CEFDA01-645

Task Title: TW2-TPHN-NBDES1: SUPPORT TO NEUTRAL BEAM PHYSICS AND TESTING 1

INTRODUCTION

The European concept for a 1 MeV, 40 A negative ion based accelerator for the neutral beam system on ITER, the SINgle GAP, SINGle APerture (SINGAP), is an attractive alternative to the ITER reference design, the so-called MAMuG (Multi-Aperture, Multi-Grid) accelerator. A prototype SINGAP accelerator has been used for several years and produced D^- beams of 910 keV, 30 A/m^2 [1]. The measured beam profiles on the target agreed well with those predicted by calculations. However certain design features of the prototype accelerator prevented the production of beams with the optical quality required for ITER [2], i.e. a beamlet divergence of ≤ 7 mrad and beamlet aiming within ±2 mrad of that specified. Therefore a new “ITER-like” accelerator has been designed and built in order to demonstrate that the beam optics required for ITER can be achieved with a SINGAP accelerator.

2005 ACTIVITIES

VOLTAGE HOLDING

940 kV were obtained without any breakdowns over a main acceleration gap of 350 mm. Gas was added to the vacuum tank in order to suppress the dark current [3]. The pressure needed was 0.07 Pa. This is higher than the predicted pressure of 0.03 Pa for ITER [4]. Higher voltages were not attempted in order to minimize the risk of breakdowns at higher voltages damaging the 1 MV power supply.

MODELING

Particle trajectories for the SINGAP ITER Neutral Beam System have been calculated and the overall conclusion is that it will be feasible to use SINGAP in ITER. One of the main advantages of using SINGAP is the possibility to perform on-axis and off-axis heating of ITER by simply displacing the grounded grid.

A sensitivity scan on the ITER SINGAP system was performed for different values of beam current, extraction voltage, pre-acceleration voltage and post acceleration voltage. The beam transmission was found to be relatively insensitive to changes of extraction voltage or pre-acceleration voltage. A small variation of the post acceleration voltage (≤ 5 %) is also found not to change the transmission considerably. However a change of 10 % of the current density gives a change in the transmission of 7 %. This is due to the relatively large change in space charge that goes with the change in current density. Because the kerb remains fixed, the beamlet divergence goes off. It is the beamlet steering and not the divergence of the individual beamlets that cause the transmitted power to drop rather rapidly.

The calculations were validated with dedicated experiments and were in general found to be correct. However two important issues that were found by experiments and that did not show up in any calculation were the flipping mode where the beam profile could easily change from a peaked profile to a hollow by simply change some parameters with a small amount and the relatively large halo.

EXPERIMENTS

The experimental campaign was performed initially with 3 apertures in the plasma grid. We quickly found a relatively low transmission of only 50-60 %. With the current limit of 100 mA from the MV power supply we had to reduce the number of apertures to 1 in order to have the possibility to perform high current density shots. Most experiments were therefore done in this configuration with a single aperture. The low transmission was traced down to be caused mainly by stripping losses and ionization of background gas. The maximum transmission achieved was 80 % but only with a low pressure in the accelerator and therefore a relatively low main acceleration voltage due to that the dark current cannot be suppressed at low gas pressures (figure 1).

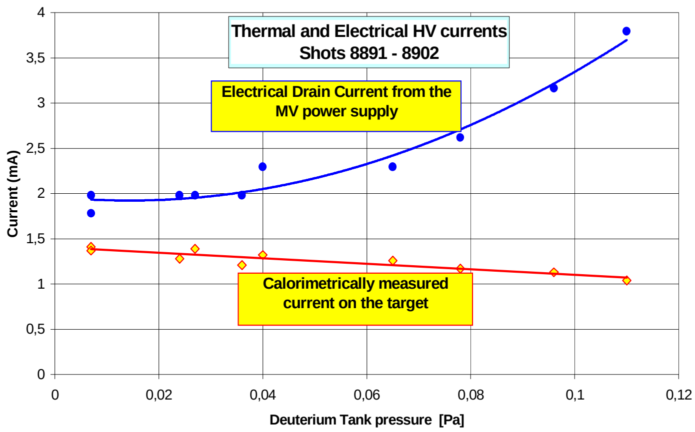

Figure 1: Electrical drain current and calorimetrically measured current vs. background D_2 pressure. The calorimetric current decreases with pressure and the drain current increases with pressure. The post-acceleration voltage was 225 kV and the magnetic suppression filter was present inside the anode

A measurement of the electron leakage through the extraction grid was performed using argon in the discharge instead of the usual deuterium. In this way no negative ions were produced but plenty of electrons. We found that for an extraction voltage of 1.6 kV only 1.7 ±0.4 % of the electrons leaked through the extraction grid. This corresponds well with calculations.

Originally a 3 mm extraction gap (distance between plasma grid and extraction grid) was chosen. With this gap, in the accelerator, we found two interesting features. Firstly we discovered that the beamlets have a bi-Gaussian power density distribution (70 % with a divergence of ≈4-5 mrad and 30 % with a halo) as opposed to the single Gaussian with 2.5 mrad divergence of the simulation. The fraction of the total power that is seen as a halo varies between 15 % while operating at low current densities without Cs to 30 % during caesiated high current density operation. Secondly we saw that the beamlet could flip between a peaked power density profile and a hollow density profile. The onset of the "flip-mode" could happen when small (≈10 %) changes in various parameters such as extraction voltage, bias and arc power were done. The reason for this is not fully understood (figure 2).

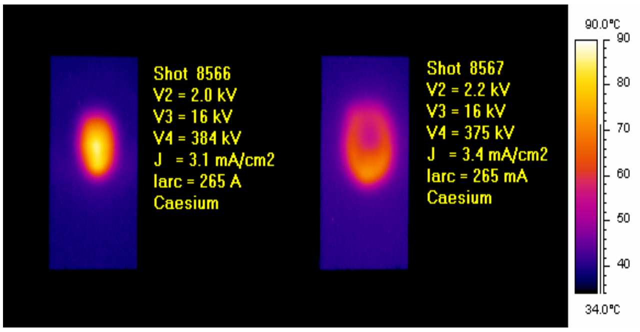

Figure 2: The thermal images of the target for two almost identical pulses. A small change in the extraction voltage V2 triggered a large change in the beamlet optics. The beam shifts from being peaked in shot 8566 to hollow in shot 856. The only difference between the two shots is the small increase of the extraction grid votage(V2) in shot 8567

After extending the extraction gap to 6 mm we discovered that the "flip-mode" disappeared, even when varying the extraction voltage, bias or the arc power within a relatively large range. However the fraction of the total power seen as a halo, did not change when the extraction gap was increased and the remained at 30 %.

The best performance that was obtained with the ITER-like accelerator was achieved with the extraction gap extended to 6 mm. It yielded in all respects very similar beam optics as with the 3 mm gap. The most important feature though was that it was now possible to increase the current density to 167 A/m^2 with deuterium. This is 67 % higher than previously achieved with any SINGAP configuration. This was done at 700 kV. The best performance ITER-relevant shot was pulse 9886 which had the following parameters:

- 727 keV, 120 A/m^2 D$^-$ =18.5 mA for one beamlet.
- 3.9 mrad horizontal divergence, 5.5 mrad vertical divergence
- 31 % halo

Attempts to run at higher voltages failed due to breakdowns in the main acceleration gap.
Only very limited experimental time has so far been done with the 6 mm extraction gap.

CONCLUSIONS

HV conditioning pulses have demonstrated that the "ITER-like" accelerator can hold 940 kV without breakdowns. D$^-$ beams have been produced with caesium at 580 keV with a current density of 150 A/m^2. The best ITER-relevant shot displayed good beam optics (3.9 mrad divergence horizontally, 5.5 mrad vertically) and was performed at 727 keV, 120 A/m^2 D$^-$ = 18.5 mA for one beamlet. This new record was achieved after the gap between the plasma grid and the extraction grid was increased from 3 mm to 6 mm. The quoted current densities are derived from the calorimetrically measured power on the graphite target with an infrared camera.

The experiments have so far confirmed some aspects of the design of the new "ITER-like" accelerator, but not all. In particular the experimental data show that the beamlets have a bi-Gaussian power density distribution (70% of the power can be described by a beamlet divergence of ≈4-5 mrad and 30% is in a halo) as opposed to the single Gaussian with 2.5 mrad divergence of the simulation. The fraction of the total power that is seen as a halo varies between 15% while operating at low current densities without Cs to 30% during caesiated high current density operation.

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CEFDA03-1129

Task Title: TW3-TPHI-ICRDES1: ITER ICRF ANTENNA AND MATCHING SYSTEM DESIGN

INTRODUCTION

The objective of the activity was to propose an update of the ITER ICRH system Reference Design. As part of this task [2] conduct on the electrical design of an ICH launcher based on an in-vessel tuning system, were completed by studies on matching control algorithm suitable for a fully automatic operation of the system, matching procedure, and systems regarding arc protection.

After a description of the general ITER-like structure scheme and its properties, this paper focuses on the description of the proposed upgrade and the consequences on the overall performance of the system, followed by briefs comments other topics such as the automatic array control strategy, matching procedure, arc detection and array protection, which are important aspect, part of in the design studies.

2005 ACTIVITIES

ITER-LIKE STRUCTURE (ILS) LAYOUT

Most of the Ion Cyclotron (IC) launchers currently used are simple toroidal arrays of two or four elements, powered and phased to determine a desired radiation pattern. In many systems, however, in the attempt of reducing the strap maximum voltage, the array elements are themselves binary poloidal arrays, with the two radiating elements (referred as straps) conductively connected by a simple T-junction and strip line connections. This type of layout tends to increase the overall inductance of the array elements and is strongly affected by changes in both bulk plasma loading and local conductivity between current and ground potential. This layout tends also to increase the overall inductance of the array elements, and does not allow a full vectorial control of the RF currents actually coupled to the plasma, which is affected by changes in both bulk plasma loading and local conductivity between current and ground potential.

In the Resonant Double Loop (RDL) structure [1] tuning elements are connected in series with the straps, the power division is resonantly obtained without artificially increasing the inductance of the system. This scheme presents the advantage to allow the vectorial control of the load currents. For this reason the RDL circuit was selected as basic array structure for the ITER IC array. In the ITER IC system design, the original RDL structure was modified as shown in figure 1, in order to achieve in addition, a significant resilience to fast resistive load variations, such as those due to ELMs [3]. In this electric scheme referred to as ITER-like structure (ILS), unlike in the original one, the input Voltage Standing Wave Ratio (VSWR) can be limited below a specific value, independent of resistive load variations, which depends on the circuit input resistance.

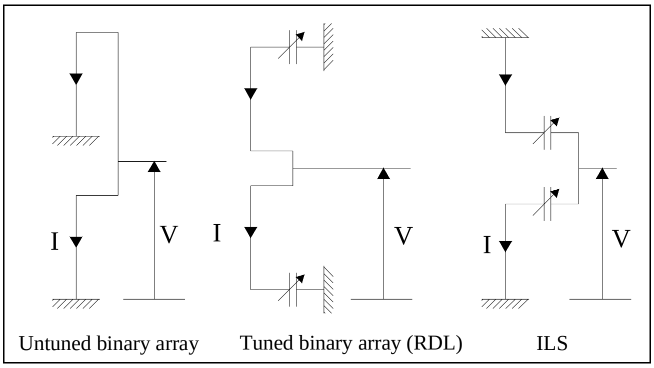

Figure 1: Types of array elements used in current IC H&CD systems

ARRAY LAYOUT

The array design update proposed are a simplification and an upgrade of the reference design keeping unchanged the general ILS scheme but with layout modifications allowing significant improvement of efficiency and reliability. The main objectives of the modification were to upgrade the array performance by improving the dielectric strength in most part of the array. These great simplifications of the array layout were also conducted with the idea to make the maintenance easier (in Hot cell and possibly in situ), and to reduce cost and all aspect related to waste management.

The first modification proposed is the increase of the poloidal order from eight to twelve ILS. This change was possible thanks to the modification of the geometry of the tuning system and Vacuum Transmission Line (VTL) and to the change the strap layout and position of the short circuit of the mid plane ILS.

The new strap layout with the short circuit in the mid-plan on the ILS has some potential advantage compared with the geometry of the RD. This configuration allows a more compact layout for the antenna housing, an improved symmetry in the strap loops, independent of the first wall profile, and shorter strap feeder. 3D FEM modelling also suggest that the toroidal components of the currents in the plasma facing components of the array at ground potential are also reduced. This feature is in general beneficial in order to minimize sheaths potentials [4].

In the FDR design, the tuning elements considered consist of a short-circuited (SC) stub tuner, which poses a number of unresolved issues related to its dimensions, actuation and voltage stand off. The replacement of this long short circuited structure using high current, sliding contacts operating in severe environment by a tuning component consisting on a compact variable Open Circuit (OC) transmission line is proposed. On figure 2b, the layout of the tuning network for one IL structure, as proposed in the FDR, with tuning stubs and coaxial chokes is sketched. These chokes can be eliminated if the tuning stubs are accommodated in re-entrant cavities in the VTL (as shown in figure 2a), now providing itself the necessary decoupling of the tuning stubs from ground potential and leading to a significant reduction of the space requirements. The VTL features now an elongated cross section: as in both designs the VTL is the first stage of a multi sections, λ/4 transformer, it can be reduced to a standard circular cross section in one stage transition.

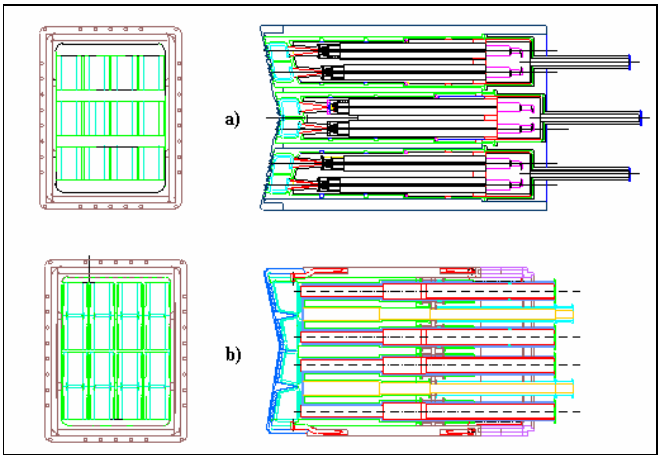

Figure 2: Proposed updates:
a) updated design
b) reference design

The OC stub would be submitted to the same voltage distribution along its length as the SC stub reaching a maximum value at the open circuit. In order to further improve the overall dielectric strength in the tuning system, the basic idea is to isolate from the torus vacuum the volume within the port plug where the voltages are the highest. The use of dielectric enclosures consisting in ceramic septa (figure 3) appears to be viable way to proceed. These dielectric septa should however be sufficiently shielded from neutron flux so that mechanical and dielectric degradation of the ceramic material minimized. In this localised private vacuum, additional pumping will allow to strongly improve the dielectric strength with comparison to the unpredictable torus vacuum. This vacuum barrier close to the first wall also permits maintenance of equipment physically located in the port plug, during machine shutdown periods, without the need of venting the torus. However in any case these ceramic components have neither tritium containment nor machine safety functions, which are assigned to other dielectrics components of the same type, positioned in locations within the port plug, where the neutron flux and fluence are reduced to a negligible value.

Based on the above changes, a simpler, more compact modular tuning system can be designed, completely enclosed in the port plug, without modifying any interface with vacuum vessel, blanket or other ITER subsystems and vacuum/tritium boundaries.

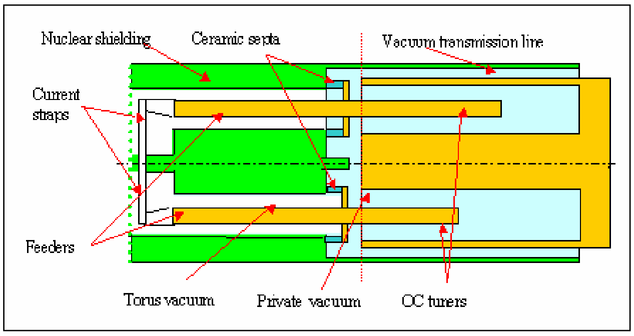

Figure 3: Sketch of a tuned ILS according to the proposed changes

AUTOMATIC ARRAY CONTROL STRATEGY, MATCHING PROCEDURE, ARC DETECTION AND ARRAY PROTECTION

The studies highlight the fact that automatic control of the array is a crucial question to be addressed in the design studies. The match conditions in the relatively complex poloidal/toroidal array such as the ITER IC launcher are affected by inter element coupling and asymmetries. A tight control of the array current pattern is an essential requisite for controlling the power flow in an array of inductively coupled elements fed by multiple sources.

A detailed matching procedure is also an important issue to consider. Therefore a strategy to electrically characterize the array elements on a reproducible load (air and/or vacuum), prior to plasma operation was studied. The low losses under this loading condition ensure all control loops to operate at their maximum gain and possible servo instabilities can be readily detected. This electrical characterization aims at establishing reproducible initial condition for the control loops.

As important as the matching procedure and the array control, the arc detection and array protection is an essential control function, especially in ITER, where: breakdown damage in the plasma facing components may result in leaks of coolant, repairs of breakdown damage in such components would require in any case the replacement of the whole array or array module. In any case the consequences will remain severe and may lead to long shut down implying venting of the torus. It is therefore essential for any RF arc, consequent to a voltage breakdown, to be rapidly identified against fast load variations, detected and extinguished before leading to non negligible damage. The method used in current system is unsuitable for reliably discriminating arcs from fast load variations. The result is that these protection systems have in general an over concerned response (in particular when plasma coupling is low) and cut the RF power when they should not. As ITER operation is fully driven by the auxiliary H&CD systems, an unforeseen an abrupt lack of auxiliary power in a high β operation would have a major disruption as likely consequence. This would obviously be acceptable only if a fault condition in one of the auxiliary heating subsystems would cause a more severe damage. Preliminary studies of a system based on vectorial monitoring of RF current and voltage and closed-loop control of current in all array elements were made, offering promise for an efficient, load independent breakdown control. A more detailed analysis of arc detection with this method is ongoing and will be reported in a future study.

CONCLUSIONS

Numbers of changes in the ITER FDR ICH design are proposed, to simplify the system and to improve its reliability keeping unchanged the design concept and interfaces. Issues not sufficiently covered in the FD report were also addressed. At present stage this design has to be refined from an engineering point of view. This task implying a more detailed mechanical description of the array including support and cooling, completed by a more accurate EM analysis and a detail thermal analysis will be pursued in the coming year. In the meantime the development of ad-hoc components is pursue. The main element to develop is the compact tuning system, it is planned within two years to design, built and experimentally demonstrate the performances of this component.

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CEFDA05-1271

Task Title: TW5-TPHI-ITERDES3: DESIGN OF THE ITER ICRF ANTENNA FOR THE INTERNAL AND EXTERNAL MATCHING CONCEPTS

INTRODUCTION

The ITER Ion Cyclotron Heating and Current Drive (ICH&CD) system is designed to couple 20 MW of power from a single antenna (equivalent to a power density of ~9.3 MW/m^2 at the antenna) in the frequency range 40-55 MHz for a variety of ITER plasma scenarios. This requirement, together with the need to provide robust coupling in the presence of ELMs, has focused attention on the development of an integrated design for the antenna and matching system which will satisfy the ITER performance requirements [1] while operating reliably within the burning plasma environment. The reference design for the ITER ICRF system [2] developed as a result of studies performed during the ITER EDA Extension Phase has established a reference antenna design which is based on the Resonant Double Loop (RDL) concept with “conjugate T matching” for ELM-resilience. The matching system is internal to the antenna port plug and uses variable capacitive elements. This design concept provides the basis for the ITER-like ICRF antenna now being developed within the JET-EP project and which will be tested in JET beginning in 2006. In the “reference” design of the JET-EP ITER-like antenna the internal tuning elements are capacitors.

2005 ACTIVITIES

STATUS OF THE DESIGN ACTIVITY AND BACKGROUND

During the ITER CTA, further design work was carried out for the development of the ITER ICRF system conceptual design, using both the reference approach of internal matching, with capacitors as tuning components [3], and an “external” matching concept with tuning components located adjacent to the ITER ICRF port [4]. Subsequent studies [5], [6], [7], [8] have addressed further issues concerning the design and electrical performance of the ITER antenna for both design concepts. Reliable coupling at high power density, particularly in the presence of rapid changes in loading resistance, such as produced by ELMs, is regarded as the critical issue for the performance of the ITER ICH&CD system. Asymmetries and direct coupling between straps can significantly degrade the resilience to load variations and the acquisition of the match, in particular in a compact array such as the ITER IC array. The activities conducted under EFDA contracts in 2004 addressed the electrical performance of the ITER antenna for both internal and external matching concepts [5], [6]. The issues addressed were the dependence of the antenna coupling on poloidal phasing and current amplitude imbalance (in particular associated with the resonant pair matching), the evaluation of ELM resilience, and the study of matching control algorithms in the presence of inter-strap coupling and load asymmetries. These studies have highlighted further issues concerning the development of a matching scheme and matching control algorithms. Although these more specific issues will be addressed by a separate task, such task will be connected, both in scope and time-scale, to the Contract described here. The matching studies conducted in 2004 also resulted in changes in both internal and external matching design, as summarized below:

- For the external matching design, the optimization of load resilience in the presence of mutual coupling indicates the need of an additional impedance transformer between the conjugate-T connection and the main transmission line. This removes the need for Klopfenstein tapers and requires the insertion of an additional line stretcher and of an adjustable stub for each of the four conjugate-Ts circuits. Additional modifications include smaller changes in the 4-port junction and feeder plate design.

- For the internal matching design more substantial modifications are proposed. These modifications include an increase of the poloidal order of the array from four to six straps to reduce strap voltage and void volumes, an increase that was already included in the analysis of [5]. They also include a change in the design of the tuning components and in the lay out of the VTL, with the introduction fixed and movable sections. All the components that might require more frequent maintenance are positioned in the movable section, which could be serviced without breaking the torus vacuum. With the new design the capacitors are in a region of reduced neutron flux compared to the old design, and their design is modified. The dielectric strength of the high E-field volume is increased by creating a high local vacuum around the capacitor, isolated from the torus neutral pressure via dielectric enclosure. The tuning circuit includes a pre-tuner located at the antenna end and a trimmer located at the generator end.

The detailed analysis of the two designs, of the changes proposed and a further development of both designs towards meeting all the ITER requirements is the subject of the activity described in this task. This work is the continuation of the task TW3-TPHI-ICRDES3 which produced a conceptual design study of the 2 options.

TASK OBJECTIVES

The scope of this task is to carry out more detailed design work on both internal and external matching concepts to bring them to a level of detail that ensures that both designs can be made compatible with the ITER design constrains, in particular:

- To provide coordination of the design effort subject matter of this Contract for the progress of the internal matching design and of the external matching design, including liaising with the ITER IT. Some direct interaction with the US PT might also be necessary.

- To work in collaboration with the ITER IT Task Officers and the ITER-Garching Drawing Office in order to refine, detail and modify the designs according to problems and solutions identified in the process of integration of both design in the ITER environment.

The objectives of the task are:

- To demonstrate that the designs can be made compatible with the design constraints for installing in a mid-plane port and that the designs respond to the functional requirements for ITER.

- To progress towards the full integration of the designs in the ITER system in preparation for choosing which of the two concepts shall be used for the ICRF antenna final design. This decision is anticipated in early 2007, after the results of the JET-EP antenna will be available.

TASK ORGANIZATION

The Task requires the coordination of the entire design effort as well as the liaising with the EFDA responsible officer and with the ITER IT. This coordination work is required as a specific deliverable. To ensure a coherent development of the design studies, a regular exchange of information will be promoted through a series of Technical Progress Meetings. Typically progress meetings will be held approximately every 3 months. These meetings will be also aimed at reporting progresses on the IT Task to the ITER IT, and shall be attended by at least one representative of all the EU Association involved in the activity.

The first (“Kick-off Meeting”) to be held at the start of the contractual period to agree:

- The initial organization of the work and the initial time-schedule of the interaction with the ITER IT Task Officer and ITER Garching Drawing Office (in particular relating to activities which require work in Garching with the ITER Drawing office)

- The time-schedule of subsequent meetings.

- The procedures and modalities for the exchange of information between the parties involved: EFDA, ITER-IT, ITER Garching Drawing Office and EU Associations.

A final closeout meeting will be held at the end of the activity, as specified in the IT Task

DESCRIPTION

The Task requires the person responsible for the coordination deliverable to work in Garching with the ITER Drawing Office for the length of time require by the activity, with a minimum period of presence in Garching of two weeks as required by IT Task Description.
Some of the activities of this Task require the ITER IT to provide EFDA CSU Garching and the EU Associations with input information, deriving from other IT Tasks with the US PT, indispensable for implementing the activities. It is responsibility of the ITER IT to timely provide those in formations and to maintain coordination among the IT Tasks.

TASK DESCRIPTION

CEA is in specially in charge of the development of the design for the internal matching concept will include the following activities:

a) CEA will take responsibility for the coordination and leadership of the design effort of this subtask:

- CEA will make a proposal regarding the time schedule and modality of the collaboration with ENEA-Frascati and ENEA-Consorzio RFX described in activities 5.2.1 to 5.2.6. This proposal will be discussed at the kick-off meeting, and an agreement will be reached among all parties (ITER, EFDA, CEA and ENEA). The agreed proposal will be documented in the minutes of the meeting. Time schedule and modality of the collaboration could be revised, if necessary and if agreed by all parties, in subsequent meetings.

- CEA will be responsible to ensure that all the relevant information is passed to ENEA Frascati and Consorzio RFX.

- ENEA (Frascati and Consorzio RFX) will be, on the other hand, responsible to provide results and information to CEA within the commonly agreed time schedule.

- CEA will provide, as part of the intermediate and final report, an executive summary of the overall results and integration of the activities described in 5.2.1 to 5.2.6

b) i) On the basis of the technical input from CEA on the internal matching concept design, ENEA-Frascati will produce a detailed electromechanical design: ENEA-Frascati will analyze, using the codes ANSYS Multiphysics, HFSS wave propagation and TOPICA, the E-field and current maps in all array components. This analysis will be performed both in condition of free radiation and for one plasma loading (agreed with the IT) in the frequency range of 40-55 MHz. They will evaluate performances and operational limits of the design in the two cases, based on operational limits agreed with the ITER IT

ii) On the basis of the technical input from ENEA Frascati, CEA will describe in detail critical elements of the present design, including:

- The vacuum seal between the private vacuum and the torus vacuum.
- The construction of the capacitor elements, including alignment accuracy needed.

- The Safety related components (such as vacuum barriers, rupture disks, etc)

- The RF monitoring probes

- Other elements within the scope of the work which are identified as critical

iii) CEA will provide the required input for the thermal analysis

c) On the basis of the technical input from CEA, ENEA—Consorzio RFX will evaluate support and cooling methods. Based on the results of this evaluation, CEA will revise cooling and supporting elements of the design:

i) ENEA-Consorzio RFX (in collaboration with CEA) will Calculate weight of straps, center conductors, capacitor elements, vacuum transmission line, etc. that are "hot" to rf voltages. They will provide a preliminary study of methods for cooling and supporting these elements [details of cooling passages are not required at this stage, but general routes of coolant into and out of "hot" components are to be devised; likewise, dielectric supports (if needed) are to be designed].

ii) After the implementation of activities 5.2.5 and 5.2.6, and based on the results of analysis done as part of these activities, ENEA-Consorzio RFX will implement numerical models to verify the cooling efficiency and induced thermo mechanical stresses as well as the stresses in the cooling element support.

iii) Based on the analysis performed by ENEA-Consorzio RFX as part of activities 5.2.5 and 5.2.6, CEA will revise cooling and supporting elements of the design.

d) CEA will work with IT and Garching Design Office: Representatives of CEA will visit IT-Garching to incorporate the antenna concept design into a midplane port, so that it satisfies the constraints of the current ITER port designs and other related constraints. PT members will supply the expertise on their design, and the Garching Drawing Office will make a CATIA model of the concept that meets the requirements. This will be carried out at a mutually-agreed date among the IT TO, the Garching Drawing Office, and the PT.

e) CEA will revise the design based on results of 5.2.3 and radiation/shielding analysis. The ITER IT (based on results from a US PT task, ref. ITA 51-04) will provide a preliminary evaluation of the radiation shielding capability of the design based on the CATIA model that is the output of 5.2.3. Based on this analysis and any problems discovered while integrating the design into the ITER midplane port, revise the design to ameliorate any mechanical, electrical, or shielding problems. CEA will continue to work with the ITER-Garching Drawing Office and US neutronics analysts as needed, since more than one iteration might be needed

f) On the basis of technical input from CEA, ENEA-Consorzio RFX will perform thermal analysis. They will carry out thermal analysis of the antenna structure (excluding the Faraday shield), including calculations of heat loads from rf losses, direct heat flux from the plasma, and volumetric heating of components from neutron and gamma radiation. Volumetric heating (power deposition) of antenna components from neutron and gamma radiation will be supplied by the IT (based on results from a US PT task, ref. ITA 51-04) for this analysis. ENEA-Consorzio RFX will perform finite element analysis, will evaluate the implications of the results for the specification of the in-vessel components and will made recommendations in order to obtain an efficient cooling system with acceptable temperatures in all parts of the antenna structure.

g) On the basis of technical input from CEA, ENEA-Consorzio RFX will evaluate mechanical response of antenna "hot" components to disruptions. A self-consistent approach to the analysis of disruption forces for the ITER antenna "hot "components", based on the results found in EFDA contracts 03-1131 and 03-1132, will be developed by ENEA RFX and ….

This self consistent approach will be applied to both system designs (Internal and external matching concept design). Based on this self-consistent approach, ENEA-Consorzio RFX will perform a 3D electro-mechanical analysis in order to calculate the mechanical response of antenna components to a disruption, and to provide the necessary engineering analysis and design support. ENEA-RFX will evaluate the implications of the results for the specifications of in-vessel components, and will make recommendations in order to obtain a feasible design with acceptable stresses and displacements.,

STATUS REPORT

The contract was officially signed on the 28th of november, 2005.
The coordination meeting n°1 took place in Cadarache on the 16th of january 2006 with representatives from all associations involved in the task.
All documents are available on the task ft site ftp://ftp.cea.fr/incoming2/y2k01/ITERDES/. During this meeting, detailed execution organisation and associated planning have been reviewed. The work is progressing on the mechanical structure analysis, and a design review is schedules at the end of march in Garching, together with 3D model integration of the antenna in the ITER model, with the help of the ITER drawing Office.
Note that the new task sharing of the ICRH package procurement is perturbing the work organisation, since some tasks originally devoted to USPT will not be performed and have to be redistributed in Europe. Specifically, the neutron shielding analysis, which outcome is of importance for the structural analysis, may suffer some delay.

REFERENCES

[1] Technical Basis for the ITER Final Design Report (in partic, PDD Section 2.5, Additional Heating and Current Drive), july 2001.

[2] ITER Design Description Document 5.1, Ion Cyclotron Heating and Current Drive System, july 2001.

[3] Final Report on EFDA Contract 02/676, “ICRF Antenna and System Design (Internal Matching)”, august 2003.

[4] Final Report on EFDA Contract 02/675, “ICRF Antenna and System Design (External Matching)”, june 2003.

[5] Intermediate Report on EFDA Contract 04/1129, ”ITER ICRF antenna and Matching system design (internal matching)”, september 2004

[6] Intermediate Report on EFDA Contract 04/1130, “ITER ICRF antenna and Matching system design (external matching)”, october 2004

[7] Intermediate Report on EFDA Contract 03/1132, ”ITER ICRF antenna and Matching system design (external matching)”, january 2004

[8] Final Report on EFDA Contract UKAEA 03/1131, ”ITER ICRF antenna and Matching system design (external matching)”, april 2004

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TW5-TPHI-ICRFDEV

Task Title: DEVELOPMENT OF HIGH PERFORMANCE CAPACITORS FOR THE ITER ION CYCLOTRON ARRAY

INTRODUCTION

The objective of the activity to be covered during the next two years is to design, build and test a Compact Vacuum Tuner (CVT) compatible for an integration in the ITER Ion Cyclotron Heating and Current Drive launcher. This high power tuning device is designed to fulfill ITER in-vessel EM, mechanical, thermal, nuclear and Remote Handling specifications (RH). In the ITER array two CVTs would be combined in a two-straps “ITER-like structure” (ILS) which is the basic element of the ITER Ion Cycloton array and features a significant resilience to load variations, such as those due to ELMs. The device, however, can be used for general high power cw impedance matching applications.

2005 ACTIVITIES

PRINCIPLES OF OPERATION

The CVT operates on the principle of a capacitively loaded transmission line, as sketched in figure 1. The combination of the three sections of the circuit is electrically equivalent to a high power factor series resonant circuit, with capacitive or inductive response depending on the component values and frequency. Large variations of the input reactance X_{in} can be obtained for small displacements of the electrodes of load capacitor, which can be accommodated by the flexible length of the short-circuited section. As consequence, the device needs no sliding contacts. In ITER applications, a capacitive input reactance is required for matching, and it is of interest to minimize the RF electric field in the section 1 (cf. figure 1) of the device, since in this section the dielectric is the torus “vacuum”, whose dielectric rigidity is difficult to predict. The highest electric field in the system occurs in sections 2 and 3, and, in order to extend the power performances of the device, an improved vacuum is maintained in this volume isolated from the torus vacuum by a dielectric septum. The movable electrode assembly, including cooling, actuation and provision for pumping in the private volume, is separable from the fixed electrode and can be removed from the rear for repairs and/or maintenance by simple, manually assisted, or by RH operations, without affecting the torus vacuum, which is isolated by the dielectric septum.

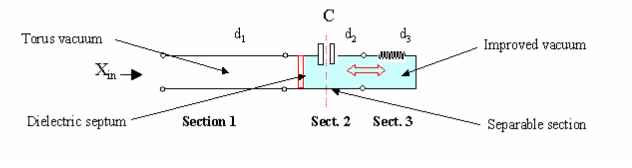

Figure 1: Equivalent circuit of the CVT

CVT OUTLINE SPECIFICATIONS

Mechanical

The CVT is an adjustable two port coaxial device, with different input and output characteristic impedances, featuring an outer diameter not exceeding 250 mm and a length not exceeding 0.5 m. These dimensions are fully compatible with the ITER IC array layout proposed in [1]. The layout of the tuner is sketched in figure 2.

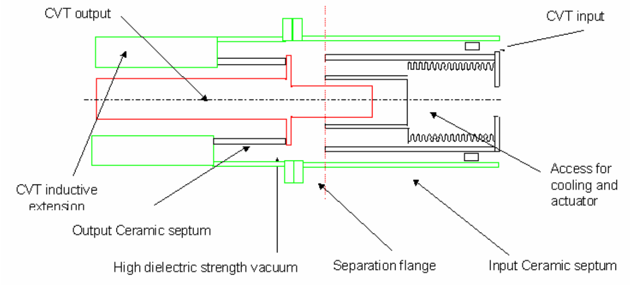

Figure 2: Sketch of the CVT

The CVT is mechanically split in a front and a rear sections, connected by a sealed junction. The outer conductor of the front section, including only fixed components, is joined and electrically connected to the in-vessel Vacuum Transmission Line (VTL) body. The central conductor is joined to the strap feeder. The removable section is mechanically assembled with a ceramic, and is connected to the fixed section by a “leaky” vacuum-sealed junction. The seal to be completely vacuum tight, but simply to maintain a low conductance toward the torus “vacuum” in the fixed section, since the vacuum in the removable section is dynamically maintained by a getter pump. Coaxial coolant channels coming from the strap feeder and from the actuating shaft cool the fixed and movable electrodes respectively.

The tuner is water-cooled and operates under high vacuum, using the same type of technology of commercial vacuum coaxial capacitors. This, together with the reduced dimensions, permitted by the enhanced internal dielectric strength and water cooling, allows a compact design of the overall tuning system, which can be housed in the one ITER main equatorial port, still maintaining space for maintenance operations and even for the in-situ replacement of faulty components.

The device is designed to be connected, in series/parallel combination with one or more similar structures, to a single incoming transmission line, thus providing power division and impedance matching of an even number of radiating elements, and still maintaining the capability of an independent control of the currents in each matched load.

In ITER in-vessel applications, it is of interest to provide an adequate nuclear shielding to the input ceramic septum and therefore the CVT will be located in a recessed position with respect to the tokamak first wall, and connected to the strap by a section of coax line. In this section, relying on the torus “vacuum” as dielectric medium, the VTL is exposed to a TEM field increasing from the strap input to the CVT output where it reaches its maximum value. As the torus “vacuum” dielectric rigidity is difficult to predict, it is important to minimize the E-field value with a suitable choice of the feeder geometry and characteristic impedance. It is also important to minimize the electric field in the region of the ceramic septum so as to ensure low dielectric losses.

The highest electric field in the system occurs in the private vacuum region, in which an ion pump maintains a high dielectric strength.

The CVT output may include a short section of coaxial line (CVT inductive extension), which serves to different purposes, depending on the application. For ITER in-vessel use the coax is used to connect the CVT to the current straps input and retracts the ceramic components included in the CVT from the first wall so that they are sufficiently shielded from neutron flux. In other applications, such as in a trimmer structure, the section is used to transform the output reactance of the CVT from capacitive to inductive.

The input assembly of the CVT, including movable components, cooling, actuation and ion pump is separable from the output section and can be removed from the rear for repairs and/or maintenance by simple operations, without any effect on the dielectric properties of the medium outside the CVT output. This can be used to replace CVT components in case of fault without damaging the torus vacuum.

Cooling

All components of the CVT are designed to be water-cooled. Typical inlet coolant temperature for ex-vessel operation is 40°C at a pressure below 0.3 MPa. However, the CVT version designed for ITER in-vessel is designed to be cooled at the temperatures and pressures of the ITER Blanket (CVT output) and Vacuum vessel (CVT Input). In the ITER in-vessel applications, the CVT output section is connected to the cooling loop of the blanket (150°C, 30 bar). The CVT input section, which contains flexible components, is cooled at lower pressure by a dedicated coolant loop at the Vacuum Vessel coolant loop temperature and pressure (100°C, 8 bar). In the event of a leak through a fault in the flexible component, the coolant is contained within the output dielectric septum and rapidly de-pressurized by a rupture disk exiting the coolant at the input section end and preventing any pressure build-up on the output ceramic septum (figure 2).

Electrical

The CVT is designed to provide at its input terminals a capacitive reactance range X_{in} = 13 – 25 Ω, with an accuracy of 0.02 Ω over the whole specified dynamic range. The dynamic range covers current estimates for matching the ITER array structures over frequency and load ranges. The accuracy is adequate for matching the ILS in vacuum and on plasma. The CVT is designed to fulfill the (recently reduced) maximum RF electric field specifications in ITER “vacuum” (1500 V/mm parallel to B_0 and 3000 V perpendicular to B_0). The design in fact aims to significantly lower values (1000 V/mm parallel to B_0 and 2000 V perpendicular to B_0). The maximum electric field limit in the private vacuum is consistent with the above values.

Vacuum boundaries and safety

The ceramic septum in the CVT has no function of vacuum/tritium containment and has safety relevance during ITER operation. These functions are performed by other system components according to ITER specific requirements. The failure mode analysis of the CVT and its safety assessment, according to ITER rules will be performed as part of the detailed design.

Interfaces with the torus and Remote Maintenance

The CVT interfaces with the ITER IC plug in (and not directly with the ITER vacuum vessel) for auxiliaries and services will be studied. The on-site and/or hot cell installation and removal of CVT pairs may be agreed with the ITER International Team. The design of the CVT that will be produced (prototype & series) might present some difference compared with the one integrated on the ITER IC launcher. Indeed, the object to be manufactured will present an interface compatible for an assembly on a test facility. Such interface might not be suitable for integration on ITER, and shall not constraint the ITER IC launcher design. For example, as it can be seen on the conceptual drawing below (figure 3), the second ceramic use on this assembly as a support will not be of no use in the IC ITER antenna.

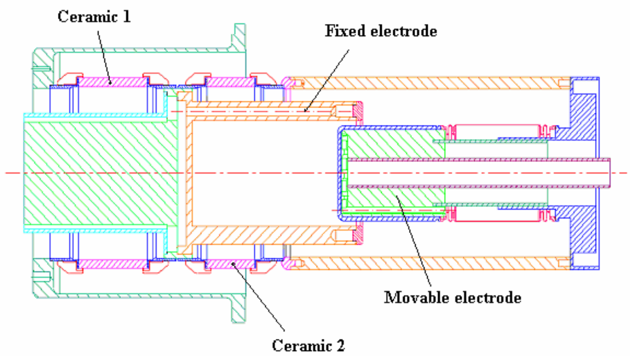

Figure 3: Conceptual design of a CVT suitable for an integration on a test rig

Neutron shielding

The neutron shielding requirements of the CVT, and the assessment of the operational lifetime estimate for the ceramic material included in the device will be performed as part of the detailed design, using as basis material irradiation studies performed under ITER task(s) during EDA.

Actuation

More than one option is investigated for the actuation of the CVT. Actuation by a stepper motor via a pinion and screw transmission (figure 4) is the simplest solution for ex-vessel application. This solution has also been adopted for in-vessel in the Tore Supra ITER prototype and has demonstrated reliability an adequate accuracy in positioning. Actuation of the capacitor bellows by means of the cooling fluid is a simpler and more elegant solution for in-vessel application and its feasibility is currently being studied.

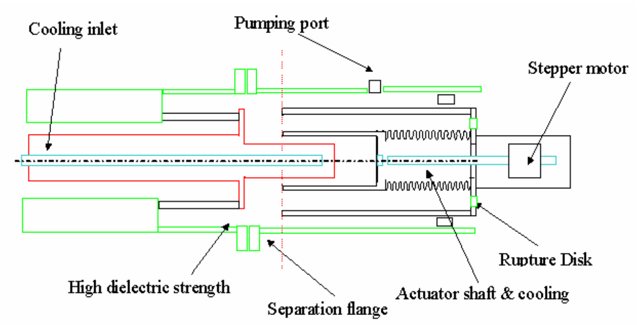

Figure 4: Provisions for cooling, vacuum and actuation

CONCLUSIONS

This R&D task will validate the principle and technological option on a crucial component for the ITER ICRH launcher in the internal matching concept promoted by CEA. The call for tender and the collaboration that will follow with the industrial company in charge of the manufacturing of the prototype and serials components will also be of great interest to acknowledge the industrial potential for the realization of complex RF component fulfilling ITER requirements.

REFERENCES

[1] G. Bosia, S.Bremond, K.Vulliez CEFDA04-1129 Contract Final report (2005)

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CEFDA02-1003

Task Title: TW2-TPDS-DIASUP4: SUPPORT TO ITER DIAGNOSTIC DESIGN: POLARIMETRY, MOTIONAL STARK EFFECT, BOLOMETRY, THERMOGRAPHY

INTRODUCTION

This contract covers four independent topics:

Bolometry — to agree a generic design of the bolometer camera head with a schematic drawing of the ITER reference bolometer module and cameras and to make a thermal analysis of the ITER reference bolometer including substrate effects at four sensor locations.

Thermography — to develop the concept of a spectrally-resolving divertor thermography diagnostic based on the use of optical fibres, to analyse the radiation environment and radiation hardness of fibres with detailed treatment of the main elements of the diagnostic chain (optical study of front end optics and its integration into the divertor cassette, performance analysis of optical design, evaluation of the suitability of different fibre types, consideration of detection system).

Polarimetry — to characterize the change of optical performance of a corner cube reflector exposed to plasma and to interpret the observed changes in the optical performance in terms of plasma processes occurring at the reflecting surfaces.

Motional Stark Effect — to perform an initial feasibility study of diagnosing the current density profile in ITER by means of the MSE diagnostic and to coordinate the European tasks with FOM, UKAEA, and VR. The main components of this feasibility study were: to show that the MSE measurement is feasible at much higher Lorentz electric field, to find a position around the machine satisfying the spatial resolution requirements, to show that the beam penetration and emissivity are high enough to compensate for the high Bremsstrahlung signal considered as the major source of noise for the measurement, to calculate the beam emitted spectrum, to evaluate the influence of the radial electric field on the measurement, and to compare the performance of MSE using both heating and diagnostic neutral beams and recommend the preferred approach.

2005 ACTIVITIES

All activities were completed by the beginning of 2005, and this last year was dedicated to organize the independent reports in its final form.

CONCLUSIONS

BOLOMETRY

The 0D thermal model, which has been verified against measurements on existing bolometers, can be used to design ITER metal resistor bolometers. The 0D model has also been verified with 3D thermal calculations.
The proposed bolometer camera design has a very low thermal resistance. These cameras, if fixed to an actively cooled support, will work at a steady-state temperature lower than 160°C with cooling time constant of the order of 100 s. Suggestions are made to improve the reference design for better thermal contacts.
In the divertor cassette, an actively cooled support is not available. An inertial rise of the sensor temperature is found. For a radiative liner at 350°C, the temperature rise is found to be 0.22°C/s. Cumulative temperature rises from shot-to-shot have to be expected.
The front plate and camera design will have to be optimised for thermal path and minimum heat load; proposals for design changes are made.
It seems feasible that appropriately designed bolometers can operate successfully in ITER with the level of cooling currently foreseen (except in the divertor, where more cooling would be preferable), provided new electronics is developed that simultaneously measures the output voltage and current in order to monitor the temperature-dependent changes taking place in the bolometer foil.
To achieve a reasonable signal-to-noise ratio in ITER, it will be important to improve the sensitivity with respect to that achieved for present-day resistive bolometers.
Mechanical stresses induced in the camera housing during disruption have been calculated and found to be acceptable at dBz/dt~70 T/s; no design modifications are required.
Recommendations. Because large thermal drifts can be anticipated for some mini cameras in ITER, it could be advantageous to check on JET the proposed method for measuring the temperature rise of the foil.To get a better prediction of the bolometer sensitivity the thermal properties of the mica foils should be accurately measured.
The measurement of the TCR of thin deposited platinum resistors is also needed.
A better diagnostic integration in the divertor cassette should be done.
The operational conditions of the divertor should be better defined.

THERMOGRAPHY

Throughout the execution of this contract there have been extensive consultations with the ITER IT. To facilitate the updating of ITER documentation this report and relevant drawings will be provided to the ITER IT. Rough estimates of the cost of various options of the ITER divertor thermography diagnostic based on optical fibres are described in the report; these are based on the cost of the Tore Supra thermography diagnostic.

Based on Tore Supra's experience and the relatively good usability of silica fibres in the near IR range in a reactor environment, a diagnostic concept has been developed that uses optical fibres as transport medium and a spectrally resolving spectroscopy approach to fulfil ITER's thermography needs in the divertor region.

An optical front end design using a few mirrors with a high throughput (N.A. = 0.22) has been found that looks at the outer and the inner divertor target. To accommodate the mirrors in the divertor cassette two of the liner-bars of the cassette have to be removed or modified. The arrangement of the measurement points on the target is either such that one fibre is pointed to each centre of a carbon tile of the divertor where the clearest measurements are expected which corresponds to a poloidal resolution of about 20 mm or the measurement points are close packed yielding a poloidal resolution in the 3 mm range. The design actually proposed can either provide the spatial resolution demanded by ITER (3 mm) or a reduced resolution (20 mm). In the (unavoidable) presence of deposits in the tile gaps, which heat up more than the bulk tile material without posing a danger, the lower spatial resolution provides about the same amount of useful information as the higher resolution and may therefore be more efficient. The difference in need of fibres between the two versions is 100 or 500 fibres. The spectral resolution of the measurement may allow discrimination of the parasitic light contribution stemming from hotspots even of microscopic sizes. The other performance criteria, on temperature range and accuracy, can also be fulfilled, provided that the optical front end and the fibres are cooled. Bremsstrahlung is limiting the possibility to measure low target temperatures in high electron density and low electron temperature conditions.

Sufficient irradiation data is only available for silica fibres to make a detailed assessment of their adequacy for ITER divertor thermography. In their case the scatter on the available data allows different interpretations of how close fibres can be brought to the divertor cassette. In the most optimistic interpretation they can go all the way from the bioshield to the external border of the divertor cassette and remain there for the lifetime of ITER. In less optimistic interpretations mirror relay optics of either 1.6 or 4.6 m length are needed. The optical layout of such relay optics still has to be found. If realised, the concept may become also interesting for imaging applications and visible light spectroscopy in that environment.

The most interesting spectral range is from 2-6 µm which makes ZrF_4, and hollow waveguide fibres (mainly made from silica capillaries) very interesting candidates. One fibre that might be worth to be fully developed in collaboration with the corresponding industries in this respect is a so-called Thermography Optimised Hollow Waveguide (TOHW) fibre, which is coaxial combination of a hollow waveguide and a conventional fibre. The radiation hardness knowledge on these fibres is still rudimentary in the spectral range of interest (except for silica fibres) but a program in collaboration with SCK·CEN Mol, Belgium, may be developed further which might improve the situation.

At the outboard edge of the cassette a retractable, replaceable multifibre connector is foreseen linking the fibres to the mirror front-end optics. A detection system similar to the Tore Supra solution is proposed with one or more prism spectrometers and 2 D detector arrays.

The procurement cost of such a diagnostic has been estimated by extrapolating from Tore Supra's working example but without taking into account further research and development costs. These costs are expected to be in the range 1-7 M€ (depending on the optical resolution required and the fibre type used) if only one cassette shall be equipped.

The implantation envelope in the divertor, the optical design and the integration into the divertor cassette are available in electronic form. The latter has been provided to ITER-IT as CATIA4 model.

POLARIMETRY

The main changes observed in the reflector following exposure to plasma during one year were (1) a material deposit (composition is not yet analysed) in the inner half of the reflector and (2) evidence of erosion in the outer region that does not follow the magnetic lines. The reflectivity measured at 118 microns shows a slight decrease, at most 10% for the corner cube mirror and no measurable decrease for plane mirrors exposed at the same time. The study of the semi reflective plates induces the conclusion that the angle of the plates must be as small as possible to minimize the errors between the perpendicular and parallel polarisation reflectivity.

MOTIONAL STARK EFFECT on heating neutral beams

The MSE measurement at high Lorentz electric field is possible using the polarimetry or ratiometric method (CEA).

The spatial resolutions were calculated for all the configurations of the diagnostic around the machine, and since the beam adjacent port was not available, our recommendation was to install the MSE diagnostic in e-port 2 (central MSE) and e-port 3 (edge MSE) both viewing HNB5. The compromise with the other diagnostics requirements proposed by ITER team was to install the central MSE diagnostic in e-port 1 viewing HNB4. This solution is equivalent from the spatial resolution point of view but a measurement over the entire profile needs the two heating beams. The spatial resolution is better than 15 cm almost everywhere, and better than a/40 around rho = 0.2 and 0.65). (CEA/UKAEA/ITER)

The high energy of the neutral beam allows a good plasma penetration, and the signal to noise estimations compared with TFTR and JET indicates that a time resolution of a few tens of ms can be envisaged (CEA/UKAEA)

The calculation of the expected MSE spectrum for 5.3 T indicates a clear separation between the σ and π components. This will allow MSE measurements with a high polarisation fraction as well as the possibility of measurements at lower toroidal field (<1T). (CEA)

The vertical large size of the beam could induce additional difficulties of measurement if the beam vertical power density profile is not constant during the discharge (UKAEA).
The influence of the radial electric field seems negligible for most scenarios. The important consequence is that the diagnostic is independent and does not need to be Er corrected. On the other hand, it does not seem possible to deduce Er directly from MSE measurements as it is done on some of the present machines (CEA).
A laboratory demonstration of an accurate MSE measurement using 4 mirrors was performed, in parallel with a modelling of the mirror properties and resulting signal (UKAEA/VR).
The possible modification of the initial polarisation due to the first mirror coating has been calculated and measured experimentally on plasma-exposed mirrors (IT Garching/VR)
To cope with polarization effects in contaminated mirrors, in-situ calibrations will be essential and will have to be integrated in the design. In parallel, simultaneous measurement of σ and π lines is proposed to control the reliability of the measurements and deduce information on the mirrors properties (CEA/UKAEA/VR).
A design of the diagnostic in port 1 and 3 compatible with a low escaping neutron flux was performed. A ray tracing allowed the positioning of the main optical elements (IT Garching).

Comparison between MSE on diagnostic neutral beam and on heating neutral beams
The feasibility of a MSE diagnostic on the Diagnostic beam in complement to the CXS diagnostic was demonstrated (FOM). The combination of two observation ports allows MSE measurements with a spatial resolution satisfying ITPA requirements. The sensitivity of the measurement on the σ/π ratio and thus to q profile is very good from these two ports.
Multi-mirror and coating effects are also in this case a major source of concern. Calibration methods based on atomic modelling of line emissions and on the use of the plasma itself are proposed.
The lacks of heating beams for some scenarios as well as the additional difficulties due to the mirror coatings indicate that the two MSE diagnostics (on HNB and DNB) are necessary on ITER. Cross checking of the measurements will then be done when possible, so as to validate each method.

REPORTS AND PUBLICATIONS

DIAG/NTT-2004.027: Thermal analysis of the ITER reference bolometers (J.C. Vallet and C. Portafaix)

DIAG/NTT-2004.029: Design analysis of Motional Stark Effect diagnostic for ITER (P. Lotte and R. Giannella)

DIAG/NTT-2005.003#1: Polarimetry, Experimental study of plasma exposure of a corner cube reflector (C. Gil)

DIAG/NTT-2005.019: Final report for the contrat EFDA 02-1003 D2.3 Thermography (R. Reichle, S. Henry, J. Miggozzi, E. Thomas, C. Walker)

DIAG/NTT-2005.018#1: Final report of the contract EFDA 02-1003 (Executive Summary)
Support to the ITER diagnostic design (P.E. Stott, C. Laviron, J.C. Vallet, R. Reichle, C. Gil and P. Lotte)

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CEFDA03-1111

Task Title: TW3-TPDS-DIASUP1: SUPPORT TO THE ITER DIAGNOSTIC SYSTEM: BOLOMETER, WIDE-ANGLE VIEWING, CALORIMETRY, q-PROFILE DETERMINATION, REFLECTOMETRY AND POLARIMETRY

INTRODUCTION

The overall objective of this task is to advance the design of several ITER diagnostic systems for which the EU has developed conceptual designs, to re-evaluate their performance for the most recent analysis of plasma conditions, and to provide support to the ITER International Team (IT) in the preparation of the relevant ITER documentation. This contract, initially consisting of six independent tasks related to six diagnostics, has been amended following an EFDA proposal to take into account the provisional diagnostic distribution between the ITER parties at that time. Five tasks remained in the amended contract:

- Detailed design analysis of bolometer cameras on the basis of the reference resistive bolometer sensor
- Design analysis of wide-angle viewing/thermography system
- Feasibility study of calorimetric measurements on ITER
- Evaluation of MSE measurements in the assessment of q-profile determination in ITER
- Contribution to the design analysis of the ITER plasma-position reflectometry system

2005 ACTIVITIES

Detailed design analysis of bolometer cameras

Studies have been mainly focused on the bolometers resistance to the severe ITER operating conditions within a harsh environment. Particularly during disruptions, plasma will release a very important radiated energy as well as induced electric currents within bolometer components which will have to stand strong thermal and mechanical constraints.

Nevertheless, it is shown that the most fragile components, such as the absorber and the mica sheet, should resist to these constraints with a large enough security factor.

To filter the bolometers from ECE waves, a multiple slits system should be considered. Unfortunately, such a system induces a loss of the radiated flux toward the absorber. This loss will have to be quantified and eventually optimised on a case to case basis.

Design analysis of wide-angle viewing/thermography system

The wide-angle viewing systems are planned in the equatorial and upper ports of ITER for real time survey during plasma operation. The system should have a high reliability and be able to show rapidly to the operator plasma wall contact and hot spots.

Up to now, the main mission for this diagnostic is to provide good measurements of the surface temperature in the range of 200-2500°C with an accuracy of ±10°C with a large field of view (for safety and operation consideration) and with the required spatial and time resolution (~ 10 ms). This is very challenging. A secondary function is also for machine safety, but in the visible range (UFOs, initial wall-damage assessment). This diagnostic can alternatively be used to study runaway electrons, visible spectroscopy or/and track pellet. According to the provided data (surface temperature and Hα light emission), this diagnostic can ultimately be used for other physic purposes as heat flux density and energy calculation or dust and layer localization. In his present requested form, this diagnostic doesn’t resolve transient events such ELM and disruption.

The study has been conducted to get a full review of the diagnostic within the ITER environment. It has shown that it is possible to have 4 equatorial port endoscopes looking at the vacuum vessel and divertor plasma facing actively cooled components with a ~ 70% coverage. At each port plug 3 lines of sight are presents, one to look on the left of vacuum vessel, one to look on the right side and finally one to look at the divertor located at the bottom of the machine. A generic optical line has been defined and can be used for all lines. Performances have been evaluated. They are within the required specifications. Nevertheless, a number of remaining topics to be addressed have been pointed out to permit to make the final choices and to improve significantly the design and overall performances.

Feasibility study of calorimetric measurements

Thermal analysis of the coolant of the blanket modules has been done and the feasibility of a calorimetric diagnostic to provide an estimate of the total neutron power has been demonstrated. A time resolution of typically 10 seconds can be expected.

The required techniques for processing the temperature measurements have been developed and exemplified with the calorimetric data recorded on Tore Supra. Provided that an initial tabulation of the flow-rate in the blanket module be done during the commissioning phase, as should be done anyway, it is shown that the required instrumentation for calorimetry could be restricted to thermometers only. Typically 200 embedded thermometers are needed to reconstruct the total neutron power. It is not necessary that these thermometers be intrusive in the pipes. Pipe surface temperatures could be used.

The technology of these thermometers is still open to discussion. A conventional approach would suggest using Pt100 sensors with the main disadvantage that it would

require 600 wires. Provided an improvement of their sensitivity and may be also of their neutron hardening, an interesting alternative could be the use of multiplexed fibre Bragg gratings as temperature sensor. Up to 8 thermometers have already been implemented in one optical fibre.
In this study we have restricted the demonstration of the powerfulness of the calorimetric diagnostic to the estimation of the total neutron and total radiated powers. We believe that it could also be interesting to use such instrumentation in the divertor cassettes to be able to separate the radiative and the convective fluxes falling on the target plates and on the dome.

Evaluation of MSE measurements in the assessment of q-profile determination

Calculations show that for the proposed MSE diagnostic on the Heating Beams, the ITER requirement (10% accuracy for i =1/q) is satisfied everywhere at the 1σ rms error. So as to satisfy the conditions used in these calculations, we recommend that the error on the measurement of the MSE angle should not exceed +/- 0.2°.
Concerning the temporary conclusions on spatial resolution, since this problem is important for the accurateness of the diagnostic, we encourage to perform new calculations with more appropriate coordinates. We nevertheless already recommend to install MSE channels in the regions of bad spatial resolution as well, in case one of the beam is off.
For ITER plasma scenarios, we recommend that if only one beam is used, to operate preferentially HNB4 to have central MSE measurements.
Two interesting questions need to be answered in future calculations: can a high density of channels compensate the bad spatial resolution? and evaluate the q-profile reconstruction with the central MSE only.

Contribution to the design analysis of the ITER plasma-position reflectometry system

Reflectometry is a radar technique operating in the microwave range and is extensively used in most fusion devices to performed electron density measurements. It is a well-established technique, which provides an excellent radial localization of measurement. Since this technique is inexpensive, provides rapid measurements (in the microsecond range), and requires very low access to the machine, it is a strong candidate to provide plasma position and plasma shape measurements on ITER.
However, long waveguide chains travelling all around the ITER vacuum chamber through complex way will be required to bring the wave from the diagnostic itself to the plasma and great care must be taken to preserve the amplitude signal from waveguide loss processes. In this task, waveguide transmission has been studied showing losses lower than 0.1 dB/m for F>25 GHz.
Due to thermal dilatation, the length of the transmission line will evolve during a shot, and it is shown that a reference to know precisely the phase dispersion due to transmission is required.
As this technique is sensitive to plasma density fluctuations and naturally suffers from parasitic reflections, 2D code has been used to analyze it. Multi-reflections are barely distinguishable from the main reflection and to separate signals, simulations have been achieved by moving the plasma 40 cm away from the blankets. Concerning fluctuations, the broadening of the reflected signal have not been conclusive. However, present simulations in 2D exhibit an amplitude signal very low (< 50 dBc) which is suspected to be too low and due to the 3D nature of this problem a simulation should be done in 3D taking into account the vicinity of the blanket. Direct experimental measurements should be envisaged.
The thermal constrains that many ITER diagnostic performing in situ measurements has to face are calculated. The maximum temperature reaches 471°C in the copper in front of the plasma. This temperature is near the limit for CuCrZr. The most important load is the nuclear heating, the assumptions used in the calculations have to be carefully checked and in particularly the peaking factor due to the gap between the block shields. The time constant of the maximum temperature is about 200 s.

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- CEA international report DIAG/NTT-2004.032: Calorimetric Analysis of the ITER Blanket Modules.(J.C. Vallet)

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CEFDA04-1206PI

Task Title: TW4-TPDS-DIASUP1: DIAGNOSTIC DESIGN FOR ITER: PORT INTEGRATION

INTRODUCTION

ITER requires an extensive set of diagnostic systems to provide several key functions such as protection of the device, input to plasma control systems and evaluation of the plasma performance. These diagnostics system are to be integrated inside the vacuum vessel of ITER by means of water cooled stainless steel structure (60 t, 2m x 2m x 4 m) named port plug structure. The port plug structure must perform basic functions such as providing neutron and gamma shielding, supporting the first wall armour and shielding blanket material, closing the vacuum vessel ports, supporting the diagnostic equipment (see figure 1). Although the required analyses were associated with those port plugs (EQ01,UP01, UP14 and L16) where Europe and more particularly CEA may have a certain responsibility in term of diagnostics, CEA has focused on the design and diagnostic integration in the generic equatorial port plug EQ01. The specific CEA contributions were to perform, associated to this port, general engineering (including CAD effort), structural and thermal analysis [1].

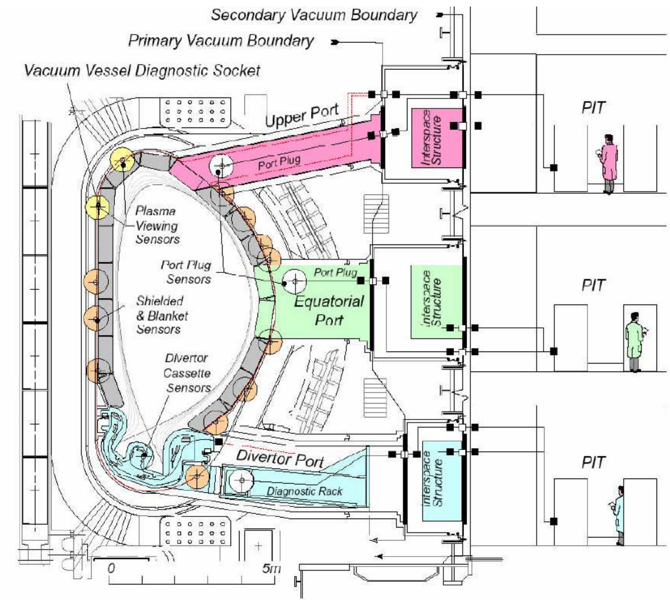

Figure 1: ITER vertical section

2005 ACTIVITIES

DIAGNOSTIC PORT INTEGRATION

According to the specifications of the contract EFDA 04-1206 D1.2, CEA contributed to a part of the design study of the ITER port integration. It considered:

(a) CAD models review and integration on port plug generic EQ01,
(b) Structural assessment of the ITER equatorial port plug EQ01,
(c) Thermal assessment of the ITER equatorial port plug EQ01,
(d) Dynamic transient and seismic response of the ITER equatorial port plug EQ01.

In complement to this contract, synthesis of guidelines used in EFDA studies done by CEA on ITER diagnostics and diagnostic port plug variant analysis (EQ01,UP01, UP14 and L16) have also been carried out.

(a) CAD models review and integration on port plug generic EQ01

To perform the CAD model review of the equatorial port plug EQ01 several requests to the ITER design office have been done for the CATIA CAD models recovery and the comprehension of those models.

Then some actions have been performed in order to carry out this task: CATIA transfer V4 V5, reconstitution of the assemblies, checking of the interfaces, finding inconsistencies, adding missing features (see figure 2).

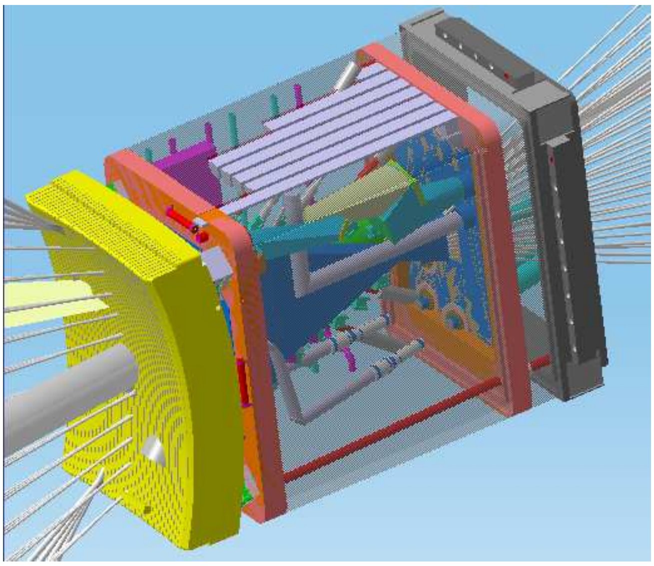

Figure 2: 3D view of the equatorial port plug EQ01

Eventually, the result of our work has been integrated in the ITER DO data base via the passive mode of the Virtual Product Management system ENOVIA.

(b) Structural assessment of the ITER equatorial port plug EQ01

For this static mechanical assessment five models of the equatorial port plug have been produced in CATIA V5: a very simplified model named beta model, a model without top beam, a model with top beam welded and two models with top beam bolted (see figure 3 for terminology).

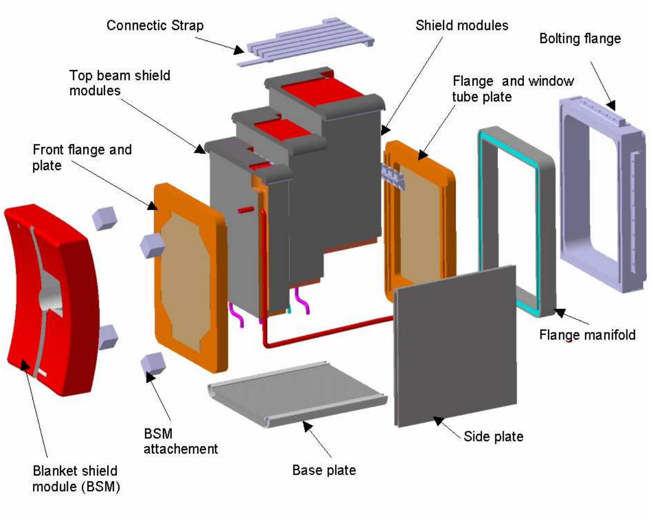

Figure 3: 3D exploded view of the equatorial port plug

The beta model enabled us to understand the structural behaviour of the port plug, to check the stresses and displacements order of magnitude, and to check that the analysis module of CATIA V5 is well mastered.
Self weight and three kind of disruption conditions have been taken into account (CD27ms, fu-VDE, fd-VDE). Those cases of loads have been applied to each of the five models.
The CD27ms case of loads is the worst one for the structure and only the model with the top beam welded seems to have characteristics to resist to it.
Concerning this model, the maximal Von Mises stresses reach 173 MPa (no safety margin towards the yield stress), this stress is localised at the level of the BSM attachment system. The maximal displacement (see figure 4) of the structure reaches 2.23 mm (8.97 of safety margin toward the minimal gap with the Tokamak).

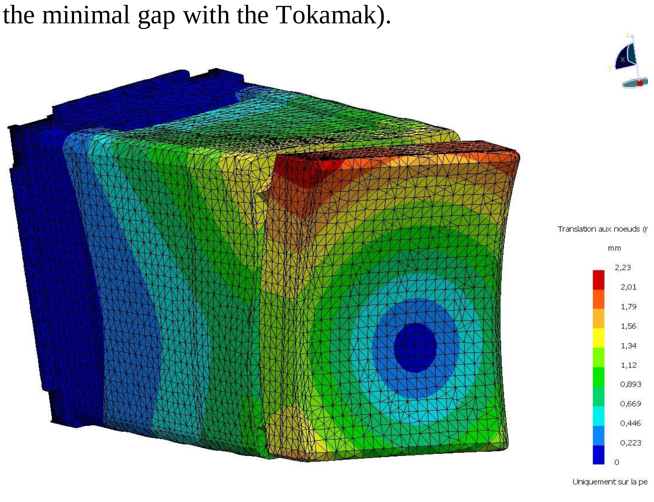

Figure 4: Displacements of the equatorial port (disruption)

Concerning the design of the port plug, top beams are very important for the rigidity of the whole structure. If the top beams remain to be bolted, the bolting attachment system needs to be reviewed.
Moreover because of the high level of stress in localised area, deeper analyses are required for attachments of the port plug to the vacuum vessel and the BSM attachment system.

(c) Thermal assessment of the ITER equatorial port plug EQ01

In this assessment, the thermal behaviour of the port plug structure in regard to the neutronic loads has been estimated. For this first estimation, four different studies have been carried out: i) the study of the side and base plates, ii) the study of the shield modules, iii) the study of the front plate and flange iv) the study of the window tube plate.
For these studies a 60°C water temperature increasing and 350°C of maximal SS temperature have been considered as specification according the CEA's experience in inner vessel actively cooled components.
For each element, the models take into account the initial CATIA V5 design and all the thermal calculations, in steady state conditions, have been performed with the finite element calculation code ANSYS. For each model, the initial concept of cooling system is analysed and some ameliorations are proposed.

i) The side plates and the base plate have got an efficient cooling system, the maximal SS temperature reaches 117°C and the number of cooling channels can be reduced from 27 to 13 (see figure 5).

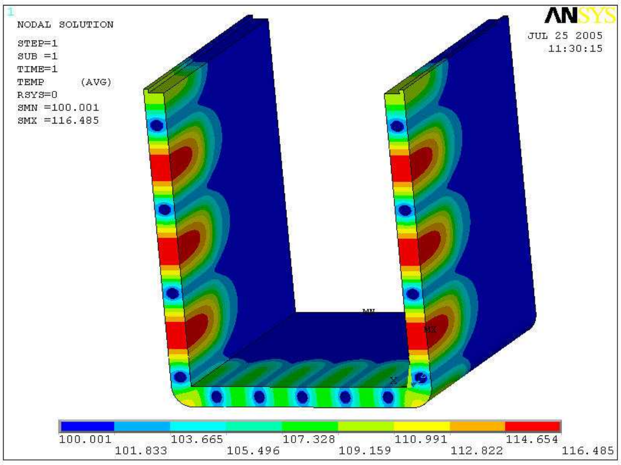

Figure 5: Side and base plate temperature map

ii) Concerning the shield module 1 which is the most thermal loaded shield module, a proposition (peripherical groove and 5 pipes) of cooling circuit is proposed and the maximal SS temperature reaches 581°C. This proposition could be updated with a new diagnostic implementation in order to reach the specifications. The shield module 2 has been calculated with a peripherical groove and 2 pipes of cooling (Tmaxi=361°C). For the shield module 3 a peripherical cooling groove will be enough for cooling.

iii) Concerning the front plate and flange, in spite of the three cooling grooves, the maximal temperature reaches 830°C. This element needs to be reviewed in term of cooling.

iv) The window tube plate doesn't need to be cooled, the welded contact with the flange is enough for its thermalisation.

(d) Dynamic transient and seismic response of the ITER equatorial port plug EQ01

Dealing with the transient calculations, the radial moment is the most stressing load, as it entails 95.7% of the deviational effects, but the dynamic behaviour of the model is far from plasticity. In addition, it investigates the shear stiffness of the port-plug.

Any way, dynamic effects are very limited. But the specifications are not met in term of stress:

- The maximum displacements are very low and do not exceed 3 millimeters even in a case of resonance (see figure 6).
- The maximum stress is more than twice the yield strength.
- The maxima occur at some sensible locations, that is to say the embedding locus and the BSM attachments. That was predictable, and an effort has to be done on the design of the attachments and on the cuttings of the top-beam on the in future improvements of the port plug.

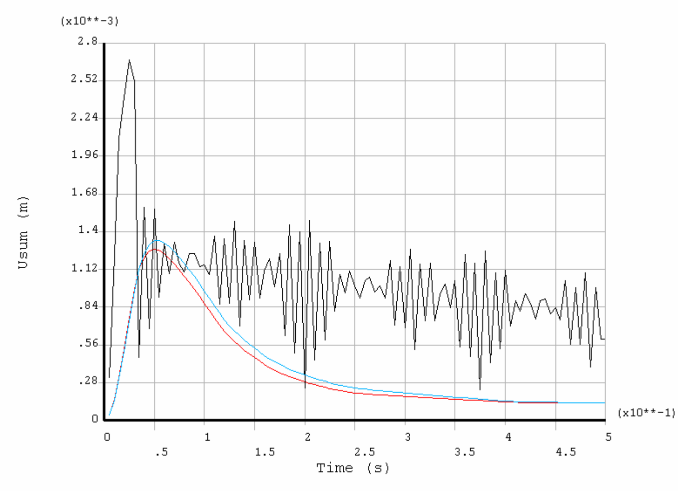

Figure 6: Forced resonance phenomenon of the port plug

The process of the dynamic modal and transient analysis of equatorial plug is well mastered, and can be performed on a much more realistic model. At this stage, a lot of improvements have to be done, to better fit the up-to-date design of the port plug, and the reality of the different applied loads. To be discussed is the interest of a homogenization method in order to consider water cooling into a fictive equivalent material behaviour. For instance, it will permit to light the model, compared to modeling every cooling structure that will implies meshing singularities.

Further investigations could also lead to consider the shield modules by implementing the model with them. In fact dynamic effects could be increased a lot with this surplus mass, even if the calculation of the critical mass before resonance seems to be a pledge of confidence.

For the seismic calculations, the ASME Design Response Spectrum and the ground spectra and soil conditions in the CEA-Cadarache site with low-frequency horizontal seismic isolation spectrum have been considered. The resulting displacement values at the level of the port plug are very low in the order of magnitude of 10^{-4}m (see figure 7) and can be neglected. The first assumption of inputting a constant spectrum was enough to give an accurate idea of the port plug behaviour. It is validated by the fact that harmonic responses of the Port-Duct do not present any peak, and the natural frequencies of the Vacuum Vessel spreading between 0.5 and 7 Hz.

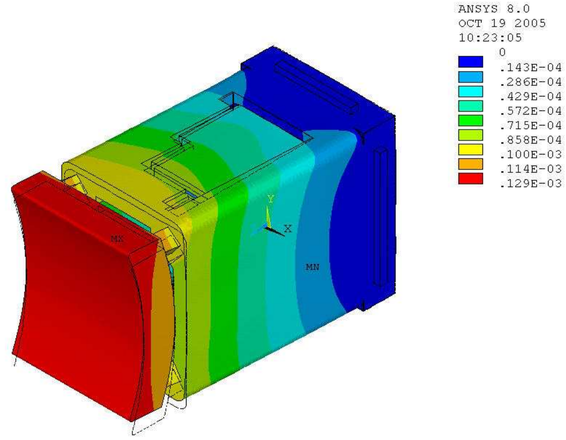

Figure 7: Mode combined displacement for a Cadarache vertical seismic excitation (in meters).

This dynamic assessment permits to know with reliability that the Equatorial Port-Plug meets the specifications for both the disruption and the seismic case, at the current stage of its design, and according to all the assumptions and hypothesis that have been taken.

CONCLUSIONS

Concerning the diagnostic port integration task, the design review and the performed analysis enable us to understand the mechanical and thermal behaviour of the port plug under several case of load. The design with top beam welded appears to be consistent in term mechanics, nevertheless local calculations at the level of the attachment devices remain to be done. Concerning thermal, the far forward shield module and the front plate and flange reach a very high level of temperature, their water-cooling circuit remains to be optimized.

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CEFDA04-1206MD

Task Title: TW4-TPDS-DIASUP1: DIAGNOSTIC DESIGN FOR ITER: MAGNETIC DIAGNOSTICS

INTRODUCTION

The EU will supply the magnetic diagnostics for ITER. Past EFDA contracts [1-3] have mainly considered and optimized position and coil performance. Many outstanding technical issues are still to be analyzed and developed to fully implement the magnetic diagnostic.
While the magnetic diagnostic includes a wide diversity of sensors in interaction with the ITER vacuum vessel and located in various places, the task involves 4 partners: EPFL-CRPP which ensures the task coordination, ENEA-RFX, CEA and CIEMAT. It is also conducted in very close interaction with the ITER International Team (IT).
The objective of the 2005 CEA activity deals with the analysis of the general design of the magnetic diagnostic focusing on the outer vessel tangential and normal coils (A.01), the external continuous poloidal Rogowski loops (A.04) and the inner vessel partial and continuous flux loops (A.02).

The addressed overall activities are:

(a) The review of the implementation of the magnetics diagnostic systems.

(b) The beginning of the outline design of specific types of sensors

(c) The planning of the full development of the ITER magnetics diagnostic

(d) The definition of the future design, R&D and performance analysis

(e) The analysis of the needs for electronics (mainly the integrators)

(f) The assessment of the existing documentation and the support of the ITER IT in the writing of procurement specifications for the magnetics diagnostic

During this task, a special care was devoted to the improvement of the design, the material choice and the construction technique of the ex-vessel coils and external Rogowski. The sources of measurement errors have been investigated as well.

2005 ACTIVITIES

OUTER VESSEL TANGENTIAL AND NORMAL COILS (A.01)

The outer radial and tangential field coils set-up is a supplementary set used to measure the plasma current, the plasma equilibrium and the plasma low frequency MHD activity. The available space for their installation implicates that the coils have a very small radial dimension to avoid clash with the vacuum vessel thermal shield during assembly and operation. The winding case is 7x57x250 mm^3 in the areas where the radius of curvature of the vacuum vessel is big and 7x57x125 mm^3 in the areas where the radius of curvature of the vacuum vessel is smaller. In these winding cases, the effective area of the ex-vessel coils must be respectively 2 m^2 and 1 m^2. The outer vessel coils will be mounted on the outer surface of the vacuum vessel (figure 1). On the basis of [4], the number of sensor is set to 60 tangential field sensors plus 60 radial field sensors which appear acceptable with respect to the plasma reconstruction error.

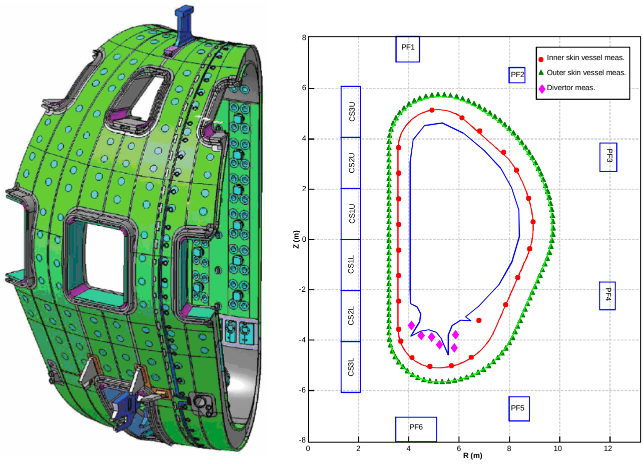


Figure 1: Location of ex-vessel tangential and normal coils

The present design uses enamelled copper wire on a ceramic bobbin. In order to reach the ITER specifications and make easier the manufacture of the coils, several shapes of mandrel have been designed and studied (figure 2).

The coil of shape (a) reaches the objectives in terms of available space and effective area but it is extremely hard to wind. The coil shape (b) have too big radial dimension (2 mm in excess) but they are easier to wind because of their elliptic shape and smaller number of layers. Finally, the coils with shape (c) are no longer considered because they are very hard to wind (mandrel diameter = 2 mm and mandrel length = 250 mm) and the winding case is much bigger than allowed.

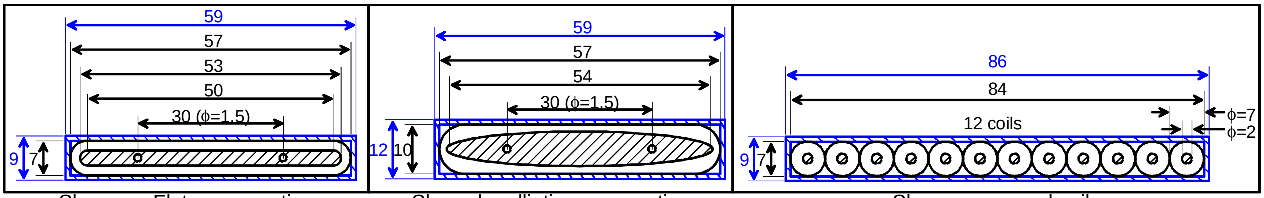


Figure 2: Cross section of the coils that have been studied as radial and tangential coils

Table 1: Characteristics of the coil

	Shape a	Shape a	Shape b	Shape c (12 coils)
Coil Outer Dimension	7x57x250 mm	7x57x125 mm	10x57x250 mm^3	10x84x250 mm^3
Number of layer	8	8	6	10
Coil effective area	2.122 m^2	1.061 m^2	2.182 m^2	2.061 m^2
Cable length	907 m	455 m	674 m	1668 m
Coil resistance at 293K	873 Ω	437 Ω	650 Ω	1606 Ω
Coil inductance	270 mH	135 mH	270 mH	-
Cut-off frequency	515 Hz	515 Hz	384 Hz	-

Enlarging the radial coil dimension is not possible because the "official" clearance between the inner part of the vacuum vessel and the thermal shield is set to 11 mm. Of this, a margin of 1 mm has been taken. Of the remaining 10 mm, 7 mm have been allocated to the winding, 2 mm to the casing and 1 mm for packing material. Therefore, with such a margin and avoiding machining of the vessel, the available space cannot be enlarged up to 7 mm.

Using shape (a) elongated coils the winding issues are:

a) The winding length is rather big (250 mm / 980 turns). Therefore each layer is already hard to do. In fact, each turn must join the previous one in order to fill totally the layer, then, this work must be performed on 8 layers without leaving gap.

b) Coils using a flat part on the former are difficult to wind, in particular, because it is essential to keep the contact between the cable and the coil former at any time which is impossible to achieve with a flat part on the former. Some freedom is left to the cable with respect to the coil former. This defect allows the cable to move more or less freely preventing the winding of the next layer. One solution could be the use of heat sealing cable. After a layer is wound, the coil is heated to fix the layer.

c) This coil needs 8 layers to get an effective area of 2 m^2. This is already a great number of layers with such elongated coil.

d) Because the cable is not in contact with the coil former, the radial coil OD may be bigger than the theoretical value.

e) The cable OD is 0.25 mm which is relatively small. The cable is probably fragile and need special attention.
An alternative solution to the expected winding problems could be the use of kapton foil where copper track are designed inside in the same way than a printed circuit. Adjusting the track design and the connexion between the layers, a 2 m^2 coil seems to be achievable. The copper track in the insulating foil could be straight lines with electrical connexions on both ends. The electrical connexion must be "oriented" in one direction at the beginning of a wire and in the opposite side at the end of the cable. Using an insulating foil of 50 µm thickness and a copper cable of rectangular cross-section (25 x 150 µm) the resistance of the coil will be at least 4 times bigger. In order to keep enough space for the electrical connexions, only 490 turns per layers (490 turns / 245 mm) have been considered. In that case, the connexions wideness could be 250 µm and 12 layers are necessary to get a 2 m^2 coil with a flat coil former of dimensions 50x5.8x245 mm^3 which is more comfortable. In return, ensuring good electrical connexions between the layers is an important issue and needs R&D.
Concerning the ex-vessel coils operation, one must address the issue of the vacuum vessel thermal expansion. This effect may change the coils orientation and make them sensitive to stray field. More, during the vessel expansion and extra field could be integrated by the coils.

EXTERNAL CONTINUOUS POLOIDAL ROGOWSKI LOOP (A.04)

The external continuous Rogowski is a separate backup facility measuring the plasma current. It can also procure information to calculate the plasma shape and position. This system is sensitive to the total vessel current. However, it suffers less from the effects of integrator drift. Therefore, the external Rogowski provides a potentially valuable backup in case of drift of the in/ex-vessel systems for long pulse operation.

The external Rogowski is located in grooves into the TF coil casing on a poloidal contour (figure 4). The groove diameter is big enough (typ. 14.5 mm) to accommodate a 12 mm OD coil and it should be set in a poloidal plane to simplify the path and avoid magnetic pick-up. In this space it is possible to make a Rogowski having 2 layers. The Rogowski should survive for the lifetime of the TF coil. The coil expands and contracts during the cool-down / warm-up cycles (a few cycles 4K-300K) and also expands and twists during each pulse (~ 10 mm, a few 10^4 cycles). In some places, the Rogowski former must be bended with a radius of curvature of 100 mm in order to bypass elements.

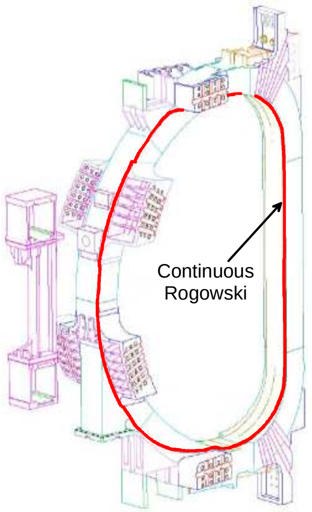


Figure 4: View of the Rogowski route on the TFC casing

The electrical parameters of the designed Rogowski are:

Coil Outer Dim	12 mm
Cable diameter	1 mm (conductor 0.75 mm)
# layers	2 (ϕ_1=9.0 mm et ϕ_2=11.0 mm)
# turn per layer	13600 (length = 34m pitch = 2.5 mm)
Cable length	860 m
Coil mutual inductance	80 mV.s/MA
Coil resistance @ 4K	331 mΩ (33 Ω @ 293K)
Coil inductance	4.0 mH
Coil capacitance	213 pF
Cut-off frequency	>1.5 kHz (on 50Ω)

Using a Rogowski coil, it is important to ensure that the winding is as uniform as possible. A non-uniform winding makes the coil susceptible to magnetic pickup from adjacent conductors or other sources of magnetic fields. This could be ensured by making two helicoidal grooves in the former of the Rogowski; one having a positive pitch, the other one with a negative pitch (figure 5).

A model has been made to point out the main issues in the coil manufacture (figure 6). First, making two grooves on the mandrel requires a pitch bigger than 2.5*ϕ_{cable} (=2.5 mm) between each turn to still have matter for the second layer. The groove depth is also an important parameter and must be just bigger than the cable OD. The bending hasn't been tested

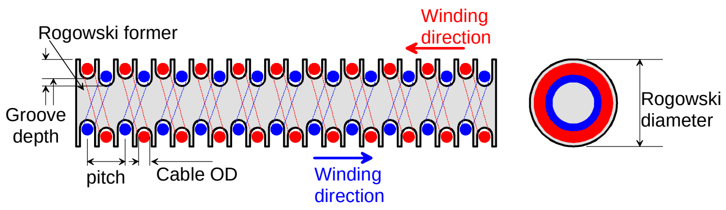


Figure 5: Example of grooves in a Rogowski for uniform winding.

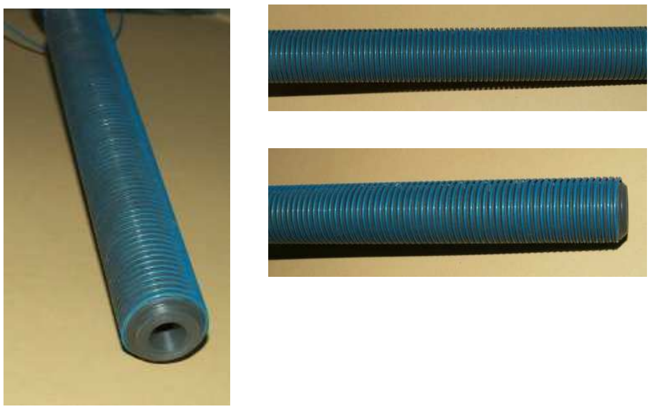


Figure 6: Photos of the Rogowski model made at CEA (cable is blue)

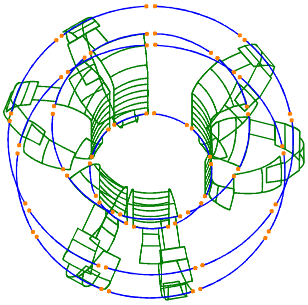
A thermal analysis has also been performed in order to ensure that the stress on the cable is low enough during the TF coil cooling down. In particular, the stress on the cable has been calculated to be much smaller than the Copper Young modulus.

INNER VESSEL PARTIAL AND CONTINUOUS FLUX LOOPS (A.02)

The flux loops, together with the Equilibrium coils and divertor coils are used to measure the plasma equilibrium and vertical speed. The continuous flux loops are also used to define the loop voltage and acts as a supplementary measurement to get the plasma current. The partial flux loops procure a supplementary set of measurements to define the plasma MHD activity. The inner vessel equilibrium partial and continuous flux loops are already well defined in [5], [6]. This set-up is composed of 4 independent continuous flux loops and 6 sets of 20 saddle loops (partial loops) (figure 7).

The continuous flux loops are attached to the vessel thermally and mechanically with frequent spot welded stainless steel clips. The loops have 9 special welded and re-weldable joints (figure 7) at each sector which allows removing the joint and re-instating it by remote handling techniques in case of sector repair or replacement. The loops are simply made from 2 mm diameter MI cable (conductor diameter=1.5 mm). Their simplicity make this set-up extremely reliable and robust therefore, no maintenance is anticipated. The radial dimension of the continuous flux loops is inhomogeneous:

R=3.573 m; R=5.755 m; R=7.276 m; and R=6.768 m.



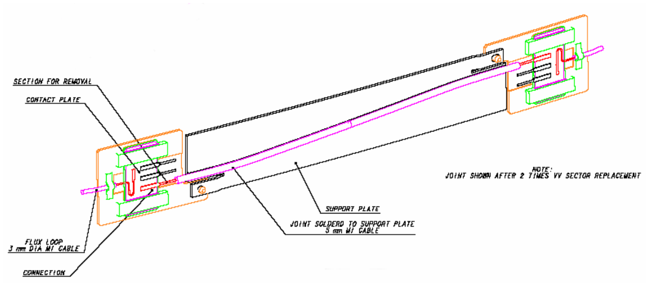


Figure 7: Inner vessel equilibrium flux loops implementation (blue=continuous flux loops, green=saddle loops). On the left, a schematic view of the Continuous flux loops joint

Table 2: Associated electrical parameters:

	R=3.573m	R=5.755m	R=7.276m	R=6.768m
Cable length (m)	22.45	36.16	45.72	42.52
Loop resistance at 300K (mΩ)	220	350	440	410
Loop inductance (μH)	39.5	67.1	86.9	80.3
Cut-Off frequency (Hz)	890	830	810	815

CONCLUSIONS

Three kinds of ITER magnetic sensors have been reviewed. Manufacturing procedure and recommendations have been made. In particular, the ex-vessel tangential coils exhibit the more severe constraints: the available radial dimension is very small (7 mm), the requested area is rather big (2 m^2) and there exist a big discrepancy in their dimensions. Other solutions have been suggested but R&D is required and models must be performed to ensure that such coils are feasible. On the other hand, a radial coil in the same winding pack is easier to produce.

The design of the external Rogowski coil has been refined. In particular, a former on which grooves making a double screw is proposed to ensure a regular winding. A model has been produced at CEA. The path in the TFC casing has also been defined in collaboration with the ITER IT.
The inner vessel tangential and partial flux loops set-up is very simple, because it is made of MI cable arranged around the torus or making saddle loops. We highlighted the special attention that must be devoted to the mounting, because they have big radial dimensions and they must define a horizontal plane in order to measure only the vertical flux. During the plasma, the vessel thermal expansion could damage the loop. Therefore it is recommended to leave an extra length of cable at some places.
In general, the vessel thermal expansion effects have been highlighted as a potential source of error. A model of the vacuum vessel representing its thermal behaviour must be developed. In the same way, the eddy current in the structure must be modelled in a future work.

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TW5-TPDC-IRRCER-D03

Task Title: ASSESSMENT OF IR FIBRES FOR THERMOGRAPHY APPLICATIONS, INITIAL GAMMA INDUCED EFFECTS, THEN NEUTRON IRRADIATIONS FIBRE SELECTION AND PROVISION, DIAGNOSTIC PREPARATION AND MEASUREMENTS

INTRODUCTION

Fibres can play a useful role for ITER e.g. for spectrally resolving thermography in particular when operational in the IR (Infra Red) range [1]. The fibres will be subjected to neutron and γ doses depending on the proximity to the core of the tokamak. Relevant and reliable radiation hardness data are only available for silica fibres and generally only up to a wavelength of 1.7 µm. Tore Supra has successfully used ZrF_4 fibres transparent up to 4.5 µm in the recent past [2]. These fibres have a spectral band-width, transparency, working temperature and mechanical flexibility adequate for ITER thermography applications, but little is known about their radiation hardness. Presently there are two main manufacturers known to us of that type of fibre: *Reflex Analytical* and *Le Verre Fluoré*. With the conclusion of the EFDA contract TW5-TPDC-IRRCER-D03 a formalisation of the already existing collaboration with the SCK·CEN Mol was achieved, which permits the CEA to use SCK·CEN facilities to irradiate IR fibres. The preparation of a spectrometer and its ancillary parts for autonomous IR measurements of fibres under irradiation was the first step of this task and the main achievement of 2005. This preparation permits now to envisage the second step, which is a first campaign of automated measurements in march 2006 at the γ irradiation facility RITA of the SCK·CEN Mol.

2005 ACTIVITIES

PREPARATION FOR AUTONOMOUS IR MEASUREMENTS

The most interesting radiation effect measurements are made on-line with equipment installed next to the irradiation source. The standard equipment that is available at SCK·CEN Mol is limited at 1.7 µm maximum wavelength. Our main interest is beyond that wavelength, with a particular interest in the range around 3-5 µm, but eventually also up to 10 µm. With financial support from the region PACA (Provence Alpes Côtes d'Azur) we have acquired a spectrometer set-up that was programmed at the CEA to do such measurements in an autonomous way and which will be at the SCK·CEN Mol for the duration of the irradiation measurements.

Figure 1 shows the main elements of the spectrometer set-up for transmission measurements of a fibre, which is the primary use of this set-up. In this condition a light source is used to provide broadband spectral illumination. This light is passed through a filter-wheel, chopped, spectrally selected by the TRIAX spectrometer, then passed either through a fibre to be measured or directly onto a detector and finally synchronously analysed.

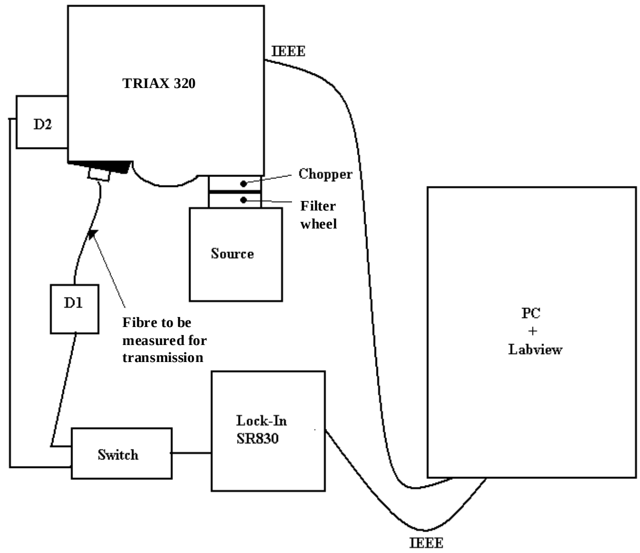

Figure1: Set-up for automatic transmission measurements

The light source is a Globar type light source operating at 1450°K which provides a continuous illumination with useful intensity in the spectral range of 800 nm to 10 µm. The filter-wheel is equipped with 5 high-pass filters with cut-on wavelengths at 600 nm, 1030 nm, 1970 nm, 3620 nm, and 6000 nm. This allows to avoid the superposition of different spectral orders of the light diffracted off the gratings of the spectrometer. The chopper is used at 345 Hz. The TRIAX 320 spectrometer is equipped with 3 gratings (table 1). The choice of the grating, the wavelength, the width of the slits and the position of an internal mobile mirror are remotely controlled. The mobile mirror allows to send the spectrally selected light either through the fibre to be measured to detector D1 at the far end of the fibre or directly to the reference detector D2. As detectors we use – depending on the wavelength range of interest - Peltier-cooled PbSe (< 4.8 µm) or HgCdTe (< 10 µm) single channel devices at –30°C or –40°C respectively. A switch that is synchronised with the mirror position connects the detector that receives light with the lock-in amplifier SR 830. All these elements are controlled via an IEEE interface from a PC running a custom made Labview application. The same Labview application controls also the power of the Globar light source (and other components) to prolong its lifetime during irradiation exposure campaigns of a duration of weeks or months which are expected to be necessary for interesting fibres. The program that operates the set-up requires as input spectral range and resolution for the spectrometer and sensitivity and filtering time constant for the detection. It selects grating and filter, switches from reference to measurement and does such runs at pre- programmed intervals.

Table 1: Gratings of the TRIAX 320 spectrometer

Number of grating	Blaze wavelength (nm)	Lines per mm	Optimum spectral range (nm)
1	1000	300	800 - 1350
2	2000	300	1350 - 2900
3	5000	150	2900 - 10000

In another configuration, the same elements of the spectrometer set-up can be used to measure radio-luminesence or Cherenkov radiation in the fibre, effects that appear at relatively high dose rates. One possibility to do so, is to replace the light source by the fibre which is irradiated and use detector D2 for measurements.

RESULT OF PRELIMINARY IRRADIATION EXPERIMENT

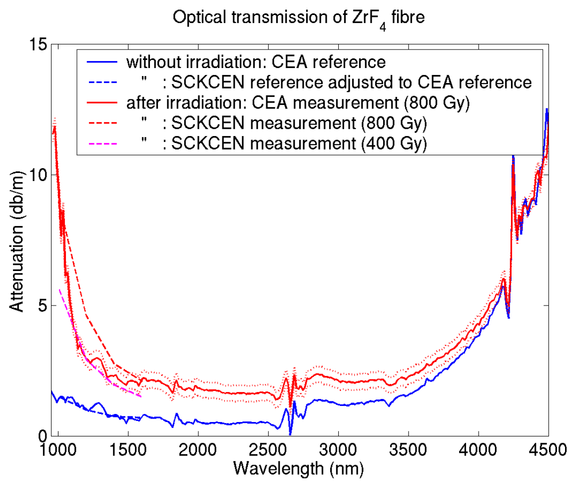

Figure 2: Attenuation measurement of exposed and unexposed ZrF_4 fibres (Reflex Analytical).

A preliminary experiment with γ irradiation of a ZrF_4 fibre (Reflex Analytical) from Tore Supra [2] has been performed in the beginning of 2005 by Benoit Brichard (SCK·CEN) in an informal collaboration between CEA-Cadarache and SCK·CEN Mol in Belgium. The results (after 30 minutes of gamma exposure) were significantly (4-5 orders of magnitude) worse than the best silica results in the NIR (Near Infra Red) range at 1.5 µm. The described set-up (figure 1) has been used to measure the attenuation of light up to 4.5 µm in the exposed ZrF_4 fibre as well as in un-exposed reference ZrF_4 fibres (figure 2). In the IR range above 3.5 µm the additional attenuation in the exposed fibre was relatively small – which is encouraging.

CHOICE OF FIBRES FOR FIRST IRRADIATION CAMPAIGN IN MARCH 2006

For the irradiation campaign in March 2006 we dispose of 2 types of ZrF_4 fibres from *Le Verre Fluoré* of 2 m length, further ZrF_4 fibres from *Reflex Analytical* (3.3 m) and hollow fibres (polymicro) of the internal diameter of 750 µm and 500 µm. The hollow fibres have spectral transmission up to 10 µm and no darkening fibre core, which makes them potentially interesting, despite their relatively low basic transmission. Standard silica fibres will also be irradiated to study their behaviour in the wavelength range 1.7-2.3 µm. To be able to measure online effects we use long patch-cords fibres of 11 m length made of ZrF_4.

OUTLOOK

A sapphire fibre will soon become available for tests. Other candidates that are under discussion are chalcogenide and holey (Bandgap) fibres.

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