Bv ramp up effect in Spherical Tokamaks

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1. Introduction

The vertical magnetic field (B\(_V\)) in a tokamak, which provides the equilibrium, produces also poloidal magnetic flux that penetrates the plasma and can increase the plasma current. Experiments on MAST confirm these predictions [1]. B\(_V\) has two effects on the plasma. The first effect represents the inductive mechanism of current increase, on a time scale of the plasma heating characteristic time scale (fast time). For illustration of that effect the change of the poloidal flux in the plasma due to the increase of \(\beta_{pol}\) from 0.2 to 1 is shown in Fig.1 for the MAST configuration. Magnetic surfaces move outwards (Shafranov shift), which results in an increase of plasma current on each flux surface simultaneously. Secondly the poloidal flux through the torus hole makes a contribution to the external loop voltage, and due to this the plasma current increases on the resistive time scale. The overdrive condition corresponds to a regime when the value of the additive current due to the B\(_V\) effect is so large that the total plasma current keeps constant or even rises without change in central solenoid current. Investigations of the overdrive condition in the MAST tokamak and predictions for a Spherical Tokamak Power Plant (STPP) are presented.

2. Model

The simplest model that includes the effect of Bv ramp up consists of the poloidal flux \(\psi\) evolution equation written in the “toroidal flux radius”, \(\rho\), coordinate:

\[
\sigma(T_e, n) \frac{\partial \psi}{\partial t} = \frac{J^2 R_0}{\mu_0 \rho} \frac{\partial}{\partial \rho} \left( G_2 \frac{\partial \psi}{\partial \rho} \right) - \frac{V'}{2\pi \rho} j_{ext}
\]  

(1)

and the magnetic equilibrium requirement. Here \(\sigma\) is the plasma conductivity, G\(_2\) is the metric coefficient, J is the poloidal current, \(j_{ext}\) is the current density including the bootstrap and other currents externally driven (not Bv). To determine the equilibrium the plasma shape is prescribed. The plasma current inside surface \(\rho\) expressed by the formula

\[
I_{pl}(\rho) = \frac{G_2}{\mu_0} \frac{\partial \psi}{\partial \rho}
\]

(2)
can increase due to the increase of $G_2$ keeping the poloidal and toroidal fluxes constant (inductive mechanism). The effect of additional flux through the torus hole can be included in the boundary condition for eq. (1):

$$\frac{d\psi}{dt} \bigg|_{\text{edge}} = -U = -U^{Bv} - U^{CS} - U^{pl},$$

(3)

where contributions from $B_v$, from central solenoid (CS) and from plasma current are taken into account. For calculations for MAST $U^{Bv}$ is taken from the experiment, and for STPP we take it from calculations with the free boundary equilibrium code (EQFB). The plasma pressure increases due to the heating or density rise that changes the equilibrium condition increasing the $G_2$ factor. For high enough $\beta_p$ this contribution to the current becomes higher than the resistive losses and the plasma current remains constant (or increases) with low external loop voltage ($\frac{d\psi}{dt} \bigg|_{\text{edge}} = -U^{Bv}$). That is the “overdrive condition”. Modelling calculations are based on the ASTRA transport code [2]. Electron temperature and density are taken from the experiment on MAST. The rise of ion temperature $T_i$ is used in order to scan the $\beta_p$ as $\sigma$ does not depend on $T_i$. The plasma current was prescribed as a boundary condition according to the formula (2) instead of (3).

3. Experiment on MAST and calculations

The modelling is demonstrated for 2 shots from MAST with different $U^{CS}$ shown on Fig.2. For the time period [200ms, 250ms] the central electron temperature was approximately constant $\sim 1$keV. We use these shots to fit our model. In the calculations the plasma current evolution is prescribed and the necessary loop voltage is obtained as a result of calculations. The poloidal flux at the edge is shown on Fig.2 together with the experimental values. The model gives good agreement with the experiment.

In shot #7085 the contribution from $B_v$ at $\sim$zero $U^{CS}$ is clearly seen. Around the time $=140$ms $U_{\text{loop}}=0.1V$, the CS current is constant ($U^{CS}=0$), $B_v$ current produces a positive loop voltage, major radius does not change (Fig.3): $U^{Bv}$ is close to 0.1V. Clearly $U^{Bv}$ is proportional to $d\beta_p/dt$ (if geometry is fixed), so $U^{Bv} \sim 0$ when $d\beta_p/dt$ close to 0. Prescribing $U^{Bv}$ according to these estimates we calculate the parameters for overdrive condition shown on Fig.4 for two different electron temperatures 1keV and 1.5keV. The boundary uncertainties connect with fast ion component which model calculations do not take into account. Experimental MAST points are shown also on this plot. We see that MAST parameters are close to the overdrive boundaries.
4. Towards to the ST Power Plant

Because of the absence of the CS in the STPP other sources of the poloidal flux must be used. Preliminary experiments on JT-60U demonstrate plasma formation and current drive without the CS [3]. Fig.5 shows a plasma formation scenario without use of the CS flux on MAST. Plasma was formed using the merging compression technique and then the current was to be ramped and sustained using NBCD, EBWCD and Bv ramp. In these preliminary experiments EBW power was not enough to provide effective heating and CD, however, a short flat-top on plasma current has been achieved.

The scenario for current ramp up from 7MA to 31MA was produced for the STPP configuration [4] with our model. The ion and electron temperature was calculated...
with the CPTM model [5] normalised by the H-factor 1.6 for the $\tau(y,2)$ scaling law. The scenario for poloidal field currents was calculated with EQFB code [4]. The plasma current, the poloidal flux at the edge ($\psi_{\text{EQFB}}$) and the poloidal flux obtained by the $\psi$ transport equation ($\psi_{\text{ASTRA}}$) are shown on Fig.6. We see that the scenario is not self-consistent: ~20 voltseconds is spent by plasma but external flux produces on average even negative loop voltage ($U_{\text{loop}} = - \frac{d\psi_{\text{EQFB}}}{dt}$). But after 20sec code EQFB confirmed the zero loop voltage obtained by the model calculations. At the last stage of the ramp up scenario the plasma current rises from 22MA to 31MA with zero loop voltage at the edge due to the $B_v$ ramp up effect.

5. Conclusion

Poloidal flux from $B_v$ coils increases plasma current by inductive and resistive ways on different time scales. We have built a model which describes this effect. We define the criterion for overdrive condition and show that the MAST operational area is close to the overdrive condition level using the model calculations. For the STPP parameters, calculations show the possibility to ramp up plasma current due to the $B_v$ ramp up effect.

References