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Response of the imaging cameras to hard radiation during JET operation

*Alexander Huber[a], Gennady Sergienko[a], David Kinna[b], Valentina Huber[c], Laurent Mercadier[b], Itziar Balboa[b], Sean Conroy[d], Simon Cramp[b], Vasili Kiptily[b], Uron Kruezi[b], Horst Toni Lambertz[a], Christian Linsmeier[a], Guy Matthews[b], Alberto Milocco[b,e], Sergey Popovichev[b], Philippe Mertens[a], Scott Silburn[b], Klaus-Dieter Zastrow[b] and JET contributors**

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[a]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[b]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK
[c]Forschungszentrum Jülich GmbH, Supercomputing Centre, 52425 Jülich, Germany
[d]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[e]University of Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

The analysis of the radiation damage of imaging systems is based on all different types of analogue/digital cameras with uncooled as well as actively cooled image sensors in the VIS/NIR/MWIR spectral ranges. The MCNP code has been used to determine the neutron fluence and energy distribution at different camera locations in JET. An explicit correlation between the sensor damage and the neutron fluence has been observed. Sensors show an increased dark-current and increased numbers of hot-pixels. Uncooled cameras must be replaced once per year after exposure to a neutron fluence of ~1.9-3.2×10^{12}neutrons/cm^2. Such levels of fluence will be reached after ≈14-22 ELMy H-mode pulses during the future D-T campaign. Furthermore, dynamical noise seen as a random pattern of bright pixels was observed in the presence of hard radiation (neutrons and gammas). Failure of the digital electronics inside the cameras as well as of industrial controllers is observed beyond a neutron fluence of about ~4×10^9 neutrons/cm^2. The impact of hard radiation on the different types of electronics and possible application of cameras during future D-T campaign is discussed.

Keywords: CCD, Camera, Radiation Damage, Hot pixels, Image, Camera cooling

1. Introduction

In magnetic fusion devices of the next generation such as ITER, high neutron and gamma-ray yields could be detrimental to the applied diagnostic equipment such as video imaging systems as well as to electronic components of machine control systems. Semiconductor devices are particularly sensitive to the radiation, both ionizing (formation of traps at the Si/SiO2 interface with energy levels within the silicon bandgap) and non-ionizing (displacement damage effects) [1]. Defects degrade the performance of CCD image sensors by increasing the average dark-current and dark-current non-uniformity, which result in the appearance of individual pixels with high dark-currents (“hot-pixels”).

In this contribution, we would like to summarize the experience of camera operation acquired during the D-D experimental campaigns on the JET machine.

2. Experimental Details

The analysis of the radiation damage of imaging systems is based on all different types of cameras:

- 4 operations cameras, colour CCD (Cohu DSP 3600 Series 3611) with uncooled as well as actively cooled image sensors (sensor: Sony ICX419AKL, pixel size: 8.6μm (H)×8.3μm (V))
- 12 protection NIR CCD cameras (Hitachi KP-M1AP; sensor: Sony ICX423AL pixel size: 11.6μm (H)×11.2μm (V))
- 7 scientific digital CCD cameras (Allied Vision Technologies (AVT) Pike F-100B) in NUV/VIS wavelength range with uncooled as well as actively cooled image sensors (sensor:KAI-1020M, pixel size: 7.4μm×7.4μm)
- 4 MWIR CMOS cameras with actively cooled (78K) image sensors (sensor: InSb, Pixels: 320 x256 with pixel size 25μm×25μm and 640 x512, with pixel size 30μm×30μm).

The cameras are mostly located at the top of the machine as well as at the equatorial plane and distributed across the different octants (see Fig.1 for the location of the protection NIR CCD cameras on JET).

Additionally, the impact of hard radiation on the different types of electronics such as electronic inside cameras, frame grabbers, PLC control unit will be discussed in this contribution.

Neutron transport calculations have been performed using the MCNP6 [2] code in order to determine the neutron flux/fluence and energy distributions at different locations in the JET tokamak, using an advanced JET model. JET biological shield and penetrations as well as all significant components such as diagnostics were modelled in detail. Simulations were performed for D-D toroidal plasma discharge sources with Gaussian-shaped neutron energy spectrum with peak energy of E_c=2.5MeV and the FWHM=16.6keV. To keep the statistic error of the simulations below 5% the code used relative large numbers of source neutrons, in the order of 6×10^9.

author's email: A.Huber@fz-juelich.de

The primary measurements of the neutron emission intensity from JET discharges are provided by a set of fission chambers which, combined with MCNP calculations, finally deliver the neutron fluence at locations of each JET cameras.

3. Radiation effects on Camera Sensors

3.1 Impact of the radiation on the uncooled cameras

It should be distinguished between the damage to individual images, which only occurs during radiation with production of the dynamical hot pixels and image

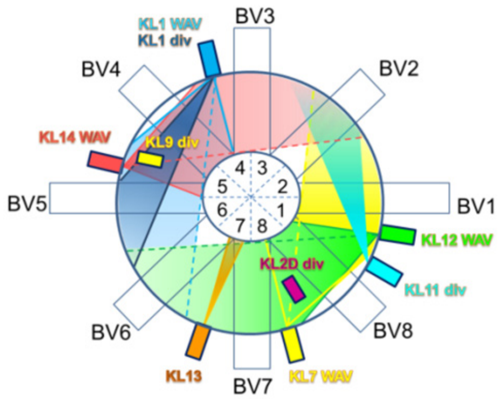

Fig.1 Top view of the JET tokamak. Field of Views (FoV) of protection NIR CCD cameras.

effects resulting from permanent damage of image sensors after heavy radiation. The last one results in the generation of the static hot pixels.

To investigate the impact of the radiation on the CCD, a digital camera type AVT Pike 100B with uncooled sensor was installed in the JET Torus Hall. The

Fig.2. Evolution of the camera background image with the radiation exposure time.

camera was fixed on the KL1 endoscope in Octant 4 and was oriented in toroidal direction. “Dark” exposures of the camera during the JET operations with closed lens cap for detection of dark current noise and hot pixels have been applied. The camera was operated in free running mode with 1 Mega Pixel resolution at the bit rate of 8 bits with the exposure time of 20 ms.

3.1.1 Permanent damage of the camera sensor

Fig.2 shows the evolution of the camera background image during the time period from 21/02/2009 to 23/10/2009. The total number of neutrons produced over this time period is 2.93×10^{19} neutrons corresponding to the neutron fluence in the area of camera location of ~1.2×10^{12} neutrons/cm^2. At the beginning the image shows only a little number of the bright pixels which increase during the test. At the end of the test period, the camera suffered from serious radiation damage which can be seen by numerous bright pixels (static hot pixels) randomly distributed across the entire sensor. Fig.3

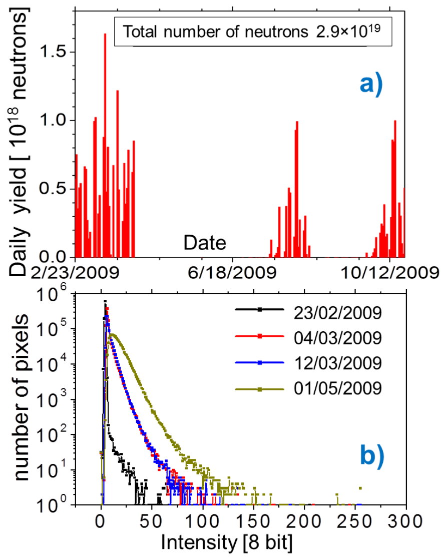

Fig.3 a) the daily neutron dose during the testing period b) histograms of pixel brightness at four selected times during the test

shows the daily neutron yield during the reported test period. The yield strongly depends on the experimental program which was carried out on JET during this time. Additionally, Fig. 3b shows histograms of pixel brightness during the testing time. The image sensors show an accumulative degradation due to radiation damage: the growing of the average dark level of the pixels, growing standard deviation of the dark level, increasing of number of static “hot” pixels which are saturated.

3.1.2 Temporary damage of the camera sensor

The generation of the dynamical hot pixels on the camera sensor during the exposure time has been clearly observed during the JET experiment. Fig. 4a shows the distributions of the cameras pixels as function of the intensity deviation from the mean value during the JET plasma phases with additional NBI heating (red curve) and during the pure ohmic heating alone. The last phase does not contribute to the neutron generation. During the NBI phase we observed nearly symmetrical distribution broadening indicating the creation of the dynamical hot pixels. Fig.4b presents the difference between two distribution shown in Fig.4a. About 3270 pixels, 3% of the total amount of the sensor pixels, are temporarily affected by neutrons and gammas. Such a relatively large number of dynamical hot pixels requires an on-line software for their handling in real-time to avoid any wrong interpretation. Such software has been successfully integrated into the JET real-time protection system based on the video imaging recording.

3.2 Hot Spot Pixel definition and identification

When pixels are damaged by radiation, they can suffer enhanced dark current and they appear to be much brighter than surrounding pixels. Such pixels are called hot pixels. In this study, the identification of the hot

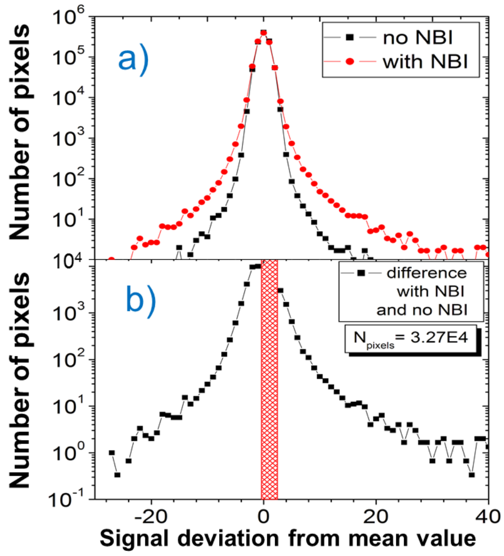

Fig.4a. Dynamical evolution of hot pixels during the NBI phase and during the ohmic phase of the typical JET 15MW NBI plasma pulse. Fig.4b gives the difference between two

spots was performed by application to the image of a second-order derivative edge detection filter the aim of which is to emphasize the regions of rapid intensity change. The Laplacian is used here for edge detection [3] and the hot pixels have been defined by selection of pixels where the signal exceeds a certain threshold. This threshold is chosen as 5-6 σ, where σ is the standard deviation of the image for new cameras before installation on the JET machine.

Fig. 5 shows the evolution of hot pixels of one of the operation colour CCD camera with uncooled sensor as function of the total neutron yield accumulated during the four consecutive days of experiments. The daily cumulative neutron total is always zero at the beginning of a day, because the first pulse is usually a dry run, with

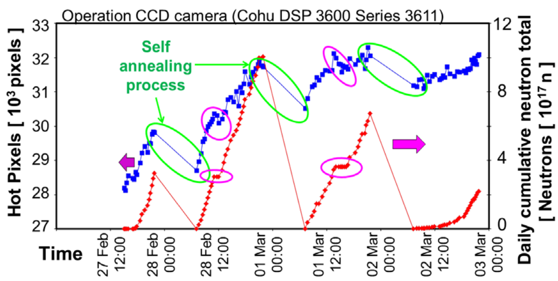

Fig.5. Evolution of hot pixels on the sensor of the operation of uncooled camera as function of the daily neutron yield.

no neutron emitted. A good correlation between the hot spots and the neutron yield has been observed: the cumulative neutron total for one day behaves the same way as the number of hot pixels. We can see that the number of hot pixels is higher for the last pulse of one day than for the first pulse of the following experimental day. Additionally, during non-operating periods (marked by green cycles) the numbers of the hot spots are reduced exhibiting the self-annealing of the camera. During the plasmas heated by ohmic heating alone, where the neutron emission is negligible, the camera performance is not affected indicating the link between hot pixels and neutrons. The self-annealing can be explained by a rearrangement of the silicon oxide layers as well as of the silicon bulk (diffusion/recombination of pairs of electron-hole and vacancy/interstitial pairs (Frenkel

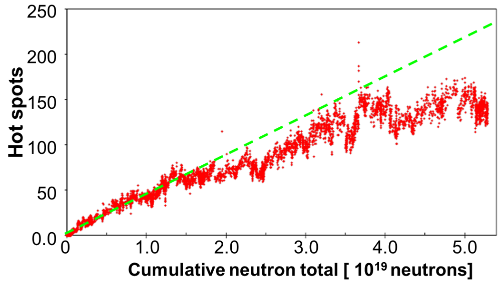

Fig.6. Hot spots (group of hot pixels) as function of cumulative neutron total on the uncooled camera used for operation

pairs) that would prevent the formation of stable defects or would even remove the traps and defects induced by neutrons. The graph on Fig.6 represents the hot spots of the operation camera against the cumulative neutron total. The total number of neutrons 5.2×10^{19} produced over the time period between 08/03/2006 and 21/02/2007 corresponds to a neutron fluence in the area of the camera location of ~ 3.4×10^{12} n/cm^2. We can see at the beginning a linear trend on the growth of hot pixels indicating the good correlation of the former quantity with the neutron fluence. The operation during this time period results in increased numbers of hot pixels as well as in an increased dark current making the further use of the camera impossible: about 10% pixels were affected by neutrons and gammas. Based on the JET experience, each operation camera must be replaced once/year after a neutron yield of ≈3-5×10^{19} neutrons amounting to the neutron fluence ~1.9-3.2×10^{12} n/cm^2.

3.2 Impact of the radiation on the cooled cameras

Based on the experience made with uncooled cameras discussed in section 3.1, all scientific cameras (AVT) Pike F-100B) as well as operation cameras have been upgraded and operated since 2009 with actively cooled sensors and do not show any significant visible damage. Cooling a video sensor to -20°C significantly reduces the dark current and eliminates "hot" pixels. Also, none of MWIR CMOS cameras with actively cooled (78K) image sensors shows any signature of the radiation damages. The reduction of radiation-induced damages due to sensor cooling could be explained by temperature dependent diffusion and recombination processes of pairs of electron-hole and vacancy/interstitial pairs (Frenkel pairs) which prevents the formation of stable defects or leads to the removal of the traps and defects induced by neutrons. The cameras must be kept all the times in frozen conditions. Defrosting of the sensor leads to a partial recovery of the defects inside the sensor and, correspondingly, to an increase of the dark current and to the appearance of hot pixels. However, the number of recovered hot pixels is much less than the number of hot pixels in the camera operated with un-cooled sensor from the beginning.

4. Radiation effects on the electronics

Radiation produced during operation of JET could be detrimental to electronic components and systems used to control and to protect the JET machine. Especially, the first wall protection system [4] based on the imaging diagnostics requires fulfilling sharp demands that allow a reliable operation of the JET tokamak. Radiation could impact the electronics inside the cameras as well as the periphery electronic components responsible for the data capture and the control of the imaging system.

4.1 The impact of radiation on the camera electronics

Seven AVT Pike F-100B cameras with active cooled sensors have been operated since 2010 [5]. This camera is a commercial product and contains electronic components, such as IEEE 1394b three-port cable transceiver/arbiter, 32bit microcontroller and Numonyx™ embedded flash memories, all of which are sensitive to the neutron influence. It has been observed that the camera periodically terminated the FireWire connection with PC in the experiments when the NBI power exceeded 9MW in a pure deuterium plasma. Once the connection was terminated, it was possible to run the camera again only by power-off-power-on cycling. Fig.7 shows the numbers of losses of the FireWire connections as function of the total neutrons emitted during the time period between the power cyclings of the cameras. We can see that camera loses with high probability the connection with the PC when the total neutron yield

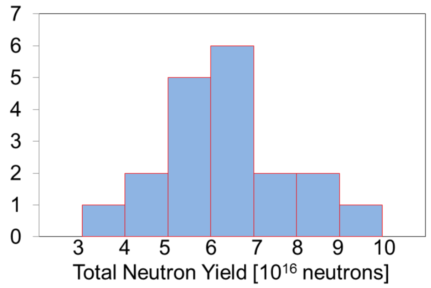

Fig.7. Radiation effects on electronics of AVT Pike F100B cameras (FireWire connection).

reaches the value of about 6-7×10^{16} neutrons. The total number of 6-7×10^{16} neutrons corresponds to 3-4 pulses with P_{NBI} of about 20 MW and amounts to n-fluence in the area of the camera location of ~2.0-2.4×10^{9} n/cm^{2}.

Malfunction of the electronics of MWIR CMOS cameras most probably due to the impact onto the flash memory has been observed. Failure of the digital electronics inside the cameras requires the re-installation of the firmware software after a total fluence of about 1.6×10^{18} neutrons corresponding to about 1 month of operation and to a neutron fluence in the area around 4.3×10^{9} n/cm^{2}.

4.2 The impact of radiation on the periphery electronics

The JET protection imaging system [4] contains 13 analog monochrome CCD cameras (HITACHI KP/M1AP) operating in the near infrared spectral region to measure the surface temperature of the plasma-facing components. Frame grabbers convert the analog output of the CCD cameras into a digital, 8-bit, Gigabit Ethernet signal. They are located inside the Torus Hall and suffer from exposure to the neutrons/gammas. A loss of the time vector has been observed with the frequency of once/month. The one month of operation amounts to a total neutron yield ≈2.7×10^{18}n and to a neutron fluence of ~0.4×10^{10} n/cm^{2}. The malfunction is probably due to impact of the neutrons onto the electronics inside of the module or due to false triggering affecting the optical reset signal.

On JET, the control of the scientific video system (control of the filter exchanger, camera cooling, sensor temperature monitoring) is based on the Simatic S7-PLC (Programmable Logic Controller) technique. PLC is located inside the cubicle positioned on top of transformer iron in the JET Torus Hall. One time per month, the PLC PC loses the connection with the PLC module (corresponds to total neutron yield of about 2.8×10^{18} neutrons, fluence ~4.0×10^{9} n/cm^{2}).

5. Summary

During the JET D-T campaign an obvious correlation between sensor damage and the neutron fluence has been observed. There is a definitive impact on some image parameters, like an increased dark-current and increased numbers of hot-pixels. The operation of the cameras at room-temperature demonstrates a strong sensor damage which requires the camera replacement once per year after exposure to a neutron fluence of ~1.9-3.2×10^{12}n/cm^{2}. For the comparison of the JET result with other irradiation facilities, the characterization of neutron fluence from the JET source in terms of equivalent monoenergetic neutron fluence has been performed. The fluence of ~1.9-3.2×10^{12}n/cm^{2} from the JET source corresponds to ~0.62-1.06×10^{12} n/cm^{2} equivalent silicon displacement fluence at 1 MeV. Such levels of fluence will be reached after ≈14-22 ELMy H-mode pulses (ref. #74176, 4.5MA/3.6T, P_{NBI}=25MW, t_{NBI}=6s) during the future D-T campaign. It was demonstrated that cooling sensors down to -20ºC can essentially reduce the effect of the radiation damage and increase the lifetime of the image sensor. Furthermore, the generation of a significant amount of dynamic hot pixels (≈3% the total amount of the sensor pixels) was observed in the presence of hard radiation (neutrons and gammas). Malfunction of the digital electronics inside the cameras, frame grabbers, as well as of industrial PLC controllers is observed beyond a neutron fluence of about ~4×10^{9} n/cm^{2} (corresponds to ~0.6-1.6×10^{9} n/cm^{2} equivalent silicon displacement fluence at 1 MeV)

Acknowledgments

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