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MEASUREMENT OF POPULATION INVERSIONS AND GAIN IN CARBON FIBER PLASMAS

By

H. Milchberg, C.H. Skinner, S. Suckewer, D. Voorhees

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PRINCETON, NEW JERSEY

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MEASUREMENT OF POPULATION INVERSIONS AND GAIN IN CARBON FIBER PLASMAS

H. Milchberg*, C.H. Skinner, S. Suckewer, D. Voorhees

Plasma Physics Laboratory
Princeton University
Princeton, New Jersey 08544

ABSTRACT

A CO_2 laser (~ 0.5 kJ energy, 70 nsec pulse width) was focussed onto the end of an axially oriented, thick (35-350 μ) carbon fiber with or without a magnetic field present along the laser-fiber axis. We present evidence for axial-to-transverse enhancement of the CVI 182Å ($n = 3 \rightarrow 2$) transition, which is correlated with the appearance of a population inversion between levels $n = 3$ and 2. For the $B = 0$ kG, zero field case, the maximum gain-length product of $k\ell \approx 3$ ($k \approx 6$ cm^{-1}) was measured for a carbon fiber coated with a thin layer of aluminum (for additional radiation cooling). The results are interpreted in terms of fast recombination due mostly to thermal conduction from the plasma to the cold fiber core.

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*Present address: AT & T Bell Laboratories, Murray Hill, N.J. 07974

Recently, several groups have presented experimental evidence for significant gain in the soft X-ray region. An axial enhancement of E = 100 of stimulated emission over spontaneous emission, and a corresponding gain-length product of 6.5 has been achieved in a recombining plasma produced by the interaction of a CO_2 laser with a carbon disc in the presence of a B = 90 kG magnetic field.[1] A different approach, electron excitation of neon-like selenium, has produced gains of $k\ell = 5$-7 at the Novette Laser facility at Livermore.[2] A separate experiment,[3] also based on a selenium-coated plastic foil, reported a gain-length product $k\ell = 4$ on the CVI 182Å line from fast recombination due to rapid cooling by selenium radiation. A gain-length of 1 - 2 cm^{-1} has also been reported[4] in Al XI at 105.6Å.

In previous experiments with carbon fibers, Pert et al.[5] adopted an approach in which a thin ($\lesssim$ 6 μ diameter) carbon fiber was transversely illuminated by a line-focussed Nd-glass laser. Gain-lengths $k\ell \lesssim 5$ were reported on the CVI 182Å transition. The results were interpreted in terms of a detailed theoretical model based on hydrodynamic expansion of a cylindrical plasma with attendant adiabatic cooling inducing fast recombination and gain.[6]

In our work, based on radiation cooling of a plasma confined in a magnetic field, investigation of different targets and the resultant plasma geometries[7,8] indicated that end-on illumination of a carbon fiber could produce a long, thin plasma suitable for high gain.

The experimental setup has been presented previously.[9] Briefly, a 5 x 10^{12} W cm^{-2}, 50-80 nsec FWHM CO_2 laser pulse was focussed onto the end of a carbon fiber supported by spider webs in an evacuated chamber inside a 90 kG solenoidal magnet (see Fig. 1). The laser focal spot was a 200 μ x 400 μ ellipse. The CO_2 laser beam, fiber, and magnetic field were aligned along a common axis. The fiber targets were 4-5 mm long and ranged in diameter from

35-350 μ. Fibers in the range 70-350 μ were fabricated from number 2H pencil leads, or by placing together two or more 35 μ diameter fibers. The narrow fibers were cut from graphite strands. Some fibers were coated with a thin layer of aluminum for additional radiation cooling. XUV grazing incidence and air wavelength monochomators observed the plasma emissions from the entire fiber in both transverse and axial directions. The XUV instruments were absolute intensity calibrated in situ by the branching ratio technique using a specially designed portable vacuum spark.[10] The vacuum spark was also used to measure the relative sensitivity of the axial and transverse XUV instruments. Laser-produced plasmas from calibration fibers oriented perpendicular to both axial and transverse instruments were used to confirm the relative sensitivity and extend the absolute intensity calibration to shorter wavelengths (25-80Å).[8]

Figure 1 shows framing camera images in the visible wavelength range of the laser-axial fiber interaction, with and without the magnetic field present.[10] In both cases the plasma extended along the length of the fiber. For B = 90 kG, the plasma was well contained and elongated, while for B = 0 the plasma extended over a larger volume and much of the support strands was heated. Since the lower charge states of carbon have strong radiative transitions in the visible wavelength range, care must be taken in interpreting the framing images in terms of the CVI geometry. In particular, the plasma generated by the support strands is only heated to low charge states by the fringe of the laser beam, but nevertheless appears with high intensity in the B = 0 kG image (at B = 0 kG the plasma expanding from the fiber appears to increase the interaction of the laser beam fringe with the support strands). The transverse width of the plasma image is also weighted to the lower charge states and is much larger than the region containing

CVI. However, the framing images do give a qualitative picture of the plasma and show a long, thin plasma geometry suitable for generating high gain. The laser interaction along the fiber is not, at present, well understood and may be facilitated by a hollow electron density profile[11,12] produced at the fiber tip or may be promoted by hot electrons generated in the laser-plasma interaction.[13]

Rapid recombination of totally stripped carbon, C^{6+}, can produce population inversions between levels $n = 3$ and 2, and gain on the CVI 182Å ($n = 3 \rightarrow 2$ transition). In the experiment, gain was measured by two independent methods: (a) from the ratio of axial to transverse CVI 182Å emission and (b) from the absolute level of the population difference between levels $n = 3$ and 2. In the first method, the ratio of axial to transverse signals was normalized by the relative sensitivity of the axial and transverse instruments as determined from the spark and 'perpendicular' fiber calibration. The enhancement, E, is defined as the ratio of stimulated plus spontaneous axial emission to spontaneous emission in the transverse direction. In the absence of gain, E should be unity. To avoid the possibility that the fiber obscured part of the plasma from the view of the transverse instrument, we conservatively take only a measured $E > 2$ as evidence for gain. In fact, the measured value of E was never less than 0.8 which gave us confidence that both axial and transverse instruments viewed essentially the same plasma.

Figure 2 shows the results from the fiber shot having the highest enhancement. The time history of the CVI 182Å ($3 \rightarrow 2$ transition) line emission is shown for a 4.7-mm-long, 35-μ-diameter carbon fiber without the magnetic field. The fiber was coated with ~ 8000Å of aluminum. The enhancement was measured to be $E \approx 6$ and, in the small signal approximation, can be related to the gain-length product, $k\ell$ by $E = [\exp(k\ell) - 1]/k\ell$. This yields $k\ell \approx 3$ corresponding to $k \approx 6$ cm^{-1}. At the peak of the CVI 33Å emission, the population inversion ratio N_3/g_3: N_2/g_2 was measured to be 4.3:1. Here N is the population and g the statistical weight. While direct measurements of the CVI geometry in the fiber plasma were not available, a spatial scan of a similar plasma generated from a thin (300 μ) carbon blade was performed on a shot to shot basis (the blade target was usable for many laser shots). For B = 0 kG, the width of the CVI 182Å emission was measured[7] to be less than 200 μ. If, on this basis, the fiber plasma diameter is taken to be 150 μ, the absolute intensity calibration yields a CVI n = 3 population of 2×10^{15} cm^{-3}. For this population with a 182Å Doppler-broadened line at 10 eV, the calculated gain is $k \approx 8.2$ cm^{-1} and is consistent with the gain measured from the 182Å intensity ratio. The effect of the aluminum coating is positive, but no systematic investigation of these coatings was undertaken. The region near 10 eV and below is propitious for three-body recombination, and temperatures in this region have been measured in our recombining carbon plasmas.[10] The brightness temperature of the axial emission calculated from the measured intensity of 4.2×10^4 watts sr^{-1}, (area $1.8 \times 10^{-4} cm^2$) is 2.2 keV, much higher than the temperature of the recombining plasma.

Figure 3 shows the results from 16 fibers, 8 with a 90 kG magnetic field present. The B = 90 kG data show no population inversion and no significant axial enhancement. The B = 0 kG data, however, show both population inversions and enhancements. The correlation of observed population inversions with enhancement is strong evidence for stimulated emission. There was no obvious correlation of gain with fiber diameter, as slight variations in laser focal spot alignment caused some scatter in the data and impeded a more systematic study.

Rapid cooling after the laser pulse is required in order to generate fast recombination and high gain. Three possible mechanisms for this are considered: hydrodynamic expansion, heat conduction to the cold fiber core, and radiation cooling.

In the carbon fiber plasma calculations of Pert et al.,[5,6] the effectiveness of expansion cooling relies on the high initial density ($n_e \lesssim 10^{21}$ cm^{-3}) and small initial diameter ($\lesssim$ 6 μ) of the plasma. However, as the size of the fiber increases, it is less likely that it will be fully ionized for a given laser pulse. In principle, the incomplete ionization of the fiber core would provide a low temperature heat sink which could cool the surrounding plasma much more rapidly than adiabatic expansion. This has been shown in a simple calculation in which the rates of cooling due to expansion and thermal conduction are separately calculated and then compared.[10] The rate of conduction cooling was calculated from the time-dependent, classical radial heat flow equation, while expansion was taken to occur with the radial component of the ion thermal velocity, with the temperature controlled by the adiabatic equation of state. In this calculation, it is assumed that at the end of the laser pulse, an axisymmetric annular plasma of outer radius r_p and temperature T_p is situated around a cold fiber core of radius r_f and temperature $T = 0$. Beyond $r = r_p$, the plasma density and temperature drop quickly due to expansion during the laser pulse. This low density, outlying plasma is not important for achieving high gain, and it is neglected. During the laser pulse, not treated explicitly in the calculation, heat is thermally conducted from the absorption region to the continuously ablating, cold fiber surface.

Figure 4 shows the ratio of the instantaneous rates of thermal conduction cooling to expansion cooling for a wide range of plasma and fiber geometries. Here ν denotes the cooling rates, and $n_e = 10^{19}$ cm^{-3} and kT_p = 300 eV are electron densities and initial temperatures typical for CO_2 laser-produced plasmas. In this regime of relatively large fiber diameter, conduction cooling is at least an order of magnitude faster than expansion cooling. Conduction cooling is thus expected to reduce the plasma temperature long before expansion reduces the plasma density appreciably. This is a desirable outcome on the basis of the large absolute population density required for lasing action.

Radiation cooling of a pure carbon fiber plasma can be shown to be less effective than conduction cooling.[10] The presence of impurities such as aluminum should increase the cooling rate.[9]

For B = 90 kG, and if little magnetic flux is excluded from the plasma, the classical electron thermal conductivity decreases by a factor of ~ 200 for the conditions of Fig. 4. This can remove conduction as a cooling channel. The absence of inversion and enhancement for B = 90 kG in Fig. 3 might also be explained by increased electron collisional coupling between CVI levels n = 2 and n = 3 at the higher densities maintained by the field.

In conclusion, correlated population inversions and gains have been demonstrated for carbon fiber plasmas with the largest gain being ~ 6 cm^{-1}. Thermal conduction to the relatively cold fiber core remaining after the laser pulse is proposed as the dominant cooling mechanism.

Future experiments will investigate, in more detail, the nature of the axial laser-fiber coupling, and the effect of varying the thicknesses of aluminum coatings on the population inversions and gains.

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FIGURE CAPTIONS

Fig. 1 Carbon fiber target coated with a thin layer of aluminum for which the highest gain was observed. Framing images of the CO_2 laser-fiber interaction at $B = 0$, 90 kG.

Fig. 2. CVI 182Å intensities for the fiber target in Fig. 1 with an enhancement $E = 6$ and a gain of 6 cm^{-1}.

Fig. 3. Enhancement (E) vs population inversion for 16 fiber shots. Open circles: $B = 0$ kG, no Al coating; solid circles: $B = 90$ kG, no Al coating; open/solid triangles: fibers with 8000Å aluminum coating ($B = 0$ and $B = 90$ kG, respectively).

Fig. 4. Calculated instantaneous rates of thermal conduction cooling and expansion cooling for various fiber and plasma radii (r_f and r_p) for a temperature of 300 eV and electron density 10^{19} cm^{-3}.

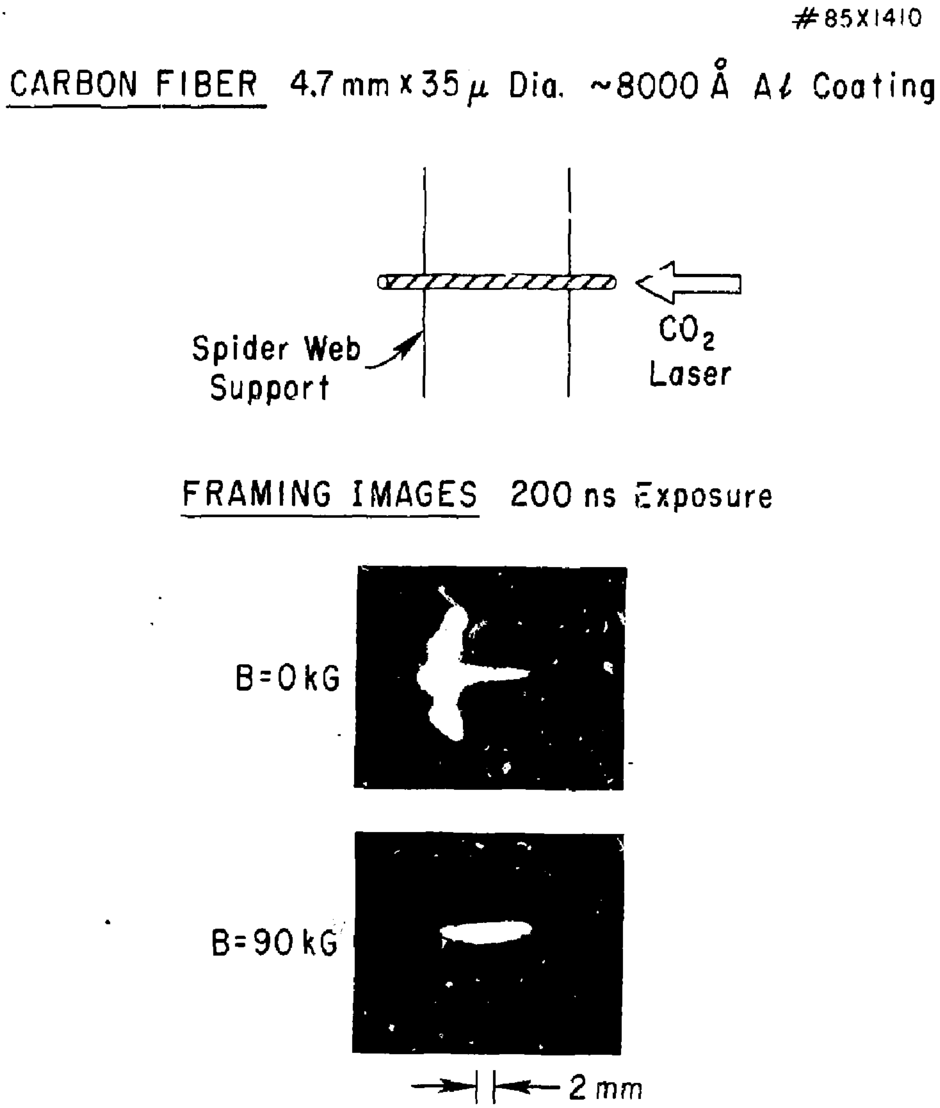
#85X1410
CARBON FIBER 4.7 mm x 35 μ Dia. ~8000 Å Aℓ Coating
Spider Web Support
CO₂ Laser
FRAMING IMAGES 200 ns Exposure
B=0 kG
B=90 kG
2 mm

Figure 1

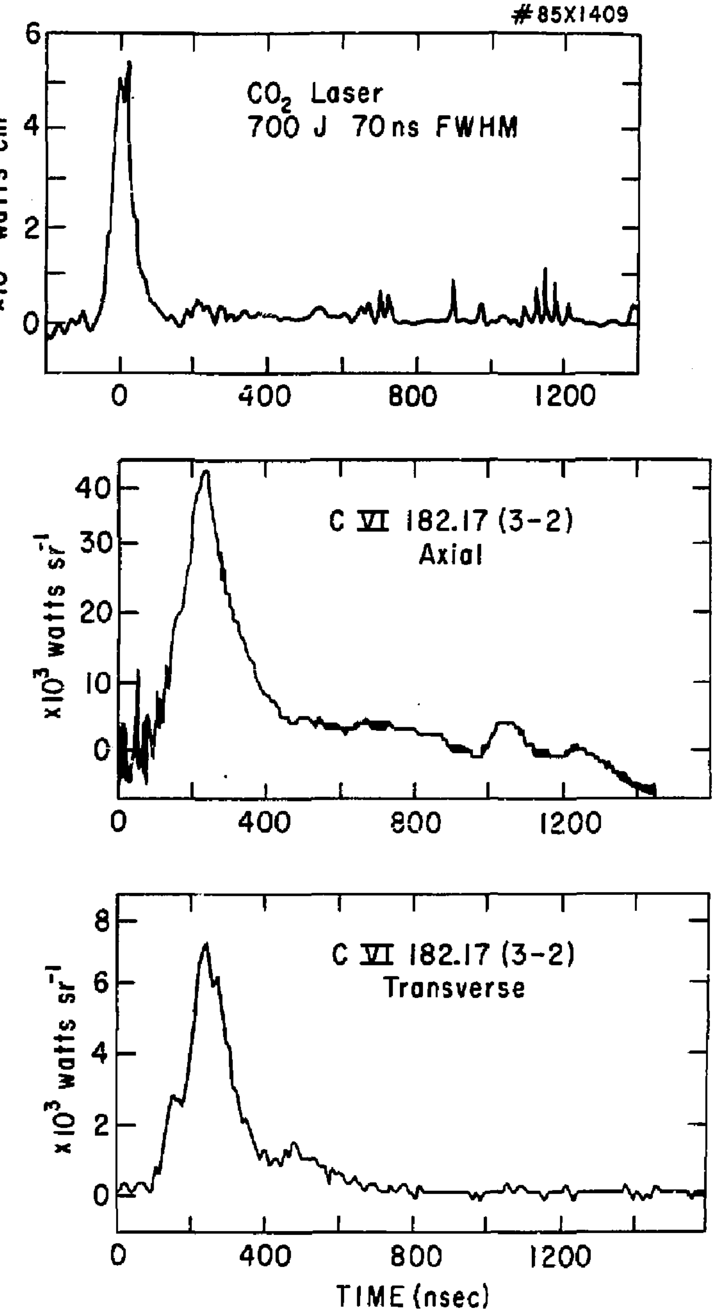
#85X1409
CO$_2$ Laser
700 J 70ns FWHM
x10^{12} watts cm^{-2}
6
4
2
0
0
400
800
1200
C VI 182.17 (3-2)
Axial
x10^3 watts sr^{-1}
40
30
20
10
0
0
400
800
1200
C VI 182.17 (3-2)
Transverse
x10^3 watts sr^{-1}
8
6
4
2
0
0
400
800
1200
TIME (nsec)

Figure 2

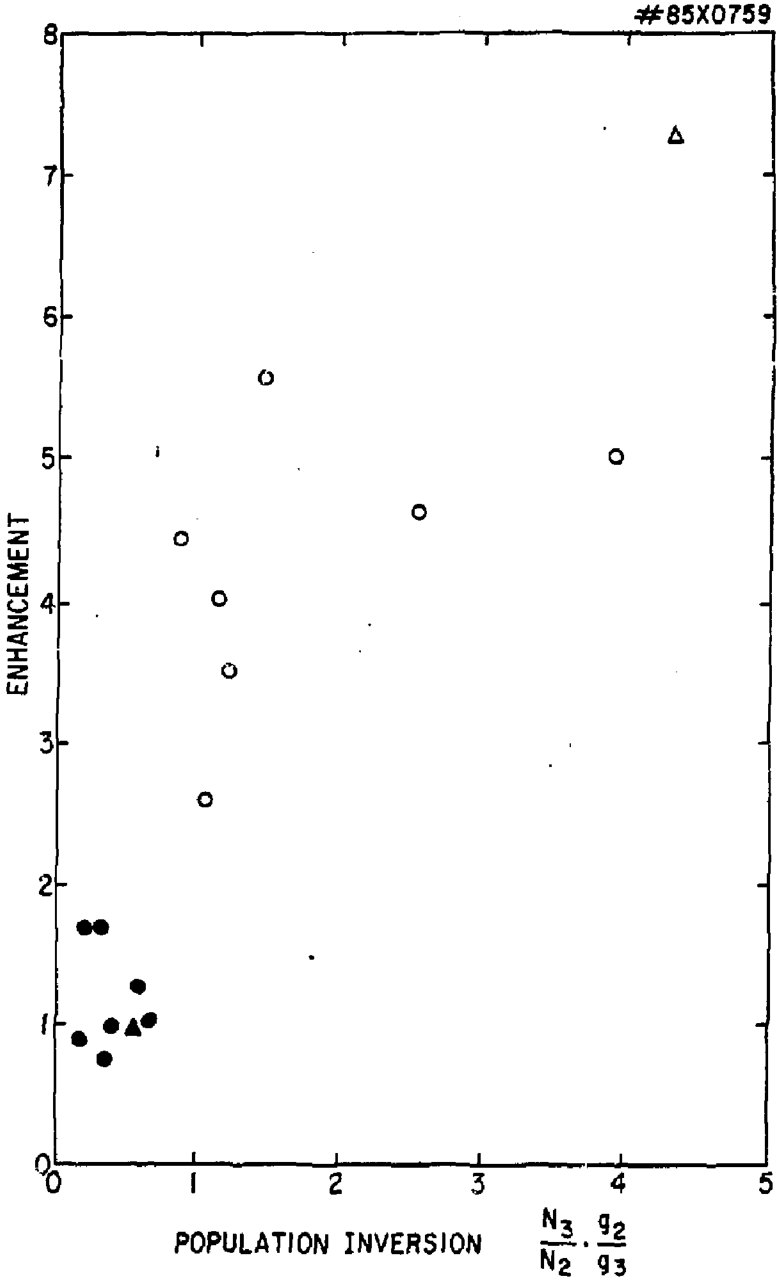
#85X0759
ENHANCEMENT
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
POPULATION INVERSION $\frac{N_3}{N_2} \cdot \frac{g_2}{g_3}$

Figure 3

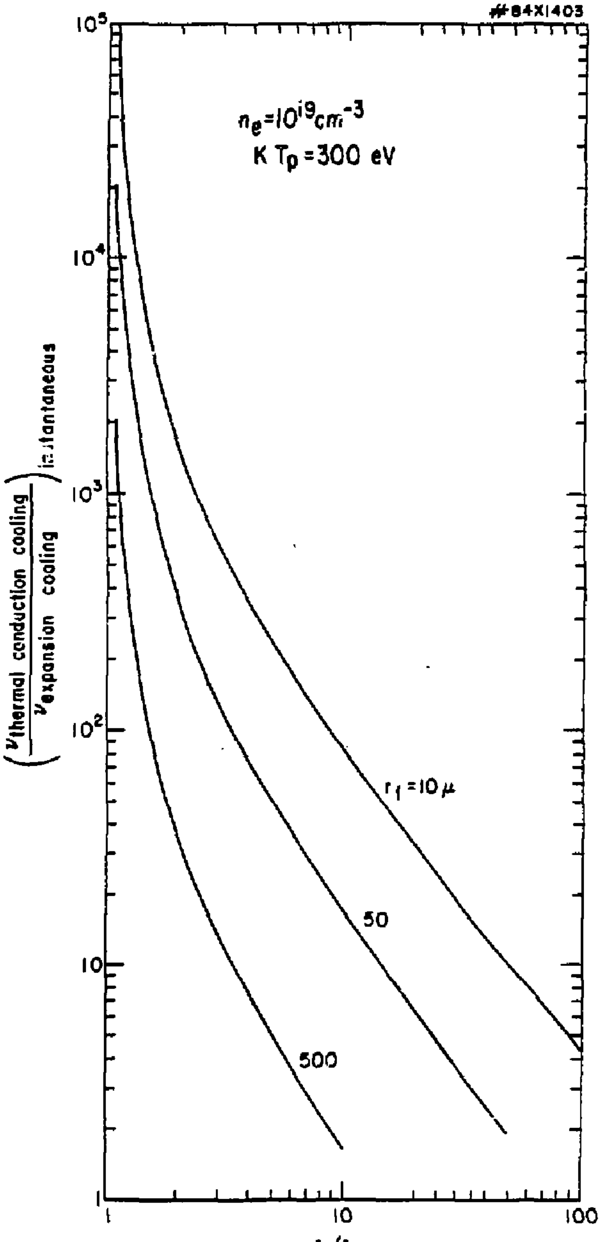
#84X1403
$n_e = 10^{19} cm^{-3}$
$KT_p = 300$ eV
$\left(\frac{\nu_{\text{thermal conduction cooling}}}{\nu_{\text{expansion cooling}}}\right)_{\text{instantaneous}}$
r_p/r_f
$r_f = 10\ \mu$
50
500
10^5
10^4
10^3
10^2
10
1
1
10
100

Figure 4

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