Design and Development of Probe for the Measurements of Runaway Electrons Inside the GOLEM Tokamak Plasma Edge

Pravesh Dhyani[1], Vojtěch Svoboda[1], Valeriia Istokskaia[1,4], Jan Mlynář[1,2], Jaroslav Čeřovský[1,2], Ondřej Ficker[2], Vladimir Linhart[3]

[1]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague, Czech Republic*

[2]*Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic*

[3]*Department of Dosimetry and Application of Ionizing Radiation, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague, Czech Republic*

[4]*ELI Beamlines, Dolní Břežany, Czech Republic*

Runaway electrons (RE) can severely damage the first wall of the fusion grade machines like ITER [1]. Repeatable discharges with high loop voltage and low-density in the GOLEM tokamak [2] (aspect ratio R_0/a = 40cm/8.5cm with Molybdenum limiter ring) pose good experimental conditions for the study of the RE. In the GOLEM tokamak HXRs are generally seen in all phases of the plasma discharges, i.e. breakdown, current flat-top and disruption. Interestingly, it has been observed that during the magnetohydrodynamic (MHD) activity, particularly when tearing modes excite, HXRs are emitted due to interactions of RE with plasma facing components inside the machine. Preliminary analysis reveals similar dependence of HXR amplitude (A_{HXR}) on normalized toroidal electric field ($E_\phi T_e/n_e$, normalized by Dreicer electric field [3]), poloidal magnetic fluctuation amplitude ($\dot{B}_\theta$) measured by B-dot probes in the Mirnov garland and $\tilde{B}_\theta/B_\theta$, as shown in figure 1. The data does not clearly indicate the main cause of the RE generation, i.e., whether it is externally applied toroidal electric field or internally induced parallel electric field due to the magnetic reconnections during the tearing mode excitation in low density plasma discharge in the GOLEM tokamak. To understand the main cause of the RE generation, the knowledge of location of runaway generation needs to be understood. Another important aspect is the energy distribution inside the RE beam. In general, HXR generated by the interaction of RE with the plasma facing materials are measured outside the machine. Previously, there have been some efforts for the local and spectral measurements [4, 5] of the RE inside TEXTOR. More efforts are needed in the direction of direct measurements of the RE. On the basis of the TEXTOR probe, design and development of a probe is underway for the spectral measurement of RE energy locally inside the GOLEM tokamak, in the vicinity of the last closed flux surface (LCFS) of the plasma.

The probe design is based on the simulation results of the FLUKA code [6, 7] that estimates the energy absorbed by the filters of high-density materials and scintillating crystals characterized with different light yield and density. In the presented simulation results, NaI(Tl) crystals combined with stainless steel (S.S.) as a supra-thermal electrons filter were tested. Being sensitive to HXRs and electrons, NaI(Tl) crystal was chosen for high energy beam measurements. However, flexible design of the probe will allow other scintillating crystals and filter materials inside the probe head, that consists of four crystals of length ~ 8 mm, diameter ~ 2 mm inside a cylindrical graphite housing (wall thickness ~ 2.5mm).

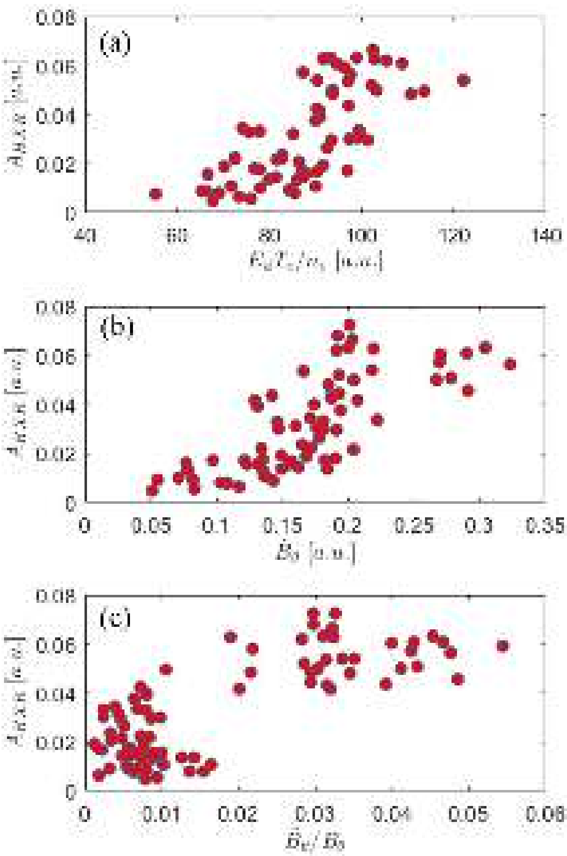

Figure 1. HXR signal amplitude (A_{HXR}) shows linear dependence on (a) normalized electric field ($E_{\phi}T_e/n_e$) (b) magnetic fluctuations ($\dot{B}_{\theta}$) amplitude and (c) $\tilde{B}_{\theta}/B_{\theta}$.

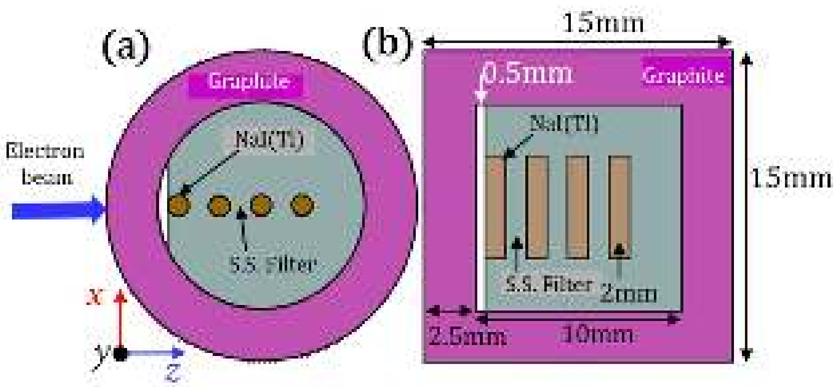

Figure 2. (a) Top and (b) side view of the four NaI(Tl) crystal probe head built in the FLUKA graphical interface Flair

Figure 2 shows top and side views of the simulated probe built in the FLUKA graphical interface Flair [8]. In this article, we have primarily focused on the simulation results of the 1-10 MeV pencil like mono-energetic electron beam interaction with the four NaI(Tl) scintillation crystals aligned in the direction of the beam incidence as shown in figure 2. The beam energy is filtered by the S.S. filters before the absorption on the crystal in each step (except the first one).

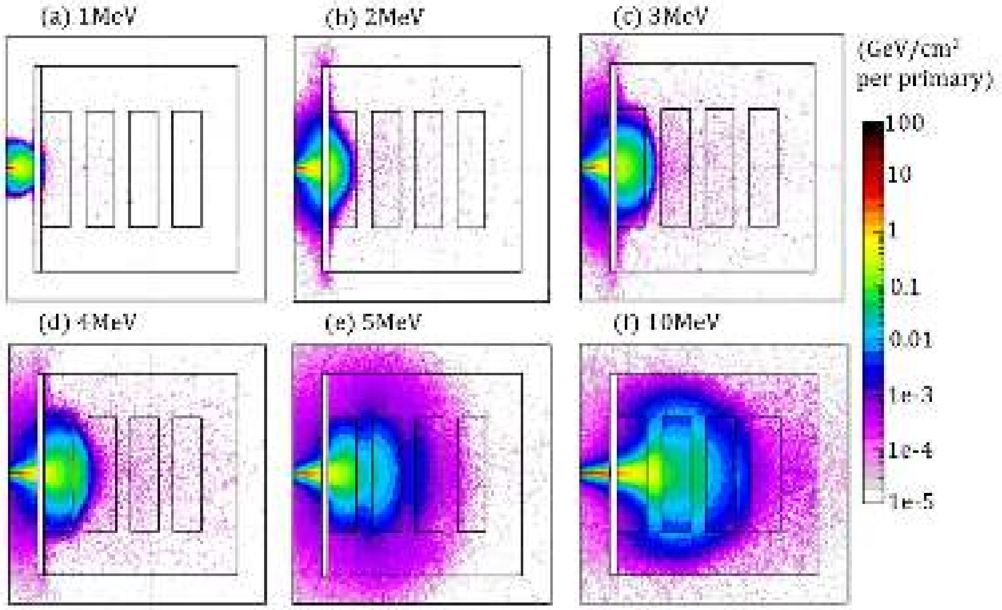

Figure 3. Side view of the distribution of energy deposition (GeV/cm^2 per primary) on NaI(Tl) crystal and S.S. filters with pencil like monoenergetic electric beam of energy (a) 1MeV, (b) 2MeV, (c) 3MeV, (d) 4 MeV, (e) 5MeV, (f) 10MeV.

Side view of the energy density deposition (GeV/cm^2-primary) on the probe (figure 3) by monoenergetic electron beams (1-10MeV) depicts that the higher the beam energy, the more it will contribute to the signals in a crystal and the more it can penetrate inside the probe head. It is clearly seen that the most part of the 1MeV beam energy was deposited on the graphite case (fig. 3a). In practical case of high energy beam having wide energy range, to evaluate energy spectrum of the beam, total light signal from the crystals for a RE beam, can be written as [5]: $I_1 = \alpha n_1 + \alpha n_2 + \alpha n_3 + \alpha n_4$, $I_i = \alpha n_i + \cdots + \alpha n_4$, and $I_4 = \alpha n_4$, where α is the light intensity produced by one electron, $I_i$is the light produced by i^{th} crystal, and n_i is the number of electrons with energies between two minimum energies defined for the i^{th} and the $(i+1)^{th}$ crystals. Since, NaI(Tl) produces visible light around ~420nm, optical components have been chosen to transmit signals around this wavelength. Upon fabrication, the light signal produced by the crystals will be transmitted to a photo-multiplier tube (Hamamatsu-R58) via optical fibers.

In summary, FLUKA simulation results show that NaI(Tl) is a good candidate for the spectral measurement of the RE beam energy, since the amount of energy deposited by monoenergetic beam in the crystals is different as shown in figure 4. Further simulations will be carried out using GEANT4 and FLUKA codes, to interpret the signals obtained during the experiments. In GOLEM tokamak experiments, we measure HXR outside the machine that has S.S. (density ~ 8.0 g/cm3) vacuum vessel of 0.2mm surrounded by a copper (density ~ 8.96 g/cm3) donut shaped shield of thickness 10mm. Reported simulation results indicate that 2.5mm thin graphite (density ~ 2.1 g/cm3) shield was able to absorb 1MeV beam effectively, indicating that the RE beam in the GOLEM tokamak has energy much higher than 1MeV, in general.

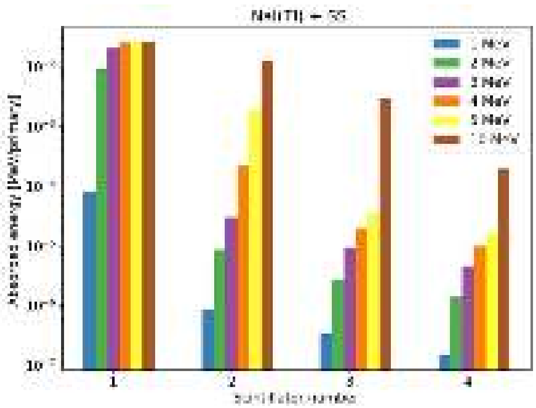

Figure 4. Energy deposited in NaI(Tl) crystals with S.S. filter in the case of 1,2,3,4,5,10 MeV monoenergetic electron beams.

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