Progress in ICRF Control and Reliability

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

Oak Ridge National Laboratory

DOE Peer Review of RF Technology Program
Oak Ridge, TN
May 9, 2000

ornl

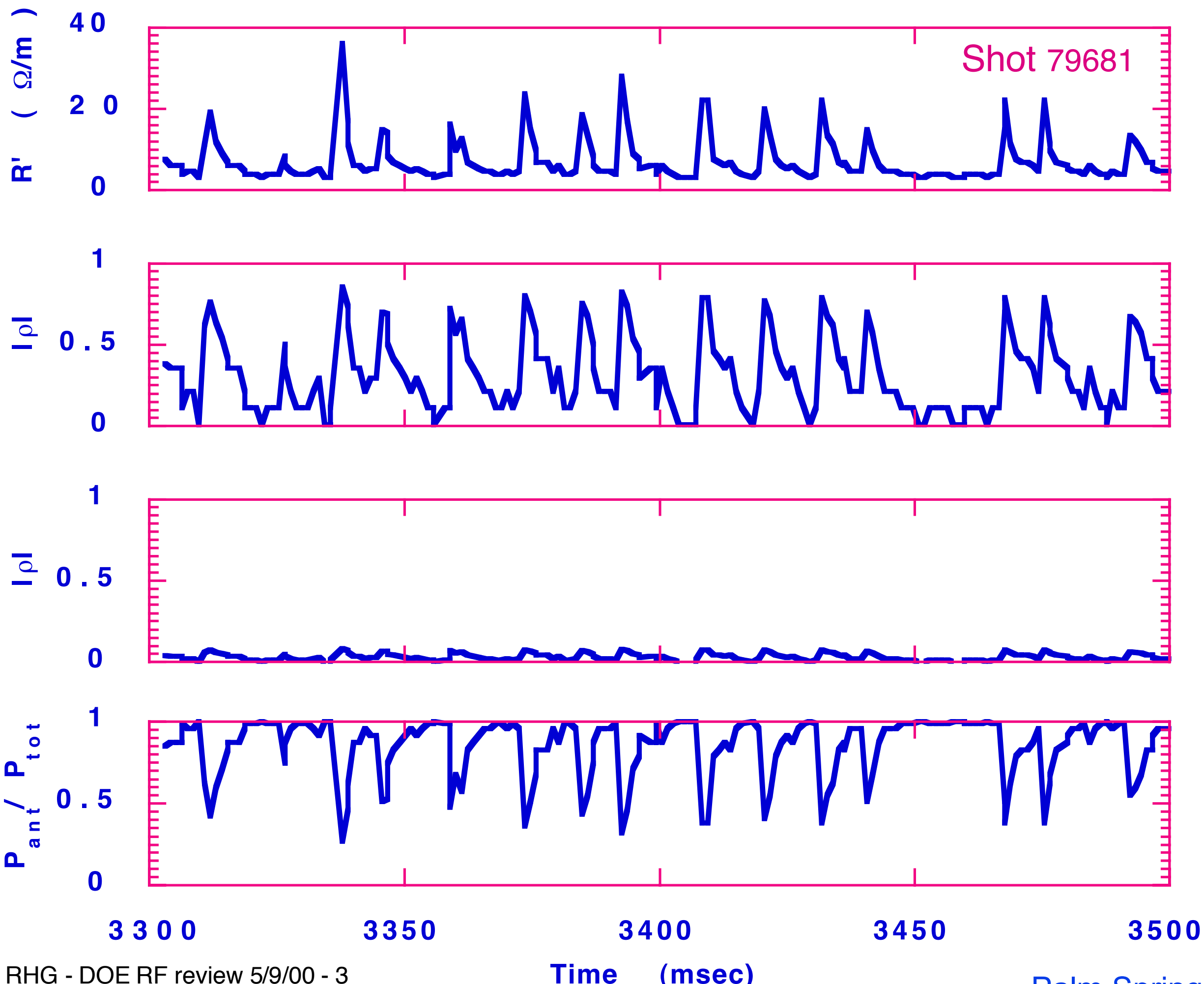
Development areas

- ELM resilient operation
  - hybrid power splitter ELM dump
  - Wideband matching (WBM)
- Arc localization
  - acoustic techniques
  - RF techniques
- Arc/ELM discrimination
- passive RF network analysis
  - JET crossover impedance modification
  - ASDEX-U antenna modification
  - arc/ELM discrimination
  - ELM dump
  - decoupler

ornl

Passive Matching System was first simulated using FDAC

- FDAC calculation using loading data from DIII-D ELMing plasma
- On average, 85% of generator power is coupled to antennas



Resistive loading data

Calculated reflection coefficient, ANTENNA SIDE of splitter

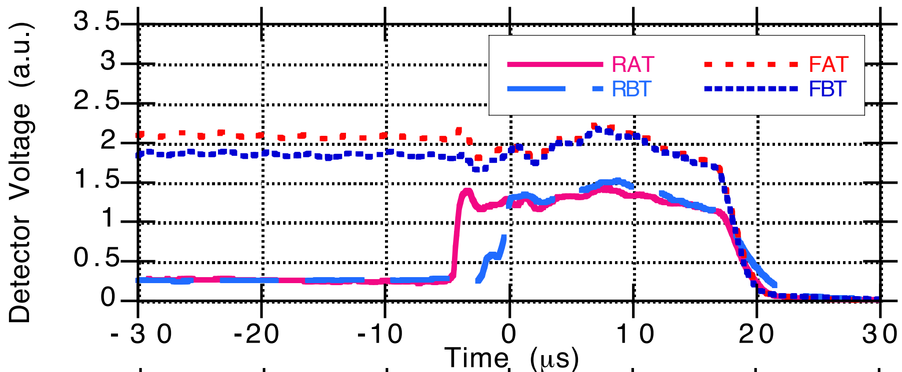
Calculated reflection coefficient GENERATOR SIDE of splitter

Calculated fraction of input power coupled to antennas

Palm Springs RF Top. Conf., May '95

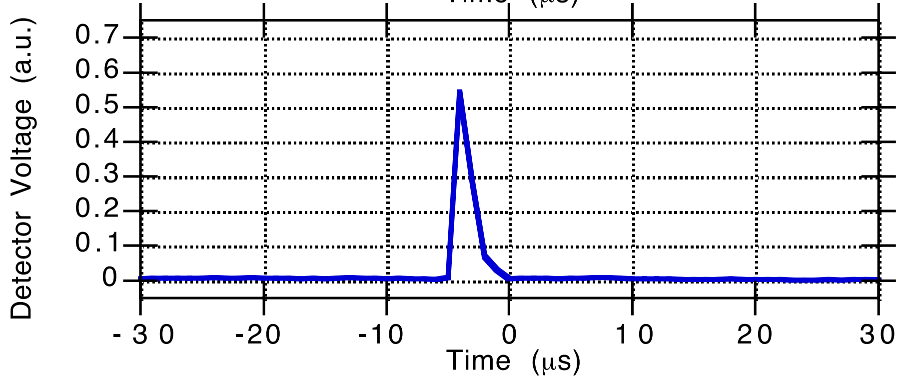
ornl

Measurements confirmed simultaneous reflection cancellation - Results presented at IPP-Garching



Voltages sides A and B

RAT - A reflected
RBT - B reflected
FAT - A forward
FBT - B forward

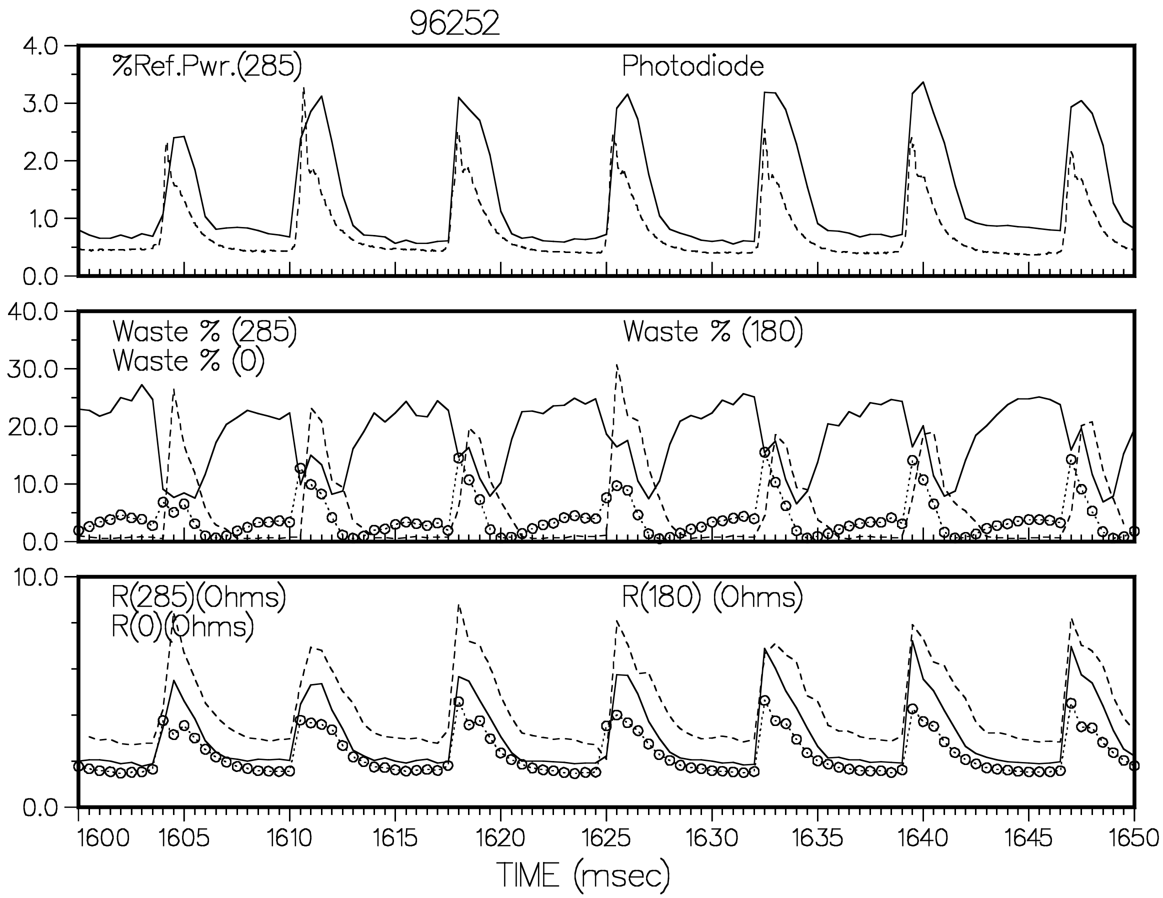


Reflected voltage at generator

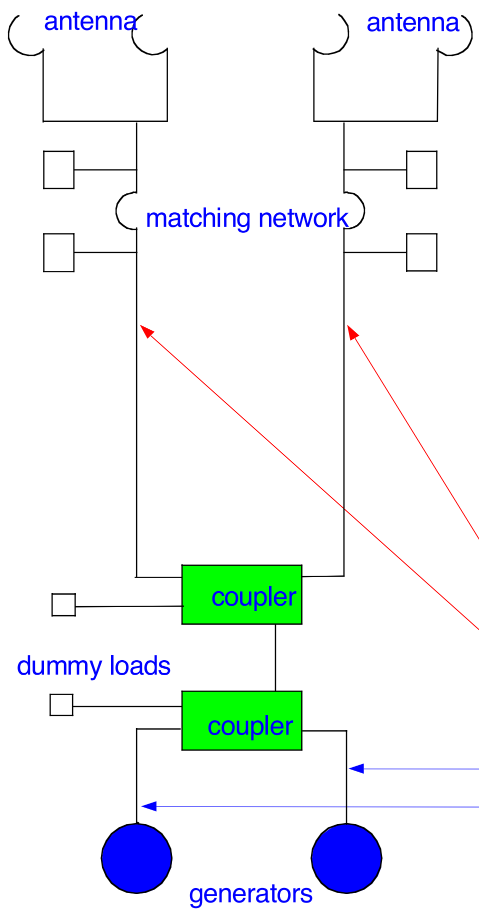
- Fast measurement of rare simultaneous side A/B arc made during plasma operation (shot 86649)
- During period that side A reflected voltage is high, with side B low, reflected wave is clearly seen at generator
- During period with both reflected voltages high, reflected wave at generator is suppressed
- Almost all arcs occur on one side only – are seen at generator – ELMs are not

ornl

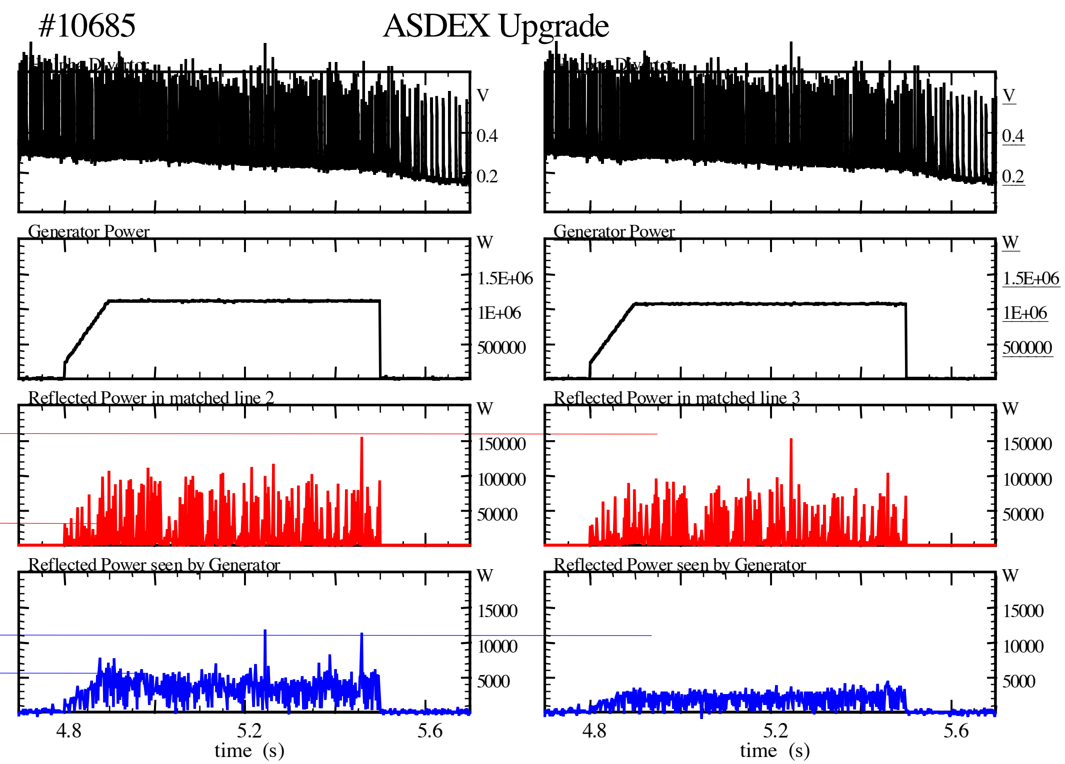
Operation of the DIII-D FWCD Systems in ELMing H-mode Discharges



Reflection Due to ELMs Strongly Reduced by use of 3dB Couplers at ASDEX-U



Compare the reflected power in the matched line
to the reflected power seen by the generators



Max-Planck-Institut für Plasmaphysik
EURATOM Assoziation

98.195

note: produced ~ 50% power increase into ELMing plasmas!

ornl

Generator Power is greatly increased through the use of a hybrid coupler

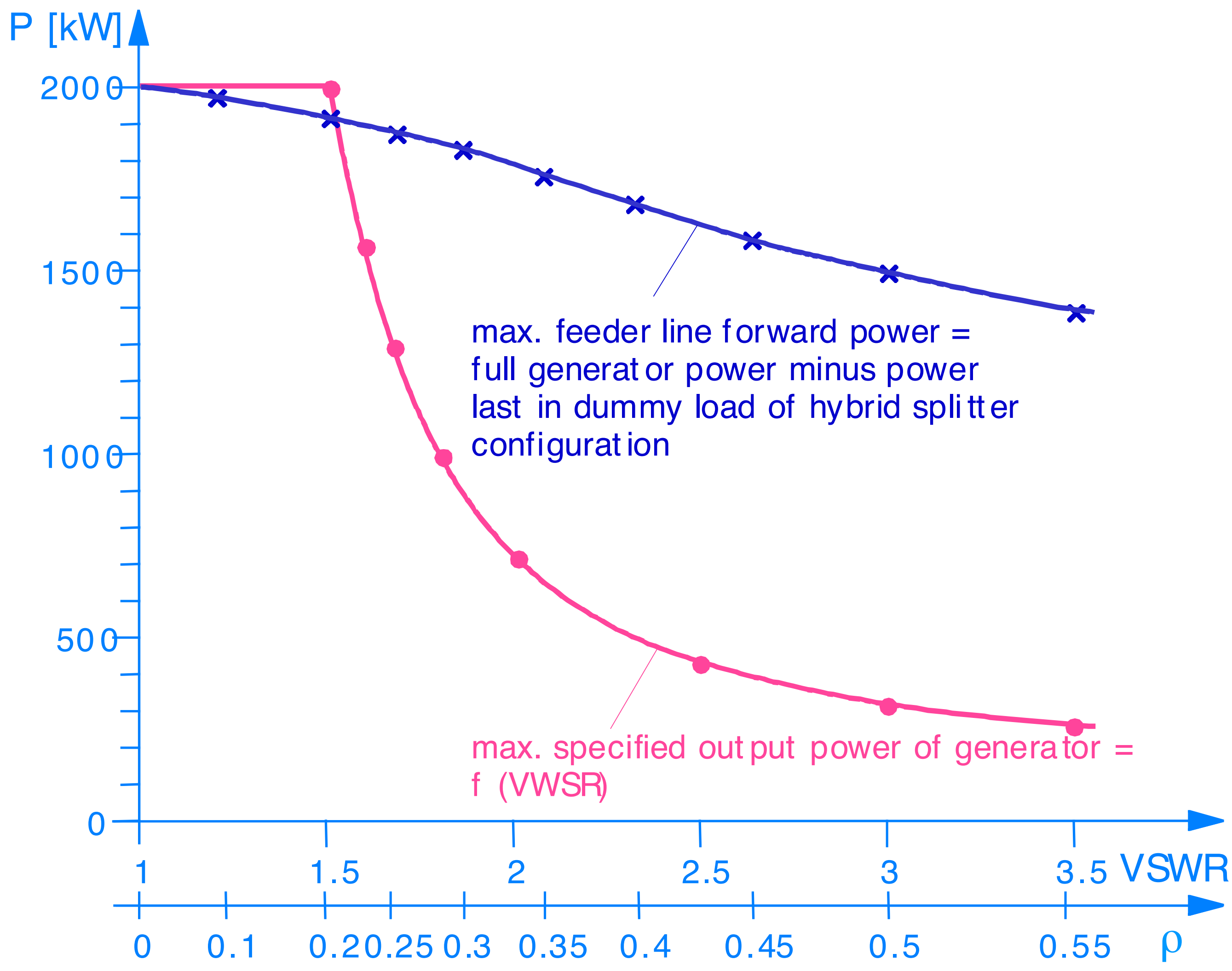
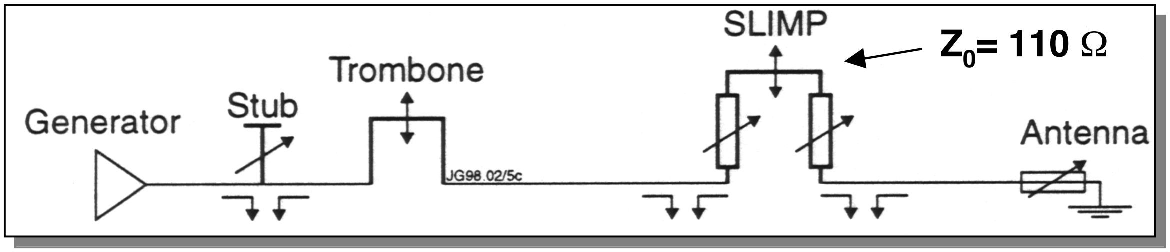


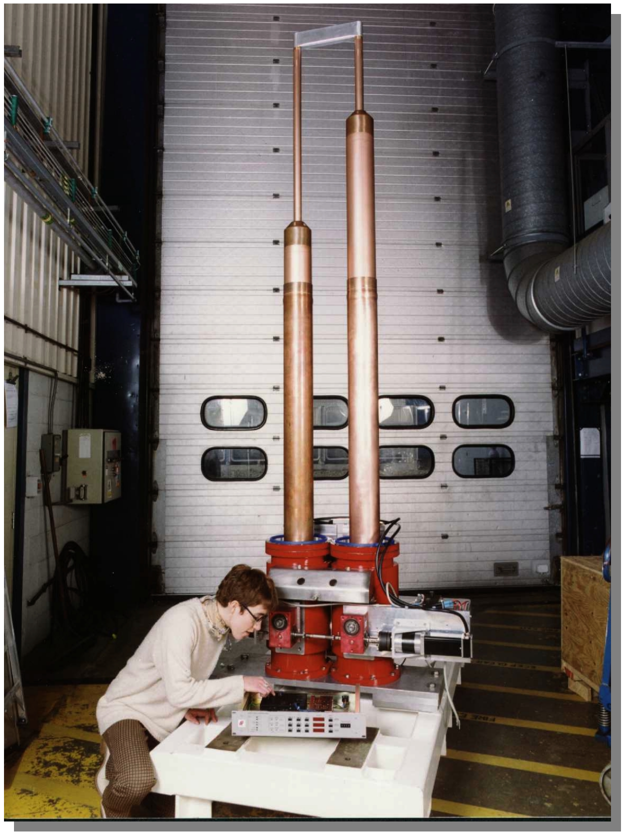
Fig. Comparison of Gen. Power with / out Use of Hybrid

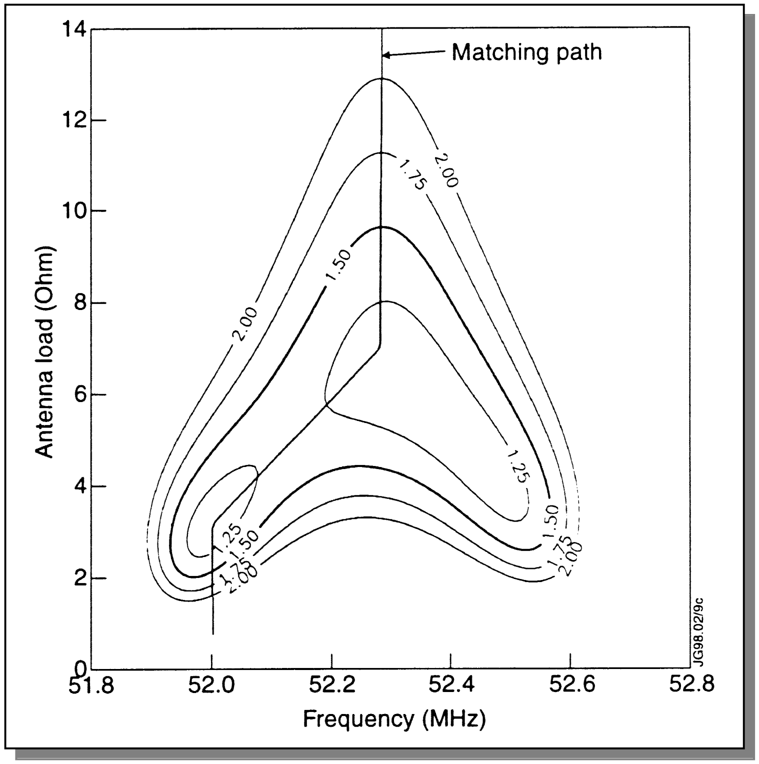
Use at JET currently being considered

- Simultaneity of ELMS at different ports will be measured in May 00
- ORNL will model anticipated performance using FDAC
- Incorporation of hybrid couplers for ELM resilient operation incorporated into JET ICRF enhancement proposal
- Use of passive ELM handling compatible with and complementary to frequency shift matching system
  - Biggest drawback, loss of efficiency, is eliminated by frequency shift matching
  - Voltage transient at anode eliminated, removes need for adjustable line lengths on matched side of stub tuners

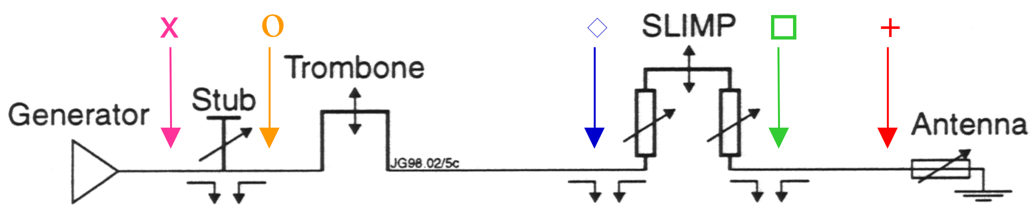
The JET wideband matching "SLIMP" system





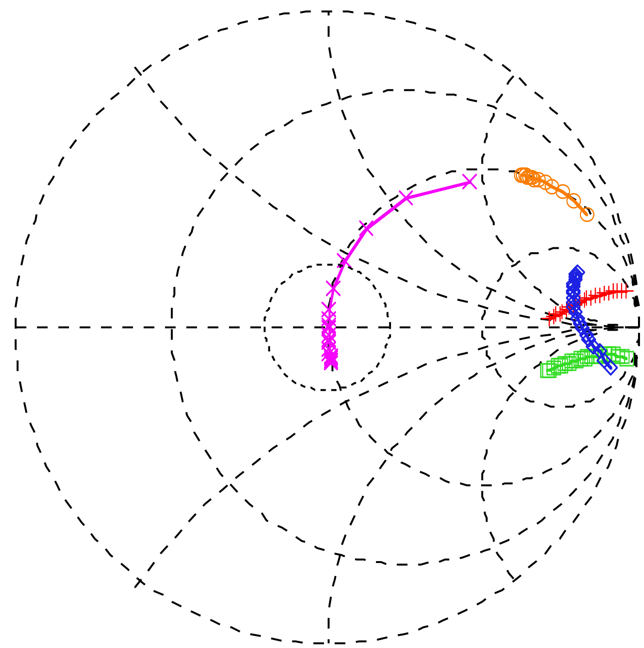


Wideband matching method



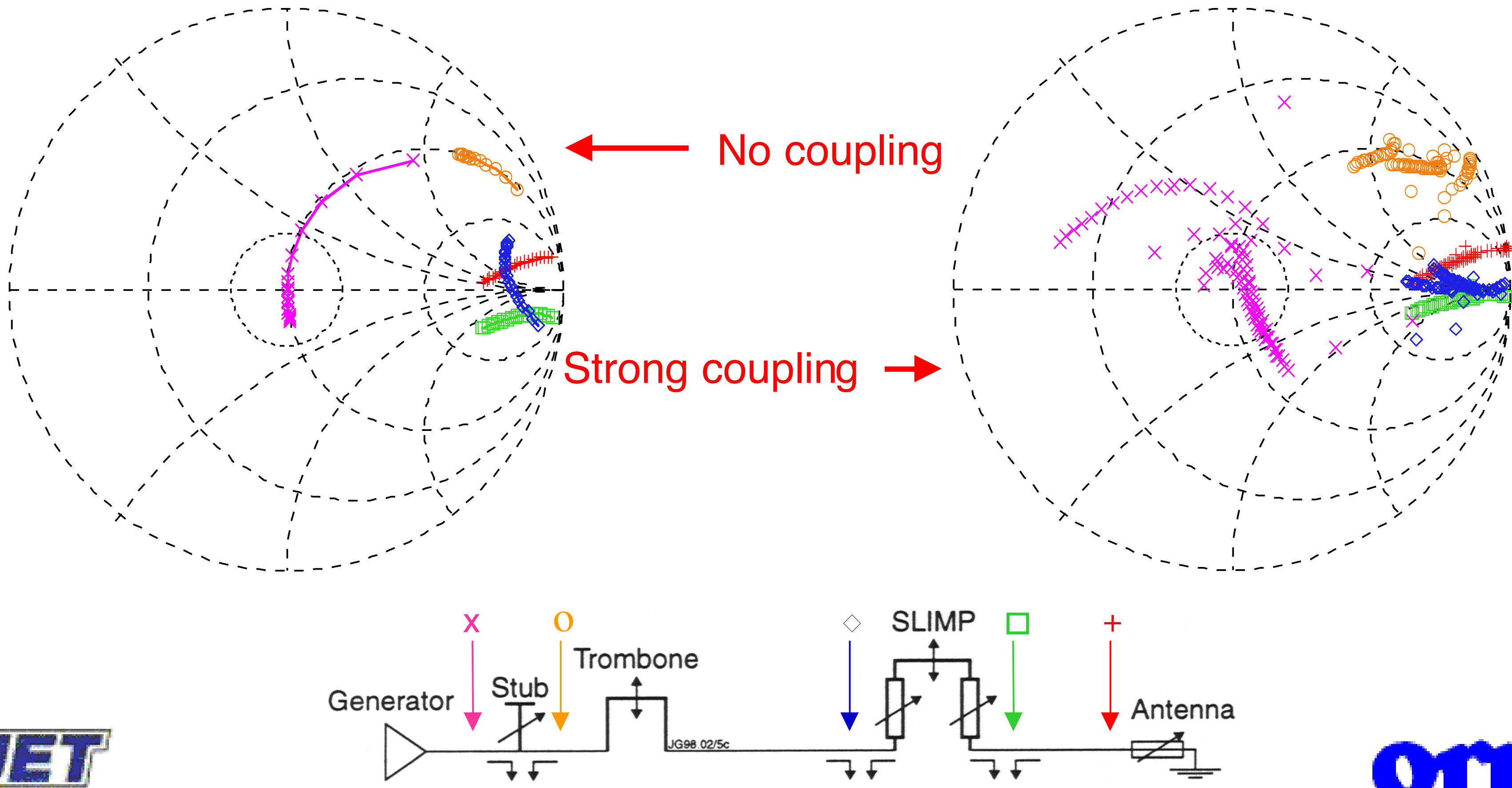
- Pre-matching SLIMP transforms change in reflection coefficient (ρ) magnitude to change in angle
- Frequency is shifted for each R value the proper amount to put ρ on the $R = Z_0$ line on the load side of the stub
- Stub adds susceptance to minimize $|\rho|$ at generator

Input impdedances at marked locations



WBM technique has trouble with π/2 phasing and strongly coupled antennas

- Problem caused by greatly reduced effective loading on one strap
- ORNL will model performance of actual system with FDAC



JET

ornl

Status of JET wideband matching system

- SLIMP has operated at high power on module C
  - "SLIMP off" case tested (high impedance lengths minimized), does not reduce power handling
  - Algorithm for setting SLIMP lengths successfully tested by sweeping frequency and varying outer gap radius to change loading
- Commissioning of other modules to take place starting in May
- Fast frequency shift control circuitry will be commissioned this summer

RHG Assignment to JET

- WBM fast frequency commissioning
- FDAC modeling of WBM performance with mutual impedances
- ELM simultaneity measurements
- Investigate implementation of arc localization on JET
- Participate in antenna enhancement discussions, facilitate ORNL involvement modeling enhancements

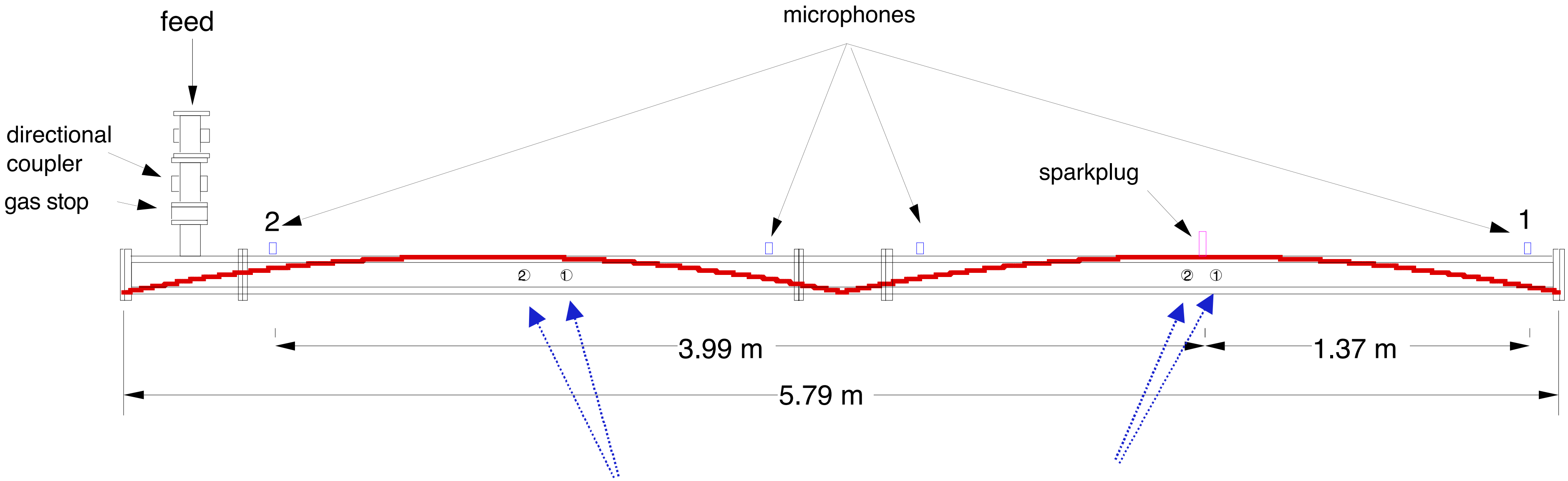
ornl

Impact: WBM relevance to US program

- WBM technique can significantly increase attractiveness of RDL configuration if it can be successfully applied to it
  - Highest power density conventional antenna is RDL
  - Biggest drawback - internal matching components
  - Tore Supra is developing alternates to capacitors, but require external matching in addition to internal pre-match
  - Frequency-shift matching can greatly reduce external matching requirements, allow RDLs to be used more effectively in plasmas with loading transients
- JET has developed general approach to dual-resonance matching - we will apply to RDL design where internal matching and external matching are integral to overall matching system design
- Developing WBM for RDLs will greatly enhance performance capabilities of this high power density launcher

Arc localization / impedance measurement test line

- DIII-D 6” coax test line



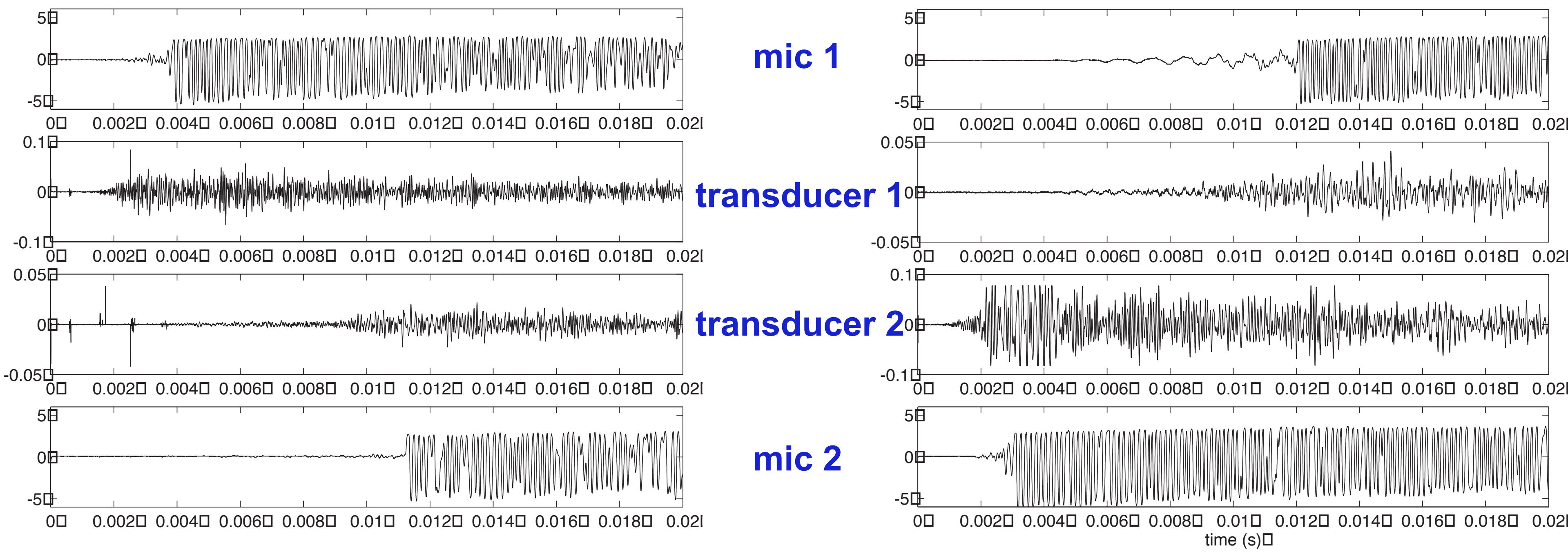
Arc positions determined independently by microphones 1 and 2 (indicated by circles)

- Arcs produced at spark plug and near other voltage maximum (by applying higher power)

Acoustic measurements

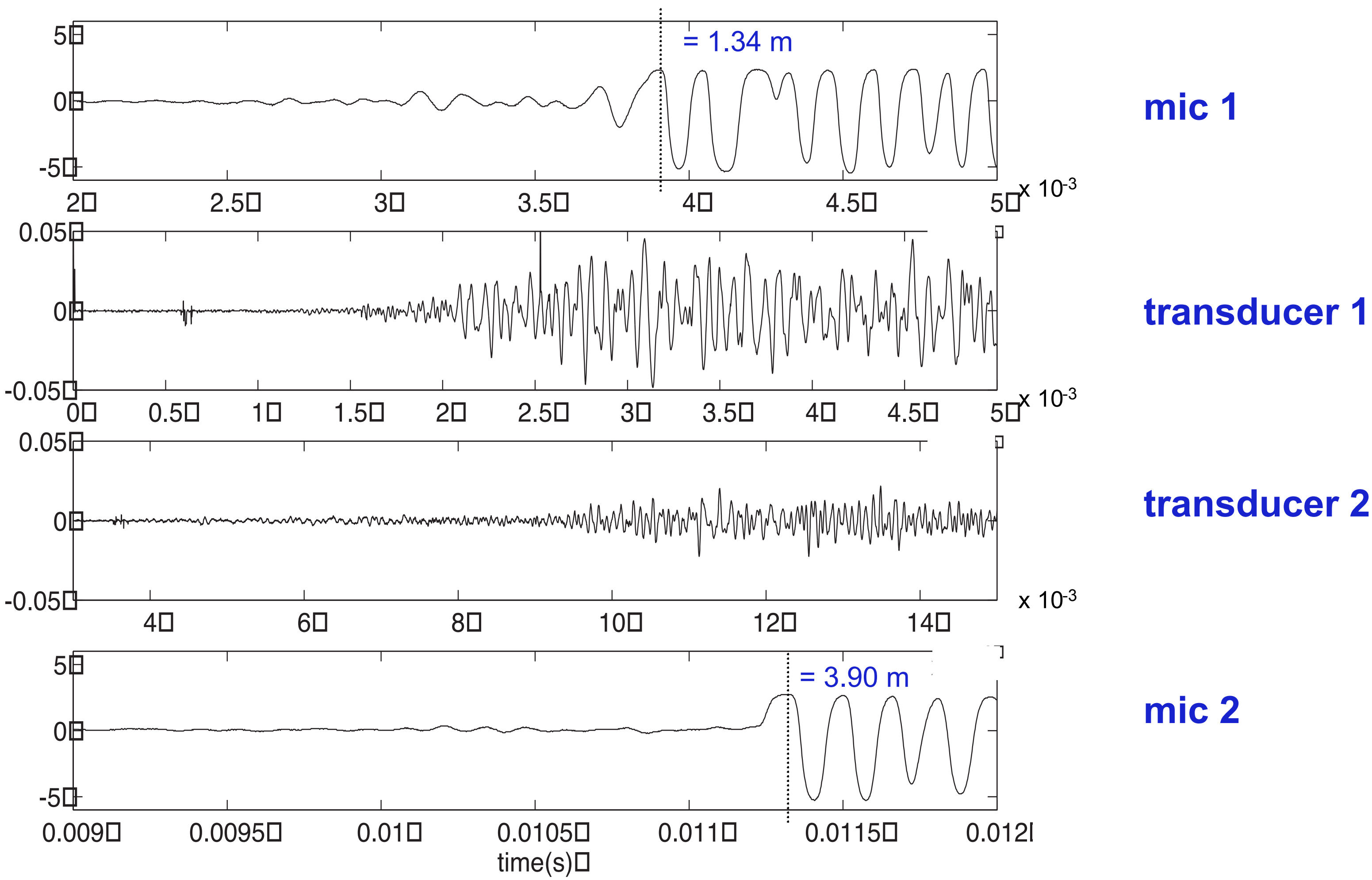
Arc near sparkplug, P = 30 kW

Arc near other voltage maximum, P = 60 kW

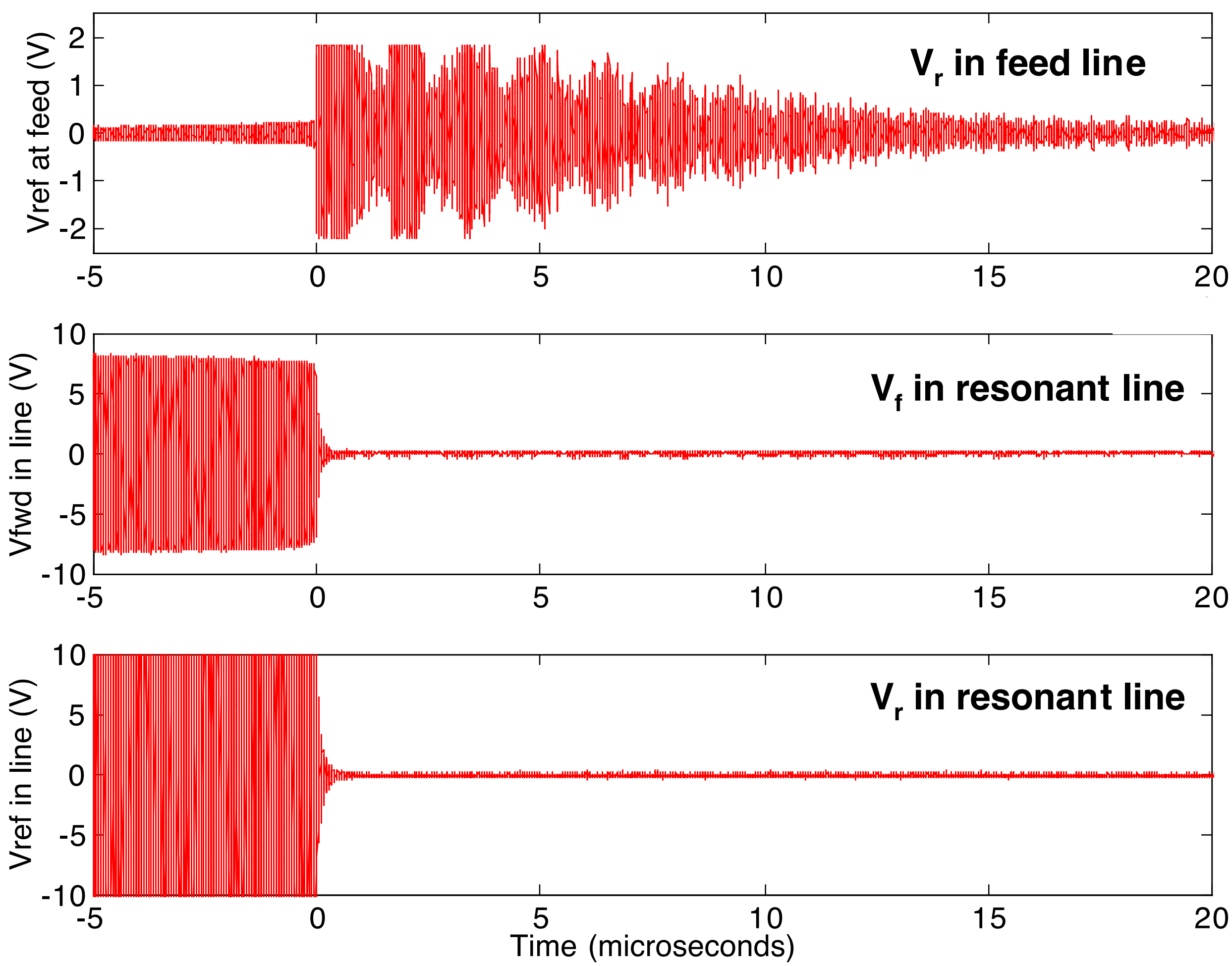


- **Microphones measure sound through gas**
- **Transducers measure sound through coax metal walls**

Acoustic measurements with expanded time axis



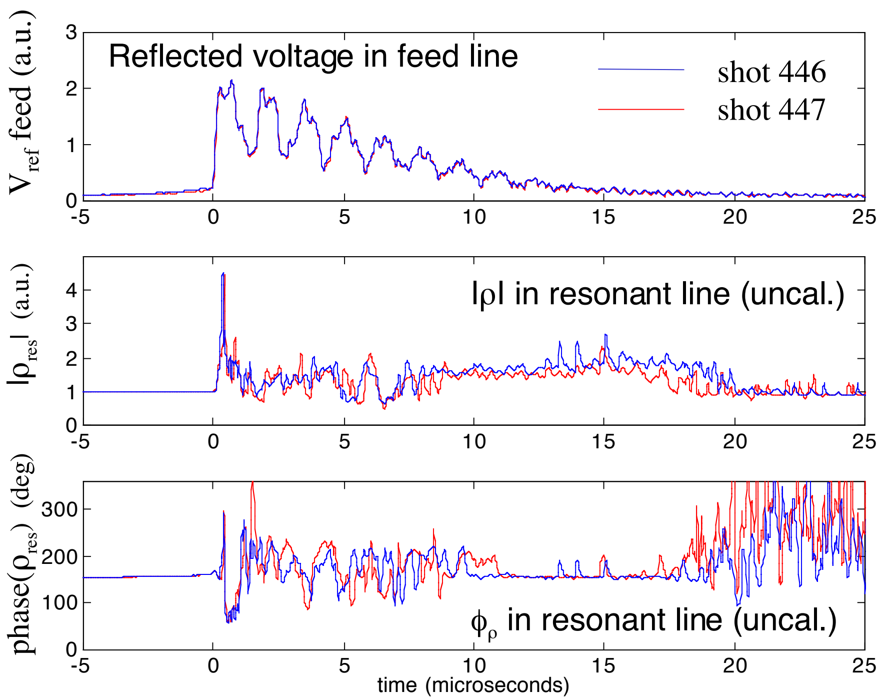
Raw arc data



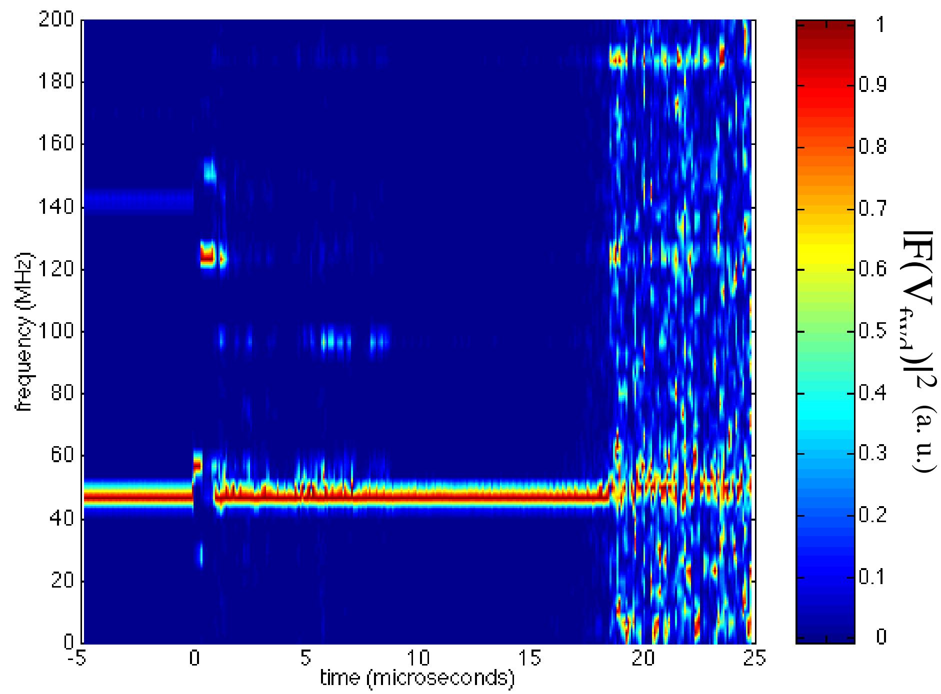
- Voltages in resonant line drop sharply, but remain at finite amplitude, with measurable phase and frequency for > 20 μs

RF measurements: A repeatable ~1μs transient is followed by 9-10 μs of less stable behavior

Arc parameters in feedline and resonant line



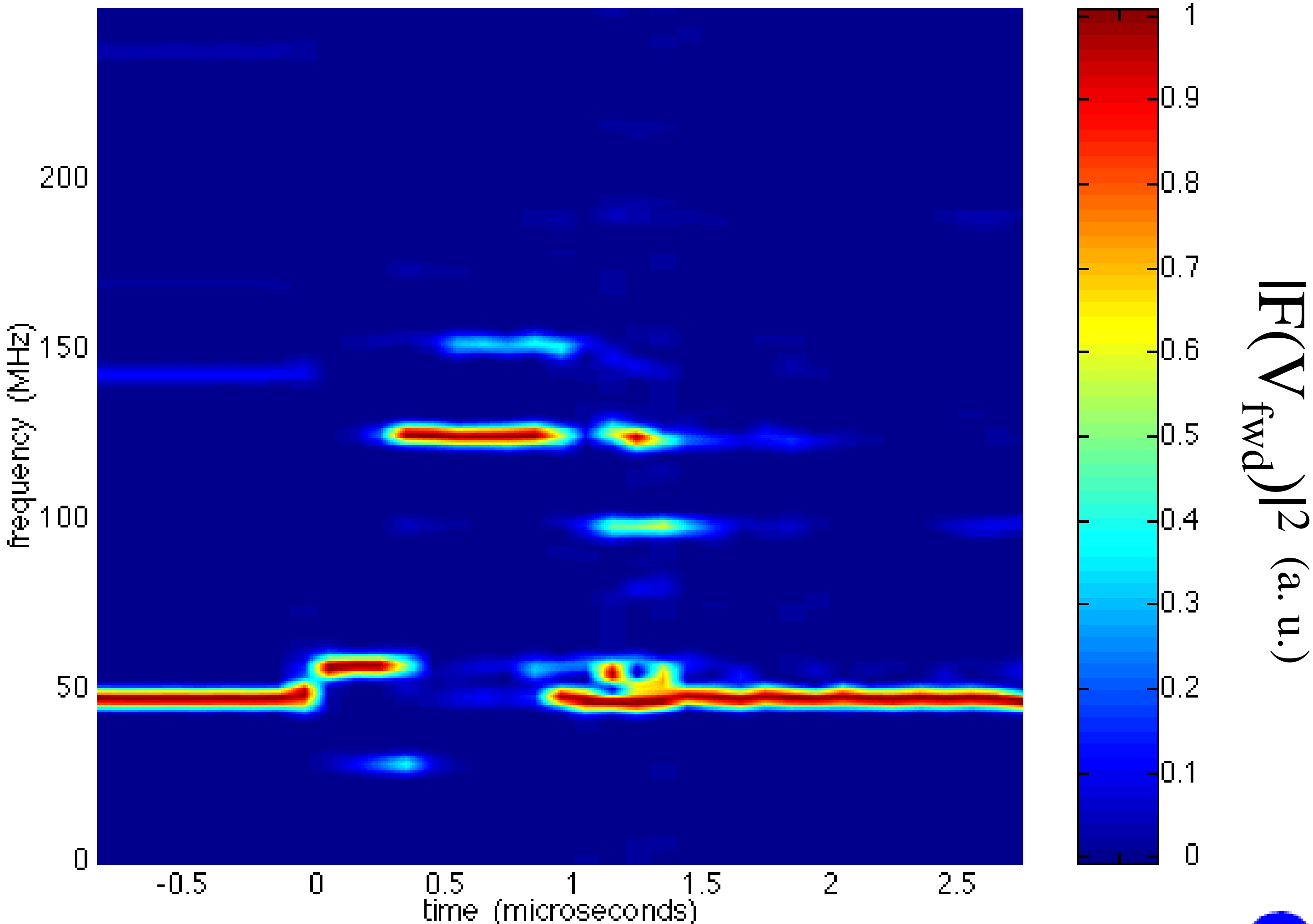
Running Fourier transform of fwd pwr in resonant line



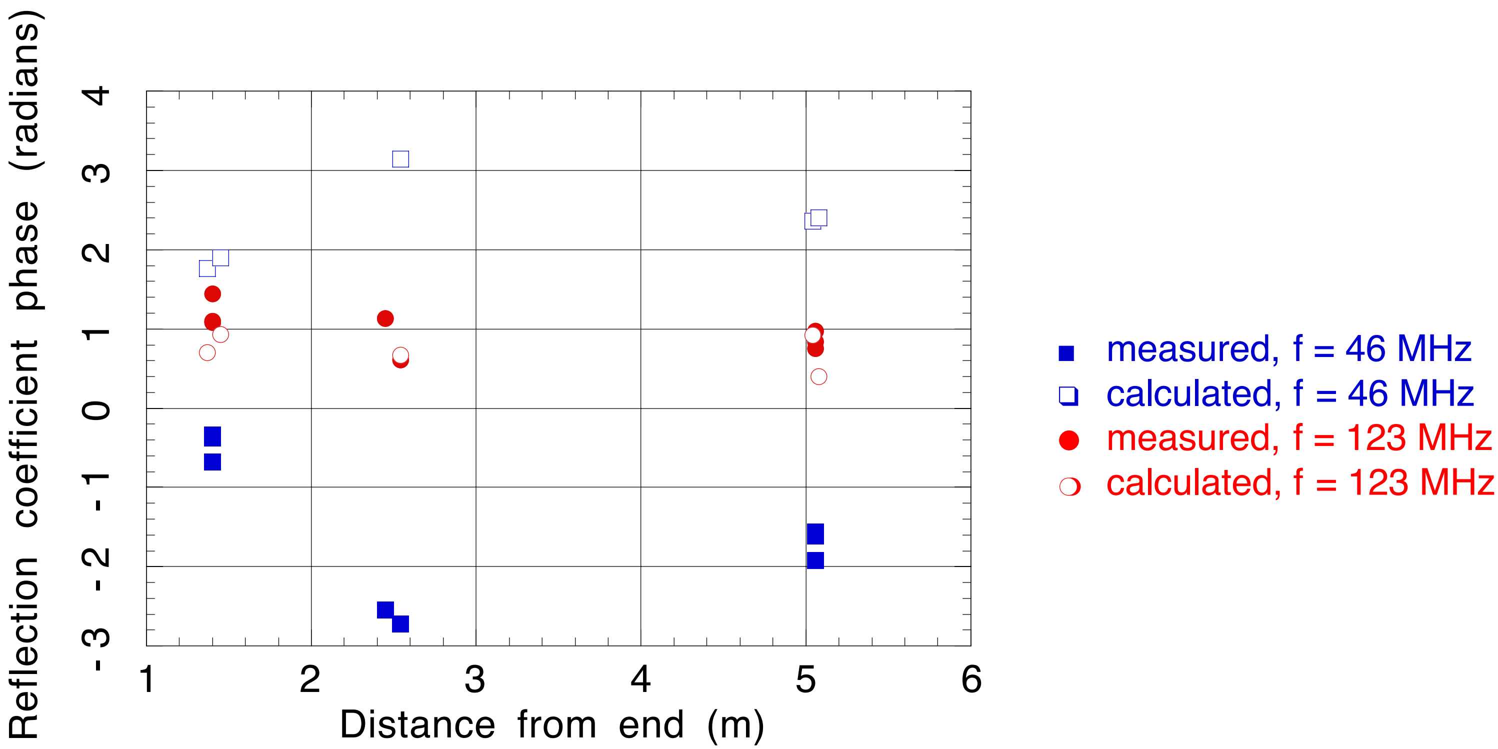
- Two shots shown to indicate reproducibility
- Arc starts at t= 0μs, appears to extinguish near t =10μs

ornl

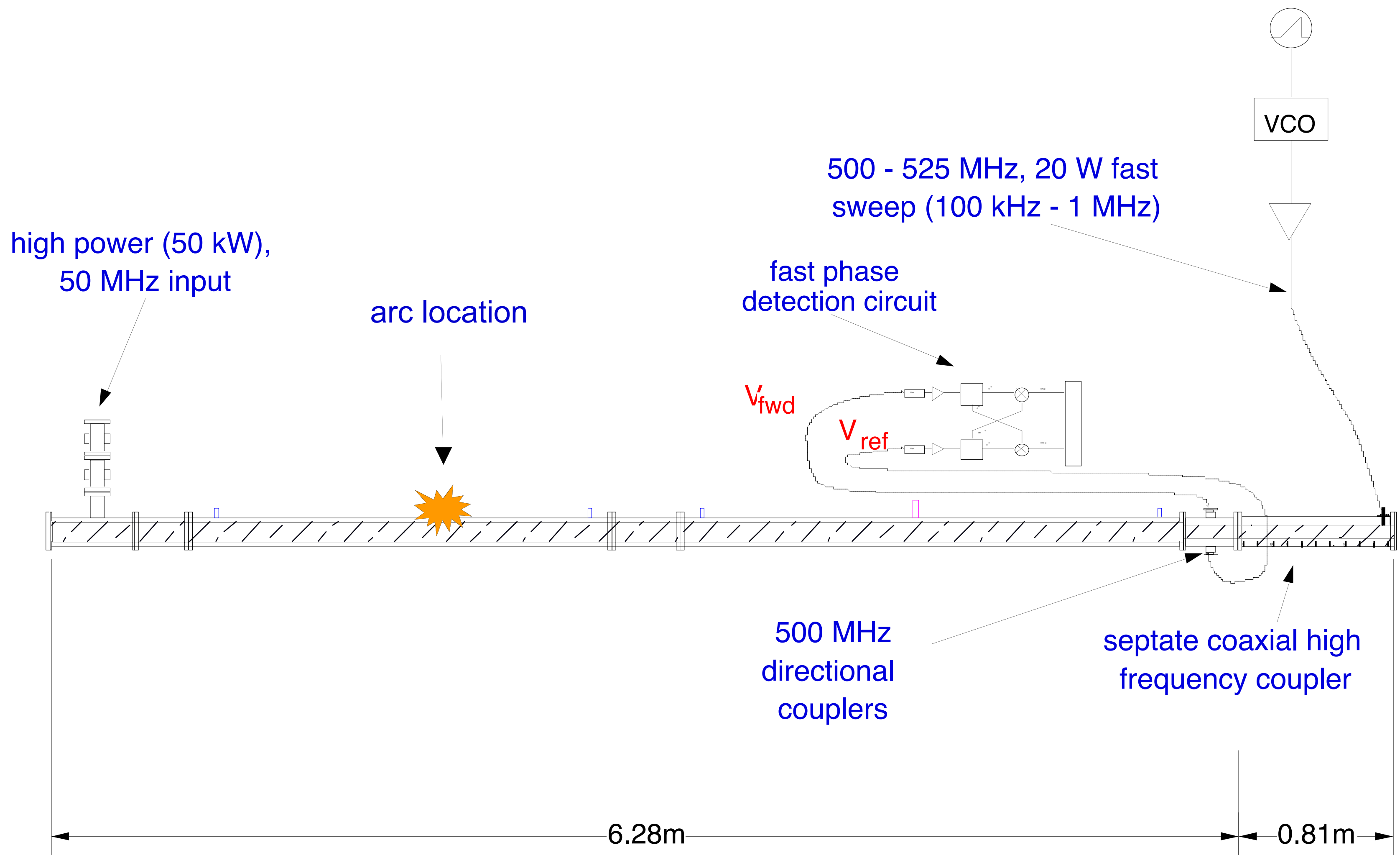
1µs transients in RF frequency are observed



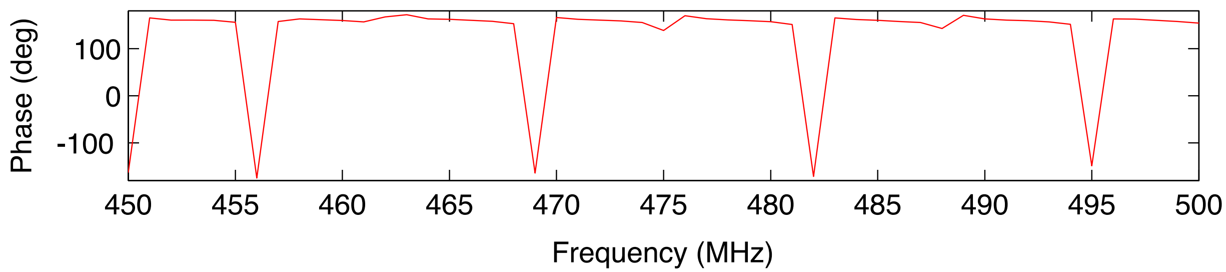
Phase of the reflection coefficient varies with arc location at f=46 MHz, but not at f=123 MHz



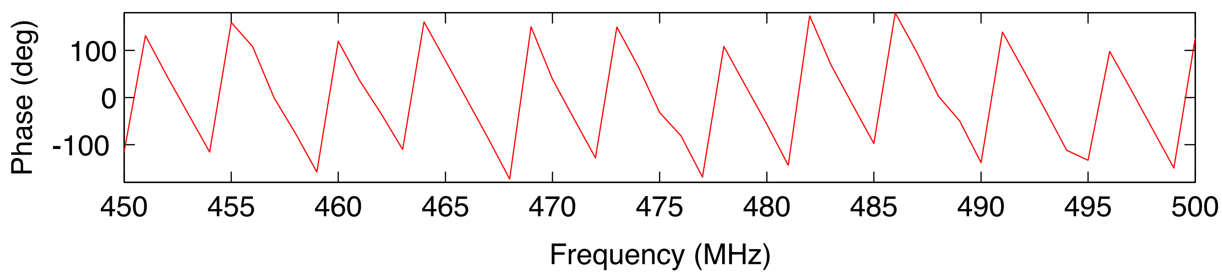
Swept frequency arc localization test rig



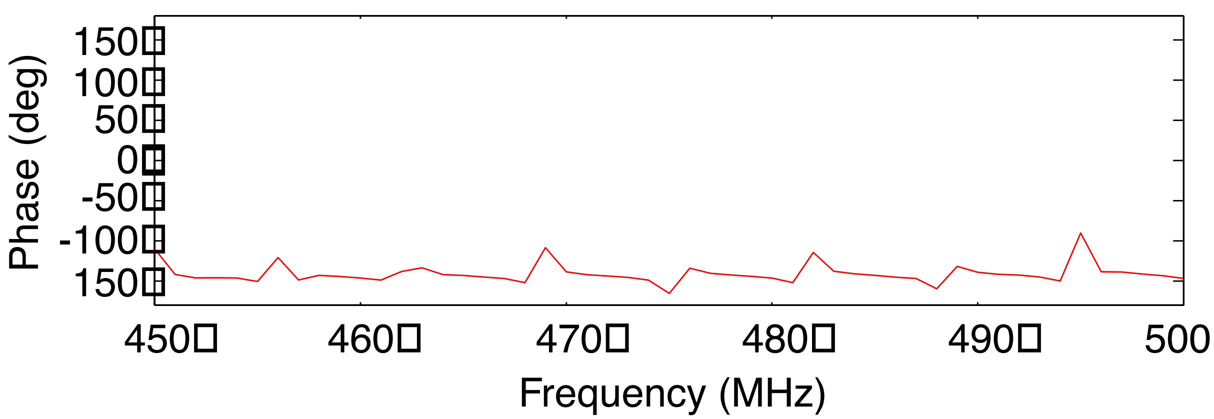
To determine distance to arc, reflection coefficient phase measured while frequency is swept, electrical length added to make phase again stationary with frequency



Phase at arc



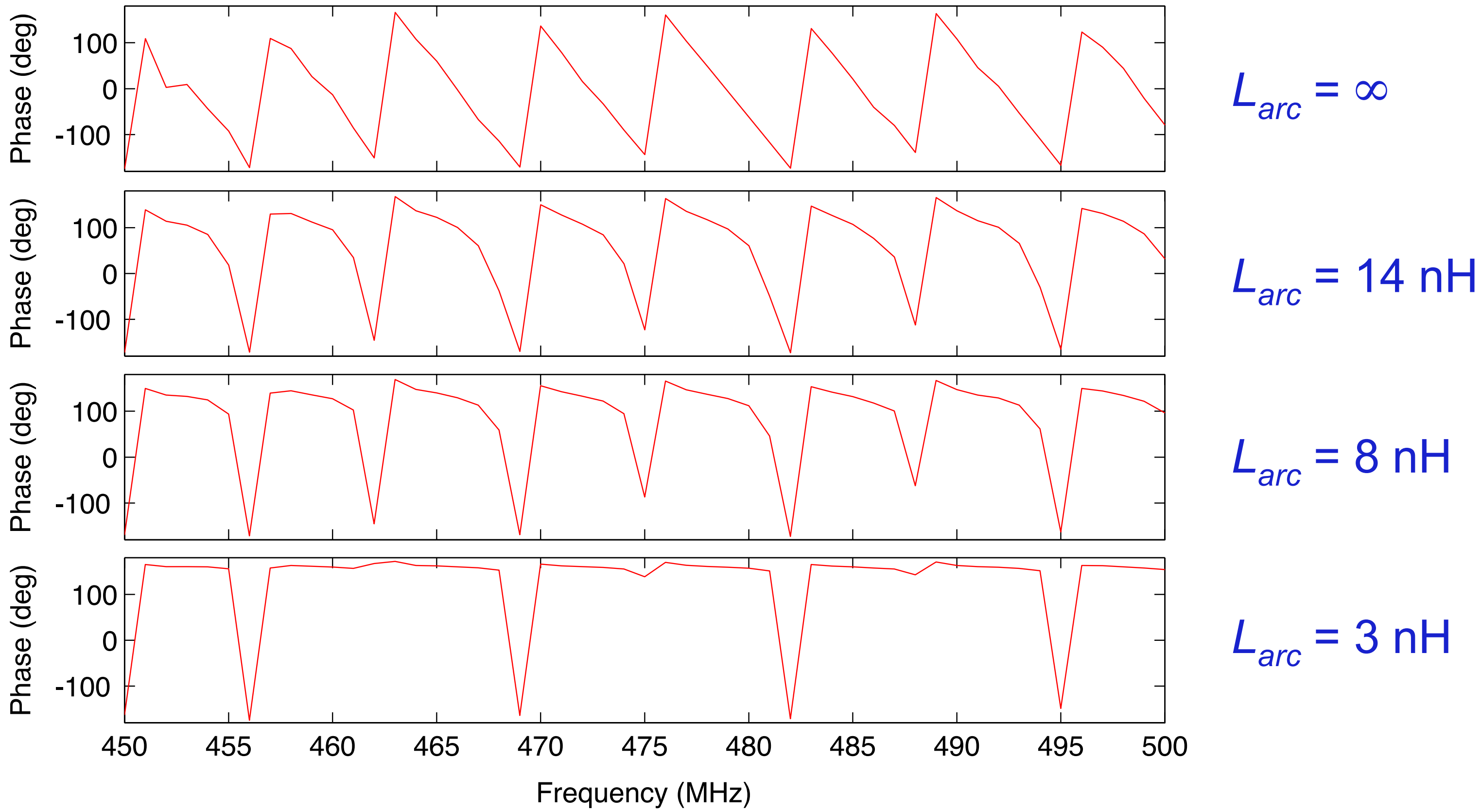
Phase at directional coupler



Phase at directional coupler multiplied by $e^{2\beta d}$, d = distance to arc

High inductance arcs have a reduced influence on the reflection coefficient phase

- Phase of reflection coefficient (= V $_{reflected}$ / V $_{forward}$) measured directly on the generator side of the arc location



Use of baseline data restores sensitivity to arc location

Baseline Subtraction:

$$\rho'_{b=} = \rho_b e^{2\beta l}, \rho'_{t=} = \rho_t e^{2\beta l}$$

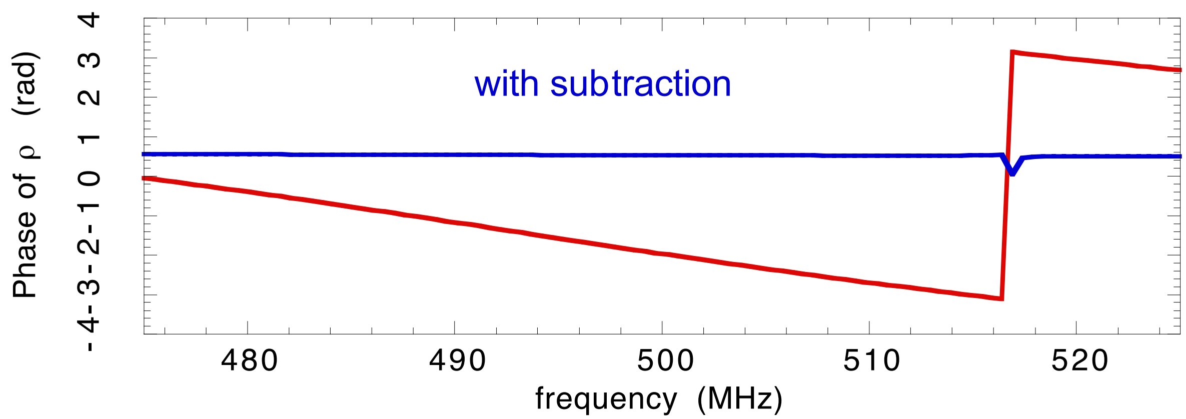
$$y_b = \frac{1-\rho_b}{1+\rho_b}, y_t = \frac{1-\rho_t}{1+\rho_t}$$

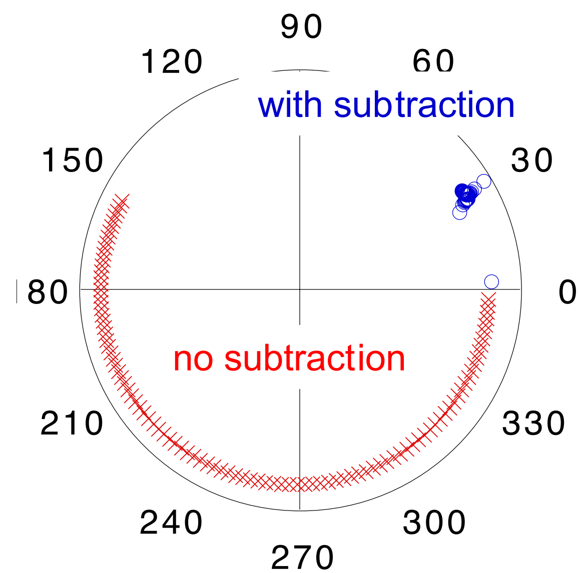
$$y_a = y_t - y_b$$

$$\rho_a = \frac{1-y_a}{1+y_a}$$

subscripts:

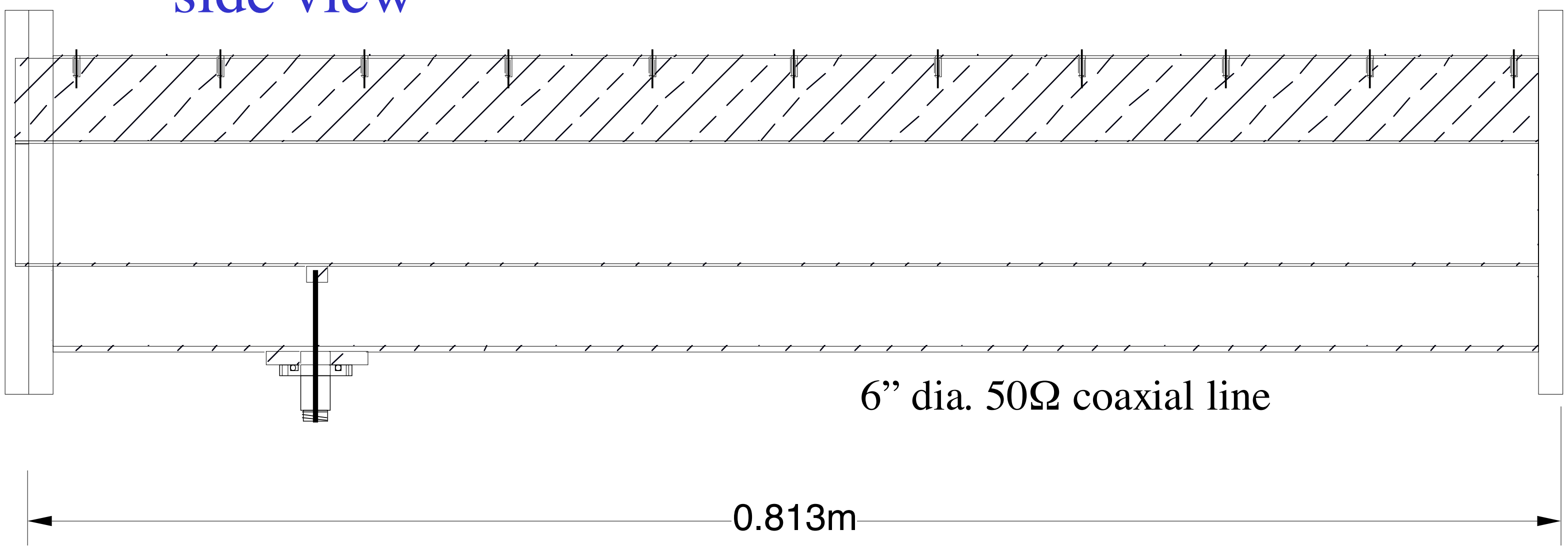
b=baseline
t=total
a=arc



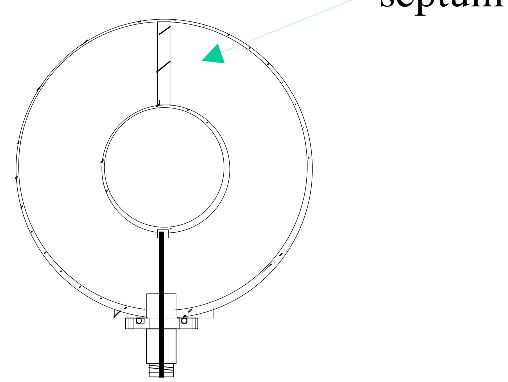


A septate transmission line is an efficient high frequency diplexer

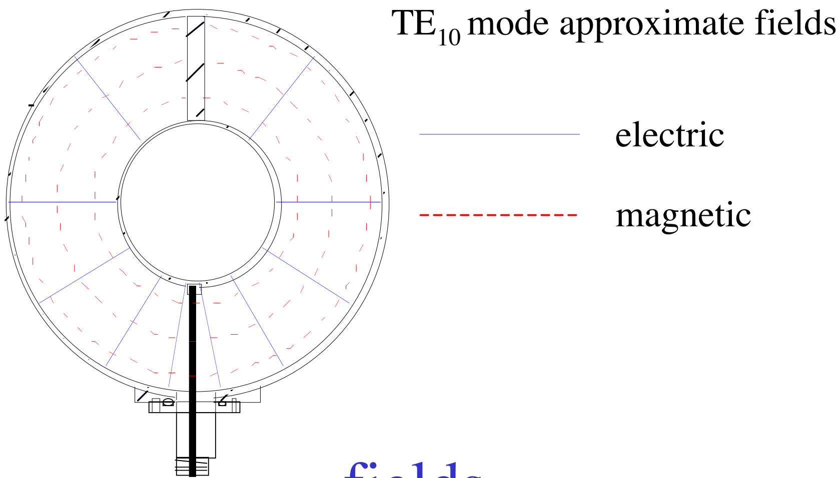
side view



end view



Fields, Cutoff Frequencies, and attenuation in septate coupler



fields

$$H_z \propto \cos\frac{\phi}{2}\left[J_{1/2}(k_c\rho) - \frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$E_\rho \propto \frac{1}{k_c^{\,2}\rho}\sin\frac{\phi}{2}\left[J_{1/2}(k_c\rho) - \frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$E_\phi \propto \frac{\omega}{k_c^{\,2}}\cos\frac{\phi}{2}\left[k_c J'_{1/2}(k_c\rho) - \frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}k_c Y'_{1/2}(k_c\rho)\right]\sin(\beta z)$$

$$H_\rho \propto \frac{\beta}{k_c^{\,2}}\cos\frac{\phi}{2}\left[k_c J'_{1/2}(k_c\rho) - \frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}k_c Y'_{1/2}(k_c\rho)\right]\cos(\beta z)$$

$$H_\phi \propto \frac{\beta}{k_c^{\,2}\rho}\sin\frac{\phi}{2}\left[J_{1/2}(k_c\rho) - \frac{J'_{1/2}(k_c a)}{Y'_{1/2}(k_c a)}Y_{1/2}(k_c\rho)\right]\cos(\beta z)$$

cutoff wavenumber

$$(2k_c a - \tan(k_c a))(1 + 2k_c b\tan(k_c b)) - (2k_c b - \tan(k_c b))(1 + 2k_c a\tan(k_c a)) = 0$$

cutoff frequencies

50Ω: 447.9 MHz

25.7Ω: 382.0 MHz

attenuation - 50Ω, 66 cm @ 50 MHz

52.1 dB

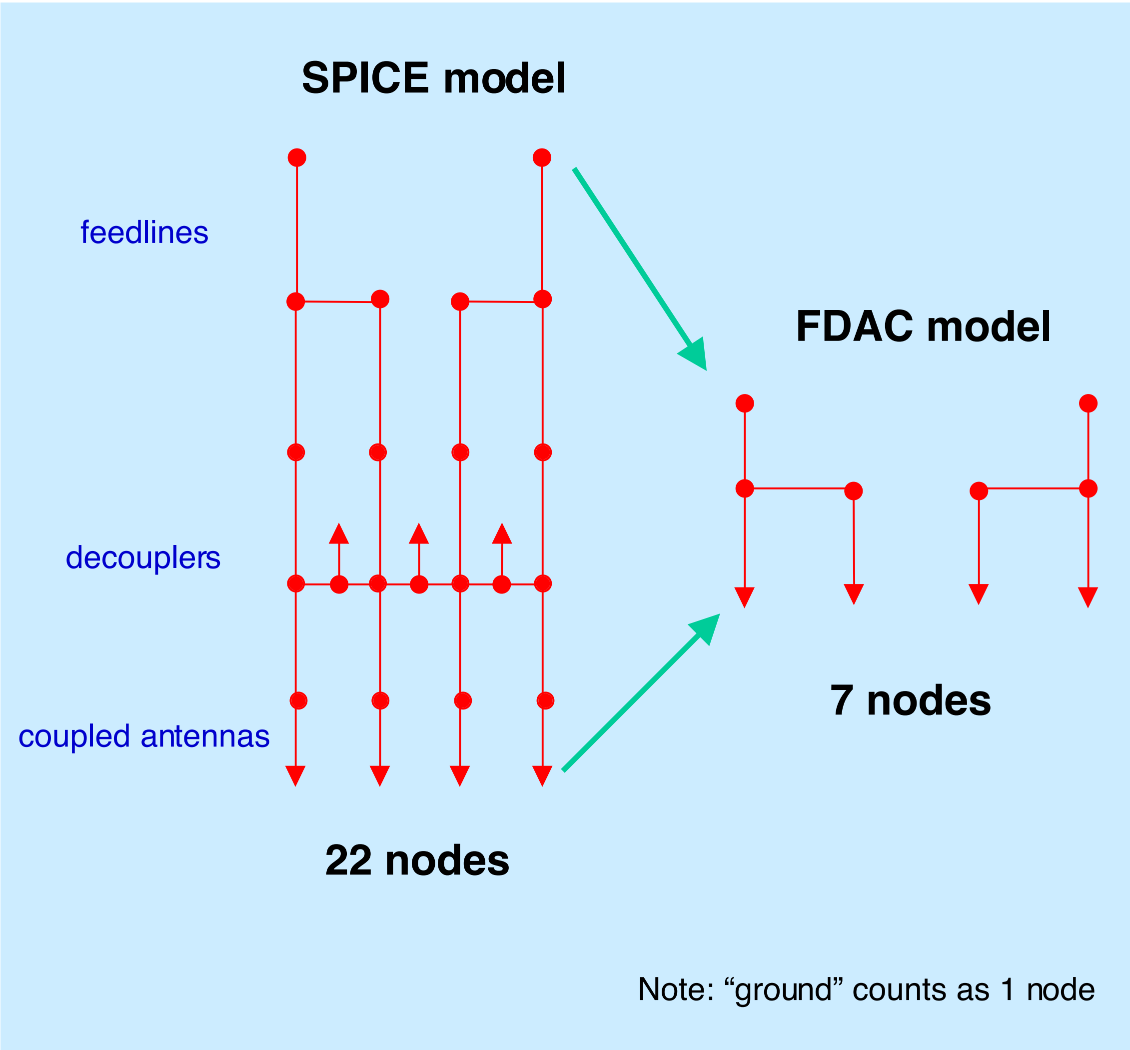
ornl

Near-term possibilities for arc localization systems

- There is interest in installing arc localization systems at JET and NSTX (possibly DIII-D as well)
- JET has 30 kV limit during plasma, but ~ 45 kV limit in pressurized lines during plasma, wants to know where breakdown is occuring
- Complicated NSTX feed system is a good application for swept frequency technique with single high frequency feed point

ornl

FDAC Algorithm



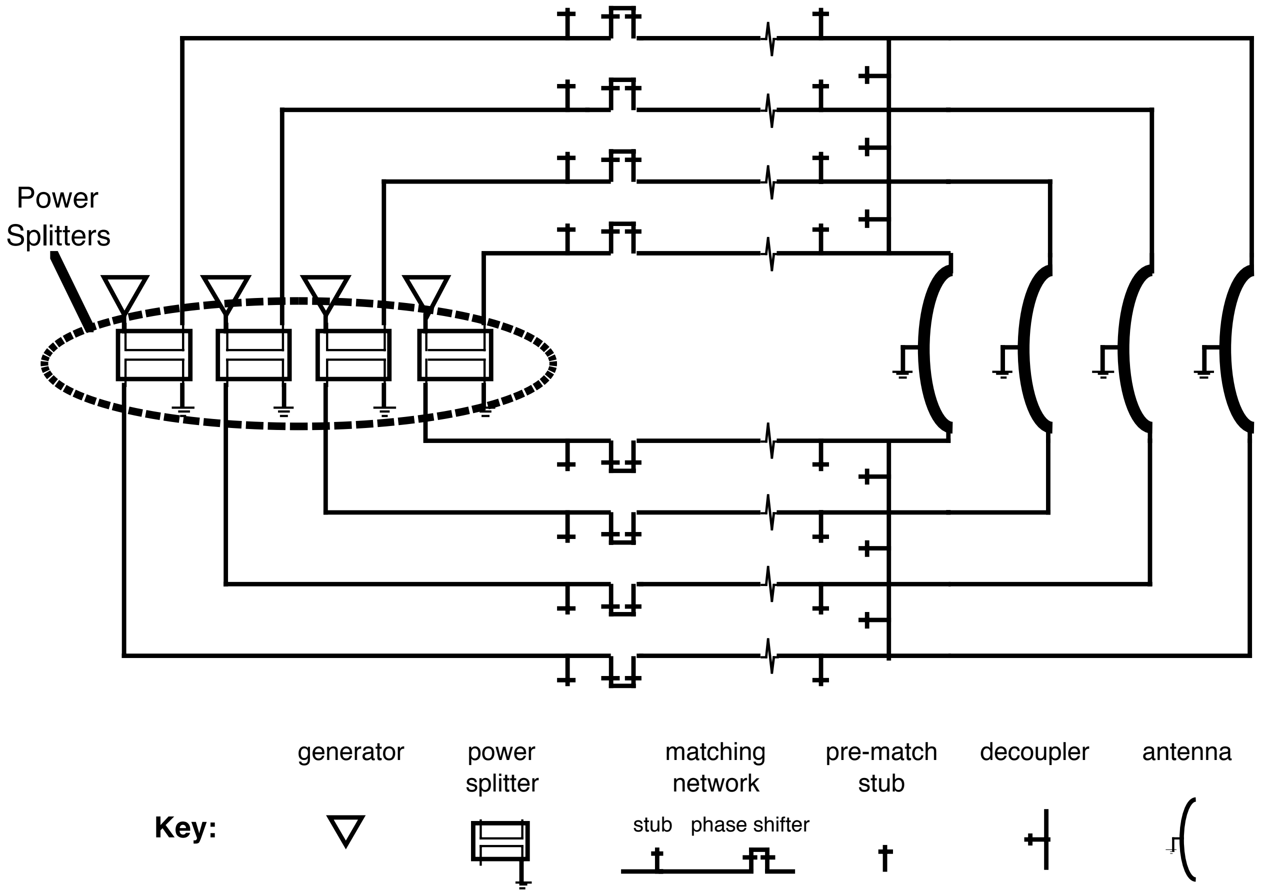
- Lossy coupled transmission line model
- Multiple coupled lines including shunt connections collapsed into single ABCD transform equation set:

$$V_{out} = \mathbf{A}V_{in} + \mathbf{B}I_{in}$$

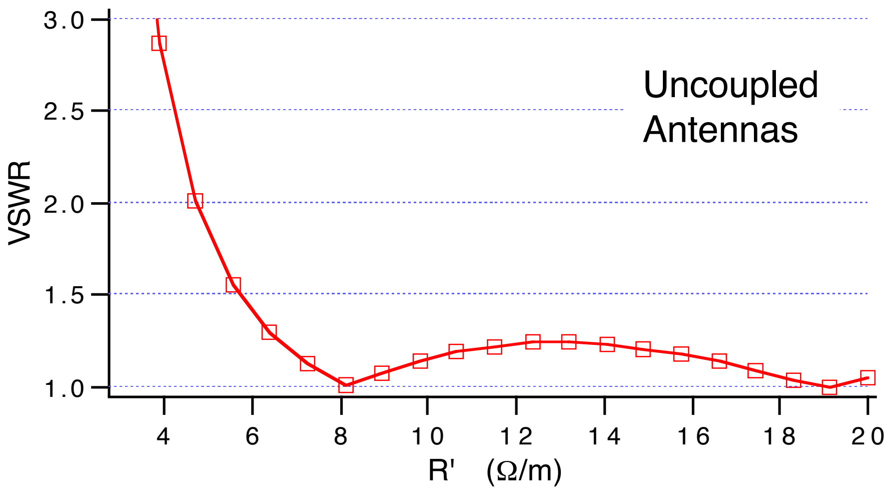
$$I_{out} = \mathbf{C}V_{in} + \mathbf{D}I_{in}$$

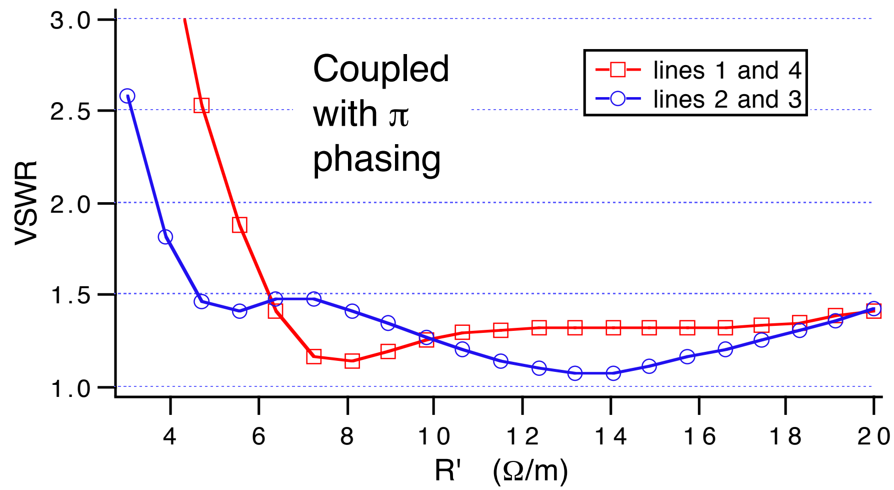
- Common components pre-modeled by equivalent ABCD transforms
- Simultaneous equation matrix solved to determine currents and voltages at nodes
- Size of matrix to invert to calculate I,V at nodes greatly reduced. Substantial speedup of parameter scans, optimiz-ation calculations, etc.

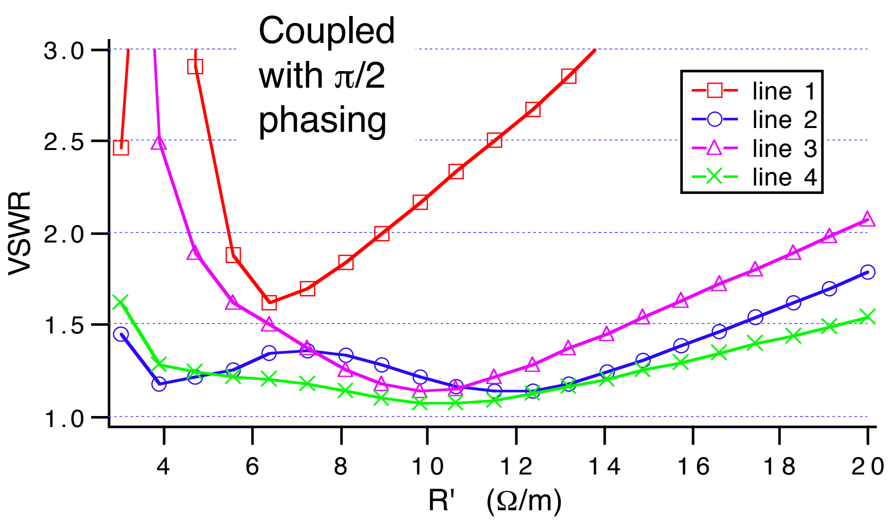
The FDAC code can be used to build quick coupled transmission line models of complicated networks



Example: calculation of the effect of antenna mutual impedances on performance of wideband matching system for ITER configuration





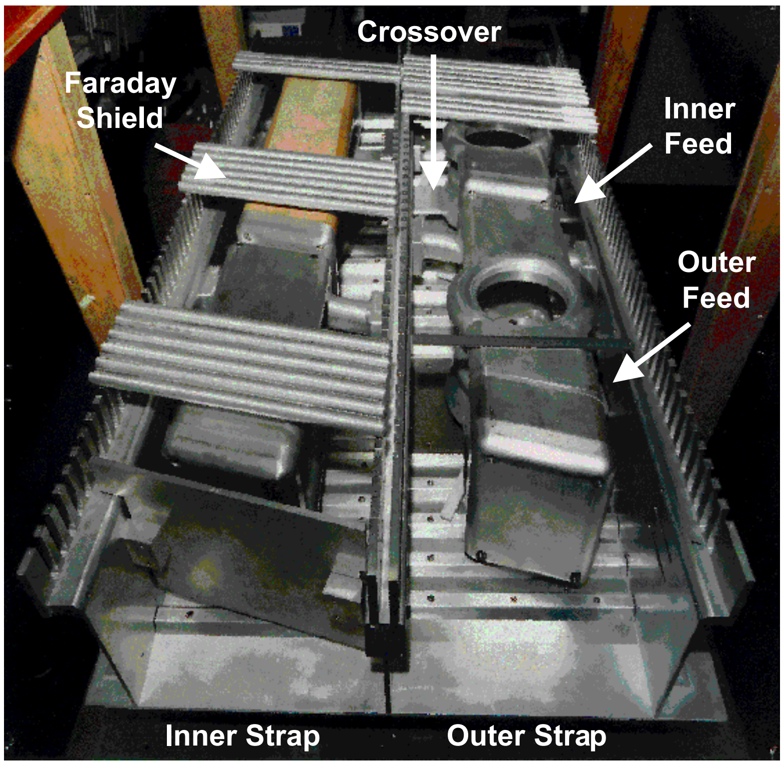


- Unacceptably high VSWR occurs on the phase lagging line (line 1) for frequency shift matching with π/2 phasing

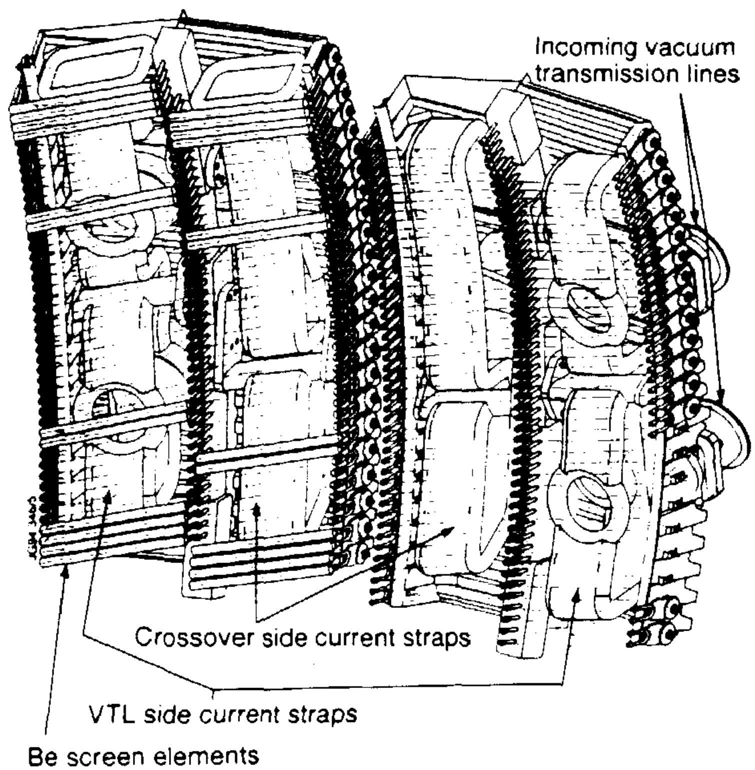
ornl

FDAC can also model complicated antenna circuit behavior: example: JET A2 Antennas - high impedance crossover resulted in reduced inner strap loading

flatbed mockup

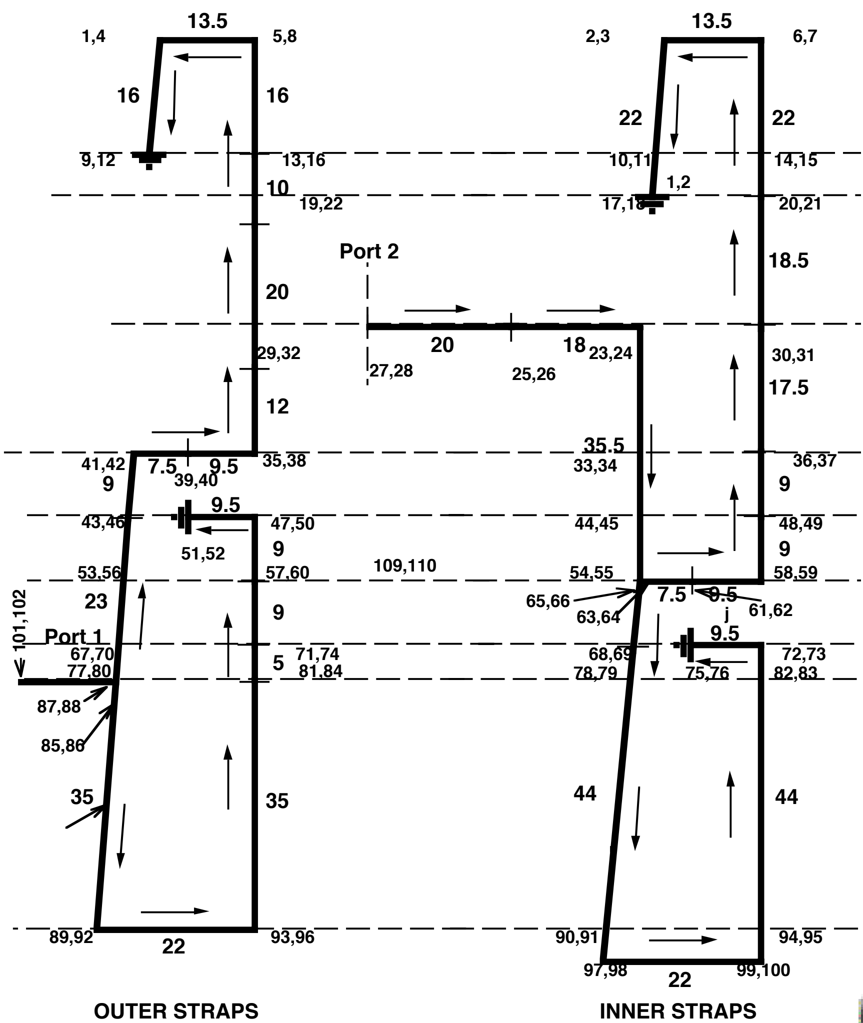


actual antennas



ANTMOD Model for the JET A2 Flatbed Antenna

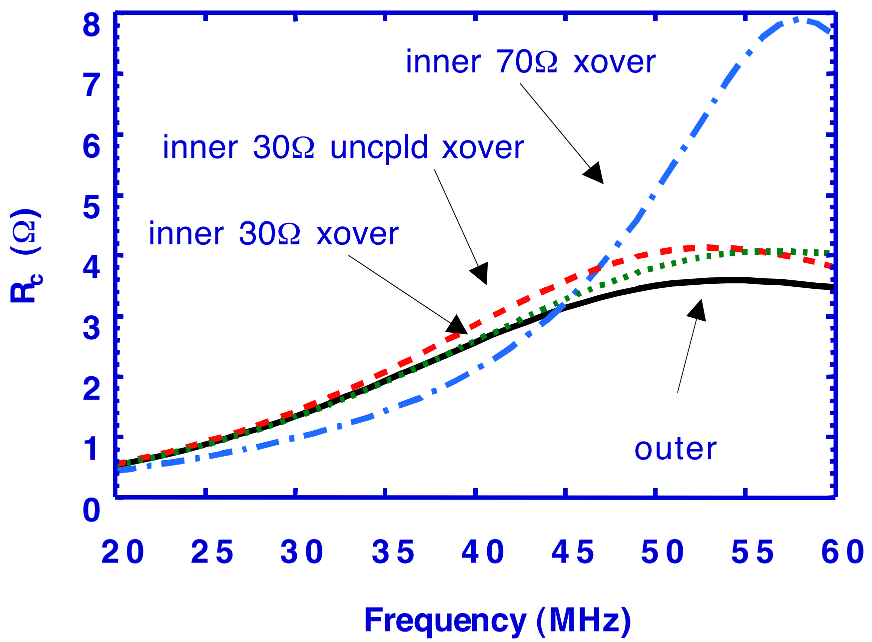
JET A2 MOCKUP GEOMETRY



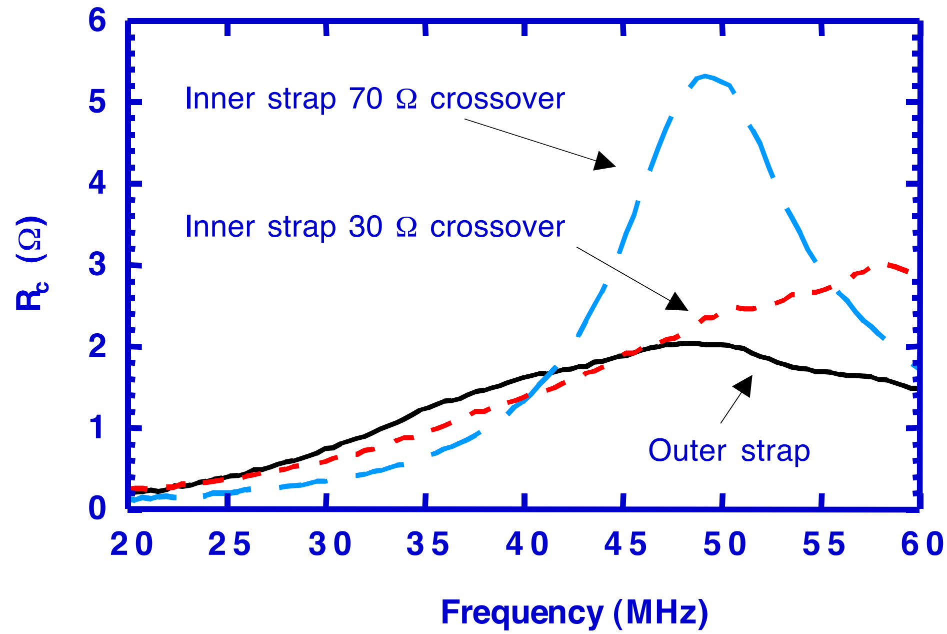
- Each antenna is divided into sections with varying Z_o and v_ϕ
- Modelled as coupled cascaded lossy transmission lines
- FDAC will reduce number of nodes required compared to ANTMOD: one node per network junction as in SPICE

Lowering the crossover impedance from 70Ω to 30Ω improves inner/outer strap loading symmetry

ANTMOD Model

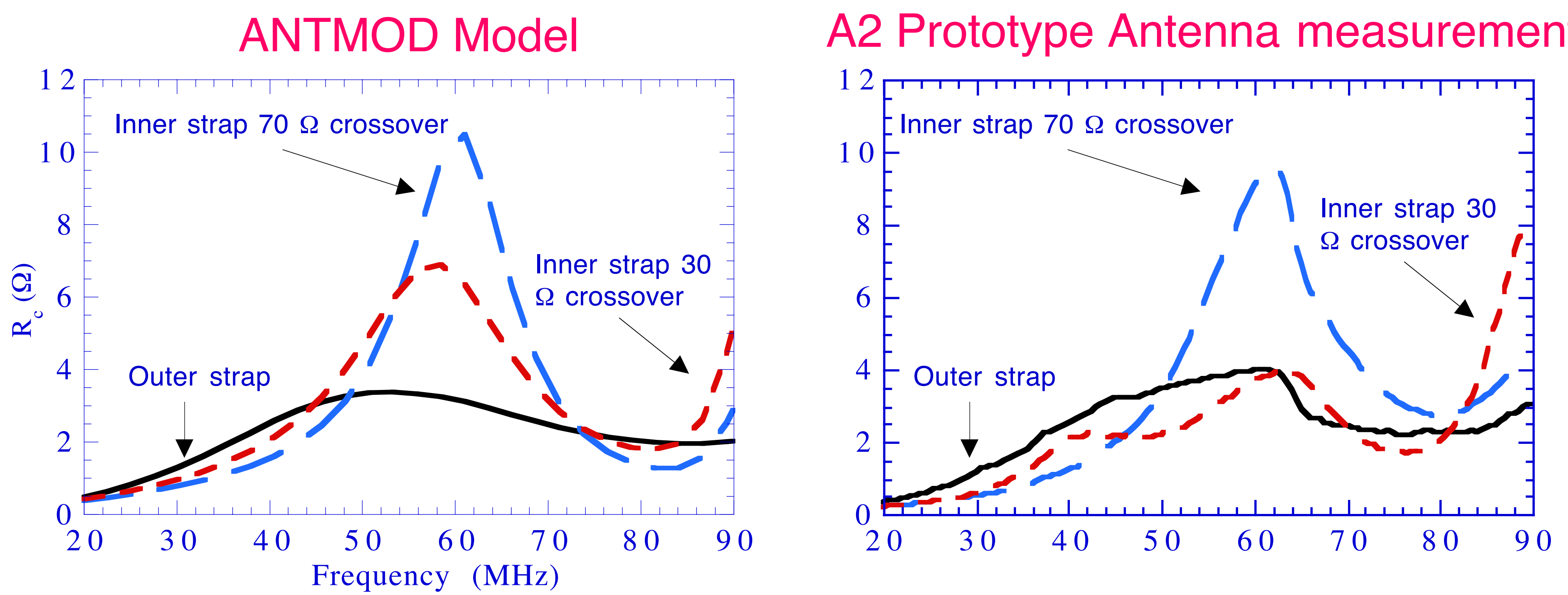


Flatbed measurement



- Addresses goal of increasing inner strap loading at frequencies < 40 MHz
- Good agreement between ANTMOD lossy coupled transmission line model and measurement is observed

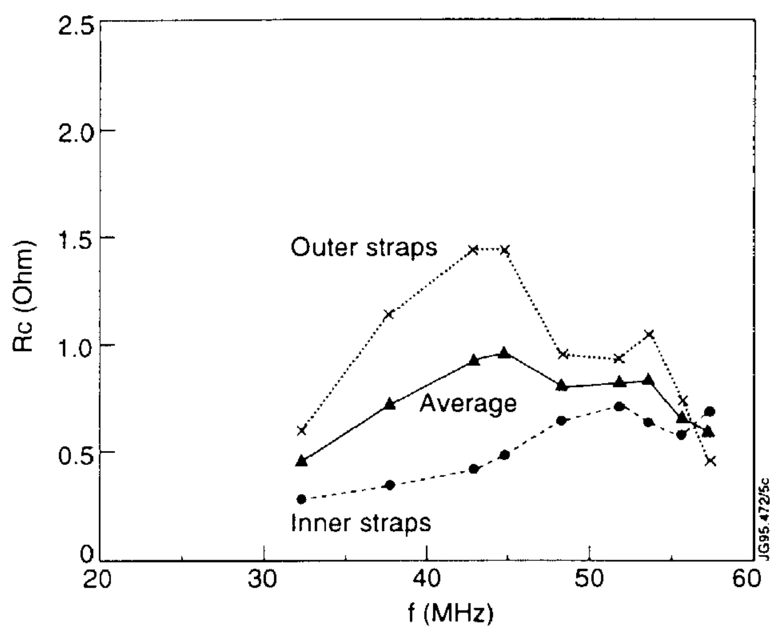
Unlike the flatbed mockup, there is significant inner/outer strap residual asymmetry in actual A2 antenna loading after crossover modification



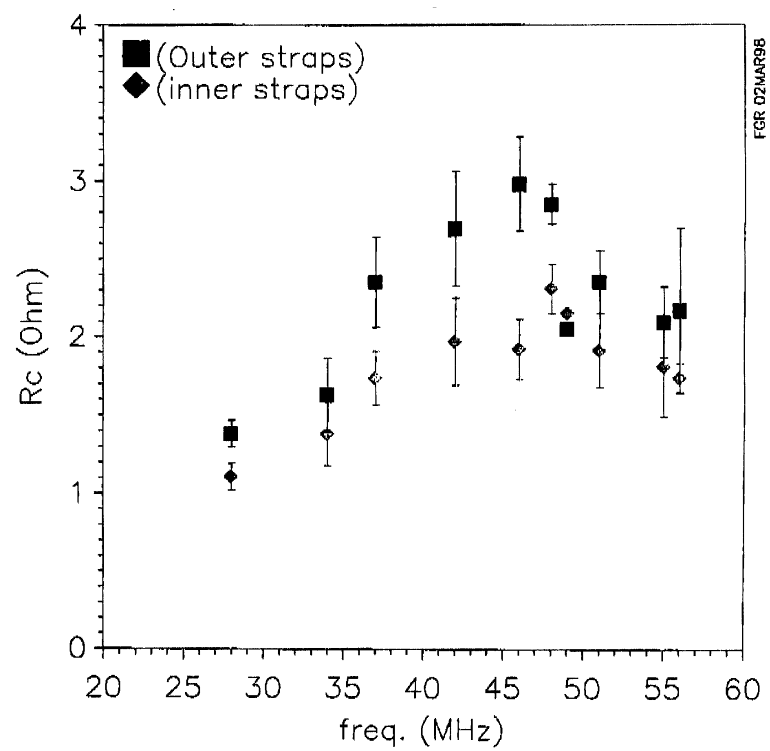
- Some improvement in low frequency loading is still observed

JET Loading Measurements in H-mode plasmas showed improved loading symmetry after crossover modification

Before crossover modification



After crossover modification



Impacts of ORNL RF Network Modeling Codes:

- FDAC used to predict performance of hybrid coupler ELM resilient (ELM dump) circuits
  - devices later used to couple high power to ELMing H-mode plasmas at DIII-D and ASDEX-U
- ANTMOD lossy cascaded coupled transmission line model used to determine circuit frequency dependent behavior of antennas
  - used to improve symmetry of JET A2 antenna coupling (together with mockup measurements)
  - similar work done to symmetrize ASDEX-U antenna coupling
  - method adopted by ASDEX-U to modify antennas to couple to wider range of plasma shapes
- Decoupler development
  - FOCSL - predecessor to FDAC used for JET decoupler modeling
  - JET decoupler led to DIII-D design
  - DIII-D design now used on NSTX
  - Phased operation of strongly coupled ICRF antennas has become increasingly routine
- Other work includes development of arc/ELM discrimination techniques, examination of coupling effects in WBM, and adoption of WBM to RDL configurations

Summary

ORNL work has had and will continue to have a significant impact in the areas of ICRF control and reliability

- Investigation into use of hybrid couplers in passive high power ELM resilient circuits was enabled by JET decoupler work
  - has resulted in routine operation with ELMing plasmas at DIII-D and ASDEX-U
  - use at JET under consideration
- JET decoupler work also led to installation of decouplers at DIII-D, improving current drive capabilities. Now in use at NSTX. Phased operation, once difficult, now nearly routine
- Acoustic arc detection has located arcs to within < 8 cm in 6m line. RF technique with baseline subtraction looks very promising
- Decoupler modeling needs led to FDAC & ANTMOD, which enabled improvements in crossover feeds on JET and ASDEX-U. Improved "SPICE like" version in progress.

ornl