Status and plan of LHFW(Lower Hybrid Fast Wave) current drive research in VEST

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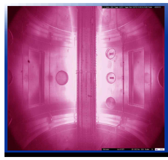
Contents

Introduction
The slow wave and fast wave in LHW range

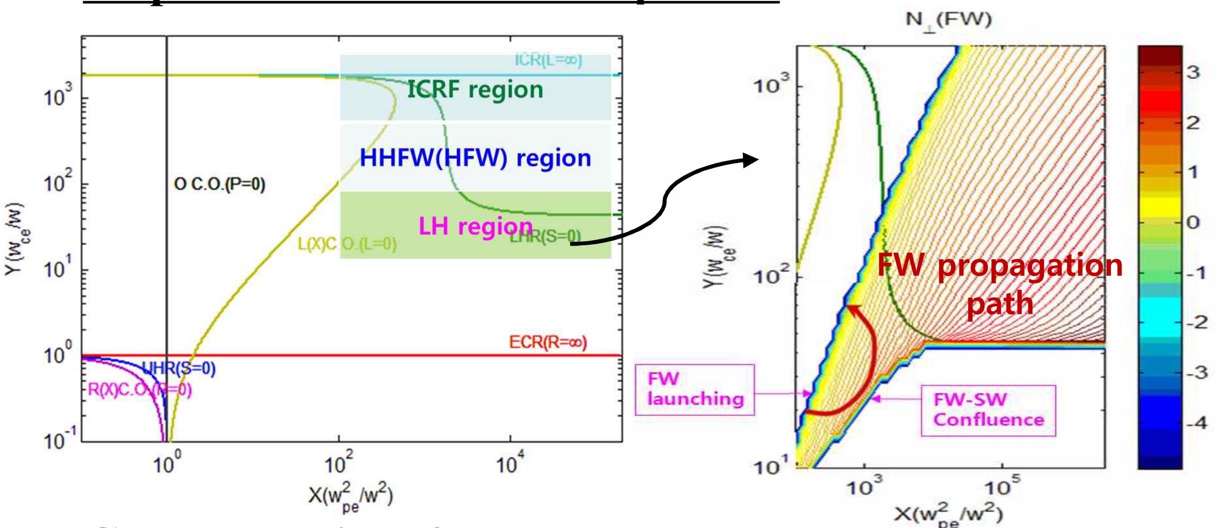
- **The slow wave in LH (Lower Hybrid) resonance range**
  - ✓ LHCD has been utilized as the most efficient current drive method in tokamaks.
  - ✓ **However, the density limit and strong electron Landau damping of slow wave make it hard to penetrate into the core plasma region in a reactor grade plasmas.**
  - ✓ Alternative central or off-axis current drive method should be researched for high density and high temperature plasmas.

- **The fast wave in LH (Lower Hybrid) resonance range**
  - ✓ Because of the less favorable polarization, electron Landau damping of the fast wave in this range is weaker, but still nonnegligible [1].
  - ✓ **The fast wave branch of LH waves could be a good candidate for the central electron heating and current drive due to its penetration and damping in more high density plasmas.**
  - ✓ **It is suggested that the current drive scheme utilizing the LHFW which exist between lower hybrid frequency and electron cyclotron frequency is researched in VEST device.**



Research Status
Analytic study of LHFW

- **Dispersion relation in cold plasma** $\omega_h < \omega < \omega_{ce}$



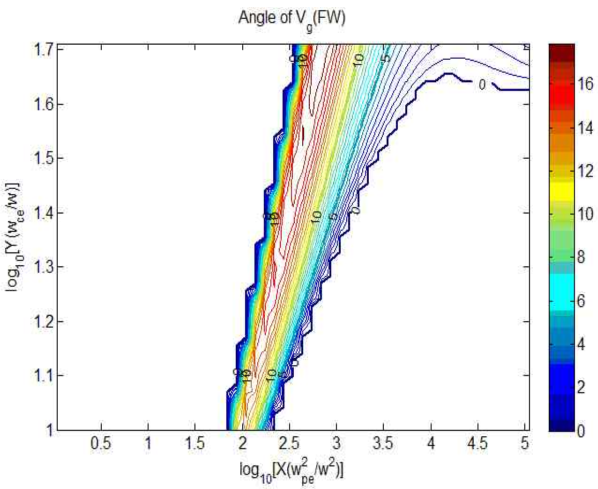
✓ Same dispersion relation form with ICRF and HHFW region.

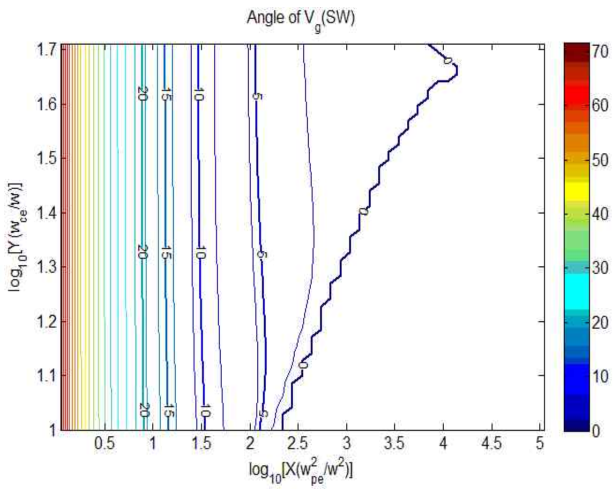
✓ Slow Wave (LHSW)

✓ **Fast Wave (LHFW)**

$$N_\perp^2 \cong \begin{cases} -\dfrac{P(N_\parallel^2 - S)}{S} & : SW \\ -\dfrac{(N_\parallel^2 - R)(N_\parallel^2 - L)}{(N_\parallel^2 - S)} & : FW \end{cases}$$

- **Group velocity of the slow wave and fast wave (propagation characteristics)**



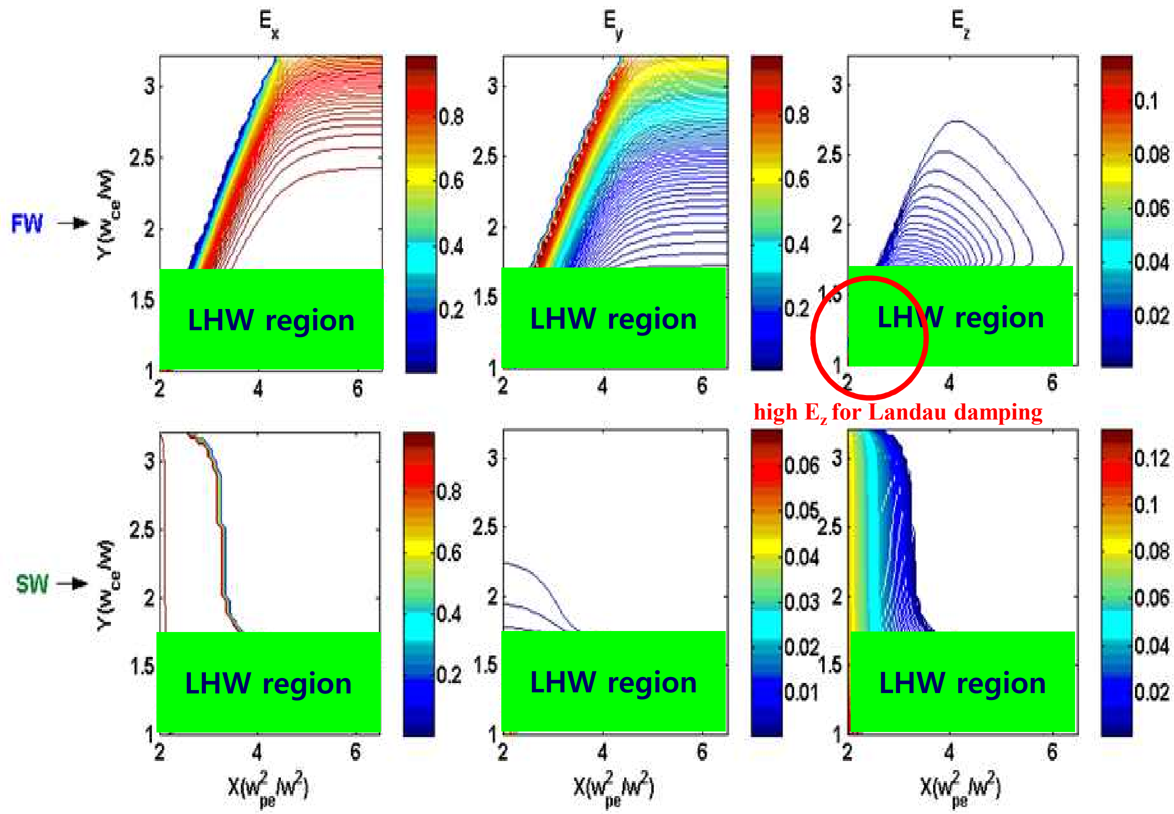


✓ Angle of the group velocity perpendicular to the magnetic field.

✓ **LHFW can transfer the energy into the more high density plasma region than LHSW.**

Analytic study of LHFW

- **Polarization of the slow wave and fast wave (absorption characteristics)**



- ✓ Possible current drive mechanisms are Landau damping and Magnetic pumping for fast waves.
- ✓ **In LHW region, well above the frequency of ICRF and HHFW, LHFW has considerably higher Ez polarization that can accelerate the resonant particles by Landau damping.**

$$P_{LD}^{\alpha} \cong \frac{\omega}{8\pi}\frac{\omega_{p\alpha}^2}{\omega^2}\cdot 2\sqrt{\pi}\frac{\omega^3}{|k_{ll}|^3 v_{th\alpha}^3} e^{-\frac{\omega^2}{k_{ll}^2 v_{th\alpha}^2}} \cdot |E_z|^2$$

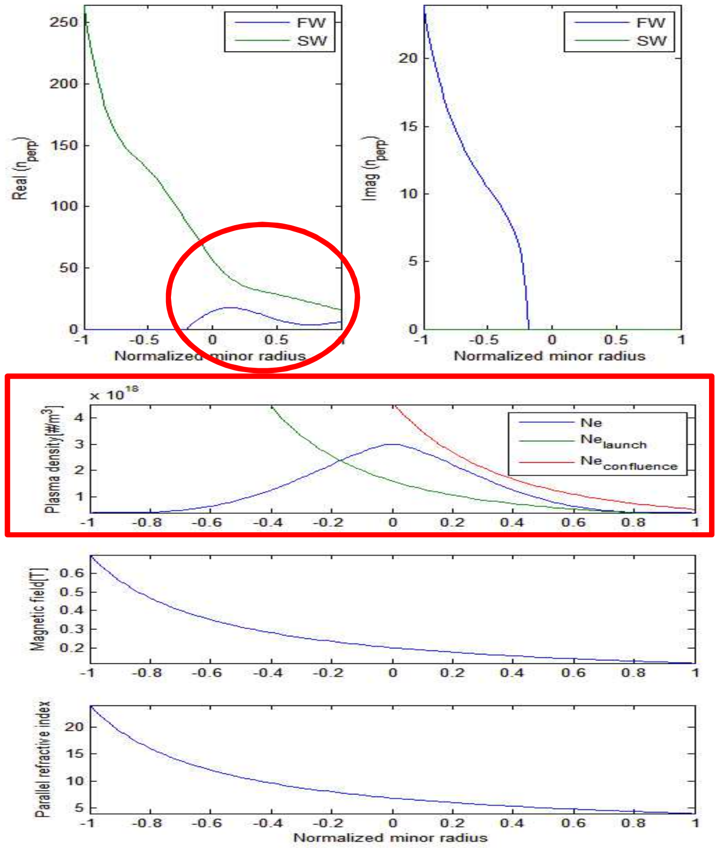
Research Status
Analytic study of LHFW

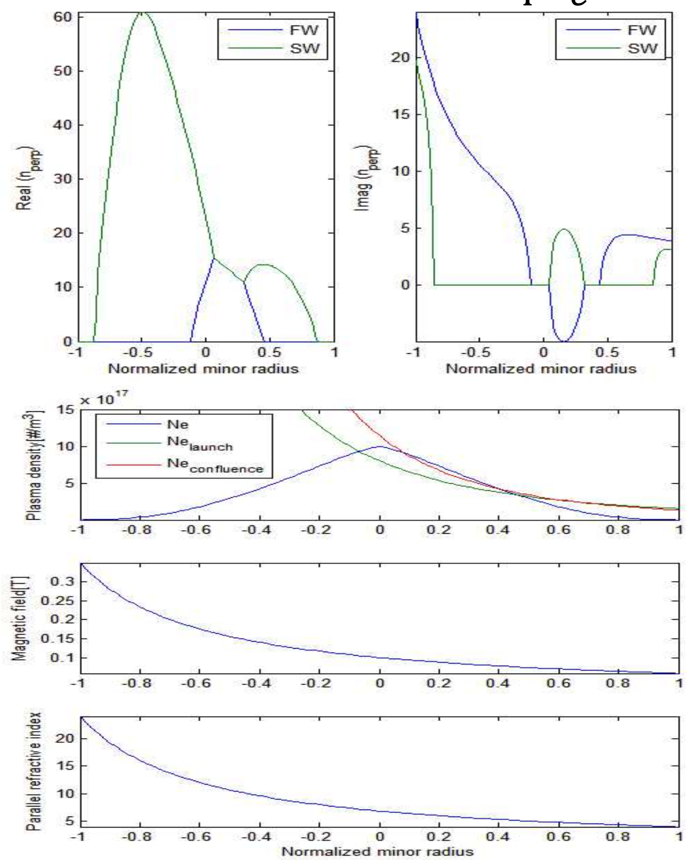
- **Propagation of LHFW on VEST (accessibility condition)**

$$n_{launch} \cong \frac{m_e \epsilon_0}{e^2}(N_\parallel^2 - 1)\omega\omega_{ce}$$

$$n_{launch} < n_e < n_{confluence}$$

$$n_{confluence} \cong \frac{1}{4}\frac{m_e \epsilon_0}{e^2} N_\parallel^2 \omega_{ce}^2$$





<f=500[MHz], n_0= 3x10[18][#/m[3]] B_0=0.2[T], $n_\parallel$=4.0>

<f=500[MHz], n_0= 1x10[18][#/m[3]] B_0=0.1[T], $n_\parallel$=4.0>

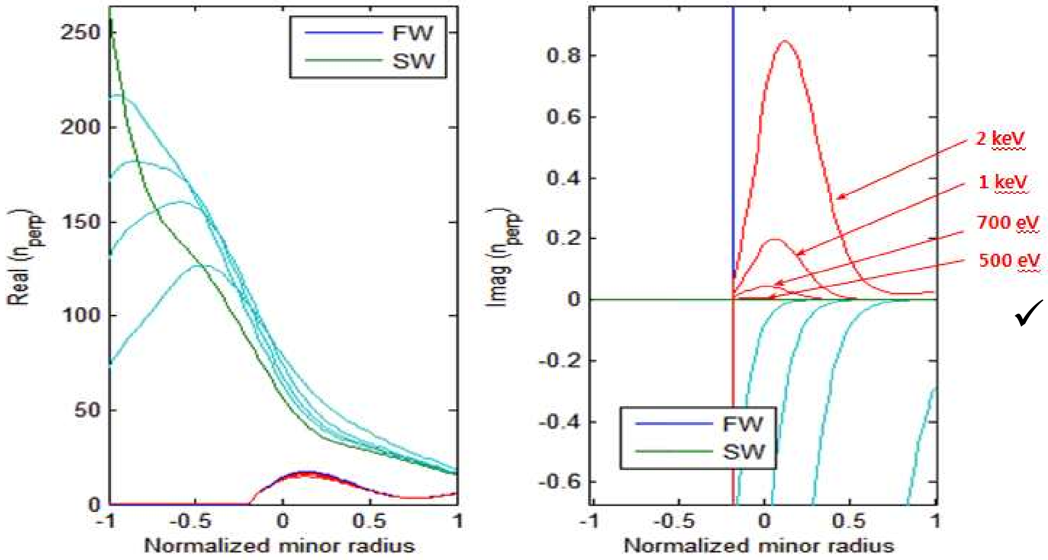
Accessibility condition is satisfied.

Accessibility condition is not satisfied.

Research Status
Analytic study of LHFW [2]

- **Absorption of LHFW on VEST**

The imaginary part of dispersion is obtained considering kinetic effect.



f=500[MHz], n_0= 3x10[18][#/m[3]] B_0=0.2[T], $n_{\parallel}$ =4.0

- ➢ **Te > 500 eV : Absorption is possible.**
- ➢ **Te > 1keV : Single pass absorption is possible.**

$$N_{\perp r} \simeq \begin{cases} \left(-\frac{P(N_\parallel^2 - S)}{S}\right)^{1/2} & SW \\ \left(-\frac{(N_\parallel^2 - R)(N_\parallel^2 - L)}{(N_\parallel^2 - S)}\right)^{1/2} & FW \end{cases} \qquad N_{\perp i} \simeq \begin{cases} N_{\perp r,SW}\,\pi^{1/2}\eta^3\exp(-\eta^2) & SW \\ N_{\perp r,FW}\dfrac{\pi^{1/2}\eta^3\exp(-\eta^2)}{-1+\dfrac{\omega_{ce}^2 N_\parallel^2}{\omega_{pe}^2}} & FW \end{cases}$$

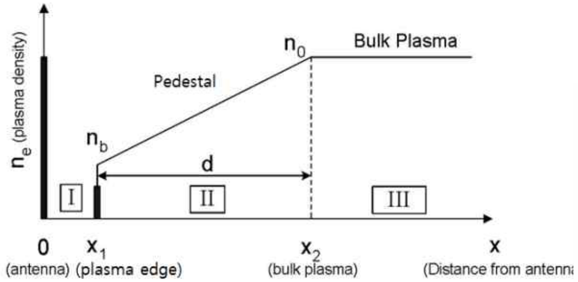
η is the ratio of wave phase velocity to electron thermal velocity.

- ✓ The perpendicular refractive index of SW is typically much larger than that of FW. And the absorption is associated with the real perpendicular wave number and the Landau resonance condition.
- ✓ The imaginary of refractive index of LHFW depends on the plasma density, magnetic field and parallel refractive index. **It is usually very small when it starts to propagate in edge plasmas where the density is low but it gets considerably higher as it propagates into central plasma region.**
- ✓ As the temperature increases the imaginary part of LHFW increases dramatically in central region.

Coupling efficiency calculation (1D full wave simulation) [2]

Coupling of LHFW on VEST

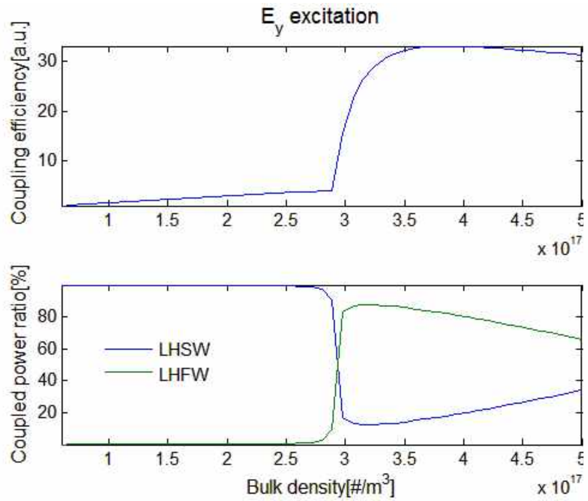
- ✓ The coupling efficiency is calculated with 1D full wave simulation code developed for the study of XB mode conversion efficiency [3].
- ✓ The coupling efficiency and coupled power ratio for E_y antenna excitation to launch LHFW and for E_z excitation to launch LHSW are shown.
- ✓ The coupling efficiency by E_y excitation is much lower than that by E_z excitation if the bulk density is less than about 3×10^{17} #/m^3 which is the LHFW launching density. However, it is almost 10 times greater than if LHFW start to propagate. **It means that LHFW can be more efficiently coupled to plasmas than LHSW in high density and high density gradient plasmas.**



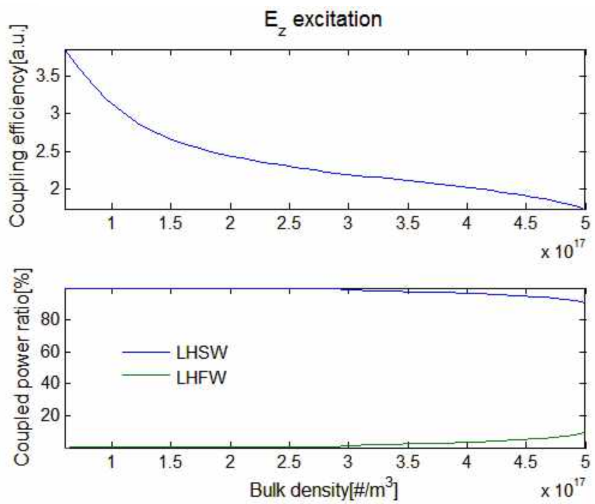
Density profile for coupling calculation

Parameters	Values
B_0	0.2 T
Frequency	500 MHz
$N_{\parallel}$	4.0
N_0	$6\times10^{15} \sim 5\times10^{17}$ #/m^3
N_b	4×10^{15} #/m^3
$d(X_2-X_1)$	3 cm
X_1	2 cm

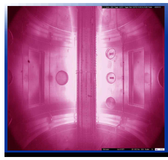
Parameters for coupling calculation on VEST



Coupling efficiency and ratio for E_y excitation



Coupling efficiency and ratio for E_z excitation



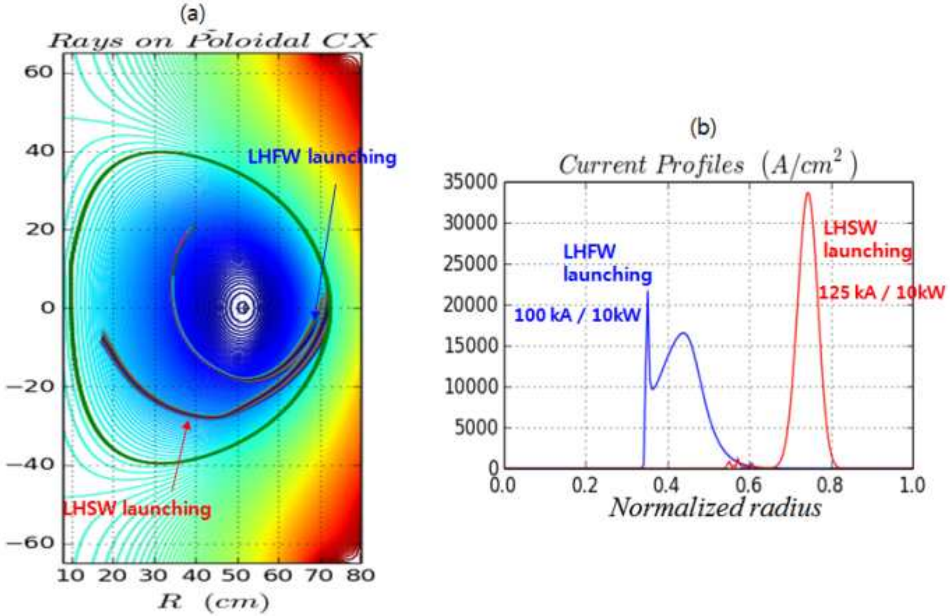
Research Status
Ray tracing simulations of LHFW on VEST [2]

- **Ray tracing simulation**

✓ The parallel refractive is 4.0 which satisfies the accessibility condition for the given magnetic field and RF frequency.

✓ The propagations and driven currents are calculated with GENRAY code for LHFW and LHSW launching cases on VEST.

✓ **The LHFW can propagate into more central region and the driven current is comparable to that of LHSW.**



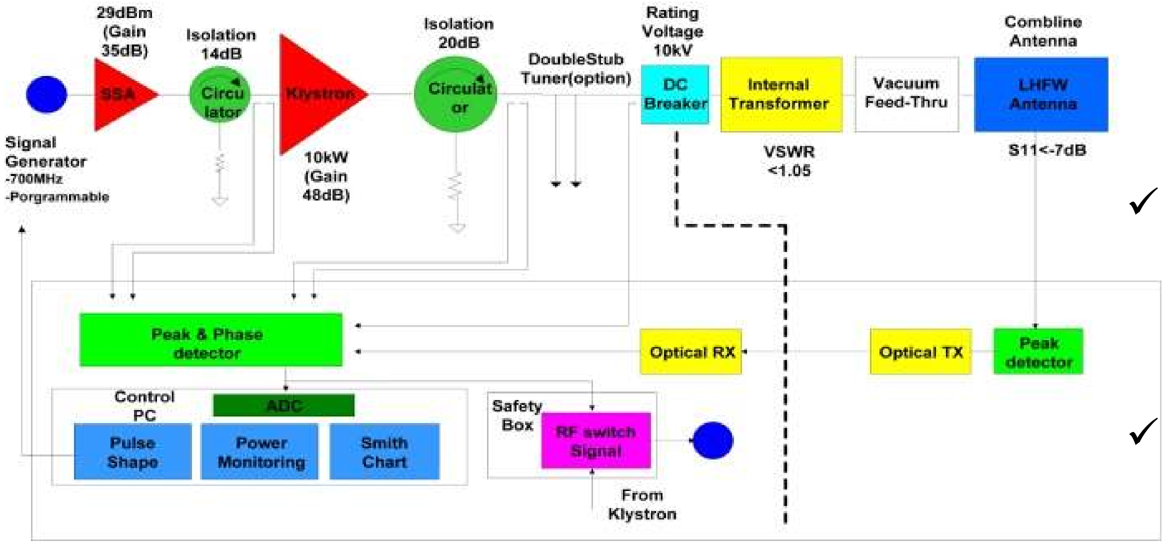
Ray tracing : (a) ray, (b) driven current profile

Parameters	Values
B_0	0.2 T
Frequency	500 MHz
$N_{\parallel}$	4.0
Core density	3×10^{18} #/m^3
Edge density	4×10^{17} #/m^3
Core temperature	3 keV
Edge temperature	0.2 keV

Parameters for ray tracing calculation on VEST

Research Status
LHFW RF system [2]

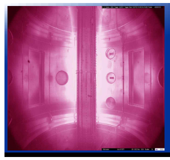
- **Schematic of LHFW RF system**



Components	Values
Signal generator	500kHz~1.3GHz(13dBm)
Solid state amplifier	35dB (max 29 dBm)
Circulator(SSA)	14dB isolation, 75 W
Klystron	10 kW UHF Harris system for broadcasting
Circulator(Klystron)	20 dB isolation, 15 kW
DC breaker	Rating 10kV, VSWR<1.05
Internal transformer	VSWR<1.05,for matching
Vacuum feed-thru	High vacuum< 10^{-7} mbar
Power line	3-1/8" EIA coaxial
Inter-digital antenna	$N_{\parallel}$: 3~5, VSWR < 3

Specification of LHFW RF system components

- ✓ Collaboration with Korea Atomic Energy Research Institute and Kwangwoon university.
- ✓ The RF system is designed to utilize 10 kW UHF broadcasting klystron and LHFW antenna.
- ✓ The RF power of about 10 kW is transmitted to inter-digital antenna through coaxial transmission line, 10kV rating DC breaker, matching internal transformer in wide band and high vacuum compatible feed-thru.
- ✓ The power and voltage signals are digitized and monitored through peak-phase detector and ADC.



Research Status
LHFW RF system [2]

■ Klystron

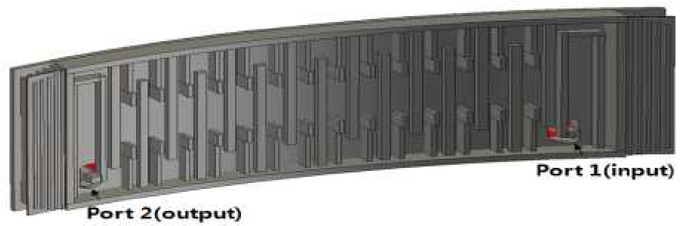
✓ The klystron is prepared by refurbishing an old UHF broadcasting system of Korea which has been hold by SNU..

Parameters	Values
Frequency	470~700 MHz
Output power	37.5 kW
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	145 V
Magnet current	32 A
Collector cooling	Water 2.0 gal/min
Body cooling	Water 1.5 gal/min
Magnet cooling	Water 2.0 gal/min
Gun cooling	Forced air 50 ft^3/min

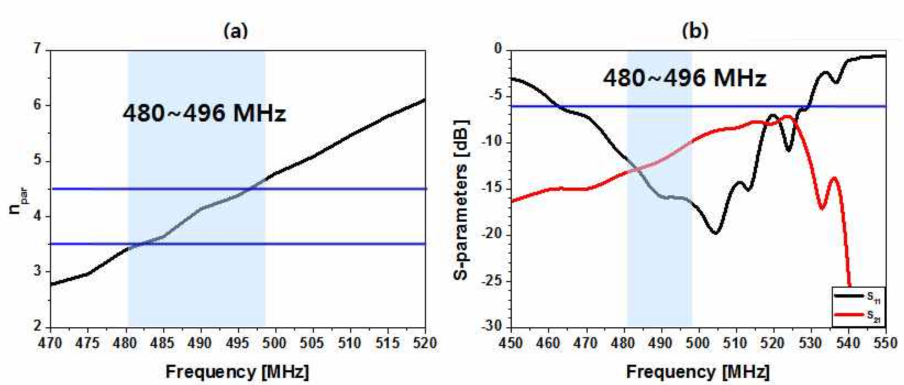
Specification of klystron

■ Antenna

✓ In 480~496 MHz frequency range, the parallel refractive index is between 3.5 and 4.5 and the S-parameters S11 and S12 are less than -10 dB.



Curved antenna for LHFW RF system on VEST



Parallel refractive index spectrum (a) and S-parameters (b) of curved inter-digital antenna designed.

Research Plan
Development of diagnostic tools

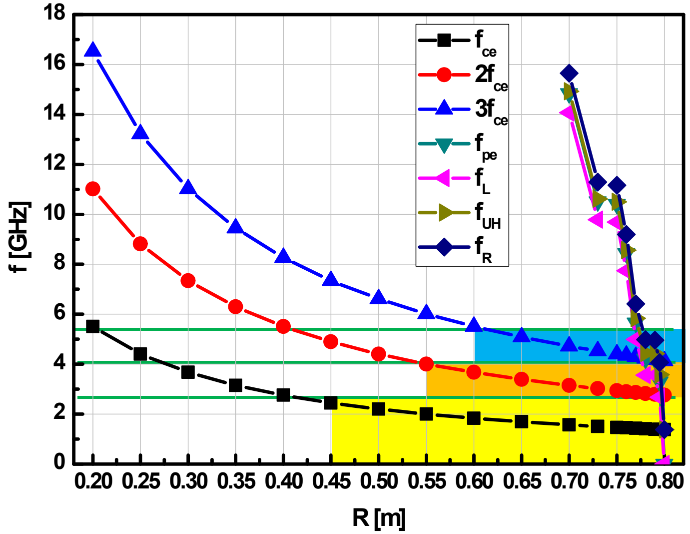
- The diagnostic tools such as magnetic probe and EBE (Electron Bernstein wave Emission) radiometer are being prepared to analyze the wave propagation and absorption characteristics via wave number and electron temperature.

- **Magnetic probe**
  - ✓ Direct measurement of fast wave and slow wave component utilizing the different wave polarization during the coupling experiment.
  - ✓ We will benchmark the magnetic probe developed in TST-2 group [4].

- **EBE radiometer**
  - ✓ Electron temperature diagnostics by easily achieved blackbody condition in overdense ST plasma [5].
  - ✓ Edge density profile measurement(triple probe), EBW mode conversion efficiency calculation(1D full wave code), and RF spectrometer system are being prepared and tested.

Research Plan
Development of diagnostic tools

- **Frequency ranges for VEST plasma**



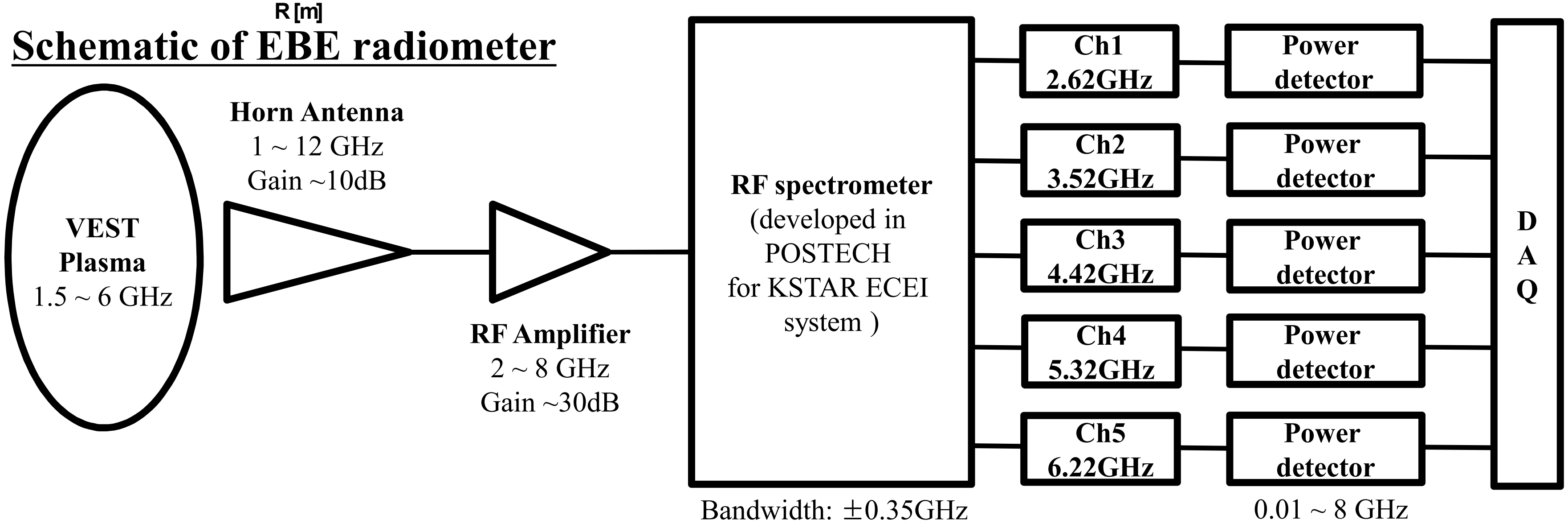
✓ Ohmic plasma, B_0~0.1T, I_p ~ 70kA(~15ms)

✓ Edge density is measured with triple probe.

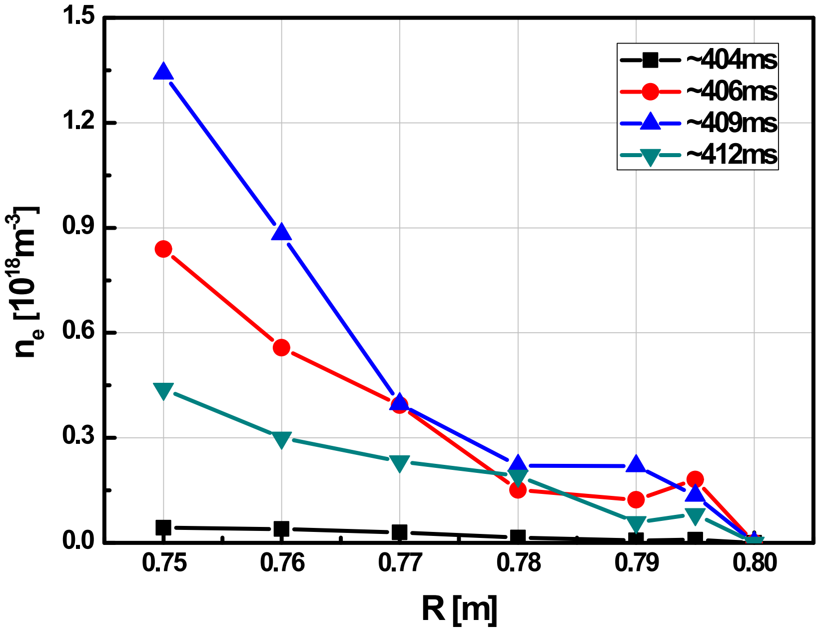
✓ Fundamental (R>0.45m), 2^{nd} (R>0.55m), 3^{rd} (R>0.6m) harmonic emission

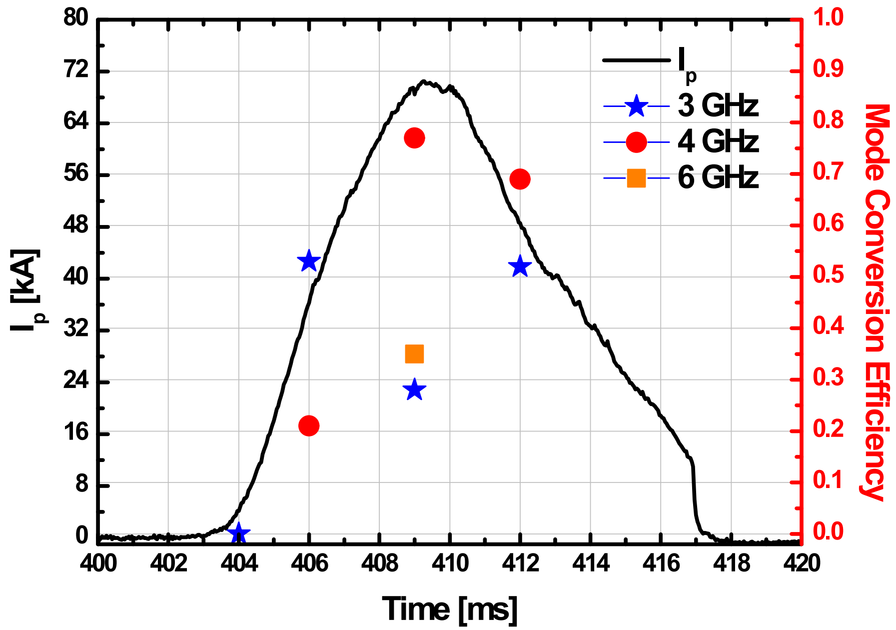
✓ Target frequency: **1.5GHz < f < 6GHz** (fully fundamental, partially 2^{nd} & 3^{rd} harmonic)

- **Schematic of EBE radiometer**

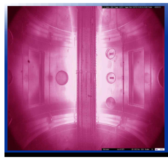


- **The mode conversion efficiency calculation**
  - ✓ B-X mode conversion (MC) process.
  - ✓ MC efficiency is calculated from a 1D full wave code.
  - ✓ Electron density profiles are measured with triple probe near the edge MC region.
  - ✓ Experimentally measured radiation signal will be divided by calculated MC efficiency to estimate the EBE intensity.





~404ms: I_p initiation **~406ms**: I_p ramp-up **~409ms**: I_p flat-top **~412ms**: I_p ramp-down



Research Plan
Coupling experiment

- **Accessibility condition of LHFW** $n_{launch} < n_e < n_{confluence}$

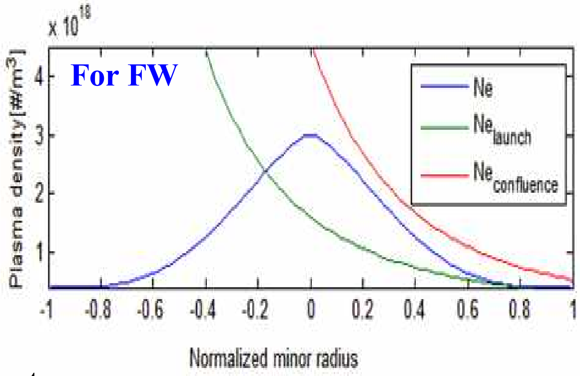
✓ The same confluence avoidance condition for LHFW and LHSW

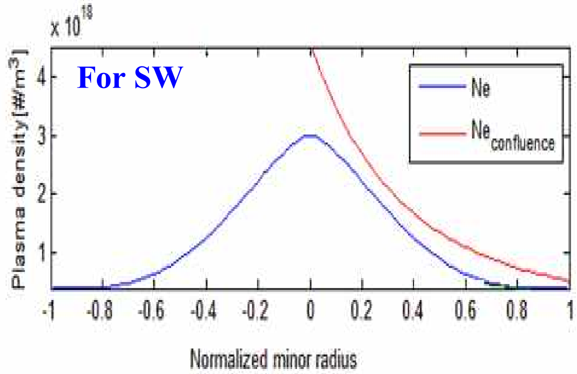
✓ The launching density is usually several hundred times more than that of LHSW $n_{launch} \sim 3 \times 10^{17} m^{-3} @ B_0 \sim 0.2T$

➢ **The coupling efficiency will be the key factor to apply the LHFW current drive scheme to reality.**

$$n_{launch} \cong \frac{m_e \epsilon_0}{e^2}(N_\parallel^2 - 1)\omega\omega_{ce}$$

$$n_{confluence} \cong \frac{1}{4}\frac{m_e \epsilon_0}{e^2} N_\parallel^2 \omega_{ce}^2$$





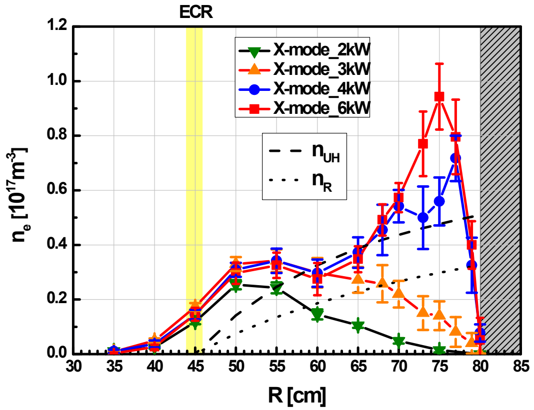
- **LHFW coupling experiment**

✓ In 2016, fast wave coupling will be investigated to increase the coupling efficiency through the developed coupling model and edge density measurement with control.

✓ We already know that EBW heating in VEST pre-ionization phase makes the plasma density profile localized near the edge UHR layer by collisional damping.

✓ **Initial edge plasma density for LHFW to propagate into plasmas could be generated by EBW.**

✓ Installation of RF systems and fast wave coupling experiments are planned in 2017.



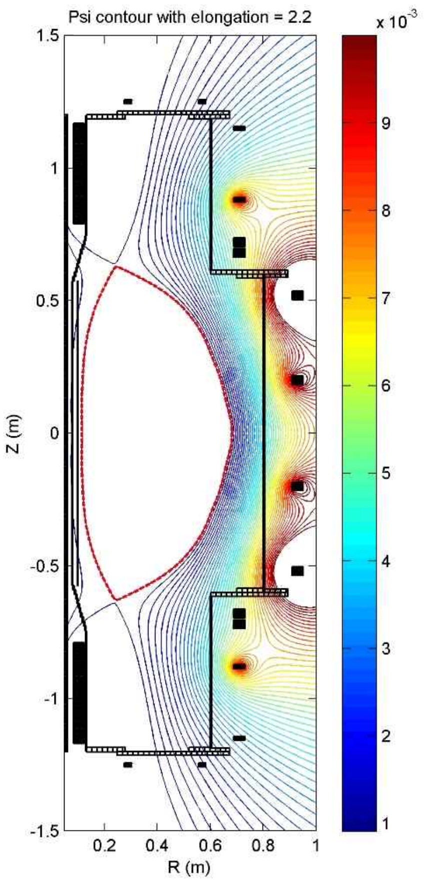
Pre-ionization plasma produced by EBW heating (B_0 ~0.1T)

Research Plan

Current drive experiment

- **Installation of RF system on VEST device and current drive experiment**

< VEST target plasmas>



✓ **Target: figure of merit ~ 0.1 A/m²/W(Proof of principle)**

(LHW slow wave : ~ 0.3 $A/m^2/W$, ICRF fast wave : ~0.04 $A/m^2/W$)

* lower efficiency than LHW slow wave, but more central current drive

✓ **Installation of RF system and coupling experiment (2017)**

- ✓ RF comb-line antenna installation and test on VEST
- ✓ Commissioning of RF system
- ✓ Coupling experiment at low RF power level

✓ **Heating and current drive experiment (2018)**

- ✓ Assist the plasma current ramp-up
- ✓ Attempt central and off-axis RF heating and current drive
- ✓ Target plasma: R_0(0.35 m), a(0.25 m), I_p(>80 kA), κ(>2.3), t_{pulse}(>20 ms)

  T_e(100 eV ~ 1 keV), n_e($1x10^{17}$~$5x10^{18}$ #/m^3)

Summary

- In view of wave propagation and absorption in high density and high temperature plasmas, the fast wave branch of LH waves could be a good candidate for the central electron heating and current drive.
- To investigate the feasibility of LHFW current drive, analytic study and ray tracing simulations have been carried out on VEST (Versatile Experiment Spherical Torus).
- The RF power systems with 500MHz, 10kW klystron and $n_{||}$(~4) variable comb-line antenna are being developed in collaboration with Korea Atomic Energy Research Institute and Kwangwoon university.
- In 2016, fast wave coupling will be investigated to increase the coupling efficiency through the developed coupling model and edge density measurement. Installation of RF systems and fast wave coupling experiments are planned in 2017 and the LHFW current drive experiments will be attempted in 2018.

Reference

[1] Marko Brambilla, “Kinetic Theory of Plasma waves; Homogeneous Plasmas”, Oxford university press, 1998.

[2] S.H. Kim, S.H. Jeong, H.W. Lee, B.J. Lee, J.G. Jo, H.Y. Lee, and Y.S. Hwang, "Heating and current drive by fast wave in lower hybrid range of frequency on Versatile Experiment Spherical Torus", submitted to ISFNT-12 held in Jeju of Korea 14th~18th. Sep. (2015).

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[5] P. C. Efthimion et al., “New electron cyclotron emission diagnostic for measurement of temperature based upon the electron Bernstein wave”, Review of Scientific Instruments 70, 1018 (1999).