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Study of Runaway Electrons in GOLEM Tokamak

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ABSTRACT: High loop voltage and low-density plasma discharges at the GOLEM tokamak present favorable conditions for the study of the runaway electrons (RE). A probe is being designed and developed for the spectral measurement of the RE energy inside the last closed flux surface of GOLEM tokamak plasma. Design of the probe is based on simulation results of the FLUKA code that estimates the energy absorbed by the scintillating crystals and filters of various densities. In the simulations, graphite, stainless steel and molybdenum were tested to filter the supra-thermal electrons. Since having different light yield, YSO (Y_2SiO_5: Ce), NaI(Tl) and plastic (EJ-200) scintillating crystals were chosen for the simulations.

KEYWORDS: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - probes; X-ray detectors; X-ray detectors and telescopes

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1 Introduction

GOLEM tokamak [1] is a small size tokamak with major radius, $R_0 = 0.4$ m and poloidal Molybdenum limiter with minor radius, $a = 0.085$ m. Vacuum vessel of the GOLEM tokamak is a continuous stainless steel (S.S.) torus of thickness ~ 0.2 mm, which is enclosed by the 10 mm thick toroidal shape copper shield. Typical plasma parameters in the GOLEM tokamak discharges are: toroidal magnetic field near the plasma center $B_\phi \sim (0.4\text{–}0.5)$ T, plasma current $I_P \sim (0.3\text{–}0.4)$ kA, central electron temperature $T_{e0} \sim (40\text{–}60)$ eV. In GOLEM tokamak due to the high loop voltage (U_{loop} ~4 V–6 V) and low electron density (line average density $\overline{n}_e \sim 10^{18}\,\mathrm{m}^{-3}$–$10^{19}\,\mathrm{m}^{-3}$), the RE are generated in the breakdown, current flat-top and disruption phases during a plasma discharge, in general. Magnetohydrodynamic (MHD) activity, particularly, the tearing mode excitation, may also induce parallel electric field to trigger the runaway electron (RE) generation [2].

However, location of their generation, dynamics inside the plasma and energy distribution in the RE beam remain unresolved issues. After the interaction with the plasma facing components, RE produce HXRs that are generally measured outside the tokamaks. Only in a few cases, efforts leading to the direct measurements of the RE and HXRs inside the plasma have been reported so far [3, 4]. Therefore, a probe is being designed for the local measurements of the RE inside the last closed flux surface (LCFS) of the GOLEM tokamak plasma. RE density in the tokamak plasma depends on applied and internally induced electric fields, electron density, electron temperature and Z_{eff}. For the GOLEM tokamak plasma conditions, RE density can be up to ~ $(10^{14} - 10^{16})\,\mathrm{m}^{-3}$ [5] based on the maximum estimated RE current fraction in the order of units of percent, the fact that average RE velocity should be in the range of tenths of speed of light and also because the RE may be localized only in a small region compared to the plasma cross-section. The average velocity is strongly dependent on the maximum achieved energy, but also on the distribution function. Simplified 0D models [6] of RE primary generation are very sensitive to plasma parameters, but if used carefully, they support the estimate of the RE density described above. The electric field in GOLEM tokamak is typically more than two orders of magnitude higher than the critical field limit defined as $E_c = n_e e^3 ln\Lambda / 4\pi\varepsilon_0^2 m_e c^2$ [6] which should lead to very significant RE generation, however impurities and other influences make the situation more difficult and the RE generation is not as dominant as expected.

2 Design considerations for the RE measuring probe

In this article, we discuss simulation results and design considerations of the scintillation probes that will be used for the direct measurement and energy resolution (fraction of beam energy between $\boldsymbol{E}$ and $\boldsymbol{E} + \Delta\boldsymbol{E}$) of the RE inside the LCFS. The Monte-Carlo simulation code FLUKA [7, 8] was employed to simulate the energy deposition in the probe due to the interactions between the 1 MeV/10 MeV monoenergetic pencil-like electron beam and the probe, which consists of four crystals. Figure 1 shows simulated four-crystal probe's cut view in the x-z and y-z planes and in 3D, built in the FLUKA graphical interface Flair [9]. The probe consists of four cylindrical scintillation crystals (length = 8 mm, diameter = 2 mm), pictured in brown color, which are shielded by material of thickness (1 mm), called filters (pictured in gray). To avoid direct exposure of the crystals to the plasma, scintillators and filters are housed inside a hollow cylindrical graphite cover (wall thickness = 2.5 mm).

In the four-crystal scintillation probe, crystals are aligned in the direction of the RE beam incidence and remain in the shadow region of the previous crystal (except the first one). Radiation shielding effect of the materials was used to filter the RE of different energies. The transmittance of the monoenergetic HXRs is defined by the output intensity relative to the input, I/I_0. This is expressed as a function of the thickness x and the beam energy E [10]: $I/I_0 \propto \exp[-\mu(E_X)x]$, where μ is the linear attenuation coefficient, which is proportional to the interaction cross section depending on E_X. For a RE beam having a wide energy range, the light intensities produced in the crystals can be written as [3]: $I_1 = \alpha n_1 + \alpha n_2 + \alpha n_3 + \alpha n_4$, $I_i = \alpha n_i + \ldots + \alpha n_4$, 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 $(i + 1)^{\text{th}}$ crystals.

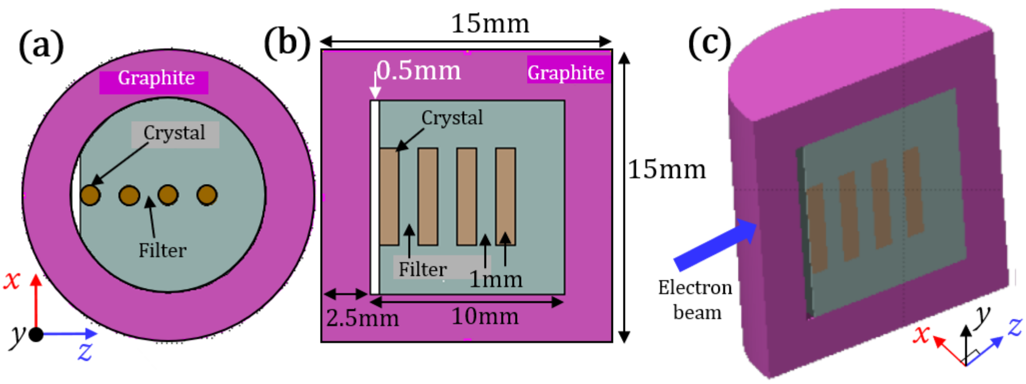

Figure 1. Geometry of the target scintillation probe assembly implemented in the FLUKA code showing (a) x-z plane (top view), (b) y-z plane (side view) and (c) 3D cut view. A pencil-like electron beam in the $\vec{z}$ direction was used in the simulations.

In order to minimize plasma perturbations and the RE beam energy losses, walls of the probe housing were kept as thin as possible, which is limited by machining facility and capacity of heat load intake inside the plasma edge. Heat flux of the thermal and runaway electrons can damage the probe inserted inside the last closed flux surface (LCFS). Moreover, RE of a few tens of MeV can strike the plasma facing components and easily propagate through several cm of low atomic number material and even melt high atomic number materials surface [11]. Although such high energies are not expected in Golem, a possible application on other machines requires that the issue is addressed. Low-Z graphite having high melting point ∼ 3600°C and poor shielding properties can withstand the high temperature plasmas for few tens of milliseconds absorbing only the low-energy part of the RE beam, without perturbing the plasma.

3 Simulation results

To filter the RE of different energies, molybdenum (Mo, density = 9.33 g/cm^3), Stainless steel (8.0 g/cm^3) and graphite (2.1 g/cm^3) were tested in combination with scintillating crystals of different density and light yield, particularly, YSO (4.4 g/cm^3), plastic (EJ-200) scintillator (1.05 g/cm^3) and NaI(Tl) (3.67 g/cm^3).

In the following section we discuss the simulation results of the FLUKA code. In the simulations, energy of the incident pencil-like monoenergetic electron beam was set as 1 MeV and 10 MeV. Figure 2 shows the deposition of energy density (GeV/cm^2 per primary) in the probe (YSO crystals with Mo filters inside the Graphite housing) by the 1 MeV electron beam (number of electrons in the beam = 10^5). Similar results were found also for the S.S. and Graphite filters, which clearly indicates that nearly all the energy is deposited in the graphite housing and no energy is deposited in the crystals. In the GOLEM tokamak, however, HXRs are generally observed in the NaI(Tl) and YAP crystals outside the machine which means that the energy of the HXR must be higher than few hundreds of keV as the HXR need to penetrate relatively thick metallic structures.

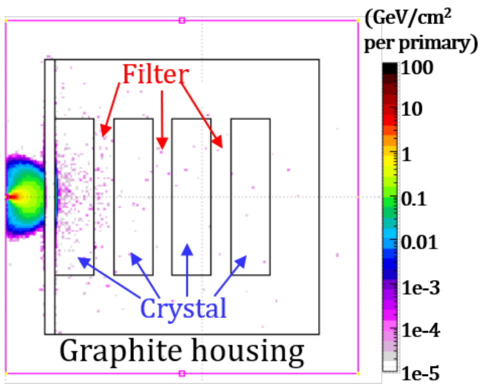

Figure 2. Energy deposited in the YSO crystals by 1 MeV electron beam.

In figure 3, side and top views of the energy deposition in the YSO crystals by the 10 MeV electron beam with (a) Mo, (b) S.S. and (c) Graphite filters have been plotted. Side and the top views of the energy distribution by the 10 MeV beam in the plastic and NaI(Tl) scintillators with Graphite and S.S. filter are shown in figure 4. Comparison of figure 3 and 4, clearly shows the highest deposition of energy density in the first YSO crystal, which is more than ∼ 3 GeV/cm^2 per primary electron (red colour region), whereas in the case of the first plastic crystal, it is less than 1 GeV/cm^2 per primary (yellow colour region). The total energy deposited in each YSO, NaI(Tl) and plastic crystals per primary electron is plotted in figure 5.

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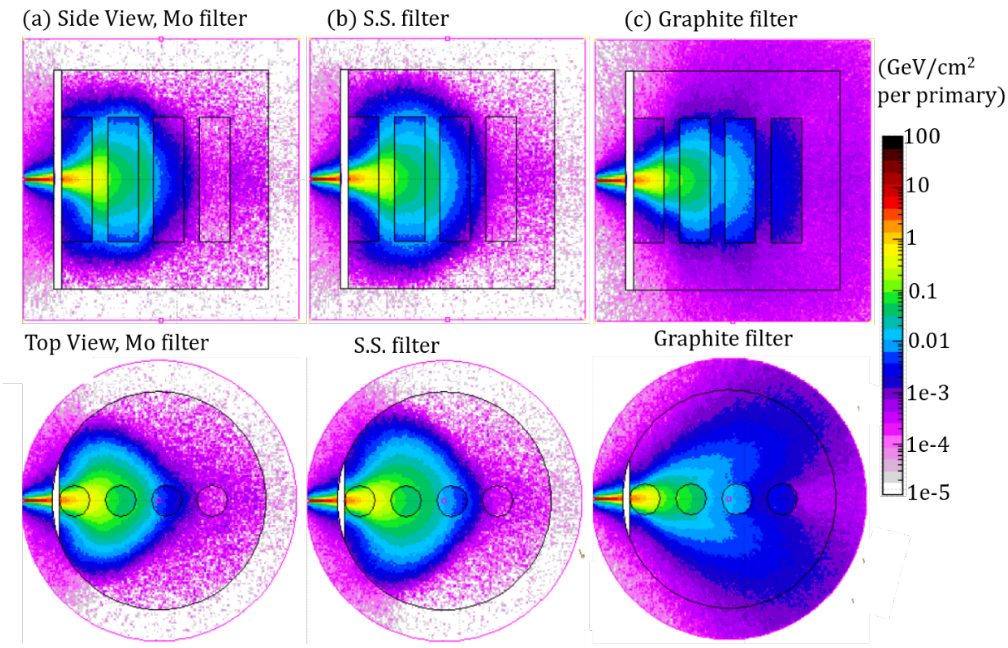

Figure 3. Side view (top) and top view (bottom) of energy deposition (GeV/cm^2 per primary) on the probe using YSO crystal by 10 MeV electron beam with (a) Mo, (b) SS, (c) Graphite filters.

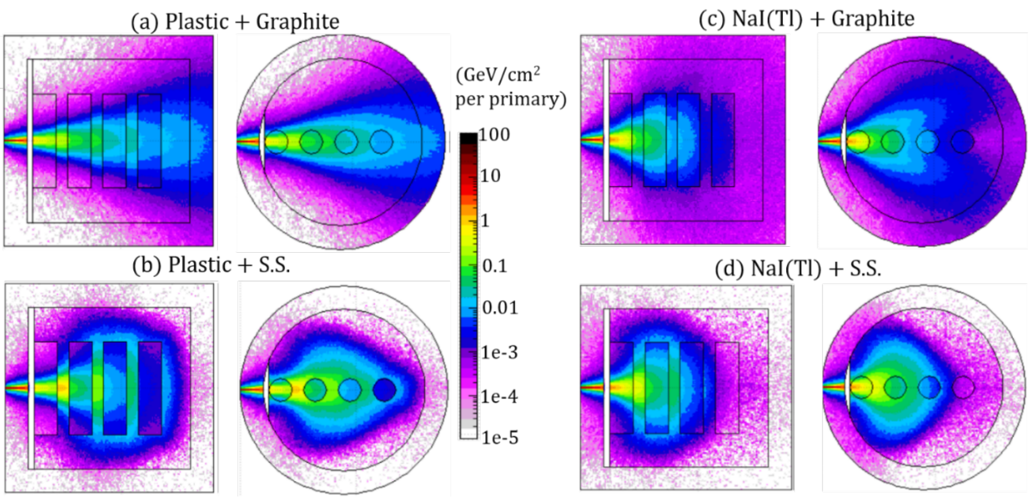

Figure 4. Side and top views of the energy deposited (GeV/cm^2 per primary) in the probe by 10 MeV electron beam on (a) plastic crystals + Graphite filters, (b) plastic crystals + S.S. filters, (a) NaI(Tl) crystals + Graphite filters, (a) NaI(Tl) crystals + S.S. filters

As this can be seen, the lower the density of the filter material, the farther the electrons penetrate in the probe. YSO and NaI(Tl) crystals with numbers 1–3 have noticeable energy deposition when graphite and S.S. filters are used. In case of Molybdenum filters the signal is comparatively lower in the third crystal. Hence, Graphite and S.S. seem to be a reasonable choice to achieve a satisfactory signal in the crystal 3 in the GOLEM tokamak. Being low density material, each plastic crystal

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absorbs low and equivalent amount of energy (figure 5), which makes it an inadequate candidate to resolve the RE energy. High and unequal amount of the absorbed energy in the YSO and NaI(Tl) crystals with Graphite and S.S. filters make them requisite candidate for the spectral measurements of the RE at the GOLEM tokamak.

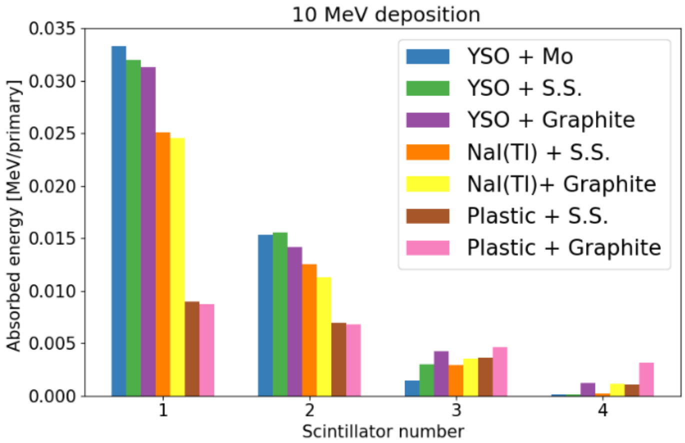

Figure 5. Energy absorbed by YSO, NaI(Tl) and plastic crystals in combination with Mo, S.S. and Graphite in the case of 10 MeV electron beam.

4 Design of the probe assembly

Now we briefly discuss the design of the probe assembly. Probe development will be done in two phases. In the first phase, a single-crystal probe will be fabricated to test signal amplitude, mechanical and optical assemblies. Relying on the results of the single crystal probe measurements, a four-crystal probe assembly will be developed for the energy resolved measurements of the RE.

A three-dimensional geometry and schematic diagram of the single-crystal probe head is shown in figure 6. For adjusting the probe head position inside the plasma, a rotary- feedthrough will be used to align crystal array in (or opposite to the) the plasma current direction. Optical signal in the crystals due to the RE incidence will be transmitted to the photo multiplier tube (PMT) using optical fibers. Since NaI(Tl) and YSO have maximum emission at wavelength $\sim$ (415–420) nm, Hamamatsu-R580 PMT has been chosen due to its highest response at wavelength around 420 nm,

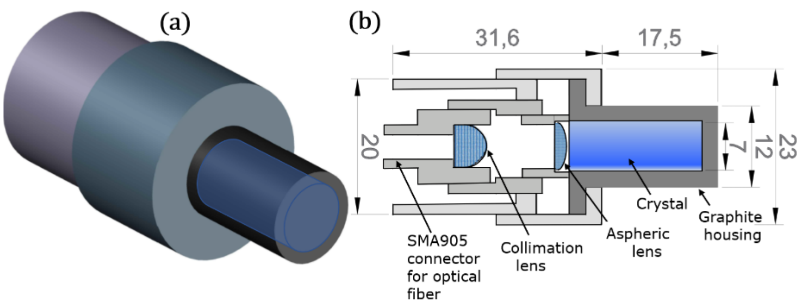

Figure 6. Single crystal probe head (a) 3D drawing, (b) Schematic drawing (dimensions are given in mm).

spanning in the range ~ (300–650) nm. To minimize the losses, signal from the crystal will be carried to the optical fiber via aspheric lens and collimating lens. Optical fibers have been chosen for the transmission of the wavelength range of interest stated above. It is expected that the light yield of the crystal will depend on number of incident electrons and energy of passing electrons [4]. Further simulations are planned for the determination of the signal amplitude as a function of electron number and energy.

Acknowledgments

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