Study of Runaway Electrons in GOLEM Tokamak

Pravesh Dhyani[a], Vojtěch Svoboda[a], Valeriia Istokskaia[a,d], Jan Mlynář[a,b], Jaroslav Čeřovský[a,b], Ondřej Ficker[b], Vladimír Linhart[c]

[a]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague, Czech Republic*
[b]*Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic*
[c]*Department of Dosimetry and Application of Ionizing Radiation, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague, Czech Republic*
[d]*ELI Beamlines, Dolní Břežany, Czech Republic*
E-mail: praveshdhyani@gmail.com

ABSTRACT: High loop voltage and low-density discharges at GOLEM tokamak present favorable conditions for the study of runaway electrons (RE). A probe is being designed and developed for the spectral measurement of the RE energy inside and near the GOLEM tokamak plasma edge. Design of the probe is based on simulation results of the FLUKA code that estimates the energy absorbed by the filters of various densities and scintillating crystals. Simulations performed for the monoenergatic electron beams of 1MeV and 10MeV suggest that the RE at the GOLEM tokamak may have energy much higher than 1MeV. In the simulations, graphite, stainless steel and molybdenum were tested to filter the supra-thermal electrons. Since having different light yield, YSO $\left(Y_2SiO_5:Ce\right)$, NaI(Tl) and plastic (EJ-200) crystals were chosen for the simulations.

KEYWORDS: Runaway electrons, FLUKA code, scintillators.

Corresponding author.

Contents

1. Introduction

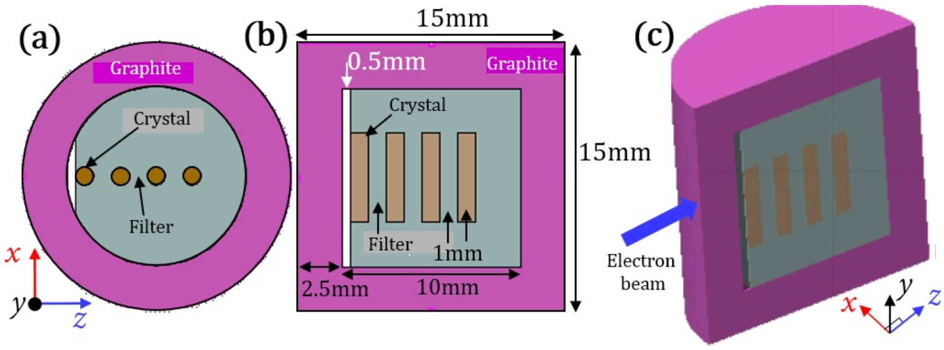
In GOLEM tokamak [1] due to the high loop voltage and low electron density, the RE are generated in the breakdown, current flat-top and disruption phases during a plasma discharge, in general. Magnetohydrodynamic (MHD) activity, particularly, the tearing mode excitation, may induce parallel electric field to trigger the RE generation [2]. However, location of their generation, dynamics inside the plasma and energy distribution in the RE beam remain unresolved issues. RE, after the interaction with the plasma facing components, produce HXRs that are generally measured outside the tokamaks. Only a few efforts for the direct measurements of RE and HXRs inside the plasma have been reported [3, 4] so far. Therefore, a probe is being designed for the local measurements of RE inside the last closed flux surface (LCFS) of the GOLEM tokamak plasma. Vacuum vessel of the GOLEM tokamak (major radius = 40cm, minor radius = 8.5cm), a continuous stainless steel (S.S.) donut of thickness ~0.2mm, is enclosed by the donut shape 10mm thick copper shield.

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 E and $E+\Delta E$) of the RE inside the LCFS. The FLUKA code [5, 6], which is based on Monte-Carlo simulation, employed to simulate the energy deposition in the probe due to the interactions between the 1MeV/ 10MeV monoenergetic pencil-like electron beam and the probe, consisted 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 [7]. The probe consists of four cylindrical scintillation crystals (length =8mm, diameter =2mm), pictured in brown color, which are shielded by material of different thickness (1mm), 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=2.5mm).

In the four- crystal scintillation probe, crystals are aligned in the direction of 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 [8]: $I/I_0 \propto \exp\left[-\mu(E_X)x\right]$, where μ is the linear attenuation coefficient, which is proportional to the interaction cross section depending on E_X . For a RE beam having 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 $i+1$ ¿ ¿ ¿ crystals.

Figure 1.



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

In order to minimize the perturbation to the plasma and RE beam energy losses, wall of the probe housing was kept as thin as possible, which is limited by machining facility and capacity of heat load intake inside the plasma edge, where electron density and electron temperature are n_e $10^{19} m^{-3}$ and T_e $10\,eV$. Heat flux of the thermal electrons and RE can damage to 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 [9]. Low-Z graphite having high melting point $3600^o C$ and poor shielding properties can withstand in the high temperature plasma for few tens of milliseconds and absorbs only low energy part of the RE beam and does not perturb the beam effectively.

3. Simulation results

To filter the RE of different energies, molybdenum (Mo, density = 9.33g/cm^3), S.S. (8.0g/cm^3) and graphite (2.1g/cm^3) were tested in combination with scintillating crystals of different density, particularly, YSO (4.4g/cm^3), plastic (EJ-200) scintillator (1.05g/cm^3) and NaI(Tl) (3.67g/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 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 for the S.S. and Graphite filters also, 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 indicates that RE generated in the GOLEM tokamak may have energies much higher than 1MeV.

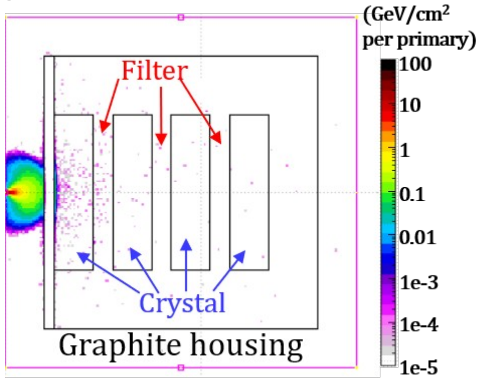


Figure 2. Energy deposited on YSO crystals by 1MeV electron beam.

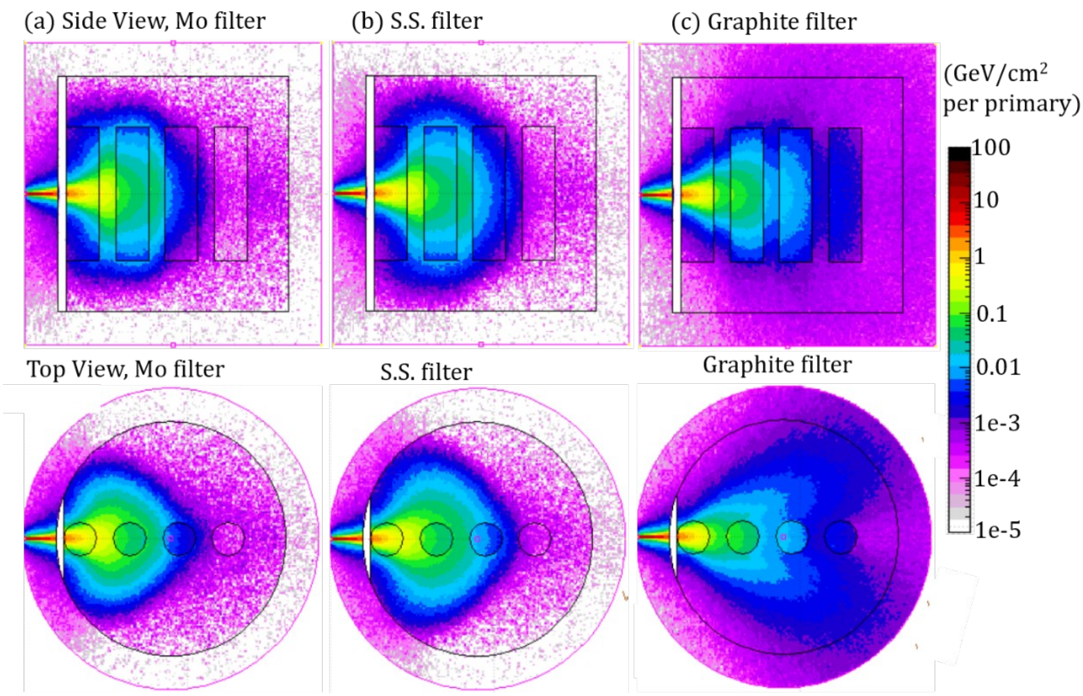


Figure 3. Side view (top) and top view (bottom) of energy deposition (GeV/cm^2 per primary) on YSO probe by 10 MeV electron beam with (a) Mo, (b) SS, (c) Graphite filters.

In figure 3, side and top views of the energy deposition in the YSO crystals by the 10MeV 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 10MeV 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 (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.

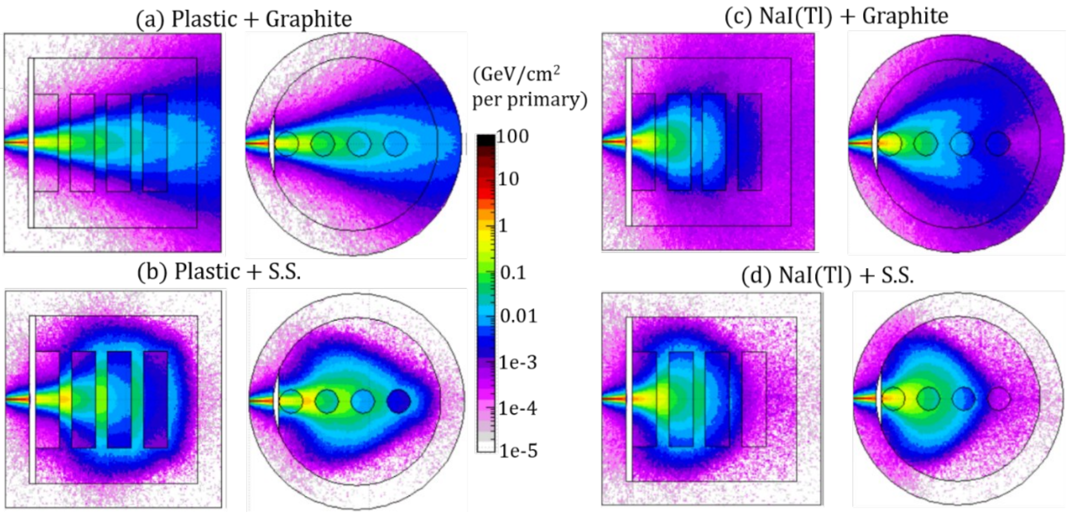


Figure 4. Side and top views of the energy deposited (GeV/cm^2 per primary) in the probe by 10 MeV electron beam on (a) plastic crystals + Graphite filters, (b) plastic crystals + S.S. filters, (a) NaI(Tl) crystals + Graphite filters, (a) NaI(Tl) crystals + S.S. filters

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. seems to be a reasonable choice to achieve a good signal in the crystal 3 in the GOLEM tokamak. Being low density material, each plastic crystal 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 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.

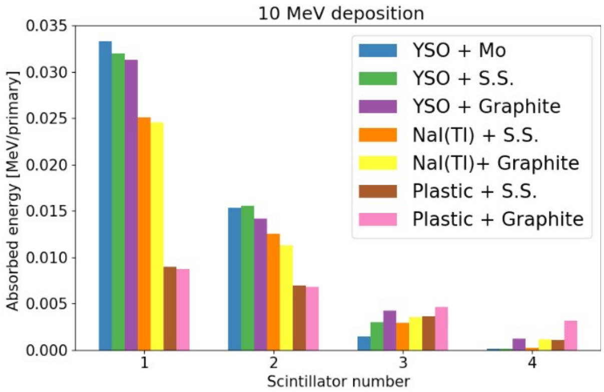


Figure 5. Energy absorbed by YSO, NaI(Tl) and plastic crystals in combination with Mo, S.S. and Graphite in the case of 10 MeV electron beam.

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.

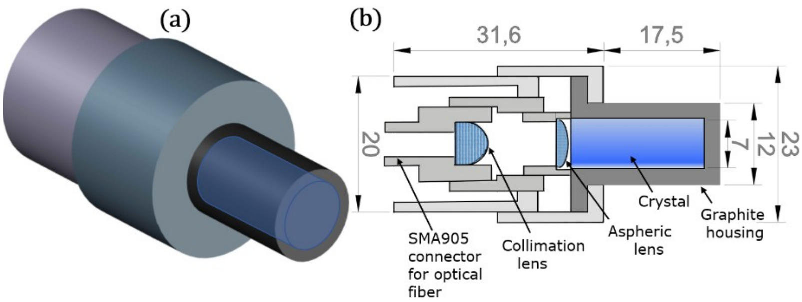


Figure 6: Single- crystal probe head- (a) 3D drawing, (b) Schematic drawing (dimensions are given in mm)

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 ~(415-420)nm, Hamamatsu-R580 PMT has been chosen due to its highest response at wavelength around 420nm, 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 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 signal amplitude as function of electron number and energy.

Acknowledgments

The work has been supported by the Operational programs RDE CZ.02.1.01/0.0/0.0/16_019/0000778: Centre of Advanced Applied Sciences, and CZ.02.2.69/0.0/0.0/16_027/0008465: International Mobility of Researchers CTU.

References

[1] V. Svoboda et al., *Multimode Remote Participation on the GOLEM Tokamak*, *Fusion Engineering and Design* **88(6-8)** (2011) 1310.

[2] P.V. Savrukhin, *Generation of suprathermal electrons during magnetic reconnection at the sawteeth crash and disruption instability in the T-10 tokamak*, *Phys. Rev. Lett.* **86** (2001) 3036.

[3] T. Kudyakov et al., *Spectral measurements of runaway electrons by a scanning probe in the TEXTOR tokamak*, *Rev. Scientific. Inst.* **79** (2008) 10F126.

[4] T. Kudyakov et al., *High energy electron crystal spectrometer*, *Rev. Scientific. Inst.* **80** (2009) 076106.

[5] A. Ferrari et al., *FLUKA: A multi-particle transport code* (Program version 2005). No. INFN-TC-05-11 (2005).

[6] *G. Battistoni et al., The FLUKA code: Description* and *benchmarking*, *AIP Conference proceedings,* **896(1)** (2007).

[7] V. Vlachoudis, *FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA.* Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, (2009).

[8] S. Kobayashi et al., *Tungsten alloys as radiation protection materials*, *Nuclear Instruments and Methods in Physics Research A* **390** (1997) 426-430.

[9] G F Matthews et al., *Melt damage to the JET ITER-like wall and divertor, Phys. Scr.* **2016** (2016) 014070.