MeV range bremsstrahlung measurements of the runaway electron distribution function in disruption mitigation experiments at the ASDEX Upgrade and JET tokamaks

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Introduction

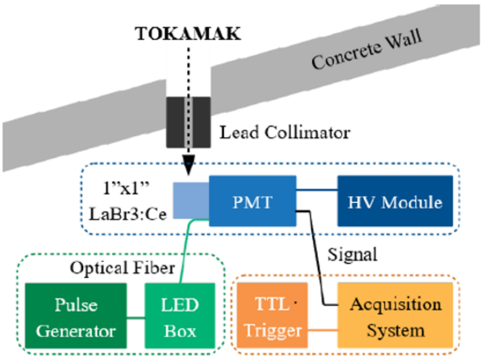
The generation of runaway electrons (REs) is one of the major threats for the realization of a fusion power plant and their mitigation is the subject of an intense research effort worldwide. Techniques relying on massive gas (MG) or shattered pellet injection (SPI) have been developed and are currently under test in major tokamaks. However, the extrapolation of the experimental results to ITER is a challenging task, due to the significantly different RE physics regimes that are expected at ITER. A detailed understanding of the physics underlying the generation and dissipation of the REs is therefore mandatory.

In recent years, progress in the development of gamma-ray spectroscopy (GRS) systems with MHz counting rate capabilities [1, 2] have made it possible to develop dedicated instruments for RE studies [3, 4, 5]. GRS measures the energy spectrum of the bremsstrahlung hard x-ray (HXR) emission of MeV range REs as they slow down in the plasma after a disruption. From the measured HXR spectrum, information on the RE energies is obtained using deconvolution, with a typical temporal resolution of a few ms. In this paper, we present the instruments that are available for this task both at the ASDEX Upgrade (AUG) tokamak and at the Joint European Torus (JET), with examples of results.

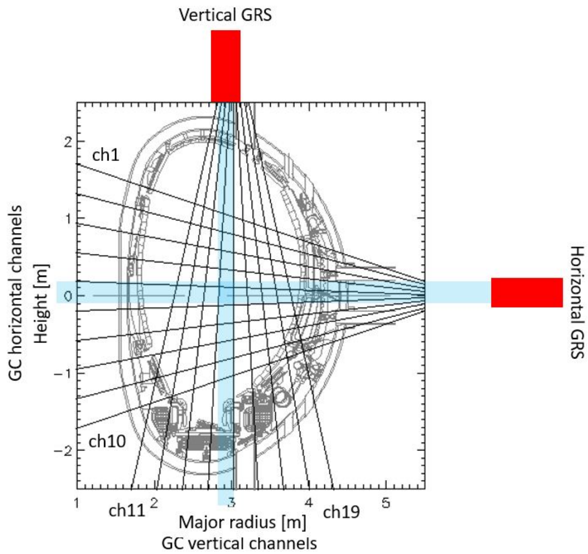
Instrumentation at ASDEX Upgrade and JET

A dedicated gamma-ray spectrometer, dubbed REGARDS (Runaway Electron GAmma Ray Detection System), has been installed on a radial line of sight at the AUG tokamak [5]. Figure 1a shows a sketch of the system. A hole in the wall of the AUG torus hall, as well as a lead collimator, define the REGARDS line of sight. The instrument is based on a 1"x1" cylindrical high resolution $LaBr_3$ scintillator equipped with a fast digitization system and a LED for control and monitoring (C&M) purposes.

At JET, a range of instruments, originally developed for fast ion studies, is used. These are two gamma-ray spectrometers, both based on a large 3"x6" cylindrical $LaBr_3$ crystal and with collimated vertical and



(a)



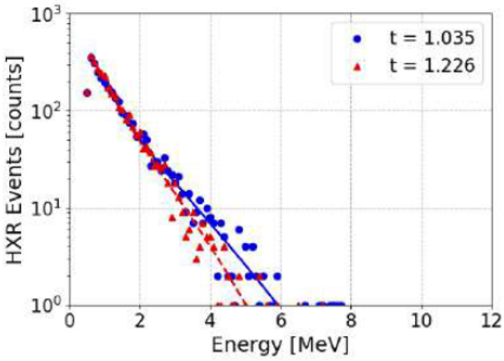
(b)

Figure 1: (a) Schematics of the REGARDS detector installed at the ASDEX Upgrade tokamak. (b) Arrangement of the gamma-ray spectrometers and lines of sight (labelled by numbers) of the gamma-ray cameras at the JET tokamak.

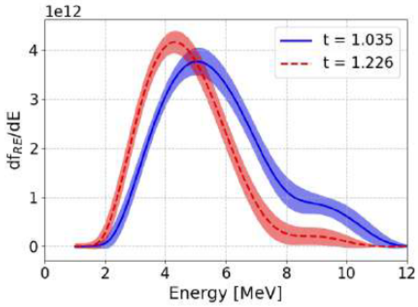
horizontal lines of sight (see figure 1b). The large spectrometers are complemented by two gamma-ray cameras (GCs), one vertical and one horizontal. These are made by 19 detectors in total and that observe the plasma along collimated lines of sight defining a grid in the poloidal cross section. An image of the HXR emission can be made from the raw GC data after tomographic inversion.

From the HXR spectrum to the RE energies

As GRS measures the HXR spectrum from bremsstrahlung of the REs, rather than the RE phase space, a way to infer information on the RE energies from the measured HXR emission is required. In broad terms, the problem is similar to fast ion measurements by GRS, where one needs to determine the fast ion energies from the spectral features of the gamma-ray lines induced by nuclear reactions between the energetic ions and impurities. In case of fast ions, however, a calculation of the expected energy distribution is often available and synthetic diagnostics can be used to predict the corresponding detector signal. A benchmark of the simulations is therefore possible by a direct comparison between the synthetic diagnostics and actual data. In RE experiments, instead, the distribution function is most often not well known and information on the RE energies need to be inferred without a model. Building on the pioneering work of [2], deconvolution methods can be adopted to infer the most likely RE energy distribution from data, albeit with some uncertainty. The most successful method has been the first order Tikhonov algorithm [5], that is nowadays routinely used for velocity space tomography for fast ion studies [6]. Figure 2a shows an example of the HXR spectrum measured in discharge #35887 at ASDEX Upgrade and at two different times, t=1.035 s and t=1.226 s. Changes in the high energy slope of the spectrum are



(a)



(b)

Figure 2: (a) HXR spectrum measured in discharge #35887 at ASDEX Upgrade at the times t=1.035 s and t=1.226 s (b) RE distribution function as obtained by a deconvolution of the data in panel (a) using the Tikhonov first order inversion method.

reflected in a different shape of the deconvolved RE distribution functions (see figure 2b), where results at t=1.226 s show a more pronounced population of REs in the E=8-12 MeV range, compared to the distribution at t=1.035 s.

Evolution of the RE mean energy and tomography

Non-uniqueness of the solution in a deconvolution process can affect the resulting RE distribution function, whose fine details may thus not be fully reliable. On the other hand, the average energy obtained from the integral of the distribution ($< E_{RE} >$) is expected to be a robust estimator of the mean RE energy, and its evolution throughout the discharge. HXR measurements with spectrometers, both at AUG and JET, provide a time trace of $< E_{RE} >$. Figure 3 shows an example of this measurement for discharge #35887 in a MGI experiment at AUG. Data show a relatively constant mean energy until 15 ms after the disruption is triggered, followed by a linear decay. Despite the relative simplicity of this trend, which is shared by many MGI discharges at AUG and JET, a simple 1D test-particle model taking into account collisional drag and synchrotron emission fails to describe data at most of the times [5], particularly when $< E_{RE} >$ decays. This suggests that data on $< E_{RE} >$ may be of interest to benchmark the more detailed numerical tools for RE studies presently under development in the tokamak fusion community.

Besides information of $< E_{RE} >$ vs time, at JET the GC can provide an image of the HXR emission in the poloidal plane after tomographic inversion. The result depends on the accurate knowledge of the magnetic equilibrium and its fast evolution during the disruption. When compared with a picture from the JET visible cameras, for discharge #95774 we find that the HXR emission is consistent with its visible counterpart, but is also significantly more located in the core (see figure 4).

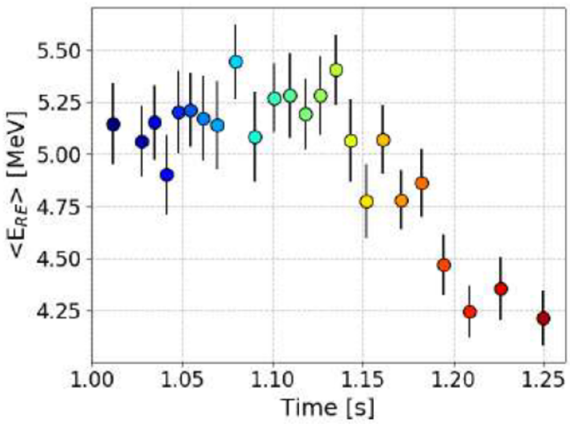


Figure 3: Evolution of the average RE energy $< E_{RE} >$ as a function of time in discharge #35887 at ASDEX Upgrade as determined from HXR data.

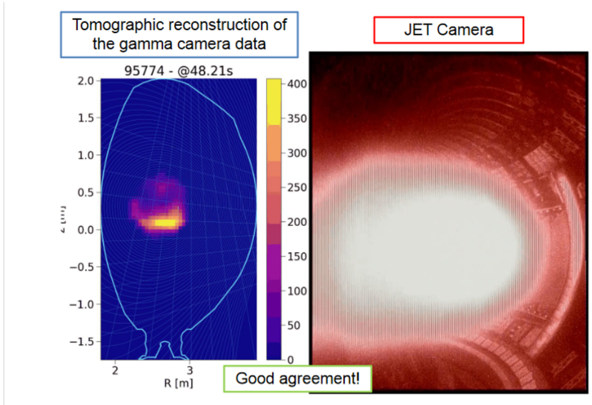


Figure 4: (left) Tomographic inversion of the HXR emission data measured by the JET gamma-ray camera for discharge #95774 at t=48.21 s and (right) data from the visible camera in the same discharge and at the same time.

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