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DESIGN OPTIMIZATION OF THE WATER-COOLED COIL FOR THE LEIR EXTRACTION SEPTUM

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Abstract

A pulsed septum magnet (SMH40) is used for heavy ion extraction from the Low Energy Ion Ring (LEIR). A non-conformity on the coil cooling circuit required to consolidate the septum blade design and related manufacturing process. A stringent failure analysis, including structural analysis and computational fluid dynamics (CFD), combined with destructive and non-destructive testing, has allowed to identify an initial design weakness. Subsequently, a new manufacturing process has been developed, fully validated by numerical computation and after production of a 1:1 prototype. The achieved leak-tightness and cooling performance, as well as the optimization of the manufacturing process, shall therefore significantly increase the operational life cycle. This paper describes results from the initial root cause analysis and summarizes the design iterations and final results.

INTRODUCTION

The SMH40 consists of a conducting coil embedded into the gap of a C-shaped ferromagnetic yoke. A homogeneous magnetic field is generated in the gap of the yoke to deflect the extracted ion beam by 130 mrad [1,2]. The water cooled coil contains a septum blade and two return conductors. The septum blade and vacuum chamber minimize the stray field in the field free region of the circulating beam in every 3.6 s when the beam passes. The SMH40 septum blade consists of:

- A 900 mm long and 4.5 mm thick oxygen free electronic grade copper conductor. The long tapered edges of the conductor minimize stray field and constrains the septum blade in between the yoke and the vacuum chamber. Together with the placement of the cooling channels, tapering of the edges of the conductor allows for good current uniformity in the septum blade [3].
- The cooling channel is a 1734 mm long and ∅ 2 mm U-shaped 316L stainless steel tube embedded into a groove in the conductor. The cooling channel is assembled to the conductor via vacuum brazing.
- A 0.5 mm thick 316L stainless steel reinforcement plate, vacuum brazed on the back of the conductor.
- An additional copper connection piece with compression tube fittings connects the water supply to the cooling channel. The design has changed several times in the past, aiming for high robustness.
- Contact between the septum blade and the yoke is electrically insulated with Al_2O_3 coating and Kapton®.

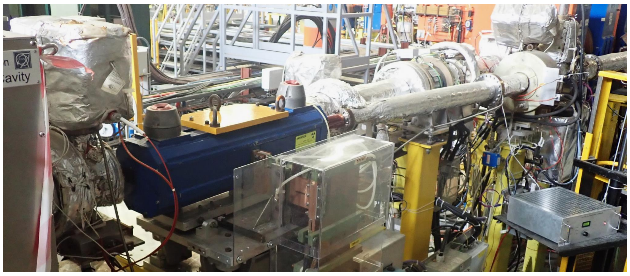

Figure 1: Photograph of the septum magnet SMH40 (blue device). Beam direction from left to right.

Operational Conditions

The septum blade needs to withstand the Lorentz force every 3,6 seconds generated by the excitation magnetic field, in addition to LEIRs Ultra High Vacuum pressure (UHV).

$$F_{magnetic} = I_{peak} \cdot l_m \cdot \frac{B_{field}}{2} = 8.7\,\mathrm{kN} \qquad (1)$$

The conductor is also subjected to thermal loads due to the 28 kA peak current. Demineralized cooling water shall stabilize the septum blade temperature therefore:

$$P = \dot{m} \cdot c_{water} \cdot \triangle T = I^2_{septum} \cdot R_{septum} = 40\,\mathrm{W} \qquad (2)$$

Internal pressure because of the cooling water. Water flow in the cooling channel is approximately $1\,\mathrm{L\,min^{-1}}$ with an inlet pressure of 25 bar. Table 1 shows the main parameters of the SMH40.

Table 1: SMH40 Parameters [3,4]

Description	Value	Unit
Peak current SMH40	28	kA
Magnetic inductance	2.3	µH
Magnetic field in the gap	0.779	T
Repetition time (Total cycle)	3.6	s
Flat top duration	400	µs
Effective septum thickness	10	mm

HISTORY AND FAILURE ANALYSIS

A failure of the septum blade would result in the shut-down of the SMH40, since the septum blade will

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need to be replaced with a spare. The septum blade design has seen several iterations due to repairs and component replacements over the last 20 years. In the first generation, an observed fracture in the exposed cooling channels occurred due to material fatigue after approximately 6 years of operation (6 million pulses/year). Finite Element Analysis (FEA) indicated 95 MPa material stress in this area due to the hyperstatic support constraint [1].

Subsequently a new design, the third generation, was developed in 2017 which failed acceptance test due to severe leakage. A metallurgic inspection showed excessive alloying of the brazing layer in between the conductor and the reinforcement plate. This is given by the gap clearance and a result of the water leak on the septum blade. In addition to the manufacturing failure, CFD analysis has indicated that achieving the required volume flow results in a high static pressure (28 bar), high local velocities, and high dynamic pressure (4 bar). A high hydraulic impedance indicates an increased risk of internal abrasion in the cooling circuit.

The failure analysis has indicated that the connection between the water supply and the internal cooling circuit of the septum blade is the most critical area for structural robustness and leak-tight properties in all design generations. A Quality Control (QC) system with a Manufacturing & Inspection Plan (MIP) has been developed to further improve the manufacturing procedure.

NEW DESIGN CONCEPT AND PROTOTYPING

The new septum blade is required to be compatible with existing equipment, it shall also provide enhanced robustness for an increased amount of operational cycles. Therefore, design challenges include the optimization of the cooling circuit without increasing the overall conductor dimensions while avoiding early fatigue in the fragile areas. A Design based on the manufacturing orientated approach was used, allowing for cost reduction during prototyping and final manufacturing.

Brazed Sample Study

Brazed samples were manufactured and tested to verify the leak-tight properties of the brazed joints (Fig. 2). All Cu-SS joints were brazed with Pd287 (Ag86 Cu27 Pd5) at 850 °C. All Cu-Cu joints with Ag272 (Ag72 Cu28) at 780°C under a vacuum of approximately 10^{-6} mbar. Stainless steel parts were coated with Ni prior to brazing to improve adhesion [2]. The sequence of the three brazing cycles is different per sample. The following observations were made:

- Extensive alloying is observed in the brazing layer with the copper base metal in sample A. Although less severe, cavities that formed due to diffusion of the Brazing Filler Metal (BFM) into the copper base metal, are comparable to the cavities observed in the third generation septum blade. Alloying of the BFM occurred during re-brazing of the sample in the third cycle.
- The brazed socket joints contain less cavities in the brazing layer than brazed lap joints.
- The brazing layer is better distributed in the socket joint if the BFM is placed above the joint during the vacuum brazing process, instead of in a groove below the joint.

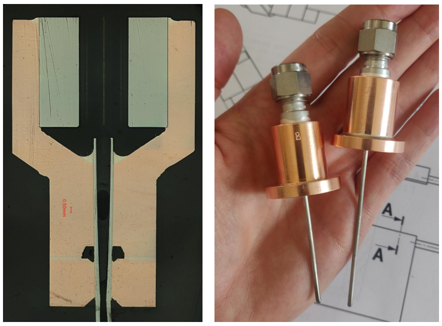

Figure 2: Left: optical microscopy by the CERN internal microscopy service of a brazed sample. Right: photograph of two samples.

Concept Design

Four concepts of the connection between the cooling supply and internal cooling circuit were developed with the knowledge obtained from the sample study. Differences between the concepts are given by the orientation and placement of the inlet and outlet. Concept 1 and 2 contain a separate copper block with compression tube fittings brazed on the conductor in a 45° angle for accessibility. The tube shall be bent 45° and brazed with a socket joint into the copper block. Concept 3 contains hose clamps and concept 4 is machined from one solid block of copper. Structural and hydraulic properties of each concept are shown in Table 2.

Table 2: FEA and CFD Computation During Operational Conditions of Four Different Concepts [5]

Parameter	**Unit**	**1**	**2**	**3**	**4**
Maximum stress	MPa	33	57	35	56
Maximum deformation	μm	35	33	37	85
Static water pressure	bar	2,4	12,7	4	3,9
Dynamic water pressure	bar	0,5	0,7	0,3	0,4

Concept 1 has been selected to be further detailed. Numerical computation has shown that it has good hydraulic and structural properties in addition to improved manufacturability and accessibility [1].

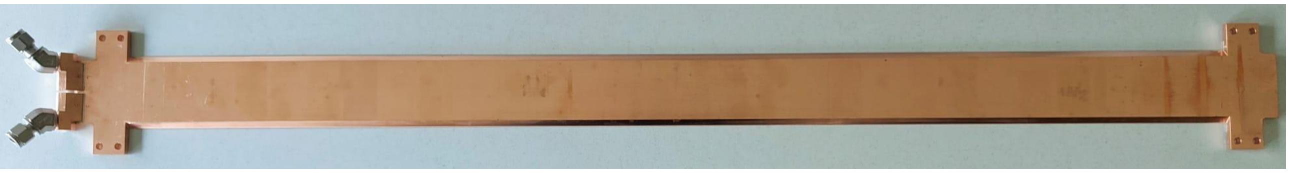

Figure 3: Photograph of the full length fourth generation septum blade (approximately 1000 mm long and weighs 2.1 kg).

Detailed Design

A 1:1 scale prototype of the critical area was manufactured and brazed to test the leak-tight properties and learn from the manufacturing procedure (Fig.4). The prototype has proved to be leak tight with a static pressure test at 50 bar for one hour.

Several improvements have been implemented based on the prototype development. Amongst others these mainly includes the two-part cooling connector, as well as parallel and perpendicular surfaces to apply constraints during the vacuum brazing. In addition, degassing holes for brazing have been implemented together with an increased clearance between cooling channel and conductor.

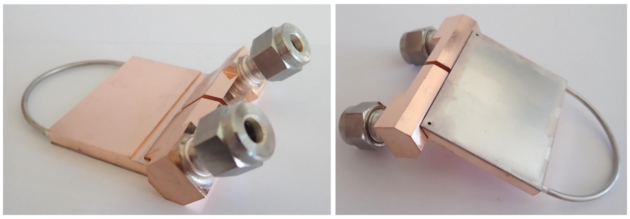

Figure 4: Photograph of the top and bottom side of the 1:1 scale prototype of the critical area.

RESULTS AND FINAL INTEGRATION

FEA computations have indicated a maximum material stress of 32 MPa when the vacuum chamber is pumped down to the UHV range and the magnet is pulsed at peak current (Fig. 5 and Table 3). This value is expected to be well below the fatigue limit when subjected to millions of cycles.

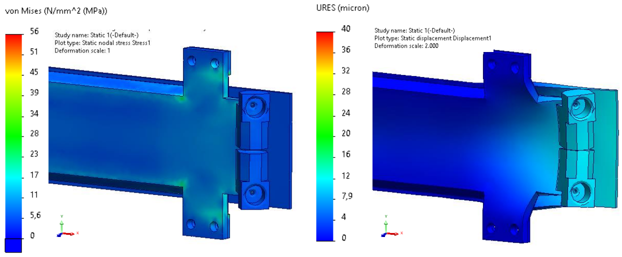

Figure 5: FEA computations. Left: material stress, Right: exaggerated deformation (scale x2000).

The highest fluid velocity and dynamic pressure are expected in the transition between the inlet and the cooling channel (Figure 5 and Table 3). An improvement to decrease the risk of internal abrasion is that high velocity areas are located inside the stainless steel cooling channel, instead of inside the softer copper parts.

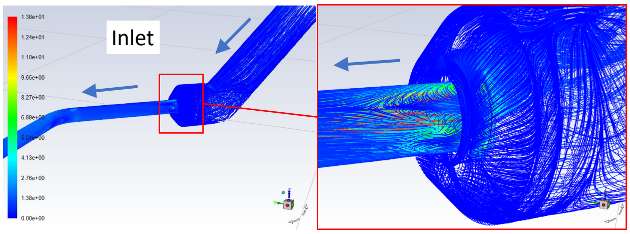

Figure 6: CFD computation of the maximum velocity in the transition area of the inlet and cooling channel.
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Table 3: Computation Results of the 1st Generation, 3rd Generation and the New Generation Septum Blade [5]

Parameter	**Unit**	**1st**	**3rd**	**New**
Max stress	MPa	95	18	32
Max deformation	µm	17	12	33
Max velocity	$\mathrm{m\,s^{-1}}$	17	32	13.8
Static water pressure	bar	4	28	4
Dynamic water pressure	bar	0.4	4	0.5

Two full length septum blades have been manufactured, and were tested to be leak-tight with a water pressure test at 50 bar for one hour. The septum blade has been installed on the SMH40 in April 2023 (Fig. 3).

CONCLUSION

The redesign and manufacturing of a new septum blade for the SMH40 has been successfully carried out. This was required since previous designs have shown non-conformities, mainly induced by material fatigue, resulting in leakages. The work required a functional and failure analysis of all previous septum blade generations. The new design has been optimized with respect to the mechanical robustness and in view of the required vacuum brazing process. The optimization of the cooling channel has been carried out using CFD. A short 1:1 prototype has proven the required leak rate and allowed to define the manufacturing procedures, including quality assurance and inspection plan. Two full length septum blades have subsequently been manufactured, and the SMH40 magnet equipped with the new system. The final commissioning is currently ongoing.

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