RF Modeling/Loading/Diagnostics

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DOE Peer Review of RF Technology Program

Oak Ridge, TN

May 9, 2000

ORNL Antenna Modeling and Diagnostics Outline

Antenna modeling: method and approach

- Development History by Selected Examples
  - TFTR
  - JET
  - JT-60
- NSTX
  - HHFW coupling theory and general antenna analysis
  - Detailed analysis and integration into power distribution system
  - Mockup array
  - NSTX measurements
  - Plasma loading analysis
- Edge Physics/RF Sheaths
  - Experiments on DIII-D and Tore Supra
  - ITER analysis (collaboration with Lodestar)

Computational and experimental tools are needed for the design of antennas and the analysis of their operation

RF/Plasma Theory tools are needed for rf power coupling, wave propagation, power deposition, etc. Emphasis on plasma interactions, but basic antenna geometry needs to be considered.

- PISCES (2D full wave)
- RANT3D (3D with plasma surface impedance BCs)
- PLASMAIMP and GLOSI (1D cold and warm plasma slabs)

Antenna Design and Analysis tools are needed to characterize the electrical properties of the antenna. Emphasis on detailed geometry.

- 2D and 3D Magnetostatic Codes
- ARGUS (3D electromagnetic)

Coupled Transmission Line tools are needed to design and analyze the power distribution system. Joins the plasma interaction with antenna characteristics.

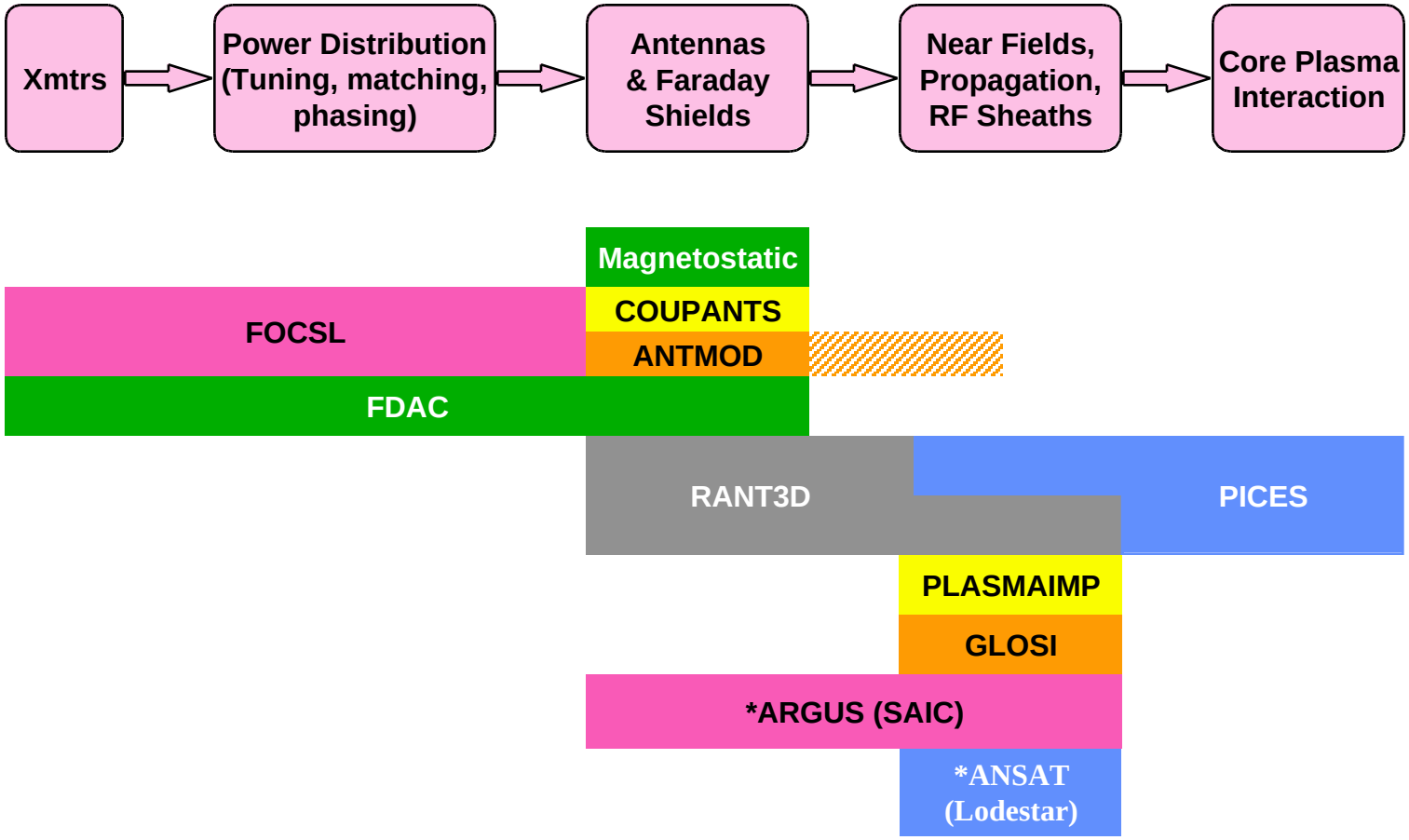
- FDAC/Mathcad

Edge diagnostics are needed for accurate plasma profiles and antenna/edge plasma interactions.

- Microwave reflectometer
- Loop and Langmuir probes
- IR cameras and thermocouple arrays

A set of codes is used in the design and analysis of an integrated rf system

RF codes used at ORNL and their domains of application



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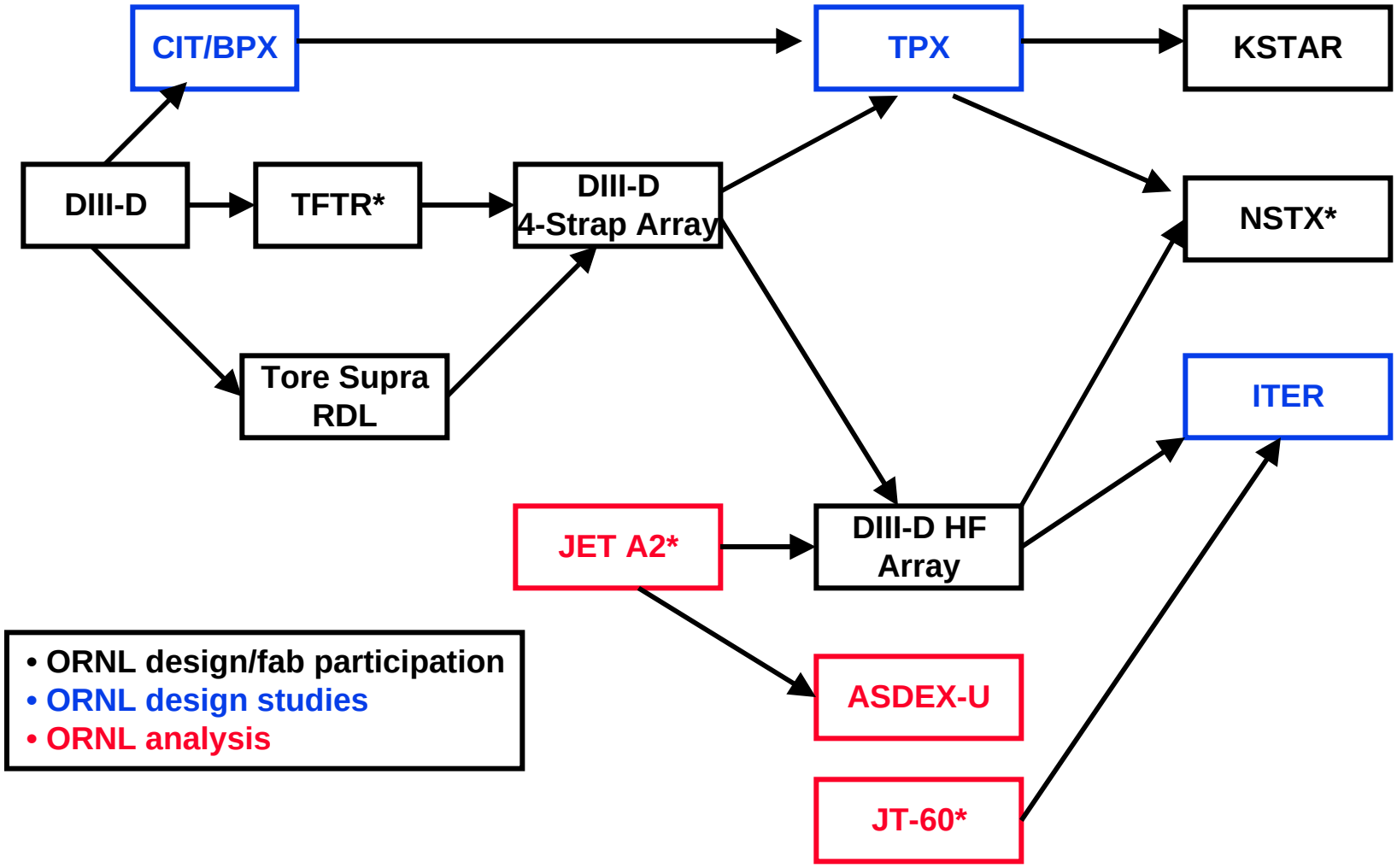
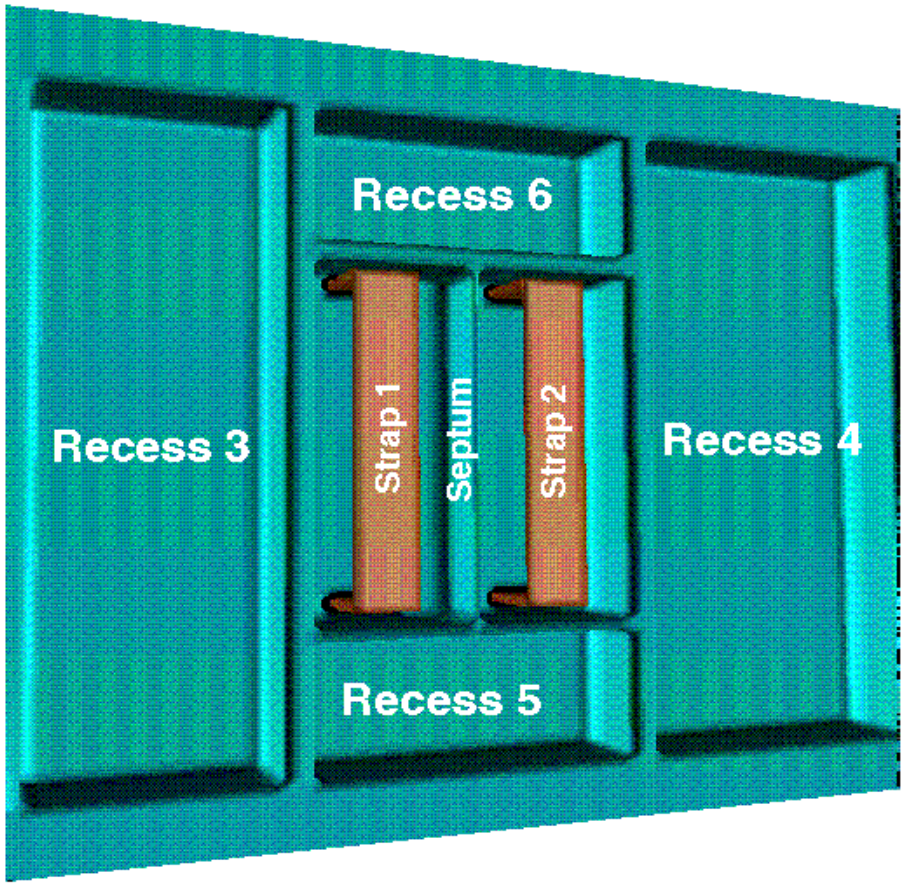
Modeling/Analysis/Diagnostic Techniques Developed On One Experiment Were Applied To Subsequent Projects



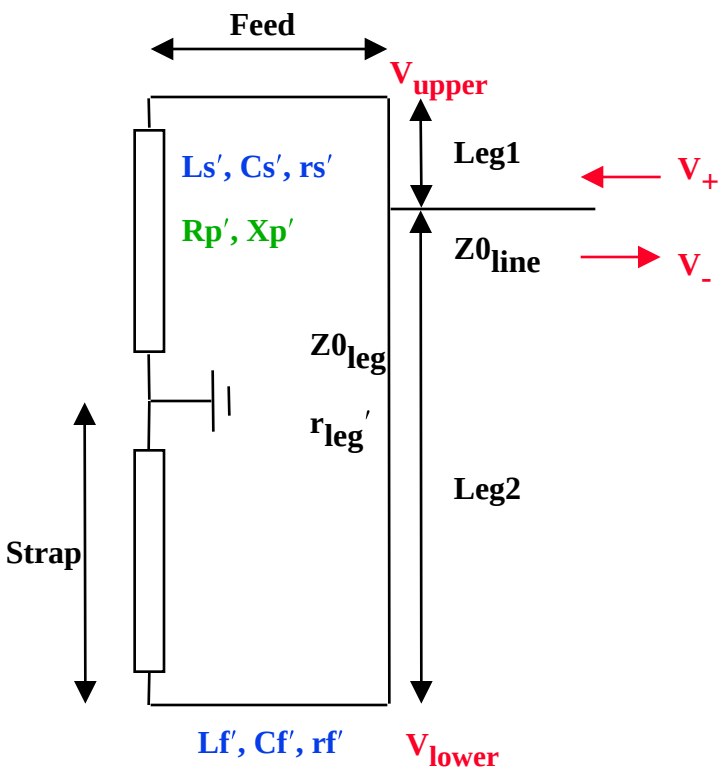
- ORNL design/fab participation
- ORNL design studies
- ORNL analysis

Analysis of TFTR Bay M Antenna required 3D antenna model for plasma coupling, antenna characteristics, circuit parameters, and density profiles

RANT3D model confines return currents to frame structure

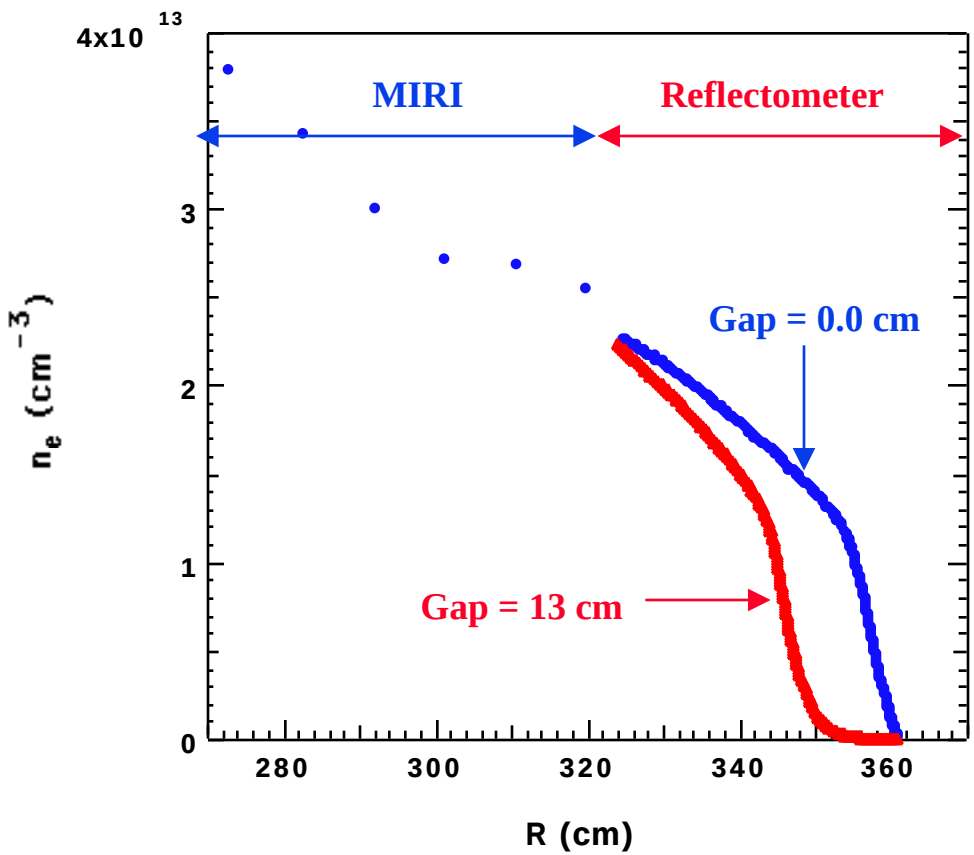


Accurate circuit model needed to transform radiation resistance to measured electrical loading



TFTR Density Profile Measurements from the Microwave Reflectometer in Bay K

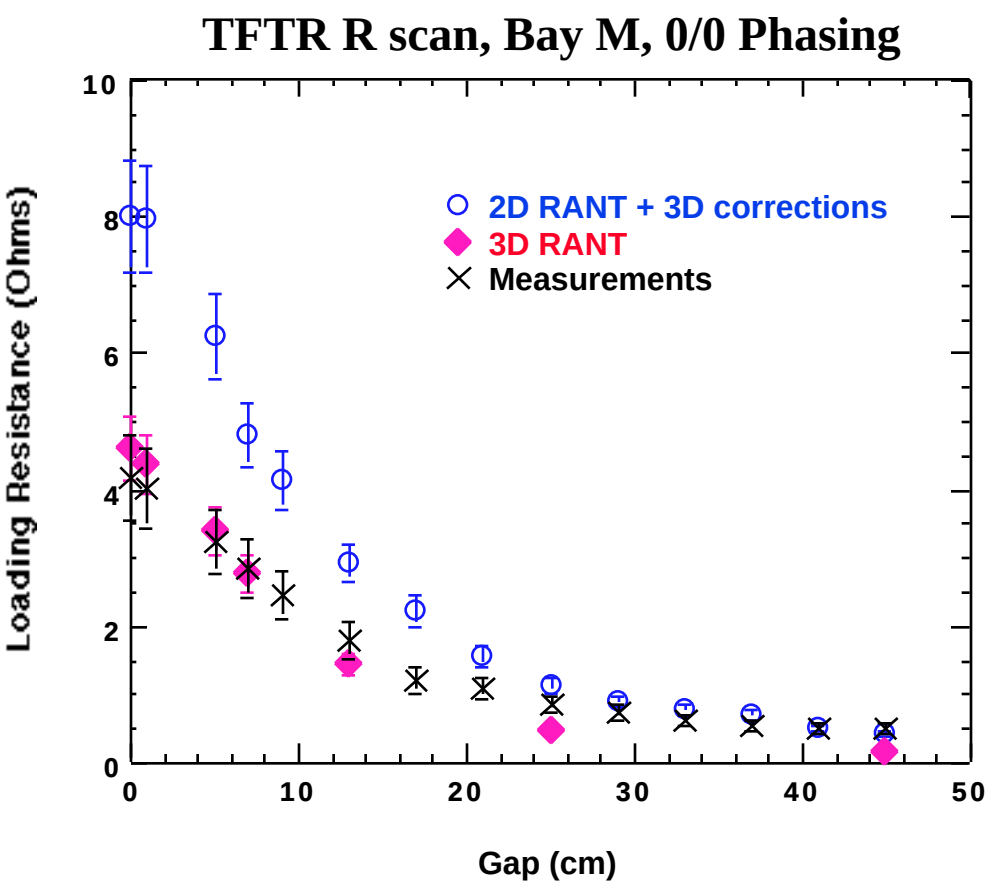
Plasma Density Profiles as the Plasma Position Is Varied



- **Dual frequency, differential phase, X-mode reflectometry system operating 90 to 118 GHz**
- **Launcher in the center of Bay K ICRF antenna**
- **Measured density profiles to less than 1×10^{11} cm^{-3}.**
- **Differential phase reflectometry gives**
  - significant reduction in density fluctuation sensititvity.
  - reduced fringe multiplicity gives unique measure of phase.

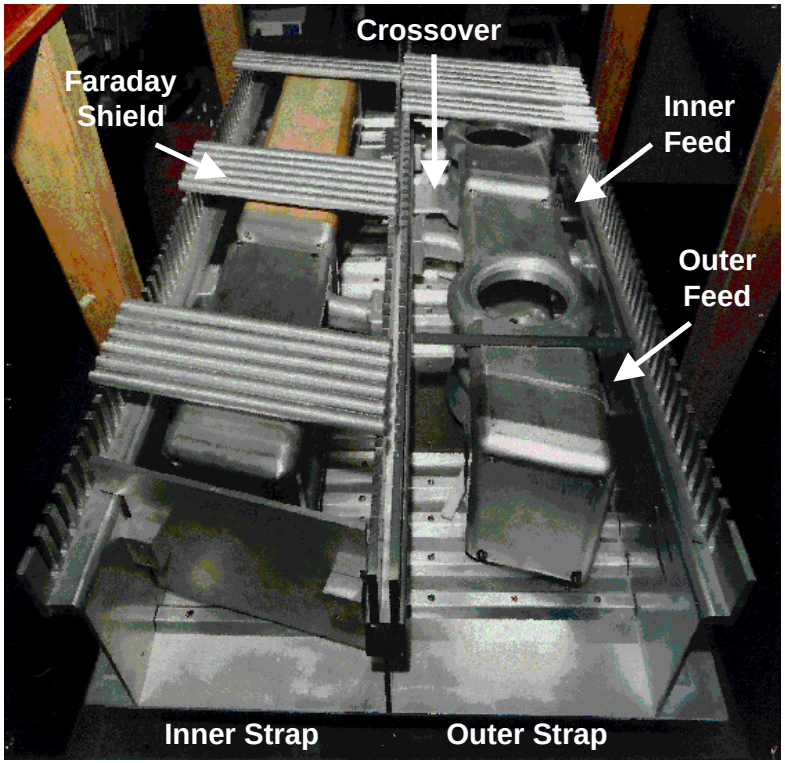
Comparison of 2D and 3D Loading Calculations to TFTR Bay M Antenna Measurements (Monopole Phasing)

3D model is accurate at small gaps even for monopole phasing and predicts reactive loading better than 2D model

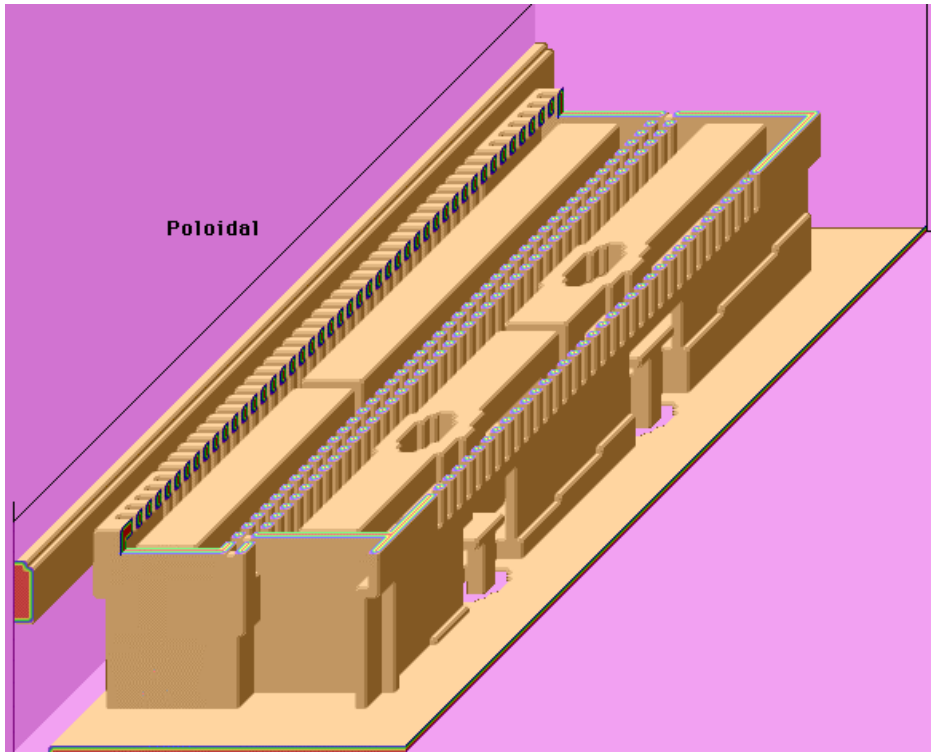


- Correct return currents requires 3D model <u>and</u> recesses around the antenna frame.
- 3D corrections to 2D calculations not valid for small gaps and small phase shifts between straps.

JET A2 Array: gave experience with asymmetric parallel loops and encouraged development of 3D and coupled transmission line modeling

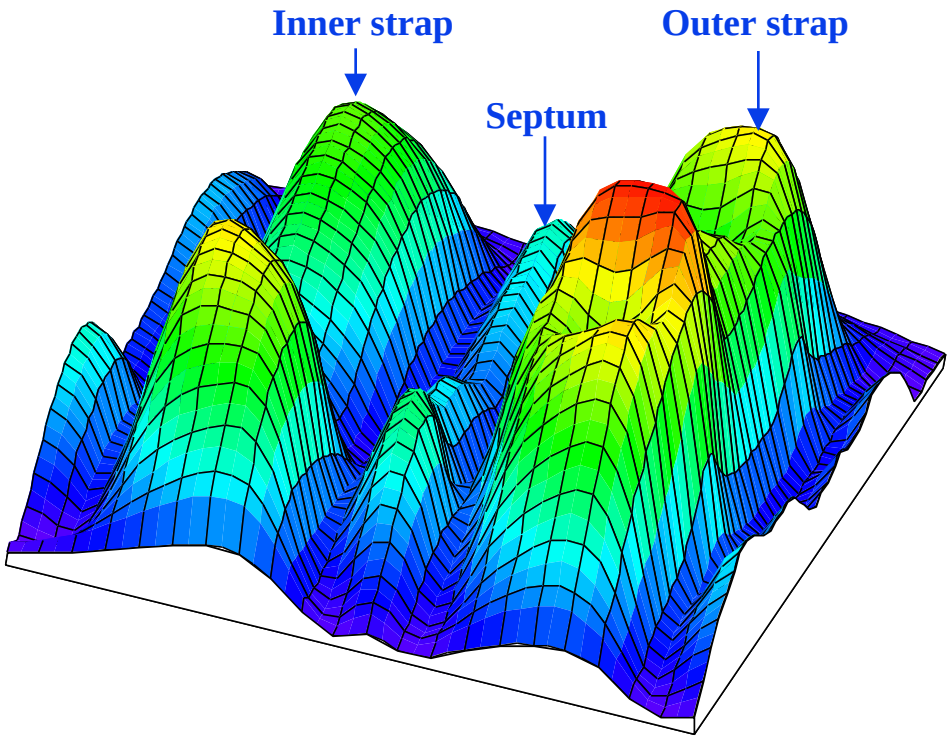


Full scale mockup of one JET A2 Antenna module, with most of the FS tubes removed to expose the straps

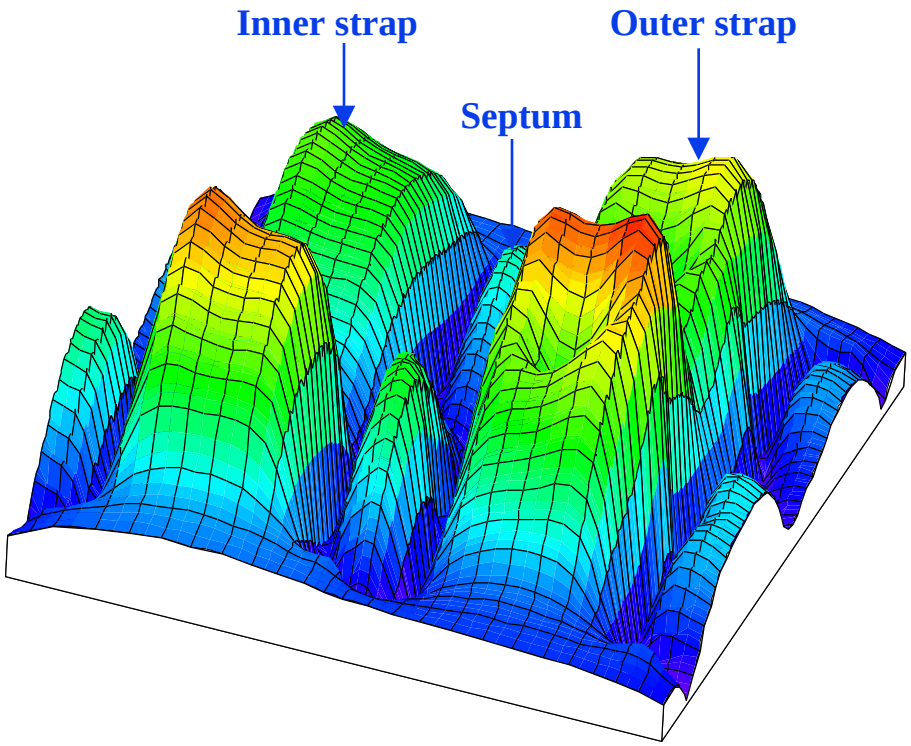


ARGUS model of the JET A2 Antenna with FS cut away to expose the straps.

Good agreement between measurements and modeling for detailed rf field distributions.



Measured Toroidal B-field

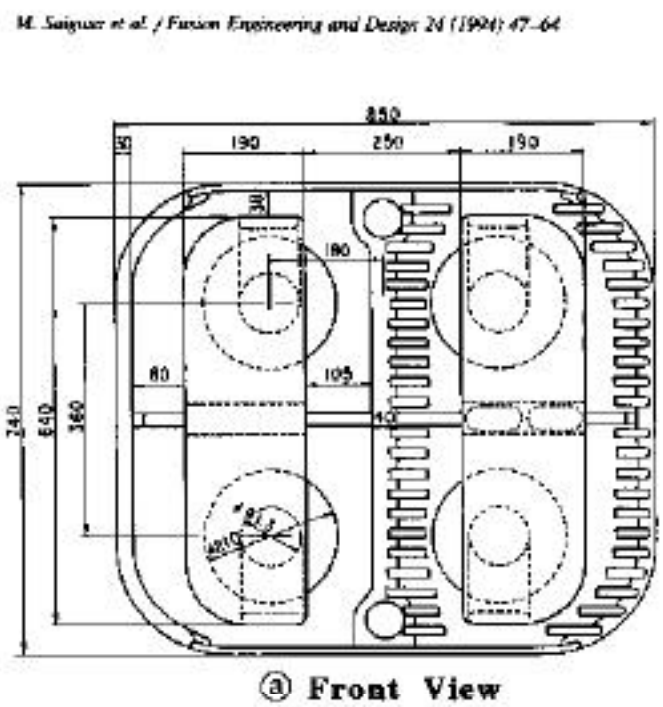


Calculated Toroidal B-field

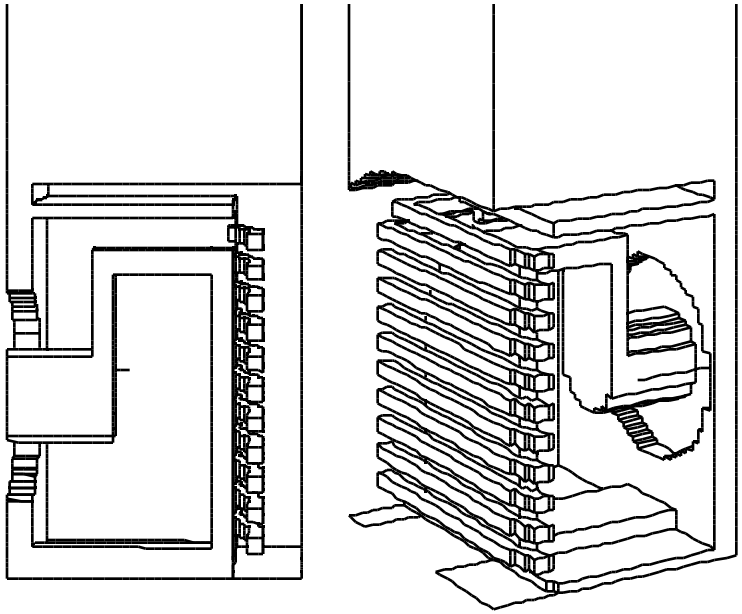
Plasma Loading Calculations for the JT-60U ICRH Antenna

- Collaboration between JAERI (Fujii and Moriyama) and ORNL (Ryan and Carter) was part of U. S.–Japan Fusion Cooperation Program (1996).
- Motivation was to benchmark codes and analytic techniques against measurements.
- JT-60U antenna is similar in size and shape to one quadrant of proposed ITER antenna.
- The JT-60U antenna was operated with large gaps between the antenna and the plasma separatrix, similar to those envisioned for ITER.
- Calculations were performed using only engineering drawings and density profile data as provided by JAERI (no supplementary measurements of antenna properties).

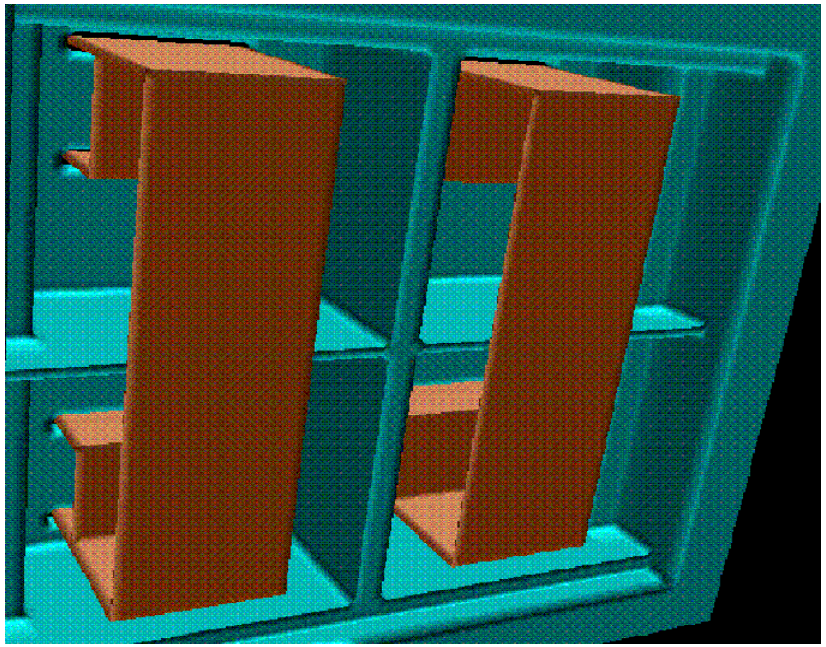
ARGUS Model of the JT-60U Antenna (One-strap)



- One of four straps is modeled.
- Faraday shield has rectangular cross-section.
- The strap has no poloidal curvature, but does have rounded ends.
- Vacuum fields.



Plasma Loading from RANT3D used with calculated transmission line parameters



RANT3D GEOMETRY

Circuit Parameters from Magnetostatic Calculation

Current Strap: $L' = 2.56e\text{-}7$ H/m, $C' = 1.46e\text{-}10$ F/m
($v_{phase} = 0.545$ c, $Z_0 = 41.9\ \Omega$)

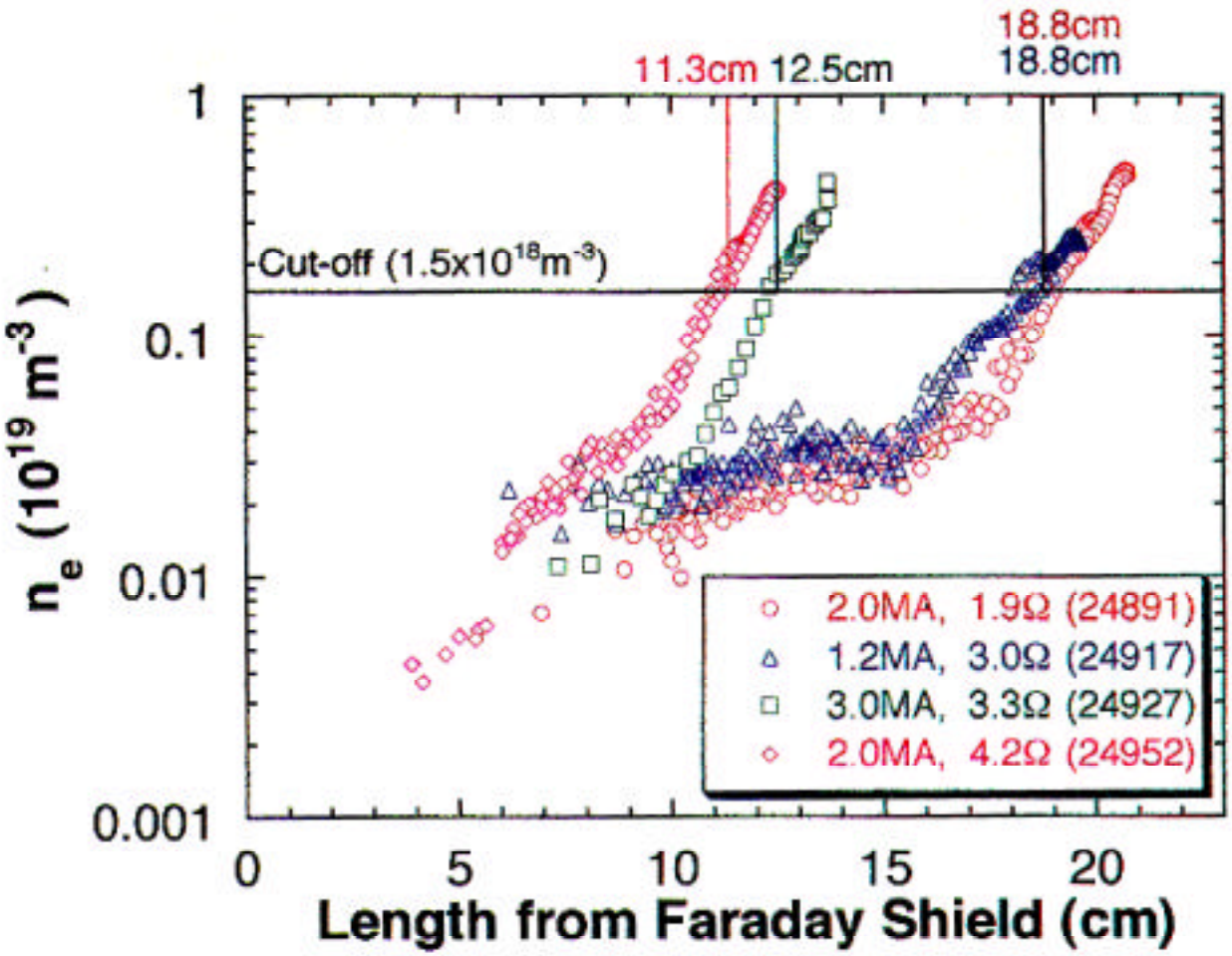
Radial Feed:	$Z_0 = 64.8\ \Omega$	length = 16.5 cm
Rear Feed:	$Z_0 = 79.4\ \Omega$	length = 14.5 cm
Transition:	$Z_0 = 85\ \Omega$*	length = 8.0 cm

Circuit Parameters from ARGUS Calculation

Current Strap: $L' = 2.63e\text{-}7$ H/m, $C' = 1.97e\text{-}10$ F/m
($v_{phase} = 0.46$ c, $Z_0 = 36.5\ \Omega$)

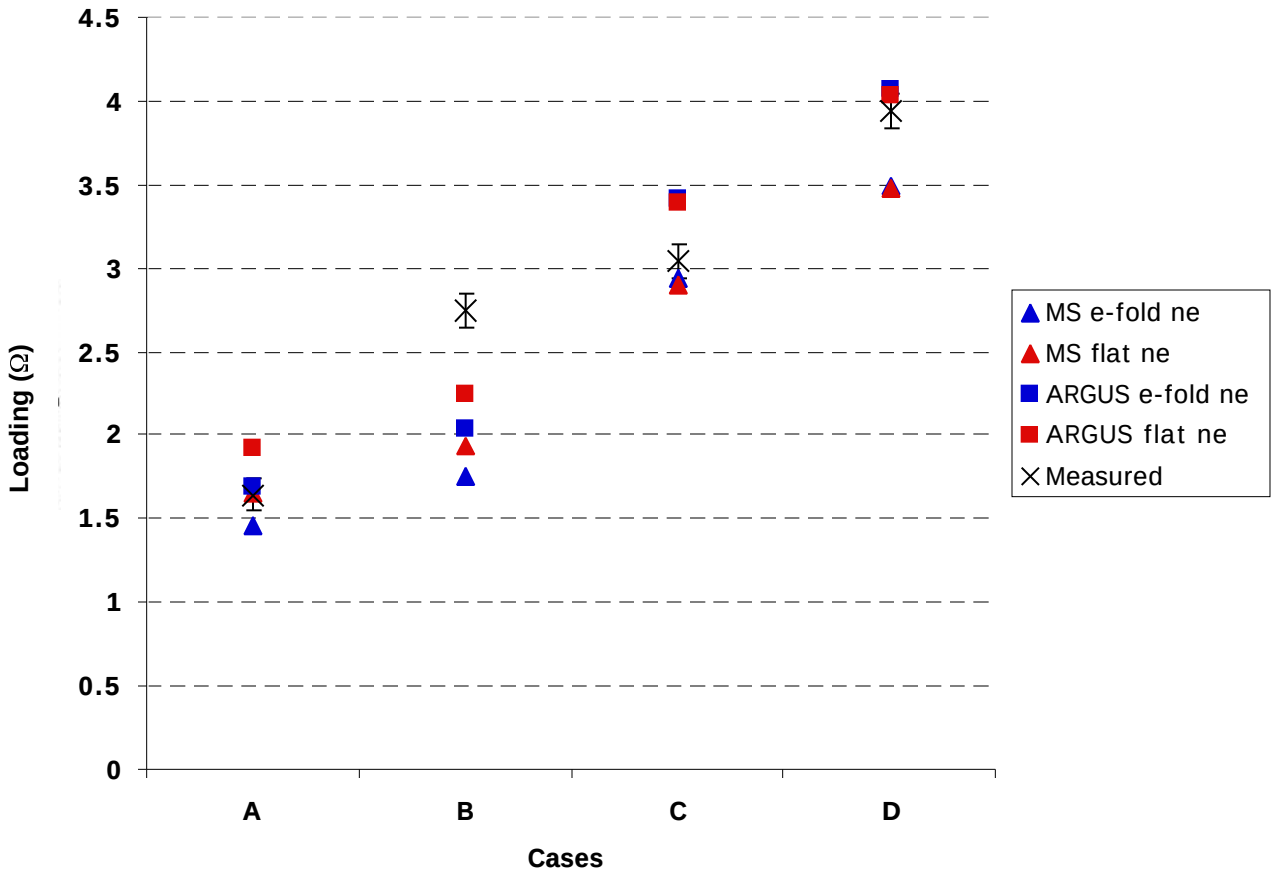
Effective Feed: $Z_0 = 66.4\ \Omega$ length = 39.0 cm

Edge Density Profiles and Corresponding RF Loading Measurements on JT-60U (f = 116 MHz, B = 3.9 T, 5% H)



- Edge density measured with fast reciprocating probe (N. Asakura, et al, Rev. Sci. Instrum. 66, 5428(1995))

Loading Calculations Based on Specific Loading (R´) from RANT3D and TL Parameters



- **Blue values extrapolate the density from the last measured point to the FS using the fitted e-folding length.**
- **Red values use constant density between the last measured point and the FS.**

What We Learned From These Exercises

The TFTR loading analysis emphasized that accurate 3D antenna modeling, circuit analysis, and plasma profile information is needed to account for measured loads.

The JET A2 antenna study gave us experience in asymmetrical, parallel-fed antenna arrays.

- Were able to predict the current division between top and bottom straps as a function of frequency and its effect on the plasma load.
- Predicted the effect of the cross-over strap impedance on loading asymmetries and suggested modifications which were implemented.
- Similar analysis and cross-over strap modifications were made on ASDEX-U antennas.
- Experience was directly applied to the DIII-D HF antenna array designs.

The JT-60 collaboration forced us to develop effective methods of remote communication and was the first successful prediction of loading based on antenna blueprints and profile measurements.

- Demonstrated the importance of the radial feed as an impedance transformer and how it would affect the load at other frequencies.
- The large gap (> 15 cm) had direct application to the ITER antenna design.

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ORNL made a lot of calculations and worked closely with PPPL to make the best choices for the NSTX antenna design

1997, RANT3D used to provide “best guess” for many new issues involved with HHFW in NSTX.

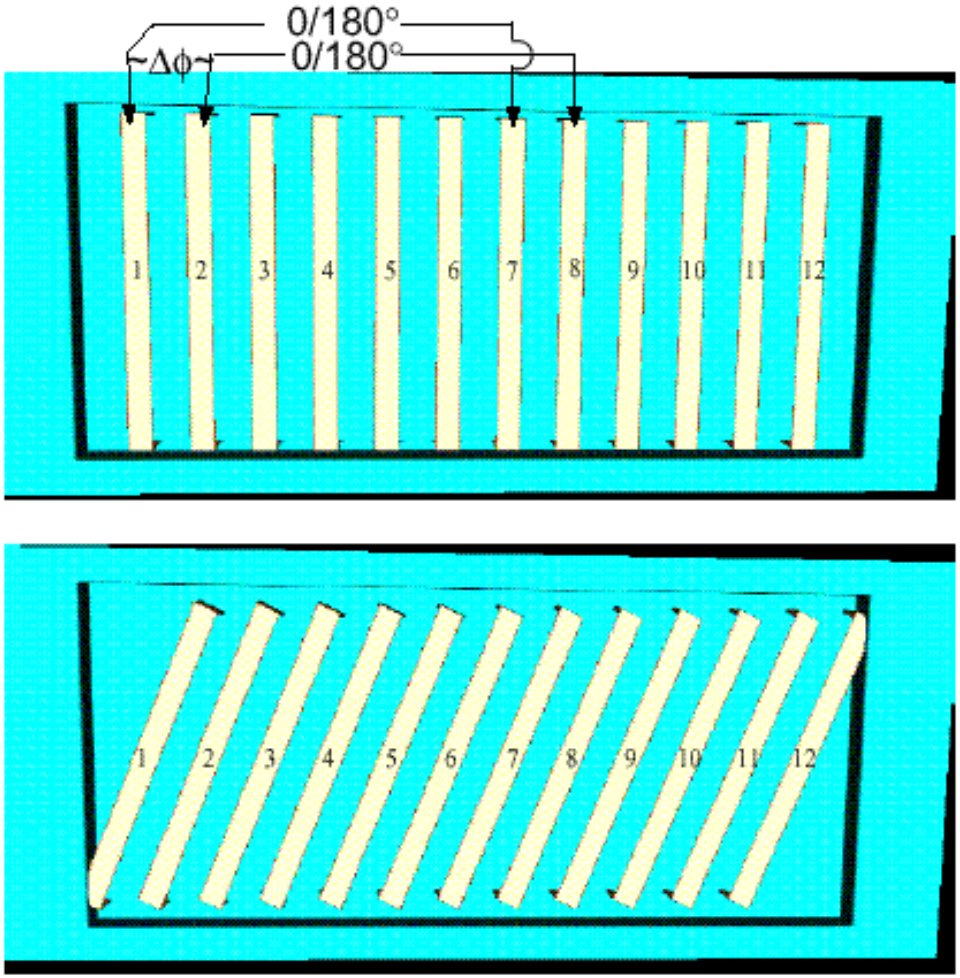
- Plasma profiles were assumed; measured profiles are now available.

Many effects were considered in the design.

- Loading (especially during startup), septa effects on spectrum, and impact of “flat” vacuum vessel wall.
- Tilting vs. non-tilting straps; impact on edge excitation.
- Phase requirements for efficient current drive.
- Penetration into plasma at moderate to high β.
- Effects of moderate to high β and warm/hot ions on current drive efficiency.

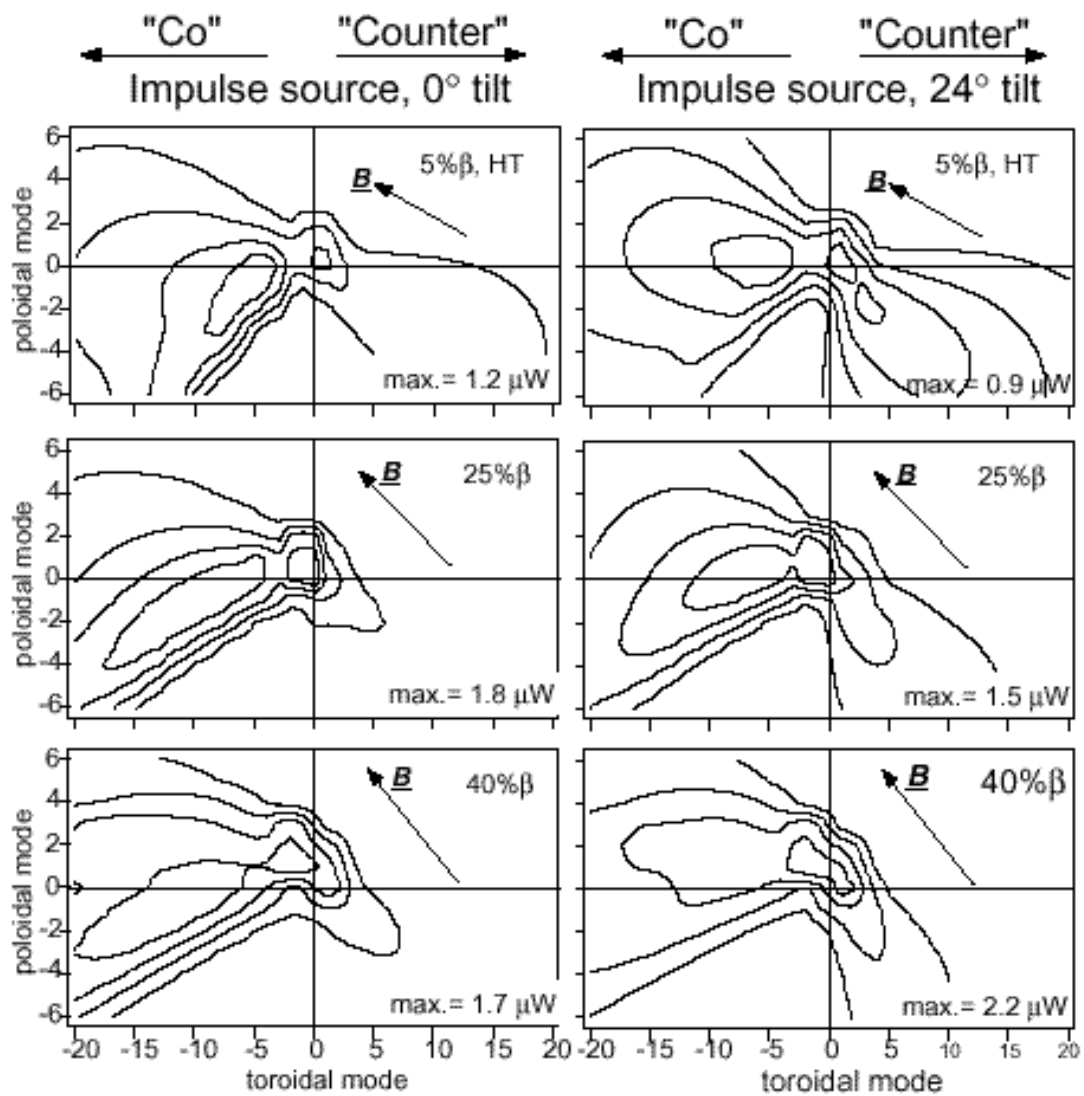
Preliminary NSTX Designs Were Analyzed in 3D

- Number of straps needed for current drive requirements was decided.
- Tilted vs. vertical straps studied.
- Evaluated straps connected in resonant pairs (1-7, 2-8, …) for both 0° and 180° lengths.
- Assumed density profiles consistent with boron nitride local limiters.



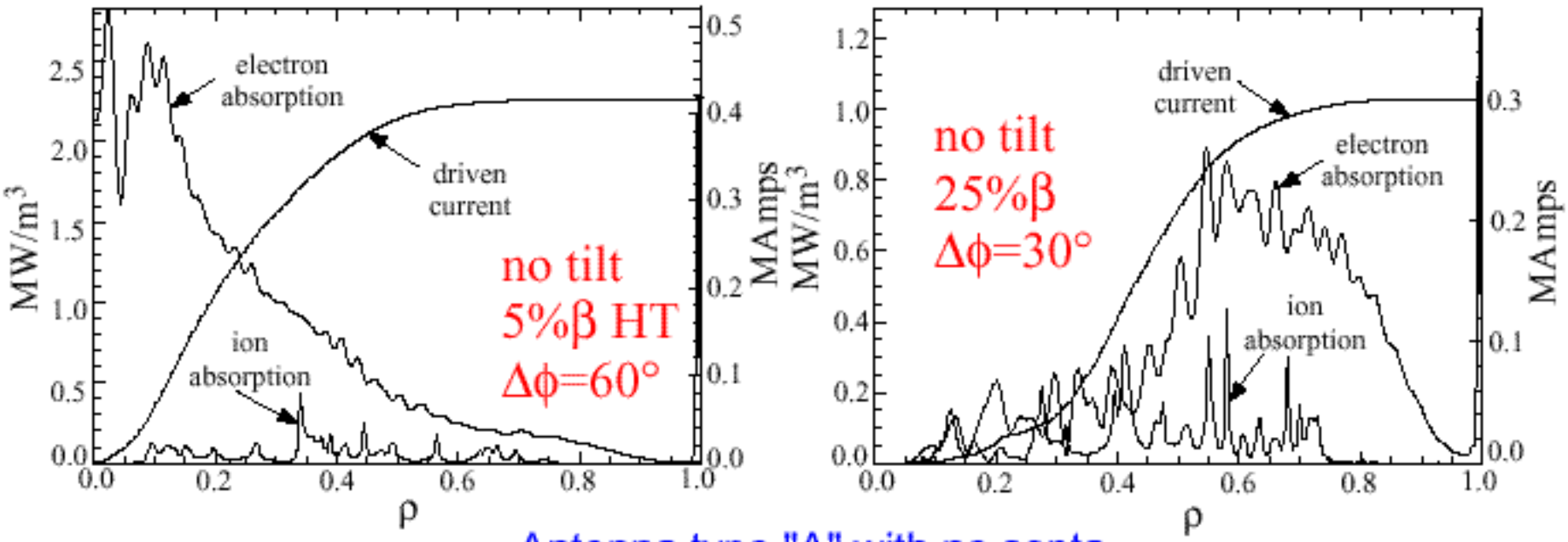
Uniform Fourier excitation is a good survey tool. Plasma response gives design target for optimum mode coupling.

- Compare tilted vs. vertical straps for three different β cases.
- Co-current drive direction is favored.
- Tilting helps loading only in 40% β case, and then only marginally.
- **Vertical strap design was chosen, saving money on antenna fabrication.**



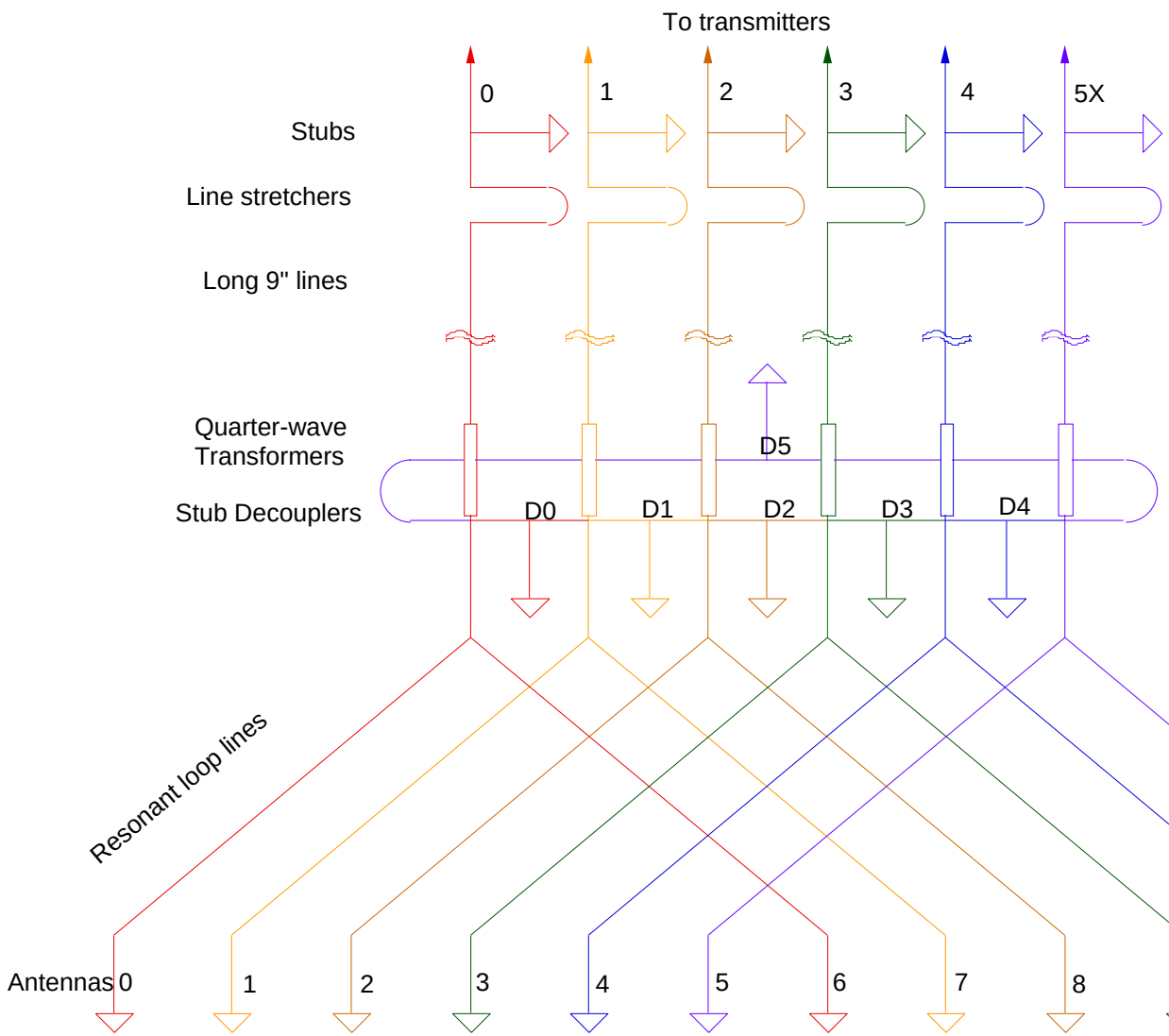
HHFW damping on species from PICES. Broad current profile for 25% β

- Central current drive for 5% β ($T_e = T_i = 1$ keV). Phasing may control current profile.
- Off-axis current drive expected for 25% β ($T_e = 4$ keV).
- 5% H impurity absorbs 12% of power at 25% β ($T_i = 1$ keV)



Antenna type "A" with no septa

Schematic of tuning and matching system; variation of the TPX 6-element array design was adopted.

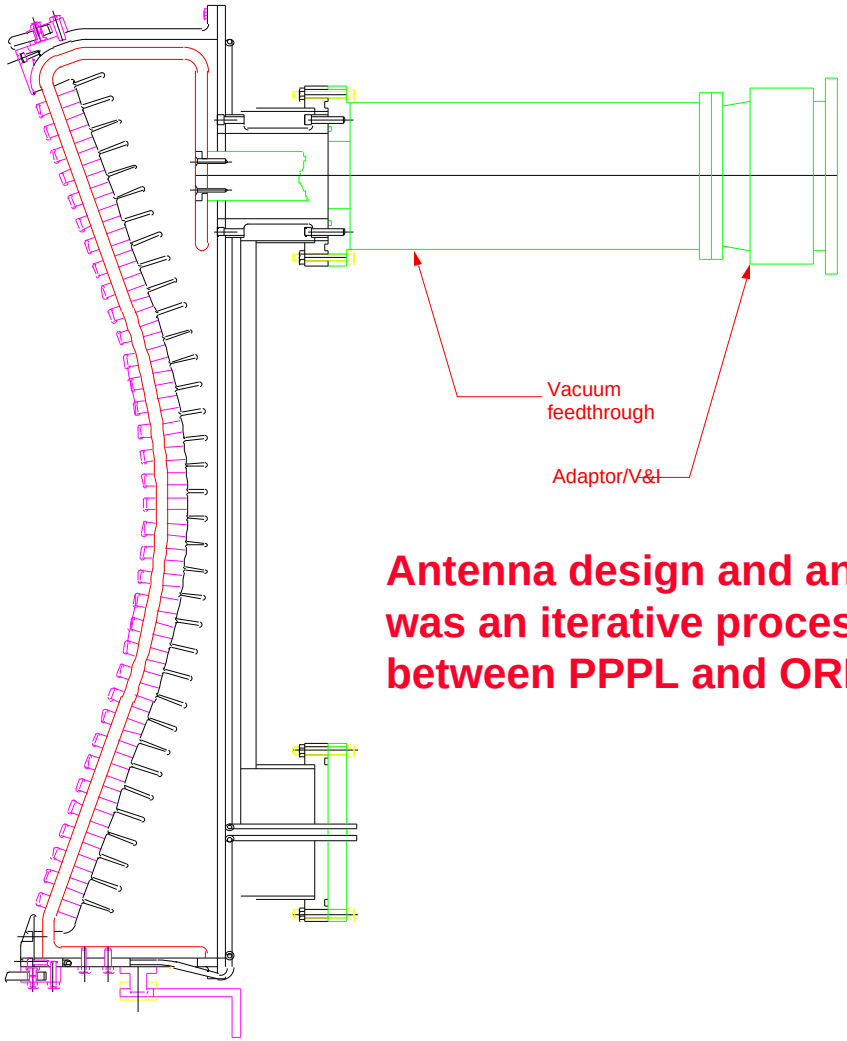


12 current straps
6 resonant loops
6 stub decouplers
6 quarter wave transformers
Strap 0-6, 1-7,... connected in loop, usually π phasing

Design allows rapid phase shift between transmitters and thus spectral control during pulse.

Straps Modeled as Coupled Transmission Lines

Electrical Parameters from 2D Analysis



Antenna design and analysis was an iterative process between PPPL and ORNL

Z_0 = 27.5 Ω, L = 20 cm

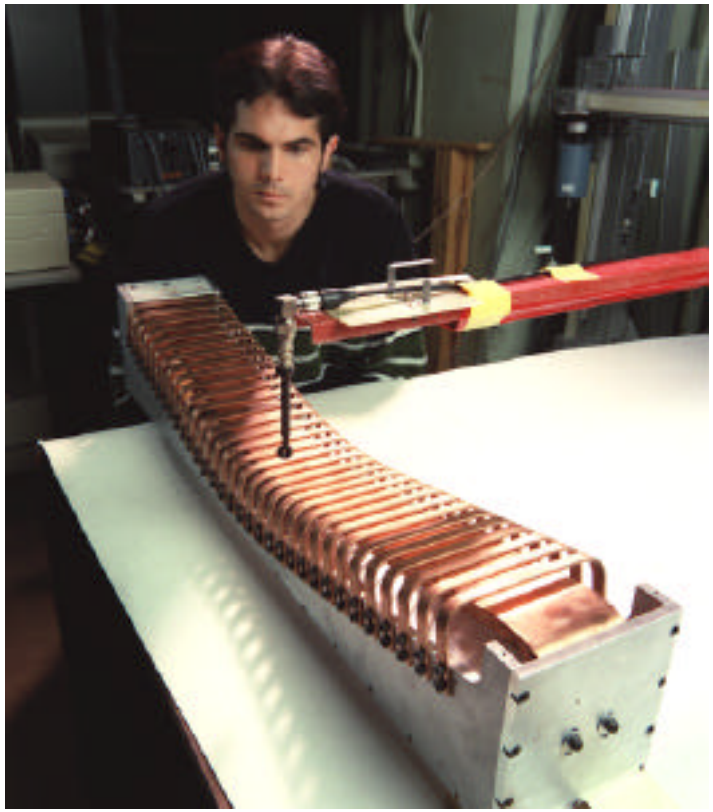
Z_0 = 53 Ω
v_p = 0.52 c
k = 14%
L = 30 cm

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

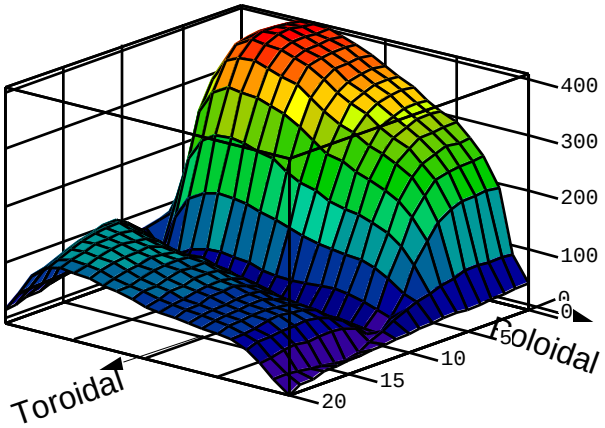
Characteristic impedance (Z_0), phase velocity (v_p), and coupling coefficient (k) for each section of antenna strap

Full scale mockups were fabricated to verify design expectations.

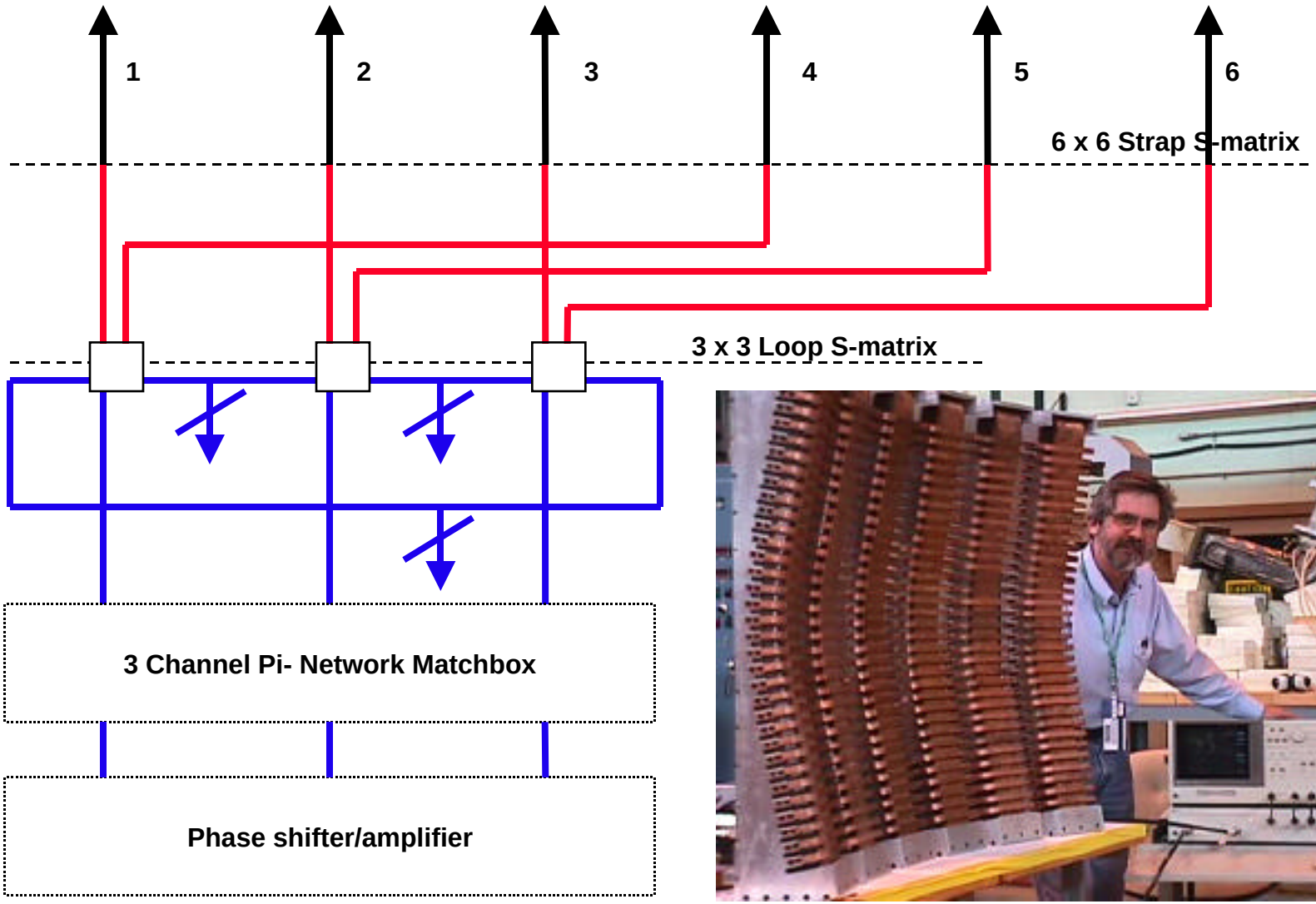


Measurements Made With Network Analyzer:

- **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)**



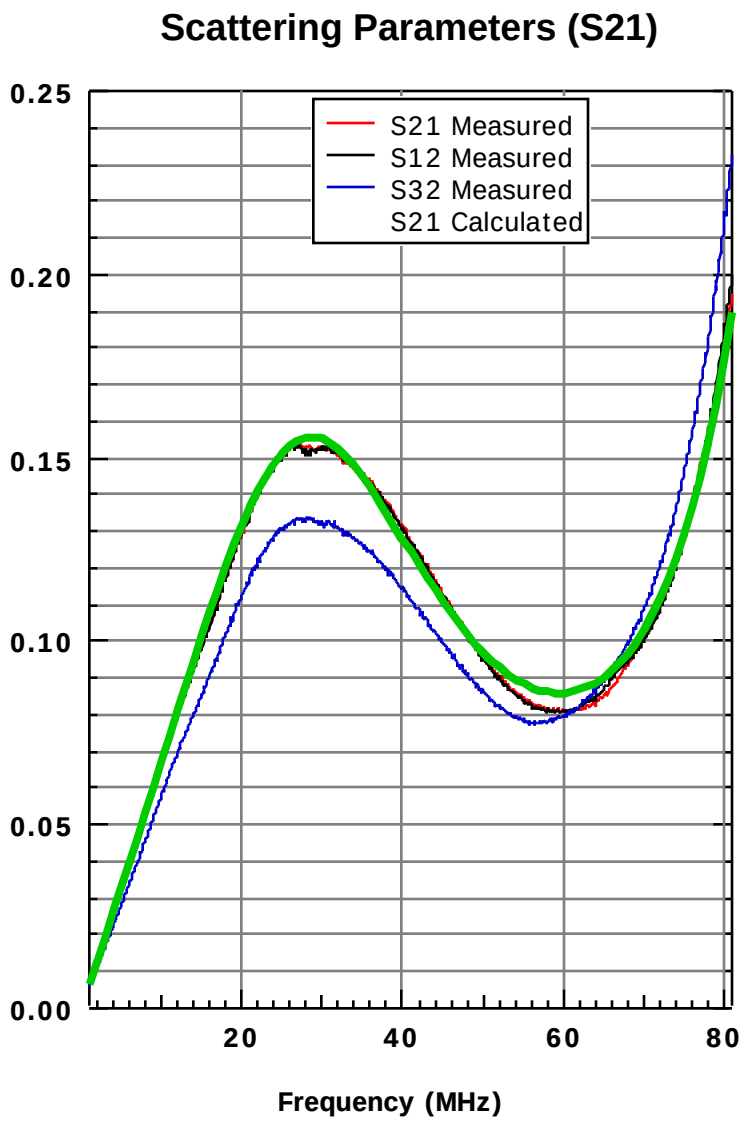
Mutual coupling measurements and decoupler operation studies were made on a 6-element mockup array

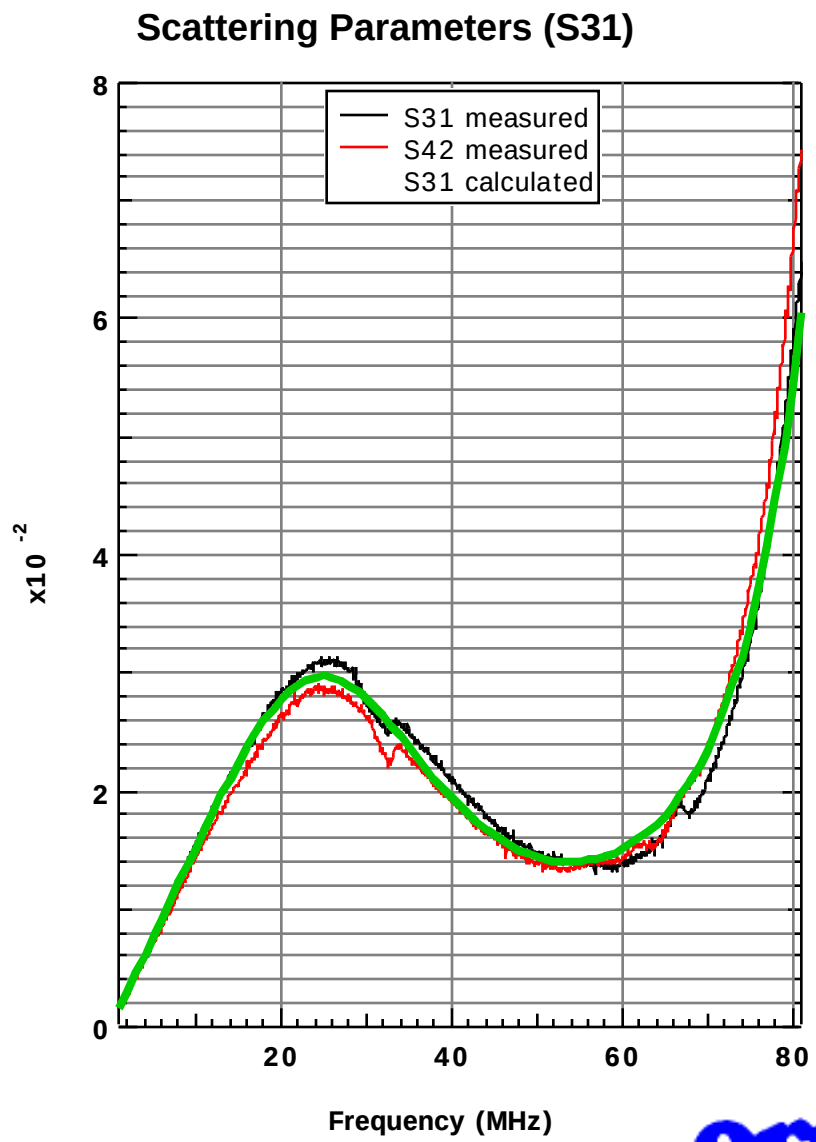


Calculated Values For Antenna Array Were Adjusted to Match Mockup Measurements

		Calculated Design Values	Values To Match Mockup Measurements
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

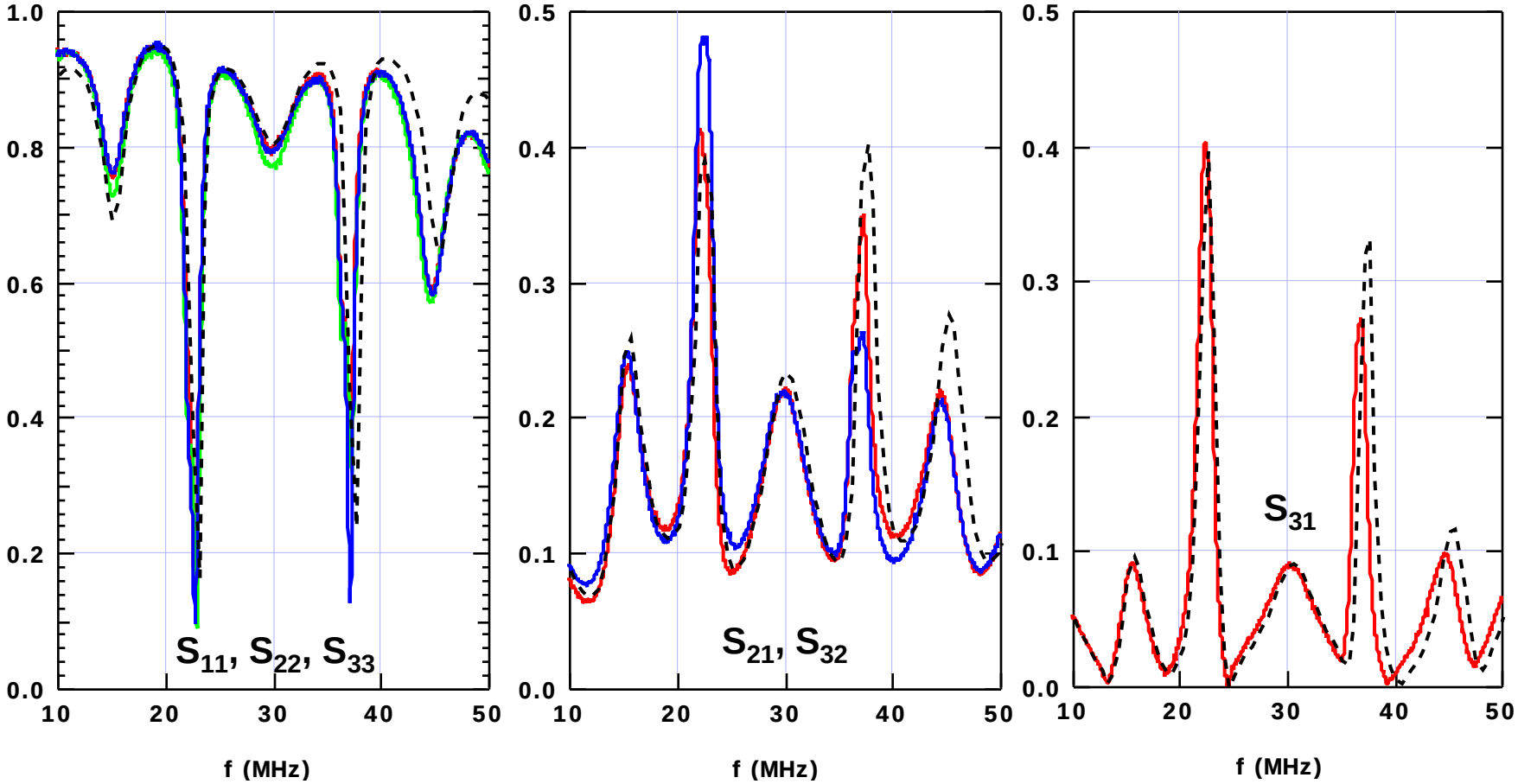
6X6 Scattering Matrix Measured At Array Inputs and Compared to TL Model



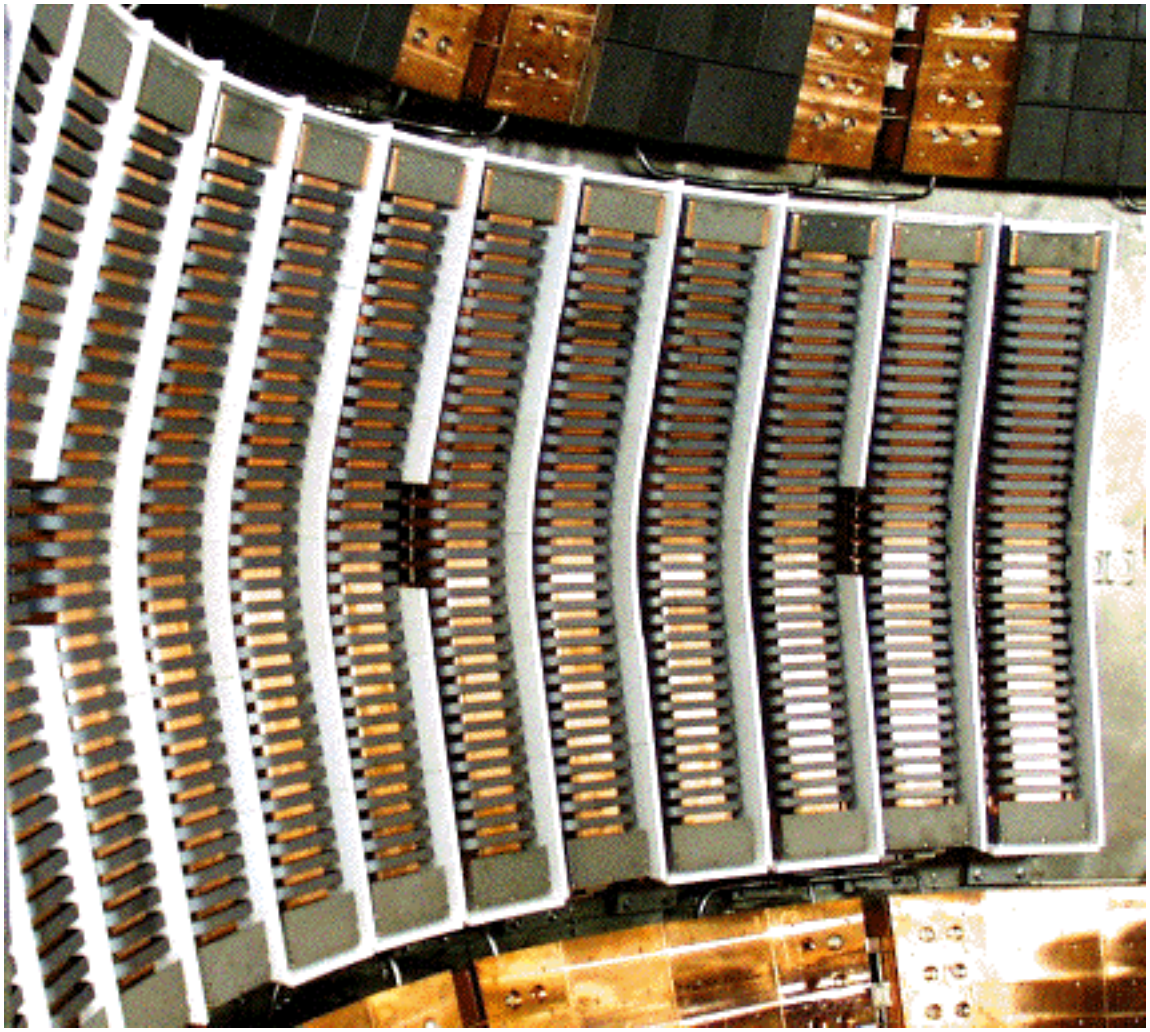


3X3 Scattering Matrix Measured At Loop Ts and Compared to TL Model

- **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**

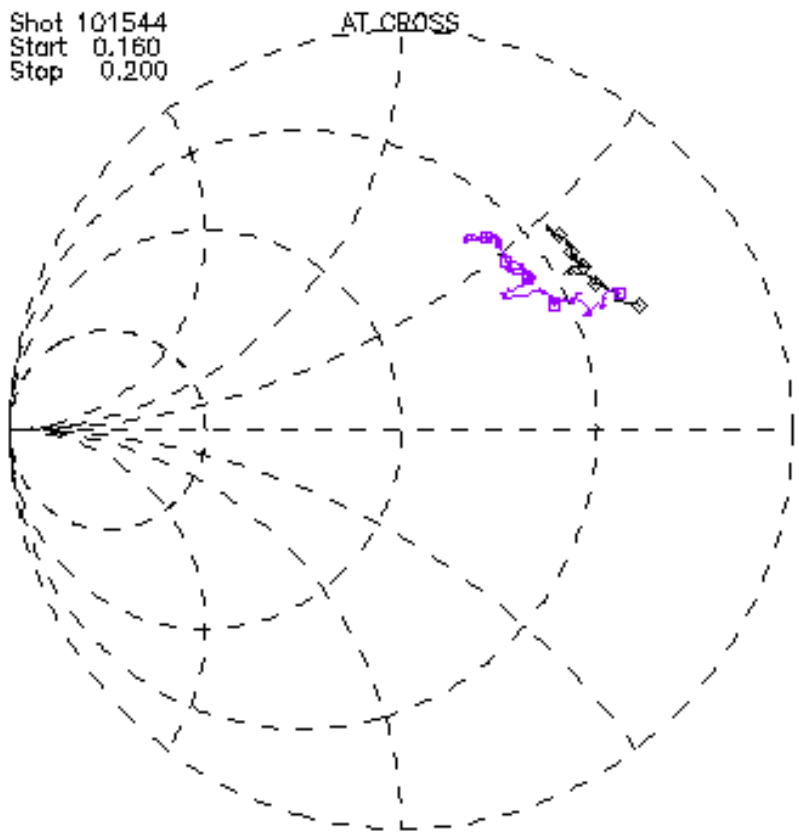


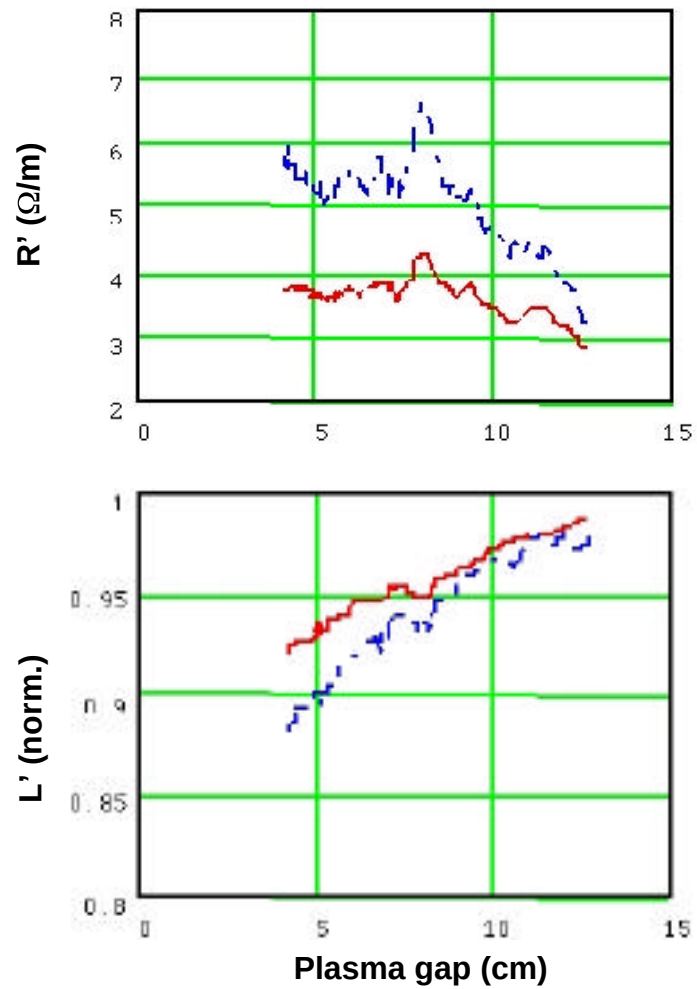
Vacuum Measurements Have Made On The NSTX Array To Refine The Network Model



- Individual Strap Measurements Were Made in July-Aug, 1999 (12x12 S-matrix)
- Post facto measurements of the four resonant loops (4x4 S-matrix) and as connected to two transmitters (2x2 S-matrix) were made in January 2000
- Additional measurements will be made in May-June, 2000.

Analysis of 8-strap, 2-transmitter operation is concerned with plasma loading and observed asymmetries





Reflection coefficient measured at match can be transformed to the loop inputs and finally expressed in terms of specific loading at the straps vs gap.

Ongoing analysis of NSTX HHFW is looking at the changes in the array characteristics by the plasma

- Waves in the plasma edge cause power transfer between the straps in phased arrays.

- This effect is more pronounced in NSTX HHFW than in previous modeling efforts
  - Open antenna design interacts with plasma.
  - Straps have intrinsic large mutual coupling.
  - Large poloidal field component, magnetic shear, broad SOL in density profile give rise to asymmetric plasma response.

    Indications that coupling between straps in the presence of plasma is <u>asymmetric</u>.

- Developing methods to calculate the full array impedance matrix in presence of plasma, using RANT3D.

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Edge Physics/RF Sheaths

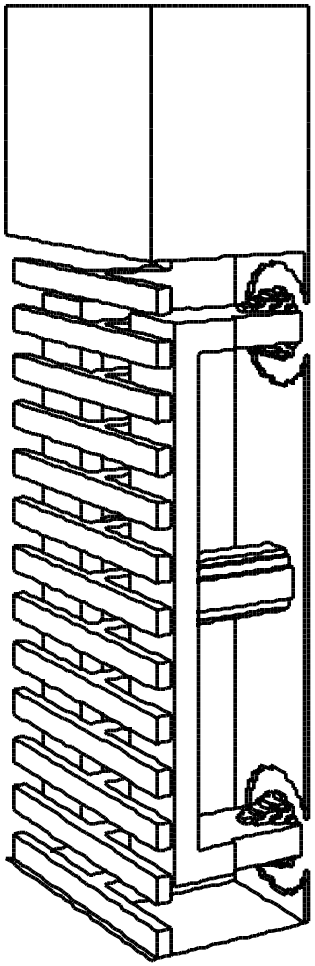
RF sheaths and anomolous heating of plasma facing components can ultimately limit the high power pulse length and give rise to impurity generation and antenna damage.

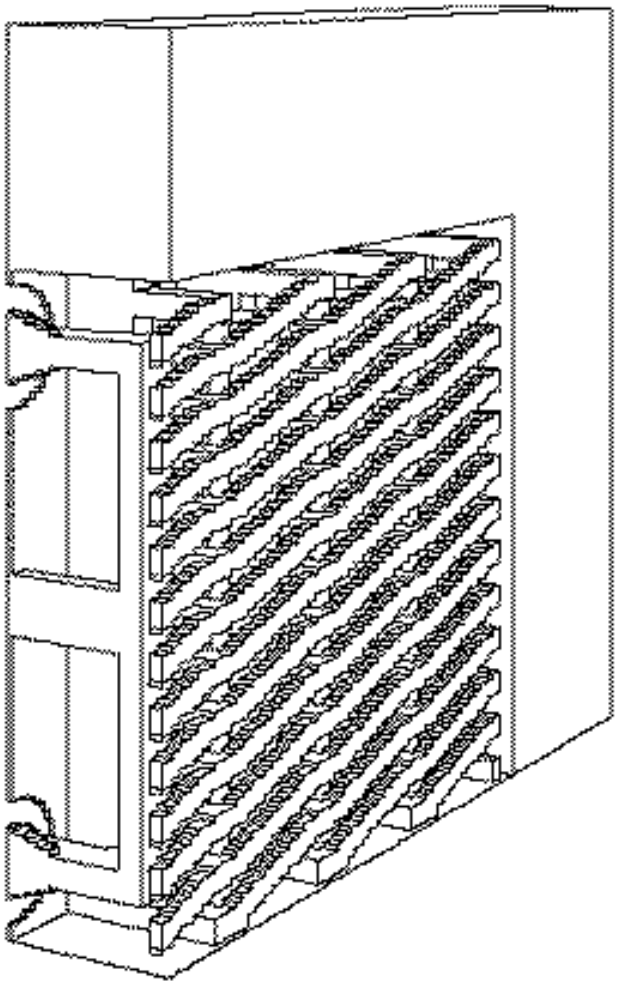
ORNL depends on collaborations for edge physics experiments

- FS vs no FS on DIII-D (Pinsker, Petty, Swain)
- Long pulse experiments on Tore Supra (Beaumont, Haste, Thomas, Harris, Goulding, Carter)
- Future experiments on NSTX

ORNL has collaborated with Lodestar Research to predict anomalous heating from rf sheaths on ITER (D'Ipollito, Myra, Ryan)

ORNL collaborated with Lodestar to predict the heating distribution on the ITER antenna array due to rf sheaths





Lodestar RF Sheath Analysis: ARGUS/ANSAT Results

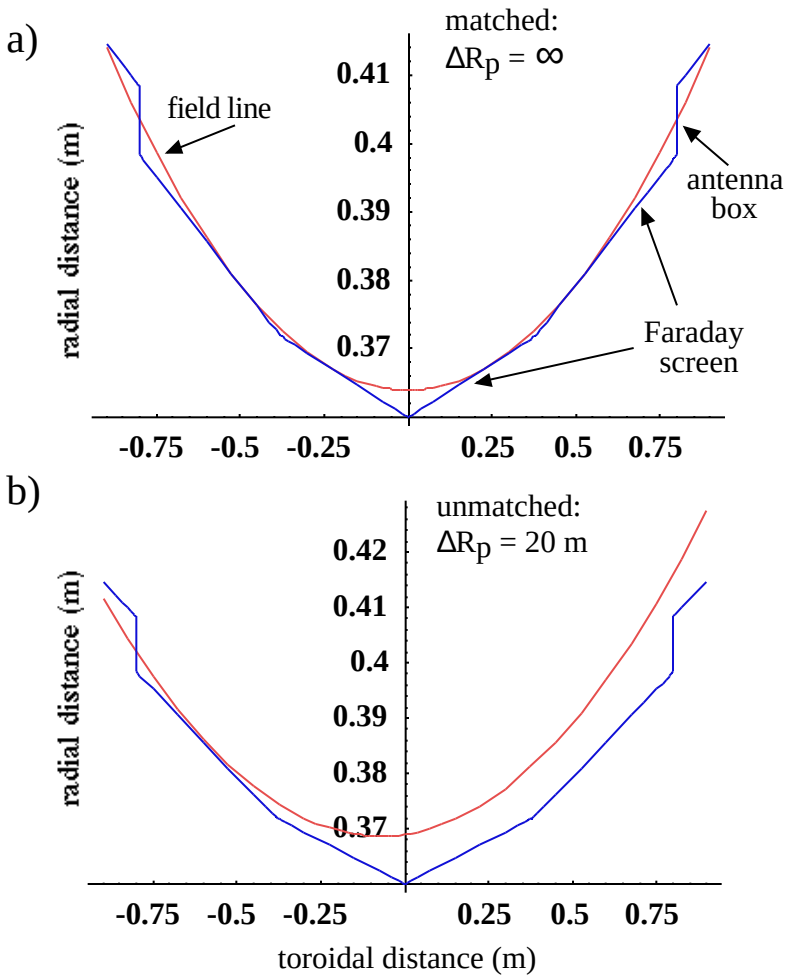
classes of sheaths:

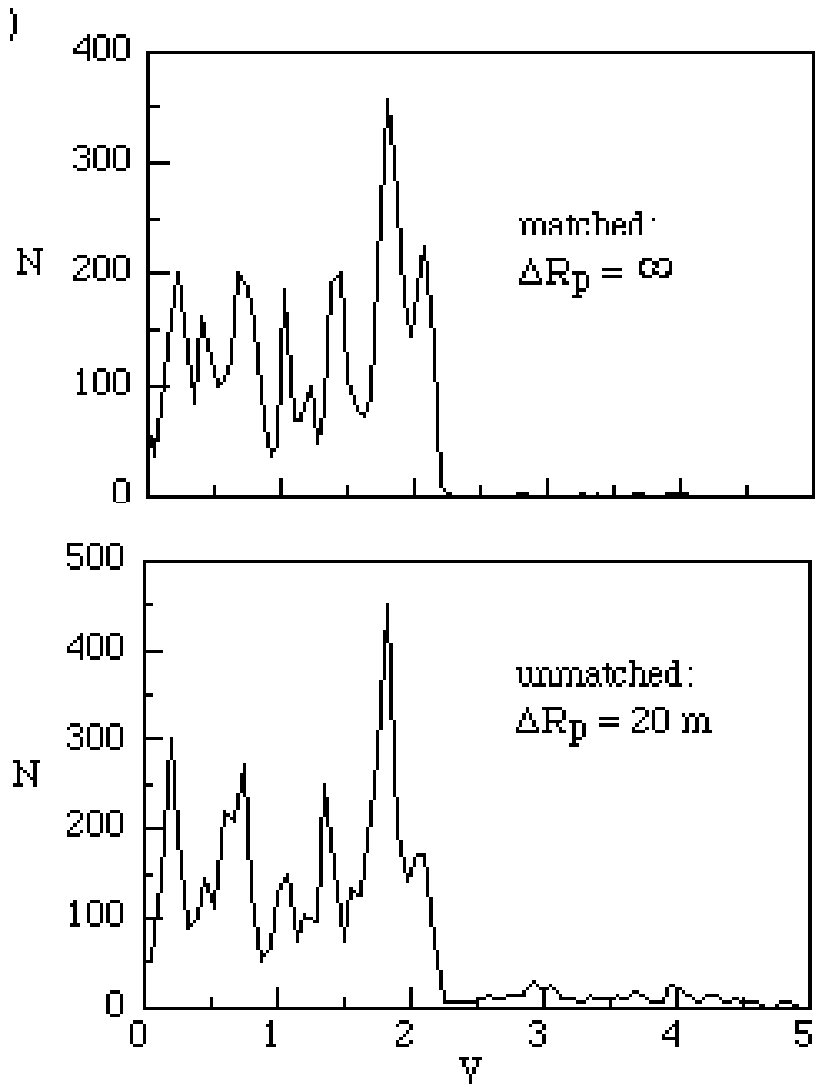
- gap sheaths (between adjacent FS bars)
- front-face sheaths (front face of FS due to toroidal curvature)
- antenna box sheaths (on walls in front of FS)

Large antenna box sheaths exist in monopole phasing and are the most important class of sheaths.

Highest sheath voltages occur poloidally near centers of each strap due to poloidal variations in strap current.

Lodestar RF Sheath Analysis:
Effect of Poloidal Curvature Mismatch

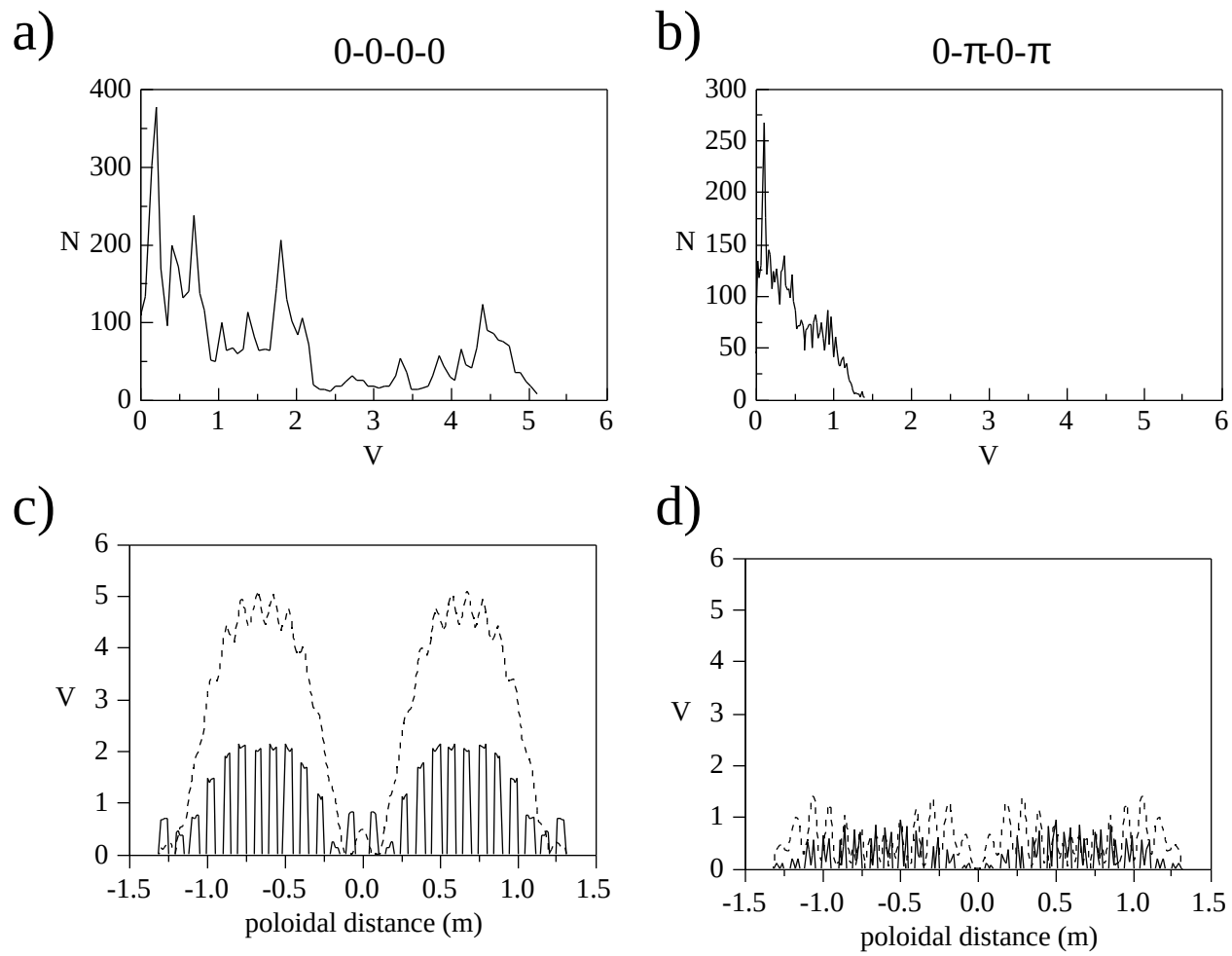




Lodestar RF Sheath Analysis: Effect of Antenna Phasing on Sheaths

Histograms of number of sheaths N vs. the sheath voltage V for monopole and dipole phasings.

Poloidal variation V(y) of the sheath voltage. Solid lines describe the gap sheaths, and dotted lines the antenna box sheaths.



Summary

- Antenna modeling profits from close cooperation between rf theory, technology, and engineering.
- ORNL collaborates with the best rf experimenters in the world, keeping us abreast of developments and giving us broad experience.
- Development of design/analysis tools enables us to tackle new designs with a high degree of confidence.
- Interesting new results coming from NSTX are leading us to new code developments and analysis techniques.