ICRF Operation Experience on Alcator C-Mod

Workshop on Outstanding Issues in ICRF Technology

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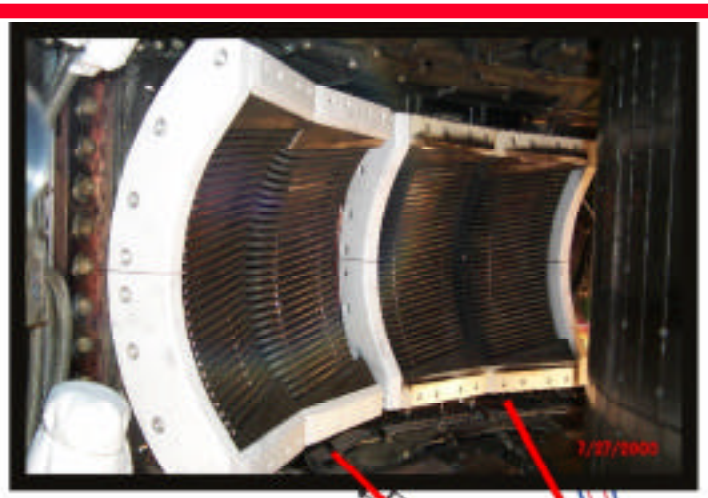
S. J. Wukitch,* R.L. Boivin,* J.A. Goetz,† J. Hosea,+ J. Irby,* W.D. Lee,* E. Marmar,* A. Mazurenko,* E. Nelson-Melby,* M. Porkolab,* G. Schilling,+ and J.R. Wilson+

*PSFC MIT, †University of Wisconsin, + PPPL Princeton University

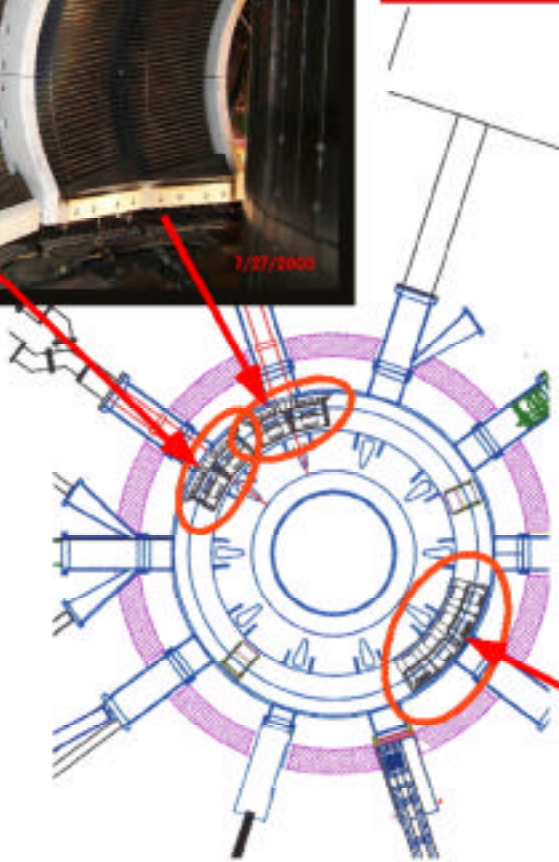
Outline

1. Introduction to ICRF on C-Mod.
2. E and D-port antenna operation.
3. J-port antenna operation experience.

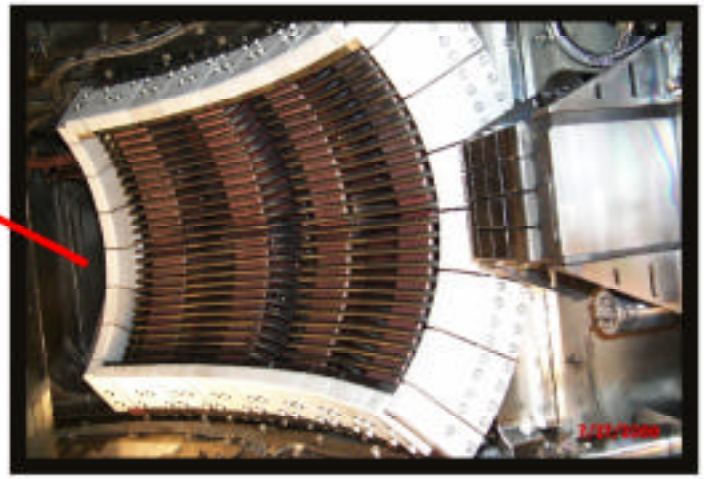
Overview of C-Mod ICRF System



2 two strap (D and E ports)
Fixed frequency (80 MHz)



4 strap antenna (J - port)
Variable frequency 40-80 MHz



Antenna Operational Summary

D and E-port antennas have operated reliably:

- maximum injected power 3.5 MW.
  - » 2.5-3 MW is routine.
- Maximum voltages ~40 kV.
- Vacuum condition to 40 kV.
  - » Have conditioned to 49 kV.

Vacuum feedthru limits power operation.

- Changed center conductor bellows from welded to electro-formed.
- Removed ceramic insulators from 4” coax and pressurized with SF6.

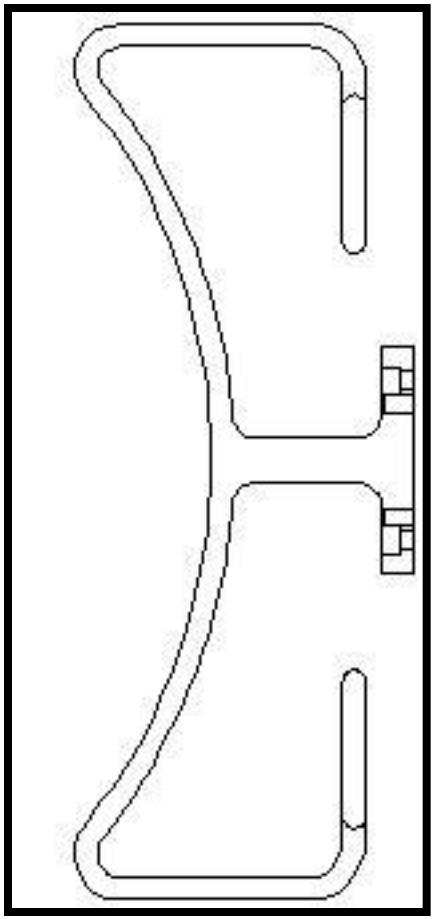
Phase shifters and stub tuners have been reliable.

- Replaced push-pull rod with G7.
- Pressurized with dry N2.

D and E-port Antennas

Two 2-strap, fast wave antennas couple the power into the plasma

- End fed, center grounded straps
- operated with straps current out of phase
- antennas driven with resonant loops
- operated with Faraday screens aligned with B-field pitch.
- Protection tiles are BN.
- peak $n_\varphi = 10$ in vacuum spectrum
- antenna power density ≤ 10 MW/m^2
- voltage handling capability ≤ 50 kV
- Protection tiles are 0.8 cm behind limiter.
- Faraday screen is 1.3 cm behind limiter.
- Strap is 1.8 cm behind limiter.
  - » Density decay length ~0.3 cm.

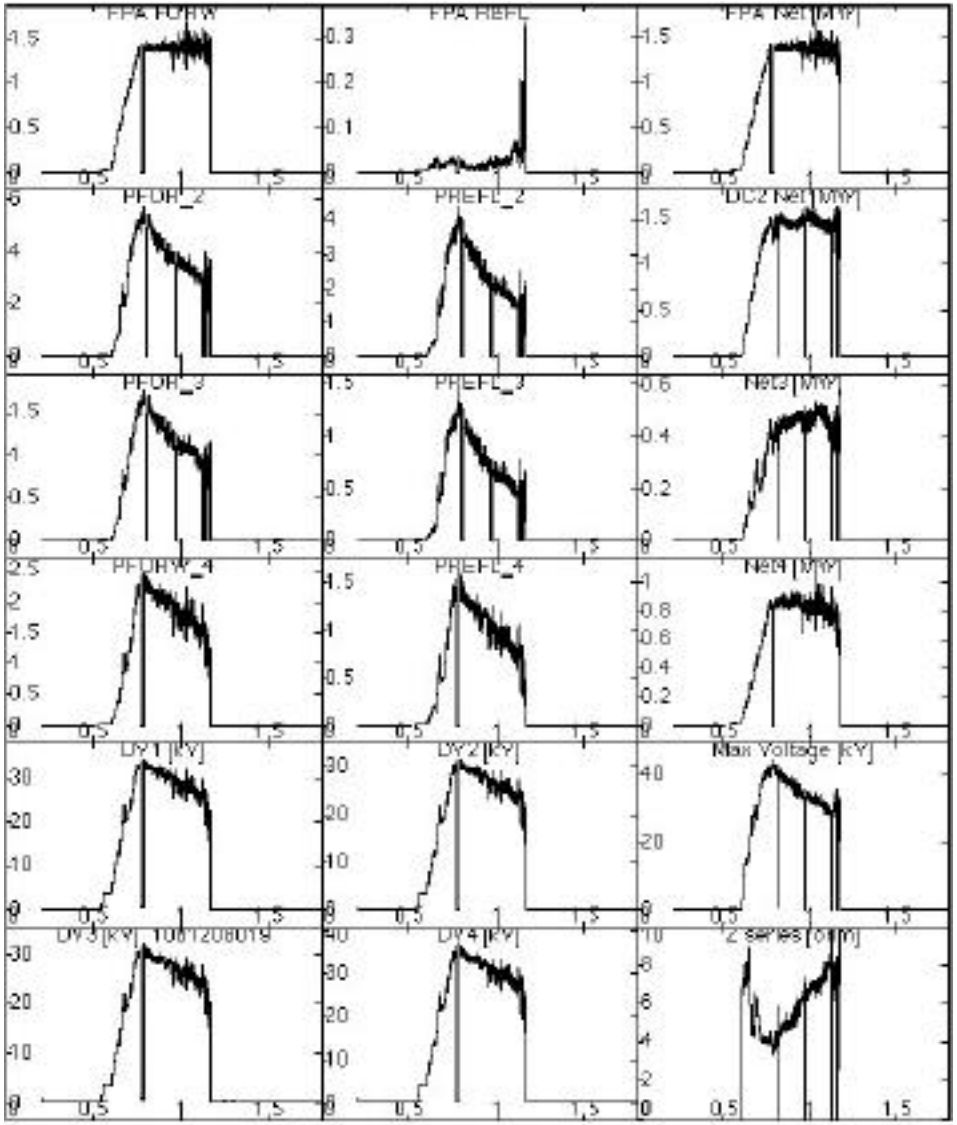


Example of High Voltage Operation

Operational voltage limit is set to ~40kV.

Obtain discharges with ~40 kV.

- Elm-free H-modes
- High plasma current discharges
  - » Voltage increases with plasma current.



E-port BN Tile and Faraday screen after Operation

Impurity influx decreased with BN compared to Mo tiles.

Damage is below BN and in front of the current strap edge.

Other than discoloration, there is minor damage to BN.

- BN proved not to be detrimental to plasma operation.

Resonant Loop Configuration

Feedthrus

3λ Loops

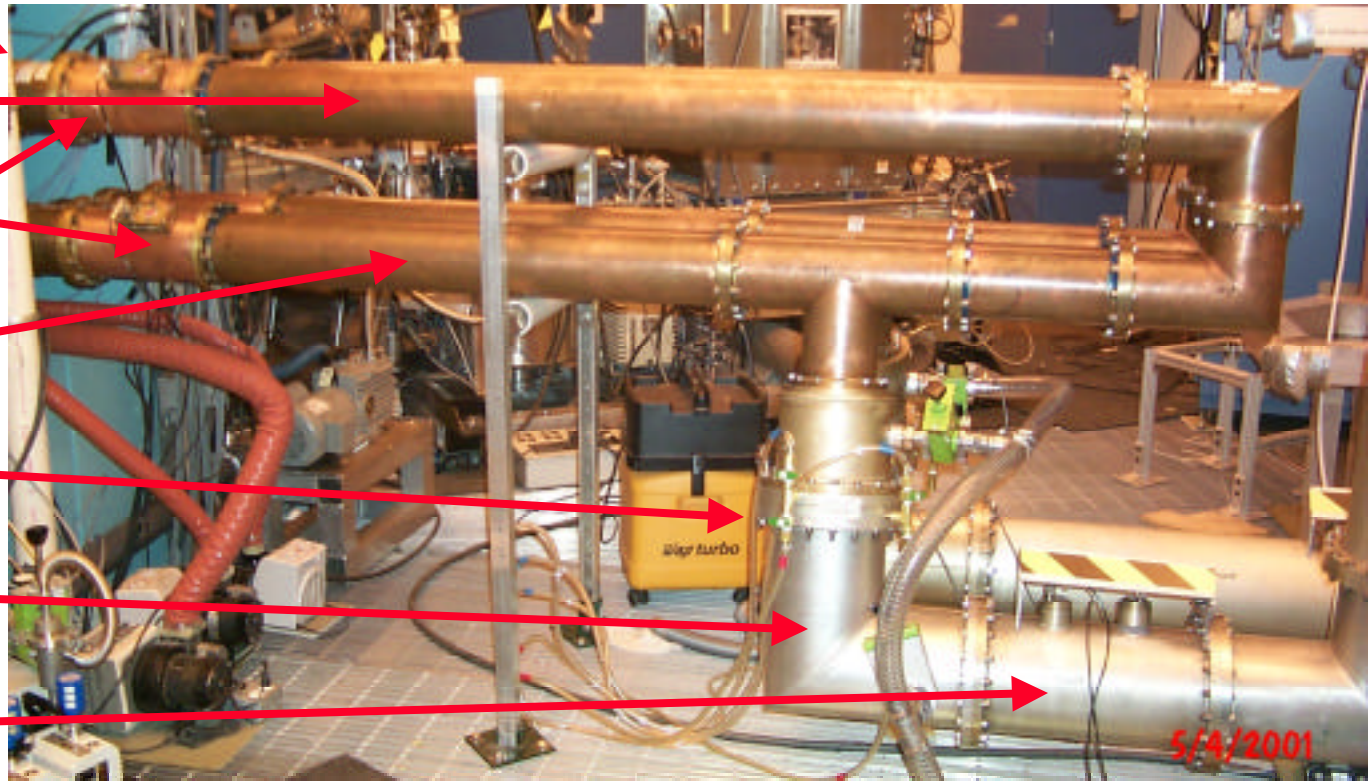
Voltage probes

SF_6 pressurized

Gas barrier

N_2 pressurized

λ Loop



Feedthrus and 4” coax required SF6 and removal of insulating supports to achieve reliable operation.

No arcing problems in the 6” and 9” coax sections.

Matching Network

Stub tuner

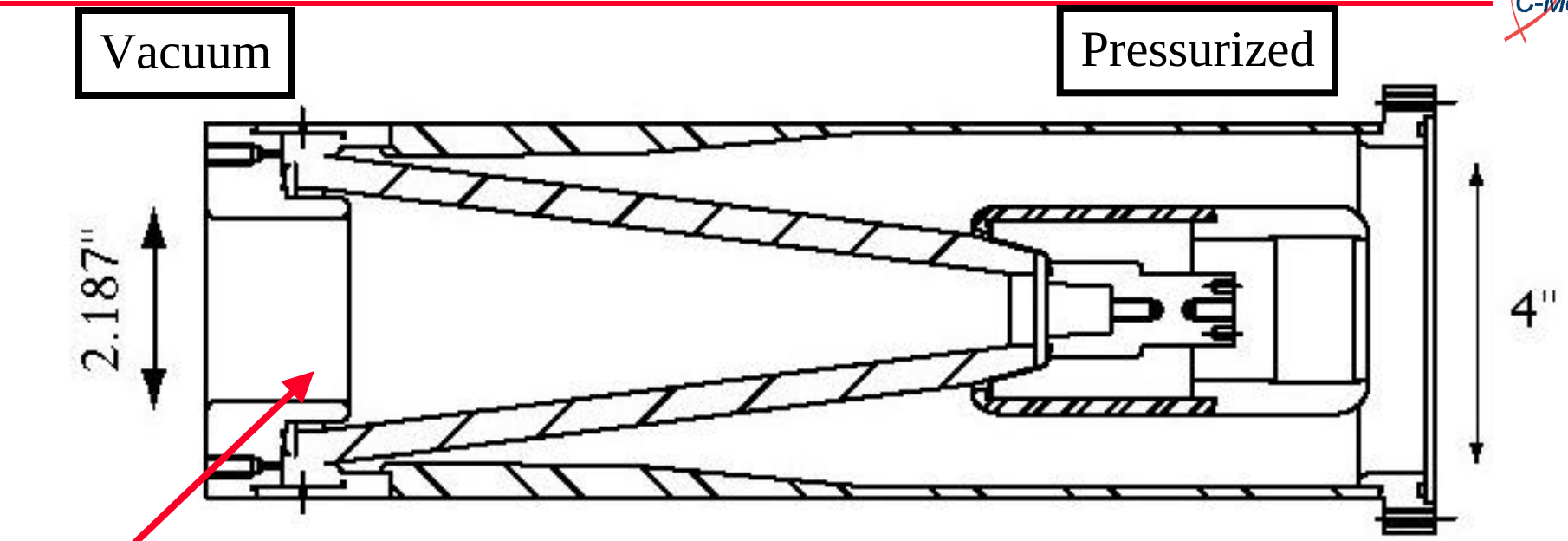
Phase shifter

DC breaks

Cu shroud to reduce leakage

Problem free except for the push-pull rod material replacement.

Vacuum Feedthru

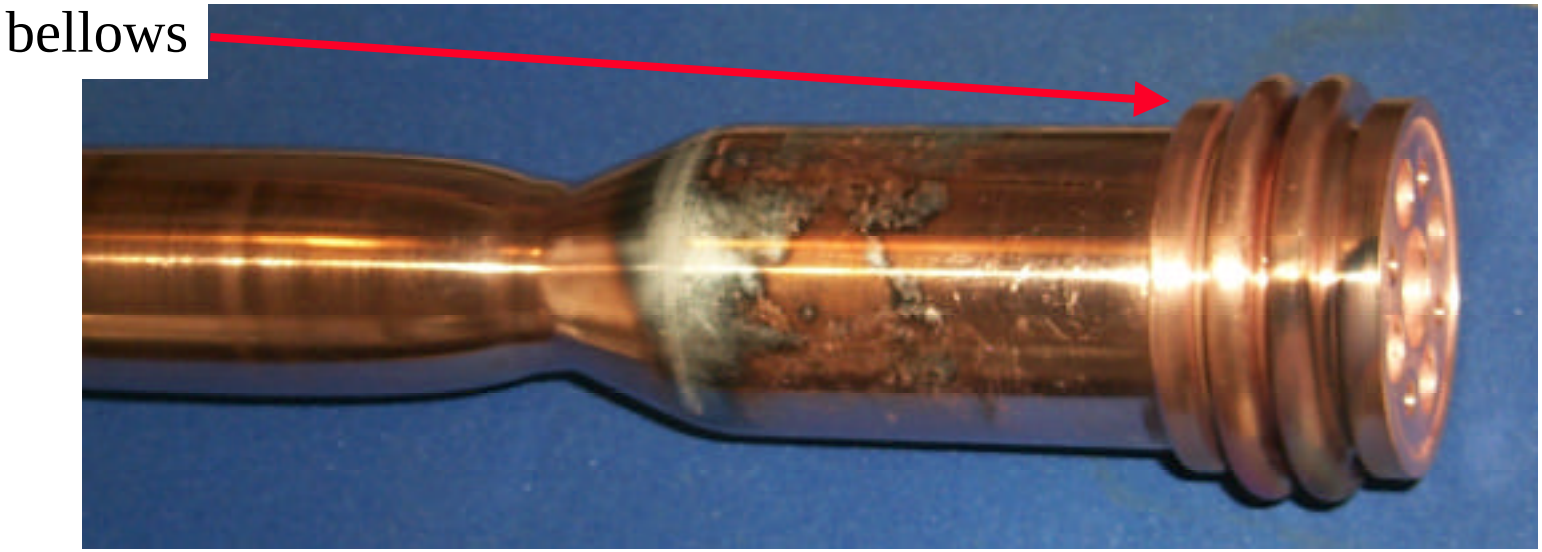


Appears to limit maximum voltage.

First voltage maximum appears on pressurized side.

Initial failure on pressurized side required grit blasting.

Center Conductor



Bellows section was welded and appeared to cause arcing.

- Replaced welded with electro-formed and voltage operation improved to ~40 kV.

Arc damage is from vacuum conditioning to ~50 kV.

- ~2 MV/m assuming 50 kV max.
- Plan to model using new software from CST.

J-port Antenna Summary

2x2 MW variable frequency transmitters (40-80 MHz).

4-strap, fast wave antenna heats efficiently up to 2.5 MW.

Operating to 15-20 kV in plasma.

- Tested up to 40 kV into the C-Mod.
- Arc damage is concentrated where E-field is parallel ambient B-field.
- Arc damage is concentrated where surface is contaminated.

RF-plasma interaction limits input power.

Antenna driven with decoupled resonant loops.

» $(0,\pi,\pi,0)$ with peak $n_\varphi \approx 8$

» $(0,0,\pi,\pi)$ peak $n_\varphi \approx 4$

Faraday screen is aligned to toroidal B-field.

For Effective <2.5 MW Antenna Operations, Several Modifications were Required

Eliminated the arcing between top and bottom Mo protection tiles by improving the grounding.

- Most likely candidate for impurity injections seen at power >1.3 MW.
- Installed shorting straps between tiles.

Shield the Faraday screen rod ceramic insulators from plasma and antenna strap to prevent arcing.

- Installed stainless steel shields.

Modified antenna arc protection to limit energy available to dissipate in an arc during conditioning.

- Reduced the threshold forward power to 50 kW and
- Modify conditioning procedure to limit pulse widths below 50 kW.

Other Modifications

Optimize antenna spectrum for heating.

- Required change in transmission line configuration.

Replaced Mo protection tiles with BN tiles to reduce impurity influx.

RF grounded the antenna box to eliminate possible parasitic loading.

- No evidence that this improved the heating efficiency.

Added enclosure around the antenna to prevent deposition behind the antenna.

To Improve Antenna Operation Beyond 2.5 MW...

Reduce RF-plasma interaction at antenna corners and Faraday screen.

- Found the front BN protection tiles are ~4 mm closer to the plasma than the side limiters.
- Exposed metal surfaces appear to damaged.

Improve voltage limit.

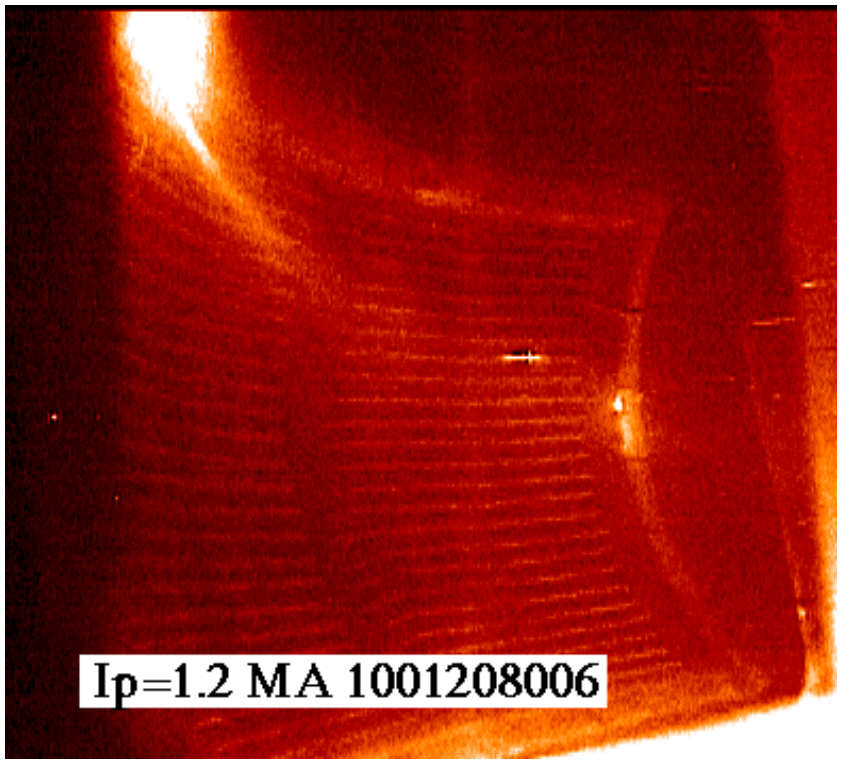
- Damage appears to follow B-field.
- Stripline and septum are heavily damaged.
- Straps #2 and #3 back plate feedthrus are damaged.

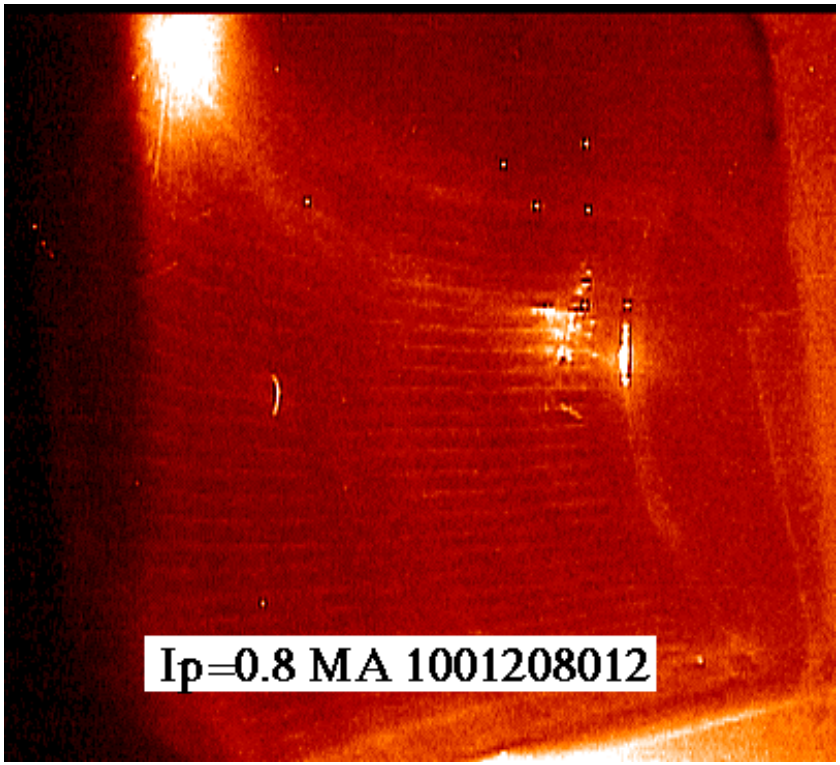
Limit energy delivered during an arc.

- Damage suggest 100-1000 J are absorbed.

Prevent breakdown in vacuum feedthrus.

Camera Images Suggest Hot Spots are Connected



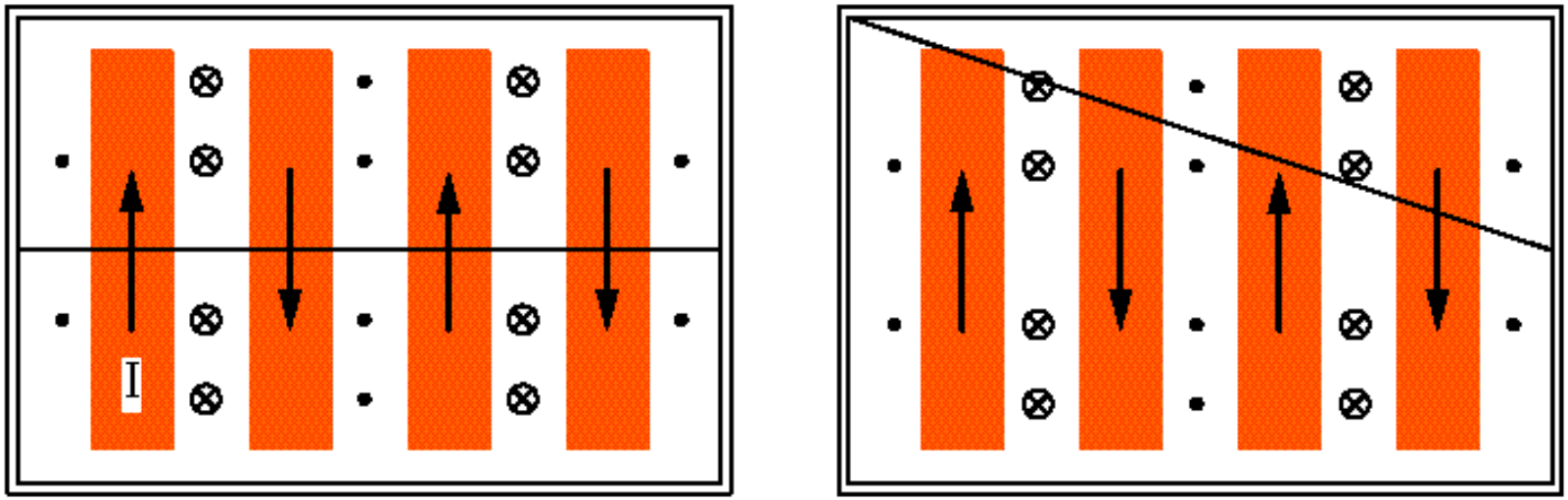


Side hot spot location is consistent with field line pitch.

Hot spot location varied with plasma q.

Obtain highest voltage on longest field line.

Electric Field Develops on Field Line



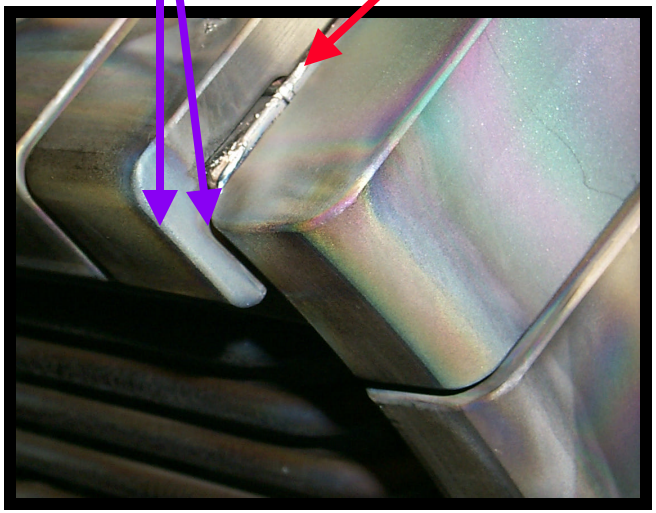
Field line pitch results in nonzero B-flux linkage to field lines connecting surfaces results in RF E-field.

- Due to frequency, ions cannot respond and electrons are preferentially expelled.
- Plasma maintains neutrality by rectifying voltage to accelerate ions and a enhanced sheath potential develops.

Invessel Observations - January 2001

Upper right corner showed melting

- Small gap present
- BN front tile is “proud” of side tile



BN tiles are coated but still insulating

Severe Arc Damage was Found between Striplines and Septum

Arcing appears to be along field lines.

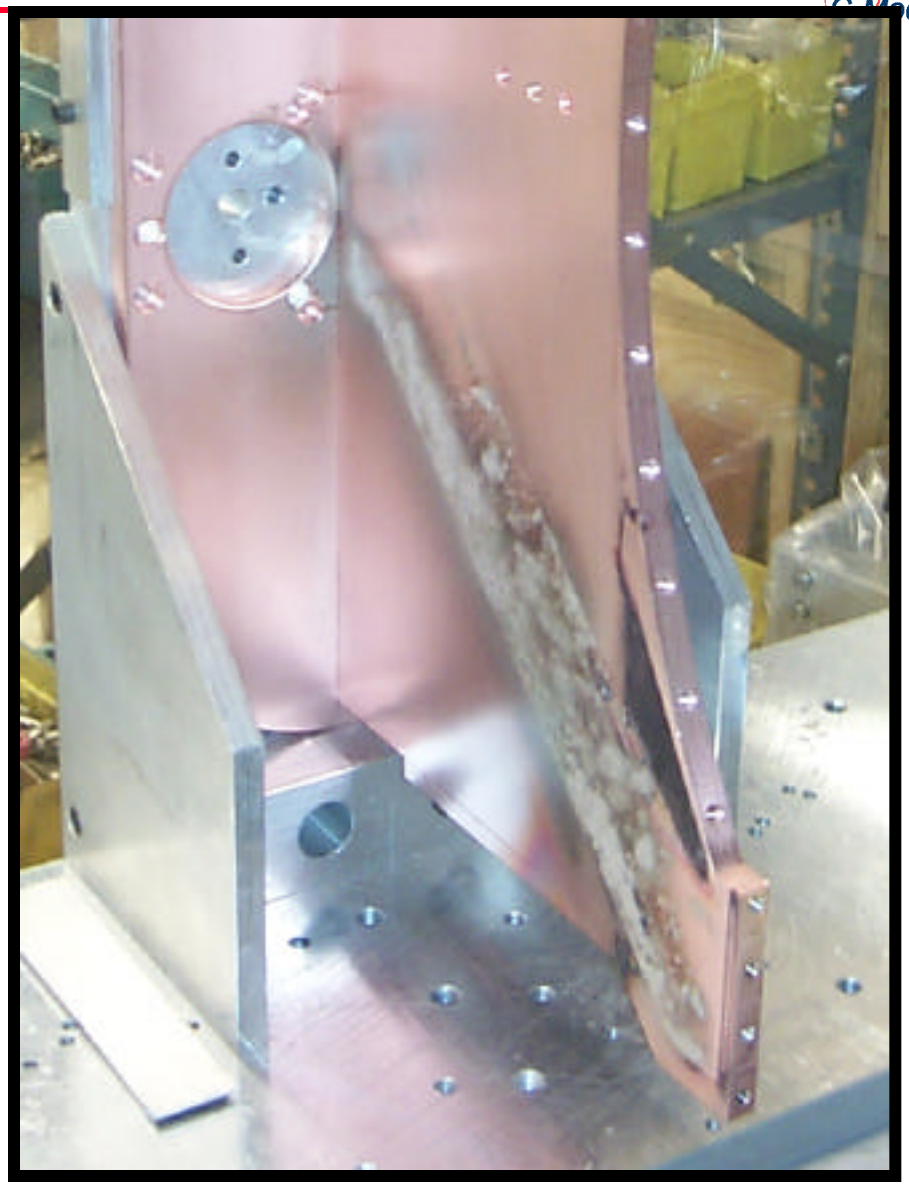
Damage suggests 100-1000 J are deposited - insufficient arc protection.

Most Severe Damage is on the Lower Striplines

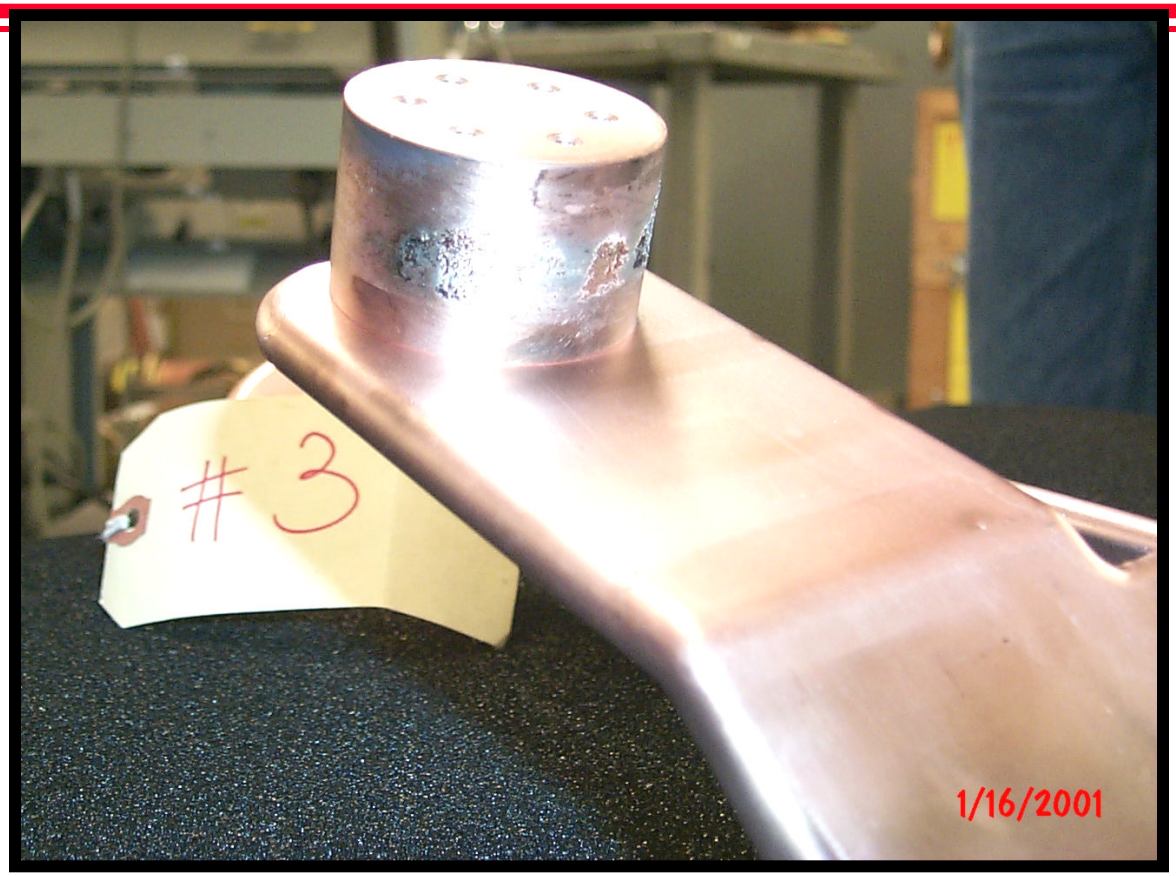
Strap #2 and #4 were connected to same xtmr during high power operation.

Strap #4 feed sagged ~0.25”.

- Arc damage was low compared to where it should be when made up on stand.
- Disruption forces allowed a bolt connection to relax.



Back Plate Feedthrus were Damaged



Appears to be along magnetic field.

Only straps #2 and #3 had damage.

Arcing Mechanism is Unclear

Calculations for field emission initiated breakdown requires local electric fields of GV/m.

- Peak RF electric fields are ~3 MV/m.
- FE initiated breakdown begins ~20 MV/m (imperfections result in local GV/m fields).

Gas breakdown seems unlikely.

- Mean free path is >> electrode spacing.
- Minimum in Paschen curve is ~torr - cm.
- Nonlinear effects due to nonuniform electric fields could trap electrons.

Electron multipactoring initiated breakdown requires lower fields or longer path lengths.

- Long paths exist between stripline and vacuum vessel wall.
- Multipactoring is a resonant condition.

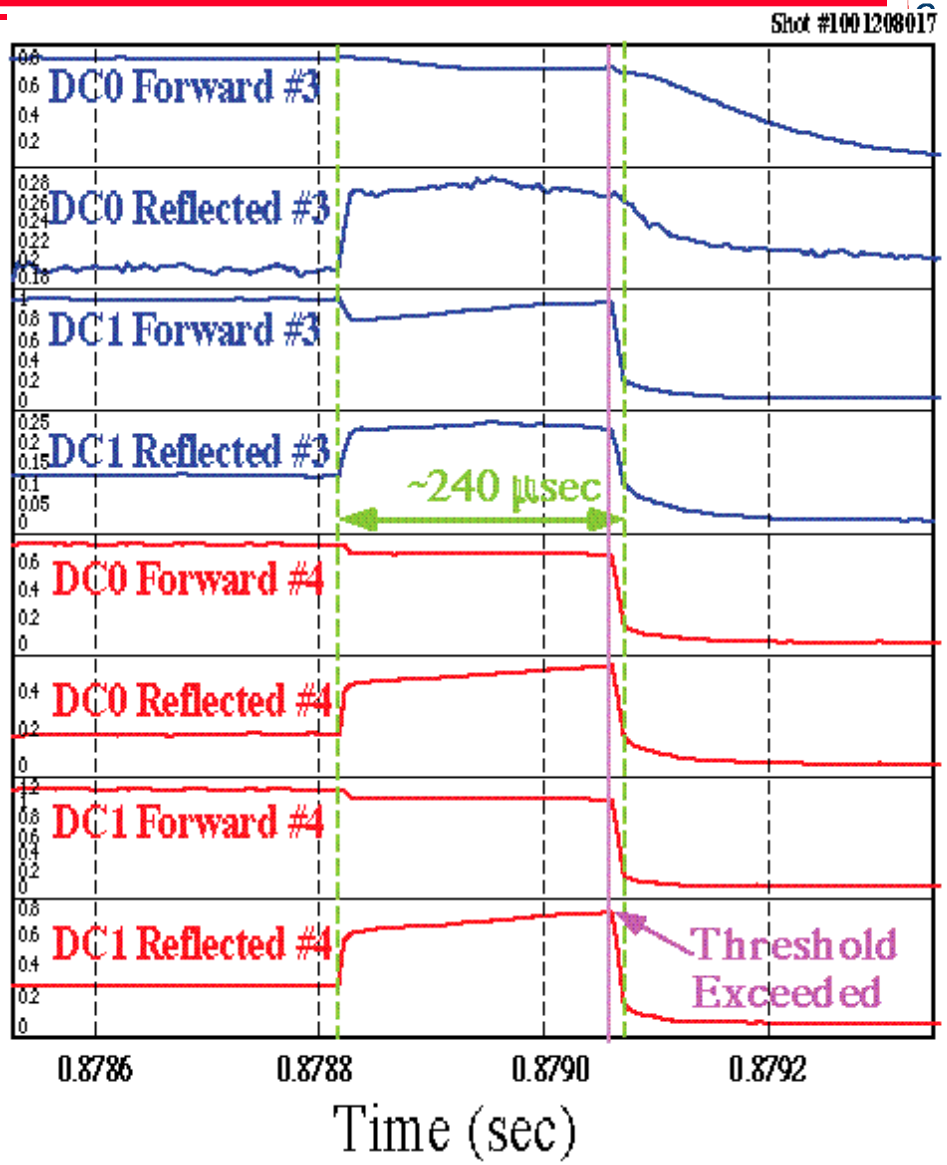
Excessive Energy is Deposited During Arcs Resulting in "Low" Reflected Power

Arc protection circuit monitors ratio of reflected to forward power.

- Trip level is set to ~40%.
- Transmitter is turned off ~5 usec.

Arcs in a low Q system could result in a partial reflection.

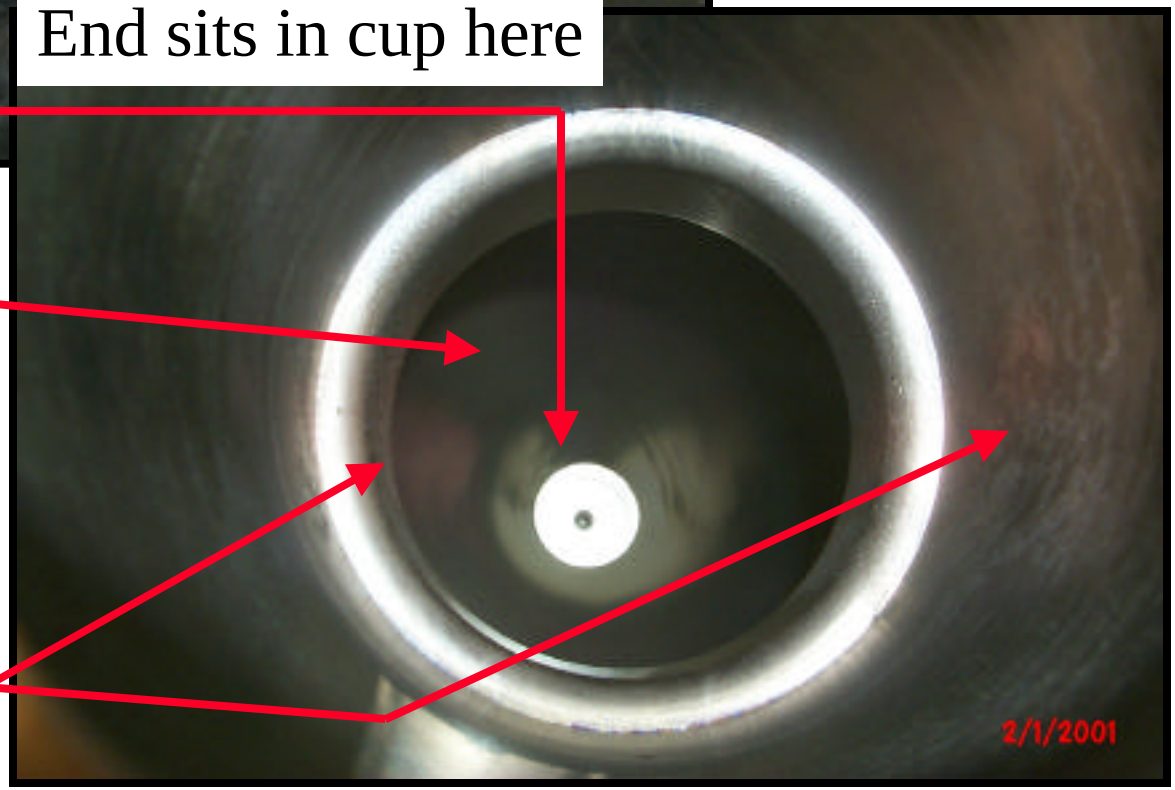
- Reflected to forward ratio < 40%.



Vacuum Feedthrus are Damaged

Antenna side

End sits in cup here



Ceramic should be white.

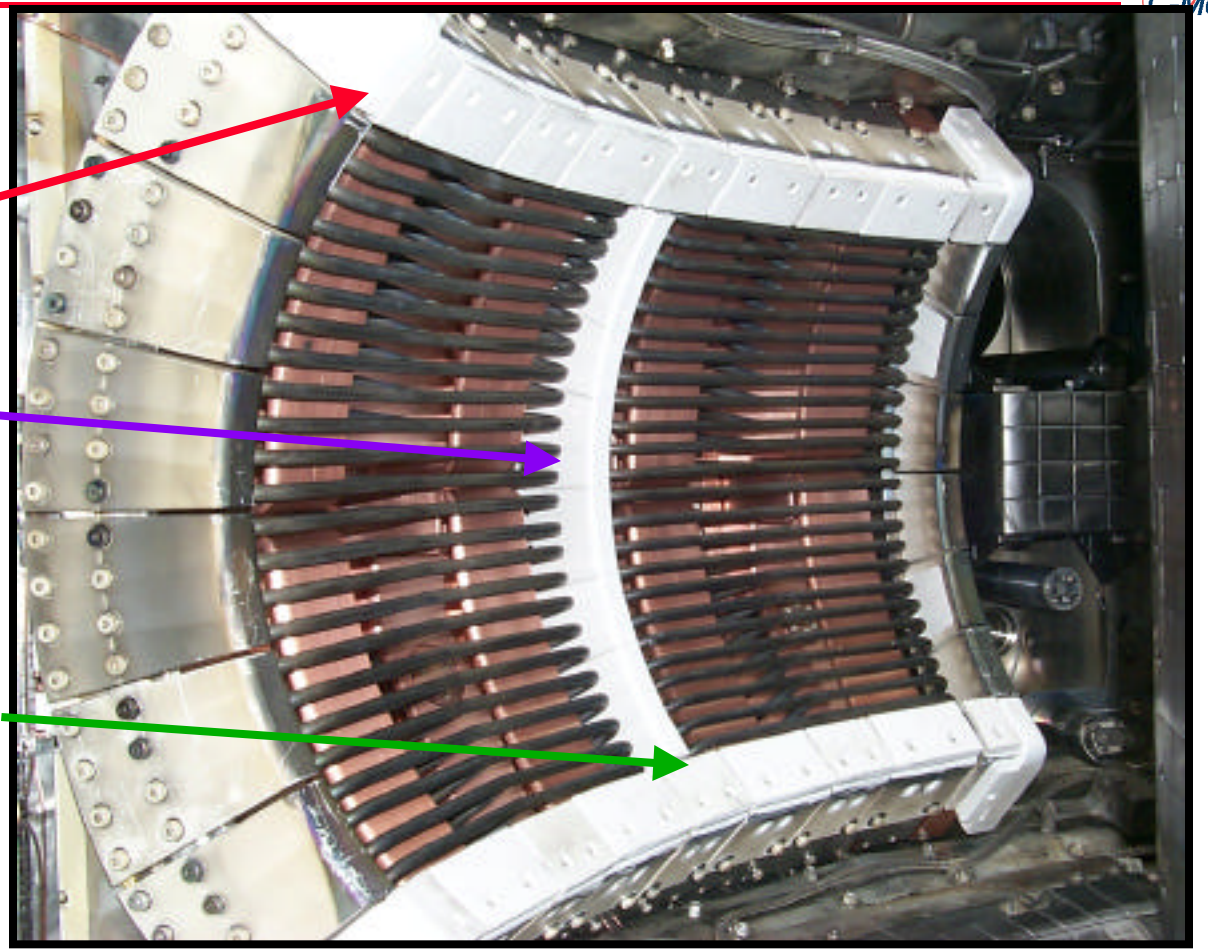
Note Cu deposition on stainless.

Reduce RF-Plasma Interaction

Align front protection tiles with side tiles.

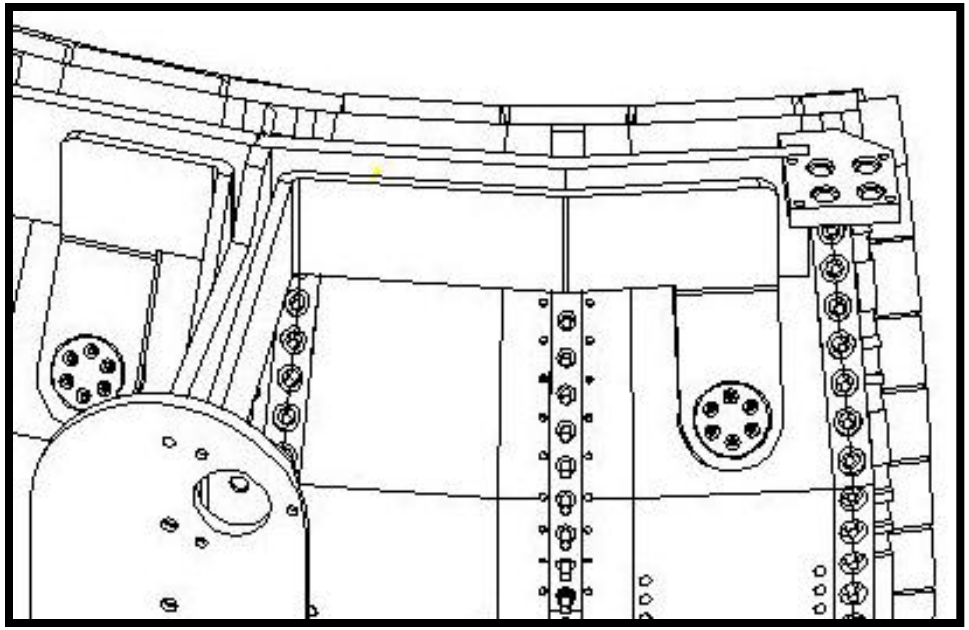
Install septum to reduce field line connection length.

Cover all metal surfaces with BN tiles.

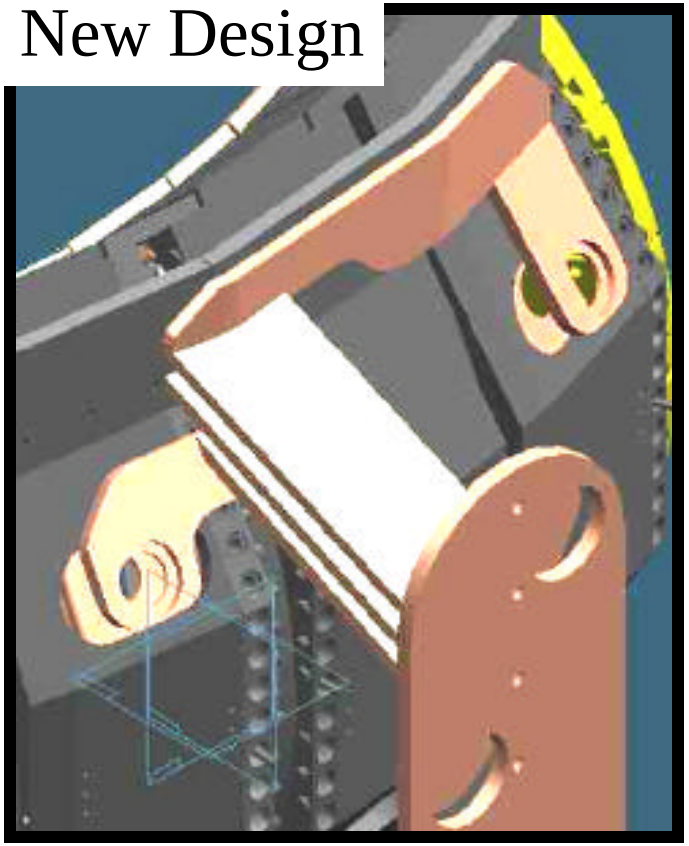


Improve Voltage Limit by Modifying Antenna Feeds

Previous Design



New Design



Use magnetic field to insulate electrodes.

- Orient feeds so RF E-fields are perpendicular to static B-field.

Reduce peak electric fields.

- Increased electrode spacing from 1 cm to 1.5 cm.

Stripline Detail

Lead impedance is ~ 55 Ω.

- Tapered transition from 52 Ω to ~100 Ω.

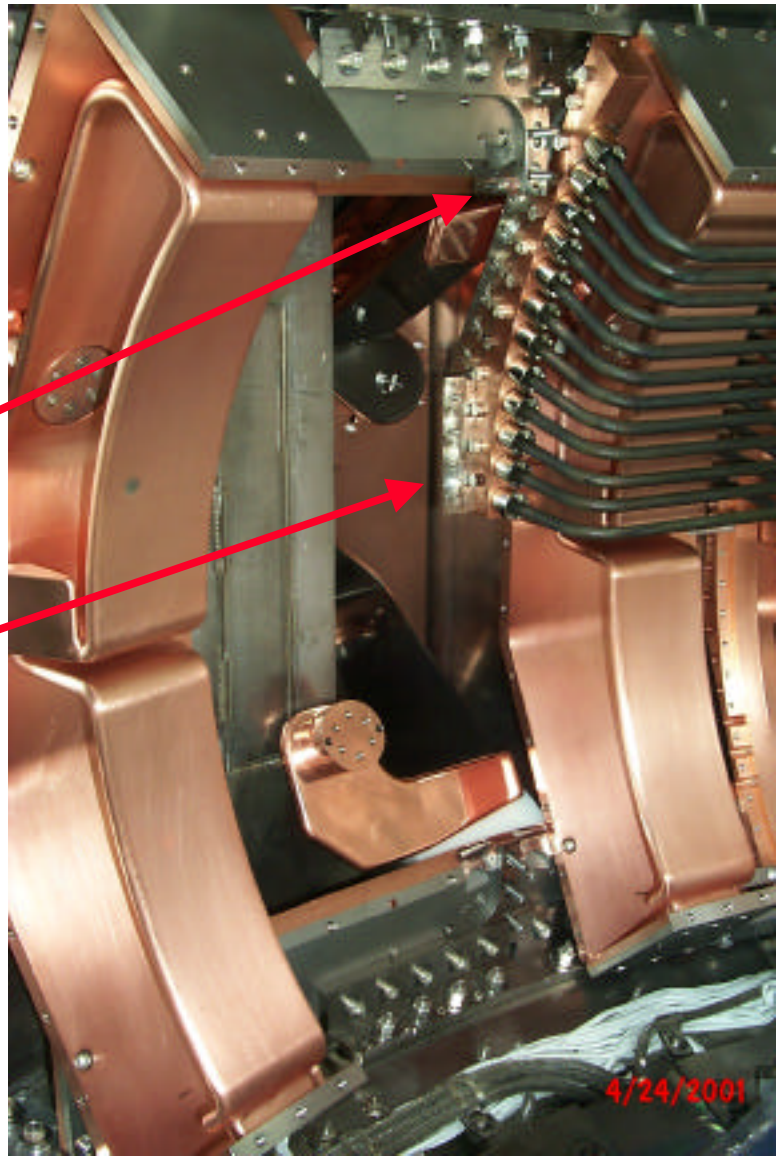
Design Aspects Could Limit Maximum Voltage

Transition from horizontal to vertical stripline could result in higher voltage.

Bridge plate has finger stock contact with ground.

Back plate bridge has ~0.75 mm step.

Bolt head is not recessed.



Improve Arc Protection

Decrease the trip level from 40%.

Shut down both transmitters when one receives a fault.

Use voltage phase balance for arc detection.

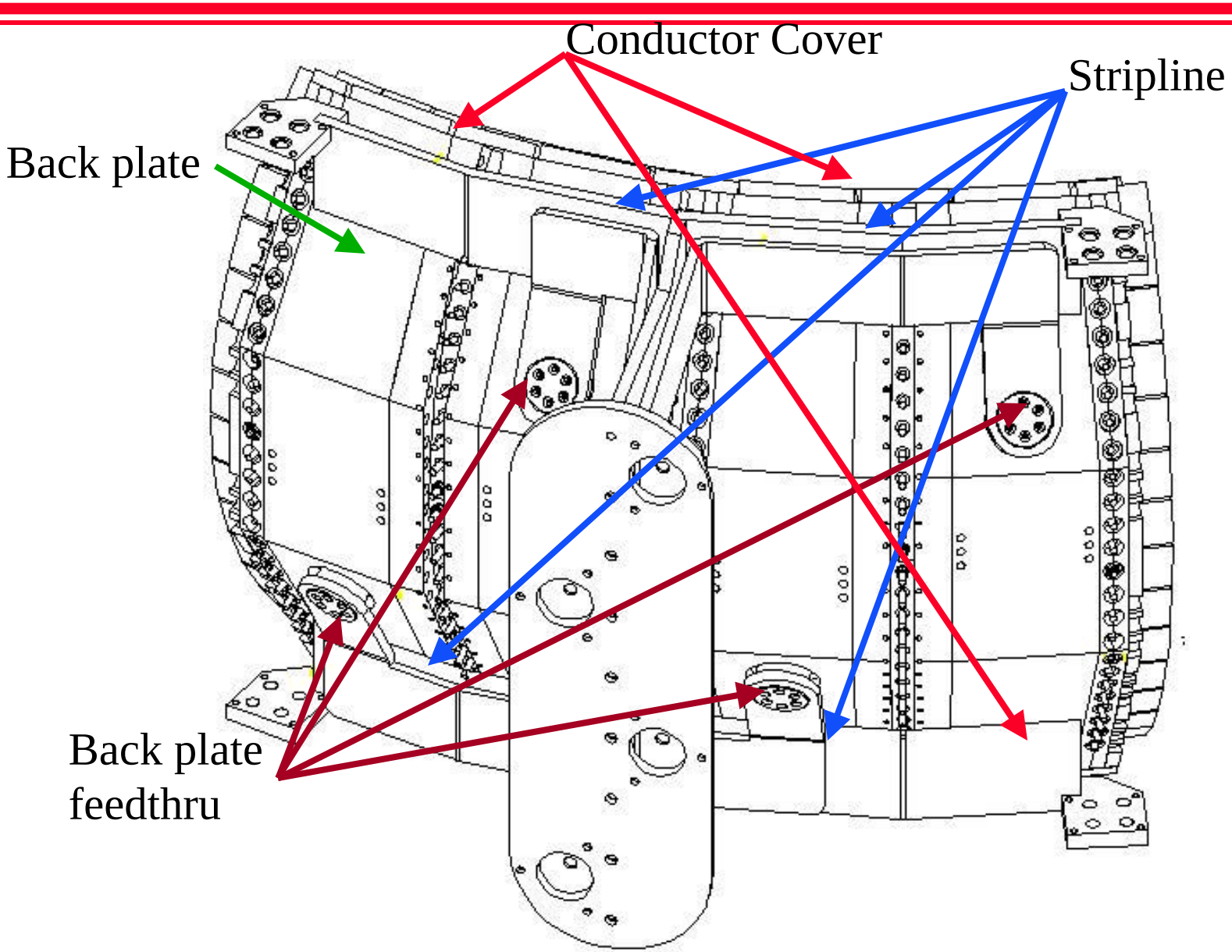
- Present arc detection relies solely on ratio of reflected to forward power.
- Damaged D-port antenna when operated with broken current phase monitor.

Plan to investigate using the current amplitude and phase balance for arc detection.

Increase number of forward/reflected power measurements

Implement acoustic localization technique for discriminating vacuum side from pressurized side arcs.

Original J-Port Antenna (Rear)



Conclusions

To obtain <2.5 MW operation, several modifications were required:

- Eliminated the arcing between top and bottom Mo protection.
- Shielded the Faraday screen rod ceramic insulators from plasma and antenna strap.
- Modified antenna arc protection to limit energy available to dissipate in an arc during conditioning.

Improvements are needed to increase power handling and reliability of 4-strap antenna.

- Reduce peak E-fields,
- Utilize magnetic shielding,
- Improve surface finish, and
- Utilize voltage probe phase to detect arcs.