Maturing ECRF Technology for Plasma Control

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DIII-D NATIONAL FUSION FACILITY — PPPL PRINCETON PLASMA PHYSICS LABORATORY — PSFC — CPI — ORISE — GENERAL ATOMICS

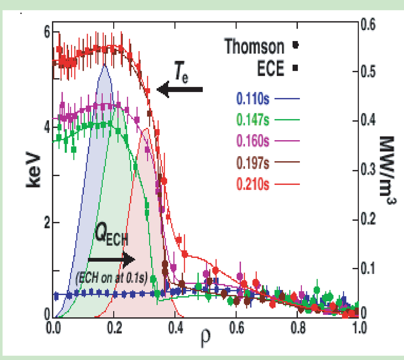
Abstract

The availability of high power ≈1 MW, long pulse length, (effectively cw), high frequency, >100 GHz, gyrotrons has opened the opportunity for enhanced scientific results on magnetic confinement devices for fusion research worldwide. This has led to successful experiments on electron cyclotron heating, electron cyclotron current drive, non-inductive tokamak operation, tokamak energy transport, suppression of instabilities and advanced profile control leading to enhanced performance. The key development in the gyrotron community that has lead to the realization of high power long pulse gyrotrons is the availability of edge cooled synthetic diamond gyrotron output windows, which have low loss and excellent thermal and mechanical properties. In addition to the emergence of reliable high power gyrotrons, ancillary equipment for efficient microwave transmission over distances of hundreds of meters, polarization control, diagnostics and flexible launch geometry have all been developed and proven in regular service.

ELECTRON CYCLOTRON HEATING/ ELECTRON CYCLOTRON CURRENT DRIVE

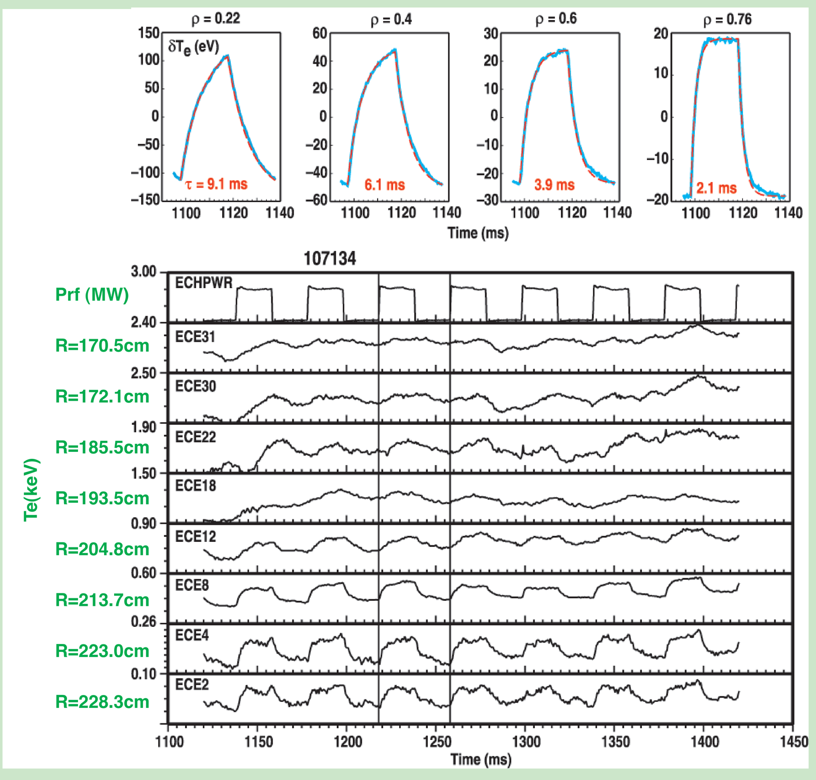
DIRECT ELECTRON HEATING GENERATES AN ELECTRON INTERNAL TRANSPORT BARRIER

- Profiles flat or slightly hollow inside barrier.
- Barrier location expands ahead of ECH heating location.
- Barriers with nearly identical profiles have been observed with co- and counter-ECCD and pure heating (radial launch).



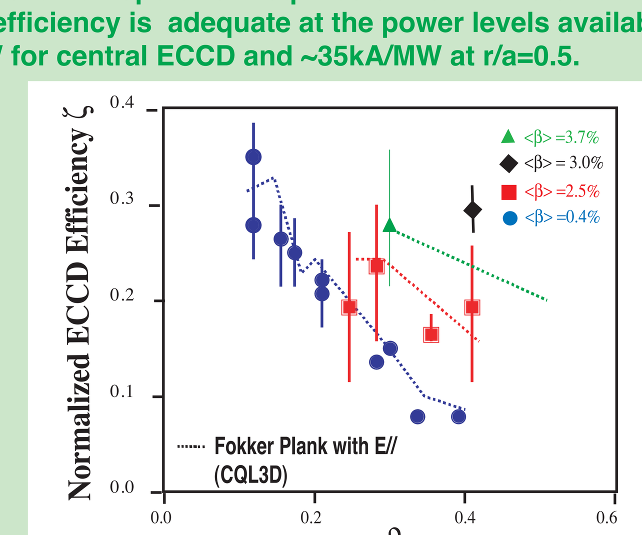
MODULATED ECH IS USED FOR TRANSPORT STUDIES

By modulating the applied rf, the flow of heat in the plasma can be observed with the ECE diagnostic. The shape of the local response gives the local incremental confinement time and the phase of the response gives the deposition profile. The DIII-D gyrotrons can be modulated at frequencies up to 10 kHz. Modulated ECH was used to study the "heat pinch," flow of energy against the gradients, in the electron channel.

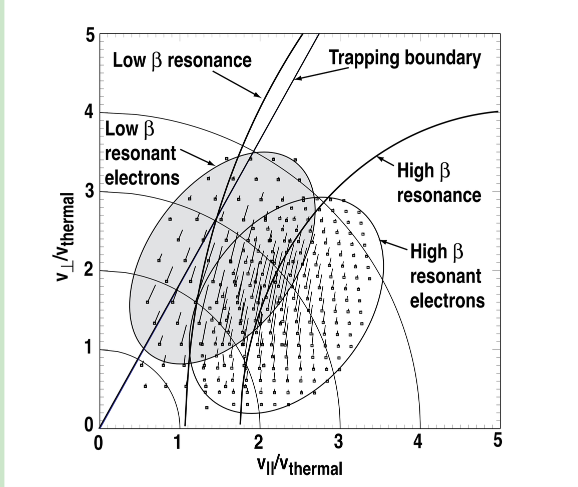


EFFICIENCY OF OFF-AXIS ECCD LEADING TO ADVANCED TOKAMAK OPERATION

Advanced tokamak operation requires current drive off-axis. At high beta, the ECCD efficiency is adequate at the power levels available, yielding ~60 kA/MW for central ECCD and ~35kA/MW at r/a=0.5.

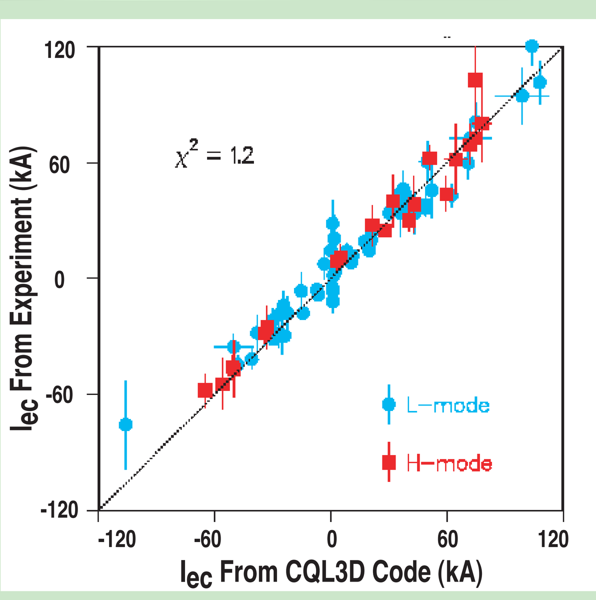


As the current drive location is moved off-axis, the efficiency decreases at low beta. At high beta, relevant for advanced tokamak operation, the efficiency remains high.



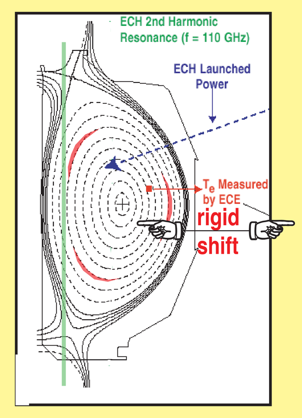
The explanation for this beta dependence is that trapped electrons reduce the current drive efficiency at low beta. At high beta, the EC resonant electrons are far from the trapping boundary and the efficiency does not decrease as the ECCD location moves off-axis.

MEASURED ECCD FROM MSE DATA IS IN GOOD AGREEMENT WITH FOKKER-PLANK CODE INCLUDING $E_{||}$ EFFECT

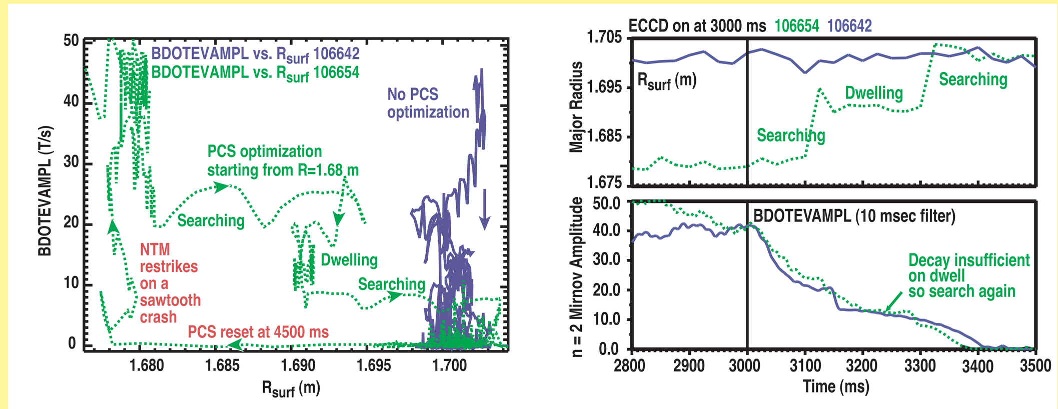


SUPPRESSION OF INSTABILITIES

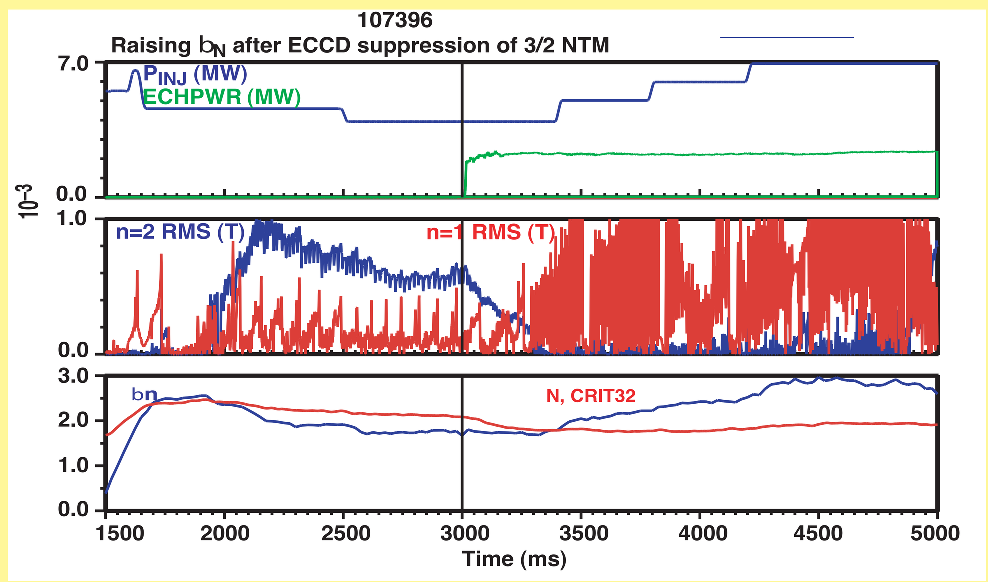
A "SEARCH AND SUPPRESS" ALGORITHM WAS USED TO KILL NEOCLASSICAL TEARING MODES (NTM) WITH ECCD



The Plasma Control System was used to sweep the islands in steps past the second harmonic EC resonance. At each step, the sweep was halted to allow the amplitude of the n=2 Mirnov signal to be checked. In this case the NTM was suppressed in two steps when the major radius reached 1.70m.



FULL SUPPRESSION OF THE m/n=3/2 NEOCLASSICAL TEARING MODE WAS ACHIEVED WHEN 2.0 MW OF ECCD WAS APPLIED AT THE LOCATION OF THE 3/2 ISLAND

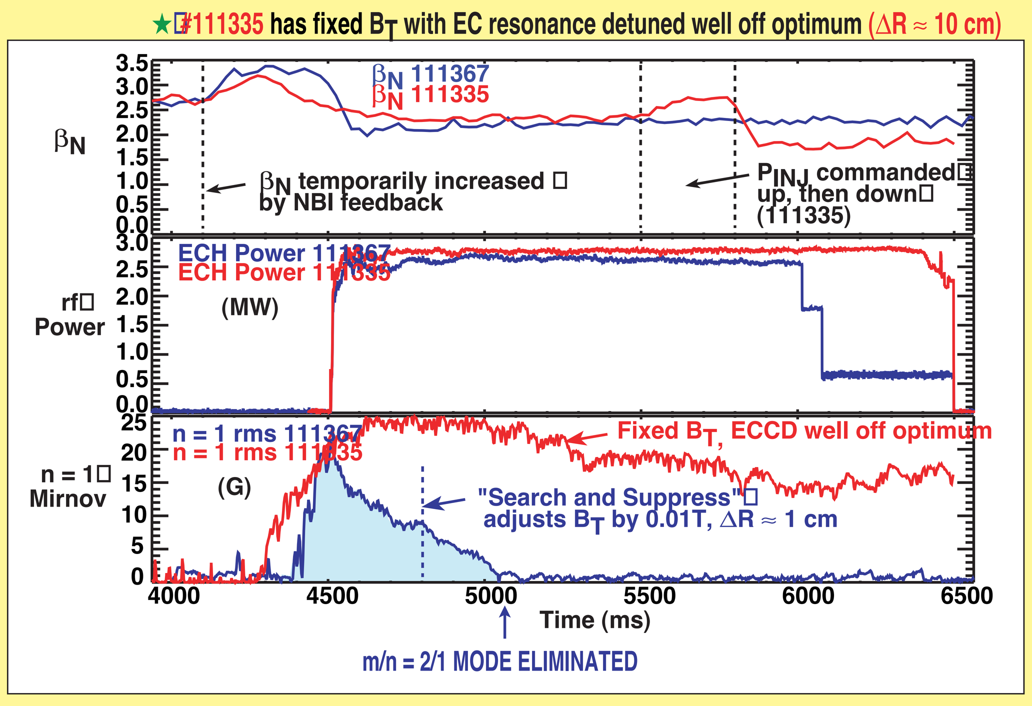


Increase in NBI power gave higher β-n following suppression of the NTM

COMPLETE SUPPRESSION OF THE m/n = 2/1 MODE WAS ACHIEVED FOR THE FIRST TIME USING 2.7 MW OF 110 GHz ECCD

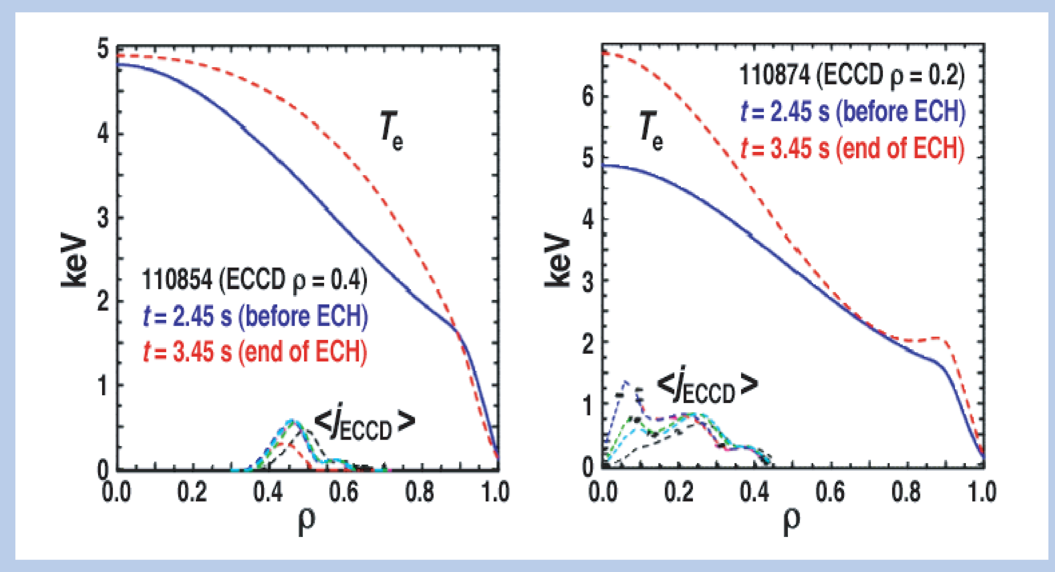
- β_N is feedback controlled to temporarily rise to excite the mode
- Location of ECCD optimized (#111367) by toroidal field feedback

★#111335 has fixed B_T with EC resonance detuned well off optimum (ΔR ≈ 10 cm)



m/n = 2/1 MODE ELIMINATED

STRONG HEATING OF ELECTRONS OBSERVED WITH ECH AIMED FOR CURRENT DRIVE AT ρ = 0.2 AND 0.4

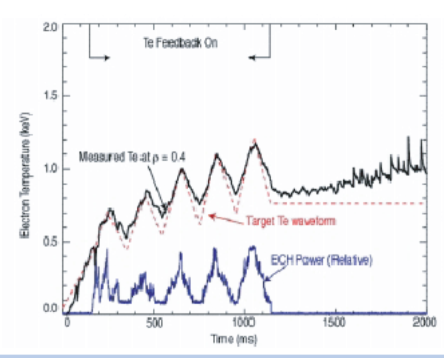


PROFILE CONTROL

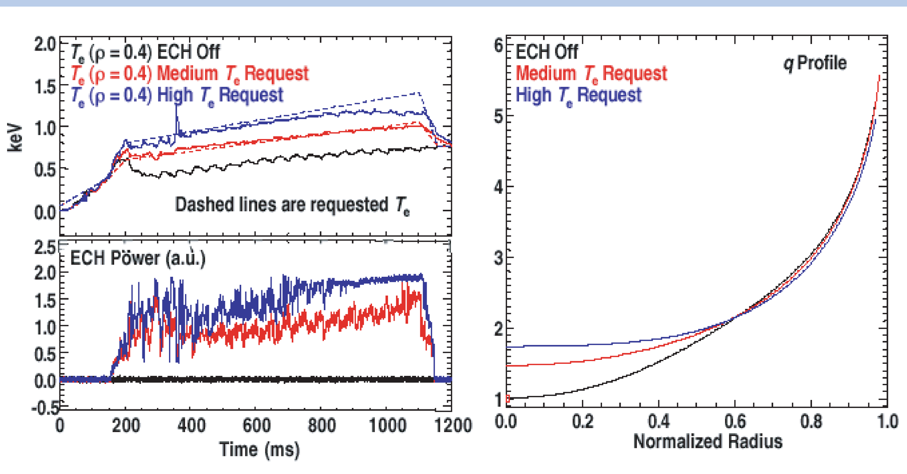
THE ECH SYSTEM DEMONSTRATED DYNAMIC CONTROL OF THE PLASMA TEMPERATURE FOR THE FIRST TIME IN 2002

The DIII-D plasma control system compares T_e measured by ECE at a specific location with a target evolution and modulates the ECH power to reduce the difference.

Demonstration: A sawtooth target waveform is tracked by the ECE signal as the ECH power is modulated. The energy confinement time controls the decreasing temperature and prevents the excellent agreement seen when the temperature increases

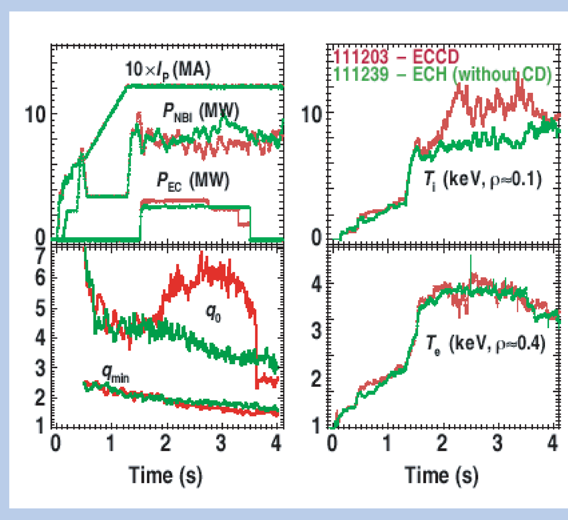


STUDIES SHOW THAT SYSTEMATICALLY INCREASING Te RESULTS IN LESS CURRENT PENETRATION

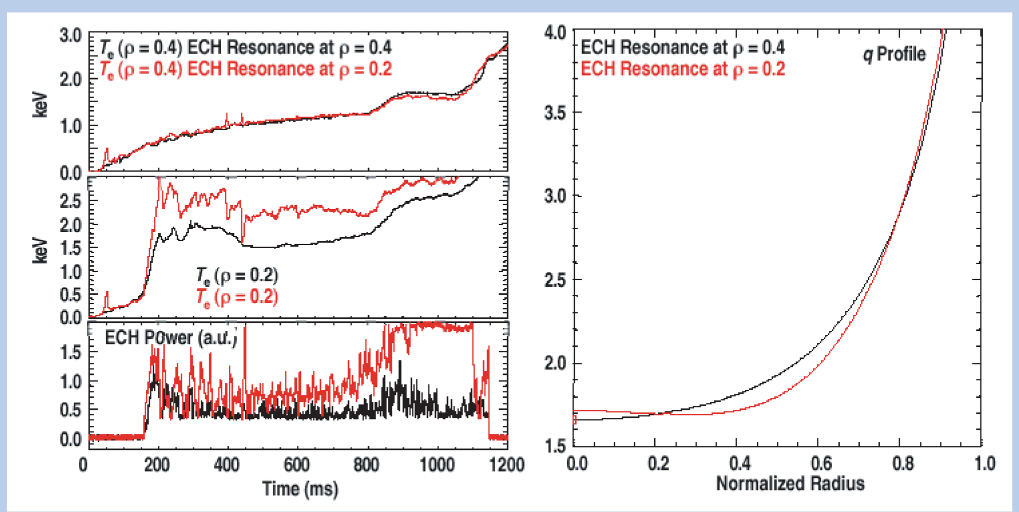


ECCD CURRENT PROFILE CONTROL HAS BEEN DEMONSTRATED IN HIGH BOOTSTRAP AT REGIME PLASMAS

- ECCD current profile control consistent with simulations.
  - Cases with and without (not shown) ECCD had similar current profile evolution.
  - Five gyrotrons for 2 sec aimed at ρ = 0.4.
- Transport affected as well: ITB appears in ion channel with ECCD.
  - Both Ti (0) and Te (0) larger with ECCD than radial launch.

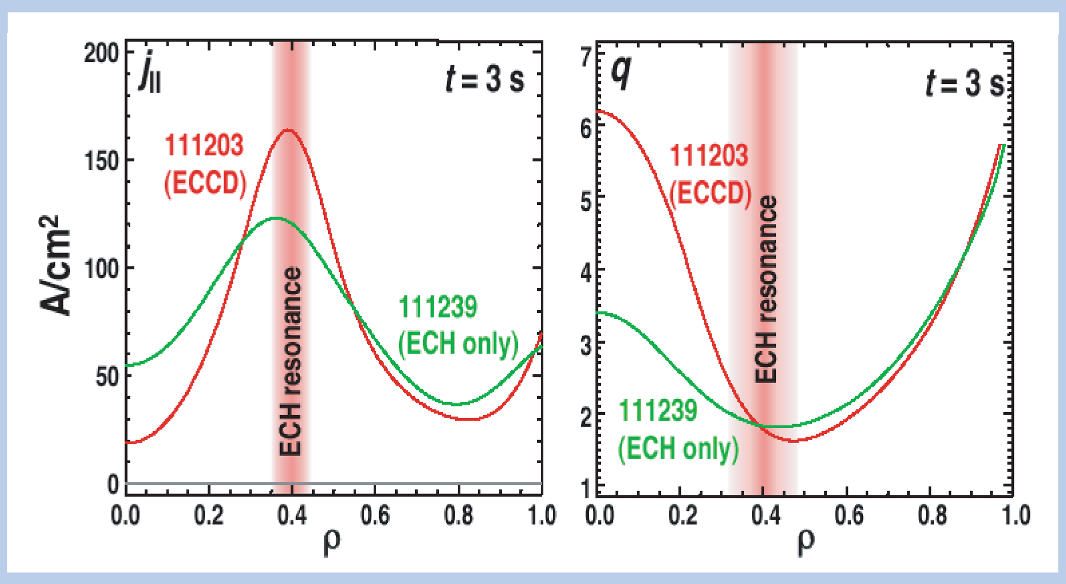


CHANGING ECH DEPOSITION LOCATIONS ALTERS CURRENT PROFILE EVOLUTION



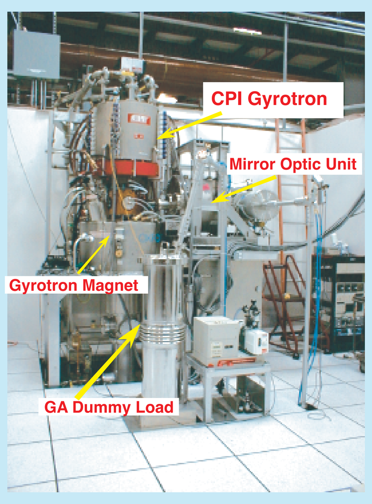
- PCS using ECE signal at ρ = 0.4
- Higher central Te leads to more inverted q profile

CURRENT PROFILE RESPONCE TO ECCD IN HIGH BOOTSTRAP FRACTION AT PLASMAS

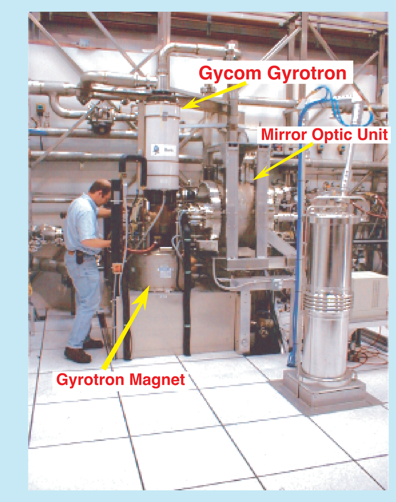


5 Gyrotrons, P_{ech} > 2 MW, ρ = 0.4, Δt = 2 s

THE 6 MW 110 GHz ECH SYSTEM FOR THE DIII-D TOKAMAK

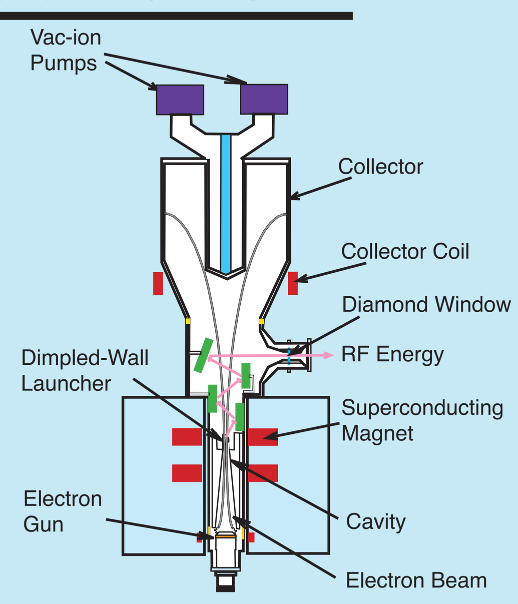


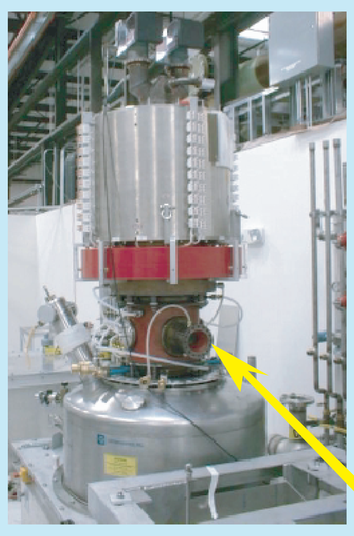
- 3 750 kW, 2 s, GYCOM gyrotrons
- 3 1000 kW, 10 s, CPI gyrotrons
- 6 41 to 95 m 31.75 mm dia, evacuated corrugated waveguides
- 3 Dual 2-mirror steerable launchers ±20° toroidal, ±20° poloidal

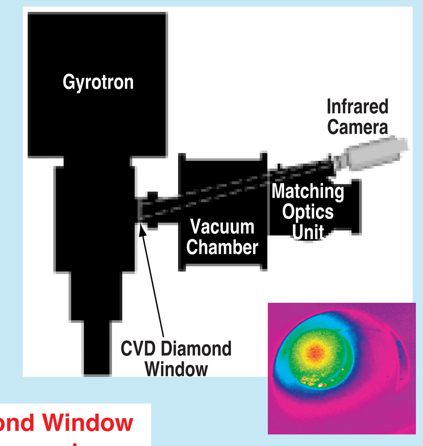


CPI 110 GHz 1 MW, 10 s GYROTRON

- Single anode magnetron injection type electron gun (diode)
- Over-modedcavity, $TEM_{22,6}$ eff ≈ 33%
- Internal mode converter with Gaussian output
- 4 mirror line with corrective optics
- Single disk CVD diamond output window, edge cooled
- Single collector sweep coil (4 Hz)
- Two 20 l/s vac ion pumps

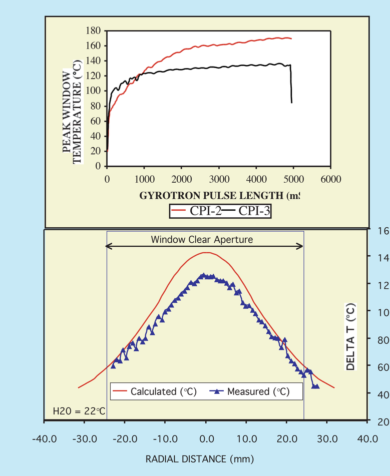






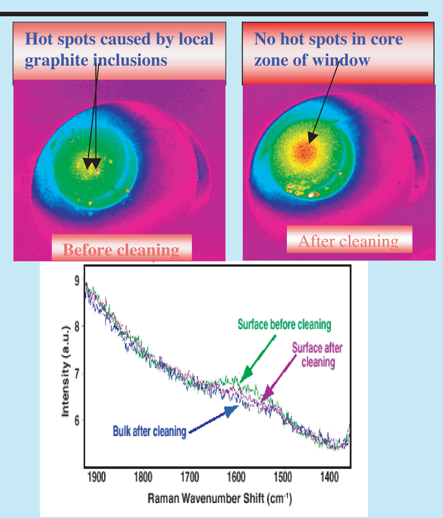
THE PEAK WINDOW TEMPERATURE REACHES A STEADY STATE LEVEL BELOW 170 °C AFTER 3 s

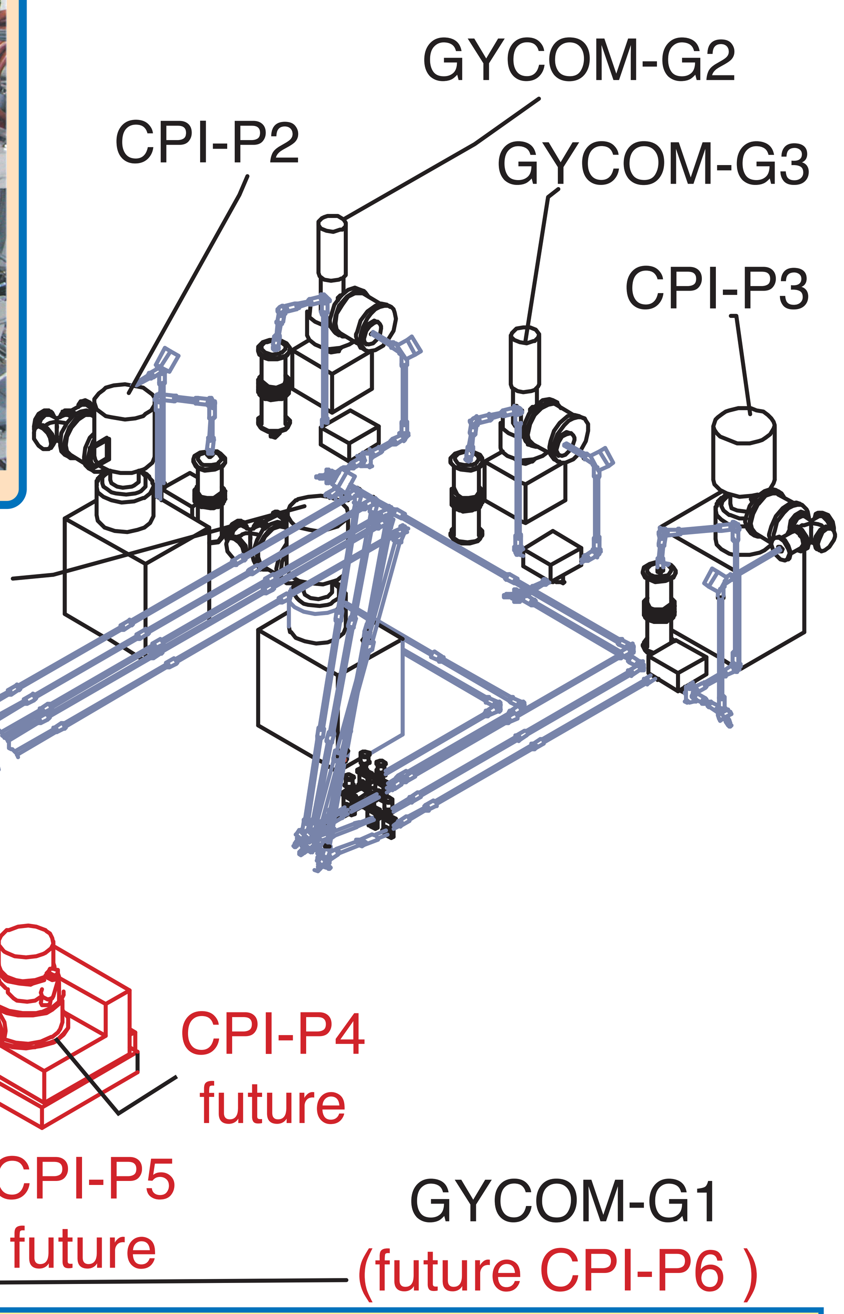
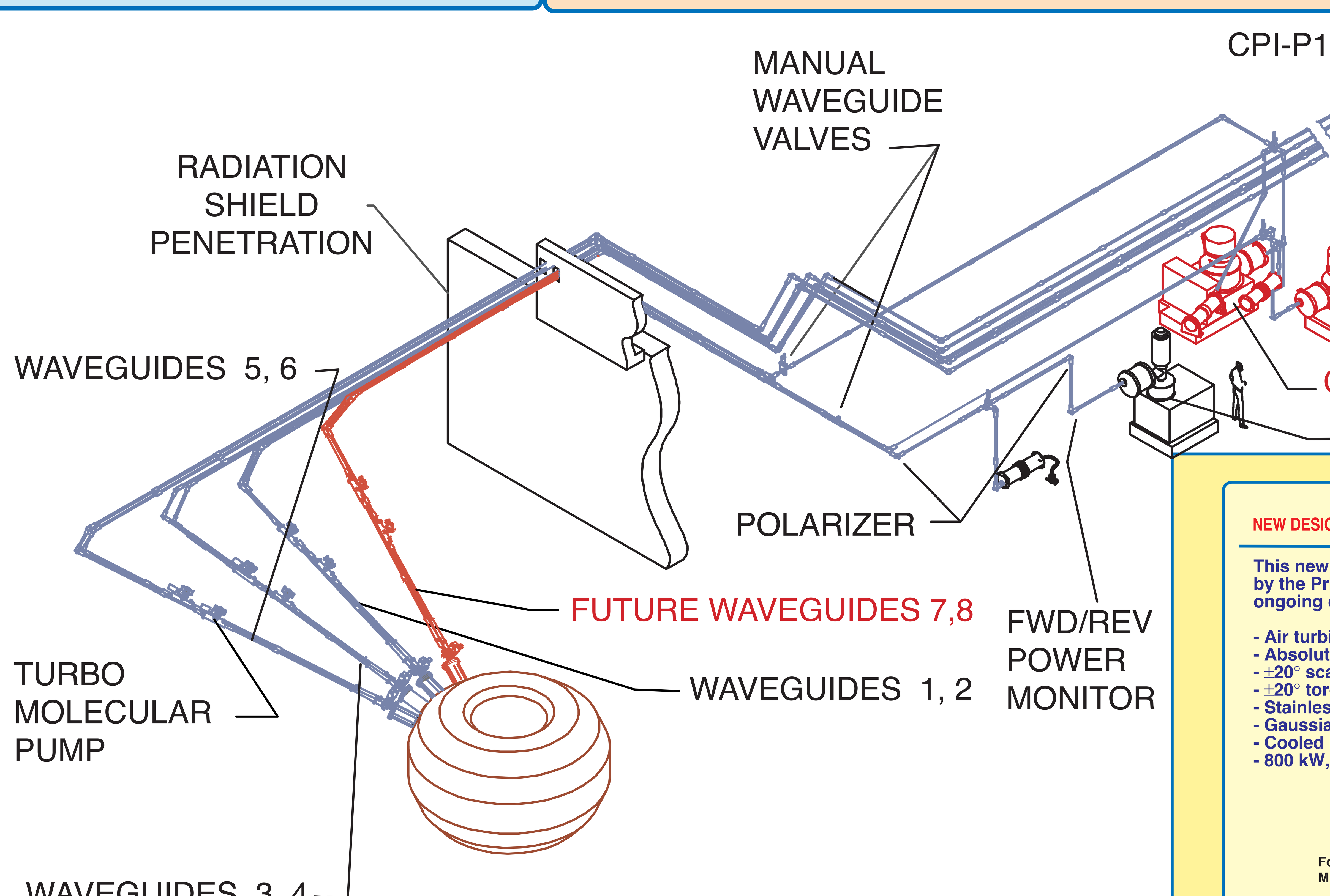
- The peak temperature of 140°C is below the 175°C design limit
- CVD diamond is a good IR window which complicates the window temperature measurements. The IR background inside the gyrotron fluctulates with the collector coil sweeping
- The rf output beam appears to be Gaussian like, and is very close to calculations



THE APPLICATION OF CVD DIAMOND WINDOWS HAS NOT BEEN WITHOUT CHALLENGES

- Several CVD diamond windows have failed due to contamination.
- Raman scattering measurements on the Tin Man window were made on the gyrotron, which verified the presence of graphite on the surface.
- "Hot spots" also were seen in the IR measurements of the window temperature during operation.
- The window was grit blasted with 3 micron alumina. This reduced the graphite and eliminated most of the "hot spots" from the IR measurement.

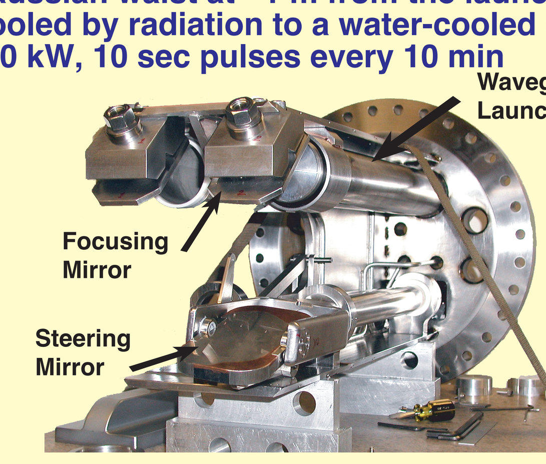


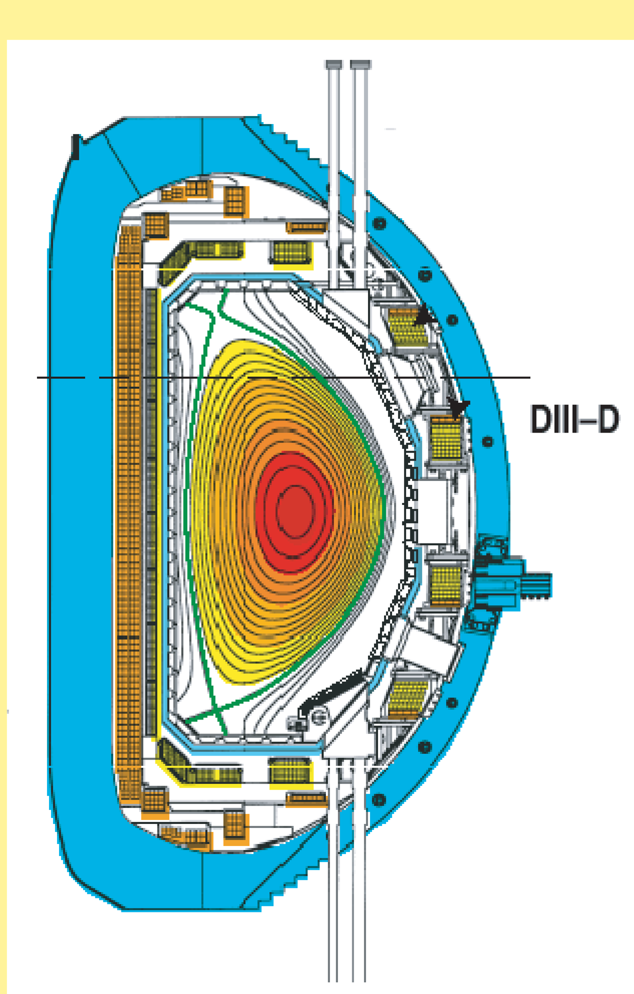



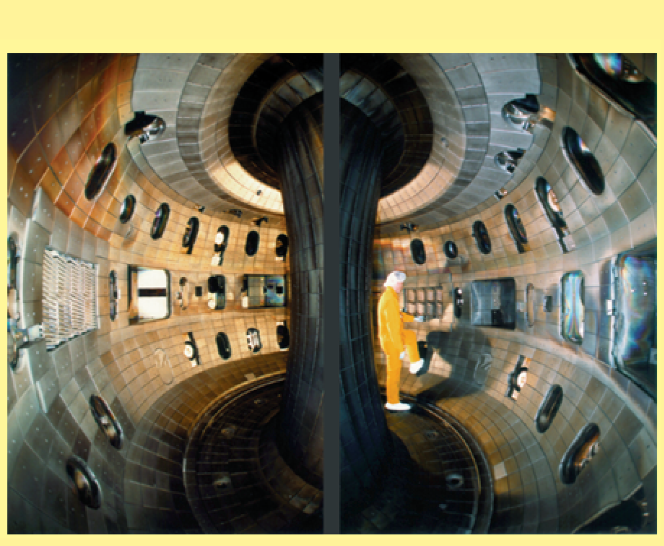
NEW DESIGN DUAL WAVEGUIDE LAUNCHER

This new launcher design has been developed and built by the Princeton Plasma Physics Laboratory as part of an ongoing collaboration.

- Air turbine drives, 10°/sec scan rate
- Absolute digital position encoders
- ±20° scan range poloidally (the upper half plane in DIII-D)
- ±20° toroidally (maximum co and counter-current drive)
- Stainless steel 60 mm diameter launch waveguides
- Gaussian waist at ~1 m from the launcher
- Cooled by radiation to a water-cooled shroud
- 800 kW, 10 sec pulses every 10 min





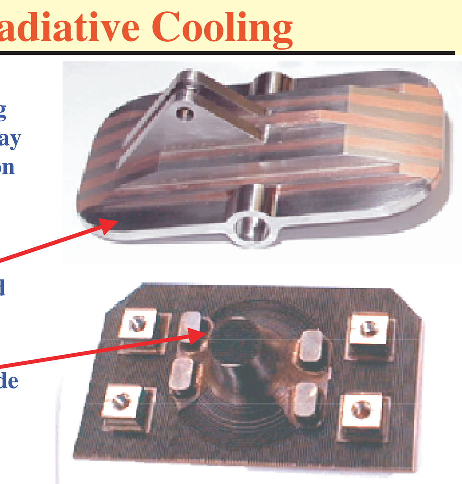


Summary

- Long pulse (~10s) 1 MW 110 GHz gyrotrons are now operational on the DIII-D tokamak
- CVD diamond output windows have been shown to support 1 MW power levels without over heating
- Steerable launchers allow for on & off-axis rf power deposition, and for co, radial and counter injection
- Evacuated low-loss waveguide allow for convenient routing of the rf power from the gyrotron hall to the tokamak using very little space

Two Steering Mirror Designs have been Developed to Support 800 kW, 10 s Pulses using only Radiative Cooling

- To minimize surface distortion caused by rf heating, the steering mirrors are designed to wick away heat, while keeping the disruption induced eddy currents at a minimum.
  - The Cu/SS design uses alternate slabs of copper and stainless steel
  - The Glidcop® design uses a slug of copper on the backside over the hot spot.
- Both designs use oxidized (blackened) backs to radiate the absorbed power.



State of the art Waveguide Components have been Developed for the DIII-D ECH System

The Development of a 1 MW, cw, Gyrotron Required the Development of a 1 MW Calorimetric Dummy Load

- A new compact mode-conversion dummy load [John L. Doane, Int. J. Infrared and Millimeter Waves, 14, 363 (1993)] is now in service.
- Absorbs about 75% of the incident HE1,1 mode and can be operated cw at 1.0 MW.
- This load is backed by a standard Inconel dummy load which takes the remaining 25% of the power.
- The combination is extremely black with rapid calorimetry response.