Multi-design Innovative Cooling Research & Optimization (MICRO): a novel proposal for enhanced heat transfer in DEMO

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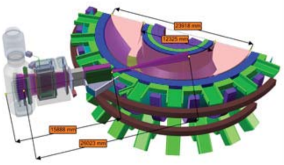
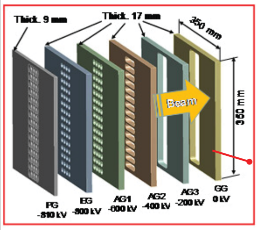
INTRODUCTION

The project, called Multi-design Innovative Cooling Research & Optimization (MICRO), aims, on one hand, to verify the present solution applied inside the MITICA experiment and, on the other, to perform further improvements in the heat transfer process with an acceptable pressure drop and reliable manufacturing process.

A comprehensive parametric investigation has been carried out with the goal of comparing various design options and establishing a standard approach to apply in several devices, characterized by comparable heat loads both in terms of spatial distribution and amplitude. The main advantages rely on the possibility to extend the fatigue life-cycle of different high thermal stress components and to investigate the possibility to employ alternative dielectric fluids instead of water.

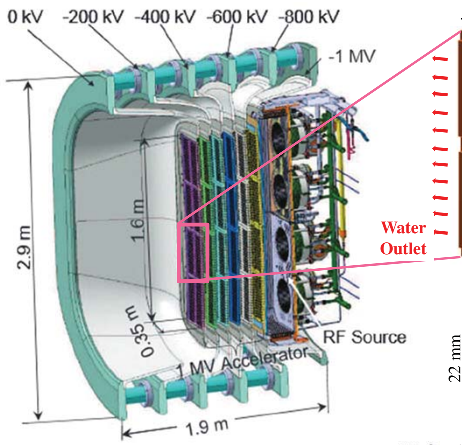


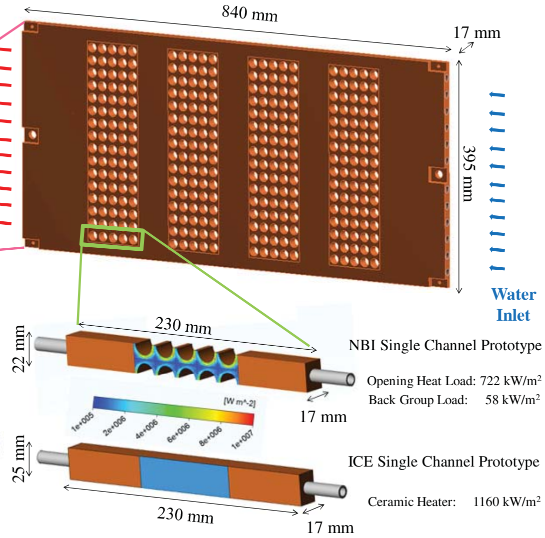


Such design solutions would in fact allow the exploitation of less performing fluids in terms of cooling capability. Despite the unavoidable deterioration of the cooling performances such approach would represent a significantly advantageous option with respect to the existing ultra-pure water technologies. This is particularly relevant in view of DEMO and future power plants characterized by higher efficiency and reliability.

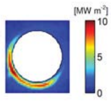
Conceptual CAD of DEMO NBI and under evaluating grids concepts (circular apertures, vertical and horizontal slots, large window)

DESIGN OVERVIEW





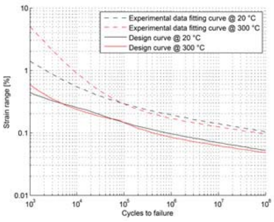
The spatial load distribution is a crucial element for the definition of high performing cooling system design. The focus is now on one of the most challenging cases: the **beam halo loads**.



Design of the MITICA beam source. A focused view of the overall accelerating grid is shown on the left, while graphical representation of the single channel prototypes (SCP) in NBI and ICE configurations are visible below. On the bottom left a spatial estimation of the heat flux taken in input.

OBJECTIVES

The main driver for the fatigue life is the different thermal expansion along the grid, leading to a sharp concentration of **stress** and **strain** between the aperture area (heated by particle) and the frame area (not heated). The goal is to **lower the temperature gradients** to the maximum reasonable extent.



Fatigue verification of electrodeposited copper used for the grids. Strain range must be below 0.169% to perform 50000 beam on/off cycles.

CONSTRAINTS

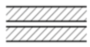
- **Pressure drop:** SCPs should not exceed a Δp greater than **1.8 bar** (6 bar in segment model).
- **Thermo-Mechanical properties:** peak temperature as low as possible and in any case lower than **300°C**.
- **Structural requirements:** minimum gap of **1.5 mm** (channel walls-heated surface) and **1 mm** (cavity or external boundary).
- **Vibration and Erosion:** water velocity limit on channel walls precautionary set **15 m/s**.
- **Geometrical constrain:** presence of a **6.4 x 4.4 mm** cavity hosting the SESM magnets
- **Technological limit:** required penetration depth (7 mm) limit the mill minimum diameter to **1.2 mm**.

NOVEL ENHANCED PROPOSALS

After an extensive CAE campaign, ten innovative design have been considered of technical interest and worth to be manufactured as prototypes. The present MITICA cooling solution acted as the starting point for the development and optimization of the novel proposals. Two parallel guidelines have been followed: approaching the channel walls to the heat load footprint (thus **reducing the thermal conducting resistance**) and increasing the laminar heat transfer coefficient with the **introduction of turbulence**. These solutions can be categorized in four classes:

Option A represents the original cooling solution and the most suitable design to test the analytical correlations from literature.

A) Straight Channel

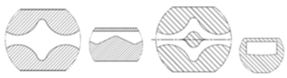


Option B1 is the solution applied inside the MITICA experiment, with a doubling channel in correspondence of the apertures

B1) NICE Channel

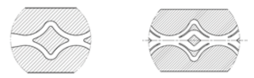
Option C1 and C2 propose a single channel where the increasing channel height is compensated by lowering its depth.

C1) Duned Channel *C2) Duned Drag Channel*



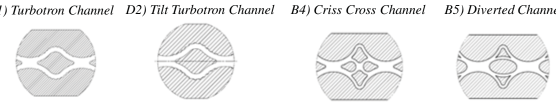
Options B2, B3, B4, B5 are characterized by an increased streamline curvature (overall bend amplitude is increased from 12 mm to 17 mm) in order to further enhance the coupling with the thermal loads. The cooling solutions differ in the design of the different sub-channels

B2) NICE Upgrade *B3) Baffle Channel*



Option D1 and D2 recall the present project solution with the introduction of 11 additional ribs acting as turbulent injector devices

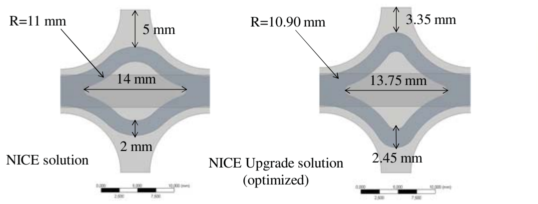
D1) Turbotron Channel *D2) Tilt Turbotron Channel* *B4) Criss Cross Channel* *B5) Diverted Channel*



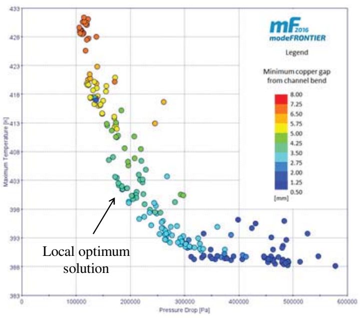
Details sections of SCP designs (ICE Configuration) along longitudinal plane representing a single cooling module contained between two virtual beam aperture region.

OPTIMIZATION STAGE

Once the basic features of the novel designs have been individuated, their geometries have been parameterized in order to perform the optimization of the channel shape aimed at improving the cooling performances while containing pressure drops, fluid velocity and channel topology within the given requirements.



The application of the optimization process to the present project design solution has led to a substantial decreasing of copper maximum temperature (143.48°C to 129.02°C) with a promising improving of fatigue life due to the minimization of temperature gradients.

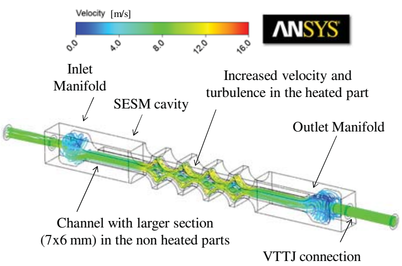


Schematic representation of NICE design pre and post optimization (left), bubble chart showing the pareto region in a Tmax -Δp plot (right).

RESULTS

The different proposals have been evaluated in steady state CFD simulations, assessed with sensitivity analyses and compared in term of fluid-dynamics characteristics. Particular attention was given to pressure drop, laminar velocity and cooling performances.

Design Solution	NBI Configuration			ICE Configuration		
	Δp [bar]	T_{max} [°C]	V_{wall} [m/s]	Δp [bar]	T_{max} [°C]	V_{wall} [m/s]
✓ Baffle Channel	1.83	120.86	16.68	1.76	61.75	16.43
Criss-Cross Channel	1.76	130.02	15.13	1.67	67.32	15.24
Diverted Channel	1.79	123.54	15.51	1.68	62.95	15.82
✓ Duned Channel	1.56	131.96	14.04	1.49	68.59	13.57
Duned Drag Channel	1.78	126.44	13.66	1.70	64.89	12.95
✓ NICE Channel	1.29	143.48	12.60	1.22	73.83	12.57
NICE Upgrade	1.78	129.02	15.06	1.68	66.78	15.47
Turbotron Channel	1.72	134.91	15.52	1.64	69.48	14.86
Tilt Turbotron Channel	1.70	133.64	14.67	1.59	68.83	14.42
✓ Straight Channel	0.92	178.31	9.29	0.85	84.58	9.14

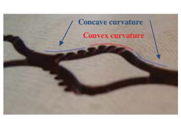


Legend:
- ✓ Present Project Design
- ✓ Best Thermal Behaviour
- ✓ Best Hydraulic Behaviour
- ✓ Best Coupled Thermal-Hydraulic Behaviour

Effect of Baffle design on water turbulence and schematic description of SCP concept (above) and table with results obtained with CFD simulations

MANUFACTURING

The different SCP prototypes have been manufactured in a single copper slab. All the designs have been realized with high accuracy during the milling operations, demonstrating the technological reliability of the manufacturing process. The realization of the inclined ribs was the only issue due to the employment of a 3-shaft milling rather than a 5-shafts one. The different channel wall curvature encountered by the mill while penetrating the material did not allow the tool to accomplish the design realized on the CAD. The ribs were then eventually realized just in those regions characterized by a curvature that did not turn from concave to convex along milling direction.



SCP copper slab (right) and detailed view of the inclined ribs in Tilt Turbotron concept (left)