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On RF frequency of LHCD system for KSTAR*

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Abstract

The Lower-Hybrid Current Drive (LHCD) system provides efficient bulk current drive at a low plasma density, off-axis current-profile control, and electron heating. The original design of RF frequency for the LHCD system was 3.7 GHz. However, we consider the RF frequency to be changed from 3.7 GHz to a frequency between 4.6 GHz and 5.7 GHz in order to increase the plasma density limit above which wave damping is mostly in ions, reducing therefore drastically the current drive efficiency. In this paper, we present results on power flux, $N_{||}$ values, and the power reflection coefficients in 3.7 GHz, 5.0 GHz, and 5.7 GHz LHCD system together with the RF loss analysis.

Introduction

- On Lower-hybrid (LH) heating, we first consider the density limit above which wave damping is mostly in ions, reducing therefore drastically current-drive efficiency. The higher LH-wave frequency, the higher the density limit. The current-drive efficiency becomes small as the density increases for a given LH-wave frequency. The LSC (Lower-hybrid Simulation Code) code shows that a higher LH frequency is required in a high density for the same current-drive efficiency as in the lower density. LSC code simulations are necessary for the investigations on the current-drive efficiency for LH-wave frequencies (5.0 - 5.7 GHz). But, there exist some results of the LSC-code simulation for the 3.7 GHz LH-wave.

- Next, we consider the available high power CW klystrons for higher frequencies. There are no high power CW klystrons available for frequencies between 5.0 GHz and 5.7 GHz. Therefore, we are going to develop a suitable one.

- For the LH launcher (waveguide antenna), we consider the optimum $N_{||}$ spectrum. The LH-wave can be injected with $N_{||}$ spectrum in some range by adjusting the phase shift between waveguides in the antenna. But, the $N_{||}$ must be larger than $N_{||\mathrm{acc}}$ (the accessible $N_{||}$) for the LH-wave penetration through the tokamak plasma. $N_{||\mathrm{acc}}$ depends on the LH wave frequency for the given plasma density and the toroidal magnetic fields. $N_{||\mathrm{acc}}$ becomes large for the high LH-wave frequency. On the other hand, $N_{||} \sim 1/(f_{\mathrm{LH}}\, b)$, where f_{LH} is the LH wave frequency and b is waveguide width of the antenna. $N_{||}$ becomes small for the high LH-wave frequency. It means that b must be very small for $N_{||}$ larger than $N_{||\mathrm{acc}}$. The practical manufacturing and cooling of waveguide antenna is difficult with small b. This paper shows $N_{||}$ values as a function of b, the corresponding power flux in the launcher, $N_{||\mathrm{acc}}$ contour lines in the tokamak plasma, and the power losses through the transmission systems of two kinds of LHCD systems.

Density limit for LH wave frequency

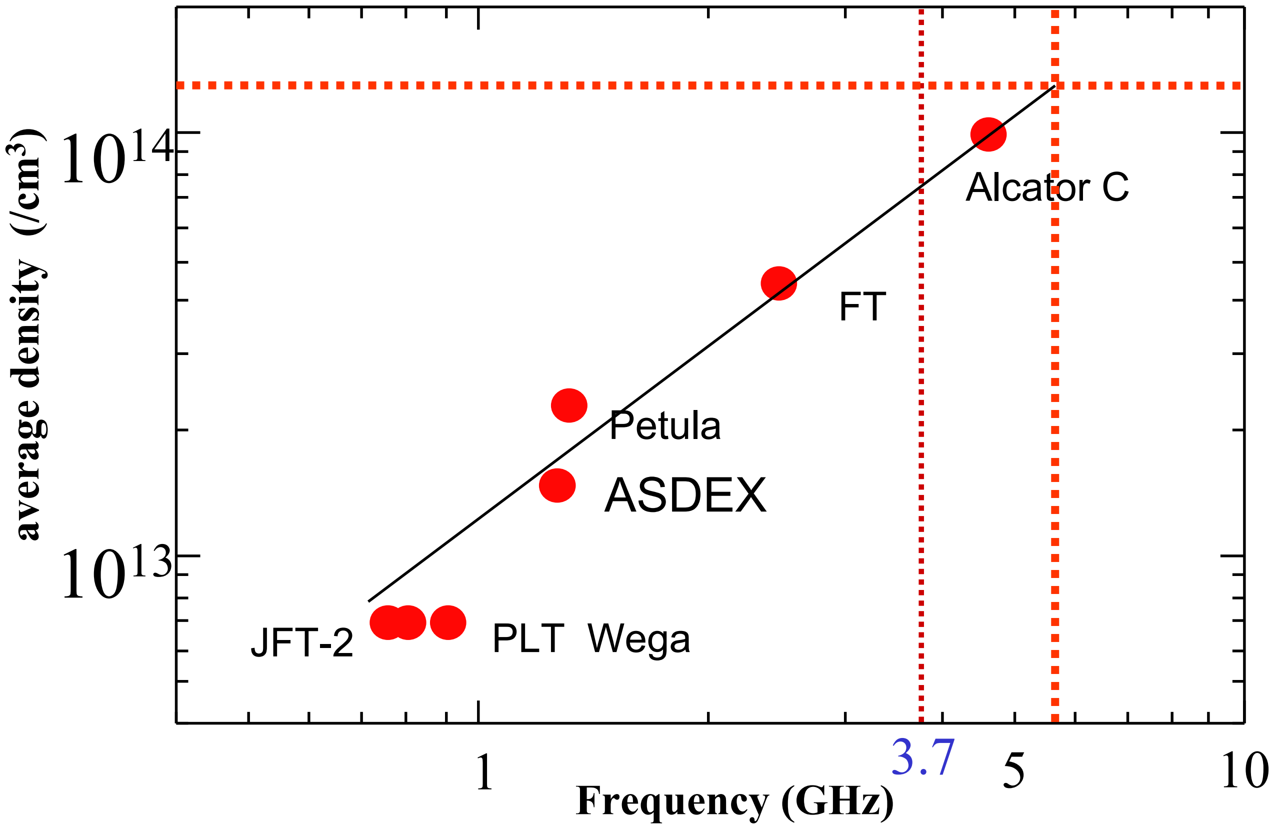


Figure 1. Average density limit vs. **LH-wave frequency**. Frequency should be high enough to satisfy the high “density limit”. This is an empirical law found in several machines, which shows that for a given frequency there is a density above which damping is mostly in the ions, reducing therefore drastically the current drive efficiency.

Profile shaping by 3.7 GHz LHCD [*LSC*-code]

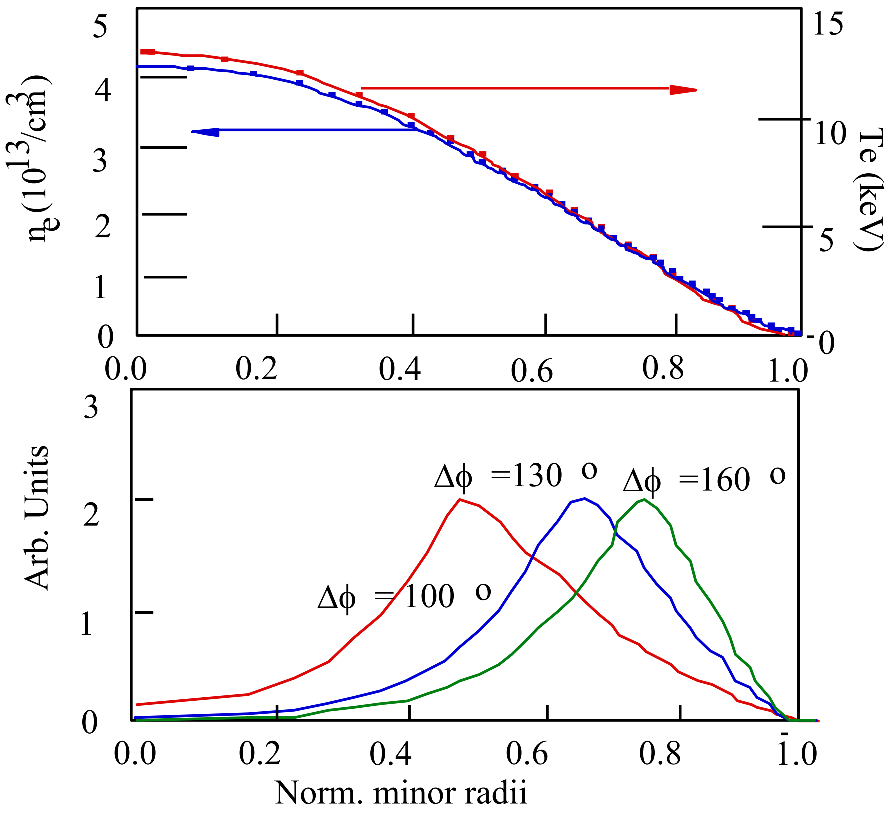


Figure 2. RF current obtained by launching three spectra in a 2 MA discharge with density and electron temperature profiles as shown. Frequency is 3.7 GHz, power 1.5 MW. The label $\Delta\phi = 100^0$ corresponds to a spectrum peaked at $N_\parallel = 2.2$, $\Delta\phi = 130^0$ to $N_\parallel = 2.8$ and $\Delta\phi = 160^0$ to $N_\parallel = 3.3$. The RF current in approximately 400 kA in the 130^0 case.

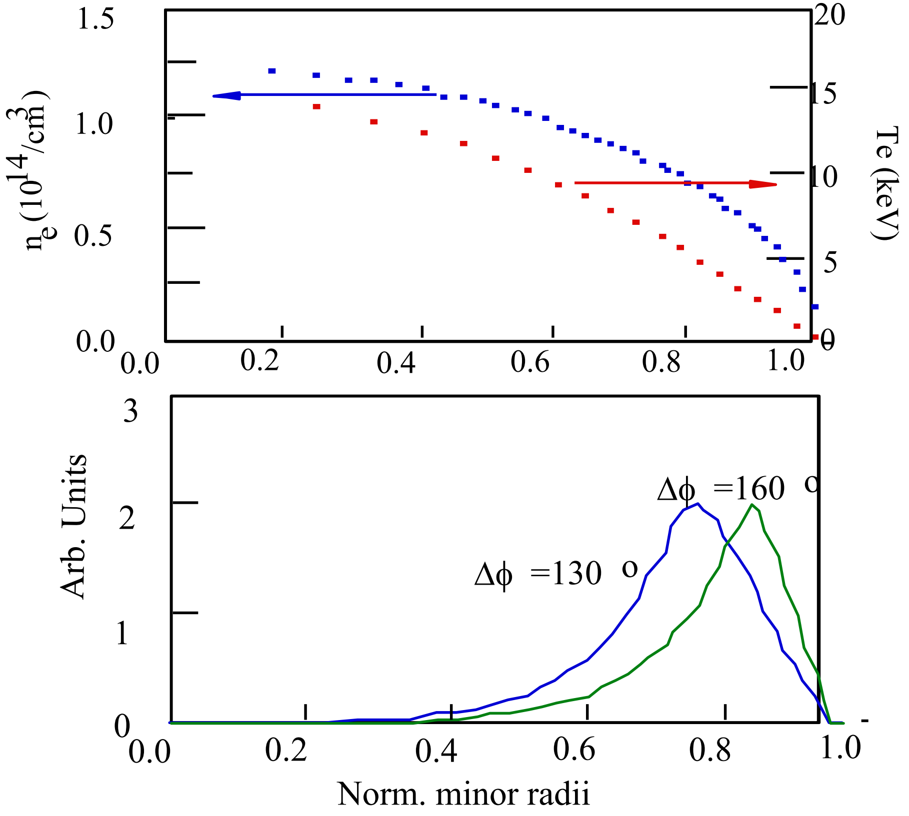
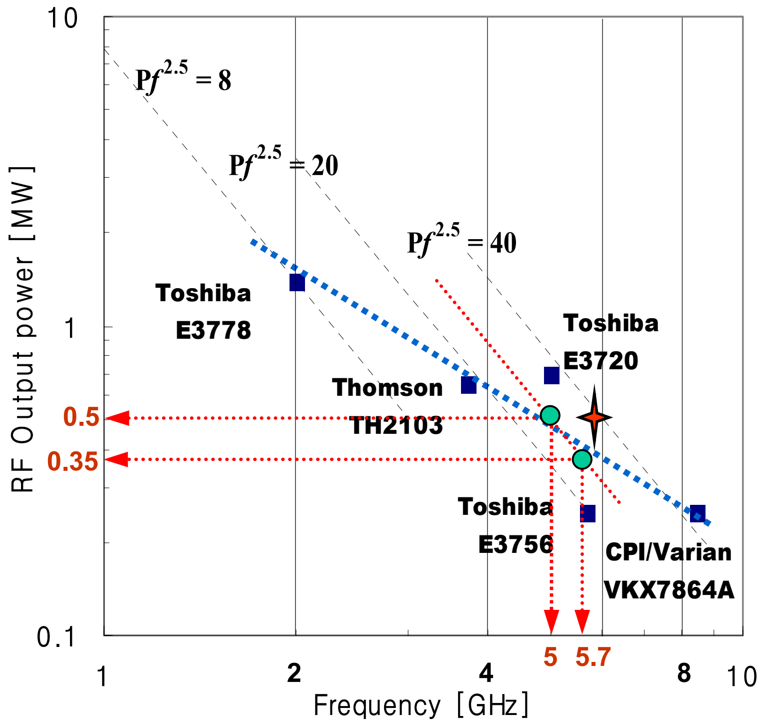


Figure 3. RF current generated in a higher density case. In case of $\Delta\phi = 130^0$, the driven current is ~ 150 kA.

State-of-the-art for high power CW klystrons

$$P f^{2.5}[\mathrm{MW \cdot GHz}] = \text{Constant}$$



[Ref; S. Maebara *et al*., Fusion Tech. (1994) pp 561-564]

Figure 4. RF output power vs. **operating frequency** for the available klystrons. The circle symbol indicate the RF powers and frequencies considered as LHCD klystron parameters.

Project	Manufac. (model)	Frequency (GHz)	Power (MW)
JET & Tore-supra	Thomson TH2103	3.7	0.65 @10 s 0.5 @ 5 s
JT-60	Toshiba E3778	2	1.4 @ CW
ITER (prototype)	Toshiba E3720	5	0.7 @ 15 μs
KSTAR (proposal)	Toshiba (E3756)	5.7	0.25 @ CW
KSTAR (upgrade)	Toshiba (E37XX)	5.7	0.5 @ CW
JPL (not for fusion)	CPI/Varian VKX-7864A	8.5	0.25 @ CW

Table 1. The available klystrons. There is no high power CW klystron available for frequencies between 5.0 GHz and 5.7 GHz.

$N_{||}$ and reflection coefficients of launcher [*Brambilla* code]

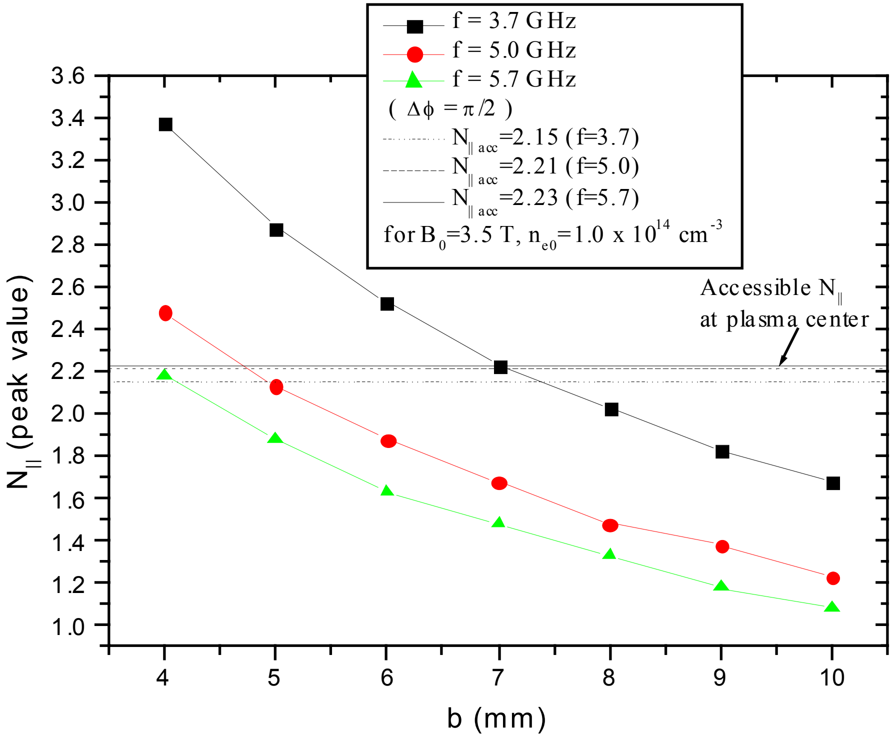


Figure 5. ***$N_{||}$*** values as a function of ***b***, waveguide width in the antenna. The horizontal lines show the accessible $N_{||}$ values at the tokamak plasma center. The phase shift between waveguides is fixed to 90°.

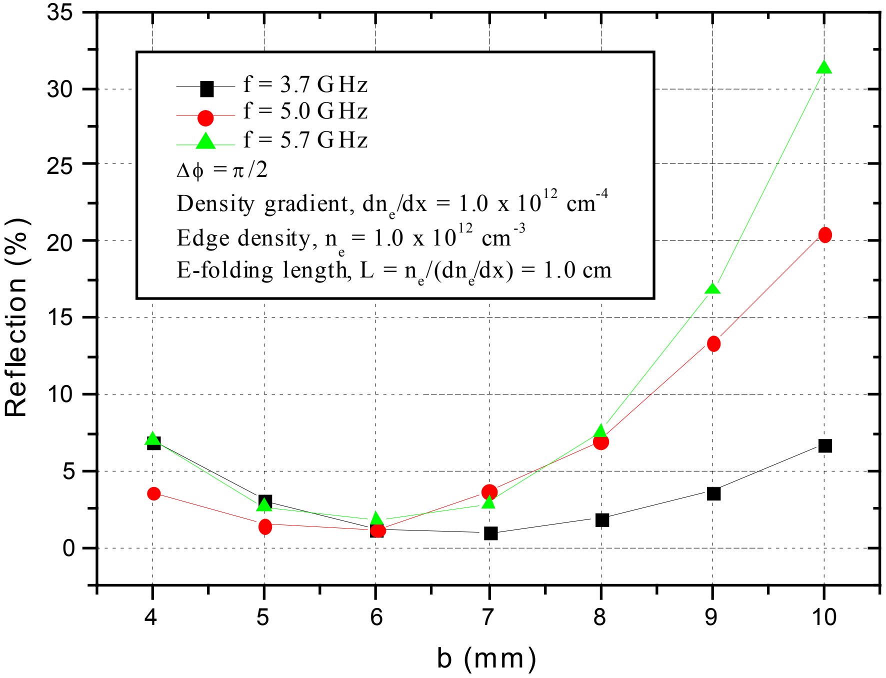


Figure 6. Reflection coefficients as a function of ***b***. The phase shift is 90° and both the density gradient and the edge density at the front of antenna are 1.0 x 10^{12} cm^{-3}. The minimum power is reflected when *b* is 6 m for the 5.0 GHz and 5.7 GHz.

Power flux density in a waveguide antenna

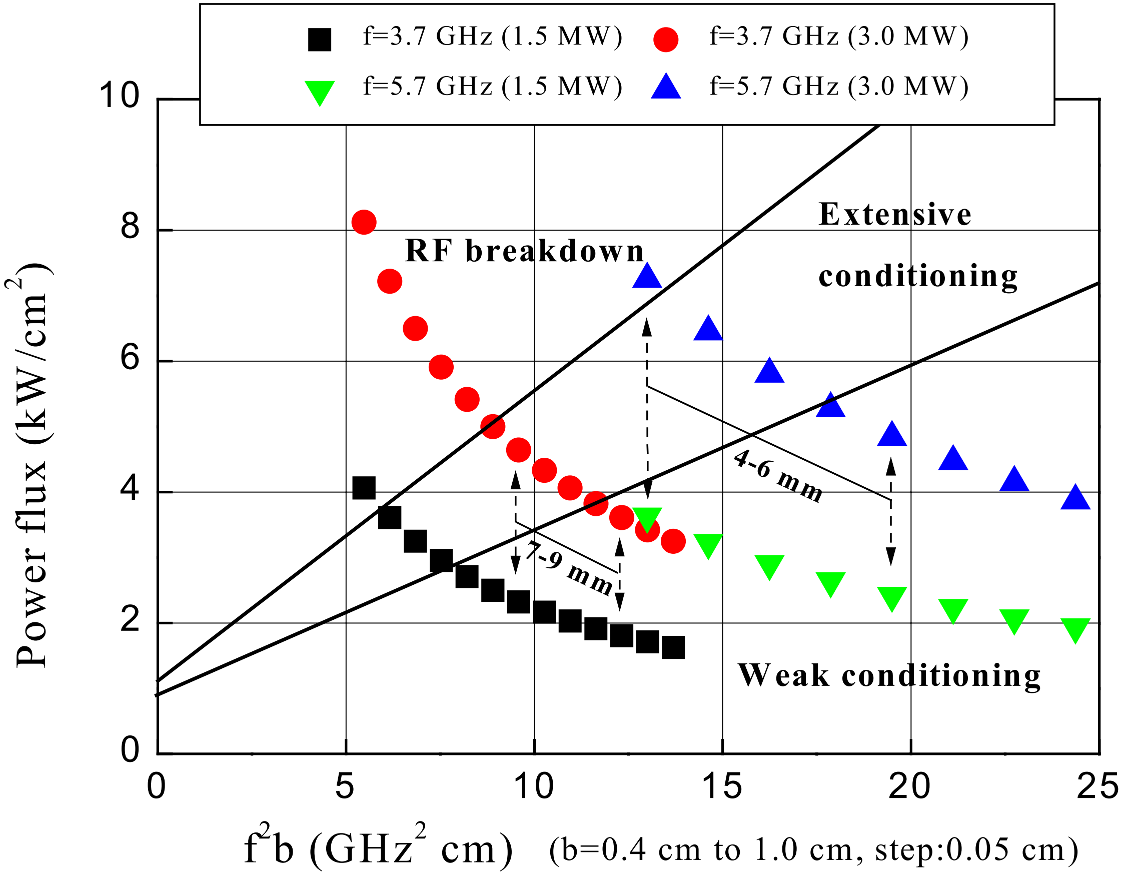
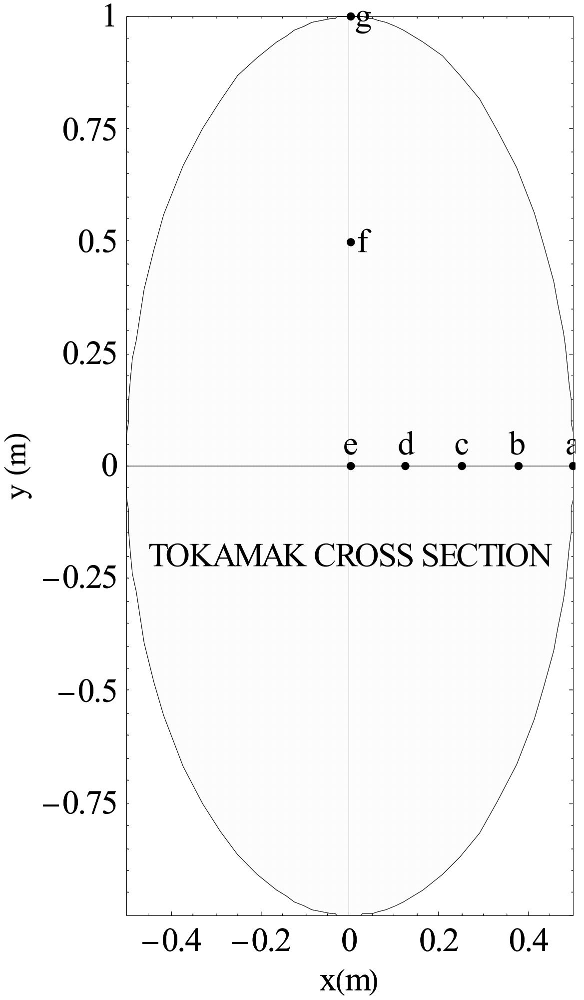
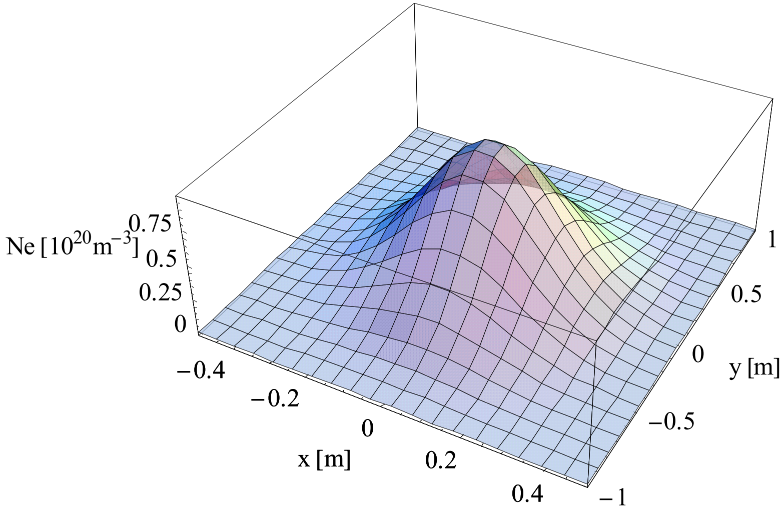
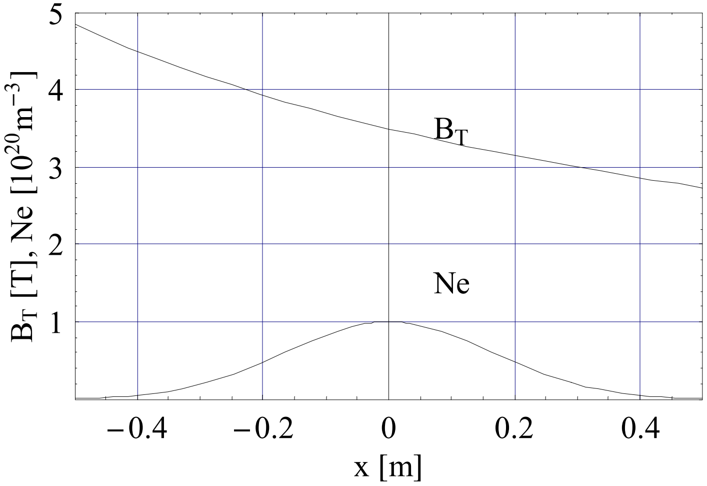


Figure 7. The power flux in a waveguide antenna as a function of ***f*²*b*** for frequencies of 3.7 GHz and 5.7 GHz. The power flux for 3.7 GHz is calculated with standard S-band waveguide and C-band waveguide for 5.7 GHz. The power flux for 5.0 GHz will be near to the power flux of 5.7 GHz. Since it is desirable to operate launcher with a weak conditioning, *b* = 5 ~ 6 mm is suitable for the 5.0 GHz and 5.7 GHz.

Plasma density and toroidal B field profiles in tokamak

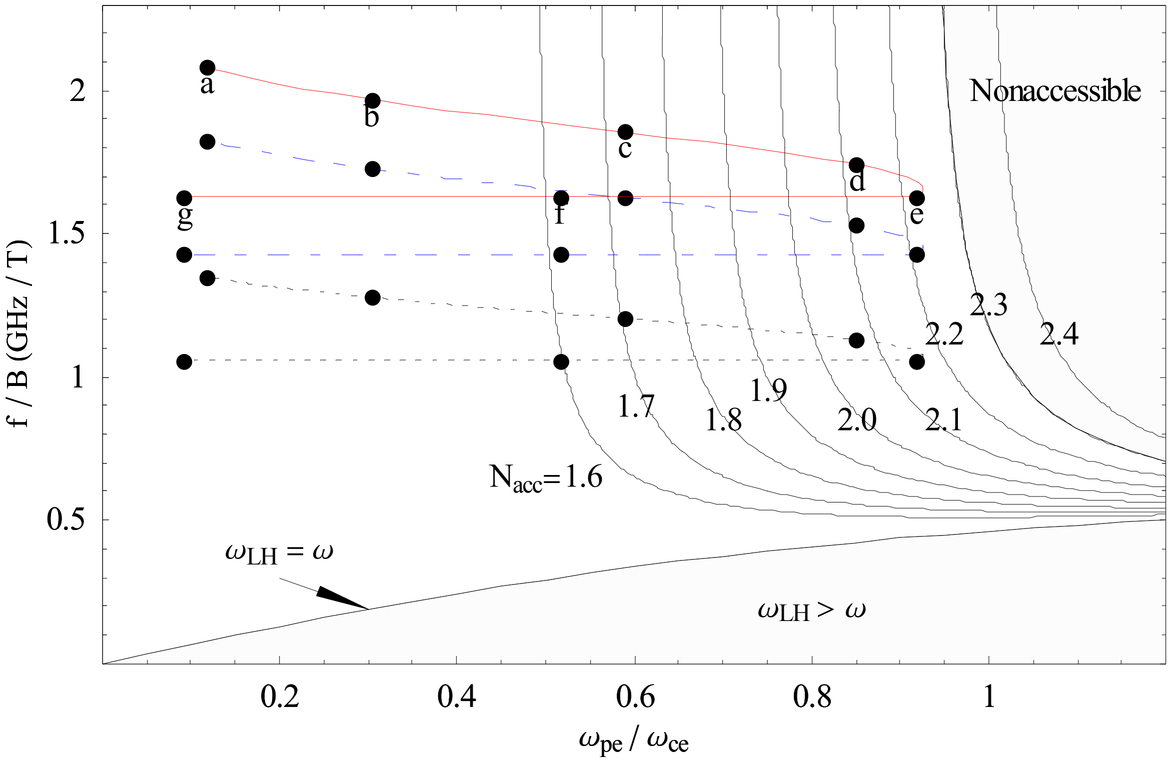






$$n_e[r] = n_{e0}\, Exp[-\alpha\, r^2],\ \ B_T[x] = B_0\,\frac{R_0}{R_0 + x} \qquad (n_{e0} = 1.0\times 10^{20}\, m^{-3}, \alpha = 18.42,\ R_0 = 1.8\ m,\ B_0 = 3.5T,\ r^2 = x^2 + 0.5y^2)$$

Lower Hybrid wave penetration and accessibility



$$\frac{\omega_{LH}}{\omega} = \left[\frac{\omega_{pi}^2/\omega^2}{1+\omega_{pe}^2/\omega_{ce}^2}\right]^{1/2}$$

$$N_{\parallel acc} = \frac{\omega_{pe}}{\omega_{ce}} + \left[1+\frac{\omega_{pe}^2}{\omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega^2}\right]^{1/2}$$

Let $u = \omega_{pe}/\omega_{ce}$ and $v = f/B_T$,

$$\frac{\omega_{LH}}{\omega} = \left[\frac{784u^2}{\gamma A v^2(1+u^2)}\right]^{1/2}$$

$$N_{\parallel acc} = u + \left[1+u^2 - \frac{784u^2}{\gamma A v^2}\right]^{1/2}$$

Figure 8. The ***f*/*B*** vs. ω_{pe}/ω_{ce} in a tokamak, where ***f*** is the LH launched frequency and ω_{pe} and ω_{ce} are plasma frequency and cyclotron frequency. This figure shows the accessible $N_{\parallel acc}$ from 1.6 to 2.4, the positions (a-b-c-d-e-f-g), and $\omega_{LH}/\omega = 1$ line as a function of *f*/*B* and ω_{pe}/ω_{ce}. The lower hybrid frequency ω_{LH} and $N_{\parallel acc}$ depend on plasma density and toroidal B fields and are given by above equations. The red solid line is for the *f* of 5.7 GHz, the blue dash line for the *f* of 5.0 GHz, and the black dash line for the *f* of 3.7 GHz. The "a" is the plasma limiter position (x=50 cm) and "e" is the tokamak center (x = 0.0) in horizontal direction, and the "f and g" is the vertical positions as shown in the previous graph. When the launched frequency w is smaller than the lower hybrid frequency, ion heating occurs. But, the launched frequencies of 3.7 GHz, 5.0 GHz, and 5.7 GHz are all larger than the lower hybrid frequency ω_{LH} with a given tokamak plasma and toroidal *B* field profiles as shown in the previous graphs.

Power losses in transmission lines

Table 2. The power losses in transmission systems of two kinds of LHCD systems for the lengths of 40 m, 60 m, and 80 m.

Options		***3.7 GHz LHCD***		***5.7 GHz LHCD***	
		1.5 MW	3.0 MW	1.5 MW	3.0 MW
Attenuation (dB/m)		0.017[a]	0.017	0.043[b]	0.043
Total power loss	L = 40 m	217 kW (14 %)	434 kW (14 %)	490 kW (33 %)	980 kW (33 %)
	L = 60 m	314 kW (21 %)	628 kW (21 %)	672 kW (45 %)	1344 kW (45 %)
	L = 80 m	403 kW (27 %)	806 kW (27 %)	821 kW (55 %)	1642 kW (55 %)

a. WR284 waveguide (inner dimension is 72.14 mm by 34.04 mm (S-band)).
b. WR159 waveguide (inner dimension is 40.39 mm by 20.19 mm (C-band)).

Summary

- For the high plasma density in order of 10^{14} cm^{-3}, the higher frequency (> 3.7 GHz) is required for the high current-drive efficiency from LSC-code simulation. Therefore, we consider the LH-wave frequency of **5.0 GHz** or **5.7 GHz**.
- From the state-of-the-art of high power CW klystrons, the required power of CW klystrons can be decided with the same scaling law $Pf^{2.5} \sim 30$ for both frequencies of 5.0 GHz and 5.7 GHz. The power of 500 kW corresponds to 5.0 GHz and 350 kW to 5.7 GHz. Thus, the minimum requirements of the power are to be **400 kW** for the 5.0 GHz and **250 kW** for the 5.7 GHz.
- The optimum waveguide width *b* of the launcher will be **5 mm or 6 mm** and the corresponding $N_{||}$ value is **1.88 or 2.13**. The $N_{||}$ value of 1.85 is less than the $N_{||acc}$ (*2.21 for 5.0 GHz, 2.23 for 5.7 GHz*) in the tokamak center for the LH frequencies of 5.0 GHz and 5.7 GHz. In this case, the LH-wave cannot penetrate into the tokamak center so that an on-axis current drive cannot be happened. But, the $N_{||}$ value can be adjusted to a higher value than 1.85 with the higher phase shift than 90° for an on-axis current drive. Or, we can keep the $N_{||}$ value of 1.85 for **an off-axis current drive**.

Table 3. The conclusion on RF frequency of LHCD system for KSTAR.

Frequency	**Power**	***b***	$N_{\|\|}$
5.0 GHz	**400 kW**	**5 or 6 mm**	**2.13 or 1.88**
5.7 GHz	**250 kW**	**5 mm**	**1.88**