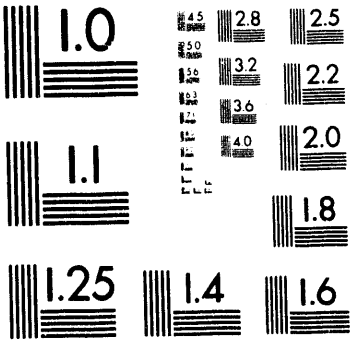
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Experiments on Nonlinear Absorption of ECH Waves in MTX
and a Comparison with Theory*

Barry W. Stallard, *S.L. Allen, J.A. Byers, T.A. Casper, B.I. Cohen, R.H. Cohen, C.J. Lasnier, M.E. Fenstermacher, J.H. Foote, E.B. Hooper, M.A. Makowski, W.H. Meyer, J.M. Moller, B.W. Rice, T. D. Roglien, G.R. Smith, K.I. Thomassen, R.D. Wood*
Lawrence Livermore National Laboratory, CA
and
K. Hoshino, K. Oasa, K. Odajima, T. Ogawa (JAERI, Tokai, Japan)
and T. Oda (Hiroshima University, Hiroshima, Japan)
and T. Ogo (Fukuoka University of Education, Fukuoka, Japan)

ABSTRACT

Intense pulse electron cyclotron heating (ECH) experiments have been carried out on the MTX tokamak. Rf pulses at 140 GHz, peak power of 1-2 GW, and 25 ns pulse length were generated by the ETA-III/IMP FEL and transported guasi-optically to MTX for o-mode launch. Because of the intense rf electric fields (~250 keV/cm), reduction of plasma absorption by nonlinear effects were expected and several rf beam geometries ($k_{\parallel}$ gradient) were investigated to study their effect on the absorption. As predicted by theory, measurements of beam transmission showed increases compared to low power (2 kW). For these experiments x-ray, ECE, and Thomson diagnostics showed evidence for localized absorption at the cyclotron resonance and hot electron production. A comparison of these results with the orbit following code ORPAT will be presented.

INTRODUCTION

Experiments to study the non-linear absorption of intense pulse microwaves have been carried out in the MTX tokamak. These experiments were motivated to explore the efficacy of very high peak power and high average power plasma heating using new technology capabilities of the FEL. The LLNL FEL consists of the electron linear accellerator ETA-III and IMP wiggler[1] operating as an amplifier. Typical beam pulses of 2 kA, 6 MeV energy, and 40 ns pulse length were injected into the wiggler (5 m length and 10 cm period), colinear with approximately 7 kW of 140 GHz drive power provided by a gyrotron oscillator. This drive power coupled 2 to 3 kW power to the TE_{11} mode in 3.25 cm waveguide. With optimized tapering of the wiggler field, we achieved a peak output power of 1 to 2 GW. The FEL output power was transported quasi-optically to the MTX tokamak over a 34 m distance using six mirrors mounted within a 50 cm diameter evacuated pipe. There was no vacuum window between the FEL output and the tokamak. The final mirror optic located 242 cm from the input duct to MTX focused the beam to a 2 cm diameter waist (1/e power diameter). The design transport efficiency of the system is 89%. Fig. 1 show a typical rf pulse measured at the FEL output. For the experiments reported here the FEL was operated single pulse at a 0.5 Hz rate . Brief testing of the FEL in burst mode at 2 kHz showed the capability of high average power output.

In order to study the nonlinear heating physics beams with two different geometries were injected into MTX as shown in Fig. 2. At the resonance the beam spot sizes were similar but the toroidal gradient in $k_{\parallel}$ differed by a large factor. For the first experiments a circular beam was injected into the smooth wall input duct of 2 cm width, 30 cm height, and 22 cm length.

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For this beam the diameter in vacuum at the plasma resonance was 3.6 cm and the spread in $k_{\parallel}$ was $\Delta k_{\parallel}/k_{\parallel} \approx 0.1$. For a second series of experiments we injected the beam into a corrugated vertical side wall duct, tapered in the horizontal direction (the side wall normal to the horizontal electric field for the o-mode). The Gaussian-shaped input beam coupled to the HE_{11}-like mode and the length of the 3.4:1 down taper was set to reconstruct the HE_{11} mode at the output[2]. The beam size at the resonance in vacuum was elliptical and elongated in the horizontal direction with dimensions 4.8 x 3.6 cm. This beam had a $k_{\parallel}$ spread $\Delta k_{\parallel}/k_{\parallel} \approx 0.35$.

NON-LINEAR ABORPTION OF INTENSE PULSE ECH

At 1 GW peak power the electric fields of the microwave beam at the resonance are $\tilde{E} \approx 250$ kV/cm. Electrons are heated so rapidly that their relativistic mass increase causes the electron gyro period and the wave fields to fall out of phase, and electrons become trapped in the wave (phase space ``buckets"). As they stream through the beam the electrons perform rapid adiabatic excursions up and down in energy as their gyrophase changes. Upon exiting the beam the adiabaticity of the electrons is broken and of a fraction of these electrons retain high energy.[3] For an FEL beam with no gradients in $k_{\parallel}$ in a plasma with no gradients in magnetic field, the absorption is reduced from the predictions of linear theory. The situation is different if the gradients are non-zero. For a gradient in $k_{\parallel}$ electrons trapped within the wave can be adiabatically raised to higher energy (rising buckets) if gradients are not too large.[4] This effect increases heating. Under certain conditions the absorption can exceed the predictions of linear theory.

Other nonlinear effects can be important for intense electric fields. At a 1 keV plasma electron temperature the electron quiver velocity is $\tilde{v}/v_e \approx 0.4$, where $v_e=(T_e/m)^{0.5}$ is the electron thermal velocity, and nonlinear effects are expected to be important in determining plasma absorption and heating.[5]

~~parametric effects,~~

Non-linear modeling

The code ORPAT was used to model nonlinear absorption at the resonance[6]. ORPAT follows the guiding center orbits of electrons as they stream through the FEL beam, keeping track of the gyro phase. The beam profile varied toroidally to model the experiment and a flat pulse of 20 ns duration approximated the beam pulse shape. For radial zones near the resonant surface the heating of electrons from an ensemble of electrons from a Maxwellian target plasma was calculated as they transited the beam. The beam amplitude was attenuated by the absorbed energy , but the phase front curvature was assumed unchanged. Plasma refraction of the FEL beam in the vertical direction reduces the electric field intensity at the resonance. To take this into account the ray tracing code TORAY modeled the refraction and a refraction factor R_1 was calculated giving the reduction in beam intensity at resonance compared to the vacuum value. As described in the next section, for comparison between ORPAT and experimental beam transmission to the wall oposite the injection port, an additional refraction factor R_2 was defined. The resulting beam transmission intensity at the beam center is given by:

$$T_2 = R_1 R_2 \int T(z,y=0)\, dz,$$

where T(z,y) is the absorption at the resonant layer and y (z) is the vertical (toroidal) direction. The integration in z models absorption on the calorimeter tiles described below.

EXPERIMENTAL RESULTS

In MTX experiments we inferred the ECH absorption for central resonance (B_{tor}=5 T) from measurements of beam transmission. Because the plasma heating experiments were carried out for single FEL pulses with typical energy 20 J, bulk heating of the plasma could not be measured. However, for some of our data generation of hot electrons was observable on several fast diagnostics: second harmonic ECE, soft x-rays (JAERI provided), and Thomson scattering measurements of the hot electron tail. The beam transmission diagnostics consisted of a calorimeter on the inside wall opposite the input port, which was segmented poloidally to measure the transmitted beam vertical profile, and a single point measurement at the approximate beam center using a fundamental mode waveguide horn connected to an rf reciever. The input FEL beam pulse shape and spatial profile was measured at both the FEL output and the tokamak input using similar waveguide horns (both fixed and movable probes) and calibrated rf receivers. Total beam calorimeter (JAERI) measured the FEL pulse energy at the tokamak input. Using the measured pulse shape the peak power was determined.

Injection with smooth wall

Fig. 3 shows the transmission, measured by the central absorbing tiles of the calorimeter, as density was scanned, for the FEL beam injected into the smooth wall duct. The electron temperature of the target plasma was nominally 1 keV but varied from about 0.8 to 1.6 keV. The peak power of the FEL pulse was about 1 (±0.2) GW. The inferred transmission is given by normalizing the meaured transmission with plasma to the value without plasma. Each measured transmission value was also nomalized to the total pulse energy for each shot. There is considerable scatter in the data but the transmission exceeds by a large factor the transmission at low power (~ 2 kW) obtained with the gyrotron driver only. The source of the scatter is not fully understood. There is scatter in the electron temperature of the target plasma but no apparent correlation of transmission with the electron temperature variations.

Also shown in the figure is the modeling of transmission using ORPAT for an average FEL power <P> = 0.75 GW. Although the peak power was ~1 GW, the lower value was used to take into account the time average of the FEL pulse. Within the scatter of the data the theory and measurements are in agreement. For the low power data the transmission curve for linear theory agrees closely with the measurements. For these experiments fast ECE and Thomson measurements were not available but fast x-ray measurements at 180 deg. toroidal angle from the injection port showed no evidence for hot electrons.

Injection with tapered wall

Similar transmission measurements were made for the divergent FEL beam. These results are shown in Fig. 4 and compared with the no taper data. For this beam geometry greater absorption is inferred. This data also has large scatter and also no apparent correlation with electron temperature. However, the data is clearly below the no taper data and in reasonable agreement with ORPAT.

For the tapered wall experiments fast diagnostic data were available. These measurements show clear evidence for hot electrons and localization of heating near the resonant surface. Thomson data measured on axis at the resonance is presented in Fig. 5 for target plasma parameters $n_{e0} = 0.65 \times 10^{20}$ m^{-3} and T_{e0} = 1.5 keV. The open triangles show the measured data for a shot without the FEL. The dashed line curve is the best fit for a Max-

wellian distribution[7], relativistically correct to order $(v_e/c)^2$. The solid circles show the signal with the FEL. To increase the signal to noise ratio in the tail of the scattered spectrum, we averaged six shots from similar discharges. The increased signal at high energy shows the presence of hot electrons. These data are in agreement with the nonlinear theory. To model the Thomson scattering expected from the nonlinear heating, we used the ORPAT code to calculate the electron energy distribution at the Thomson observation port located 120 deg from the FEL port. The orbits of electron with a heated distribution $F(E)_0$ at the FEL port were followed as they drifted 120 deg around the torus to determine $F(E)_T$ at the Thomson port. From a fit of this distribution to a 2 temperature Maxwellian the calculated scattered spectrum was derived. The fit is somewhat insensitive to the fit of the hot component. For the solid curve in the figure best fit parameters were T_{e0} = 1.55 keV and T_{eh} = 10 keV.

Fast x-ray measurements in Fig. 6 show that absorption is localized to near the magnetic axis. For this data the observation port was xx deg from the FEL port. Plasma parameters are shown for a shot with FEL injection at 200 ms. Expanded fast x-ray traces for the central channel nearest and several adjacent channels, spaced at 3.8 cm intervals are shown. Only the central channel shows a signal which decays in about 15 microsec. This decay rate is consistent with a hot electron component of about xx keV.

Inside and outside wall ECE measurements also confirm the presence of hot non-thermal electrons. A heterodyne receiver on the inside (JAERI) and a grating polychrometer view the plasma. Typical data for the inside signal show an abrupt increase followed by a decay time of ~ 20 microsec; the outside signal shows an abrupt increase and then decrease with no slowly decaying signal. This behavior is expected for non-thermal electrons. Because of their relativistic mass increase, the non-thermal electrons radiate at a lower frequency than the local cyclotron frequency. This radiation is accessable to the inside view antenna but must pass through an absorbing resonance before reaching the outside antenna.

For experiments with the tapered input duct we looked for evidence of backscattering from the plasma. The rf probe viewing the plasma was a small waveguide horn connected to a calibrated rf receiver and located near the FEL input axis. Only backscattered frequencies down shifted > 200 MHz from the FEL frequency could be distinguished by the available receiver (bandwidth ≈ 400 MHz). Backscattered signals near ion cyclotron frequencies f_{ci}≈24 MHz could be discriminated only by the two way transit time delay (~12 ns) between the probe and the plasma. We scanned the receiver for down-shifted signals ≤ 1.3 GHz (~f_{pi}). Our measurements showed no evidence for backscattering. From our measurements an upper limit for backscattered power is $P_{back}/P_{FEL} < 2 \times 10^{-5}$.

CONCLUSIONS

Our experiments clearly demonstrate the reduction in absorption for intense pulse ECH and the ability to increase the absorption by control of the beam geometry. The data is also in good agreement with nonlinear modeling, including the production of hot electrons. For our parameters we have seen no evidence for parametric instabilities as expected from the theory. Initial testing of the FEL at high repetition rate indicates that high average power operation can be achieved and the prospects for operation at shorter wavelengths look promising. Bulk heating remains to be demonstrated.

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The FEL for MTX Operates Reliably at High Power (1-2 GW)

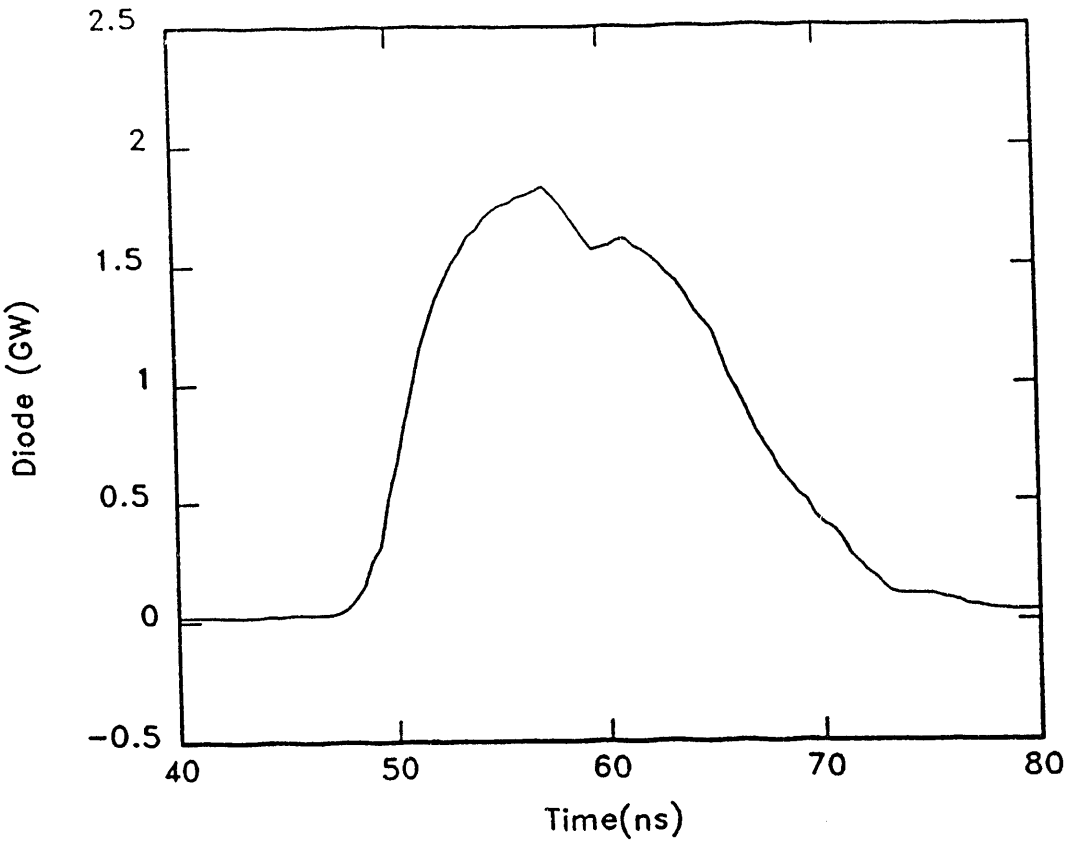


Fig.1

Fig. 2

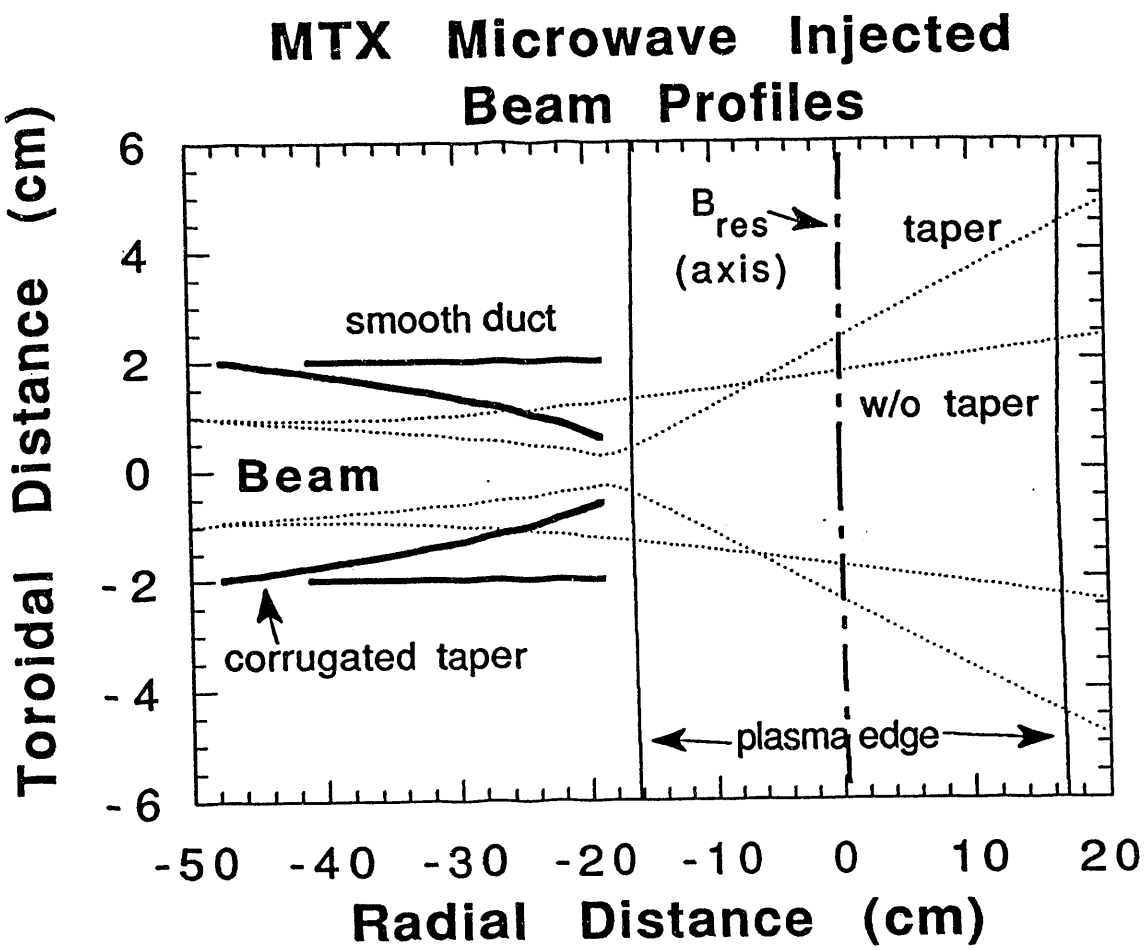
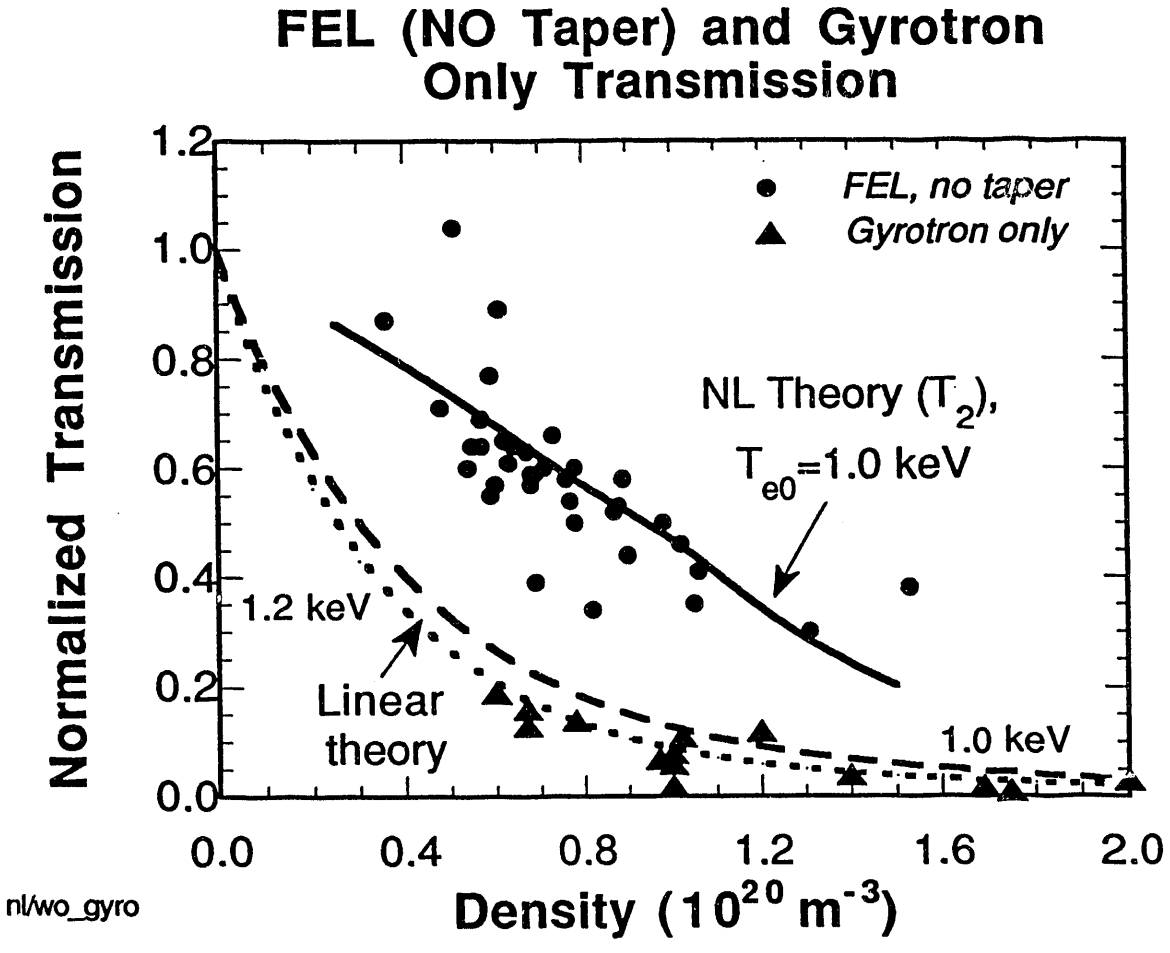
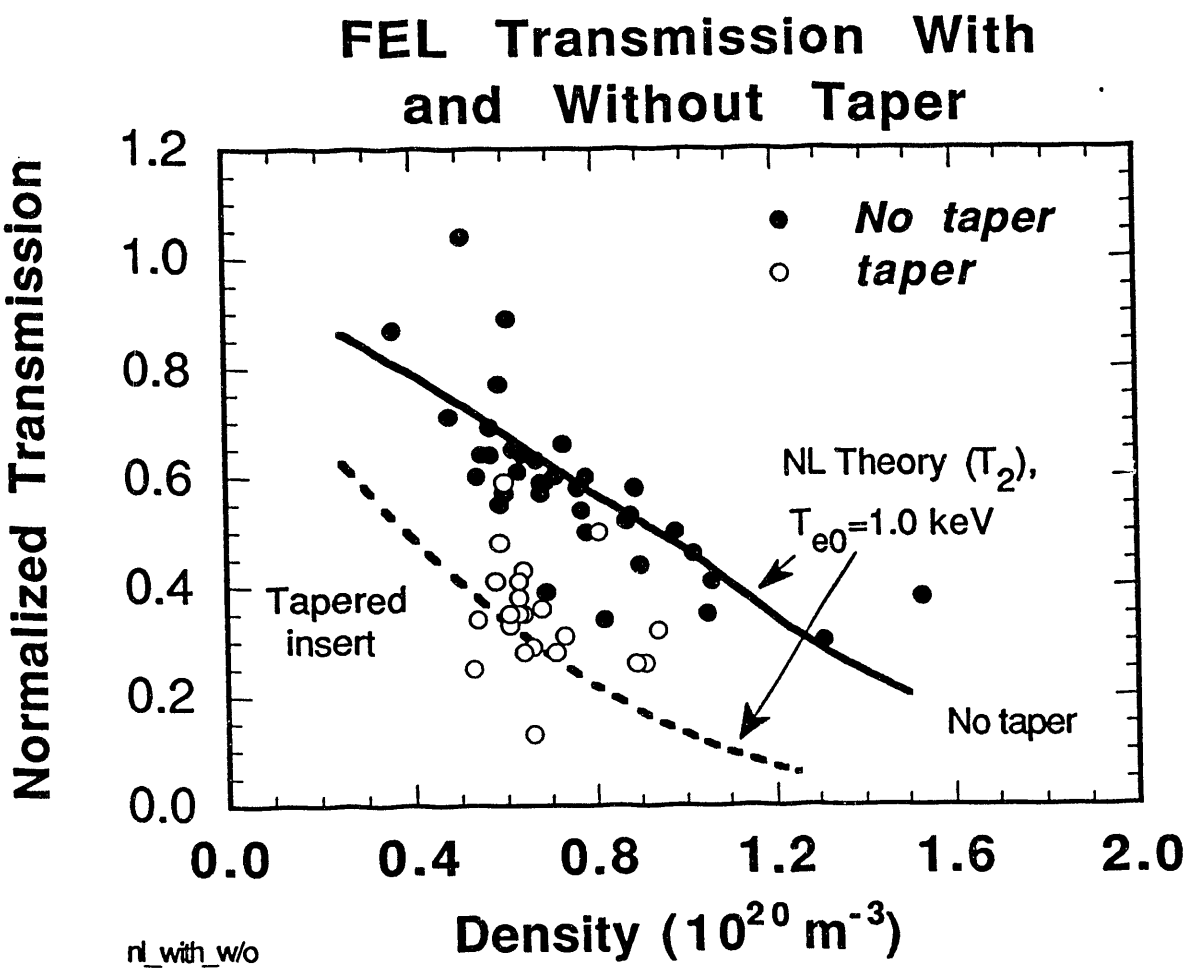

MTX Microwave Injected
Beam Profiles
Toroidal Distance (cm)
6
4
2
0
-2
-4
-6
smooth duct
Beam
corrugated taper
B res
(axis)
taper
w/o taper
plasma edge
-50
-40
-30
-20
-10
0
10
20
Radial Distance (cm)

Fig. 3



nl/wo_gyro

Fig. 4


FEL Transmission With and Without Taper
Normalized Transmission
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1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Density (10^{20} m^{-3})
No taper
taper
NL Theory (T_2),
T_{e0}=1.0 keV
Tapered insert
No taper
nl_with_w/o

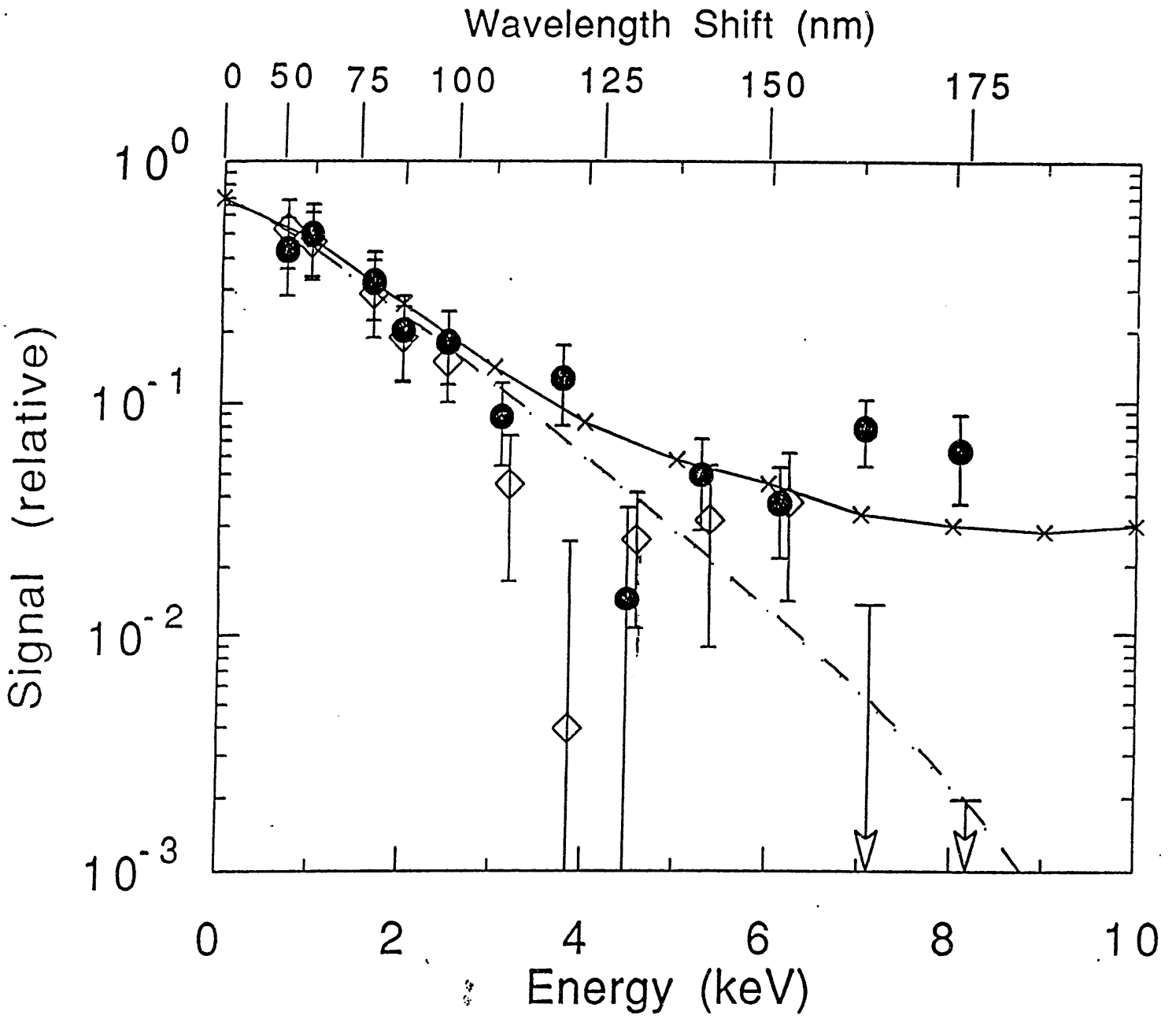
Wavelength Shift (nm)
0
50
75
100
125
150
175
10^0
10^{-1}
10^{-2}
10^{-3}
Signal (relative)
0
2
4
6
8
10
Energy (keV)

Fig. 5

JAERI Fast X-Ray Diagnostic Shows Localized Response to FEL

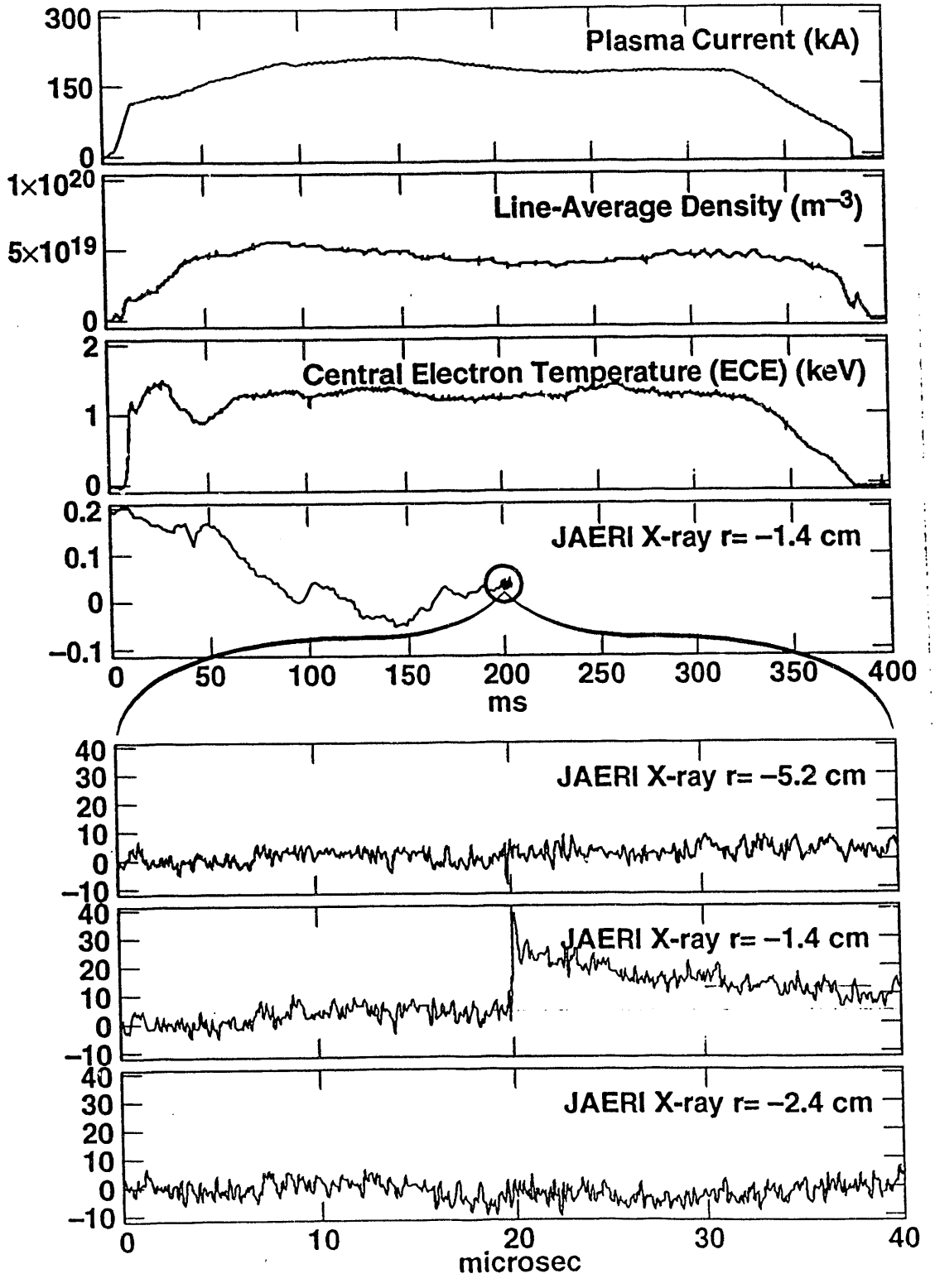

Fig. 6

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