Massachusetts Institute of Technology

Plasma Science & Fusion Center

Plasma-material interactions & RF sustainment for steady-state tokamaks

Dennis Whyte

Plasma Science and Fusion Center

Acknowledgements to many colleagues including

P. Bonoli, R. Parker, S.G. Baek R. Mumgaard, Y. Popaly, B. LaBombard, G Wallace, N. Fisch, M. Garrett, G. Olynyk, B. Sorbom, J. Sierchio, and more

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Current Drive: Make-or-Break Unsolved Issue for tokamaks as fusion energy systems

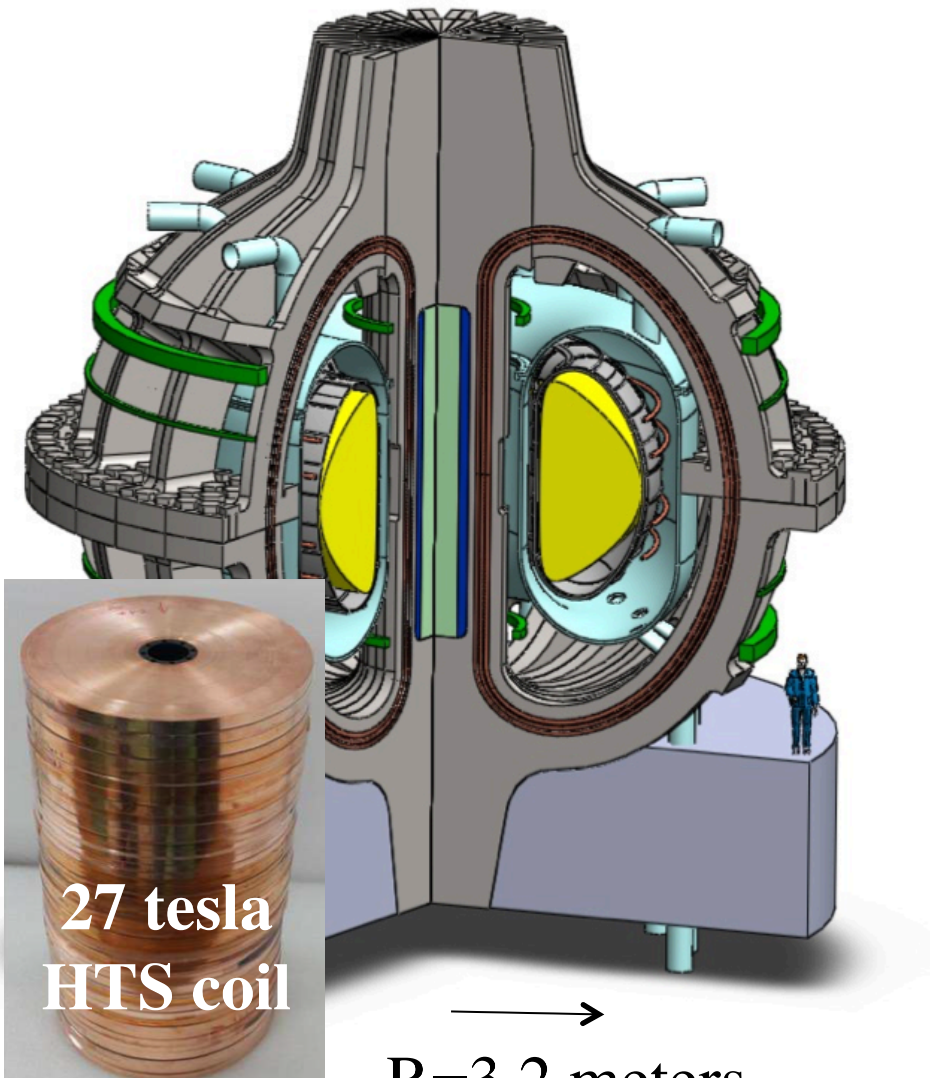
- **Failing or success of current drive will determine the fate of robust steady-state tokamak**
  - **Recirculating power → Need high efficiency**
  - **Disruption / transient avoidance → Current profile control**
  - **Achieving high gain + high H + moderate bootstrap → Both of the above!**

- **Coupled technical and scientific challenges of current drive in a 24/7 reactor environment**
  - **Coupling in power + launcher survival**
  - **Controlling current drive location**
  - **Efficiency**

- **Recent technology (high-B superconductors) and conceptual breakthroughs (high-field launch + α channeling) provide much brighter prospects for steady-state tokamak reactor.**

New HTS technology → ARC Fusion Pilot
23 T peak field + size of JET/TFTR

B. Sorbom, et al Fusion Eng Design (2015)



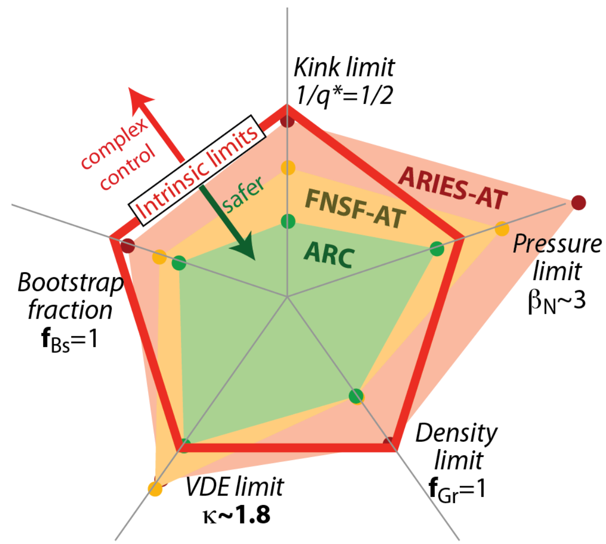
R=3.2 meters

500 MW fusion power

~350 MW GROSS electricity

~250 MW NET electricity

Operates away from all limits



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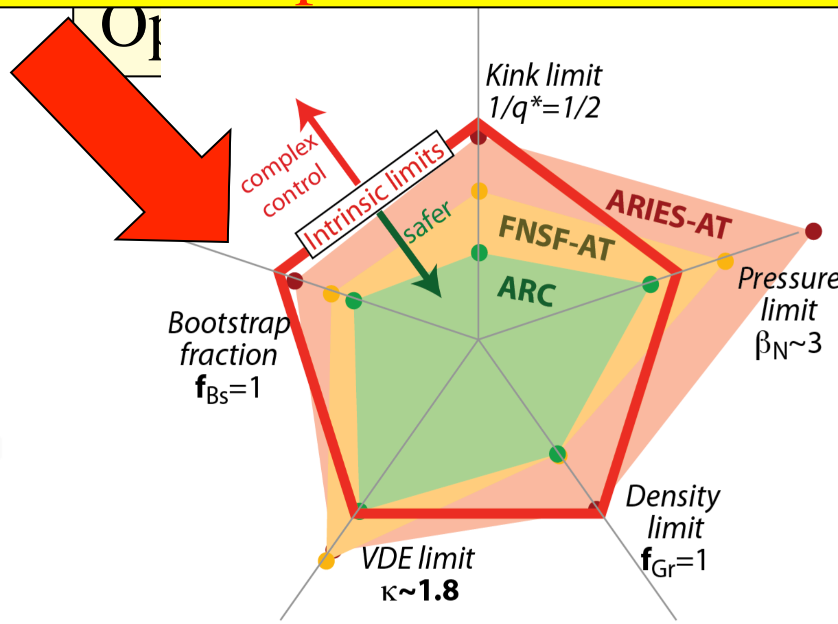
Op ... ts

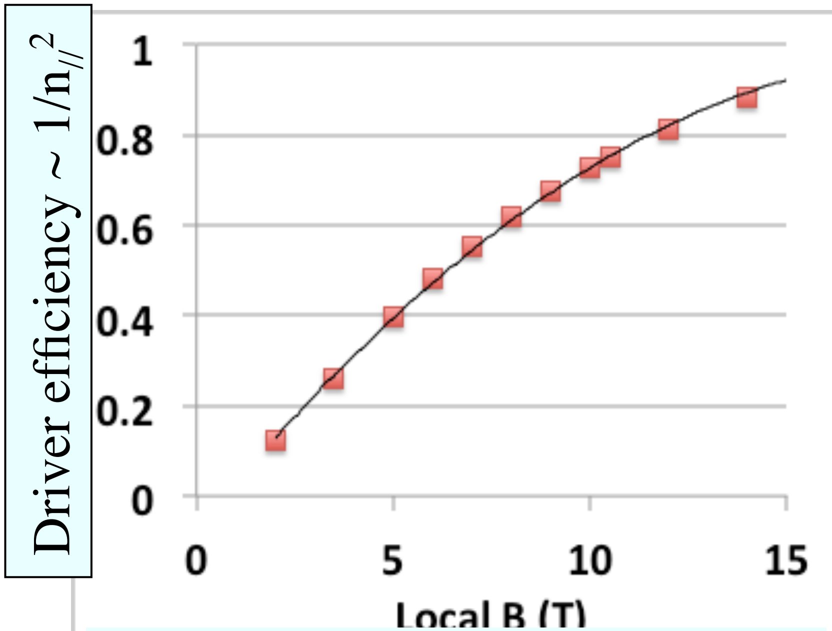
**Grand Challenge:
Continuous, efficient reliable current drive for 35 % I_p**

R=3.2 meters



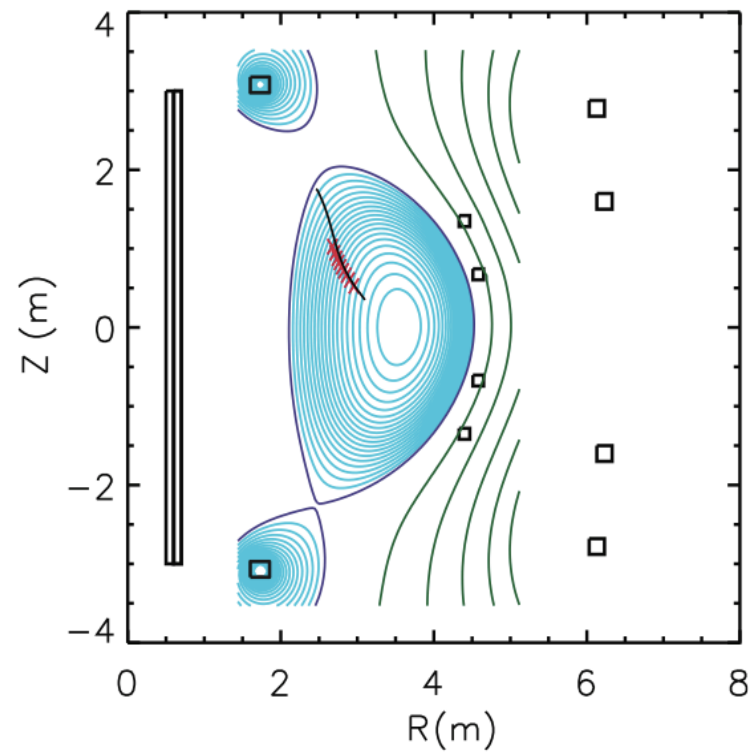
Key ARC innovation:
High-field launch + high B synergy → Steady-state

Improved LHCD efficiency at local high field



$$n_{//} = \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \left(\frac{\omega_{ci}}{\omega_{RF}}\right)^2} \simeq 1 + \frac{3.2 n_{20}^{1/2}}{B}$$

High-field-side LHCD launchers



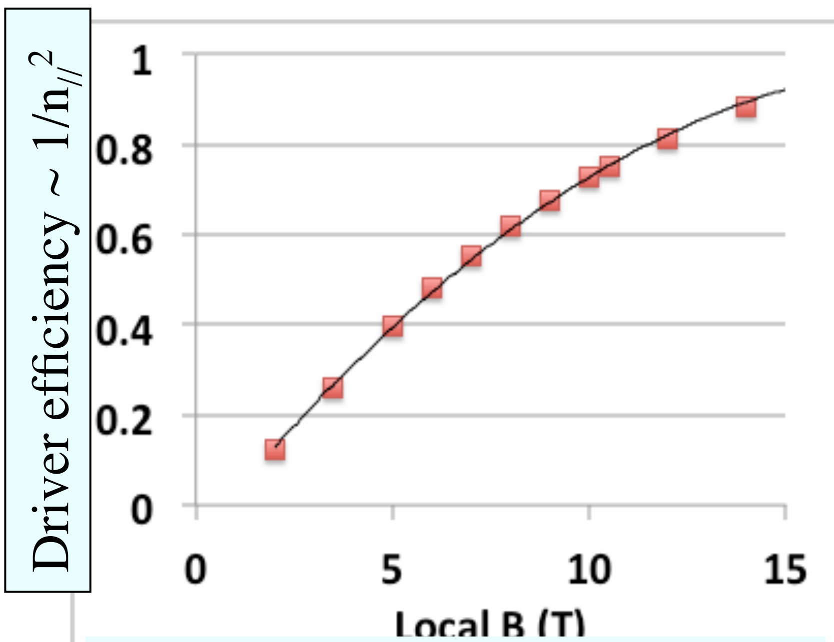
Drivers provide ~ 37% of current but only 7% of heating
→ Control with high gain!

VOLUME 45, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1980

Creating an Asymmetric Plasma Resistivity with Waves

N. J. Fisch and A. H. Boozer
Princeton University, Plasma Physics Laboratory, Princeton, New Jersey 08544
(Received 16 April 1980)

efficiency at local high field



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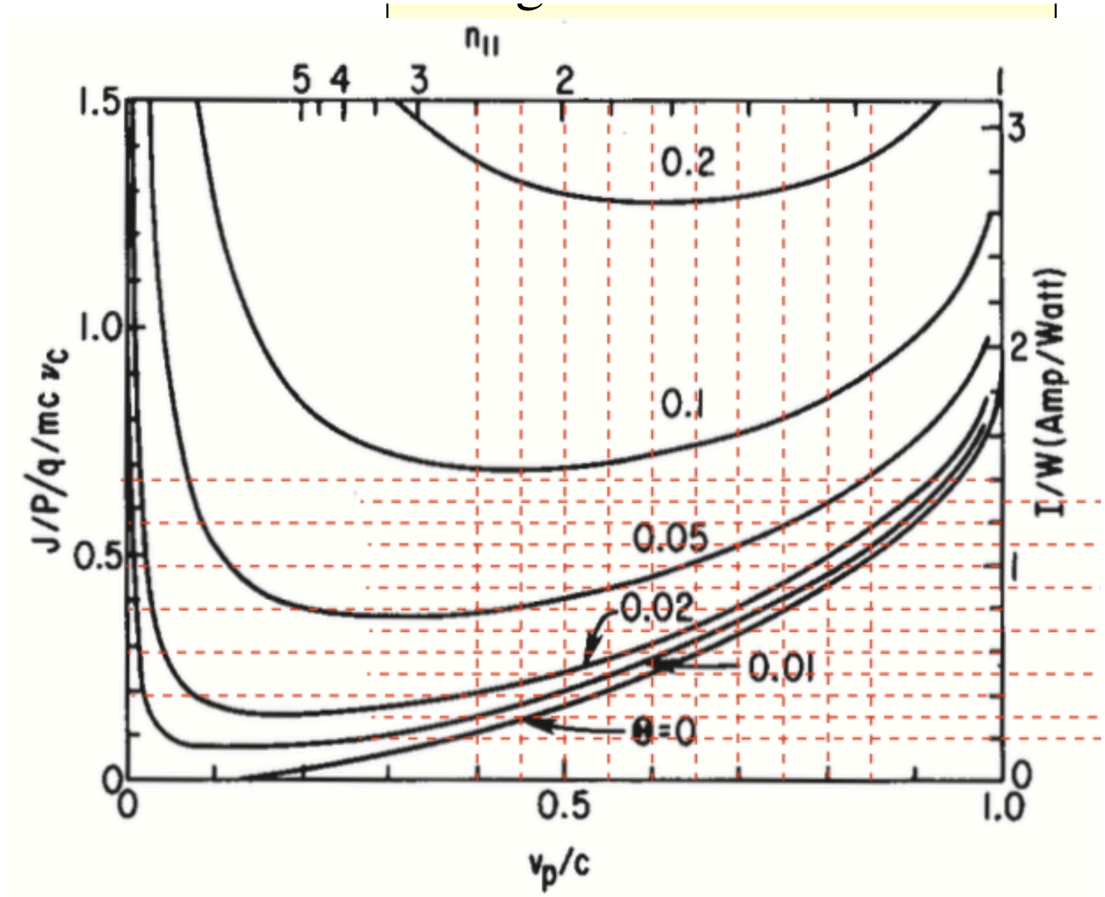

Karney, Fisch Phys. Fluids 28 (1985)

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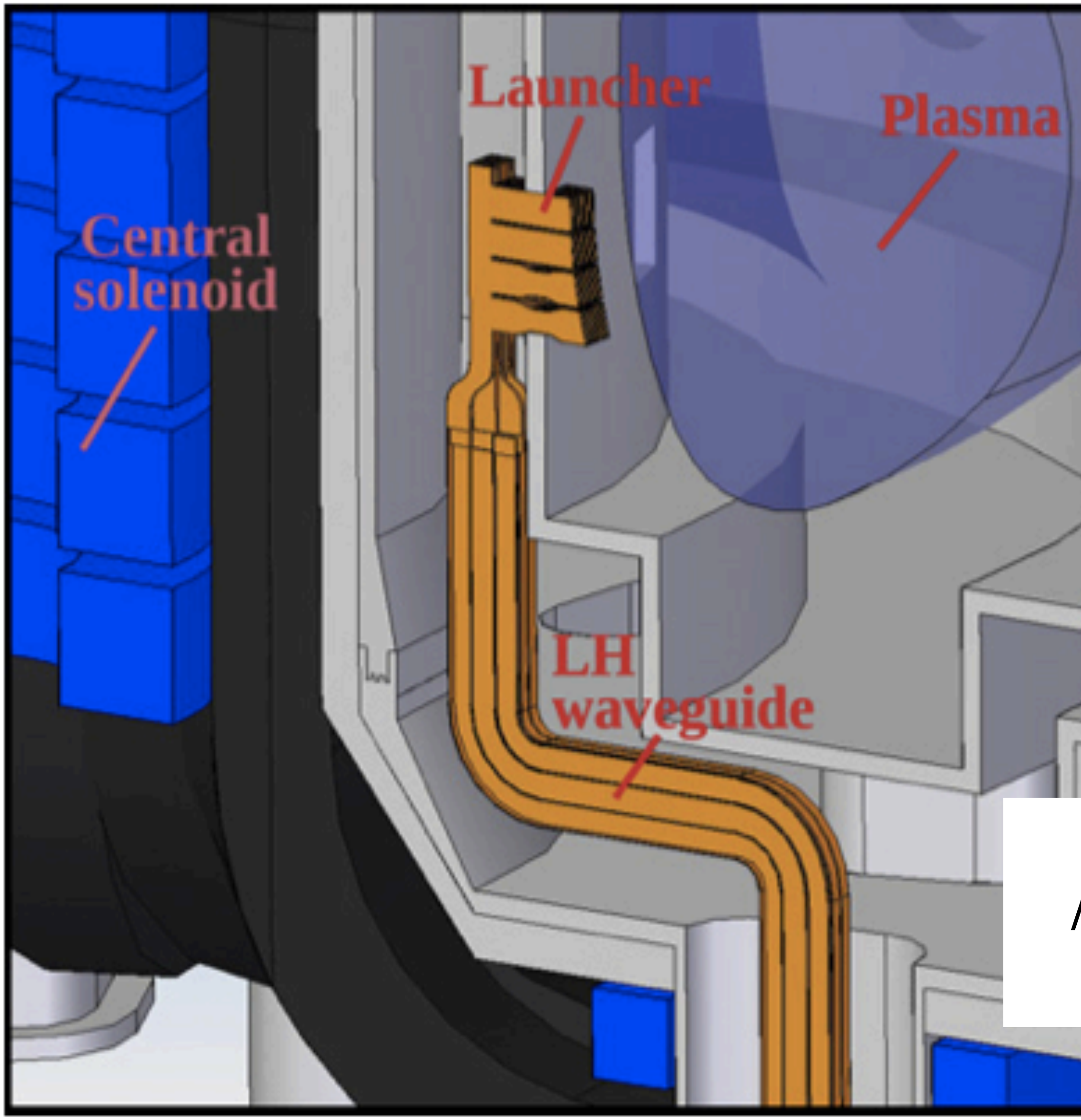
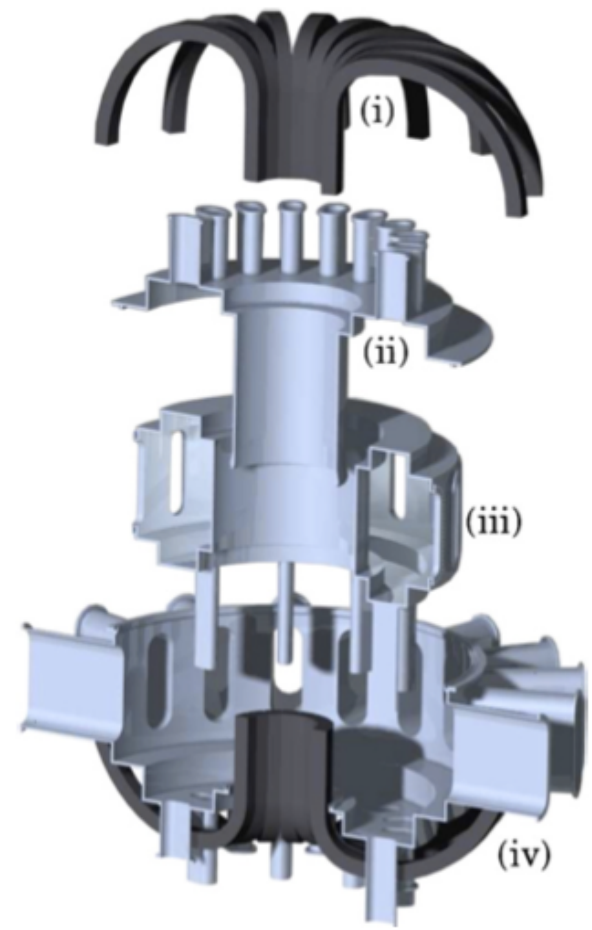
- Lea

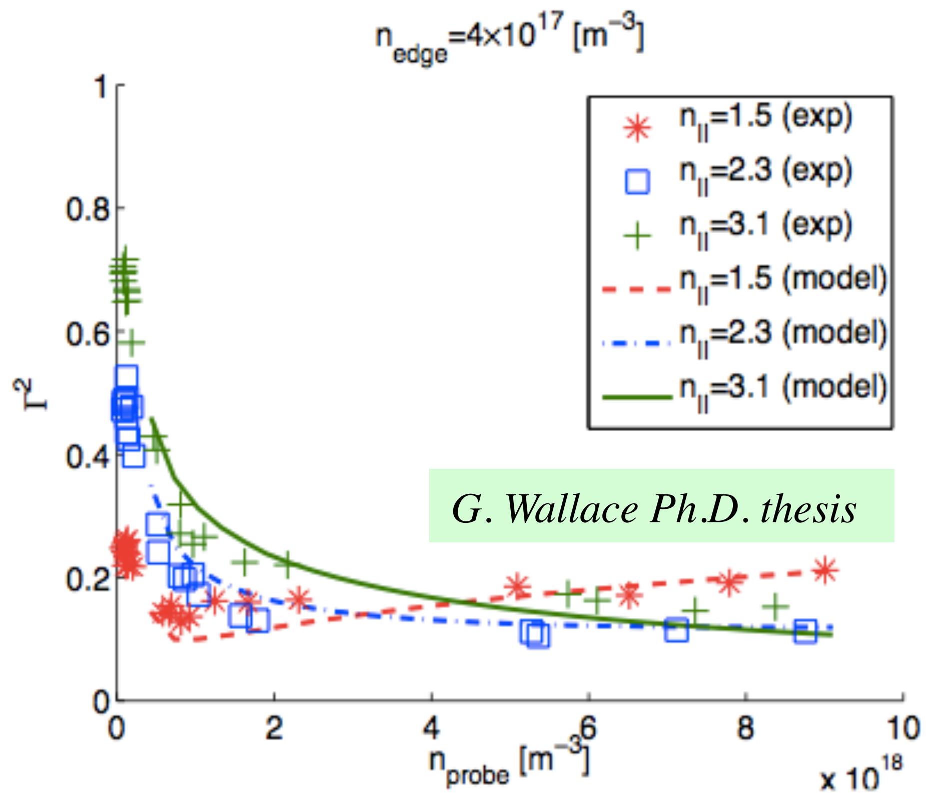




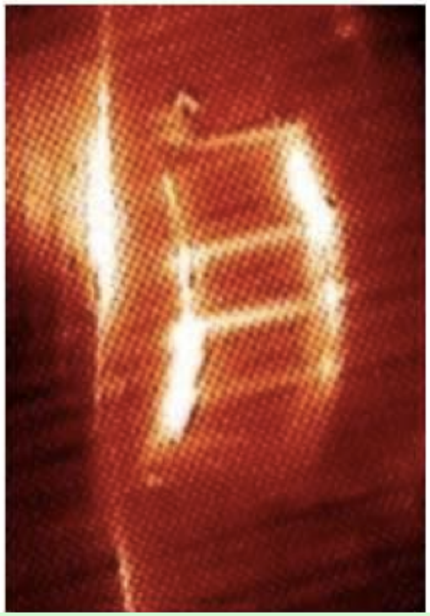
Vulcan "24/7 Tokamak" /w Demountable HTS coils (FED 2012)

Mike Garrett (student): why not fit LH launcher on the high-field side "corner" in ~10 cm radial space between the inner high-T vessel and outer VV?

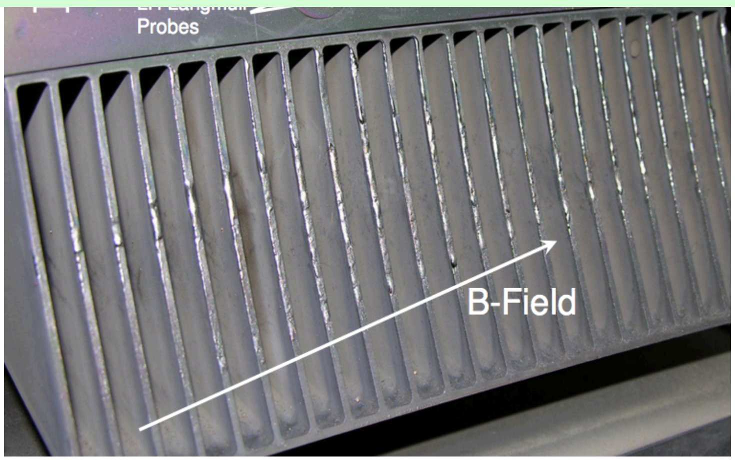
Wave coupling sets irreducible plasma contact at launcher → PMI challenge



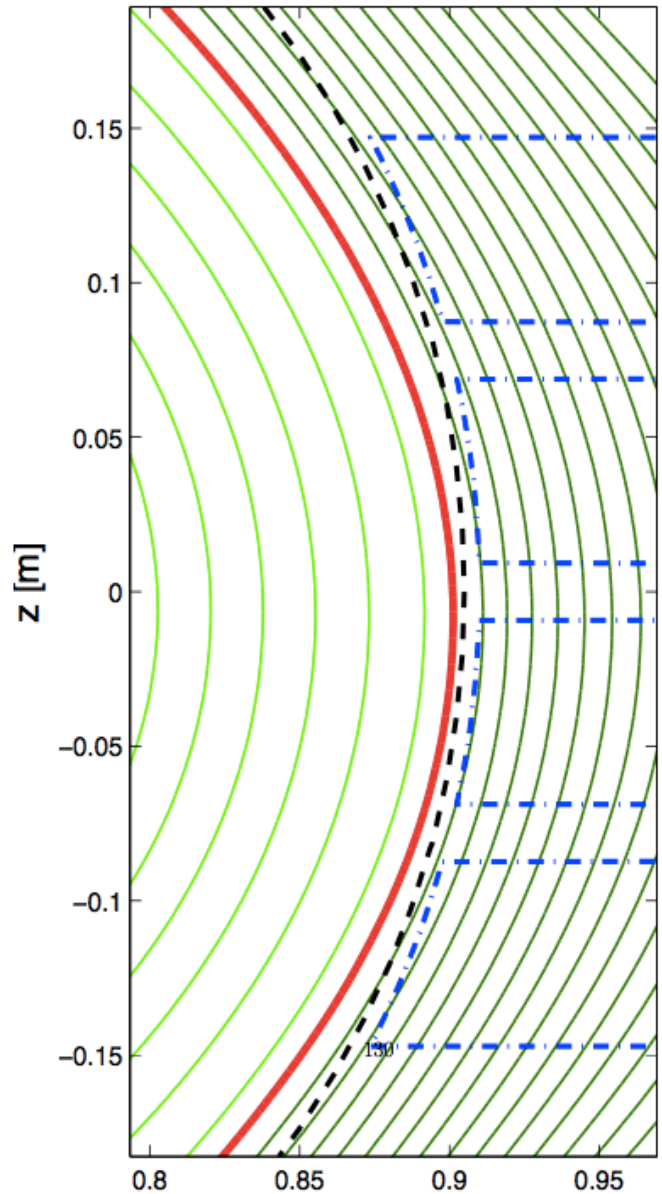
G. Wallace Ph.D. thesis

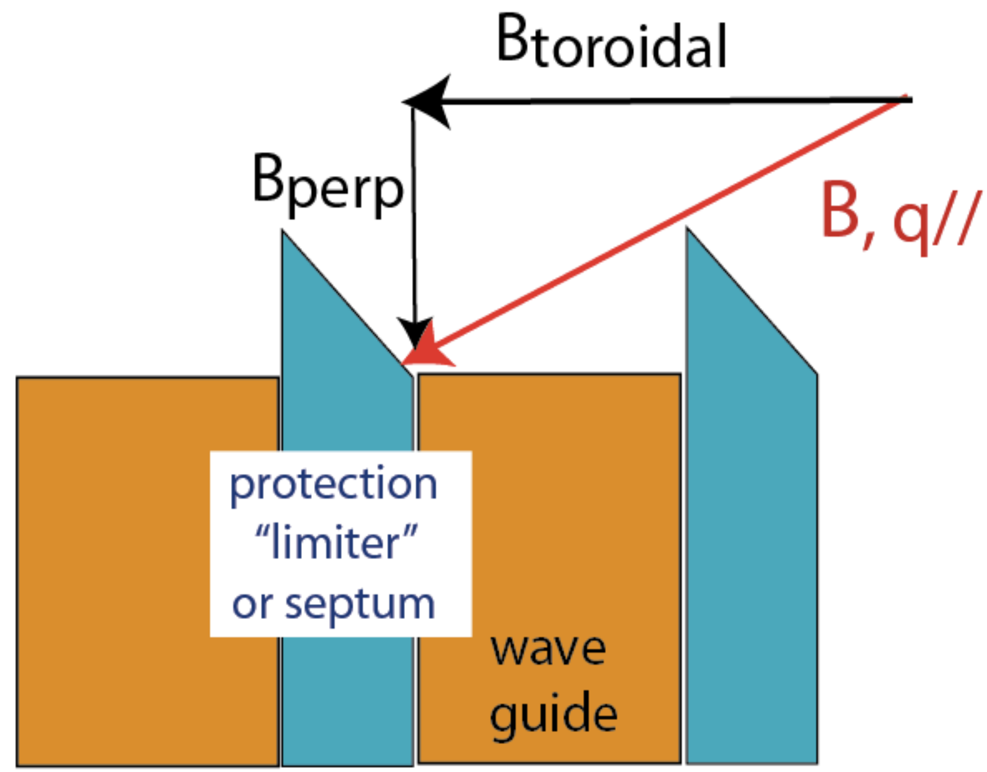


Plasma-launcher interactions in Alcator C-Mod



Geometry plays defining role in PMI of non-axisymmetric launcher structures



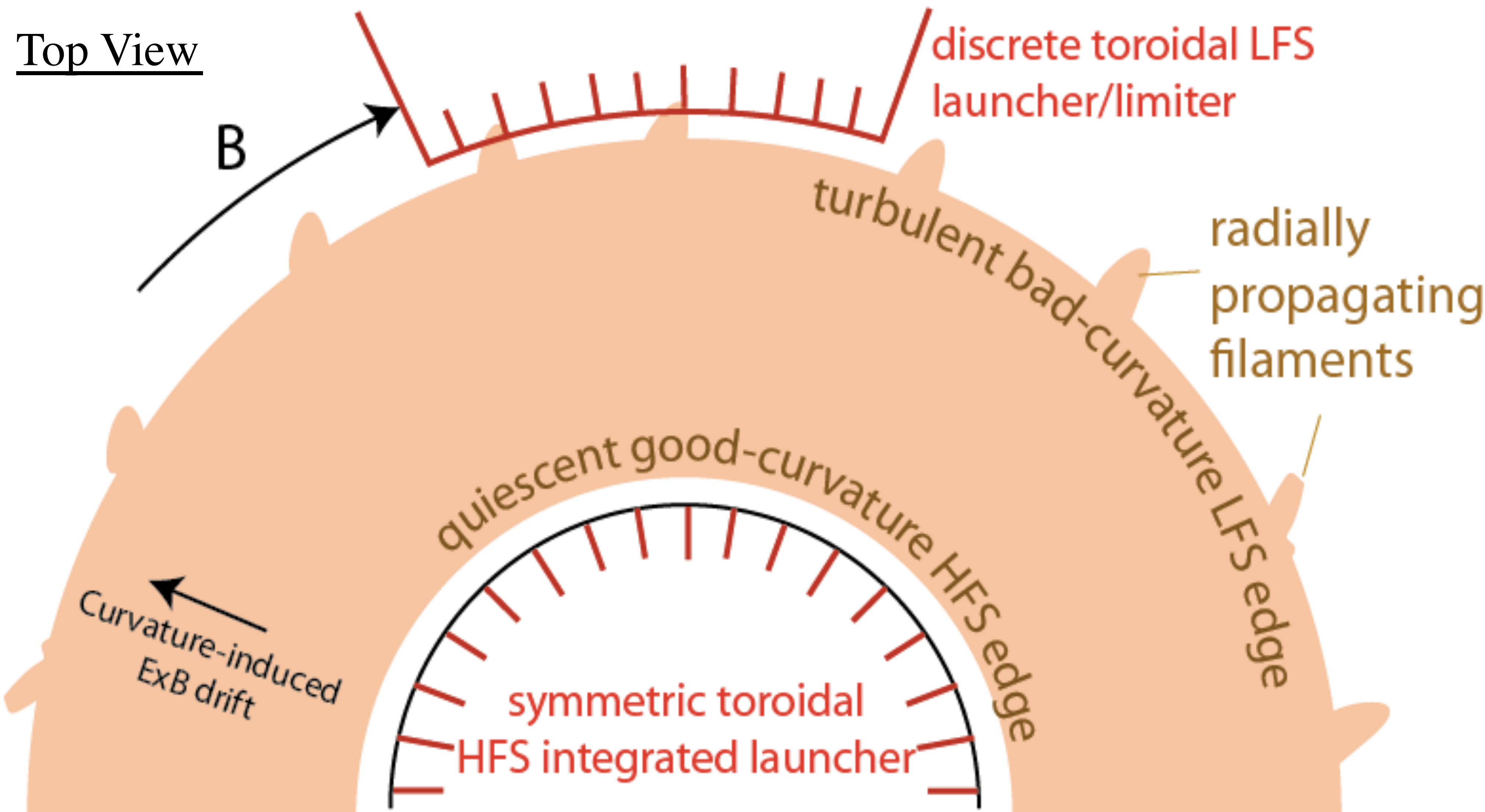


Heat flux & erosion challenge to launcher is severe for Low-Field Side launchers

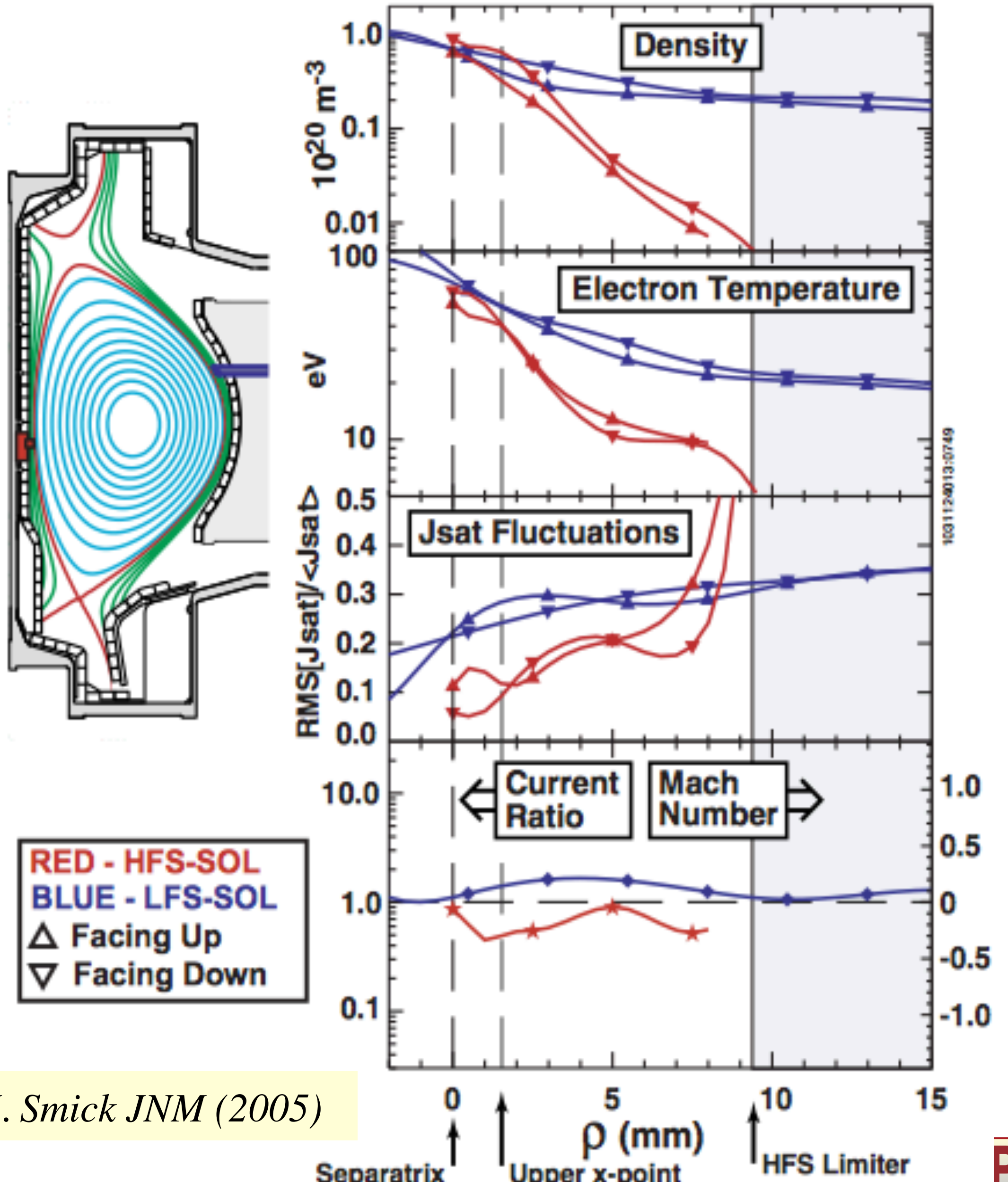
	LFS (min. n_e)	LFS (+local source)
n_e (m^{-3})	10^{18}	~$4x10^{18}$
T_e (eV)	10	20
q// (MW/m^2)	0.5	~ 2.5
// Flux (ion/s/m^2)	$3x10^{22}$	$2x10^{23}$
B_{perp} / B	~ 0.2	~ 0.2
q (MW/m^2)	0.2	1
Erosion rate (mm/year)	~ 6	~30

This is the "upstream" location of the SOL.
No chance of controlling q or erosion through // SOL physics

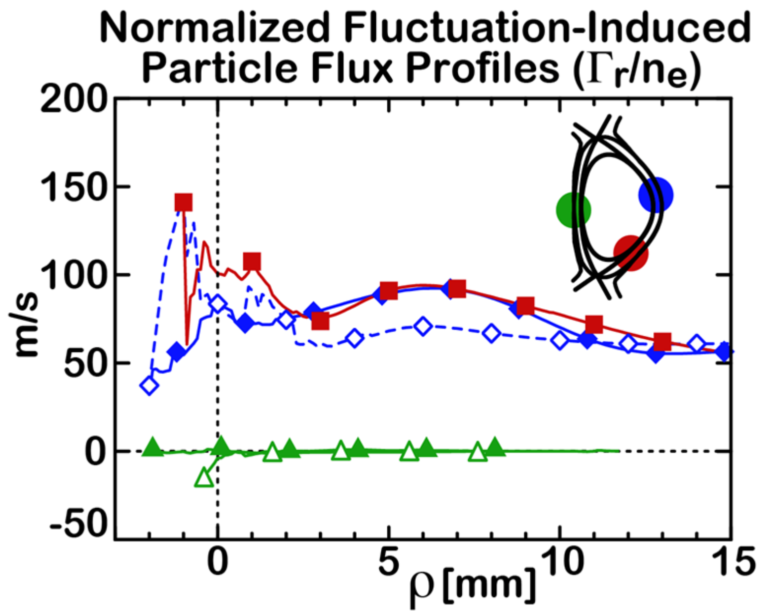
Basic plasma geometry and stability argue for High-Field Side launchers to solve PMI issues

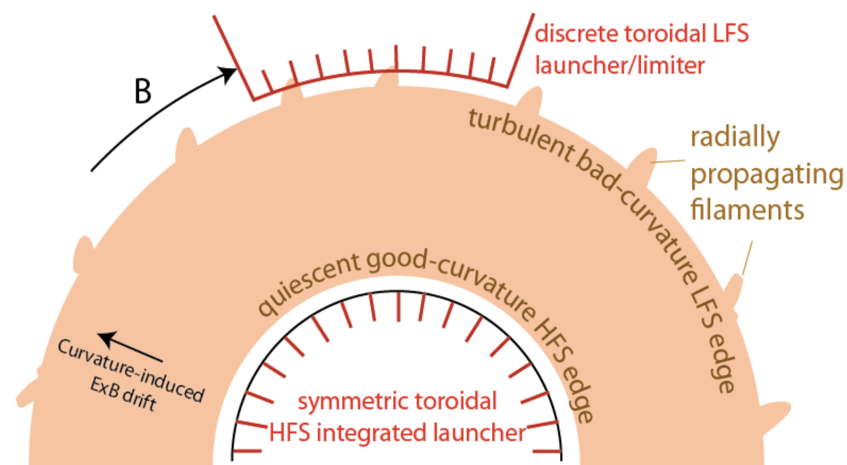


The answer lies in the quiescent HFS SOL, particularly found in double-null configuration



N. Smick JNM (2005)

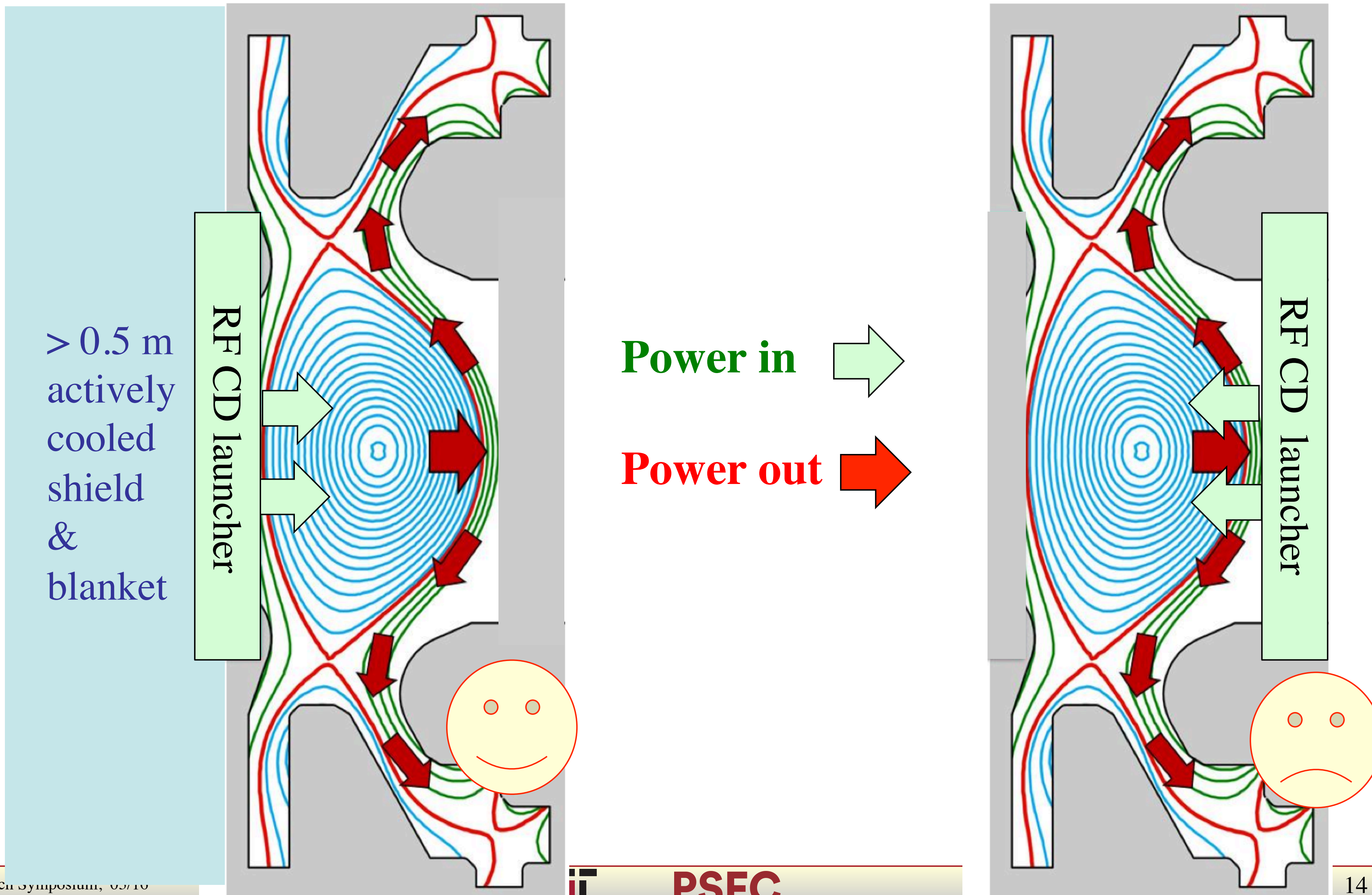




Heat flux & erosion challenge to launcher structure mitigated by HFS launch B-field geometry & good curvature

	LFS (min. n_e)	LFS (+local source)	HFS (min. n_e)
n_e (m^{-3})	10^{18}	~4×10^{18}	**10^{18}**
T_e (eV)	10	20	**10**
q// (MW/m^2)	0.5	~ 2.5	**0.5**
// Flux ($ion/s/m^2$)	3×10^{22}	2×10^{23}	**3×10^{22}**
B_{perp} / B	~0.2	~0.2	**~0.04**
q (MW/m^2)	0.2	1	**0.04**
Erosion rate (mm/year)	~ 6	~30	**~ 1**

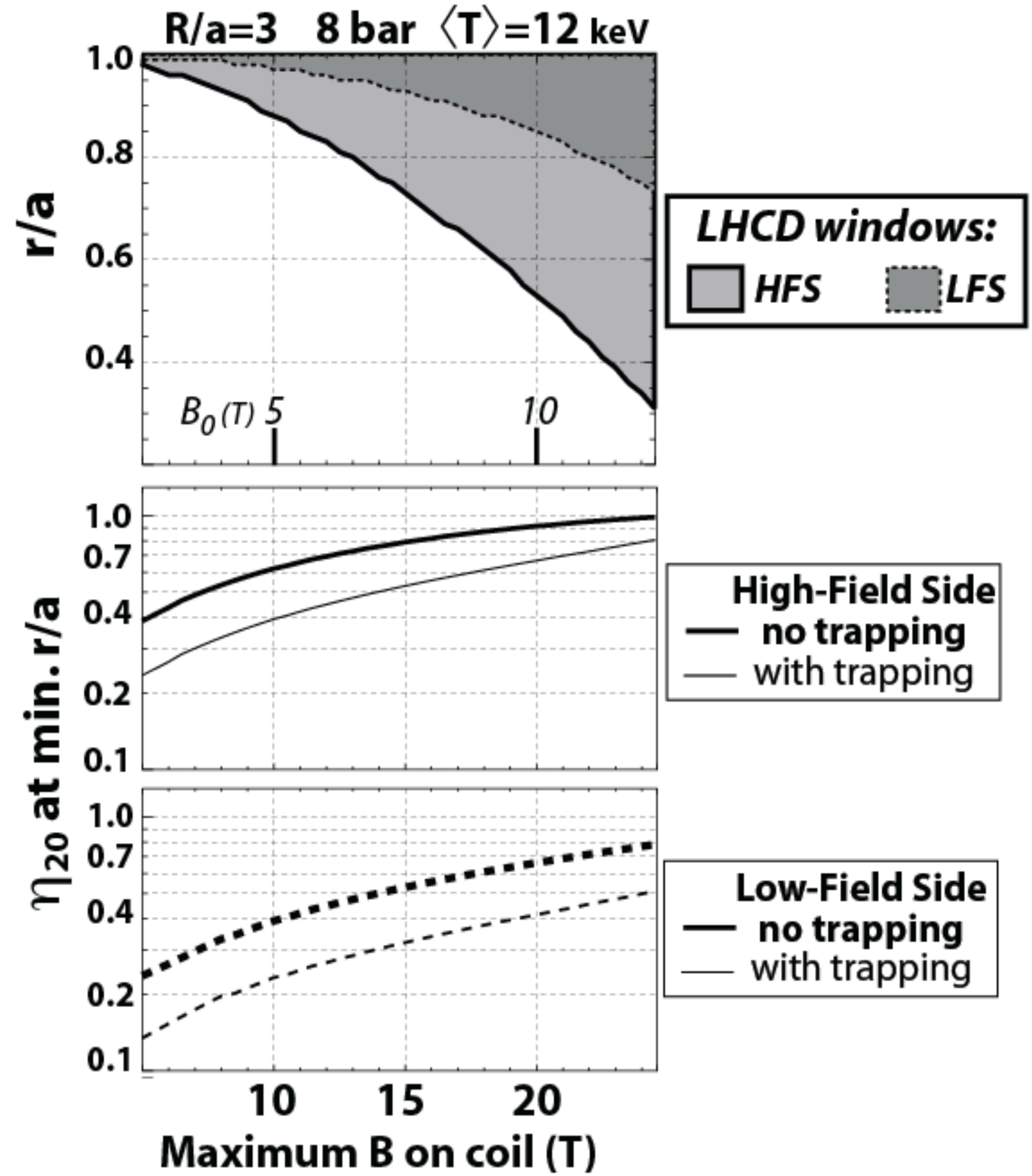
Reactor power exhaust favors HFS launch and blanket space allows HFS launch



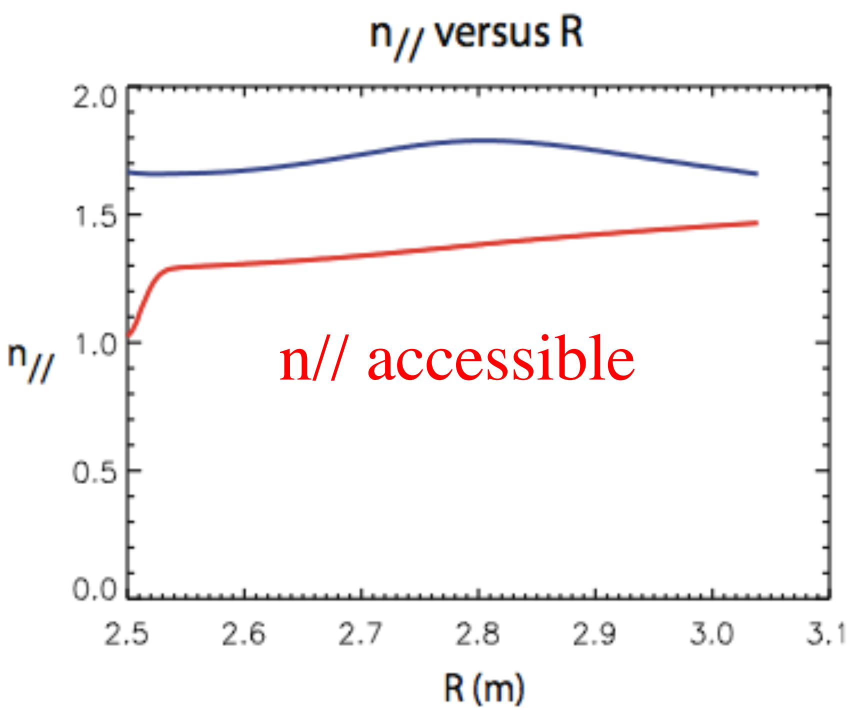
HFS vs. LFS Launch in prototypical FNSF conditions

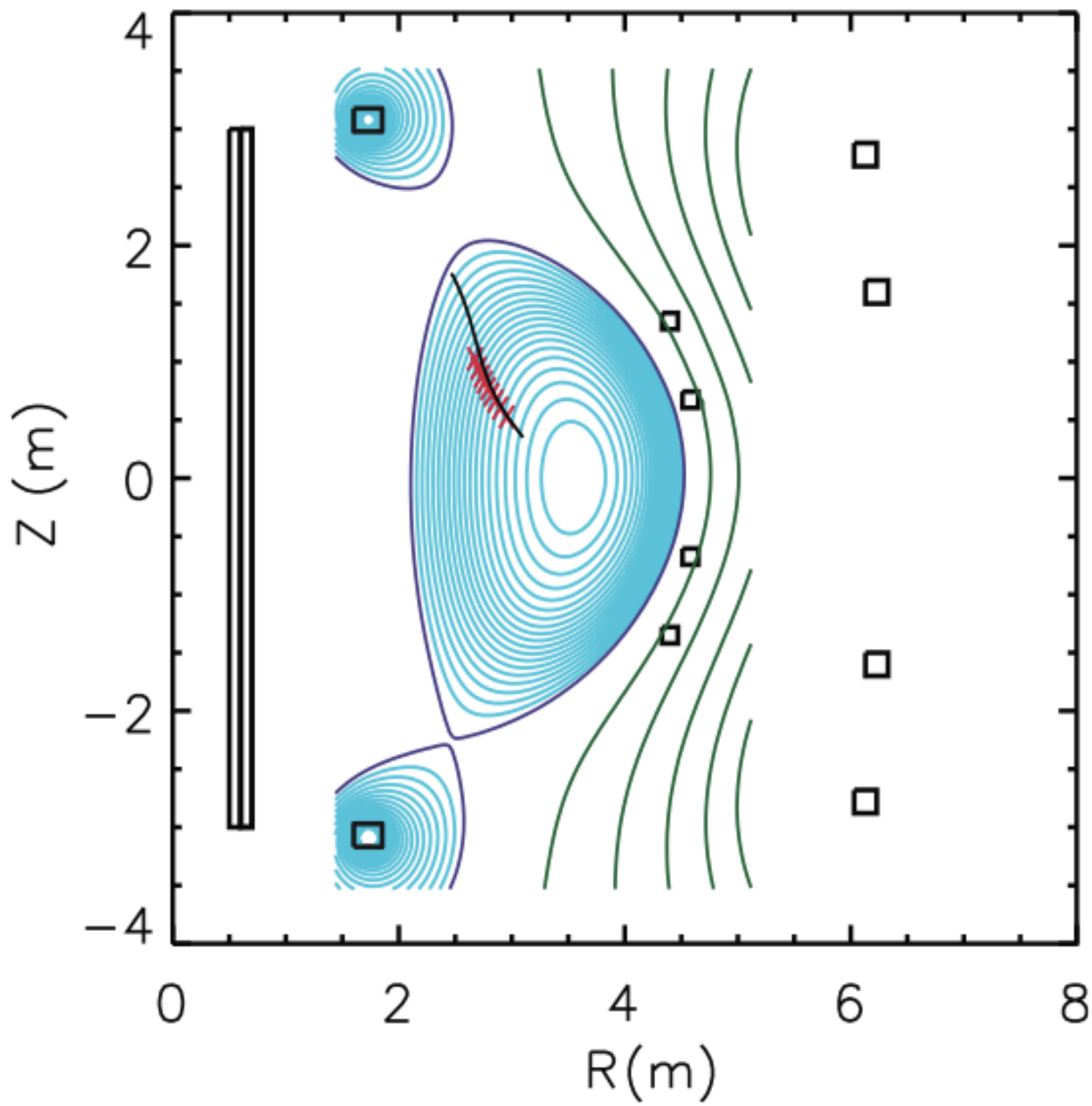
- HFS can provide CD much deeper into the plasma

- Efficiency improves due to both lower n// and lower trapping effects.

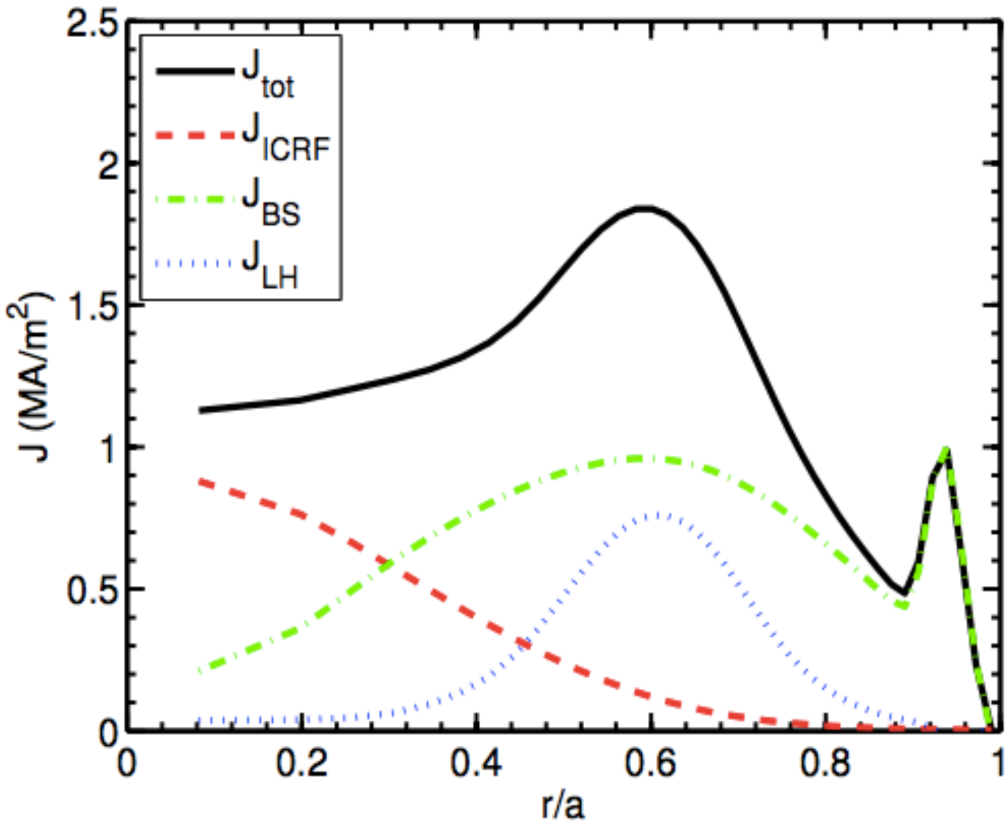


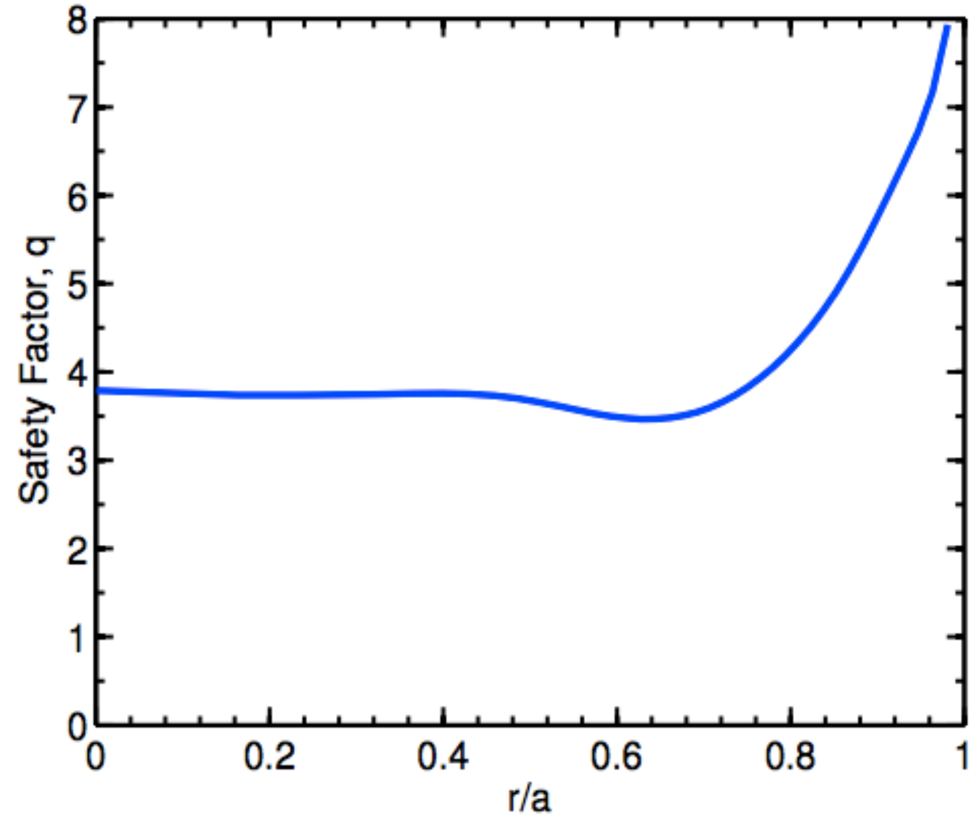
ACCOME has optimized large advantages of HFS-LHCD + poloidal launch location near X-point for ARC



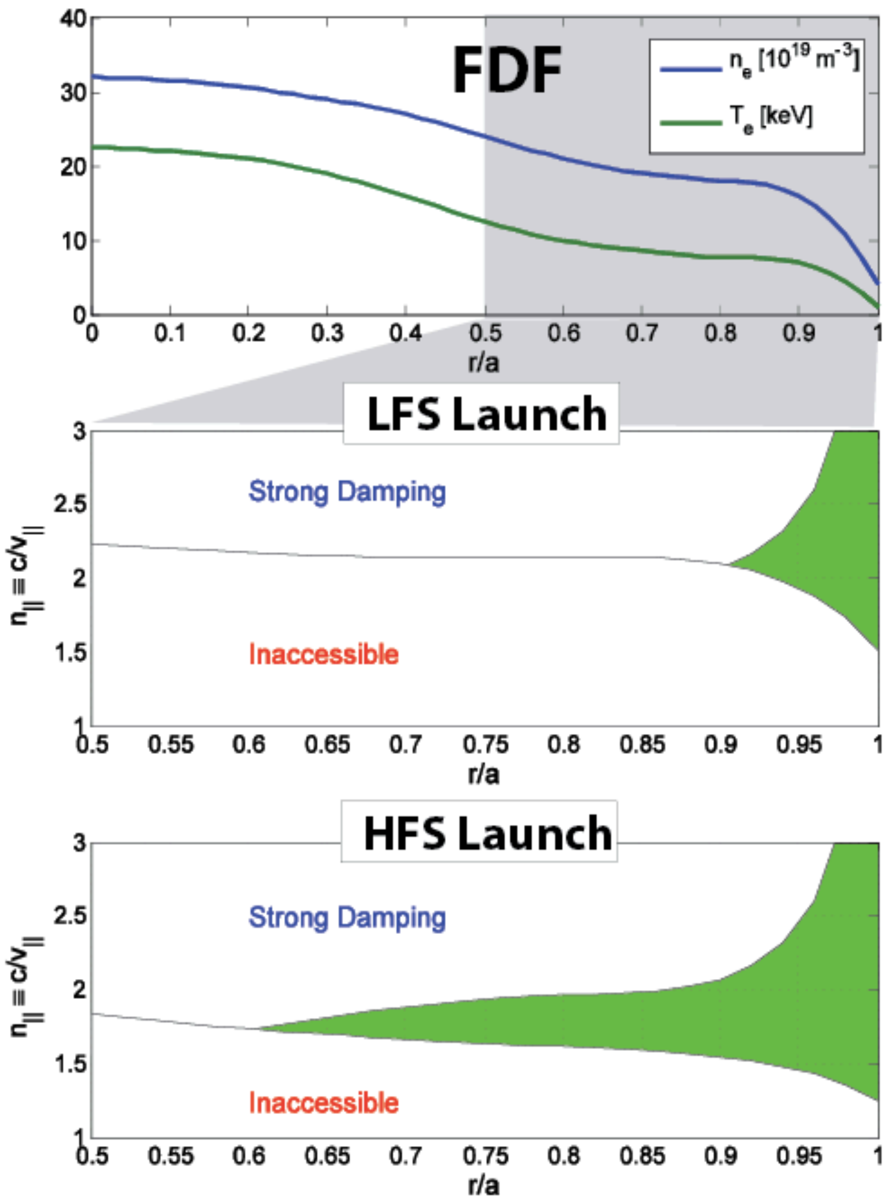


Optimized CD efficiency leads to substantial control of AT current profile below no-wall β_N limit





HFS-launch overcomes limitations of LFS LHCD in other designs



G. Wallace

ARC design: HFS launch at high B provides "Robust" steady-state with high gain + control

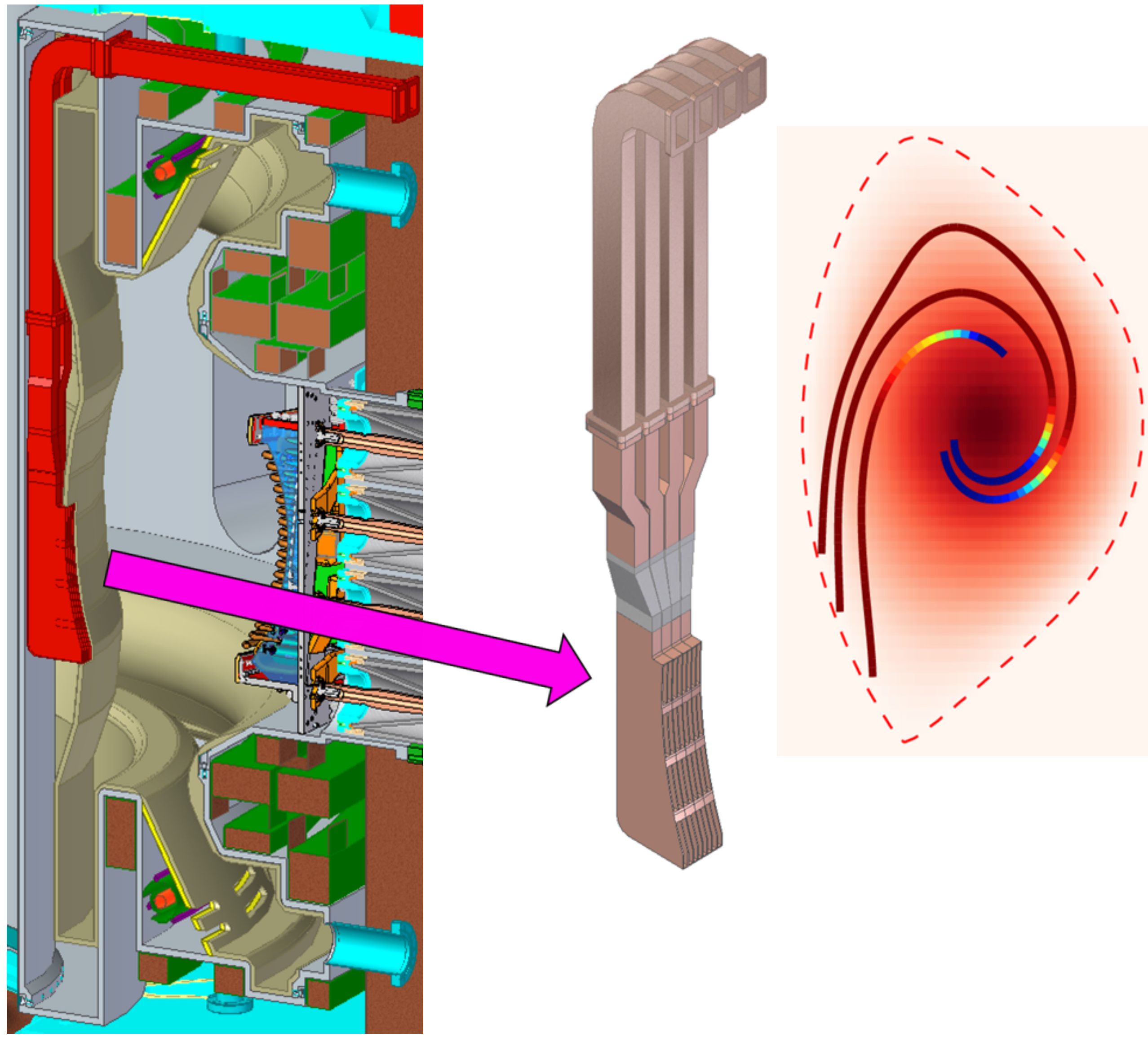
DT device	ε	κ	η_{20}	n_{20}	β_N (~3 no-wall limit)	q*	R (m)	B (T)	Q_p	I_{CD}/I_{BS}
FDF *(FNSF)*[1]	0.28	**2.3**	**0.12 (ECCD)**	2.2	**3.7**	2.8	2.7	5.5 **(Cu)**	**2.6**	~30%
ARIES-AT[2]	0.25	**2.2**	**0.25 (LH)**	2.2	**5**	**2.1**	5.2	5.8 (SC)	50	**~10%**
ARC	0.35	**1.9**	**> 0.4**	2	**2.5**	**~ 5**	3.3	9.2	**15**	**~40%**

1 V. Chan et al. NF (2011) 083019 & A. Garofalo IAEA 2012

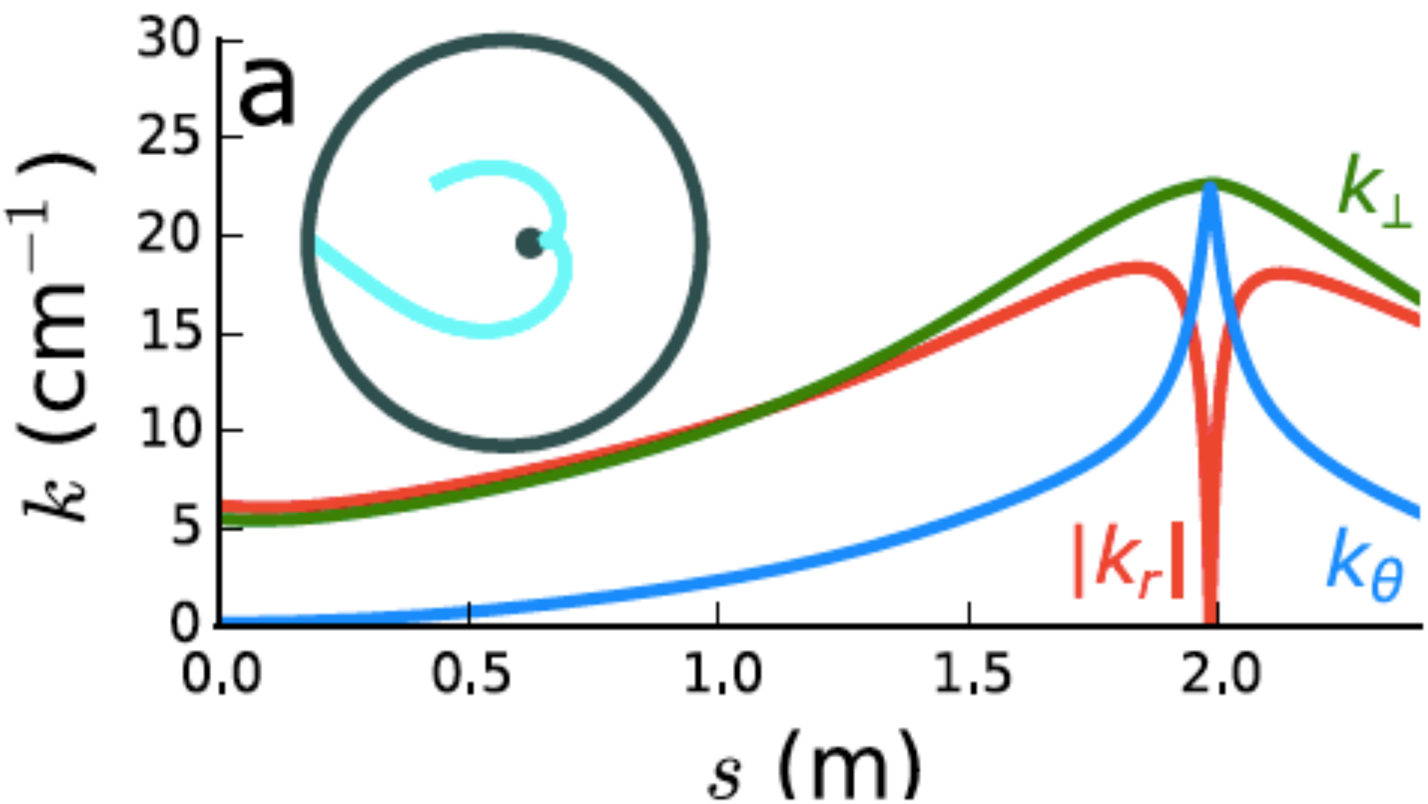
2 F. Najmabadi et al. FED (2006) 3.

ADX: Purpose-built HFS access to demonstrate LHCD solutions in reactor-matched boundary plasma

- **Launcher PMI & heat flux control**
- **Explore magnetic balance effect near DN**
- **RF isolation from ICRF → high Te target plasmas**
- **CD efficiency & j(r) control versus launched n// and plasma density**



HFS launch opens an exciting window to improve access to alpha-channeling → ultimate "answer" to extremely efficient CD efficiency

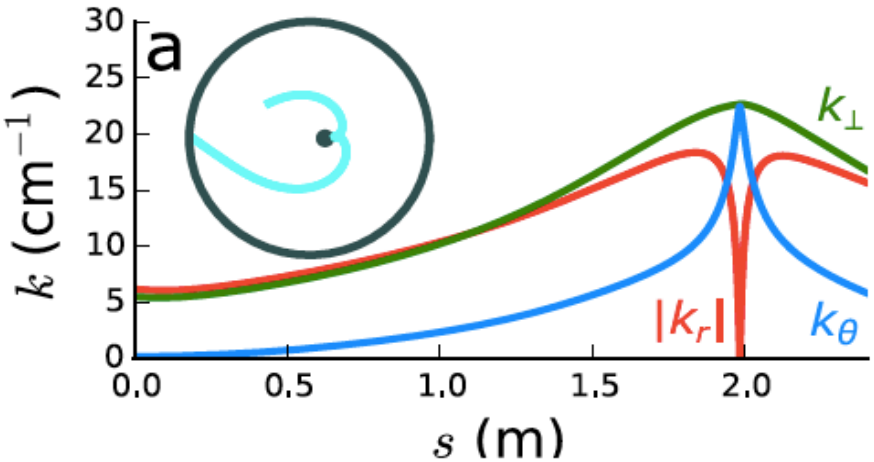


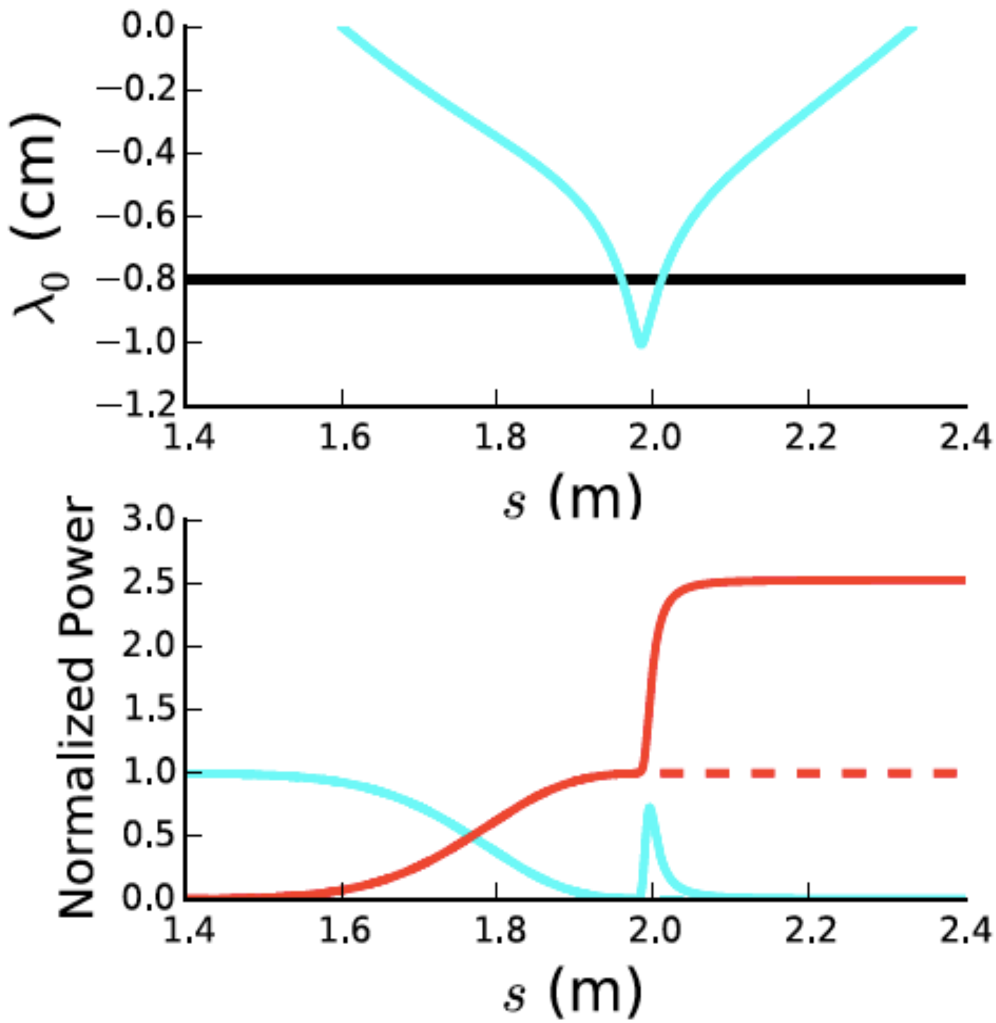
PHYSICS OF PLASMAS **22**, 112103 (2015)

Alpha channeling with high-field launch of lower hybrid waves

I. E. Ochs,[1] N. Bertelli,[2] and N. J. Fisch[1,2]
[1]*Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08540, USA*
[2]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*

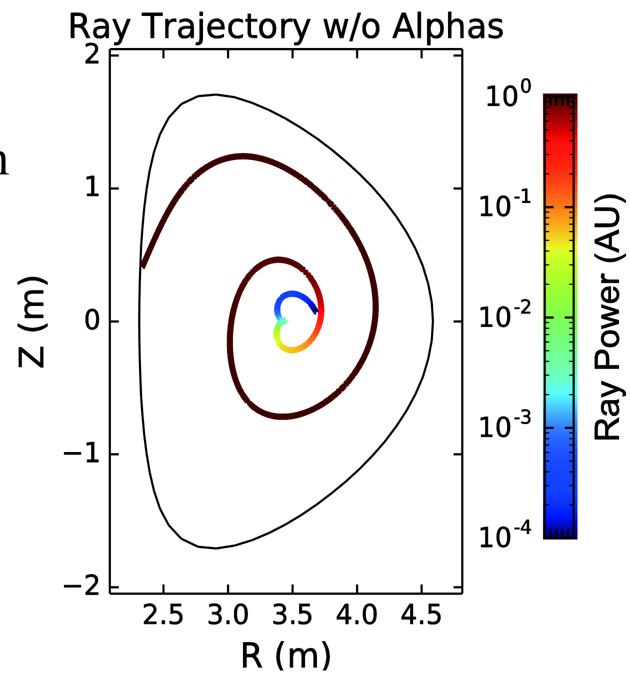
HFS launch opens an exciting window to improve access to alpha-channeling → ultimate "answer" to extremely efficient CD efficiency

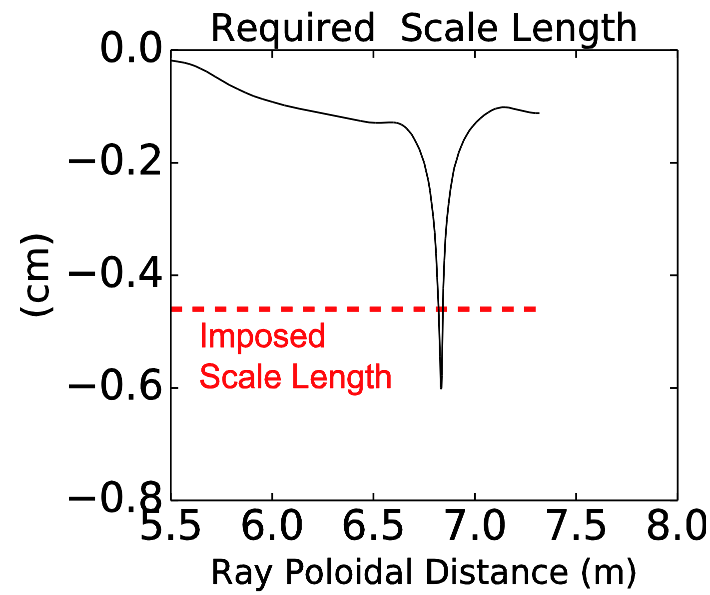


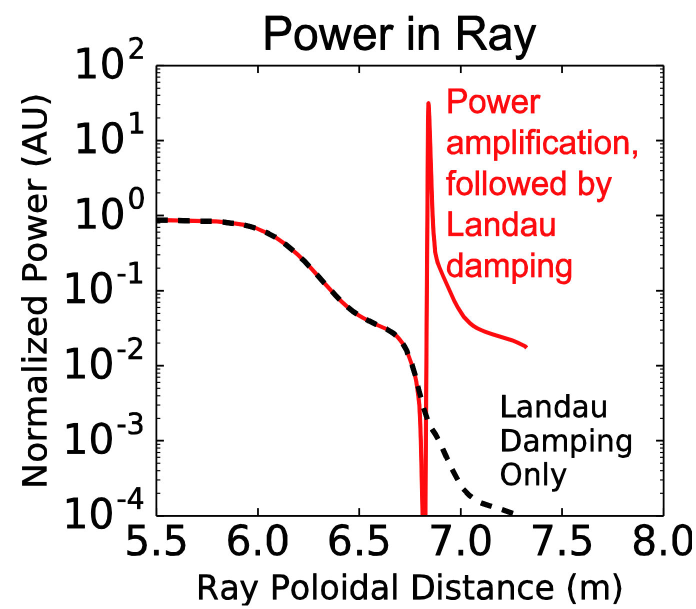


HFS launch → channeling effect in ARC-like plasma

- R0= 3.45 m, a= 1.14 m
- 9.9 T, 10 MA
- T_{e0} = 15 keV
- n_{e0} = 1.2×10^{20} m^{-3}
- f_0 = 2.4 GHz
- $N_{\|, init}$ = 1.55







- With HFS launch, LH wave could penetrate to hot core at reactor-relevant densities, providing the proper condition for the channeling effect.
- Challenges
  - PDI onset [Porkolab, 1977]
  - Use of the multi-wave RF-mediated diffusion system to ease the required the steep spatial gradient [Fisch, 1995]

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