Results from HHFW System Operation on NSTX*

D. W. Swain[#], J. R. Wilson[§], P. M. Ryan[#], J. B. Wilgen[#], J. Hosea[§], M. D. Carter[#], and the NSTX team

[#]Oak Ridge National Laboratory,
[§]Princeton Plasma Physics Laboratory

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Abstract

The HHFW system on NSTX has operated with the full 12-antenna, 6-transmitter configuration, delivering over 2 MW reliably for pulse lengths over 100 ms and over 4 MW for short pulses. Good HHFW heating has been observed.[1] Various phasings of the antenna system have been used, including both co- and counter-current drive phasing. A circuit model of the full 12-antenna coupled system has been developed that gives good agreement with vacuum measurements. When it is used to extract the effects of the plasma on the rf circuit, pronounced asymmetries in antenna loading are observed, even when antenna phasing is symmetrical (e.g., $0\pi0\pi0\pi$…..). The asymmetry appears to be caused by the large pitch angle of the magnetic field at the antennas (≥ 45°). Time-resolved edge density profiles in front of the antenna were measured using a microwave reflectometer. Using the measured profiles, the loading of the plasma on the antenna has been calculated. The results of the calculations will be presented and compared with the measurements.

[1] B. Leblanc, this conference.

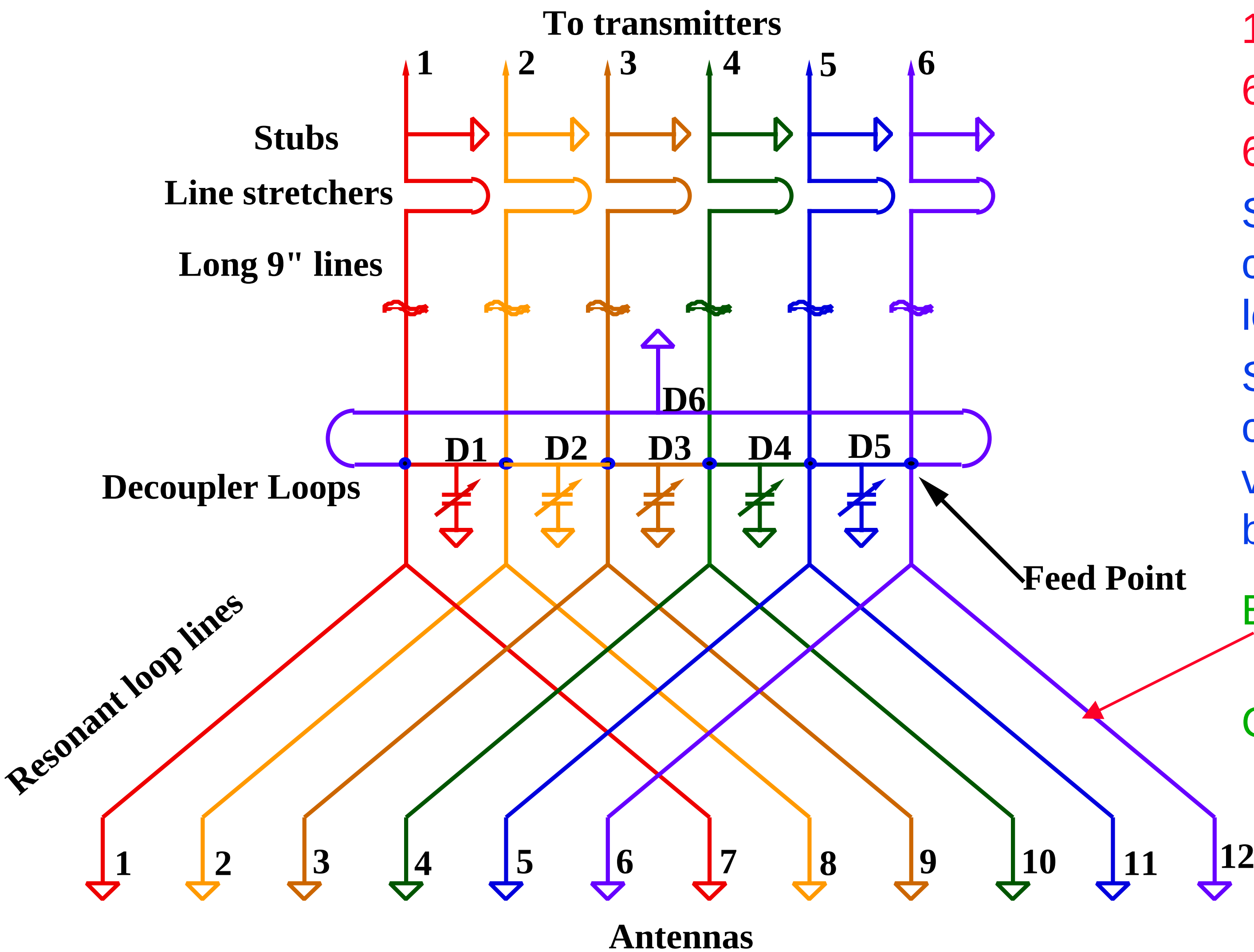
Summary and conclusions

- Improved operation capability:
  - 6 transmitter, 12 antennas, 2.5 MW "standard" shots, 4 MW short-pulse.
- Observe significant asymmetry of plasma loading on rf system due to large poloidal field/toroidal field.
- Appears to be explained by Z-matrix calculation using RANT3D.
- Good antenna loading, in agreement with design assumptions.
- Although reflectometer sees *large* density fluctuations, RF loading ≈ constant, probably because antenna spatially averages fluctuations.

- Loading predictions with active phasing indicate that system should work OK for phasing changes during a shot (but needs changes in decouplers)

- Heating results - data taken at different phasings. All cause similar increase in plasma stored energy as measured by magnetics
  - 0π0π0ππ0π0π0 Slow phasing, good electron heating ($k_z \approx 14\ m^{-1}$)
  - 00ππ00ππ00ππ Fast phasing, poor electron heating ($k_z \approx 7\ m^{-1}$)
  - -π/2 CD Co-current drive phasing, ($k_z \approx 7\ m^{-1}$), poor electron heating

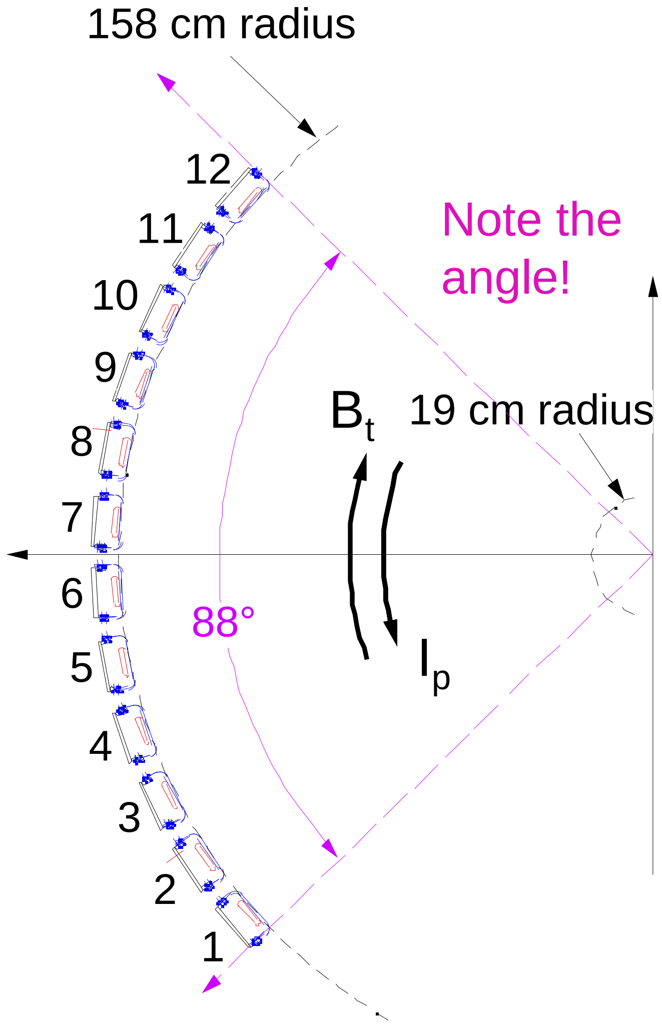
Design configuration: Each transmitter drives two current straps in resonant loop configuration with decoupling circuits



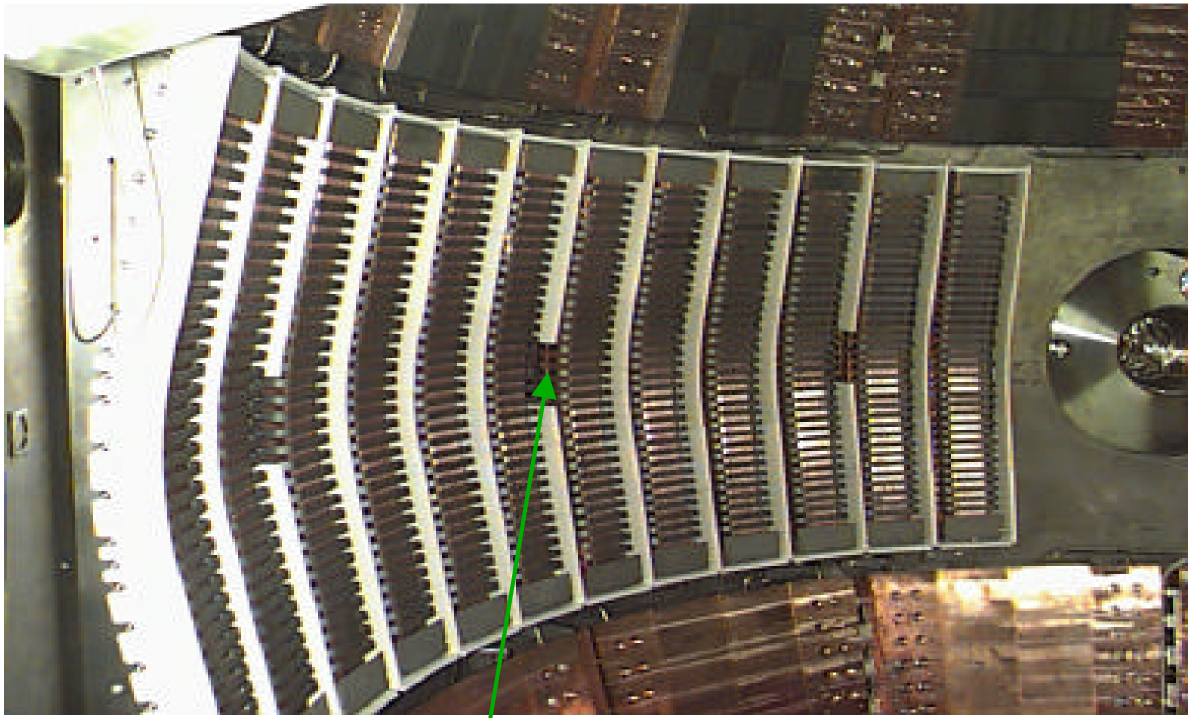
- 12 current straps
- 6 resonant loops
- 6 stub decouplers
- Strap 0-6, 1-7,... connected in resonant loops
- Substantial inter-strap coupling ($k_{21} \approx 0.1$ in vacuum) compensated for by decouplers
- Electrical length of each loop is 2 λ
- Currents in straps at each end are out of phase (π phasing)

12-strap antenna array takes up almost 90° toroidally

Cut through antenna midplanes, viewed from above

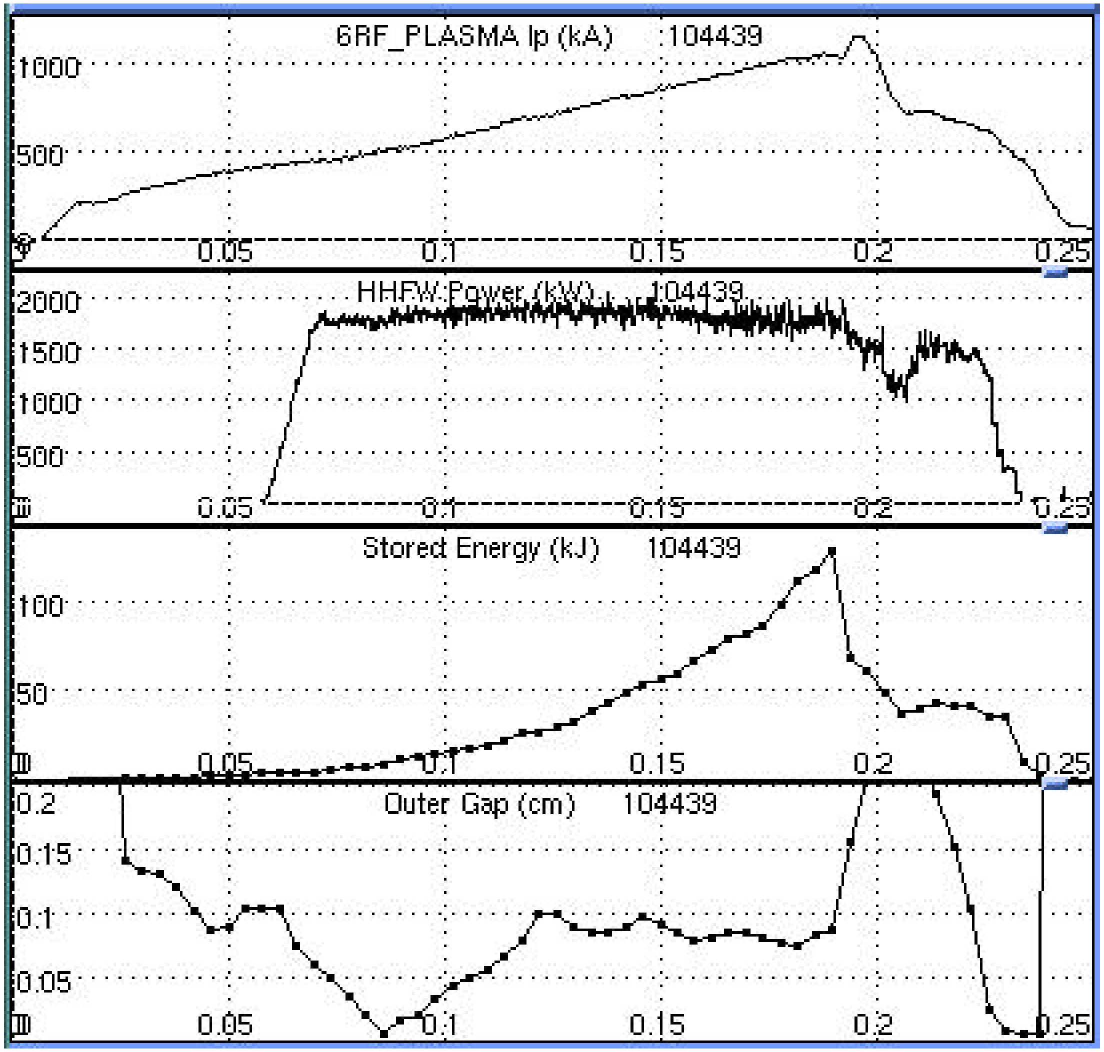


NSTX antennas installed in the vacuum vessel
BN limiters surround each antenna



Location of ORNL microwave reflectometer used for edge density profile measurements

Detailed analysis of 104439 – a "typical" shot

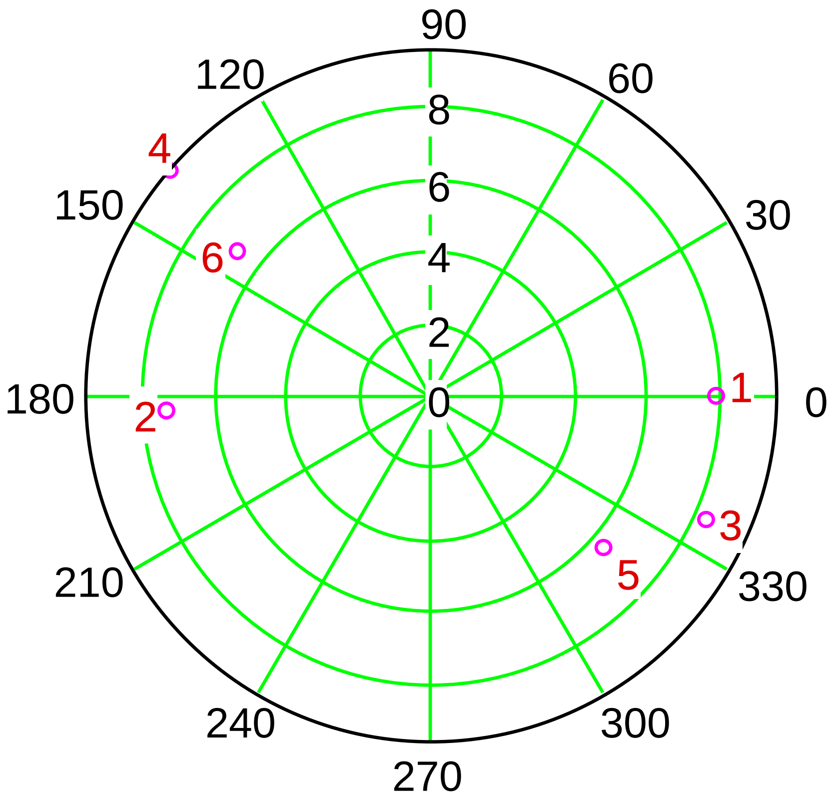


- B_0 = 0.35 T, D_2 fill gas, 3 MW of neutral beams.
- I_p ramp to 1 MA
- P_{rf} =1.8 MW, starting at 60 ms to keep $q_0 > 1$.
- Phase at feed points *approximately* 0π0π0π
- W_{mag} increases to ≈ 120 kJ; disruption at t ≈ 190 ms.
- Scan of outer gap from 10 to 1 cm and back from 70 – 120 ms

Phasing between transmitters was *almost* 0π0π0π, but not quite.

NSTX

Phases of rf voltages at feed points during shot



Loops 1 and 2 driven with almost exact π (180°) phasing.

25° shift of loop 3 from ideal 0°

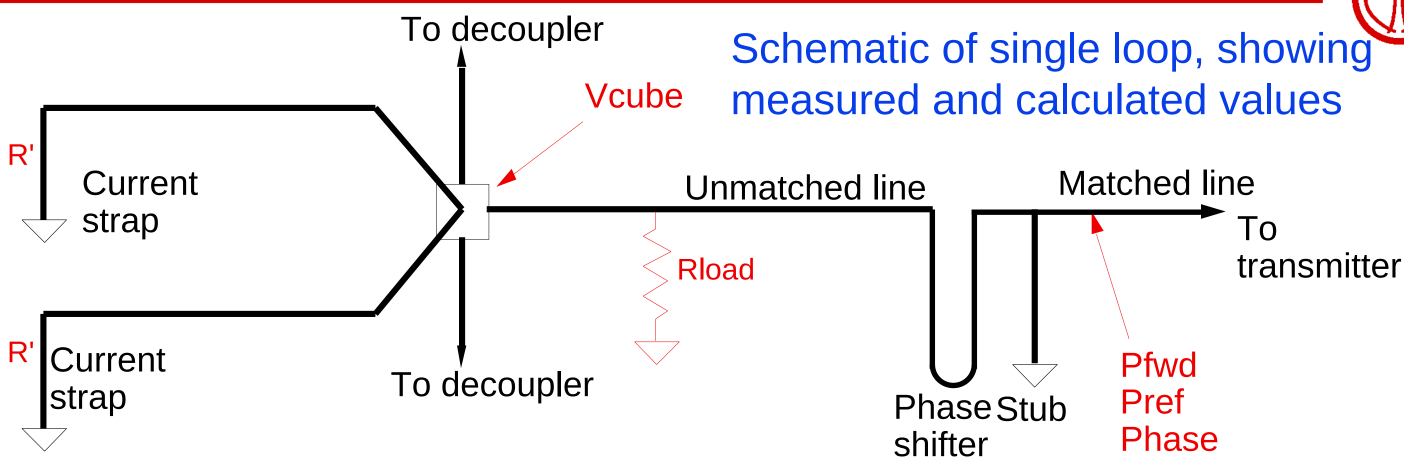
Loops 4 – 6 about 45° from ideal

This should not make much difference in antenna loading using a "standard" antenna electrical model.

It makes a *significant* difference based on modeling of 12-antenna system with RANT3D

ornl

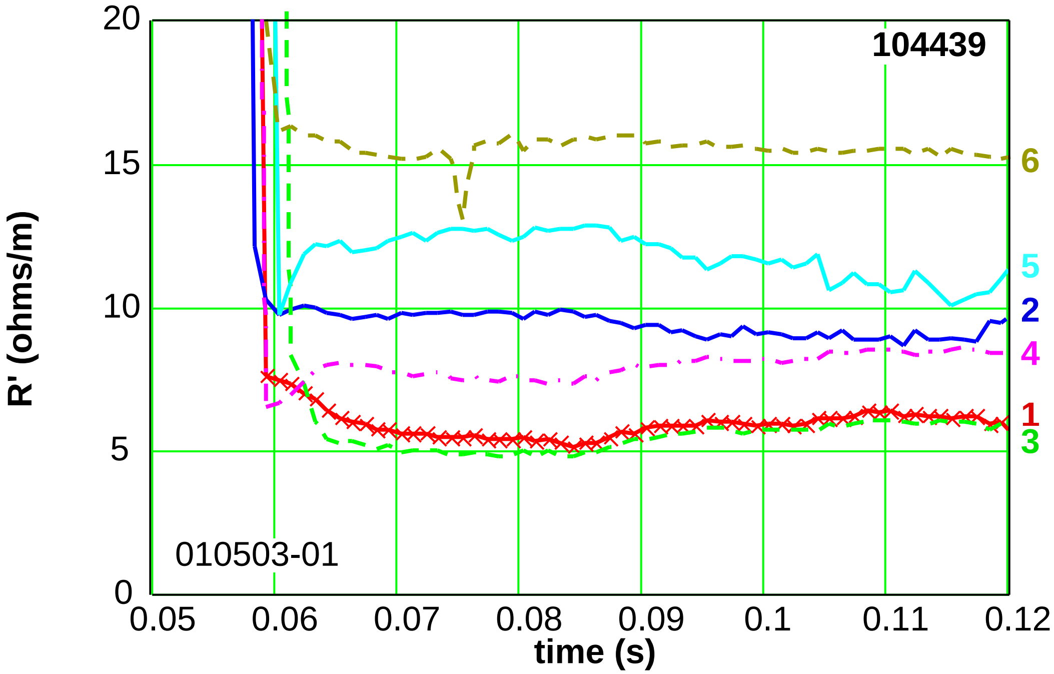
How effective loading (R'_{eff}) is calculated for each loop

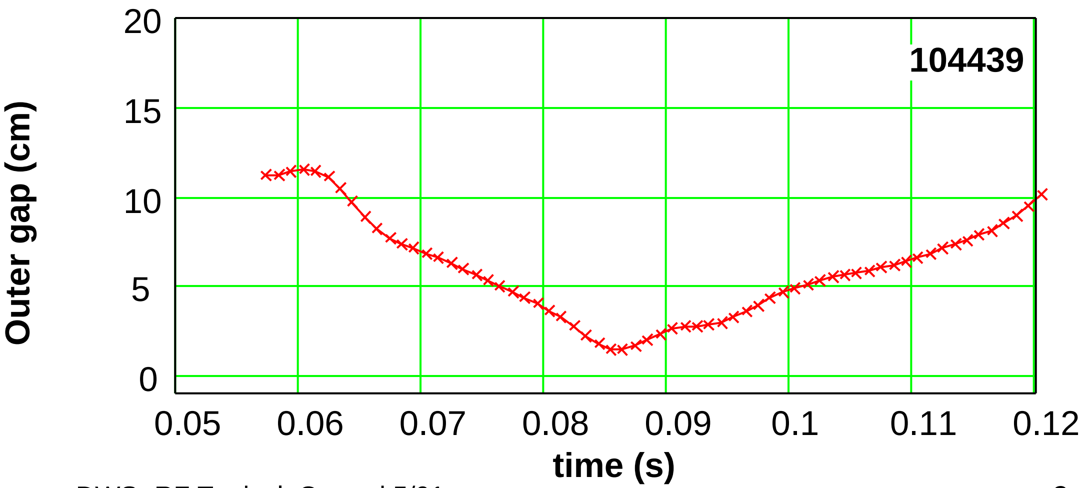


Schematic of single loop, showing measured and calculated values

- From measured values of P_{fwd}, P_{ref}, and phase, compute the reflection coefficient ρ at the measurement points (transmitter side of stubs).
- Translate ρ along the lines to the stub positions.
- Compute rho on the unmatched side of the stub (ρ_u) by removing the parallel admittance of the stub.
- Calculate R_{load} (shown in the figure) that will give the same $|\rho_u|$ on the unmatched side of the line, using $R_{load} = 50 (1 - |\rho_u|)/(1 + |\rho_u|)$
- From R_{load} determine R'_{eff}, the loss/m that needs to be put in the circuit model of the current straps, using the equation R'_{eff} (ohms/m) $\approx 0.74\ R_{load}$ (ohms).

Experimental R'$_{eff}$ shows little change with time, but significant difference from one loop to another





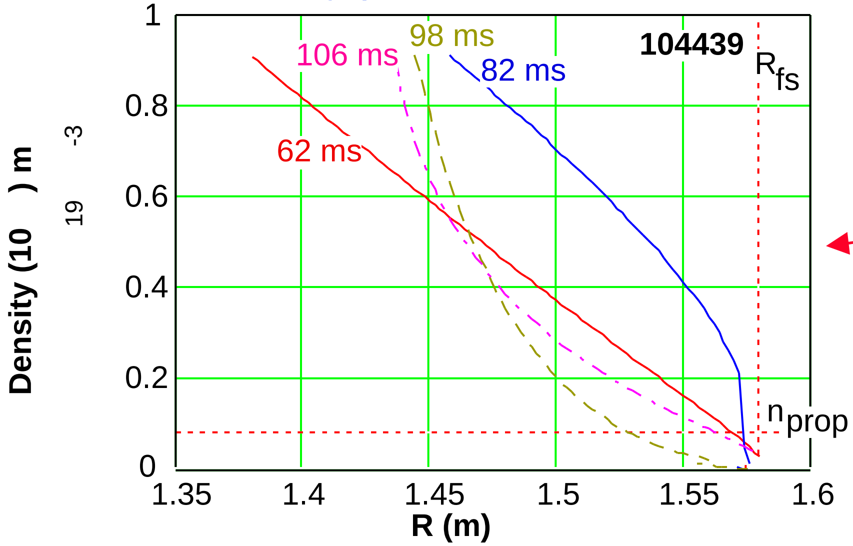
Top figure shows calculated R'$_{eff}$ for loops 1 – 6 during a portion of the rf pulse .

Bottom figure shows distance from outermost closed flux surface to antenna (outer gap).

Why is loading almost constant during large gap scan, but different from one loop to the next?

More mysteries – density profile is fluctuating like crazy!

Density profiles at 4 times

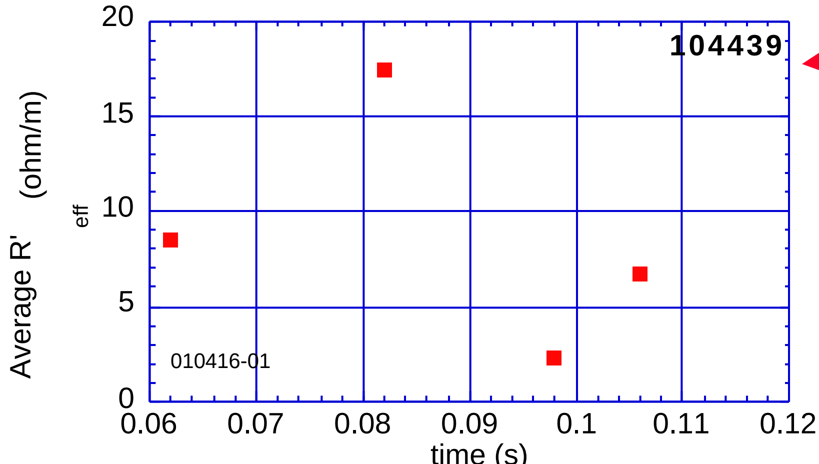


ORNL microwave reflectometer measures localized density profile in midplane of HHFW antenna array.

Sees large changes with time.

Freq. sweep to meas. density profile takes ≈ 200 μs, comparable to density fluctuation time.

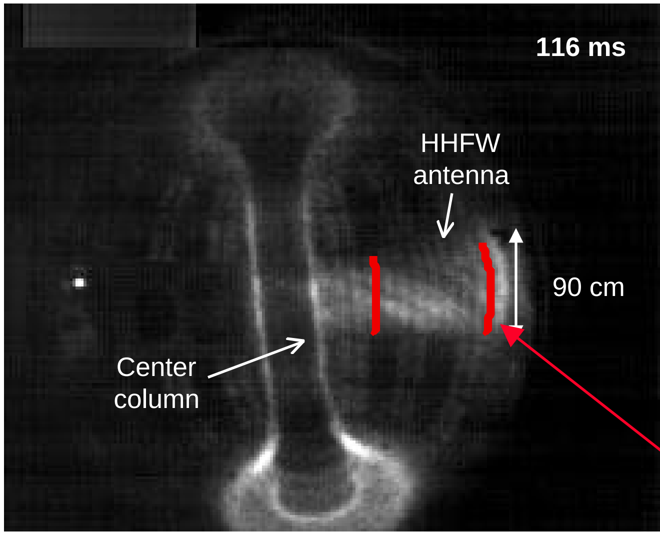
Avg. R'_{eff} from RANT3D for 4 density profiles

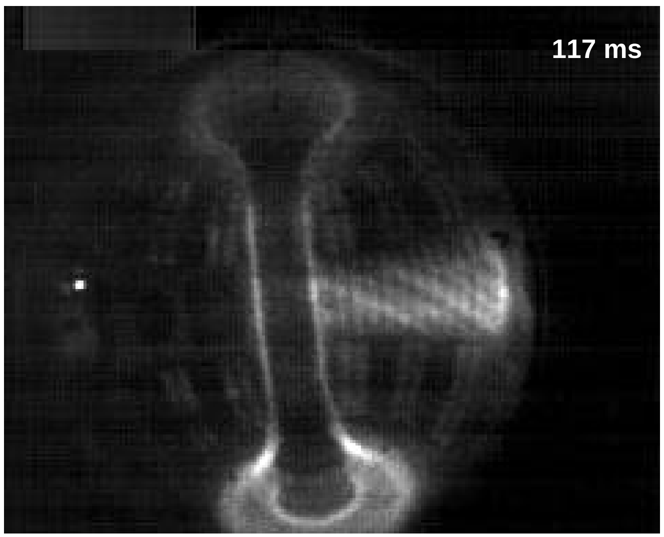


RANT3D predicts significant changes in R'_{eff} using the 4 measured profiles shown.

Why don't we see changes on experimental measurements?

Proposed answer: Density fluctuations are much smaller scale than antennas, so they are averaged over.





Pictures from R. Maqueda[1] of edge turbulent filaments over the HHFW antenna.

"Illuminated" by natural recycling from the Faraday shield.

20 μs exposure time, no interference filter.

Red curves show approx. locations of two of the antennas (e.g, antennas 7 and 12) that are connected together in one loop.

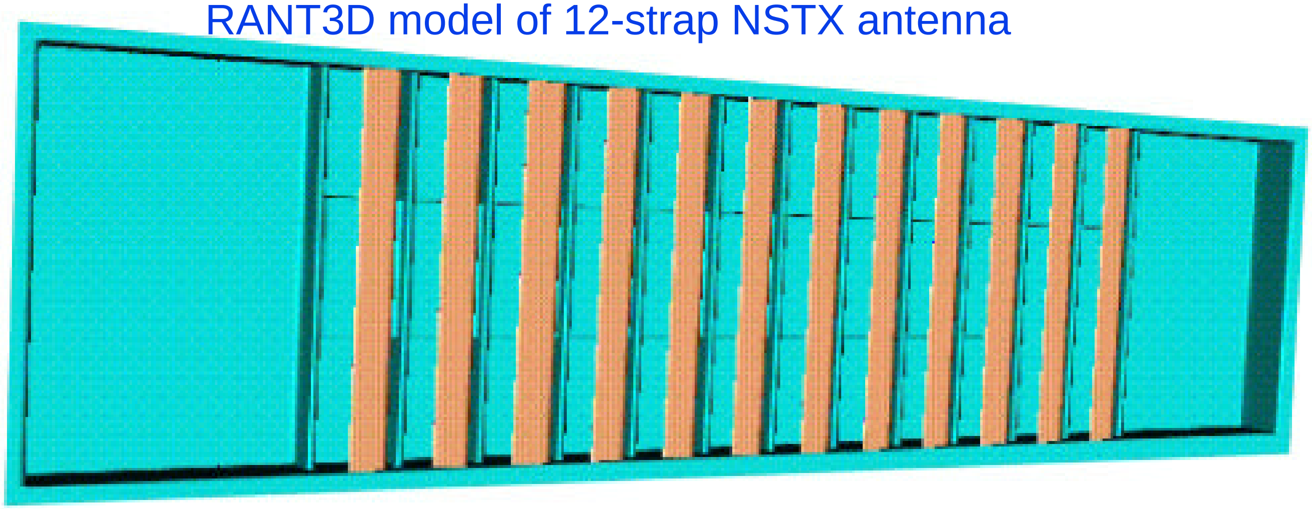
Presence of striations is *independent* of presence of rf. Pictures were taken with $P_{rf} = 0$.

[1] R. Maqueda et al. "Edge turbulence measurements in NSTX by gas puff imaging", *Rev. Sci. Instr.* **72**, 931 (2001).

Why the large difference in loading from loop to loop?

We need to look at detailed calculation of plasma loading for coupled antenna system using RANT3D.

RANT3D model of 12-strap NSTX antenna



- 12-strap antenna system
- Planar geometry for antenna straps and plasma
- Curvature of straps from back plane approximated by adding recesses in model
- Measured plasma density profile
- Pol. and tor. magnetic fields **B**(x) from EFIT reconstruction of equilibrium.
- GLOSI code computes impedance in Fourier space at plasma “edge”
- Calculate 12x12 impedance matrix for actual straps

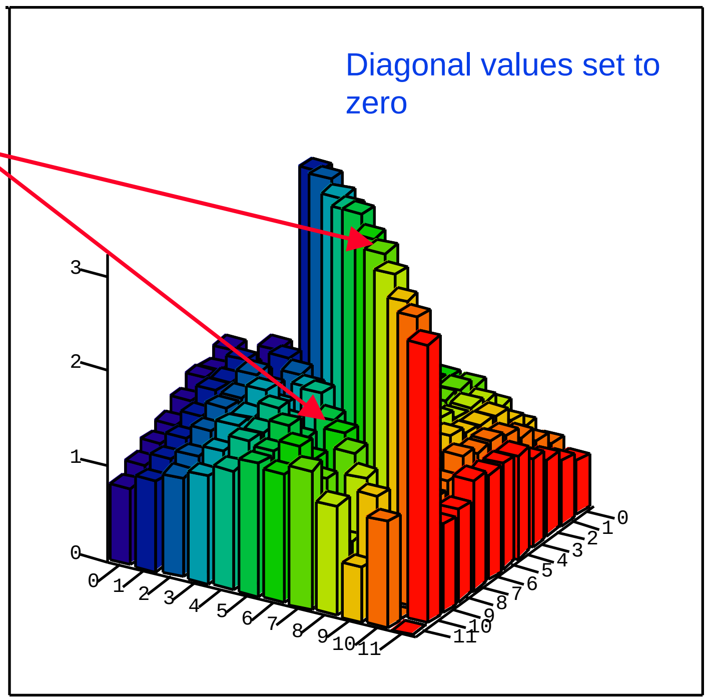
RANT3D computes asymmetric impedance matrix for 12 straps with plasma

12 x 12 Z matrix –

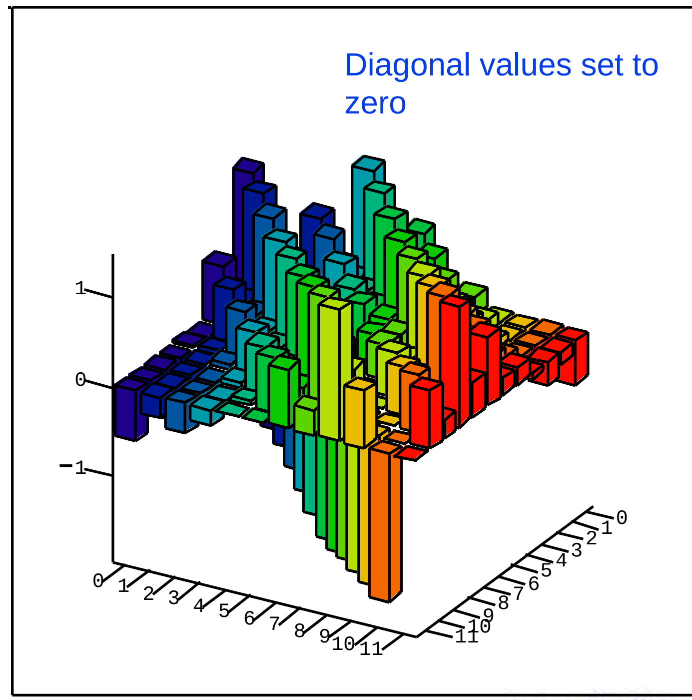
- Represents the impedance of a 12-antenna system.
- Completely describes the electrical properties of the antenna system in the presence of plasma.
- With no plasma Z matrix is symmetric. Large poloidal field causes asymmetry.
- Coupling between adjacent straps is changed significantly by plasma.

Real and imaginary parts of Z matrix for 62-ms density profile of 104439.

Note asymmetry of components next to diagonal!



Re(Zo)



Im(Zo)

Z matrix results used to compute response of rf circuit

$$d\mathbf{V}/dx = \mathbf{Z'}\, d\mathbf{I}/dt$$

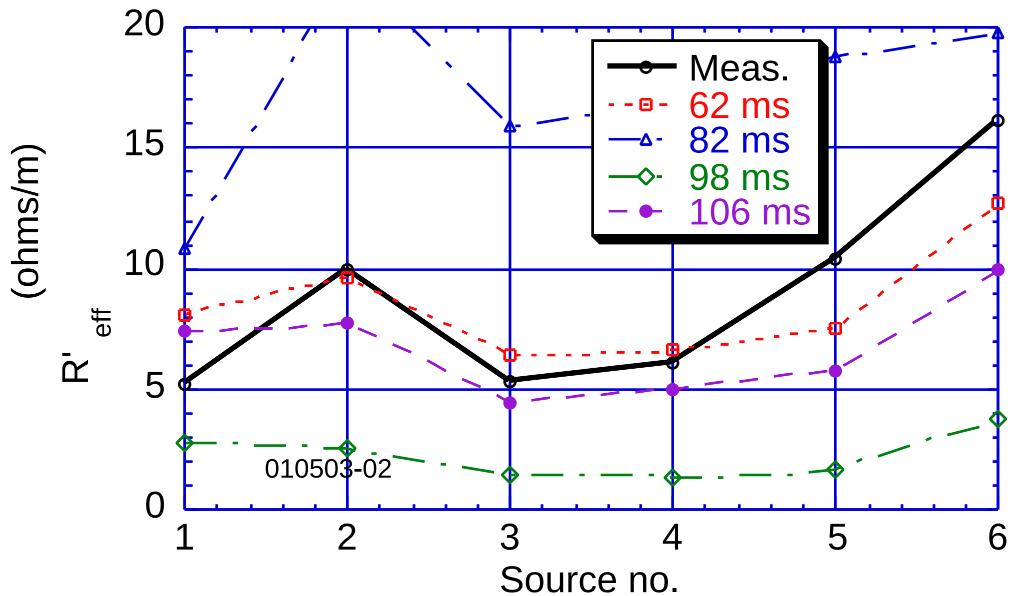
$$d\mathbf{I}/dx = j\omega \mathbf{C'}\, \mathbf{V} = j\omega C'\, V$$

Coupled circuit equations

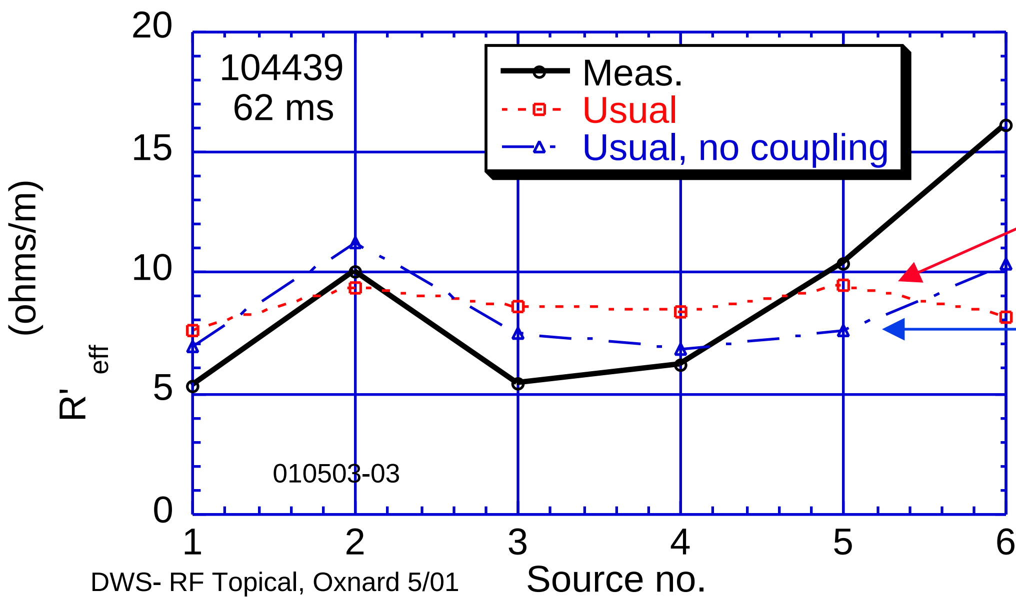
- Z' 12 x 12 matrix from RANT3D
- C' diagonal matrix (dominated by strap-Faraday shield capacitance)

- Solve coupled circuit equations for antennas and resonant loops using Z matrix from RANT3D
- Analyze circuit response with specified driving power and phase
- Get calculated values for R'_{eff} for each loop.

RANT3D Z matrix reproduces experimental results



- Measured data shows low R' on loop 1, high on 2, low on 3 and 4, high on 6.
- RANT3D Zmatrix gives similar *qualitative* results.
- *Quantitiative* values depend on which density profile is used in the calculation.

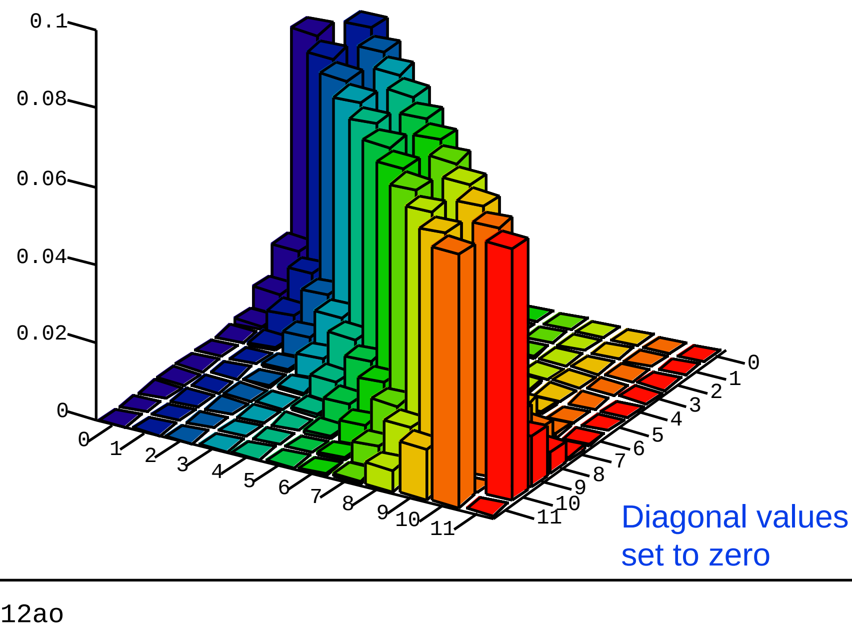


- Usual coupled-strap model with $Z'_{ij} = R'\delta_{ij} + j\omega M'_{ij}$ shows
  - R' fairly independent of strap location if usual model used with vacuum mutuals
  - If (extreme case) inter-strap mutuals are set to zero, agreement is better, but Z-matrix results better still.

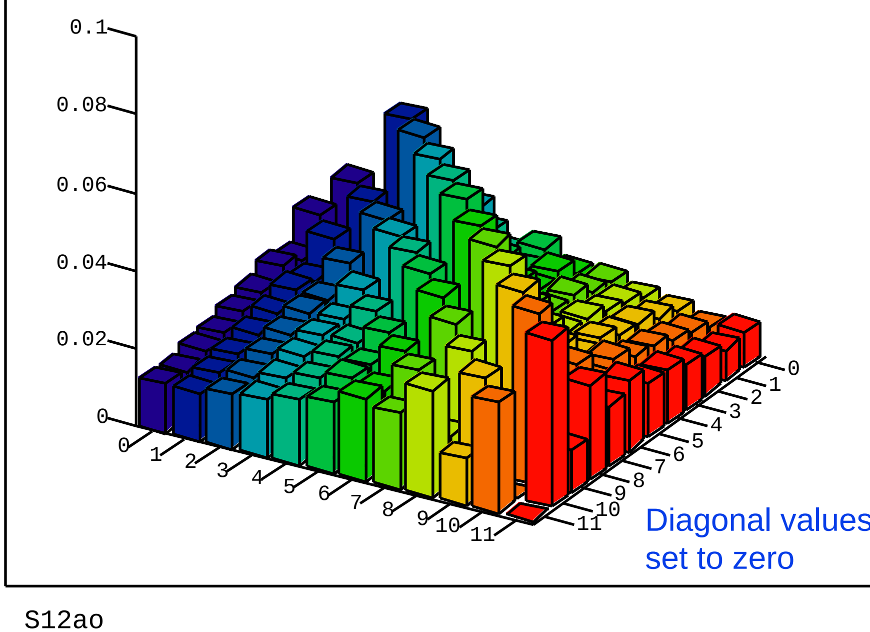
Plasma *reduces* nearest-neighbor coupling but *increases* coupling between more distant neighbors

NSTX

12x12 Antenna S-matrix in Vacuum
(usual model, agrees w. measurements)



12x12 Antenna S-matrix with Plasma
(calculated using RANT3D)

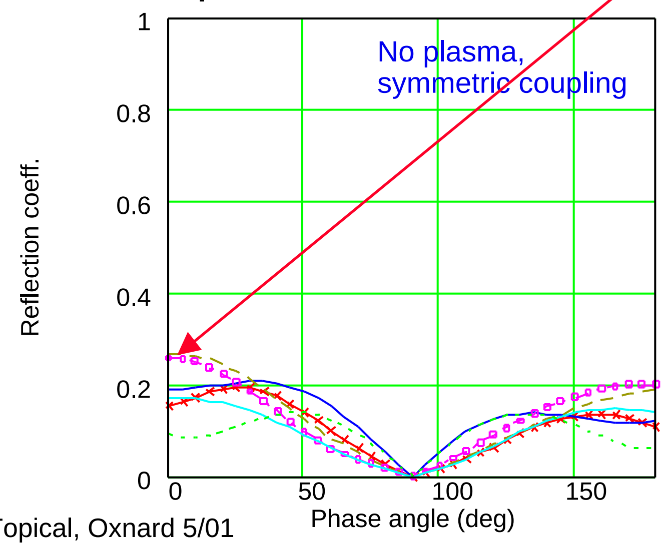


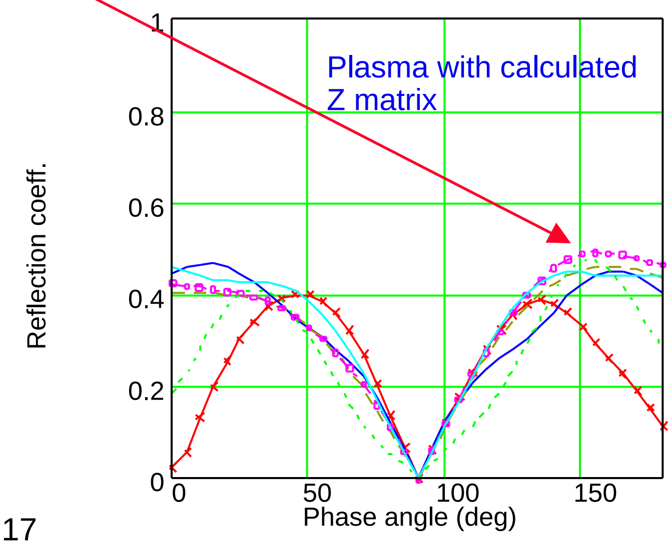
Similar results seen elsewhere (e.g., DIII-D), but degree of change is striking.

- Plasma propagation begins very close to antenna
- Asymmetry also has effect

Plasma increases reflected power for phase shift during shot

- Decouplers set for vacuum coupling between straps
- Plasma significantly modifies strap coupling by
  - decreasing inter-strap coupling
  - introducing asymmetry
- This results in significantly higher reflected power as phase angle between sources is changed.
- *Gedanken experiment*
  - Phasing between sources set at 90°, tuning systems set for perfect match.
  - Phase angle between sources swept from 0° to 180° *without* changing tuning system settings (e.g., like during a shot).
  - Max ρ increases from ≈ 0.25 to ≈ 0.5

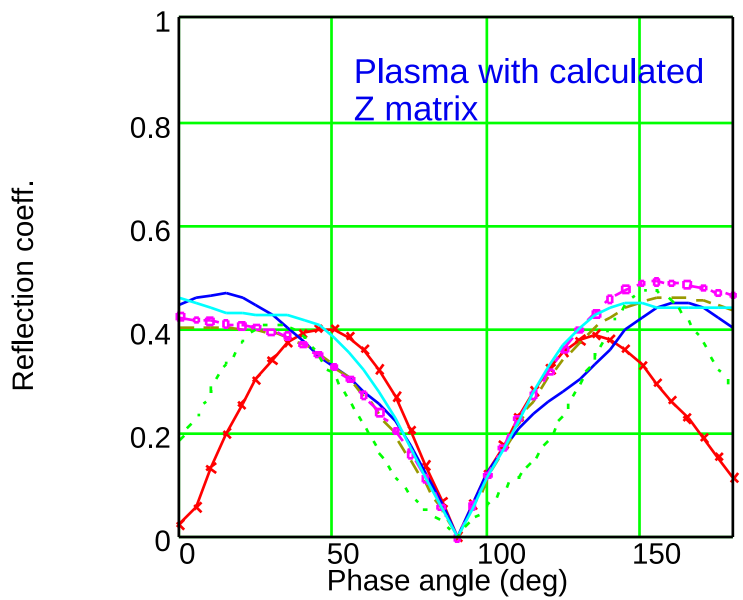


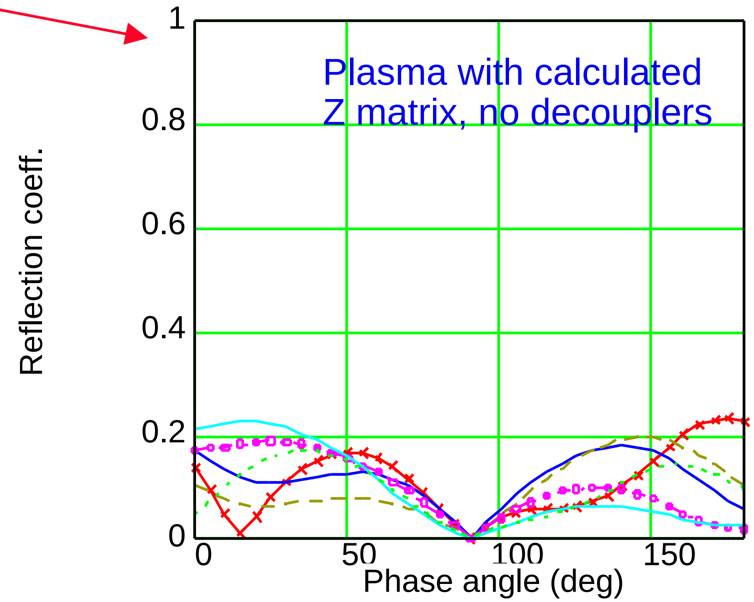


Changing decouplers should reduce angular dependence of reflection coefficient

We want to be able to change inter-strap phasing during a shot

- Need to decrease decoupler effects in system, because plasma decreases inter-strap coupling relative to vacuum coupling.
- Eliminating the decouplers causes a significant improvement in angular response.





Optimization of decouplers will give acceptable angular change in rho.

Phasing of antennas – heating and loading results

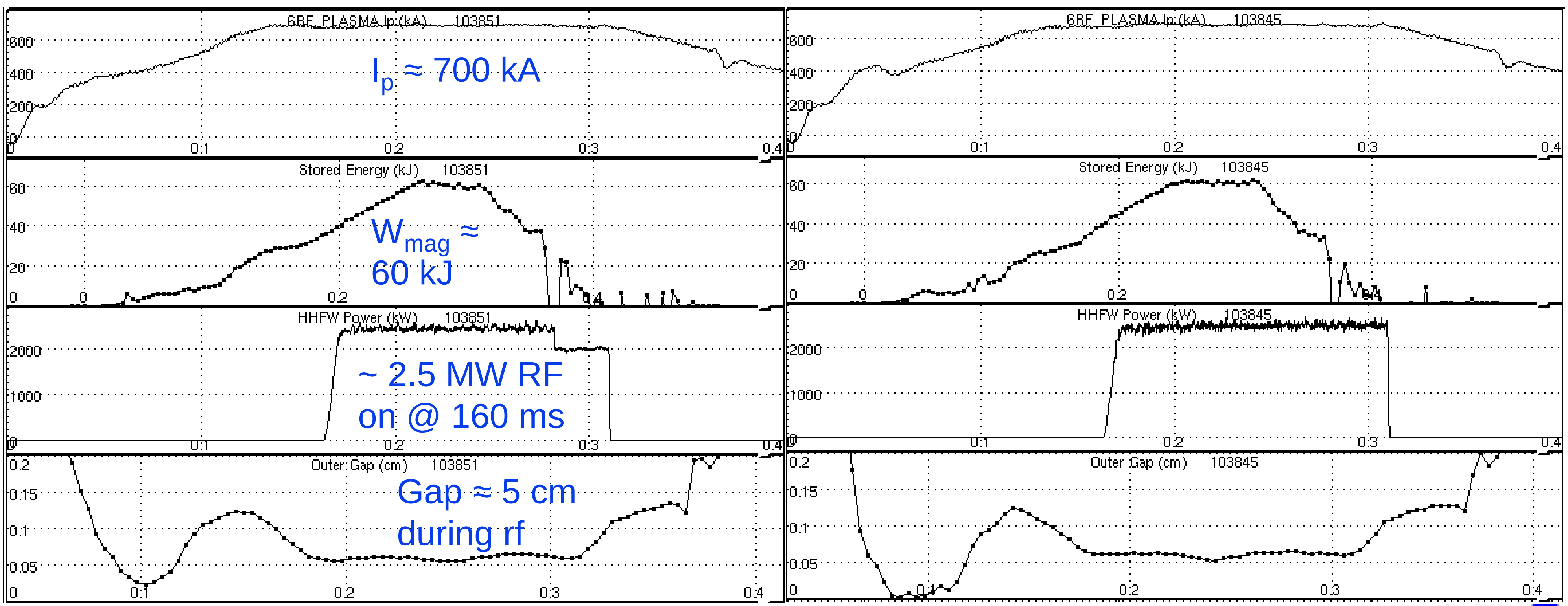
Heating and Phasing summary –

- *Total* stored energy change is fairly independent of phasing
- *Electron* heating depends on phasing
  - Good for slow phase velocity phasing (0π0π0π)
  - Not good for fast phasing (00ππ00) or co-CD phasing w. π/2 between transmitters.
- Loading depends on phasing

Heating – 3 “typical” RF shots + comparison no-rf shot

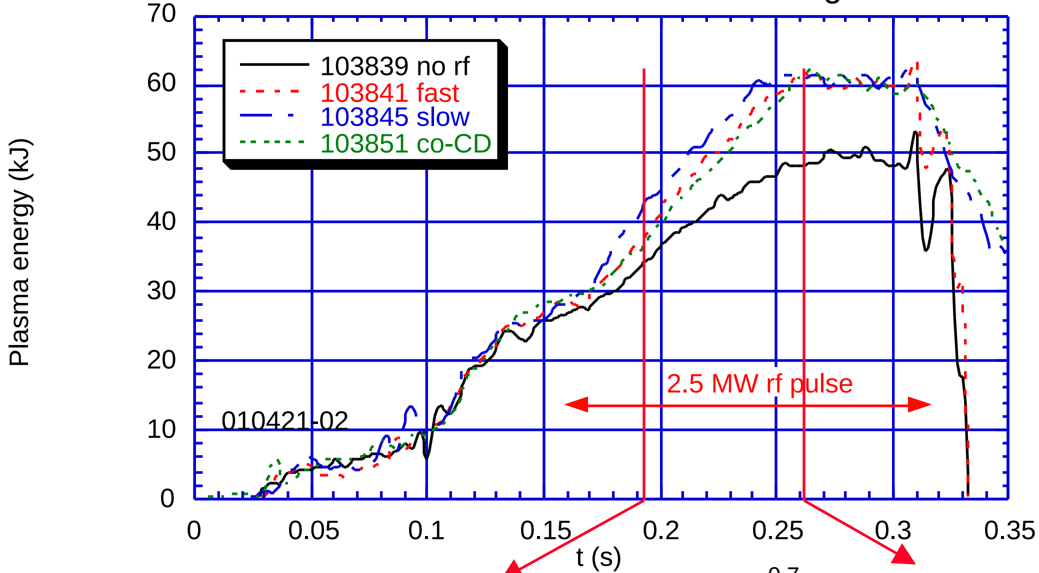
- 103851 — Co-CD phasing with -π/2 phasing between transmitters
- 103845 — Slow phasing with 0π0π0π from transmitters
- 103841 — Fast phasing with 00ππ00 from transmitters
- 103839 — No rf comparison shot

Co-CD | Slow



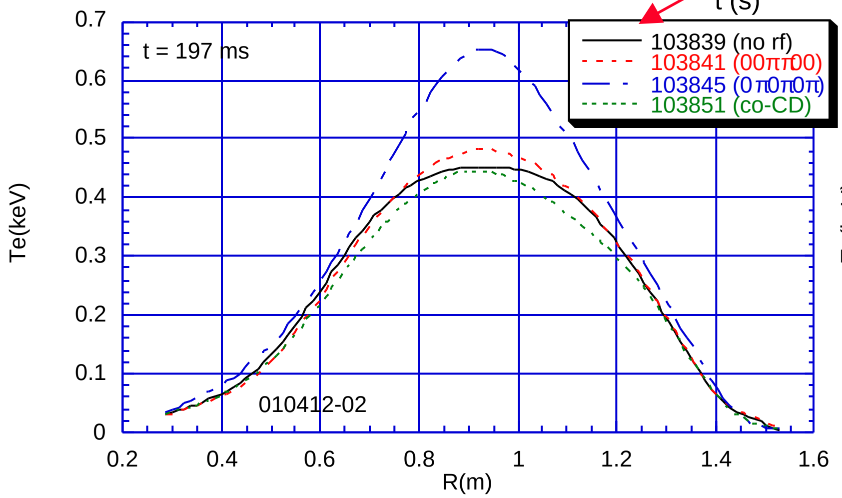
Same stored energy for all rf; T_e increases only for slow phase wave

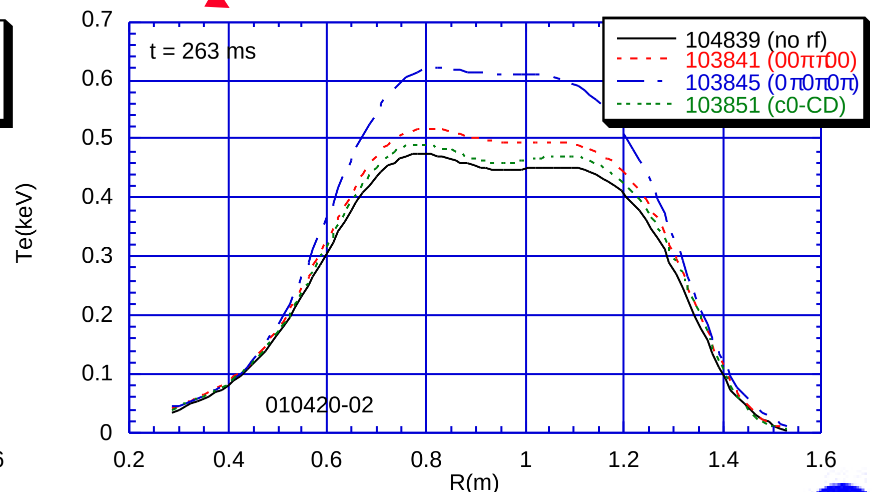
All rf shots show approx. the same W_{mag}; slow phase velocity heats earlier.



W_{mag} from S.Sabbagh
T_e from B. LeBlanc

- Slow phase velocity shows significant electron heating.
- Fast and co-CD shots do not.





RF measurements indicate asymmetric loading, changing with phasing

- R'$_{eff}$ changes significantly with phasing
  - Loops 5 and 6 higher than loops 1 - 4
- Significant effects of non-ideal phasing in these shots also.
- Impedance at cubes shifted from all-real, as seen in 1999 runs; equivalent to inductance decrease of straps.