Analytical and numerical assessment of thermally induced pressure waves in the IFMIF-DONES liquid-lithium target

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Analytical and numerical assessment of thermally induced pressure waves in the IFMIF-DONES liquid-lithium target.

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***Abstract*— The intended steady-state operation conditions of the IFMIF-DONES target system are based on the D+ beam stationary running at full nominal power (5 MW). Nevertheless, critical situations can occur in case of unavoidable sudden events like beam trips. The instantaneous variation in the heating power deposited in the lithium when the beam is rapidly switched between-on and -off states leads to the thermal expansion, which is compensated by the compression of the target material, resulting in locally high pressures and a pressure wave propagating through the target towards the back wall. Besides tensile stress of the back wall structure caused by shock pressure waves, undesirable cavitation may occur, when pressure waves are reflected leading to negative pressures.**

For this purpose, analytical and numerical thermo-hydraulic analyses of the effects generated in the lithium during the beam-on/beam-off switches are performed. The pressure wave development inside the Li- target has been analysed numerically with the CFD code Star-CCM+. The simulation of the thermal induced pressure in the Li-target shows that for normal operation conditions peak pressures of about 0,3 MPa can be reached. In both “beam-on” and “beam-off” cases a zone with a negative static pressure flow is forming in the Li-target. The results obtained from analytical and numerical analyses of the thermally induced pressure waves are discussed concerning potential cavitation and stability of the lithium free-surface flow. Simulation results served as input for the analysis of fatigue effects occurring in the target structure during sudden beam-on/beam-off events.

***Index Terms*—IFMIF-DONES, Lithium Target, Pressure waves, CFD**

I. Introduction

In the projected IFMIF-DONES (International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source) [1] a neutron flux with a broad energy distribution covering the typical neutron spectrum of a (D-T) fusion reactor will be generated. This is achieved by utilizing Li(d,xn) nuclear reactions taking place in a liquid lithium (Li) target when bombarded by a deuteron beam with a beam footprint between 200 mm × 50 mm and, optionally, 100 mm × 50 mm. The energy of the deuterons (40 MeV) and the current of the accelerator (125 mA) have been tuned to maximize the neutrons flux to get irradiation conditions comparable to those in the first wall of a fusion power reactor in a volume of around 0.5 l that can house around 1000 small specimens.

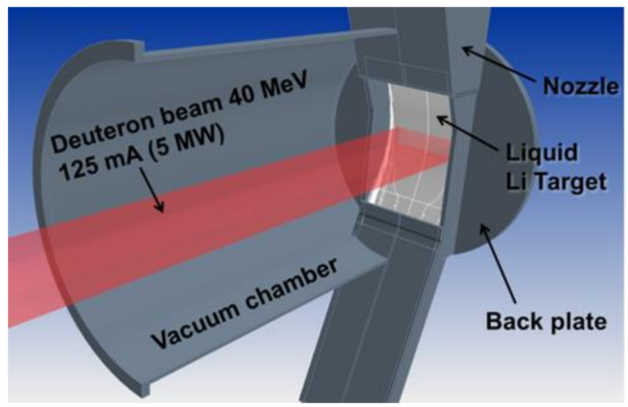

Fig. 1. Schematic view of the IFMIF-DONES target assembly

The intended steady-state operation conditions of the IFMIF-DONES target system are based on the deuteron beam stationary running at full nominal power (5 MW). Nevertheless, critical situations can occur in case of unavoidable sudden events like beam trips. Starting with steady-state operation conditions when the beam is suddenly cut off, the pressure inside the window region will significantly decrease due to the inertia of the liquid metal flow and the thermal relaxation due to the sudden cooling down. Once the flow field conforms to the beam-off conditions, the pressure will increase again when the beam starts. Heating power deposited in the lithium leads to the thermal expansion, which is compensated by the compression of the target material, resulting in locally high pressures and a pressure wave propagating through the target towards the back wall. Successively generated pressure waves may superimpose and accumulate resulting in critical deformation and stresses in the target structure. Besides tensile stress of the back wall structure, undesirable cavitation may occur when pressure waves are reflected leading to negative pressures.

For this purpose, analytical and numerical thermo-hydraulic

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analyses of the effects generated in the Li-target during the sudden beam-on/beam-off switches are performed.

II. Analytical assessment of thermally induced pressure wave during sudden beam-on conditions

This thermally induced positive pressure wave can be compared to the pressure wave resulting from the instantaneous closure of a valve in e.g. pipeline system [2]. During the constant heat deposition of the D^+ beam, the flow field will conform to the new conditions of the expanding liquid metal. At the switch off of the beam the thermal expansion of the lithium suddenly stops and the flow field which is conformed to the expansion rate of the liquid metal might lead to cavitation. This behaviour again is similar to water hammer phenomena of an instantaneously closing valve in e.g. pipeline systems. Water hammer phenomena can be analysed by the Rigid column theory. Rigid column theory ignores the compressibility of the fluid and the elasticity of the walls of the surrounding structure whereas a full analysis includes compressibility and elasticity. For instantaneous valve closure the pressure profile of the water hammer pulse can be approximated using the Joukowsky equation also known as the ‘‘fundamental equation of water hammer’’ [3]:

$$\partial p/\partial t=\rho\cdot c\cdot\partial v/\partial t \quad (1)$$

where p is the pressure, c is the speed of sound in the considered fluid, ρ the fluid density, v the fluid velocity and t is the time. Using rigid column theory the peak pressure for an instantaneously closing valve can be estimated using the following simplified Joukowsky equation:

$$\Delta p=\rho\cdot c\cdot\Delta v \quad (2)$$

where Δp is the magnitude of the pressure wave, and Δv is the change in velocity. In the following the simplified Joukowski equation for the peak pressure of an instantaneously closing valve is modified to estimate the peak pressure of the thermally induced pressure wave by the proton pulse. The velocity change Δv of the liquid metal is assumed to be the velocity of the thermal expansion of the liquid metal v_{exp}:

$$\Delta p=\rho\cdot c\ v_{exp} \quad (3)$$

To apply Eq. (3) it is necessary to determine the expansion velocity v_{exp} which represents the mean expansion velocity within the heated volume. v_{exp} can be estimated from mass conservation equation:

$$\partial\rho/\partial t+\nabla(\rho V) = 0 \quad (4)$$

Assuming the extension of Li in beam (x) direction the x-component of the expansion velocity is:

$$v_{exp} = (\beta\cdot\dot{q})/(\rho_0\cdot c_P) \quad (5)$$

Where β is the thermal volumetric expansion coefficient of the liquid metal, c_P is the isobaric specific heat and $\dot{q}$ is the spatial profile of the heat flux. For $\dot{q}$ = 500MW/m^2, c=5000m/s and ρ_0=510kg/m^2 the maximum peak pressure Δp=8.6x10^4 Pa. The evolution of the pressure wave in the target for different beam on/off situations is analysed and presented in the next section.

III. Numerical analysis.

A. Numerical methods and model description

The pressure wave development inside the Li-target has been analysed with a fluid-dynamic code Star-CCM+[4]. The unsteady process is modelled on the basis of compressible Euler equations with an additional source term $q(t, x, y, z)$ in the energy equation, responsible for the beam action. For this purpose the heating power distribution for IFMIF-EVEDA operation conditions [5] (two deuteron beams) is applied with the scale factor of 0.5.

In the simulation a Volume of Fluid method (VOF) [6] has been used to compute the Li/Ar-atmosphere interface. The surface tension is modelled using the continuum surface force model formulation by Brackbill et al. [7]. The potential cavitation in the liquid lithium is reproduced by the Rayleigh-Plesset model, which includes the influence of bubble growth acceleration, as well as viscous and surface tension effects:

$$R\frac{dv_r}{dt}+\frac{3}{2}v_r^2=\frac{p_s-p}{\rho_l}-\frac{2\sigma}{\rho_l R}-4\frac{\mu_l}{\rho_l R}v_r \quad (6)$$

where p_s is the saturation pressure for given temperature, p is the local pressure in the surrounding liquid, σ is the surface tension, ρ_l and μ_l are the density and dynamic viscosity of fluid respectively.

The Cartesian coordinate system x, y, z is used in calculations with the X-axis directed along the beam. As shown in figure only the half of the target flow with symmetrical conditions is modelled. The lithium flow is conditioned by a two-step nozzle, which is also included in the computational domain consisting of 4.5×10^6 fluid cells? (See Fig. 2).

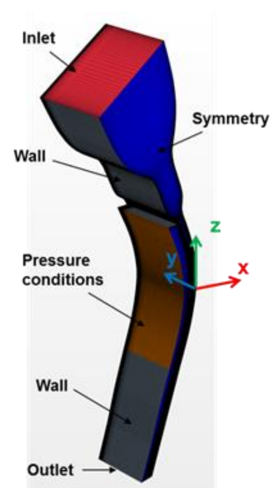

Fig. 2. Computational domain of the Li-target.

The mean inlet velocity is equal to 1.875 m/s, which corresponds to the mean nozzle outlet velocity of 15 m/s. The pressure applied to the pressure boundary conditions is of 10^{-3}

Pa. The simulation assumes a constant inlet temperature of 250◦C and the thermo-physical data have been taken from Ref. [8]. The no-slip condition is adopted on the wall. The elasticity of the target structure is not considered, so the wave fully reflects on the wall.

Maximum time step approximation for transient simulation resolving acoustic phenomena can be estimated as $\Delta t_{max}=\Delta x/c$, where c is a speed of sound in lithium (~5000 m/s) and Δx=0.2 mm is the minimum grid size. Since the beam is treated as being continuous, the minimum time step in simulations cannot fall below the time period between beam pulses $\Delta t_{min} > T=6\text{x}10^{-9}$ s. As an appropriate value of the time step in the simulations is determined $\Delta t=5\text{x}10^{-8}$ s.

B. *Simulation results*

As in the analytical assessment the first case analysed is the sudden switch-on of the beam energy. In Fig. 3 the resulting pressure development in the Li-target is depicted. Fig. 3(b) displays a maximum pressure of 0.325 MPa which is reached at 1.2 μs after the switch-on of the beam.

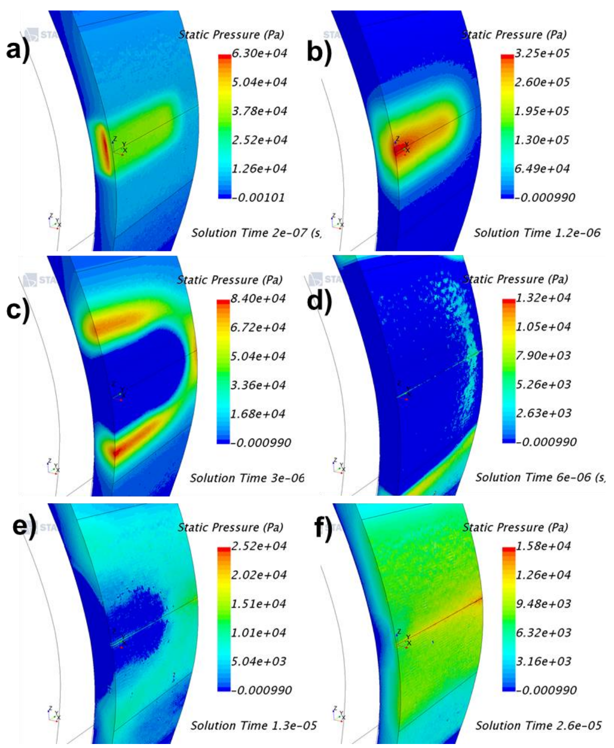

Fig. 3. Static pressure evolution in case of sudden switch-on of the beam.

During the next microseconds the high pressure zone spreads in all directions. This leads to the forming of negative pressure area in the full thickness of the lithium jet (Fig. 3(c)). As shown in diagram Fig. 4 the peak value of pressure wave decreases with the distance from the heating source. After about 30 μs the pressure distribution in the target is recovered (Fig. 3 (d)). The hydraulic characteristics of the lithium flow during this time are not affected from the pressure wave. The maximum value of detected velocity fluctuations caused by the pressure wave does not exceed 0.5% from the average lithium velocity of 15 m/s.

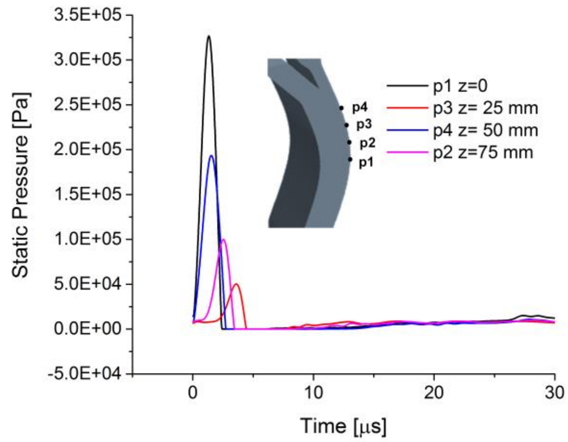

Fig. 4. Static pressure evolution in case of sudden switch-on of the beam. Diagram of static pressure as function of time measured on the back wall.

Figures 5 and 6 illustrate the next case with the sudden beam loss. Immediately after the switch-off of the beam the area with the negative pressure grows rapidly. The pressure recovery time is of about 30-35 μs.

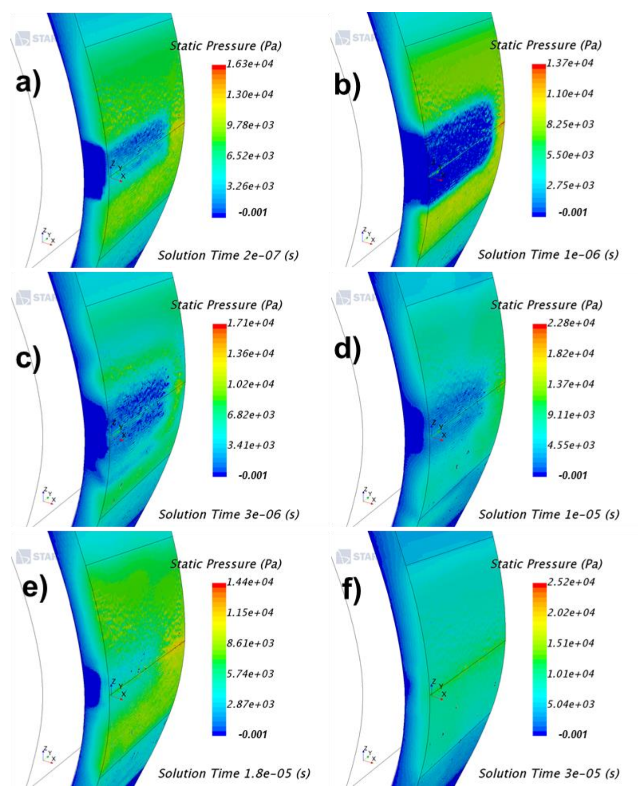

Fig. 5. Static pressure evolution in case of sudden beam loss.

In both "beam-on" and "beam-off" cases simulations detect no occurrence of cavitation in the zone with the negative pressure. The reason is a very low saturation pressure of liquid lithium. The Li-target operation temperatures vary between 250 and 300 °C. Assuming the absolute lithium purity the saturation pressure of lithium in this temperature range is of the order of 10^{-5}–10^{-4} Pa. In relation to the equation (6) to balance the force of growth of vapour bubbles with the minimum diameter of 1mm the saturation pressure of lithium must be about 10^3 Pa, which corresponds to the temperature well over 1000 °C.

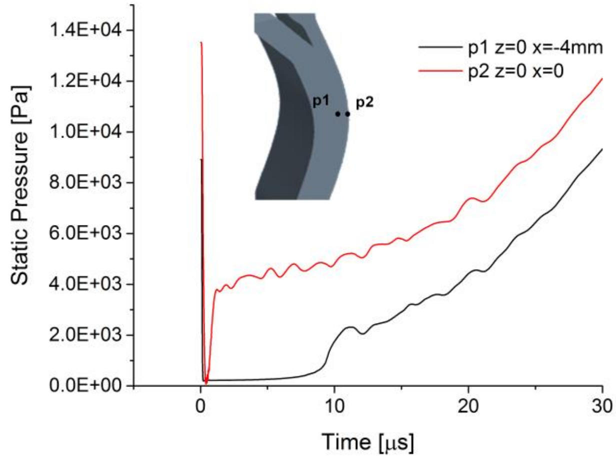

Fig. 6. Static pressure evolution in case of sudden beam loss. Diagram of static pressure as function of time measured near the maximum of the heat source (p1) and on the back wall (p2).

In the next stage the sudden events like beam trips "beam-off/beam-on" are analysed. Diagram in Fig. 7 shows maximum static pressure on the back wall (x=0, y=0, z=0) calculated for different time intervals. While in the first micro second calculations show the rapid grow of the negative pressure for all cases, the value of the peak pressure after the sudden switch on of the beam energy is dependent on the time span of the beam trip. The longer is the time span between switching off and on of the beam, the greater is the pressure rise. For beam trips with the time span more than 40 µs the peak pressure reaches its maximum value, which corresponds to the value of the initially discussed sudden "beam-on" case.

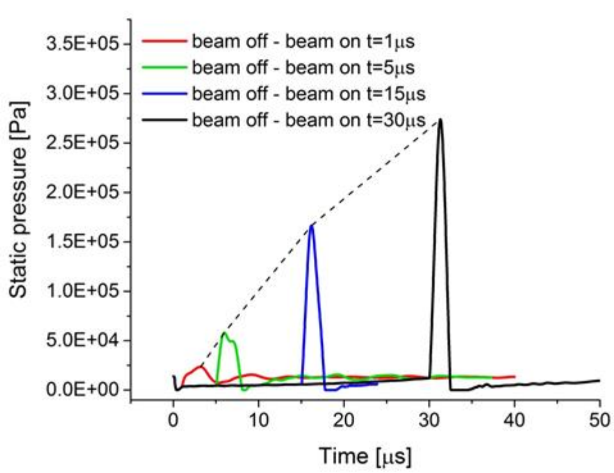

Fig. 7. Maximum static pressure measured on the wall (x=0, z=0) during sudden beam trips between Δt=1.0 and 30 µs

The maximum pressure during the switch on of the beam energy inside the Li-target can be reduced by using a ramped deuteron beam current resulting in a ramped heat deposition. The influence of the steepness of the ramp on the maximum pressure inside the target body is displayed in Fig. 8.

The figure shows that the ramp time of 0.1 µs corresponds to the sudden "beam-on" case. For a ramp-time of 2.5 µs the maximum pressure is reduced by a factor of 2, resulting in a peak pressure of approximately 0.175 MPa. Choosing the ramp time of 20 µs leads to the pressure reduction factor of about 10 and the maximum pressure of 0.03 MPa. After weak pressure oscillations, the initial condition of the target-flow is achieved without formation of negative pressure areas.

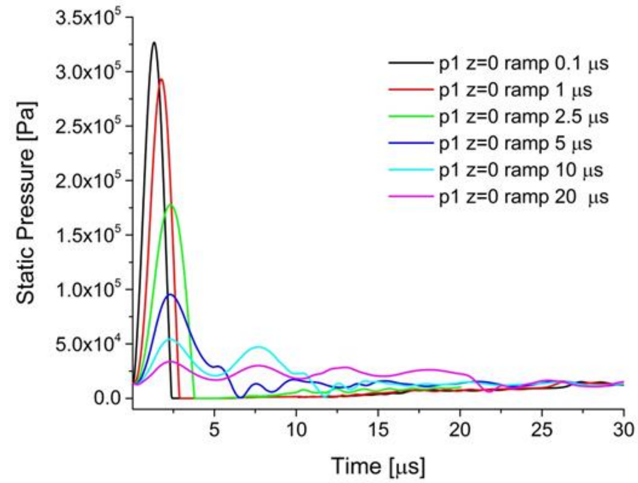

Figure 8. Maximum static pressure measured on the wall (*x*=0, *z*=0) for different ramp-up times.

IV. Conclusion

Analytical and numerical thermo-hydraulic analyses of the effects generated in the IFMIF-DONES lithium target during the beam- on/beam-off switches are performed.

The simulation of the thermal induced pressure in the Li-target shows that for the sudden "beam-on" operation conditions peak pressures of about 0.3 MPa can be reached.

In both "beam-on" and "beam-off" cases the negative static pressure within the Li-target flow is forming. Activated cavitation model detect no occurrence of cavitation in the negative pressure area. Simulation does not show the influence of pressure wave on the Li-flow behaviour and stability of the Li-free-surface.

Simulations of beam trips showthat the longer is the time span between switching off and on of the beam, the greater is the pressure rise. For beam trips with the time span more than 40 µs the peak pressure reaches its maximum value.

The ramped heat deposition will reduce the peak pressure in the target. For the rump time of 20 µs the initial static pressure in the target remains nearly unchanged.

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