CFD studies for the n_TOF Target #3

PRR

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Outline

• CFD Studies overview
• Key setup considerations
• N2 Cooling circuit optimized design
• Final design cooling performance
• Moderators flow
• Conclusions
CFD Studies overview

Study objectives

• Estimate the cooling performance of the nitrogen circuit;

• Design and optimize the nitrogen cooling circuit;

• Input to the design of the cooling station;

• Input to the Thermo-mechanical analyses.

Heat Transfer Coefficient

Pressure drop

Nitrogen volume

Lead slices
CFD Studies overview

- Design and optimize the nitrogen cooling circuit

I. Preliminary analytical estimation of nitrogen flow between plates of nitrogen;

II. Preliminary CFD simulation comprising only lead slices, and a simplified nitrogen volume of channels with no anti-creep plate.

III. Multiple simulations to analyse and optimize the configuration of inlets and outlets; No anti-creep modelled.

IV. Wet are sensitivity study and definition of baseline anti-creep plate;

V. Sensitivity studies and optimization of anti-creep plates and cradle geometries;

VI. Final design mesh studies and analytical estimation;
Key setup considerations

Lead slices
- Allowed heat flux on the exposed “wet area” surfaces – direct contact with nitrogen;
- Remaining surfaces adiabatic.
  - Surfaces in contact with the cradle, stiffeners and anti-creep plates.

Nitrogen volume
- Smooth no-slip wall (zero wall velocity) with allowed heat flux on the exposed “wet area” surfaces – direct contact with lead.
- Remaining surfaces adiabatic, smooth no-slip walls.
  - Inlet and outlet tubes, cradle ducts and vertical grooves, anti-creep plates and vessel walls.
Key setup considerations

Setup

• Steady-State
  • Prescribed mass flow and outlet absolute pressure;
  • $S$ FLUKA energy deposition @ $1.66e12p^+/s$. 15mm $\sigma$
• Shear-Stress-Transport (SST) turbulence model with near wall treatment for low-Reynolds

*Transient beam analyzed in R. Esposito´s presentation*
N2 Cooling circuit optimized design

Inlets

CFD Studies overview | Key setup considerations | N2 Cooling circuit optimized design | Final design cooling performance | Moderators flow | Conclusions
N2 Cooling circuit optimized design

Cradle

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N2 Cooling circuit optimized design

Anti-creep plate

Obstruction rib
Gap
Rib

N2 Velocity
89.5
80.6
71.6
62.7
53.7
44.8
35.8
26.9
17.9
9.0
0.0
[m s⁻¹]

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N2 Cooling circuit optimized design

Outlets
Final design cooling performance

Representative cases:
A. 800 Nm3/h; Outlet pressure = 7650 Pa.
B. 1000 Nm3/h; Outlet pressure = 11000 Pa.
C. Creep scenario with flow = Case A.
C.+ Case C with extra creep

Creep studies indicate 0.64mm after two target life-times of operation

(R. Esposito)
Final design cooling performance

Lead temperatures

- Slice 2 & 6 with higher temperatures for all cases. <100°C @ steady-state for normal operation.
- Creep may raise SS temperature by 25% in slice 2.

![Graph showing lead temperatures]
Final design cooling performance

Lead temperatures

- Cradle & anti-creep designed to channel most of the flow to the beam “hot spot”.

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High flow speed in obstruction ribs passage
Flow velocity increased due to fluid separation
High flow speed in cradle ducts
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![CFD study results showing lead temperatures and flow velocity](image)

- Peak surface temperature
- Average velocity profile

Final design cooling performance

Lead temperatures – HTC’s Analytical estimation

- Coherent with the CFD results: 12% to 29% higher HTCs

(Gnielinski correlation)
Final design cooling performance

Target pressure drop

- Between 4.7 and 7.0kPa. 6% increase in case C+.
- Coherent with analytical results. E.g. Case B:

<table>
<thead>
<tr>
<th>Flow [Nm³/s]</th>
<th>Pressure drop [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>800</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
</tr>
<tr>
<td>C</td>
<td>795</td>
</tr>
<tr>
<td>C+</td>
<td>796</td>
</tr>
</tbody>
</table>

(Loss coefficient method: PKN, ASHRAE & I.E.Idelchik coefficients)
Final design cooling performance

Higher speed locations of nitrogen – E.g. case B

- 87 m/s
- 13-40 m/s
- 65 m/s
- 90 m/s
Moderators flow

Brief assessment of stagnated flow in the moderators

- No critical locations with stagnated water found.
- Energy eq. not modeled -> Actual buoyancy currents might mitigate further stagnated flow

Horizonal Moderator (Steady state)

Vertical Moderator (Steady state)
Conclusions

N2 Cooling circuit – CFD studies
► CFD studies made in parallel with Mechanical Design of the target, thermo-mechanical studies & development of the Cooling station. -> Constant feedback and collaboration;
► Extensive CFD-based design-optimization successfully done. Focused on inlet/outlet configuration, cradle and anti-creeep plates design:
  ► Steady-state temperatures below 90°C in lead (15mm σ & 1.66e12p⁺/s);
  ► Pressure drop between 4.7 and 7.0kPa.
  ► N2 Velocities along the “beam spot” < 40m/s. Specific locations with velocities less than 90m/s;
► Conservative creep degraded scenario done: +25% max temperature & +6% pressure drop;
► Analytical estimations coherent with CFD results.

Moderators circuits – CFD studies
► No stagnated water expected to occur.
Thank you!
Backup
Target Consolidation

- Current target(#2):
  - Single core of pure Lead;
  - Water cooled;
  - Presents issues regarding corrosion/contamination.

- Upgrade target design
  - +operation reliability
  - no corrosion/contamination
  - Avoid cladding solutions

- Solution: N2(gas) cooled design with sliced core.
  - +new cooling station
Target Consolidation

Constrains & Requirements for the N2(gas) cooled design:

- Key requirements
  - Identical or better physics performance (1.66e12 p/s, 15mm σ);
  - Average (Steady-state) temperature in the Lead below 100°C;
  - Cooling circuit compatible with some sort of anti-creep structure;
  - Integration: Target is confined to a very limited space/”pool”.

- Cooling specs/constrains:
  - Gas cooled (N2), to avoid corrosion/contamination risks;
  - Supply at 20°C, to avoid external condensation;
  - ~Atmospheric pressure;
  - Flow 700-1000 Nm³/h.
  - Pressure Drop as low as possible.

Limited due to re-use of existing pipes to the pit & to comply with target vessel.
Computational Fluid Dynamics

**Numerical method to analyze fluid flows 😊**

- Short summary of the process:
  - Define our Fluid Geometry/volume & solid Domains(if CHT);
  - Discretized the domain(mesh);
  - Setup physics: Properties, models, boundary conditions, flow conditions;
  - Run simulation;
  - Analyze and post process results.

- CFD gives us the possibility to explore and comprehensively understand fluid flows.

Essential if we want to optimize it!
Brief design overview

- Lead core
  - 6 lead slices
  - Spaced 10mm

![Diagram of lead core design with dimensions: 600 mm Channel, 150 mm, 50 mm, and 600 mm.](image)
Brief design overview

- Cradle (Al)
  - Has two inlets for the cooling
  - Distributes the N2 through the channels between lead slices.
Brief design overview

- Stiffeners (Al)
  - To hold the lead in place together with the cradle
  - No fluid passage on the sides
Brief design overview

- N2 passes in between each lead slice and on the downstream face (6 channels with forced convection)
Brief design overview

- Anti-creep plates (Al)
  - Provide anti-creep structure
  - & shape of the cooling channels
  - One per channel and on the upstream and downstream faces
Brief design overview

- Tie rods and screws to hold lead slices, anti-creeep plates, stiffeners and cradle together.

Diagram showing:
- Anti-creeep plates
- Tie rods
- Stiffeners
- Cradle
- N2
Brief design overview

- Vessel (INOX)
- Cradle fixed to the vessel with tie rods
- 2 inlets & 2 outlets

N2 cooling circuit optimized design

Final design cooling performance

Moderators flow

Conclusions
Brief design overview

Moderators cooling circuit

N2 Pipes
CFD design iterations: outlets/inlets position

- Iterations to define inlets/outlets:
  - Minimize pressure drop
  - Distribute homogeneously flow amongst cooling channels.

Flow separation

Where? how many?
Dimensions?

Less 30% pressure drop with optimized configuration
CFD design iterations: Align flow with beam axis

- Iterations to direct the N2 flow into the beam axis:
  - Enhance cooling

Obstruction of the moderator + tilted beam

Max mass Flow/Velocity not aligned with beam/hottest surface locations.

Top view temperature distribution at beam height.

Top view of channels velocity at beam height. (No anti-creep).

Face view of downstream channel velocity. (No anti-creep).
CFD design iterations: Align flow with beam axis

- Iterations to direct the N2 flow into the beam axis:
  - Enhance cooling

Meanwhile, Vertical moderator enlarged and outlets readjusted

Flow still not aligned after introduction of a multi channel anti-creep plate.
CFD design iterations: Align flow with beam axis

- Iterations to direct the N2 flow into the beam axis:
  - Enhance cooling

Increased space for flow at the end of the channels
Deflector aligned with beam direction
Maximum temperature reduced by 13%
CFD design iterations: Anti-creep optimization

- Iterations to optimize flow through anti-creep plates:
  - Enhance cooling

- Obstruction ribs to direct the flow to the beam axis
  - Defining gaps with ribs
  - Vertical position in the channels
  - Shape
  - Length
  - Width
  - Gaps

Aim to increase the cooling in beam region

Top view scheme

Obstruction rib

N2 in Gaps is not connected

N2 in Gaps is connected

10 mm
CFD study process

1) Preliminary analytical calculations showed cooling with N2 is possible *(Francesco Dragoni)*;

\[
T_{N2,in} + \frac{q_{in} + q_{sys}}{\rho c_p N_2} \leq \max T_{W,1,2} = T_{N2,ext} + \frac{q_{N2}}{\dot{n}_{in} a^2}
\]

2) CHT (Solid Thermal + CFD) Steady-state (SS) simulations, considering only the channels with no anti-creep plate reinforced the possibility of N2 cooling;

3) CHT SS studies focusing on optimizing outlets configuration and cradle flow distribution path;

4) Wet area sensitivity simulations;

- IEDR.
CFD study process

5) Baseline anti-creep structure was considered in the simulations;

6) Multiple sensitivity simulations were done to understand possible optimization parameters;

7) New anti-creep concept based on learnings + further optimization of ac & cradle;

8) Integration/definition of pipes outside the target vessel;

9) Transient studies;

10) Final analytical + simulation setup validation/verification.