Editors' Suggestion

Massively Multiplexed Electrohydrodynamic Tip Streaming from a Thin Disc

Z. Wang,[1] Y. Tian,[1] C. Zhang,[1] Y. Wang,[2,*] and W. Deng[1,3,†]

[1]Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology (SUSTech), 1088 Xueyuan Ave., Shenzhen 518055, China

[2]Department of Radiation Oncology, Peking University Shenzhen Hospital, No. 1120, Lianhua Road, Shenzhen 518036, China

[3]Center for Complex Flows and Soft Matter Research, Southern University of Science and Technology (SUSTech), 1088 Xueyuan Ave., Shenzhen 518055, China

(Received 27 July 2019; revised 9 October 2020; accepted 14 January 2021; published 12 February 2021)

We report an experimental study on the multiple tip streaming enabled by an externally wetted thin disc in electric fields. The electrohydrodynamic stress acting on the liquid-air interface triggers an interfacial instability that develops into multiple radial liquid ligaments at the rim of the disc. The scaling law suggests that the wave number is inversely proportional to the square of the peak electric field at the rim, which is determined by the combined thickness of the disc and the attached liquid layer. The thin disc edge effectively intensifies the electric field, which in turn leads to spacing between ligaments as short as 30 μm for ethanol, generating over 1000 cone jets for a 1 cm diam thin disc.

DOI: 10.1103/PhysRevLett.126.064502

Liquid tip streaming is a conical flow that converges into a singularity or stagnation point, and the destabilization of such point grows into a cone jet, that is, an erupting tip and a fluid filament [1]. The driving force of the converging flow is a pressure gradient established by either fluid dynamic [2], electrohydrodynamic (EHD) [3], pneumatic [4], acoustic [5], or centrifugal [6] force fields. One prominent example is the EHD tip streaming or Taylor cone [7], which refers to the conical tip from a drop charged beyond the Rayleigh limit or exposed in an intense external electric field [3]. EHD tip streaming plays important roles in thunderclouds in nature [8] as well as practical applications including electrospraying [9], electrospinning [10], mass spectrometer [11], and ultrahigh resolution printing [12]. The Taylor cone can also be formed from a pendent drop on a round capillary in an electric field. As the electric field strength is increased, the initial single Taylor cone splits into multiple smaller cone jets emanating from a single bore and fanning out at an angle of ~45° with respect to the axis of the capillary. Usually, this so-called multijet mode [13,14] can only achieve a maximum multiplexing level of ~20. In this Letter, we report the massively multiplexed tip streaming from an externally wetted thin disc in an electric field. The number of jets increases as the electric field is raised, in agreement with the scaling law derived. The thin disc effectively intensifies the electric field at its edge, which in turn leads to the spacing between ligaments as short as 30 μm for ethanol in a typical experimental setup using a disc of 10 μm in thickness and 1 cm diam, forming over 1000 cone jets.

Experimental.—Figure 1(a) shows the experimental setup. The core component is the umbrella shaped assembly of a center tube and a round thin disc. The center tube is a 1-mm diam blunt stainless tube which is connected to a syringe pump to supply the liquid at a flow rate Q. The liquid used is 200 proof ethanol (surface tension $\sigma = 0.022$ N/m and electric conductivity $\kappa = 3 \times 10^{-5}$ S/m). The disc is made of stainless steel foils of various thicknesses, including 5, 10, 30, and50 μm. The 10 μm thickness disc provides a good trade-off between the thinness and rigidity. The disc diameters are 3, 5, 8, 10, or 12 mm. The disc is cut out of the foil by a laser marker which uses two scanning mirrors to steer a pulsed laser beam. The disc also has a 1-mm diam round hole drilled at the center, allowing the disc to be tightly attached to the center tube. Before testing, the disc is thoroughly cleaned by soap water, deionized water, and isopropanol. Then the disc is treated by ozone plasma to improve liquid wetting. A concentric ring electrode is positioned at the same plane of the disc. The inner and outer diameter of the ring are 26 and 34 mm, respectively. A dc high voltage V_d is applied between the disc and the ring electrode. For the 5-mm disc, the distance between the disc rim to the inner diameter of the ring is $H = 10.5$ mm. A digital camera (Nikon D5300) coupled with a long working distance microscopic object lens captures the image from the top [Fig. 1(a)]. Key parameters for this experiment are the disc thickness, disc diameter, ring electrode diameter, Q and V_d. The flow rate we tested ranges from 6 to 18 mL/h for the 5-mm disc. Typical voltages applied are from 5 to 10 kV.

Phenomenology.—Figure 1(b) shows representative images of the EHD tip streaming from a thin disc as we increase the voltage. Multiple equally spaced jets are issued from the wetted disc edge, forming a highly symmetric radial pattern. As V_d is raised, the number of cone-jets N increases rapidly, and the diameter of jets shrinks. This is

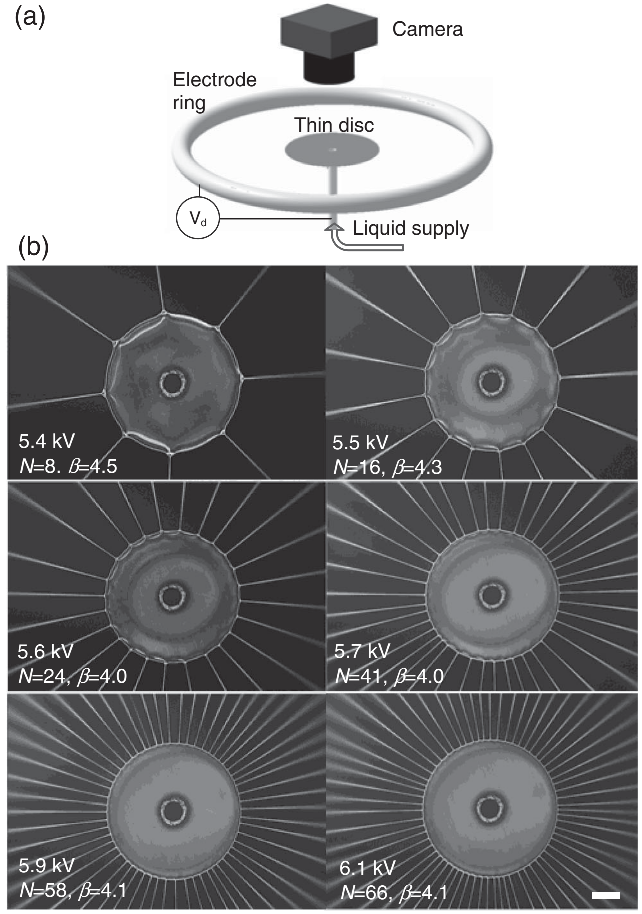

FIG. 1. Multiplexed EHD tip streaming from a thin disc. (a) The schematic of the experimental setup. (b) The number of cone jets N increases as the voltage is increased. β is the ratio between the interjet spacing and the cone base diameter. Liquid: ethanol; flow rate: 6 mL/h; disc diameter: 5 mm; disc thickness: 10 μm. Scale bar: 1 mm.

because the fixed total flow rate Q is partitioned by a factor of N for each jet, which reduces the jet diameter d_j according to the scaling laws of Taylor cone jets [15]:

$$d_j \propto (Q/N)^{\alpha}, \tag{1}$$

where α is a scaling power of $1/3$ or $1/2$ depending on the property of a specific liquid. For the liquid used in this work, the measured scaling power is $\alpha = 0.53$, which is close to $1/2$ and is expected for ethanol [16].

Figure 1(b) also suggests the jet diameters do not vary significantly from cone to cone in our experiments. The jets undergo Rayleigh-Plateau instability and break up into droplets with diameter of ~1.9 times of the jet diameter [17]. The uniform jet diameters ensure overall quasimonodispersity of droplet size. Therefore, the multiplexed EHD tip streaming has meaningful practical implications in material processing such as the spray drying route for making micro- or nanoparticles, because the throughput (liquid flow rate) can be increased by a factor of N while maintaining the jet diameter unchanged; or the average jet diameter can be reduced by a factor of N^{α} if the total liquid flow rate is fixed.

We also noticed that, as the voltage increases, both the interjet spacing and the cone base diameter decreases, but their ratio β is approximately a constant of ~4. This will be explained shortly.

A close examination of the liquid layer profile reveals that the liquid-air interface is not entirely parallel to the disc surface. The liquid forms a torus near the edge [Fig. 2(a)] as schematically shown in Fig. 2(b). We denote R_t as the

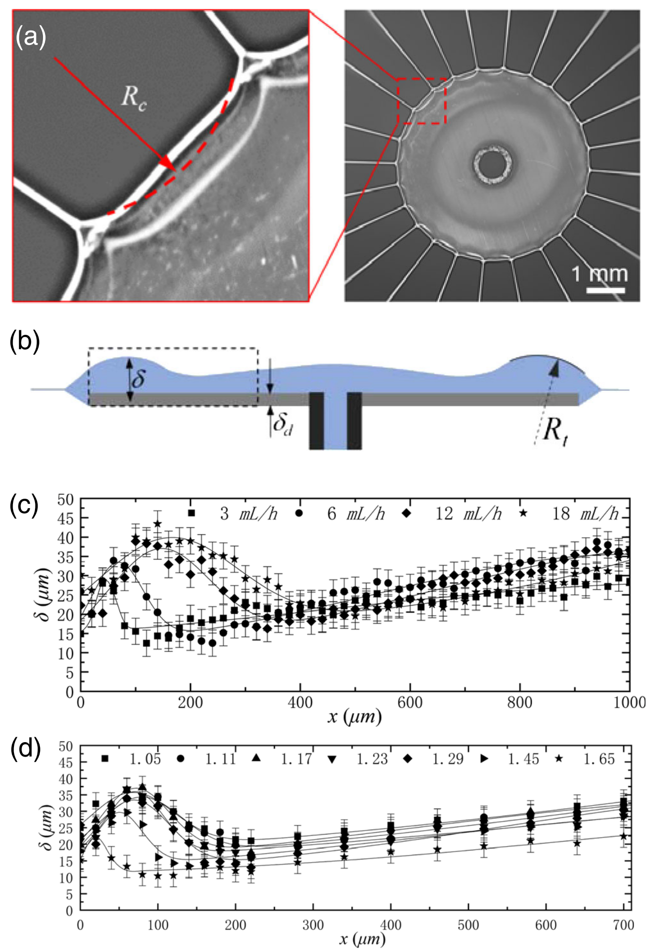

FIG. 2. The structure of the torus liquid layer. (a) Top view photograph of the liquid layer. The appearance of the light reflection on the liquid layer suggests the surface has a concave curvature R_c. (b) Schematic of the cross section of the liquid layer. R_t is the convex curvature of the torus near the edge, δ is the rim thickness, δ_d is the disc thickness. (c) Liquid film profiles in a radial direction with different flow rates at the fixed voltage of 8.4 kV. Disc diameter is 8 mm. (d) Liquid film profiles in a radial direction with different electric Bond number Bo_e. $Q = 6$ mL/h and disc diameter is 8 mm. (c) and (d) correspond to the dashed rectangle region in (b), and $x = 0$ corresponds to the disc edge.

radius of curvature of the liquid torus, and R_c as the radius of curvature of the concave surface between two neighboring cones along the azimuth direction near the edge [Fig. 2(a) and 2(b)]. R_c scales with the intercone separation λ because the Taylor cone has a constant half-cone angle of about 49.3°. We noticed that R_t is comparable with R_c.

We quantitatively characterized the liquid film profile with a confocal laser scanner (KEYENCE LT-9031M). Figures 2(c) and 2(d) suggest that the liquid film has two distinct regions: the relatively flat advection region and the toroid rim region. For the flow rate from 3 to 18 mL/h, the profiles of the advection region of the films are very similar: the film become thinner as they flow radially toward the edge, and the profiles of the advection region are approximately the same for different flow rates [Fig. 2(c)]. Near the edge of the disc, the film gradually bulges up and enters the rim region. The maximum rim thickness δ does not vary significantly for different Q, especially from 6 to 18 mL/h. The key difference is the width of the toroid rim: lower flow rate forms narrower toroid.

The effect of electric field.—The simple thin disc geometry allows us to solve the electric field near the disc edge (E_d) by means of conformal mapping of a thin ellipsoid [18]

$$E_d = C\frac{V_d}{\sqrt{H\delta}}, \tag{2}$$

where C is a geometry correction factor of order 1, δ is the rim thickness (the combined thickness of the disc and liquid layer). A minimum electric field E_0 is required to enable electric stress to overcome the surface tension, or $\sigma/\delta \sim \varepsilon_0 E_0^2/2$. Here σ is the surface tension coefficient. The corresponding minimum voltage V_0, defined as the onset voltage [17], is therefore $V_0 = (2\sigma H/C^2\varepsilon_0)^{1/2}$. The electric Bond number that compares the electric stress to surface tension has the form

$$\mathrm{Bo}_e = \frac{\varepsilon_0 E_d^2 \delta}{2\sigma} = \frac{V_d^2}{V_0^2}. \tag{3}$$

In other words, Bo_e can be viewed as the dimensionless electric field intensity.

The approximately equal interjet spacing λ observed in experiments suggests a periodic development of perturbation with the wave number $k = 2\pi/\lambda$. To obtain a scaling law of the wave number, we compare the electric stress $\varepsilon_0 E_0^2/2$ with the capillary pressure σk, or

$$k \sim \varepsilon_0 E_0^2/\sigma \sim \mathrm{Bo}_e/\delta. \tag{4}$$

For the same electric filed, we found from experiments that Q/U_r is approximately constant [16], where U_r is the liquid radial velocity at the torus liquid surface. This

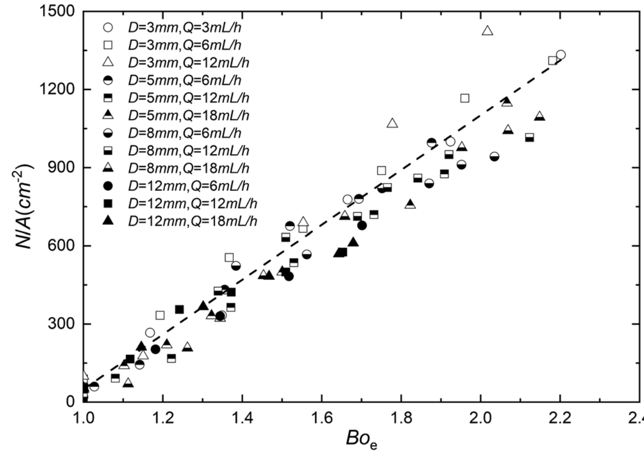

FIG. 3. The number of jets per disc area (N/A) vs the electric Bond number (Bo_e) for different flow rates and disc size.

suggests that δD is approximately constant because of mass conservation.

We conducted a series of experiments with different disc diameters, flow rates, and Bo_e. We found that as N/A is plotted against Bo_e, the data approximately collapse on a single straight line (Fig. 3). Here A is the disc area. This suggests that N/A, or the number of jets per disc area, is proportional to the electric Bond number minus one for the parameter range tested in this work:

$$N/A \propto (\mathrm{Bo}_e - 1). \tag{5}$$

According to relationship (5), $N/A \propto (N/D)(D/A) \propto k/D \propto (\mathrm{Bo}_e - 1)$. Coupled with $k \sim \mathrm{Bo}_e/\delta$, it can be deduced that $\delta D \sim \mathrm{Bo}_e/(\mathrm{Bo}_e - 1)$. This result is consistent with the decrease of δ with increasing Bo_e observed in Fig. 2(d).

The spacing of the cone jets λ can be estimated by $\lambda \propto \delta/\mathrm{Bo}_e$, or $\lambda = \beta\delta$. Here β is the ratio between the interjet spacing and the cone base diameter, which is inversely proportional to Bo_e. This is experimentally supported by results shown in Fig. 1(b), in which N is increased from 8 to 66 while β is approximately a constant of 4 because the voltage did not vary much (from 5.4 to 6.1 kV).

Discussion.—The lower limit of δ is the disc thickness δ_d, which suggests that the tip spacing could be as small as $\beta\delta_d$. We verified this minimum tip spacing experimentally (Fig. 4). For the 10-μm thick, 1-cm diam disc charged at 9.4 kV, the interjet spacing measured is 30 μm. The spacing estimated using relationship (4) is ~40 μm, which is in decent agreement with the measured value. Such short spacing corresponds to over 1000 jets that are densely distributed at the edge (Fig. 4). The thin disc is able to achieve such a massive level of multiplexing because it has two vastly distinct characteristic lengths: first, the small

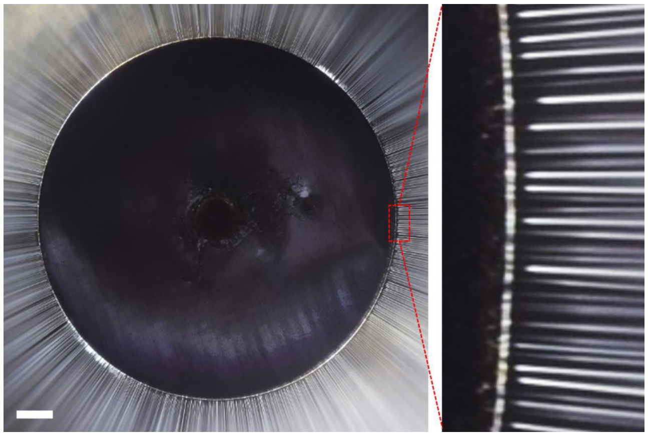

FIG. 4. Massively multiplexed EHD tip streaming with a thin disc. Disc diameter: 10 mm; disc thickness: 10 μm. Voltage: 9.4 kV. The liquid is ethanol supplied at 6 mL/h. Scale bar: 1 mm. The length of the magnified area is 1 mm, in which 35 cone jets are anchored, corresponding to an average interjet spacing of ∼30 μm and >1000 cone jets in the entire perimeter of the disc.

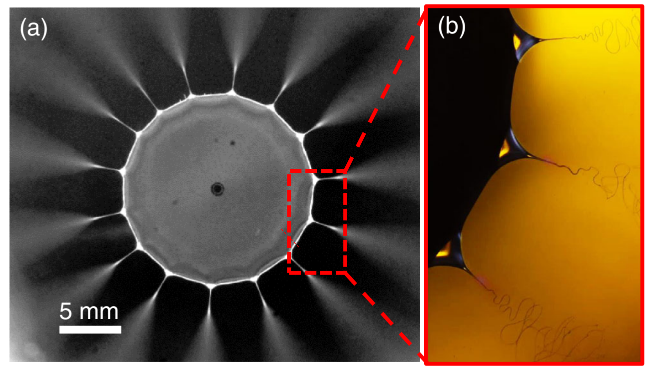

FIG. 5. Multiplexed electrospinning based on the multiplexed EHD tip streaming from a thin disc. (a) Photograph of 15 cone jets of 3% PVB polymer solution in ethanol (exposure time: 25 ms). (b) The details of the whipping fibers emerging from the Taylor cones (image was taken with a 5 ns flash).

thickness of the thin disc that establishes a very intense electric field; second, the nonsmall perimeter (a few centimeters) of the disc that provides sufficient length for anchoring a large number of cone jets.

It is insightful to compare the disc EHD tip streaming with the multi-jet mode using a single capillary of ∼millimeter size bore, in which the cones often move and even spin around the axis of the capillary. To overcome such rather unsteady operation from the capillary with a flat end, sharp features (e.g., grooves) were required [14] at the outlet of the tube to preferably anchor these jets. In contrast, the multiple tip streaming from a thin disc is very stable without grooves or teeth. This may be because the liquid film is thin and the viscous effect is sufficiently strong to damp against perturbations. [19] demonstrated an axisymmetric system that forms up to 40 Taylor cones for electrospinning on the perimeter of a 9-cm diam "bowl." The bowl design with 90° edge and 9-mm liquid layer depth lead to longer wavelength of the interfacial instability, and the ∼1 cm intercone spacing is comparable with the liquid layer depth [19].

The thin disc also provides the benefit of stabilizing the tip streaming. For a single Taylor cone of low-viscosity liquid suspended on a capillary, recirculation cells appear inside the tapering liquid meniscus, jeopardizing the cone stability at low flow rates [20]. A sharpened insert protruding from the mouth of the feeding capillary has been used to break the recirculation cell and improve the stability of low-viscosity liquids [21]. The disc used in this work also serves as a planar insert, which helps to reduce the recirculation and stabilize the liquid flow.

The multiplexed EHD tip streaming based on the thin disc may operate with other liquids with moderate surface tension, including viscoelastic liquids. For example, we tested 3 wt % polyvinyl butyral (PVB) solution in ethanol, which leads to a new multiplexed electrospinning configuration (Fig. 5).

The high intensity of the electric field on the disk edge may potentially cause electrochemical reaction and emitter deterioration, which has been observed on electrospray emitters based on hypodermic needles [22]. To examine this concern, we inspected the edge of a freshly machined disc and one operated for 50 h by scanning electron microscopy. We found no visible sign of deterioration of the disc edge [16]. We attribute this finding to the much larger edge region of the disc (a circumference of centimeters) than that of the hypodermic needle (essentially a point of a few microns). The slow deterioration of the electrospray emitter structure against electrochemical reaction could be another technical advantage of the disc configuration.

In summary, we report an experimental study on multiple electrohydrodynamic tip streaming formed around the circumference of a disc of thin stainless steel foil. The sharp disc edge effectively intensifies the electric field, which triggers the interfacial instability that leads to multiple Taylor cone jets. The spacing between Taylor cones is as short as 30 μm for ethanol, corresponding to over 1000 cone-jet electrosprays for a 10-μm thick disc of 1 cm in diameter. This massive multiplexing level makes the thin disc a compact and inexpensive device to realize a large number of tip streaming and atomization without sacrificing droplet monodispersity.

W. D. thanks supports from National Science Foundation of China (11932009, 12041601, 11872199) and Guangdong Provincial Innovation and Entrepreneurship Project (2017ZT07C071). This work is partially supported by the Sanming Project of Shenzhen (SZSM201612041).

[*]Corresponding author.
yuenan.wang@gmail.com
[†]Corresponding author.
dengww@sustech.edu.cn

[1] Y. Tseng and A. Prosperetti, J. Fluid Mech. **776**, 5 (2015).
[2] I. Cohen, H. Li, J. L. Hougland, M. Mrksich, and S. R. Nagel, Science **292**, 265 (2001).
[3] R. T. Collins, J. J. Jones, M. T. Harris, and O. A. Basaran, Nat. Phys. **4**, 149 (2008).
[4] A. M. Gañán-Calvo, Phys. Rev. Lett. **80**, 285 (1998).
[5] A. Saha, S. Basu, and R. Kumar, J. Fluid Mech. **692**, 207 (2012).
[6] P. Eisenklam, Chem. Eng. Sci. **19**, 693 (1964).
[7] G. I. Taylor, Proc. R. Soc. A **291**, 159 (1966).
[8] L. G. Smith, Q. J. R. Meteorol. Soc. **81**, 23 (1955).
[9] J. F. de la Mora, Annu. Rev. Fluid Mech. **39**, 217 (2007).
[10] T. J. Sill and H. A. von Recum, Biomaterials **29**, 1989 (2008).
[11] J. B. Fenn, M Mann, C. Meng, S. Wong, and C. Whitehouse, Science **246**, 64 (1989).
[12] J. Park *et al.*, Nat. Mater. **6**, 782 (2007).
[13] M. Cloupeau and B. Prunet-Foch, J. Electrost. **22**, 135 (1989).
[14] M. H. Duby, W. Deng, K. Kim, T. Gomez, and A. Gomez, J. Aerosol Sci. **37**, 306 (2006).
[15] A. M. Gañán-Calvo and J. M. Montanero, Phys. Rev. E **79**, 066305 (2009).
[16] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.126.064502 for additional data and figures on jet diameter, disc durability, surface flow velocity, as well as a video showing how the fine ethanol jets form around the perimeter of the thin disc.
[17] K. Tang and A. Gomez, Phys. Fluids **6**, 2317 (1994).
[18] D. G. Zill and M. R. Cullen, Advanced Engineering Mathematics, 3rd ed. (Jones & Bartlett Publishers, Sudbury, 2006).
[19] N. M. Thoppey, J. R. Bochinski, L. I. Clarke, and R. E. Gorga, Nanotechnology **22**, 345301 (2011).
[20] E. J. Vega, J. M. Montanero, M. A. Herrada, and A. M. Gañán-Calvo, Phys. Fluids **22**, 064105 (2010).
[21] A. J. Acero, J. M. Montanero, C. Ferrera, M. A. Herrada, and A. M. Gañán-Calvo, J. Micromech. Microeng. **22**, 115039 (2012).
[22] N. Rebollo-Munoz, J. M. Montanero, and A. M. Gañán-Calvo, EPJ Web Conf. **45**, 01128 (2013).