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A new approach to the solution of the vacuum magnetic problem in fusion machines

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Abstract

The magnetic vacuum topology reconstruction using magnetic measurements is essential in controlling and understanding plasmas produced in magnetic confinement fusion devices. In a wide range of cases, the instruments used to approach the problem have been designed for a specific machine and to solve a specific plasma model.

Recently, a new approach has been used for developing new magnetic software called FELIX. The adopted solution in the design allows the use of the software not only at JET but also at other machines.

In order to reduce the analysis and debugging time the software has been designed with modularity and platform independence in mind. This results in a large portability and in particular it allows using the same code both offline and in real-time.

One of the main aspects of the tool is its capability to solve different plasma models of current distribution. Thanks to this feature, in order to improve the plasma magnetic reconstruction in real-time, a set of different models has been run using FELIX.

FELIX is presently running at JET in different real-time analysis and control systems that need vacuum magnetic topology.

Keywords: Vacuum magnetic problem solution; Machine independent

1. Introduction

For an optimum control of a tokamak discharge an accurate evaluation of the plasma parameters needs to be performed. One of the main objectives is the identification, with high accuracy, of the plasma boundary.

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The control of the vertical position and the shape of the plasma, for example, requires precise plasma boundary geometric parameters including *x*-point (upper and lower in case of quasi double null configuration), strike-points (separatrix crossing position in the divertor region) and gaps (distance between vessel and plasma boundary). High time resolution in the reconstruction is also required due to the dynamics of the plasma evolution.

Usually the design of the algorithms and codes is strongly machine dependent allowing their use only for a specific machine. A different point of view has been adopted in order to develop a set of tokamak independent tools without any specific JET information embedded. All the needed data are stored in a configuration database where a clear detailed model of the tokamak is provided. Then this database is used to build the real-time application.

A new code sort called FELIX has been recently developed. FELIX is a collection of tools that allows a real-time code to be constructed from the description of a tokamak.

The first section shows how the magnetic problem for a generic machine can be addressed. The second focuses on the real-time codes aspects of the algorithm. In the third some examples of the models implemented for the JET plasma boundary are reported.

2. Magnetic problem approach

A machine-oriented approach has been removed from the design of FELIX. The idea of developing a simple machine-independent instrument for solving the problem of magnetic reconstruction has resulted in a collection of hierarchical databases implemented on computer files using a human readable syntax. The function performed by the algorithm is completely determined by the information contained in three databases: Machine Configuration File (MCF), Program Configuration File (PCF) and Transitional Configuration File (TCF).

FELIX can be considered as a collection of algorithms able to move from the description of the machine contained in the databases into a runnable program.

2.1. Machine Configuration File, MCF

The main database, called Machine Configuration File, includes a detailed description of a machine from the magnetic point of view. The geometry of the electro-magnetic elements of a machine in addition to information about how the power supplies, the coils and any external discrete components are connected to form the circuits, are collected in the database. The plasma geometry parameters to be reconstructed, such as the definition of gaps, are also part of the stored information.

The MCF database is organised into groups:

- Elements: concentrated elements, generators, combined coils, etc.
- Circuits: the connection between elements of the tokamak circuits.
- Geometry: elements and structures of the machine.
- Plasma: measurements of the plasma geometry.

Each group includes a collection of objects described by a given set of rules in a script language fashion. An example is shown in Fig. 1 where the

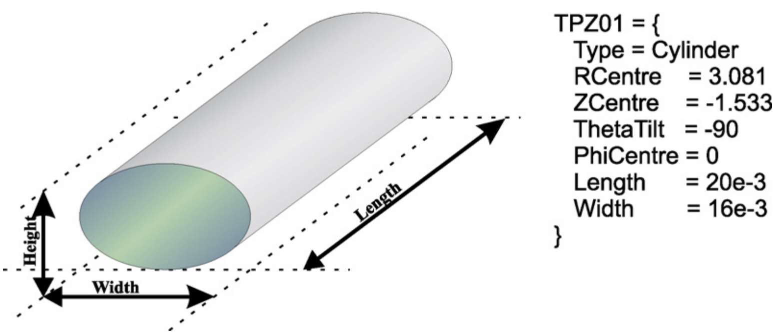

Fig. 1. Coil model approximation and equivalent description using the rules adopted in the MCF Geometry group.

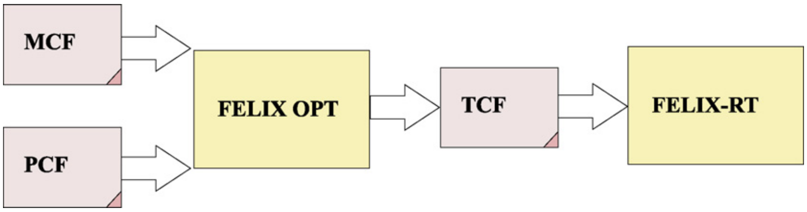

Fig. 2. Connections between MCF, PCF and TCF.

approximate implementation of a JET divertor coil is shown together with the MCF description.

The MCF database includes not only the entire magnetic description of the machine but also the models developed to solve different magnetic problems. Different boundary reconstruction algorithms or even equilibrium reconstruction models could be included in the MCF.

It is clear that the adopted set of rules in the structure of the MCF is not machine-dependent. Any fusion machine could be represented using the objects contained in the database. Presently an MCF for JET is available and extensively used.

2.2. *Program Configuration File, PCF*

In order to avoid writing different code for each application, the instruction of what computations are needed is contained in the Program Configuration File. Starting from the MCF database the user chooses what inputs are needed to drive the system, whether the plasma is present and which model is used for its representation, what passive structures have to be included and which method is used to describe them, what model of a circuit to use and what are the results to generate. All this information is stored in the PCF.

The database is structured in the same way as the MCF organising the information into groups:

- CodeInputs: defines the inputs available to the code.
- CodeOutputs: the choice of currents, voltages, fluxes, fields, gaps for the outputs.
- Components: the lists of elements of Circuits and of Plasma to be activated.
- Link: enables the link between calculations.
- Signals: inputs, outputs and links.

2.3. *Transitional Configuration File, TCF*

The last database, Transitional Configuration File, allows the implementation of FELIX as an embedded program. FELIX real-time (FELIX-RT) uses TCF as input in order to execute the listed computations. The database contains the results of the analysis and optimisation algorithms, FELIX-Opt, in a form that simplifies the implementation of the real-time code.

In order to be consistent with the other databases and because some of the information contained in the MCF and PCF are directly moved into the TCF the same organisation in groups is adopted:

- Checks: before executing the code.
- Dynamic: describes the dynamic states and the matrices needed to update them.
- Coefficients: describes the coefficients needed to calculate magnetic flux and fields.
- Outputs: describes some of the outputs as linear combinations of inputs.
- Base: the description of the bases used for the magnetic flux.
- Regions: the set of bases for each region.
- Plasma: measurements of the plasma geometry.

The scheme in Fig. 2 shows the links between the three identified configuration files. From the MCF (machine description) and PCF (choice between different models and solutions in the MCF), applying an optimisation, the TCF (independent by the specific machine) is prepared to be loaded and executed by FELIX-RT.

3. FELIX real-time

The design of the FELIX real-time reflects the philosophy adopted in the design of MCF, PCF and TCF.

The algorithm recovers all the needed information from the TCF.

The code is able to interpret the TCF and build all the objects contained. Then the objects chain is executed in sequence.

The code is essentially divided into two parts. The first part takes care of the modelling of the magnetic field by executing the objects described in the Dynamic, Coefficients and Outputs groups. The code implements a set of linear operations between elements as specified by the entries of the TCF. Some of the calculations upgrade the estimate of the currents in the passive structures and in the circuits, some produce a list of coefficients to be used to calculate the vacuum field, others calculate outputs that are linearly dependent to the inputs and statuses (such as currents voltages fields and fluxes).

The second part derives the plasma shape information requested in the Plasma group starting from the last closed surface of the magnetic flux.

There may be conditions to the validity of the adopted model for the magnetic flux map. For instance, the plasma centre might need to be contained within a certain area or the plasma current should be higher than a threshold. These values are specified in the TCF as checks (Checks group) to be performed on a selection of entries before any other computation is executed. If any check fails, the application will report the exception and an action is taken.

Many of the objects within the Plasma group require calculating the flux or the field on a large number of points. This process is accelerated by decomposing the magnetic field in a number of vectors and providing the weights to these vectors as output of the Coefficients group calculation. Most of the computation complexity is moved into calculating the value of these vectors in the desired locations of the poloidal plane. This job is performed once by the FELIX-RT initialisation routine which processes first the Regions and Base sections and then provides the pre-calculated vectors in each point of the poloidal plane required by any of the Geometry group objects.

A large number of plasma topology objects can be solved by FELIX like XPoint (*x*-point identification), Limiter (plasma touching vessel position), Boundary (plasma boundary identification), Gap/StrikePoint (given a geometric path identify the intersection with the plasma boundary), Probe (calculate flux or field in a given set of locations) and Saddle (calculate the flux for a saddle coil structure).

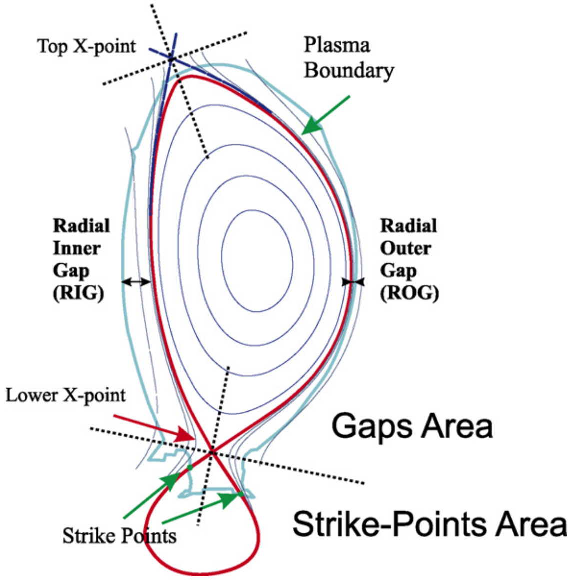

Fig. 3. Plasma geometry identification. *x*-Points top and lower, gaps, strike points are some of the objects identified by Felix.

Particular attention has been given to the design of the objects in order to obtain more precise results compared to the previous version of the reconstruction algorithm, called XLOC [1], that FELIX-RT is now going to replace.

One of the most interesting improvements is in the calculation of the rotation angle of the axes of the saddle point relating to the *x*-point allowing to separate the poloidal plasma section into two zones, below and above the *x*-point. With this information it is possible to calculate gaps or strike-points in the proximity of the *x*-point without the risk of identifying the wrong boundary cross flux, see Fig. 3.

Another improvement has been obtained in the *x*-point identification. This is a 2D minimum problem that is solved in XLOC using the Newton–Raphson method. Unfortunately that method requires the evaluation of the flux in arbitrary positions that cannot be pre-calculated increasing the elaboration time.

In order to improve the performance a new method has been tested. A pre-calculated grid provides the magnetic flux or field map in a area where the *x*-point is possibly located. Using the Steepest Descent method on the two components of the poloidal field, the *x*-point location is determined in the grid. At that point a polynomial with order of 3 or 4 is used to interpolate the flux around the *x*-point allowing the calculation of the co-ordinates in analytical form. This new method gives good results in terms of speed while giving at the same time accurate estimates.

The connections between inputs, outputs and status are implemented using entry names. All the signals are stored on a single user provided structure called Dynamic Data Buffer (DDB), where all the code objects have access.

This design, as will be shown in the next paragraph, introduces a high degree of flexibility in the code, allowing the use of the same algorithm in many applications.

3.1. Software design

The recent development of the real-time system at JET has required a redesign of XLOC [2] so that it could be used as a component of the many real-time codes such as Shape Controller [3], Walls protection system [4], BetaLi [3] or QProfile [3]. XLOC was therefore transformed into a modular object oriented code, more flexibility was introduced and, as a result, many copies are operating in real-time at JET.

FELIX-RT is replacing XLOC and has been designed with the same object-oriented approach but with a new concept in the applications development. FELIX-RT is now part of a collection of real-time codes, called the Generic Application Module (GAM), that can be connected all together to build an entire application. The links between GAMs are guaranteed by entry signal names. The DDB database stores all inputs, outputs and intermediate data provided by the GAMs, as FELIX-RT itself does.

Each algorithm, GAM, is inserted in the execution chain after extensive testing to reduce the possibility of errors and, consequently, reduce the debugging time. Moreover, because each GAM works using a configuration file, any change does not imply the recompilation of the entire application.

FELIX-RT, as many other GAMs, is written in C++ and can be compiled for different platforms (Windows, LINUX, SOLARIX, VxWorks). Given the configuration files, the application runs in the same way in all different platforms. This feature allows the testing and debugging of the application on a non-real-time system.

Even if the application is not a unique embedded code the adopted implementation does not significantly compromise the speed needed for the real-time applications. In fact, the FELIX-RT elaboration time is comparable to the old XLOC.

4. Magnetic models

The magnetic boundary of a plasma can be identified by solving the Grad-Shafranov equation. A general approach consists of solving the entire equilibrium equation, while a second approach solves the problem only in the vacuum region. In this section a few methods that implement the second approach are described.

4.1. Taylor expansion models

As mentioned previously FELIX-RT is replacing XLOC code. For that purpose a proper TCF has been prepared in order to allow FELIX-RT to implement the same plasma model.

In XLOC the poloidal plane of the machine is divided into five regions where a local Taylor polynomial expansion with a different expansion centre, is used to interpolate the flux outside the plasma. Applying the Grad-Shafranov condition in the vacuum region, the space of solutions is reduced to a set of combinations of its coefficients where only $\nabla \times B = 0$ (no current sources in the vacuum) is satisfied.

Each polynomial is fitted using different sets of magnetic measurements. The continuity between regions is assured by adding constraints, tie points, at the edge of the regions. In real-time the calculation of the magnetic flux around the plasma is reduced to a linear relation between the external measurements and the polynomial coefficients.

Thanks to the feature of FELIX-RT, a problem in the polynomial expansion has been identified in XLOC. Some combinations of coefficients were incorrect, introducing fake current sources able to corrupt the reconstruction details.

Starting from the MCF, a correct set of polynomials has been derived. Different orders of polynomial have been tested showing that the best compromise in terms of the level of accuracy and computational time is with an 11 order expansion.

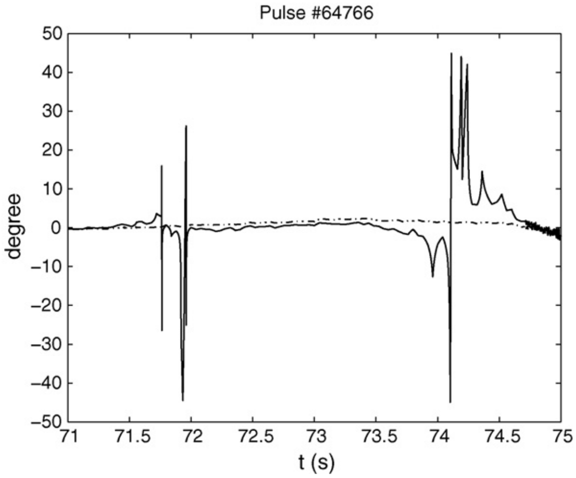

Fig. 4. x-Point rotation angle. Old model XLOC (—) and new expansion model (– · –).

A clear indication of the improvement from the new polynomial expansion, can be seen in Fig. 4, where the comparison between the XLOC based model and new corrected model rotation angles of the x-point is shown.

4.2. Filamentary based model (I)

For more than 10 years of use at JET the XLOC code has shown a high level of reliability and a good behaviour in case of sensor failure. On the other hand, the code has shown an inability of reconstruct the shape accurately for smaller plasmas, and during fast events.

In order to improve the reconstruction under all plasma conditions an alternative plasma model has been implement by introducing a number of current filaments to describe the plasma [5]. In this condition, even if the real plasma distribution is different, outside the boundary the magnetic field produced by the model can be practically indistinguishable.

If the external field sources are well known, the portion of magnetic measurements due to the plasma current can be easily obtained by subtracting the component due the poloidal magnetic field coils. In JET the presence of an important iron structure makes this approach impossible.

Given the measurement of both components of the magnetic field on a closed line surrounding the plasma section on the poloidal plane, it is possible to separate the contribution of the magnetic field due to the plasma

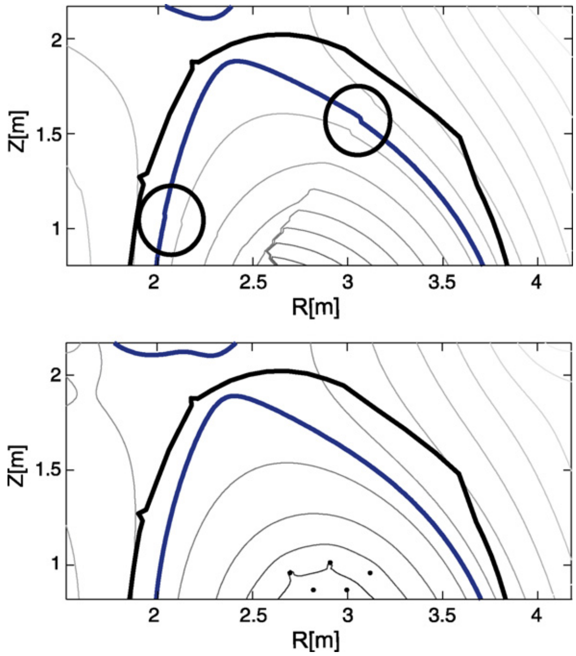

Fig. 5. Comparison between Taylor expansion model (left) and filamentary model (right) boundary reconstructions.

(and other possible internal sources, such as the divertor coils) from that produced by any external source. The current moment method [6] is used to solve the problem.

The currents in the plasma filaments and iron are calculated using consecutive corrections. Starting from the main plasma moments identified by using the magnetic measurements, the plasma current is smoothly distributed between the set of plasma filaments. The measurements are then recalculated, using the plasma filaments and the current in the poloidal circuits, and compared with the real ones. The resulting differences are distributed between the iron filaments. This linear process allows the calculation of the current in the filaments from the product of a matrix and the external measurements. This model can be translated in the TCF language allowing FELIX-RT to solve the algorithm in real-time.

An example of the results obtained using this model approach is reported in Fig. 5. The boundary identified by using XLOC is compared with the boundary obtained with the filamentary model. The improvement in the shape, in particular in the area of connection between the XLOC regions, is clear.

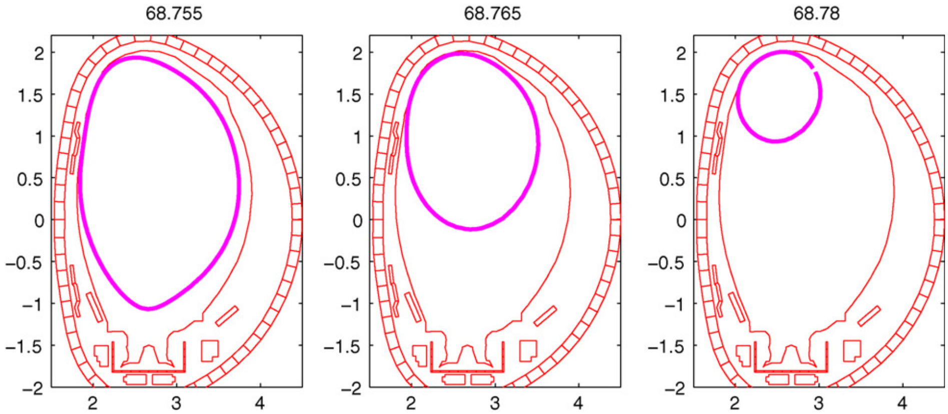

Fig. 6. Reconstruction of the evolution of the plasma shape during a disruption obtained using the CREATE model.

4.3. Filamentary based model (II)

A similar filamentary approach has been developed using a different method to approximate the iron and the passive structure.

The CREATE-MSW tools [7] incorporate a linearised iron model, eddy current model in the state-space form and a plasma model as a set of fixed filaments carrying currents obtained as linear combinations of plasma current moments (measured as linear combinations of magnetic signals). As in the model of Section 4.2, the solution is reduced to a single matrix that links magnetic measurements and current in the poloidal circuits with plasma and iron filaments.

One of the main features with this tool is the ability to identify models using very few filaments for the plasma approximation not present in the approach described in the previous section. It could be helpful for the plasma reconstruction in all the plasma phases. The plasma shape control could be applied even during the start-up phase of the discharge or during disruptions phase as illustrated in Fig. 6.

FELIX-RT is able to switch from one model to the other as a function of the plasma position.

5. Conclusion

Recent developments in the magnetic vacuum reconstruction, in particular for real-time control, have been reported in this paper. An innovative approach, FELIX, allows instruments for many tokamak machines to be provided. A set of well-formulated machine-independent rules allow the creation of a database describing any tokamak from the electromagnetic point of view. The collected information is then the starting point for the initialisation of the real-time code FELIX-RT.

Thanks to the features of FELIX, different solutions for the boundary reconstruction, polynomial and filamentary based models, have been tested.

A few improvements have been obtained in the plasma geometry identification and some new solutions for increasing the performance and the accuracy in the results are still under test. A new x-point identification algorithm has been developed and a new strategy in the gaps/strike-points calculation is currently under investigation. A smooth transition between limiter, single null and double null configurations, more accurate gap and strike-point calculations and detailed boundary reconstruction are now systematically available.

A flexible approach to the magnetic reconstruction, together with the modular design of real-time codes has been demonstrated recently by using FELIX in a large number of real-time applications at JET.

In the near future this innovative instrument will be tested in other machines. Solutions for FTU [8] and RFX [9] are under development.

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