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Monte Carlo simulation of the thermal radiation heat load to the cryogenic mirror and vacuum system of the Einstein Telescope

Xueli Luo*, Stefan Hanke, Katharina Battes and Christian Day

Institute for Technical Physics, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany

*E-mail: Xueli.Luo@kit.edu

Abstract. A third-generation underground gravitational wave (GW) observatory, known as the Einstein Telescope (ET), will be developed by European countries together. It is designed as an equilateral triangle with 10 km long arms, 200 to 300 meters underneath the ground, and with detectors being located in each corner. Any two adjacent arms comprise two independent interferometers, of which one interferometer will detect low-frequency gravitational wave signals (ET-LF), while the other will be optimized for operation at higher frequencies (ET-HF). In order to reduce seismic noise, thermal noise and other systematic noise, the beamline pipes require ultra-high or high vacuum conditions. In addition, the mirrors of ET-LF will be cooled to cryogenic temperatures below 20 K. Obviously, the mirror at this temperature will adsorb gases as a frost layer, degrading its optical properties and increasing laser power absorption. In this study, systematic Monte Carlo simulations are used to assist the development of the cryopump concept to fulfil the requirements regarding to pressure and frost mitigation aspects of ET-LF, and obtain the radiation heat loads for the corresponding cryogenic supplies at different temperatures, which are important information for the planning of the cryogenic infrastructure.

1. Introduction

The Einstein Telescope (ET) is a design concept for a third-generation European gravitational wave detector that will be about 10 times more sensitive than today's instruments. Fig. 1 shows the current proposal of ET, which is basically an equilateral triangle with 10 km long arms. The detectors of the interferometer are located in each corner, and any two adjacent arms will comprise two independent interferometers, of which one (ET-LF) will detect low-frequency gravitational wave signals, while the other (ET-HF) will be optimized to detect gravitational wave signals at higher frequencies [1].

In our previous work [2], systematic Monte Carlo simulations were carried out to assist to develop a concept for the vacuum pumping systems of ET-LF, which is based on cryopumps and can fulfill the requirements regarding to pressure and frost mitigation aspects. In this study, a matrix of the radiation exchange factors of the system are obtained from 55 independent Monte Carlo simulations, in which the emissivity of each surface is included, and the radiation heat loads for the cryogenic supplies at different temperatures are calculated according to the areas and temperatures of every radiating and diffuse reflecting surfaces. These results are important to finally develop the real and robust cryopumps of ET-LF, and provide necessary information for the cryogenic plants.

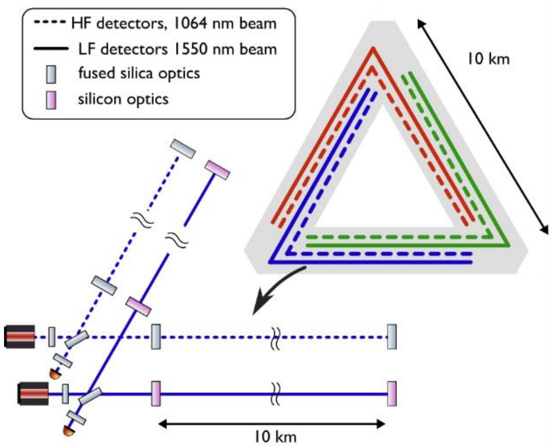

Figure 1. The proposed Einstein Telescope: a third-generation European gravitational wave observatory.

2. Vacuum simulation and the configuration of the cryopumps of ET-LF

The vacuum systems of ET in this study are high or ultrahigh vacuum and will be mainly in free molecular flow regime. In this case, the Knudsen number *Kn* – the ratio of the mean free path of the molecules to the typical size of the vacuum system is much greater than unity (eg. *Kn* >10), and the gas flow is mainly determined by the geometrical structure of the system since the collision between the gas molecules is negligible.

The free molecular flow can be simulated with Test Particle Monte Carlo (TPMC) method. In last years, we have developed a versatile TPMC code ProVac3D (abbreviation from Profile of the Vacuum of 3D complexity). Unlike other common TPMC codes which only record the hitting positions of the test particle trajectories, ProVac3D uses the gas molecules of real mass, temperature and velocity as the test particles, and the hitting times of the test particles are also calculated. This novel feature makes it able to obtain local molecular number density in the system [3-6]. If the number of the test molecules simulated is N_{mc} and v_i is the volume of a small cell (with index i) implemented at the location of interest, which is virtual and transparent, and t_i is the corresponding sum of time-of-flight of all test molecules passing this cell and recorded in the simulation, the local molecular number density is:

$$n_i = \frac{Q}{k_B T}\frac{t_i}{v_i N_{mc}}, \tag{1}$$

where ambient temperature $T=0°C$ is used to convert the total input gas throughput Q (in Pa m^3 s^{-1}) into the molecule number flow rate (molecules/s). Corresponding local pressure is:

$$p_i = k_B n_i \langle T_i \rangle, \tag{2}$$

where $\langle T_i \rangle$ is the average temperature of all test molecules passing this cell and recorded in the simulation.

Vacuum simulations were carried out in stepwise approaches with ProVac3D code in the supercomputer, and helped us to develop a concept of the vacuum pumping systems of ET-LF [2]. As shown in Fig. 2, the gas loads from the adjacent tower in the left side will be mainly pumped by 1 m long cryppump at 4 K for hydrogen pumping and additional 19 m long cryopump at 80 K for heavy gases such as water vapor. In right side from the tower to the beam pipe, a 10 m long cryopump at 80 K is enough to decouple the vacuum of the beam pipe from the tower and to achieve the requirements. The results from vacuum simulations show this configuration of the crypumps can fulfil the requirements of the pressures and frost mitigation aspects, and provide a reasonably long monolayer built-up time of water on the mirror at 10-20 K in the tower [2].

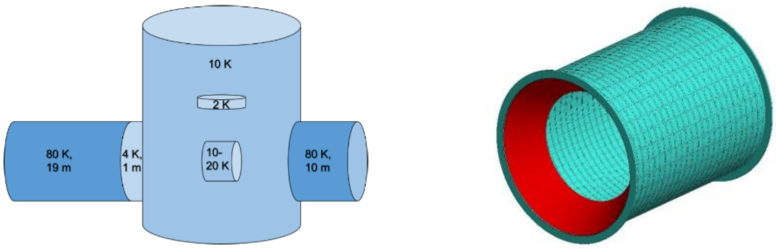

Figure 2. The concept of the cryopumps at both sides of the cold mirror of ET-LF (left) and 80 K cryopump segment with integrated baffle (not in scale).

3. Simplified model for heat load simulation and the simulation approaches

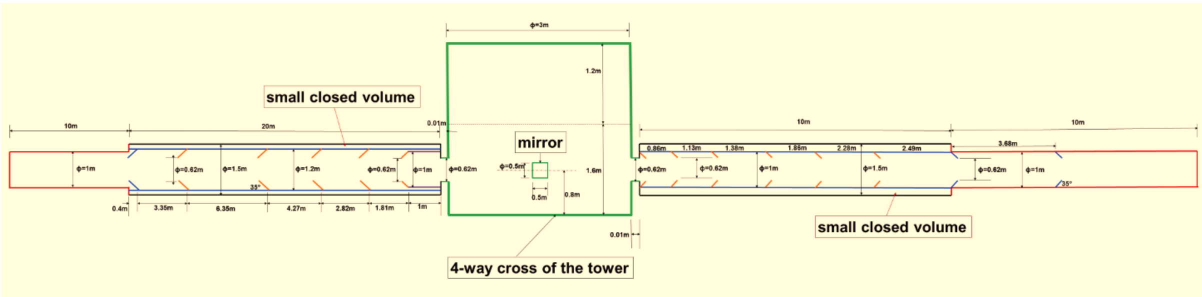

Figure 3. Simplified model for thermal radiation simulation (not in scale).

The assessment of the heat loads to the cryogenic supplies at different temperatures is necessary in the design of the cryopump. In this study, we just focus on the simulation of the thermal radiation heat load because it is the major contribution of the heat load of a vacuum system at low temperature, and the losses, thermal conductivity by supports and all details are not considered. For this purpose, the conceptual configuration in Fig. 2 is further developed into a simplified simulation model including cold baffles to protect the mirror additionally from the radiation coming from the 80 K cryopump. As shown in Fig. 3, the components (zero thickness in simulation) at different temperatures are marked with different colors: green ones at 2 K, blue ones at 80 K, red ones at 300 K, violet ones at 4 K, orange ones at 10 K, and black ones at 300 K. Baffles of conic shape are implemented, and most of them are at 10 K, but several baffles are at 80 K. On each side of the tower, one 1 m long tube of 1 m diameter at room temperature (300 K) is added and their far ends are truncated to close the simulation model as an enclosure. Only the inner surfaces of the outermost components of the enclosure are emitting thermal radiation into the enclosure, but two surfaces of the components inside the enclosure are emitting thermal radiation. Moreover, two surfaces of the components inside the enclosure even can have different emissivities.

There are three different approaches to simulate the heat load from thermal radiation and their pros and cons of are listed in Table 1.

Table 1. Three different simulation methods and their pros and cons

	Pros	Cons
View factor method	Arbitrary temperature and emissivity Simulation quick	Errors from shadowing effect Hard to solve a matrix equation sometimes (Errors from sparse matrix)
Radiation exchange factor method	Shadowing effect included Calculation of heat load from radiation exchange factors High precision	Arbitrary temperature but emissivity included Simulation relatively slow
Direct Monte Carlo Ray Trace simulation	Shadowing effect included Only one simulation Heat loads directly recorded	Big disadvantage for the component of small area & low emissivity & low temperature (T^4 dependent) Fixed temperature and emissivity Hard to simulate with large number of test particles => Low precision

In this study, we will use the Radiation Exchange Factors (REF) methods [7]. Compare to the view factor method, the advantage of this method is that the shadowing effect is automatically included because the ray trace is followed as in the direct Monte Carlo simulation, and the part of a surface under the shadow is inherently unreachable. However, if the system has N irradiating surfaces, we need to simulate independently N times. In each simulation, only one surface is considered as the source of the radiation. When the thermal radiation coming from the source (photon) hits another surface in the system, will be absorbed or reflected (diffuse reflection used in this study) according to the emissivity ε of this surface because the reflectivity is assumed as 1-ε, and the ray trace of the photon will be followed until it is absorbed. Obviously, we need simulate a huge number of test particles (i.e. photons) to achieve high prevision, and then the head load to i^{th} surface (i=1 to N) is derived,

$$\dot{Q}_i = -\sigma\varepsilon_i A_i {T_i}^4 + \sum_j^N \sigma\varepsilon_j A_j {T_j}^4 R(j \to i), \quad (3)$$

where σ is Stefan-Boltzmann constant, A and T are the area and the temperature of the surface, respectively. The matrix R is the result of N independent simulations, and its component R(j→i) represents the absorption probability of the i^{th} surface when the j^{th} surface is the source. This equation is easy to understand: the first term is the energy irradiated from one surface, and the second term is the energy this surface obtained, coming from all surfaces including itself. Finally, one surface will emit (give out) energy when the sum value is negative, and will get energy as the thermal radiation heat load when it is positive.

It is possble to simulate the theraml radiation heat load with the Direct Monte Carlo Ray Trace simulation method, in which the test particles (photons) will come from every irradiating surfaces propotional to the first term in Eq. (3), and the heat load of each surface is obtained by recording the energy absorbed by it in the simulation. However, this will need much more test particles to compensate the big disadvantage for the component of small εAT^4.

4. Simulation results

ProVac3D code was already successfully used to simulate the thermal radiation heat load of the ITER pre-production cryopump [8]. Here, another advantage to use ProVac3D in both vacuum simulation and the simulation of the thermal radiation heat load is that we need only adapt the simulation model used in vacuum simulation and consider the test particles as the thermal photons. In this study, 55 independent TPMC simulations were carried out because there are 55 irradiating surfaces in the model shown by Fig. 3. The reflection from each surface is considered as diffuse reflection, and the reflectivity is taken as 1-ε. The system is divided into 5 spaces by 4 virtual planes, which are implemented in the simulation model. In this way, the simulation time is highly accelerated because we only need to consider the surfaces in the same space in each simulation step. Moreover, it makes us able to check the simulation correctness by conservation law of the test particles in each space. In each simulation, 10^{12} test particles were simulated with 2000 CPUs of the supercomputer in parallel. Finally, the matrix R of the radiation exchange factors of the system is obtained with high precision, and the thermal radiation heat load to each surface is calculated from Eq. (3). The results are listed in Table 2.

Table 2. Simulation results of the heat load of ET-LF

	80 K system	3.7 K system	10 K system	Mirror (10 K)	Cryostat (2 K)
System with10 K baffles in cryopumps	7.1 kW	1.65 W	43 W	1.3 mW	263 mW
No baffles in cryopumps (80 K in simulation)	7.2 kW	2.41 W	-	3.4 mW	892 mW
Total value for ET-LF with baffles	85.2 kW	20 W	516 W	-	3.2 W

Please note: (1) the emissivity of the mirror ε=0.01 is used in this table, but the expected value for the thermal radiation is ε ~ 0.5. The influence will be discuused in next section; (2) the values without baffles (2nd row) are actually calculated with the baffles at 80 K, and will be also discussed in next section; (3) the total head loads of ET-LF with baffles (3rd row) are calculated from the values in the 1st row by a factor of 12 for entire ET-LF (4 regions per interferometer in a triangle configuration with 3 interferometers). For 80 K system (unshielded cryopumps in simulation), the heat load to it will be reduced by 50-60% to ~ 52 kW due to a passive shielding between pump and beam pipe.

5. Sensitivity study

5.1 Influence of baffle temperature

As shown in Fig. 3, baffles of conic shape are included in simulation model, and most of them are at 10 K, but baffles at the warm ends of a cryopump towards a beam pipe are at 80 K. From Eq. (3) of the REF method, the temperatures of the irradiating surfaces are free input parameters independent of the TPMC simulation. So it easy to check the influence when all baffles are at 80 K by only exchanging their temperatures in Eq. (3), and the results are listed together in Table 2. We can see that the head load to the 10 K mirror will increase 2.6 times, and the heat load to the cryostat will increase 3.4 times. This means that the inner baffles at 10 K would be worthwhile.

5.2 Influence of mirror emissivity

However, emissivity is the parameter included in the REF method, and we need repeat TPMC simulations to obtain the matrix R depending on the emissivities. This is done for different mirror emissivity ε=0.01(in previous section 4), ε=0.1, ε=0.3, and ε=0.5. Fig. 4 shows that the heat load to the mirror is almost proportional to the mirror emissivity. So the heat load to the mirror is about 59 mW when its emissivity is at the expected value of ε=0.5. However, the effects to other components is negligible because it is a tiny component at low temperature.

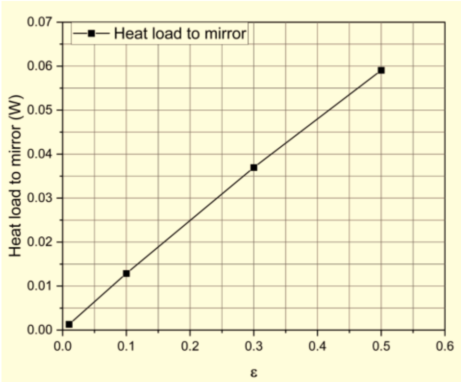

Figure 4. The heat load to the mirror when its emissivity is changing.

6. Conclusions and outlook

Systematic Monte Carlo simulations were carried out to obtain the pressure profiles along the beamline of ET-LF, and a design configuration of the cyropumps of ET-LF (Fig. 2) was suggested in our previous work [2]. Subsequently, our in-house TPMC code ProVac3D is used in this study to simulate the matrix (55 × 55) of the radiation exchange factors (REF) of the system, and then thermal radiation heat loads for the corresponding cryogenic supplies of the system at different temperatures are obtained. Theoretically, the sum of the heat loads should be zero since the whole system is an enclosure. Of course, it would not be zero in simulation because of inevitable numerical and statistical errors. However, the simulated ratio of the sum of the heat loads to the sum of the thermal radiation from all surfaces in the system is less than 5×10^{-10}, which shows a very high simulation precision.

The assessment of the heat loads of ET-HF was done with the same method based on the cryopump concept worked out for this region with different boundary conditions and requirements. There, a one side cryopump is sufficient, consisting of a 9 m 80 K pump with a central 1 m 3 K section. The combined heat loads for the cryopumps of all 12 LF towers and 12 HF towers of the entire ET result in the need for 75 kW at 80 K and 70 W at 3 K. Asking therefore preliminarily for a cryogenic plant infrastructure of ~100 kW at 80 K and 100 W at 3 K is the current outcome of this work. The next steps will refine these numbers by adding some towers requiring additional small cryopumps.

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