# Progress of ITER ion cyclotron transmission line and matching system tests including 6 MW resonant ring operation

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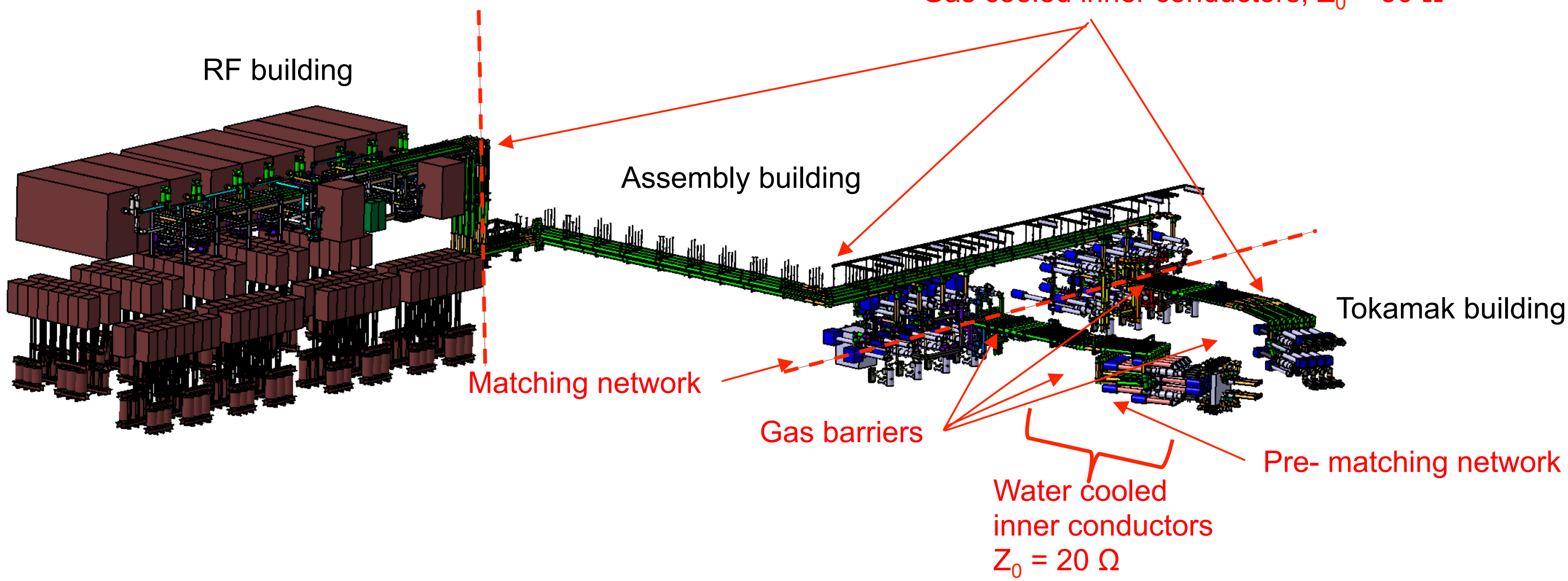
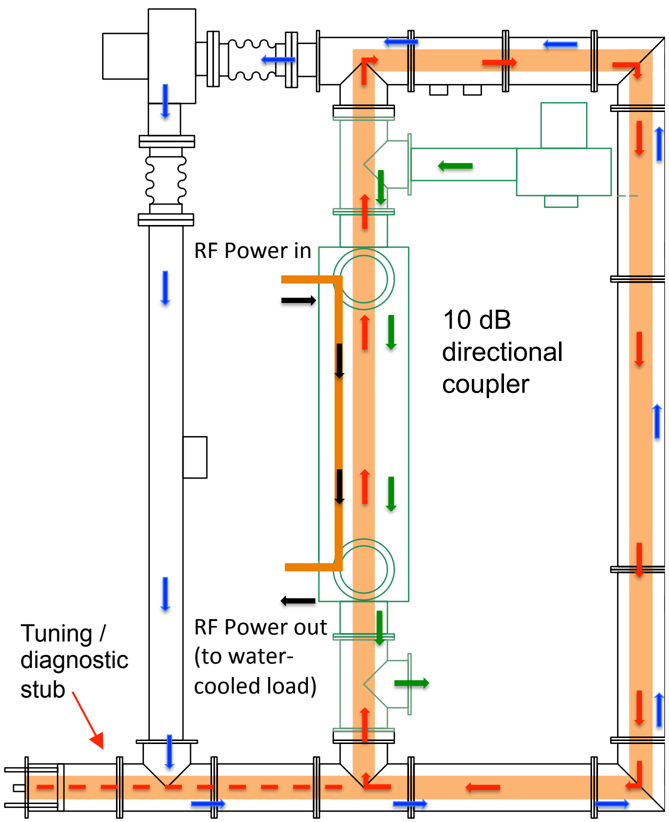
# ITER ion cyclotron transmission line and matching system

- Provides matching of two antennas, each with 24 radiating elements fed through 2 poloidal X 4 toroidal feeds.
- Provides arbitrary toroidal phasing of mutually coupled elements, and passive ELM resilience through the use of an extensive decoupling network and hybrid power splitters
- Up to 3 MW net power per line at high VSWR at antenna feeds (40 MW power upgrade)
- Up to 6 MW net power per line at low VSWR ( < 1.5 ) in lines between rf building and matching network (40 MW upgrade)
- Total length of all low VSWR lines ~ 1 km, with gas cooled inner conductors



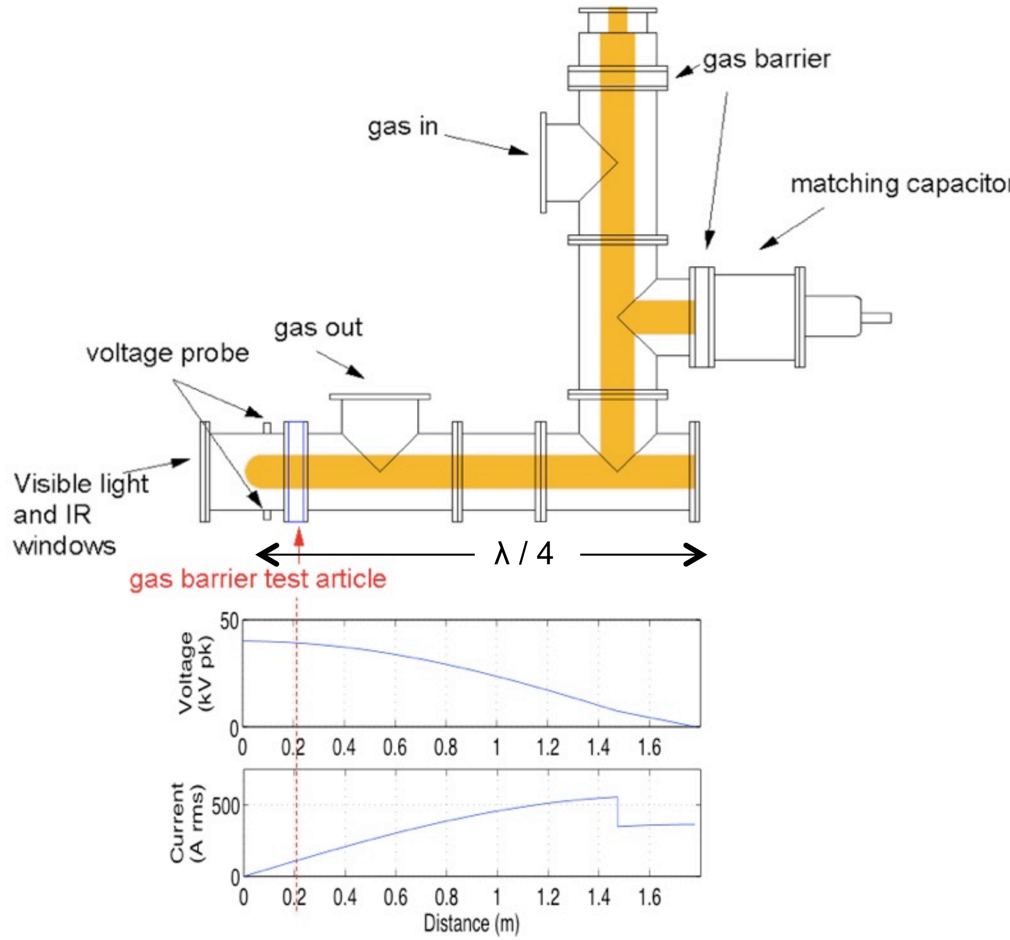
# The Resonant Ring and Resonant Line Test Stands – Principles of operation

- Resonant ring utilizes directional coupler to build up high circulating power with very little reflection. Useful for investigating cooling and testing transmission line components designed for low VSWR regions



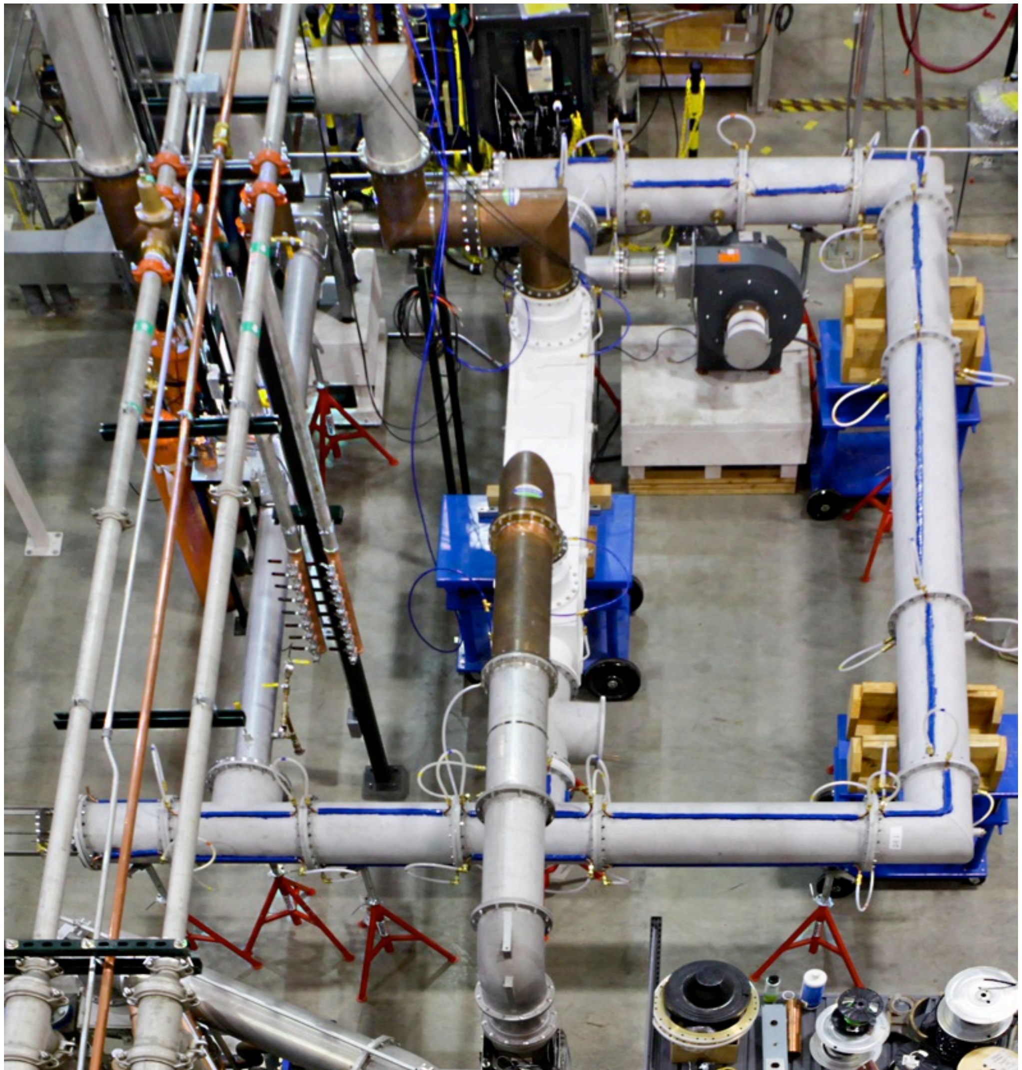

**Black: rf power from transmitter = 320 kW**
**Red: rf power in ring = 6 MW**
**Green: gas flow through 10 dB coupler (filtered building air)**
**Blue: pressurized gas flow through resonant ring and stub ($N_2$, 3 bar abs pressure)**

- Resonant line uses an impedance matched line feeding into a quarter-wave resonator. This produces high voltage and electric fields at the open end for voltage handling tests of components such as gas barriers

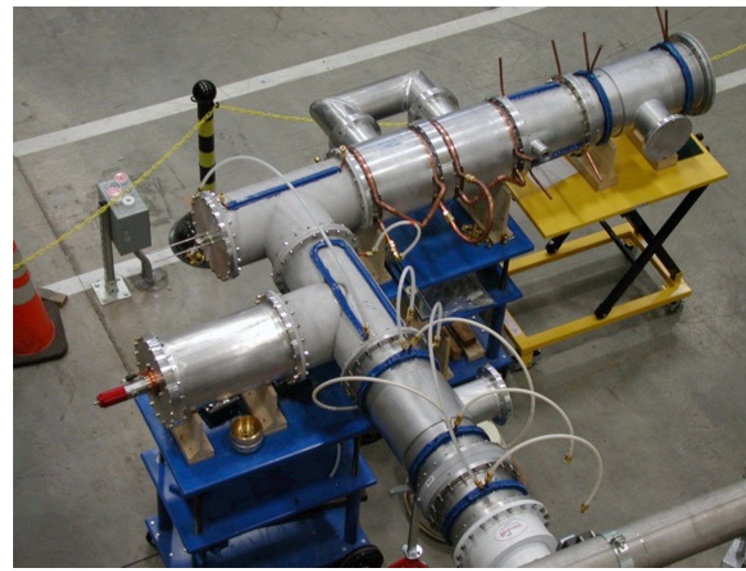


# Resonant ring and resonant line

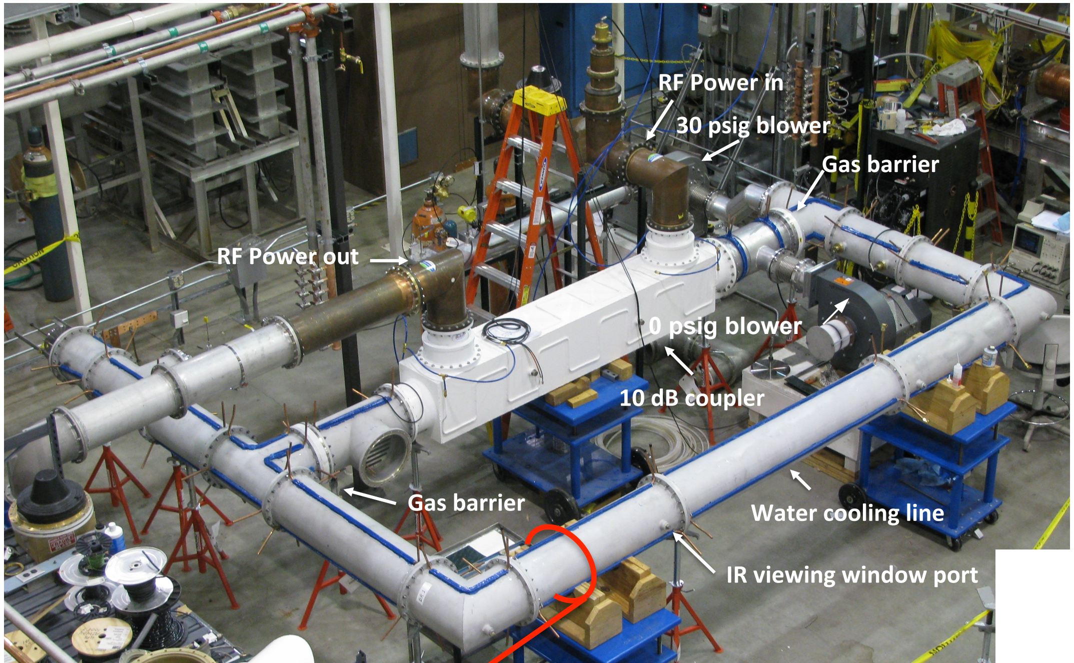
- Resonant ring



- Resonant line

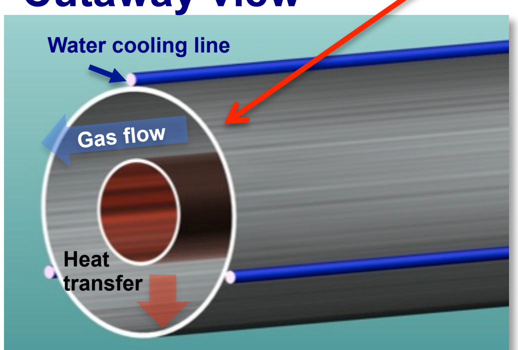


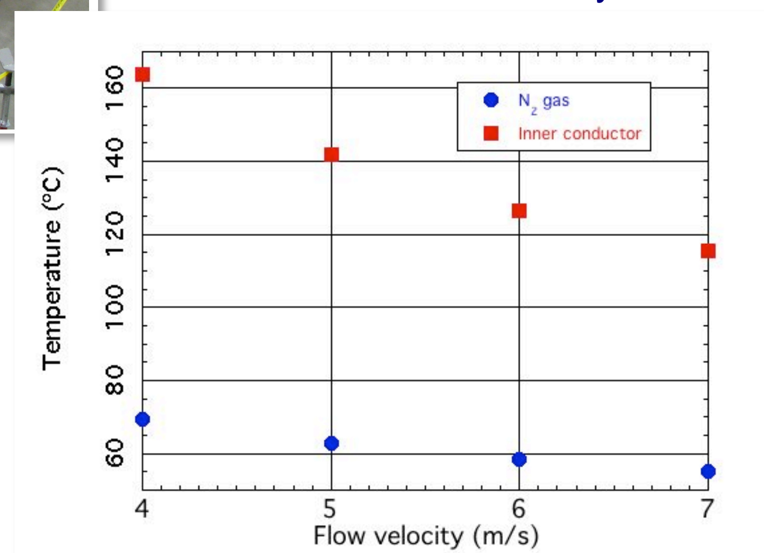
# The resonant ring has been used to confirm the feasibility of forced gas cooling of the ITER ion cyclotron transmission lines




- RF current (up to 650 A) flows in copper inner conductor and aluminum outer conductor, generates up to 1kW/m heat
- Turbulent gas at a pressure of 3 bar abs. efficiently transfers heat from inner to outer conductor, where it is removed through water cooling lines
- Direct water cooling of the inner conductor would be difficult: a water leak occurring in any of the hundreds of joints in the > 1 km long transmission line network would immediately halt

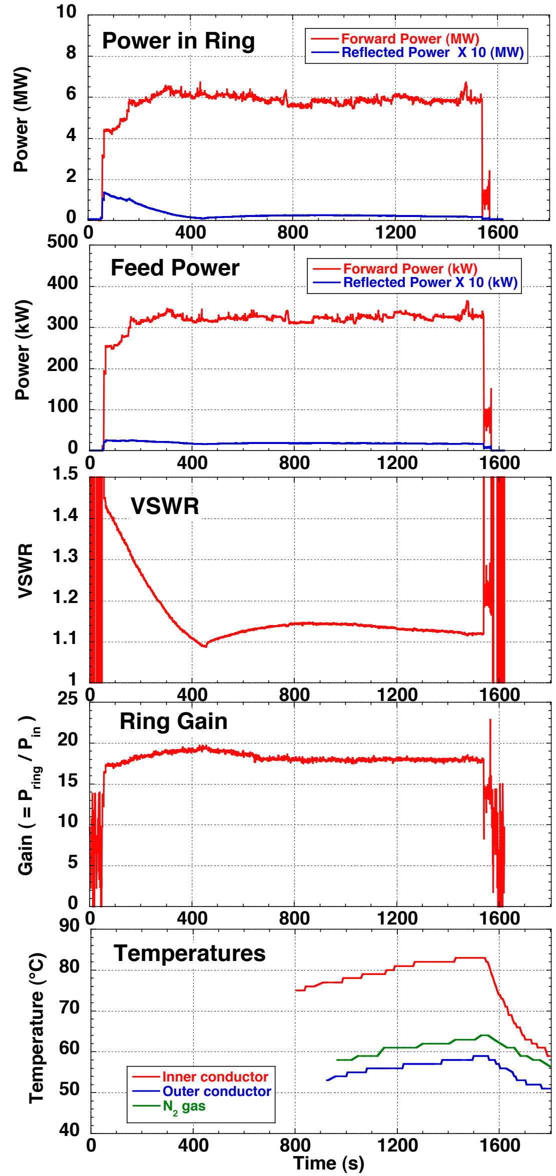
## Cutaway view



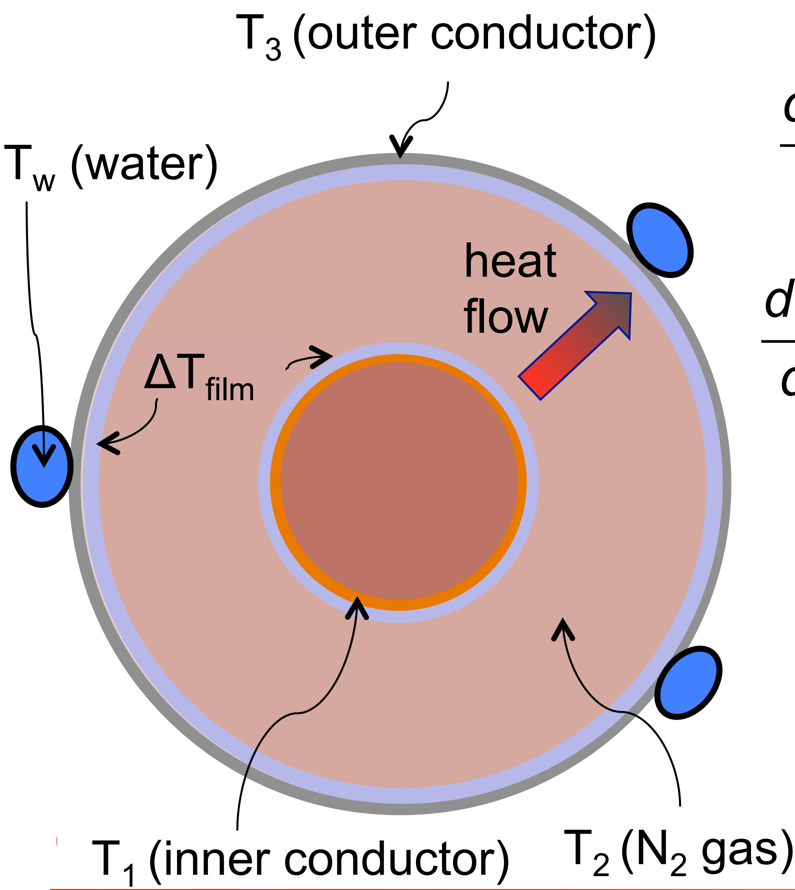
# A 25 minute long 6 MW pulse has been achieved

- Other parameters; gas pressure- 0.3 Mpa (3 bar absolute), gas circulation velocity: 6 M/s
- Ring operation very stable during pulse
- Low reflected power in ring (VSWR < 1.15) and feed line, with no need to make adjustments during pulse
- Input power ~ 320 kW, gain ~ 18X, 6 MW circulating power
- Maximum observed temperature on inner conductor ~ 83 °C. Design temperature limit is 150 °C (using dry $N_2$ gas to prevent oxidation of Cu surface)
- **ITER transmission line cooling approach validated**



# 800 s long pulse has been modeled using simple heat transfer model

- Turbulent flow produces near-uniform gas temperature, low ΔT in gas
- ΔT ignored except at film drops at inner conductor and outer conductor surfaces




$$\frac{dT_1}{dt} = \frac{Q'_{inner} - \pi D_{inner} h_{inner} \left(T_1 - T_2\right)}{\rho_{Cu} A_{cu} c_{p-Cu}}$$

$$\frac{dT_2}{dt} = \frac{\pi D_{inner} h_{inner} \left(T_1 - T_2\right) - \pi D_{outer} h_{outer} \left(T_2 - T_3\right)}{\rho_{gas} A_{gas} c_{v-gas}}$$

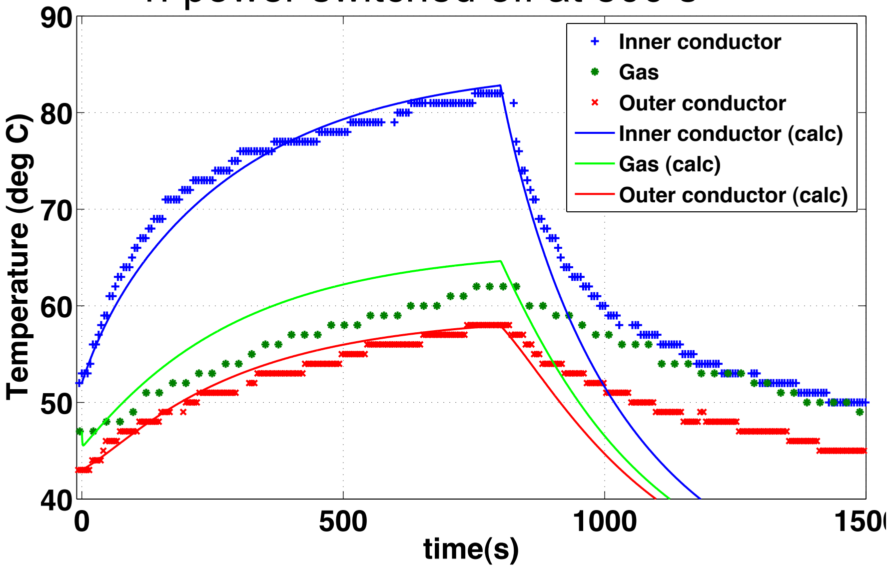
$$\frac{dT_3}{dt} = \frac{Q'_{outer} - \pi D_{outer} h_{inner} \left(T_2 - T_3\right) - h_{water} \left(T_3 - T_w\right)}{\rho_{Al} A_{Al} c_{p-Al}}$$

- *Q´* is heat generated (kW/m) by rf dissipation in inner or outer conductor surface (~760 W/m total assumed)
- *D* is diameter of inner or outer conductor,
- *ρ* is density, *A* is cross-sectional area,
- $c_p$ *and* $c_v$ are specific heats
- h is film heat transfer coefficient: $h = Nu \bullet k / D_h$ where *Nu* is the Nusselt number, k is the thermal conductivity , and $D_h$ is the equivalent hydraulic diameter

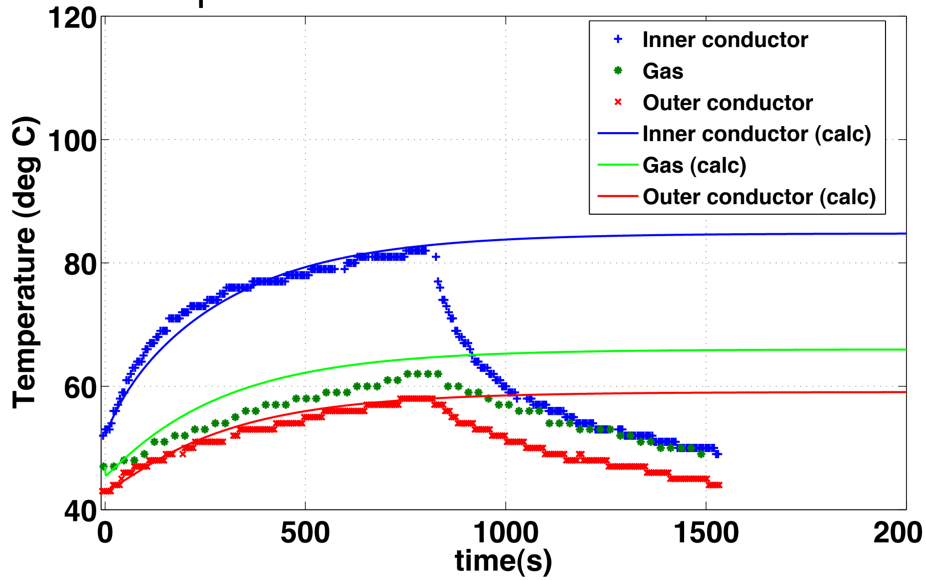
# Initial modeling results

- Model agrees reasonably well with data during temperature rise after rf turned on, but does not agree with decay after turnoff
- Model does not include thermal inertia due to mass of cooling connection pipes and fan housing, etc.
- Modeling suggests temperature reached is close to equilibrium

Temperatures vs time,
rf power switched off at 800 s

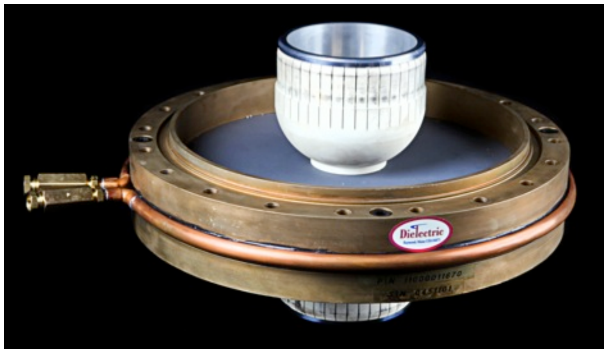



Temperatures vs time,
rf power not switched off in model



# Three types of gas barriers will be tested on resonant line tester

## Edge-cooled aluminum nitride

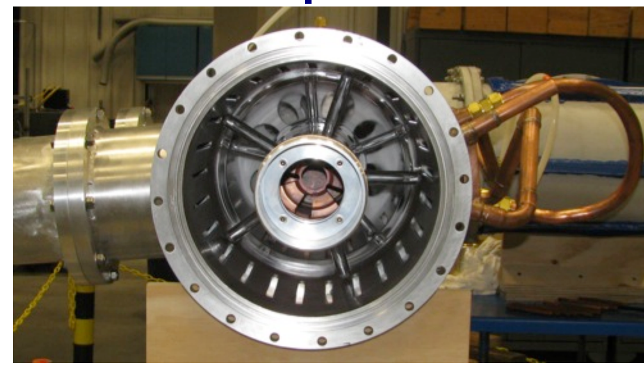



- Advantages
  - Very high thermal conductivity (k ~ 180 W/ m - °K) limits thermal stress
  - High power inner conductor connector
- Disadvantages
  - High dielectric constant ($\varepsilon_r$ ~ 9) increases electric field peaking and rf power dissipation in ceramic
  - Elastomer pressure seals

## Gas-cooled quartz

- Advantages
  - Low dielectric constant ($\varepsilon_r$ ~ 3.8) minimizes electric field peaking and rf power dissipation in quartz
  - Low insertion force inner conductor
  - Metal o-ring seals
- Disadvantages
  - Very low thermal conductivity (k ~ 1.4 W/ m - °K) – could require water-cooled inner conductor

## Conical gas cooled quartz

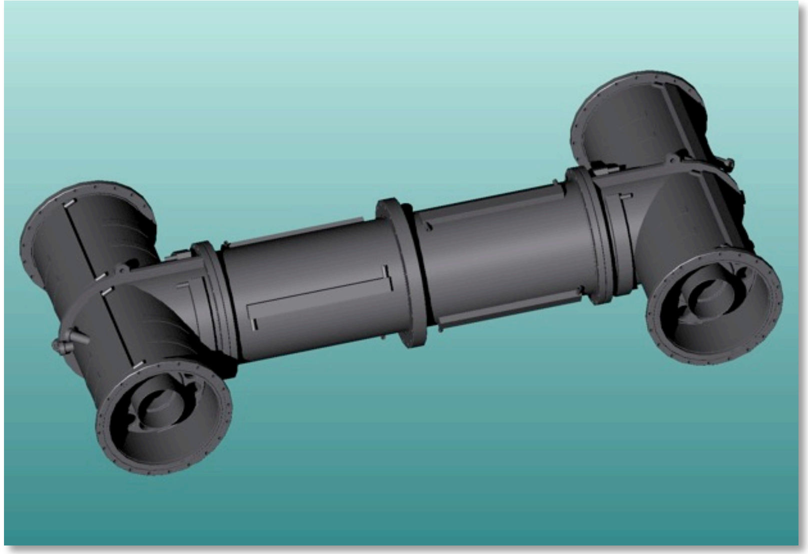


- Advantages
  - Low dielectric constant
  - Conical barrier shape reduces electric field
  - Gas baffles direct gas flow onto quartz
- Disadvantages
  - Conical barrier requires large increase in length
  - Elastomer pressure seals (but tritium compatible)

# Some of the other transmission line and matching components to be tested

6 MW 4-port coaxial switch


20 – 300 pF high voltage vacuum capacitors



6 – MW hybrid power splitter

# List of all components to be tested (does not include control and instrumentation)

- Three gas barrier designs
- $Z_0$ = 50 Ω, gas cooled straights and elbows
- $Z_0$ = 20 Ω, water cooled straights, elbows and tees
- 6 MW Hybrid power splitter
- 4-Port Switch
- 50-ohm Stub Tuner
- 20-ohm Stub Tuner
- 50-ohm Phase Shifter
- 20-ohm Phase Shifter
- Directional couplers and voltage probes
- Compliance components
- Bellows and/or quick-connects
- Vacuum capacitors, with capacitor water cooling loop and purification system
- Four-Port Switch
- Six way cube

# Summary

- A resonant ring test stand for use in gas cooling tests, and tests of gas cooled components, has operated successfully at a power level of 6 MW for 1500 s (25 m).
- The feasibility of the use of forced gas cooling of low VSWR high power transmission line has been demonstrated. The maximum measured inner conductor temperature for 6 MW @ f = 46.9 MHz, VSWR= 1.15, at the end of the 1500 s pulse was 83° C, compared to the 150 °C operating limit for the inner conductor, with temperatures reaching near equilibrium values.
- Some additional gas cooling tests will be performed in the resonant ring, including 3600 s tests @ VSWR = 1.5.
- This will be followed by a set of tests of prototype components used in the ITER Ion Cyclotron transmission line and tuning and matching system.