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Voltages in Toroidal Pinch Experiments

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VOLTAGES IN TOROIDAL PINCH EXPERIMENTS

by

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ABSTRACT

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In toroidal experiments, such as Screw Pinches, Belt Pinches, and Reversed Field Pinches, with both toroidal and poloidal magnetic fields, quite complicated E-fields exist. For an appropriate design one should however, know what voltages occur between the various coils, the stabilizing shell, the plasma itself, the pumping stations, and diagnostic equipment.

In this report an attempt is made to give a systematic description of the voltages that develop between coils and objects placed inside of them. Two types of coils are considered, one without an external return flux, analogous to the toroidal field coil; and one with external return flux, analogous to the poloidal field coil. Possible methods of grounding are discussed. The Appendix describes what voltages are to be expected in the ZT-40 Reversed-Field Pinch experiment under construction at the Los Alamos Scientific Laboratory.

I. INTRODUCTION

Voltages across small coils and coils with iron cores can be measured without problems; the magnetic flux is concentrated in a region far from the voltmeter and its leads. However, for large coils without iron cores, problems arise because the voltmeter and its leads cannot avoid the flux region. The integral $\oint \mathbf{E} \cdot d\mathbf{l}$ is then no longer zero, but equal to $-d\phi/dt$. Voltages, defined as $\int \mathbf{E} \cdot d\mathbf{l}$ then depend on the integration path and should therefore not be reported without information on the location of the measuring leads. The use of the word "potential" is then misleading and incorrect.

To illustrate this: on the outer conductor of coaxial cables and on the outside of wave-guides and microwave cavities no voltages can be measured; on the inside however, E-fields exist and voltages can be measured.

According to the standard rule $E_{\parallel}$ is zero at the surface of a metal. Actually, the resistivity of the metal causes a remaining E-field, which is an order δ/L smaller than the E-fields at some distance from the metal. At high frequencies the skin-depth δ is small compared to the characteristic dimension L of the coil, which makes it reasonable to neglect $E_{\parallel}$.

In this report we consider toroidal machines with both toroidal and poloidal B-fields, as used for experiments on Screw Pinches, Belt Pinches, and Reversed Field Pinches. We have two different types of coils in these machines. The theta coils generate an internal longitudinal B-field, but have, in a toroidal machine, no external return flux. This is true for the external θ -coil and also for the θ -currents in the plasma. The situation is different for the toroidal currents in the primary ϕ -coil and in the plasma. These two " ϕ -coils" have the field configuration of a plasma loop and the flux that returns outside the loop is essential. Clearly we have to distinguish between the ϕ - and the θ -coils when voltages between all sorts of objects and these coils are studied.

II. COILS AND OBJECTS

The two types of coils are shown in Fig. 1. The θ -coil is toroidal, or infinitely long, and has no external return flux. The ϕ -coil is short and has an appreciable field on the outside. If no ferromagnetic cores are used, the return flux is spread out over space; with cores the flux is concentrated inside the iron.

We consider now various objects that could be placed inside the coils and study the voltages between the object and the coil and the influence of grounding. The objects considered are shown in Fig. 2 and are listed as follows.

1. A metal shell with a gap. The B-field enters the volume surrounded by the shell and causes an E_{θ} -field near the gap. For the rest the E_{θ} -field near the surface of the shell is zero.
2. A number of conductors, distributed over the circumference, and all connected to the center. These conductors distribute the E_{θ} -field rather smoothly, especially when there are many conductors. The connection with the center is necessary to not let the capacity between the coil and the conductors determine the distribution of the E-fields. The θ -coils wound

around the I_ϕ -coil (the shell) can be considered as objects of this type, on the outside of the I_ϕ -coil.

3. A resistive layer for instance used to shield against the E-field in the feed point of the coil, distributes the E_θ -field evenly. The E_θ -field is of course only present if the resistance of the layer is high enough to permit flux to penetrate. On the other hand the resistance has to be low compared to the impedance of the capacity between the resistive layer and the coil.
4. A highly conducting compressible plasma. The flux can now move in because the plasma can be compressed. In a stationary coordinate frame we have also here an evenly distributed E_θ -field; in a coordinate frame that moves with the plasma the E-field is zero.

The E-fields between coil and object are basically the same for the objects 2, 3, and 4, because the E-field at the surface of the object is for all three given by $\dot{\phi}/2\pi r$, where ϕ is the flux inside a circle with radius r .

III. FLOATING OBJECTS

We consider now the E-fields between the coil--of whatever type--and the object. We introduce the voltage difference V_{co} between coil and object, measured along a radius

$$V_{co} = \int_{coil}^{object} E_r dr \quad .$$

To find V_{co} we calculate $\oint E \cdot d\mathbf{l}$ for a small contour in a sector $\Delta\theta$ (Fig. 3). For the direction of the B-field and the sense of rotation chosen, a negative $d\phi/dt$ is enclosed. This corresponds to a positive $\oint E \cdot d\mathbf{l}$ for the small contour. Along the coil surface the E-field is zero, except near the feed point; along the object the E-field is zero (except near the gap) when it is a shell, or equal to $rB/2$ in the case of distributed conductors, a resistive layer or a plasma. The contribution to the integral along the two radii is

$$- V_{co}(\theta) + V_{co}(\theta + \Delta\theta) = (dV_{co}/d\theta)\Delta\theta \quad .$$

The value of $dV_{co}/d\theta$ can then be found; over most of the circumference this quantity is positive and either small, if only the flux change between the coil and a shell contributes, or large for the three objects where the flux change in the whole sector $\Delta\theta$ counts. At the feedpoint of the coil we have a strong positive E_θ that has to be compensated by a strong negative $dV_{co}/d\theta$; in the same way we need a large positive $dV_{co}/d\theta$ at the gap in the shell. At the right hand side of Fig. 3 $dV_{co}/d\theta$ is plotted as a function of θ ; also plotted is V_{co} found by integration. The integration constant determines the level of these curves. The situation where the object floats is plotted, which means that in the absence of any connection to the outside world the total displacement current from coil to object has to be zero, in other words $\int V_{co} d\theta$ has to be zero. How these voltage levels change when ground connections are made will be discussed later.

An alternative method to rapidly determine the direction of the various E-fields is to analyze how the magnetic energy streams in or out of the system. For a rising magnetic field, the energy comes in as a Poynting flux $(\underline{E} \times \underline{B})/\mu_0$ through the feedpoint of the coil (at $\theta=\pi$). From there the energy stream branches and flows between shell and object. The central area is filled through the gap at $\theta=0$ in the case of the shell, and in the case of the three other objects by a flow that is evenly distributed over all θ -values. Given the direction of B, one can find the direction of E unambiguously from the direction of the energy flow $\underline{E} \times \underline{B}$.

The voltages discussed here are voltages measured along the shortest path, the radius. Such voltages are important for the insulation between θ -coils and shell or for the insulation between shell and plasma (through the insulating vessel or near the tubulations).

IV. VOLTAGE MEASUREMENTS

The results of voltage measurements depend on the precise location of the voltmeter leads. To illustrate this we consider the voltmeter in Fig. 4. For a θ -coil the voltmeter will read no voltage, or only a very small one caused by the Ohmic resistance. For a ϕ -coil the leads enclose a part of the return flux and this leads to a voltage across the impedance of the voltmeter. The return flux is distributed outside the coil for an air core coil; for an iron core the

Fig. 1.

The two types of coils considered. The θ -coil is infinitely long or closes up on itself, and has therefore no external return flux. The ϕ -coil is short and has a large outside field. The ϕ -coil can have the form of a toroidal shell or of a plasma ring.

Fig. 2.

Four different objects, described in the text, placed inside a coil.

Fig. 3.

Electrical fields and voltages between a coil and an object placed inside it. In (a) the object is a shell with a gap on the left. In (b) and (c) the voltage between coil and object and its derivative with respect to θ are shown as function of θ for a shell (b) or for distributed conductors, a resistive layer or a plasma (c).

voltage seen depends on whether a core is enclosed or not. Of course if ever the cores saturate, the location of the leads is again more critical. The important thing in all those cases is what flux is enclosed by the contour formed by the leads. A change of this flux creates an integral $\oint \mathbf{E} \cdot d\mathbf{l}$, which shows up, not along the metal measuring leads where $\mathbf{E}=0$, but across the high impedance voltmeter.

In other measurements, such as the one shown in Fig. 5, where the voltmeter is connected to a shell, one cannot define the closed contour all the way in the metal. To go back from the shell to the coil one has to jump across the local gap (dotted line). In doing that one sees the integral $\int \mathbf{E}_r \cdot d\mathbf{r}$, which equals the local V_{co} . This voltage and a possible enclosed $-d\phi/dt$ value will contribute to the voltmeter reading. It would seem that the choice of where to jump from one piece of metal to the other would make the final voltmeter reading ambiguous. This is fortunately not true, jumping at some other point may change the integral $\int \mathbf{E} \cdot d\mathbf{r}$ that one sees while jumping, but it also changes the location of the contour and thereby the enclosed flux, and those two effects cancel. Of course one can often save mental effort by choosing a simple path and by "jumping" at locations where the voltage is known.

What voltage is eventually measured depends on the location of the voltmeter leads, on the type of coil (θ or ϕ , air core or iron core) and on whether the measuring leads cross a gap or not. To avoid crossing of gaps it is a sensible rule not to have any leads going through the center of a toroidal machine, unless it is absolutely necessary (θ -coils and diamagnetic loop).

It is important to work out what voltages can appear in various circuits, not only for voltage measurements, including electrostatic probes, but also to work out what insulation is required to prevent breakdown, or how the routing of leads can be changed to reduce voltages to diagnostic equipment and pumps, for instance.

V. GROUNDING

In the situation of Fig. 3 the object was floating inside the coil; in other words the net displacement current from coil to object was zero. By making a ground connection one can change the level of the voltage V_{co} . The ground connection of course should then carry a displacement current

$$i = C_{co} \, d/dt (V_{\text{grounded}} - V_{\text{floating}}) ,$$

where C_{co} is the capacity between coil and object. For the usual capacitor bank discharge, all voltages and derivatives of voltages have the shape as shown in Fig. 6. Especially during the first peak of dV/dt a large current has to flow through the ground connection to the ground side of the capacitor bank. The inductances in the connection form an LC-circuit with C_{co} . Clearly, to ground effectively, the resonant frequency of that LC-circuit has to be higher than the frequencies in the steep voltage front. Compared to this the later slower voltage changes can be easily handled.

It is not easy to give general rules on what ground connections are useful and permissible. We therefore discuss a particular example (see Fig. 7a), a shell in two pieces inside a single turn coil. Without any ground connection each half of the shell floats. The voltage between coil and shell remains small (Fig. 7b) because each half of the shell follows, on the average, the voltage of the nearby part of the coil. This means that the gap in the shell at $\theta=180^\circ$ has to hold the full voltage, whereas there is very little voltage across the gap at $\theta=0^\circ$. A situation in which both gaps would carry the same voltage is more desirable; even though it leads to higher voltages V_{co} (see Fig. 7c).

In a ϕ -coil this situation can be obtained quite easily. First of all because there is no plasma in the center of the coil, a connection along a diameter can be made and that gives the required voltage distribution (Fig. 7d). For this type of coil one can also install a closed ring at a large distance from the coil. The circulating current induced in such a ring can be reasonably small because it encloses the flux inside the coil as well as a large fraction of the return flux. Grounding wires can now run from diametrically opposite points of the ring to the two shells (Fig. 7e). The dotted connections to the grounded side of the coil are possible but not necessary; regardless of whether these connections are made or not, the voltages are distributed as shown in Fig. 7c.

In a ϕ -coil it is much harder to ground properly. A plasma occupies the center of the coil and there is no outside return flux. Any closed loop outside the coil then encloses the uncompensated flux inside the coil, and will carry a large current that can be reduced by having a large impedance distributed around

Fig. 4.
No voltmeter reading without return
flux outside the coil.

Fig. 5.
Voltmeter connected to a shell inside
a coil. To work out what the volt-
meter reading will be, one has to jump
back from shell to coil to close the
contour.

Fig. 6.
Current, voltage, and time de-
rivative of the voltage for the
standard discharge of a capaci-
tor bank. The peak in dV/dt re-
quires a large current in a ground-
ing connection.

Fig. 7.

Methods of grounding of two half-shells inside a coil (a). The groundings change the voltage between coil and shell from (b) to (c). For a ϕ -coil methods (d) and (e) are available; for a θ -coil only method (f) can be used. The dotted extra ground connections are optional.

the loop. Inductances are undesirable because of possible resonance effects in the grounding currents. Figure 7f shows a solution with resistors in the loop. The resistance should be large enough to keep the current in the loop ($V/2R$) much smaller than the current in the coil. On the other hand one should have the resistors small enough to have very little voltage drop caused by the displacement currents that flow between top and bottom. The dotted connection is optional here also.

VI. E-FIELDS INSIDE THE SHELL

The E-fields inside a shell with gaps are discussed by Stotland and Khil¹ and in an internal report by the Padua group.² As soon as some plasma has been produced, all E_r -components--except homogeneous ones related to diffusion--are pushed back into the insulating material of the vessel and in the space between shell and vessel. All that remains in the dilute plasma are homogeneous E_z -fields, and E_θ -fields linear in r . In a slightly later phase, strong currents, skin effect, and motion of the plasma change those fields again.

APPENDIX

APPLICATION TO THE ZT-40 EXPERIMENT

A description of the ZT-40 Reversed-Field Pinch Experiment, presently under construction at Los Alamos, is given in Reference³. A sketch of a part of the ZT-40 torus is given in Fig. A-1 with the coordinate system used. We consider a sector between two adjacent feed plates, $360/n$ degrees long, where n is the number of feed plates on the full torus. Also shown is one θ -coil fed by a coaxial cable coming in at about $\theta = 210^\circ$. The central conductor of this cable will be negative when energized by the bias field bank and positive when energized by the fast I_θ -bank (the reverse B_ϕ -bank). The side of the feed plate, which is in full view in Fig. A-1, is connected to the ground side of the mixer.

First we consider the voltage V_{cs} directly between the θ -coils and the shell. The θ -coils are well-grounded for ϕ -voltages by the θ -current mixer. The shell is grounded for ϕ -voltages at one side, the left hand side in Fig. A-1 of each active feed plate. The θ -voltage of course shows up across the gap at the inside ($\theta=180^\circ$) of the shell.

Fig. A-2 shows the voltage between the θ -coil and shell as a function of θ when only the θ -bank has been fired. The parasitic inductance between the cable and the metal shell leads to a slow increase of the voltage from $\theta=210^\circ$ on. Because of this the voltage across the gap is smaller than the voltage at the end of the cable. The voltage is negative and a few kilovolt for the bias bank and positive and around 50 kV for the fast I_θ -bank.

We now consider the voltage between the θ -coils and the shell when only the ϕ -bank has been fired. In Fig. A-3 this voltage is shown as a function of ϕ for two values of n . Note that ϕ increases from right to left, to make a comparison with Fig. A-1 easier. The location of the cores is shown; no voltage is shown for the θ -coils underneath the cores because the value there does depend on how the cables to those coils come in. The full lines show the voltages under normal operation, the dotted lines show the voltage distribution that would occur if the iron cores were driven into saturation. Note that under normal operating conditions no voltage appears for $n=12$, but that for other n a voltage as high as $1-n/12$ times the feed plate voltage shows up.

When both banks are fired simultaneously one should add the voltages at each moment and for each θ and ϕ during the programming. This should be worked out in more detail for each case, especially when fewer than 12 feed points are used.

Secondly, we consider the voltage V_{sp} , between the shell and the plasma. This voltage is important in the sense that it could cause breakdown through the ceramic, through the O-ring or glass seals of the torus, or possibly through a tubulation to the shell. A breakdown through a tubulation to diagnostic equipment or to a pump is not a matter of V_{sp} but of a voltage between plasma and "infinity." Near the ground side of a feed plate this voltage and V_{sp} are the same, but when less than 12 feed plates are used the situation is more complicated. When only the I_θ bank has been fired, the voltage V_{sp} is as shown in Fig. A-4 as a function of θ . The plasma floats with respect to the shell and a possible grounding through the pump ports (at $\theta=0^\circ$) does not change that for this example. Figure A-5 shows the situation as a function of ϕ when only the ϕ -bank has been fired. Without any grounding the plasma will float (full lines). A grounding past the plug to the pumpstand may take place; such a situation for $n=12$ is shown as a dotted line. The pump stand is 9° in space away from the middle of the feed plate, which corresponds to 12×9 degrees in the plot of Fig. A-5.

With less than 12 feed plates, the grounding is more complicated. If the θ -coils and the pump stands are both connected to the same ground (the mixers), the voltage between pump and plasma will be equal to $V_{sp} + V_{cs}$. Addition of appropriate graphs, such as Figs. A-3 and A-5 are for $n=12$, then gives the voltage between pump and plasma. Both this approach and a more general argument about where the primary and secondary fluxes are, show that the voltages are the same for all four pump stands. Grounding is therefore possible and should not introduce circulating currents. The ground connections should be in one plane with the main axis of the torus and should be at a reasonable distance from the cores to avoid effects of fringing fields and possible saturation. The grounding currents will be larger for smaller n because the voltage on the capacity between plasma and shell (approx 5 nF) is affected more.

Fig. A-1.

Sketch of a part of the ZT-40 torus showing the coordinate system, one feed plate and one θ -coil.

Fig. A-2.

Voltage between the θ -coil and the shell as a function of θ . Only the θ -coil has been energized.

Fig. A-3.

Voltage V_{cs} shown as a function of ϕ for two values of n . Only the ϕ -bank has been fired. The location of the iron cores is indicated. The full lines show the voltage when the cores operate normally; the dotted lines show the voltage when the cores are saturated.

Fig. A-4.

Voltage between the shell and the plasma as a function of θ . Only the θ -coil has been energized.

Fig. A-5.

Voltage between shell and plasma as a function of ϕ for $n=12$. The full line shows the voltage when the plasma is floating; the dotted line shows the effect of grounding to the pumpstand.

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