Performance of the Extended ICRF System on Alcator C-Mod

G. Schilling, J. C. Hosea, B. LeBlanc, C. K. Phillips, J. R. Wilson, *Princeton University Plasma Physics Laboratory, Princeton, NJ,* and P. T. Bonoli, W. D. Lee, E. Nelson-Melby, M. Porkolab, S. J. Wukitch, *MIT Plasma Science and Fusion Center, Cambridge, MA*

The experimental capability of the Alcator C-Mod tokamak has been considerably extended through an upgrade of its ICRF heating and current drive system. A new four-strap single ended antenna built by PPPL has been installed, and both the older 2 MW transmitters and the newer units have been rebuilt for greater reliability and high power output into plasmas. Plasma heating capability is now 4 MW source power at 80 MHz plus 4 MW source power at 40-80 MHz. The new antenna will also allow phased operation for current drive, with 4 MW of source power for directed launch at 40-80 MHz. System performance, initial results, and projections of physics performance will be presented.

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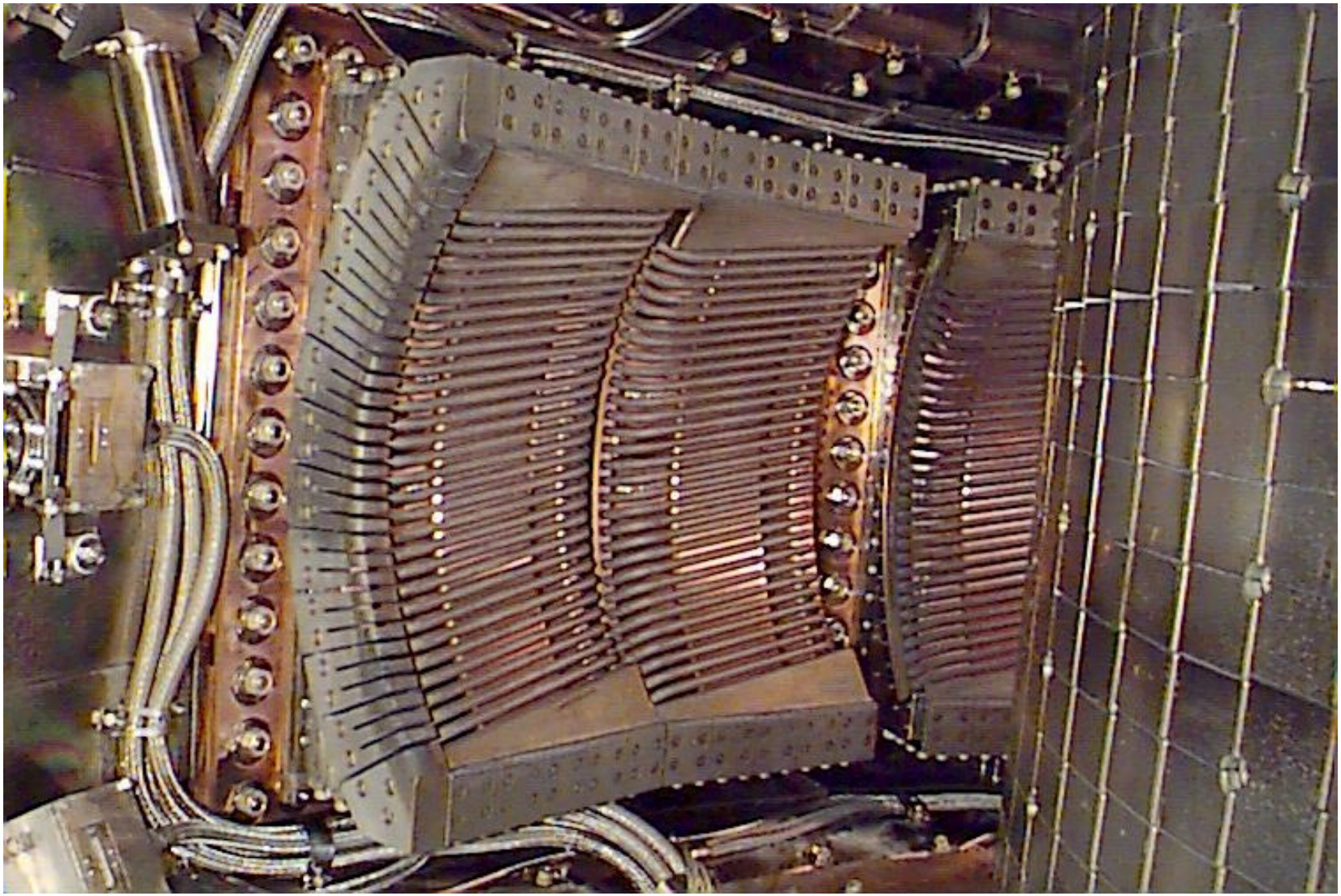
Existing ICRF system

- Two 2-strap center-ground fast wave antennas at D- and E-Ports
  - adjacent current straps hard-wired with $(0,\pi)$ phasing
  - antennas driven with resonant loops
  - vacuum spectrum peak $n_\phi = 10$
  - antenna power density up to 10 MW/m^2
  - antenna voltage capability up to 40 kV

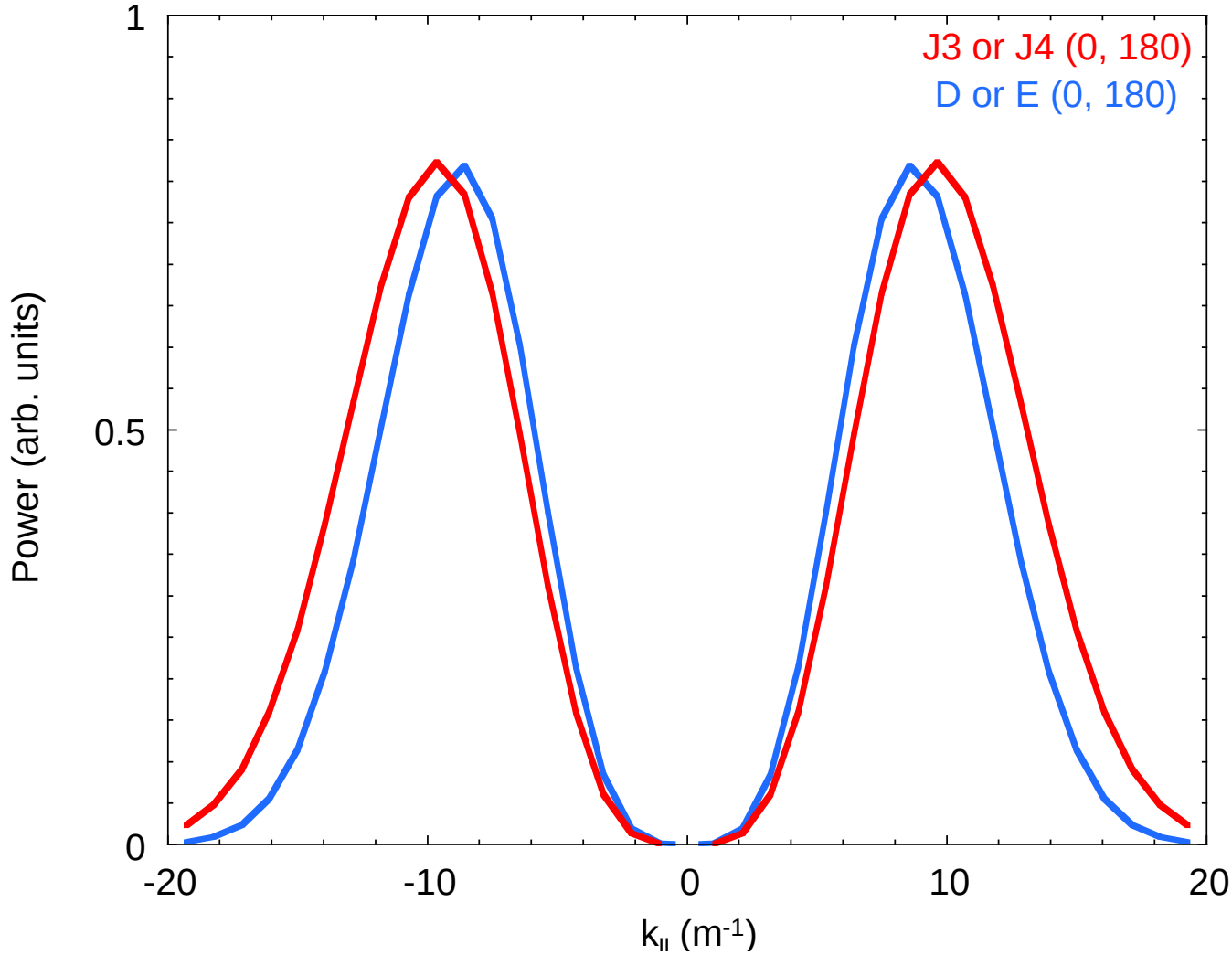
- Two 2-MW transmitters operating at 80.0, 80.5 MHz

- Up to 3.5 MW rf power into plasma

Photograph of existing antennas inside C-Mod



2-strap antenna launched spectrum



Physics accomplished with existing system

- Plasma heating source for most of C-Mod experiments
  - D(H) at 2.6-6.9 Tesla
  - D(^{3}He) at 7.3-8.0 Tesla

- RF-specific studies
  - absorption efficiency as function of minority concentration
  - transition from minority to mode conversion heating as function of minority concentration
  - off-axis minority heating

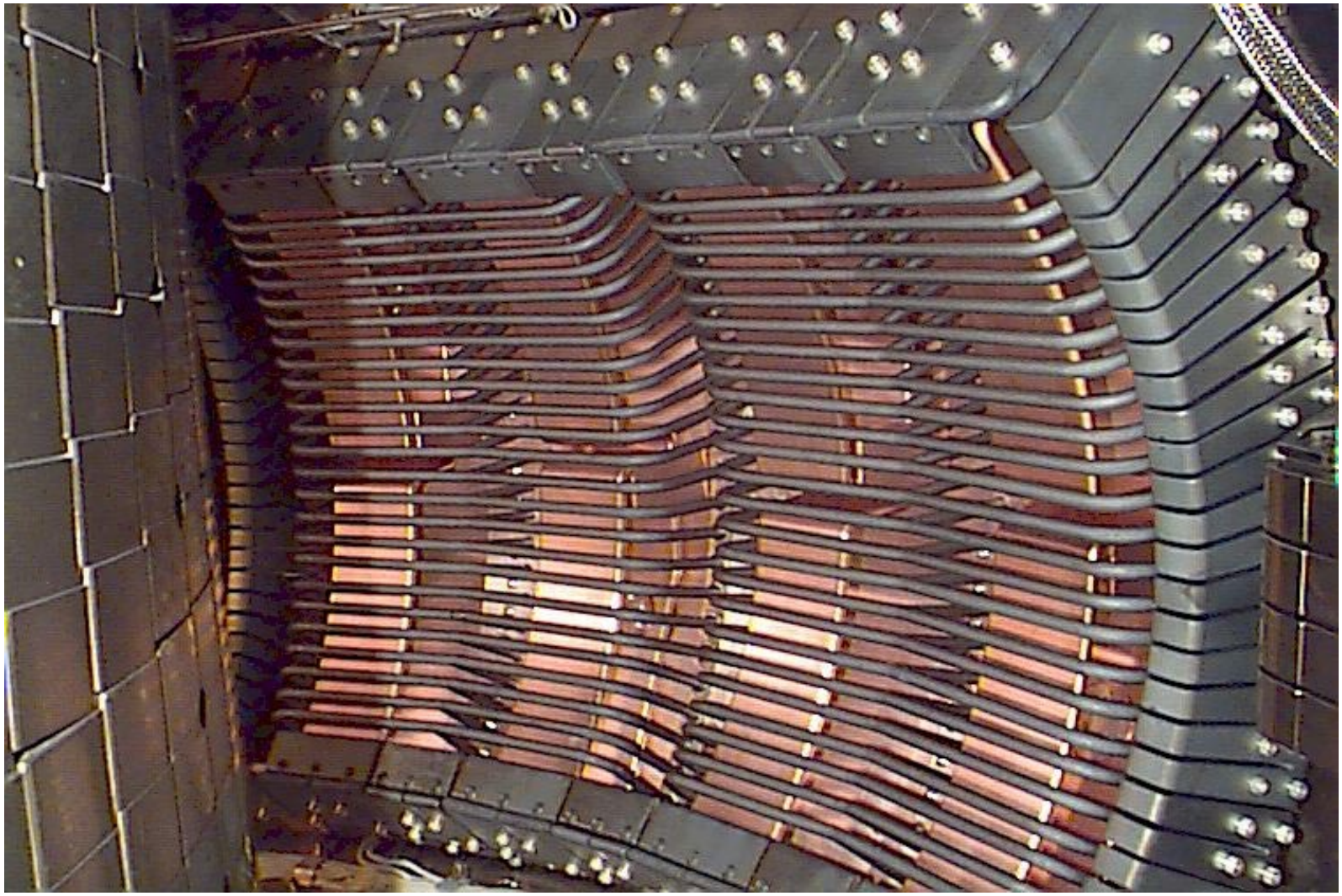
ICRF system upgrade

- New 4-strap single-ended antenna
  - heating phasing (symmetric)
  - current drive phasing (asymmetric)

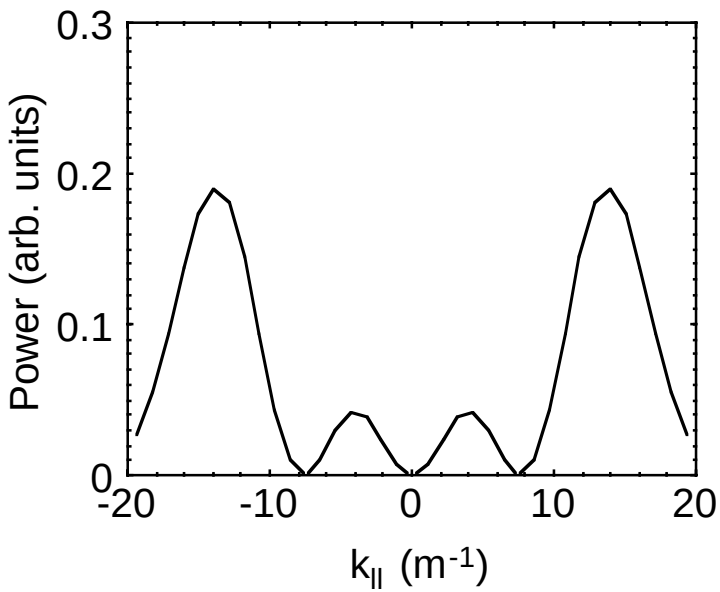
- 2 additional transmitters
  - 2 MW rf power output each
  - tunable 40-80 MHz
  - plan to operate at 43, 60, 78 MHz

- Total rf source power now 4 MW at 80 MHz + 4 MW at 40-80 MHz

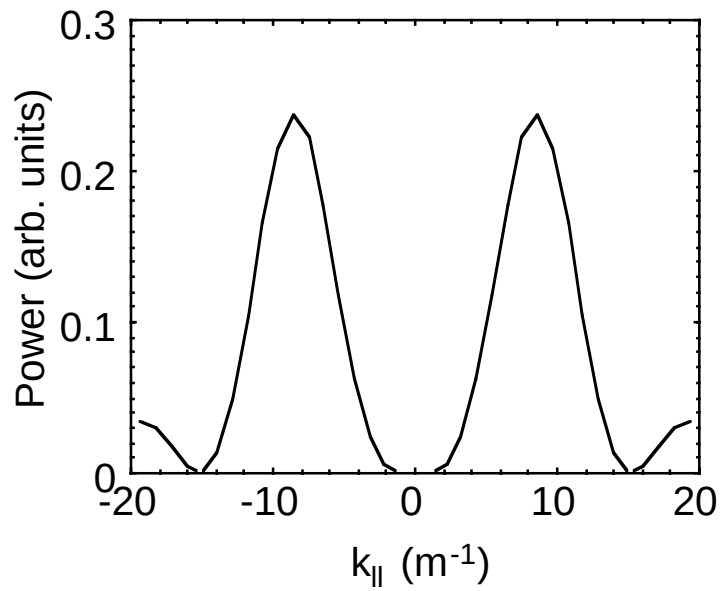
Photograph of new PPPL ICRF antenna inside C-Mod



New antenna launched spectrum for symmetric phasing

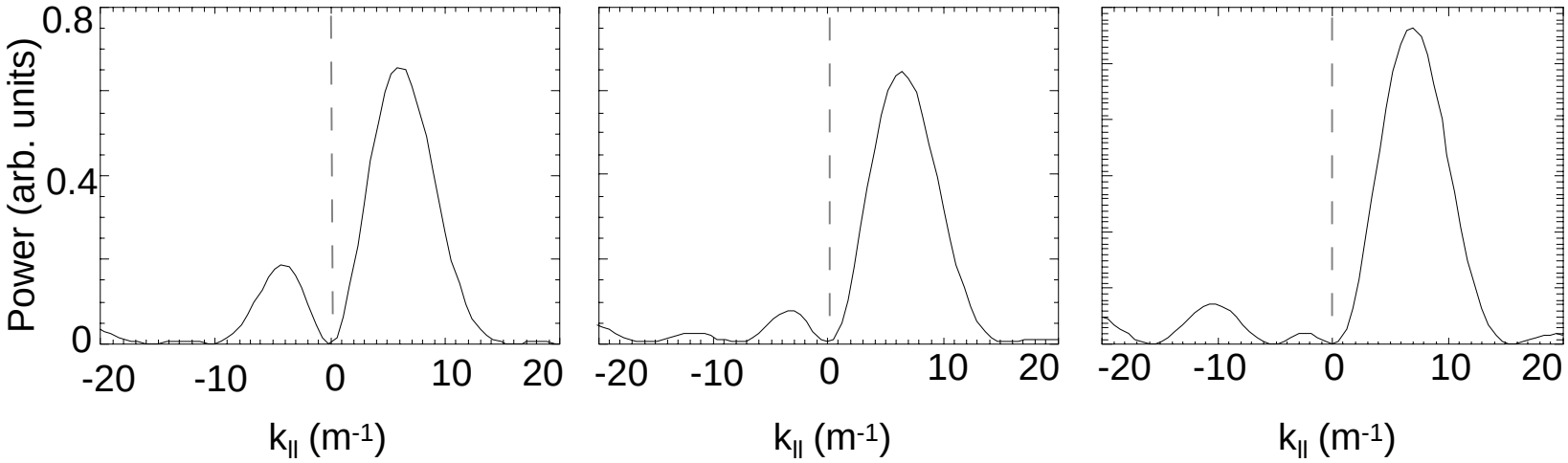


(0, 180, 0, 180)



(0, 180, 180, 0)

New antenna launched spectrum for asymmetric phasing



(0, 60, 180, 240) (0, 90, 180, 270) (0, 120, 180, 300)

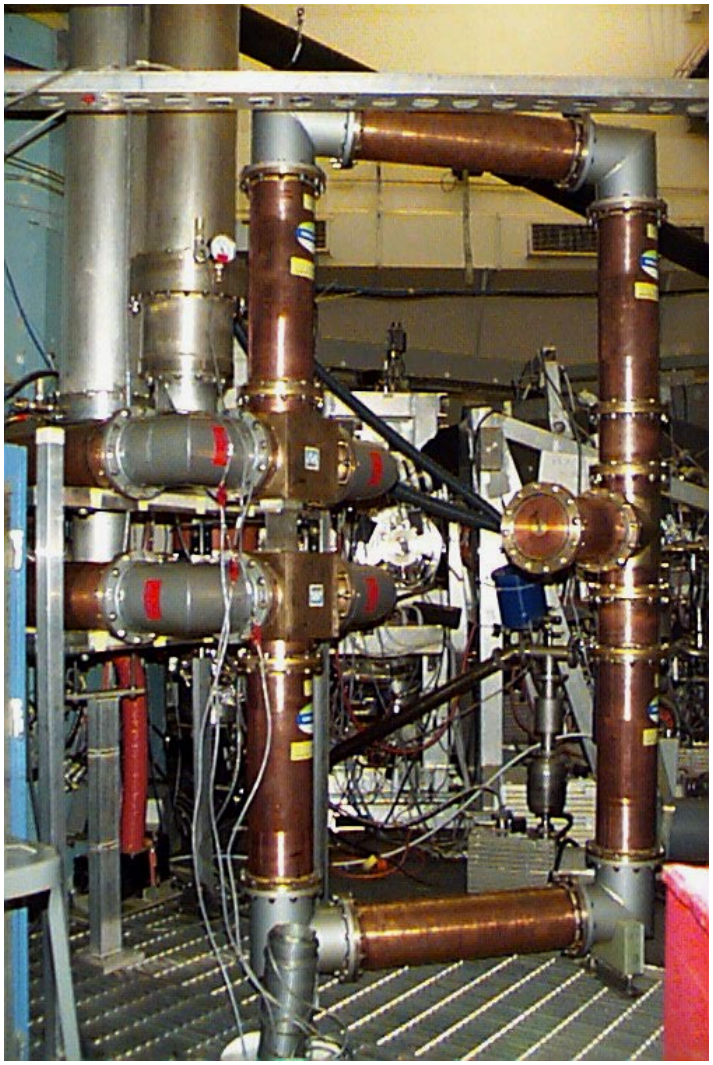
New antenna hookup

- 1. Resonant loops attached to alternate straps
  - current straps 1 and 3 180° out of phase
  - current straps 2 and 4 180° out of phase
  - arbitrary transmitter phase between (1, 3) and (2, 4)
  - operated with heating phasing (0, 180, 180, 0)
- 2. Resonant loops attached to adjacent straps
  - current straps 1 and 2 180° out of phase
  - current straps 3 and 4 180° out of phase
  - arbitrary transmitter phase between (1, 2) and (3, 4)
  - operated with heating phasing (0, 180, 0, 180)
- Decoupler to compensate mutual strap inductance for phased operation

New antenna hookup design

- Represent antenna as 4-port network with S-parameters as measured on test stand
- Represent external loops as connected transmission line segments
- Resonate each loop separately at the driving frequency
- Adjust the decoupler dimensions to merge the in/out of phase position of the resulting loop resonances and insure that the cross-admittances Y_{12} and Y_{21} vanish

Photographs of the resonant and decoupler loops

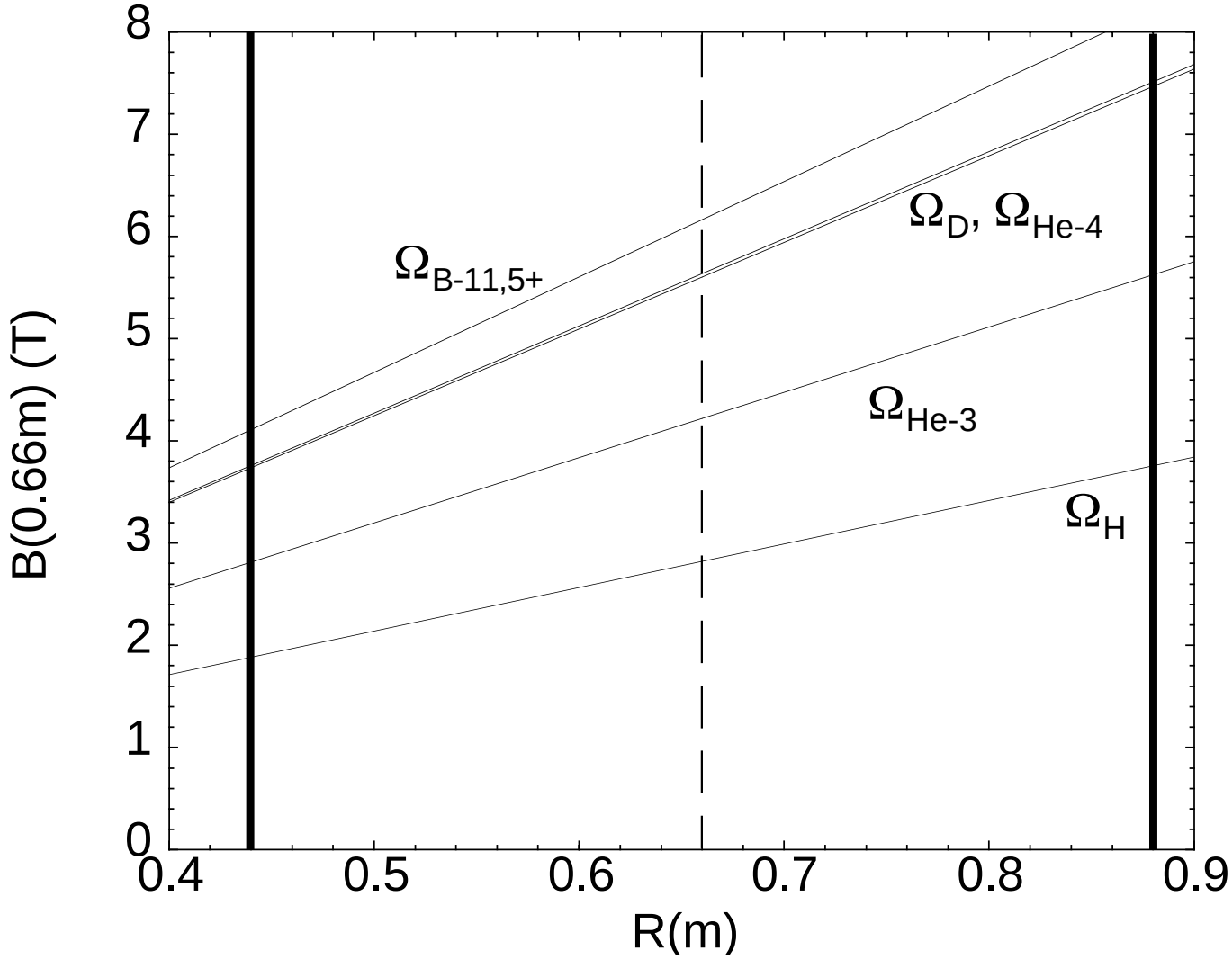


Physics goals of the upgraded ICRF system

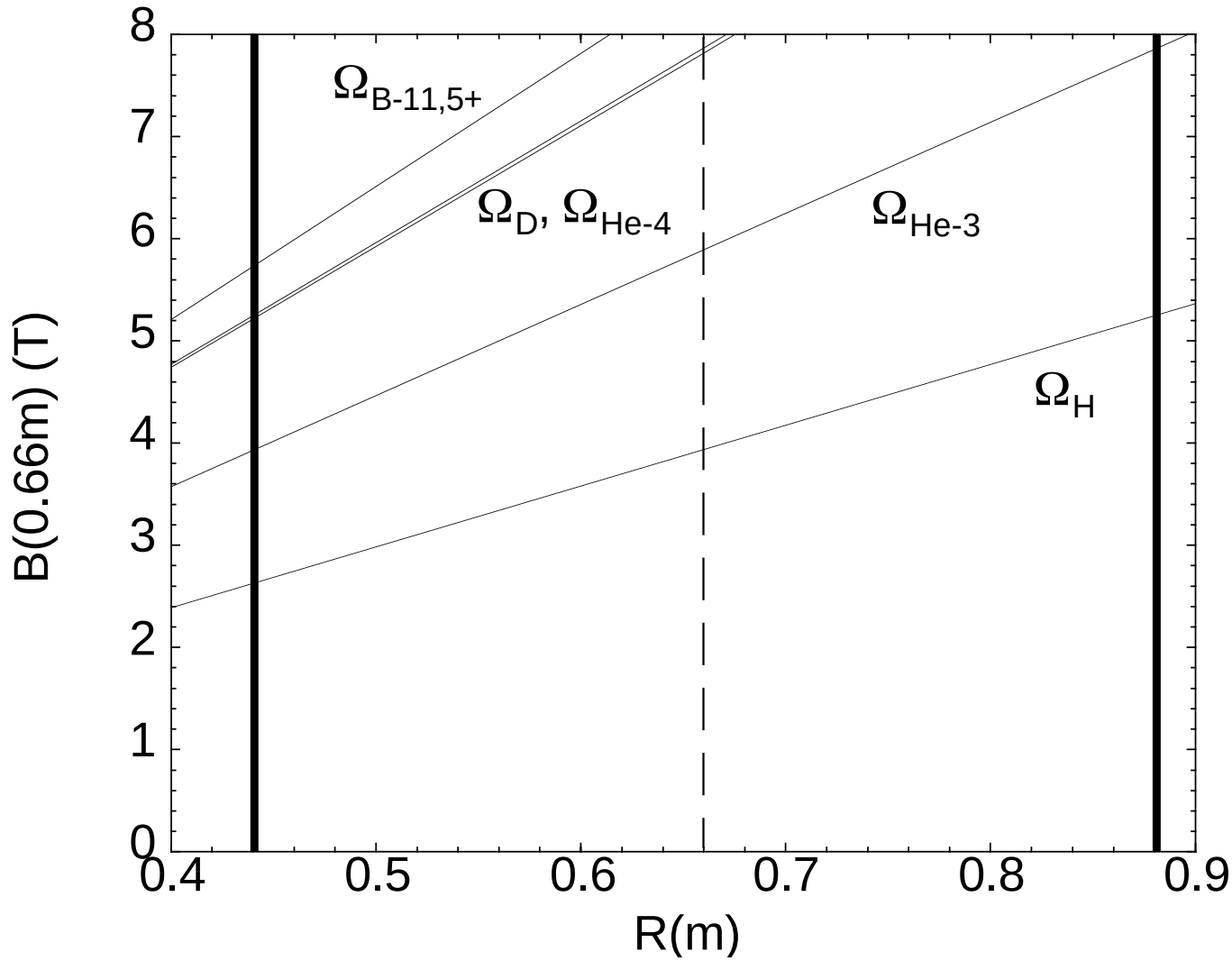
- Heating scenario and power deposition depend on resonance placement

- This is determined by toroidal field and rf frequency
  - toroidal field up to 8 Tesla
  - rf frequency planned for 43, 60, 78/80 MHz

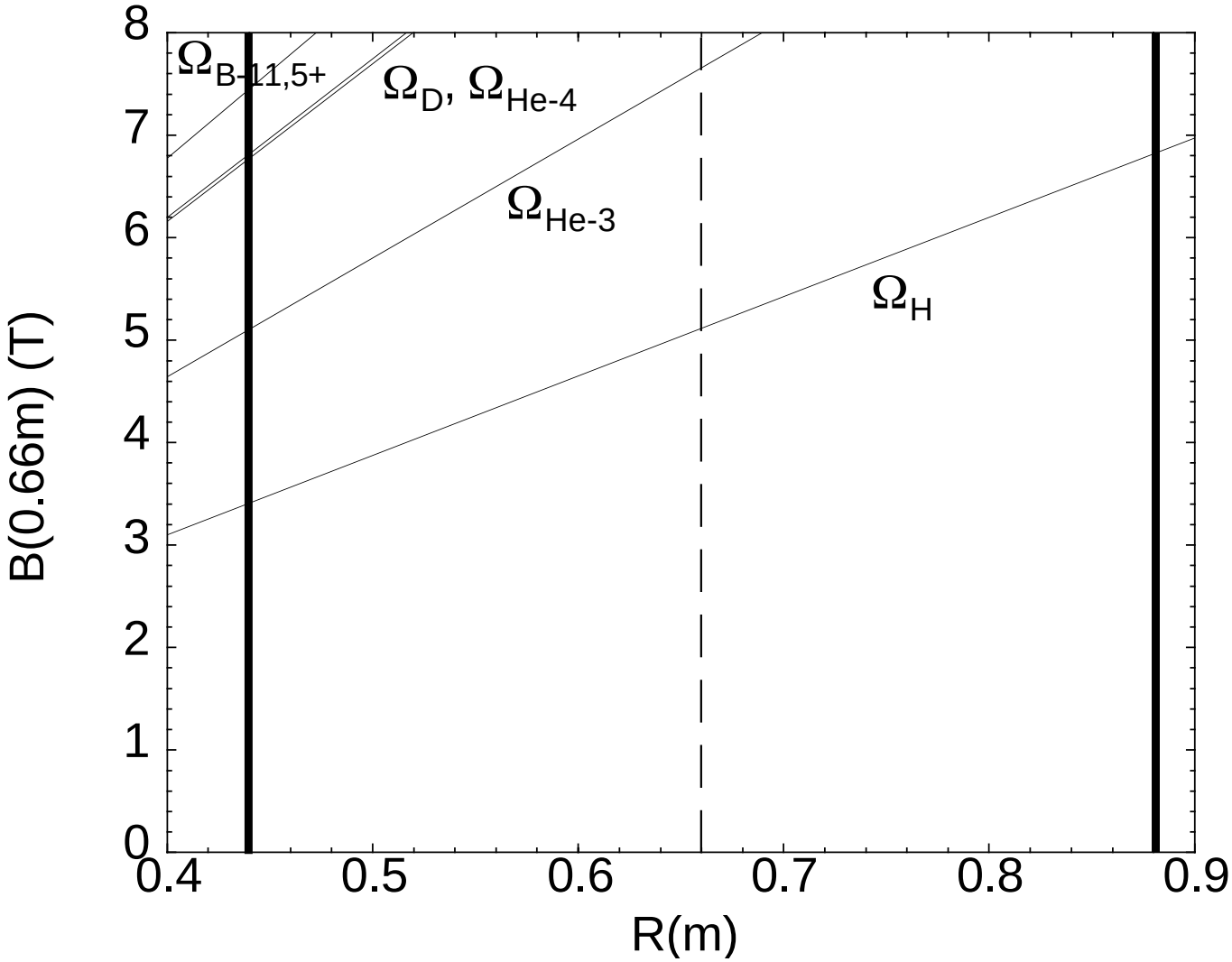
C-Mod ICRF ion resonances at 43 MHz



C-Mod ICRF ion resonances at 60 MHz



C-Mod ICRF ion resonances at 78 MHz



Increased ICRF power and flexibility extends physics (1)

- High power heating in H-mode plasmas
  - D(H) ion cyclotron heating at 5.4 Tesla and 78 MHz + 80 MHz
  - D(^{3}He) ion cyclotron heating at 7.9 Tesla and 78 MHz + 80 MHz
- Three ion species plasma heating
  - D(^{3}He, H) ion cyclotron heating/mode conversion heating at 60 MHz + 80 MHz
- Heating high $ß_n$
  - D(H) off-axis ion cyclotron heating at 4.4 Tesla and 60 MHz + 80 MHz

Increased ICRF power and flexibility extends physics (2)

- Current drive experiments will focus on mode conversion current drive, 60 MHz + 80 MHz D(^{3}He, H)
  - scoping experiments will begin with fast wave current drive at 1.5 Ω_D and ion cyclotron current drive
- RF-generated rotation experiments will
  - test rf-generated **toroidal** rotation theories
  - investigate mode converted ion Bernstein wave driven **poloidal** flow
- Begin experiments to stabilize sawteeth and MHD instabilities
- Additional diagnostics will measure core rf waves and characterize power deposition for direct electron heating

Doubling available auxiliary heating power allows us to:

- Exceed the H-mode threshold at 5.4 Tesla by a factor 2 - 3
- Push past the H-mode threshold at 8 Tesla
- Investigate the EDA mode at lower q values
- Explore high power divertor operation
- Achieve higher $ß_n$ up to 2 at 5.4 Tesla with multiple frequency operation

Improving the directed wave launch allows us to:

- Explore further plasma rotation with directed waves without external momentum input
- Explore flow shear suppression of turbulence through off-axis mode conversion current drive
- Attempt to form an internal transport barrier through flow shear generation
- Develop the capabilities to control the radial electric field through toroidal rotation
- Extend the pellet enhanced performance (PEP) mode

System performance and initial results (1)

- We have performed extensive rework of the ICRF transmitters
  - high voltage system upgrades to increase output tube fault protection as well as increase output power
  - control system upgrades to increase antenna fault protection, operating reliability, and operational flexibility

- The new antenna has been vacuum conditioned to 40 kV

- Plasma operation is fully under way

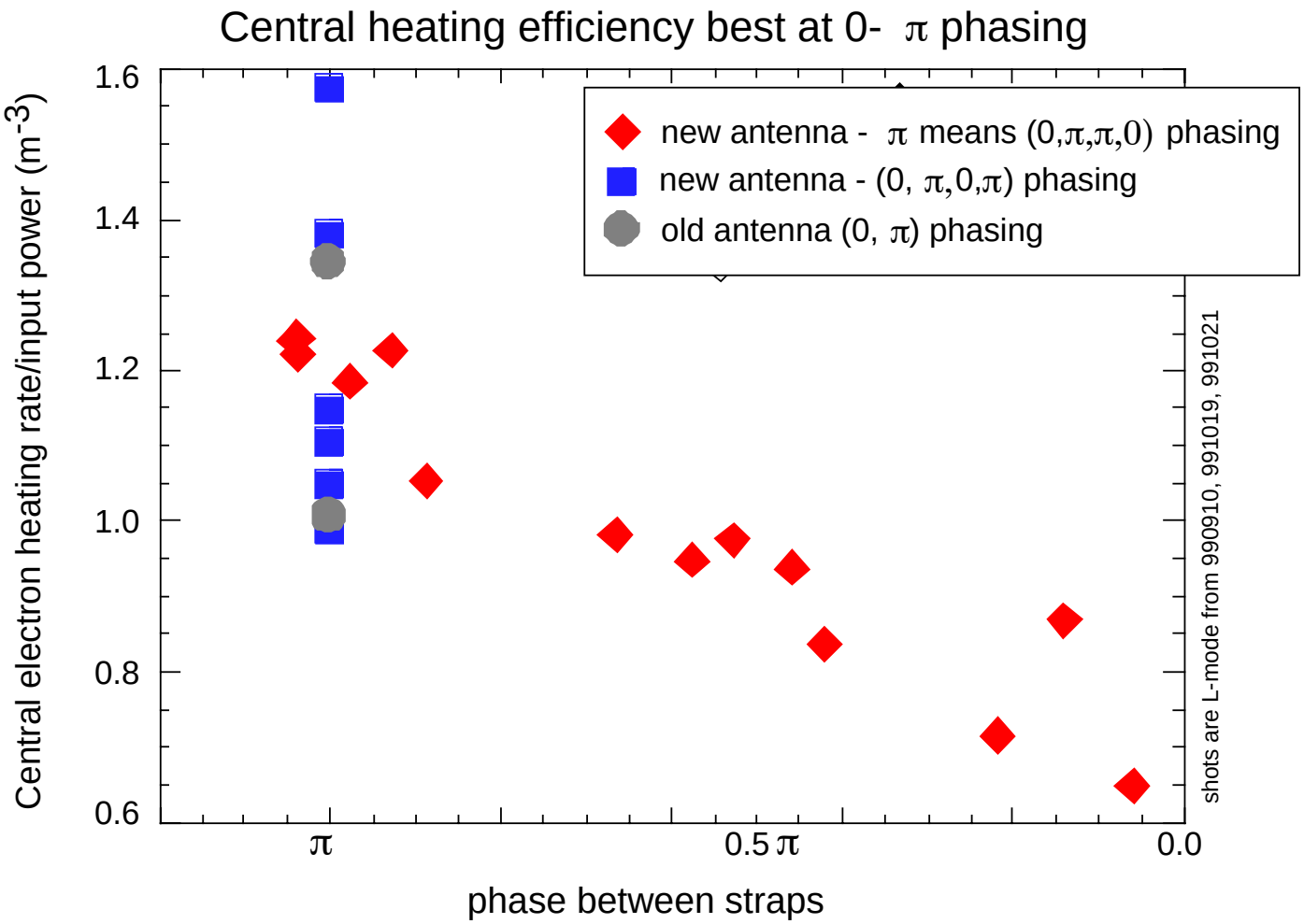
System performance and initial results (2)

- In the D(H) hydrogen minority heating regime at 78 MHz the new antenna has achieved ~1.5 MW power into the plasma with both (0, 180, 180, 0) and (0, 180, 0, 180) current strap phasing in phasing comparison experiments, and ~3 MW with (0, 180, 0, 180)

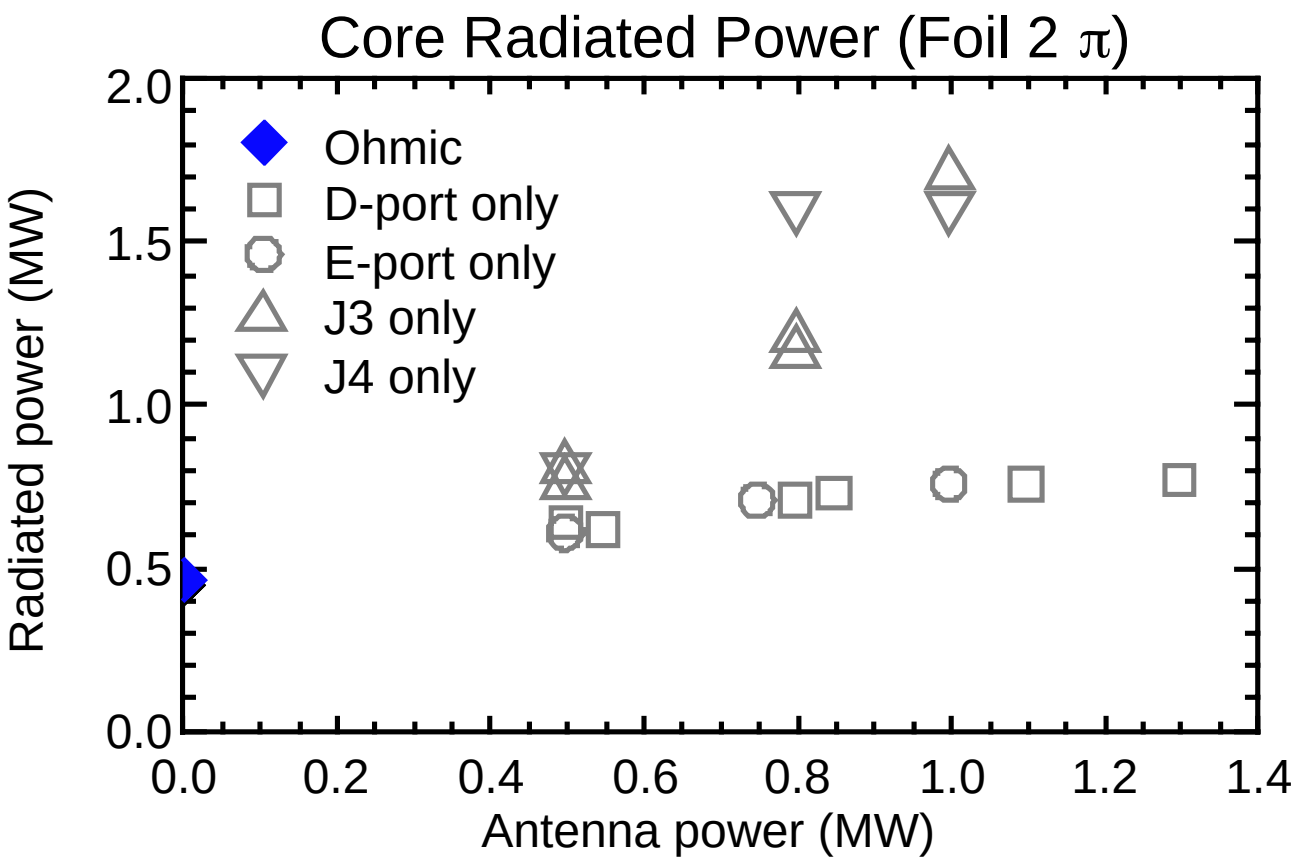
- Preliminary heating studies show heating comparable to the older antennas, but with higher levels of impurity generation (Ti, C and Mo possibly from the front tiles)

- Total power with all 3 antennas together has been pushed up to 5 MW for brief periods

Initial results - central electron heating vs phase (J. Terry)



Initial results - impurity generation (B. Lipschultz)



Summary

- The C-Mod ICRF system has been upgraded through the addition of two transmitters and a new 4-strap antenna
- Heating power will be doubled to 8 MW at ~ 80 MHz
- Heating and current drive power of 4 MW will be available at 43, 60 and 78 MHz
- This upgrade will considerably extend the range of physics investigations possible on the C-Mod tokamak

See also the following talks and posters on C-Mod RF

- Session QI2
  - Bonoli
- Session RO2
  - Terry, Taylor
- Session KP1
  - Marmar, Wukitch, Nelson-Melby, Bonoli, Phillips, Parker