# Reply to "Comment on 'Electric fields from steady currents and unexplained electromagnetic experiments'"

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It is shown that the Lorentz contraction of the mean spacing between moving electrons $\Delta_e$ in a stationary current-carrying conductor, and the consequent use of different volumes for charged subsystems in different states of motion, are in complete agreement with all fundamental physical laws. In particular, this approach is capable of describing in a consistent way the exploding-wire phenomenon, contrary to the claims given in the preceding Comment [Singal, Phys. Rev. E **48**, 4138 (1993)].

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## I. INTRODUCTION

It is shown in this paper that all the objections raised in [1], on the treatment of a current-carrying conductor (CCC) presented in [2] and [3], are groundless. In particular, it will be seen that, contrary to the claims given in [1], the definition of the charge neutrality of a CCC in terms of the Lorentz-invariant charges $\Delta Q$ [3] and the explanation of the exploding-wire phenomenon in terms of second-order electric fields [2], are neither confusing nor self-contradictory but quite clear and consistent.

## II. NO ADVANTAGE IN USING THE USUAL APPROACH

Let us explain the approach from [3] [for an infinite wire with current (IWC)], and [4] (for a closed CCC), and discuss the objections from [1]. When a macroscopic charge is an invariant, and why the charge contained in a section of a CCC is not an invariant is discussed in detail in [5], there is no need to repeat it. Furthermore, it is explicitly shown in [6] that the transformation law for the charge-current-density four-vector and for the charge $\delta Q=\rho dV$ can be derived from the relativity of simultaneity and the invariance of an elementary charge $e$. It implies that these transformation laws do not depend on the possible relation between $\Delta_e$ and $\Delta$, $\Delta_e=\Delta$ for the usual approach, while $\Delta_e=\Delta/\gamma$ for the approach [3,4], where $\Delta$ is the mean distance between stationary ions and $\Delta_e$ between moving electrons in a CCC at rest, and $\gamma=(1-v^2/c^2)^{-1/2}$. Of course this conclusion, together with the conclusion that both choices for $\Delta_e$ are in the same position with respect to Maxwell's equations and the Lorentz force law (as discussed in [7], which is the reply to the objections raised in [8]), hold for both an IWC and for a closed CCC. Furthermore even *for a closed current loop at rest, and for both approaches, the total charge Q is zero,* as it was before a current was established, and also the time independence of charge densities and fields exists in a steady state [4] and [7]. There is only one length scale in the conventional approach for the case of a CCC (an IWC or a closed CCC) at rest, and thereby it is natural to use only one volume element, that one of the wire, i.e., of the lattice of ions, for both the moving electrons and stationary ions. However, when the assumption $\Delta_e=\Delta/\gamma$ is accepted, and the total number of electrons remains the same as it was before a current was established, then necessarily the moving electron subsystem in a closed CCC at rest must shrink to a smaller length as discussed in [4], [7], [5], and [2]. Hence, there are now two length scales in a *stationary* current loop, one for moving electrons determined by $\Delta_e$, and the other for stationary ions determined by $\Delta$. The electron subsystem is accordingly constrained to move in the contracted volume $V/\gamma$, which is appropriate to the contracted $\Delta_e$, while the stationary ions are contained in the volume $V$ as before the current was established. This discussion shows that the use of different volumes for the charged subsystems in a relative motion is not in contradiction with any physical law. The charges contained in such different volumes are the Lorentz-invariant charges $\Delta Q$ introduced in [3].

## III. ADVANTAGE IN USING THE APPROACH WITH $\Delta_e=\Delta/\gamma$

There is an even more convincing argument which supports the validity of the contraction of $\Delta_e$, and the use of different volumes for the ions and the electrons in different states of a relative motion. Namely, if $\Delta_e=\Delta$ is assumed, then a ring with current rotating in $S$, i.e., the laboratory frame, is charged, $Q'\neq 0$, while the same ring at rest is charge neutral, $Q=0$. However when $\Delta_e=\Delta/\gamma$ is assumed, then the ring with current is always charge neutral, if it was neutral before a current was established. We sketch here the proof for these assertions for a one-dimensional (1D) closed (circular) current loop, while the detailed discussion for a wire of finite cross section is exposed in [9].

Let us suppose, as in the usual approach, that $\Delta_e=\Delta$ for a stationary ring with a current. Then, $\lambda_-=-\lambda_0$, and $Q$ for the whole ring is zero, $Q=(\lambda_0-\lambda_0)L=0$, where $L=2\pi R$, and $R$ is the radius of the ring. Let this 1D ring now rotate; for simplicity let it be with such velocity that the free electrons are at rest. Due to the rotation the mean spacing between moving ions in $S$ is contracted

 

$\Delta'_+ = \Delta/\gamma$, and therefore $\lambda'_+ = \gamma\lambda_0$. [Note that the primed quantities here refer to the ring rotating in $S$, and all measurements are performed in a *single* inertial frame of reference (IFR), i.e., in $S$, on objects at rest and on the same but moving objects by means of the set of units belonging only to $S$. It is shown in [10] that such an "unusual" picture of the relativistic kinematic effects is actually equivalent to the common one, in which the time and length measurements are performed in *different IFR's*.] However, the mean spacing between stationary electrons now, in the rotating ring, $\Delta'_-$, will not change in the same way as $\Delta'_+$, i.e., it will not be equal to $\Delta/\gamma$, since in the stationary ring the mean spacings for the ions and the electrons were supposed to be the same, although their states of motion were different. Consequently $\lambda'_-$ will not be equal to $-\gamma\lambda_0$. *When these different charge densities are multiplied by the same volume, that is one of the contracted "wire," i.e., of the contracted lattice of ions, $L/\gamma$, then the total charge $Q'$ will be $\neq 0$.* Remember that in the conventional approach, when calculating the charges for stationary or moving wires, the charge densities are always multiplied by only one volume, that being one of the lattice of ions. Thus, in the usual treatment $Q = (\lambda_0 - \lambda_0)L = 0$, while $Q' = (\gamma\lambda_0 - \lambda_0/\gamma)(L/\gamma) \neq 0$, (we have here supposed that $\Delta'_- = \gamma\Delta$ and accordingly $\lambda'_- = -\lambda_0/\gamma$). We see that both fundamental physical laws, the conservation, and the invariance of charge are invalidated in the conventional treatment of a CCC.

In the approach [2–7] $\Delta_e = \Delta/\gamma$ in the stationary ring with a current, which means that the electrons are, due to their motion, closer together than the ions. Their charge density is enhanced $\lambda_- = -\gamma\lambda_0$, but since the number of electrons is not changed by setting up a current they must move on a smaller ring with the length $L/\gamma$. The total charge $Q = \lambda_0 L - (\gamma\lambda_0)(L/\gamma) = 0$, as in [4] and [2]. In the rotating ring $Q'_+ = Q_+$, as in the usual approach. However, the electrons, which are now at rest, are farther apart than they were when moving in the stationary ring, and therefore $\Delta'_- = \Delta$ and $\lambda'_- = -\lambda_0$, whence $Q'_- = (-\lambda_0)L = Q_-$ and $= -Q'_+$. The total charge $Q' = Q'_+ + Q'_- = 0$, as it should be. This means that, contrary to the usual approach, the theory from [2–7], and [9] is in complete agreement with all fundamental laws.

## IV. THE EXISTENCE OF THE EXTERNAL SECOND-ORDER ELECTRIC FIELDS

When the contraction of $\Delta_e$ is accepted, then there are electric fields outside a stationary infinite wire with current [3], and a stationary ring with current [4]. The experiments of Edwards, Kenyon, and Lemon [11] were compared with this theory in [4], and a good agreement is obtained. However, it is erroneously argued in my work [4] that the average value of the potentials $\langle \Phi^+ + \Phi^- \rangle$ is also different from zero; $\Phi^+$ is the potential induced by the positive ring with stationary ions and the length $L = 2\pi R$, while $\Phi^-$ is the potential induced by the moving electrons situated on the contracted length $L/\gamma$. This mistake does not influence in any way either the validity of the theory developed in [2–7] (and [9]) or the other comparison with the experiments from [11]. Recently, new experiments [12] have been reported. Contrary to the claim given in [1] the electric fields outside superconducting Nb and Nb-Ti coils have been detected in the individual runs and these potentials have been of the proper functional dependence ($\propto I^2 L$) and of the order of magnitude obtained from the theory in [4]. The fields were not obtained in the Faraday-cage configuration, which agrees with both the usual approach and the approach of [3] and [4]. The magnitudes (and the sign) of the potentials differed markedly from run to run, which led the authors of [12] to argue that all potentials observed in [11] and [12] are caused by a classical source, the stray charges on teflon insulators. However, their results do not exclude the possibility that together with this classical source there are potentials induced by the source predicted in our approach [3] and [4]. Namely the potentials predicted in [3] and [4] exist always for a stationary CCC, but they can be changed by the stray charges whose magnitudes and the configurations are uncontrolled in different runs. This shows that it will be possible to experimentally check the theory from [2–7] in the experiments with superconducting wires only after removing the uncontrolled effects (stray charges).

## V. ALTERNATIVE APPROACH CAPABLE OF EXPLAINING THE EXPLOSION OF WIRES

The last objection from [1] refers to the explanation of the exploding-wire phenomenon. We note once again that the longitudinal electric force between two current elements lying in the same straight line, Eq. (4) in [2], which is caused by the charges $\delta Q = (1-\gamma)\lambda dl$, Eq. (4) in [3], is equal up to the factor $\frac{1}{2}$ to the force obtained from the Ampère force law, Eq. (4) in [13]. When, for instance, the Ampère forces are utilized for the calculation of the specific tension $T_x/i^2$ across plane $X$ intersecting the wire $AB$ [Fig. 2, and Eqs. (7), (8), (13), and (18) in [13]], then the forces [Eq. (1) in [13]] between current elements on both sides of the intersection are summed up. In the same way this tension can be calculated in our approach using the charges $\delta Q$, the second-order electric fields induced by these charges, Eq. (5) in [3], or the expression for $\mathbf{E}_{1,\mathrm{ext}}$ from [2], and the force $d\mathbf{F}^r_{2,E}$ from [2] generated by $\mathbf{E}_{1,\mathrm{ext}}$. In both cases [13] or [2,3], the force exerted by current element $i_1 dl_1$ upon the other current element $i_2 dl_2$ is calculated at the "location" of the current element $i_2 dl_2$, and the tension across the intersection is obtained by summing these forces. In [14] the meaning of tension across the interface is the same as in [13], i.e., as explained here. The author of [1] misunderstood this fact.

Furthermore, it is argued in [1] that the explanation of the explosion of straight wire in terms of the electric forces $d\mathbf{F}^r_{2,E}$ is not correct since: "· · · every element of a straight wire is surrounded by current elements on either side along the wire length and any longitudinal force component should symmetrically get canceled." To disprove this objection we recall the consideration performed in [13] (remember that the forces from [13] and [2] are equal up to the factor $\frac{1}{2}$). First, it is noted in [13] that *an infinitely long straight conductor has to be treated as a closed circuit,* which is, of course, a physical case. Then, when performing the macroscopic current-element analysis in Sec. III, it is obtained that if $l \gg a$, for an $a \times a$ square-section conductor of straight length $l$, *the important midplane tension is largely independent of any further increase in length.* Furthermore, it is shown that in the case of Fig. 3 in [13], where $l/a = z = 1000$, *over 80% of the midplane tension is being contributed by the repulsion of in-line elements, which means that when dealing with very long straight conductors one may ignore the return circuit.* Thus, the fact that in experiments one deals, even in the case of long straight wires, with closed circuits of finite size, and also that a current-element utilized in the computer-aided finite-current-element analysis must be of finite size, gives that, contrary to the objection from [1], there is a finite tension in long straight metallic conductors. This tension in our approach is produced by the electric forces from [2,3], and it can cause the explosion of wires at high pulse currents.

Recently some new experiments [15] were performed with intention to detect the longitudinal forces. The experimental arrangement in the first type of the experiments contained a free armature which can oscillate in the vertical direction under the action of the longitudinal forces. In the second type, the rupture of the straight aluminum wire, as in [13], has been reported. The negative result of the experiment with the movable armature led the authors to conclude that the explosion of wire is not caused by the longitudinal forces, either of the Ampère type or some other type, e.g., that one proposed in [2]. However, the authors of [15], in a similar way as many others (e.g., Ref. [9] in our Ref. [2], and all Graneau's experiments with railguns), did not take into account zeroth-order surface-charge distributions, and consequently $\mathbf{E}^0_{\text{ext}}$ and $d\mathbf{F}^0_{2,E}$, which were discussed in [2]. The electric fields ($\mathbf{E}^0_{\text{ext}}$) can be very high in "railgun" experiments, and there are the components of these fields along the armature (thus giving the longitudinal forces), which are induced by the surface charge distributions in the upper and lower plate, and in the rods *DE* (see Figs. 2 and 5 in [15]). Furthermore, it is not allowed in any approach to include the contributions from the forces induced by the parts of the movable armature in the calculation of the total axial force on that armature (see Secs. III D and III E in [15]), since the forces from the parts of the armature itself ("internal" forces) cannot move the armature as a whole. If these forces could be able to set in motion that armature, then a man could lift himself by dragging his hair as in Baron Munchausen's narratives. Therefore the negative result of the experiments [15] with the movable armature does not mean that there are no longitudinal forces, as claimed in [15], but, in fact, show (within the accuracy of the experiment) that the other parts of the circuit (which generate the "external" forces), the plates, rods, and the part of the central conductor under the armature, do not produce a net longitudinal force on the armature as a whole. In the approach from [2] the total force on the armature is determined by the sum of all external electric forces $d\mathbf{F}^0_{2,E}$ and $d\mathbf{F}^r_{2,E}$ exerted by the other parts of the circuit on the armature. We believe that the symmetry in the experiment [15] caused the cancellation of the external forces on the armature, but probably the most important contributions arise from those parts of the circuit which are the closest to the ends of the armature. To check this hypothesis one would need to perform the experiments (not the calculation, as done in [15]) with the experimental arrangement without the symmetry.

In contrast to the experiments with the movable armature, where only the external forces are effective, in the experiments with the rupture of the wires [15], Sec. IV, only the "internal" longitudinal forces, exerted by some parts of the wire on the other parts of the same wire, are the most effective in both approaches, the Ampère force law and the approach from [2]. Thus, the explanation of the explosion of straight wires observed also in [15] in terms of the longitudinal forces $dF^r_{\text{long}}$ [Eq. (4) in [2]] still remains as a quite possible explanation.

In that way we have shown that, contrary to the assertions in [1], the approach of [2–7] is a correct and consistent approach, which is in accordance with all physical laws, and it is capable of explaining the experiments from [12] and [15].

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