Loading and Asymmetry Measurements on the NSTX ICRF System*

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What are we up to, and why?

NSTX HHFW system:

- Most complicated rf system on a fusion experiment (I think).
  - 12 current straps, 6 transmitters, strong mutual coupling among straps
- Plasma parameters differ from conventional tokamaks and stellarators
  - Low magnetic field, high harmonic heating ($\omega/\omega_c \approx 10$ for present experiments)
  - High magnetic field pitch angle ($\geq 45°$)
- So new, interesting physics regime to study rf heating and coupling

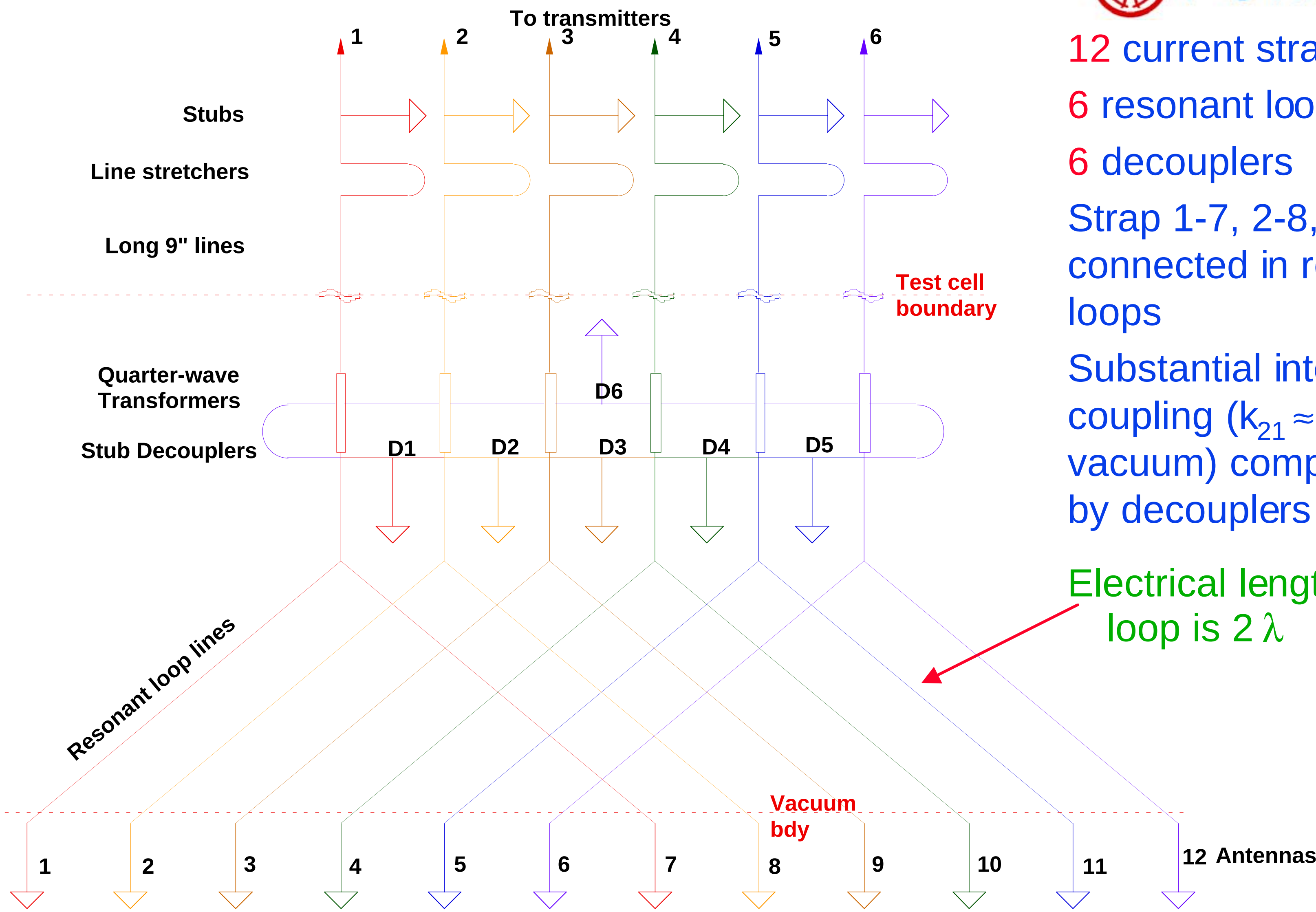
We want to understand how the plasma affects the rf system:

- 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

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



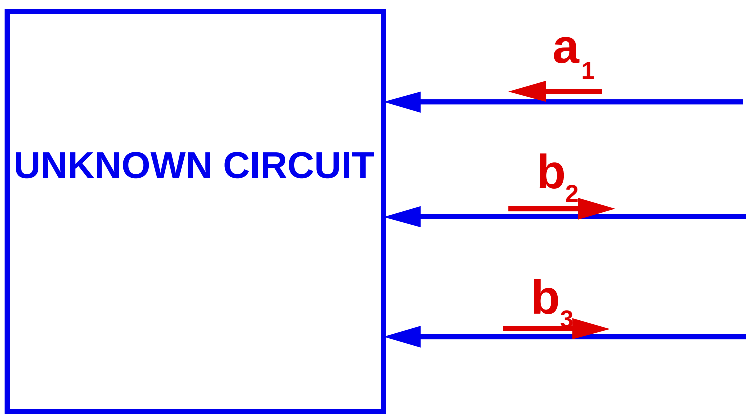
- 12 current straps
- 6 resonant loops
- 6 decouplers
- Strap 1-7, 2-8,... connected in resonant loops
- Substantial inter-strap coupling ($k_{21} \approx 0.1$ in vacuum) compensated for by decouplers

Electrical length of each loop is 2λ

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

The S-matrix is the scattering matrix of an unknown 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?

1. Start with a given $\boldsymbol{a}$ vector, and measure the response (the $\boldsymbol{b}$ vector)

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

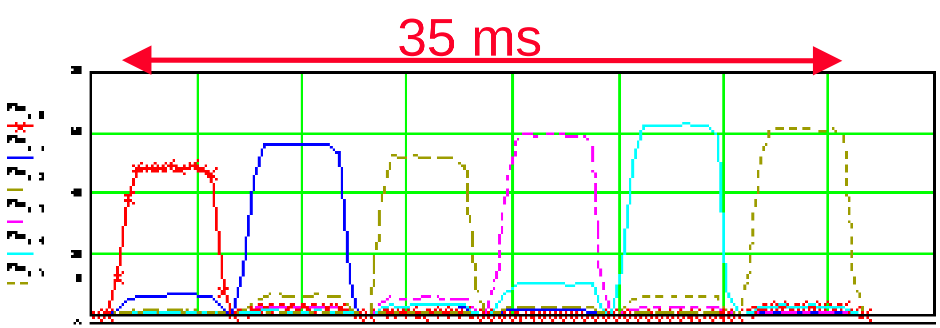
2. Do this for six *linearly independent* $\boldsymbol{a}$ vectors, combine to make a 6 x 6 A matrix and B matrix.

$$B = S \cdot A$$

3. Since the $\boldsymbol{a}$ vectors are independent, the inverse of A exists, so

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

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



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

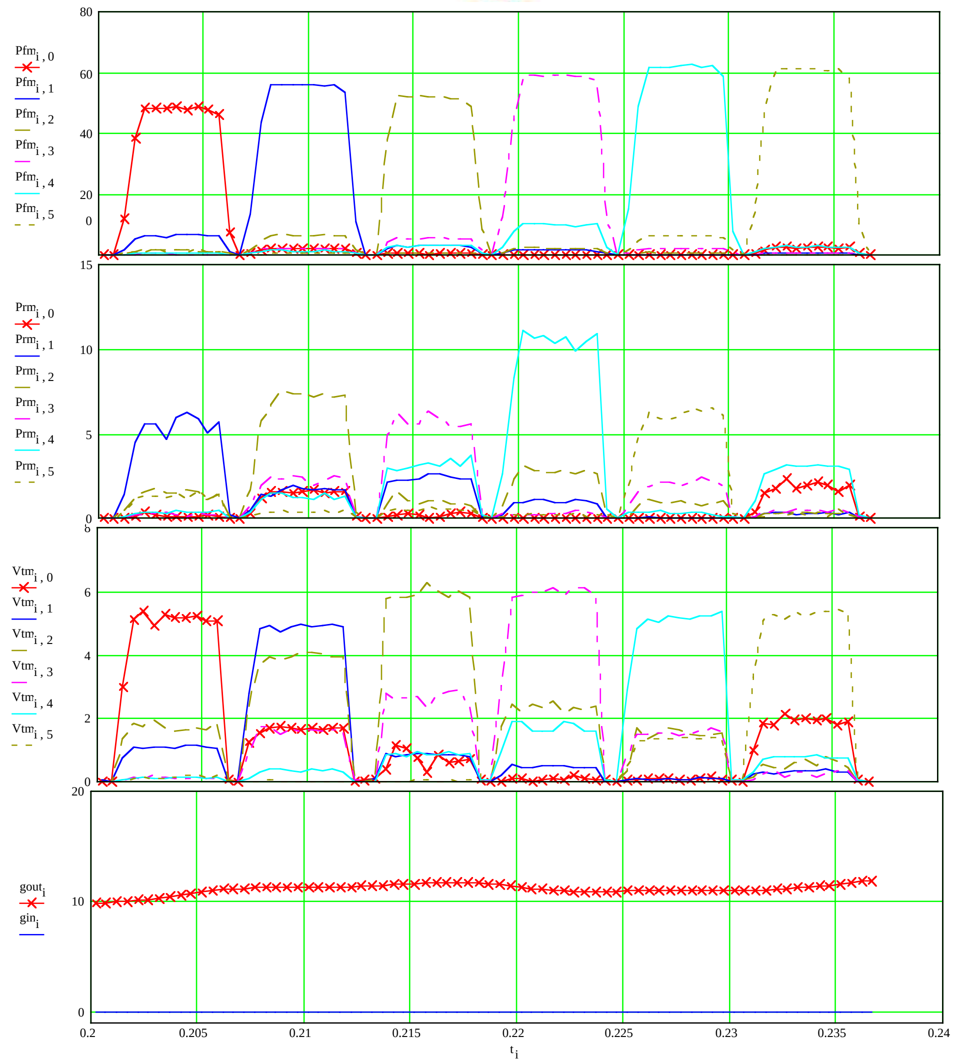
What do we measure?

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]

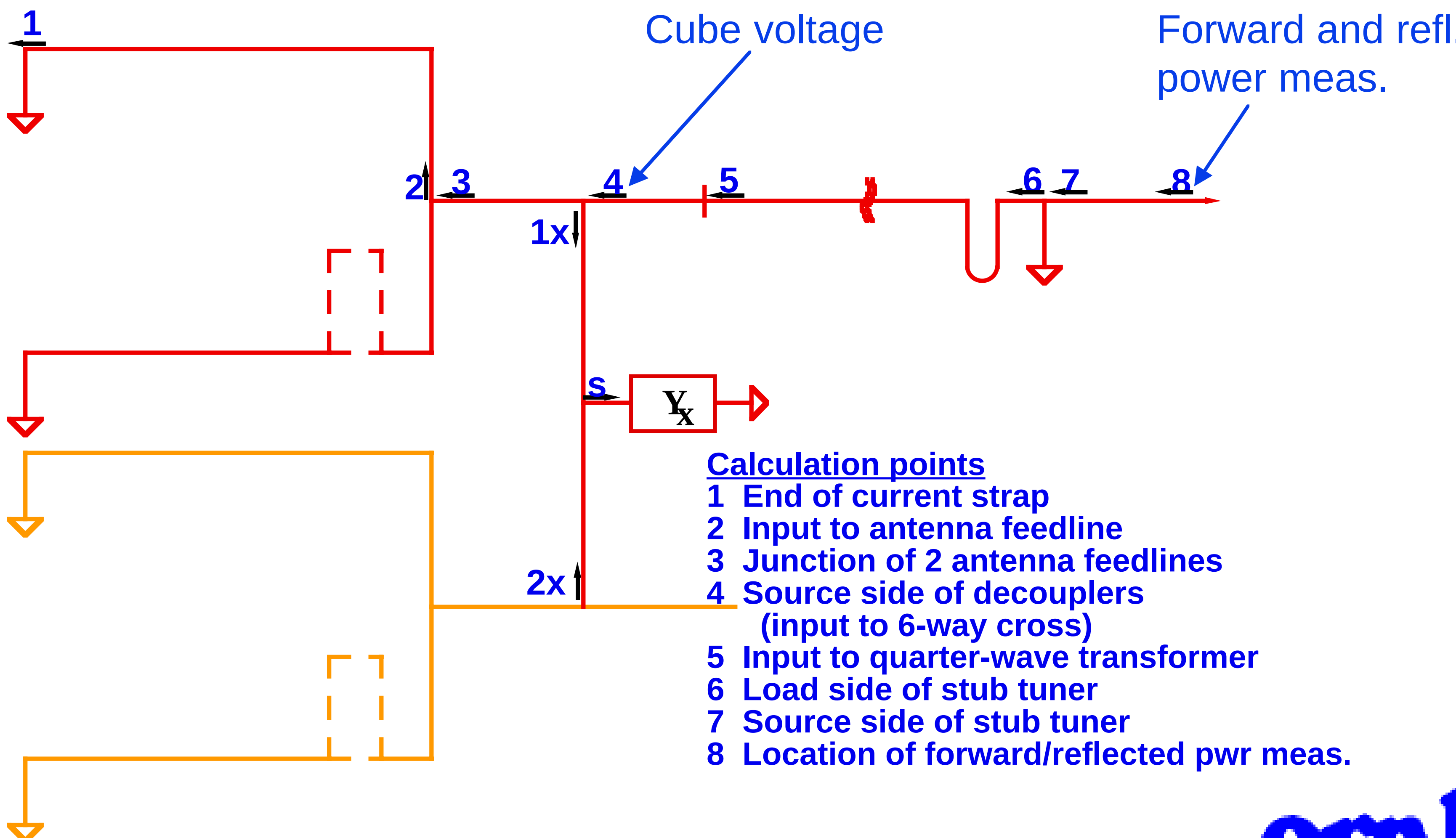
Inner and outer gaps (cm)
[distance of plasma separatrix from inner and outer limiters]



S-matrix is calculated at different places in rf system

From measured quantities, can calc. ***a*** and ***b*** voltage vectors at points 4 - 8.

Will discuss S4: S-matrix at input to resonant loop and decoupler circuit.



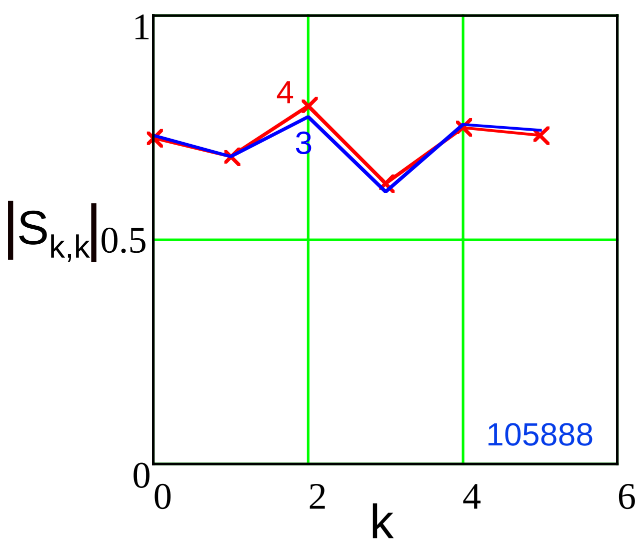
Calculation points

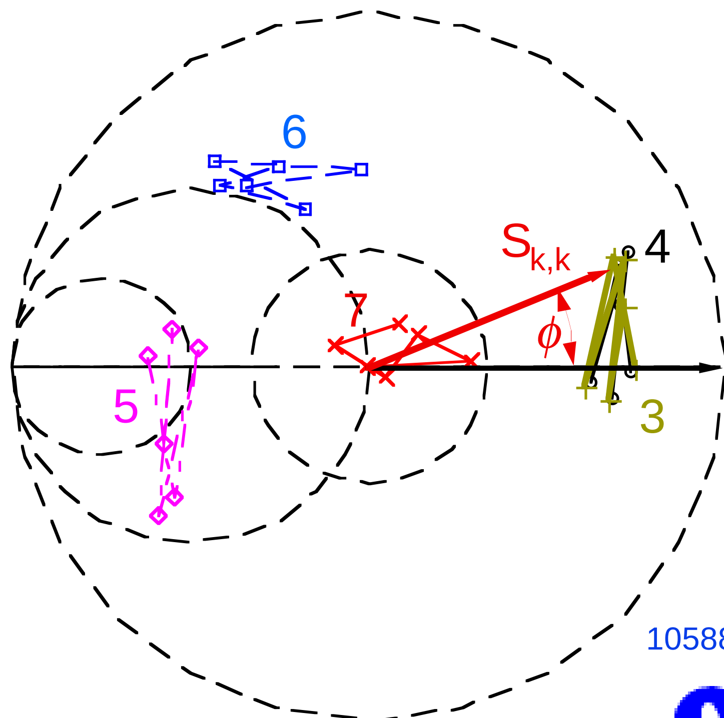
1 End of current strap
2 Input to antenna feedline
3 Junction of 2 antenna feedlines
4 Source side of decouplers (input to 6-way cross)
5 Input to quarter-wave transformer
6 Load side of stub tuner
7 Source side of stub tuner
8 Location of forward/reflected pwr meas.

Behavior of diagonal components of S matrix

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

- In vacuum, $S_{k,k} \approx 1 + 0j$
- 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 $S_{k,k}$ some angle ϕ, usually between 0° and 45°, depending on plasma parameters.

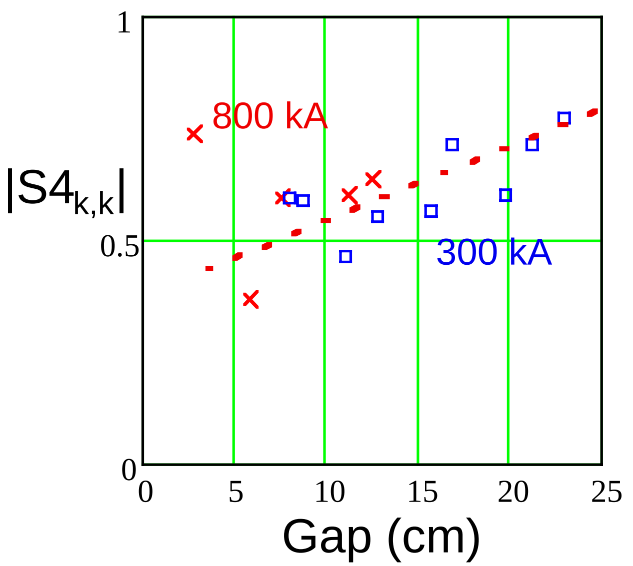


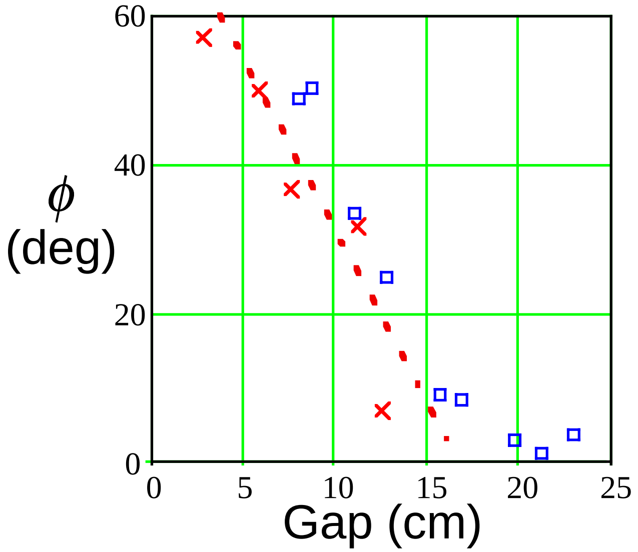


Changes of $S_{k,k}$ with plasma parameters

- $|S_{k,k}|$ decreases as gap decreases (in agreement with plasma loading increasing for smaller gap)
- Relatively independent of plasma current

- Rotation angle ϕ increases as gap decreases (in agreement with decreasing gap lowering self-inductance of current strap)
- Relatively independent of plasma current



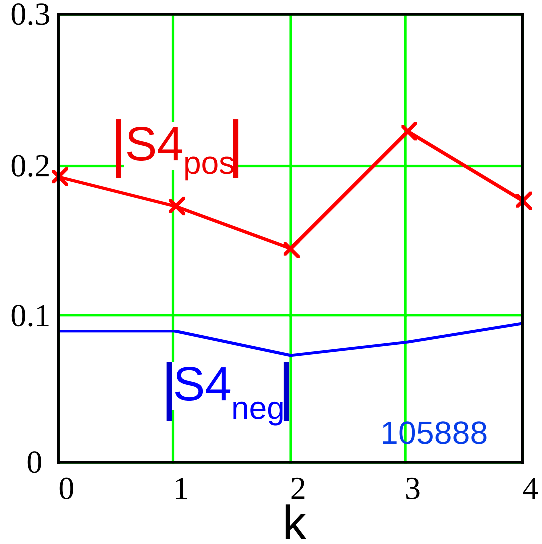


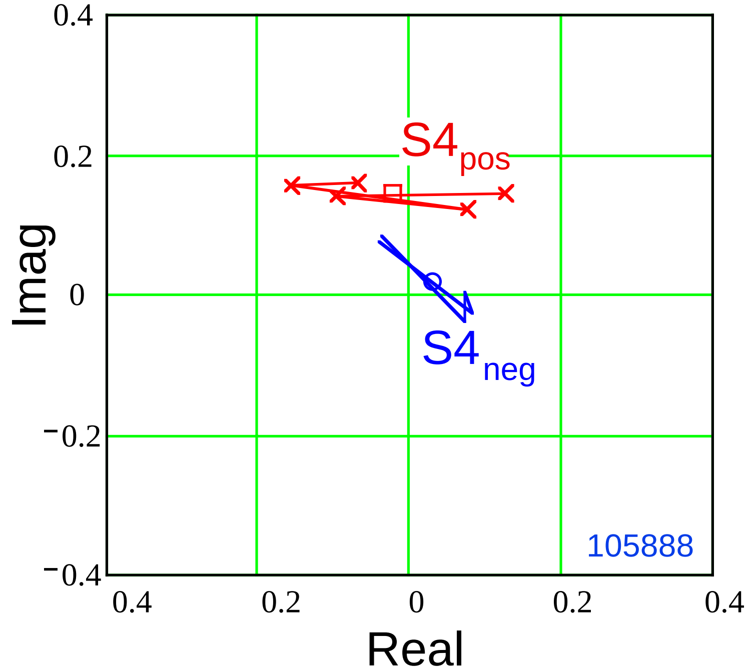
Behavior of off-diagonal terms

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

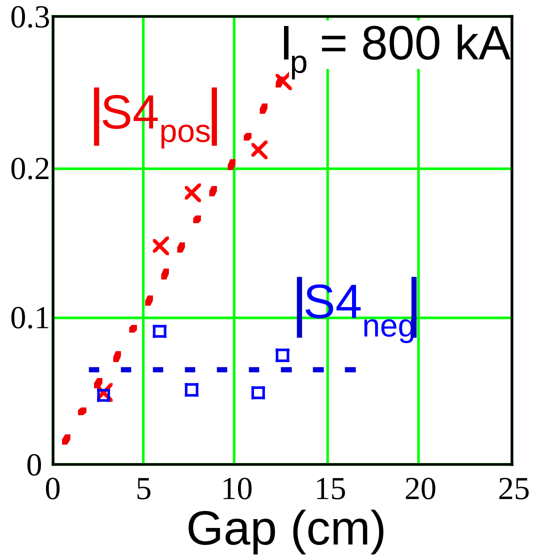




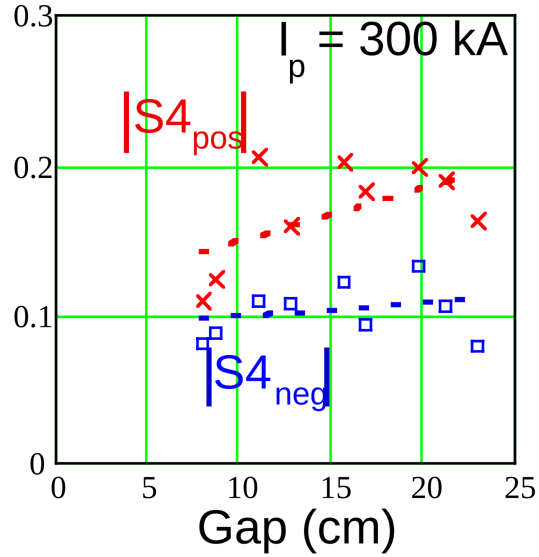
Note: Significant errors in calculation since off-diagonal terms are substantially smaller than on-diagonal terms, so small errors have greater effect.

Changes of off-diagonal terms with plasma parameters

- Inter-strap coupling asymmetry (ratio of $S4_{pos}$ to $S4_{neg}$) is larger for higher I_p
- Asymmetry increases as gap increases (at least for 800 kA shots)



For I_p = 800 kA, angle of toroidal field at antenna is ≈ 34°



For I_p = 300 kA, angle of toroidal field at antenna is ≈ 18°

Summary – progress has been made, still work to do

Qualitatively good agreement with expectations:

√ • Higher pitch angle of field line should give larger asymmetry (RANT3D calc.)

√ • Loading should increase as gap decreases

√ • Phase angle of diagonal terms should increase as gap decreases (self-inductance of current strap is lowered)

We observe asymmetry to increase as gap increases. Should it?

We're still working to compare *quantitatively* with RANT3D calculations.