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B. W. Stallard, J. A. Byers, E. B. Hooper
M. A. Makowski, S. Meassick, B. W. Rice
T. D. Rognlien, J. Verboncoeur

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B. Stallard, J. Byers, B. Hooper, S. Meassick, B. Rice,
T. Rognlien, and J. Verboncoeur
Lawrence Livermore National Laboratory, Livermore, CA, 94550
M. A. Makowski
TRW, Redondo Beach, Ca. 90278

Abstract

The Microwave Tokamak Experiment (MTX) at LLNL is investigating the heating of high density Tokamak plasmas using an intense pulse FEL. Our first experiments, now beginning, will study the absorption and plasma heating of single FEL pulses (20 ns pulse length and peak power up to 2 GW) at a frequency of 140 GHz. A later phase of experiments also at 140 GHz (FY 90) will study FEL heating at 5 kHz rate for a pulse train up to 50 pulses (35 ns pulse length and peak power up to 4 GW). Future operations are planned at 250 GHz with an average power of 2 MW for a pulse train of 0.5 s. The microwave output of the FEL is transported quasi-optically to the tokamak through a window-less, evacuated pipe of 20 in diameter, using a six mirror system. Computational modelling of the non-linear absorption for the MTX geometry predicts single-pass absorption of 40% at a density and temperature of $1.8 \times 10^{20}m^{-3}$ and 1 keV, respectively. To measure plasma microwave absorption and backscatter, diagnostics are available to measure forward and reflected power (parallel wire grid beam-splitter and mirror directional couplers) and power transmitted through the plasma (segmented calorimeter and waveguide detector). Other fast diagnostics include ECE, Thompson scattering, soft x-rays, and fast magnetic probes

Introduction

Intense pulse FEL electron heating of a tokamak plasma will soon begin (Summer, 1989) in the MTX experiment at LLNL. In addition to technology demonstrations for the FEL and microwave transport system, important physics issues to be addressed in the initial experiments are the reduction in absorption (from linear theory) by non-linear effects, the significance of parametric instabilities which may cause backscatter, and the possibility of beam filamentation. The initial phase of experiments at 140 GHz will investigate the absorption of single FEL pulses with 20 ns pulse duration and up to 2 GW peak power. The short pulse electromagnets of the ELF wiggler limit heating to a single FEL pulse per plasma discharge [1]. A second phase of experiments (FY 90), using the IMP wiggler with DC magnets [2], will heat at higher power (35 ns pulses and peak power up to 4 GW) and at a 5 kHz rate for a pulse train of 50 pulses. These

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experiments will focus on multi-pulse heating, radial transport of FEL absorbed power, and ECH of pellet-fuelled plasmas.

ECH Transmission

The transport of FEL output power to the tokamak is accomplished by six mirror quasi-optical transmission, as shown in Fig. 1. The transmission system is window-less and mirrors are enclosed within a 50 cm diameter evacuated pipe. To avoid the need of an achromatic jog in the transport pipe for the e-beam which drives the FEL, two additional mirrors (J_0 and J_1) were added to the original design previously described [3]. Mirrors J_0, M_2, and M_4 are focussing optics, and the remaining mirrors are flats. The dominant output mode of the wiggler is TE_{01} in WR 229 rectangular waveguide (5.82 cm x 2.91 cm). Using the MTH code [4] the overall transmission efficiency at 140 GHz is 89%. Most of the loss is clipping of side-lobe power of the mode at the first three mirrors. For the second phase of experiments using the IMP wiggler the waveguide mode will be TE^{o}_{11} in 3.25 cm circular waveguide. To transport this mode mirrors J_0 and M_2 must be modified. The final optic (M_4) focusses the microwave beam into an elliptical cross-section (about 6:1 ellipticity) for transmission through the narrow port of MTX (4 cm horizontal x 30 cm vertical x 22 cm duct length.)

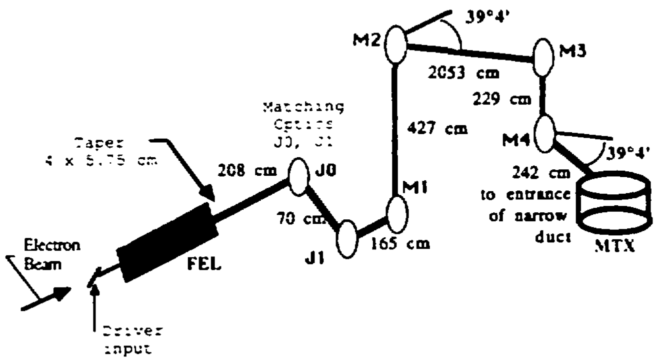

Figure 1: MTX microwave transport. Design for 140 GHz (not to scale).

Non-linear Absorption

Because of the intense electric fields of the FEL beam (E_{max} ~ 200 to 300 keV/cm), the absorption is non-linear and reduced from the linear theory value [5]. The expected absorption was modelled by the following multi-step process: 1) the calculated beam profile at the port entrance (MTH code) is decomposed by Fourier analysis into the appropriate set of waveguide modes excited by the incident beam, 2) the waveguide modes are propagated to the end of the 22 cm long duct, taking into account the differential phase shift between modes, 3) the MTH code calculates the electric field at the plasma using diffraction theory and the mode amplitudes and phases at the duct exit, and 4) attenuation of the beam and heating of electrons as they pass through the beam

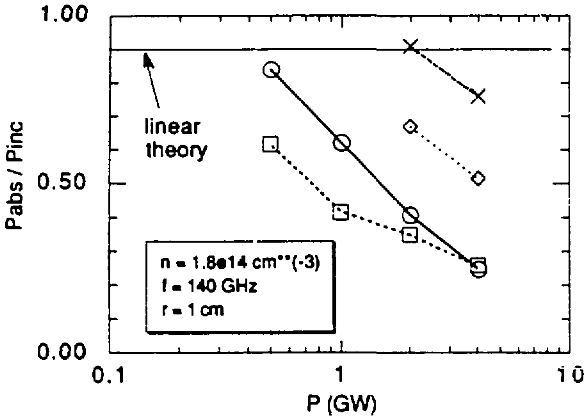

Figure 2: Fraction of incident power absorbed for various cases. (o) Smooth duct; dashed curves are corrugated: (□) no taper, (◇) 2:1 taper, (x) 4:1 taper.

are computed using the orbit code ORPAT. The differential phase shift between modes after propagation along the duct produces significant distortion in the electric field profile at the plasma and also increases wall electric fields to $E \sim 0.5\ E_{max}$ at the duct exit. For the smooth wall duct the calculated single-pass absorption is ~ 40% for 2 GW power and plasma parameters $n_{e0} = 1.8\text{x}10^{20}\text{m}^{-3}$ and $T_{e0} = 1$ keV. The variation with power is shown in Fig. 2.

To increase the absorption efficiency and reduce wall electric fields, we are exploring the use of parabolic down-tapers with smooth or corrugated side walls (corrugations on vertical walls, perpendicular to E, with corrugation depth and period $\lambda/4$ and $\sim \lambda/3$, respectively) [6,7]. The electric field profile incident upon the entrance port is near Gaussian and strongly couples to the lowest order hybrid mode HE_{11} of the corrugated waveguide. A 4:1 taper of 25 cm length can fit within the entrance port.

The increase in absorption through use of the taper results from the reduced electric field and the greater beam divergence ($k_\perp$ spread) at the plasma caused by diffraction from the small beam waist near the duct exit [5]. Fig. 2 compares several down-tapers in the corrugated duct with the un-tapered, smooth wall duct. Absorption with the 4:1 taper is more than double the absorption at 2 GW and equal to the linear absorption value.

Absorption and Fast Response Diagnostics

To measure single pulse absorption several diagnostics have been developed to measure forward and reflected power at the input port and the power transmitted through the plasma. From these measurements the single-pass absorption can be inferred. We measure forward and reflected power by 1) a parallel wire grid beam splitter oriented at 45 deg to the beam axis and 2) single mode waveguides near the beam center on M_4, viewing the forward and reflected directions. The wire grid is a diffraction grating where the electric field and grid wires lie in the plane of incidence. For wire diameter 0.005 in and wire spacing $\lambda/d = 0.086$, the coupling coefficient is 0.023 [8]. Mirror optics focus the coupled power onto fast response photon drag detectors. On the inside wall we measure power transmitted through the plasma by 1) a small microwave horn located near the beam center and 2) a segmented calorimeter consisting of 2 cm x 9 cm (toroidal direction) silicon carbide tiles, backed by thermisters, and segmented in the poloidal direction. The calorimeter can measure a large fraction of the total transmitted power and the effects of plasma refraction.

In addition to direct measurements of absorption, the localization and magnitude of heating can be assessed using various diagnostics with fast time response ($\leq 1\ \mu$sec). These include soft x-rays, Thomson scattering, an ECE polychrometer, and fast magnetic probes. The time scale for equilibrium after injection of an FEL pulse is estimated to be several μsec (Alfven times and toroidal equilibrium of initially trapped electrons). Because the fractional energy increase for a single pulse is small ($\Delta W/W \sim 1\%$), measurement of the energy increase for a single pulse, although difficult, may be possible using fast magnetic probes. For time scales $< 100\ \mu$sec, the vacuum wall of the MTX vessel is flux conserving. The estimated magnitudes of field changes for the initial experiments are poloidal (toroidal) field $\delta B_\theta \sim$ few gauss ($\delta B_T \sim (\frac{1}{10})\delta B_\theta$). If successful, these measurements will be useful to study the plasma transient response and also to measure single pulse heating.

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