Determination of edge plasma parameters by a genetic algorithm analysis of spectral line shapes

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Comparing an experimental and a theoretical line shape can be achieved by a Genetic Algorithm (GA) based on an analogy to the mechanics of natural selection. Such an algorithm is able to deal with complex non linear models, and can avoid local minima. We have used this optimization tool in the context of edge plasma spectroscopy, for a determination of the temperatures and fractions of the various populations of neutral deuterium emitting the Dα line in two configurations of Tore Supra : ergodic divertor and toroidal pumped limiter .

1 Introduction

Spectroscopic observation of spectral lines in the visible is widely used for characterizing edge plasmas in Tokamaks. Earlier spectroscopic measurements of the visible lines observed in edge plasmas have revealed the coexistence of several neutral populations with different temperatures near the plasma boundary [1, 2]. A good example of such an analysis is given by the Dα spectral line shape on which up to four different neutral populations have been identified, and related to specific production processes [1, 3]. Such information is of interest for understanding the recycling and emission processes of deuterium atoms in the scrape-off layer. For the conditions where Zeeman-Doppler spectra are observed, the temperature and fraction of each population may be determined quite accurately, if an adequate fitting procedure is used. We have used a previously developed Zeeman-Doppler line shape model including neutrals produced by molecular dissociation, charge exchange, and reflection for obtaining synthetic spectra [3]. Such spectra are fitted to the experimental profiles to obtain a set of model parameters. The quality of the fit is quantified for each profile by a merit (or fitness) function χ^2 which has to be minimized. The difficulty of this optimization procedure lies in the fact that there are many parameters to determine in edge plasmas, like the temperature and relative fraction of each of these populations. In addition, the volume of spectroscopic data obtained from Tokamaks is generally very large, and many of the spectra are affected by noise. One thus needs a reliable and robust optimization technique, which is fast enough to analyze a large number of spectra with a reasonable amount of computer time.

2 Optimization techniques

Many automated optimization techniques have been used in the past for analyzing spectral line shapes. A classical technique consists in the search of a minimum following the steepest descent in the landscape formed by the fitness function. Clearly, this method -or any other type of hill climbing technique such as the conjugate gradient method- are local methods suited for cases with a well defined extremum. The landscape is however often quite different from this ideal case, and exhibits many local minima, sometimes separated by high mountains. The problem of finding the global minimum is then a difficult task, for which most of the classical techniques are

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inefficient. More robust techniques have thus to be applied in such cases, like the simulated annealing methods [4], which use an analogy with the thermodynamics of a cooling liquid or metal. If a liquid is cooled slowly, it will reach a crystal state of minimum energy for this system. It is this gradual lowering of the temperature which is known as annealing. Applying the method of annealing to our problem would consist in associating an "energy" to the fitness function, and searching the minimum energy for our system. This can be done by assuming that the probability of an energy change follows a Boltzmann law. The search procedure thus uses a familiar Metropolis algorithm, where the temperature acts as a control parameter. The simulated annealing method is robust in the sense that it is a global method able to find the global minimum among many local minima. We have first considered using it for our line shape fitting problem, but since the dependence of the cooling rate is case dependent, we rather choose another global method based on a genetic algorithm. Genetic Algorithms (GA) are optimization techniques [5, 6] which are both robust, efficient, and global. They are based on an analogy with the mechanics of natural selection. Natural selection is a process during which individuals better adapted to their environment are preferentially bred. Two key ingredients are observed in this process: i)inheritance: parents transmit their fitness to their offsprings, and ii)variability: at any given time individuals of varying fitness must coexist in the population. During the 20th century, the development of genetics has allowed to understand how the genetic material of two parents is passed on to their offsprings. Inheritance is assured by the combination of complementary portions of the parents genetic material. In the course of this process, alteration of some gene values occasionally occurs, and this together with the fact that an offspring receives genes from two parents, is the source of variability. Genetic algorithms are a class of computerized search techniques which mimic a simplified version of the biological evolutionary process, but retains both inheritance and variability. They are able to find rapidly a solution in a complex search space, avoiding the problem of local minima. They also have the property of being weakly sensitive to the presence of noise on the data, a feature that is unfortunately common in magnetic fusion spectra. Their reliability, robustness and speed have been strong motivations to adapt them to a variety of physical problems, including Mössbauer spectroscopy, nuclear magnetic resonance, and X-ray plasma spectroscopy [7].

3 Genetic algorithm

We describe in this work the use of a GA in the case of the edge plasma spectroscopy, and its implementation on a parallel computer, for which such techniques are naturally suited. The first step of this optimization technique consists in encoding the model parameters in binary or decimal strings. In the language of GA, we then have a chromosome containing several genes. The value of each gene is chosen within an interval of values, a choice which allows to impose specific physical constraints to each parameter. For our spectroscopy problem, we consider an initial sample of many individuals (typically about 500), whose size remains fixed during the evolution. Each individual has a single chromosome and corresponds to a line shape $L(\omega)$ whose fitness is evaluated by comparing the model to the experimental data by a χ^2 statistical estimator

$$\chi^2 = \frac{1}{N-P} \sum_{i=0}^{N-1} \frac{1}{\sigma_i^2} [L_i - L(\omega_i)]^2, \qquad (1)$$

where N is the number of experimental points (ω_i, L_i), P the number of independent parameters, and σ_i the standard deviation for the measurement error of the experimental point i. At this point it is interesting to note the possibility of adding with a very simple change in the code a new parameter. This simply results in a sample of individuals having each a larger chromosome. The GA modifies this initial random sample using three operators. Selection is a process during which the fittest individuals have the greatest probability to survive. We use a steady state GA [8] which renews ten percent of the population at each new generation, with randomly chosen individuals. A fraction of the entire new population is then submitted to crossover and mutation. The chromosome of the selected individuals (their default fraction is 0.85) are recombined by crossover of a part of their genes. Mutations are allowed to occur at a very low rate (default is 0.005), and consists in the random change of one bit in a binary string (gene). Although mutations generally result in an individual which is less fit, they occasionally produce a change that improves the sample, and help the whole process in avoiding local minima. To these three basic GA operators, one usually adds the component of elitism, which consists in copying intact in the offspring population, the fraction of fittest members of the parent population (its default value is 10 percent of the population). On a Compaq ES40 octo-processor computer, we used a parallel version of our GA which assumes that the program is linked with the MPI parallel library. One processor is dedicated to the master process which consists in the generation of a random initial population, and its evolution with genetic operators. All the other processors are slave processes computing the evaluation function. We have found (Fig. 1) that the GA succeeded in locating the global minimum in about 1000 steps with a population of 500 individuals.

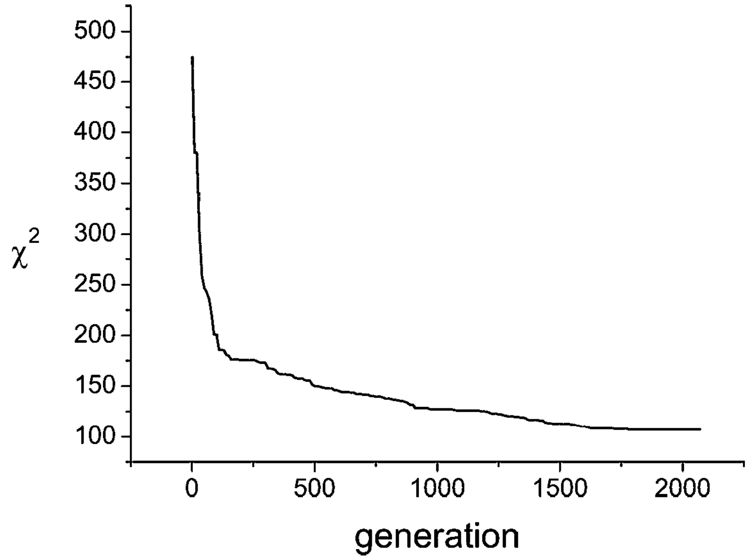

Fig. 1: Fitness as a function of the number of generations for a population of 500 individuals.

4 Line shape of $D\alpha$

We have used a GA [8] to fit Zeeman Dα/Hα spectra observed in Tore Supra, broadened by the Doppler effect. Both Dα and Hα spectra are calculated, since a small fraction of hydrogen is present in the edge plasma, and the two lines are generally visible and overlapping. The Hα line contributing the total emission with a varying proportion according to vessel conditioning and plasma parameters is integrated to the fitting procedure assuming it has the same line shape as Dα. Similarly to previously developed models [1, 2], our evaluation function retains several populations of neutrals [3]: cold neutrals resulting from the dissociation of molecules desorbed from the surface, warm neutrals obtained by charge exchange with the plasma ions. In the case of asymmetric spectra, we also add a population of reflected atoms, which is directed toward the spectrometer. Considering that each of these populations leads to a Gaussian line shape (except the reflected atoms assumed to have a half gaussian distribution) with a different temperature, we are thus a priori left with the determination of temperatures and relative fractions of several populations. The fitting procedure can be used to investigate the relevance of the choice of the number of populations retained. The number of populations identified by the GA fit can usually easily be detected since the addition of an unnecessary population does not significantly change the fitness parameter. Since the line shape is broadened by Doppler effect, the profile of a Zeeman component is proportional to the sum of the velocity distribution function for each population, each of them weighed by its relative fraction a_k. The magnetic field splits the atomic levels, and introduces a dependency of the line shape with regard to the line of sight. Using the Doppler profile of the k^{th} population $L_{D,k}$, the line shape may be written as a sum over the number of populations retained:

$$L(\omega) = \sum_k a_k \sum_{i,f,j} L_{D,k}(\omega - \omega_{if}) |\vec{\epsilon}_j . \vec{D}_{if}|^2, \quad (2)$$

where the second sum is over all the initial i and final f states of the Zeeman-split radiative transition, and over the two polarization vectors $\vec{e}_j (j = 1, 2)$ belonging to a plane perpendicular to the wave vector of the observed radiation. $\vec{D}_{if}$ is the emitters dipole element between states i and f. For the conditions of the edge plasma of Tore-Supra, the fine structure of $D\alpha$ may be neglected, and the line consists in general of a central component π, and two lateral σ components. Finally, our model includes a convolution with the instrumental profile of the spectrometer employed.

5 Application to the observation of $D\alpha$ spectra in Tore Supra

We have analyzed the spectra obtained from 2 different machine configurations, corresponding to : 1) Recycling from the ergodic divertor (ED), with lines of sight tangential to the magnetic field. 2) Recycling at the Toroidal Pumped Limiter (TPL) with vertical lines of sight nearly perpendicular to the magnetic field.

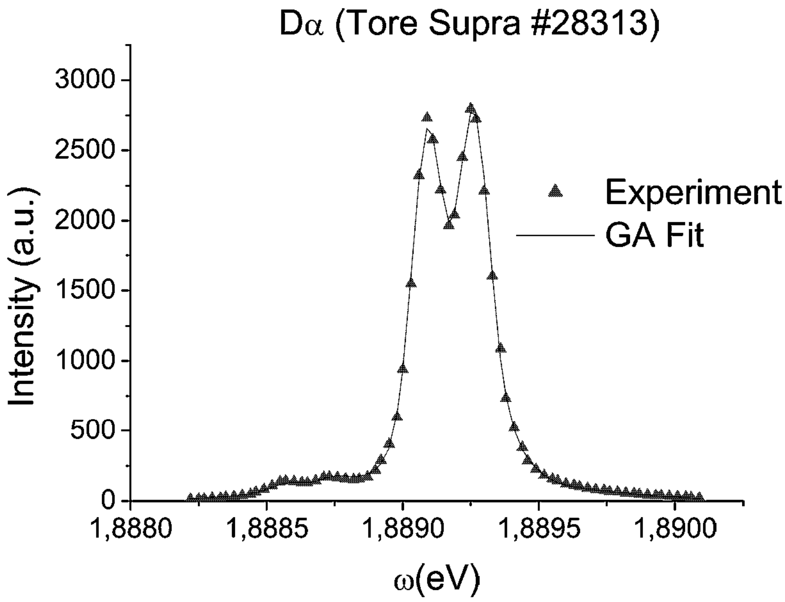

Fig. 2: Comparison of the experimental (Tore Supra shot #28313) and model profile of $D\alpha$ for a Tore Supra configuration using the ergodic divertor

5.1 Ergodic divertor configuration

Until the end of 1999, Tore Supra was equipped with a wall integrated ergodic divertor, a device concentrating the incident particle fluxes on cooled neutralizer plates. The spectroscopic measurements were done by telescopes directed tangentially along the magnetic field lines, and observing a hot spot of the edge plasma in the first 8 cm above the neutralizer plates. Most of the line shapes generally exhibit two nearly symmetric sigma components, and we present here the GA analysis of a line shape taken in the stationary phase of shot #28313, a typical ohmic discharge using the ergodic divertor. The fit shown on figure 2 uses the typical GA tunings described previously. The corresponding set of parameters is the following: a fraction of 52 percent of cold atoms with a kinetic temperature of 1.5 eV, plus 18 percent at 6 eV, a warmer charge-exchange population fraction of 18 percent at 96 eV, and 12 percent of a reflected neutral population at 9 eV. A cold neutral population fraction of 50 percent or more has been found previously [1, 3] for such ergodic divertor or axisymmetric divertor edge plasmas, and our GA algorithm thus confirms these early fits performed with classical optimization methods. The existence of several cold atom populations is consistent with the knowledge of more than ten molecular dissociation processes leaving the resulting atoms in a well defined kinetic energy between 0.3 and 7.8 eV [1]. The fit is clearly improved if a population with a blue shifted VDF is included in the model. Such a population corresponds to neutrals reflected toward the line of sight. We have used for its modelling an initial half-Maxwellian VDF, undergoing a relaxation due to elastic collisions with ions [3]. The last population determined by the GA fit is a warm population at 96 eV, probably resulting from charge exchange reactions. The temperature and fraction of this population are mainly determined by the line wings of the line shape. One thus should not exclude that a non maxwellian tail behavior of the line shape could explain this observation. Work is in progress for determining the line shape resulting from the emission in an edge plasma with strongly fluctuating parameters [9].

5.2 Toroidal Pumped Limiter configuration

In the TPL configuration, the line of sight is nearly vertical and perpendicular to the TPL surface. A polarizer is used in an attempt to remove the sigma components, but since the line of sight is not exactly perpendicular to the magnetic field, a small contribution of these components is seen on the spectra, and has been taken into account in the modelling. The spectrum analyzed is taken in a reference ohmic shot (shot 30459), belonging to the 2002 campaign which included long duration shots of more than 4 minutes. A convolution with the slightly asymmetric apparatus function is included in the modelling. Even after this convolution has been performed, the analysis reveals that an additional asymmetry affects the line shape. We thus have added a reflected neutral population which has significantly improved the fit. The following populations are determined by the GA: 32 percent of cold atoms at 2 eV, 24 percent of charge exchange atoms at 35 eV, 19 percent of reflected atoms at 62 eV, and 25 percent of charge exchange atoms at 495 eV. The analysis of other shots confirms that a significant fraction of neutrals with a kinetic temperature of several hundred eV is predicted by the GA, if a gaussian distribution is assumed. Again the existence of a gaussian profile at several hundred eV may be questioned in the light of the studies in progress on non maxwellian line shapes due to the fluctuations of plasma parameters.

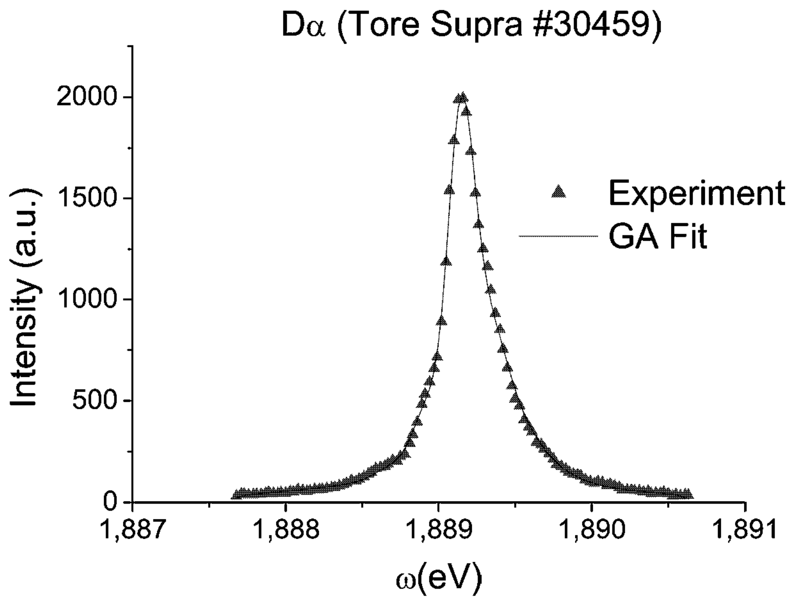

Fig. 3: Comparison of the experimental (Tore Supra shot 30459) and model profile of $D\alpha$ for a Tore Supra configuration using the Toroidal Pumped Limiter

6 Conclusion

We have investigated the possibility of using genetic algorithms for analyzing the spectra emitted in edge plasmas. GA are robust and versatile optimization methods which can find a global solution in a complex parameter space. They also have the property of being easily adapted to parallel calculation, which makes them suitable even for CPU-intensive problems. We have used this method for analyzing the different neutral populations present in the plasma edge near the ergodic divertor or toroidal pumped limiter of the Tore Supra Tokamak. This can be achieved by fitting the observed $D\alpha$ spectra to a Zeeman-Doppler line shape model including the contribution of several populations of neutral emitters. Using the GA fit, the neutral emitters are separated into up to 4 populations which can be identified as resulting from molecular dissociation reactions, charge exchange, or reflection. In all the edge plasmas studied, a significant fraction of neutrals emit in the line wings, leading to neutrals with a temperature up to a few hundred eV if a Gaussian line shape is assumed. This conclusion could be modified if the line wing exhibits a non Gaussian behavior. In another work we will thus analyze how the plasmas fluctuations due to low frequency turbulence may affect a line wing.

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