Research Article

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Design and Commissioning of a 10 Mev Cyclotron Accelerator Cooling System

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Abstract

The proposed cooling system is designed with a high reliability factor and considering the economic issues and costs based on the use of a 40ton chiller for temperature changes of 4.5 to 10 degrees Celsius, which is able to continuously control the water temperature in this range. In this system, the parts of magnet coil, cavity, power transmission line, ion spring and radiofrequency current amplifier with an inlet water flow of 195L/min are fed from an air-cooled chiller at a height of 40 meter the roof of the building along with a vertical industrial water pump of 4 KW and has been done in CST software , we showed the distribution of surface flow on the cavity and determined the hottest point of the cavity and used Solid Works software to geometrically model it. The magnet system was made up of hollow layer coils with a square outer cross-sectional area to the side of 8 mm and an inner cross sectional area of a circle with a diameter of 4 mm, and for the power transmission line due to a change in the impedance of 50 ohm when the temperature increased, the cooling system was use .In the PIG ion spring with a power consumption of 500 watt and The amplifier part of the water pressure limit lamp is set at 3.5 bar pressure for optimal cooling. In this study, practical solutions are presented in the optimal design and commissioning of the cyclotron accelerator cooling system.

Keywords: Cyclotron Cooling System, RF Cavity Cooling, Thermal Analysis, CST Simulation, Magnet Thermal Management.

Introduction

A cyclotron is a type of particle accelerator that uses a radio frequency (RF) electric field to impart energy to particles. In the design of a 10 MeV cyclotron, the cooling system is of paramount importance. Initially, it is necessary to calculate the components requiring cooling in terms of thermal analysis and required parameters such as mass flow rate of cooling water, inlet water temperature, and water flow pressure. Subsequently, based on the parameters of these components, the overall cooling system is designed. In this project, a highly reliable cooling system has been designed through the use of an industrial control system (PLC) with independent temperature, pressure, and flow sensors to monitor the central chiller's performance, and a redundant design (utilizing two water pumps: a main 4 KW pump and a 1 KW backup pump operating in a staged pumping system, with the backup pump on standby). The design also incorporates high-quality components, precise preventive maintenance, and consideration of economic factors and cost optimization. The main components—including the magnet coil, RF cavity, power transmission line, ion source, and RF amplifier tube—are cooled by a central chiller located 40 meters away on the building's rooftop, using a 1500-liter tank of deionized water. Only the target section is cooled by helium gas due to the extremely high-power density and intense heat concentration in the target region, which is prone to creating hot spots. This necessitates a coolant with exceptional heat transfer capacity and complete chemical stability. Helium, with its high thermal conductivity and low viscosity, can effectively dissipate the concentrated heat.

The study and development of cooling systems for accelerators have a history as long as the devices themselves. Early cyclotrons operating at lower energy ranges often used simple cooling with air or ambient-temperature water. Over time, with the shift toward higher energies and extremely high-power densities, research has moved toward more advanced cooling systems. In recent decades, numerous papers have generally addressed cooling in accelerators. These studies have primarily focused on cooling key components such as magnets and RF cavities, establishing deionized water as the primary coolant due to its high specific heat capacity, availability, and relatively low cost. However, many of these studies have not provided detailed thermal analyses for each component considering actual heat loads or the design of integrated control systems, often remaining at an overview level. For example, one paper employed a water-based cooling system for medical cyclotrons [1], while another used helium gas for target cooling in high-power accelerators [2], and a third examined the importance of industrial PLC control in cooling systems [3]. In contrast, this paper addresses the overall cooling system of the cyclotron with considerable precision. The main gap that this paper aims to fill is moving from this general perspective toward a precise engineering design based on numerical analyses and incorporating all operational parameters and high-reliability requirements. Unlike previous papers that discussed the topic generally, this paper provides detailed insights into each section relative to the chiller's cooling capacity. Thermal analyses in this study were conducted using CST software, and all calculation results incorporate a safety factor of 1.5 as a basis for enhancing the safety and reliability of the overall system [4].

Final Chiller Capacity

In this article, the cooling capacity of the central chiller is 40 real tons of refrigeration. For the design of the 10 MeV cyclotron cooling system, the total heat load of the system was calculated using Formula No. 1 as the basis.

$$Q = mC_p\Delta T \tag{1}$$

The total chiller capacity was estimated by unit conversion (1 TR = 3.517 KW) to be 140.68 KW. The total volumetric flow rate was estimated at 3.365 kg/s. The mass flow rate of cooling water for this heat load, considering the design constraint of a maximum permissible temperature rise for water passing through the system, was calculated to be approximately 201.9 L/min. This value is a common standard in the design of cyclotron cooling systems. An important design constraint is the maximum permissible temperature rise of the water as it passes through the system, which was set at 10°C. This value is considered a common standard in the design of cyclotron cooling systems [5].

Thermal Analysis of the RF System

Cavity

In a 10 MeV cyclotron, the cavity or resonant cavity is the most complex mechanism for heat generation and the most critical part in terms of heat transfer. This sensitivity is due to the concentrated heat generation from surface currents and the direct impact of temperature on the cavity's resonant frequency. Figure 1 shows the temperature distribution analysis for the cavity in CST software. We determined that the temperature distribution process is not uniform across different regions of the cavity, and we require cooling at its center. The cavity specifications are also provided in Table No. 1. These specifications determine the amount of cooling water flow rate required, calculated based on Formula No. 1, and we specified this value in Table No.1. The design and operational parameters of the cyclotron RF system are summarized in Table 1. The RF cavity is constructed from OFHC copper (Oxygen-Free High-Conductivity Copper) to minimize electrical losses and operates at a resonant frequency of 71MHz. The system functions with an accelerating voltage of 42 kV and an input RF power of 15 kW. To dissipate the heat generated by ohmic losses, a cooling system with a flow rate of 24 liters per minute has been designated. A characteristic impedance of 50 ohms has also been designed to optimize power matching between the source and the cavity.

Table No 1: Cyclotron Cavity Specifications

Characteristic	Value
71 MHz	Resonant Frequency
OFHC Copper	Cavity Material
42 kV	Dee Voltage
Input Power Level	RF Signal Power
50 Ω	Characteristic Impedance
24 L/min	Cooling Water Flow Rate

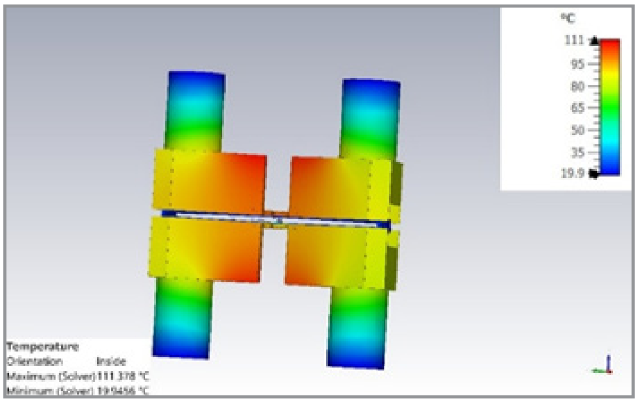

Figure 1: Temperature Distribution Analysis

The primary mechanism of heat generation in the cavity is resistive loss due to surface currents, described by Equation No. 2, which has a direct dependence on the square of the tangential magnetic field (H) on the surface. Using Equation No. 2, the relationship between the tangential magnetic field and the heat generated on the surface can be observed, concluding that the heat generated on the cavity directly depends on the magnetic field on the surface [6].

$$P_w = \frac{1}{2}\sqrt{\frac{\mu f}{\sigma}} \mid H^2 \mid \delta s \tag{2}$$

In this relation, μ is magnetic permeability, f is RF frequency, σ is electrical conductivity, δs is surface element area, and H is the tangential magnetic field. Each cavity is an RF resonator whose initial dimensions can be estimated by solving Maxwell's equations. Using Equation 3, derived from solving Maxwell's equations for a cylindrical cavity, an initial estimate of the cavity radius is obtained [7].

$$y = \frac{2.405\, C}{2\pi f} \tag{3}$$

In Equation 3, C is the speed of light, f is the resonant frequency, and y is the cavity radius.

RF Transmission Line

The RF transmission line is a critical component in cyclotrons, responsible for transmitting RF power from the source to the cyclotron's vacuum accelerating chamber. This transmission line must transfer power with minimal losses and be impedance-matched to the source and load to minimize wave reflections. A key feature of the transmission line in a cyclotron is active cooling due to Joule losses caused by skin effect surface currents at high frequencies (MHz range), which heat the transmission line [8]. The specifications of the transmission line for this article are in Table No. 2, and the exponential distribution in the 10 MeV cyclotron's RF transmission line, simulated using CST software, is shown in Figure No. 2 The design parameters of the RF power transmission line are presented in Table 2. This transmission line is designed with a characteristic impedance of 50 ohms for transmitting an average power of 15 kW. The line dimensions vary within the range of 1.8 to 3 inches, optimized based on impedance considerations and thermal losses. A cooling system with a flow rate of 5.5 liters per minute has been implemented to dissipate heat generated by ohmic losses, ensuring the line temperature remains within the permissible operational range.

Table 2: RF Transmission Line Specifications

Value	Characteristic
Original text "3-1.8" is ambiguous	Transmission Line Dimensions
50 Ω	Characteristic Impedance
15 kW	Average Power
5.5 L/min	Cooling Water Flow Rate

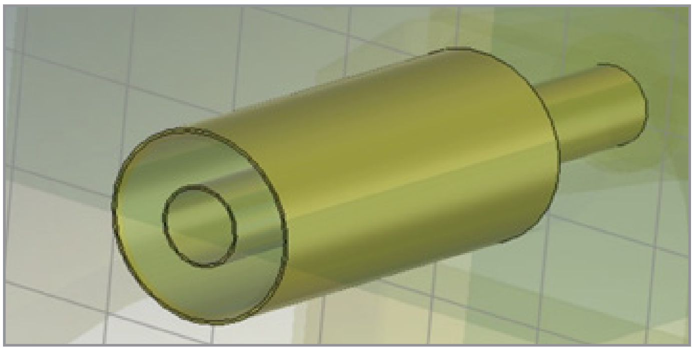

Figure 2: Transmission Line Simulation

Figure No. 2 shows the exponential distribution, typically highlighting hot spots at connections or bends in the transmission line, which we optimized in the design. To reduce losses, we used vacuum coaxial transmission lines [9].

Wave Equation and Characteristic Impedance

For a coaxial transmission line, the characteristic impedance Z_0 is calculated from Equation No. 4:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right) \tag{4}$$

Where D is the inner diameter of the outer conductor (in meters), d is the outer diameter of the inner conductor (in meters), and ε_r is the relative permittivity of the dielectric (approximately 1 for air or vacuum).

Heat Transfer Equations for Cooling

The heating rate of the transmission line due to ohmic losses must be dissipated by the cooling system. The energy balance equation is calculated from Relation No. 5.

$$P_{loss} = mC_p\Delta T \tag{5}$$

Where P_"loss" is the thermal power loss (Watts), C_p is the specific heat capacity of water, m is the mass flow rate of cooling water, and ΔT is the inlet-outlet water temperature difference.

Thermal Expansion and Impedance Change:

With increasing temperature, the physical dimensions of the line change, calculated by Equation No. 6:

$$\Delta L = \alpha_L L_0 \Delta T \tag{6}$$

Where α_L is the coefficient of thermal expansion of the material.

This expansion changes the ratio D/d and consequently Z_0. Therefore, we performed temperature control and thermal expansion management to stabilize Z_0 and prevent increased losses, achieving the optimal state for this part. The overall calculation results for this part of the cyclotron cooling system are shown in Table No. 2. Based on all the indicated parameters, it can be concluded that for the RF power transmission line cooling system, water with a mass flow rate of 90 grams per second and an initial cooling temperature of 293 Kelvin is suitable and effective. [10]

RF Power Amplifier Tube

The RF power amplifier tube generates significant heat in its amplifier tubes, requiring efficient heat dissipation to prevent efficiency reduction, operational frequency shift, and physical damage. The design and optimization of the cooling system for the RF power amplifier tube involve performing calculations and thermal analysis. Using Equation No. 7, we measure the required volumetric water flow rate and the thermal power that must be dissipated.

$$\text{Flow Rate (L/min)} \approx \frac{14.3 \times Q(\text{KW})}{\Delta T} \tag{7}$$

Where the thermal power to be dissipated $Q = P_{in} \times (1 - \eta)$.

The electrical input power to the tube in this article $P_{in} = 91\ \text{KW}$. The tube efficiency η=50%.

For cooling this part, the required volumetric flow rate is calculated for dissipating Q≈45.5"KW" of heat. Using catalogs and applying a 10% safety factor and the constraint that the inlet water pressure must not exceed 3.5 bar, we determined the flow rate.

Thermal Analysis of the Magnet

The magnet is a fundamental and crucial component in cyclotrons, responsible for focusing the particle beams and guiding them on a spiral path. In the design reviewed in this article, the magnet consists of a four-sector structure employed to increase magnetic field concentration and resonance. One of the challenges in magnet design and construction is the discrepancy between computer simulation results and operational data. Generally, simulation accuracy increases by considering more parameters and physical effects. Among these, thermal phenomena, specifically heat transfer, are key factors that can affect magnetic field performance and consequently the overall efficiency of the magnet.

This article presents and examines a precise numerical simulation of heat dissipation and its effects on magnetic field stability in an isochronous cyclotron. In the studied 10 MeV cyclotron, the magnet coils require an efficient cooling system to prevent a severe current drop and subsequent reduction of the magnetic field. These coils are designed in a layered configuration and are cooled using hollow conductors with low longitudinal conductivity. The geometric specifications of these conductors feature a square external cross-section with a side length of 10 mm and a circular internal cross-section with a diameter of 5.7 mm, through which the coolant flows. Figure No. 3 shows the temperature distribution in one of the layers.

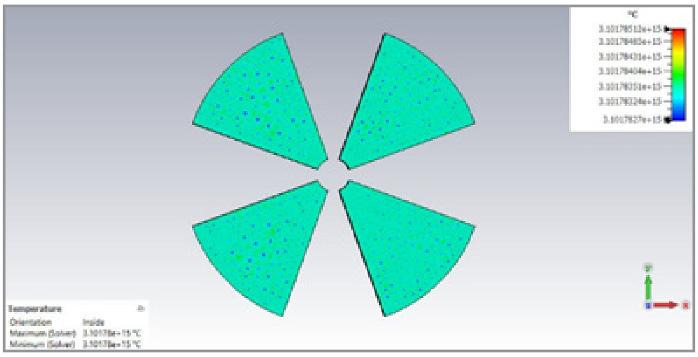

Figure 3: Temperature Distribution

This figure relates to the temperature distribution in a coil layer. The heat transfer simulation for the cavity part was performed using Computational Fluid Dynamics (CFD) with the CST software, utilizing the k-ε turbulence model with Standard Wall Functions. The conductive heat transfer equation and the convective heat transfer equation at the solid-fluid interface were applied, with boundary conditions for external surfaces in contact with air (heat transfer coefficient), coolant inlet temperature of , and internal heat generation in the coils made of OFHC copper (electrical conductivity 5.8×10^7 "S/m" , thermal conductivity) [11]. The coolant used was triple-distilled deionized water with standard thermophysical properties.

Ion Source

The ion source used in the 10 MeV cyclotron is a Penning Ionization Gauge (PIG) type cold cathode ion source. This source, which plays a vital role in providing the necessary ions for the acceleration process, is controlled and supplied by the central cooling system. Optimal performance and temperature management of this source, especially in the cathode region, are essential for achieving a stable and reliable ion beam current. Thermal management is a major challenge in the design and operation of PIG ion sources. The heat generated by ion bombardment and high discharge current, if not properly dissipated, can lead to cathode deterioration, reduced ion production efficiency, and beam instability. In this article, the technical specifications of the PIG ion source are provided in Table No. 3, and the results of the ion source temperature distribution study are presented in Figure No. 4, where we simulated the temperature distribution using CST software.

Table 3: Ion Source Specifications

Cold Cathode PIG		Type
Tantalum		Cathode
Triple-Distilled Deionized Wate		Coolant
internal	Type	Injector
H^-	ion	
Diameter	0.5 mm	Aperture
Height	4 mm	
copper		
Voltage	KV 0.1-2	Arc
Current	3Amp	
Hydrogen	Type	Gas Flow Rate
3-10 kg/s	Flow rate	

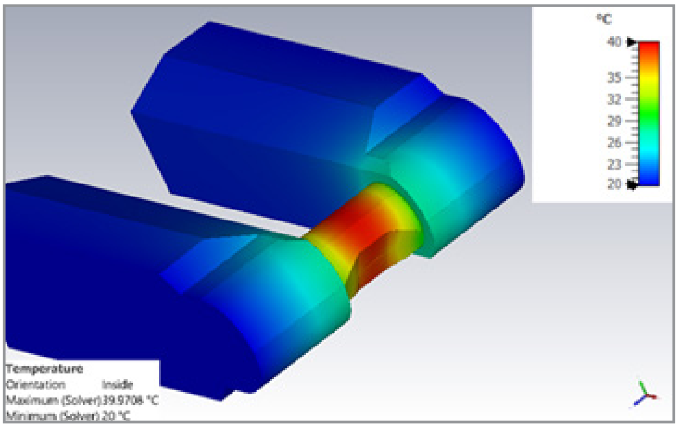

Figure 4: Thermal Distribution in the Ion Source

As observed in Figure No. 4, the highest temperature concentration occurs in the center, which is the main region of ion bombardment and electrical discharge. In this article, the cooling system design effectively transfers this heat through cooling channels and prevents local overheating. The PIG ion source, supported by the central cooling system, is capable of providing a stable ion current for the 10 MeV cyclotron. Figure No. 4 and its temperature distribution analysis demonstrate the effectiveness of the cooling system design in maintaining the ion source within a safe and optimal temperature range. This thermal stability is a necessary condition for the long-term and reliable operation of the ion source and, consequently, the entire cyclotron device [12]. The results indicated that the maximum cathode temperature is 1992 Kelvin, which is significantly below the cathode's melting point, and the maximum deformation at the cathode edges is approximately 0.2 millimeters [13].

Central Cooling System

The cooling system is considered one of the most vital parts of an advanced cyclotron. The stable and reliable operation of main components such as magnetic coils, cavity, target, and amplifiers depends on the system's ability to dissipate the generated heat. In this project, to enhance reliability, efficiency, and control integration, an integrated Central Cooling System has been used to meet the cooling needs of all these sections. In a cyclotron, a significant portion of energy appears as heat in various components. Ineffective dissipation of this heat can lead to thermal stresses, changes in material properties, asymmetric expansion, and ultimately reduced efficiency, fault generation, and even serious damage to the device. The central cooling system designed for this cyclotron, considering an integrated architecture, provides the possibility of centralized management and monitoring of vital parameters.

The Main Components of the Central Cooling System, which form a Closed loop, Include:

Circulation Pumps
Heat Exchangers
Pressure Sensors
Temperature Sensors
Flow Sensors
Control Valves and Fittings

Advantages of employing a central system include integration, reliability, centralized control and monitoring, smart automation, and safety. Furthermore, the cooling fluid, being water, cannot be ordinary water due to the presence of voltage on various components and must be deionized water (distilled water) to prevent electrical breakdown and current flow. Also, since the feed water for the entire cyclotron is supplied from a single source, and the feed water temperature for the magnet and cavity cooling system is considered to be , this must be taken into account, and the cooling water temperature for the ion source should also be set to . The cathode and other components do not have extensive machining or frequent maneuvering, so their cooling must be handled through their associated parts. From a vibration perspective, the feed water velocity inside the pipes must be more than 5 meters per second.

Conclusion

The design and optimization of the cooling system for a storage cyclotron is not only an engineering challenge but also a critical factor in ensuring the stability, efficiency, and longevity of the device in the long term. In this research, key design considerations, including the very high thermal load in the RF cavity, ion source, magnet, and transmission line, were comprehensively analyzed. The performed thermal analyses confirm that the proposed design, based on a two-stage cooler with triple-distilled deionized water, is capable of dissipating heat with high efficiency and maintaining temperature fluctuations within a desirable range. This thermal stability ultimately leads to a high-quality ion beam. Furthermore, the integration of an intelligent monitoring and control system via PLC provides optimal detection and reaction to anomalies, significantly increasing system reliability. In conclusion, it can be stated that the designed cooling system provides an effective and practical response to the complex needs of the studied cyclotron.

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