Loading and Asymmetry Measurements on the NSTX ICRF System*

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Abstract

The HHFW system on NSTX has operated with the full 12-antenna, 6-transmitter configuration, delivering over 3 MW reliably for pulse lengths over 100 ms and over 4 MW for short pulses. Good HHFW heating has been observed. 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 ($\geq 45°$). Time-resolved edge density profiles in front of the antenna were measured using a microwave reflectometer and Thomson scattering. Using the measured profiles, the loading of the plasma on the antenna (including the asymmetry) has been calculated using the RANT3D code and is compared with the measurements.

Outline of presentation

Introduction – Why are we doing these studies?

Description of the NSTX rf system

Measurements of S-matrix: Technique and data

Calculation of S-matrix using RANT3D full-wave code

Comparison of measurements and calculations:

- Diagonal components of S-matrix, and resulting loading and impedance change
- Off-diagonal terms, showing asymmetrical changes in inter-antenna coupling in presence of plasma

Conclusions

Introduction – why are we doing these studies?

NSTX High-Harmonic Fast Wave (HHFW) system:

- Critical for heating and for driving current to achieve long-pulse non-inductive operation
- Plasma parameters differ from conventional tokamaks and stellarators
  - Low magnetic field, high harmonic heating ($\omega/\omega_c \approx 10$)
  - High magnetic field pitch angle ($\geq 45°$)
- So new, interesting physics regime to study rf heating and coupling

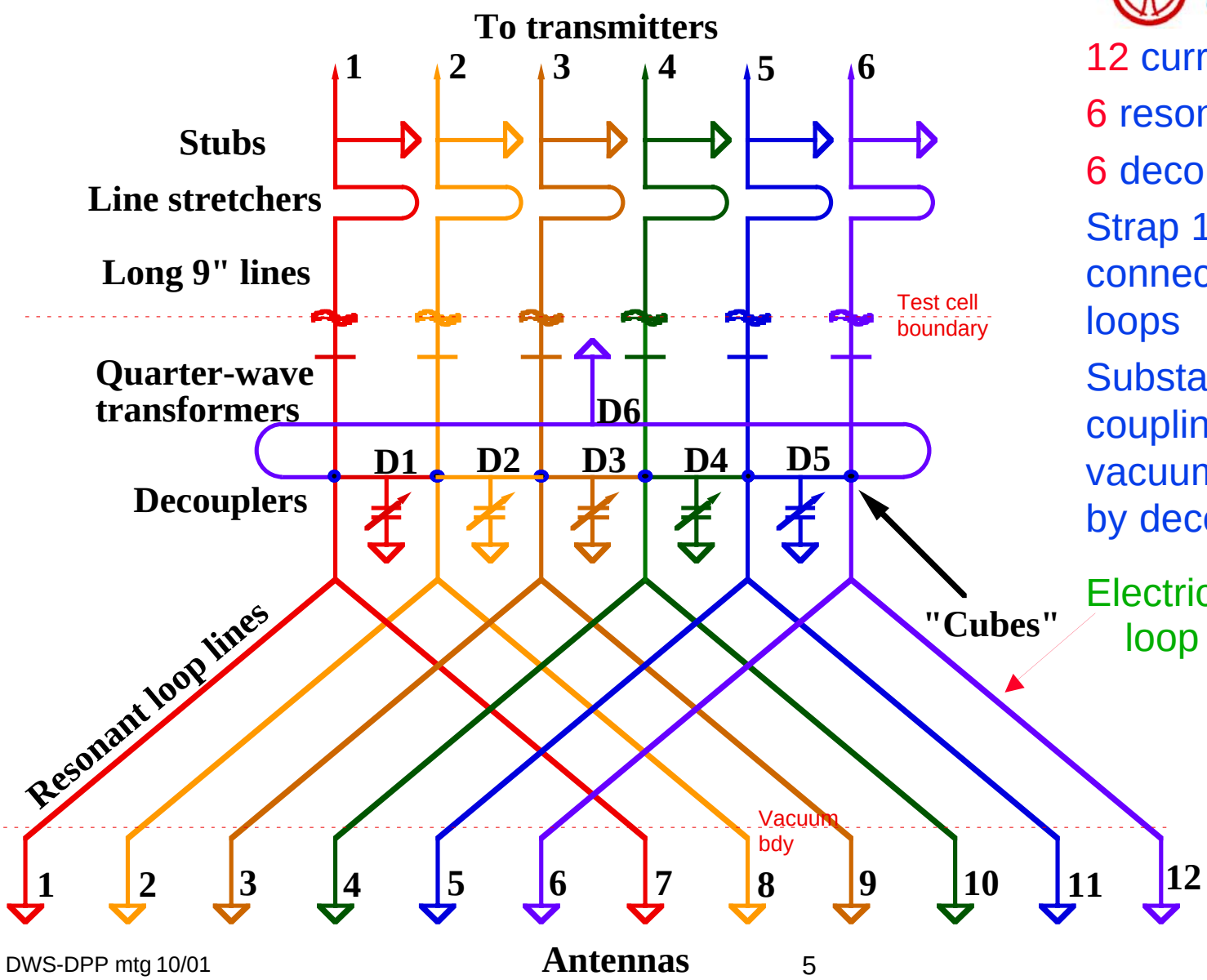
We want to understand how the plasma affects the rf system:

- Coupling of power to the plasma (plasma loading)
- Inductance of each strap
- Inductive coupling between straps

Results will affect the ability of the rf system to

- Heat
- Drive current
- Dynamically change CD efficiency during a shot

NSTX rf system description



12 current straps

6 resonant loops

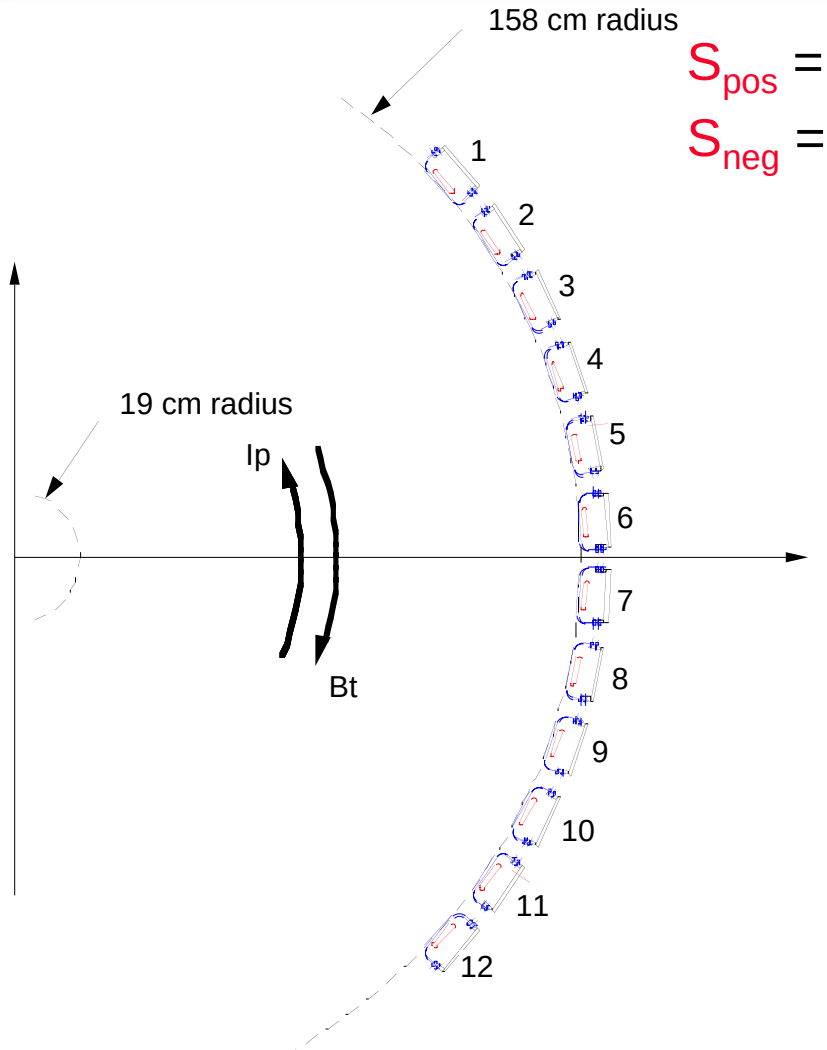
6 decouplers

Strap 1-7, 2-8,... 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 2λ

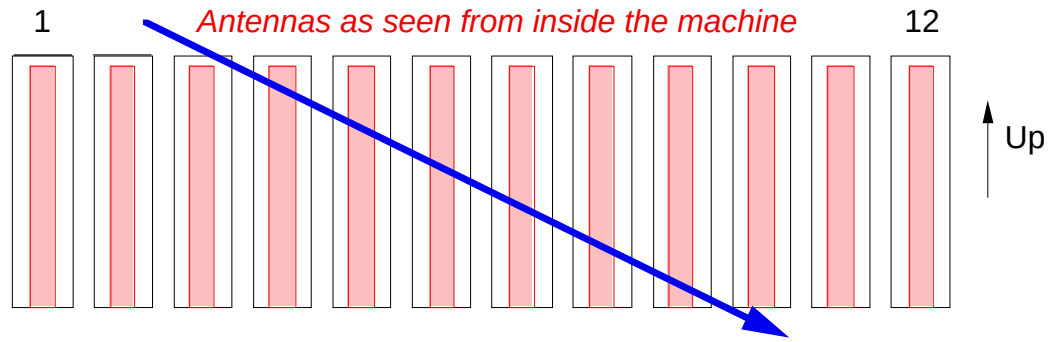
Antenna geometry



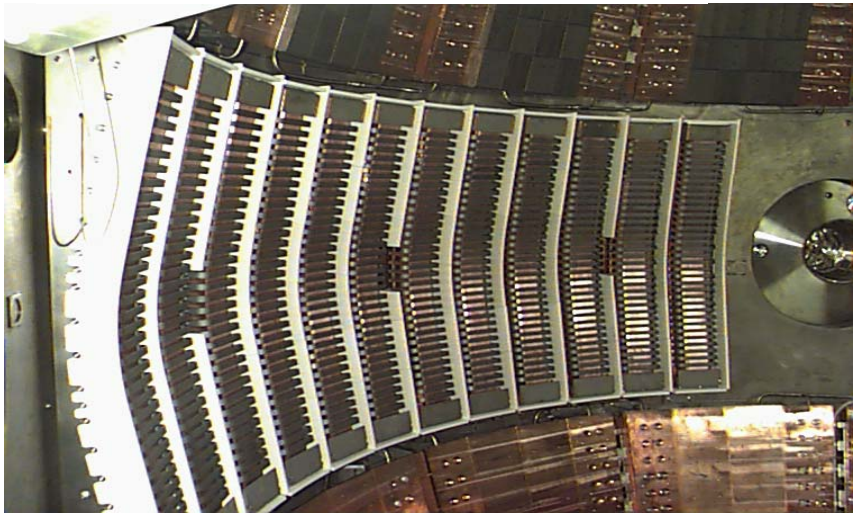
NSTX HHFW Antennas

S_{pos} = S-matrix element from strap n to strap n+1

S_{neg} = S-matrix element from strap n+1 to strap n



NSTX antennas installed in the vacuum vessel



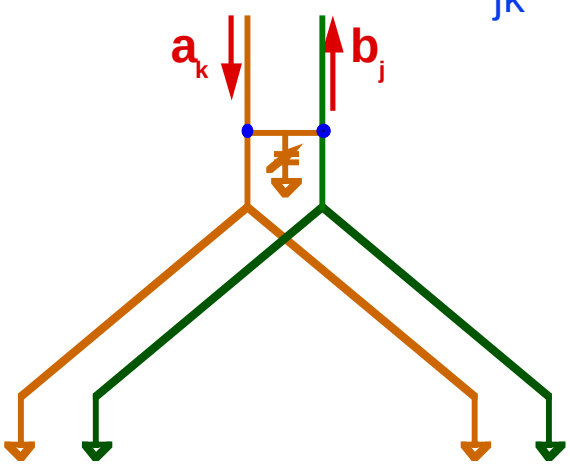
Measurements of the S-matrix

We have carried out experiments to directly measure the S-matrix during plasma operation.

The S-matrix is the scattering matrix of an electrical circuit with one (or several) input/outputs

$S_{jk} = b_j/a_k$

$\boldsymbol{b} = S \bullet \boldsymbol{a}$



a_k = amplitude of forward wave down line *k* toward circuit

b_j = amplitude of reflected wave on line *j* away from circuit

The S-matrix describes the behavior of the rf system *independent* of the circuits that are connected to it.

NSTX has a 6 x 6 S-matrix, with six transmitters and transmission lines.

How do we measure the S matrix in real NSTX 12-strap system?

1. Start with a given ***a*** vector, and measure the response (the ***b*** vector)

$$\boldsymbol{b} = S \bullet \boldsymbol{a}$$

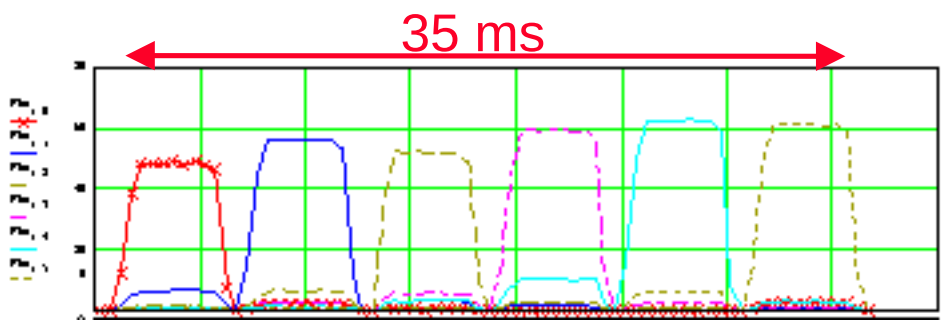
2. Do this for six *linearly independent* ***a*** vectors, combine to make a 6 x 6 A matrix and B matrix.

$$B = S \bullet A$$

3. Since the ***a*** vectors are independent, the inverse of A exists, so

$$S = B \bullet A^{-1}$$

Practically, we do this by firing all six transmitters sequentially in a short time.



Basic assumption: Plasma conditions *do not change* during this time.

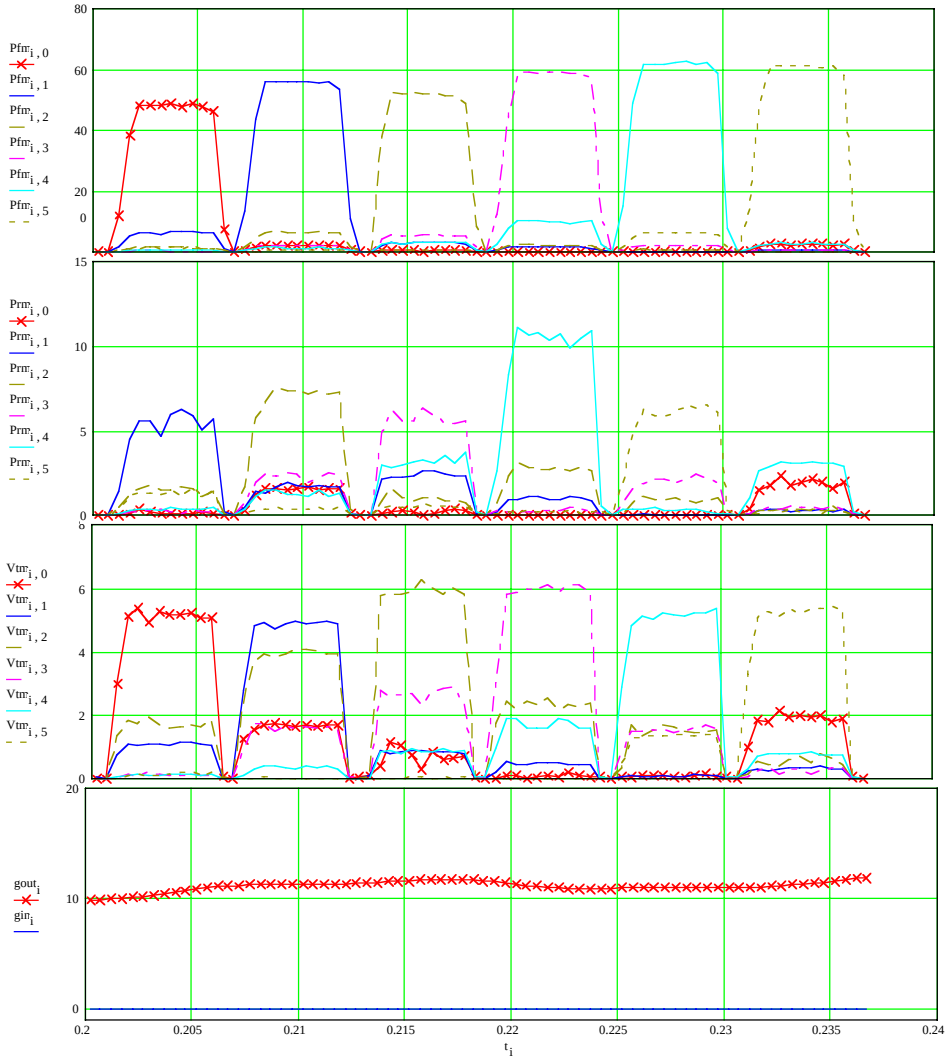
What do we measure?

Forward power (kW)
[on transmitter side of tuners]

Reflected power (kW)
[on transmitter side of tuners]

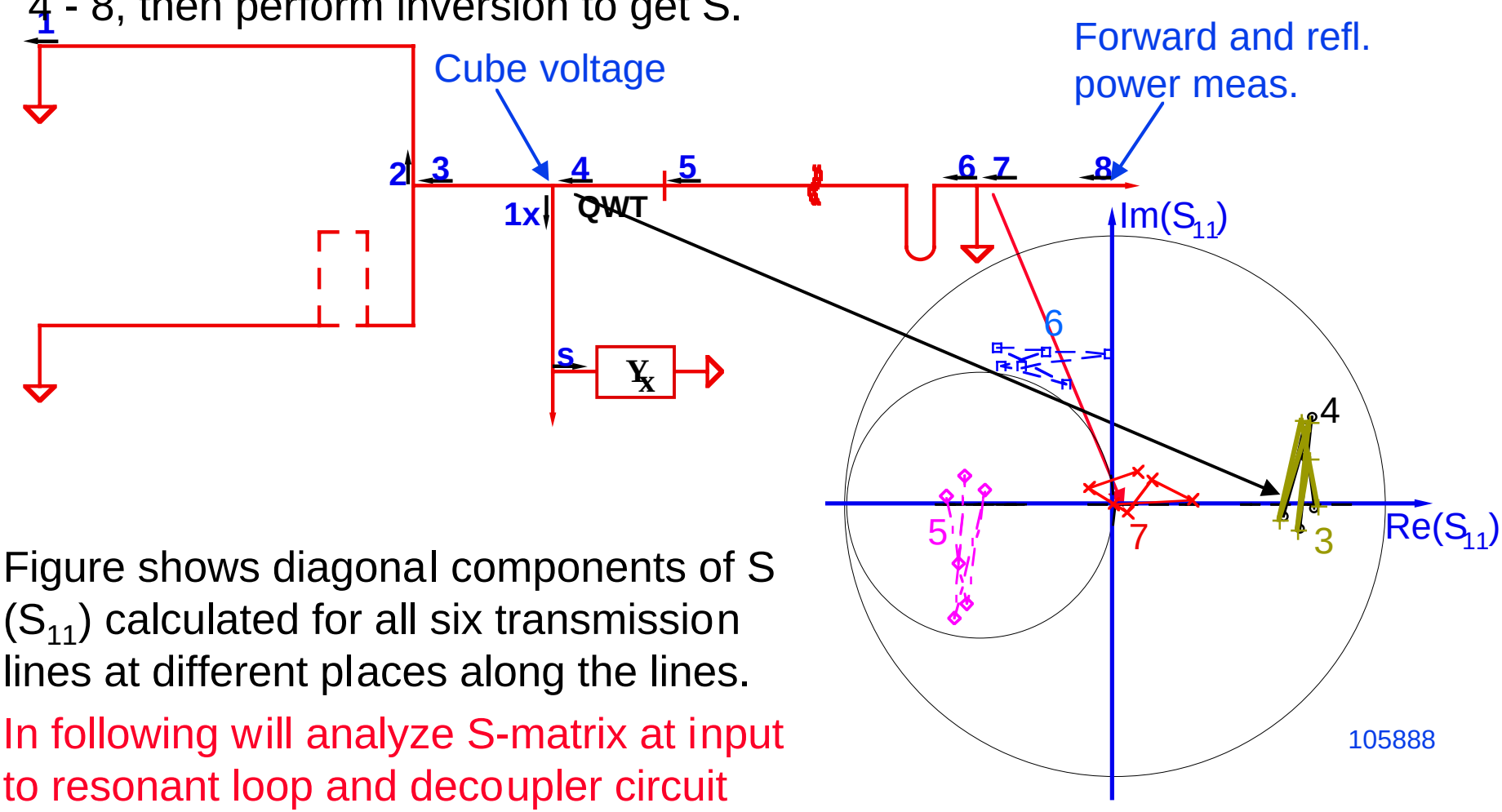
Voltages on cubes (kV)
[junction of transmission lines with resonant loops and decouplers]

Inner and outer gaps (cm)
[distance of plasma separatrix from inner and outer limiters]



We compute the S-matrix at different places in rf system

From measured quantities, can calc. ***a*** and ***b*** voltage vectors at locations 4 - 8, then perform inversion to get S.



S_{11} at different locations along transmission lines

Figure shows diagonal components of S (S_{11}) calculated for all six transmission lines at different places along the lines.

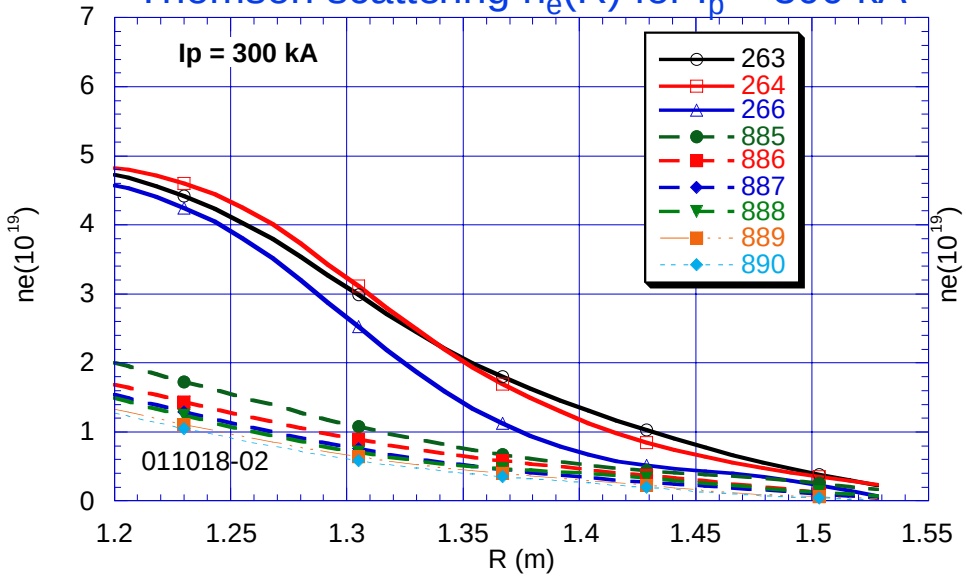
In following will analyze S-matrix at input to resonant loop and decoupler circuit (S4 in notation used).

We measure S-matrix as function of plasma current and plasma position

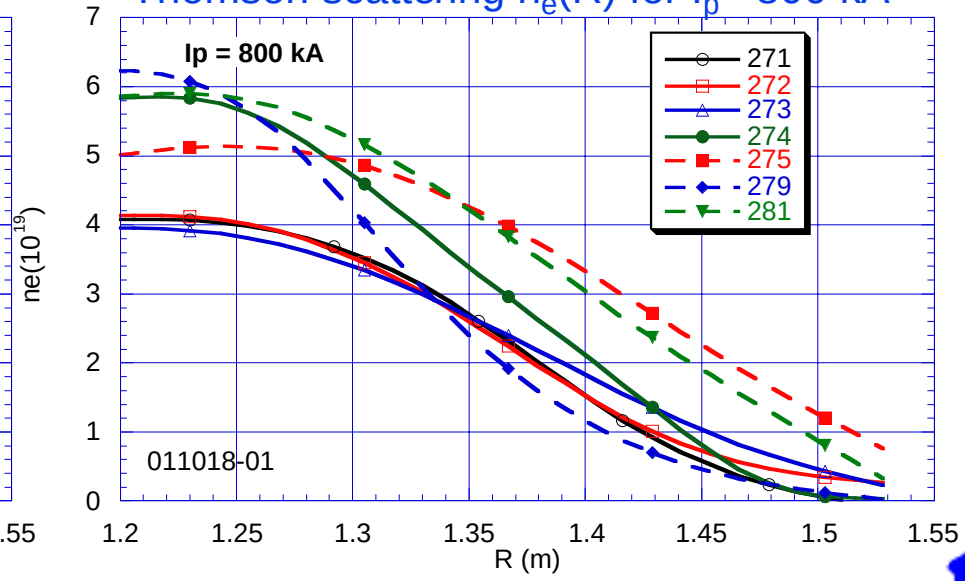
General conditions for pulsed-transmitter S-matrix measurements

- B_{tor} = 0.45 T
- Mixture of He and D_2
- I_p = 300 kA and 800 kA (corresponds to B-field pitch angles of ≈ 18° and 35°)
- n_0 = 1.5 – 4.5 x 10^{19} m^{-3} (300 kA shots) or 4 - 6 x 10^{19} m^{-3} (800 kA shots)
- Scanned "outer gap" (from EFIT magnetic equilib. code) to obtain data for different plasma profiles near the antenna

Thomson scattering $n_e(R)$ for I_p = 300 kA



Thomson scattering $n_e(R)$ for I_p =800 kA



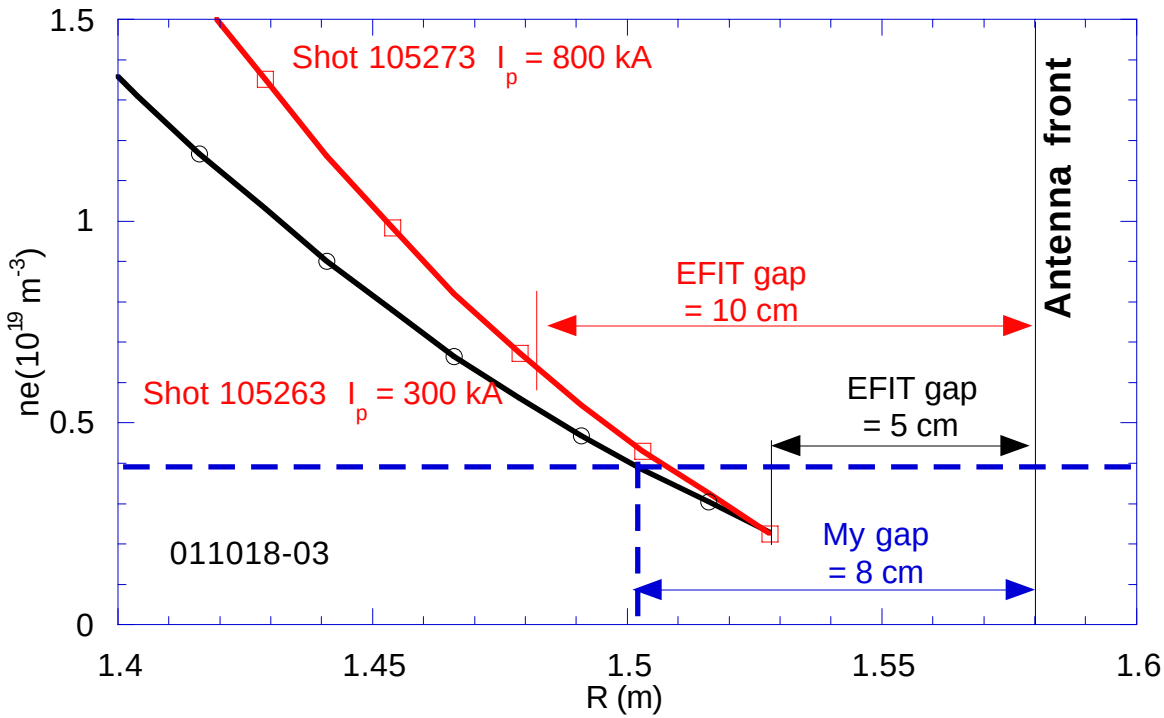
Outer gap used in our rf analysis is different from EFIT outer gap

EFIT magnetics equilibrium code definition:

- "Outer gap" = distance from antenna to last closed flux surface
- But different current plasmas will have very different "gaps" even though density profiles (which counts for rf) may be very similar.
- This is not a good variable for rf loading studies

Definition of "outer gap" used in this analysis:

- Distance from antenna to location where $n_e = 0.4 \times 10^{19}\ m^{-3}$



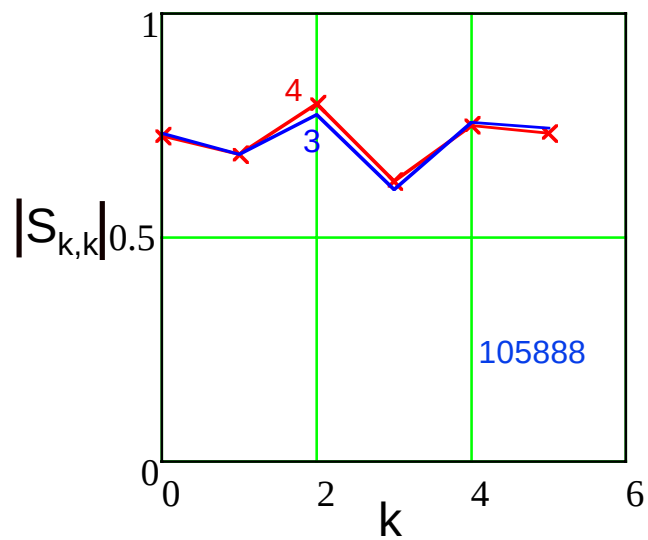
Density profiles from Thomson scattering for 300 and 800 kA shots (courtesy of TS group)

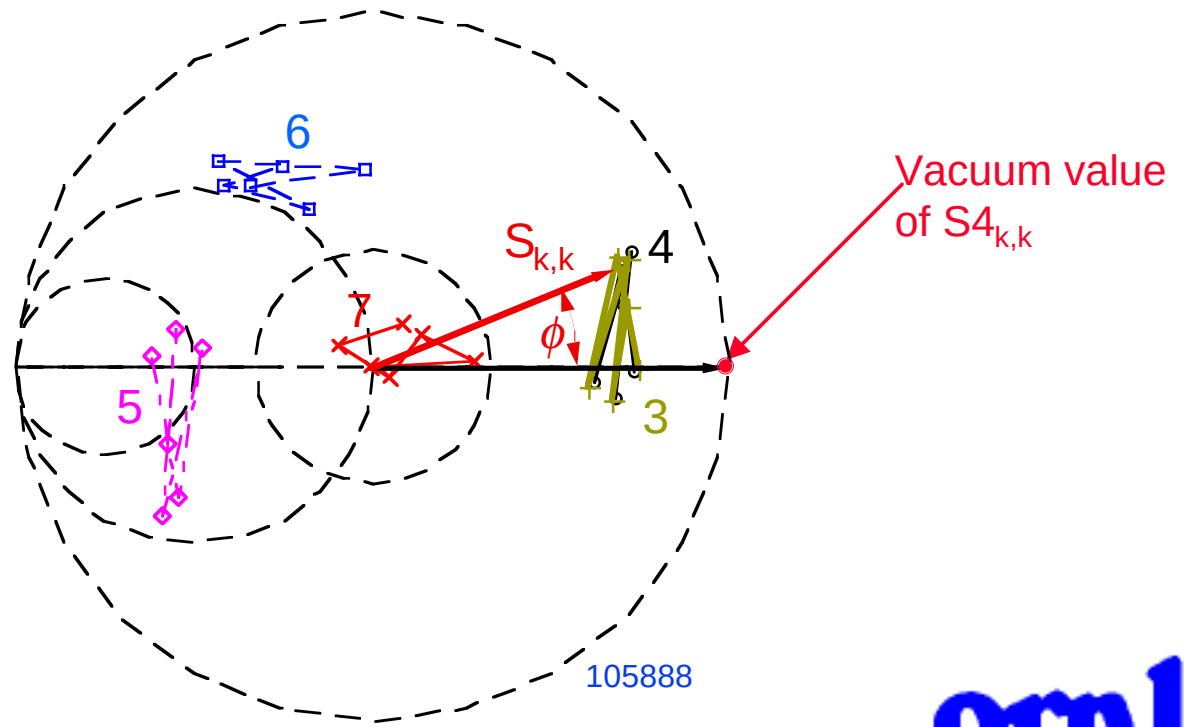
Results: behavior of diagonal components of S-matrix

$S4_{k,k}$ behaves about as expected qualitatively

- Each shot gives 6 values for $S4_{k,k}$, one for each of the six transmission lines
- Plasma presence drops magnitude of diagonal terms to between 0.5 and 1.
  - Magnitude gives plasma loading resistance R.
  - Magnitudes are the same to within experimental error bars
- Presence of plasma also rotates angle of $S4_{k,k}$ some angle ϕ, usually between 0° and 45°, depending on plasma parameters.

Meas. $|S_{11}|$ for each of the six transmission lines vs. line number, at line locations 3 and 4





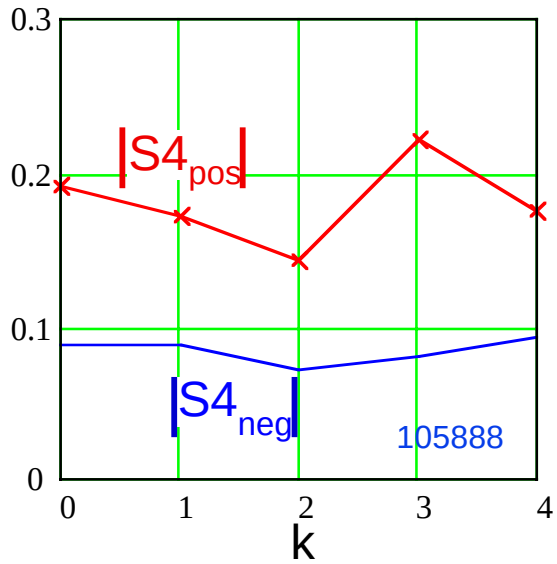
Off-diagonal terms show significant asymmetry

S4 between adjacent loops (looking *into* antenna loops and decouplers) –

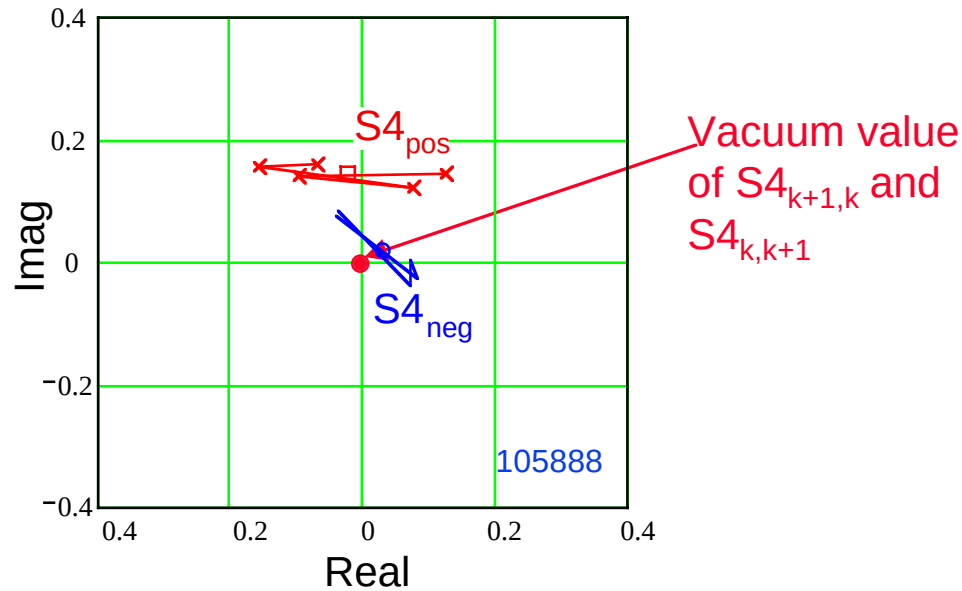
- In vacuum, S4pos = S4neg ≈ 0 + 0*j* (decouplers are set to make this so)
- Plasma *reduces* inter-strap coupling, particularly in positive direction

$S4pos_k$ is coupling *from* loop k *to* loop k+1
$S4neg_k$ is coupling *from* loop k+1 *to* loop k

$|S_{pos}|$ and $|S_{neg}|$ vs. line number, at location 4 on transmission line



S_{pos} and S_{neg} at location 4 on transmission line plotted in complex plane

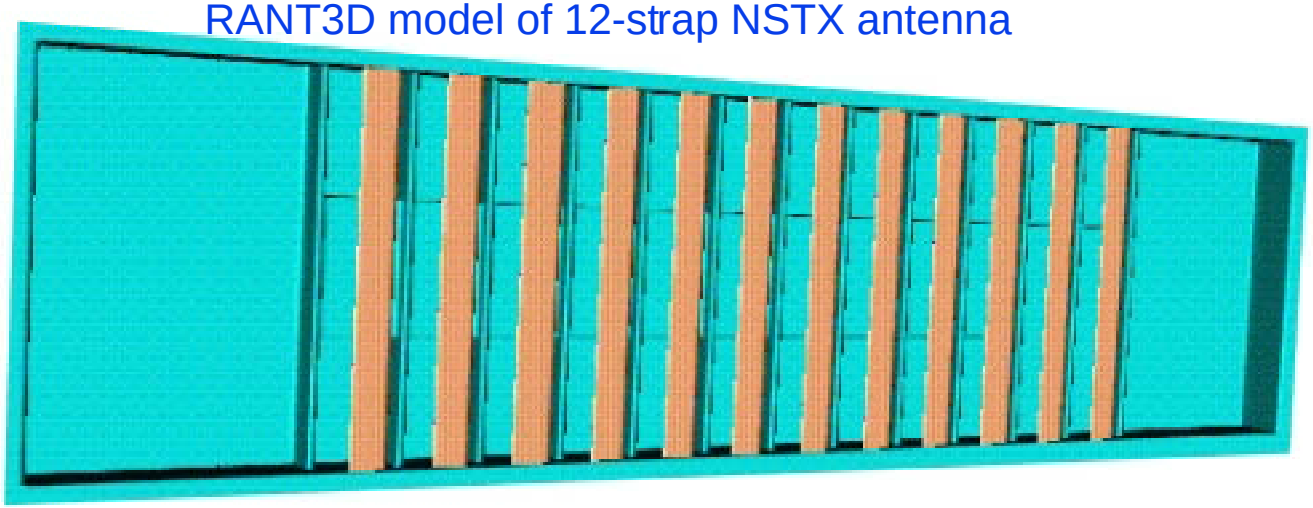


Note: Since off-diagonal terms are substantially smaller than on-diagonal terms, small errors have greater effect and cause larger scatter in inverted matrix values.

Calculation of S-matrix using RANT3D

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

Carter has generalized RANT3D to calculate "impedance matrix"

Skip this unless you're REALLY interested in gory details!

- 1. Set up coupled antenna structure in RANT3D, with multiple current straps.
- 2. Run GLOSI to compute the plasma input impedance in Fourier space at the plasma "boundary", given density profiles and magnetic field profiles and angles.
- 3. Specify the currents on each strap, and assume that they are UNIFORM poloidally, (v_{phase} infinite).
- 4. Run RANT3D to calculate the electric fields E everywhere, in particular at the strap locations.
- 5. Define the power from each strap to be $P_k = 0.5 \int (E \quad J_k)$, where the integral is taken over the strap height. Because of the assumption that J is uniform poloidally, this can be written $P_k = 0.5\, J_k \int (\sum E_{kj}) = 0.5\, J_k\, (\sum Z_{kj} J_j)$
- 6.By carrying out the calculation of P_k for special cases, the Z matrix can be evaluated:
  - Set only one current non-zero, so $P_k = 0.5\, Z_{kk}\, J_k^2$ gives the diagonal terms of Z.
  - Set only two currents non-zero, so $P_k = 0.5\, (Z_{kk}\, J_k^2 + Z_{kj}\, J_k\, J_j)$, use Z_{kk} from above to subtract and obtain Z_{kj} for $k \neq j$.
  - Repeat above for all pairs of currents.

RANT3D computes asymmetric impedance matrix for 12 straps with plasma

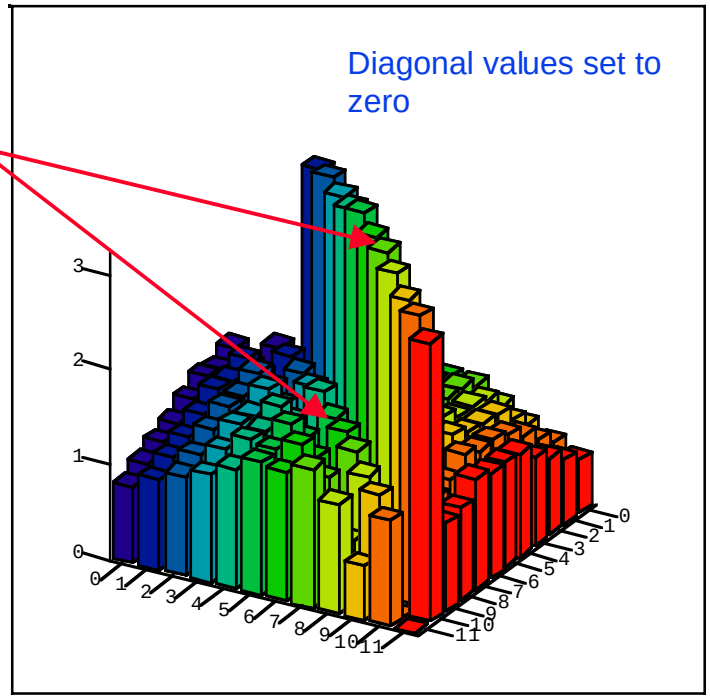
12 x 12 Z matrix –

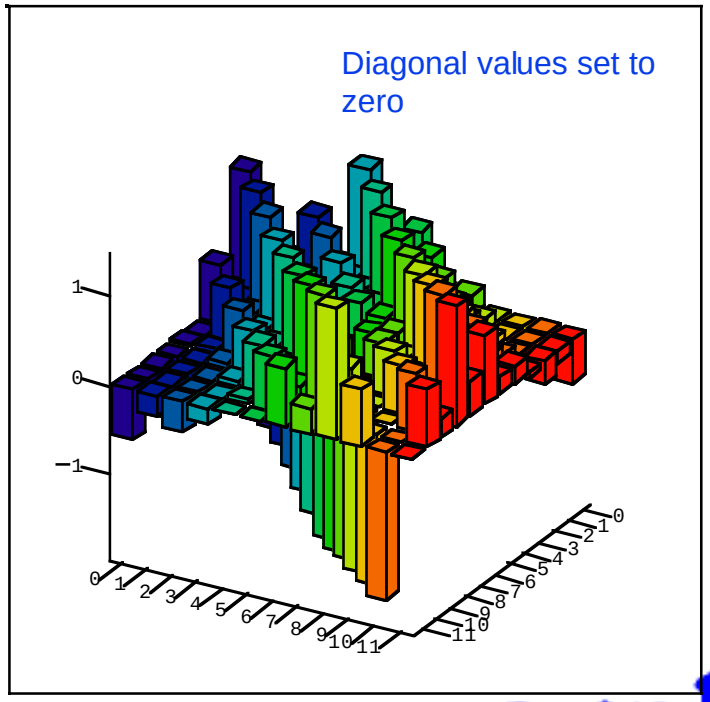
- Represents the impedance of a 12-antenna system.
- Completely describes the electrical properties of the antenna system in the presence of plasma.
- With no plasma Z matrix is symmetric. Large poloidal field causes asymmetry.
- Coupling between adjacent straps is changed significantly by plasma.

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

Note asymmetry of components next to diagonal!

Results are sensitive to density profile used in calculations.





The RANT3D results and a transmission line model are used to calculate the S-matrix to compare with measurements

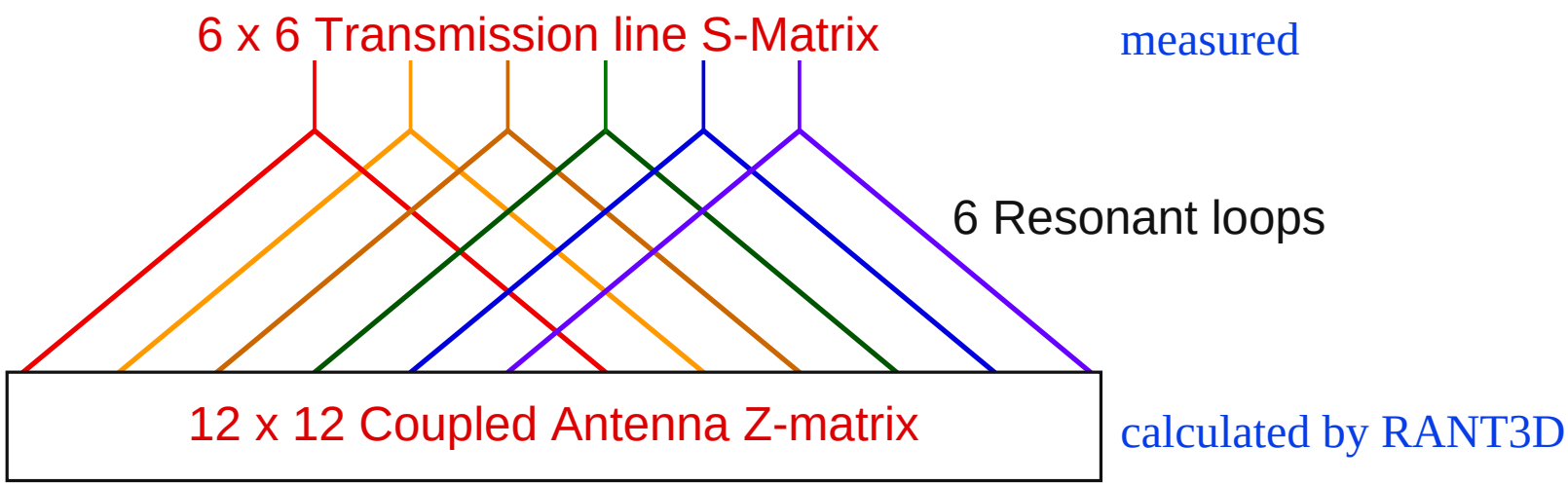
$$d\mathbf{V}/dx = \mathbf{Z'}\, d\mathbf{I}/dt$$

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

Coupled circuit equations

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

- Solve coupled circuit equations for resonant loops using 12 x 12 Z matrix from RANT3D to represent 12 antennas
- Calculate 6 x 6 S-matrix S4 for six transmitter lines to compare with measurements



Comparison of measurements and calculations:
for diagonal components of S4

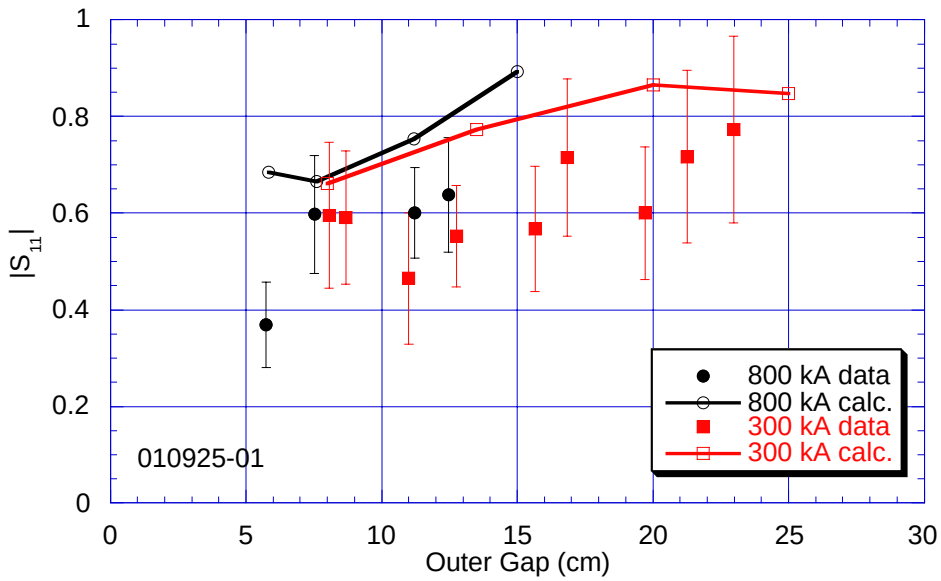
Magnitude of $S4_{k,k}$ –

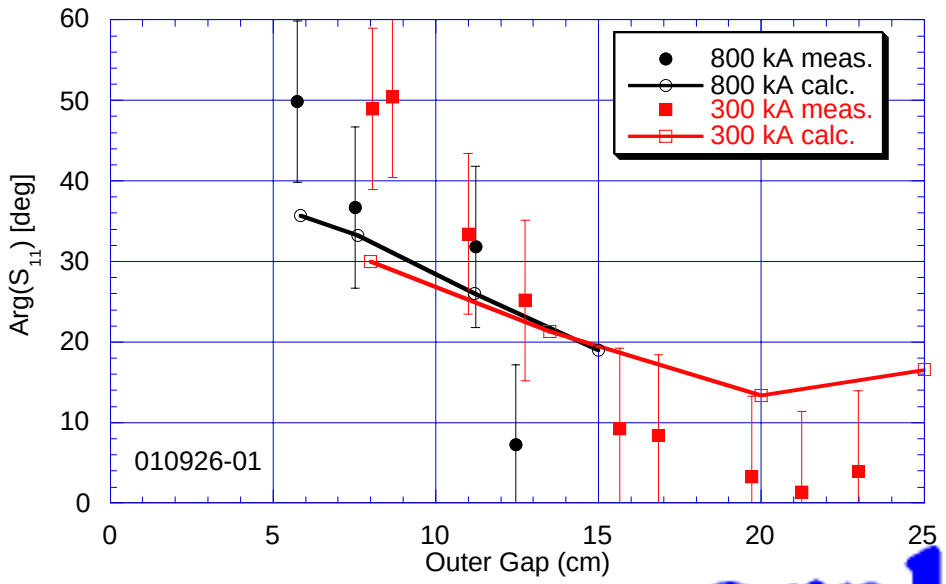
- Increases as gap increases (=> lower plasma loading at larger gap, as expected)
- No significant variation with I_p (=> density profile is main determinant of loading)
- Modeling gives higher values than data, especially for large gaps

Angle of $S4_{k,k}$ –

- Increases as gap decreases (=> lower strap self-inductance as plasma gets nearer)
- No significant variation with I_p

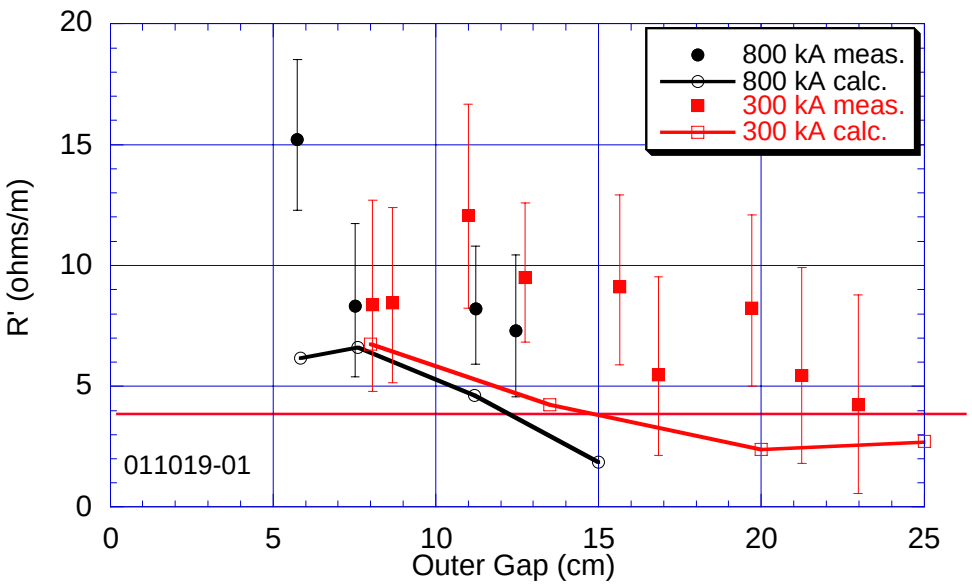
Reasonably good agreement between measurements and calculations of $S_{k,k}$





Plasma loading (R') is adequate to couple full power to plasma

R' = resistive loss/length (ohms/m) needed in current strap to give meas. (or calc.) value of $S4_{k,k}$ (conventional parameter to compute for plasma loading)



RF system design criterion:
Deliver full power for R' = 4 Ω/m

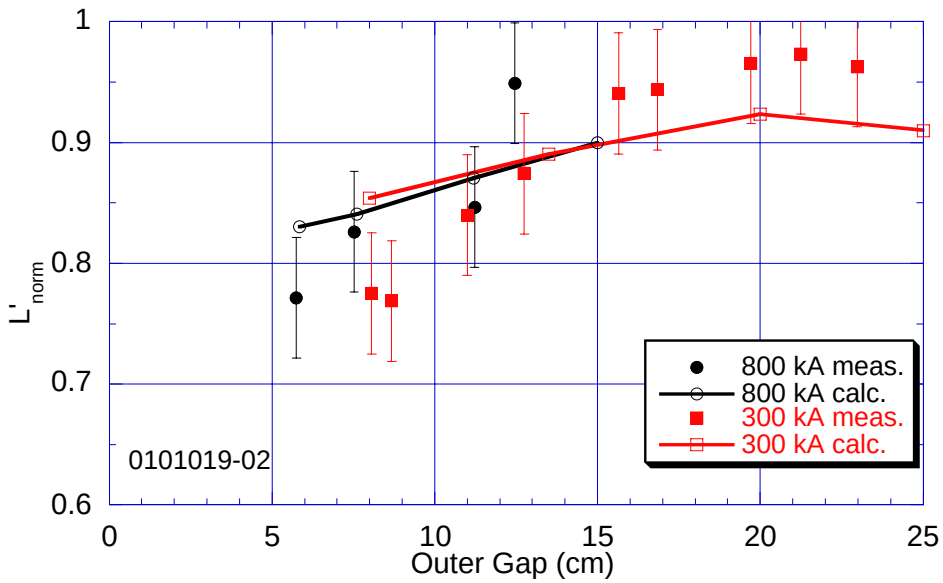
Meas. R' appears higher than calc., esp. at large gaps; error bars are large.

Actual loading is higher than system design requirements, allowing operation with lower voltages and currents in rf system.

Changes in strap self-inductance (L') from S-measurements

$L'_{norm} = L'/L'_{vac}$, where

- L' and L'_{vac} are the inductance/length (hy/m) in the presence of plasma and vacuum only, respectively



Results are about as expected; strap self-inductance decreases as plasma is moved closer to antennas.

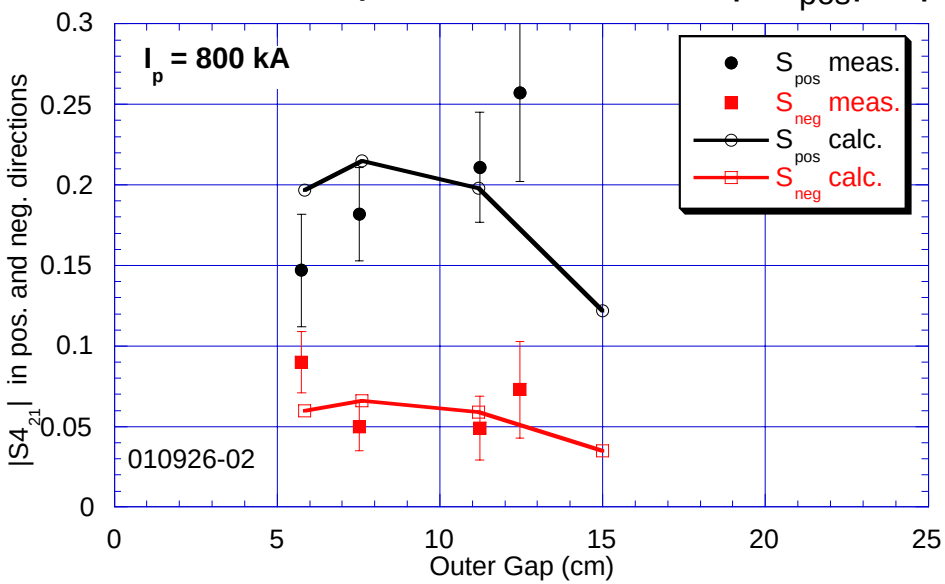
Comparison of measurements and calculations:
for off-diagonal terms

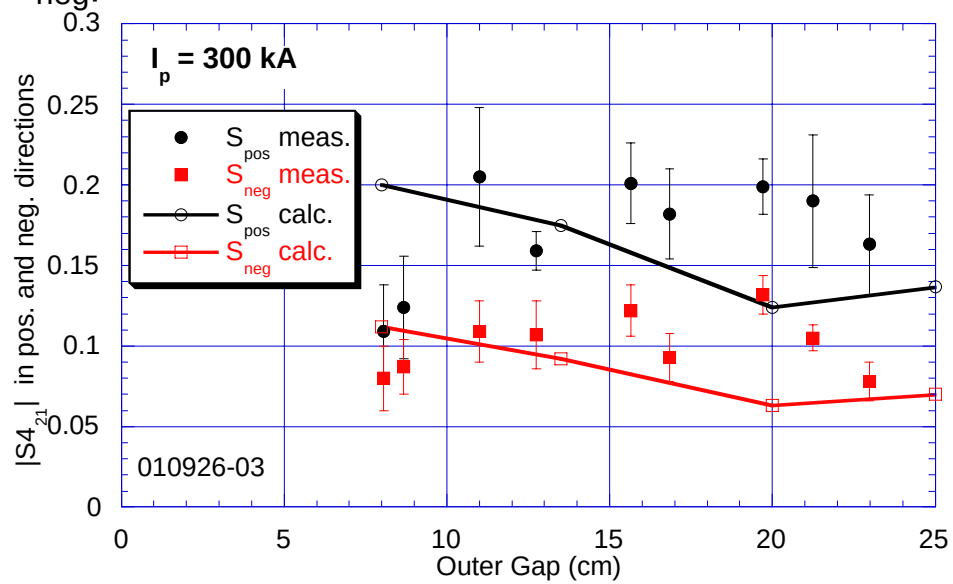
Asymmetry –

- Significant asymmetry observed and calculated
  - $S4_{pos} \approx 0.2$ for both 300 and 800 kA data
  - $S4_{neg} \approx 0.06$ at 300 kA, ≈ 0.11 at 800 kA

Behavior with outer gap

- Agreement for small gaps, but expect magnitude of S4 to decrease as gap increases (for vacuum case $|S4_{pos}| = |S4_{neg}| \approx 0$

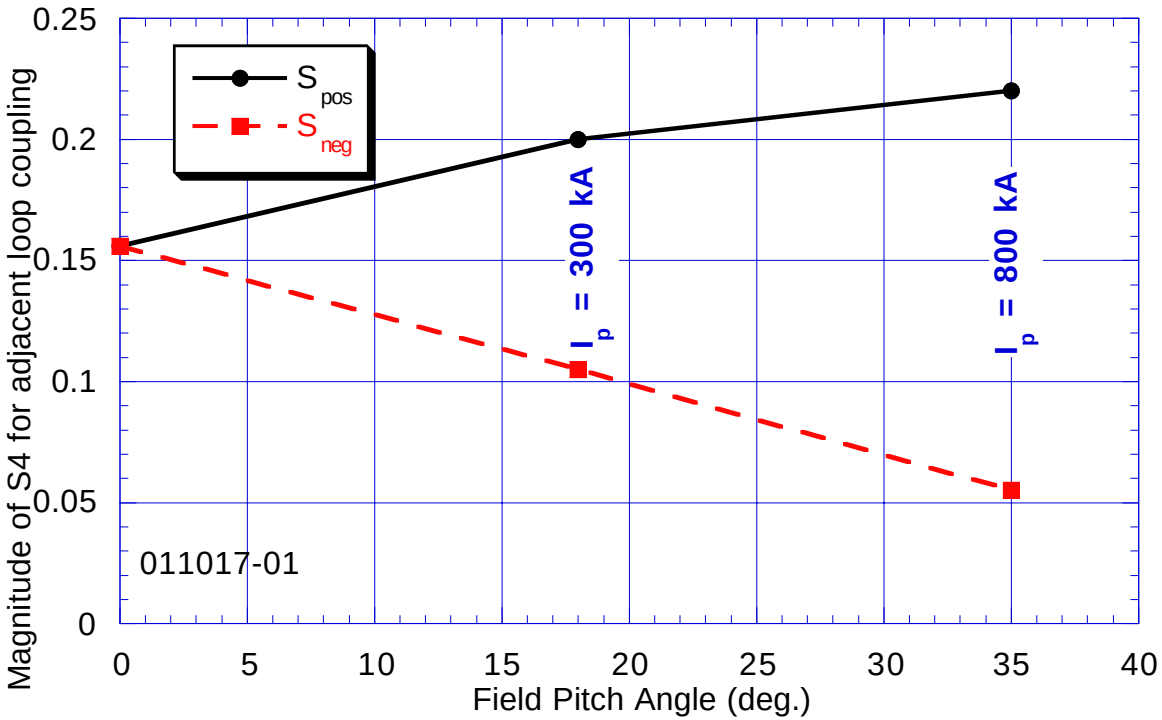




Calculated values depend sensitively on details of density profile, so difficult to get results that exactly match the measurements.

Asymmetry is caused by rotation of magnetic field

Plot shows RANT3D results for 8-cm gap. 300 and 800 kA points from preceding plots; 0° point is calculated by setting B_{pol}= 0 while increasing B_{tor} so that |B| remains constant.



Asymmetry is present in all tokamaks, but more pronounced in NSTX (and other ST's) because of large rotation angle of B.

Conclusions

NSTX provides a good test bed for rf physics in largely unexplored regimes.

We have measured (over a range of plasma conditions):

- Plasma loading and changes in antenna inductance.
- Asymmetry in antenna coupling caused by large pitch angle of B relative to antennas.

Experiments and theory are in reasonable agreement:

- Plasma loading measurements (e.g., R') are in approximate agreement with theory; measurements tend to be larger than calculations.
- Changes in reactive part of impedance can be explained by change in self-inductance of current straps, also in agreement with theory.
- Coupling between adjacent antennas observed to exhibit strong asymmetry. This agrees with calculations of asymmetry from RANT3D/GLOSI codes.

Results provide increased confidence in our understanding of rf physics and rf system operation on NSTX.