THERMO MECHANICAL STUDY OF THE ESS DTL

P. Mereu*, M. Mezzano, C. Mingioni, M. Nenni, INFN, Torino, Italy
F. Grespan, A. Palmieri, A. Pisent, INFN-LNL, Legnaro, Padova, Italy

Abstract

The Drift Tube Linac (DTL) of the European Spallation Source (ESS) is designed to operate at 352.2 MHz with a duty cycle of 4% (3 ms pulse length, 14 Hz repetition period) and will accelerate a proton beam of 62.5 mA pulse peak current from 3.62 to 90 MeV.
In this paper the main issues regarding the thermo-mechanical 3D details of the DTL are addressed and a Computational Fluid Dynamics (CFD) model is proposed and validated against experimental data. The results of these simulations are used to properly design the DTL cooling system.

DTL DESIGN

In the ESS accelerator the initial warm linac section is composed by Ion Source, Low Energy Beam Transport line (LEBT), Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport line (MEBT) and DTL. INFN-LNL is in charge of the design and production of the DTL.

The DTL is a 38.8 m long system, divided in five tanks; each tank is a stand alone structure, composed of four 2 m long modules made of AISI 304L stainless steel with internal electro-copper deposition. The Drift Tubes are positioned in the girder, a precisely machined alluminum alloy structure, which is housed in the upper part of each module [1].

DRIFT TUBE CFD MODEL

The Drift Tubes (DTs) are made by a Cu-OFE body and an AISI 304L Cu-plated stem. The DTL comprises 4 types of DT, depending on the components inside the body: Permanent Magnet Quadrupole (DT-PMQ), Beam Position Monitor (DT-BPM), ElectroMagnetic Dipole (DT-EMD), Empty body. The internal layout of a DT-PMQ is shown in Figure 1. Each DT is cooled by water at 30 °C. The water enters the stem through a G1/4" fitting, flow down into the gap between stem and mid-pipe, goes around in the gap between DT body and mid-pipe, flows trough the holes on the bottom, flows back into the separation cylinder-sleeve gap and finally goes into the internal pipe up to the outlet G1/4" fitting. The BPM and EMD DT has a slightly different solution since there are electrical cables passing through the stem; in those cases the inner pipe contains cables and the water return path is in the gap between mid and inner pipe.

Experimental Tests

Prototypes of DT-PMQ and DT-BPM, both machined at INFN-TO mechanical workshop and assembled by vacuum brazing at INFN-LNL, were tested at INFN-TO in order to measure the hydraulic characteristic in terms of pressure drop vs flow rate. The test bench included 2 pressure transducer upstream and downstream the DT mock-up, a flow meter on the supply and a series of regulating valve. Connection between DT and pressure transducers was made by an 8 mm diameter pipe 0.5 m long on both sides. Measures were taken also on a single duct section 0.5 m long to exclude from dataset the contribution of connecting pipes. For each configuration the pressure drop was measured at 9 values of flow rate spanning from 4.5 to 8 l/min.

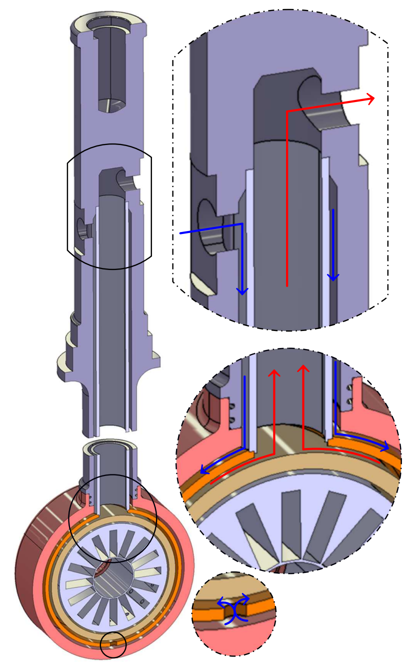

Figure 1: Internal layout of a DT-PMQ with water distribution.

Computational Model

The computational domain of the CFD model includes the fluid volume inside the DT and 80 mm of pipe on both inlet and outlet. A 10 M-cells mesh gives grid independent results on pressure drop at nominal flow of 5.7 l/min, as checked by a Richardson-Roache [2] extrapolation on grids of 5 M, 10 M and 16 M cells size.
Computations were performed for the DT-PMQ using ANSYS Fluent solver and the k-ϵ *RNG* turbulence model, at flow rates between 4 l/min and 8 l/min. Results of computations are shown in Figure 2.

SKID DESIGN

A simplified scheme of the DTL cooling system (SKID) is shown in Figure 3. The SKID, of 4 m × 5 m maximum footprint with height of 4 m, will produce water at 30 °C for

* paolo.mereu@to.infn.it

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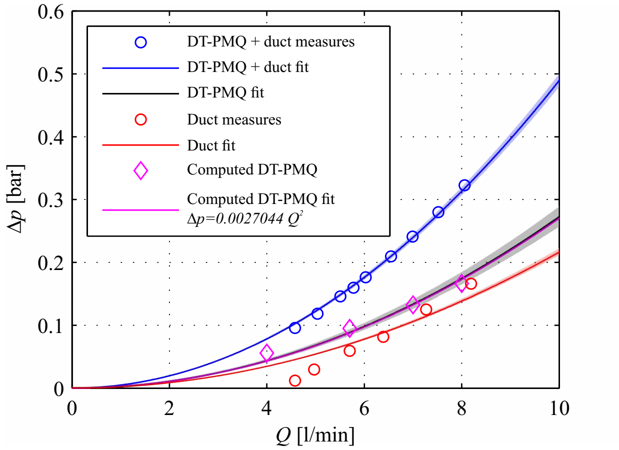

Figure 2: Experimental measures, CFD simulations and corresponding best fits.

the 5 Tanks with the only purpose of DTL cooling, without a feedback for resonance frequency regulation.

The heat removed from RF structures is transferred to facility chilled water, with design temperature of 25 °C, in a water/water plate heat-exchanger; from the distribution manifold there are 5 different secondary loops, each one with a automatic flow regulation valve and a three-way valve for supply temperature regulation. Another distribution manifold, one for each tank and located above the DTL in the accelerator tunnel, provides the cooling lines for every RF structure, including: Tank walls and covers, Tuners, Post-Couplers (PCs) and Drift Tubes. From return manifold the main line goes into a mixing tank and again in the plate exchanger. An independent purification loop, including a dedicated pump and ion bed resin filters, take a maximum of 3% of nominal flow from the mixing tank. Every utility has a dedicated valve which keeps the flow constant to design value, while temperature control is done at Tank level with a mixing three-way valve.

In Table 1 is shown an estimation of the thermal loads for the DTL. Thermal loads Φ on RF utilities consider a 5% duty cycle, while the flow estimation Q is done imposing the velocity in channel section. The velocity is fixed to 1 m/s in Tank channels, a mean value of 3.5 m/s in Drift Tubes and 3 m/s in RF flange PCs, Tuners and Covers inlet. Both thermal loads and cooling flows were precautionary increased of 25%.

Table 1: DTL Heat Loads and Cooling Flow

Tank	$\Phi[kW]$	$Q[m^3/h]$
1	60.38	64.74
2	59.70	50.85
3	63.38	50.49
4	62.22	47.71
5	66.39	44.93
Tot.	311.07	258.72

Table 2 summarizes the pumps dimensioning parameters. The prevalence estimation H is done considering the longest utility line, which corresponds to Tank 4 wall channels. It was considered both continuous and localized pressure drop.

Table 2: SKID Pumps Dimensioning

Pump	N.	$Q[m^3/h]$	$H[m]$
Main	1	270	20
Secondary	5	72	41
Purification	1	8	10

RF-THERMOMECHANICAL ANALYSIS

The work aims to evaluate the frequency loss due to thermal deformations in the first and last cell of ESS-DTL using an integrated two way coupled ANSYS HFSS/Mechanical analysis in Workbench environment, validating results through a benchmark with COMSOL Multiphysics [3]. A correlation between frequency loss Δf along Tank 1 and DT convective heat exchange coefficient h_{DT} was then investigated. In the following, Tank convective coefficient h_T was supposed constant.

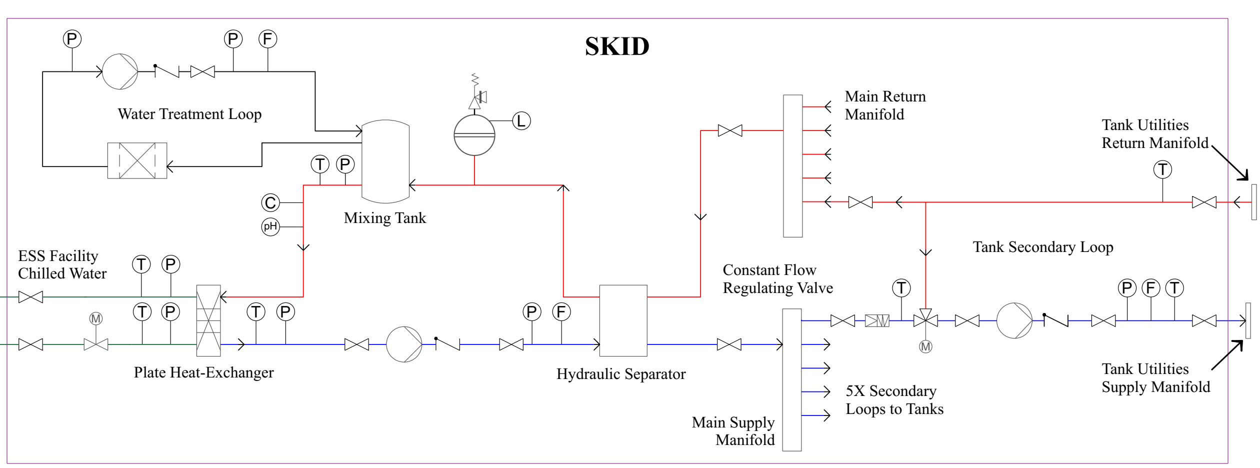

Figure 3: Functional scheme of the SKID proposed.

Table 3: Simulations Results ANSYS vs. COMSOL

	ANSYS			
	$f_1[MHz]$	$f_2[MHz]$	$\Delta f[kHz]$	$\Delta l[\mu m]$
T1C1	348.625	348.61	15	0.8
T5C22	348.018	347.984	34	13.5
	COMSOL			
	$f_1[MHz]$	$f_2[MHz]$	$\Delta f[kHz]$	$\Delta l[\mu m]$
T1C1	347.489	347.476	13	0.7
T5C22	347.852	347.813	39	15.5

ANSYS HFSS/Mechanical Coupled Analysis

The EM field of both first (T1C1) and last (T5C22) cell of the ESS-DTL and their eigenfrequency was evaluated in HFSS. The resulting thermal load was then imported in a coupled static thermo-mechanical ANSYS Mechanical simulation in order to evaluate both temperature and deformation distributions along the beam axis Δl.

The h_{DT} and h_T were estimated in 8000 W/m^2/K using the Dittus-Boelter correlation, assuming a constant 1.25 m/s stem velocity (corresponding to a 4 m/s inlet velocity). The deformation field obtained was then used as a boundary condition for the RF simulation in order to evaluate the deformed cell eigenfrequency (*Loop simulation*). The difference between undeformed and deformed cell represents the frequency loss due to EM induced thermal load. The obtained results were then validated against similar COMSOL Multiphysics simulations (Table 3).

$h - \Delta f$ Modulation

A *Loop simulation* was performed on first (T1C1) and last (T1C60) cell of Tank 1 in order to point out the frequency loss modulation against h_{DT}.

Two cooling configurations were considered: one with constant h_{DT} on both first and last cell and one with first cell less cooled than last cell; h_T was kept constant in both simulations to focus the attention only on h_{DT} influence on frequency loss. In Table 4 results are presented.

Table 4: $h - \Delta f$ Modulation Results

	T1C1	T1C60	T1C1	T1C60
h_{DT} $[\frac{W}{m^2K}]$	8000	8000	4000	10000
h_T $[\frac{W}{m^2K}]$	8000	8000	8000	8000
f_1 $[MHz]$	348.625	347.804	348.625	347.804
f_2 $[MHz]$	348.610	347.771	348.604	347.774
Δf $[kHz]$	15	33	21	30
$\Delta f_{(T1)}$ $[kHz]$	18		9	
$\dot{m}_{DT}$ $[l/min]$	7.9	7.9	3.3	10.5

The frequency loss from the first configuration to the second ($h_{lastDT} > h_{firstDT}$) is halved, so the variation from first to last cell is smoother, giving a more uniform EM field [4]. An indication of the DT inlet mass flow, corresponding to the h_{DT} used in the simulations, was obtained using again the Dittus-Boelter correlation (Equation 1) considering the geometrical factor $GF = \frac{A_{stem}}{A_{inlet}}$ which correlate inlet to stem velocity. The mass flow modulation leads to an almost constant frequency loss along Tank 1.

$$\dot{m} = GF \frac{\mu A_{inlet}}{D_{stem}} \left(\frac{h D_{stem}}{0.023\, k\, Pr^{0.4}} \right)^{\frac{5}{4}} \qquad \left[\frac{kg}{s} \right] \tag{1}$$

where A is the section area and D the hydraulic diameter; the $stem$ and $inlet$ subscripts refer respectively to stem supply and DT inlet cross-sections.

CONCLUSION

This paper covers three different topics inherent the DTL cooling. First, a CFD model was developed, in order to correlate the cooling flow on a Drift Tube to the corresponding pressure drop, and it was validated against experimental data on DT prototypes. Starting from CFD analysis, a parametric model is under development for a quick evaluation of pressure drop in different Drift Tubes cooling geometries.

The next part of the article covers the SKID system dimensioning. An estimation of the thermal loads and cooling flows was made in each Tank, while pumps prevalence was evaluated considering the maximum pressure drop in the entire DTL.

Finally, a coupled RF/thermo-mechanical analysis on the first and last cell in the entire DTL was performed, in order to evaluate a retro-feedback of the deformations distribution and so the consequent changes in the eigenfrequency. Results were then validated with a COMSOL-ANSYS benchmark. The two simulation codes produce almost the same output, thus validating the analysis. Finally, the influence of the convective thermal coefficient h on the cell eigenfrequency was investigated: applying different values of h on the first and last cell of the 1st Tank, it can be seen that the variation in frequency is smoother compared to a constant h configuration.

Concluding, the described work will be used for a better calibration of every RF utility, in order to ensure an optimal cooling flow and thus approach better the design operating frequency.

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