Current Density Profiles for KSTAR LHCD*

백 채현, 배 영순, 최 은미, 조 무현, 이 문종, 남궁 원
포항공과대학교

* *Work supported by KBSI and KAERI*

Abstract

The KSTAR LHCD system employs powerful 5.0-GHz microwaves to produce non-inductive current and to control the current density profiles in the tokamak. It is assumed that microwave power of 1.5-MW from 4 klystrons is effectively coupled to the KSTAR plasmas. Using the Lower-Hybrid Simulation Code (LSC), we obtained non-inductive current drive effects depending on temperature and density distributions of tokamak plasmas. The parallel index of refraction ($n_{||}$) can be adjusted from the phase control between adjacent multi-junctions of Launcher structure. We present the LH current drive efficiency and current density profiles.

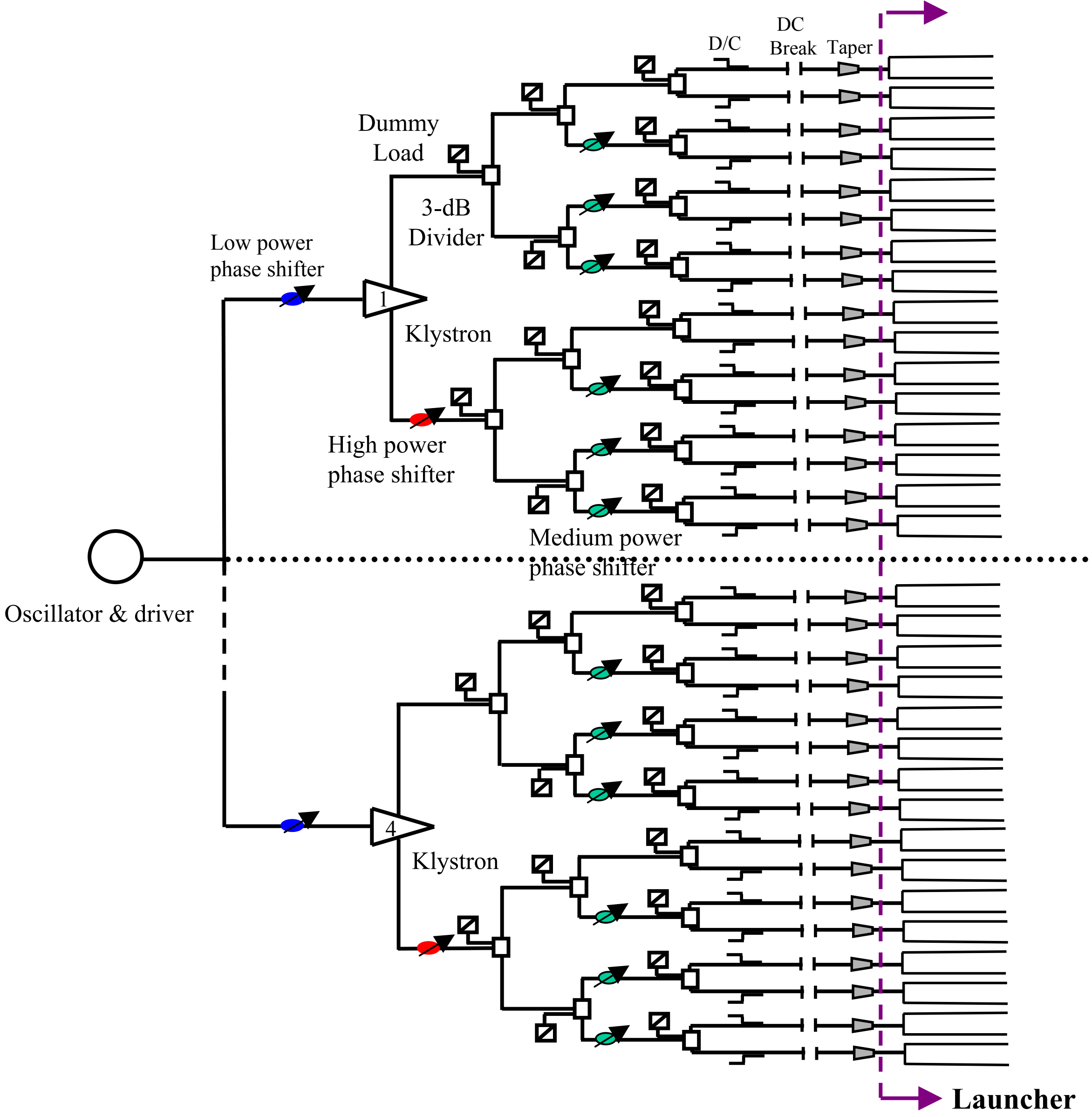
Introduction

- Current Drive Efficiency (η_{CD}) on LSC simulation
  - Temperature dependence.
  - Effect on the various refractive index ($n_{||}$)

- Current density profile
  - Controlling the currents density profile with various $n_{||}$

- LH-ray trajectory in tokamak
  - Understanding LH ray propagation for current drive

LHCD System



☐ **Microwave Source: 4 Klystrons**

- **Frequency: 5.0 GHz**
- **Power: 4 × 500 kW**

☐ **Wave-guide Networks**

- **4 - way Networks**

☐ **3dB Power Divider Networks** (60 ea)

☐ **Phase Shifter Networks** (32 ea)

- **Low Power Phase Shifters: 4 ea**
- **High Power Phase Shifters: 4 ea**
- **Medium Power Phase Shifters: 24 ea**

☐ **Launcher**

- **Phased wave-guide array**

  ⟹ 4 Rows × 32 Columns
- **Width of each wave-guide: 0.55 cm**
- **Height of each wave-guide: 4.75 cm**
- **Thickness of each wave-guide: 0.15cm**
- **Phase difference of each array**

  ⟹ 60° ~ 150°

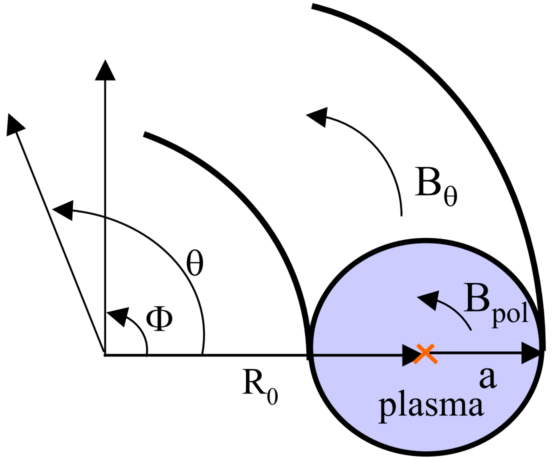
LSC simulation

- Plasma Profile

$n_e(a) = 1.0\times10^{18}\ m^{-3}$ (edge density)

$n_e(0) = 1.0\times10^{20}\ m^{-3}$ (central density)

$T_e(0) = 21$ keV (central temperature)

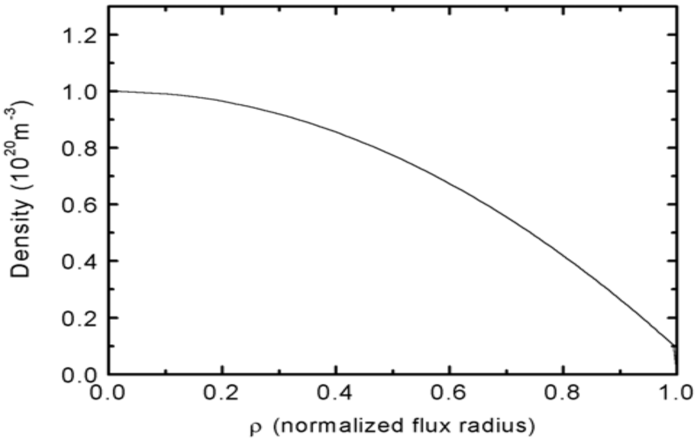


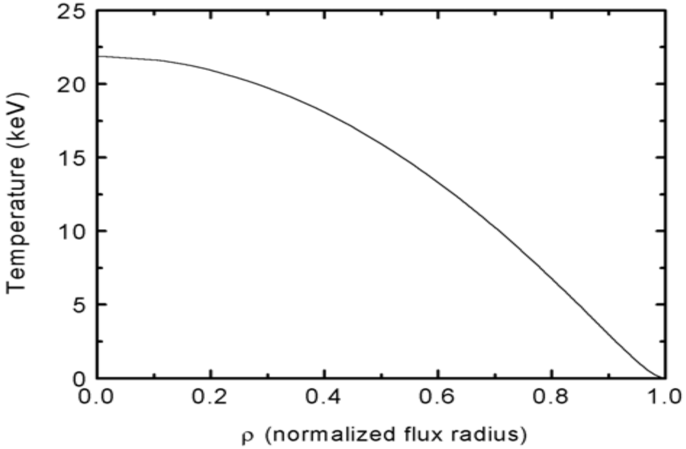
R_0: major radius -1.8 m

a: minor radius - 0.5 m

Φ: poloidal direction

θ: toroidal direction





ρ (normalized flux radius) = $\sqrt{(\varphi-\varphi_{min})/(\varphi_{max}-\varphi_{min})}$

φ: poloidal flux

Current Drive Efficiency and q-factor

□ Current Drive Efficiency [1]

$$\eta_{CD} = \overline{n}_e R_0 I_{LH} / P_W \ (10^{20}\,m^{-2} AW^{-1})$$

$\overline{n}_e$: line averaged density (m^{-3}), R_0: major radius (m), I_{LH}: RF driven current (MA)

P_W: injected RF power (MW)

□ q-factor [2]

$$q(\varphi) = \frac{rB_\theta(\varphi)}{2\pi} \int ds_{pol} \frac{1}{r^2 B_{pol}}$$

B_θ: toroidal B field, B_{pol}: poloidal B field ($B_{pol} = \sqrt{B_r^2 + B_z^2}$), $ds_{pol} = \sqrt{dr^2 + dz^2}$

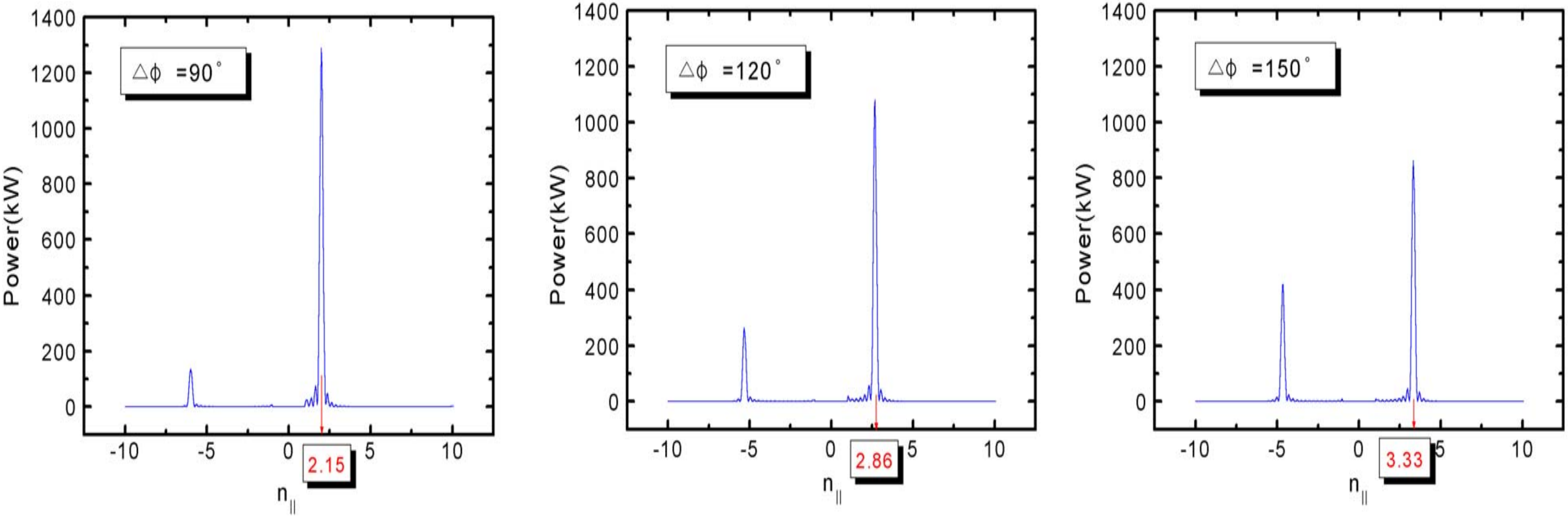
□ Reversed magnetic shear [2]

$$s = \frac{\rho}{q}\frac{dq}{d\rho}$$

ρ: normalized flux radius, q: safety factor

$n_{||}$ spectrum [Brambilla code]

5.0 GHz



Edge density: $n_e(a) = 1.0 \times 10^{18}\ m^{-3}$

Height = 4.75 cm, Width = 0.55 cm, Septum = 0.15 cm for each wave-guide

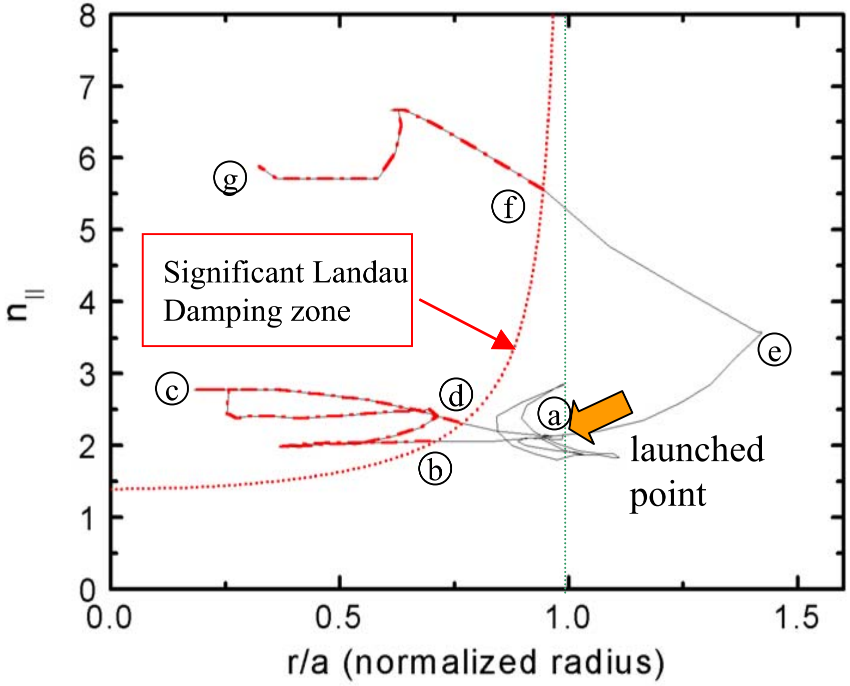
$n_{||p}$: peak value of $n_{||}$ spectrum

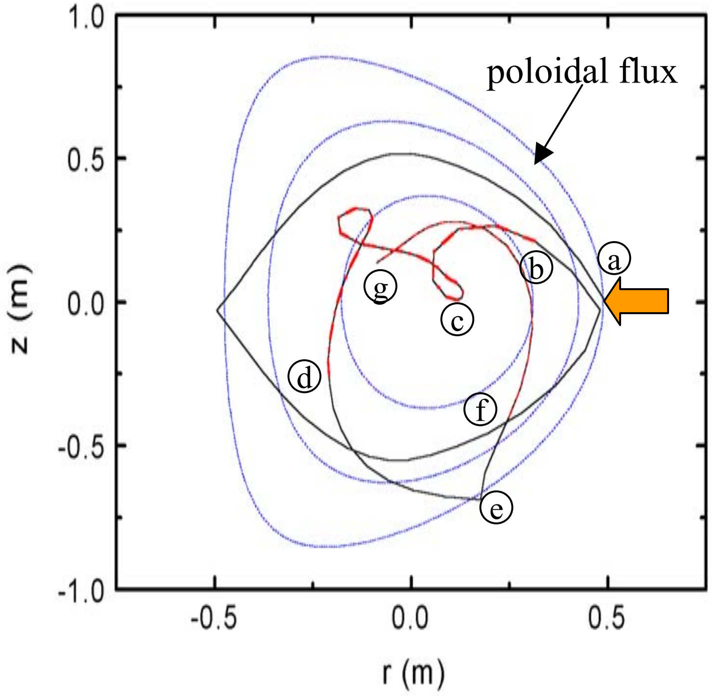
LH-ray trajectory

Power: 1.5 MW

Phase difference ($\Delta\phi$): 90 °

Condition for significant Landau Damping: $n_{\parallel}^{c} \geq \frac{6.5}{\sqrt{T_e\,(\text{keV})}}$ [3]





ⓑ- ⓒ - ⓓ, ⓕ- ⓖ : Significant Landau Damping zone

a (minor radius) = 0.5 m

Current Drive Efficiency (η_{CD})

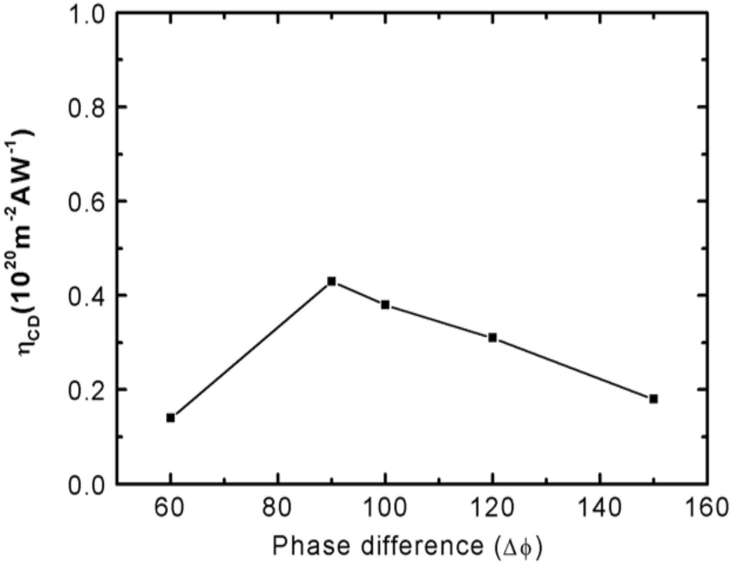
- Current Drive efficiency (η_{CD}) on LSC simulation for KSTAR

$$\eta_{CD} = \bar{n}_e R_0 I_{LH} / P_W \quad (10^{20}\ m^{-2} A W^{-1})$$

$$(R_0 = 1.8\ m,\ P_W = 1.5\ MW,\ \bar{n}_e \sim 0.6 \times 10^{20}\ m^{-3})$$

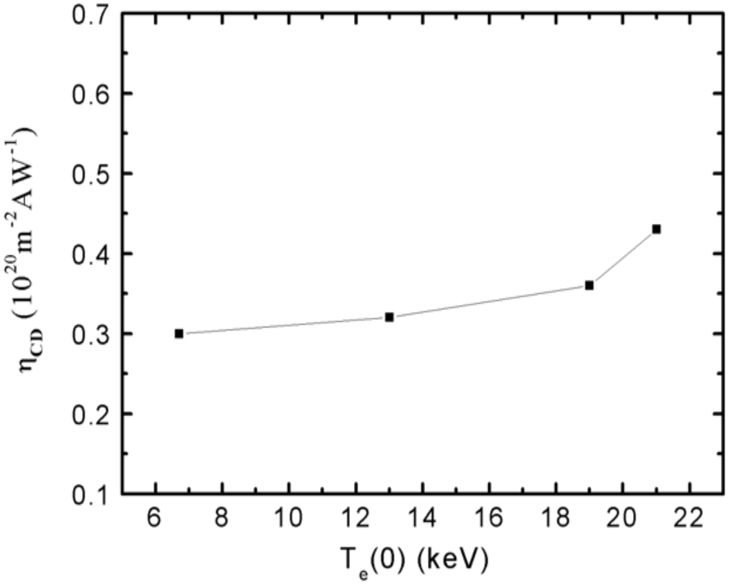
♦ CD efficiency η_{CD} vs. $\Delta\phi$ [4]

$n_e(0) = 1.0 \times 10^{20}\ m^{-3}$, $T_e(0) = 21$ keV



♦ CD efficiency η_{CD} vs. $T_e(0)$ [5]

$\Delta\phi = 90$ °, $n_e(0) = 1.0 \times 10^{20}\ m^{-3}$



Current Density Profiles

Frequency: 5.0 GHz

Power: 1.5 MW

Ploidal cross section (minor radius a = 0.5 m)

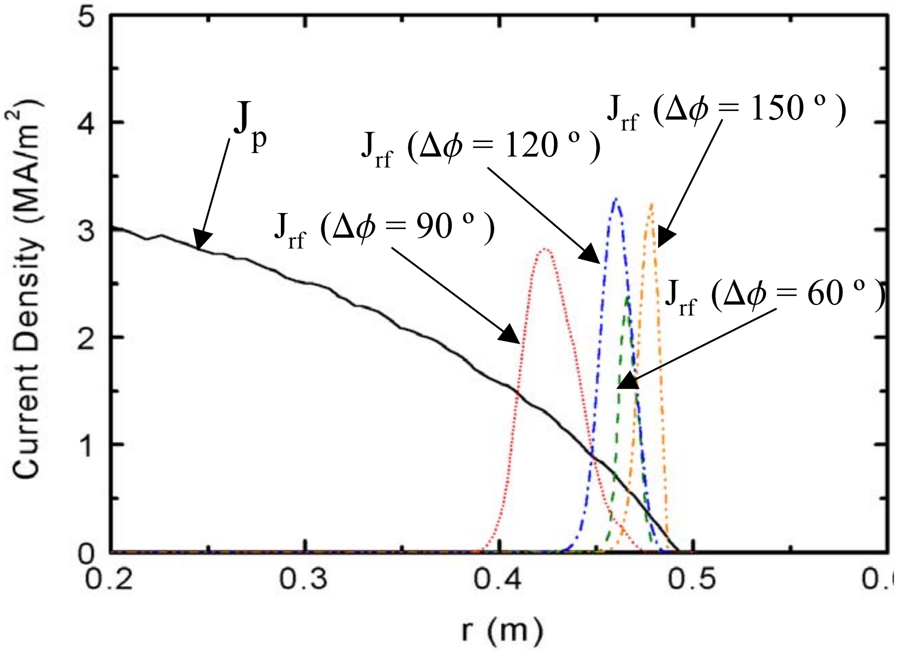
I_P= 1.95 MA (toroidal plasma current)

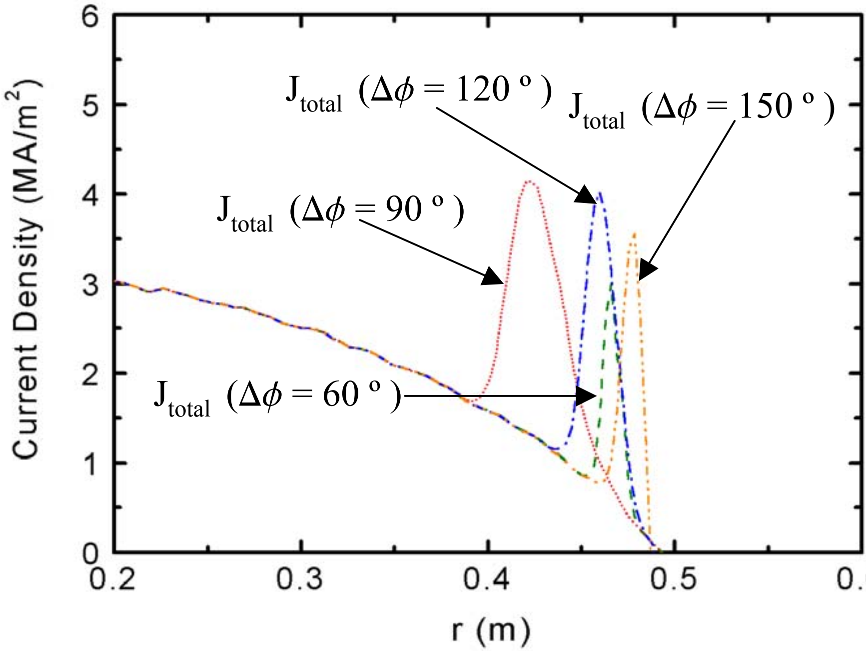
I_{rf} ($\Delta\phi$ = 60 °): **0.2 MA**

I_{rf} ($\Delta\phi$ = 90 °): **0.59 MA**

I_{rf} ($\Delta\phi$ = 120 °): **0. 43MA**

I_{rf} ($\Delta\phi$ = 150 °): **0.25 MA**





J_p: plasma current density

J_{rf}: rf driven current density (LH current)

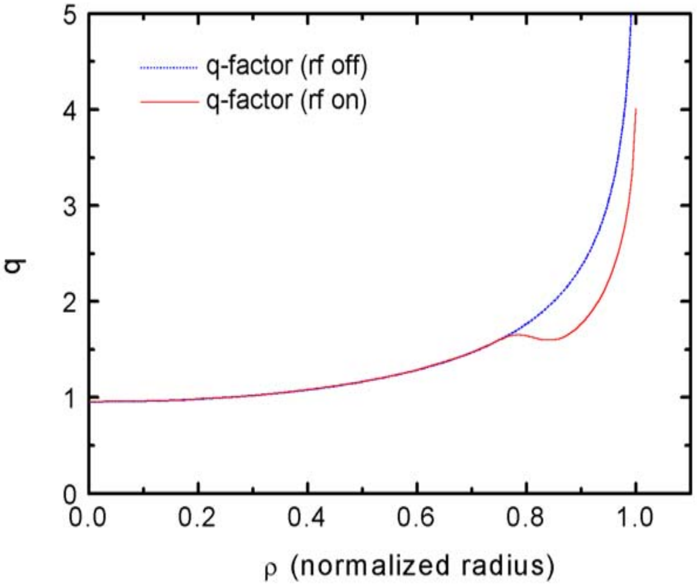
J_{total}: Total current density profile ($J_{total}=J_p+J_{rf}$)

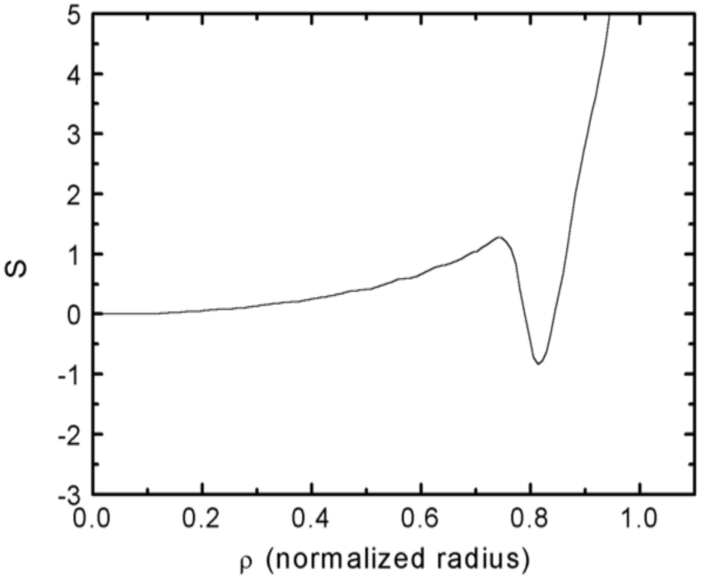
Reversed magnetic shear

- q-factor: $q(\varphi) = \dfrac{rB_\theta(\varphi)}{2\pi}\int ds_{pol}\,\dfrac{1}{r^2 B_{pol}}$
- Reversed magnetic shear: $s = \dfrac{\rho}{q}\dfrac{dq}{d\rho}$ ρ: normalized flux radius

B_θ: toroidal B field, B_{pol}: poloidal B field ($B_{pol} = \sqrt{B_r^2 + B_z^2}$), $ds_{pol} = \sqrt{dr^2 + dz^2}$

Power = 1.5 MW, $\Delta\phi = 90^o$





Conclusions

◇ LSC simulation for frequency 5 GHz and power 1.5 MW

- $\eta_{CD} = 0.43\times10^{20}\,\mathrm{m^{-2}AW^{-1}}$

  ($R_0 = 1.8$ m, $I_{LH} = 0.59$ MA, $\overline{n}_e \sim 0.6\times10^{20}\,\mathrm{m^{-3}}$, $P_W = 1.5$ MW)
- CD efficiency of the high temperature is better than that of the low case.
- CD efficiency at phase difference 90 ° is more efficient.
  - $n_{\parallel p} = 2.15$ ($\Delta\phi = 90°$)
- LH-Ray propagation for significant Landau Damping
  - $n_{\parallel}^{c} \geq \dfrac{6.5}{\sqrt{T_e\,(\mathrm{keV})}}$
- Controlling the current density profiles with various $n_{\parallel}$

References

[1] C. F. F. Karney and N. J. Fisch, “Current in wave-driven plasmas,” Phys. Fluids **29** (1), 180 (1986).

[2] D. W. Ignat, E. J. Valeo, S. C. Jardin, “Dynamic modelling of lower hybrid current drive,” Nuclear Fusion **34** (6), 837 (1994)

[3] P. Bonoli, “Linear theory of lower hybrid waves in tokamak plasmas,” in *Wave Heating and Current Drive in Plasmas*, Edited by V. Granastein and P. Colestock (Gordon and Breach, New York, 1985), Chapter 4.

[4] S. Bernabei, A. Cardinali, G. Giruzzi, G. T. Hoang, D. Ignat, R. Kaita, M. Okabayashi, F. Paolelli, and S. von Goeler, “Investigation of lower hybrid wave damping in the PBX-M tokamak,” Phys. Plasmas **4** (1), 125 (1997).

[5] E. Barbato, “Recent progress in lower hybrid current drive theory and experiments,” Plasma Phys. Control. Fusion **40**, A63 (1998).