THERMO-MECHANICAL SIMULATIONS OF THE FREQUENCY TUNING PLUNGER FOR THE IFMIF HALF-WAVE RESONATOR

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Abstract

In the framework of the International Fusion Materials Irradiation Facility (IFMIF), which consists of two high power CW accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV [1], a Linear IFMIF Prototype Accelerator (LIPAc) is presently under design for the first phase of the project. A superconducting option has been chosen for the 5 MeV RF Linac, based on a cryomodule composed of 8 low-beta Half Wave Resonators (HWR), 8 Solenoid Packages and 8 RF couplers. The initial solution for the frequency tuning system of the HWR was an innovated system based on a capacitive plunger located in the electric field region, allowing a large tuning range of ±50 kHz, while keeping the cavity rigid enough to fulfill the Japanese regulations on pressurized vessel. Following the cold test results obtained on HWR equipped with the first design of plunger in 2011 [2], the project decided to change the tuning system by a more conservative solution based on the HWR wall deformation.

Nevertheless RF and thermal simulations were realized to understand the previous test results and the conceptual design of a new plunger in niobium was proposed to resolve the issue. The mechanical constraint is to sufficiently deform the plunger to tune the cavity while staying in the elastic range of the niobium material. For the thermal simulations, all the non-linear properties of the materials and the effects of the RF fields are taken into account: thermal conductivity and surface resistance are depending on the temperature, RF fields computed with dedicated software are leading to thermal dissipations in the materials and the vacuum seal.

FIRST DESIGN OF THE HWR PROTOTYPE TUNING SYSTEM

The low-β HWR prototype, whose RF and mechanical design has already been presented in [3] is made of niobium with a titanium helium vessel and niobium-titanium alloy flanges.

The tuning system is based on a capacitive plunger located in the electric field region of the HWR, perpendicular to the beam axis. This plunger, filled with liquid helium, is connected to a thin membrane – 1.7 mm thick – via a 5 mm stem where the tuning force is applied. In order to clean the cavity, the whole tuning system is dismountable from the cavity body and a Garlock Helicoflex joint is used for the vacuum tightness.

For mechanical reasons, the membrane was made of niobium-titanium alloy, whereas the stem and the plunger are made of pure niobium. The membrane can be deformed in the range of ±1 mm which is sufficient to achieve the required tuning sensitivity of ±50 kHz.

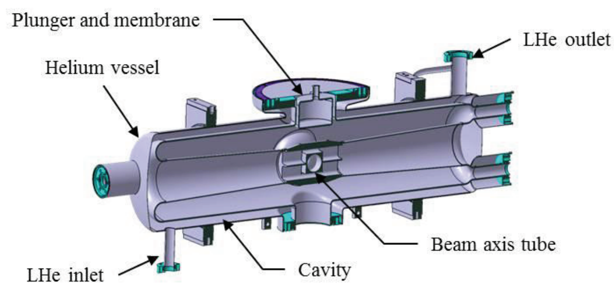

Figure 1: the IFMIF HWR prototype.

Vertical Test Results

After a proper preparation at IPN Orsay (BCP treatment, high pressure rinsing and assembly in an ISO 4 clean room), the prototype equipped with the tuning system was tested in a vertical cryostat at 4.2K.

Several multipactor barriers were observed starting at very low accelerating field (fist barrier at 12 kV/m) and up to 500 kV/m. To pass these barriers, the input power was increased on the incident antenna but the consequence was a quench of the NbTi membrane at the $E_{acc} \geq 1$ MV/m.

According to RF simulations, the magnetic field distribution over the membrane shows a maximum value of ~20% of peak field located on the centre of the membrane, which represents ~ 2.5 mT (Figure 2). This value may be sufficient to heat the membrane until its critical temperature.

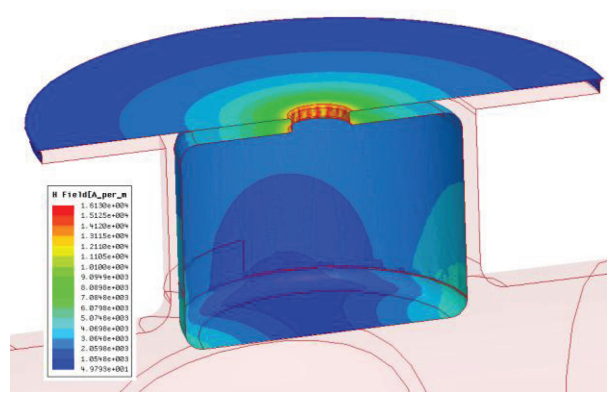

Figure 2: H-field in the plunger region.

Thermal Model of the Tuning System

In order to understand the behaviour of the tuning system, a thermal model has been developed taking into account all the non-linear properties of the materials and the effect of the RF field.

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The thermal phenomena in the tuning system are:

- Convection with liquid helium inside the plunger and on the niobium-titanium flange
- Heat flux generated by the H-field on the RF surfaces of the membrane, the plunger and the flange, and
- RF dissipation in the seal (Figure 3).

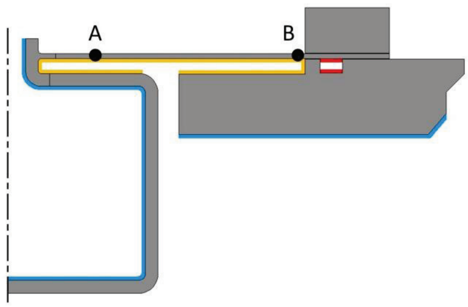

Figure 3: thermal loads on the 2D axis symmetrical model: in blue, the convection with the liquid helium, in orange, the RF losses, in red, the seal dissipation.

To determine the heat flux on each RF surface, the surface resistance of the niobium and the niobium – titanium alloy between the working temperature (4.2 K) and the critical temperature (9.2 K) at the cavity frequency must be introduced in the model. For both materials, the R_{BCS} was calculated using Halbritter's model [4], the parameters for the niobium can be found in [5] and the ones for the niobium-titanium alloy in [6].

As the thermal conductivity of the niobium is strongly dependent of its residual resistance ratio (RRR), the model developed in [7] was used to calculate this parameter between 4 K and 9.2 K. For the niobium-titanium alloy the temperature dependent thermal conductivity was given by the materials thermal properties database CryoComp.

In theory, the gasket placed in a groove on the niobium-titanium flange of the cavity does not produce RF dissipation. The plunger membrane is pinched between two flanges and so its contact with the rim of the cavity flange forbids the penetration of the field inside the gasket groove. In practical, the flatness of the contact surface of the two pieces is not perfect, and a gap may exist. The H-field value on the gasket is not calculated with the 3D software HFSS because of the scale difference between the gap flange (sub-millimeter scale) and the cavity (meter scale). Simulations on a simplified geometry made with 2D code Superfish show that whatever the size of the gap, 90% of the field on the rim penetrate on the gasket (Figure 4).

As the gasket is made of normal conducting material, its surface resistance is in the order of several milli-ohms at 175 MHz. In the worst case (i.e. half of the surface of the seal affected by the field) up to 25 W are dissipated at the nominal accelerating field.

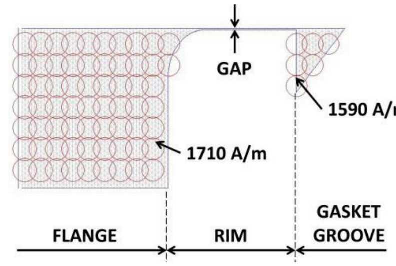

Figure 4: 2D simulation results of the influence of the gap between the membrane and the flange of the cavity on the gasket (H-field values are given for 4.5 M/m, the nominal accelerating field).

The thermal model was implemented in the finite element software Cast3M. The non-linear resolution procedure PASAPAS was modified and a new sub-procedure that redefines the RF heat load at each iteration has been introduced. For each boundary element, there is a surface resistance value attached at each element of the mesh. At each iteration this value is updated depending on the temperature of the element.

Simulation Results and Analysis

First, some simulations were done with no dissipation in the seal, heat load coming only from the RF field. For several values of the accelerating field, the peak temperature of the NbTi membrane (point A on Figure 3) is recorded. The result is presented in Figure 5: the higher the accelerating field, the warmer is the membrane. Above E_{acc} = 4.2 MV/m, the peak temperature is above the critical temperature of the niobium-titanium alloy.

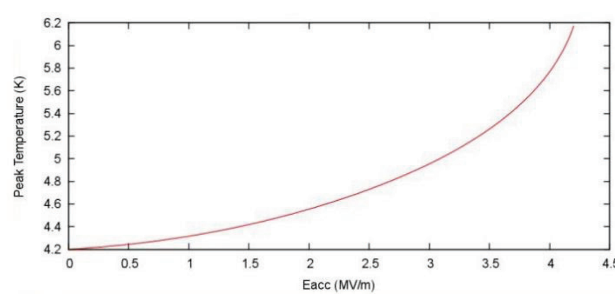

Figure 5: peak temperature of the membrane versus the accelerating field in the cavity (no dissipation in the seal).

The simulations show that even with the optimistic case of no dissipation in the seal, the RF losses lead to self-heating of the membrane due to the poor thermal conductivity of the niobium-titanium alloy.

Then the accelerating field was set at 1 MV/m, and simulations were done with several values for the power dissipated in the seal. Like before, the peak temperature of the membrane (point B on Figure 3) is recorded. Only 1.1 W is needed to reach the critical temperature of the material. The cause is the poor thermal conductivity of the niobium-titanium alloy which does not allow a good propagation of the heat in the material.

ALL-NIOBIUM PLUNGER TUNING SYSTEM

The previous thermal simulations have shown that the combination of the dissipated power in the seal, the poor thermal conductivity of the material and the high field due to the stem of the plunger can lead to a thermal quench of the membrane. These points were taken into account when designing a new all-niobium plunger tuning system.

Mechanical Design

The all-niobium tuning system was designed considering the following constraints:

- The overall dimensions are similar to the previous system in order to test it without modifying the cavity prototype.
- The displacement of the bottom surface of the plunger must be ±1 mm to achieve the frequency cavity tuning requirements.
- The system must sustain the atmospheric pressure with vacuum inside the cavity at room temperature.
- At room and helium temperatures, the stress must stay under the elastic limit of the niobium.

The resulting geometry is presented on Figure 6. There is no more liquid helium inside the plunger, the stem which was needed for manufacturing and was the cause of the field reinforcement has been suppressed. But as the length of the membrane is reduced and its flexibility is consequently limited, a flexible element similar to a wave was introduced.

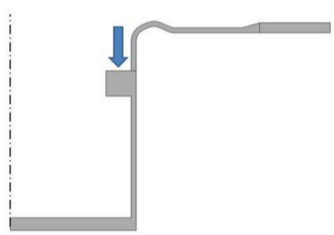

Figure 6: geometry of the niobium plunger. The arrow represents the force applied by the actuator.

The actuator force is no longer applied in the centre but on the side wall of the plunger. To achieve the ±1 mm displacement, a force of 4300 N is needed which can be easily delivered by the actuator designed for the first tuning system and slightly modified to be adapted to this system.

Thermal Design

The previously described thermal model was used to simulate the new plunger tuning system. First, RF simulations were done on the new geometry which showed that the field amplitude has marginally changed on the rim of the cavity flange. Indium seal is used instead of Helicoflex seal. The surface resistance is about the same (indium is superconducting under 3 K), but the surface of the indium seal affected by the RF field is much smaller. The dissipated power is estimated at 1.5 W at the nominal accelerating field.

A first simulation was carried out with no liquid helium cooling except the existing one on the bottom of the niobium-titanium flange of the cavity. At the nominal accelerating field, the plunger temperature is homogenous at 8.2 K, too close to the critical temperature to be acceptable.

We also observe that the dissipated power in the indium seal in the predominant heat source. It is necessary to prevent this heat to propagate along the niobium plunger. A second simulation was carried out with helium cooling on one side of the anchor piece of the actuator system. The plunger temperature is reduced to 5 K for the coolest part to 5.8 K for the warmest part (Figure 7).

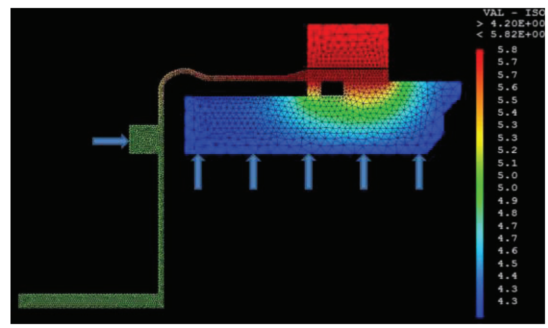

Figure 7: thermal simulation result. The blue arrows represent the liquid helium cooling.

CONCLUSION

The RF and thermal simulations made on the first tuning plunger allowed to understand the vertical test results and the limitations of the design.

In parallel of the design studies of the all-niobium plunger, the principle of tuning the cavity with a capacitive plunger was abandoned by the project and replaced by a more conservative solution of HWR deformed by beam noses compression. According to the project decision, a new tuner design is in progress.

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