NSTX

Modeling the Phase Control System for the NSTX High Harmonic Fast Wave Antenna Array

P. M. Ryan, M. D. Carter, D. W. Swain, R. H. Goulding

Oak Ridge National Laboratory

J. R. Wilson and R. Majeski

Princeton Plasma Physics Laboratory

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Outline

- HHFW Heating/Current Drive on NSTX
- Design and Analysis of the HHFW System
- Measurements On Mockup Array
- Measurements On NSTX Array
- Present Status of HHFW System

NSTX at Princeton Plasma Physics Laboratory

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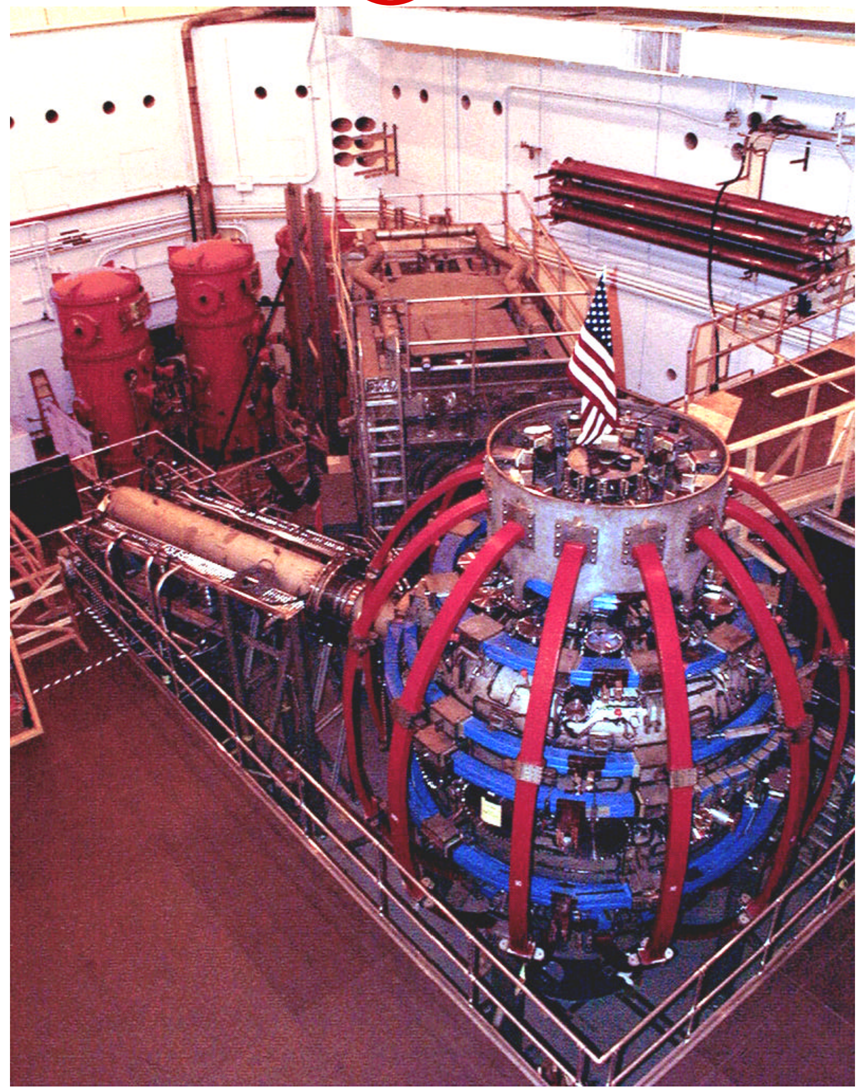
- NSTX is a spherical (small aspect ratio) tokamak (R_0 = 0.8 m, a/R_0 = 1.25).
- Low magnetic field (B_T = 0.32 T)
- High plasma current (I_p = 1 MA)
- High beta operation (β = 5–40%)
- RF auxillary heating needed to test β limits
- Electron heating and directional wave spectrum needed to extend pulse length and drive non-inductive plasma current s.
- The 30 MHz operating frequency corresponds to $5\omega_H$ or 10 ω_D (High Harmonic Fast Waves).
- Current drive efficiency needs directional wave spectrum → multi-element array.
- Phase control needed to match wave phase velocity to electron thermal velocity during plasma heating.



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Design Objectives and Constraints

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- **Objectives**
  - 12-strap array for current drive efficiency (directional spectrum)
  - Variable inter-element phasing (30°– 150°) during a shot
  - 30 MHz operation
  - 6 MW delivered to plasma (5% to 40% β)
  - Operation should be possible with fewer than six transmitters.
- **Constraints**
  - Use six existing transmitters
  - Limit voltage to ≤ 25 kV on straps, ≤ 35 kV on transmission lines
  - Loading may vary by factor of two during a shot

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HHFW Power Distribution System

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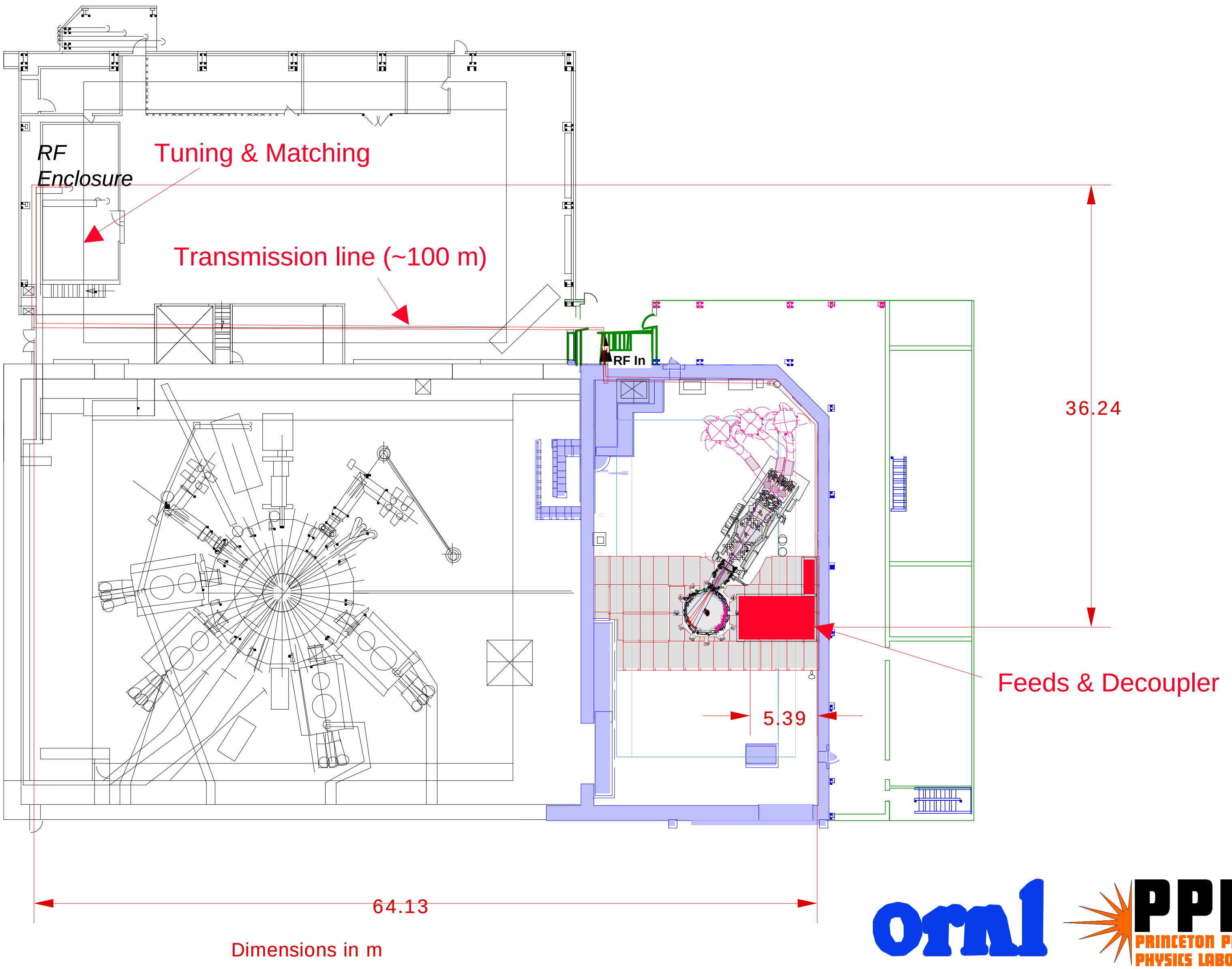

High Harmonic Fast Wave (HHFW) System Overview

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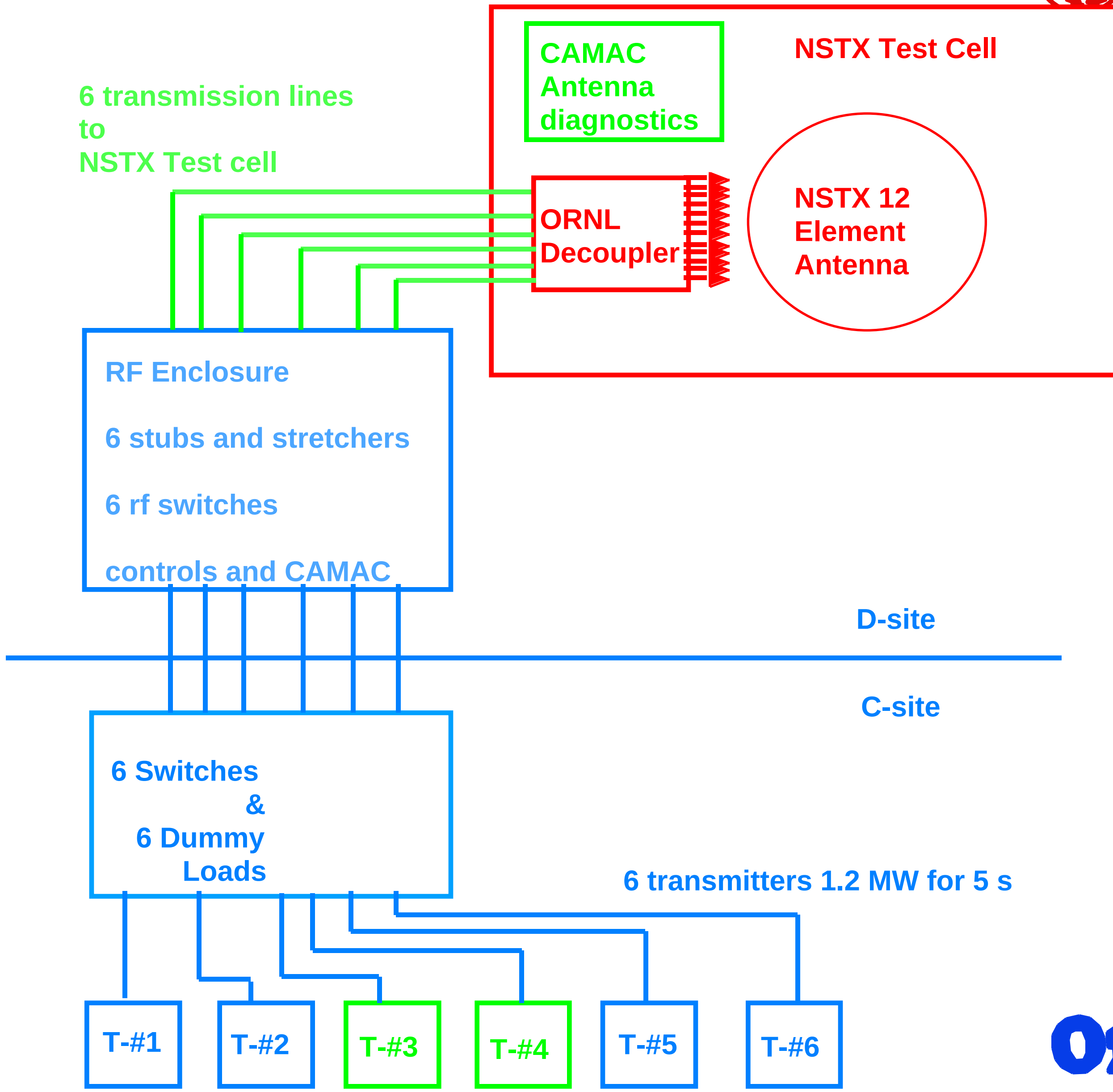

NEW

MOVED OR MODIFIED

INPLACE

HHFW System Design:
12 straps, 6 transmitters, 6 decouplers

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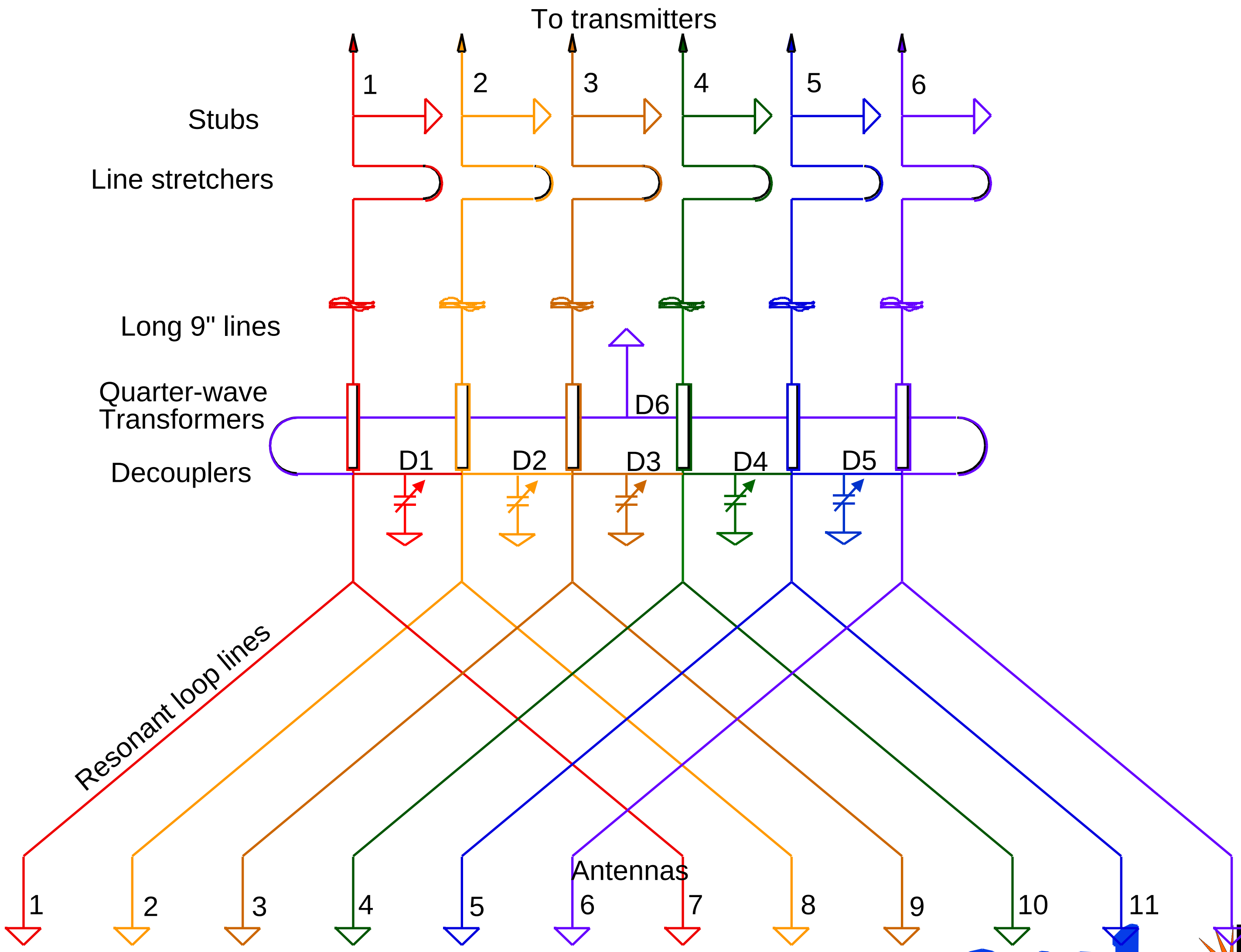

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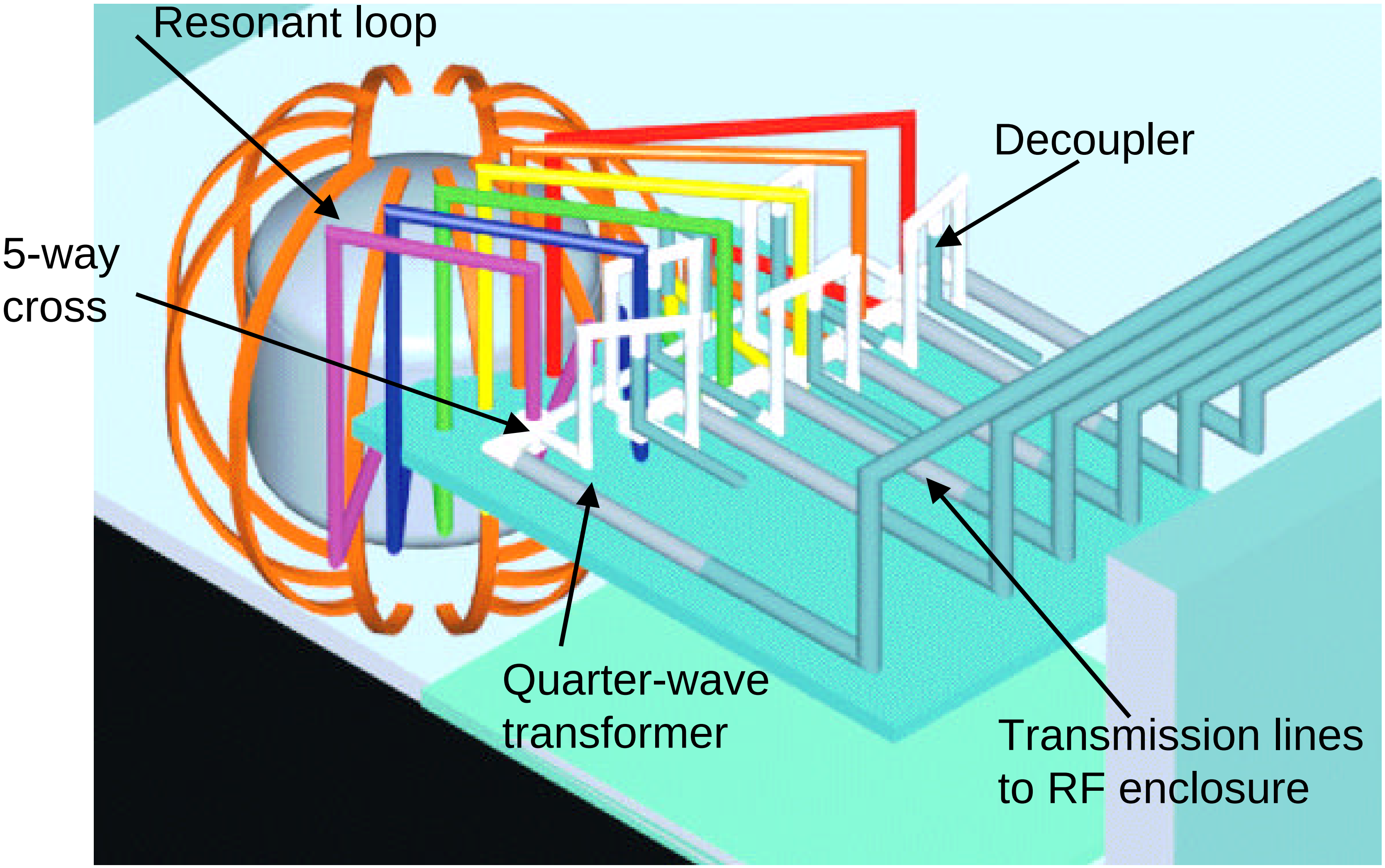
Layout of HHFW System



HHFW Power Transmission System

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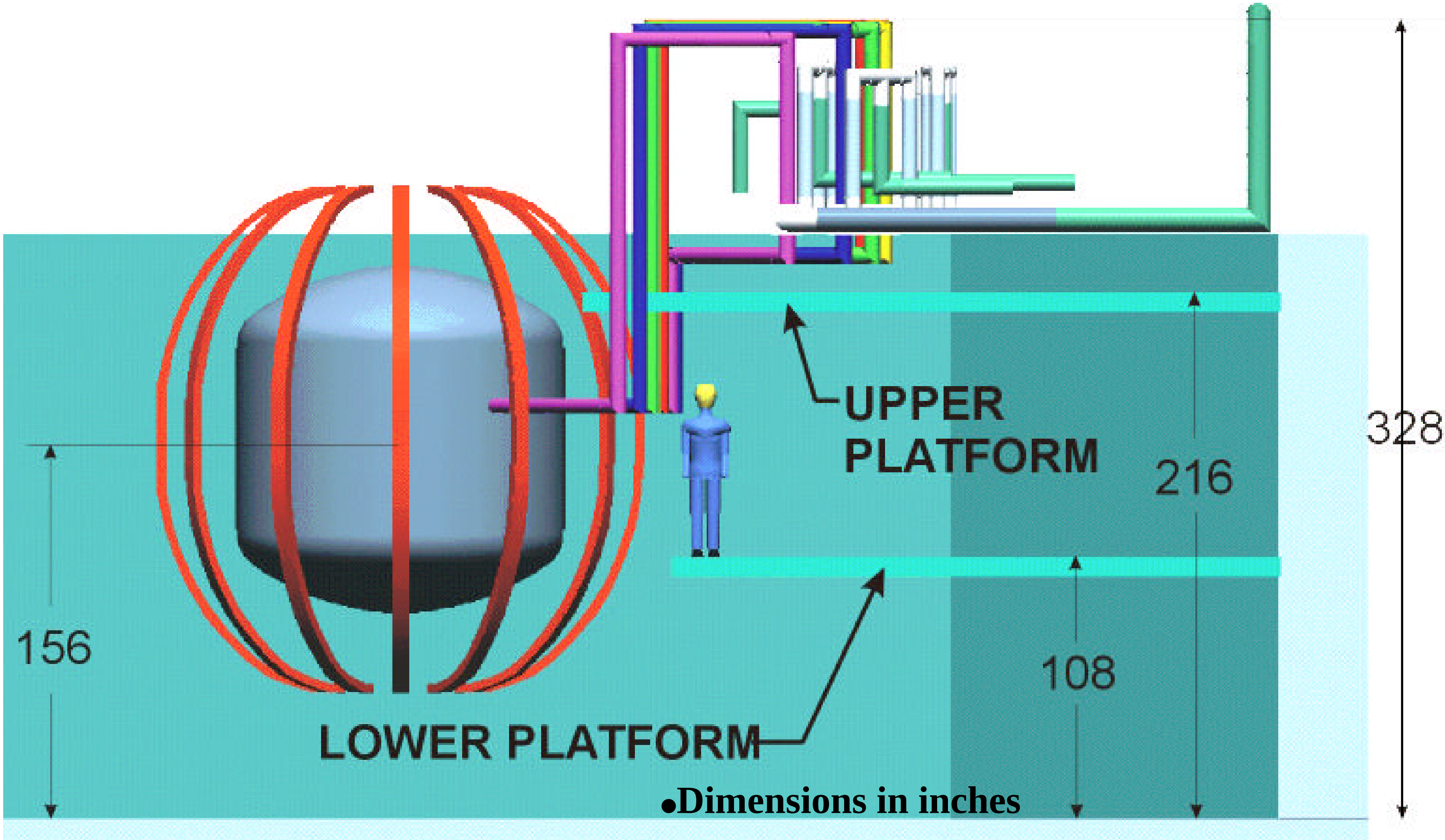
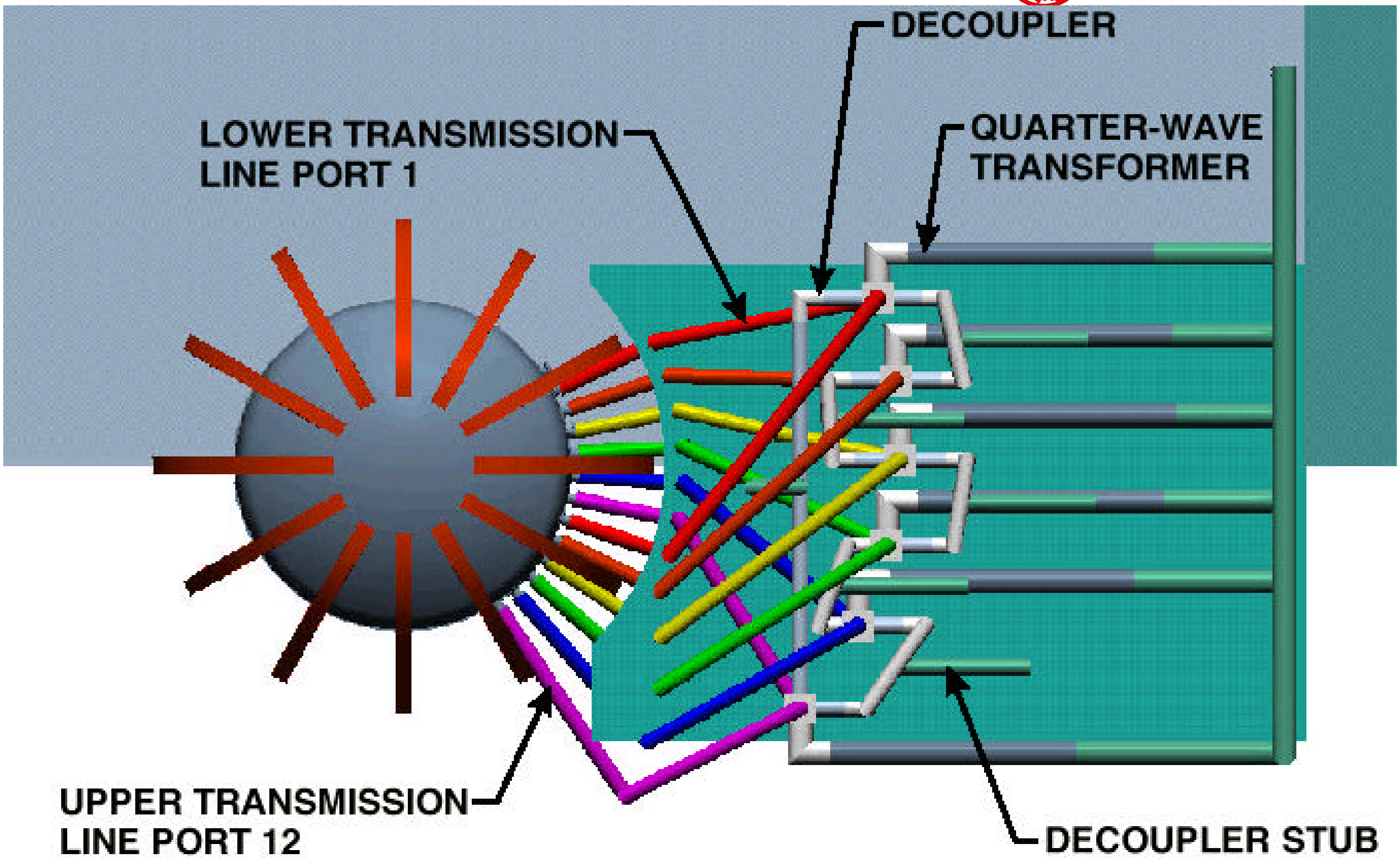


- Dimensions in inches

Top View Shows Resonant Loops



12-strap antenna array takes up almost 90° toroidally

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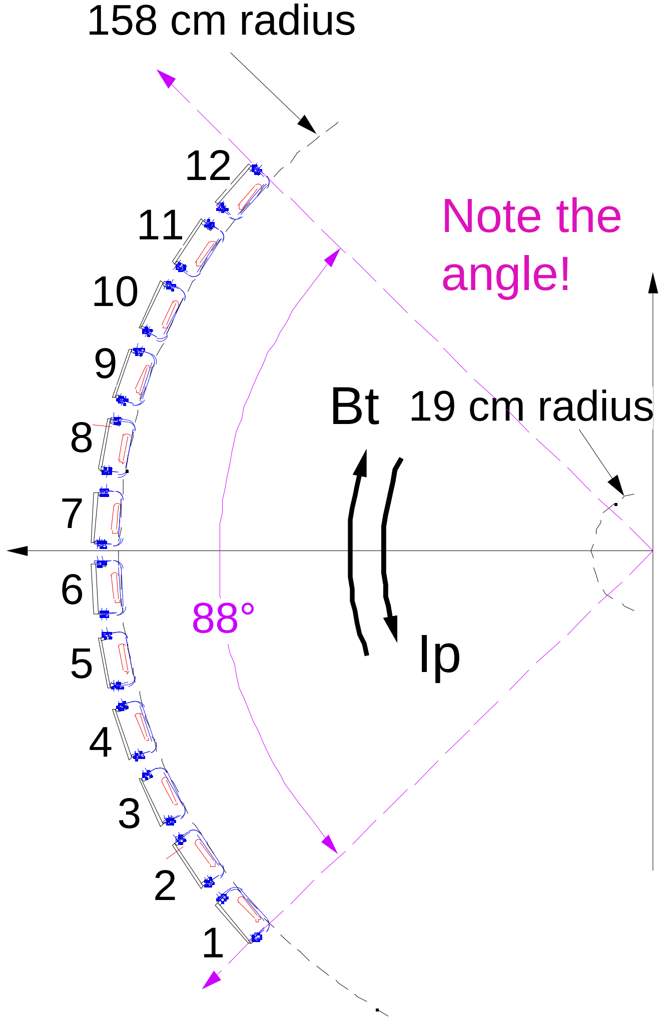
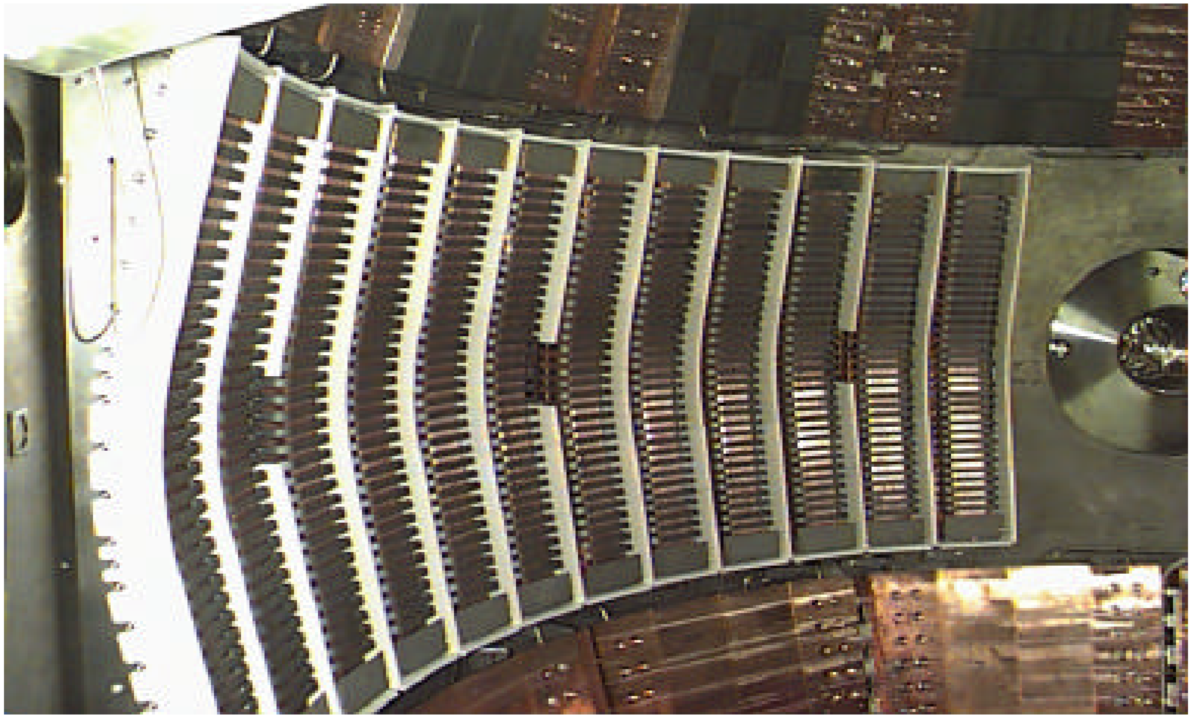
Cut through antenna midplanes, viewed from above



NSTX antennas installed in the vacuum vessel
B_4C limiters surround each antenna



Straps Modeled as Coupled Transmission Lines

Electrical Parameters from 2D Analysis

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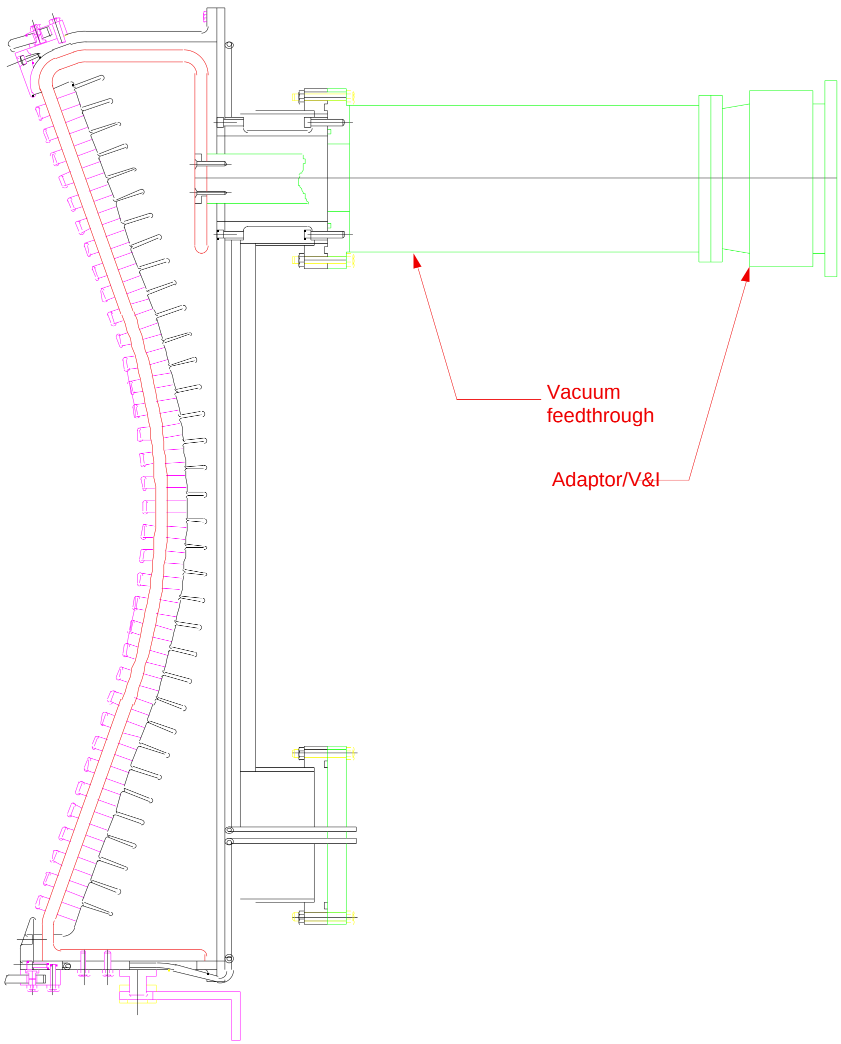

Z_0 = 27.5 Ω, L = 20 cm

Z_0 = 53 Ω
v_p = 0.52 c
k = 14%
L = 30 cm

Z_0 = 48 Ω
v_p = 0.57 c
k = 9%
L = 30 cm

Z_0 = 53 Ω
v_p = 0.52 c
k = 14%
L = 30 cm

Characteristic impedance (Z_0), phase velocity (v_p), and coupling coefficient (k) for each section of antenna strap

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System Operation: Voltages in system < 35 kV

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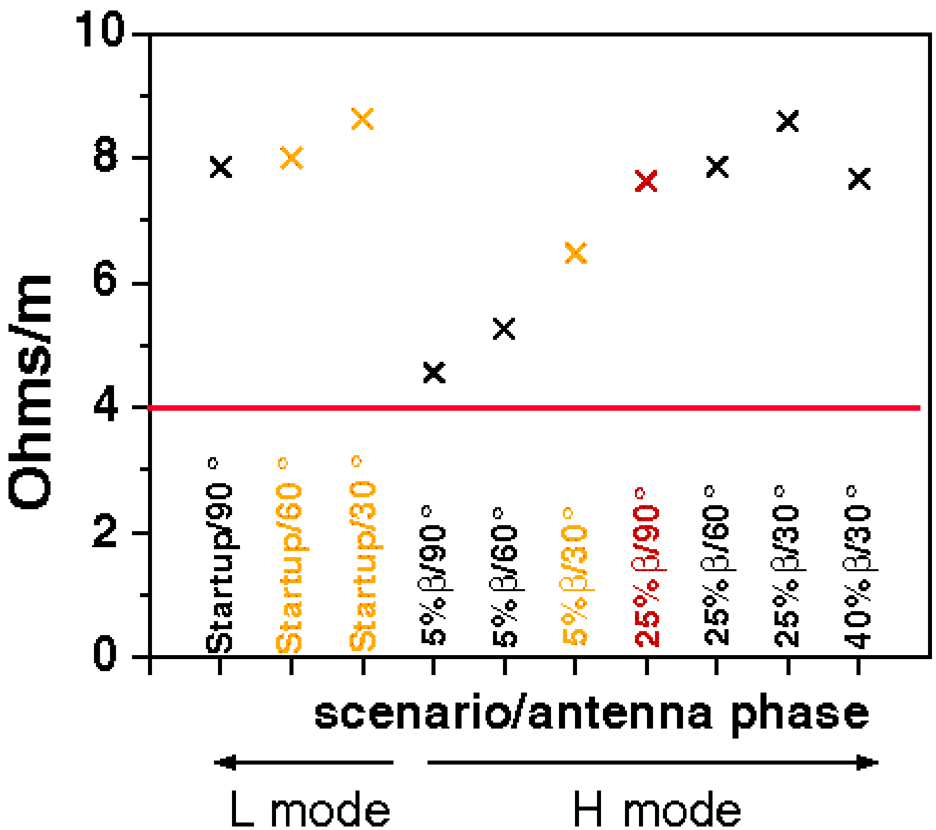
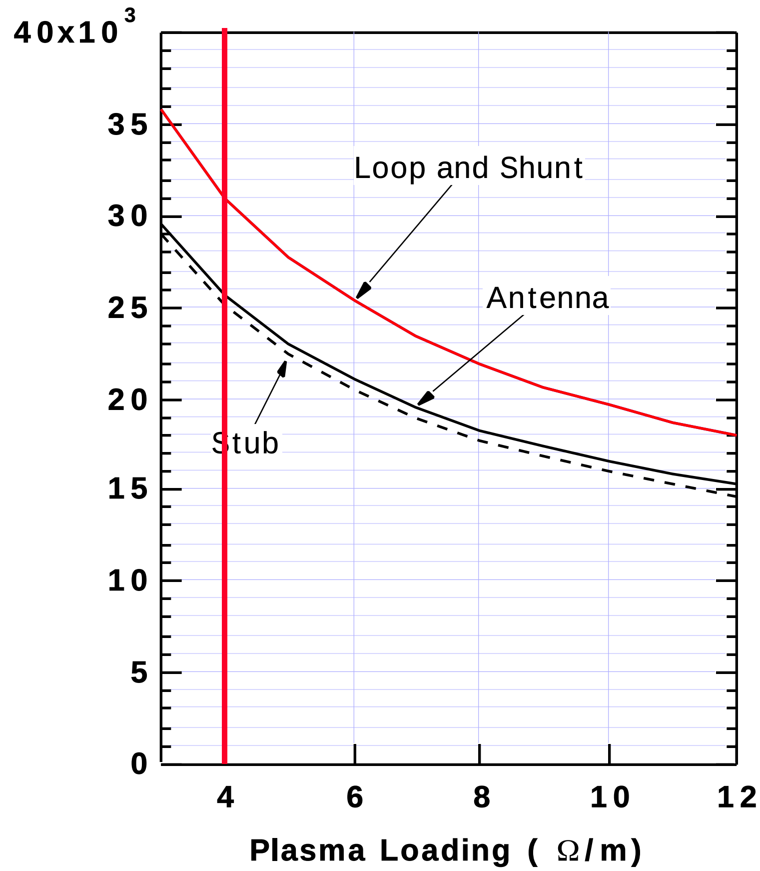
- Load resistance > 4 ohms/m for expected operating conditions
- Antenna voltage ≤ 25 kV





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Transmitters furnish equal power, ~ 50% of capability

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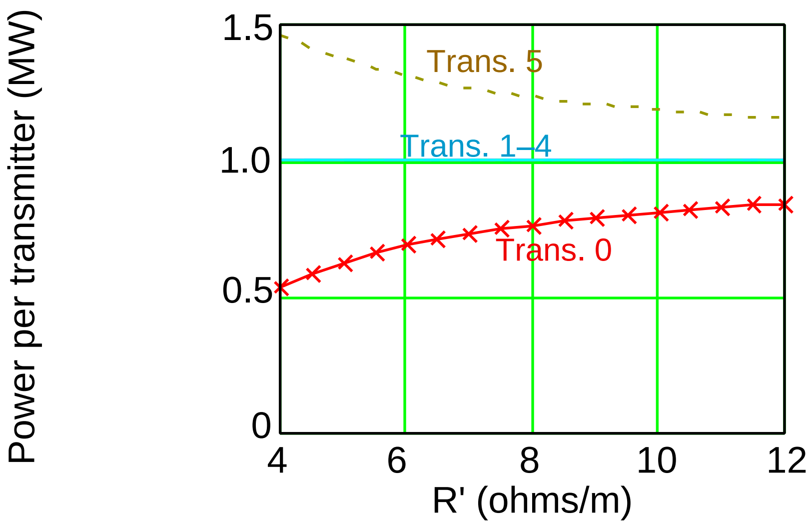
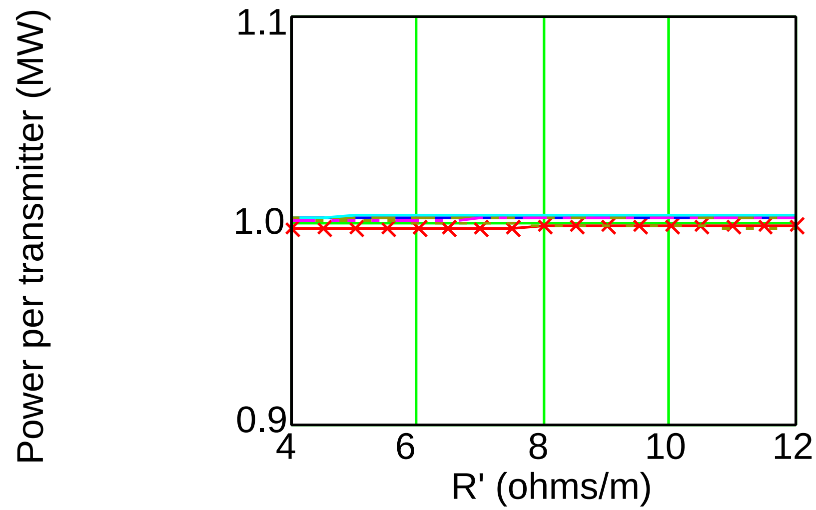
For interstrap phasing other than 0 or 180°, equal ***current*** (and voltage) in all resonant loops requires different ***power*** to each loop

One effect of decouplers is to balance the power from each transmitter

Power to six resonant loops to obtain equal currents in straps



Power from transmitters (showing effect of decouplers on power)



Interstrap phasing = 90° P_{total} = 6 MW

Each transmitter can deliver 2 MW into matched load.

1 MW/transmitter gives plenty of headroom and increases reliability.

Active phase control operation is possible with decouplers

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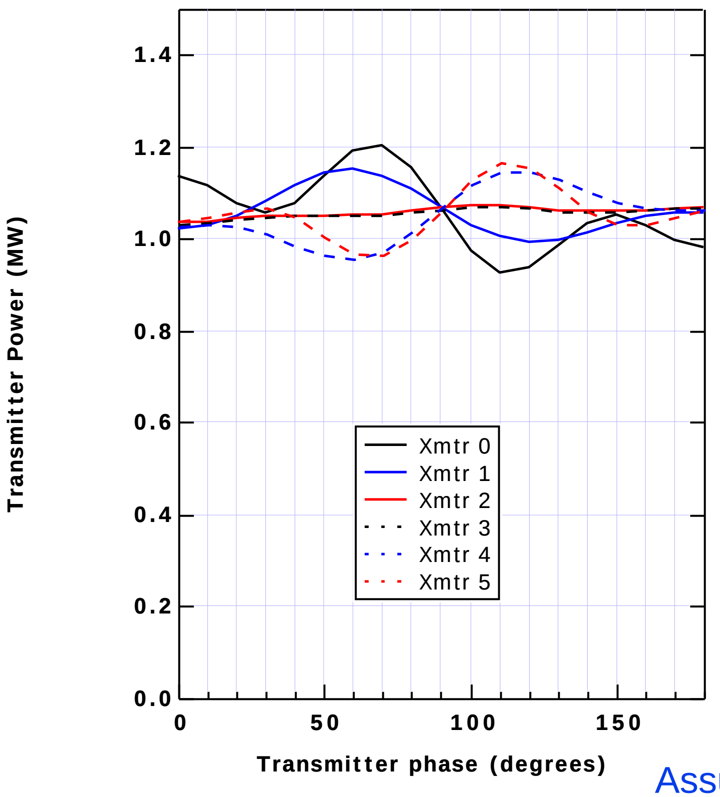
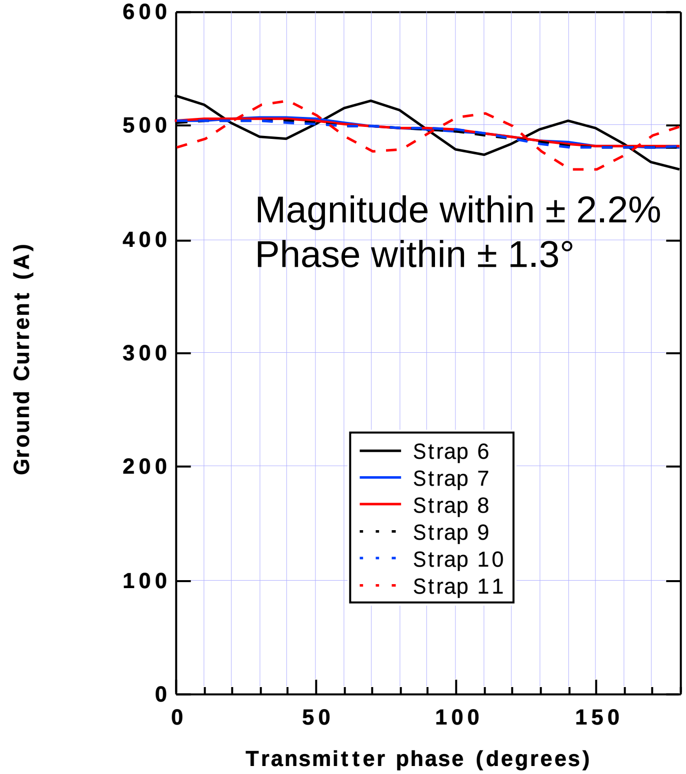
For typical plasma conditions and assuming plasma loading (R') is kept *constant*, power per transmitter and currents in strap ground are insensitive to phase between antennas





Assumptions:

- Tuned for exact balance at 90°
- Total power 6 MW
- Currents in straps 0-5 equal

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Need active control of plasma position

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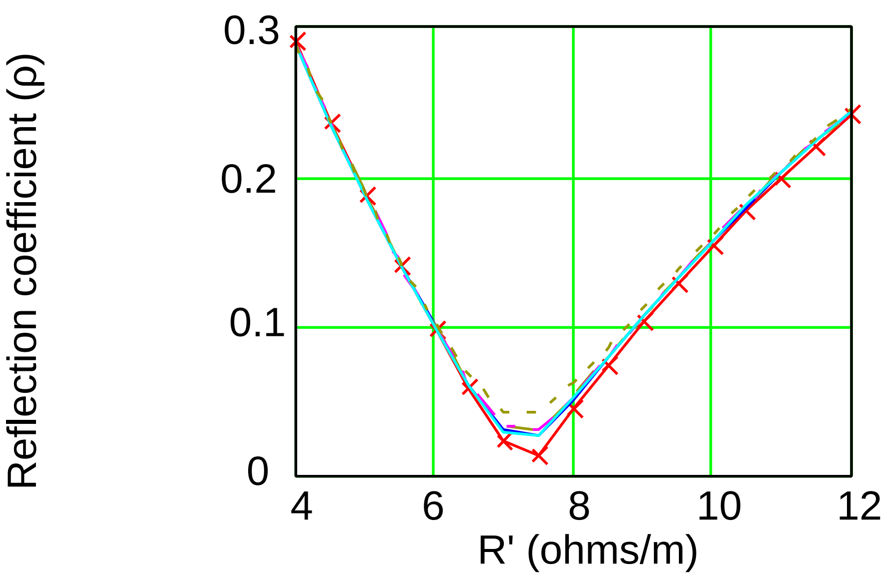
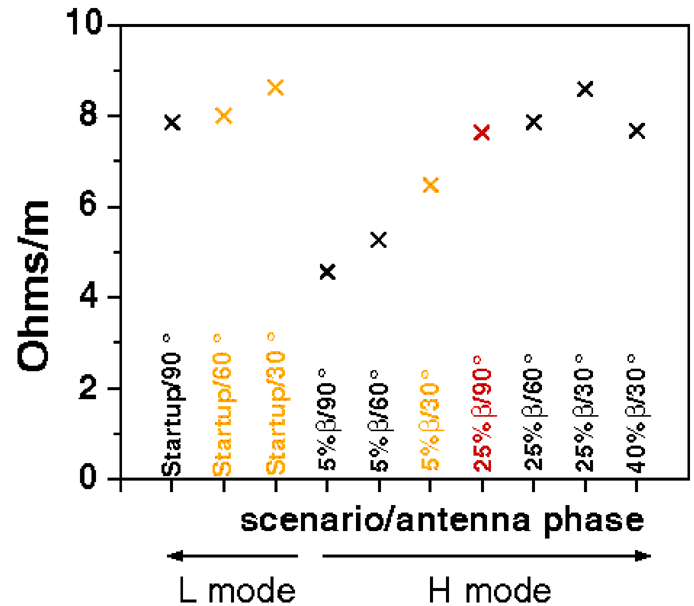
- For fixed plasma loading (R’), reflected power does not depend on phase.
- For constant phase, reflected power ***does*** depend on plasma loading



Loading changes during evolution of the discharge can be caused by:

- L-H transition (~ factor of two)
- Changes in plasma β that cause changes in density gradients
- Changes in interstrap phasing



Fast plasma position control can maintain plasma loading during shot evolution

~ 2.5 cm shift in plasma edge will compensate for factor of 2 change in loading

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One transmitter dropping out increases power reflected to other transmitters slightly

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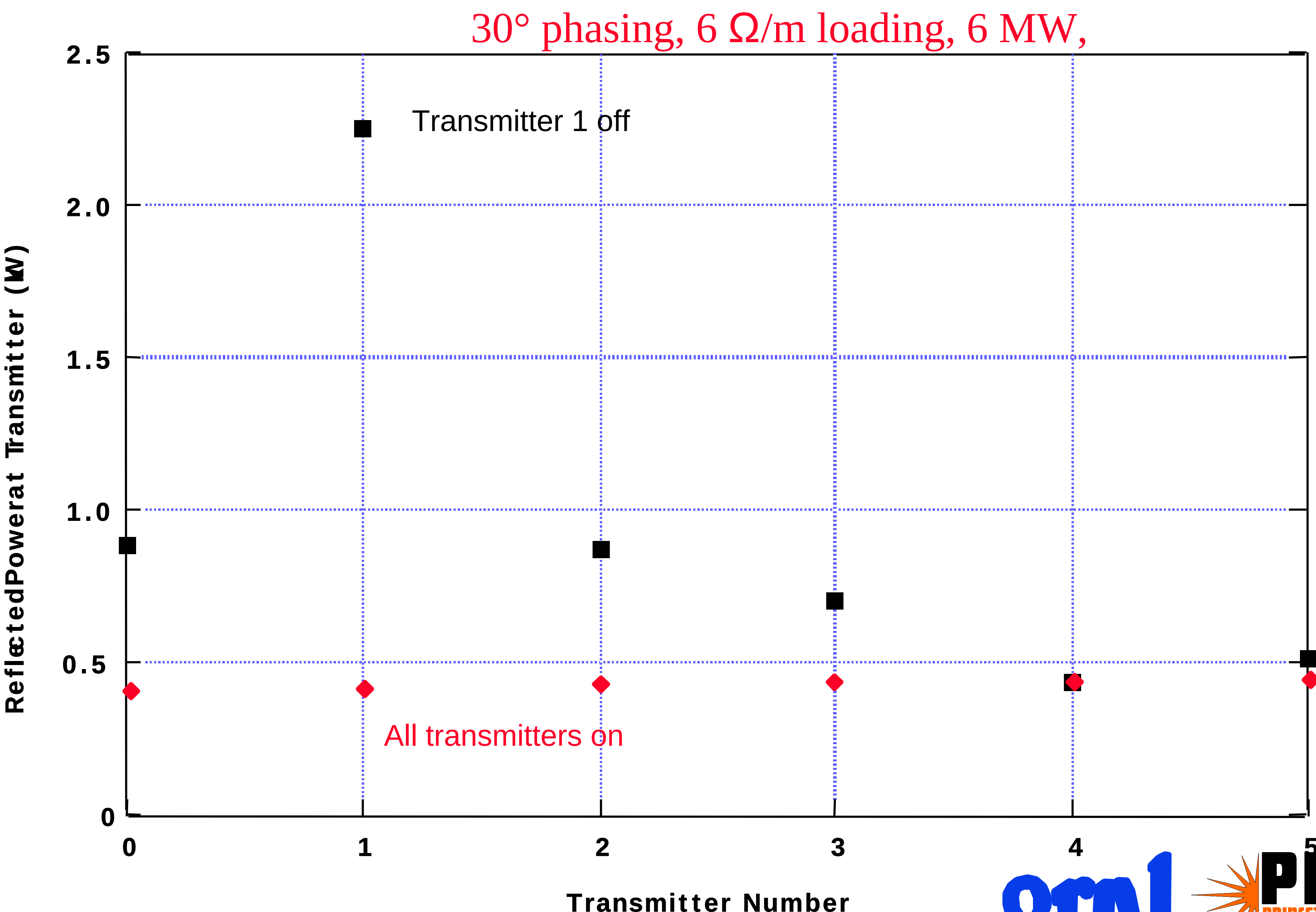

Mockup Measurements at ORNL

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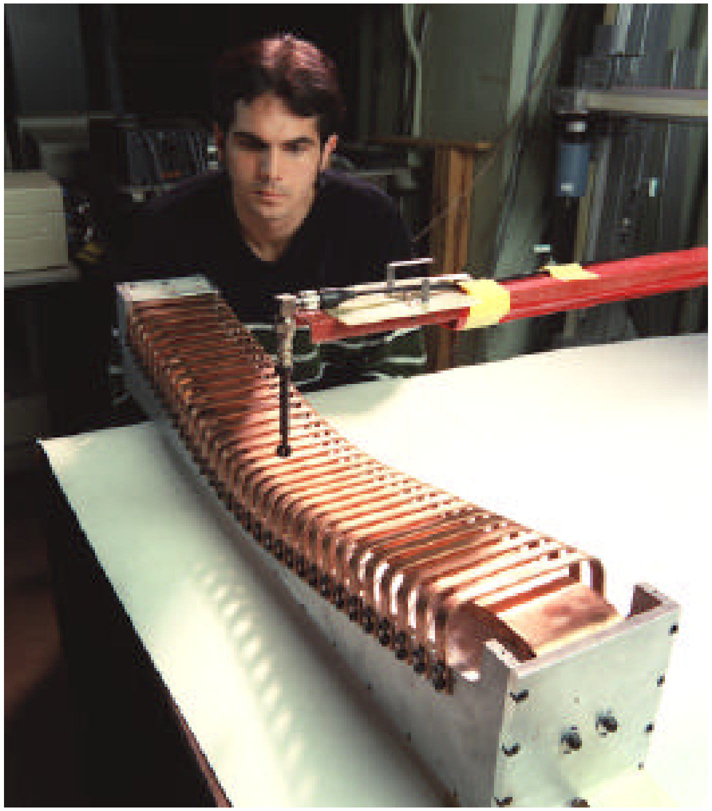
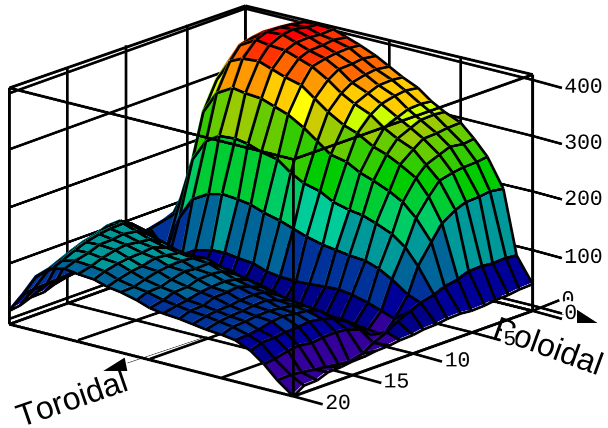


Measurements Made With Network Analyzer:

- **Time Domain Reflectometry (Z_0 of antenna sections)**
- **Resonant Frequencies (Phase velocity along strap)**
- **Transmission coefficient (interstrap coupling.**
- **B-dot probe measurements (field pattern mapping)**



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TDR Determination of Z_0 for NSTX Mockup

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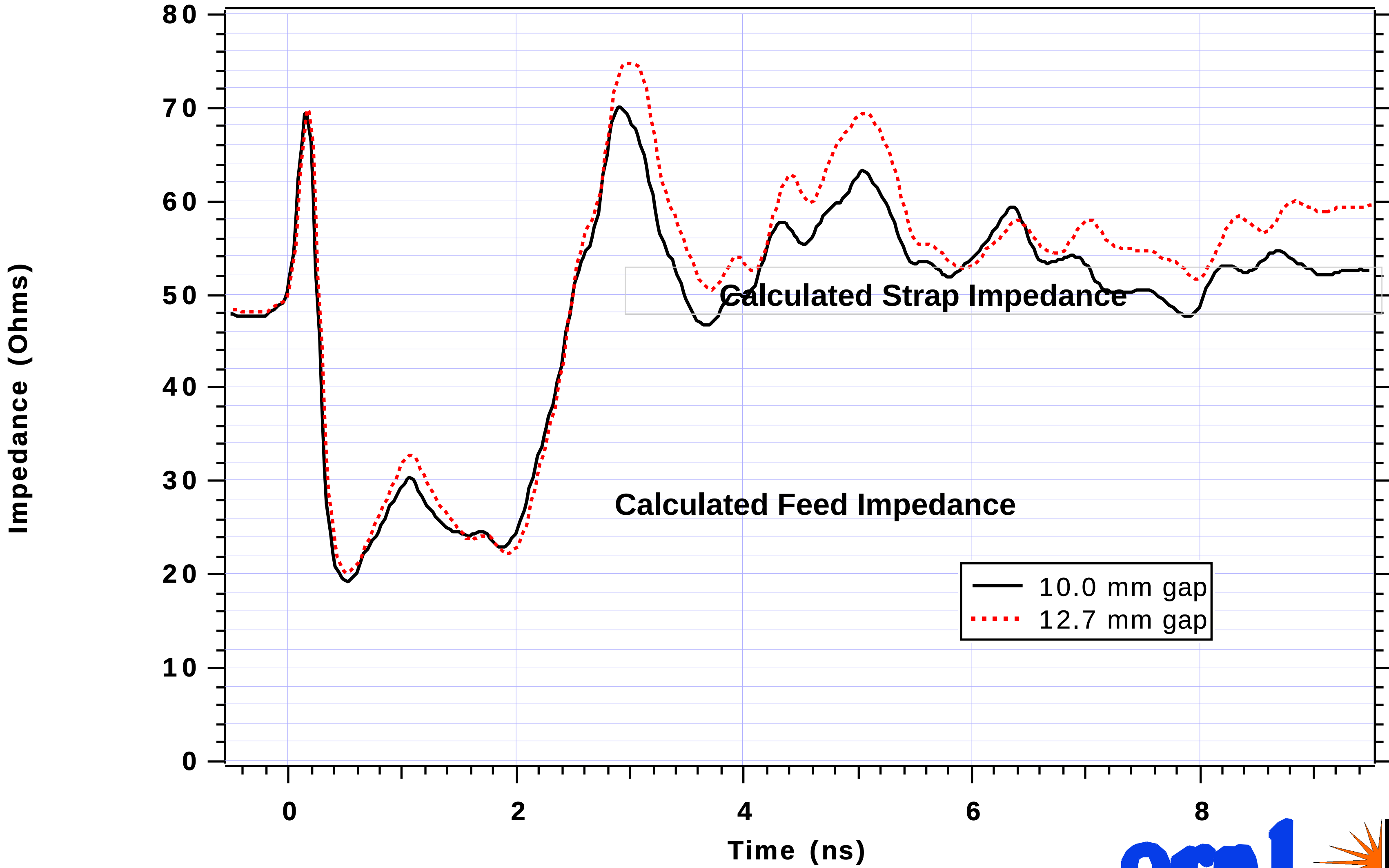

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Calculated Values For Antenna Array Were Adjusted to Match Mockup Measurements

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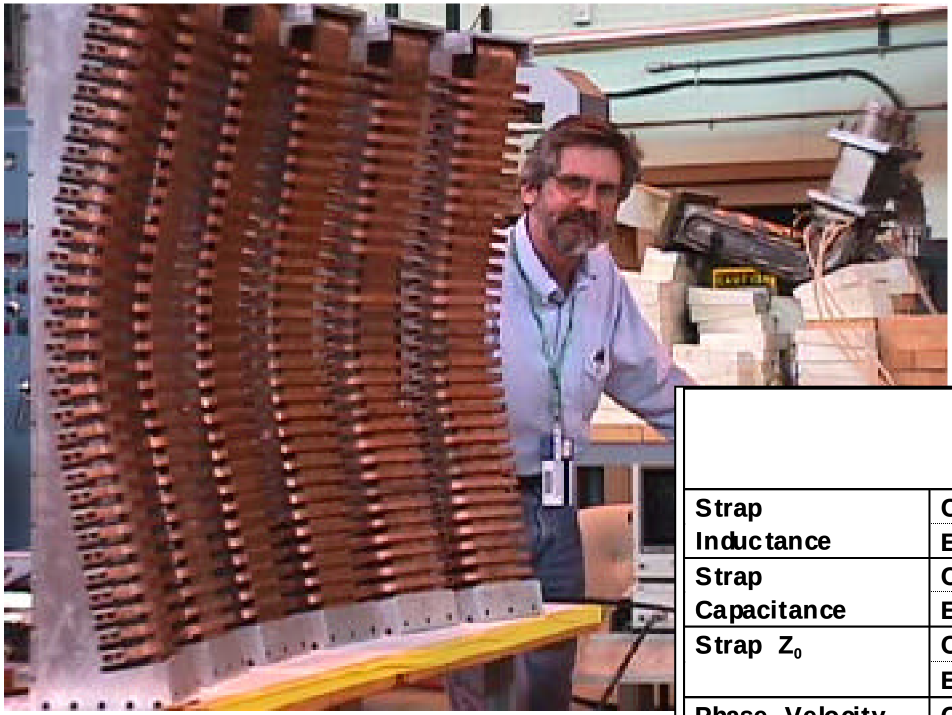

Full-scale, 6-element mockup array was fabricated and tested at ORNL

		Calculated Design Values	Values To Match Mockup Measurements
Strap Inductance	Center	2.81e-7 H/m	2.94e-7 H/m
	Ends	3.39e-7 H/m	3.57e-7 H/m
Strap Capacitance	Center	1.21e-10 H/m	1.12e-10 F/m
	Ends	1.21e-10 H/m	1.08e-10 F/m
Strap Z_0	Center	48 Ω	52 Ω
	Ends	53 Ω	58 Ω
Phase Velocity	Center	0.57 c	0.58 c
	Ends	0.52 c	0.54 c
Inductive Coupling, k_{12}	Center	0.09	0.08
	Ends	0.14	0.10
Inductive Coupling, k_{13}	Center	*	0.02
	Ends	*	0.02
Strap Length	Center	0.30 m	0.285 m
	Ends	0.30 m	0.285 m
Feed Length		0.20 m	0.35 m
Feed Z_0		27.5 Ω	26 Ω

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Connections For the 6-Element Array

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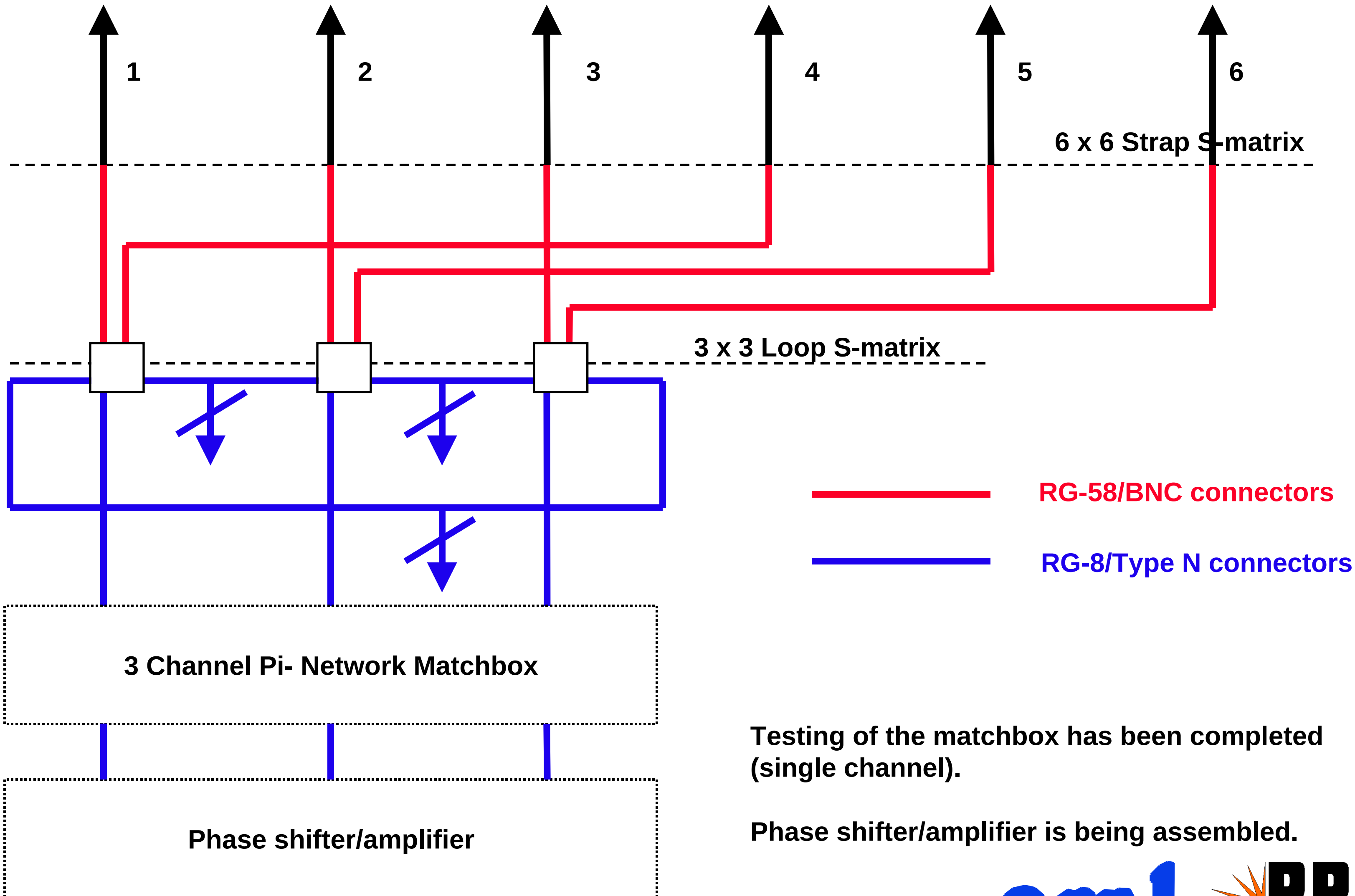

Testing of the matchbox has been completed (single channel).

Phase shifter/amplifier is being assembled.

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6X6 Scattering Matrix Measured At Array Inputs and Compared to TL Model

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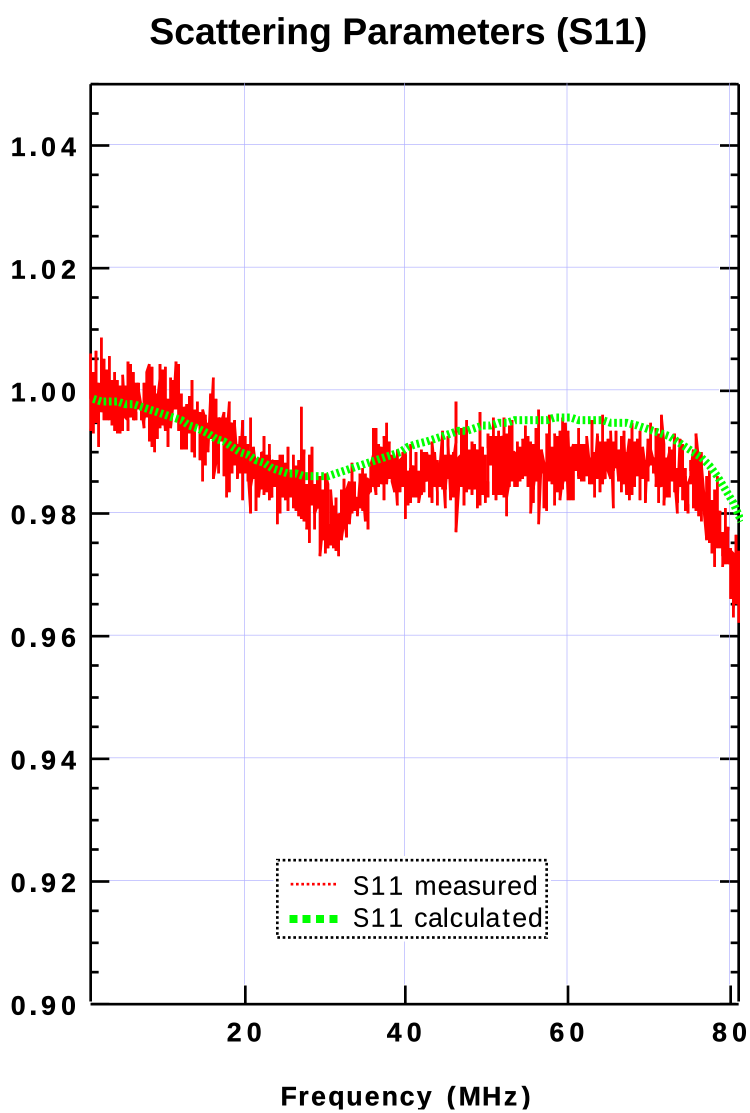

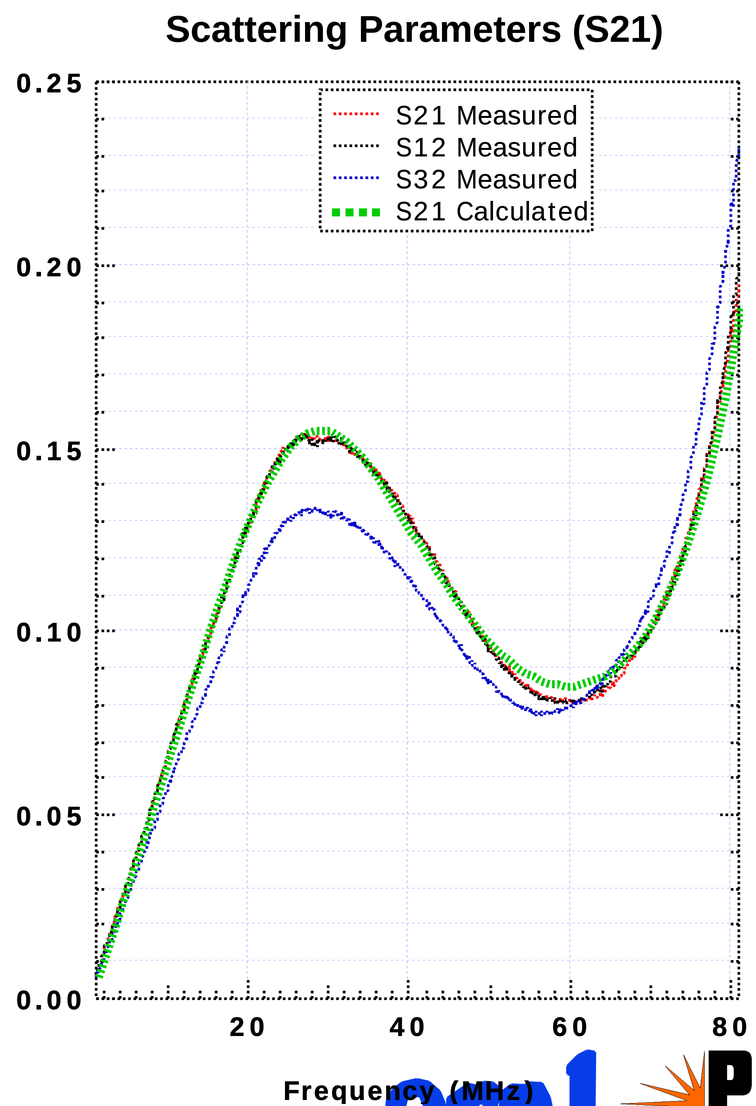

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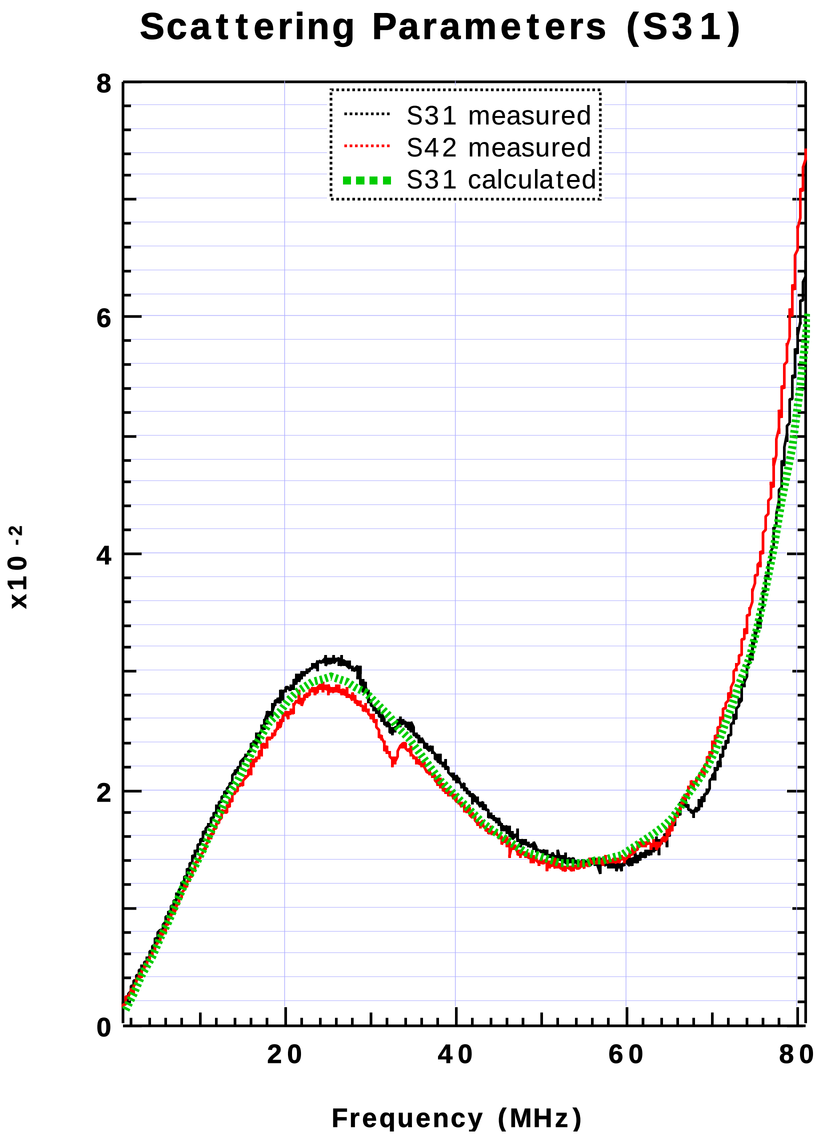
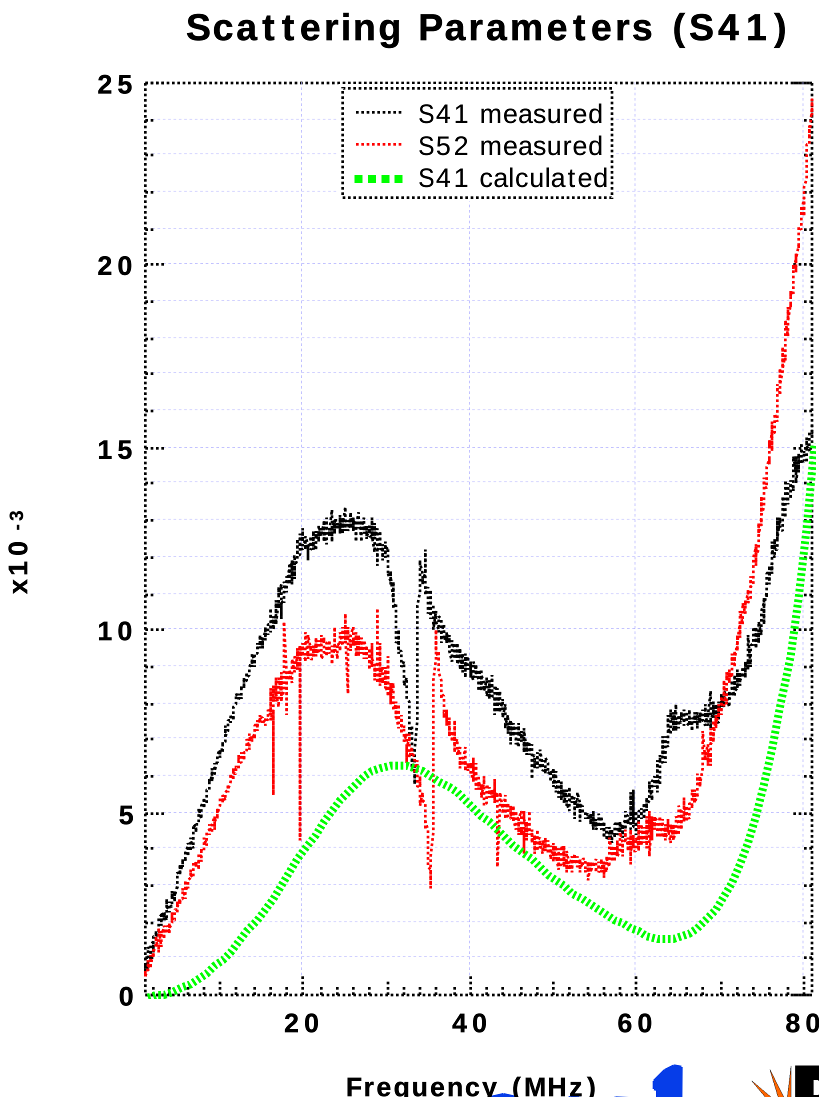
6X6 Scattering Matrix Measured At Array Inputs and Compared to TL Model

NSTX





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3X3 Scattering Matrix Measured At Loop Ts and Compared to TL Model

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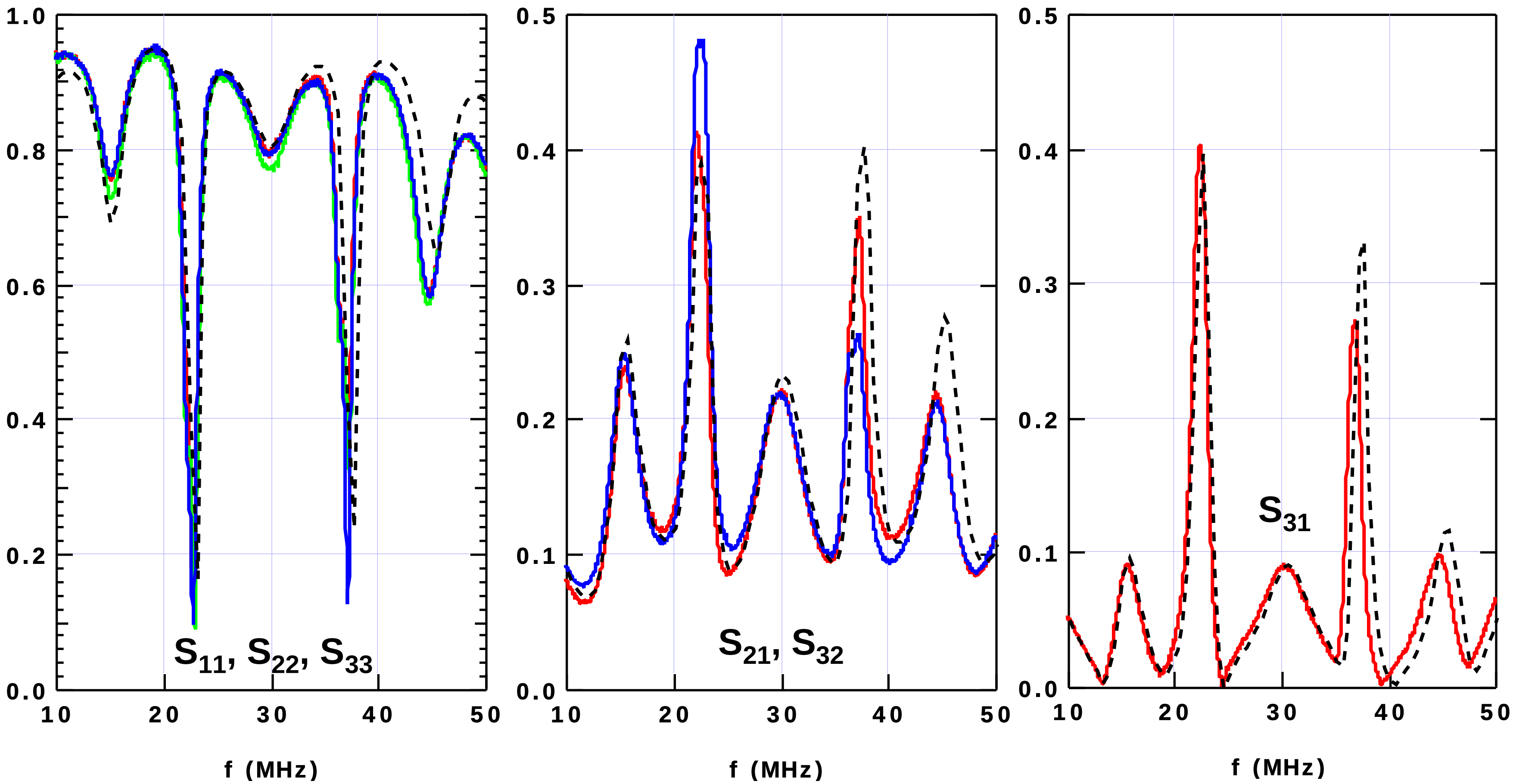
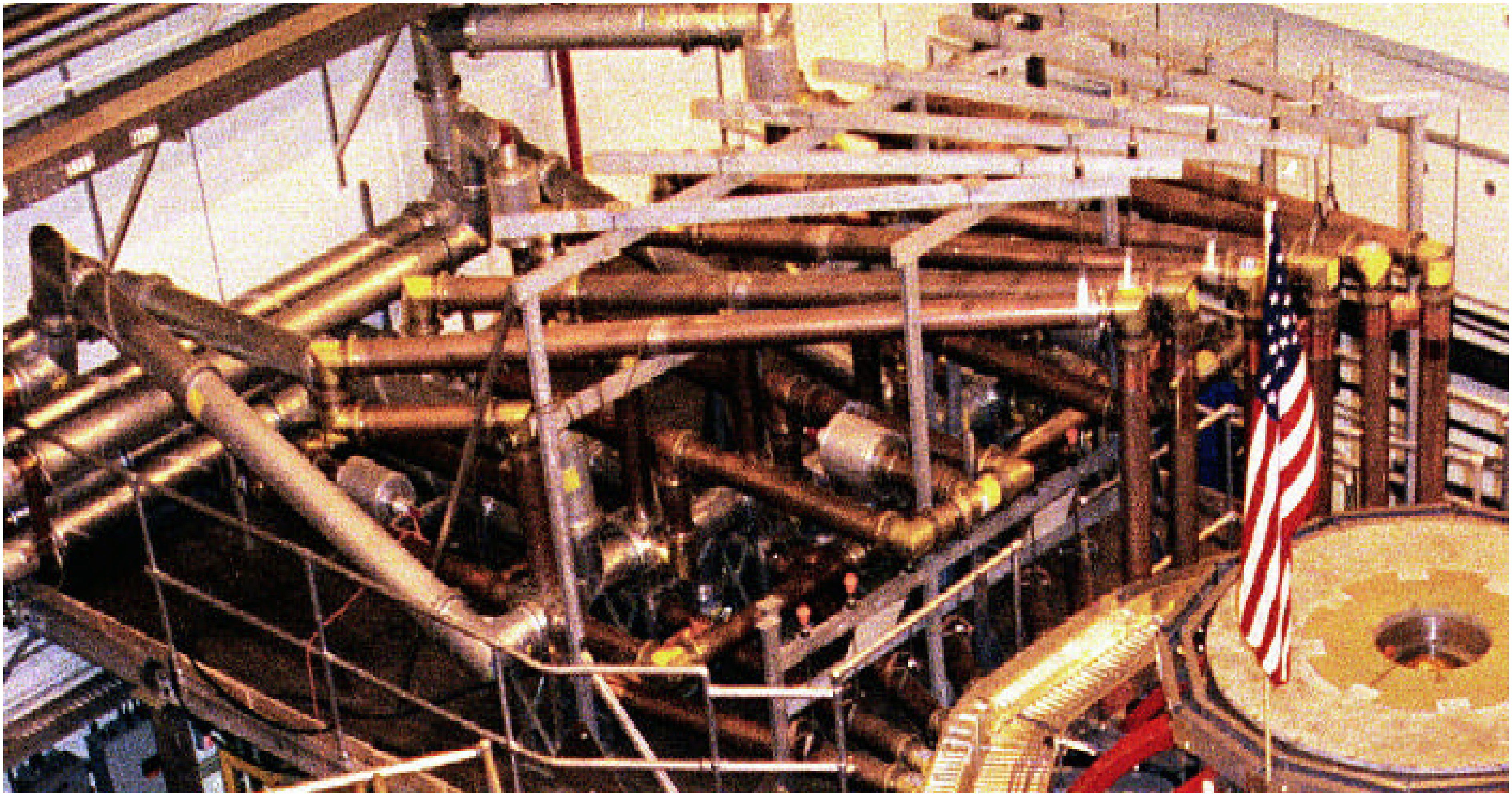
- Solid lines are measured, dotted lines are modeled values
- Difficulty in matching over frequency range due to the dispersive nature of RG-58 cable/BNC connectors used in resonant loops



Adjusting The Resonant Lengths

- **Want to set loop lengths so they are resonant at 30 MHz <u>when decoupled from the other straps</u>.**
- **Shorts placed at positions that are normally high impedance points at 30 MHz removes the straps' response at that frequency (i. e., "decouples" them) so that resonance lengths may be set in isolation.**
- **Convenient high impedance points at 30 MHz are at the strap feed points and at the feed points of the resonant loops.**
- **Loop 3 is shorted at T when adjusting the decoupler between loops 1 & 2.**
- **Decouplers provided ~ 30–35 dB isolation between loops.**

12-Strap, 6-loop System with Decouplers Now Operational



12 Strap Operation: Power Coupling Between Loops WITHOUT Decouplers Present

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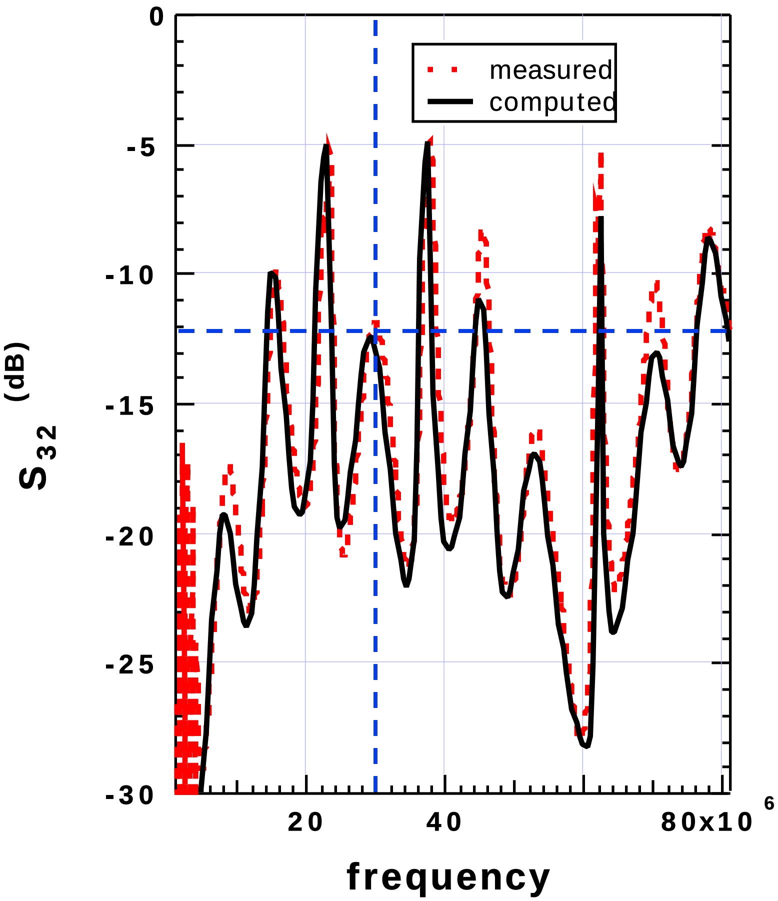
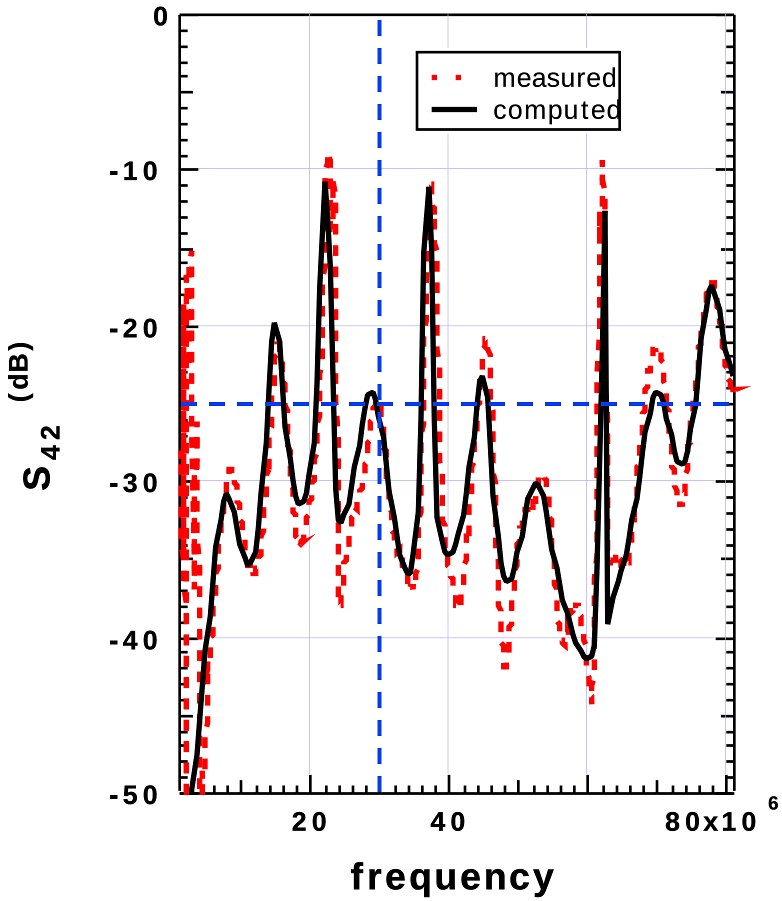
-12 dB coupling between adjacent lines at 30 MHz



-25 dB coupling between next to nearest neighbor lines



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12 Strap Operation: Power Coupling Between Loops WITH Decouplers Present

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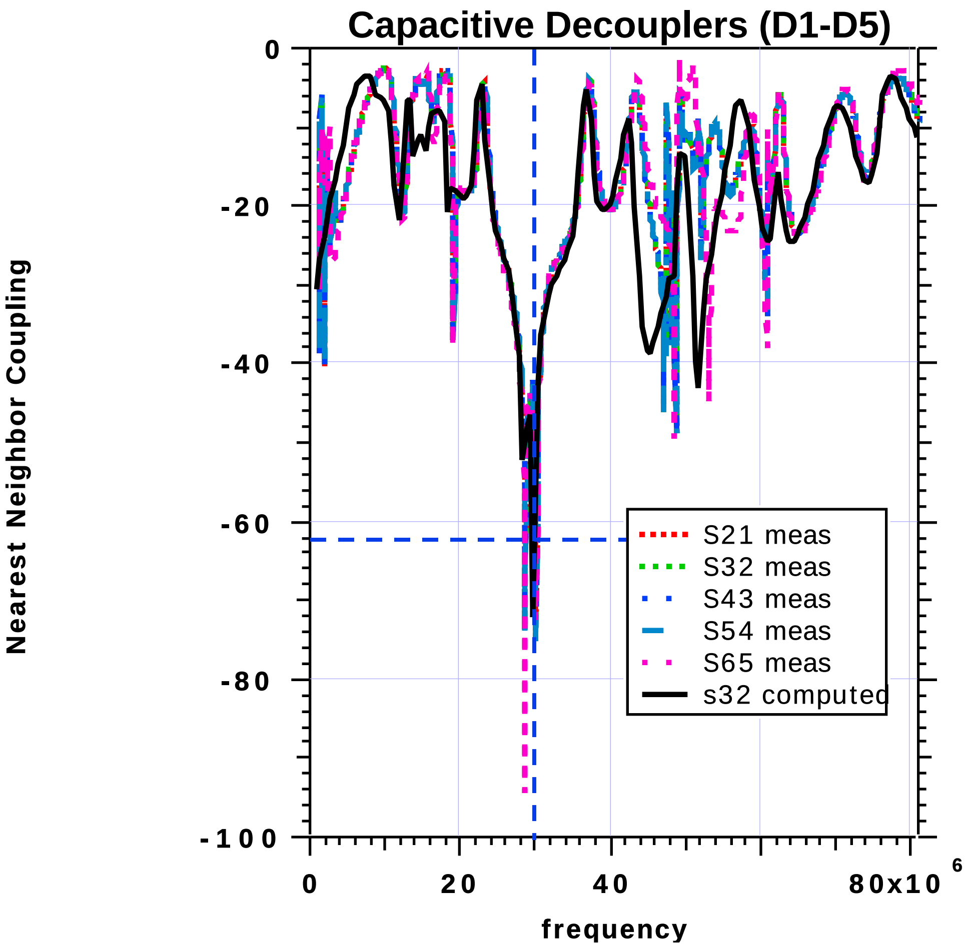
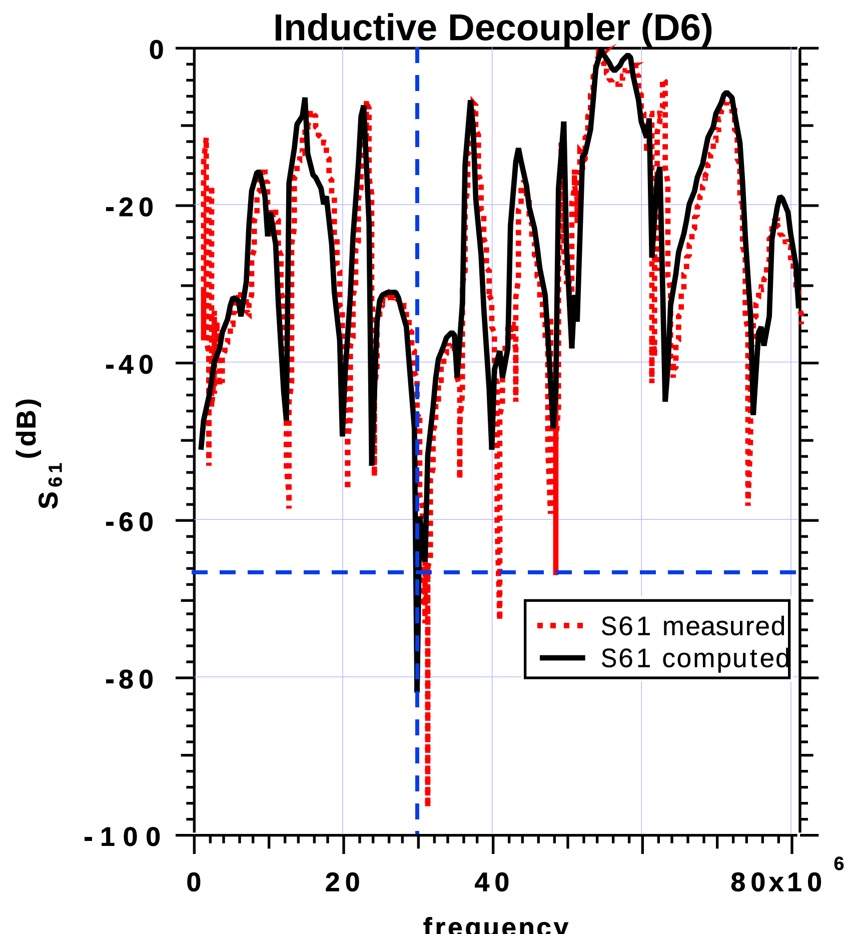
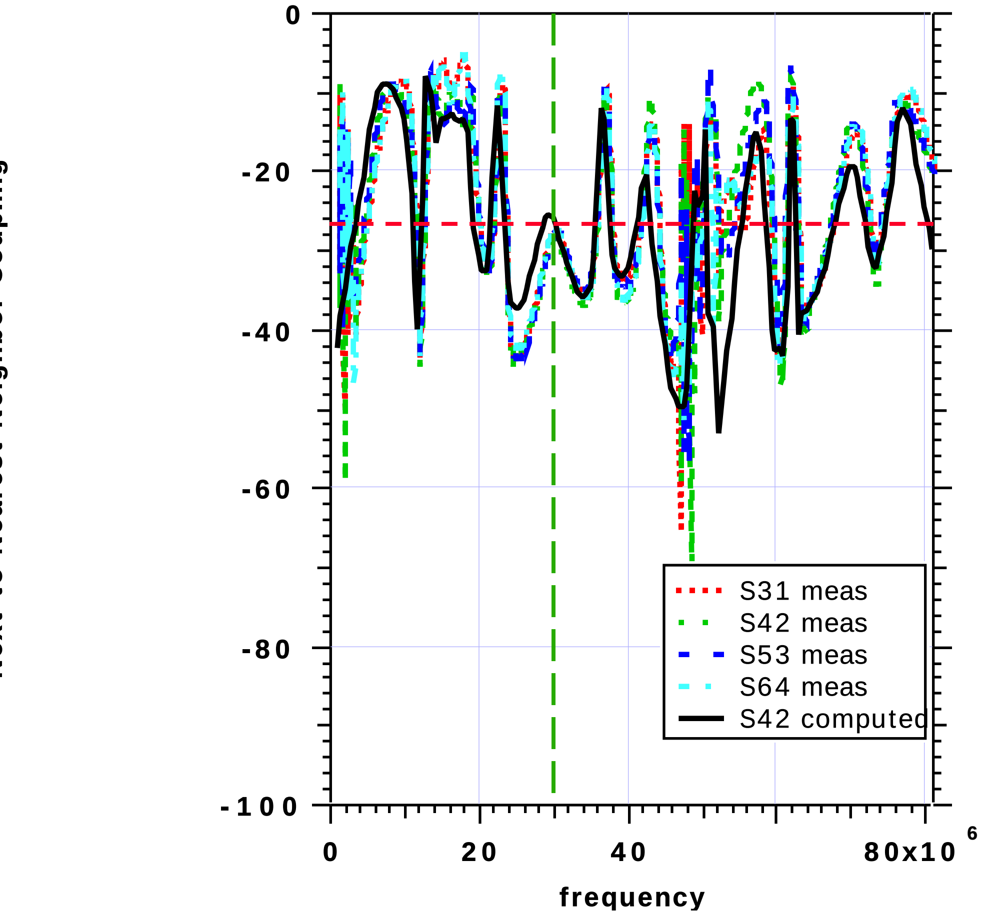
Decouplers reduce power transmission between adjacent lines to –50 to –60 dB





Adding decouplers does not change next-to-nearest neighbor coupling, but adding T/M elements increases it.

Coupling between next-to-nearest neighbors remains around -25 dB



S-matrix on antenna side of T/M =

0.9829	0.0003	0.0503	0.0034	0.0261	0.0001
0.0003	0.9828	0.0002	0.0510	0.0034	0.0260
0.0503	0.0002	0.9820	0.0004	0.0508	0.0034
0.0034	0.0510	0.0004	0.9816	0.0002	0.0506
0.0261	0.0034	0.0508	0.0002	0.9826	0.0003
0.0001	0.0258	0.0034	0.0506	0.0003	0.9829

Power traveling from the loops to the transmitters is reflected at the T/M elements, increasing the effective coupling between alternate transmitters. This increases the problem of phase control/matching during vacuum conditioning

S-matrix on transmitter side of T/M =

0.0569	0.0010	0.1230	0.0081	0.0634	0.0020
0.0011	0.0611	0.0012	0.1243	0.0086	0.0629
0.1230	0.0012	0.2275	0.0026	0.1241	0.0081
0.0081	0.1244	0.0026	0.2248	0.0012	0.1235
0.0634	0.0012	0.1241	0.0012	0.0586	0.0010
0.0020	0.0629	0.0081	0.1235	0.0010	0.0594

12 Strap Operation With Decouplers:

Vacuum S-matrices show some residual coupling

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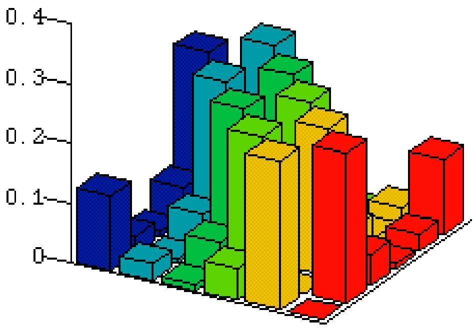
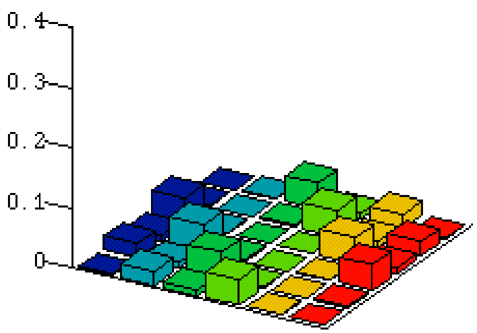
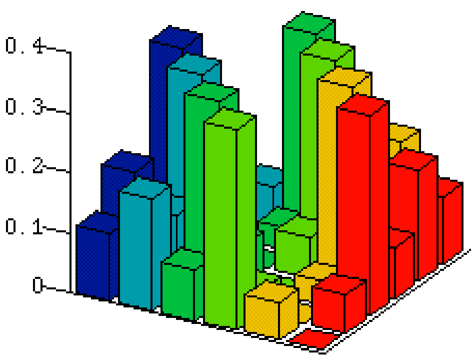
(Diagonal values suppressed)



Strong nearest neighbor coupling without decoupling loops



At feedpoints, the decoupling loops cancel nearest neighbor interactions



Load-matched transmitters see two coupled triplets (1-3-5 and 2-4-6)

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PLASMA SIGNALS CONFIRM DECOUPLING

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Forward Power (W) | Reflected Power (W) | Antenna Voltage (V)

Line 1

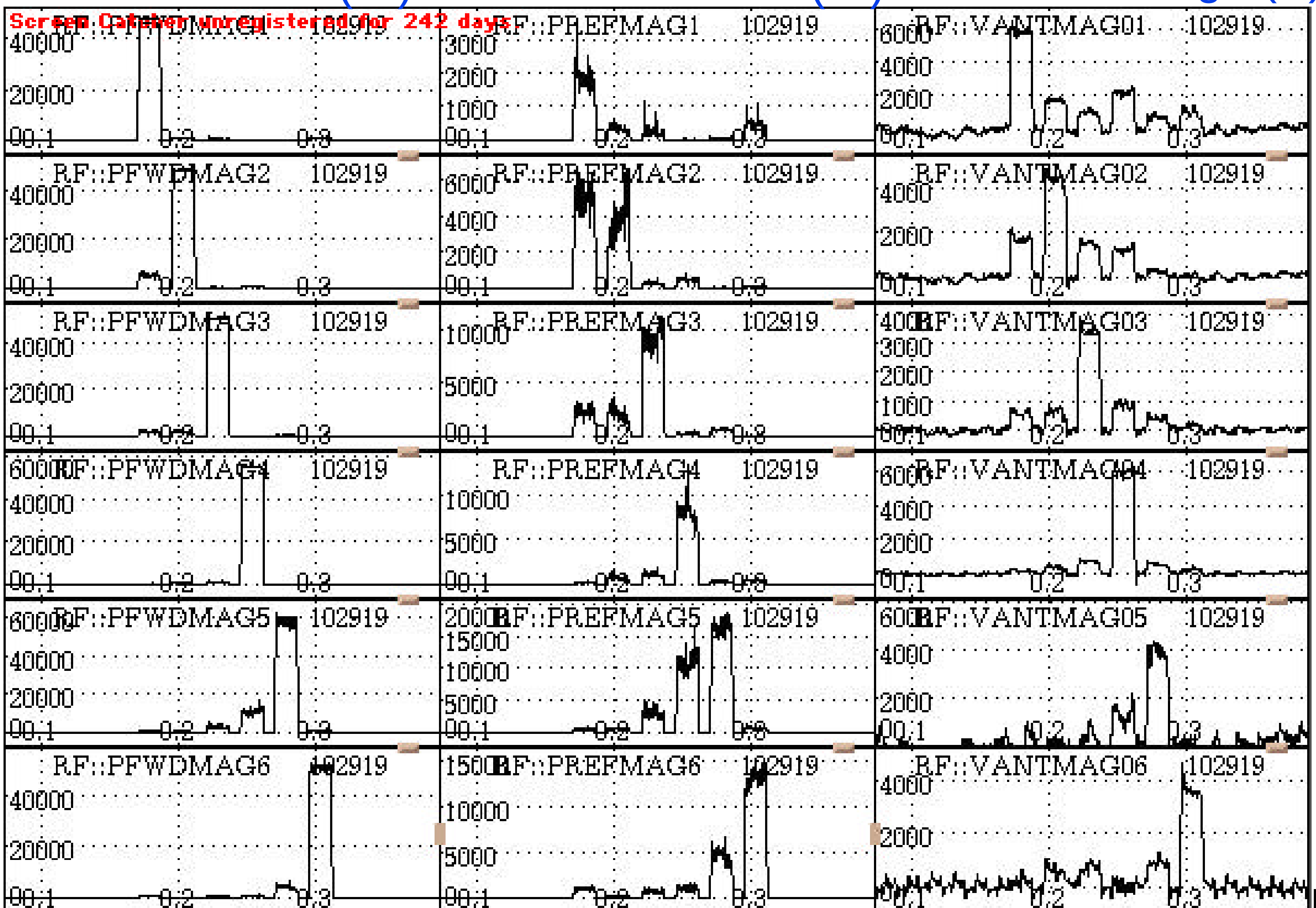
Line 2

Line 3

Line 4

Line 5

Line 6



Time (s) Time (s) Time (s)

Measurements Indicate Asymmetrical Loading/Coupling With Plasma

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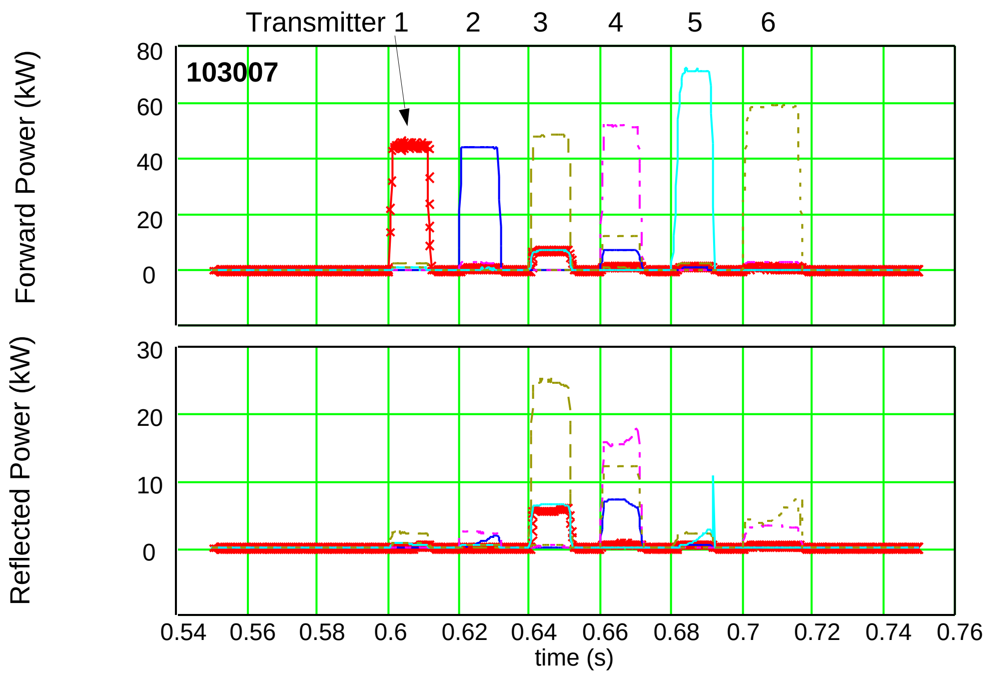

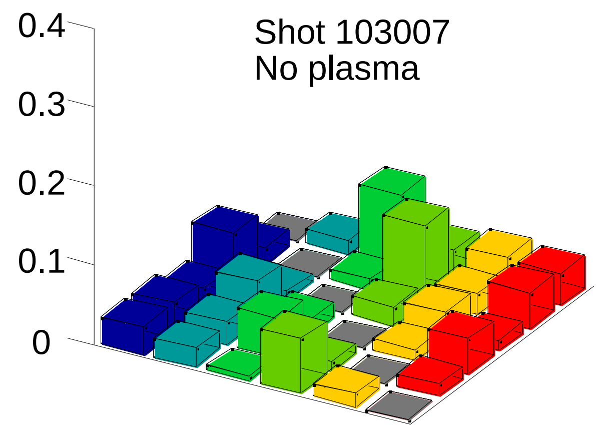

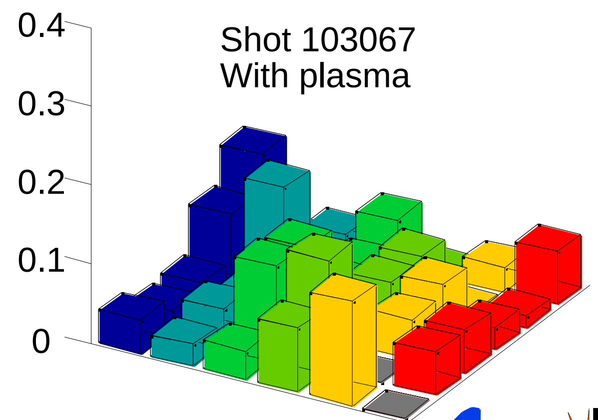

Scattering matrices can be generated from forward/reflected power measurements at the match.

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