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

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Motivation

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.

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 will detect low-frequency gravitational wave signals (ET-LF), while the other will be optimized for operation at higher frequencies (ET-HF).

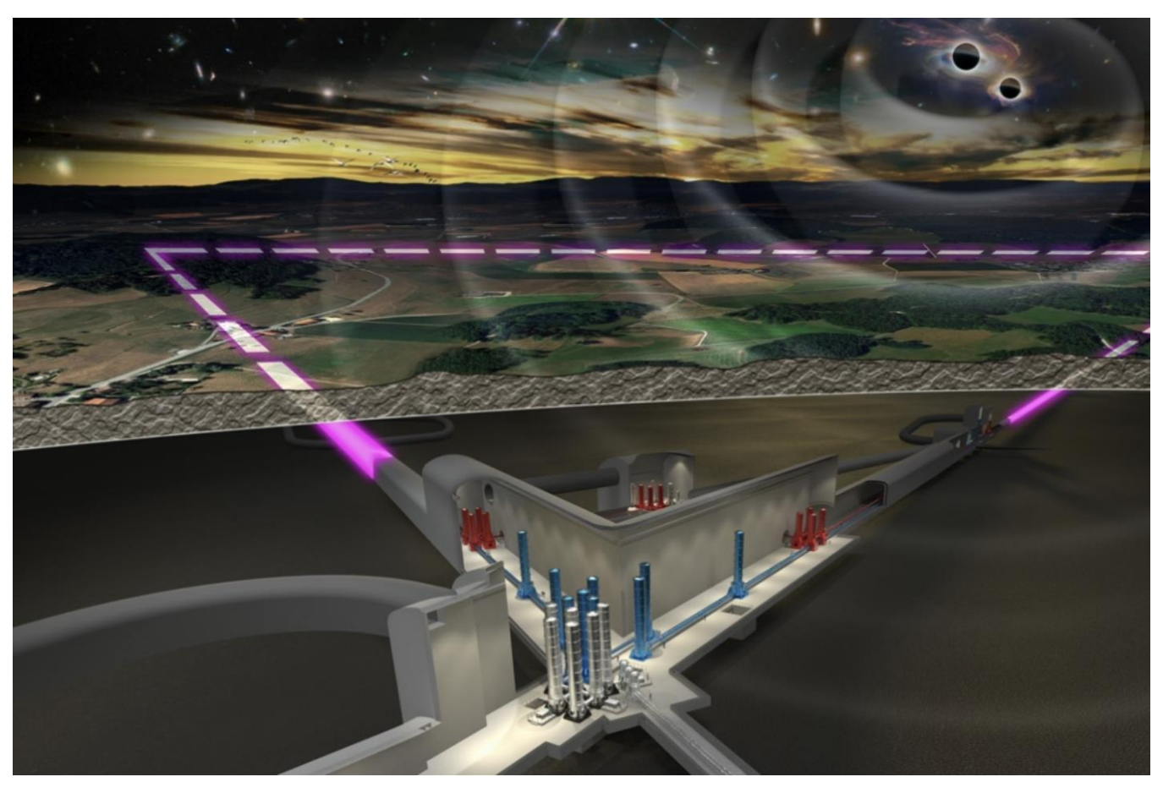
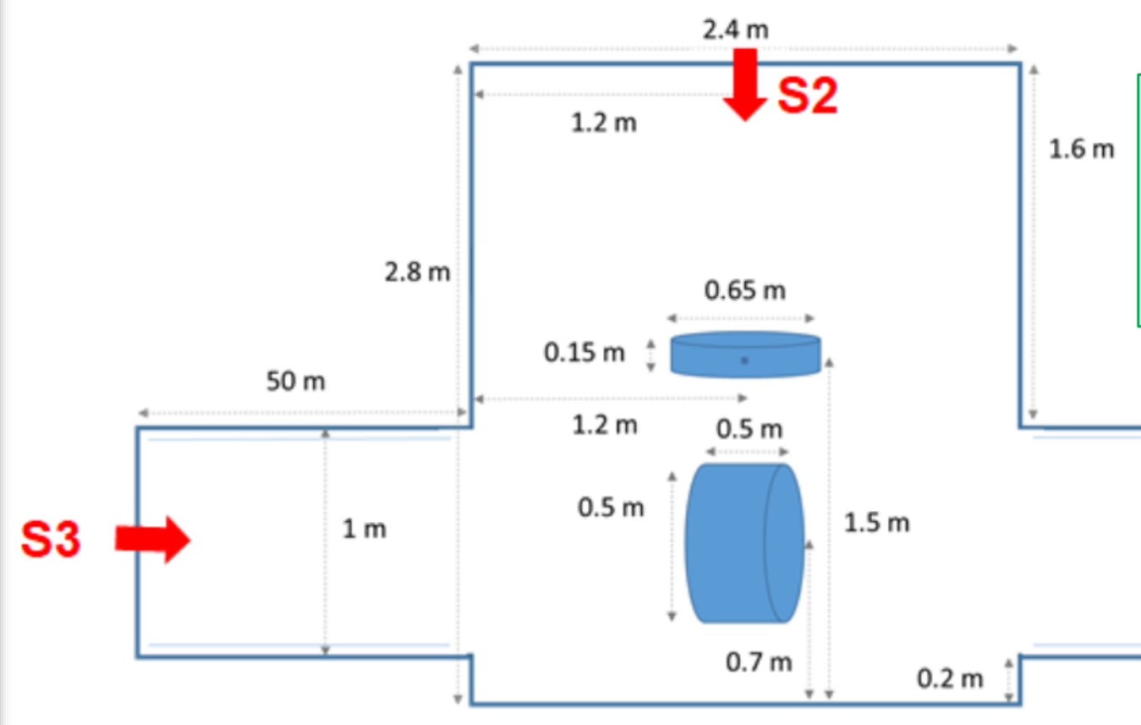


Fig. 1 The proposed Einstein Telescope gravitational wave observatory

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 presentation, systematic Monte Carlo simulations are used to (1) assist to develop the vacuum pumping systems, based on cryopumps; (2) obtain the radiation heat loads for the corresponding cryogenic supply and for the mirror.

Vacuum simulation



S1: distributed outgassing from the beam pipe wall
S2: gas flow from upper part of suspension tower
S3: gas flow from adjacent tower

1 km beam pipe with 3 pump stations for H_2

Fig. 2 Complete ProVac3D vacuum simulation model (not in scale)

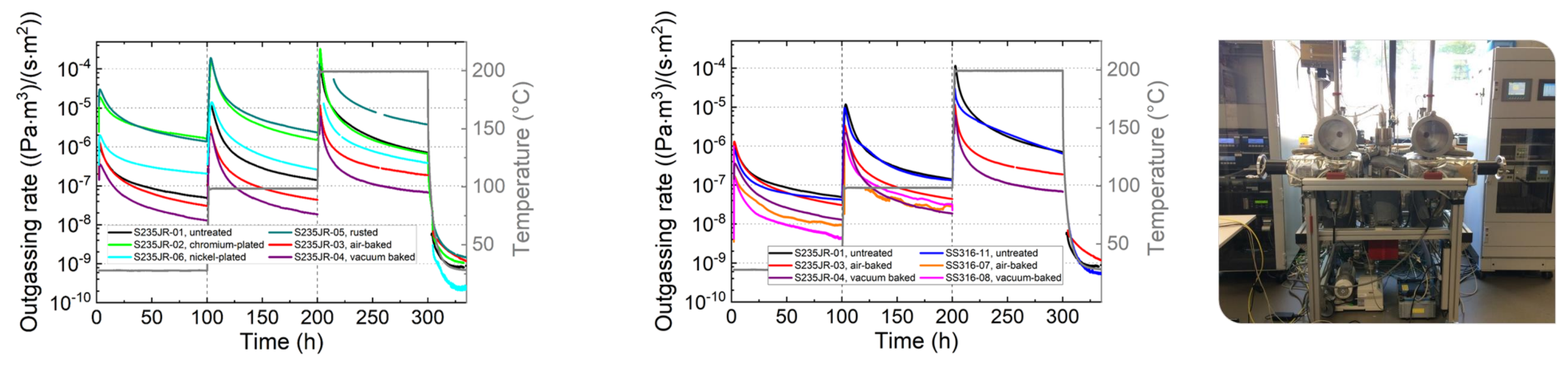


Fig. 3 Outgassing behaviour of mild steel (left) measured in our OMA setup (right)

➢ **Beam pipe vacuum is mainly dependent to the outgassing, and tower vacuum is almost decoupled from the beam pipe by cryogenic pumping.**

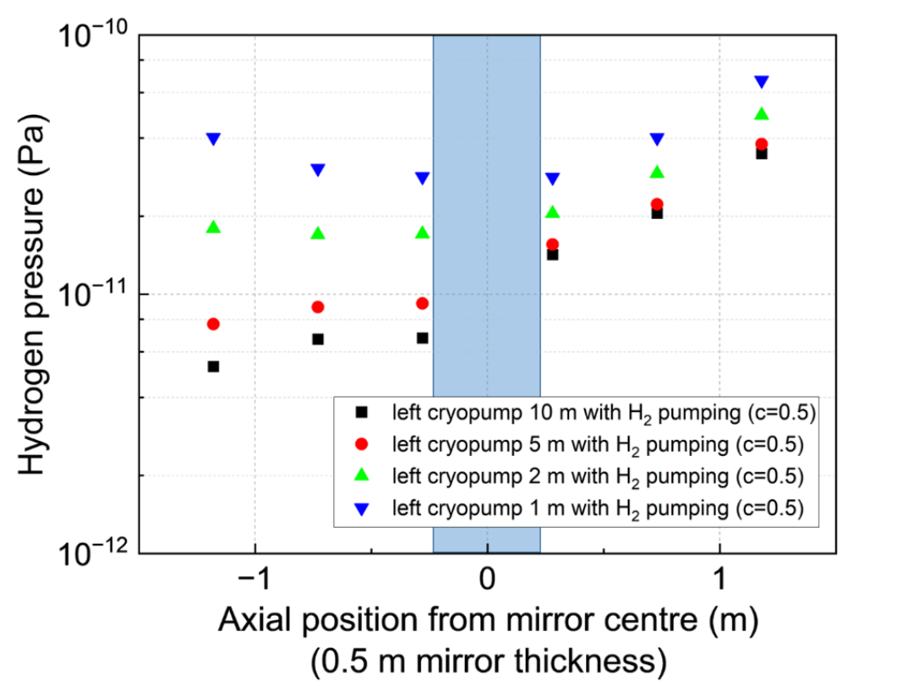


Fig. 4 Results for hydrogen

- Hydrogen pumping needed only on the left side for the adjacent tower flow
- 1 m left H_2 pumping sufficient
- Pressure around mirror well below requirement

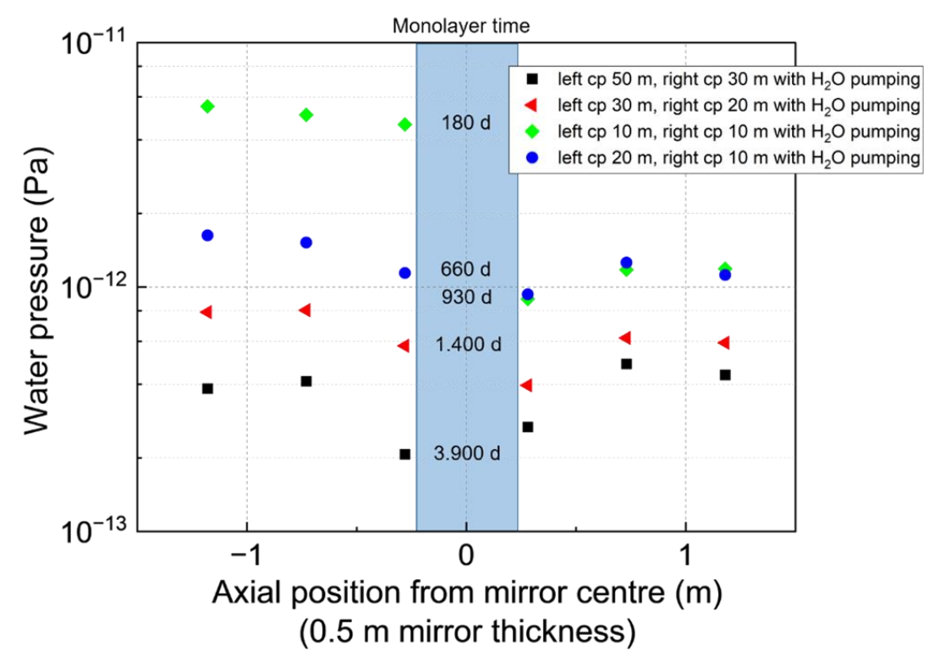


Fig. 5 Results for water

- Water frost formation rate drives pump design for 80 K
- One monolayer water ice deposition time is ~2 years
- Tight thermal budget of mirror at constant T

- All gas sources managed for hydrogen and water (non-sticky and sticky ones)
- Cryopumps:
  H_2O: 20 m left + 10 m right
  H_2: 1 m left
- **Pressure requirements fulfilled:**
  H_2: 3×10^{-11} Pa
  H_2O: 1×10^{-12} Pa
- Water frost on the mirror:
  Water ice build-up ~2 years for 1 ML

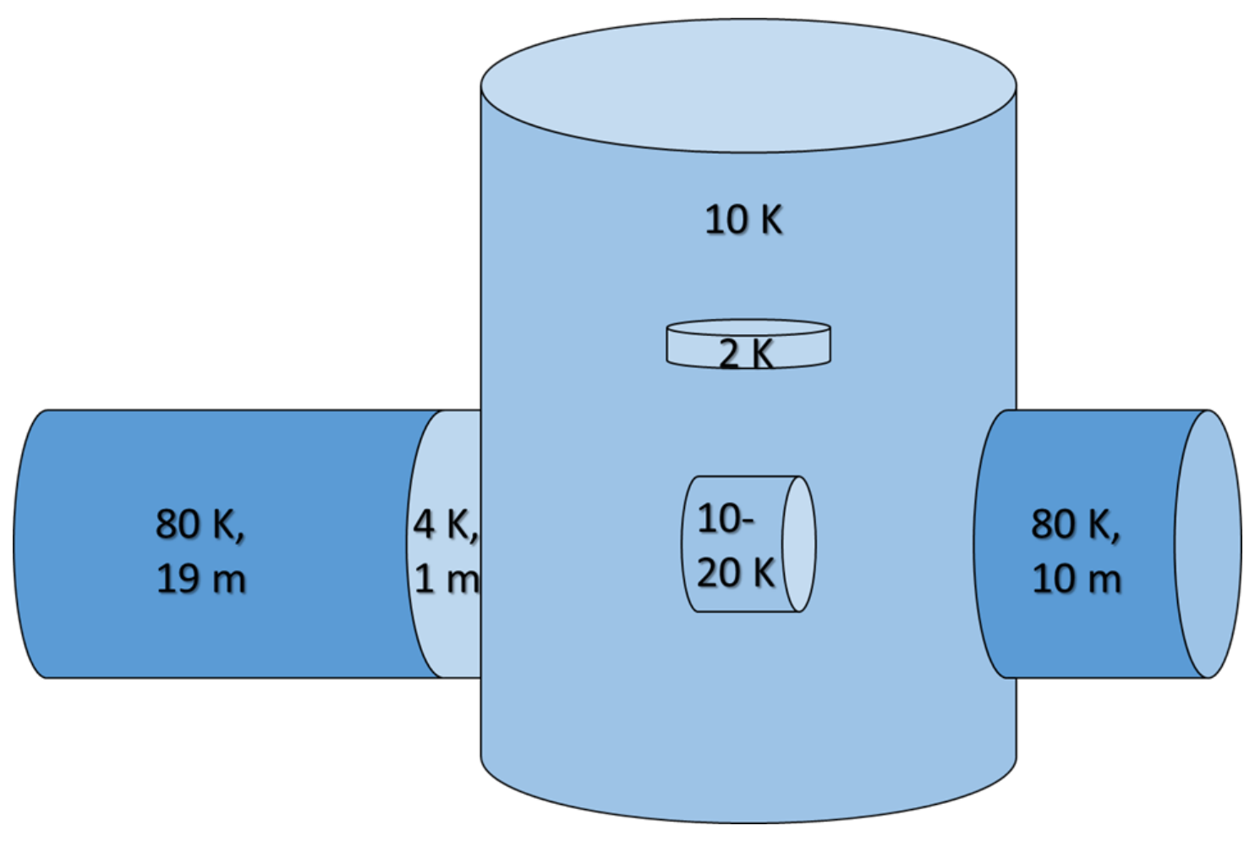


Fig. 6 Design configuration of the cryopumps of ET-LF (not in scale)

Heat load simulation of ET-LF

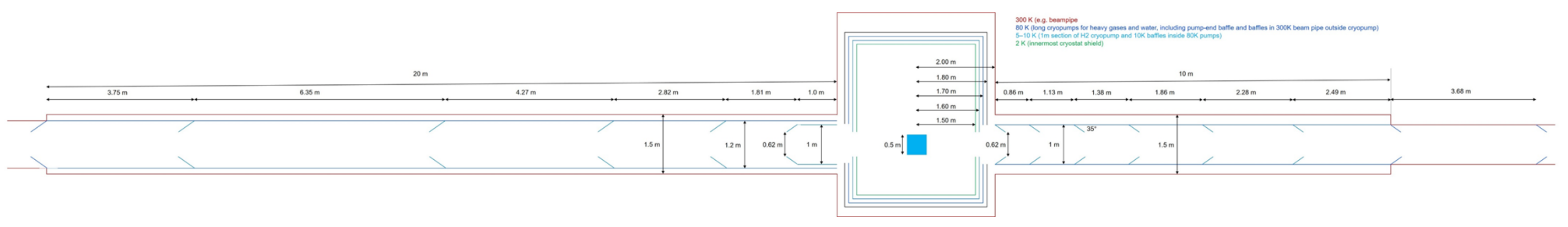


Fig. 7 ProVac3D simulation model of ET-LF (not in scale)

- Radiation exchange factor (REF) method used
- Also with ProVac3D code as vacuum simulations before
- Now all surfaces (55) in the model are radiating and absorbing according their temperatures and emissivities
- Both cryopumps with all their baffles included
- Mirror included for its thermal load investigation
- Baffles @10K to manage the heat load on the mirror

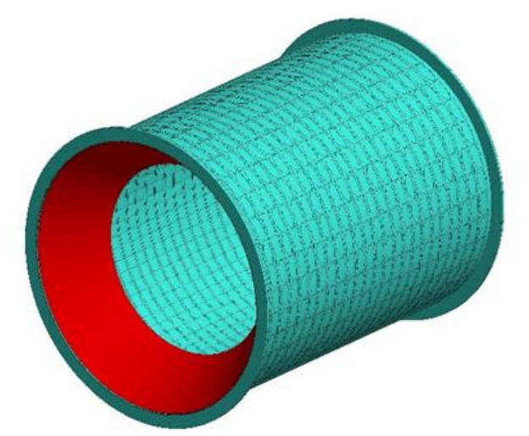


Fig. 8 Concept of a tubular cryopump segment with baffle

Table 1 Three different simulations 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 (REF)	Shadowing effect included Calculation of heat load from radiation exchange factors High precision	Arbitrary temperature but emissivity included Simulation relatively slow High precision
Direct Monte Carlo Ray Trace simulation	Shadowing effect included Only one simulation Heat loads directly recorded	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

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

where σ is Stefan-Boltzmann constant, the matrix R is the results of 55 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 emitted from one surface, and the second term is the energy this surface obtained, coming from all surfaces. Finally, one surface will emit energy when the sum value is negative, and will get energy (thermal radiation heat loads) when it is positive.

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

	80 K system (1)	3.7 K system	10 K system	Mirror (2) (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 (3)	~52 kW	20 W	516 W	-	3.2 W

(1) 80 K pump unshielded, and the heat load to it will be ~50-60% due to a passive shielding between pump and beam pipe.
(2) Mirror of ε=0.01 (99% reflectivity), and the heat load to it is almost proportional to ε; Expected: ε=0.5
(3) Factor 12 of the simulated value for entire ET-LF (4 regions per interferometer in a triangle configuration with 3 interferometers)
Note: Losses, thermal conductivity by supports and all details are not yet considered.

Conclusions and outlook

- Systematic Monte Carlo simulations are carried out to obtain the pressure profiles along the beamline of ET-LF, and a design configuration of the cyropumps of ET-LF (Fig. 6) is suggested.
- With this configuration of the cyropumps, the pressures in the tower and in the arm are decoupled and the requirements regarding to pressure and frost mitigation aspects can be fulfilled.
- Thermal radiation heat loads for the corresponding cryogenic circuits of the system at different temperatures are obtained with radiation exchange factor (REF) method.
- In this method, all 55 surfaces in the model are radiating and absorbing according their temperatures and emissivity, and the matrix (55 × 55) of REF is obtained from the simulation.
- ProVac3D, a novel and versatile Test Particle Monte Carlo (TPMC) simulation code developed by ourselves, is used both in vacuum simulation and in heat load simulation.
- To guaranty the simulation precision, at least 10^{12} test particles are simulated with 2000 CPUs of a super computer in parallel.
- Ideally, the sum of the heat loads should be zero since the whole system is an enclosure. In simulation, the ratio of the sum of the heat loads to the sum of the thermal radiation of all surfaces in the system is less than 5×10^{-10}, which shows a very high simulation precision.
- Together with the assessment of the vacuum and the radiation heat load of ET-HF which is going on in a similar way, important information to the cryogenic plant can be provided.

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