

PROPOSAL TO MEASURE THE SYNCHROTRON-ČERENKOV EFFECT

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Summary

I propose to measure the interference between the synchrotron radiation and Čerenkov radiation of 1 GeV electrons. The detector is a 5-m-long He-filled Čerenkov counter surrounded by Helmholtz coils which can produce up to 100 Gauss magnetic field. The signal is an oscillation in the radiation rate as a function of gas pressure in the vicinity of the Čerenkov threshold.

Requirements from Brookhaven Laboratory are:

- A 1 GeV electron beam in the LESB (B4) beam line;
- Two threshold Čerenkov counters in the beam line;
- About 25 feet of floor space along the beam, not nearby the MPS magnet;
- A magnet power supply of 0-500 amps capability;
- 100 hours of beam time at 10^{12} protons per pulse on the B target.

(Submitted to the Brookhaven National Laboratory)

If a charged particle moves with velocity $\beta = v/c$ through a gas of index of refraction n such that $n\beta > 1$ then Čerenkov radiation is emitted. If in addition a magnetic field exists along the path of the particle then synchrotron radiation will also be emitted. The usual perception of these two effects is that they are distinct, but this is not fundamentally so. In particular, if the frequency of the synchrotron radiation overlaps that of the Čerenkov radiation, and if the gas pressure is near the Čerenkov threshold so that both kinds of radiation are emitted very close to the forward direction, then substantial interference may be expected. As synchrotron radiation is primarily polarized in the plane of the orbit (perpendicular to the magnetic field) the interference effect is much more dramatic for this polarization.

The theory of the combined radiation effect has been worked out both classically^{1,2} and quantum mechanically³, and several suggestions have been made as to possible experiments to detect the interference effect⁴⁻⁹. However to date the effect has not been observed. This is probably because the interference effect is pronounced only in conditions in which less than one photon is emitted per charged particle in a laboratory-sized detector.

We propose to detect the interference effect by observing optical photons radiated by an electron beam which passes through a magnetized gas volume. If the applied magnetic field is to be large compared to the earth's field, and the radiation rates not too small, it turns out that the electron beam energy should be about 1 GeV, and the field about 100 Gauss. Thus the LESB (B4) beam line at BNL would be very suitable, as it can yield a good flux of electrons at 1 GeV.

Figure 1 shows a sketch of the very simple detector. An 8-in-diameter, 5-m-long pipe is filled with He gas below atmospheric pressure. Helmholtz coils wound above and below the pipe provide a field of 100 Gauss for about 1800 amp-turns current. The heat generated in the coils will be about 2.5 kW, so the coil will be water cooled. I would like to power the magnet with a supply provided by BNL, if possible. This could be a quadrupole supply capable of 0-500 amps, and perhaps should have an actual quadrupole connected in series to provide the inductance needed to stabilize the supply. The length of the radiator is limited to 5 m so that the deflection of the electron beam is only 2" for a 100 Gauss field. A flat mirror deflects the optical radiation onto a 5" diameter phototube. A polarizing filter selects the desired orientation of the polarization of the light. The interference effect is more pronounced if the bandwidth of the light is limited. I plan to integrate over the range 300-500 nm.

The expected counting rate as a function of He pressure is shown in Figure 2

for an applied magnetic field of 80 Gauss. The calculation is based on the formalism of Ref. 9, with the aid of a tabulation of certain Airy functions in Ref. 8. The Appendix summarizes the formalism.

The experiment consists of measuring the 'pressure curve' for several magnetic fields, including of course zero field. In the vicinity of the strongest rate oscillation, there will be only 1 detected photon per 100 incident electrons, taking into account the quantum efficiency of the phototube. To obtain 1% statistical accuracy at each data point, about 10^6 incident electrons will be required. Similarly it is desirable to know the pressure to 1%, and to have a beam energy spread of less than 1%. Less than 1% of a radiation length of material should lie between the He gas volume and the last beam magnet.

A possible layout of the experiment in the B4 line is shown in Figure 3. The polarity of the beam would be negative to minimize the proton content. From the beam-line summary of Bunce¹⁰ I infer that the 1-GeV pion flux (at the production target) might be 2×10^6 for 10^{12} protons on target. This is in a $\pm 3\%$ momentum bite. The momentum slit would be stopped down to yield about $\pm 1/2\% \Delta p/p$, reducing the flux to about 3×10^5 pions per pulse. I estimate that the electron flux in a $1/2'' \times 1/2''$ spot might be 3% of the pion flux, or 10^4 electrons per pulse (of 10^{12} protons on target). To veto on muons, pions and heavier particles in the beam, it would be useful to have two threshold Čerenkov counters in the beam line, before and after the last dipole. I believe existing counters at BNL would suffice for this. For additional e/π separation, I would use a 3×3 array of BGO crystals, viewed by a single 5'' phototube, after the detector (Figure 1). This array should be capable of 1% energy resolution at 1 GeV. I hope for an overall e/π separation of better than 10^4 so that the signal in the detector due to beam pions would be less than the synchrotron radiation for electrons at 60 Gauss.

To avoid the stray field of the MPS magnet, which is a few Gauss along some of the B4 line, it would be advantageous to locate the detector towards the rear of the experimental hall, as indicated in Figure 3.

With a flux of 10^4 electrons per pulse, a typical datum point obtained with 10^6 incident electrons will require about 100 pulses, or 3 minutes of beam time. A pressure curve of 50 data points will require about 3 hours of beam time, and likely an equal amount during which the pressure is changed. The entire experiment would consist of 4 curves, at 0, 30, 60 and 90 Gauss field. Thus about 24 hours of beam time are required. I have requested 100 hours to allow for considerable beam tuning, and safety margin.

There will be essentially no data analysis required (other than possible correction for temperature variation if this exceeds 1° K). The results will be submitted for publication in Physical Review Letters.

Appendix

The existing theory^{2,3} of the synchrotron-Čerenkov effect does not calculate this as an interference phenomenon. Rather the radiation rate is calculated directly for the general case of a charged particle moving through a gas which is also in an external magnetic field. Then the usual expressions for synchrotron radiation and Čerenkov radiation emerge as the appropriate limiting cases.

The general radiation rate for the number of photons emitted by an electron per meter of flight path and per eV of optical bandwidth is⁹

$$\frac{d^2 N}{d\omega dL} \left(\frac{\text{photons}}{\text{eV m}} \right) = 0.12 \left(\frac{H(\text{kG})}{\omega(\text{eV})E(\text{GeV})} \right)^{2/3} [P_1(x) + P_2(x)],$$

where E is is electron energy, ω is the photon energy, H is the magnetic field,

$$x = 3.06 \times 10^5 \left(\frac{\omega(\text{eV})E(\text{GeV})}{H(\text{kG})} \right)^{2/3} \left[2\Delta n - \left(\frac{mc^2}{E} \right)^2 \right],$$

Δn is the deviation of the index of refraction from 1, mc^2 is the electron rest energy, and the $P_j(x)$, $j = 1, 2$ are defined in terms of Airy functions by

$$P_j(x) = \left(j - \frac{5}{2} \right) Ai'(-x) + \frac{x}{6} + \frac{x}{2} \int_0^x dt Ai(-t).$$

Index 1 refers to polarization in the plane of the orbit (perpendicular to the magnetic field). Figure 4 shows the functions $P_j(x)$ in the interference region. A table of these functions, and their asymptotic expansions are found in Ref. 8.

As shown in Figure 2, the synchrotron-Čerenkov effect yields a considerable enhancement in the radiation rate for pressures just below the Čerenkov threshold. In this regime the angular distribution cannot have the form of a 'shock wave' characteristic of Čerenkov radiation. Indeed, throughout the interference region the angular distribution is not expected to show any discontinuity, but should exhibit a narrow peaking in the vicinity of the Čerenkov angle (when non-zero), as well as secondary maxima at other angles.⁵ This behavior would be a good topic for future experimental study.

References

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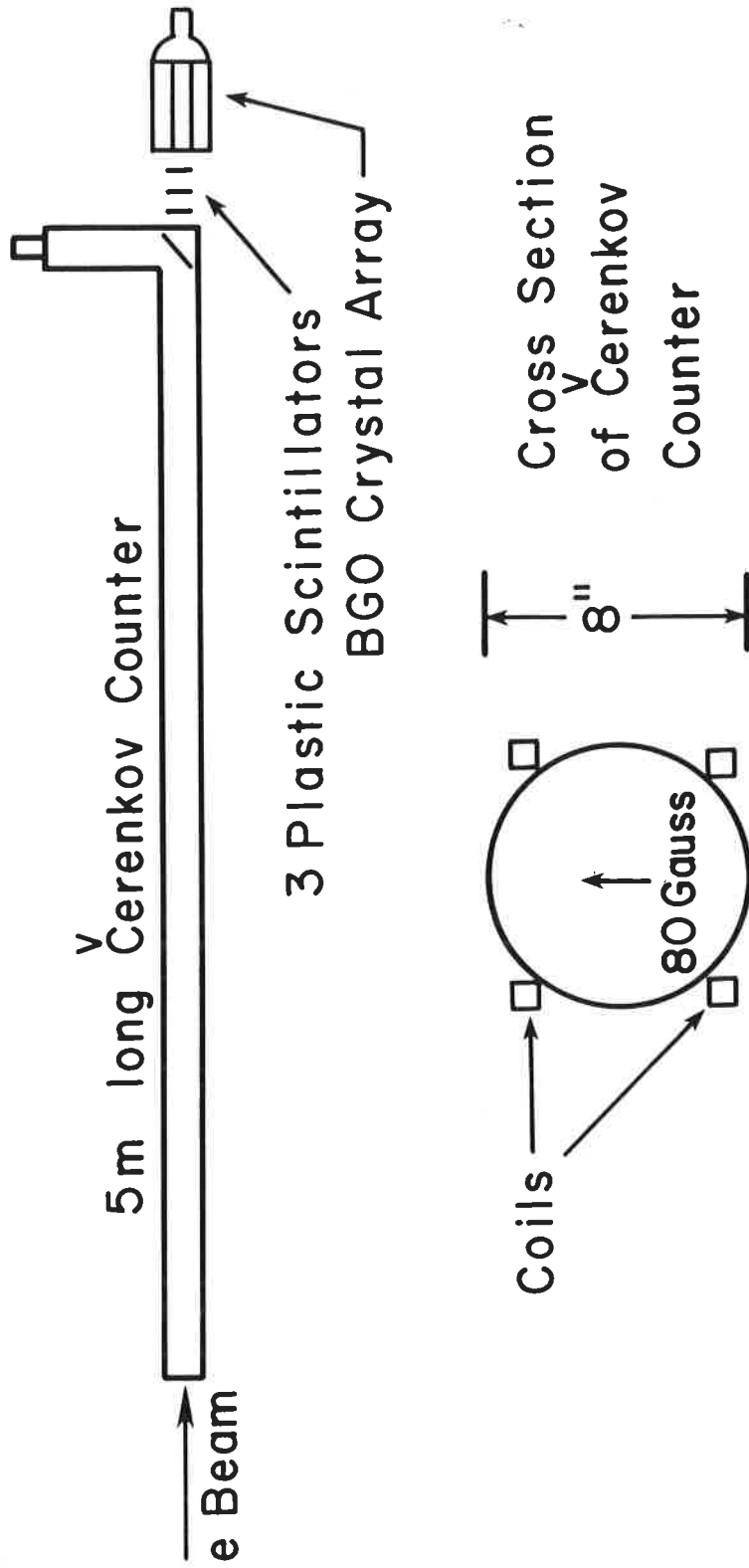


Fig. 1. Sketch of the proposed detector.

Optical Photons Detected Per Electron

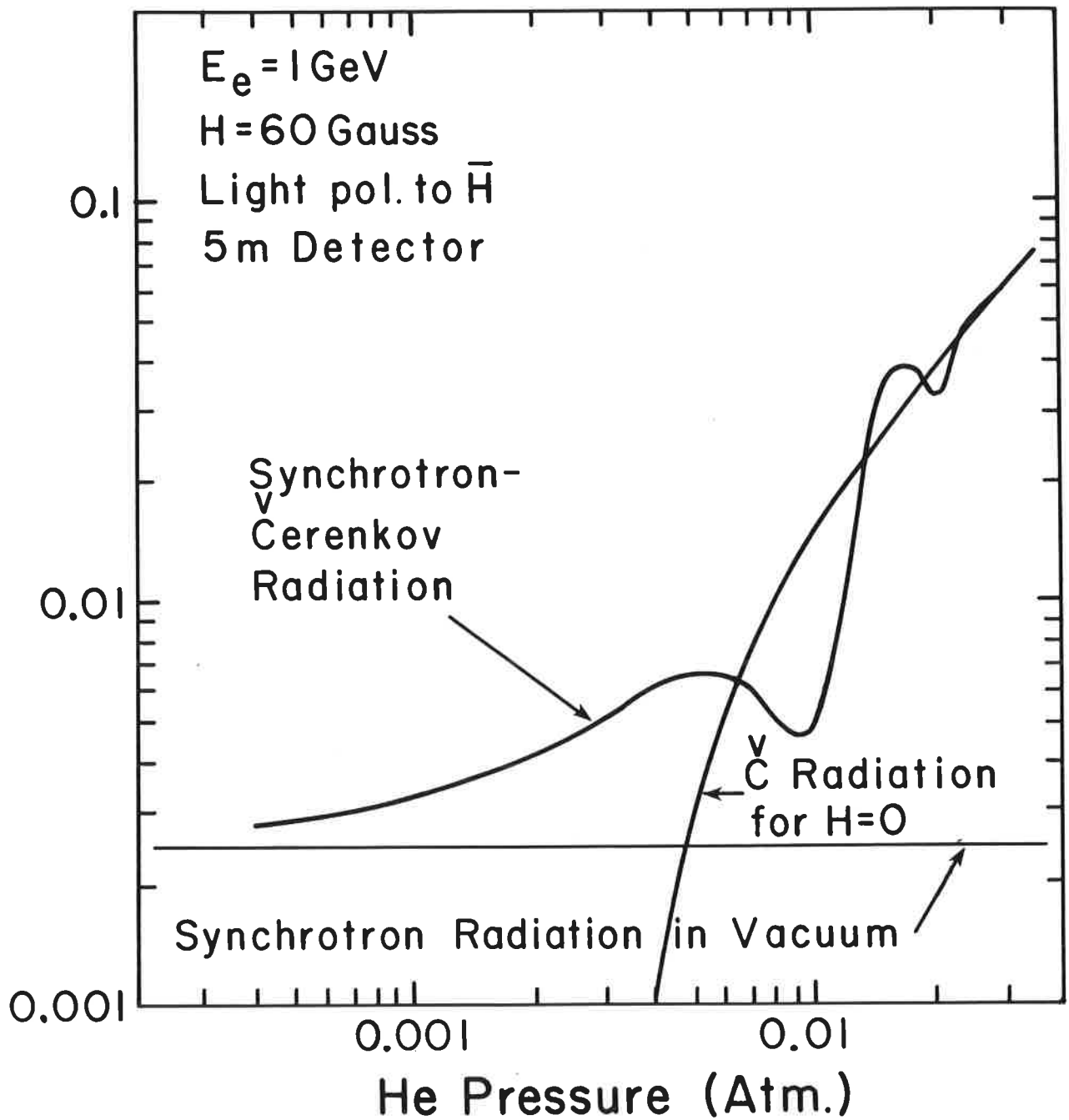


Fig. 2. Calculated rates for the synchrotron-Čerenkov radiation in the proposed experimental configuration, including phototube efficiency.

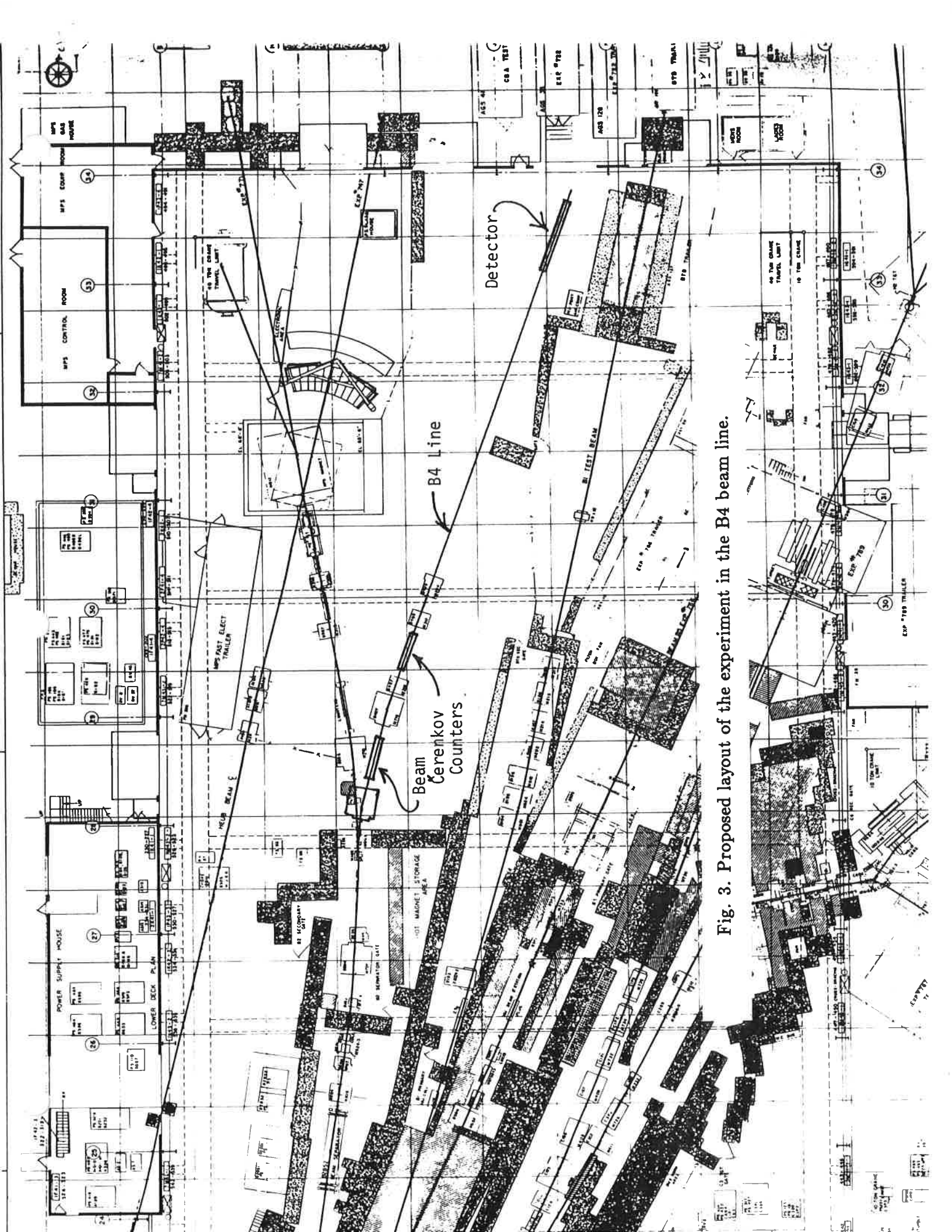


Fig. 3. Proposed layout of the experiment in the B4 beam line.

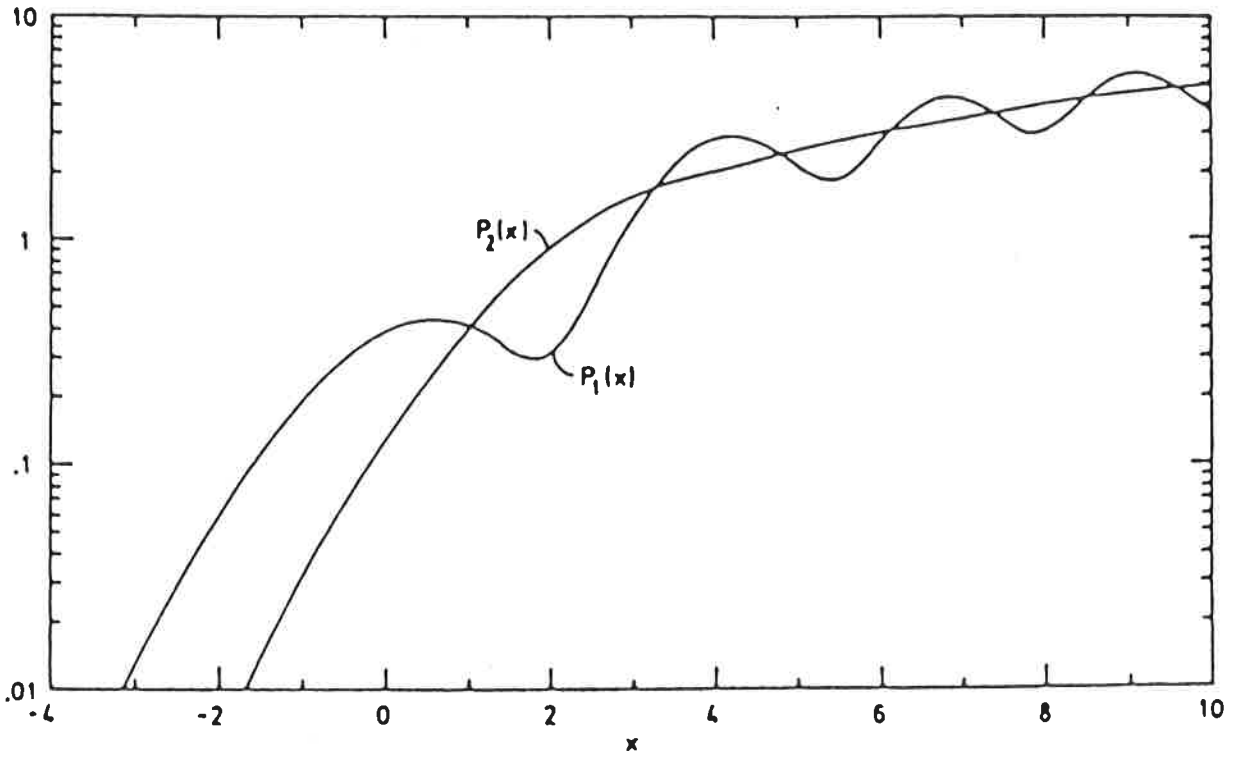


Fig. 4. The synchrotron-Čerenkov functions $P_1(x)$ and $P_2(x)$.