Path towards RF Sustainment of Steady State Fusion Reactor Plasmas

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High field side launch of lower hybrid current drive offers an integrated solution to off axis current drive scalable to reactor environment.
Efficient, robust, steady state current drive is required to make the tokamak a viable concept for fusion electricity.

- Power required for current sustainment is a major constraint upon plant efficiency.

RF actuators have been long recognized as essential tools for steady state tokamak.

- Experiments with full RF current driven where done 1980s to demonstrate potential of a steady state tokamak.
- Efficiency limits and reactor studies indicated tokamak based on this physics was uneconomical.

Seek external off axis-current drive that augments bootstrap current.

- Maximizing bootstrap current minimizes the off axis current drive demand.
- Bootstrap fraction scales with $\beta_N$. 
Steady State Tokamak Reactor Requires Efficient Off-Axis Current Drive

From a variety of reactor studies, optimum current profile is peaked off axis.

- Aids in achieving desired plasma stability and confinement.
- Ideal-wall $\beta_N$ limit rises as current profile is broadened
- External off-axis current drive supplements bootstrap current profile $0.6<\rho<0.95$.

Efficient off-axis current drive compatible with high temperature plasmas and scalable to reactors is yet to be demonstrated.

Adapted from Kessel et al., FST 67, 2015.
Utilizing optimized poloidal placement on HFS, LHCD coupler is used to drive off-axis current.

As for all off-axis current actuators, a number of physics and technological risks remain:

• Current drive efficiency,

• Driven current profile (location and profile width),

• Coupling,

• RF associated impurity contamination.

In a reactor environment, PMI issues associated with coupling structures are similar to the first wall.

• Identified as a potential show-stopper

• RF launchers near the plasma edge lack credible solutions.

• Erosion <1 mm/year and minimize impact on TBR
Tokamak power exhaust strongly favors HFS launch. Injecting power from HFS removes the launcher from high heat flux region.

- Conventional approach has launchers facing into high heat exhaust and turbulent plasma.

In reactor, ~0.5 m of actively cooled shield and blanket region.

- Innovative RF launchers can be accommodated.
HFS Launch Greatly Improves RF Core Physics

HFS launch increases local B:

Wave accessibility: $n_{||acc} \sim \sqrt{n_e / B}$

Wave penetration: $n_{||abs} \sim \sqrt{30 / T_e}$

Current drive efficiency $\propto 1 / n_{||}^2$

High temperature and density pedestals limit LFS LHCD penetration, FDF [1].

Window opens for LHCD if waves are launched from HF.

HFS LH Launch Shows Dramatically Improved Wave Penetration and Driven Current Profile


- \( f_0 = 5 \text{ GHz} \quad n_{\parallel} = 1.9 \) (90% directivity) \( P_{\text{LH}} = 10 \text{ MW} \).

With HFS launch, wave penetration and current drive efficiency (~40% increase) are improved.

Broad current drive profile is obtained for HFS launch as needed for MHD stability.

HFS \( \eta_{\text{CD20}} = 0.34 \) (A/W/m²)

LHS \( \eta_{\text{CD20}} = 0.24 \) (A/W/m²)

Demonstrate the HFS SOL is ideal for RF antennas

Transport in tokamak sends heat and particles to low field side scrape off layer (SOL)

Expect coupling to remain quiescent.

- Expect reduced scattering from turbulent density perturbations.
- ELMs are attenuated in single null and do not reach HFS in double null.

N. Smick et al, Nucl. Fusion 53 (2013)
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Steep HFS SOL Density Profile Allows for Coupling Optimization
  • Lower density measured in HFS Double Null (DN) plasmas:
    • Potential to optimize coupling through magnetic balance.
  • Density control at launcher by adjusting inner gap
    • Control of inner gap more precise than outer gap

N. Smick, B. LaBombard, C.S. Pitcher, Journal of Nuclear Materials, 2005
Demonstrate the HFS SOL is ideal for RF antennas

Magnetic flux balance is found to control plasma flows (specifically parallel flows) in the HFS SOL, which can be used to further enhance impurity screening.

- Measurements show that impurity penetration is a factor of \(~3\times\) smaller on HFS compared to LFS at DN, despite the extremely narrow SOL profiles.
- Likely due to low turbulent transport on the HFS.

HFS SOL control tools are:

- Inner Gap and Magnetic balance to mitigate
  - Density at the launcher
  - PMI on launch structures
- Magnetic Balance
  - SOL flows and impurity screening

B. LaBombard et al. Nucl. Fus. 57 (2017)
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Coupler is well protected from energetic particles.

- Few unconfined fast particles on HFS
- Energetic electron orbits shift to LFS
- Heat load is dominated by thermal plasma

Lost \( \alpha \) orbit, born at 3.5 MeV, \( r/a=0.6 \)
Primary Risk is Lack of Experimental Demonstration

Great advantage to validate HFS LHCD wave physics and demonstrate that common challenges to RF are largely mitigated by HFS RF launch.

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DIII-D AT Discharges offer Opportunity to Validate HFS LHCD

Demonstrate efficient off-axis current drive compatible with high performance plasmas that is scalable to reactors.

• Provide q profile control without fueling or significant torque with modest power.

Retire risks associated with HFS wave propagation and SOL benefits for RF actuators.

• Existing diagnostics would provide experimental data to validate RF simulation tools.
• Assess SOL-RF actuator interaction.

For DIII-D $q_{\text{min}} > 2$, seek to broad current profile consistent with high bootstrap fraction

Adapted from C. Holcomb PAC 2017.
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For DIII-D $q_{\text{min}}>2$, seek to broad current profile consistent with high bootstrap fraction.

- Seek external current drive source peaked $0.6<\rho<0.8$.
- Current density $\sim 40 \text{ A/cm}^2$ is required for current profile control.

Adapted from C. Holcomb PAC 2017.
LHCD from LFS is unattractive due to coupling and penetration issues, as shown for DIII-D discharge 147634 ($q_{\text{min}} \sim 1.5, 1.66 \, \text{T}$).
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HFS LHCD has excellent wave penetration and localized absorption.

- Single pass absorption with driven current peaked $\rho \sim 0.7$.
- 150 kA/MW coupled and approaching 40 A/cm² required for current profile control.
- Simulations indicate raising $B_T$ or lower $n_e$ will allow current profile control with 1 MW coupled.

HFS LHCD augment DIII-D current drive actuators:

- Off-axis neutral beam: $\sim 18$ kA/MW, $\rho \sim 0.5$
- Vertical launch ECCD: $\sim 28$ kA/MW, $\rho \sim 0.6$.
- Helicon CD: $\sim 65$ kA/MW, $\rho \sim 0.5$.
- HFS LHCD: $\sim 150$-200 kA/MW, $\rho \sim 0.7$
Utilize coupler technology tested in LFS experiments.

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Demonstrate that AT based tokamak discharges can be operated in steady state.

- Assess HFS LHCD off axis current drive efficiency.
- Is HFS LHCD scalable to FNSF-AT like reactor?

Validate HFS wave core propagation and wave coupling.

- Validate wave propagation and current drive physics models?
- Is the coupling improved due to quiescent edge conditions and magnetic balance control of edge density profile?
- Is wave propagation and coupling scalable to FNSF-AT like reactor concept?

Assess HFS SOL benefits for RF actuators.

- Are coupling structures near the HFS SOL compatible with high performance plasmas?
Successful DIII-D experiment would bring HFS LHCD to TRL 4-5 level.
  • Technical readiness level for a DIII-D experiment is high.

Active cooling challenge and material lifetime would require additional experiments.
  • WEST is a potential candidate with higher field and long pulses.

Source efficiency and efficient antennas should be improved over present level.
  • Present ~5 GHz klystron efficiency is ~45%.
  • Build upon recent work by the High Efficiency International Klystron Activity (HEIKA).
  • Klystron efficiency has been simulated to reach 90% with successful tests up ~75% independent of beam perveance.
  • Coupler directivity is ~70% but could improve with refinement on physics requirements allowing for optimized designs.

RF and material testing programs are required to investigate manufacturing couplers, waveguides, and antennas from reactor relevant materials.
Potential for U.S. Leadership in RF Sustained, Steady-State AT Operation

Opportunity to demonstrate efficient off-axis current drive compatible with high performance plasmas and scalable to reactors.

- Potential for the broadest possible current profile.
- Prospective tool for current profile control with 150-200 kA/MW 0.6<r<0.8

HFS LHCD is virgin physics area where clear leadership can be established.

Retire physics risks associated with HFS LHCD.

Demonstrate that common challenges for LHCD (coupling, impurities, and thermal load) are largely mitigated by locating the LHCD coupler on HFS.