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Impedance Measurements on the LHC Injection Kicker Prototype

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Summary

The longitudinal beam coupling impedance of an LHC injection kicker model (not yet fully equipped) has been measured by means of the coaxial wire method. To get a reasonable estimate of the impedance, three contributions should be taken into account. These contributions are the effect of the ferrite yoke which absorbs electromagnetic energy, the effect of the cold and hot conductors which alter the shape of the TEM-like field of the beam, and possibly cavity resonances in the tank. Since the bench measurement of this model indicates very high energy deposition in this structure with the LHC beam, also another model in which the ferrites and the tank are shielded from the beam by an alumina tube which has a number of metal strips on the inner surface, was examined. The comparison of two measurements shows good reduction of the coupling impedance by this beam screen technique.

1 Introduction

The injection kickers designed for the LHC consists of 4 units for each beam [1]; each of these units has a C-magnet (traveling wave magnets of 2670 mm length each) with a single turn coil. These systems will inject proton beams into the LHC at the energy of 450 GeV. To achieve the required high kick strength of 1.3 Tm, a comparably low characteristic impedance for the traveling wave kicker has been chosen. Here we will show the need to add beam screens to protect the kicker ferrite from the beam and to reduce the beam coupling impedance. These beam screens will consist of longitudinal copper strips applied on the ceramic (on the inner surface of the beam tube) without ohmic contact between them to avoid eddy currents during the rise and fall of the kicker magnetic field.

A simplified cross section of injection kicker is shown in Fig. 1. This plot is a schematic cross section of a magnet cell with C-shaped ferrite yoke and 2 ceramic matching capacitors mounted between high voltage (hot) and ground (cold) plates. The relatively long filling

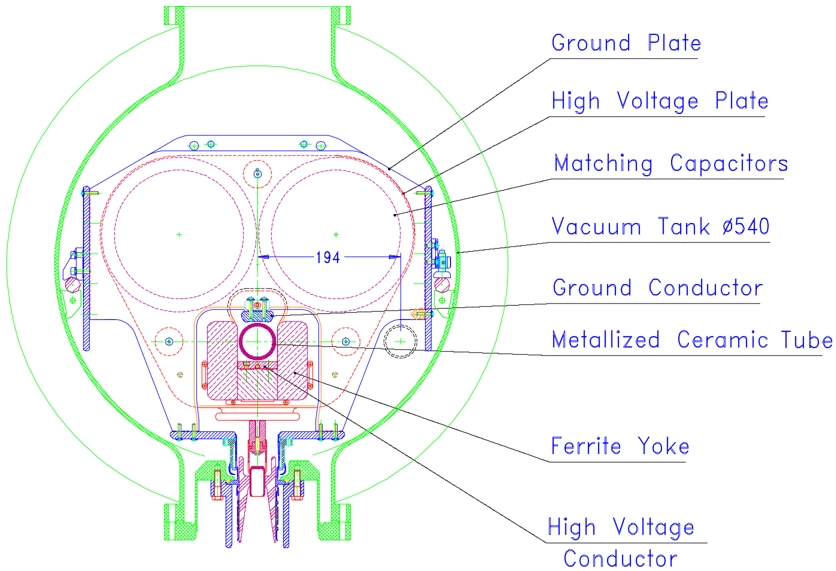

Figure 1: Schematic cross section of the LHC injection kicker magnet.

time permits to build a magnet of about 2670 mm length using capacitors of 4.04 nF per cell (33 cells of 80.5 mm) in 3600 mm vacuum tank. This will be achieved by means of high voltage / high frequency grade 1 ceramic plate capacitors. Outgassing tests have shown that these capacitors can be used under high vacuum provided that clamped connections are used instead of the usual brazed ones. The magnet will be housed in a cylindrical vacuum tank of 540 mm diameter.

2 Measurement Procedure

Impedance measurements were done on an LHC beam injection kicker prototype using a HP 8753D vector network analyzer (VNA) and the coaxial wire method [2]. The data of the VNA were stored on disk using the HP-VEE (Hewlett-Packard Visual Engineer Environment) code.

The coaxial wire method is a convenient bench method for the simulation of charged particle beams. It is based on the assumption that a bunch of a highly relativistic beam has an electromagnetic field distribution very similar to that of a short pulse on a coaxial line (TEM field). For longitudinal coupling impedance measurements, the test bench set-up consists of a single conductor (wire) in the center of the vacuum chamber, at the position of the beam.

Since the characteristic impedance Z_c of the device under test (DUT) is higher than $R = 50\ \Omega$ line impedance of the cables which connect VNA and the DUT, a matching resistor of resistance $R_m = Z_c - R$ is added in series at each end of the wire. With matching resistors, there is impedance mismatch from the cable to the DUT which lowers the transmission coefficient S_{21DUT} of the DUT with a factor of $s = (R + R_m)/R$. This factor s takes into account the effect of both matching resistors. After the measurement, S_{21DUT} should be corrected by multiplying it by s.

The longitudinal coupling impedance Z is obtained by using the "standard" log formula or the "improved" LOG formula [3]:

$$Z_{log} = -2Z_c \ln\left(\frac{S_{21DUT}}{S_{21ref}}\right), \tag{1}$$

$$Z_{LOG} = Z_{log}\left[1 + \frac{jc}{2\omega l_F}\ln\left(\frac{S_{21DUT}}{S_{21ref}}\right)\right], \tag{2}$$

where $l_F = 2670$ mm is the length of the ferrite. The reference transmission coefficient S_{21ref} is $\exp(-j\omega l/c)$, where $l = 3740$ mm is the length of the DUT. Since S_{21DUT} is always accompanied by S_{21ref} in the formulae, the ratio S_{21DUT}/S_{21ref} is measured directly with VNA by using the electrical delay option in VNA.

3 Measurement without Shielding Strips

The mechanical length of the DUT is 3740.5 mm, including round extension tubes of $D_1 = 60$ mm inner diameter. The cold conductor is connected to the outside by the round extension tubes. For the hot conductor, we always have a capacitor 100 pF at each end. With $d = 6$ mm wire diameter, the characteristic impedance is

$$Z_c = 60 \ln\left(\frac{D_1}{d}\right) = 138\ \Omega. \tag{3}$$

From an S_{11} measurement in the time domain, Z_c was found as 135 Ω for the round extension tube. This would lead to 85 Ω matching resistor. Since the nearest standard value is 82 Ω, we chose this value ($R_m = 82$ Ω) for this measurement. But probably a matching resistor of 91 Ω would have been a better choice. We may use a formula for two parallel conducting plates configuration with $D_2 = 54$ mm horizontal aperture of the C-shaped ferrite:

$$Z_{c2} \simeq 60 \ln\left(1.27\frac{D_2}{d}\right) = 146\ \Omega, \tag{4}$$

which is not so different from the value indicated above.

In the VNA, 12.49 ns (which corresponds to the length of the DUT) electrical delay was set to measure S_{21DUT}/S_{21ref} directly. Figure 2 shows the S_{21} parameter (the amplitude and the phase). The raw data are shown as dotted lines. To correct the mismatch, the amplitude of S_{21} should be multiplied by $s = (50 + 82)/50 = 2.6 = 8.4$ dB. The solid lines show the corrected data. Also, since the phase measured by the VNA has ambiguity of $n \times 360°$, this should be corrected as shown in this figure.

Figure 3 shows the real and imaginary parts of the longitudinal coupling impedance by using Eqs. (1) and (2). The difference of two formulae is within 10% at high frequencies. The dashed lines show the result of the analytical formula [4] for a model shown in Fig. 4. Since the strong peaks of the resonances in the tank is not observed in the figure, it seems that these resonances are damped by the ferrite block and their effect for the coupling impedance is relatively small. Also the agreement of the measured result and the analytical formula

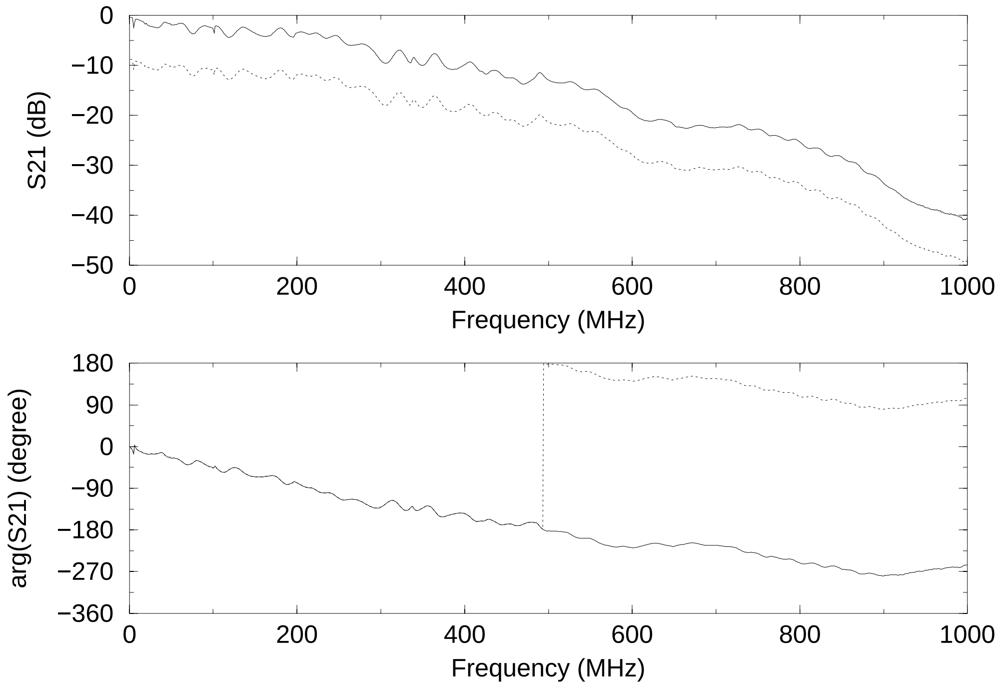

Figure 2: Measured S_{21} of the injection kicker prototype without shield. Electrical delay is corrected in the VNA. The dotted and the solid lines show the raw and the corrected data, respectively. Note that there is no indication of cavity resonances from the tank, which would show up beyond 300 MHz.

supports this. Therefore we can forget the tank in the next measures: the vacuum tank has no effect in the measurement results, and in particular we do not observe a "by-pass" effect via microwave modes in the vacuum tank as it was seen with the SPS MKE kicker [3].

4 Estimation of the Power Dissipation in the LHC Injection Kicker

The LHC RF frequency is 400.79 MHz, with a harmonic number $h = 35640$. The nominal bunch separation is $t_{sep} = 24.95$ ns, corresponding to 10 RF cycles, and the r.m.s. bunch duration at collision energy is $\sigma_t = 0.25$ ns. Assuming a Gaussian longitudinal distribution, the nominal LHC bunch population $N_b = 1.05 \times 10^{11}$ protons corresponds to a peak current $I_{peak} = eN_b/(\sqrt{2\pi}\sigma_t) = 26.81$ A. As a consequence of several gaps for injection and dump kickers, the LHC bunch pattern is not uniform and there are "only" $M = 2835$ bunches, instead of $h_b = h/10 = 3564$ which corresponds to uniform filling. The nominal average beam current is thus $I_{av} = 0.536$ A, instead of $I_{avu} = 0.674$ A corresponding to uniform filling.

The beam current can be written as follows:

$$I(t) = I_{av}\left[1 + 2\sum_{n=1}^{\infty} a_n \cos(n\omega_b t) + \text{side bands}\right], \tag{5}$$

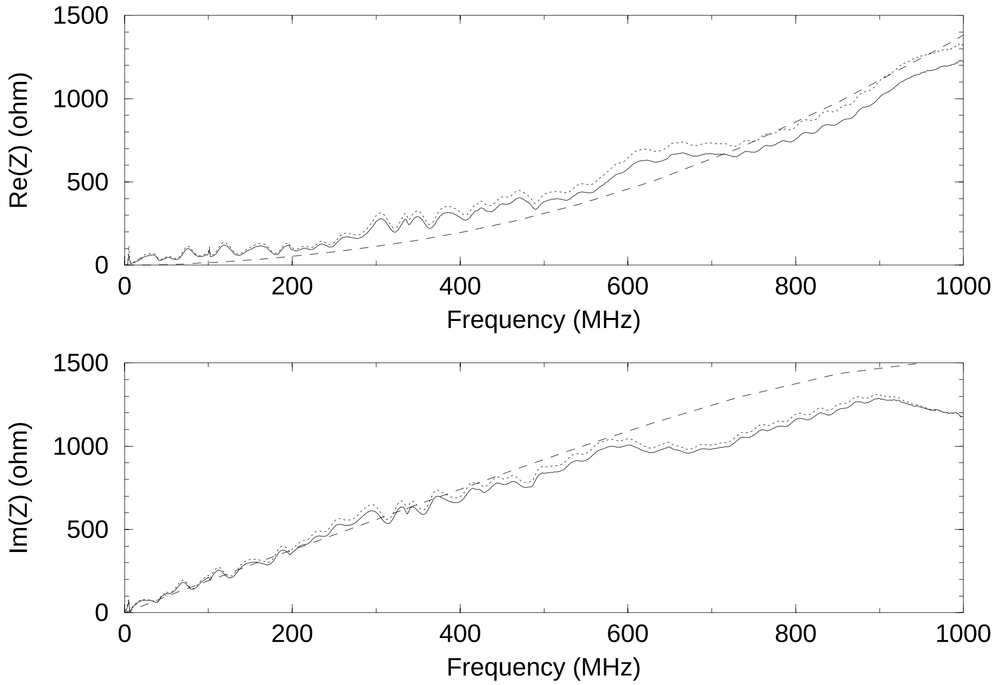

Figure 3: Longitudinal coupling impedance of the LHC injection kicker with C-shaped ferrites inside tank. The solid and dotted lines show the result by the standard log formula (1), and the improved LOG formula (2), respectively. The dashed lines are by the analytical formula for Model 2 in [4]. For ferrite, Philips 4A4 ferrite properties [5] are used.

where $\omega_b = h_b\omega_0 = 2\pi \times 40.08$ MHz is the angular bunch frequency. Fourier coefficients for Gaussian bunches are

$$a_n = \exp[-(n\omega_b\sigma_t)^2/2]. \tag{6}$$

The parasitic power dissipated in a kicker with longitudinal impedance $Z(\omega)$ can be written as a sum over positive harmonics of the bunch frequency

$$P = 2I_{av}^2(h_b/M)\sum_{n=1}^{\infty} a_n^2 \mathrm{Re}[Z(n\omega_b)]. \tag{7}$$

Here, we have assumed the coupling impedance is broad band, and taken into account the contributions of the sidebands by introducing the factor h_b/M.

Table 1 shows the first 30 coefficients a_n and a_n^2. Since $2I_{av}^2 h_b/M = 0.722$ A^2 is not far from 1 A^2, the coefficients a_n^2 practically give the power dissipated in a 1 Ω impedance at the corresponding frequency. For example, the power dissipated in a 1 Ω impedance around 800 MHz (n = 20) is $0.722a_{20}^2 = 0.147$ W. The Fourier component

$$P_n = 2I_{av}^2(h_b/M)a_n^2 \mathrm{Re}[Z(n\omega_b)] \tag{8}$$

is shown in Fig. 5 as a function of the frequency. The peak value is about 200 W / harmonic at 600 MHz. The total power deposition is at least 3.0 kW using the impedance data up to 1 GHz.

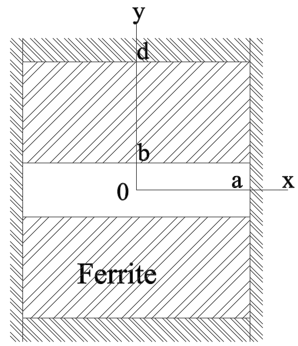

Figure 4: Cross section of a model for analytical calculation of the longitudinal coupling impedance. The beam moves along z (out of the page).

n	a_n	a_n^2	n	a_n	a_n^2	n	a_n	a_n^2
1	0.998	0.996	11	0.786	0.619	21	0.417	0.174
2	0.992	0.984	12	0.751	0.565	22	0.383	0.146
3	0.982	0.965	13	0.715	0.511	23	0.350	0.122
4	0.969	0.938	14	0.678	0.459	24	0.319	0.102
5	0.952	0.906	15	0.640	0.409	25	0.289	0.084
6	0.931	0.867	16	0.602	0.362	26	0.261	0.068
7	0.907	0.823	17	0.563	0.318	27	0.235	0.055
8	0.881	0.776	18	0.526	0.276	28	0.211	0.044
9	0.851	0.725	19	0.488	0.239	29	0.188	0.035
10	0.820	0.672	20	0.452	0.204	30	0.168	0.028

Table 1: Fourier coefficients of current and power spectra for the LHC beam.

Slightly different results will be obtained using non-Gaussian distributions (e.g. parabolic). It should also be kept in mind that the ultimate beam current is a factor 1.6 higher than the nominal one and that the real, non-symmetric LHC bunch pattern corresponds to a Fourier line spectrum containing all revolution harmonics, i.e. not necessarily integer multiples of the bunch frequency. Thus we could expect for the ultimate beam current a dissipated power of more than 7 kW in a single injection kicker tank, unless measures for impedance reduction are taken.

5 Measurement with Shielding Strips

Since the effect of the resonances in the tank was found to be negligible for this kicker, and since installing the ferrites inside the tank is a mechanically difficult and tedious work, later measurements were done without the tank. The beam screen is a plexiglas tube of 40 mm inner diameter and 50 mm outer diameter with 30 longitudinal strips applied on the inner surface of the plexiglas (about every 2 mm). These strips are without contact between each other, except at one end to avoid loop currents during the rise and fall of the kicker

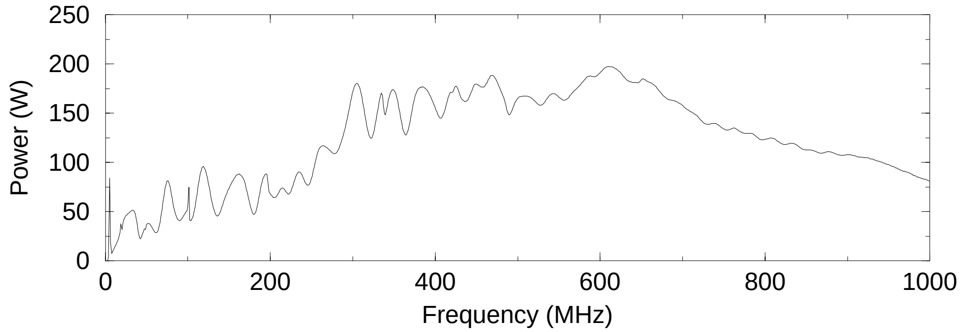

Figure 5: Power dissipation (nominal beam) in the ferrite block per harmonics, as a function of the frequency. The coupling impedance values are without shielding strips, using improved LOG formula.

magnetic field. The characteristic impedance is $Z_c = 60 \ln(40/6) = 113.8\ \Omega$, with 6 mm wire diameter. The measured value (S_{11} - time domain) was 108 Ω, leading to a nearest standard value for the matching resistor of $R_m = 56\ \Omega$. So, we should multiply the measured S_{21DUT} by $s = (56 + 50)/50 = 2.1 = 6.5$ dB. Again, a choice of 62 Ω for the matching resistor would have probably been better.

The results are shown in Figs. 6 and 7.

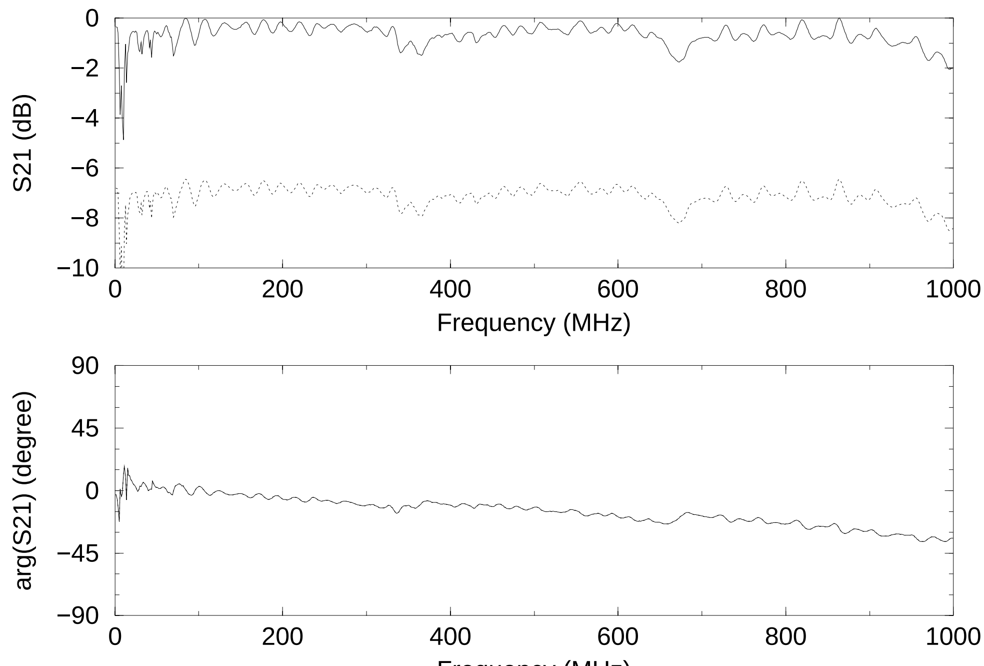

Figure 6: S_{21} for the injection kicker prototype with shielding. The dotted and solid lines show the raw data and the corrected data, respectively.

The dissipated power obtained by summing up all impedances at frequencies $40, 80, \cdots$ MHz in Fig. 7 up to 1 GHz amounts to 130 W for the nominal beam. However this seems to be a rather pessimistic value, since the fast variations of the impedance displayed in Fig. 7 are a measurement artifact and related to multiple reflections in the bench set-up.

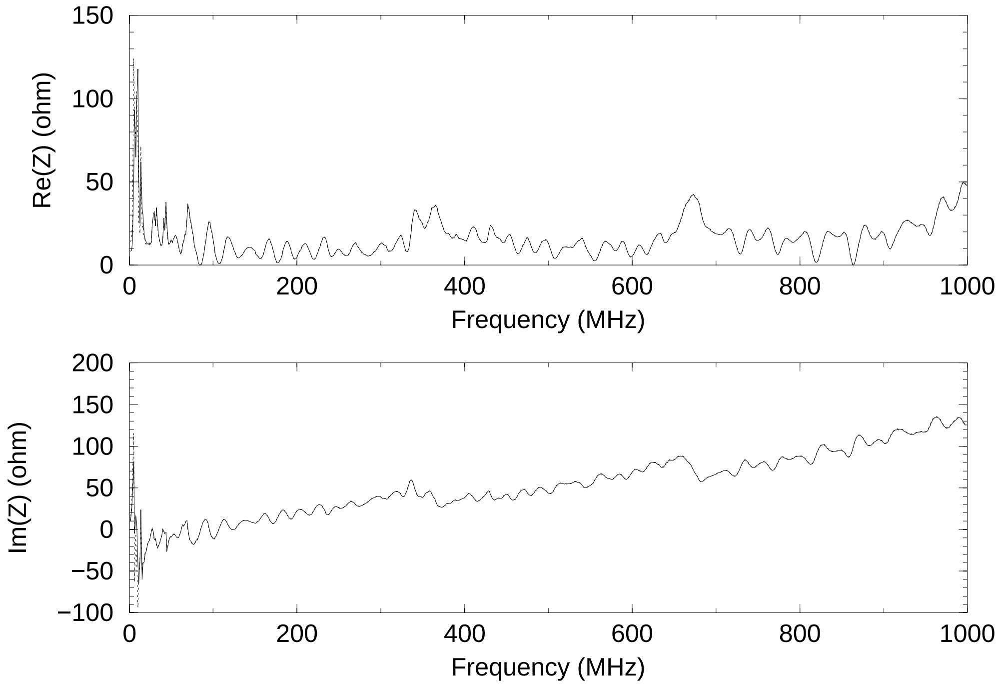

Figure 7: Longitudinal coupling impedance of the LHC injection kicker prototype with shielding.

6 Conclusions

We showed that the ferrites dampen sufficiently the resonances in the vacuum tank (if the cold conductor is connected to the ground) and therefore we can do measurements without the tank. Also the measured results show that the strips inside the plexiglas tube provide effective reduction of the real and imaginary part of the coupling impedance.

The strip resonances predicted in calculations by G. Lambertson [6] could not be seen in these measurements. This is very likely due to the fact that the presence of the highly lossy ferrite near the strips would completely dampen such resonances. However, further tests should be done, once a prototype of a complete kicker with copper strip ceramic tube is available.

7 Acknowledgments

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