Feedback Current Profile Control in the Advanced RFP

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In the advanced reversed field-pinch (RFP), the scaling of energy confinement time with plasma current and density is improved substantially compared to the conventional [1,2] RFP. This may be numerically simulated by an ad-hoc electric field, adjusted to generate a tearing mode stable parallel current density profile. In the present work a current profile control algorithm based on feedback of the fluctuating electric field $\mathbf{E}_f$ in Ohm's law, is introduced to the resistive MHD code DEBSP. Energy confinement time is increased with more than a factor of three for one case, and for another case poloidal beta exceeds 50%. It is found that in the stationary state, a formation appears in the parallel current profile, which spontaneously becomes hollow.

Introduction

In the RFP, the dynamo effect is responsible for driving the configuration into a minimum energy state. This process may manifest itself by a saw tooth-like behaviour in relevant plasma parameters. The dynamo is caused by current driven tearing modes, leading to MHD turbulence and ergodic magnetic field lines. While the strong turbulent behaviour is responsible for energy redistribution and thus the driving mechanism of the self-organisation to the minimum energy state, this is also believed to be the mechanism behind anomalously large particle and energy fluxes.

Earlier investigations on Current Profile Control (CPC) of the RFP suggest that energy confinement time could be increased substantially (a threefold improvement) by the introduction of an ad hoc electric field near the reversal surface [3,4]. This electric field has the form of a Gaussian with three associated parameters (associated to location, width and magnitude of the distribution). The field has the effect of flattening the parallel current profile, reducing the effect of current driven tearing modes and hence heat transport. However, the introduction of three free parameters make optimisation difficult. Therefore, a one parameter automatic CPC scheme has been developed.

Feedback

The introduction of feedback systems to improve energy confinement in the RFP has been discussed extensively during the last years, both numerically and experimentally [3-5]. In

this work, the numerical plasma fluid code DEBSP [6,7] has been used for simulating an RFP plasma with a near-optimal feedback system. In its original form, DEBSP solves the resistive MHD equations by integrating in time, using a semi-implicit time step algorithm. A feedback system is introduced which takes the fluctuating dynamo field $\mathbf{E}_f = - \langle \mathbf{v} \times \mathbf{B} \rangle$ from Ohm's law as input signal. A general feedback control system is sketched below.
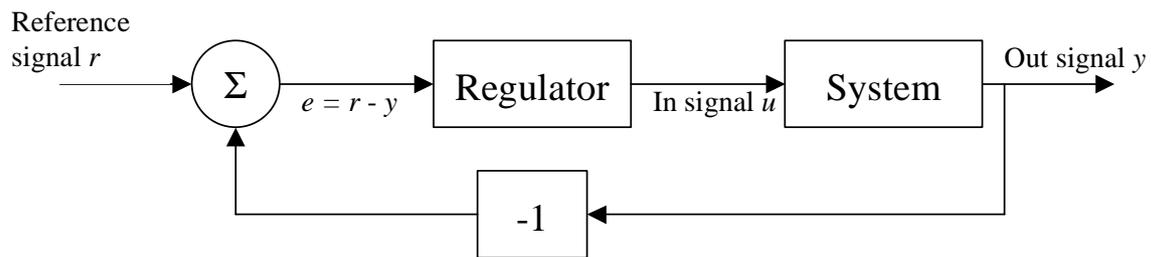
The DEBSP code is the 'system'. The output signal $\mathbf{y} = \mathbf{E}_f$ is the signal to be controlled, and the problem is thus to design the 'regulator' for it to follow the reference signal $\mathbf{r}$:

$$\mathbf{r} = \mathbf{E}_f^{ref} = 0 \tag{1}$$

In other words, the regulator should yield a signal $\mathbf{u}$ as to force $\mathbf{r} - \mathbf{y}$ converging towards 0. To control the evolution, a term is added to the momentum equation in the DEBSP code:

$$p \frac{d\mathbf{v}}{dt} = \mathbf{J} \times \mathbf{B} - \nabla p + \alpha \mathbf{E}_a \tag{2}$$

and another one in Ohm's law:

$$\mathbf{E} = -\langle \mathbf{v} \times \mathbf{B} \rangle + \eta \mathbf{J} + \mathbf{E}_a \tag{3}$$

Proportional feedback

The first approach in designing a regulator system was here to feedback only a term proportional to $\mathbf{E}_f$. The proportional regulator has thus the following appearance:

$$\mathbf{E}_a(t) = -k_P \mathbf{E}_f(t) \tag{4}$$

Since the proportional term has no intrinsic memory, the system develops into an oscillating state. As the proportionality coefficient k_P is increased, finally an unstable state is reached. Figure 1 monitors three cases of different k_P. Compare with the reference case in figure 2.
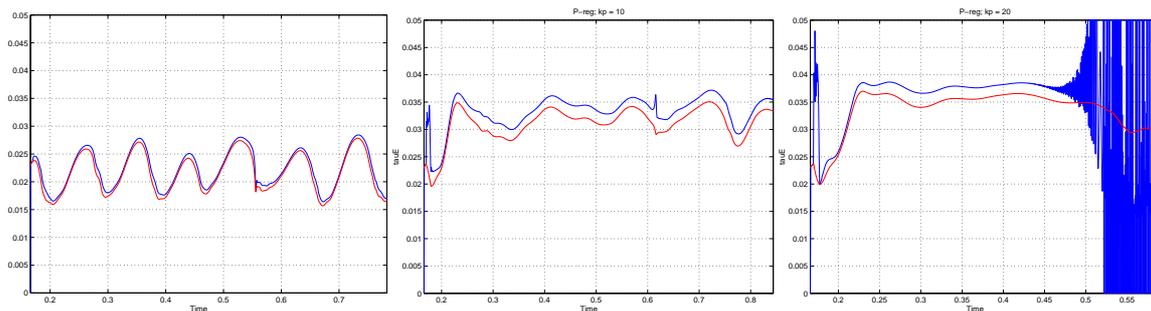
Fig 1. From left to right: $k_P = 1.6$, $k_P = 10$, $k_P = 20$. Energy confinement time is monitored with and without the inclusion of regulator power input: $\tau_{E\text{tot}}$ and τ_E.

Integrating feedback

To achieve a steady non-oscillating state, the feedback loop has to include an acquiring term, i.e. an integral term. The integrating regulation scheme has the following appearance:

$$\mathbf{E}_a(t) = -k_I \int_0^t \mathbf{E}_f(t)dt \approx -k_I \sum \mathbf{E}_f(t)\Delta t \tag{5}$$

To investigate the effect of the magnitude of the feedback coefficient k_I, an array of cases were tried. The case chosen to be presented here has a regulator coefficient $k_I\Delta t = 0.0002$.
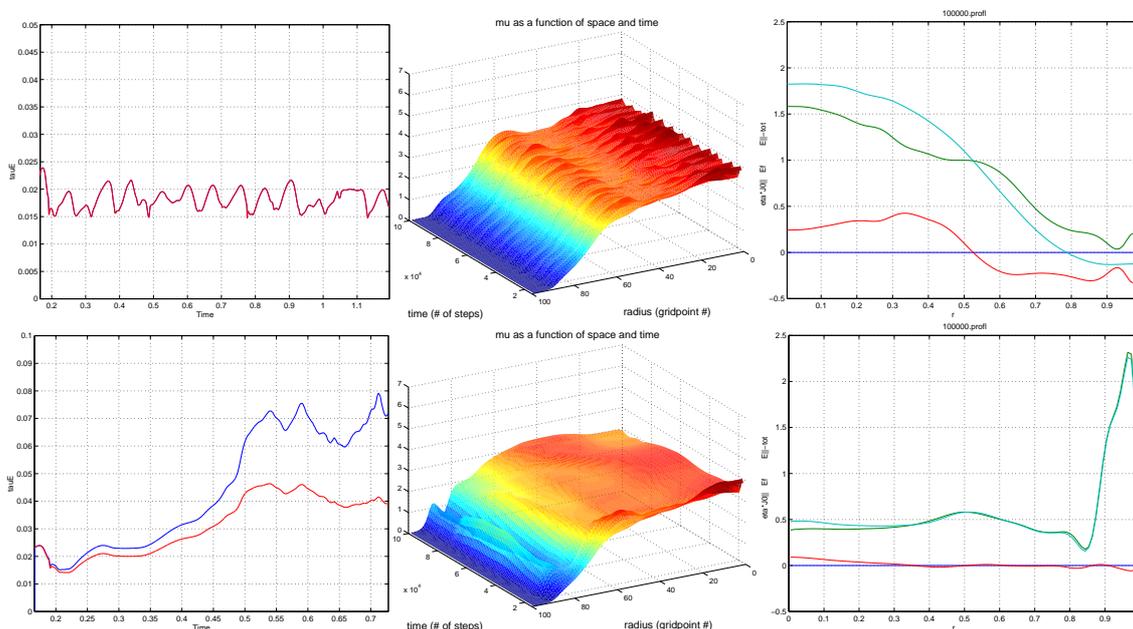

Fig 2. Above: reference case. Below: integrating regulator case. From left to right: $\tau_{E\text{tot}}$ and τ_E, μ-profile ($\mu = \mathbf{J}\cdot\mathbf{B}/B^2$), profile of the electric fields E_f, $\eta J_0^{\parallel}$ and $E_{tot} = E_f + \eta J_0^{\parallel}$.

As seen in figure 2, a more than threefold increase in energy confinement time τ_E is present in the integrating regulator case compared to the reference case. Also to be noted, the total energy confinement time (with feedback input power taken into account) $\tau_{E\text{tot}}$ is exceeding

τ_E. This implies that regulator input power is negative in those intervals, thus power is drawn from the plasma.

The feedback system spontaneously creates a formation which appears in the μ-profile close to the reversal surface. This formation is not unlike the Gaussian shaped field used in earlier CPC-schemes. The μ-profile is flattened in the core plasma, and is slightly hollow. This reduces current driven tearing modes. For higher k_I cases the μ-profile is even more hollow, but the energy confinement time deteriorates.

Another feature that appears when different cases are compared is that poloidal beta β_θ is strongly correlated to the magnitude of the feedback coefficient k_I. In two cases, β_θ reaches around 50% (45% and 53% respectively).

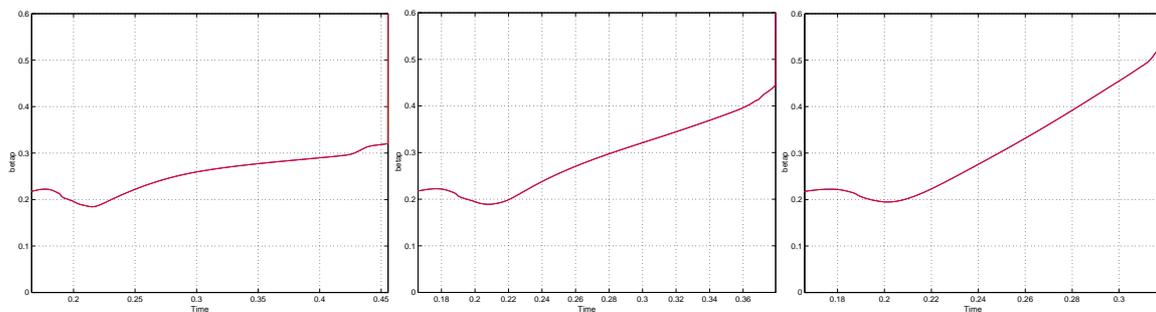*Fig 3*. Poloidal beta β_θ for the feedback cases of $k_I \Delta t = 4 \cdot 10^{-4}$, $k_I \Delta t = 6 \cdot 10^{-4}$, $k_I \Delta t = 10^{-3}$.

Conclusions

The objective of the active current profile control is to reduce the fluctuating electric field $\mathbf{E}_f$. As can be seen in the profile-plots, this objective is effectively fulfilled, and $\mathbf{E}_f$ is virtually flat. Energy confinement is improved by a factor of about three. Poloidal beta has been observed to reach 50% for some cases.

The aim for the future is to use the regulator to optimise behaviour with respect to energy confinement and thereby produce scalings for the advanced Reversed Field Pinch.

References

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