Potential of Lower Hybrid Fast Wave
as an efficient current drive method in future fusion reactor

Technical Meeting on Long Pulse Operation of Fusion Devices

IAEA HQ in Vienna, Austria

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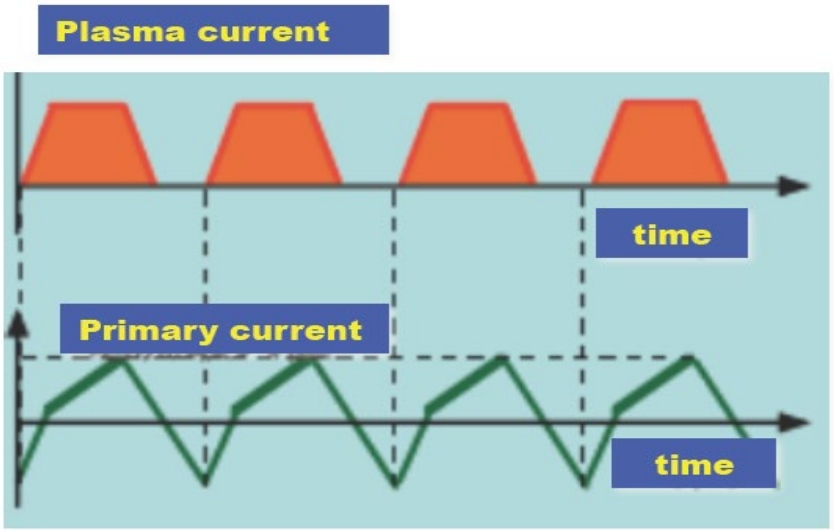
I. Introduction to LHFW

Continuous Current Drive (1)

- The **continuous current drive** is one of the key issues toward steady-state operation of **tokamak fusion reactor**.

"Plasma Current" is necessary for good confinement!!
To sustain plasma current, inductive loop voltage is necessary.

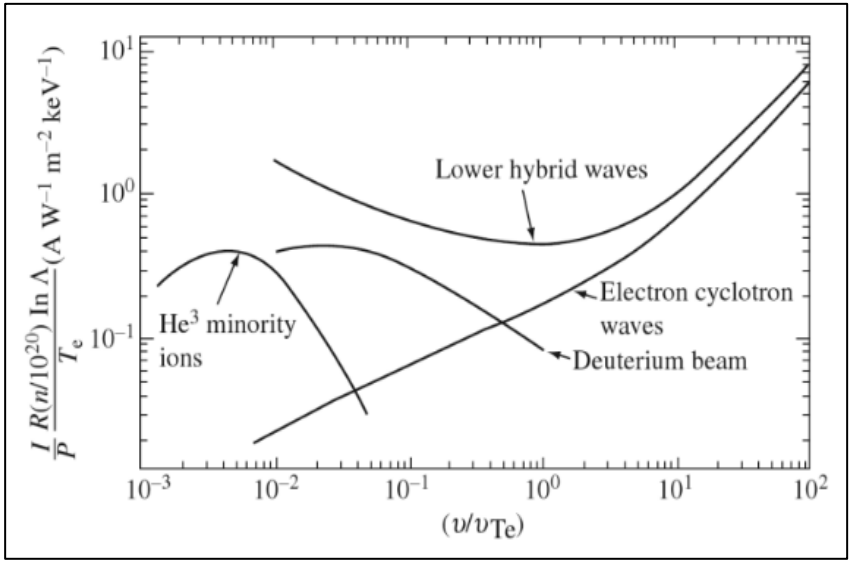
-> Non inductive current sustainment is necessary.



M. Kikuchi

Continuous Current Drive (3)

- The most efficient external current drive scheme is LHCD which uses the slow wave in lower hybrid frequency range (LHSW).



Scheme	Current drive efficiency η : A/m²/W	Machine
LHCD	~ 0.34 (3.6 MA)	JT-60U
ICRF	~ 0.04 (180 kA)	DIIID
ECCD	~ 0.03 (150 kA)	TCV
NB	~ 0.05 (340 kA)	TFTR

Tokamaks (2004) J. Wesson

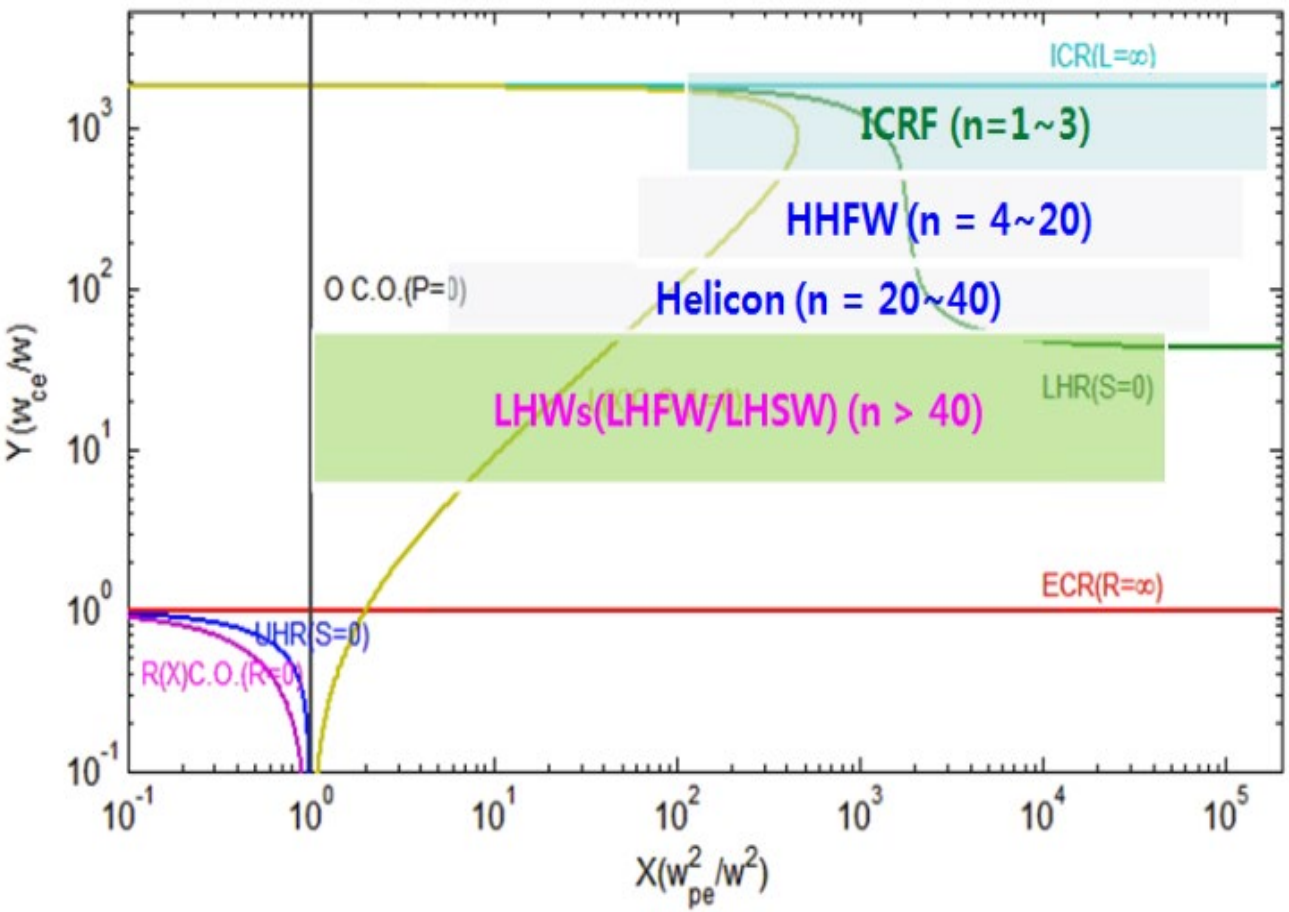
- It, however, has density limit. And it is difficult to expect that it will work well in reactor grade high density plasmas.

Introduction to LHFW(1)

Lower Hybrid Fast Wave in CMA

- **Fast Waves on CMA diagram**

<H_2 plasmas, $n_{||}$=2>

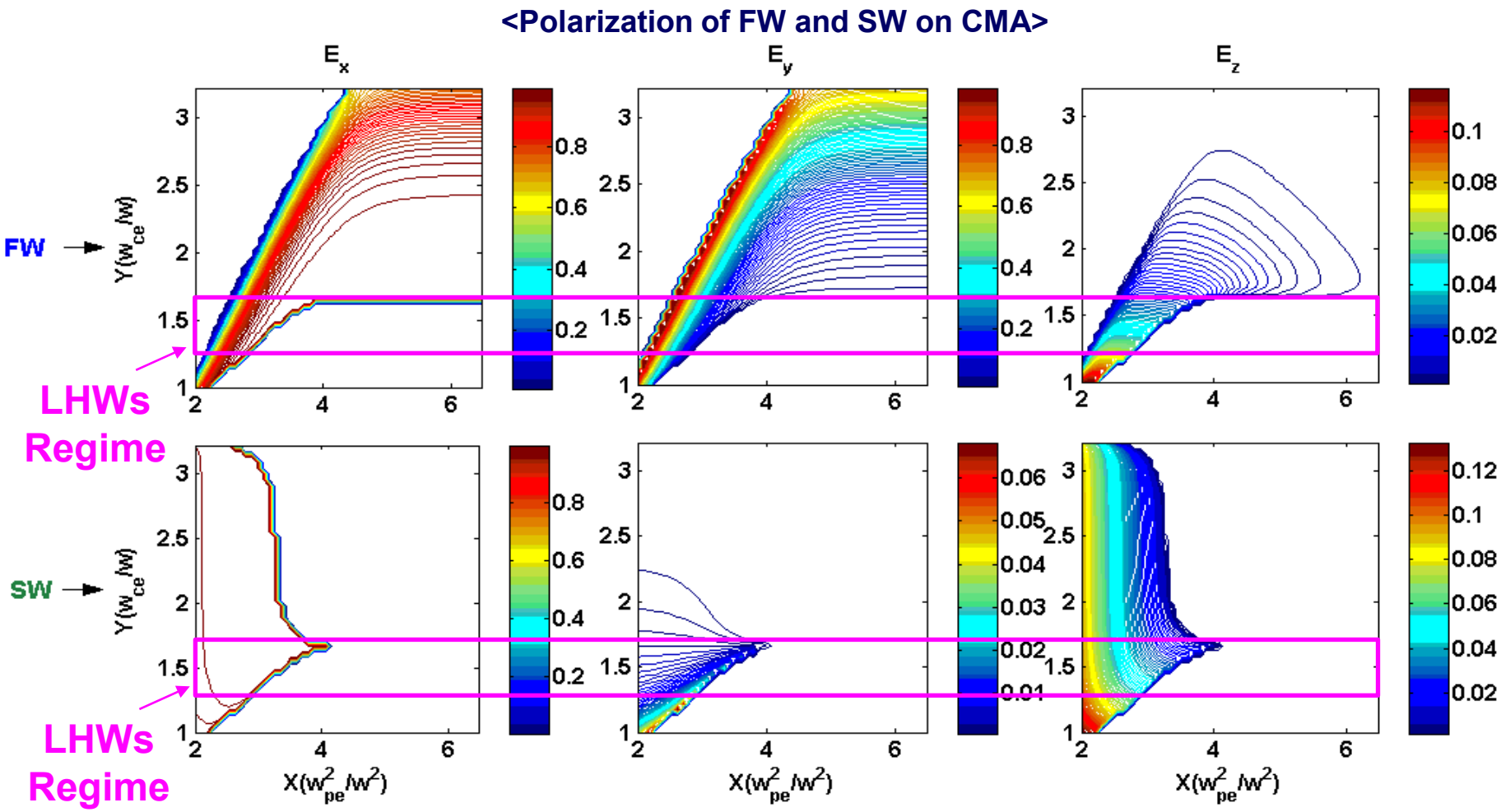


- LHFW is a kind of whistler wave between lower hybrid resonance and electron cyclotron resonance.

$$2\omega_{lh} < \omega << \omega_{ce}$$

Advantages of LHFW(1)

High parallel electric field E_z to B

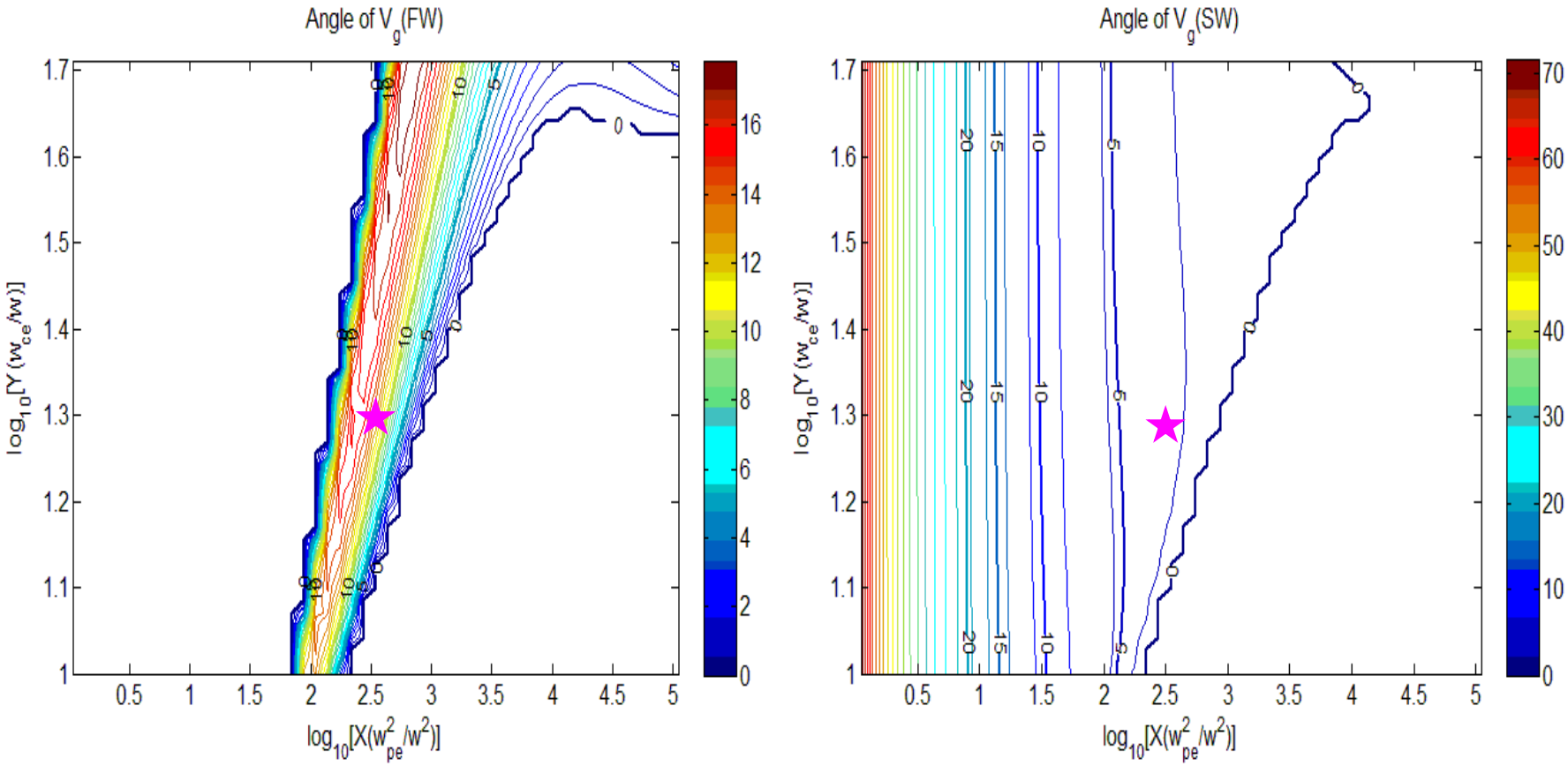


❑ It has <u>favorable polarization for current drive.</u>

Advantages of LHFW(2)

More perpendicular V_g to B

<Angle of Group Velocity V_g to magnetic field of LHFW and LHSW>

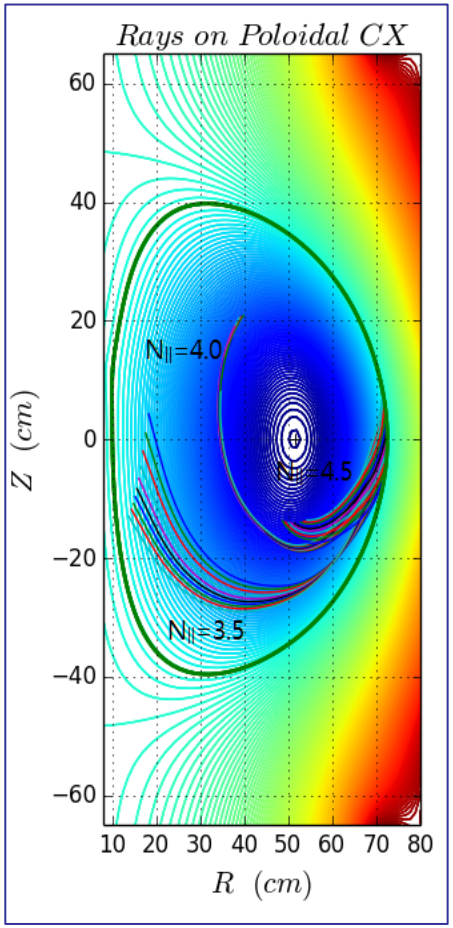


- It has <u>deep penetration property in high density compared to LHSW</u>.

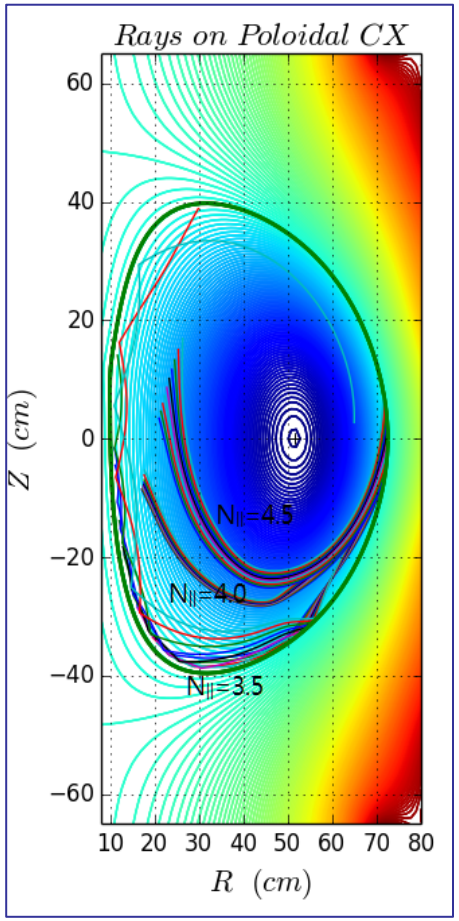
RAY tracing simulation (GENRAY)

- Comparison between LHFW and LHSW launching

LHFW

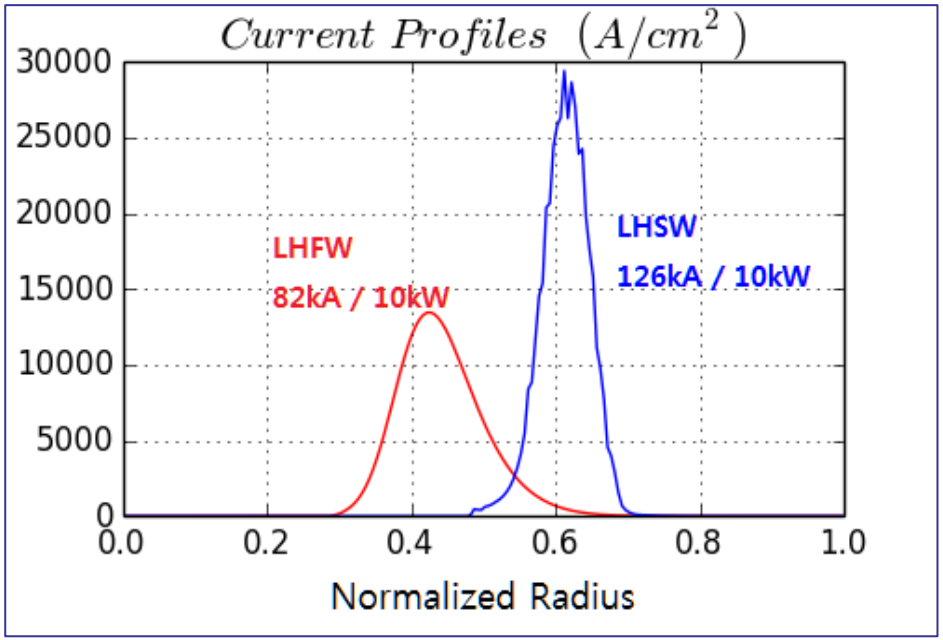


LHSW (LHCD)



(0.2T/ 500 MHz / 3x10^{18} #/m^3/ 3 keV)

- LHFW can propagate into central region.
- In addition, the current drive is comparable to LHSW.

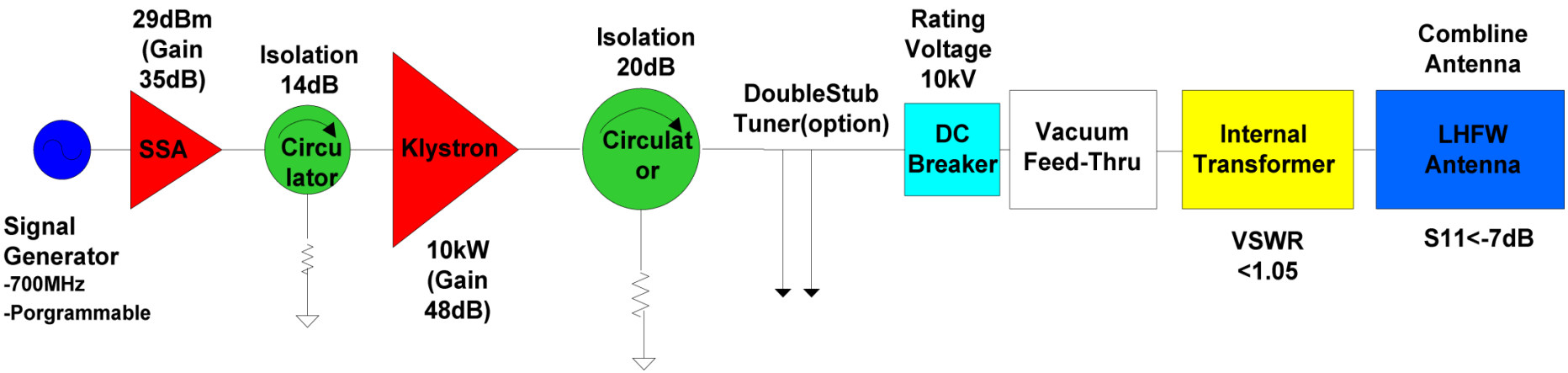


(0.2T/ 500 MHz / 3x10^{18} #/m^3/ 3 keV/ $N_{||}$=4)

II. RF system & LHFW CD Experiment on VEST at SNU

RF System for LHFW experiment on VEST

❑ Schematic of LHFW System



- Frequency : UHF (500 MHz)
- Power : Klystron (10 kW)
- Antenna : Comb-line traveling wave antenna

RF System for LHFW experiment

Klystron RF Power

- **Klystron 10 kW UHF (~500MHz)**

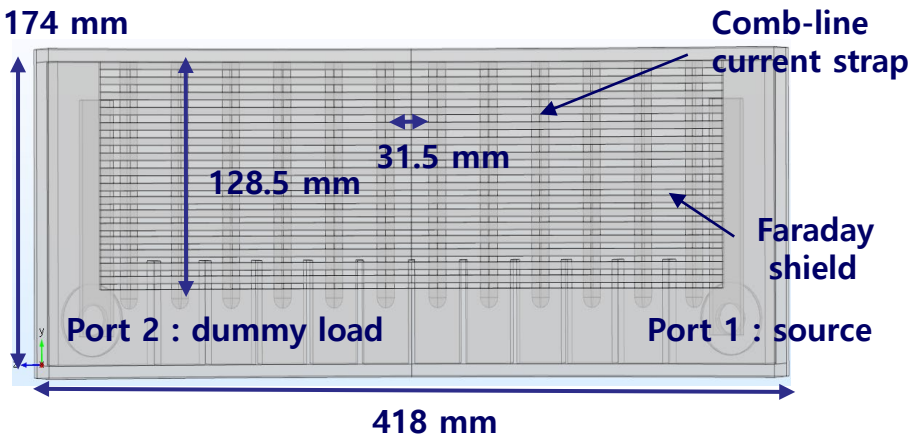
	Varian
Frequency	500 MHz
Output	37.5 kW
Drive Power	600 mW
Gain	48 dB
Beam voltage	19.5 kV
Beam current	5.4 A
Electrode voltage	19.5 kV
Heater voltage	7 V
Heater current	17 A
Body current	50 mA
Magnet Voltage	85 V
Magnet Current	32 A
Magnet Cooling	Water(2.0 gal/min)
Cooling(Collector)	Water 1.5 gal/min
Cooling(Body)	Water 2.0 gal/min
Cooling(Gun/Heater)	Forced Air 50 ft^3/min

- **It was prepared by refurbishing old UHF broadcasting system provided from KAPRA.**

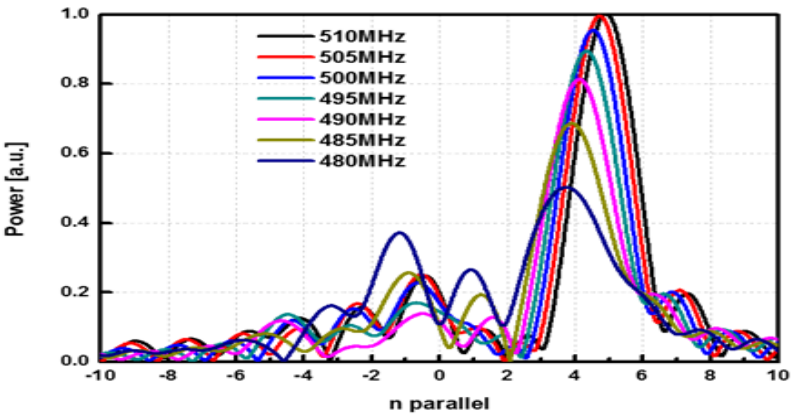
RF System for LHFW experiment

Comb-line Antenna

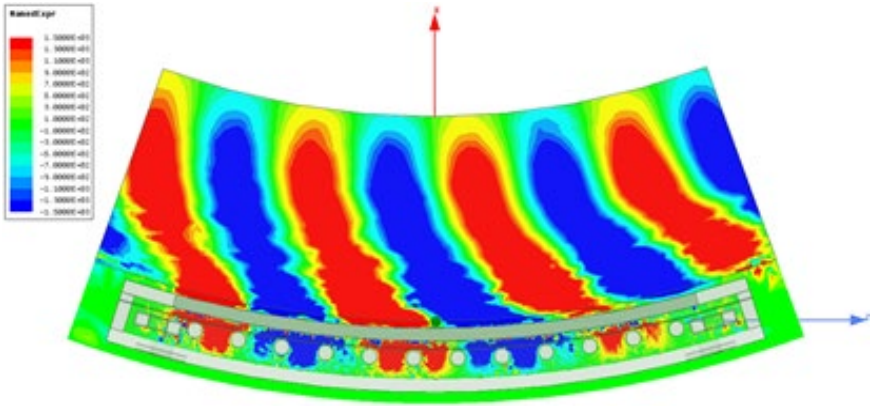
➢ Comb-line Antenna Structure



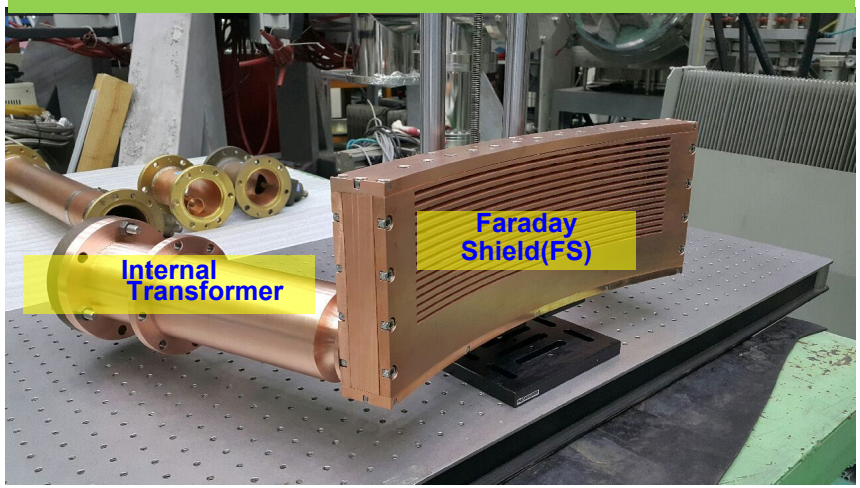
➢ Parallel Wave Number of Antenna



➢ Plasma Simulation with Antenna : E_y field



➢ Comb-line Antenna with FS + Internal TR

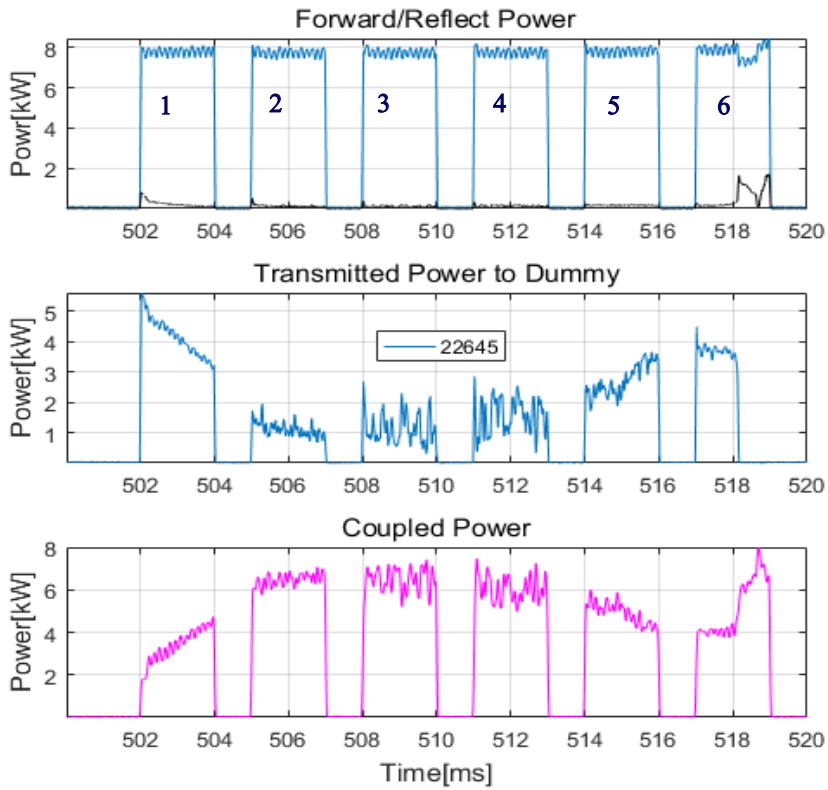


❑ The antenna was developed in collaboration with KwangWoon University.

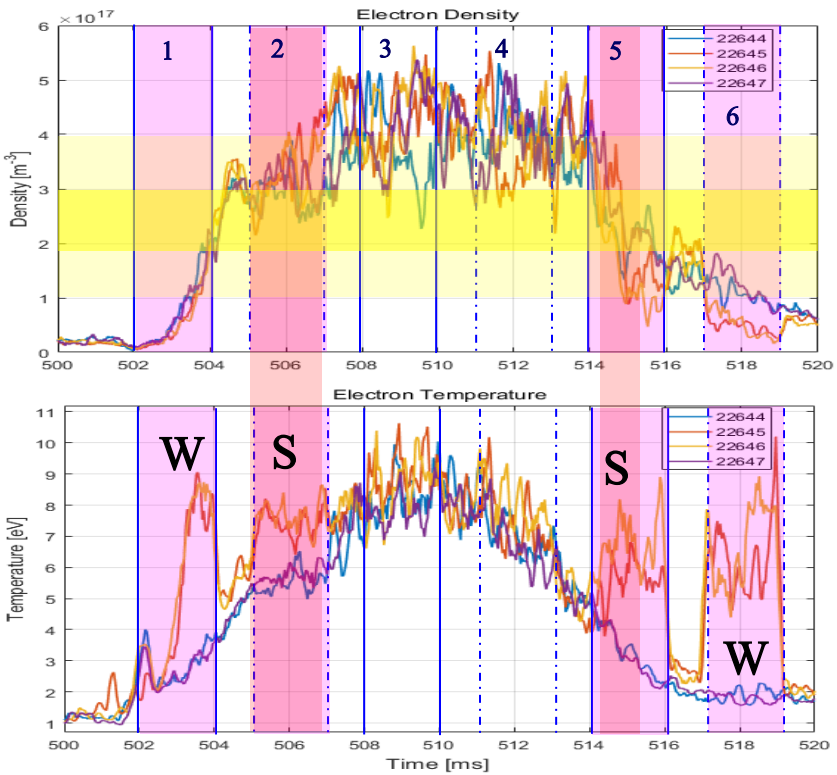
LHFW CD Experiment

RF Powers & Change of Plasma Parameters

RF Powers



Density(T) & Temperature(B)

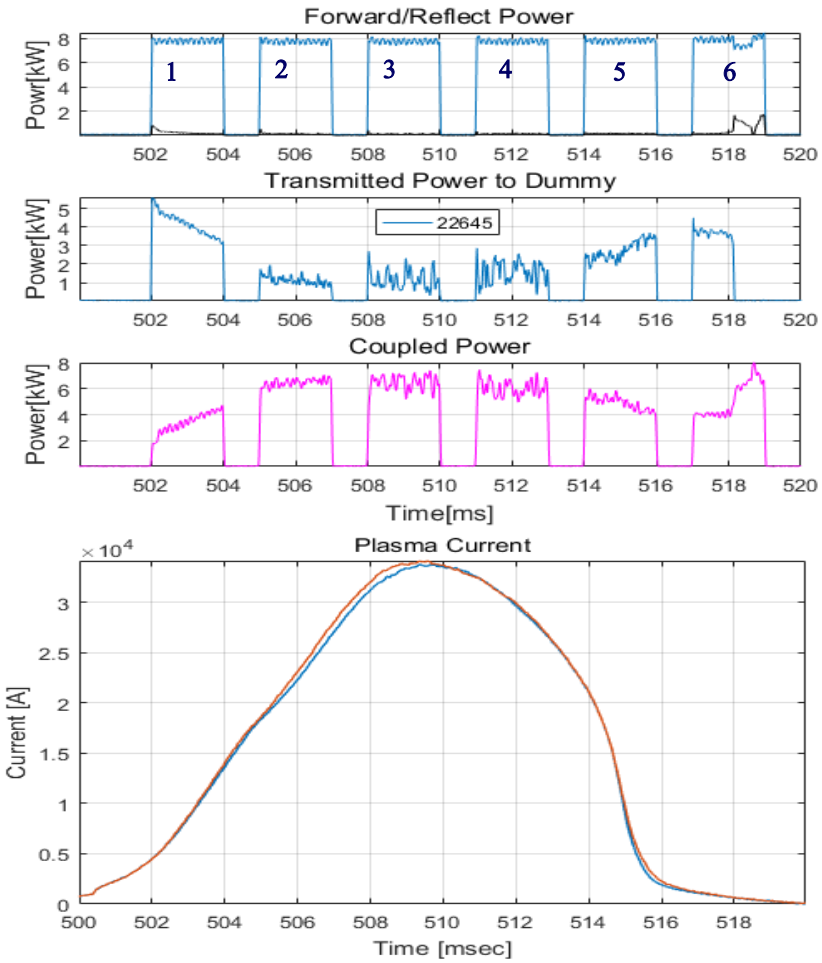


- Change of plasma temperature and density are measured.
- Particularly, sharp increases of electron temperature are observed when coupling is good and plasma density is low.

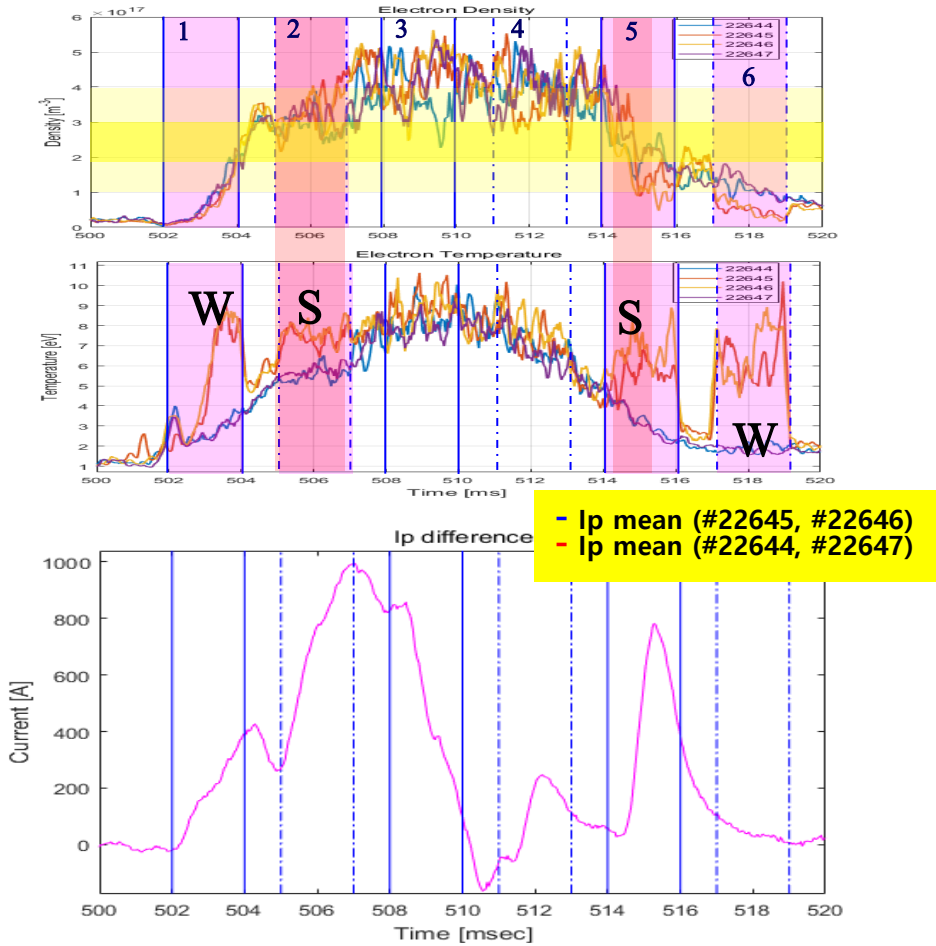
LHFW CD Experiment

Current driven by LHFW

RF Powers & Plasma Current(Ip)



Difference of Ip between w/RF & w/o RF

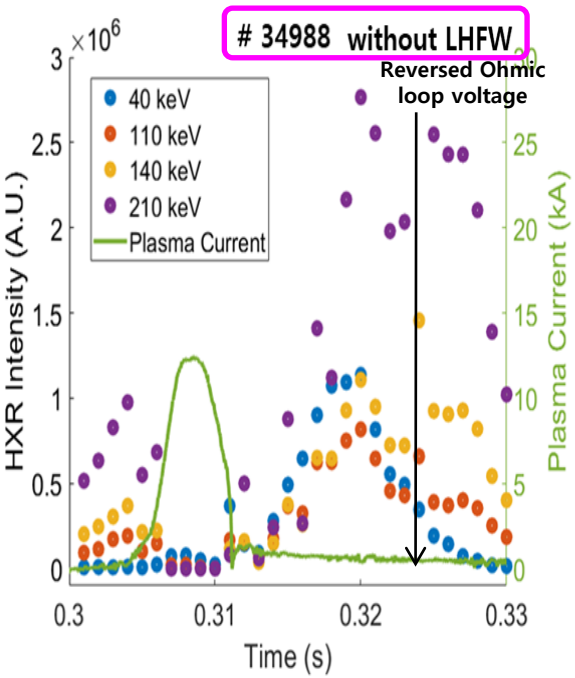


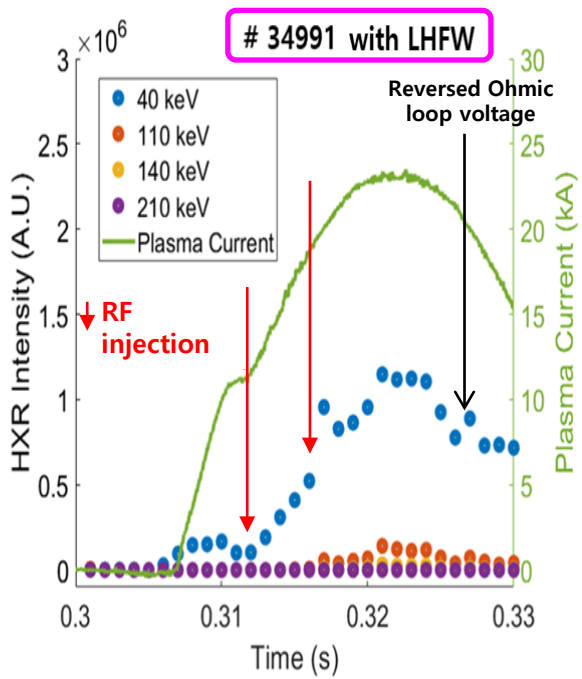
- In accordance with RF injection, plasma current is increased obviously .

Measurement of Hard X-ray

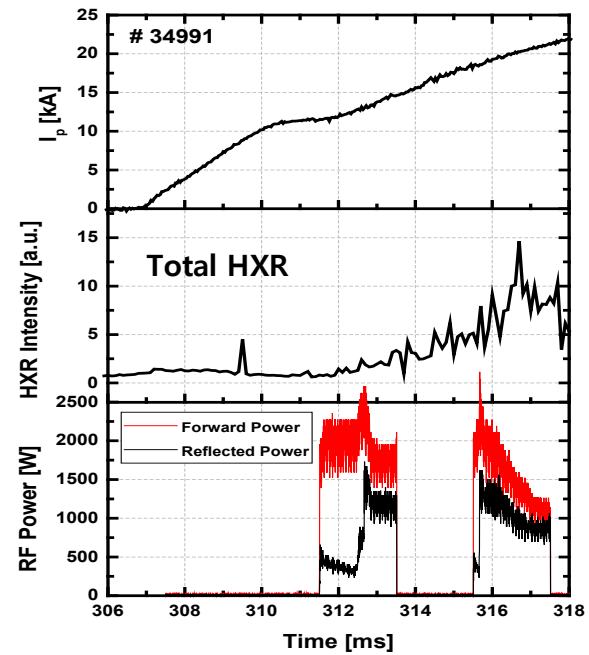
Change of HXR energy spectrum

Comparison of time evolution of HXR energy spectrum





RF Power with Ip & HXR



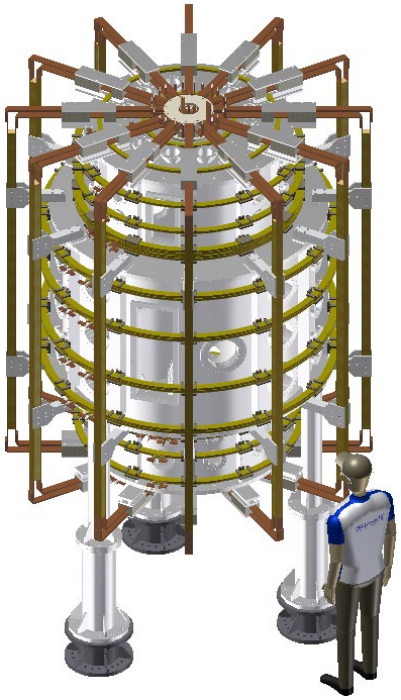
- W/O LHFW, HXR rise-up and fall-down is observed after the tokamak shot when plasma density is low and loop voltage is alive. HXR by RE is usually suppressed when the density is high during the shot.
- With LHFW, HXR signal increases only at 40 keV even in high density during the shot.
- Interestingly, plasma current is doubled up by LHFW triggering. (RF assisted Ohmic Current Drive)

III. Possibility of LHFW CD on KSTAR

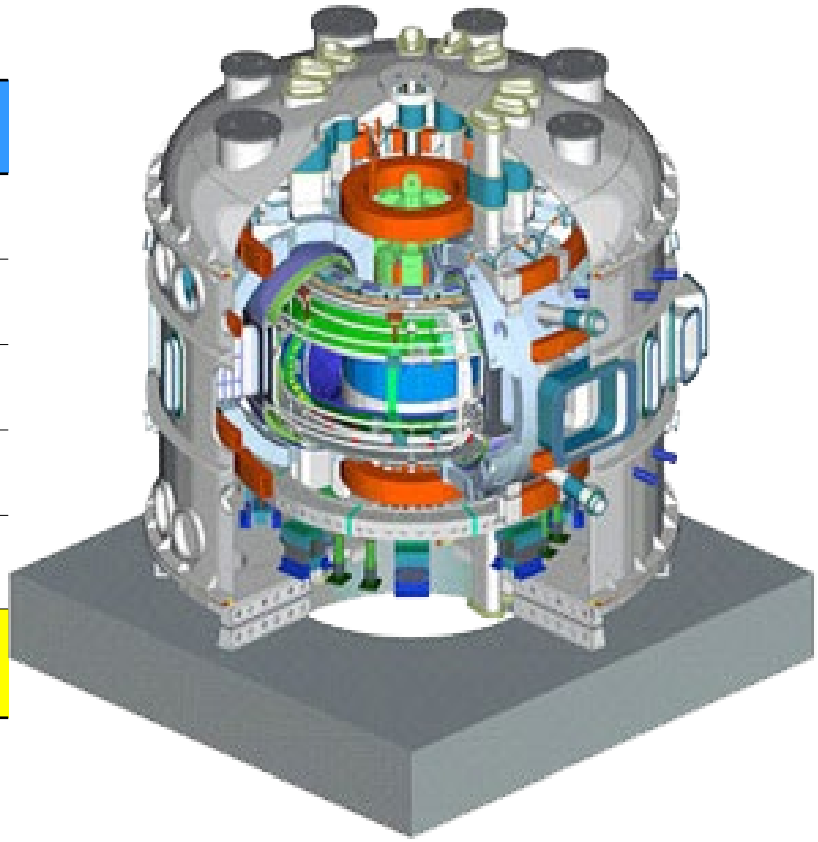
LHFW on VEST & KSTAR

LHFW Frequency

VEST → **KSTAR**



VEST	Parameter	KSTAR
0.43	R0 [m]	1.8
0.33	a [m]	0.5
0.2	B_0 [T]	2.0
H	Ion species	D
130	f_{lh} [MHz]	925
~ 390	f_{LHFW} [MHz]	~2775

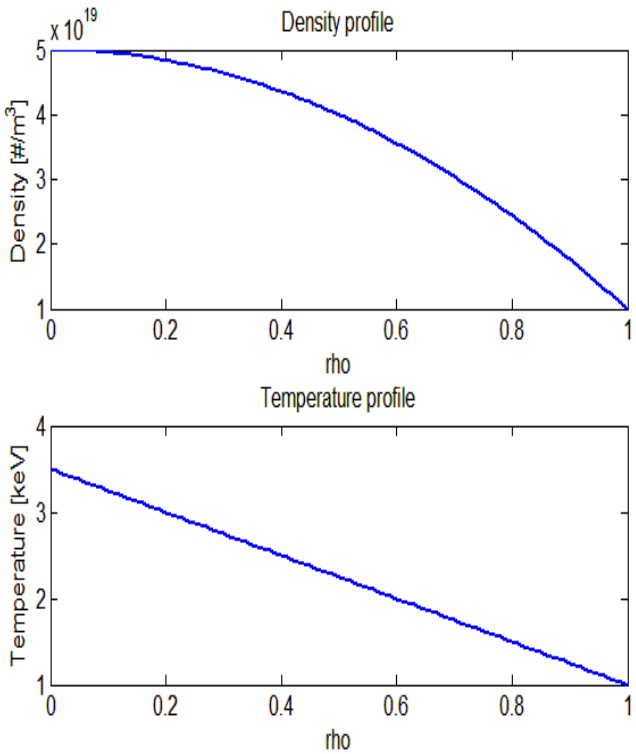


- A suitable RF frequency for LHFWCD on KSTAR will be about 2.45 GHz considering commercial MW source.

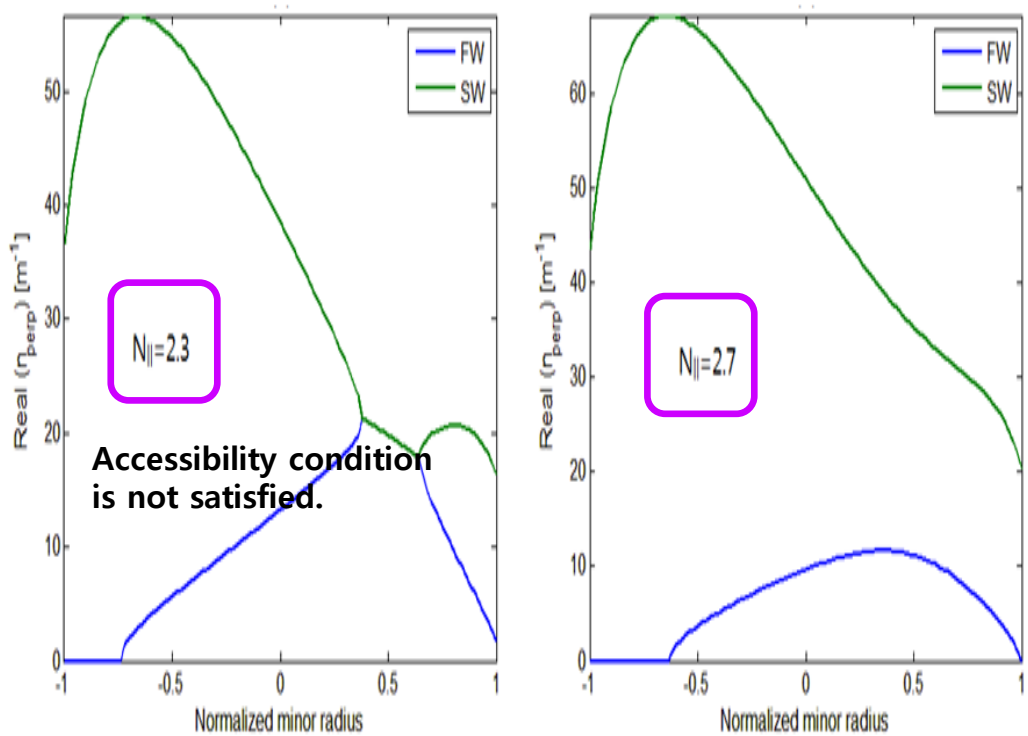
LHFW on KSTAR

$N_{\square}$ spectrum

KSTAR Ne / Te (H-mode)



Dispersion Relation ($N_{\perp}$ vs. $N_{||}$)

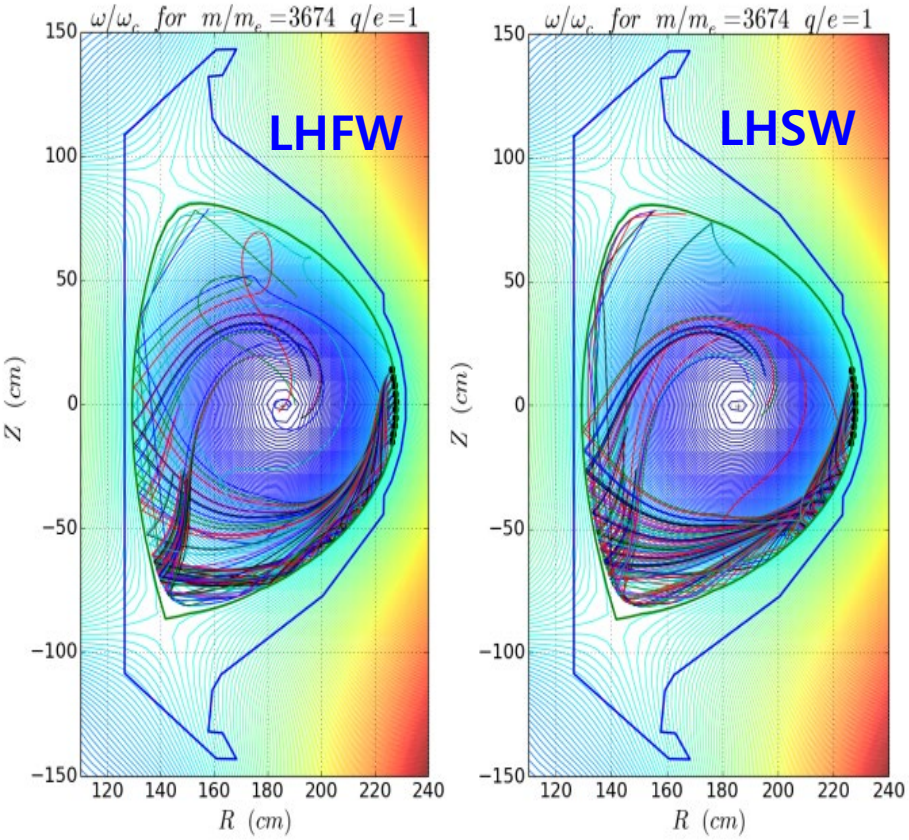


- **Antenna parallel wave number should be determined carefully to avoid Stix-Golant accessibillty condition.**

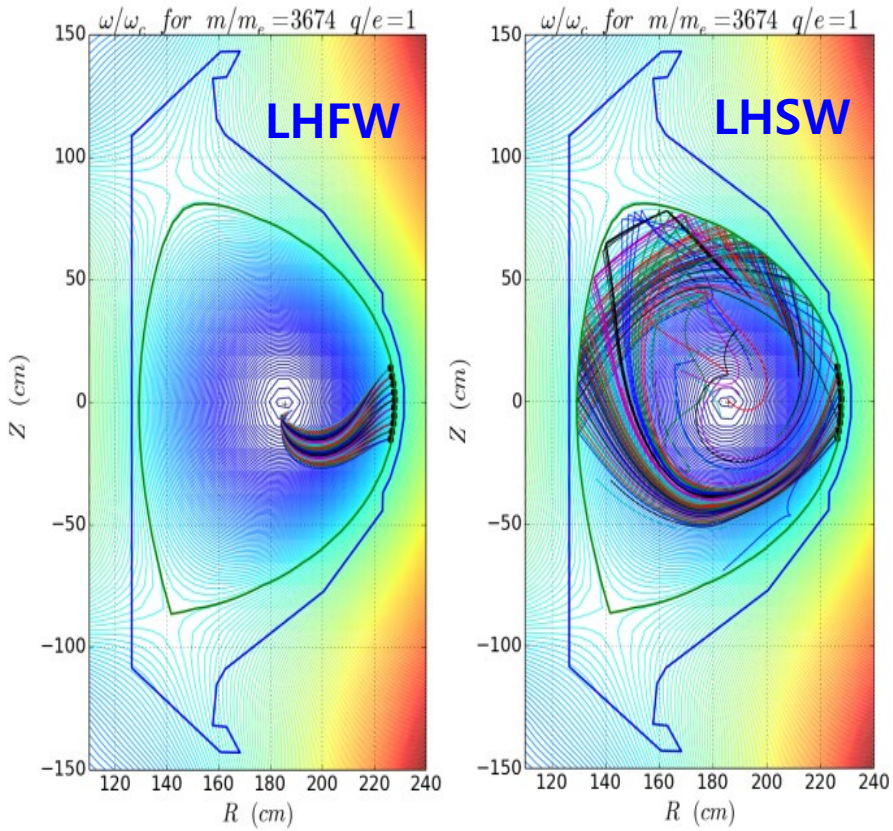
LHFW on KSTAR

LHFW Ray Trajectory

$N_{||}$ = 2.3



$N_{||}$ = 2.7

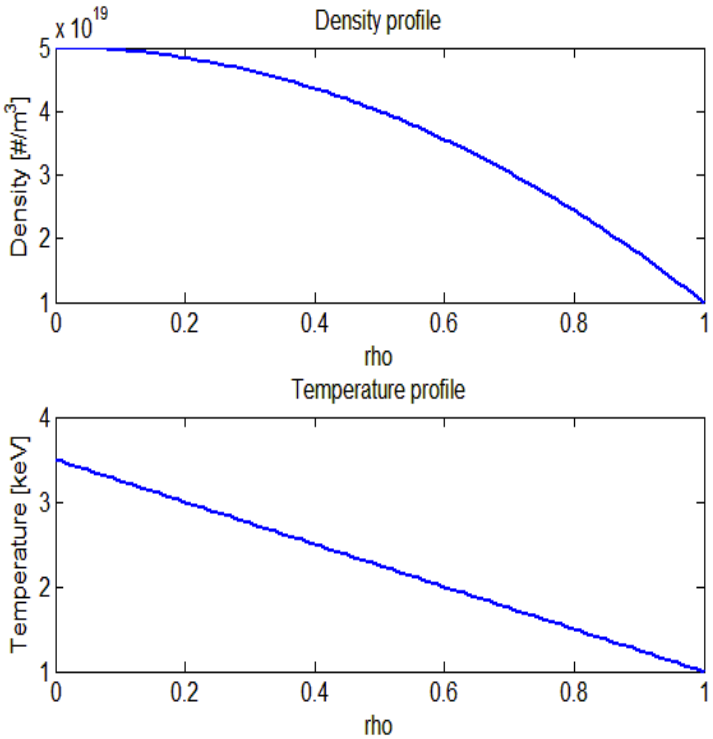


- Via ray tracing simulation, it is confirmed that suitable normalized parallel wave number is 2.7.

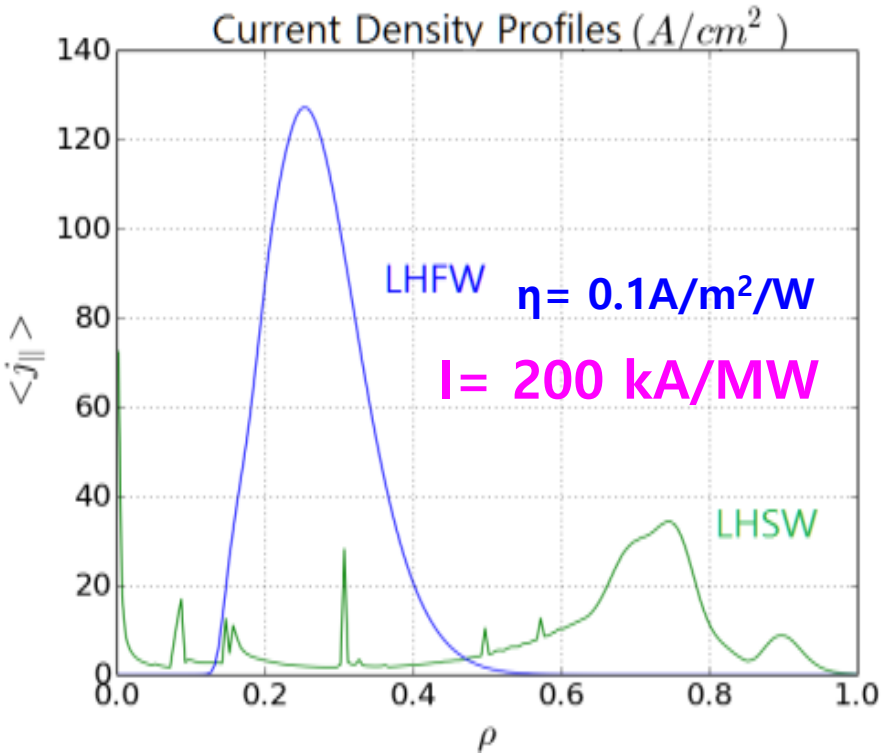
LHFW on KSTAR

LHFW Current Drive

KSTAR Ne/Te profile



KSTAR Current profile



IV. Potential of LHFW on Future Fusion Reactors

Potential of LHFW in FFR

Current Drive Efficiency

Scheme	Current drive efficiency η : $A/m^2/W$	Machine
LHSW (LHCD)	~ 0.34 @ L-mode	JT-60U
LHFW	CD feasibility confirmed	VEST
LHFW	~ 0.1 Numerical Cal. @ H-mode Not optimized	KSTAR

LHFW
~ 0.3 $A/m^2/W$
Expected by optimization

Future Fusion Reactor
(DEMO/STEP/ARC/…)

Parameters	Value
R [m]	3 ~ 7
n_e [$10^{20}m^{-3}$]	1 ~ 5
Power [MW]	10
I [MA]	0.1 ~ 1

LHFW has considerable potential to be used for the SSO of FFR.

Thank you for your attention !

Disadvantages of LHFW

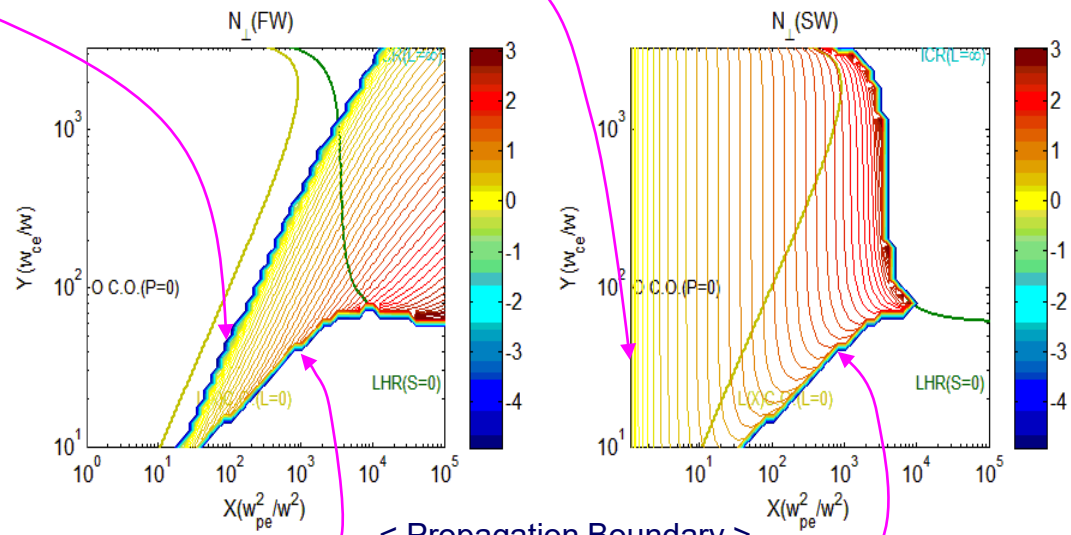
Coupling & Accessibility

❑ Launching density

$$n_{launch} \cong \begin{cases} \dfrac{m_e \varepsilon_0}{e^2}\omega^2 & LHSW \\ \dfrac{m_e \varepsilon_0}{e^2}\left(N_{\parallel}^2 - 1\right)\omega\omega_{ce} & LHFW \end{cases}$$

* High density is required to launch LHFW compared to LHSW. $\sim \dfrac{\omega_{ce}}{\omega} N_{\parallel}^2$

☞ **Coupling Problem**



< Propagation Boundary >

❑ Accessibility condition.

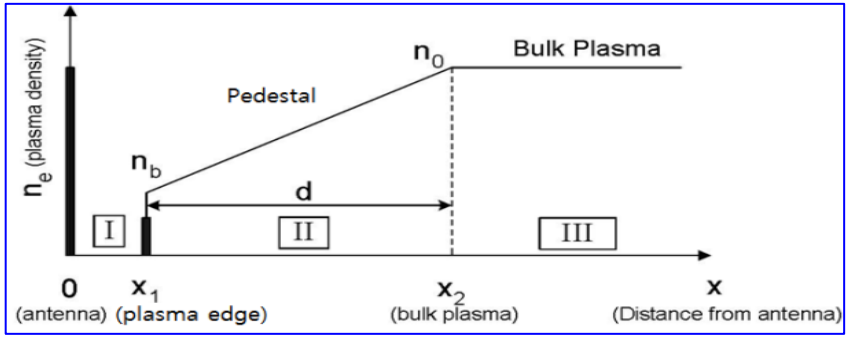
$$n_{confluence} \cong \frac{1}{4}\frac{m_e \varepsilon_0}{e^2} N_{\parallel}^2 \omega_{ce}^2$$

* The same accessibility condition as LHSW should be satisfied.

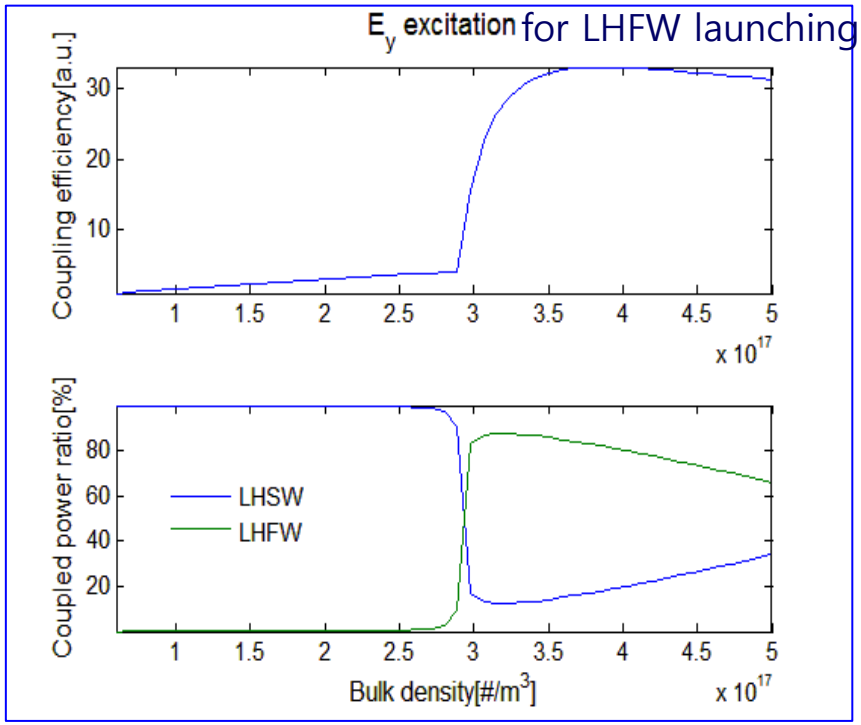
* The confluence density condition above is a more **generalized accessibility condition**.

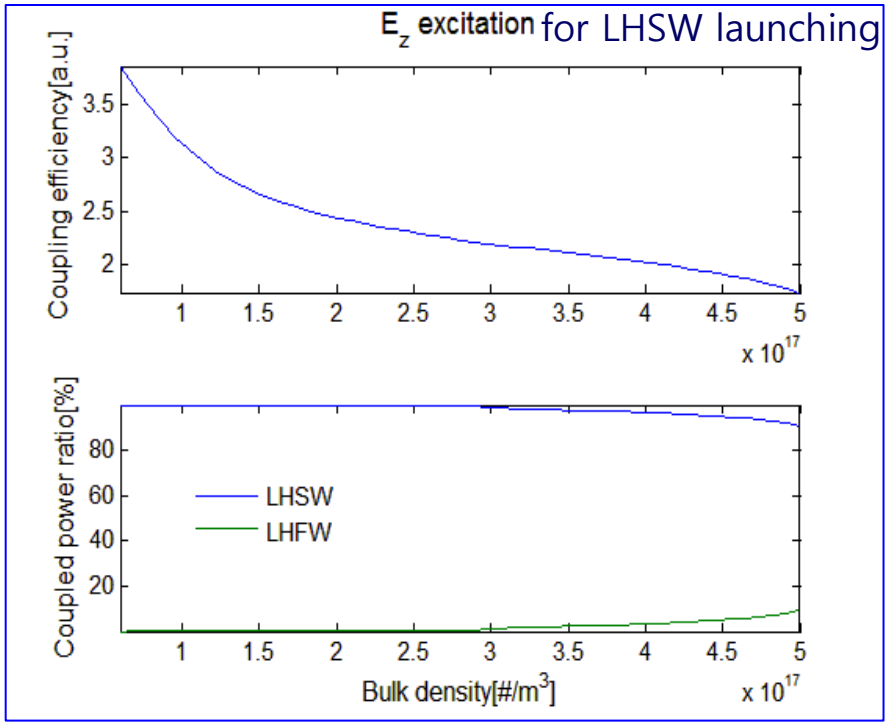
Coupling efficiency (1D full(cold)+WKB boundary at RHS)

- Comparison between LHFW and LHSW launching



Parameters	Values
B_0	0.2 T
Frequency	500 MHz
$N_{\parallel}$	4.0
n_0	6×10^{15} ~ 5×10^{17} #/m^3
n_b	4×10^{15} #/m^3
$d(X_2-X_1)$	3 cm
X_1	2 cm

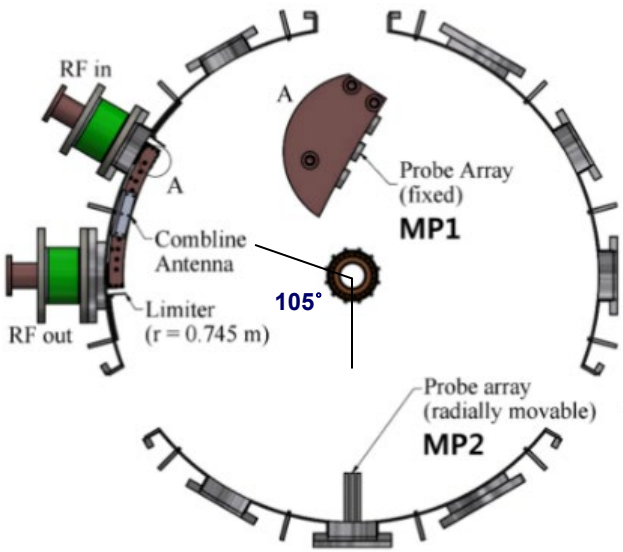




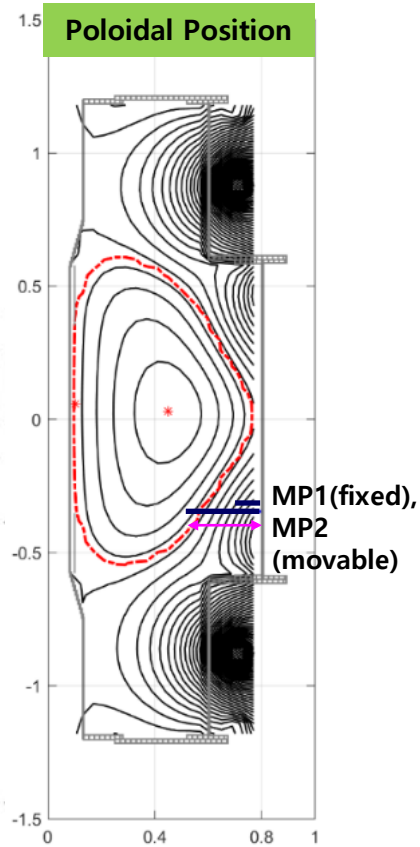
Wave Number Measurement Setup

❑ Wave B measurement Position

Toroidal Position



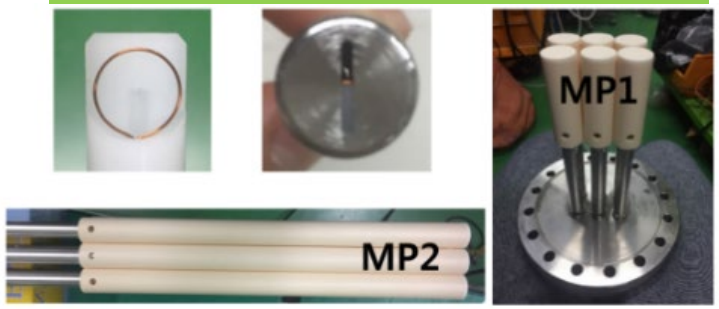
Poloidal Position



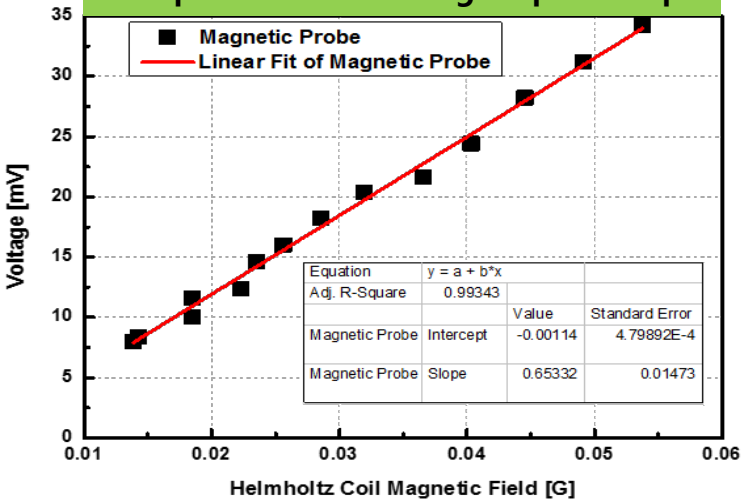
- The toroidal position of MP2 was determined considering pitch angle of about 30 kA shot and vertical position of the VEST port.
- MP2 was planned to detect LHFW propagation not for 100 kA shots but for 25~35 kA shots.

❑ Wave B dot probes

MP1(fixed, $n_{||}$), MP2(movable, $n_{\square}$)

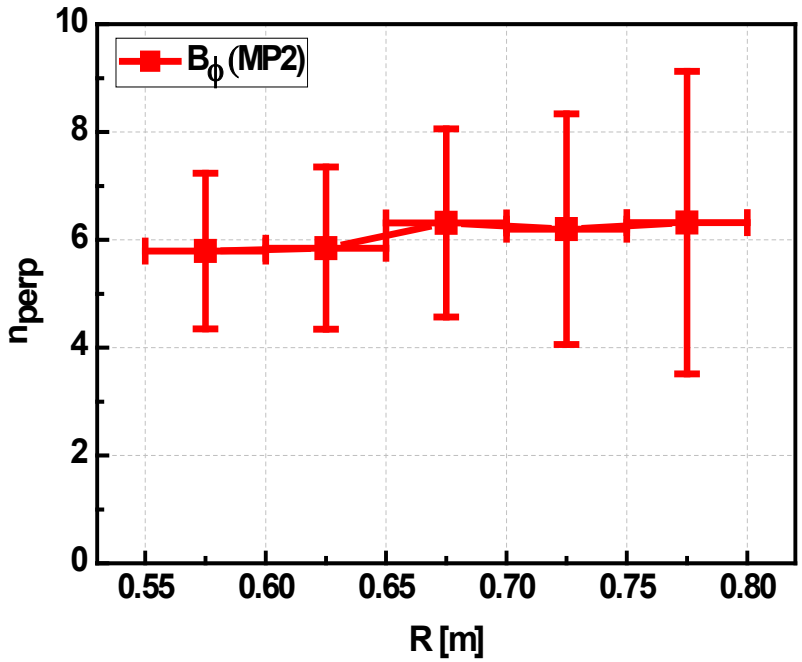


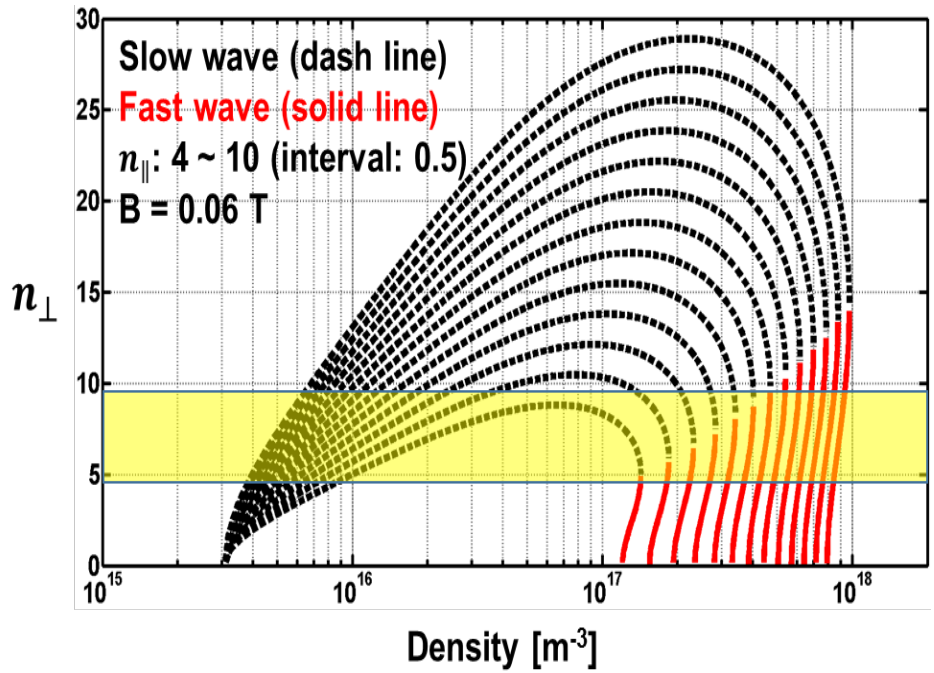
Amplitude check of signal picked up



$N_{\square}$ measurement for identification of wave branch

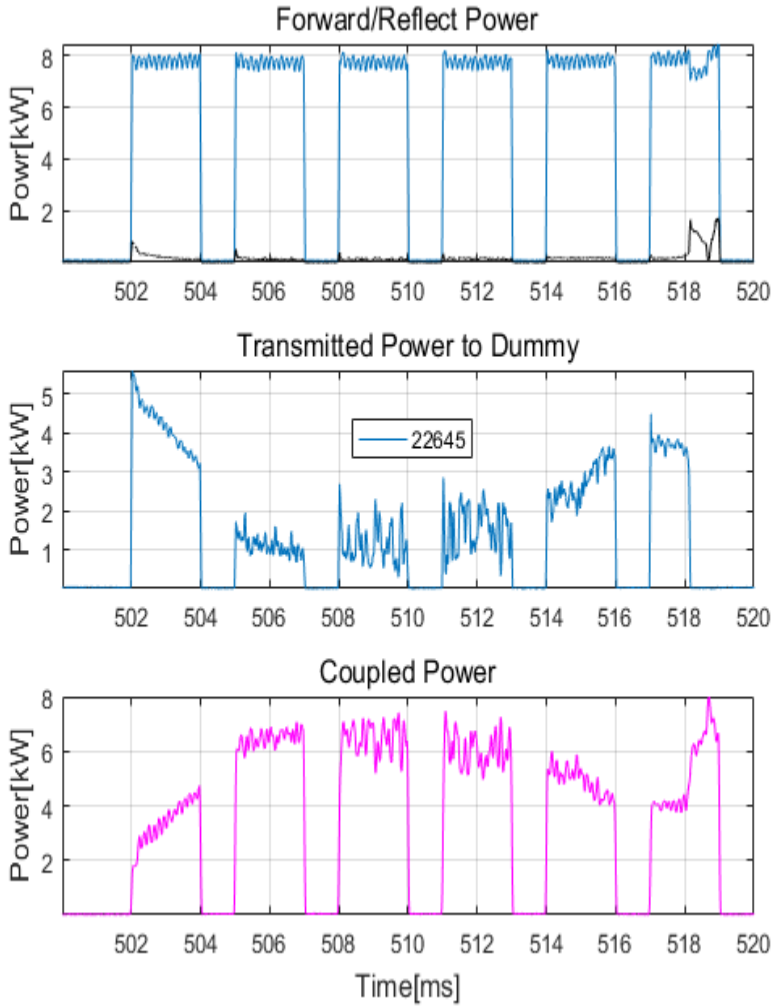
- $n_{\square}$ is measured with radially movable MP2 to confirm that the propagating wave is a fast wave.(shot to shot measurement for 25 kA shots)

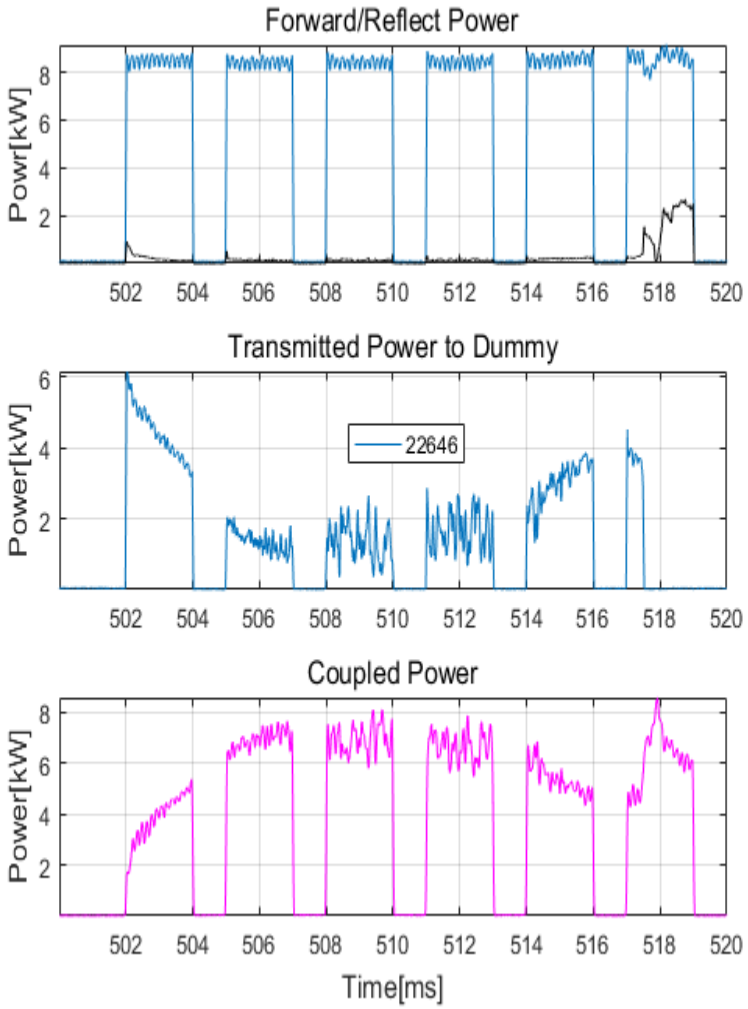




- The detected $n_{\square}$ is in agreement with calculated perpendicular wave number.
- Therefore, measured wave branch is LHFW.

Reproducibility of LHFW Coupling

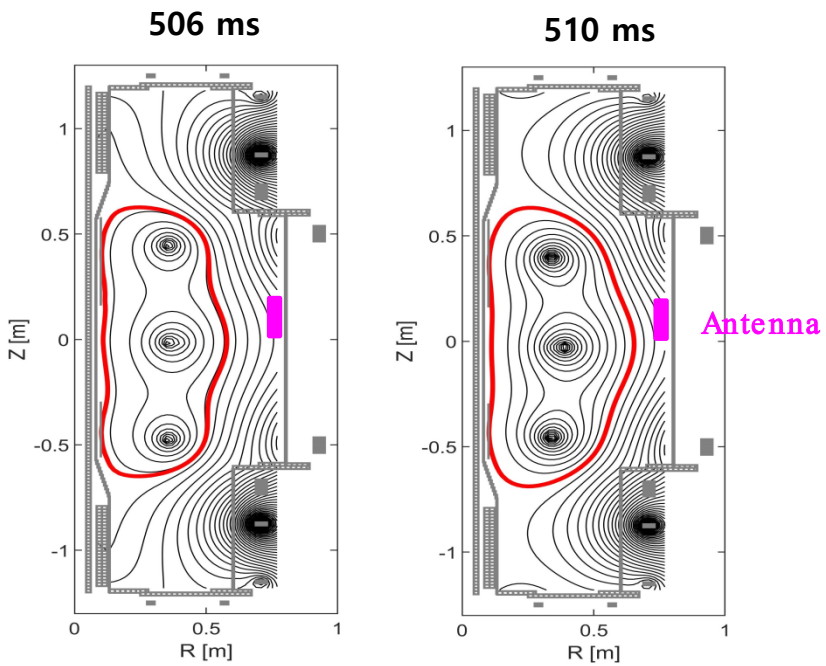




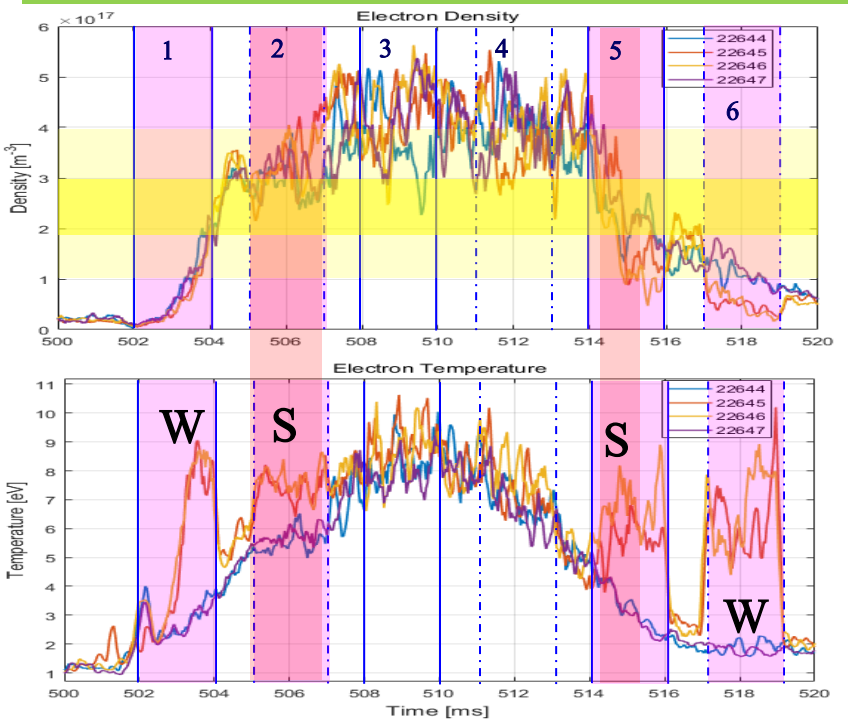
LHFW Experiment at 0.15 T(5)

Plasma Equilibrium & Change of Plasma Parameters

Plasma Equilibrium



Density(T) & Temperature(B)

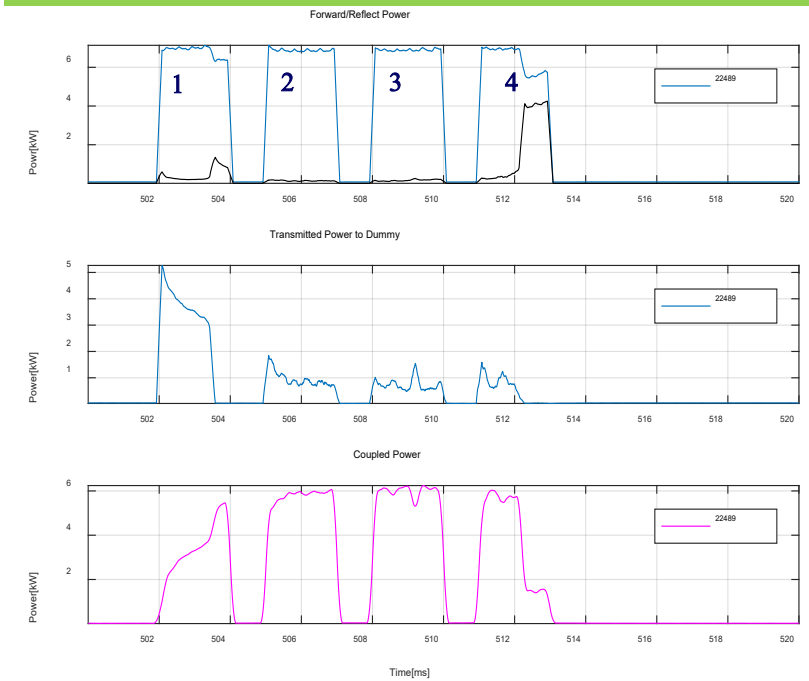


- Considering Equilibrium at 506 ms & 510 ms, for the time period of #1 and #6 the LCFS is much more distant from LHFW antenna. It means that the plasma which LHFW faces is mostly SOL plasma.
- In that case most power is deposited to SOL plasma and it is difficult to expect considerable current drive by coupling to the core plasma inside of LCFS.

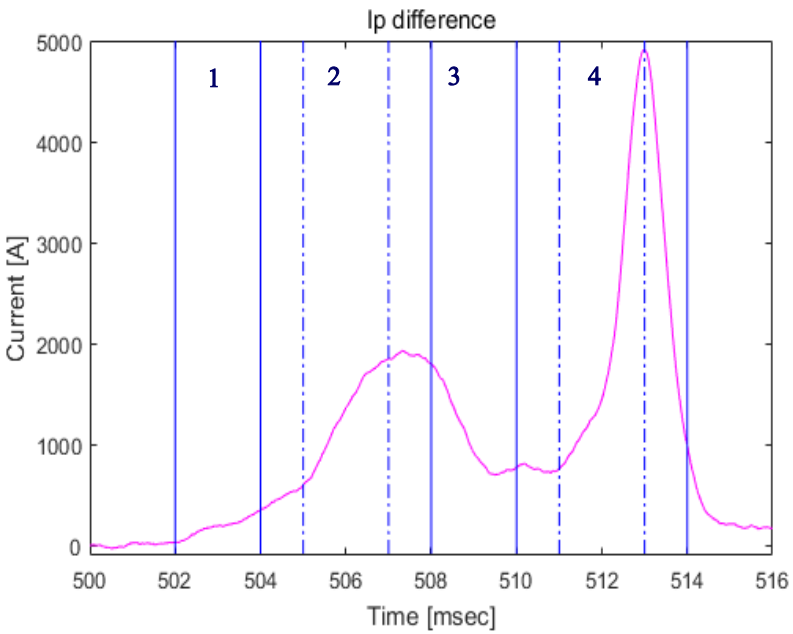
LHFW Experiment at 0.15 T

Driven Current by the LHFW : Another Shot

RF Powers & Plasma Current(Ip)



Difference of Ip for w/RF & w/o RF

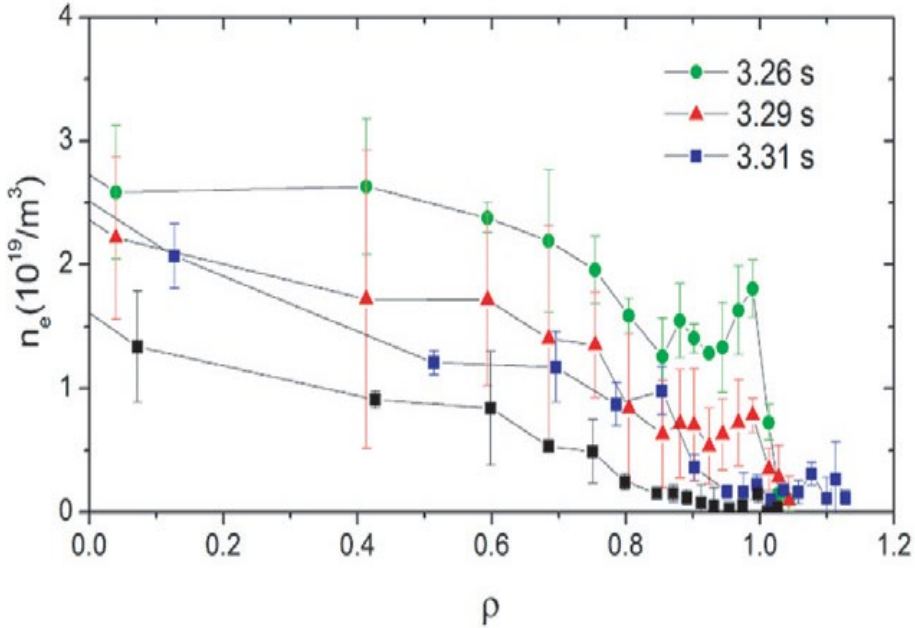


- It is hard to discern the increase of plasma current directly since the Ohmic to RF power ratio is about 10 and the target Te is so low that efficienct CD is difficult.
- However, the difference of plasma current clearly shows the relation to the RF power coupling and plasma parameter changes.

LHFW in KSTAR

Density Profile for LHFW Coupling

KSTAR H-mode Ne Profiles (Thomson Scattering & Reflectometer)



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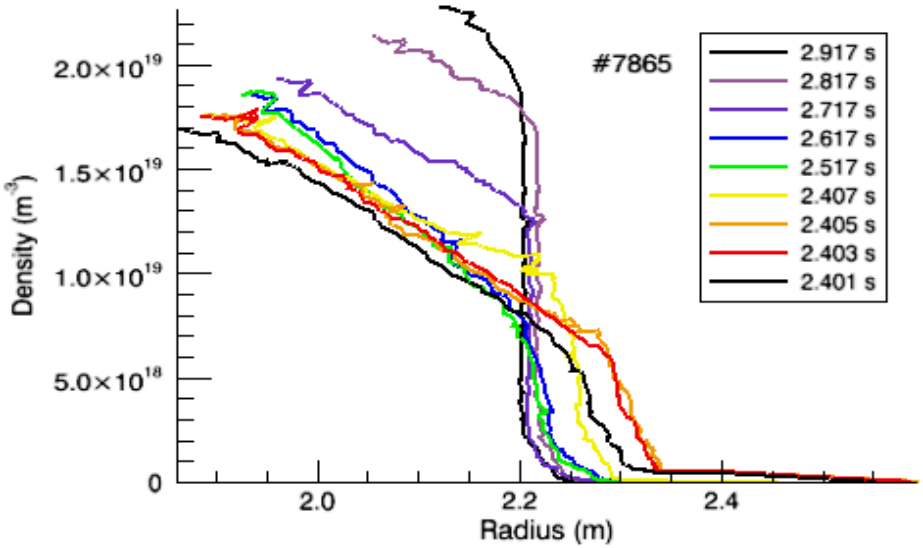
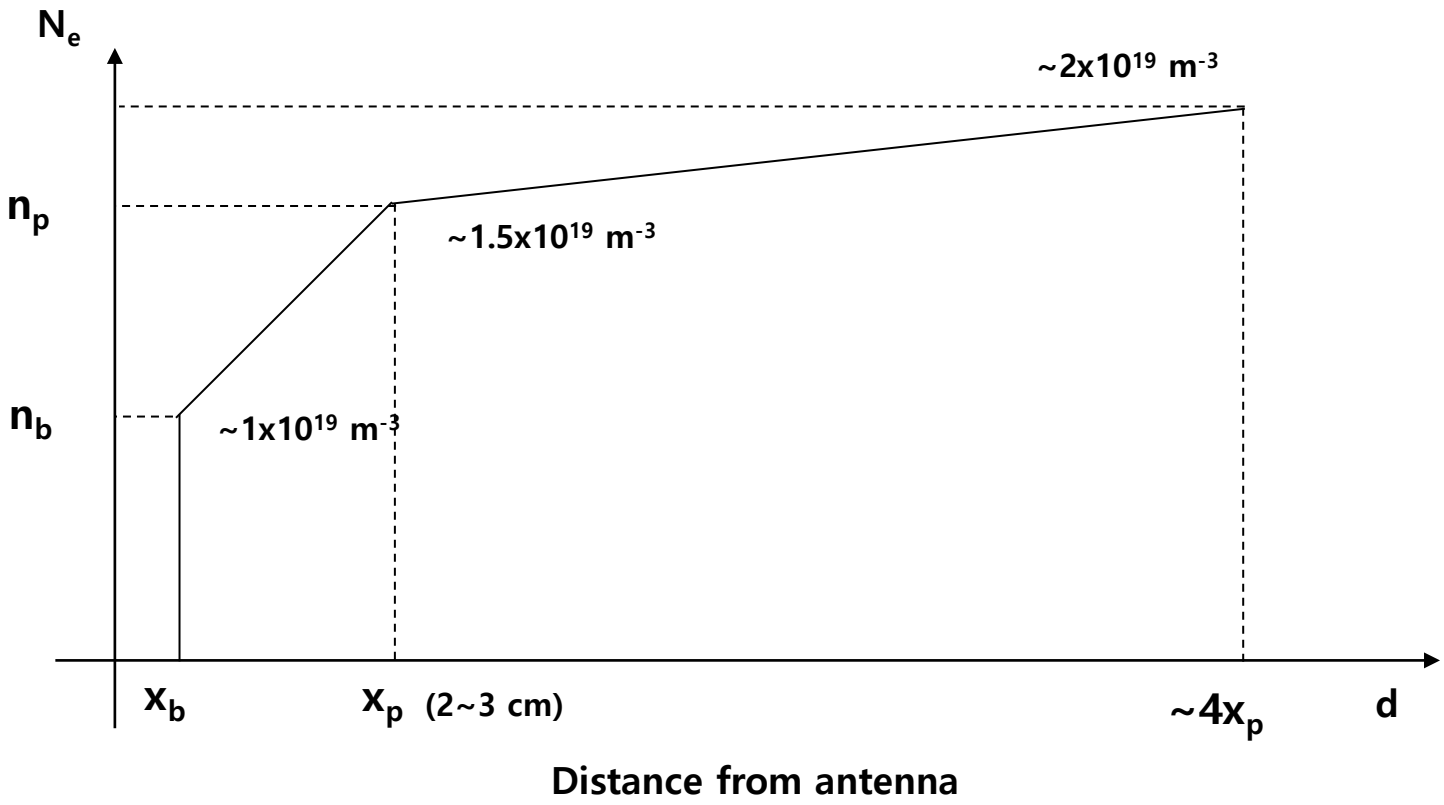


KSTAR reflectometry, Dr. Seo (KFE)

LHFW in KSTAR

Density Profile for LHFW Coupling

Ne model for Coupling Eval.



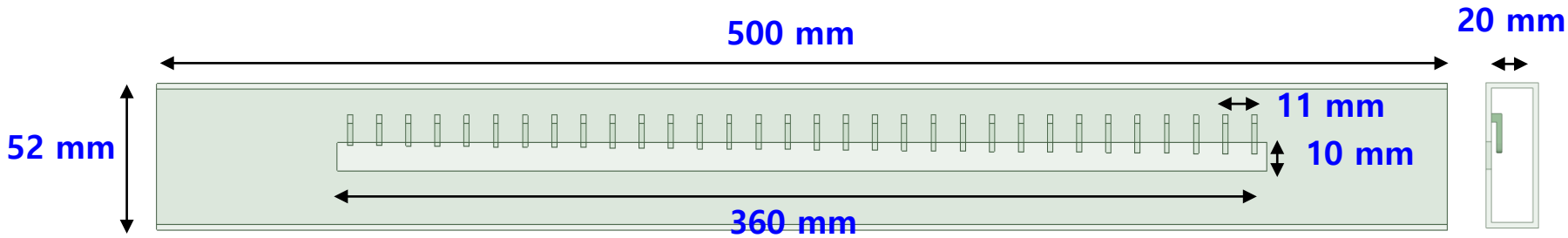
LHFW on KSTAR

LHFW Antenna

Traveling Wave Type - Slotted Waveguide Antenna for LHFW

- ❑ Simple Structure / High Power Transmission
- ❑ Load-resilent / No Matching Components

TW-SWA Model in Preparation

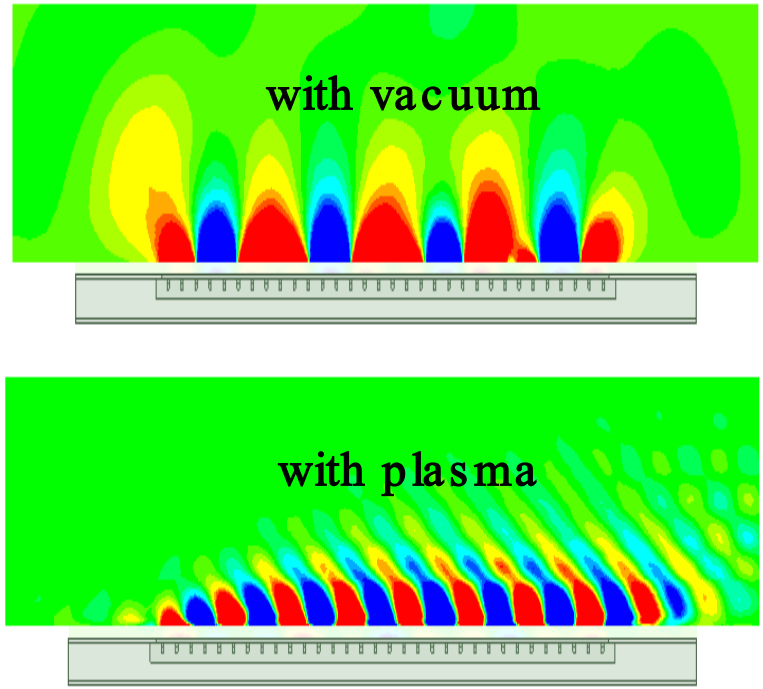


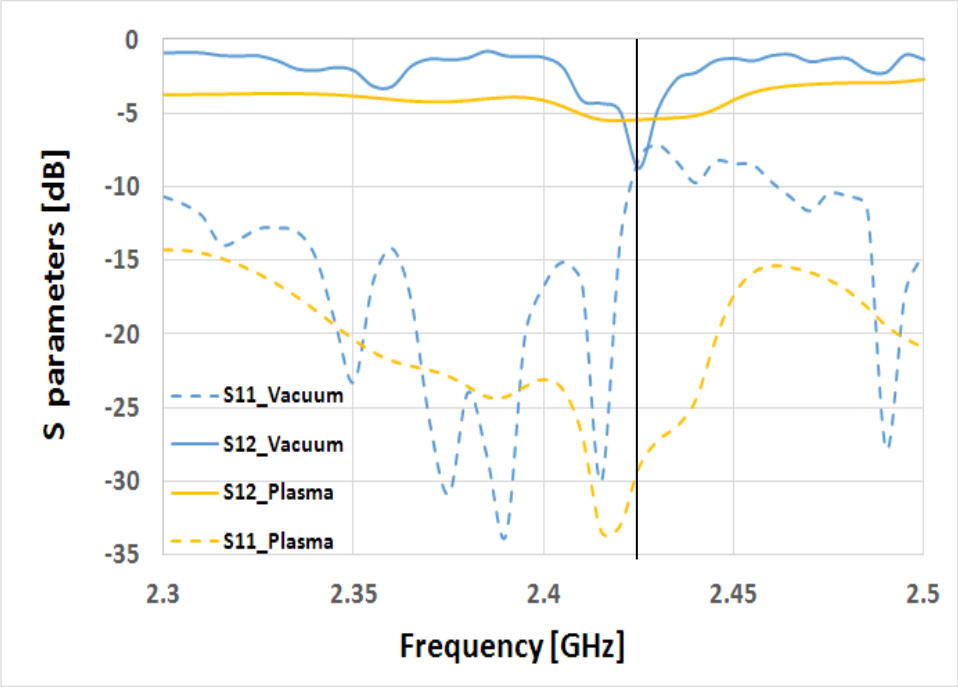
- ❑ Rectangular Waveguide with Slot & Radiators ← Basic Concept, Dr. Wi (KFE)
- ❑ Waveguide filled with a dielectric material
- ❑ Frequency : 2.45 GHz / $N_{\parallel}$: 2.7

LHFW in KSTAR

LHFW Antenna

Antenna Radiation Pattern & S parameters





- More than half the RF power can radiate toward vacuum chamber without plasma.
- About 70% of RF power can be coupled to plasma with reflection less than 1 %.