Distributed and Asynchronous Bees Algorithm Applied to Plasma Confinement

A. Gómez-Iglesias 1), F. Castejón 1), A. Bustos 1), M.A. Vega-Rodríguez 2)

1) Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, Madrid, Spain
2) University of Extremadura, Cáceres, Spain.

E-mail contact of main author: antonio.gomez@ciemat.es

Abstract. A generic distributed optimization process applied to improve plasma confinement in TJ-II stellarator is here presented. This process is based on the distributed evidence gathering and processing of bee swarms. Due to its distributed schema, this algorithm can be implemented in a distributed computing infrastructure. Grid computing paradigm fulfils all of the computational requirements of this distributed optimisation model. This method is applied to the optimisation of the neoclassical transport in the stellarator previously mentioned.

1. Introduction

Optimised magnetic configurations meeting multiple optimisation criteria are a key topic in the design of stellarator reactors. Several optimisation criteria may be considered and implemented in the optimisation algorithm with the aim of obtaining optimised magnetic configurations.

One of the criteria which can be considered is the reduction of the neoclassical transport. That is the case presented in this paper, in which the confinement of fast particles and the improvement of the MHD stability are the basic targets of the optimisation process. The omnigeneity property guarantees a good confinement of fast particles, while the Mercier stability and the ballooning stability are the main modes that are considered for improving MHD stability.

In this work, we show the development of an algorithm based on metaheuristics to look for such an optimised configuration. A metaheuristic is a combinatorial solving process applied to problems in which a method to find the solution to that problem does not exist. This combinatorial process tries to maximise or minimise a function defined by the user, which is called target function [1]. All the metaheuristics have some commonalities like the exploration of the phase space or the use of a population of candidate solutions. The use of a set of solutions represents the main difference when compared to other optimisation techniques. For our optimisation, we have introduced three different criteria: the minimization of the neoclassical transport by reducing the average of the drift, the Mercier criterion and the ballooning stability.

The equilibrium is calculated using the VMEC (8.46 version) 3D equilibrium code [2]. Mercier criterion is also calculated by VMEC. Those configurations not satisfying the criterion for a given radius are not considered regardless the value of the target value; configurations satisfying the criterion until a given value receive a penalty in the final evaluation. The ballooning stability code COBRA [3] has been introduced in the process in order to include this stability property in the search of the optimised stellarators.

This is a large-scale problem which requires of a large amount of computational resources to be solved. The size of the solution space is huge and it becomes virtually impossible to explore all the possible configurations. Even using metaheuristics the evaluation of a several candidate solutions required a large number of computational resources. Here, grid computing the grid is used to carry out this optimisation. The algorithm developed is adapted to this distributed environment.

2. The Implementation of the Workflow in a Heterogeneous and Distributed Computational Environment

The workflow application required to calculate the equilibrium is as shown in Fig. 1.

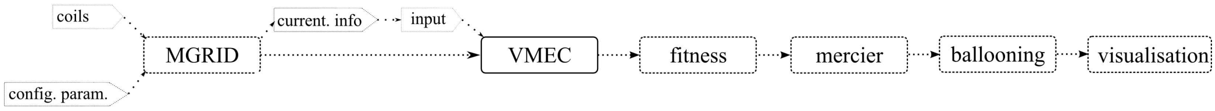


FIG. 1. Workflow to estimate the equilibrium and its Mercier and ballooning stability.

2.1. Optimisation Functions

The best quality of the confinement from the neoclassical point of view is guaranteed by the isodinamicity. This is equivalent to keep the particles stuck to the field lines, hence reducing the neoclassical transport to the classical one. As this is materially impossible, there are alternatives of quasi-isodinamicity [4] that tend to reduce the radial excursions of the particles as much as possible. The method proposed here is based on the reduction of the drift, thus trying to decrease the radial excursions of the particles. This implies the minimization of the following objective function:

$$F_{fitnessfunction} = \sum_{i=1}^{N} \left\langle \left| \frac{\vec{B} \times \vec{\nabla} |B|}{B^3} \right| \right\rangle_i \tag{1}$$

In this equation, i is the magnetic surface label and B is the confining magnetic field, tangent to the magnetic surface.

2.1.1. Mercier criterion

Beyond the neoclassical transport minimisation, it is necessary to assess the magnetic configuration from the stability point of view. The accomplishment of the Mercier criterion is mandatory. This implies the stability of the modes that satisfy that are well localised radially and extended toroidally and poloidally.

2.1.2. Ballooning modes stability

Besides Mercier stability criterion, the Ballooning mode stability is also imposed in order to cover the main possible instabilities that can appear in a stellarator plasmas. In this way both toroidally localised and radially localised modes are considered. Ballooning modes appear in zones of unfavourable curvature, which are much more difficult to identify in a stellarator than in a tokamk. As has been stated above, the COBRA code [3] can perform such stability analysis quickly enough top be included in our optimization procedure.

3. Distributed and Asynchronous Bees Algorithm

The DAB algorithm is a metaheuristic process designed to solve large-scale computational problems using distributed environments. It is based on the foraging behaviour of honey bees [5]. It evolves a population consisting of a set of individuals, where each individual represents an equilibrium configuration calculated with VMEC. The algorithm explores the solution space defined by the Fourier modes describing the plasma. Each of the Fourier modes is a chromosome; thus, and individual is made up of a set of chromosomes. Due to the fact that all the individuals are independent, the amount of communication between the processes evaluating the individuals is low. Thus, grid computing techniques are suitable for this process. With the grid some problems arise due to its distributed, heterogeneous and non-centralised paradigm. These problems are related to the management of the remote execution, considerations about the computer architecture in which the evaluation is being carried out and the different elements suitable to fail.

The algorithm is based on two processes:

- Exploration: this process explores the solution space, which has to be carried out in such a way that all the main areas of the solution space should be explored in a well-balanced way (high dispersion). In our case, this balance is assured by creating a set of individuals, obtaining their distances to the previously selected individuals and selecting the individual with the higher distance.

- Exploitation: this process introduces convergence in the algorithm when good configurations have been found. Using good configurations, the exploitation mechanism evolves these candidate configurations by introducing small changes in the original individuals.

These two processes run on the grid, following a master-slave model with a decentralized intelligent behaviour where the information is distributed among all the resources involved in the optimisation process. Due to the grid paradigm, a great detail can be introduced in parallel to these to processes without increasing the Wall Clock (WC) time. Thus, in the exploitation method a new sub-method based on local searches can be used in order to carry out and in-depth exploitation of the best configurations found so far.

The main objective of this algorithm is to achieve an optimal usage of the computational resources, maximizing the computing time and reducing the deadlocks and bottlenecks. Hence, there are not dependencies among all the different sub-processes running concurrently in a distributed environment.

The DAB algorithm proposes the skeleton of the optimisation procedure. For the different processes and sub-processes, different techniques can be implemented. For example, local search procedures or Monte Carlo techniques can be applied for the exploitation of the best configurations found. Also various measurements can be introduced for a different exploration of the solution space.

The algorithm can be configured in order to specify several grid parameters and also to establish the range of values for the elements involved in the optimisation which can be explored.

4. Optimisation of TJ-II

As mentioned before, this optimisation is a large-scale problem in which the number of computational resources needed is huge. Fig. 2 shows the wall-clock time required to find optimised configurations and the evolution of the value given by the target function. The time shown in the figure is the wall-clock time. The total execution time for this optimisation is 21,000 hours.

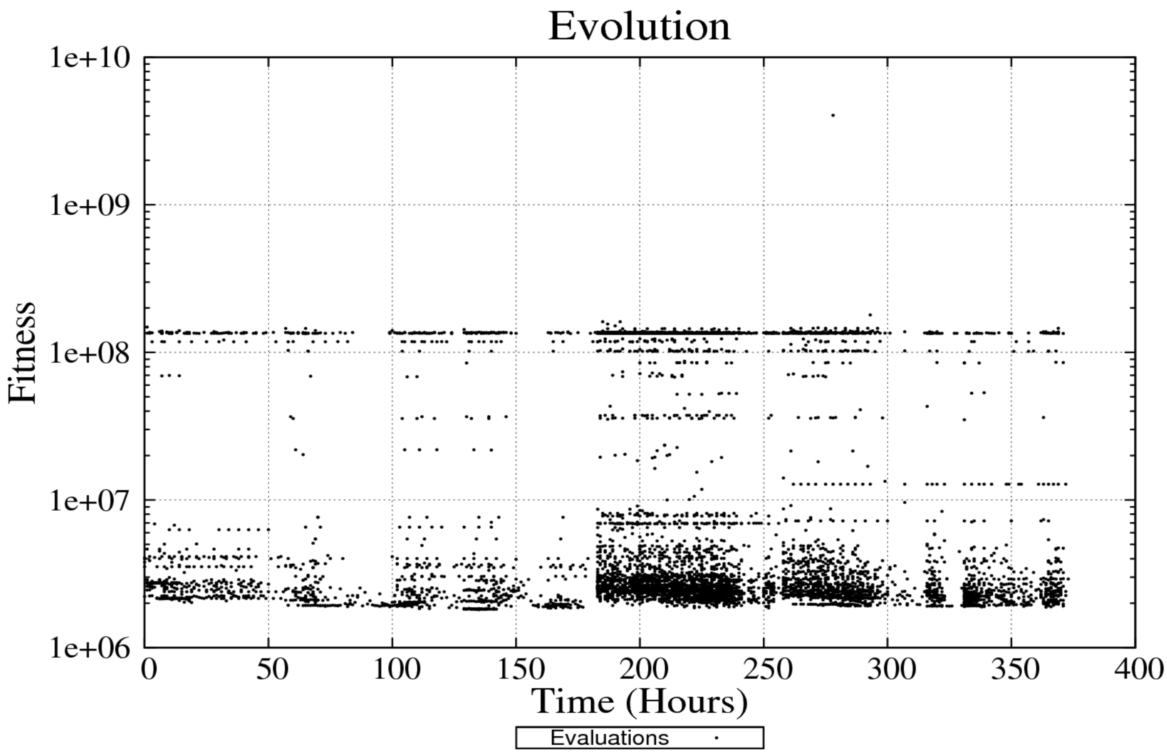


FIG. 2. Evolution of the optimisation process.

The optimisation is focused on the TJ-II stellarator *Ref\s*, in operation in Madrid since 1997. This stellarator belongs to the old generation of non-optimised devices. It presents, nevertheless, an extremely low Shafranov shift, which allows the equilibrium to exist and to be stable at large values of plasma pressure [6].

One of the main problems in metaheuristics is the size of the solution space. It is mandatory to delimit the range of values that each chromosome may take. This is critical not only in terms of exploration but in terms of final results: it is very difficult to evolve from very bad starting configurations. For this reason, we have allowed the input Fourier modes that describe the plasma boundary to vary only ±15% from a given initial configuration. In this way we keep a configuration still very similar to the TJ-II one with improved characteristics.

We have started from the 42_100_68 configuration, which is characterised by its indentation that makes it suitable for a flux expansion divertor development [7]. This configuration presents, nevertheless, a shallow magnetic well, which reduces the Mercier β limit to 0.3%. This configuration is taken as input for the algorithm in order to improve its characteristics.

The algorithm is able to find optimised configurations quickly when compared to other metaheuristics [8]. The number of computational resources which it can use at the same time eases this search. However, it takes some time to find optimal configurations. After some thousands of evaluations the algorithm has converged and found a configuration with improved characteristics, thus showing the effectiveness of the DAB algorithm for this purpose. The final configuration presents a diminishing of the neoclassical target function given by Eq.1 of 23,84%. The Mercier criterion can be seen in Fig. 3 while the ballooning stability is displayed in Fig. 4.

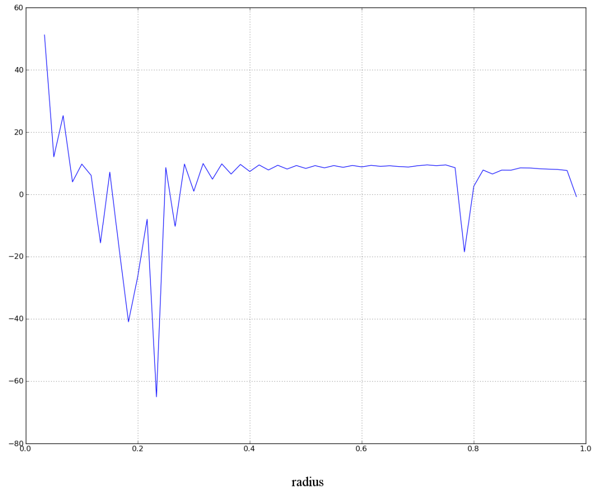


FIG. 3. Mercier criterion for the best configuration found.

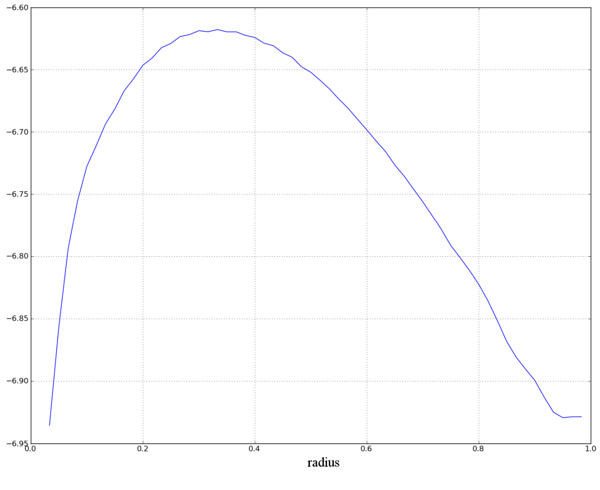


FIG. 4. Ballooning stability for the best configuration found.

Fig. 5 shows the cut of the magnetic surfaces both for the starting configuration at two toroidal angles $\phi=0$ (left) and $\phi=(\pi/2)$ *rad* (right). These two cuts must be compared with the ones shown in Figure 6 that correspond to the optimised configuration for the same toroidal angles. In these two figures, one can appreciate that the main variation observed in the optimised configuration is that a larger fraction of the plasma is located close to the high magnetic field in the optimised case which corresponds to the region closer to the central conductor. This configuration still presents flux expansion, which would make it suitable for flux expansion divertor studies.

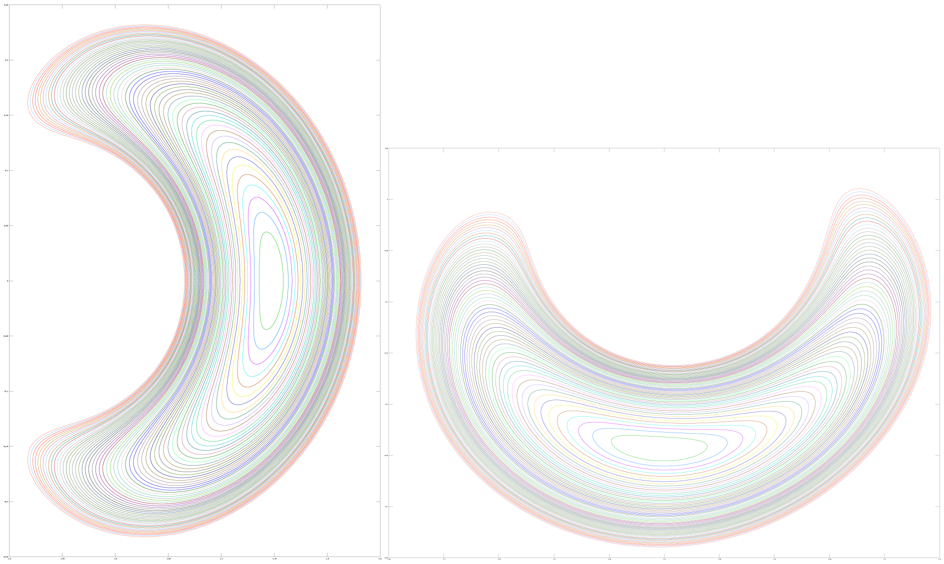


FIG. 5. Cross-section of the magnetic surfaces for the initial configuration.

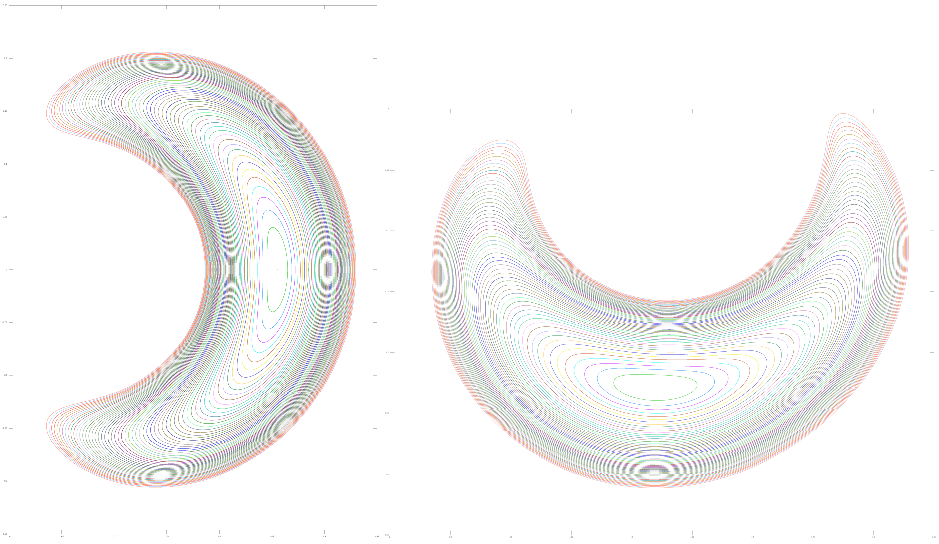
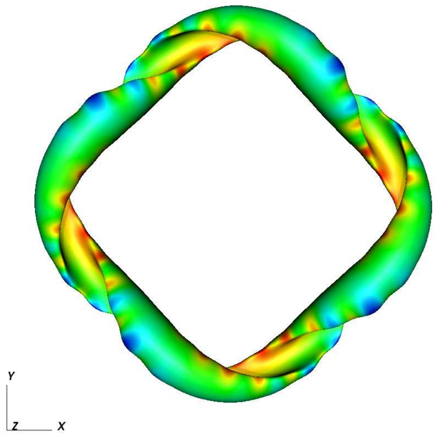
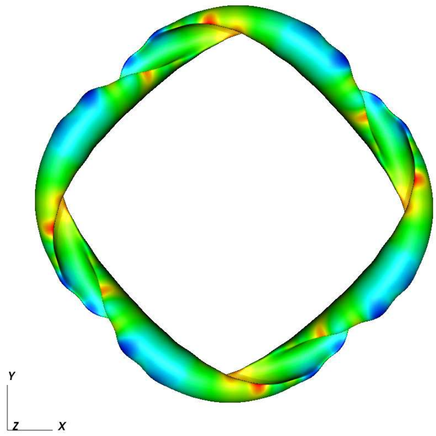


FIG. 6. Cross-section of the magnetic surfaces for the best configuration.

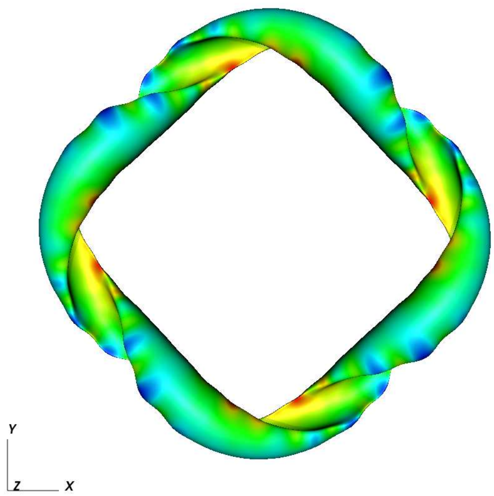
Figure 7 shows the plot of the last closed magnetic surface of the starting, an intermediate and the optimised configurations.



a) Original configuration



b) Intermediate configuration



c) Best configuration

FIG. 7. Plasma confined in three different configurations

5. Summary

A new metaheuristic algorithm has been developed. The DAB algorithm is an evolutionary algorithm based on the foraging behaviour of honey bees. The algorithm takes advantage of the grid computing paradigm, thus having access to a huge computing capability. It has been successfully applied to the optimisation of a stellarator.

The algorithm can be configured to restrict the solution space and can be also adapted to different grid infrastructures.

The final configuration obtained with the algorithm presents clear improvements, showing the capability of the algorithm for the purpose of stellarator optimisation.

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