Development of gamma-ray spectrometers optimized for runaway electron bremsstrahlung emission in fusion devices

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ABSTRACT

An optimized hard X-ray (HRX) spectrometer was designed to collect information from Bremsstrahlung emission in the MeV range runaway electrons (RE) generated during disruptions. The detector is based on a cerium doped lanthanum bromide scintillator crystal (LaBr3:Ce) coupled with a photomultiplier tube. The diagnostic allows for measurements of high hard X-ray fluxes in excess of 1 MHz with a wide dynamic range up to 20 MeV. The diagnostic was tested at the tokamak ASDEX Upgrade. The results achieved are promising and suggest the possibility of inferring information on the runaway electron energy distribution in tokamaks using deconvolution techniques.

INTRODUCTION

The production of relativistic REs during disruptions can potentially compromise the integrity of plasma-facing-components in large tokamaks and hinder operations [1]. Runaway electron production, control and mitigation are therefore currently one of the main topics studied in midsize and large-scale tokamaks. Information on the runaway electron energy distribution can be extracted by measuring the bremsstrahlung radiation emitted by the interaction between the beam and the post disruption plasma. In this work, we discuss the design of a custom hard X-ray spectrometer that can reliably measure the bremsstrahlung spectrum up to tenths of MeV with a high rate capability (> 1 MCps): the Runaway Electron GAmma-Ray Detection System (REGARDS).

EXPERIMENTAL SETUP

The REGARDS system can be divided into three distinct components: the hard X-ray (HXR) detector, the gain control system and the acquisition system. A schematic representation of the diagnostic can be found in figure 1.

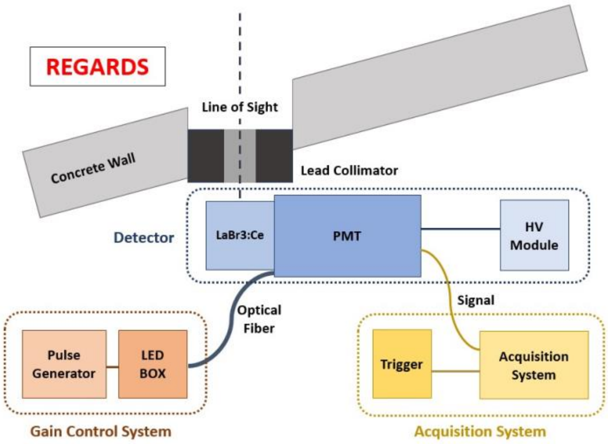

Fig. 1: A schematic representation of the REGARDS diagnostic.

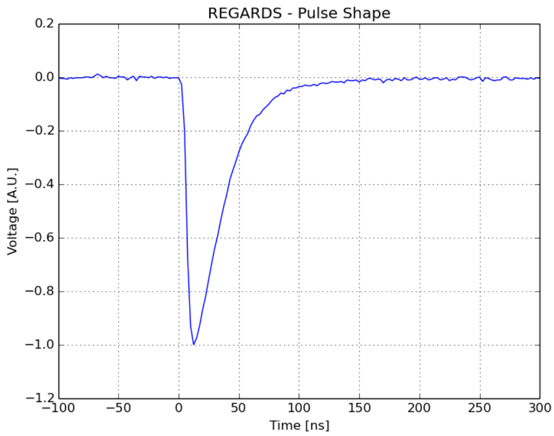

Fig. 2: A typical HXR signal from the REGARDS detector.

The HXR detector is made by a cerium doped lanthanum bromide (LaBr3:Ce) scintillator crystal coupled to a photomultiplier tube (PMT). The cylindrical scintillator measures 1 inch in diameter and 1 inch in length and it was manufactured by Saint-Gobain. The PMT used was manufactured by Hamamatsu (model R9420-100-10).

PMTs performances can be influenced by the presence of strong evolving magnetic fields. The detector was embedded in two layers of magnetic shielding to mitigate the influence of the external tokamak magnetic fields. The first layer is composed by a magnetic shield case by Hamamatsu (model E989-03) that covers the PMT. The second layer is a custom-made soft iron pipe that surrounds the whole detector and provides further shielding. Furthermore, the detector gain was monitored during the plasma discharge. This is achieved using a gain control system. The gain control system is composed by an electrical pulse generator, a blue LED and an optical fiber. The pulse generator (model 577 by Berkeley Nucleonics) is used to fire the blue LED (model NSPB500AS by Nichia) at a constant rate of 10 kHz. The light emitted by the LED is collected by an optical fiber and guided to the photocathode of the PMT. The gain control system was designed to mock the scintillation of a high energy photon of approximately 14 MeV interacting with the LaBr3:Ce crystal. During off-line analysis the gain stability of the detector can be assessed by retrieving the LED pulses by pulse shape discrimination techniques and monitoring their relative magnitude. This system can be also used to correct small gain shifts. In REGARDS the signal generated by the PMT is directly digitized by the ADC. The acquisition system (ADC model NI5772 with PXIe-7976 FlexRIO module by National Instruments) allows for continuous data collection at a 400 MHz sampling rate for more than 10 s. This is crucial to

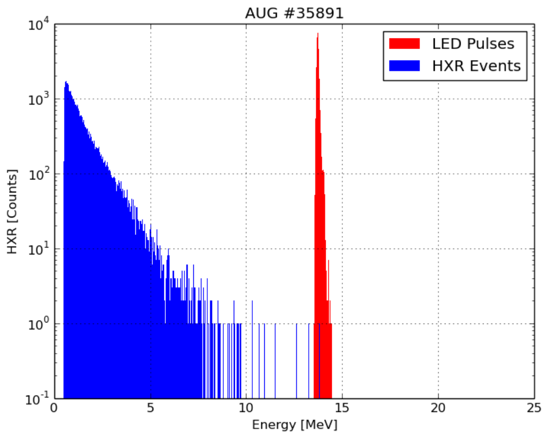

Fig. 3: Typical HXR spectrum measured during a disruption with RE formation at AUG.

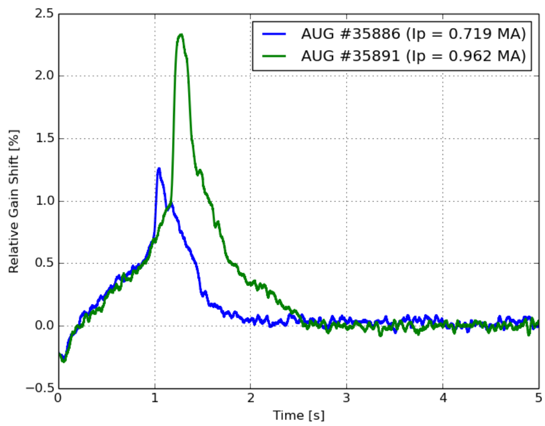

Fig. 4: Time trace of the detector relative gain shift during the discharge.

allow pile-up detection and recovery under high HXR fluxes.

RESULTS

The REGARDS system was installed and tested at the tokamak ASDEX Upgrade during the 2019 MST1 T08-AUG campaign. The detector was placed in front of a radial view line of the machine, outside of the torus hall. A custom-made cylindrical lead collimator was used to reduce the incoming HXR flux. The PMT was operated at a relatively low supply voltage of -570 V to achieve a broad dynamical range of 20 MeV and to reduce the gain shift at high counting rates.

A typical HXR spectrum collected during a RE event is shown in figure 3. The energy of the RE bremsstrahlung emission (in blue) is mostly exponential with maximum HXR energies in the order of 10 MeV. In figure 3 the LED pulses used as reference are marked in red. The relative gain shift for two RE discharges obtained by monitoring the LED pulses is plotted in figure 4. Before the disruption is triggered (at t = 1.008 s for discharge #35886 and at t = 1.186 s for discharge #35891) there is a steady shift in the detector's gain due to the magnetic field ramp-up. This effect is proportional to the magnetic field intensity (Ip before the disruption is 0.719 MA for discharge #35886 and 0.962 MA for discharge #35891) and it counts for about 1%. After the disruption is triggered a sudden increase in the gain shift is caused by the high HXR flux. This effect is responsible for an additional 1.5% in the gain shift. The total gain shift for the REGARDS system is under 3% even in conditions of high HXR fluxes in excess of 1 MCps.

DISCUSSION AND CONCLUSION

During the tests performed at ASDEX Upgrade REGARDS proved to be a stable and reliable spectrometer even under high HXR flux. The capability of accurately measuring the RE bremsstrahlung emission in the MeV range opens the possibility of reconstructing the RE energy distribution using deconvolution techniques such as Tikhonov Regularization, Single Value Decomposition or Richardson Lucy Algorithm [2]. This information is of a great importance to understand RE beam formation, to assess the effectiveness of different RE mitigation techniques such as massive gas injection (MGI), shattered pellet injection (SPI) and magnetic resonant perturbation (RMP) and to validate first principle calculations.

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