ICRF Compatibility with Metallic PFCs: Implications for ITER *

55th APS DPP Annual Meeting

Denver, CO USA Nov 14-18, 2013

S.J. Wukitch, D. Brunner, M.L. Garrett, A. Hubbard, D.A. D'Ippolito, B. Labombard, C. Lau, Y. Lin, B. Lipschultz, D. Miller, J. Myra, R. Ochoukov, M.L. Reinke, and J.L. Terry

Key Results:

1. Low-Z seeding enhances ICRF performance through reduced core impurity contamination and increased reliability.

2. Novel field aligned ICRF antenna has improved ICRF antenna performance.

*Work supported by US DoE awards

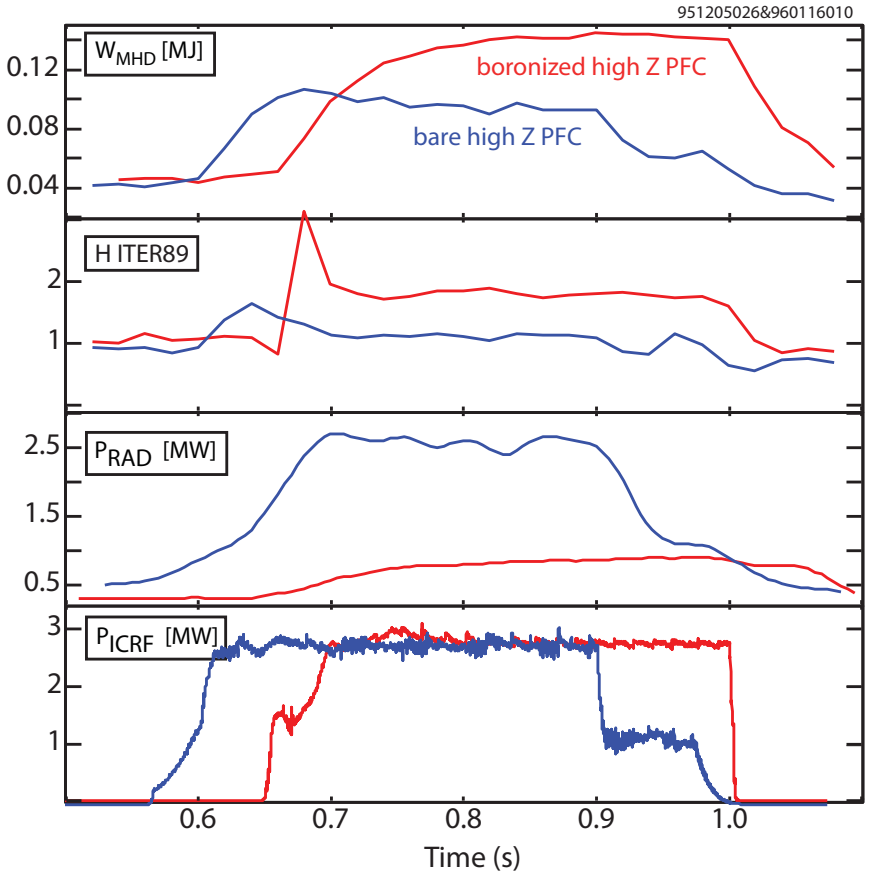
For Devices with High Z PFCs, A New Approach to ICRF Antennas is Required

ICRF antenna operation compatibility requires minimal impurity contamination, load tolerance, and high voltage and power handling.

High Z impurity contamination with ICRF antenna operation is universally observed.

Underlying physics is yet unclear and detailed phenomenology often differs.

- C-Mod and JET with ILW[1] have important RF impurity sources away from the antenna.
  - Local source at antenna is present but not dominant.
- ASDEX-U data indicates RF source is the RF limiters.[2]
  - B coated RF limiter tiles significantly reduced impurity contamination.



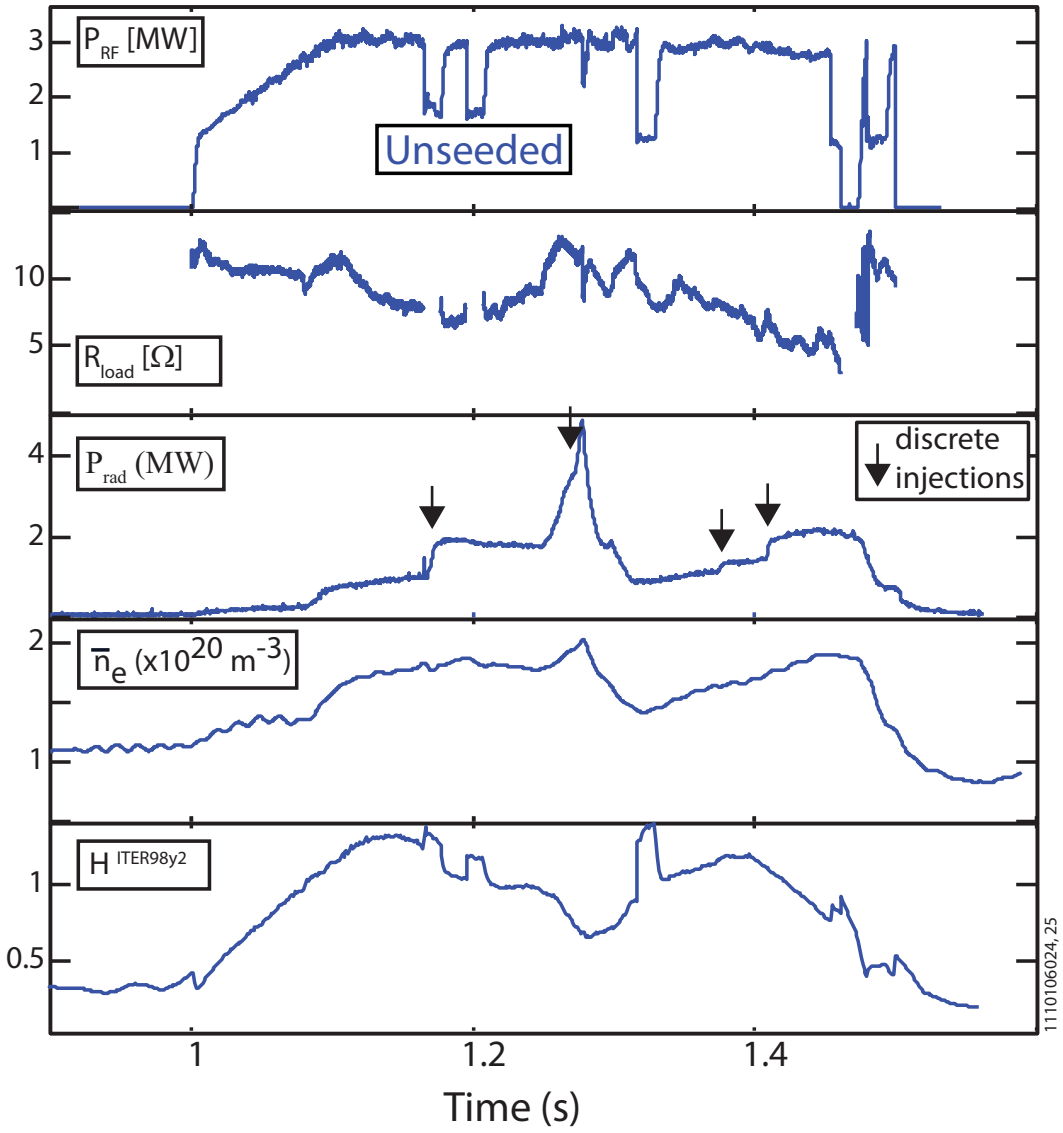
Adapted from Greenwald et al., Nucl. Fusion **37**, 793 (1997).

1. V. Bobkov et al., 20th Int. Conf. on Plasma-Surface Interactions, Aachen (2012).
2. R. Neu et al., 20th Int. Conf. on Plasma-Surface Interactions, Aachen (2012).

Operational Approach Found to Ameliorate High Z Impurity Contamination with ICRF

For discharges with high power to density ratio, the RF and plasma performance degrades.

- Discrete injections deteriorate plasma quality.



Operational Approach Found to Ameliorate High Z Impurity Contamination with ICRF

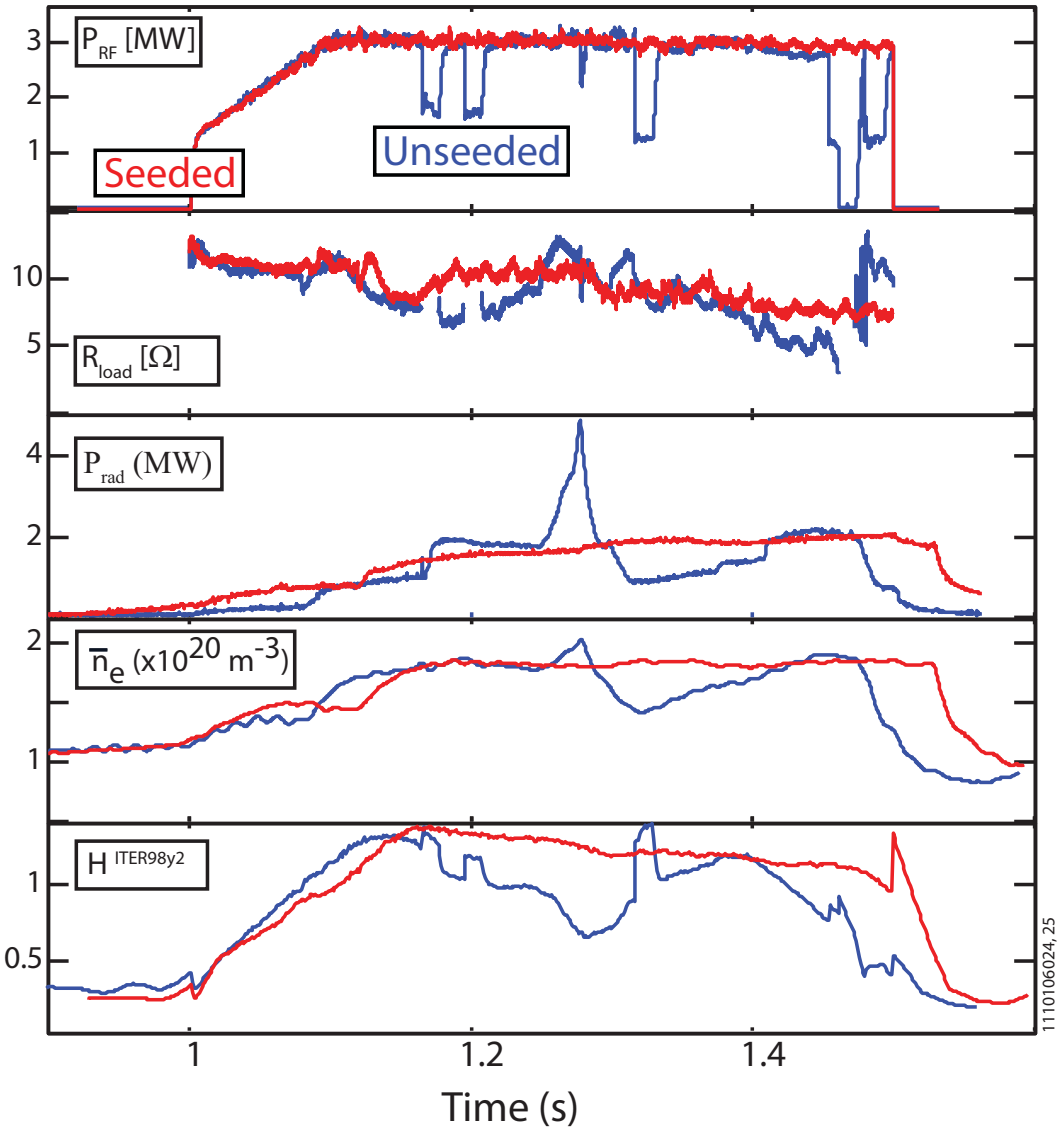
For discharges with high power to density ratio, the RF and plasma performance degrades.

- Discrete injections deteriorate plasma quality.

Found nitrogen or neon seeded discharges provided much improved ICRF performance.

- Faulting is significantly reduced.
- Antenna loading has less fluctuations.
- Radiated power is controlled without discrete injections.
- Plasma performance is maintained.

Caveat: requires boronization to obtain high performance.

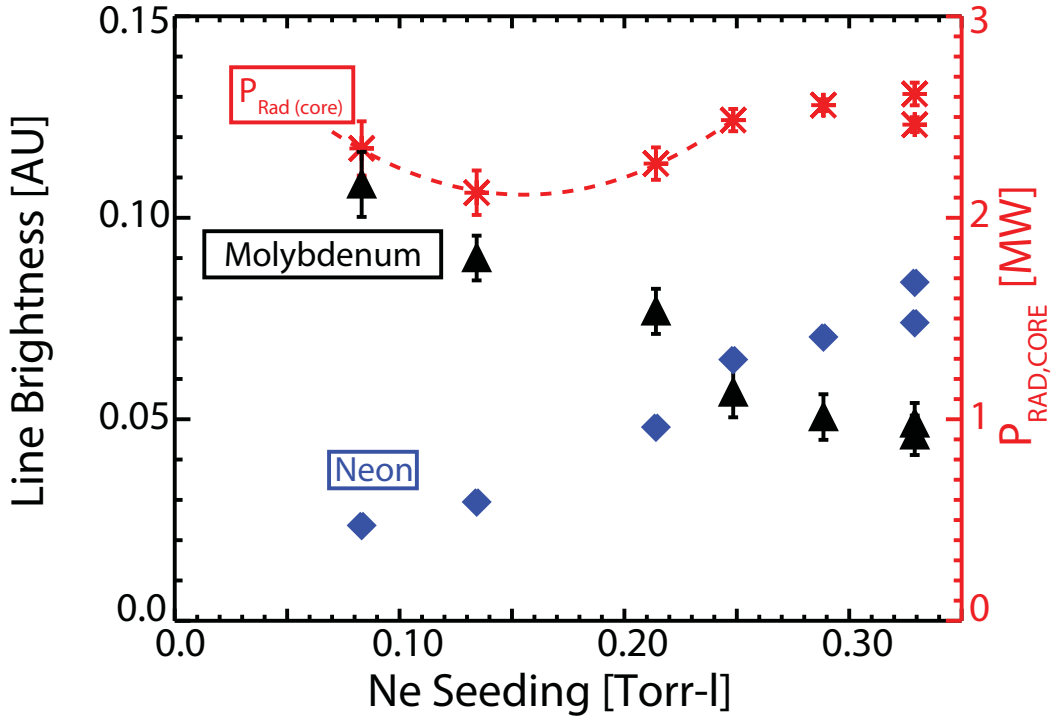


Optimum Seeding Level is Experimentally Identified

Core Mo is reduced as Ne seeding is increased.

Radiated power has a minimum.

- Too much neon degrades plasma performance.



Optimum Seeding Level is Experimentally Identified

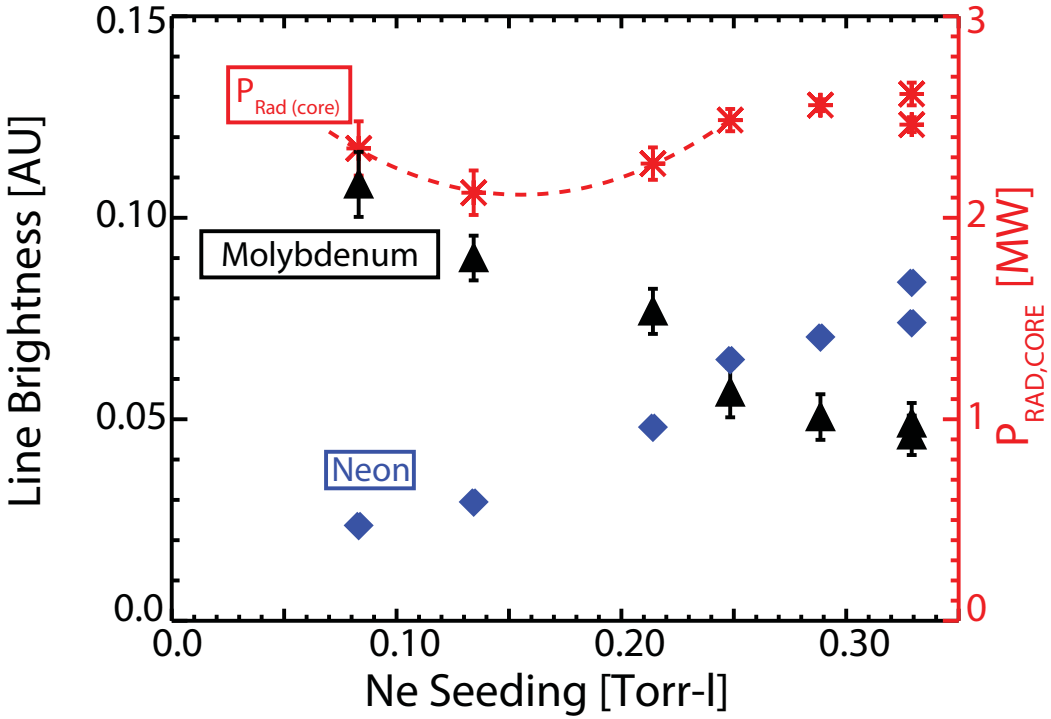
Core Mo is reduced as Ne seeding is increased.

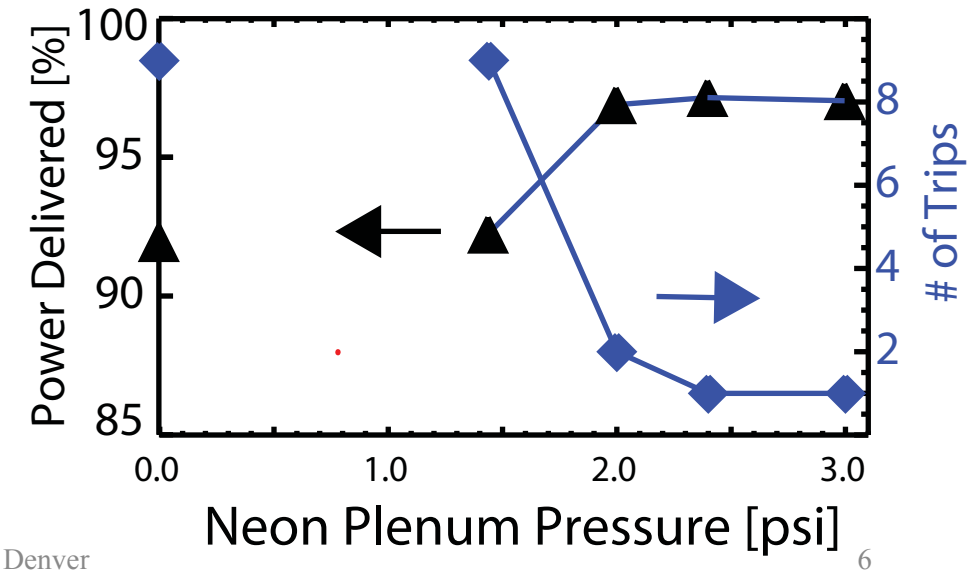
Radiated power has a minimum.

- Too much neon degrades plasma performance.

Improvement saturates at small amount of low-Z impurities injection.

- Compatible with seeding required for radiative divertor.





Observed Reduction in Plasma Potential with Low Z Seeding

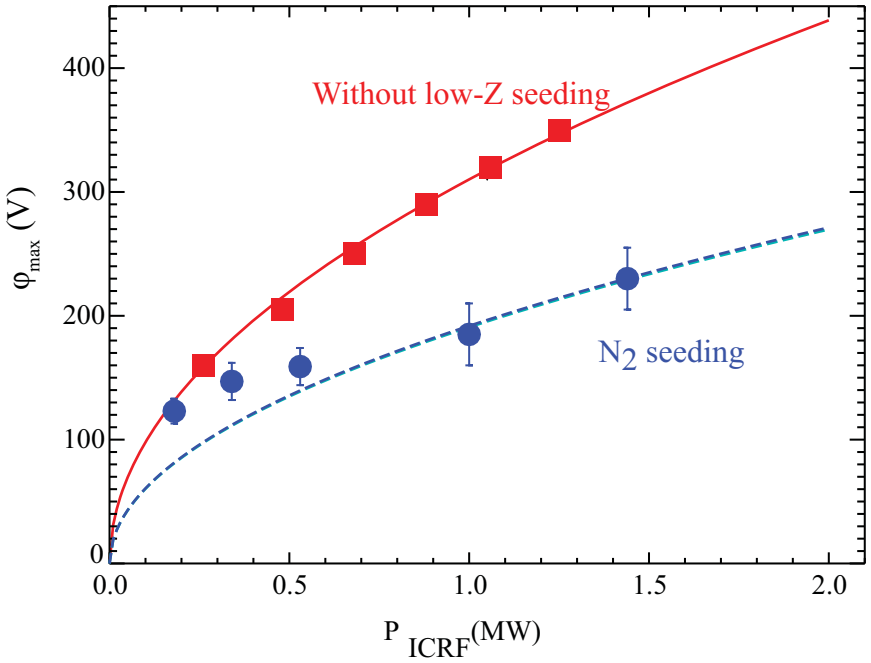
Core impurity control with seeding was unexpected.

- Impact energy, $E=3ZT_e+2T_i$, scales with charge.

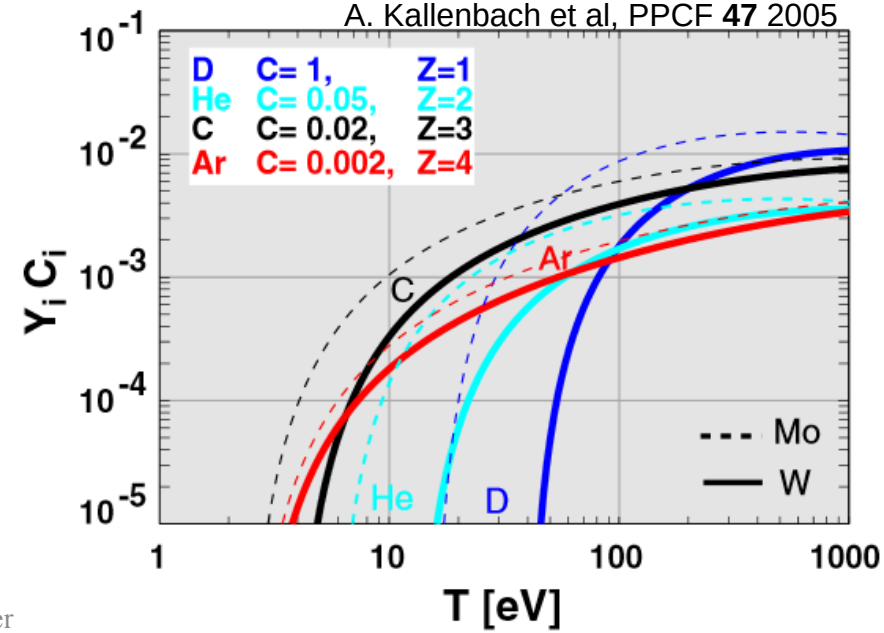
Unexpected decrease in RF enhanced plasma potential is observed with low Z seeding.

Speculate low Z seeding is modifying sheath-induced sputtering.

- Sputtering yield decreases quickly with T_e and seeding reduces local temperature may reduce sputtering.



A. Kallenbach et al, PPCF **47** 2005



Observed Reduction in Plasma Potential with Low Z Seeding

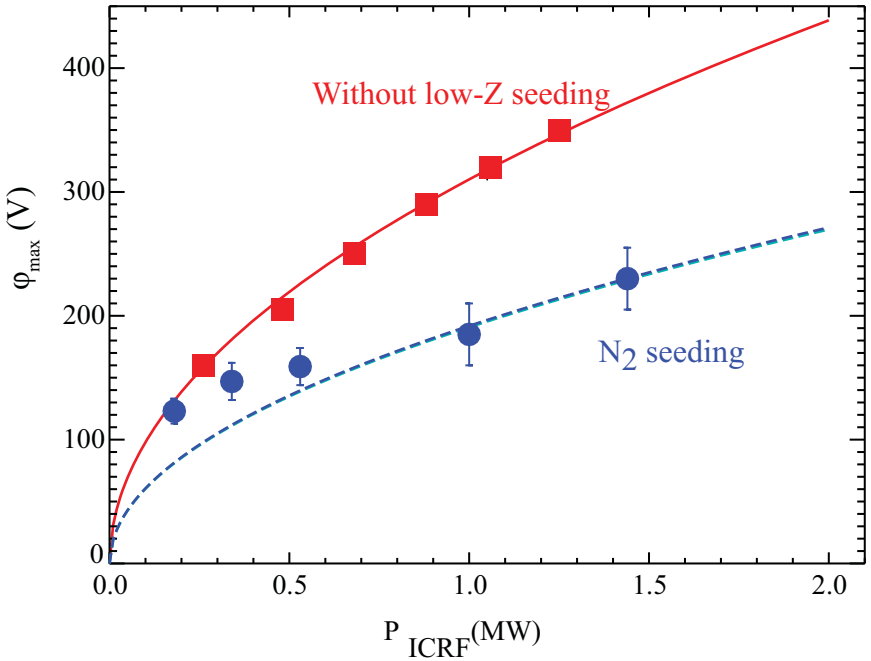
Core impurity control with seeding was unexpected.

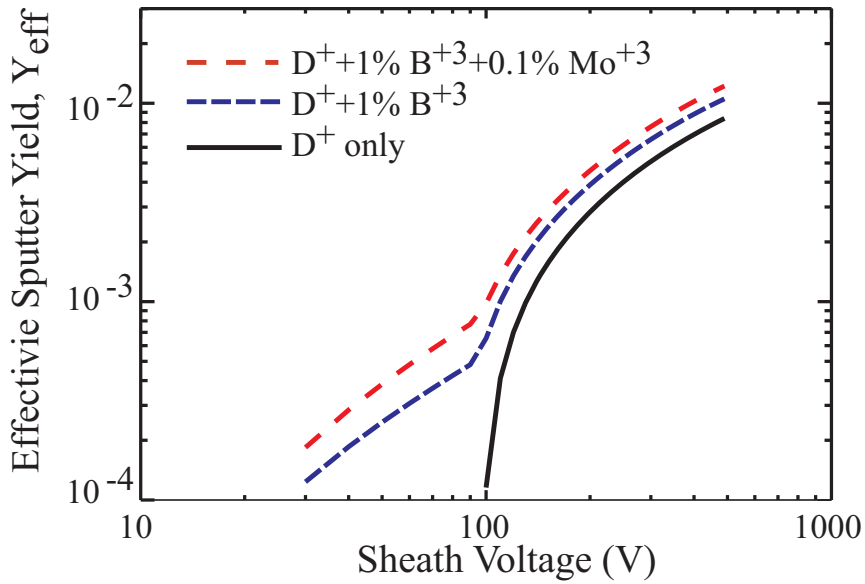
- Impact energy, $E=3ZT_e+2T_i$, scales with charge.

Unexpected decrease in RF enhanced plasma potential is observed with low Z seeding.

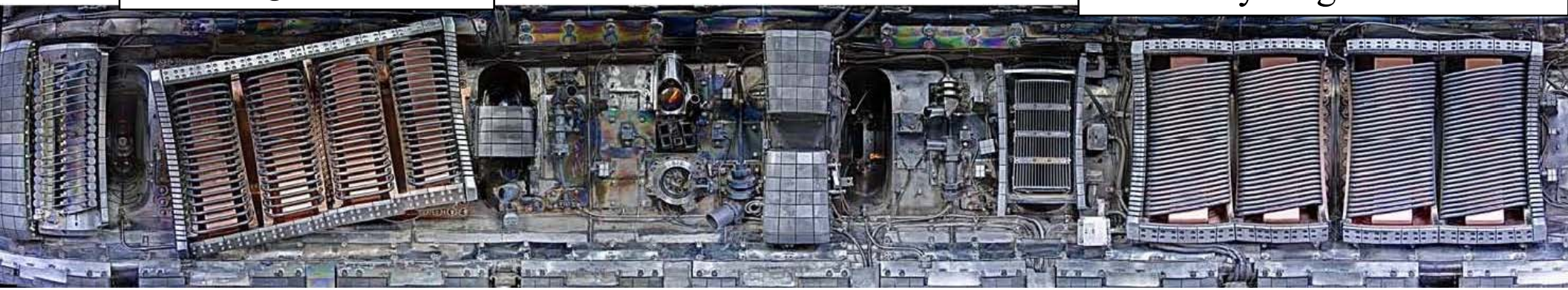
Speculate low Z seeding is modifying sheath-induced sputtering.

- Sputtering yield decreases quickly with T_e and seeding reduces local temperature sputtering may be reduced.
- Observe lower RF enhanced plasma potential – lowers sputtering.





Utilize Field Line Symmetry to Reduce Impurity Contamination with ICRF



Field align antenna to minimize integrated RF $E_{||}$.

- ICRF impurity contamination is thought to be a result of enhance RF sheaths driven by unwanted $E_{||}$ fields.
- Reduce integrated $E_{||}$ and impurity contamination should be reduced.

Field Aligned Antenna	Toroidally Aligned Antennas
Antenna straps, septa, and side protection tiles are normal to the **total** magnetic field.	Antenna straps, septa, and side protection tiles are normal to the **toroidal** magnetic field.

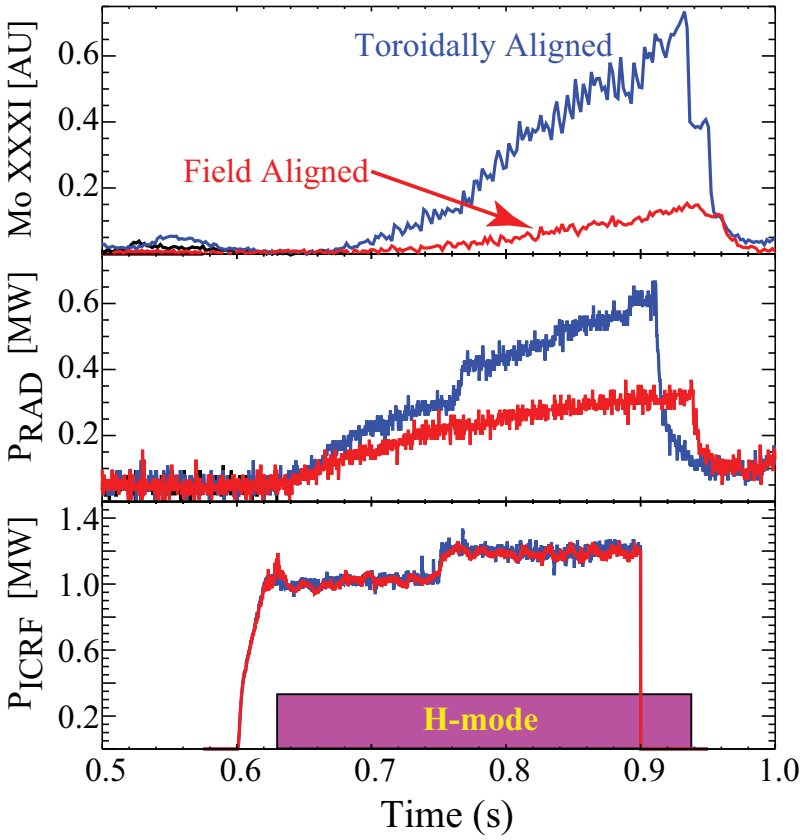
In H-mode, Field Aligned Antenna has Lower Impurity Contamination

Core Mo is significantly lower for Field Aligned antenna compared to Toroidally Aligned antennas.

- Rise time on the core Mo content is significantly slower for the Field Aligned antenna than the Toroidally Aligned-antennas.

Field Aligned antenna has lower radiated power.

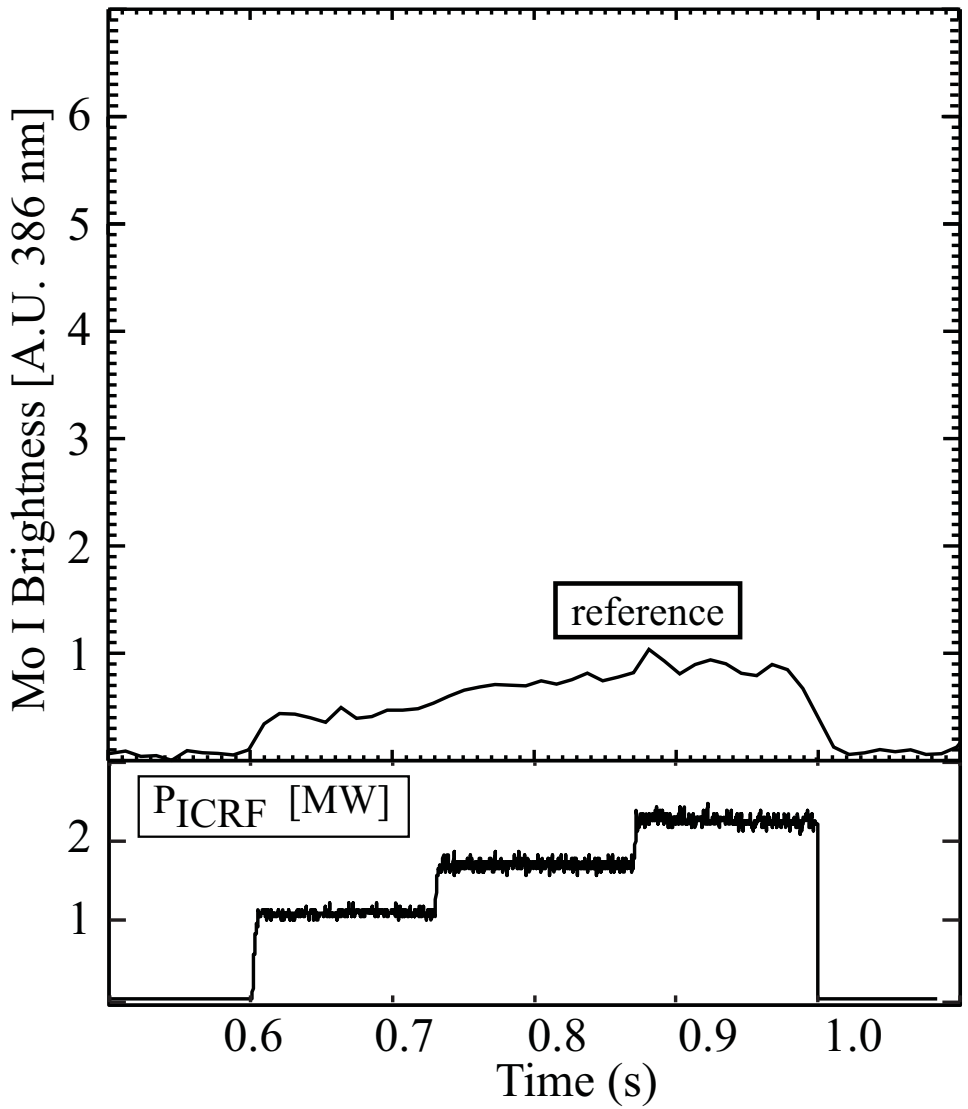
- Radiated power is ~20-30% lower than for the Toroidally Aligned antennas in EDA H-mode.



Molybdenum Source at the Field Aligned Antenna is Remarkably Low

Antenna limiter is often a primary impurity source.

- spectroscopic view to monitor the local Mo I source at each antenna.



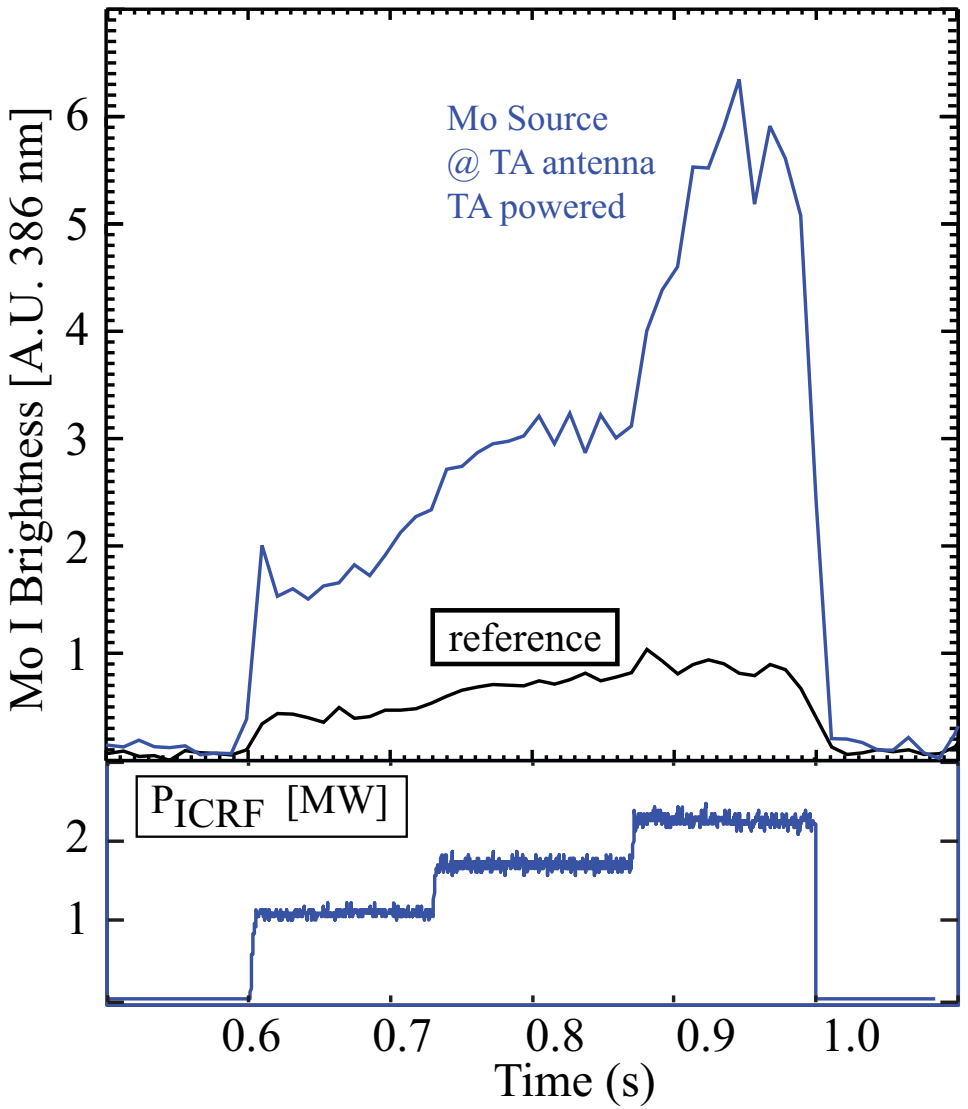
Field Aligned Antenna Molybdenum Source is Remarkably Low

Antenna limiter is often primary ICRF source.

- spectroscopic view to monitor the local Mo I source at each antenna.

Strong Molybdenum I signal is observed from the toroidally aligned antenna when it is powered.

- Mo source at the Toroidally Aligned antenna increases with each power step.



Field Aligned Antenna Molybdenum Source is Remarkably Low

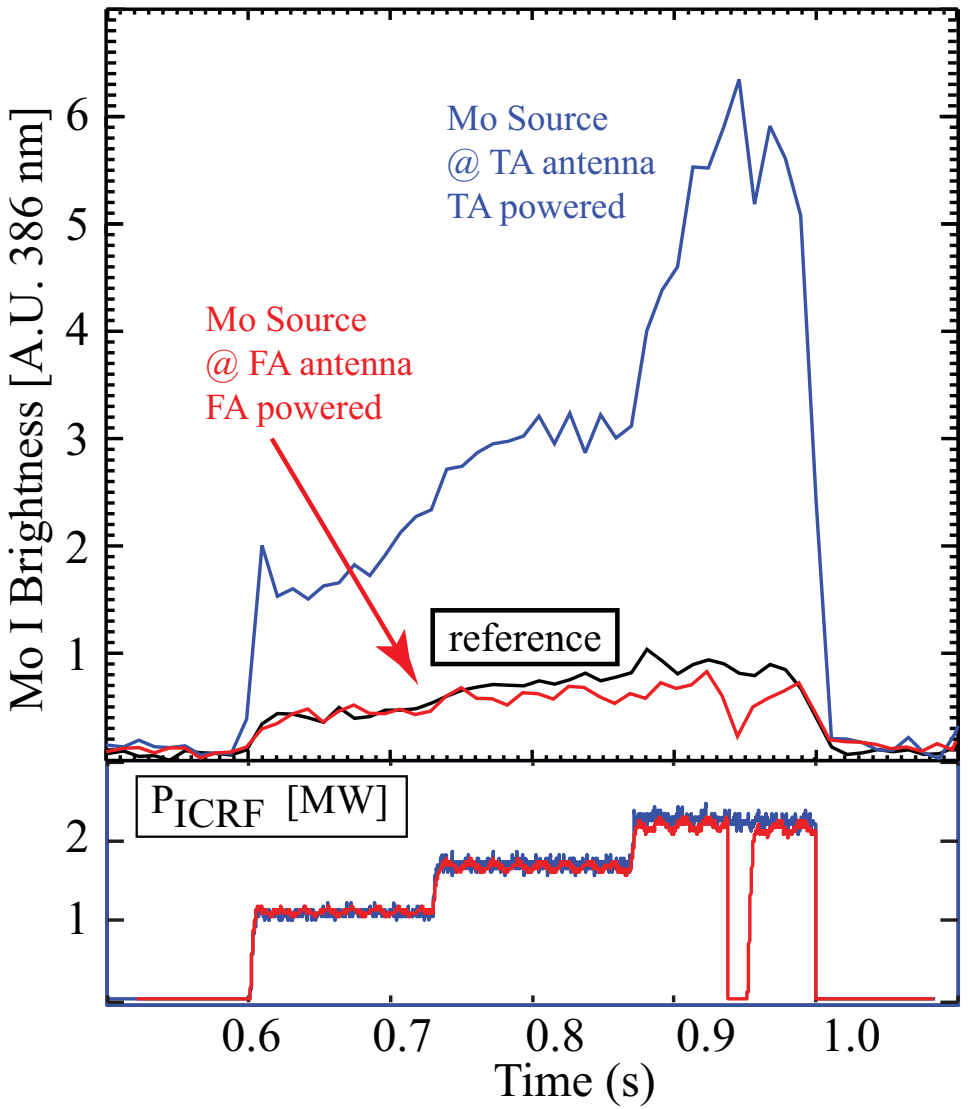
Antenna limiter is often primary ICRF source.

- spectroscopic view to monitor the local Mo I source at each antenna.

Strong Molybdenum I signal is observed from the toroidally aligned antenna when it is powered.

- Mo source at the Toroidally Aligned antenna increases with each power step.

Molybdenum I signal from the FA antenna is similar to the reference when Field Aligned antenna is powered.



RF Enhanced Energy Deposited is Low with FA Antenna Powered

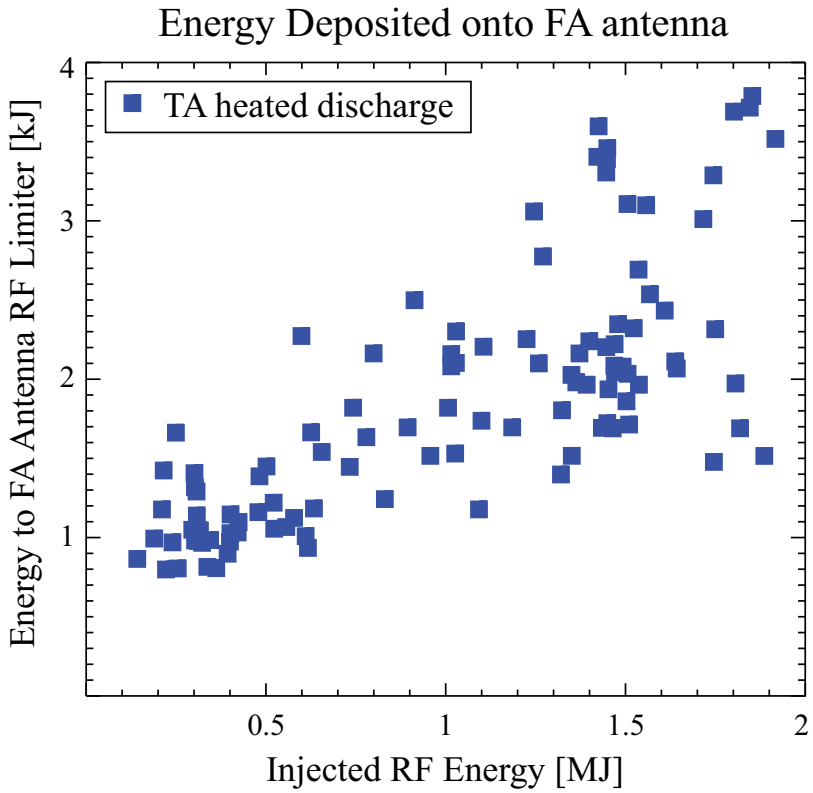
For ITER, antenna design assumes an RF enhanced heat flux of 6 MW/m^2.

- ~125 kW out of 20 MW or 0.625%
- JET and Tore Supra have measured 2-10% and ~3.5% respectively.

Analyze thermocouple data over wide range of parameters.

Discharges heated by the toroidally aligned antenna establish a reference.

- Energy deposited due to hot plasma.



RF Enhanced Energy Deposited is Low with FA Antenna Powered

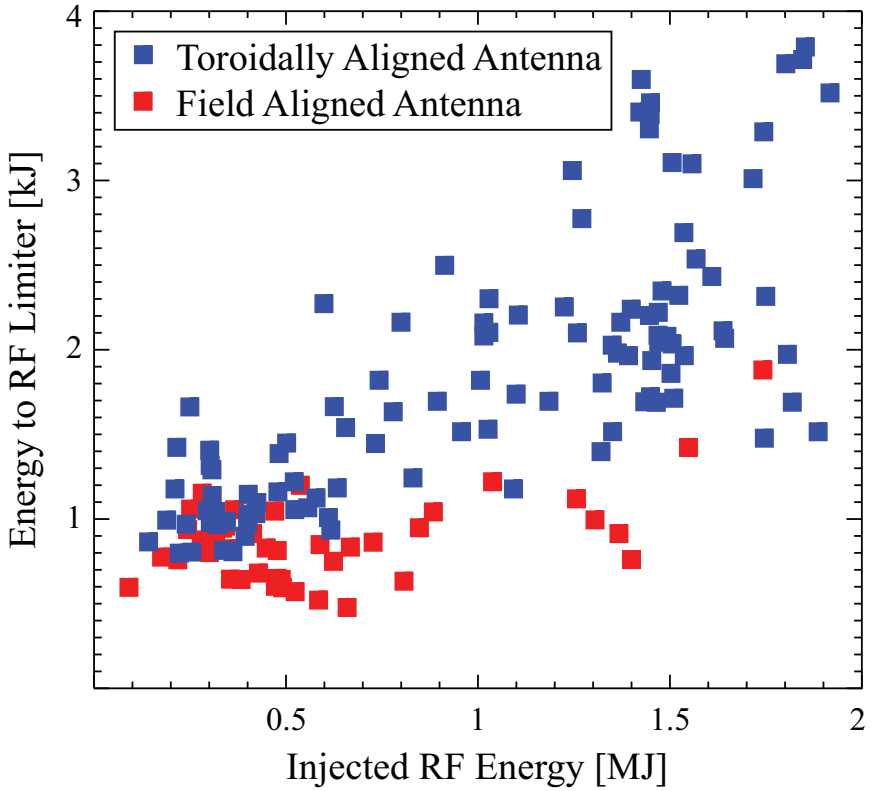
For ITER, antenna design assumes an RF enhanced heat flux of 6 MW/m^2.

- ~125 kW out of 20 MW or 0.625%
- JET and Tore Supra have measured 2-10% and ~3.5% respectively.

Analyze thermocouple data over wide range of parameters.

Discharges heated by the toroidally aligned antenna establish a reference.

- Energy deposited due to hot plasma.



Discharges heated with the FA antenna have lower total energy deposited on limiters.

Estimate the total power deposited as a fraction of the coupled RF energy

- Total deposited energy is ~6 kJ for 1.5 MJ injected or 0.4%.

Field Alignment Improves Antenna Load Tolerance

To maintain coupled power to the plasma, an ICRF antenna needs to be load tolerant

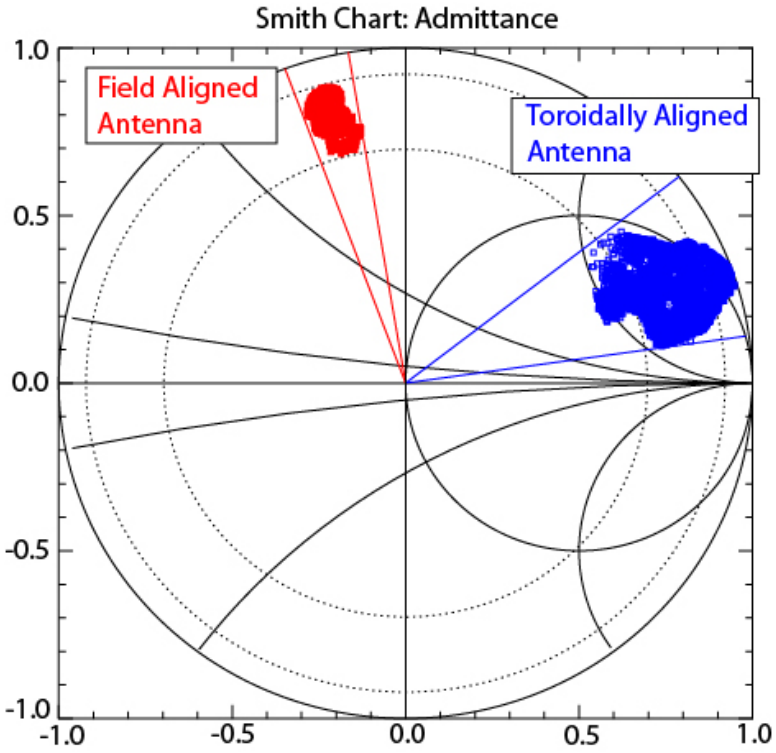
- either intrinsically
- or through external matching.

Field aligned antenna has improved load tolerance.

- Reflection coefficient from Field Aligned antenna occupies less area than Toroidally Aligned antenna.
- Impedance variation is reduced.

Field aligned antenna impedance change is largely resistive change.

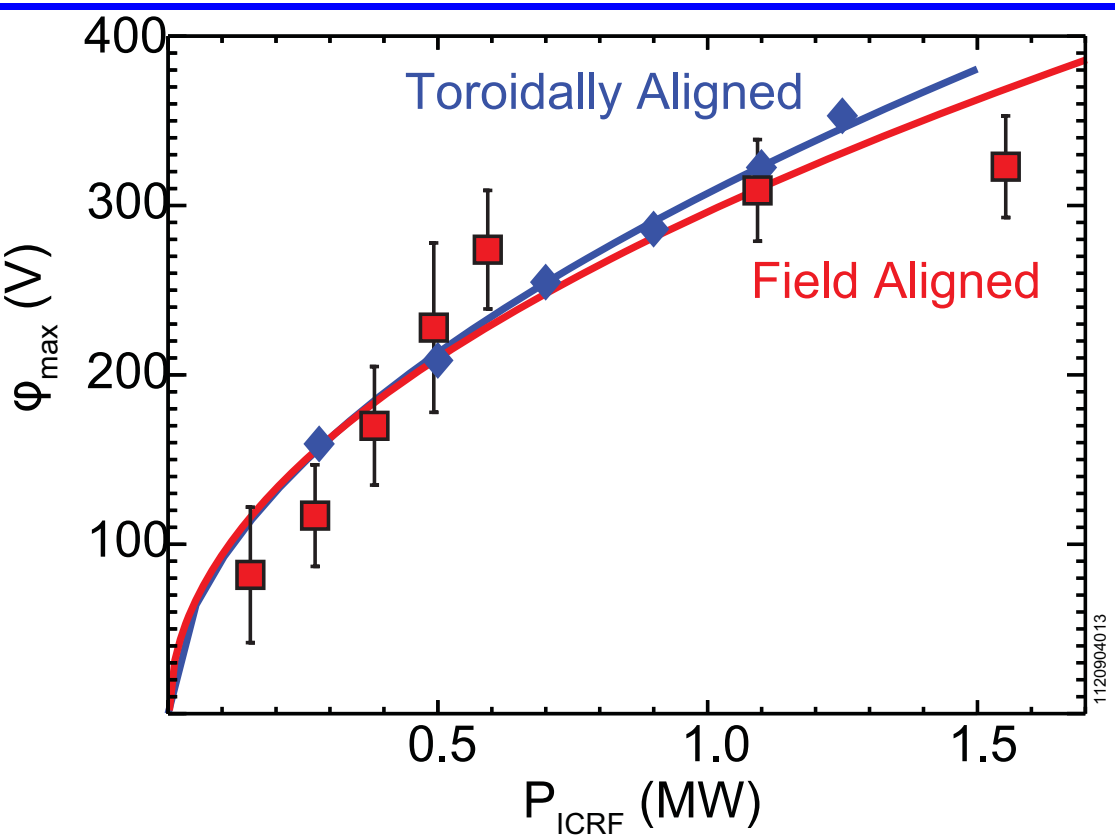
- Toroidally aligned antenna resistive and reactive variation is observed.



Physics Understanding of Field Aligned Antenna Behavior is Incomplete

Despite improved performance, measured potential for Field Aligned and Toroidally Aligned antennas are similar.

- Challenge to hypothesis that lower integrated $E_{||}$ will lower RF enhanced sheaths.
- Furthermore, difficult to reconcile lower impurity sources and contamination with $E_{||}$ unchanged.



For ITER, antenna area is specified, therefore a field aligned antenna would result in a ~40% reduction in area for the antenna.

- Power density and voltages would be challenging.
- High strength, high melting temperature materials for the antenna may allow higher power densities.
- New devices would have freedom to find different engineering design solution.

Summary

Low-Z seeding enhances ICRF performance through reduced core impurity contamination and increased reliability.

- Reduced RF enhanced plasma potential.
- Addresses reliability but still require boronization to minimize impurity contamination issues.
- Load tolerance requires external solution.

A field aligned antenna has superior performance compared to a toroidally aligned ICRF antenna.

- reduced impurity contamination and impurity sources,
- has low RF enhanced heat flux, and
- is more resilient to load variations than toroidally aligned antennas.
- Primary trade off for ITER is area, ~40% reduction without significant design changes.