LLNL-CONF-403743

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Diagnostic Components in Harsh Radiation Environments: Possible Overlap in R&D Requirements of IC and MF Systems

J. L. Bourgade, A. E. Costley, R. Reichle, E. R. Hodgson, W. Hsing, V. Glebov, M. Decreton, R. Leeper, J. L. Leray, M. Dentan, T. Hutter, A. Morono, D. Eder, W. Shmayda, B. Brichard, J. Baggio, L. Bertalot, G. Vayakis, M. Moran, T. C. Sangster, L. Vermeeren, C. Stoeckl, S. Girard, G. Pien

May 9, 2008

17th Topical Conference on High-Temperature Plasma Diagnostics
Albuquerque, NM, United States
May 11, 2008 through May 15, 2008

Diagnostic Components in Harsh Radiation Environments: Possible Overlap in R&D Requirements of IC and MF Systems

J.L. BOURGADE[1], A.E. COSTLEY[2], R. REICHLE[3], E.R. HODGSON[4], W. HSING[5], V. GLEBOV[6], M. DECRETON[7], R. LEEPER[8], J.L. LERAY[1], M. DENTAN[2], T. HUTTER[3], A. MOROÑO[4], D. EDER[5], W. SHMAYDA[6], B. BRICHARD[7], J. BAGGIO[1], L BERTALOT[2], G. VAYAKIS[2], M. MORAN[5], T.C. SANGSTER[6], L. VERMEEREN[7], C. STOECKL[6], S. GIRARD[1] and G. PIEN[6].

[1]*CEA/DAM Ile de France, Bruyères le Châtel, 91297 Arpajon Cedex, France*
[2] *ITER Organization, Cadarache, France*
[3] *Ass. EURATOM-CEA, DSM/IRFM, CEA-Cadarache, 13108 St. Paul-lez-Durance, France*
[4] *EURATOM/CIEMAT fusion association 28040 Madrid, Spain*
[5]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[6]*Laboratory for Laser Energetics (LLE), University of Rochester, 250E. River Rd, Rochester, NY 14623*
[7] *SCK·CEN, EURATOM Ass. Belgium, Boeretang 200, B-2400 Mol, Belgium*
[8] *Sandia National Laboratory, Albuquerque, New Mexico*

Abstract: The next generation of large scale fusion devices - ITER/LMJ/NIF – will require diagnostic components to operate in environments far more severe than those encountered in present facilities. This harsh environment will be induced by fluxes of neutrons, gamma rays, energetic ions, electromagnetic radiation, and in some cases debris and schrapnel, at levels several orders of magnitude higher than those experienced in today's devices. For several years the question of possible synergy between inertial and the magnetic confinement research has been pursued by members of the respective communities. A first joint workshop specifically devoted to the identification and promotion of these synergies was organized in France, at Aix-en-Provence from June 27th to 29th, 2007. The workshop was attended by about 50 invited specialists. The participants identified a number of subject areas where common overlapping interests could benefit from additional interactions and meetings: windows, optical fibres, mirrors, cables, electronic components and 14 MeV neutron sources. In this paper we summarise

the findings of these working groups. We put the discussion into context by including a brief description of the environments and the physical effects that have to be handled.

1 INTRODUCTION

The next large fusion facilities - ITER for magnetic fusion (MF) and LMJ or NIF for inertial confinement fusion (IC) - will generate far more severe environments than those experienced thus far (Figures 1 and 2). For IC, the neutron, gamma fluxes, electromagnetic radiation, and in some cases debris and schrapnel, will be orders of magnitude higher than on present devices [1]. For MF, in addition to higher neutron and gamma fluxes and electromagnetic radiation, the neutron fluence will be orders of magnitude higher [2].

Many of the components of diagnostic systems will be subjected to these harsh environments. As a consequence, radiation induced phenomena will occur in the materials of the diagnostic components and have to be taken into account in diagnostic design for the first time. Preparation R&D is on-going in both the IC and MF communities. The obvious question is, is there anything to be gained by a closer association of the work in these two areas? This question has been addressed at discussions at fusion conferences and especially at the international workshop on Advanced Diagnostics for Magnetic and Inertial Fusion, Varenna, September 2001, and at the 15th Topical Conference on High-Temperature Plasma Diagnostics, San Diego, April 2004. Following these discussions, a dedicated workshop to address this topic was held in Aix-en-Provence, June 2007. In this paper we present the results of the discussions at that workshop focusing on the possible common R&D needs.

2 IC AND MF ENVIRONMENTS: SIMILARITIES AND DIFFERENCES

Diagnostic components in both the IC and MF environments will be subject to high levels of neutrons, gamma rays and x-rays. In addition, in MF there can be energetic ions and neutral particles whereas in IC there can also be a powerful electromagnetic pulse (EMP) and shrapnel from the imploding target. While some of the potentially damaging radiations are the same in nature, the dose levels, dose rates, energy spectra and durations are very different. But probably the most significant difference is in the pulse length: these will be very short in IC (< 300 ns) and very long in MF (> hundreds of seconds). As a consequence, prompt effects (during the pulse) will dominate in IC, while for MF in addition to prompt effects, accumulative effects (long term changes) will also be important. The typical radiation levels expected in the location of the most exposed diagnostic components for ITER and LMJ are shown in Table 1.

These levels of radiation can have two types of deleterious effects. They can induce changes in the physical properties of the materials and thereby affect the performance characteristics of the measuring sensor. For example, the high levels of ionizing radiation can change the conductivity of insulators (Radiation Induced Conductivity (RIC)) and thereby change the load on a sensor. The changes can be prompt or permanent. Secondly, the radiation can lead to the generation of spurious signals; for example radiation induced EMF can occur in mineral insulated cables and lead to spurious voltages. Similarly, radioluminescence in windows and optical fibres can lead to spurious signals in optical systems. There are at least 10 different types of phenomena that can occur at significant levels and have to be considered. These are listed in Table 2 along with the diagnostic components that can potentially be affected in both MF and IC, and the principal effects expected.

At the workshop in Aix-en-Provence the different MF and IC environments, and the different environmental physical effects, were considered. Four areas were identified where there could be useful synergy in the on-going preparations for the diagnostic systems: optical components, especially fibres, windows and mirrors, cables, electronics and neutron diagnostics. Dedicated discussions were held in each area.

3 OPTICAL FIBRES, WINDOWS AND MIRRORS

Optical fibres have several applications in both IC and MF. Common applications are their use as a distributed measuring system on the components of the fusion machines (eg strain gauges or temperature sensors and as high speed transmitters of data. In IC they are also used in the monitoring of the performance of the main drive laser (for example, pulse intensity and synchronization). In MF they are also used as components in the plasma diagnostic systems: for example, they are used as transmitters of optical signals from the diagnostic equipment in the port-plugs or the nearby port cells to the remote (typically 50 m) spectrometers and detectors in the diagnostic building, and as a sensor on the plasma current through the Faraday effect. They can also be used as a radiation monitor by measuring scintillation. These applications require radiation resistant fibres and the wavelength regions of common interest are UV to visible (for the sensor applications) and the mid IR (high speed data transfer).

The principal radiation effects that have to be considered are radiation induced absorption (RIA) and radioluminescence (RIL). RIA is mainly a function of dose: both ionization and displacement damage produce a build up of defects (impurity and vacancy related) which leads to enhanced absorption bands in the UV to IR range. RIL in contrast is a function of dose rate, and is caused by excitation of impurity and vacancy defects through electron and hole ionization production. Both RIA and RIL depend strongly on irradiation temperature, and for most candidate fibre materials, are less severe at higher temperatures due to reduced defect stability and quenching.

Extensive R&D on candidate materials has been carried out. This has shown that for the common applications fluorine-doped fibres and pure-silica optical fibres are of interest. Further radiation tests are needed and a collaboration, including the exchange of candidate fibres as part of the future R&D programmes, would be beneficial. Hydrogen-loading has also been shown to substantially reduce RIA (but causes an increase in RIL) and further tests by the IC community of H-loaded pure silica core fibres are planned in order to evaluate the behaviour under pulsed radiation conditions. The effect of the hydrogen loading will be also be studied in the UV range and will be of common interest.

In both fields there is a need to further develop models that predict the optical changes induced by the radiation and particularly the multiscale modelling based on *ab-initio* calculation approach [3]. This is a challenging step towards a deeper understanding of radiation effects in silica-based materials. It is known that the fabrication process of silica fibres plays an important role and must be considered in parallel. An accurate control of the fabrication parameters of the optical fibre is important and requires close collaboration of the researcher, the fibre supplier and the fibre manufacturer. This aspect is of considerable interest for both fusion communities.

Windows and mirrors are both components of common interest but were only briefly covered during the workshop due to limited time. In MC (ITER) they are essential transmission components for optical systems, and in IC for the laser ignition beams. Suitable radiation resistant window materials, in general fused silicas such as KU1, with acceptable RIA and RIL are available for MC applications. However the high radiation flux level during the IC pulse may make RIL a problem. It is probable that surface degradation of the windows and mirrors is the main area of common concern for the two communities. Surface degradation due to radiation damage, erosion (including shrapnel bombardment), or contamination lowers the laser damage threshold and in the case of windows can lead to failure. Hence *in-situ* protection (shutters) or cleaning (low energy laser pulses) are certainly activities of common interest.

4 CABLES

Possible synergies in cable issues include the type of cable and the three main radiation effects; RIC, RIEMF and Radiation Induced Electrical Degradation (RIED). It is expected that MF systems will use mainly MI cables, which are well suited to low voltage and low frequency applications, as well as being vacuum compatible, and suitable for high temperature operation. Moreover they are robust and radiation tolerant. In contrast due to the limited bandwidth of MI cables, IC uses standard PTFE/CH high frequency dielectric cables. As a result the specific component overlap is low.

For the radiation effects, RIC is of interest for both communities, but manifests itself in different ways (steady-state vs. transient effects). An extensive database exists for MI cables from which materials and cables with suitable properties can be selected, and for MF RIC is a problem which can be accommodated. For IC, although RIC may play a role in EMP, it is not the only factor and so the overlap is low. This is also the case for RIED, which is not expected to be a problem for the next step IC systems due to the relatively low doses and temperatures. In contrast RIEMF is important for both systems. For the MF systems the radiation induced voltages/currents, in combination with thermal effects (TIEMF) are significant, and have been extensively studied. In IC radiation-induced pulses also play an important role, but the origin is unclear, and may be a combination of effects such as RIC and RIEMF, as well as EMP. Due to the timescale of the effects being so different in the two systems, the overlap is very limited, although some joint work on modelling to understand the physical phenomena involved could be beneficial. While EMP is a major concern for IC, in general it does not play an important role in MF. In addition to cables, connectors and feedthroughs are important components in both types of installations, but as the cable types are largely different, there is limited overlap in this respect.

5 NEUTRON DIAGNOSTICS

Measurement of the absolute level of the neutron emission is required in both IC and MF experiments and dedicated neutron diagnostics are included in the diagnostic sets for this purpose. The diagnostics (detectors, spectrometers etc) have to be calibrated absolutely but the very different characteristics of the IC and MF plasmas has resulted in different techniques being developed. In IC, the plasma is essentially a point source and the neutron emission can be measured using relatively small, absolutely calibrated, neutron detectors located behind collimators at long distances (5 – 100 m) from the target. In MF, the plasma is an extended source and integration over the volume is required to obtain the total neutron emission. Moreover, in MF some physics studies require the spatial dependence of the neutron emission to be measured. This is measured by using multiple, different, lines of sight with a collimator and detector on each one and the employment of tomographic inversion procedures.

While the sources are different in spatial extent and time duration, both IC and MF neutron diagnostic systems require absolutely calibrated detectors and powerful, well characterised neutron sources, are needed for these calibrations. In both IC and MF, copper foil samples, activated to a known amount, are used as cross calibration sources. A second approach is to use a proton-recoil detector, where the absolute sensitivity is calculated based on the well-known n, p elastic scattering cross section and geometry. In IC, a third approach is to calibrate detectors on the OMEGA laser at closer distances from the target and scale detector sensitivity with distance at the NIF or LMJ. The OMEGA absolute DT calibration is known to better than 10% [4]. In principle, detectors for MF experiments could also be calibrated on OMEGA.

In MF, the extended nature of the source means that the spatial dependence of the sensitivity of the neutron system is needed and this is obtained by *in-situ* calibrations: in these a source of known intensity is moved inside the tokamak vacuum chamber and the response of the neutron detectors is recorded. For ITER, a powerful source with an intensity ~ 10^{11-12} n/s is needed. Account needs to be taken of the potential screening and scattering effects of the structure that is supporting the neutron source and this is done by use of the MCNP code.

The similarity of these measurements means that there are several areas of common interest: in particular, selection and performance of neutron detectors and spectrometers, the calibration of detectors using copper activation and the use of the proton-recoil detector. Collaboration and exchange of information on available neutron sources, and possibly joint development, could be beneficial.

6 ELECTRONICS

Radiation can damage or destroy electronic components or sensors, corrupt signals in analogue or digital circuits, corrupt data in memories, etc. Neutrons, gammas and ionized particles produce indirect and direct ionizing effects inside electronics components, and in optical and electrical links. These effects can appear progressively, due to cumulated ionization or cumulated atomic displacements, or instantaneously, due to a single highly ionizing particle (the so-called Single Event Effect (SEE)), or due to a strong blast of ionizing particles.

In IC, the penetrating ionizing particles are produced during the very short time of the experiment (picoseconds to nanoseconds). Neutrons and a percentage of gammas can escape from the highly compressed target and these particles are sufficiently energetic to pervade outside the target chamber. Upsets and latch-up of electronics can also occur from both gamma fluxes and neutrons (SEE).

In ITER the design approach is, as far as possible, to locate electronics behind shielding where the radiation levels are substantially lower (several orders of magnitude) than the first wall values. However, it may not always be possible to locate electronics in such shielded locations and some radiation hard electronics will be needed.

Experience from using electronics in radiation environments, for example on high energy physics experiments such as at CERN, has shown that it is essential to have a well developed strategy which includes elements such as a good characterizing of the environment, precise knowledge of the operating conditions of the electronic component, identification of known radiation hard components or qualification of new components, and the use of special architectures in the electronic circuit design to reduce radiation effects. A strategy along these lines was used at the ATLAS and CMS experiments at CERN [5].

7 CONCLUSIONS

Both the IC and MF communities are actively engaged in preparing for burning plasma experiments and extensive diagnostic systems are being prepared in each case. Some components of these diagnostic systems will unavoidably be located in the harsh radaition environments close to these plasmas. While the plasmas are very different in scale and duration, some areas of common interest exist; especially windows, optical fibres, mirrors, cables, neutron sources and detectors, and electronic components. Closer collaboration, exchange of information and possibly joint development in these areas is likely to be mutually beneficial.

The workshop in Aix-en-Provence was judged to have been a success and the participants and the scientific committee plan to organize a second workshop. Provisionally it is planned that the NIF team will organize the workshop and it will be held on the west coast of the USA in 2009.

Acknowledgement

Part of the work of this paper was undertaken within the framework of ITER Transitional Arrangements (ITA). These are conducted by the Participants: the European Atomic Energy Community, Japan, India, the People's Republic of China, the Republic of Korea, the Russian Federation, and the United States of America, under the auspices of the International Atomic Energy Agency. The views and opinions expressed herein do not necessarily reflect those of the Participants to the ITA, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the former ITER EDA Agreement.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] J.L. Bourgade et al, Rev. Sci. Instrum., 75, 4204 (2004), and this proceedings.
[2] G. Vayakis, E. R. Hodgson, V. Voitsenya and C. I. Walker, Fusion Science and Technology, **53**, No 2, 699 (2008).
[3] M. M. G. Alemany and J. R. Chelikowsky, Phys. Rev. B 73, 235211 (2006).
[4] M. J. Moran, V. Yu. Glebov, C. Stoeckl, R. Rygg, and B. E. Schwartz, Rev. Sci. Instrum. **76**, 023506 (2005).
[5] M Dentan, 'Overview of the ATLAS Policy on Radiation Tolerant Electronics', http://doc.cern.ch/yellowrep/2000/2000-010/p270.pdf

Figure Captions

Figure 1: Neutron and gamma fluxes on diagnostic components during operation for 500 MW on ITER. The solid curves are from a simplified 1D equivalent (cylindrical) model of the machine. This averages out the effect of gaps and does not include diagnostic penetrations [2].

Figure 2: Neutron and gamma fluxes in the locations of diagnostic components during full performance shots on (a) LMJ and (b) NIF [1].

Table 1. MF (ITER) and IC(LMJ) Radiation Environment Comparisons (approximate numbers only)

Location	Radiation	MF (ITER)	IC
Radiation level at first wall	Neutron Flux	3×10^{18} (/m^{2}s)	5 10^{18} n/shot 1.5 10^{16} n/m^2 @ 1ns equivalent to 1.5×10^{25} (/m^{2}s)
	Neutron Fluence (end of life)	3×10^{25} (/m^2)	10^{21} n/30 years 3×10^{18} (/m^2)
	Ionizing radiation (gamma rays) dose rate (Gy/s)	2×10^3	10^{10}
	Energetic ion/atoms flux (/m^{2}s)	5×10^{19}	-
Radiation level at first diagnostic component location (near gaps in blanket modules for MF, inside a SID-DIM for IC)	Neutron Flux	1×10^{17} (/m^{2}s)	5 10^{16} n/m^2 @ 0.5ns equivalent to 10^{26} (/m^{2}s)
	Typical neutron damage rate (dpa/s)	10^{-8}	negligible
	Neutron Fluence (end of life) (/m^{2}s)	2×10^{24}	10^{19} (/m^2)
	Typical neutron damage (end of life) dpa	0.1	negligible
	Ionizing radiation (gamma rays) dose rate (Gy/s)	10^2	10^{10}
	Energetic ion/atoms flux (/m^{2}s)	10^{18}	-
	Nuclear heating (MW/m^3)	1	0
	Typical operating temperature (˚K)	520	293
	Atmosphere	Vacuum	Air
Other	EM pulse	-	Yes (kV/m @ 1 GHz)
	Shrapnel	-	Yes (1-10 km/s) @ ~30 µm