High power density launchers

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CEA, IPP-Garching,...

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Outline

- Introduction
- ITER high voltage R&D antenna
- RF / edge plasma interactions (Tore Supra)
- Folded waveguide

RF Heating and Current Drive Issues for Fusion Reactors

- High power density is the holy grail of auxiliary heating.
  - Less surface area exposed to plasma
  - Less encroachment on blanket and shielding hardware
- Reactors will operate for long pulse lengths.
  - Active cooling of antenna components will be required.
  - First-wall coatings must last.
- Maintenance should be reasonable
- Strategies/requirements for maximizing ICRF power density
  - Maximize antenna loading
  - Maximize voltage handling capabilities
  - Minimize internal electric fields at plasma interface
  - Provide constant load to RF generators
  - Minimize localized power deposition caused by RF/edge plasma interactions
  - Eliminate ceramics in or near vacuum vessel

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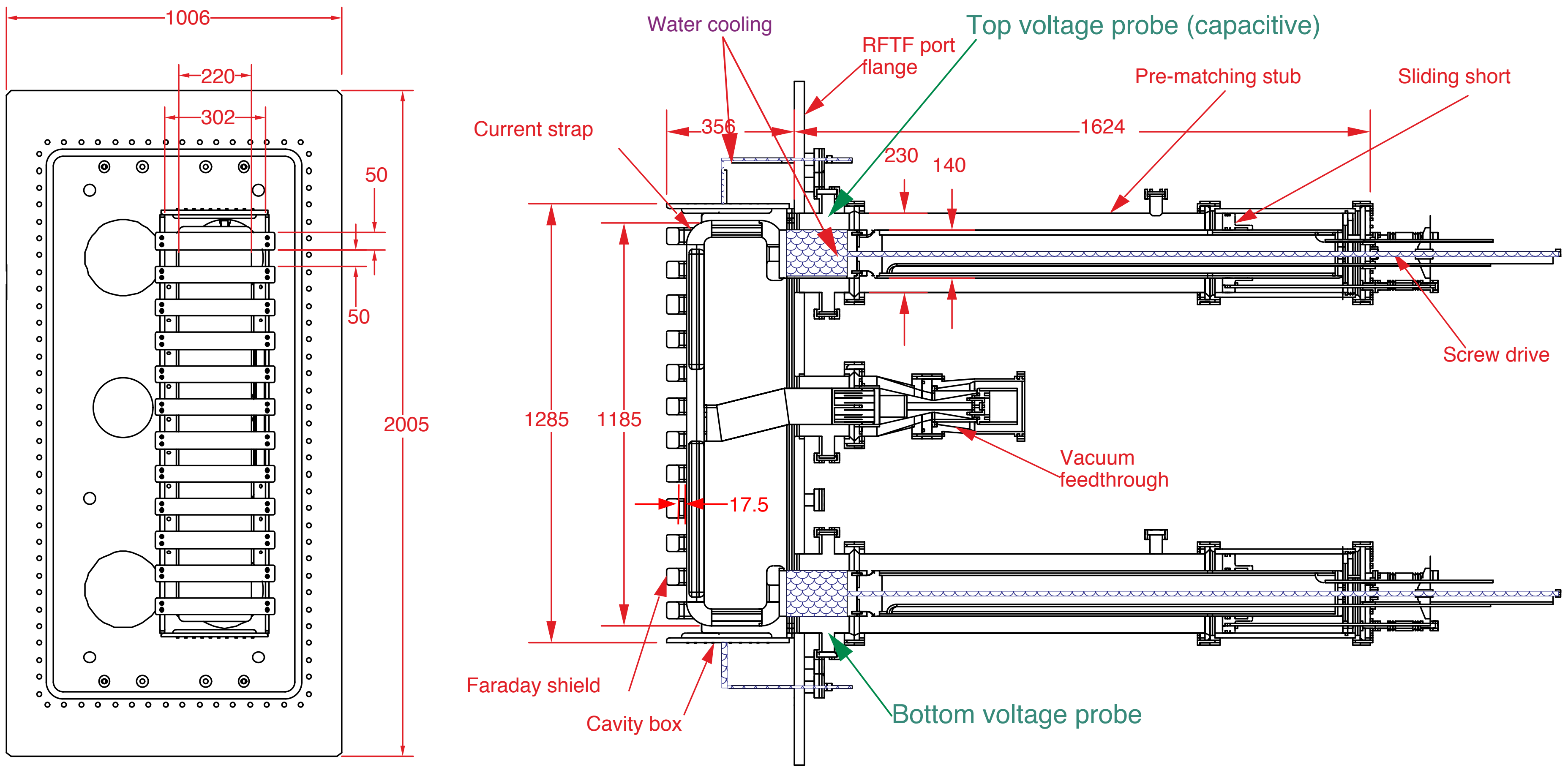
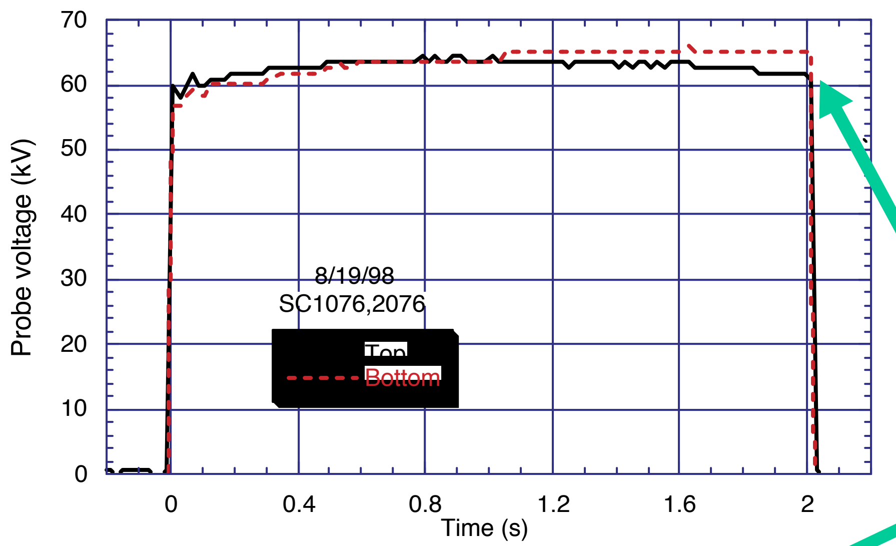
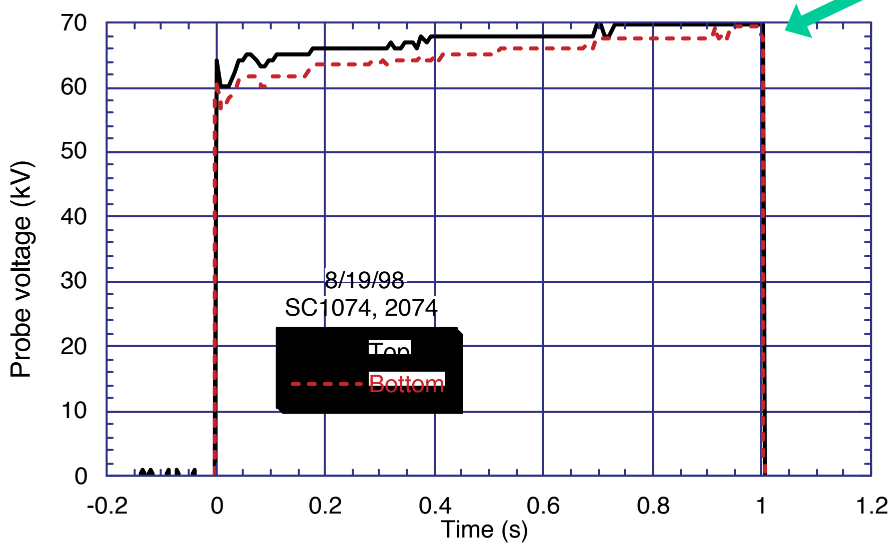
ITER high voltage R&D antenna



RDL design capable of sustaining exceptionally high RF voltages

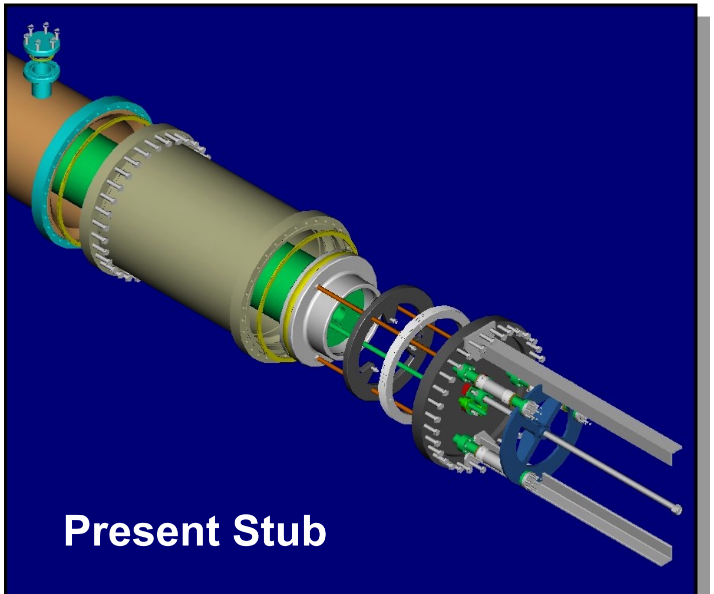


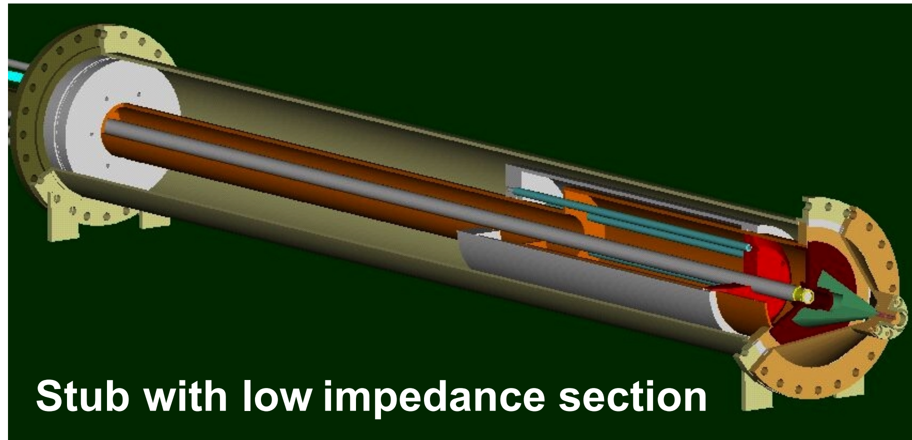


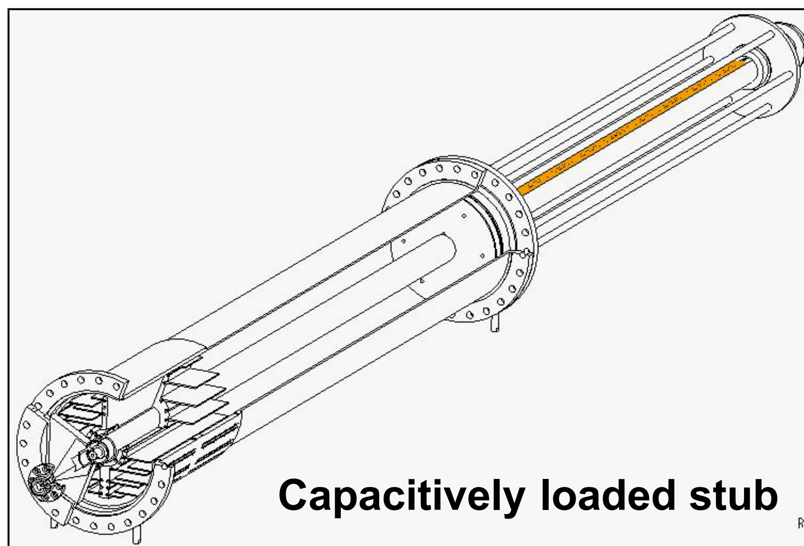
Results:

- Measured peak voltage of ~72 kV for 0.1s – corresponds to > 2 kA maximum strap current
- > 60 kV for 2 s
- > 65 kV for 1 s
- Voltage during long pulses limited by outgassing in stubs and antenna box

Voltage handling capabilities of internal structures of advanced compact stub designs will be tested in the ORNL vacuum RF breakdown test line







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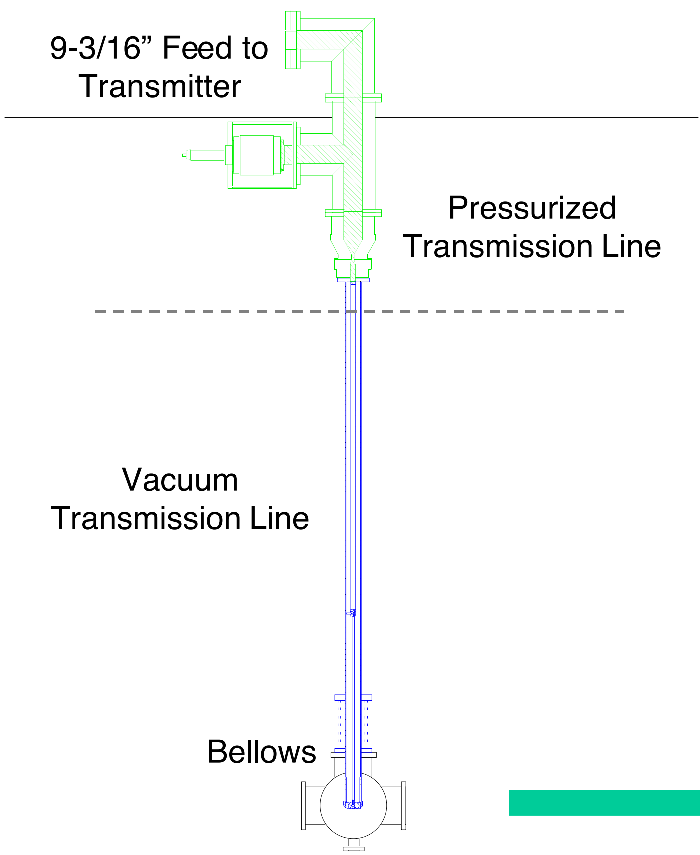
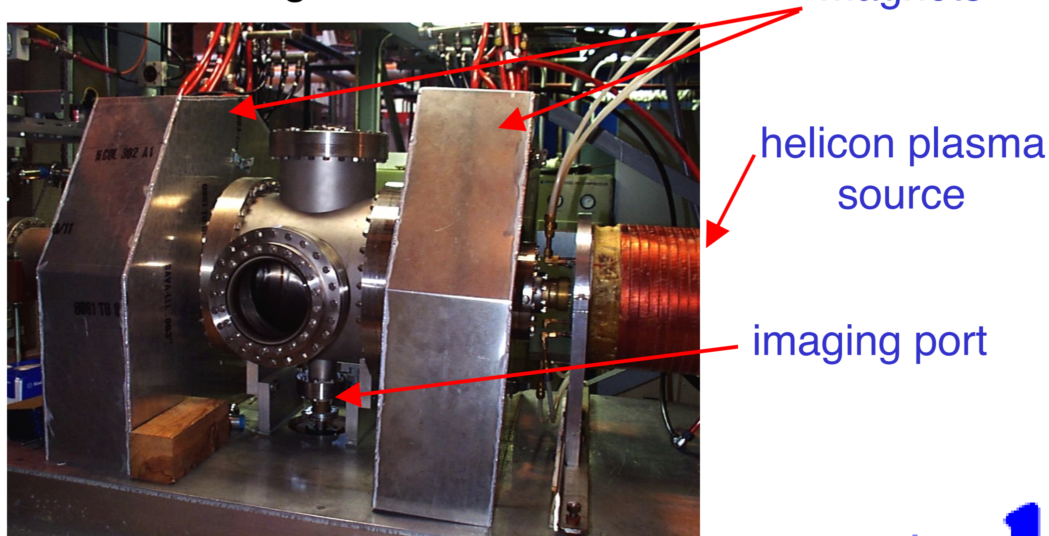
RF Breakdown Test Line on Mini-RFTF



- The apparatus mounts vertically on mini-RFTF.
- An identical vacuum transmission line (shown in blue) will be used on ASDEX-Upgrade.
- The only active cooling is on the variable end of the capacitor.
- Diagnostics will include
  - Voltage and current probes
  - Fast CCD camera
- Tests to begin this summer



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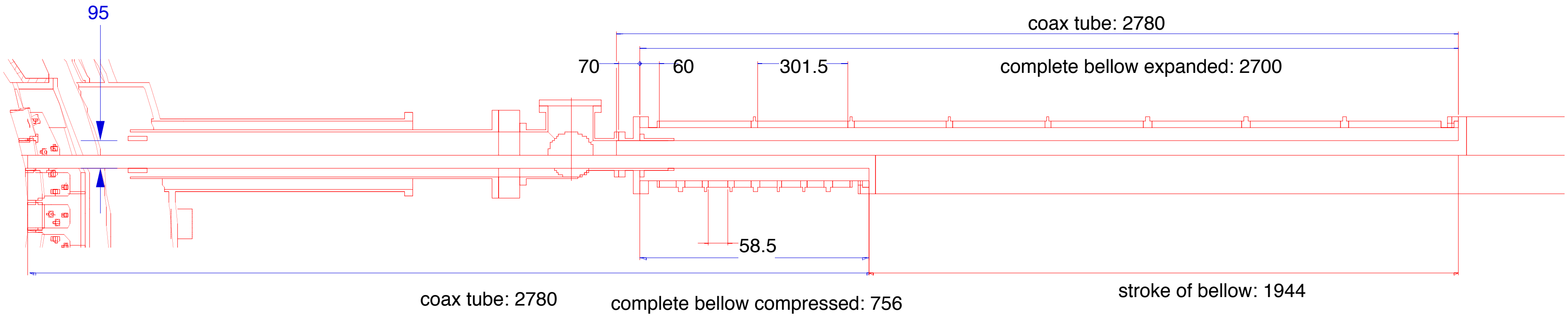
High voltage breakdown tests at ASDEX-U



- Test line uses modified fixture originally built for materials studies
- Voltage standoff of simple electrode geometries will be tested in first wall environment
- Gate valve allows electrodes to be interchanged and baked without breaking vacuum in main vessel
- Can also be used for RF/edge plasma interaction studies
- High voltage breakdown experiments at ASDEX-U will begin in Spring 2001

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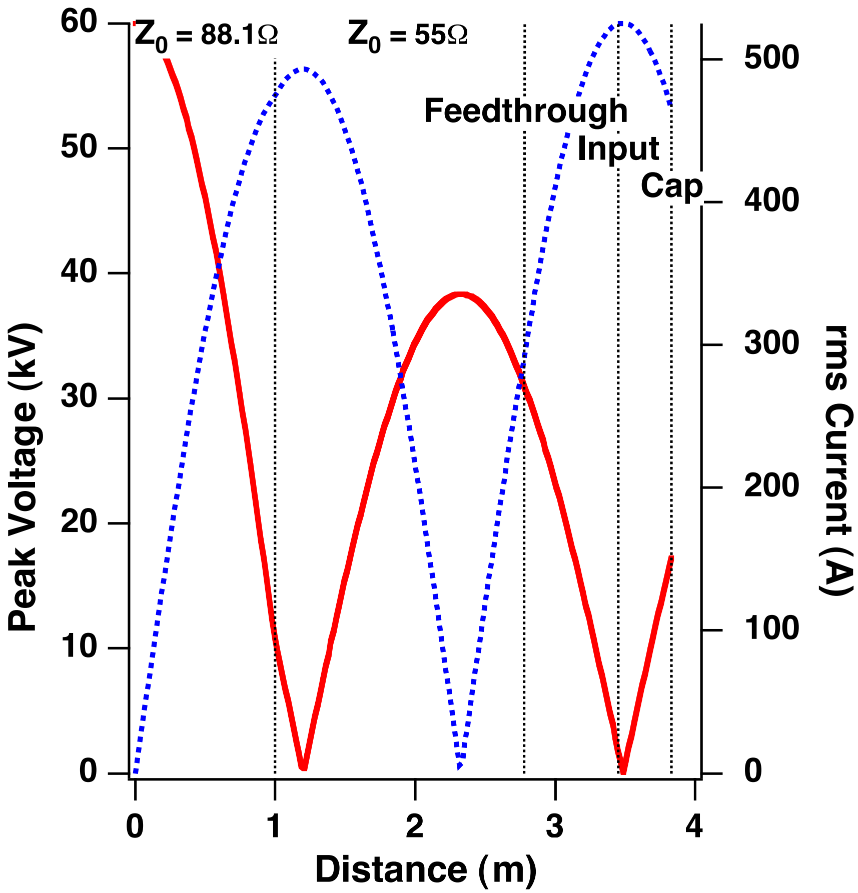
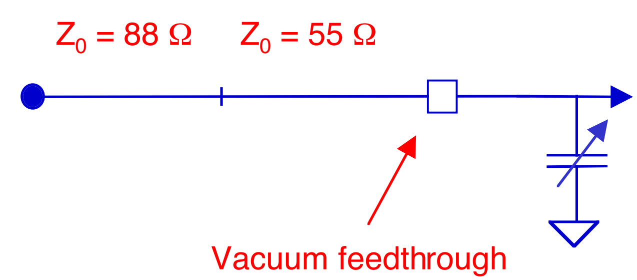
Voltage peaks at the open end and is much lower at the feedthrough



- 28 kW input power required to reach 60 kV with stainless steel outer and copper inner conductors.
- A 100 ms pulse will cause a 0.4 °C rise in the outer conductor temperature at the location of the current maximum and a 2.4 °C rise in the high-Z inner conductor.



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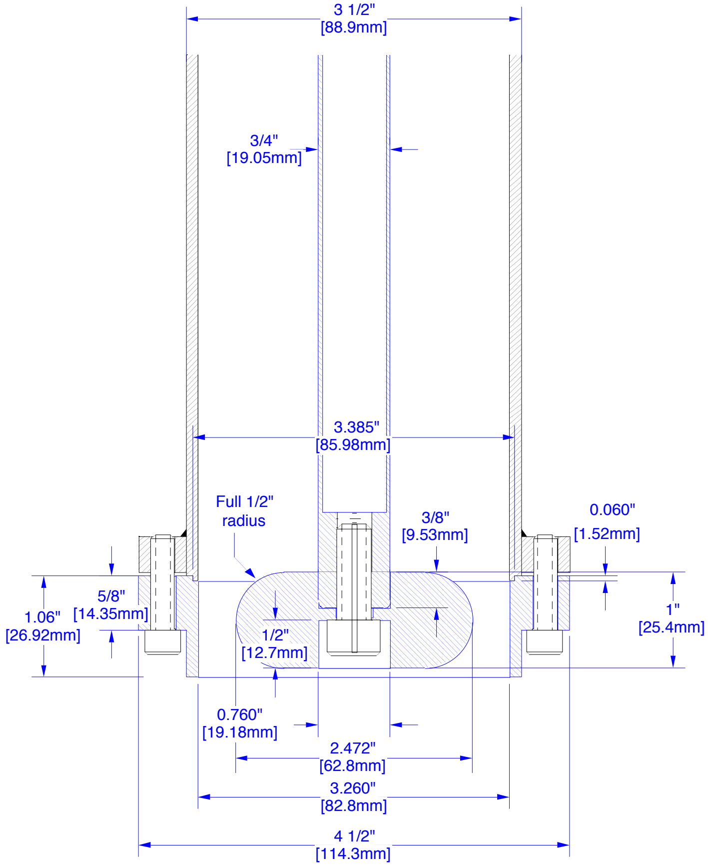
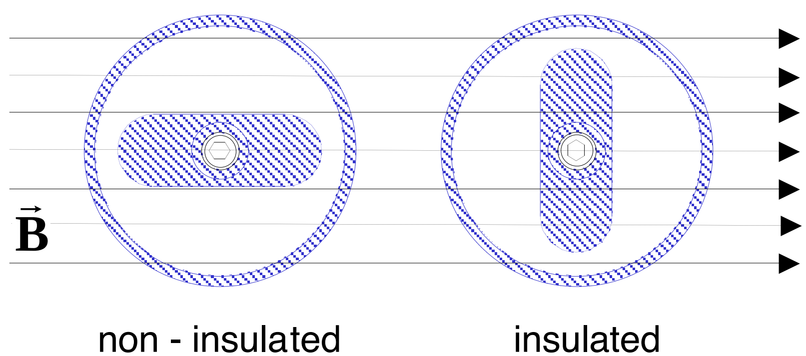
End electrode geometry designed to produce high electric field



- Both inner and outer conductor end pieces can be removed easily to test different configurations or materials.
- An asymmetric end electrode shape can allow the effects of magnetic insulation to be investigated



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Areas to be investigated

- Overall goal: systematic study of rf arcs under controlled conditions to investigate effects of electrode geometry, surface conditions, magnetic field, gas, uv light, and plasma on threshold voltage for breakdown
- Near term experiments:
  - effects of gas pressure, plasma density, magnetic field, and UV radiation level on RF voltage standoff
  - compare with and without conditioning
  - effect of gas adsorption and/or plasma on subsequent voltage standoff
  - effects of turnoff delay, pulse length, and rep rate on conditioning speed and effectiveness
  - Paschen (pd) dependence at high voltages?
  - optimum Z_0 for coaxial vacuum line (radius of curvature vs gap)

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Antenna surface heating is another important factor in ICRF operational power limits

- The Tore Supra RDL antennas can inject power fluxes ≥ 12 MW/m^2
  - power limit for non-dipole operation is due to surface heating of antenna plasma facing structures
  - with 4 cm plasma gap and 90° phasing, limit can be as low as 1 MW per launcher (6 MW/m^2)
- Caused by RF/plasma interactions which act to produce a concentrated power flux over small areas of the structures
- Power flux can be estimated from IR measurements
- Possible mechanisms include electron acceleration through RF inductive fields and rectification of voltages present on antenna box due to finite inductance of structure

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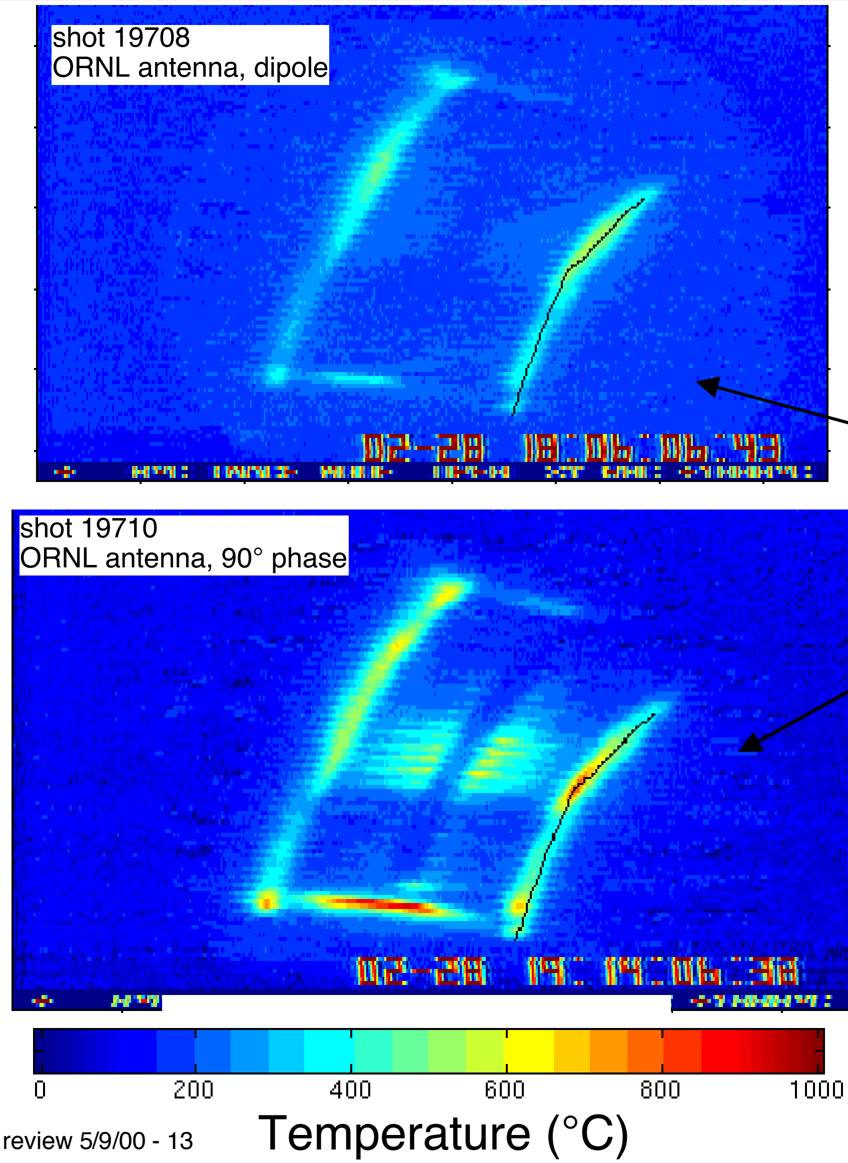
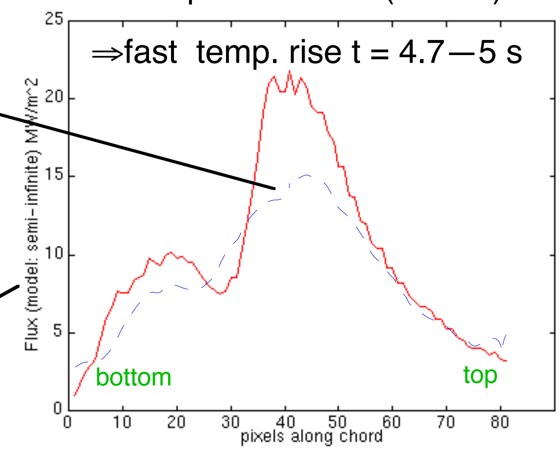
Fast temperature rise ↔ high transient fluxes (max . 15-20 MW/m2) for both dipole and FWCD phasing

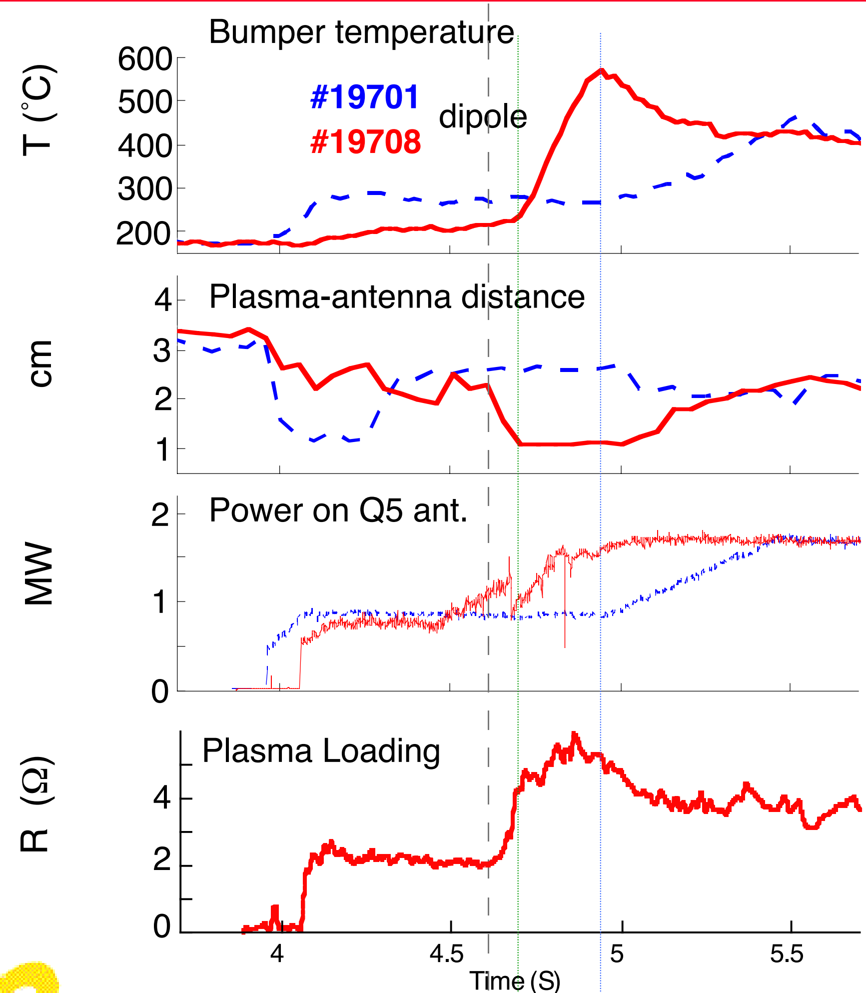
- Small gap and high power (2 MW)



Heat flux along contour shown at initial temperature rise (inertial)



Peak temperature reached depends on power and plasma/antenna gap



Shot 19701: Power ramped above 1 MW with gap > 2.5 cm. Max temp = 420°C.

Shot 19708: Power ramped above 1 MW with gap ~ 1 cm. Max temp = 585°C.

- Plasma loading increases rapidly w/decreasing gap
- Indicates higher density in front of antenna; results in enhanced surface heating

After ~ 5.5s power, gaps, and temperatures are equal

← Temp decrease follows shortly after plasma loading decrease

← Bumper temp increase begins in shot #19708

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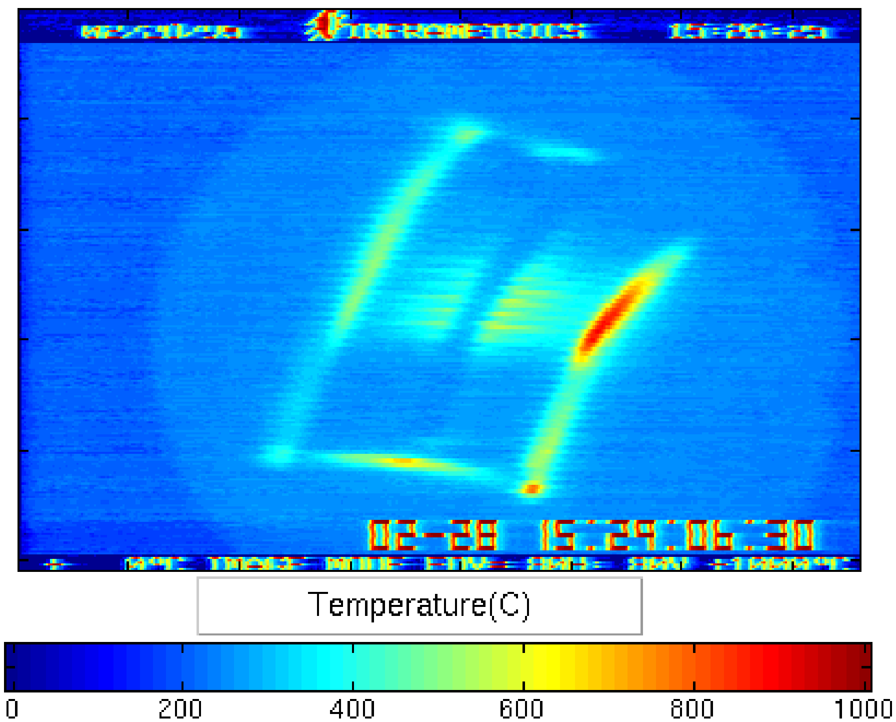
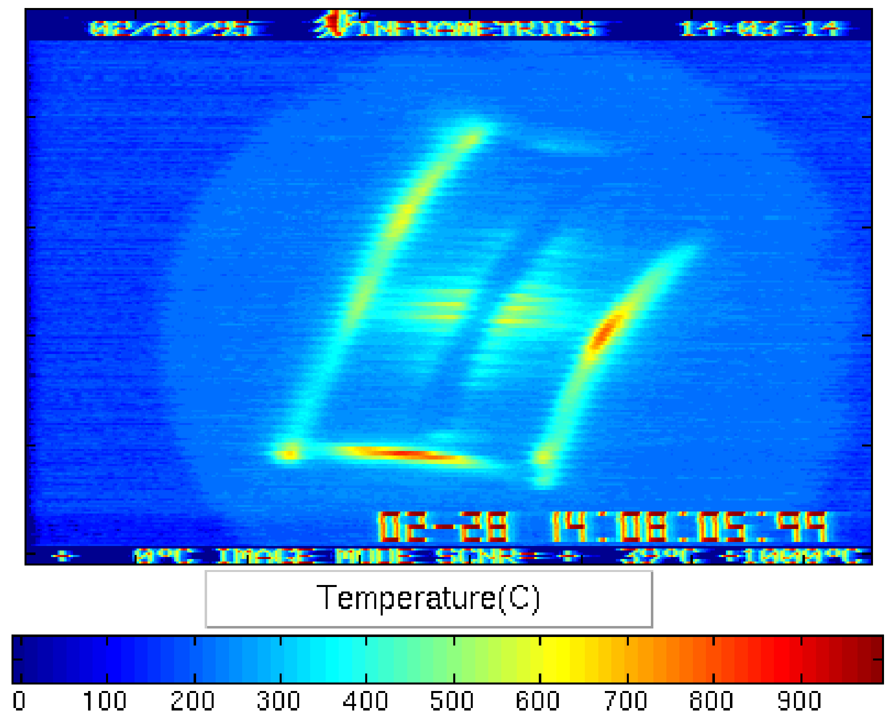
Heating at bottom corners affected by ICRF wave propagation direction

- ORNL Antenna

Phase of RF current = $+\pi/2$

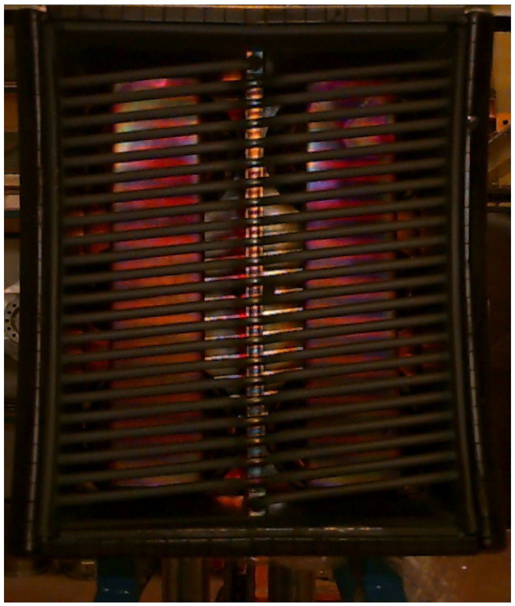


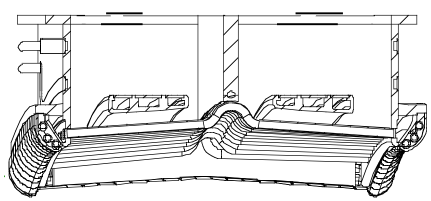
Phase of RF current = $-\pi/2$



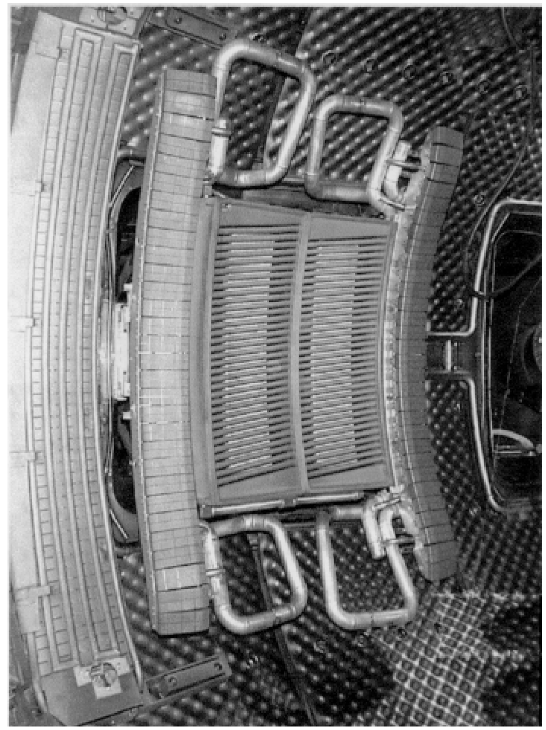
Future schedule/work

ORNL antenna





CEA Antenna with new poloidal limiters



•Tiles attached to CuCrZr substrate through gradient bonding process

- Machine operation recommencing in Spring 2001
- Scheduling problems due to slow delivery of CIEL limiter tiles by Plansee will result in only two ICRF launchers being available in 2001
- ORNL antenna will be modified for compatibility with new poloidal limiters and operated in 2002
- Will compare hot spot formation on two antennas, now with identical limiters, hot spot formation with old and new limiters

Folded Waveguide and Waveguide ICRF launchers

- Motivation
  - Achieve high power density > 2 kW/cm^2
  - Compact size
  - Polarization and launch spectrum flexibility
  - Low Electric fields near the plasma
  - All metal, rigid structure
  - Internally matched
  - Low mutual coupling in arrays
- Applications
  - Small devices and small port size devices
  - Reactors
  - Current drive arrays

Folded Waveguide Development History

- Extensive hardware development
  - Recent low and high power tests
  - Previous hardware tests
  - Electromagnetic modeling- ARGUS and EMAS
  - Thermal modeling
  - Disruption force modeling

- Successful Development FWG unit
  - 1/2 & 1/4 wavelength configurations

- TFTR/DIIID/PBX unit completed and available for testing
  - High power tests complete and largely successful
    - Achieved > 500 kW on RFTF for 1 sec pulses with two face plate versions
  - Looking for new suitable tokamak or stellarator for POP tests

TFTR/DIIID/PBX/ET/TEXTOR FWG

57 MHZ FOLDED WAVEGUIDE
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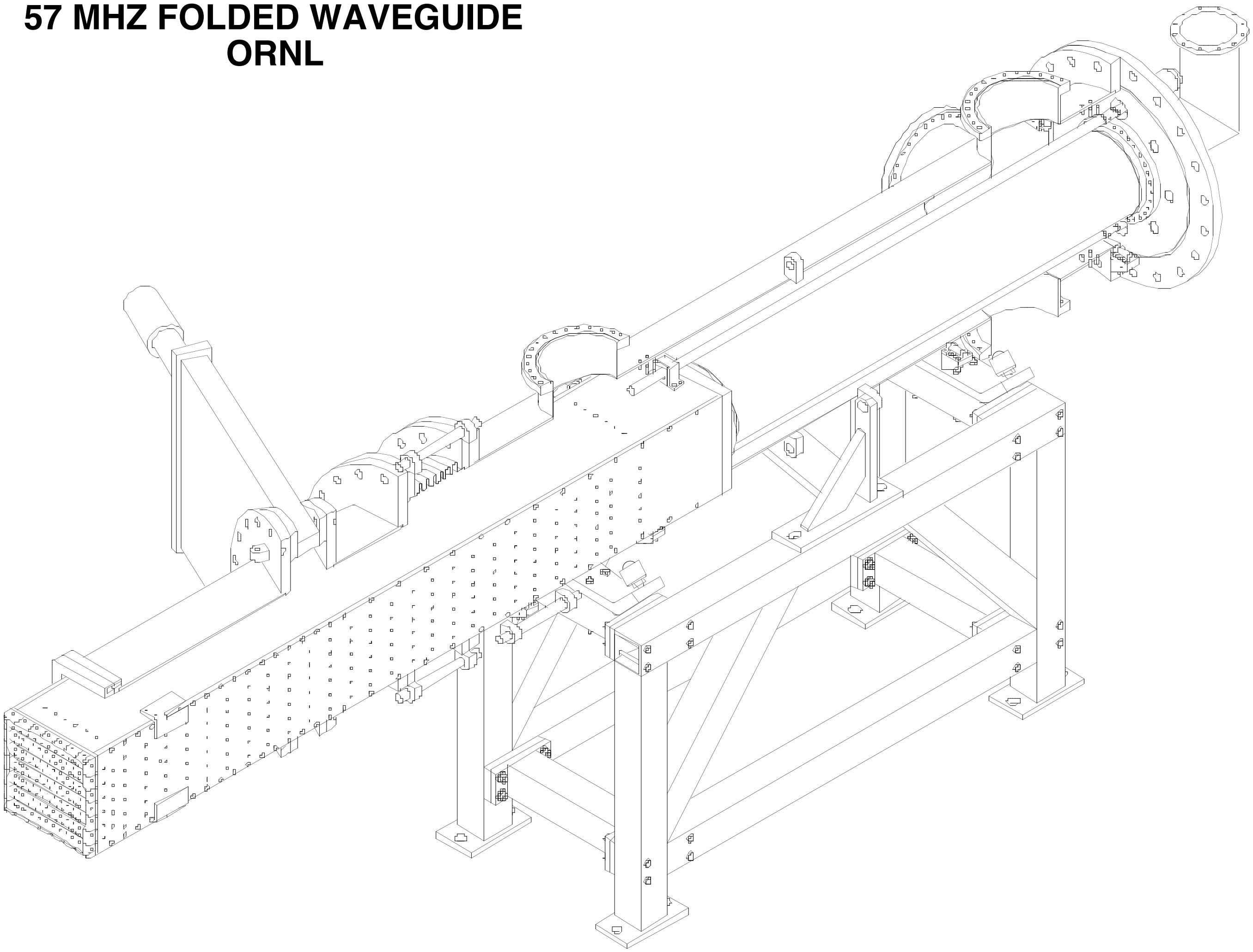
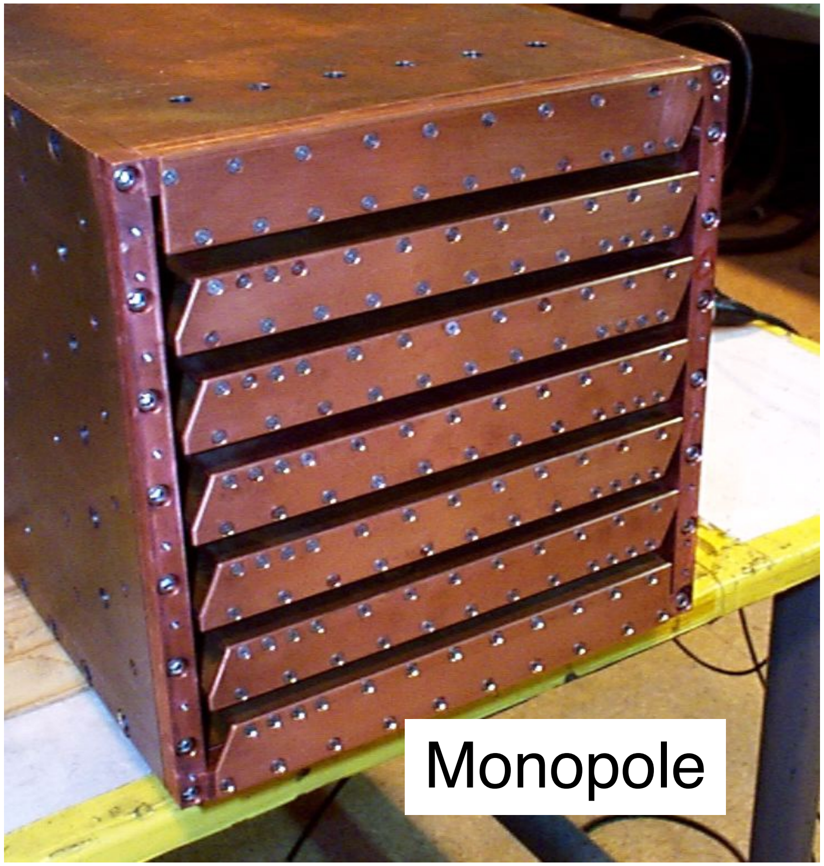
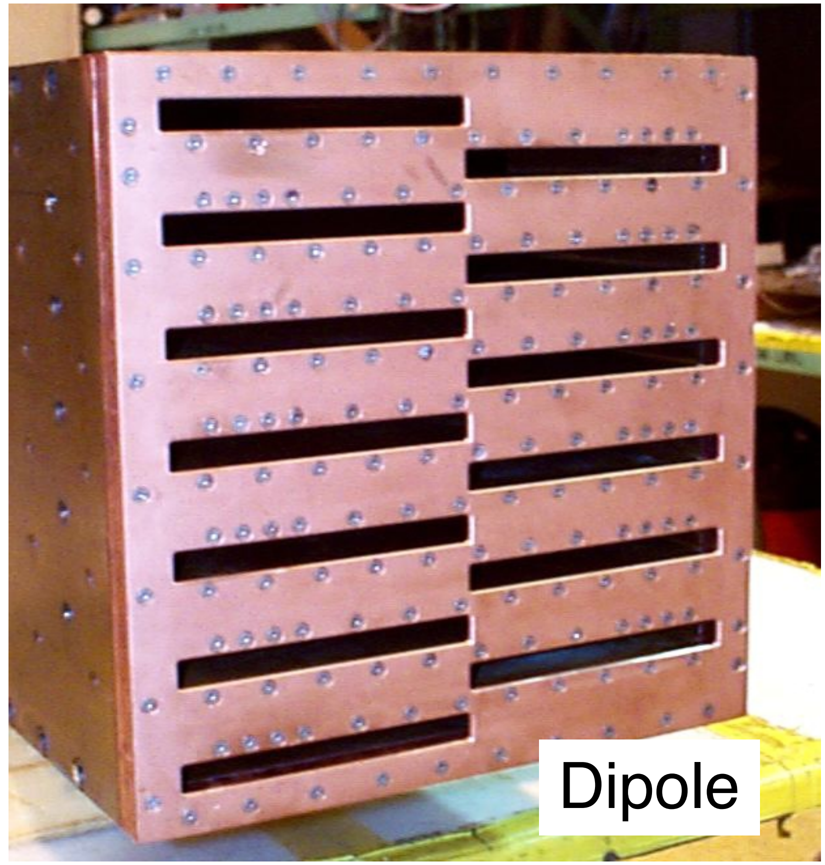


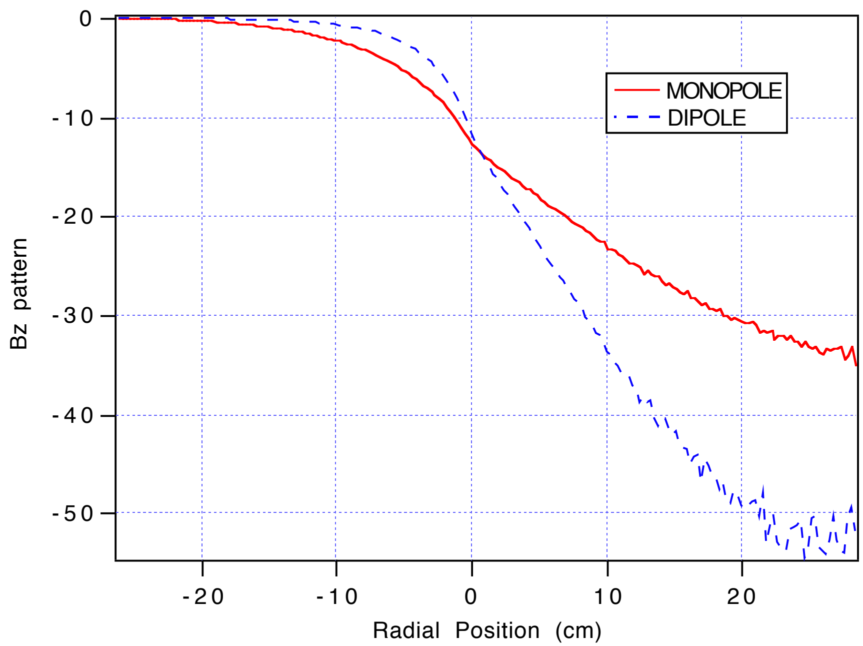
Monopole and Dipole Face Plates

Two RFTF test configurations shown without bumpers





Low power measurements



Radial field variation

Loading and efficiency measurements

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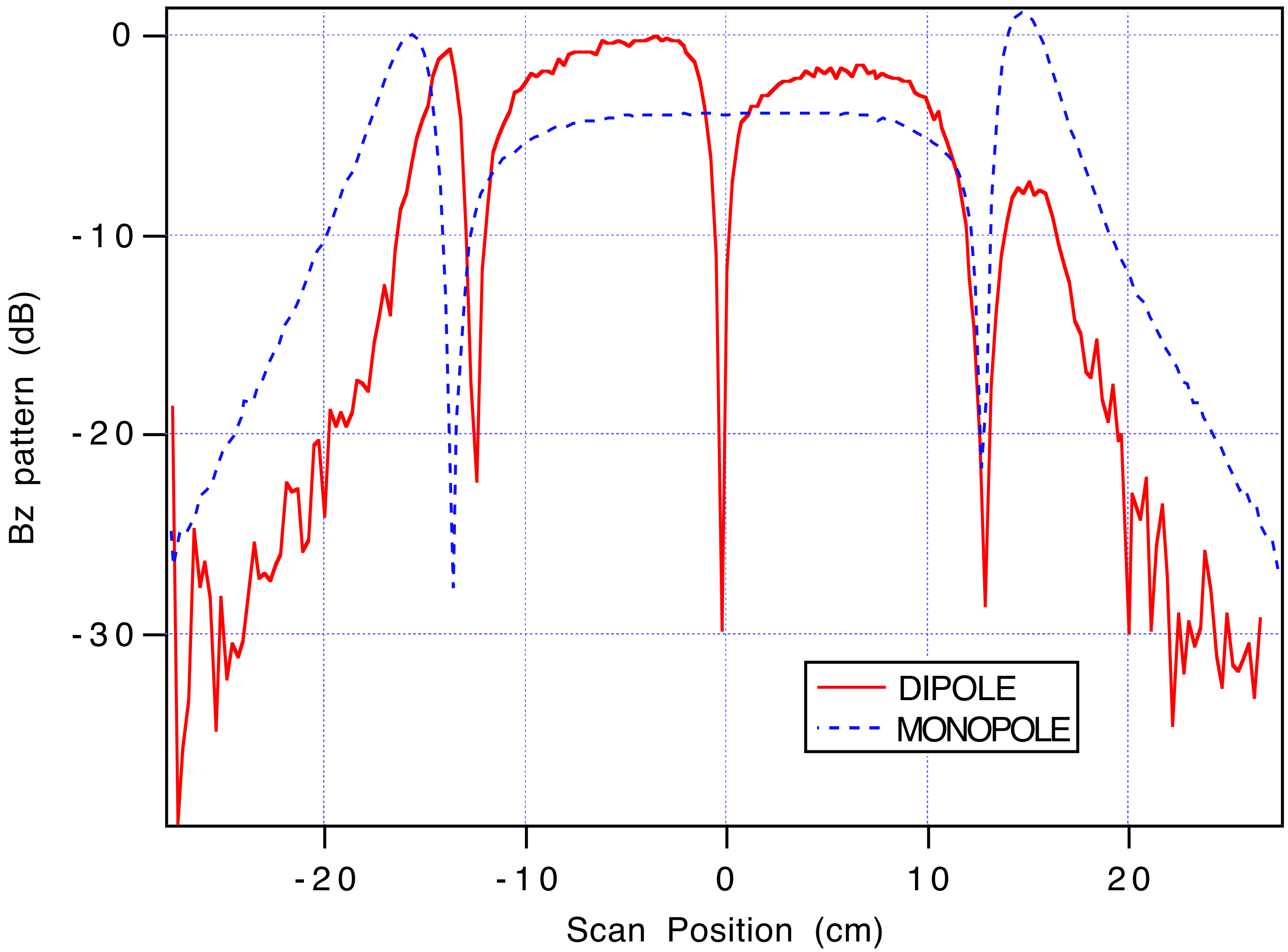
“Toroidal” Bz pattern measurements

5 mm spacing



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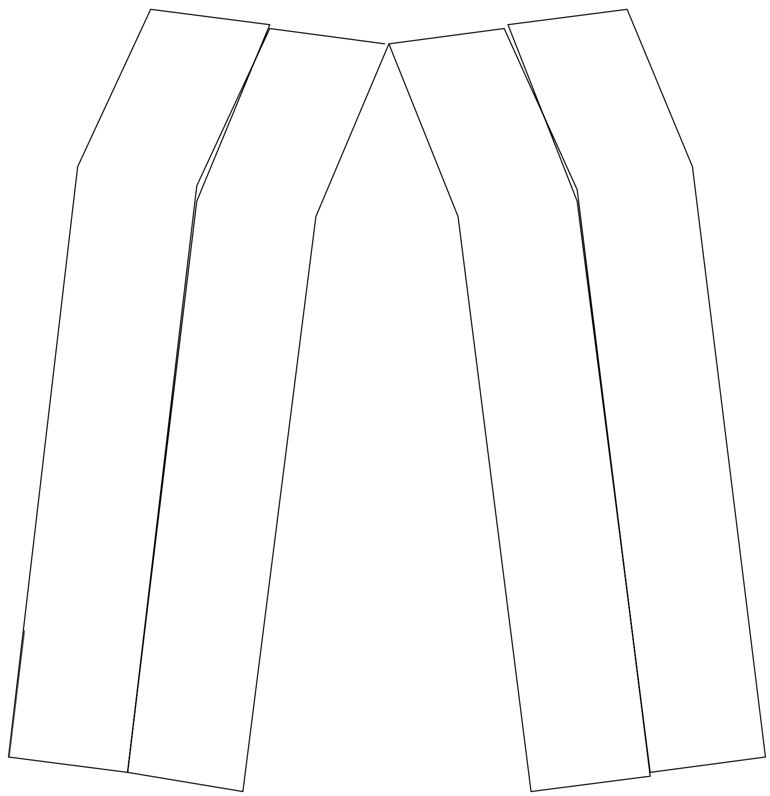
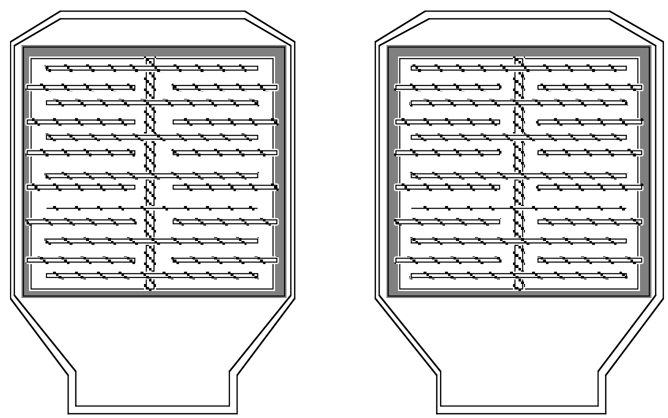
>4MW 120 MHz FWG FWCD array feasible for DIII-D



Top view



Front View

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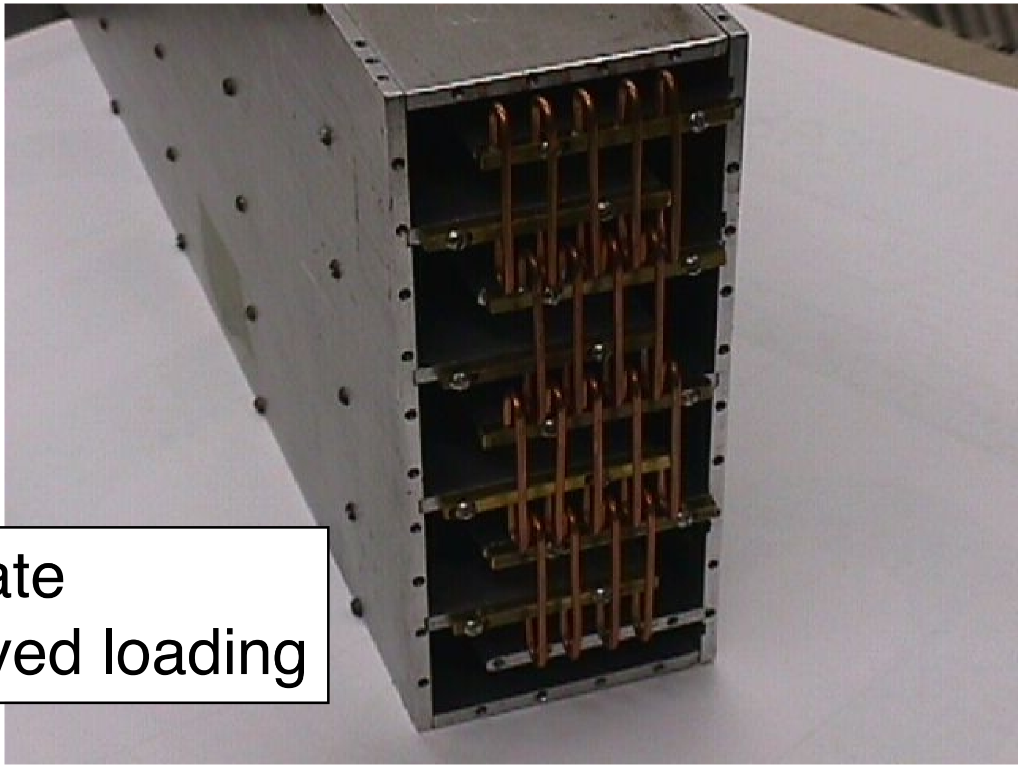
Potential FWG testing sites

- DIII-D
  - TFTR unit available and could be used for heating
  - Current drive array looks feasible
- CMOD
  - High power density allows room for proposed LHCD launcher by combining 2 ICRF heating antennas
- Electric Tokamak (ET) at UCLA
  - Port available
  - 80 MHz transmitter available
- NSTX- HHFW/IBW possibilities
- Tore-Supra
  - Long pulse capability of interest
  - Prototype completed
- Textor
  - Significant interest
  - 38 MHz version required to match available power

Improved face plate designs

- Improve coupling
- Options for launch spectrum
- Improve disruption strength



Wire face plate
Gives improved loading

Many interesting waveguide configurations

- Folded waveguide- several variations
- Stacked stripline
  - Used at U. Wisc.
- Folded stripline
  - Small development unit
- Ridged waveguide- open end
  - Good candidate for reactor for ICRF heating
- Ridged or rectangular waveguide with shorting strap launcher
  - Considered for NCSX at 350 MHz
- Folded waveguide feeding loops for CD
- Single super-power klystron and ridged waveguide transmission capable of >20 MW per unit

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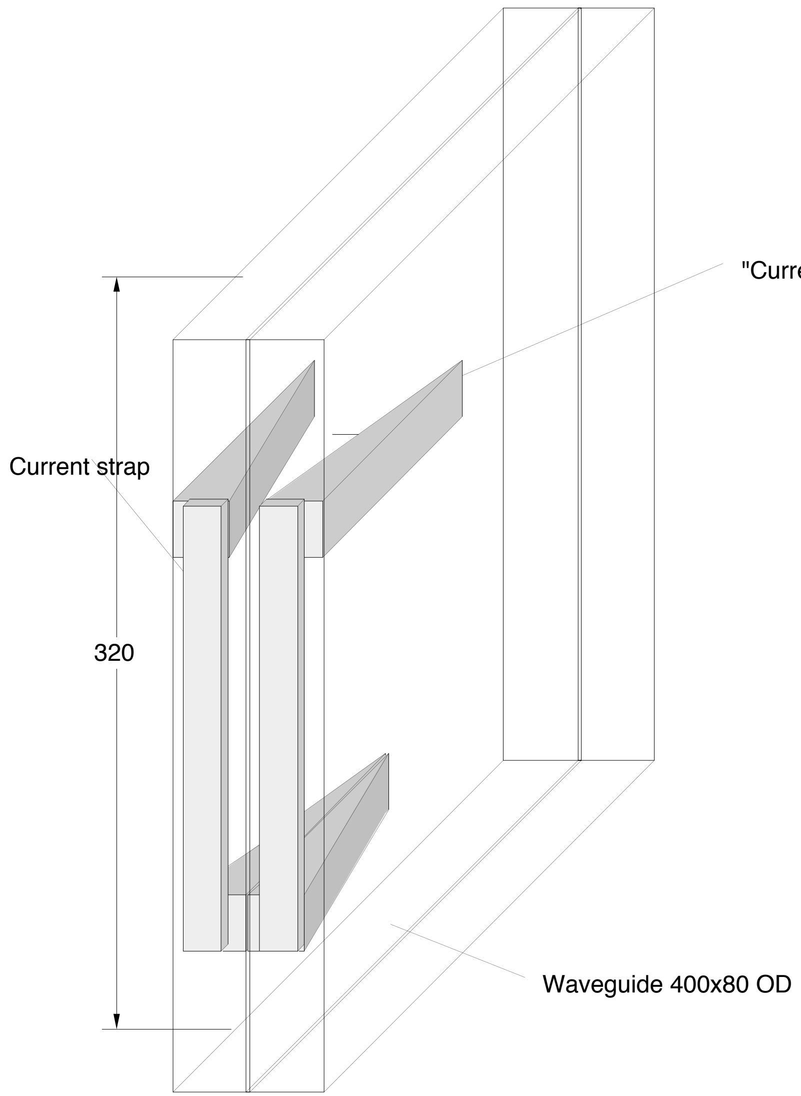
FTU / IGNITOR/NCSX? Waveguide FW launcher



- Dual 400 MHz waveguide input
- Fits high field tokamak ports
- High power sources available
- Waveguide to Current strap conversion
- Adjustable launch spectrum
- HHFW launch on NCSX proposed
with compact 350 MHz unit

Summary

- Increased power density necessary for continued viability of ICRF as auxiliary heating system in future large fusion devices
- ORNL has been deeply involved in high power density launcher development
  - Folded waveguide (20 - 40 MW/m^2 predicted power flux)
  - Resonant double loop (Tore Supra, TFTR, ATF, ITER R&D prototype, present ITER baseline design) > 10 MW/m^2 proven capability
- ORNL is investigating several approaches to increased power density
  - Voltage/electric field standoff (in conjunction with ASDEX-U
  - Edge plasma/RF interactions, improved RDL matching components (with Tore Supra)

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