ENHANCEMENT OF HEAT REMOVAL USING CONCAVE LIQUID METAL TARGETS FOR HIGH-POWER ACCELERATORS

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ABSTRACT

The need is increasing for development of high-power targets and beam dump areas for the production of intense beams of secondary particles. The severe constraints arising from a megawatt beam deposited on targets and absorbers call for nontrivial procedures to dilute the beam. This study describes the development of targets and absorbers and the advantages of using flowing liquid metal in concave channels first proposed by IFMIF to raise the liquid metal boiling point by increasing the pressure in liquid supported by a centrifugal force. Such flow with a back-wall is subject to Taylor-Couette instability. The instability can play a positive role of increasing the heat transfer from the hottest region in the target/absorber to the back-wall cooled by water. Results of theoretical analysis and numerical modeling of both targets and dump areas for the IFMIF, ILC, and RIA facilities are presented.

I. INTRODUCTION

The need is increasing for development of high-power targets in the megawatt range and beam dump areas for the production of intense beams of secondary particles (IFMIF, SNS, RIA, LHC). The energy of the beam of accelerated ions or part of it passing through the whole system and secondary products including photon radiation should be absorbed by targets and so-called dumpers. Targets and dumpers that can absorb beam energy and remove absorbed heat must have an acceptable lifetime of years. This lifetime is determined mostly by the damage produced by particles and photons interacting with the material. The damage can be microstructural (point defects, clusters of defects, sputtering, secondary electron emission) and macroscopic resulting in increased hardening, decreased ductility and heat conduction, swelling, embrittlement, or blistering.

The severe constraints arising from a megawatt beam deposited on targets and absorbers call for nontrivial procedures to dilute the beam and secondary products. Heat conduction of solid materials does not remove enough heat; thus, rotating wheels and liquid metal flow targets and dumps are considered as potential solutions.

The problem of high-power (1 MW or more) heat removal exists for many accelerator projects (e.g., RIA, SNS, IFMIF, linear colliders). The liquid metal flow targets and dumpers seem most suitable for removing heat (and possibly radioactive isotopes). The open surface (windowless) liquid metal flow has advantages, but there exist concerns of possible cavitation with liquid metal splashing and evaporation with subsequent contamination. The closed-surface liquid metal flow targets have problems with the lifetime of the solid shield. Thus, both types of open and closed surface targets and dumpers are being investigated for future accelerators. The cavitation is due to a bubble boiling at low (close to zero) outside pressure. The pressure distribution is determined by distribution of the energy deposit with a maximum at the Bragg peak, at which cavitation is possible. A concave target with a curvature radius, R_c, of tens of centimeters was suggested to avoid cavitation (Fig. 1) by pressure increasing as a result of centrifugal force, $F_c = \rho V_0^2 / R_c$.

The Taylor instability is inviscid. Viscosity results in dumping of instability, but at Taylor number $Ta = Re\xi > 41.6$, $\xi^2 = d/R_c$, (R_c is the curvature radius, d is the depth of flow, and L is the length of the target) the role of viscosity is negligible. The increment of instability is about $\gamma \approx V_0/\sqrt{2}R_c$, which is large enough to form vortexes during the flight time, $\tau_u = L/V_0$, $\tau_\gamma/\tau_u = R_c/\sqrt{2}V_0$.

Such concave liquid metal flow targets can be useful for future accelerator projects such as RIA, SNS, and ILC [1,2,3] needing to remove heat and radioactive isotopes from the target and dumper. The concave flow is subject to Rayleigh-Taylor instability, which results in formation of so-called Taylor vortexes along the flow direction. In experiments [1], strong nonhomogeneities at the flow surface are a consequence of the Taylor vortexes.

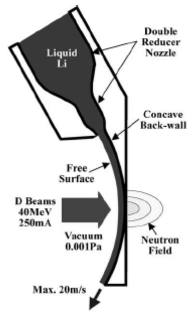

Fig. 1. Concave liquid flow for the IFMIF target [1].

The concave flow is subject to Rayleigh-Taylor instability, which results in formation of so-called Taylor vortexes along the flow direction. In experiments [1], strong nonhomogeneities at the flow surface are a consequence of the Taylor vortexes inside the flow. The existence of these vortexes can play a positive role in liquid mixing, thereby decreasing the average temperature.

II. DEVELOPMENT OF TAYLOR VORTEXES

The Couette flow of a liquid between two rotating cylinders is unstable, with excitation of wavy structure near velocity threshold, the so-called Taylor-Couette vortexes with regular structure (ordered flow) at moderate velocity, and with transition to fully developing turbulence at higher velocity [4]. The Taylor vortexes in the case of the concave wall of interest here are called Goertler vortexes.

These vortexes can be excited by a corresponding roughness of the nozzle, to develop a vortex at the beam spot area. It is possible to work in two regimes: ordered flow with vortexes and turbulent flow at high Ta>400 if the flow has enough time for turbulence to develop. We plan further investigation of heat removal at the turbulent regime with possible enhanced heat conduction due to convection.

In the following section, we discuss a case of ordered flow. The increment is maximal for lowest wavenumber kd=1, namely, single vortex. We emphasize that the wavelength of vortexes is determined by the flow width d because the velocity changes on distance d exceeding the viscosity length $\delta^2=\nu t$, $d>>\delta\approx10^{-2}$ cm, $\nu(Li)=10^{-2}$ cm^2/s.

The formation of vortexes with the necessary magnitude can be controlled by the distance between the inlet and spot area and the initial magnitude of perturbations.

II. INFLUENCE OF TAYLOR VORTEXES ON AVERAGE TEMPERATURE

To show the influence of the Taylor vortexes on heat transfer, we consider the following 2D model problem with surface heating: flow with velocity V_0 in the Y-direction limited by the wall at a distance depth $L_x=L$ and infinite in the Z-direction heated by power W(y)= const(y)=W_0 (Fig. 2).

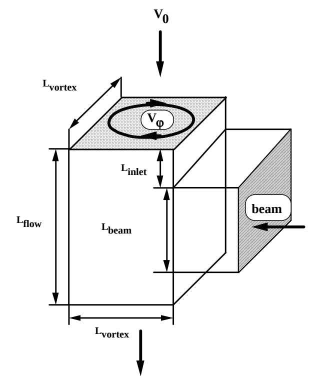

Fig. 2. Model of heat transfer in liquid Li heated by a 40 MeV proton beam.

The energy conservation equation is

$$\frac{\partial T}{\partial t}=\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-\frac{1}{Pe}\left(V_x\frac{\partial T}{\partial x}+V_y\frac{\partial T}{\partial y}\right),\ t=z/V_0 \qquad (1)$$

where Pe is the Peclet number. The boundary conditions are

$$T(L,y,t)=0,\ \kappa\frac{\partial T}{\partial y}(0,y,t)=W_0 \qquad (2)$$

with symmetry conditions at y=0,L_y

The Green solution is used to describe the Taylor-Green vortex.

$$u=-\sin\pi x\cos\pi y,\quad v=+\cos\pi x\sin\pi y$$
$$P=1/4\rho(\cos 2\pi x+\sin 2\pi y) \qquad (3)$$

The average temperature at the surface x=o is practically the same: $T_{aver}=T_0$ determined by the heat flux to the surface W_0. It is possible to decrease the average temperature when heat has no time to spread over the flow volume if the time of flight, τ_u, is less than the time of heat conduction, τ_u, that is, $Pe=\tau_u/\tau_\kappa<<1$, $\tau_\kappa= L^2/kC_p$ where k is the heat conduction, C_p is the specific heat.

Let us consider the case corresponding to the IFMIF facility. Lithium flow with depth L_x=2.5 cm moving with velocity $V_y= V_0$ =(10-

20) m/s is heated by the proton beam with E=40 MeV, power W= 1 MW, and spot size in Y-direction L_y=5 cm, Pecle numer Pe<10^{-4}, thus, heat conduction can be neglected during the flight time, τ_u. Flow moving along a concave wall with curvature R_c of tens of centimeters is subject to Taylor instability and part of the translational energy E $=1/2\rho V_o^2$ is transferred into vortex energy $E_\perp=1/2\rho V_\perp^2$ with decreasing velocity V_y to V $<V_0$. From the energy and momentum conservation laws, the ratio between energy can be estimated as $V_{\perp\approx}$ V and $E_\perp \leq 1/4$ E .

The temperature distribution corresponds to the energy deposit. The maximal temperature of T_{max}=182 ˚C is at the Bragg peak x= λ=20 mm.

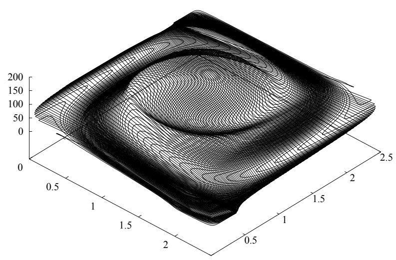

Fig. 3. Liquid rotation.

In the presence of the vortex, Eq. (1) with velocity corresponding to Eq. (3) was solved by using the particle-in-cell method. Results of calculations are presented in Fig. 3. The maximal temperature decreases to T_{max}= 132 ^{o}C from T_{max}= 182 ^{o}C as a result of a liquid rotation. The maximal temperature is determined by the time when the liquid crosses the region with maximal energy deposit at x=λ. In terms of the average temperature distribution, the ordered flow solution of the stationary problem of flow with surface heating is practically the same as in the absence of vortexes.

III. SUMMARY

Development of high-power targets and beam dump areas will become increasingly important for the production of intense beams of secondary particles (for example, for IFMIF, SNS, RIA, LHC). The severe constraints arising from a megawatt beam deposited on targets and absorbers will require complex procedures to dilute the beam. This study describes the development of targets and absorbers and the advantages of using flowing liquid metal in concave channels, first proposed by IFMIF, to raise the liquid metal boiling point by increasing the pressure in liquid supported by a centrifugal force. The Taylor-Couette instability can increase the heat transfer from the hottest region in the target/absorber to the back-wall cooled by water. At the laminar stage of the instability with a certain wave number of vortexes (the ordered flow), the average temperature decreases as a result of liquid rotation, leading to shorter time of flight of the liquid across the region with maximal energy deposit (the Bragg peak). The vortex forms for 1-2 rotation times because growth time of the Taylor instability, $\tau_\gamma=\gamma^{-1}$, is close to the rotation time: $\tau_\gamma \approx \tau_u$. A greater decrease in temperature can be achieved by using a flow with turbulence at high Taylor number, Ta>416, determining by high Reynolds number. For the case presented here, the velocity is rather high, Re>10^5, and turbulence arises. To reach necessary turbulence regime, one must use a channel long enough to exceed the time of development of the secondary instabilities due to velocity shear [4]. We plan to undertake further investigations of heat transfer in liquid flow moving along a concave wall in the turbulence regime.

Acknowledgments

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