ELECTROMAGNETIC, THERMAL, AND STRUCTURAL ANALYSIS OF A THOMX RF GUN USING ANSYS

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Abstract

Photocathode RF guns are used in the first stage of electron beam generation and acceleration. The RF gun of THOMX is a 2.5 cell standing wave copper cavity with resonance frequency of 2998.55 MHz at 30 °C under vacuum. The metal photocathode such as copper or magnesium is inserted into the backplane of the cavity. Due to high repetition rates up to 50 Hz with the average dissipated power into the internal surfaces up to 1.5 kW, causing a heating and deformation of the cavity shape. Therefore, the cooling system of the device has to be well designed to take under control the deformations of the structure, providing a temperature increase as small and uniform as possible. For this purpose a fully coupled electromagnetic-thermal-structural finite element analysis on this gun has been performed with Ansys workbench. Numerical results show that the gun could operate at 3 µs RF pulse length and 50 Hz repetition rate with an average dissipated power of 1.5 kW. The gun average temperature is around 30 °C while the incoming water temperature is around 24°C. Internal speed of water is 2.5 m/s which corresponds to 15 l/min for the incoming water. The total pressure drop is around 0.4 bar.

INTRODUCTION

ThomX is a Compton source project in the range of the hard X rays (45/90 keV). The machine is composed of a 50-70 MeV injector Linac and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The final goal is to provide an X-rays average flux of $10^{11}/10^{13}$ ph/s. The ThomX project [1] was recently funded and a demonstrator will be built on the Orsay University campus.

RF guns are used in the first stage of electron beam generation and acceleration in particle accelerator [2]. They are copper structures with different internal shapes fed by RF klystrons and they can work at different frequencies (from few hundred of MHz up to several GHz) depending on the different applications. RF photoinjectors are the ultimate choice to generate short electron pulses of high bunch charge with extraordinary low transverse emittance.

The proposed 2.5 cell RF Gun for ThomX operates with a nominal body temperature of 30 °C in the π mode at the S-band frequency of 2998.55 MHz under vacuum. The electrons are emitted on the cathode through a laser that hit the surface and are then accelerated by an axial longitudinal electric field component. The beam energy at the exit of the RF Gun is about 5 MeV for an input peak RF power of 6 MW.

A thermally stable operation of the gun cavity is mandatory to prevent from parasitic RF amplitude and phase jitters, which in turn are converted into energy and timing jitters of the beam bothering the performance of subsequent components of the accelerator. In these injectors the photocathode is exposed to electric field in the range of several ten MV/m to confine space charge forces just at their origin. Operating at high repetition rates such high field levels requires average power levels of several kW. Hence the cooling system of the Gun has to be well designed to take under control the deformation of the structure, providing a temperature increase as small and uniform as possible. For this purpose a complete simulation has been performed with the multi-physics package of the finite element analysis code ANSYS [3].

RF-THERMAL-STRUCTURAL COUPLED ANALYSIS ON THE RF GUN

The commercial finite element analysis (FEA) code ANSYS provides the ability to link electromagnetic to thermal and structural analyses as shown in Fig.1.

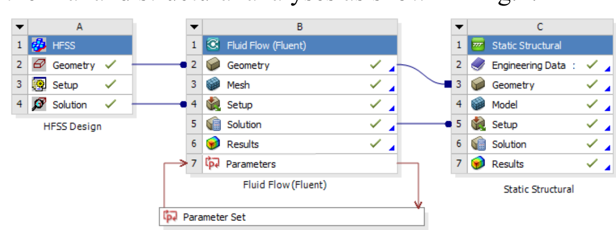

Figure 1: ANSYS Workbench Analyses Schematic.

ANSYS provides the high frequency (HF) analysis module and associate elements. This module has been applied to evaluate the RF loss and the consequent temperature distribution in the gun body. A coupled field analysis by a unique code is more efficient respect to using different specialized software. In fact the exchange of information between electromagnetic field simulators and structural/thermal simulators can be difficult and can lead to errors. In case of multi-physics code like ANSYS this exchange of information between different modules is a built-in feature of the software, so that the model can be established by one single software and related data can be transferred more efficiently and easily in between elements.

Electromagnetic Analysis

The RF gun of THOMX is a 2.5 cell standing wave copper cavity with a resonance frequency of 2998.55

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MHz at 30 °C under vacuum, operating on the TM_{010} accelerating mode and field phase advance per cell is π. The THOMX RF gun geometry is inspired from the probe beam photo-injector (PBPI) of CTF3 [4] already designed and constructed by LAL. RF power is fed through one waveguide coupler only; the waveguide located 180 deg. opposite the input one, its main purpose is to cancel the field dipole component. The RF cavity shape, as proposed, has several innovative electromagnetic features, including Z-coupling and enhanced cell-to-cell coupling to produce higher mode separation, elliptical irises to reduce surface electric field, symmetric couplers for dipole mode minimization, racetrack geometry to minimize quadrupole field components. It is externally fed only by one side, avoiding the need of power splitter and making the whole assembly much more compact, easier to handle and cost efficient.

The RF gun was designed, machined and brazed in-house, followed by final tuning. The gun after the final brazing step is shown in Fig. 2.

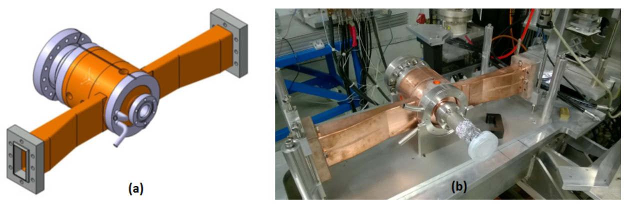

Figure 2: ThomX RF gun (a) 3D model design (b) Prototype after final brazing.

The electromagnetic analysis is performed using the ANSYS Electromagnetics (HFSS), which determines the resonant mode frequencies and electromagnetic field distribution. The accelerating electric field on the cathode for the THOMX gun is 100 MV/m for an input RF power of 10 MW at 3µs RF pulse length and 50 Hz repetition rate as shown in Fig. 3. Also from the picture of the electric field amplitude inside the structure and on the cell surface (Fig. 3), we can see that the peak value on the iris area is about 110 MV/m.

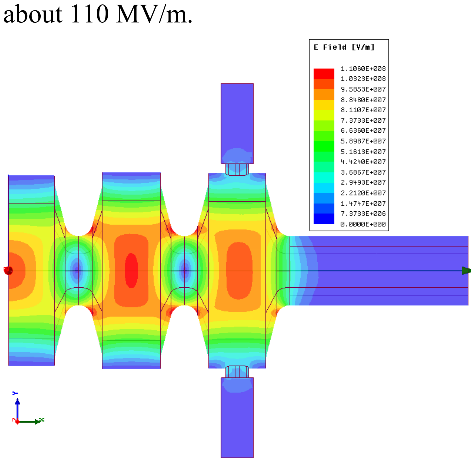

Figure 3: The electric field amplitude in photocathode gun

Cyclic thermal stresses produced by RF pulsed heating due to intense magnetic fields that is usually at the coupling slot area may become a cause of significant material deformations. EM Simulations show that magnetic field reaches a peak equal to $H_{max}= 4.10^5$ A/m for an input RF power of 10 MW. This field value causes a temperature rise of about 60 °C for a RF flat top pulse length of 3 µs, which is below the threshold of 110 °C in the case of copper. As general experimental rule, if this pulsed heating exceeds ~ 110 °C serious damage to the coupler region has a high probability of occurrence.

The average heat flux (power loss density) obtained for 3 µs RF pulse length and 50 Hz repetition is shown in Fig. 4 the maximum heat flux at the coupling slot area is 150 kW/m^2. The average dissipated power on the internal cavity surfaces is 1.5 kW. The main gun parameters are given in Table 1.

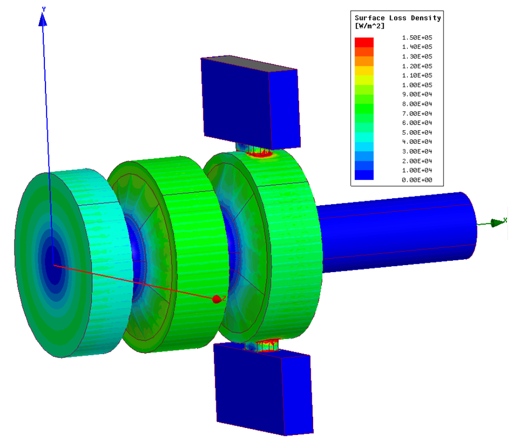

Figure 4: The heat flux for 10 MW peak power at 3 µs RF pulse length and 50 Hz repetition rate.

Table 1: Main RF parameters of the THOMX Gun

Parameters	Simulated Values
π-mode Frequency	2998.55 MHz
Quality factor Q	15000
Shunt impedance	49 MΩ/m
Peak Accelerating field	100 MV/m @ 10 MW
Filling time	0.7 µs
Repetition rate	50 HZ
RF pulse, input RF Power	3µs, ≤ 10 MW
Esurf/Eacc	1.07
Average dissipater power	1.5 kW

Thermal Analysis

The heat source for the thermal simulation is the power loss of the accelerating mode on the cavity walls. This RF heating, if not properly dissipated, may result in excessive structural stress, deformations, and the accelerating frequency shift. The computed power loss is then imported and applied as a heat flux load (W/m^2) to the surface of the metal body of the Gun. The metal part is comprised of two different materials, copper and stainless steel. The cooling system is directly made in the copper cells. It's composed by one feeding pipe and runs through the gun body with two parallel small pipes (Fig. 5).

In the thermal analysis performed with ANSYS FLUENT, we assume an overall 50 Hz repetition rate, with 3 μs RF pulse length and thus, with 10 MW peak power, that means an average dissipated power of 1.5 kW. Water velocity inside tubes (diameter 8 mm) is set to 2.5 m/s, this value derived from considerations channels pressure and corrosion problems. Higher values of fluid velocity, until 3 m/s, could be in case adopted. The inlet water temperature is 24 °C and the ambient temperature is 22 °C. Natural convection with air on the external surface is taken into account as boundary conditions.

The temperature distribution calculated in the gun body is represented in Fig. 5. The temperature distribution is uniform throughout the whole gun body with an average value of about 29.6 °C and a peak value of 33°C at the photocathode area. The temperature of the cells diameter, which has the larger impact on the gun resonant frequency, is between 29 and 31°C.

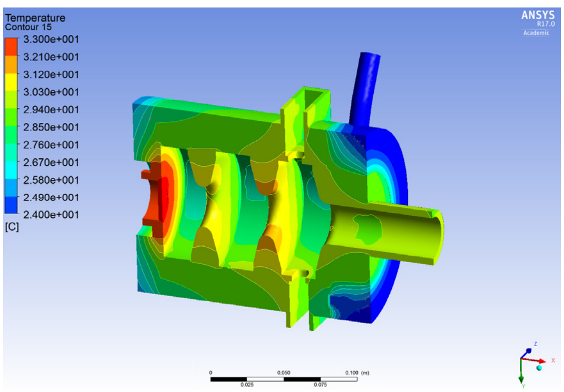

Figure 5: Gun body temperature distribution.

The related cooling water temperature distribution inside tubes is depicted in Fig. 6. The maximum temperature rise is about 1.4°C and the pressure drop is around 0.4 bar for 2.5 m/s water flow rate.

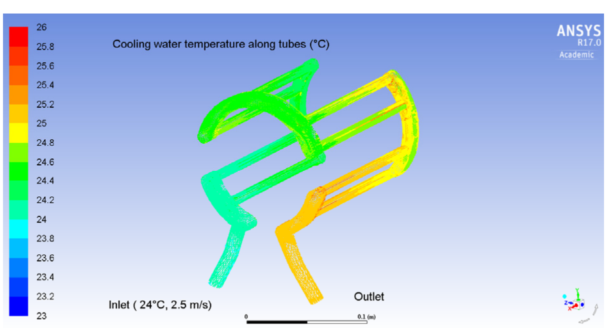

Figure 6: Coolant temperature distribution.

Structural Analysis

After obtaining the thermal solution, the structural solution may be calculated by applying the thermal analysis results as a load in the model. The goal of the model is to evaluate the deformations, due the thermal load acting on the gun body. The total deformation (displacement) calculated is depicted in Fig. 7. The maximum deformation is about of 25 μm. The deformation calculated on the inner surfaces, in radial direction, is below 20 μm.

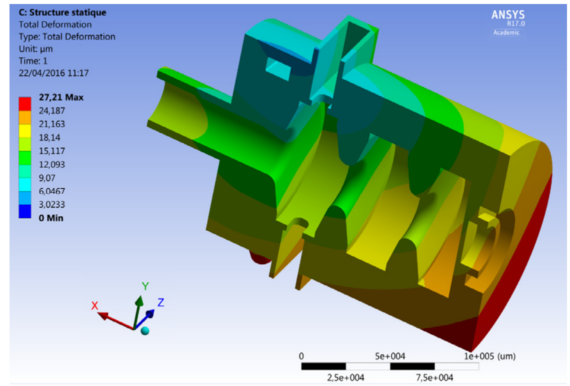

Figure 7: Gun body total deformation.

The local stress caused by the RF heating should be controlled below the yield stress of the annealed oxygen free copper, 62 MPa [5]. At the slot coupling area the peak Von Misses stress is 18 MPa (Fig. 8), which is marginal but in the safe region.

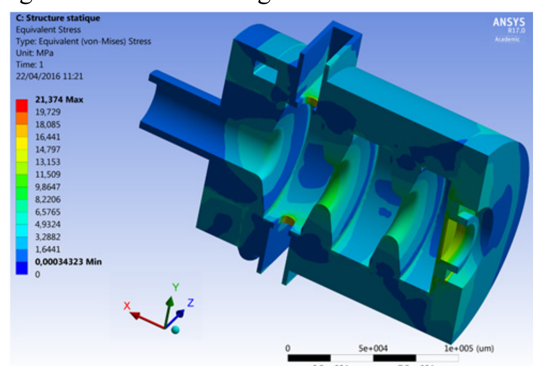

Figure 8: Gun body equivalent Von-Mises stress for 1.5 kW average load.

CONCLUSION

The present coolant channel design in 2.5 cell photocathode gun seems adequate for 50 Hz operation at 100 MV/m peak gradient and 3 μs RF pulse length with 2.5 m/s water flow rate. A novel approach of complete RF-Thermal-Structural simulation in the same FEA mesh environment for the full model has been used. By using one program for all the simulations any problems of transferring loads between different softwares were eliminated. RF Gun prototype for THOMX was constructed and the RF characteristics were confirmed. High power test is foreseen using the PHIL photoinjector test line at LAL Orsay.

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