Electro-osmotic (EO) flow distribution near the boundary

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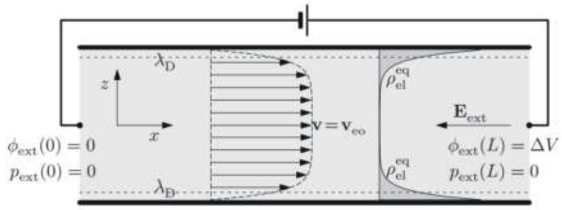
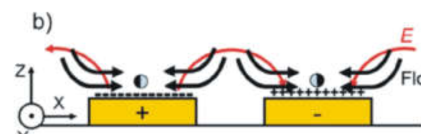
Classic picture of EO flows in a channel implies an applied electric field along the channel (see the sketch), where the EO is established parallel to the channel walls. The EO reaches its maximal value far from the Debye length and decreases to zero near the walls.

In our case (A) there is no electric field applied from an external source, but only due to the potential difference at the uncovered region (zeta = + 27 mV) and the gold-covered region (zeta =   40 mV). Also, the charged plates are in the same plane (but not at the opposite sides of the channel), therefore, the electric field is not parallel to the surface but it has both normal and tangential components (see (A)). Note that EO flows parallel to the surface are generated by the tangential component of the electric field. From the configuration of the experimental setup it is clear that the electric field is the strongest near the boundary, same as its tangential component. Therefore, we can expect that the strongest EO flow is located at the boundary (see (A)).





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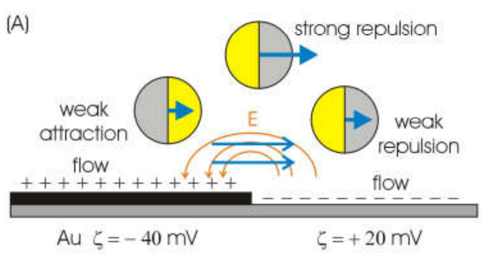

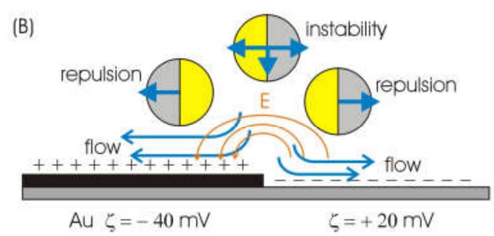

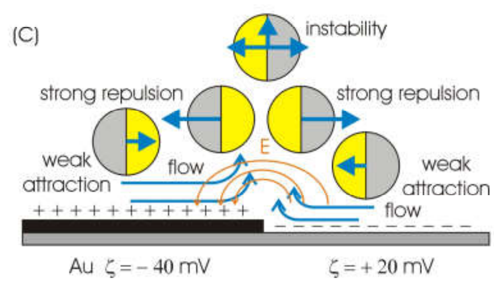

1. Single EO flow

The situation with a single EO flow is shown in (A).

Advantages:

- It looks consistent with the classic textbook description of the EO flow in a channel.

- It explains the observed repulsion of JPs from the boundary, including the observed repulsion of JPs that entered the gold-covered region deep inside and still are repelled back to the uncovered region.
Disadvantages:
- It is not clear if it explains the observed lifting (although could be just because of the EO flow is a shear flow which exerts the lifting force on a particle).

2. Two opposite EO flows

This case is represented in panels (B) and (C).
The situation with two EO flows is consistent with that described in the ACS Nano paper (see the figure). Indeed, if we imagine that the gap between two electrodes shrinks and finally disappears, then the ACS Nano case turns to our case with two oppositely charged plates touching each other. Then, in principle, we can expect that the two flows (as considered in the ACS Nano paper) should just approach each other.

[Comment: here I do not completely understand, why there are two flows? In principle, the EO flow is maximum far from the surface where the electrolyte is the same on the left and on the right from the boundary, and I expect the flow should be homogeneous but not two oppositely directed flows. I can imagine two opposite flows only near the surface as the uncovered and the gold-plated regions attract oppositely charged ions.]

Direct mapping of the situation discussed in the ACS Nano paper should lead to the case shown in (B), where two EO flows are directed from the boundary.
Advantages:
- This EO flow picture is consistent with the ACS Nano paper (direct mapping).
- It explains the repulsion from the boundary.
Disadvantages:
- It does not explain the lifting force.

Alternatively, if the two EO flows are directed toward the boundary (as suggested in the PowerPoint presentation of Tao) (see (C)), then it explains the lifting force.
Advantages:
- This EO flow picture explains the lifting force as the two flows meet each other and create a normal flow direct upwards.
- It explains the weak attraction at some distance from the boundary.
- Also, it can explain the strong repulsion very close to the boundary as the JP is lifted upwards by the up-streaming EO flow.
Disadvantages:
- It implies that JPs should behave similarly at the opposite side of the boundary, but the observations imply different behavior.

Summary:

It looks like two possible scenarios of the EO flows are possible: one implying a single EO flow which seems to be consistent with the textbook classical picture of the EO flow in a channel. The other scenario implies that there are two EO flows that converge (and the JPs are "focused" in this point where the EO flows converge). The second scenario perhaps could be explained by the prevalence of ions of different charges in the layer of sufficient thickness (again, what is the Debye length here?) such that they generate two flows in the opposite directions (as the electric field is always directed in the same direction: from positive to negative, by convention, as shown in all the sketches in the figure). If the Debye length is large enough, this can explain the existence of the two opposite EO flows. Although, according to the theory of the EO flow, it looks like far from the surface, over the distances larger than the Debye length, the flow should be single! Altogether, this implies that the flow distribution can be very complicated in this case (two flows near the surface that tend to degenerate in a single flow away from the surface). On the phenomenological side, the resulting potential due to the hydrodynamic EO flows that acts on the JPs clearly shows a strong repulsion at the boundary and weak attraction near the boundary, as follows from the observed behavior. Possible models are shown below for two-flow configuration and for single-flow configuration.