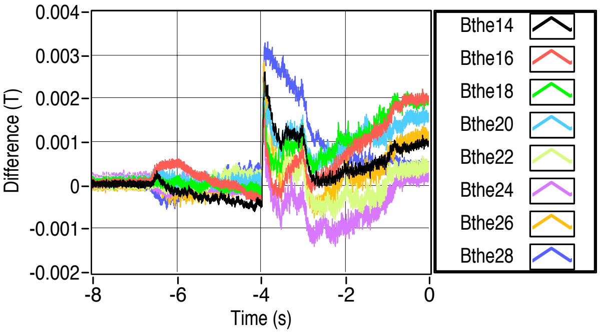

Figure 5: *Measured and calculated probe response difference prior to discharge.*

Conclusion

Improvement of the calibration of the poloidal field current measurements from the present 1% to better than 0.1% is needed to significantly reduce the fitting tolerance of magnetic probe and flux loop measurements for magnetic equilibrium reconstruction.

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