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SYNCHROTRON RADIATION MEASUREMENTS FROM A PLASMA IN A MAGNETIC MIRROR MACHINE *

by

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Post, et al.,[1] have shown in the "Table Top" device that under certain conditions a "hot-electron plasma" can be confined in a magnetic-mirror configuration for periods of several milliseconds. In a similar experiment, shown schematically in Fig. 1, the synchrotron (Trubnikov[2]) radiation emanating from such a "hot-electron plasma" (kT_e = 50 keV, B_0 = 60 kG) was measured to have a peak value greater than 1.0 mw/Ster., integrated over the 4.0 mm to 0.1 mm wavelength region.

The plasma was generated by a deuterium loaded titanium washer stack source[3] (2 μfd, 6 kV) which injected plasma into a trapping magnetic mirror field that rises to a maxiumu mid-plane value of 8.0 kG in 50 μsec. This trapped plasma is then further compressed by a pulsed mirror field (mirror ratio 1.5:1) which rises in 500 μsec. to a maxiumum mid-plane value, which for these experiments was varied between 28 kG and 60 kG. The field decay time constant was 20 msec. The base pressure in the vacuum chamber was 2×10^{-7} Torr. before the source was fired. A uniform bias field of 20 Gauss guides end loss electrons which escape from the magnetic mirror region onto an aluminum target (0.004 inch thick). The x ray produced by the electrons striking this target are then collimated and impinge on a NaI(Tℓ) crystal, mounted directly on a photomultiplier. The x ray flux is limited in order to resolve individual photon pulses without pulse "pile up". The

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resulting single photon pulse height distribution is related to a Maxwell distribution ($1/2\ mv_{\perp}^2 = kT_e$) to obtain a measure of electron temperature. For data taken at 28 kG, the temperature of the electrons was found to be 25 keV. If it is assumed that the magnetic moment ($\mu = w_{\perp}/B$) is a constant, then $kT_e \approx 50$ keV at the maximum field of 60 kG. No measurement of ion temperature was made; however, the maximum ion orbit size in the initial bias field limits the probable final ion energies to less than 600 eV.

To measure the synchrotron radiation emanating from this "hot electron plasma," a cryogenic InSb far infrared photodetector was connected to the experiment as shown in Fig. 1. This detector, which operates at 1.8° K in an 8.0 kG field with a bias current of 25 μA, had a measured sensitivity of 0.5 V/mW at 4 mm wavelength, and a response time shorter than 1 μsec. From the data of Putley,[4] which gives the relative sensitivity as a function of frequency (sensitivity decreases at shorter wavelengths), it was possible to establish a lower bound on the value of the measured radiated power. The attenuation of the radiation in the hollow metal light pipe, which guides the radiation to InSb crystal, can be included in the over-all system sensitivity.

Fig. 2 shows the synchrotron radiation (middle trace) and the corresponding single x ray photon pulses from the end scintilator (lower trace) in relation to the magnetic field (upper trace) whose maximum midplane value was 28 kG. For this magnetic field the plasma exhibited no gross instabilities and the synchrotron radiation intensity decreased slowly both due to a decreasing number of plasma electrons and a decreasing magnetic field.

Fig. 3 shows the synchrotron radiation signal and corresponding x ray signal for a magnetic field whose maximum mid-plane value was 60 kG. For this magnetic field, the synchrotron radiation intensity was almost an order of magnitude larger and the plasma exhibited a gross instability, which began after 1.2 msec. For intermediate values of the magnetic field the peak radiation increased with increasing field accompanied by a gradual onset of the instability.

This instability resulted in a rapid loss of plasma as seen by the sudden decrease in synchrotron radiation signal and a corresponding sudden and brief increase in the x ray signal, which we assume indicates a large flux of electrons leaving the mirror. During the period after the peak magnetic field occurs and before the plasma becomes unstable, the total radiation intensity entering the light pipe, integrated over the 4 mm to 0.1 mm wavelength region, is greater than 1.0 mW/Ster. Allowing for a factor of two for additional radiation from scattering in the experiment chamber (which is consistent both with geometrical considerations and the results of Harding, et al.[5] on measurements from Zeta) we have greater than 0.5 mW/Ster. emitted from the plasma.

A far infrared monochrometer will be used in future experiments to gain detailed information on the spectral distribution and harmonic content of the observed synchrotron radiation. For the present experiments, NaCl filters of various thicknesses were used to show that some of the radiated power occured at frequencies above the cyclotron frequency. This portion of higher harmonic radiation increased with increasing plasma temperature (higher magnetic field), as predicted from theory.[6]

The total synchrotron radiation per steradian emitted from an optically thin plasma, (which is the situation for these experiments) at 90° with respect to the magnetic field can be calculated. For a single electron of velocity v perpendicular to the magnetic field we have, in mks units, a power radiated[7]

$$P_{\perp} d\Omega = d\Omega \frac{e^4 B^2 v^2}{128\pi^2 m_0^2 \epsilon_0 c^3} \frac{4 + 3\, v^2/c^2}{(1 - v^2/c^2)^{3/2}}$$

where the symbols have the usual meanings. Integrating over a relativistic two dimensional Maxwellian distribution, we obtain

$$\frac{P_\perp}{B^2} = \frac{.178\ 10^{-23}}{kT + 511}$$

$$\left[1.055 \cdot 10^9\ kT + 1.678 \cdot 10^7\ (kT)^2 + 8.69\ 10^4\ (kT)^3 + 1.68\ 10^2\ (kT)^4\right] \quad (1)$$

where $P_\perp$ is the perpendicular radiated power measured in watts per steradian per electron, B the magnetic field in Webers per square meter, and kT the mean electron energy in keV. Assuming the magnetic moment of the electrons is constant during compression (kT proportional to B), from Eq. (1) the radiated power is found to increase approximately as the 3.3 power of the magnetic field within the range of interest. The measured value of radiation intensity was found to vary with this same power of the magnetic field to within 10 percent which is within the experimental error. For a given radiation intensity, Eq. (1) gives the relation between plasma temperature and total number of radiating electrons. For the 60 kG peak magnetic field, the total number of radiating electrons is approximately $10^{11}/cm^3$, which agrees to within an order of magnitude with an estimate based on measurement of the electron flux escaping from the mirror region.

As a concluding remark, we note that a far infrared source of the intensity observed in these experiments would have numerous application in far infrared spectroscopy.

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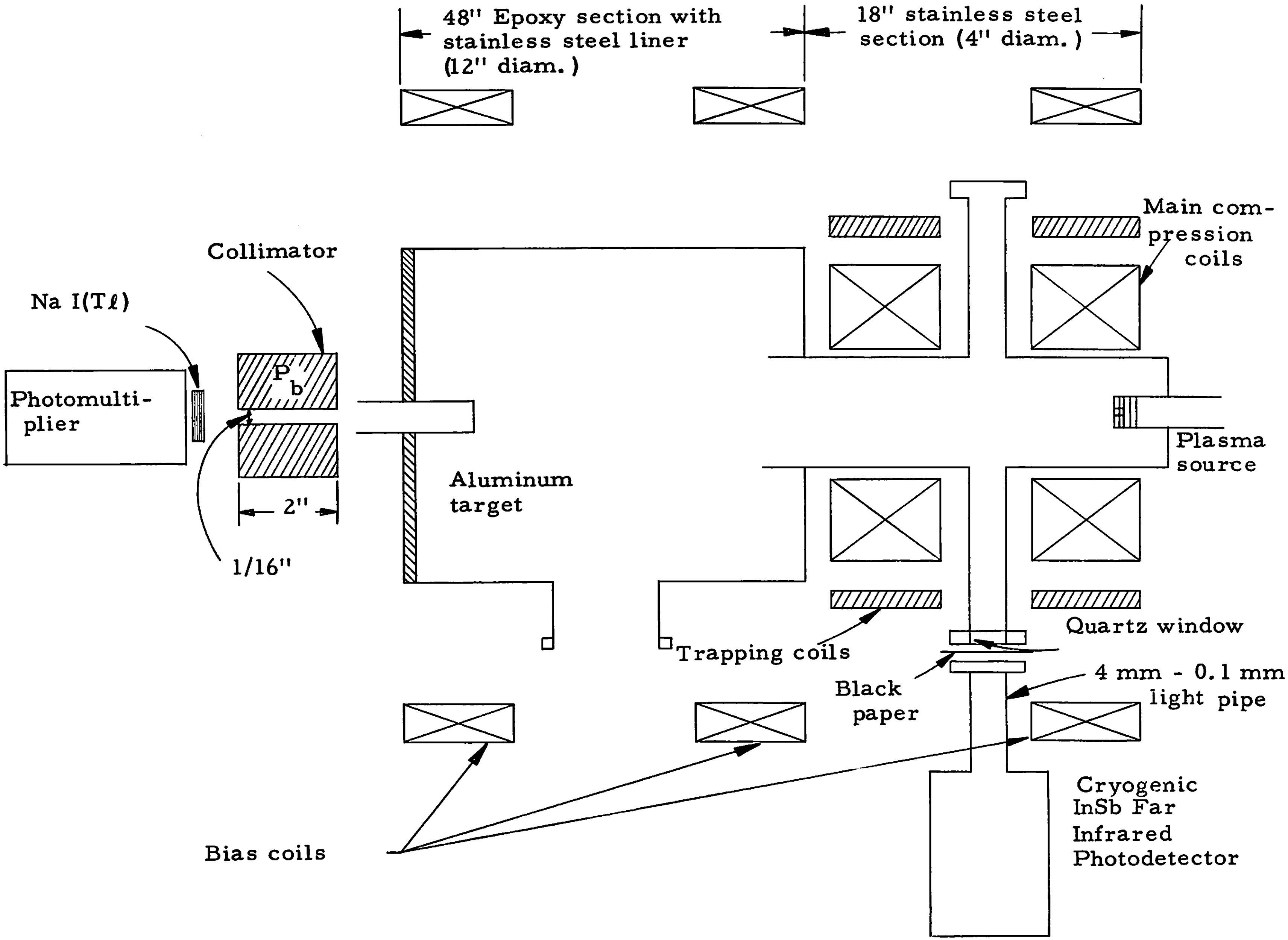
FIGURE CAPTIONS

Fig. 1. Experimental arrangement.

Fig. 2. Sweep speed one msec/cm, base line included with each trace.
Upper trace: magnetic field, 28 kG maximum.
Middle trace: synchrotron radiation directly from detector (.005 v/cm).
Lower trace: single x ray photons from end loss (165 kV/cm).

Fig. 3. Sweep speed 200 μsec/cm.
Upper trace: x ray photons from end loss.
Lower trace: synchrotron radiation (.01 v/cm).



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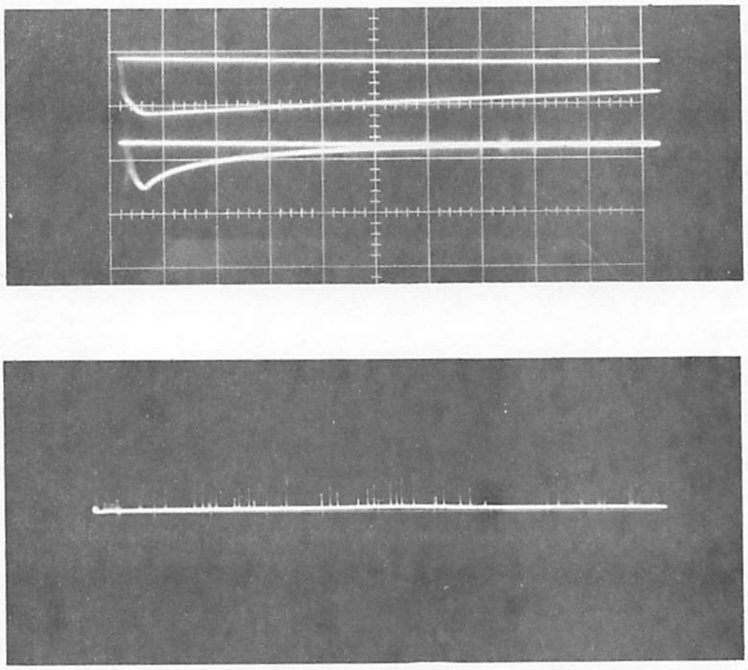

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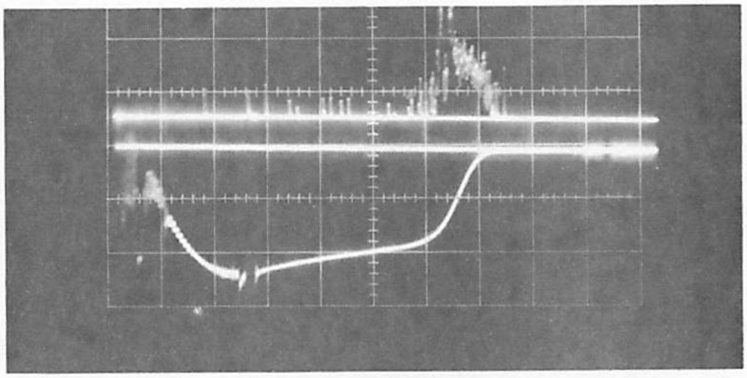

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