Plasma Science and Fusion Center
Massachusetts Institute of Technology

RF HEATING AND CURRENT DRIVE ACTUATORS IN A FUSION NUCLEAR ENVIRONMENT

G.M. Wallace, MIT Plasma Science and Fusion Center, 27 March, 2022

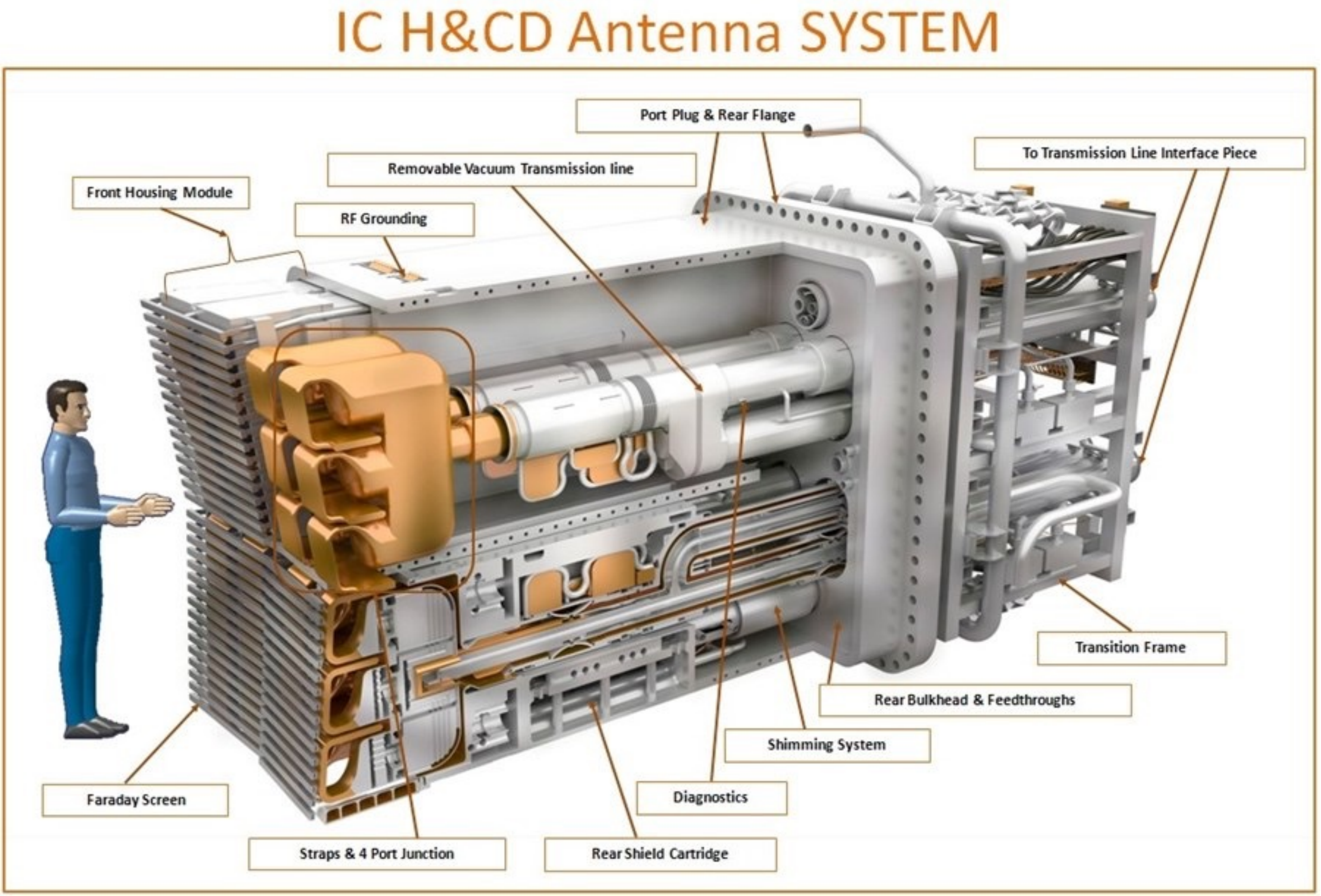
Robust, efficient, reliable RF actuators required for nearly all fusion power plants

- Fusion power plant will require very long pulses at high duty cycle (if not true steady state operation) and infrequent maintenance to be economical
- H&CD antennas will need to operate for months-years without failure or maintenance
- Need robust, efficient, reliable RF heating & current drive actuators
- Remainder of this talk will focus on work done as part of the FESS FNSF study, but lessons are broadly applicable to a variety of fusion reactor concepts

Key takeaways from this talk

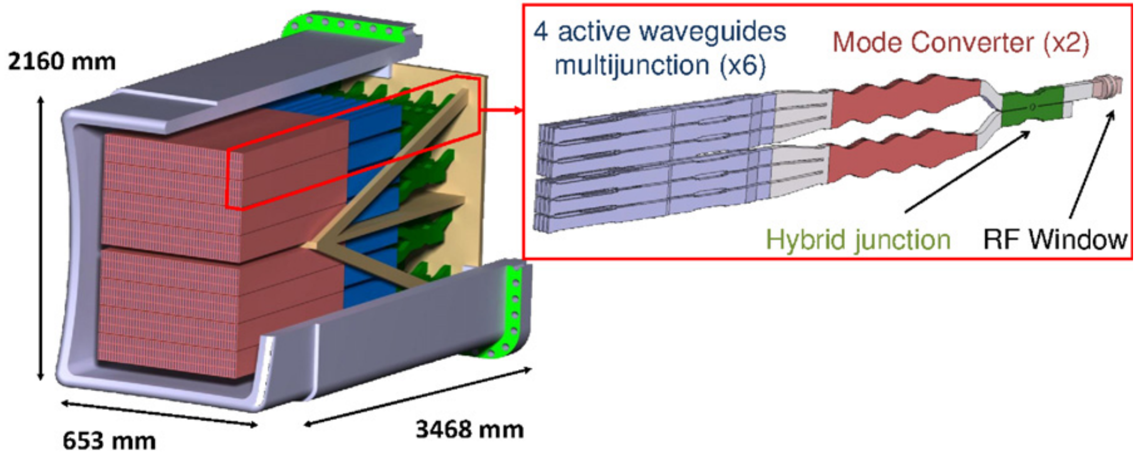
- Integrate antennas into first wall structure better for shielding and TBR as compared to port-plug style designs
- Locate antennas on the high field side wall to ameliorate many issues, at the tradeoff of engineering complexity
- Need to develop new structural materials to build antenna structures that will be compact and long-lived

ITER antenna designs based on port plug concept



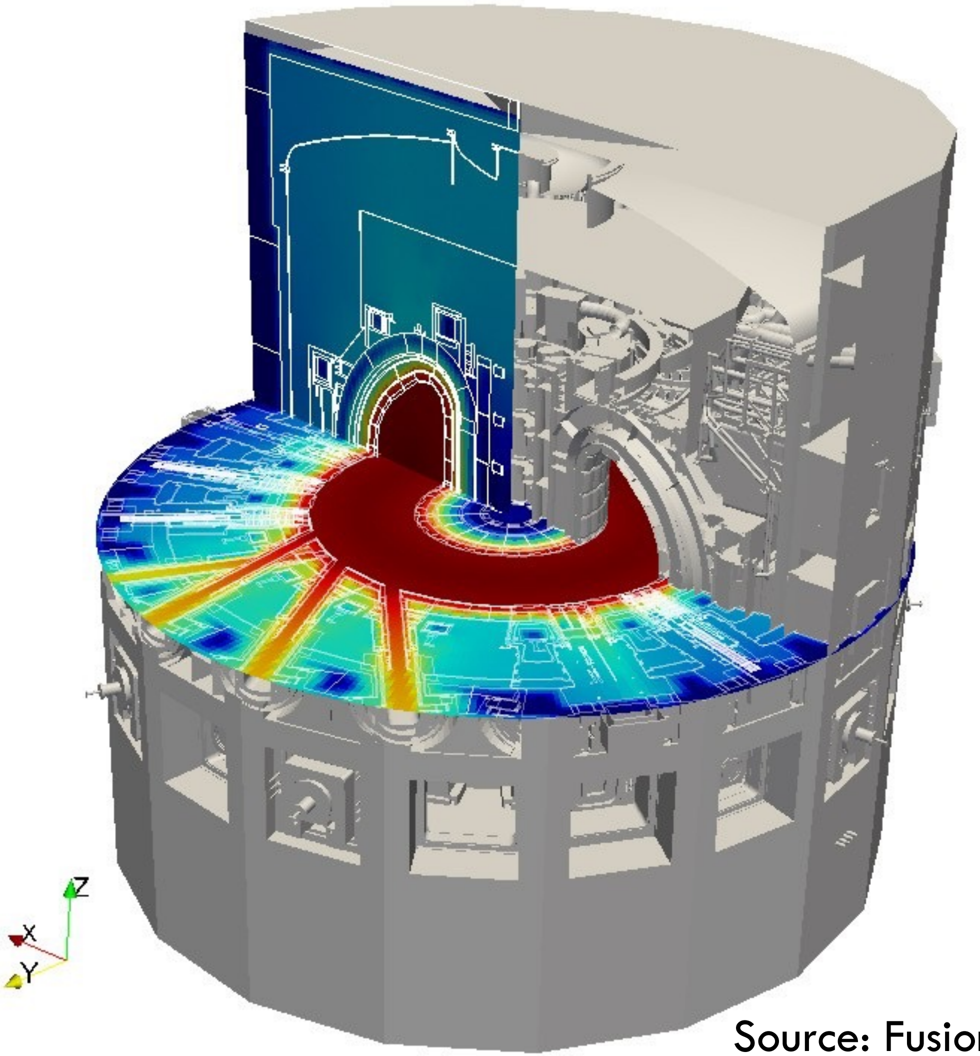
ITER LHCD antenna (proposed)

J. Hillairet et al. / Fusion Engineering and Design 87 (2012) 275–280



Neutron flux outside blanket/shielding increased with port-plug type antennas

- Streaming of neutrons through void space in the antenna structures allows neutrons to escape
- Displacement of breeding material in area near LFS mid-plane lowers TBR

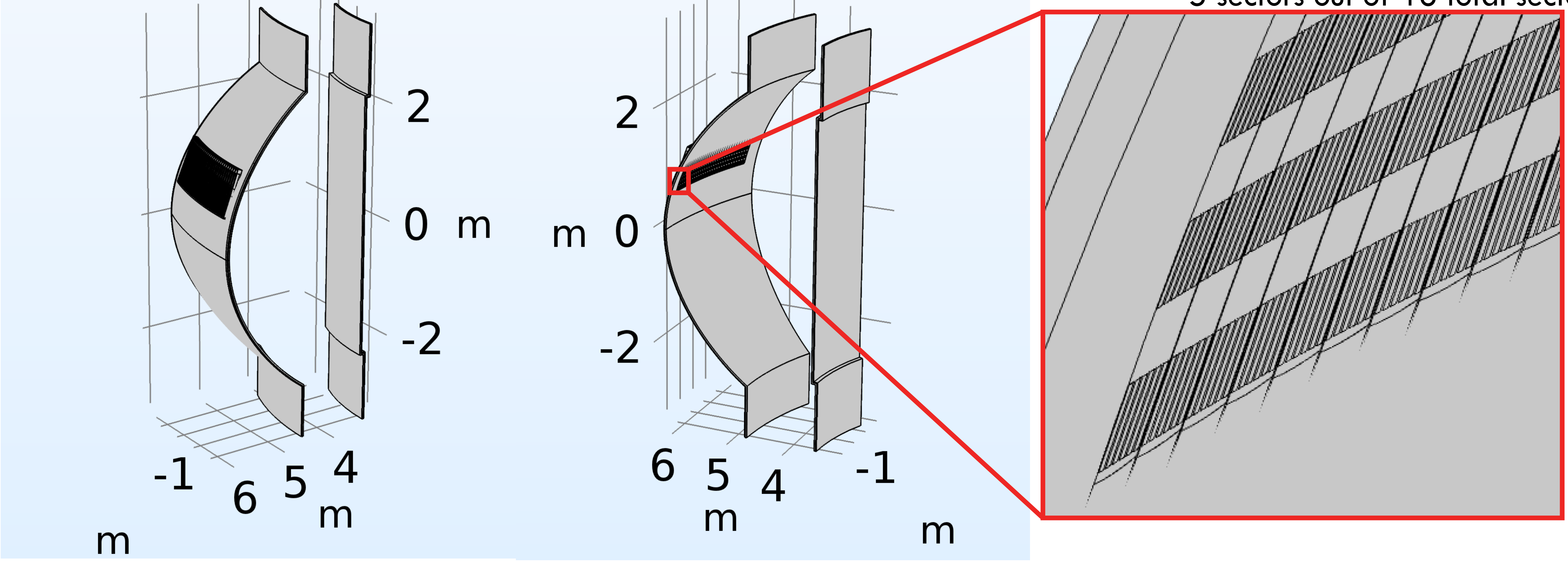


Source: Fusion For Energy

Antenna modules integrated into blanket sectors

30 modules/sector

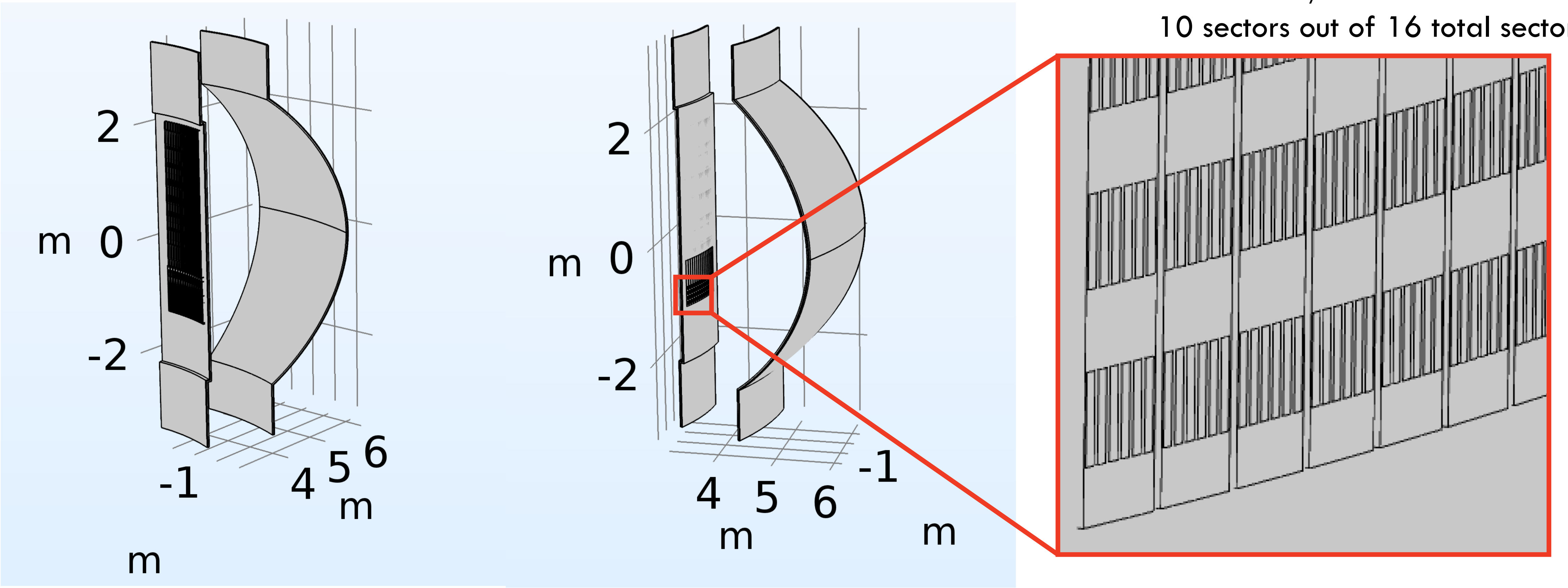
5 sectors out of 16 total sectors



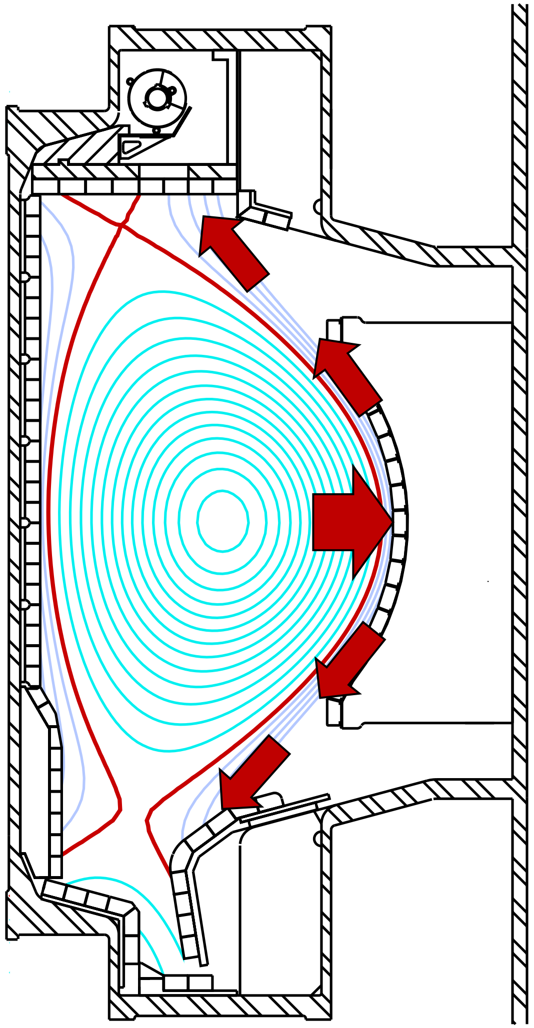
Antenna modules integrated into blanket sectors

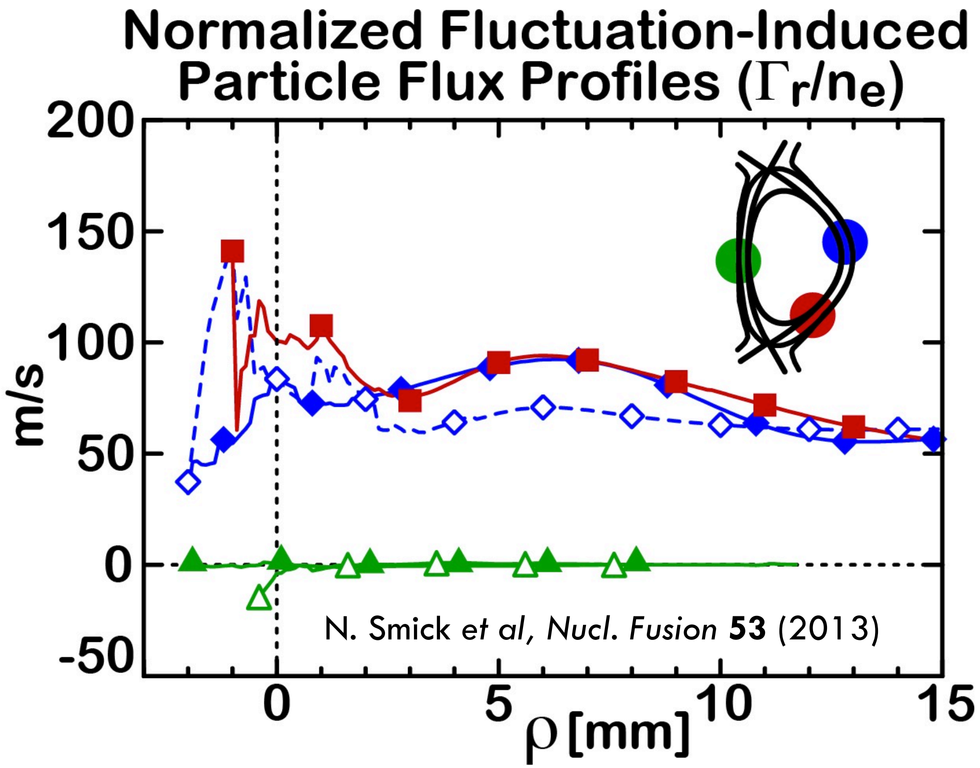
15 modules/sector

10 sectors out of 16 total sectors



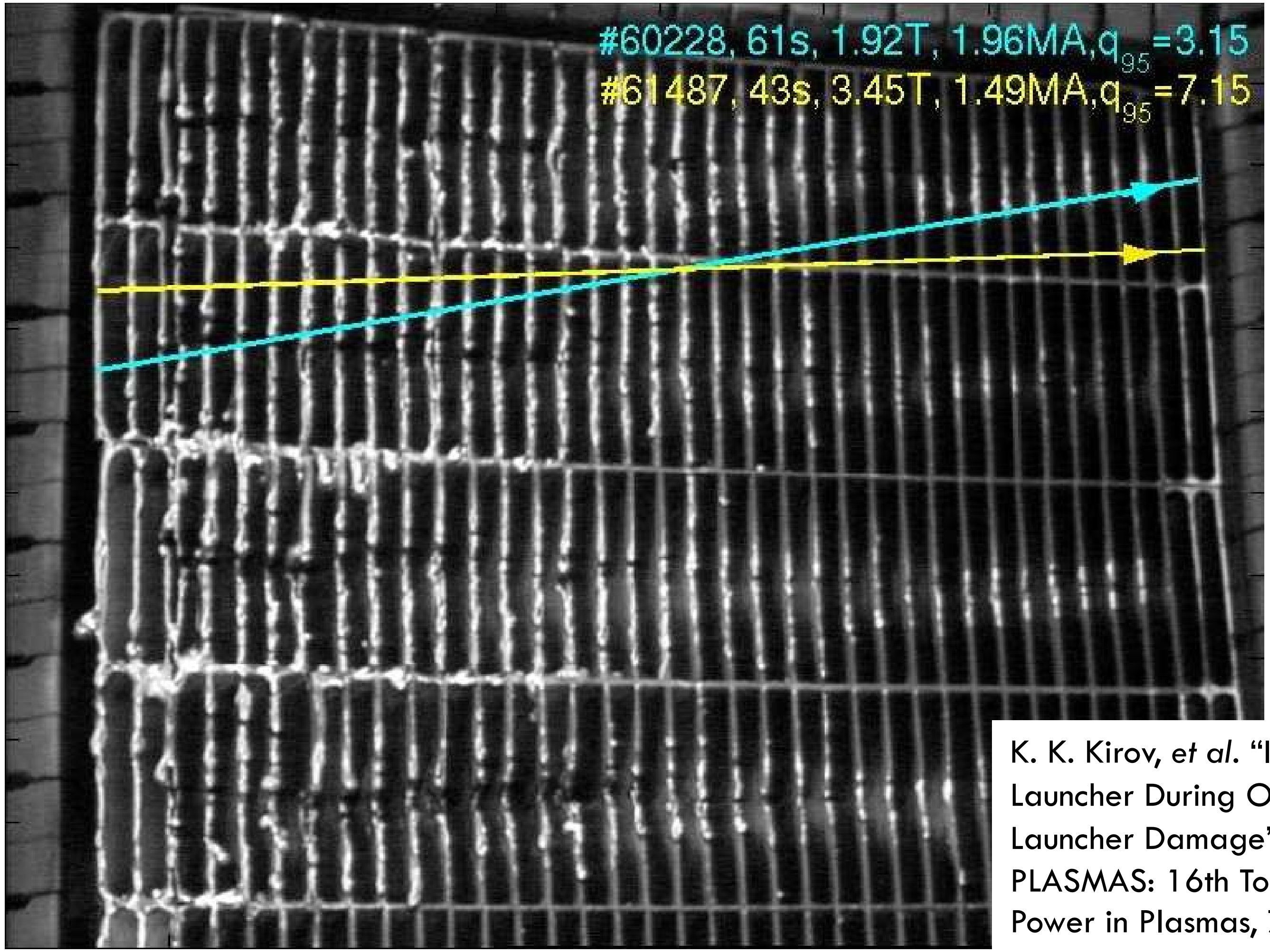
Quiescent HFS SOL is ideal for RF antennas





- Transport in tokamak sends heat and particles to low field side scrape off layer (SOL)
- ELMs do not reach HFS in double null
- Reduced scattering from density perturbations
- Less damage due due to turbulent plasma flux

Antennas in existing experiments show significant damage after short duration

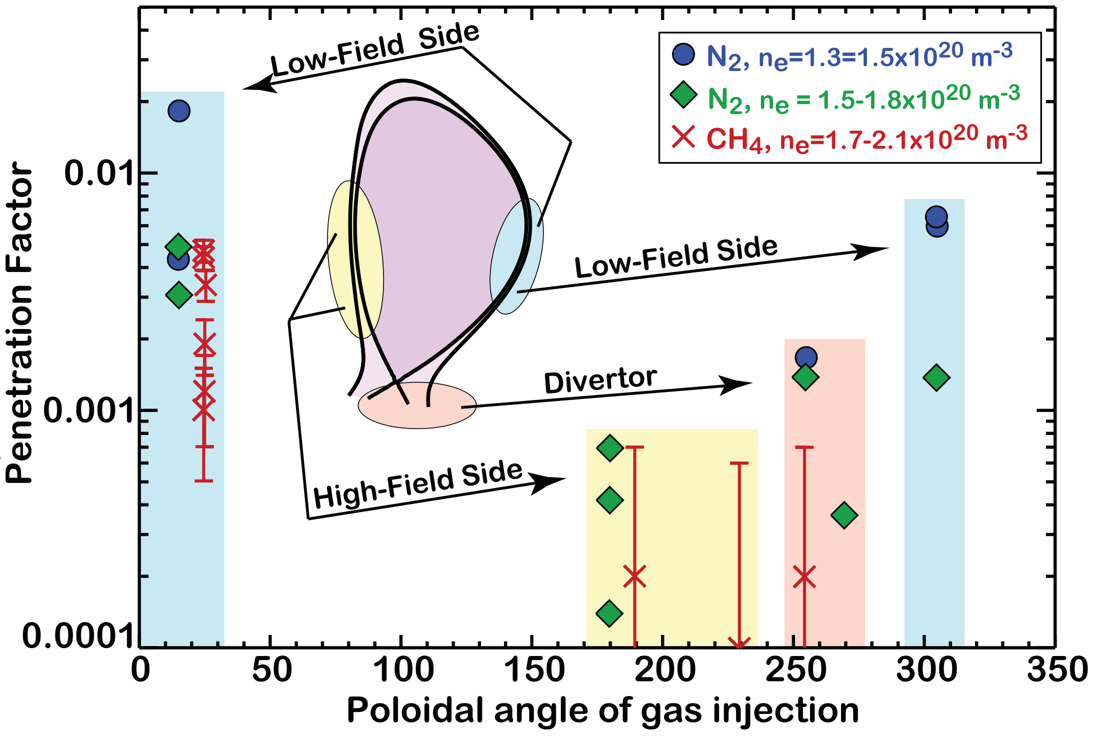


JET

K. K. Kirov, *et al.* “Impurity Radiation From The LHCD Launcher During Operation In JET And Investigation Of Launcher Damage” RADIO FREQUENCY POWER IN PLASMAS: 16th Topical Conference on Radio Frequency Power in Plasmas, 787(1):315–318, 2005.

Good impurity screening on HFS will reduce high-Z contamination from RF

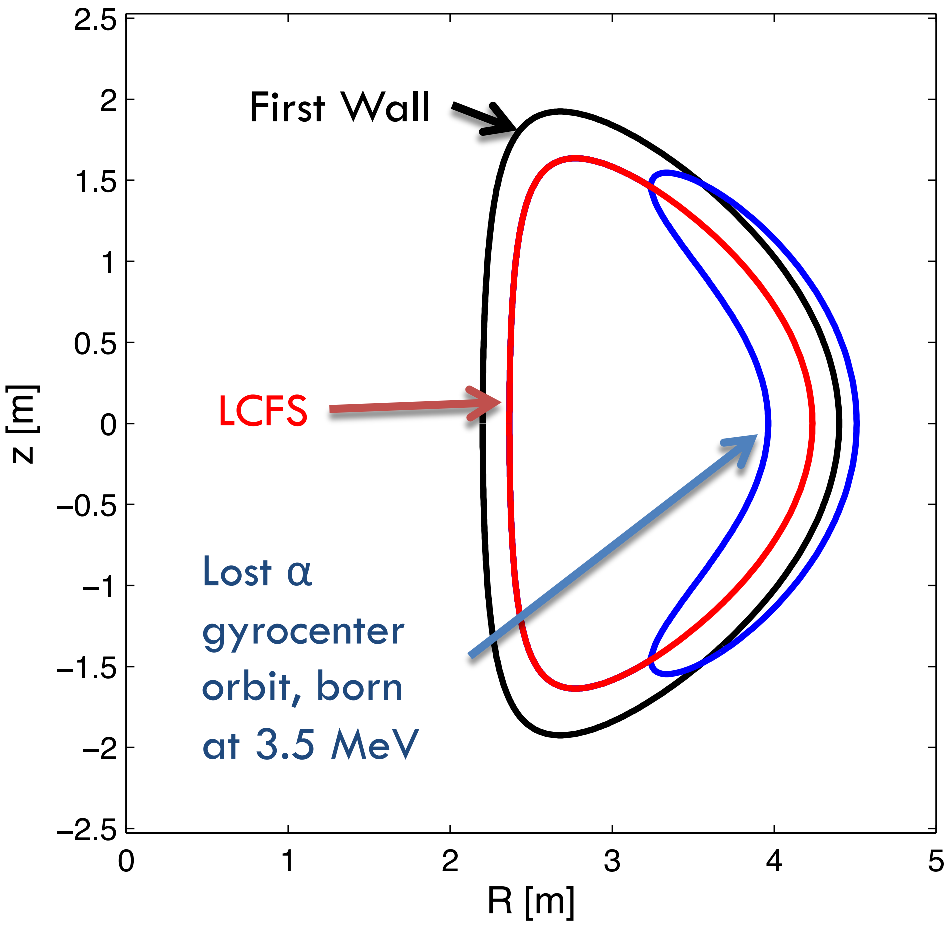
- High power RF (particularly ICRF) in high-Z environment often results in impurity generation
- Measurements show impurities penetration is 10x smaller on HFS



G.M. McCracken, et al, J. of Nuc. Mat., Vol 241–243, p. 777-781, 1997
B. LaBombard et al Nucl. Fusion **55** 053020 (2015)

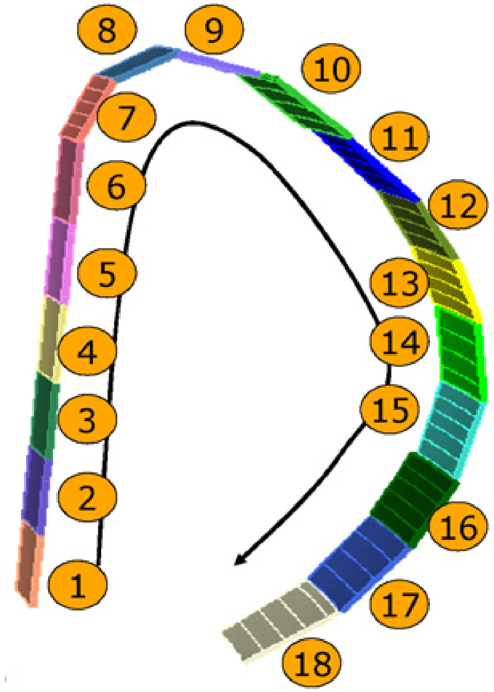
Fewer unconfined fast particles on HFS

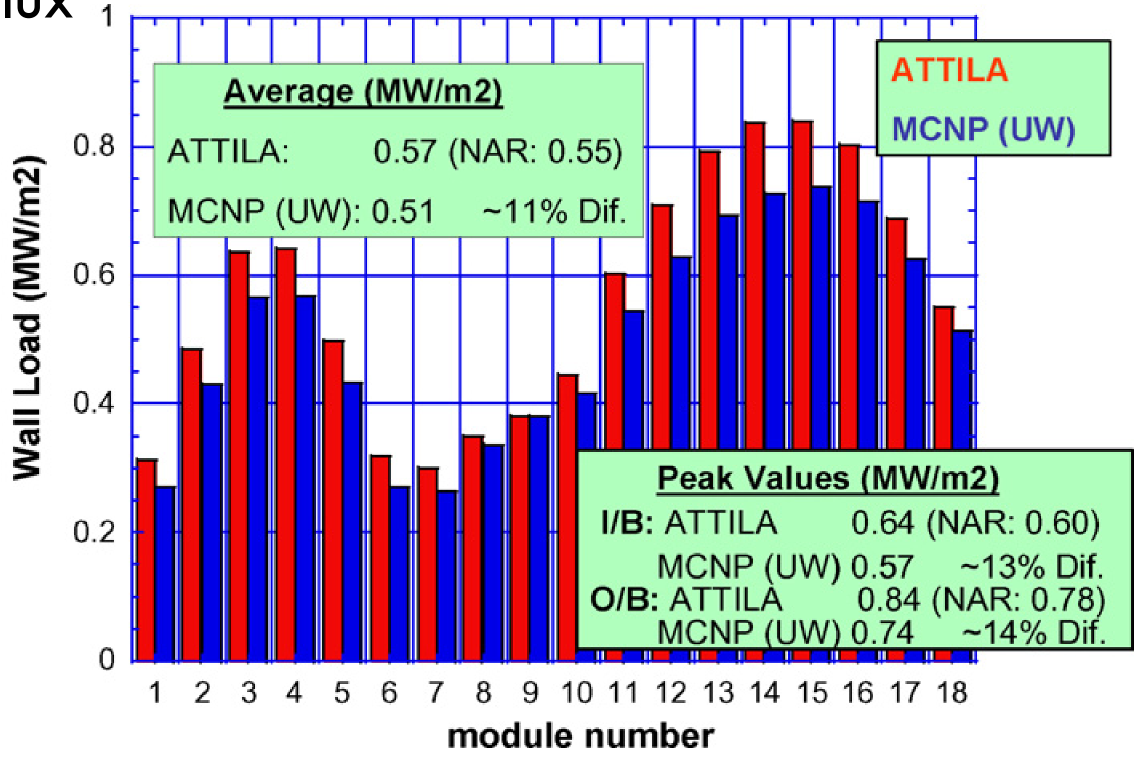
- Fast particles can cause severe damage to in-vessel components
- Majority of fast ions (ICRF minority heating and/or fusion-α's) exit on LFS
- Runaway electron orbits shift to LFS as well
- TF ripple trapped particles exit on LFS



HFS mid-plane has 25% lower neutron wall loading than LFS mid-plane

Simulated ITER neutron flux





Mahmoud Z. Youssef, Russell Feder, Ian M. Davis, Fusion Engineering and Design 83 (2008)

Even lower neutron wall loading occurs at the HFS locations that are off the midplane, #1, 6, and 7

Also best location for current drive!

Less maintenance required for HFS antennas due to less extreme conditions

- Lower PMI and neutron flux extends lifespan of materials on HFS
- Use resilient materials (molybdenum, tungsten?) for HFS antenna plasma facing components
- Replace antenna when you replace sector/blanket module
  - Unlikely you would be able to replace port-plug antennas more sooner, since any maintenance will be very infrequent in a power plant
- Trade-off some engineering complexity for increased longevity

Are HFS RF systems practical for a tokamak reactor?

- Don't think in terms of retrofitting to existing designs
- Be willing to take on some additional engineering
- Design around the HFS RF systems from the start
- It gets easier in a bigger device
  - RF system component sizes are set by $1/f$ (where $f \propto B_t$)
  - Space constraints relax with larger size

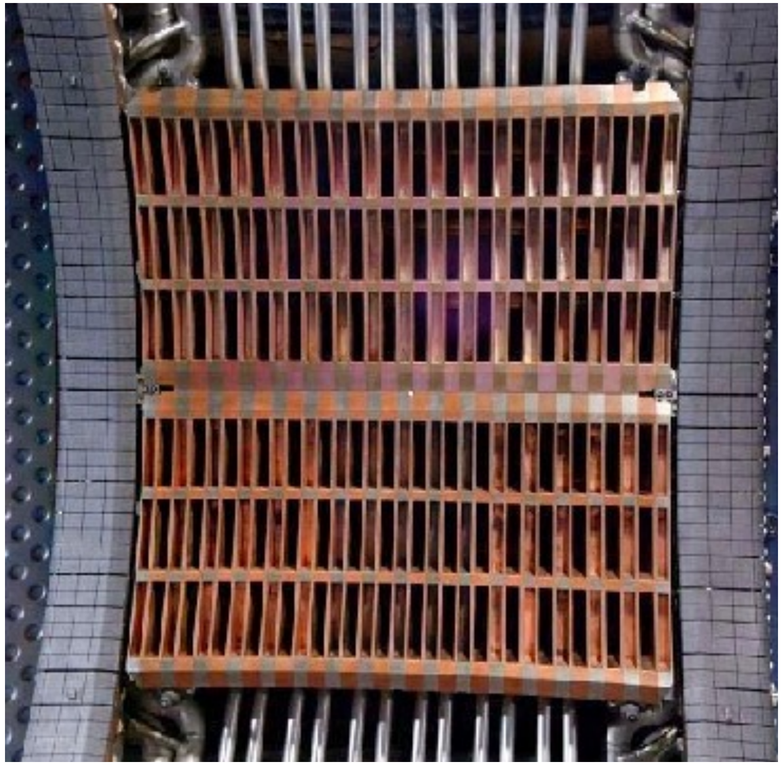
That said, there is a HFS LHCD system designed and under construction for DIII-D right now with minimal perturbation to the existing divertor and HFS wall

RF antennas are **plasma facing components** with many hard to satisfy materials needs

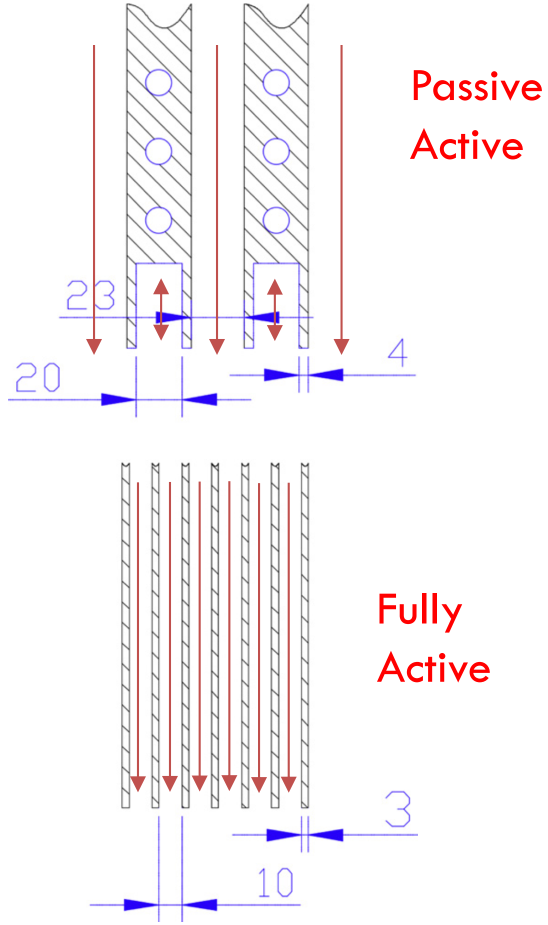
- Low RF losses → high electrical conductivity
- High heat flux → high operating temperatures, high thermal conductivity
- High neutron flux → stability of physical properties and reduced activation
- Disruption forces → high strength
- Structures tuned to specific frequency → Precise manufacturing + predictable dimensional effects
- Example in this presentation is for LH (~5 GHz) but requirements apply to other frequencies as well

Making the case for better antenna materials: cooling a fully-active multijunction antenna

- Passive Active Multijunction (PAM) antennas alternate passive and active waveguides to provide space for cooling of waveguides within the structure
- Fully Active Multijunction (FAM) doubles power density of antenna vs PAM ➔ half as much wall area ➔ smaller impact on TBR, shielding, etc



D. Guilhem *et al.*, "ITER-like lower hybrid Passive Active Multi-Junction antenna manufacturing and tests," *SOFE 2011* doi:10.1109/SOFE.2011.6052318

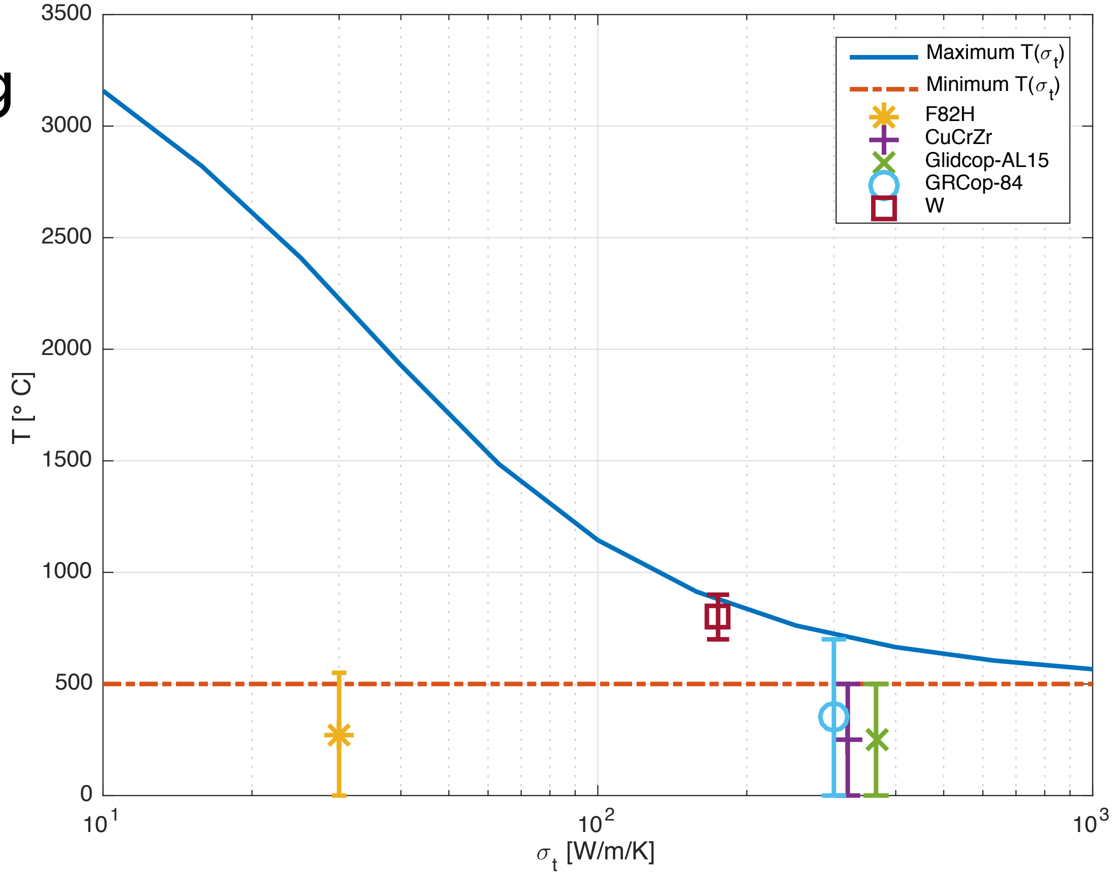


M.H. Li, et al. *Fusion Engineering and Design* 147 (2019) 111250

High thermal conductivity allows for fully active antenna with high directivity at reasonable temp

- GRCop-84 looks quite promising except for the waste disposal rating
  - Replace Nb with another Group 5 element?
    - V seems like it's unlikely to contribute to activation issues
  - Or develop another alloy that has similar high temperature, high strength properties
- Brittleness of tungsten is an issue

Example: fully active LH antenna with fixed septum = 1.5 mm



Fixed electrical conductivity = 2e7 [S/m]

No available material simultaneously meets all requirements

Material	Thermal conductivity [W/m/K]	Electrical conductivity [S/m]	Waste Disposal Rating (WDR)	Temperature window [°C]
RAFM	44.5	2e6 (needs coating)	5.0e-2	<550
Tungsten	175	2e7	6.3e-1	700-900
CuCrZr	320	3e7	3.6e-1	<500
GRCop-84	300	6e7	2.4e3	<700

Nb content

Decay Heat (MW/m^3)

Time	RAFM	W	CuCrZr	GRCop-84
0	0.307	0.466	1.047	0.961
5.3 m	0.287	0.320	0.763	0.700
3.7 d	0.019	0.140	0.018	0.031
1 y	0.008	0.007	0.013	0.012

*for currently available materials

Compromises for all available structural materials

- Tungsten: tradeoff between slightly wider septa or temperatures slightly outside nominal operating window
  - Possible to reinforce to avoid brittleness at low T?
- CuCrZr: ΔT is reasonable, but unlikely to keep T on leading edges low enough given low maximum operating temperature
- RAFM: surface coatings can overcome RF losses, but still needs passive-active type structure due to poor thermal conductivity→ ~ twice the impact on shielding/breeding
- GRCOP-84: Similar ΔT to CuCrZr and higher allowable T, but WDR is very high → **develop new alloy without Nb**?

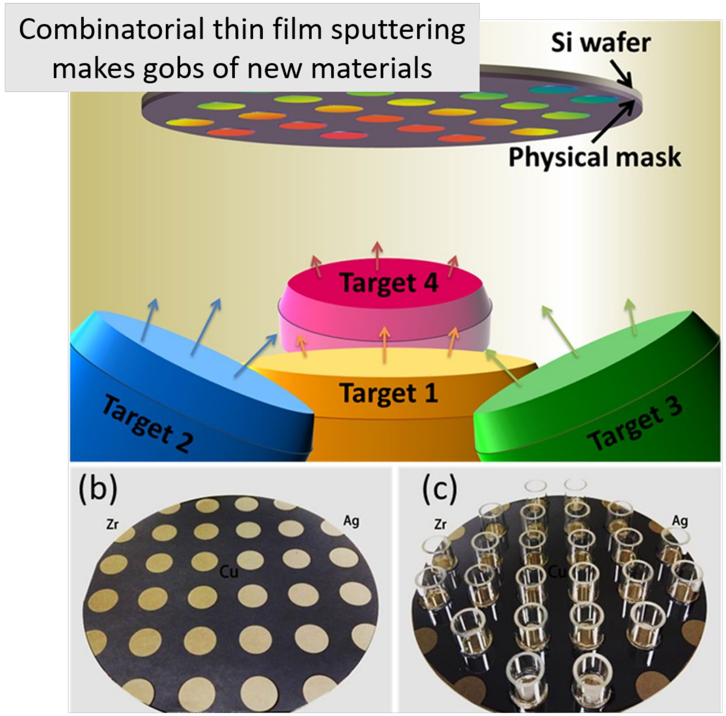
RF antenna structural material "wish list"

- Thermal conductivity > ~200 W/(m K)
- Operating temperature range up to 700°C
- Yield strength > ~250 MPa, ultimate strength > ~500 MPa
- CTE similar to RAFM alloys

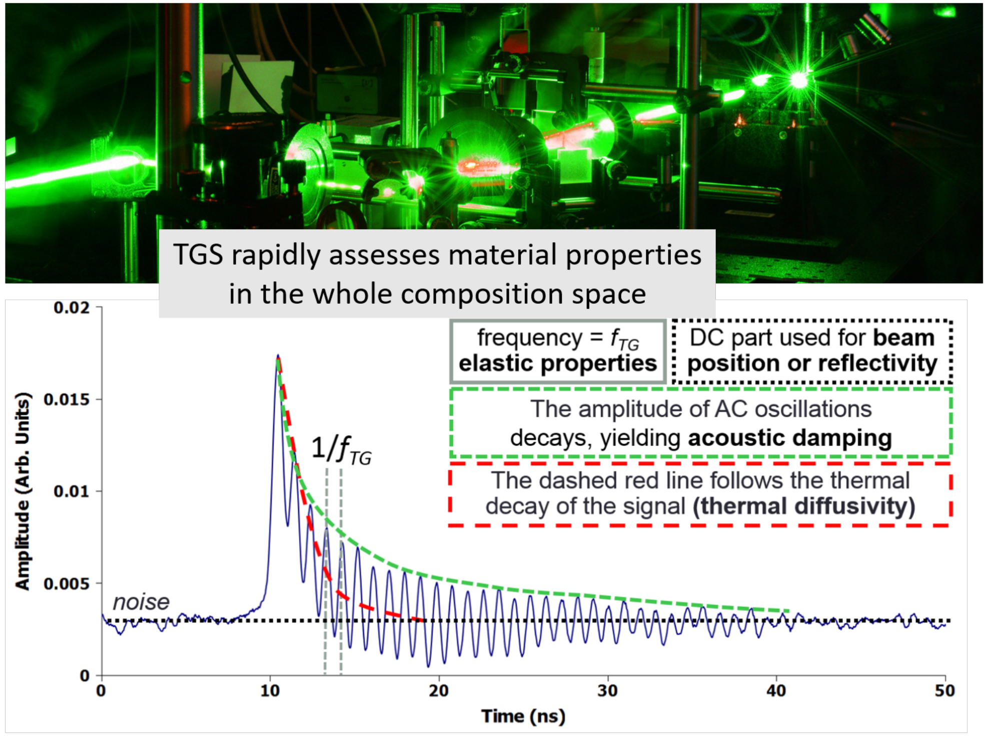
Will help in other areas like PFCs, blankets, etc as well

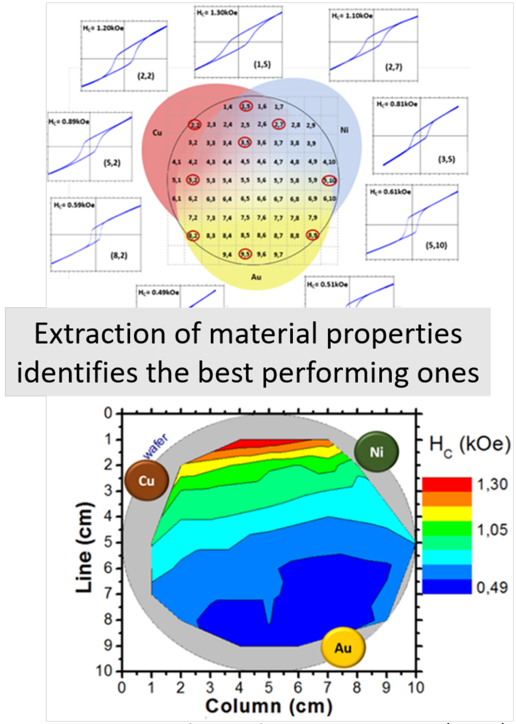
- Electrical conductivity > ~3e7 S/m, or maybe not?
  - Lower electrical conductivity for structure may help reduce disruption loads
  - More R&D needed for coatings that will survive in high temperature environment with neutrons
- Compatible with 3-D additive manufacturing for complex geometries
- See G.M. Wallace, T. Bohm, C.E. Kessel, *Fusion Science and Technology* (2021) for more details

Rapid development pathway for high performance RF materials



Y. H. Liu et al., *Sci. Rep.* 6:26950 (2016)





G. Giannopoulos et al., *Sci Rep* 8:15919 (2018)

- Thin film approach generates many alloy samples to test simultaneously
  - TGS for thermal properties
  - 4-point electrical conductivity measurement

First step: Create Cu-Cr-Nb thick film system to benchmark against GRCop-84

Si wafer

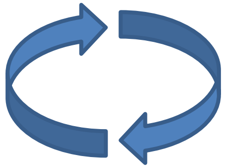
Nb target

Cr target

Cu target

Iterative material development plan: irradiate, measure, adjust, repeat

- Create thin film sample
  - Test thermal/electrical properties
  - Neutron and/or ion beam exposure



- "Zoom in" on promising areas of wafer for further study
  - Additional testing/irradiation cycles
- Create larger samples of best candidates for structural testing
  - Yield strength, temperature limits
- Additional RF compatibility tests
  - Sheaths/impurity generation
  - Thermionic/field/secondary electron emission

Future work

Many other systems would benefit from improved materials

- Passive stabilizing plates need to be highly electrically conductive and high strength while minimizing impact on TBR
  - Existing design for FNSF uses W plates between primary and secondary blanket flow paths
- Divertor and first wall would benefit from higher thermal conductivity
- Radiation hardened dielectrics would benefit diagnostics, perhaps blankets

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