Exploring high-field side RF launchers and current-drive in the ADX, Vulcan, ARC conceptual tokamak designs

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High-field side RF launchers could be a game-changer on many fronts

- **Placing RF launchers on the high-field side (HFS) where the plasma is quiescent provides a solution to the heat flux and erosion launcher issues for steady-state.**

- **Placing RF launchers at the HFS near null-point optimizes ray penetration and propagation to help avoid parasitic losses in the boundary and the CD "density limit"**

- **HFS lower-hybrid current drive (LHCD) provides improved CD efficiency, mid-radius CD and current profile control in FNSF/Pilot plasmas that allow high-gain with good control**

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Our HFS launch ideas were born out of conceptual design to solve PMI issues: Vulcan[1]

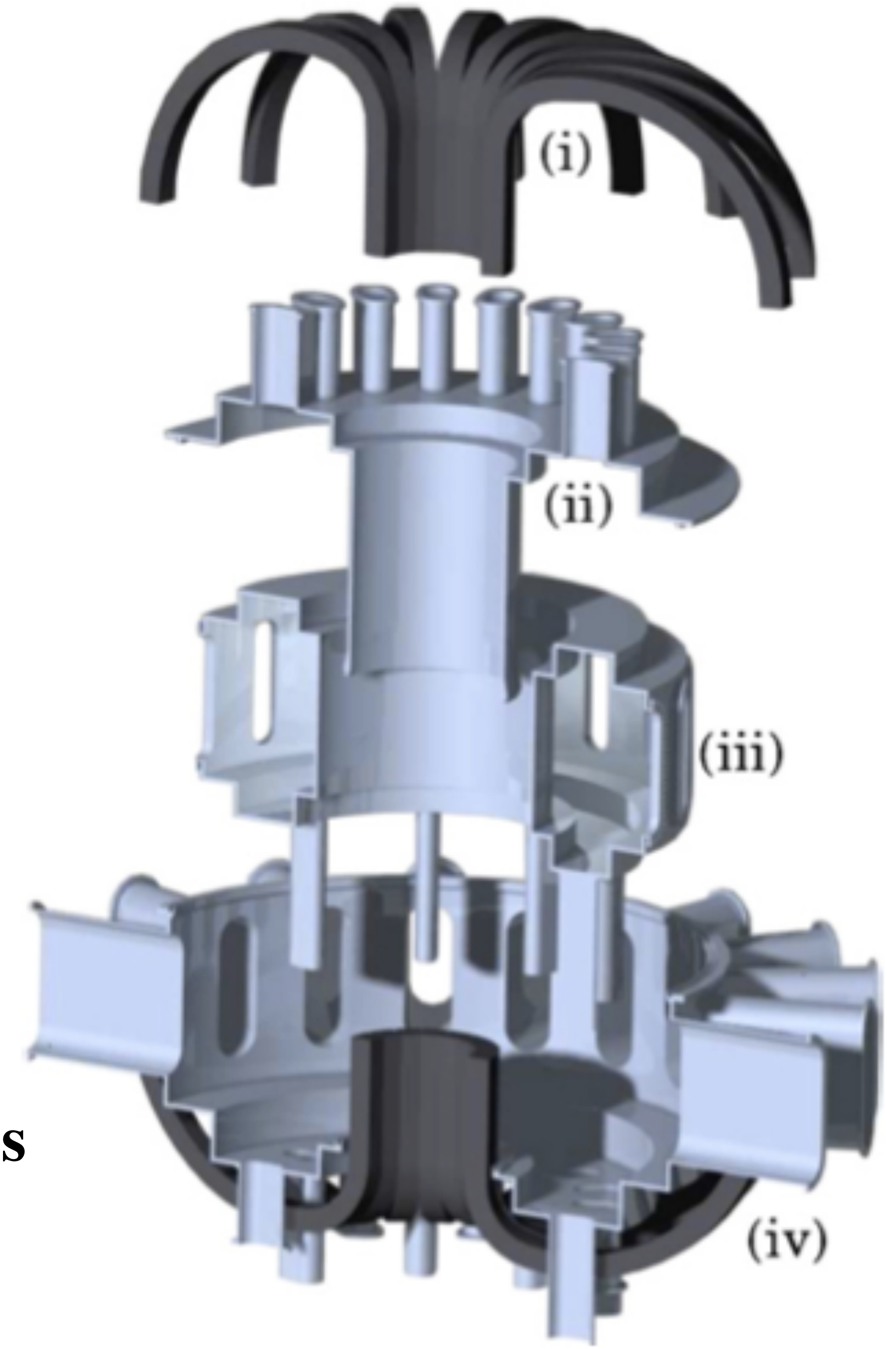
- **Conceptual design of a small "wind-tunnel" to bridge knowledge gaps from now to reactor SS and PMI**
  - **~10^2 second pulses → 30,000,000 seconds**
  - **Power density: P/S~1 MW/m^2 so P=20 MW at R=1.2 m**
  - **For divertor similarity $n_{20} \sim 1/R^{2/7}$ → $n_{20} \sim 3\text{-}4$ in Vulcan**
  - **For divertor similarity: SOL β → B ~ 7 T matched to reactor**
  - **High-temperature materials**

- **And needs truly SS plasmas for cumulative PMI effects**

- **Leads to choice of HTSC (high-temperature super conductors)….**

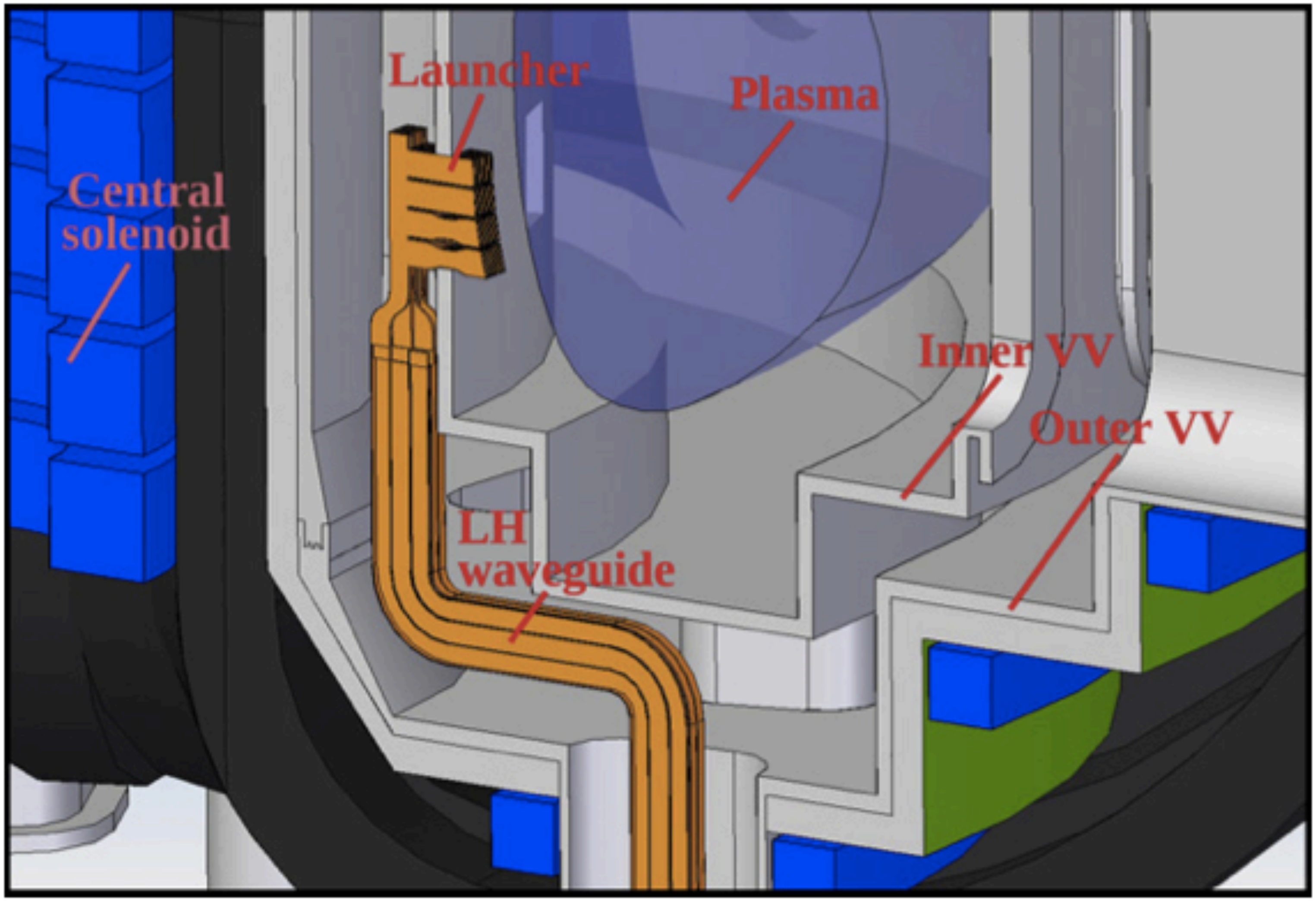
1 Fusion Engineering & Design Special Issue March (2012)

Vulcan



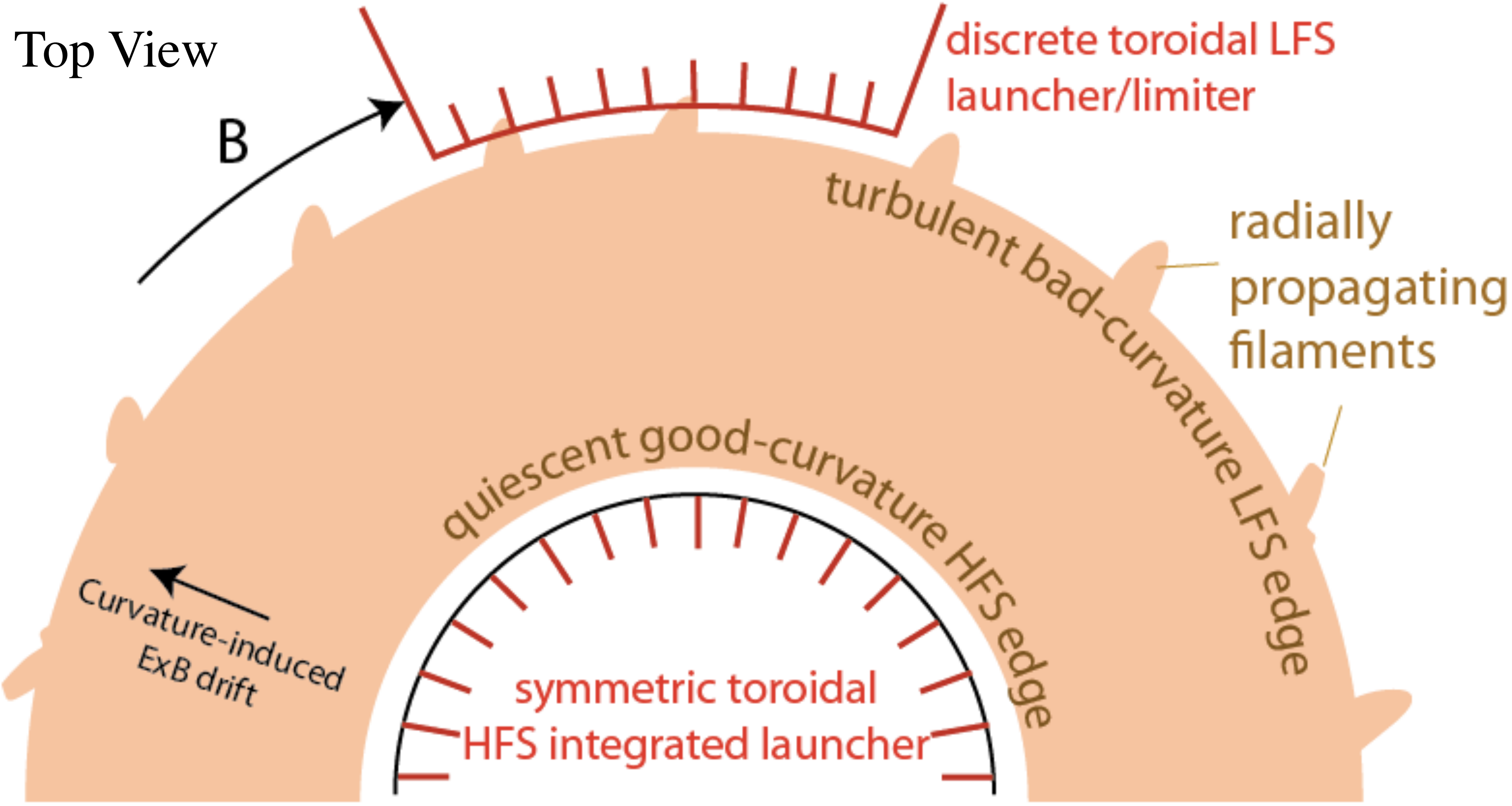
Demountable coils
R~1.2 m, B~7 T

- Con lge
  gap
- And
- Lea



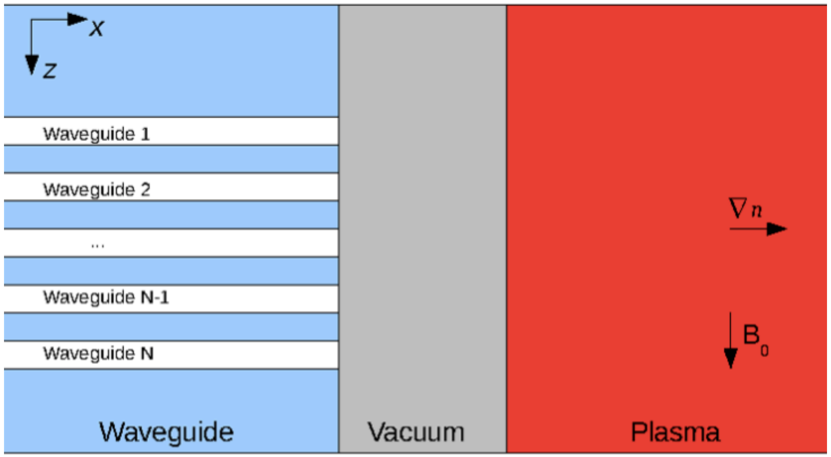
Mike Garrett (student): why not fit LH launcher on the high-field side “corner” in ~10 cm radial space between the inner high-T vessel and outer VV?

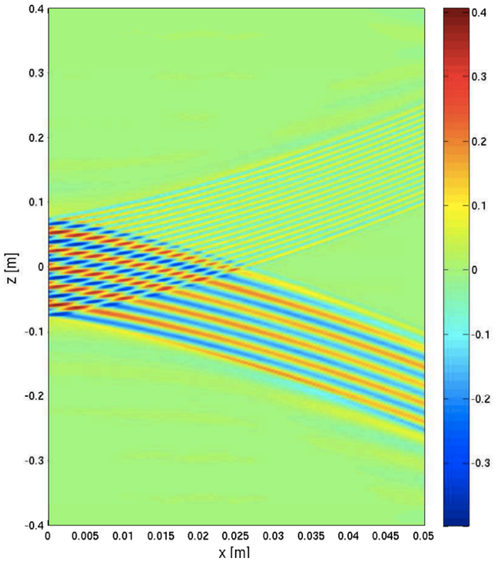
Basic plasma geometry and stability argue for HFS to solve launcher PMI issues



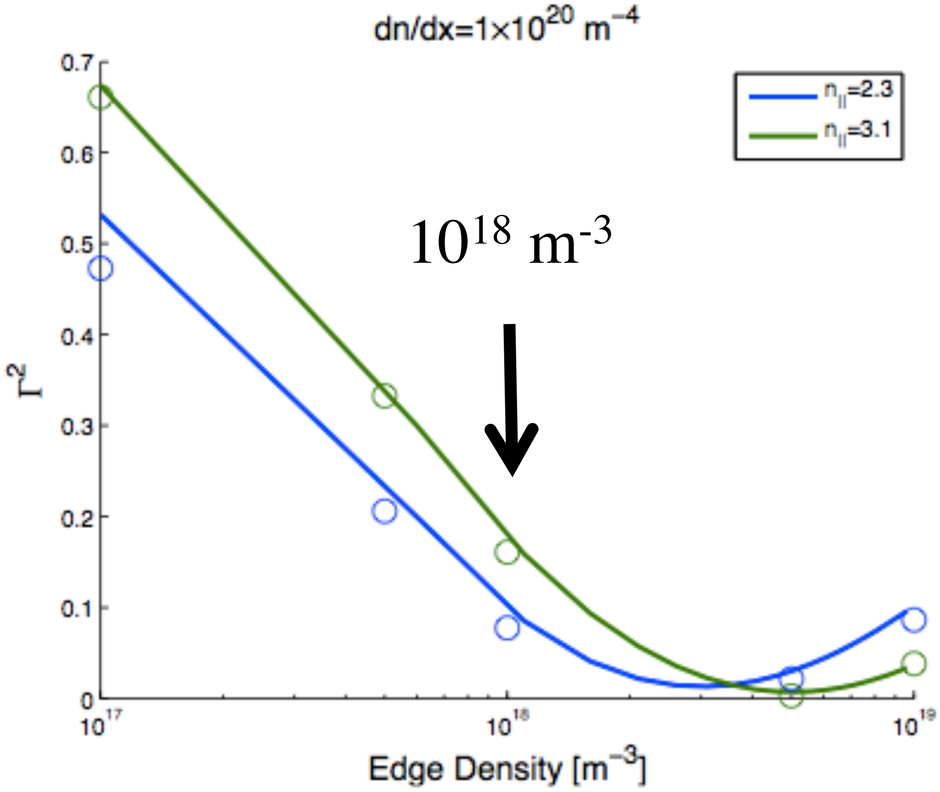
Wave coupling sets irreducible plasma contact at launcher

- **Lower-hybrid Slow Wave**





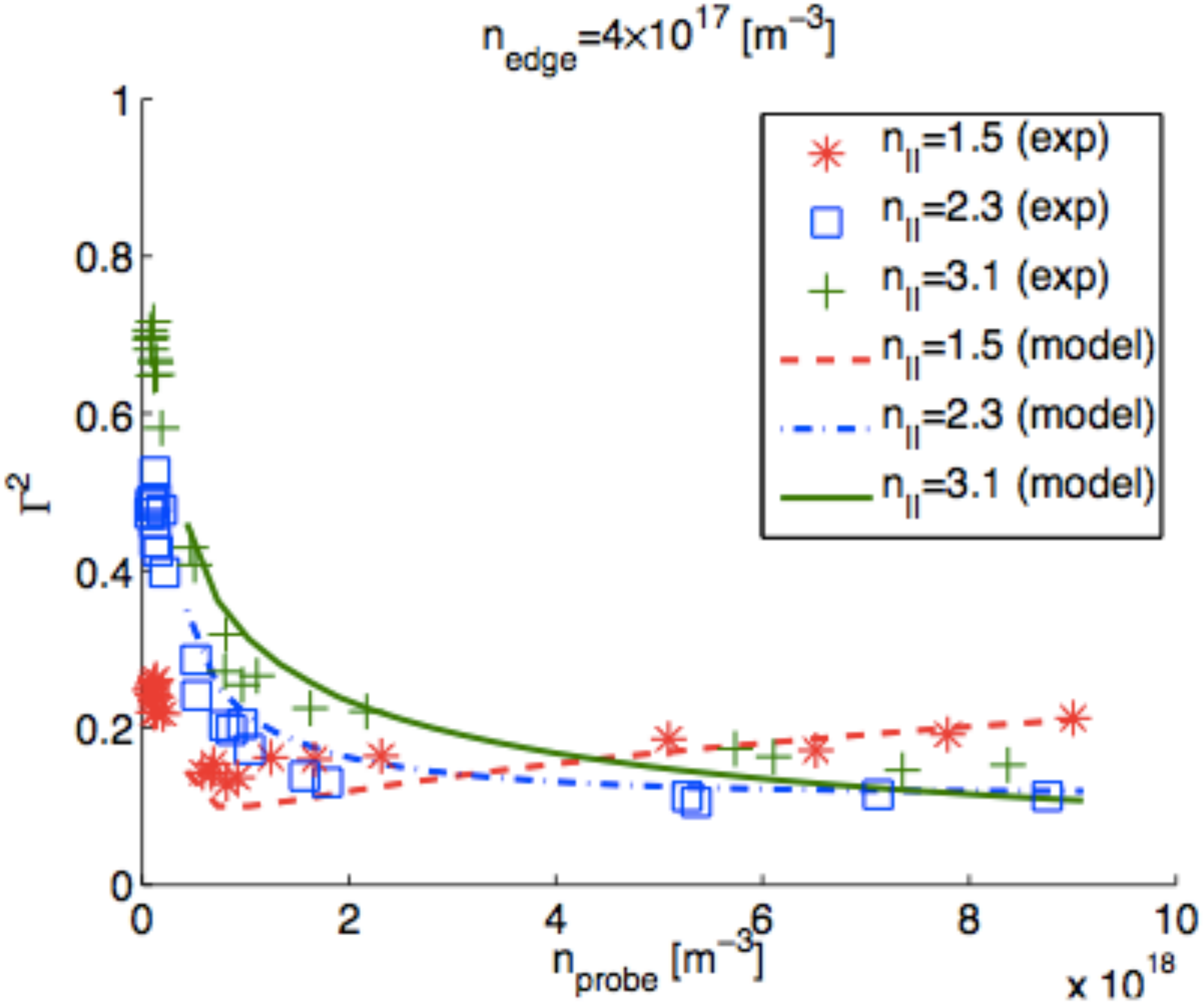
models



$10^{18}\ m^{-3}$

G. Wallace Ph.D. thesis

Wave coupling sets irreducible plasma contact at launcher



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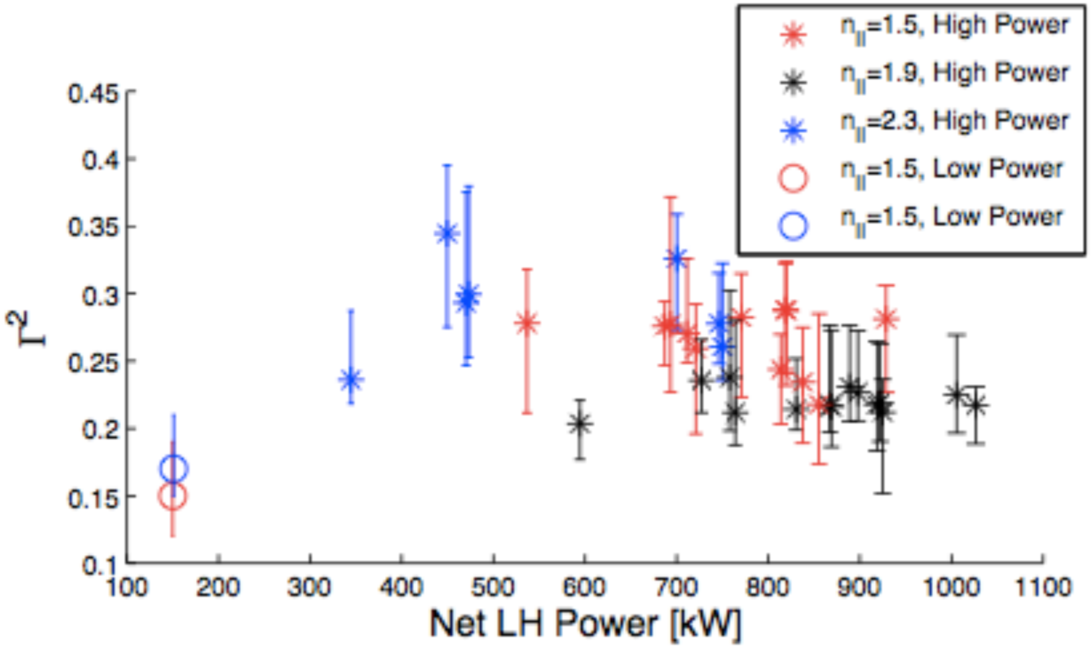
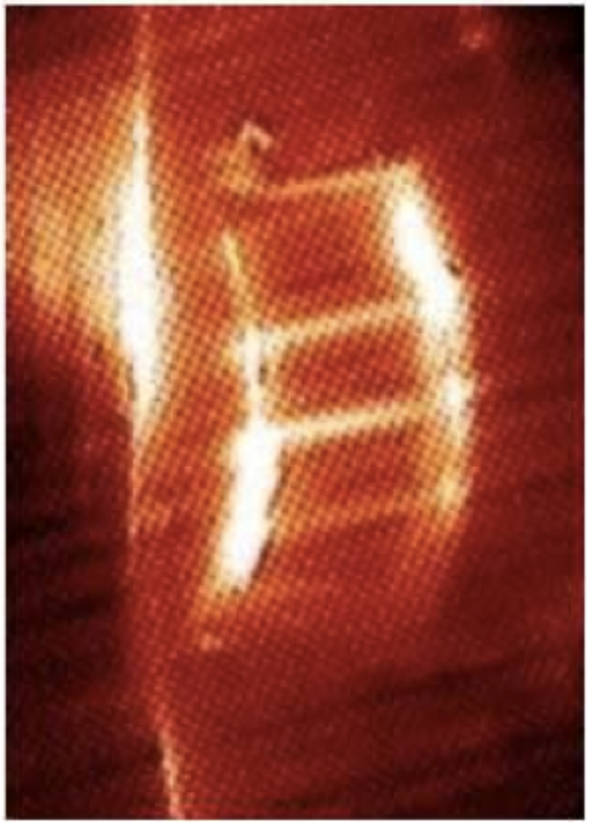
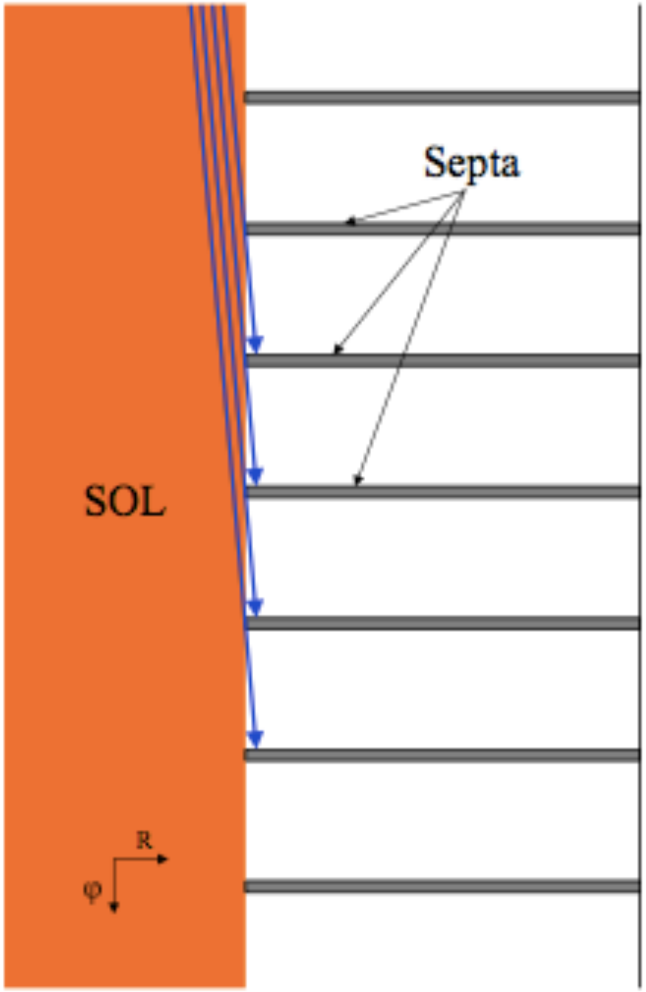
High power density LFS launch has non-linear interaction /w SOL
e.g. making plasma in front of launcher

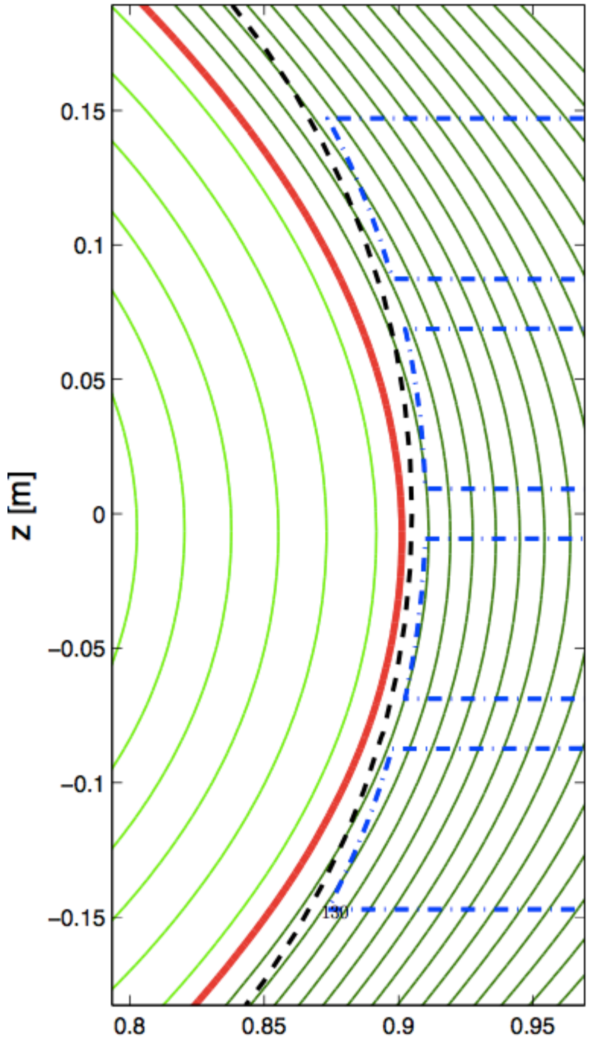




G. Wallace Ph.D. thesis

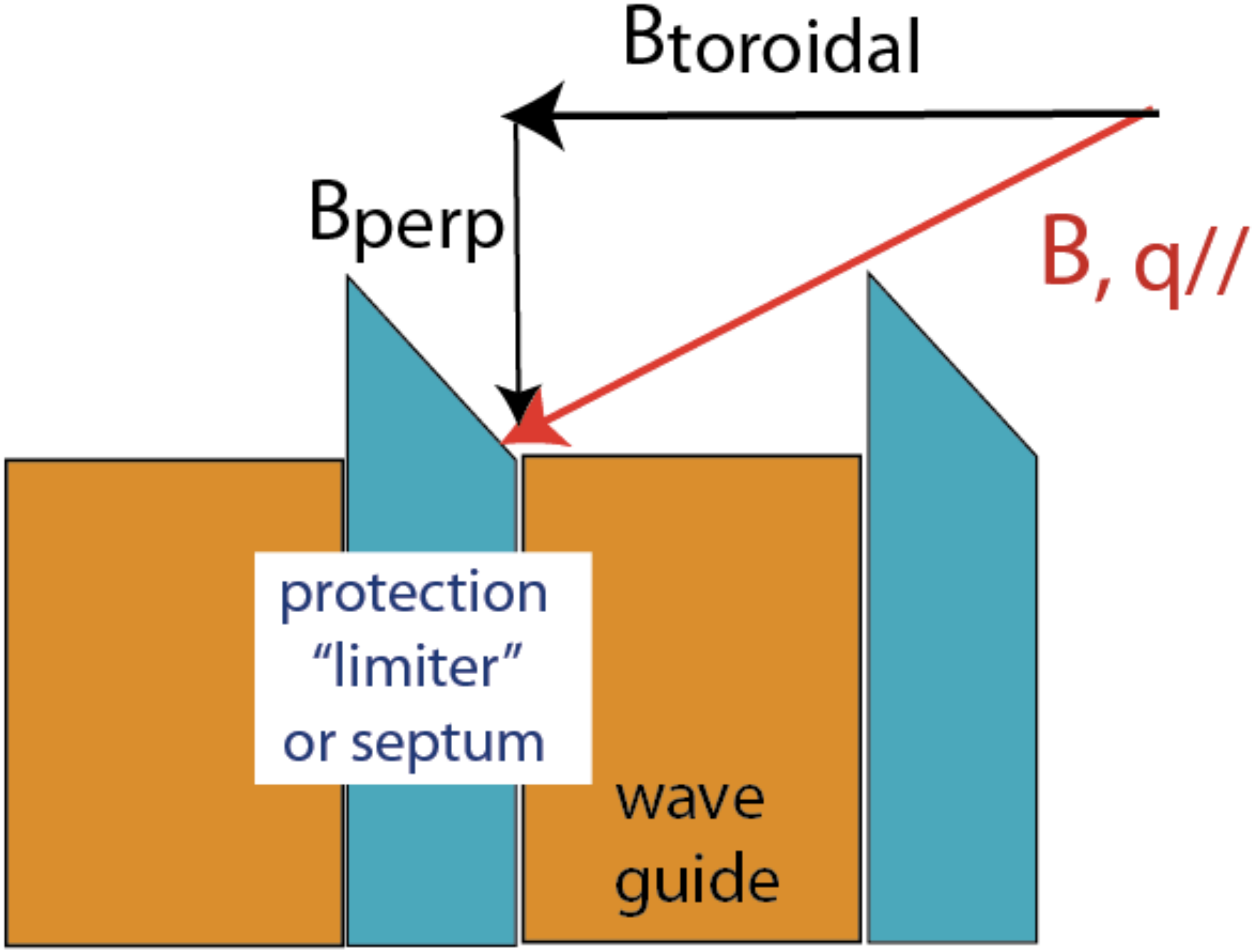
Geometry plays defining role in PMI of non-axisymmetric launcher structures





G. Wallace Ph.D. thesis

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



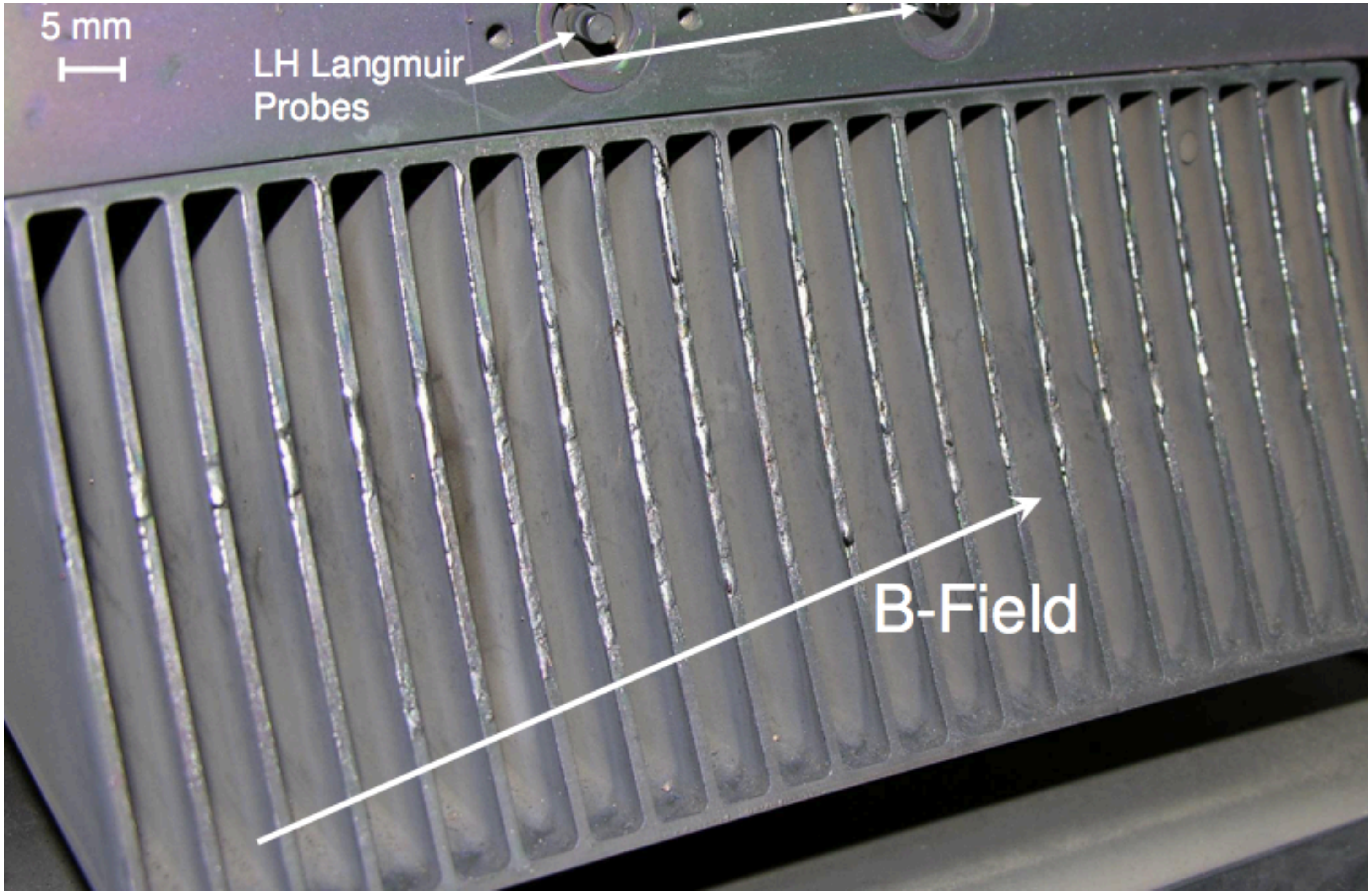
Heat flux & erosion challenge to launcher is severe for LFS launchers

	LFS (min. n_e)	**LFS (+local source)**
n_e (m^{-3})	10^{18}	$\sim 4 \times 10^{18}$
T_e (eV)	10	20
q// (MW/m^2)	0.5	~ 2.5
// Flux ($ion/s/m^2$)	3×10^{22}	2×10^{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.

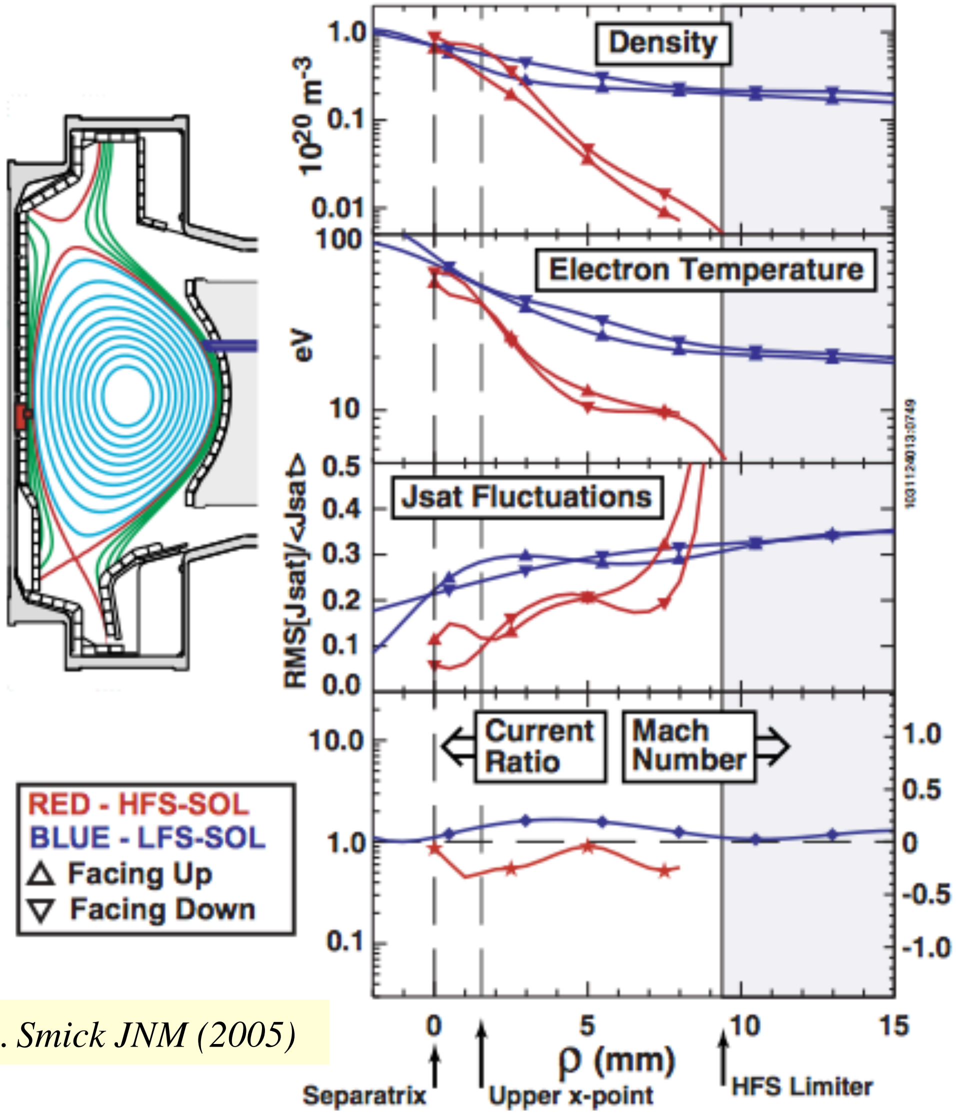
No chance of controlling q or erosion through // SOL physics

Heat flux & erosion challenge to launcher is severe for LFS launchers

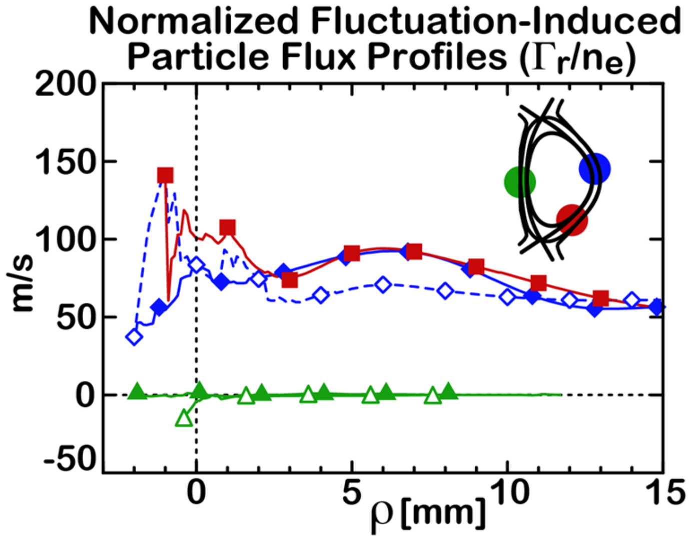


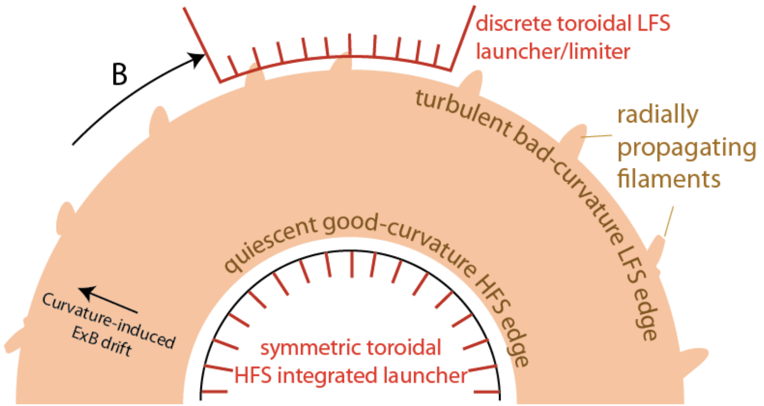
G. Wallace Ph.D. thesis

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



N. Smick JNM (2005)

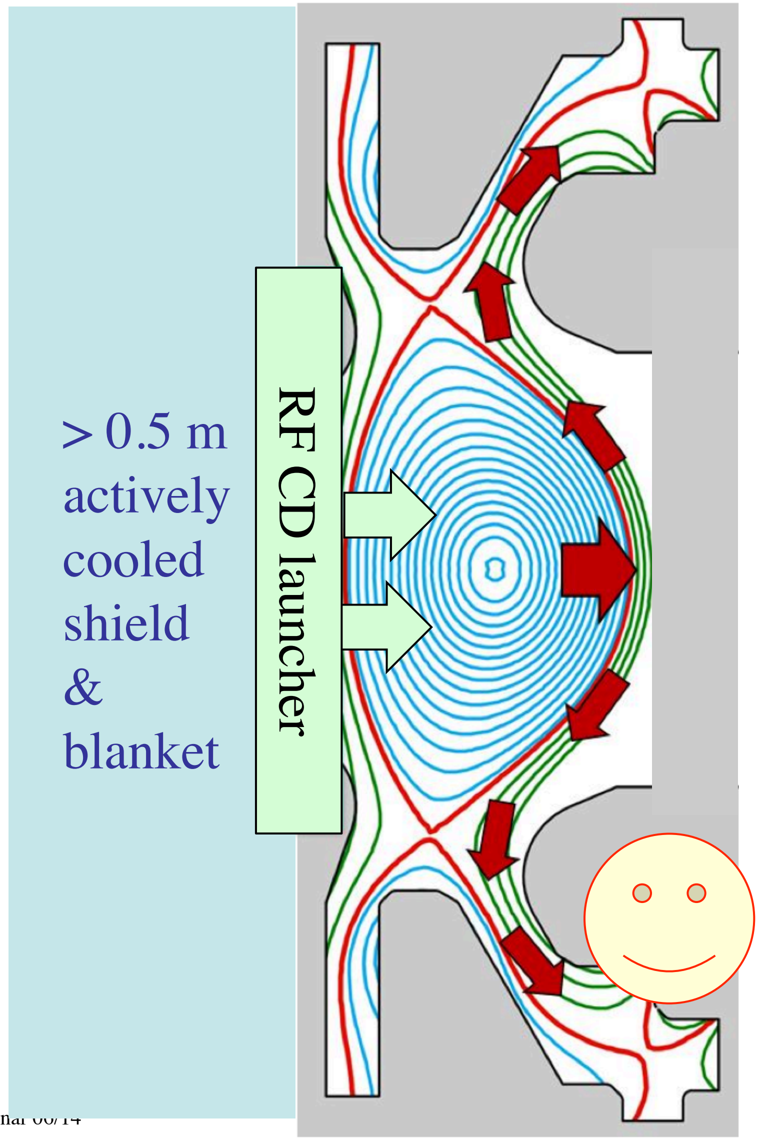




Heat flux & erosion challenge to launcher structure mitigated by HFS launch B-field geometry & good curvature

	LFS (min. n_e)	LFS (+local source)	HFS (min. n_e)
n_e (m^{-3})	10^{18}	~4x10^{18}	10^{18}
T_e (eV)	10	20	10
q// (MW/m^2)	0.5	~ 2.5	0.5
// Flux (ion/s/m^2)	3x10^{22}	2x10^{23}	3x10^{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 HFS space allocation allows HFS launch

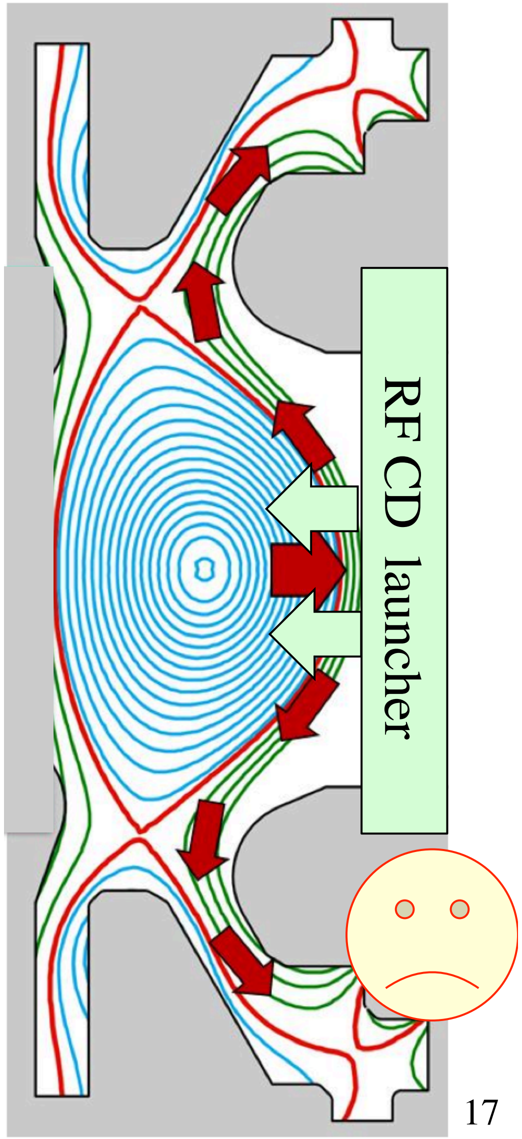


> 0.5 m actively cooled shield & blanket

RF CD launcher

Power in ⇨

Power out ➡



RF CD launcher

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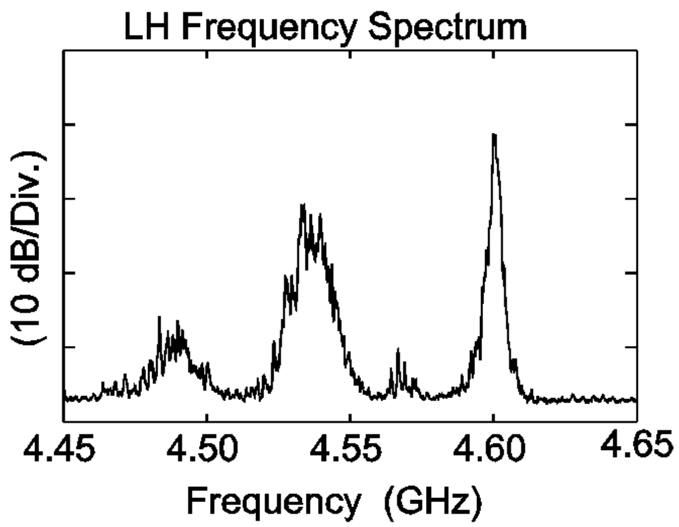
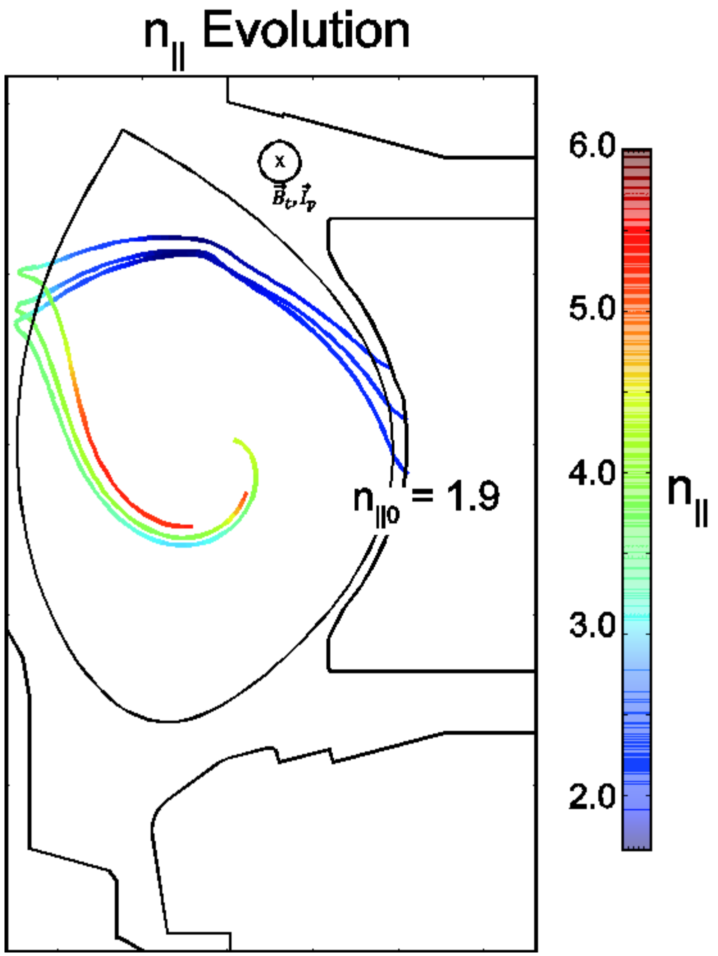
The LHCD “density limit” results from refraction & SOL absorption/instability

Collisional absorption

$n_{||}$ upshift

Parametric Instability



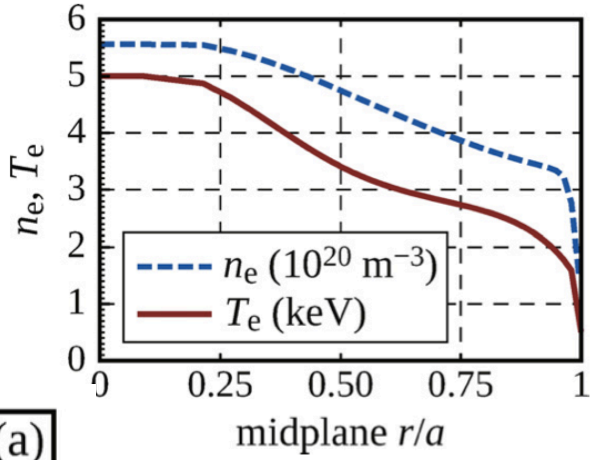


S. Baek Ph.D. thesis

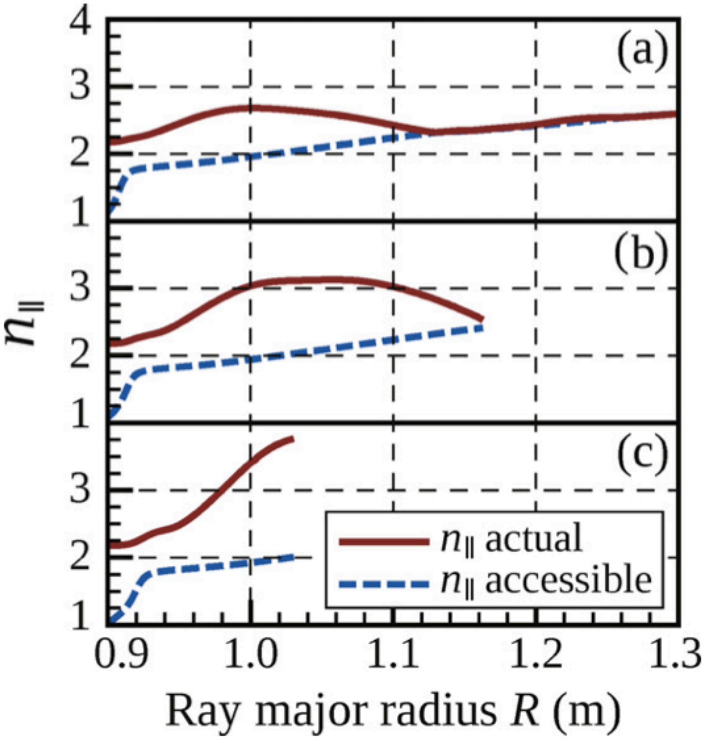
Accessibility key to HFS launch physics

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

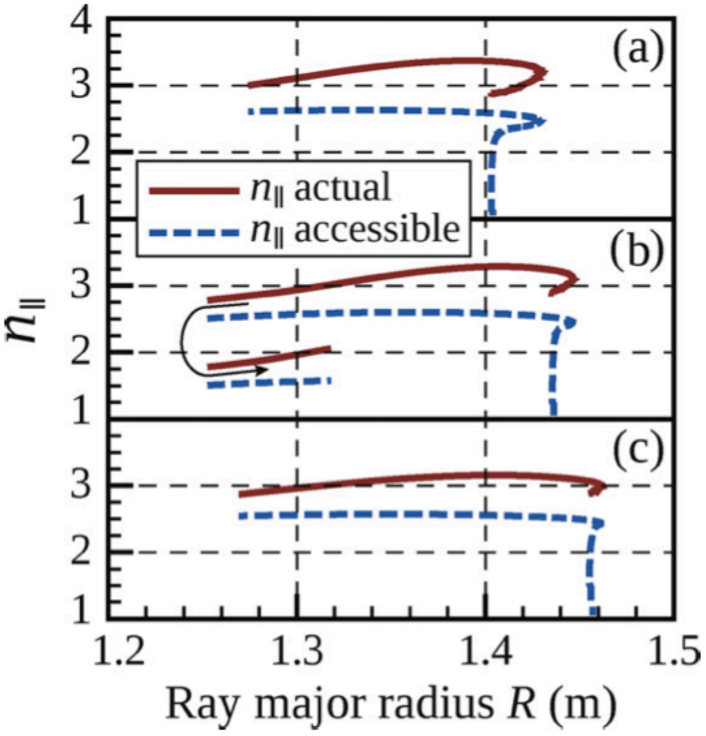
Vulcan
R=1.2 m



HFS
High-Field Side



LFS
Low-Field Side

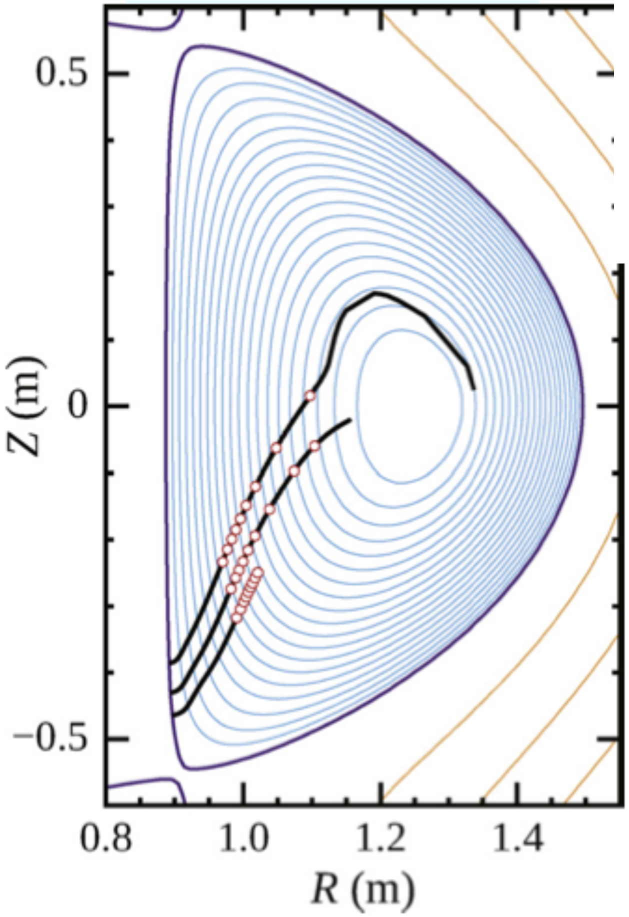


Propagation favors HFS launch near poloidal null

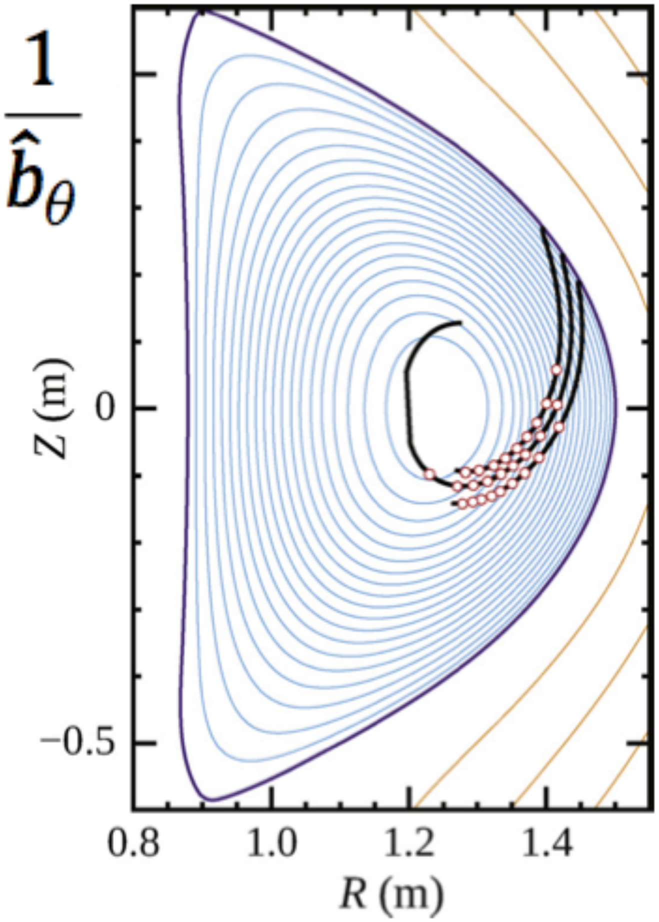
$\eta_{20} \sim 0.12 \sim \frac{1}{n_{//}^2}$

$\eta_{20} \sim 0.07$

$$\frac{v_{g,r}}{v_{g,\theta}} \cong -\frac{\omega^2}{\omega_{pe}^2}\frac{k_r}{k_\parallel}\frac{1}{\hat{b}_\theta}$$



ACCOME
Simulations
Of Vulcan
{no solution
@ LFS MP}



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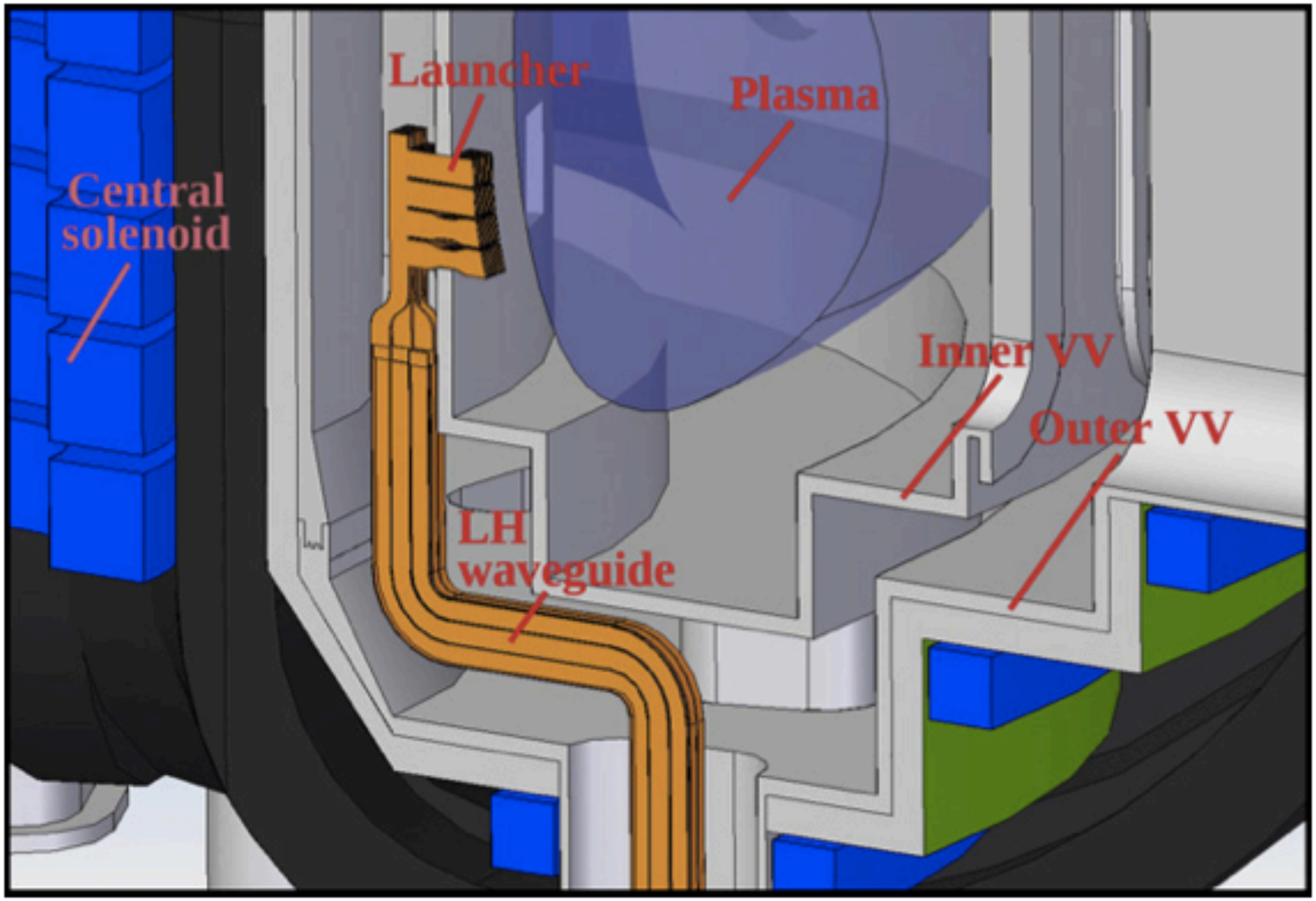
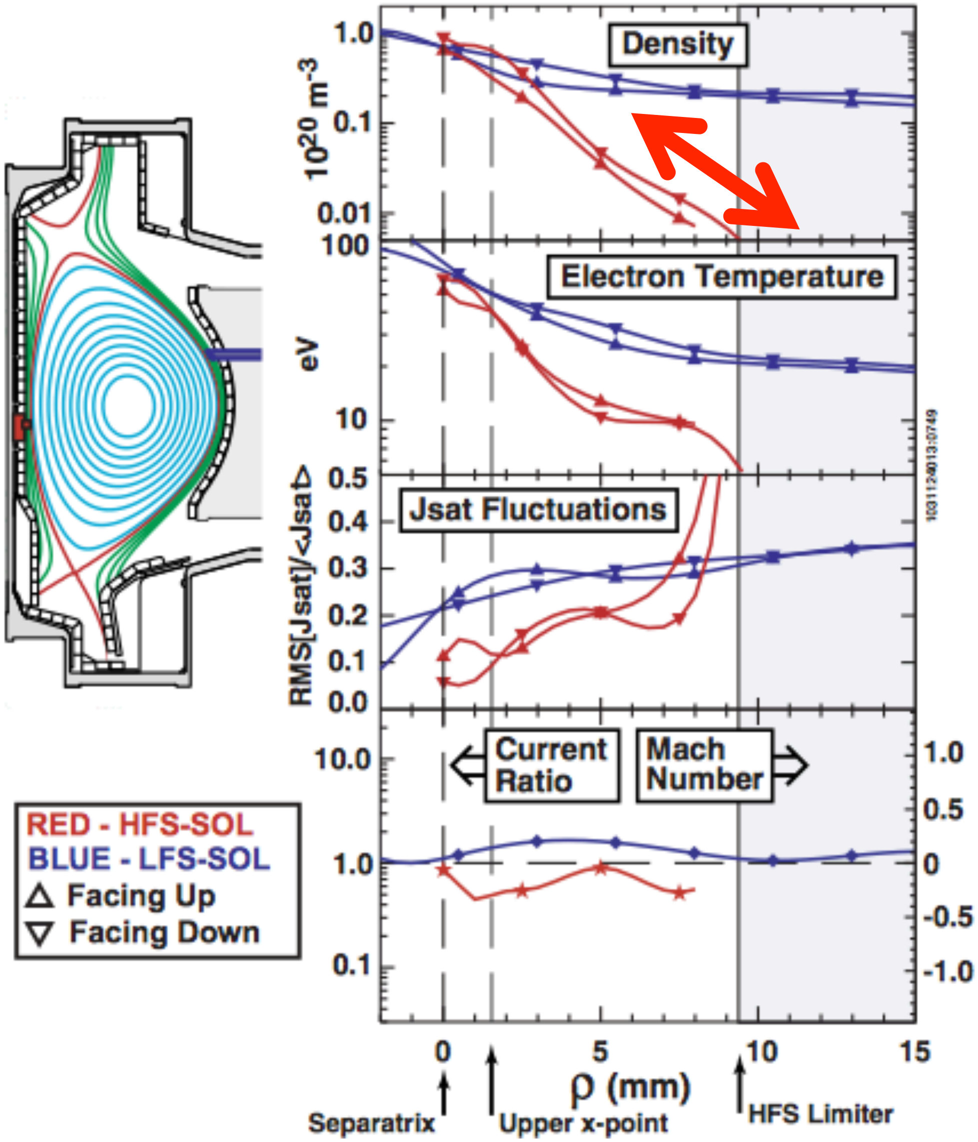
Erosion rate (mm/year)	~ 6	~30	~ 1

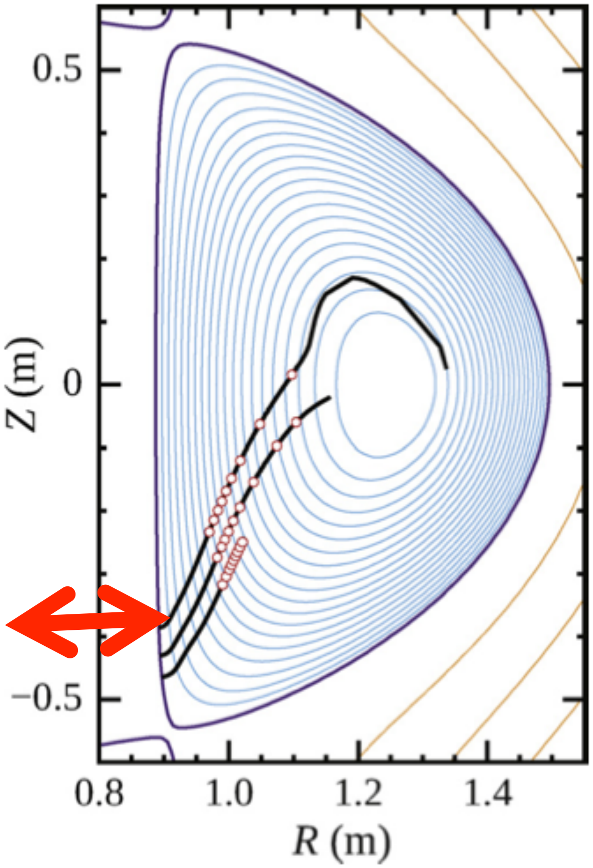
- Con lge
gap
  - ➢
  - ➢
  - ➢
  - ➢
  - ➢
- And
- Lea



HFS launch near null also minimizes length and power losses in small area waveguides
→ Efficient transmission to ~50 MW/m^2 launched

Coupling control =
Inner gap control in DN





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Accessibility and damping increase CD efficiency using HFS launch

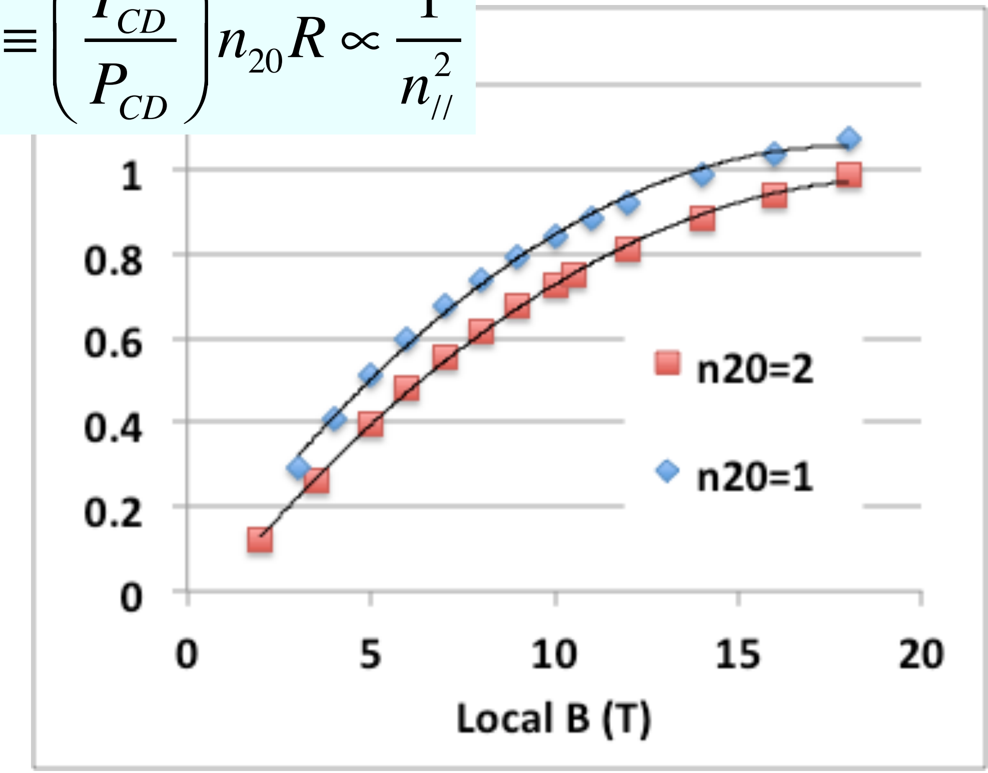
Accessibility

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

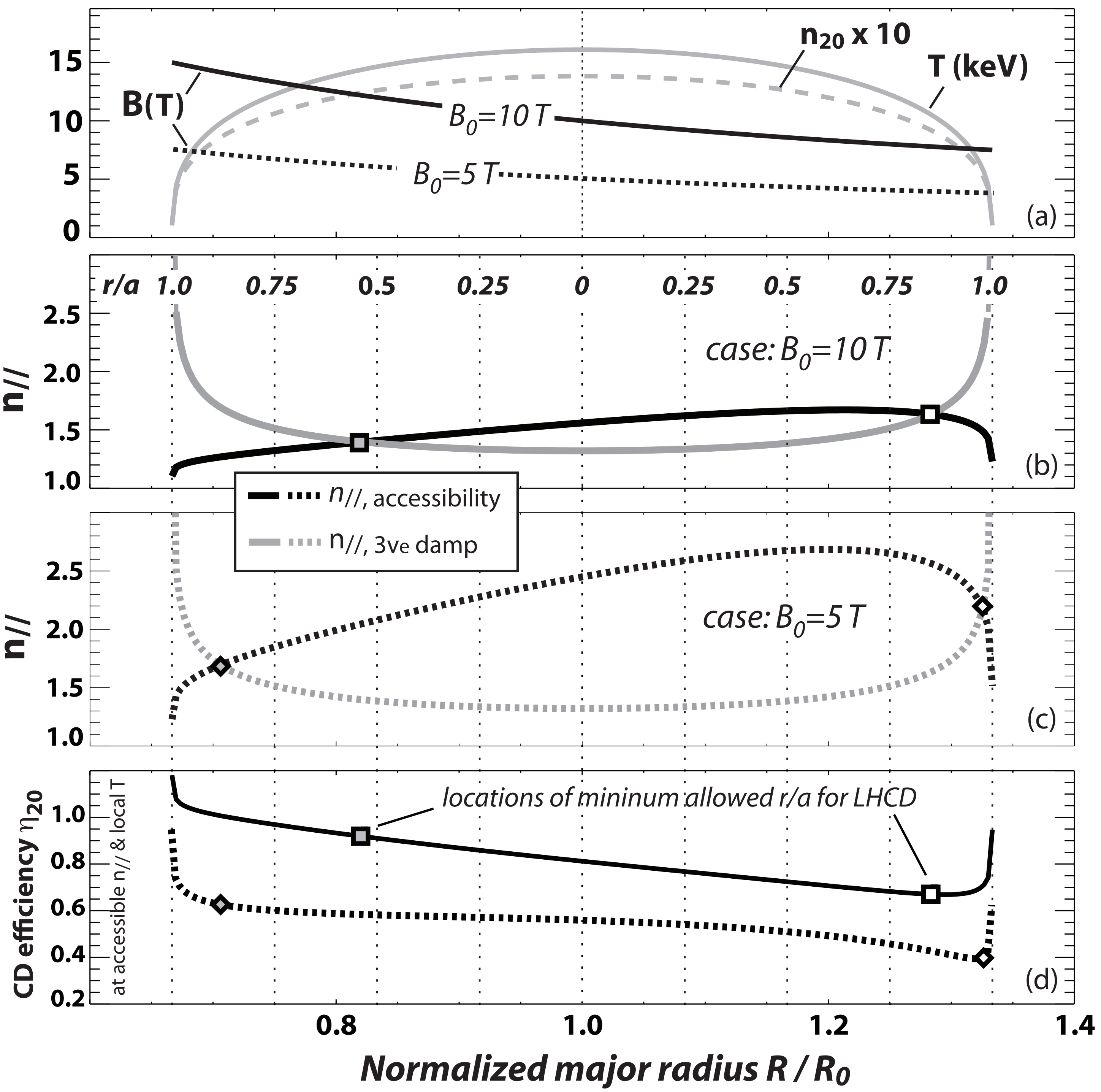
Damping

$$T_e \simeq \frac{30}{n_{//}^2}$$

$$\eta_{20} \equiv \left(\frac{I_{CD}}{P_{CD}}\right) n_{20} R \propto \frac{1}{n_{//}^2}$$



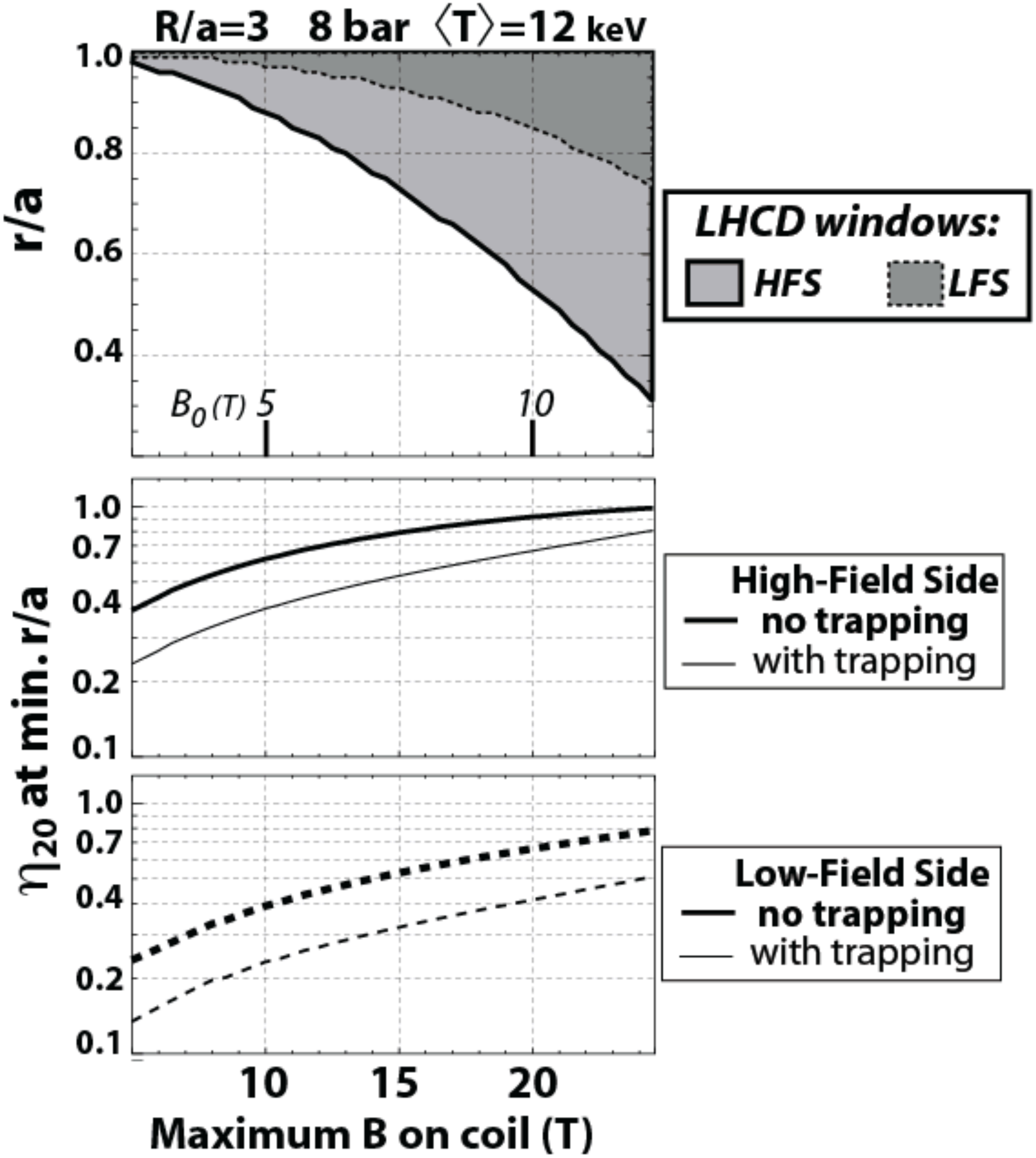
HFS-LHCD + high B = Excellent CD access & control for DT fusion device



<T>~12 keV
8 bar

HFS vs. LFS Launch in prototypical FNSF conditions

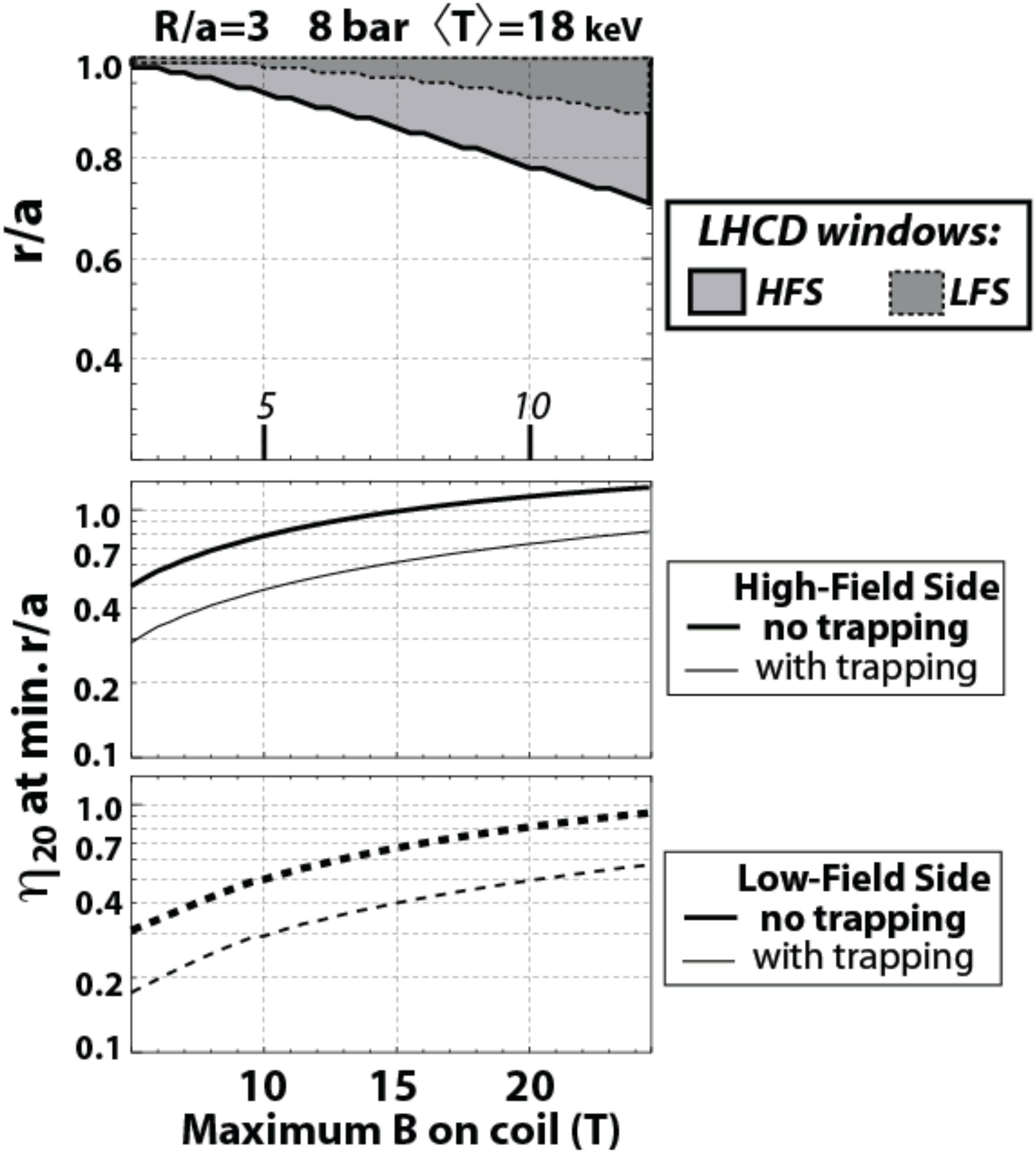
- HFS can provide CD much deeper into the plasma
- Efficiency improves due to both lower n// and lower trapping effects.



HFS vs. LFS Launch in prototypical reactor conditions

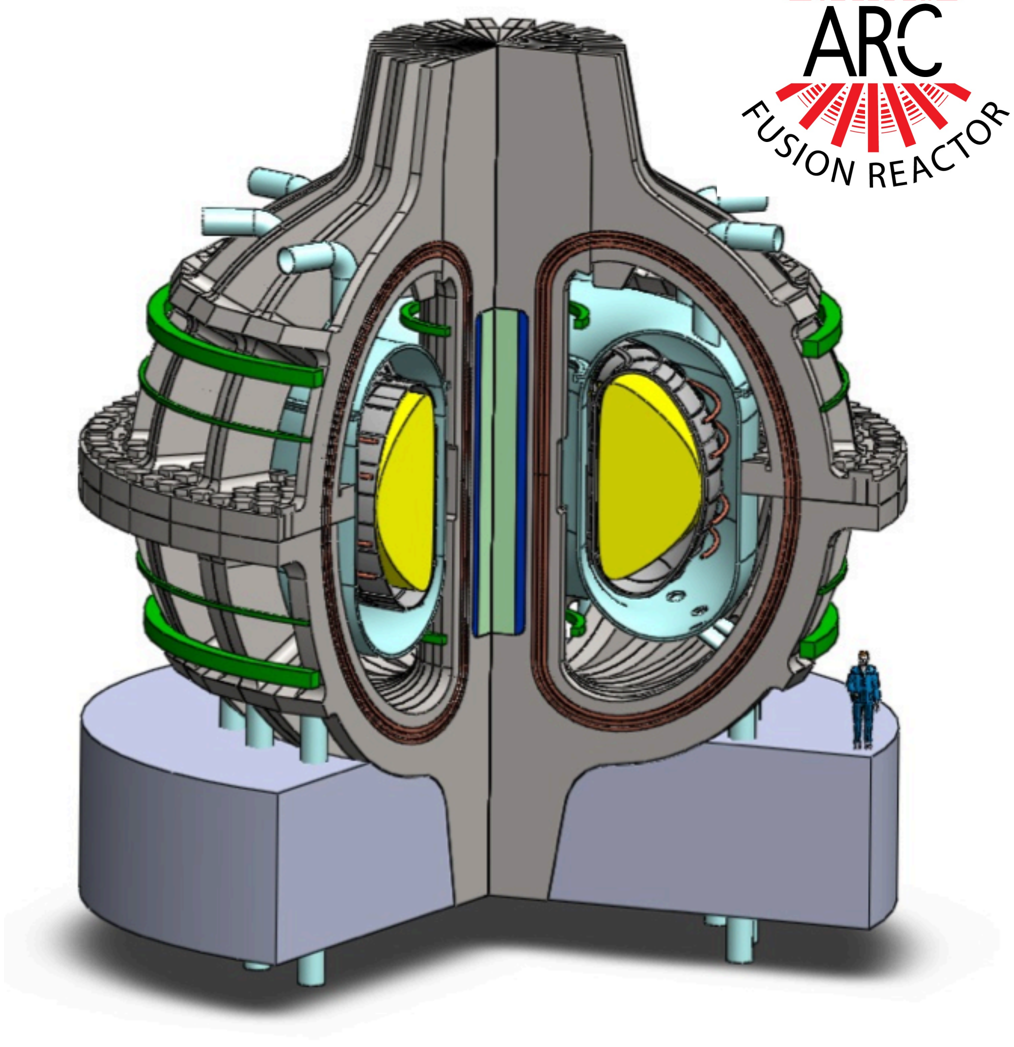
- Penetration more difficult than with lower T typical of FNSF

- Still favors HFS



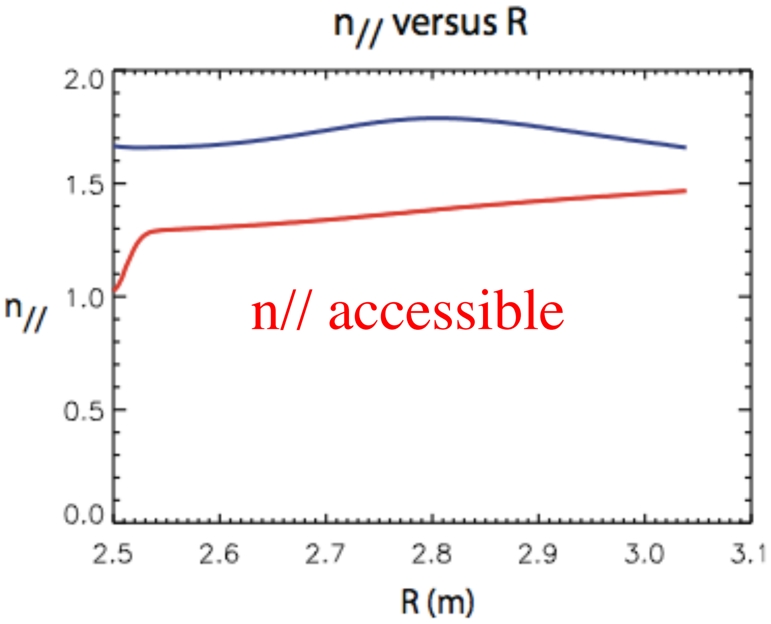
ARC: JET-sized high-gain DT device using HFS-LHCD & high B

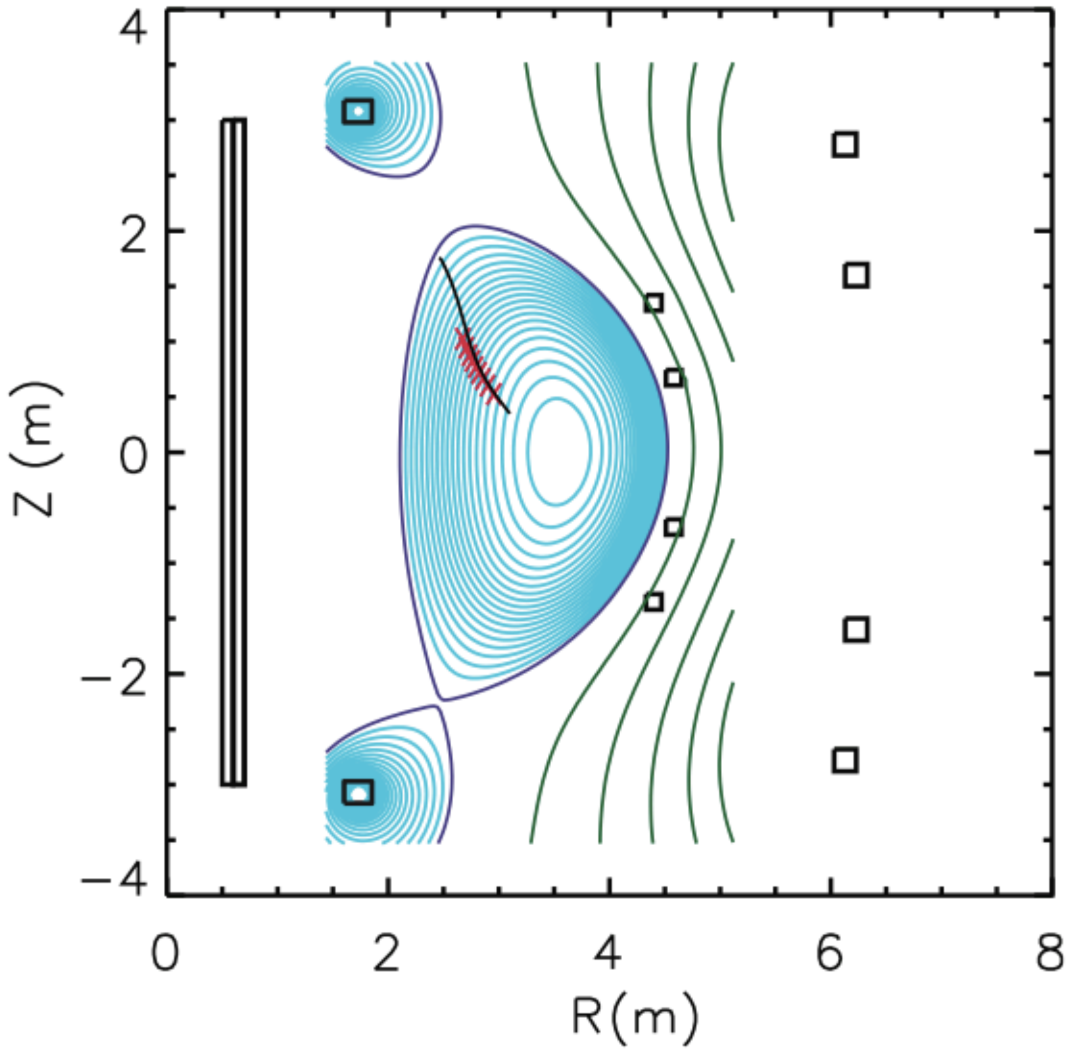
AFFORDABLE, REPLACEABLE, COMPACT
ARC
FUSION REACTOR



Design parameter	Symbol	Value	Unit
Fusion power	P_f	525	MW
Total thermal power	P_{tot}	708	MW
Plant efficiency	η_{elec}	0.50	
Total electric power	P_e	354	MW
Net electric power	P_{net}	268	MW
LHCD coupled power	P_{LH}	25	MW
ICRF coupled power	P_{IC}	15	MW
Power multiplication factor	Q	4.11	
Major radius	R_0	3.3	m
Ellipse semi-minor radius	a	1.1	m
Ellipse elongation	κ	1.8	
Toroidal magnetic field	B_0	9.2	T
Plasma current	I_p	7.8	MA
Bootstrap fraction	f_{BS}	0.63	
Tritium Breeding Ratio	TBR	1.11	
Avg. temperature	T_0	13.9	keV
Avg. density	n_0	1.3	10^{20} m^{-3}
Toroidal beta	β_T	1.9	%
Internal inducance	l_i	0.668	
Normalized beta	β_N	2.59	
Safety factor at $r/a = 0.95$	q_{95}	7.2	
Minimum safety factor	q_{min}	3.5	

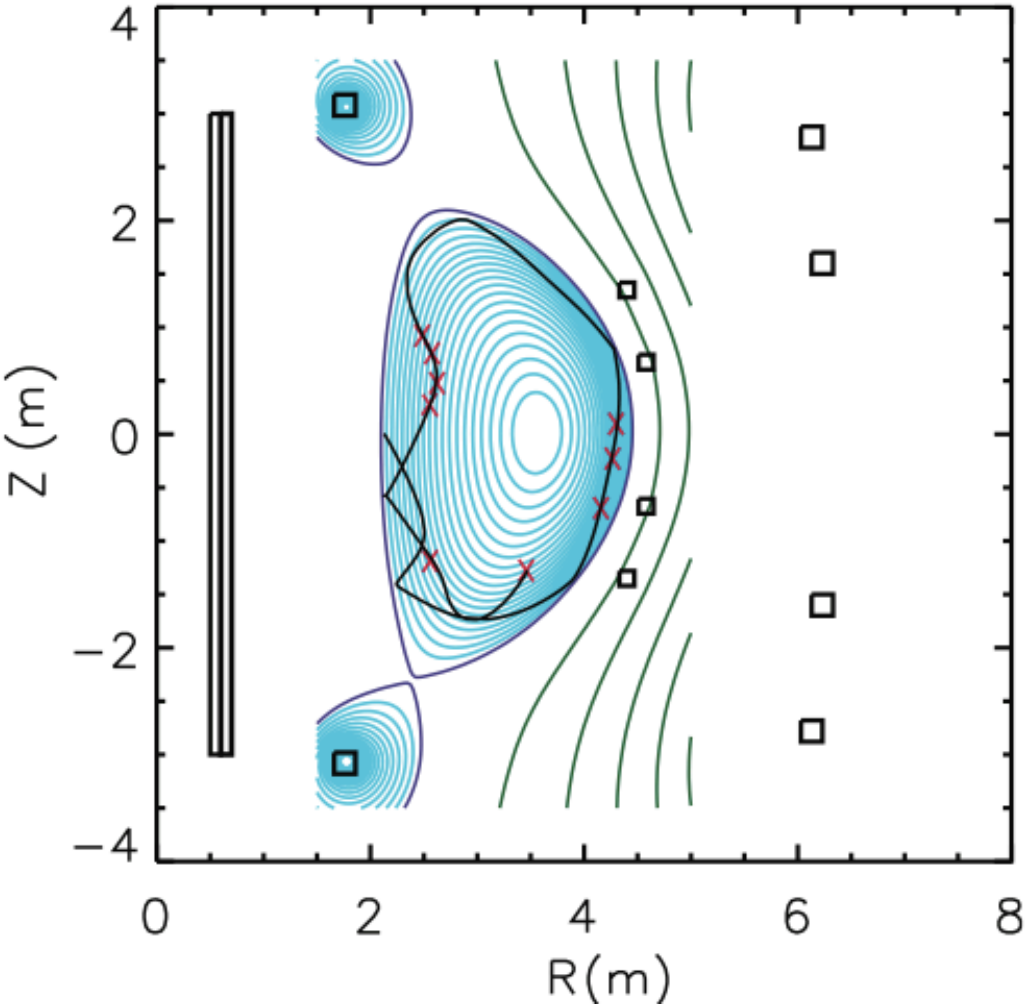
ACCOME has optimized large advantages of HFS-LHCD + poloidal launch location near X-point for ARC


n// accessible



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

Poor
Penetration
/w HFS
Midplane
launch



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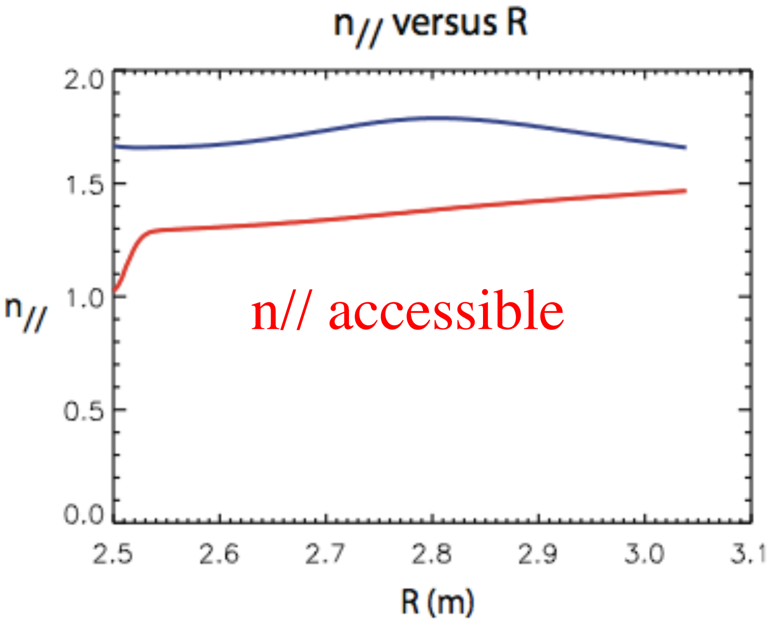
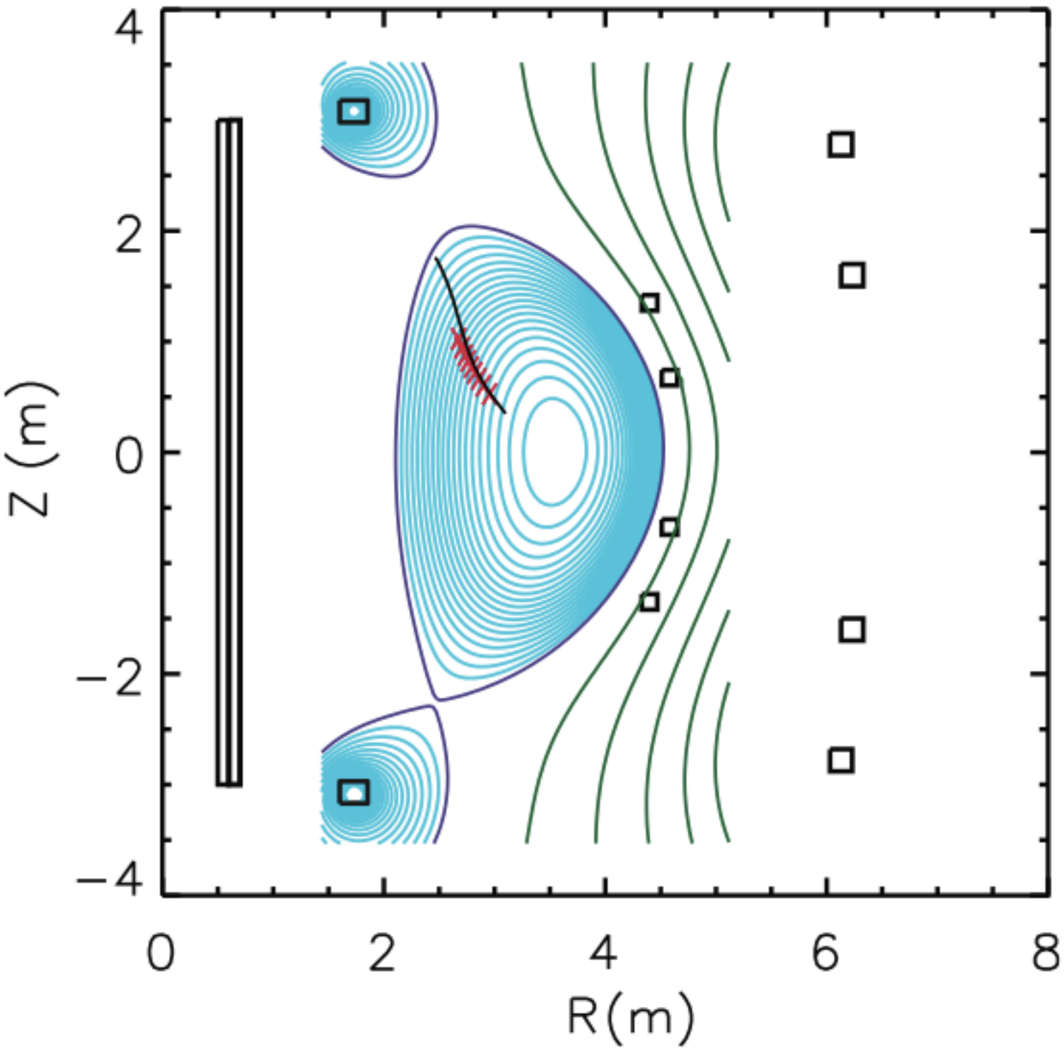
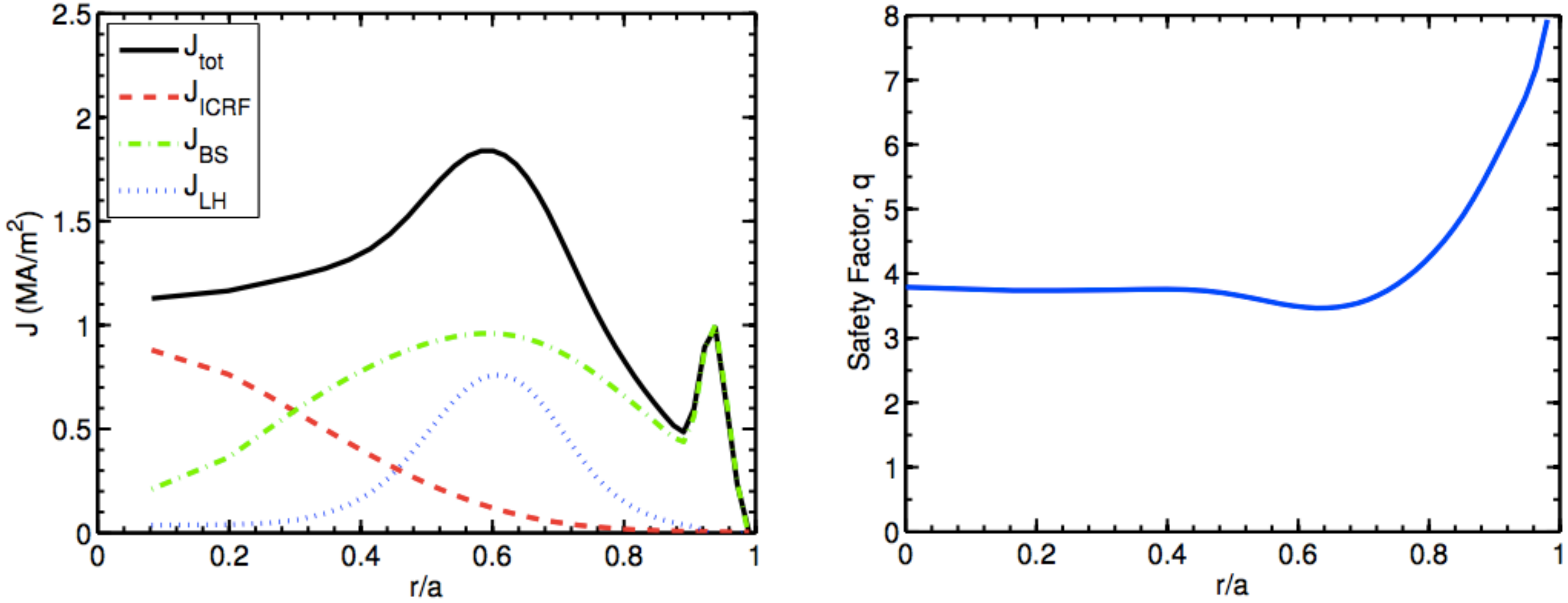


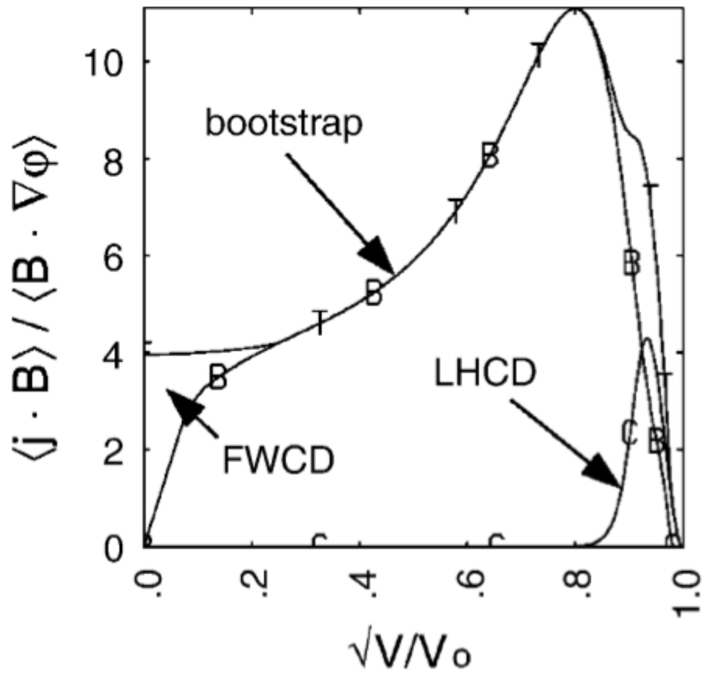


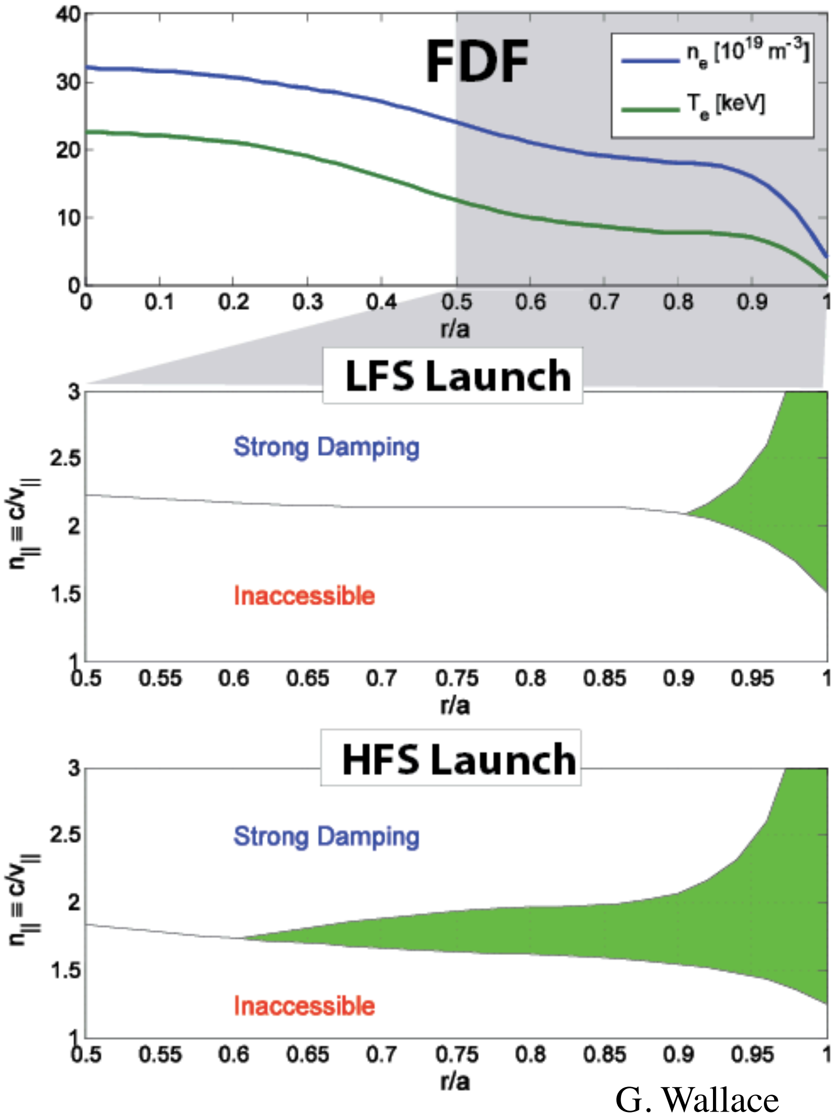
Optimized CD efficiency leads to substantial control of AT current profile below no-wall β_N limit



HFS-launch overcomes limitations of LFS LHCD in other designs

ARIES-AT





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

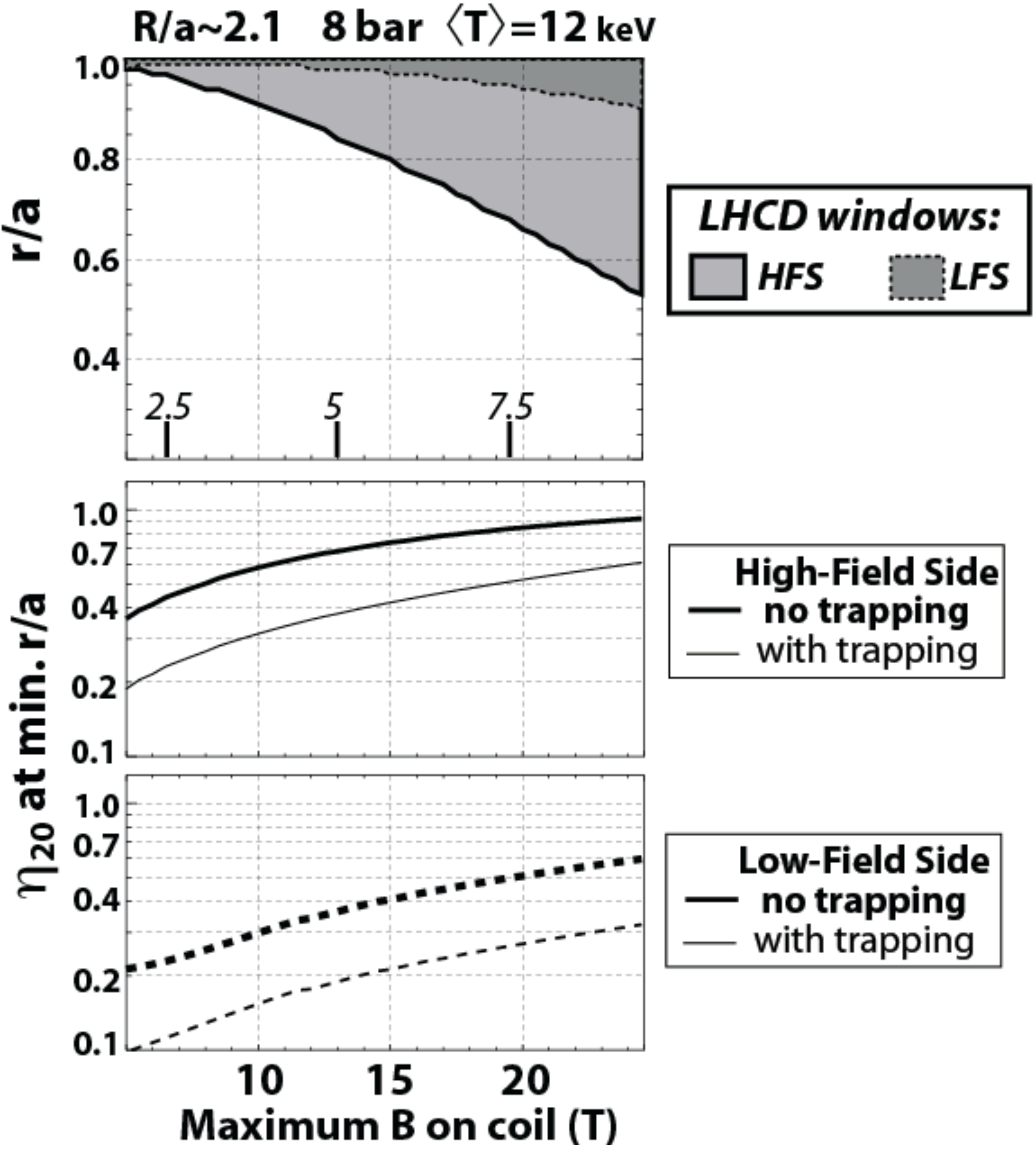
DT device	ε	κ	η_{20}	n_{20}	β_N **(~3 no-wall limit)**	**q***	**R (m)**	**B (T)**	Q_p	I_{CD}/I_{BS}
FDF *(FNSF)*[1]	0.28	**2.3**	**0.12** **(ECCD)**	2.2	**3.7**	2.8	2.7	5.5 **(Cu)**	**2.6**	~30%
ARIES-AT[2]	0.25	**2.2**	**0.25** **(LH)**	2.2	**5**	**2.1**	5.2	5.8 (SC)	50	**~10%**
ARC	0.35	**1.9**	**> 0.4**	2	**2.5**	**4.5**	3.3	9.2	**15**	**~50%**

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

[2] *F. Najmabadi et al. FED (2006) 3.*

HFS vs. LFS Launch in low aspect ratio FNSF

- Higher B_{peak} needed for reactivity
- HFS vs. ~zero access from LFS
- Trapping effects more important



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- Placing RF launchers on the high-field side (HFS) where the plasma is quiescent provides a solution to the heat flux and erosion launcher issues for steady-state.

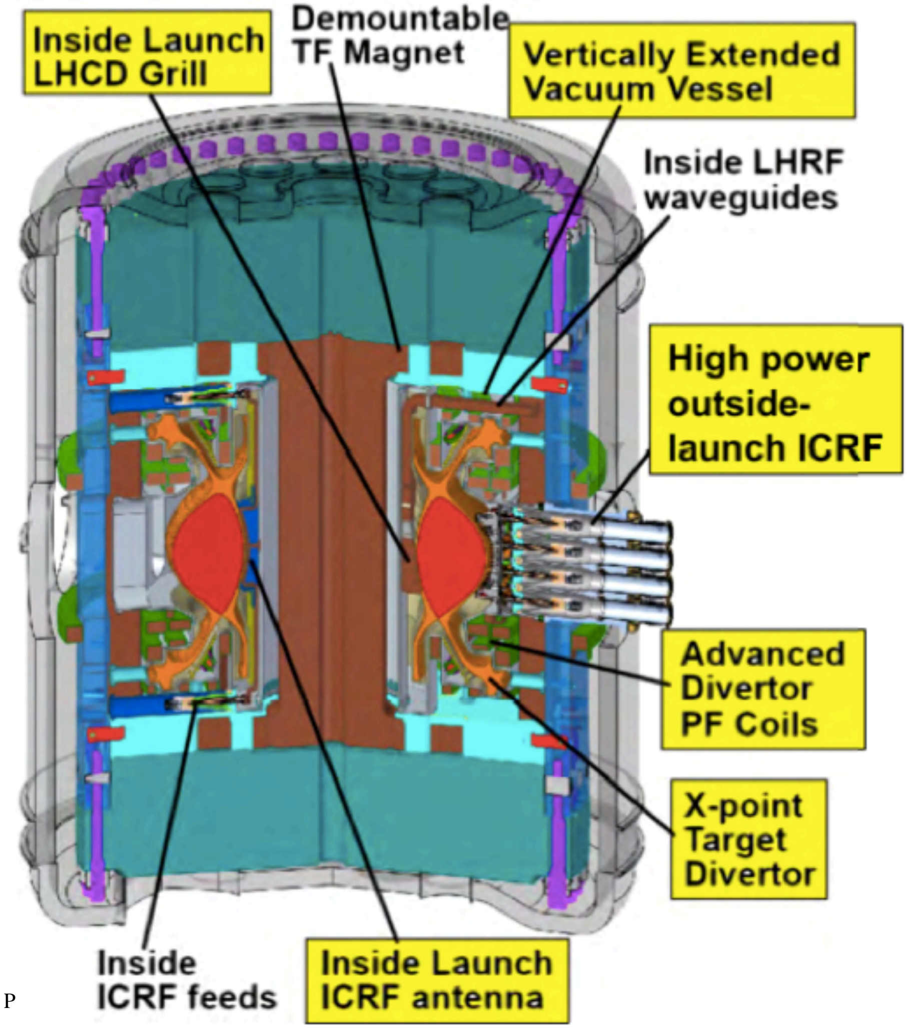
- Placing RF launchers at the HFS near null-point optimizes ray penetration and propagation to help avoid parasitic losses in the boundary and the CD "density limit"

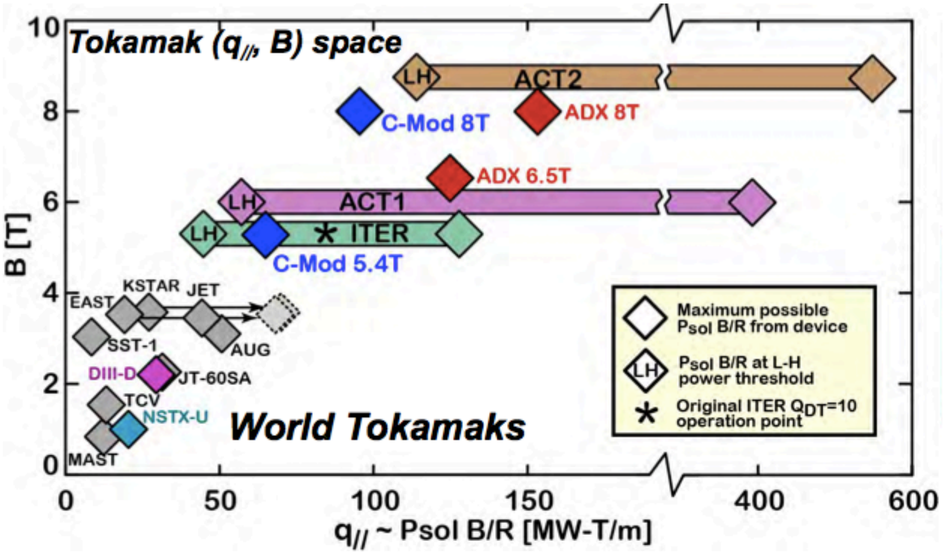
- HFS lower-hybrid current drive (LHCD) provides improved CD efficiency, mid-radius CD and current profile control in FNSF/Pilot plasmas that allow high-gain with good control

- **The proposed ADX, with purpose-built HFS launchers, provides an near-term exciting opportunity for integrated RF + edge solutions.**

ADX: a national program to solve critical boundary & RF issues for FNSF & beyond

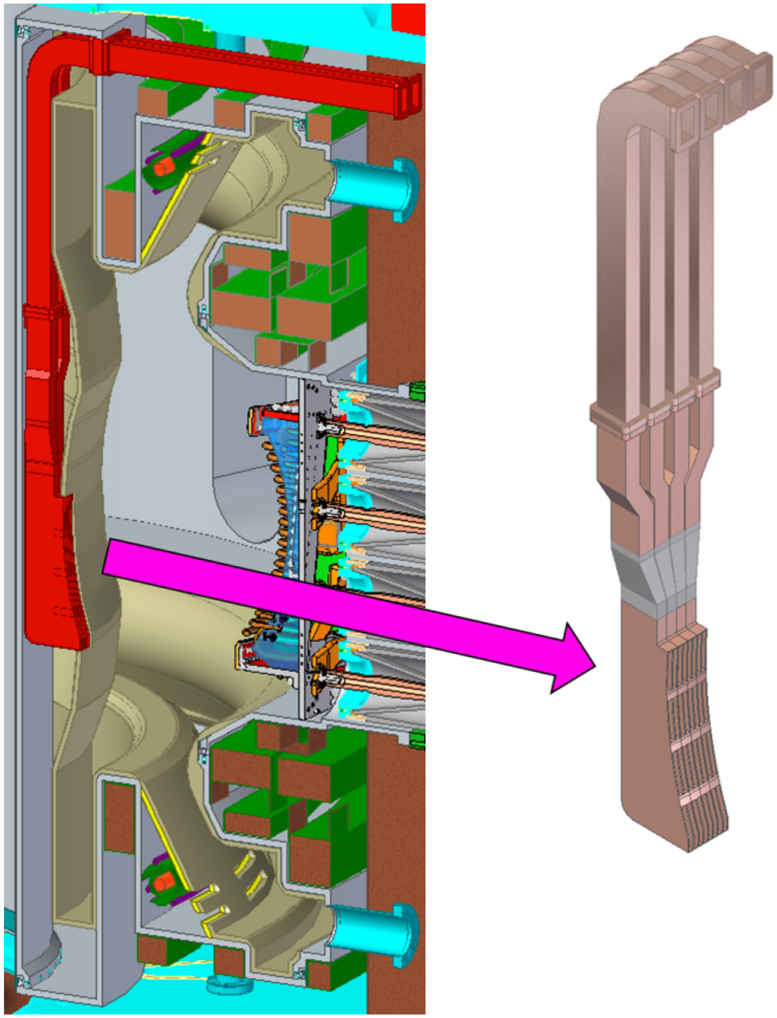
Advanced Divertor Experiment

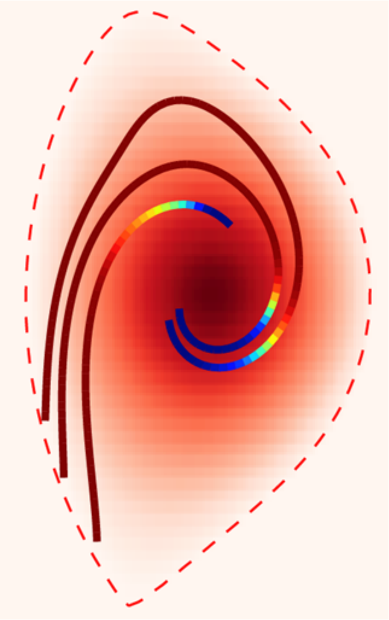




ADX: Feature-built HFS access to demonstrate LHCD solutions

- **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**





n// = 1.6
I-mode target

ICRF may also benefit greatly from HFS launch

Inside launch provides direct access to mode conversion
(FW → IBW) layer

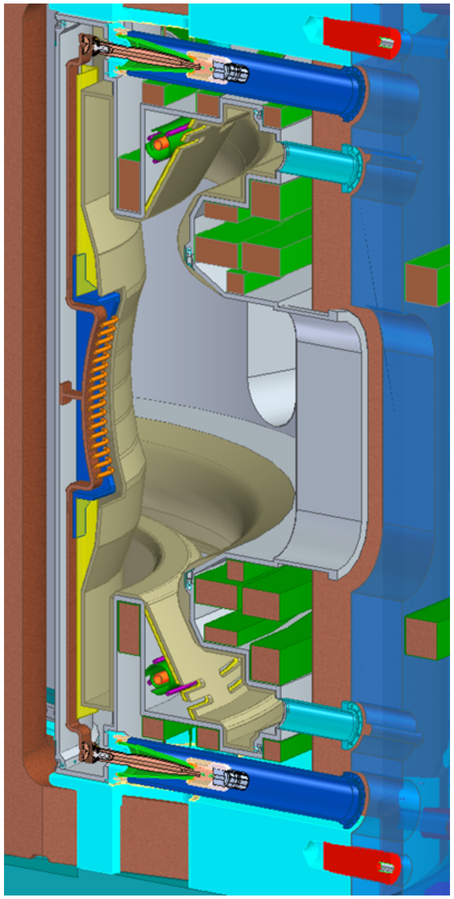
Reduced energetic ion tails

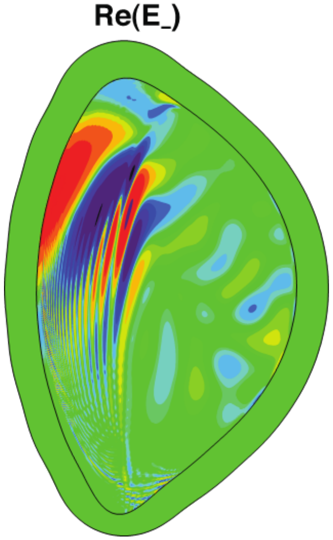
More flexibility w.r.t. minority species

Reduced edge potentials
- Natural field alignment reduces slow wave E//
- Strong single pass absorption avoids FW in SOL

PMI benefits:

- Kinder, gentler SOL
- Excellent impurity screening

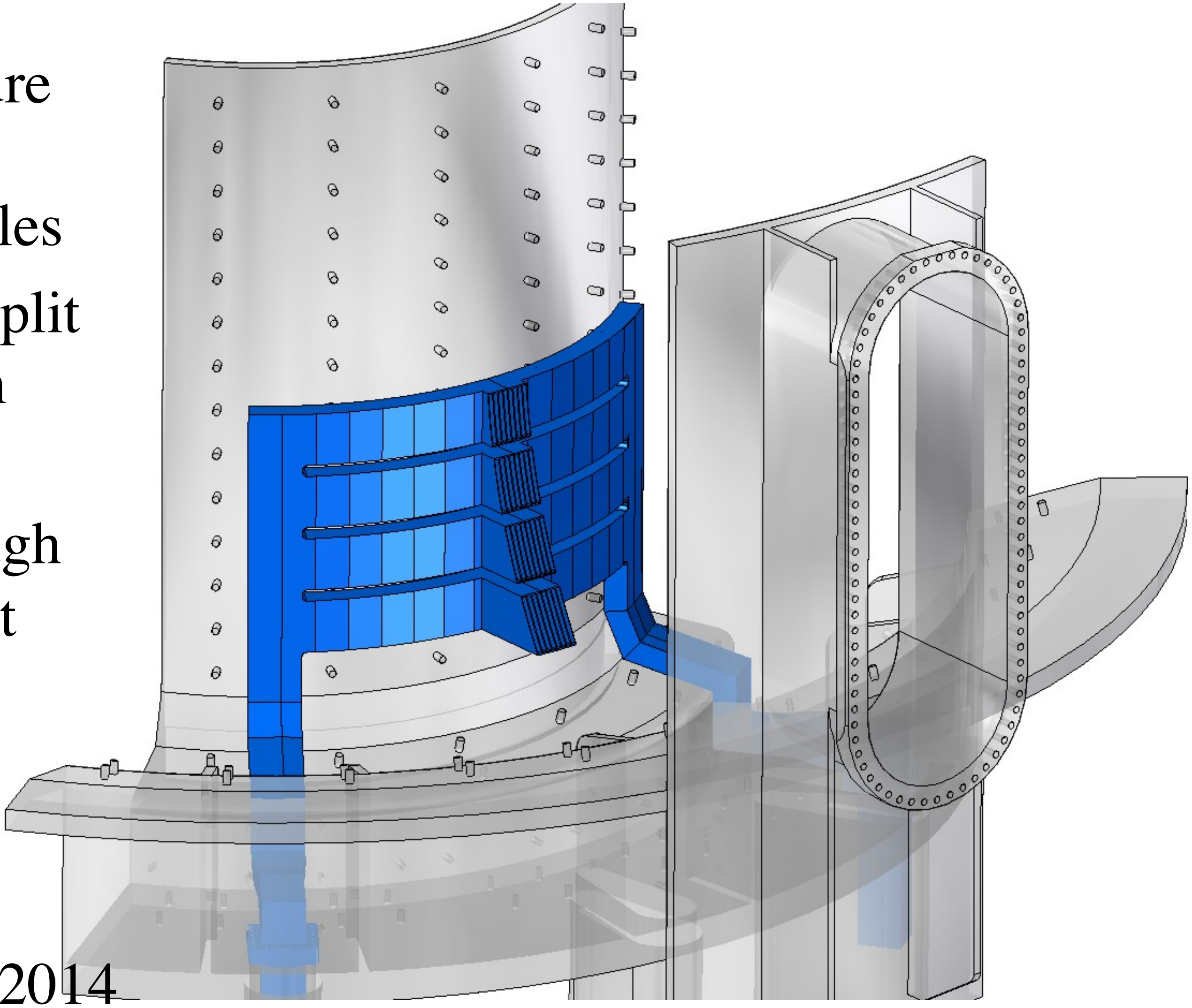




TORIC simulation
for flow drive:
B = 5.4 tesla,
f = 80 MHz,
15% H in D, n_φ = -10,
40% to electrons,
30% to H 1st harmonic
and 30% to D 2nd harmonic

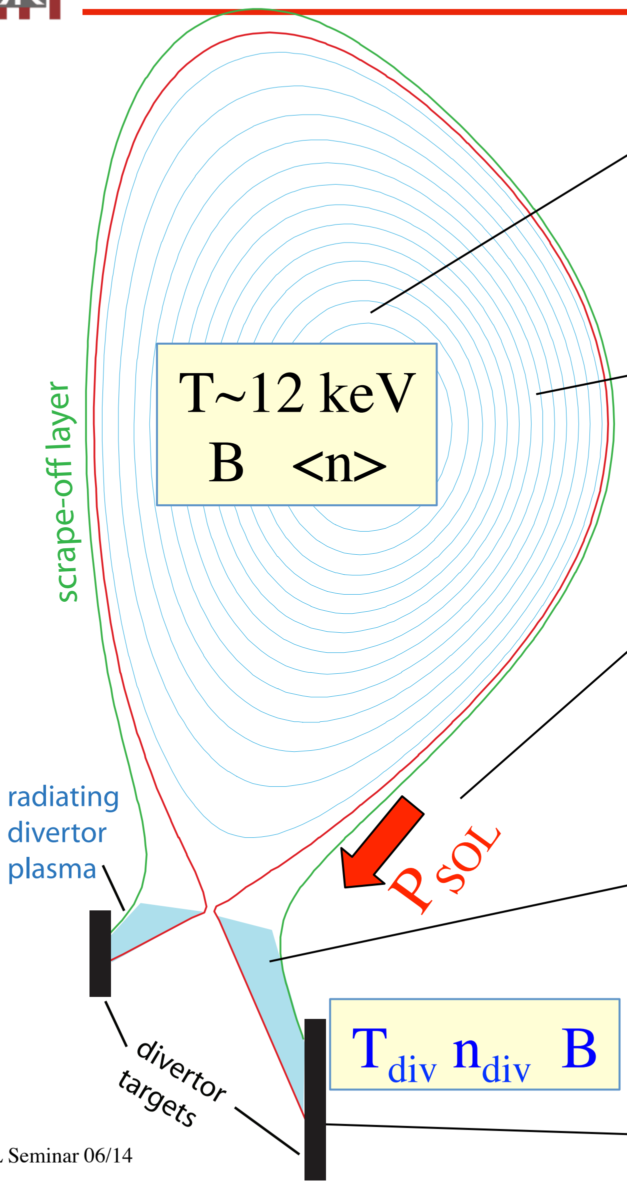
Vertical ports used to feed power to HFS LHCD launcher

- Launcher structure bolted to inner cylinder under tiles
- 4-way poloidal split for each klystron
- 2x WR187 waveguide through each vertical port



G.M. Wallace, EPS2014

Dimensionless parameters of RF + boundary + PMI compel near-term study at reactor density and B



$$\frac{\langle n\rangle}{\left(p_f\langle\sigma v\rangle_{DT}^{-1}Q_{Dt}^{-1}\right)^{1/2}}\rightarrow\langle n_{20}\rangle\simeq 2$$

Fusion nuclear physics

$$\frac{\omega_{pe}}{\omega_{ce}}\sim\frac{\langle n\rangle^{1/2}}{B}$$

RF current drive

$$\frac{P_{div}}{P_{SOL}}\sim\frac{n_{div}^{2}\,f\left(T_{div}\right)}{\langle n\rangle^{2}}\sim\langle n\rangle^{2}f\left(T_{div}\right)$$

Divertor radiation dissipation

$$\frac{T_{div}}{E_{atom}}\sim T_{div}\qquad\frac{n_{div}\langle\sigma v\rangle_{atom}}{\nu_{atom}}\sim\langle n\rangle^{2}$$

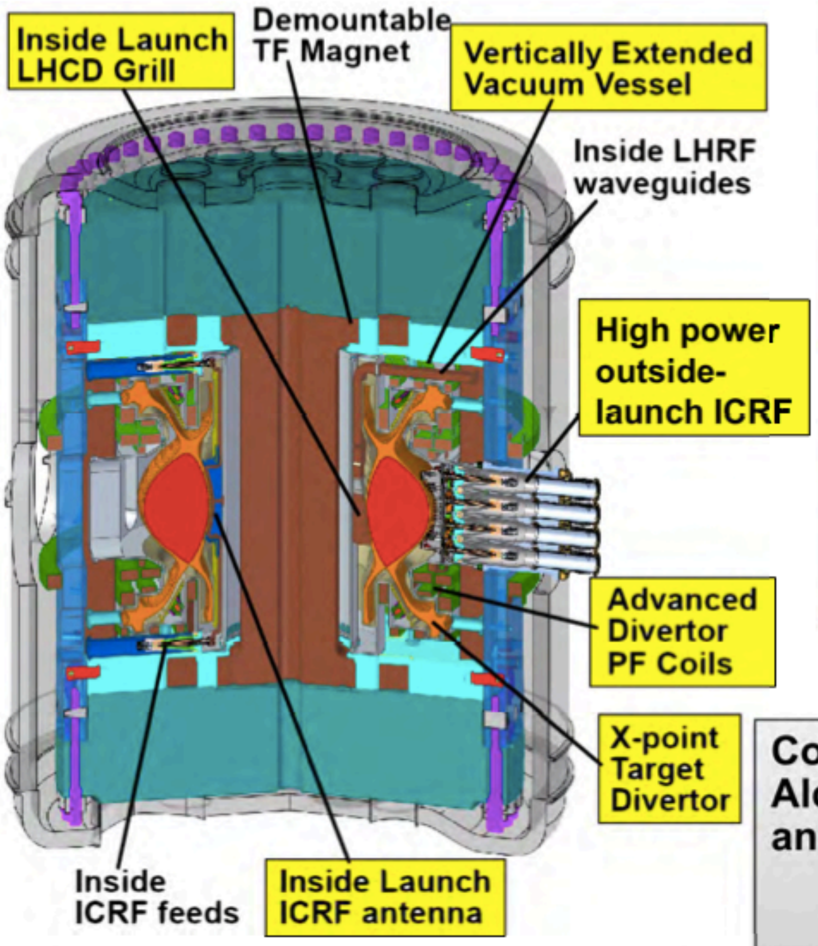
Divertor atomic physics

$$\frac{\lambda_{MFP}}{\rho_i}\sim\frac{B}{n_{div}}\sim\frac{B}{\langle n\rangle^{2}}$$

PMI physics

ADX: A resource-effective national facility to develop integrated boundary & RF current drive solutions required for steady-state FNSF

Advanced Divertor Experiment



Infrastructure presently supporting C-Mod is valued at $200M

LaBombard FESAC

- Development platform for Advanced Divertors
- Reactor-level $q_{||}$, B, plasma pressures

  P_{sol} B/R ~ 125
  => above ITER, Q_{DT}=10
  operating point (90)

- Development platform for low PMI, efficient RF
  - Inside launch LHCD
  - Inside launch ICRF

Cost estimate with reuse of Alcator C-Mod components and siting at MIT:
$3M design (2 yr)
$36M hardware
+$32M construction (4 yr)
$71M

<u>FNSF "drivers"</u>
P/S > 1 MWm^{-2}
n20 ~ 2
q// ~ PB/R > 100

⇩

<u>ADX integration</u>
Detached
~Nil div. erosion
Non-inductive
H$_{98}$ ≥ 1

⇩

<u>Steady-state</u>
<u>FNSF solutions</u>

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Conclusion:
Synergy of HFS-LHCD and high B-field provides very attractive advance reactor designs

1. **Much better accessibility at HFS which is set by *local* density and B, not global parameters.**

2. **Moving launcher to HFS "corner" near X-point makes rays propagate radially, not poloidally**

1. + 2. = 3. Strong single pass absorption <u>at launched "minimum" n//</u> → controllable and highly efficient CD at mid-radius

4. **Launcher protection and minimal PMI due to good curvature on HFS.**

Accesses operation of robust steady-state device with high performance AWAY from limits.

Extra slides

- **Points**

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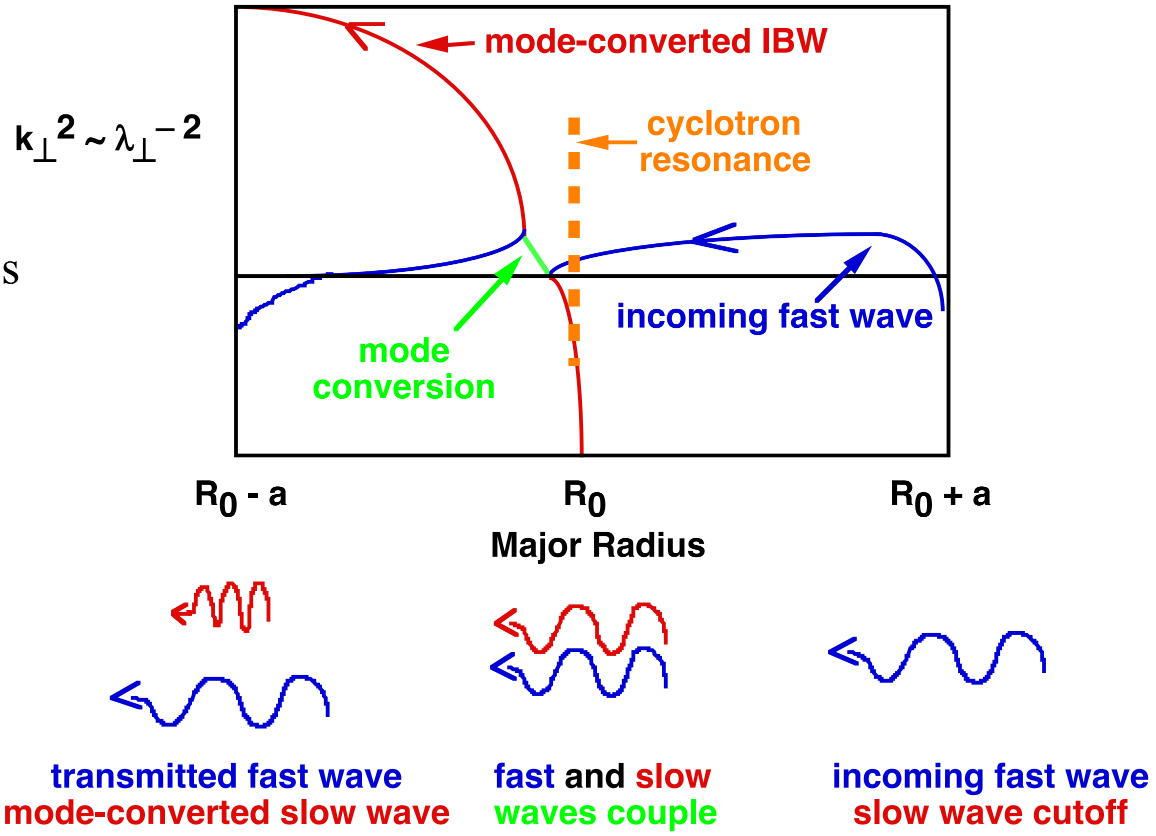
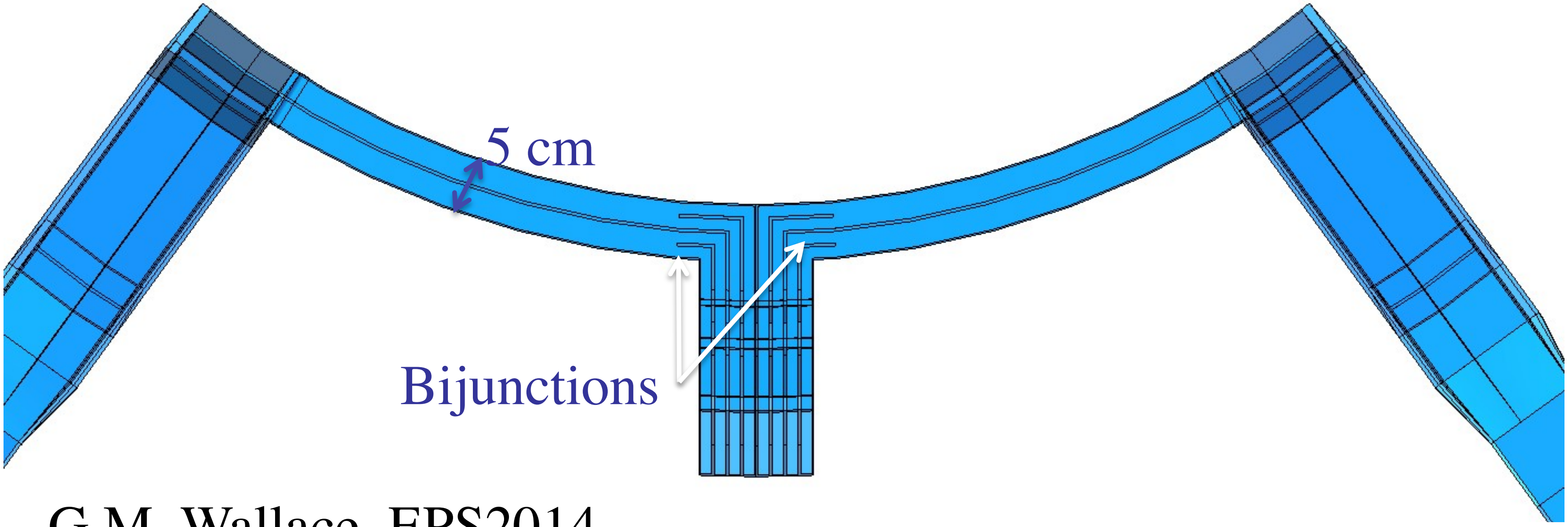


Bonoli SciDac 2007

Minimal space required for launcher on inner wall

- Each klystron feeds 4 row bi-junction
- 4 klystrons feed each launcher (4x8 array)
- Port space available for 3-4 HFS launchers (3-4 MW source power)



G.M. Wallace, EPS2014

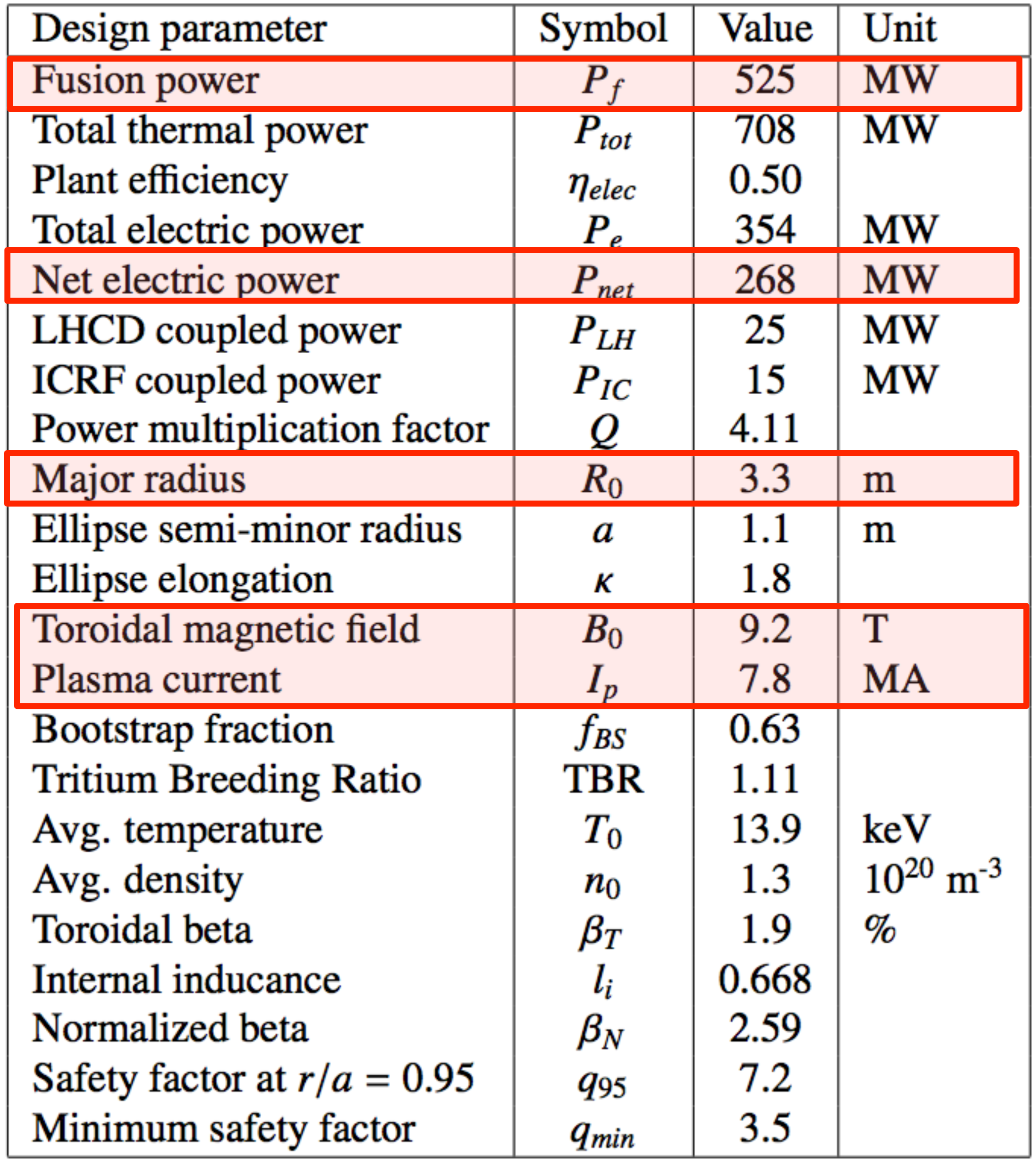
A RF current drive option for low-A designs is highly desirable…not obvious that beams are viable even for FNSF

Beams issues:
- extended confinement boundary, neutron streaming, TBR ↓
- lifetime limited
- Standard E_{beam} ~100 keV → ~0.1 m penetration @ n_{20}~2

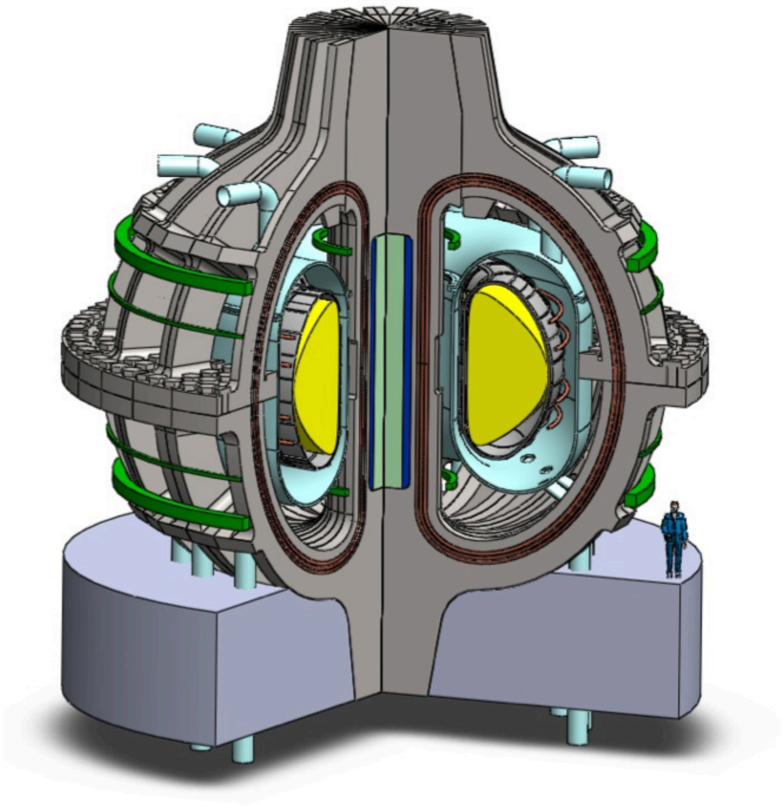
Reactor studies (e.g., the ARIES series) recognized that neutral beams are not suitable for reactors

FESAC 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."

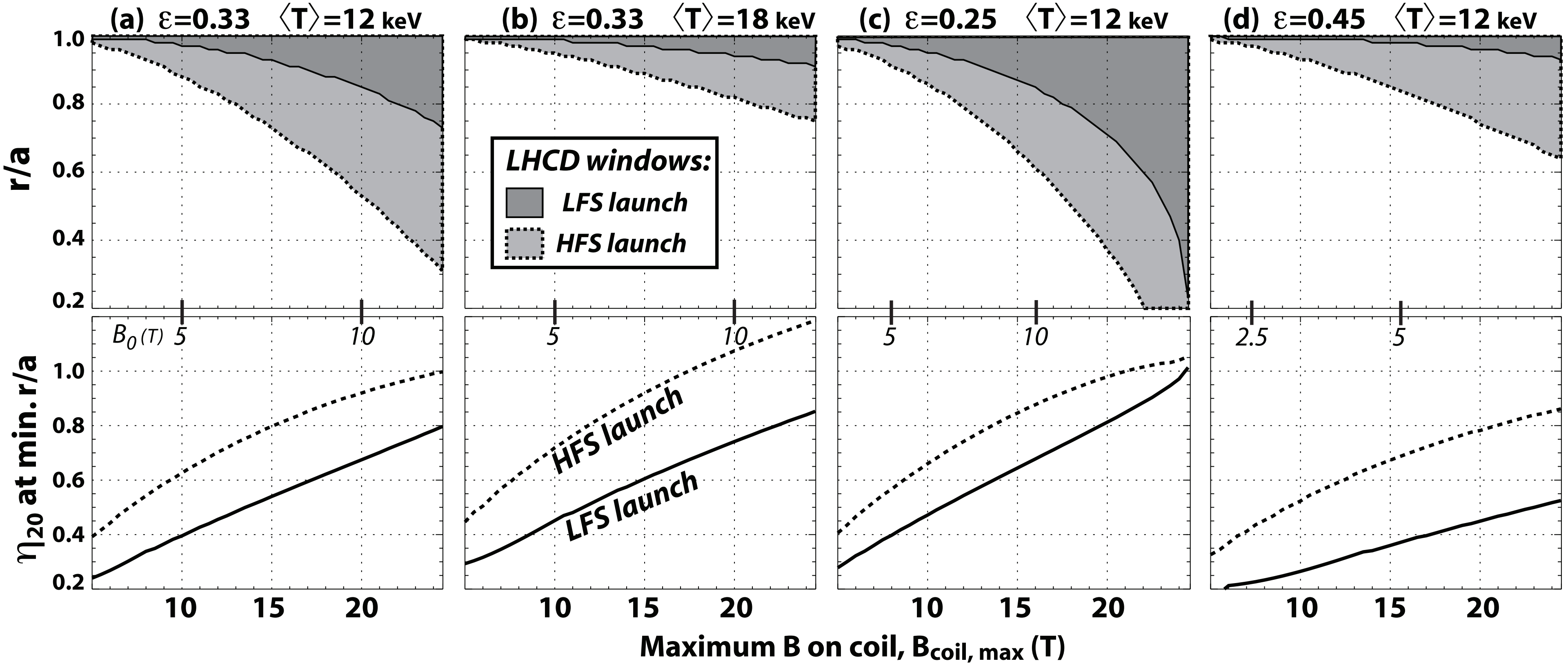
ARC “Pilot”: JET-scale, $Q_e \sim 4$



Design parameter	Symbol	Value	Unit
Fusion power	P_f	525	MW
Total thermal power	P_{tot}	708	MW
Plant efficiency	η_{elec}	0.50	
Total electric power	P_e	354	MW
Net electric power	P_{net}	268	MW
LHCD coupled power	P_{LH}	25	MW
ICRF coupled power	P_{IC}	15	MW
Power multiplication factor	Q	4.11	
Major radius	R_0	3.3	m
Ellipse semi-minor radius	a	1.1	m
Ellipse elongation	κ	1.8	
Toroidal magnetic field	B_0	9.2	T
Plasma current	I_p	7.8	MA
Bootstrap fraction	f_{BS}	0.63	
Tritium Breeding Ratio	TBR	1.11	
Avg. temperature	T_0	13.9	keV
Avg. density	n_0	1.3	10^{20} m^{-3}
Toroidal beta	β_T	1.9	%
Internal inducance	l_i	0.668	
Normalized beta	β_N	2.59	
Safety factor at $r/a = 0.95$	q_{95}	7.2	
Minimum safety factor	q_{min}	3.5	



HFS-LHCD+ high B: Excellent penetration @ <T>~12 keV, high efficiency, > & low aspect ratio can be used!



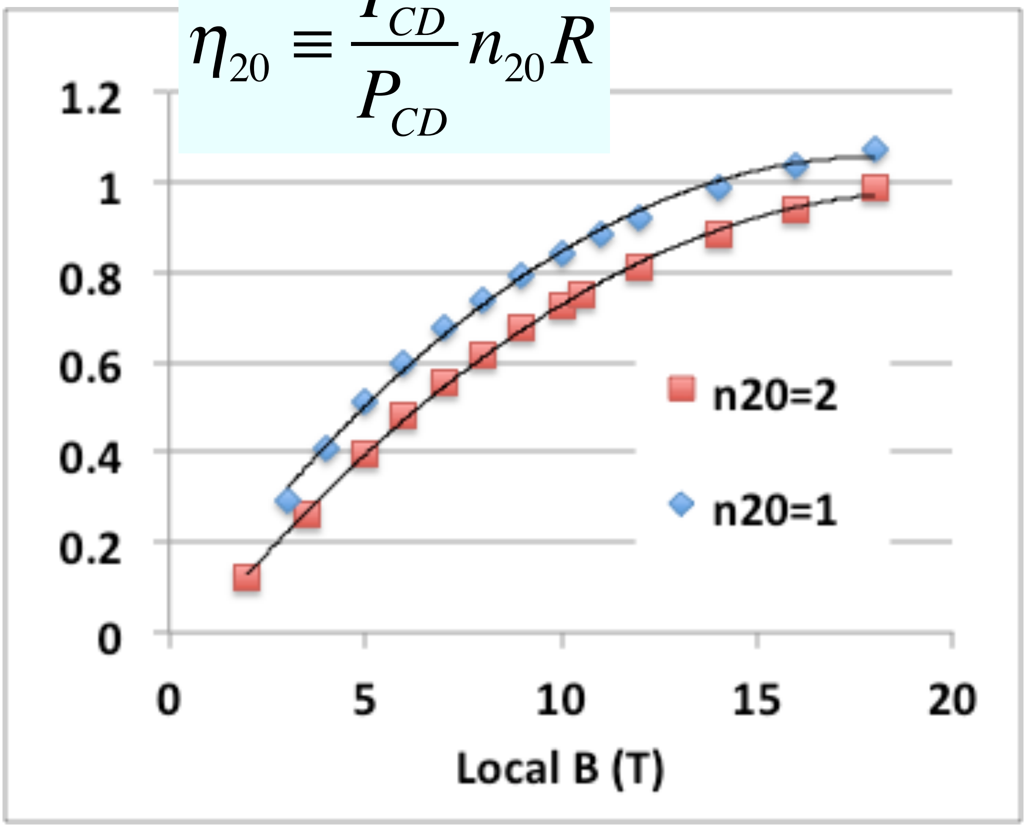
p_{th}~ 0.8 MPa

Intrinsic improvement in CD efficiency at high local B makes LHCD + high-field launch a natural choice

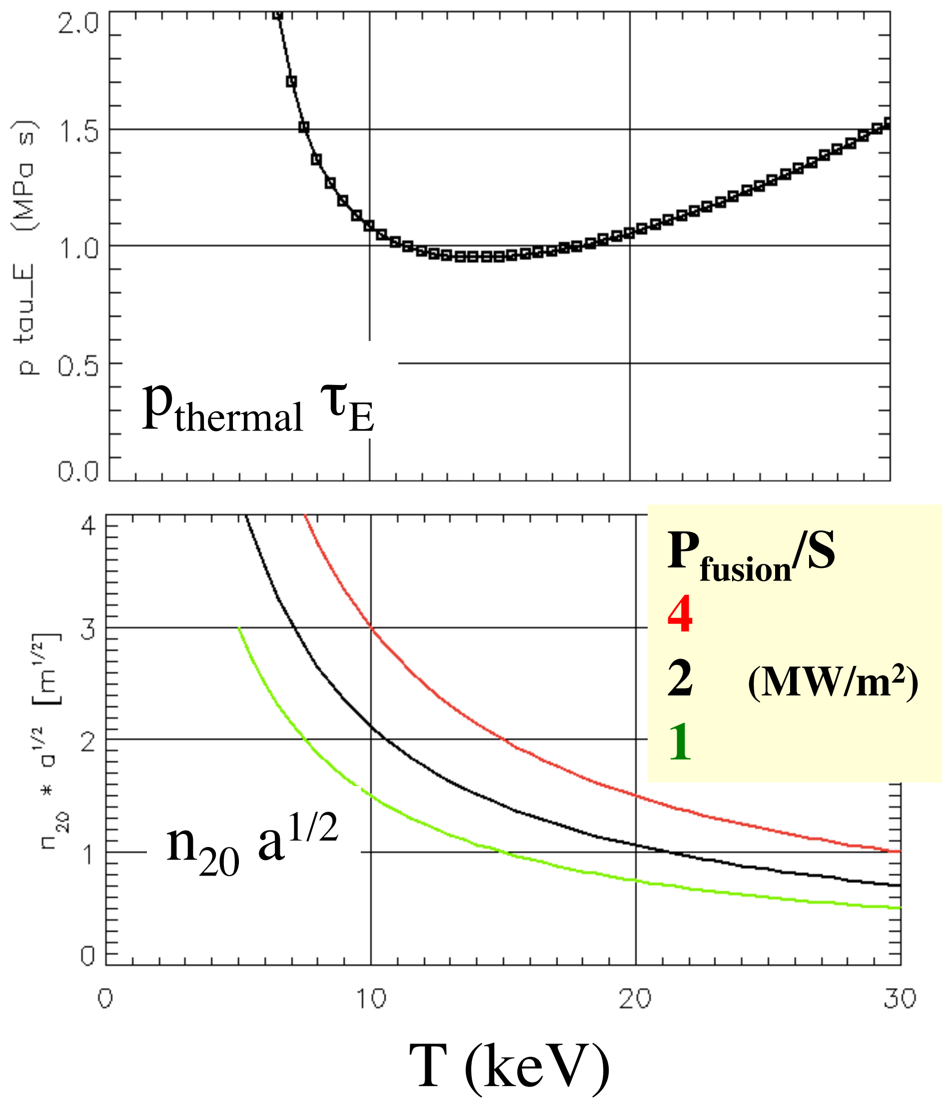
Strong single pass absorption <u>at launched "minimum" n//</u> → controllable and highly efficient CD at mid-radius

Launcher protection and minimal PMI due to good curvature on HFS.

$$\eta_{20} \equiv \frac{I_{CD}}{P_{CD}} n_{20} R$$



Basic DT considerations: Core operating point highly constrained



- **Lawson criterion for gain**
- **<T> ~ 12 – 18 keV**

- **Fusion power density is <u>primary</u> design point**
- **Sets required pressure →**
- **Density n_{20}~2**

ARC "Pilot" highlights synergies found at small-scale + high B + demountable

- **Students used standard fusion design tools**
  MCNP
  COMSOL
  ACCOME

- **Design goals:**
  1) ~ 100's MW fusion power
  2) robust steady-state
  3) small as possible but..
  4) 20+ full power years
  5) can achieve $Q_{electric} > 1$