Impact of beam-induced heat loads on the transient operation of the cryogenic plants of the Future Circular Collider

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Introduction

During the beam operational cycle, circulating beams induce dynamic heat loads on the cryogenic system. This, in turn, requires that several parameters in the cryogenic plants are adjusted to accommodate the variations of refrigeration power needed to control the temperature of the beam-screen. Nevertheless, the time constants of these parameters are not necessarily compatible with the dynamic heat loads resulting from the circulating beams, making the cryogenic plants design a top priority issue.

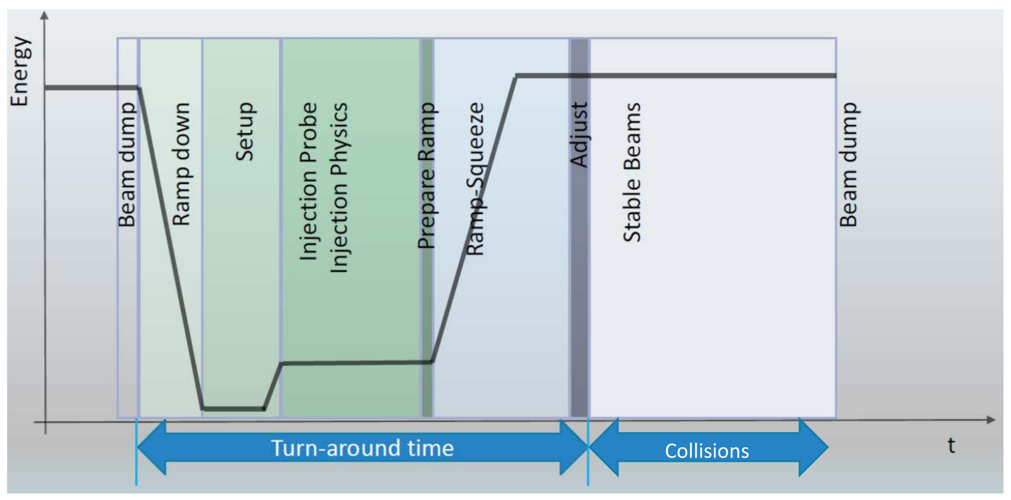
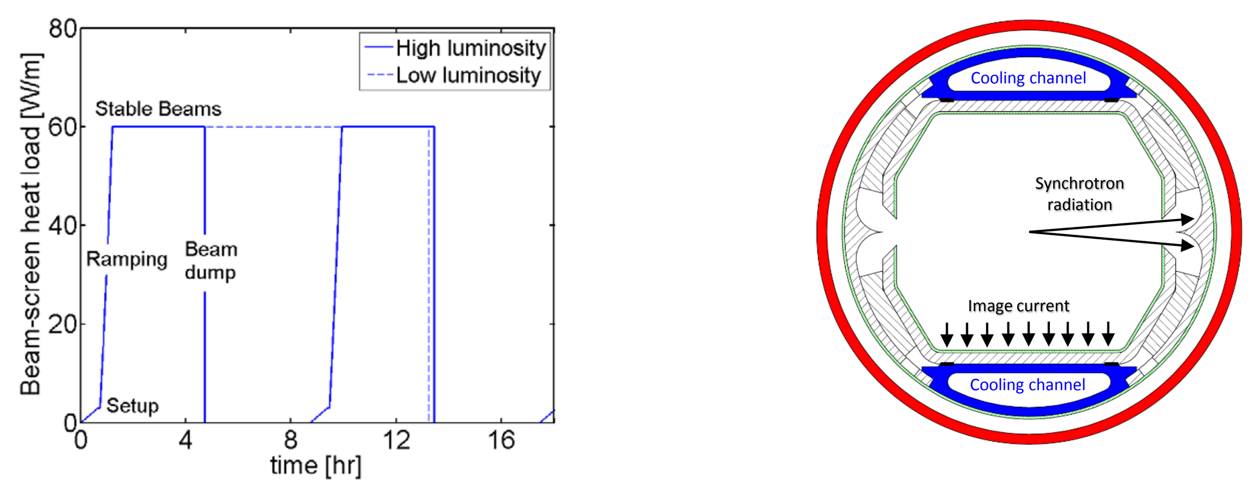


Figure: Beam operational cycle

Beam cycles

Two beam cycles were considered in this study: the high-luminosity beam, with a total beam cycle of about 9 hours and, low-luminosity, with a total beam cycle of about 16 hours.

When charged particles are radially accelerated, emission of synchrotron radiation takes place. The radiated power has a specific solid angle with respected to the beam direction and depends to the fourth power of the beam energy. The implication is a sharp increase of synchrotron radiation occurs as a result of the progressive increase of the beam energy.



Figures: Dynamic heat loads resulting from the circulating particle beams

Modelling of the cryogenic distribution system

Helium is used as a cooling fluid and it is supplied by means of a cryogenic distribution system adjacent to the magnetic lattice.

The helium flow is cooled by a turbo-Brayton cycle using a mixture of neon-helium as working fluid. The flow of helium circulates in cooling channels of the beam screen to ensure its operation between 40 and 60 K. In order to ensure the beam screen temperature does not exceed 60 K at any given location in the arc, helium is supplied at 40 K and an identical mass flow rate of 71 g/s is fed into each individual half-cell.

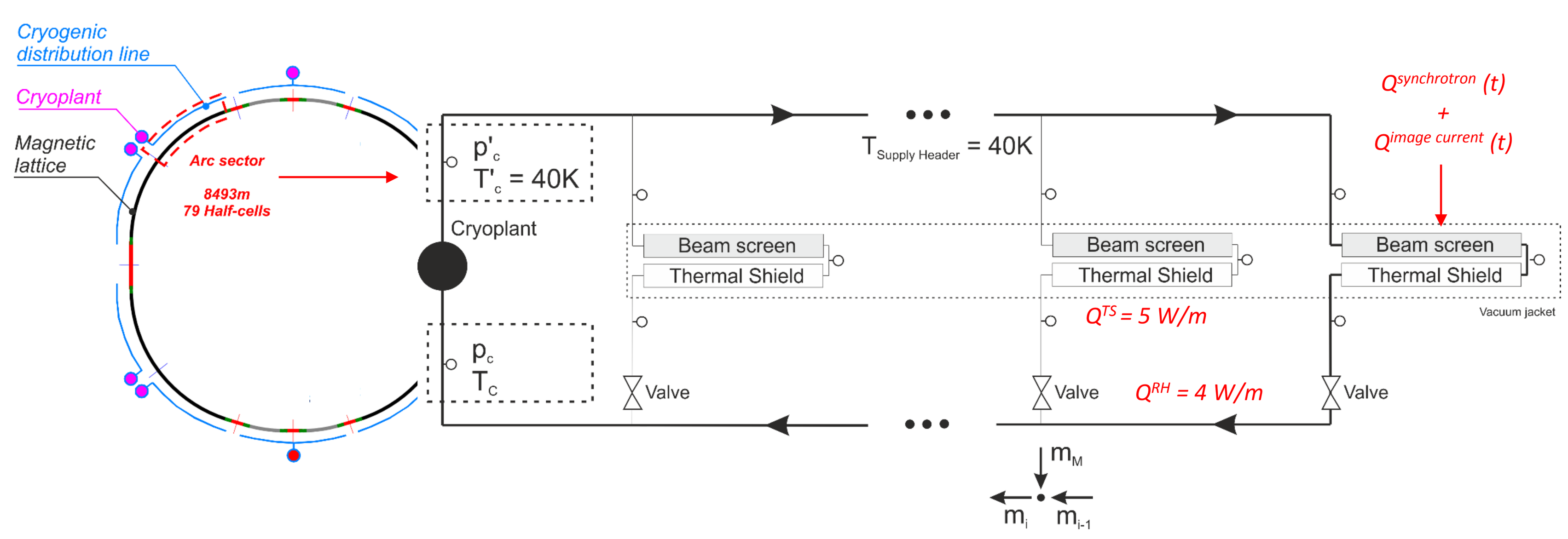


Figure: Schematic of the cryogenic distribution line and respective heat loads

A mathematical model based on the Navier-Stokes and the energy equations was used to predict the behaviour of the helium flow in the cryogenic distribution line.

Pipe elements: $$M \cdot c_p(T^M) \cdot \frac{\partial T^M}{\partial t} = -\alpha \cdot (T^M - T^{He})$$

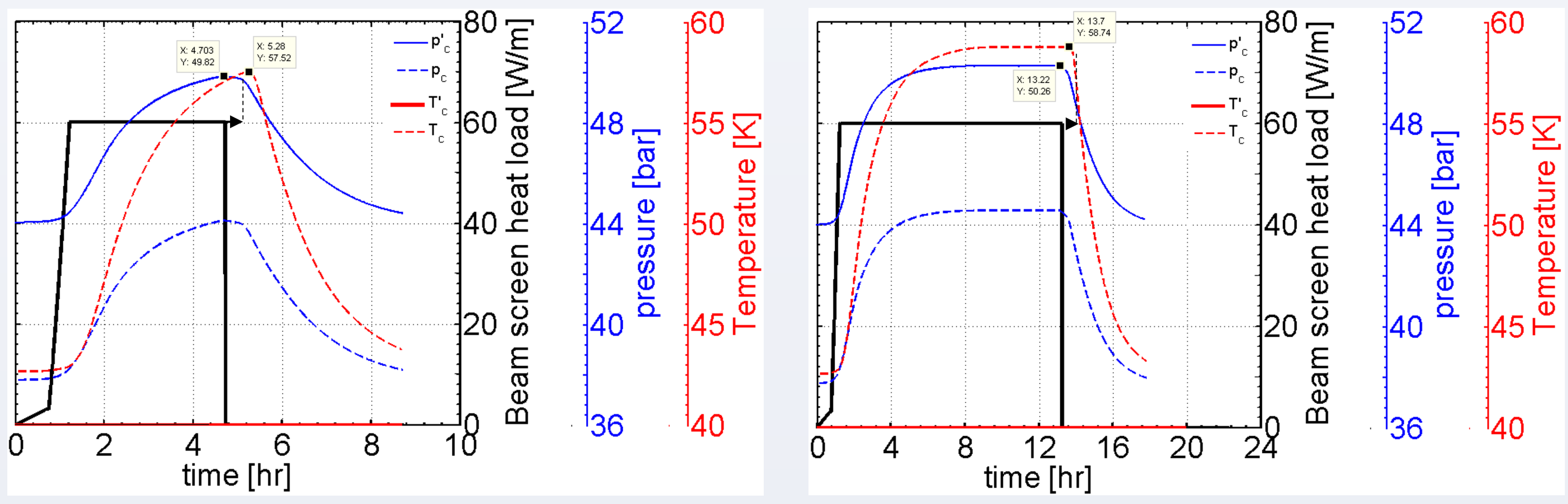
Helium flow: $$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} = \frac{1}{\rho A} \cdot \alpha \cdot (T^M - T^{He}) + \dot{Q}_{dynamic\ heat\ loads}$$

Under the assumption that the temperature gradients across the pipelines are small, the equations can be reduced to a set of one-dimensional partial differential equations. The differential equations can then be discretized by the method of finite differences.

In order to avoid large variations of helium inventory in the cryogenic system due to the beam-induced heat loads, the discharge pressure of the compressor units is deliberately changed throughout the beam cycle so as to maintain a constant helium mass.

Results

1. Helium pressure and temperature behavior due to beam-induced heat loads:

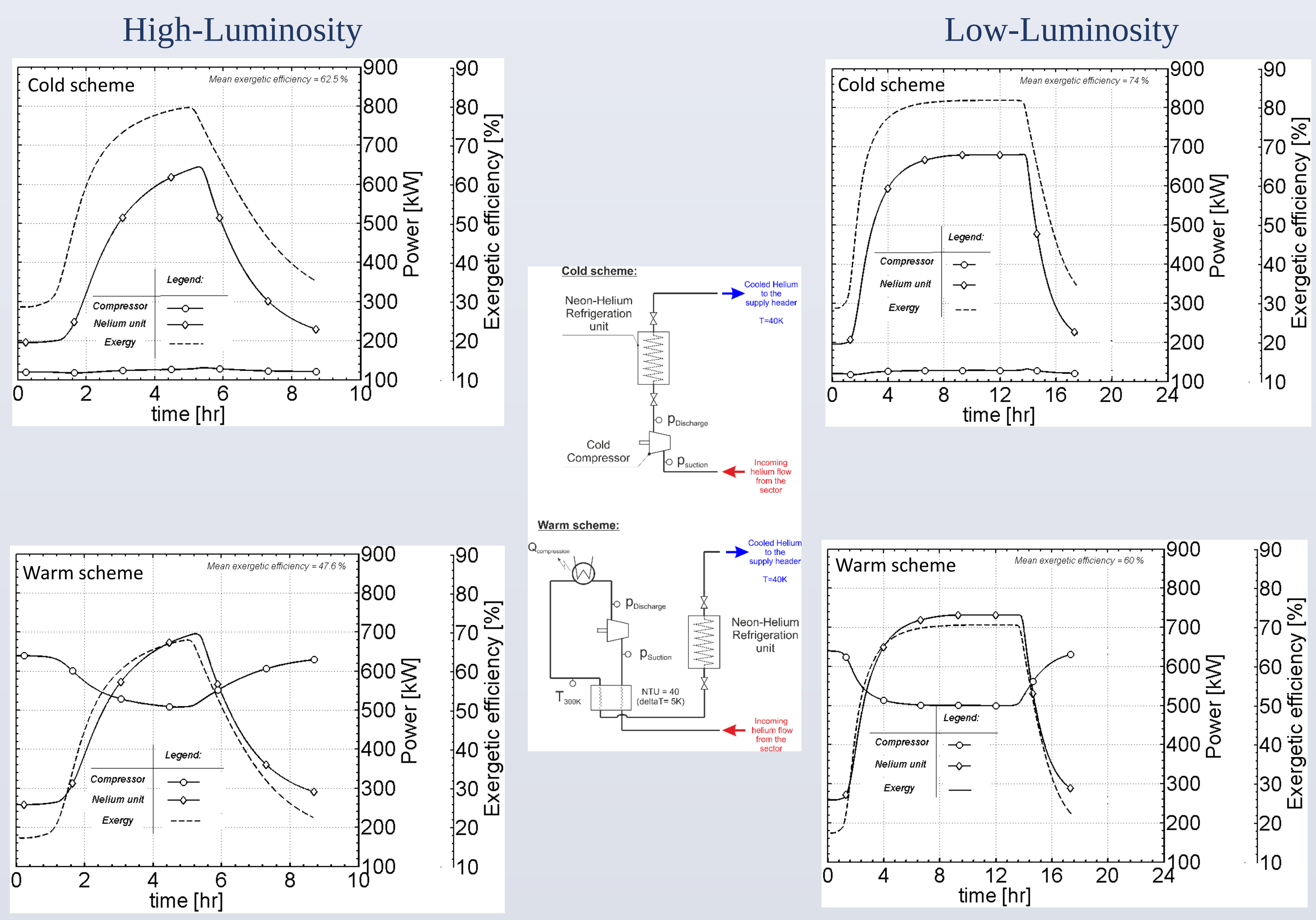


Figures: Beam screen heat load, pressure and temperature evolution over a high- and low-luminosity beam cycle.

The pressure and temperature at the beginning of the supply header are shown by a solid line (p'_c and T'_c, respectively). The corresponding pressure and temperature in the return header is shown by a dashed line (p_c and T_c, respectively).

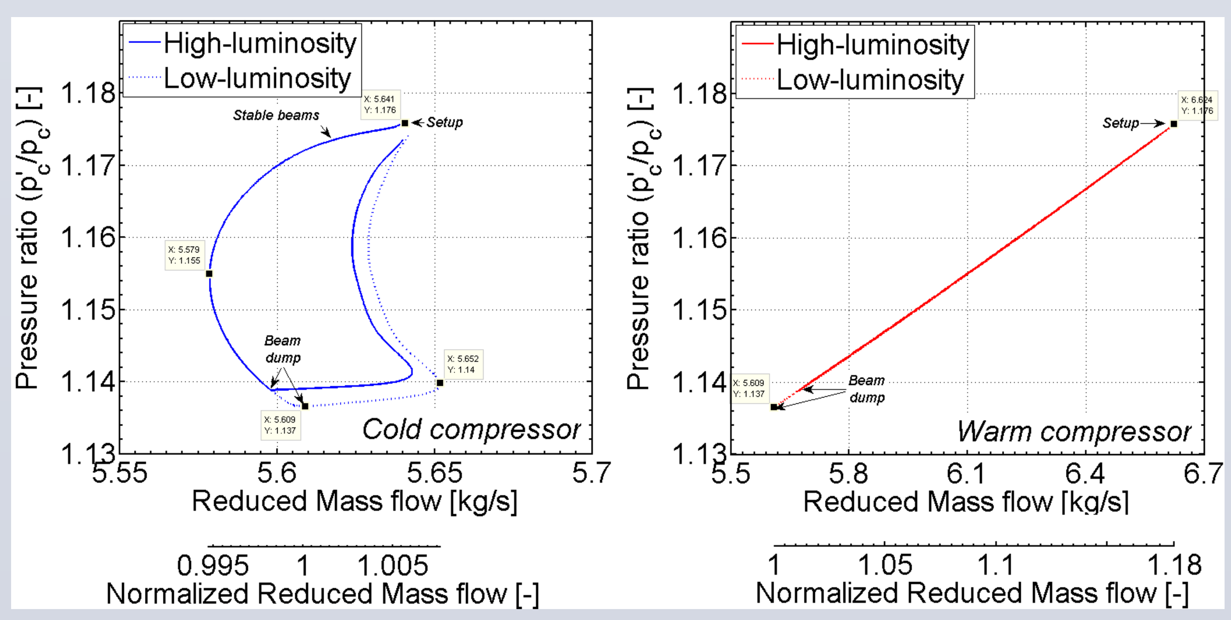
Whilst no beam-induced heat loads are present after the beam dump, it can be observed that T_c continues to rise for about 40 mins until it eventually starts decaying. These stems from the thermal inertia of the thermal shield and the return headers.

2. Refrigeration power and exergetic efficiency:



The results show that the power required by the cold compressor is substantially smaller than that of the warm compressor. Additionally, the cold scheme presents a notorious advantage with regard to exergetic efficiency. This stems from the inefficiency pertaining to the heat exchanger and could be improved by considering a higher NTU.

3. Compression fields



Compressors can operate at conditions other than those for which they are rated. However, in extreme cases, operation at conditions far from rated ones can even result in complete breakdown in flow, known as compressor stall and surge. The reduced flow variation is less than 1 % for the cold compressor and 18 % for the warm compressor. These variations are small and fully compatible with the operating ranges of already existing state-of-the-art industrial solutions.

Conclusions

In this study, the transient operation of the future cryogenic facilities was evaluated. Towards that end, a mathematical model was built to simulate the helium flow in the cryogenic distribution line. The outcome enabled to evaluate the exergetic efficiency of different cryogenic plants configurations and the compression fields resulting from beam-induced heat loads. These results represent the building-block for a technically consistent and economically viable solution for the future cryogenic facilties.