RF Actuators for Steady-State Tokamak Development

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The US should emphasize development of RF actuators for steady-state (SS) scenarios– a critical issue for achieving SS in ITER, FNSF and beyond.

Exciting opportunities exist for the US to lead in innovative research aimed at developing reactor relevant RF actuators which will enable realization of driven SS tokamaks.

The 2007 FESAC report identified two major Gaps relevant to this presentation which "will remain even after current programs complete their research"

Gap G-2. Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas, including first wall and divertor interactions.

Gap G-7. Integrated understanding of RF launching structures and wave coupling for scenarios suitable for DEMO (& FNSF) and compatible with the nuclear and plasma environment.

Neutral Beam Injection has been the workhorse for AT development. However, NBI does not extrapolate well for reactors:

- Extension of radio nuclide confinement boundary
- neutron streaming
- reduction in tritium breeding ratio (TBR) due to port penetrations
- Feasibility and cost of >1 MeV steady-state beam development
- Steady-state lifetime and reliability

Consistent with a number of reactor studies (e.g., the ARIES series) FESAC also recognized that neutral beams are not suitable for reactors, concluding that:

"RF schemes are the most likely systems to be used and will require significant research to achieve the level of reliability and predictability that are required."

Heating and Current Drive methods are linked to field: higher field → improved plasma performance, higher power density, more reactor compatible launchers

HCD Method	Frequency	ITER (~5 T)	CD Efficiency $\eta = n_{20}IR/P$	Comments
Ion Cyclotron (ICRF, FW)	$\omega \sim \omega_{ci}$	50 MHz	0.3-0.4 in core NA for off-axis	Excellent heater; Core CD needs development.
Lower Hybrid Fast Wave (HFFW, HHFW, Helicon, …..)	$\omega < \sqrt{\omega_{ci}\omega_{ce}}$	1 GHz	0.3-0.4 Suitable for off-axis CD	Needs development. Reactor compatible launcher possible at high field.
Lower Hybrid Slow Wave	$\omega > \sqrt{\omega_{ci}\omega_{ce}}$	5 GHz	0.3-0.4 Suitable for off-axis CD	Waveguide launcher, reactor compatible. RF CD method of choice in tokamaks
Electron Cyclotron	$\omega \sim \omega_{ce}$	170 GHz	0.3 near core Lower for off-axis	mm wave technology Launcher is reactor compatible.
Electron Bernstein Wave	$\omega \sim \omega_{ce}$	NA	??	Needs development. May be applicable for startup and sustainment of STs

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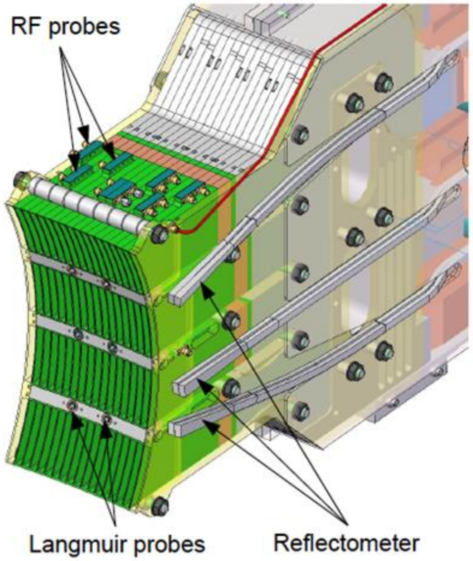
Current drive by the slow lower hybrid wave is the most efficient and well developed RF off-axis current drive method

C-Mod Lower Hybrid Experiment:

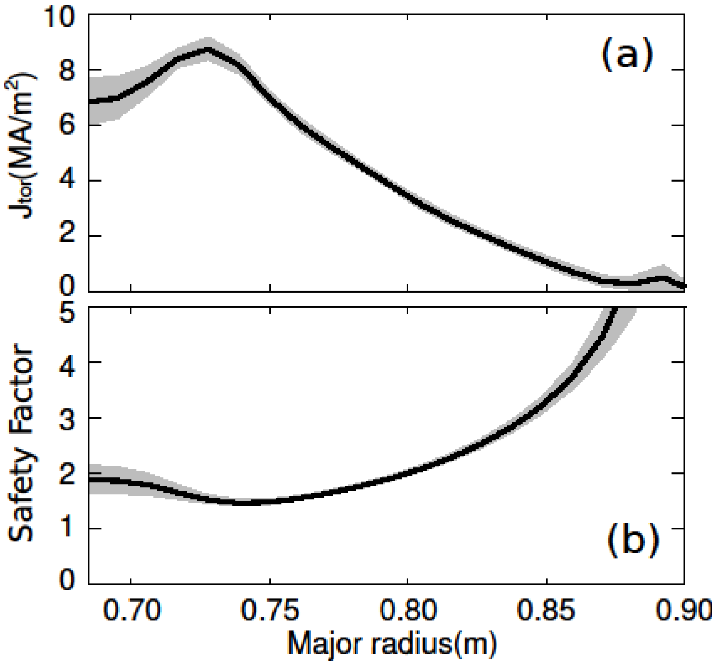
- Waveguide grill, adaptable for reactors



- 0.5 MA driven, $\bar{n}$= 0.5x10^{20} m^{-3} , P ≈ 1 MW, several current redistribution times
- High engineering CD efficiency:

$$\eta = \frac{n_{20} I R}{P} = 0.2 - 0.4 \text{ A·m/W}$$

- But efficiency degrades for $\bar{n} \gtrsim 1\text{x}10^{20}$ m^{-3}



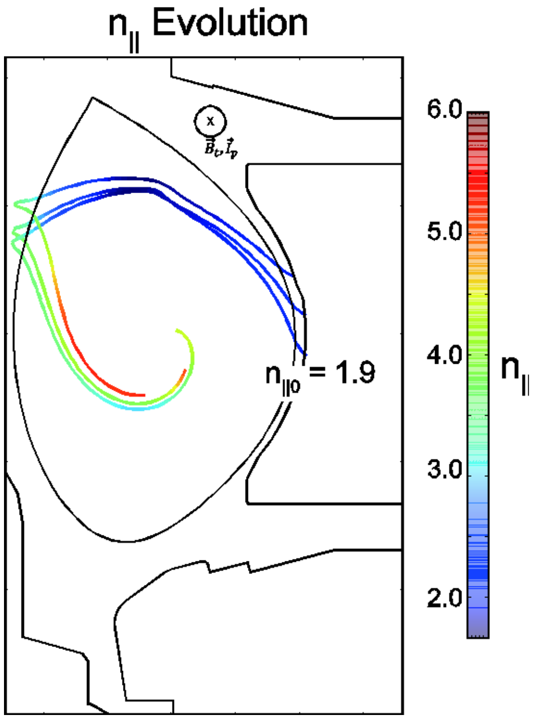
C-Mod example of current density and flat shear profiles in full non-inductive LHCD plasma, in line with AT scenarios.

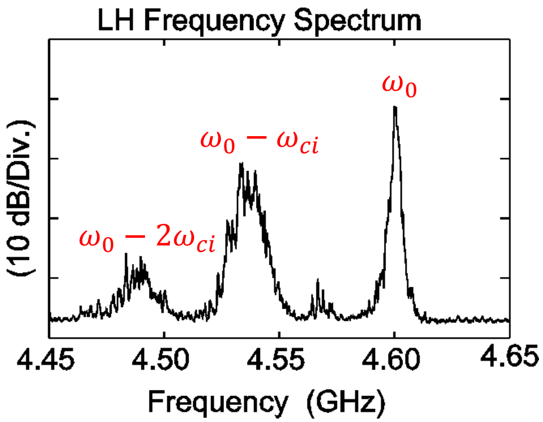
At high density, $\bar{n} \gtrsim 1x10^{20}$ m^{-3} , LHCD efficiency drops rapidly due to interactions in the inner SOL

Collisional absorption

$n_{||}$ upshift

Parametric Instability





Sidebands displaced from pump by harmonics of cyclotron frequency at edge.

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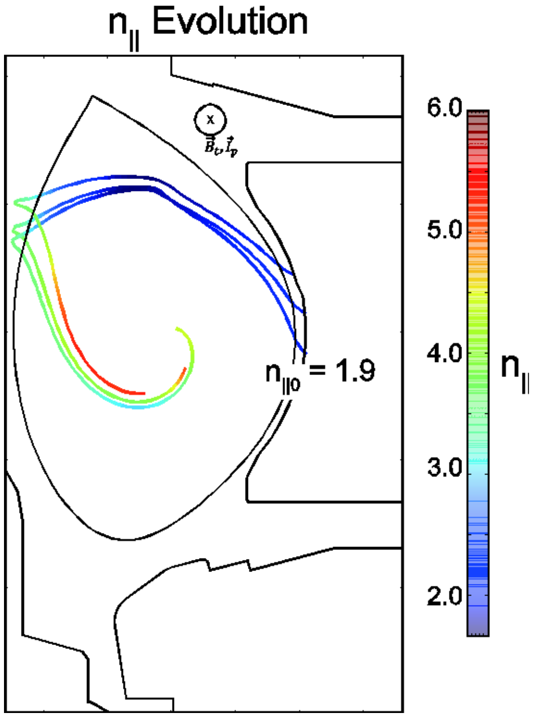
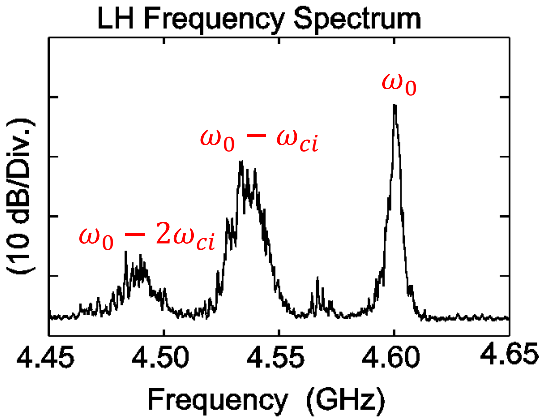




Sidebands displaced from pump by harmonics of cyclotron frequency at edge.

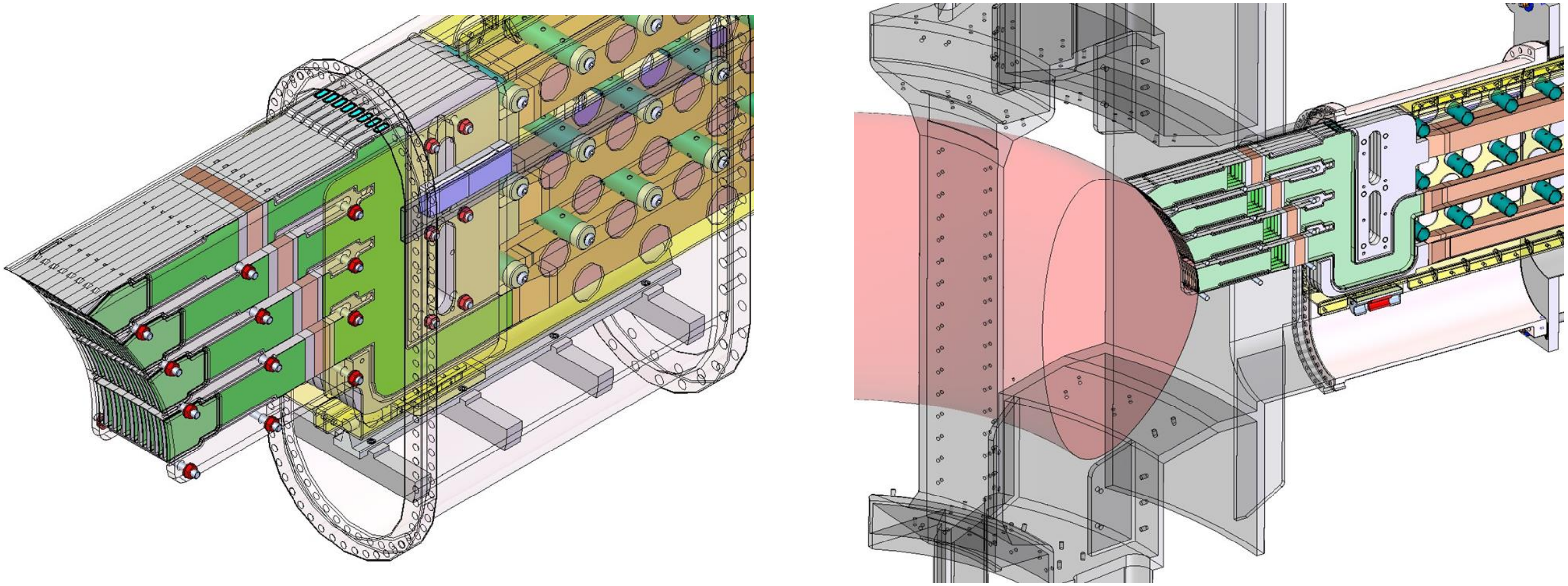
The solution is to enhance “single pass” absorption. This can be done by:

- Increasing T_e (some success has been achieved in C-Mod with mode conversion heated helium plasmas.)
- Moving the launcher off the midplane to take advantage of a toroidal effect which causes an upshift of $n_{||}$ and increases Landau damping

Optimizing location of LH launcher can substantially improve efficiency and j(r) control.

This is the basis for an upgrade of the C-Mod LH system, referred to as “LH3”, and the proposal to mount LHCD antennas on the inner wall in ADX and ARC.

Combined with the present launcher, LH3 would double the LHCD power to the plasma (1 → 2 MW), enable physics-rich synergy between the two launchers, and test efficacy of off mid-plane launcher location: higher efficiency, flexible j(r) control



- 800 k$ and 1 year from “go ahead” required to fabricate launcher and initiate experiments
- Project is on hold, pending FES decision on whether to proceed.
- LH3 simulations predict full non-inductive regimes feasible with f_{BS} > 50% in C-Mod

Completing the LH program on C-Mod would build confidence in LHCD physics understanding and simulations, and verify advantage of off mid-plane launch

Moving a lower hybrid coupler off the midplane has led to new possibilities for LHCD: Inside Launch!

Advantages of inside launch:

Higher field: Increases the window for accessibility and high efficiency:

$$\sqrt{1-\frac{\omega_{pi}^2}{\omega^2}+\frac{\omega_{pe}^2}{\omega_{ce}^2}}+\frac{\omega_{pe}}{\omega_{ce}} < n_{\parallel} < \sqrt{\frac{30}{T_e(keV)}}$$

Inside launch also eliminates need for port-mounted systems in FNSF or pilot plant.

In addition:

Quiescent edge plasmas: Weaker PMI issues, better coupling, excellent impurity screening, minimal turbulent scattering.

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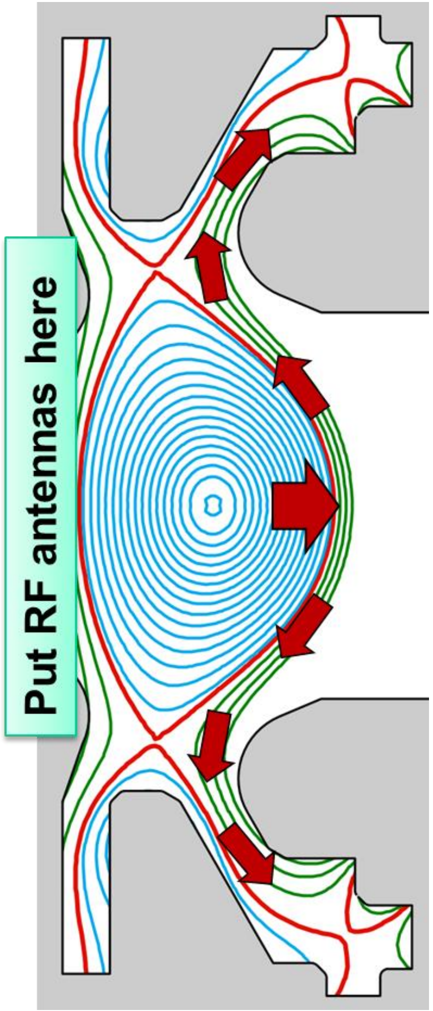
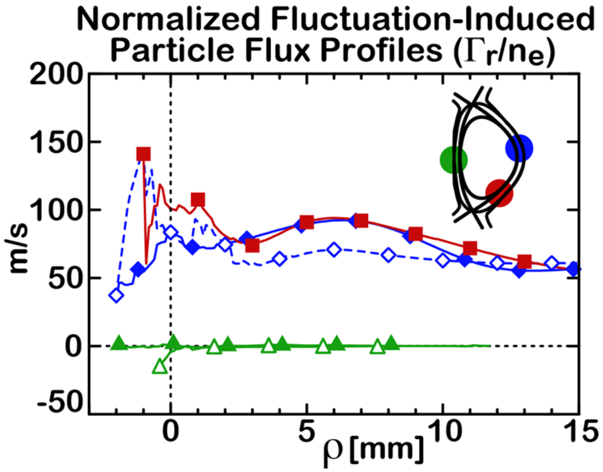



Normalized Fluctuation-Induced Particle Flux Profiles (Γ_r/n_e)

C-Mod – Smick NF 53 (2013) 023001

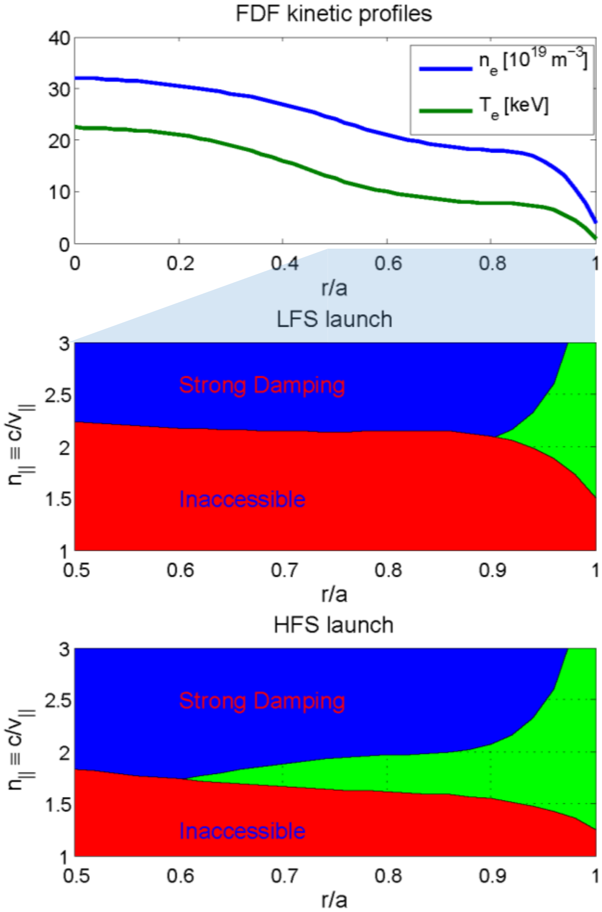
Inside launch is a “win-win” concept:

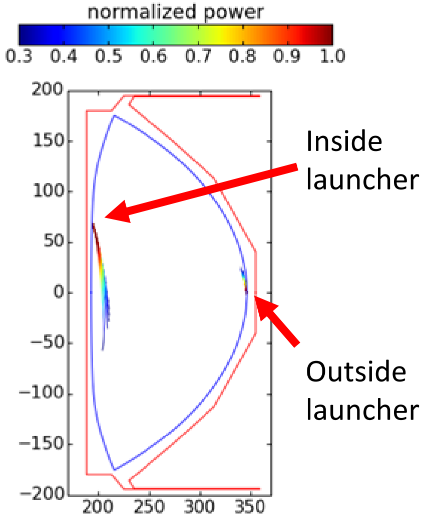
Higher field improves wave physics, increasing window for accessibility and high efficiency, plus

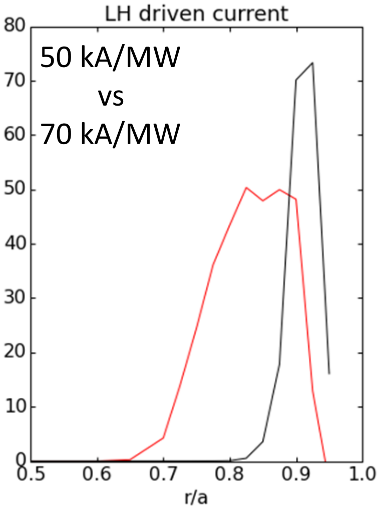
A Quiescent edge! Gap G-7

As an example of high field advantage, inside launch for lower hybrid slow wave opens window for current drive in FNSF-AT

- The FNSF-AT is a moderate field (~ 5.5 T) tokamak designed by GA as a platform for a Fusion Nuclear Science Facility (FNSF)
- The window (shown in green) for slow lower hybrid wave penetration is defined by the onset of Landau damping and the wave accessibility limit:
- The window is significantly larger for inside launch and allows lower $n_{\|}$ to penetrate, which improves efficiency since $\eta \sim \frac{1}{n_{\|}^2}$.
- The larger window also allows more freedom in control of J(r)







In this example, off axis LHCD current drive region extends for 0.85 < r/a < 0.95 to 0.65 < r/a <0.95 and η increases by 40%

But is inside launch practical?

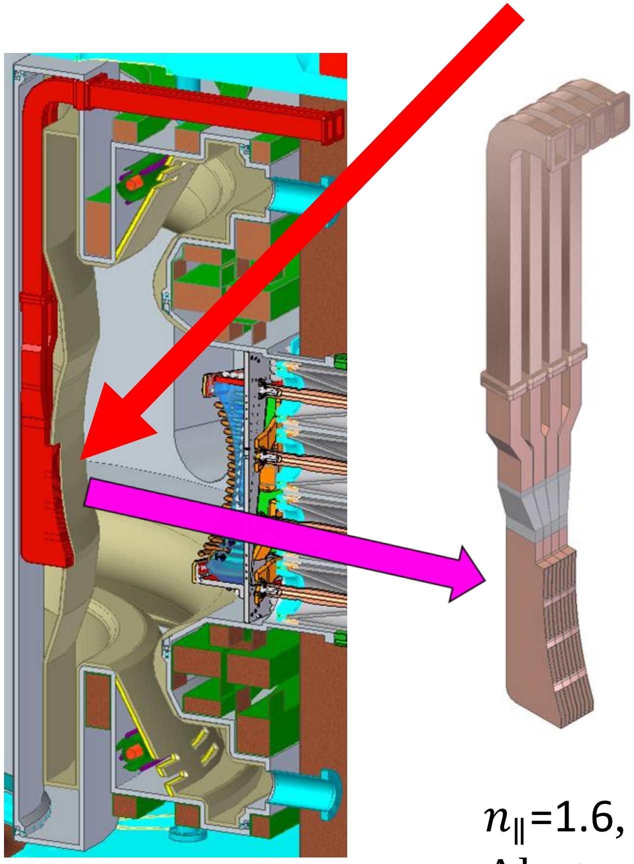
Yes, if integrated into machine design!

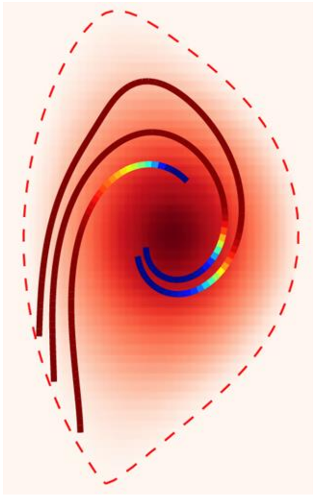
A conceptual design has been developed for ADX (see next talk by Brian LaBombard)

Splitter and multi-junction C-Mod and Tore-Supra fabrication techniques produce compact LHCD launchers that can fit on the inside wall.

- Strong single pass absorption
- Low $n_{\|}$ launch, takes advantage of high field and geometric upshift
- High efficiency
- Benefits of quiescent edge plasma

Below midplane launch optimizes wave penetration and absorption





$n_{\|}$=1.6, Equilibrium from Alcator C-Mod I-mode

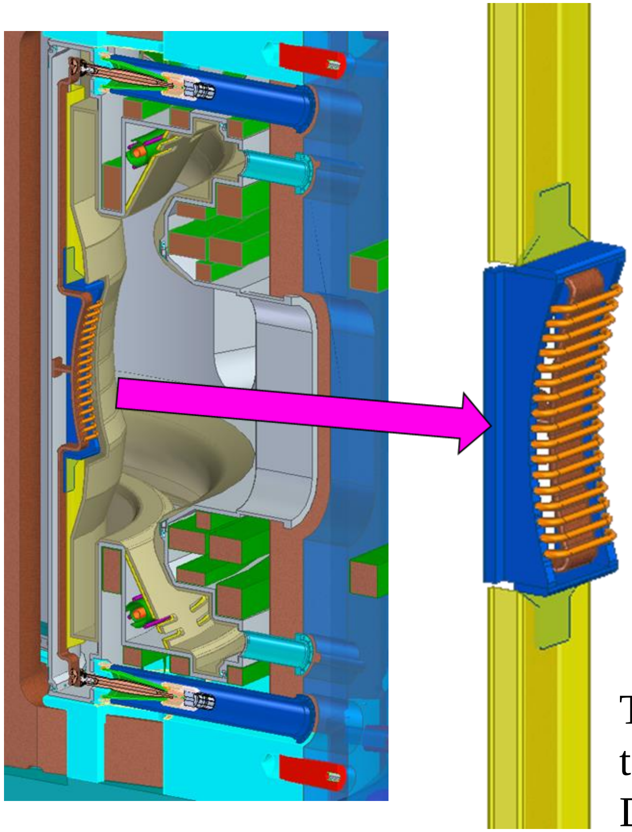
What about ICRF?

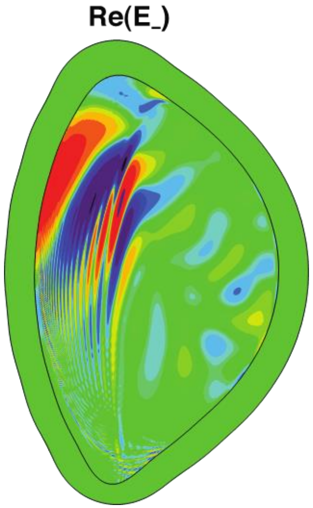
Inside launch provides direct access to mode conversion (FW → IBW) layer, e.g., 50-50 D-T heating in reactor

Reduced production of energetic ion tails and impact on antenna structures.

Same great PMI benefits:

- Kinder, gentler SOL
- Excellent impurity screening
- Lower neutral pressure





FW mode-conversion to IBW with efficient flow drive and heating

TORIC simulation: B = 5.4 tesla, f = 80 MHz, 15% H in D, n_φ = -10, 40% to electrons, 30% to H 1st harmonic and 30% to D 2nd harmonic

Summary

Development of RF actuators for steady-state tokamak regimes is critical to prepare for proceeding with FNSF/Pilot Plant and DEMO designs.

Completion of the C-Mod Lower Hybrid experiment would confirm understanding of a critical issue in LHCD physics and verify the advantages of off-midplane launch

Moving LH and ICRF launchers to the inside wall has huge potential “win-win” regarding wave physics and performance, and minimizing PMI issues (Gap 7)

Developing inside launch requires a purpose-built device. The ADX concept discussed in the next talk would provide an excellent platform for developing *integrated* steady-state scenarios driven by RF actuators.

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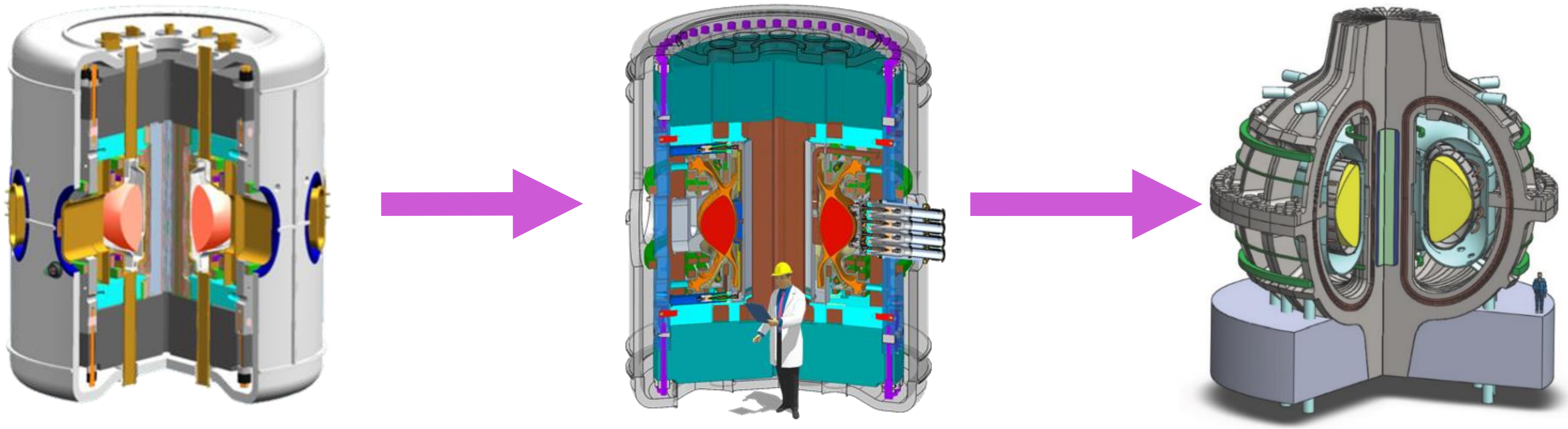
A coherent plan toward a high field FNSF/Pilot Plant:



C- Mod Lower Hybrid Physics

ADX Integrated RF SS Scenario

ARC FNSF/Pilot Plant

What benefits accrue to other RF schemes from Inside Launch (in addition to quieter SOL)?

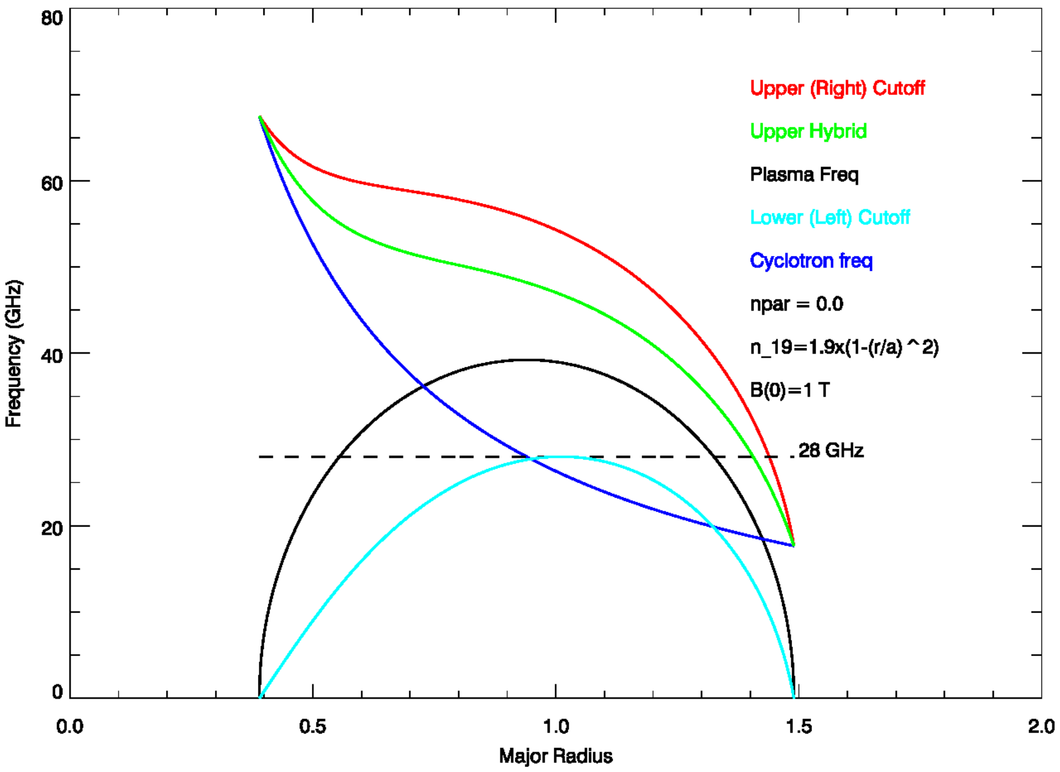
Fast lower hybrid wave $\left(\omega < \sqrt{\omega_{ci}\omega_{ce}}\right)$

Higher field at inner wall permits reactor relevant waveguide transmission and launchers, for example slot-loaded[†] or slow-wave waveguides.

ECH/EBW

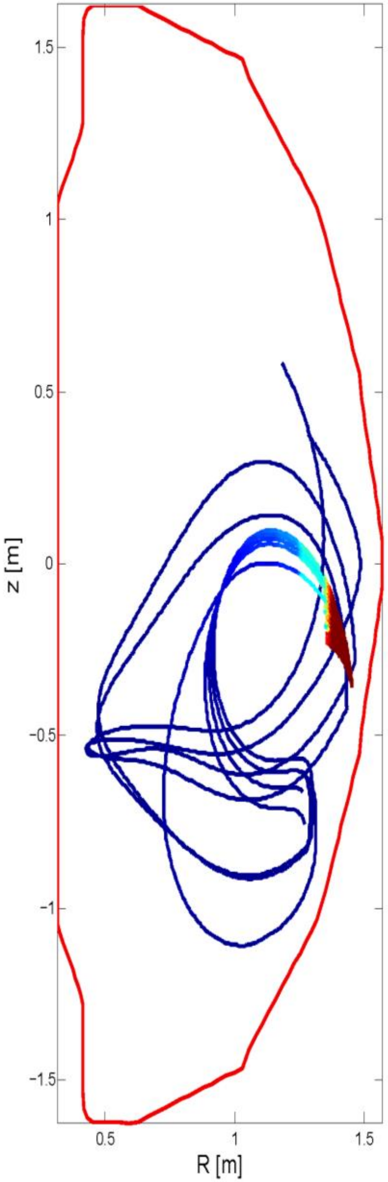
Inside X-mode launch permits direct access to upper hybrid resonance (for frequencies less than the maximum value of the right cutoff) and conversion to EBW – May be useful for ST startup.

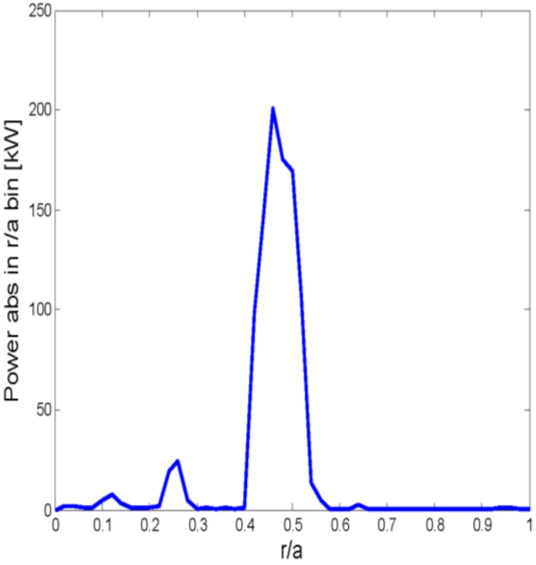
Example of direct access to UH layer and EBW mode conversion @ $n \approx$ 2x10^{19} m-3 in NSTX-U. Densities up to 7x10^{20} m^{-3} are possible at higher frequency, and higher *n* is possible with higher B.



[†] Colborn, J. A., Parker, R. R. , et .al., Nucl Fusion **31** (1991) 960.

A quick look suggests that the Helicon could be effective in NSTX-U





f = 100 MHz

$n_{\|}$ = 2 – 4

B_T = 1 T

$n_{20}(0)$ ~ 1

T_e (0) ~ 1.6 keV

LH3 simulations show regime with fBS > 50% could be realized