Capability of the 110 GHz Installation on the DIII-D Tokamak

John Lohr

Y.A. Gorelov, K. Kajiwara, Dan Ponce, R. Prater,

R.W. Callis, J.R. Ferron, C.M. Greenfield,

R.J. LaHaye, R.I. Pinsker, M.R. Wade*, R.A. Ellis†

DIII-D National Fusion Facility

General Atomics

***Oak Ridge National Laboratory**

† Princeton Plasma Physics Laboratory

2002 Meeting of the American Physical Society

Division of Plasma Physics

Orlando Florida

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Outline

- The 110 GHz ECH system
  - Installation
  - Components
  - Capabilities and performance
  - CVD Diamond windows
- Experiments
  - Transport and power deposition (Casper LO1.003)
  - ECH/ECCD efficiency (DeGrassie LO1.011)
  - NTM suppression (Petty LO1.007, Prater QP1.075)
  - Feedback control of injected rf power (Wade LO1.008)
  - Advanced tokamak operation (Murakami FI1.002, Greenfield LO1.002, St. John RP1.032)
- Summary and future plans

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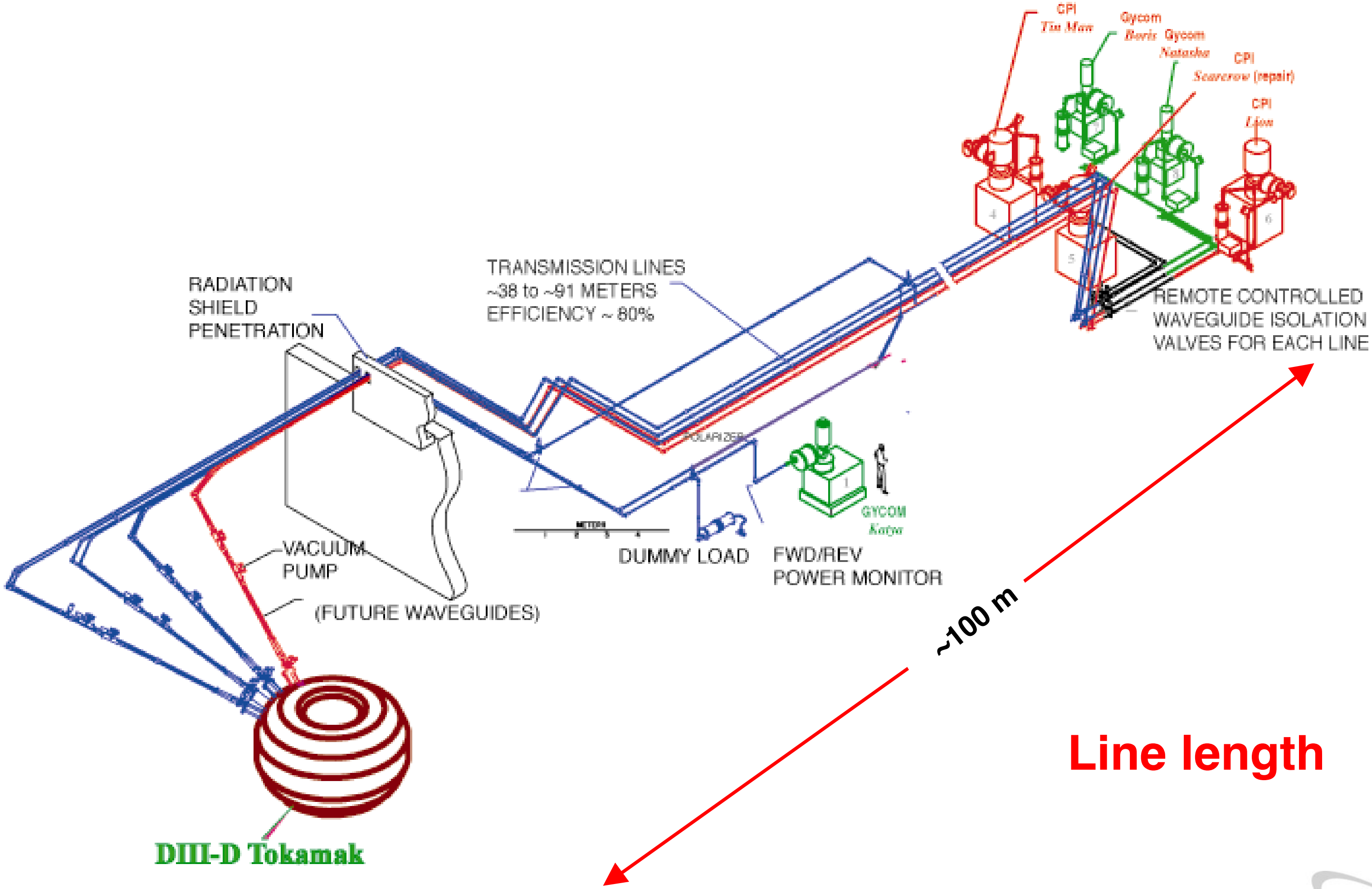
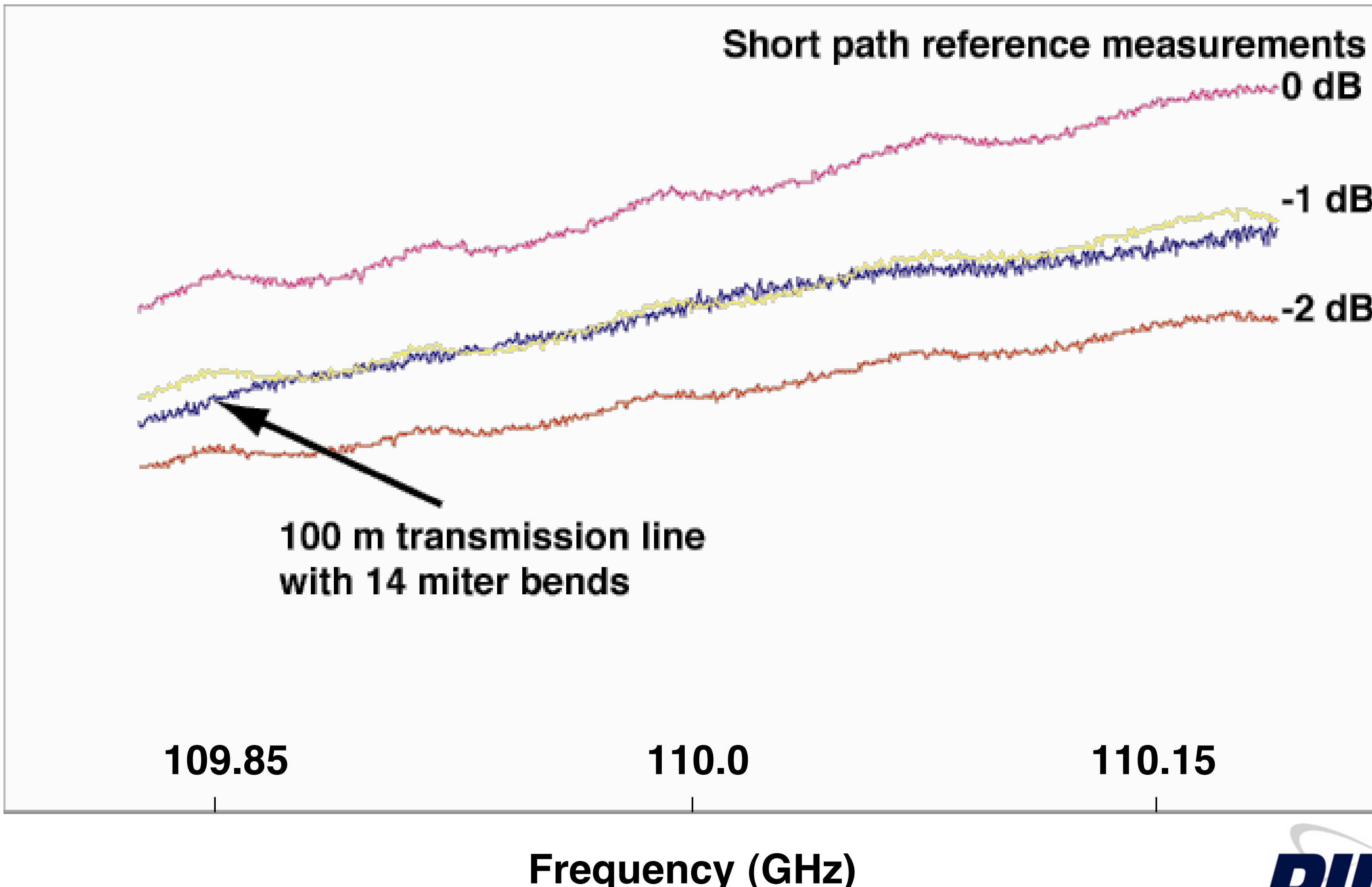
The DIII-D ECH Installation

The DIII-D ECH System



Transmission Line Efficiency >80% for 100m Length



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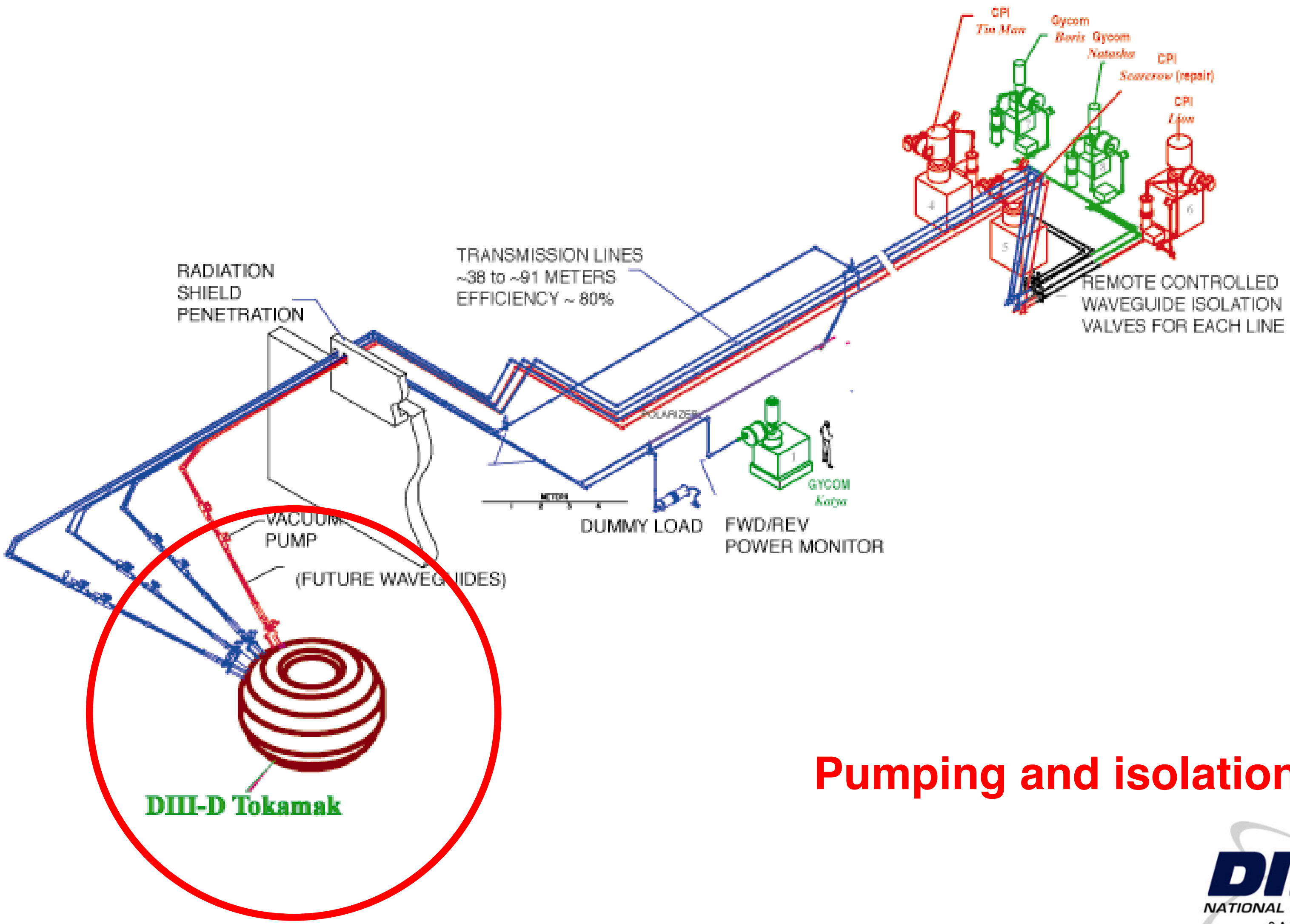
The DIII-D ECH System



Pumping and isolation

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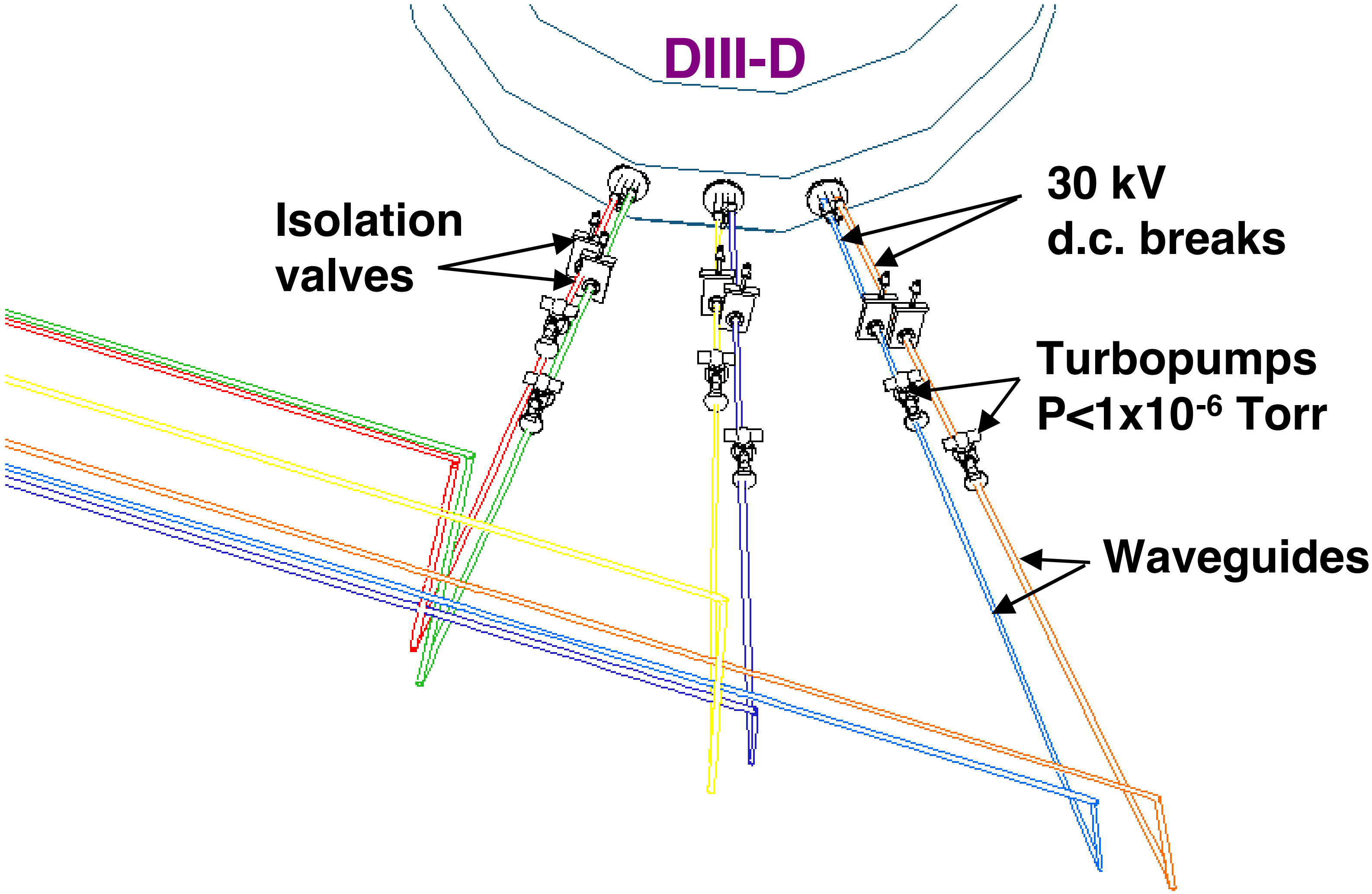
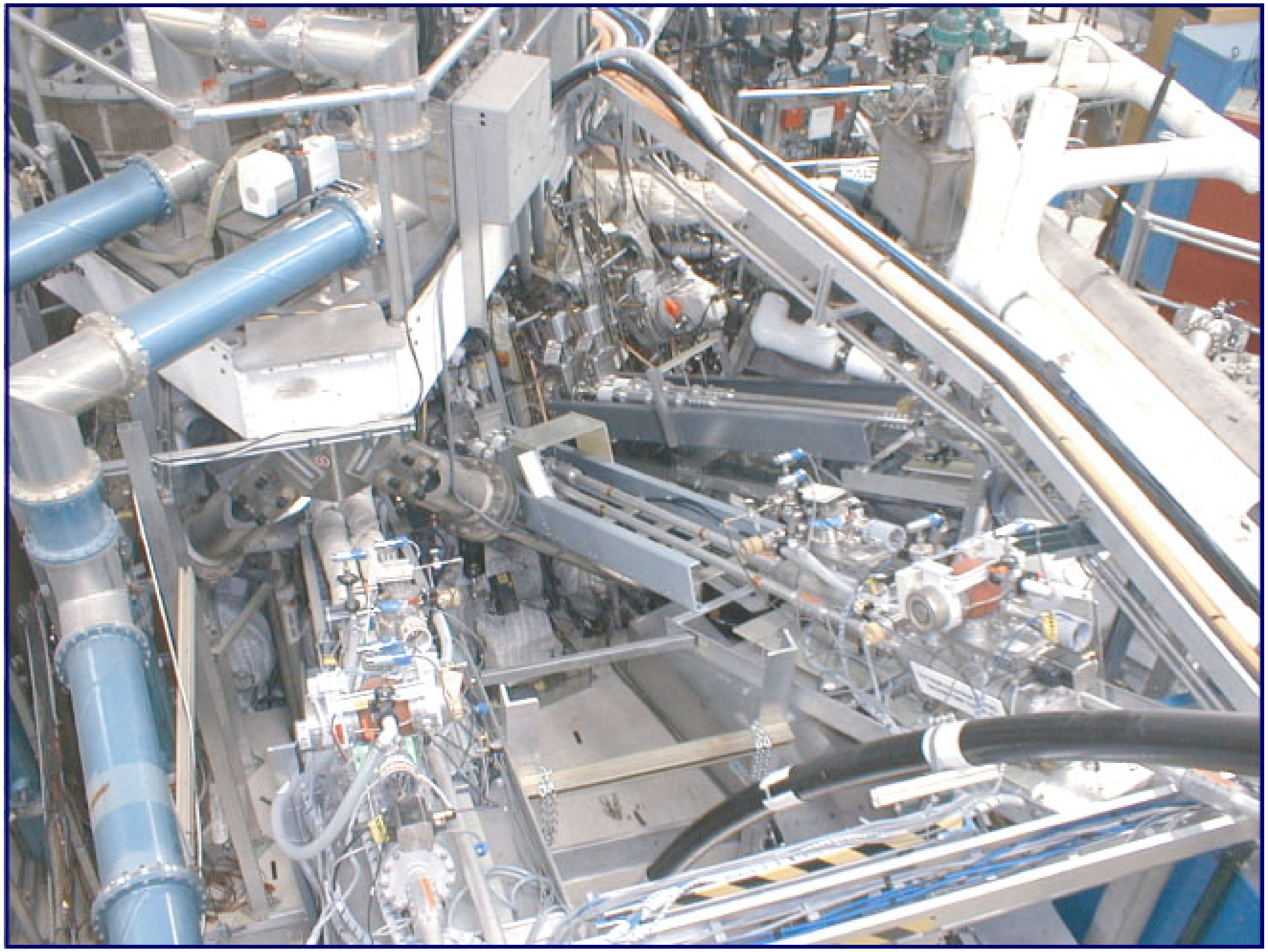
Waveguide Lines at DIII-D



ECH Waveguides at DIII-D



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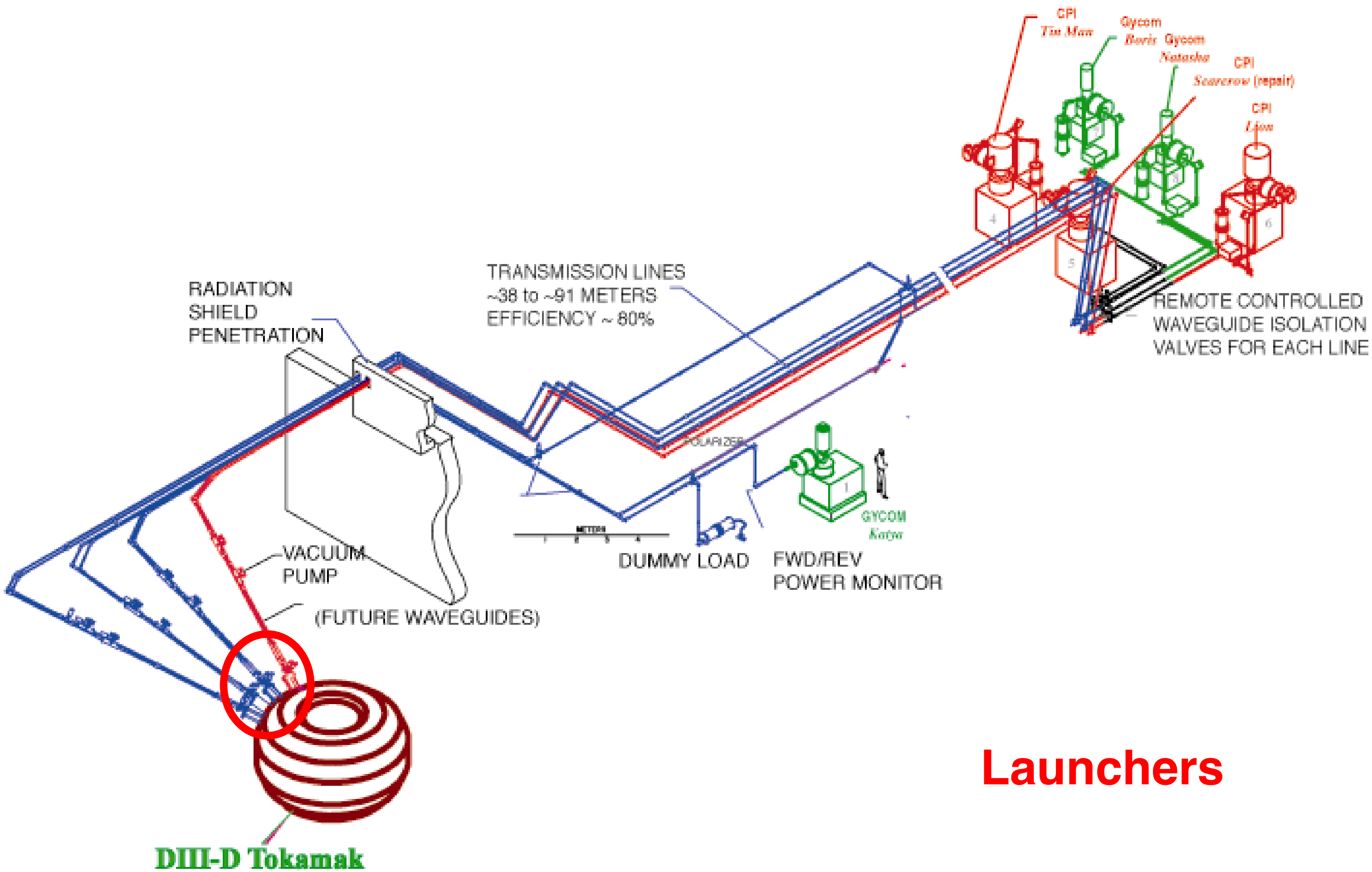
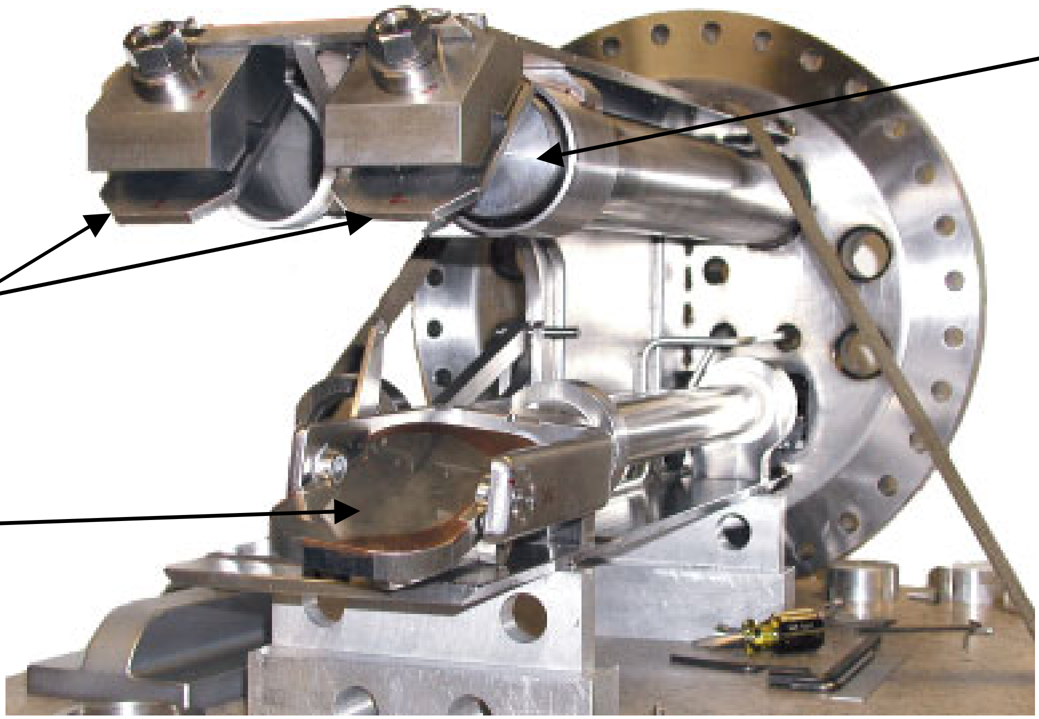
The DIII-D ECH System



Articulating Launchers



Weakly focusing Glidcop mirror

60 mm dia
Launch waveguide

Flat steering mirror (one shown)

- Three fully articulating dual launchers are now installed on DIII-D
- Two launchers have fast mirror scan capability

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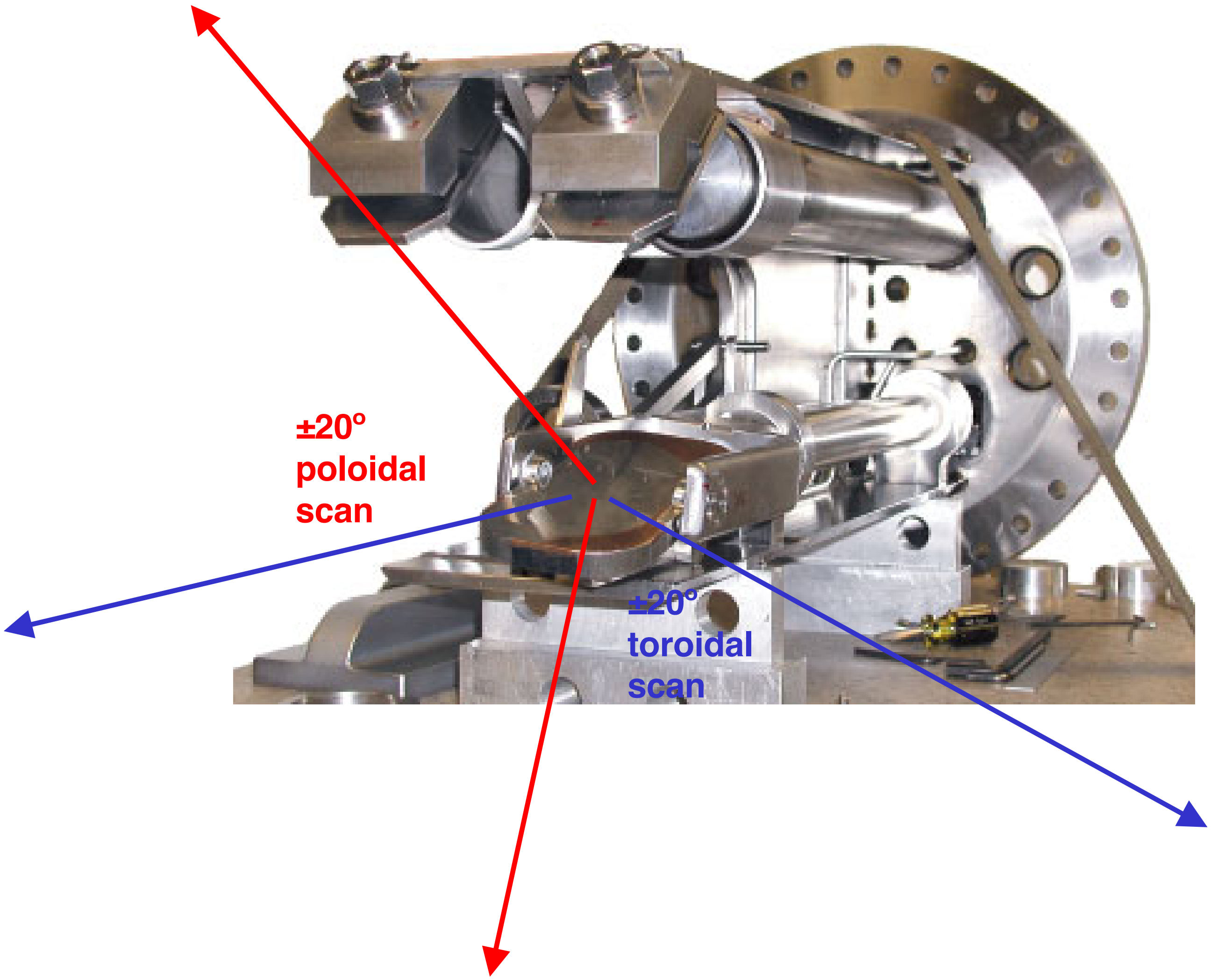
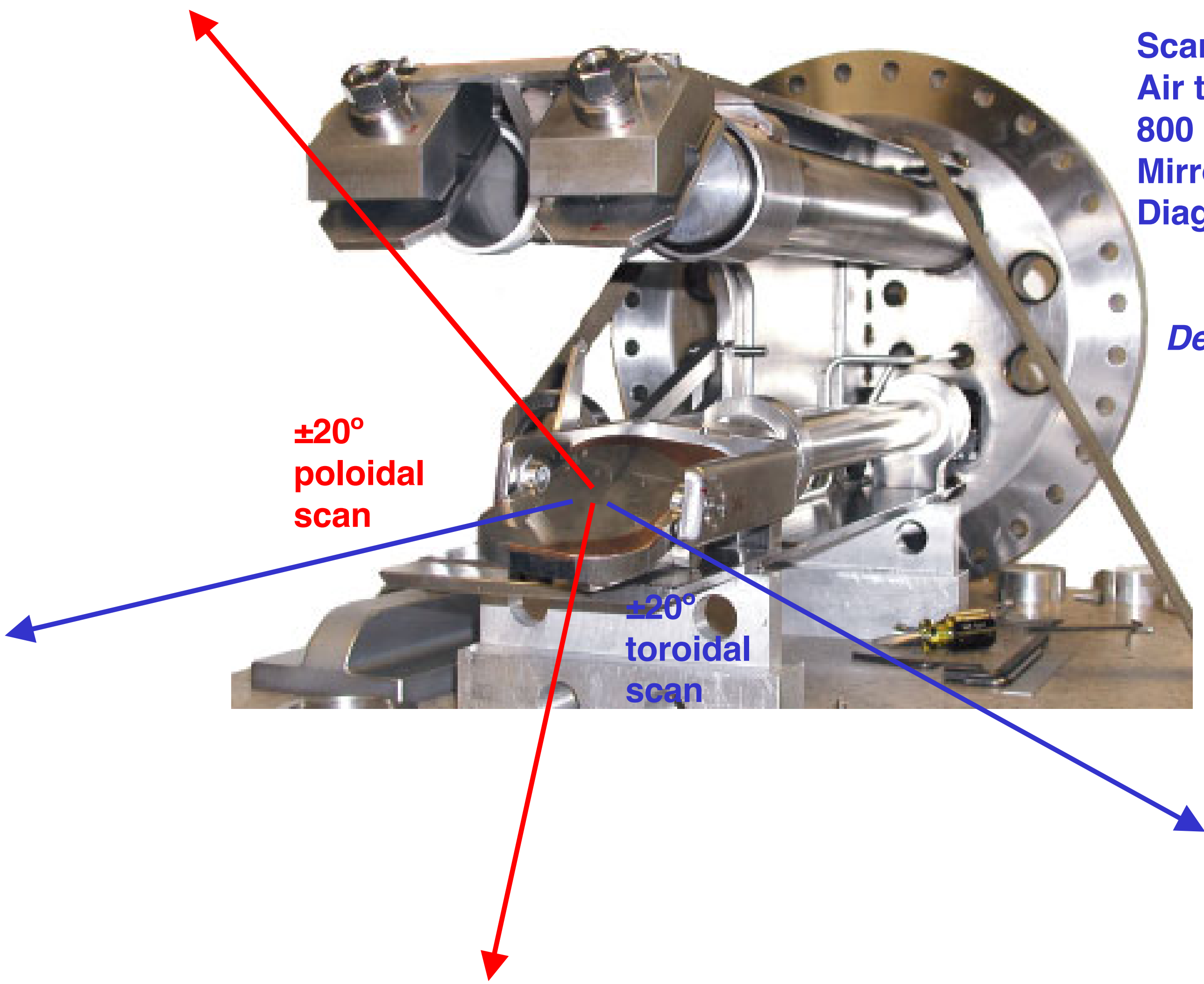
Articulating Launcher Scan



Articulating Launcher Scan



Scan rates ~10°/sec
Air turbine drive motors
800 kW, 10 sec pulse every 10 min
Mirrors cooled by radiation
Diagnostics:Langmuir probes
TV cameras
RTD thermal monitors

Designed and built by PPPL

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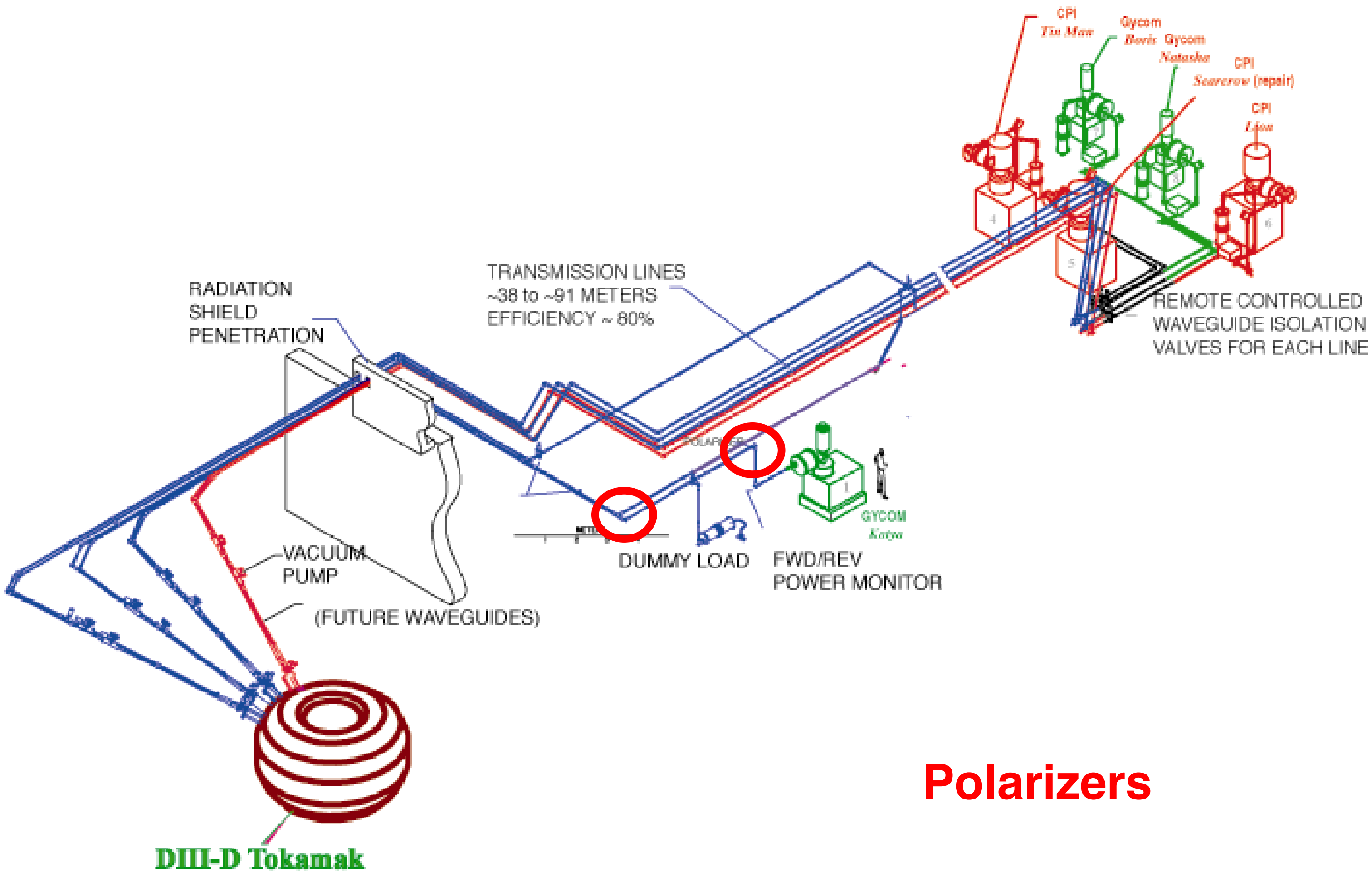
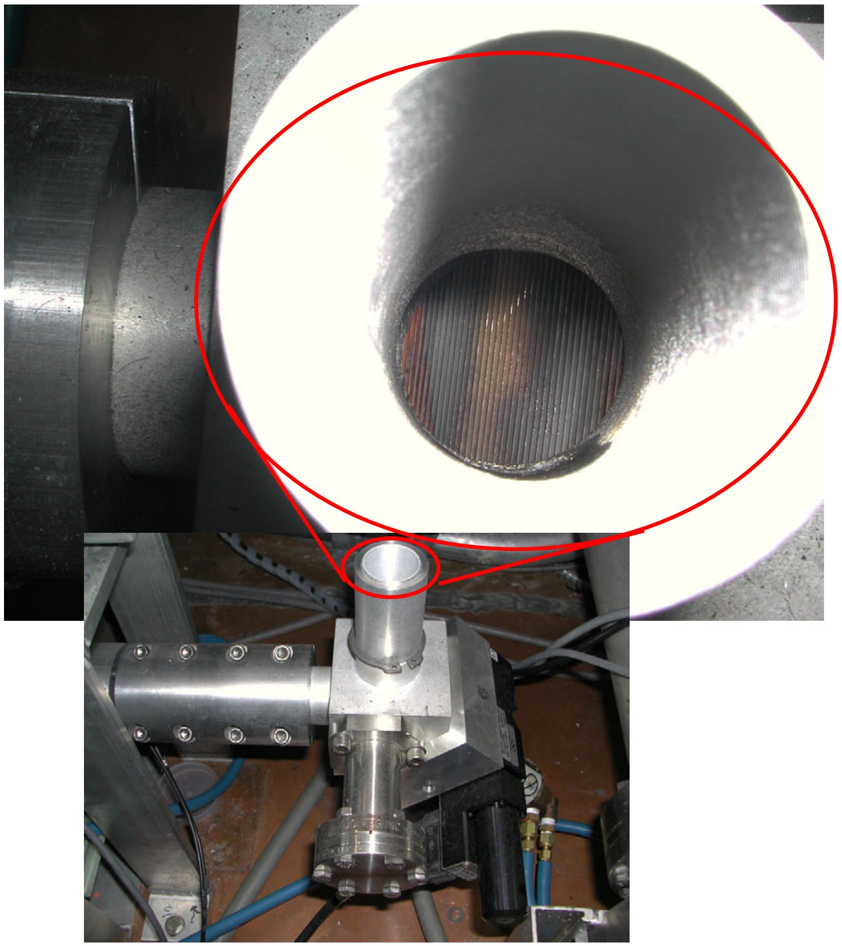
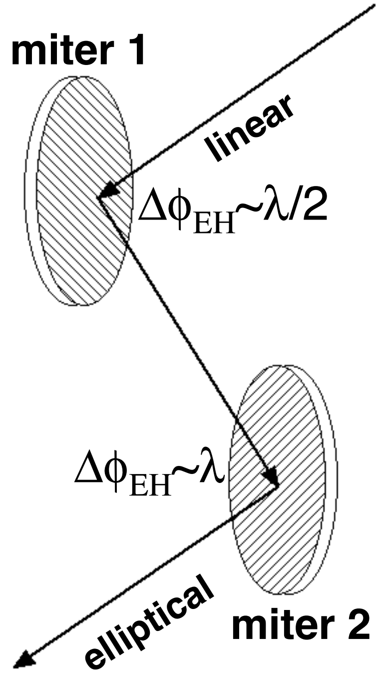
The DIII-D ECH System

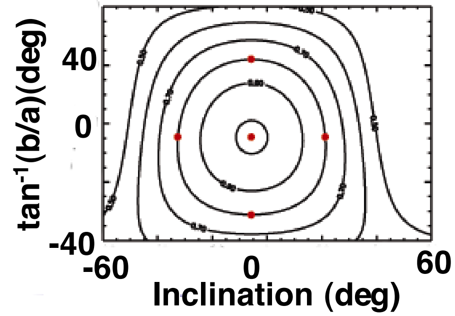


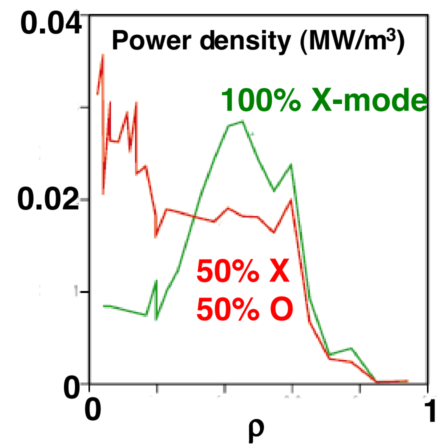
Polarizer Pairs Give Arbitrary Elliptical Polarization in Vacuum Under Remote Control





Polarizers are two grooved miter mirrors and produce arbitrary elliptical polairzation.





The measured power deposition profile becomes a polarization diagnostic.

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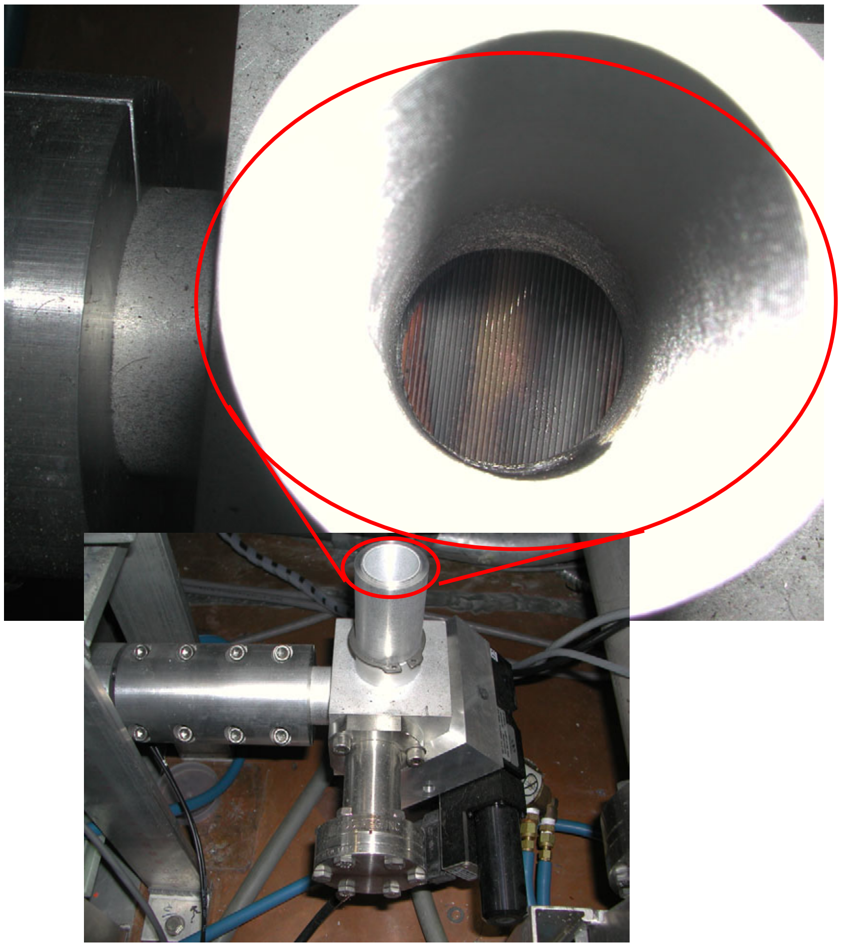

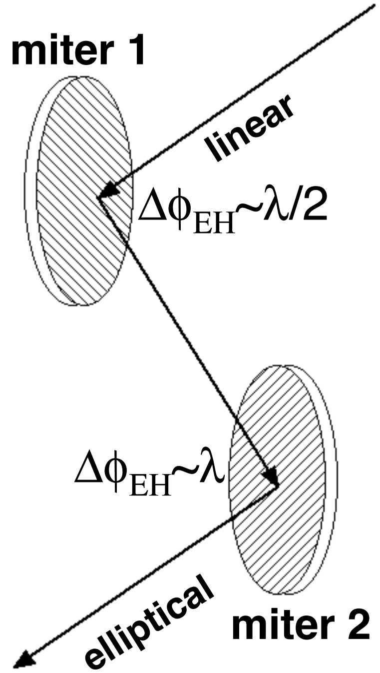

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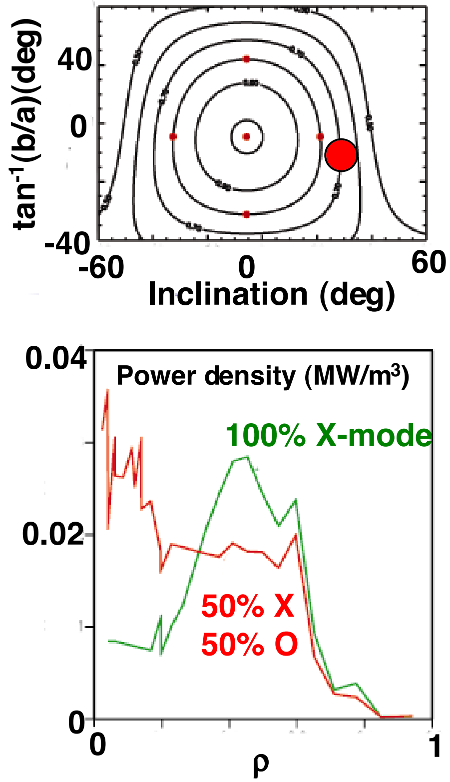

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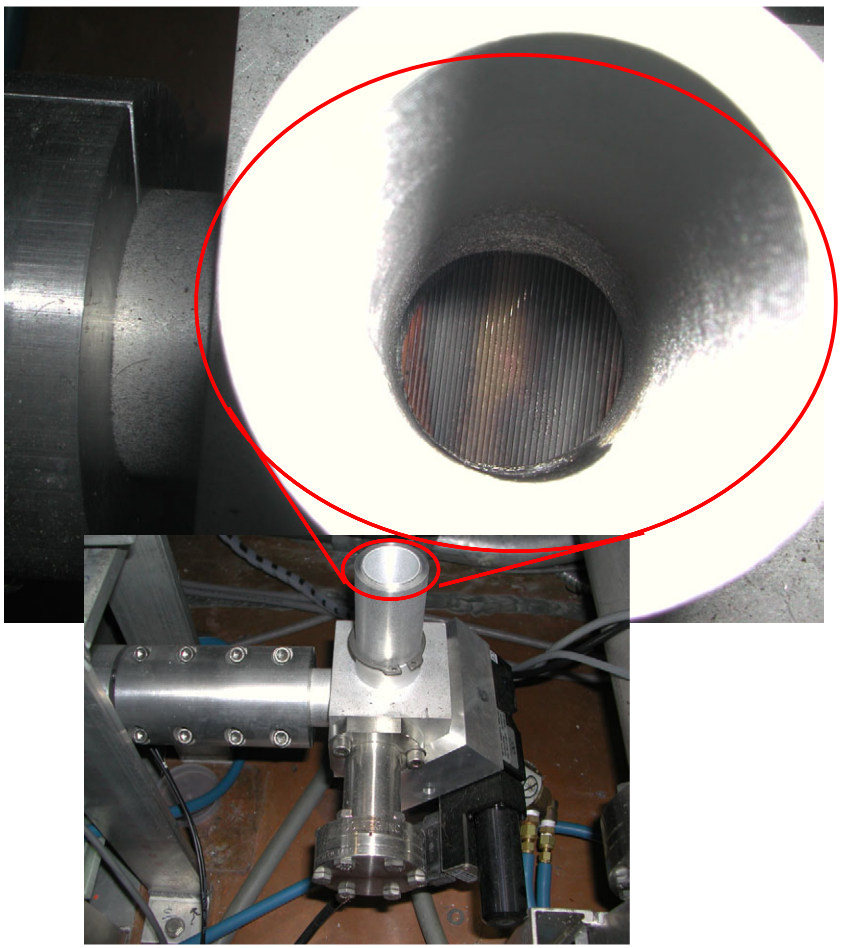

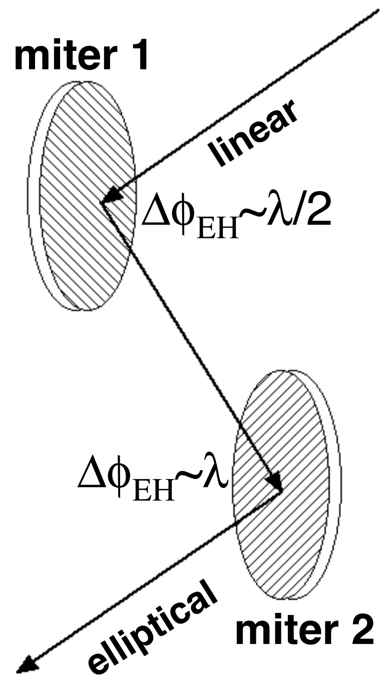

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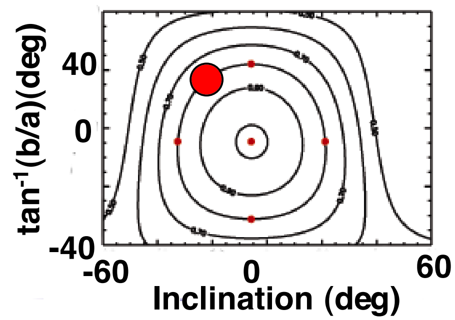

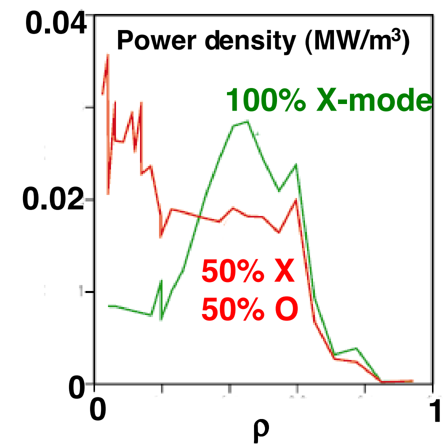

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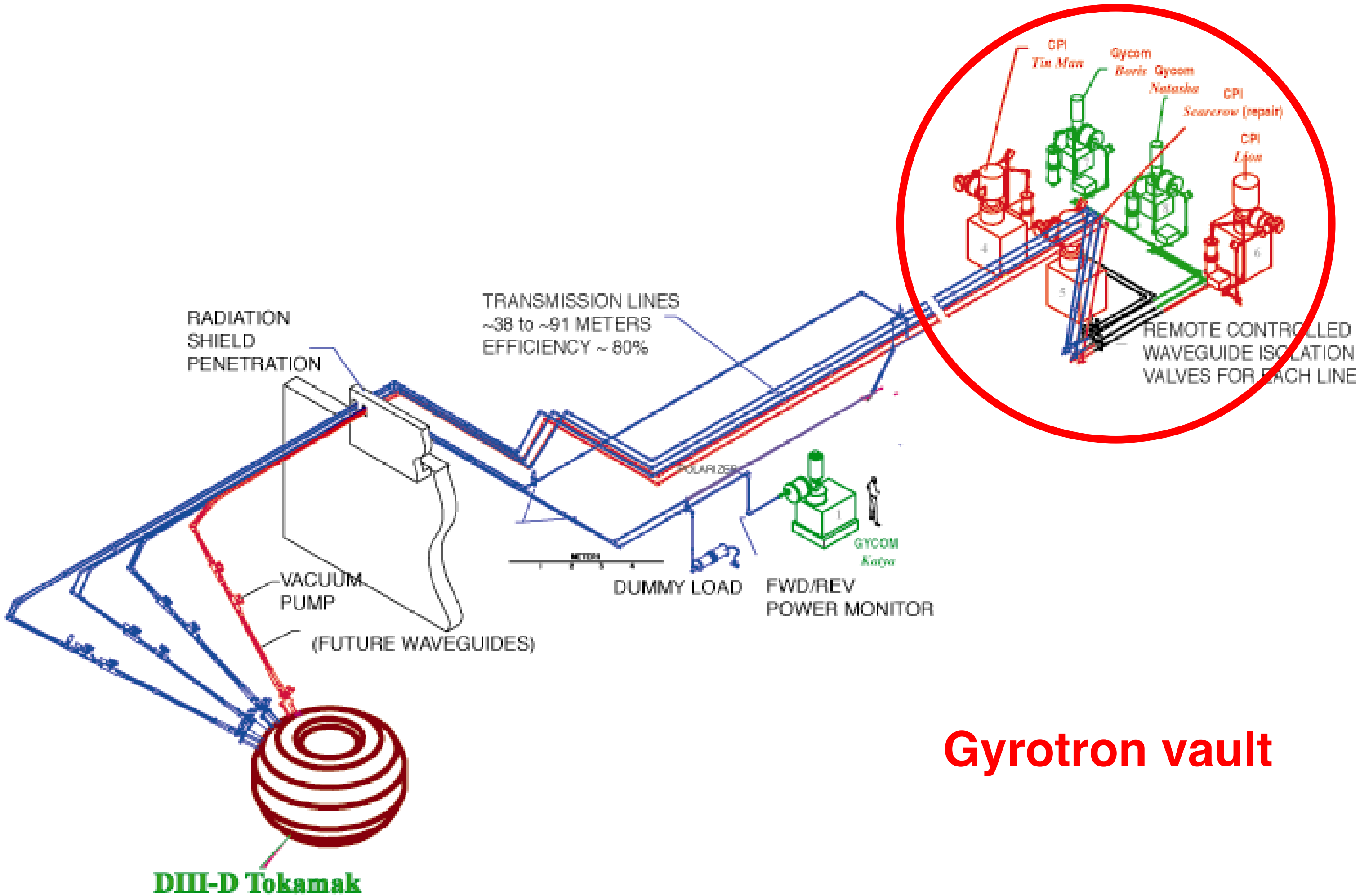
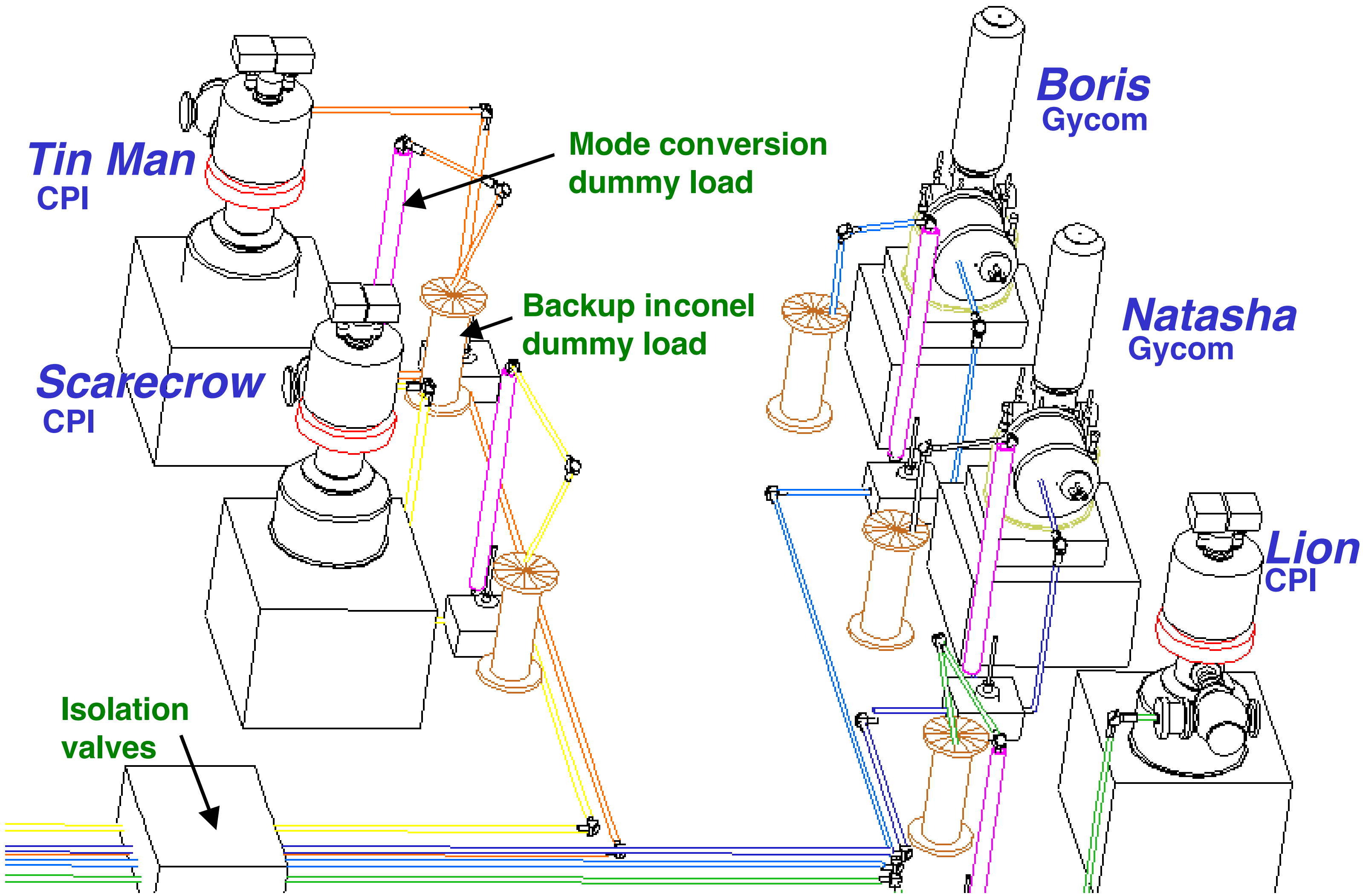
The DIII-D ECH System



ECH Gyrotron Vault



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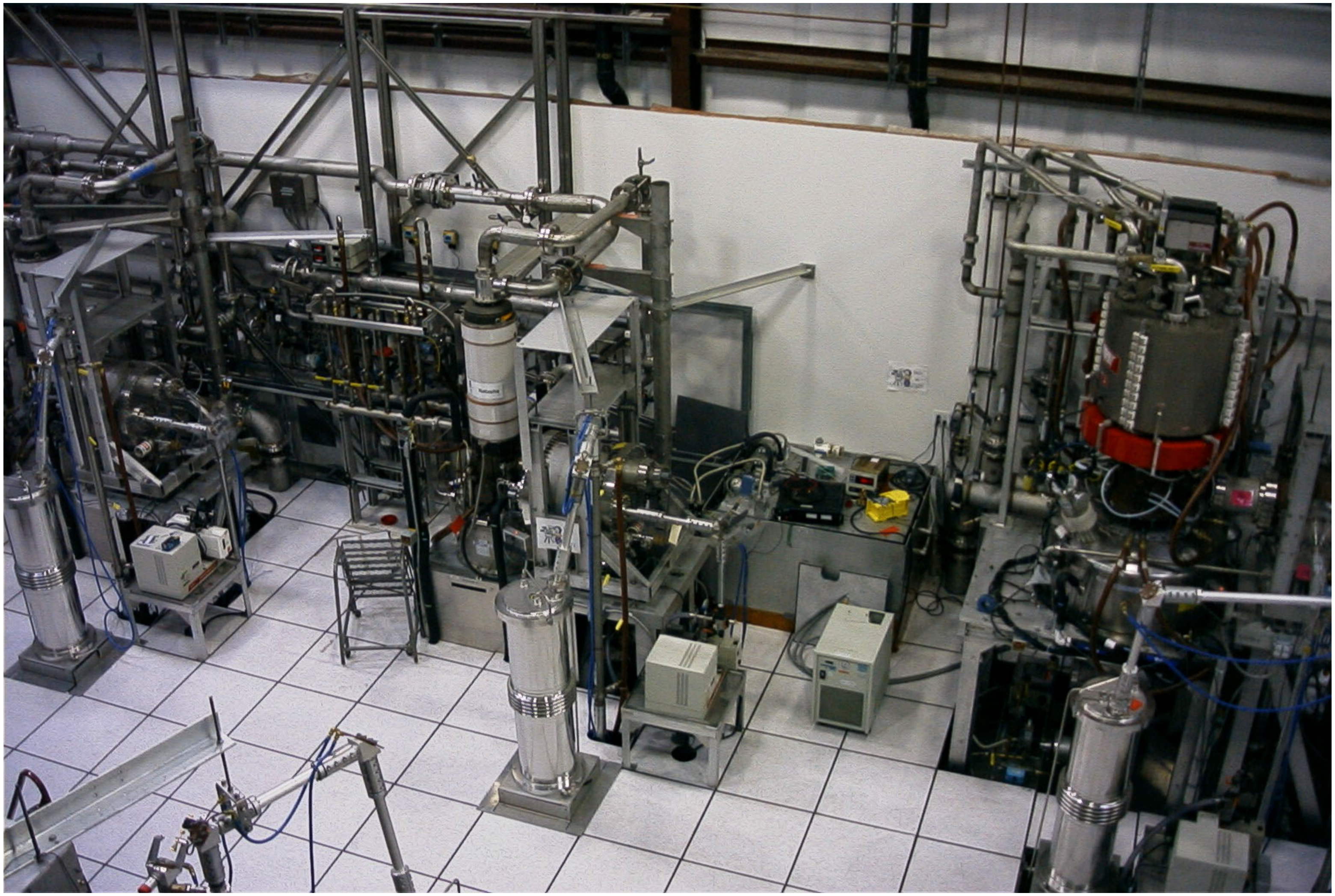
ECH Gyrotron Vault



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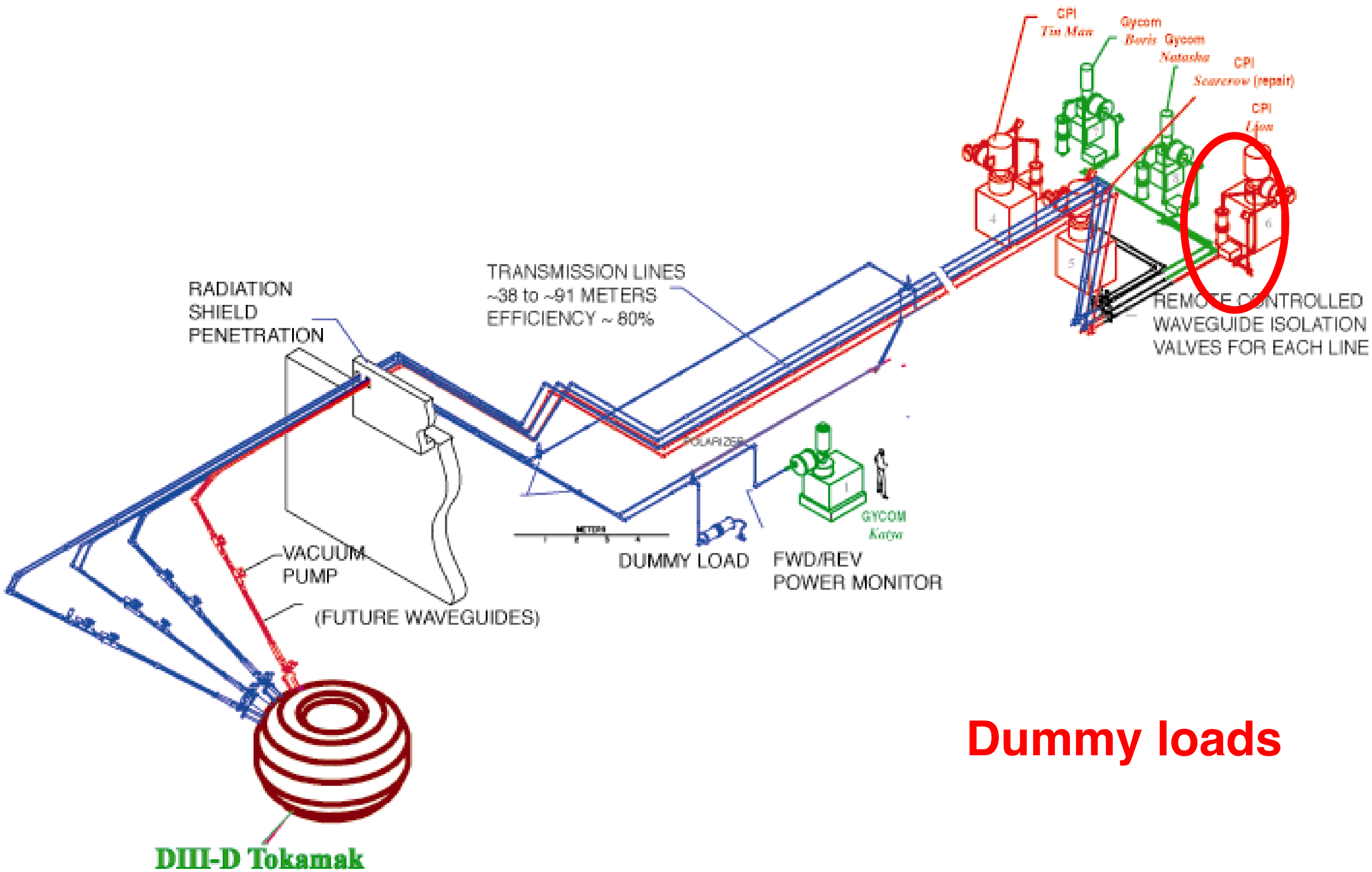
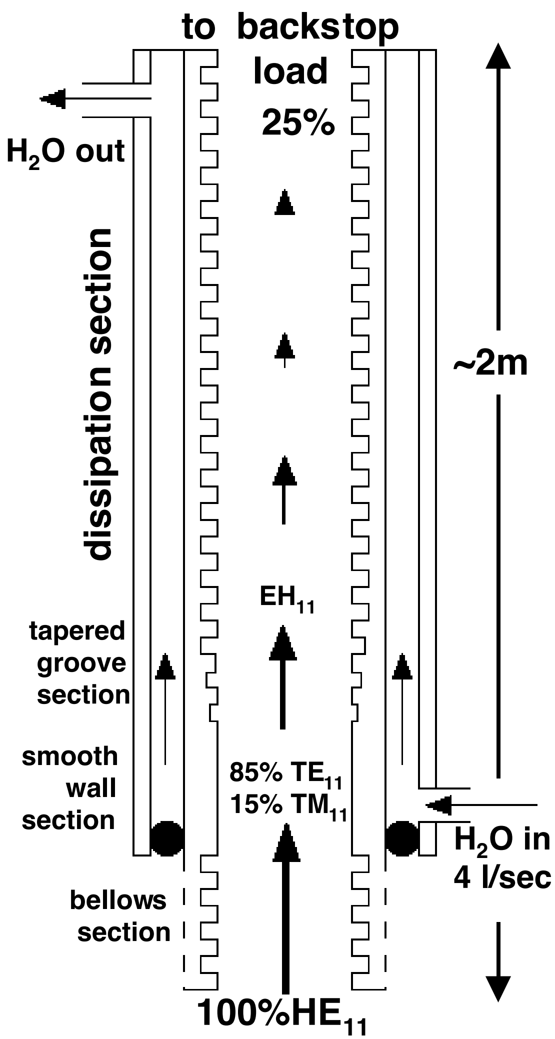


Dummy loads

Dummy Loads for 1 MW cw (they're not just pieces of pipe)



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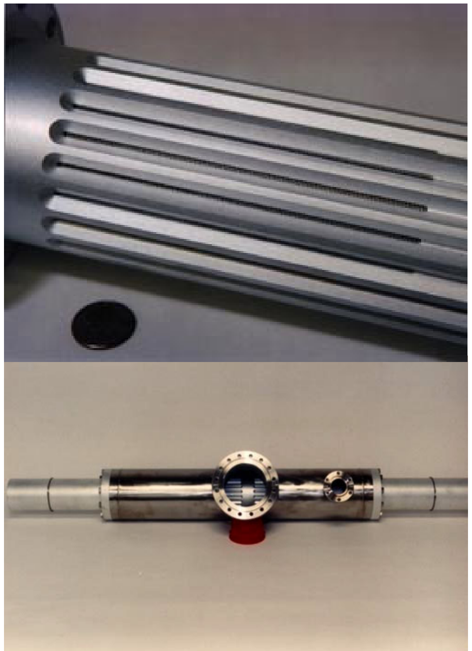
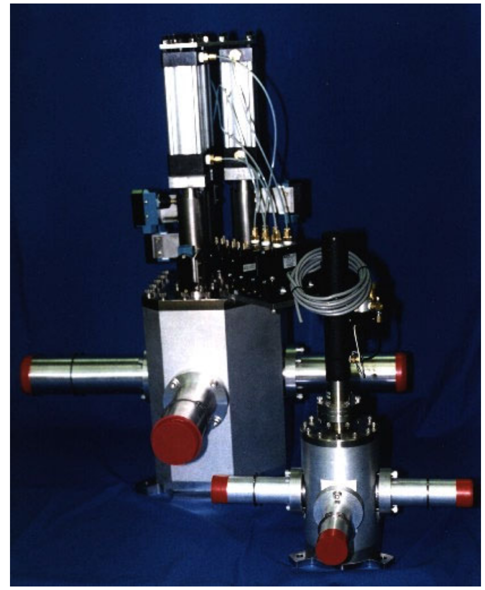
Unique Components

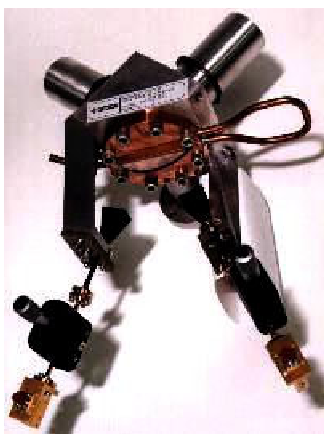
Vacuum pumpouts



Bellows and other specialized components

Waveguide switches





Power monitor miter bends

Corrugated vacuum waveguides

Miter bends and polarizing miter bends

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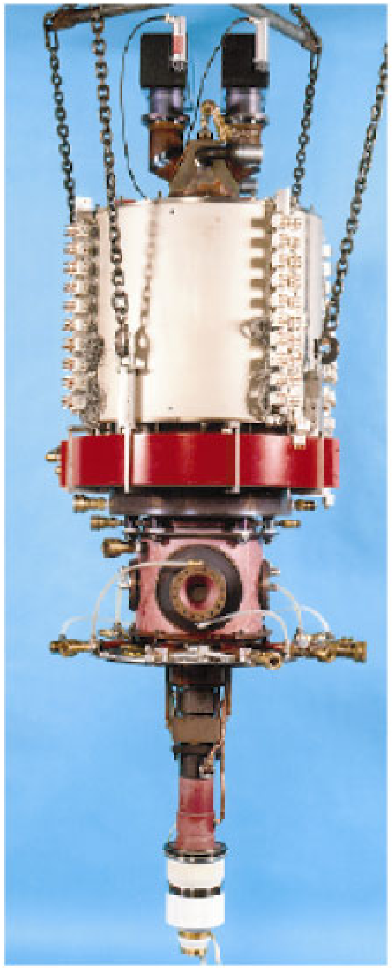
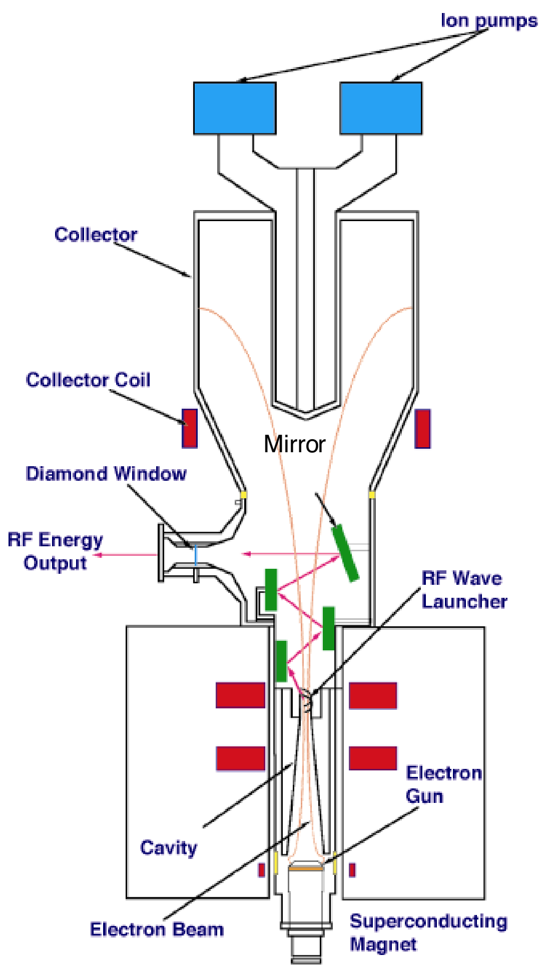
Modern 1 MW Class Gyrotrons at 75-170 GHz





- Production, R&D
- CPI (US)
- Gycom (Russia)
- Thales (France)
- Toshiba (Japan)
- R&D
- MIT, CCR, UMd, UW (US)
- IAP, StPSTU (Russia)
- FzK, CRPP, U. Stuttgart (EU)
- JAERI, Fukui Univ. (Japan)
- U. Helsinki (Finland)
- deBeers, Fraunhofer Inst (EU)

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DIII-D Gyrotron Parameters and Power Balance

GYROTRON NAME (mfg)	PULSE LENGTH (SEC)	V_{beam} (kV)	I_{beam} (A)	EFF (%)	P_{win} (kW) (%)	P_{mou} (kW) (%)	P_{gen} (kW)
Katya (G1) (Gycom)	2.1	72	31	31	33 3.7	173 25	699
Boris (G2) (Gycom)	2.1	69	30	37	30 3.9	136 18	775
Natasha (G3) (Gycom)	2.1	69	30	30	25 4.1	123 20	611
Tin Man (P2) (CPI)	5.0	80	40	30	2.1 0.22	69 7	955
Lion (P3) (CPI)	5.0	78	41	31	2.8 0.28	42 4	983
Scarecrow (P1) (CPI)	10.0	82	26	25	1.6 0.3	N/A	531

P_{Σ}=4.554 MW

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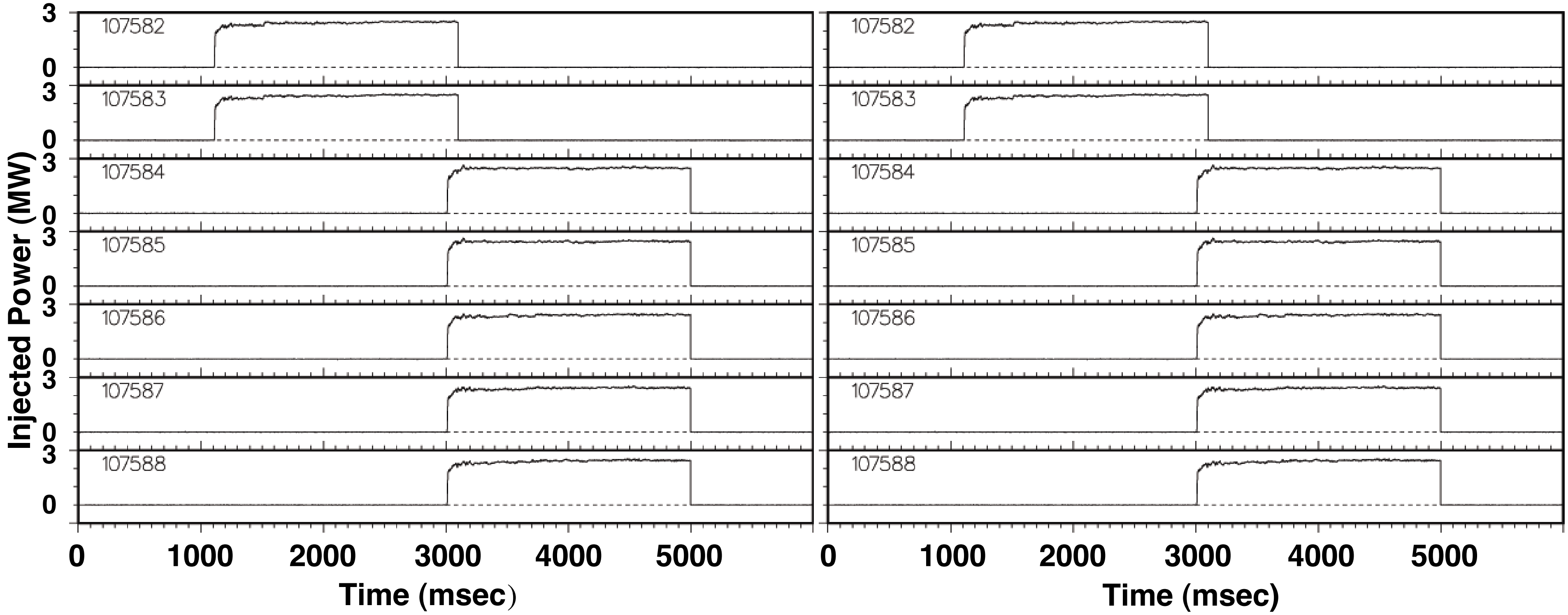
ECH Reliability is Comparable to NBI

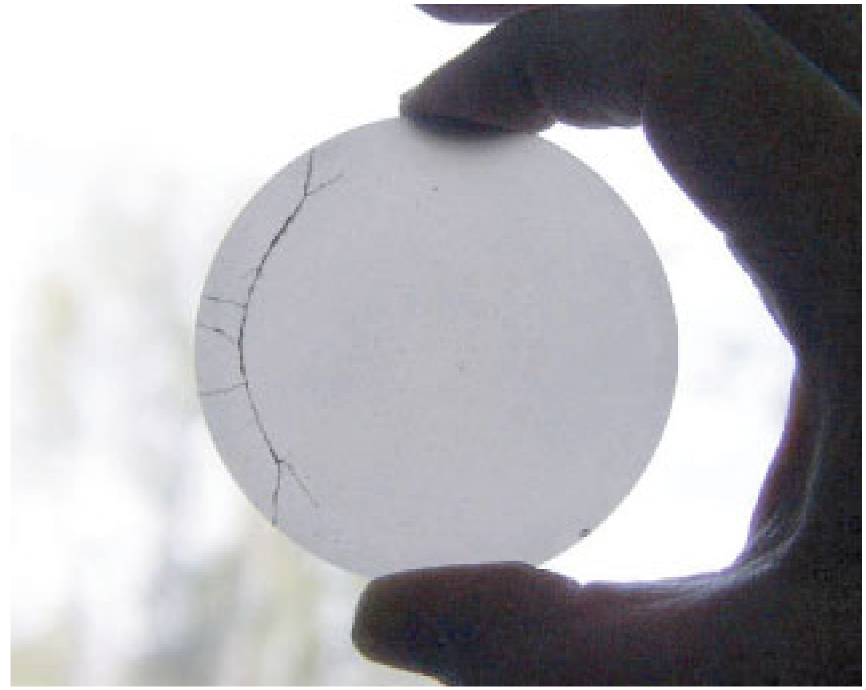
14 Consecutive shots with 4 gyrotrons



CVD Diamond Windows for Gyrotrons

Diamond is the Answer, but with a Learning Curve

Chemical Vapor Deposition diamond disks for high power gyrotron output windows



Scarecrow window found broken under the aluminum braze when the leaking flange was removed

Early difficulties with CVD diamond windows...

- Corrosion of aluminum based flange brazes
- Stresses arising during the braze process
- Surface contamination arising during brazing
- Surface contamination arising during bakeout
- Surface contamination arising during cleaning(!)
- Hydrogen “end bonding” increasing losses
- Failure due to arc initiated in dummy load

…have been addressed and resolved

- Hard brazes, Au/Cu and others have been successful
- Arc detection and prevention are high priority
- More measurements of tan(δ) are being made
- Raman scattering has been developed to diagnose contamination
- Surface cleaning by grit blasting with alumina and "aqua regia" acid etch have been successful

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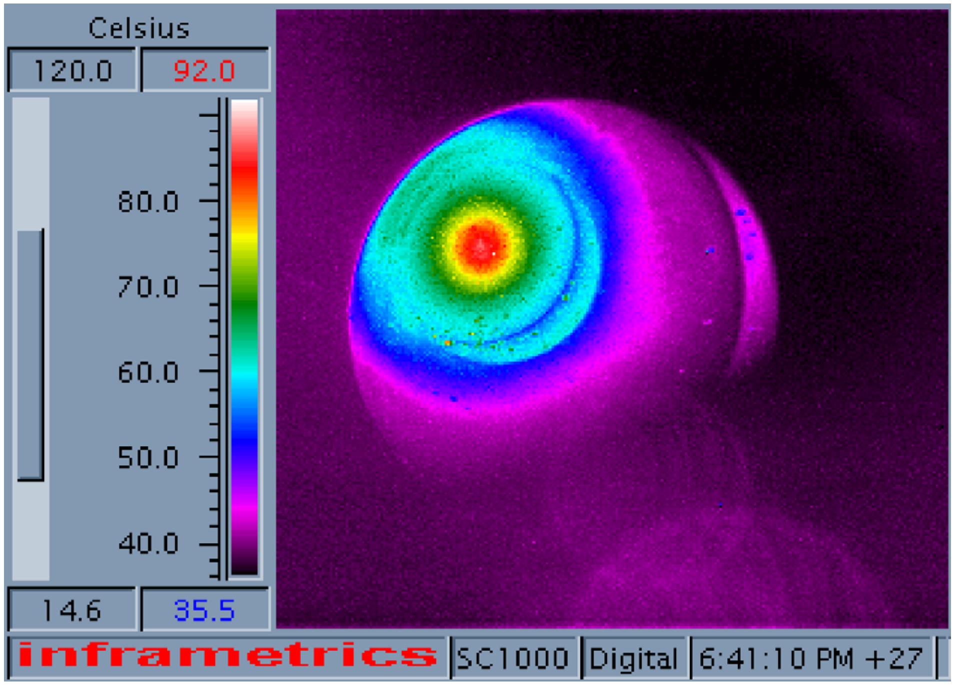
CVD Diamond Window IR View



- **A 5.0 second pulse at 800 kW, 110 GHz from the CPI *Tin Man* gyrotron at DIII-D**
- **Window parameters:**
  - **1.1 mm thick**
  - **50 mm clear aperture**
  - **tan(δ)<5x10^{-5}**
  - ***K*>1.2 kW/m-K (4xCu)**
  - **Yield stress ~350 MPa**
  - **~$100k**

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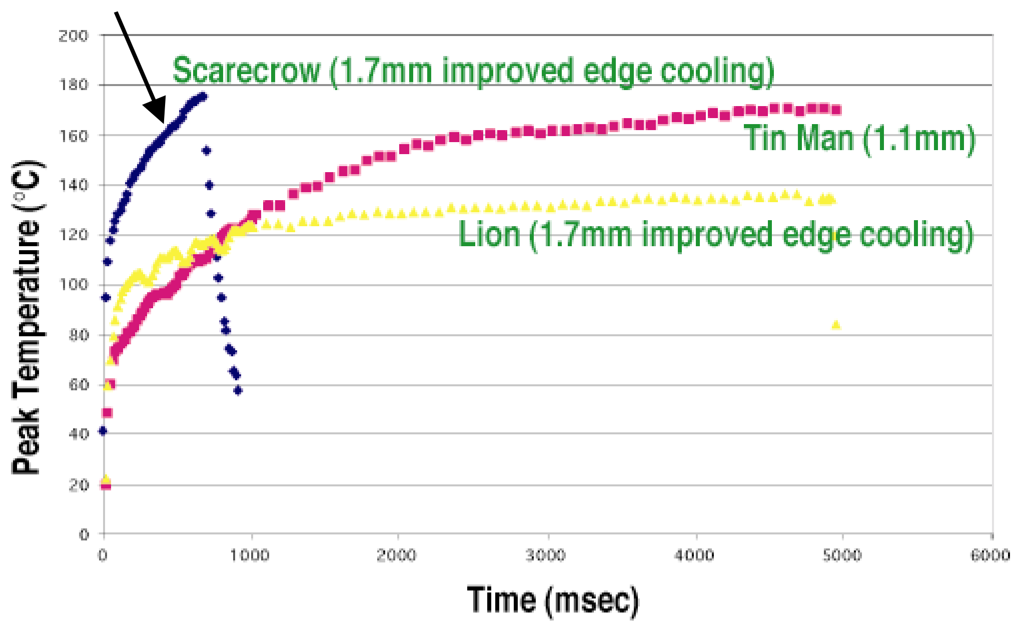
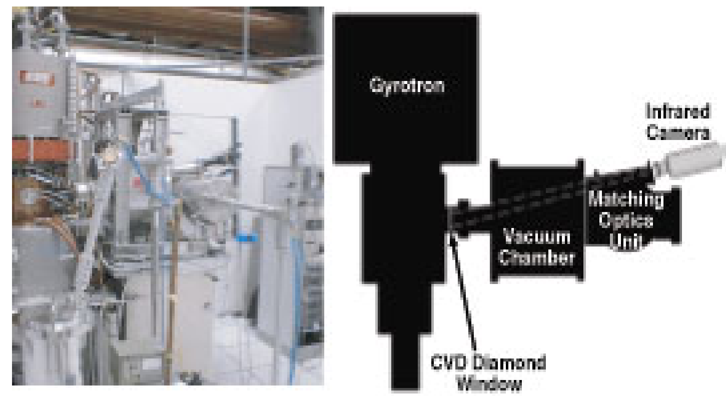
CVD Diamond Thermal Performance Measurements are Difficult

(coating? higher emissivity?)



Thermal equilibrium after ~3 sec, but substantially different performance from window to window possibly due to unintended contaminant coatings



Typical installation and geometry for window IR measurements

CVD diamond is the viable solution to the gyrotron window problem

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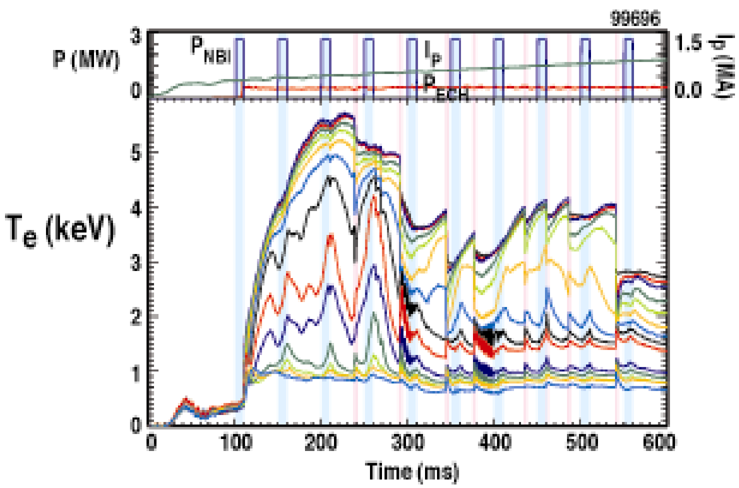
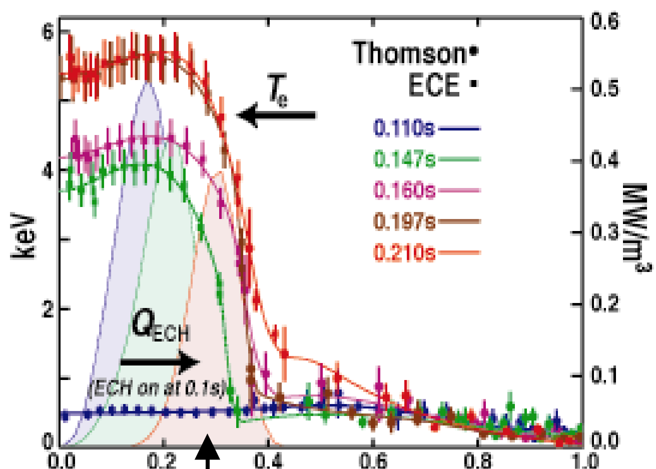
ECH and ECCD Experiments on DIII-D

ECH: Transport Barrier Formation with Perpendicular Injection





- ECH applied early to a discharge with negative central shear
- $\chi_e < 0.1\chi^{neo}$
- Barrier lies just inside the $2\nu_{ce}$ resonance
- ETG mode stabilized by the large Shafranov shift
- Record T_e=15 keV for DIII-D has been achieved this way

Power deposition profile width is ~8 cm at the 10% contour

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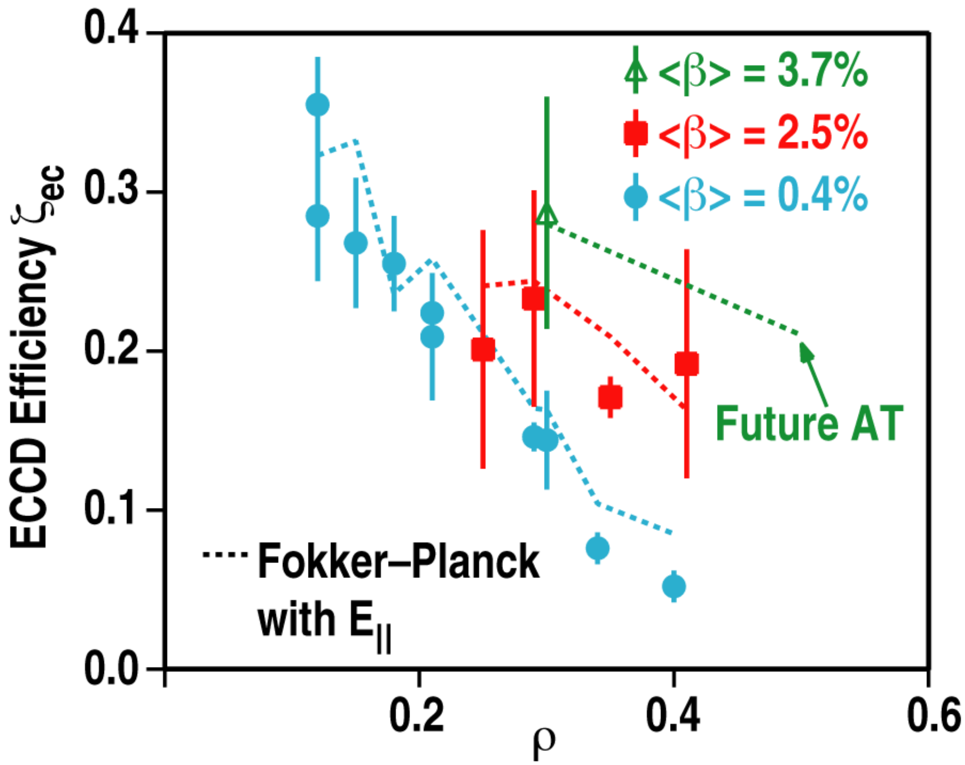
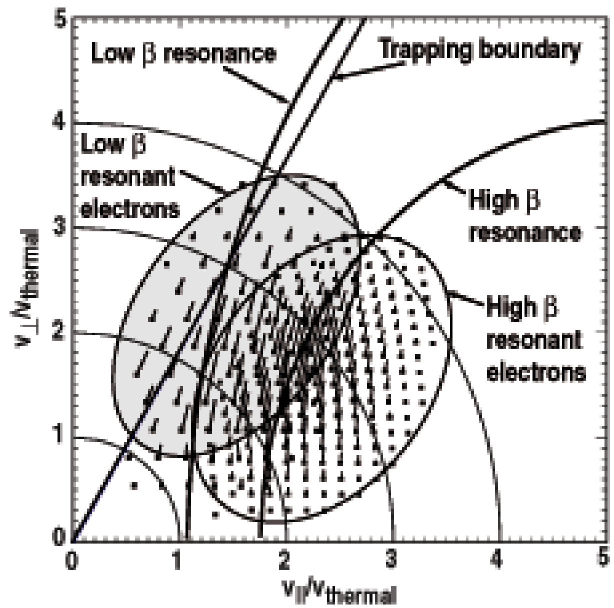
ECCD Efficiency is High





- $I_{ECCD} \leq$ 140 kA for P_{RF}=2.2 MW
- High efficiency for off axis ECCD
- Adequate for advanced tokamak

- The efficiency stays high for off-axis drive if the plasma pressure, β, is high, because the resonant electrons are far from the trapping boundary.

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Use of ECCD to Suppress Instabilities

NTM Stabilization

1. Island width for m/n=3/2 ~ 7 cm

2. -10dB width of j_{ECCD} is ~ 8 cm and -3 dB width is about 3 cm

A good match between ECCD and island widths

3. About 1-2 cm accuracy is required, but some misalignment is OK

4. Within the island, $\nabla p \sim 0$, so the missing bootstrap current must be restored artificially to stabilize the tearing mode.

5. For P_{EC}~2 MW, $j_{ECCD} \approx 2\ j_{bootstrap}$ at the q=3/2 surface

Adequate driven current with available power

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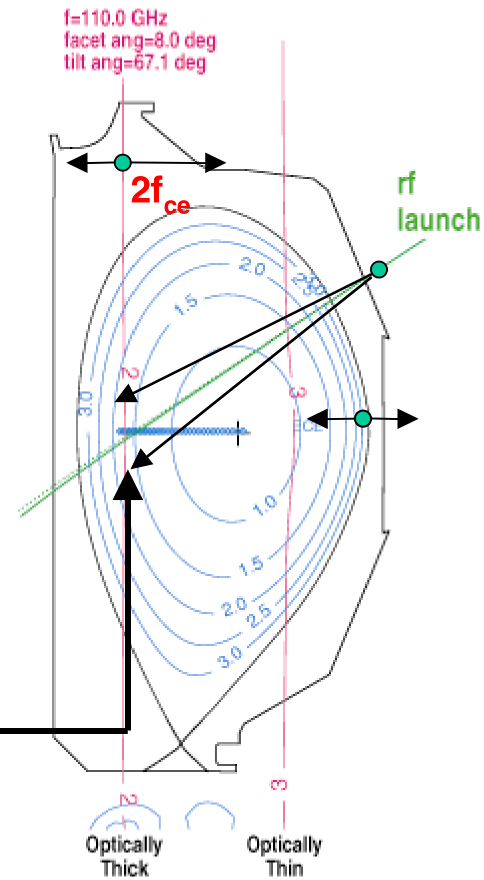
Hitting the Islands with ECCD

The absent current can be restored by ECCD, but the current must be driven exactly at the islands to within about ±1-2 cm.



Power is absorbed at the intersection Of the rf beam and the $2f_{ce}$ resonance

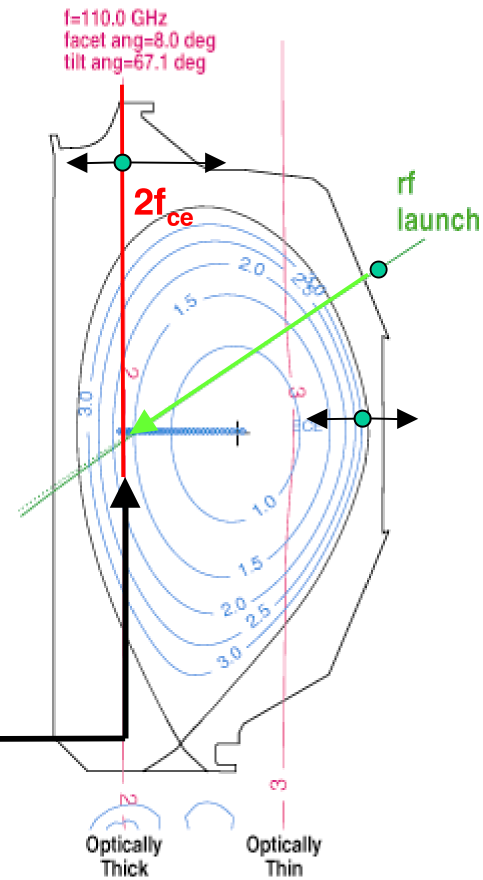
The ECCD can be placed at the island location by:

- Changing B_T
- Moving the plasma
- Changing the injection angle

~±1 cm radial accuracy required

Hitting the Islands with ECCD

The absent current can be restored by ECCD, but the current must be driven exactly at the island. How can you hit the islands exactly?



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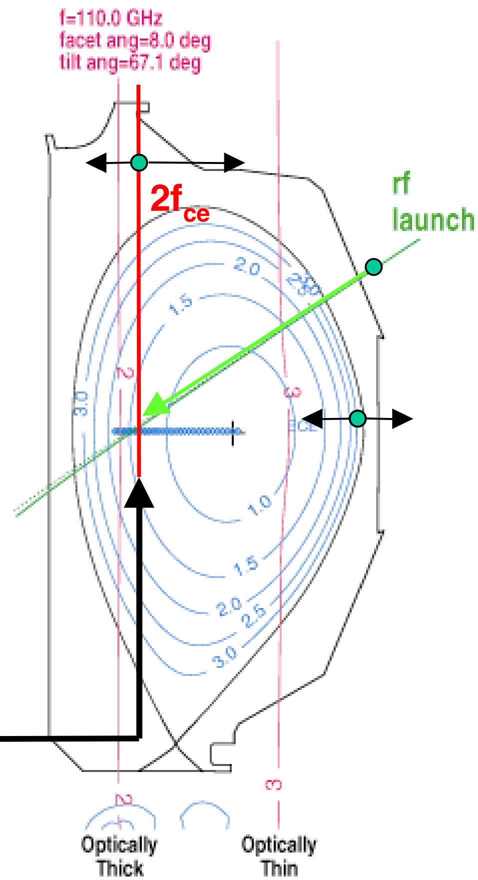

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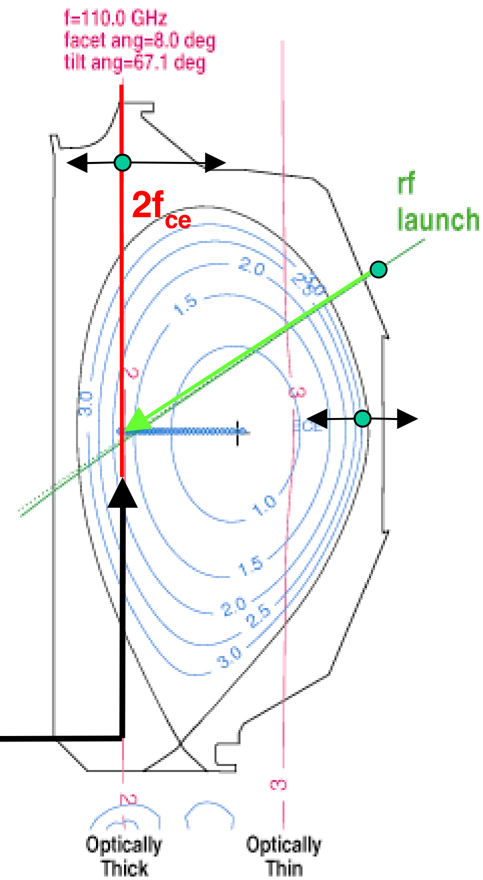

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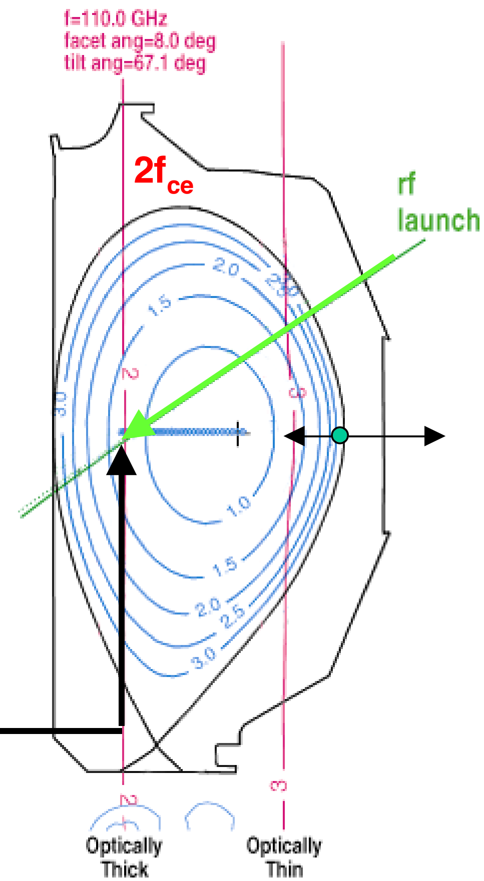

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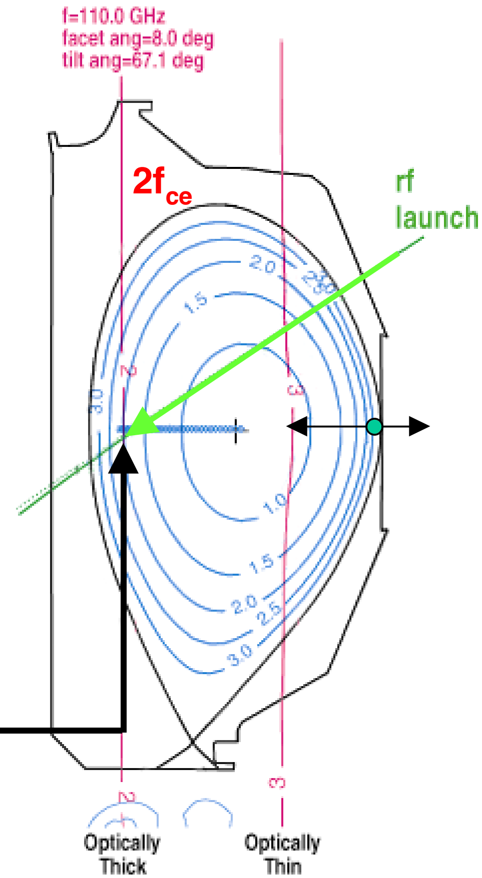

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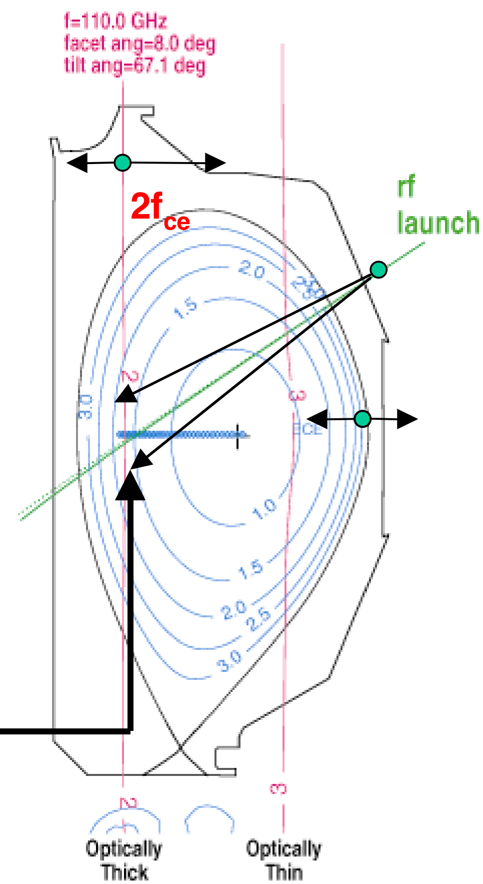

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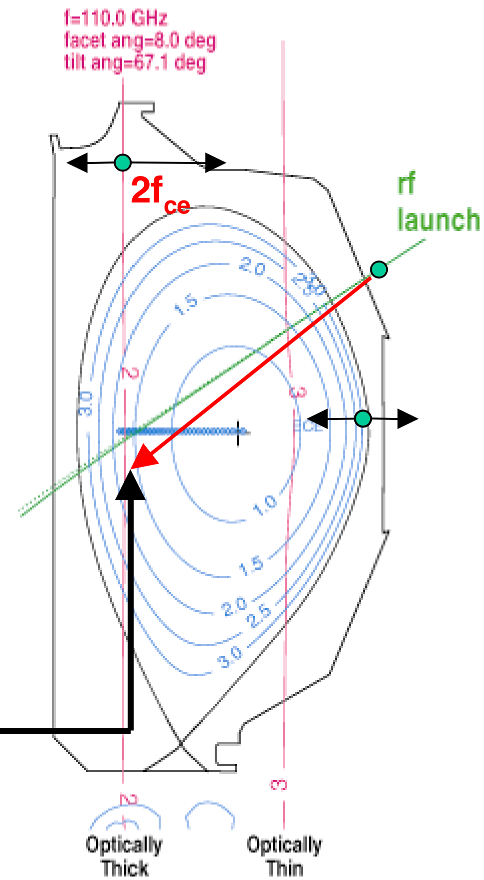
Hitting the Islands with ECCD

The absent current can be restored by ECCD, but the current must be driven exactly at the island. How can you hit the islands exactly?



Power is absorbed at the intersection Of the rf beam and the $2f_{ce}$ resonance

The ECCD can be placed at the island location by:

- Changing B_T
- Moving the plasma
- **Changing the injection angle**

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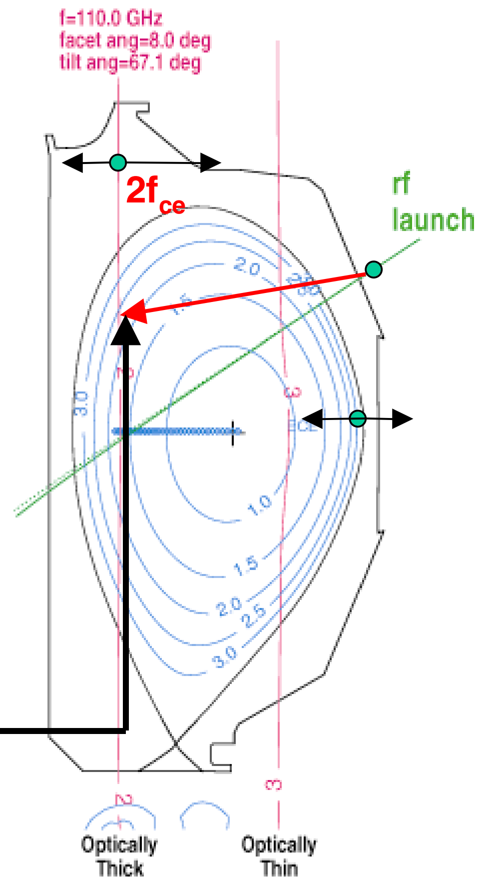

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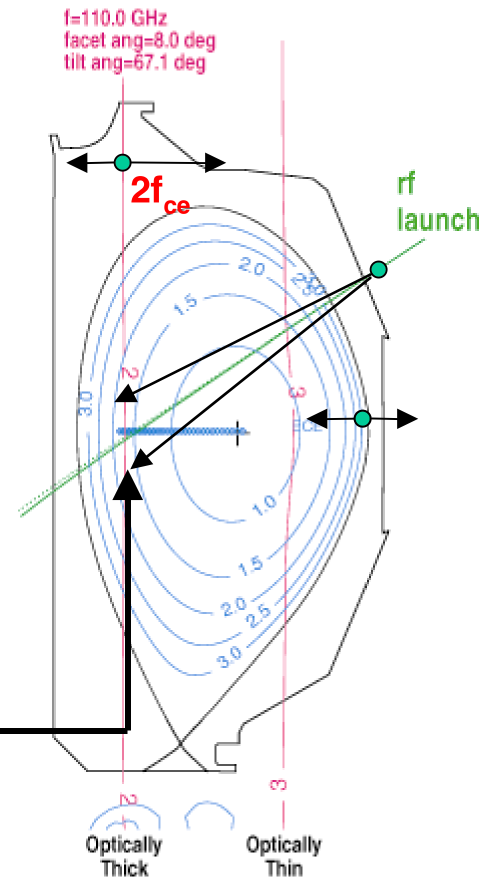

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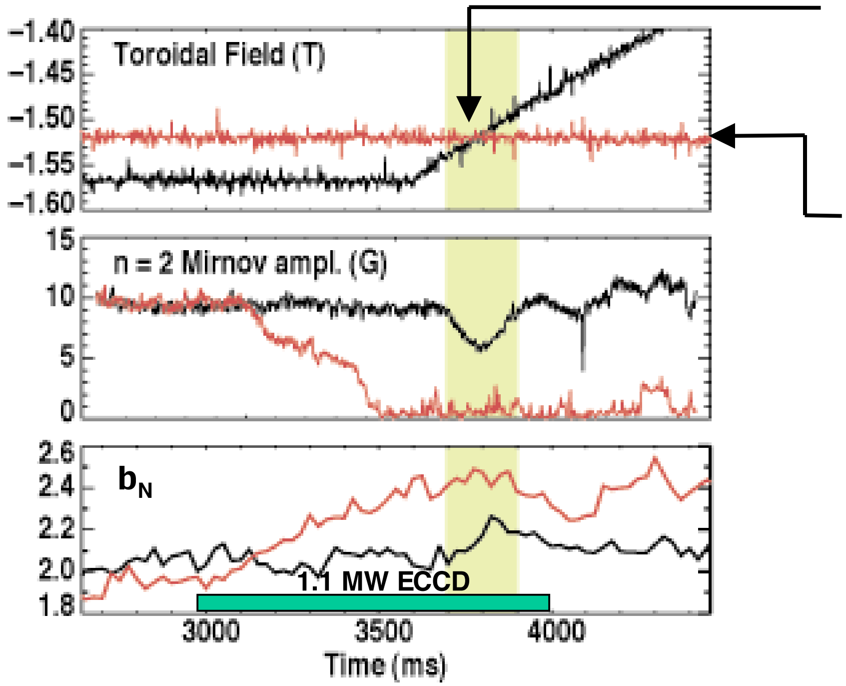
NTM Stabilization: Varying Tokamak B_T Varies ECCD Location



For this B_T the NTM begins to die during B_T sweep

When B_T is constant at the proper value, as determined by the B_T sweep, the mode is completely eliminated

When the mode is eliminated, plasma pressure increases

Two shots…one with B_T sweep, one with constant B_T

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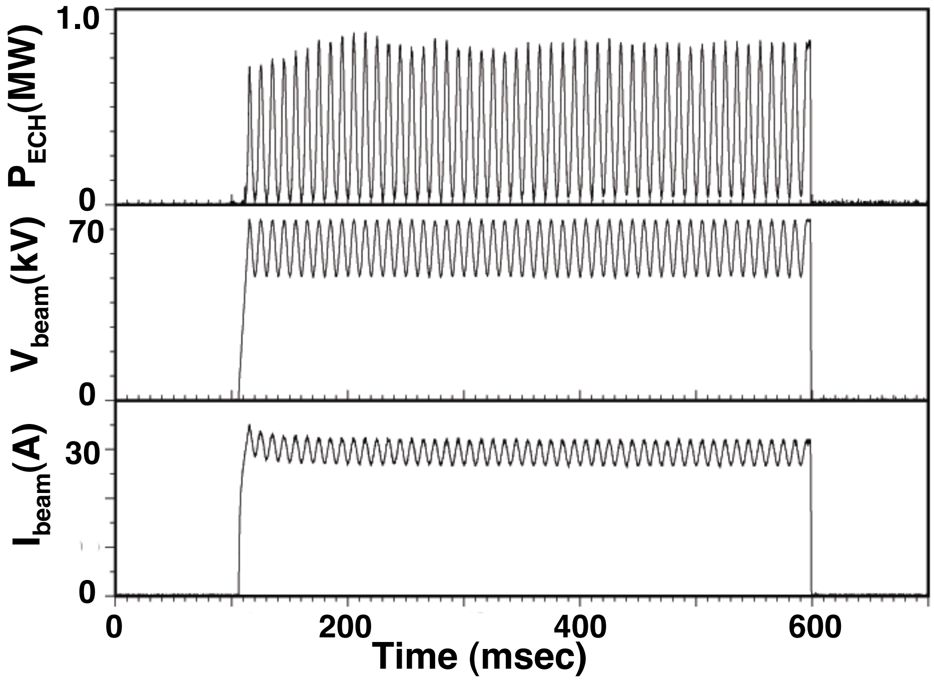
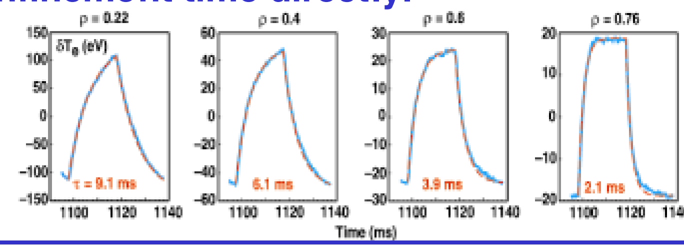
Modulating and Controlling the ECH Power

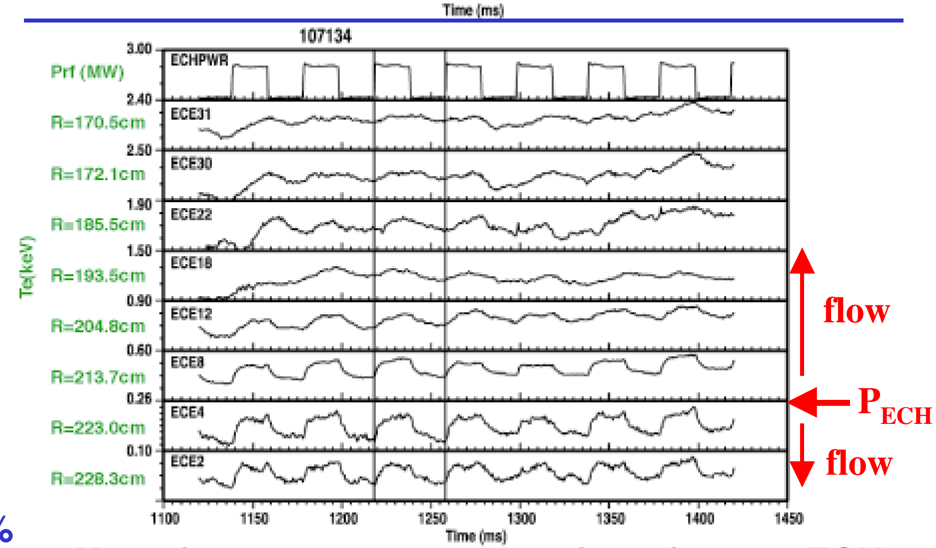
Output Power Modulation



Sinusoidal modulation of a single gyrotron. A 30% decrease in the beam energy yields a 20% decrease in the beam current and a 100% modulation depth. Modulation at up to 10 kHz has been demonstrated.

The shape of the time response of T_e at the location of the ECH power deposition gives the local incremental electron energy confinement time directly.





Use of square wave modulation of all the ECH gyrotrons to study deposition profiles and energy transport in the electron channel

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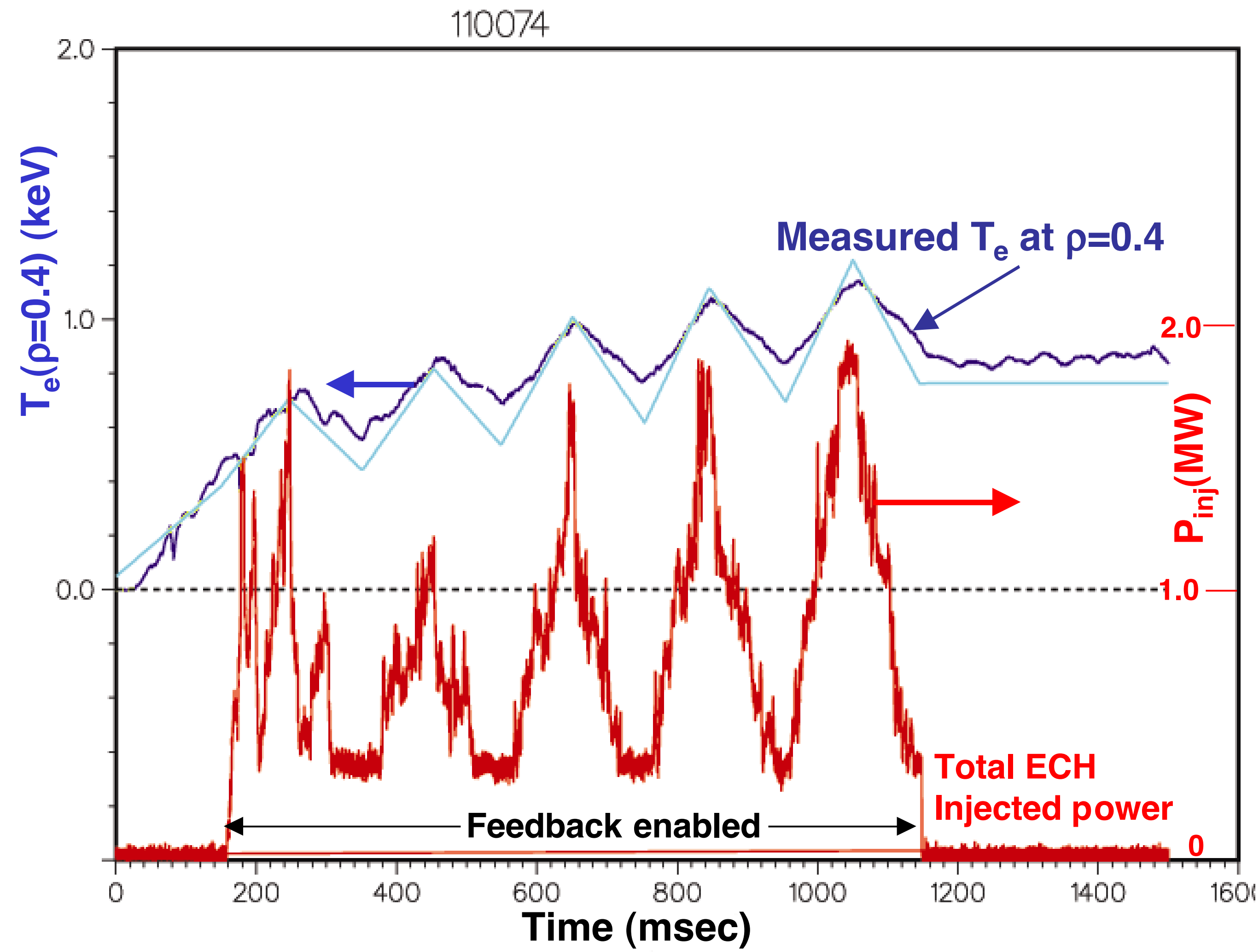
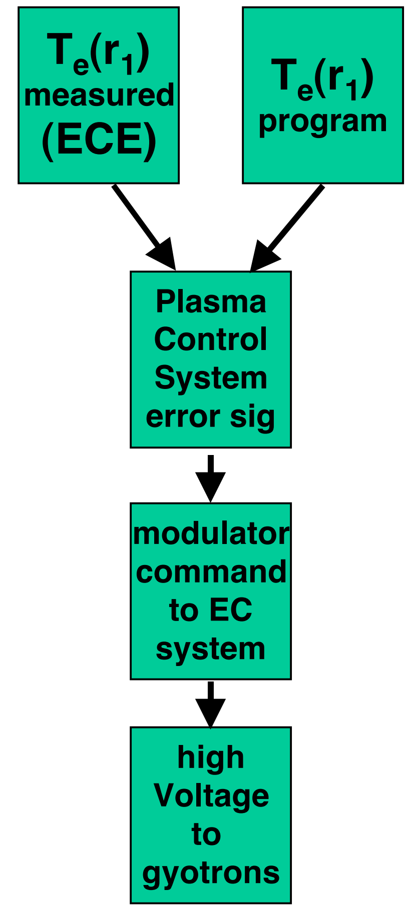
Feedback Control of ECH Power





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Summary

- ECH is a reliable tool for magnetic fusion research
- High power millimeter sources and components have been developed
- Physics of ECH/ECCD is understood
- A unique new group of experiments is being explored
  - control of MHD instabilities
  - transport studies
  - profile control
  - advanced tokamak operation
- Future plans for the DIII-D installation
  - 3 new gyrotrons 110 GHz, 1 MW, 10 sec pulse length
  - 8 gyrotrons operating from 4 flexible launchers
  - ~5 MW injected rf power by 2005