# IMPACT OF SOFT IRON IMPELLERS IN THE CADARACHE DYNAMO EXPERIMENT

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*Summary* Numerical simulations of the kinematic induction equation have been performed applying an axisymmetric model configuration of the Cadarache dynamo. The results demonstrate the important influence of the soft iron material used for the flow driving impellers in this experiment. The localized high permeability and the particular symmetry of the model provide for a selective enhancement of the axisymmetric azimuthal field which can qualitatively explained by paramagnetic pumping at the fluid-disk interface.

## A NUMERICAL MODEL FOR THE CADARACHE DYNAMO EXPERIMENT

After the successful dynamo experiments conducted in Riga and Karlsruhe, the Cadarache dynamo is only the third facility that has been able to demonstrate fluid flow driven self-generation of magnetic fields in a laboratory experiment [1]. The Cadarache dynamo is based on a von-Kármán like flow of liquid sodium driven by two counter-rotating impellers that are located close to the end-caps of a cylindrical vessel (left panel in figure 1). However, despite of extensive numerical and experimental efforts the very nature of this dynamo and its surprising properties still remain nebulous. Firstly, dynamo action is obtained only when (at least one of) the flow driving impellers are made of soft iron with a relative permeability $\mu_{\rm r} \approx 65$ [2]. Moreover, and in apparent contradiction with Cowling's anti-dynamo theorem, the geometric structure of the observed magnetic field is dominated by an axisymmetric field [3]. Numerical simulations of the kinematic induction equation that are based on a mean von-Kármán like flow model and a permeability distribution that roughly resembles the flow driving impellers in the experiment show that both phenomena (i.e. the exclusive occurrence of dynamo action with soft iron impellers and the axisymmetry of the magnetic field) are closely connected [4].

Here we illuminate the process that is responsible for the domination of the axisymmetric field mode in more detail, and we propose a preliminary concept how our model can be expanded to explain the observed dynamo properties. For this purpose we conduct numerical simulations of the kinematic induction equation in an axisymmetric configuration assuming a nonuniform relative permeability $\mu_{\rm r} = \mu_{\rm r}(\boldsymbol{r})$ distribution. Then the induction equation reads:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times\left(\boldsymbol{u}\times\boldsymbol{B} + \frac{1}{\mu_{\rm r}\mu_0\sigma}\frac{\nabla\mu_{\rm r}}{\mu_{\rm r}}\times\boldsymbol{B} - \frac{1}{\mu_{\rm r}\mu_0\sigma}\nabla\times\boldsymbol{B}\right), \qquad (1)$$

where $\boldsymbol{u}$ is the prescribed (mean) flow, $\boldsymbol{B}$ the magnetic flux density and $\mu_0$ the vacuum permeability ($\mu_0 = 4\pi\times 10^{-7}$Vs/Am). The central expression on the right hand side of Eq. (1) proportional to $\sim \nabla\mu_{\rm r}\times\boldsymbol{B}$ represents the *paramagnetic pumping* [5] which is responsible for the suction of magnetic field into the regions with large permeability. Furthermore, this term is also responsible for the selective amplification of an axisymmetric toroidal field mode [6].

Equation (1) is time stepped using a hybrid finite volume/boundary element method. The simple grid-based scheme respects insulating boundary conditions and allows a direct consideration of localized internal distributions of large relative permeability. The flow field $\boldsymbol{u}$ is prescribed by the so called MND-flow [7] and the soft iron material of the impeller disks is modelled by two axisymmetric disk-shaped domains (see right panel in figure 1).

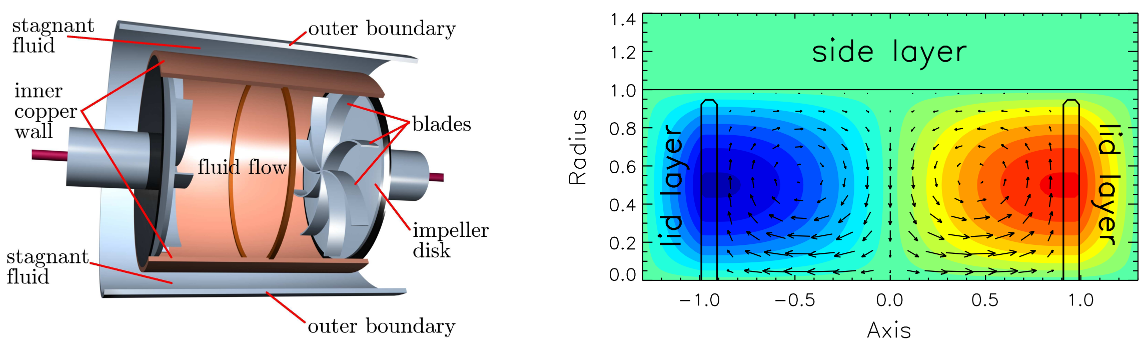


**Figure 1.** Sketch of the Cadarache dynamo (left panel) and mean axisymmetric flow field applied in the kinematic simulations (right panel). The disk-like structures (denoted by the black curves) close to the end-caps represent the high-permeability domains in the simulations. Two disk-like sub-domains with radius $R_{\rm imp} = 0.95$ are located in the intervals $z \in [-1.0; -0.9]$ and $z \in [0.9; 1.0]$ and represent soft iron disks of thickness $d = 0.1$.

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## PARAMAGNETIC PUMPING AND THE AXISYMMETRIC EIGENMODES

From the numerical solutions of the linear system (1) we extract the leading eigenmodes and the corresponding eigenvalues in terms of field growth-rates $\gamma$. We observe two distinct classes of axisymmetric eigenmodes, a purely toroidal mode that is amplified by paramagnetic pumping at the fluid-disk interface and a mixed mode consisting of a poloidal and a toroidal contribution that is rather insensitive to the disk permeability (fig. 2). In the limit of large $\mu_{\rm r}$ the purely toroidal axisymmetric mode is close to the onset of dynamo action with a growth-rate that is rather independent of the flow field. It is located near to and in the high permeability disks and becomes the leading mode when $\mu_{\rm r}$ exceeds a critical value (marked by the vertical dotted curve in the right panel of fig. 2). This mode is also the dominant mode in the experimental relevant regime ($\rm Rm \approx 30...50$), i.e. its (negative) growth-rate exceeds the growth-rate of any non-axisymmetric eigenmode which only becomes dominant for larger magnetic Reynolds number. A simplified analytical model confirms the numerical scaling behavior of the purely toroidal mode $\propto \mu_{\rm r}^{-1}$ which is typical for a free decay mode. The analytical model also explains why the overall decay time of the dominant azimuthal axisymmetric field is determined by the purely toroidal mode although this mode is localized to a very small volume. It is important to note that in our axisymmetric configuration the purely toroidal mode is decoupled from any poloidal field component and hence is not able to exhibit dynamo action.

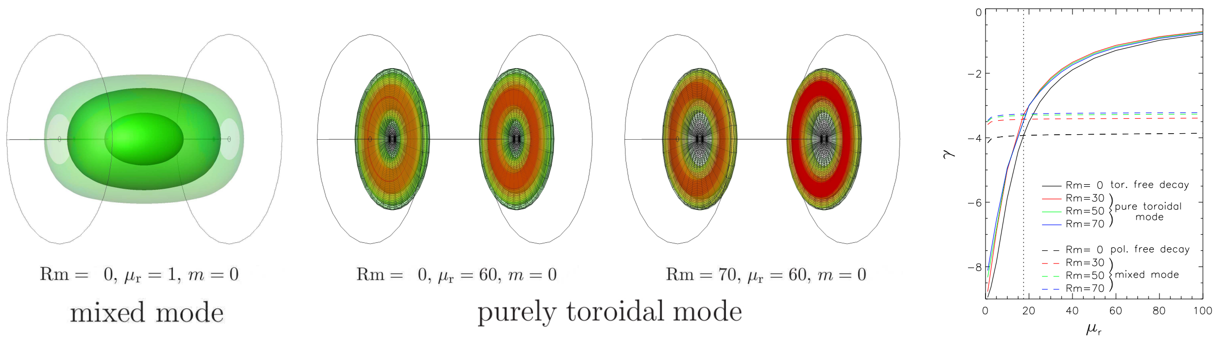


**Figure 2.** Field structure and growth-rates for the axisymmetric ($m0$) eigenmodes. The iso-surfaces on the left hand side present the magnetic energy density of the $m0$ mode for various sets of the control parameters $\rm Rm$ and $\mu_{\rm r}$. The plots on the right hand side shows the corresponding growth-rates of the $m0$ eigenmodes (solid curves: purely toroidal mode, dashed curve: mixed mode).

## CONCLUSIONS

Our numerical model of the Cadarache dynamo shows that soft iron impeller disks considerably promote a toroidal axisymmetric eigenmode whereas any poloidal contribution (incorporated in the mixed mode) is hardly affected. The purely toroidal mode and its strong amplification by paramagnetic pumping at the fluid-disks interface can be obtained only by explicitly considering the internal permeability distribution. This mode does not exist in case of highly conducting disks or in simulations that use idealized boundary conditions like vertical field conditions ($\boldsymbol{B} \times \boldsymbol{n} = 0$) or the thin-wall approximation from [8].

The separation into purely toroidal and mixed mode can be overcome e.g. by a non-axisymmetric permeability distribution that resembles an assembly of blades attached to the disks. Such a coupled eigenmode is even more likely to facilitate the occurrence of dynamo action when a further source term like the $\alpha$-effect is considered that is necessary to break the restriction imposed by Cowling's theorem. The particular coupling mechanism provided by such a non-axisymmetric permeability distribution might give a hint why dynamo action is absent in experiments with the fluid flow driven by an impeller system composed of soft iron disks and stainless steel blades.

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