In-vessel scintillation probe for direct detection of runaway electrons at the GOLEM tokamak

Lukas Lobko[1,2], **S. Malec**[1], **M. Tunkl**[1,2], **O. Zapadlik**[3], **O. Ficker**[1,4], **J. Cerovsky**[1,4], **V. Svoboda**[1] **and G. I. Pokol**[1]

[1] Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Czechia
[2] Department of Applied Physics, Ghent University, 9000 Ghent, Belgium
[3] CRYTUR, s.r.o., Turnov, Czech Republic
[4] Institute of Plasma Physics of the CAS, Prague, Czechia

E-mail: `lobkoluk@fjfi.cvut.cz`

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Abstract. The generation, physics, and mitigation of runaway electrons (REs) are of major importance for tokamak operation, as energetic RE beams can cause severe damage to plasma-facing components. Owing to its low plasma density and high toroidal electric field, the GOLEM tokamak provides favorable conditions for runaway electron studies, particularly in recently developed long-discharge regimes.

In this work, a rather novel diagnostic, the DDRE (Direct Detection of Runaway Electrons) probe, is presented. In contrast to conventional RE diagnostics based on secondary radiation, the DDRE probe measures runaway electrons directly via their interaction with in-vessel scintillation detectors. The probe consists of a cascade of thin scintillation pins combined with a collimator and a rotatable probe head, enabling measurements at various radial positions and viewing angles. The scintillation light is transported via optical fibers and detected by silicon photomultipliers.

The design of the first manufactured prototype is described together with FLUKA simulations demonstrating the main performance characteristics, including background hard X-ray suppression, energy response, and strong selectivity in the energy–pitch-angle phase space. The expected challenges, limitations, and planned future developments of the diagnostic are also discussed.

Keywords: runaway electrons; in-vessel diagnostics; scintillation detector; pitch-angle measurement; GOLEM tokamak; collimated particle detection

1. Introduction

This section provides a brief introduction to the GOLEM tokamak together with an overview of the basic physics of runaway electrons and their detection principles.

1.1. *GOLEM tokamak*

The GOLEM tokamak is a small-sized device operated at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. Its experimental program combines educational activities with scientific research, with a strong focus on the development and testing of plasma diagnostics.

GOLEM features a circular plasma cross-section limited by a molybdenum limiter and operates without a divertor. Although its basic plasma parameters are modest, recent technological upgrades have significantly enhanced its operational capabilities, as summarized in Table 1.

Owing to its relatively high repetition rate of approximately three minutes between discharges and the comparatively mild operational environment, GOLEM provides an excellent test bed for the development of novel diagnostics. In addition, the combination of high loop voltage U_{loop} and low electron density n_{e} strongly favors the generation of runaway electrons at experimentally accessible levels.

Table 1. Main GOLEM tokamak parameters after the recent upgrades: toroidal magnetic field B_{T}, plasma current I_{p}, plasma duration t_{p}, plasma flattop duration t_{flattop}, plasma electron temperature T_{e}, loop voltage U_{loop}, plasma electron density n_{e}, major radius R and minor radius a. The listed values represent approximate maximum values currently achievable in selected operational scenarios.

Parameter	Current
B_{T} [T]	0.8
I_{p} [kA]	14
t_{p} [ms]	50
t_{flattop} [ms]	25
T_{e} [eV]	≥ 100
U_{loop} [V]	4–10
n_{e} [$10^{18}\,\mathrm{m}^{-3}$]	1–10
R [m]	0.4
a [m]	0.085

1.2. *Runaway electrons*

Runaway electrons (REs) are an inherent phenomenon in tokamak plasmas arising when the accelerating force due to the toroidal electric field exceeds the collisional friction force acting on electrons. As the electron energy increases, the collisional drag decreases, leading to a positive feedback mechanism in which a fraction of the electron population is continuously accelerated to relativistic energies. [8, 3]

Due to their non-thermal nature and high kinetic energies, runaway electrons are difficult to control and are eventually lost from confinement, typically impacting plasma-facing components. At larger devices, the resulting localized power deposition can cause severe material damage.

A key parameter governing the onset of runaway electron generation is the critical electric field E_{c} [4] defined as

$$E_{\mathrm{c}} = \frac{n_{\mathrm{e}} e^3 \ln\Lambda}{4\pi\epsilon_0^2 m_{\mathrm{e}} c^2}, \tag{1}$$

where n_{e} is the electron density, e the elementary charge, $\ln\Lambda$ the Coulomb logarithm, ε_0 the vacuum permittivity, m_{e} the electron mass, and c the speed of light. When the local electric field exceeds E_{c}, even transiently during the plasma current ramp-up, runaway electrons can be generated.

For the GOLEM tokamak, E_{c} is of the order of $10^{-4}\,\mathrm{V\,m^{-1}}$, whereas the toroidal electric field typically reaches values of the order of $1\,\mathrm{V\,m^{-1}}$. GOLEM therefore provides favorable conditions for the generation of runaway electrons. With the recently implemented long-discharge scenarios reaching up to 50 ms, runaway electrons with energies exceeding 1 MeV are expected, although their detailed energy distribution has not yet been systematically explored.

1.3. *Runaway electron detection principle*

Runaway electrons can be broadly classified into two categories: confined electrons remaining inside the plasma column and electrons that are lost from confinement and impact plasma-facing components. The detection principles for these two populations are fundamentally different.

When runaway electrons strike solid materials, their kinetic energy is converted predominantly into bremsstrahlung hard X-ray radiation with photon energies ranging from tens of keV to several MeV or even more in large machines. This radiation can penetrate thick structures and is therefore commonly detected using scintillation or semiconductor detectors located outside the tokamak vacuum vessel. The measured hard X-ray signal provides indirect information about the runaway electron population and is widely used as a standard diagnostic technique.

An example of the detection of released REs at GOLEM is in Figure 1, where various scintillation detectors placed outside the tokamak chamber measure HXR radiation. In this long-discharge regime, it can be seen that runaway electrons are firstly released from the plasma slightly before 10 ms time and are continually released basically during the whole discharge duration.

This example also very nicely describes the typical problem, which standard size scintillation crystals mounted on a photomultiplier tube (PMT) have - losing voltage gain of PMT in high HXR fluxes. In this case, LYSO detector (purple) is sensitive only in high HXR intensities. This probe starts approximately from 20 ms measure very high fluxes and around 30 ms the signal is already saturated even for this low sensitivity sensor. It means that signals from other presented scintillation detectors, which are much more sensitive and thus should measure much higher intensity, are not reliable for most of the plasma duration.

Detection of REs confined in the plasma is generally more complicated. One way is to build specific radiometer to measure ECE (electron cyclotron emission). ECE measures electromagnetic radiation emitted by relativistic electrons undergoing gyromotion in a strong magnetic field. For runaway electrons, this emission is non-thermal and relativistically shifted, typically appearing in the microwave to sub-THz range. [9, 13]

Another way is to observe synchrotron emission from IR to UV spectra. [11, 16] Both ECE and synchrotron diagnostics provide valuable but indirect information on confined runaway electrons; however, their interpretation is limited by relativistic effects, strong pitch-angle dependence, line-of-sight geometry, and the need for detailed forward modeling. An overview of various diagnostic methods for runaway detection can be found in [3].

The diagnostic method proposed in this paper aims to detect runaway electrons in a more direct manner by measuring their collisions within the sensitive volume of a probe inserted into the plasma column. The design of the first manufactured prototype is presented, together with complementary FLUKA simulations and a discussion of the key challenges and limitations of the approach.

The most closely related work is reported in [7], where a similar diagnostic concept was first proposed for the GOLEM tokamak. However, the probe design presented there was not yet sufficiently mature for routine operation or practical exploitation on GOLEM.

A comparable approach was successfully implemented earlier on the TEXTOR tokamak [12], targeting significantly higher runaway electron energies, albeit without any collimation for pitch-angle discrimination, which is harder to achieve for higher RE energies.

More recently, a partially related concept was applied at the TCV tokamak [14], where the scintillator-based fast-particle loss detector (FPLD), originally developed for fast-ion loss measurements, was also found to be sensitive to runaway electrons within a specific region of velocity-space.

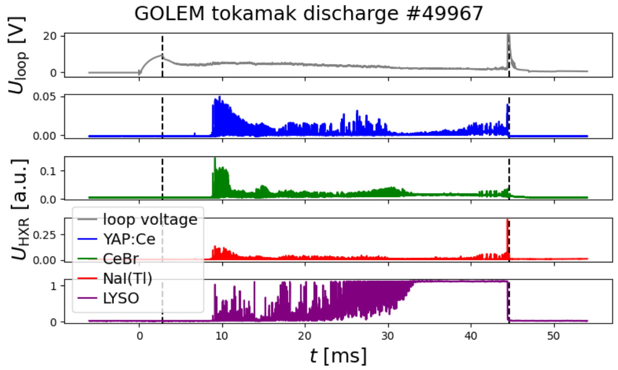

Figure 1. Temporal evolution of raw voltage $U_{\rm HXR}$ of various scintillation detectors mounted on PMT/SiPM, derived from HXR radiation emitted by runaway electrons, is depicted. Black vertical dashed lines indicate plasma breakdown and the disruption at the end; GOLEM discharge #49967 (online [10]).

2. DDRE probe design

This section describes the design of the first manufactured prototype of the DDRE (Direct Detection of Runaway Electrons) probe developed in collaboration with CRYTUR, s.r.o. [5], a Czech company specialising in scintillation crystals.

2.1. Overall probe concept

For the direct detection of runaway electrons, the probe is inserted into the edge of the plasma column. A CAD rendering of the probe mounted on a manipulator inside a segment of the GOLEM vacuum vessel is shown in Figure 2. The probe can be radially displaced and rotated to adjust the viewing angle with respect to the local magnetic field.

Runaway electrons entering the probe through the collimator aperture interact with the scintillation pins located in the probe head. The scintillation light is transmitted through shielded optical fibres to an optical feedthrough flange and subsequently to silicon photomultipliers (SiPMs), where the electrical signals proportional to the deposited energy are recorded using a fast data acquisition system.

The present probe geometry was designed to be compatible with the existing GOLEM vacuum flanges; however, the optical fibre routing and the mechanical interface can be readily adapted to other devices.

2.2. Mechanical structure

The probe was designed with a strong emphasis on modularity and vacuum compatibility. All components

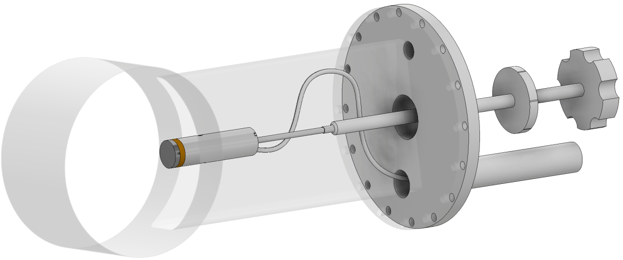

Figure 2. CAD model of the DDRE probe inserted into a segment of the GOLEM tokamak vacuum vessel. The probe is mounted on a movable manipulator allowing radial positioning and adjustment of the viewing angle with respect to the local magnetic field.

can be fully disassembled and no adhesives are used. A detailed view of the probe structure is shown in Figure 3. From top to bottom, the main components are the molybdenum collimator (grey) housing the scintillation pins, the scintillator holder (brown), and the structural core (dark blue), which supports all mechanical elements. The optical fiber connectors and a substantial fraction of the fibers are enclosed within a stainless-steel protective tube (transparent color).

The overall dimensions of the probe are approximately 89 × 25 mm (length × diameter), thereby minimizing the perturbation of the plasma and limiting the thermal load on the probe. The screws and internal volumes were designed to be compatible with high-vacuum operation as well.

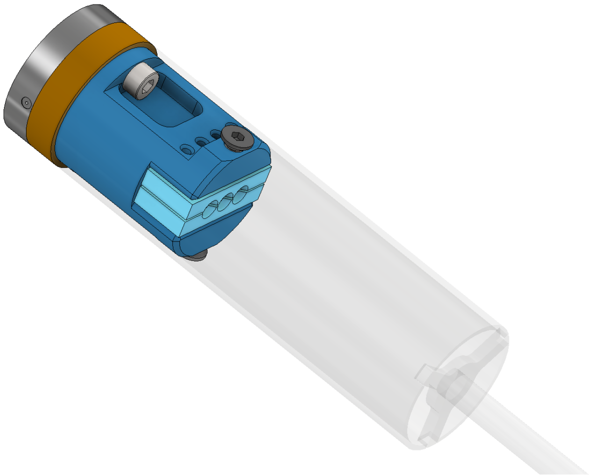

Figure 3. Detailed structure of DDRE probe: collimator (grey), scintillator holder (brown), structural probe core (dark blue), optical fibers holder (light blue), protective tube (transparent color).

2.3. Probe head and scintillation pins

A close-up of the probe head is shown in Figure 4. In the first prototype, three identical scintillation pins (yellow) are positioned along a single line of sight behind a molybdenum collimator with a 7.5×0.5 mm (length × diameter) pinhole. The narrow aperture defines the acceptance of the pitch angle and limits the particle flux to the first crystal. The modular design allows for easy replacement with another collimator for different types of measurements.

For the detector itself, the CRYTUR manufactured YAP:Ce scintillator (cerium-activated yttrium aluminum perovskite) was selected (technical parameters overview in [6]). YAP:Ce is a high-melting-point oxide crystal (melting point 1875 °C), which provides good thermal stability of the scintillator material itself under elevated surface temperatures. It is non-hygroscopic. The small decay constant of approximately 25 ns strongly reduces pulse pile-up effects at high particle fluxes, possibly allowing for reliable discrimination of individual events for energy spectra measurements. The light output is approximately 25 000 photons per MeV of absorbed energy, which is well suited for single-electron detection.

The scintillation pins have dimensions of 6×0.8 mm (length × diameter). In combination with the relatively low effective atomic number $Z_{\text{eff}} \approx 33$ of YAP:Ce, this geometry significantly suppresses the response to background hard X-ray radiation originating from runaway electrons impacting plasma-facing components. The pins are coated with a $1\,\mu$m zirconium layer for light tightness and to reduce sensitivity to low-energy photons. A reduction of the coating thickness is planned in future versions to improve the energy resolution.

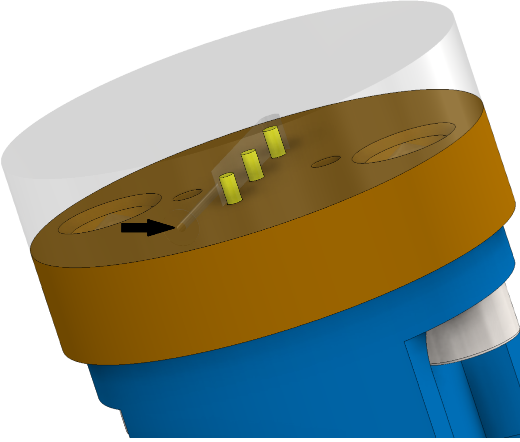

Figure 4. Close-up view on the DDRE probe head geometry. The collimator (transparent) hides three scintillation pins (yellow) placed in a one line of sight. Black arrow points to pinhole entrance.

3. FLUKA simulations of the DDRE probe response

This section presents the main performance characteristics of the first manufactured DDRE probe prototype obtained from Monte Carlo particle transport simulations. All simulations were carried out using the FLUKA code. [2, 1]

3.1. Discrimination between runaway electrons and hard X-rays

This subsection demonstrates the ability of the DDRE probe to discriminate between runaway electrons directly impacting the scintillation pins and background hard X-ray radiation. A monoenergetic electron beam with an energy of 1 MeV and a monoenergetic hard X-ray beam of the same energy were simulated using the FLUKA code. Both beams were injected along the collimator axis in a homogeneous magnetic field of $B = 0.5\,\mathrm{T}$.

Figure 5 compares the spatial distribution of deposited energy density inside the probe for both particle types. While the 1 MeV runaway electron beam is efficiently absorbed already in the first scintillation pin, the hard X-ray beam penetrates the entire probe volume with only a weak and nearly uniform energy deposition.

Quantitatively, approximately 66 % of the total energy of the 1 MeV electron beam is deposited in the first scintillation pin, whereas only 0.156 % and 0.0136 % are deposited in the second and third pin, respectively. In contrast, the three scintillation pins absorb comparable fractions of the hard X-ray beam energy, with a total deposited fraction of approximately 2.5 %.

These results indicate that the DDRE probe exhibits strong intrinsic sensitivity to charged particles while being weakly sensitive to penetrating photon radiation, possibly enabling efficient suppression of the hard X-ray background.

3.2. Multi-layer scintillation detector response

The first manufactured DDRE prototype contains three identical scintillation pins arranged along a single line of sight behind the collimator pinhole. This configuration was chosen to enable initial testing of the signal intensity and dynamic range of the detection system.

The first scintillation pin acts as a thin detector and is primarily intended for the measurement of the deposited energy spectrum. Figure 6 shows the event-by-event energy deposition spectra obtained from FLUKA simulations for two representative runaway electron energies. To emulate a realistic detector response, a reduced effective scintillation light yield of 2000 photons per MeV was assumed (typical light yield for YAP:Ce is about 25 000 photons/1 MeV [6]), and Poisson statistics were applied to account for photon counting fluctuations. Despite the moderate light yield, the primary energy peak remains clearly identifiable, indicating that energy-resolved measurements are feasible, although further optimization is required to improve the energy resolution.

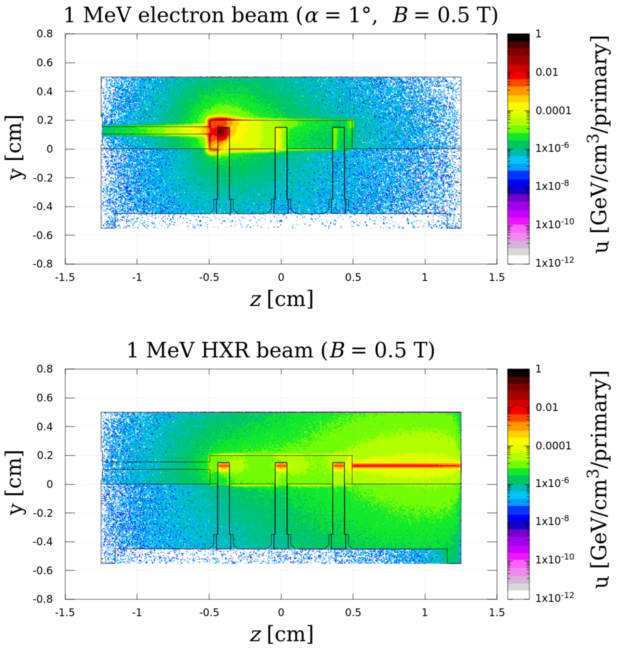

Figure 5. Energy deposition density u of the particle beam penetrating the DDRE probe from left to right in the homogeneous mag. field $B = 0.5$ T. The black row symbolizes the direction of both the initial position of the beam and the mag. field orientation. Upper figure: 1 MeV electron beam with pitch angle $\alpha = 1$; Bottom figure: 1 MeV HXR beam.

The second and third scintillation pins are intended to serve as validation channels, particularly in high-flux conditions where pile-up or saturation effects in the SiPMs may occur. In addition, the relative response of the three pins provides a means to discriminate the background hard X-ray contribution, as penetrating photons deposit comparable and typically small amounts of energy in all scintillators, in contrast to the strongly localized deposition characteristic of runaway electrons.

3.3. Energy-pitch angle space response

Owing to the use of a narrow collimator pinhole, only runaway electrons with specific combinations of energy and pitch angle α (defined as the angle between the electron velocity vector and the magnetic field line) can

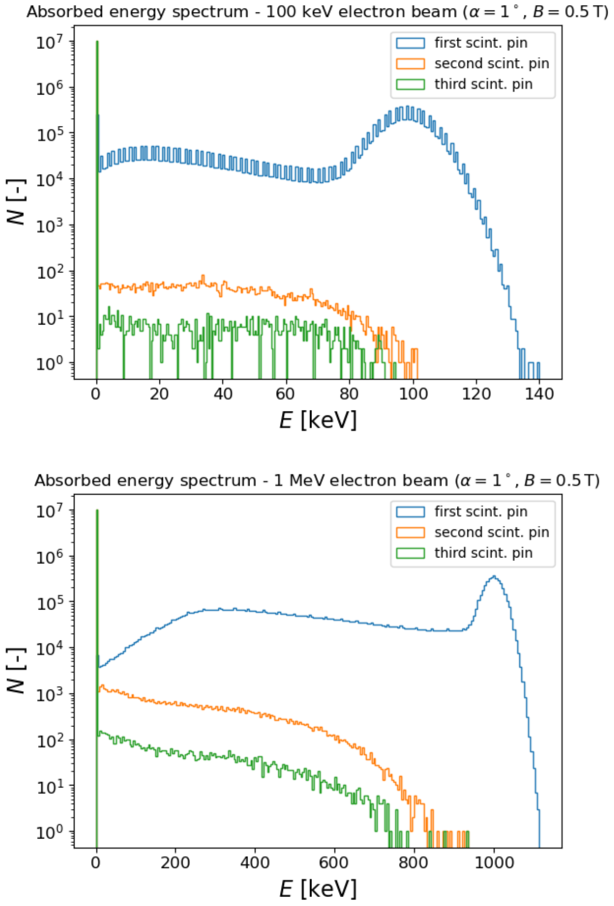

Figure 6. Absorbed energy spectra E (N is number of events) for all three scintillation pins from the electron beam (10^7 events simulated) with pitch angle $\alpha = 1^\circ$ and homogenous magnetic field $B = 0.5$ T oriented along the collimator pinhole. Upper figure: 100 keV electron beam; Bottom figure: 1 MeV electron beam.

effectively enter the sensitive volume of the probe head (Figure 7). As the runaway electron energy increases, the range of admissible pitch angles rapidly decreases.

Consequently, the detection of runaway electrons with energies of several hundred keV or higher requires pitch angles not exceeding approximately 3°, with the highest detection probability for $\alpha \leq 2^\circ$. Pitch angles in the range $(3^\circ - 4^\circ)$ are transmitted only for electron energies around 100 keV.

At low energies, of the order of several tens of keV, a noticeable reduction of the DDRE probe response is observed. In this regime, the 1 μm zirconium protective layer covering the scintillation pins constitutes a non-negligible energy barrier, preventing low-energy electrons from reaching the scintillator.

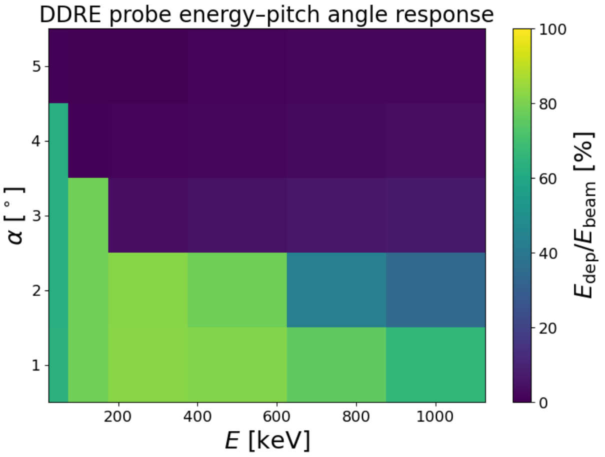

Figure 7. Fraction of the total runaway electron beam energy deposited in the first scintillation crystal as a function of the initial electron energy E and pitch angle α, obtained from FLUKA simulations with 10^7 monoenergetic electrons per point. The map represents the transmission function of the DDRE probe, demonstrating strong selectivity of the collimator in the (E, α) phase space.

4. Expected challenges and future developments

4.1. Testing of different collimator concepts

The modular design of the DDRE probe enables straightforward implementation and testing of different collimator geometries. A critical challenge is the accurate alignment of the probe with the local magnetic field direction, which is required for runaway electrons to enter the probe through the narrow pinhole aperture.

To mitigate this limitation, a collimator design with a significantly wider acceptance cone is currently under development; however, this comes at the expense of reduced pitch-angle discrimination. In addition, an alternative configuration is being investigated in which the individual scintillation pins are spatially separated, each being equipped with its own collimator pinhole, thereby providing simultaneous sensitivity to different pitch-angle ranges.

In the present single-line-of-sight configuration, the scintillation pins are positioned as close to each other as possible. However, the probe layout can be readily modified to increase their mutual separation, enabling measurements of local spatial profiles of the runaway electron population.

4.2. Testing of different scintillation pin geometries

As shown in Figure 5, a substantial fraction of the incident runaway electron beam is scattered onto the surrounding collimator walls. The present probe corresponds to the first manufactured prototype, in which the emphasis was placed on simple and robust geometries.

Following the initial experimental testing, further optimization of the DDRE probe is foreseen in order to improve the achievable energy resolution, as suggested by the results in Figure 6. This will be pursued by reshaping the inner collimator surfaces and the scintillation pins, since the current cylindrical pin geometry is not optimal for minimizing scattered contributions. Additional improvements will include reducing the thickness of the protective coating on the crystals and optimizing the optical coupling to the SiPM.

4.3. Thermal loads and material erosion

A significant limitation of in-vessel particle diagnostics is their exposure to high heat fluxes. An overview of damage mechanisms affecting plasma-facing components on a wide range of tokamaks is presented in [15]. In that study, a Cherenkov probe equipped with a molybdenum alloy front surface suffered severe erosion when deployed in the TCV tokamak.

Although such behavior is not expected at the GOLEM tokamak due to its substantially lower power levels, thermal erosion remains an important parameter to be assessed during the first experimental campaign with the DDRE probe. Depending on the observed degradation, further optimization of the collimator geometry, such as the removal of sharp edges, may be required. If necessary, the probe design also allows the implementation of a reciprocating mechanism to limit the exposure time to high heat loads for potential use on larger tokamaks.

4.4. Local magnetic field measurement

The interpretation of the DDRE probe measurements critically depends on the probe orientation with respect to the local magnetic field direction. A planned upgrade of the probe therefore includes the integration of miniature Mirnov coils for in situ measurement of the local magnetic field vector.

The current probe design already incorporates two dedicated apertures intended for the installation of these sensors. Such measurements would significantly improve the reconstruction of the runaway electron pitch-angle distribution, which is generally very hardly accessible with conventional runaway electron diagnostics. Achieving reliable pitch-angle information, at least under selected plasma conditions, is considered one of the key objectives of the DDRE probe development.

5. Conclusion

A rather novel in-vessel diagnostic for runaway electrons, the DDRE probe, has been presented. The probe enables direct detection of runaway electrons via their interaction with thin scintillation crystals, providing an alternative to conventional diagnostics based on secondary radiation.

The modular mechanical design allows straightforward modification of the collimator geometry and scintillation pin configuration, facilitating adaptation to specific experimental requirements. FLUKA simulations demonstrate a strong suppression of the background hard X-ray signal and indicate that, with further optimization of the collimator and scintillator geometries, energy-resolved measurements of runaway electrons are feasible.

The narrow collimator aperture introduces a pronounced selectivity in the $(E,\ \alpha)$ phase space, effectively acting as a pitch-angle filter. This feature offers the prospect of obtaining information on the runaway electron pitch-angle distribution, which is hardly accessible with existing diagnostics.

The main challenges and planned upgrades have been outlined, with particular emphasis on the integration of miniature Mirnov coils for in situ measurement of the local magnetic field vector. This development is expected to significantly improve the interpretation of the measured data and represents a key step in the further evolution of the DDRE diagnostic.

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