Novel Reactor Relevant RF Actuator Schemes for the Lower Hybrid and the Ion Cyclotron Range of Frequencies

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26th IAEA Fusion Energy Conference
Kyoto, Japan
October 24-29, 2016

PSFC Plasma Science and Fusion Center Massachusetts Institute of Technology

PPPL PRINCETON PLASMA PHYSICS LABORATORY

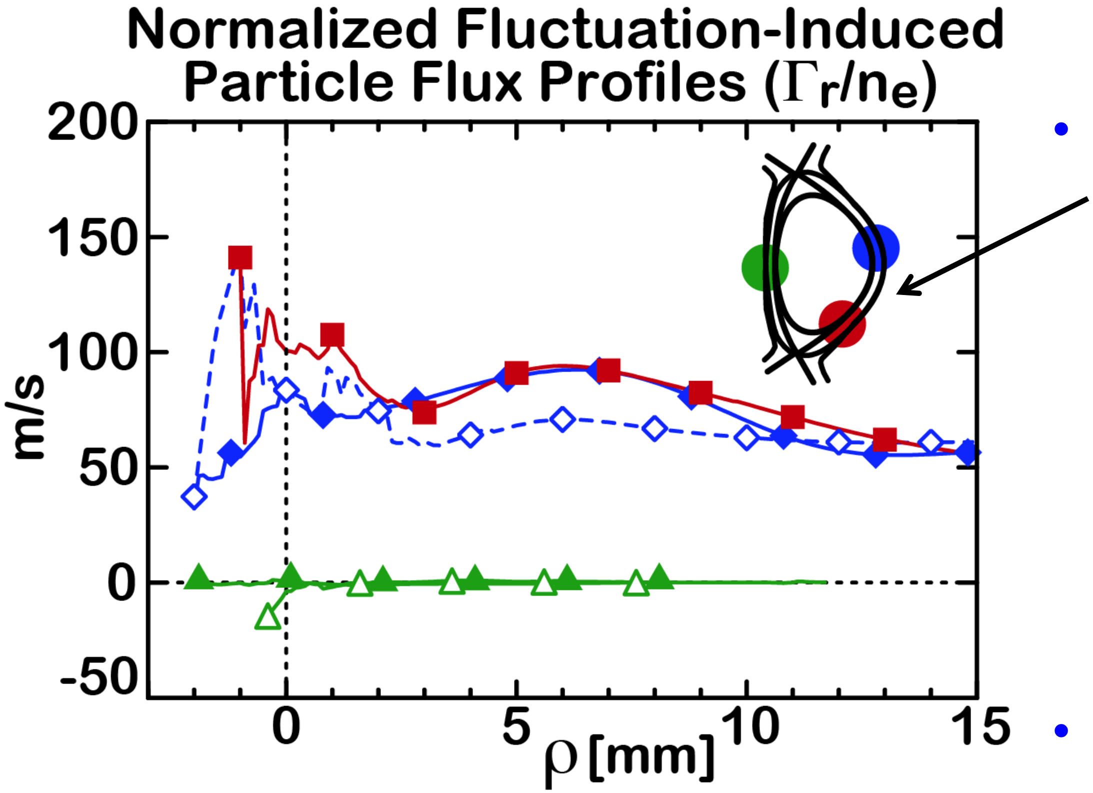
Alcator C-Mod

Application of RF power in a fusion reactor is challenging

- Survivability is a major issue because of the harsh environment $\rightarrow$ 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



N. Smick et al, Nuc. Fusion (2014).

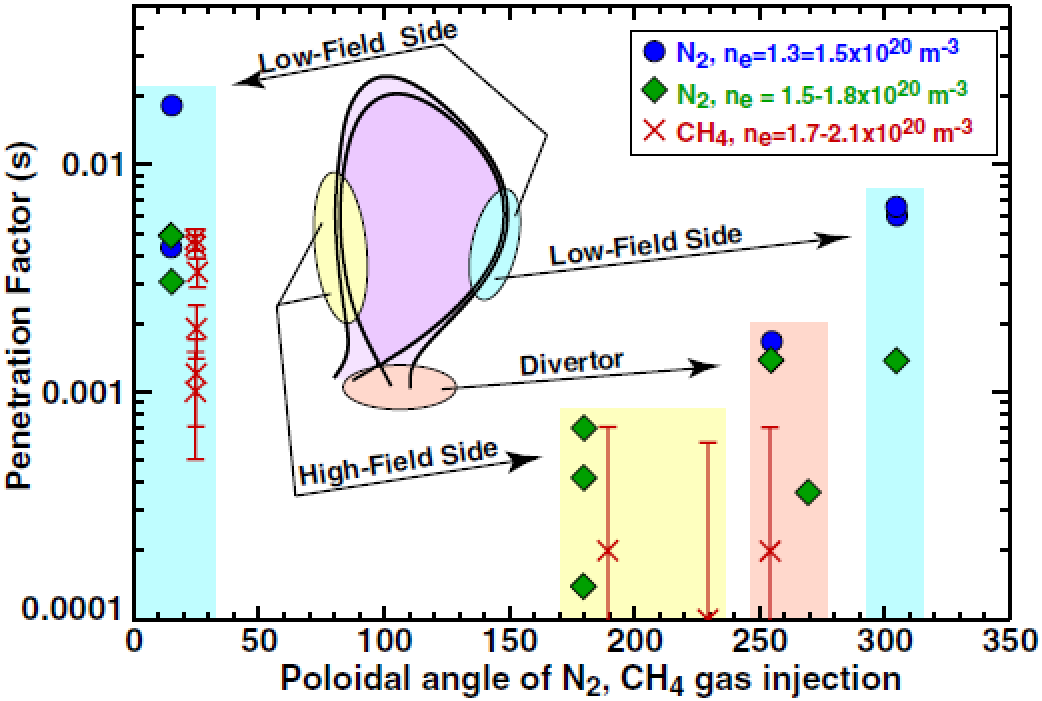
- Transport in tokamak sends heat and particles to low field side SOL:
  - Forces the RF launcher to be placed farther away from the plasma → reduces wave coupling and increases parasitic absorption.
- HFS placement of launcher allows small antenna – plasma gap with good coupling.

- 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).**



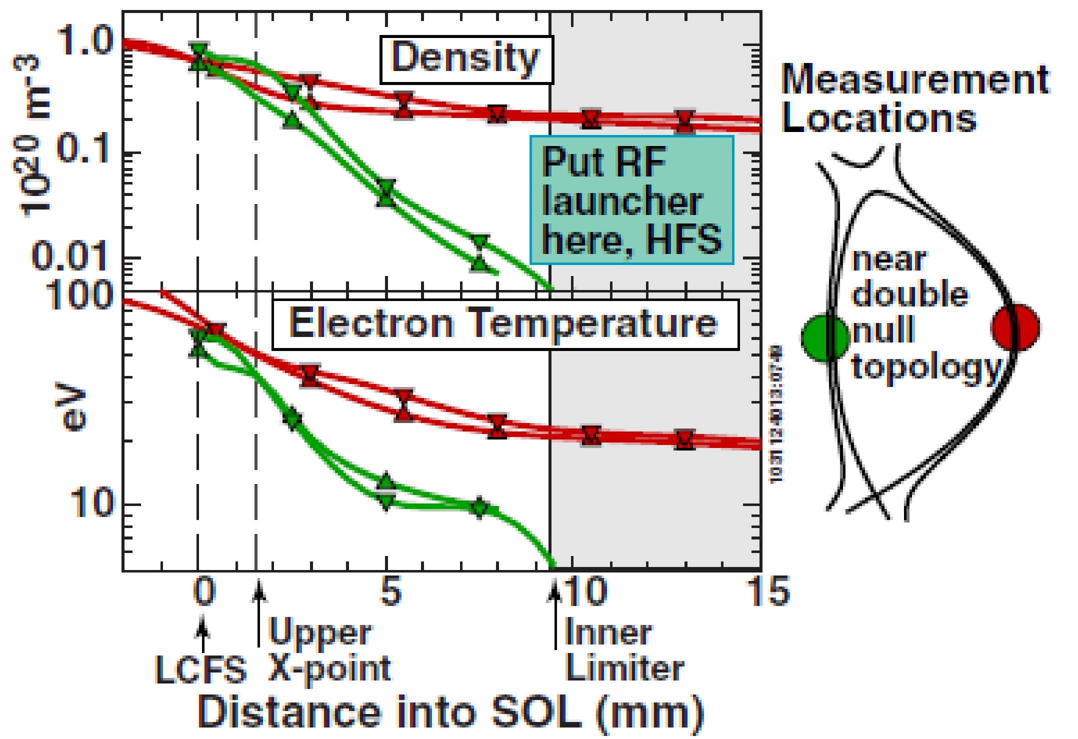
[1] G. McCracken, *et al*, Phys. Plasmas **4** (1997) 1681.
[2] B. LaBombard et al, Nuclear Fusion **55** (2015) 053020.
[3] B. LaBombard *et al*, this conference, EX/P3-6.

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**

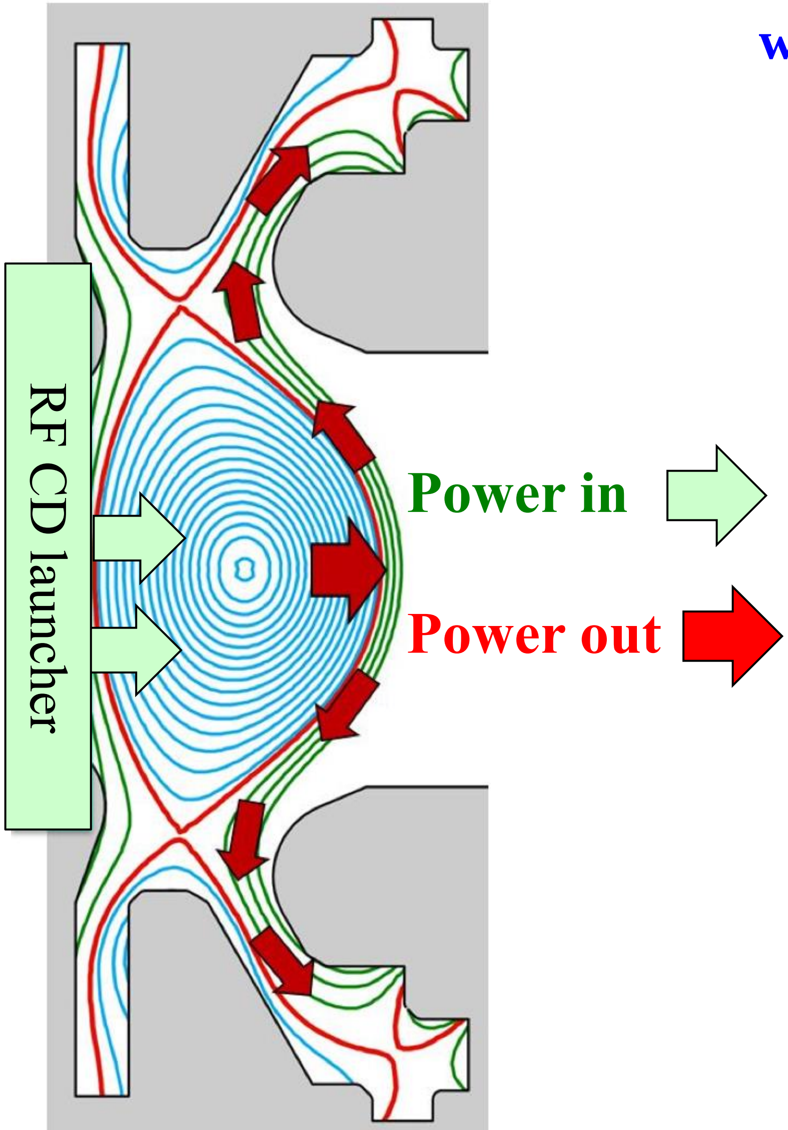
- Because of steep profiles, the local density at HFS launch structures can be precisely controlled by adjusting the upper/lower X-point flux balance and/or distance from the last-closed flux surface to launcher



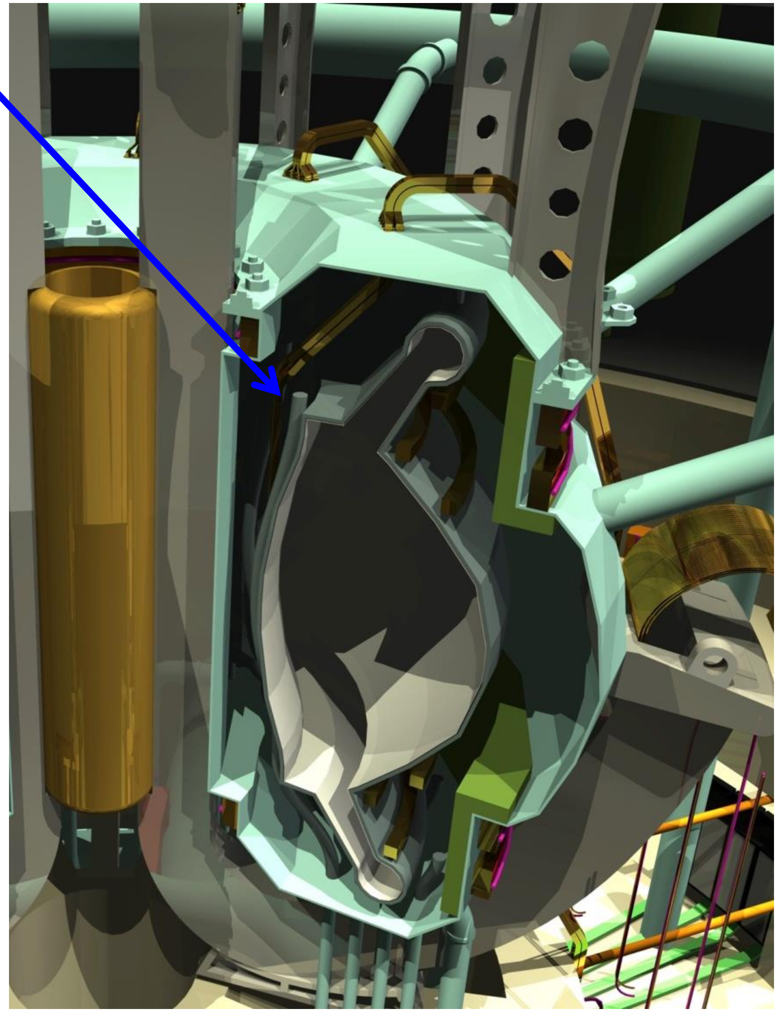
[1] S. G. Baek *et al*, Nuclear Fusion **55** (2015) 043009.

[2] B. LaBombard et al, Nuclear Fusion **55** (2015) 053020.

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



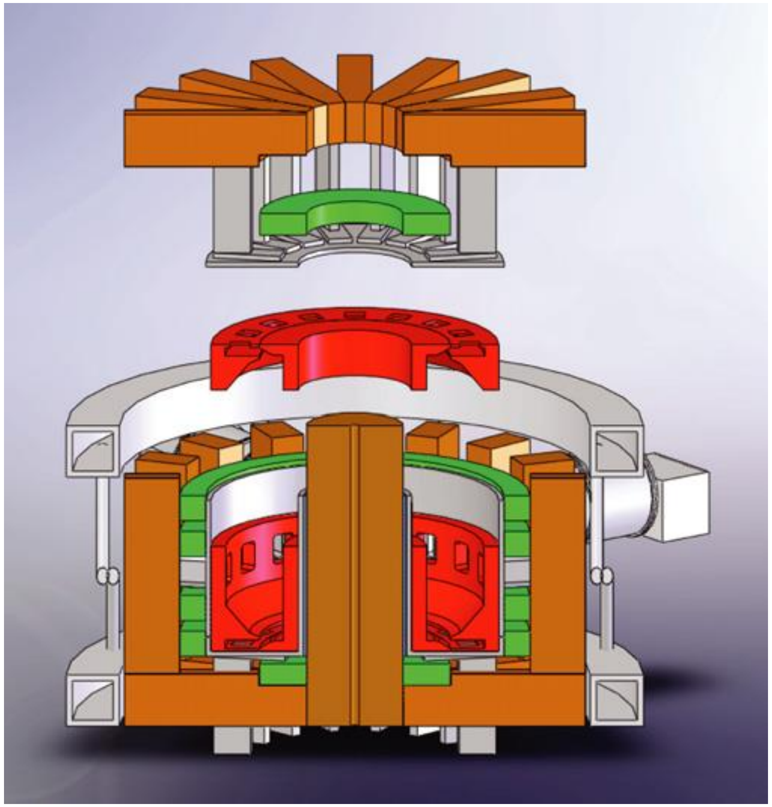
ARC rendering showing path of LH waveguides through blanket on HFS [1]



[1] Courtesy of K. Filar.

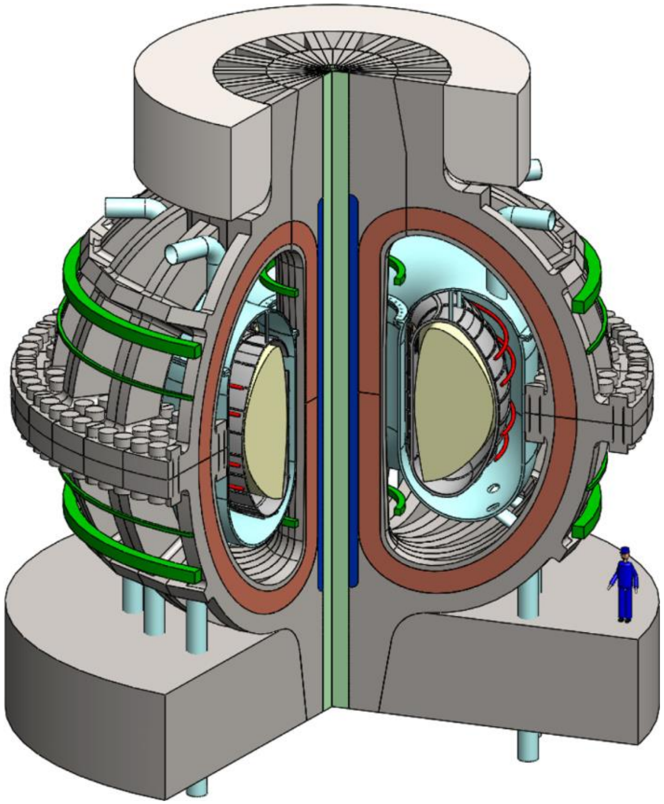
II. Core physics implications of HFS placement of LHRF actuators for reactor design

Fusion nuclear science facility FDF



V.S. Chan *et al*, Nucl. Fusion 51 083019 (2011).

Compact reactor concept ARC



B. N. Sorbom *et al*, Fusion Eng. and Design 100 378 (2015).

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:**

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

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

- **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.***

[1] M. Brambilla Nuc. Fusion **19** (1979) 1357.
[2] M. Brambilla Physics of Plasma Close to Thermonuclear Conditions (Brussels, 1980) 291.

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

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

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

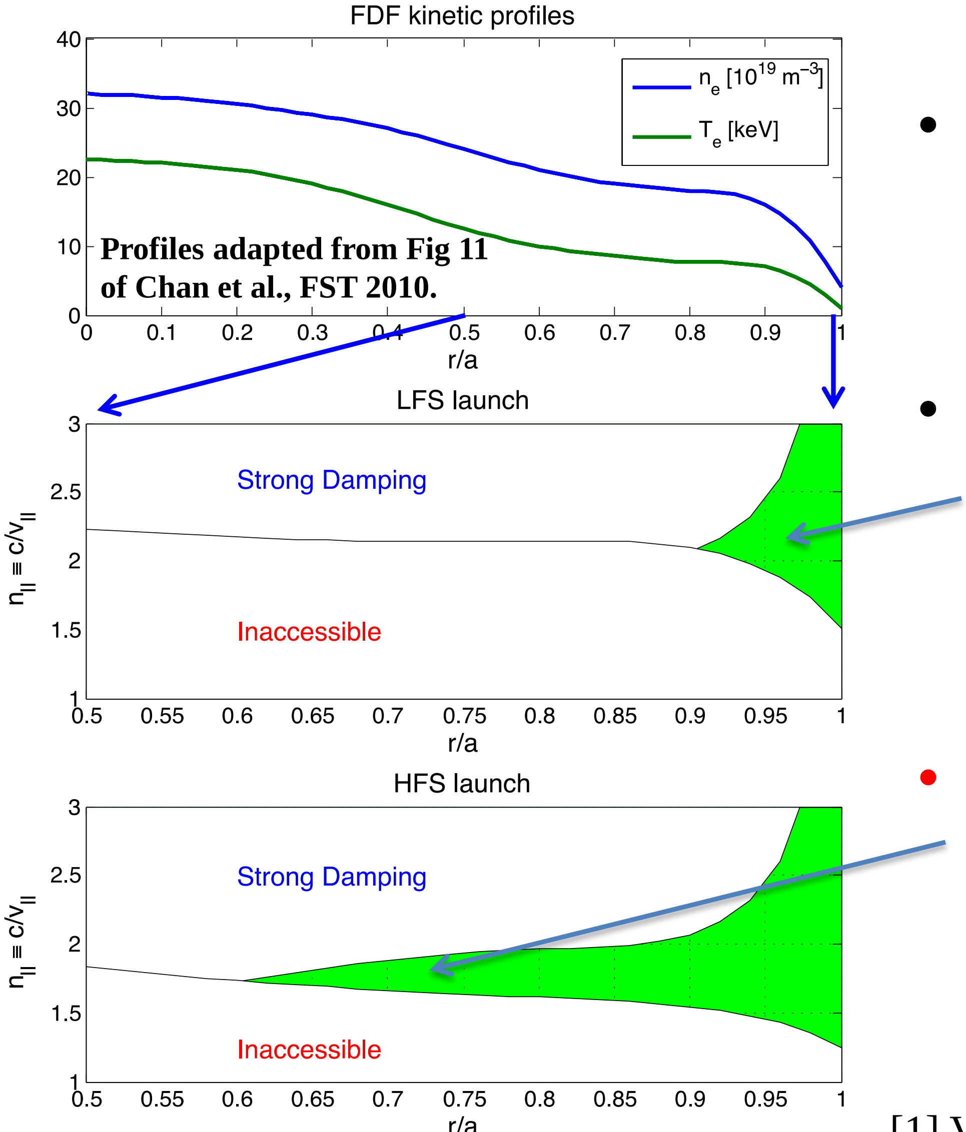
- **As wave penetrates to higher T_e, CD efficiency increases due to momentum conserving corrections in the background collision operator characterized by $\Theta = T_e(\text{kev}) / (m_e c^2)$ [2].**

- **Effect of particle trapping is reduced on high field side**

[1] N. J. Fisch, Phys. Rev. Lett. **41** (1978) 873.

[2] Karney & Fisch, Phys. Fluids **28** (2985) 116 (1985).

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

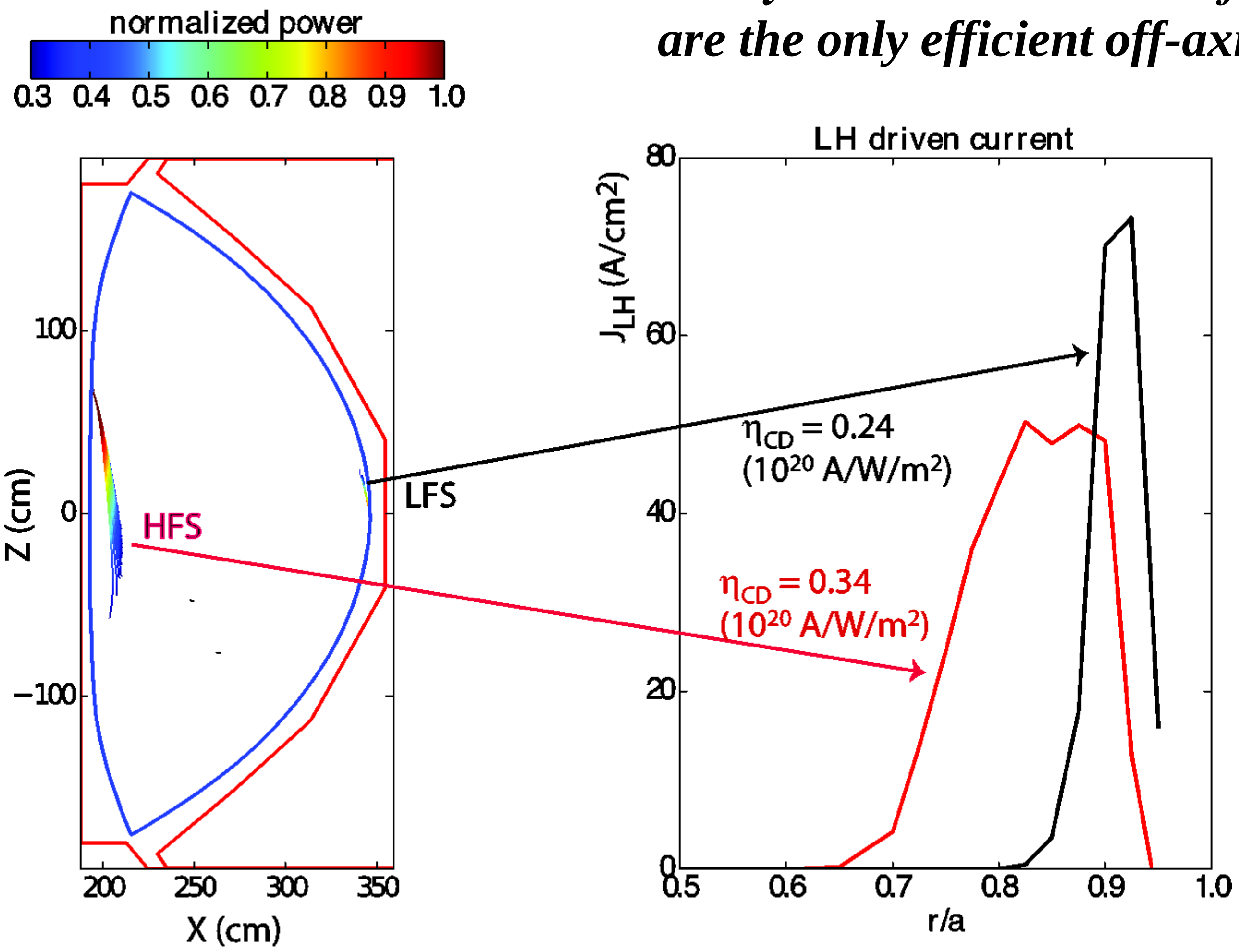


- Higher |B| improves wave accessibility at high density
- High temperature and density pedestals limit low field side LHCD in FDF
- Window opens for LHCD if waves are launched from the high field side

[1] V.S. Chan *et al*, Nucl. Fusion **51** 083019 (2011).

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 GHz

$n_{//}$ = 1.9

(90% directivity)

P_{LH} = 10 MW

[1] V.S. Chan *et al*, Nucl. Fusion **51** (2011) 083019.

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]:

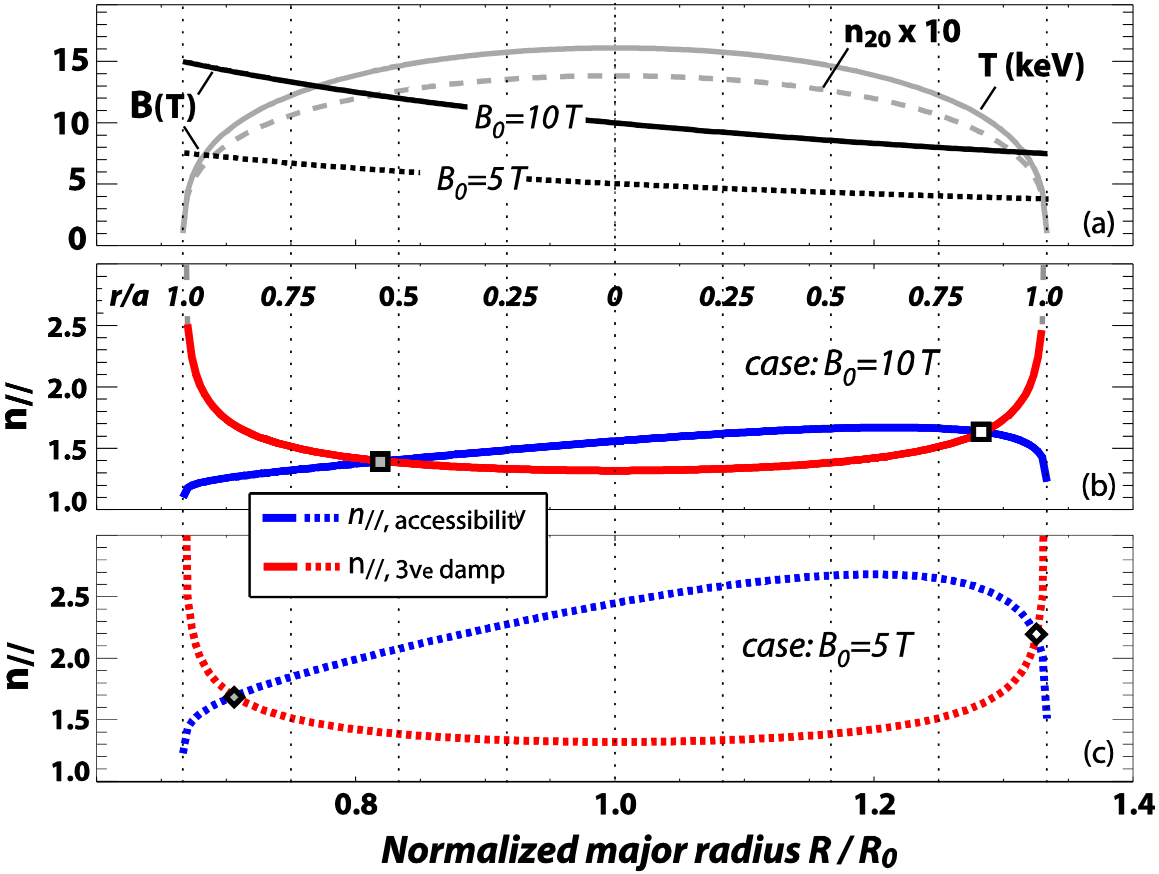
$n_{//}$ = 1.5 - 1.6, f_0 = 8 GHz (bi-directional spectrum).

B_0 = 9.25 T, I_p = 8 MA

a = 1.1m R_0 = 3.3 m

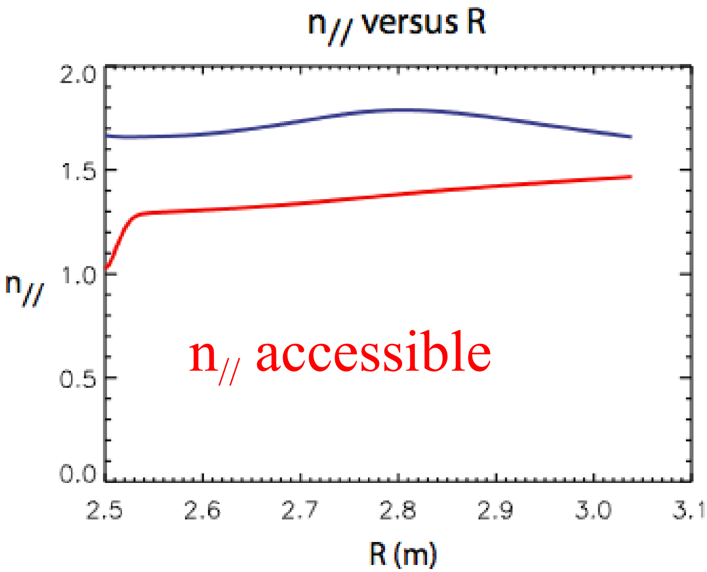
$n_e(0) = 1.75 \times 10^{20}$ m^{-3}

$T_e(0) \sim T_i(0)$ = 26 keV



[1] B. N. Sorbom *et al*, Fusion Eng. and Design **100** 378 (2015).

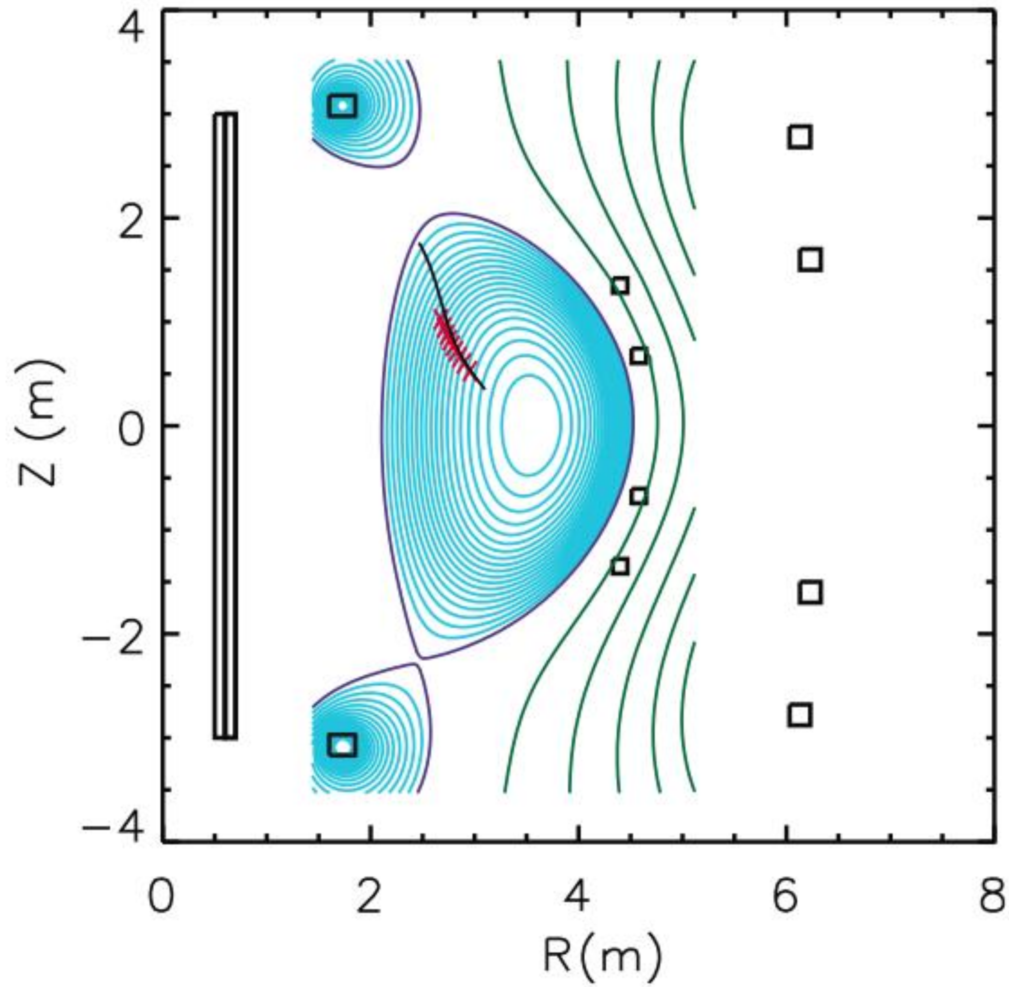
ARC Design combines HFS placement of LH actuator with optimized poloidal launch location



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

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

Balance the effects of toroidicity and poloidal field in $k_{//}$ [1, 2]



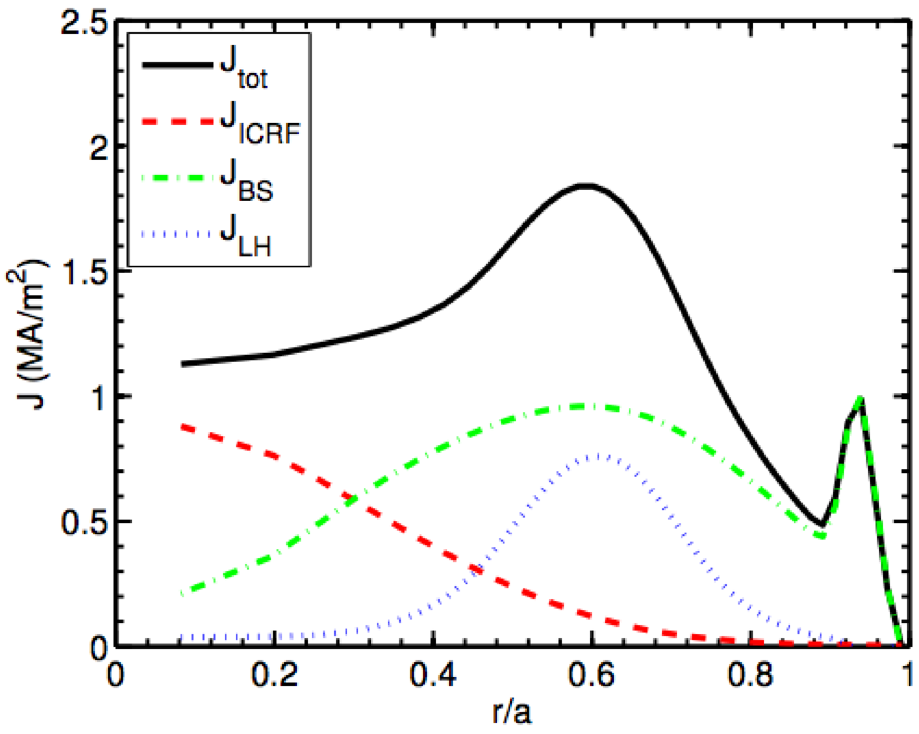
[1] P. T. Bonoli Phys. Fluids **25** (1982) 359.
[2] Y. Podpaly *et al*, FED **87** (2012) 215.

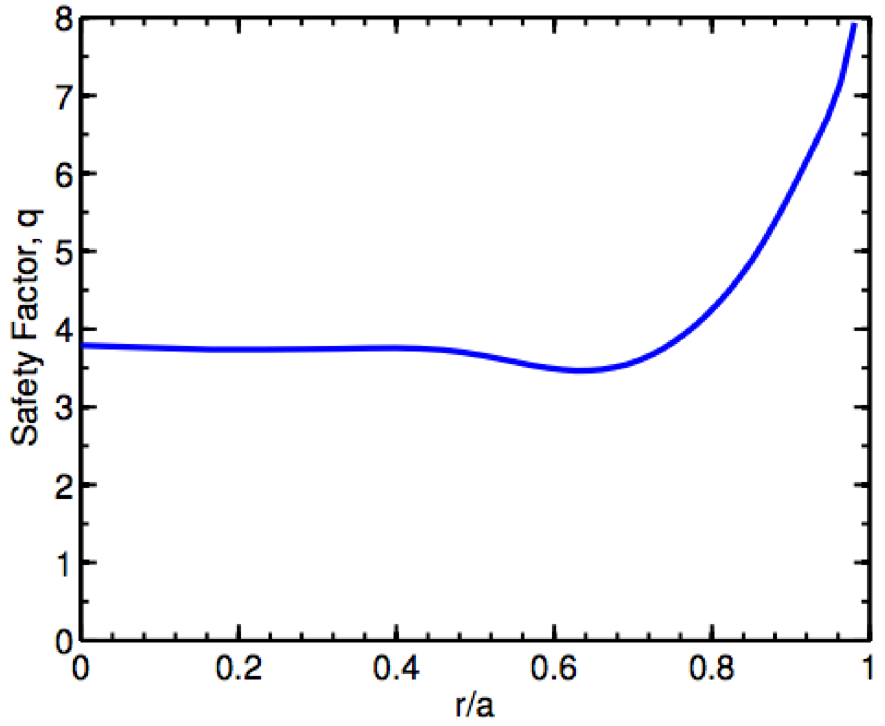
Optimized CD efficiency leads to substantial control of AT current profile below no-wall β_N limit *and at densities which give significant bootstrap fraction.*

I_p = 7.75 MA I_{BS} = 4.88 MA f_{BS} = 0.63 β_N = 2.59 (%-m-T/MA)

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

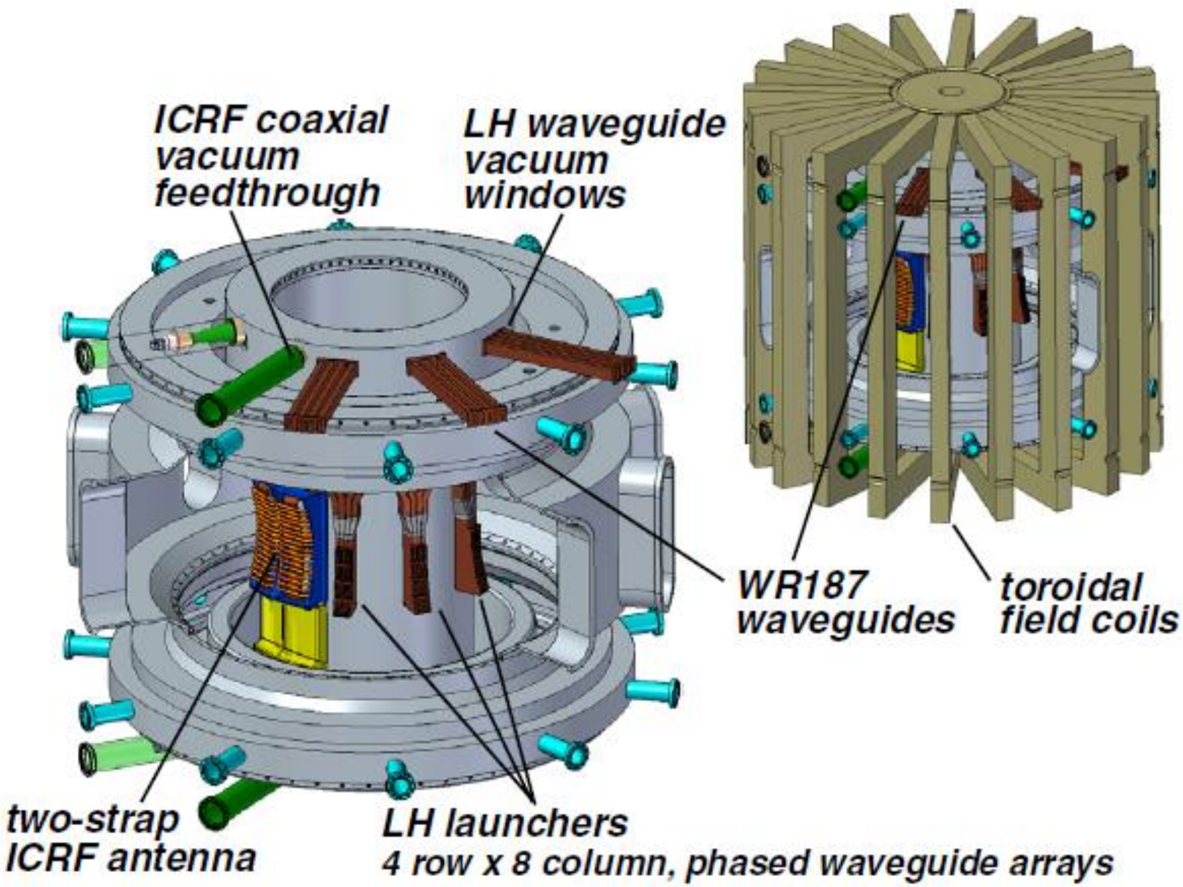
P_{IC} = 13.6 MW I_{IC} = 1.1 MA





III. The proposed *A*dvanced *D*ivertor and RF tokamak e*X*periment (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 = 90-120 MHz (ICRF)

  10 MW source

  f_0 = 4.6 GHz (LHRF)

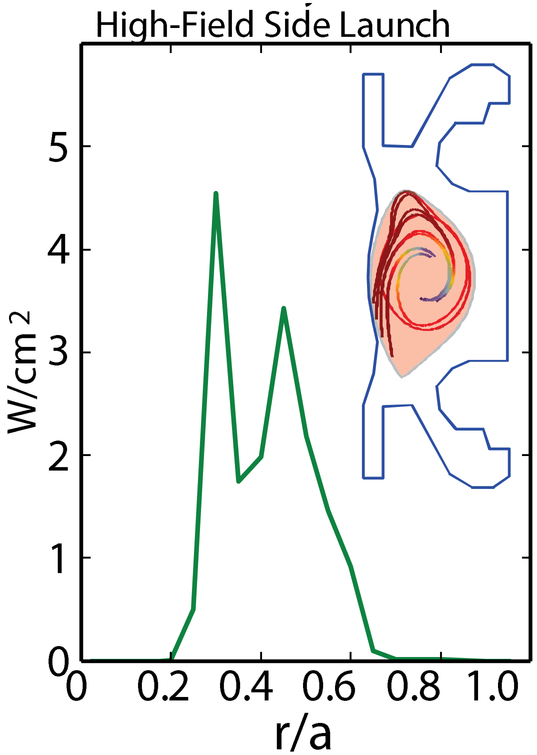
  4 MW source

[1] B. LaBombard et al, Nuclear Fusion **55** (2015) 053020.

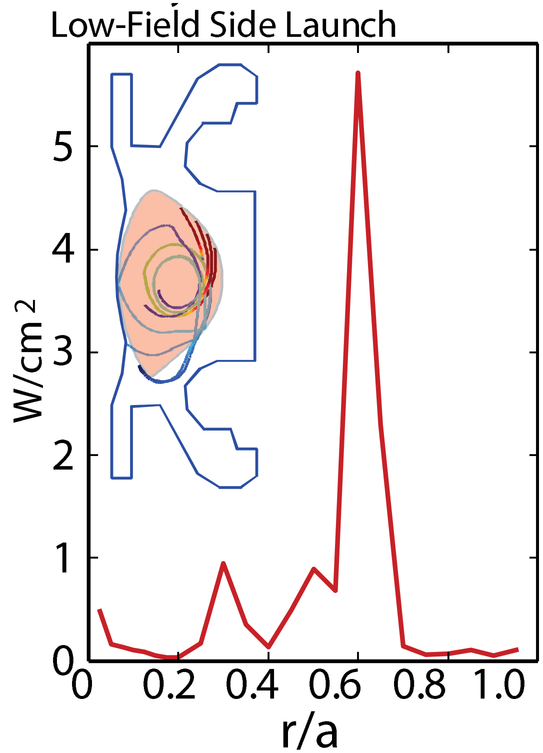
HFS + off mid-plane launch in ADX demonstrates feasibility of generating LH current density profiles that are desirable for AT operation

- ***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***

η_{CD} = 0.17 (10^{20} A/W/m^2)



η_{CD} = 0.14 (10^{20} A/W/m^2)



- **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

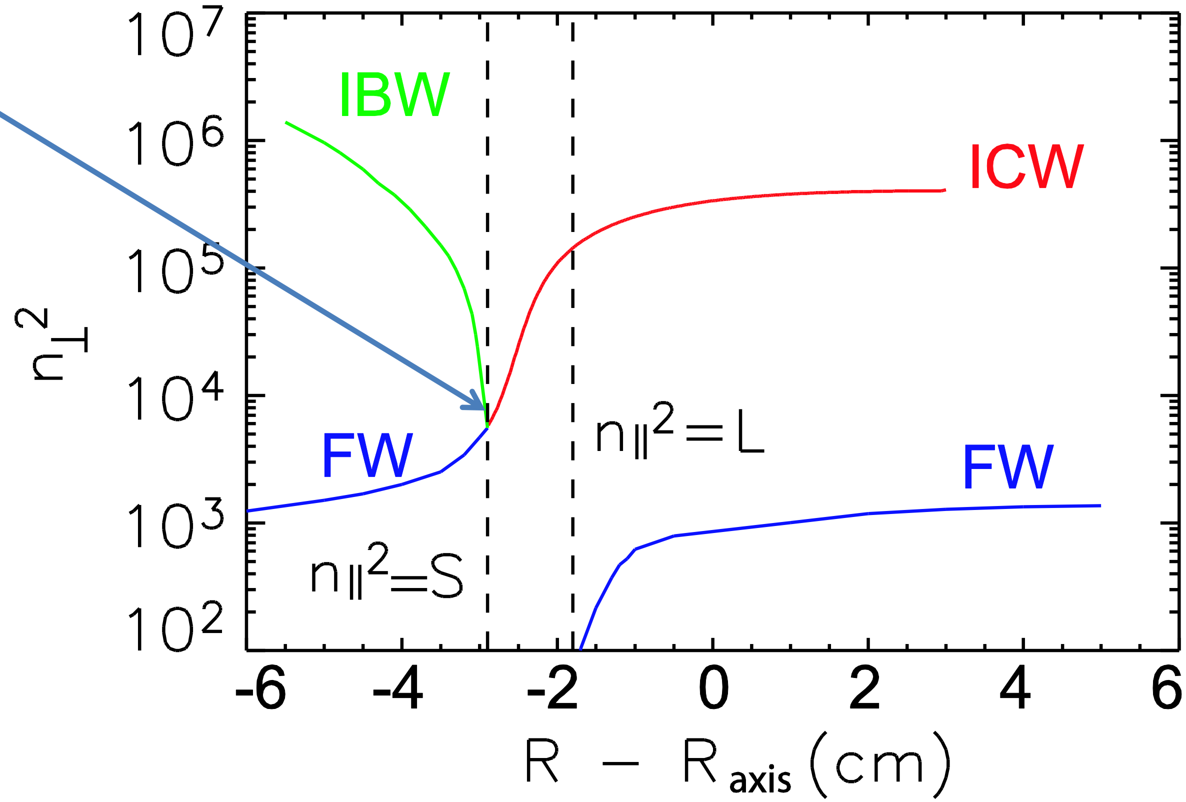
  P_{LH} = 4 MW

[1] B. LaBombard et al, Nuclear Fusion **55** (2015) 053020.

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*

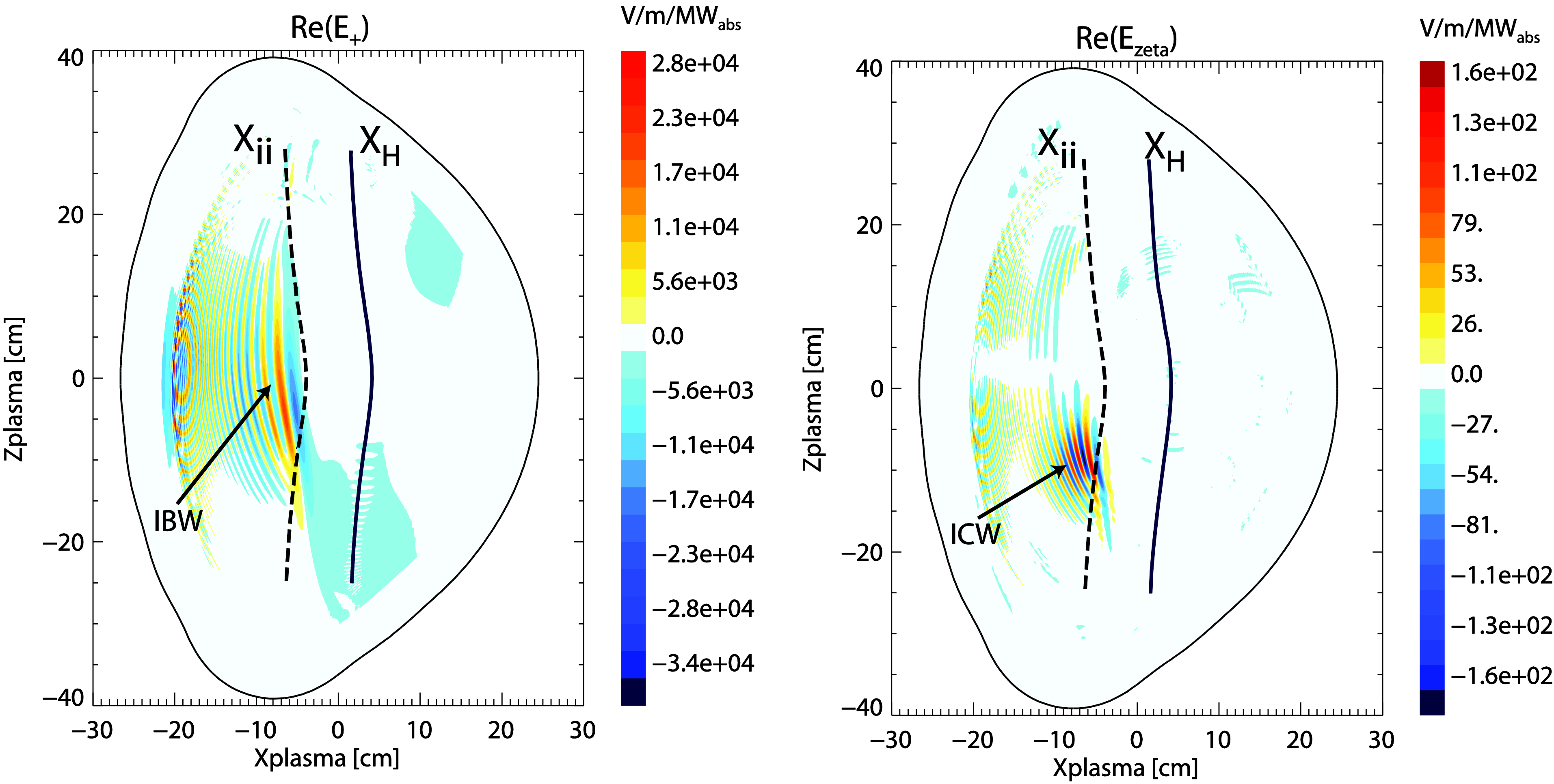
For HFS launch the FW branch connects directly to IBW / ICW



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 <u>at launched "minimum" $n_{//}$</u> 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.**

Related Presentations at this Meeting

- **OV/2-5: E. Marmar *et al*, "Overview of High-Field Divertor Tokamak Results from Alcator C-Mod"**
- **EX/P3-6 : B. LaBombard *et al*, "Plasma profiles and impurity screening behavior of the high-field side scrape-off layer in near-double-null configurations: prospect for mitigating plasma-material interactions on RF actuators and first-wall components"**
- ***EX/7-1: G. M. Wallace et al, "Influence of the Scrape Off Layer on RF Actuator Performance" → Next Talk in this Session***
- **FIP/P7-6: D. G. Whyte *et al*, "Smaller and Sooner: Exploiting High Magnetic Fields from New Superconductors for a More Attractive Fusion Energy Development Path"**