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

P. T. Bonoli, S. G. Baek, B. LaBombard, Y. Lin, T. Palmer, R. R. Parker, M. Porkolab, S. Shiraiwa, B. Sorbom, G. M. Wallace, D. G. Whyte, J. C. Wright, and S. J. Wukitch

Plasma Science and Fusion Center, MIT, Cambridge, MA 02139

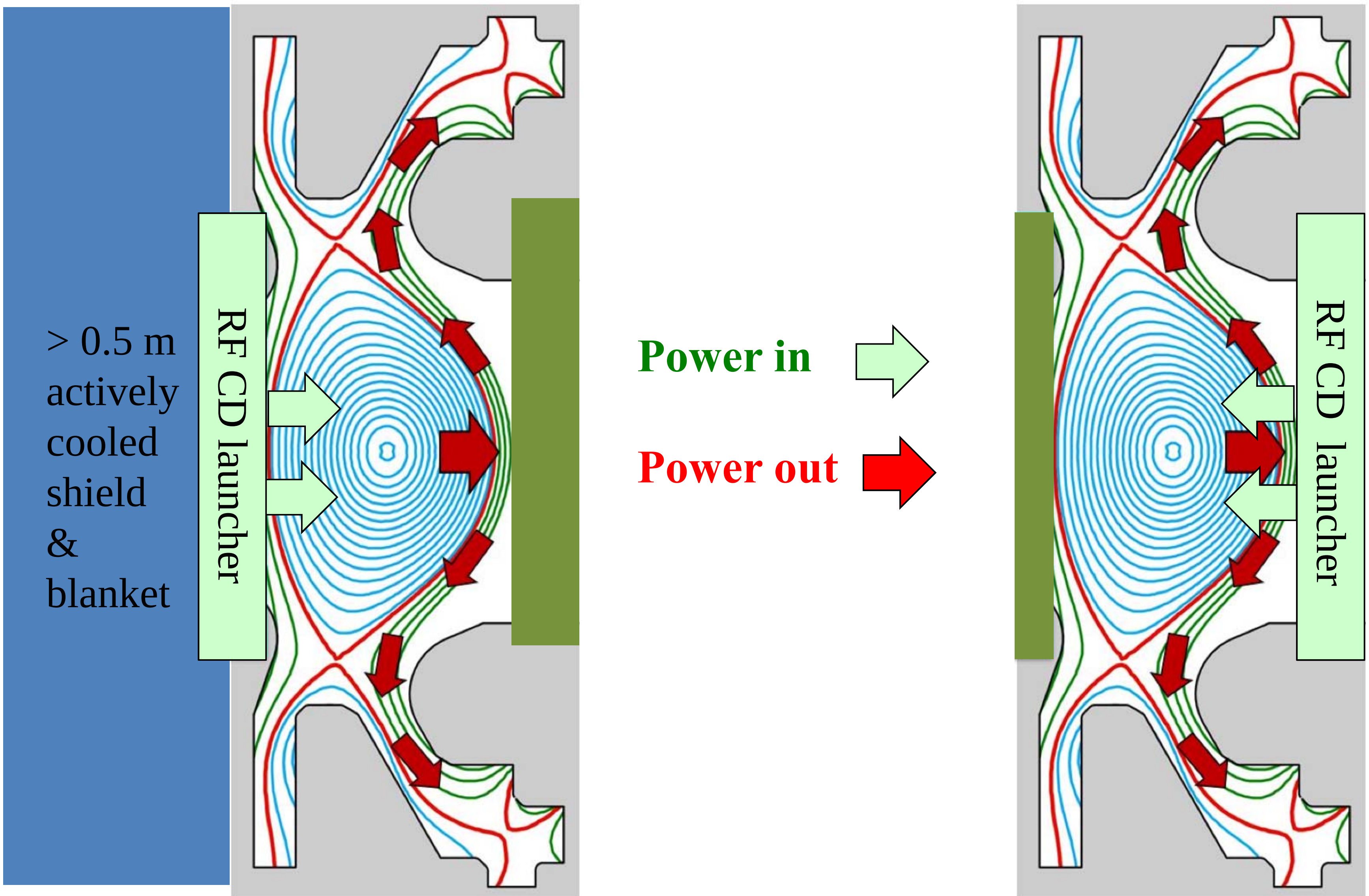
56th Annual Meeting of the American Physical Society
Division of Plasma Physics

New Orleans, Louisiana
October 27-31, 2014

Overview

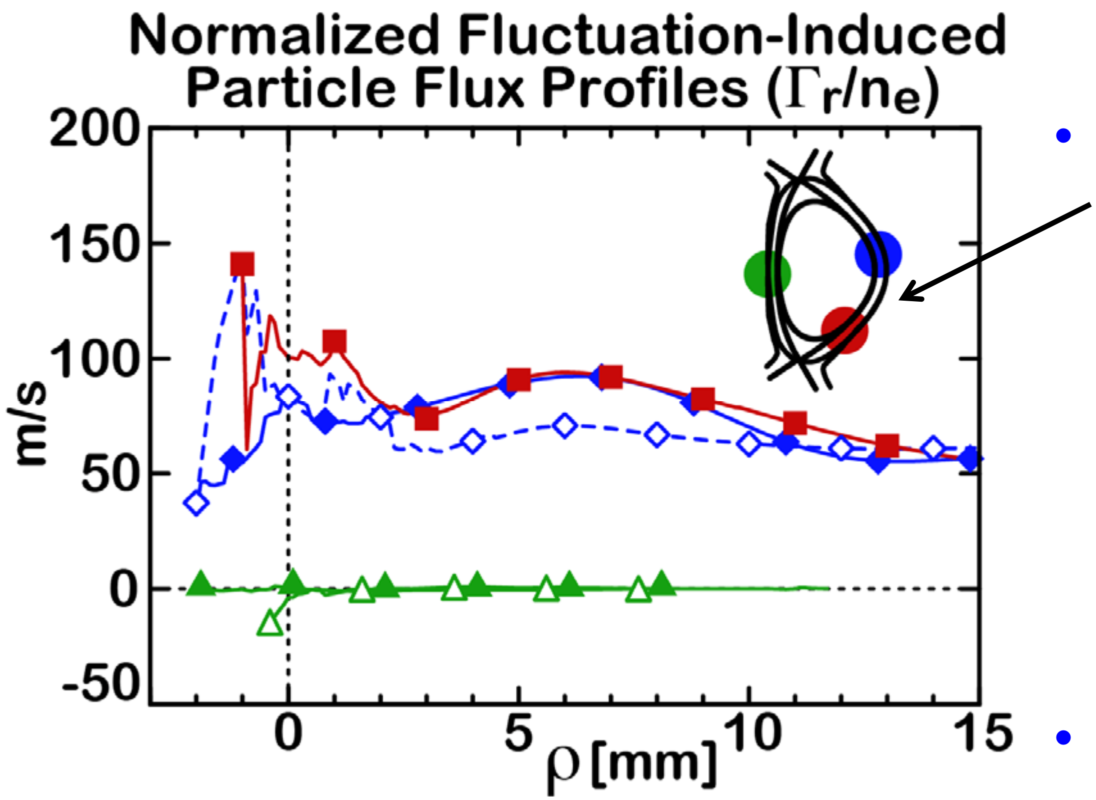
- **Application of a RF power in a fusion reactor is challenging:**
  - Survivability is a major issue because of the harsh environment → high heat fluxes and plasma-wall-interactions.
  - High density reduces the current drive (CD) efficiency of lower hybrid current drive (LHCD) and can lead to parasitic scrape off layer (SOL) losses.
  - High pedestal temperatures limit the penetration of LH waves.
  - Ion cyclotron range of frequency (ICRF) power can generate energetic ion tails, resulting in fast ion losses or destabilizing energetic populations of fusion alpha particles.
  - 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.**

Reactor power exhaust favors HFS launch and HFS space allocation allows HFS launch



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



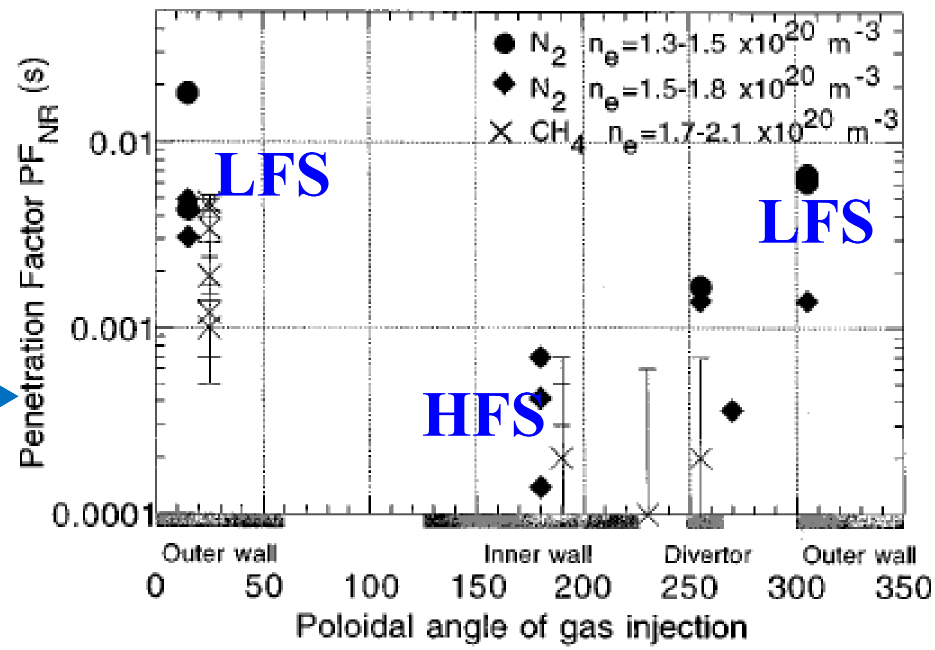
N. Smick et al, Nuc. Fusion (2014).

- **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

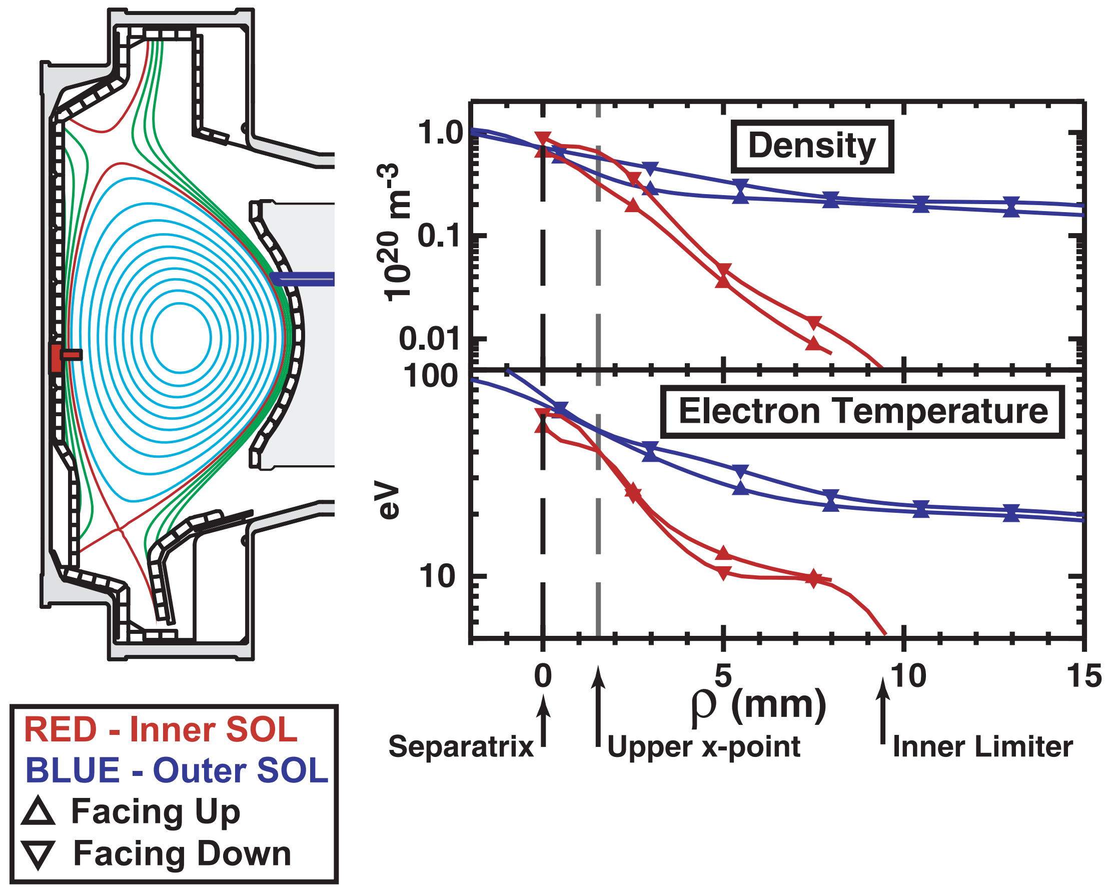
- **Strong impurity screening measured in Alcator C-Mod for HFS SOL [1]:**
  - Strong poloidal asymmetry observed in the penetration factor for nitrogen and methane.
- **Mitigates effects of impurity generation from plasma-wall interactions due to RF sheaths (for example).**



[1] McCracken, *et al*, PoP 4 (1997) 1681.

High Field Scrape off layer may also mitigate parametric decay processes

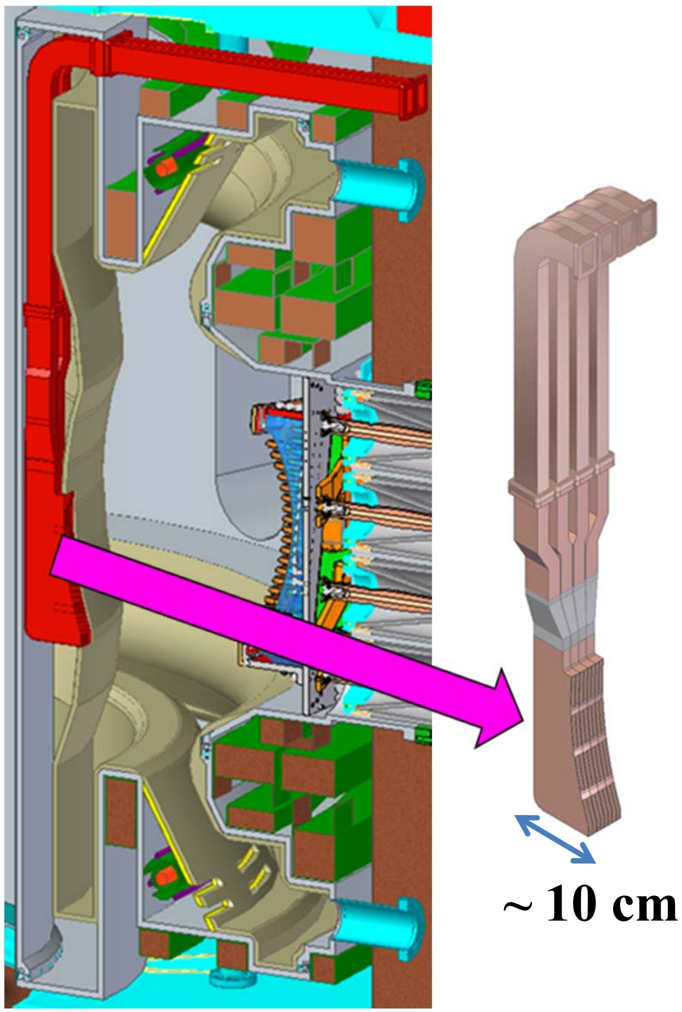
- **Significantly lower density measured in HFS Double Null (DN) plasmas on C-Mod:**
  - Lower SOL densities on HFS relative to LFS may suppress parametric decay instability (PDI) [1].
  - Steep density gradients at HFS reduce growth rates of convective cells driven by RF fields.



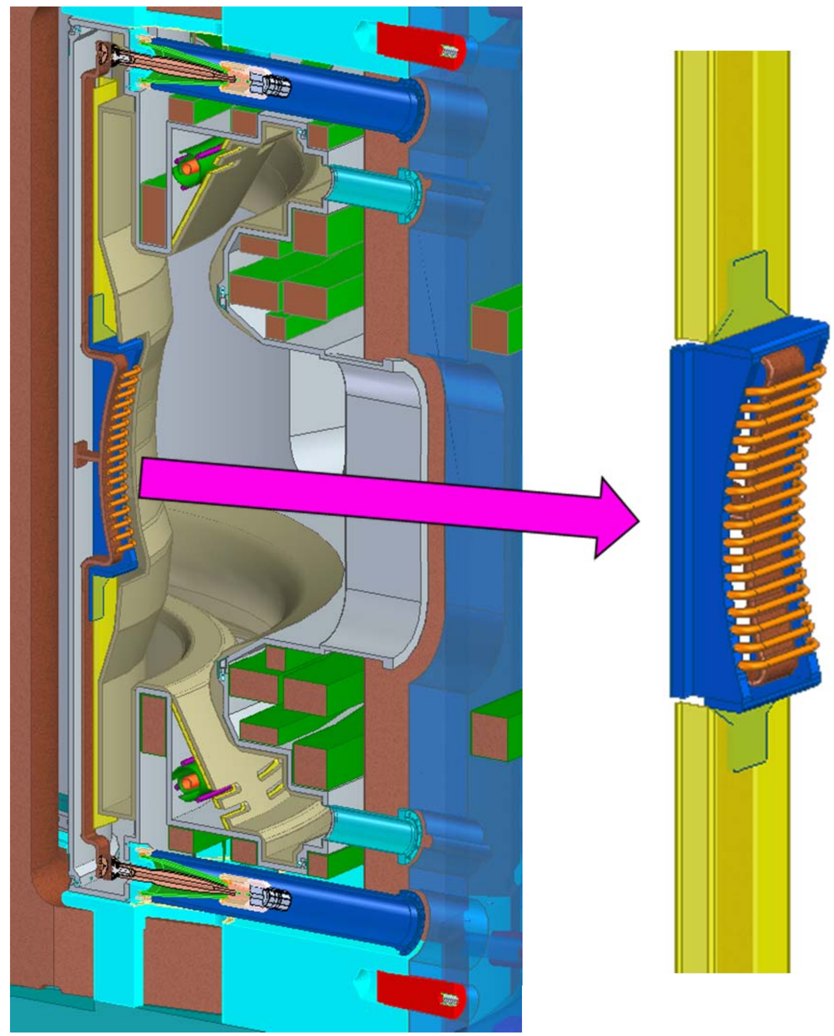
[1] S. G. Baek *et al*, APS-DPP (2014)

The proposed ADX Facility [1] will establish the engineering and physics of high field side RF launchers

ADX HFS LHRF Launcher



ADX HFS ICRF Launcher



[1] B. LaBombard et al, FEC-2014 (2014).

II. Physics of LH wave propagation, absorption, and current drive from the high field side of a tokamak

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] ($v_{//} / v_{te} \approx 2.5\text{-}3$) 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**, 1357 (1979)
[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 waves penetrate farther into the plasma core there is a reduction in particle trapping at smaller minor radius:**
  - **And particle trapping may be further reduced through HFS damping.**

- **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].**

[1] N. J. Fisch, PRL **41**, 873 (1978).
[2] Karney & Fisch, PoF **28**, 116 (1985).

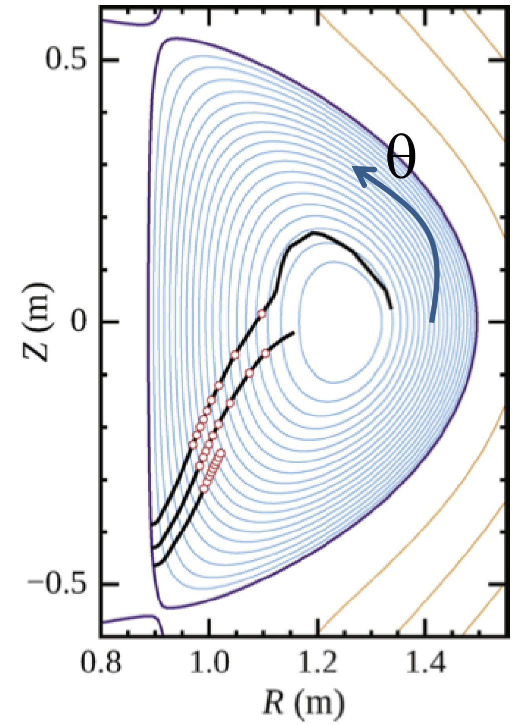
Poloidal "steering" of the LH wave provides further control of the injected wave $n_{//}$

- Initial variation of the poloidal mode number at launch is quite different for θ = (0, π) as compared to θ = (π/2, 3π/2) [1]:

$$n_{\|} = \frac{k_{\|}c}{\omega} = \left(\frac{m}{r}\frac{B_\theta}{B} + \frac{n_\phi}{R}\frac{B_\phi}{B} \right)\frac{c}{\omega}, \qquad \frac{dm}{d\theta} \propto k_{\|} q(r) \sin\theta$$

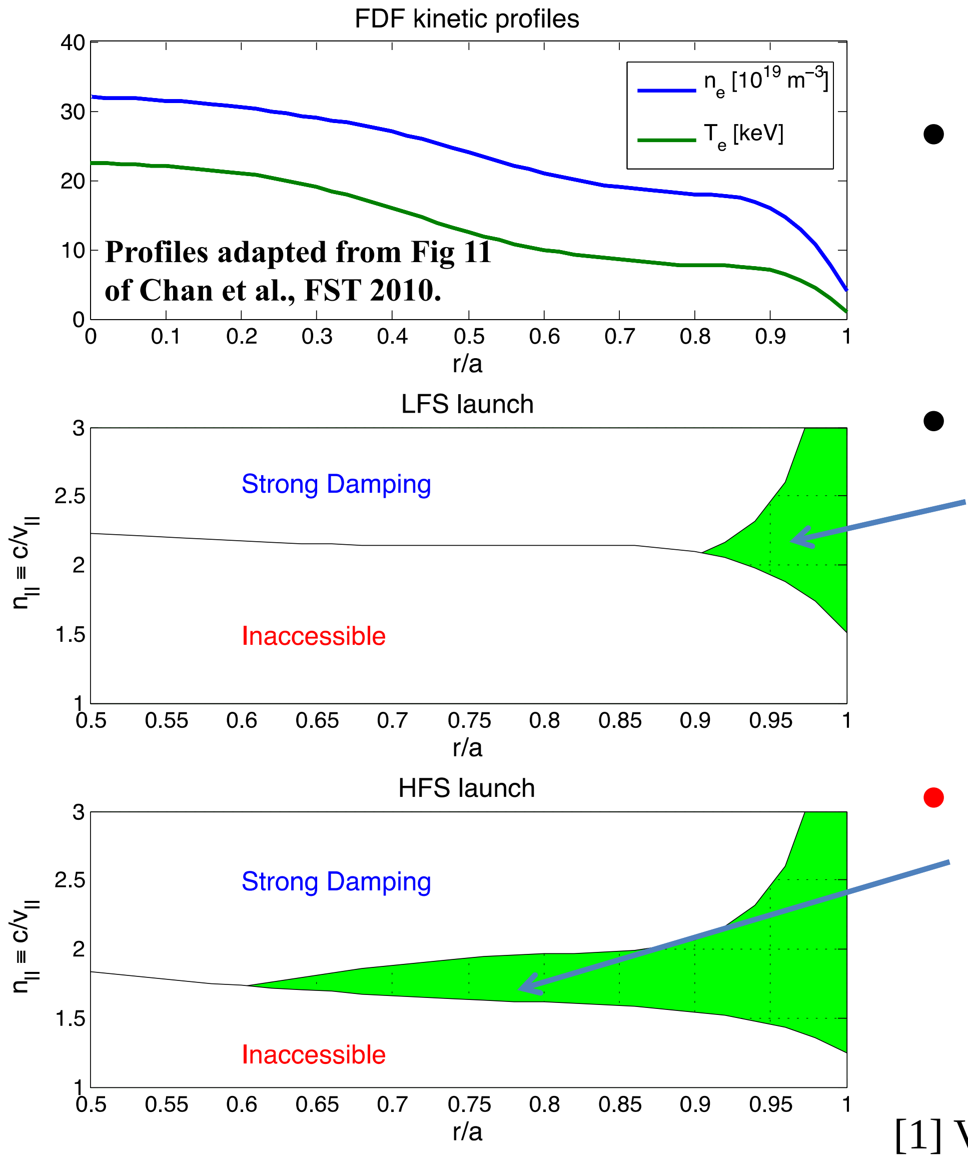
- Optimization of poloidal launch position makes it possible to keep $n_{//} \approx$ constant along the ray path by balancing the effects of toroidicity, and poloidal field in $k_{//}$, resulting in improved radial penetration [2].

$$\frac{v_{g,r}}{v_{g,\theta}} \cong -\frac{\omega^2}{\omega_{pe}^2}\frac{k_r}{k_{\|}}\frac{B}{B_\theta}$$



[1] P. T. Bonoli PoF **25**, 359 (1982).
[2] Y. Podpaly *et al*, FED **87**, 215–223 (2012).

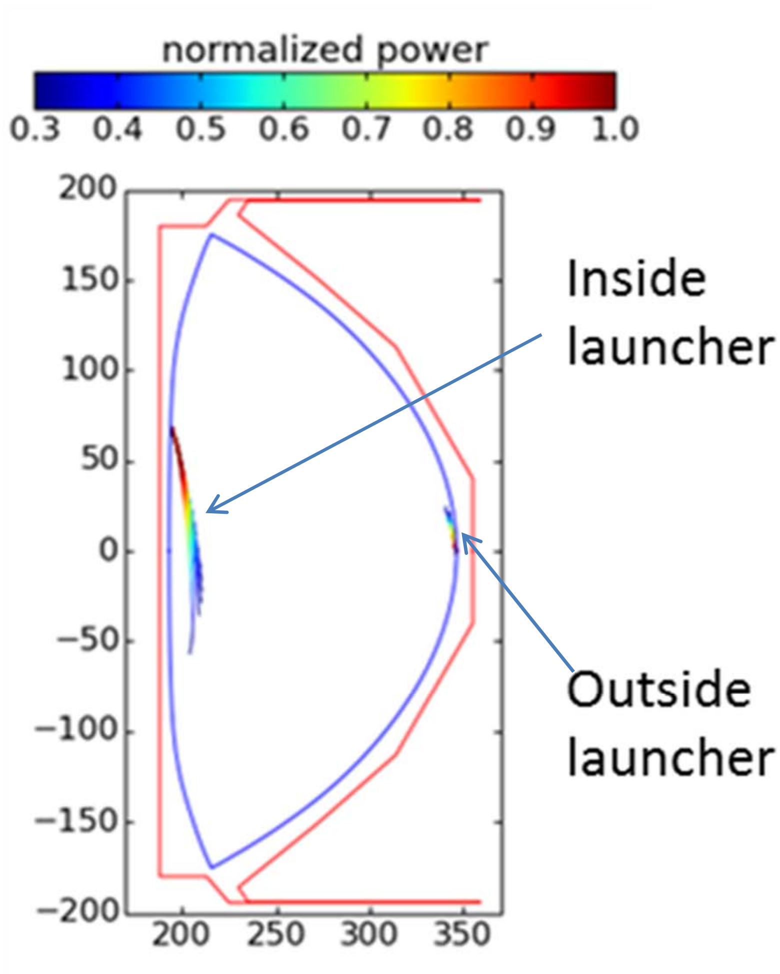
HFS launch in an FNSF [1] enables damping well inside pedestal vs. no penetration with LFS launch

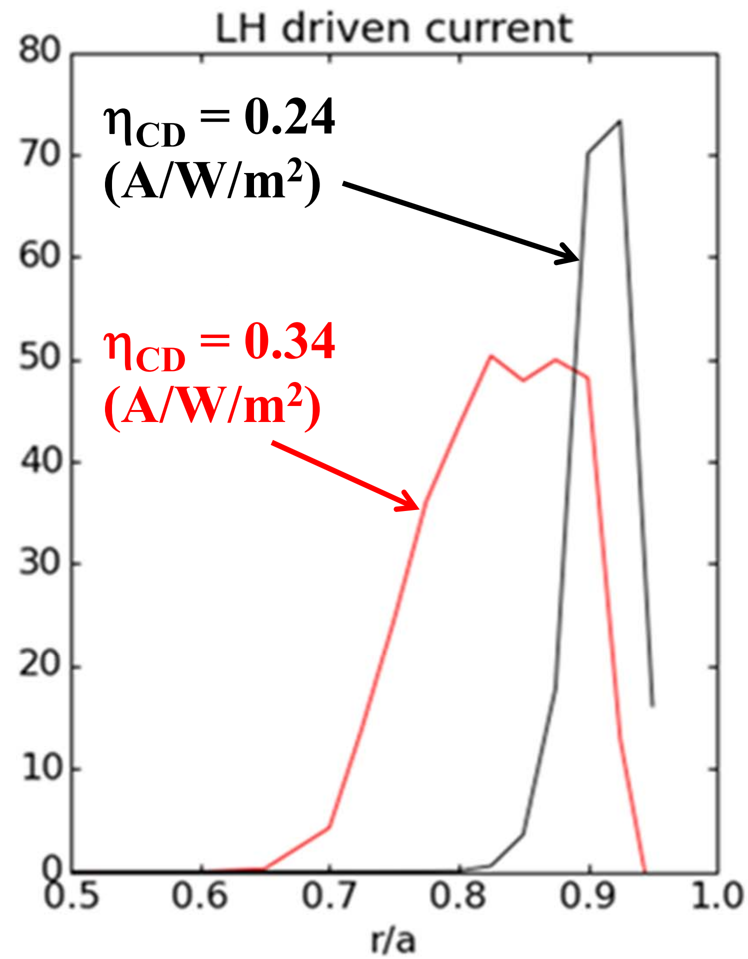


- Higher |B| improves wave accessibility at high density
- High temperature and density pedestals limit LFS LHCD in a reactor (e.g. FDF [1])
- Window opens for LHCD if waves are launched from HF

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

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

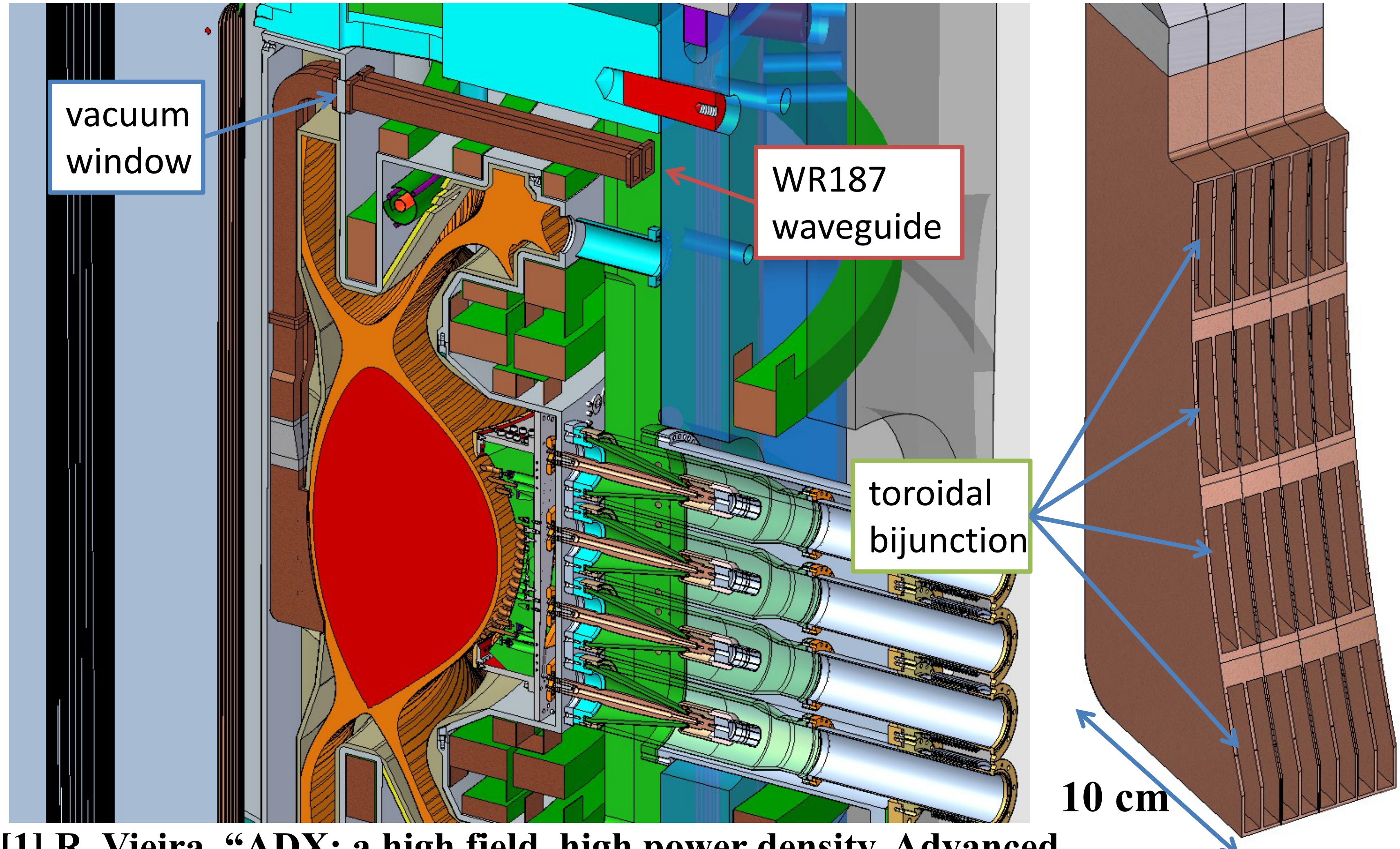




[1] V.S. Chan *et al*, Nucl. Fusion **51** 083019 (2011).

f_0 = 5 GHz $n_{//}$ = 1.9 (90% directivity) P_{LH} = 10 MW

LHCD antenna is an integrated part of the ADX design which will study the integrated PMI / core physics mission of HFS LHRF



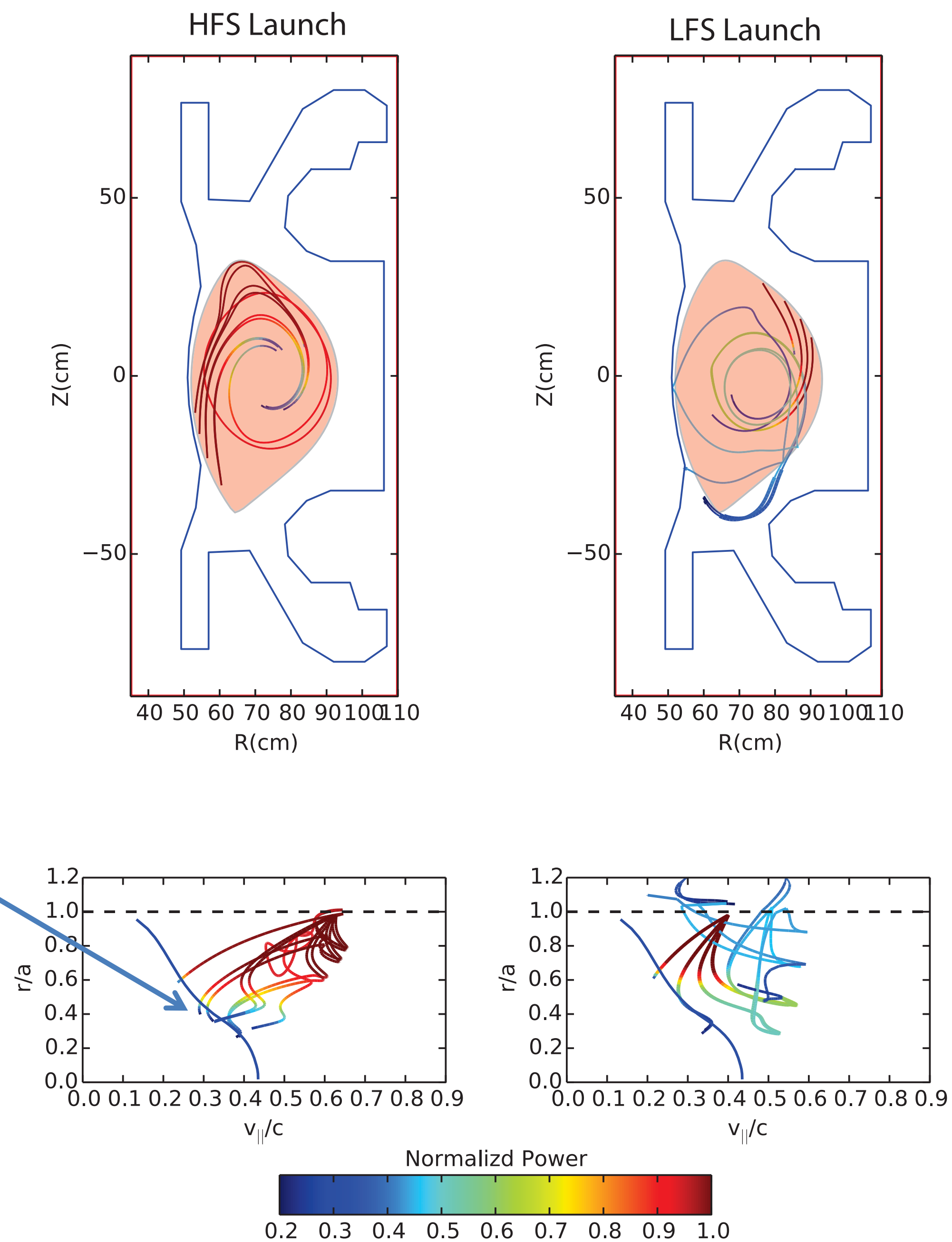
[1] R. Vieira, "ADX: a high field, high power density, Advanced Divertor test eXperiment", APS (2014) Poster TP8.00002.

HFS + off mid-plane launch makes it possible to maintain high CD efficiency as n_e is increased in ADX

- **Plasma target parameters:**
  - B_0 = 5.6 T, I_p = 1.0 MA
  - R_0 = 0.725 m, a = 0.205 m
  - $n_e(0) = 1.8 \times 10^{20}$ m^{-3}
  - $T_e(0)$ = 5.5 keV

- ***High CD efficiency maintained as n_e is increased.***
  - $n_{//}$ = 1.6 (unidirectional)
  - f_0 = 4.6 GHz
  - η_{CD} = 0.17 (10^{20} A/W/m^2)

- For comparison, CD efficiency from LFS is η_{CD} = 0.14 (10^{20} A/W/m^2).



S. Shiraiwa et al., APS (2014), TP8.00003.

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

Concept forms the basis for the LHCD system in ARC [1, 2]:

$n_{//}$ = 1.5 - 1.6, f_0 = 8 GHz

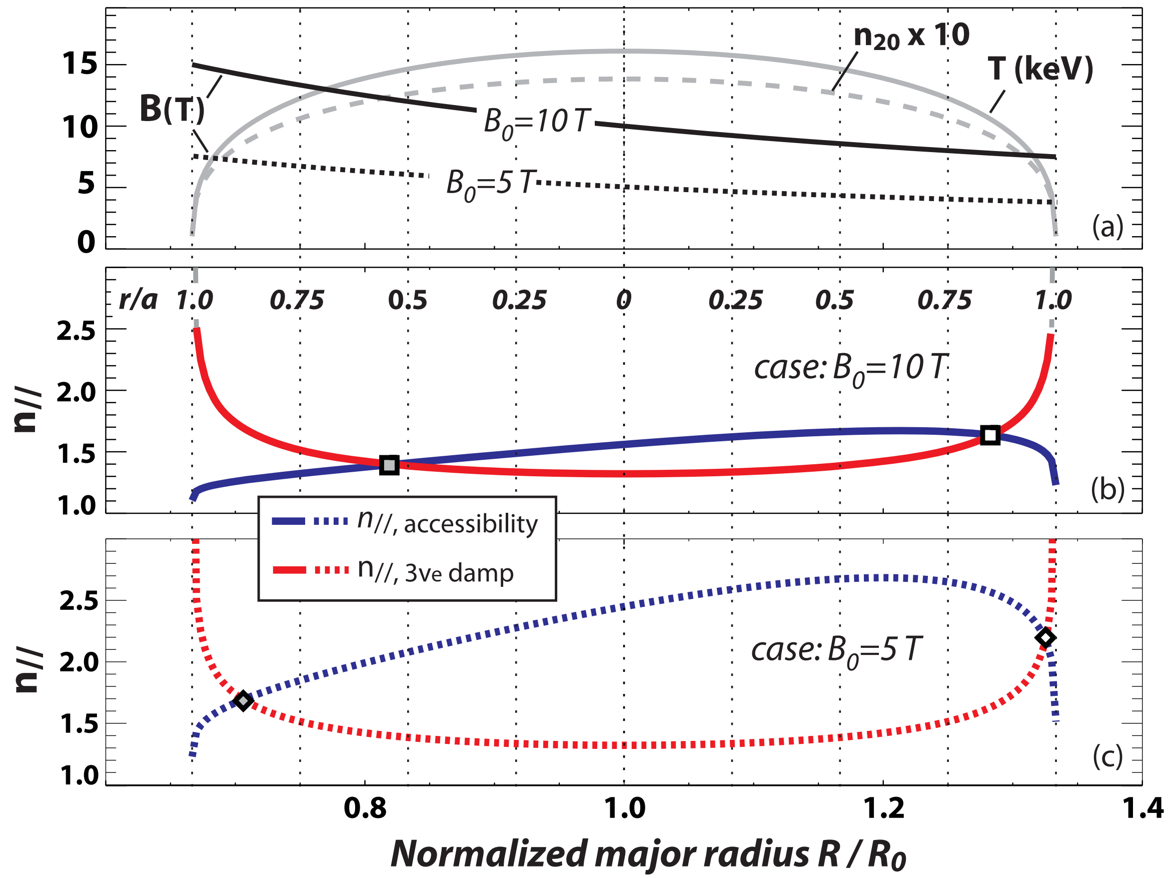
(bi-directional spectrum).

B_0 = 9.25 T, I_p = 8 MA

a = 1.1m R_0 = 3.3 m

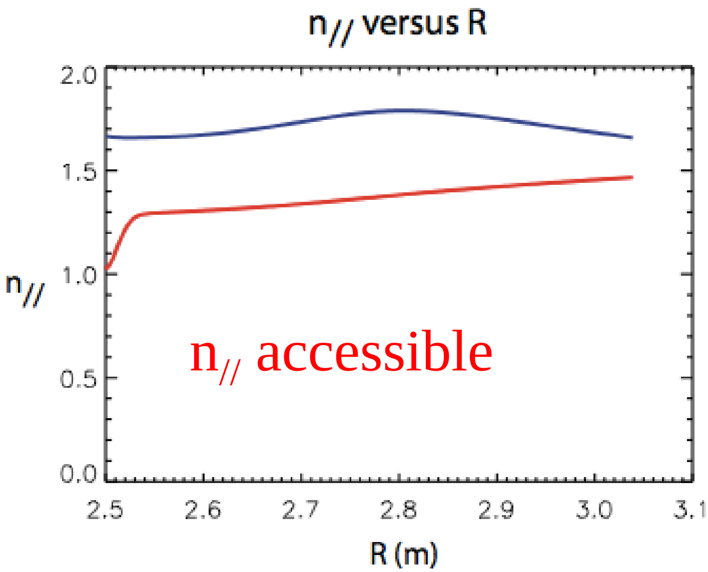
$n_e(0) = 1.75 \times 10^{20}$ m^{-3}

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



[1] B. N. Sorbom *et al*, submitted to Fusion Eng. & Design.
[2] B. Sorbum *et al*., APS (2014) TP8.00005.

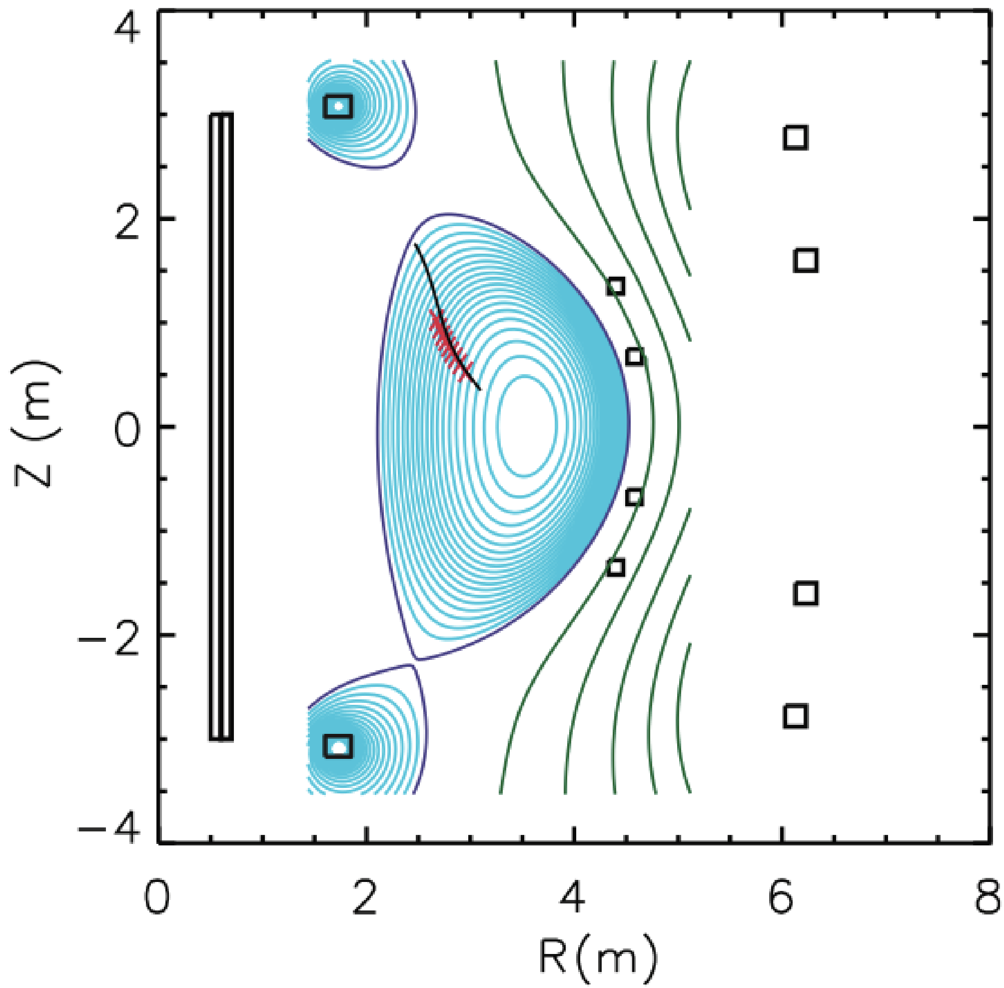
ACCOME [1] code been used to optimize HFS LHCD + poloidal launch location for the ARC Reactor Design



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 $k_{//}$



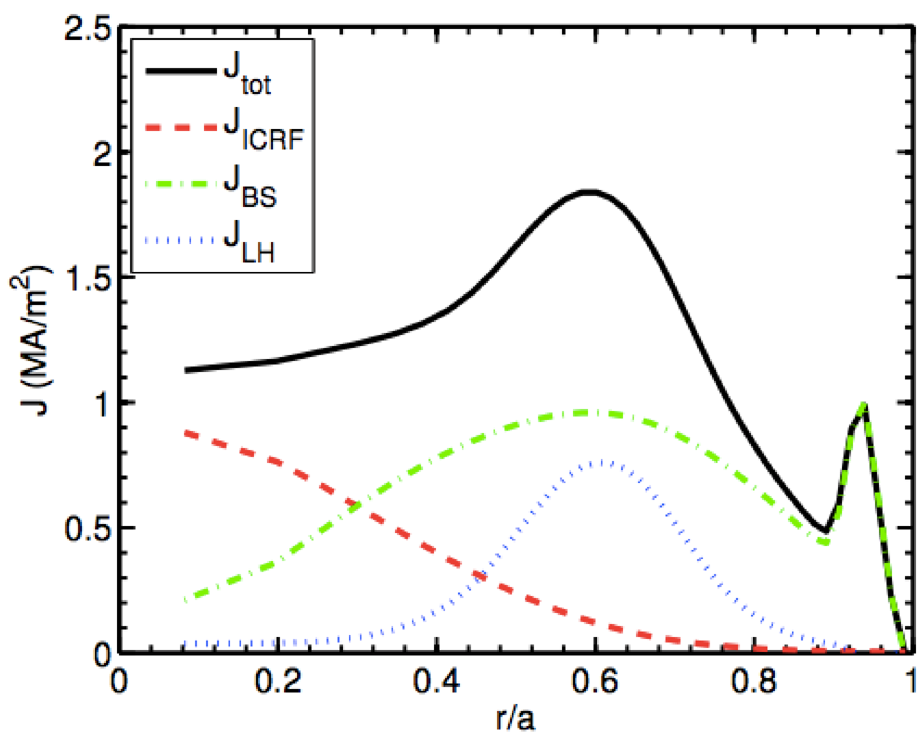
[1] R. S. Devoto *et al*, NF (1992).

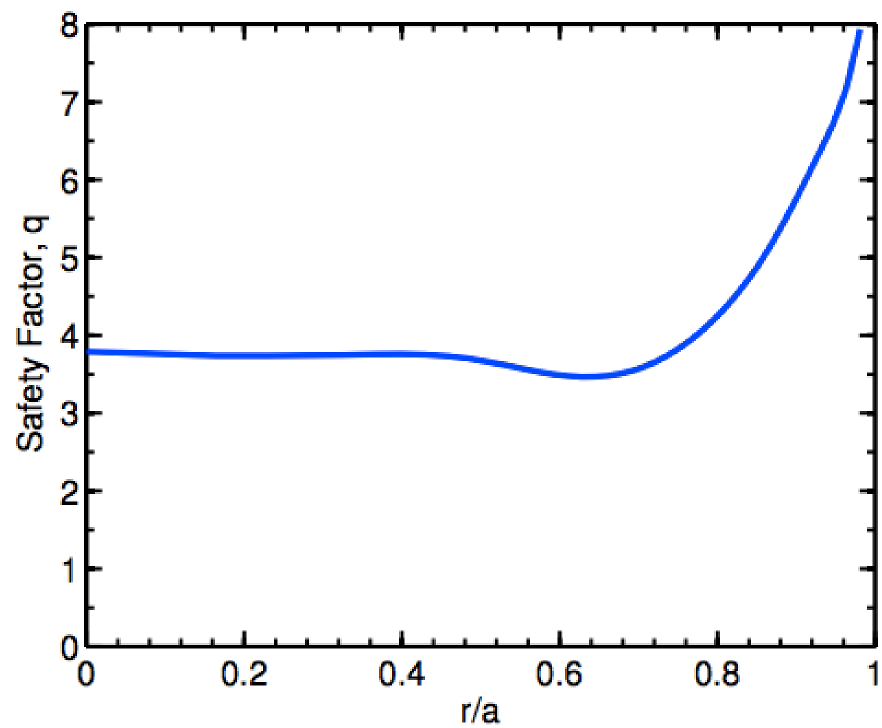
ARC Design → Optimized CD efficiency leads to substantial control of AT current profile below no-wall β_N limit *and at densities which give significant bootstrap fraction.*

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 $\eta_{CD\text{-}IC}$ = 0.40 (10^{20} A/W/m^2)





LH fast wave physics may be promising with HFS launch

- **Using a lower frequency (~ 1 GHz) improves LH wave accessibility, allowing $n_{//} \approx 1.3 - 1.4$.**

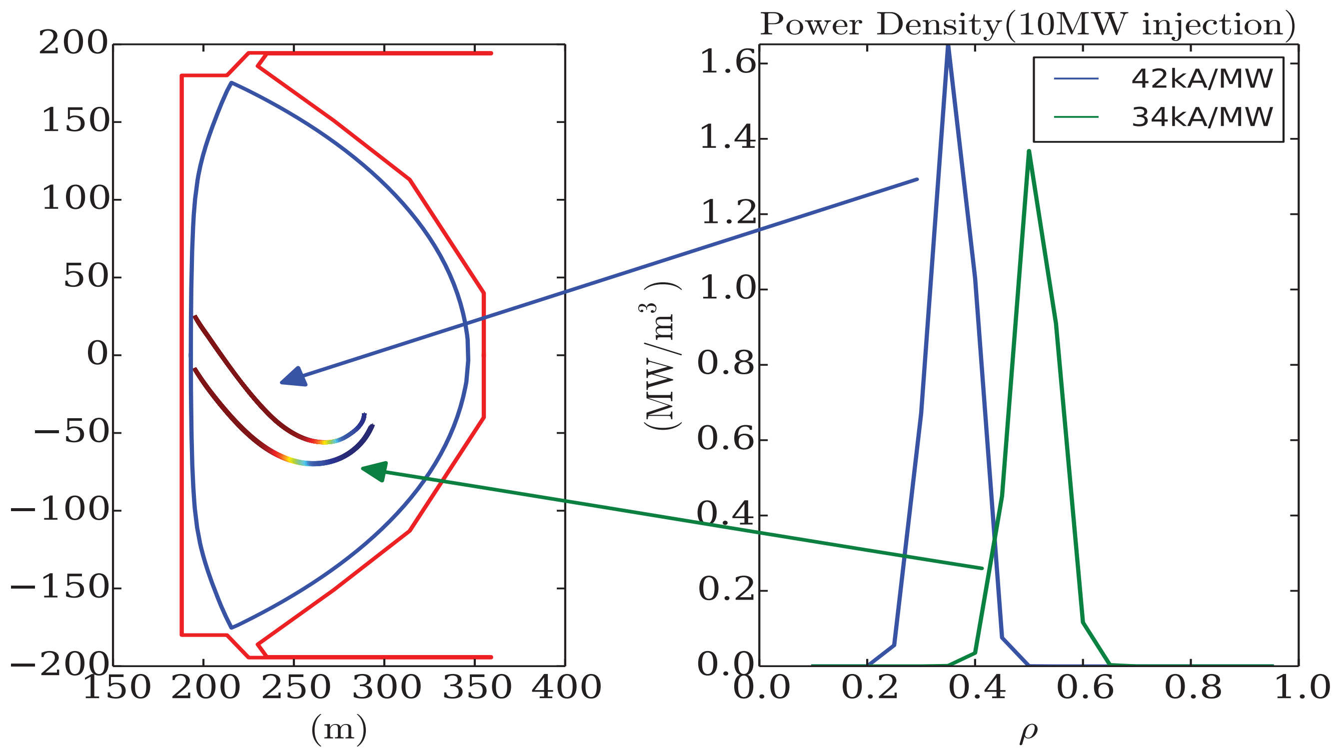
- **Assuming wave absorption via transit time magnetic pumping (TTMP) and electron Landau damping (ELD):**
  - **Lower launched $n_{//}$ reduces ELD allowing penetration to higher T_e**
  - **Higher |B| reduces TTMP $\propto B^{-2}$ which should also allow penetration to higher T_e.**
  - **Opens the possibility of using the LH fast wave for core current drive at $r / a \leq 0.5$ with HFS launch.**

- **This physics regime will be investigated on the DIII-D tokamak at ~ 500 MHz [see R. I. Pinsker, "Whistlers, Helicons, Lower Hybrid Waves: the Physics of RF Wave Absorption Without Cyclotron Resonances", APS(2014) CT2.00001].**

- **Outstanding questions:**
  - **Suitability for launching via slotted, slow-wave waveguide.**
  - **Possible absorption on fusion alpha particles.**

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

Studies using an FNSF-AT plasma (FDF[1]) have found *core current drive is possible* with HFS launch of LH fast wave



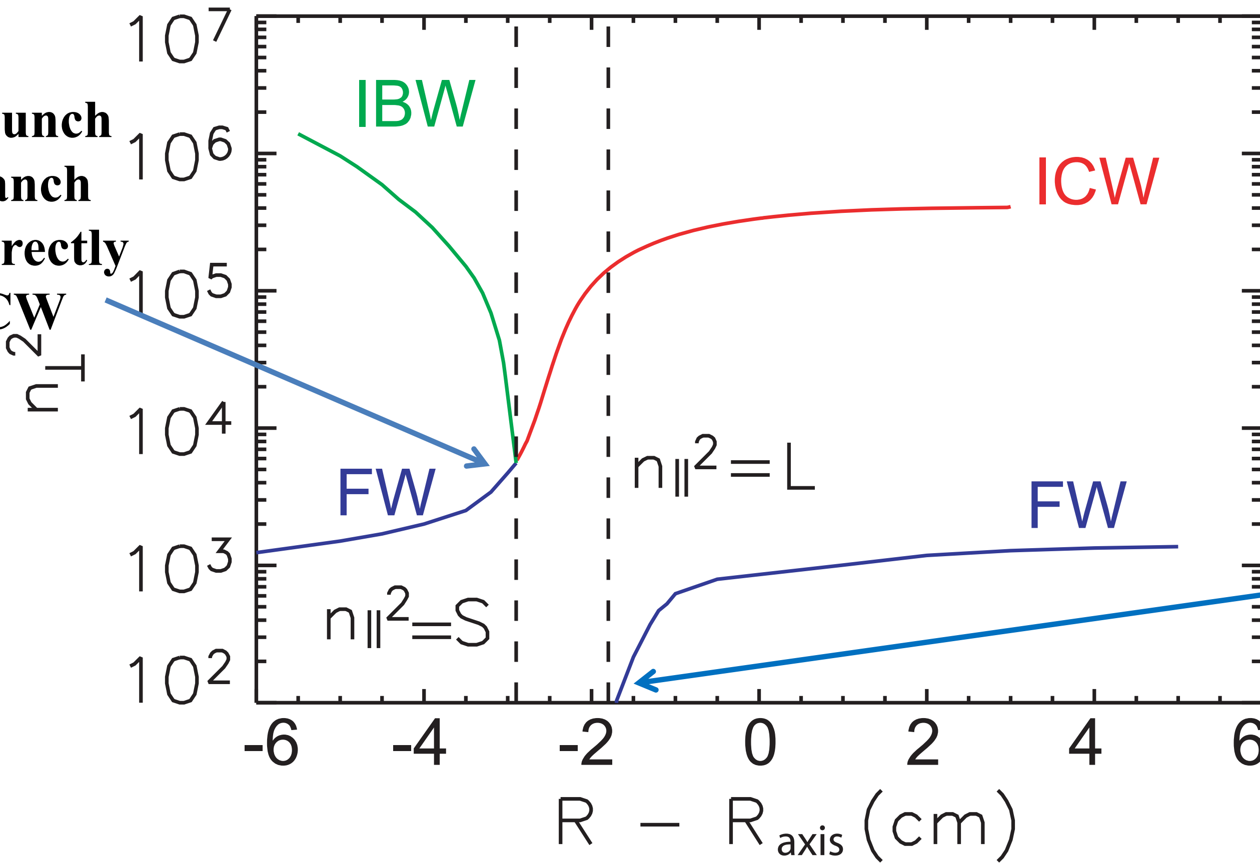
- **Launched $n_{\parallel} = 1.3 \pm 0.1$, $f_0 = 1$ GHz → improved wave accessibility**
- **$\eta_{CD} \sim 0.3$ A/W·m^{-2} @ $\rho = 0.3$**

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

III. Physics of ICRF wave propagation, absorption from the high field side of a tokamak

ICRF fast waves launched from the HFS [1] will directly mode convert to ion Bernstein waves (IBW) and ion cyclotron waves (ICW) [2]

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



For LFS launch the FW must tunnel to the IBW / ICW branches

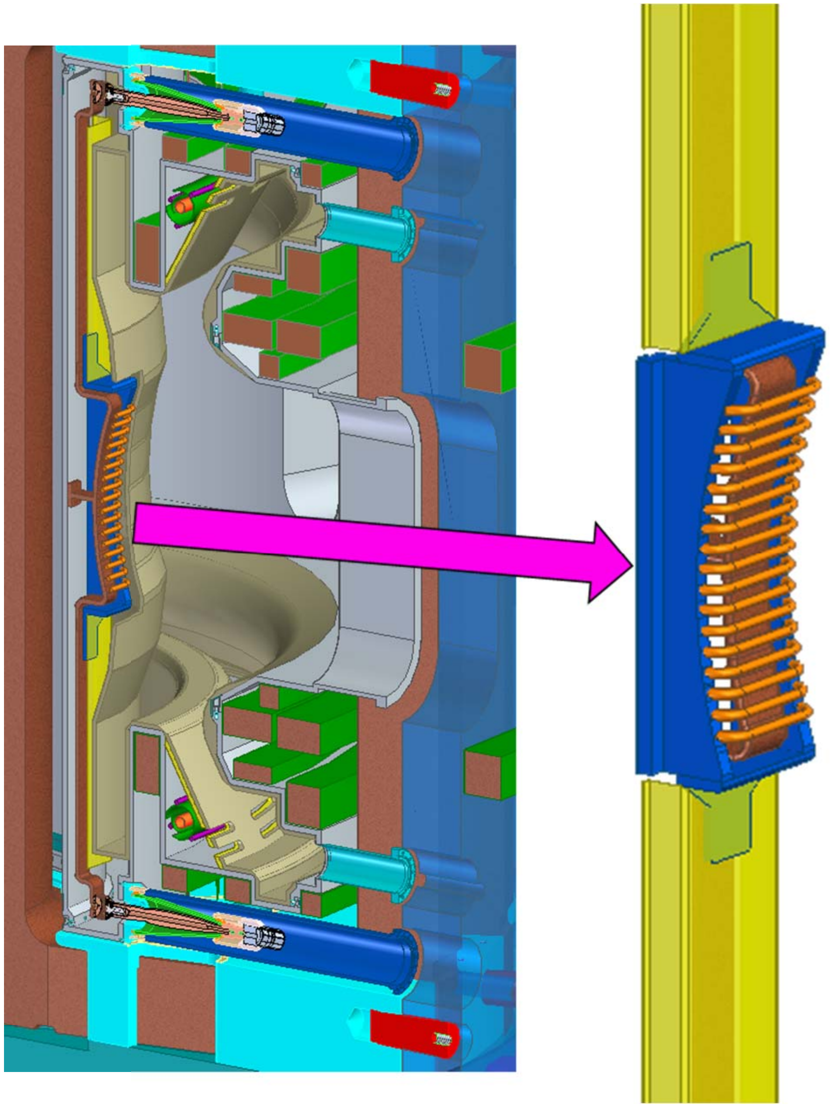
- **Opens the possibility of strong single pass absorption scheme that avoids generation of fast ions as with minority heating scheme from the LFS.**

[1] Equipe TFR, Plasma Physics, **24**, 615 1982
[2] E. Nelson-Melby et al, PRL **90**, 155004 (2003)

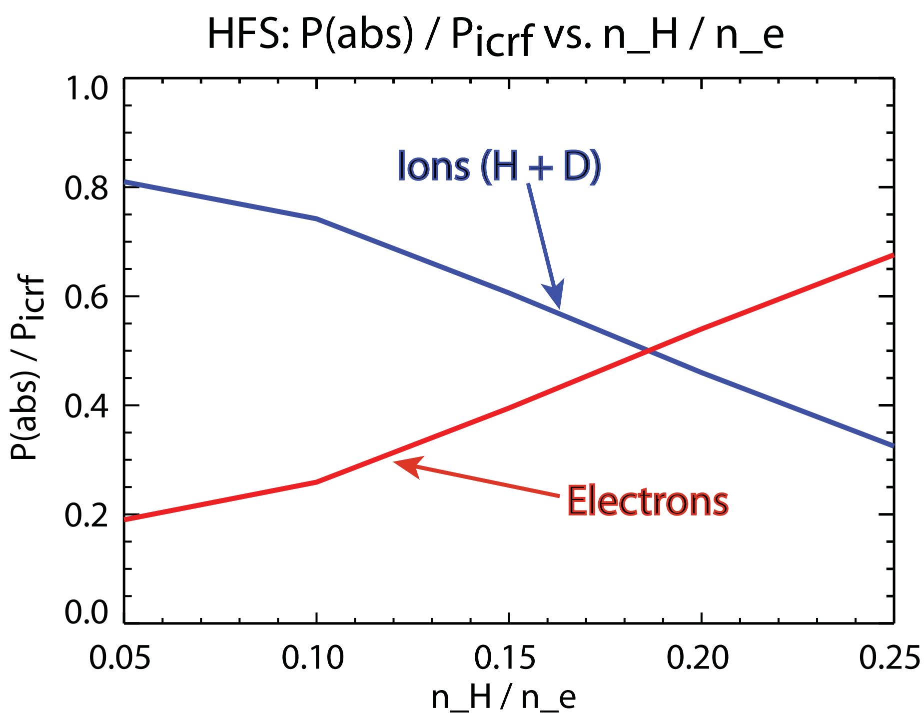
HFS ICRF launcher is planned for the ADX facility

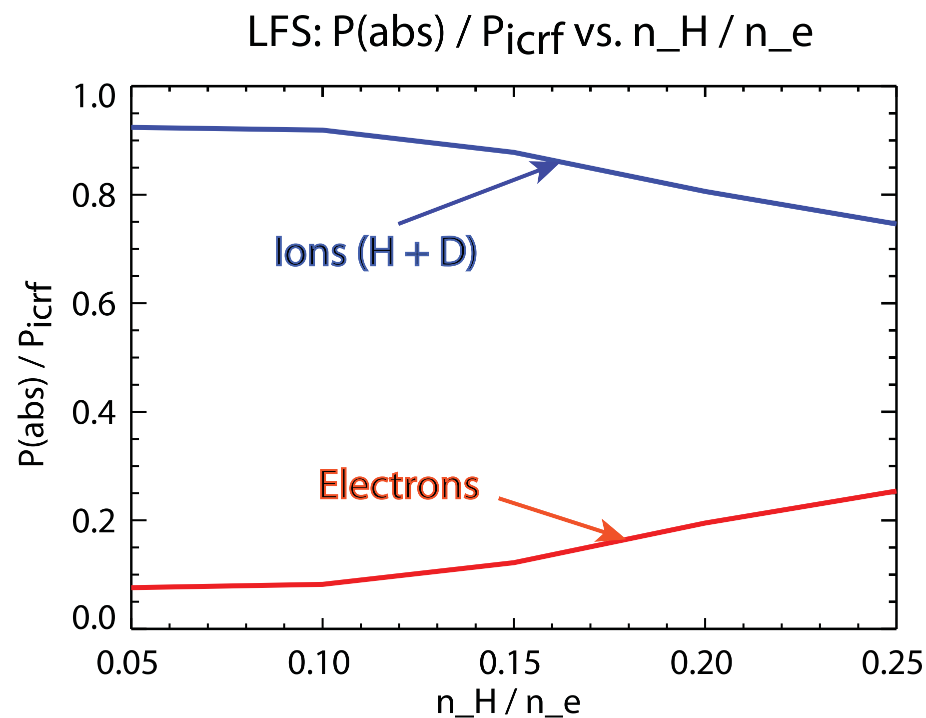
- **HFS ICRF launcher is integrated into machine design.**

- **ADX will test the hypotheses that the natural field alignment, 100% single pass absorption, and low impurity penetration of the HFS result in a robust ICRF actuator.**



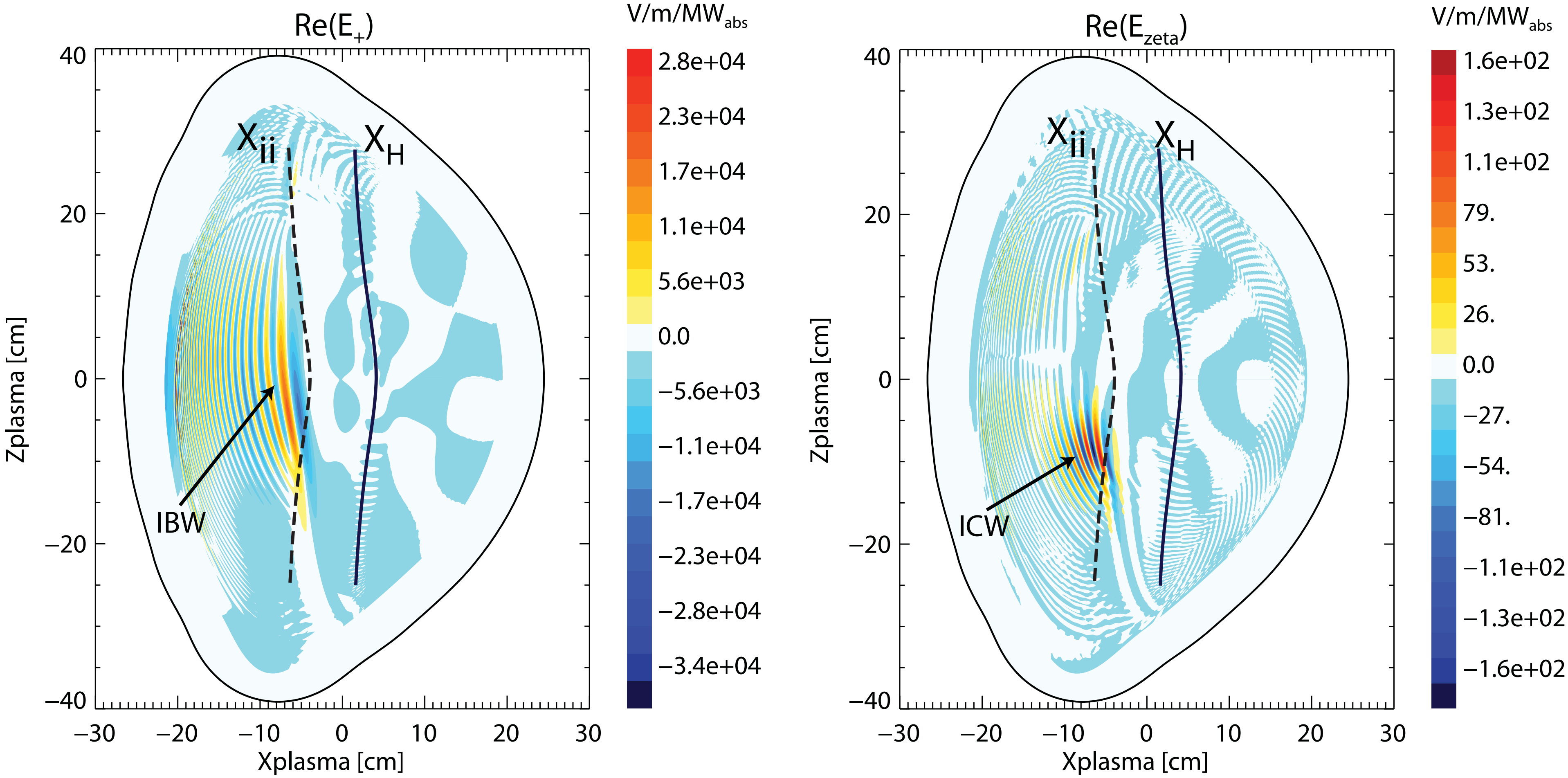
TORIC field solver simulations confirm strong electron absorption via mode converted IBW with HFS launch





- **As n_H / n_e increases to ~ 0.15, the P(abs) to electrons increases dramatically for HFS launch, consistent with strong mode conversion to IBW.**
- **P(abs) to electrons remains low for LFS launch because mode conversion to IBW and ICW is weak from LFS for D(H).**

With HFS launch, the ICRF field structure reveals presence of mode converted IBW along the mid-plane and ICW off the mid-plane



- **For n_H / n_e = 0.15 (shown above) the incident fast wave power is absorbed nearly 100% via mode conversion.**

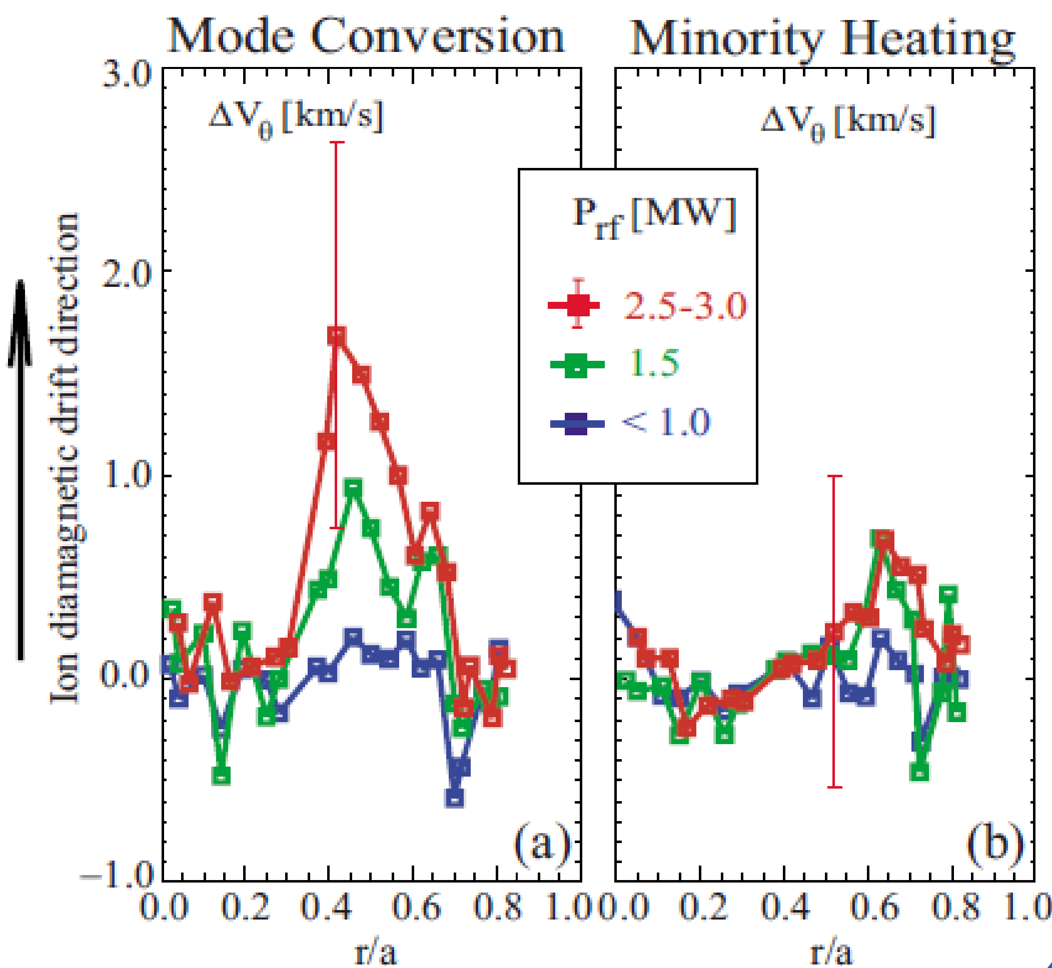
Summary and Conclusions

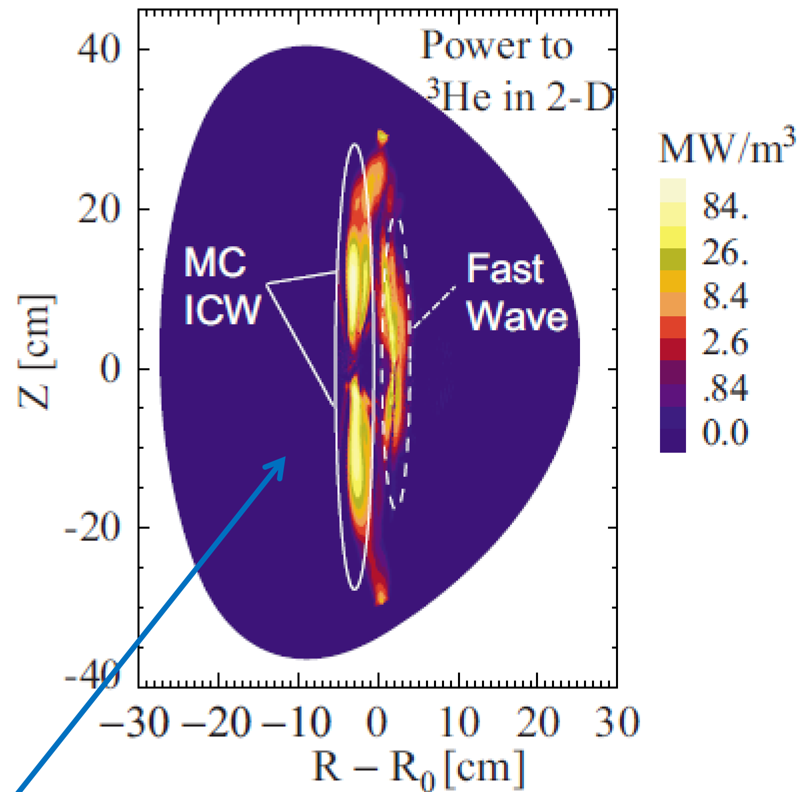
- **High field side placement of LHRF and ICRF launchers in double null configurations represents an *integrated edge to core solution* for the use of LHRF and ICRF actuators.**
- **Reduced particle and heat fluxes provide launcher protection with minimal PMI:**
  - **Quiescent SOL with lower densities may suppress parasitic losses due to PDI and wave scattering.**
  - **Effective impurity screening to mitigate deleterious effects of PMI on core plasma.**
- **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.**
- **Direct access to IBW / ICW mode conversion layers on HFS provide complete absorption of incoming fast wave with no energetic ion tail formation:**
  - **Absorption partition between electrons and ions is controllable through the minority hydrogen concentration.**

Related Presentations at this Meeting

- **PO3.00010 : S. G. Baek, "Spectral measurements of lower hybrid waves in the high-density multi-pass regime of Alcator C-Mod"**
- **PO3.00011 : I. C. Faust, "Power balance of Lower Hybrid Current Drive in the SOL of High Density Plasmas on Alcator C-Mod Tokamak"**
- **TP8.00003 : P. T. Bonoli, "Optimizing LHCD launcher using poloidal steering on Alcator C-Mod and ADX"**
- **TP8.00002 : R. Vieira, "ADX: a high field, high power density, Advanced Divertor test eXperiment"**
- **TP8.00004 : W. M. Beck, "ICRF Actuator Development for Alcator C-Mod and ADX"**
- **TP8.00005 : B. Sorbom, "ARC: A compact, high-field, disassemblable fusion nuclear science facility and demonstration power plant"**
- **JP8.00033 : S. P. Harris, "Transition From High Harmonic Fast Wave to Whistler / Helicon Regime in Tokamaks"**
- **CT2.00001 : R. I. Pinsker, "Whistlers, Helicons, Lower Hybrid Waves: the Physics of RF Wave Absorption Without Cyclotron Resonances"**

Mode converted IBW and ICW were used in C-Mod and TFTR to drive significant poloidal flows [1, 2]





[1] Y. Lin *et al*, PoP **16**, 056102 2009.
[2] C. K. Phillips *et al*, NF **40**, 461 2000.

- **ΔV_θ found to scale with P_{rf}**
- **Full-wave analysis [1] indicates strongest flow drive regime associated with ICW damping on ions at ^{3}He resonance**