Radiation-tolerant data links for fusion reactors: from serial electrical data link to parallel optical data link

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The future thermonuclear reactor is a complex installation that will require permanent monitoring and frequent maintenance operations. The high-gamma dose rates, the high neutron fluence and other radiochemical hazards call for the use of remote-handled equipment. The radiation acceptance level of the instrumentation data links is therefore a key issue. In this paper, we first review the different approaches considered up to now to address this issue. Then, we discuss the new alternatives brought by the Wavelength Division Multiplexing (WDM) capabilities of fibre optic technology.

Rationale

The future International Thermonuclear Experimental Reactor (ITER) will require permanent monitoring during the plasma burn, involving plasma diagnostics, sensing and communication applications [1, 2].

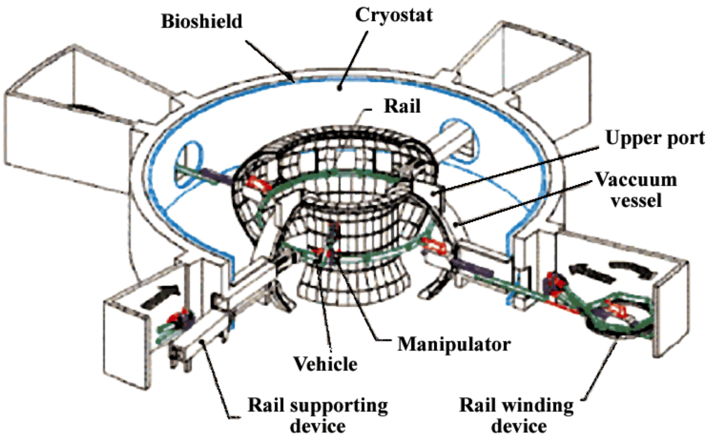

Figure 1: Divertor test platform (Brasimone, Italy)[3]

The reactor maintenance will require frequent replacement of heavy in-vessel components such as tiles, divertor modules, among other plasma facing components. These operations have to be performed in a hazardous radiological environment: 10 kGy/h gamma dose rate,temperatures going from $50^{o}C$ to $200^{o}C$, total gamma dose of 100 MGy. Radiochemical hazards due to chemically toxic or reactive materials produced during the deuterium-tritium reactions and activated dust, originating from the plasma facing components, make the maintenance operations even more difficult[3]. Operators have to use remote-handled equipment to ensure their safety. The interconnections between this equipment and the control unit become therefore a crucial issue in the reliability of ITER instrumentation links[2].

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The data link architectures envisaged up to now for ITER instrumentation are based on existing electronic multiplexing techniques, using digital data transmission and time domain multiplexing. This approach requires to use a large amount of radiation-sensitive electronics, restricting therefore both the radiation-tolerance and the bandwidth of the ITER link. In this paper, we propose a new analog fibre optic data link design based on COTS components, taking advantage of the fibre WDM capabilities to implement a distortion-free data transmission. We briefly compare the analog link with the digital link architecture in terms of radiation-acceptance level, intrinsic performance and architecture complexity. We discuss the pros and the cons of the analog implementation of the ITER instrumentation data link.

Digital opto-electronic serial data link for ITER

Digital transmission has been first considered since it allows greater flexibility in protecting data from noise and other non-ideal effects in the link and in optimizing the bandwidth usage. Analog/digital (ADC) or digital/analog converters (DAC) are necessary to digitize analog signals produced by the sensors. To reduce the amount of connecting links with the control unit, serialisers and deserialisers are required to send all the binary data over a single link, together with electronic multiplexers. The extreme environment of ITER also requires heavy shieldings against electromagnetic interference (EMI) to guarantee distortion-free data communication. The use of opto-electronic components to carry the digitized data over long distances has been considered as a trade-off between umbilical management and electromagnetic shielding. Such architecture is schematically depicted in Fig. .

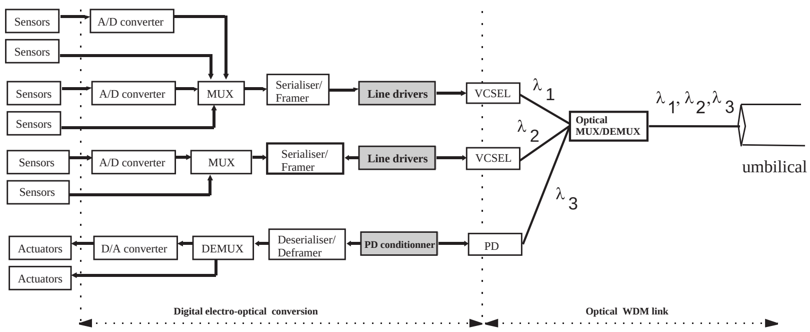

Figure 2: Digital opto-electronic serial link for the ITER instrumentation link

***Radiation-hardened electronics* -** State-of-the-art COTS digital electronic multiplexing circuits can only resist to accumulated doses up to 10 kGy using discrete components with a multiplexing capacity of a few MHz[4]. CEA (France) is currently developing radiation-hardened ADC, DAC and serialisers for nuclear robotics. Their radiation-acceptance level is about 100 kGy at a gamma dose-rate of 10 Gy/h[5].

***Optoelectronic digital emitter/receiver under radiation* -** Optoelectronic emitters and receivers have been extensively tested to evaluate the radiation resistance of the digital opto-electronic data link [6]. Among other emitters, the Vertical Cavity Surface Emitting Lasers (VCSEL) is the most promising candidate for the ITER link. Recently, Berghmans has showed that the VCSEL lasing threshold current remains unaffected by gamma radiation up to 10 MGy whereas the external efficiency η is lowered[6]. Used as digital emitter, the VCSEL efficiency reduction results in a decrease of the signal-to-noise ratio and, therefore, an increase of the bit-error-rate. A digital driver for VCSELs has been developed to operate at 1 MHz up to a 1 MGy total gamma dose[6].

The radiation resistance of commercially available semiconductor photodiodes (PD) is the weak point of a digital opto-electronic data link up to now in terms of reliability and signal-to-noise ratio decrease.

***Radiation-tolerant COTS optical fibre* -** Both multimode and singlemode COTS optical fibres have already shown a satisfactory radiation resistance, even when irradiated inside a nuclear core[7, 8]. Multimode pure silica core fibres have been extensively tested up to GGy gamma dose levels, showing a typical radiation-induced attenuation lower than 5 dB/m at 850 nm[7]. The SMF28 singlemode fibre shows a radiation-induced attenuation of about 10 dB/m [8]. However, since the length of fibre in remote-handling applications exposed to severe ionizing radiation is short, COTS optical fibre is suitable for transferring optical data in ITER instrumentation links.

Radiation-tolerance of the digital opto-electronic link

The radiation acceptance level of the digital opto-electronic serial data link is at the most 100 kGy at a modulation frequency of 1 MHz. It is limited by the lack of MGy-tolerant COTS electronics and reliability issues in the high-speed semiconductor photodiodes required for tool actuation. The radiation-induced losses in the connecting optical fibre are no longer a limitation, in the infra-red wavelength window.

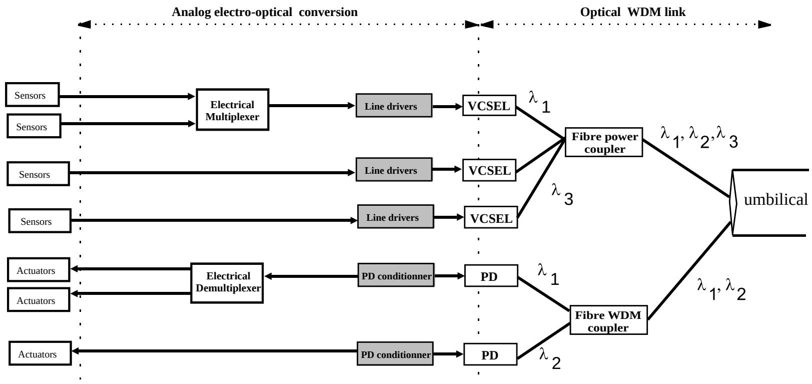

Figure 3: Analog optical parallel link proposed for the ITER instrumentation link

Analog optical parallel link for ITER

The electronic components in charge of the analog-to-digital conversion are very radiation sensitive. We therefore propose, as a way to improve the link radiation-tolerance, to keep the sensor signal in its analog format and to use it to directly modulate opto-electronic emitters. The limitation of a low bit-rate analog data transmission is its greater sensitivity to losses appearing along the link. Major error sources are the radiation-induced losses and the bending losses along the connecting optical fibre. Error correction schemes need therefore to be implemented. A schematic picture of a possible optical analog optical link is given in Fig. .

Optoelectronic analog emitter/receiver under radiation - The radiation-induced limitations put forth for the digitally-driven VCSELs are lowered once we consider the VCSEL as an analog modulator. The optical power is still sufficient to guarantee optical data transfer and the linear response versus the driving current remains linear.

In low-bit-rate analog data link, the relaxed bandwidth response criteria means that optical detectors ranging from photomultiplier electron tubes to pyrometers could be considered as potential photodetectors. Analog data encoding opens therefore new ways towards the development of radiation-hardened photodetectors.

All-fibre optical multiplexer/demultiplexer - Several optical wavelengths can be used to transmit, in parallel, several analog sensor signals. This allows to set up easily redundant and distortion-free data transmission, using wavelength-separated optical emitters and all-fibre multiplexers/demultiplexers.

Conventional wavelength-flattened COTS fibre optic couplers can be used to multiplex in one fibre the optical signals, originating from the sensors.
Wavelength-selective demultiplexers can be employed to split the different signals needed to operate the actuators. Being bidirectional, one single component could even operate as multiplexer and demultiplexer at the same time reaching the highest level of multiplexing achievable. We already demonstrated the radiation resistance of COTS fused fiber optic WDM couplers up to 10 MGy[4]. The radiation-induced channel drift can be compensated using wavelength-tunable optical emitters in the ITER control room[4].

Error-correction schemes - Basic error correction schemes can be implemented to ensure distortion-free and redundant optical data transmission. With a limited amount of electronics, one could drive the same VCSEL at two currents I_1 and I_2, both proportional to the analog input signal, using of an analog multiplexer. The value obtained after subtraction of the two emitted optical powers is still proportional to the analog signal but it is independent of the radiation-induced losses along the optical link. One could also use the same output signal to modulate two wavelength-spaced VCSELs. The two optical signals can afterwards be demodulated by means of an all-fibre demultiplexer and compared for error correction.

Conclusions

The maintenance operations of the future thermonuclear fusion reactor requires the development of a radiation-resistant instrumentation data link. The limitations of the currently envisaged digital opto-electronic serial link could be overcome by implementing an analog optical data link. In principle, it could reduce the required amount of electronics to a radiation-hardened analog driver and a radiation-resistant low-speed photodetector. Multiplexing and demultiplexing optical signals can be done *passively* using fibre optic wavelength-flattened couplers and wavelength-selective couplers.

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