28 GHz Gyrotron and 4.6 GHz Klystron Heating Options for LDX

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ABSTRACT - The success of fully levitated LDX plasma operations is now motivating increasing the plasma heating power to explore the full potential of high beta plasma stability in a dipole magnetic configuration. Adding 28 GHz gyrotron and 4.6 GHz klystron electron cyclotron heating using sources available at MIT is being evaluated. A Varian model VGA-8050M 28 GHz gyrotron that is capable of 200 kW in 0.1 s pulses or 10 kW CW is on site, and the output of one 250 kW, 0.5 s klystron at the adjacent C-Mod site could be transmitted to LDX. Adding these sources would significantly increase maximum heating power above the present 15 kW maximum to access higher beta plasmas. Heating at 28 GHz in particular, would be above cutoff for plasma densities up to the 10^{13} cm^{-3} range which are presently not accessible with the current low power 2.45 to 10.5 GHz heating sources. Overmoded waveguides would be used for both 28 and 4.6 GHz to efficiently transmit the 100+ kW power levels into LDX to heat at the electron cyclotron fundamental and harmonics.

Introduction

High-power microwave heating sources available at MIT could be implemented with modest effort to increase LDX plasma density and pressure

So far successful levitated plasmas have been achieved with a maximum of 15 kW of microwave heating power
- 2.45 GHz magnetron, 2.5 kW
- 6.4 GHz klystron, 2.5 kW
- 10.5 GHz klystron, 10 kW

A 200 kW, 28 GHz gyrotron is currently located adjacent to LDX as shown above right, but needs to be made operational
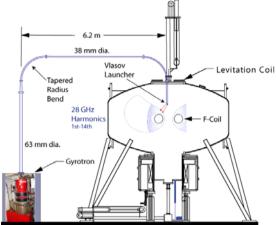- Requires high voltage power for the electron gun
  - 80 kV, 8.0 A for 200 kW, 0.1s pulses
  - 40 kV, 0.87 A for 10 kW, CW
- A total of 1960 A current for 4 main coil and 2 gun coil magnets
- Cooling water connections for magnets, gyrotron collector, and body

A 3 MW, 4.6 GHz 12 klystron system is located a little over 100 m away at the C-Mod site
- An efficient waveguide could bring power from one 250 kW klystron to LDX

The possible implementation of these additional sources of microwave heating to significantly increase LDX plasma performance are described and details of the waveguide transmission lines given

28 GHz Gyrotron Heating

One possible geometry for 28 GHz X-mode launched heating perpendicular to the magnetic field. The heating beam would be directed at the fundamental and 2nd harmonic electron cyclotron resonances.

Circular TE$_{02}$ Transmission Line Attenuation

The gyrotron output is mainly in the circular TE$_{02}$ mode. A mode filter or converter will be used (not shown) if necessary to achieve a pure mode for transmission.

Assuming copper waveguide with a conductivity of 5.88 x 10^7 mhos/m, the TE$_{02}$ mode loss at 28 GHz for the transmission line components shown above are:

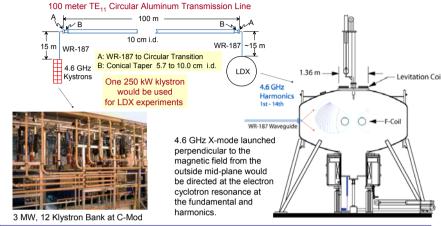|		
63 mm diameter	-0.004 dB/m	3.5 m	-0.014 dB
38 mm diameter	-0.021 dB/m	5.0 m	-0.105 dB
Two bends 38 mm dia.	-0.042 dB/m	3.2 m	-0.134 dB

The total ohmic transmission losses are calculated to be about 5% (-0.25 dB). It is reasonable to expect a transmission efficiency to the plasma of 90% allowing another 5% losses for the window and taper.

Many of the 28 GHz transmission components are available or easily fabricated.

Valsov Launcher, Circular Guide

28 GHz TE$_{02}$ 38 mm dia. corrugated tapered radius bend

$$\alpha = sin^{-1}\left(\frac{k_{cn}}{k}\right)$$
$$k_{cn} = \frac{v_{02}}{a} \quad k = 2\pi/\lambda$$
v_{02} root of $J'_0(v) = 0$
a, waveguide radius
TE$_{02}$ $v_{02} = 7.016$
$a = 17.5$ mm

$$L = 2a\cos\alpha \qquad 30\ mm$$

4.6 GHz Klystron Heating

100 meter TE$_{11}$ Circular Aluminum Transmission Line

A: WR-187 to Circular Transition
B: Conical Taper 5.7 to 10.0 cm i.d.

One 250 kW klystron would be used for LDX experiments

3 MW, 12 Klystron Bank at C-Mod

4.6 GHz X-mode launched perpendicular to the magnetic field from the outside mid-plane would be directed at the electron cyclotron resonance at the fundamental and harmonics.

- Overmoded circular TE$_{11}$ for main 100 m waveguide run to reduce loss
- Fundamental rectangular WR-187 to negotiate bends at input and output
- Aluminum tubing is proposed for the 100 m run to reduce costs
  → Al conductivity 2.50 x 10^7 mhos/m

100 mm dia. Al wg	-0.004 dB/m	100 m	-0.4 dB
WR-187	-0.02 dB/m	30 m	-0.6 dB

- If another 0.5 dB loss is allowed for a total loss of 1.5 dB, then it may be possible to transmit up to 175 kW from one klystron to LDX

Rectangular TE$_{01}$ / Circular TE$_{11}$ Transmission Line Attenuation

Simple Rectangular to Circular Transition
http://www.ham-radio.com/sbms/techpapers/K6BLG/circ_rect.html

TE$_{01}$ → TE$_{11}$

Homogenous Transition, Cutoff Wavelengths Equal

$$\lambda_c = 2a = \frac{2\pi r}{1.8114} \longrightarrow r = \frac{1.8114}{\pi}a$$

WR-187, 47.55 x 22.15 mm → 55.73 mm dia.

Quarter Wavelength Matching Section

$$Z' = \sqrt{Z_{in} \cdot Z_{out}} \qquad \text{Power-Voltage Impedance Matching Condition}$$

$$Z_{in} = \frac{2b}{a} = 0.932 \quad Z_{out} = \frac{2r}{r} = 2 \quad Z' = \frac{2b'}{a} = 1.365$$

$$b' = \sqrt{b \cdot r} \qquad a' = 51.5\ mm \quad b' = 35.2\ mm$$

Transition Length, 4.6 GHz

$$\lambda_g = \frac{\lambda_o\lambda_c}{\sqrt{\lambda_c^2 - \lambda_o^2}} \qquad \frac{1}{4}\lambda_g = 22.37\ mm$$

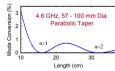95% of quarter guide wavelength to account for shunt capacitance $L_{tran} = 21.25$ mm

Parabolic Circular Taper
J. L. Doane, Inter. J. Infrared & Millimeter Waves, 5, 737-751, 1984

Taper Lengths for which Mode Conversion Vanishes

$$L_n = \frac{K_o\left(a_2^2 - a_1^2\right)}{P_o\lambda}\left[\left(\frac{n\pi}{K_o\ln(a_2/a_1)}\right)^2 - 1\right]^{\frac{1}{2}}$$

a_1, a_2 input and output radii, $a_1 = 27.8$ mm, $a_2 = 50$ mm

for TE$_{11}$ –TM$_{11}$ conversion $K_o = -0.65$, $P_o = 0.90$

4.6 GHz, 57 - 100 mm Dia. Parabolic Taper
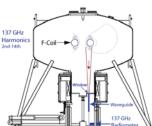
A taper length as short a 16 cm (n=1) could be used but a length of 32 cm (n= 2) would be better because TE$_{12}$ mode conversion loses (not shown) would be lower at longer length. Other possible modes for conversion from TE$_{11}$ at 4.6 GHz do not propagate in 100 mm diameter

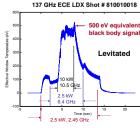**Parabolic Profile** → $a(z) = \sqrt{a_1^2 + 2Fz}$ $F = \left(a_2^2 - a_1^2\right)/2L$
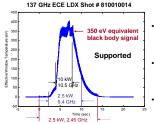
137 GHz ECE Measurements

- A 137 GHz radiometer was installed to view ECE directed vertically downward from the high field region of LDX
  - max. LDX field is 3.25 Tesla on inside F-Coil
  - only harmonic emission observed at 137 GHz
- Radiometer noise temp. 3000 K with 3 GHz double side band
- 35 mm dia. 1.1 m long ceramic waveguide from radiometer to fused quartz window for HE$_{11}$ mode launched field-of-view
  - 1.9 dB insertion loss
  - another 7.0 dB attenuator inserted to prevent radiometer saturation after initial observations
- Field of view at plasma ~0.3 m 1/e² dia. encompassing >12 harm. partially obstructed by F-Coil catcher (not shown)

Ceramic waveguide
137 GHz radiometer

View of 137 GHz radiometer setup on floor below LDX. A short run of Al corrugated waveguide with a miter bend connects to the ceramic waveguide

Radiometer calibrated to window with liquid nitrogen black body

Non linearity of microwave IF detector diode taken into account by:

$$KP_{in} = V_{out}\left(1 + \alpha V_{out}\right)$$

$K = 59.72$ mV/eV
  from LN$_2$ calibration at window

$\alpha = 0.01$ mV/mV
  for typical HP-33330 zero bias schottky diode detector used here

137 GHz ECE LDX Shot # 810010018

500 eV equivalent black body signal
Levitated
10 kW 10.5 GHz
2.5 kW 6.4 GHz
2.5 kW, 2.45 GHz

137 GHz ECE LDX Shot # 810010014

350 eV equivalent black body signal
Supported
10 kW 10.5 GHz
2.5 kW 6.4 GHz
2.5 kW, 2.45 GHz

- At 137 GHz 500 eV equivalent black body signals are observed at the LDX bottom window
- This is a lower limit for the actual emission at the plasma since the plasma does not completely fill the view of the radiometer
- In F-coil supported discharges the 2.45 and 6.4 GHz sources do not produce significant hot electrons in view of the 137 GHz radiometer
- The presence of high energy electrons would make possible harmonic ECE heating at frequencies above 100 GHz