Monte-Carlo simulations of runaway electron impact on tokamak plasma-facing components

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Introduction

During a tokamak discharge, a part of the electrons in plasma can be accelerated to relativistic velocities and energies in the order of MeVs. This is due to the decreasing characteristic of the friction force on the electrons with the electron energy, because of the decreasing collisional cross-section for the suprathermal electrons. Electrons accelerated to this regime are called Runaway Electrons (RE). When a RE beam strikes the surface of the first wall, it can cause heat loads in the order of hundreds of $\mathrm{MW/m^2}$ and damage the plasma-facing components (PFC) or other tokamak parts. Unlike thermal plasma particles, RE do not deposit their entire energy directly to the surface of PFC but at a certain depth into the material. A part of this energy is converted to heat in the material and a part is radiated mainly due to the bremsstrahlung. The rest of the incident energy can be lost in the form of backscattered electrons ejected from the material. The deposition depth of the RE beam energy depends on the first wall material electron stopping power.

Numerical modeling of high-energy particle interactions with matter is typically solved by the Monte Carlo (MC) method. In this study we present results obtained mainly by FLUKA [2], which is an MC multi-purpose simulation code for the transport of high-energy particles and their interaction with matter. It can solve charged particle motion in complex magnetic fields and arbitrary geometry. FLUKA can simulate runaway electrons from 1 keV up to 1 PeV with arbitrary energy distribution. For the heat load studies, FLUKA can simulate the energy density deposited in the material by the primary particles and their products in either simplified combinational geometry or a complete CAD (Computer-Aided Design) geometry by using the DAGMC (Direct Accelerated Geometry Monte Carlo) module.

In this contribution, we present a method for sampling the runaway electron impact angle, which has been implemented in FLUKA and used to simulate energy deposition profiles for calorimetry probes used at COMPASS and GOLEM tokamaks. Predictive FLUKA simulations were conducted for JT-60SA plasma-facing components to estimate heat load levels in graphite PFC and heat sinks behind. FLUKA results were used as an input for ANSYS finite element analysis of the temperature change in the components.

Runaway electron impact angle

The profile of the deposited energy by runaway electrons depends on the impact angle on the component surface. This angle is random, however, it can be sampled, if we know the distribution of RE pitch angle $\gamma = \arctan(v_{\parallel}/v_{\perp})$, where $v_{\parallel}$ and $v_{\perp}$ is electron parallel and perpendicular velocity to the magnetic field respectively. In this work, we implemented an algorithm sampling the impact angle distribution to FLUKA with an approach inspired by the HEIGHTS code [3], however with a different derivation of the distribution. The electron impact angle is determined based on two random numbers - RE pitch angle γ and the position of the RE helix ξ against the surface. In our case, we used a uniform distribution of the RE pitch angle $\tan\gamma = [0;1]$ and uniform distribution of the spiral position $\xi = [0; p_L \cdot \tan\alpha]$, where $p_L = \frac{2\pi m_e}{eB} v \cos\gamma$ is the spiral pitch and α is the incident angle of the magnetic field on the component surface (1° in our case). The parameters of the electron spiral are illustrated in the scheme in Figure 1 on the left.

The phase angle of the electron along the spiral t is calculated based on ξ as an intersection of the spiral and the surface. With known phase angle t, the impact angle θ can be calculated using Equation 1. A histogram of the impact angles for pitch angles $\tan\gamma = 0.1, 0.2, ..., 1.0$ and for a uniform distribution $\tan\gamma = [0,1]$ can be seen in Figure 1, right. The maximum impact angle for the pitch distribution is 18.8°, while the maximum probability angle is around 11°.

$$\cos\theta = \frac{\frac{p_L}{2\pi}\tan\alpha - r_L \sin t}{\sqrt{(1+\tan^2\alpha)\left(r_L^2 + \frac{p_L^2}{4\pi^2}\right)}} \tag{1}$$

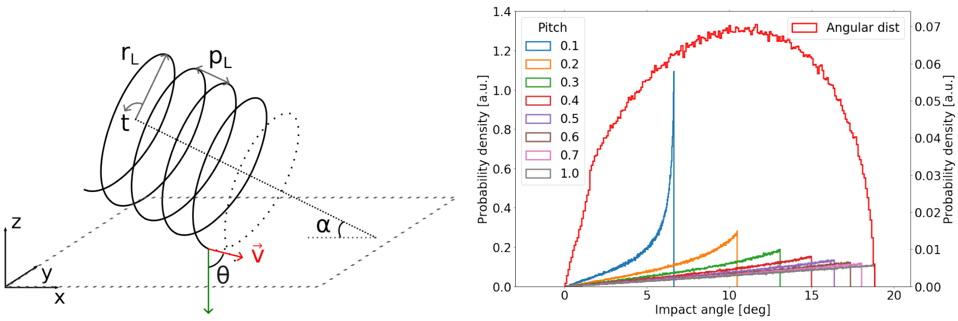

Figure 1: Left: Helix of the runaway electron impacting a surface with the spiral parameters. Right: Histogram of the impact angle for different pitch angles and uniform distribution of $\tan\gamma$.

COMPASS Calorimeter

The algorithm described above has been used first for the RE impact study of the COMPASS calorimetry probe [4]. The calorimetry probe acted as a low-field side protection limiter during RE discharges and, therefore, it was the most affected component by the impact of the runaway electron beam.

In our study, we simulated an impact of the RE beam on the front surface of the probe in a similar area, that was measured by the IR camera, for energies ranging from 1 MeV to 10 MeV, which is the maximum energy of RE in COMPASS that was found in HXR measurements [5]. The deposited energy density E_{dep} from a FLUKA simulation with $2 \cdot 10^6$ particles in the cross-section of the calorimetry probe for 10 MeV RE beam is shown in Figure 2, left.

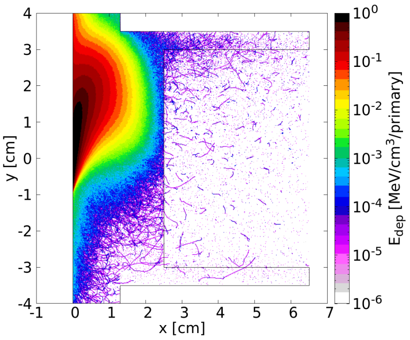

Figure 2: Deposited energy density by 10 MeV RE beam in the cross section of COMPASS calorimetry probe (left). Ratios of deposited and radiated energy to the impacting electron energy as a function of RE energy (right).

The ratio of the energy deposited in the form of heat for different electron energy is shown in Figure 2, right. It can be seen, that $96-80$ % of the electron energy is converted to heat in the probe and $0.6-7.0$ % is radiated mainly due to bremsstrahlung. The rest of the electron energy is lost due to electron scattering.

Golem calorimeter

The FLUKA analysis has been conducted for a similar probe at Golem tokamak. A photo of the first version of the probe, which was tested in the tokamak with 3 Pt100 temperature sensors, can be seen in Figure 3. This probe, however, did not measure any change in the probe temperature due to the very low energy of the Golem discharges ($E_{\text{th}} = 1-10$ J) and a relatively large volume of the probe (cylinder with a radius of 10 mm and height of 25 mm). ANSYS simulations with inputs from FLUKA of the heat loads have shown that a deposited energy of 2.5 J leads to heating of the probe by only 0.2 °C. The FLUKA simulations have shown that the electrons with energy 300 keV (maximum energy calculated from HXR measurements [5]) deposit their energy in only 0.5 mm depth and the mean deposited energy is $E_{\text{dep}} = (253.7 \pm 0.1)$ keV. It will be therefore possible to prepare a second version of the probe with a $80-90$ % smaller volume to increase temperature sensitivity.

Figure 3: Photo of the Golem calorimetry probe.

JT-60SA plasma-facing components

A predictive analysis of the RE impact on the plasma-facing components (high-field side limiter and divertor tiles) has been done for the JT-60SA. RE impact was simulated for electrons with energies based on JET HXR measurements [6] ($2-20$ MeV) with an impact angle of $1^\circ, 3^\circ$, and 10°. Heat loads were simulated in ANSYS for values predicted for ITER [7] ($10-50$ MJ/m^2 during $10-100$ ms). The divertor tiles were simulated in full CAD geometry