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Radiation Detection by Cerenkov Emission in Optical Fibers at TTF

by

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1 Introduction

When a particle beam, which is not focussed properly, impinges on a part of an accelerator, a resonator cavity for example, showers of Streustrahlung are produced. Detecting this shower can reveal the position and the intensity of the incident. In an optical fiber, the shower would be converted into Cerenkov emission [1], which subsequently would be converted into an electrical signal. By measuring the difference in travelling time and integrating the amplitude, the position and the intensity of the irradiation can be obtained. The installation of such an optical fiber alongside the accelerator would result in a “continuous” detector. Such a system can have merits as a detector for emergency shut down purposes at TTF [2] or TESLA [3] thus preventing sensitive electronic devices from radiation induced breakdown or superconducting structures from quenching. In addition, it would be helpful in beam alignment procedures and daily routines thereof.

2 Principle of measurement

The basic principle for the detection of showers is depicted in Fig.1. An optical fiber is mounted alongside the accelerator. Irradiation, which impinges the optical fiber, produces light in the fiber which then travels in both directions. The light pulses are converted into electrical signals by a photodetector located at one end of the fiber. By measuring the travelling time, the position of the incident can be obtained, and by integrating the amplitude, its intensity. Mounting the optical fiber alongside the accelerator produces a “continuous” detection system covering the whole length of the accelerator.

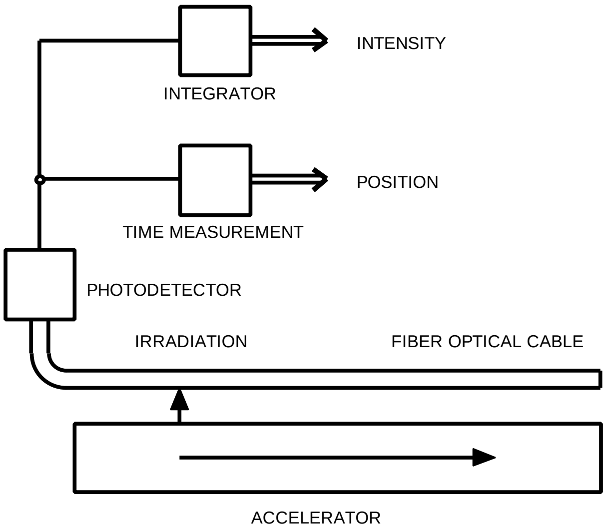

Fig. 1: Schematic of the detection of irradiation by means of an optical fiber

Upon irradiation, two different kinds of light can be produced in glass. One is the Cerenkov emission and the other is fluorescence. The latter is due to fast recombination processes of electron-hole pairs generated by the irradiation. Fluorescence is observable with decay times longer than some tens of nanoseconds. The characteristic wavelength and the decay

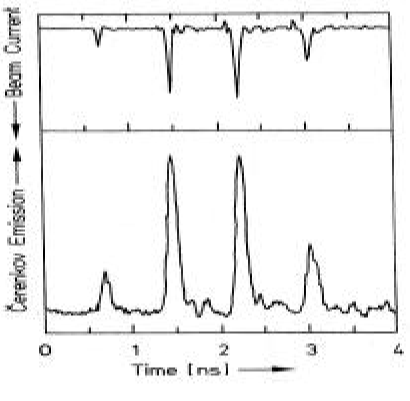

Fig. 2: Cerenkov emission generated by pulses of ps duration

time depend largely on the chemical composition of the glass. The Cerenkov emission, which is practically not influenced at all by the chemical composition of the glass, immediately follows the irradiation as shown in Fig.2 [4]. In high purity silicon fibers, only the Cerenkov emission is observable. The intensity of the Cerenkov emission depends on the wavelength. The intensity is inverse to the cube of the wavelength, i.e., the main intensity of the Cerenkov emission occurs in the near UV and tails off towards longer wavelengths.

The sensitivity with which the Cerenkov emission can be detected depends largely on the attenuation of the optical fiber. The theoretical lower limit of the attenuation vs. wavelength is depicted in Fig.3 [5]. Clearly, the attenuation is very high at short wavelengths, but decreases remarkably towards the near IR. Fig.4 shows the calculated relative amplitude of the Cerenkov emission after passing a 1000 m optical fiber, for two different core types. These curves were obtained by folding the spectral attenuation of the fiber with the spectral distribution of the Cerenkov emission. One cable (F100) has a core of high OH content and is produced for use in the UV region, while the other one (F300) has a low OH content and is meant for general purposes in the visible and near

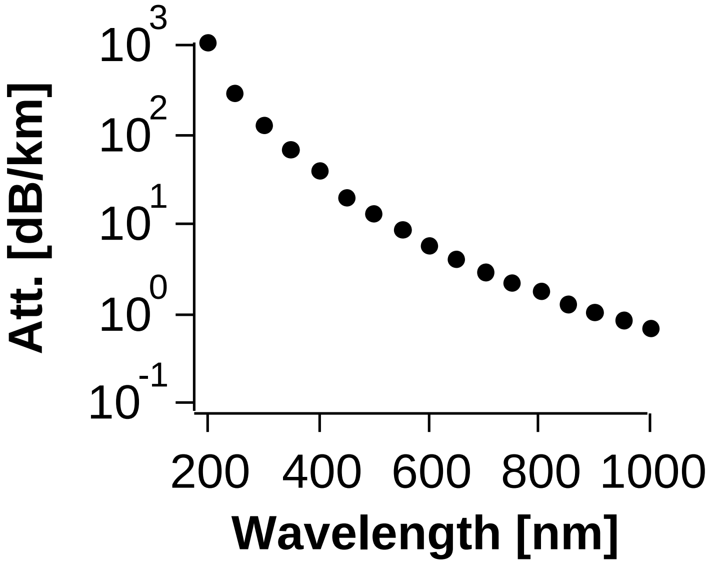

Fig. 3: Theoretical limit of the attenuation of an optical fiber.

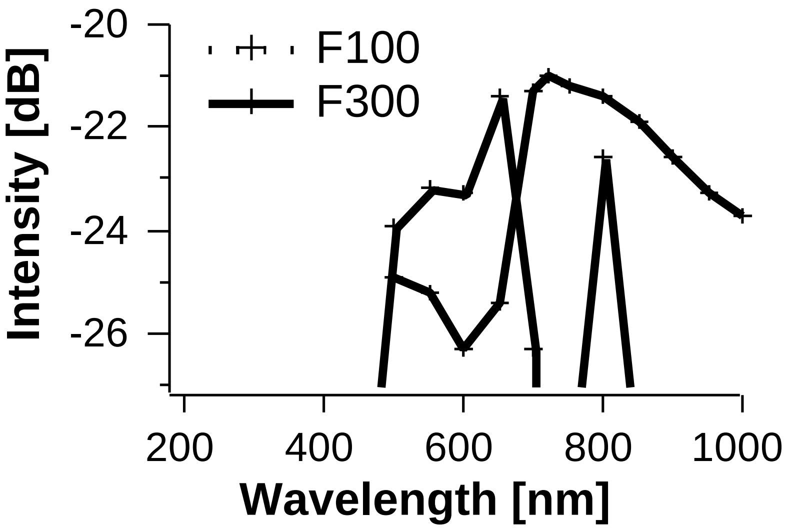

Fig. 4: Sensitivity with which Cerenkov emission can be measured. Normalized to a length of 1000m and a wavelength of 200nm.

IR. The intensity is normalized to 200 nm. The F100 type exhibits some additional attenuation in the 700 nm to 1000 nm region making its use not advisable. Below 500 nm, the attenuation of both types is too high to allow meaningful measurements at fiber length of 1000 m or longer. However, when the core material is of low OH content (F300), the intensity of the Cerenkov emission at longer wavelengths, 500 nm to 1000 nm, exhibits a deviation of only ±3 dB.

3 Preliminary experiments

3.1 Preliminary experiments at HMI

In two preliminary experiments, electron pulses of the 4 MeV van de Graaff accelerator facility ELBENA of the HMI [6] were used to demonstrate Cerenkov emission. A 100/150 µm optical fiber (Mitsubishi ST series) 50 m in length was irradiated at two points 10 m and 50 m from the photodetector. Irradiation was performed by electron pulses of 5 ns duration with peak amplitudes of up to 1 A, i.e., the maximum charge per pulse was 5 nC. The electron pulses had a diameter of about 1 cm and impinged perpendicularly the optical fiber, which was mounted approximately in the center of the beam spot. Fig.5 shows the intensity

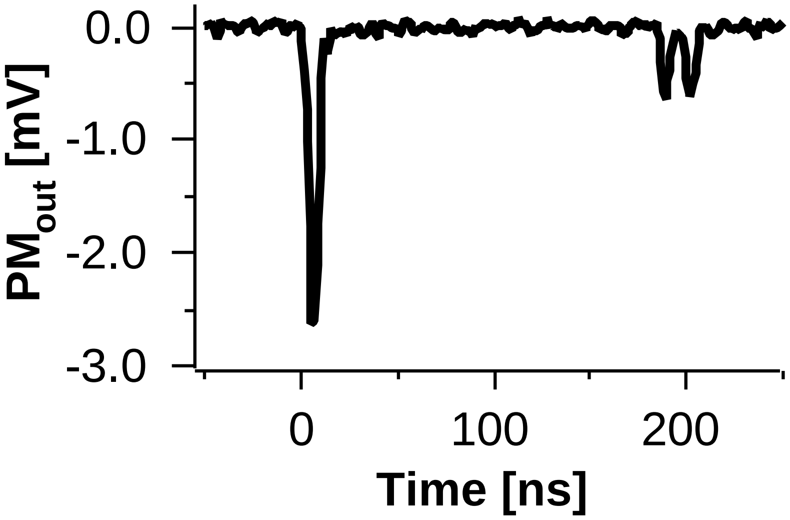

Fig. 5: Cerenkov emission of an optical fiber irradiated 10m and 50m from photodetector (see text).

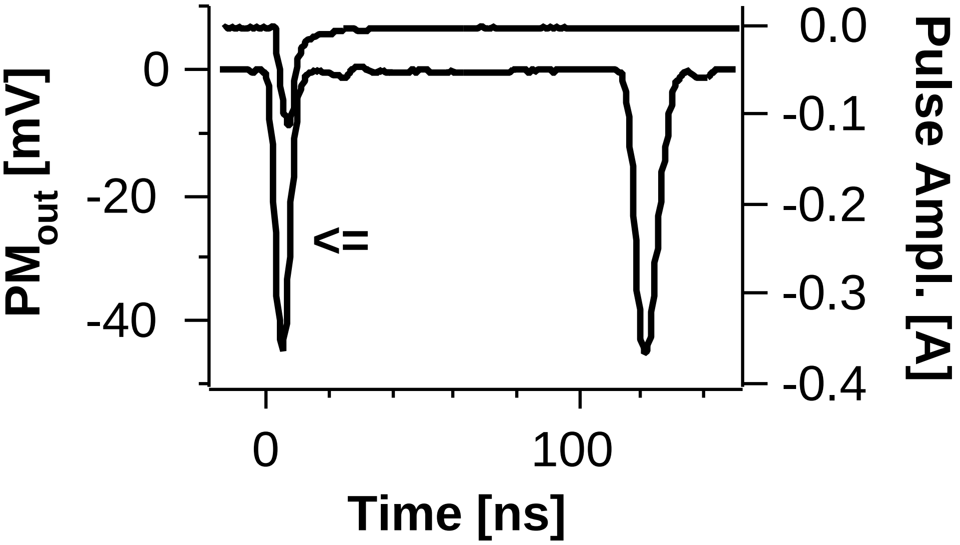

Fig. 6: Cerenkov emission and profile of beam pulse.

vs. time curve of the Cerenkov emission recorded at 650 nm. Because the fiber was irradiated at two different locations, two signals of the Cerenkov emission were observed. The first signal is caused by the irradiation at 10 m since travelling time is shorter, while the second one, a double peak, by that at 50 m. The difference in amplitude might be due to the attenuation in the fiber optical cable or due to non-uniform irradiation. The photodetector consisted of a monochromator with a 5 nm bandwidth and a 5-stage photomultiplier circuit. Since the monochromator allows harmonics and sub-harmonics to pass to some extend, the 325 nm portion of the Cerenkov emission also passed through the monochromator. Due to the dispersion of the fiber, the emission at 650 nm reached the photodetector earlier than the emission at 325 nm, thus producing the double peak. Both peaks are separated by 13.5 ns, which correlates to a difference in travelling time of 0.27 ns/m. This result might be interesting for detecting the location of a particle loss by means of measuring the difference in travelling time of two signals at different wavelengths.

In the next experiment, the same 100/150 µm optical fiber (Mitsubishi ST) was again irradiated with 4 MeV electron pulses under conditions similar to those described above. This time, the length of the fiber was 40 m, and irradiation occurred again twice, at a distance of 10 m and of 40 m from the photodetector. Fig.6 shows the trace of the Cerenkov emission and that of the beam pulse, both traces were recorded simultaneously upon a machine trigger as a function of time. A small-size photomultiplier module incorporating a nine-stage circuit was used. The optical fiber was directly connected to the photomultiplier module, thus the Cerenkov emission was recorded in the range from about 300 nm to 820 nm. A coaxial Farady-cup was used as a beam pick-up. Again the optical fiber was irradiated at two different locations producing two signals of the Cerenkov emission. Both signals are similar in amplitude. The first signal follows instantaneously the shape of the 5 ns beam pulse, while the second signal exhibits a remarkably larger width due to the dispersion of the optical fiber. From the shape of the first Cerenkov signal, a time constant of 1 ns or lower can be determined for the photomultiplier and the recording electronic circuitry.

3.2 Experiments at TTF

An optical fiber of the same type as mentioned above (Mitsubishi ST 100/150) was installed alongside TTF as depicted in Fig.7. The Cerenkov emission vs. the elapsed time after a machine trigger is shown in Fig.8. Two signals can be seen rising out of the noise. They are located close to the bunch compression chamber BC2. The machine was run under normal conditions and was properly focused, the charge per bunch was

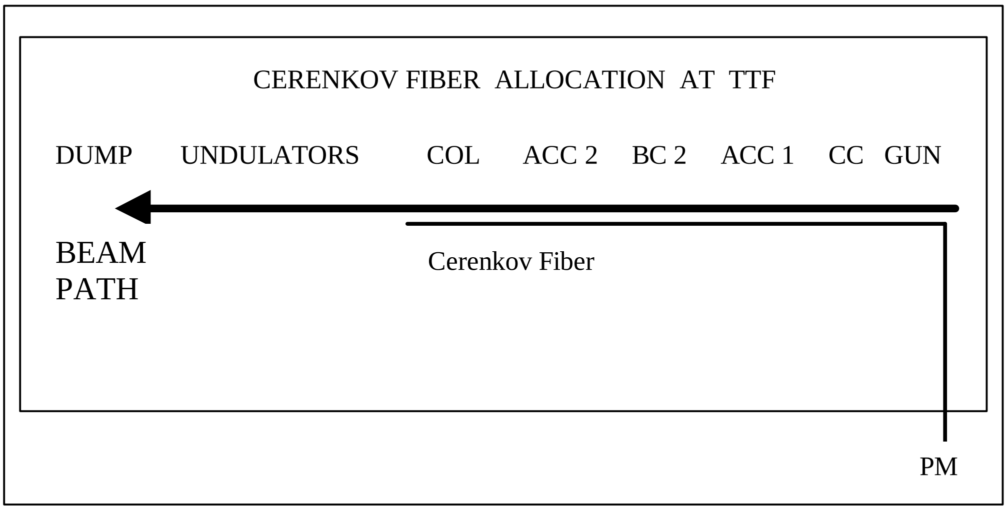

Fig. 7: Schematic of the measurement at TTF.

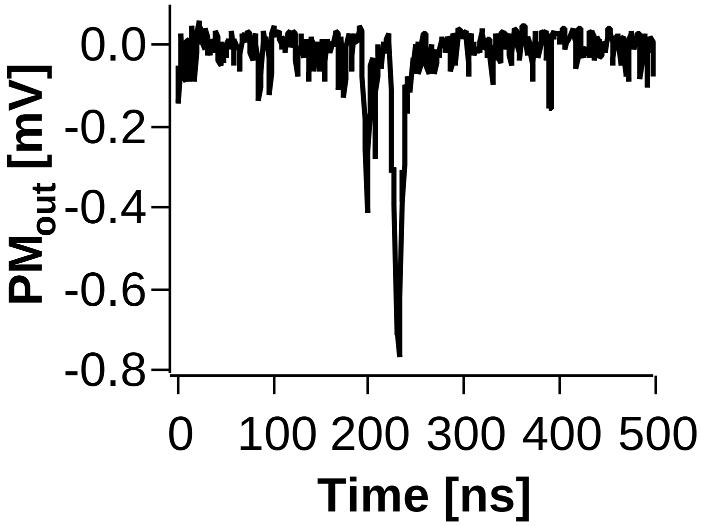

Fig. 8: Cerenkov emission at TTF under normal operating conditions. Single bunch. Trace is the average of 40 individual recordings.

1.5 nC. The noise stems from light which penetrates into the optical fiber. Fig.9 depicts the Cerenkov emission measured under similar conditions as in Fig.8, but this time the beam was slightly horizontally and vertically deflected downstream to the bunch compression chamber BC2. Beam loss was estimated to be less than 1%, lasing was still observed, and no alarm forced a machine shut-down. The amplitude of the Cerenkov emission increased 200-fold as compared with the signal in Fig.8. The width of the Cerenkov emission is 13 ns, which would indicate that a

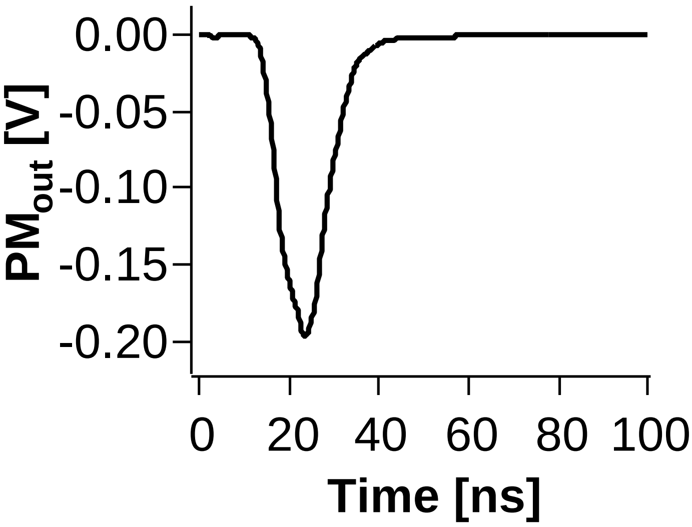

Fig. 9: Cerenkov emission at TTF, beam deflected horizontally and vertically at BC2. Beam loss less than 1%.

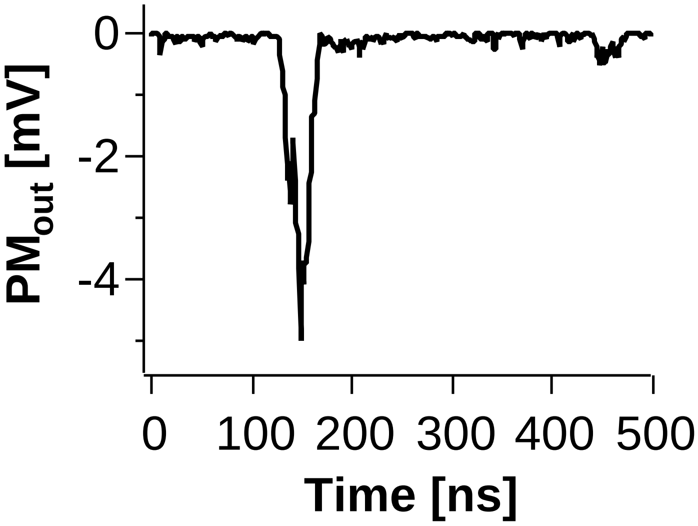

Fig. 10: Cerenkov emission at TTF. Beam deflected at dump collimator.

length of about 2.6 m of the fiber was irradiated due to the cone shape of irradiation; but the contribution of the dispersion also has to be taken into account. Further measurements were made at TTF during which the beam was dumped into the collimator absorber, see Fig.10. Here, the signal level is lower due to the larger distance between the accelerator tube and the optical fiber. It should be mentioned that the optical fiber was mounted beside the accelerator tube, a position of minimum radiation as proposed by monte-carlo calculations for TESLA [7].

3.3 Sensitivity of radiation detection

The sensitivity at TTF is estimated by using the data of the experiment depicted in Fig.9. The duration of a bunch is about 8 ps and thus smaller by three orders of magnitude than the observed Cerenkov emission. Therefore, the charge of the whole bunch can be considered in estimating the sensitivity. The beam loss needs to be estimated, since the beam monitors did not indicate any loss. The resolution of the beam monitors was in the order of 10% of the beam. On the other hand, the SASE-FEL still continued to lase. Therefore, the loss must be at least ten times smaller. Thus, we take into account a beam loss of 1% of the bunch charge, i.e., 0.015 nC, which corresponds to 9.37 x 10^8 electrons. The amplitude of the Cerenkov emission amounts to 0.2 V, this signal is 2000-fold larger than the detection limit. Also, the gain of the photomultiplier can be increased by a factor of two. Thus, the detection limit is estimated to be 2.3x10^4 beam electrons at 135 MeV per bunch as an upper value.

All the experiments described above used fiber optical cables of short length (<100 m). Using fiber optical cables up to 10 km in length, as can be proposed for TESLA, requires that attenuation must be taken into account when estimating sensitivity. The loss in sensitivity can be partly compensated by using a bundle of several fiber optical cables; the sensitivity will increase linearly with the number of cables.

4 Outlook

The experiments discussed above suggest that the measurement of the Cerenkov emission in an optical fiber provides a tool of high sensitivity for the detection of both the intensity and the location of showers. The detection is time resolved and basically allows the in-vivo measurement of radiation of each single bunch out of a train. Time resolution is mainly determined by the shape of the cone of the shower. Two applications are proposed here for use at TESLA or TTF. The first would involve the in-vivo supervision of the beam conditions based on the detection of irradiation of a single bunch in a train, while the second would serve as an emergency detector for a quick shut-down of the accelerator.

Single bunch detection. Recording the whole train of bunches with a duration of 800 µs creates a huge amount of data. For the display of the data we propose that the data should be divided into display periods, and the display screen should be divided into two parts. The display period should be a multiple of the time intervall between two consecutive bunches so that the events of five bunches, for example, are displayed. One part of the screen shows the average of the Cerenkov emission during a display period, while the other half of the screen displays the Cerenkov emission during the current, non averaged, display period. The latter could be scrolled and zoomed in order to display periods of interest. By this method, the data of one pulse train can be observed in real time. Another way would be to display only the average, but over display periods of different lengths in order to obtain fine/coarse overviews. The sample rate for acquiring data should be in the order of 1 sample/ns to 1 sample/10ns. Digital recorders with high sample rates and large memories are available, but the time required for data transfer to the computer could become crucial. A better solution would be to install a fast ADC card in a computer, which would write the data directly into the computer memory. The data might also be conveyed to a central registration computer for documentation purposes. Other necessary electronic equipment would be a fast photodetector and a wide-band dc-coupled amplifier of switchable gain.

Emergency shut down. For this application, the Cerenkov emission will be integrated over the duration of one pulse train. An alarm would be given if the integral value exceeds a preset limit. The requirements for electronic equipment is as described above.

In both applications, the condition of the optical fiber needs to be monitored. This could be done by coupling a short light flash from a laser diode or an LED into one end of the fiber optical cable and observing the signal at the other end. The time interval between consecutive trains of bunches, about 99 ms at TESLA, can be used for this test.

5 Conclusions

The installation of an optical fiber alongside the accelerator for the conversion of showers into visible light results in a “continuous” irradiation detector. By measuring the travelling time and integrating the amplitude of the light pulses, the position and the intensity of the irradiation can be obtained.

1) The detection system allows for a length of the optical fiber in the order of 1 to 10 km, depending on the sensitivity required.
2) A time resolution of 1 ns or less for the electronic equipment can be realized easily. This would correspond to a resolution of about 20 cm of the optical fiber. Wavelength dispersion and especially the diameter of the cone of the shower would limit time resolution. Dispersion can be avoided by measuring at a single wavelength using appropriate optical band-pass filters.

3) The electronic circuits for integrating the photodetector signal (dose) and for measuring the travelling time (position) would need to be developed (HMI).
4) An optical fiber with good radiation resistance is essential for long-term usage.
5) Sensitivity will increase linearly with the number of optical fibers in use and mounted in a bundle.
6) The usage of a control circuit for the optical fiber should be taken into consideration.

6 Acknowledgements

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