DOE Final Report for AWARD NO. DE-FG02-08ER41552

"Hydrodynamic and shock heating instabilities of liquid metal strippers for RIA"

PI: Prof. Ahmed Hassanein

Purdue University, West Lafayette, Indiana

June 2009

I. Introduction

Stripping of accelerated ions is a key problem for the design of RIA to obtain high efficiency. Thin liquid Lithium film flow is currently considered as stripper for RIA ion beams to obtain higher Z for following acceleration: in extreme case of Uranium from Z=29 to Z=60-70 (first stripper) and from Z=70 till full stripping Z=92 (second stripper). Ionization of ion occurs due to the interaction of the ion with electrons of target material (Lithium) with the loss of parts of the energy due to ionization, Q_U, which is also accompanied with ionization energy losses, Q_{Li} of the lithium. The resulting heat is so high that can be removed not by heat conduction but mainly by convection, i.e., flowing of liquid metal across beam spot area, as illustrated in Fig.1.

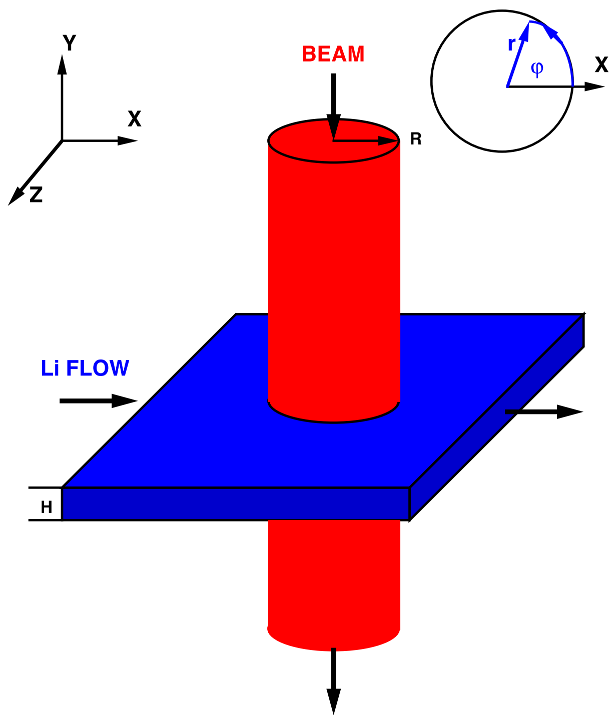


Fig.1. Beam–flowing thin liquid film interaction

The incident beam consists from bunches of ions with duration $\Delta\tau$=1 ns and repetition time τ=18 ns, thus frequency $f=\tau^{-1}$=5.55 MHz. The spot radius R is about 1 mm and required velocity of liquid **v** is about 10 m/s, thus the flight time of liquid across beam spot area $\tau_u \approx 100$ μs that $(\Delta\tau,\tau) \ll \tau_u$, and flowing liquid is under $N=\tau_u/\tau \approx 5\cdot10^3$ shots while liquid crosses the spot. At each shot temperature of liquid increases for about $\Delta T \approx 1$ K (first stripper) that result in increasing of pressure ΔP_{heat} on ~40 atm.

This arising pressure can be considered as instant in comparison with hydrodynamic times of pressure to level off in flow direction (X), $\tau_{\parallel}$=R/c_s=0.2 μs. The pressure levels off in beam direction (Y) occurs for comparable times, $\tau_{\perp}$=H/c_s=5 ns, $\tau > \tau_{\perp} > \Delta\tau$, $\tau_{\parallel} >> (\tau, \Delta\tau)$, because the film thickness H≤10 μm is quite small. The pressure jump ΔP_{heat} is much larger than the ram pressure of liquid $P_u = \rho U^2 \approx 1\,atm$ and surface tension pressure $P_\sigma = \frac{\sigma}{r}$, $P_\sigma(r = H) = 0.3\,atm$, therefore, pressure jump results in the excitation of sound waves that can excite surface capillary waves. That generates shock wave propagating along direction perpendicular to the beam as well as excites oscillations along beam direction (Fig. 2).

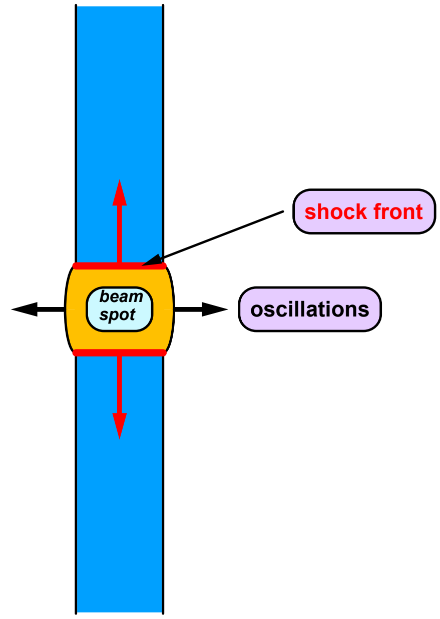


Fig.2. Schematic illustration of shock wave generation along flow and oscillations generation across flow

We studied the dynamics of these excited waves to determine conditions for film stability at the required velocities for heat removal. It will allow optimizing jet nozzle shapes and flow parameters to prevent film fragmentation and to ensure stable device operation.

II. Modeling Beam -Liquid Interactions

We utilized our High Energy Interaction with General Heterogeneous Target Systems (HEIGHTS) simulation package to study in detail the response of liquid targets and beam dump area response. Figure 2 is a schematic illustration of the various physics modules included in the HEIGHTS package in a self-consistent and integrated way to evaluate target response to intense energy deposition and hydrodynamic evolution of the material. The main modules that were used for the RIA applications are the hydrodynamic package coupled with material response including shock response to sudden beam deposition and penetration to thin liquid films.

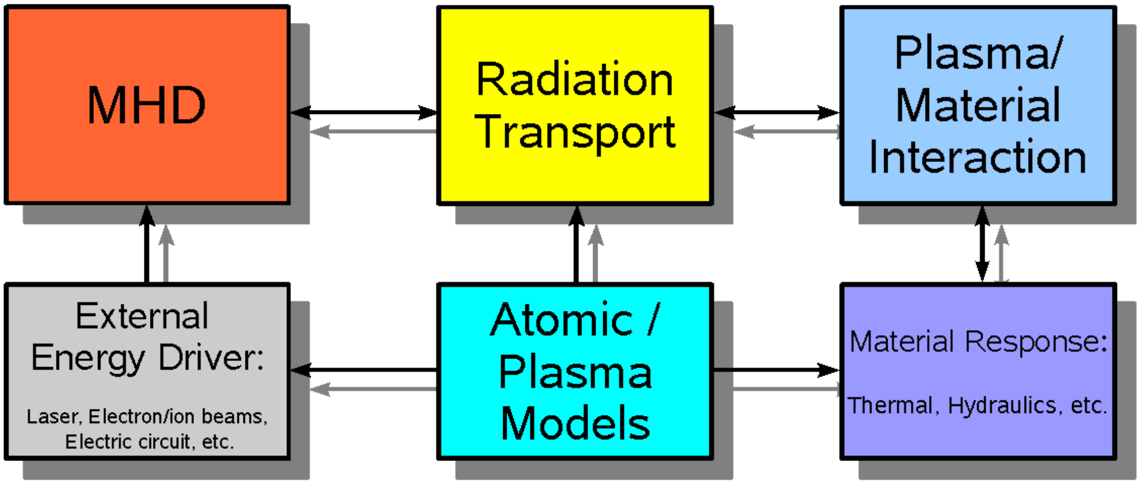


Fig.3. Schematic illustration of HEIGHTS integrated models for target response to intense power deposition

Hydrodynamic package solves the equations of motion that have the general form (in conventional nomenclature):

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{V}) = 0$$
$$\rho \frac{d\rho}{dt} = -\nabla P - \frac{\partial \pi_{\alpha\beta}}{\partial x_\beta} \qquad (1)$$
$$\frac{d\varepsilon}{dt} + P div \vec{V} + \pi_{\alpha\beta} \frac{\partial V_\alpha}{\partial x_\beta} = 0$$

Particles flux for ion beam with energy 12 MeV/amu and with power W_{in}= 12 kW was calculated from:

$$F = \langle NV \rangle A_U \varepsilon_{amu}$$
$$\langle NV \rangle = \frac{W_{in}}{A_U \varepsilon_{amu}} = 2.626 \times 10^{13} \ ions/s \qquad (2)$$

or $8.36\text{x}10^{14}$ ions/cm^2/s for spot area $3.14\text{x}10^{-2}$ cm^2

The energy loss of ion in Li during the beam crossing the film estimated according the Bethe-Bloch analytic formula:

$$\frac{dE}{dx} = 4\pi \frac{Z^2 e^4}{mv^2} n_{Li} Z_{Li} \ln \frac{2mv^2}{\bar{I}} \qquad (3)$$

Energy losses for ionization then were calculated as:

$$\frac{dE_z}{dx} = \gamma Z^2 \frac{dE_p}{dx} \quad \text{, where} \quad 0 < \gamma < 1 \tag{4}$$

We can assume $\gamma \approx 1$ for $E_p > 0.3\,MeV$.

We verified results obtained using above equations with fit formula from the experimental data of proton losses for Li [1].

Thus, energy losses of 12 MeV/amu Uranium ion for ionization of Lithium were estimated as ΔE_{Li}=1.125 MeV and the energy losses for stripping of ions from Z_{in} = 29 to Z_{out}= 62 is ΔE_U = 0.103 MeV, that is much less than ΔE_{Li}. Totally about 10% of coming beam power can be lost during penetrating through the stripper, $\Delta W \approx 1$ kW. Nevertheless, power density, W_{pulse}, and energy density, Q_{pulse}, per pulse can be quite large:

$$\begin{aligned} &W_{pulse} = \frac{\Delta W}{HS}, \quad Q_{pulse} = W_{pulse}\tau \\ &\Delta T_{pulse} = \frac{Q_{pulse}}{c_p}, \quad N_{pulse} = \frac{\tau_u}{\tau} \approx 10^4 \\ &\Delta T_{\max} = \Delta T_{pulse} N_{pulse}, \quad \Delta P_{pulse} = \Gamma c_p \Delta T_{pulse} \end{aligned} \tag{5}$$

For beam cross-section of S = 3.14x10^{-2} cm^2 and film depth of H=10 μm for ΔE=1.125MeV the maximum temperature rise can exceed 10,000 K while the temperature rise during each pulse is about 1 K. At every single shot the pressure increases up to 40 atm, but the pressure then levels off between shots, thus increasing of the pressure has a limit of 200 atm asymptotically.

These estimations show the importance of making exact calculation of stripping dynamics and corresponding energy losses.

III. Modeling predictions

The main purpose of the research during reported period was to understand most important physical phenomena that the first stripper will experience with the following liquid film flow and beam parameters. The lithium film parameters were used in this study: depth H = 10 μm, A_{Li} =

6.94100, Z_{Li}=3, ρ_0 = 0.51 g/cm^3, thermal expansion α = 46.6·10^{-6} K^{-1}, sound speed C_s=5 km/s, specific heat c_p = 2.25 J/cm^3. Beam parameters are: spot radius R=0.1 cm, initial charge of Uranium ion Z_{in} = 29, out-coming ions charge Z_{out} = 60-70, energy of ion E_U= 12 MeV/amu.

At each single shot the pressure increases up to 40 atm. Excitation of volumetric sound waves due to such pressure increase will result in oscillations of jet surface, i.e., part of energy is transformed into surface capillary waves. There are two adverse consequences:

a) Changing of film thickness with increasing of beam phase volume, and
b) Propagating disturbance to nozzle exit with following secondary jet oscillations.

The deposited energy assuming homogeneity along beam-direction spreads over the film in plane perpendicular to beam-directions mainly due to sound waves since heat conduction and convection during film flow time are negligible.

Sound wave in form of the pressure (shock) wave propagates along plane perpendicular to beam-directions during pulse at distance, Δr, and between pulses on distance, δr. These distances are less than the beam spot size:

$$\begin{aligned} \Delta r &= C_s \Delta\tau \approx 5\ \mu m \\ \delta r &= C_s \tau \approx 100\ \mu m \\ \Delta r, \delta r &<< L_r = 0.1\, cm = 1000\ \mu m \end{aligned} \tag{6}$$

During each pulse Δτ=1 ns the shock wave propagates with magnitude determined by pressure arising due to heating by the beam. Because pressure outside is basically zero (high vacuum) therefore, it is necessary expansion to compensate this thermal pressure P_{heat} by the "cold pressure", P_{cold}, due to the potential energy binding the atoms which can be found from equation of state (EOS). This EOS is presented in two-term form: the cold pressure, P_{cold}, and thermal one, P_{heat}, including both thermal energy of ions and electrons:

$$
\begin{aligned}
&P = P_{cold} + P_{heat} \\
&P_{cold} = P_{x_0}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right], \quad P_{x_0} = \frac{\rho C_s^2}{\gamma} = 32katm \\
&E_{cold} = \frac{P_{x_0}}{\gamma - 1}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma-1} - 1\right] + P_{x_0}\left[\frac{\rho_0}{\rho} - 1\right] \\
&E_{heat} = E_{T_0}\frac{\Delta T - T_0}{T_0}\frac{\rho}{\rho_0}, \quad E_{T_0} = 1.064\frac{kJ}{cm^3} \\
&P_{heat} = \Gamma E_{heat} = P_{T_0}\frac{\Delta T - T_0}{T_0}\frac{\rho}{\rho_0}, \quad P_{T_0} = 21.2katm, \quad \Gamma = 2
\end{aligned}
\tag{7}
$$

where ρ_0 and T_0 are the density and temperature of the liquid before interaction with the beam. For $\Delta T_{pulse} \approx 1$ K the corresponding pressure jump is $\Delta P_{pulse} = \Delta P_{heat} \approx 40$ atm. This arising pressure is much less than characteristic pressures both the "cold pressure", P_{x0}=32 katm, and the thermal pressure, P_{T0}=21 katm. However, this pressure jump ΔP_{pulse} is enough for sound wave excitation.

Figures 4 and 5 illustrate processes of surface deformation of free flow and possible capillary waves formation due to ions beam deposition. The complex character of energetic ions beam interaction with liquid film requires comprehensive modeling to simulate possible oscillations together with shock wave generation and determine conditions of film destruction.

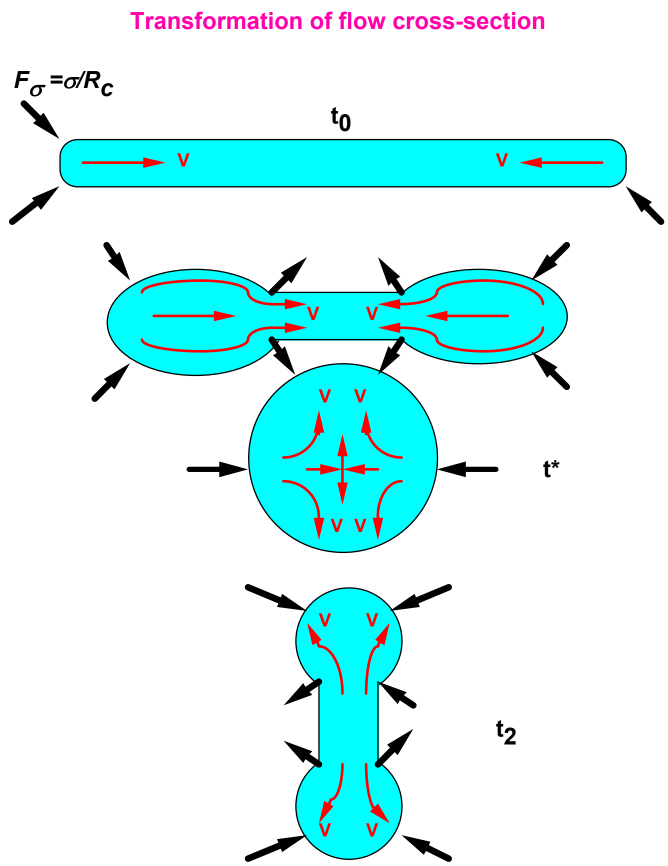


Fig.4. Free surface flow shape deformation

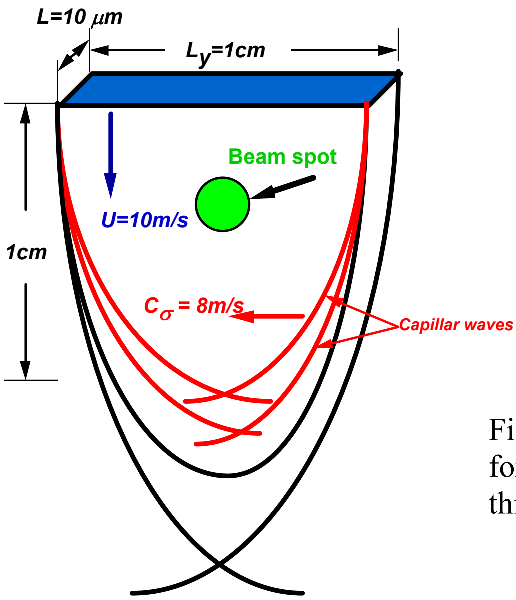
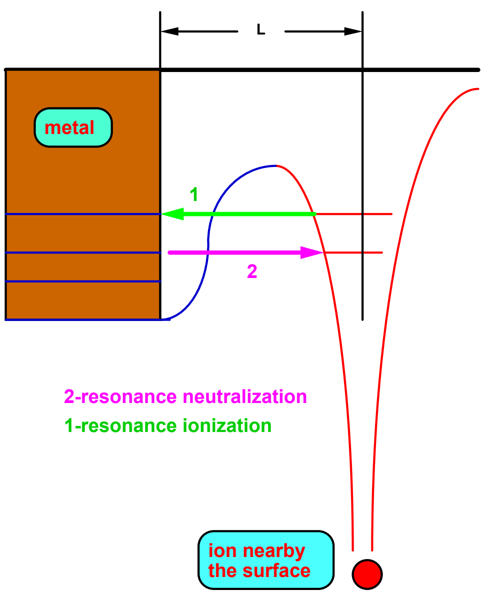


Fig.5. Schematic illustration of capillary waves formation during ions beam interaction with thin liquid flow



Another subject which was studied during the reported period is related to the atomic processes that have significant influence on stripping physics including charge losses when ion leaves film surface. Charge neutralization due to potential effects of highly charged ions also was evaluated. Figure 6 shows considered processes nearby the surface. The processes of resonance neutralization, resonance ionization and Auger neutralization of ions were analyzed.

Fig.6. Schematic illustration of charge neutralization and ionization of ion nearby the surface

Related references

1. Gott Ju.V. Particle interaction with materials at plasma investigations, Atomizdat, 1978, p.90.
2. I. Konkashbaev, P. Fischer, A. Hassanein, "Enhancement of heat removal using concave liquid metal targets for high-power accelerators", Proceedings of PAC07, Albuquerque, New Mexico, USA (2007) 2915.
3. A. Hassanein, "Liquid-metal targets for high-power applications: Pulsed heating and shock hydrodynamics", Laser and Particle Beams 18, 611–622 (2000).