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ABSTRACT.
A new Magnetic Diagnostics system has been designed for the 2005 JET experimental campaigns onward. The system, which is integrated into the existing Magnetic Diagnostics, consists of in-vessel and ex-vessel sensors, and is intended to provide an improvement in the accuracy and reliability of the present equilibrium reconstruction and iron modelling capabilities [1]. In this paper the ex-vessel system is described, which consists of an array of pick-up coils, Hall probes and flux-loops probes to be installed in the proximity of the upper horizontal iron limbs and inside the iron collar. The sensors are designed to produce an absolute measurement of the magnetic field configuration in the vicinity of the magnetic structure of the machine, which is considered valuable information for the tuning of the axisymmetric models used for plasma equilibrium reconstruction. On the basis of recent results obtained with Hall probe prototypes on JET, the choice of type and location of probes, together with other design and manufacturing issues of the ex-Vessel magnetic diagnostics are presented and discussed.

1. INTRODUCTION

In the framework of the JET EP Magnetic diagnostics enhancements, the new ex-vessel sensors are mainly intended to provide information useful for the improvement of the equilibrium reconstruction by providing a better description of the effects of the iron transformer core. The design activity is conducted in collaboration between the Association EURATOM-ENEA and the JET Operator.

2. RATIONALE AND DESIGN CONCEPTS

The equilibrium reconstruction codes for JET necessarily include an axisymmetric iron core model, whose accuracy directly affects the accuracy of the reconstruction. In fact, the equivalent axisymmetric iron model so far has been based only on simplified assumptions on the geometry and magnetic properties of the iron structure. On the basis of the available measurements (local and axisymmetric), the quantification of the errors related to the use of an axisymmetric iron model does not appear to be obvious, even though there are several qualitative hints, such as the evident instability of the reconstruction in some plasma configurations, that indicate that the error is not negligible.

The new system of ex-vessel magnetic sensors has been designed in order to provide specific information useful for the improvement of the iron core model, namely:

- axisymmetric effects on the magnetic flux pattern due to the non-linear or hysteresis effects of the iron core (initial magnetization and saturation);
- local non-axisymmetric effects on the magnetic field distribution (stray magnetic field), which are produced in the surrounding area by the partial saturation of the iron core.

Since both effects are related to the residual magnetization of the iron core and also to the initial current in the PF coils driven by the flywheel generator, the ex-vessel probe system necessarily requires an absolute measurement of the magnetic field existing at the beginning of the plasma pulse.

For this particular reason, the ex-vessel sensor system design consists of a number of Hall sensors, complemented by “local” pick-up coils and “octant average” flux loops. All these sensors are supported by rails to be attached to the iron core structure. There are in total 13 new sensors grouped in 2 subsystems, named Collar probes and Limb probes, respectively.

3. GENERAL DESIGN CHOICES AND SENSOR CHARACTERISTICS

The system consists of two different subsystems: Limb and Collar probes (Fig.1 and 2). The Limb subsystem is intended to provide the measurement of the vertical component of the magnetic field in the vicinity of the lower surface of the upper horizontal Limb and is constituted by three supporting rails, each equipped with three different sensors: a flux loops, a pick-up coil and a Hall sensor.

The three rails are symmetrical with respect to the limb and span over 1/8 of the machine along the toroidal direction, and are attached to the limb at 3 different radial positions so that the radial variation of the vertical field can be measured. The flux loops measure the average vertical field over 1/8 of the machine in the toroidal direction and 40mm in the radial direction, the pick-up coils and the Hall sensors are located on the lower surface of the limb, so as to measure the stray vertical field leaking out of the iron.

The Collar subsystem consists of two pick-up coils and two Hall sensors, located symmetrically in the space between two TF coils and attached to the bottom end of a 2m long support beam, which will be inserted in a vertical hole already existing in the iron structure (also called “iron shoe”) of the machine. The collar probes will measure both the radial and the vertical components of the magnetic field leaking out of the “iron shoe”. Their location was chosen in order to reduce the disturbance due to the toroidal field ripple.

All the flux loops and the pick-up coils have to be connected to an active analogue integration circuit in order to produce a measurement of the magnetic field or flux. Since, in order to avoid the errors caused by integrator drift, the electronic circuit used for the signal integration needs to be zeroed at the beginning of each pulse, all the flux loops and the pick-up coils can only provide a measurement relative to the initial conditions. On the other hand, the absolute value of the initial magnetic field is not really known because of the residual magnetization of some parts of the JET iron core and also because of the initial PF coil current, which is always produced by the flywheel generator at no excitation. The use of Hall sensors was therefore proposed to fill this lack of information.

The possible presence of offset or drift in Hall sensors measurements, and the consequent need of compensation, was a main concern; nevertheless with experimental tests (Section 3.2) it was verified that Hall sensors, when subjected to the typical JET working conditions, are not affected by drift on a time-scale of several months. For this reason, the Hall sensors do not need to be reset during their entire lifetime and can provide an absolute measurement if initially calibrated in a zero-flux chamber.

The Hall effect sensors are also useful during the pulse to correct those signals which are affected by the drift of the integrators and could have significant errors for low field measurement.

3.1 PROBES CHARACTERISTICS

To make the installation possible, each of the three flux loops is divided in three windings, adjacent along the toroidal direction, which will be connected in series by standard LEMO connectors. Each winding is made of enamelled copper wire sealed in the groove of a fibreglass rail. The area of the loops depends on the radial position, but the overall effective area of all the flux loops is made close to $0.5m^2$ by using different number of turns.

The pick-up coils are made of copper conductor wound on a former made of Peek. In the Collar the radial and the vertical coils are wound onto a single former. Each pick-up coil has an equivalent area of $0.368m^2$. A rough estimation for the maximum derivative of the magnetic field is about 0.8T/0.01s, which would produce a voltage lower than 50V both for the flux loops and the pick-up coils.

Hall sensors and pick-up coils are placed in a single block of Peek. A 100mA current source supplies the Hall sensors assuring a long-term stability of 0.1%, which is directly related to the measurement precision. The Hall sensors are intended to measure constant fields, so their signals are sampled at low frequency (100Hz). They can measure from low field (0.1mT) to high field (3 T), but the residual magnetization of the iron core (some mT) is expected to produce low signal.

3.2 PRELIMINARY TESTS ON HALL SENSORS

A prototype sensor with four different kinds of Hall probes was installed close to the Limb surface during the campaigns from November 2003 to March 2004. The aim was to check the long-term performances and reliability of the absolute field measurements, by comparing the behaviour of different kinds of Hall sensors under real operating conditions.

Very few data were available on the use of Hall sensors near radioactive sources, since this is not a common application. The tests were designed to assess the long-term effects on the sensors due to ionising radiation produced by the plasma (neutrons and gammas) and the activation of mechanical structure, in terms of the sensitivity to low amplitude field, signal/noise ratio and drift of the sensors characteristics.

According to semiconductor theory, sensors with lower magnetic sensitivity are less affected by radiation damage. Therefore, a trade off between magnetic sensitivity and radiation hardness was required when measuring low amplitude fields, which demanded high sensitivity sensors.

The Hall sensors tested were made of Indium Arsenide, but were characterized by different measurement range and sensitivity [3, 4]:

Probe Type	Range	Sensitivity
HGT3010, BH900	10T	lower
BH701, BH200	1.0T	higher

Indium Arsenide semiconductor material is commonly used to manufacture Hall probes for general purposes, as it exhibits low noise, low temperature dependence of sensitivity, and low to medium sensitivity. Some data on the characterization of radiation effects on Hall sensors were found in [4] only for Indium Arsenide. All the sensors had a good linear response in the whole measurement range with an error less than 1.0% at full range, and even better for lower field (< 1T).

The presence of offset or drift was assessed, since it affects directly the absolute value of the magnetic field. Two different contributions to the offset affect the measurements: the first one is related to the sensor itself and is due to manufacturing imperfections; the second one is caused by the electronic components of the acquisition system. Both effects were considered.

The residual magnetic field in the vicinity of coil P2U was measured "off pulses" (i.e. with no current in PF and TF coils) over a period of some months, using the four sensors. The curves are shown in fig.3. This proved that the drift of the four magnetic field measurement due to sensors and data acquisition over a period of several weeks was practically negligible. In fact the difference of the four measurements was less than 0.1mT over the period considered.

The probe type BH701 was considered the most suitable choice for future experiments at JET because it has enough sensitivity to measure the residual magnetization of the iron core. In fact, a field of less than 0.1 mT could be measured. BH200 has a higher sensitivity but it showed some difference in the offset declared by the manufacturer. BH701 has a magnetic sensitivity of about 10^{-2} V/T. The temperature coefficient of the magnetic sensitivity is about –0.04% °C.

4. CONSTRUCTION OF SENSORS AND SUPPORTS

The Limb sensors will be installed on fibreglass rails under Limb 3/4 in the upper part of the machine (fig.4). Suitable metal support brackets (AISI304) allow a tolerance recovery (±5mm) and a precise orientation of the sensors.

The supports of the flux loops are divided in three sections so they can be dismounted, if necessary, in order to free space in the octant.

The Collar probes are mounted at the bottom end of a fibreglass supporting beam of square cross-section and are located in the innermost port of octant 4, which is a blind port (fig.5). The probe position is chosen in order to avoid both the Toroidal field ripple and the local disturbance due to the hole in the iron shoe. The temperature in that area is not expected to exceed 80°C, which is the operating limit for the Hall sensors.

This is assured by the cooling of TF coils. However a temperature sensor is included, to compensate the temperature variation in the Hall sensors characteristics. The top of the rail has a fixing bracket, which allows a positioning tolerance of ±15mm. The position of the sensors is important because there is factor of ten between the amplitude of the radial and vertical field.

CONCLUSIONS

The peculiar requirements of the JET ex-vessel magnetic measurements have been met by a combination of specifically designed sensors. Local and space-averaged inductive sensors have been complemented with Hall sensors in order to obtain information on local and axisymmetric effects of the ferromagnetic core of the machine.

The tests already performed during the JET TTE campaign have demonstrated that the Hall sensors do not show significant drifts during several months of operation. Therefore the initial concerns regarding the long-term stability of the Hall sensors calibration in the JET environment have been overcome.

The layout and detailed design of one system has been completed. Duplication in a different part of the machine for redundancy is now being considered. The whole system will be installed by the end of 2004 and the new signals will be available during the 2005 campaign.

The new information supplied by the ex-vessel sensors will allow optimisation and evaluation of the accuracy of the equilibrium reconstruction codes by the development of a better equivalent axisymmetric model of the iron core.

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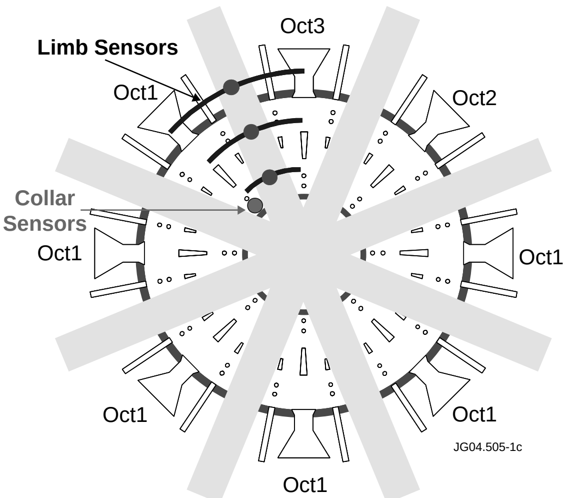

Figure 1: Upper view of the ex-vessel system.

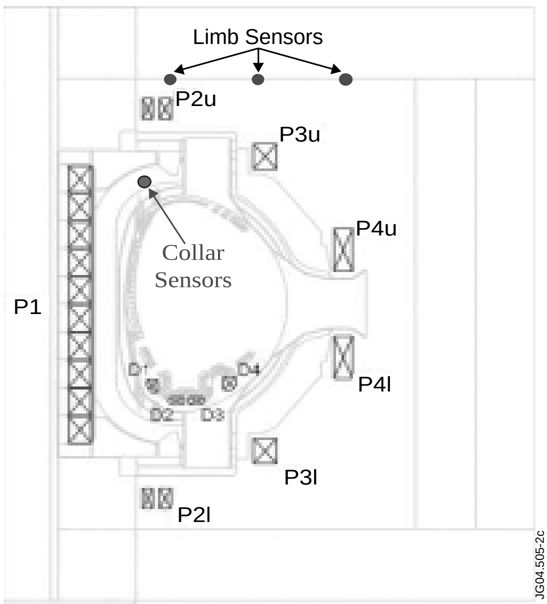

Figure 2: Location of the ex-vessel system, section view.

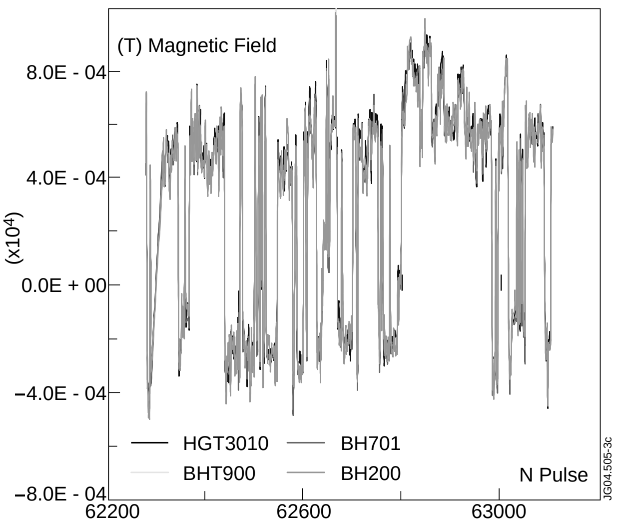

Figure 3: Measurements by 4 kinds of Hall sensors during three months (almost 1 thousand pulses).

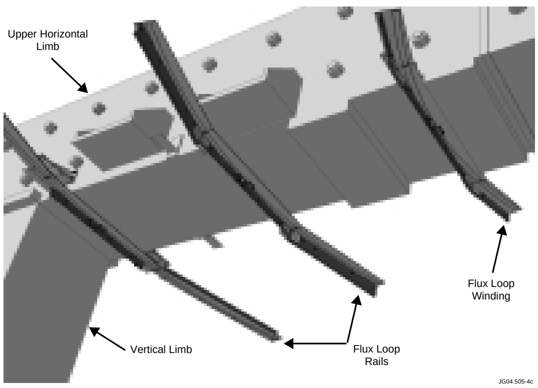

Figure 4: View of the Limb probes mounted under the Limb.

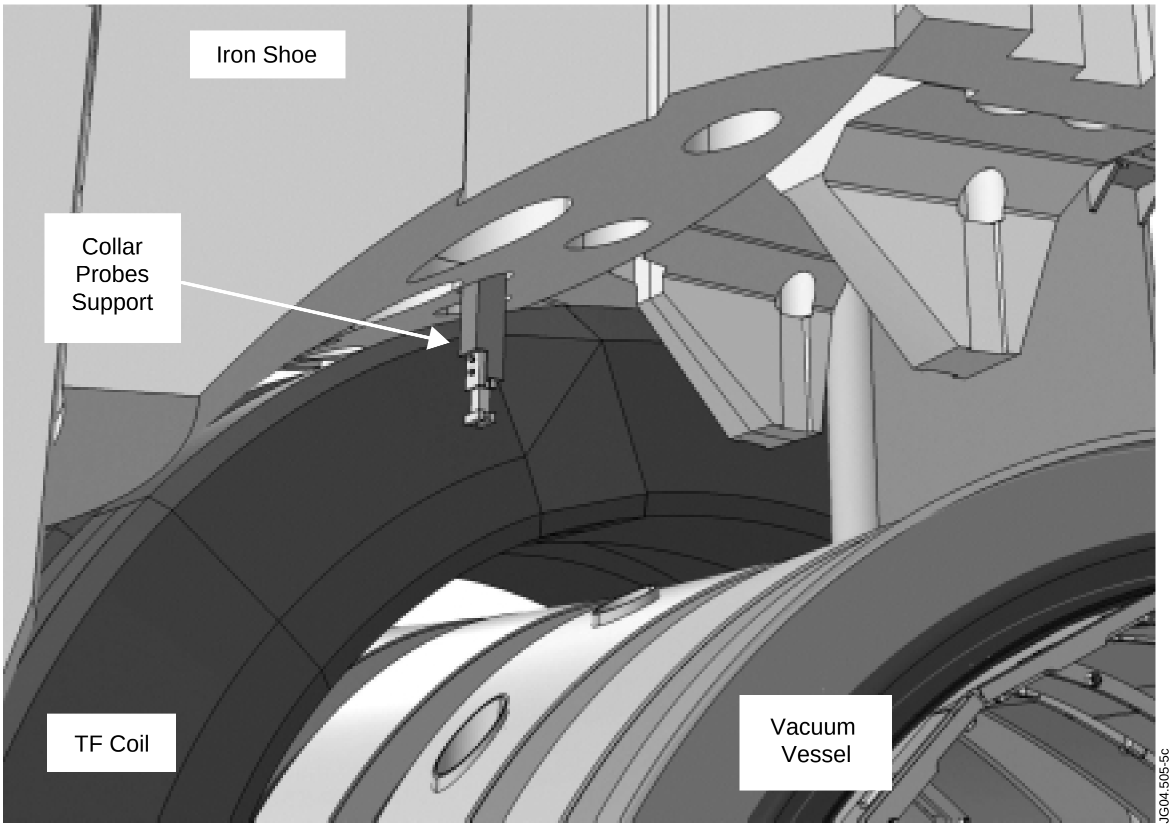

Figure 5: Bottom end of the Collar probes system.