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A CONTINUOUS LIQUID SHEET GENERATOR
FOR ION STRIPPING

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Many of the technical problems of generating a large thin liquid sheet from 0.02-0.20 μm thick ($3\text{-}40\text{ }\mu\text{g}/\text{cm}^2$) have been solved. It is shown that this perennial sheet is stable and consonant in dimension. Several ion beam species from the SuperHILAC have been used for evaluation; at 0.11 MeV/n. In one of three modes this sheet serves as an equivalent substitute for a carbon foil. The second mode is characterized by a solid-like charge state distribution but with a varying fraction of unstripped ions. The third mode gives stripping performance akin to a vapor stripping medium.

Introduction

Liquid sheets were generated years ago, with spinning cups^{1,2,3} and fan nozzles⁴. This work was directed toward the process of atomisation of a liquid under atmospheric conditions. While possible future stripper development may benefit from the use of the spinning cup technique, our approach has proved successful enough to not warrant testing along these lines.

This paper describes a followup effort to a proposed ion stripper advanced by Leemann, et. al^{5,6}. Feasibility established, large stable thin films, herein referred to as sheets were developed and subsequently tested with the SuperHILAC at Lawrence Berkeley Laboratory. The sheets are being evaluated at two constant velocity stripping stations of the SuperHILAC.

The 1.2 MeV/nucleon station currently uses carbon foils. Unfortunately access to this station has not often been available at this time. While lifetimes are at present satisfactory, ~2 hours minimum for iron ions (1.7 μA average), given future upgrades of intensity, a perennial solid sheet stripping medium would be an attractive improvement. The results from this testing are proceeding slowly and are expected to be reported at a later date.

At the 0.113 MeV/nucleon stripping station one is obligated to use fluorocarbon vapor⁷ in lieu of carbon foils, given the large beam intensities encountered (as high as 70 μA average). Gaseous stripping is appropriate for the lighter ions. As the ion projectile mass is increased ($A > 100$), a solid medium will shift the equilibrium charge state distribution to substantially higher Q/A-values, an additional attractive incentive for testing an alternative stripping target. Relevant, intense ion beams are available at this station which therefore serves well for modeling a future 1.2 MeV/nucleon ion stripper.

Description

Two 8.6 cm diameter steel discs, machined to be radially flat on one side and with a razor sharp circumferential edge, completely free from any form of irregularity, are rotated in the same direction tangentially above one another and in the same plane usually, at speeds 7500 rpm $\pm$ 2500. An unbroken continuous tubular flow of fluid is directed perpendicular to each disc close to the outer circumference.

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The nozzles are 1.5 mm diameter and are adjustable in radial (and tangential) direction for critical tuning of the sheets (See Figure 1). The axis of each disc is placed 12.5 cm from accelerator axis. Flat polyester cord belts are used to drive each disc from an intermediate pulley. A magnetically coupled drive transports rotational energy across the vacuum wall. Each of four rotating shafts utilize two superprecision bearings, force lubricated. A magnetically driven gear pump, overspecified to pump fluid with near vacuum inlet pressure is required. In order to generate thin hole-free sheets, the fluid must be filtered. We are using a painted 5 micron filter of wire cloth.

Surrounding each disc are critically shaped sheet terminators that serve to stabilize and stretch the thin sections of the sheet. The entire structure is capable of being rotated in a plane parallel to the accelerator axis. This motion serves to increase the interaction area of sheet to beam without increase to interaction diameter. Further discussion follows.

Background

The last reported films⁶ were made by directing a fine stream of oil to a tangential contact with the edge of a rotating disc, hollow ground to minimize instability. These authors found such films small, and unstable. Surface densities were greater than 20 $\mu\text{g}/\text{cm}^2$ and the background pressures ($> 25\text{ }\mu$) were unsuitable for thin films. Dow Corning 200 fluid appeared to be the only suitable fluid, unfortunately leading to carbonization from ion beam interaction.

In this development a column of fluid is directed perpendicular to a flat disc without concavity, so as to minimize surface waves. Components of velocity originating with the fluid pump were reduced by first bringing this fluid to rest on the disc. Clearly we needed a fluid with high adhesive force. Once at rest with respect to the disc, the only accelerating forces would be due to centrifugal and coriolis forces, free from pump pulsations. The disc-fluid contact point was first chosen close to the axis of rotation. This turned out to be unfavorable since the bead of fluid adhering to the disc took on a Rayleigh type instability within several spiral revolutions. When the initial fluid contact point was shifted close to the periphery, our first sheets began to appear; although they were not yet visible (or stable) because of inaccessible viewing conditions. It gradually became clear that the quantity of fluid must be tailored to move off the disc within 450° of fluid rotation and that the more interesting sections were at about 270°, clockwise from the initial fluid contact point. At least a

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third of the fluid is dumped off the disc within the first 90° of fluid bead, merging with the existent thin sheet, already formed from prior application.

In general the sheet thickness at disc perimeter is fixed as a function of degree rotation, but the gradient of sheet thickness within the first centimeter of radial sheet displacement increases dramatically with rotation. High speed photographing of the sheet (200µs/frame) indicates a sheet velocity of ~3500 cm/s, at ~270°, about full disc perimeter velocity. The sheet will exhibit minor fluctuations of thickness from disc perimeter imperfections or changes of bead size while on the disc. These imperfections show as involute patterns and are typical of sheet formation from rotary atomizers as well. (See Figure 3)

Sheet thickness is conveniently measured with white light destructive interference of the first four orders. In Figure 2 we see two sheets tuned thick enough to show color at some distance from the discs. The nozzles may be observed at the top and bottom of the illustration. An Americium source of alpha particles (5.474 MeV) was used (See reference 6) for check of interference order. Alpha energy loss, while not accurately obtained, was sufficient to assure the presence of the first order, and implied a somewhat lower density sheet than expected (15 percent). Our lowest surface density is ~5µg/cm² (~3µg/cm²), or .025µm in thickness, sufficiently thick not to be granular, i.e., the sheets are at least 20 molecules thick.

Operation:

A number of fluids have been tested at various viscosities. The hydrogen free large molecular makeup of fluorocarbon fluid appears to be best suited for the task. Relevant, this fluid produces only volatile components when fractionated from heating or radiation damage. With this new technique Fomblin (18/8) will hold together as a sheet quite well. The contact angle of the fluid is low, and adhesion is satisfactory. Our grade is: 190 centistoke, 8 x 10⁻⁹ at 20°C. In general, sheet fluid needs to be viscous, probably because the fluid will be subject to lower amplitude perturbations than otherwise. Pumping difficulties do occur when viscosities exceed 200cs. The inlet fluid pressure to the pump is set only by the fluid head and the flow characteristics of the feed line. The higher the viscosity the larger appear to be the thin sections of the sheet. At present thin areas equal or exceed 40 cm².

Sheet fluid must have a low surface tension for thin cross section. Sheet velocity likewise should be as high as possible. Our speeds are limited to ~10,000 rpm because of excess vibration, unfavorable for stable sheets.

It has been shown that the velocity of contraction at the free edge of a sheet⁴, subject only to the surface tension force, is $v_s(x) = \sqrt{2\sigma/\rho x}$ where the surface density = ρt and x = surface tension. At a critical distance from fluid source, v_s will equal the sheet velocity and a leading edge will form, perpendicular to the involutes, terminating the sheet.

Additional stability and also thinness is achieved with the terminators which serve to stretch the sheet out, reducing the effective contraction velocity by up to 20 percent. These terminators are

1 cm wide stainless steel ribbons perpendicular to the sheet. Distances from disc perimeter to terminator vary from 3 cm to 8 cm. Terminator curvature and pitch are critical for quiet draining, and lack of destabilizing dripping. The location is set empirically. Without them, thin sheets cannot be achieved.

Thin sheet tuning is realized by visually bringing the higher orders of light interference close to the disc perimeter. High disc speed, low fluid flow rates (~0.4 gpm), and careful tuning of the fluid contact point also are required. Negative effects will appear when fluid contact with the terminators deviates from the cut and try setting of terminator locality.

Thermal, electrostatic and mechanical effects are possible causes for the eventual breaking of the liquid sheet by the ion beam. Qualitatively it is evident, that for each of those processes there is a beam current threshold beyond which the sheet is locally destroyed by the beam. Without making very restrictive assumptions, however, this threshold can be calculated only for the evaporation process. In this case we assume that a beam is traversing the liquid sheet at angle θ with respect to the sheet normal, and the local mass flux in the liquid sheet is perpendicular to the incoming beam direction. The current threshold is obtained then by equating the total energy loss per unit time due to multiple scattering and the energy required to evaporate the amount of liquid flowing through the interaction volume per unit time. This yields the relation

$$I [\mu A] = [c (T - T_0) + c_{vap}] \frac{h \cdot v}{(dE/dx)}$$

where $I [\mu A]$ = particle current in μA

c = specific heat of fluid [erg/g-K]

c_{vap} = heat of vaporization of fluid [erg/g]

T = boiling point [K]

v = fluid velocity [cm/s]

h = beam width perpendicular to v [cm]

(dE/dx) = electronic stopping power⁵ of liquid [KeV-cm²/µg]

Inserting the material constants for fomblin this reduces to:

$$I [\mu A] = 0.83 \frac{h \cdot v}{(dE/dx)}$$

For an incoming beam angle $\theta = 0^\circ$ this relation has been verified reasonably well. One has to emphasize on the absence of a thickness and an angle dependence. Stated differently, for the evaporation process the threshold current is not raised by a larger angle but increases with the beam diameter perpendicular to the local mass flux in the sheet.

Results at .113 MeV/amu:

The following tests were made with the SuperHILAC. A vapor stripper utilizing fomblin is in close proximity to the sheet stripper and allowed for direct comparison of the two media. Ion beam pulse length is two milliseconds, at 36 pulses/second. Beam intensity is variable. Charge state analysis is magnetic. Spot size was controlled with collimation but the optics of the beam line precludes significant changes to the current density. Ions reported here are niobium and holmium.

Given high current beams, 100 pA or more to the stripper, the liquid sheet acts like a vapor cell and matches to within 5 or 10 percent the charge state intensities usually encountered with the SuperHILAC gas stripper. As much as 14 pA of H_2^{10+} have been produced in one charge state with either vapor or sheet in vapor mode, and 55 pA of Nb^{9+} .

Holes are formed on the sheet(s) at very low intensities; $> 10 \text{ pA/cm}^2$. The energy lost to the sheet per unit area is $\sim 1/30$ that required to vaporize. Therefore we postulate that the non conductive nature of the sheet probably accounts for electrostatic puncture. Nevertheless 10 pA of niobium impinging upon a single sheet will generate a distribution closely approximating a $4 \mu\text{g/cm}^2$ carbon foil distribution. Collected currents differed by less than 15 percent for all states greater than $8+$ even with the hole.

The hole is first observed with these low intensity beams after some fraction of the pulsed ion beam has passed downstream. In Figure 3 we can see the first signs of a hole forming. The exact time delay before appearance of the hole is dependent upon beam intensity. Notice a slight shading around the holes, possibly from a bulging of the sheet. Once the hole is formed, surface tension forces expand the hole into what appears as a tear on the sheet. Realize that this hole is continually being swept away by the inherent velocity of the sheet. See Figure 4.) The upstream circumference of the hole remains fixed, expanding slightly with high intensity beams.) The large molecules of fomblin are readily available to the beam along this crescent even with the presence of a hole. In fact photon emission is readily observed exclusively in this interaction area. A DC beam should not alter this mode of stripping.

As the beam intensity rises above $\sim 50 \text{ pA/cm}^2$ the hole is visible at an earlier time in the pulse, and the sheet does pass an increasing fraction of unstripped ions, up to ~ 45 percent the total collected particle current for a single sheet. The unstripped fraction varies with beam intensity, thickness of sheet and the number of sheets. As the flux continues to increase, the unstripped fraction drops now to a characteristic vapor like fractional distribution. A two sheet stripper does increase the collection efficiency, the uniformity of pulse shape, and also reduce at least by two, the unstripped fraction. The advantage of two sheets is that fluid for beam interaction is brought to the ion beam on opposite sides. It is disappointing that the higher charge states are not improved at least by two. A more modest 10 percent gain is seen. Strobe lighting revealed that the downstream sheet was damaged about 1.7 ms into the beam pulse, presumably by slow moving groups of fomblin molecules, $> 30\times$ the fluid molecular weight.

Figures 5 and 6 show the percentage particle current for each charge state of two ions and at several intensities to the stripper. Typically ~ 75 percent of the ions are collected after analysis. As the intensity is increased so does the distribution shift to a gaseous type. Niobium and holmium were selected to give the largest intensities of analyzable heavy ions. (Recall that the SuperHILAC stripping stations operate for fixed velocity ion beams). Charge states less than the impinging ion were too rigid to be analyzed. Beam amplitude into any one charge state may be read from the figures by

noting the particle current to the stripper, collection efficiency and the percent fraction. Of interest, the higher charge states appear to reach a rough upper limit of one to two pA.

Transition from solid to vapor is noted with greater clarity by plotting particle current against pA current into any one charge state. In figure 7 one can see the gradual transition from solid to vapor stripping when the particle current to the stripper is increased. Single and double sheet stripping data have been merged for lack of significant difference. Also data gathered with lower charge state beams not hitherto referred to, but of higher intensity are included. For example: Nb^{13+} appears to steadily drop from a 7.5 percent yield to ~ 5 percent before halting gain to analyzed intensity. Ion fluxes are $\sim 75 \text{ pA/cm}^2$. Already the effects of hole puncture can account for this disproportionate increase. As the current is further increased, we note a change from 5 percent collection to ~ 2 percent, now without further increase in yield. One could postulate that an increase in incident ion current is not available in the outer portions of the ion beam where solid stripping is occurring. Why then do we not see a factor of two increase when two sheets are used. We can suggest that the increase in incident beam power is destroying the orderly location of the sheet molecules, that large chunks of sheet are probably charged and are being driven away from areas of interaction. The chunks of sheets are released from the film at one fourth power expected for vaporization. Given a beam diameter of 0.5 cm, one calculates that at $\sim 75 \text{ pA}$ (400 pA/cm^2) the fomblin is vaporized, about where the solid and vapor curves are seen to merge.

Figure 7 shows the degradation of the sheet by a rapidly increasing yield say of the Nb^{9+} . In terms of yield from 2.5 percent to over 10 percent. Note that the vapor yields appear to increase linearly with input current. It should be mentioned that a visual inspection of the sheet interaction areas show a crescent like source of light on either one or two sides of the beam for currents below the solid-vapor merge value to be replaced by a general glow spreading along the beam line for higher intensities.

Relevant, the vaporization of fomblin will bring about a beam line pressure rise into the 10^{-5} torr range. Vacuum pumping should be improved with an upgrade to our LN trapping. D.C. ion beam operation will require further testing of vacuum system performance. While it is true that fluorine may be one of the volatile components, no problems were encountered.

Summary:

A minimum stable thickness of $\sim 5 \mu\text{g/cm}^2$ ($260 \text{ \AA}$) is routine. Thicker sheets are either tuneable or generated with rotation to the ion axis. The fluid is non-conductive. A charged ion beam will damage a sheet with a flux in excess of $\sim 10 \text{ pA/cm}^2$. Large portions of the sheet appear to explode, perhaps from electrostatic forces, generating a hole that effectively strips electrons only from the circumference of the hole. The unstripped fraction of incident ions is reduced at least by two, to ~ 10 percent (± 10 percent), by directing the moving sheets to collide on opposite sides of the ion beam. Two sheets do not increase significantly the yield in any one charge state. Rotation of the sheets will not eliminate the formation of holes. The transition thresholds appear

not to be raised from sheet rotation as anticipated. Further testing is advisable. At approximately $75 \mu\text{A}/\text{cm}^2$, the ions tested appear to reach an upper limit of current yield into any one charge state of 1 to $2 \mu\text{A}$. A vaporization mode occurs when helium or niobium ion beams are $70 \mu\text{A}$ or more in intensity. The ion flux is in the vicinity of $400 \mu\text{A}/\text{cm}^2$. The yield in any one charge state now will scale linearly with increasing incident ion intensity.

It should be noted that a sheet stripper will require substantially lower accelerator ion currents to produce equal amounts of the higher charge state ions with vapor stripping. From figure 6, we need ten times the flux with vapor stripping to match the sheet yield of H_0^{15+} . As intensity increases, this factor will decrease.

Further stripping tests will continue at higher energies. Sheet rotation will be more appropriate when thicker sheets are required. Unexpected electrostatic or mechanical sheet phenomena may become evident under these conditions. Finally, sheet separation or collimation between sheets will be mandatory for high duty factor operation.

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References

1. R.P. Fraser, N. Dombrowski, J.H. Routley, "The Production of Uniform Liquid Sheets from Spinning Cups", *Chemical Engineering Science*, 1963, v. 18, pp 315-321.
2. J.O. Hinze, H. Milborn, "Atomization of Liquids by Means of a Rotating Cup", *J. of Appl. Mechanics*, 1950, v.17, pp. 145-153.
3. N. Dombrowski, T.L. Lloyd, "Atomisation of Liquids by Spinning Cups", *Chemical Engineering Journal*, 8 (1974), pp 63-81.
4. N. Dombrowski, P.C. Hooper, "The Effect of Ambient Density on Drop Formation in Sprays", *Chemical Engineering Science*, 1962, v.17, pp 291-305.
5. J.C. Burch, Y.G. Cramer, P.B. Cramer, "Production of Very Thin Self-Supporting Oil Films for Stripping and Target Applications", *University of Wash., Annual Report 1976* p. 18.
6. B.T. Leemann, et. al., "A Liquid Film Stripper for High Intensity Heavy Ion Beams", *Proc. of 1981 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci.*, NS-28, 1981 pp 2794-2796.
7. J.R. Alonso, B.T. Leemann, "Fluorocarbon Stripping of Low Beta Heavy Ions", *Proc. of 1979 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci.*, NS-26, 1979, pp. 3718-3720.
8. N. Dombrowski, private communication. Dombrowski suggests they arise from the sudden change of direction of the liquid leaving the disc.
9. L.C. Northcliffe, R.F. Schilling, "Range and Stopping Power Tables for Heavy Ions", *Nuclear Data Tables, Section A*, v.7, 3-4, Jan 1970, Academic Press.

Fig. 1 The apparatus for sheet generation. The ion beam axis is indicated by a cross.

Fig. 2 Closeup view of two sheets, each $\sim 30 \mu\text{m}/\text{cm}^2$. The fluid 'waterfall' is below the beamline and comes from drainoff of the downstream sheet terminator.

Fig. 3 Image of sheet hole formation, $10 \mu\text{s}$ after initial beam turn on. We are observing reflected light from a synchronized strobe light. Beam intensity: $20 \mu\text{A}$.

Fig. 4 Image of sheet hole, $1000 \mu\text{s}$ after initial beam turn on. Beam intensity: $20 \mu\text{A}$.

Fig. 5 Incident beam intensity to stripper indicated. $54 \mu\text{A}$ with vapor 89 and $41 \mu\text{A}$ with 1 sheet 38 and $17 \mu\text{A}$ with 2 sheets.

Fig. 6 Incident beam intensity to stripper indicated. $15 \mu\text{A}$ with vapor. $13 \mu\text{A}$ with sheets, $6 \mu\text{A}$ with 2 sheets.

Fig. 7 Incident beam intensity vs. μA yield in 1 charge state as indicated. 'V' stands for vapor, other curves with sheets. Dashed curves show a constant indicated percent fraction for reference.

Fig. 1

XBB 848-6168

Fig. 3

XBB 839-8473

Fig. 4

XBB 839-8478

Fig. 6

XCG 849-13268

Fig. 7

XCG 849-13267

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