Initial Tests of the ITER R&D Prototype Ion Cyclotron Antenna*

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Summary

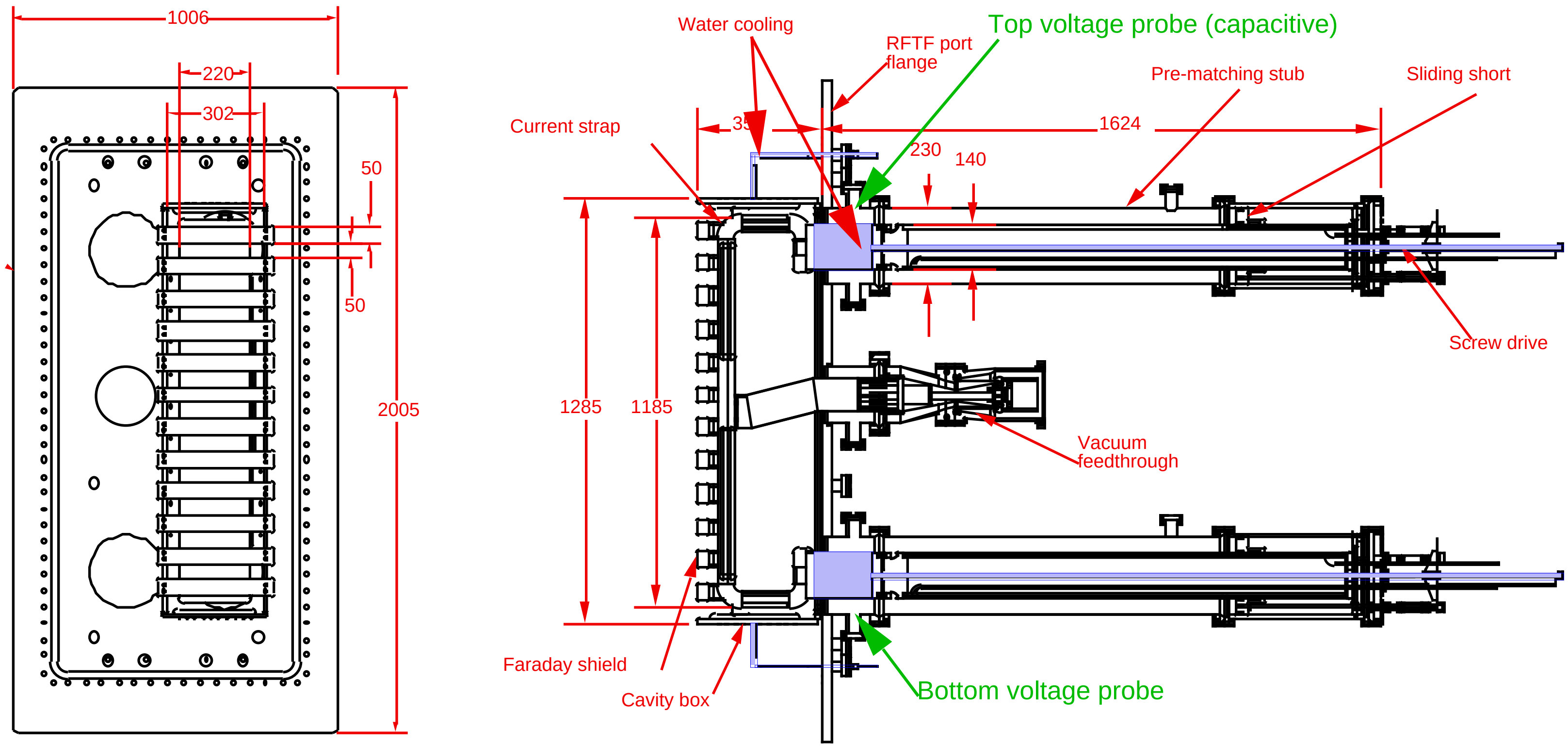
The design of the ITER ion cyclotron system utilizes an antenna of the resonant double loop configuration that must operate at relatively high voltages (≥ 45 kV) to deliver the required power to the ITER plasma.
A single-strap prototype antenna has been built and tested to ascertain the voltage and current limits it can withstand in vacuum.
Results are:

- Voltage over 70 kV for 0.1 s
- Voltage over ≈ 65 kV for 1 s
- Voltage over 60 kV for 2 s (limited by heating)

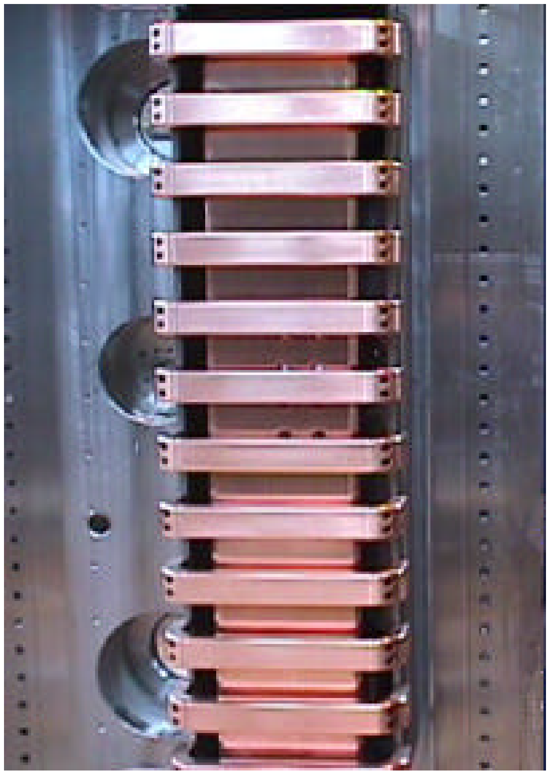
In addition, circuit parameters to model the resonant double loop configuration have been measured and agree well with calculated values.

Magnetic fields of the antenna have been measured and compared with calculations. Simple two-dimensional calculations ignoring the presence of the Faraday shield do not give a very good fit to the measurements. Three-dimensional calculations that include the Faraday shield bars are needed to give an accurate result.

Antenna Design and Construction



Details of the ITER Prototype Antenna

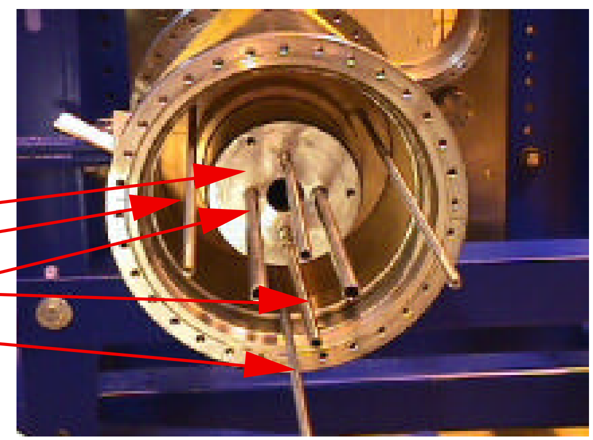


Antenna front view:
Current strap and Faraday shield
mounted on main vacuum flange

Current strap connected to water-cooled
stainless steel can at start of pre-
matching stub

Sliding short with Multilam type LA contactors
40 A per louver allows 7.7 kA peak at low
frequency.

Center conductor
Sliding short
Water cooling tubes
Push rods for short



Rear view of stub during assembly

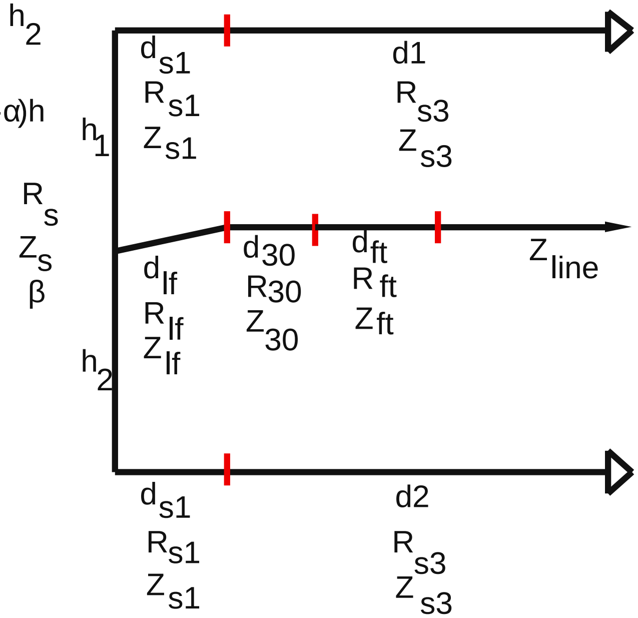
Electrical Characterization of Antenna

Antenna in RFTF is well characterized by Transmission Line Model shown below

$h = h_1 + h_2$

$h_1 = \alpha h$

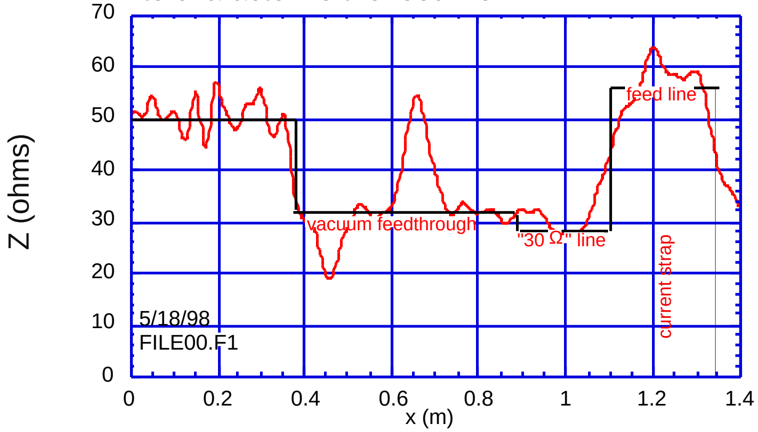
$h_2 = (1 - \alpha) h$



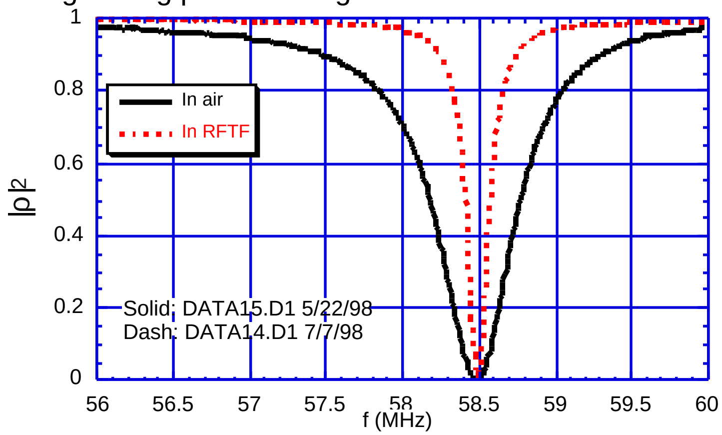
R_s	0.04 ohm/m	Losses on current strap
Z_s	40± 5 ohms	Char. impedance of current strap
β	0.72 ± 0.05	Rel. phase velocity on strap
h	1.15 m	Height of current strap
α	0.50	
d_{s1}	0.297 m	Length of top and bottom lines
R_{s1}	0.08 ohms/m	Losses in top and bottom lines
Z_{s1}	26 ohms	Char. impedance of top and bottom lines
R_{s3}	0.08 ohms/m	Losses in pre-matching stubs
Z_{s3}	30 ohms	Char. impedance of pre-matching stubs
d_{lf}	0.25 m	Length of feedline between strap and back plate
Z_{lf}	58 ohms	Char. impedance of feedline
d_{30}	0.21 m	Length of "30 ohm" vacuum coax section
Z_{30}	28 ohms	Impedance of "30 ohm" section
d_{ft}	0.51 m	Length of vacuum feedthrough
Z_{ft}	32 ohms	Char. impedance of vacuum feedthrough

Measurements of RF properties of the antenna

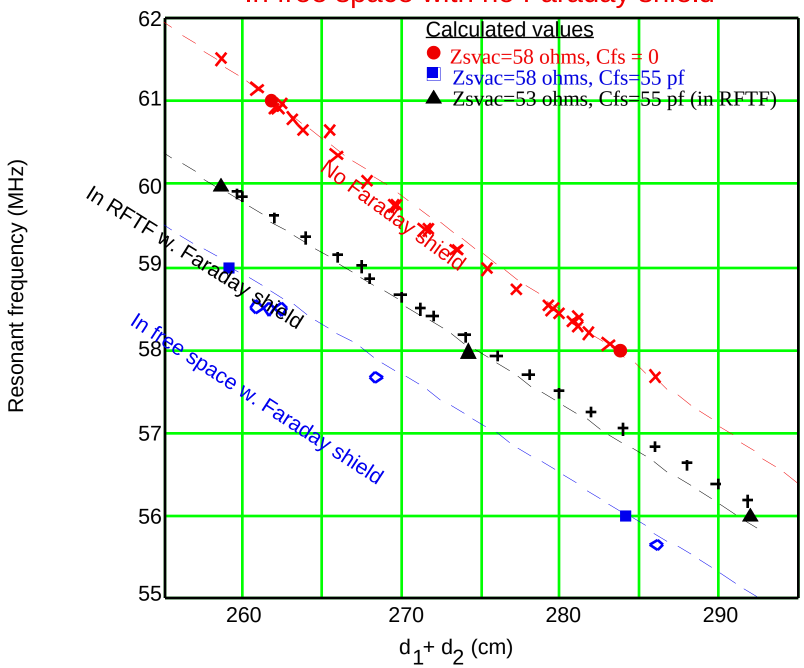
Time Domain Reflectometry measurements used to characterize the feedline



Circuit can be tuned to resonance and match in 56-60 MHz range using pre-matching stubs



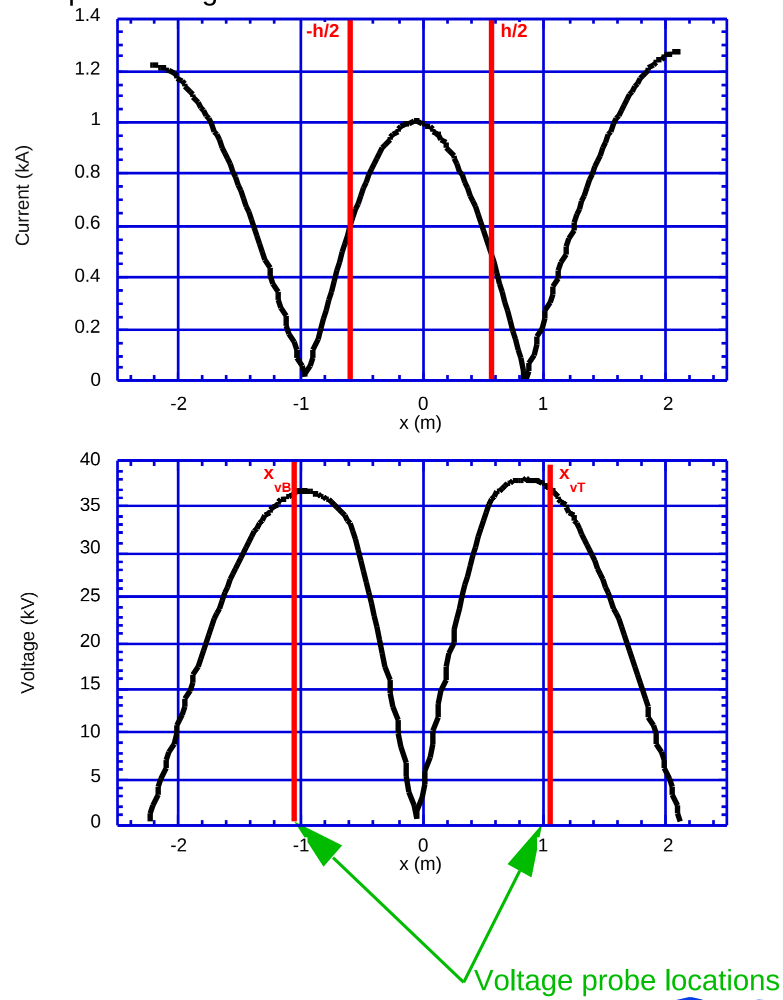
- In RFTF with Faraday shield
- In free space with Faraday shield
- In free space with no Faraday shield



Faraday shield adds about 55 pF/m capacitance to current strap, thereby reducing char. impedance from 58 ohms (free space) to about 40 ohms, and β (relative phase velocity) from 1.00 to about 0.72.

Insertion of antenna into RFTF decreases char. impedance of strap slightly because of metallic walls near antenna.

Calculation of current and voltage along resonant loop at 58.5 MHz (where most of high-power data was taken). Current normalized to 1.0 kA at center of strap, resulting in peak voltage of ≈ 37 kV.



High-Voltage Tests

Conditioning procedure

- With no water cooling, the following components were heated to ~ 150° C for about 24 hours

  Pre-matching stubs (heating tape)

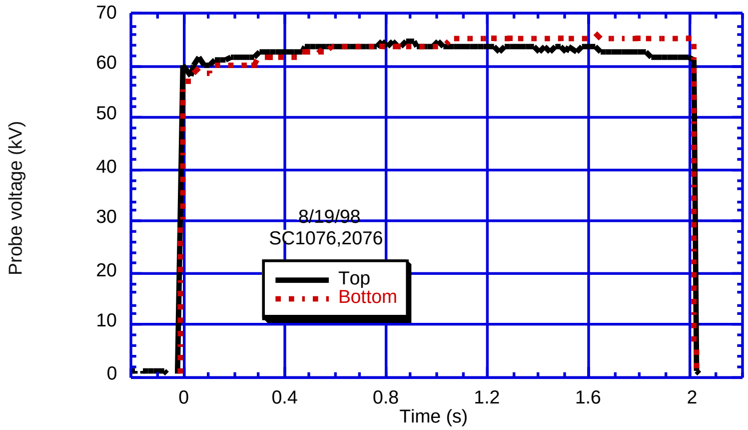
  Vacuum feedthrough (heating tape)

  Side walls of cavity (Calrod heating elements in vacuum)

- After heating was turned off, pressure was about 4×10^{-7} Torr at room temperature.
- Turned on water cooling for center conductor of pre-matching stubs and stainless steel cans at each end of Cu current strap.
- Used low-power CW rf (< 1 kW) to condition. Gradually decreased rf power until multipactor condition was encountered, then kept power at that level until multipactor went away. Then decreased power and repeated.
- Started high-power pulsing. Could rapidly get to over 50 kV range.
- Generally set the power level (which fixed max. voltage) and then increased the pulse length from 10 ms to 100 ms to 1 s.

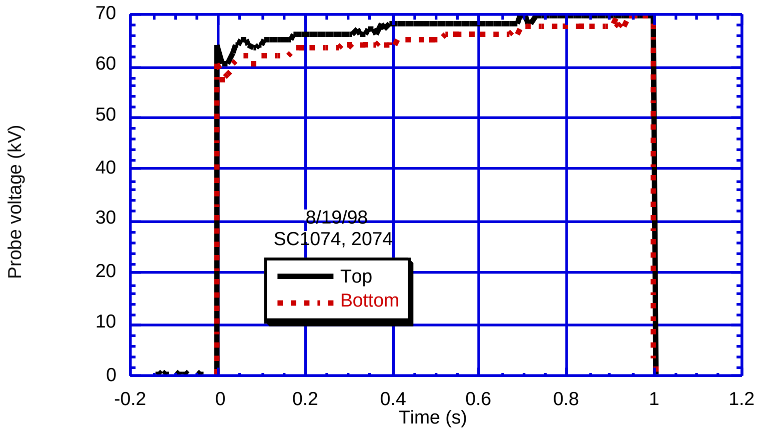
f = 58.5 MHz

Results



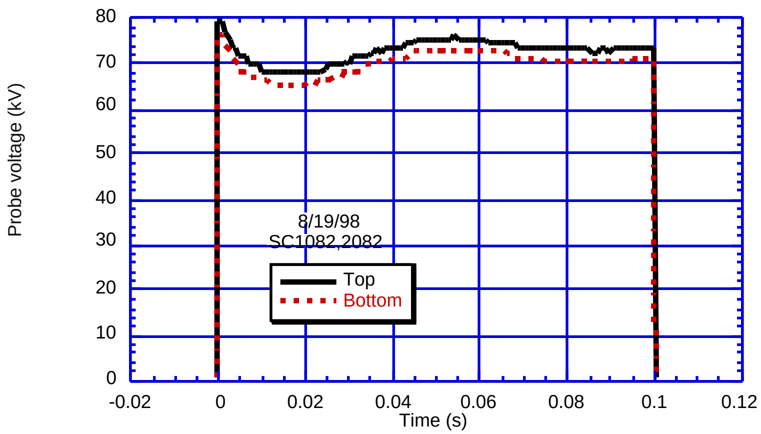
60- kV, 2-s pulse

After gradually conditioning the antenna for a couple of days, it was easy to run at over 60 kV for 1 to 2 second pulses. The antenna was very reliable at this level. Pulse length was limited by thermal heating.



65-70 kV, 1-s pulse

Difficulty with obtaining and maintaining this level. Took significant conditioning, often would break down before end of pulse.



70-kV, 0.1-s pulse

After conditioning, not too hard to achieve for short time. However, would usually break down after about 150 ms.

Observations

Pressure rise: During high-power shots the pressure rose in the vacuum vessel. For a 1-s, 60 kV pulse, pressure would rise to the low 10^{-5} Torr range. We could not eliminate this pressure increase by baking at 150° C.

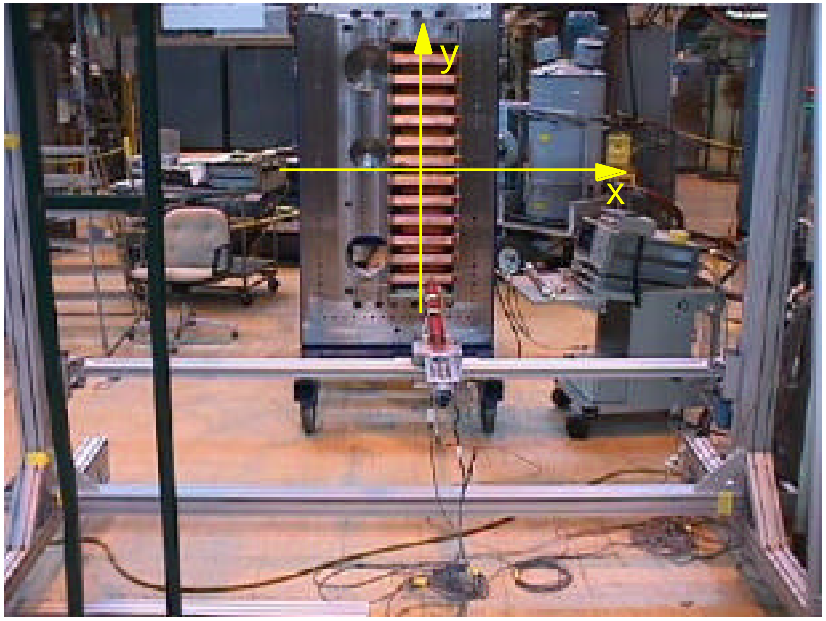
Temperature increase: The walls of the cavity and the center and outer conductors of the pre-matching stubs are Ni-plated. During a 2-s, 60 kV pulse the surface temperature of the cavity walls would exceed 250° C (measured by an infra-red camera). The wall temperature near the front edge of the cavity was > 150° C a few seconds after the shot was over, as measured by an embedded thermocouple.

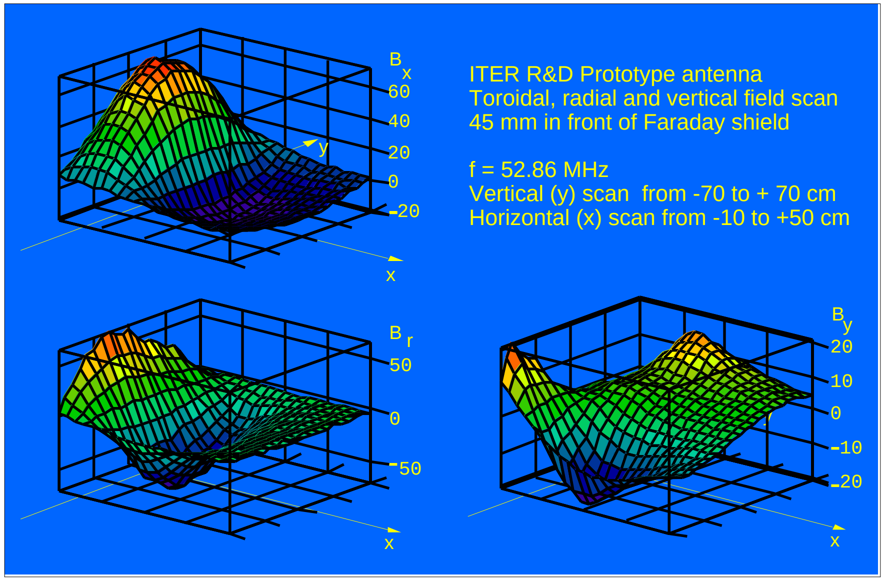
Future work

Near-term: We will instrument the antenna with acoustic and optical detectors and fast pressure gauges to better diagnose the antenna, and then carry out experiments to determine the breakdown locations and causes.

Longer term: We may test the antenna with EU-supplied pre-matching stubs if/when they are delivered (part of ITER R&D). These pre-matching stubs would allow tuning over the 40 to 70 MHz frequency range.

Magnetic Field Measurements and Calculations



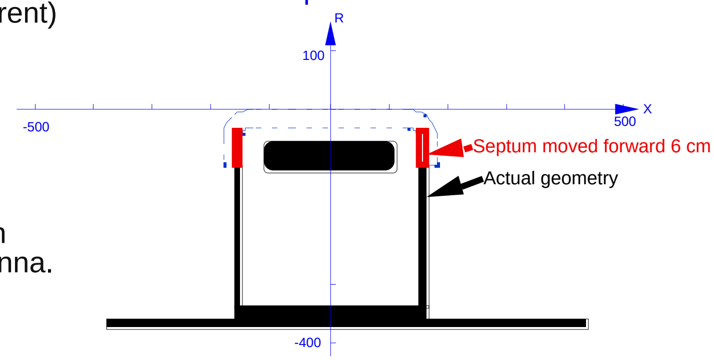


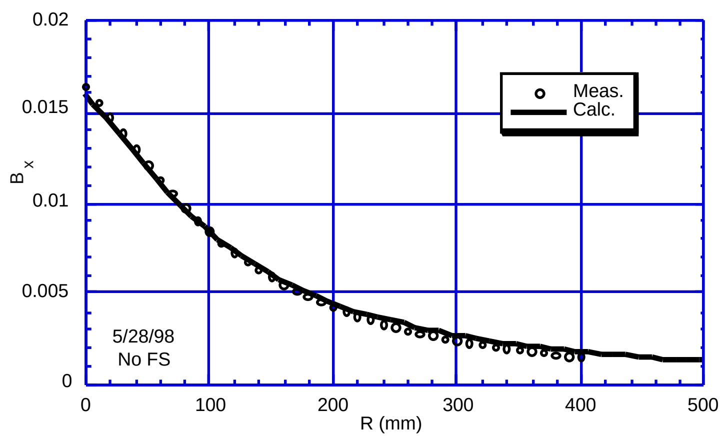
Comparison of measured and calculated fields

Two-dimensional calculations

Used 2D Laplace eq. solver
No Faraday shield
Uniform current in poloidal direction
Net current = 0 (strap current = box current)

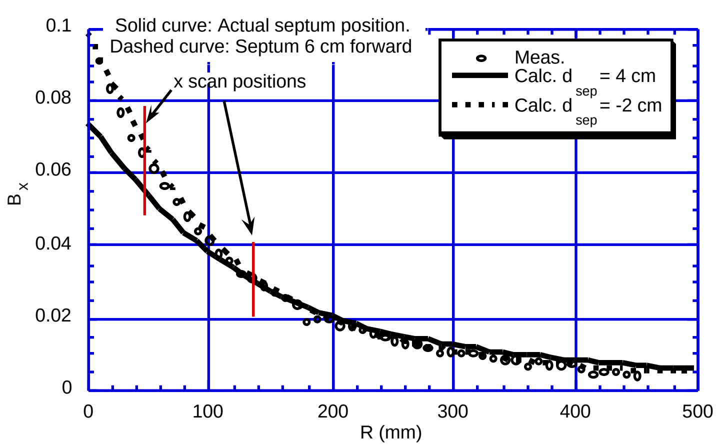
2D Laplace model





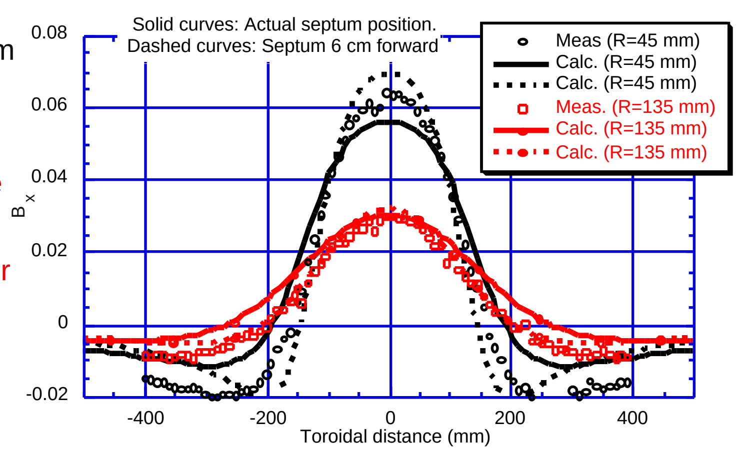
Good agreement between calc. and experiment when no Faraday shield on antenna.

Agreement not so good when FS present. Can improve agreement by artificially moving septum location in calculation forward 6 cm.



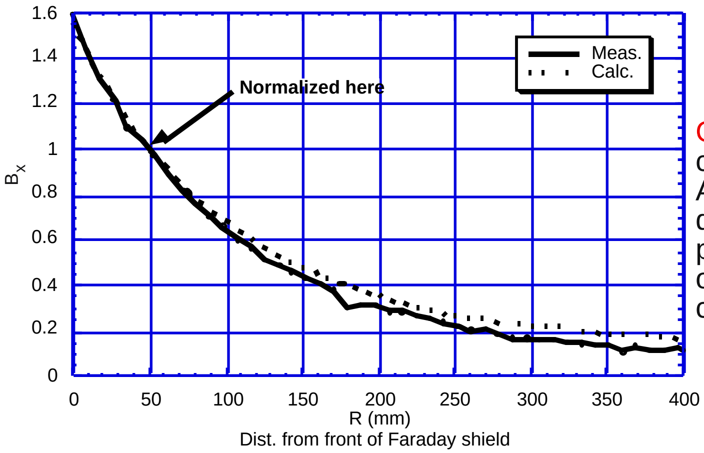
Implication: The effect of the FS is similar to moving the septum forward. Both allow return currents to flow nearer the strap.

This changes the radial decay length, k-spectrum, and loading.



Three-dimensional calculations

Used ARGUS 3D electromagnetics code
- Faraday shield included
- Solved for current poloidal dependence self-consistently
- Contained in external box; net current ≠ 0



Good agreement between calc. and meas. fields.
At large R, calc.B doesn't decrease as fast as measured, probably due to finite size of enclosing box in the calculation