Improved RF Actuator Schemes for the Lower Hybrid and the Ion Cyclotron Range of Frequencies in Reactor-Relevant Plasmas


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Application of RF power in a fusion reactor is challenging

- Survivability is a major issue because of the harsh environment → high heat fluxes and plasma-wall-interactions.
- High density reduces the current drive (CD) efficiency of lower hybrid current drive (LHCD) and can lead to parasitic scrape off layer (SOL) losses.
- High pedestal temperatures limit the penetration of LH waves.
- Ion cyclotron range of frequency (ICRF) power can generate impurities through RF sheath formation.
- Antennas mounted in radial ports take up valuable tritium breeding real estate.
- High field side (HFS) launch of ICRF and LHRF power in double null configurations represents an integrated solution that both mitigates PMI / coupling problems and improves core wave physics issues.
I. Properties of the high field side scrape off layer that make it ideal for RF launchers
Quiescent scrape off layer on HFS is ideal location for RF launchers

- Transport in tokamak sends heat and particles to low field side SOL:
  - Forces the RF launcher to be placed farther away from the plasma → reduces wave coupling and increases parasitic absorption.

- HFS placement of launcher allows small antenna – plasma gap with good coupling.

- Quiescent SOL on HFS:
  - Leads to extended launcher lifetime.
  - Reduces likelihood of wave scattering.

High field side plasma strongly screens impurities mitigating adverse effects of PMI on core plasma

- **Strong impurity screening measured in Alcator C-Mod for HFS SOL [1, 2]:**
  - Strong poloidal asymmetry observed in the penetration factor for nitrogen and methane.

- **Mitigates effects of impurity generation from plasma-wall interactions due to RF sheaths (for example).**

Steep density / temperature gradients in HFS scrape off layer favor placement of RF launchers closer to the plasma

• In near double-null topologies, HFS density and temperature profiles are extremely steep

• Encourages placement of RF launcher closer to plasma

• Because of steep profiles, the local density at HFS launch structures can be precisely controlled by adjusting the upper/lower X-point flux balance and/or distance from the last-closed flux surface to launcher

Power exhaust as well as inboard blanket space allocation in a reactor favor HFS placement of RF actuators.

ARC rendering showing path of LH waveguides through blanket on HFS [1]

II. Core physics implications of HFS placement of LHRF actuators for reactor design

Fusion nuclear science facility
FDF

Compact reactor concept
ARC


HFS antenna location improves LHCD performance by allowing use of a lower parallel refractive index $n_{||} = k_{||}c/\omega$

- LH wave accessibility [1] and the condition for electron Landau damping of the LH wave [2] ($v_{||}/v_{te} \approx 2.5-3$) determine an “access window” for wave penetration and absorption:

$$n_{||acc} \leq n_{||} \leq n_{||ELD},$$

$$n_{||acc} > \sqrt{1 - \frac{\omega_{pi}^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2}} + \frac{\omega_{pe}}{|\omega_{ce}|} \approx 1 + \frac{\omega_{pe}}{|\omega_{ce}|}, \quad n_{||ELD} \leq \sqrt{30/T_e(keV)}$$

- Improving wave accessibility by lowering $n_{||acc}$ allows access to a higher $T_e$ with faster phase velocity LH waves:
  - Can be done by raising $B_0$ through HFS launch.

Higher phase velocity LH waves (lower $n_{\parallel}$) improves current drive efficiency through several effects

- Lower $n_{\parallel}$ improves current drive efficiency because wave momentum is transferred to faster, less collisional electrons [1]:

$$\eta_{CD} \equiv \frac{n_e (10^{20} m^{-3}) I_{LH} (A) R_0 (m)}{P_{LH} (W)} \propto \frac{1}{n_{\parallel}^2}$$

- As wave penetrates to higher $T_e$, CD efficiency increases due to momentum conserving corrections in the background collision operator characterized by $\Theta = T_e (\text{kev}) / (m_e c^2)$ [2].

- Effect of particle trapping is reduced on high field side

HFS launch in a fusion nuclear science facility (FDF) [1] enables damping well inside pedestal vs. no penetration with LFS launch

- Higher $|B|$ improves wave accessibility at high density

- High temperature and density pedestals limit low field side LHCD in FDF

- Window opens for LHCD if waves are launched from the high field side

GENRAY / CQL3D simulations for FDF plasma [1] with a HFS LH launcher show dramatically improved wave penetration for off-axis CD needed for AT control.

CD by LH slow waves and fast waves ("Helicons") are the only efficient off-axis CD options.

\[ f_0 = 5 \text{ GHz} \]
\[ n_{//} = 1.9 \]
\[ (90\% \text{ directivity}) \]
\[ P_{\text{LH}} = 10 \text{ MW} \]

High magnetic field combined with HFS launch yields excellent CD access in Compact DT fusion device ARC

HFS concept forms the basis for the LHCD system in ARC [1]:

\[ n_{//} = 1.5 - 1.6, f_0 = 8 \text{ GHz (bi-directional spectrum).} \]

\[ B_0 = 9.25 \text{ T}, \quad I_p = 8 \text{ MA} \]

\[ a = 1.1 \text{ m}, \quad R_0 = 3.3 \text{ m} \]

\[ n_e(0) = 1.75 \times 10^{20} \text{ m}^{-3} \]

\[ T_e(0) \sim T_i(0) = 26 \text{ keV} \]

ARC Design combines HFS placement of LH actuator with optimized poloidal launch location

Optimization of poloidal launch position makes it possible to keep $n_\parallel \approx \text{constant}$ along the ray path:

$$n_\parallel = \frac{k_\parallel c}{\omega} = \left( \frac{m}{r} \frac{B_\theta}{R B} + \frac{n_\phi}{R} \frac{B_\phi}{B} \right) \frac{c}{\omega}$$

Balance the effects of toroidicity and poloidal field in $k_\parallel$ [1, 2]

Optimized CD efficiency leads to substantial control of AT current profile below no-wall $\beta_N$ limit and at densities which give significant bootstrap fraction.

$I_p = 7.75 \text{ MA} \quad I_{BS} = 4.88 \text{ MA} \quad f_{BS} = 0.63 \quad \beta_N = 2.59 (\% \text{-m-T/MA})$

$P_{LH} = 25 \text{ MW} \quad I_{LH} = 1.77 \text{ MA} \quad \eta_{CD-LH} = 0.31 (10^{20} \text{ A/W/m}^2)$

$P_{IC} = 13.6 \text{ MW} \quad I_{IC} = 1.1 \text{ MA}$
III. The proposed Advanced Divertor and RF tokamak eXperiment (ADX) [1] is designed to provide integrated solutions to the heat and particle flux problem. As part of this mission ADX will also address RF issues through HFS implementation of RF actuators.

- **Machine & HFS RF system parameters:**
  - \( B_0 = 5.6 \) T
  - \( I_p = 1.0 \) MA
  - \( R_0 = 0.725 \) m
  - \( a = 0.205 \) m
  - \( f_0 = 90\text{-}120 \) MHz (ICRF) 10 MW source
  - \( f_0 = 4.6 \) GHz (LHRF) 4 MW source

HFS + off mid-plane launch in ADX demonstrates feasibility of generating LH current density profiles that are desirable for AT operation

- **With HFS launch the CD profile is broad and extends from** $0.2 < r/a < 0.6$
- **LFS launch results in profile that is narrow and peaked too far off-axis**

Simulation parameters:

- $B_0 = 5.6$ T
- $I_p = 1.0$ MA
- $n_e(0) = 1.8 \times 10^{20}$ m$^{-3}$
- $T_e(0) = 5.5$ keV
- $n_// = 1.6$ for HFS launch
- $n_// = 2.5$ for LHS launch
- $P_{LH} = 4$ MW

ICRF fast waves launched from HFS will be strongly damped through a combination of mode transformation to the ion Bernstein wave (IBW) and ion cyclotron wave (ICW) and hydrogen cyclotron damping.

ADX will employ a near 100% single pass ICRF absorption scheme: This facilitates assessment of HFS ICRF antenna operation under conditions where interaction of the ICRF power with the SOL associated with multiple passes of the ICRF wavefront is eliminated.

For HFS launch the FW branch connects directly to IBW / ICW.

Hydrogen (H) “minority” in a Deuterium (D) majority plasma.

ICRF fast waves launched from HFS will be strongly damped through a combination of mode transformation to the ion Bernstein wave (IBW) and ion cyclotron wave (ICW) and hydrogen cyclotron damping.
Wave fields show very little ICRF power reaches the LFS plasma when the power is coupled from the HFS → near 100% single pass absorption.

- For $n_H / n_e = 0.15$, $B_0 = 5.6$ T, and $f_0 = 80$ MHz, the incident fast wave power is absorbed on the first pass via IBW / ICW mode conversion (~40%) and hydrogen cyclotron damping (~60%).
IV. Summary and Conclusions

• High field side placement of LHRF and ICRF launchers in double null configurations represents an integrated edge to core solution for the use of LHRF and ICRF actuators.

• Reduced particle and heat fluxes provide launcher protection with minimal PMI:
  – Quiescent SOL with lower densities allow placement of launchers closer to plasmas which may suppress parasitic losses.
  – Effective impurity screening mitigates deleterious effects of PMI on core plasma.

• HFS LHCD in a prototypical fusion nuclear science facility provides wave penetration needed for current profile control in AT operation.

• Synergy of HFS LHCD and high B-field provides very attractive advanced reactor design:
  – Much better accessibility at HFS combined with strong single pass absorption at launched “minimum” $n_{//}$ results in controllable and highly efficient CD at mid-radius.

• Proposed Advanced Divertor Test Facility (ADX) will test the engineering and physics feasibility of HFS placement of LHRF and ICRF actuators.
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