MEGAGAUSS BREMSSTRAHLUNG AND RADIATION REACTION

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1. Summary

Synchrotron radiation at high energies in intense magnetic fields is significantly altered by quantum effects. For 800 GeV electrons in 2 MG fields the total radiation rate is 30% below the classical value. The final electron energy distribution contains synchrotron 'fluctuations' in excess of 300 GeV. Quantum effects also modify the energy distribution of the electron-photon cascades on length scales of the order of 4 mm. These features cannot be obtained from the classical theory of radiation reaction.

2. Introduction

It is expected that the 'beamstrahlung' generated in the SLC interaction region will include synchrotron radiation from inhomogeneous fields up to 2.5 MG (megagauss). The angular distribution of the associated electron recoils will be modified by quantum fluctuations.[1] Synchrotron radiation under extreme conditions is also encountered in other situations --- for instance pulsar magnetospheres. An interesting feature of magnetic bremsstrahlung is that classical radiation reaction become dominant when $E^2(\text{GeV})H(\text{MG}) \gtrsim 10^4$, (for $e^{\pm}$). Since radiation damping is important for accelerator design, stochastic cooling systems, and also affects speculations concerning collective acceleration schemes it is advisable to check the reliability of the classical estimates under extreme conditions. In particular, for 800 GeV electrons in 2 MG fields, we will show that the classical and quantum mechanical descriptions of magnetic bremsstrahlung lead to discordant results.

The feasibility of experimental tests was demonstrated in a series of trials by an IIT-SLAC collaboration in 1970: single beam pulses of 19 GeV electrons were scattered by 1.5 MG 'targets' 5 mm in diameter. The shapes of the synchrotron spectra (peak ~ 12 MeV, tip ~ 200 MeV) were inferred from pair conversions in emulsions; the electron deflections were obtained directly from emulsion tracks.[2,3] These trials showed that pulsed MG techniques and high energy accelerators could be merged in sustained and reliable operation. The physics output was also satisfactory: the measured spectra agreed with theory, and many detailed cross-checks of the electron deflections with field profiles, flash X-rays, and experimental mock-ups gave consistent results. However, the overall beam deflections for all analyzed experiments were at least 7% too large.

It would be interesting to scale this experiment up to FNAL conditions: reliable pulsed facilities capable of generating 2 MG are already at hand, but special effort would be needed to extract sharp (~ 50 ns) single beam pulses of 800 GeV electrons from a secondary beam. Substantial improvements in MG-field profile calibrations could be achieved with single-mode fiber optics polarimetry. Superior target stability could also be attained with tantalum coils.

3. Quantum Theory of Synchrotron Radiation

The importance of quantum effects in synchrotron radiation is shown on Fig. 1:

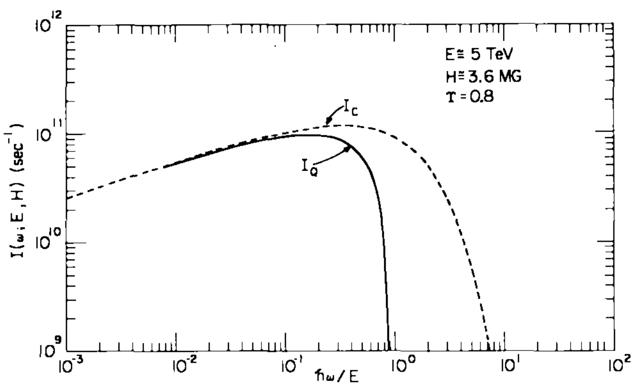

Fig. 1 Comparison of classical and quantum mechanical synchrotron spectra

Even under modest 'Desertron' conditions the classical radiation spectrum seems to violate energy conservation! Of course, if one recalls that $I_C(\omega)$ is the Fourier transform of a classical radiation rate, there is no contradiction --- only an indication that damping is important. $I_Q(\omega)$ denotes the corresponding quantum mechanical spectrum; since this describes a stochastic photon flux, the spectral tip obviously must satisfy the condition $\hbar\omega \leq E$. This pull-back of the spectral tip also implies a reduction of the total radiation rates. Fig. 2 shows that the classical Υ^2 dependence of the radiation is ultimately slowed to a $\Upsilon^{2/3}$ rate --- the ubiquitous $\Upsilon = (E/mc^2)(H/H_{cr})$ parameter scales most features of synchrotron radiation.[4] The significance of quantum corrections for the old SLAC and projected FNAL experiments is also apparent from Fig. 3. Clearly, more extreme conditions make it experimentally easier to distinguish

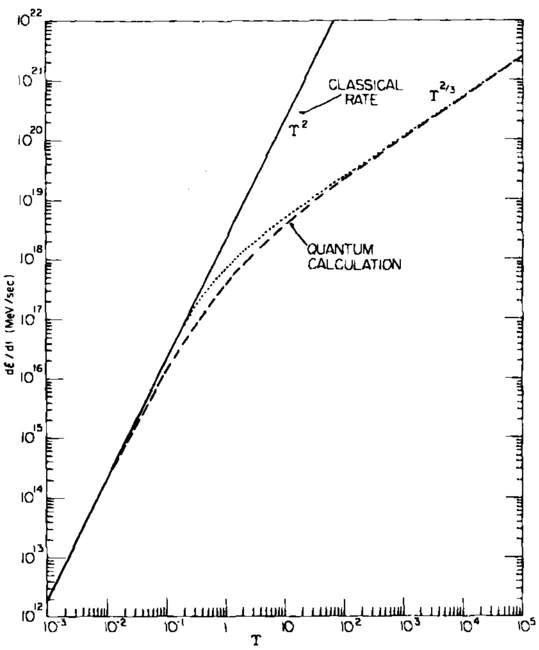

Fig. 2 Total radiation rates

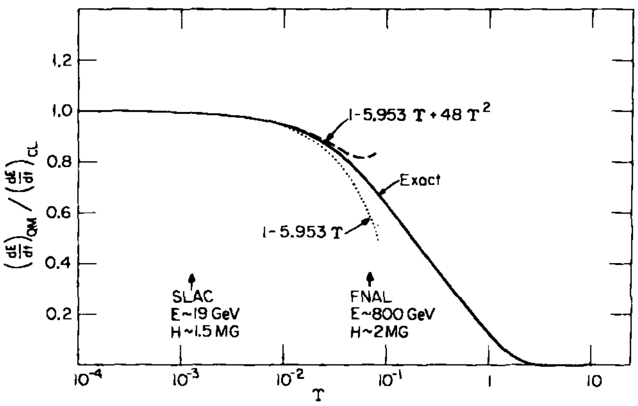

Fig. 3 Ratio of QM and CL radiation rates

deviations from classical behavior. On the other hand, the series expansions indicated for the variant curves, show that the theory becomes technically more difficult --- the usual recipes of step-by-step inclusion of higher order quantum corrections fail because the expansions become numerically useless just at the point where the quantum effects become significant.[5]

Additional features of megagauss bremsstrahlung at FNAL energies are shown on Figs. 4 and 5. It is evident that the classical and quantum mechanical spectra don't differ spectacularly when plotted on log-log paper. The photon emission rates at 1.8 MG also agree with semi-classical estimates. However --- as first noted by Sokolov and Ternov[6] --- quantum fluctuations begin to modify the electron recoils when

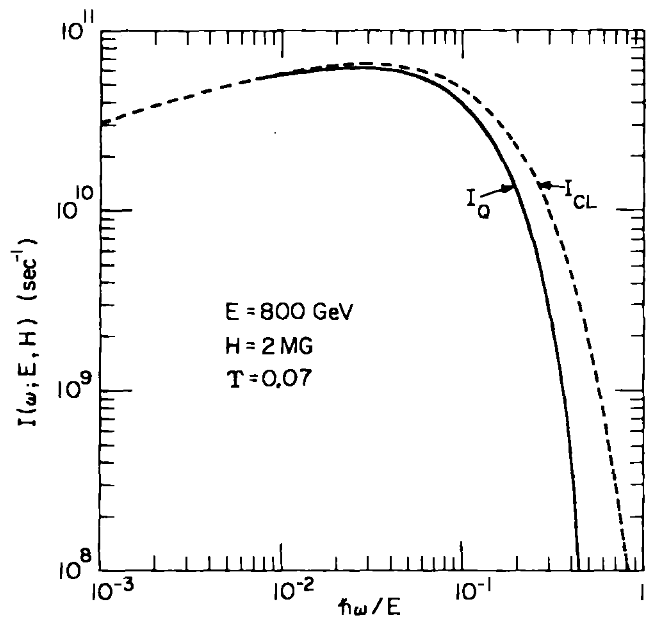

Fig. 4 CL and QM synchrotron spectra (FNAL exp.)

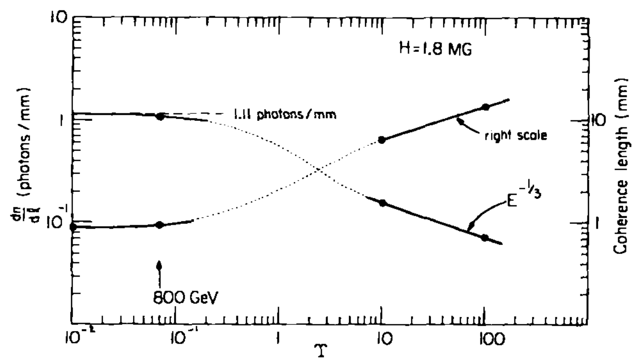

Fig. 5 Photon emission rates and coherence lengths

$E^4(\mathrm{GeV})H(\mathrm{kG}) > 10^{-3}$; and indeed under FNAL conditions these synchrotron 'scintillations' grow to enormous proportions. Fig. 6 displays the final electron energy distribution for 10^6 e^- traversing 0.84 mm of a 2 MG field. Due to the short coherence length (Fig. 5) even a modest MG target --- say with 4 mm diameter --- will catalyze a well developed electron-photon shower. The dashed histogram on Fig. 6 displays the results of a computer simulation of such a shower --- the rapid evolution of the recoil spectrum is evident.

No known variant of classical radiation reaction can simulate this dispersion of recoil electron energies. Specifically, if an ultra-relativistic electron traverses a path length ℓ normal to a magnetic field H, then its initial and final energies (E_i and E_f) are related by the Pomeranchuk formula[7] of Fig. 7. In units that today finally have become practical

$$E_{CR}(\mathrm{TeV}) \simeq 80/H^2(\mathrm{MG})\ell(\mathrm{mm}).$$

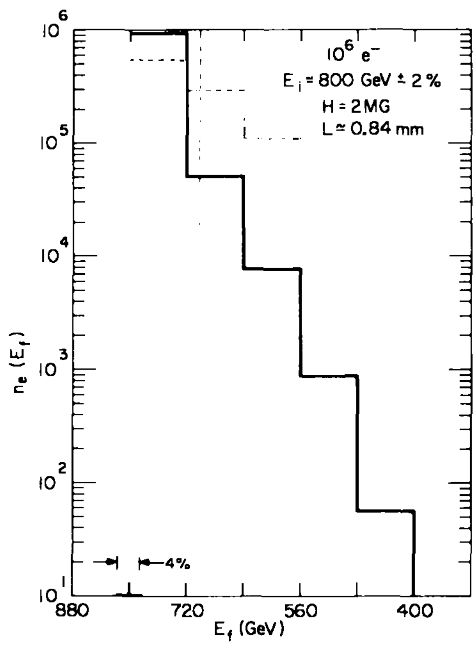

Fig. 6 Electron energy distribution

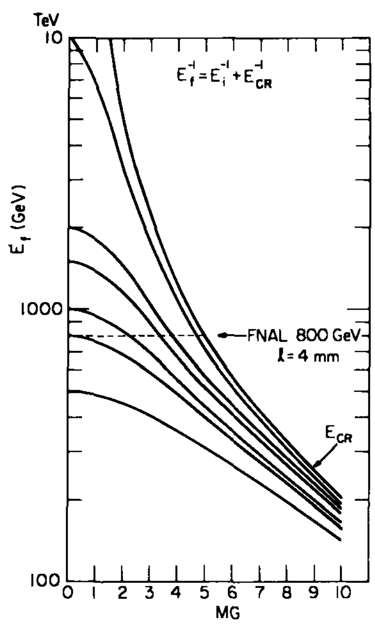

Fig. 7 Classical radiation reaction - Pomeranchuk saturation

The curves plotted in Fig. 7 clearly show the saturation effects associated with strong radiation damping. Finally, the vertical line at 700 GeV on Fig. 6 indicates the value of E_f when $\ell = 4$ mm and $E_i \simeq 800$ GeV. The classical and quantum mechanical theories differ considerably in their predictions concerning the final electron energy distribution!

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