THERMAL STABILITY OF THE NEW ESRF EXTREMELY BRILLIANT SOURCE

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Abstract

In the frame of the Extremely Brilliant Source project (EBS), studies dedicated to disturbances have been more intensively investigated. Engineering instabilities have two origins: mechanical and thermal.

Major thermal issues are:

- air conditioning presents a temperature ramp up of 2°C along the sector, in the tunnel
- storage ring requires a warm up period of 4 days for reaching stable orbit

These effects have been observed and corrected for 20 years.

With EBS requirements, we need to identify these thermal effects in order to reduce disturbances, thus improving more systematically source stability. The study is led by the comparison between present and new thermal system.

To do so, it is necessary to evaluate the heat balance in this system, as well as to identify the thermal time constant for each component.

Finite Element Analysis (FEA) models have been performed to explore the sensitivity of these thermal issues. A full scale mock-up cell equipped with a prototype girder was implemented aimed at revealing power cables influence inside. A FEA model was also developed for the present storage ring to analyze the air stream cooling process.

Although investigations have already been developed, some others remain to be achieved by the end of 2016.

OVERVIEW

This is the domain of instability. Light source storage rings errors have been investigated for a long time, however the new EBS project is faced to set new questions within the facility. The present storage ring has been operated for 25 years, and of course, it is highly compensated in many error aspects.

Instabilities We proposed to consider the closed-orbit errors, in the following breakdown:

1. Permanent static errors from the origin
2. Permanent variable errors (quick effects)
3. Errors triggered by the beam operating conditions
4. Long period errors

While the two first have mechanical origins effects (alignments, fiducialisation, vibrations, etc.), the last two have thermal origins effects. The present storage ring has two major thermal issues:

- A longitudinal gradient of 2°C between the air ventilation inlet and outlet along a tunnel quarter
- A transient warm-up period of 4 days before reaching a stable orbit

Resolving these thermal errors requires having a very fine understanding of the storage ring thermal behaviour. We have in fact to deal with a thermal system, which we need to define.

Thermal system Such a thermal system is very complex. It contains many components coupled all together. We proposed to consider the following system:

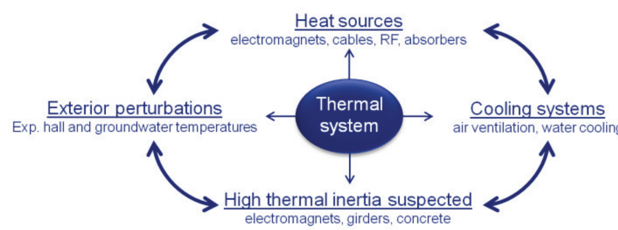

Figure 1: Thermal system of the ESRF storage ring.

As we can see in Figure 1, the thermal system is composed by four main components:

- Components heat sources: electromagnets, cables, Radio Frequency (RF), absorbers
- Two cooling systems of the storage ring: the air ventilation and the water cooling system
- High thermal inertia items: electromagnets, girders, concrete walls and slabs
- External disturbances: experimental hall and groundwater temperatures

Like any usual system vision, most of these components are coupled together.

This paper will not cover all aspects of this system; we will focus mainly on electromagnets as main heat source and thermal capacity. We will discuss also about the air ventilation of the storage ring, girders, external disturbances (experimental hall temperature), power cables and concrete slab.

Our approach is led by some parallel exploration with FEA, as well as full scale mock-ups measurements.

EXPLORATING WORKS

In order to characterize the thermal system of the ESRF storage ring, several components of the lattice were calculated with FEA. Numerical models were performed using Comsol Multiphysics package, combining Computational Fluid Dynamics (CFD), thermal and thermomechanical calculations.

CFD

Tunnel ventilation A very first 3D model was performed to study the air velocity inside the tunnel. The storage ring is divided in four sectors. At each end of the sector, air enters the tunnel at ~10m/s. It exits the tunnel at the other side. Total length of air path in each section is around 210m.

This model represents magnets and girders by cubes, which is aimed at being simplified. It gives, however, an estimation of air velocity: ~1.4m/s in the internal area of the tunnel (freeway) and ~0.7m/s in the external area (front-end side).

By reinserting this velocity field in a smaller and finer model, we noted that the air velocity was very low inside electromagnets, which behave as obstacles limiting by the way the air flow. By comparing forced convection with natural convection, we noticed that natural convection was dominating heat transfers. For that reason, we decided to only consider natural convection in the next calculations.

EBS Quadrupole Modelling directly the air flow due to natural convection around a full 3D quadrupole is very CPU and time expensive. For that reason, we chose to consider a 2D quadrupole model where inner air could flow in a cavity.

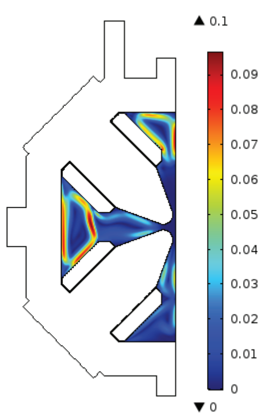

Figure 2: Air velocity (m/s) for half 2D quadrupole heated by coils.

Figure 2 shows the velocity field in the inner air volume of the quadrupole. By effect of gravity and density change, air heated by coils goes up, transfers its heat to the yoke and then goes down; it looks like a Benard roll. We note that the velocity field is almost null in the gap between coils and yoke: heat transfer in this area is mainly air-conduction driven.

Thermal Calculations

EBS Quadrupole 2D models are quick to set up, but do not represent truly the reality. We decided to exploit 2D models by computing local convective coefficients, and to introduce them into a 3D model without CFD.

The 3D quadrupole model includes the quadrupole yoke and its poles, coils, its support, and a part of the girder. The only heat source is potentially due to the coils.

Coils are directly in contact with the yoke via rubber spacers, and with poles via holders, as shown in Figure 3.

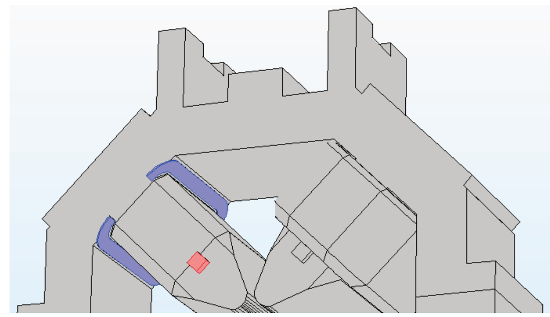

Figure 3: Rubber spacer (blue) and holder (red) of quadrupole coils.

2000W are dissipated in coils (500W each), which are cooled with water (~0.45L/min) at 24°C. Outlet water temperature is then ~40°C. We assumed that coils surfaces in front of the poles were at 24°C while those facing air at 40°C. We also assumed that the ambient air were constant at 24°C, as well as the ground temperature.

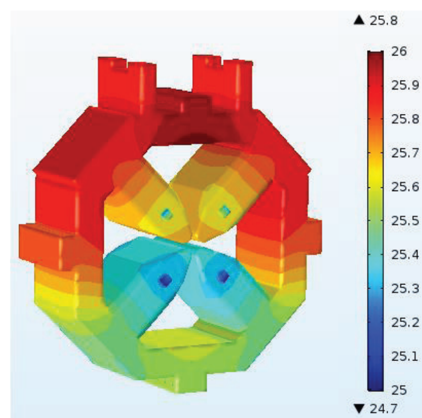

Figure 4: Temperature field (°C) in a 3D quadrupole heated by coils.

Initially at 24°C, the quadrupole reaches an average temperature of 25.4°C (+1.4°C) in ~1.5 days (99% of final state and time constant of 0.3 day).

Figure 4 shows that the upper part of the quadrupole is warmer than the lower part. On one hand, this is due to the air convection: since heated air goes up, it transfers more heat to the upper part. On the other hand, this can be explained by the fact that the lower part of the quadrupole is in contact with its support and the girder, which both behave as heat sink. We also note that holders tend to be cooler, because of their contact with coils surfaces which are at a temperature close to 24°C.

Heat balance At this state, it is necessary to determinate the thermal coupling between these different components by post-processing a heat balance.

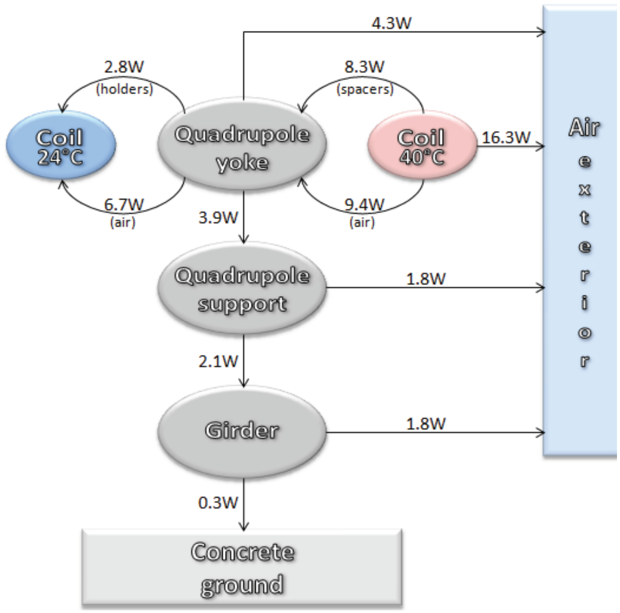

Figure 5: Heat balance of a quadrupole coupled with the girder and ambient air.

Figure 5 shows that coils both contribute to add and remove heat: 34W is added to the system and 9.5W is removed due to the coils. They globally add more heat (+24.5W).

There is a total of 24.2W of heat (1.2% of the total heat dissipated in coils) which goes in air. This amount, cumulated with other electromagnets and heat sources in the tunnel, will tend to increase the average temperature of the air flow and to create a temperature gradient between air inlet and outlet.

As previously mentioned, only natural convection is taken into consideration. If we noted that forced convection had less impact than natural convection inside the quadrupoles, this is not necessarily true for the outside of it. In the previous model, outside convective coefficients h were in the range of 2-4W/m^2/K. But it could be higher (magnitude of 10W/m^2/K) due to forced convection. In the same way, the ambient and ground temperature both set in the previous calculation at 24°C require a finer estimation.

Only 0.3W goes in the concrete slab. This value is optimist since we considered the ground temperature at 24°C (the water table temperature varies from 12 to 16°C at 2.2m from the slab surface). It could be lower in reality, modifying also the heat balance. Further investigations are then required.

Thermomechanical Calculations

The deformation of a 3D quadrupole due to the temperature was calculated. This model includes yoke, poles, quadrupole support, and contacts conditions between different parts of these components.

The initial temperature of the quadrupole is assumed to be at 24°C. The temperature field used for this calculation is the one from Figure 4.

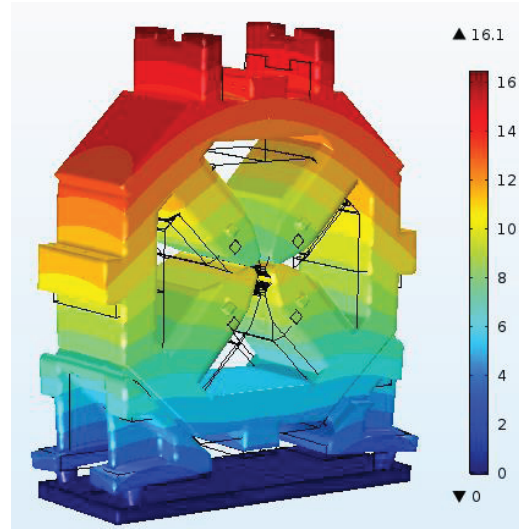

Figure 6: Total displacements (µm) in a 3D quadrupole heated by coils.

Figure 6 shows the total displacements of the quadrupole. We noticed that a temperature average increase of 1.4°C to the quadrupole would lead to a maximum deformation of 16.1µm. Poles move from 8 to 10 µm.

MOCK-UP MEASUREMENTS

Two mock-ups were operated. The first one is to study electromagnets while powered, whereas the second is to study a prototype girder with power cables running inside the central channel.

Electromagnets

An EBS quadrupole is placed on a table. It is alimented by current and its coils dissipate a total heat of 2730W of heat. Coils are water-cooled. Both inlet water and outlet temperature are measured with probes, as well as the water flow. Air cooling is run by natural convection. The quadrupole is probed with several PT100, and is also measured with thermal camera, as shown in Figure 7.

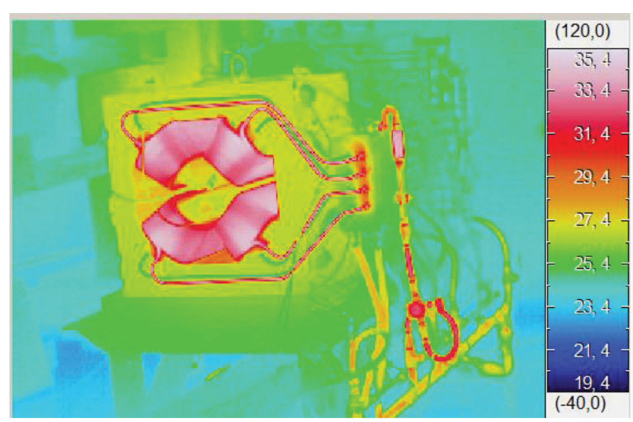

Figure 7: EBS quadrupole measured with a thermal camera.

Quadrupole yoke temperature increases from 23.9°C to 26.7°C (+2.8°C) within ~1.5 days. Through a heat balance on water, we found that 4.5% of the total heat generated in coils goes in air.

The time constant of this quadrupole is the same than the one studied with FEA. However, both temperature increase and % amount of heat in air are higher. This is due to different reasons:

First, the total heat in the coils are higher with the mock-up (2730W) than in the FEA model (2000W).

Then, in the FEA model, power cables were not modelled, whereas they were put under the table that supports the quadrupole. Cables add additional heat to the quadrupole.

Finally, the quadrupole studied experimentally is more than twice as long as the one studied in FEA, which mean that surface exchange with coils / spacers and coils / inner volume of air are higher (refer to Figure 3. For a geometrical view). Thus more heat is extracted from coils, hence a higher % of heat goes in air.

Prototype Girder

A short-time issue was led by the project manager to put electromagnets cables inside the girder, in order to save space in the freeway. This relevant idea, however, may be dangerous: the girder may indeed get deformed by the heat generated by cables. Hence we developed a full scale mock-up of a prototype girder. 32 cables (30 with 120mm^2 diameter, 2 with 70mm^2) are put in a custom tray inside the girder. Cables are powered with 90A.

The girder is confined with walls and a ceiling in order to reproduce a cell of the storage ring. A fan is added to create an air flow and enabling to measure the coupling between air and girder. In Figure 8, we can note that the fan is located in such a way that the stream is more important near a side of the girder (referring to internal zone) rather the other side (referring to external zone), similarly with the storage ring ventilation.

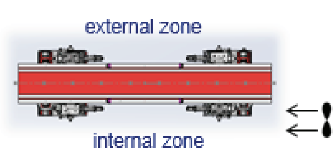

Figure 8: Location of the fan in regards to the girder.

Several probes (PT100) are put at different places of the girder (foot, up and down sides, extremities, internal and external zones). Two probes are also put on the concrete ground: one near a feet, another one far from the girder but still into the cell.

We did two series of transient tests:

1. No power in cables. Ventilation on. After a while, ventilation is switched off, still without power.
2. Ventilation off. We switched on power in cables. After a while, we switched the ventilation to 25% of its nominal flow (840m^3/h) and then to 100% (3360m^3/h)

With the first test, we noted that with ventilation, all girder temperatures were fluctuant (±0.05°C) with a period of 24h. These fluctuations are due to the variation of the surrounding experimental hall temperature during the day. Then, when with switched the ventilation off, we noted a decrease of all temperatures. This is due to the fact that the concrete slab is cooler than the ambient air. By switching the ventilation off, we reduced the coupling air/girder, hence the coupling concrete/girder is more important. In any case, we need further investigations on the concrete slab because its coupling with the girder cannot be neglected.

We the second test, we noted an increase in temperature of the girder of ~1.7°C within ~3days (time constant of 0.6day). We noted that by switching the ventilation on, temperatures were decreasing by ~25% when the ventilation is at 25% of its nominal flow, and by ~50% when ventilation is at 100% of nominal flow. We also note that the higher the air flow is, the more temperatures fluctuate (±0.15°C when 100% nominal flow), because of the increasing coupling between air and girder. We also note that concrete temperatures keep increasing slowly even after 20days, due to its high thermal inertia.

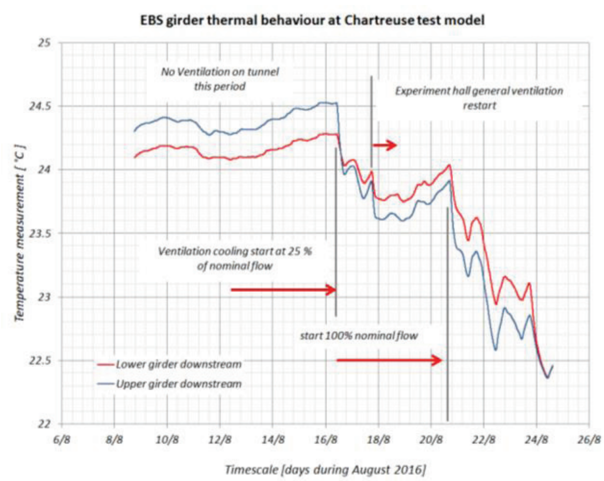

Figure 9: Temperature in the middle of the girder, up and down sides.

Figure 9 also shows interesting phenomena. When there is no ventilation while cables are powered, because the only convective regime is natural: the heat from cables goes upward due to Buoyancy forces, hence the upside of the girder (blue line) is warmer than the downside (red line). But these two curves crross and reverse when ventilation is switched on: air as heat carrier in natural convective regime is then pushed away by the forced air flow, as a consequence the upside of the girder becomes less heated.

We must also notice that the girder deformation has also been measured during these experiences. The girder tends to take a “banana” shape. Results are, however, not available yet. But the deformation is such that we abandoned the idea to place power cables inside the girder.

CONCLUSION

Thermal stability exploration requires considering it as a system: every components are coupled together. It mobilizes many experts from different domains, it is by nature a multi-physics approach. This exploration needs:

- More experimental mock-ups with many probes, which is not a common use
- More thermal simulations in order to estimate transfer functions or to implement a “thermatronic” domain.

The EBS is a new installation on an already existing facility; its thermal optimization is consequently difficult. Investigations are not completed yet. Some subjects are still under investigations. At the end, coupling coefficient will be better determined. The period of 4 days before reaching stable orbit seems to be very complex and difficult to solve, because it is probably connected with many causes. The +2°C ramp-up into a tunnel sector could be improved with extra cooling systems that we are currently studying.

A better approach would consist in considering the thermal stability at the beginning of a project.